6th Summer School on INtelligent signal processing for FrontIEr Research&Industry

Quantum Technologies for Fundamental Physics

The Science & The Quantum Technologies Landscape

Thanks to: Mina Arvanitaki, Themis Bowcock, Chip Brock, Oliver Buchmueller, Nathaniel Craig, Marcel Demarteau,
Savas Dimopoulos, Michael Doser, Gerry Gabrielse, Andrew Geraci, Peter Graham, Joanne Hewett, Rafael Lang,
David Hume, Jason Hogan,
John March-Russell, Hitoshi Murayama, Marianna Safronova,
Alex Sushkov, Chris Tully, Stafford Withington
& the UK Quantum Technologies for Fundamental Physics Program

Questions- please email Ian.Shipsey@physics.ox.ac.uk

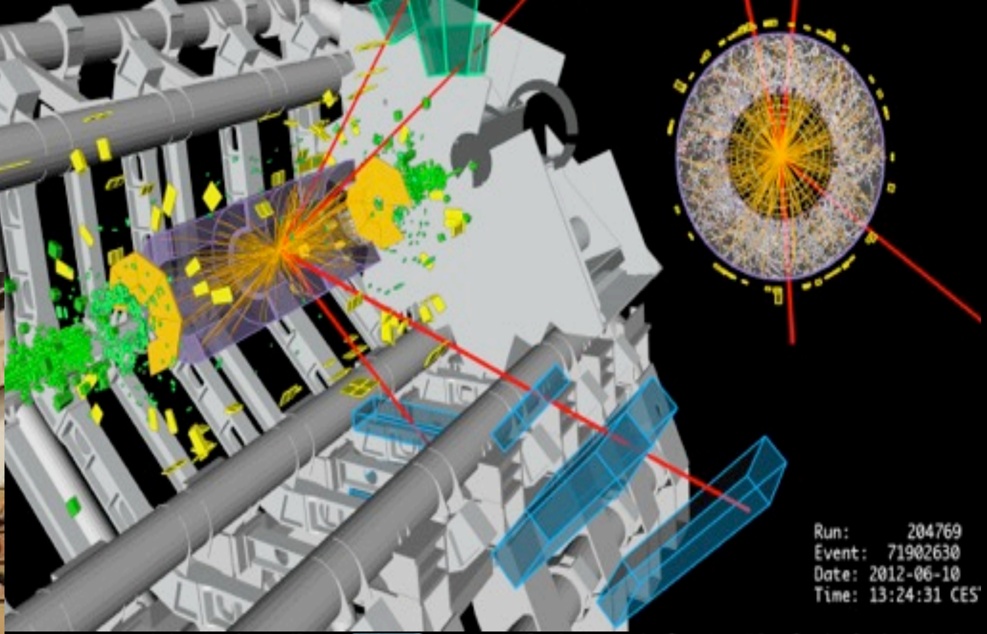
Ian Shipsey

Outline

- The Science
- The Technologies

2012.7.4

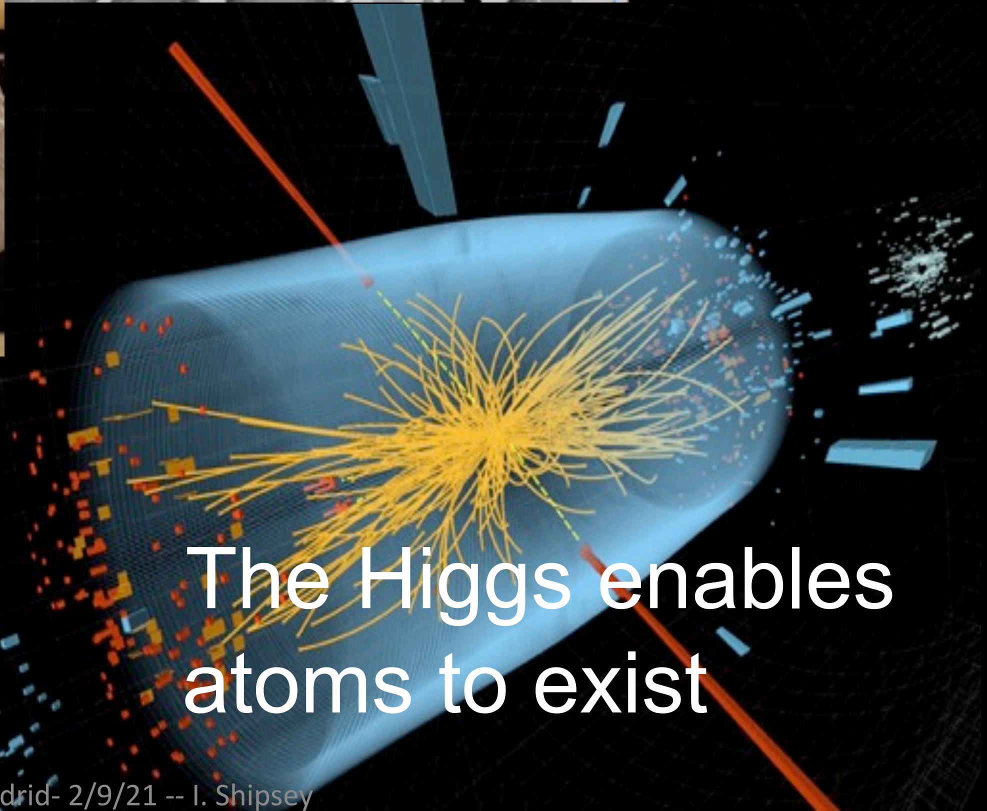
discovery of Higgs boson



theory : 1964

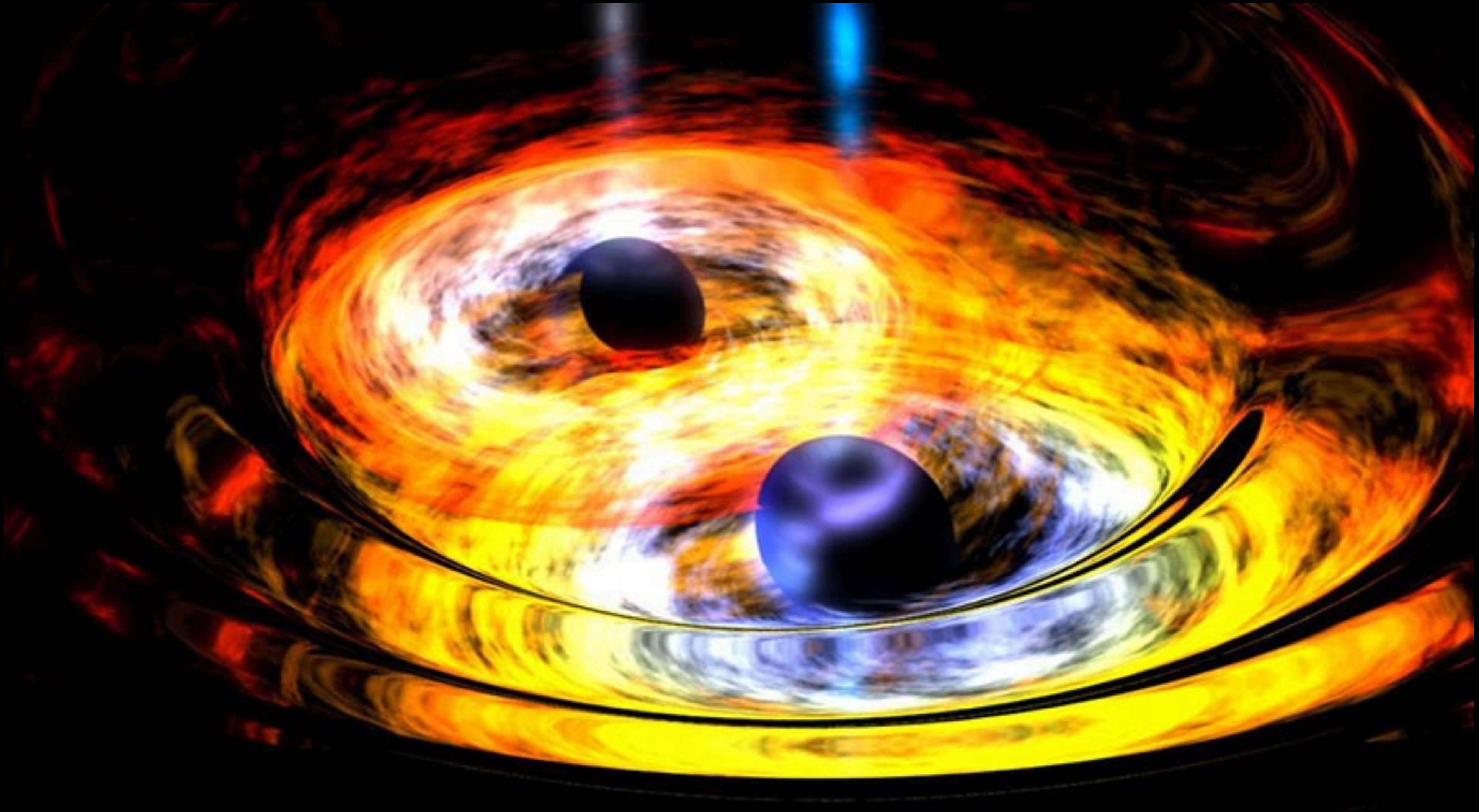
design : 1984

construction : 1998

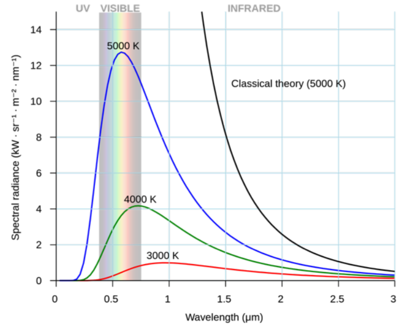


The Higgs enables atoms to exist

Detection of gravitational waves
LIGO February, 2016



Quantum 1.0



Blackbody Radiation

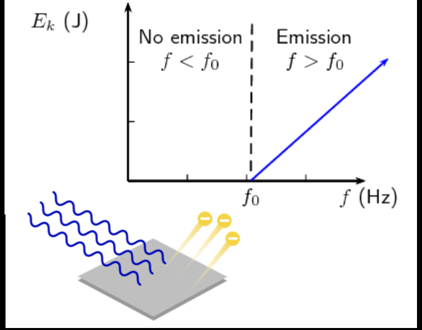
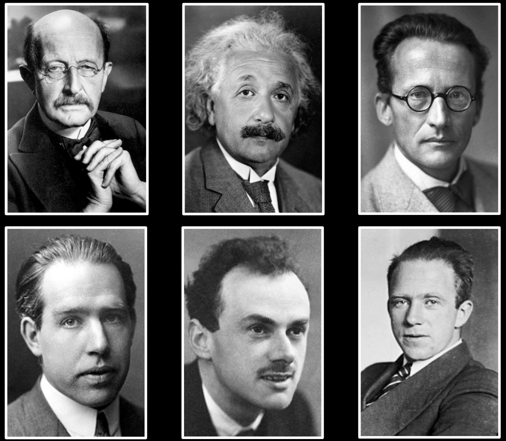


Photo-electric Effect

Quantum Mechanics



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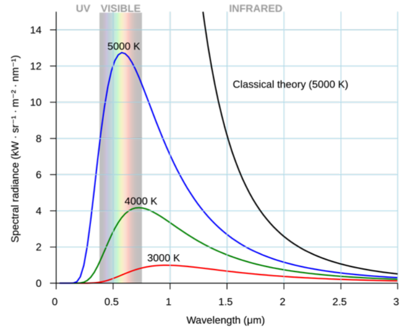

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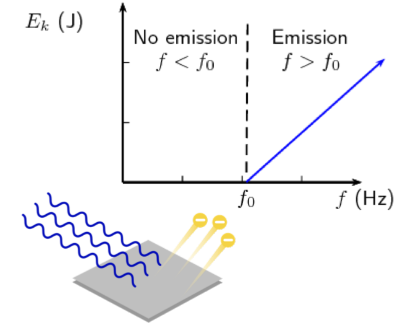

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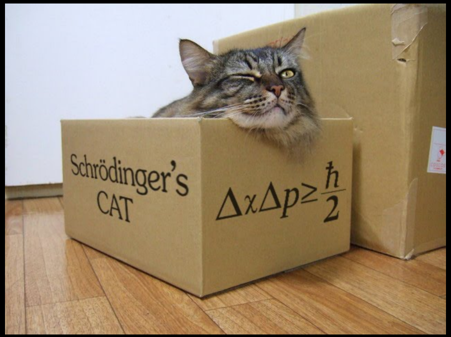
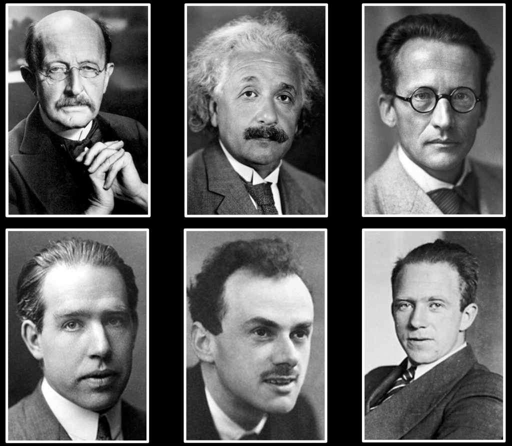


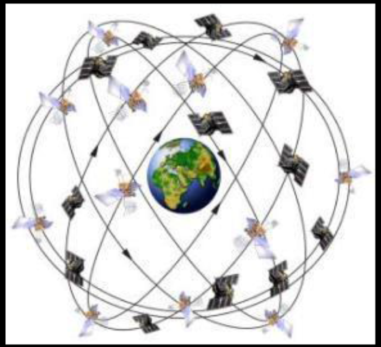
Quantum Mechanics



Exascale Computing

Laser Technology

Magnetic Resonance Imaging

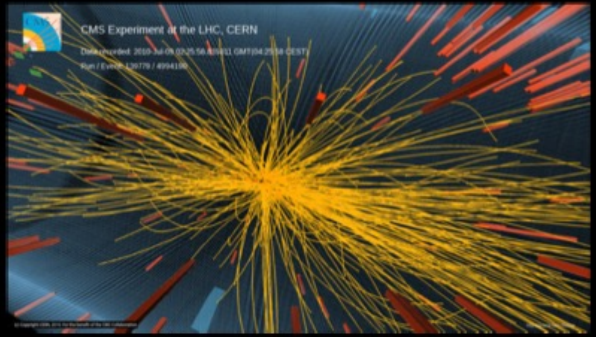


Global Positioning System

Quantum 2.0

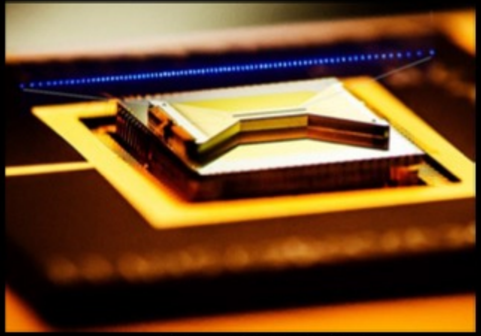
The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

AI, ML on Quantum annealer



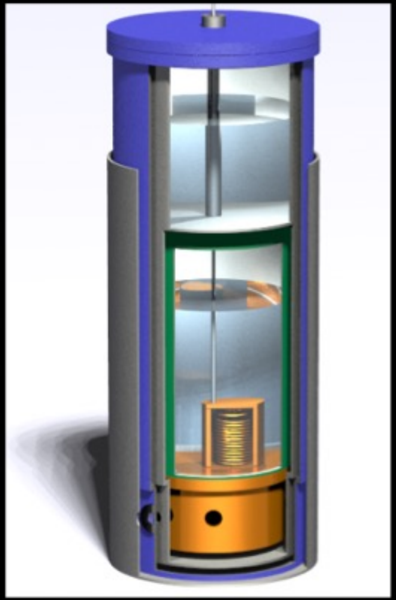
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

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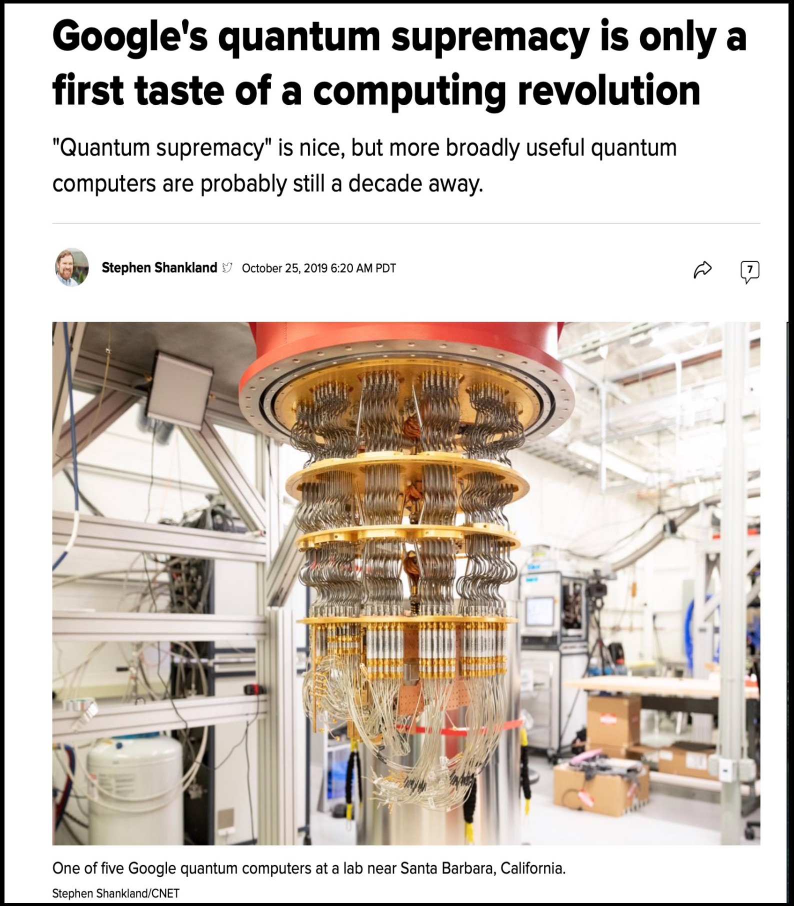


Google's quantum supremacy is only a first taste of a computing revolution

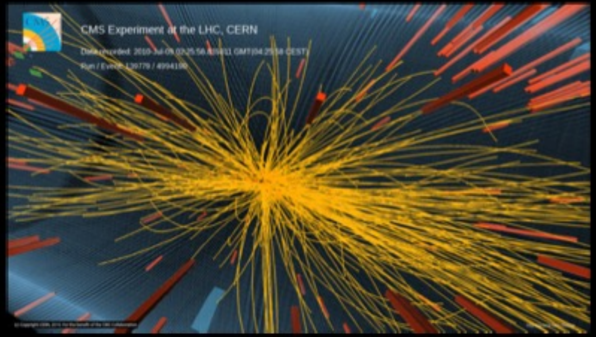
"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

Stephen Shankland October 25, 2019 6:20 AM PDT

One of five Google quantum computers at a lab near Santa Barbara, California.

Stephen Shankland/CNET

AI, ML on Quantum annealer



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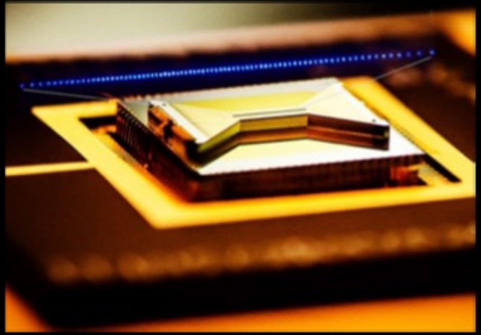

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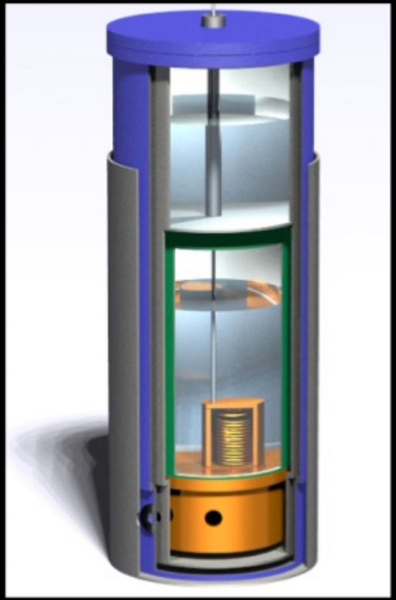


Nature (564) 87 (2018)

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical," Feynmann (1981).

You can approximate nature with a simulation on a classical computer, but Feynman wanted a quantum computer that offers the real thing, a computer that "will do exactly the same as nature,"

What if?

Quantum Internet

Quantum Artificial Neural Network

Quantum Liquid Crystals

Quantum Mind Interface

Quantum enabled searches for dark matter

Quantum Gravity

Which quantum technologies are likely to lead to disruptive discoveries in fundamental physics in the next 10-20 years?

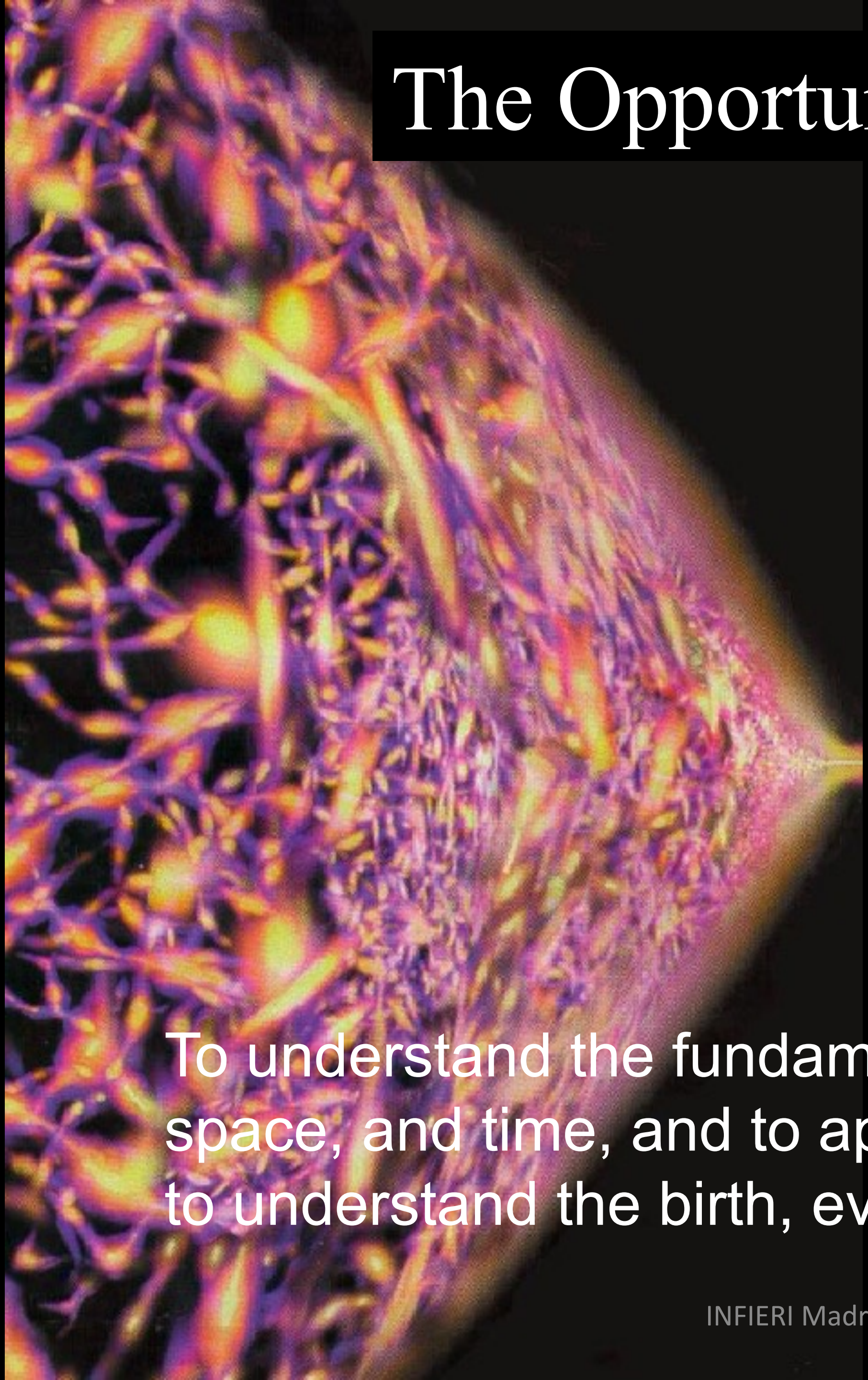
How do we define “quantum technology” and “quantum sensor”?

A technology or device that is naturally described by quantum mechanics is considered ``quantum''.

Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***.

Quantum Technology and the Elephants
Quantum Science and Technology Editorial
Marianna Safronova & Dmitry Budker

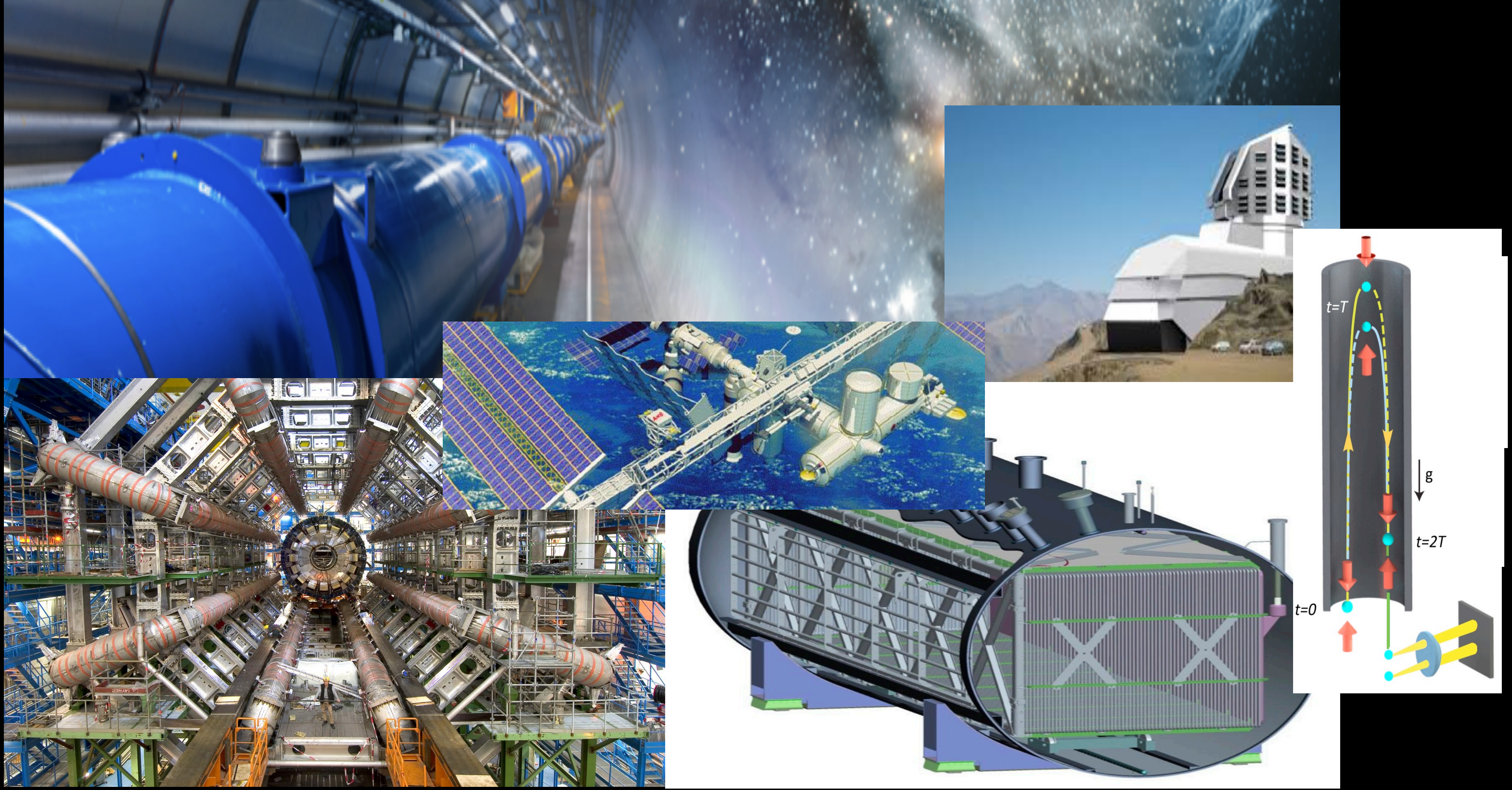
The Opportunities for Discovery



To understand the fundamental nature of energy, matter, space, and time, and to apply that knowledge
to understand the birth, evolution and fate of the universe

The Opportunities for Discovery

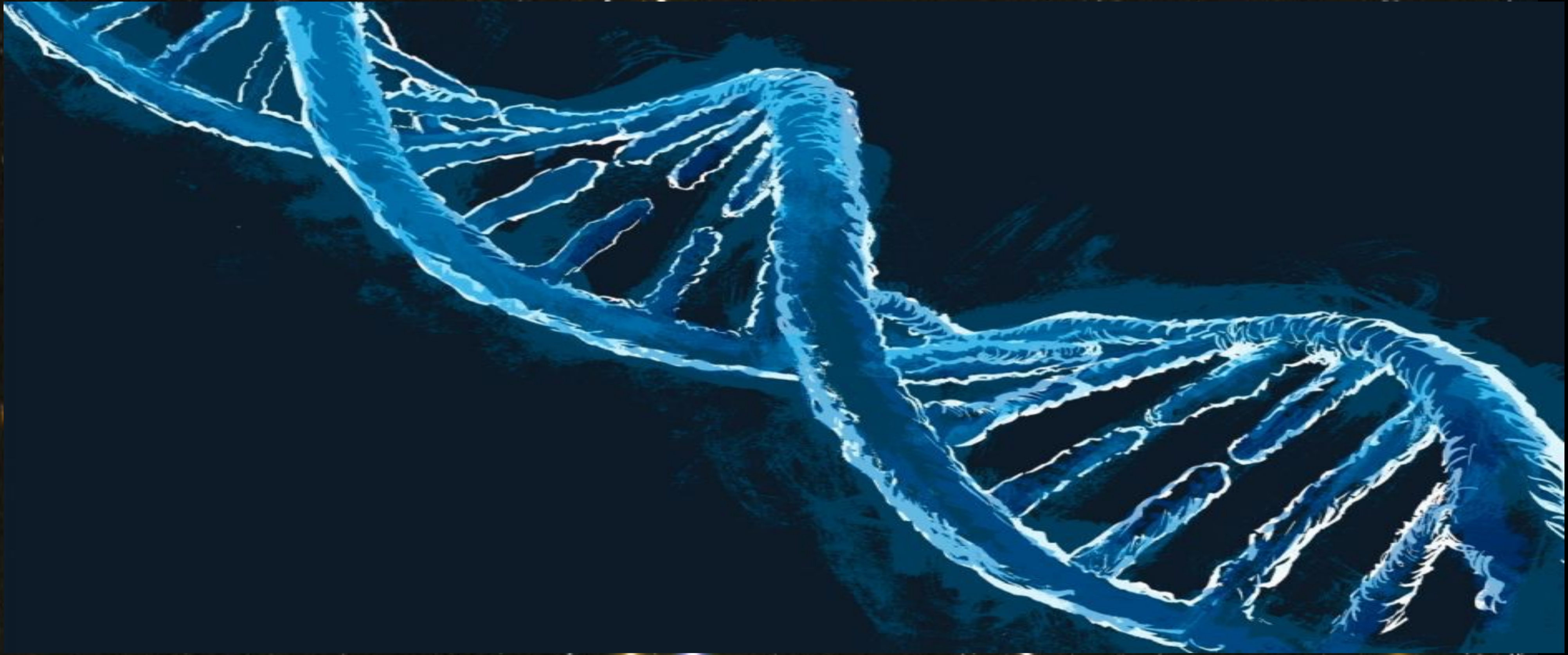
To understand the fundamental nature of energy, matter, space, and time, and to apply that knowledge
to understand the birth, evolution and fate of the universe



Our scope is broad and we use many tools: accelerator, non-accelerator & cosmological observations all have a critical role to play

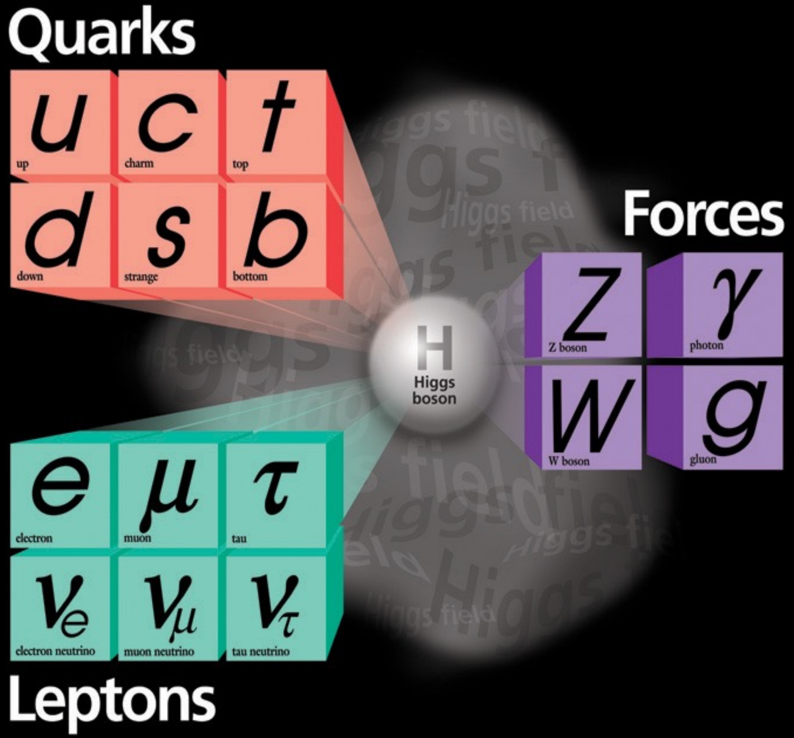
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Our community has revolutionized human understanding of the Universe – its underlying code, structure and evolution

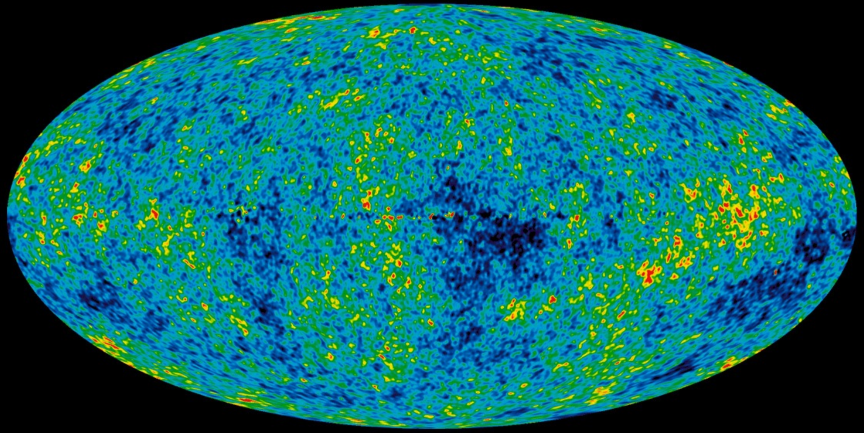


BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Particle Standard Model



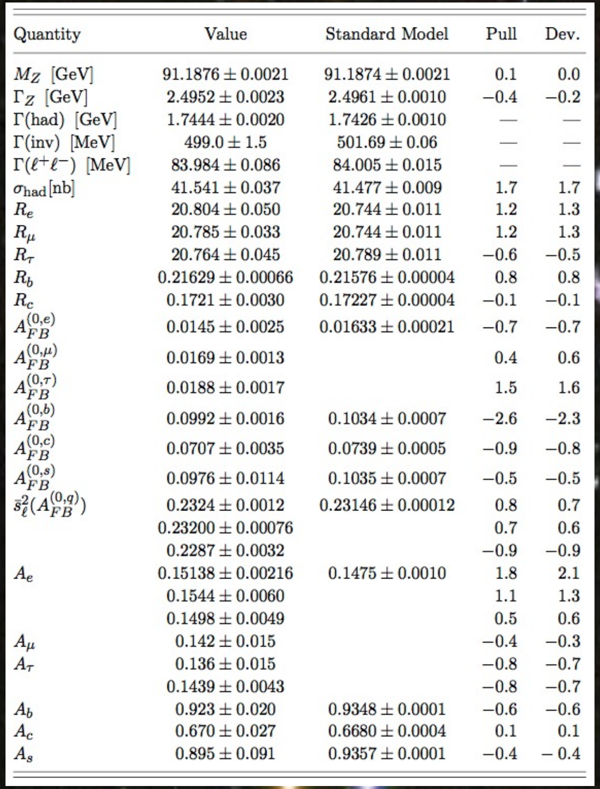
Cosmology Standard Model



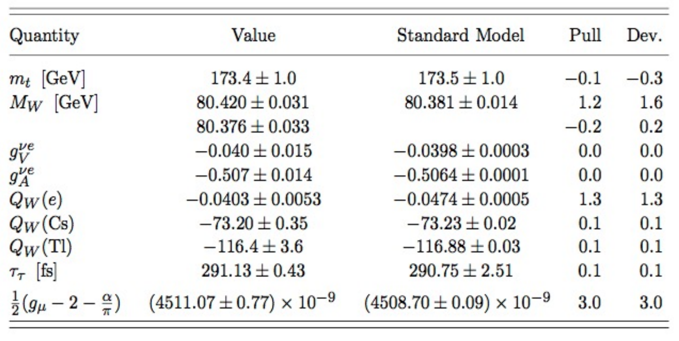
Λ_{CDM}

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

…..that are highly predictive and have been rigorously tested in some cases to 1 part in 10E12



Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0010	−0.4	−0.2
$\Gamma(\mathrm{had})$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
$\Gamma(\mathrm{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had}[nb]	41.541 ± 0.037	41.477 ± 0.009	1.7	1.7
R_e	20.804 ± 0.050	20.744 ± 0.011	1.2	1.3
R_μ	20.785 ± 0.033	20.744 ± 0.011	1.2	1.3
R_τ	20.764 ± 0.045	20.789 ± 0.011	−0.6	−0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.0030	0.17227 ± 0.00004	−0.1	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.6	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	−0.5	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.23200 ± 0.00076		0.7	0.6
	0.2287 ± 0.0032		−0.9	−0.9
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.1
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		−0.4	−0.3
A_τ	0.136 ± 0.015		−0.8	−0.7
	0.1439 ± 0.0043		−0.8	−0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	− 0.4



Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	−0.1	−0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		−0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

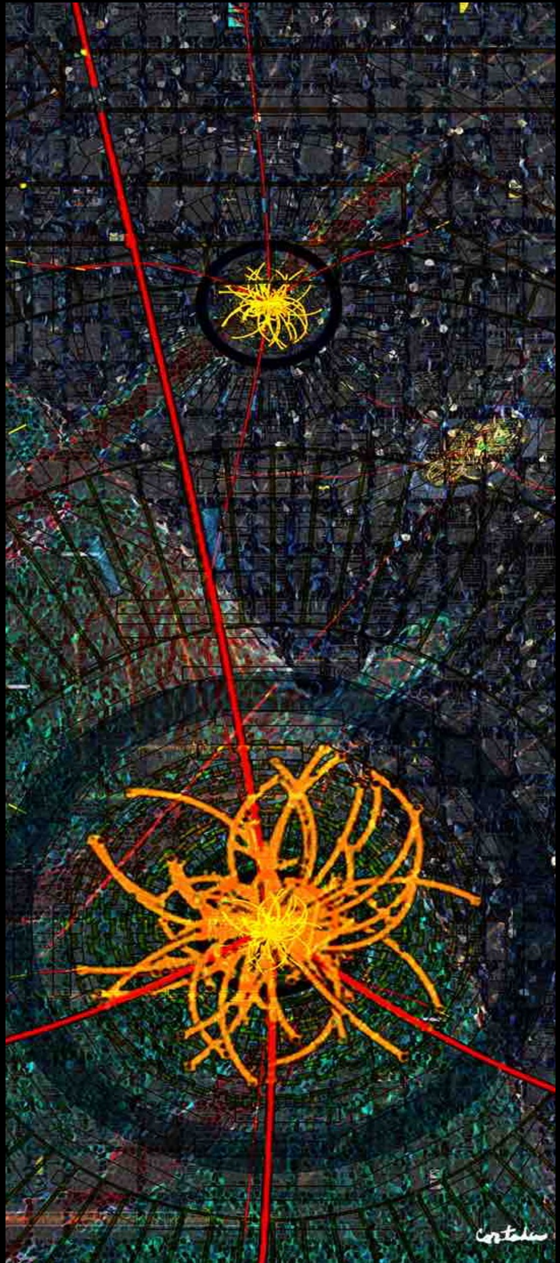
NASA, ESA/JPL-Caltech/B Mobasher (STScI/ESA) gh Energy Physics 2.0

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

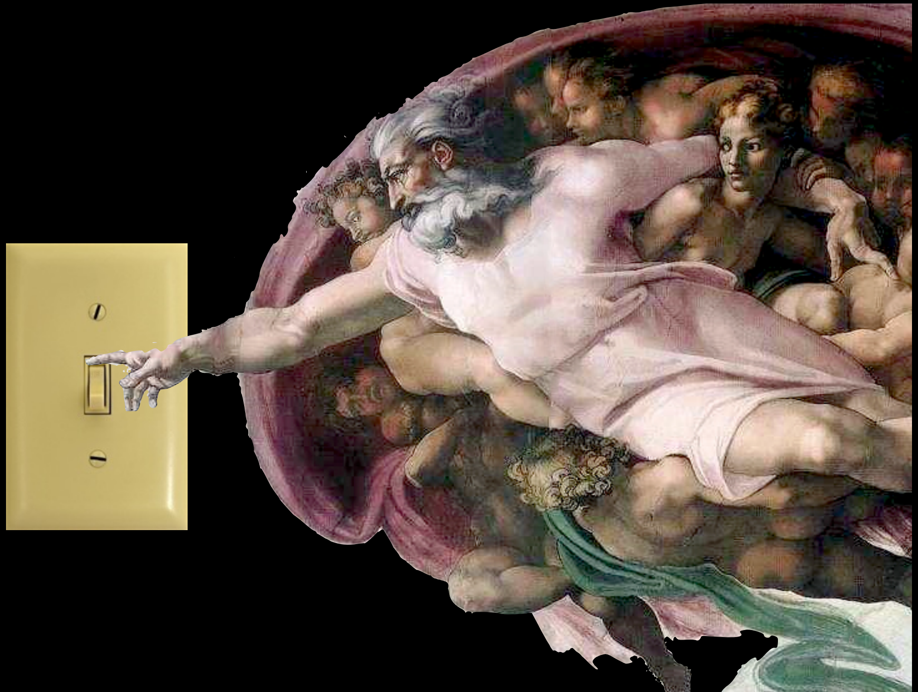
- The potential exists now to revolutionize our knowledge again.
- Despite the huge successes, there are deep and fundamental mysteries that are unanswered and for which following traditional methods of exploration and new methods combine to form the optimal approach.

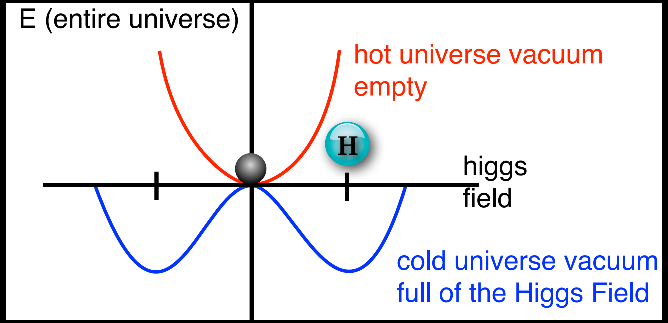
NASA, ESA, JPL-Caltech/B. Mobasher (STScI/ESA)

Mystery: The Higgs



That Spin 0 Boson Changes Everything

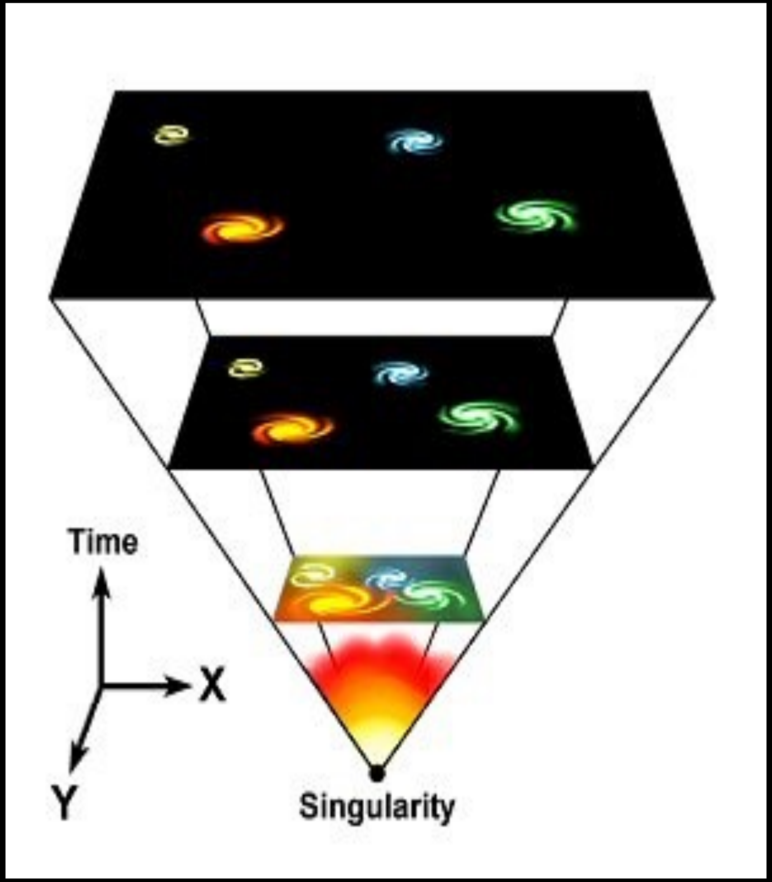


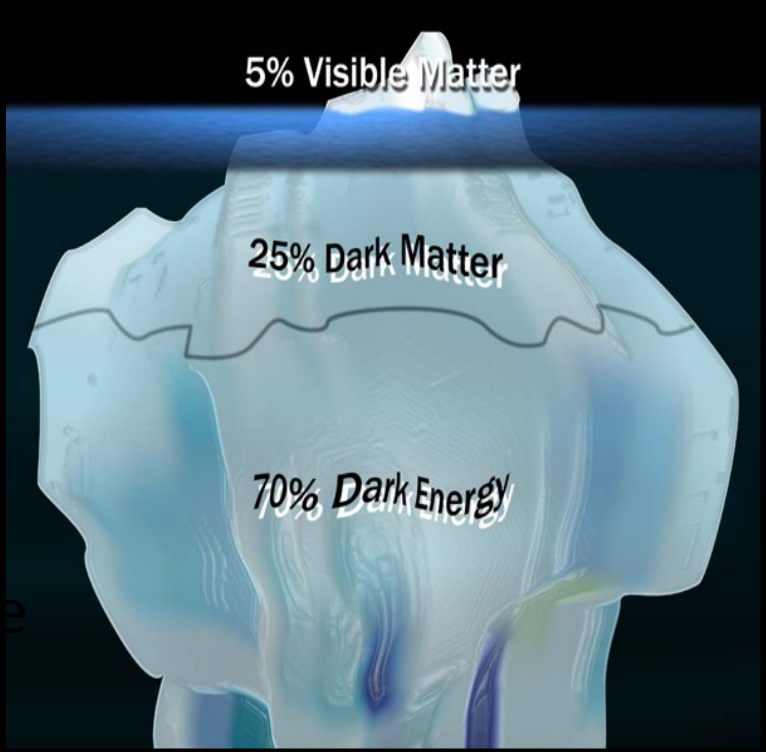


Mystery: Dark Matter

5/6

Mystery: Dark Energy





What we know: just the tip of the iceberg.

Mystery: how did matter survive the birth of the universe?

1,000,000,001

Matter

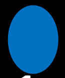
1,000,000,000

anti-Matter

The baryon asymmetry of the Universe

ASA, ESA, JPL-Caltech/B. Mobasher (STScI/ESA)

Mystery: how did matter survive the birth of the universe?



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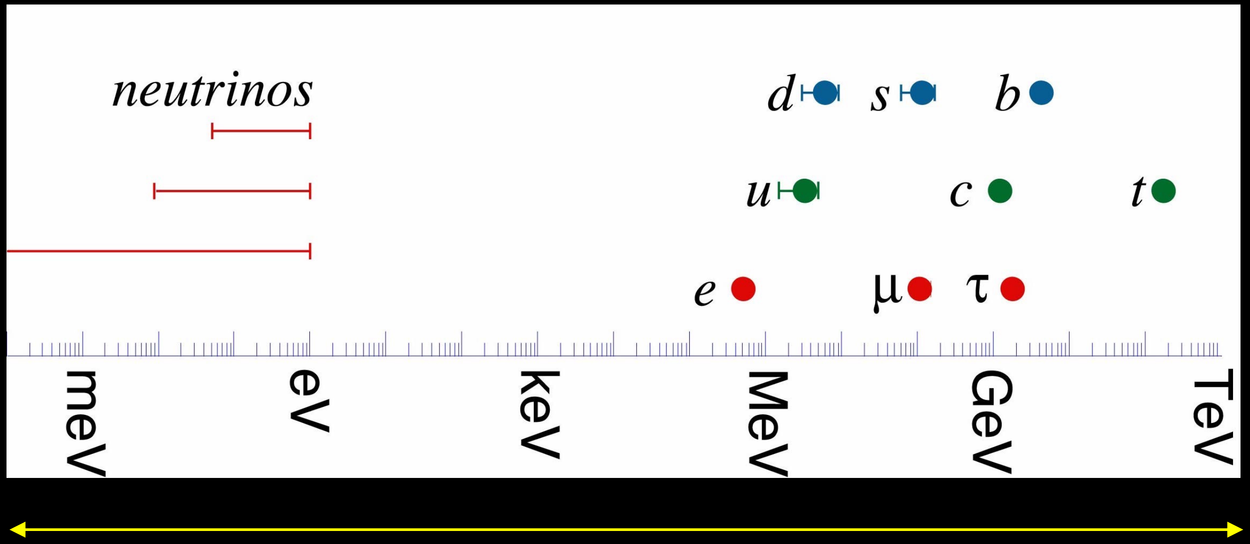
Matter

Anti-Matter

Now

Mystery: Why are there so many types of particles?



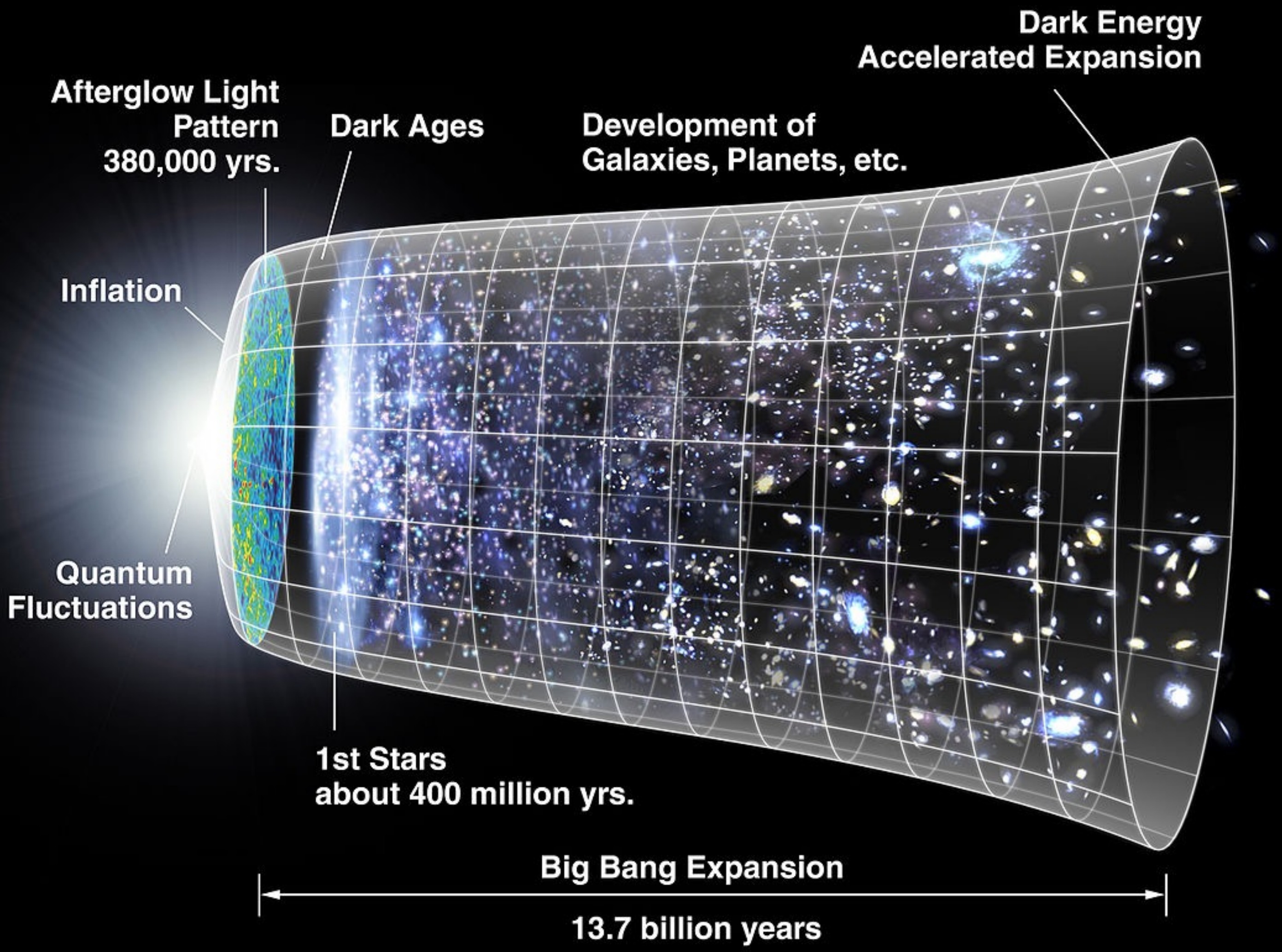
12 orders of magnitude in the masses of fermions

Why do the particles have such a large range of masses?

Why does the pattern of particles repeat three times?

Why do neutrinos have mass at all (in the Standard Model they are massless)?

Mystery: What powered cosmic inflation?



Opportunities for Discovery

Many mysteries to date go unanswered including:

The mystery of the Higgs boson

The mystery of Neutrinos

The mystery of Dark Matter

They mystery of Dark Energy

The mystery of quarks and charged leptons

The mystery of Matter – anti-Matter asymmetry

The mystery of the Hierarchy Problem

The mystery of the Families of Particles

The mystery of Inflation

The mystery of Gravity

Based on an original
slide by F. Gianotti

Outstanding Questions in Particle Physics *circa* 2011

Quarks and leptons:
- ☐ why 3 families ?
- ☐ masses and mixing
- ☐ *CP* violation in the lepton sector
- ☐ matter and antimatter asymmetry
- ☐ baryon and charged lepton number violation

EWSB
- ☐ Does the Higgs boson exist?

Physics at the highest E-scales:
- ☐ how is gravity connected with the other forces ?
- ☐ do forces unify at high energy ?

Dark matter:
- ☐ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ☐ one type or more ?
- ☐ only gravitational or other interactions ?

Neutrinos:
- ☐ ν masses and and their origin
- ☐ what is the role of $H(125)$?
- ☐ Majorana or Dirac ?
- ☐ *CP* violation
- ☐ additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- ☐ primordial: is inflation correct ?
  which (scalar) fields? role of quantum gravity?
- ☐ today: dark energy (why is Λ so small?) or
  gravity modification ?

Based on an original
slide by F. Gianotti

Outstanding Questions in Particle Physics *circa* 2021

… there has never been a better time to be a particle physicist or cosmologist!

Higgs boson and EWSB
☐ m_H natural or fine-tuned ?
→ if natural: what new physics/symmetry?
☐ does it regularize the divergent V_LV_L cross-section at high $M(V_LV_L)$? Or is there a new dynamics ?
☐ elementary or composite Higgs ?
☐ is it alone or are there other Higgs bosons ?
☐ origin of couplings to fermions
☐ coupling to dark matter ?
☐ does it violate CP ?
☐ cosmological EW phase transition

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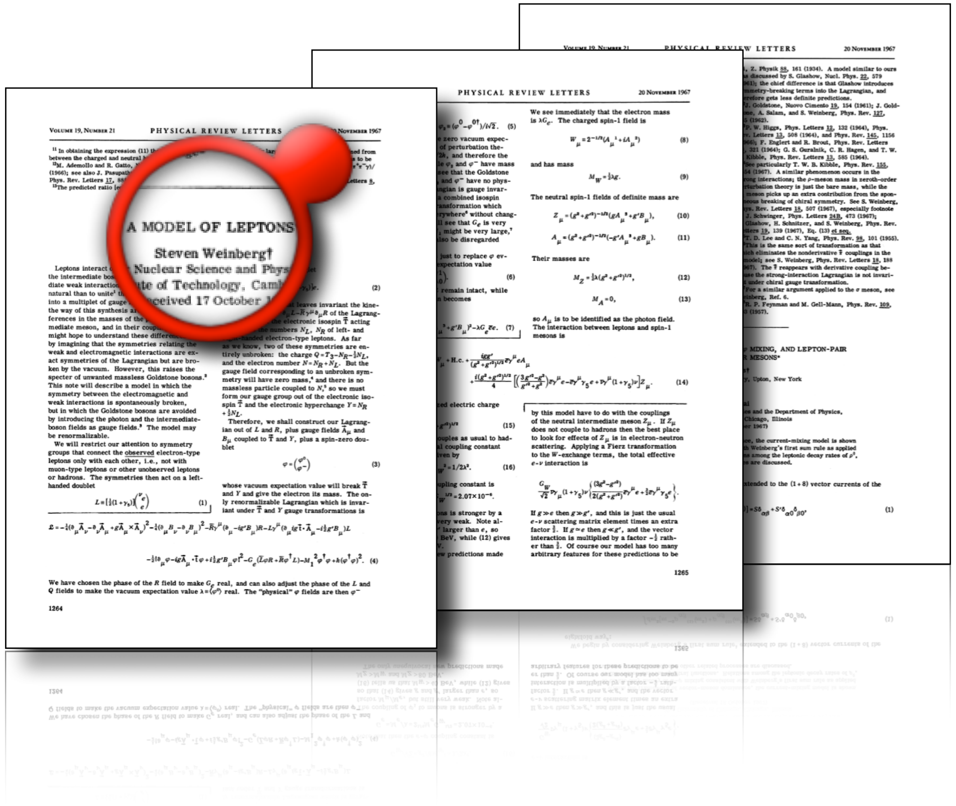
☐ *CP* violation
☐ additional species → sterile ν ?

between **1967 - 2012**



VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

A MODEL OF LEPTONS

Steven Weinberg†

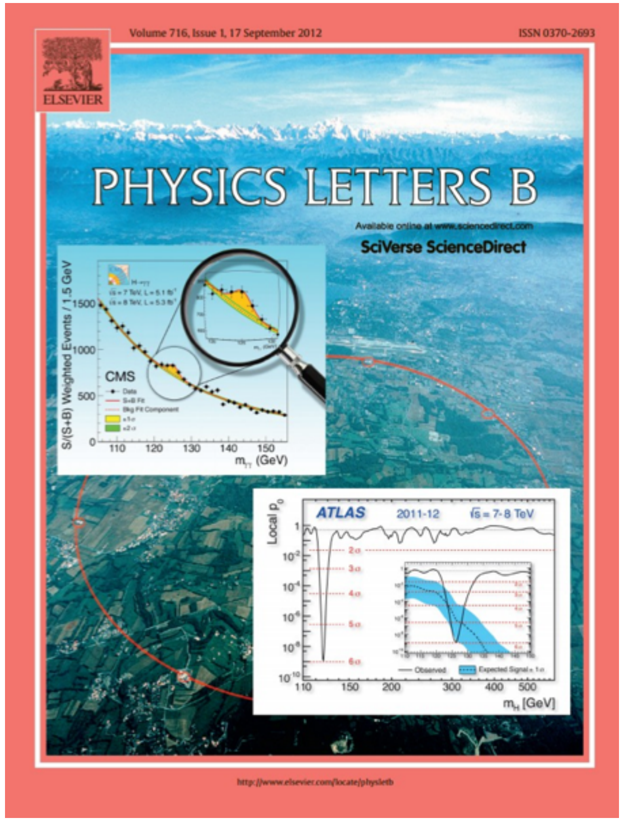
Nuclear Science and Phys

ute of Technology, Camb

ceived 17 October

1264

1265



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The Standard Model Guided Research

No-lose completion of the Standard Model

Guaranteed discoveries

Particle	Accelerator	date
W & Z	CERN SppS	(1983)
Top quark	Fermilab Tevatron	(1995)
Higgs	CERN LHC	(2012)

No-lose completion of the Standard Model

Now that the Standard Model is complete, there are no further no-lose theorems

In principle, the Standard Model could be valid to the Planck scale

No guaranteed discoveries

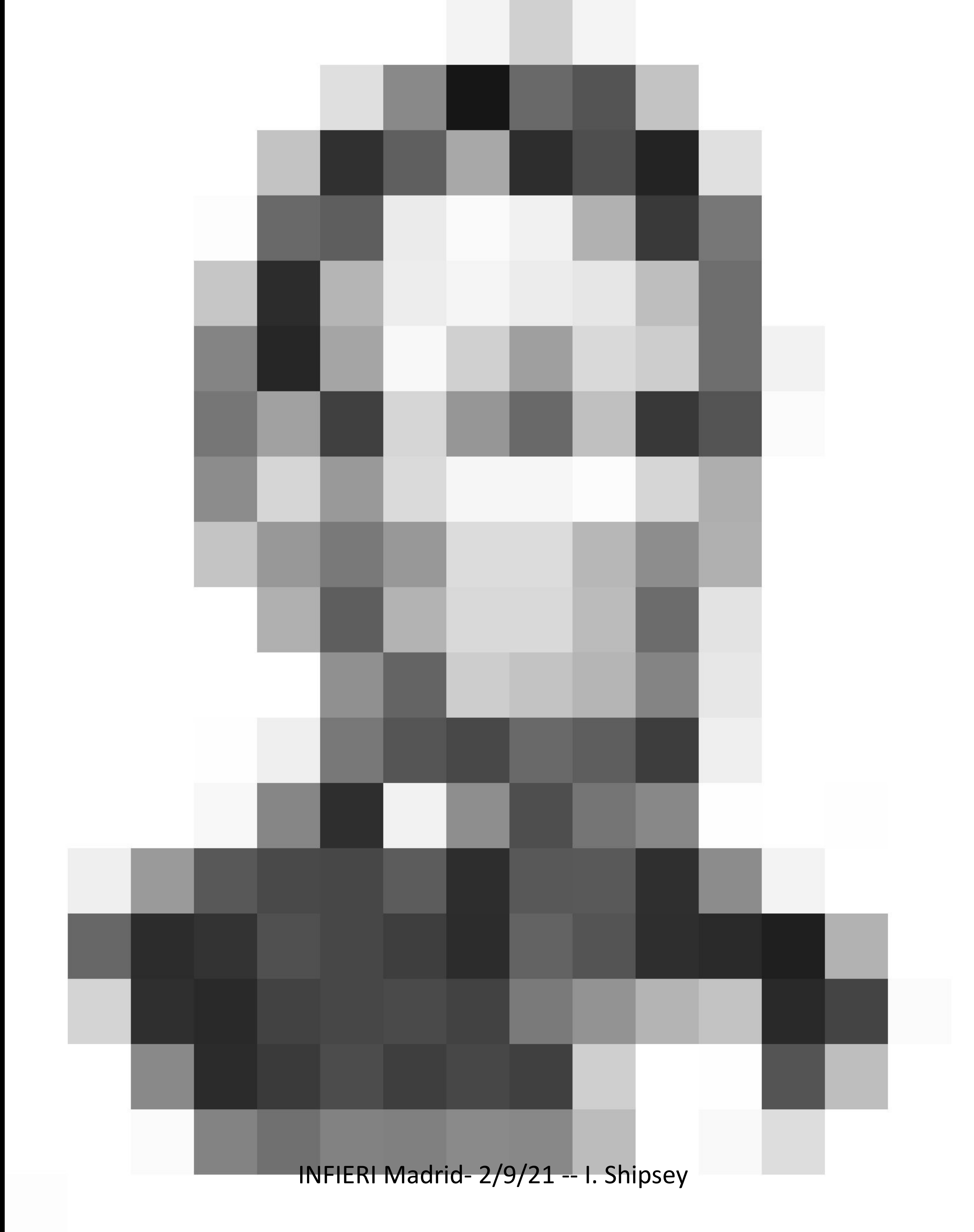
Perception & understanding *with a roadmap*

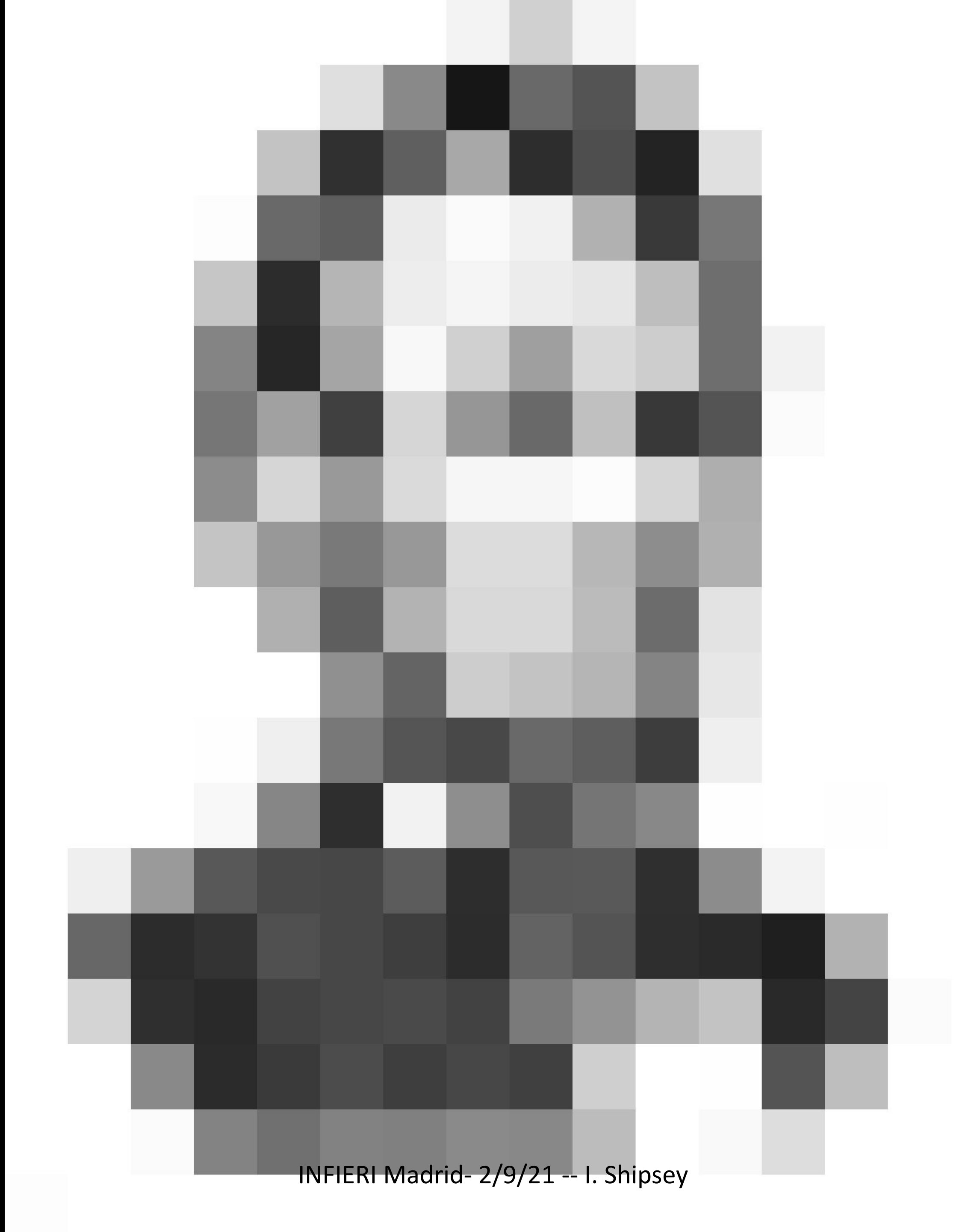
Perception is a dynamic combination of top-down (theory) and bottom-up (data driven) processing

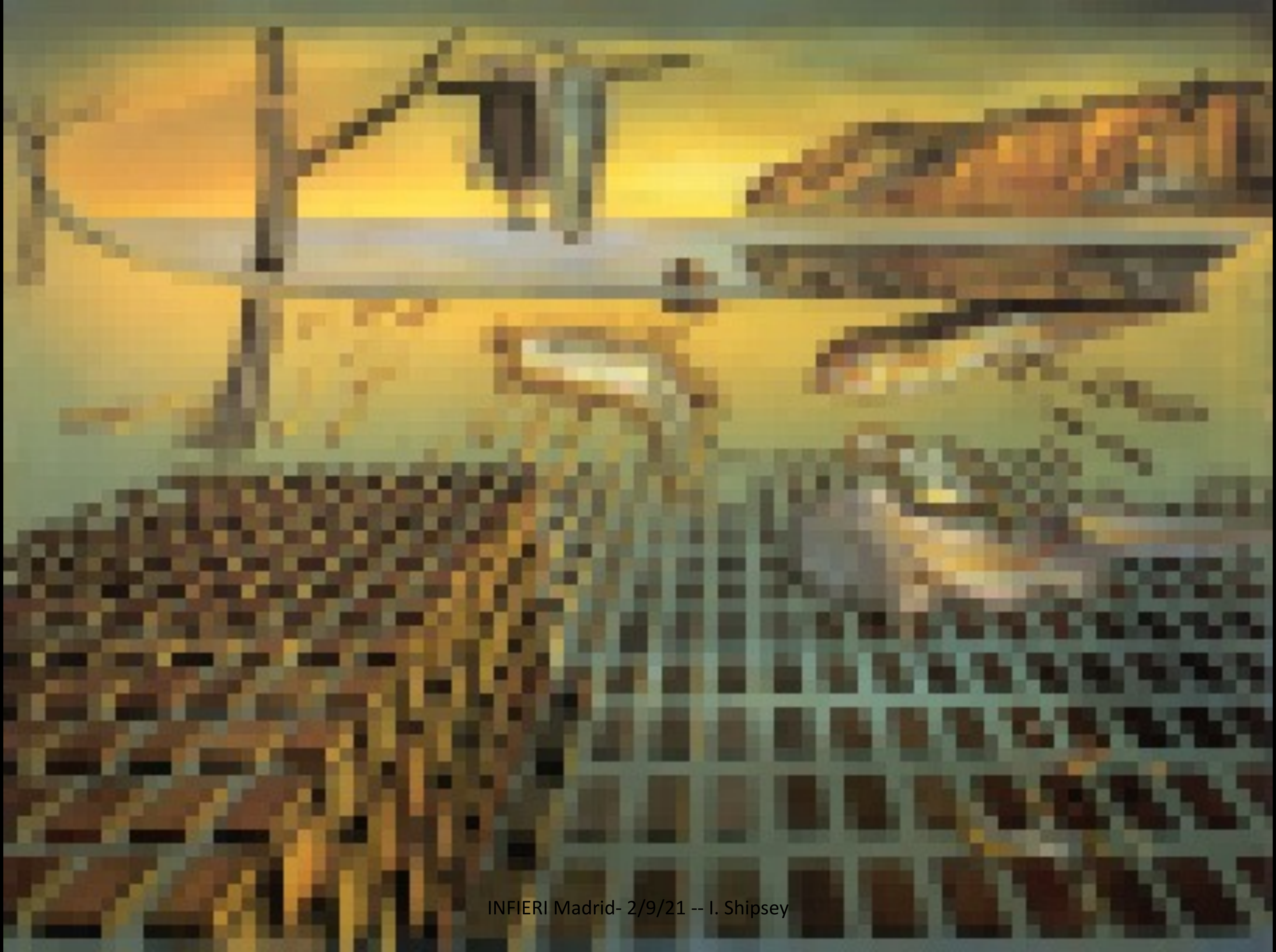
- The need for detail (quality and quantity of the data) depends on the *distinctiveness* of the object and the *level of familiarity*

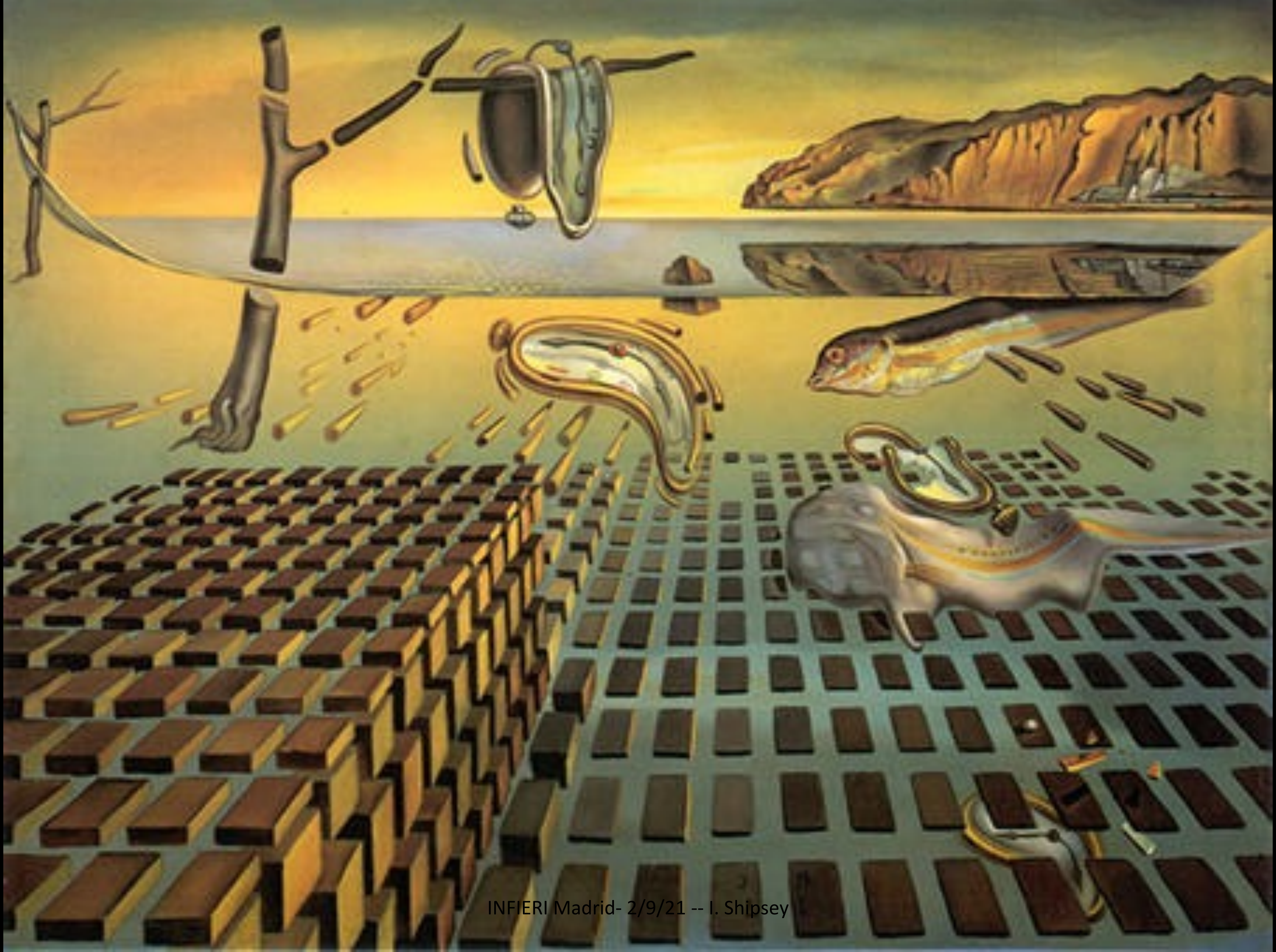
When we know the characteristics and context of what to expect (W,t,H) a little data goes a long way (top-down dominates)

Visual examples…



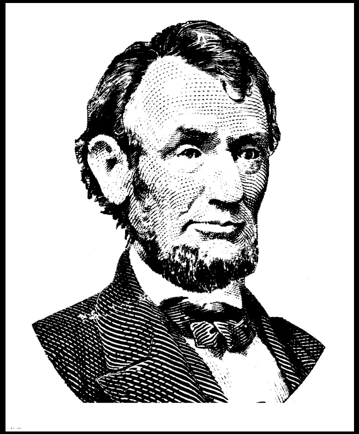






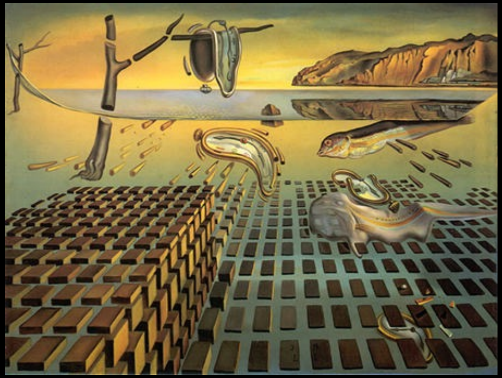
Perception & understanding

With a roadmap (theory)



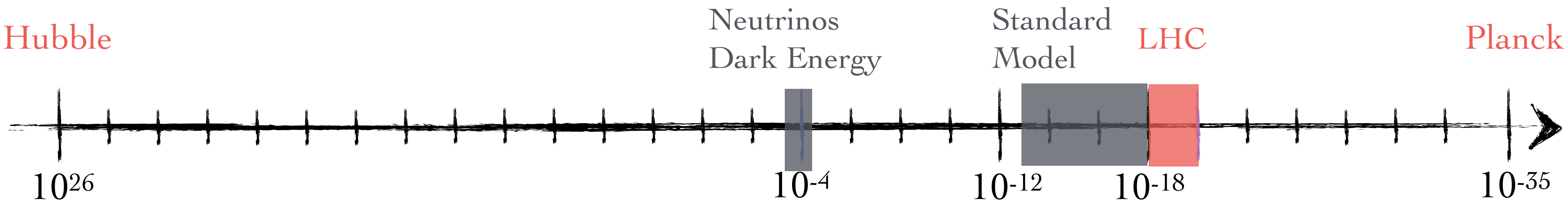
(W,t,H) a little data goes a long way (top-down dominates)

w/o a roadmap (data driven)



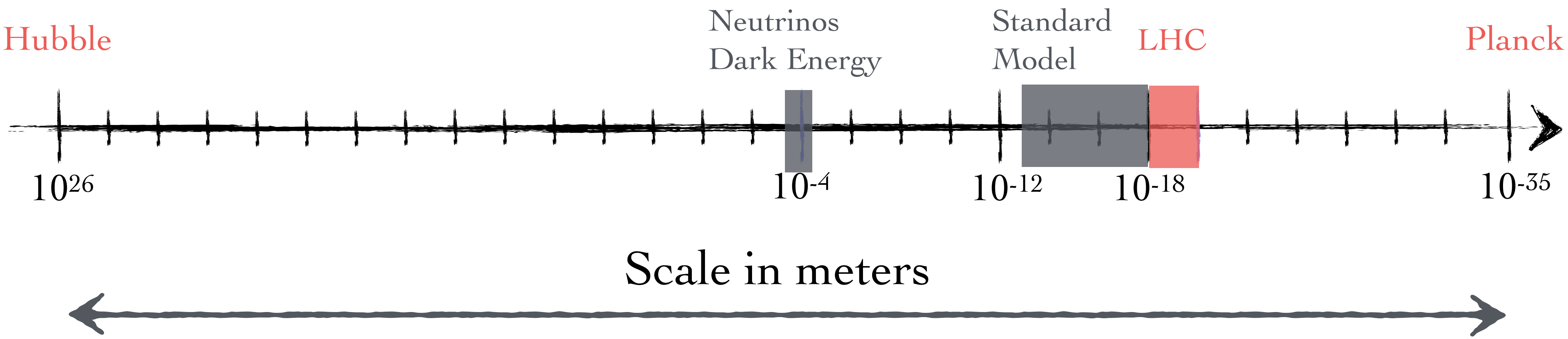
New physics need lots of data
(bottom up dominates)

The Scales in our Universe



Scale in meters

The Scales in our Universe



Hubble

Neutrinos
Dark Energy

Standard
Model

LHC

Planck

10^{26}

10^{-4}

10^{-12}

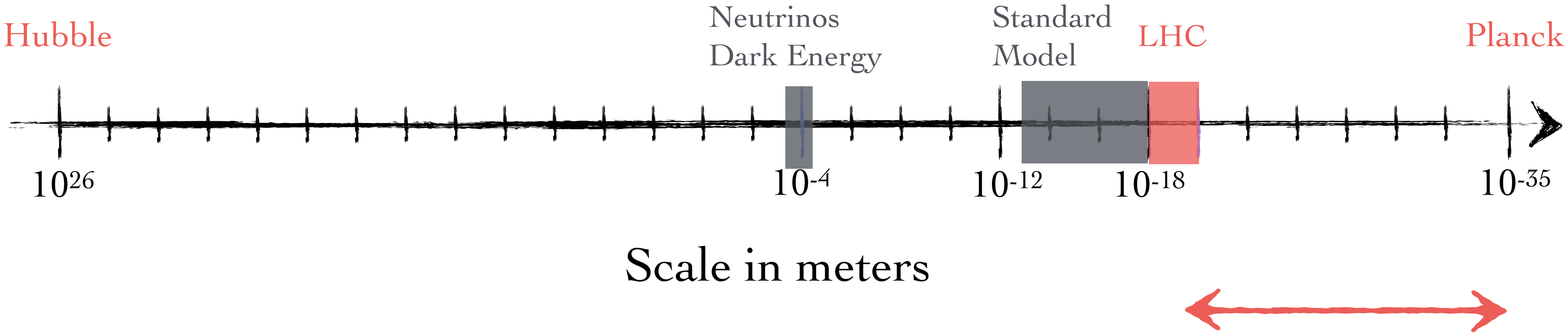
10^{-18}

10^{-35}

Scale in meters

The Cosmological Constant Problem
Why is the Universe so large?

The Scales in our Universe



Scale in meters

The Hierarchy Problem
Why is Gravity so weak?

The Origin of Small Numbers

Small Numbers and Coincidences

Naturalness - Dynamics

Problem	Solution
Hydrogen Binding Energy	$E_b = \frac{1}{2}\frac{e^4}{(4\pi)^2}m_e$
Deuteron Binding Energy Nuclear Binding Energy	$E_b \approx \frac{1}{2}\frac{1}{(4\pi)^2}\frac{m_N}{2}$
π^+ - π^o mass difference	Symmetry/Dynamics
$K - \bar{K}$ mixing	Flavor Symmetry
Electron Mass	Chiral Symmetry

Small Numbers and Coincidences

Something else…

Problem	Solution
Earth-Sun Distance	
7 eV line of ^{229}Th nucleus	
Solar-Lunar Eclipse	
Cosmological Constant	

Small Numbers and Coincidences

Something else…

Problem	Solution
Earth-Sun Distance	Environmental Selection 10^{22} suns
7 eV line of ^{229}Th nucleus	
Solar-Lunar Eclipse	
Cosmological Constant	

Small Numbers and Coincidences

Something else…

Problem	Solution
Earth-Sun Distance	Environmental Selection 10^{22} suns
7 eV line of ^{229}Th nucleus	“Look-elsewhere” effect
Solar-Lunar Eclipse	
Cosmological Constant	

Small Numbers and Coincidences

Something else…

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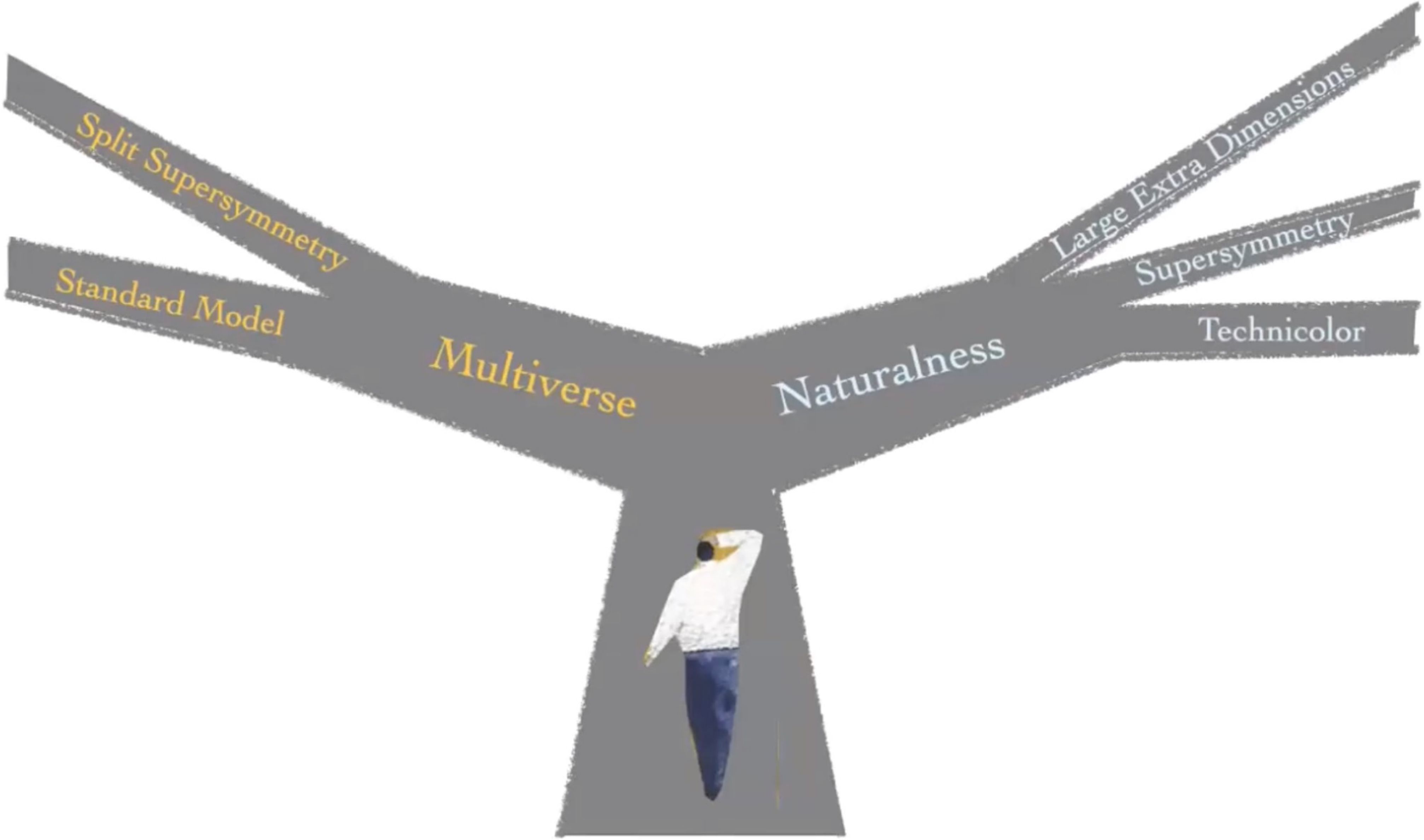
Cosmological Constant	

Small Numbers and Coincidences

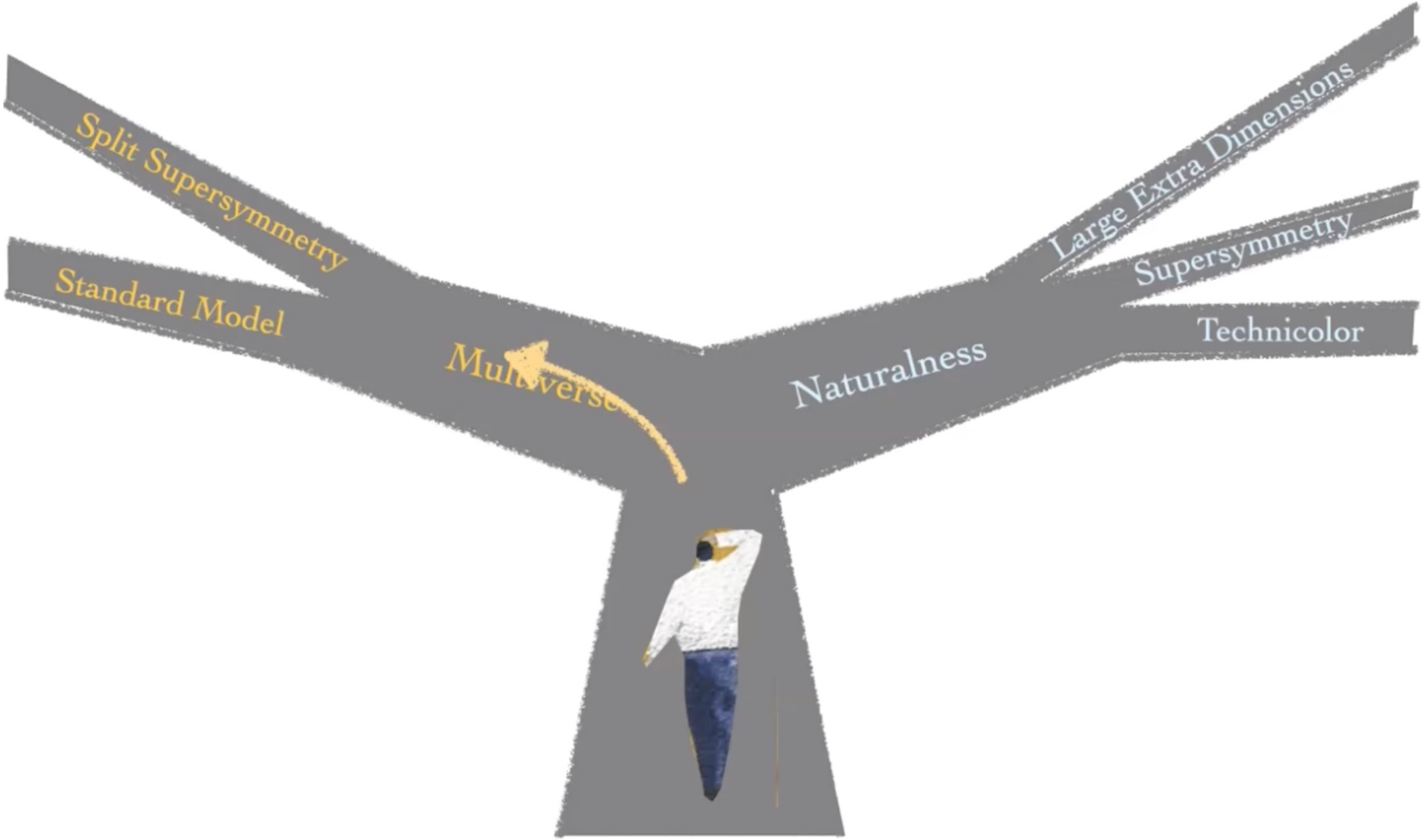
Something else…

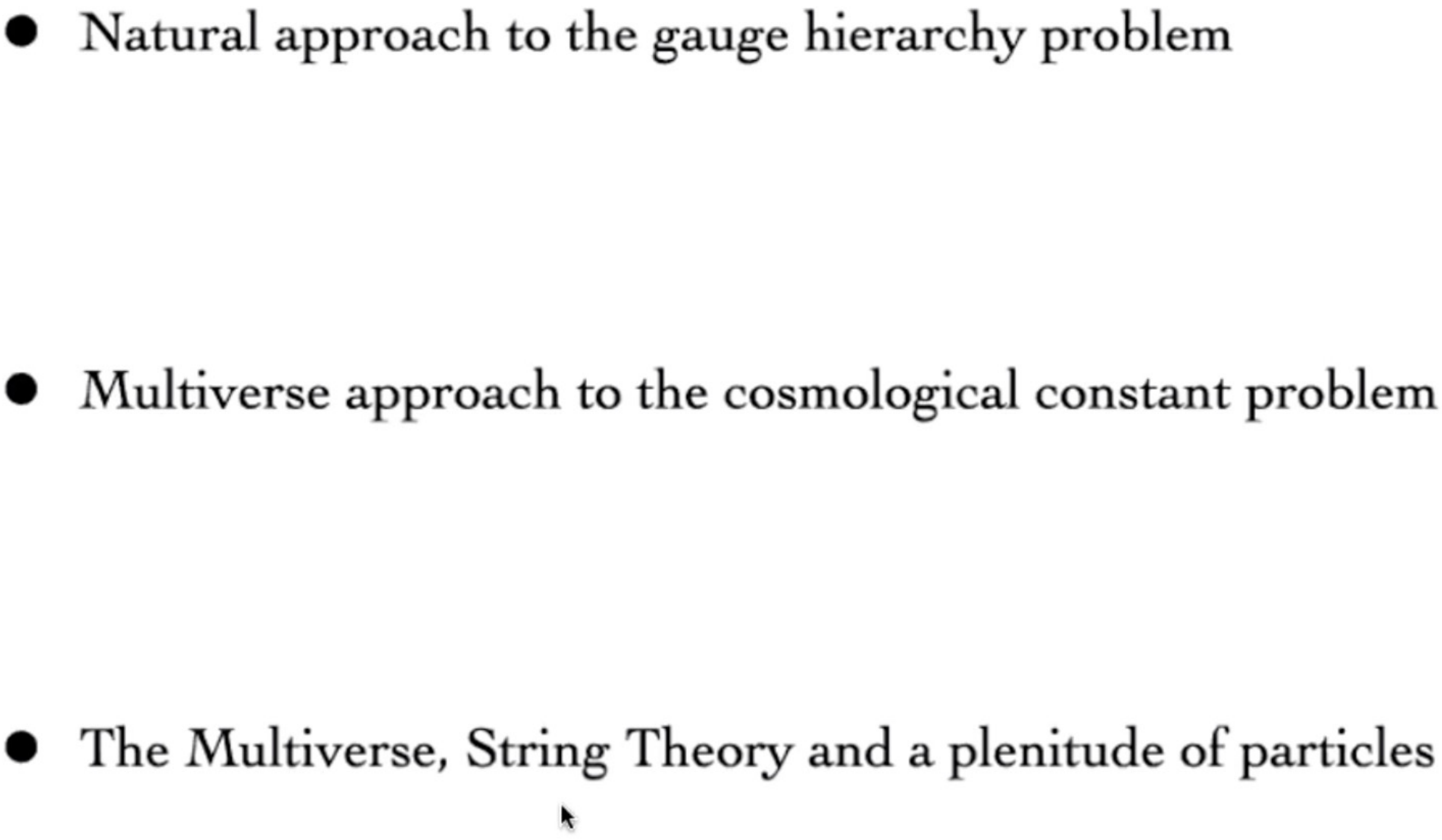
Problem	Solution
Earth-Sun Distance	Environmental Selection 10^{22} suns
7 eV line of ^{229}Th nucleus	"Look-elsewhere" effect
Solar-Lunar Eclipse	Plain Luck!
Cosmological Constant	Environmental Selection? 10^{500} universes!

At the Crossroads



At the Crossroads





- Natural approach to the gauge hierarchy problem
- Multiverse approach to the cosmological constant problem
- The Multiverse, String Theory and a plenitude of particles

- The strong CP problem

- Natural approach to the gauge hierarchy problem

- Multiverse approach to the cosmological constant problem

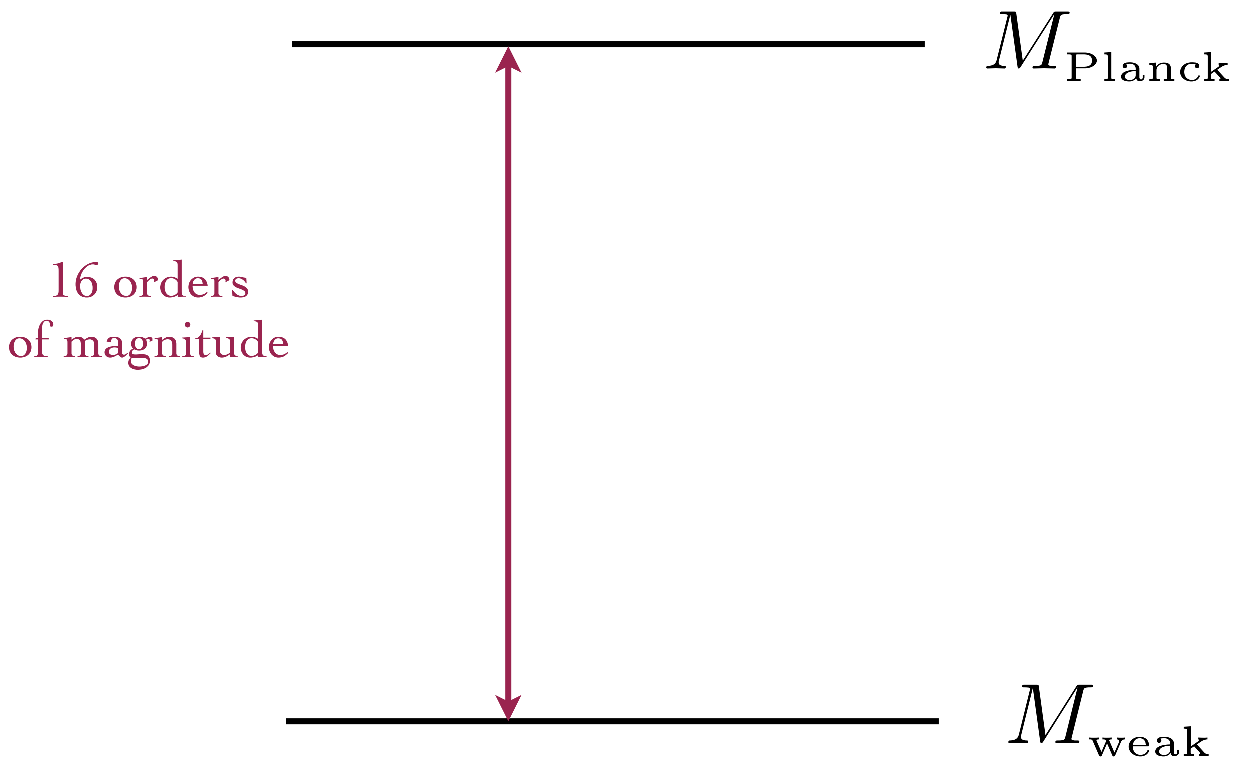
- The Multiverse, String Theory and a plenitude of particles

A plenitude of table top experiments for a plenitude of particles

The hierarchy problem

$$M_{\mathrm{Planck}} = G_{\mathrm{Newton}}^{-\frac{1}{2}} = 10^{19}\ \mathrm{GeV}$$

$$M_{\mathrm{weak}} = G_{\mathrm{Fermi}}^{-\frac{1}{2}} = 10^{3}\ \mathrm{GeV}$$



M_{Planck}

16 orders
of magnitude

M_{weak}

The hierarchy problem

$$M_{\text{Planck}} = G_{\text{Newton}}^{-\frac{1}{2}} = 10^{19}\ \text{GeV}$$

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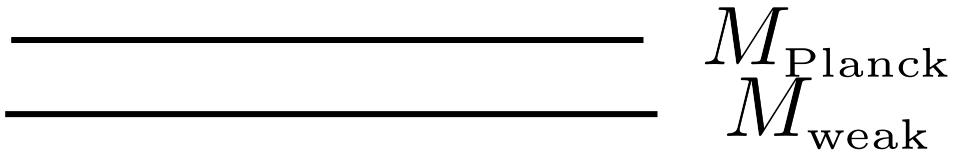
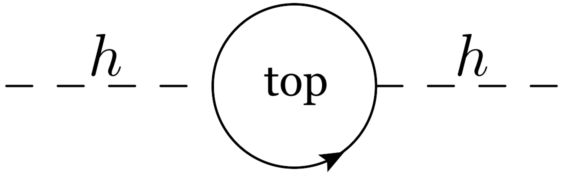


In the Standard Model:

Quantum Corrections pull the weak scale up

Quantum Corrections in the Standard Model

Note: $M_{weak} \sim \mathrm{m}_{\mathrm{higgs}}$

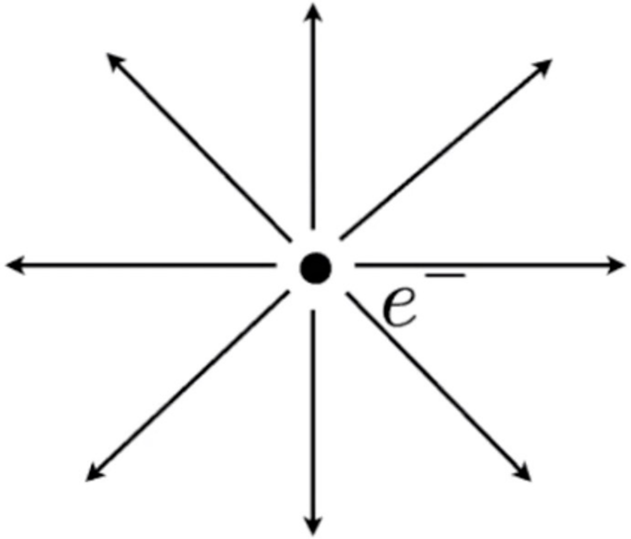


$$m^2_{\mathrm{higgs}} \propto M^2{}_{\mathrm{Planck}}$$

Need new symmetry to protect the Higgs in the Standard Model

A Historic Precedent for a New Symmetry

Non-relativistic electron self-energy



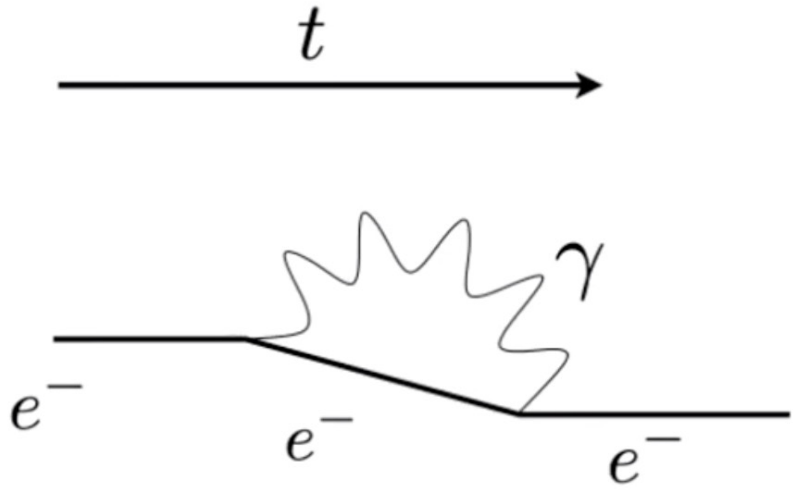
Classically

$$E = \frac{\alpha}{r_{\rm min}} = \alpha M_{\rm Planck}$$

No understanding of why $m_{\rm electron} \ll M_{\rm Planck}$

The electron mass in quantum mechanics

Without relativity



$$\alpha M_{\text{Planck}}$$

A New symmetry for the Electron Mass:
Lorentz Invariance

New Particle for the electron mass:
The positron

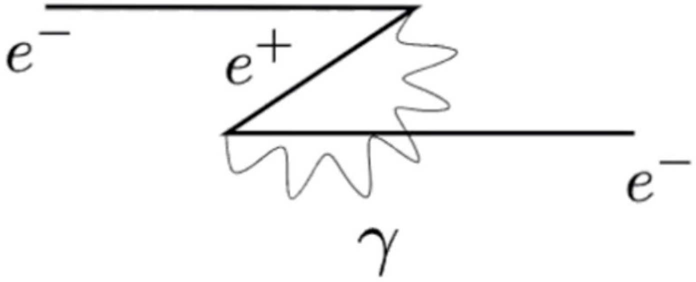
$$\begin{pmatrix} e^-_\uparrow \\ e^-_\downarrow \end{pmatrix} \longrightarrow \begin{pmatrix} e^-_\uparrow \\ e^+_\downarrow \\ e^+_\uparrow \\ e^-_\downarrow \end{pmatrix}$$

rotations

Lorentz

The Positron and Quantum Corrections

$$\alpha\left(M_{\text{Planck}} + m_e \log\frac{M_{\text{Planck}}}{m_e}\right)$$

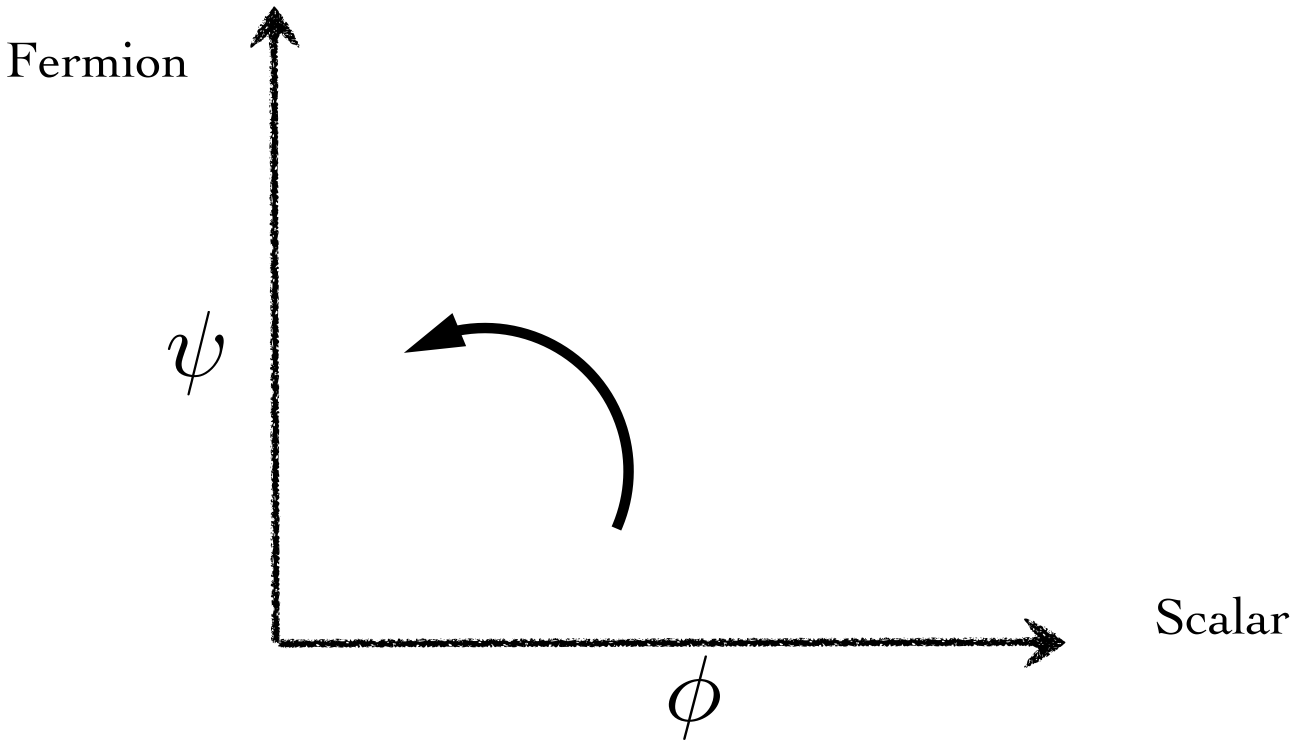


$$\alpha\left(-M_{\text{Planck}} + m_e \log\frac{M_{\text{Planck}}}{m_e}\right)$$

$$\boxed{\alpha\, m_e\, \log\frac{M_{\text{Planck}}^2}{m_e^2}}$$

No explanation why $m_e \ll M_{\text{Planck}}$ but once set, it's stable

A New Symmetry for the SM Higgs



Supersymmetric Standard Model

The Supersymmetric Standard Model

- New Symmetry: Supersymmetry

- New Particles: Superparticles

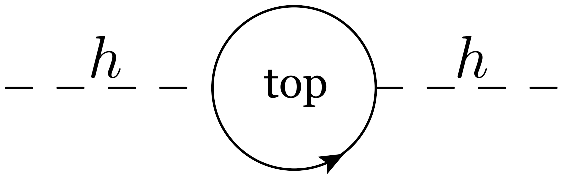
- Every particle has a superpartner:

$$\left.\begin{array}{ll}\text{lepton} & \rightarrow \text{slepton} \\ \text{quark} & \rightarrow \text{squark}\end{array}\right\}\quad \text{matter}$$

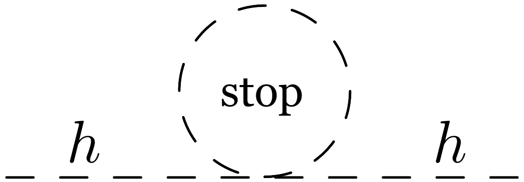
$$\left.\begin{array}{ll}\text{photon} & \rightarrow \text{photino} \\ \text{gluon, W} & \rightarrow \text{gluino, Wino}\end{array}\right\}\quad \text{force}$$

Higgs → Higggsino

Superparticles and Quantum Corrections



$$\propto {M^2}_{\text{Planck}}$$

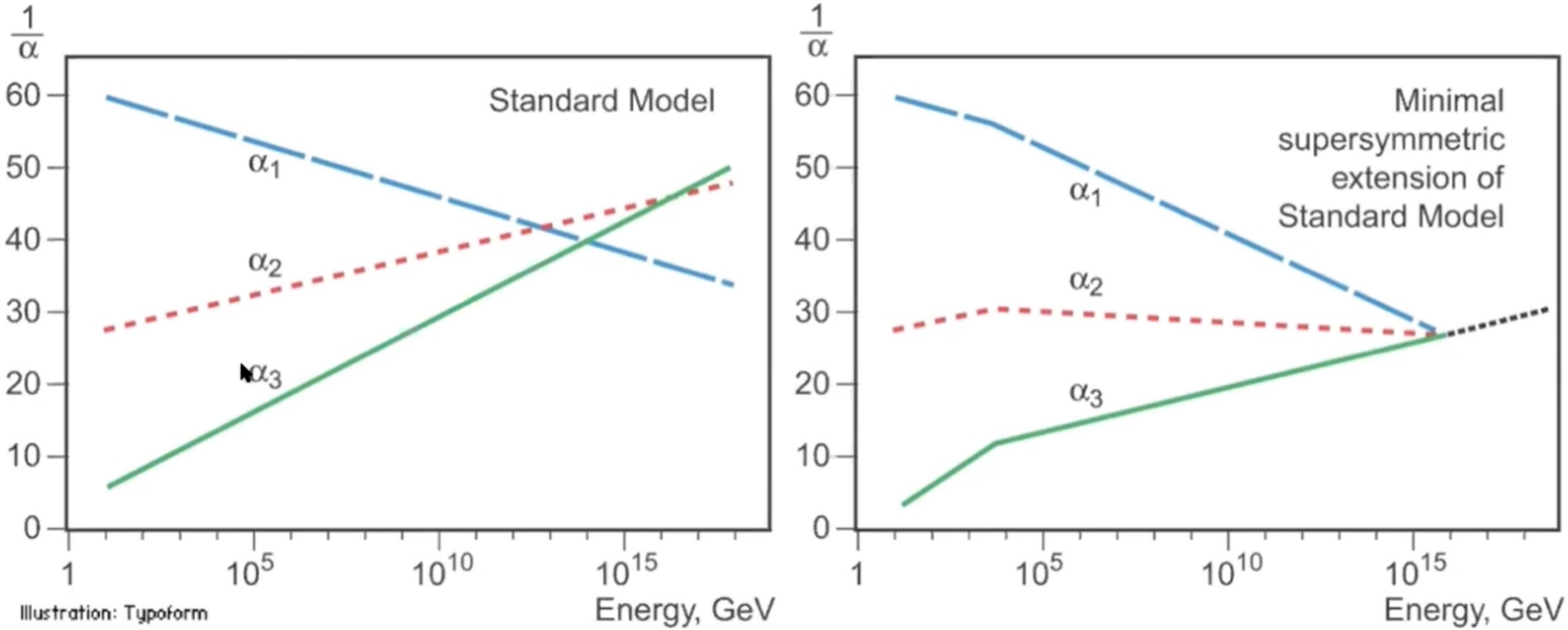


$$\propto -{M^2}_{\text{Planck}} + {M^2}_{\text{SUSY}}$$

$$\boxed{\propto {M^2}_{\text{SUSY}}}$$

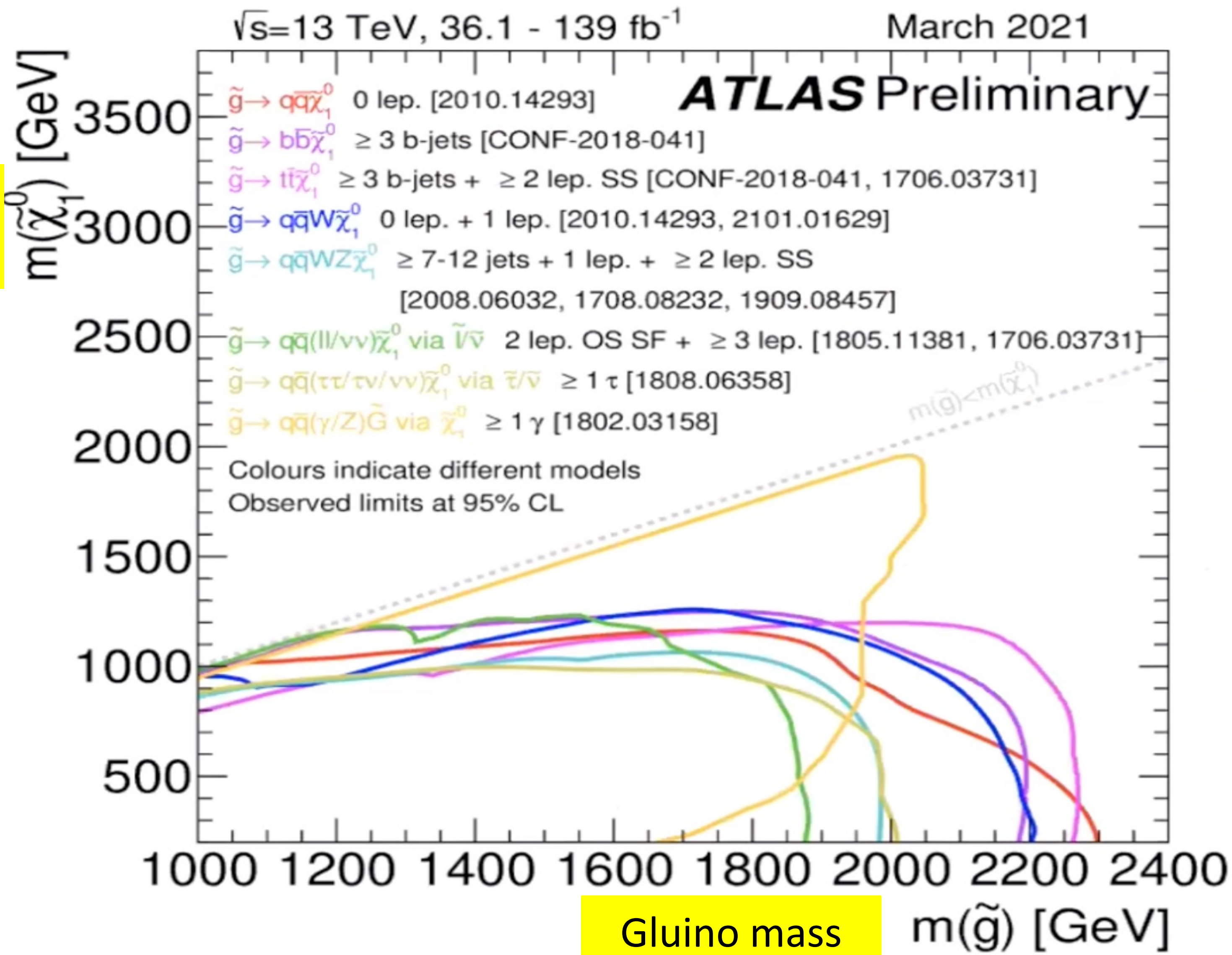
If sparticles are at the weak scale so must be the higgs

Gauge Coupling Unification



Experimentally verified in the early 1990s

The Missing Superpartner Problem



Neutralino mass

Gluino mass

Only ~4% of the complete LHC/ HL-LHC data set has been delivered to date

There is every reason to be optimistic that an important discovery could come at any time

A Zoo of Natural Ideas that can be tested at LHC

Supersymmetry: MSSM
CMSSM, NMSSM, pMSSM, XYZ-MSSM

SUSY Beyond MSSM
RPV, Extended Gauge Sectors, Dirac Gauginos

(Mini-)Split Supersymmetry

Extra Dimensions

Folded Supersymmetry

Maximally Natural Supersymmetry

Little Higgs

Twin Higgs (Neutral Naturalness)

Relaxion

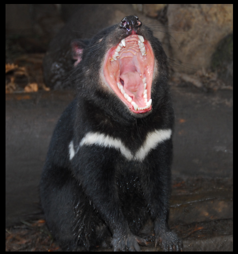
….










Slide from JoAnne Hewett

Other crucial measurements and searches @ LHC include:

Higgs width
Is Higgs elementary or composite?
Yukawa force?
Higgs self-coupling
General Searches
Anomaly Detection
Flavor anomalies
Dark sector far detectors @ LHC

(Not an exhaustive list)

The New York Times

July 23, 2025

The Other Half of the Universe Discovered

Geneva, Switzerland

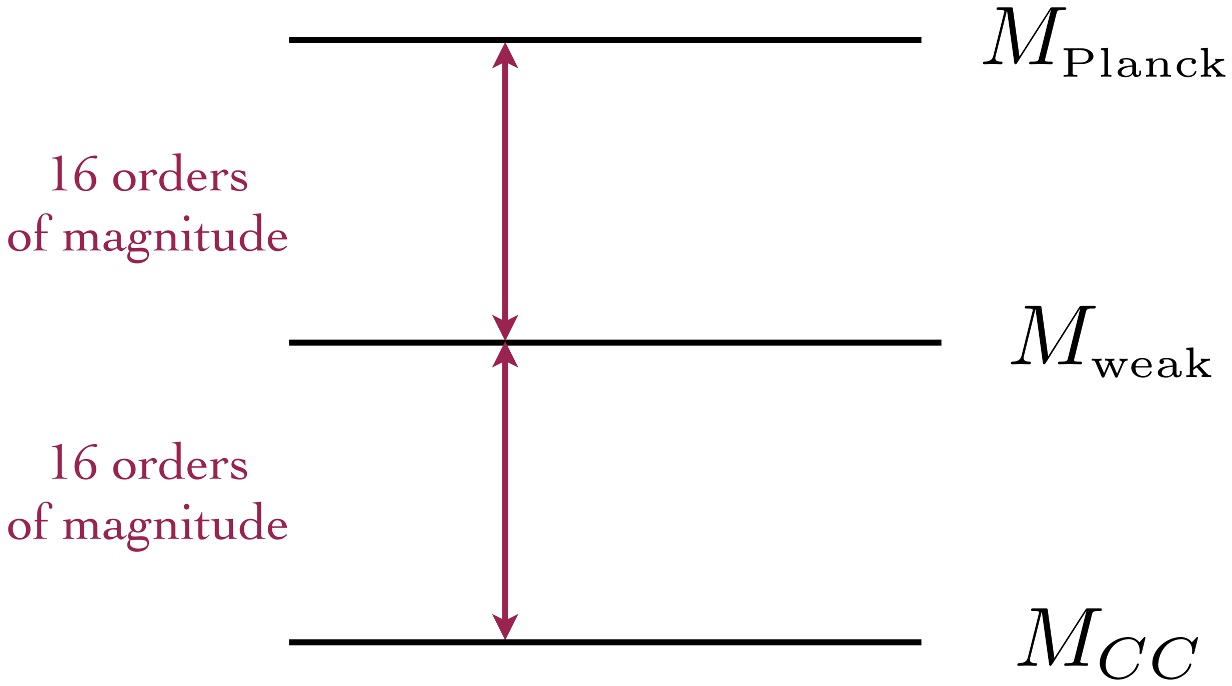
Based on a slide from Hitoshi Murayama

The cosmological constant problem

$$M_{\text{Planck}} = G_{\text{Newton}}^{-\frac{1}{2}} = 10^{19}\ \text{GeV}$$

$$M_{\text{weak}} = G_{\text{Fermi}}^{-\frac{1}{2}} = 10^{3}\ \text{GeV}$$

$$M_{CC} = \rho^{1/4}{}_{\text{vacuum}} = 10^{-12}\ \text{GeV}$$



M_{Planck}

16 orders of magnitude

M_{weak}

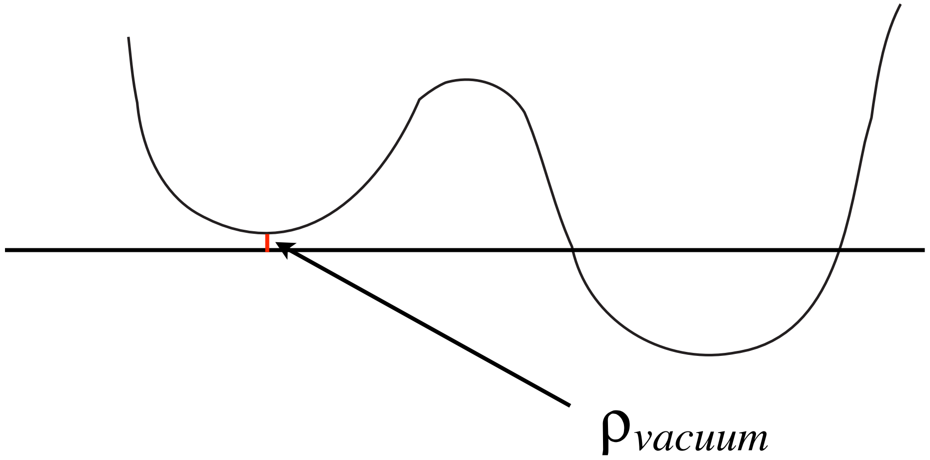
16 orders of magnitude

M_{CC}

Smallness of ρ_{vacuum} is critical for galaxies to form

In theories with few ground states ("vacua")

each, is a different particle theory,
has different physical laws

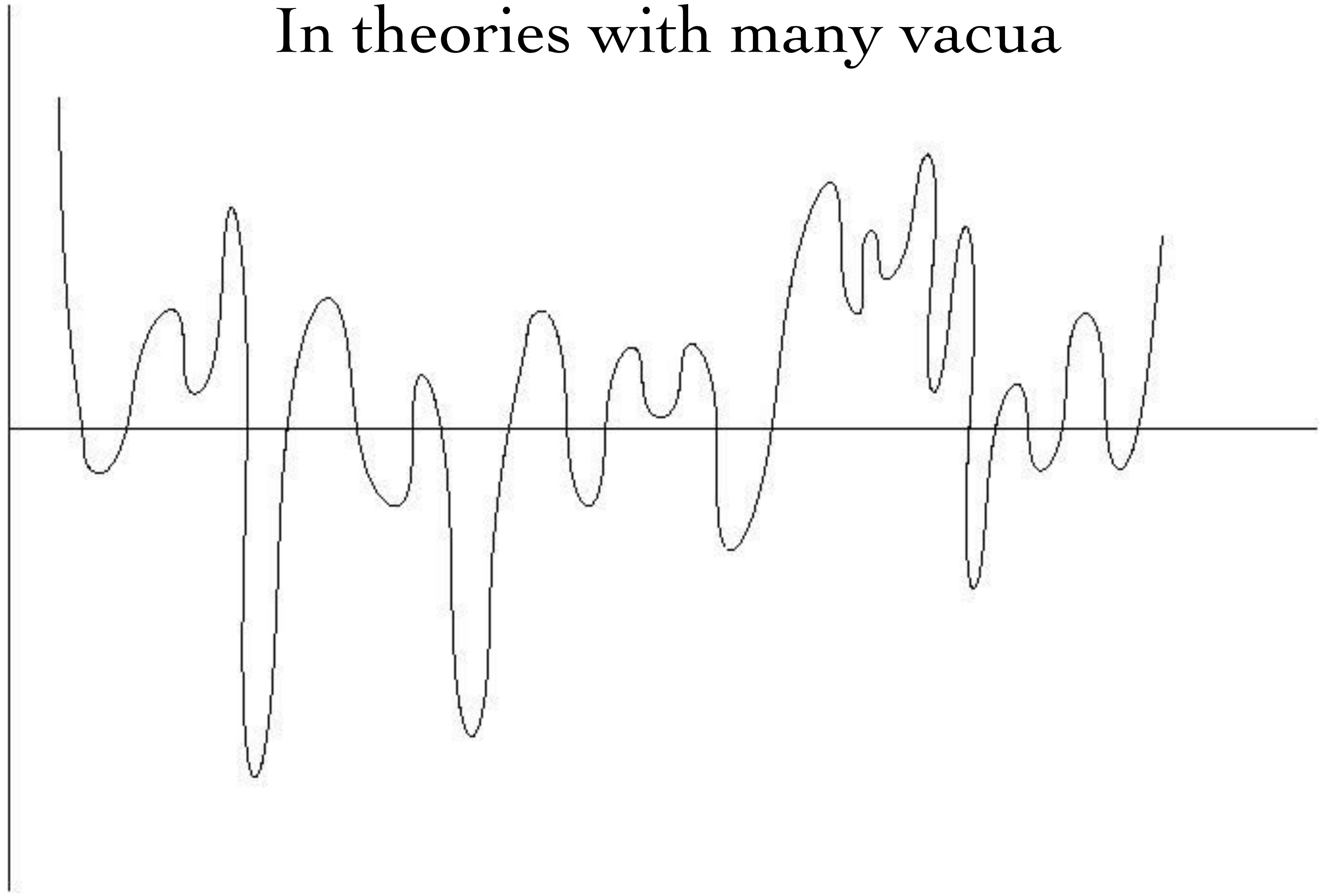


Getting $$\rho_{vacuum} \sim (10^{-15} M_W)^4$$

Such a small vacuum energy would seem unlikely but also very lucky
Since any bigger value would rip galaxies apart

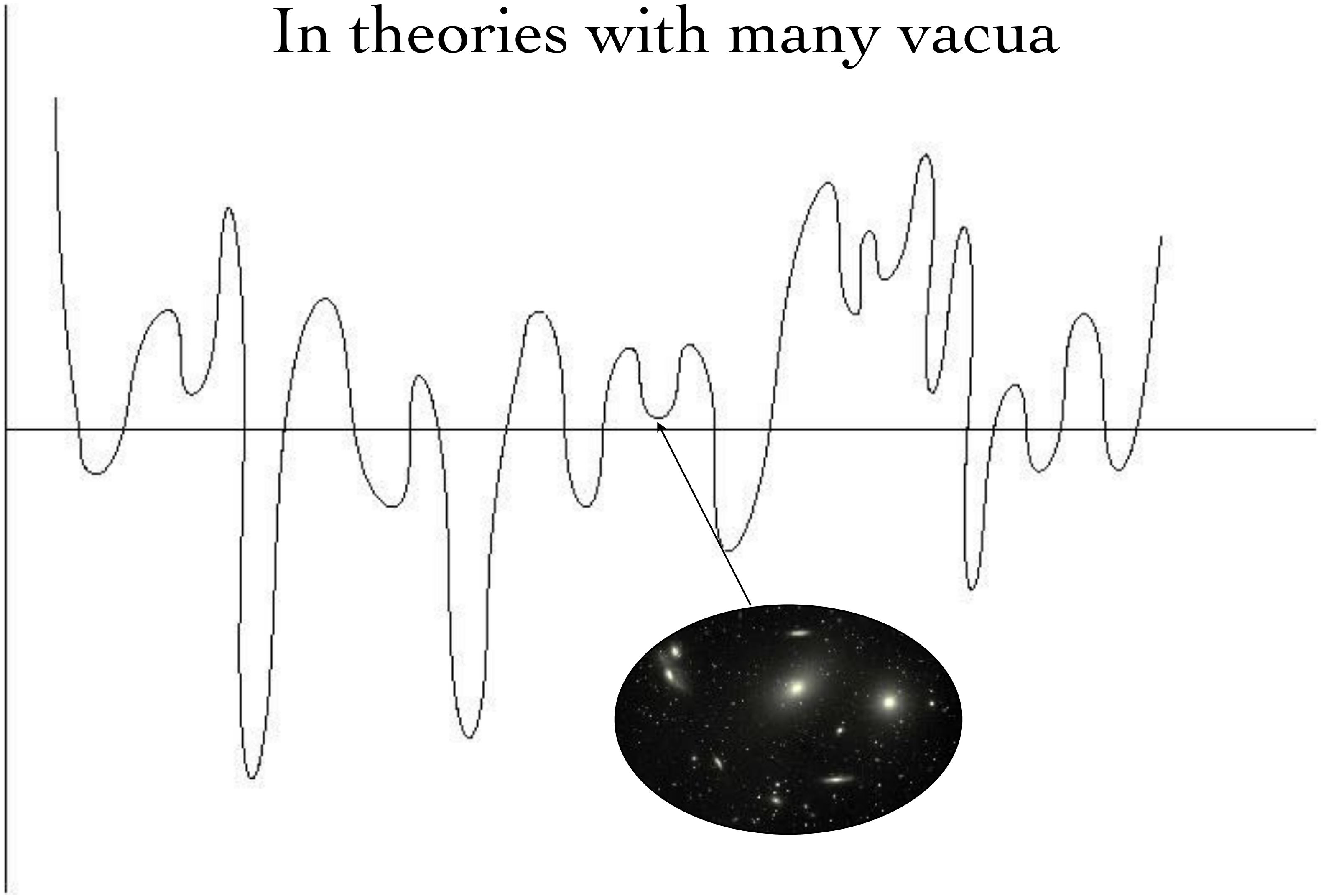
However... (Weinberg 1987)

In theories with many vacua



If there are enough vacua with different ρ_{vacuum} ,

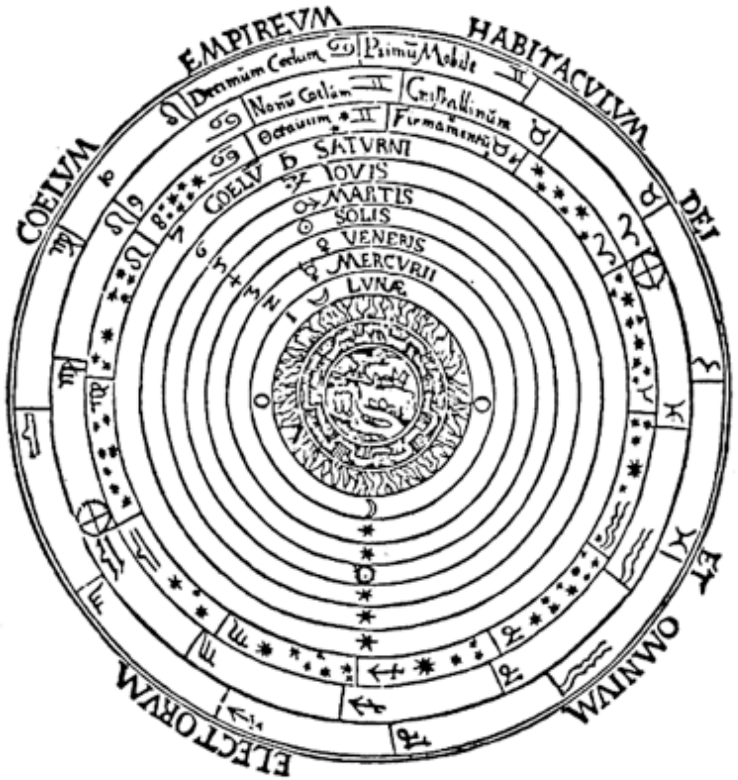
In theories with many vacua



If there are enough vacua with different ρ_{vacuum} ,

One Solar System

Schema huius præmiſſæ diuiſionis Sphærarum.



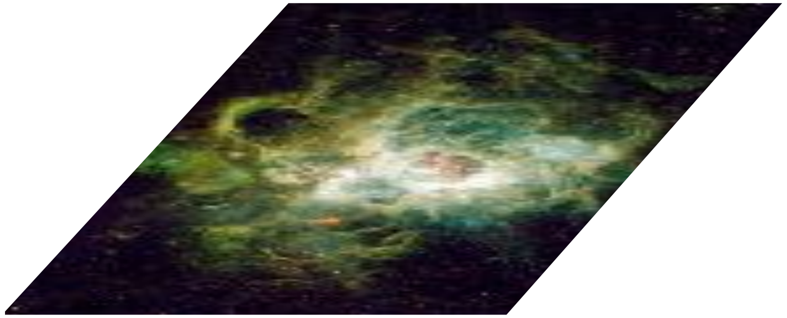
One Solar System

Many Solar Systems

Single Universe

The existence of Galaxies

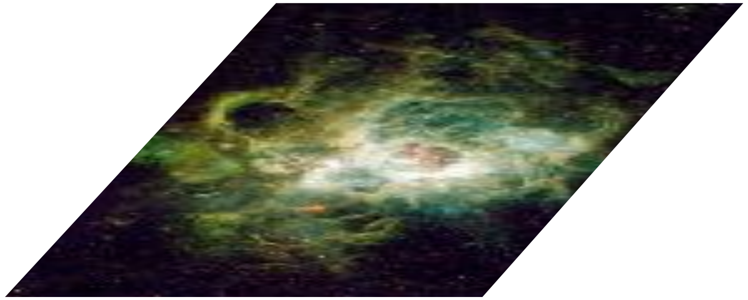
$$\rho_{\text{vacuum}} \leq 10^{-120} M_{\text{Planck}}^4$$



Single Universe

The existence of Galaxies

$$\rho_{\text{vacuum}} \leq 10^{-120} M_{\text{Planck}}^4$$



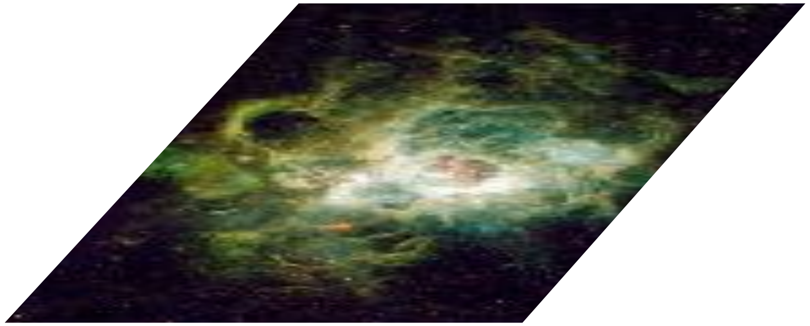
unlikely but also very lucky
Since any bigger value would rip galaxies apart

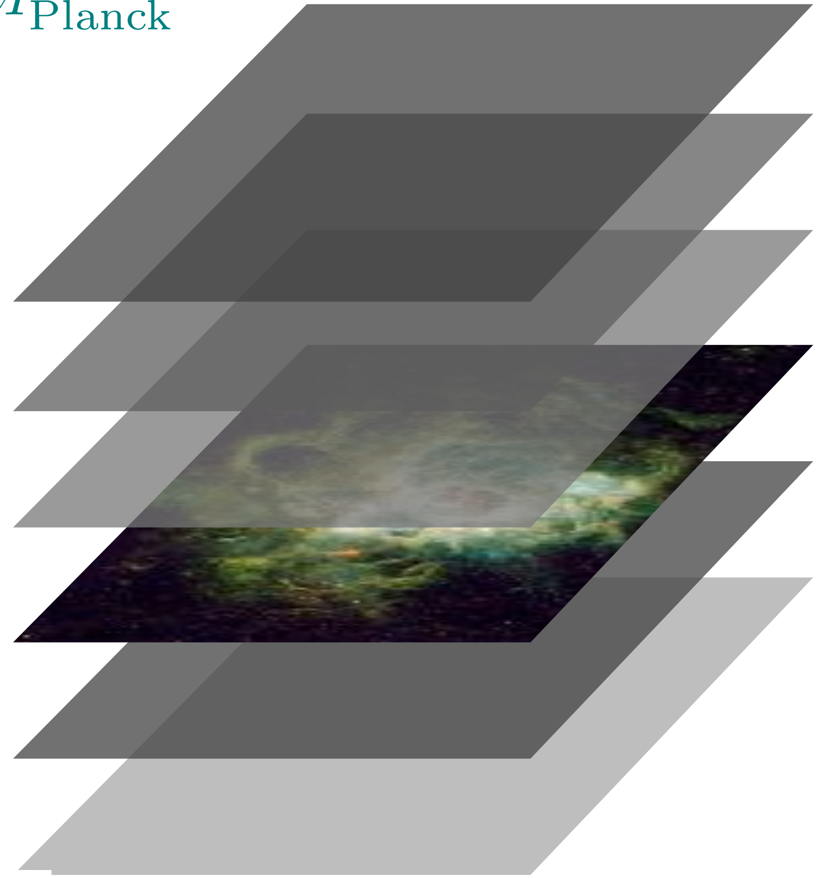
Single Universe

Many Universes

The existence of Galaxies

$$\rho_{\text{vacuum}} \leq 10^{-120} M_{\text{Planck}}^4$$





unlikely but also very lucky
Since any bigger value would rip galaxies apart

Environmental Selection

Analogies

Solar system ↔ Universe

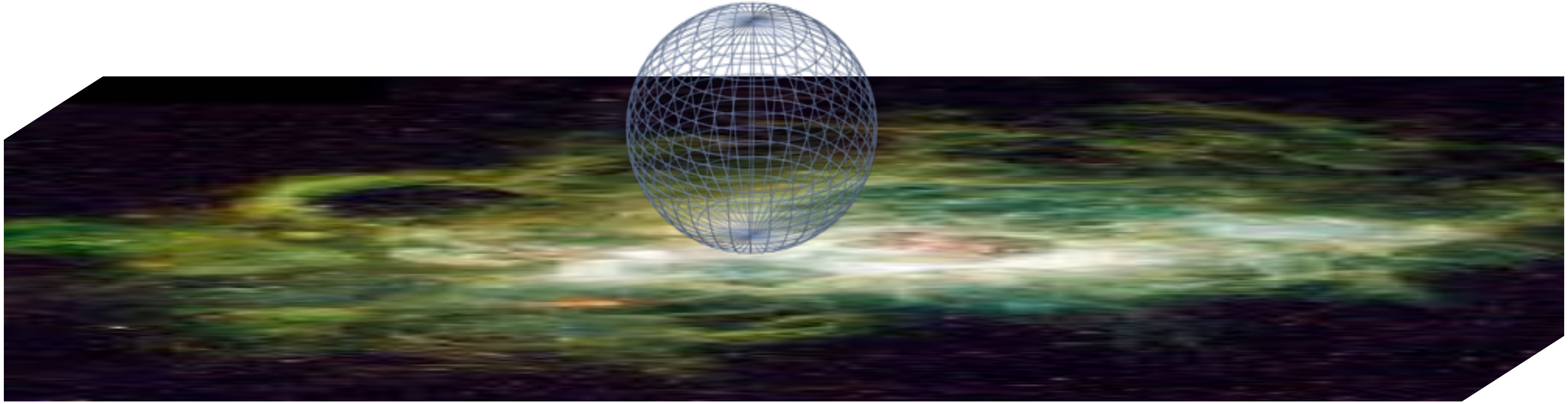
Planetary Distances ↔ Vacuum Energy

Universe ↔ Multiverse

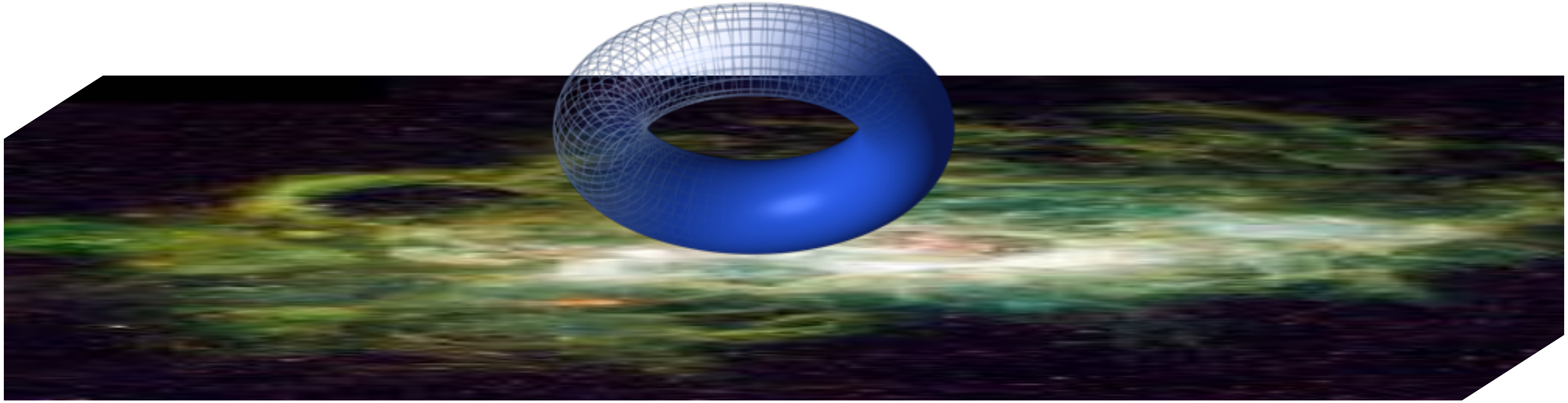
Telescope ↔ Precision and Collider Experiments

The Many Universes of String Theory

The Many Universes of String Theory



The Many Universes of String Theory



The Many Universes of String Theory

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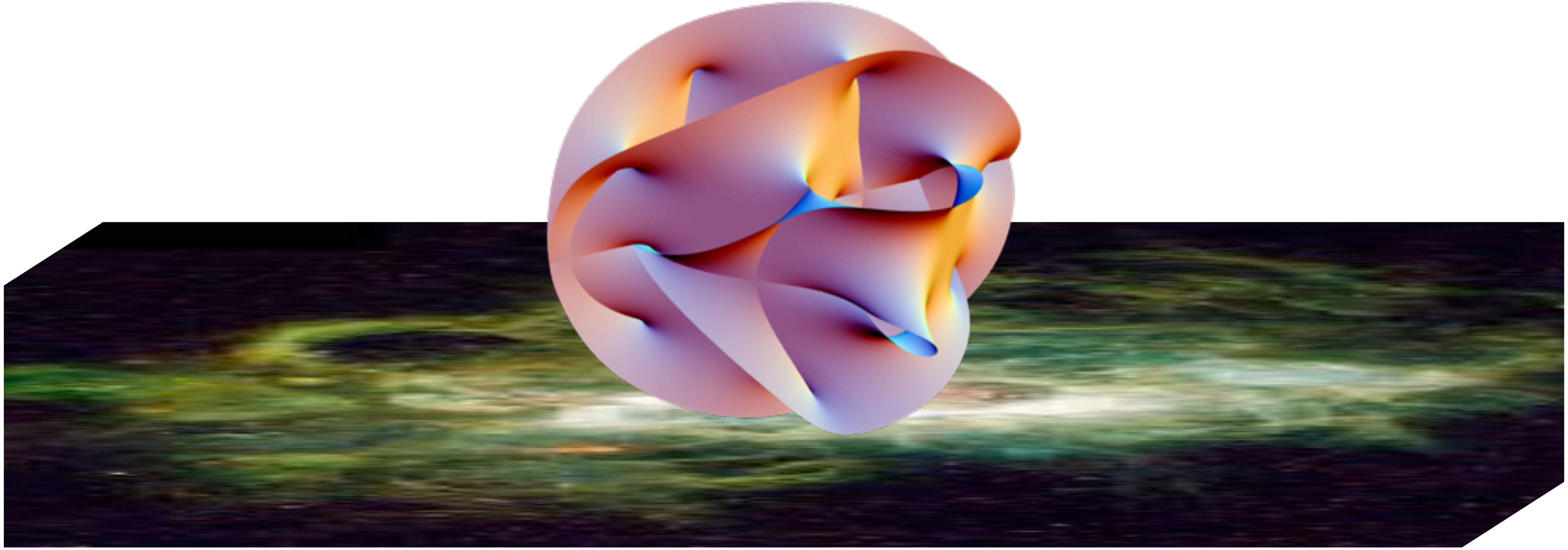
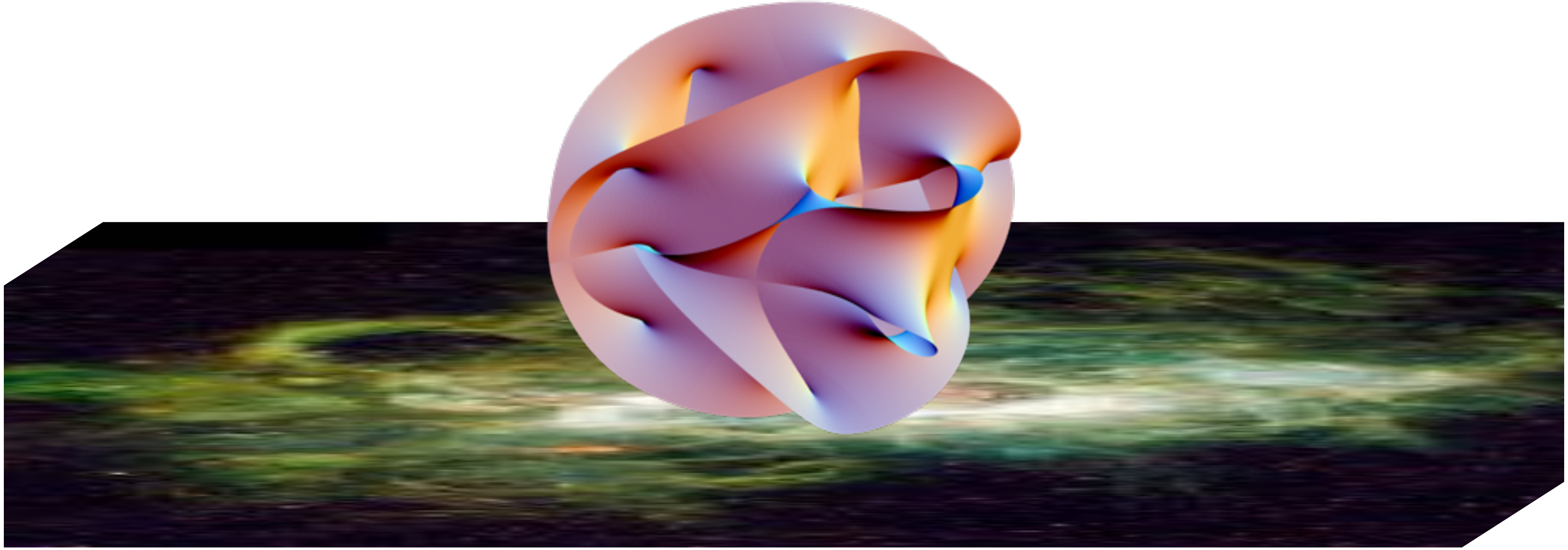


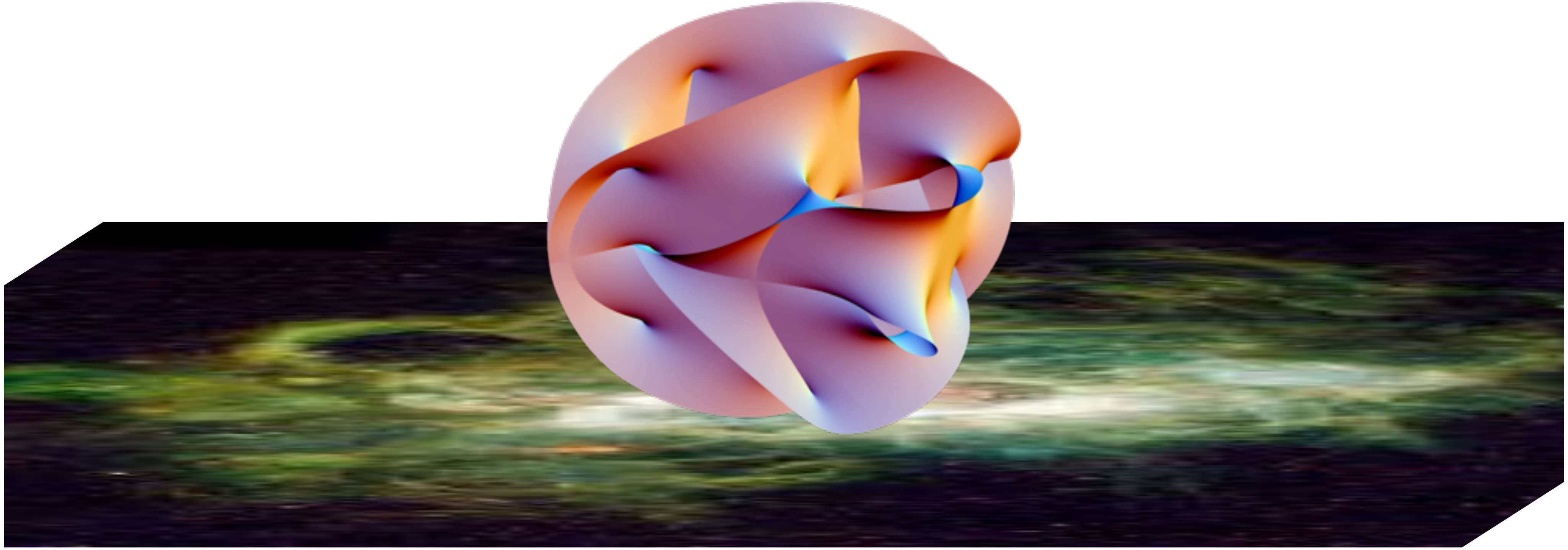
The Many Universes of String Theory



Extra dimensions of String Theory imply a Plenitude of Universes

Laws of Nature depend on the shape of the extra dimensions

The Many Universes of String Theory

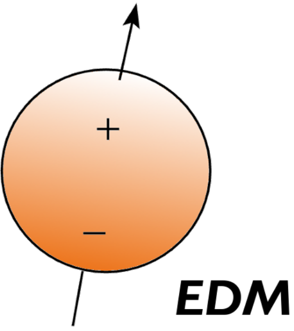


Extra dimensions of String Theory imply a Plenitude of Universes

Complexity of Extra dimensions implies a Plenitude of Particles

The Strong CP Problem

Why is the Electric Dipole Moment of the Neutron so Small?



- QCD Lagrangian has C and P violating term:
- $\mathcal{L}_{QCD} = \theta_s \frac{g_s^2}{32\,\pi^2} G^a_{\mu\nu}\,\tilde{G}^{a\mu\nu}$
- nEDM ~ e fm θ_s
- Experimental bound $\theta_s < 10^{-10}$

$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977); S. Weinberg, Phys. Rev. Lett. 40, 223 (1978); F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

The Strong CP Problem

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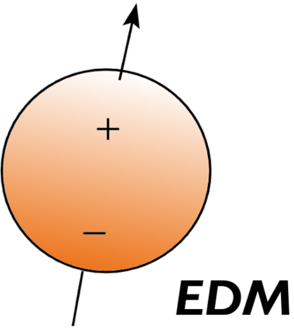

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- nEDM ~ e fm θ_s
- Experimental bound $\theta_s < 10^{-10}$
- Solution is that $\theta_s \sim a(x,t)$ is a dynamical field, an axion
- Axion field: $a(x,t) = a_0 \cos \omega_a t$, with Compton frequency: $\omega_a = \mu_a c^2/\hbar$
  f_a is the symmetry breaking scale (the axion decay constant)
- Axion mediates new forces and can be dark matter $\rho_{DM} \propto a_0^2$

Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-11}\ \mathrm{eV}\ \frac{10^{17}\ \mathrm{GeV}}{f_a} \sim (3\ \mathrm{km})^{-1}\ \frac{10^{17}\ \mathrm{GeV}}{\mathrm{f_a}}$$

A Plenitude of (Almost) Massless Particles

Spin-0 non-trivial gauge field configurations: Axion Like Particles

Spin-1 non-trivial gauge field configurations: Dark Photons

Fields that determine the shape and size of extra dimensions as well as values of the fundamental constants: Dilatons, Moduli, Radions

They all couple very weakly to the standard model

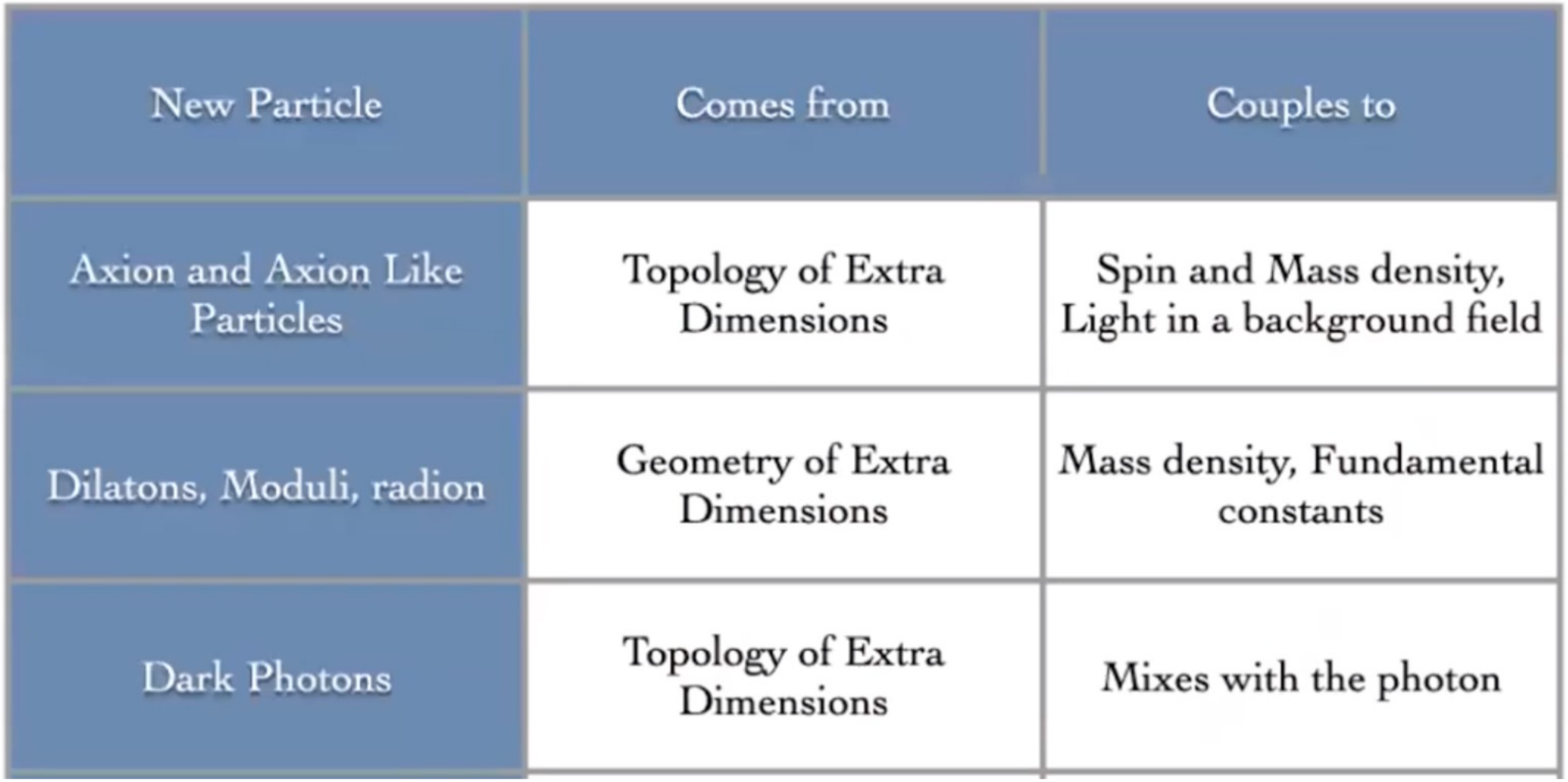
They can be extremely light

Constrained if the coupling is large enough by astrophysics, BBN, CMB…

They can mediate new forces and they are excellent dark matter candidates

Based on a slide
by Mina Arvanitaki

Summary



	New Particle	Comes from	Couples to
Spin zero CP odd	Axion and Axion Like Particles	Topology of Extra Dimensions	Spin and Mass density, Light in a background field
Spin zero CP even	Dilatons, Moduli, radion	Geometry of Extra Dimensions	Mass density, Fundamental constants
Spin one	Dark Photons	Topology of Extra Dimensions	Mixes with the photon

What could be convincing evidence for the Multiverse?

I. 120 orders of magnitude tuning for the Cosmological Constant

Are we paying the price of ignoring it?

II. Fine tuned electroweak scale

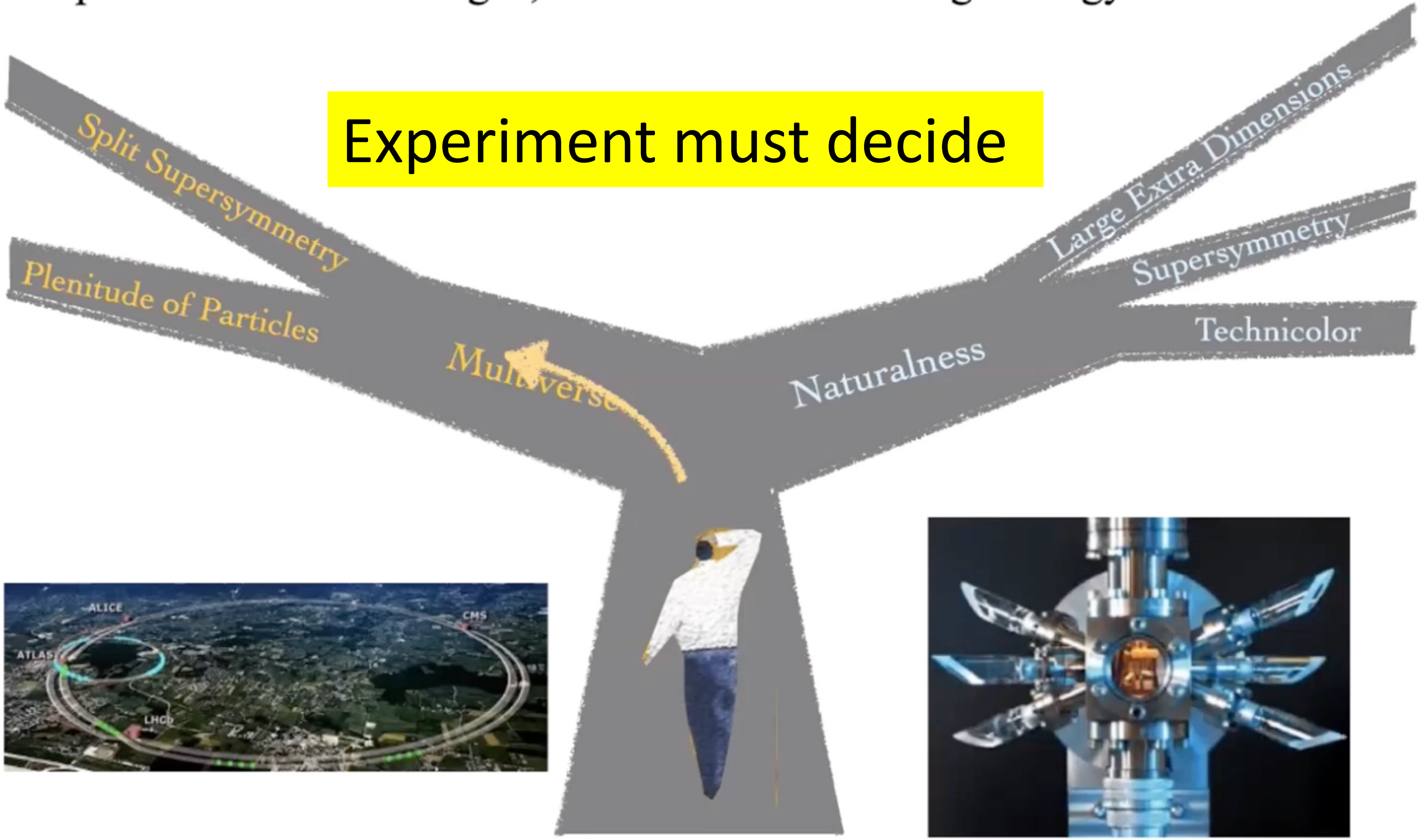
Already problematic with the absence of new physics
at LEP, LHC, FCNCs, EDMs...

III. Two or more light axions or dark photons or moduli etc.

IV. Mini-Split at a High Energy Collider

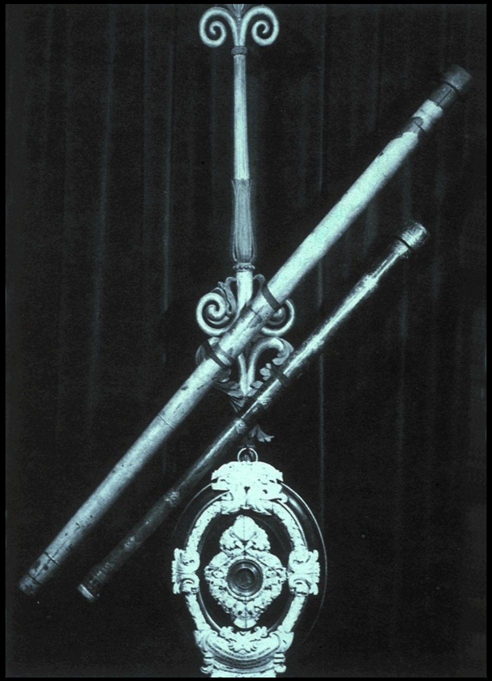
Far from being untestable, the Multiverse provides us with a plethora of opportunities for discoveries by exploiting the plethora of novel small-scale experimental breakthroughs, as well as the future high energy colliders.

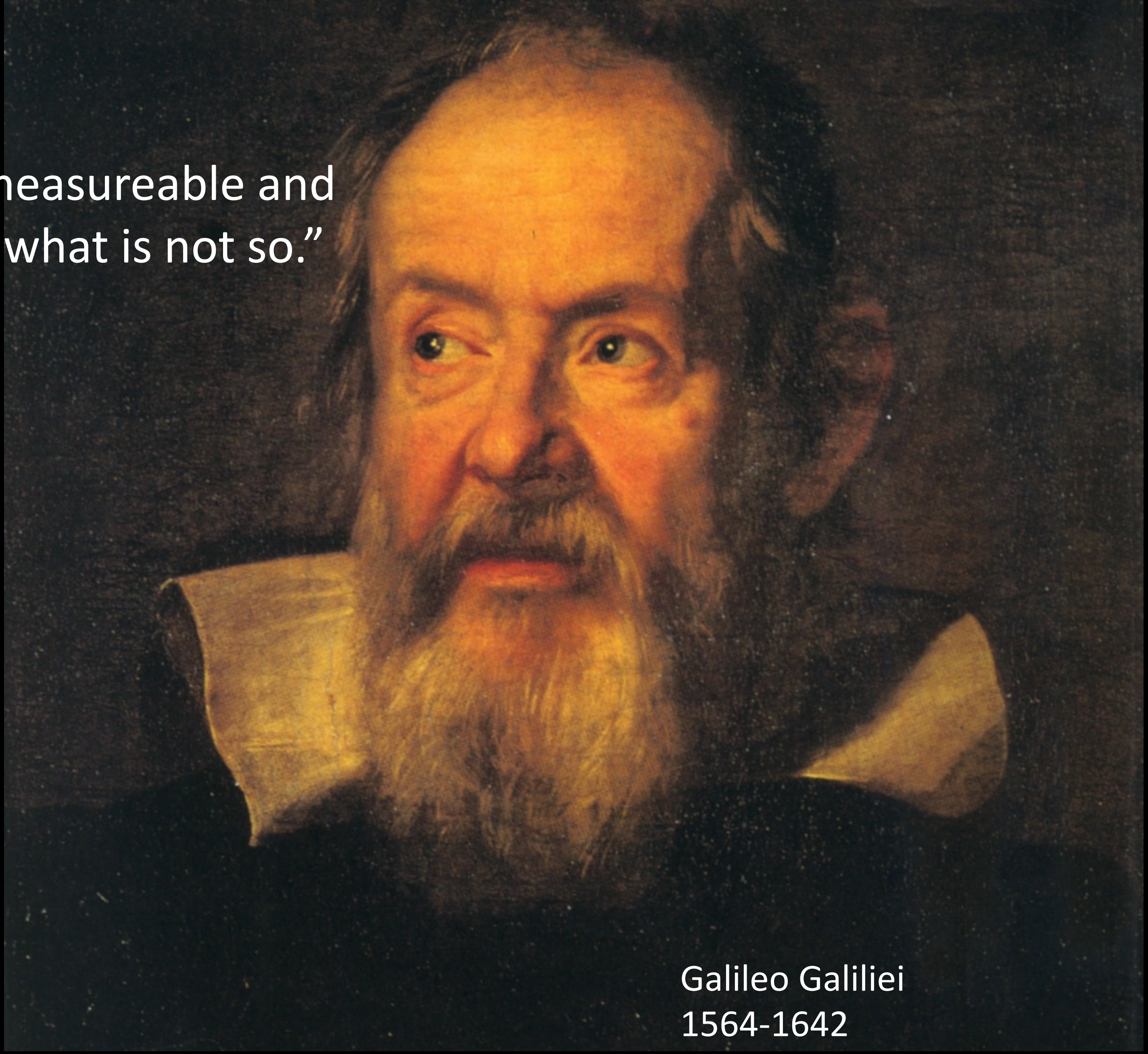
Experiment must decide



We are very much in a data driven era !

“Measure what is measureable and make measureable what is not so.”





Galileo Galiliei
1564-1642

Instrumentation: The Great Enabler

"New directions in science are launched by new tools much more often than by new concepts.

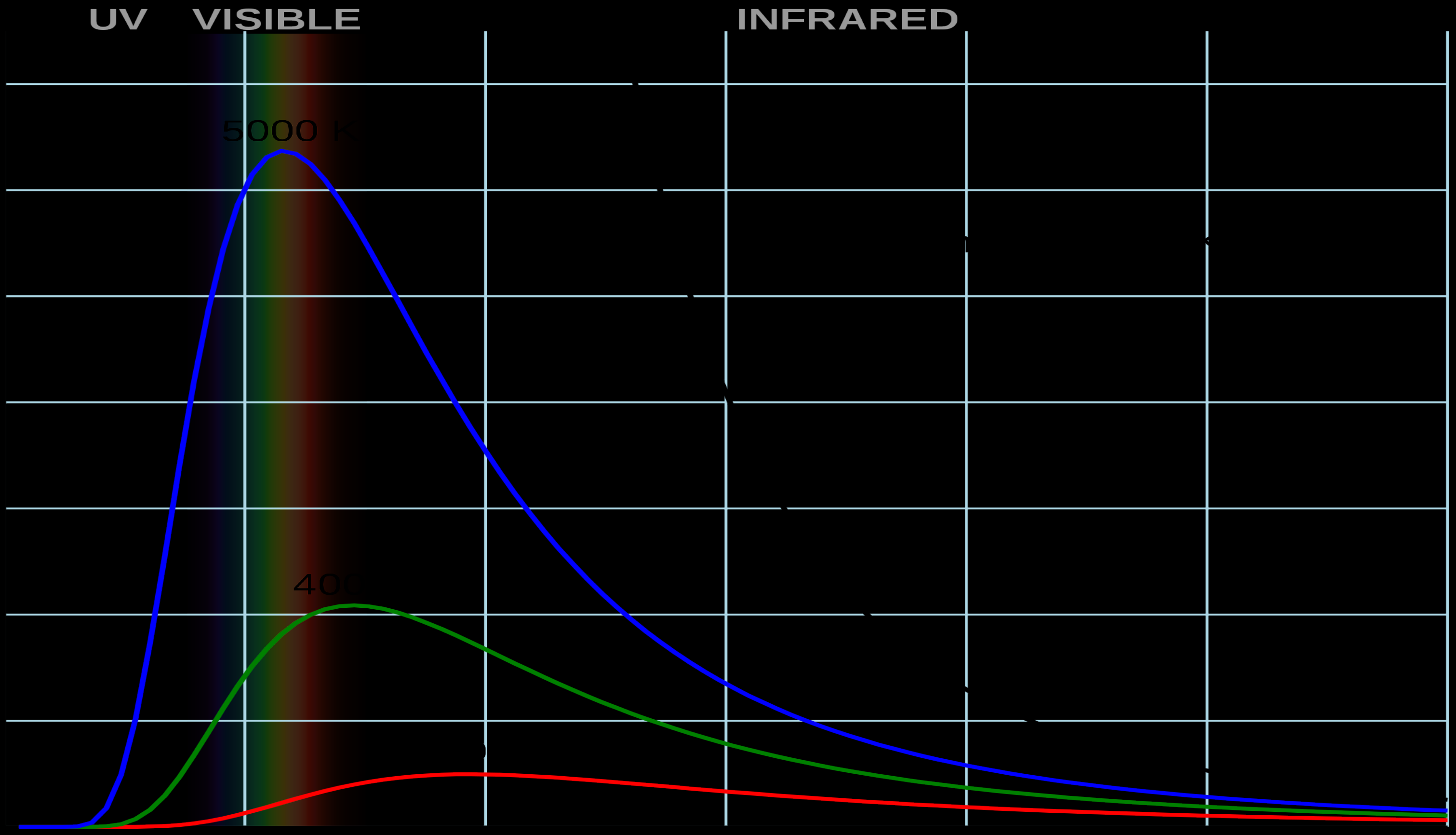
The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson

Tools i.e. precision instruments are key to discovery when exploring new territory Quantum 2.0 provides new tools

Science progresses by experimentation, observation, and theory

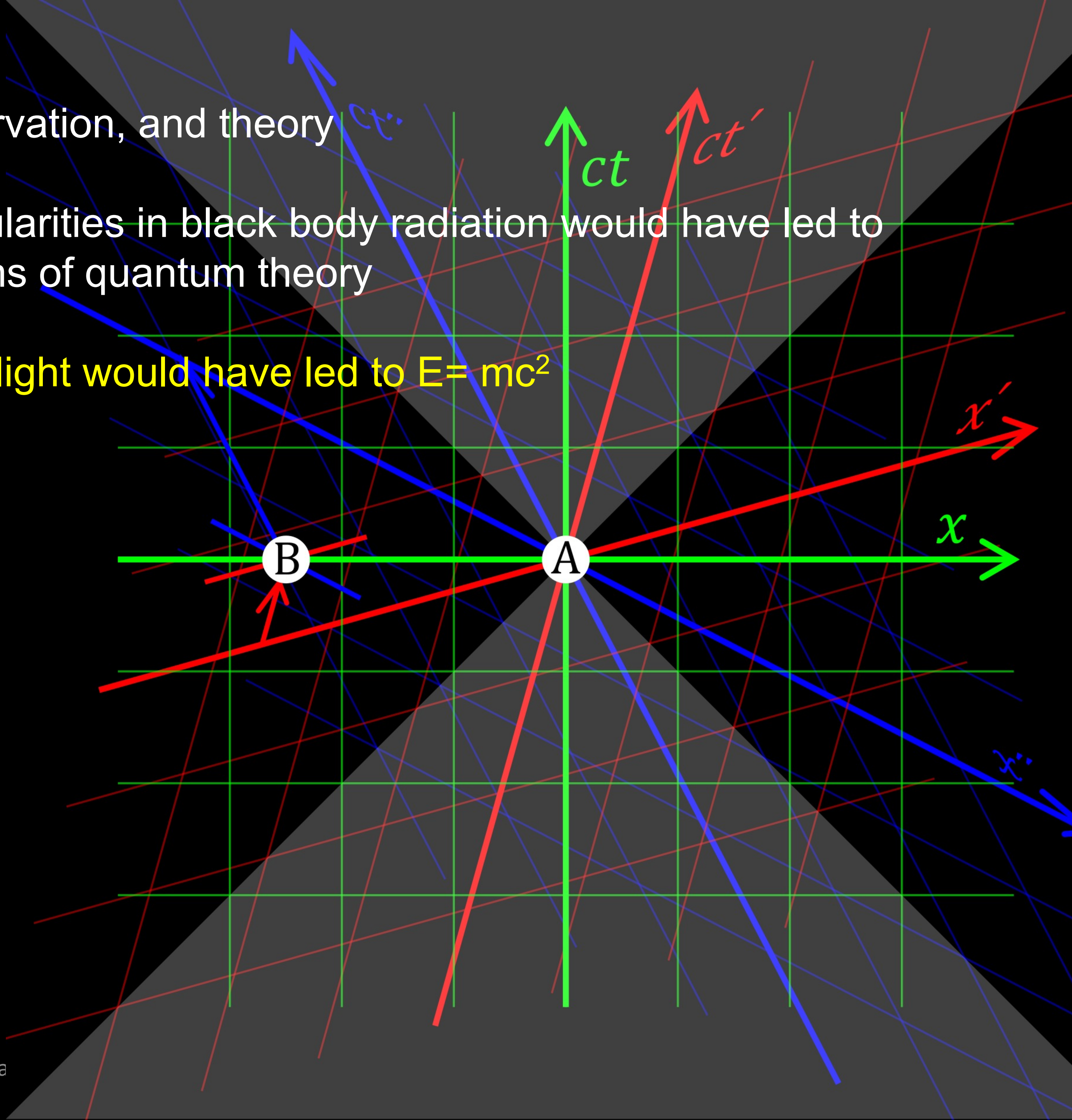
Nobody would have predicted that slight irregularities in black body radiation would have led to an entirely new conception of the world in terms of quantum theory



Science progresses by experimentation, observation, and theory

Nobody would have predicted that slight irregularities in black body radiation would have led to an entirely new conception of the world in terms of quantum theory

That pondering the constancy of the speed of light would have led to E= mc^2



Science progresses by experimentation, observation, and theory

Nobody would have predicted that slight irregularities in black body radiation would have led to an entirely new conception of the world in terms of quantum theory

That pondering the constancy of the speed of light would have led to $E= mc^2$

That special relativity and quantum mechanics would have led to anti-matter

$$(i\partial\!\!\!/ - m)\psi = 0$$

A special time in particle physics

After the establishment of quantum mechanics and general relativity
The next ~90 years have been spent exploring the consequences

Since the discovery of the Higgs we have entered an era without no-lose theorems (i.e. the Standard Model could be consistent up to the Planck Scale) an era that is data driven, similar to 1850 before Planck had interpreted the black body radiation, and Einstein had formulated Special and General Relativity

Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z,W
AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy

precision instruments are key to discovery when exploring new territory

The Confluence

- Quantum Information Science:
  - Promises, through control of quantum properties, to go beyond the Standard Quantum Limit and deliver ultimate precision;
  - Enables novel, cost-effective approaches complementary to traditional HEP approaches;

The Confluence

Particle Physics, Particle Astrophysics & cosmology has many unanswered questions

The Confluence

A perfect match at a perfect time!

Quantum Sensing has a long and distinguished history and track record of success, theoretical advances and the advent of Quantum 2.0 increases the potential

1910-1970 The physics of the superconducting state became a intellectually rich area of study (BCS).

Superconducting materials support a wealth of beautiful physical processes, some of which are highly desirable and can be used to make electronic devices, and others cause endless problems.

The good:

- Pair formation and the coherent ground state
- Pair tunnelling
- Kinetic inductance
- Pair breaking creates quasiparticles
- Magnetic sensitivity through Aharonov –Bohm effect

The bad:

- Josephson oscillating currents
- Spatial decorrelation due to scattering
- Proximity effect
- Andreev reflections at interfaces

The ugly:

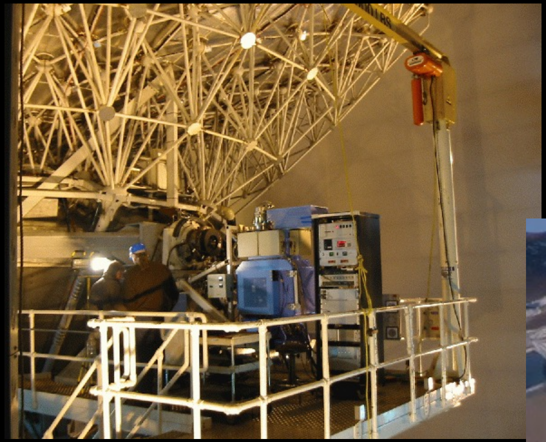
- Flux trapping in defects
- Vortex movement leading to dissipation
- Quasiparticle heating
- Gap suppression due impurities
- Material science considerations – oxides on surfaces giving TLS

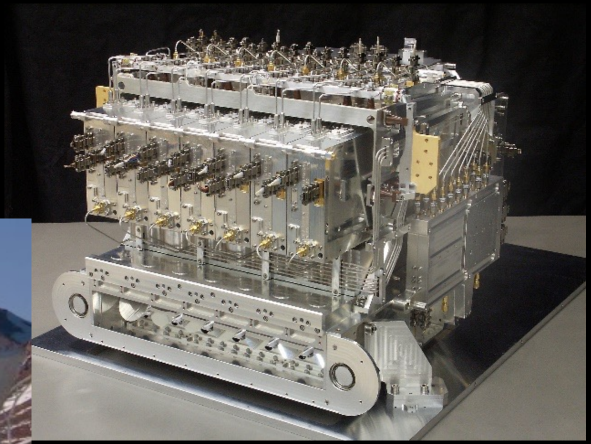
1970s Superconducting device physics started to emerge following the discovery of Cooper pair tunnelling, and the invention of the Superconducting Quantum Interference Device (SQUID).

1980s Superconducting device physics became an enabling technology for fundamental physics in the form of ultra-low-noise receivers (SIS mixers) for submm-wave astronomy (200 GHz -1 THz) .

Ground-based spectroscopy and aperture-synthesis interferometry (JCMT, CSO, IRAM, KOSMA, ALMA), and space-based telescopes (Herschel-HFI), would not have been possible without superconducting electronics.

Recently, the direct imaging of the event horizon of the black hole in M87 – Event Horizon Telescope (VLBI) – was performed using superconducting heterodyne mixers





1990s. Superconducting bolometers wre introduced in the form of Transition Edge Sensors (TES).

Arrays of bolometers (100-600 GHz) have revolutionised ground-based studies of anisotropies in the CMBR: numerous observations of early-Universe astrophysics, including detection of molecules at high-redshift z>2.

Search for B-modes, formed during the first moments of the Big Bang, is the next major challenge, which will be enabled by large superconducting polarimetric imaging arrays (CMB-S4, LiteBIRD).

Considerable innovation and success in the development of superconducting readout electronics for large arrays – time domain and frequency domain multiplexing (TDM/FDM)

Transition Edge Sensors now essential for X-ray astrophysics (ATHENA space telescope)

2000s Invention of Kinetic Inductance Detectors (KID) for large format imaging across the whole of the spectrum – achieve multiplexing through Software Defined Radio (SDR) techniques

2010 Introduction of the superconducting microwave Travelling-Wave Parametric Amplifiers (TWPA) for quantum-noise-limited amplification over large bandwidths – several variants available.

SQUID-based parametric amplifiers used for creating and reading out squeezed vacuum states.

Superconducting Nanowire Single Photon Detectors (SNSPD) used for counting optical photons

2020 – 2050 Massive opportunities for quantum-noise-limited performance and *enhanced functionality* in astronomy.

Superconducting qubits for quantum computing, superconductor/spin-system quantum memory elements are becoming commonplace.

New superconducting devices and applications are emerging – massive particle detection (low-energy electron spectroscopy)

In summary:

Submillimetre-wave wave and FIR astronomy would not exist, and its numerous discoveries would not have happened, if it were not for superconducting electronics.

Many future ground-based and space observatories (including X-ray) are entirely reliant on the existence and further development of superconducting electronics – it cannot be uninvented!

Many future space-based astronomy platforms will be launched with superconducting electronics (Athena, SPICA-variant, LiteBIRD, Earth Observation).

None of this technology was provided by industry – all of it comes out of university and government laboratories – responsibility for development, and then continuity of supply.

The impact on low-energy particle physics and quantum mechanics can be as great as the impact on astronomy.

The application of superconducting sensors/electronics to physics beyond astronomy will open up major new areas of fundamental science.

Major technological synergies between astronomy, fundamental physics, space-based science, and quantum computing and communications exist

Primary device types (an electromagnetic perspective):

- these are the ones that have survived evolutionary down-selection
- some use the superconducting coherent state, some use pair breaking
- green shows high TRL, red shows where devices are possible and needed

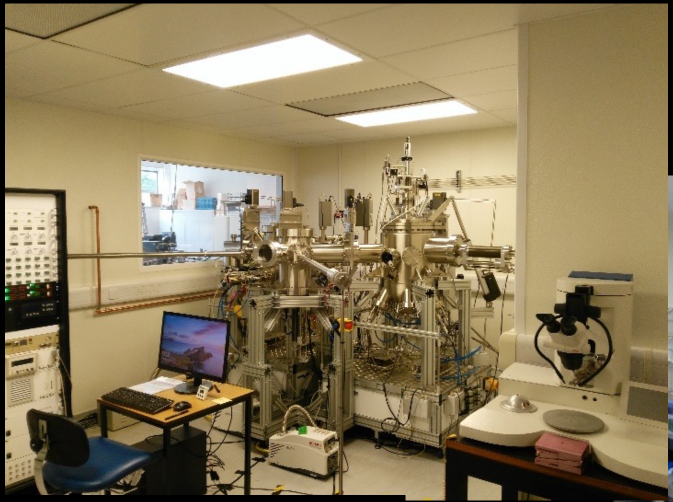
	Microwave	**Submillimetre**	**Far infrared**	**Optical**	**High energy**
	10 – 100 GHz 3 cm- 3 mm	100 GHz – 1 THz 3 mm – 300 μm	1 – 10 THz 300 – 30 μm	2 μm – 300 nm	UV, ϒray and Xray
SIS mixers		🟢			
HEB			🟢		
CEB		🟢			
TES	🔴	🟢	🟢	🟢	🟢
KID	🔴	🟢	🟢	🟢	
SNSPD			🔴	🟢	
SQUID	🟢				
JJPA	🟢				
TWPA	🟢	🔴			

- Device processing repertoire across a wide range of devices and materials:

Nb, Ta, β-Ta, Al, NbN, TiN, NbTiN, Mo, Hf, Ir, Cu, Au, AuCu, AuPd, SiO_2 SiO AlOx

- All on SIN and SoI membranes – 4 UHV deposition systems – sputtering and e-beam

- Bilayers based on proximity effect, and lateral proximity effect, can be used to `engineer' properties of films: MoAu, MoCu, TiAu, TiAl multilayers

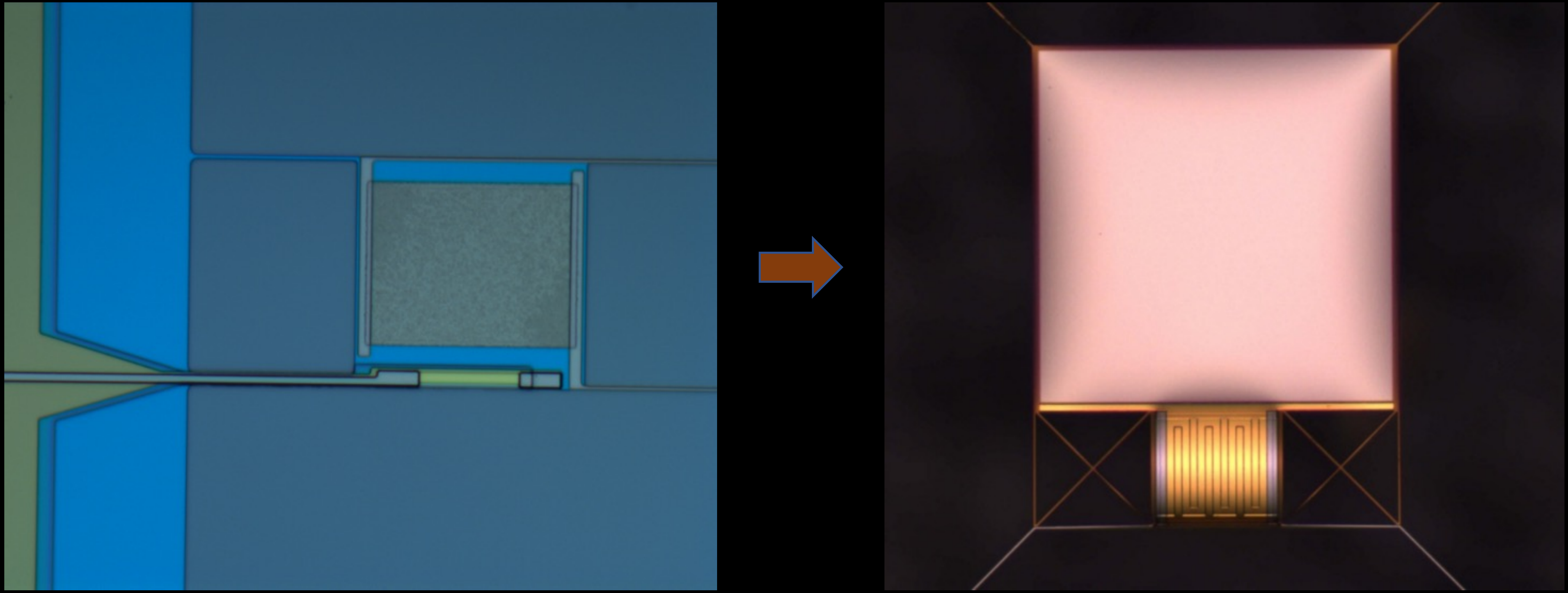


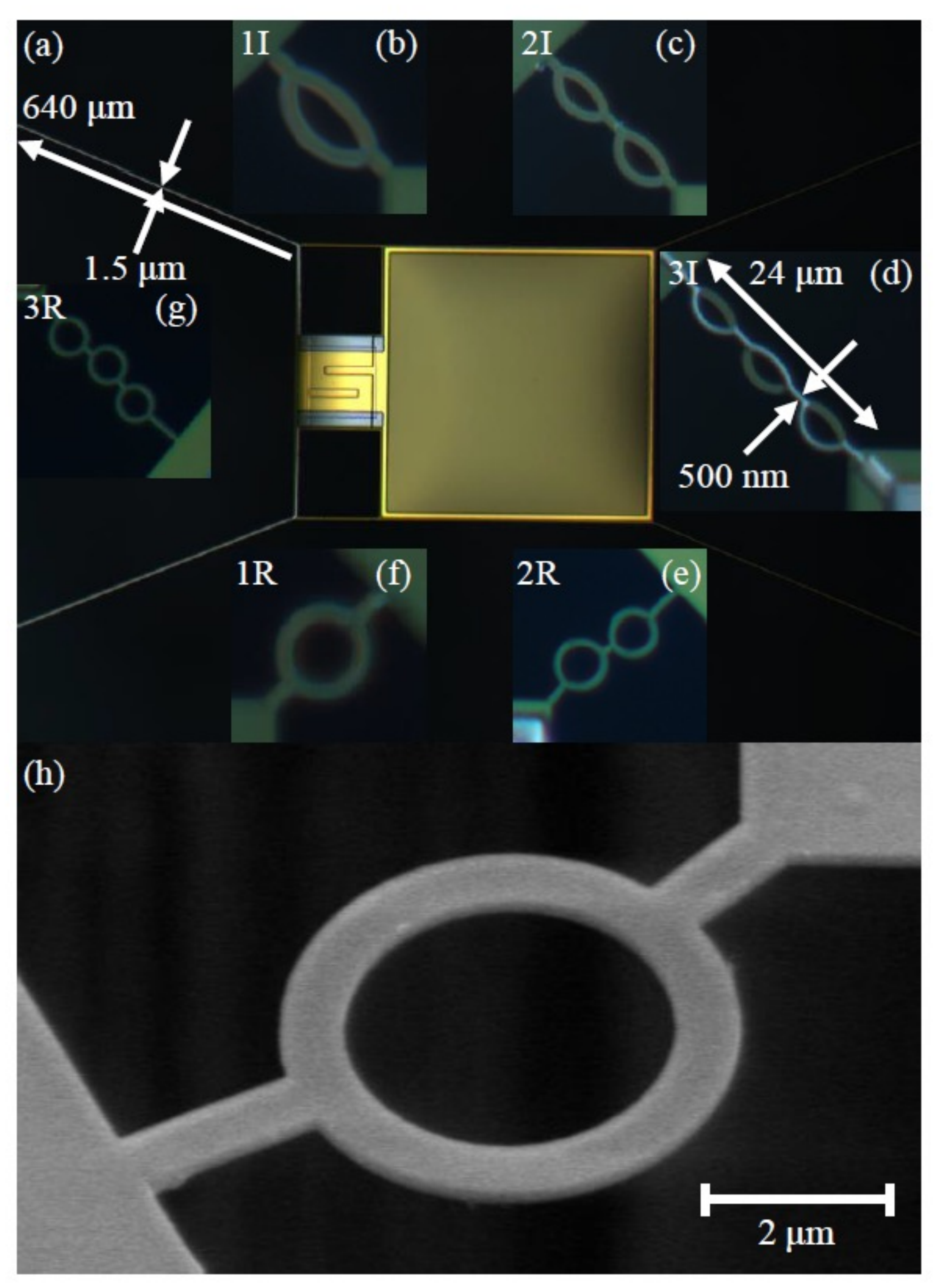
Stafford Withington
Labs @ Cambridge

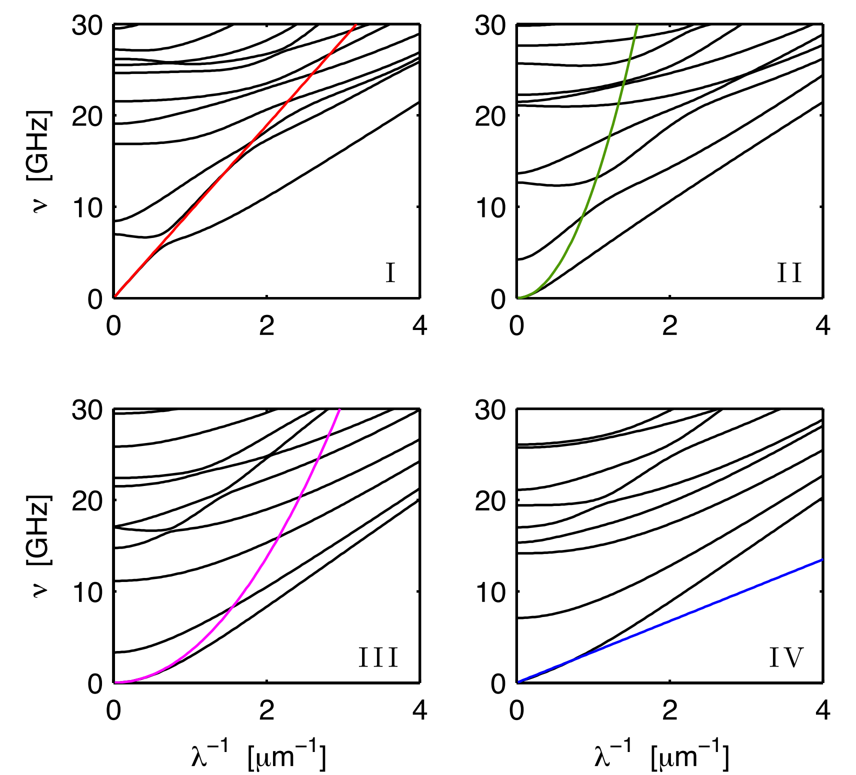
Free-space and *microstrip* coupled TESs

Submillimetre-wave (3mm – 300 µm) to infrared (200-30 µm) applications

NEPs ~ 10^{-17} - 10^{-20} WHz , Psat ~ 50 pW – 5 fW, T ~ 10 µs – 10 ms







Superconducting sensors can be combined with micromachined support structures to control thermal noise through acoustic interferometry

The noise of the TES is determined solely by phonon noise in the 4 elastic modes in the interferometer, which supports the device

Superconducting device physics is a whole technology,

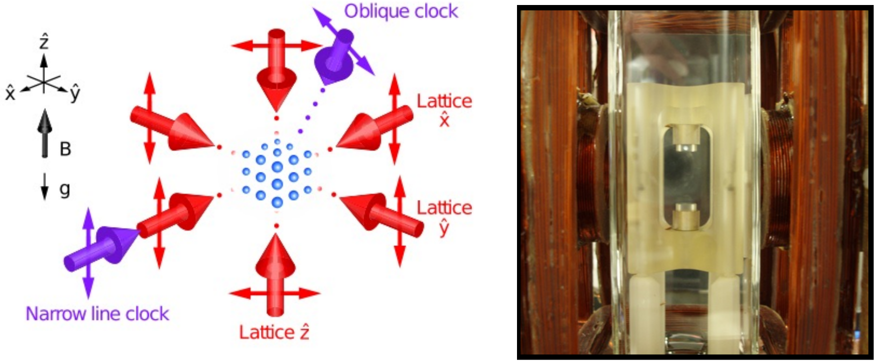
It is a thin-film technology comprising a wide portfolio of detectors, amplifiers, and mixers

It has already enabled major areas of ground and space-based experimental astrophysics

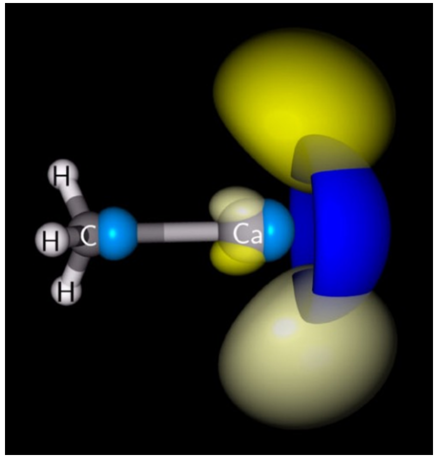
It is now being used extensively in quantum computing and communications

It can seed a new generation of fundamental physics experiments, and synergies should be sought

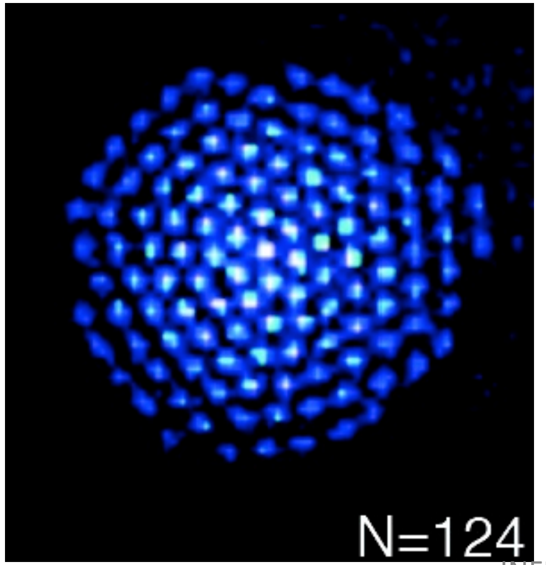
Experimental Systems



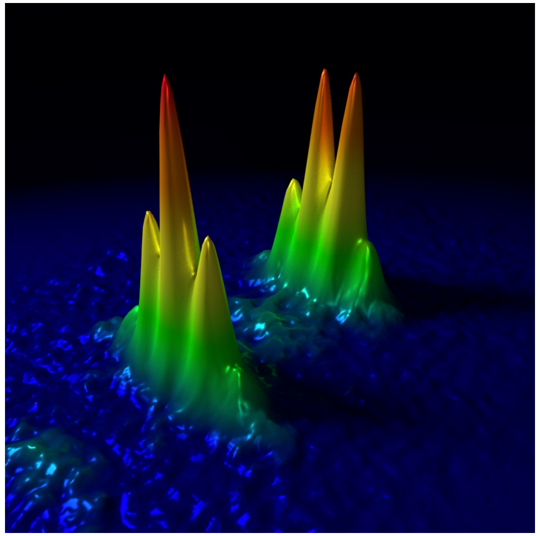
Atoms in an Optical Lattice/Cavity



Molecules

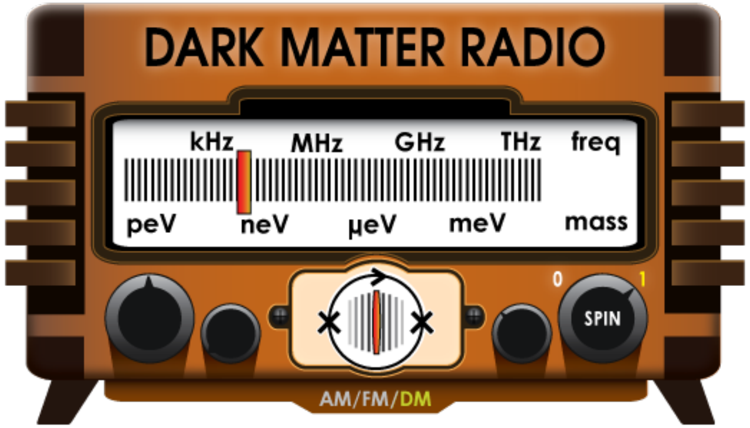


Trapped Ions

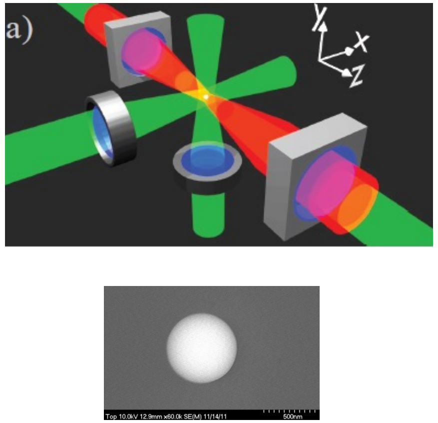


Atom Interferometers

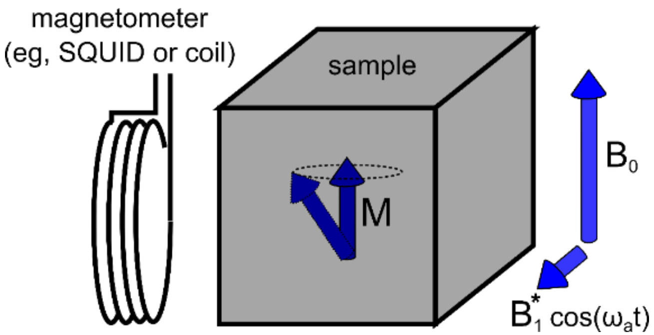
Experimental Systems, continued…



Superconducting Circuits



Nanomechanical Resonators



NMR

Commercial Quantum Annealer

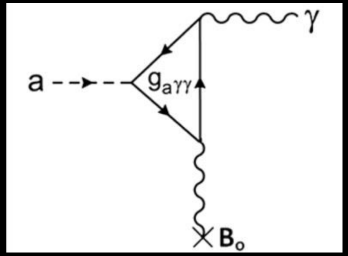
Signatures oif the Plenitude of Ultra Light Bosons

- Cosmology-independent signatures of ultra-light boson fields

- Ultra-light Dark Matter signatures

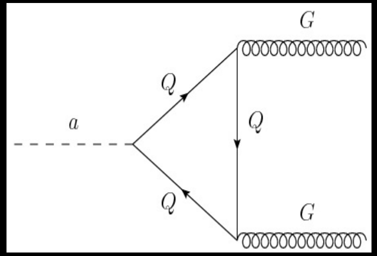
Axions (or Axion Like Particle) Couplings

- Coupling to EM Fields: $\frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$



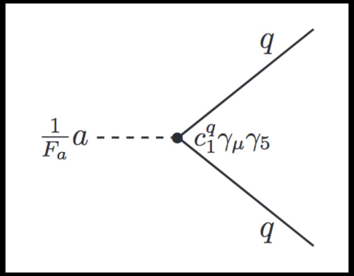
Axion – photon mixing
in a background field…

- Coupling to gluon fields: $\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$



EDM-like coupling to nucleons
Spin-coupling to nucleons

- Coupling to fermions: $\frac{\partial_\mu a}{f_a} \overline{\psi_f} \gamma^\mu \gamma_5 \psi_f$



spin coupling to fermions

Dark Photon Couplings

Couples through mixing with the Standard Model photon

$$\epsilon(\overrightarrow{E'} \cdot \overrightarrow{E} + \overrightarrow{B'} \cdot \overrightarrow{B})$$

Decouples as its mass goes to zero

Based on a slide
by Mina Arvanitaki

Moduli, dilatons and other scalars

Couple non-derivatively to the Standard Model

Examples of couplings

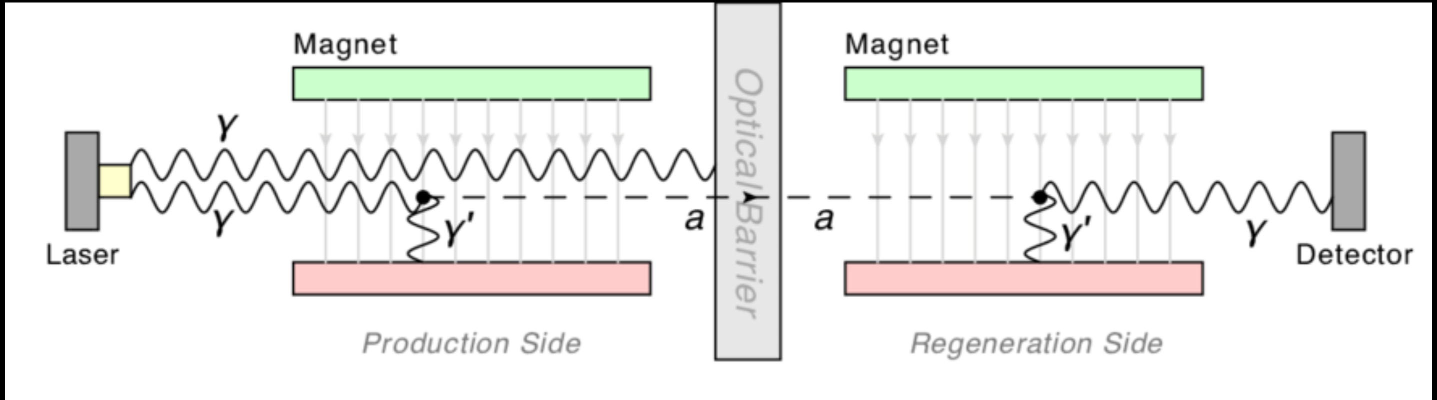
$$\mathcal{L} = \mathcal{L}_{SM} + \sqrt{\hbar c}\frac{\phi}{\Lambda}\mathcal{O}_{SM}$$

$$\mathcal{O}_{SM} \equiv m_e e\bar{e},\ m_q q\bar{q},\ G_s^2,\ F_{EM}^2, \ldots$$

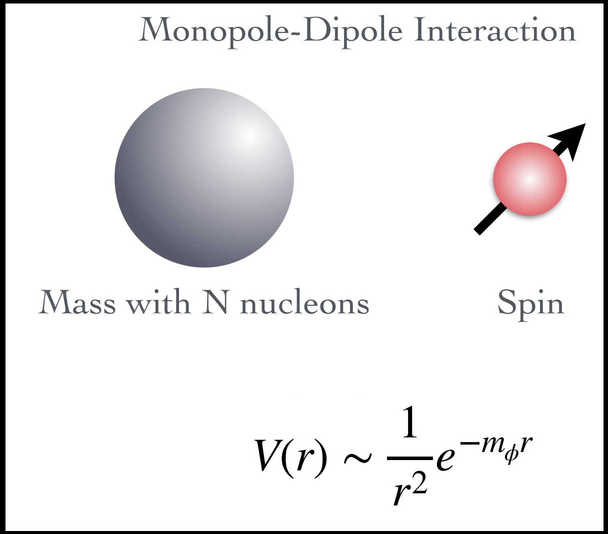
Based on a slide
by Mina Arvanitaki

Cosmology-independent Axion Signatures

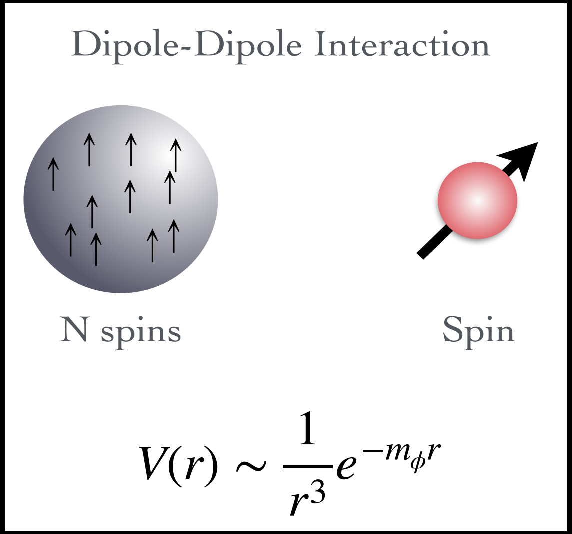
Shining light through walls



New long range forces



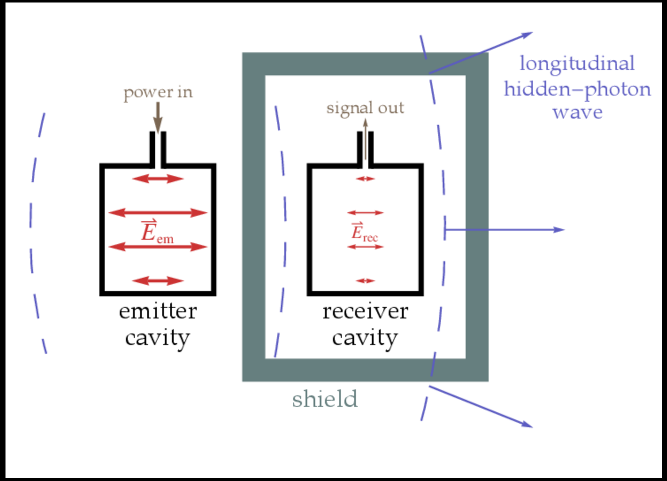
$$V(r) \sim \frac{1}{r^2} e^{-m_\phi r}$$



$$V(r) \sim \frac{1}{r^3} e^{-m_\phi r}$$

Cosmology-independent Dark Photon Signatures

Coupled cavity searches



Short range modifications to Coulomb's law

Moduli Signatures

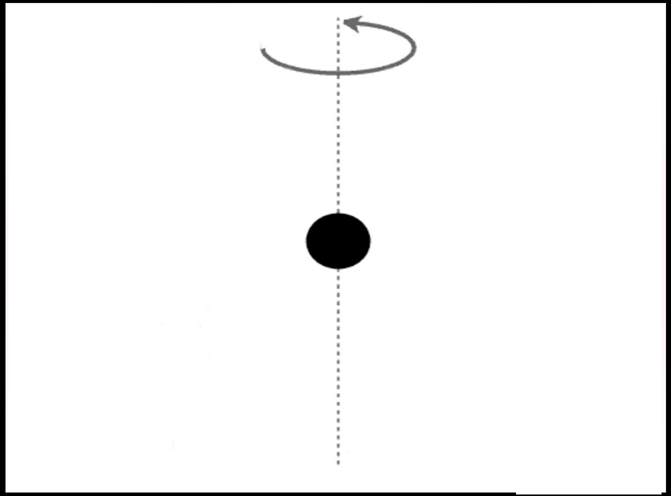
Fifth-force searches

$$V(r) \sim \frac{1}{r} e^{-m_\phi r}$$

Equivalence Principle violation searches

All boson Signatures

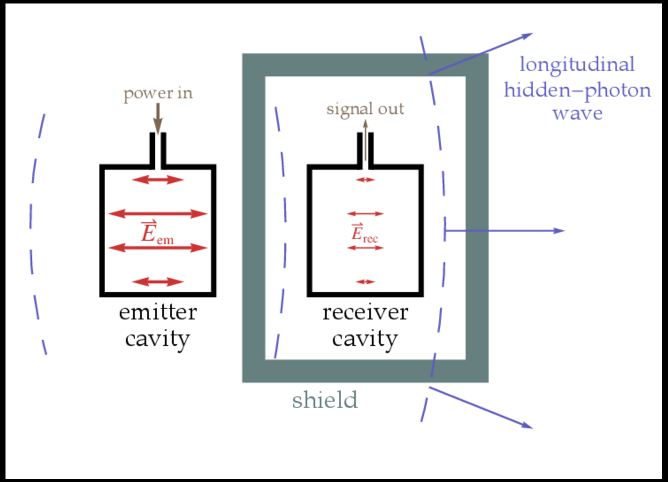
Black Hole super-radiance



Compton Wavelength comparable to the size of the Black Hole

Cosmology-independent Dark Photon Signatures

Coupled cavity searches



Short range modifications to Coulomb's law

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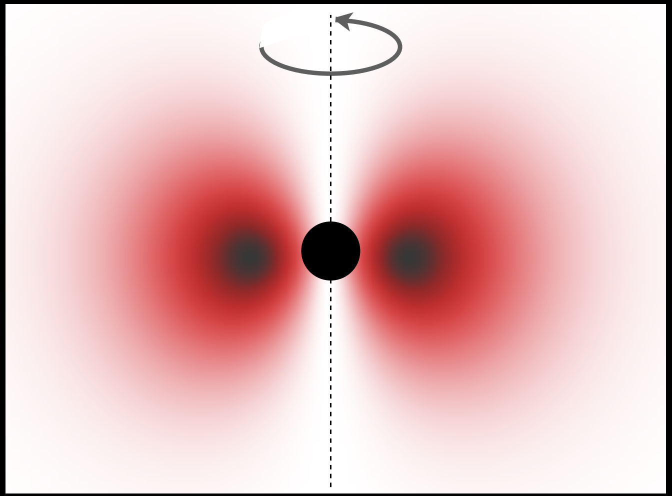


Compton Wavelength comparable to the size of the Black Hole

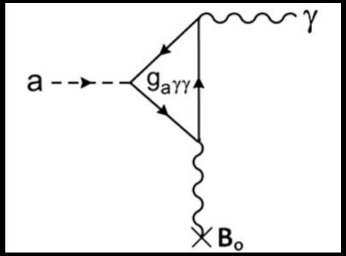
Ultra-light bosons as Dark Matter

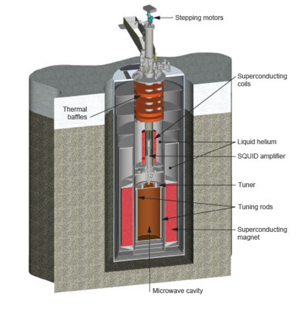
- Self-consistent Dark Matter production mechanism
  - Misalignment for scalars (m_{DM}>10^{-22}eV)
  - Inflationary production for dark photons (m_{DM}>10^{-5} eV)
- Large array of possible experimental probes
- All are absorption experiments
- Ultra-light Dark Matter is not necessarily stable

Based on a slide
by Mina Arvanitaki

Axion Dark Matter

- Coupling to EM Fields: $\frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$





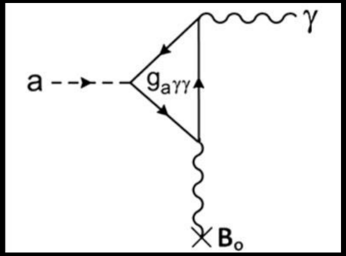
Cavity size = Axion size

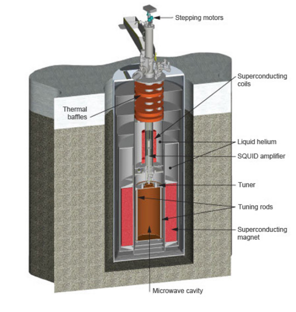
ADMX, HAYSTAC, CAST, …

Axion Dark Matter

- Coupling to EM Fields: $\frac{a}{f_a}\, F^{\mu\nu}\, \tilde{F}_{\mu\nu}$

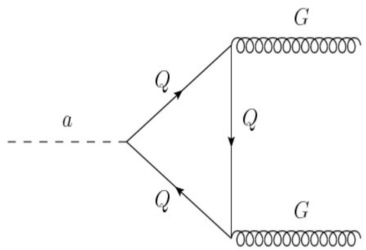
- Coupling to gluon fields: $\frac{a}{f_a}\, G_{\mu\nu}\, \tilde{G}^{\mu\nu}$

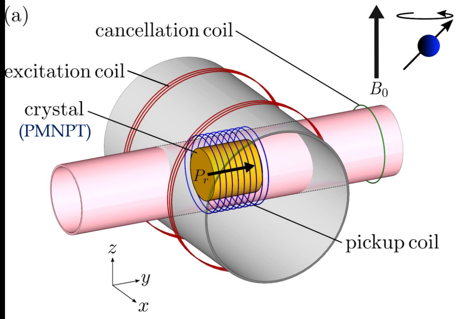




Cavity size = Axion size

ADMX, HAYSTAC, CAST, …



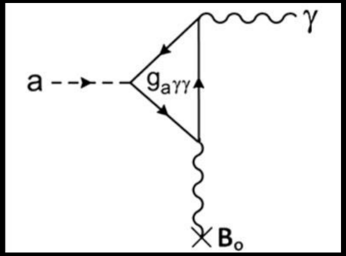


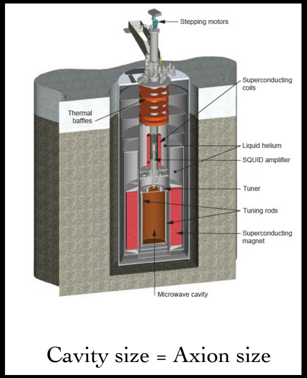
CASPER-Electric
(nucleon EDM)

CASPER-wind
Spin coupling

Axion Dark Matter

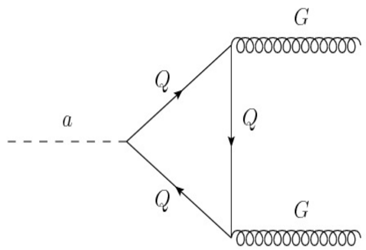
- Coupling to EM Fields: $\frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$



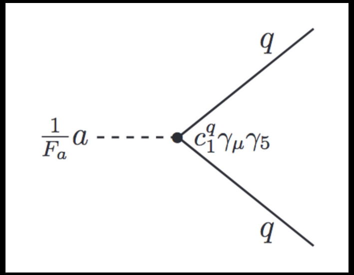


ADMX, HAYSTAC, CAST, …

- Coupling to gluon fields: $\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$



- Coupling to fermions: $\frac{\partial_\mu a}{f_a} \overline{\psi_f} \gamma^\mu \gamma_5 \psi_f$



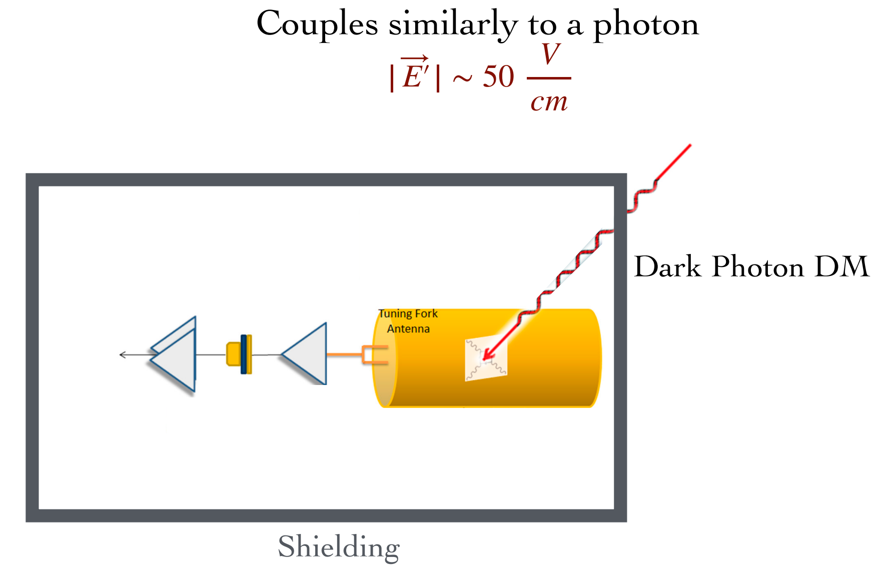
- Coupling to EM Fields: $\frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$
- Coupling to gluon fields: $\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$
- Coupling to fermions: $\frac{\partial_\mu a}{f_a} \overline{\psi_f} \gamma^\mu \gamma_5 \psi_f$

CASPER-Electric
(nucleon EDM)

CASPER-wind
Spin coupling

CASPER-Gradient
(spin coupling to axion gradient)

Dark Photon Dark Matter



Moduli Dark Matter

Causes variation of fundamental constants

- The energy splitting of atoms and nuclei oscillate with time
  - Atomic clocks & atom interferometry
- The size of atoms changes with time
  - Resonant mass detectors & oscillator searches

Ultra-light Boson Summary

The possible existence of ultra-light bosons is well-motivated

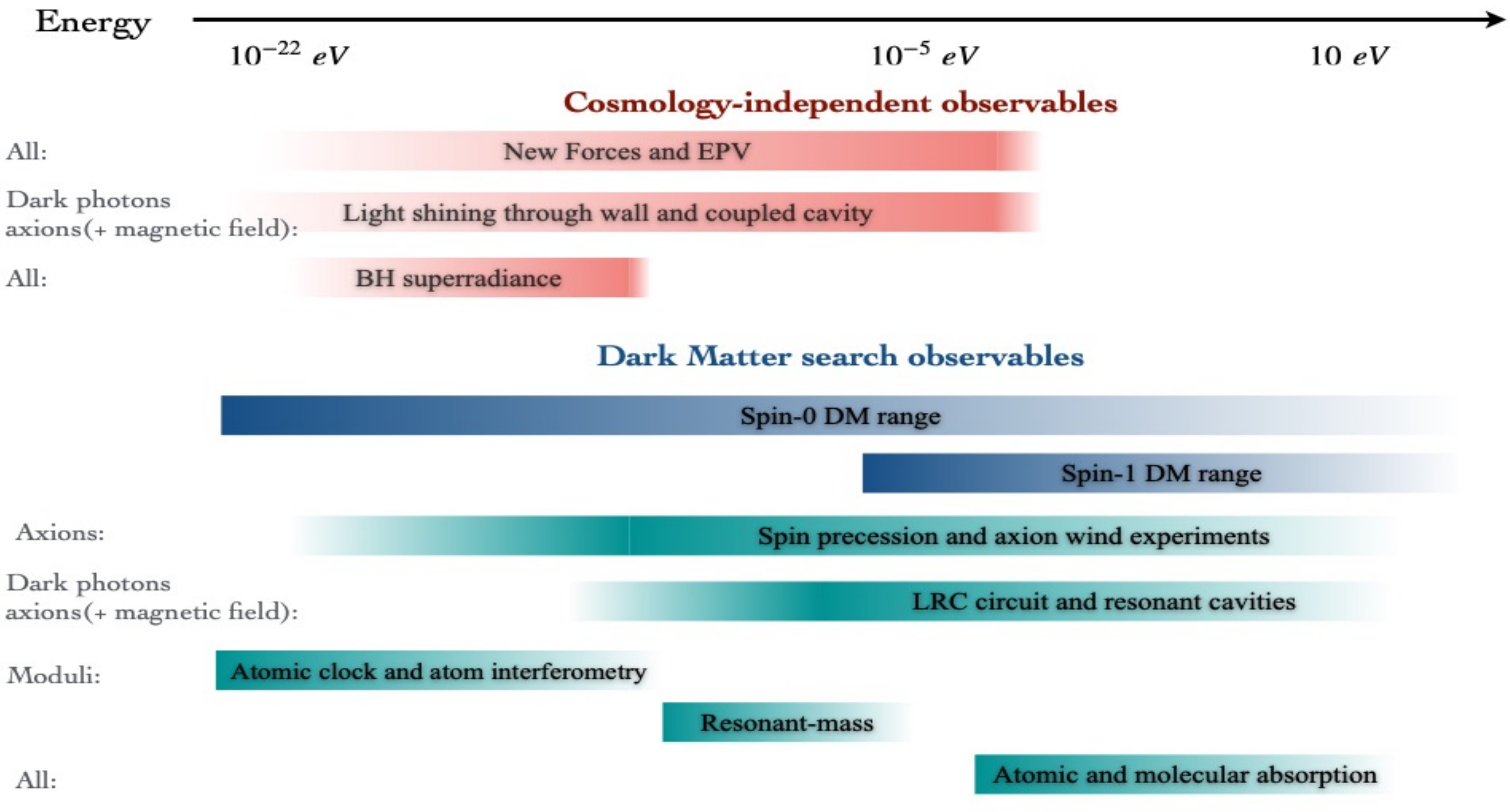
They can be probed across a wide-variety of energy scales, even solely through their gravitational interaction

They are excellent dark matter candidates.

Based on a slide
by Mina Arvanitaki

Signatures for ultra light dark bosons

Based on a slide
by Mina Arvanitaki



Energy

$10^{-22}\ eV$ $10^{-5}\ eV$ $10\ eV$

Cosmology-independent observables

All: New Forces and EPV

Dark photons axions(+ magnetic field): Light shining through wall and coupled cavity

All: BH superradiance

Dark Matter search observables

Spin-0 DM range

Spin-1 DM range

Axions: Spin precession and axion wind experiments

Dark photons axions(+ magnetic field): LRC circuit and resonant cavities

Moduli: Atomic clock and atom interferometry

Resonant-mass

All: Atomic and molecular absorption

Quantum Technologies and Particle Physics

- The nature of dark matter

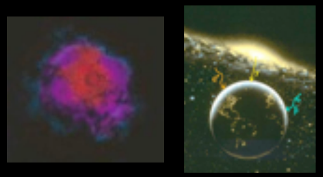
Quantum Technologies and Particle Physics

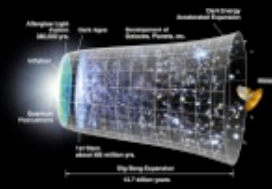
- The nature of dark matter
- The earliest epochs of the universe at temperatures >> 1TeV
- The existence of new forces
- The violation of fundamental symmetries (electron and nucleon EDMs)
- The possible existence of dark radiation and the cosmic neutrino background
- The possible dynamics of dark energy
- The measurement of neutrino mass
- Tests of the equivalence principle
- Tests of quantum mechanics
- A new gravitational wave window to the Universe:
  - LIGO sources before they reach LIGO band
  - Multi-messenger astronomy: optimal band for sky localization
  - Cosmological sources

Yellow indicates areas where ultra light bosons may play a role

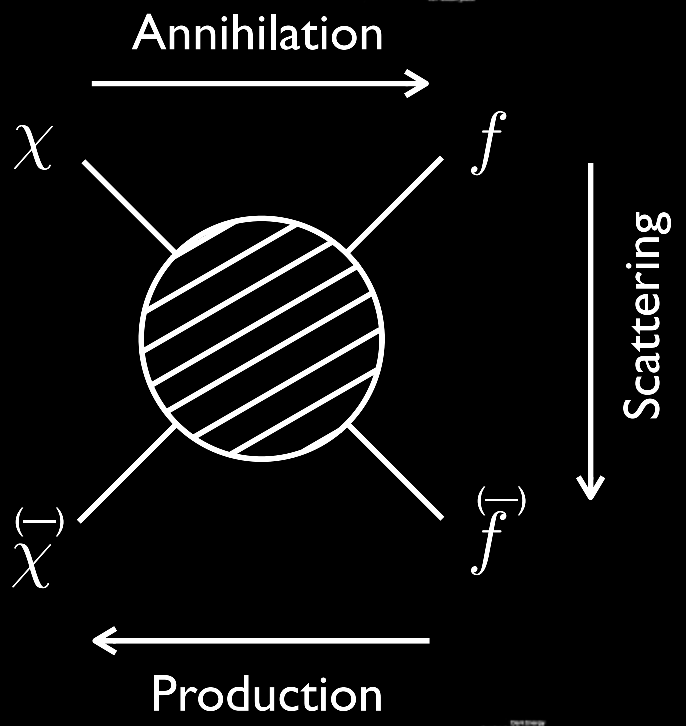
Dark Matter Experimental approaches

Indirect detection

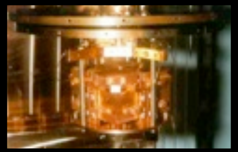


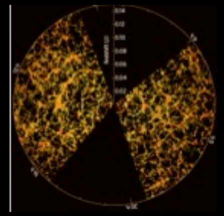


Cosmic density



Direct detection

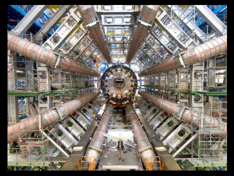


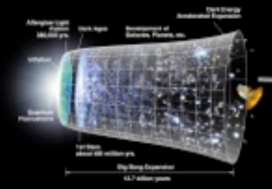


Large scale structure

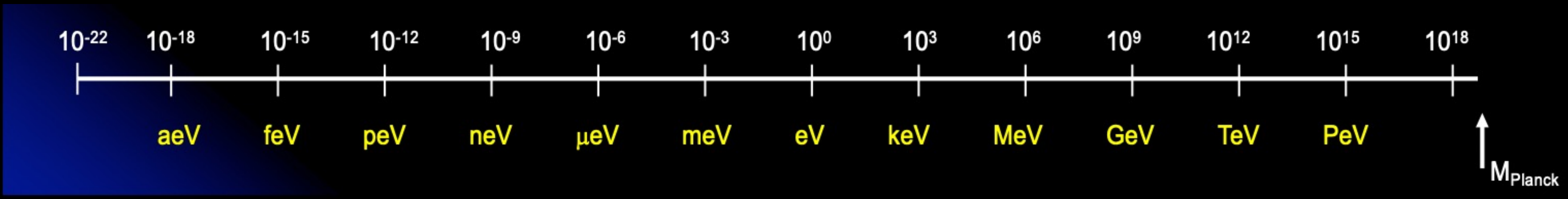
Complementary

Colliders





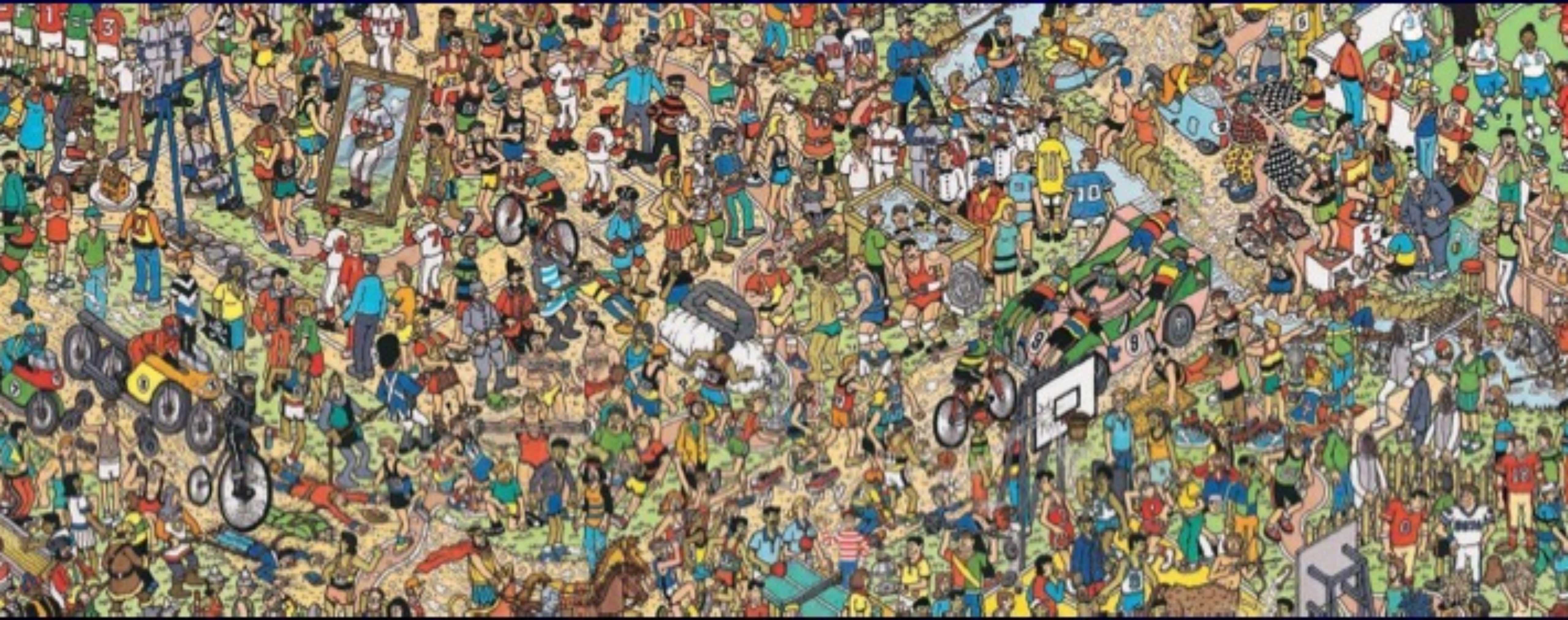
Cosmic density


10^{-22}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
M_{Planck}

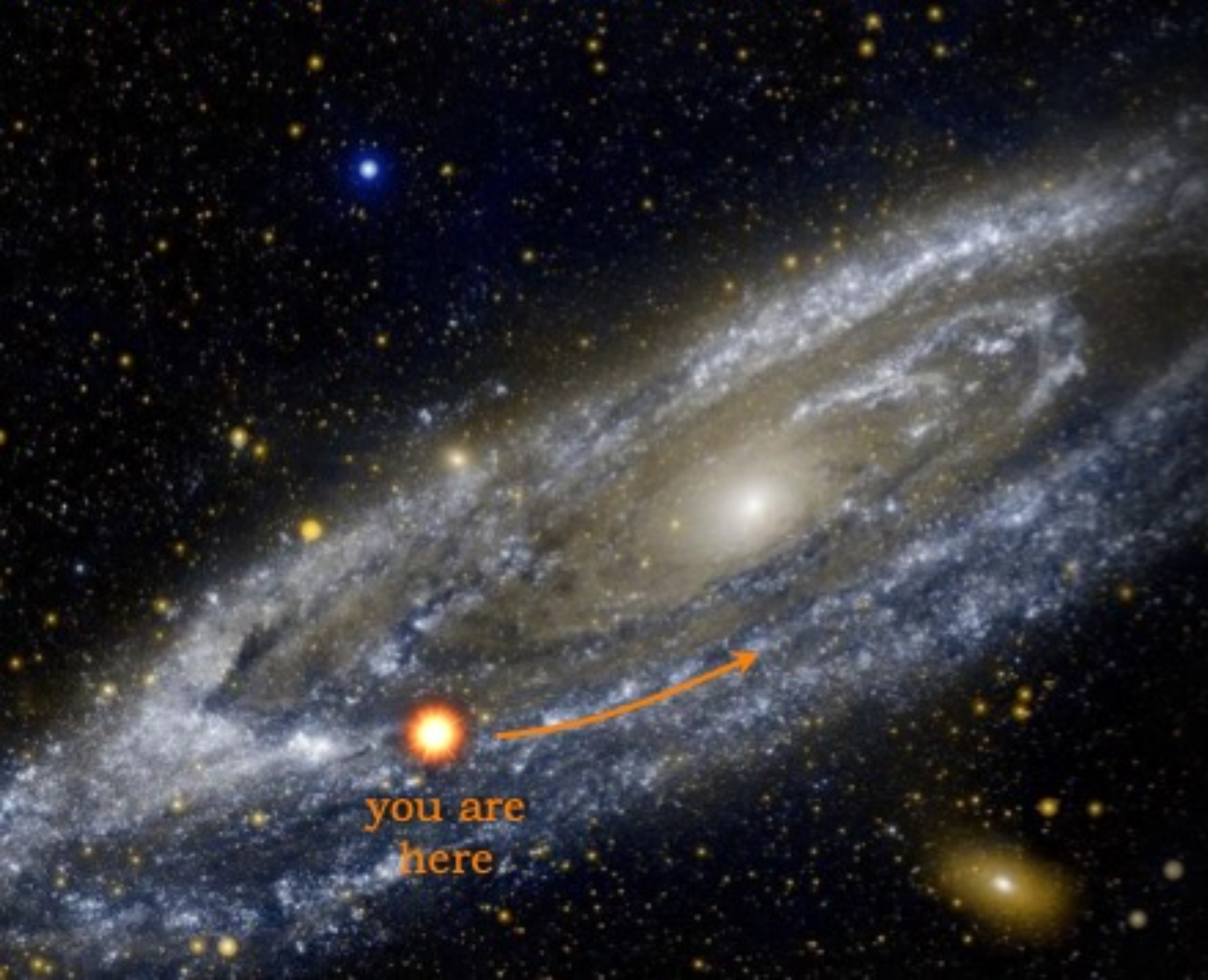
Possible Dark Matter Masses

~90 orders of magnitude

10^{-21}eV eV GeV PeV M_{Planck} kg 10^{50}eV $M_{☽}$ $M_{\odot}$



Direct Dark Matter Detection

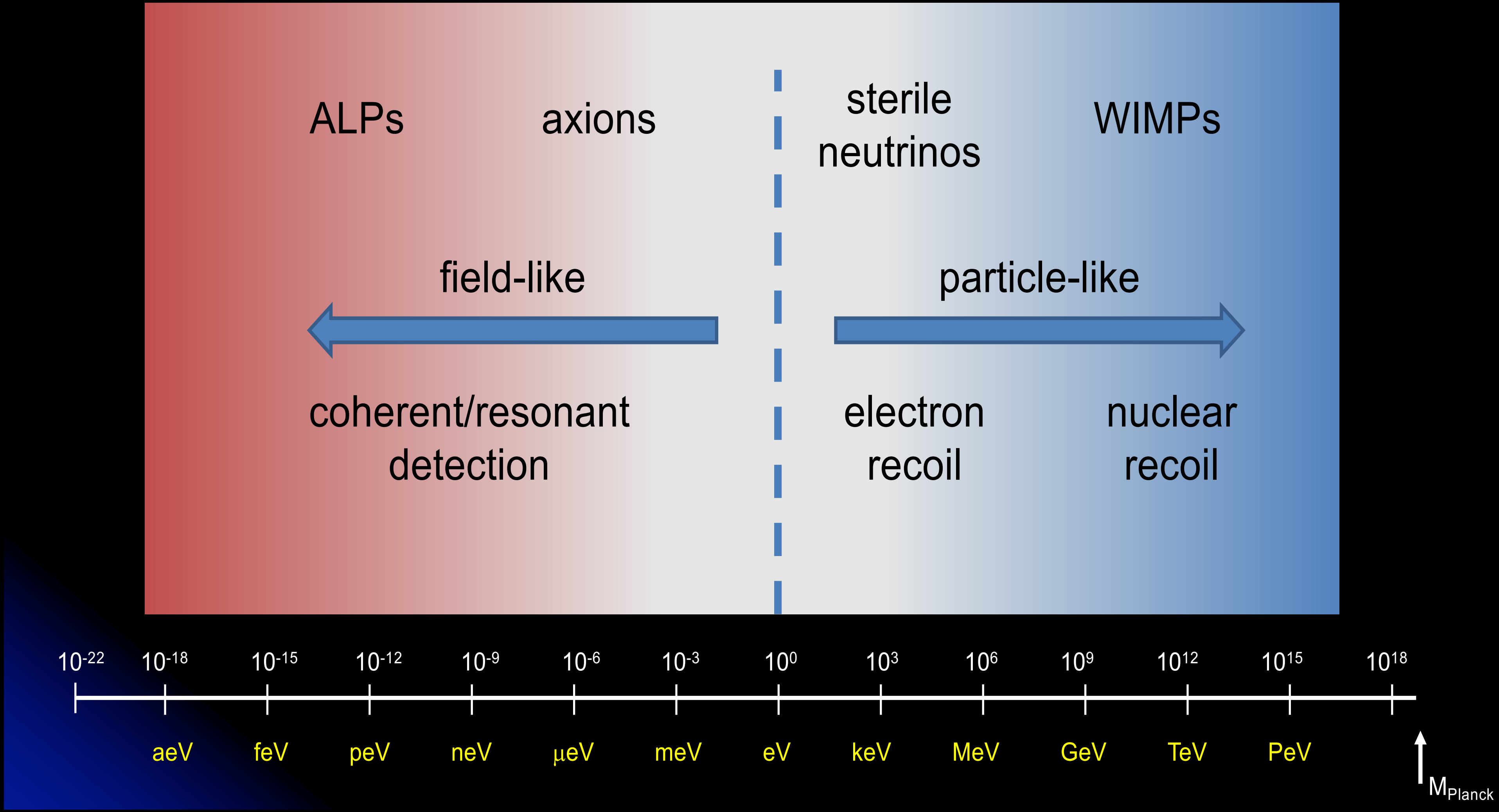


local dark matter mass density is known:

$\varrho_{\mathrm{DM},\oplus} \approx 0.3\,\mathrm{GeV/cm^3}$

aim to detect non-relativistic wind of dark matter quanta (waves or particles)

Dark Matter Searches



Quantum Technologies open a new frontier on field-like dark matter

Dark Matter Search Strategy

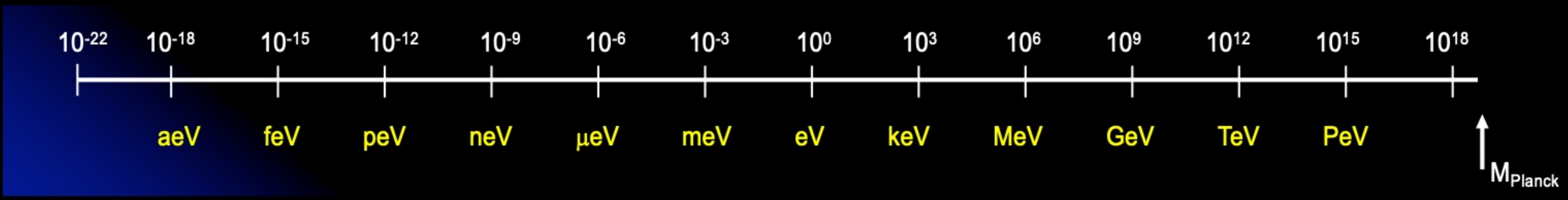
The two theoretically best-motivated candidates:

AXIONS (light)

"table top" expts with quantum sensors

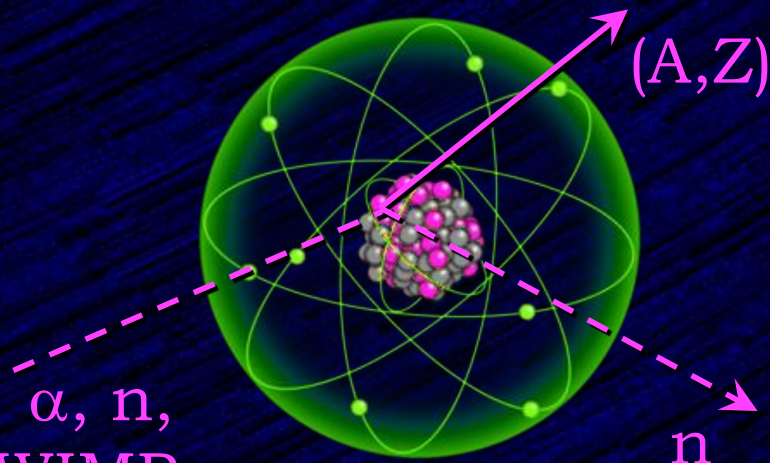
WIMPS (heavy)

Multi-ton expts deep underground



Thermal Relic Direct Detection: Nonrelativistic Scattering

Nuclear Recoils

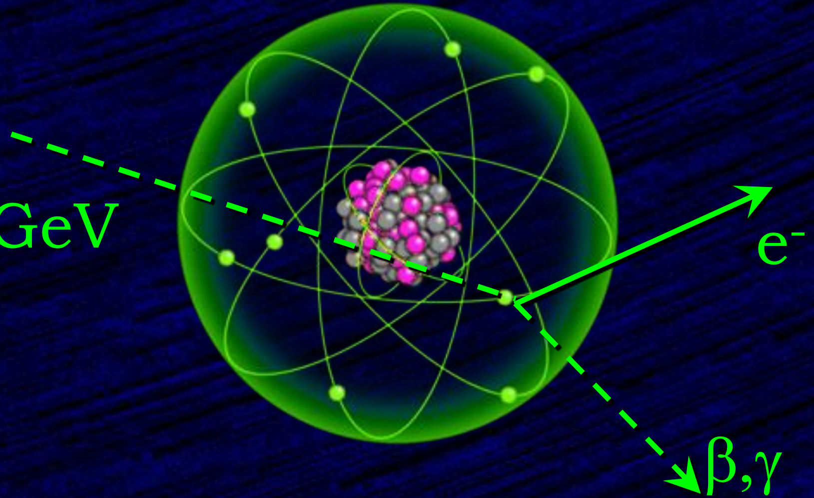


(A,Z)

α, n,
WIMPs

n

Electronic Recoils



β, γ,
sub-GeV
relic

e^-

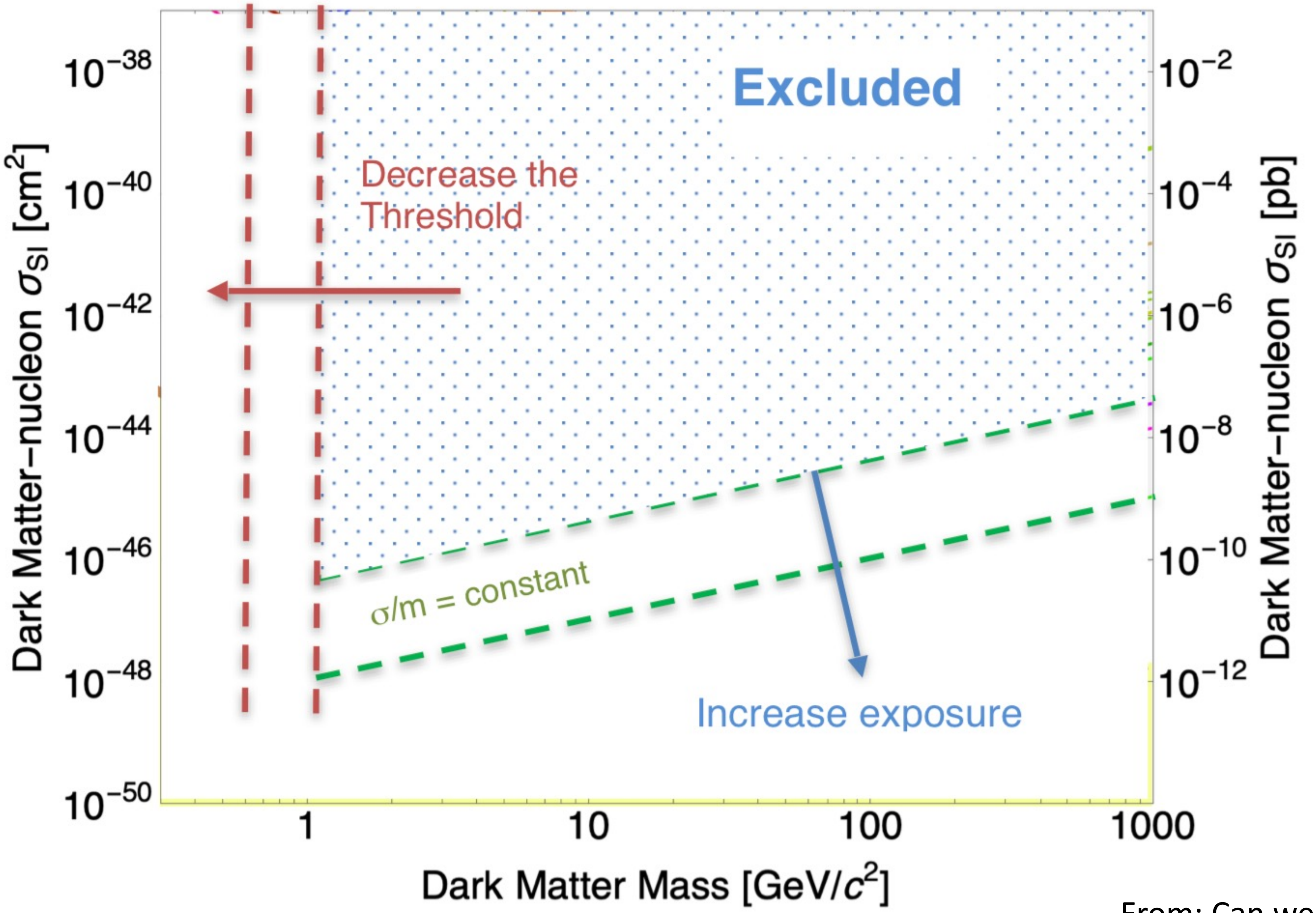
β,γ

XENONnT (LNGS) & LZ (SURF)

Similar technology, size, and timeline
Each >5000kg Xe in TPC

Both collaborations taking data this year

tection



All Nuclear Recoil limits are scaled to a local dark matter density of 0.3 GeV/c^2

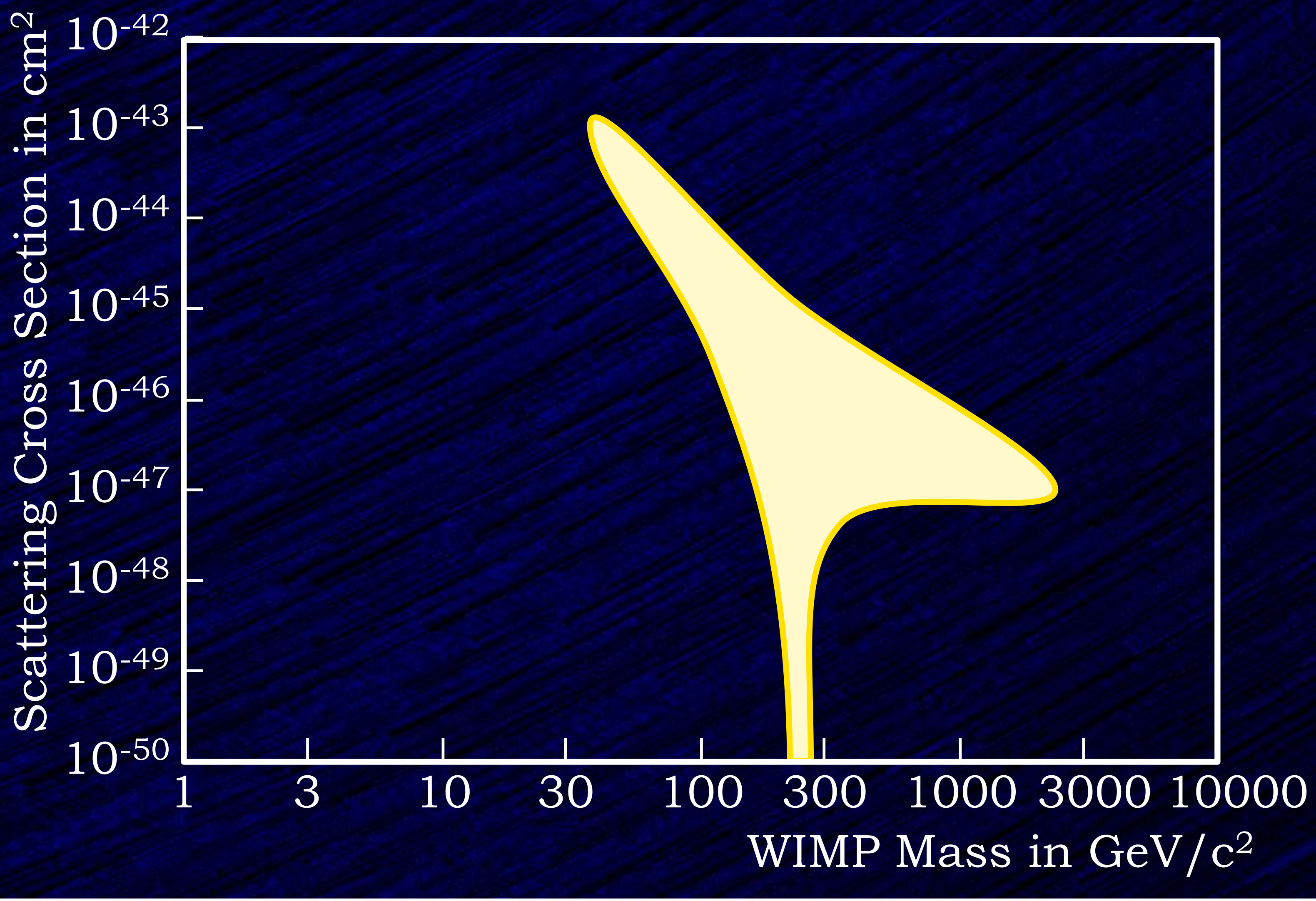
From: Can we feel Dark Matter?
at INFIERI 2021

WIMP Detection: Target

Plot Cross Section versus WIMP mass

fill with your own prior

e.g. Z-mediation through a box, Higgs-mediated, MSSM, …



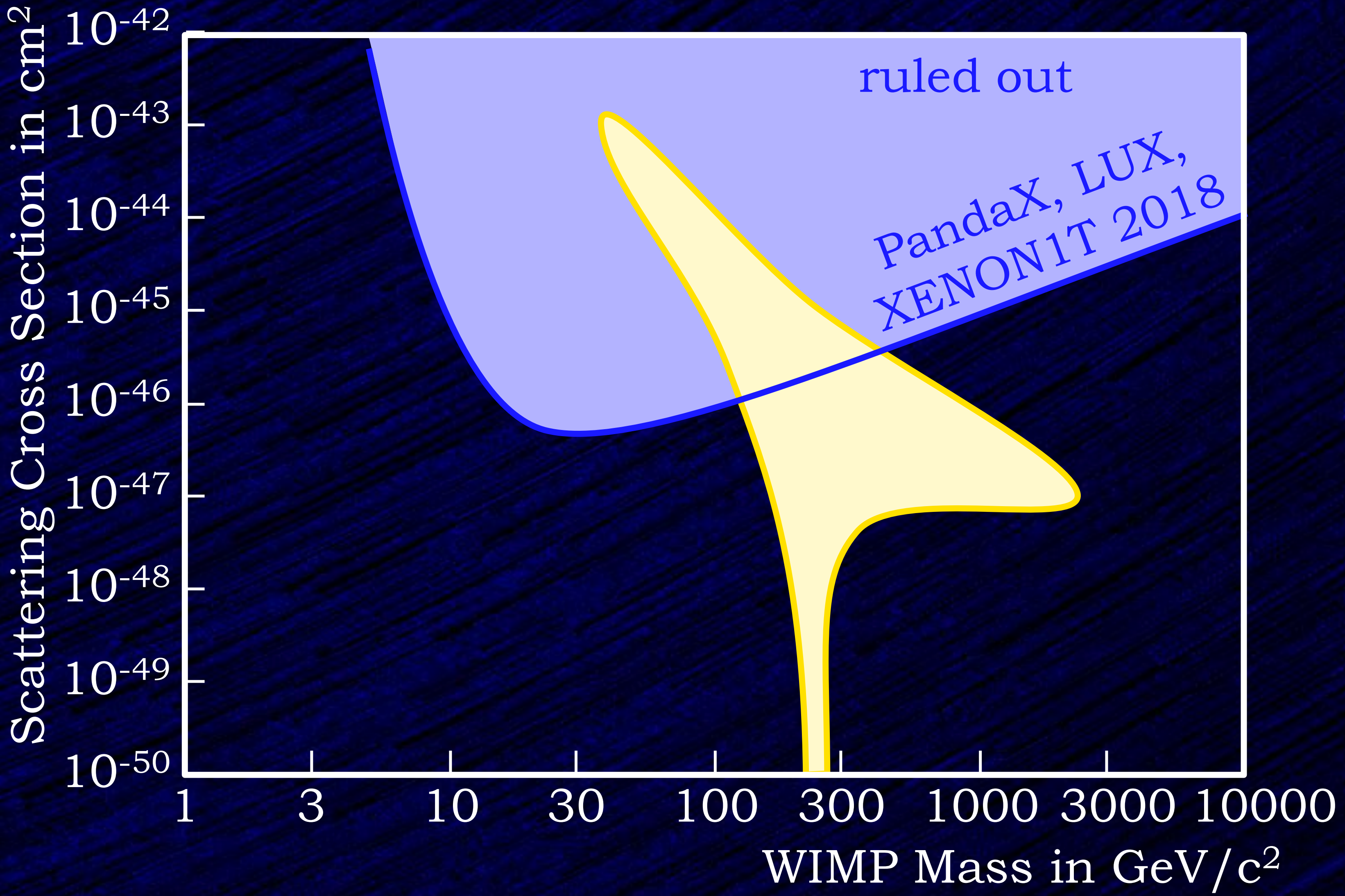
Ellis,Ferstl&Olive hep-ph/0001005

WIMP Detection: Status

Best limits all from xenon experiments

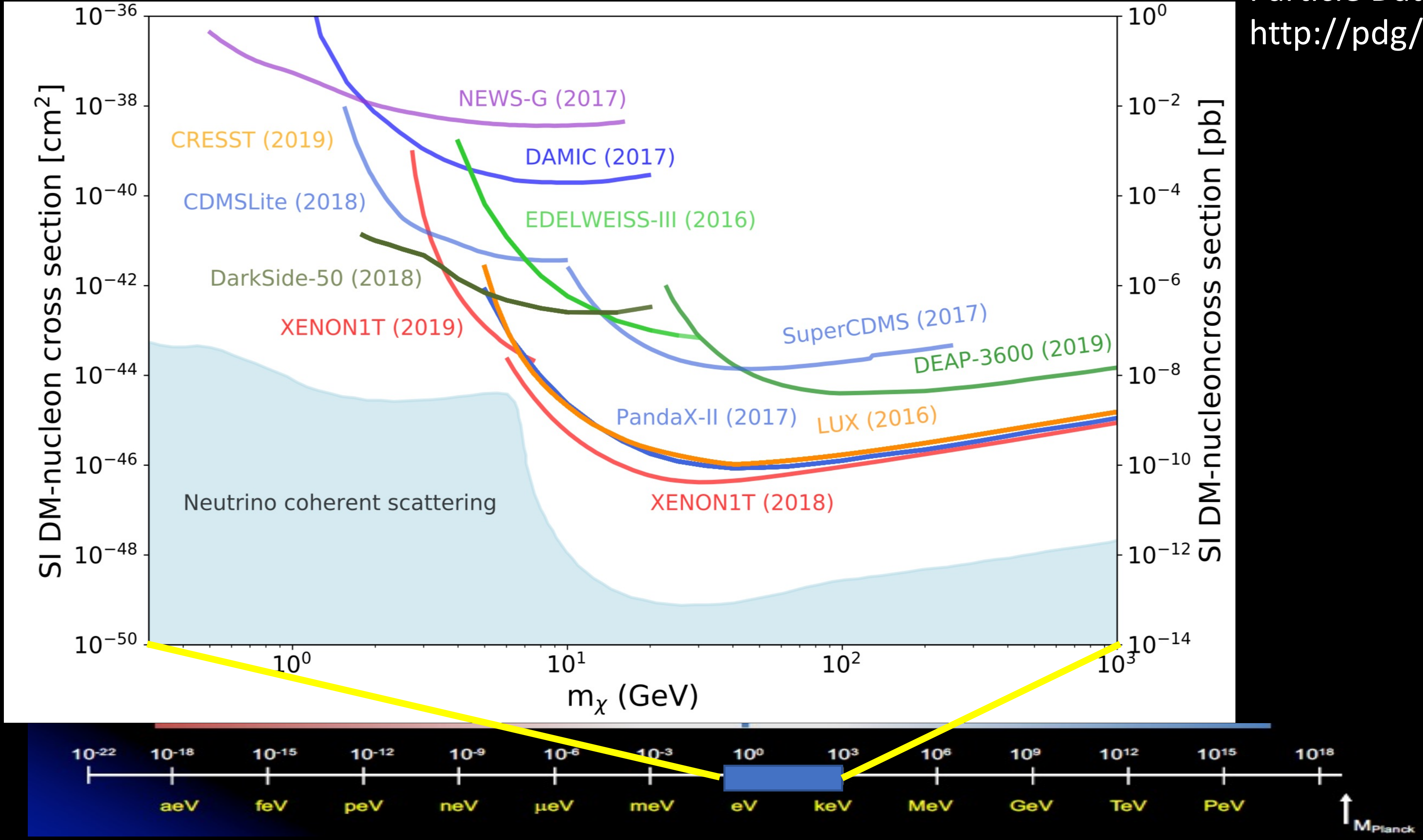
Low masses: fight threshold

High masses: number density decreases as mass density is fixed

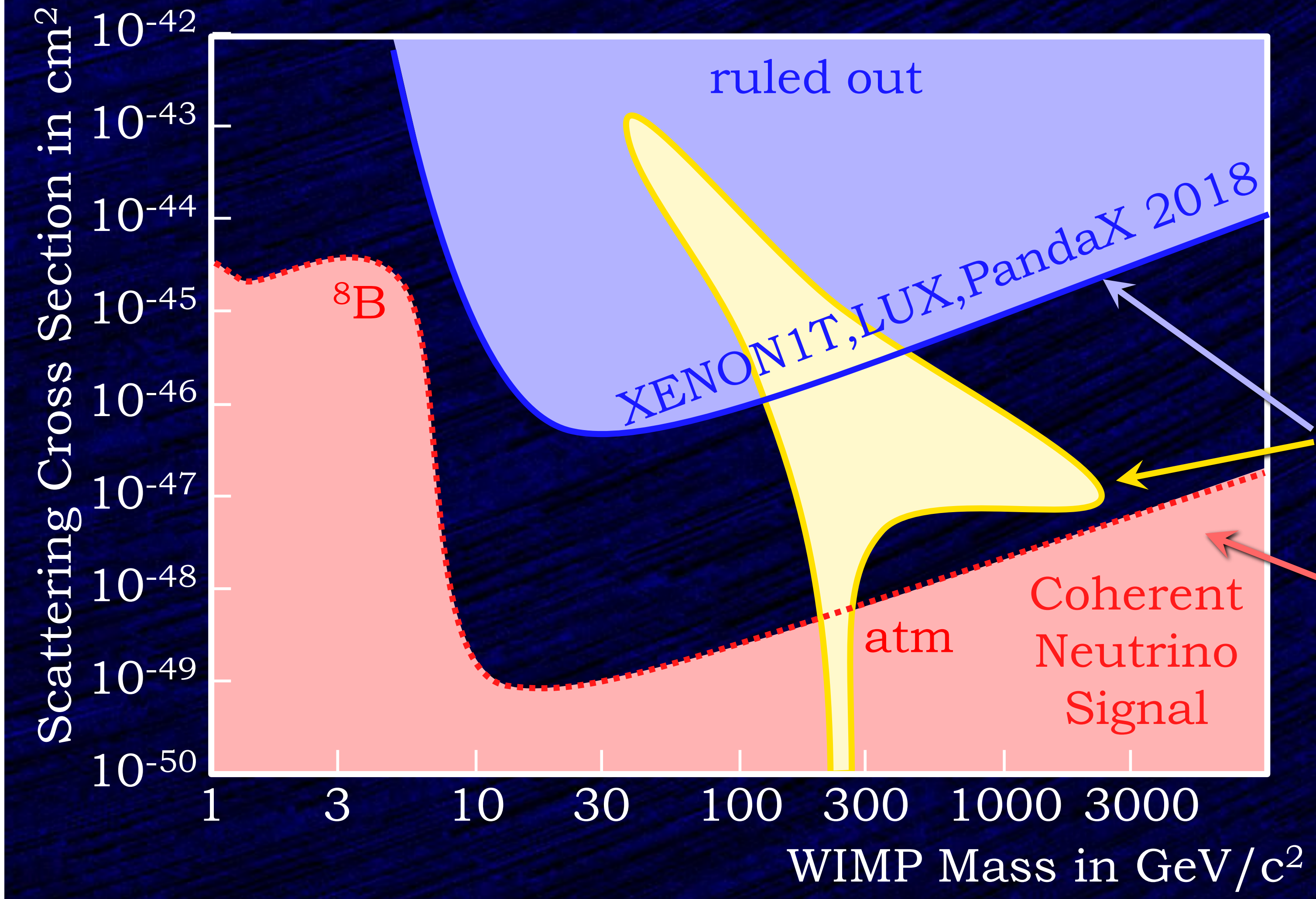


WIMP Dark Matter Searches

Particle Data Group, 2020
http://pdg/lbl/gov



Dark Matter and the Neutrino ~~Floor~~ Fog



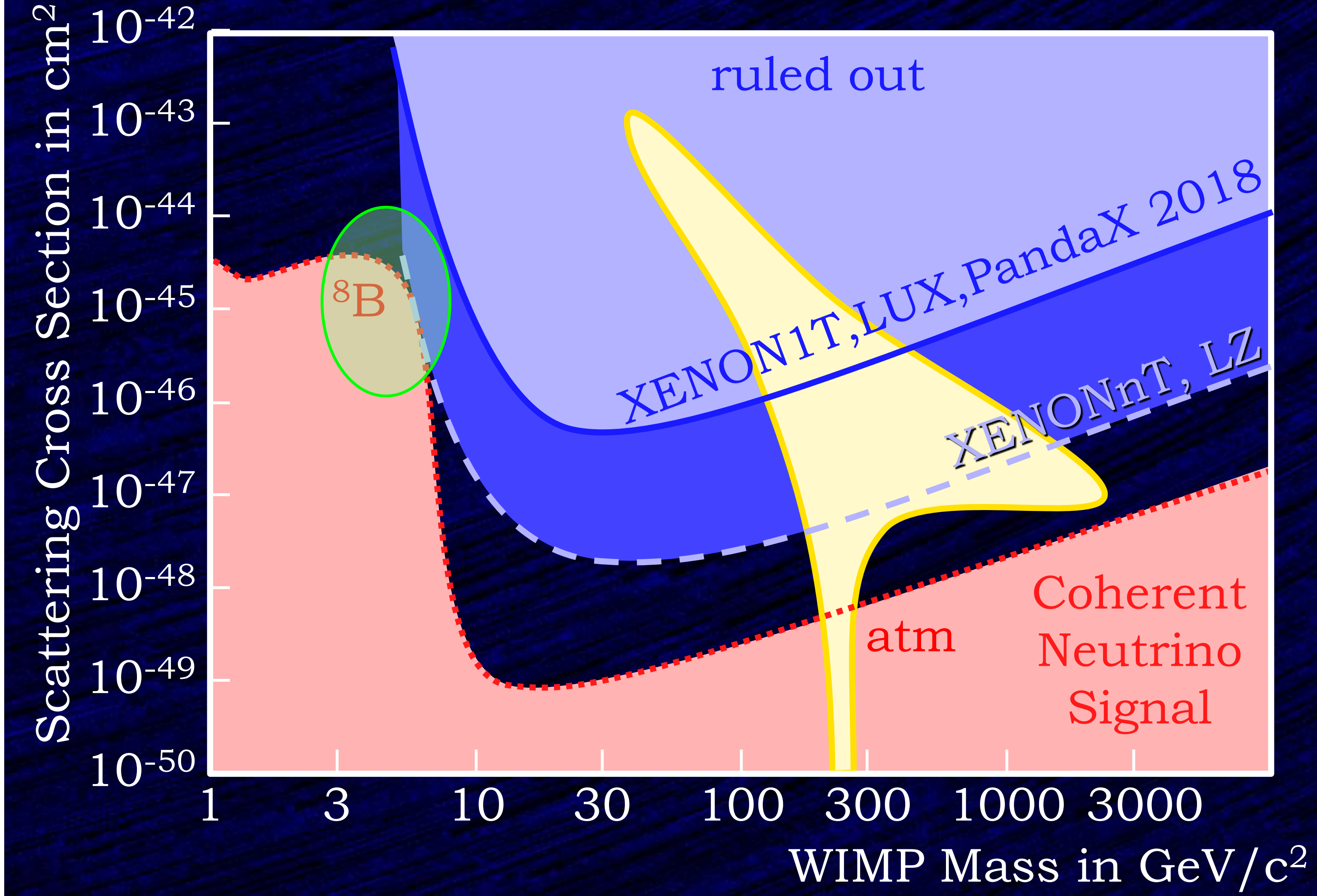
Simple scattering kinematics: degenerate in momentum

heavy WIMP, $v \sim 10^{-3}c$

Coherent Neutrino-Nucleus Scattering light ν, v~c

Billard, Strigari, Figueroa-Feliciano 1307.5458

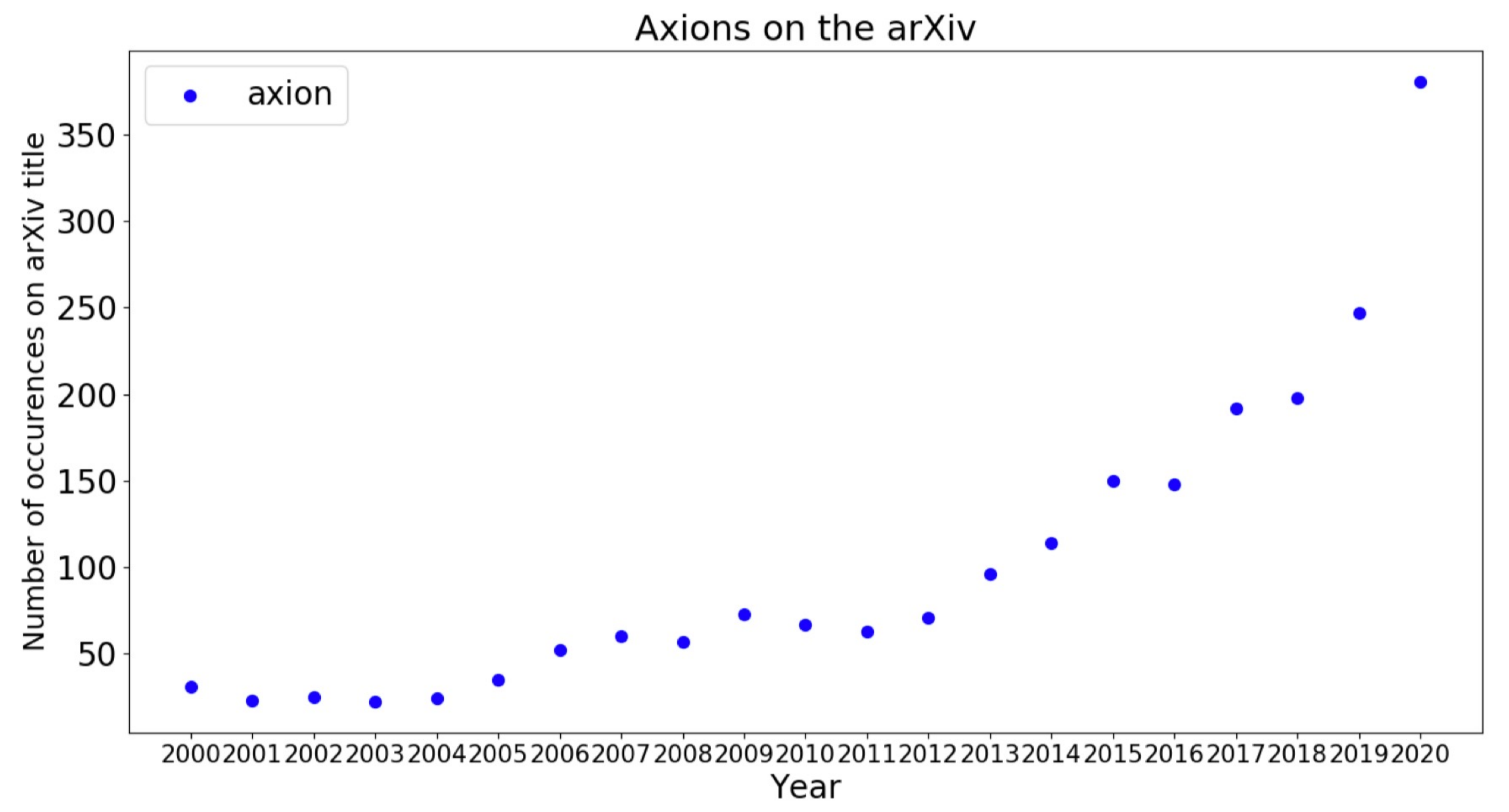
Solar ^{8}B CEνNS as soon as 2022



LZ & XENONnT: strong program going forward

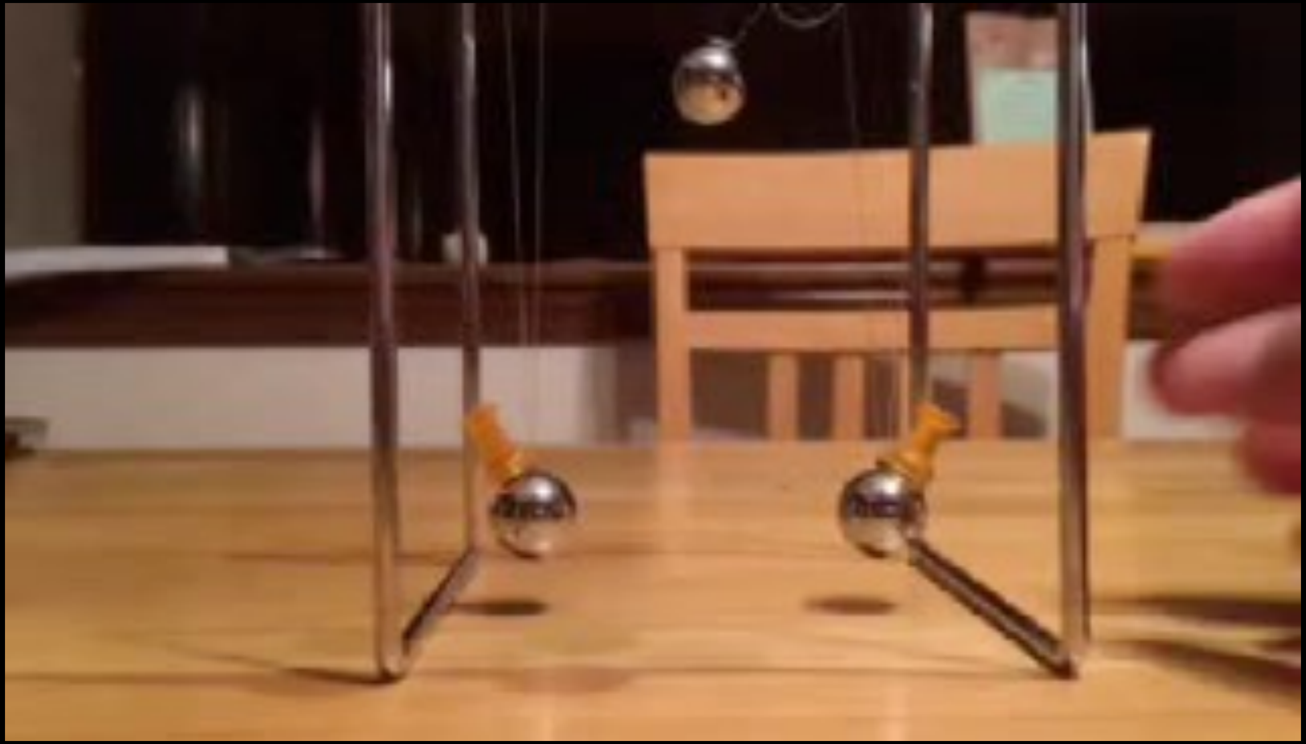
Both detectors will detect ^{8}B CEνNS

Surge of interest in axions



An oscillator (resonance) detector can accumulate the weak interactions of light dark matter over many “swings”

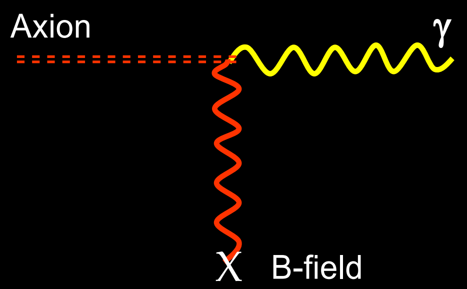
Detection oscillator

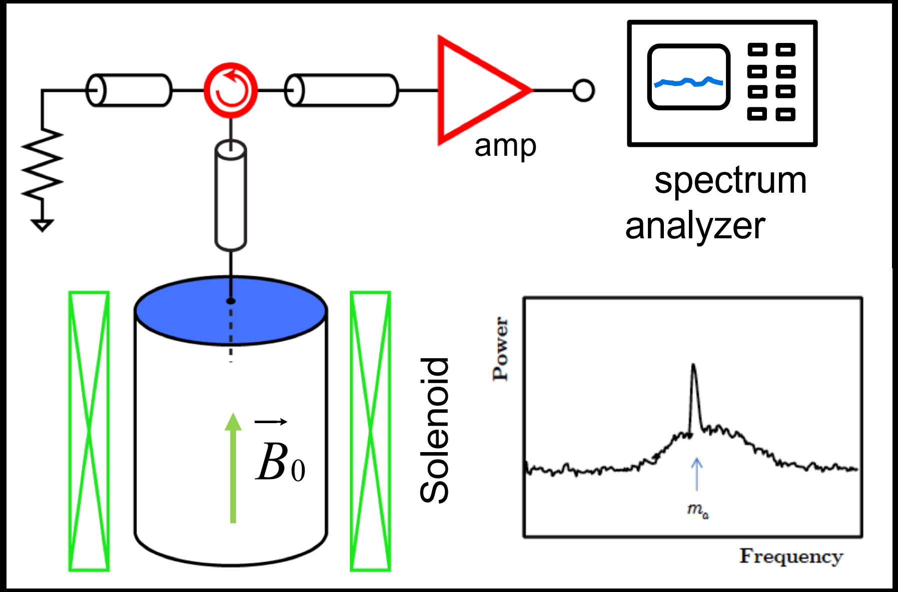


Axion wave

Cavity based searches

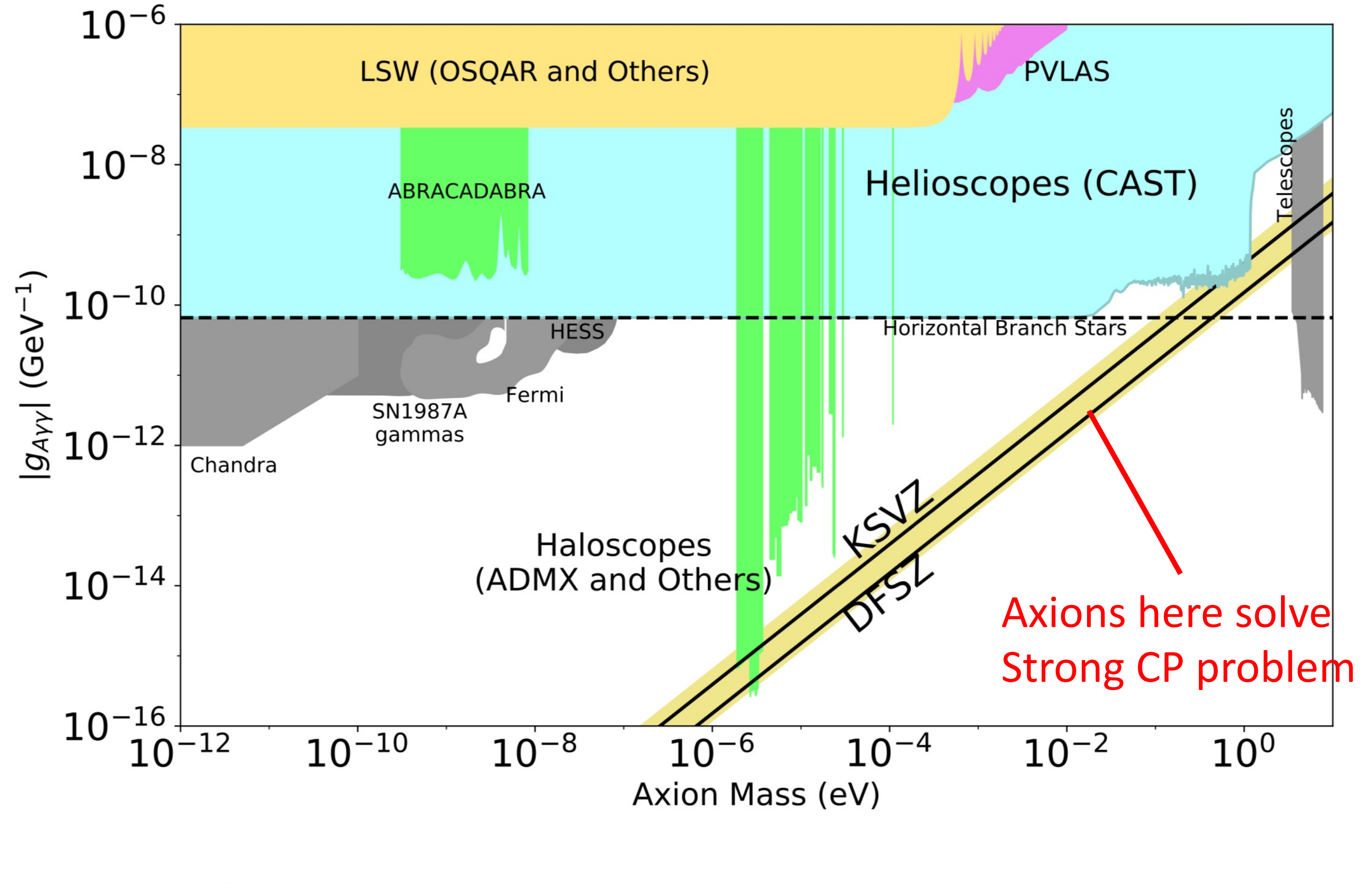
- Axions convert to microwave photons in external magnetic field (Primakov effect)





- Need to tune the cavity over a large frequency range.
- The axion to photon conversion power is very small.
- Long integration times: scanning rate $\frac{df}{dt} \sim g_{a\gamma\gamma}^4 \; \frac{1}{T^2} \; B^2$

Cavity-Based Searches



Particle Data Group, 2020
http://pdg/lbl/gov

- Most recent results start excluding the 'QCD axion' region over narrow mass window

TODAY

Dark Matter Search Strategy

The two theoretically best-motivated candidates:

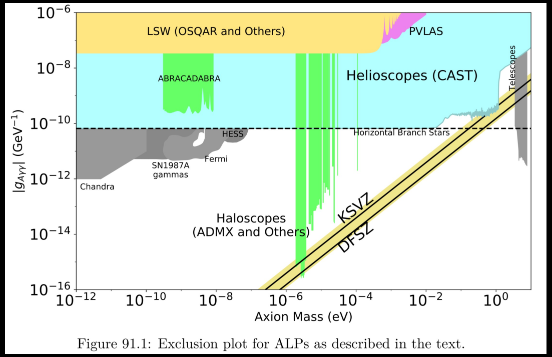
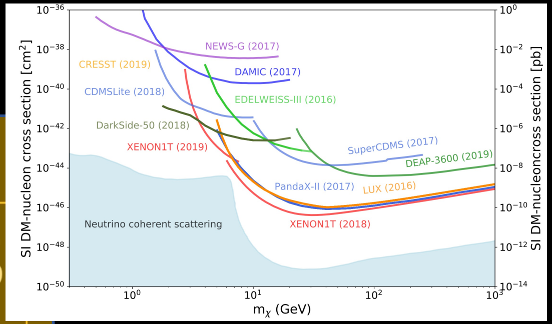


Figure 91.1: Exclusion plot for ALPs as described in the text.

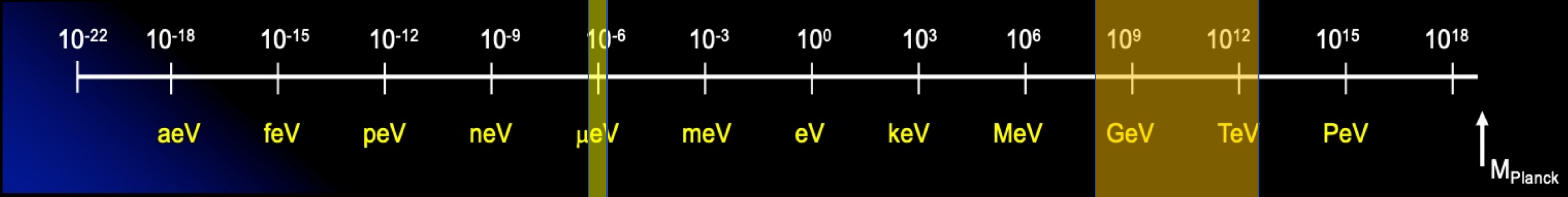
AXIONS (light)

WIMPS (heavy)



"table top" expts with quantum sensors

Multi-ton expts deep underground



FUTURE

Dark Matter Search Strategy

The two theoretically best-motivated candidates:

AXIONS (light)

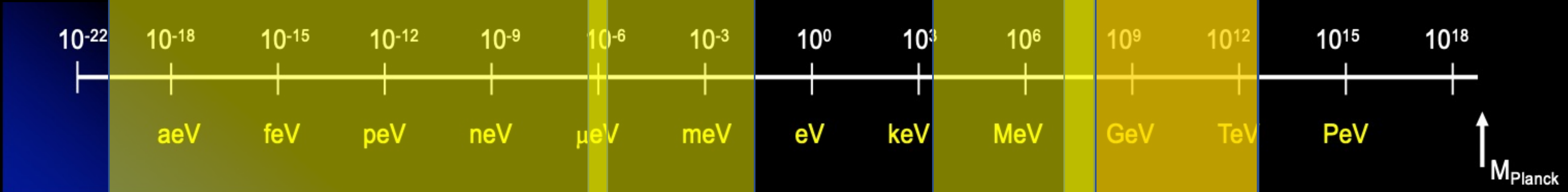
WIMPS (heavy)

Potential gain in sensitivity from Quantum 2.0

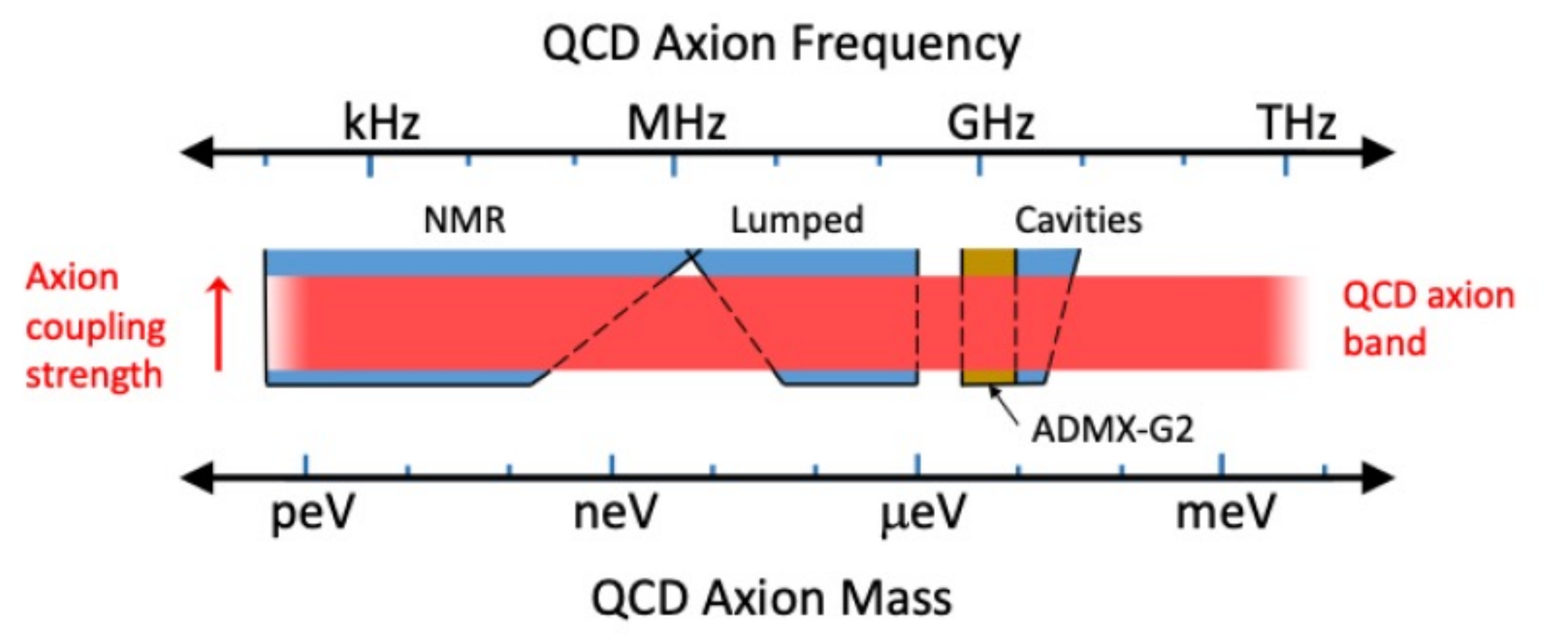
“table top” expts with quantum sensors

FIMPS
WIMPLESS
DM
SIMPS
Asymmetric
Dark Matter

Multi-ton expts deep underground



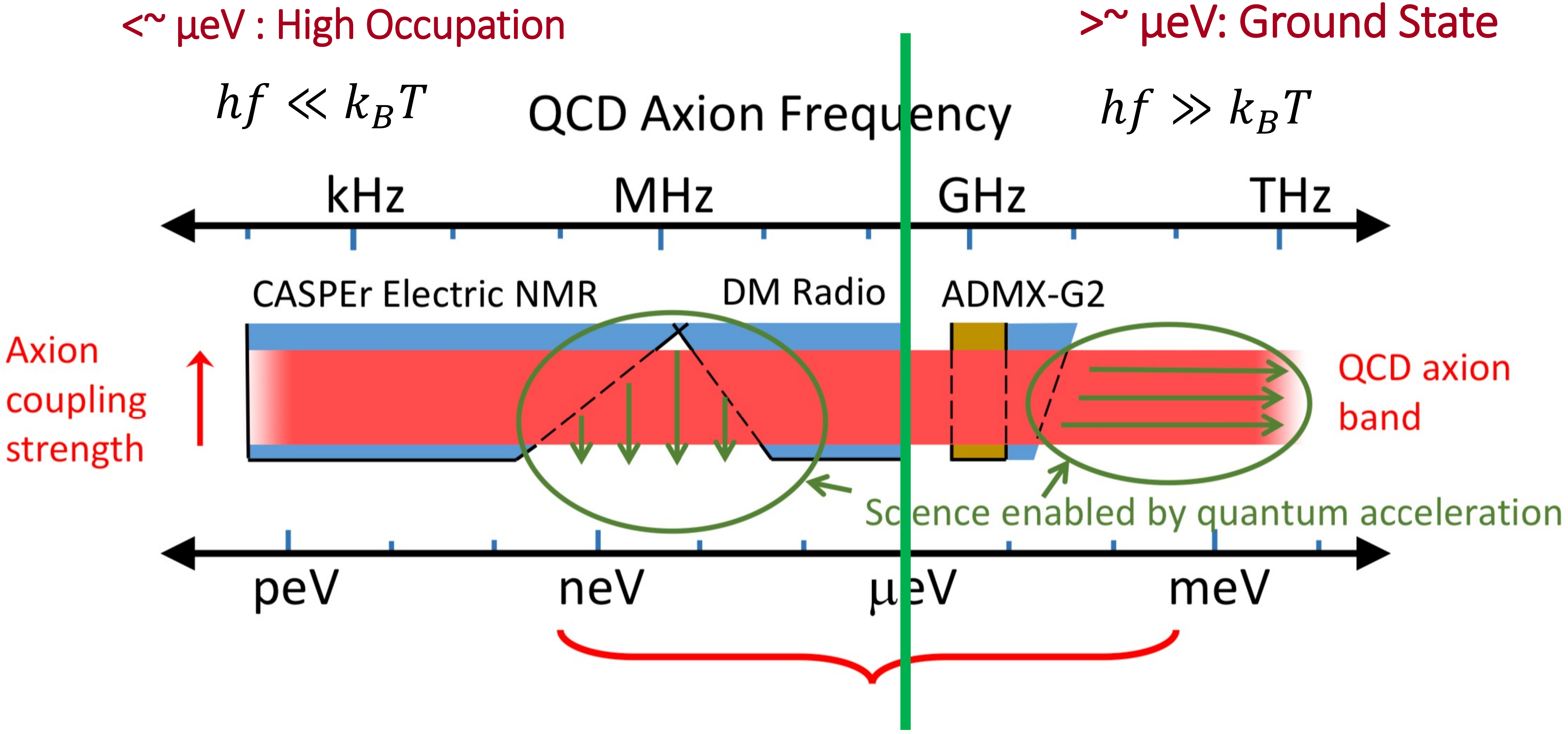
Parameter Space for QCD Axion Dark Matter



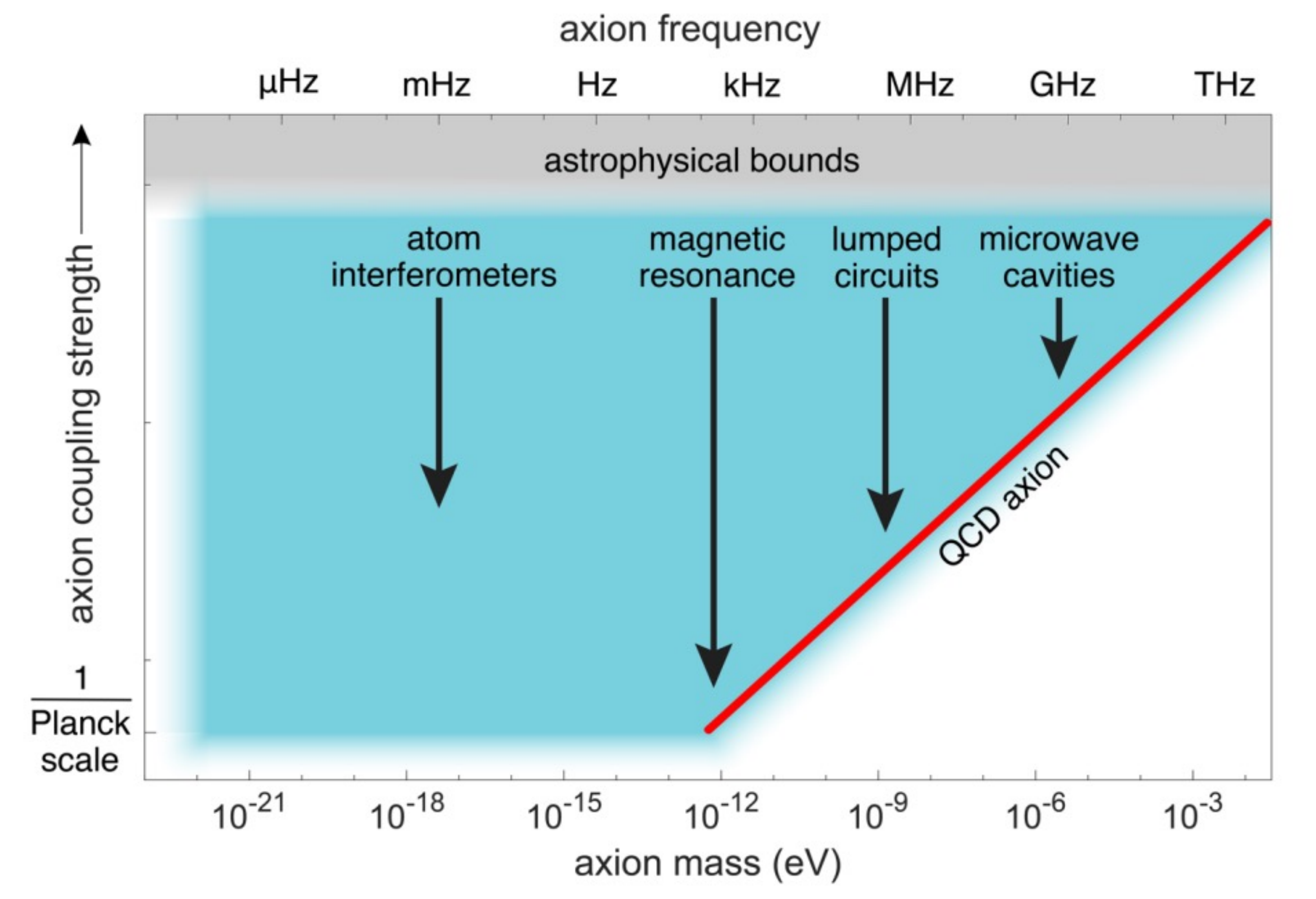
Graph: DOE OHEP BRN for
Dark Matter Small Projects
New Initiatives

3 highly complementary techniques
Need to exploit QCD and electromagnetic coupling of QCD axion to explore full mass range
For the general axion the techniques have broader overlapping mass ranges and therefore (crucially) a discovery by one can be confirmed by another
Greater sensitivity and gaps can be closed by going beyond the standard quantum limit (blue band in figure)

Science enabled by quantum acceleration



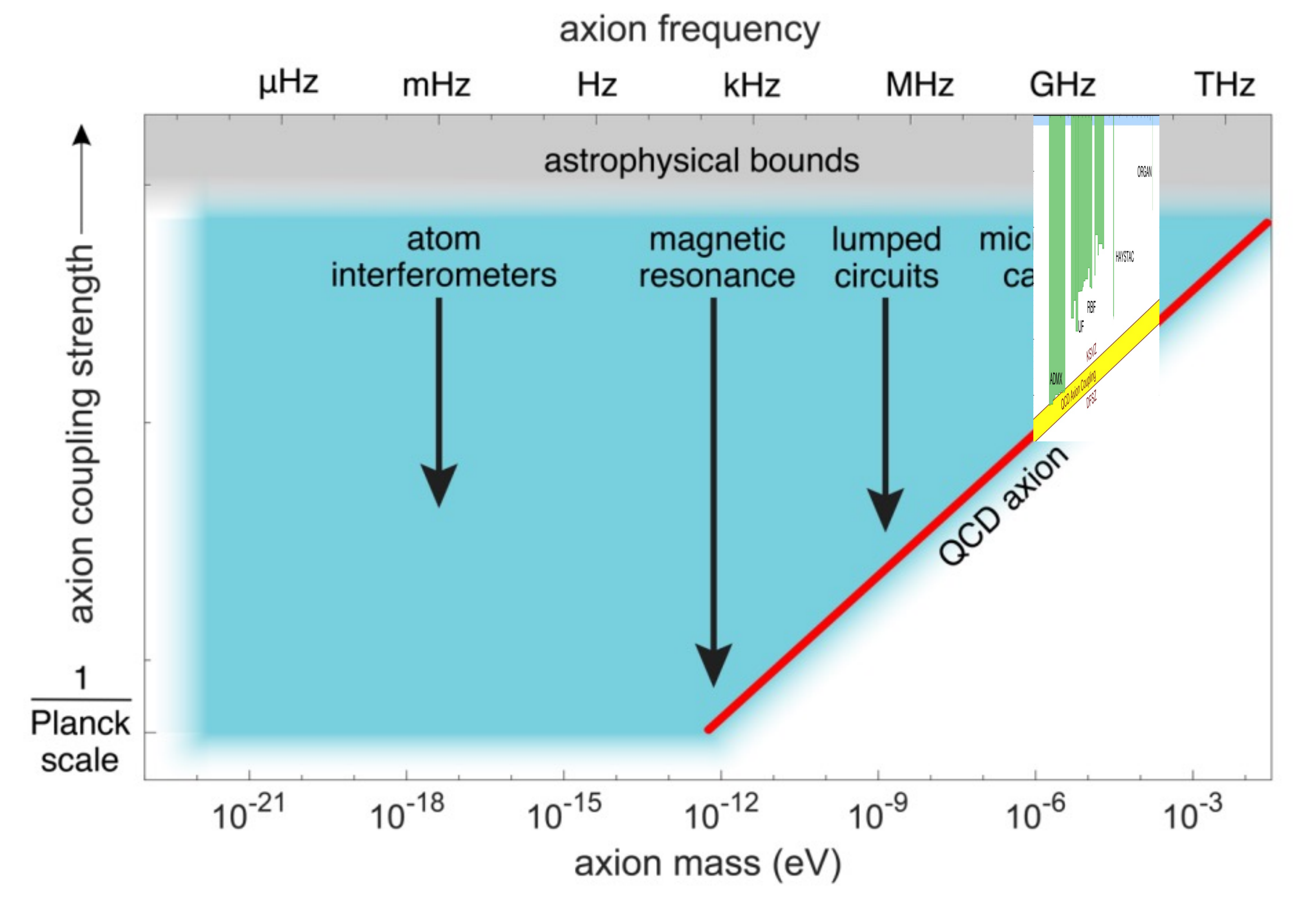
Parameter Space for General Axion Dark Matter



DOE HEP BRN
For Dark Matter
Small Projects
New Initiatives

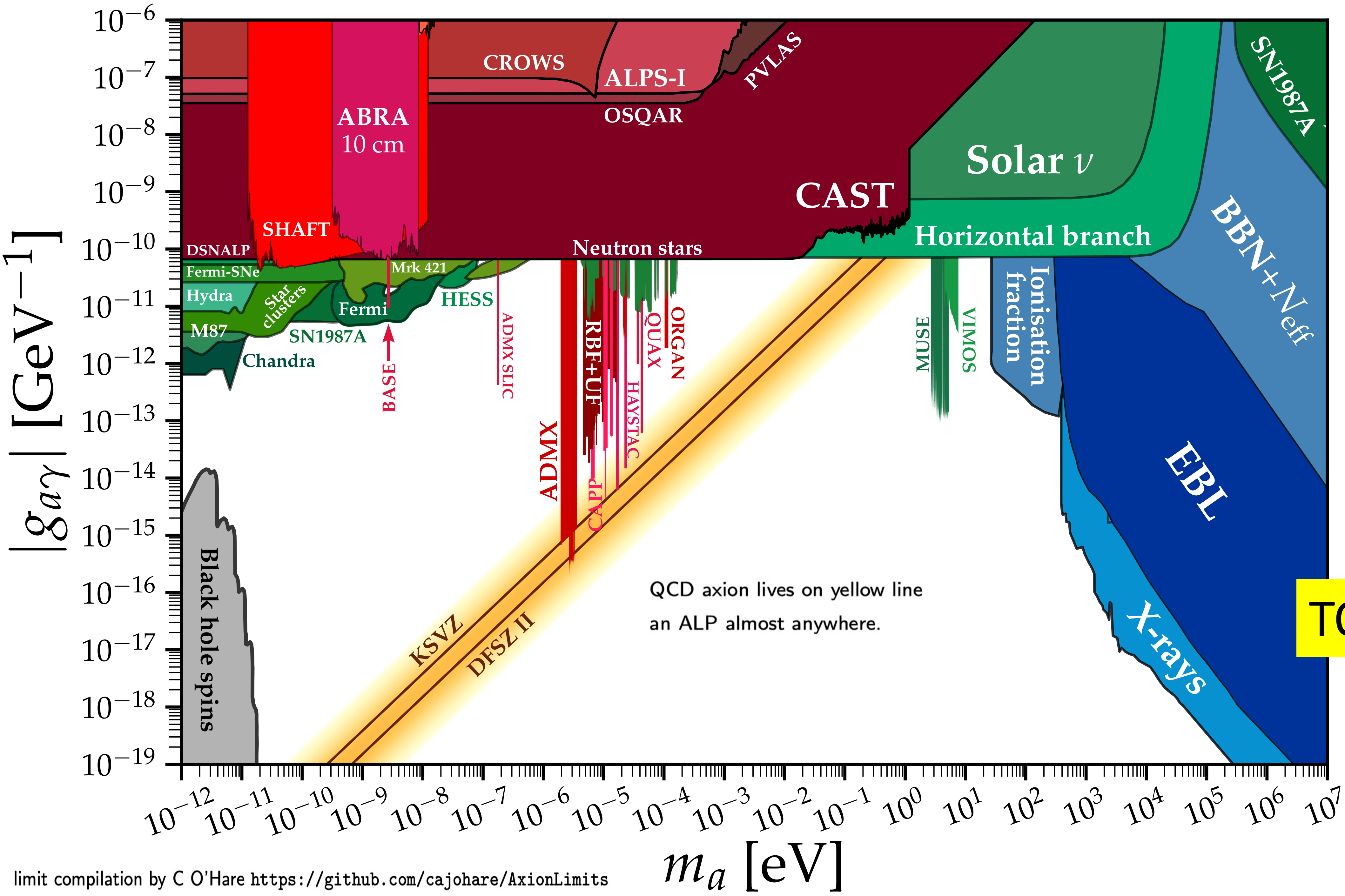
By general axion I mean any light scalar with suppressed couplings to the standard model

Parameter Space for General Axion Dark Matter



- Covering 1 – 10 GHz at DFSZ limit will take ~20,000 yrs at quantum limit, with one 9 Tesla magnet (K. Lehnert, Oxford Workshop http://www.physics.ox.ac.uk/confs/quantum2018/index.asp, HAYSTAC)

Axion
Photon
coupling

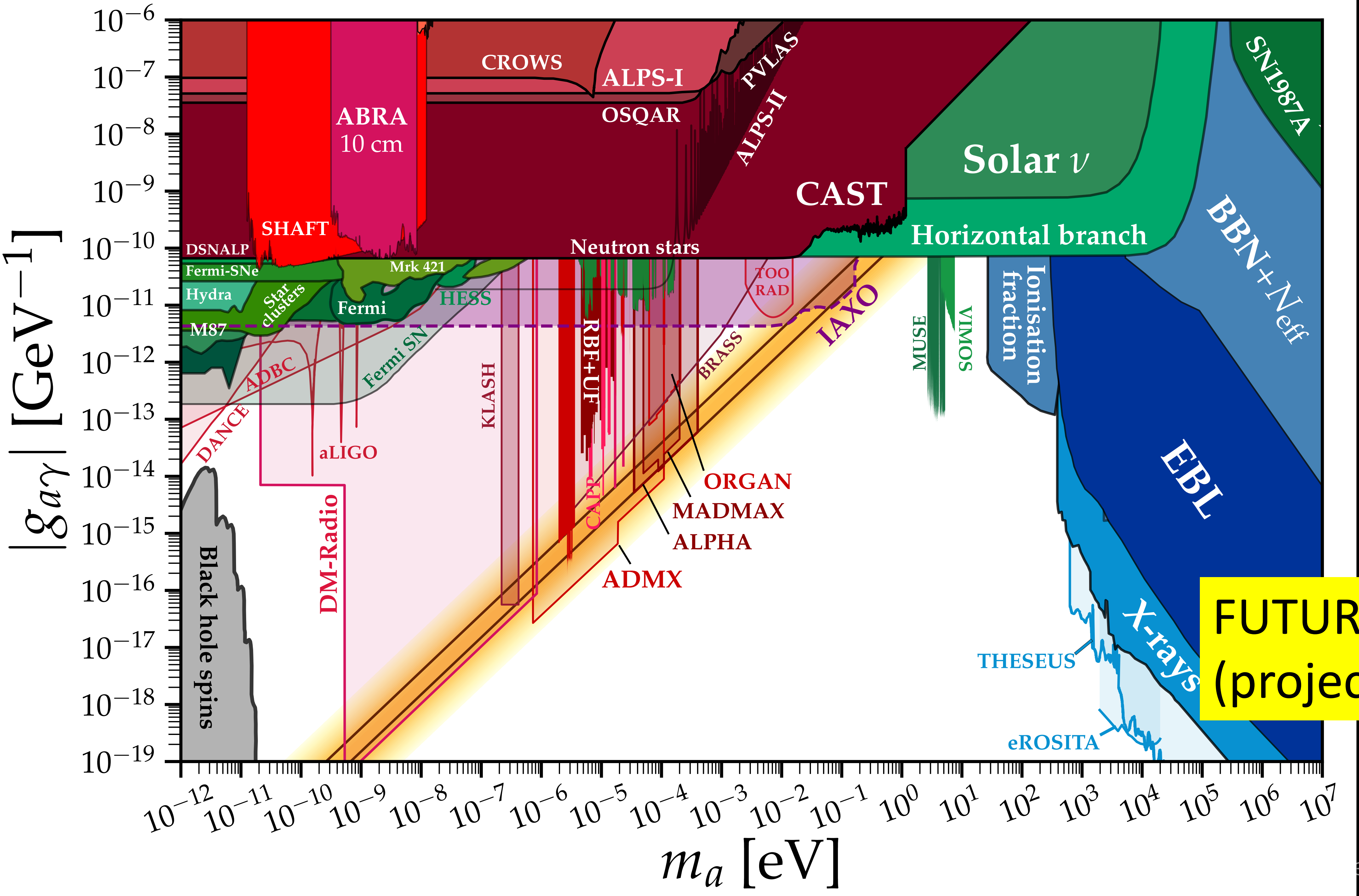


QCD axion lives on yellow line
an ALP almost anywhere.

TODAY

limit compilation by C O'Hare https://github.com/cajohare/AxionLimits

Axion
Photon
coupling



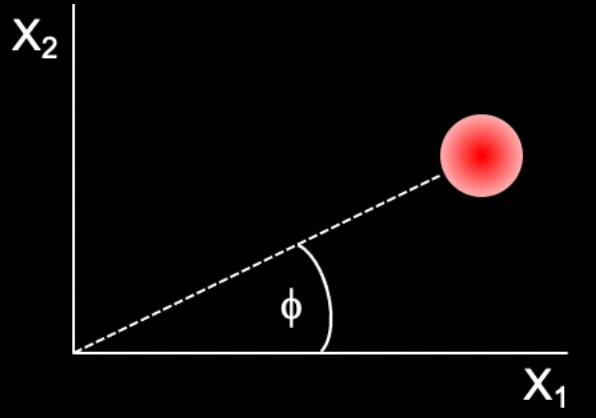
FUTURE
(projections)

Standard Quantum Limit

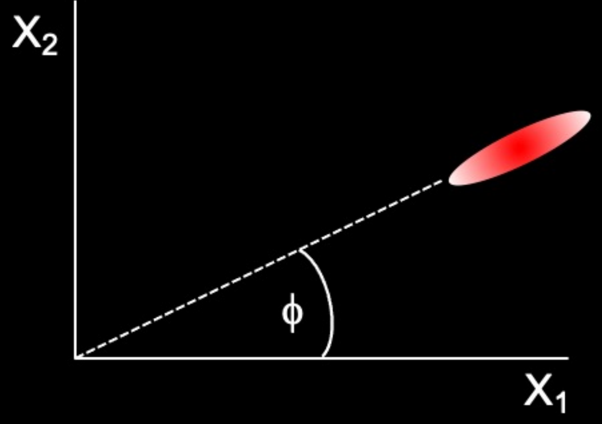
- Standard Quantum Limit: A measurement repeated N times or with N independent particles is a binomial distribution ≈ Gaussian distribution
  - Measurement precision scales as $1/\sqrt{N}$
- Fundamental limit set by Heisenberg Uncertainty Principle: $\Delta E\ \Delta t\ \geq\ \hbar/2$

$$x(t) = X_1(t)\cos(\omega t) + X_2(t)\sin(\omega t)$$

- The Standard Quantum Limit can be evaded using quantum correlations:
  - Photon counting
  - Squeezing
  - Backaction evasion
  - Entanglement
  - Cooling
  - Quantum Non-Demolition (QND)
- Noise squeezing is possible as long as uncertainty area is preserved.



Coherent Spin State



Squeezed Spin State

Slide from M Demarteau

Slide from M.Demarteau

Heisenberg Limit

- Fundamental limit set by Heisenberg Uncertainty Principle: $\Delta E \, \Delta t \;\geq\; \hbar/2$

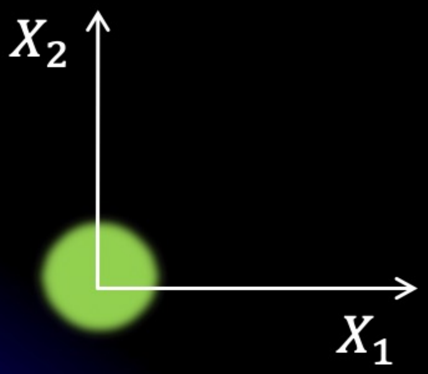
$$\Delta X \;\backsim 1\,/\,\sqrt{N}$$

Standard Quantum Limit for
N uncorrelated particles

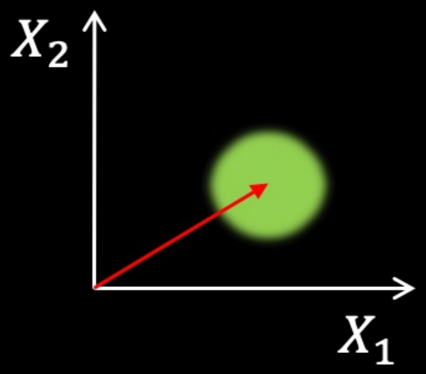
$$\Delta X \;\backsim 1\,/\,N$$

Heisenberg Limit requires
N particle entanglement

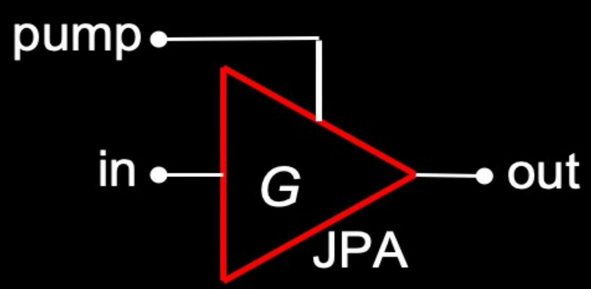
- Measure one quadrature accurately and put the uncertainty into the other quadrature.
- If this is possible, single-quadrature precision is not limited by Heisenberg.



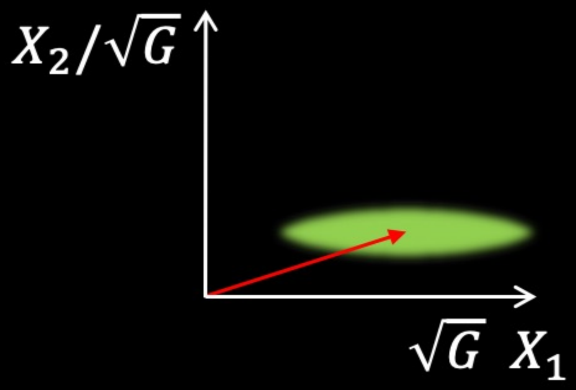
"vacuum state"



"displaced state"
(through interaction)



Amplification and
squeezing



"measurement state"

Slide from M. Demarteau

Heisenberg Limit

- Fundamental limit set by Heisenberg Uncertainty Principle: $\Delta E \, \Delta t \geq \hbar/2$

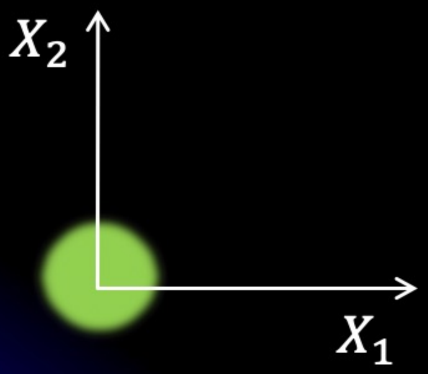
$$\Delta X \backsim 1 / \sqrt{N}$$

Standard Quantum Limit for
N uncorrelated particles

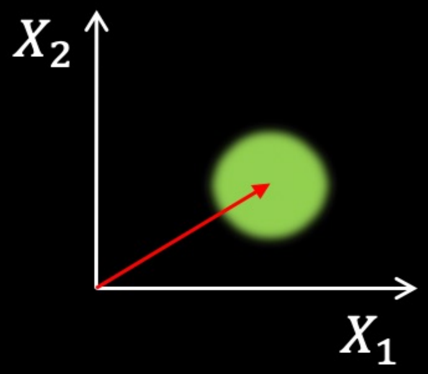
$$\Delta X \backsim 1 / N$$

Heisenberg Limit requires
N particle entanglement

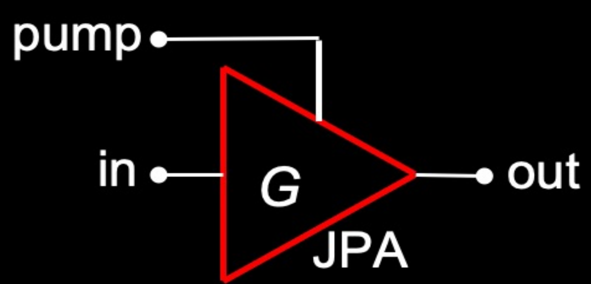
- Measure one quadrature accurately and put the uncertainty into the other quadrature.
- If this is possible, single-quadrature precision is not limited by Heisenberg.



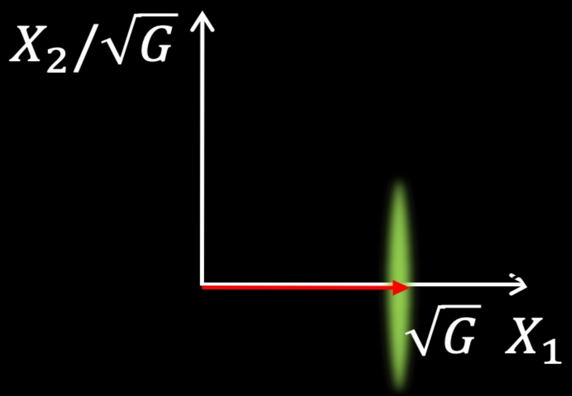
“vacuum state”



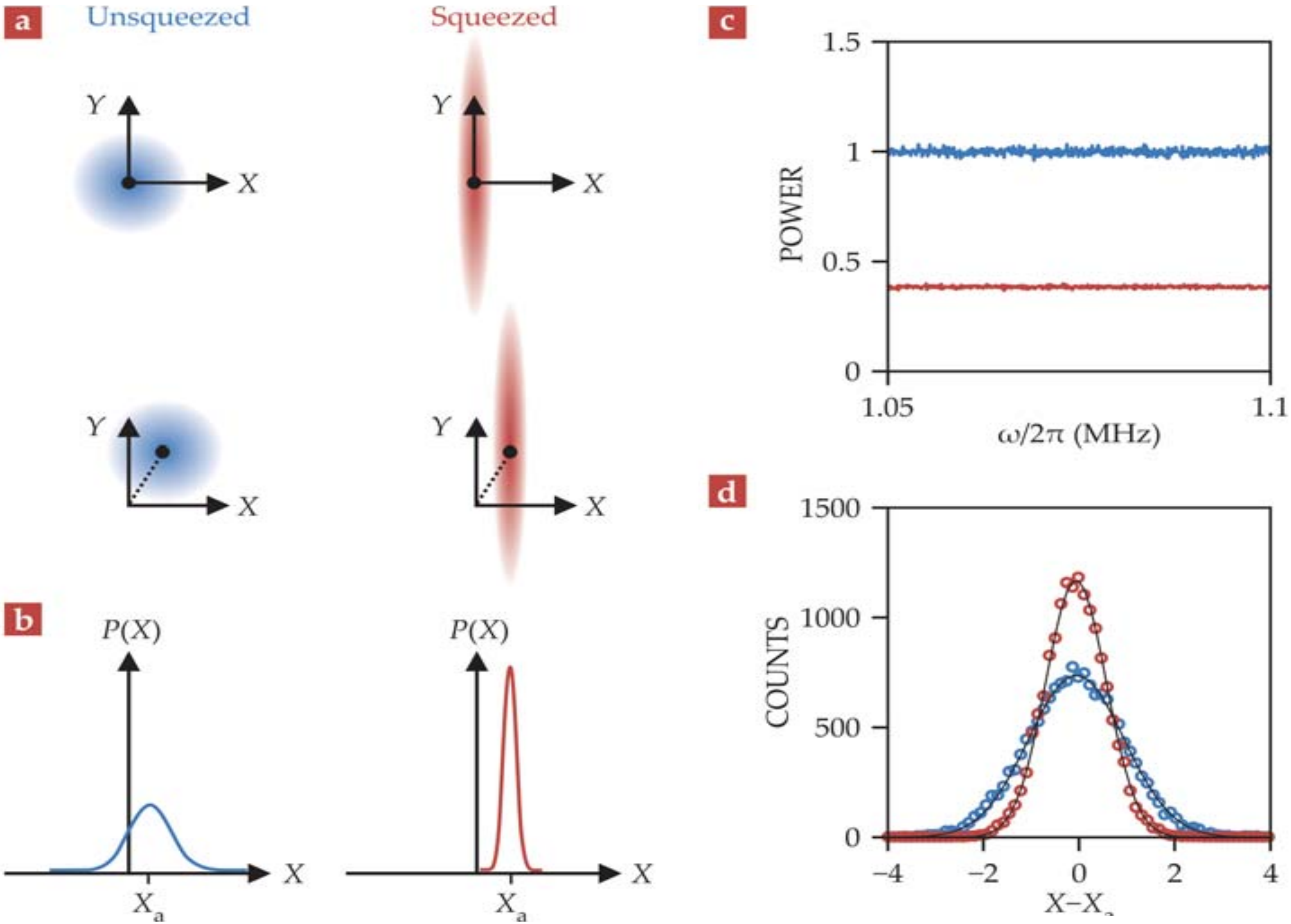
“displaced state”
(through interaction)



Amplification and
squeezing



“measurement state”

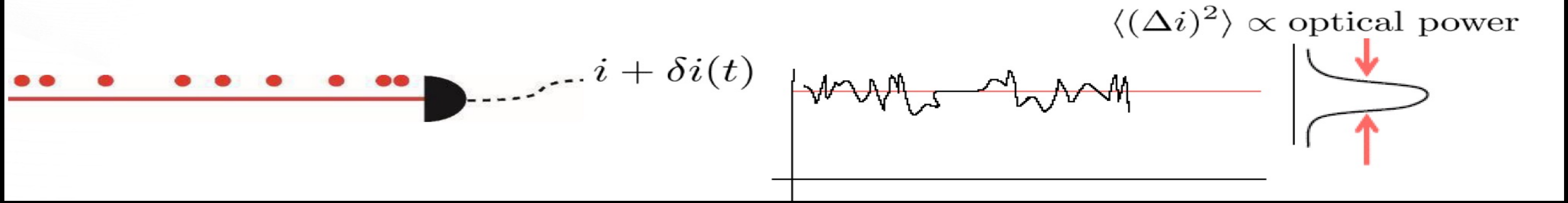


Physics Today **72**, 6, 48 (2019); doi: 10.1063/PT.3.4227

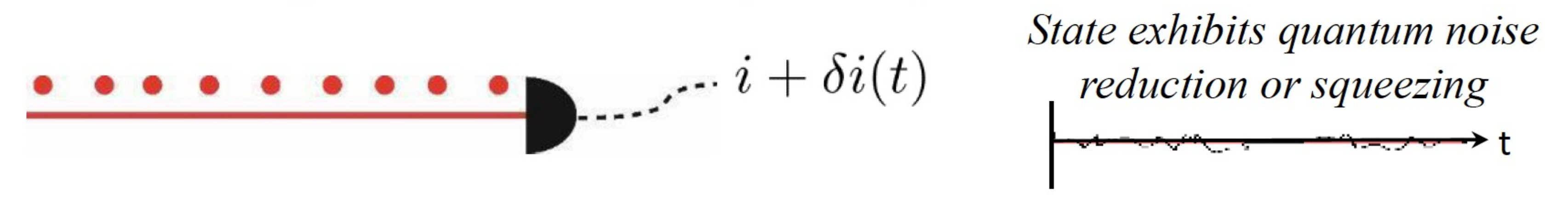
Beyond the SQL

Slide from M. Demarteau

- Quantum Noise Reduction with optical probe
  - Quantum noise can be viewed as a result of light being composed of discrete photons with a random temporal distribution.



  - This noise represents the shot noise limit (SNL) and is the minimum noise level for a classical state of light.
  - One can generate states of light with less noise in amplitude through the use of a nonlinear process that can emit pairs of photons.

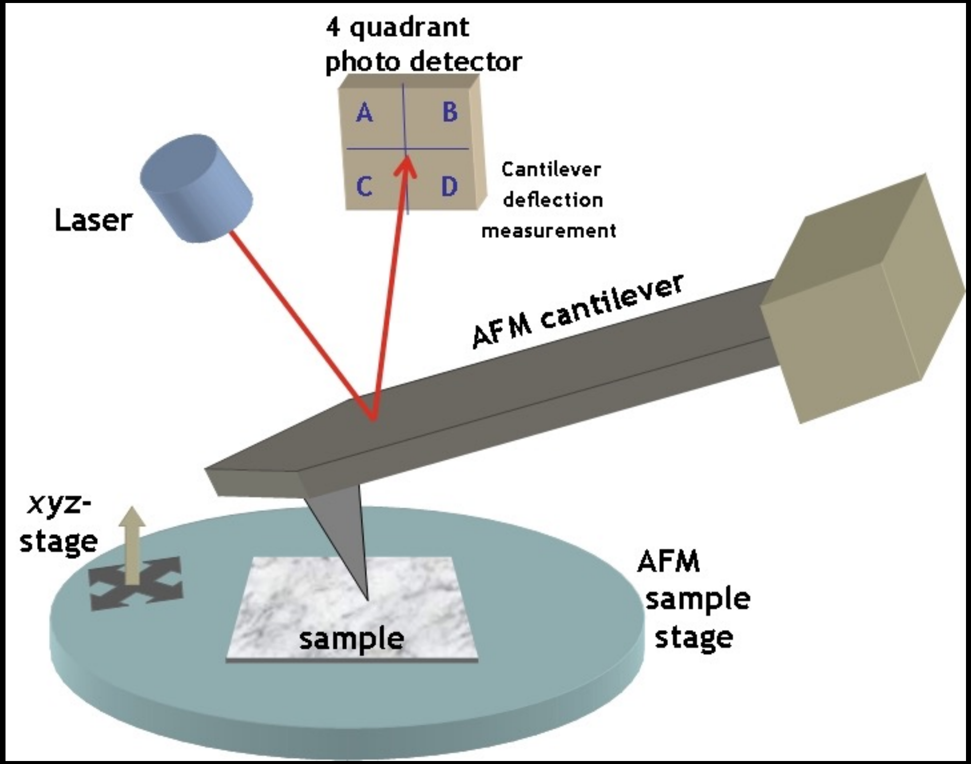


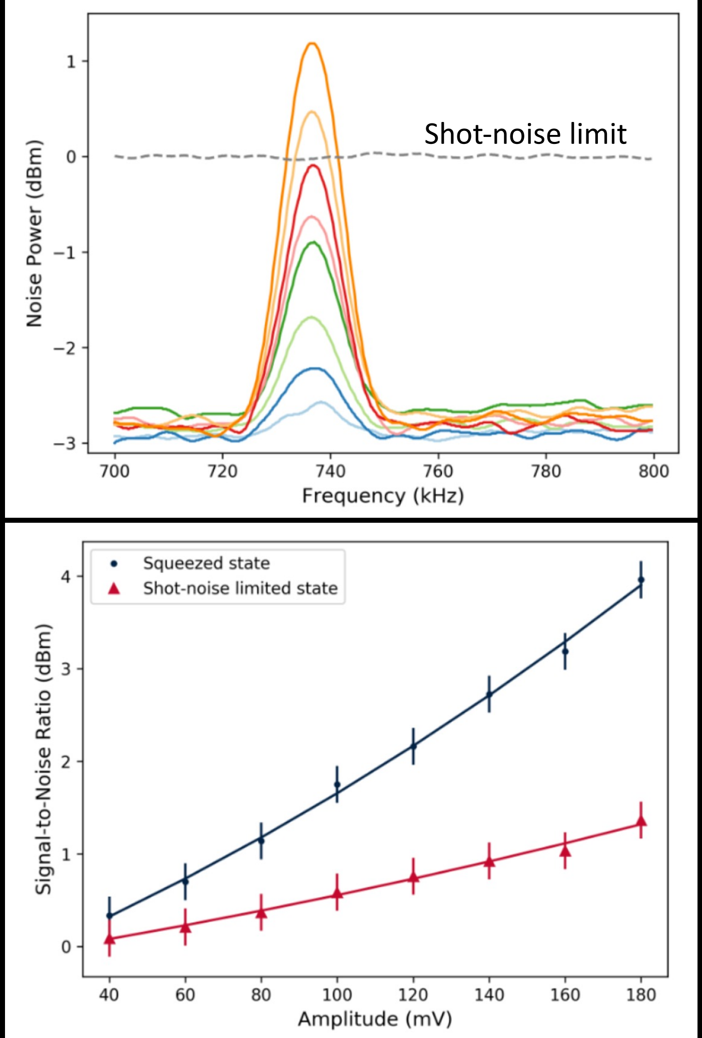
Science 321 , 544 547 (2008); Nature 457 , 859 862 (2009)

Slide from M. Demarteau

Atomic Force Microscopy

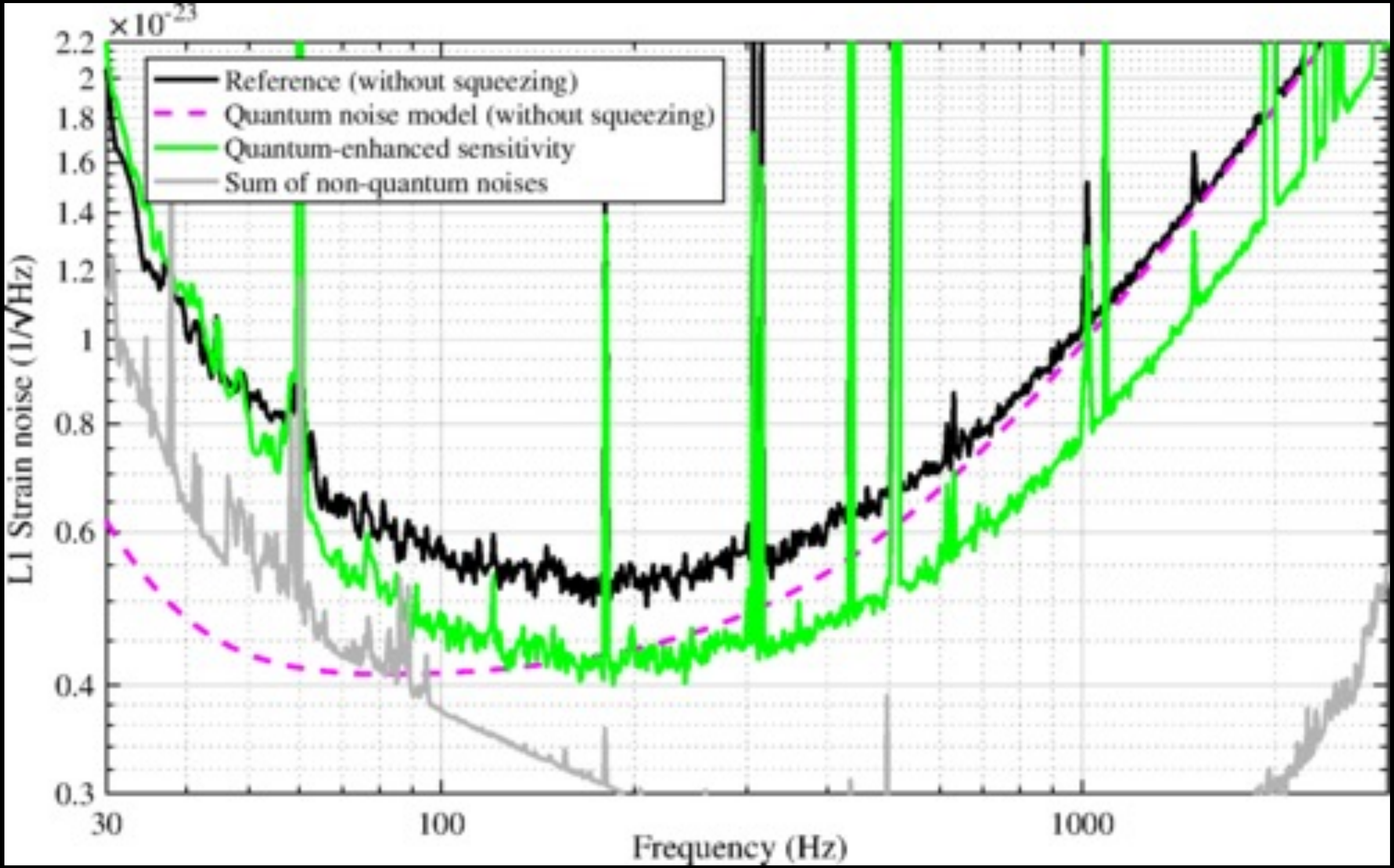
- Quantum-enhanced atomic force microscopy using squeezed probe through the application of nonlinear interferometry
- Displacement of microcantilever with quantum noise reduction of up to 3 dB below the standard quantum limit: quantum-enhanced measurement of 1.7 fm/√Hz.





Physical Review Letters 124 (23), 230504 (2020)

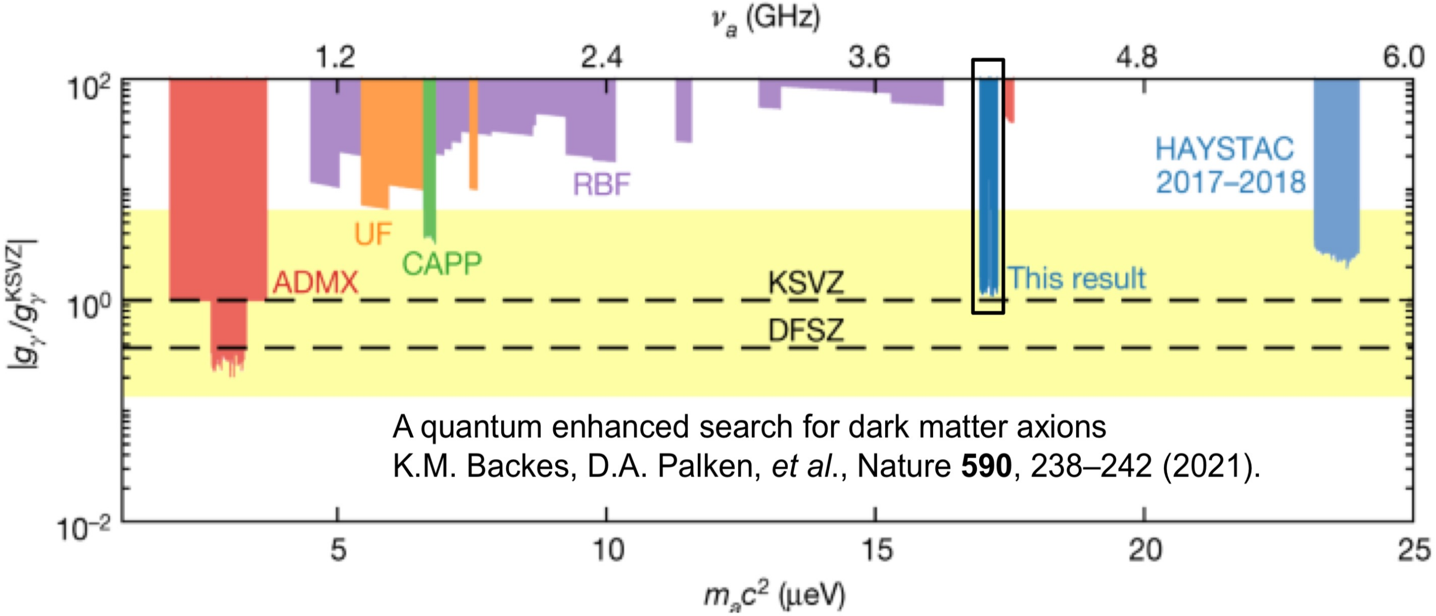
LIGO: Quantum enhanced sensing-Squeezed light for improved sensitivity



https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231107

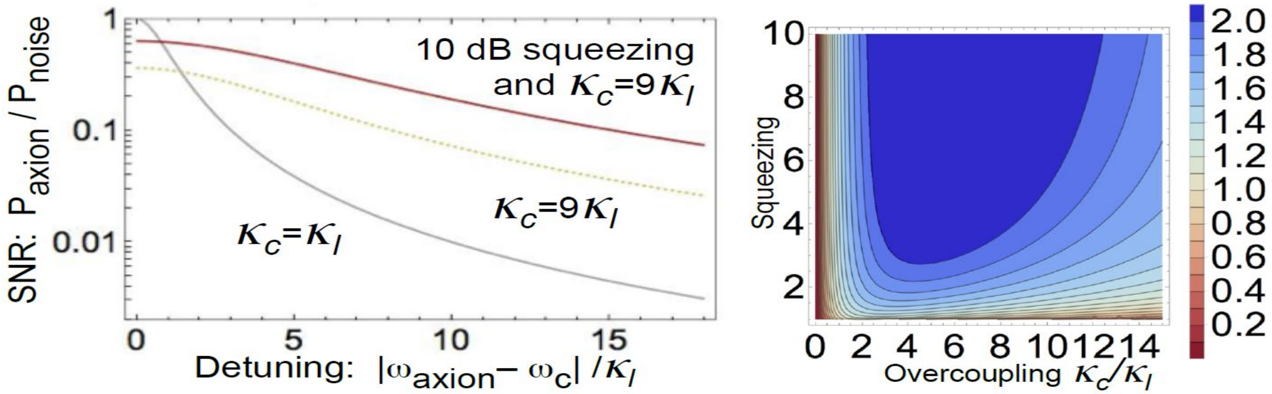
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231108

HAYSTAC: Acceleration through squeezing



A quantum enhanced search for dark matter axions
K.M. Backes, D.A. Palken, *et al.*, Nature **590**, 238–242 (2021).

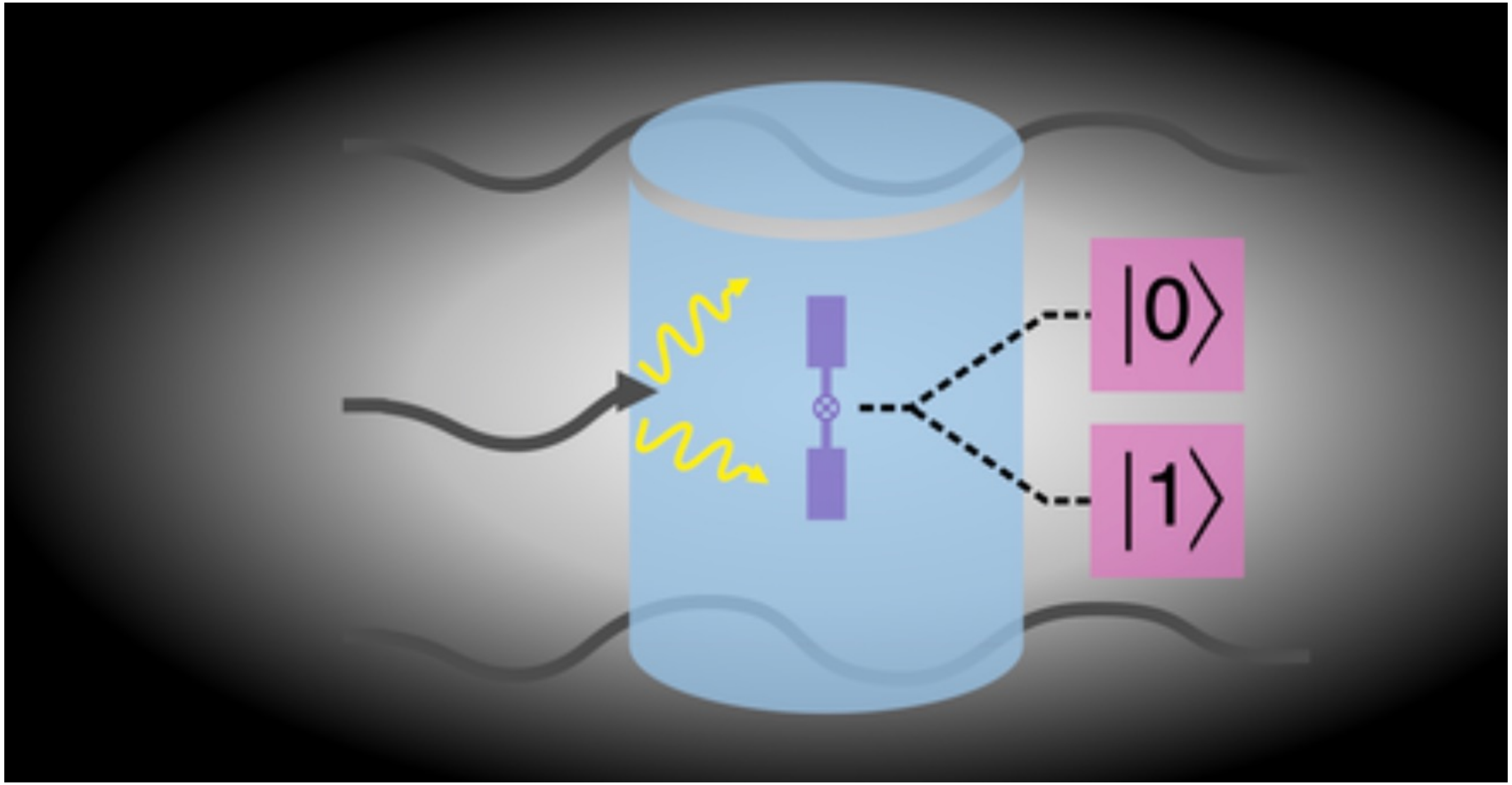
HAYSTAC run 1 & 2 combined exclusion plot



HAYSTAC Phase II squeezed state receiver projected acceleration

Droster, Alex G., and Karl van Bibber. "HAYSTAC Status, Results, and Plans." *arXiv preprint arXiv:1901.01668* (2019).

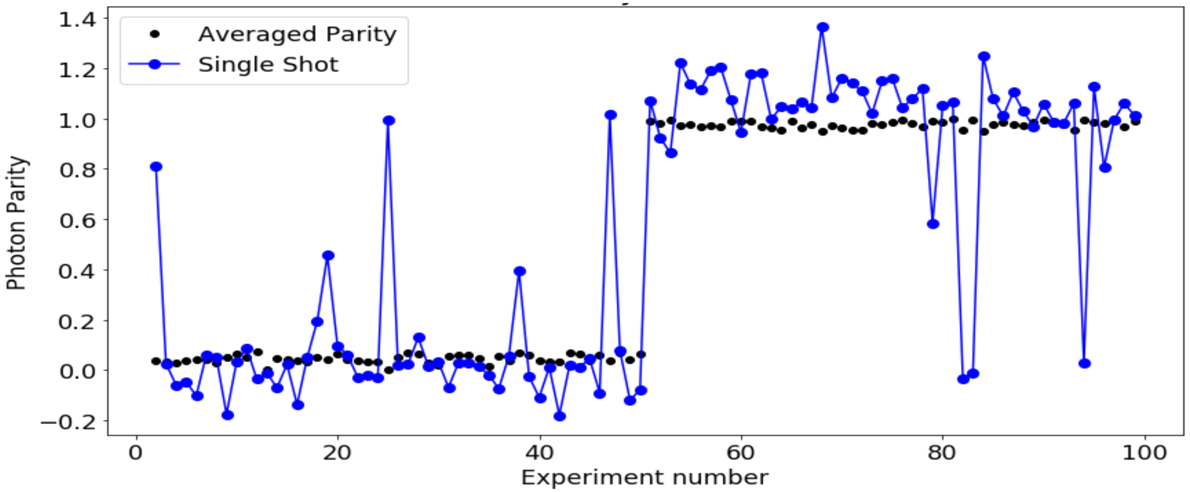
Qubits as cameras



Ground state measurement: QND photon counting

Akash Dixit, Aaron Chou, David Schuster

Repeatedly measure the clock frequency to determine whether the cavity contains 0 or 1 photon:

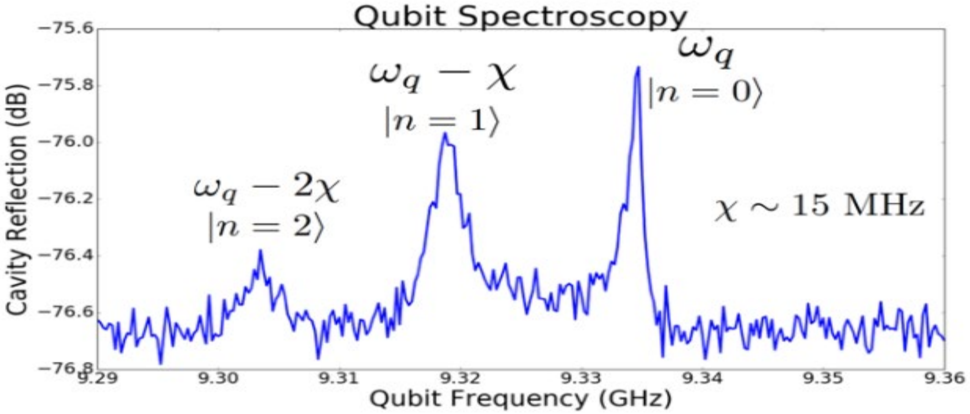


Many QND measurements agree that the cold cavity contains 0 photons

Inject 1 photon

Many QND measurements of the single photon **without absorbing it.**

Use qubit as an atomic clock whose frequency depends on the number of photons in the cavity. The electric field of even a **single photon** will exercise the non-linearity of the qubit oscillator and shift its frequency.

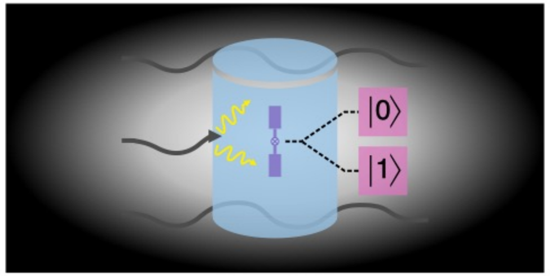


Count # of photons by measuring the quantized frequency shift of the qubit.

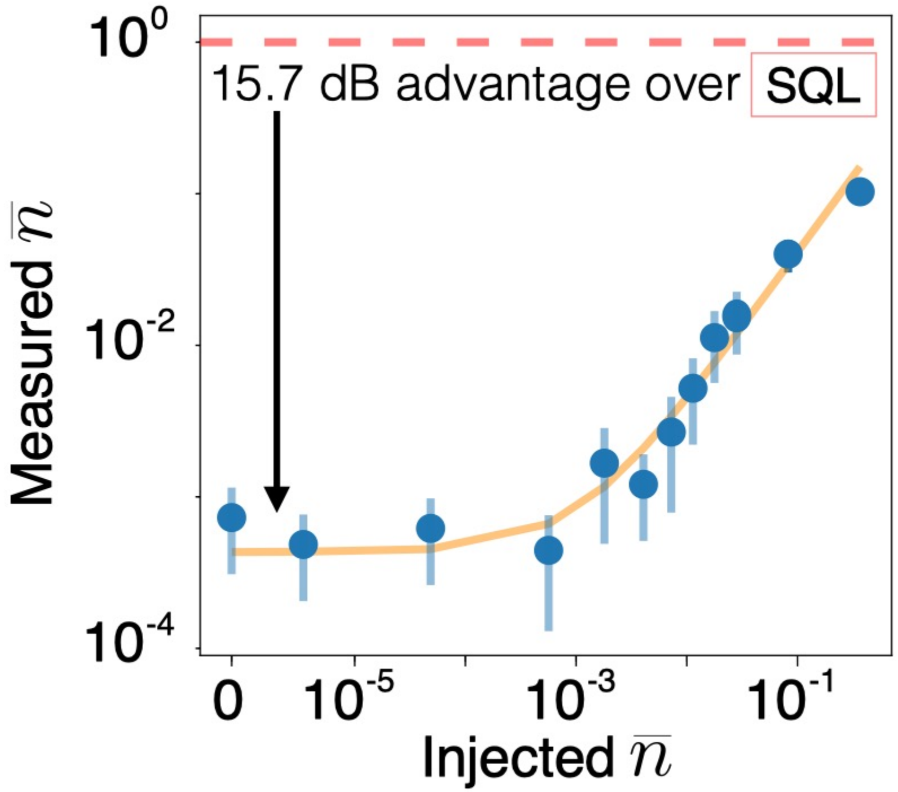
Figure Credit: Aaron Chou, FNAL

Fermilab THE UNIVERSITY OF CHICAGO HEISING-SIMONS FOUNDATION

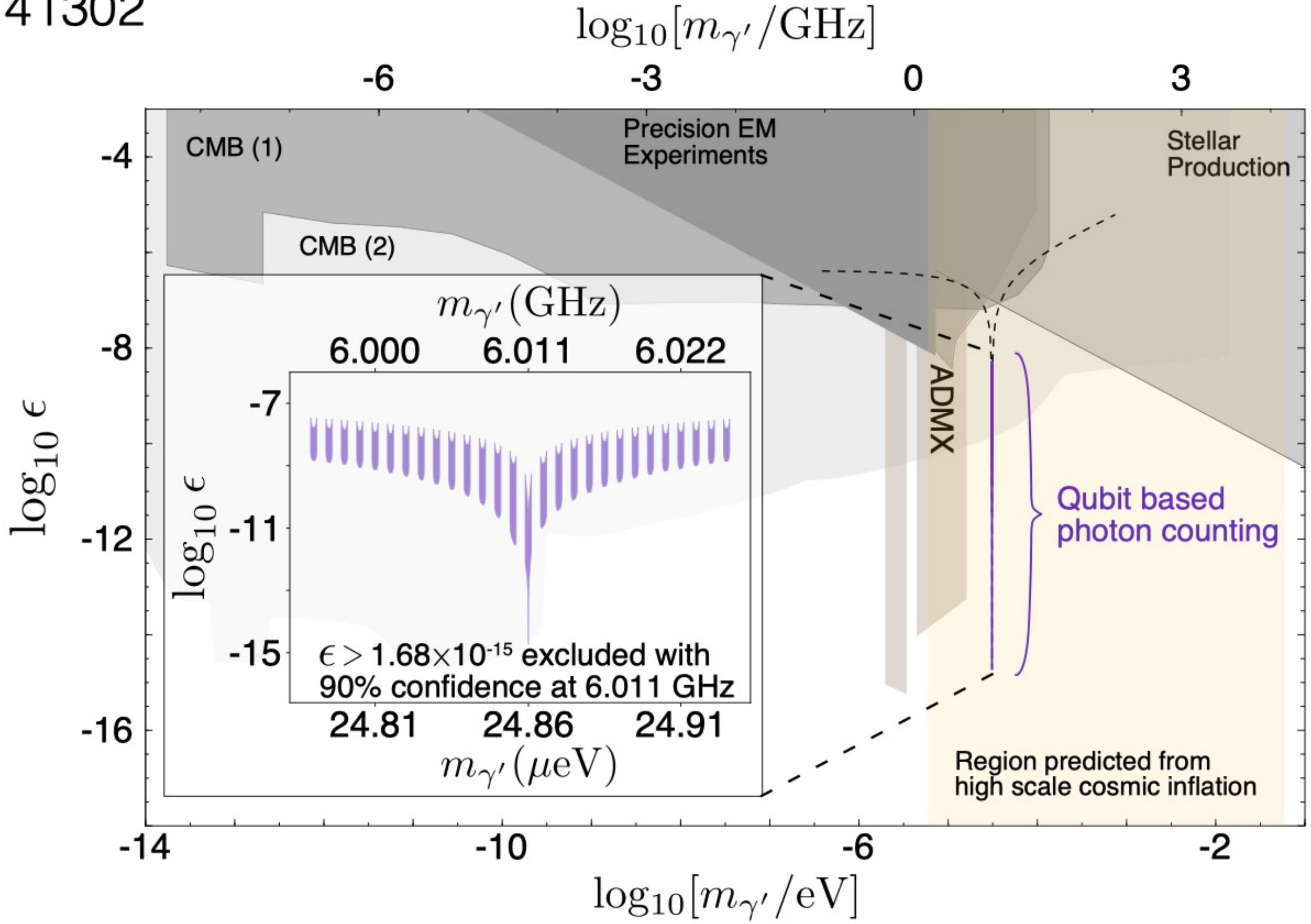
Counting photons with a qubit enables 1,300 X speed up of dark matter search



A. V. Dixit, et. al.
Phys. Rev. Lett. **126**, 141302

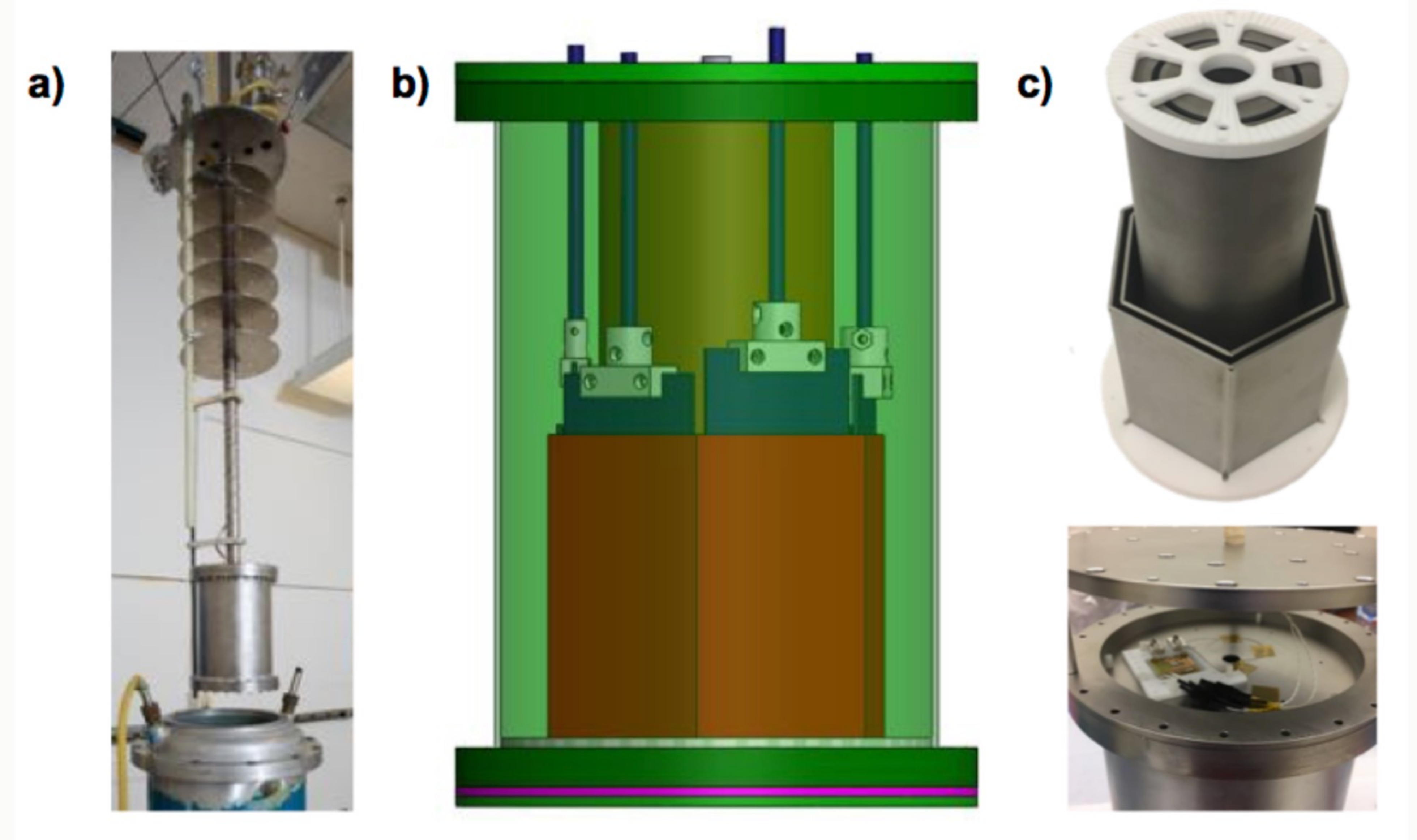


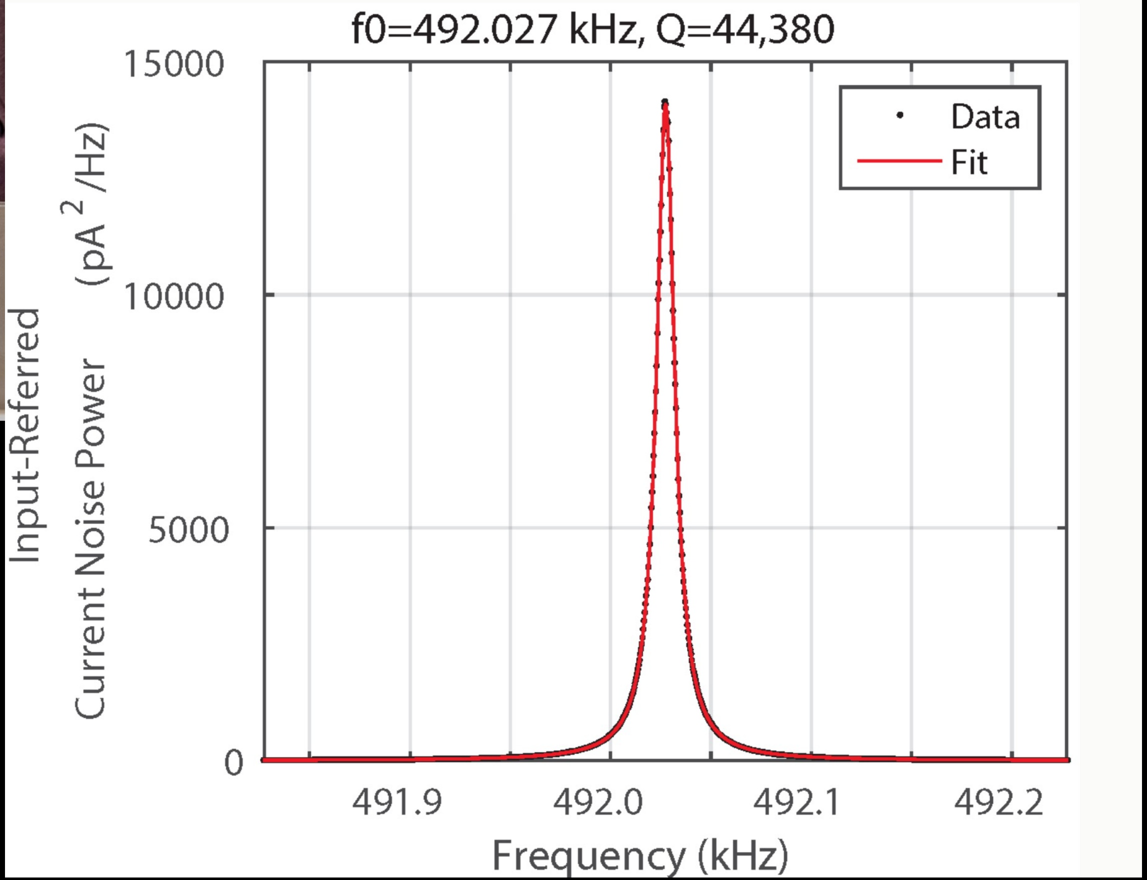
Counting single photons with a quantum bit. False positives exponentially suppressed by repeated QND measurements



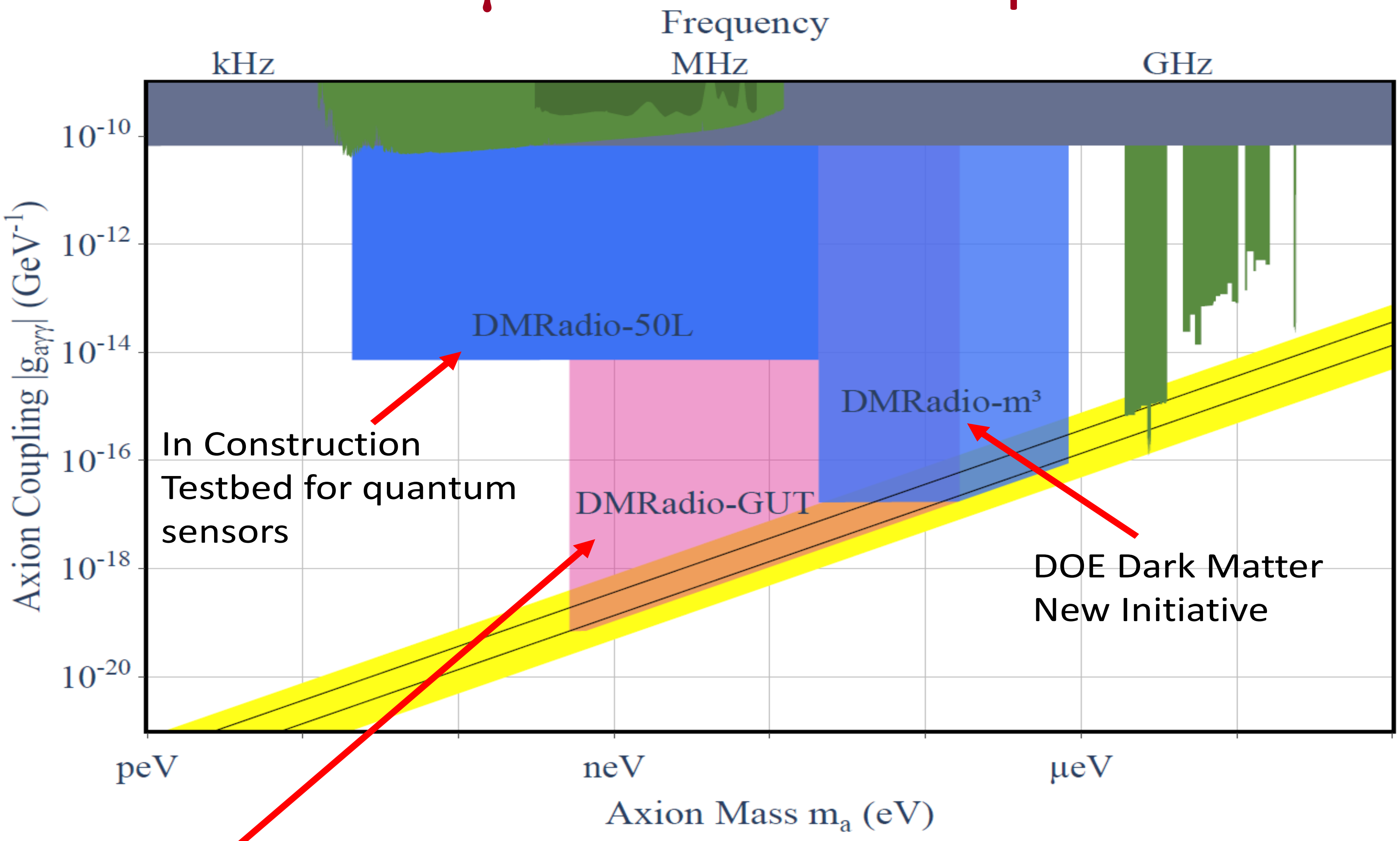
Can scan large regions of DM parameter space with qubit based detector.

Lumped Circuit Technique – Dark Matter Radio




f0=492.027 kHz, Q=44,380
15000
10000
5000
0
Input-Referred
Current Noise Power (pA ^{2} /Hz)
491.9
492.0
492.1
492.2
Frequency (kHz)
Data
Fit

< 1 μeV: DM Radio Experiment Family



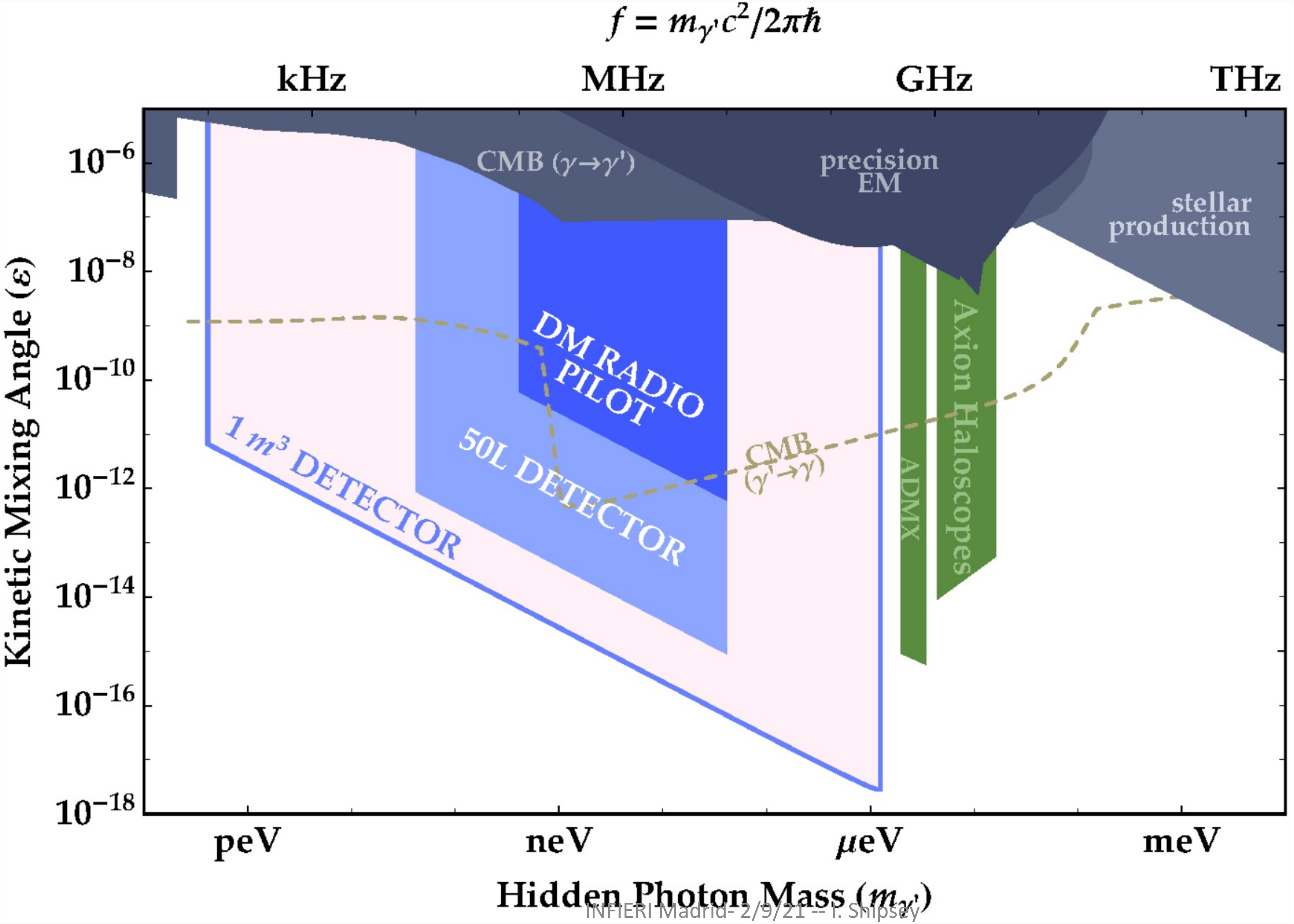
In Construction
Testbed for quantum sensors

DOE Dark Matter
New Initiative

DMRadio-GUT is a long way off!

Chaudhuri, Saptarshi. Snowmass2021-Letter of Interest
“DMRadio-GUT: Probing GUT-scale QCD Axion Dark Matter."

HIDDEN PHOTONS



Spin Precession NMR Based Axion Searches

1. Pseudoscalar light field: spin = 0, odd under parity
2. Proposed to solve the strong CP problem of Quantum Chromodynamics [PRL 38, 1440 (1977)]
3. Axion-like particles (ALPs) arise very naturally in string theories, symmetries broken at GUT (10^{16} GeV) or Planck (10^{19} GeV) scales
4. Possible couplings to standard model particles:

axion field amplitude

symmetry breaking scale

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

coupling to photons

→ Primakoff effect

coupling to gluons

→ creates nucleon EDM (electric dipole moment)

this is why axions were invented

→ spin to axion coupling:

$$\boxed{H_e \propto \vec{\sigma} \cdot (a\vec{E}^*)}$$

CASPEr-electric

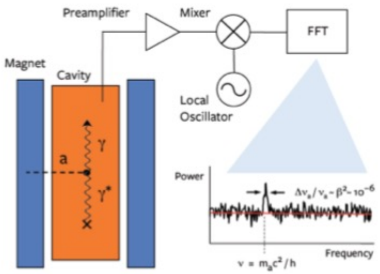
coupling to fermions

→ creates axion "wind"

→ spin to axion "wind" coupling:

$$\boxed{H_{\text{wind}} \propto \vec{\sigma} \cdot \vec{\nabla} a}$$

CASPEr-wind



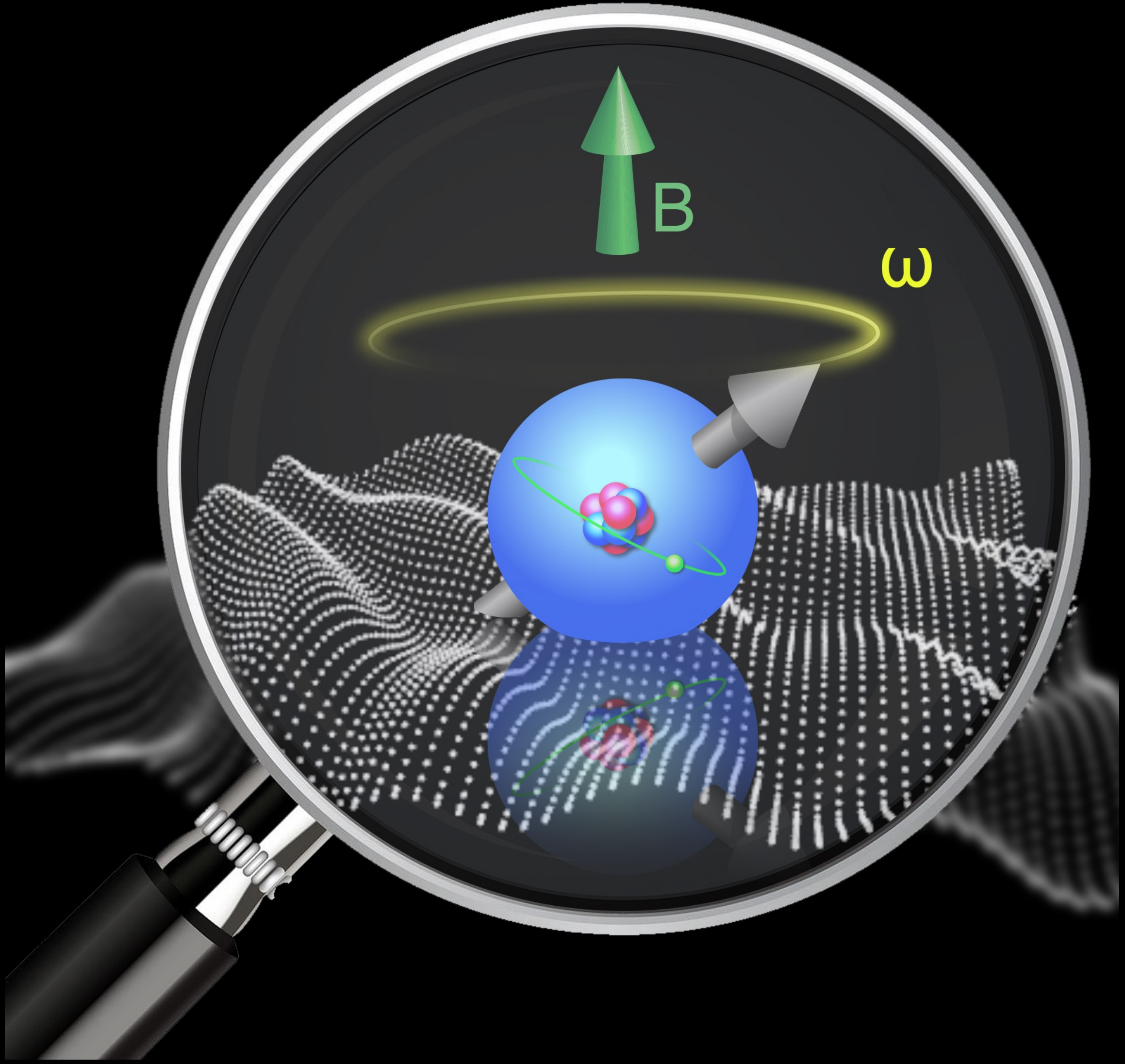
most axion DM searches: **ADMX**, HAYSTAC, …

(sensitivity all the way down to the QCD axion coupling!)

[Phys. Rev. Lett. **115**, 201301 (2015)]
[Phys. Rev. Lett. **118**, 061302 (2017)]

CASPEr (Cosmic Axion Spin Precession Experiments) will search for experimental signatures of these couplings

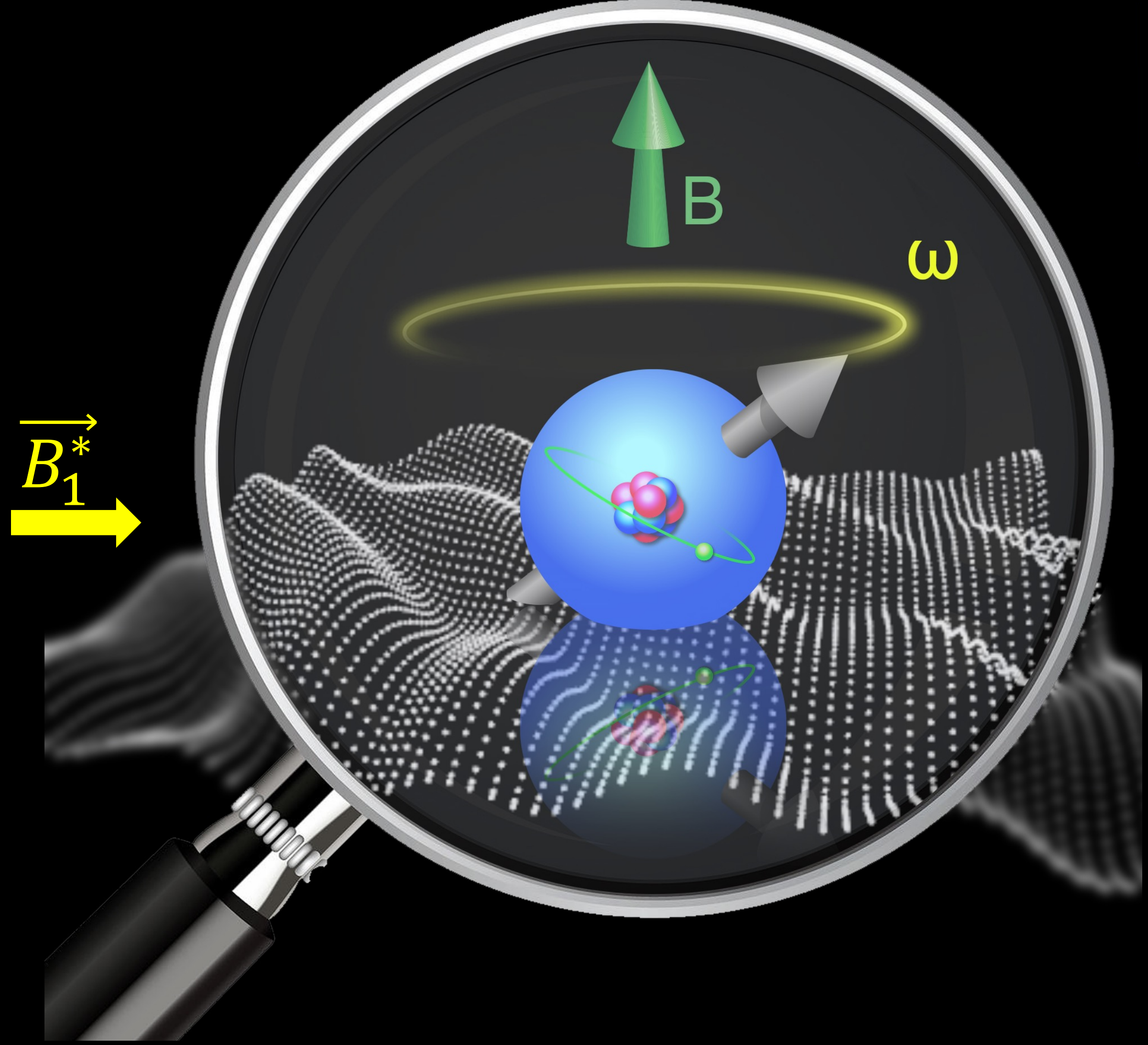
Spin Precession NMR-Based Axion Detection



- Axion-fermion coupling generates axion "wind", creating an effective B-field with well-known spin coupling: NMR technique

$$\begin{aligned}\mathcal{H}_{wind} &\propto \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{\nabla}} a \\ &= \vec{\boldsymbol{\sigma}} \cdot \vec{B}_1^* \cos \omega_a t\end{aligned}$$

Spin Precession NMR-Based Axion Detection

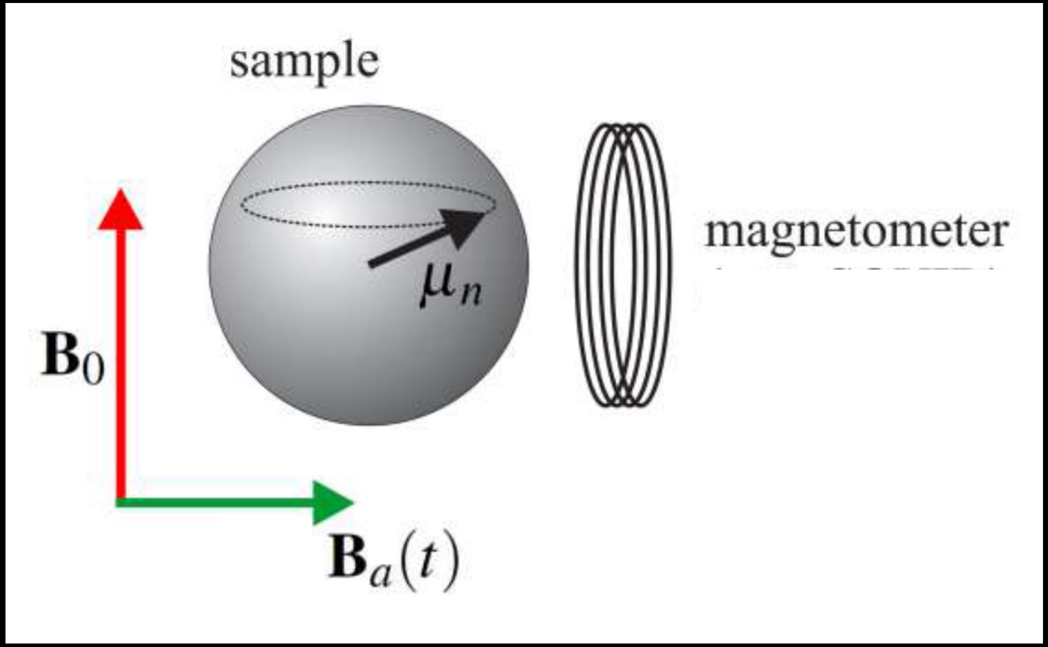


- Axion-fermion coupling generates axion "wind", creating an effective B-field with well-known spin coupling: NMR technique

$$\mathcal{H}_{wind} \propto \vec{\boldsymbol{\sigma}} \cdot \underrightarrow{\vec{\boldsymbol{\nabla}} a} = \vec{\boldsymbol{\sigma}} \cdot \overrightarrow{B_1^*} \cos \omega_a t$$

- Axion (ALP) field oscillates at a frequency equal to its mass in transverse direction

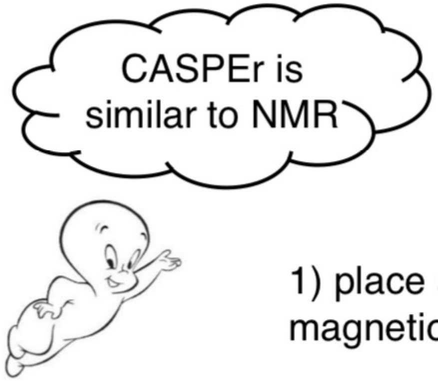
Spin Precession NMR-Based Axion Detection



- Larmor frequency = axion Compton frequency
  - Measure resonant enhancement and
  - transverse component of magnetic field

- Magnetometers used: pickup coils and SQUIDS (CASPER)

Aside: magnetic resonance

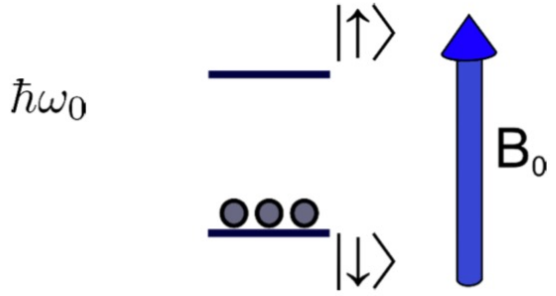


interaction: $H_{\mathrm{NMR}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}$

$$H_{\mathrm{NMR}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_0 + \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1 \cos \omega_0 t$$

- constant bias magnetic field $\boldsymbol{B}_0$
- radiofrequency (RF) magnetic field $\boldsymbol{B}_1$

1) place a spin-1/2 into an external magnetic field splits the spin states by $g\mu B_0$

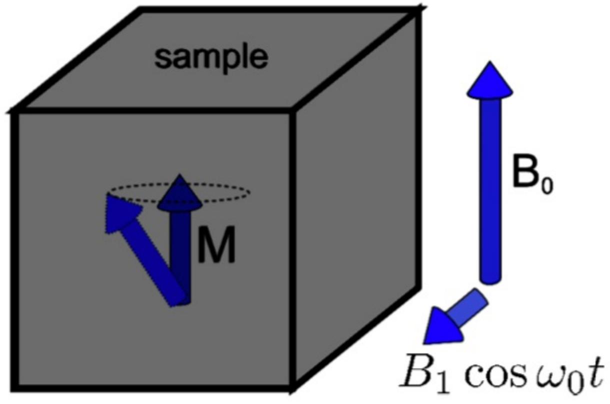


2) spin polarization (thermal or optical) in a cm^3 sample

3) resonance: $\hbar\omega_0 = g\mu B_0$

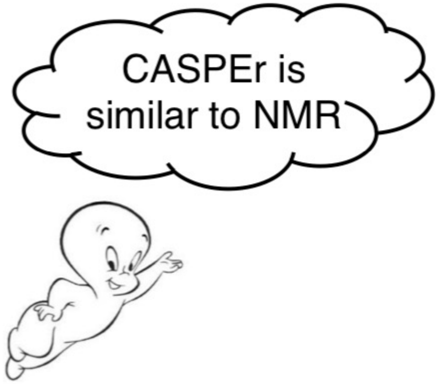
- RF magnetic field can now flip spins!
- sample magnetization tilts and precesses

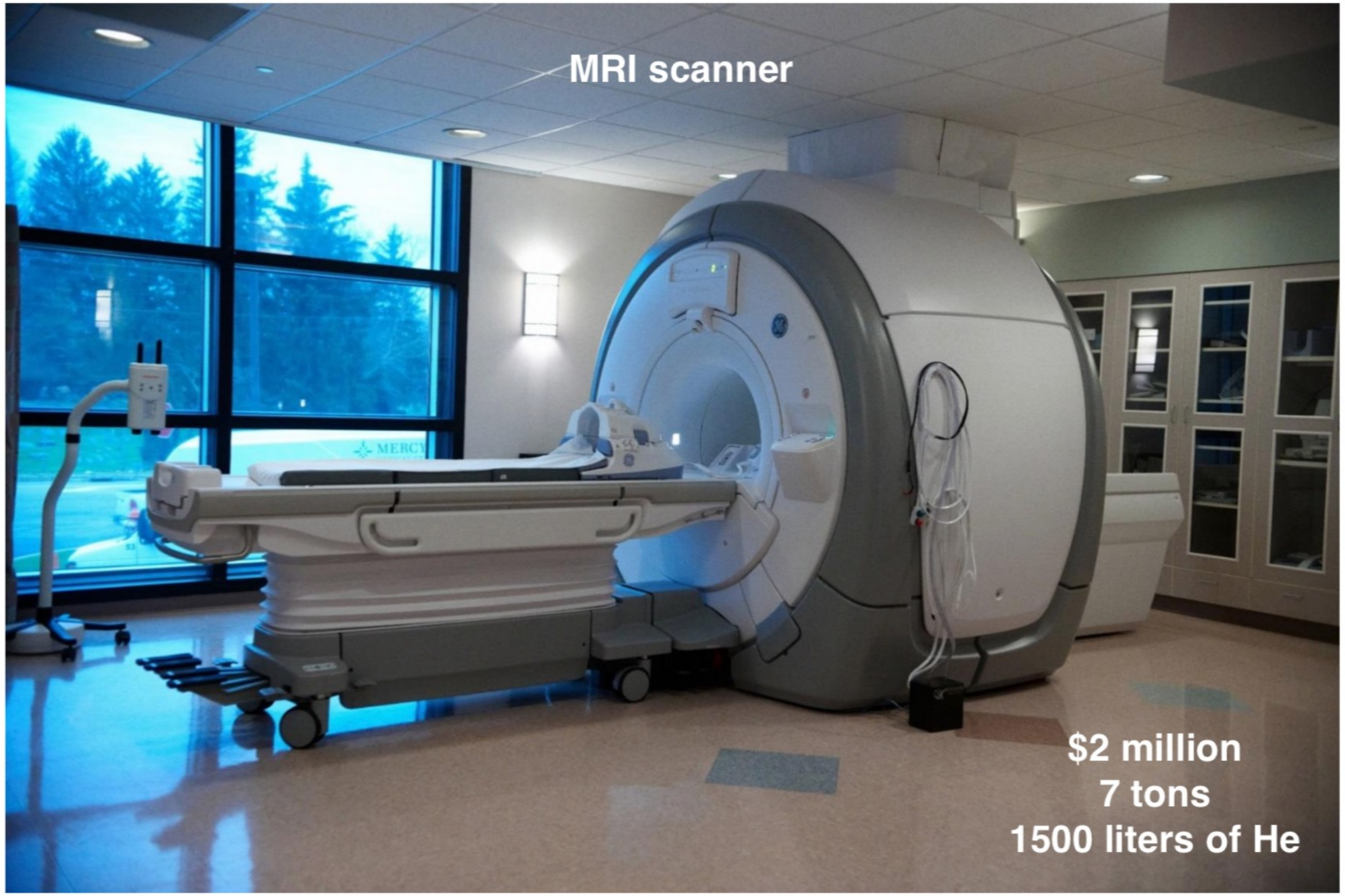
4) a magnetometer next to the sample detects the magnetic field created by this precessing magnetization



a very useful tool for non-invasive imaging (MRI, EPR) and studying molecular structure (NMR)

Aside: magnetic resonance





a very useful tool for non-invasive imaging (MRI, EPR) and studying molecular structure (NMR)

Searching for axion coupling to spin with magnetic resonance

effective interaction: $H_{\mathrm{CASPEr}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$

$$H = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_0 + \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$$

1) placing a spin-1/2 into an external magnetic field splits the spin states by $g\mu B_0$

2) spin polarization (thermal or optical) in a cm^3 sample

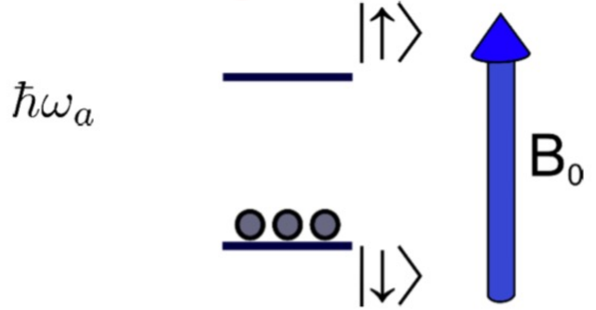
3) resonance: $\hbar\omega_a = g\mu B_0$

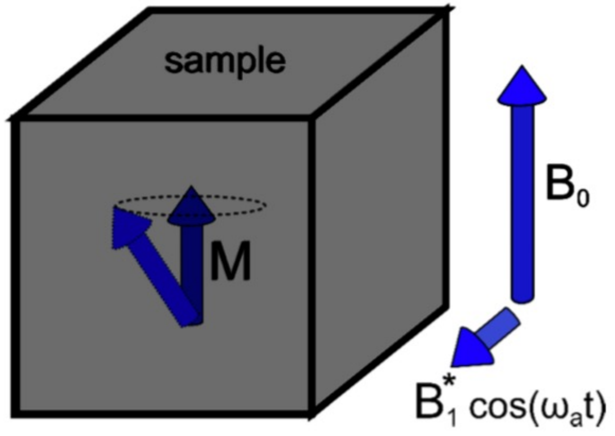
- axion-spin interaction can now flip spins!
- sample magnetization tilts and precesses

4) a magnetometer next to the sample detects the magnetic field created by this precessing magnetization

an NMR experiment with no RF magnetic field, instead axion dark matter flips spins

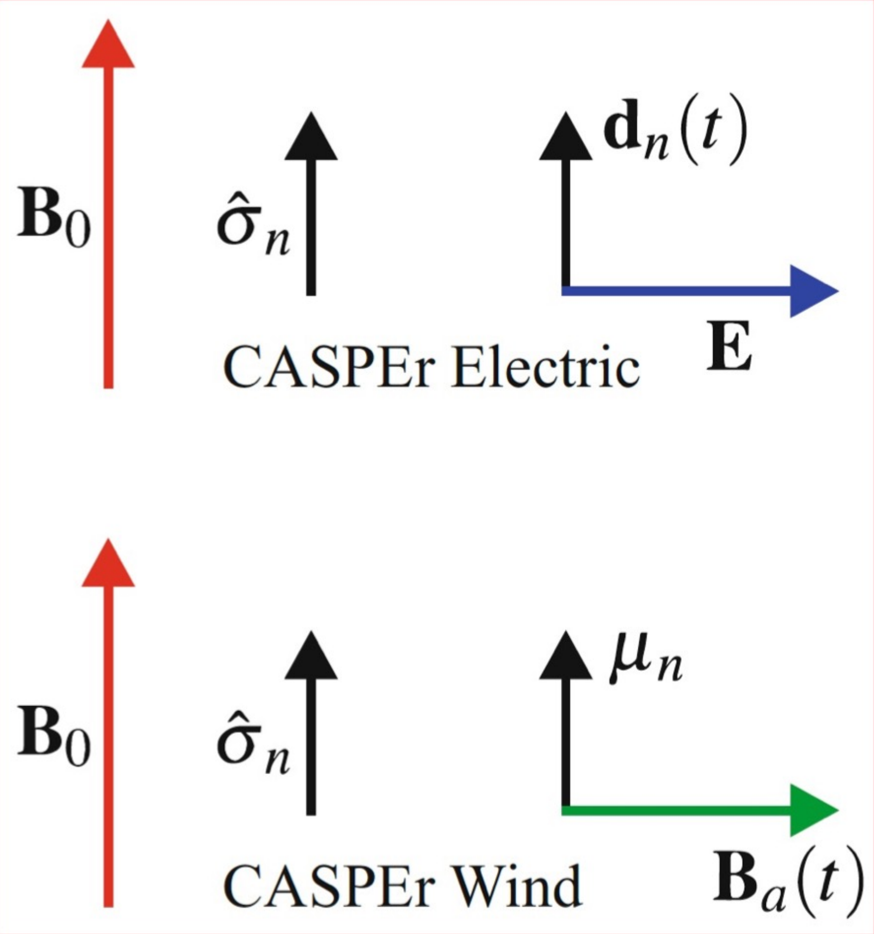
- constant bias magnetic field $\boldsymbol{B}_0$
- spin-axion interaction plays the role of the radiofrequency magnetic field $\boldsymbol{B}_1$

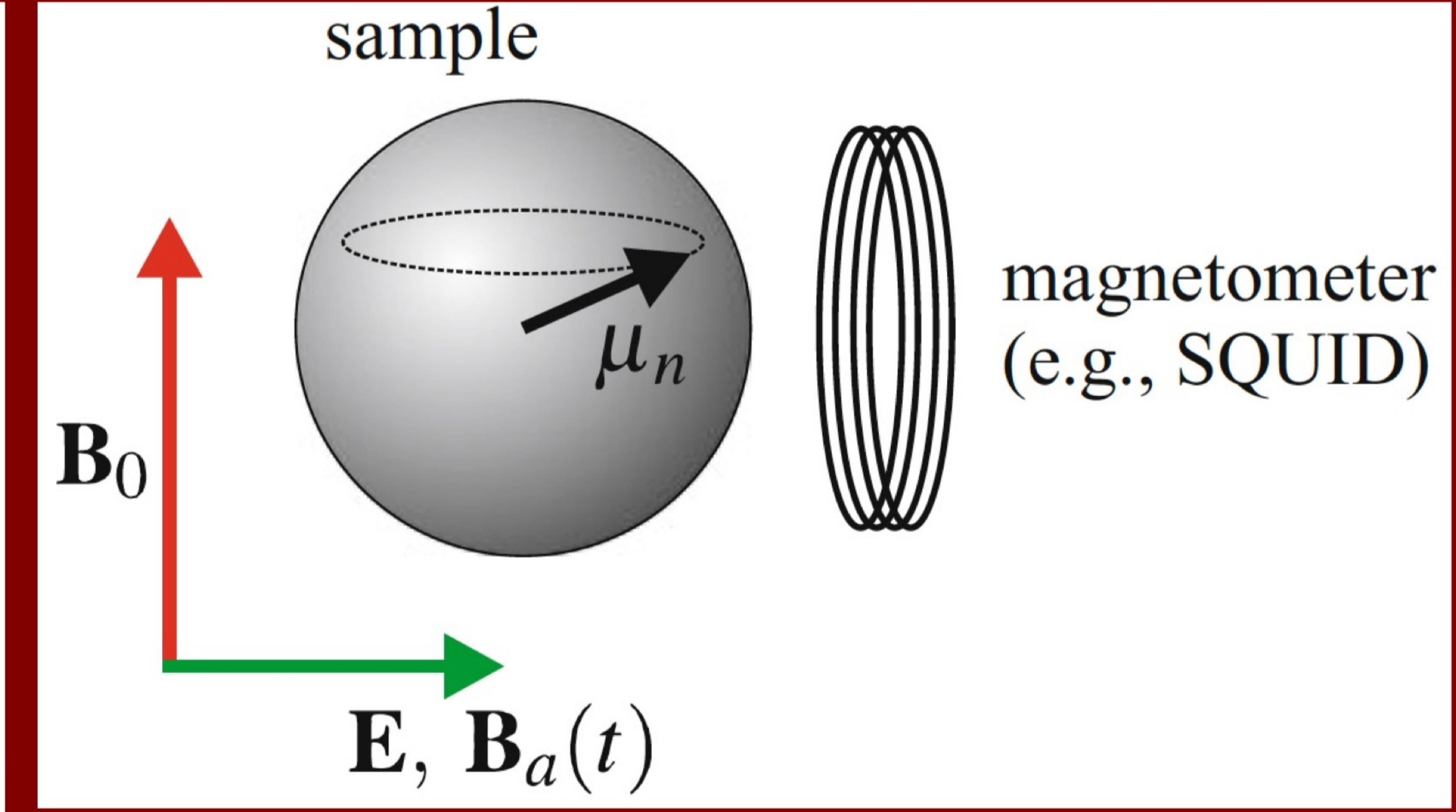




[*Phys. Rev. X* **4**, 021030 (2014)]

DM search with NMR (CASPEr)





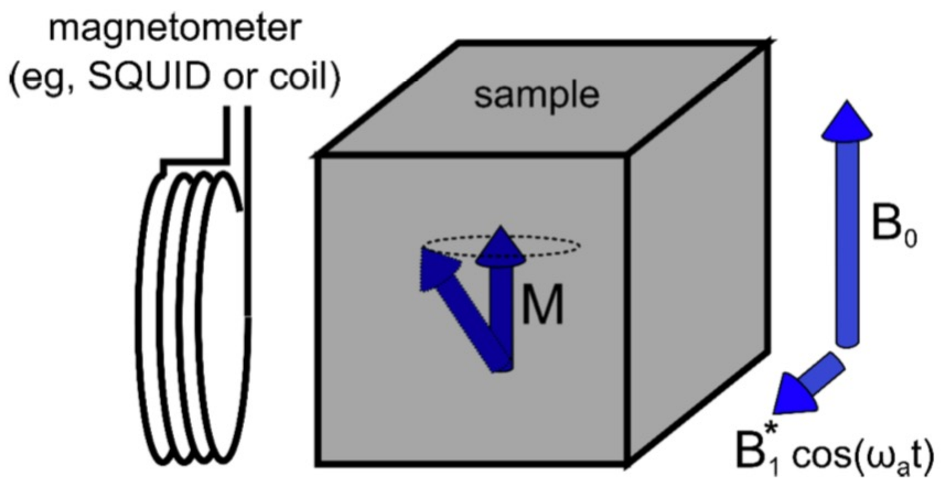
D. F. Jackson Kimball *et. al.* in G. Carosi, G. Rybka (eds.), Microwave Cavities and Detectors for Axion Research, Springer Proceedings in Physics 245, https://doi.org/10.1007/978-3-030-43761-9_13

Choosing the sample material to maximize sensitivity

effective interaction: $H_\mathrm{e} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$

1) maximize $\vec{\boldsymbol{B}}_1^* = g_d a_0 \vec{\boldsymbol{E}}^*$
2) maximize spin density
3) optimize spin coherence time

} important parameters

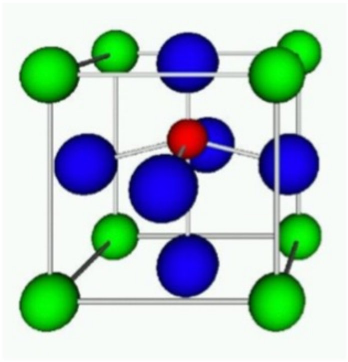


➡ sample → **ferroelectric solid**

1) **effective electric field** acting on nuclear spins: $E^* \approx 10^8\,\mathrm{V/cm}$ (similar to a polar molecule ACME [Science 343, 269 (2013)])

2) spin **density** in the solid: $n \approx 3 \times 10^{21}\,\mathrm{cm}^{-3}$

3) spin **coherence time**: $T_2^* \approx 1\,\mathrm{ms}$



used for novel piezoelectric transducers

↓

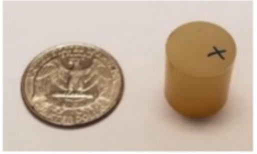
^{207}Pb spins in materials:

$\mathrm{PbTiO_3}$

$\mathrm{Pb(Zr,Ti)O_3}$ (PZT)

$\boxed{(1-\mathrm{x})[\mathrm{Pb(Mg_{1/3}Nb_{2/3})O_3}]/\mathrm{x}[\mathrm{PbTiO_3}]\ (PMN-PT)}$ ➡

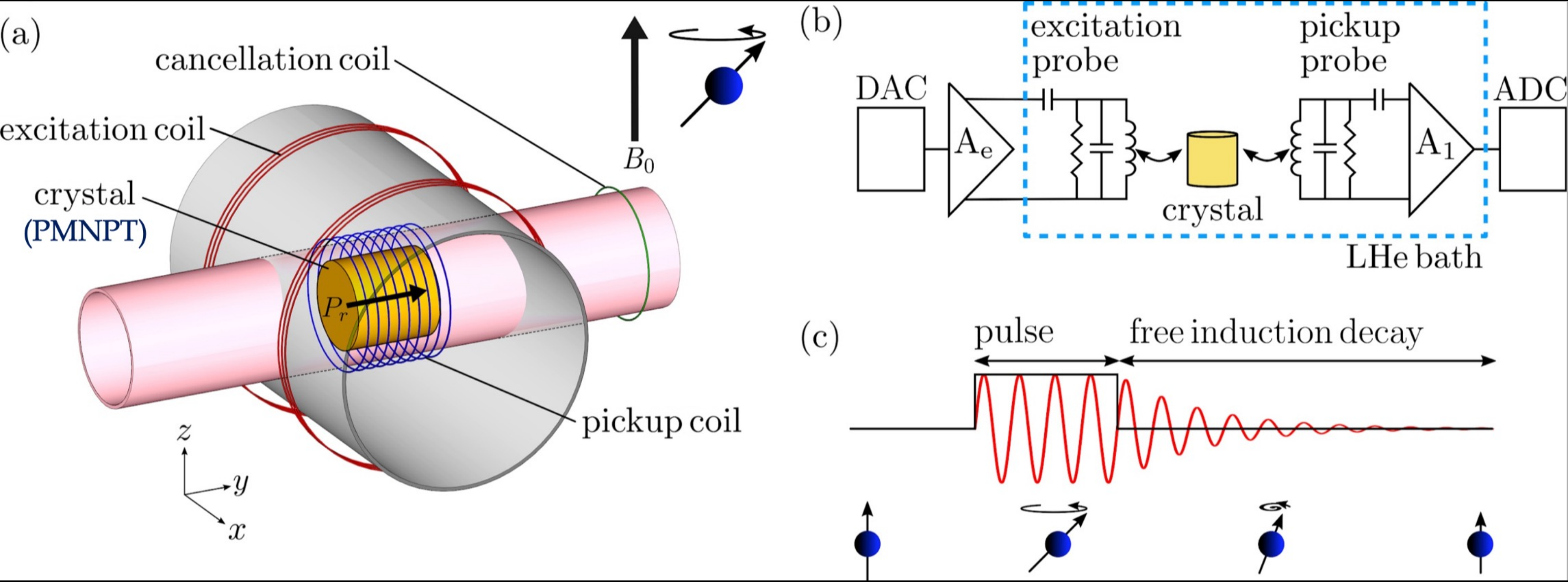
$\mathrm{Pb_5Ge_3O_{11}}$



commercially available

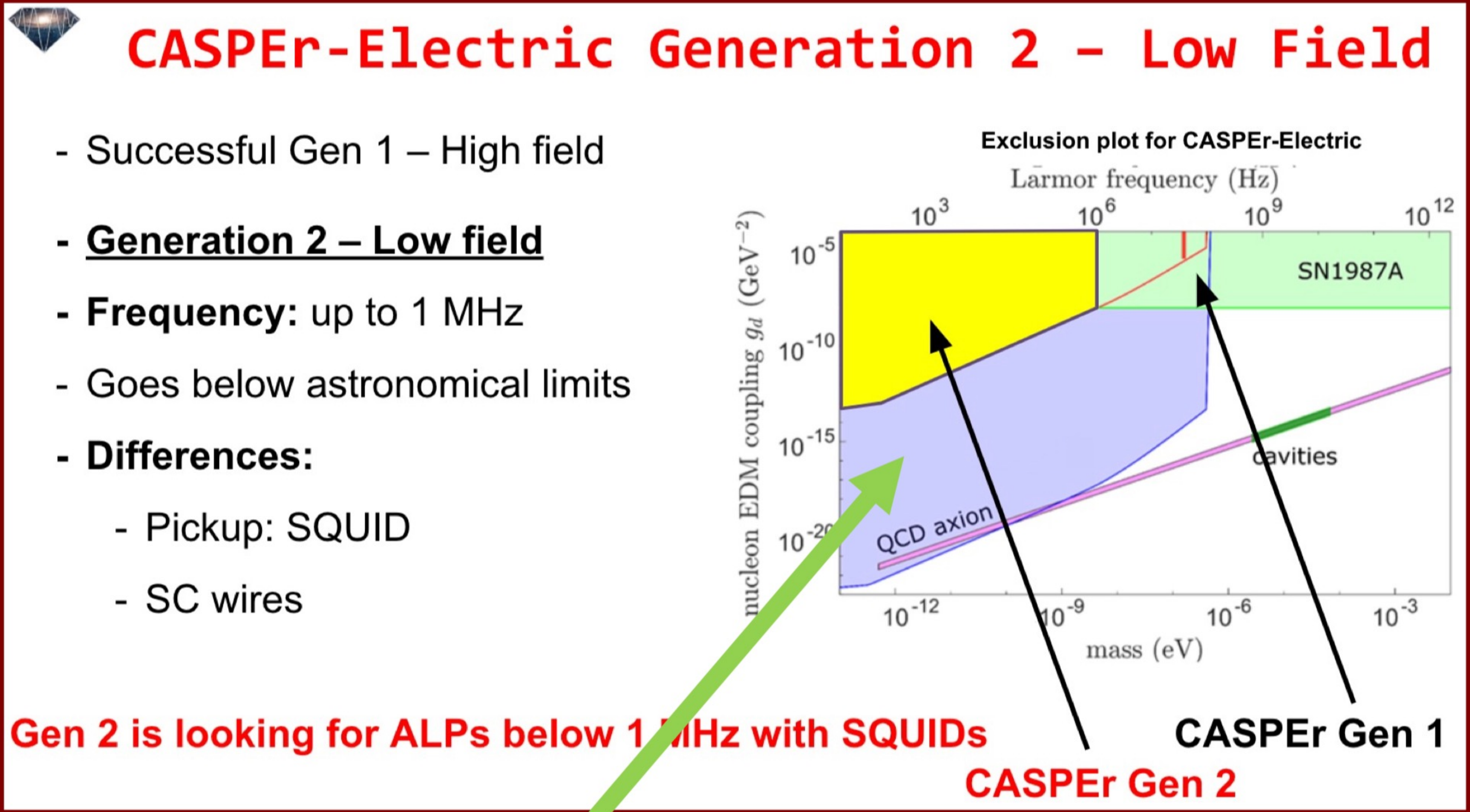
[*Phys. Rev. X* **4**, 021030 (2014)]

CASPEr Electric



Deniz Aybas, *et al*, PRL **126**, 141802 (2021)

CASPEr-Boston



CASPEr-Electric Generation 2 – Low Field

- Successful Gen 1 – High field
- **Generation 2 – Low field**
- **Frequency:** up to 1 MHz
- Goes below astronomical limits
- **Differences:**
  - Pickup: SQUID
  - SC wires

Exclusion plot for CASPEr-Electric

CASPEr Gen 1

CASPEr Gen 2

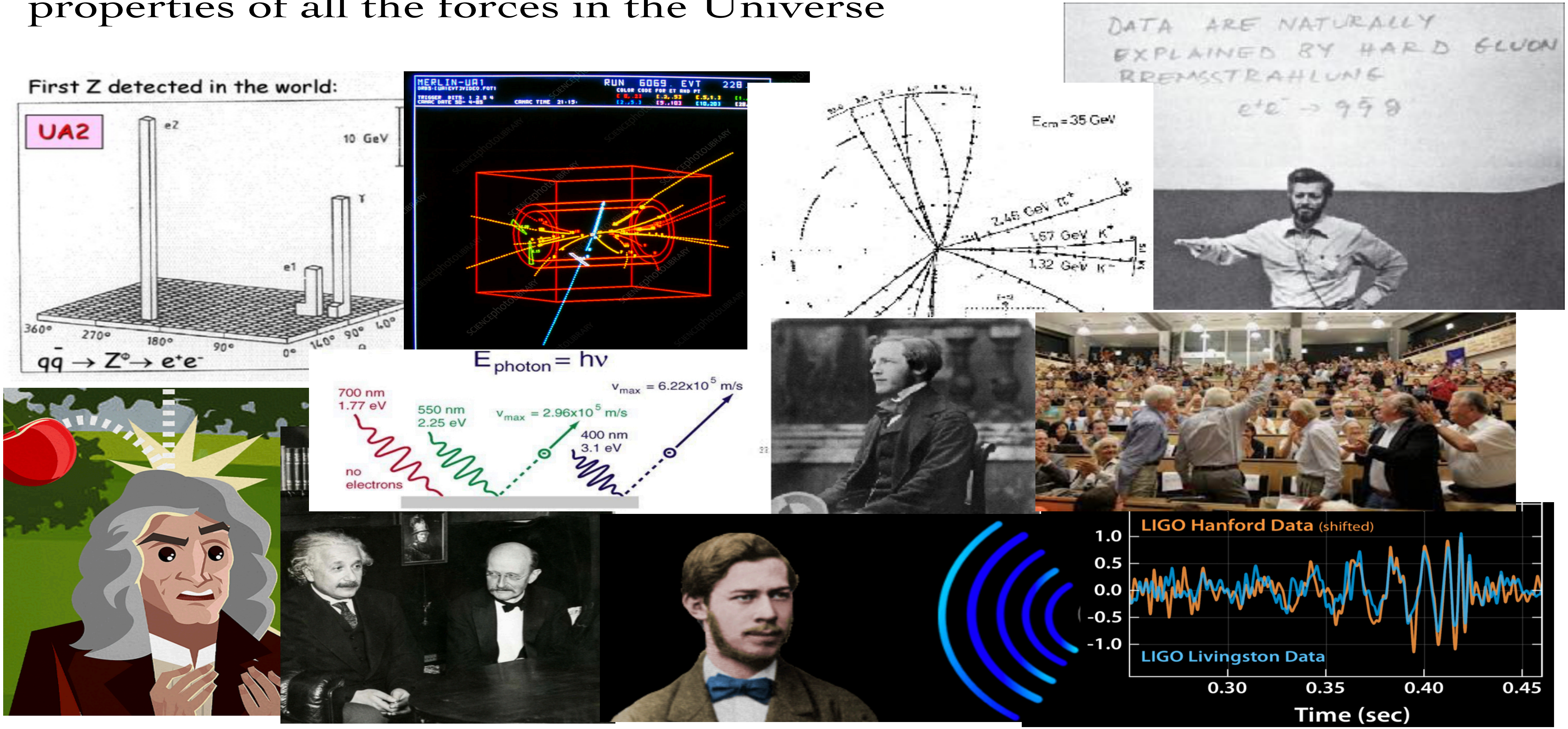
Gen 2 is looking for ALPs below 1 MHz with SQUIDs

Gen 3 : Big Sample + Hyperpolarization !

"Fifth" Forces

(BEH is already 5th!)

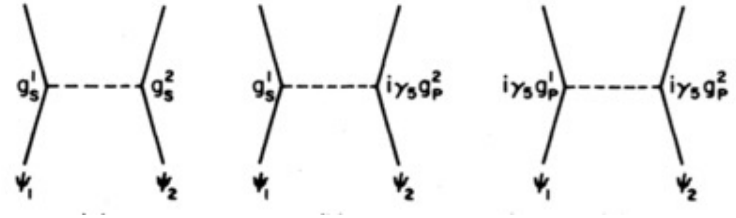
The duty of particle physics is to discover and investigate the properties of all the forces in the Universe



"Fifth" Forces

A wide variety of force laws possible even in non-relativistic limit

$$V(r)=\int\frac{d^3q}{(2\pi)^3}\frac{(\text{vertex }1)(\text{vertex }2)e^{i\vec{q}\cdot\vec{r}}}{\vec{q}^{\,2}+m_\varphi^2}$$



Eg, for just scalars & pNGBs (Moody & Wilczek 1984)

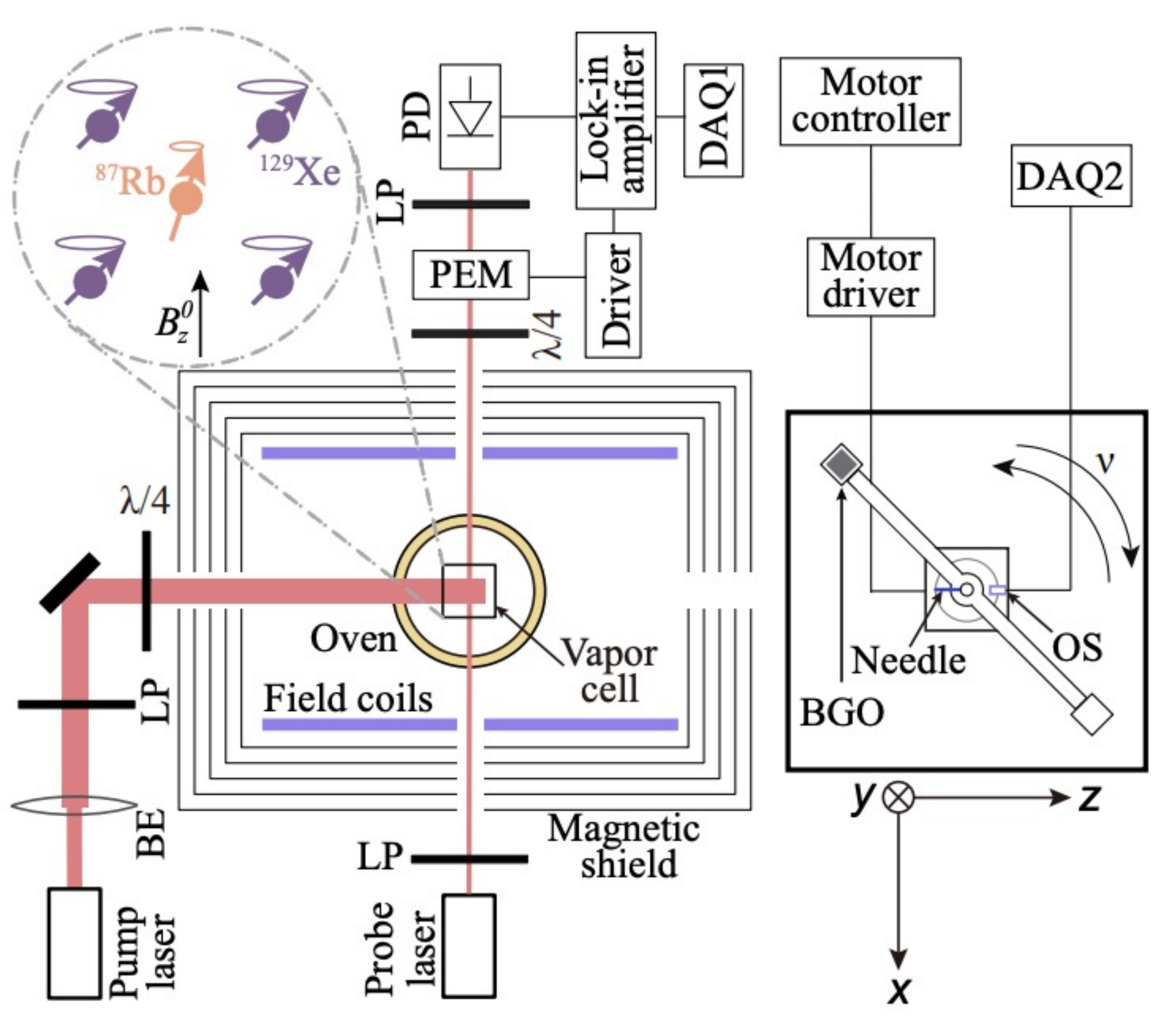
$$V(r)=\frac{-g_S^1g_S^2e^{-m_\varphi r}}{4\pi r}$$

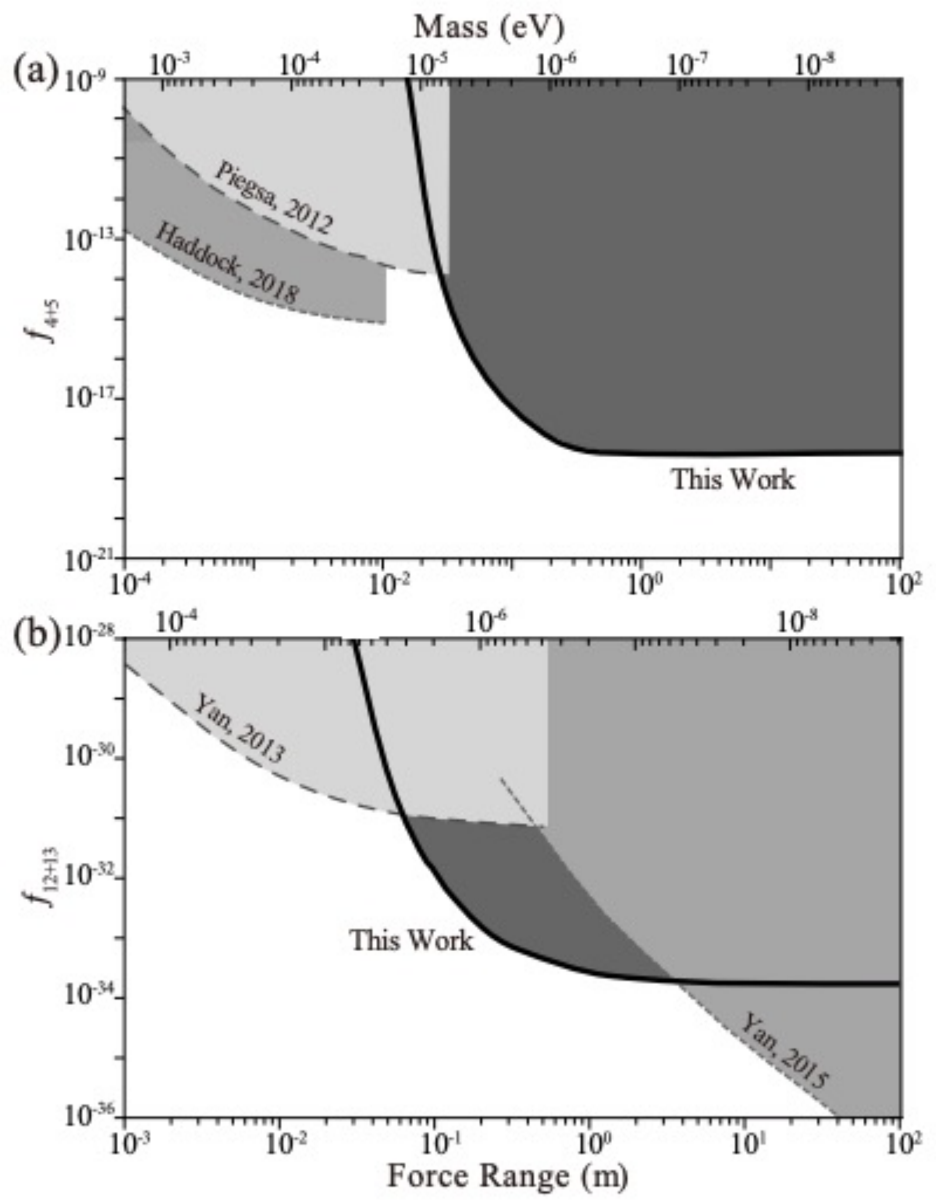
$$V(r)=(g_S^1g_P^2)\frac{\hat{\sigma}_2\cdot\hat{r}}{8\pi M_2}\left[\frac{m_\varphi}{r}+\frac{1}{r^2}\right]e^{-m_\varphi r}$$

$$V(r)=\frac{g_P^1g_P^2}{16\pi M_1M_2}\left[(\hat{\sigma}_1\cdot\hat{\sigma}_r)\left[\frac{m_\varphi}{r^2}+\frac{1}{r^3}+\frac{4\pi}{3}\delta^3(r)\right]-(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left[\frac{m_\varphi^2}{r}+\frac{3m_\varphi}{r^2}+\frac{3}{r^3}\right]\right]e^{-m_\varphi r}$$

These & other possible force laws need to be investigated on **both short and long distances.** Also modifications to gravity are poorly constrained...

Spin-Amplifier search for “fifth forces” (USTC)

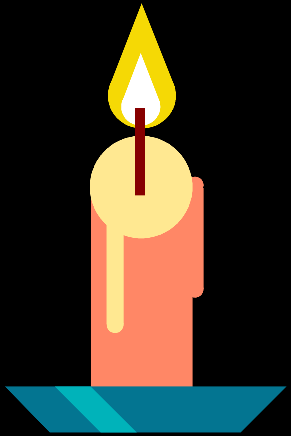




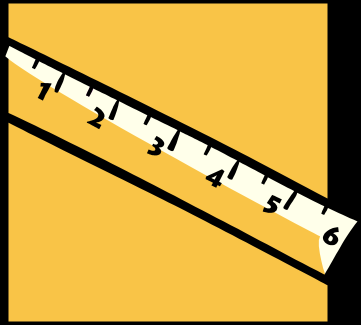
Haowen Su, *et* al, arXiv:2103.15282

Probing Dark Energy

luminosity distances of standard candles (Type 1a SNe)

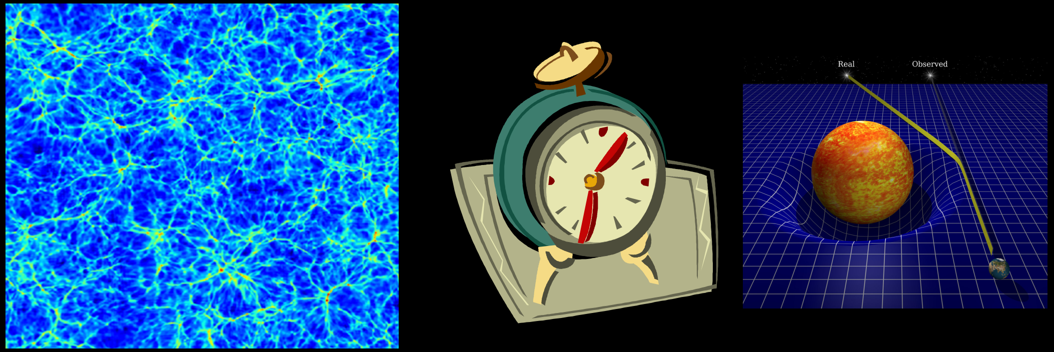


angular diameter distances of standard rulers baryon acoustic oscillations (BAO)



- **measure growth of structure as function of redshift**

- **Galaxy Cluster surveys & Weak Lensing (WL) Surveys**



Neutrinos

Neutrino Sources

Nuclear Reactors
E_ν = 1 - 10 MeV
Detected ✓

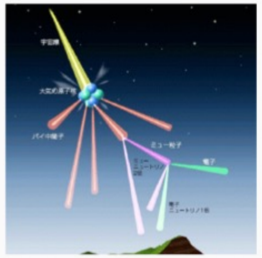
Sun
E_ν = 10.4 MeV
Detected ✓

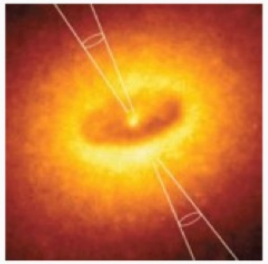
Accelerators
E_ν up to 1 2 GeV
Detected ✓

CERN J-PARC Fermilab KEK

Supernovae (SN 1987A)
E_ν = 10 MeV
Detected ✓

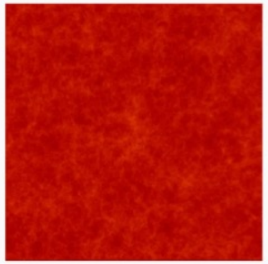
Atmosphere (Cosmic Rays)
E_ν up to 1 GeV
Detected ✓





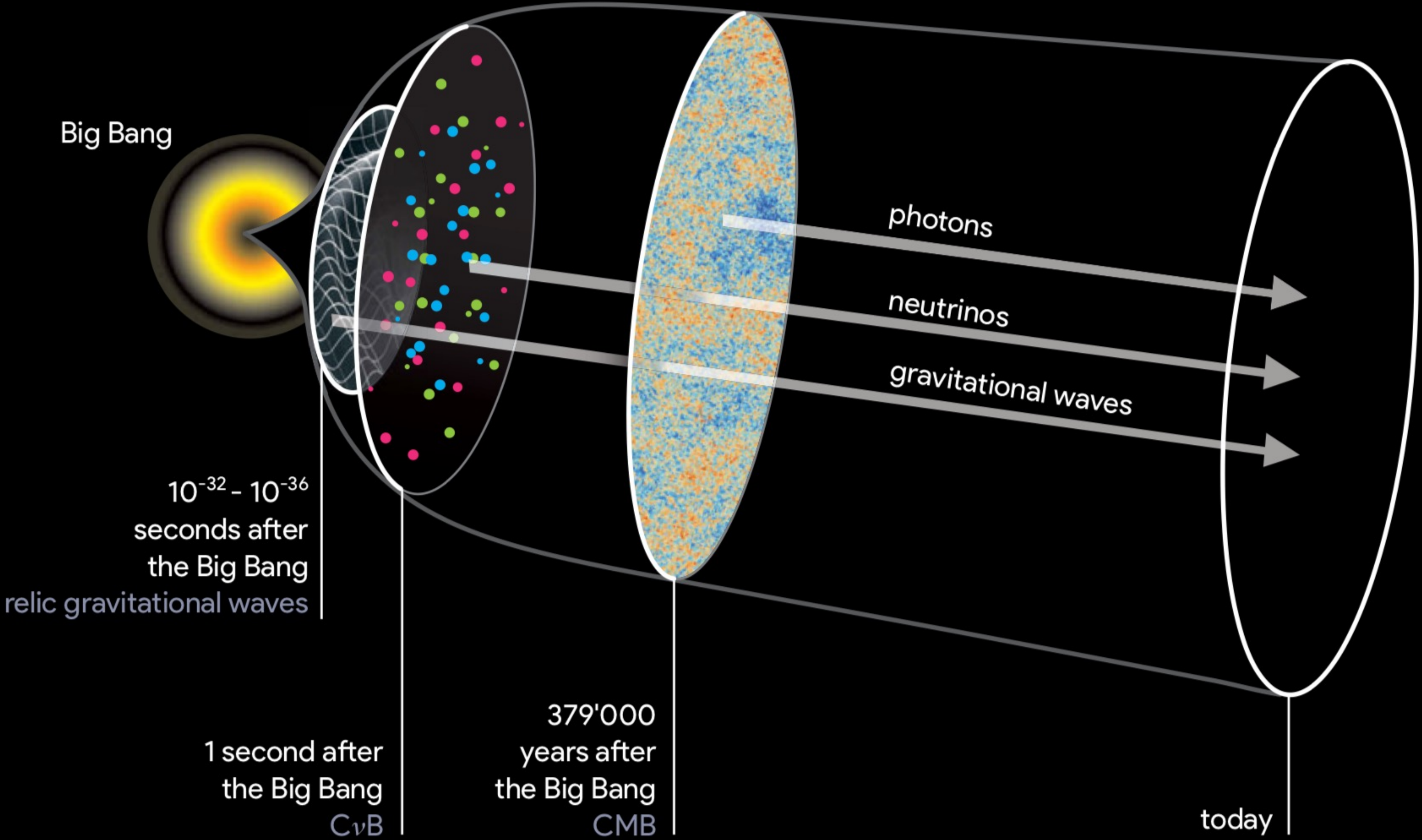
Astrophysical accelerators
E_ν ~ TeV - PeV
Detected ✓

Terrestrial radioactivity
E_ν up to 1 MeV
Detected ✓

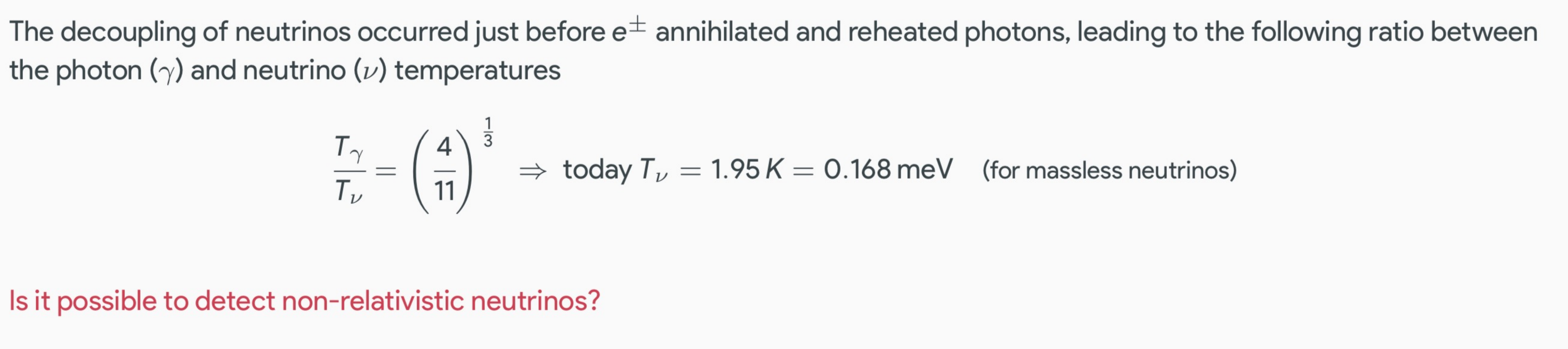


Early Universe
$E_\nu \sim 10^{-4}$ eV
Detected ✗ → Indirect evidence

Surfaces of last scattering



Direct Detection of Relic Neutrinos $(C\nu B)$



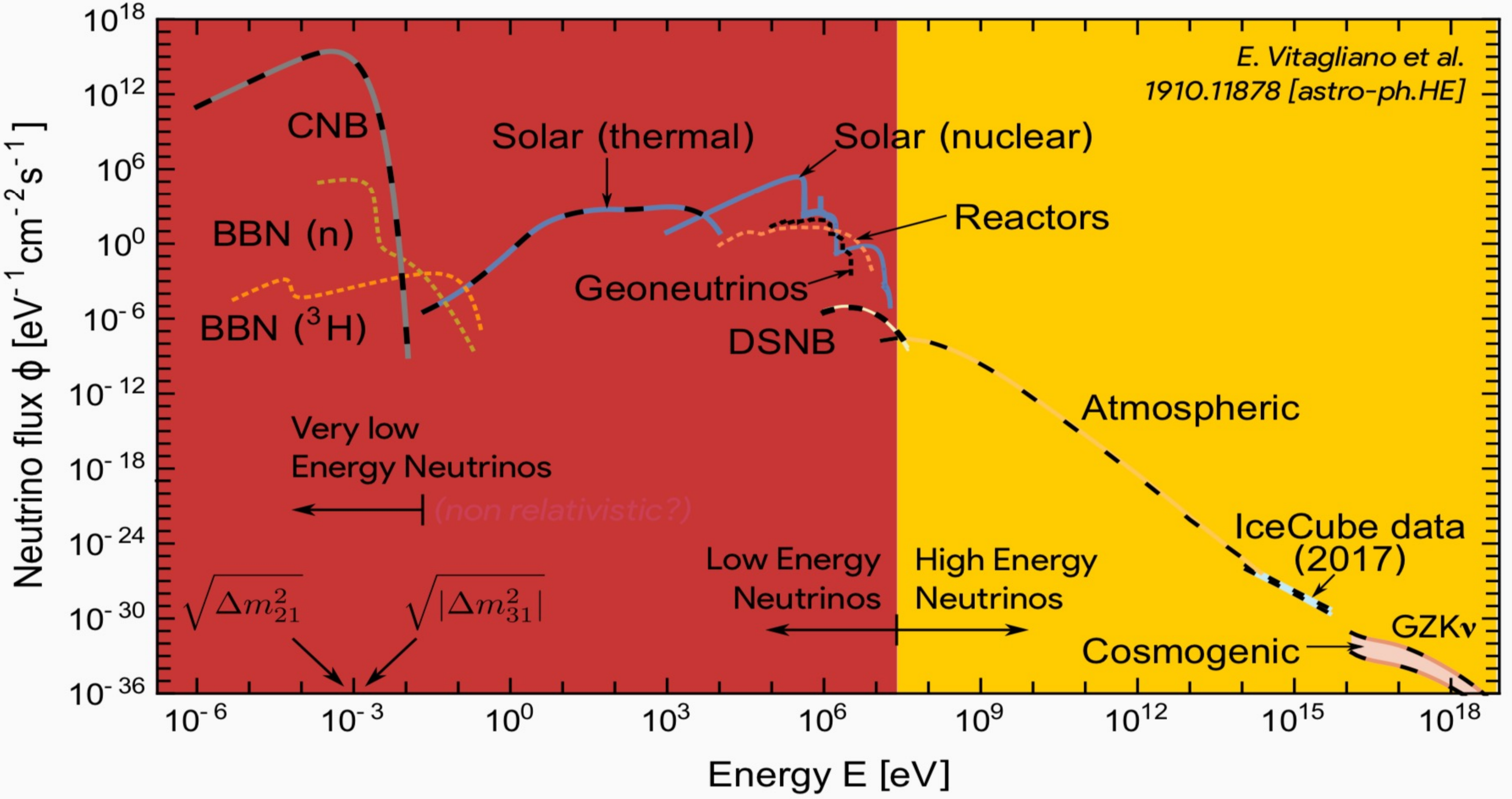
The decoupling of neutrinos occurred just before $e^{\pm}$ annihilated and reheated photons, leading to the following ratio between the photon (γ) and neutrino (ν) temperatures

$$\frac{T_\gamma}{T_\nu} = \left(\frac{4}{11}\right)^{\frac{1}{3}} \Rightarrow \text{today } T_\nu = 1.95\,K = 0.168\,\text{meV} \quad \text{(for massless neutrinos)}$$

Is it possible to detect non-relativistic neutrinos?

Yes thanks to quantum sensing!

Neutrino Spectrum at Earth

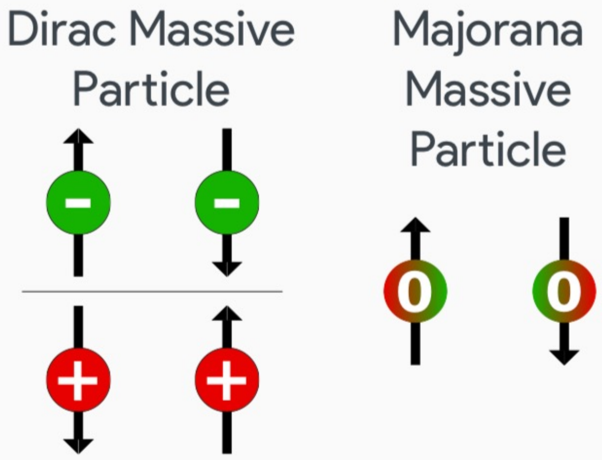


CνB is the largest neutrino density at Earth: 56 ν/cm^3 per type ($\nu/\overline{\nu}$) per flavour (e/μ/τ)

Direct Detection of CνB is the Holy Grail of Neutrino Physics

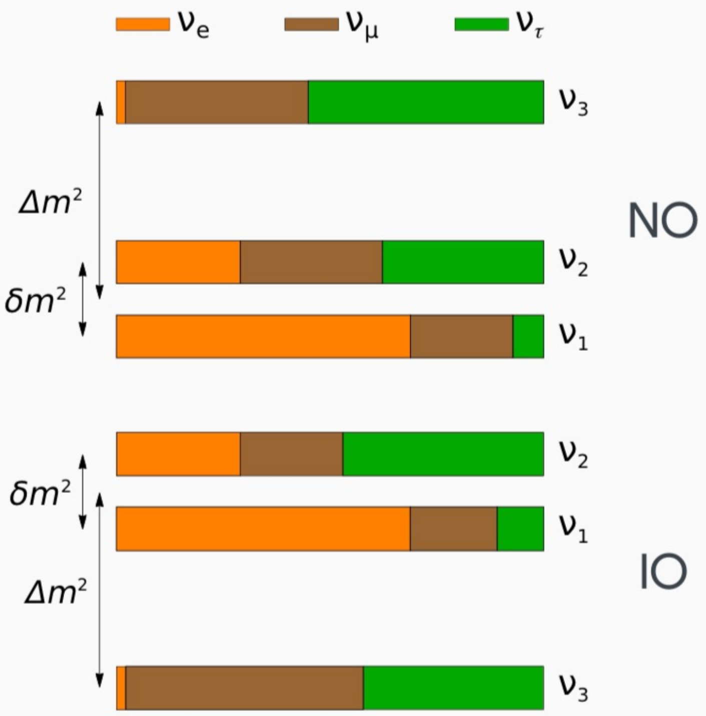
CνB is the largest neutrino density at Earth but yet it has never been measured;

- Detection of relic neutrino is a significant test of standard cosmology
- Observation of CνB would:
    - provide a window into the 1st second of creation;
    - constitute the first probe of non-relativistic neutrinos;
    - reveal the neutrino nature (through measurement of modulations/asymmetries);

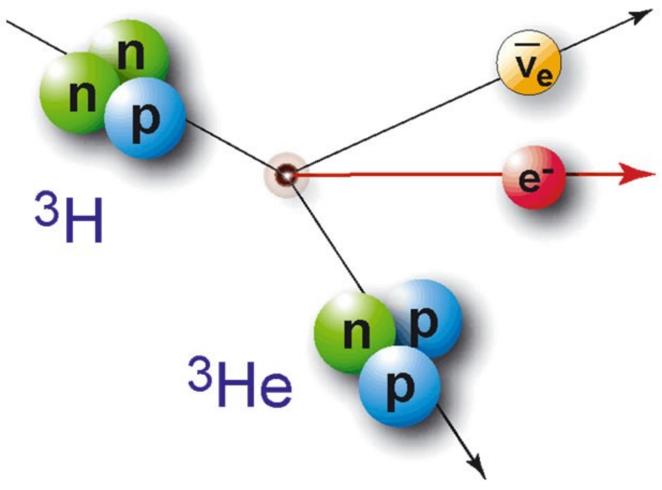


In particular

- **Neutrino mass nature**: the capture rates of non-relativistic neutrinos (on beta decaying nuclei) depends on whether their mass nature is Dirac ($\overline{\nu} \neq \nu$) or Majorana ($\overline{\nu} = \nu$)
- **Neutrino mass ordering**: relic neutrinos with an enhanced (suppressed) detection rate for normal (inverted) neutrino ordering
  (since the lightest mass eigenstate contains a large (small) fraction of the electron-neutrino flavor eigenstate)



Neutrino capture on Tritium

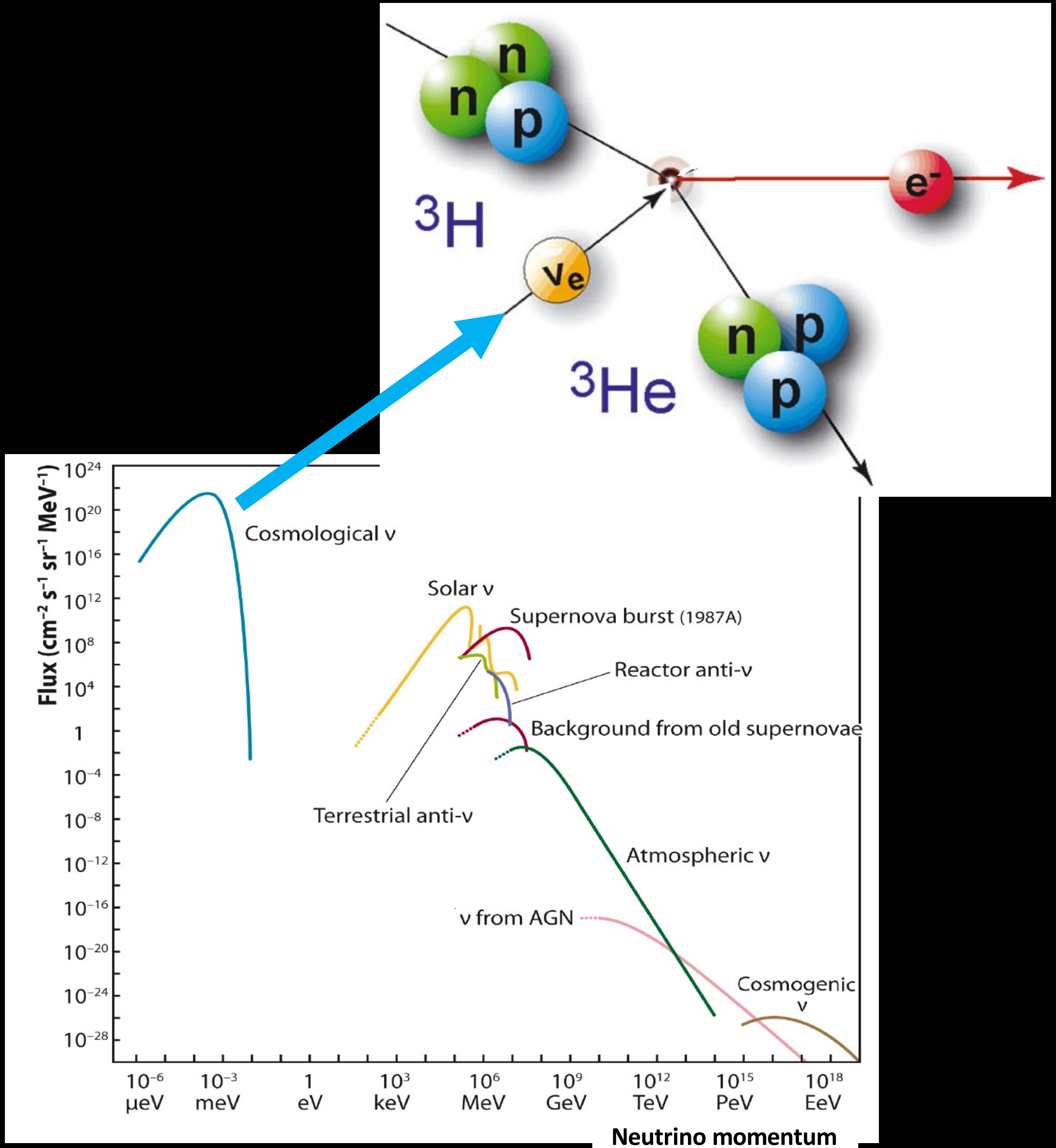


Tritium β-decay
(12.3 yr half-life)

Neutrino momentum ~ 0.17 meV

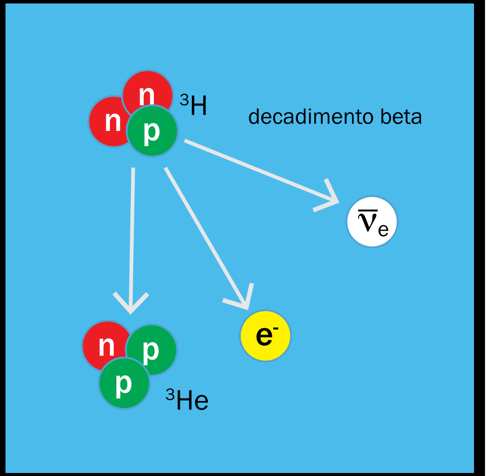
For m_ν = 50 meV,
KE = $p^2/2m$
= 0.17 meV (0.17 meV/100 meV)
= 0.3 μeV

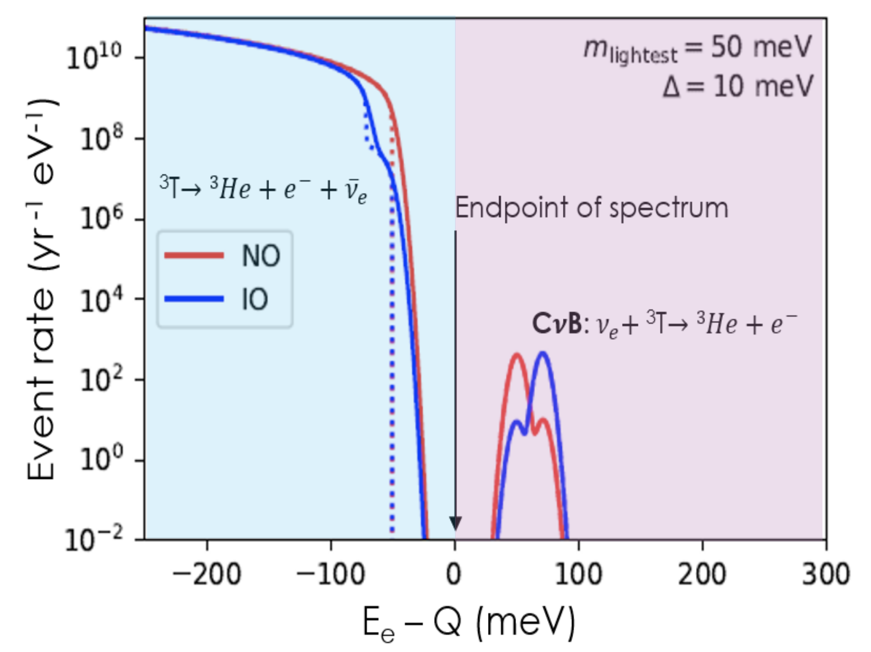
Ultra-Cold!

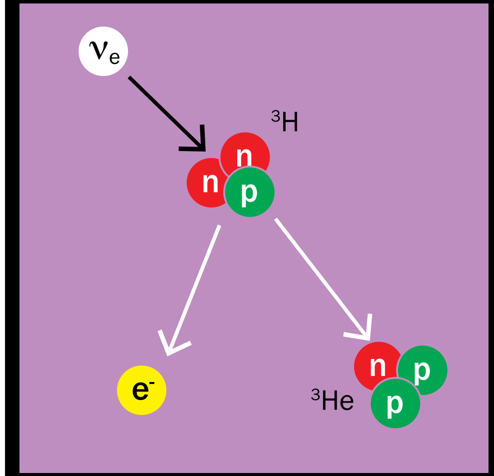


Detection Concept: Neutrino Capture

- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in **1962** [*Phys. Rev*. 128:3, 1457] applied for the first time to massive neutrinos in **2007** by Cocco, Mangano, Messina [DOI: 10.1088/1475-7516/2007/06/015] (no molecular smearing included)







What do we know?

Electron flavor expected with

m > ~50meV

from neutrino oscillations

Gap (2m) constrained to

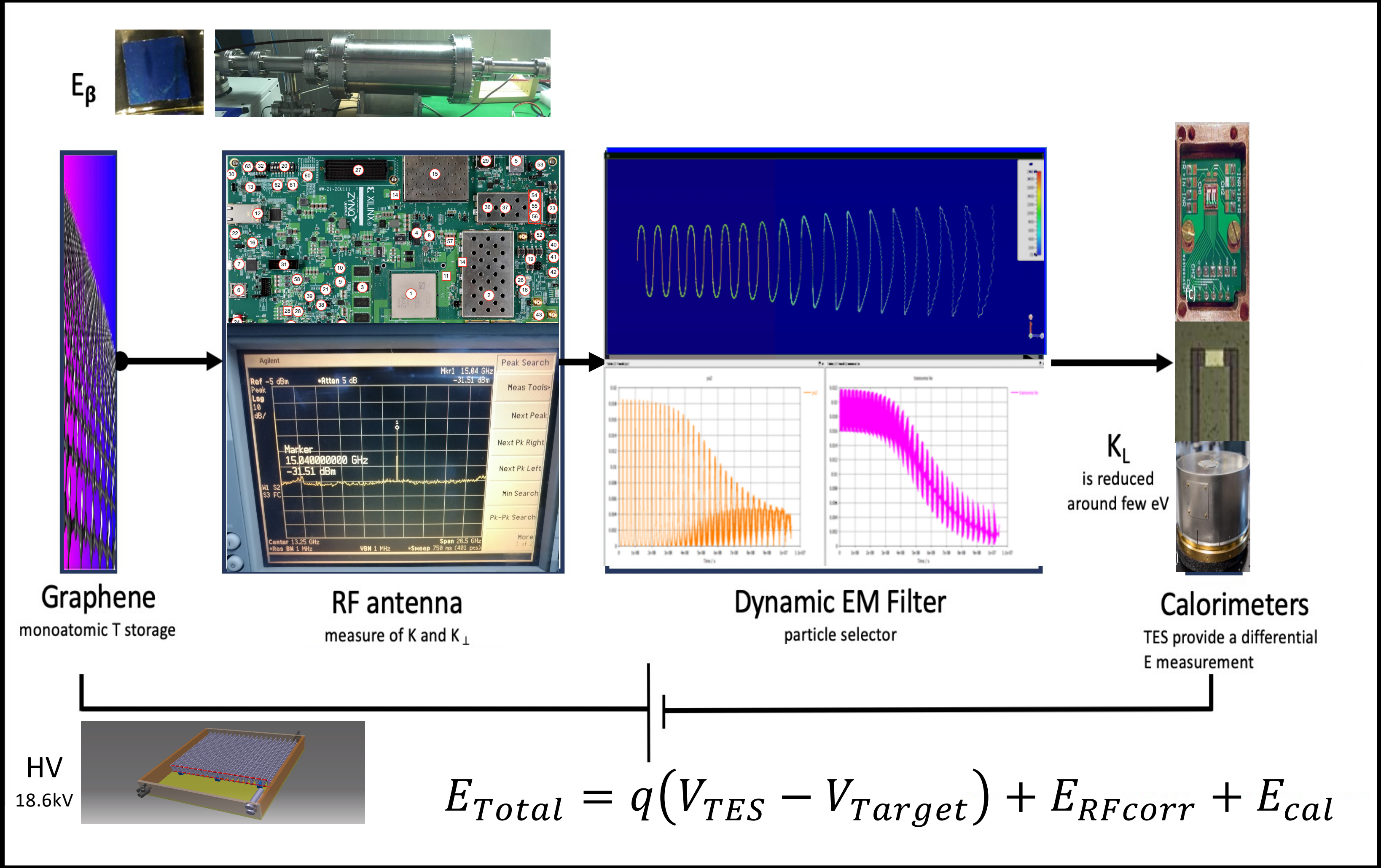
m < ~200meV

from Cosmology

Quantum Systems Impacting CNB Detection

- Kinetic Energy calculation (micro eV)
  - Detection sensitivity set by mass
- Quantum Excitations in Target Substrate
  - Minimizing Zero-Point Energy (graphene, Au(111), superfluid ^{4}He)
  - Polarized targets for mapping the sky
- 0.1fW RF detection
  - Phased arrays with Low(est) Noise Amplification methods
  - Ultimate limit set by limit on microwave photon detection
  - B^2 improvement 27 GHz @1T → 80-90 GHz @3T
  - Fast 5G/Xilinx ZNYQ RFSoC Trigger – similar to QuBit gate processing
- Superconducting dipoles with custom fringe fields
  - Novel EMF design with working iron-return-yoke mockups (1T → 3T w/SC)
  - Fast HV ramping for filter, precision HV references for target-microcalorimeter
  - Einzel Lens low energy electron transport
- TES Microcalorimetry
  - Evaluated with Fast, IR Photon Counting
  - New Thin Film prototypes for eV electron energy measurement
  - Microwave multiplexing for electron calorimeter

PTOLEMY Conceptual Block Diagram



E_β

Graphene

monoatomic T storage

RF antenna

measure of K and $K_\perp$

Dynamic EM Filter

particle selector

K_L is reduced around few eV

Calorimeters

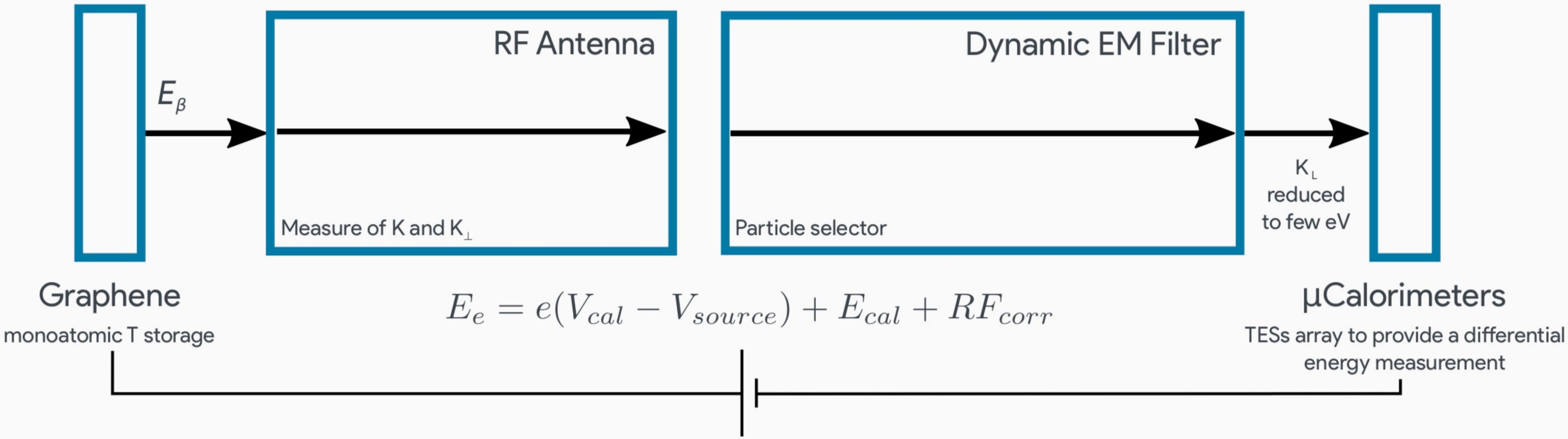
TES provide a differential E measurement

HV
18.6kV

$$E_{Total} = q\left(V_{TES} - V_{Target}\right) + E_{RFcorr} + E_{cal}$$

https://ptolemy.lngs.infn.it

PonTecorvo Observatory for Light Early-Universe Massive-Neutrino Yield (PTOLEMY)



$$E_e = e(V_{cal} - V_{source}) + E_{cal} + RF_{corr}$$

- Electrons from weakly-bound tritium originate from a cold target surface.
- Electrons drift through an RF Antenna region where the electron momentum components are measured to few eV resolution.
- Filter electrodes are set around 1 msec in advance of electrons entering filter.
- Kinetic energy of electrons drained as they climb a potential under gradient-B drift.
- Electrons of few eV in a low B field region are transported into a microcalorimeter array.

Summary

CNB direct detection is at a much more advanced phase than it was 6 years ago

- Basic principles have evolved into concrete designs
- Prototype construction has yielded good results with several publications
- Theoretical interest continues to grow with more and more PTOLEMY citations
- The particle physics community has grown more familiar with quantum material properties and techniques with new and productive collaborations

We hope to enter an exciting new phase with PTOLEMY this year with a rich experimental program focused on achieving CNB detection

Quantum Technologies for Neutrino Mass *17 members (and growing)*

UCL

UNIVERSITY OF CAMBRIDGE

NPL National Physical Laboratory

WARWICK THE UNIVERSITY OF WARWICK

Prifysgol Abertawe Swansea University

Determination of Neutrino Mass with Quantum Technologies

A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

PPTAP Workshop
Cyberspace
3 June 2021

Ruben Saakyan (UCL)

Neutrino oscillations → *$m_\nu \neq 0$* → *Window to New Physics*

Absolute mass not known → complementarity of cosmological observations and **laboratory measurements**

Model independent measurement: electron spectrum near end-point of β-decay

E. Fermi, Z. Phys. 88 (1934) 161

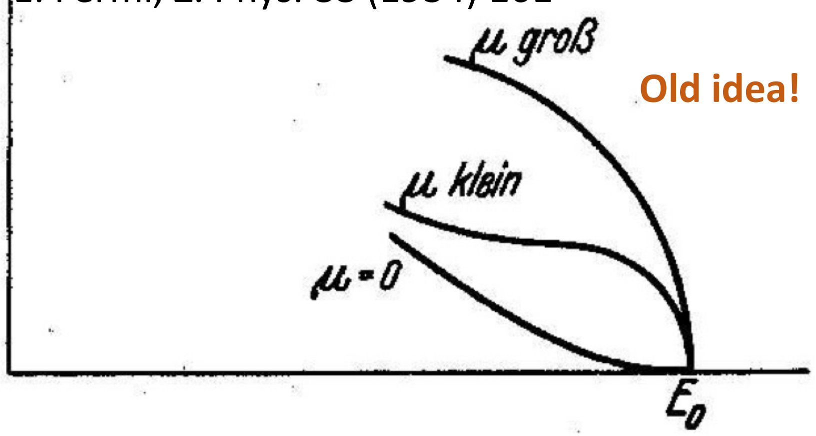
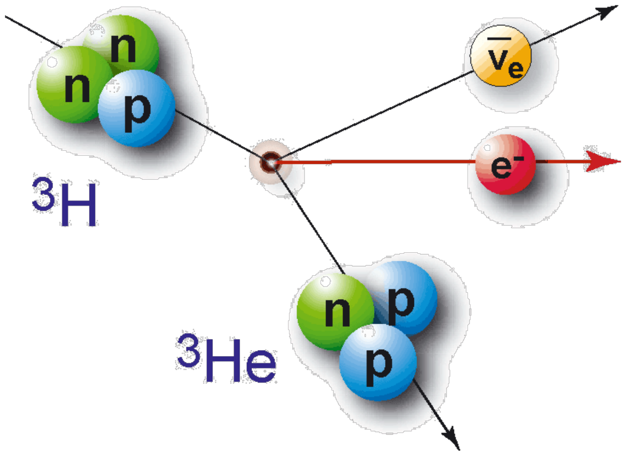
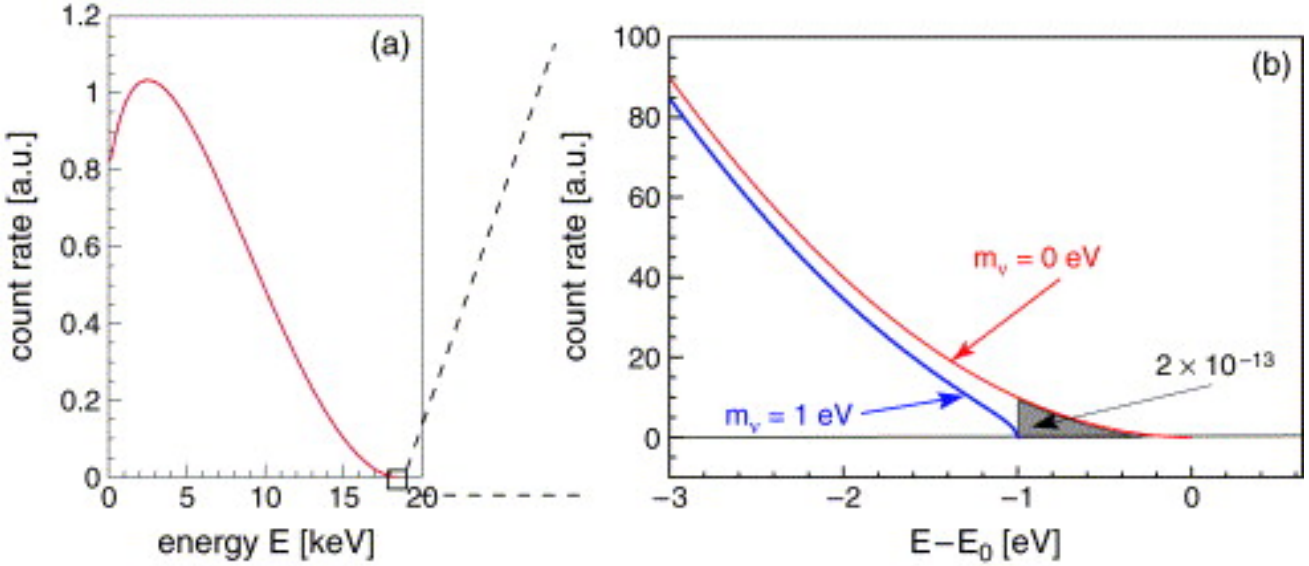


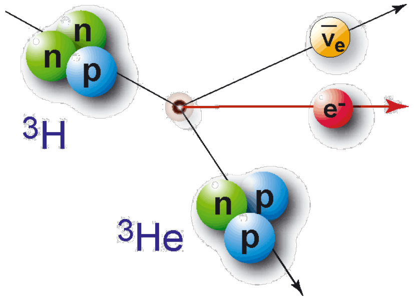
Fig. 1.

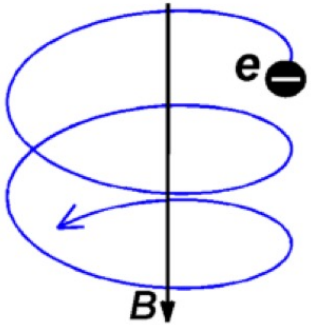
Old idea!



- **Current upper limit, < 0.8 eV (KATRIN)**
- **Lower bound (from ν-oscillations) > 0.009 eV (!)** → ***Requires a "quantum leap" in technology***







Cyclotron **R**adiation **E**mission **S**pectroscopy (**CRES**)

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

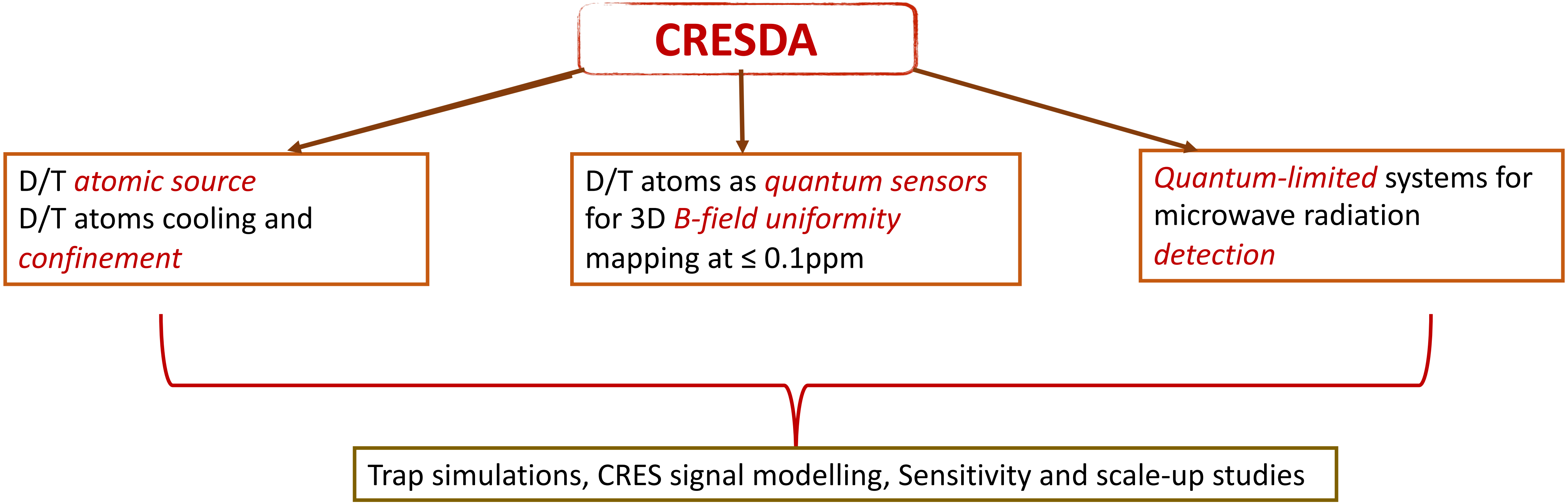
Challenges:

- ***Atomic tritium***
- ***Sub fW power***
- ***< 1ppm resolution***

Goal: To build on recent **investment** in **quantum sensors** to assess feasibility of an **experiment** capable of a positive **neutrino mass measurement** from **^{3}H *β*-decay** using **CRES** technology.

QTNM is funded for 3 years under the UKRI **QTFP** Programme

The aim is to build **CRES D**emonstration **A**pparatus, **CRESDA**, based on Deuterium-atoms but “Tritium-ready”



CRESDA

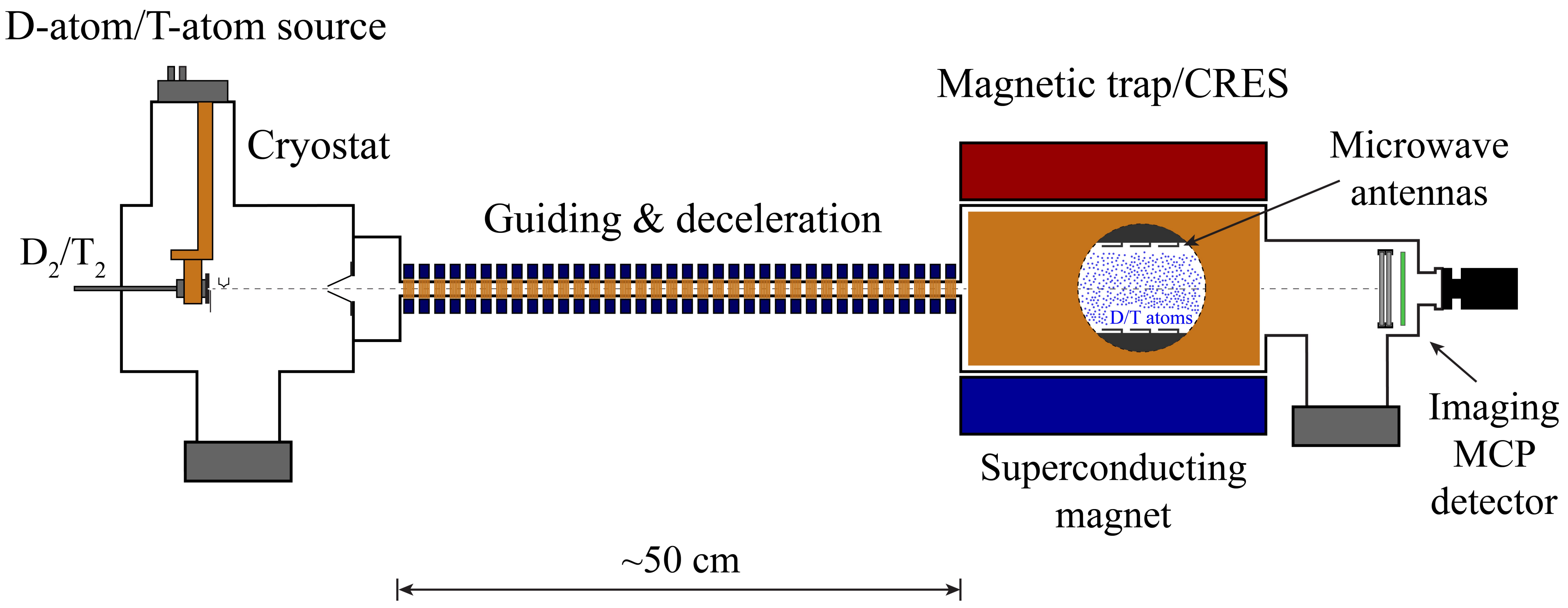
D/T *atomic source*
D/T atoms cooling and *confinement*

D/T atoms as *quantum sensors* for 3D *B-field uniformity* mapping at ≤ 0.1ppm

Quantum-limited systems for microwave radiation *detection*

Trap simulations, CRES signal modelling, Sensitivity and scale-up studies

CRESDA. Atomic Source and Atom Confinement.



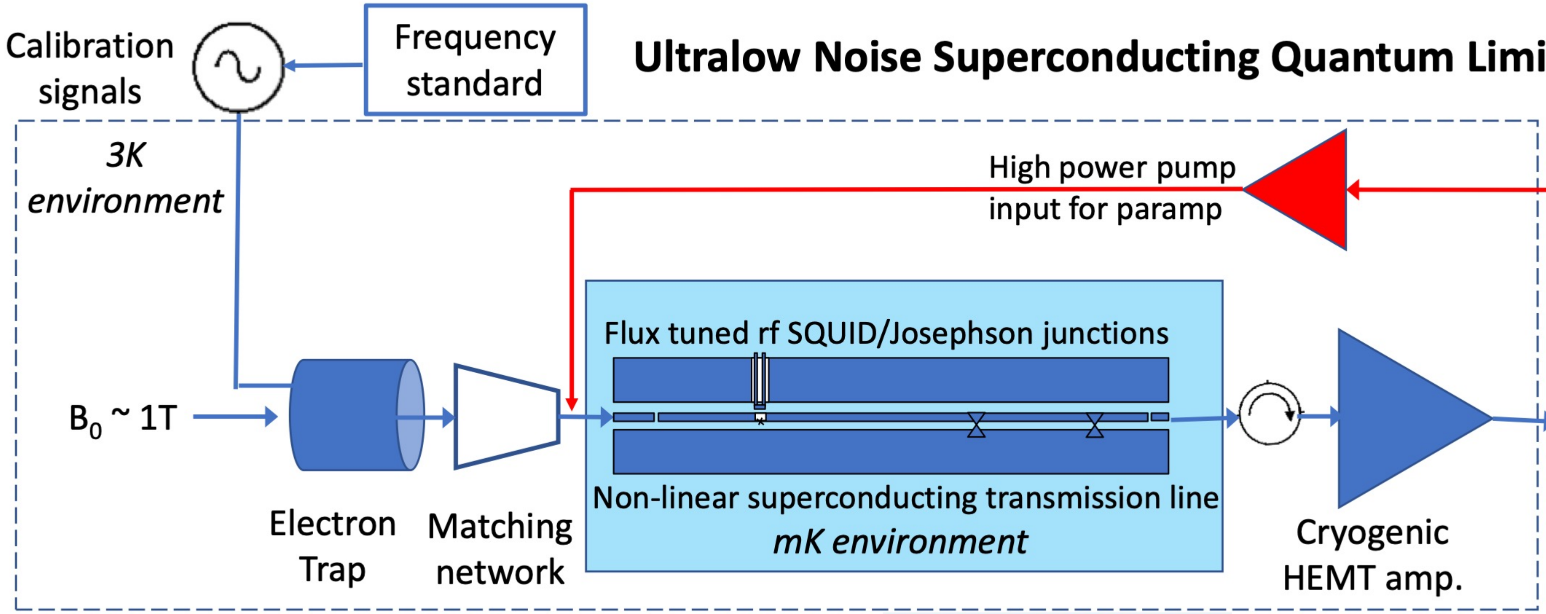
- A number of designs under consideration
- 1L CRES region with ρ~10^{12}-10^{14} cm^{-3}.
- Initially operate with D-atoms, tritium ready.

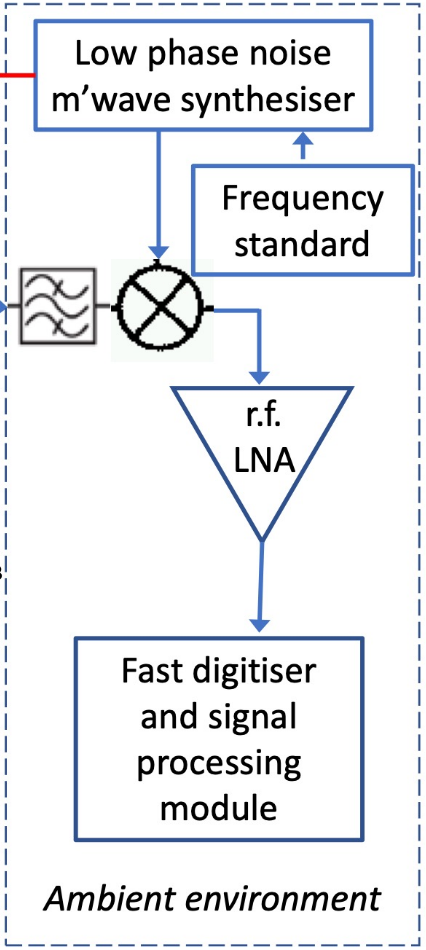
- Extensive characterisation of confined atoms (density, velocity distributions…)
- B-field mapping with ≤ 0.1ppm using D/T-atoms as quantum sensors
- D_2/T_2 background characterisation

CRESDA. Quantum MW-Spectrometer.

MW signal → Antennas → SQUID or JTWPA preamp → HEMT amp

Ultralow Noise Superconducting Quantum Limited CRES Detector

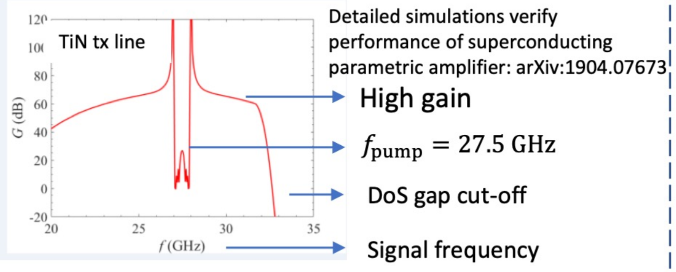




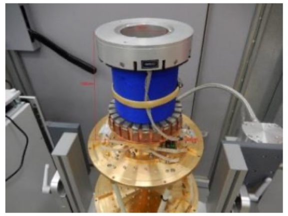
Challenge of millimetre-wave (25-30 GHz) ultra-low-noise amplifiers:

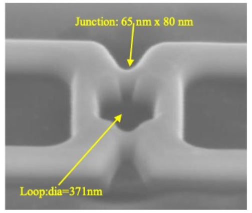
- Push superconducting microwave SQUID amplifiers up in frequency
- Push superconducting parametric amplifiers down in frequency
- High gain quantum-limited noise performance possible

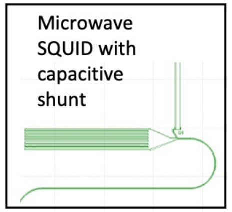
Draws heavily on major investments by funding agencies in establishing superconducting device processing and measurement labs

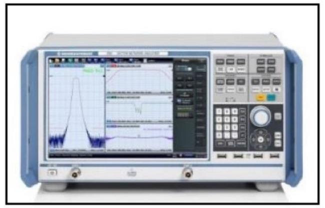


Detailed simulations verify performance of superconducting parametric amplifier: arXiv:1904.07673

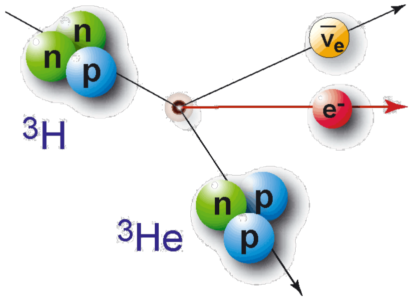






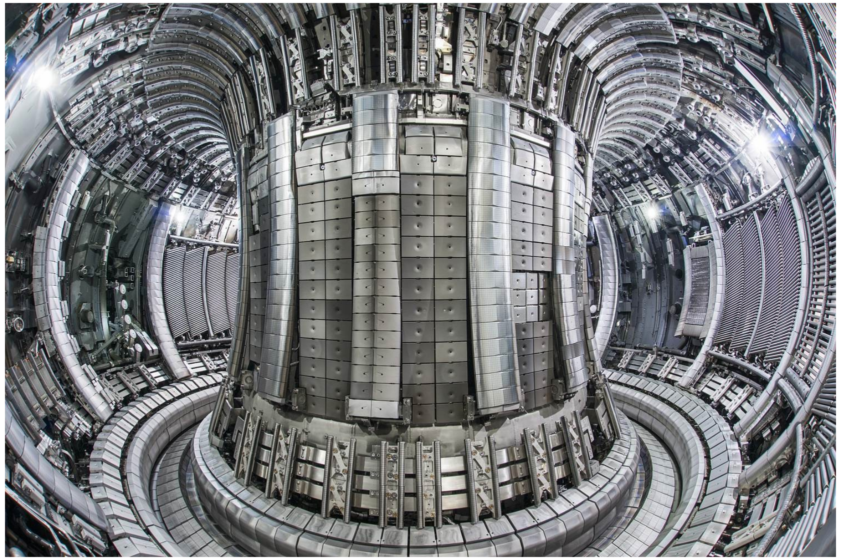


QTNM Future Outlook



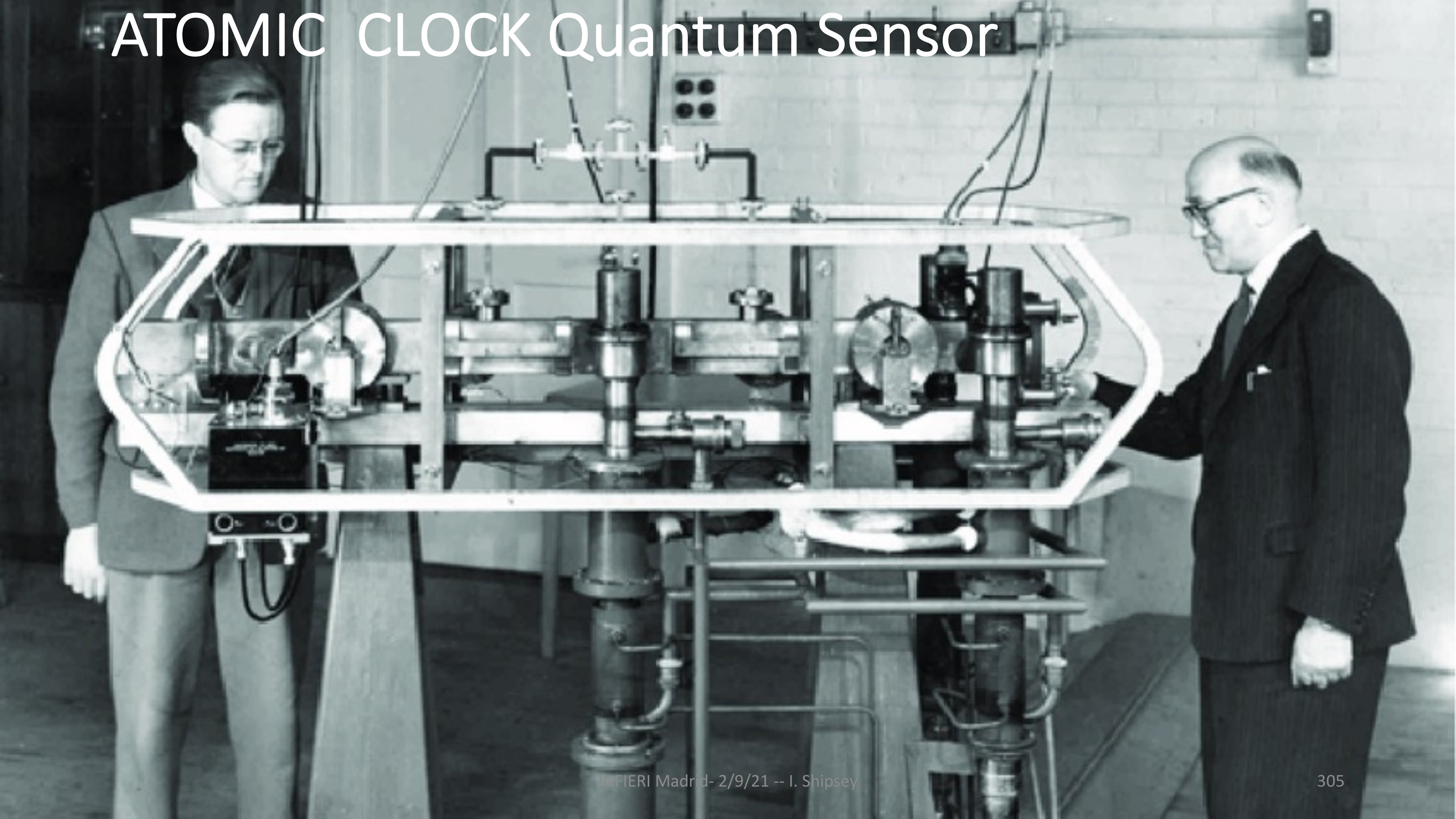
A (*VERY*) tentative timeline

- Current project: 2021-2024
  - Technology demonstration with Deuterium which is Tritium ready
- Next step. 2025-2029
  - Moving CRESDA to a Tritium facility (strong engagement with Culham)
  - Tritium phase demonstration
  - *O*(eV) sensitivity
- ”Ultimate” international project > 2029
  - Consolidate technological breakthroughs (QTNM, Project-8, …) to build and operate a detector with a phased sensitivity: 100 meV ⇨ 50 meV ⇨ 10 meV plus sterile neutrino programme

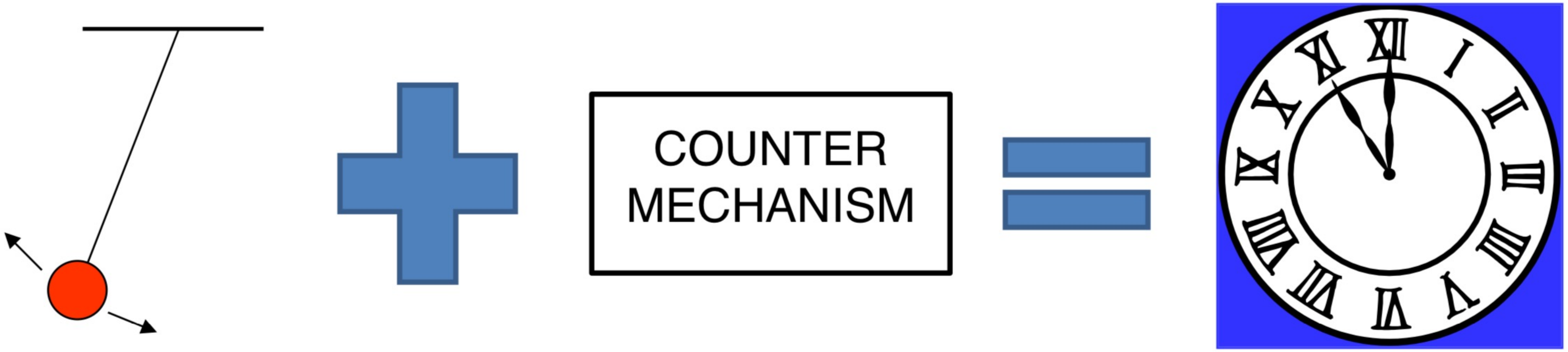


CCFE
CULHAM CENTRE FOR FUSION ENERGY

ATOMIC CLOCK Quantum Sensor



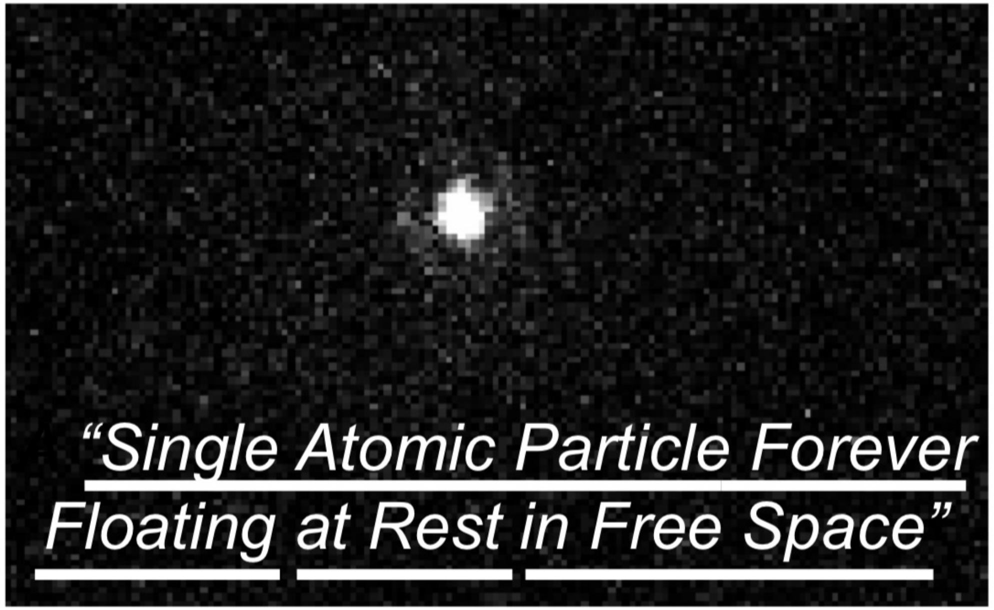
Clocks and oscillators



COUNTER MECHANISM

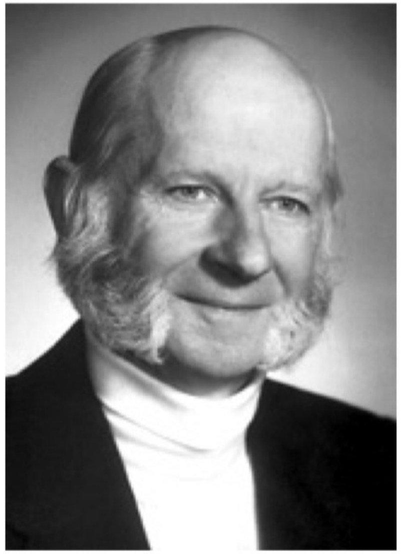
OSCILLATOR	COUNTER MECHANISM
Earth rotation	Sundial
Pendulum Swing	Clock Gears and Hands
Quartz Crystal Vibration	Electronic Counter
Cesium Atomic Vibration	Microwave Counter

Trapped Atomic Ions



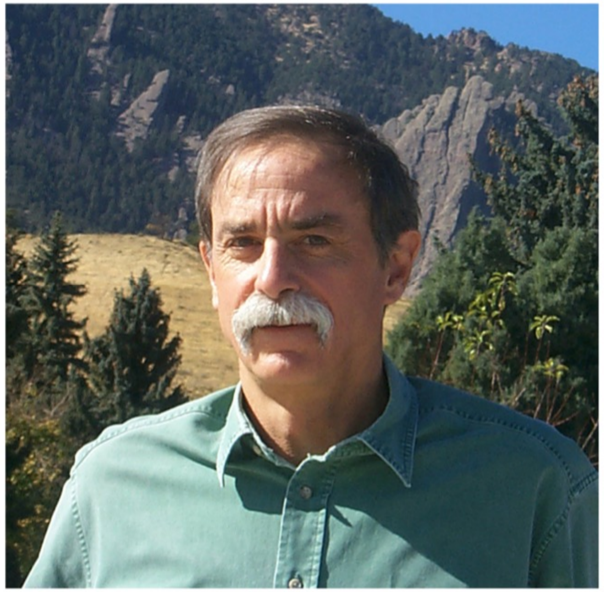
- Quantum-limited experiments
- Long interaction times
- Small relativistic shifts
- Small perturbation from EM fields

Predicted resolution of 1×10^{-18}



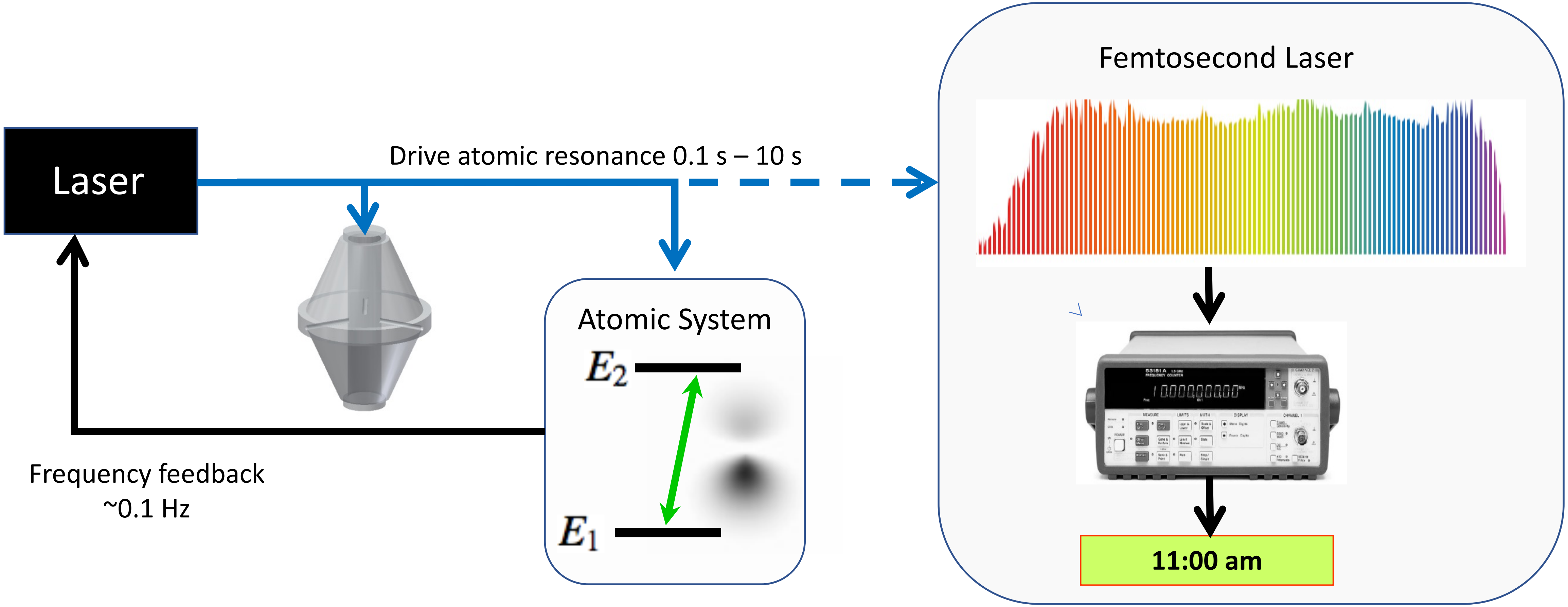
Hans Dehmelt

Hans Dehmelt 1988 *Phys. Scr.* **1988** 102



+ Strong, controllable interactions between ions

Principle of Optical Clocks



Laser

Drive atomic resonance 0.1 s – 10 s

Atomic System

E_2

E_1

Frequency feedback
~0.1 Hz

Femtosecond Laser

11:00 am

Clock frequency: $f_0 = \frac{E_2 - E_1}{h} \approx 10^{15}$ Hz

Slide credit: David Hume

Atomic Clock Performance

$$f(t)/f_0 = 1 + \epsilon + y(t)$$

Accuracy

- Systematic uncertainty in clock frequency.
- Two types of shifts
  1. **Field shifts** e.g. Zeeman shift and black body shift
  2. **Motional shifts** e.g. Relativistic Doppler

$$\boxed{\frac{\Delta f}{f} = \frac{\langle \vec{v} \cdot \hat{k} \rangle}{c} - \frac{\langle v^2 \rangle}{2c^2} - \frac{\langle \vec{v} \cdot \hat{k} \rangle^2}{2c^2} + \cdots}$$

Stability

- Average fractional frequency variations
- Typically characterized by the *Allan deviation:*

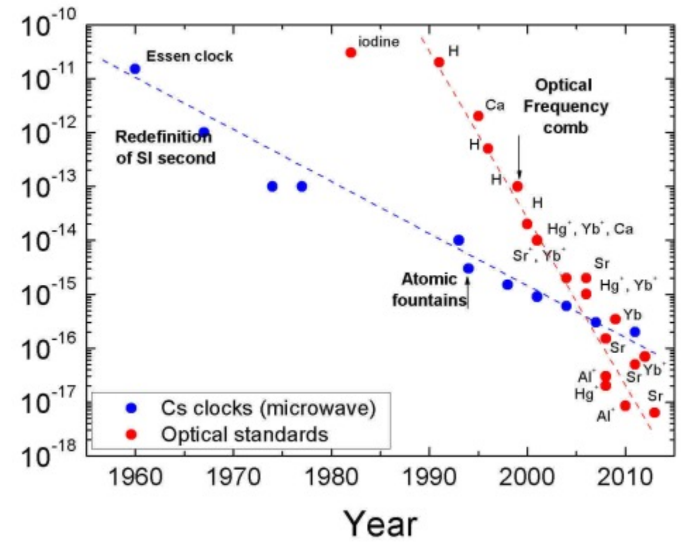
$$\boxed{\sigma_y(\tau) \cong \frac{1}{Q} \frac{1}{SNR} \sqrt{\frac{T_C}{\tau}}}$$

Slide credit: David Hume

Trends in Precision Frequency Metrology

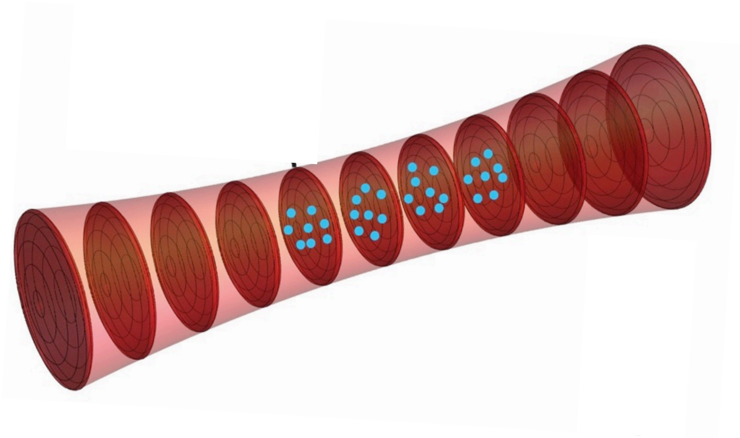
In recent years, optical frequency measurements have. . .

…improved more than 100x in accuracy



Based on a slide by David Hume

Optical Lattice Clocks and Trapped Ion Clocks



- Magic wavelength optical lattice
- Typically, 1000s of atoms
- Laser cooled to uK temperatures
- Dominant systematics: blackbody radiation, lattice light shifts

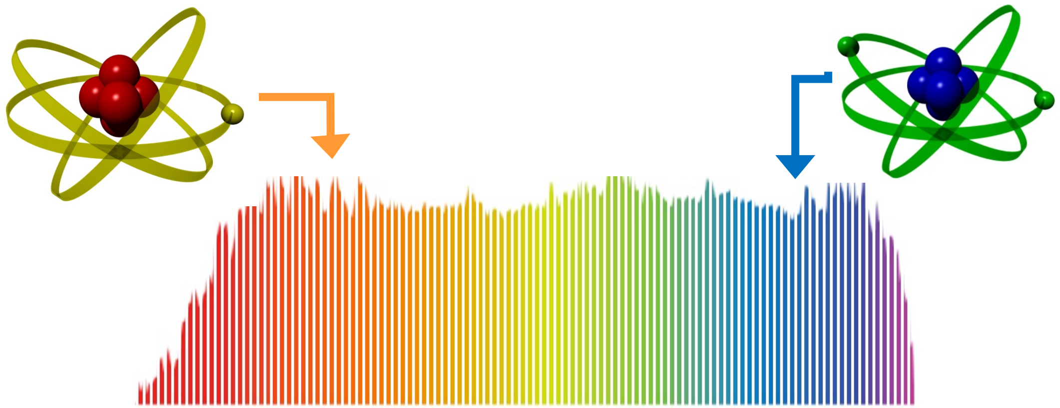
More atoms = higher stability

- RF Paul trap
- Typically, single ions
- Can be cooled to ground state
- Dominant systematics: 2nd-order Doppler, blackbody radiation

Applicable to any ionic species

Slide credit: David Hume

Searching for Spacetime-Variation in Clock Frequencies & UL Dark Matter



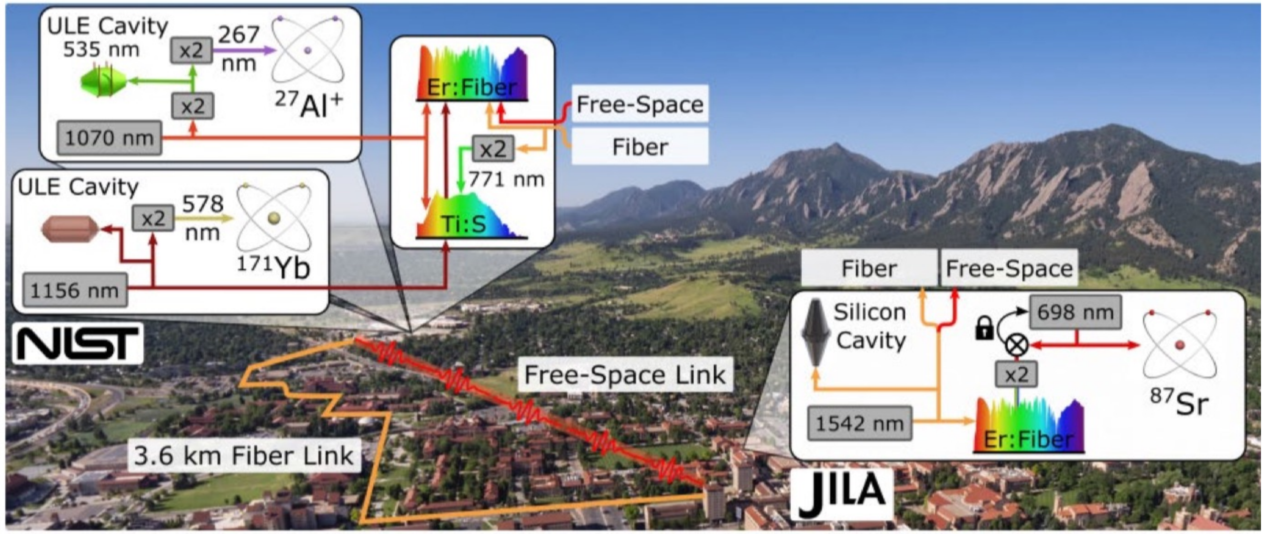
$$R(t) = \frac{\omega_1(t)}{\omega_2(t)}$$

What might cause clock frequencies to vary?

- Drifts in the fundamental constants
- Violations of relativity theory
  - Local position invariance
  - Lorentz invariance
- Coupling to exotic particles or fields
  - Ultralight dark matter (mass ~ 10^{-22} – 10^{-15} eV)
- Nothing? (Tests all the above at an unprecedented level)

Slide credit: David Hume

Boulder Atomic Clock Optical Network

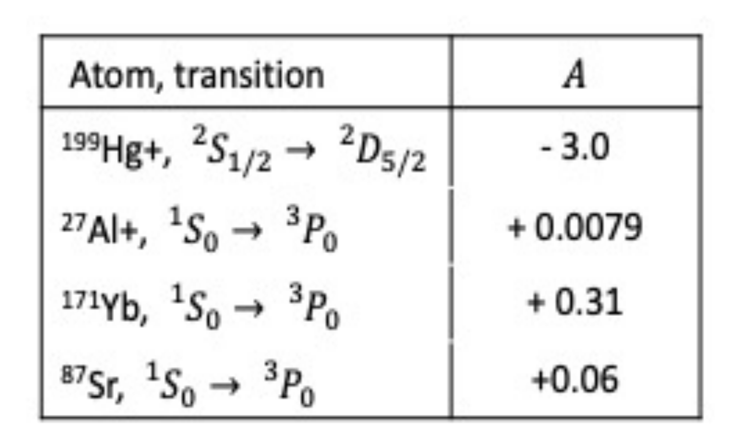


New Bounds on Ultralight Dark Matter

Searches for oscillations in the frequency ratio

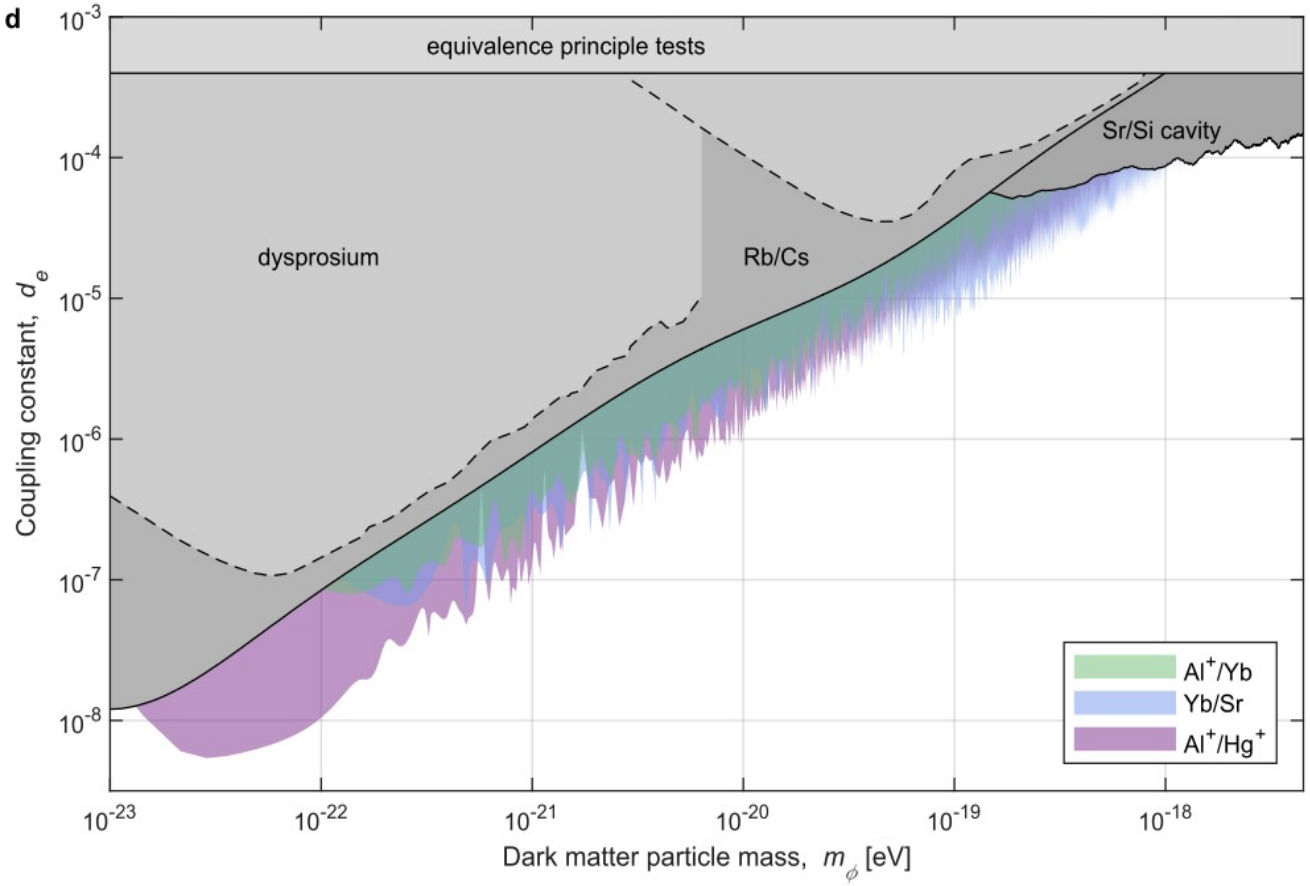
$$R = R_0 + dR\sin(\omega_{DM}t + \phi_{DM})$$

Compton Frequency: $\omega_{DM} = \frac{m_\phi c^2}{\hbar}$



Atom, transition	A
^{199}Hg+, $^2S_{1/2} \rightarrow {}^2D_{5/2}$	- 3.0
^{27}Al+, $^1S_0 \rightarrow {}^3P_0$	+ 0.0079
^{171}Yb, $^1S_0 \rightarrow {}^3P_0$	+ 0.31
^{87}Sr, $^1S_0 \rightarrow {}^3P_0$	+0.06

Depends on dark matter density (0.4 GeV/cm^3), coupling constant (d_e) and atom-dependent sensitivity



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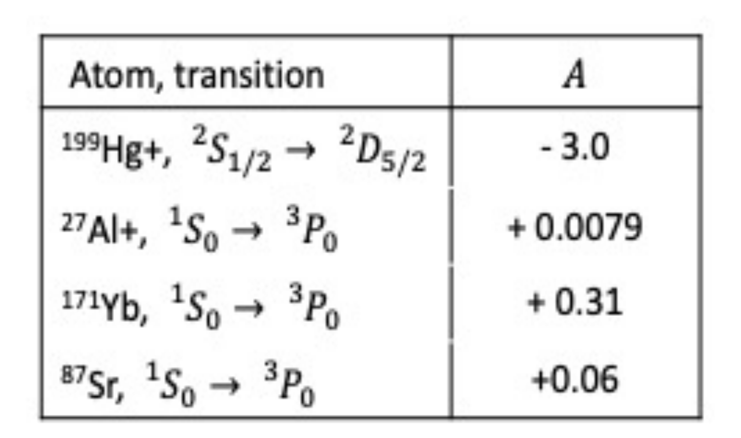

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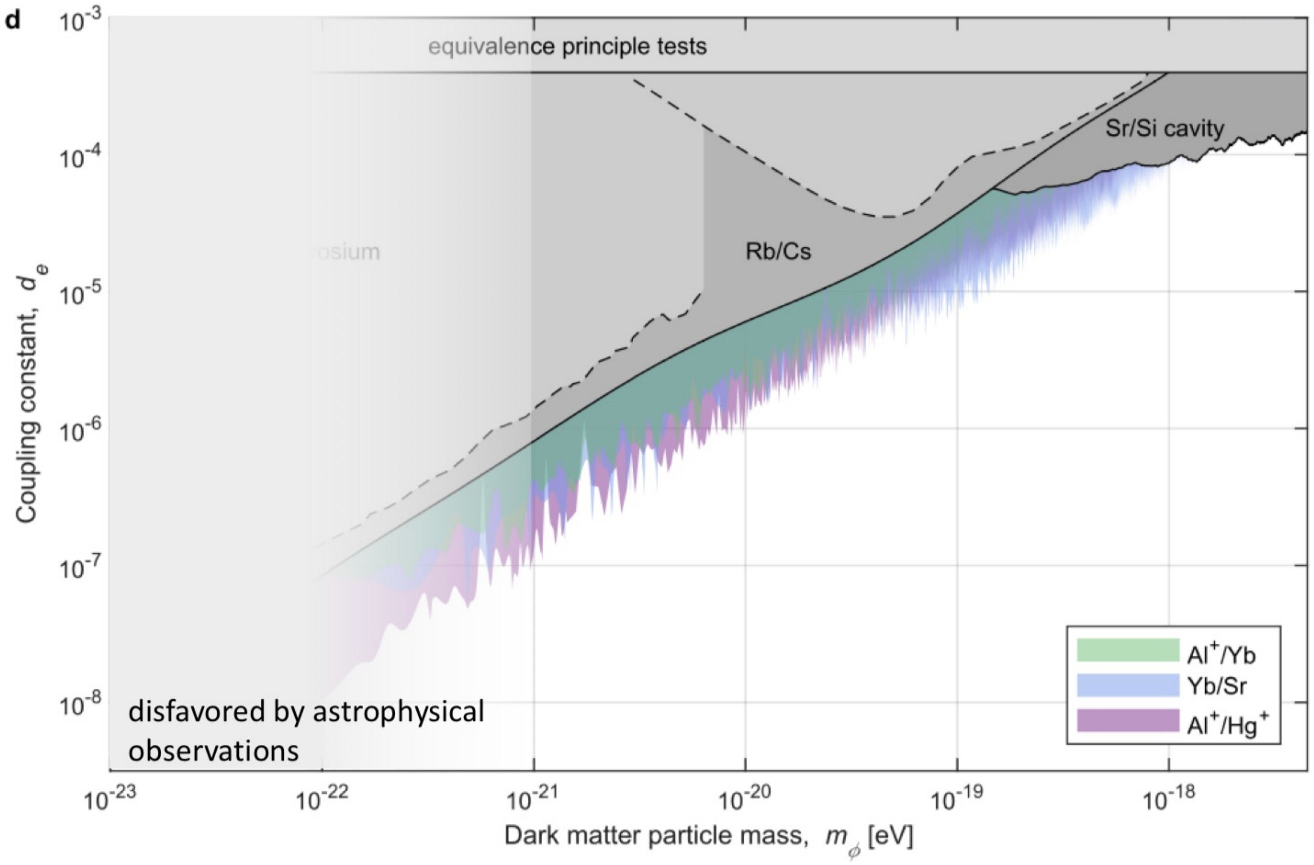
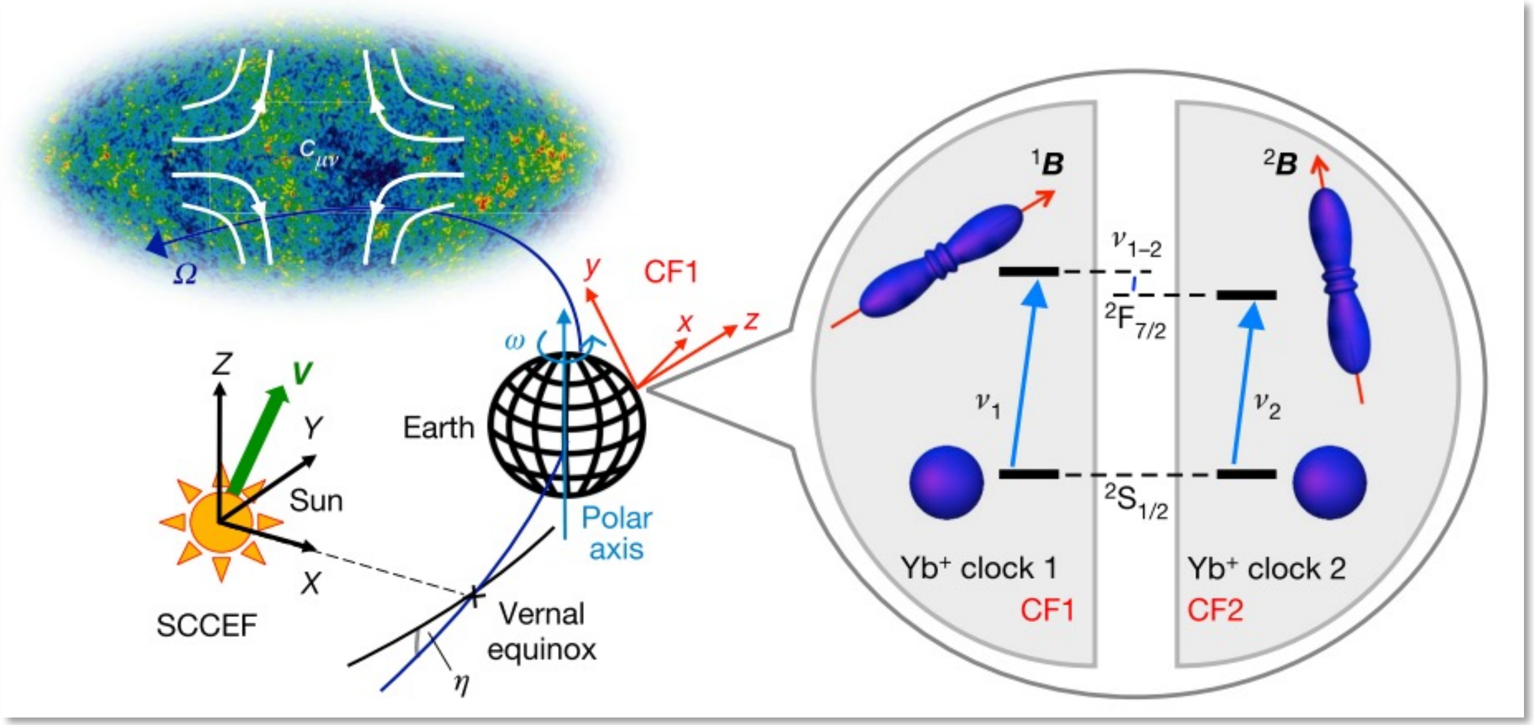


~ 10X improvement over several orders of magnitude in mass

Beloy *et al.*, Nature 591, 564 (2021)

Testing Lorentz Symmetry

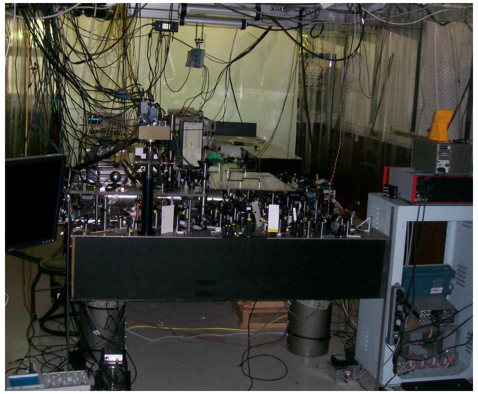


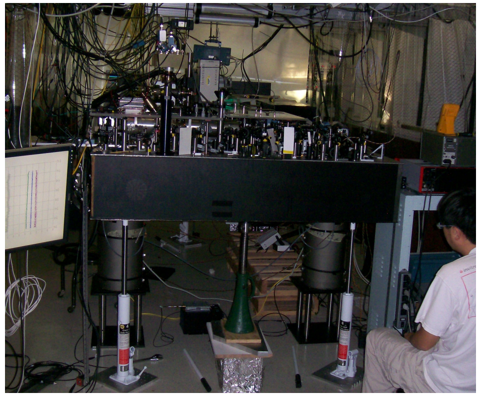
Sanner *et al.*, Nature 567, 204 (2019)

Slide credit: David Hume

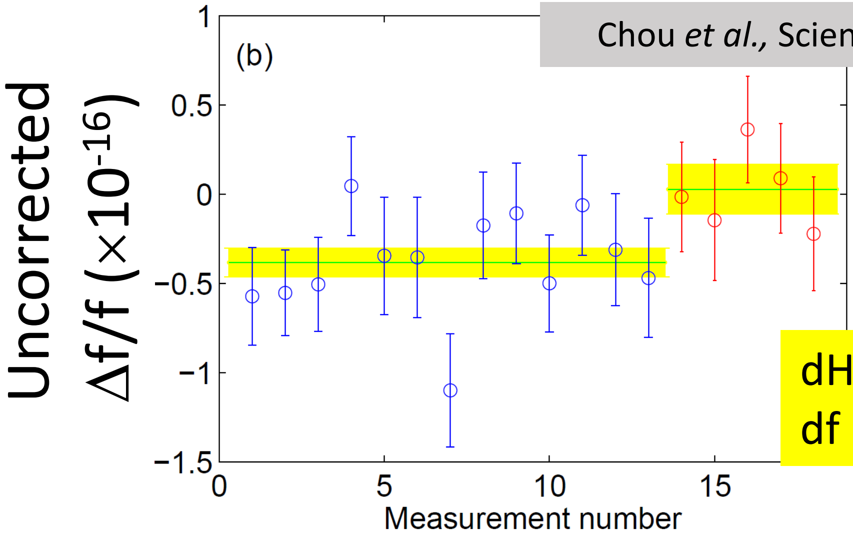
Measuring the Gravitational Redshift

$\Delta f/f = g\Delta h/c^2$ $g/c^2 \sim 1.1 \times 10^{-18}/\text{cm}$



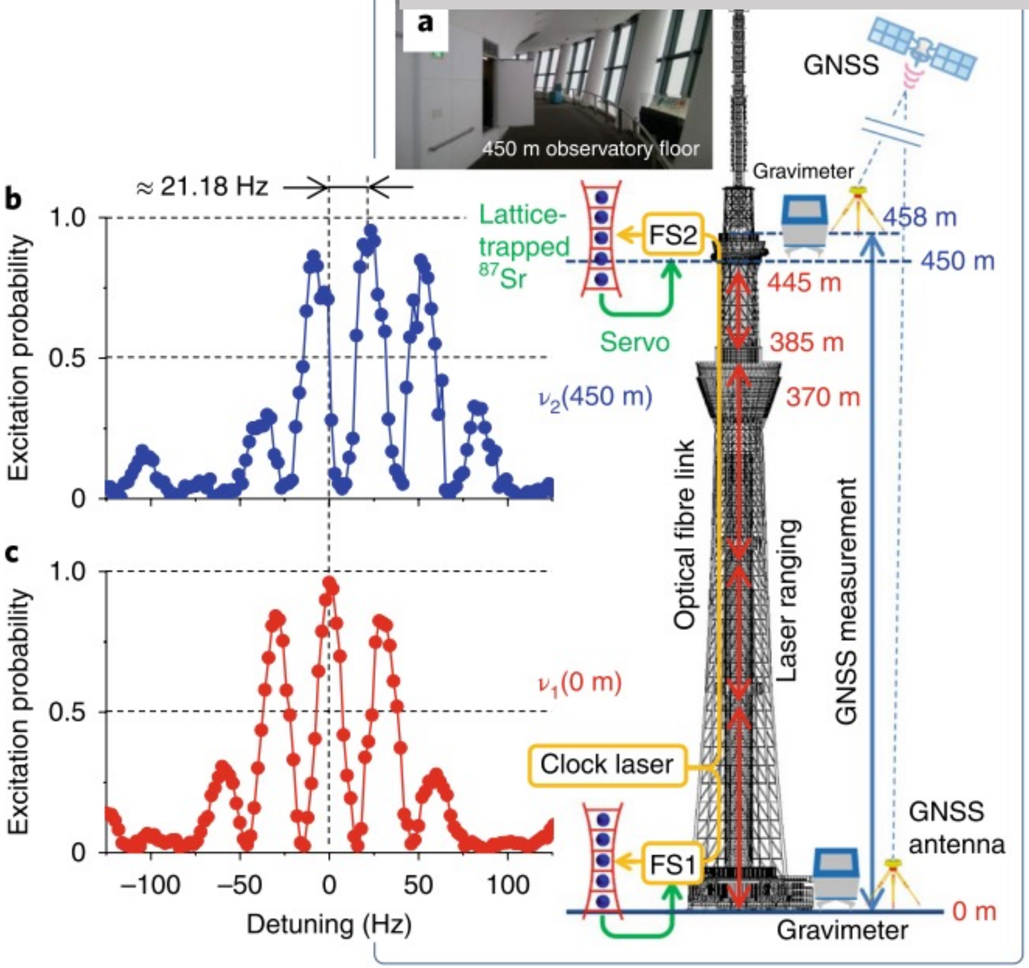


Chou *et al.*, Science 329, 1630 (2010)



dH= 33cm
df ➔ 37 \pm 15 cm

Takamoto *et al.*, Nat. Phot. 14, 411 (2020)



$$\Delta\nu/\nu_1 = (49{,}337.8 \pm 4.3) \times 10^{-18}$$

$$\bar{g}\Delta h/c^2 = (49{,}337.1 \pm 1.4) \times 10^{-18}.$$

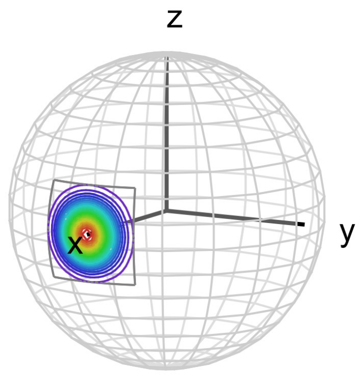
Most stringent test of GR on Earth’s surface

Quantum-Enhanced Metrology with Atoms

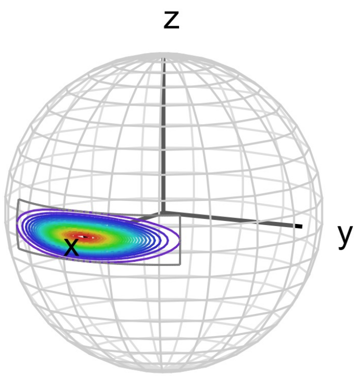
Entangled states of atoms with reduced projection-noise

Standard quantum limit → Heisenberg limit

$$\frac{1}{\sqrt{N_{Atom}}} \longrightarrow \frac{1}{N_{Atom}}$$

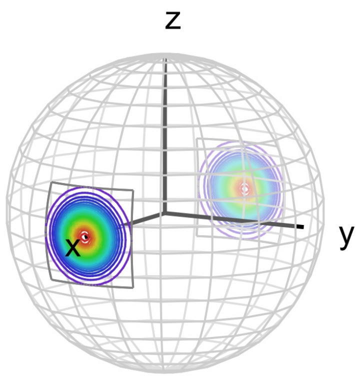


Independent spins



Spin-squeezed states

cf, Kitagawa & Ueda, PRA 47, 5138 (1993)
Pedrozo-Peñafiel et al., Nature 588, 414 (2020)



Maximally-entangled “GHZ” states

cf, Bollinger et al., PRA 54, 4649 (1996)
Monz et al, PRL 106, 130506 (2011)

At present, no high-performance atomic clock operates using entangled quantum states

Slide credit: David Hume

Improving Clock Stability

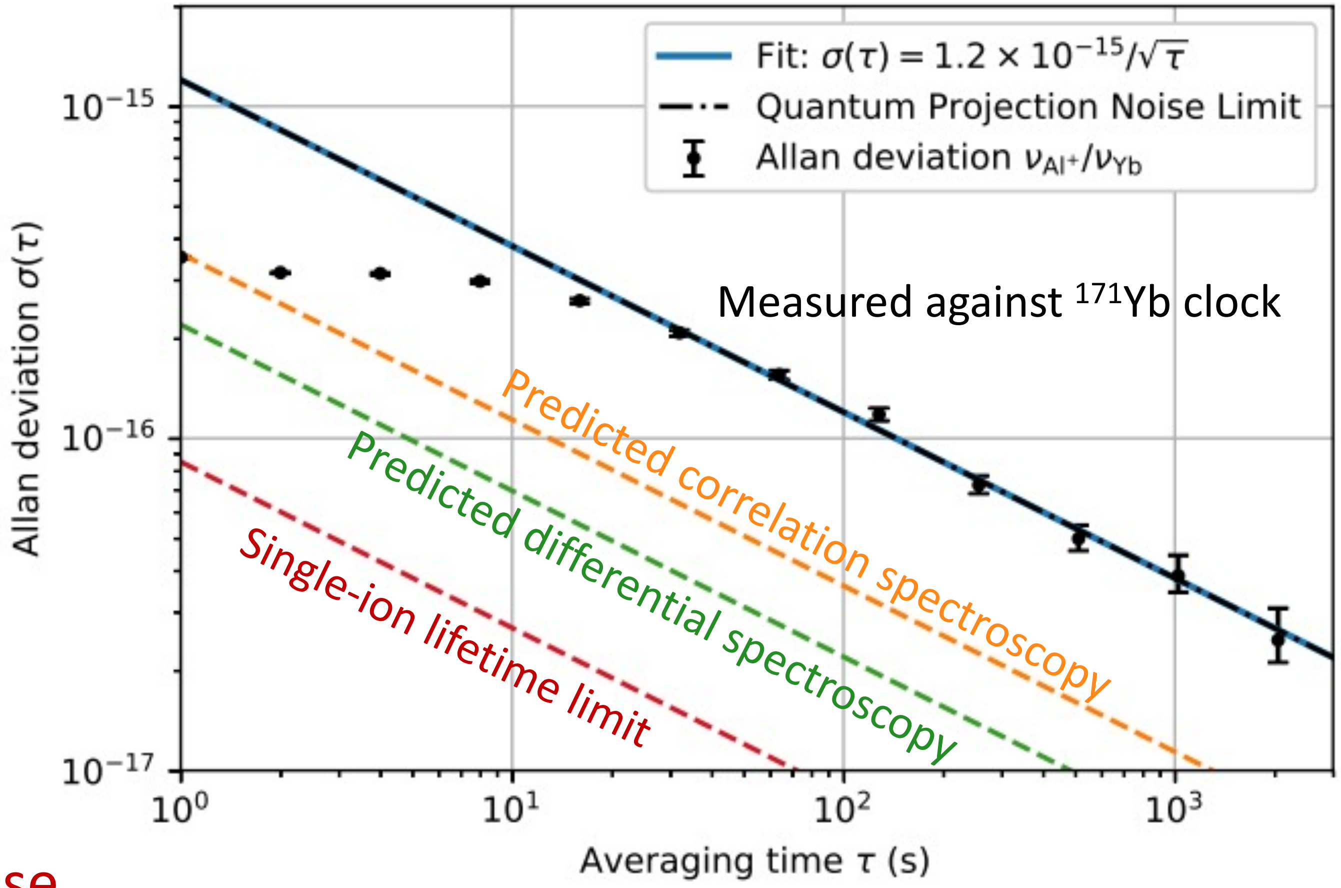
$$\sigma_y(\tau) = \frac{\Delta\nu}{2\pi\nu_0}\frac{1}{\sqrt{N_{atom}}}\sqrt{\frac{T_C}{\tau}}$$

Assuming:

- No technical noise
- Uncorrelated atomic states
- Global addressing

- Higher-stability laser
- Larger atom number
- Longer measurement (more robust operation)
- New techniques to mitigate laser noise

Example of the Al+ optical clock



Measured against ^{171}Yb clock

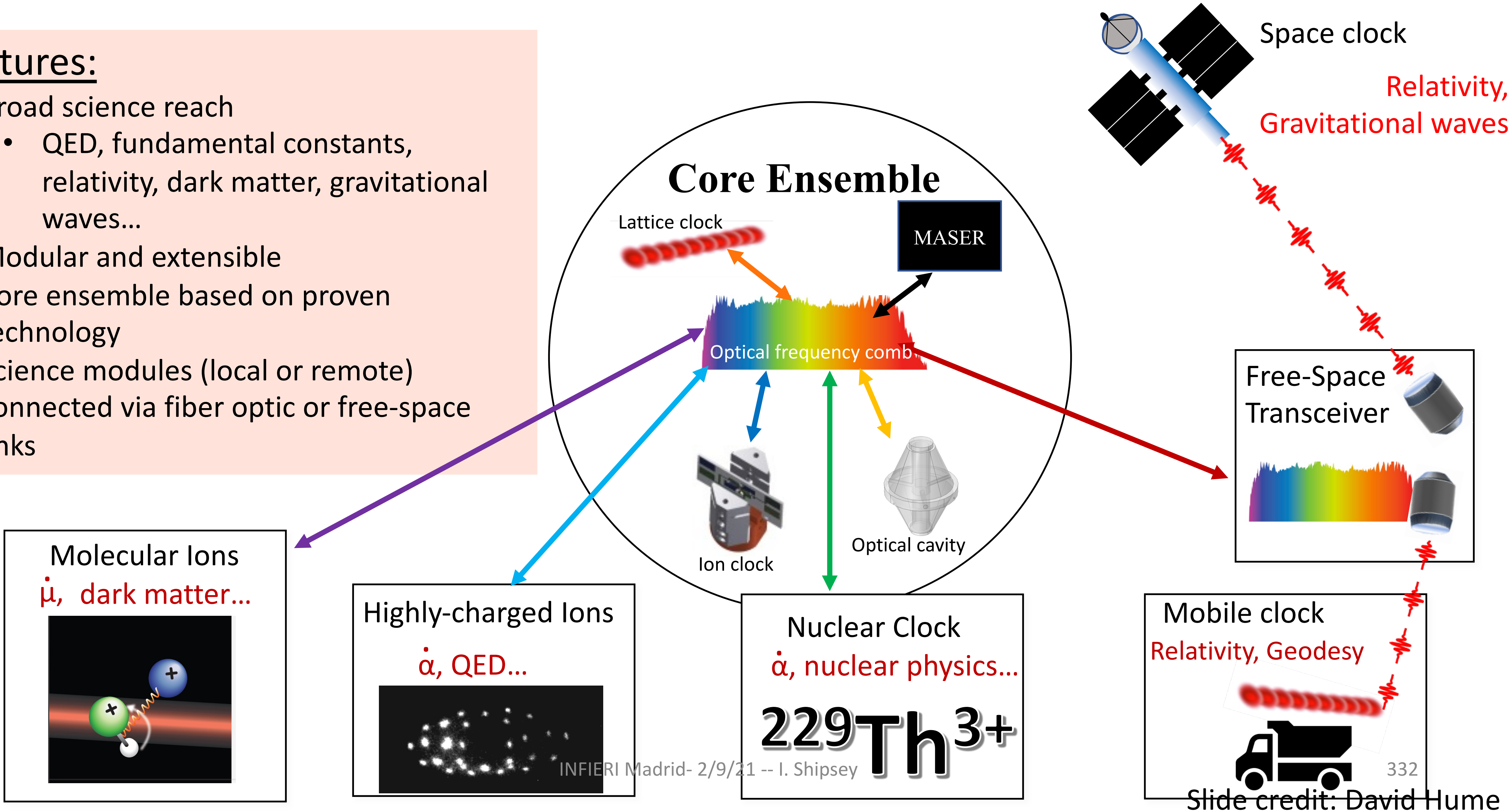
Brewer et al., PRL 123, 033201 (2018)

Slide credit: David Hume

An Atomic Observatory for Fundamental Physics

Features:

- Broad science reach
  - QED, fundamental constants, relativity, dark matter, gravitational waves…
- Modular and extensible
- Core ensemble based on proven technology
- Science modules (local or remote) connected via fiber optic or free-space links



Core Ensemble

Lattice clock

MASER

Optical frequency comb

Ion clock

Optical cavity

Space clock

Relativity, Gravitational waves

Free-Space Transceiver

Molecular Ions

$\dot{\mu}$, dark matter…

Highly-charged Ions

$\dot{\alpha}$, QED…

Nuclear Clock

$\dot{\alpha}$, nuclear physics…

$^{229}\text{Th}^{3+}$

Mobile clock

Relativity, Geodesy

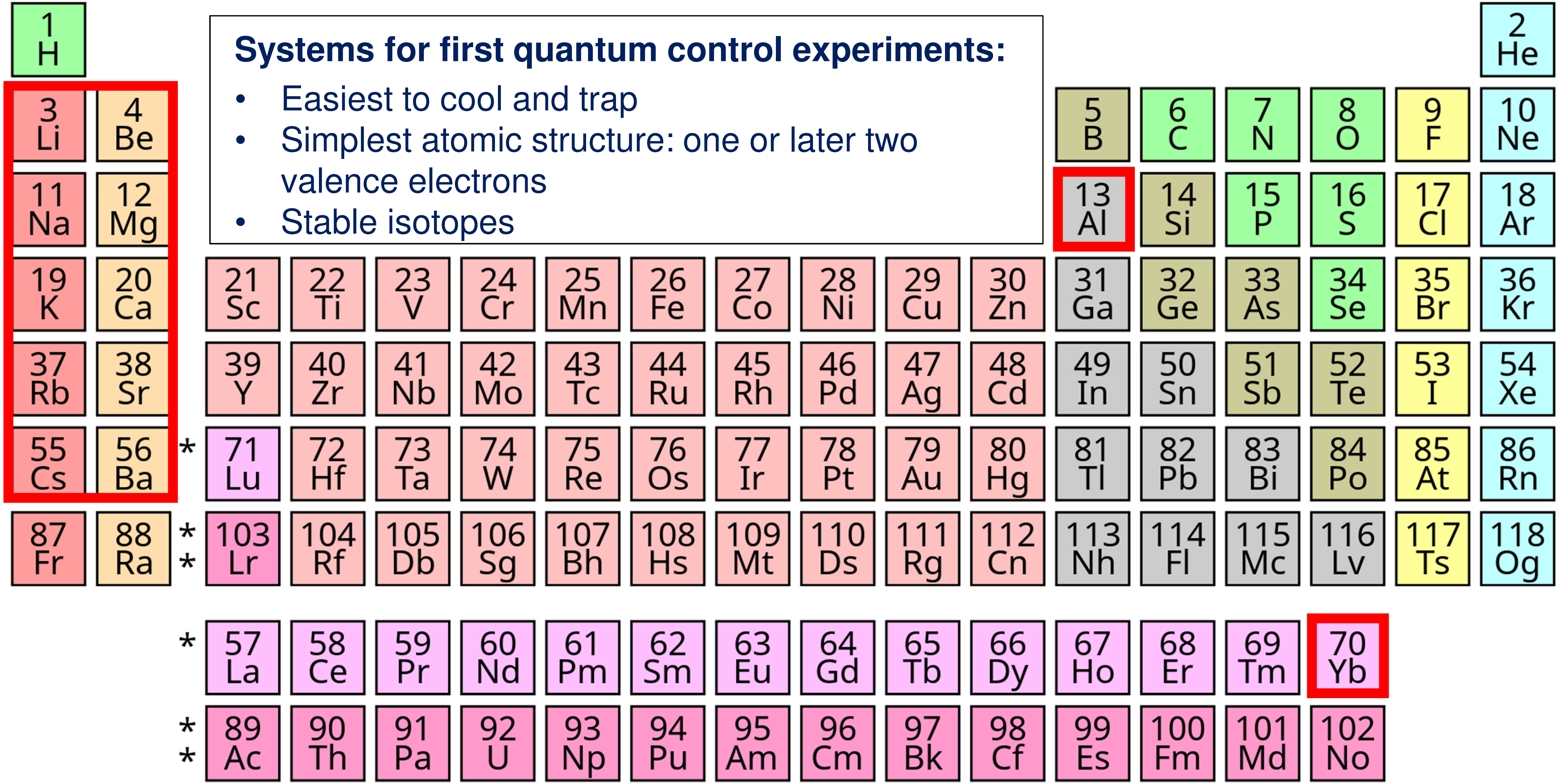
Slide credit: David Hume

Musing about future clock stability and accuracy

David Hume @ ECFA
Detector Roadmap
Open Symposium

- **Clock stability** (more foreseeable?)
  - Sr lattice clock with 10,000 atoms, 10 s probe time
    1×10^{-19} in a few minutes
  - $^{27}Al^{+}$ clock with 10 atoms, 10 s probe time
    1×10^{-19} in a few hours
- **Clock systematic uncertainty** (difficult to measure and predict)
  - Cesium clock accuracy improved by a factor of 10X/decade for many decades.
  - There has been a jump with optical clocks by about a factor of 100, but… will it continue?
  - In the case of Al+, anticipate an improvement to 1×10^{-19}

Why use novel systems?



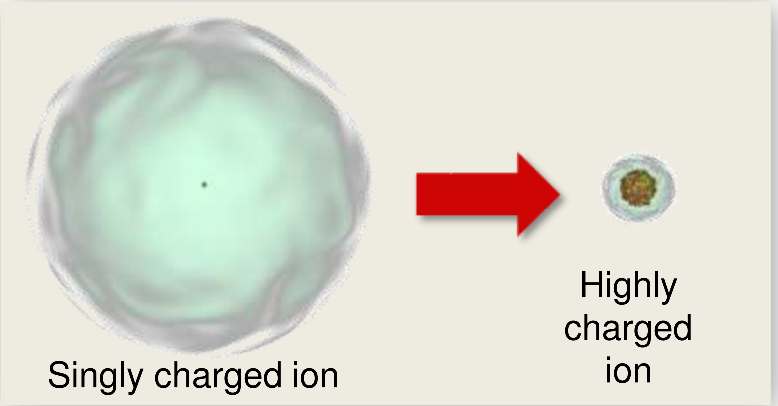
Systems for first quantum control experiments:

- Easiest to cool and trap
- Simplest atomic structure: one or later two valence electrons
- Stable isotopes

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	* 71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	** 103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		* 57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
		** 89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

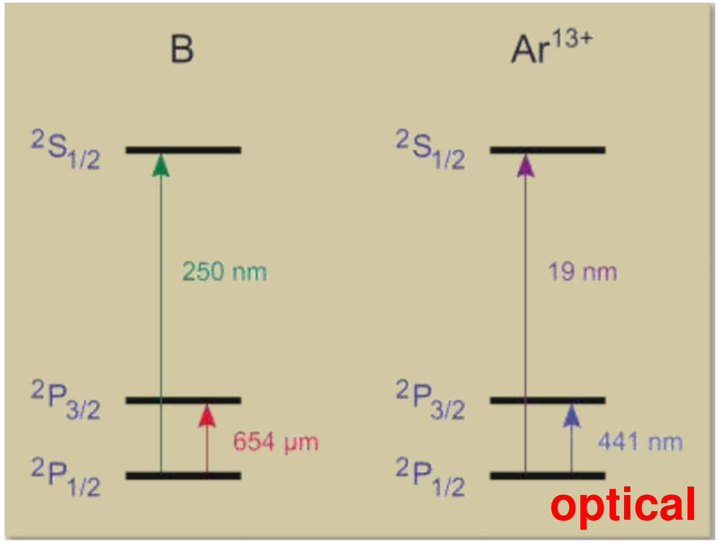
Wikimedia Commons

Novel systems: highly charged ions (HCIs)



Scaling with a nuclear charge Z

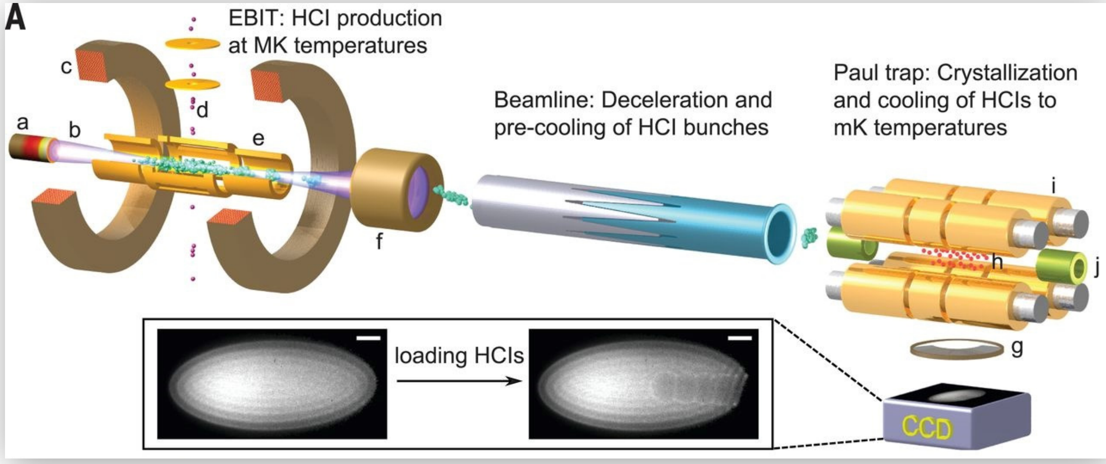
Binding energy ~ Z^2
Hyperfine splitting ~ Z^3
QED effects ~ Z^4
Stark shifts ~ Z^{-6}



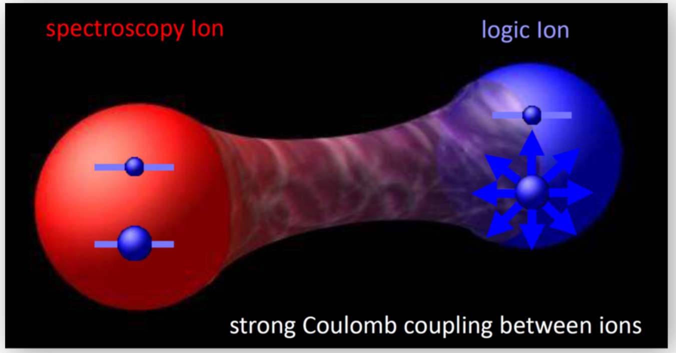
- Fine-structure, hyperfine-structure, and level-crossing transitions in range of table-top lasers
- Much higher sensitivity to new physics due to relativistic effects
- Rich variety of level structure not available in other systems
- Reduced systematics due to suppressed Stark shifts

Review on HCIs for optical clocks: Kozlov *et al.*, Rev. Mod. Phy. **90**, 045005 (2018)

HCIs for ultra-precise clocks (Paul traps): present status



No direct laser-cooling transitions: use sympathetic cooling with Be^+

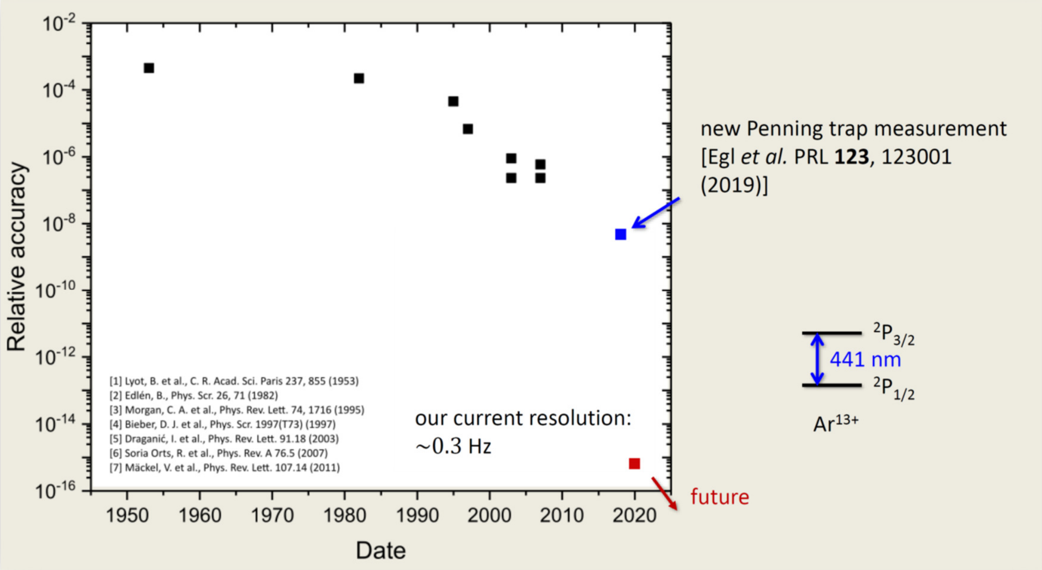


2015: First sympathetic cooling of HCIs: L. Schmöger et al., Science 347, 1233 (2015), Heidelberg

2020: Coherent laser spectroscopy of highly charged ions using quantum logic, P. Micke et al., Nature 578, 60 (2020)

7 orders of magnitude improvement !!!

First prototype optical clock, PTB, Germany



new Penning trap measurement [Egl *et al.* PRL **123**, 123001 (2019)]

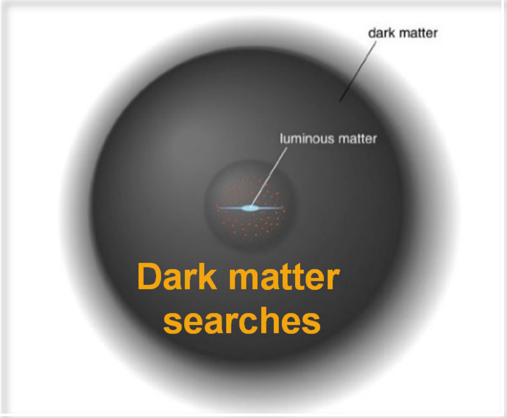
our current resolution: ~0.3 Hz

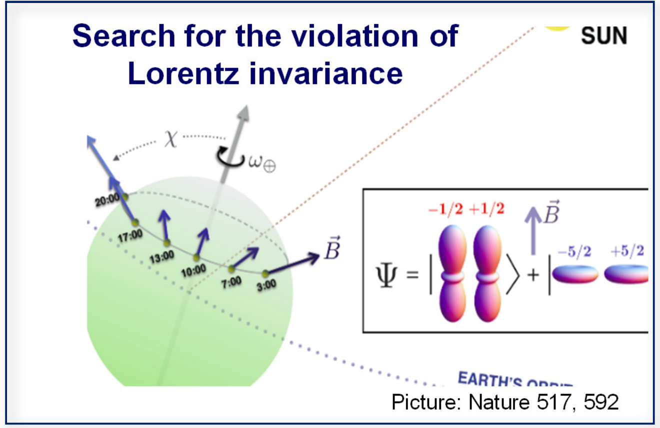
[1] Lyot, B. et al., C. R. Acad. Sci. Paris 237, 855 (1953)
[2] Edlén, B., Phys. Scr. 26, 71 (1982)
[3] Morgan, C. A. et al., Phys. Rev. Lett. 74, 1716 (1995)
[4] Bieber, D. J. et al., Phys. Scr. 1997(T73) (1997)
[5] Draganić, I. et al., Phys. Rev. Lett. 91.18 (2003)
[6] Soria Orts, R. et al., Phys. Rev. A 76.5 (2007)
[7] Mäckel, V. et al., Phys. Rev. Lett. 107.14 (2011)

HCIs for ultra-precise clocks : applications & future

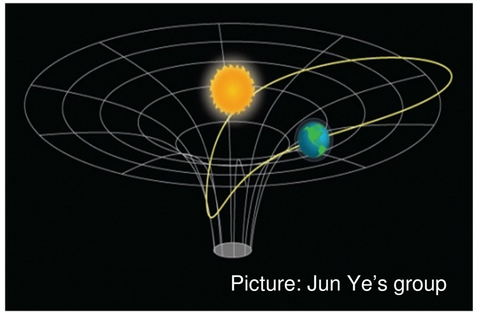
HCIs: **much larger** sensitivity to variation of α and dark matter searches then current clocks

- Enhancement factor K>100, most of present clocks K<1, Yb^+ E3 K=6
- Hyperfine HCI clocks sensitive to m_e/m_p ratio and m_q/Λ_{QCD} ratio variation
- Additional enhancement to Lorentz violation searches



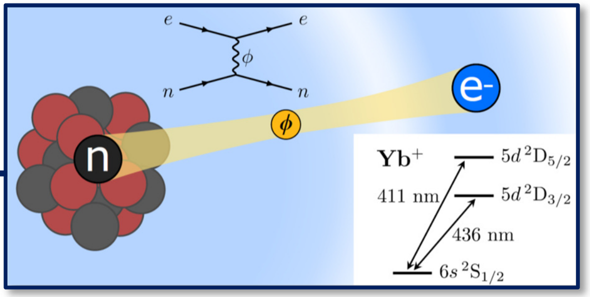

Search for the violation of Lorentz invariance

Picture: Nature 517, 592


Picture: Jun Ye's group

Tests of the equivalence principle

- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot



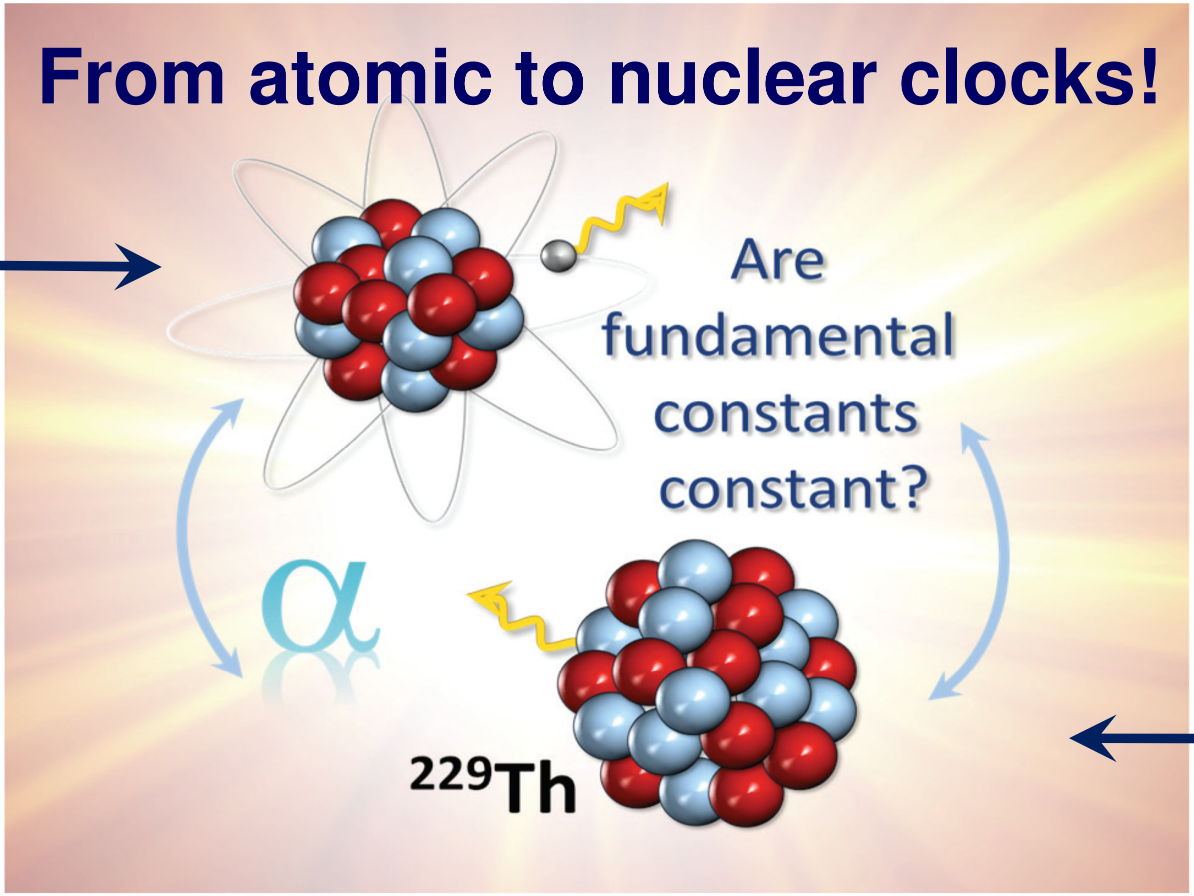
5 years: Optical clocks with selected HCIs will reach 10^{-18} accuracy
10 years: Strongly α-sensitive transitions in HCIs will reach of 10^{-18} uncertainty, multi-ion HCI clocks

https://thoriumclock.eu/

Thorium nuclear clocks for fundamental tests of physics

Thorsten Schumm, TU Wein
Ekkehard Peik, PTB
Peter Thirolf, LMU
Marianna Safronova, UDel

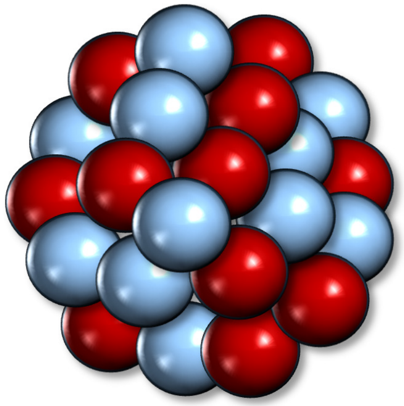
Clock based on transitions in atoms

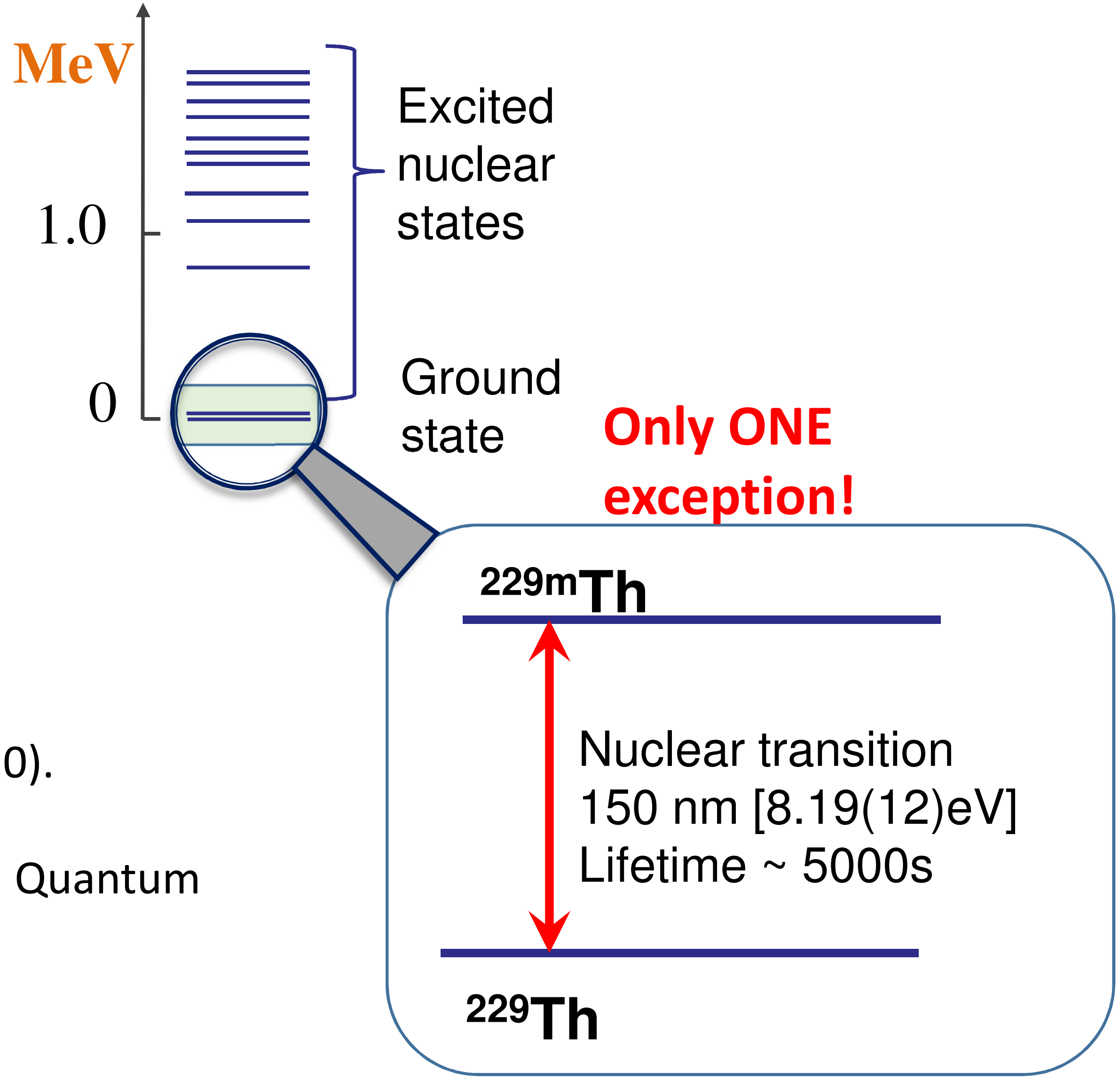


Clock based on transitions in nuclei

Obvious problem: typical nuclear energy levels are in MeV Six orders of magnitude from ~few eV we can access by lasers!

Atomic Nucleus





Excited nuclear states

Ground state

Only ONE exception!

^{229m}Th

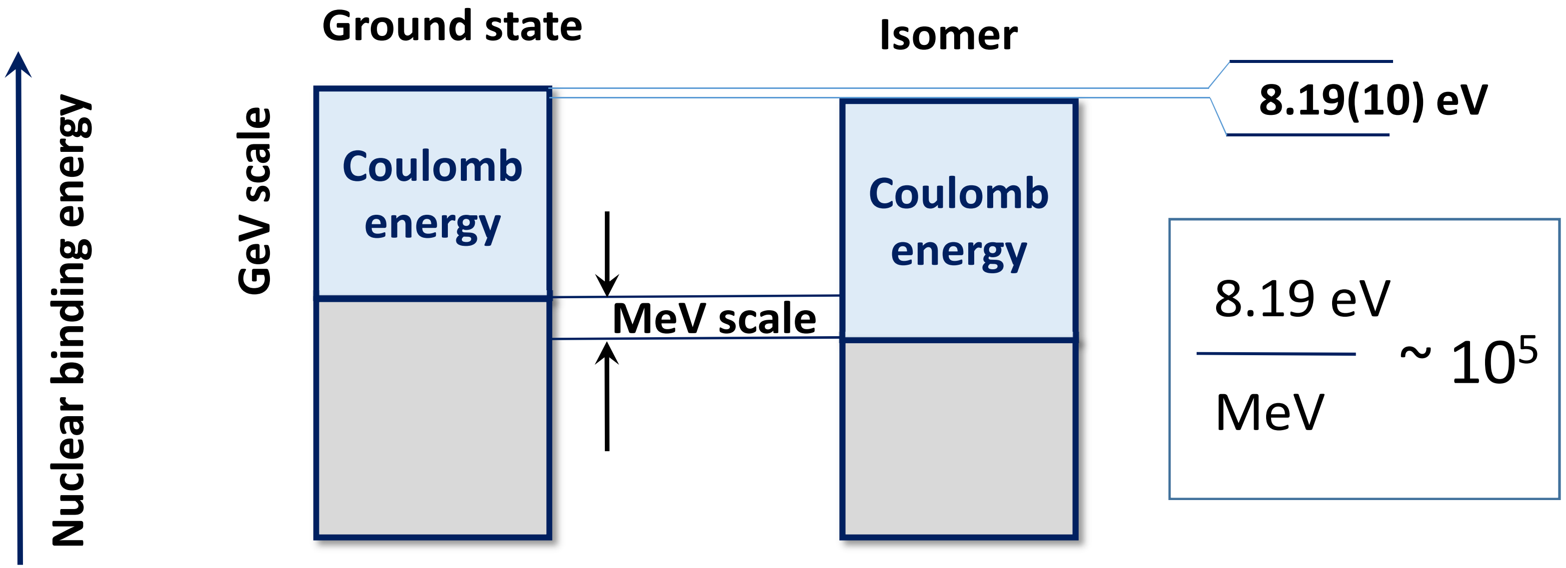
Nuclear transition
150 nm [8.19(12)eV]
Lifetime ~ 5000s

^{229}Th

Energy of the ^{229}Th nuclear clock transition:
Seiferle *et al*., Nature 573, 243 (2019)
T. Sikorsky et al., Phys. Rev. Lett. 125, 142503 (2020).

Review: E. Peik, et al., arXiv:2012.09304, in press, Quantum Science and Technology (2021).

Th nuclear clock: Exceptional sensitivity to new physics



$$\frac{8.19\text{ eV}}{\text{MeV}} \sim 10^5$$

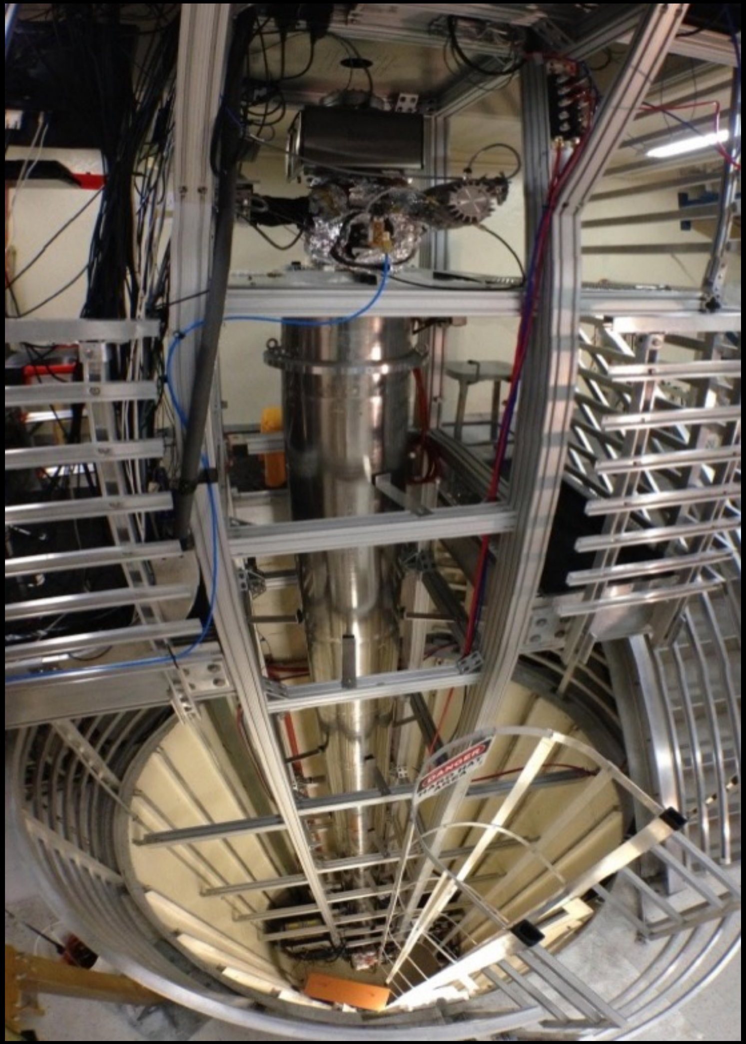
Much higher predicted sensitivity (K = 10000-100000) to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$.

Nuclear clock is sensitive to coupling of dark matter to the nuclear sector of the standard model.

5 years: prototype nuclear clocks, based on both solid state and trapped ion technologies
Measure isomer properties to establish of sensitivity to new physics
Variation of fundamental constant and dark matter searches competitive with present clock

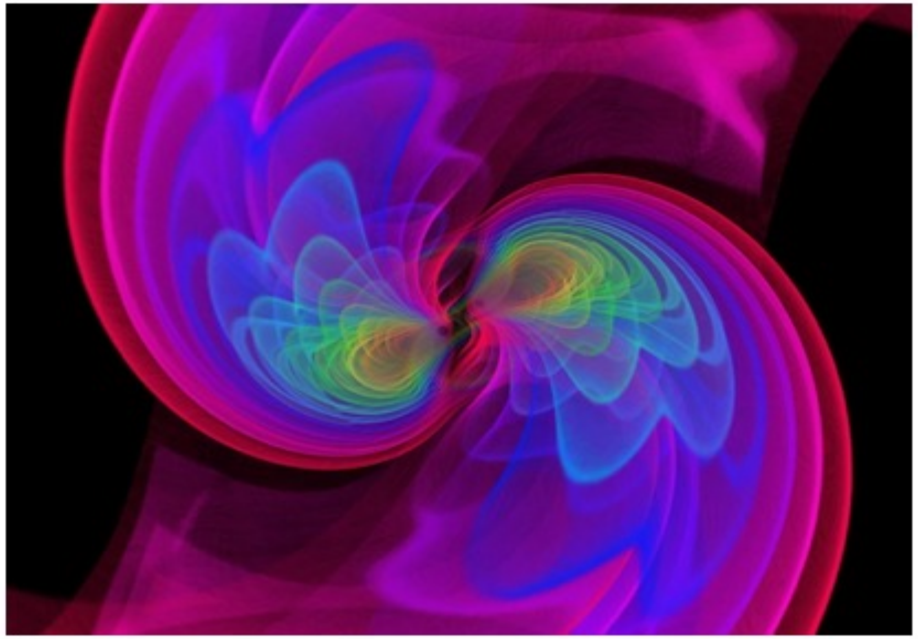
10 years: 10^{-18} – 10^{-19} nuclear clock, 5 - 6 orders improvement in current clock dark matter limits

Atom Interferometry

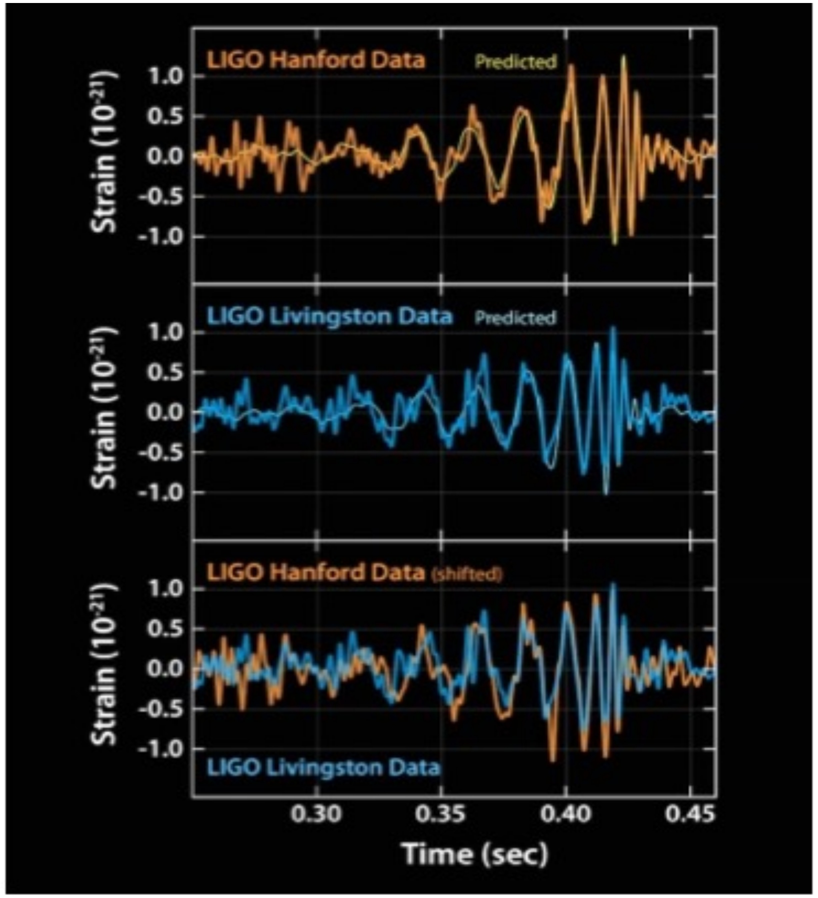


The pictures that shook the world

GW150914



1.3 billion
years
later
on earth

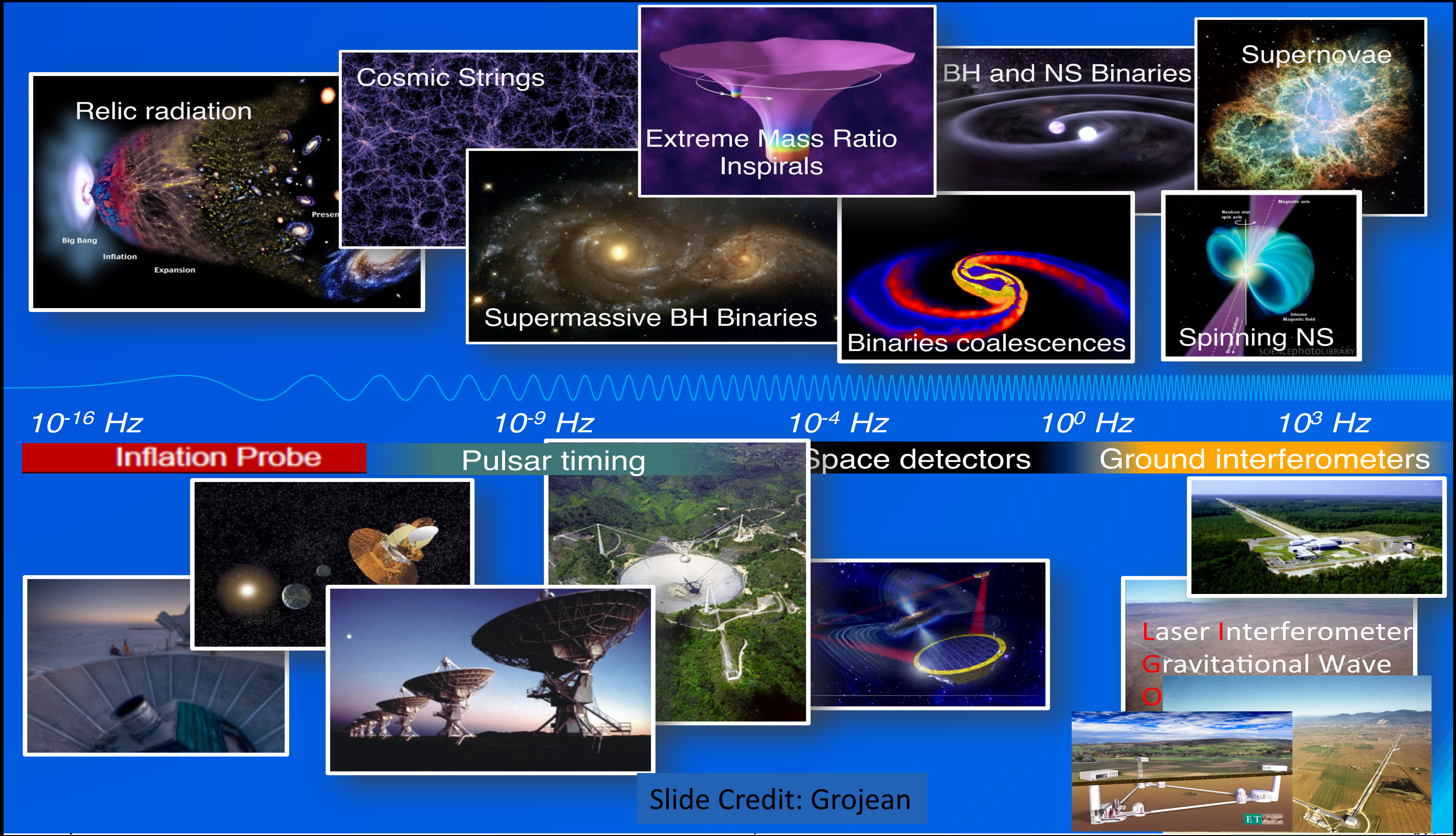


Slide Credit: Grojean

what did it teach us?

- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV $(c_g - c_\gamma < 10^{-17}$. GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity > 100 keV

Gravitational Waves: Cosmology and Astrophysics



Relic radiation

Cosmic Strings

Extreme Mass Ratio Inspirals

BH and NS Binaries

Supernovae

Supermassive BH Binaries

Binaries coalescences

Spinning NS

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

Inflation Probe

Pulsar timing

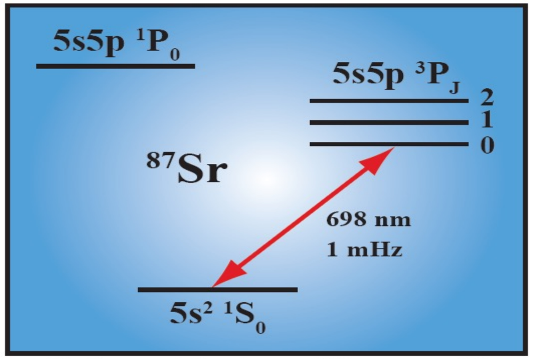
Space detectors

Ground interferometers

Laser Interferometer Gravitational Wave O

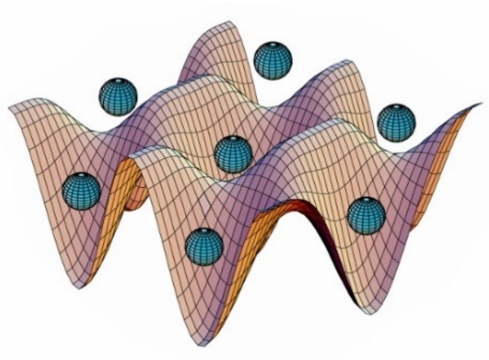
Slide Credit: Grojean

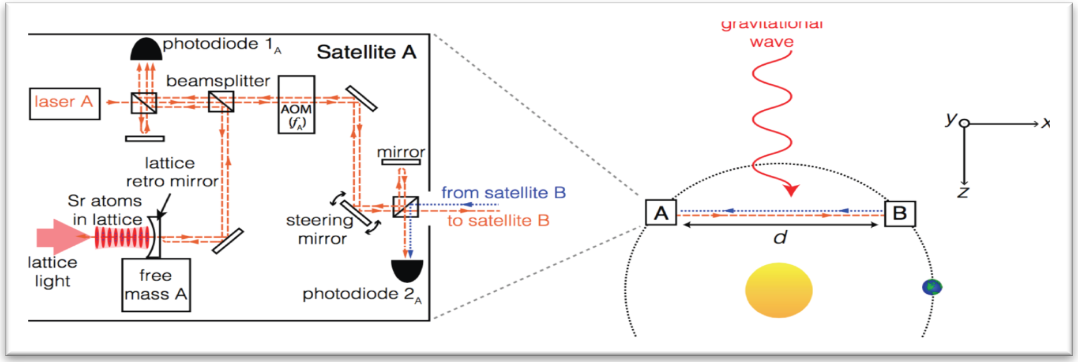
Atomic clocks and atom interferometers



- How can we leverage the incredible gains in stability and accuracy of clocks for fundamental physics?
- Atomic clocks and interferometers offer the potential for gravitational wave detection in an unexplored frequency range
- Development of new "clock" atom interferometer inertial sensors based on narrow optical transitions

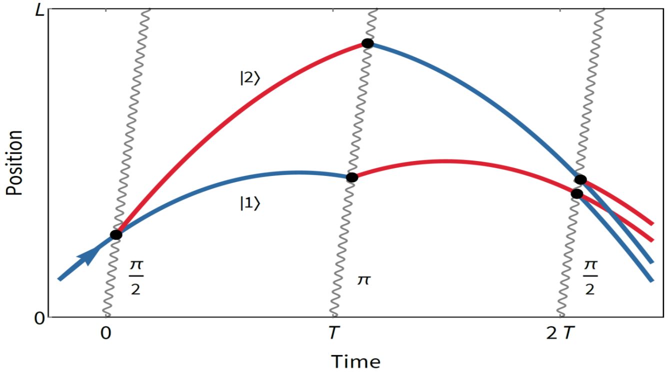
Optical lattice clocks

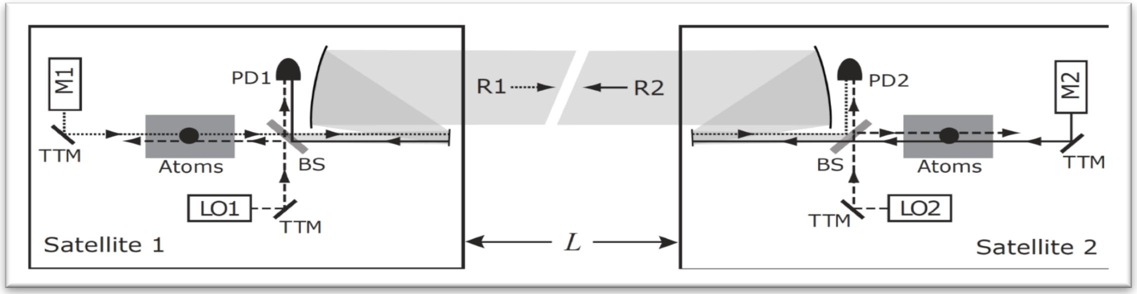




Kolkowitz et al., PRD 2016

Atom interferometers

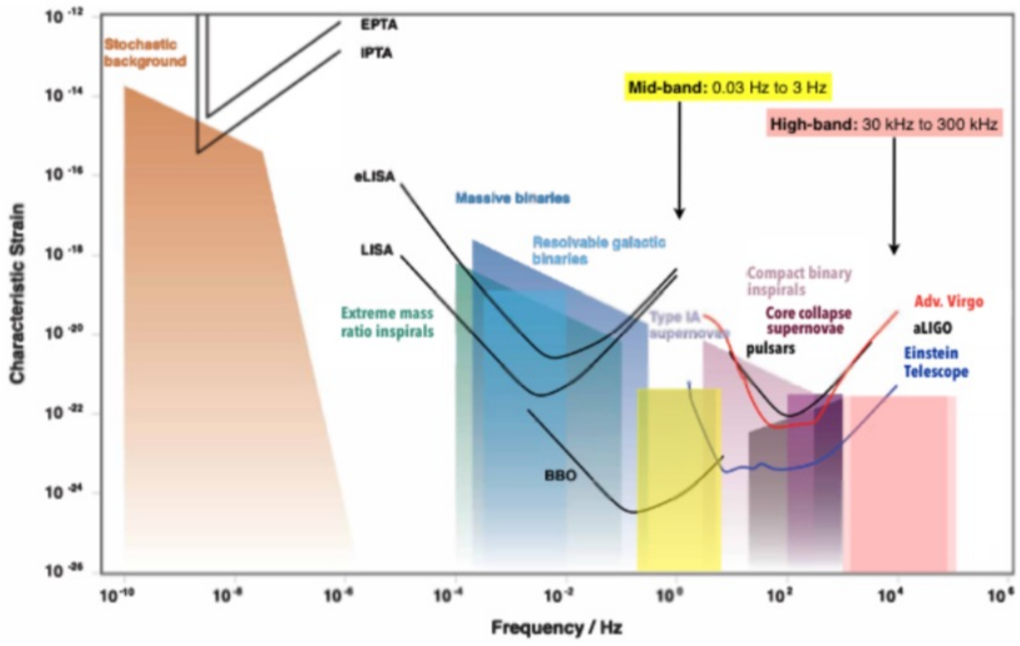




Hogan et al., PRA 2016

Slide credit: Jason Hogan

Long baseline atom interferometry science



Mid-band gravitational wave detection

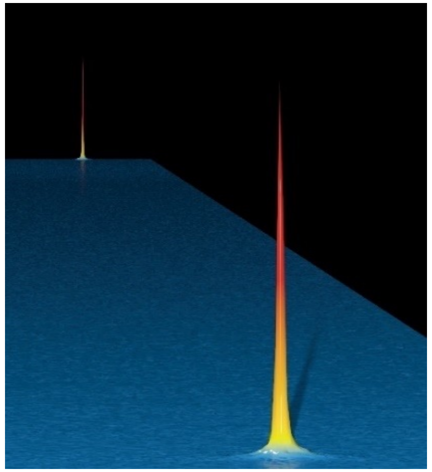
- LIGO sources before they reach LIGO ban
- Multi-messenger astronomy: optimal band for sky localization
- Cosmological sources

Ultralight wave-like dark matter probe

- Mass $<10^{-14}$ eV (Compton frequency in ~Hz range)
- Scalar- and vector-coupled DM candidates
- Time-varying energy shifts, EP-violating new forces, spin-coupled effects

Tests of quantum mechanics at macroscopic scales

- Meter-scale wavepacket separation, duration of seconds
- Decoherence, spontaneous localization, non-linear QM, …



Rb wavepackets separated by 54 cm

Slide credit: Jason Hogan

Sky position determination

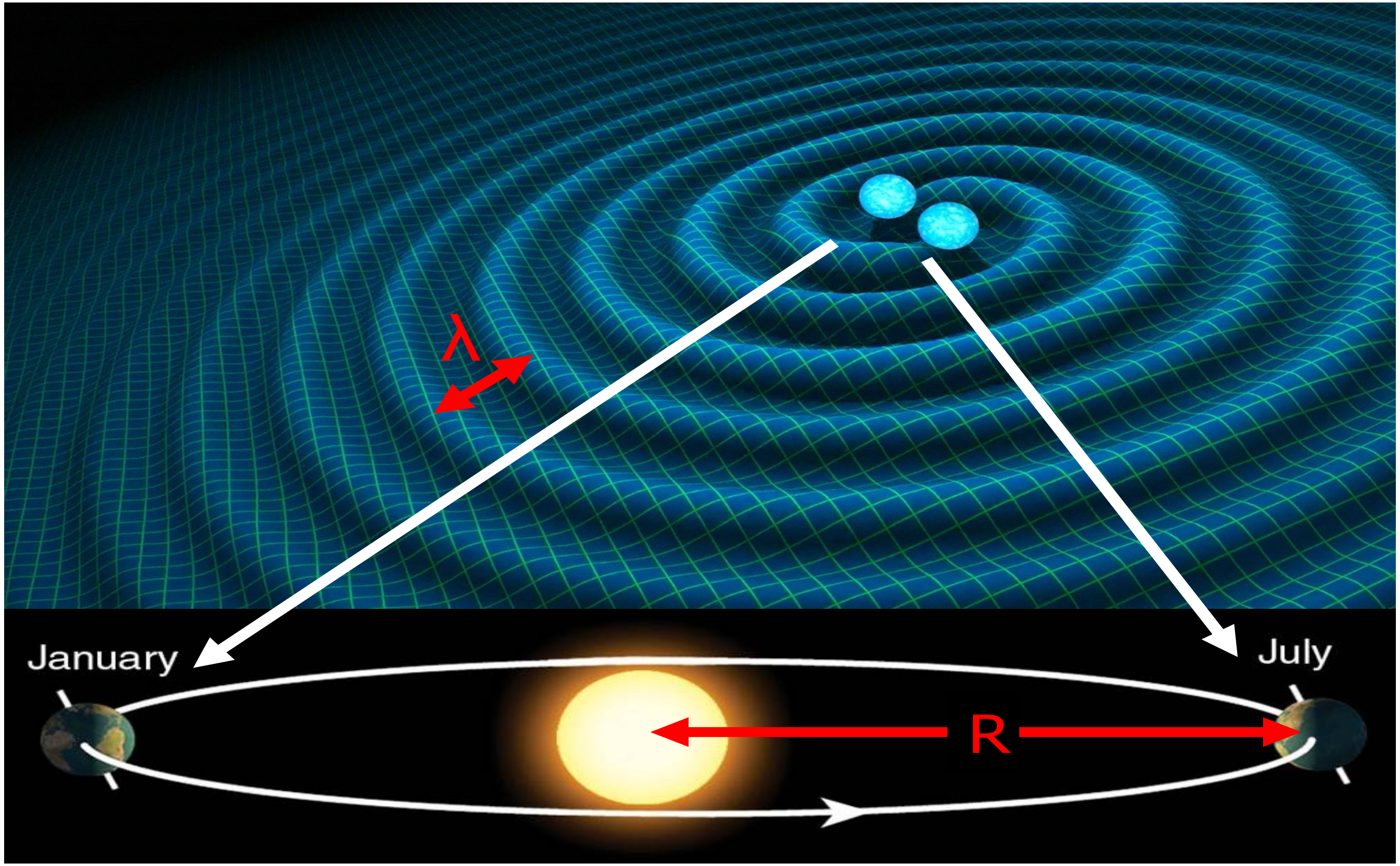
Sky localization precision:

$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

Mid-band advantages

- Small wavelength λ
- Long source lifetime (~months) maximizes effective R

Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19



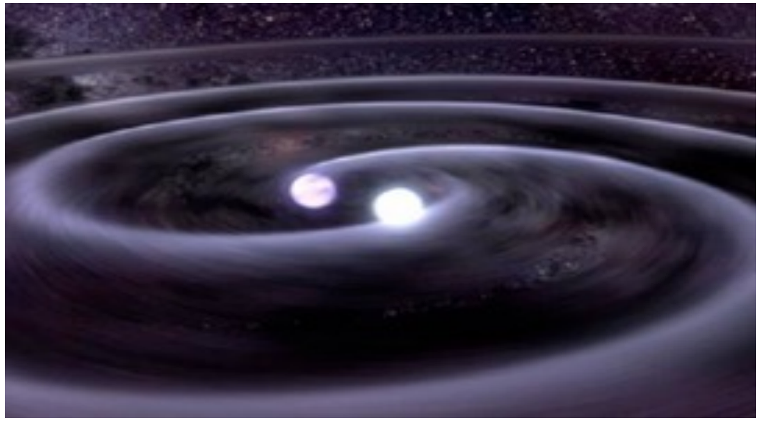
Graham et al., **PRD** 024052 (2018).

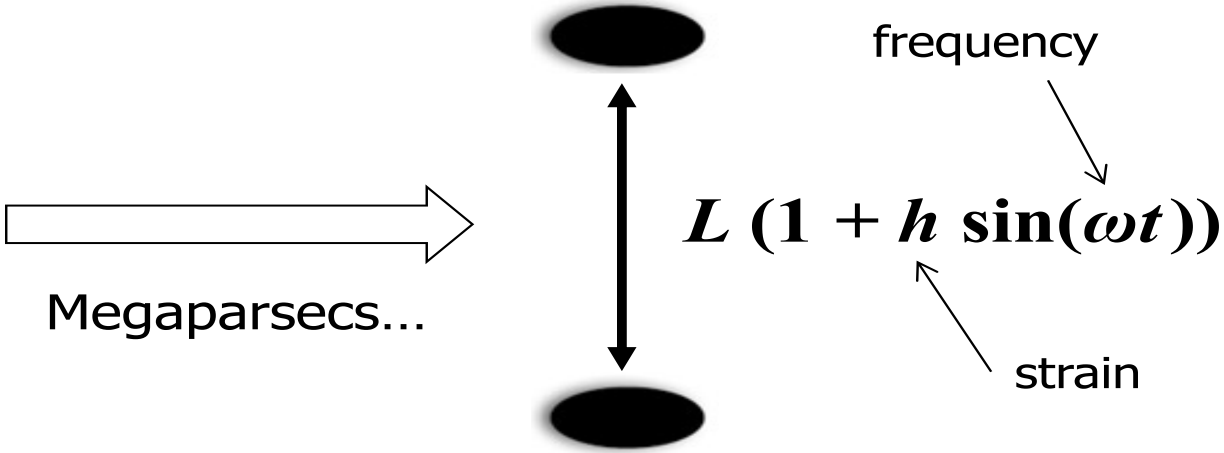
Slide credit: Jason Hogan

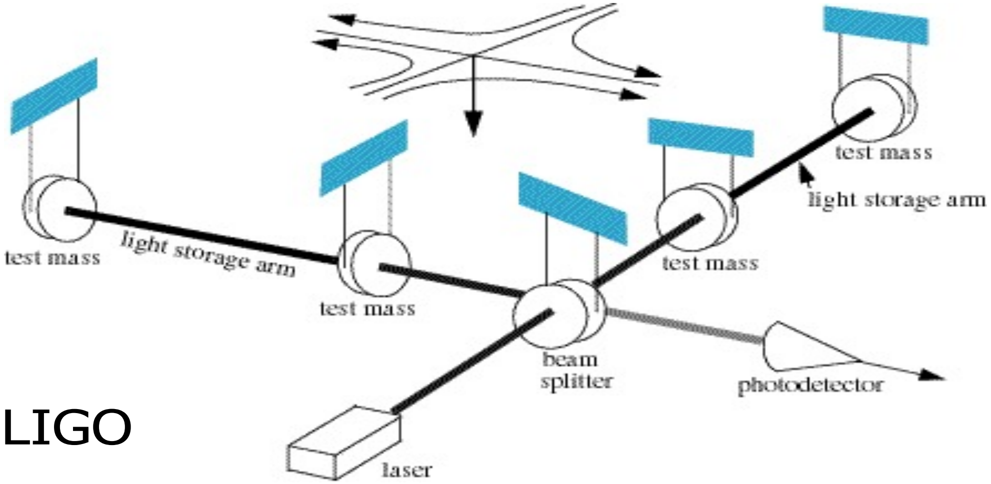
Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

Gravitational Wave Detection

$$ds^2 = dt^2 - (1 + h\sin(\omega(t-z)))dx^2 - (1 - h\sin(\omega(t-z)))dy^2 - dz^2$$







LIGO

- LIGO and other optical interferometers **use two baselines**
- In principle, **only one is required**
- Second baseline needed to reject laser technical noise

Slide credit: Jason Hogan

MAGIS concept

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

Passing gravitational waves cause a small modulation in the distance between objects. Detecting this modulation requires two ingredients:

1. **Inertial references**
   - Freely-falling objects, separated by some baseline
   - Must be insensitive to perturbations from non-gravitational forces
2. **Clock**
   - Used to monitor the separation between the inertial references
   - Typically measures the time for light to cross the baseline, via comparison to a precise phase reference (e.g. a clock).

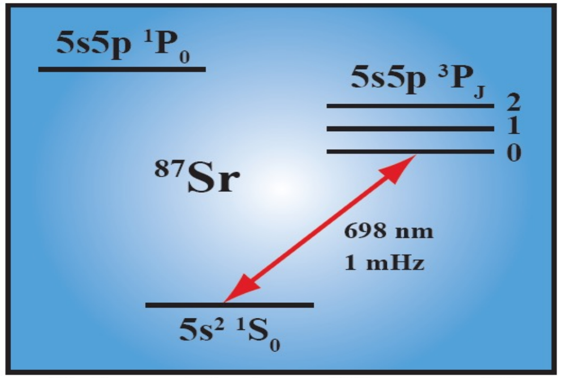
In MAGIS, atoms play both roles.

Atom as "active" proof mass: Atomic coherence records laser phase, avoiding the need of a reference baseline – **single baseline** gravitational wave detector.

Slide credit: Jason Hogan

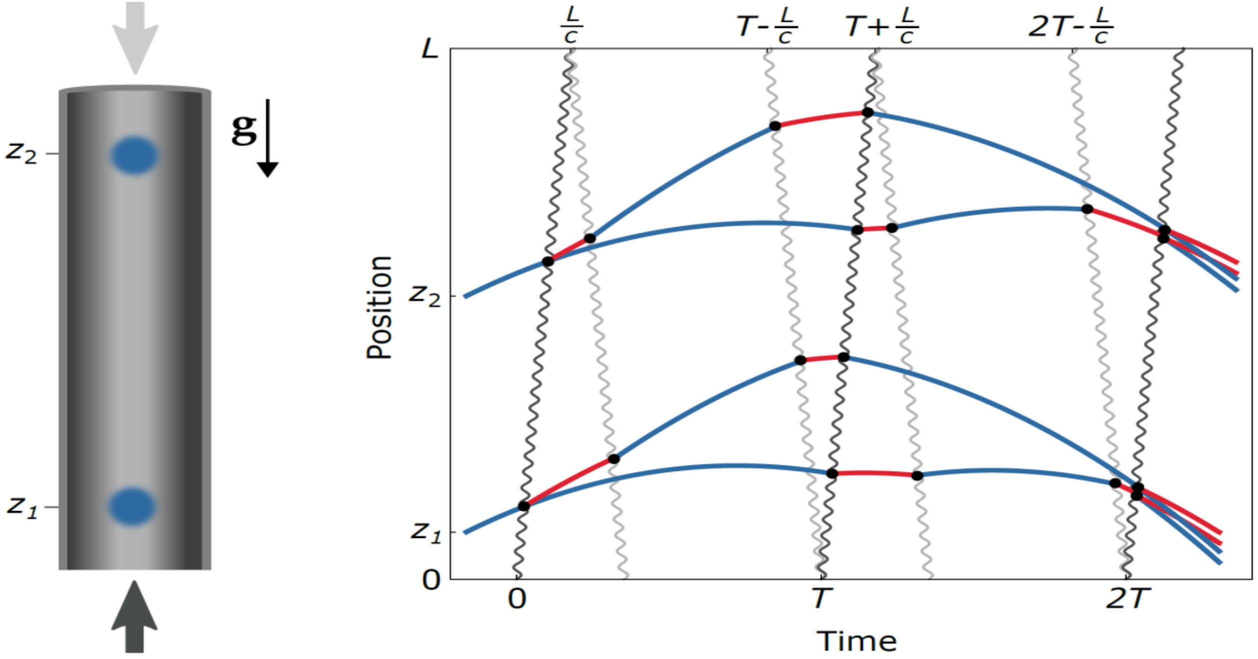
Clock atom interferometry

New kind of atom interferometry using **single-photon transitions** between long-lived **clock states**



Clock transition in candidate atom ^{87}Sr

Differential measurement (**gradiometer**) to suppress laser noise



Excited state phase evolution:

$$\Delta\phi \sim \omega_A \left(2L/c\right)$$

(variations over time T)

Two ways for phase to vary:

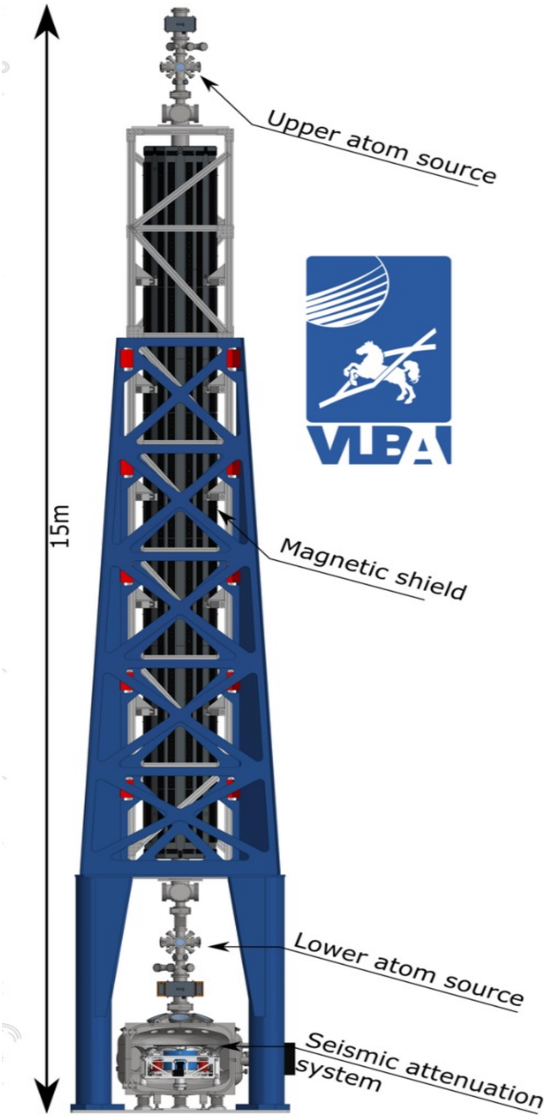
$\delta\omega_A$ *Dark matter*

$\delta L = hL$ *Gravitational wave*

Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., PRD **97**, 075020 (2018).

Slide credit: Jason Hogan

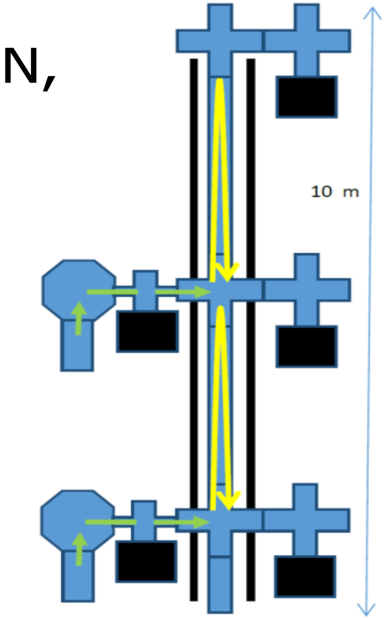
10-meter scale atom drop towers



Hannover, Germany

Wuhan, China

AION,
UK

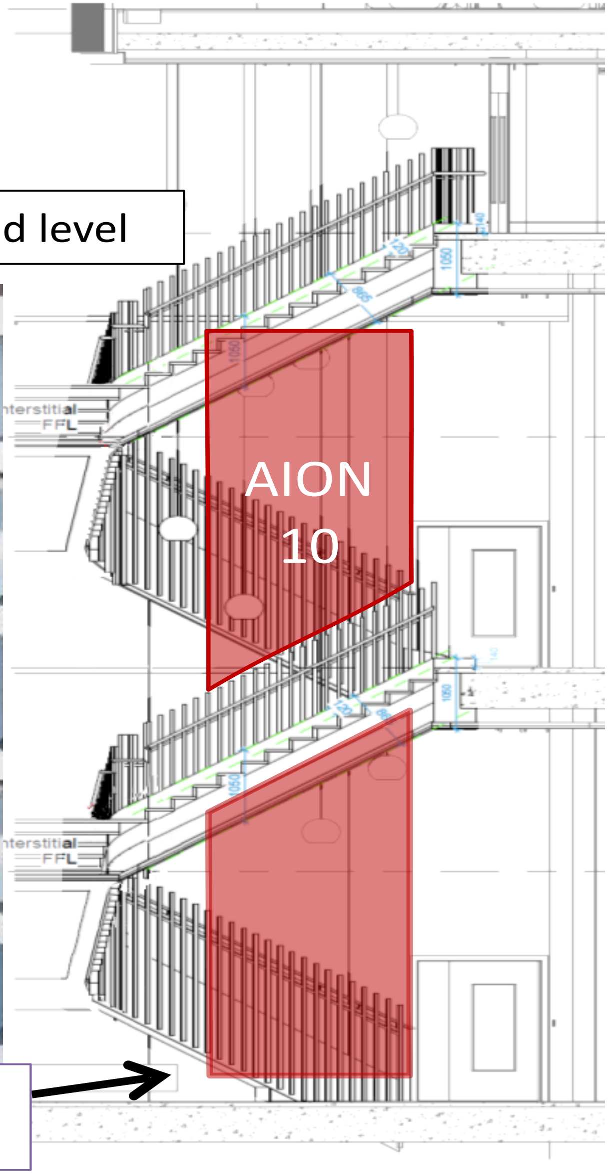


Stanford University

Planned Site for AION 10m

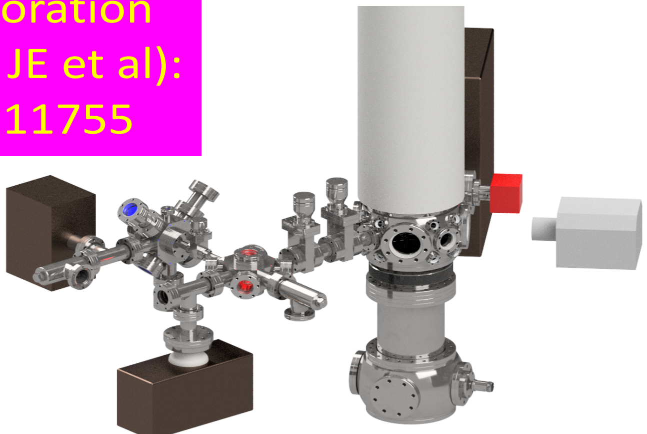
- Oxford Physics Department
- New purpose-built building
  - Low vibration
  - Temperature control
  - Laser laboratory
  - Engineering support

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755



Ground level

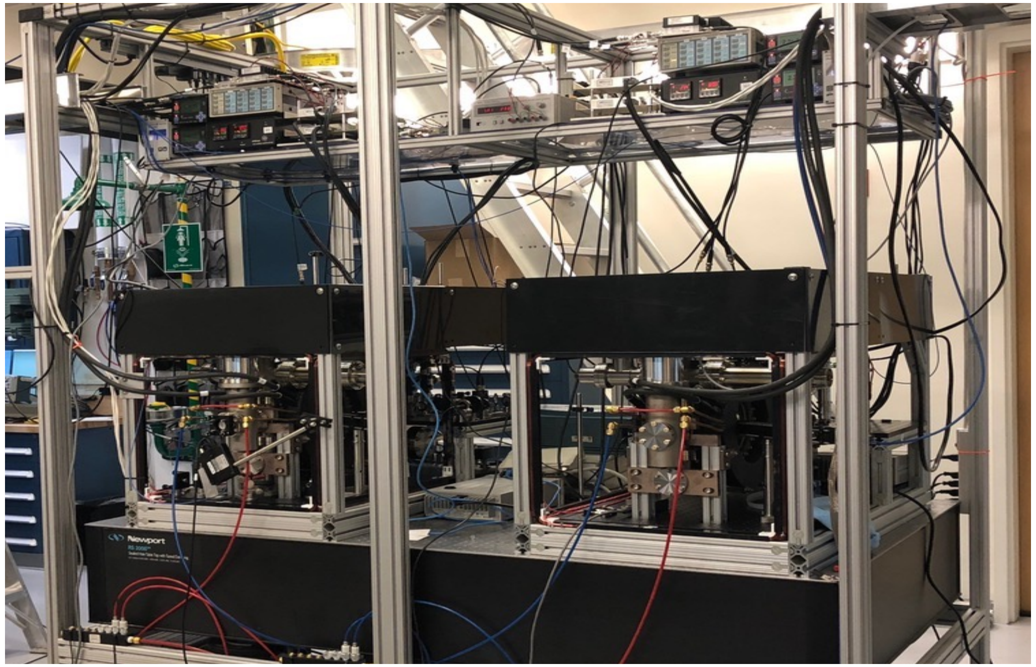
Feed through to laser lab

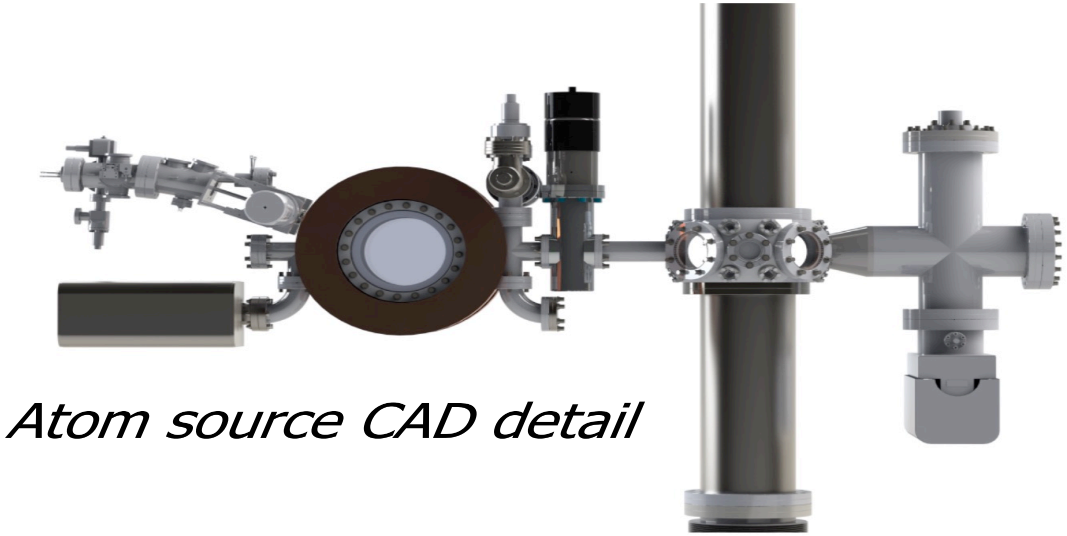


Stanford 10-meter Sr prototype

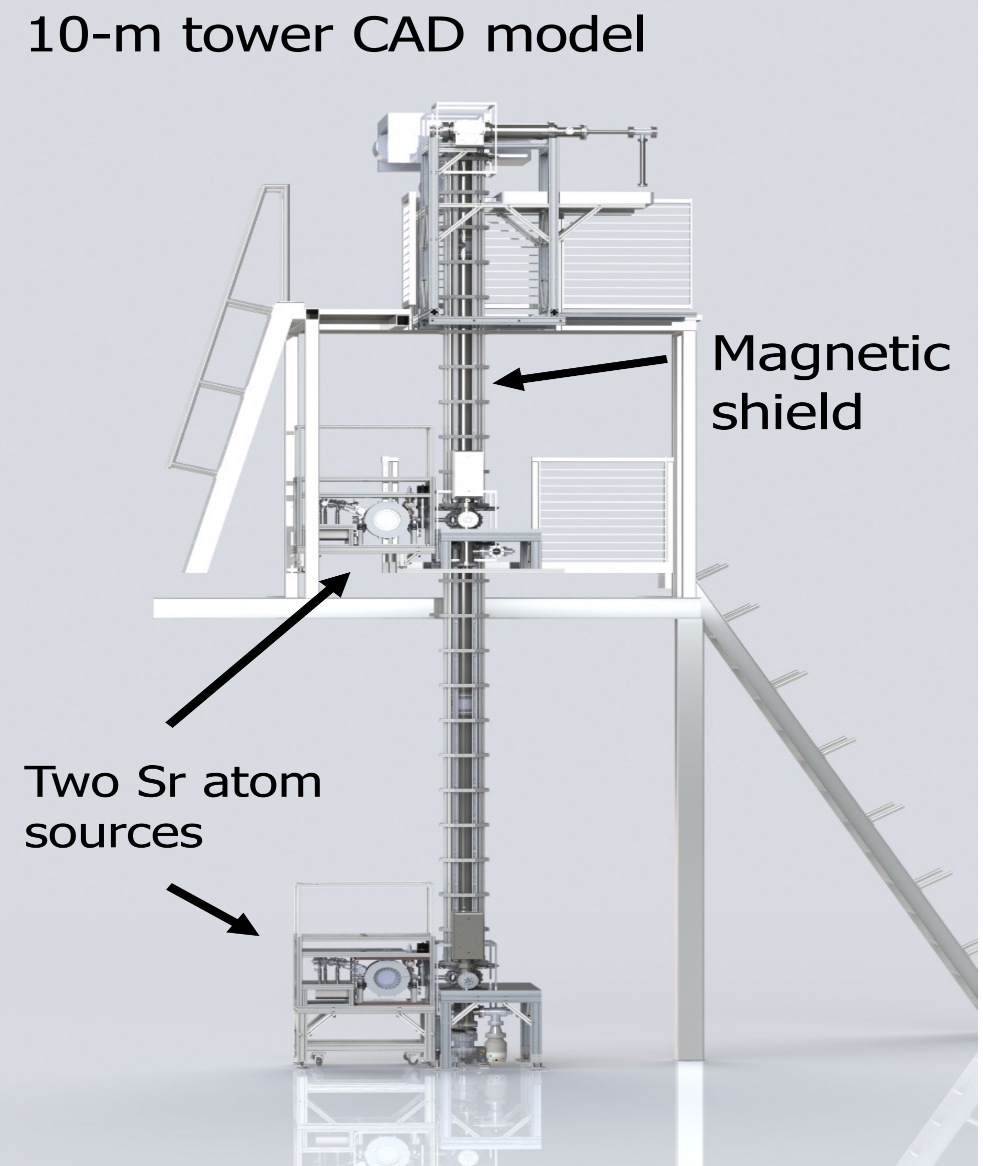
(MAGIS prototype)

Two assembled Sr atom sources





Atom source CAD detail

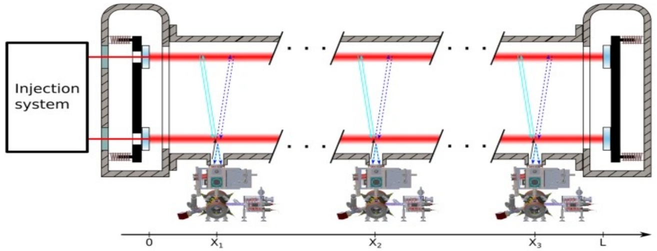


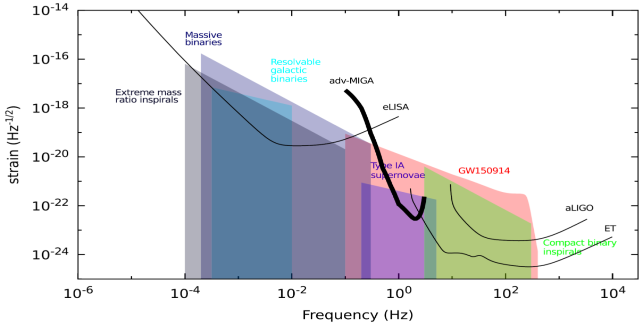
Slide credit: Jason Hogan

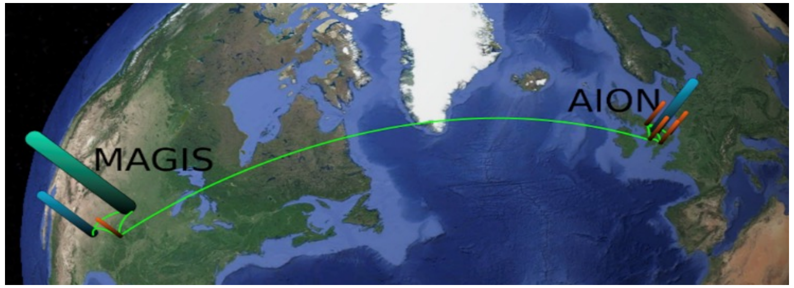
International efforts in long baseline atomic sensors

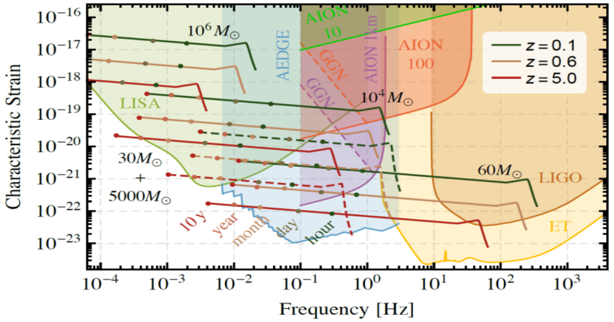
Project	Baseline Length	Number of Baselines	Orientation	Atom	Atom Optics	Location
MAGIS-100	100 m	1	Vertical	Sr	Clock AI, Bragg	USA
AION	100 m	1	Vertical	Sr	Clock AI	UK
MIGA	200 m	2	Horizontal	Rb	Bragg	France
ZAIGA	300 m	3	Vertical	Rb, Sr	Raman, Bragg, OLC	China

MIGA: Matter Wave laser Interferometric Gravitation Antenna (France)



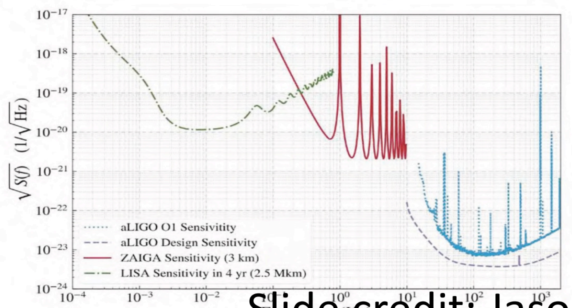






AION: Atom Interferometer Observatory and Network (UK)

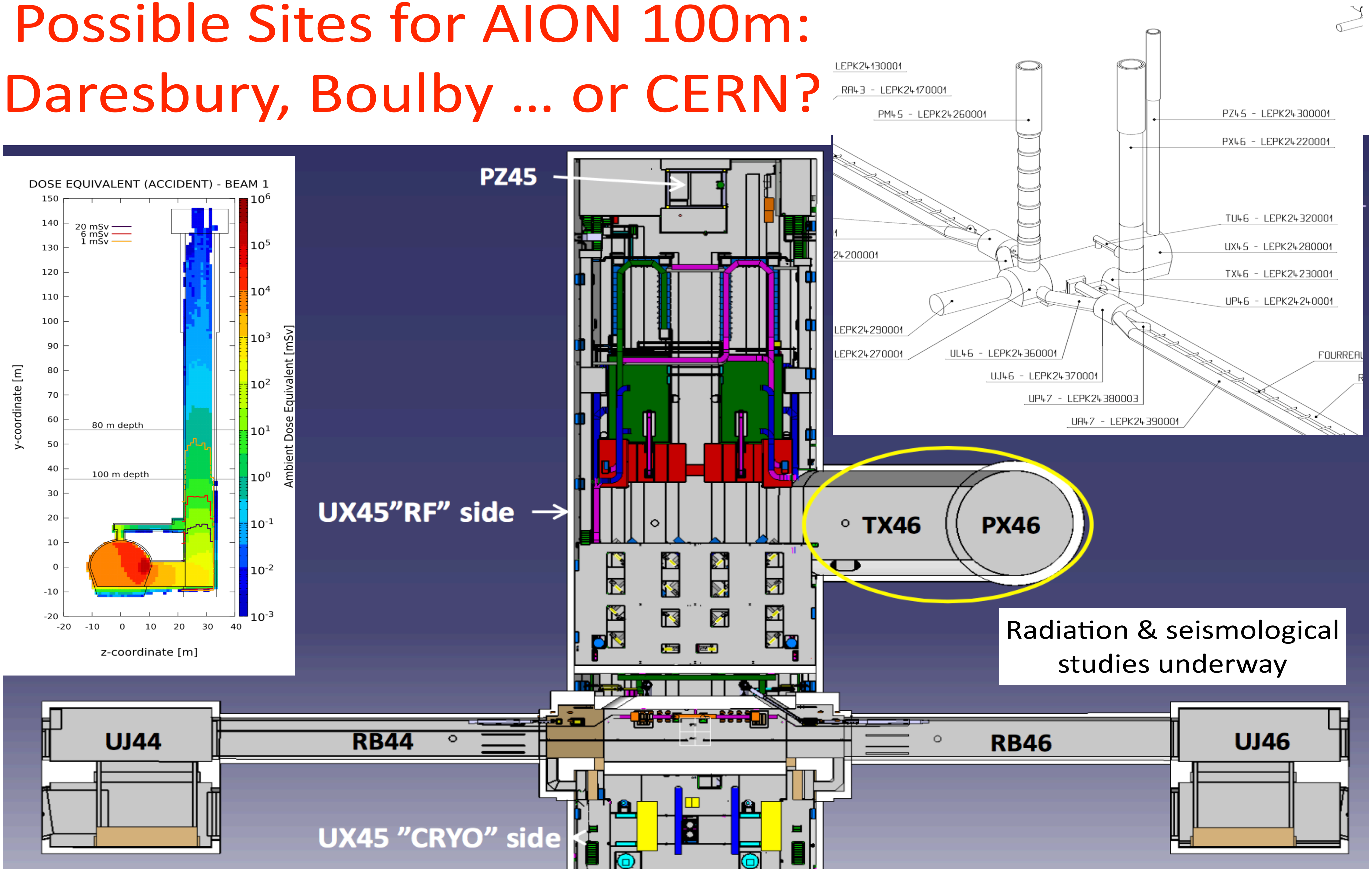
ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna (China)



Slide credit: Jason Hogan

Possible Site for AION 100m (1km?)
Boulby Mine STFC Laboratory

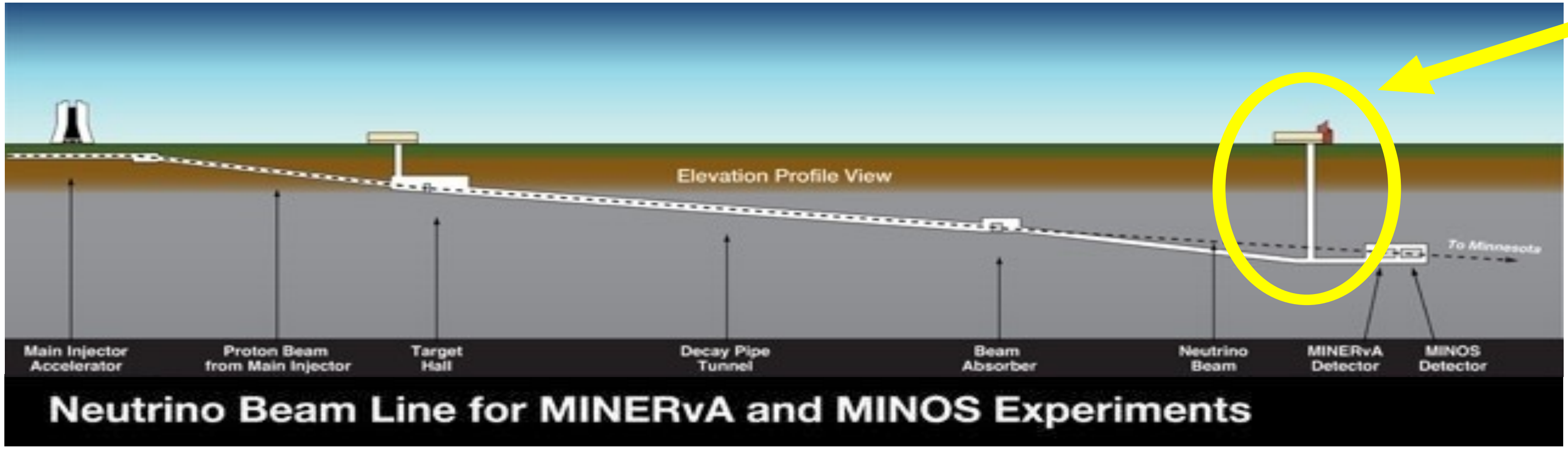
Possible Sites for AION 100m: Daresbury, Boulby … or CERN?



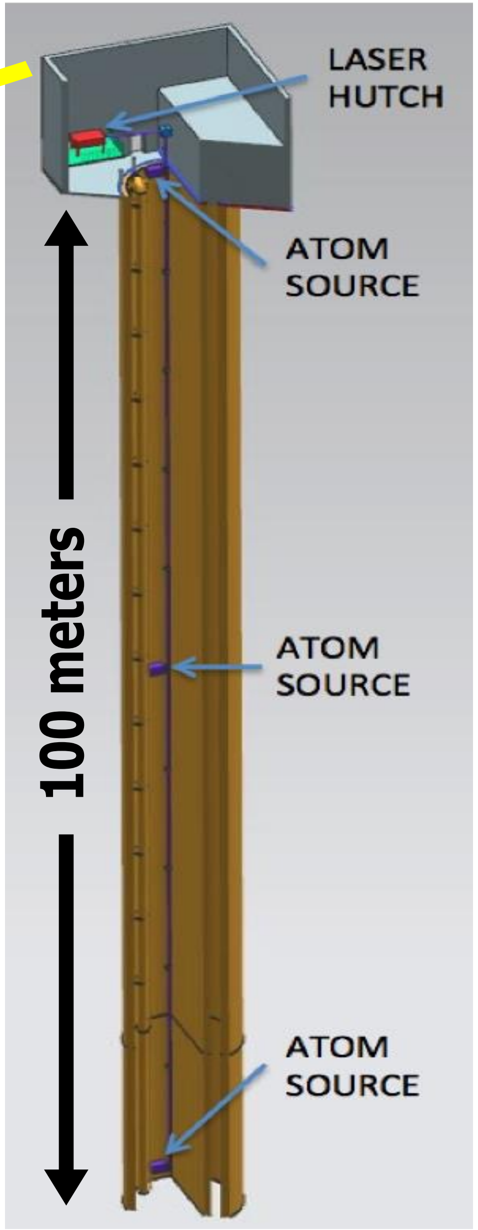
Radiation & seismological studies underway

MAGIS-100: Detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor



Neutrino Beam Line for MINERvA and MINOS Experiments

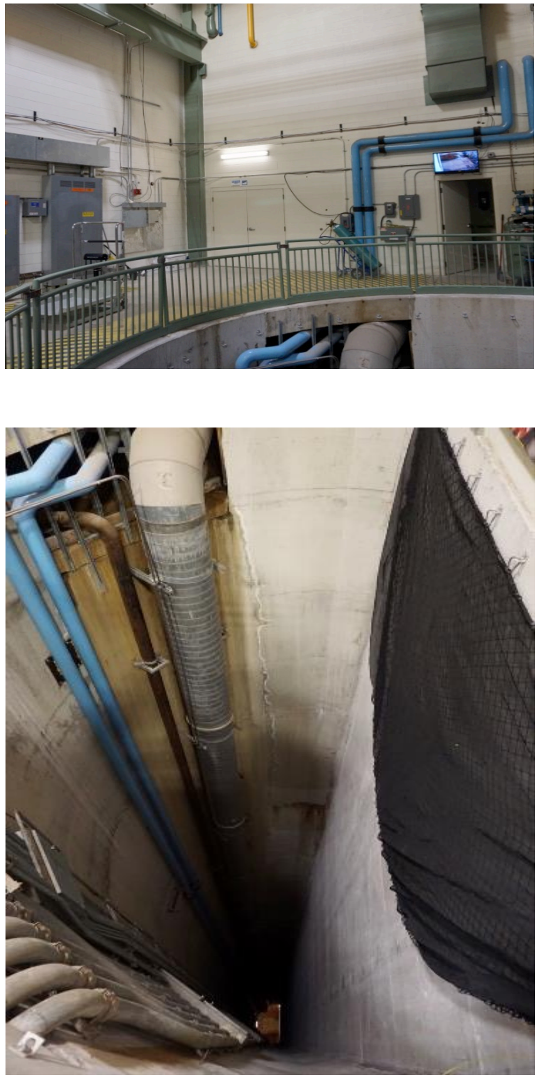


- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

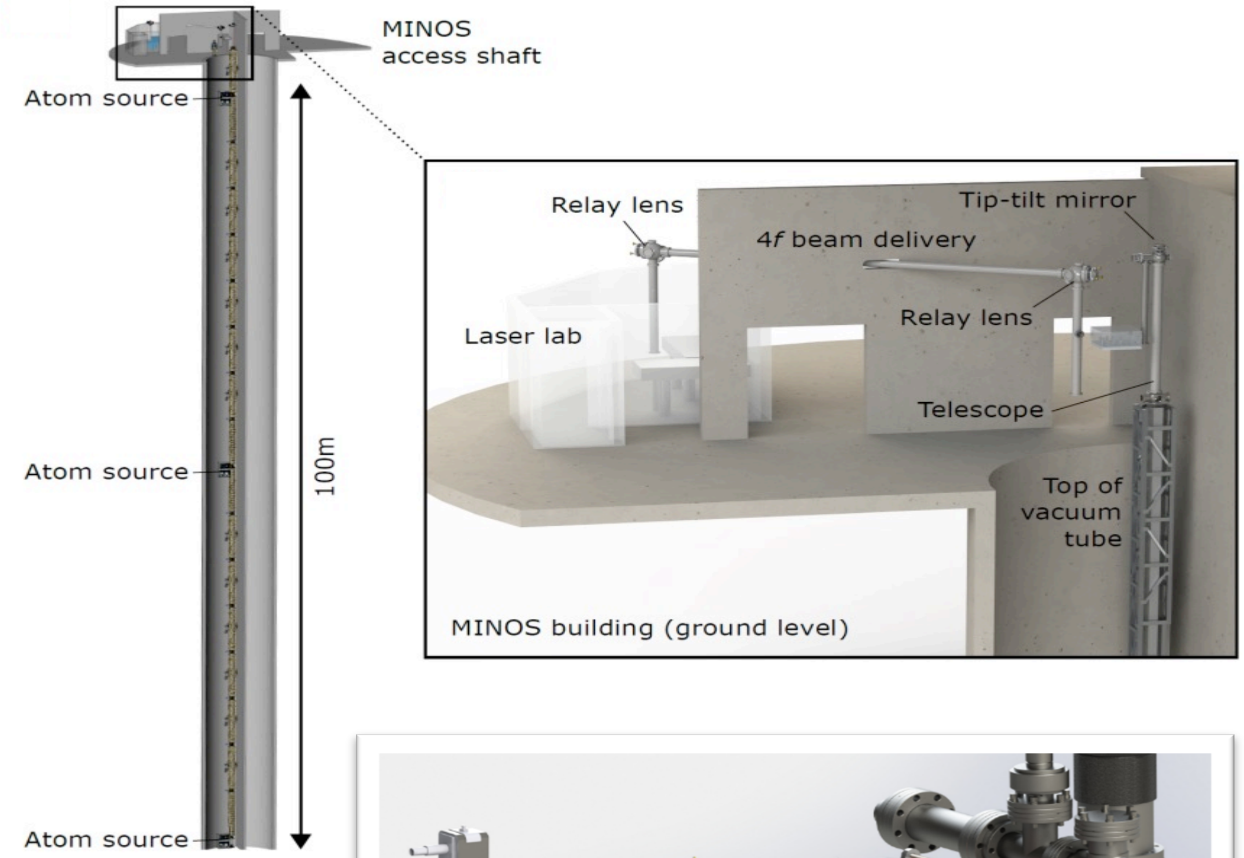
STANFORD
JOHNS HOPKINS UNIVERSITY
UNIVERSITY OF CAMBRIDGE
Northwestern University
Northern Illinois University
UNIVERSITY OF LIVERPOOL
UNIVERSITY OF OXFORD
Fermilab
SLAC

Slide credit: Jason Hogan

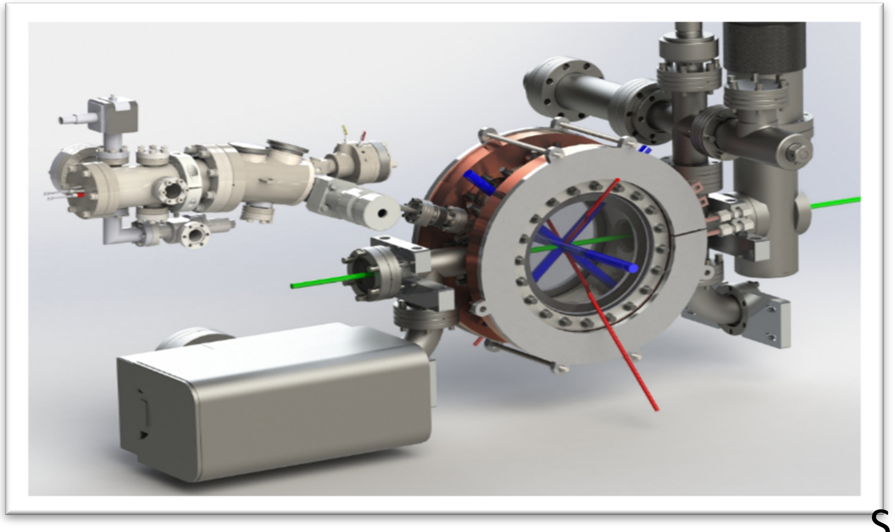
MAGIS-100 design

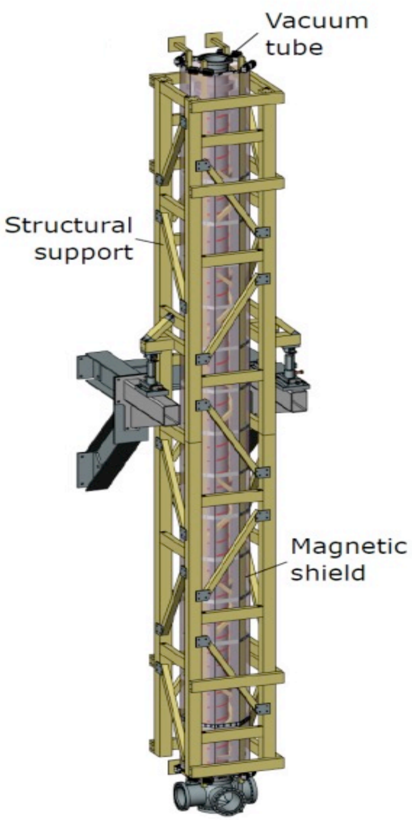


MINOS access shaft



Sr atom sources



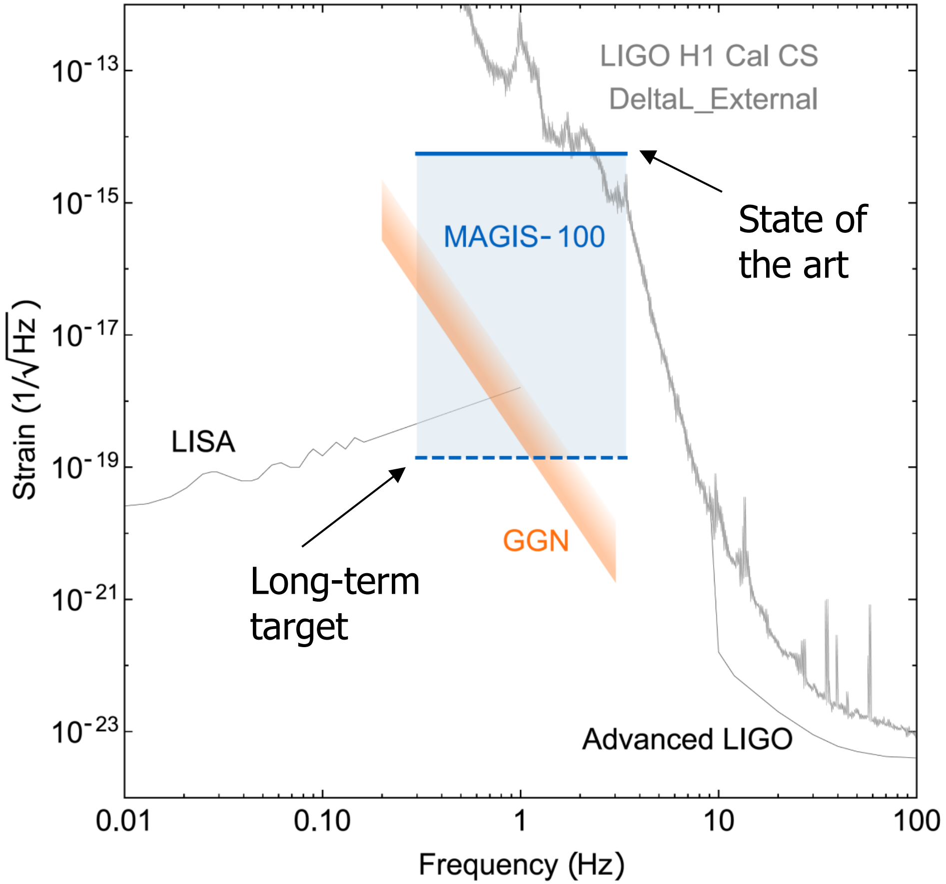


Modular section of 100 meter science region

Slide credit: Jason Hogan

MAGIS-100 projected sensitivity

Gravitational wave sensitivity

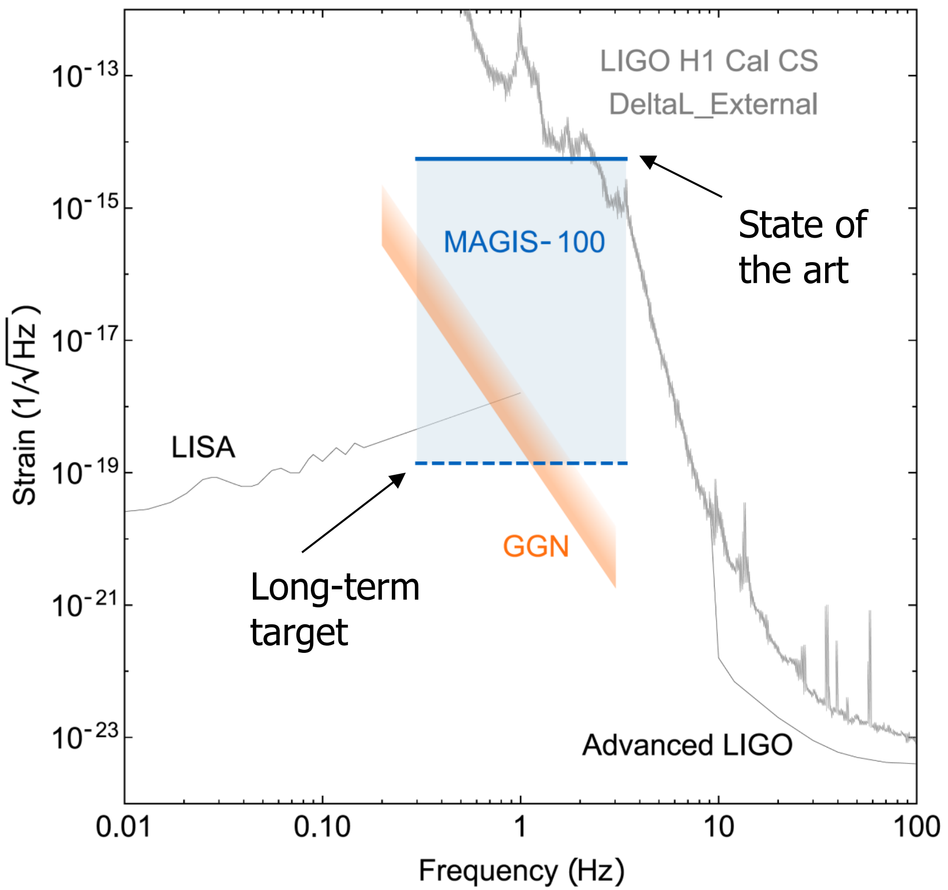


State of the art

Long-term target

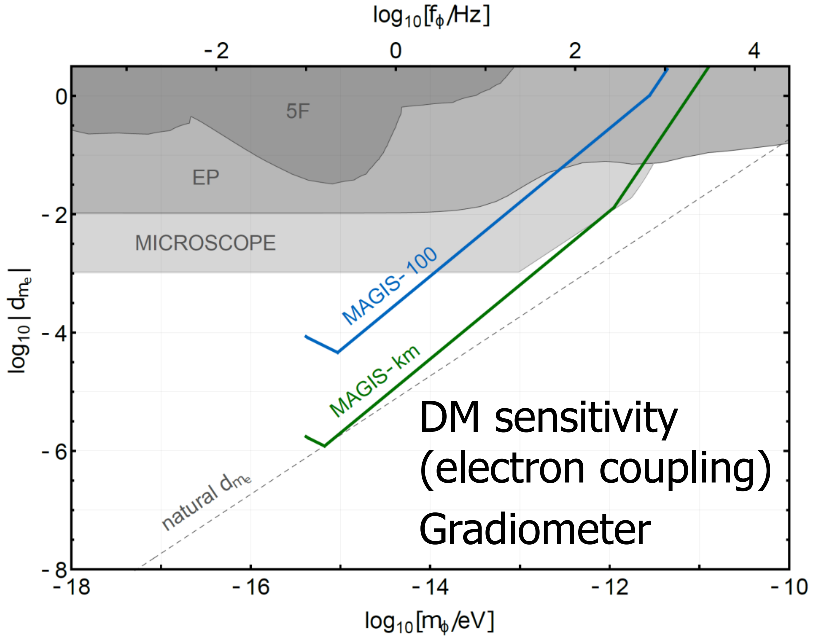
MAGIS-100 projected sensitivity

Gravitational wave sensitivity



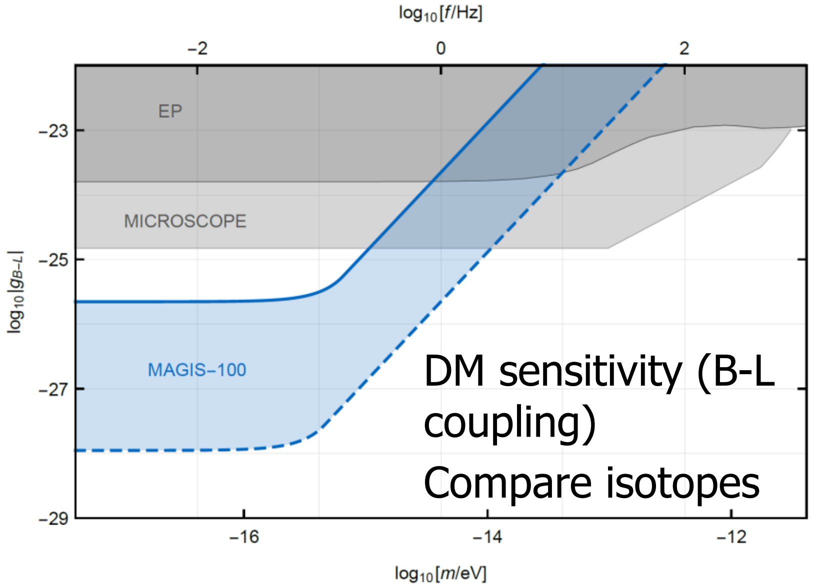
State of the art

Long-term target



DM sensitivity (electron coupling)

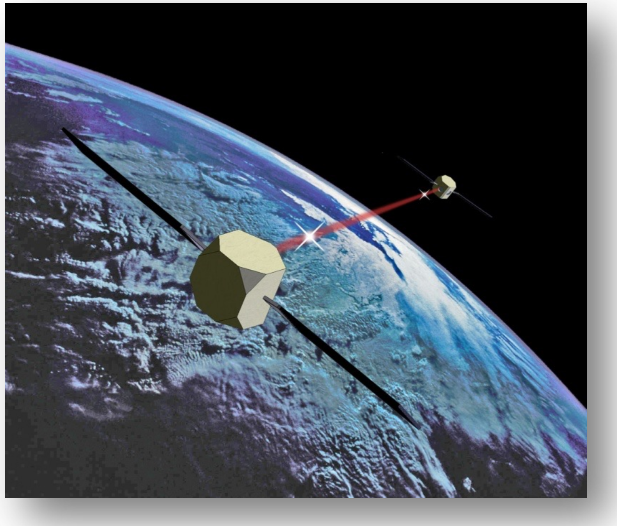
Gradiometer



DM sensitivity (B-L coupling)

Compare isotopes

MAGIS-style satellite detector



Satellite detector concept

- Two spacecraft
- Atom source in each
- Heterodyne laser link
- Resonant/LMT sequences

Example design

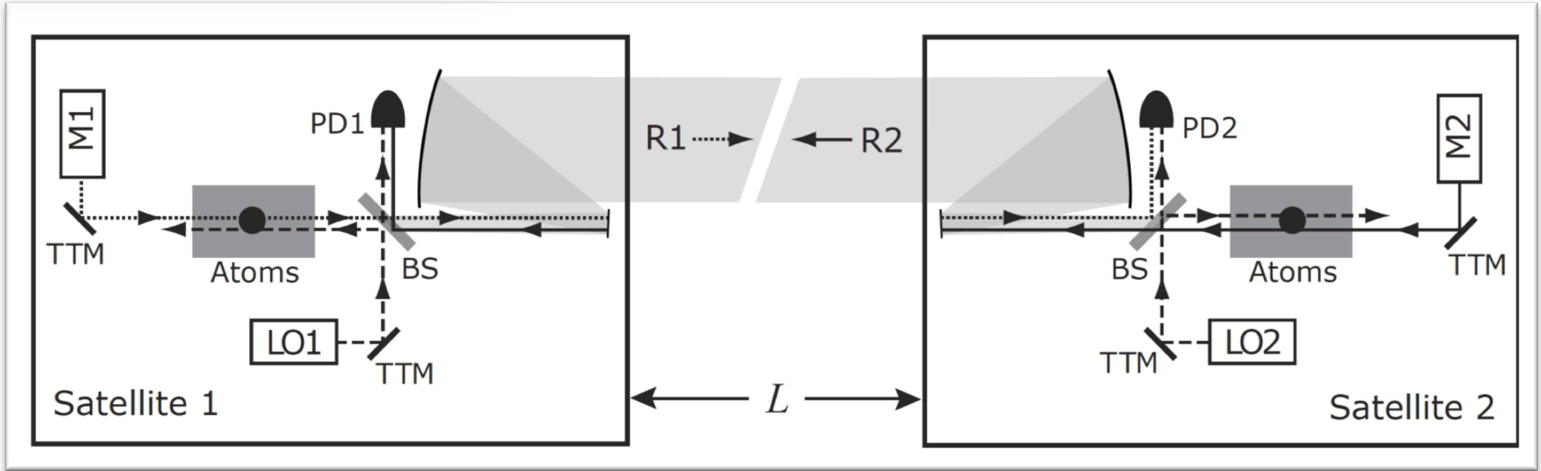
$$L = 4 \times 10^7 \text{ meters}$$

$$10^{-4}\ \text{rad}/\sqrt{\text{Hz}}$$

$$\frac{n\hbar k}{m} T < 1\ \text{m}$$

$$2TQ < 300\ \text{s}$$

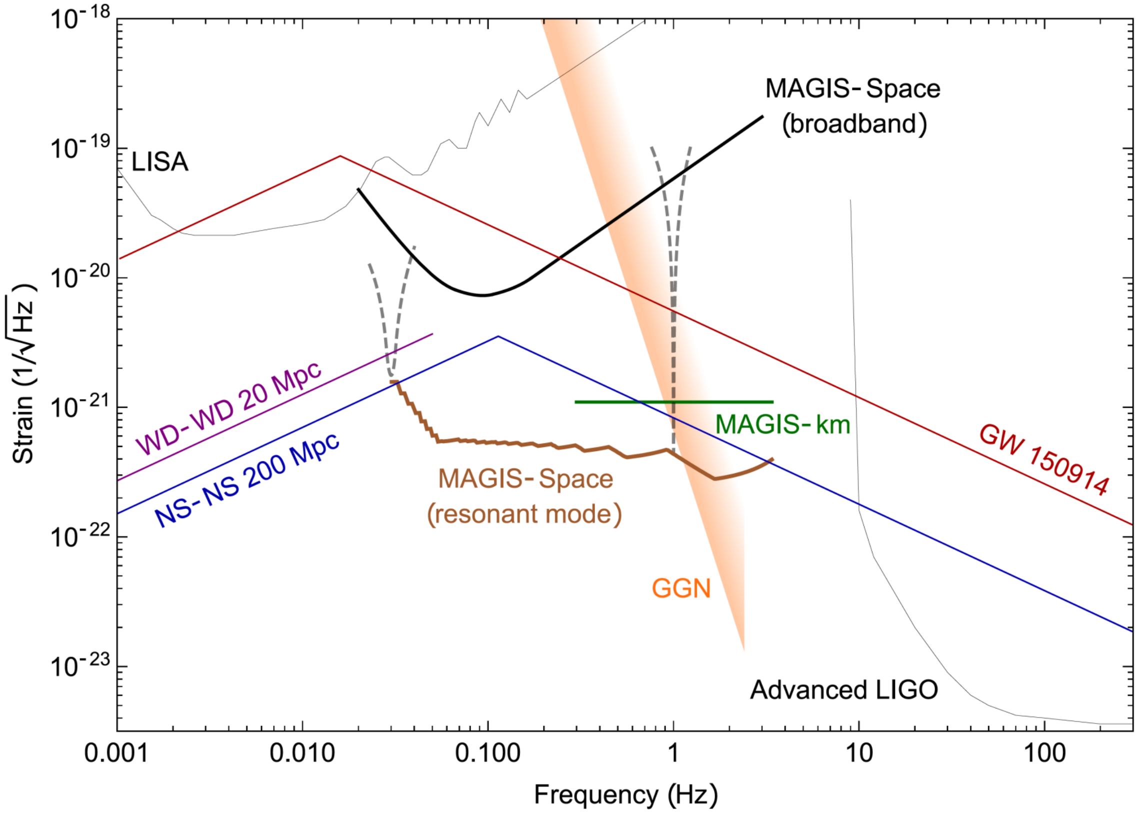
$$n_p < 10^3$$



- Heterodyne link concept analogous to LISA (synthesize ranging between two test masses)

Slide credit: Jason Hogan

Full scale MAGIS projected GW sensitivity

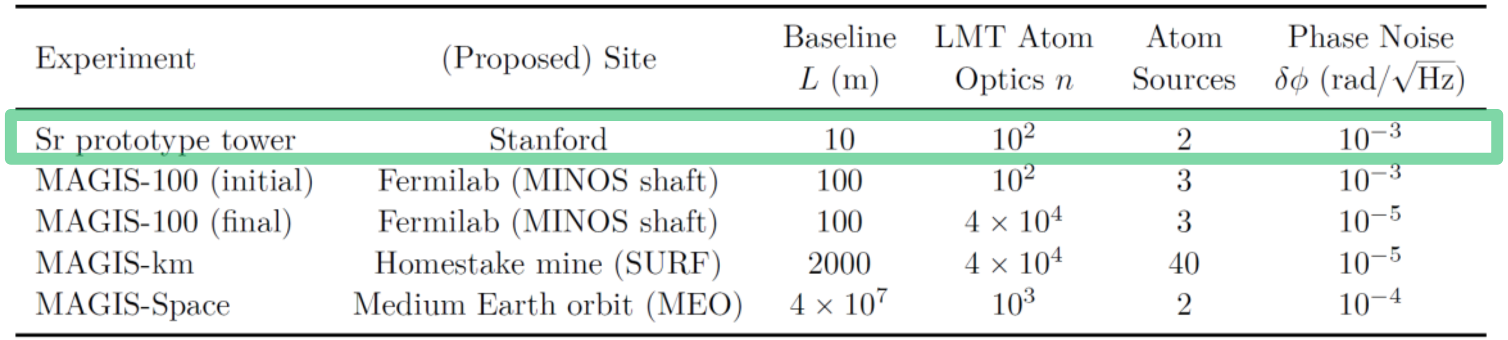


- Mid-band GW sources detectable from ground and space
- Gravity gradient noise (GGN) likely limits any terrestrial detector at low frequencies
- Longer baselines available in space reduce requirements (e.g., LMT), but can impact frequency response at high frequencies
- Flexible detection strategies possible (broadband vs resonant) with different tradeoffs in sensitivity/bandwidth

Slide credit: Jason Hogan

Development path

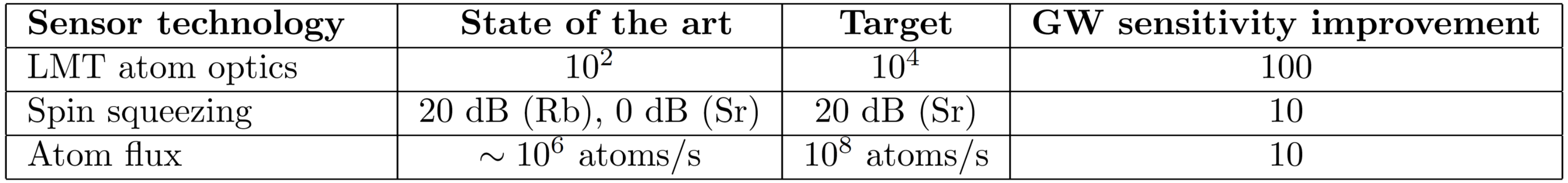
MAGIS detector development



Experiment	(Proposed) Site	Baseline L (m)	LMT Atom Optics n	Atom Sources	Phase Noise $\delta\phi$ (rad/$\sqrt{\text{Hz}}$)
Sr prototype tower	Stanford	10	10^2	2	10^{-3}
MAGIS-100 (initial)	Fermilab (MINOS shaft)	100	10^2	3	10^{-3}
MAGIS-100 (final)	Fermilab (MINOS shaft)	100	4×10^4	3	10^{-5}
MAGIS-km	Homestake mine (SURF)	2000	4×10^4	40	10^{-5}
MAGIS-Space	Medium Earth orbit (MEO)	4×10^7	10^3	2	10^{-4}

State of the art

Reaching required sensitivity requires extensive technology development in three key areas:



Sensor technology	**State of the art**	**Target**	**GW sensitivity improvement**
LMT atom optics	10^2	10^4	100
Spin squeezing	20 dB (Rb), 0 dB (Sr)	20 dB (Sr)	10
Atom flux	$\sim 10^6$ atoms/s	10^8 atoms/s	10

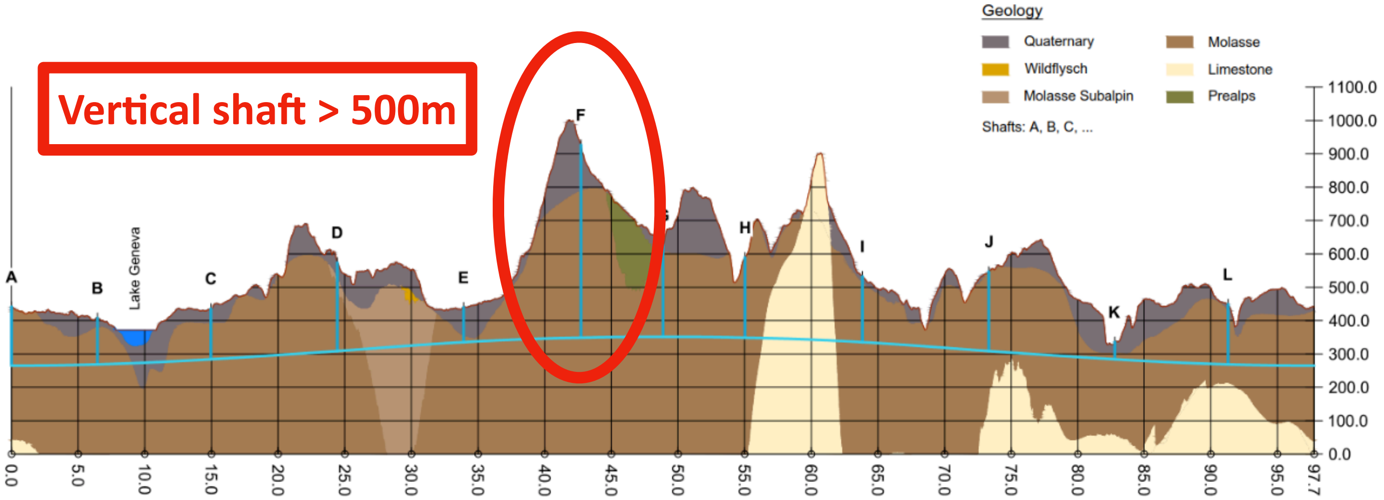
- Phase noise improvement strategy is a combination of increasing atom flux and using quantum entanglement (spin squeezing).
- LMT requirement is reduced in space proposals (longer baselines)

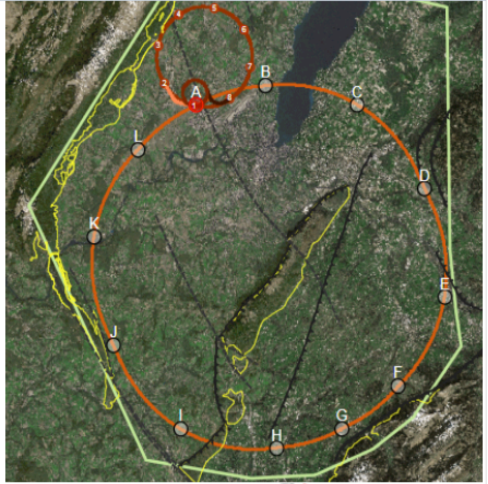
Slide credit: Jason Hogan

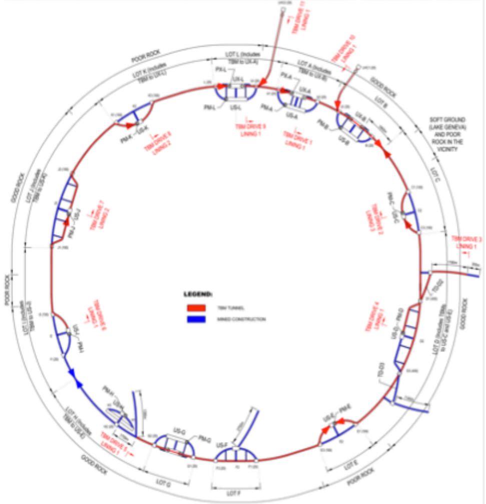
Possible Site for AION-1km?

FUTURE CIRCULAR COLLIDER

FCC implementation - footprint baseline







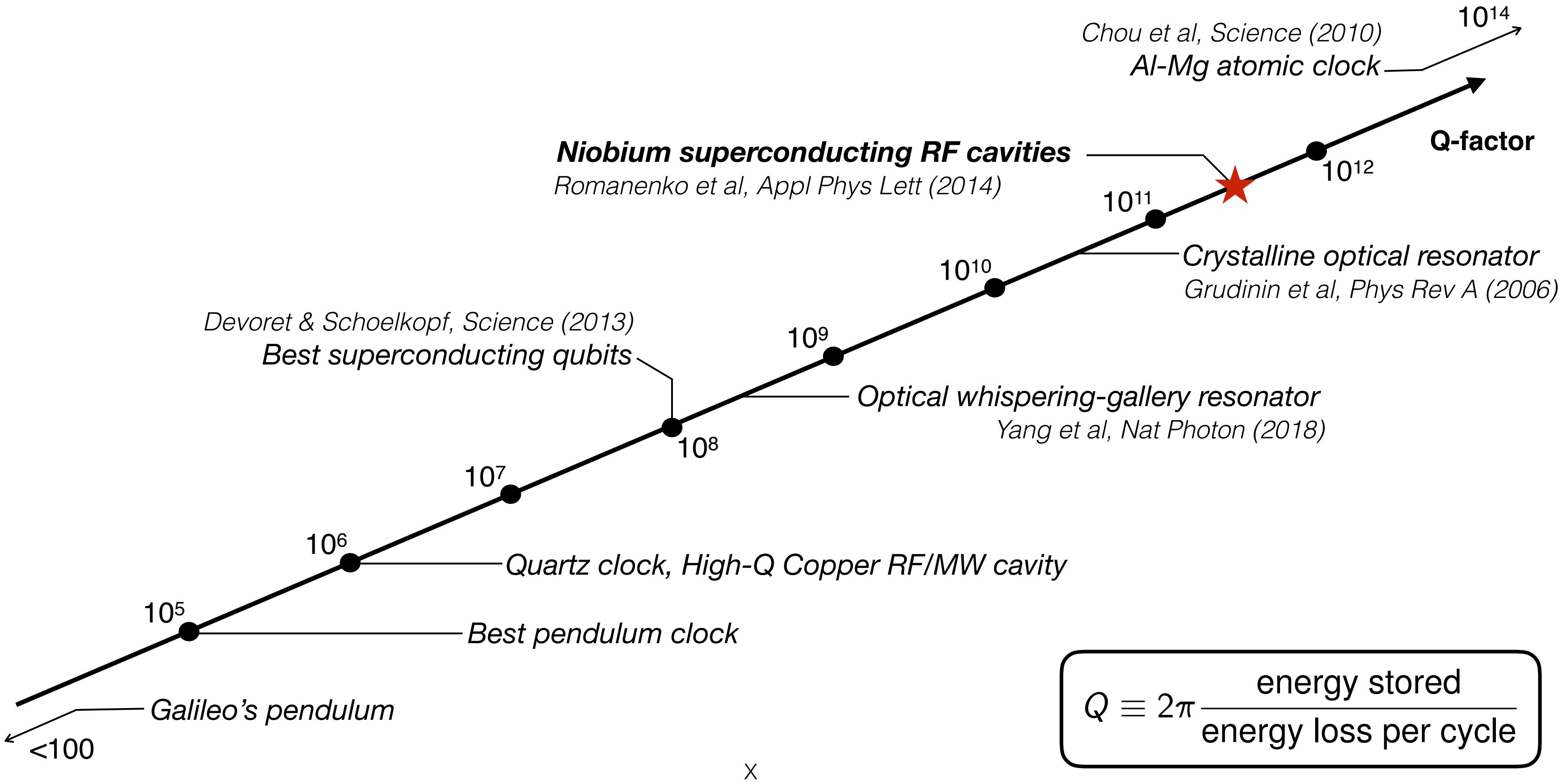
Present baseline position was established considering:

- Molasse rock preferred for tunnelling, avoid limestone with karstic structures
- low risk for construction, fast construction

- **90 – 100 km circumference**
- **12 surface sites with few ha area each**

Why SRF cavities for quantum sensing?

SRF cavities are the most efficient engineered oscillators



Q-factor

<100

Galileo's pendulum

10^5

Best pendulum clock

10^6

Quartz clock, High-Q Copper RF/MW cavity

10^7

10^8

Devoret & Schoelkopf, Science (2013)

Best superconducting qubits

10^9

Optical whispering-gallery resonator

Yang et al, Nat Photon (2018)

10^{10}

10^{11}

Crystalline optical resonator

Grudinin et al, Phys Rev A (2006)

Niobium superconducting RF cavities

Romanenko et al, Appl Phys Lett (2014)

10^{12}

Chou et al, Science (2010)

Al-Mg atomic clock

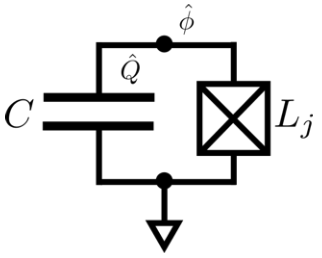
10^{14}

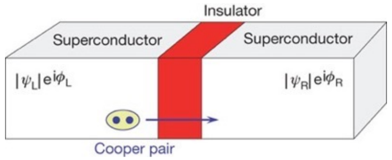
$$Q \equiv 2\pi \frac{\text{energy stored}}{\text{energy loss per cycle}}$$

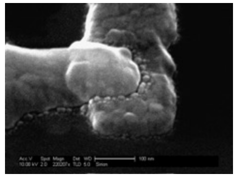
X

Advancing Superconducting Qubits for QIS, two main components

1. LC circuit with Josephson junction







"Transmon" qubits

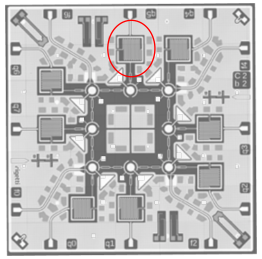
J. Koch et al, Phys. Rev. **A** 76, 042319 (2007)

+

2. Resonators (cavities)

2D

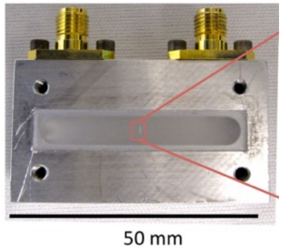
3D



Rigetti 8-qubit processor

Q ~ 10^5

$T_{coherence}$ ~ 0.000001 s



3D transmon

Q ~ 10^8

$T_{coherence}$ ~ 0.001 s

Fermilab SRF resonators

Q > 10^{10}

$T_{coherence}$ > 1 s

M. Reagor et al, Science Advances, Vol.4, no. 2, (2018)

H. Paik et al, Phys. Rev. Lett. 107, 240501 (2011)

A. Romanenko et al, Phys. Rev. Appl. 13, 134052 (2020)

The main challenge is improving the **coherence** of both key components while also **scaling up** to larger combined systems

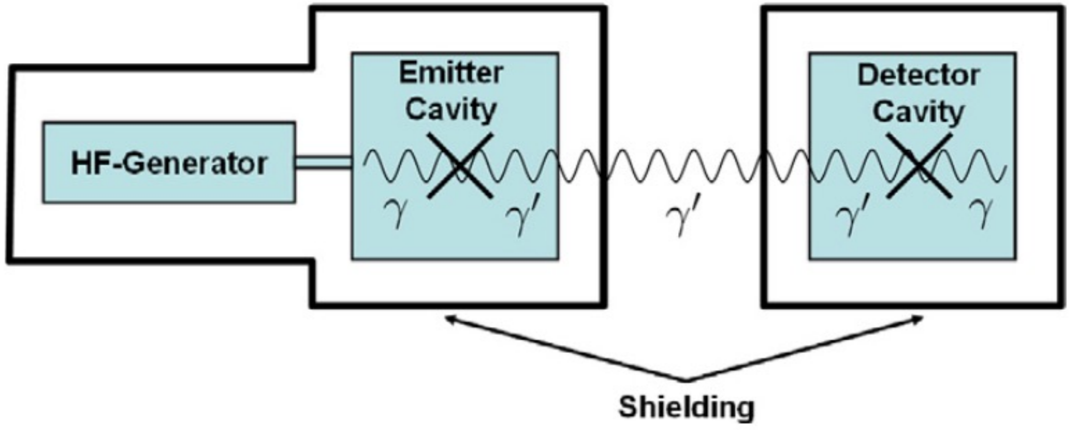
Alexander Romanenko

Dark sector search

S. R. Parker *et al*, Phys. Rev. D 88, 112004 (2013)
J. Hartnett *et al*, Phys. Lett. B 698 (2011) 346
J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)

Q_{DET}, Q_{EM} < 10^5 so far used

Looking for hidden paraphotons



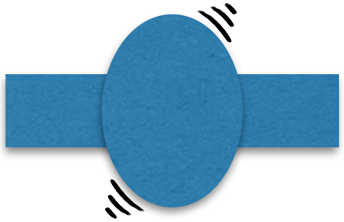
$$\frac{P_{DET}}{P_{EM}} = \chi^4 Q_{DET} Q_{EM} \left(\frac{m_{\gamma'} c^2}{\hbar \omega_\gamma}\right)^8 |G|^2$$

Q_{DET}, Q_{EM} > 10^{10} SRF can offer several orders of magnitude improvement in sensitivity to χ

Alexander Romanenko

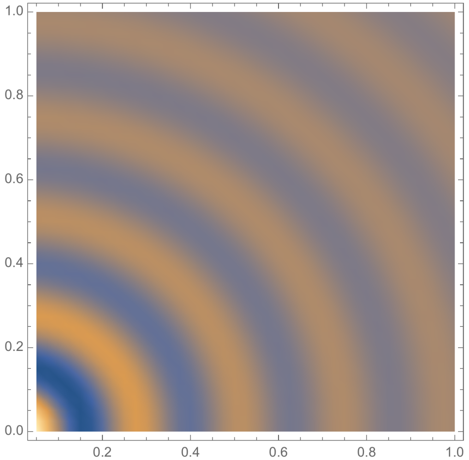
Dark Photon Search

Q> 1e9



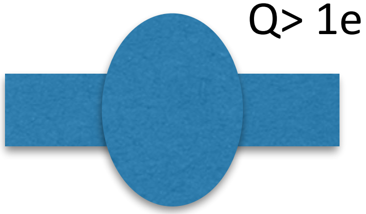
Emitter Cavity

Frequency of 1.3 GHz, excited to ~ 35 MV/m. Thats ~ 10^{25} Photons!



a dark photon field is radiated at 1.3 GHz.

Q> 1e10



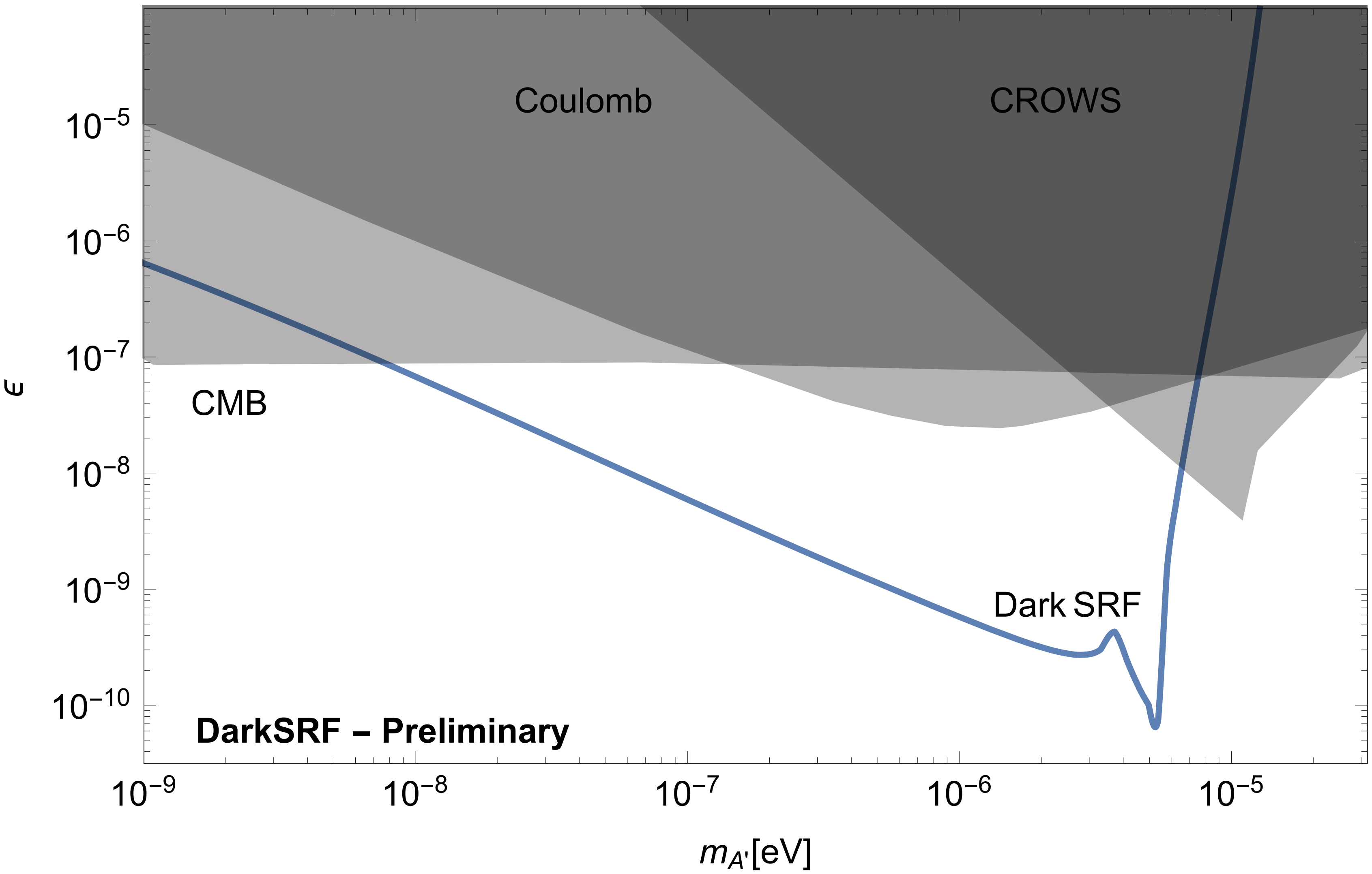
Receiver Cavity

Tuned to 1.3 GHz. Responds to dark field. Contains only thermal noise (T=1.4 K).

For correct cavity positioning $P_{\text{rec}} \sim G^2 \, \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 Q_{\text{rec}} Q_{\text{em}} P_{\text{em}}$

Alexander Romanenko

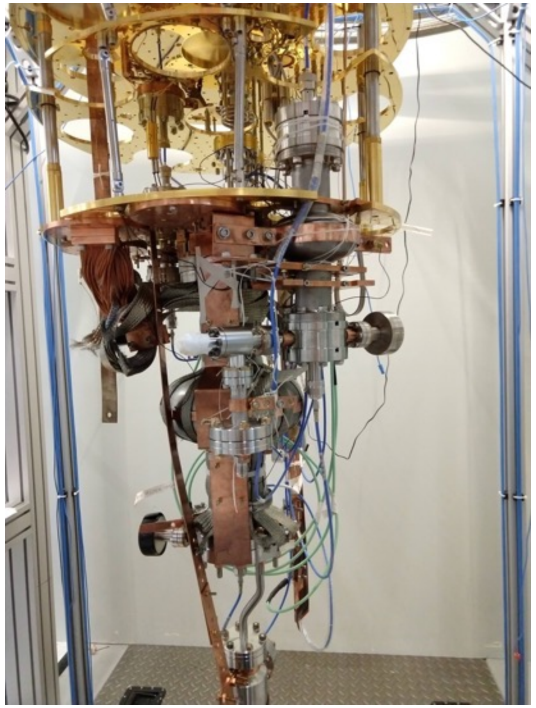
Results from run 2 – exclusion boundary pushed up to 3 orders of magnitude compared to state of the art

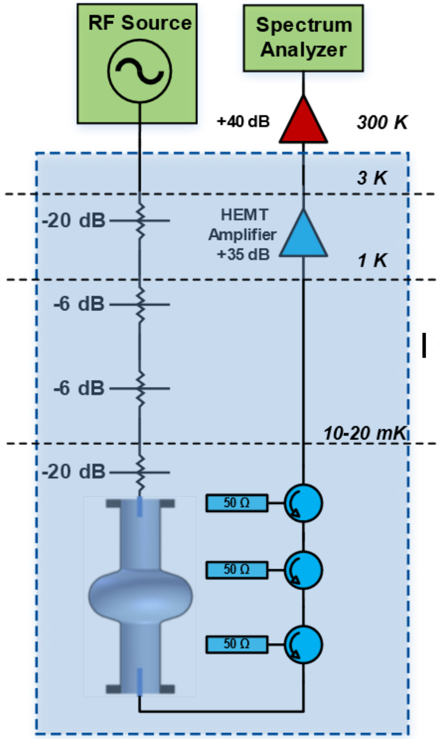


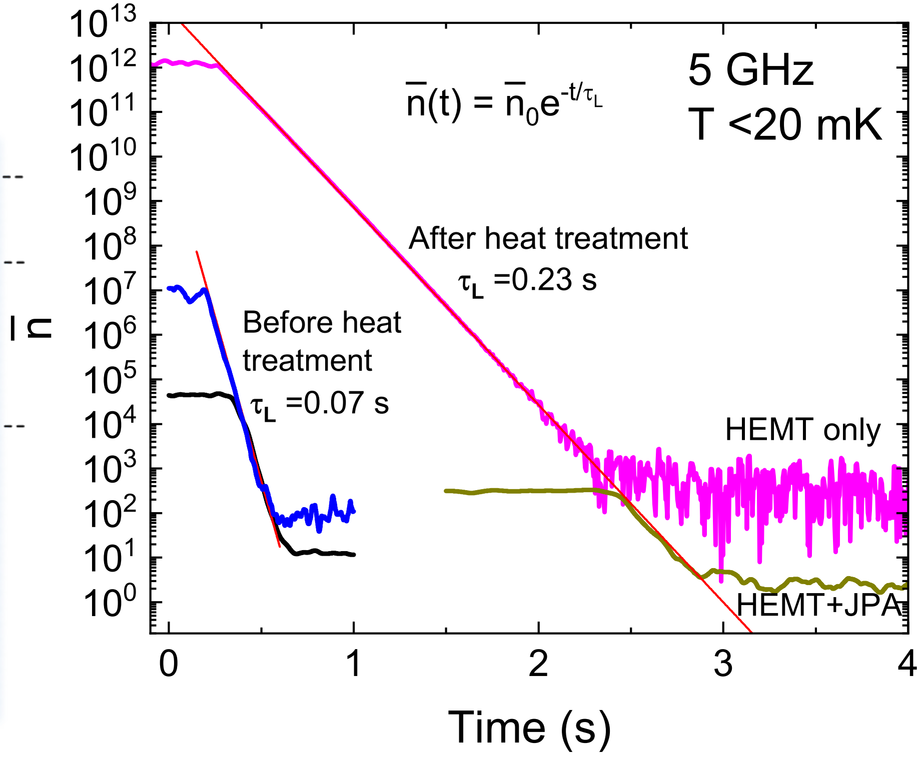
Alexander Romanenko

Further insight from measurements in quantum regime

- Exclusion of dark photons floating around in the galaxy at one specific frequency
- Could extend experiment by scanning





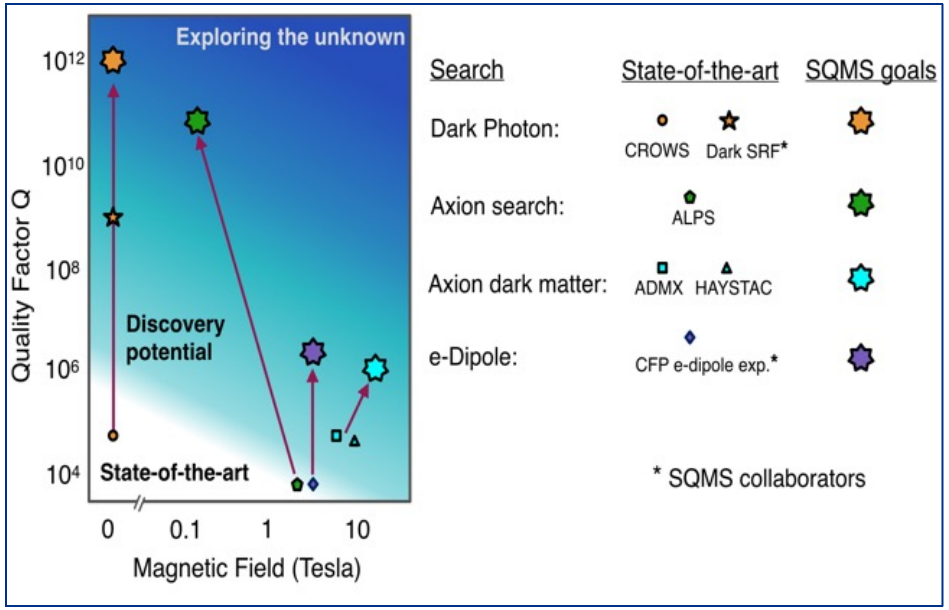


A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, and A. Grassellino
Phys. Rev. Applied **13**, 034032, 2020

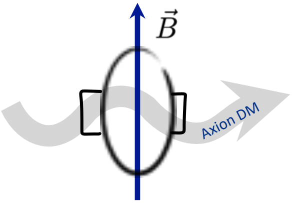
Alexander Romanenko

Science and Discovery with SQMS Technology - Sensing

- We are excited to use SQMS technology for direct exploration:
  - *Are there new long range forces?*
  - *What is the Dark Matter (DM)?*
  - *Can we probe single electrons more precisely?*



- High coherence also allows to pick up fainter signals, search for elusive particles.

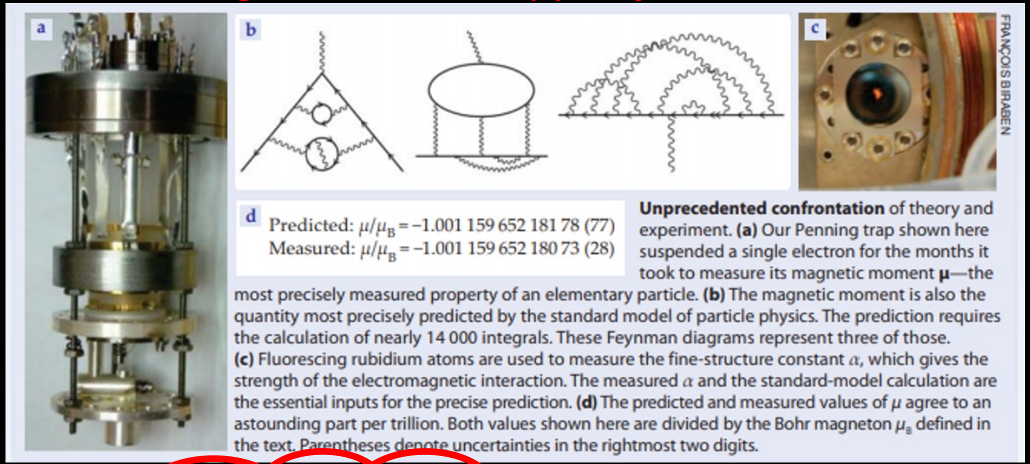


e.g. Axion DM Search -
High Q in high B field (FNAL+INFN)

Orders of magnitude in sensitivity to new physics!

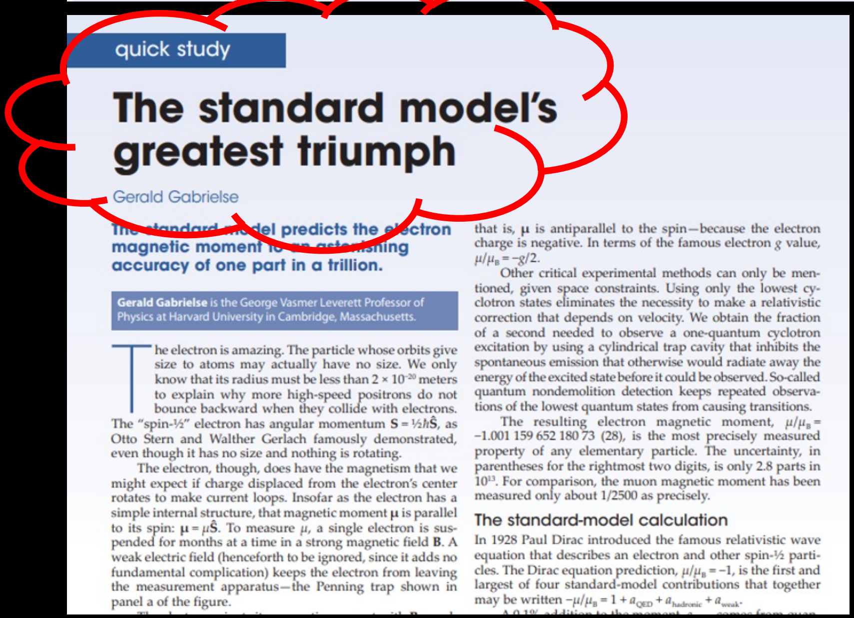
Moments

Single electron trapped for months



d Predicted: $\mu/\mu_B = -1.001\ 159\ 652\ 181\ 78\ (77)$
Measured: $\mu/\mu_B = -1.001\ 159\ 652\ 180\ 73\ (28)$

Unprecedented confrontation of theory and experiment. **(a)** Our Penning trap shown here suspended a single electron for the months it took to measure its magnetic moment **μ**—the most precisely measured property of an elementary particle. **(b)** The magnetic moment is also the quantity most precisely predicted by the standard model of particle physics. The prediction requires the calculation of nearly 14 000 integrals. These Feynman diagrams represent three of those. **(c)** Fluorescing rubidium atoms are used to measure the fine-structure constant α, which gives the strength of the electromagnetic interaction. The measured α and the standard-model calculation are the essential inputs for the precise prediction. **(d)** The predicted and measured values of μ agree to an astounding part per trillion. Both values shown here are divided by the Bohr magneton μ_B defined in the text. Parentheses denote uncertainties in the rightmost two digits.



quick study

The standard model's greatest triumph

Gerald Gabrielse

The standard model predicts the electron magnetic moment to an astonishing accuracy of one part in a trillion.

Gerald Gabrielse is the George Vasmer Leverett Professor of Physics at Harvard University in Cambridge, Massachusetts.

The electron is amazing. The particle whose orbits give size to atoms may actually have no size. We only know that its radius must be less than 2×10^{-20} meters to explain why more high-speed positrons do not bounce backward when they collide with electrons. The "spin-½" electron has angular momentum $\mathbf{S} = \frac{1}{2}\hbar\hat{\mathbf{S}}$, as Otto Stern and Walther Gerlach famously demonstrated, even though it has no size and nothing is rotating.

The electron, though, does have the magnetism that we might expect if charge displaced from the electron's center rotates to make current loops. Insofar as the electron has a simple internal structure, that magnetic moment $\boldsymbol{\mu}$ is parallel to its spin: $\boldsymbol{\mu} = \mu\hat{\mathbf{S}}$. To measure μ, a single electron is suspended for months at a time in a strong magnetic field $\mathbf{B}$. A weak electric field (henceforth to be ignored, since it adds no fundamental complication) keeps the electron from leaving the measurement apparatus—the Penning trap shown in panel a of the figure.

that is, $\boldsymbol{\mu}$ is antiparallel to the spin—because the electron charge is negative. In terms of the famous electron g value, $\mu/\mu_B = -g/2$.

Other critical experimental methods can only be mentioned, given space constraints. Using only the lowest cyclotron states eliminates the necessity to make a relativistic correction that depends on velocity. We obtain the fraction of a second needed to observe a one-quantum cyclotron excitation by using a cylindrical trap cavity that inhibits the spontaneous emission that otherwise would radiate away the energy of the excited state before it could be observed. So-called quantum nondemolition detection keeps repeated observations of the lowest quantum states from causing transitions.

The resulting electron magnetic moment, $\mu/\mu_B = -1.001\ 159\ 652\ 180\ 73\ (28)$, is the most precisely measured property of any elementary particle. The uncertainty, in parentheses for the rightmost two digits, is only 2.8 parts in 10^{13}. For comparison, the muon magnetic moment has been measured only about 1/2500 as precisely.

The standard-model calculation

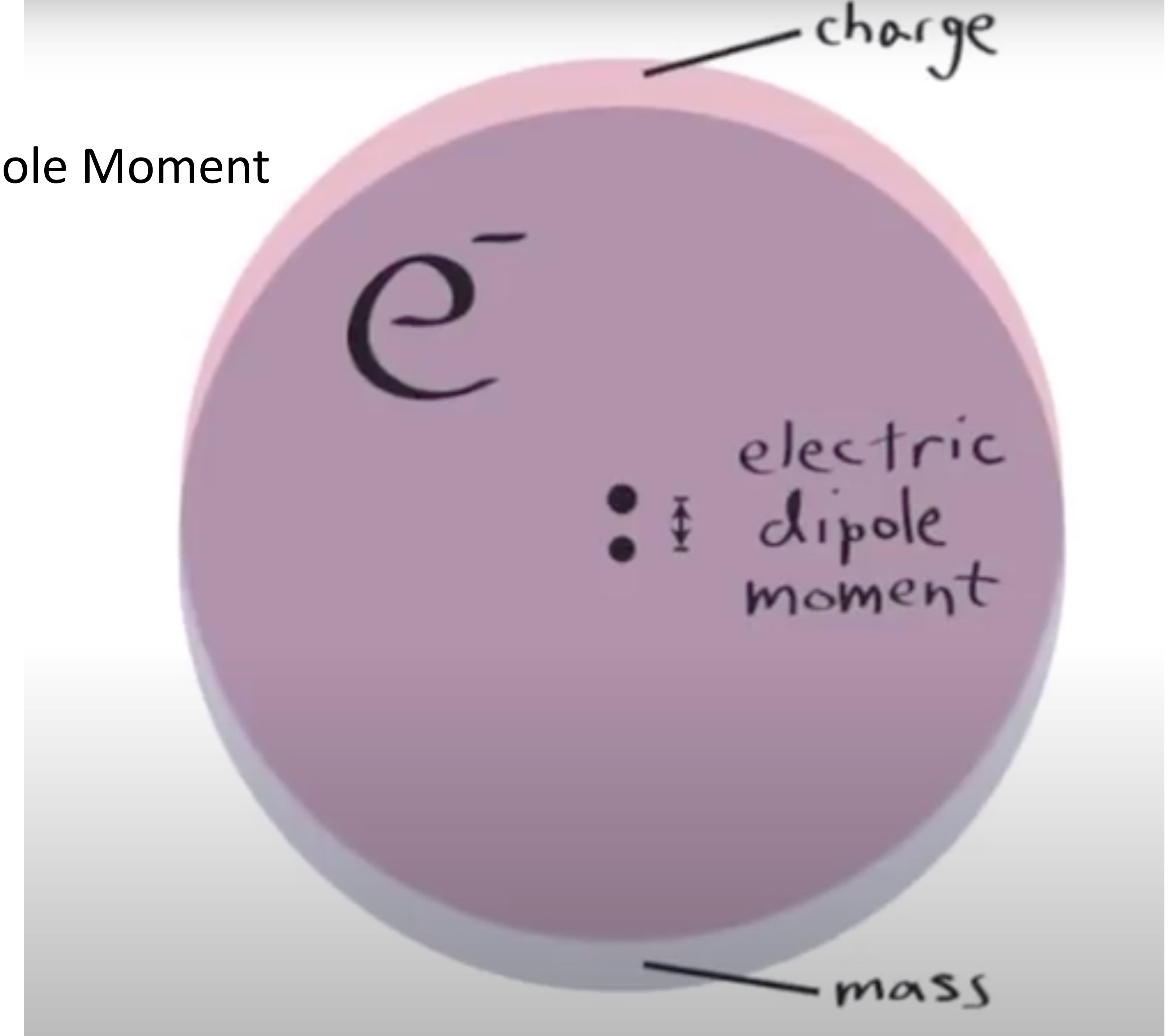
In 1928 Paul Dirac introduced the famous relativistic wave equation that describes an electron and other spin-½ particles. The Dirac equation prediction, $\mu/\mu_B = -1$, is the first and largest of four standard-model contributions that together may be written $-\mu/\mu_B = 1 + a_{\text{QED}} + a_{\text{hadronic}} + a_{\text{weak}}$.

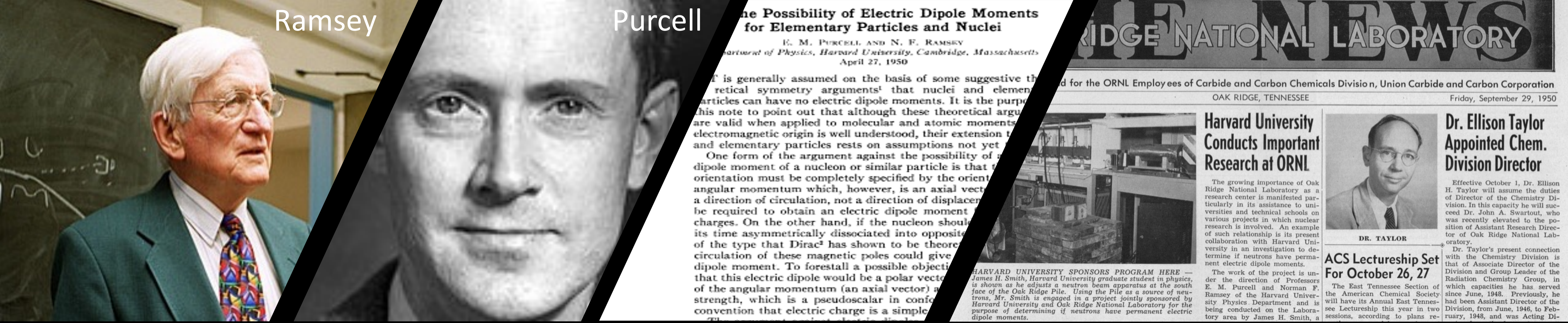
- Electric and Magnetic
  - Leptons

- Electron: "…magnetic moment is the most precisely calculated property of an elementary particle" (parts per trillion)
  - Gabrielse Physics Today 66(12), 64 (2013);
- Theory of the Anomalous Magnetic Moment of the Electron:
  - Kinoshita et al. see e.g. *Atoms* 7 (2019) 1, 28

Based on a slide by : Themis Bowcock

Electric Dipole Moment





he Possibility of Electric Dipole Moments
for Elementary Particles and Nuclei

E. M. Purcell and N. F. Ramsey
partment of Physics, Harvard University, Cambridge, Massachusetts
April 27, 1950

T is generally assumed on the basis of some suggestive th
retical symmetry arguments[1] that nuclei and elemen
articles can have no electric dipole moments. It is the purpo
his note to point out that although these theoretical argu
are valid when applied to molecular and atomic moments
electromagnetic origin is well understood, their extension t
and elementary particles rests on assumptions not yet
One form of the argument against the possibility of
dipole moment of a nucleon or similar particle is that t
orientation must be completely specified by the orient
angular momentum which, however, is an axial vect
a direction of circulation, not a direction of displacem
be required to obtain an electric dipole moment
charges. On the other hand, if the nucleon should
its time asymmetrically dissociated into opposite
of the type that Dirac[2] has shown to be theore
circulation of these magnetic poles could give
dipole moment. To forestall a possible objecti
that this electric dipole would be a polar vecto
of the angular momentum (an axial vector) a
strength, which is a pseudoscalar in conf
convention that electric charge is a simple

HE NEWS
RIDGE NATIONAL LABORATORY

d for the ORNL Employees of Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation

OAK RIDGE, TENNESSEE

Friday, September 29, 1950

HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.

Harvard University Conducts Important Research at ORNL

The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example of such relationship is its present collaboration with Harvard University in an investigation to determine if neutrons have permanent electric dipole moments.

The work of the project is under the direction of Professors E. M. Purcell and Norman F. Ramsey of the Harvard University Physics Department and is being conducted on the Laboratory area by James H. Smith, a

DR. TAYLOR

ACS Lectureship Set For October 26, 27

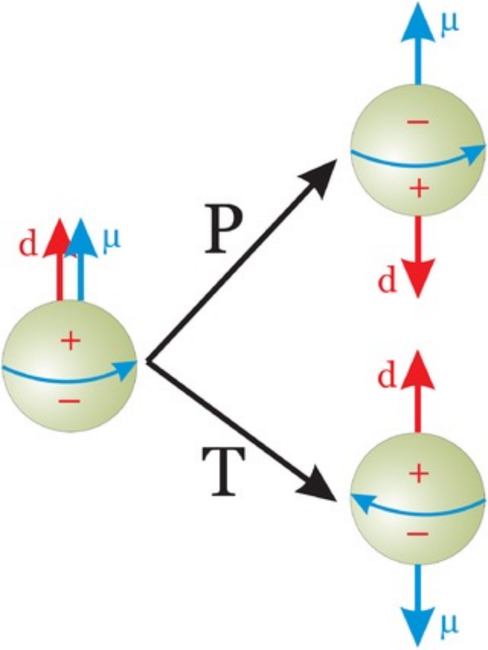
The East Tennessee Section of the American Chemical Society will have its Annual East Tennessee Lectureship this year in two sessions, according to plans re-

Dr. Ellison Taylor Appointed Chem. Division Director

Effective October 1, Dr. Ellison H. Taylor will assume the duties of Director of the Chemistry Division. In this capacity he will succeed Dr. John A. Swartout, who was recently elevated to the position of Assistant Research Director of Oak Ridge National Laboratory.

Dr. Taylor's present connection with the Chemistry Division is that of Associate Director of the Division and Group Leader of the Radiation Chemistry Group, in which capacities he has served since June, 1948. Previously, he had been Assistant Director of the Division, from June, 1946, to February, 1948, and was Acting Di-

Electric Dipole Moments



P changes sign of EDM but not spin

System under **P** or **T** is not symmetric with respect to the initial system

T reversal changes spin but not EDM

EDM of non-composite particle aligned with spin

Having CPT symmetry, the combined symmetry

CP is violated

SM value for electron/muon CP/EDM v. small

EDMs arising from the CKM-matrix vanish up to three loops for the electron (Bernreuther and Suzuki, 1991)

Baryon Asymmetry of the Universe needs more than CKM

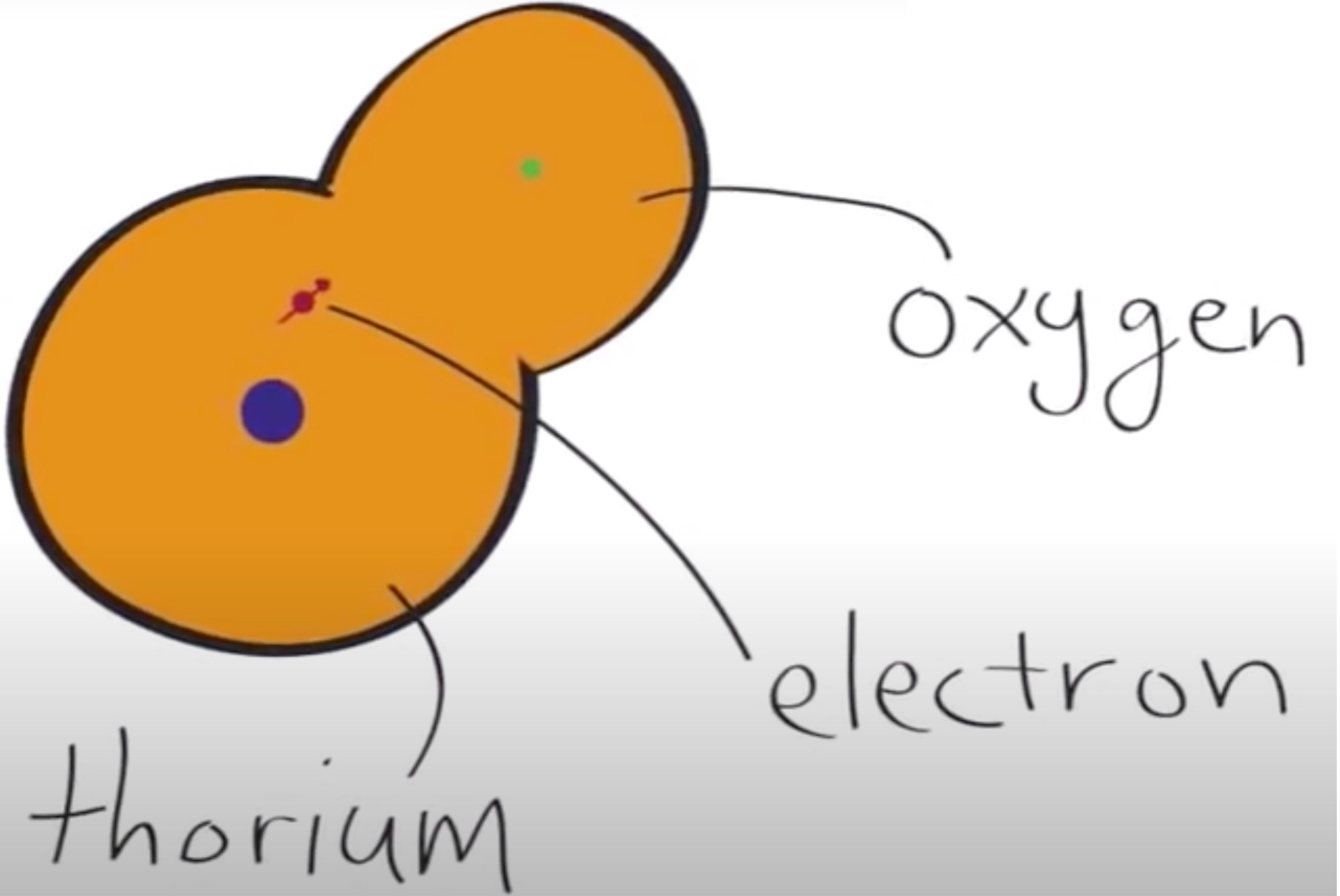
Slide credit: Themis Bowcock

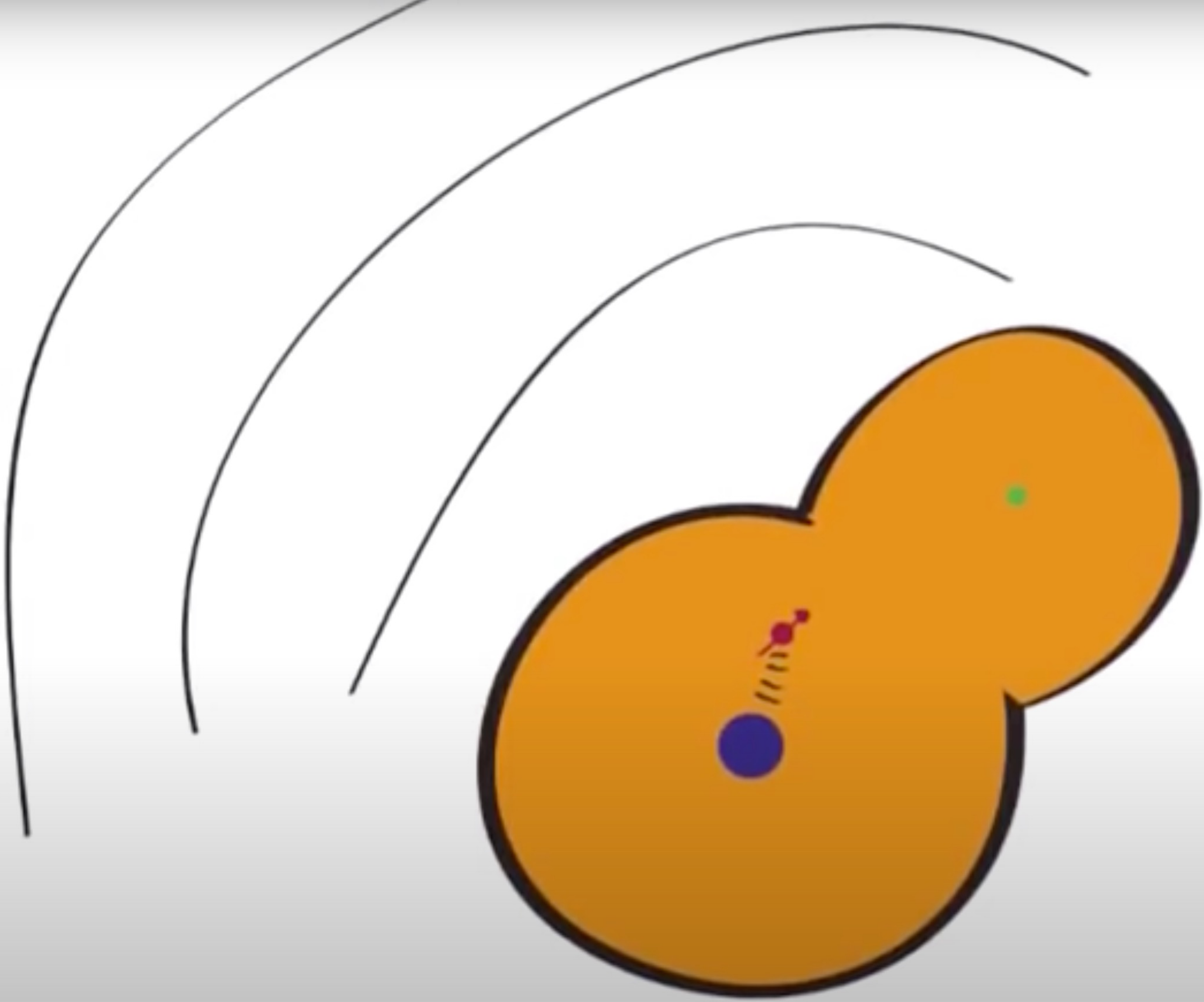
solar system

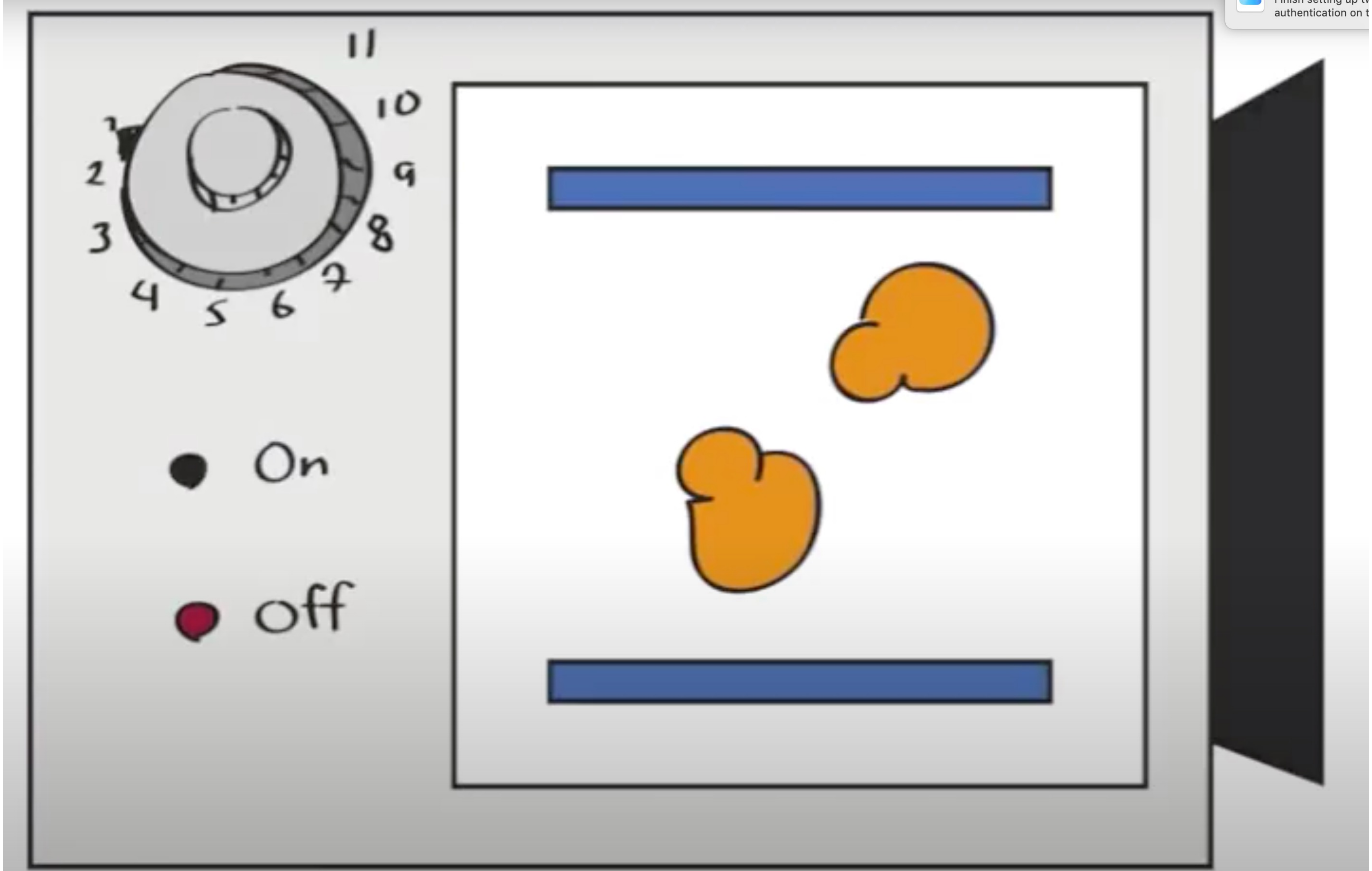
(electron)

1/10 needle

(electric dipole moment)


oxygen
electron
thorium

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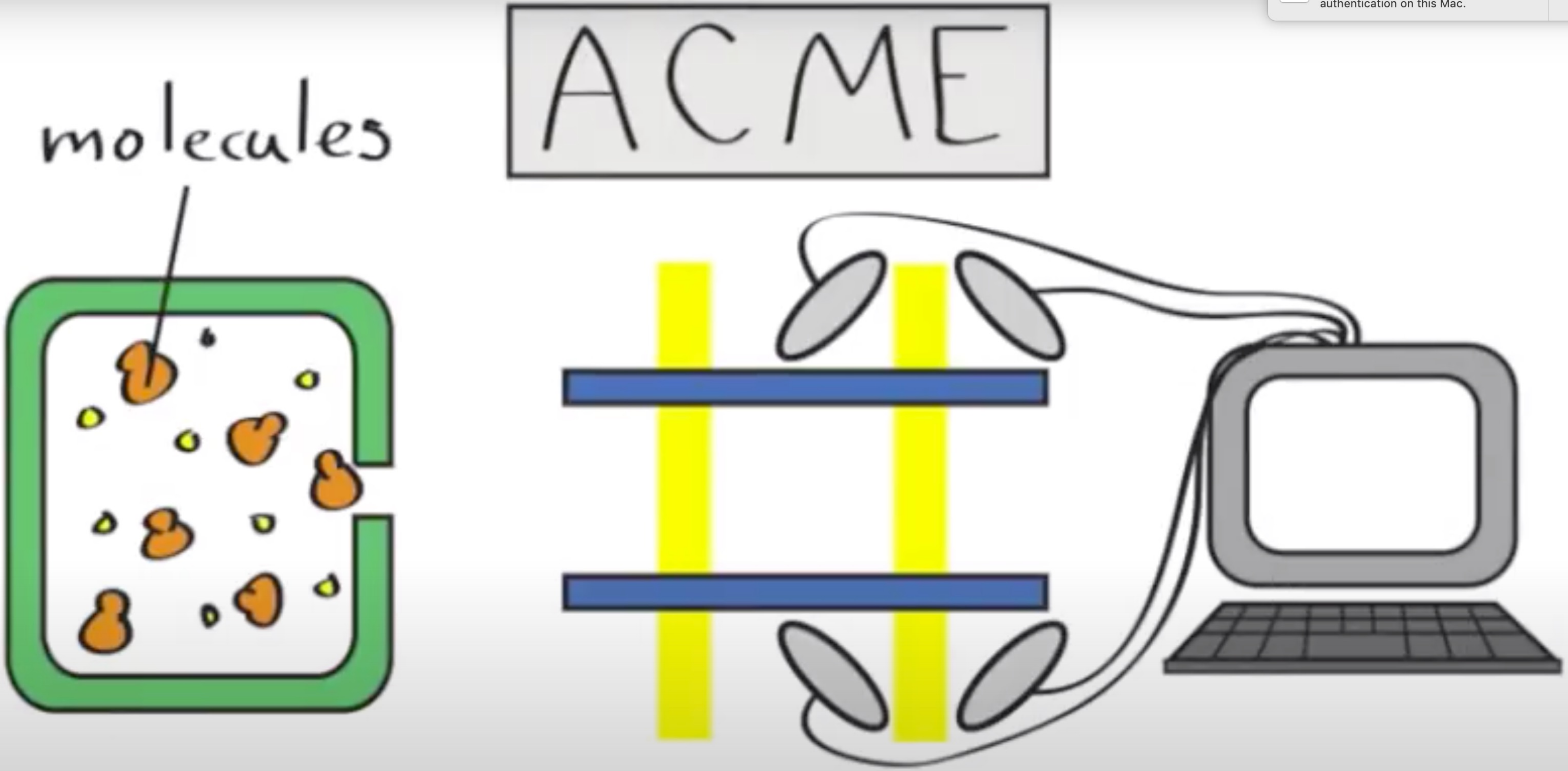

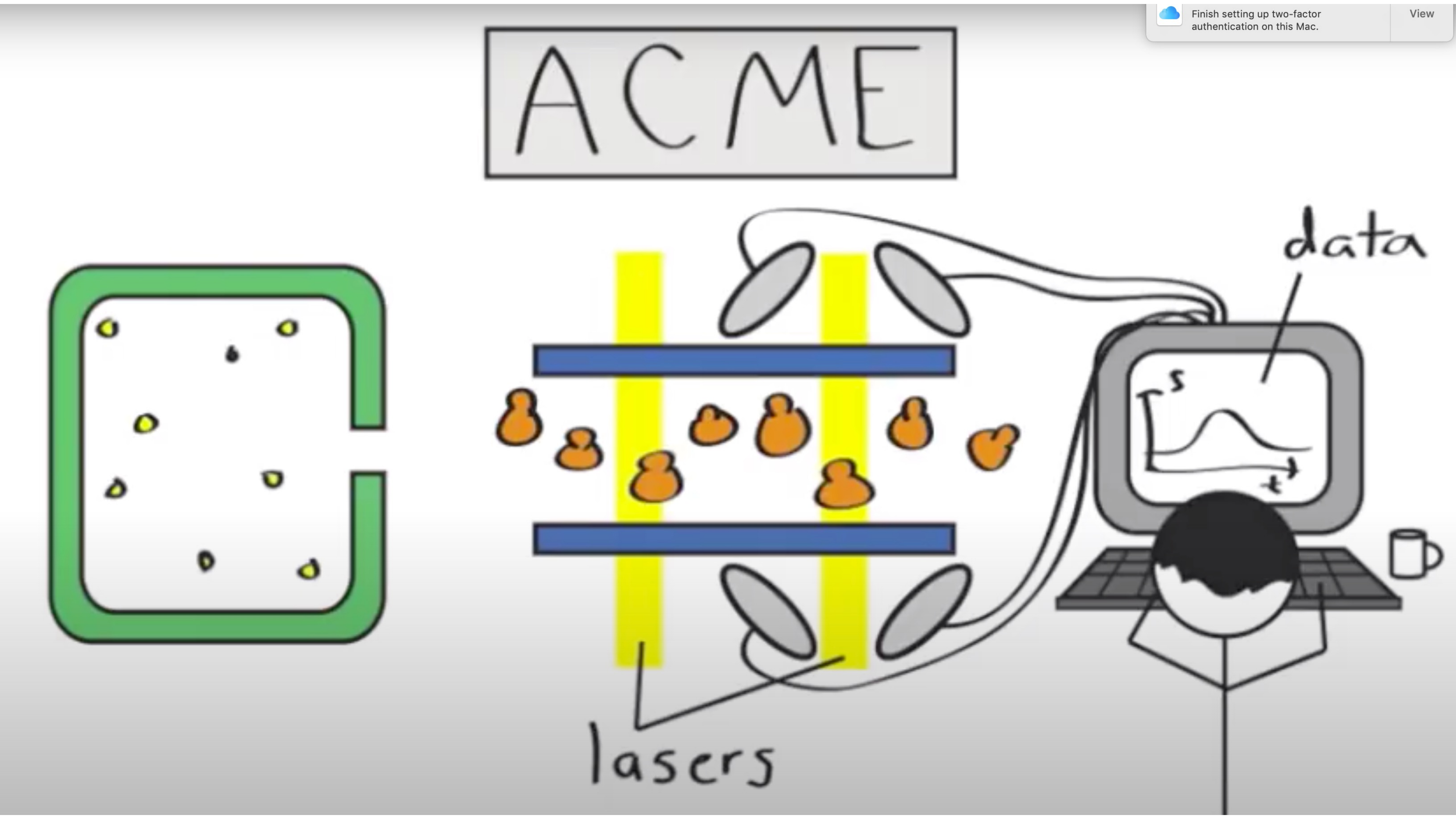
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ACME
data
s
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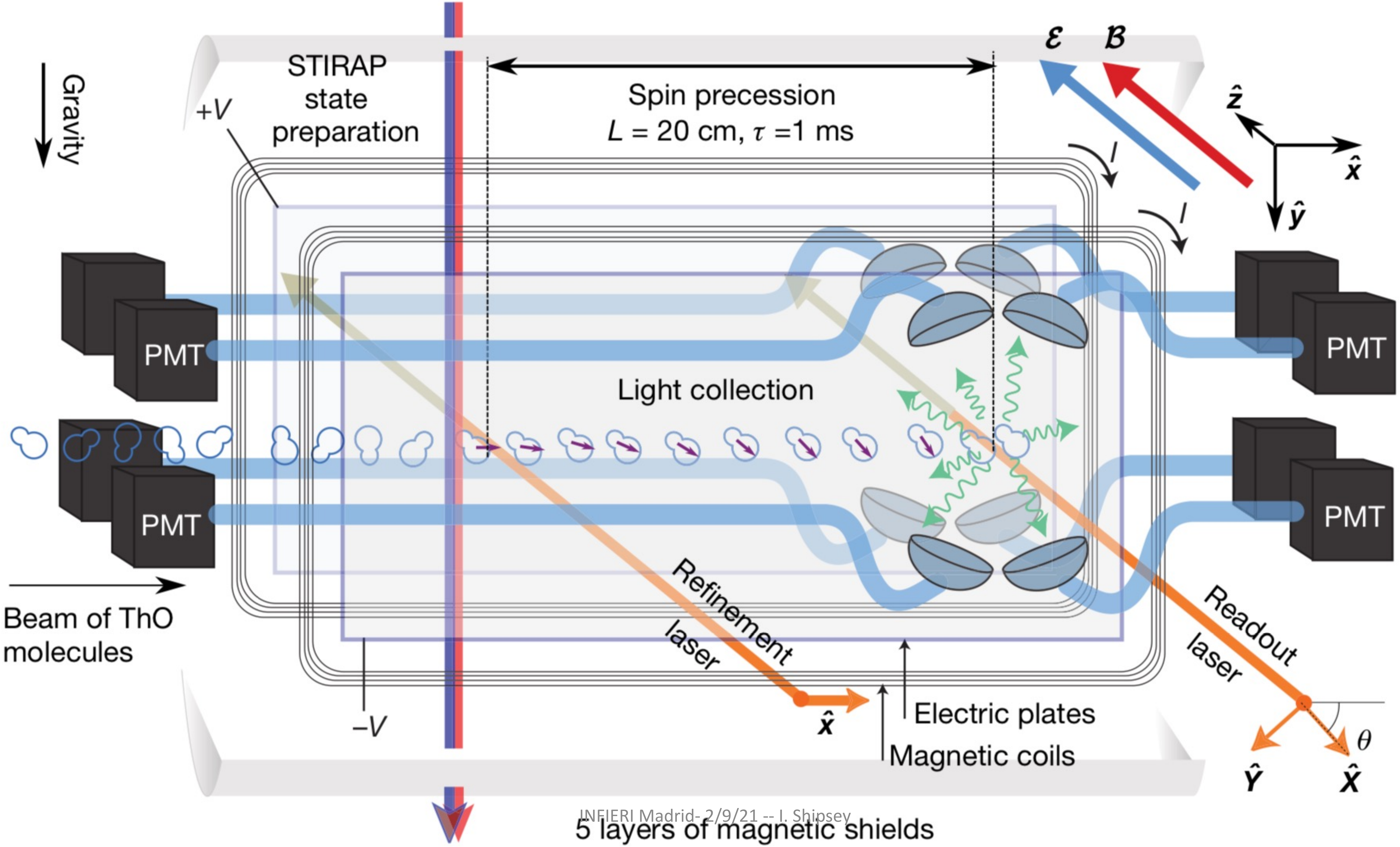

Gravity
+V
STIRAP
state
preparation
Spin precession
$L = 20$ cm, $\tau = 1$ ms
$\mathcal{E}$
$\mathcal{B}$
$\hat{z}$
$\hat{x}$
$\hat{y}$
I
I
PMT
PMT
PMT
PMT
Light collection
Beam of ThO
molecules
Refinement
laser
$\hat{x}$
Readout
laser
$\hat{Y}$
$\hat{X}$
θ
Electric plates
Magnetic coils
−V
5 layers of magnetic shields

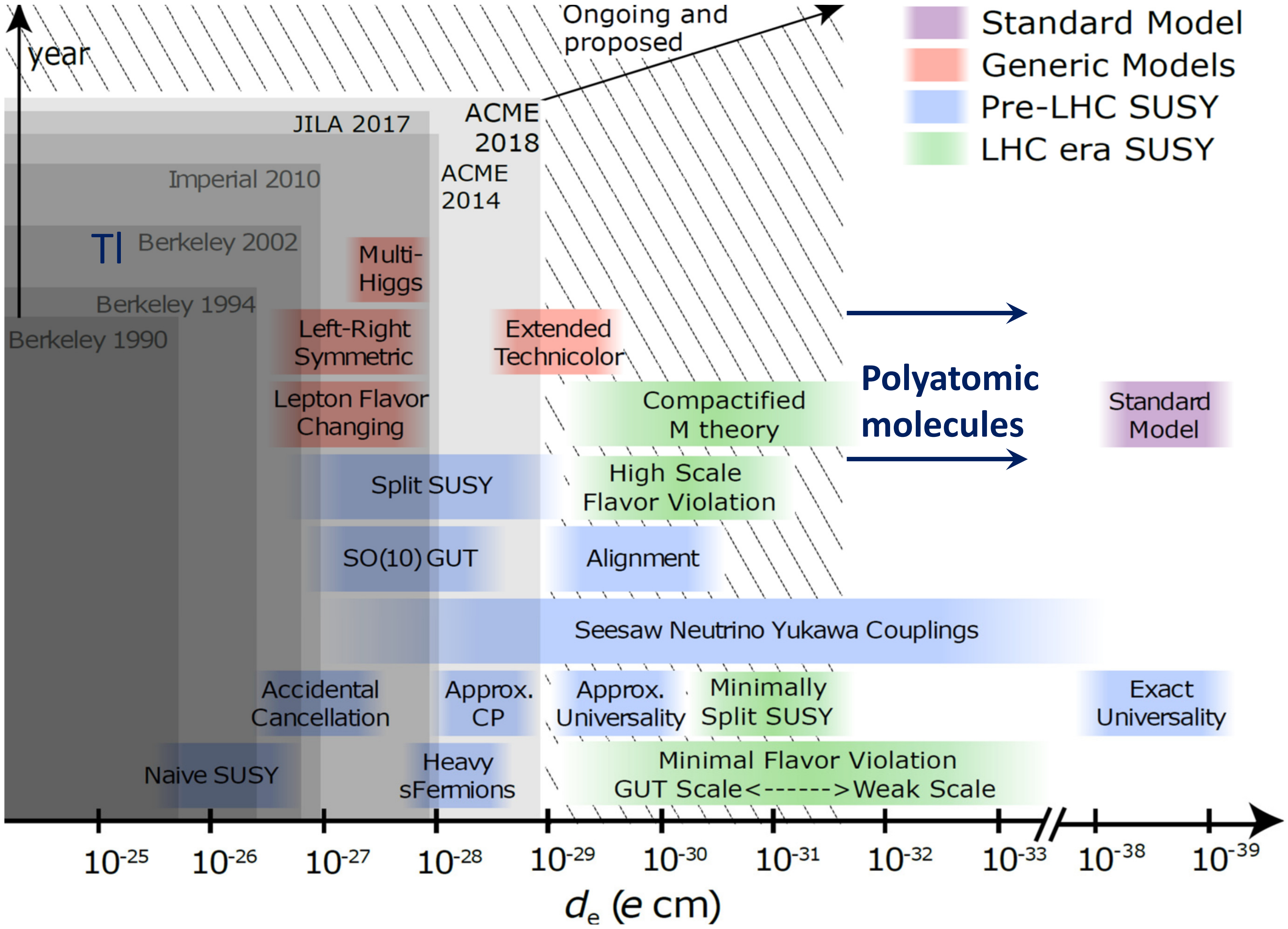


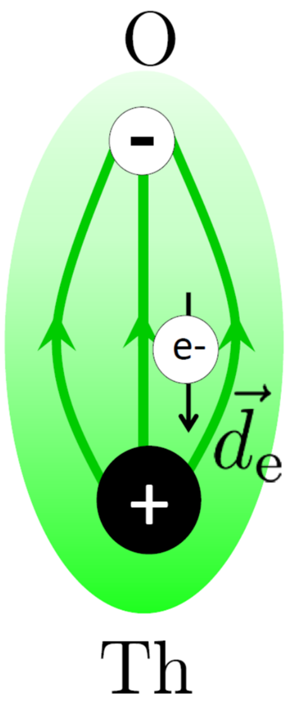
Figure is from 2020 USA AMO Decadal survey (Credit: Dave DeMille)

https://www.nationalacademies.org/amo

Searches for electron EDM with molecules

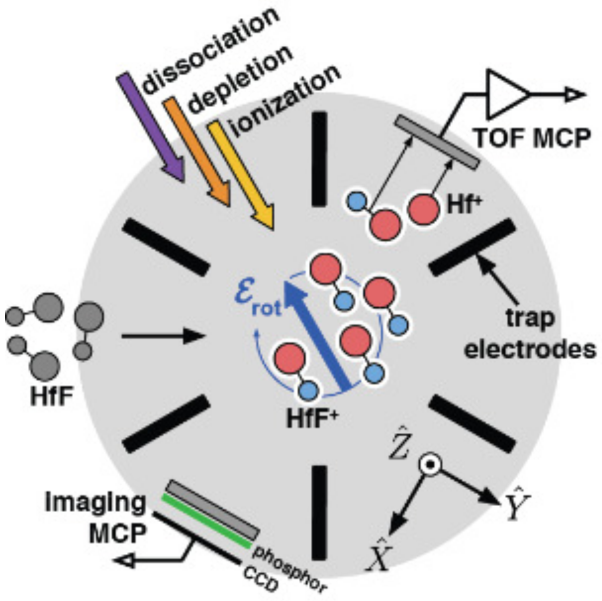
Present status: experiments with reported results

Advanced
ACME



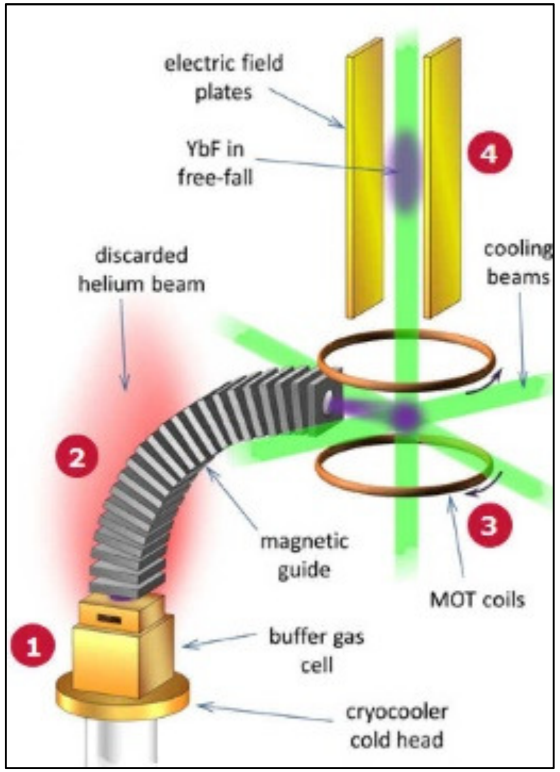
ThO

JILA eEDM



HfF$^+$, (now also ThF$^+$)

Imperial College

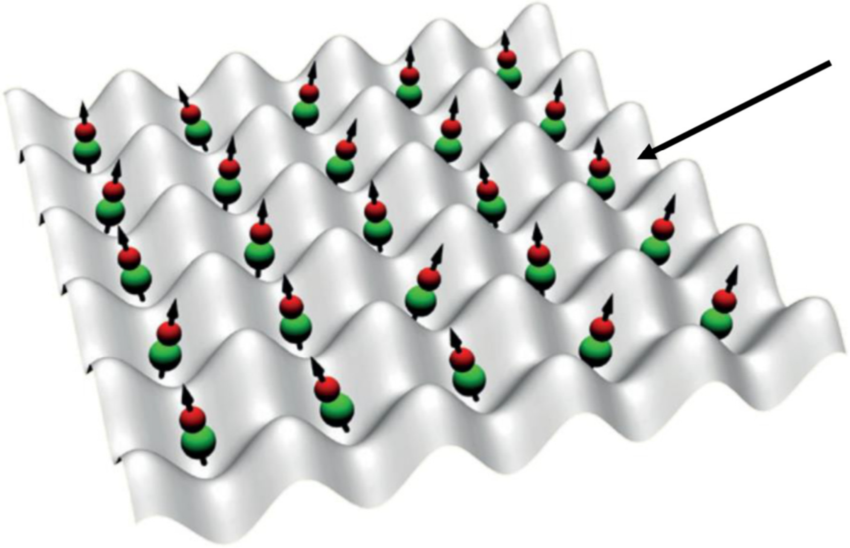


YbF

Expected an order or magnitude improvement in ~5 years

Slide credit: Marianna Safronova

Electron EDM experiments: (1) laser-cooled molecules



Heavy, polar molecule sensitive to new physics

Need to trap at ultracold temperatures

Laser slowed, cooled, and trapped in 3D: SrF, CaF, and YO
Laser-cooled, but not yet trapped: YbF, BaH, SrOH, CaOH, YbOH, and $CaOCH_3$

- 10^6 molecules
- 10 s coherence
- Large enhancement(s)
- Robust error rejection
- 1 week averaging

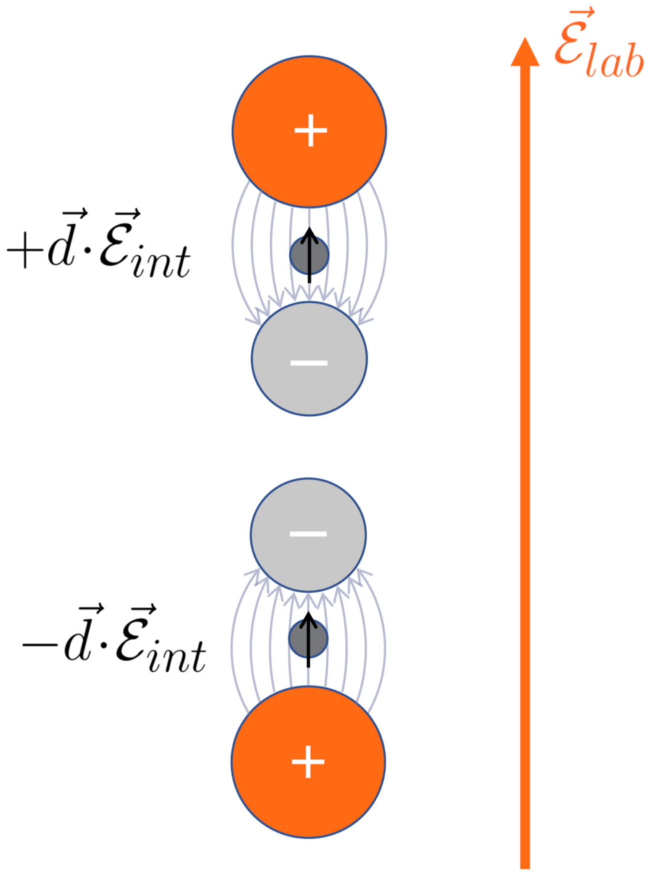
$M_{\text{new phys}} \sim$ 1,000 TeV

Even before implementing advanced quantum control, such as entanglement-based squeezing

Slide from: Nick Hutzler

Slide credit: Marianna Safronova

Electron EDM experiments: (2) internal co-magnetometer



Need "internal co-magnetometer" states

No need to reverse electric field

ACME and JILA eEDM
ThO HfF$^+$

You can not laser cool any diatomic molecule with co-magnetometer states!

Numerous internal states give rise to many leakage channels out of a cycling transition.

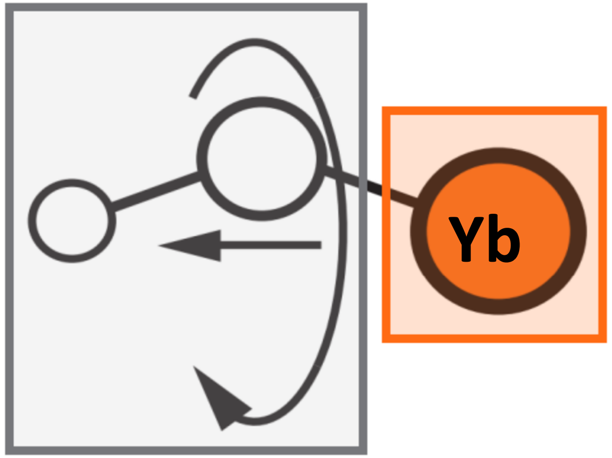
Note: there are other cooling methods besides laser cooling (sympathetic, evaporative, or optoelectrical) and trapped molecular ions enable very sensitive measurements without the need for laser cooling.

Picture from: Nick Hutzler

eEDM experiments with polyatomic laser-cooled

Caltech
Harvard

YbOH



New physics
Laser cooling

Polarization, Co-magnetometers

Proposal: Ivan Kozyryev and N. R. Hutzler, Phys. Rev. Lett. **119**, 133002 (2017)
Review: N. R. Hutzler, *Quantum Sci. Technol.* **5** 044011 (2020)

5 years: An electron EDM result with trapped ultracold YbOH, initial goal 10^{-31} e cm

8 years: Improvements in coherence time and number trapped molecules: 10^{-32} e cm

12 years: Very large numbers of trapped molecules or many operating in parallel, 10^{-33} e cm

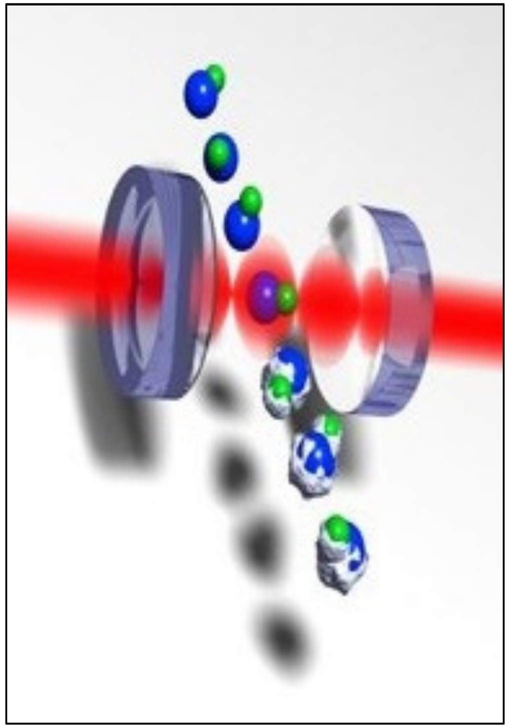
Further improvement with squeezing?

Picture & timeline from: Nick Hutzler

Hadronic T-violation searches with molecules

CP-violation in the nucleus: manifest as a nuclear Schiff moment (NSM) or nuclear magnetic quadrupole moment (MQM). Arises from nucleon EDMs, new CP-violating nuclear forces, strong force CP-violation (θ).

CeNTREX: see arXiv:2010.01451



TlF (proton EDM)

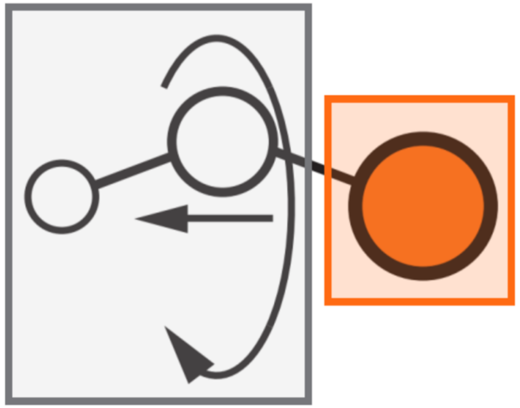
The observable signature of a Schiff moment will be a shift in the NMR frequency of ^{205}Tl nuclei when the molecules are polarized by a strong electric field.

First generation: a cryogenic molecular beam of TlF

Second generation: laser cool and trap the TlF molecules for increased sensitivity.

YbOH nuclear MQM

Theory: J. Chem. Phys. 152, 084303 (2020)

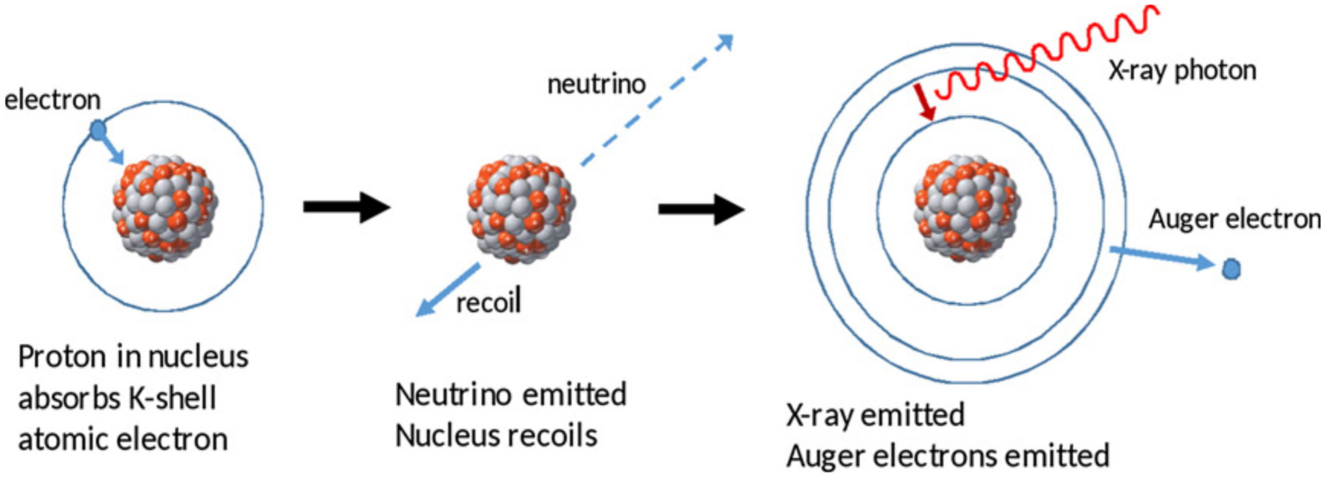


3 years:
beam-based measurements

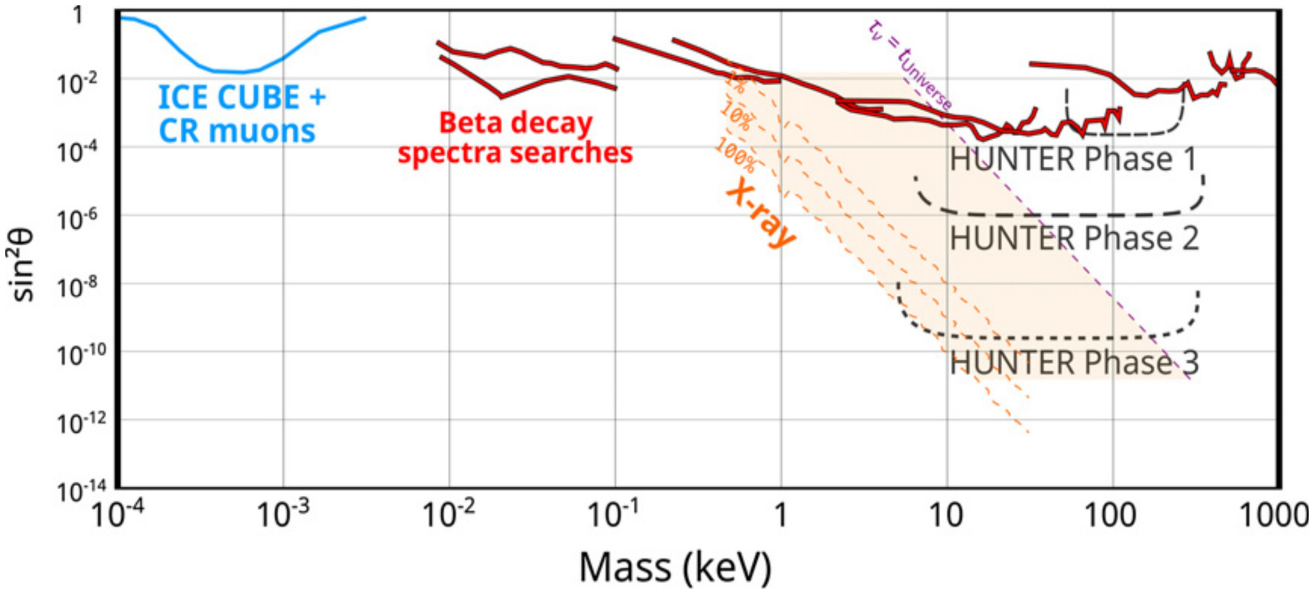
Slide credit: Marianna Safronova

HUNTER: precision massive-neutrino search based on a laser cooled atomic source

$$^{131}\mathrm{Cs} \rightarrow {}^{131}\mathrm{Xe}^* + \nu_e$$



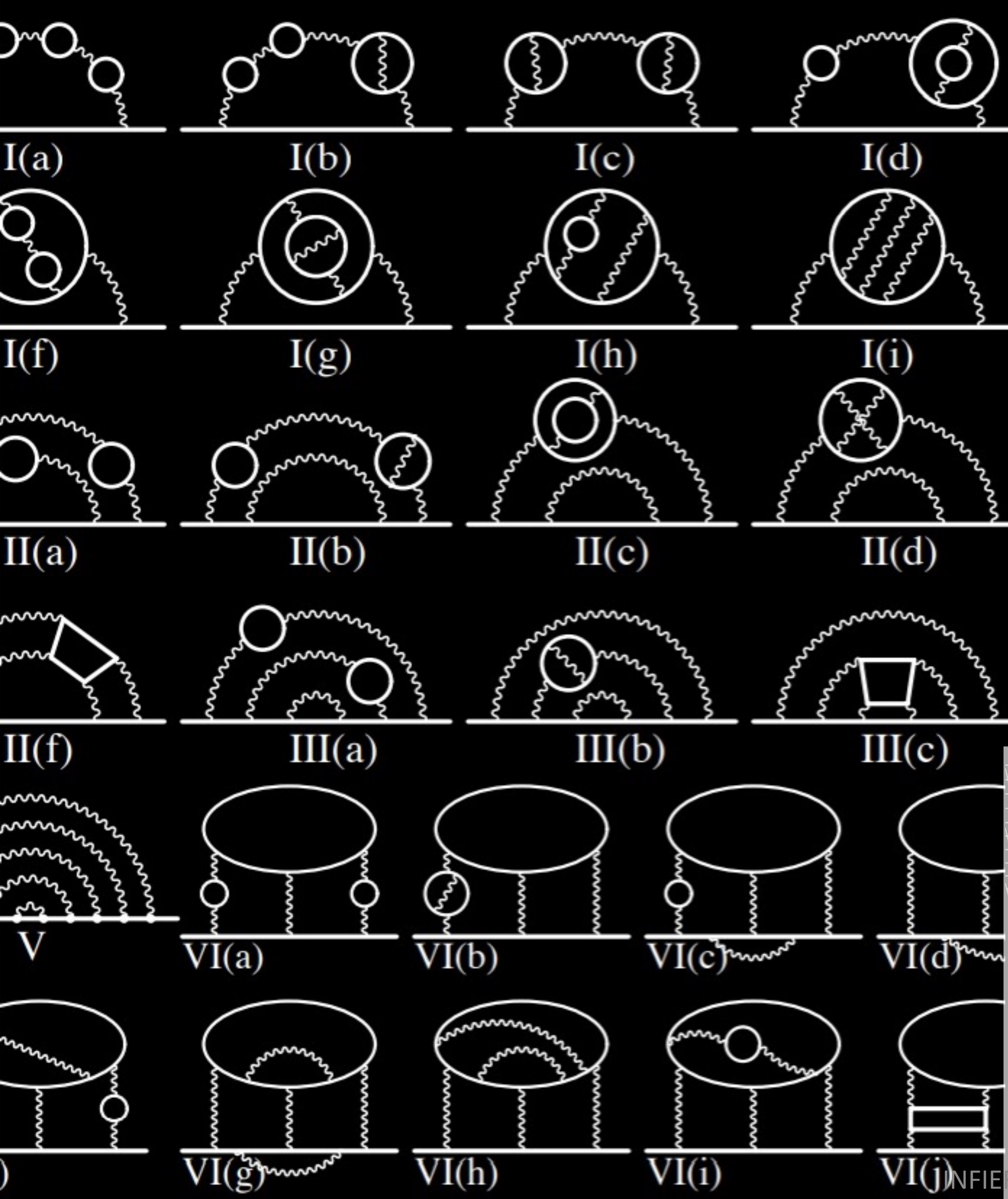
Cs atoms are trapped in a MOT. Complete kinematical reconstruction is possible, allowing the neutrino mass to be determined event-by-event.



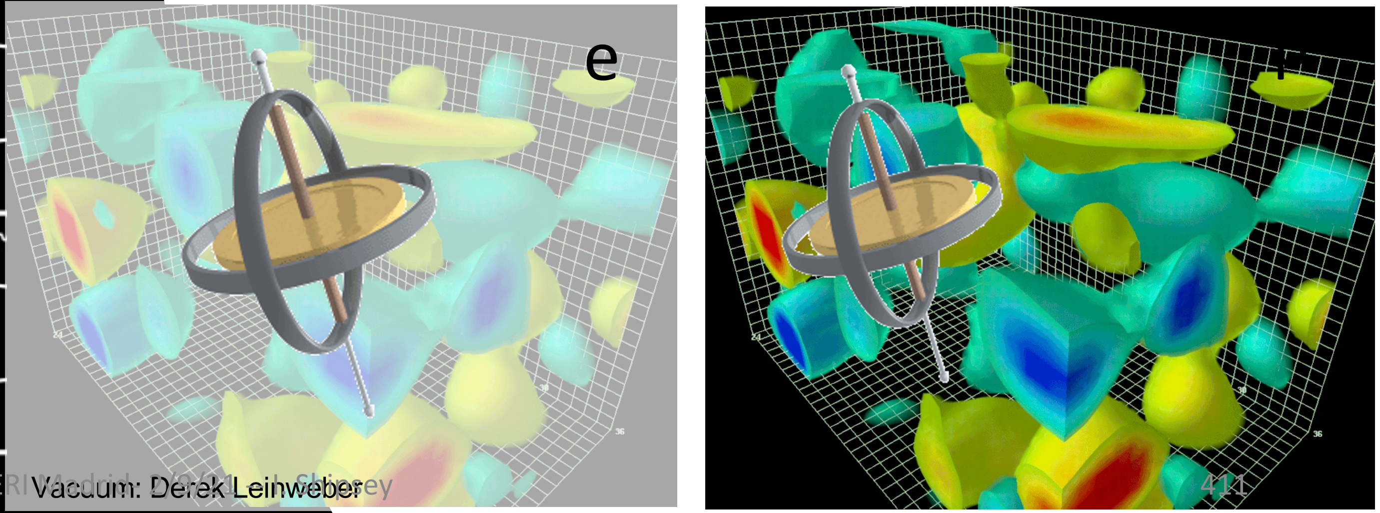
Limits on sterile neutrino coupling strength vs mass. Dashed lines (orange) show astrophysical limits permitting sterile neutrinos to be the galactic dark matter

From: C. J. Martoff *et al., Quantum Sci. Technol.* **6** 024008 (2021)

Confronting Magnetic Moments of Muon



- g-2 results
  - n.b. lattice “BMW” argument
  - Anomaly persists (dispersive calculation of HVP)
- This is of interest because the (heavier) muon is more sensitive to the vacuum
  - Larmor precession in field
  - Possible explanations: … Z’, ALPs, LQ etc.



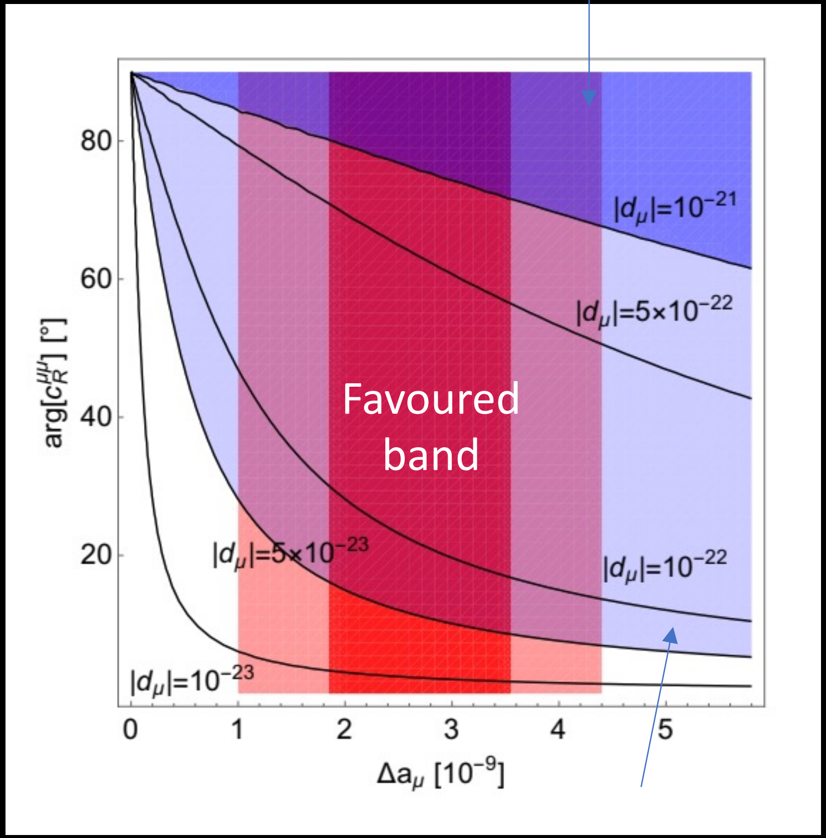
Vacuum: Derek Leinweber

Based on a slide by : Themis Bowcock

It will be important to measure Muon EDM

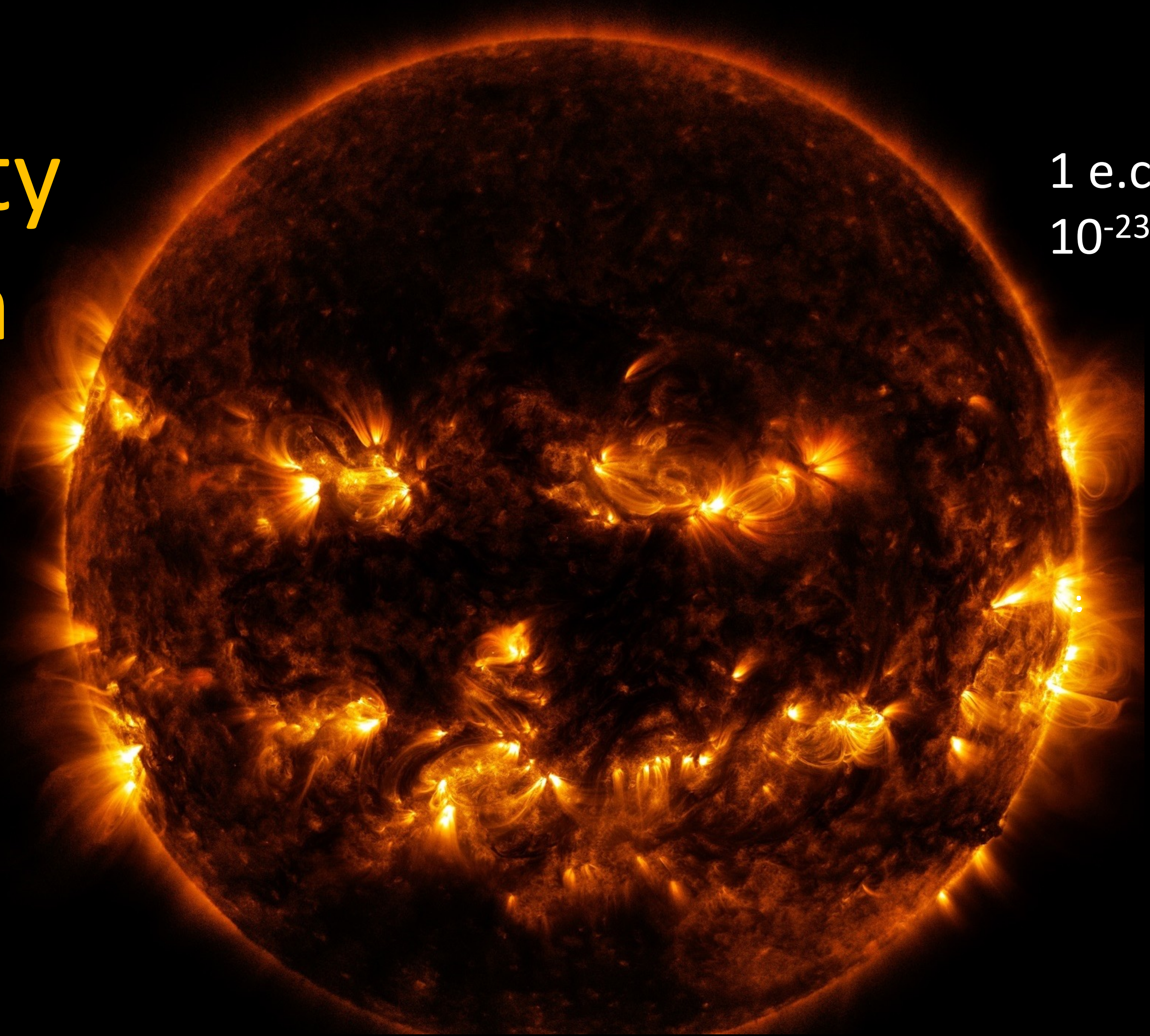
- muEDM Proposal (2021, PSI)
  - In past eEDM scaled to muEDM by ratio of masses (squared). Only results less than 10^{-27} ecm thought "useful". (LFU, MFV etc.)
  - New results from LHCb, g-2, and lack of naturalness challenges these assumptions
  - *"While some of the parameter space for d_μ favored by a_μ could be tested at the $(g-2)_\mu$ experiments at Fermilab and J-PARC, a dedicated muon EDM experiment at PSI would be able to probe most of this region" (Crivellin, Hoferichter* arXiv:1905.03789

g-2, FNAL



MuEDM, PSI

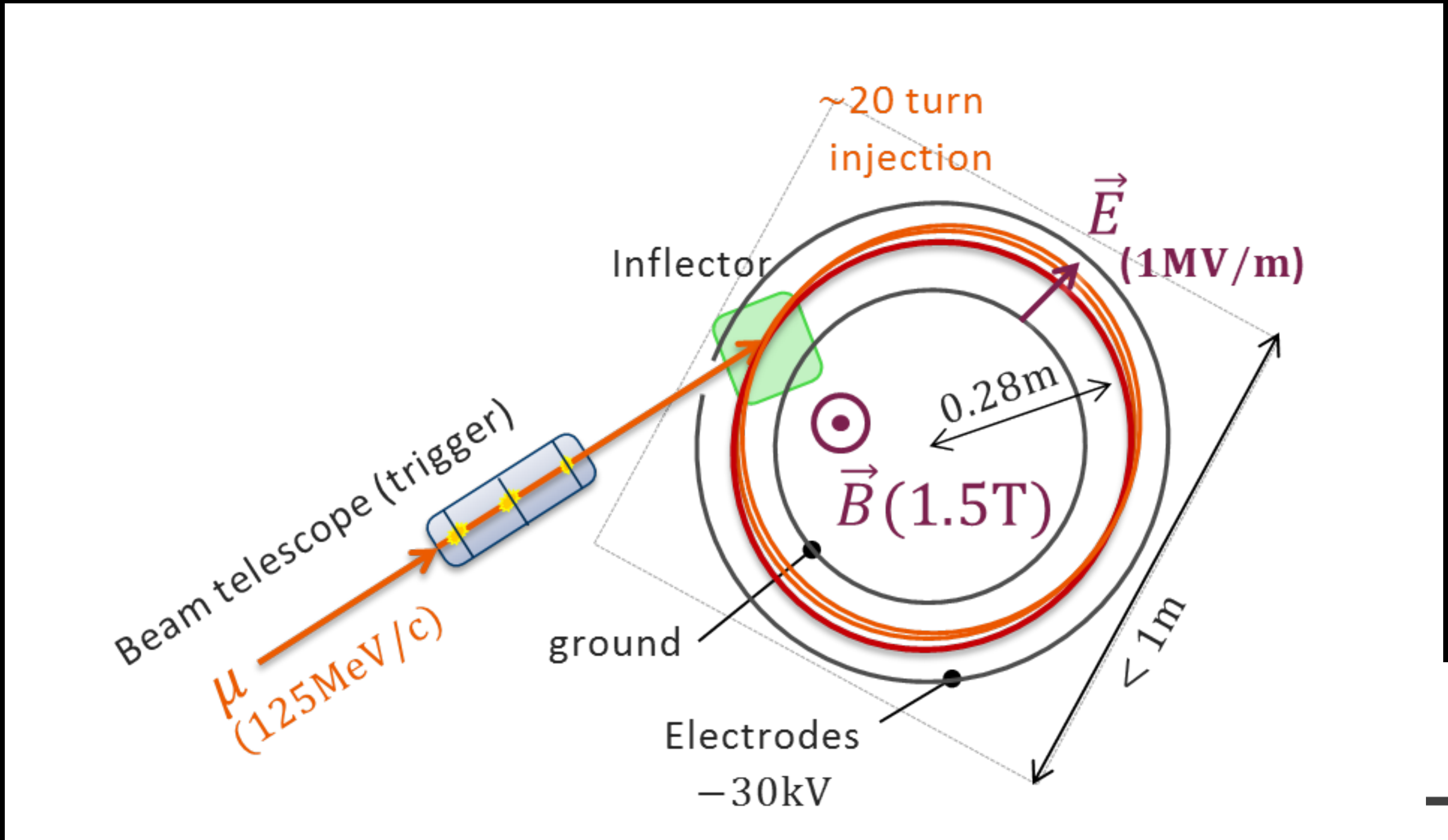
Extreme
Sensitivity
Precision

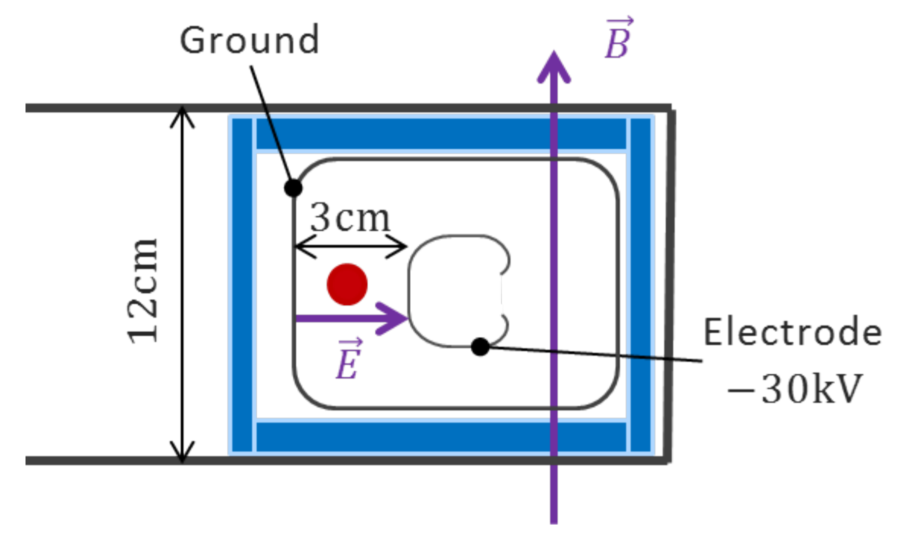


1 e.cm $\propto$ Sun Radius

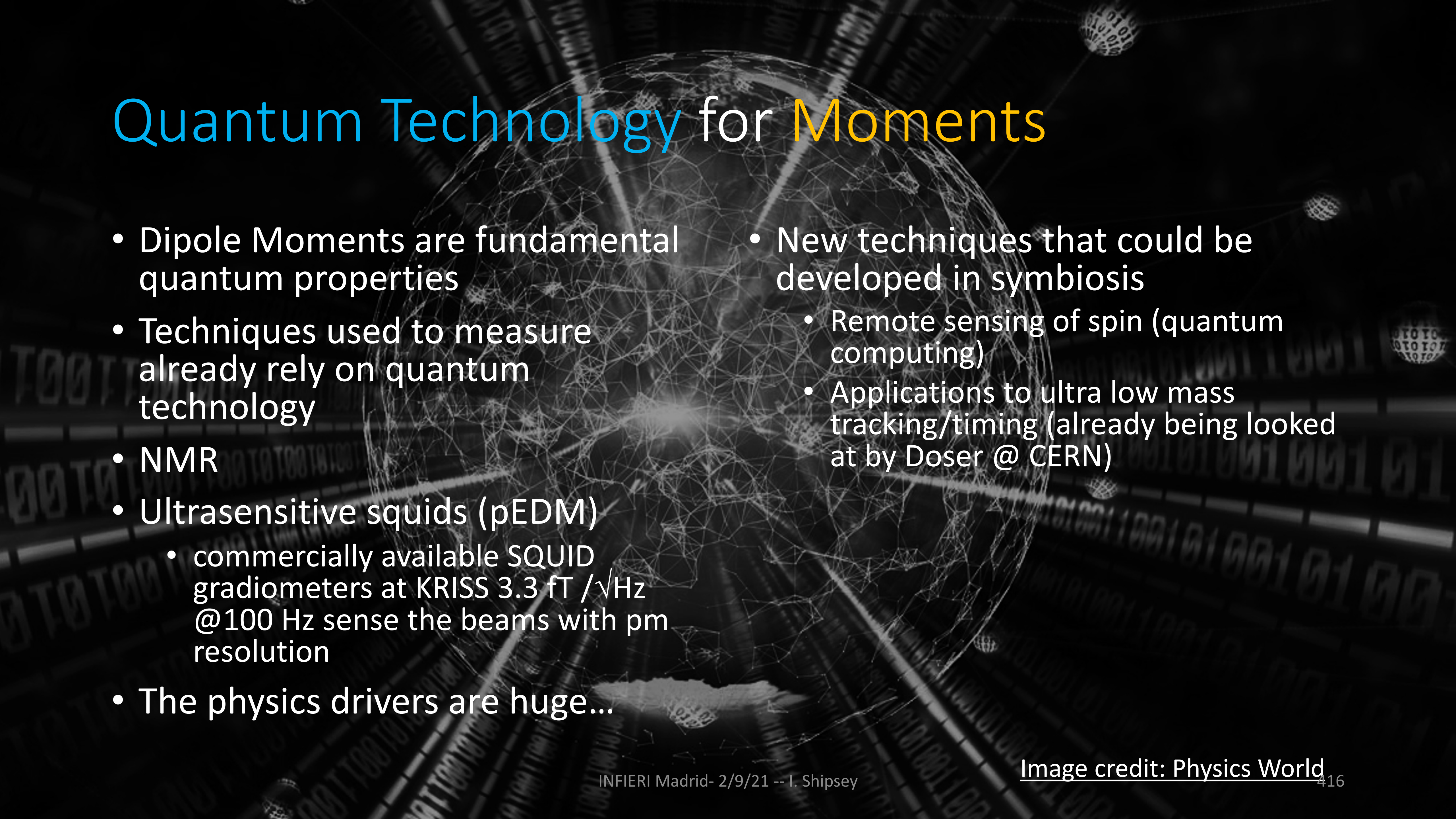
10^{-23} e.cm $\propto$ 1000 fm

muEDM Proposal (2021, PSI)





$$\sigma(d_\mu) = \frac{\hbar\gamma a}{2\tau E\bar{\alpha}P\sqrt{N}}$$



Quantum Technology for Moments

- Dipole Moments are fundamental quantum properties
- Techniques used to measure already rely on quantum technology
- NMR
- Ultrasensitive squids (pEDM)
  - commercially available SQUID gradiometers at KRISS 3.3 fT /√Hz @100 Hz sense the beams with pm resolution
- The physics drivers are huge…

- New techniques that could be developed in symbiosis
  - Remote sensing of spin (quantum computing)
  - Applications to ultra low mass tracking/timing (already being looked at by Doser @ CERN)

Image credit: Physics World

UK Research
and Innovation

QT
FP

Quantum Technologies for Fundamental Physics

A new UK Programme £40M/4 years

7 projects

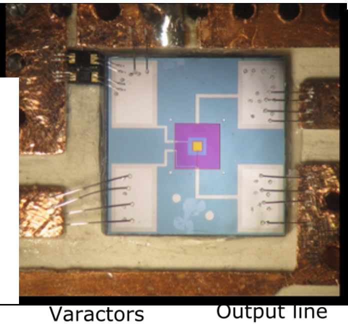
Quantum Sensors for the Hidden Sector

Sheffield, Cambridge, Oxford, RHUL, Lancaster, UCL, NPL, Liverpool

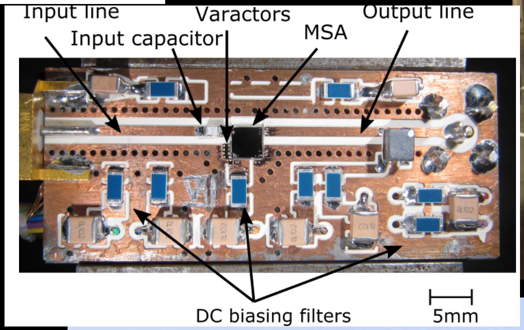
- A search for axions/ALPs using resonant conversion to microwave photons in high magnetic fields
- Initial focus on QCD axion, mass range 25-40μeV
- Collaboration with U.S. Axion Dark Matter eXperiment group, who operate the worlds most sensitive axion search, ADMX.
- **Ambition to build a UK high field (8T) low temperature (10mK) facility at Daresbury.**

See Ed Daw
talk at UK HEP Forum

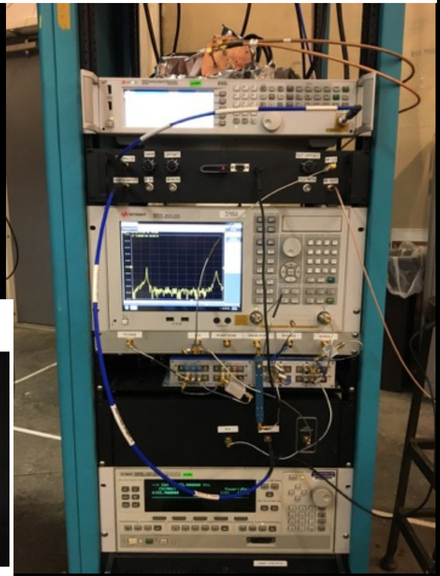
ADMX SQUID washer



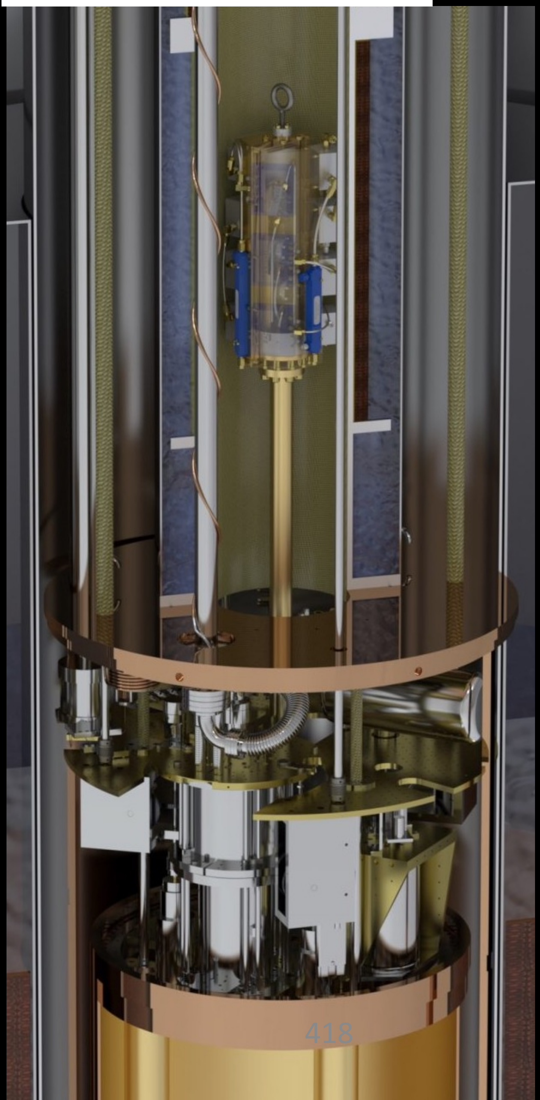
ADMX Microwave SQUID amplifier



Resonant feedback test



ADMX SQUID housing

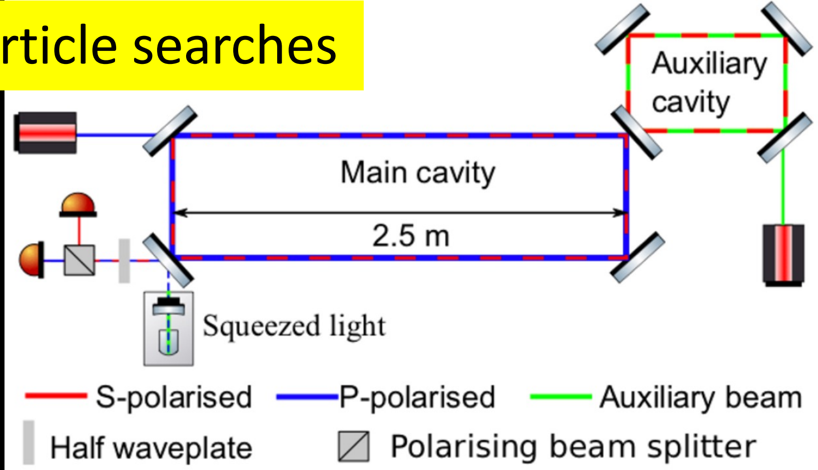


Daresbury Lab

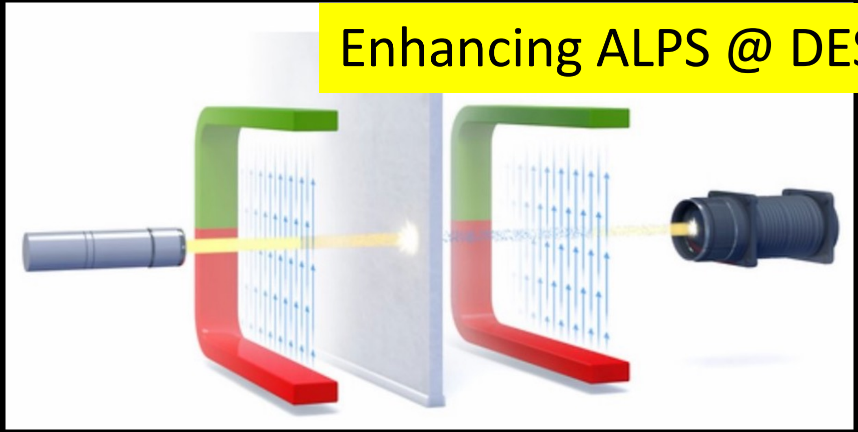
Quantum-enhanced Interferometry

Vincent Boyer (Birmingham), Animesh Datta (Warwick), Katherine Dooley (Cardiff),
Hartmut Grote (Cardiff, PI), Robert Hadfield (Glasgow), Denis Martynov (Birmingham, Deputy PI)
Haixing Miao (Birmingham), Stuart Reid (Strathclyde)

Axion-like particle searches



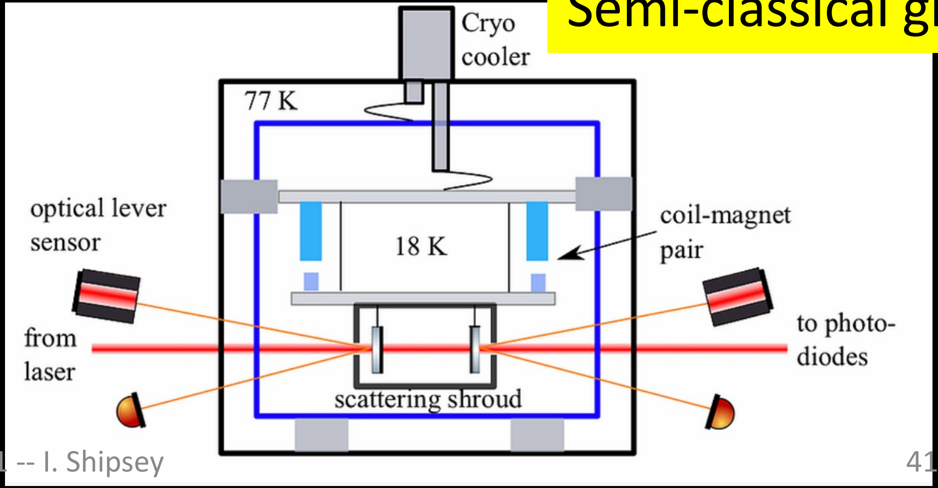
Enhancing ALPS @ DESY



Quantization of space time

See Hartmut Grote talk at UK HEP Forum

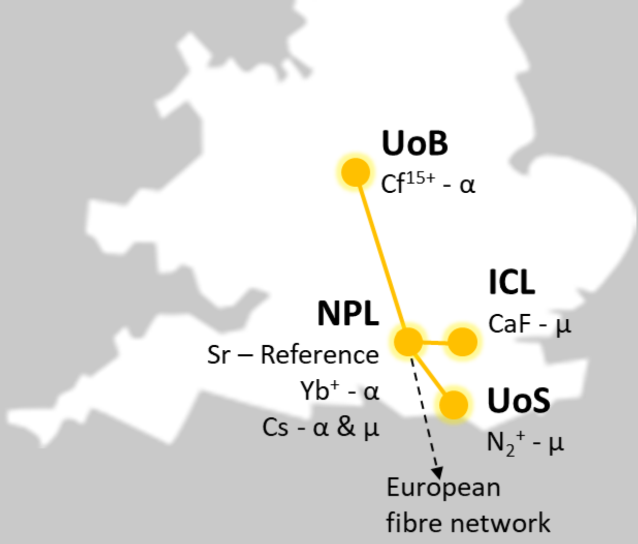
Semi-classical gravity



A network of clocks for measuring the stability of fundamental constants

G. Barontini, V. Boyer, X. Calmet, M. Chung, N. Fitch, R. Godun, J. Goldwin,
V. Guarrera, I. Hill, M. Keller, J. Kronjaeger, H. Margolis, C. Mow-Lowry, P. Newman,
L. Prokhorov, B. Sauer, M. Schioppo, M. Tarbutt, A. Vecchio, S. Worm

The aim of the consortium is to build a community that will achieve unprecedented sensitivity in testing variations of the fine structure constant, $\boldsymbol{\alpha}$, and the proton-to-electron mass ratio, $\boldsymbol{\mu}$. This in turn will provide more stringent constraints on a wide range of fundamental and phenomenological theories beyond the Standard Model and on dark matter models. The ambition of the QSNET consortium will be enabled by a unique network that connects a number of complementary quantum clocks across the UK



Clock	WP	Variations of fund. Constant
Ion clock Yb^+ (467 nm)	1	**α**
Atomic clock Sr (698 nm)	1	**Stable reference**
Atomic clock Cs (32.6 mm)	1	**μ**
Highly-charged ion clock Cf^{15+} (618 nm)	2	**α**
Molecular clock CaF (17 μm)	3	**μ**
Molecular ion clock N_2^+ (2.31 μm)	3	**μ**

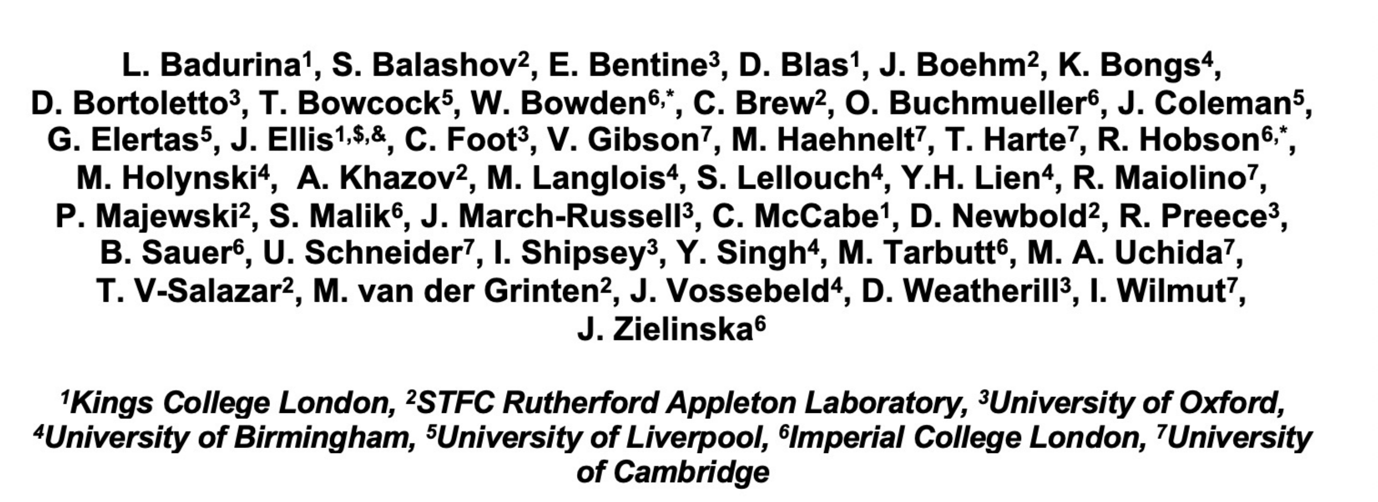
See Giovanni Barontini talk at UK HEP Forum

The AION Project

A UK Atom Interferometer Observatory and Network

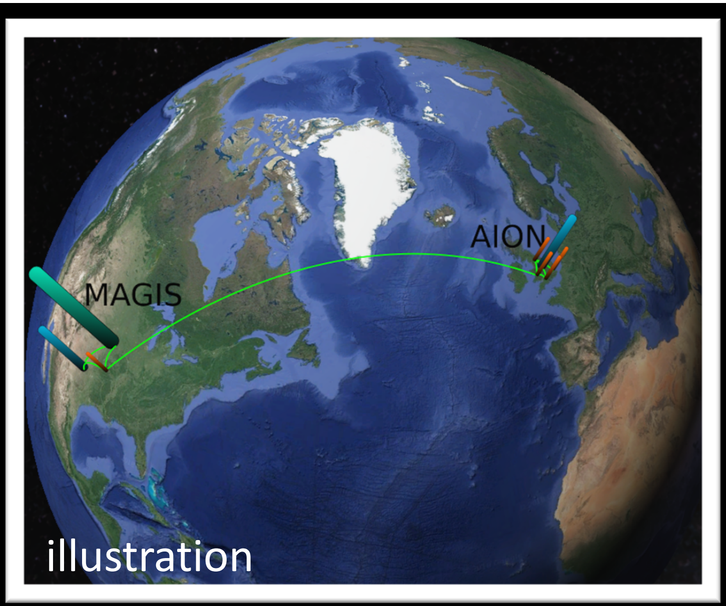
to explore Ultra-Light Dark Matter
and Mid-Frequency Gravitational Waves.

See Oliver Buchmueller
Talk at UK HEP Forum



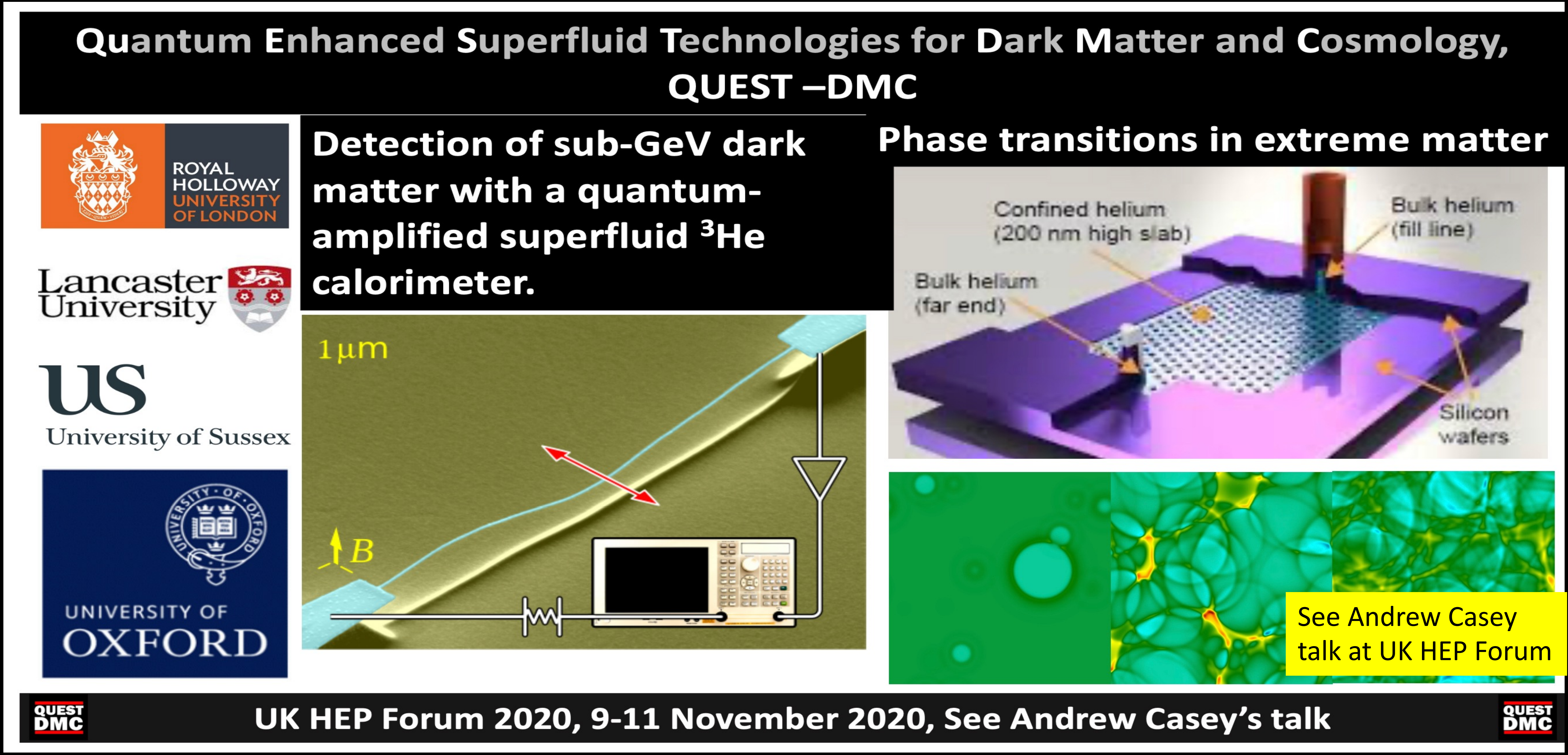
L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4],
D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5],
G. Elertas[5], J. Ellis[1,$,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*],
M. Holynski[4], A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7],
P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3],
B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh[4], M. Tarbutt[6], M. A. Uchida[7],
T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7],
J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge



Project executed in national partnership with **UK National Quantum Technology Hub in Sensors and Timing, Birmingham, UK,**
and international partnership with **The MAGIS Collaboration and The Fermi National Laboratory, US**

And in the light Dark Matter Regime



Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST –DMC

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

University of Sussex

UNIVERSITY OF OXFORD

Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter.

Phase transitions in extreme matter

See Andrew Casey talk at UK HEP Forum

QUEST DMC

UK HEP Forum 2020, 9-11 November 2020, See Andrew Casey's talk

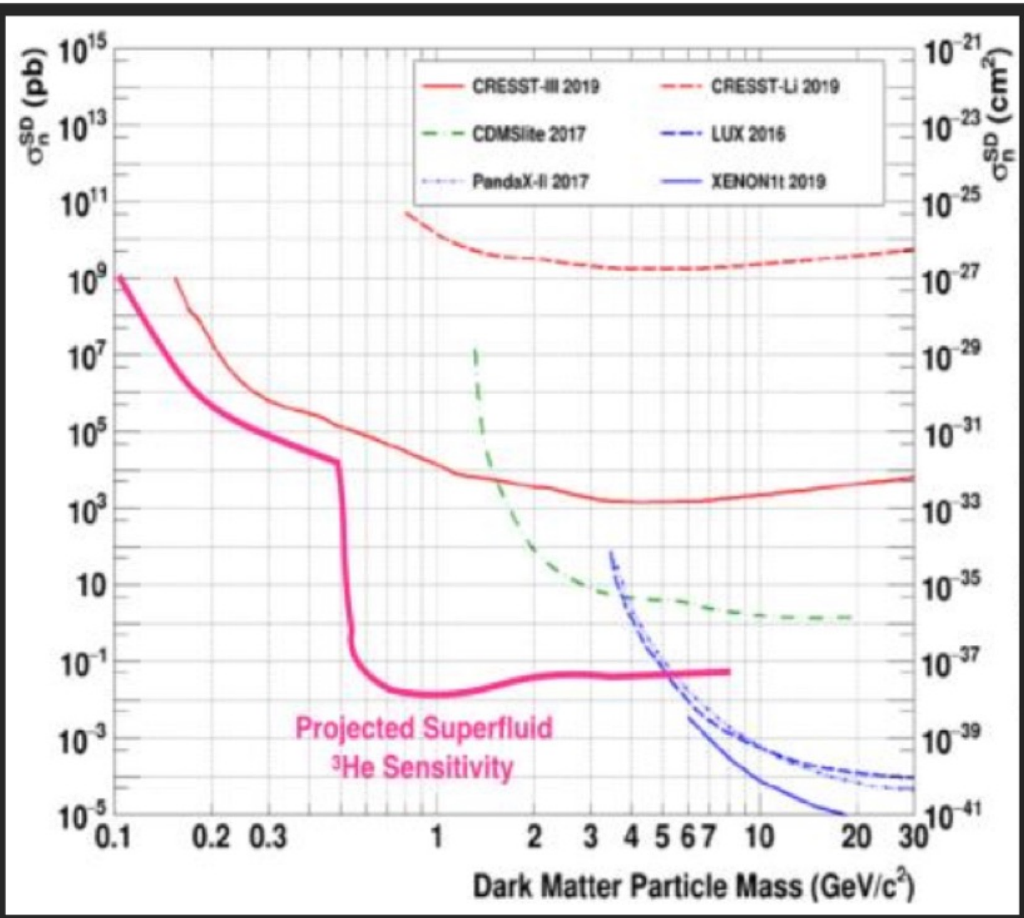
QUEST DMC

Search regime highly motivated by asymmetric dark matter

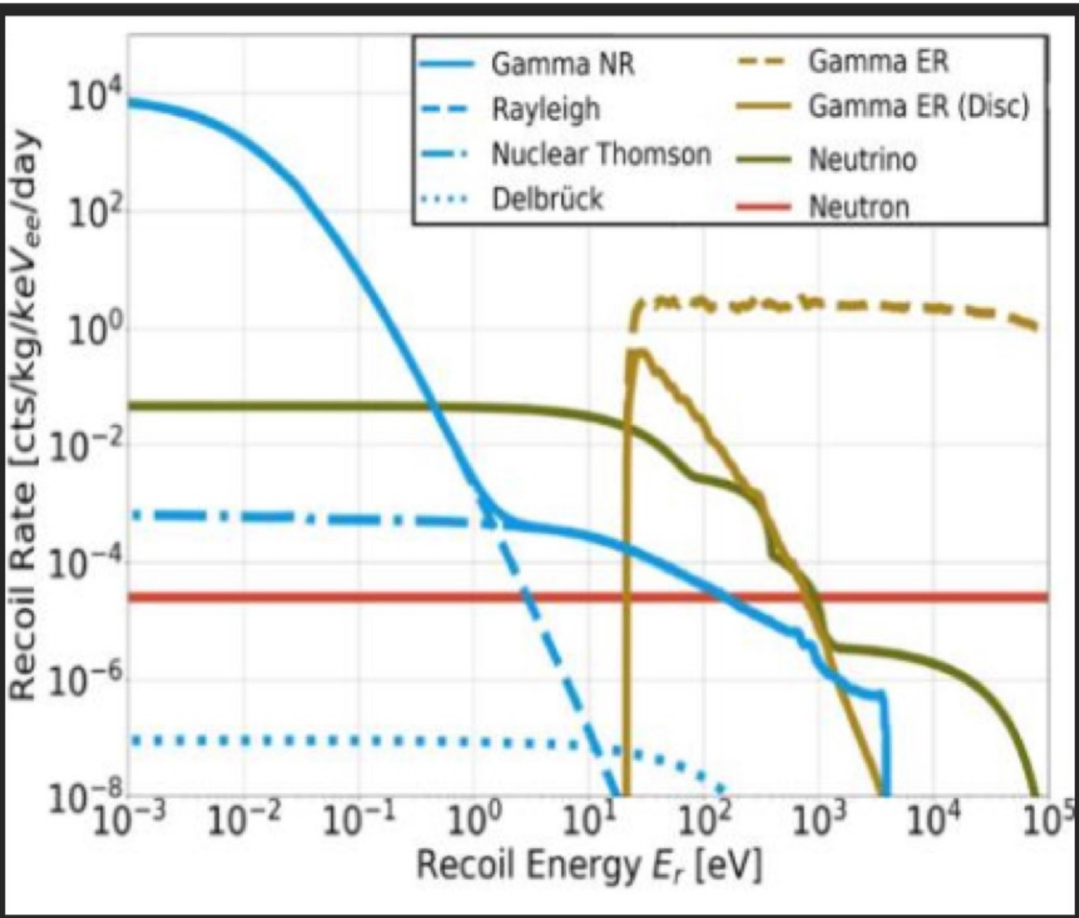
WP1: Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

Prof Jocelyn Monroe

New mass regime, sensitivity to spin-dependent interactions, predict 10 eV threshold.



A. H. Abdelhameed *et al.* (CRESST Collaboration)
Phys. Rev. D **100**, 10200 (2019)

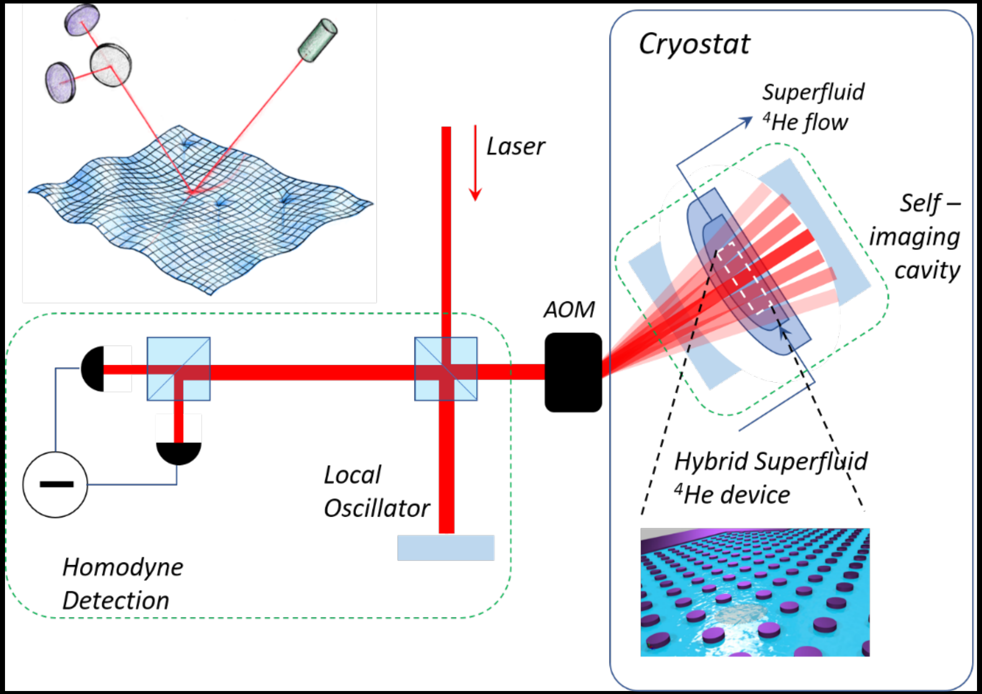


Hertel et al. Phys. Rev. D 100, 092007 (2019)

Slide credit: Andrew Casey (RHUL)

QSimFP Quantum Simulators for Fundamental Physics

Silke Weinfurtner talk
UK HEP Forum

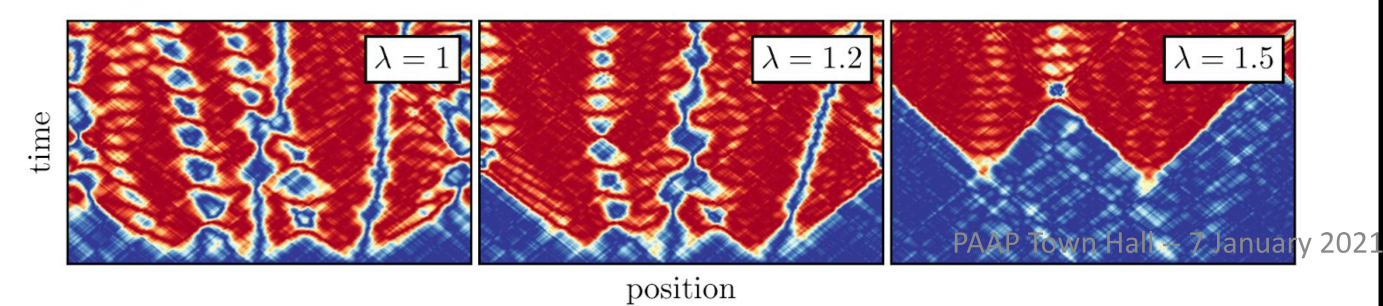


Team:

Carlo F Barenghi (Newcastle),
Thomas Billam (Newcastle),
Ruth Gregory (Durham),
Gregoire Ithier (RHUL),
Zoran Hadzibabic (Cambridge),
Friedrich Koenig (St. Andrews),
Jorma Louko (Nottingham), Ian Moss (Newcastle),
John Owers-Bradley (Nottingham),
Hiranya Peiris (UCL),
Andrew Pontzen (UCL), Xavier Rojas (RHUL),
Pierre Verlot (Nottingham),
Silke Weinfurtner (Nottingham).

Science goals:

- **Quantum vacuum**: perform experiments for quantum simulation of false vacuum decay in an inflationary multiverse setting
- **Quantum black holes**: to perform the first experiments that will allow systematic study of quantum wave-modes around quantised analogue black holes



Quantum Technologies for Neutrino Mass Consortium

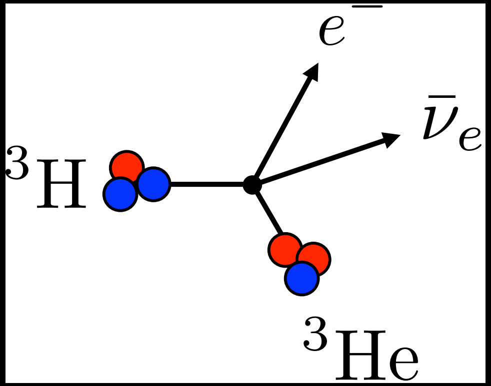
F. Deppisch[1], J, Gallop[2], L. Hao[2], S. Hogan[1], L.Li[3], R. Nichol[1], Y. Ramachers[4], R. Saakyan[1](PI), D. Waters[1], S. Withington[5]

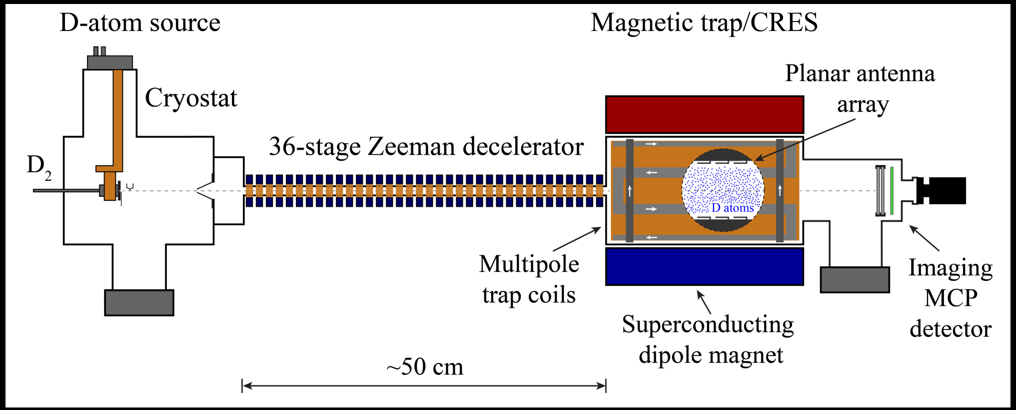
A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

3-yr proposal goal:

Technology demonstration for neutrino mass determination from ^{3}H $\boldsymbol{\beta}$-decay

- Trapping ~10^{20} D/T atoms
- B-field mapping with $\lesssim$0.1ppm precision
- Quantum limited micro-wave electronics





Ultimate goal:

Neutrino mass measurement at a Tritium facility (e.g. *Culham Centre for Fusion Energy*)

Ruben Saakyan talk

Quantum Technologies and Particle Physics

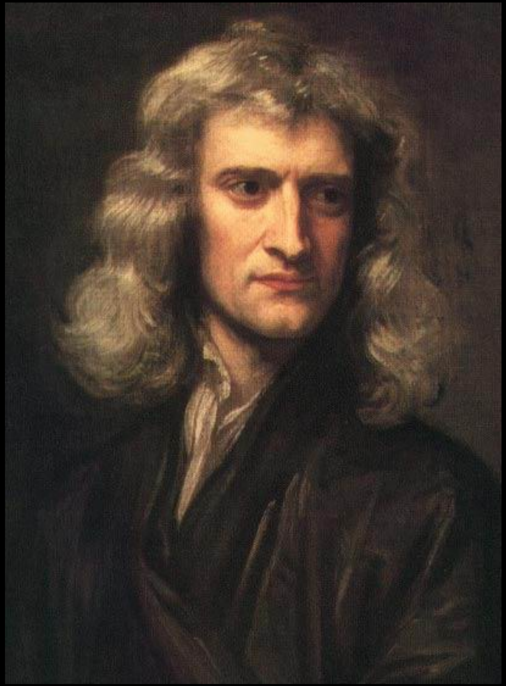
- The nature of dark matter
- The earliest epochs of the universe at temperatures >> 1TeV
- The existence of new forces
- The violation of fundamental symmetries (electron and nucleon EDMs)
- The possible existence of dark radiation and the cosmic neutrino background
- The possible dynamics of dark energy
- The measurement of neutrino mass
- Tests of the equivalence principle
- Tests of quantum mechanics
- A new gravitational wave window to the Universe:
  - LIGO sources before they reach LIGO band
  - Multi-messenger astronomy: optimal band for sky localization
  - Cosmological sources

Yellow indicates areas where
ultra light bosons may play a role

[redacted]

A healthy program needs a long term strategy with a compelling vision for the future and future scientific achievements.
This is what our field has produced and quantum sensing is an important part of that.

The attendees at this school represent the future



“What we know is a droplet, what we don’t know is an Ocean”

Sir Isaac Newton (1643-1727)

The Ocean is for your generation to explore

Thanks

To the organizers and students of this school

and to Aurore Savoy Navarro for her inspiration

Please send your questions to

Ian.shipsey@physics.ox.ac.uk