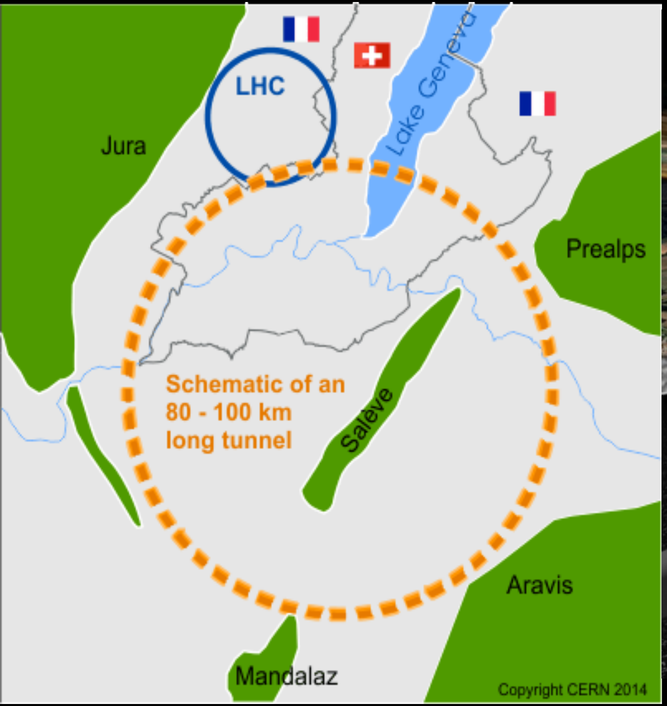
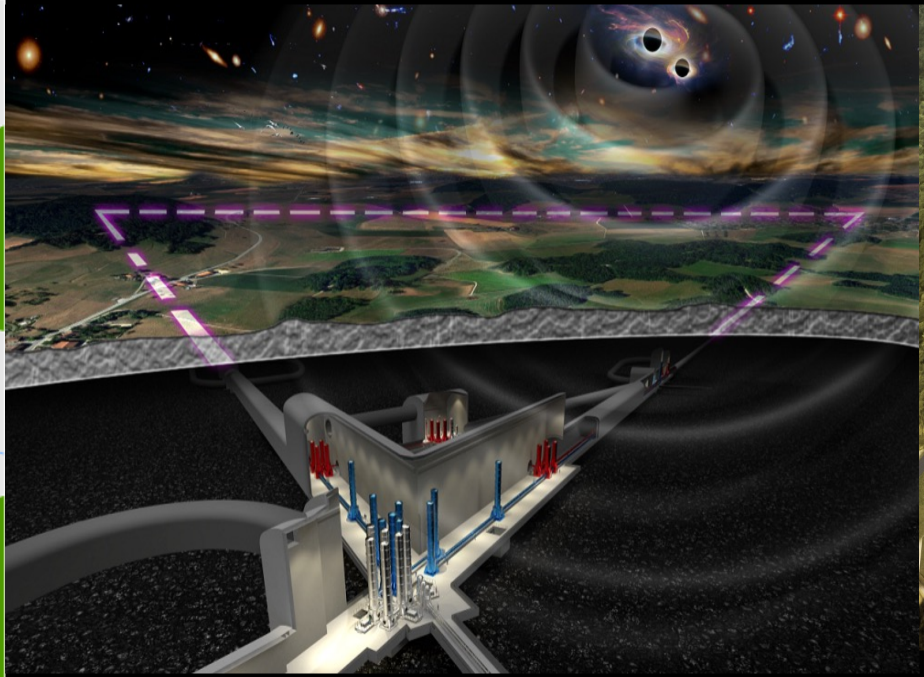
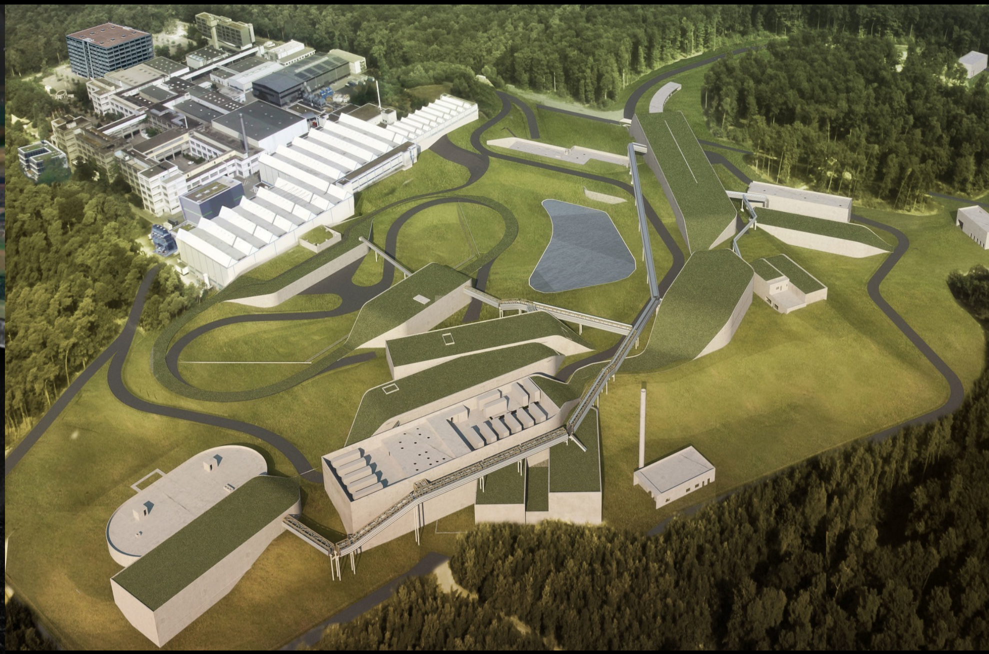
Quantum Technologies for Fundamental Physics

The Science & The Quantum Technologies Landscape





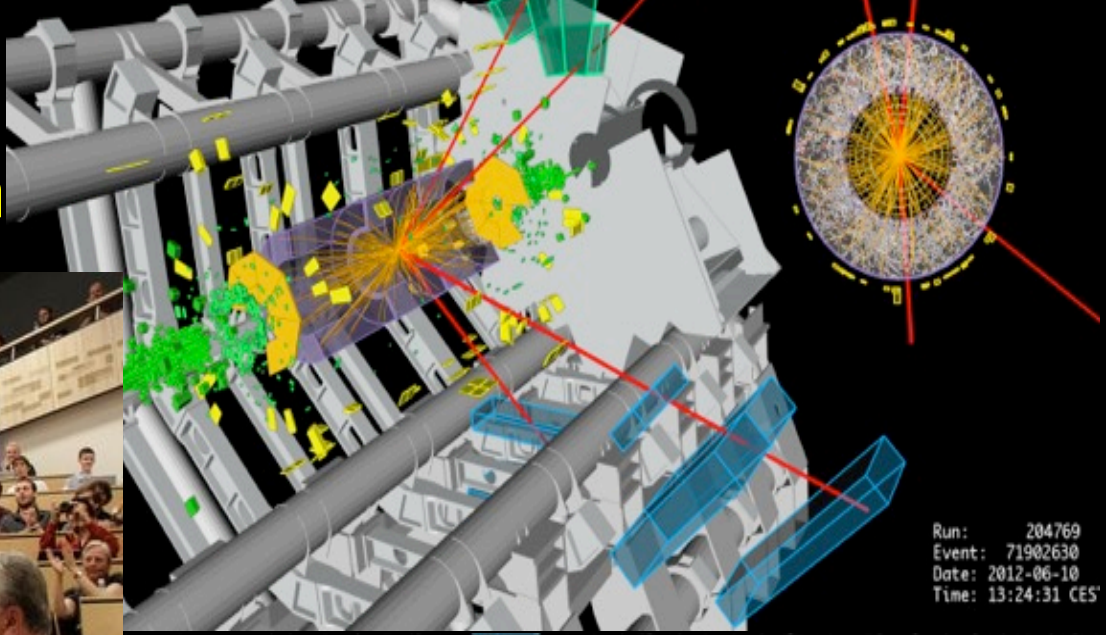


Norwegian HEP Community
June 28, 2022

Ian Shipsey, Co-coordinator, ECFA Detector R&D Roadmap & Chair, ICFA IID Panel
Oxford University

2012.7.4

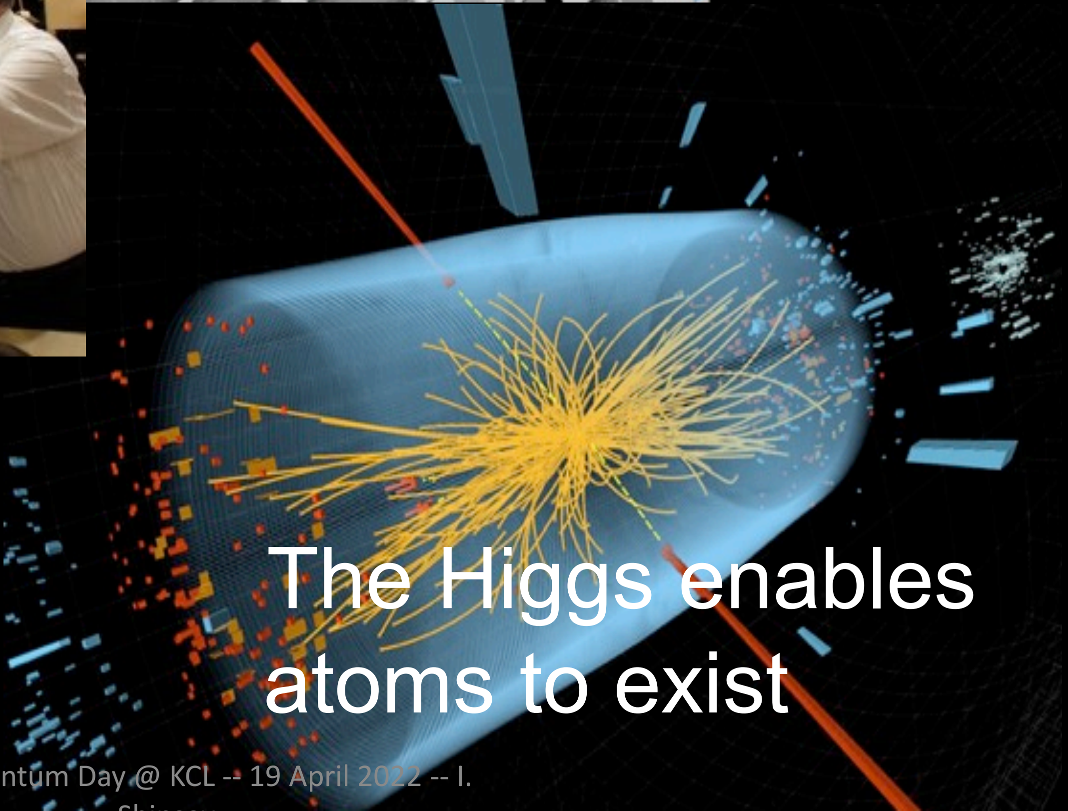
discovery of Higgs boson



theory : 1964

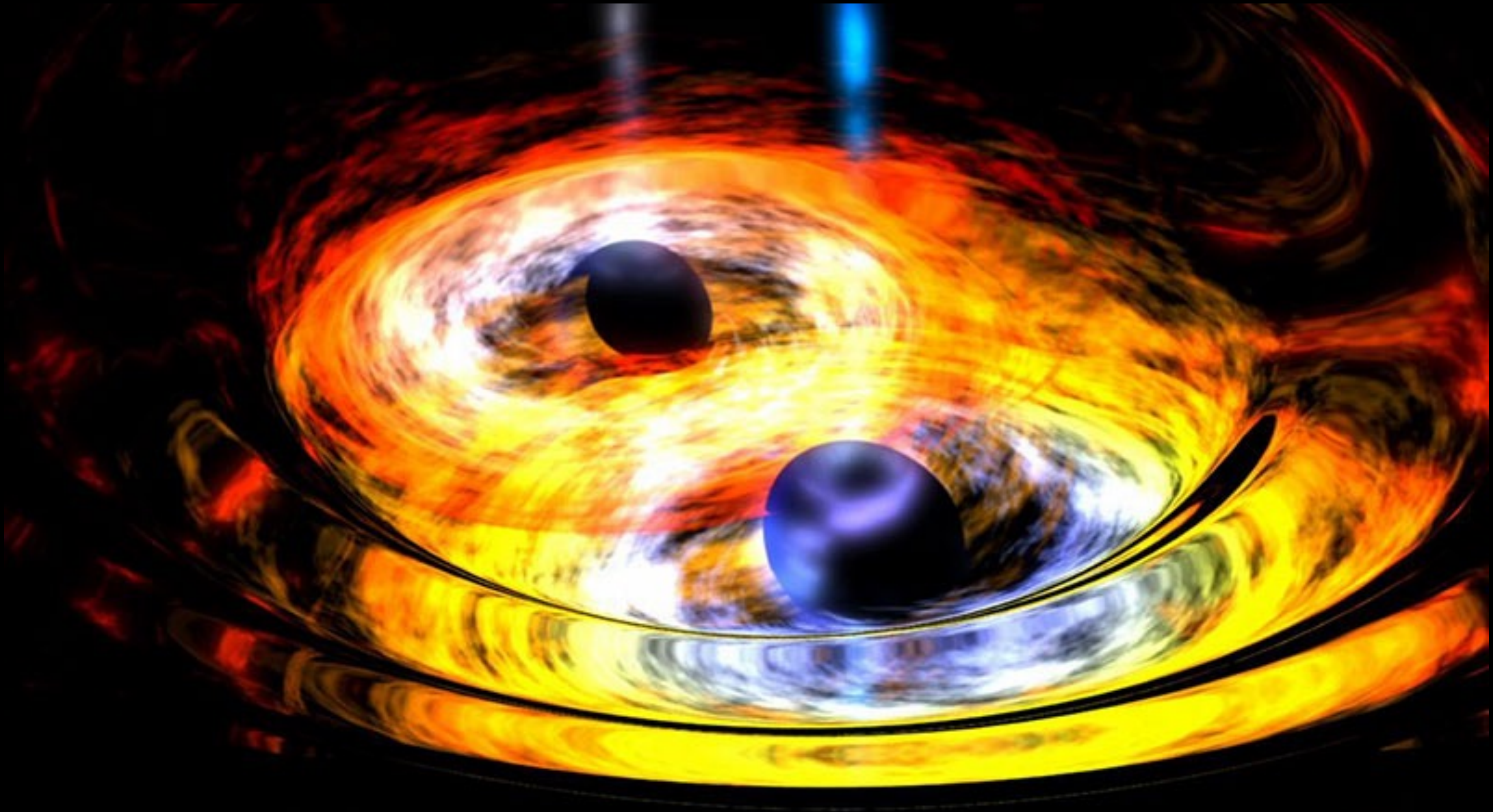
design : 1984

construction : 1998

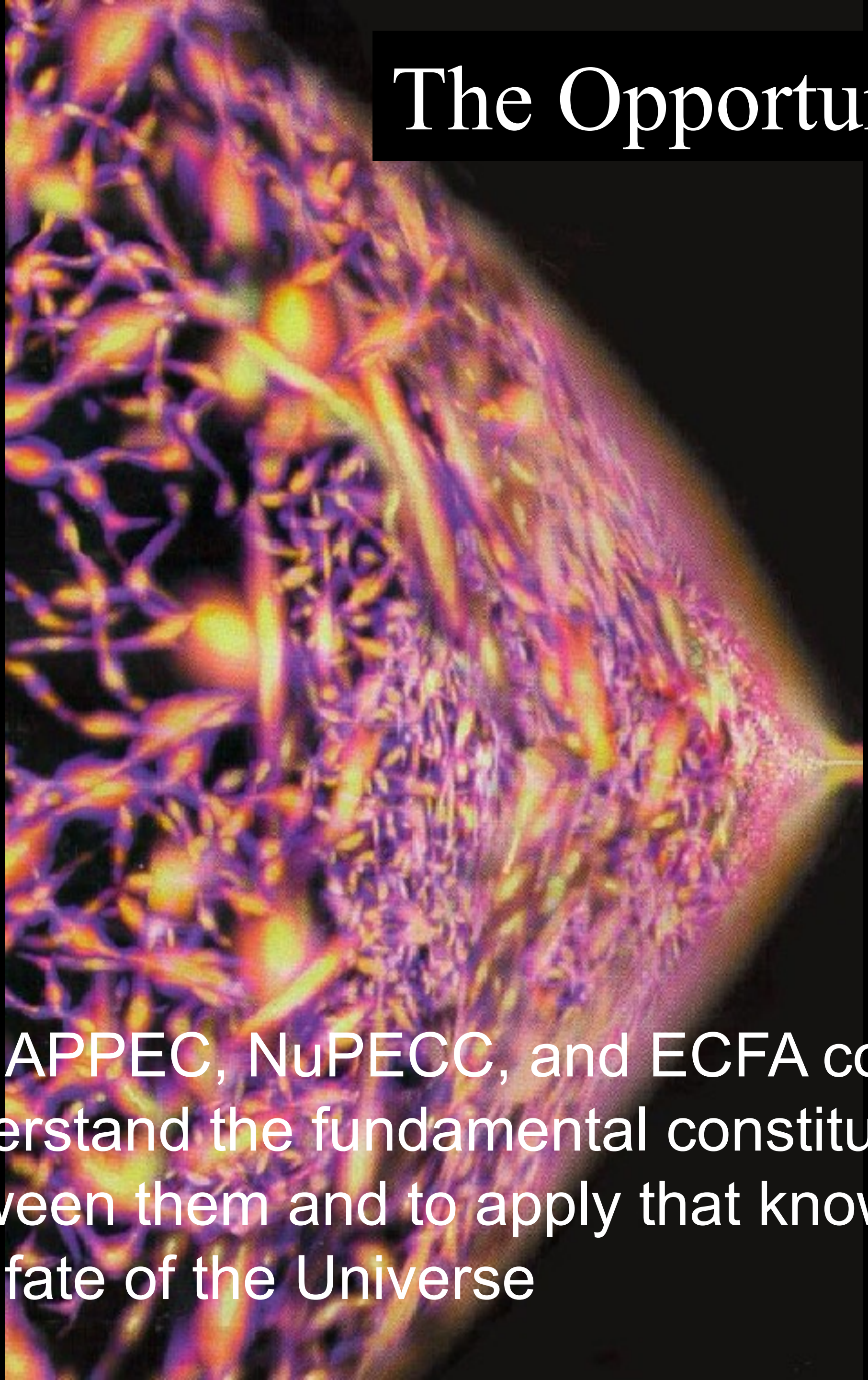


The Higgs enables atoms to exist

Detection of gravitational waves
LIGO February, 2016

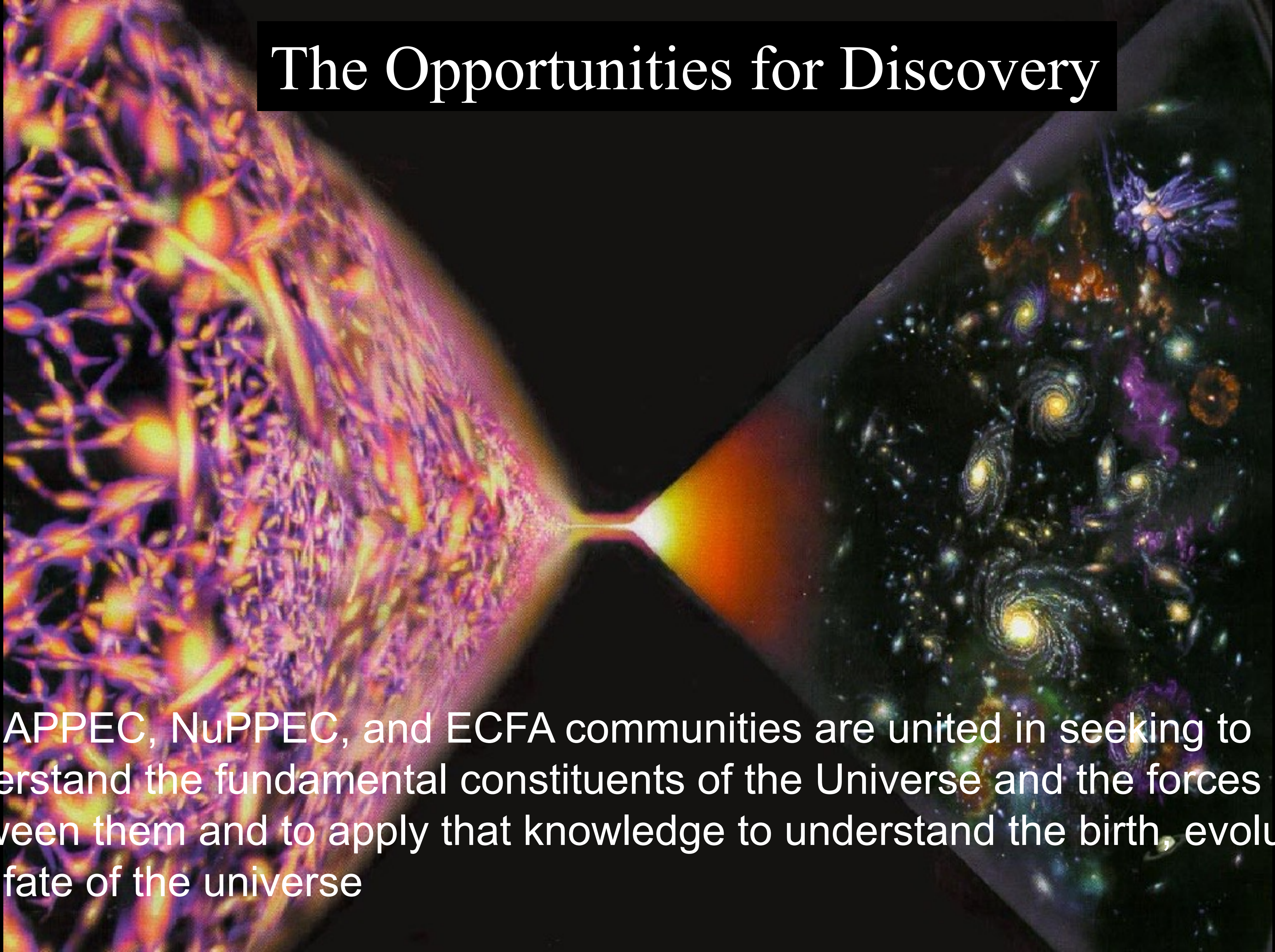


The Opportunities for Discovery



The APPEC, NuPECC, and ECFA communities are united in seeking to understand the fundamental constituents of the Universe and the forces between them and to apply that knowledge to understand the birth, evolution and fate of the Universe

The Opportunities for Discovery



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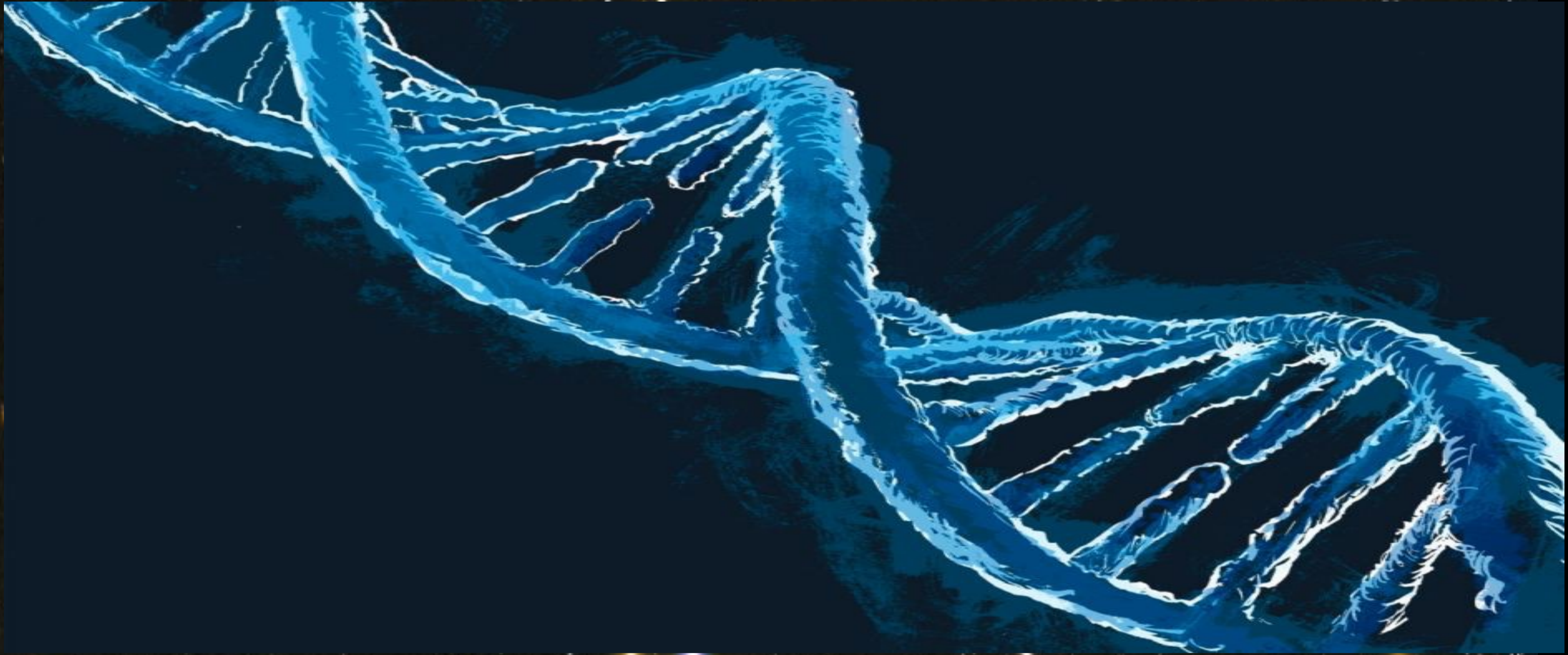
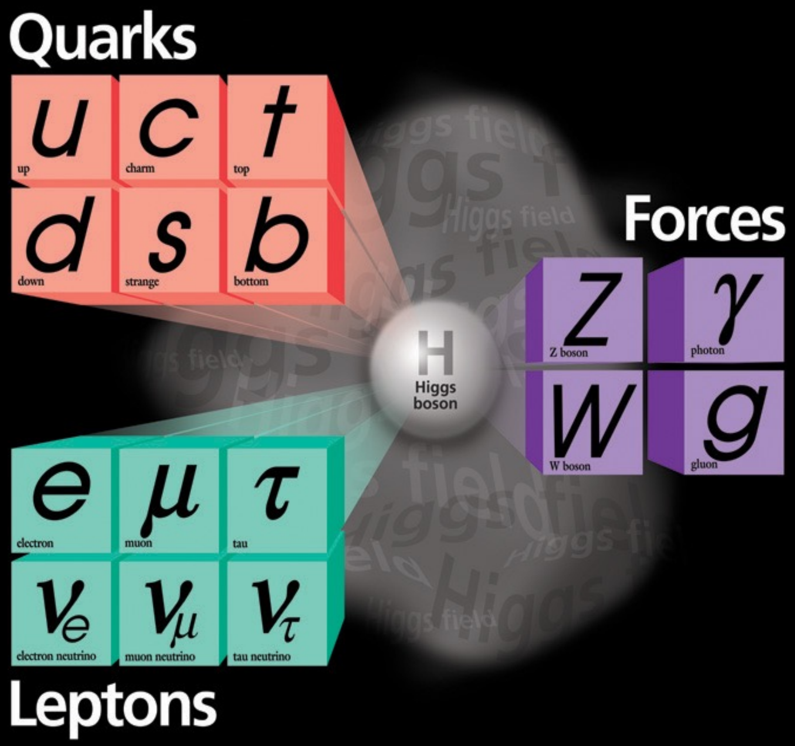
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Our communities have revolutionized human understanding of the Universe – its underlying code, structure and evolution

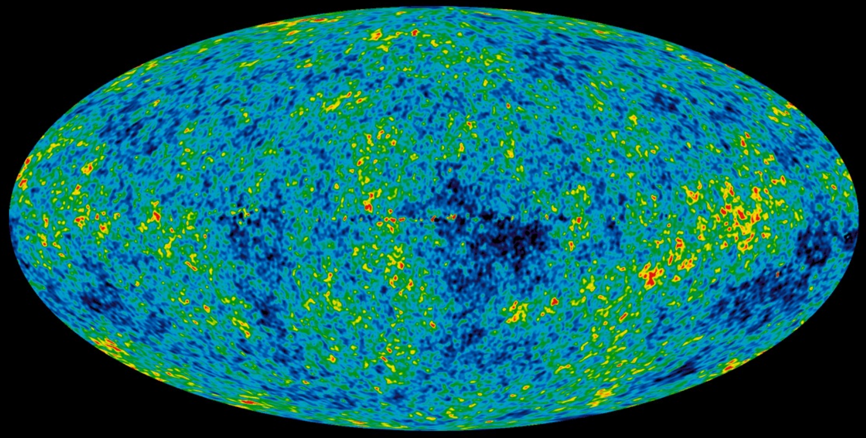


BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Particle Standard Model



Cosmology Standard Model



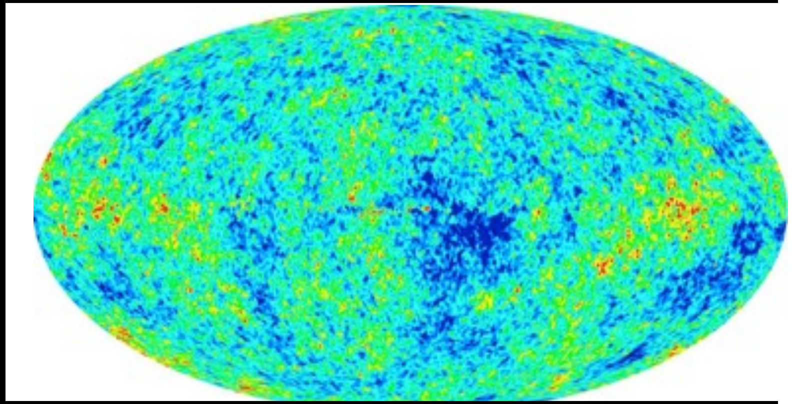
Λ_{CDM}

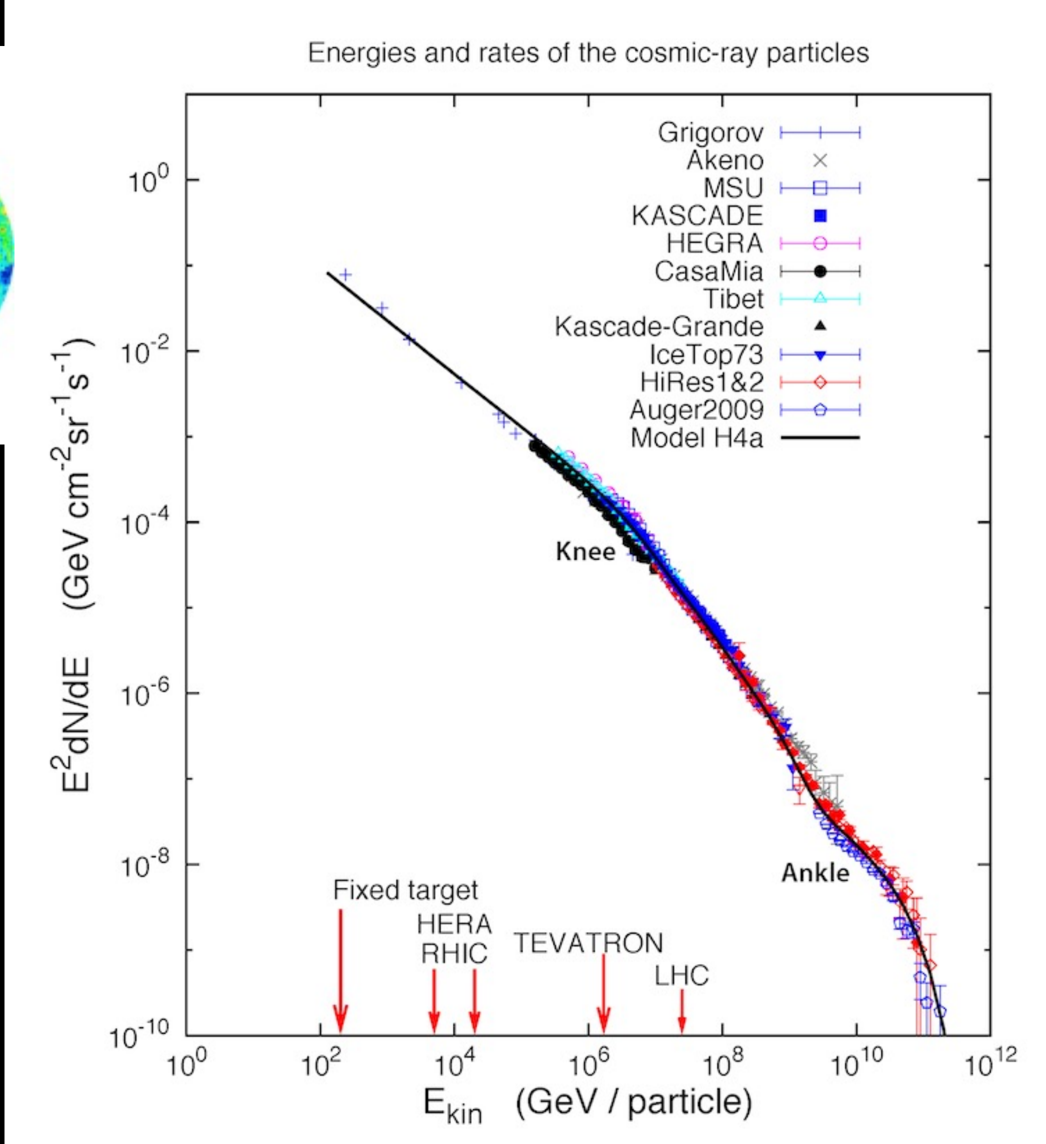
……enabled by instrumentation

APPEC
ECFA
NuPECC

Our APPEC/ECFA/NuPECC scope is broad and we deploy many tools; accelerator, non-accelerator, astrophysical & cosmological observations all have a critical role to play

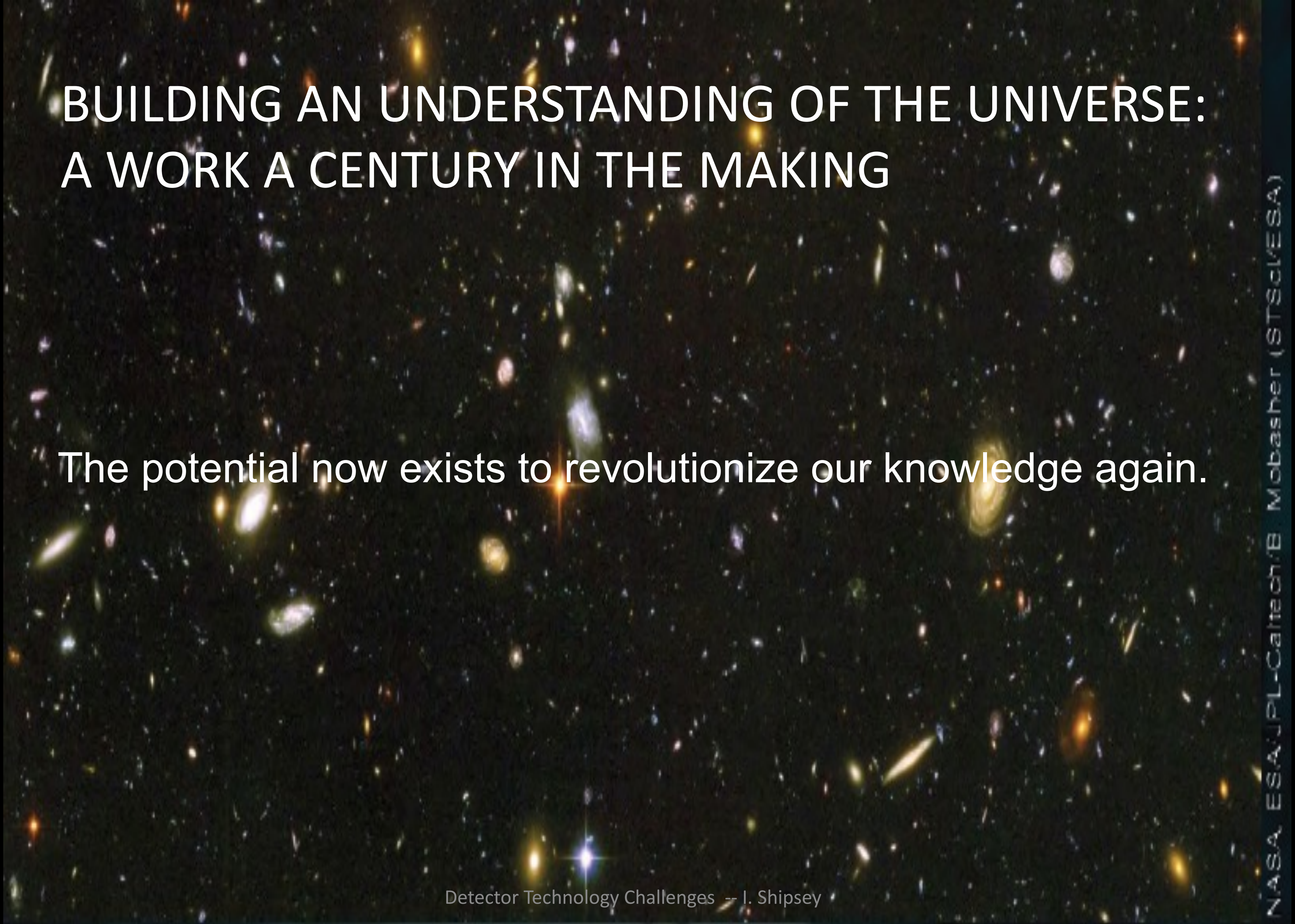
Detect & Measure over 24 orders of magnitude





A Rich Spectrum of Technologies Developed by our Community

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



The potential now exists to revolutionize our knowledge again.

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

The [redacted] 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

We are very much in a data driven era !

Current flagship (27km)

impressive programme up to 2040

ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

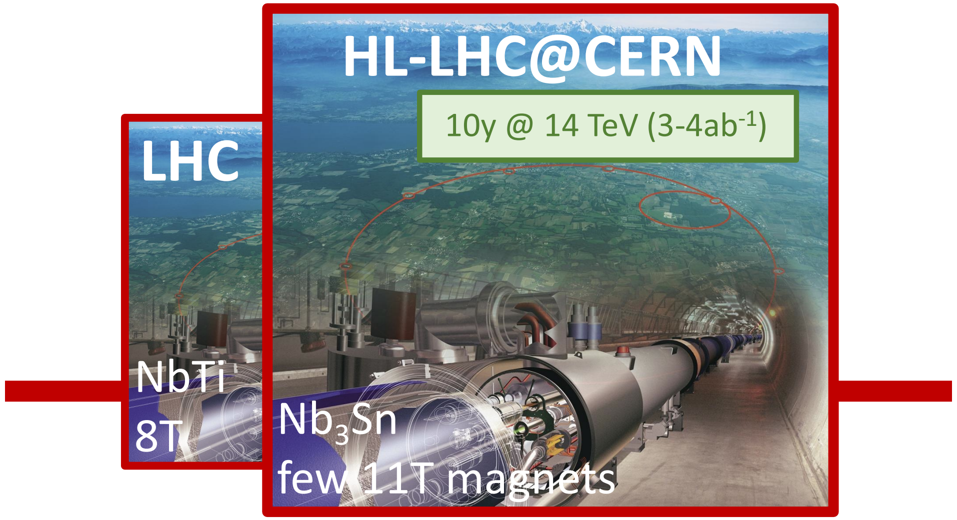
updated CDR 2007.14491

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

Current flagship (27km)

impressive programme up to 2040



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10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

Future flagship at the energy & precision frontier

Current flagship (27km)

impressive programme up to 2040

Future Circular Collider (FCC)

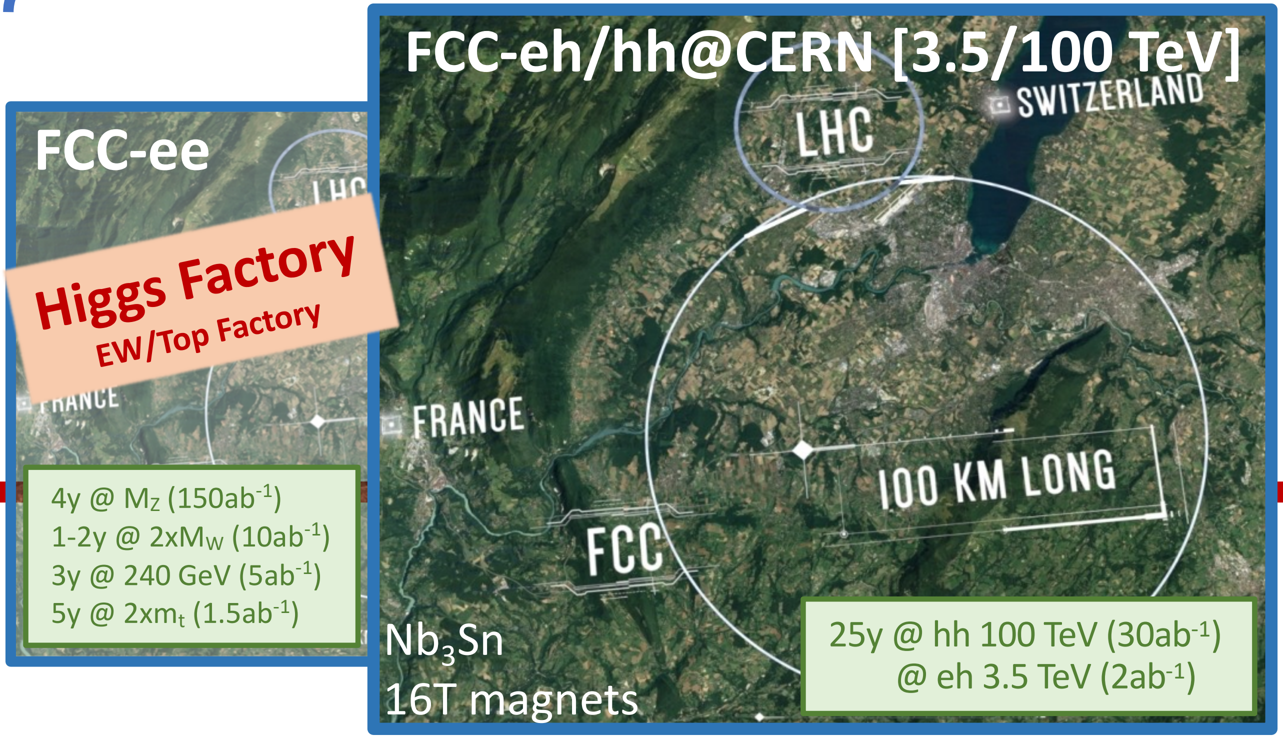
big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

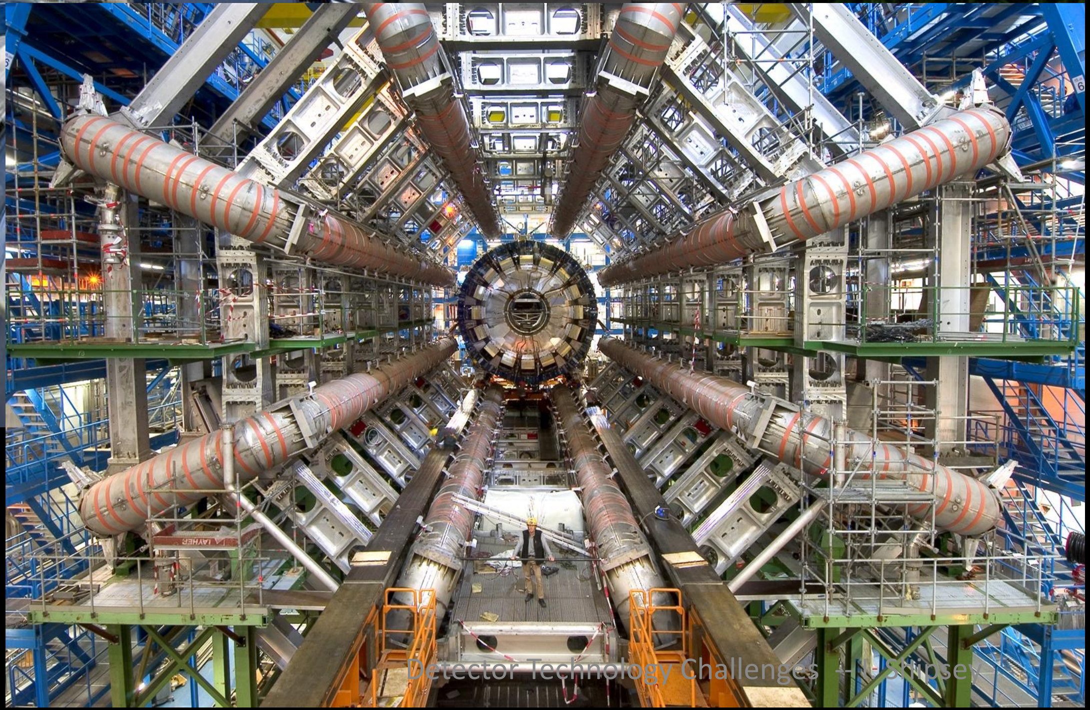


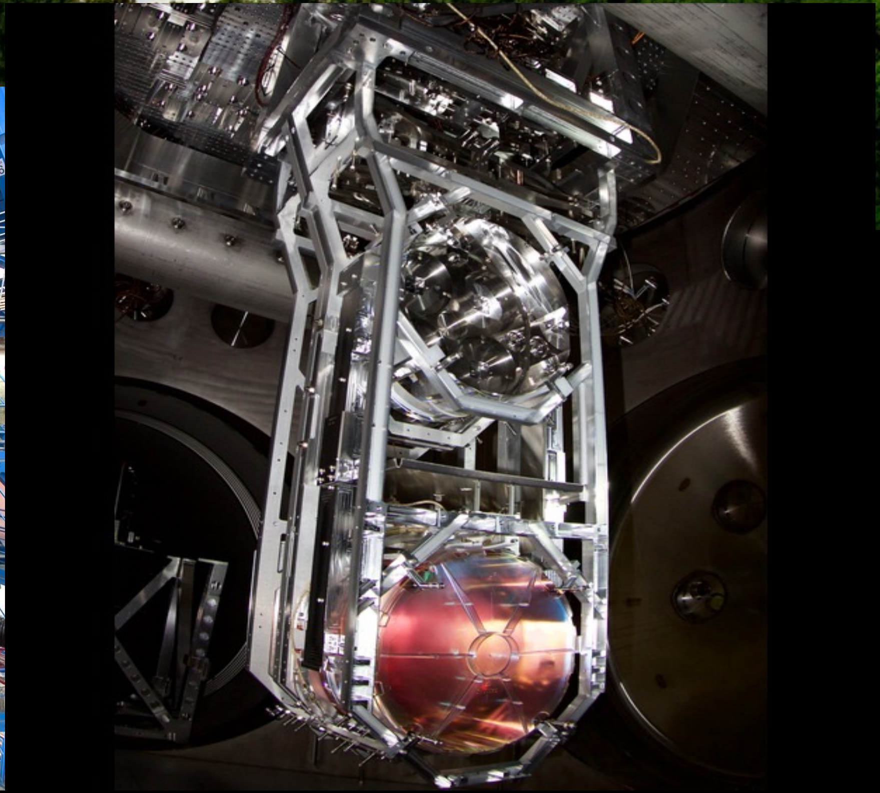
numbers assume 2 IPs for each collider (only one for FCC-eh)

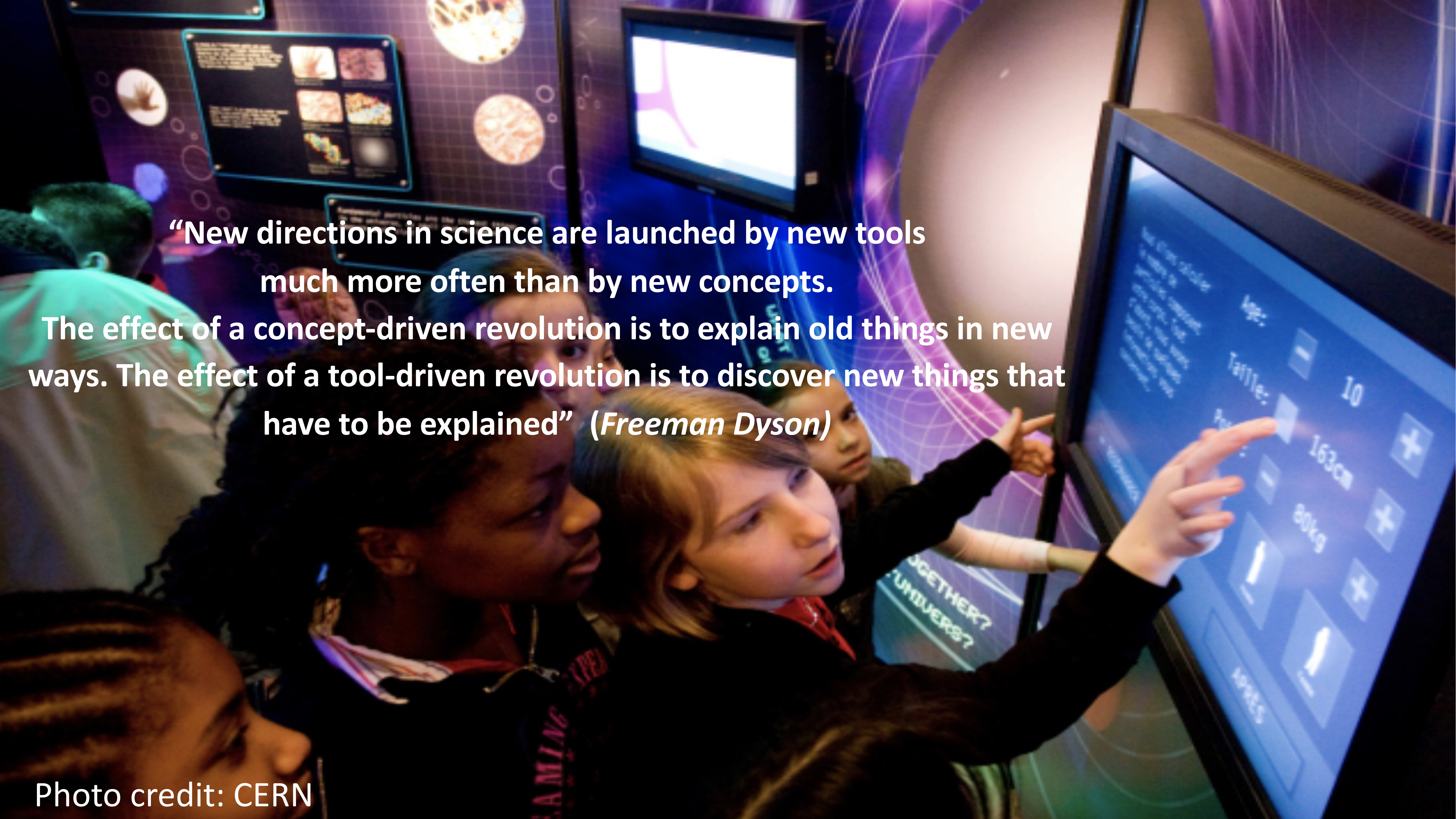
by around 2026, verify if it is feasible to plan for success (techn. & adm. & financially & global governance)

potential alternatives pursued @ CERN: CLIC & muon collider

The gestation time to realize the tools and the experiments e.g. LHC & LIGO are decades long! For the most ambitious future experiments e.g FCCee/hh & Einstein Telescope to take the data and seize the opportunities for discovery, we must develop the tools (instrumentation and facilities) we need NOW.







"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)*

Photo credit: CERN

“Measure what is measurable, and make measurable what is not so” (*Galileo Galilei*)

Photo credit: CERN

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	
AGS BNL (1960)	π N interactions	
FNAL Batavia (1970)	Neutrino Physics	
SLAC Spear (1970)	ep, QED	
ISR CERN (1980)	pp	
PETRA DESY (1980)	top quark	
Super Kamiokande (2000)	Proton Decay	
Telescopes (2000)	SN Cosmology	

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ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
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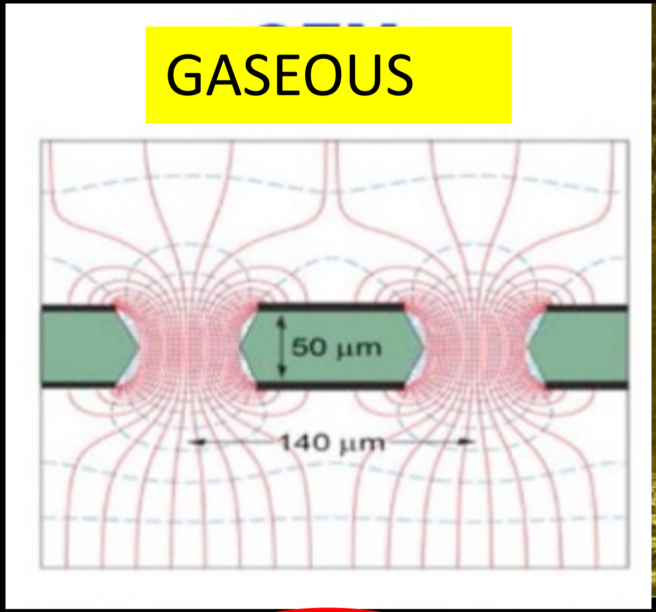
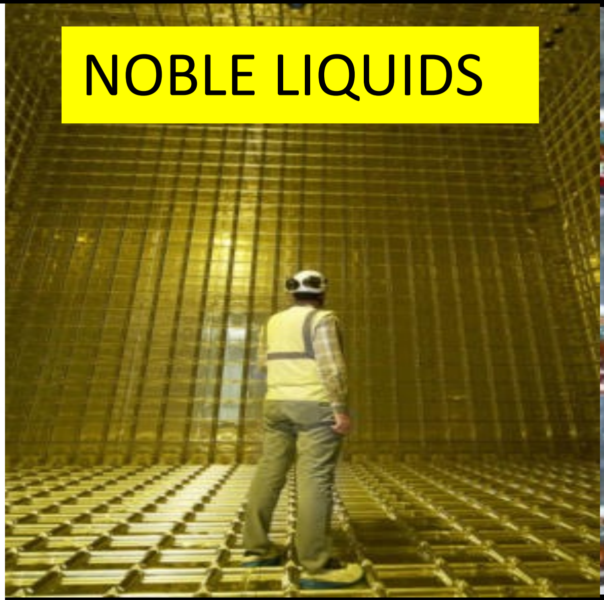
precision instruments are key to discovery when exploring new territory

Technology Classification for the ECFA R&D Roadmap

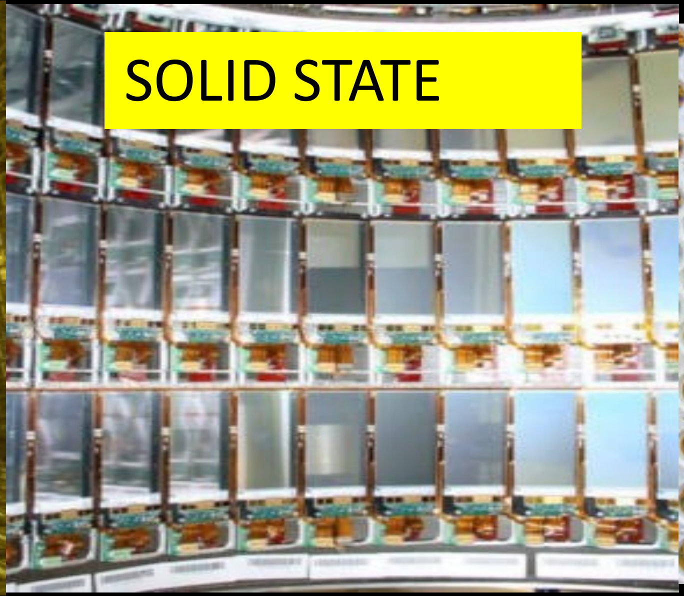
GASEOUS



NOBLE LIQUIDS

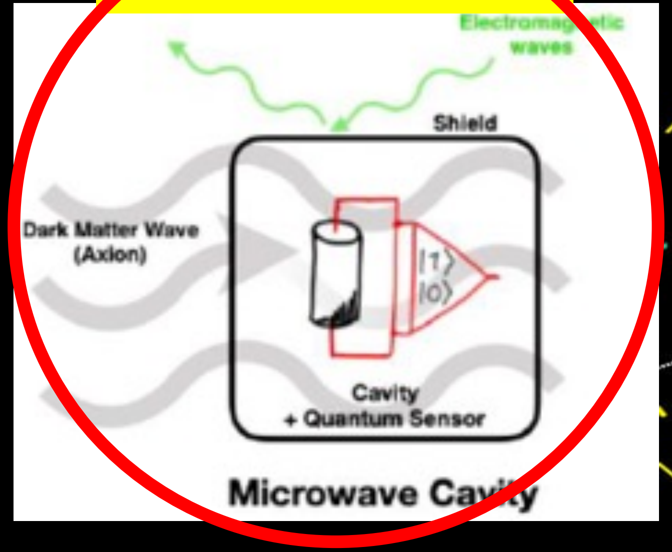


SOLID STATE

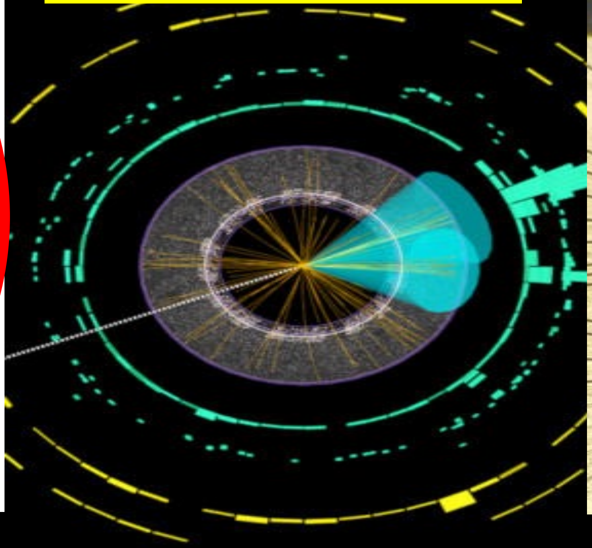


PHOTODETECTORS

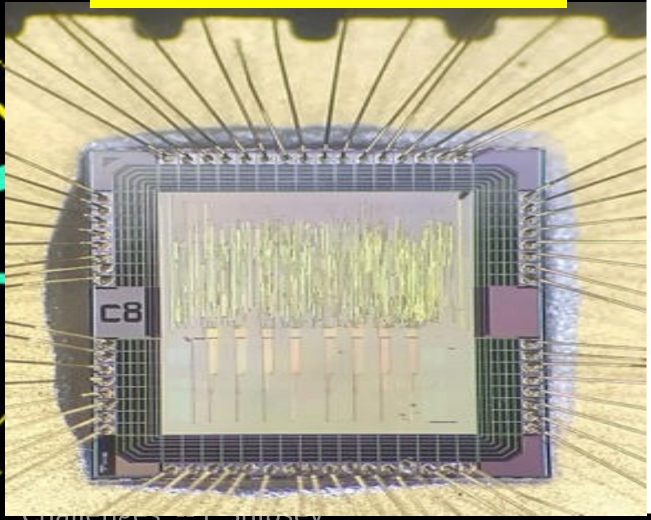
QUANTUM



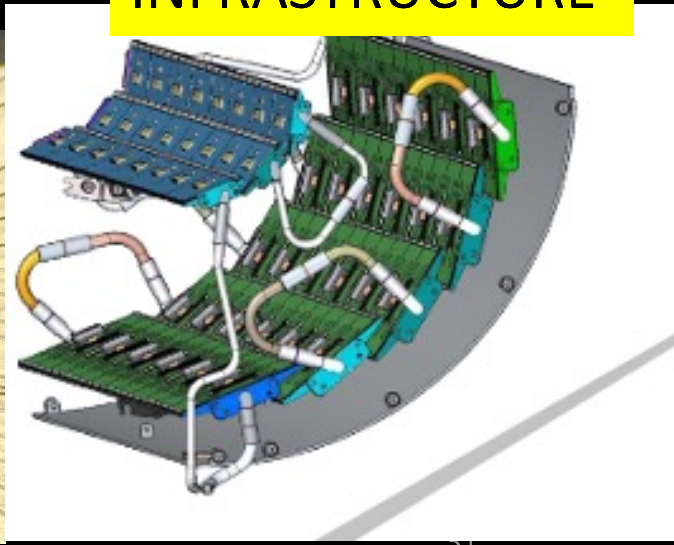
CALORIMETER



ELECTRONICS



INFRASTRUCTURE



quantum sensors register a change of quantum state caused by the interaction with an external system:

- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

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***.

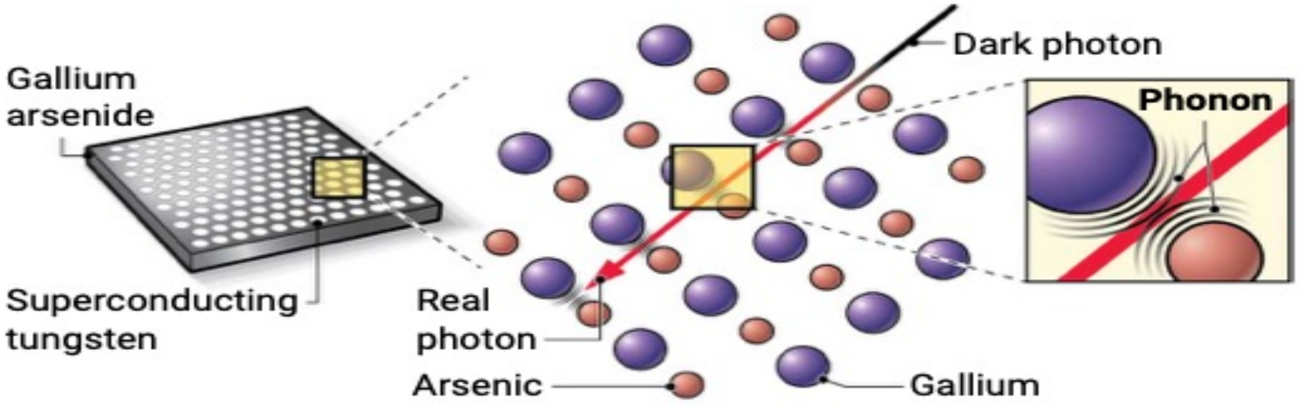
and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;

Particles and waves

Quantum detectors include devices that can detect a single quantum, such as a photon, and devices that exploit a quantum trade-off to measure one variable more precisely at the cost of greater uncertainty in another.

Just one click

A dark matter candidate called a dark photon could morph into an ordinary photon that would trigger a quantized vibration in a crystal. The vibration, or phonon, would warm superconducting heat sensors on the crystal.



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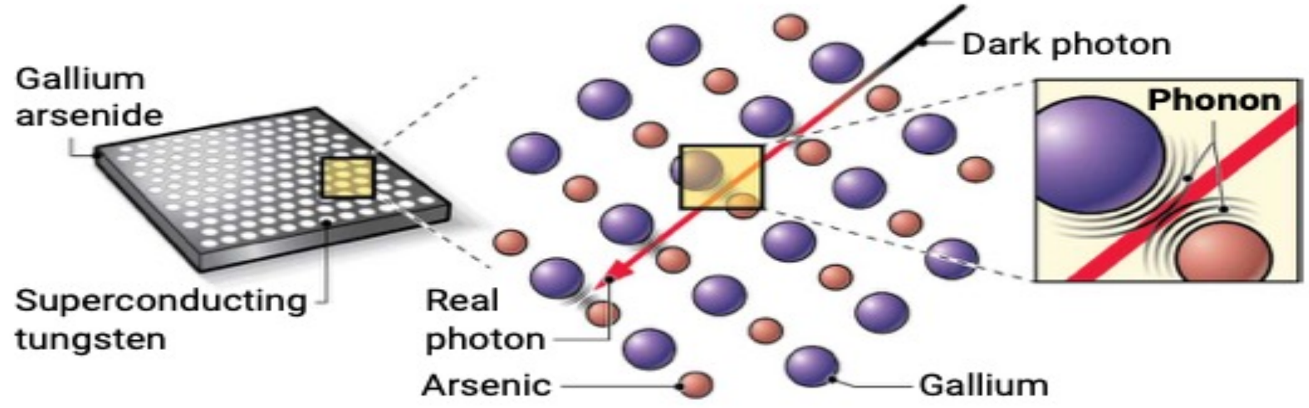
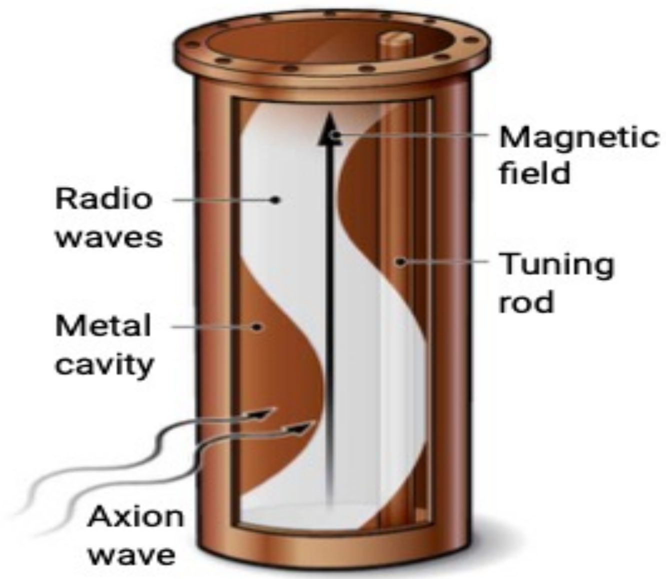
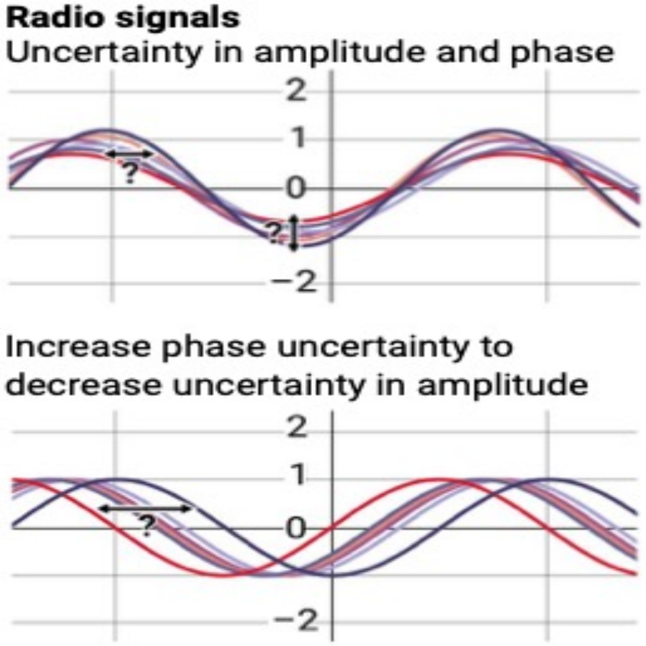


Quantum trade-off
Within a resonating cavity, a wave of hypothetical axions could transform into faint radio waves, uncertain in both amplitude and phase. Quantum techniques could reduce the uncertainty in the amplitude while increasing that in the wave's irrelevant phase.

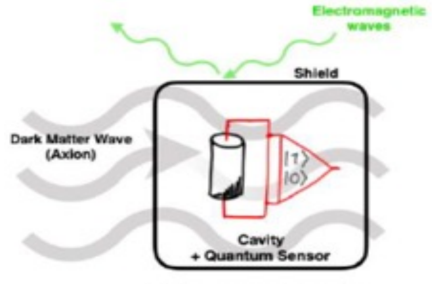




Quantum and emerging technologies

- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated**: clocks and clock networks, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, atom interferometry, …
- Several initiatives started at CERN, DESY, FNAL, US, UK, …

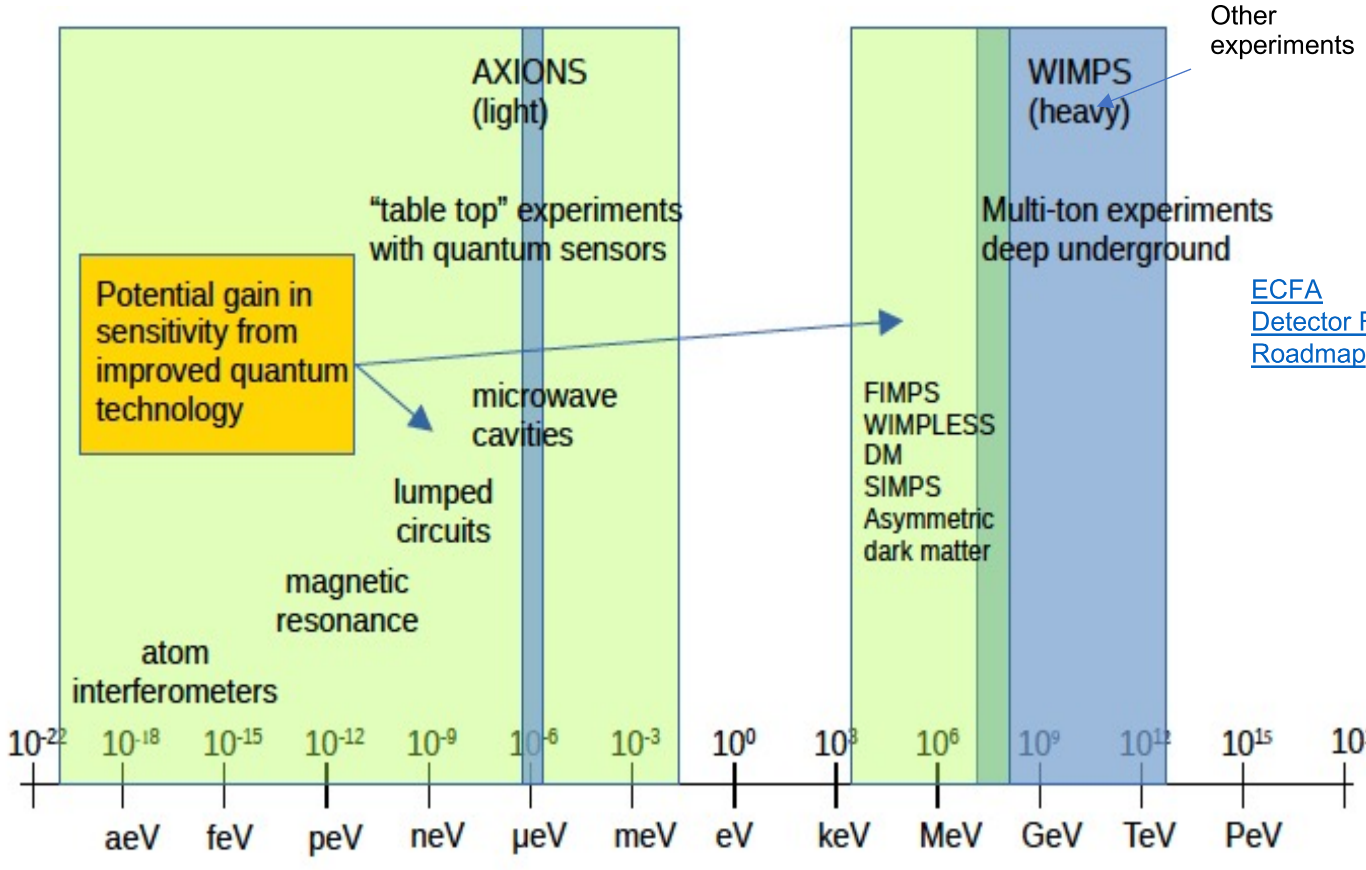
QUANTUM TECHNOLOGY INITIATIVE



Microwave Cavity

S. Golawa

Example: potential mass ranges that quantum sensing approaches open up for Axion searches

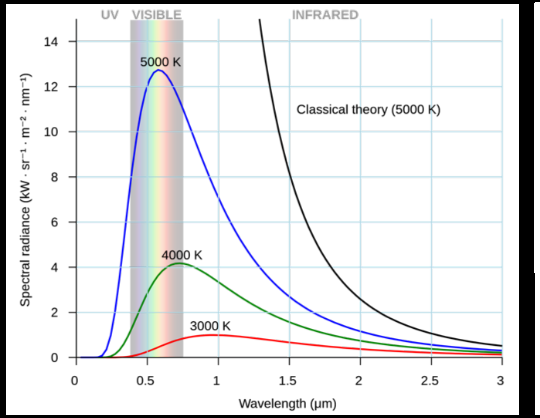


Axion mass range

ECFA Detector R&D Roadmap

Blue: now
Light green: with quantum

Quantum 1.0



Blackbody Radiation

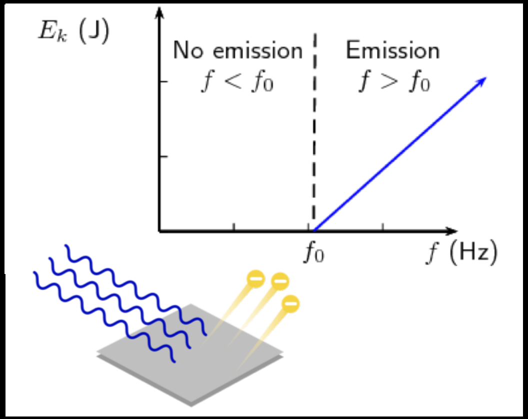
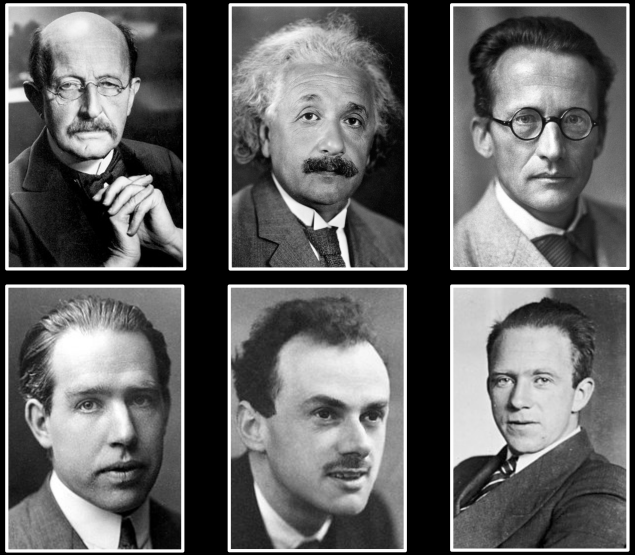


Photo-electric Effect

Quantum Mechanics



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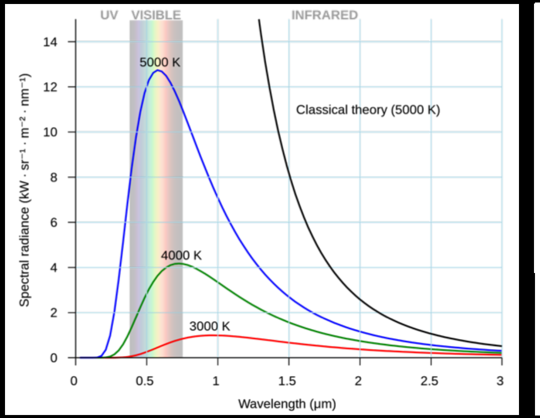

Blackbody Radiation

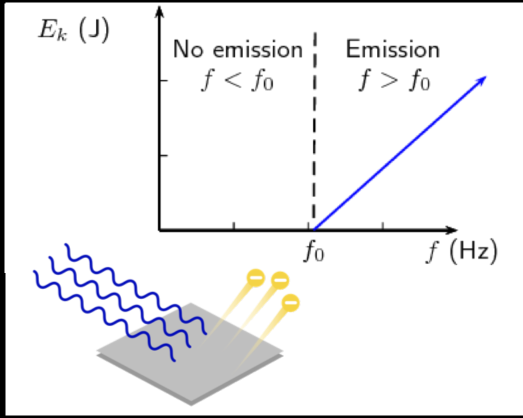

Photo-electric Effect

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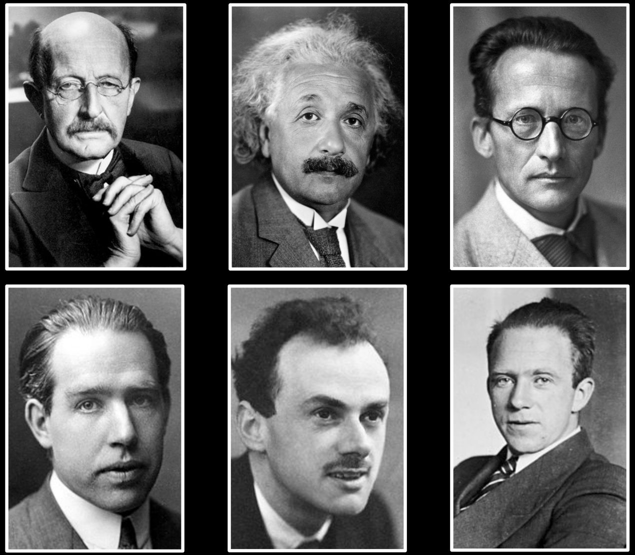
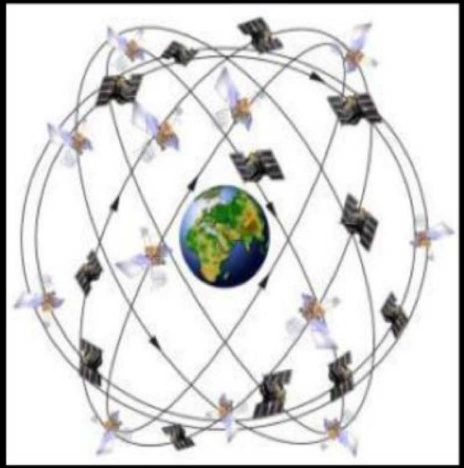


Exascale Computing

Laser Technology

Magnetic Resonance Imaging



Global Positioning System

Quantum 1.0


09:41
100 %
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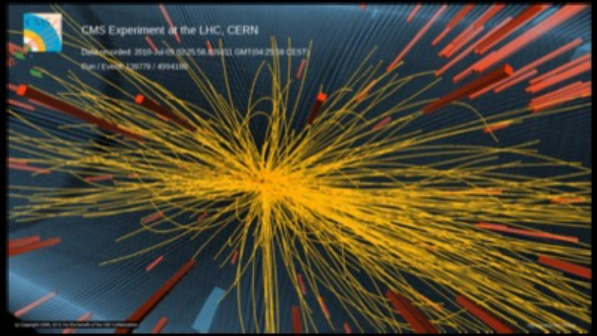
Calendrier
Photos
Appareil photo
Plans
Horloge
Météo
Wallet
Notes
Rappels
Bourse
Vidéos
iBooks
iTunes Store
App Store
Domicile
Santé
Réglages
Téléphone
Safari
Messages
Musique

Quantum 2.0

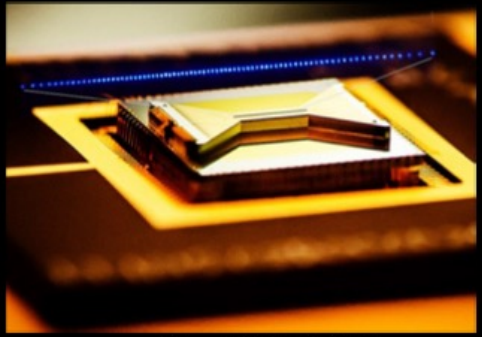
The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

AI, ML on Quantum annealer



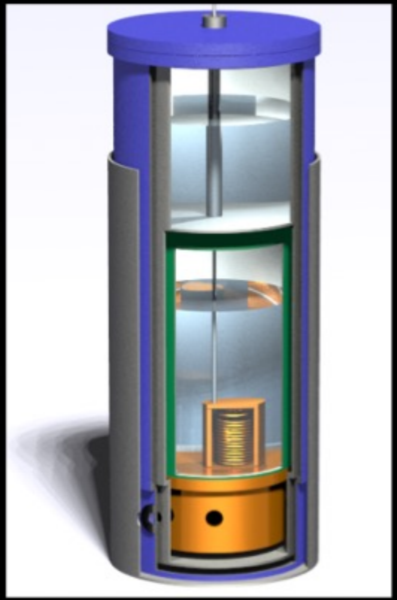
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

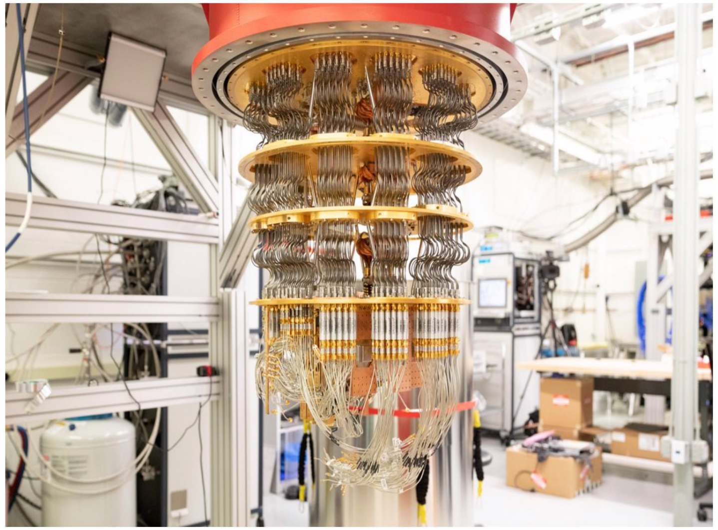
Quantum 2.0

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

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

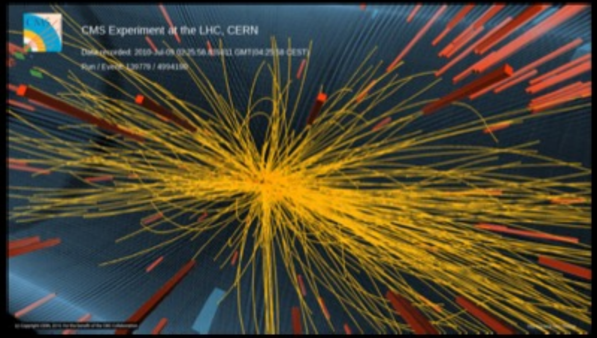
"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

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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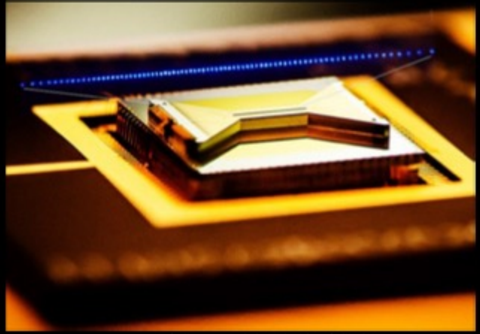

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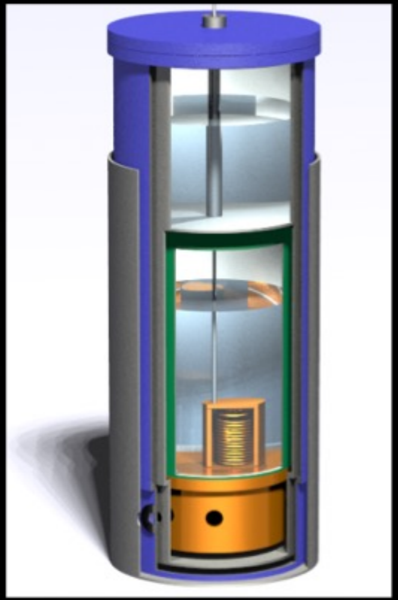

Nature (564) 87 (2018)

Quantum 2.0

09:41
100 %
mercredi
7
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Calendrier
Photos
Appareil photo
Plans
Horloge
Météo
Wallet
Notes
Rappels
Bourse
Vidéos
iBooks
iTunes Store
App Store
Domicile
Santé
Réglages
Téléphone
Safari
Messages
Musique

"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

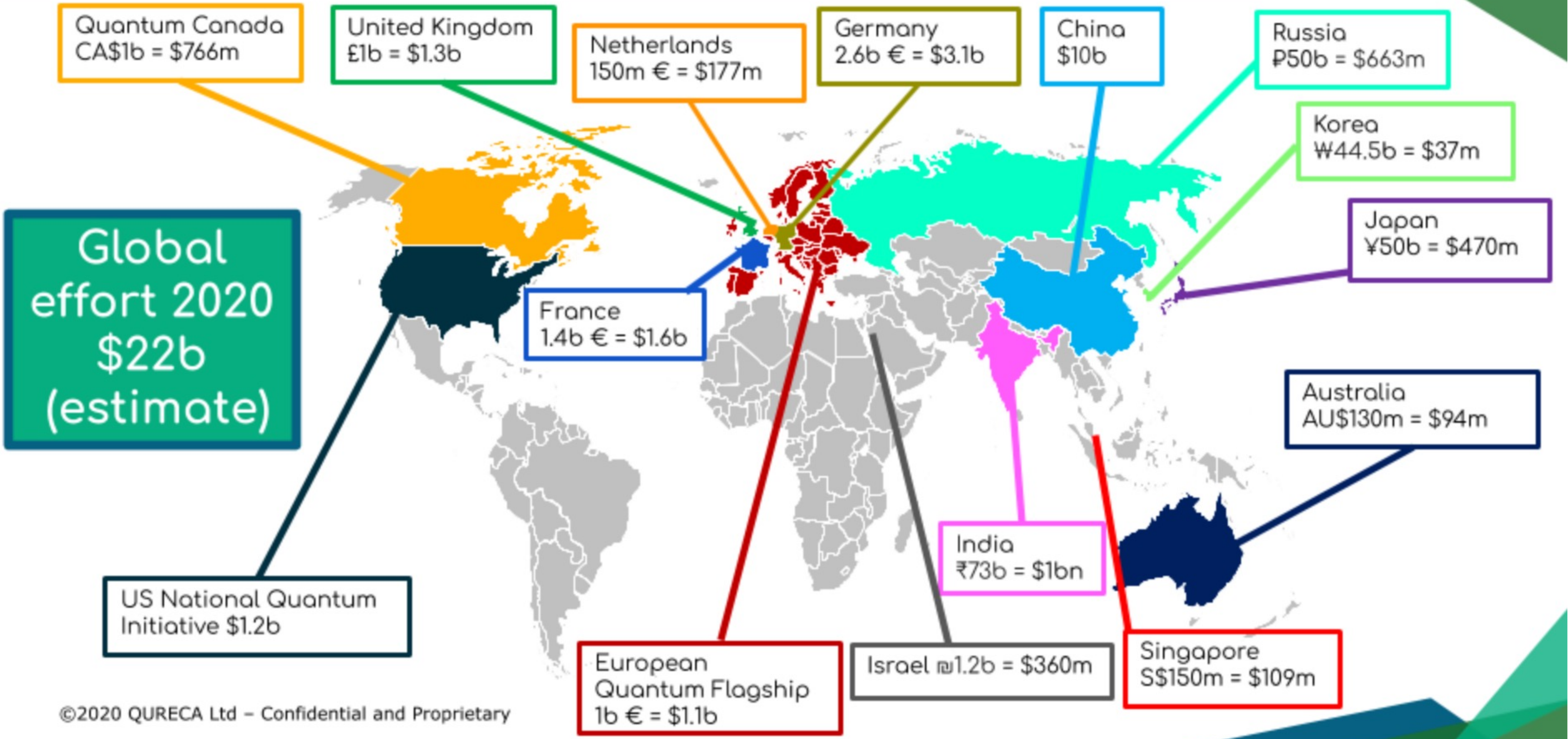
Quantum Liquid Crystals

Quantum Mind Interface

Quantum enabled searches for dark matter

Quantum Gravity

Quantum Technologies Public Funding Worldwide



£1bn UK National Quantum Technology Programme Pillars

2019

UKRI Engineering and Physical Sciences Research Council

QT Hubs, Training and Skills, CDTs
£360M

Translating research into applications

Industry-pick up points

UKRI Innovate UK

IUK, ISCF, Industry
£450M

Prototypes

Products

Spin-offs

Department for Business, Energy & Industrial Strategy

NPL National Physical Laboratory

Quantum Metrology Institute
£30M

Standards

Validation

GCHQ [dstl] Ministry of Defence

Other
£80M

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

£1bn UK National Quantum Technology Programme Pillars

2020

Science and Technology Facilities Council
Engineering and Physical Sciences Research Council

Quantum Technologies for Fundamental Physics (QTFP)
£40M

New Ideas

Attracting worldwide talent

Internationally leading science across 7 projects

National Quantum Computing Centre
£93M

Engineering and Physical Sciences Research Council

QT Hubs, Training and Skills, CDTs
£360M

Translating research into applications

Industry-pick up points

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Spin-offs

GCHQ [dstl] Ministry of Defence

Other
£80M

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Quantum Technologies for Fundamental Physics

Quantum Technologies for Fundamental Physics (QTFP) is a £40 million Strategic Priorities Fund (SPF) programme that aims to transform our approach to understanding the universe and its evolution.

The QTFP programme aims to demonstrate how quantum technologies can be utilised to investigate key fundamental physics questions such as the search for dark matter, the nature of gravity and measurements of the quantum properties of elementary particles, thus ensuring the UK remains a first rank nation in the physics and quantum communities around the world.

Seven projects have been funded under this programme:

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Search

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QTNM

QI QSNET QSHS AION QUEST DMC QSimFP

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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
- 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

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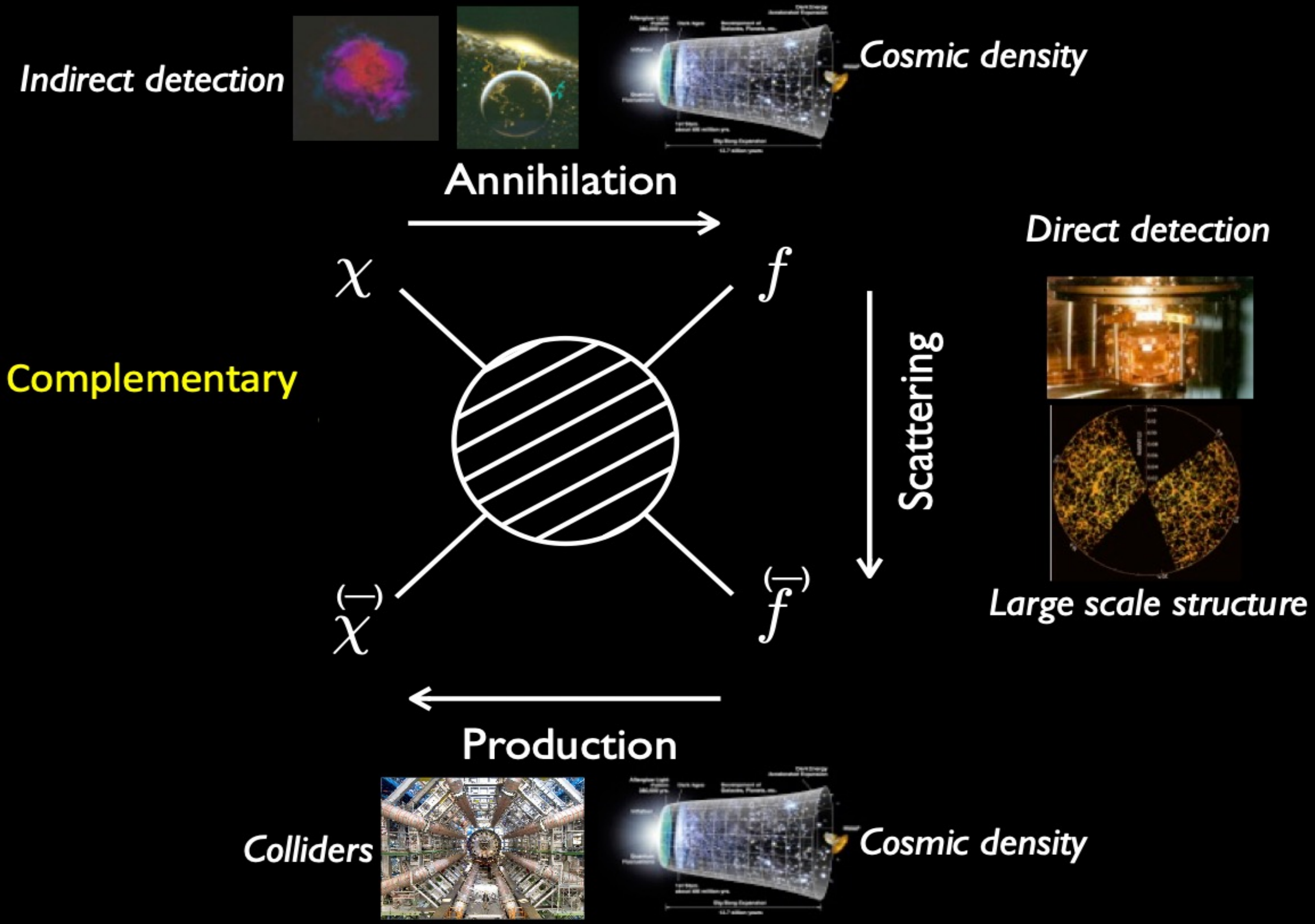
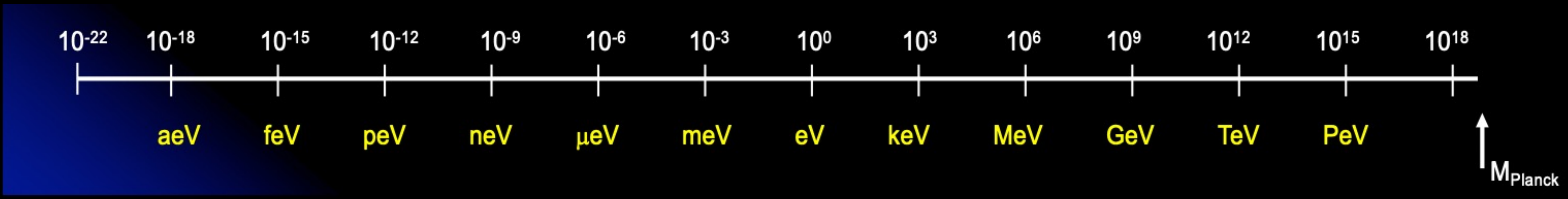
Dark Matter Experimental approaches

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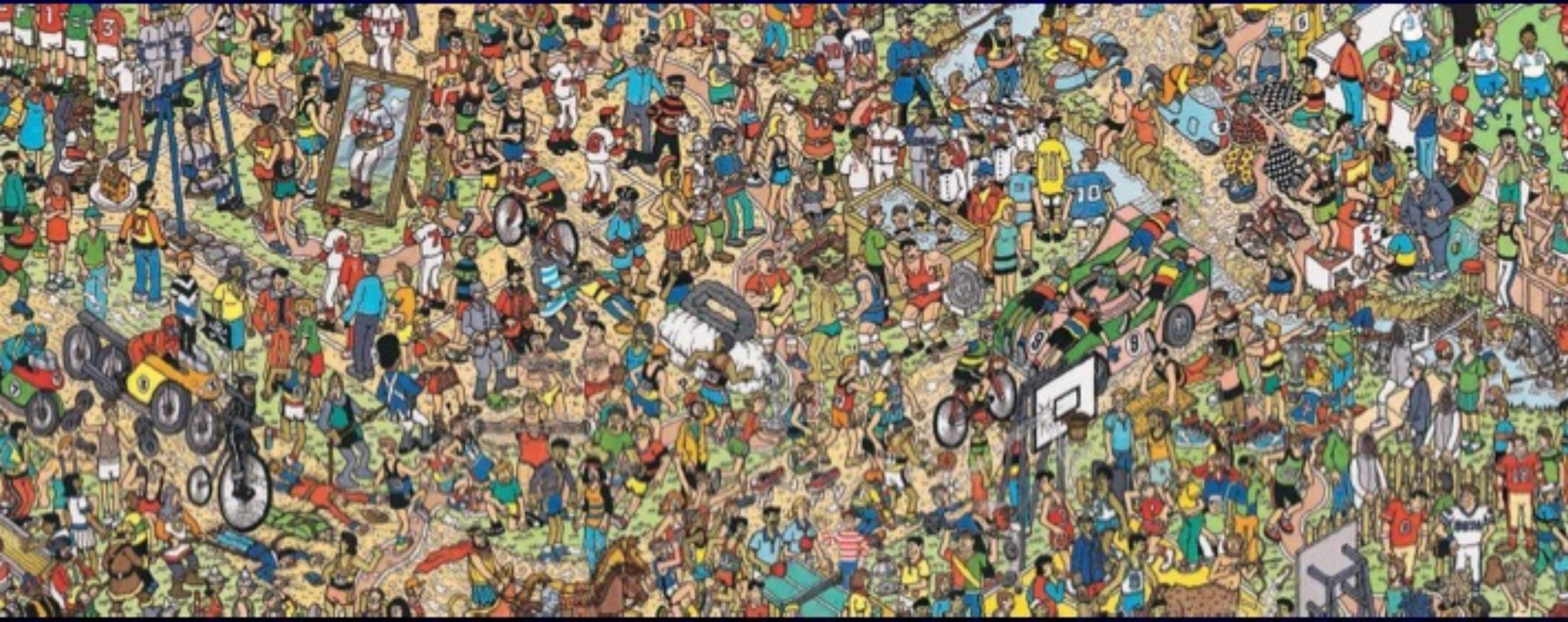
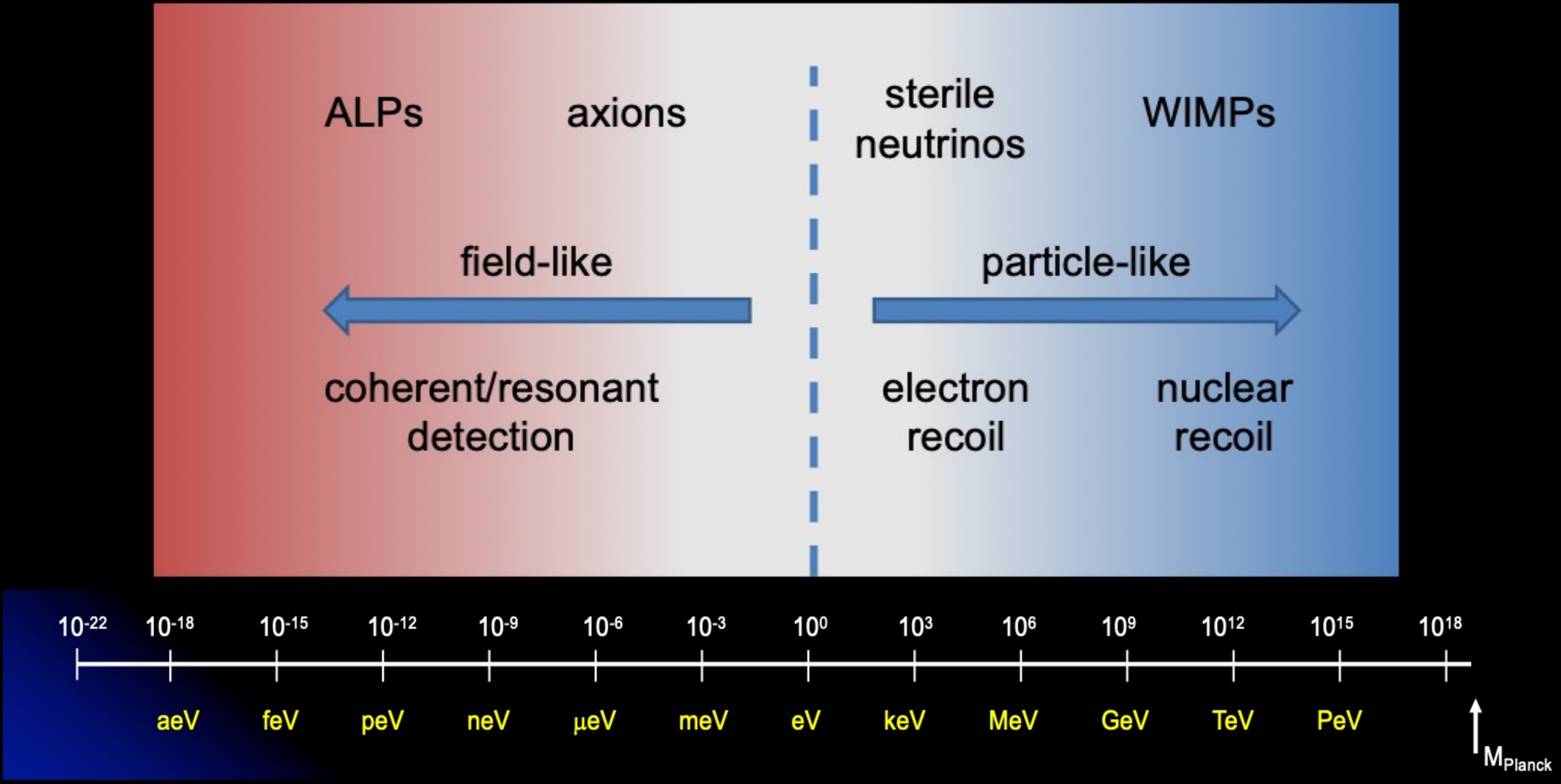
1018
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
MPlanck

Possible Dark Matter Masses

~90 orders of magnitude

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




ALPs
axions
sterile neutrinos
WIMPs
field-like
particle-like
coherent/resonant detection
electron recoil
nuclear recoil
10-22
10-18
10-15
10-12
10-9
10-6
10-3
100
103
106
109
1012
1015
1018
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
MPlanck

Dark Matter Search Strategy

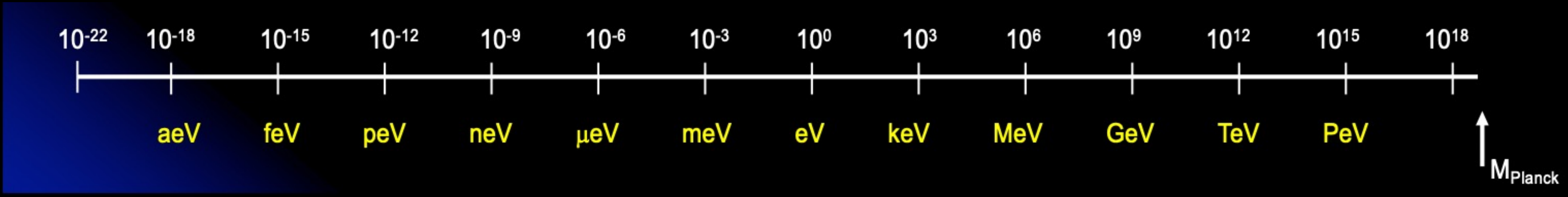
The two theoretically best-motivated candidates:

AXIONS (light)

"table top" expts with quantum sensors

WIMPS (heavy)

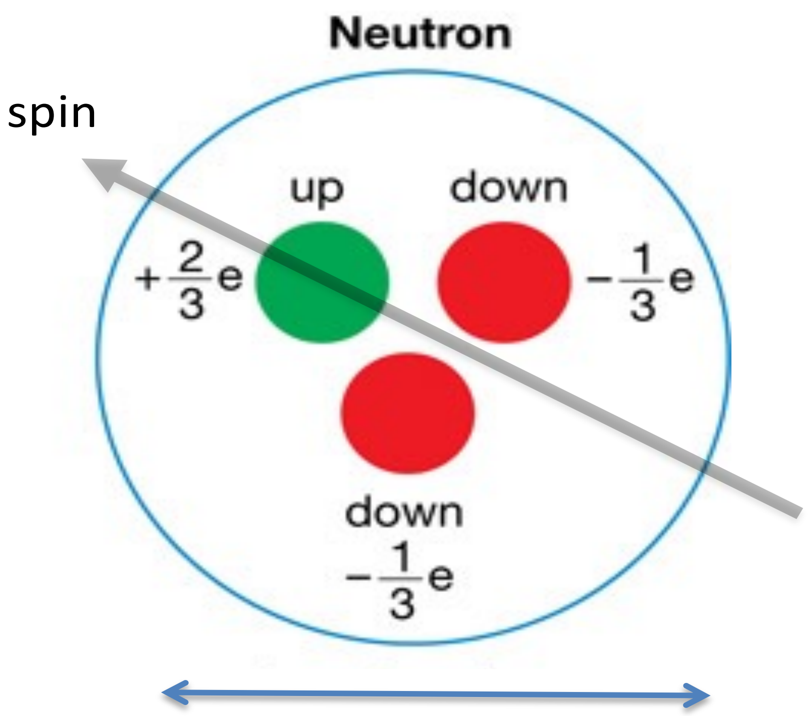
Multi-ton expts deep underground



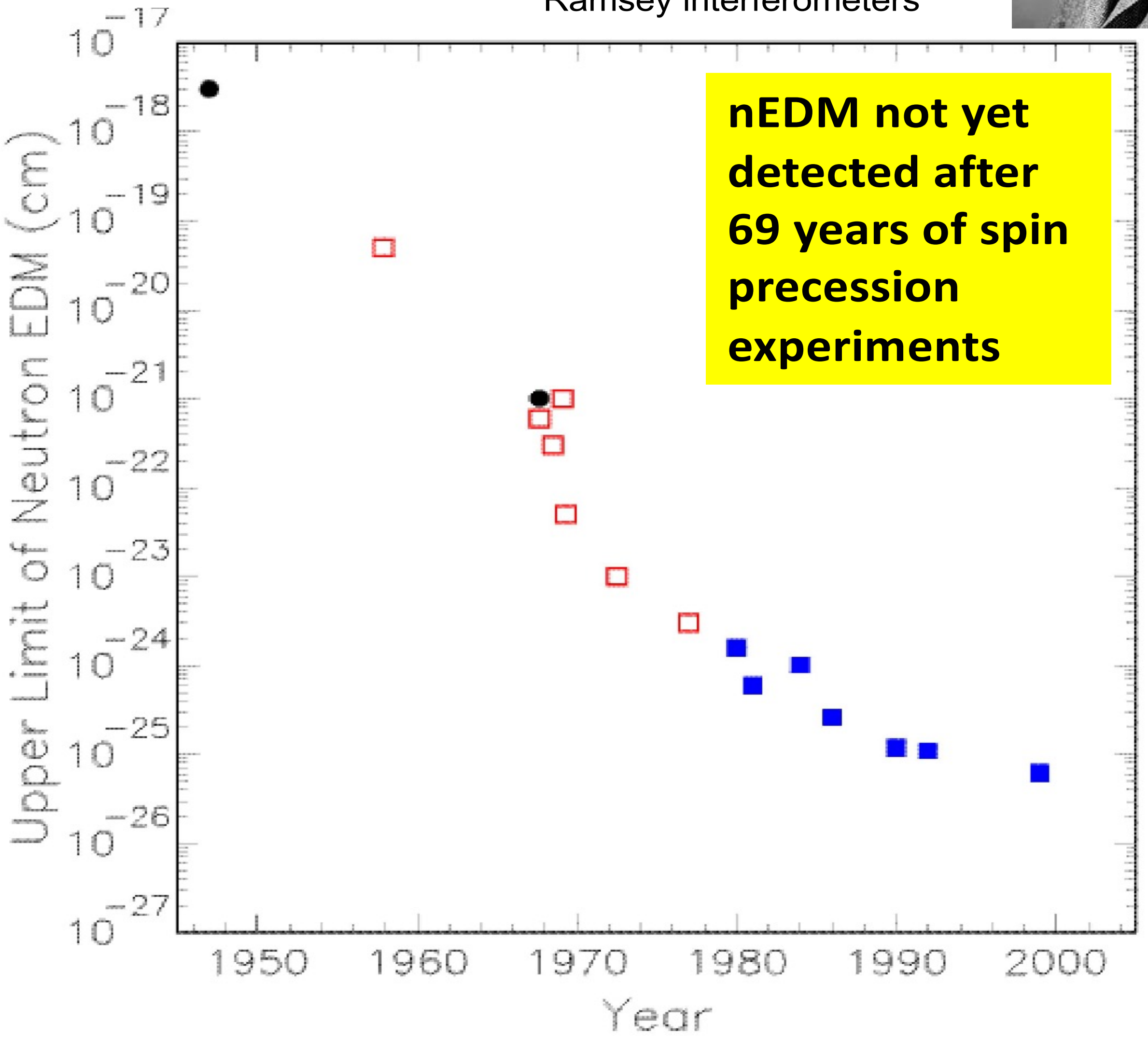
QCD axion motivated by the Strong-CP Problem:
Why is the neutron electric dipole moment so small?

Norman Ramsey
Nobel Prize 1989.
Neutrino oscillation expts are "Ramsey interferometers"

Naive estimate gives
nEDM ≈ 10^{-16} e-cm



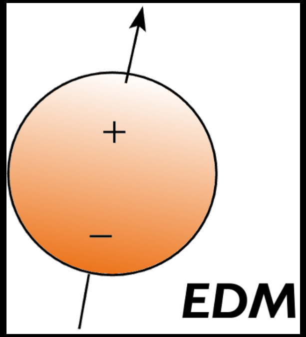
10^{-15} m



nEDM not yet detected after 69 years of spin precession experiments

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 θ_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).

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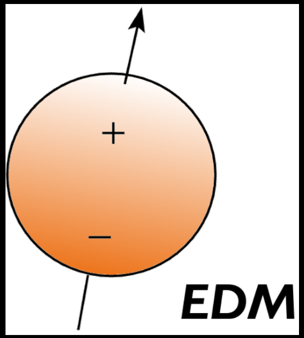

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- nEDM ~ e fm θ_s
- Experimental bound θ_s $<10^{-10}$
- Solution is that $\theta_s \sim a(x,t)$ is a dynamical field, an axion
- Axion field: $a(x,t) = a_0 \cos \omega_a t,$ with Compton frequency: $\omega_a = \mu_a c^2/\hbar$
  f_a is the symmetry 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:

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

Elements of String Theory

Credit:Mario Livio

Extra Dimensions

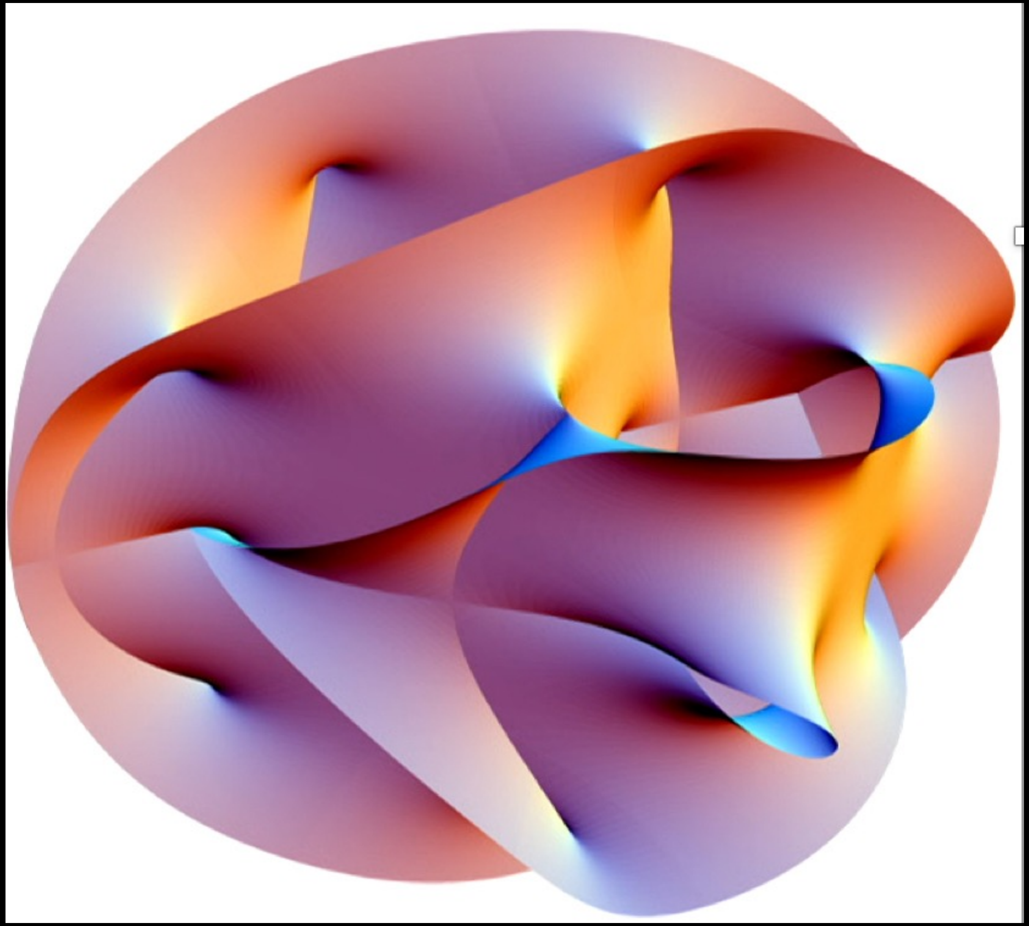
Gauge Fields

Topology

Give rise to a plenitude of Universes

A Plenitude of Massless Particles

Compactification Naturally Gives Rise to Massless Particles



In the presence of non-trivial topology
Non-trivial gauge configurations can carry no energy
Resulting in 4D massless particles

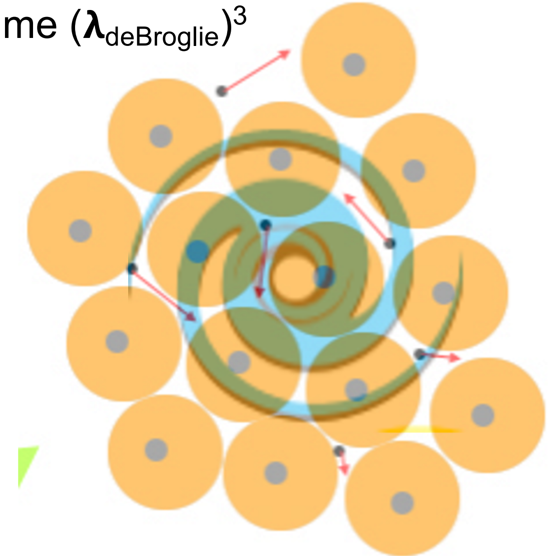
Based on a slide
by Mina Arvanitaki

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

Low mass dark matter generically takes the form of classical bosonic sine waves

Fermions: 1 DM particle per mode volume $(\lambda_{deBroglie})^3$



For **mass < 70 eV**, Pauli exclusion principle causes dark matter clumps to swell up to be larger than the size of the smallest dwarf galaxies. (Randall, Scholtz, Unwin 2017)

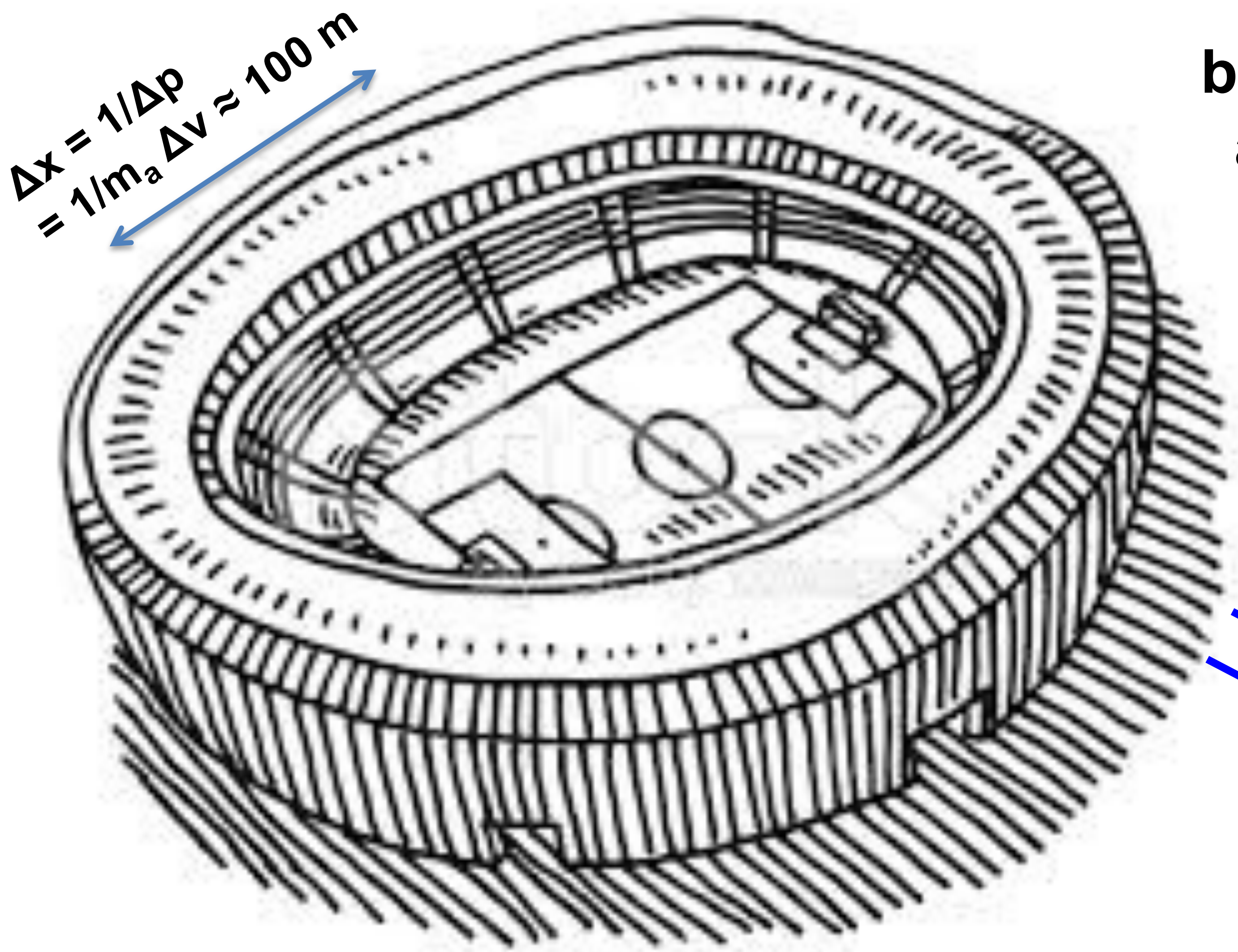
→ If lower mass, dark matter must be coherent bosonic sine waves with **macroscopic mode occupation number >>1**

Not billiard balls.

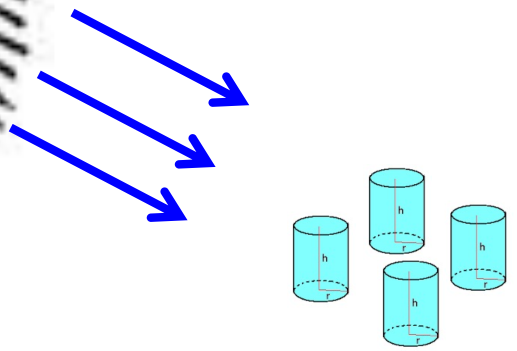
Need coherent wave detector.

e.g. 10^{-5} eV = GHz dark matter

Non-relativistic bosonic DM is like a slow CW laser with $f=m_a/2\pi$



$v \approx \Delta v \approx 300$ km/s (galactic escape velocity)



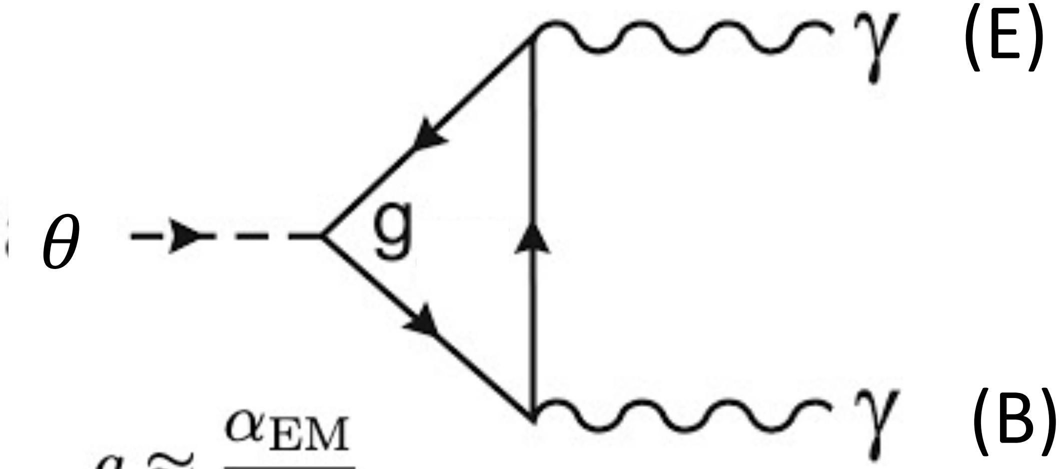
Football stadium-sized regions of coherently oscillating **classical sine waves** slowly drifting through detectors. Mean DM occupation number **N>10^{22} per mode.**

Accumulate oscillatory signals in various kinds of laboratory oscillators which are weakly coupled to the DM wave

Signal strength is independent of m_a, f_a

Wave amplitude and hence signal strength depends only on local dark matter density ρ_a !

Experimental goal:
Determine frequency of the signal and hence the axion mass



$$g \approx \frac{\alpha_{EM}}{4\pi}$$

The Dark Matter Haloscope:

Classical axion wave drives RF cavity mode

Pierre Sikivie,
Sakurai Prize 2019

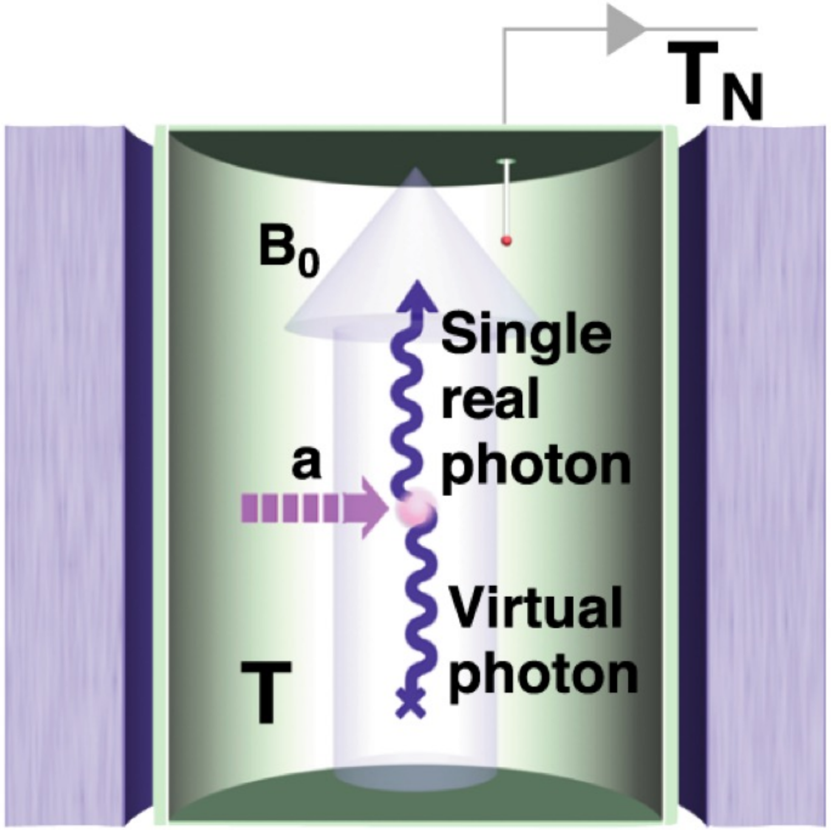
- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

$$\vec{J}_a(t) = -g\theta\vec{B}_0 m_a e^{im_a t}$$

which drives E&M via Faraday's law:

$$\vec{\nabla} \times \vec{H}_r - \frac{d\vec{D}_r}{dt} = \vec{J}_a$$

- Periodic cavity boundary conditions extend the coherent interaction time **(cavity size ≈ 1/m$_a$) →** the exotic current excites standing-wave RF fields.

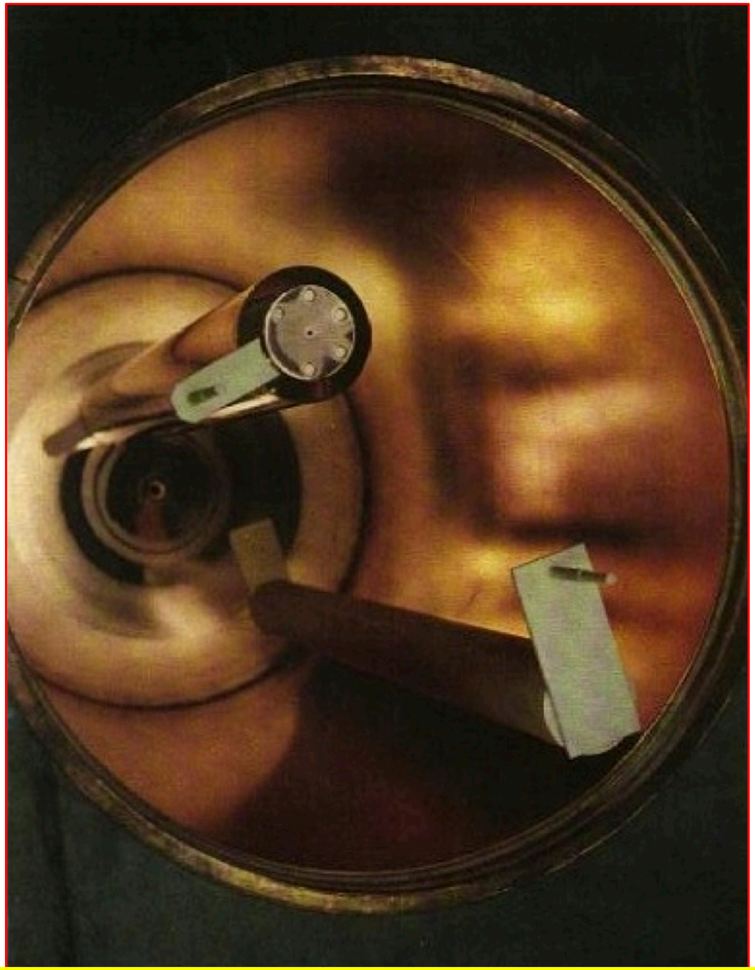


A spatially-uniform cavity mode can **optimally** extract power from the dark matter wave

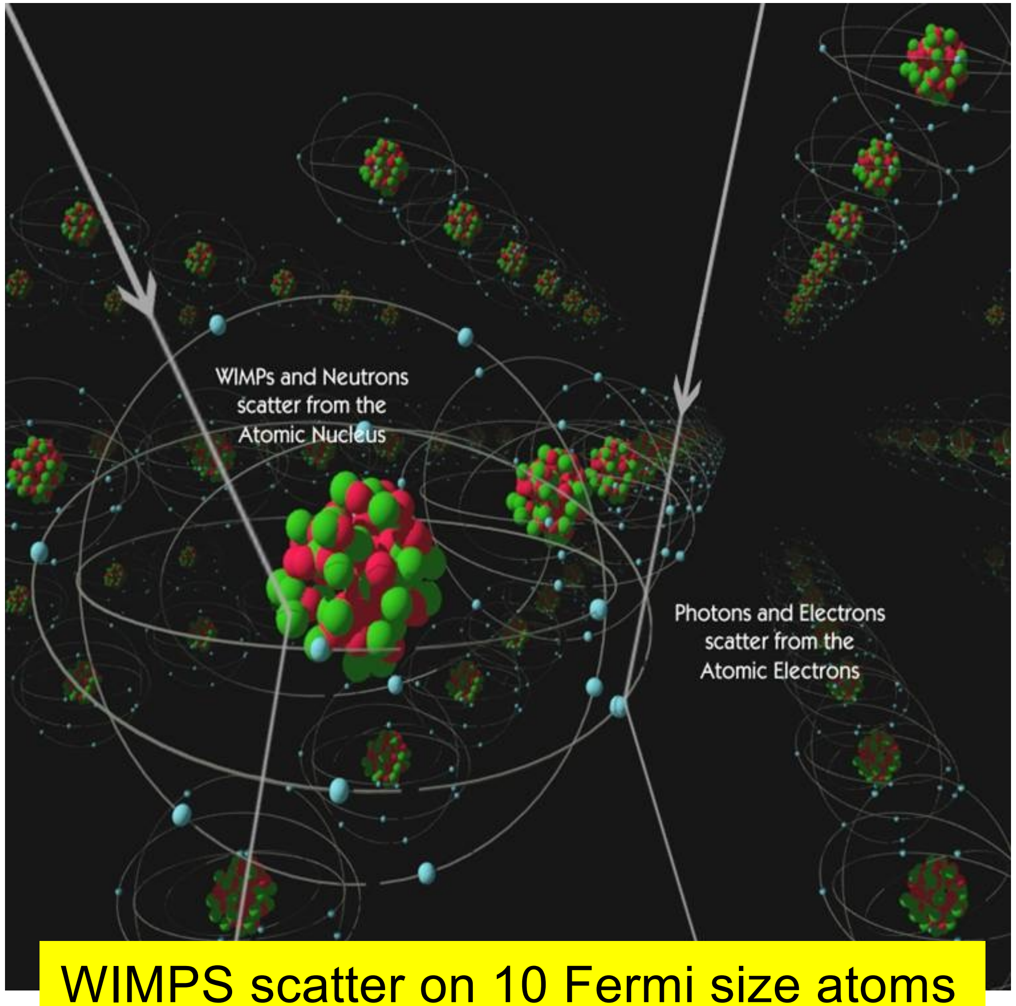
$$P_a(t) = \int \vec{J}_a(t) \cdot \vec{E}_r(t)\ dV$$

Axions vs WIMPs:

Resonant scattering requires size of scattering target = 1/(momentum transfer)



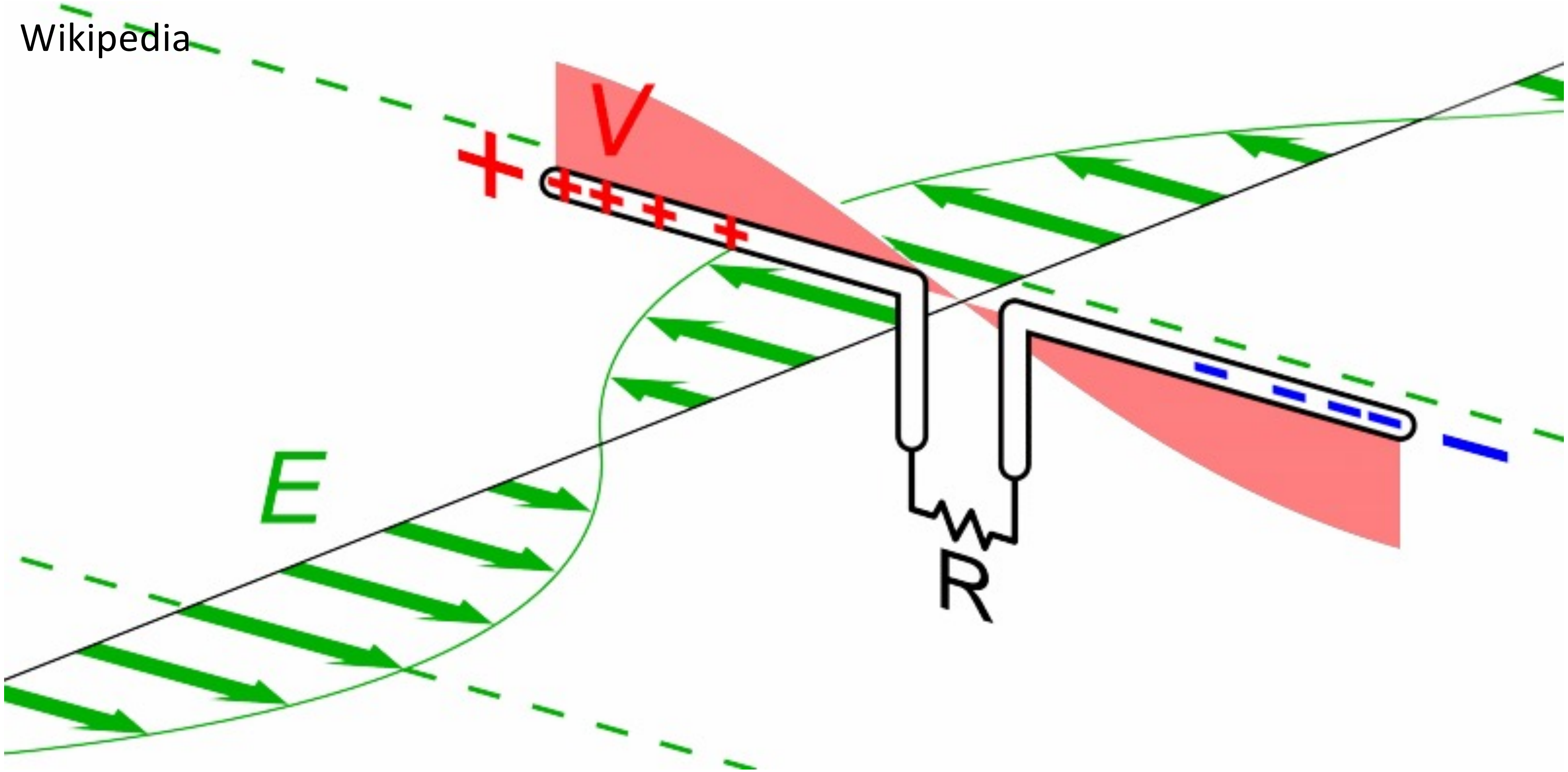
4 μeV mass axions scatter on 50cm size microwave cavities



WIMPS scatter on 10 Fermi size atoms

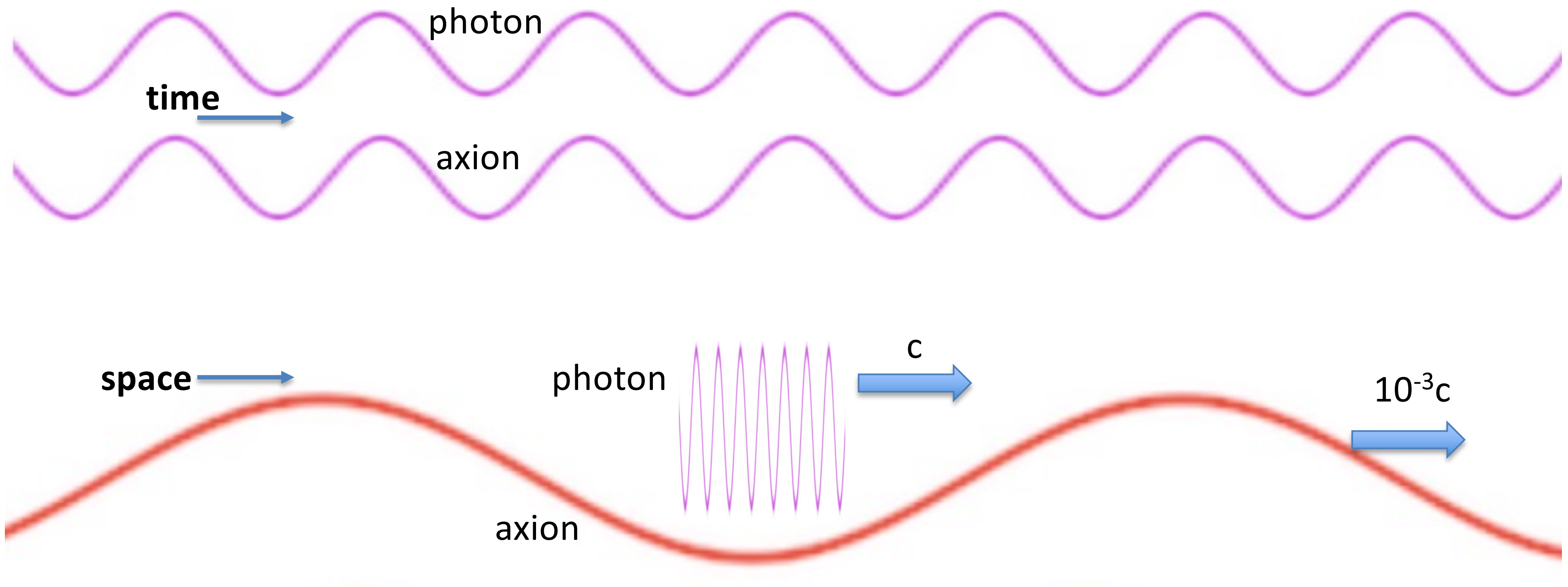
Match size of antenna to wavelength of signal

Wikipedia



Wave mechanics: scattering matrix element is proportional to spatial Fourier transform of the scattering potential, with respect to the momentum transfer

Both axion and photon waves oscillate in time at the same frequency m_a



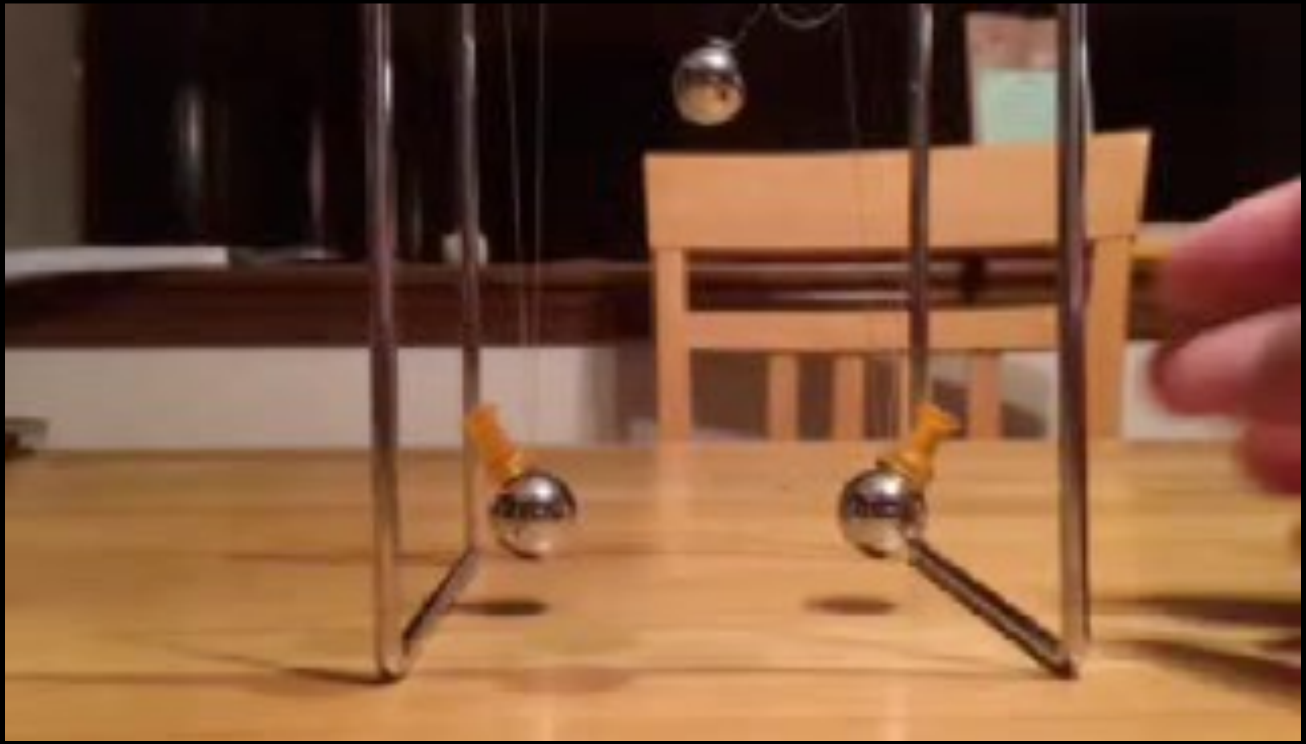
In space, the axion wave is 1000x longer and 1000x slower,
so it can coherently drive the same photon wave through Q_a=10^6 temporal oscillations.

In real life, the cavity has losses and so the photon might not live as long as 10^6 oscillations.

Usually $Q_c < Q_a$

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

Detection oscillator



Axion wave

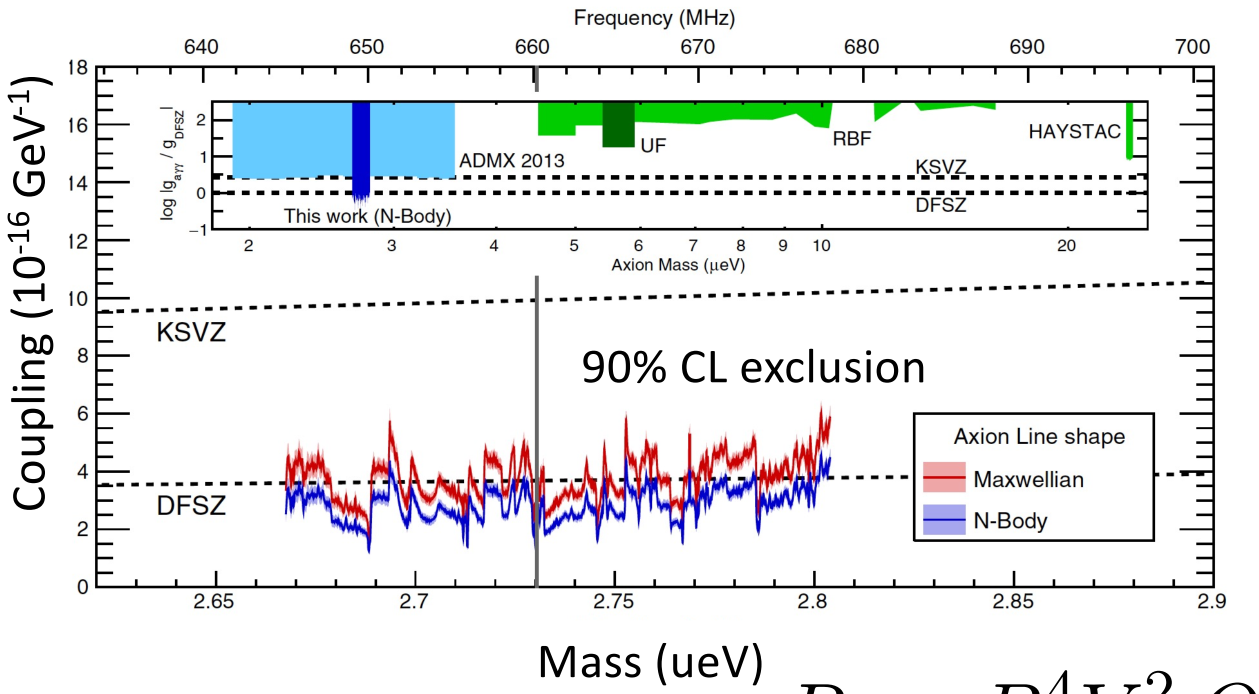
Weak coupling -- takes many swings to fully transfer the wave amplitude.
In real life, Q = number of useful swings is limited by coherence time.

2017: 30-year axion R&D program culminates in first sensitivity to DFSZ axions

PRL 120, 151301 (2018)

ADMX at U.Washington,
FNAL = DOE lead lab

Operate an ultrasensitive radio in a cold, RF-shielded box to tune in to the axion broadcast.

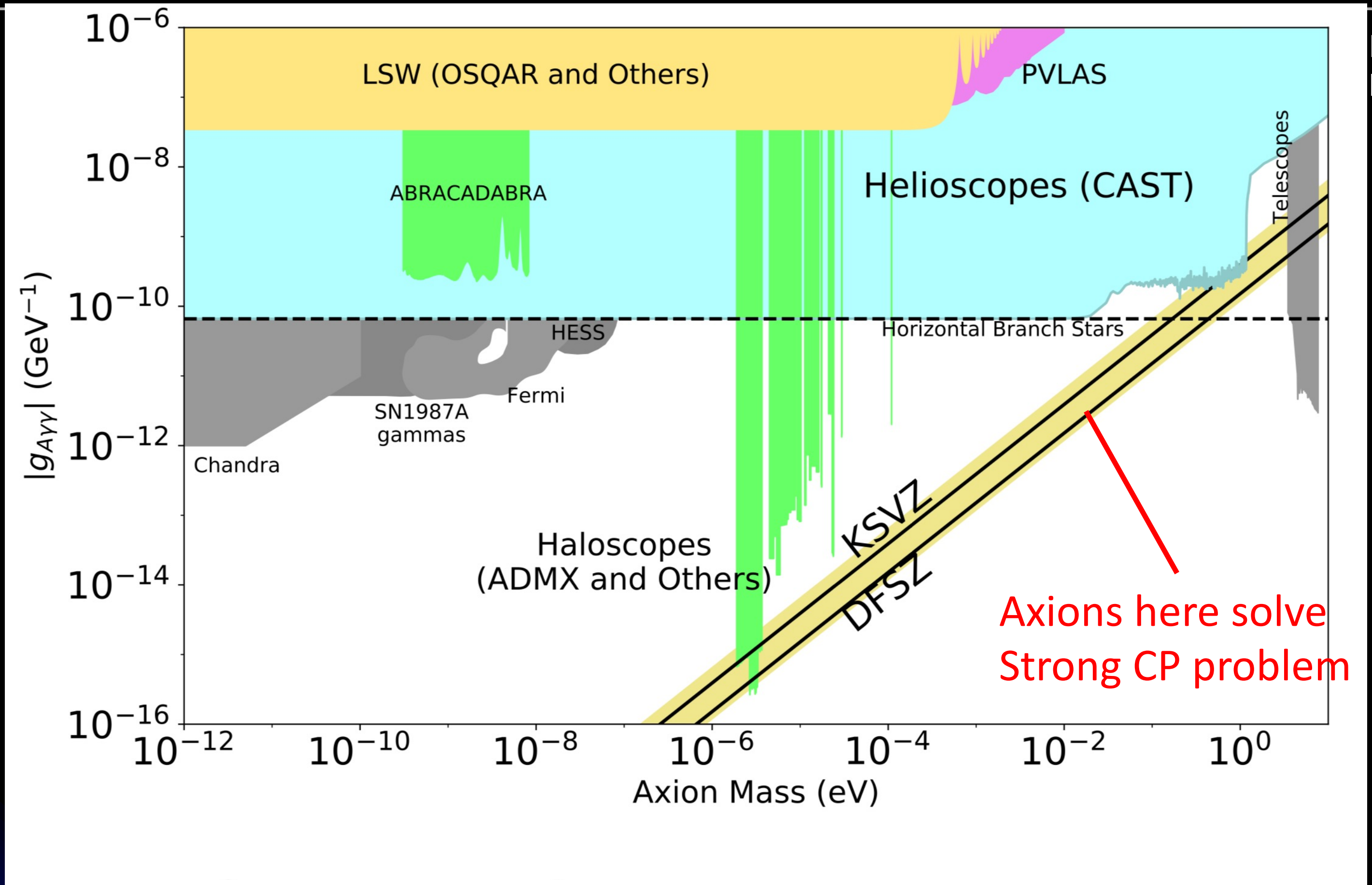


$$R \propto B^4 V_{\mathrm{eff}}^2 Q_0 / N_{\mathrm{sys}}^2$$

Look for "spontaneous" emission from local axion dark matter into the empty cavity mode.

Signal power level = 10^{-23} W
Need 15 minutes integration per radio tuning to beat thermal noise power at 500 mK.

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:

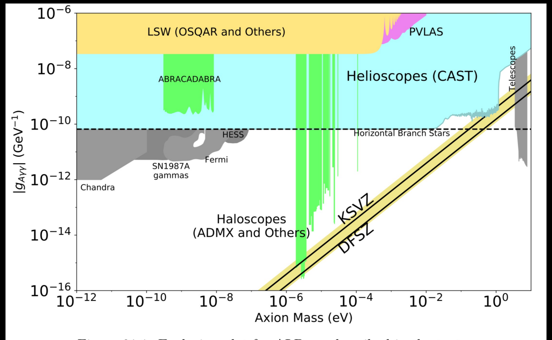


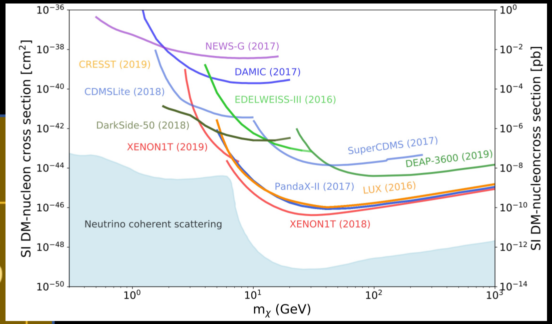
Figure 91.1: Exclusion plot for ALPs as described in the text.

AXIONS (light)

"table top" expts with quantum sensors

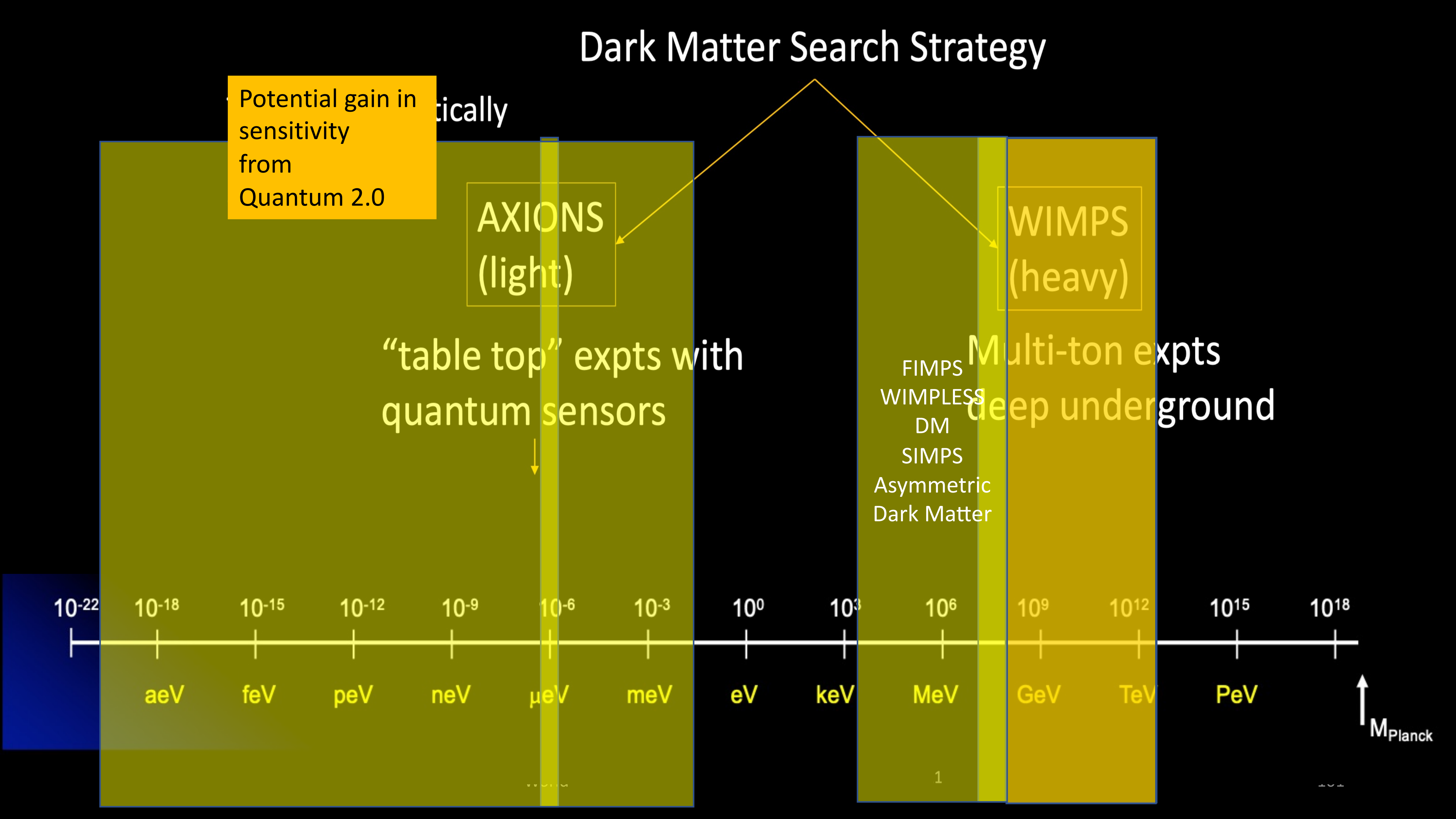
WIMPS (heavy)

Multi-ton expts deep underground

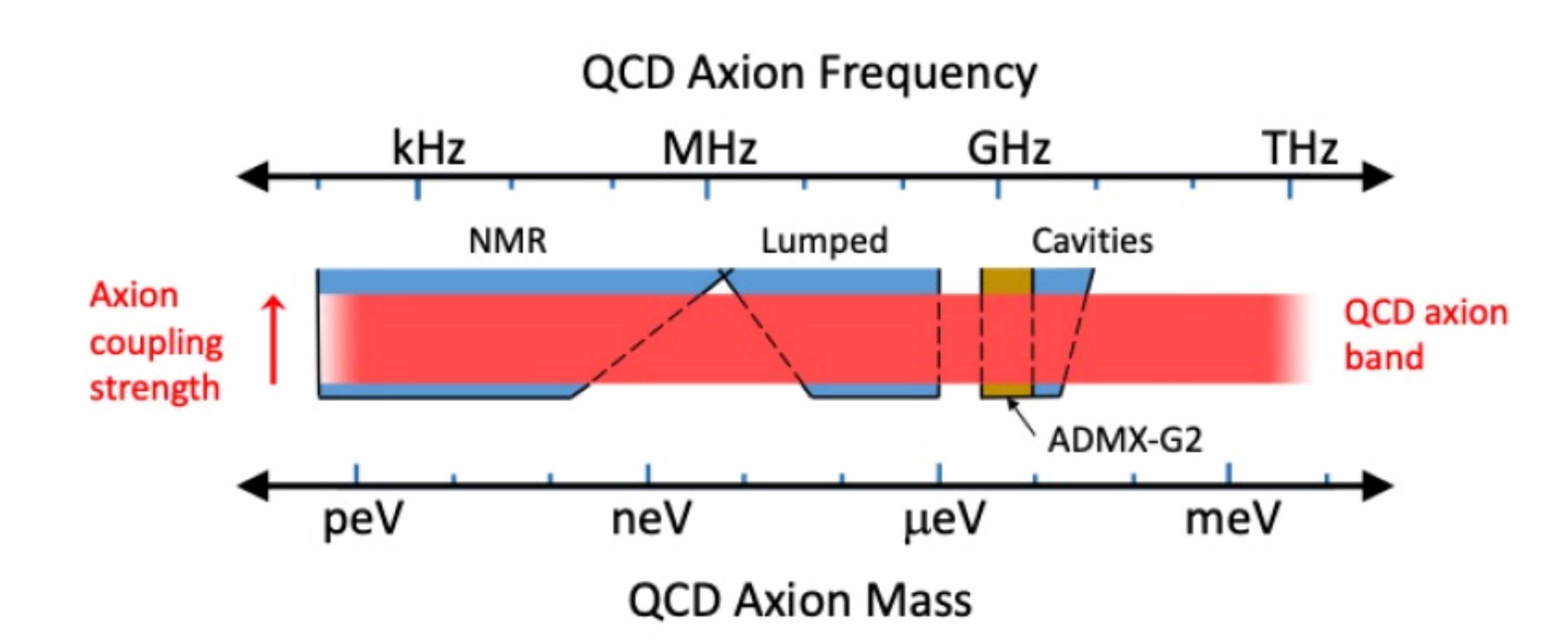


10^{-22} | 10^{-18} aeV | 10^{-15} feV | 10^{-12} peV | 10^{-9} neV | 10^{-6} μeV | 10^{-3} meV | 10^{0} eV | 10^{3} keV | 10^{6} MeV | 10^{9} GeV | 10^{12} TeV | 10^{15} PeV | 10^{18} ↑ M_{Planck}

1


Dark Matter Search Strategy
Potential gain in sensitivity from Quantum 2.0
tically
AXIONS (light)
"table top" expts with quantum sensors
WIMPS (heavy)
Multi-ton expts deep underground
FIMPS
WIMPLESS DM
SIMPS
Asymmetric Dark Matter
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}

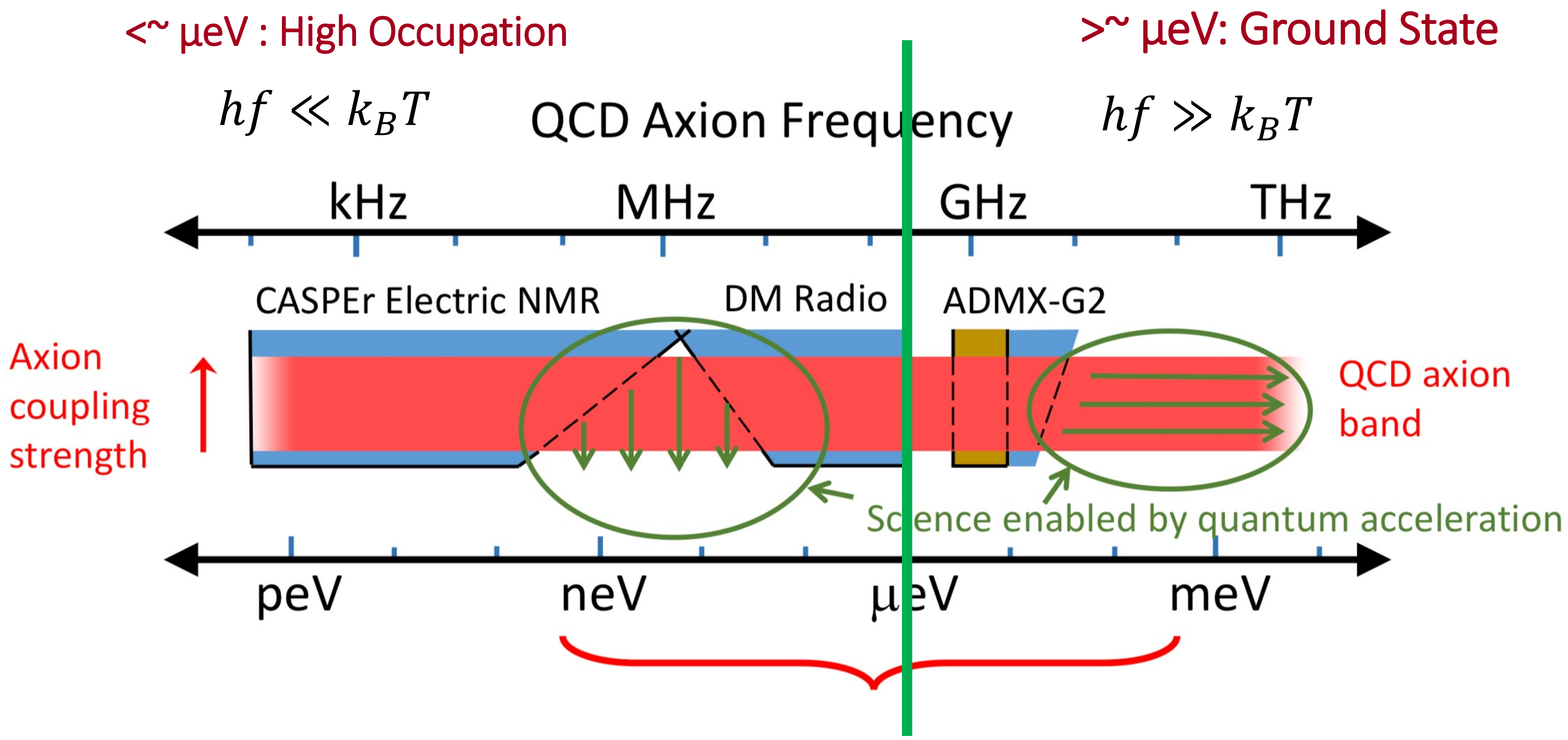
Parameter Space for QCD Axion Dark Matter



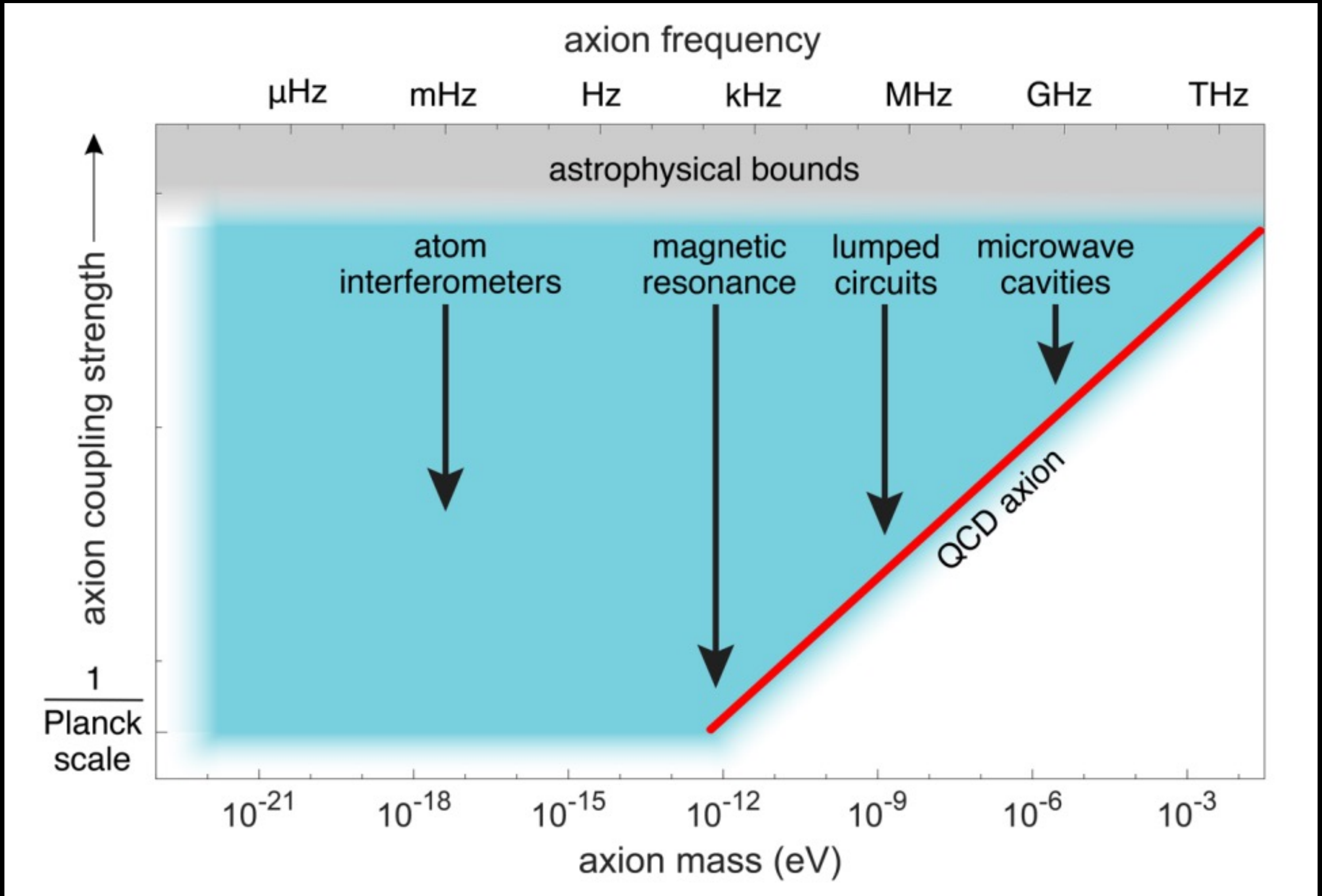
Graph: DOE OHEP BRN for Dark Matter Small Projects New Initiatives

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



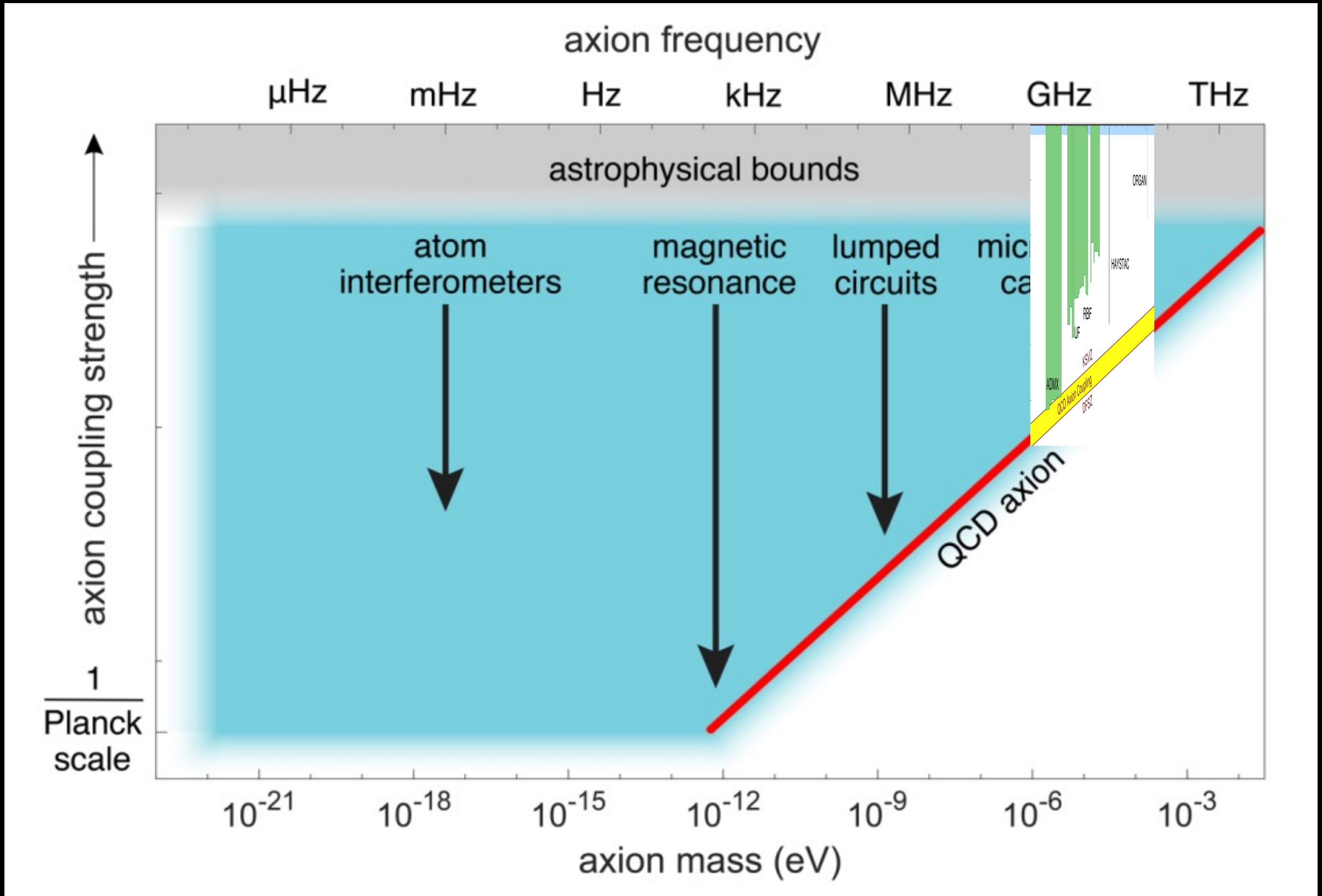
Parameter Space for General Axion Dark Matter



DOE HEP BRN
For Dark Matter
Small Projects
New Initiatives

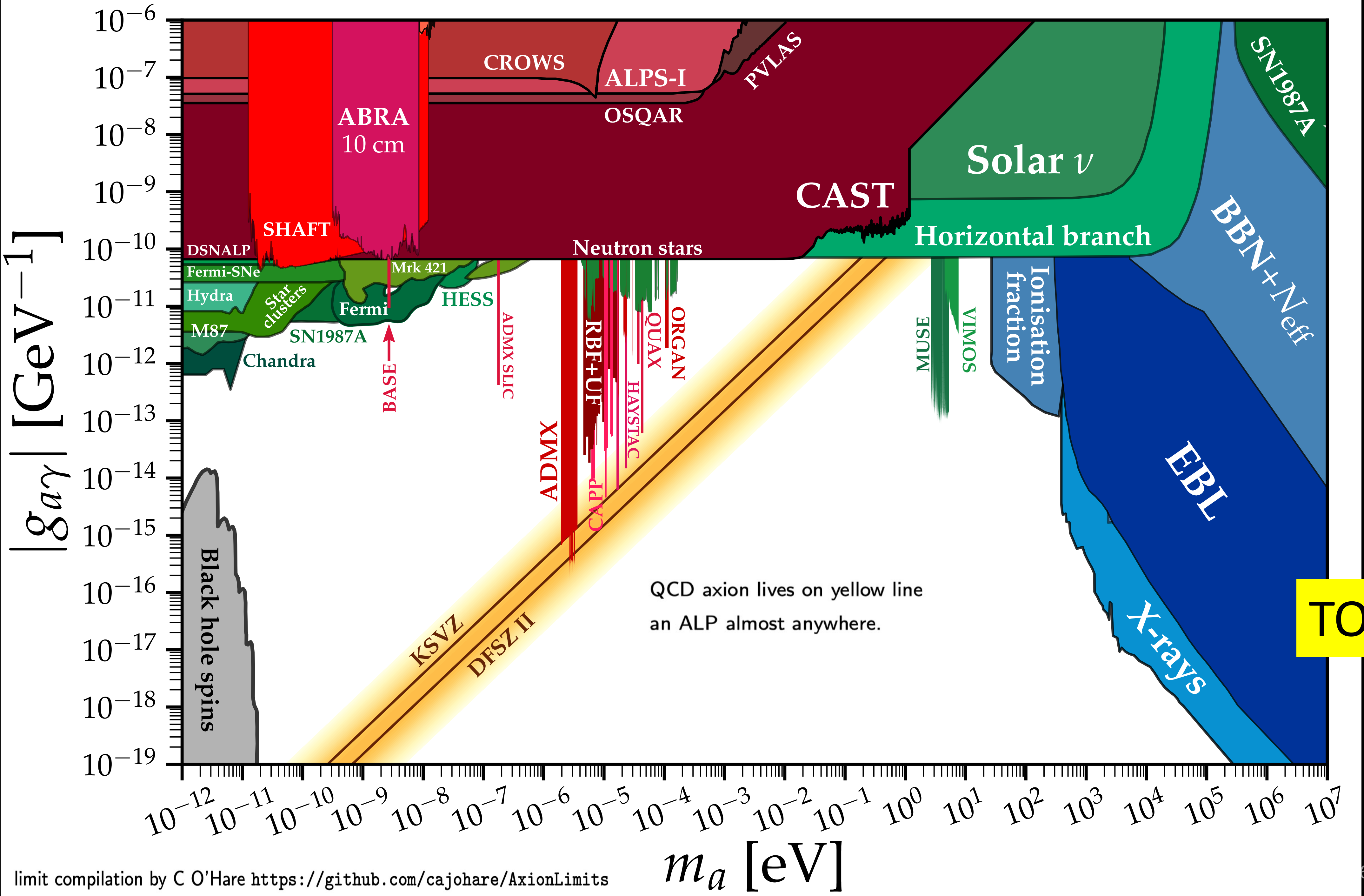
By general axion I mean any light scalar with suppressed couplings to the standard model

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)

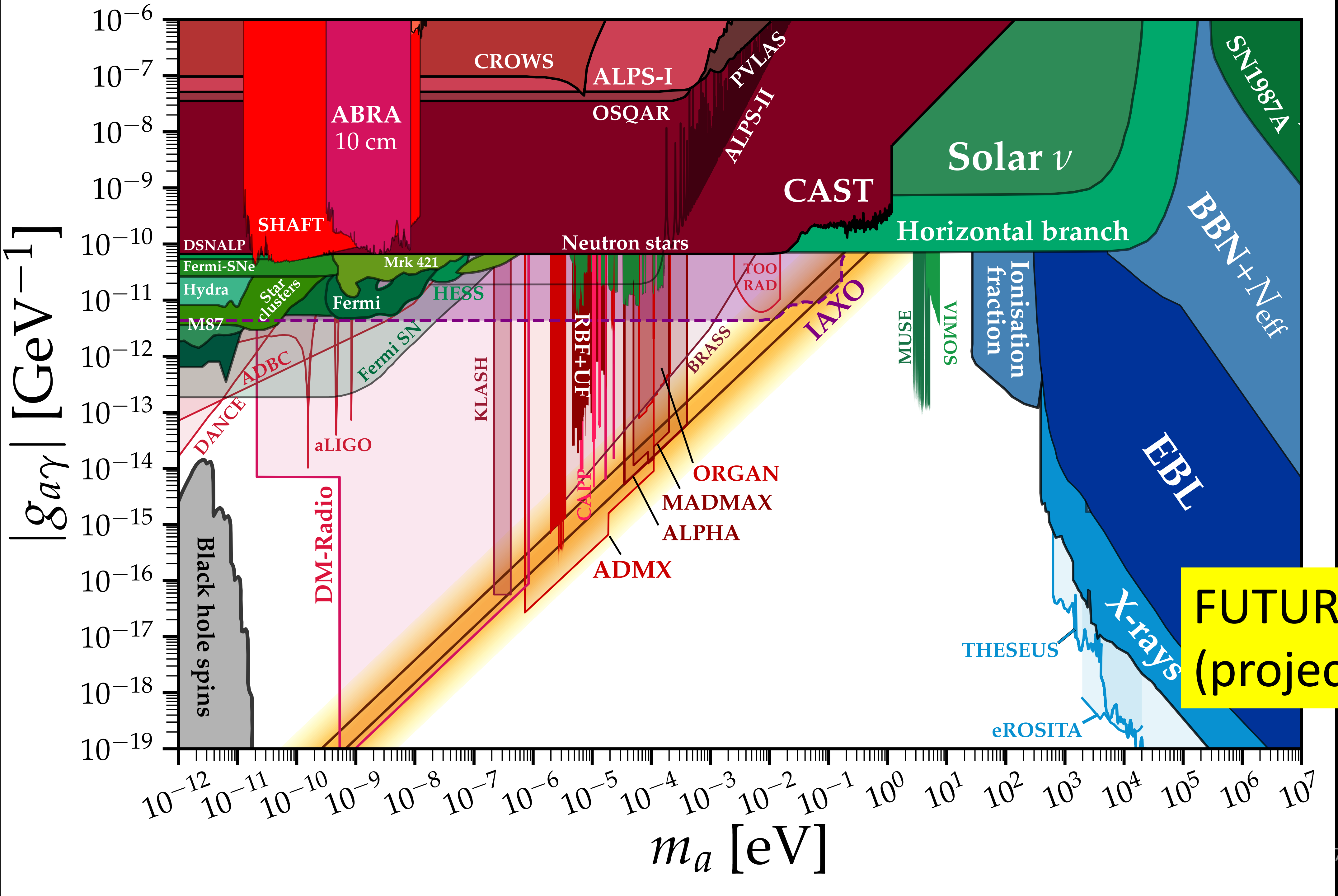
Axion Photon coupling



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

TODAY

Axion Photon coupling



FUTURE (projections)

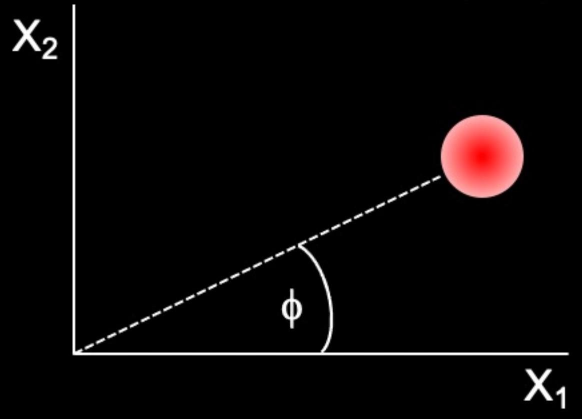
Standard Quantum Limit

- 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: $\Delta E\, \Delta t \;\geq\; \hbar/2$

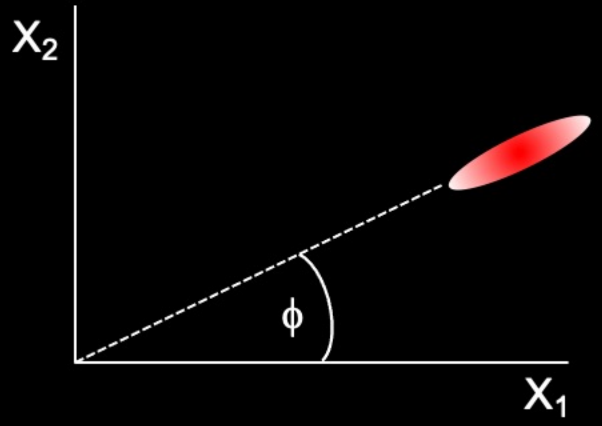
$$x(t) = X_1(t)\cos(\omega t) + X_2(t)\sin(\omega t)$$

- 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

Heisenberg Limit

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

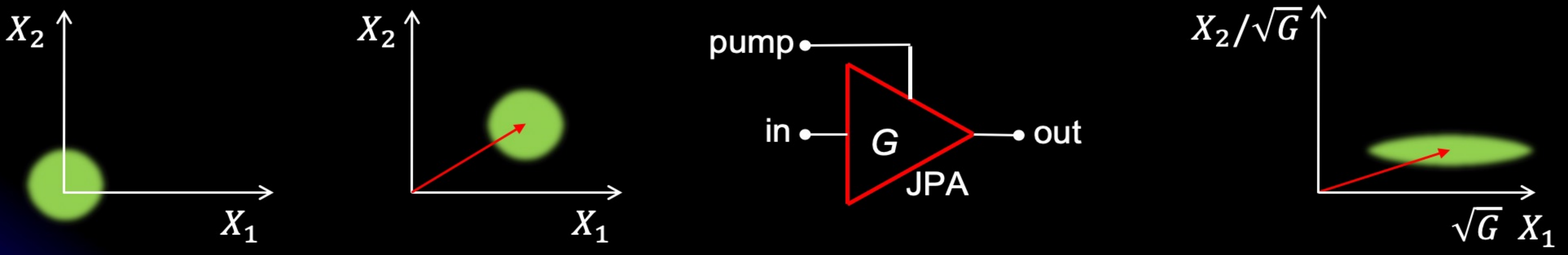
$$\Delta X \backsim 1 / \sqrt{N}$$

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

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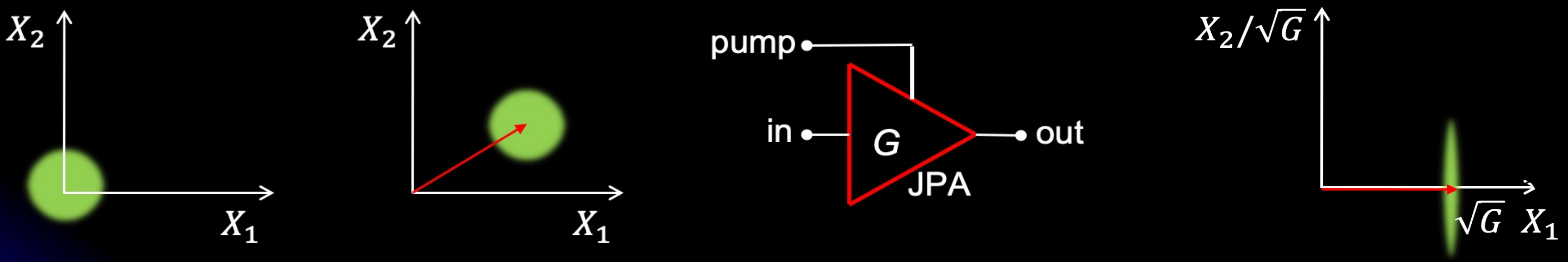
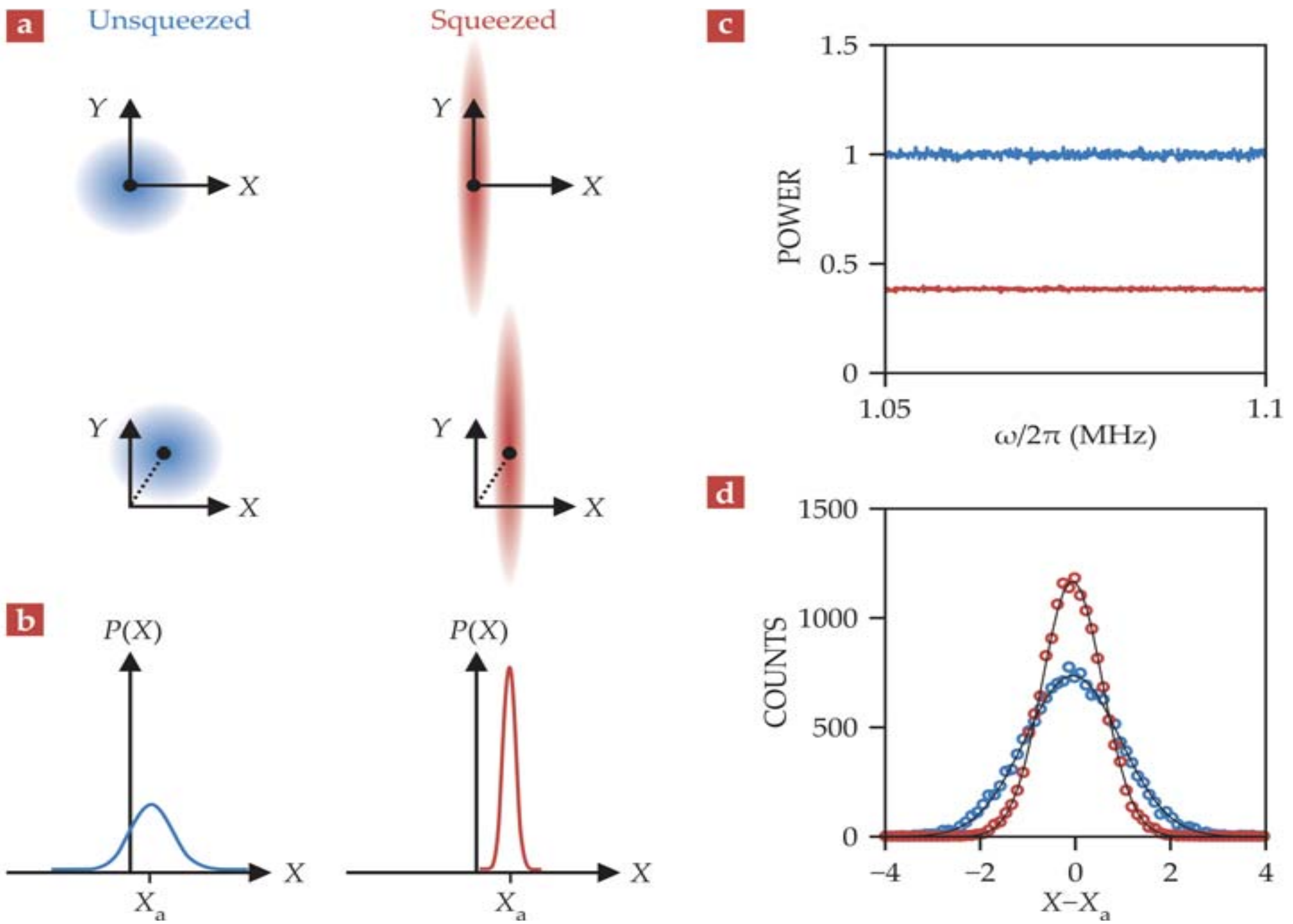


"vacuum state"

"displaced state"
(through interaction)

Amplification and
squeezing

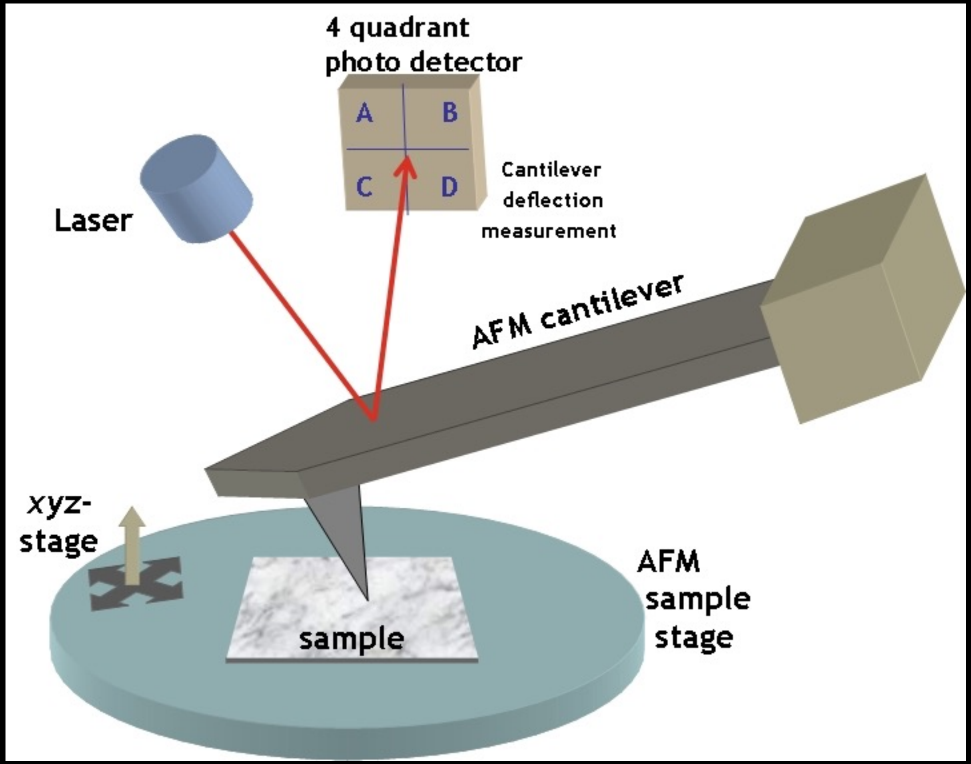
"measurement state"

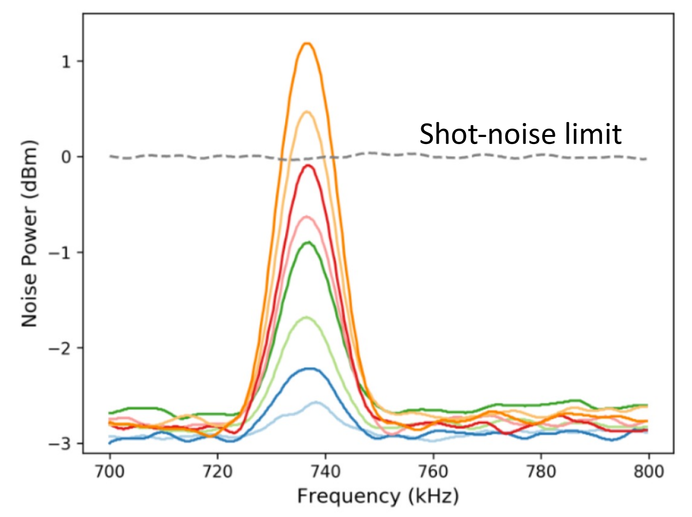


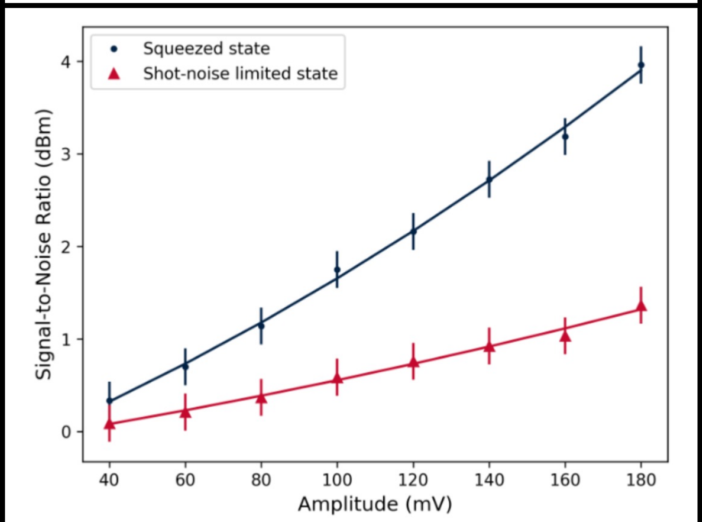
Physics Today **72**, 6, 48 (2019); doi: 10.1063/PT.3.4227

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.





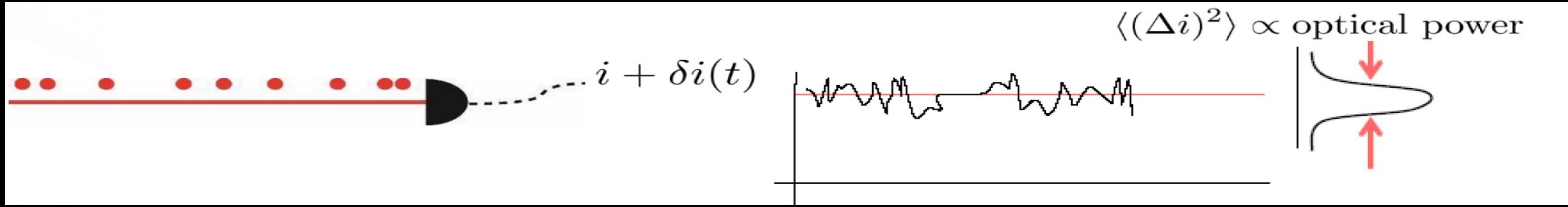


Physical Review Letters 124 (23), 230504 (2020)

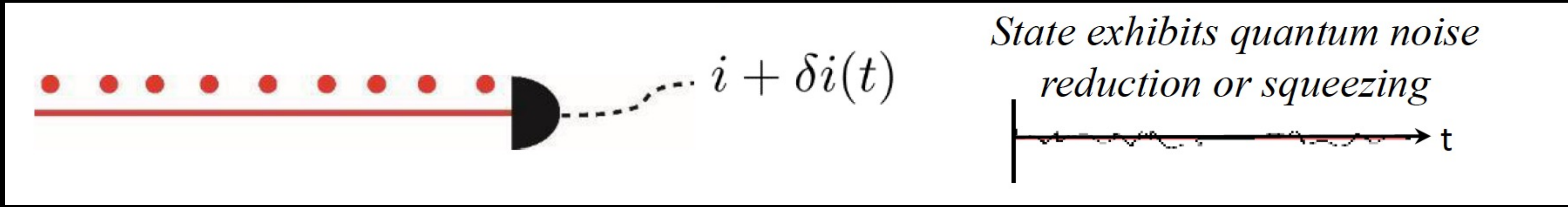
Beyond the SQL

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.

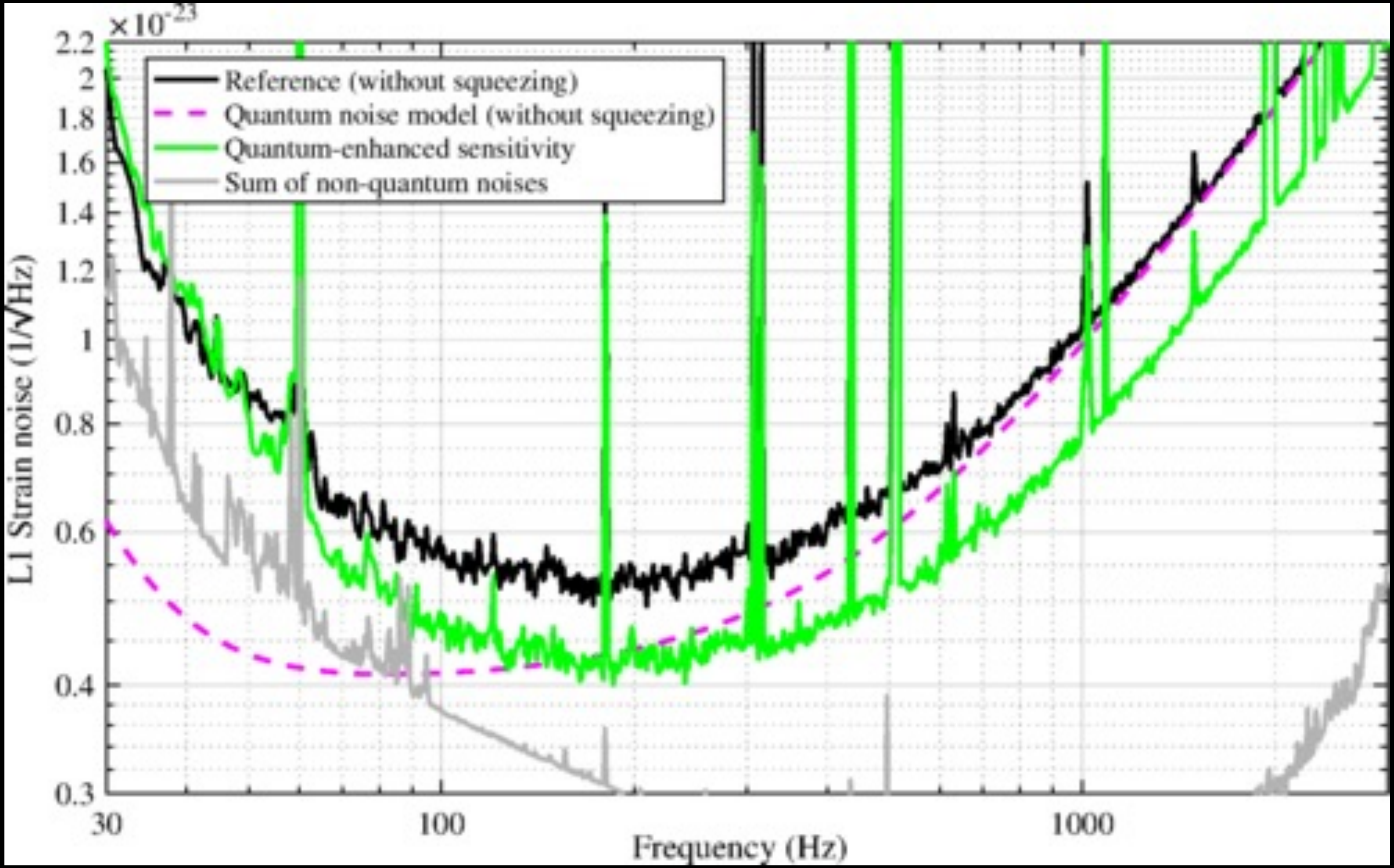


  - This noise represents the shot noise limit (SNL) and is the minimum noise level for a classical state of light.
  - One can generate states of light with less noise in amplitude through the use of a nonlinear process that can emit pairs of photons.



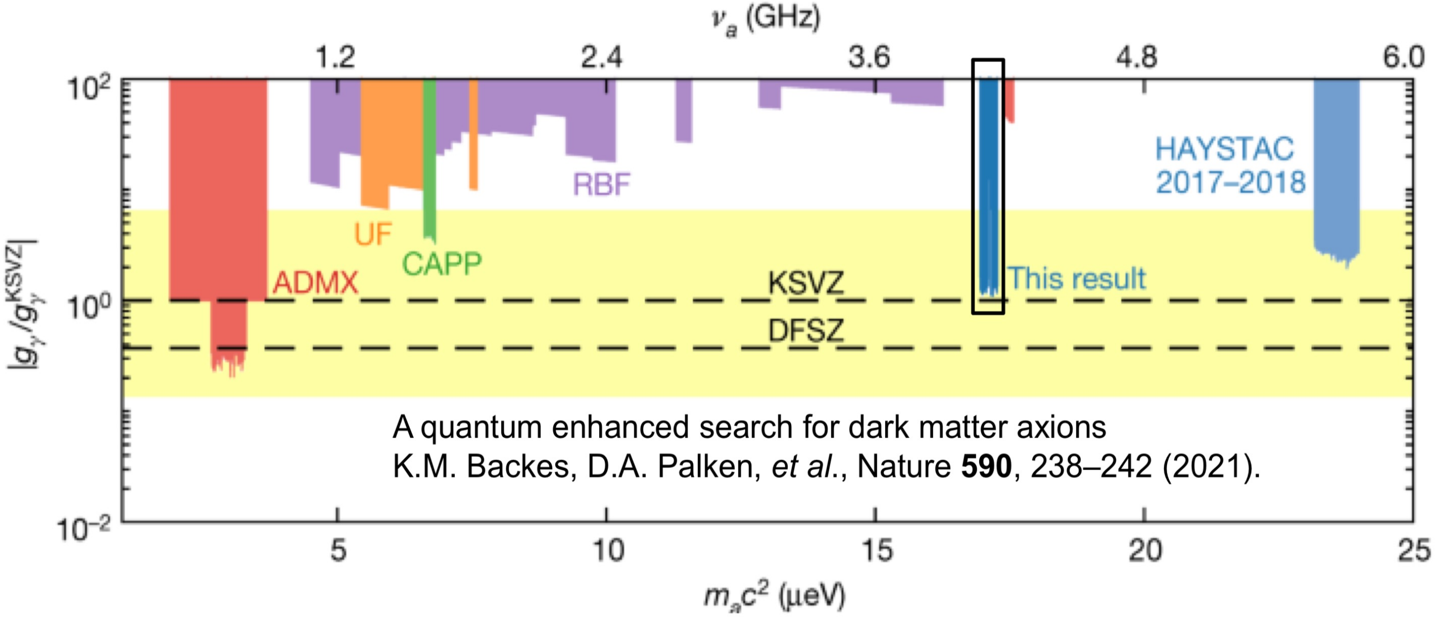
Science 321 , 544 547 (2008); Nature 457 , 859 862 (2009)

LIGO: Quantum enhanced sensing-Squeezed light for improved sensitivity

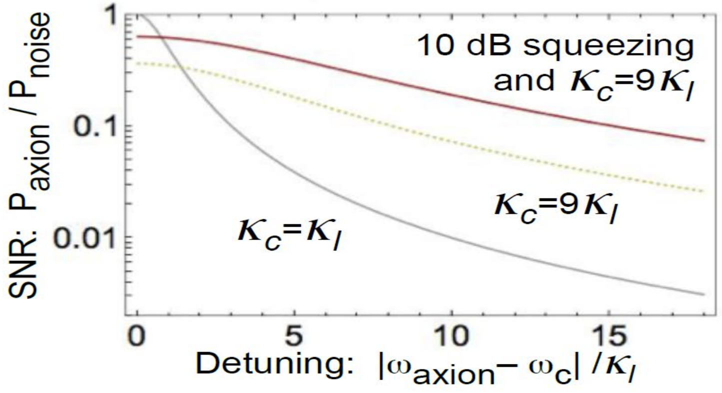


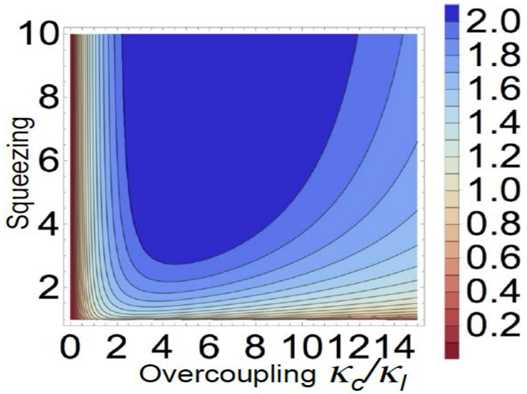
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231107
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231108

HAYSTAC: Acceleration through squeezing



HAYSTAC run 1 & 2 combined exclusion plot

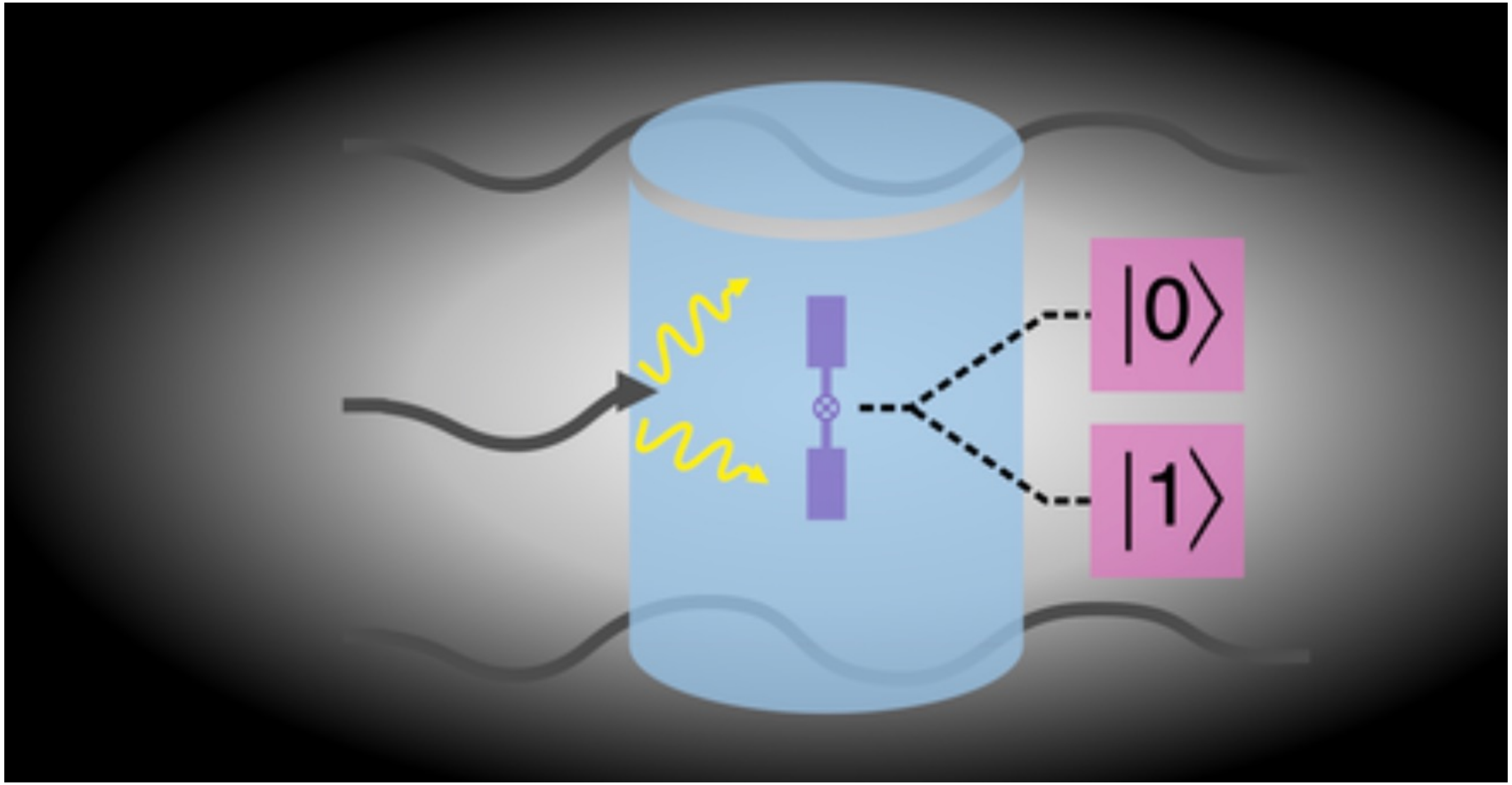




Droster, Alex G., and Karl van Bibber. "HAYSTAC Status, Results, and Plans." *arXiv preprint arXiv:1901.01668* (2019).

HAYSTAC Phase II squeezed state receiver projected acceleration

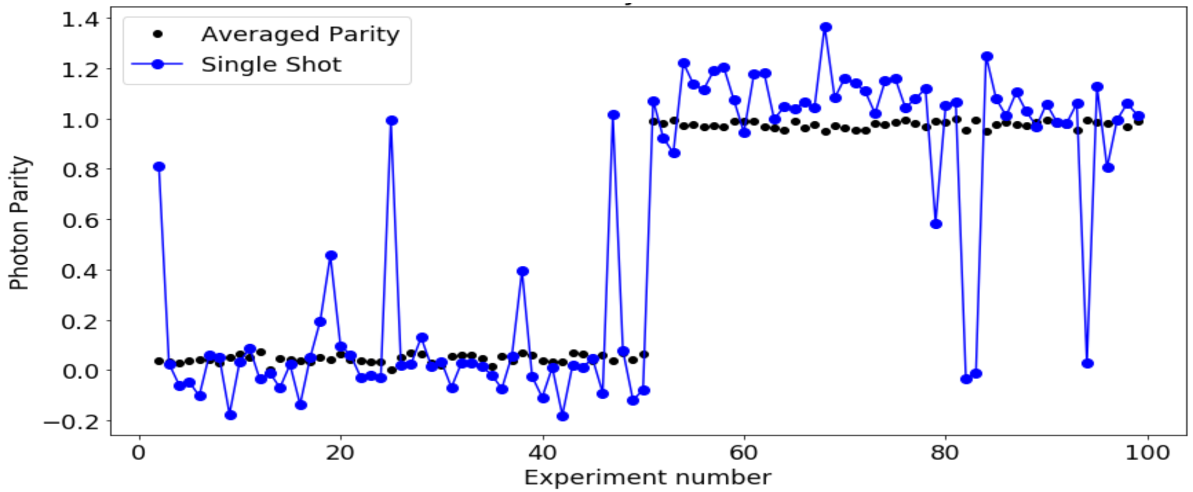
Qubits as cameras



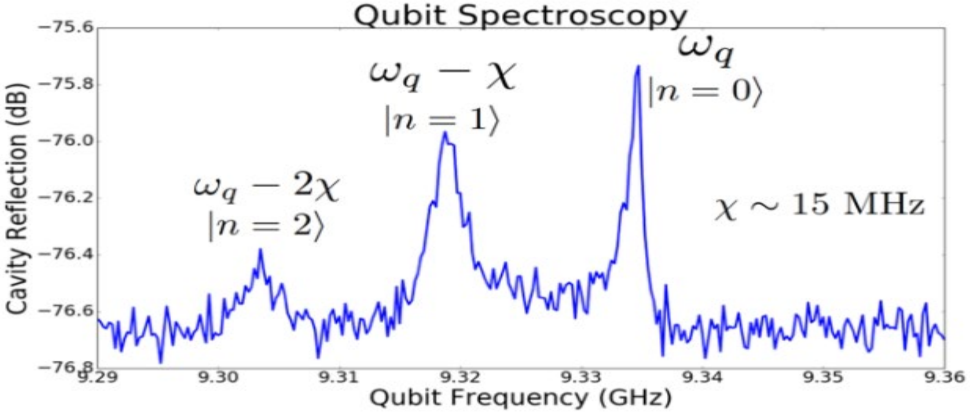
Ground state measurement: QND photon counting

Akash Dixit, Aaron Chou, David Schuster

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



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.



Many QND measurements agree that the cold cavity contains 0 photons

Inject 1 photon

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

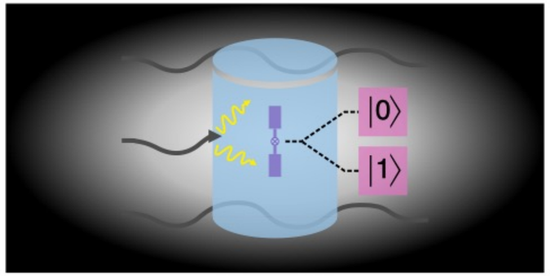
Count # of photons by measuring the quantized frequency shift of the qubit.

Figure Credit: Aaron Chou, FNAL

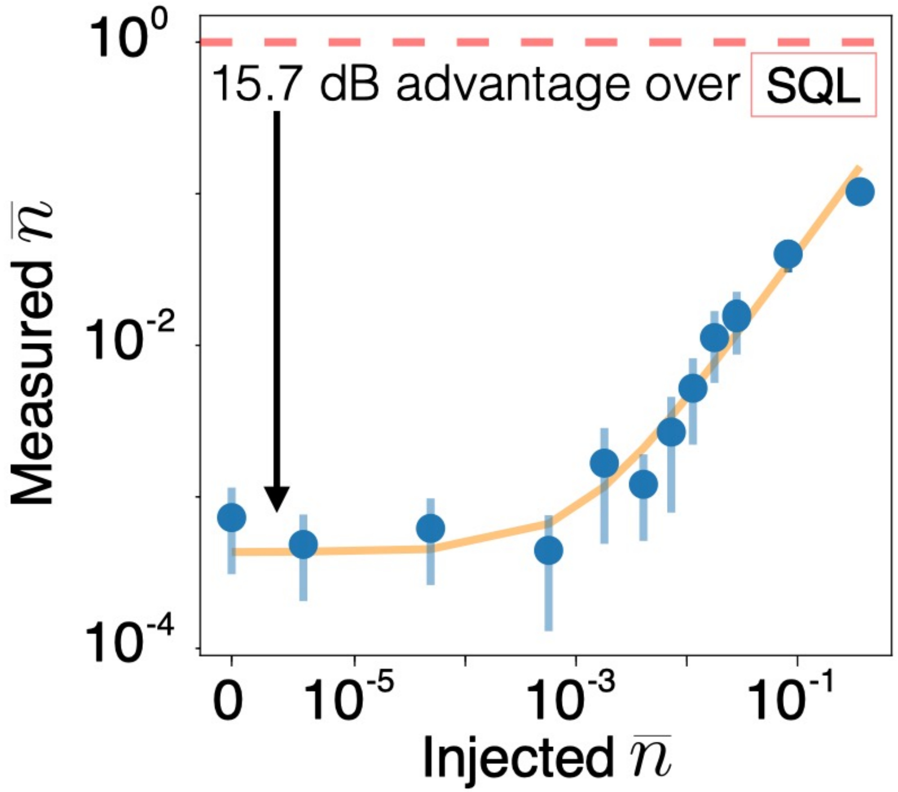
Fermilab | THE UNIVERSITY OF CHICAGO | HEISING-SIMONS FOUNDATION

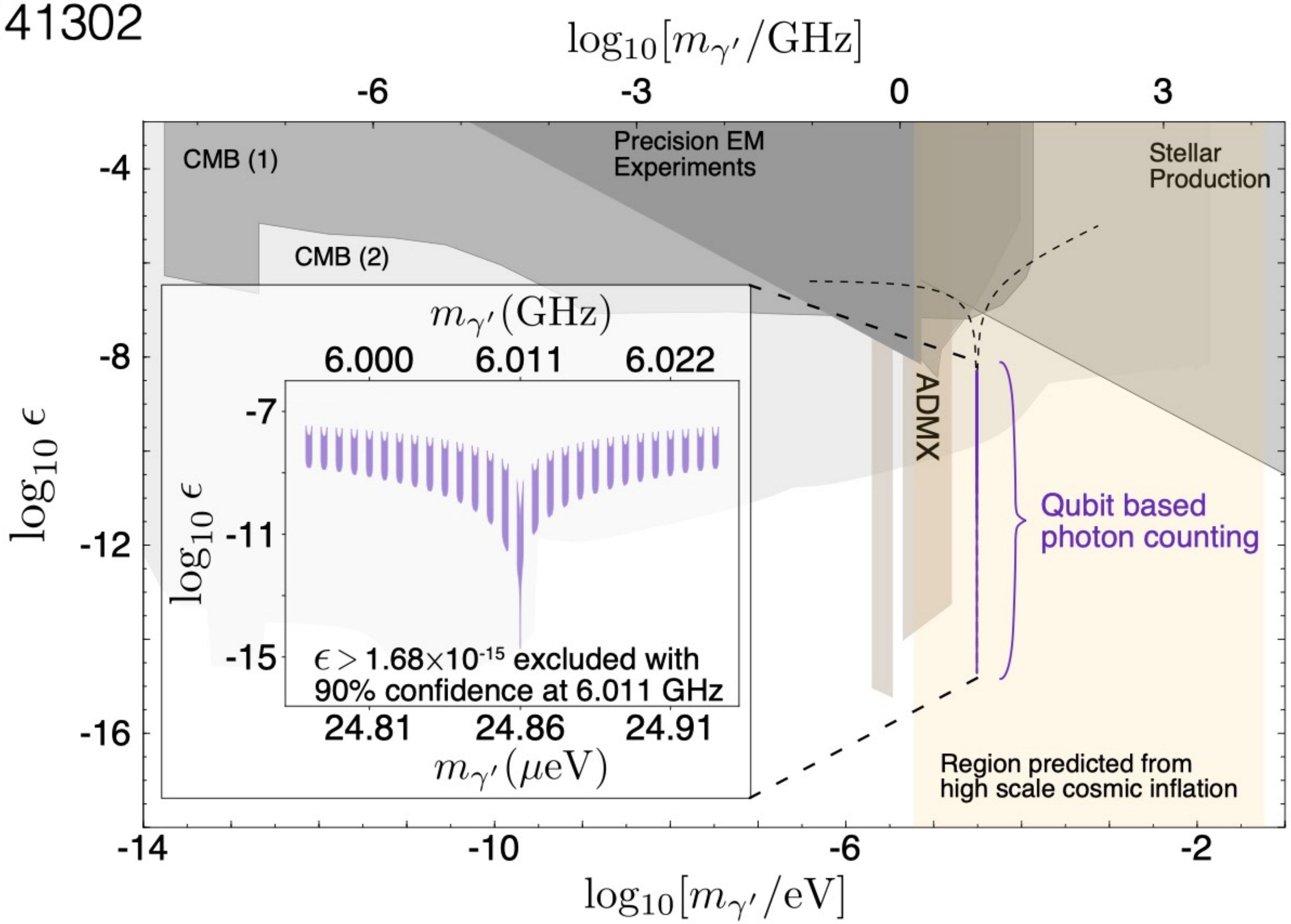
Counting photons with a qubit enables 1,300 X speed up of dark matter search

Slide credit A. Dixit



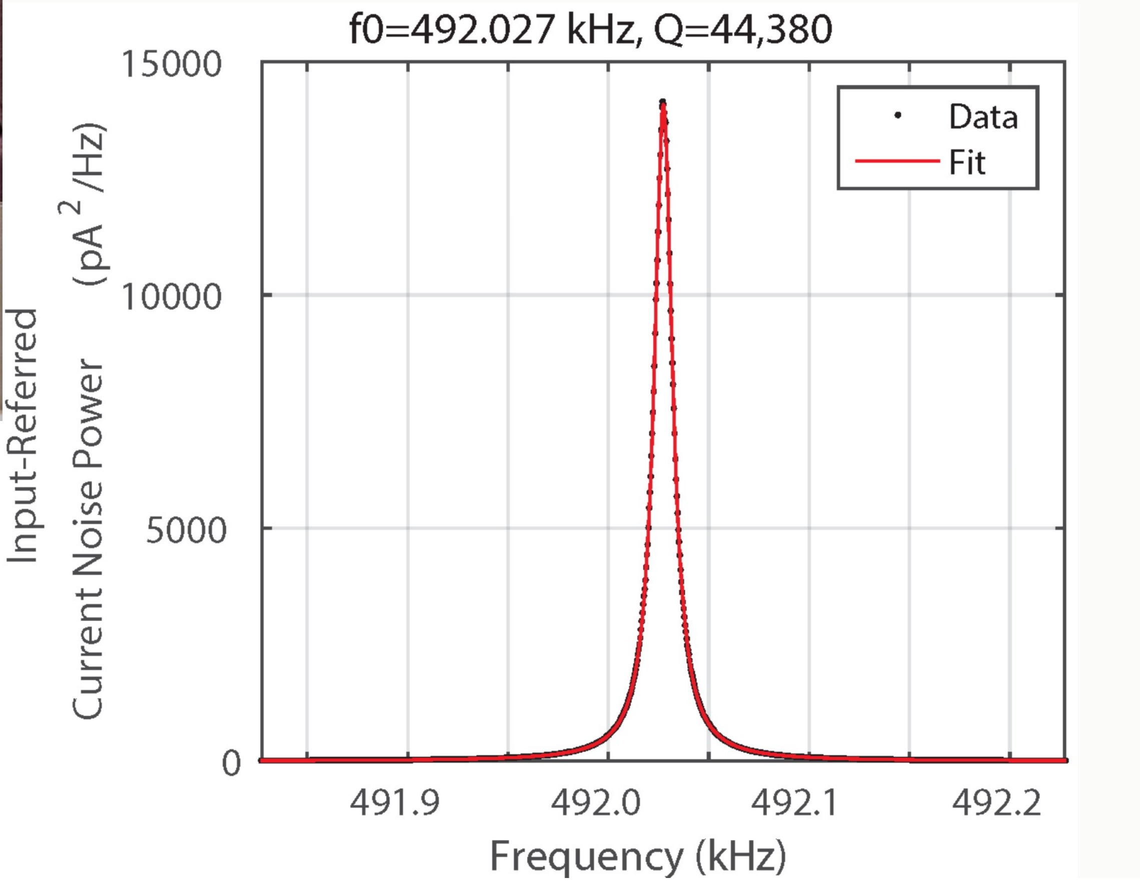
A. V. Dixit, et. al.
Phys. Rev. Lett. **126**, 141302



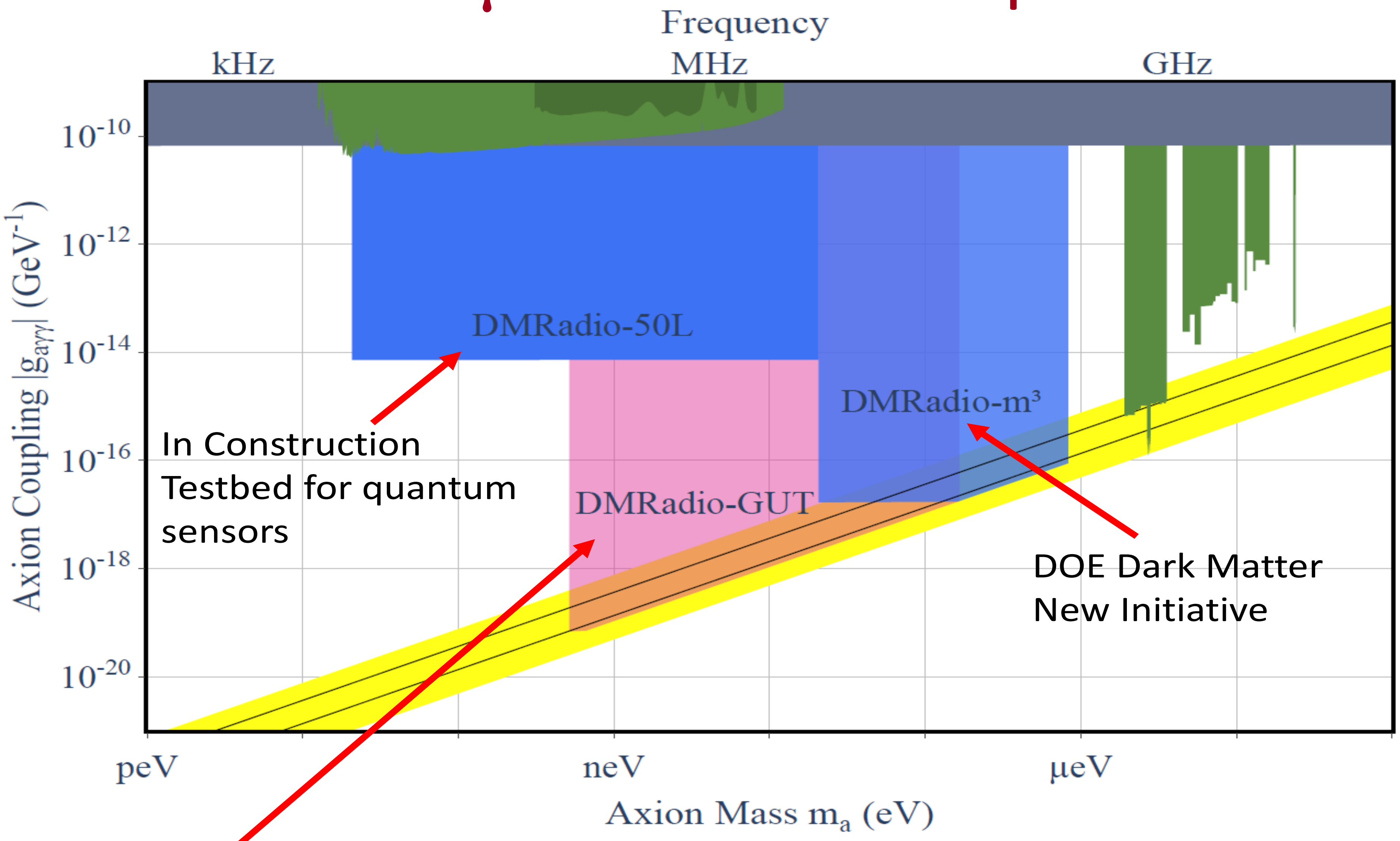


Counting single photons with a quantum bit. False positives exponentially suppressed by repeated QND measurements

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


f0=492.027 kHz, Q=44,380
Input-Referred
Current Noise Power (pA 2 /Hz)
15000
10000
5000
0
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."

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 → $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$ ← symmetry breaking scale

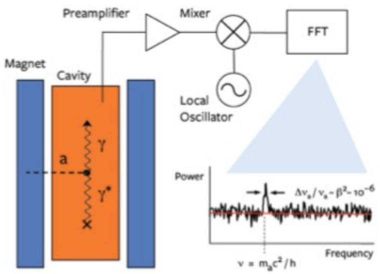
$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

coupling to photons

→ Primakoff effect

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

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



$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

coupling to gluons

→ creates nucleon EDM (electric dipole moment)

this is why axions were invented

→ spin to axion coupling:

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

CASPEr-electric

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

coupling to fermions

→ creates axion "wind"

→ spin to axion "wind" coupling:

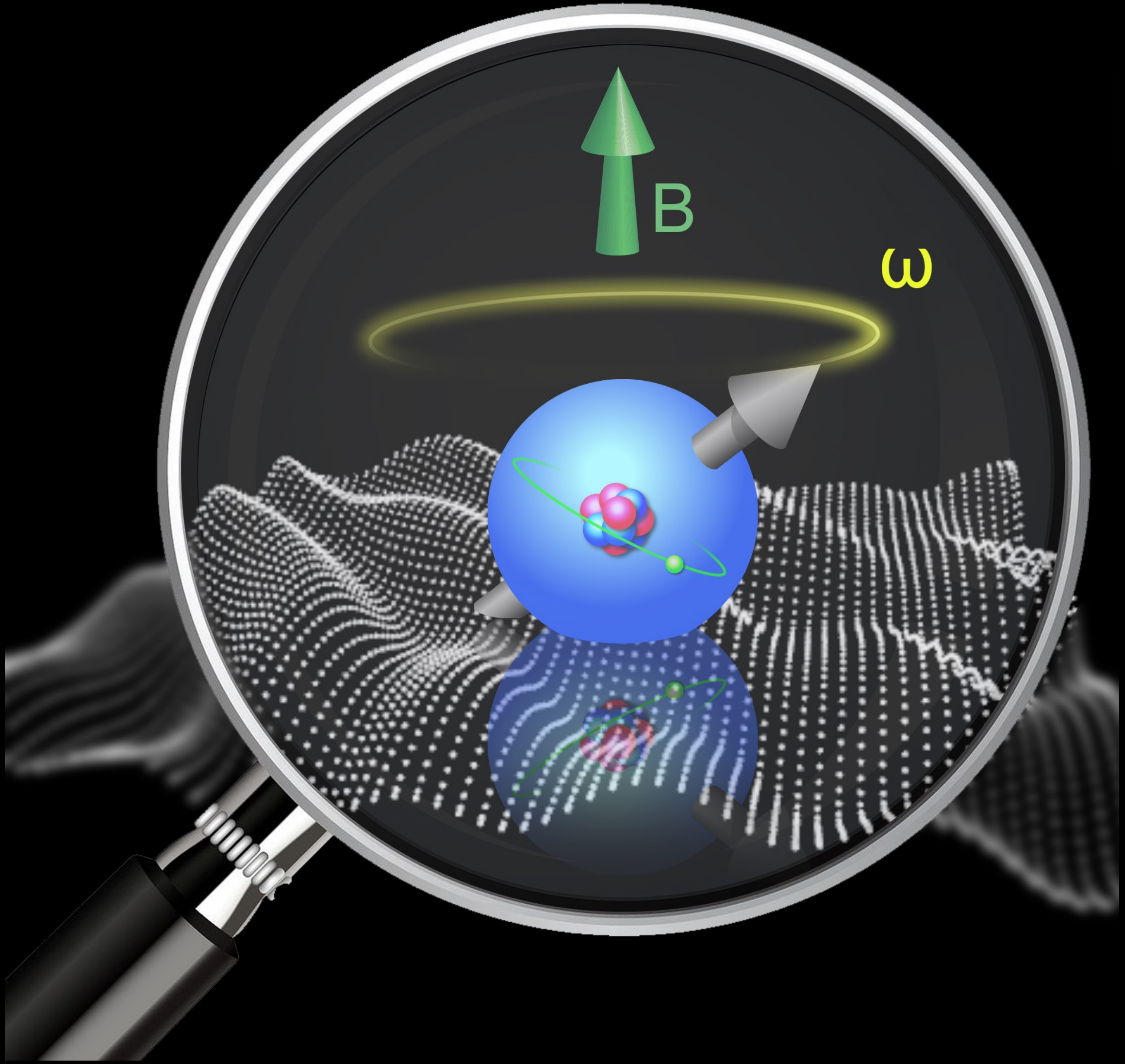
$$H_{\text{wind}} \propto \vec{\sigma} \cdot \vec{\nabla} a$$

CASPEr-wind

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

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

Spin Precession NMR-Based Axion Detection

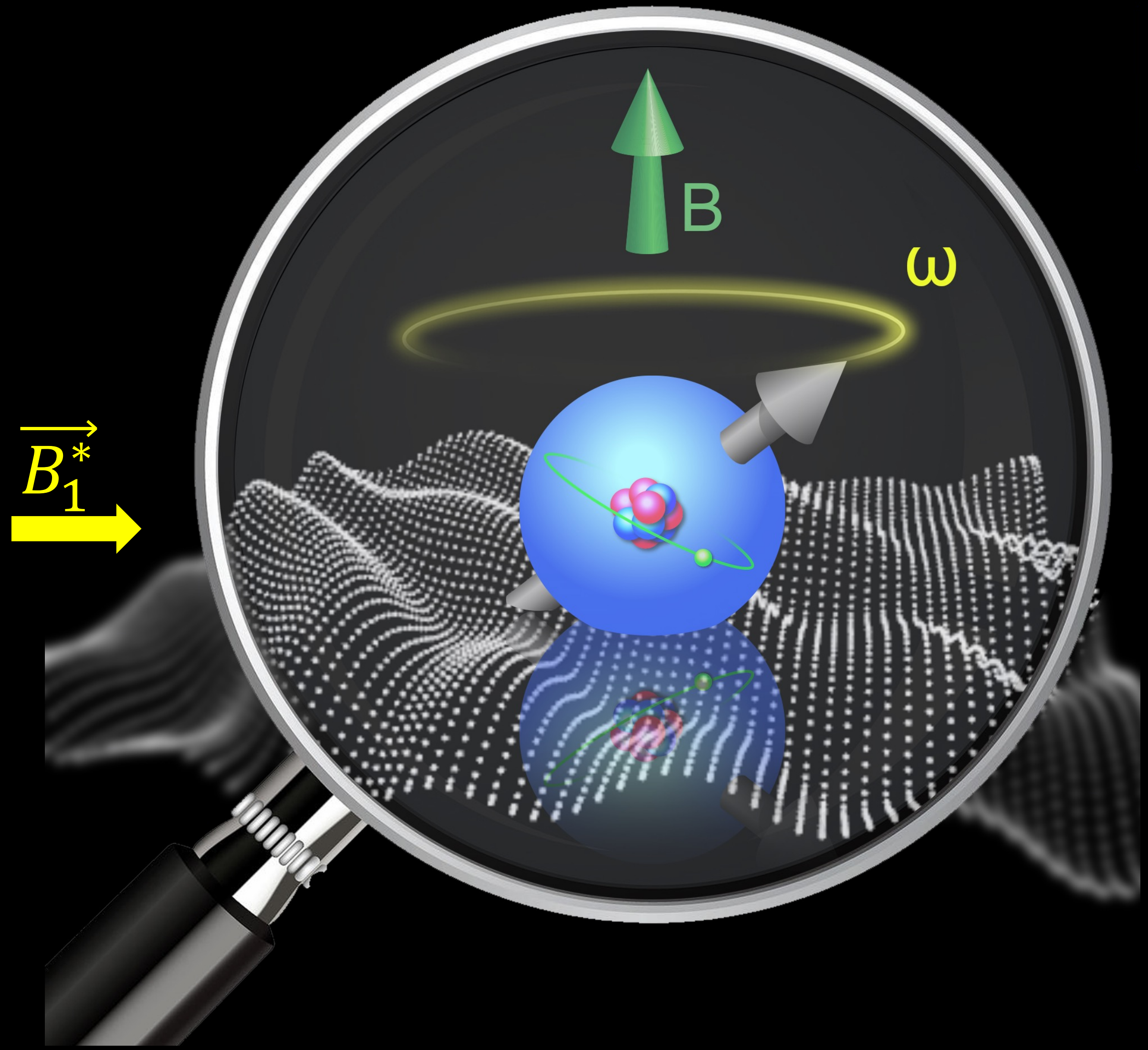


- Axion-fermion coupling generates axion “wind”, creating an effective B-field with well-known spin coupling: NMR technique

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

Slide credit: M. Demarteau

Spin Precession NMR-Based Axion Detection



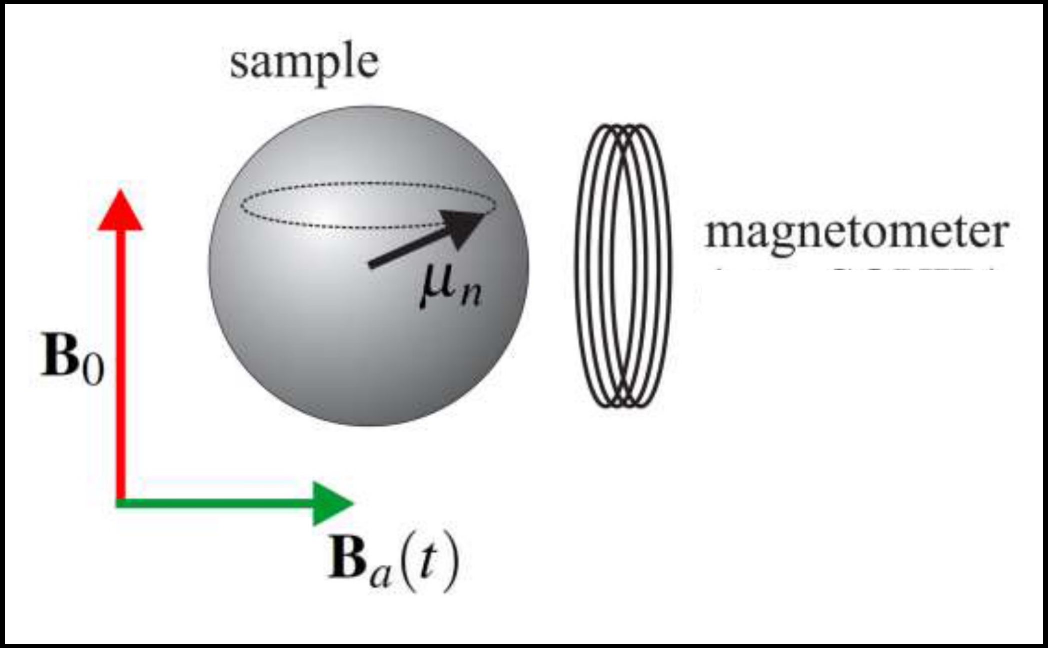
- Axion-fermion coupling generates axion "wind", creating an effective B-field with well-known spin coupling: NMR technique

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

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

Slide credit M. Demarteau

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)

Slide credit M. Demarteau

Aside: magnetic resonance

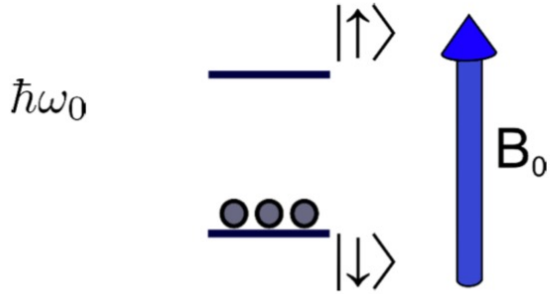
CASPEr is similar to NMR

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

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

- 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 $g\mu B_0$



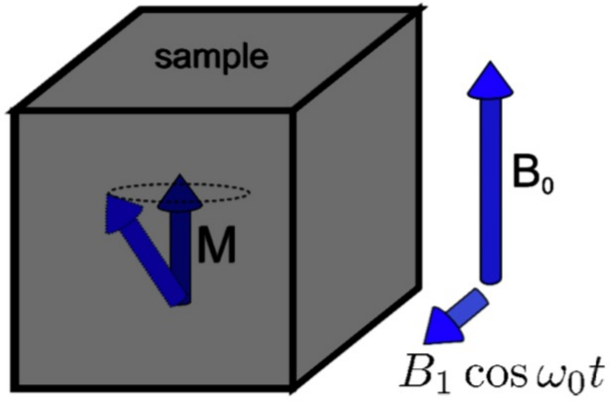
2) spin polarization (thermal or optical) in a cm^3 sample

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

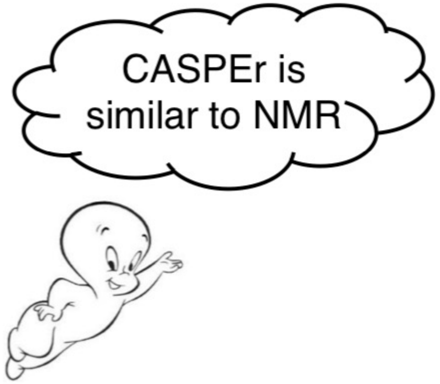


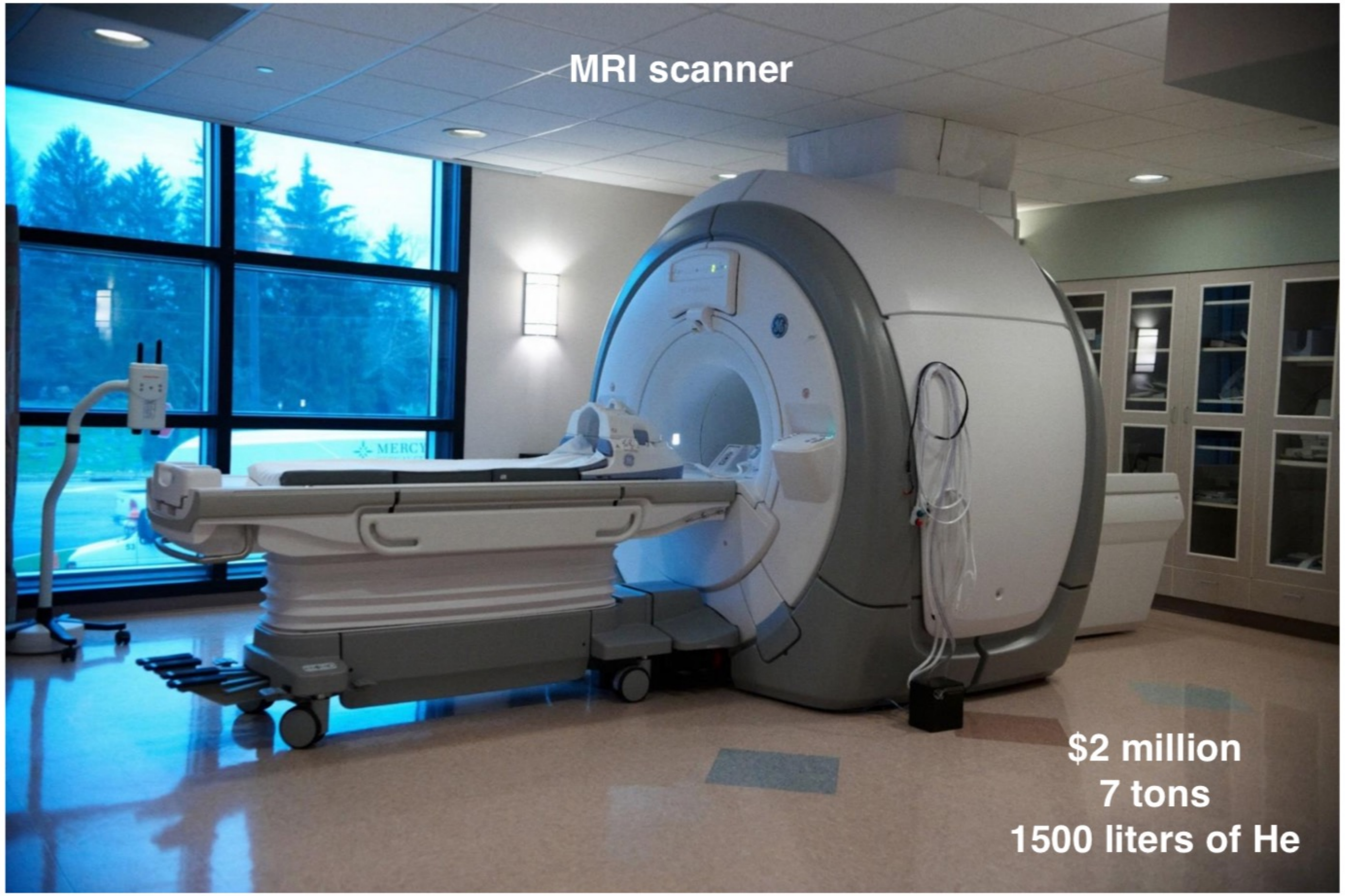
⬇

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

Slide credit Sushkov

Aside: magnetic resonance





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

Slide credit Sushkov

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

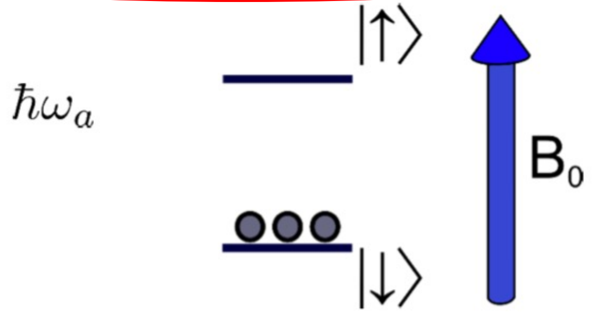
3) resonance: $\hbar\omega_a = g\mu B_0$

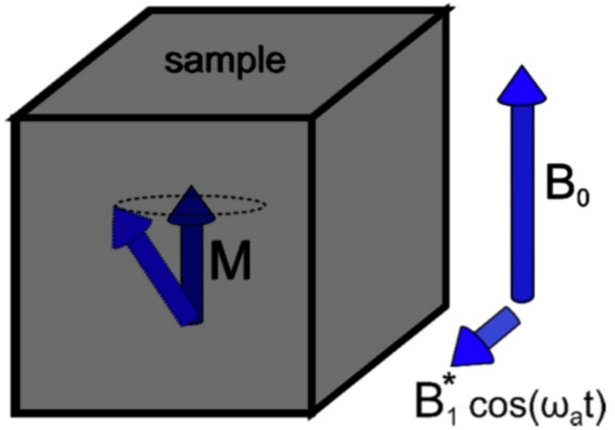
- axion-spin interaction can now flip spins!
- sample magnetization tilts and precesses

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

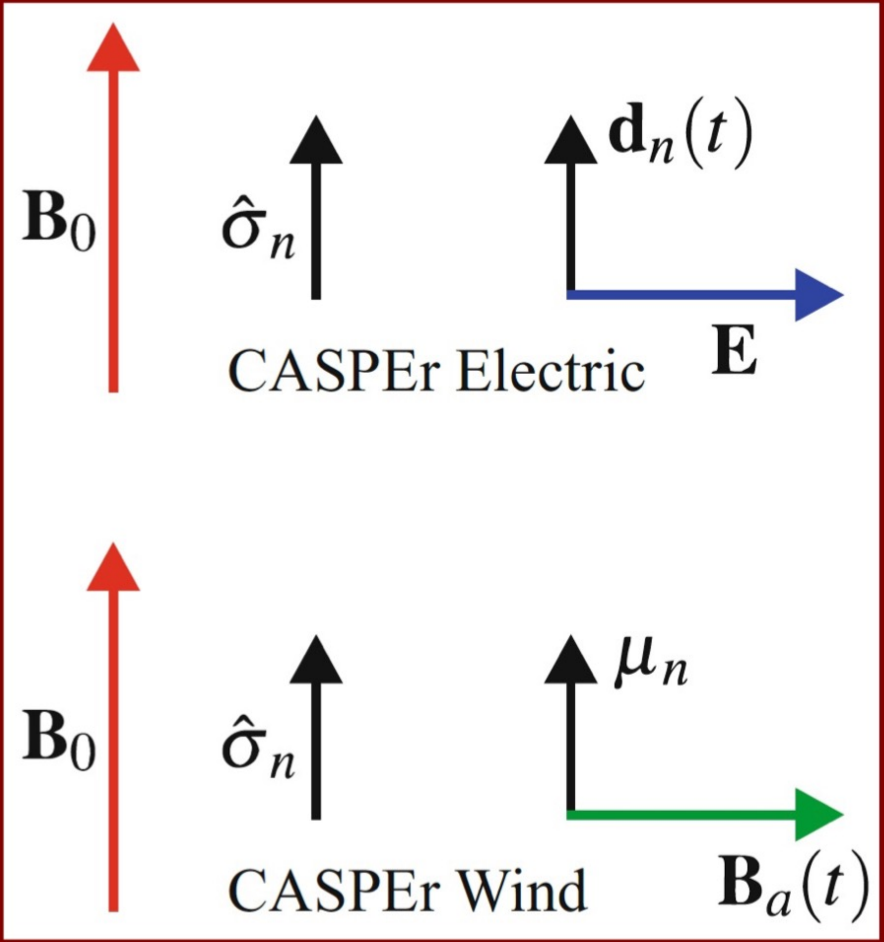
- constant bias magnetic field $\boldsymbol{B}_0$
- spin-axion interaction plays the role of the radiofrequency magnetic field $\boldsymbol{B}_1$

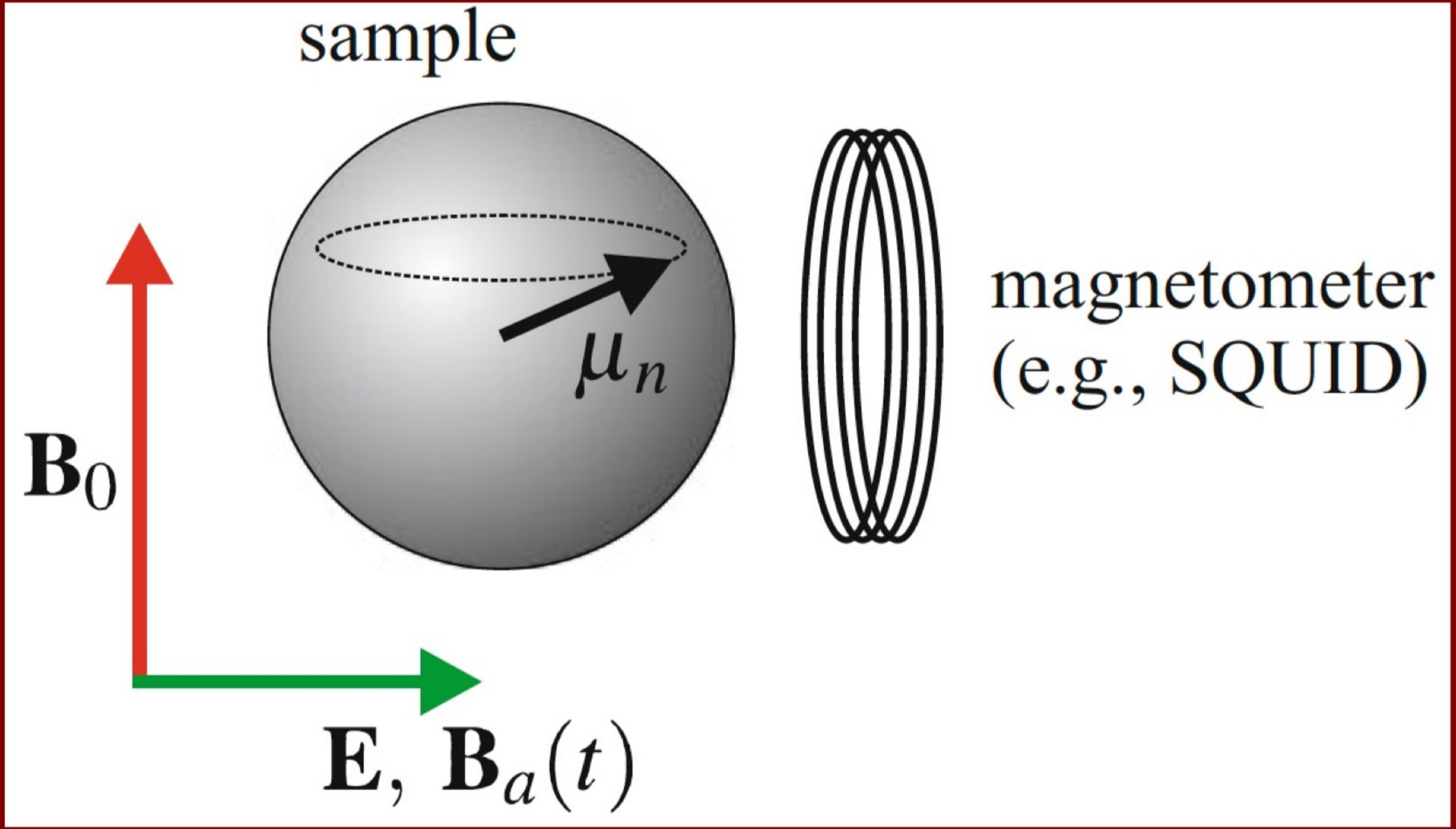




[Phys. Rev. X **4**, 021030 (2014)]

DM search with NMR (CASPEr)





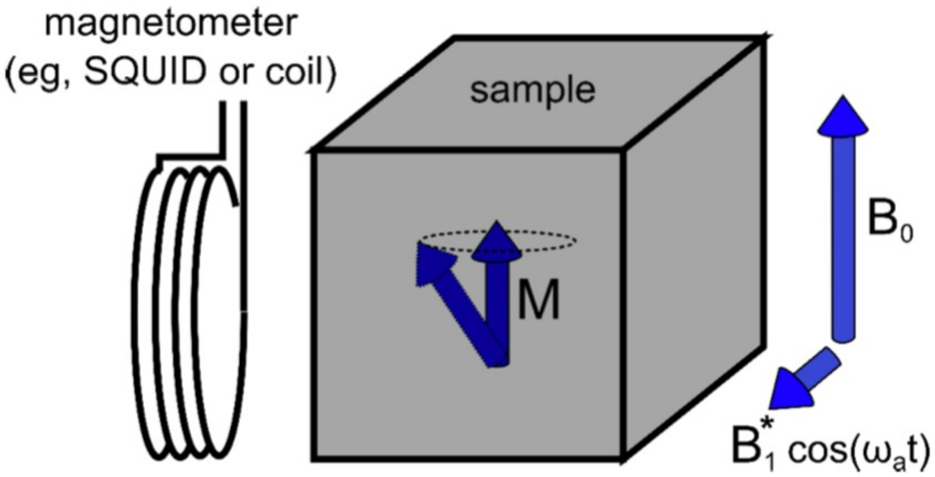
D. F. Jackson Kimball *et. al.* in G. Carosi, G. Rybka (eds.), Microwave Cavities and Detectors for Axion Research, Springer Proceedings in Physics 245, https://doi.org/10.1007/978-3-030-43761-9_13

Choosing the sample material to maximize sensitivity

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

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

} important parameters

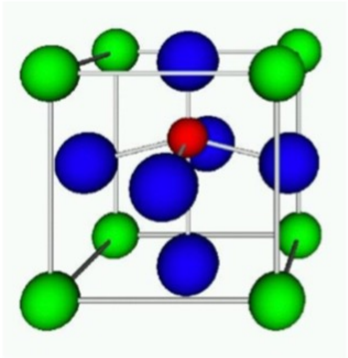


⇨ sample → **ferroelectric solid**

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

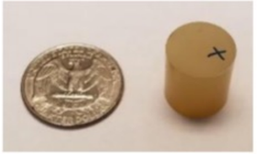
^{207}Pb spins in materials:

$\mathrm{PbTiO_3}$

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

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

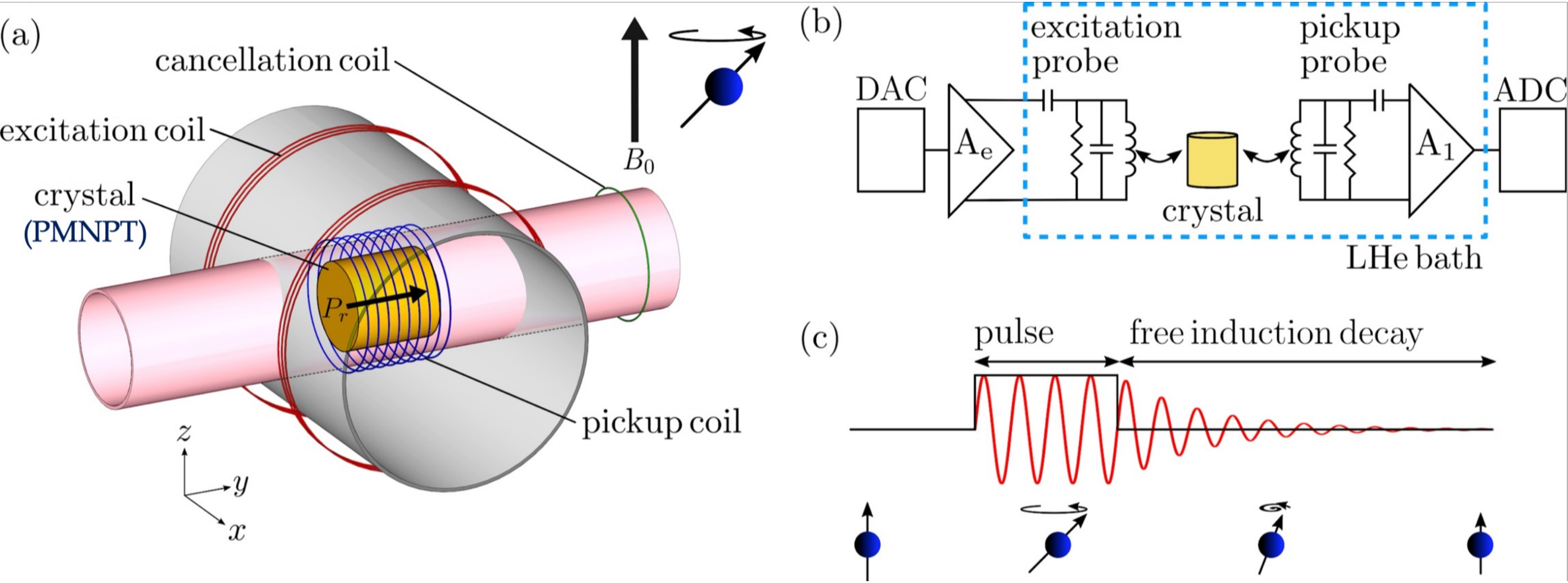
$\mathrm{Pb_5Ge_3O_{11}}$



commercially available

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

Slide credit Sushkov

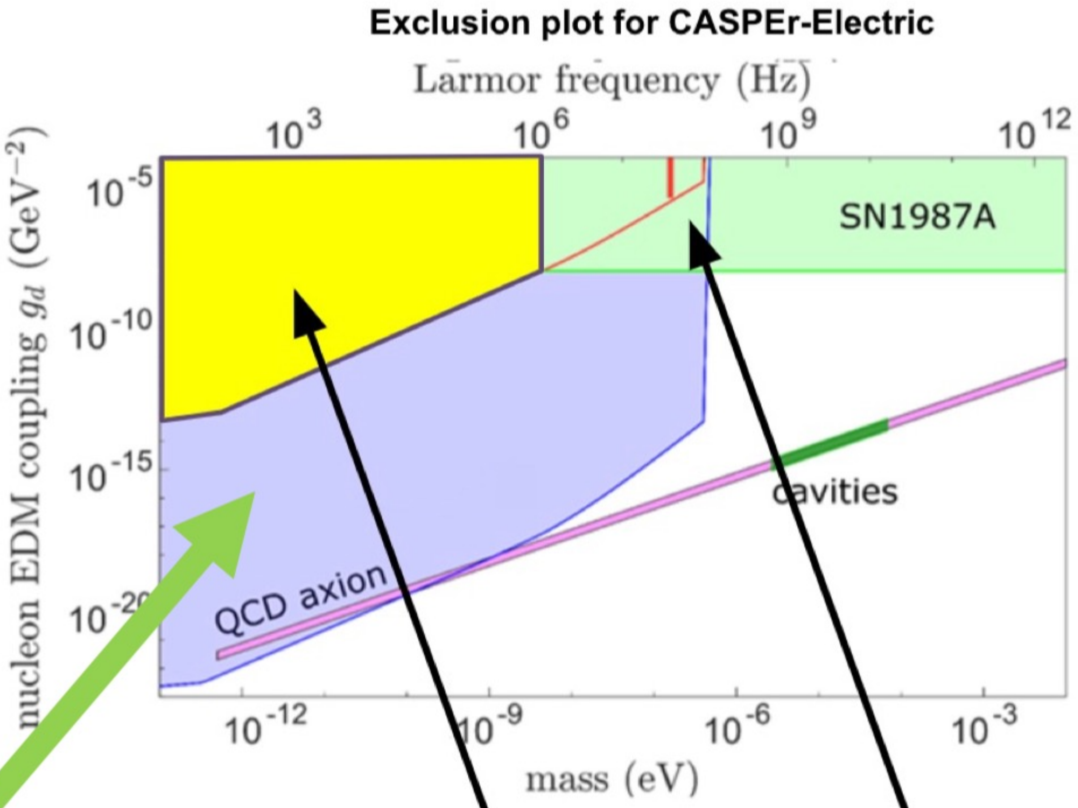


Deniz Aybas, *et al*, PRL **126**, 141802 (2021)

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



Gen 2 is looking for ALPs below 1 MHz with SQUIDs

Gen 3 : Big Sample + Hyperpolarization !

Neutrinos

Determination of Neutrino Mass with Quantum Technologies

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

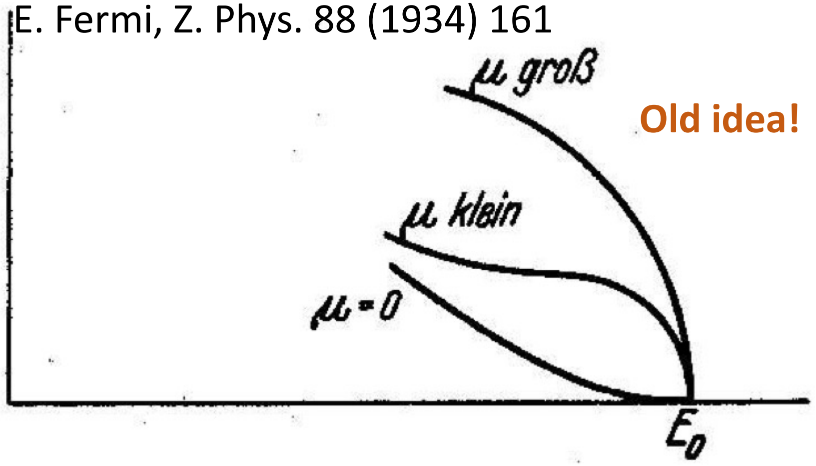
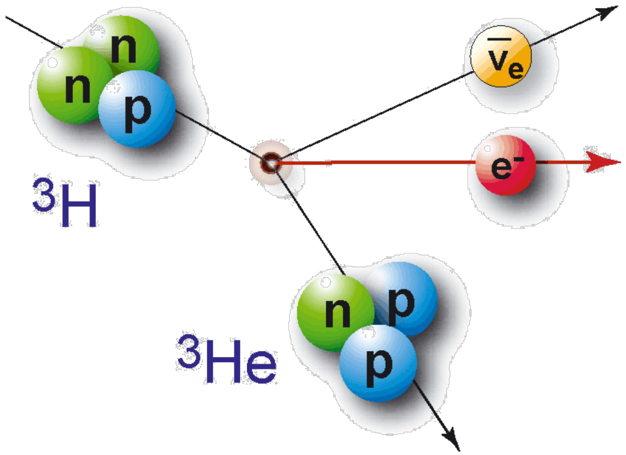
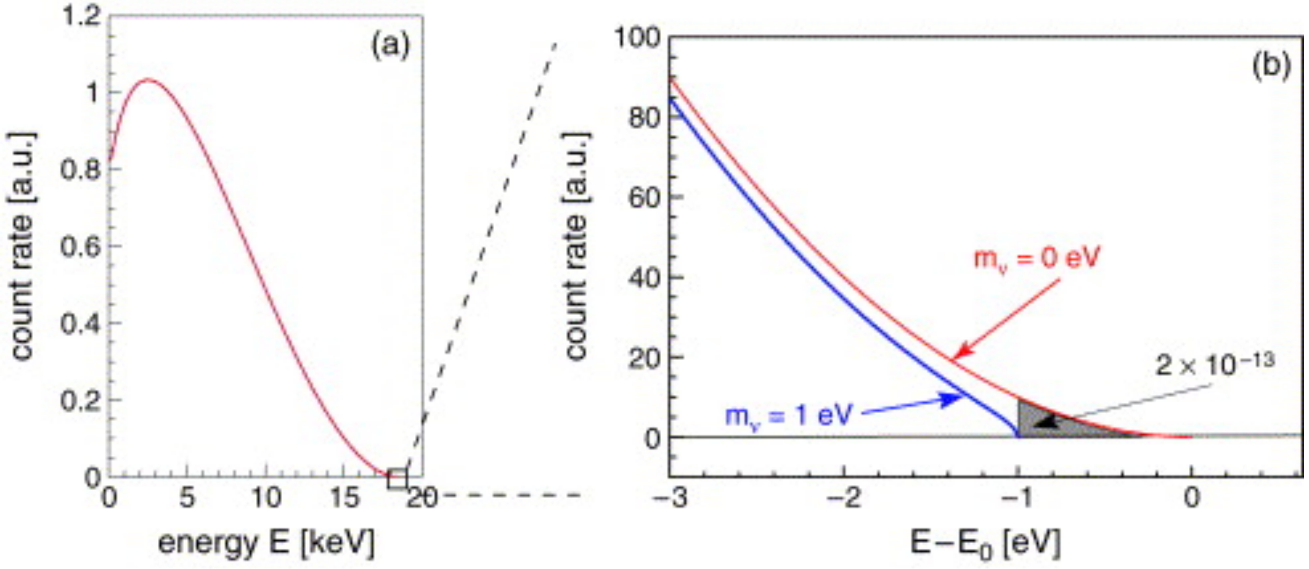


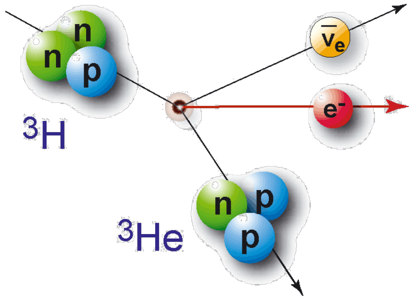
Fig. 1.

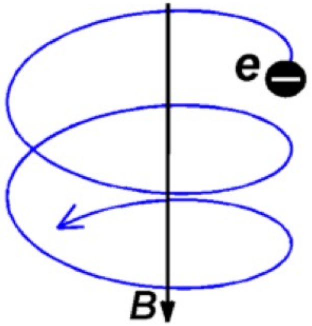
Old idea!



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







Cyclotron Radiation Emission Spectroscopy (CRES)

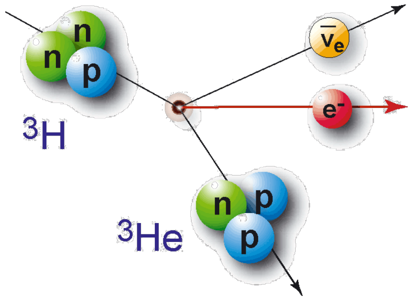
$$f = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}/c^2}$$

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 Future Outlook

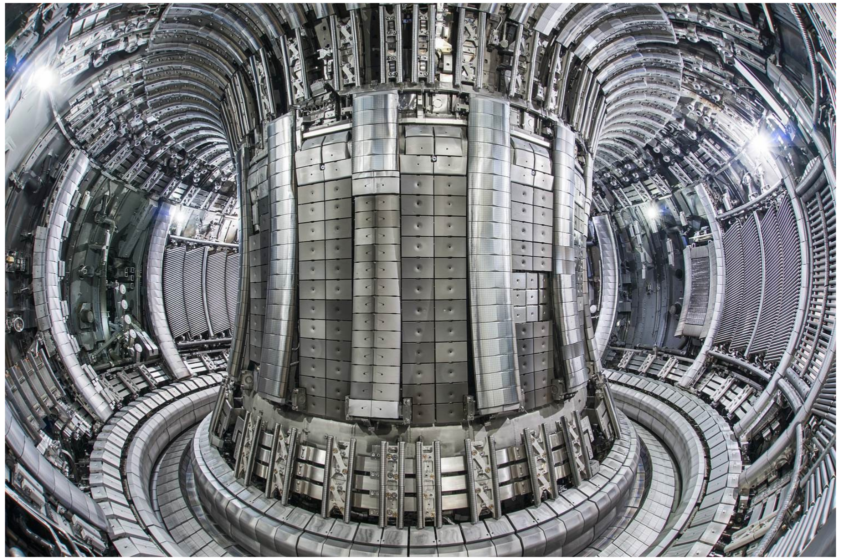


A (*VERY*) tentative timeline

- 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

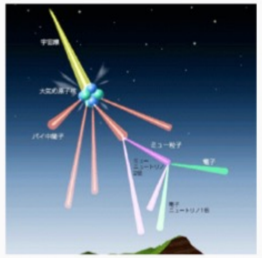
Nuclear Reactors
E_ν = 1 - 10 MeV
Detected ✔

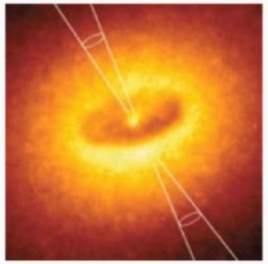
Sun
E_ν = 10.4 MeV
Detected ✔

Accelerators
E_ν up to 12 GeV
Detected ✔

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

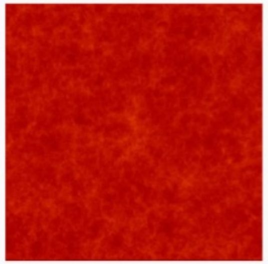
Atmosphere (Cosmic Rays)
E_ν up to 1 GeV
Detected ✔



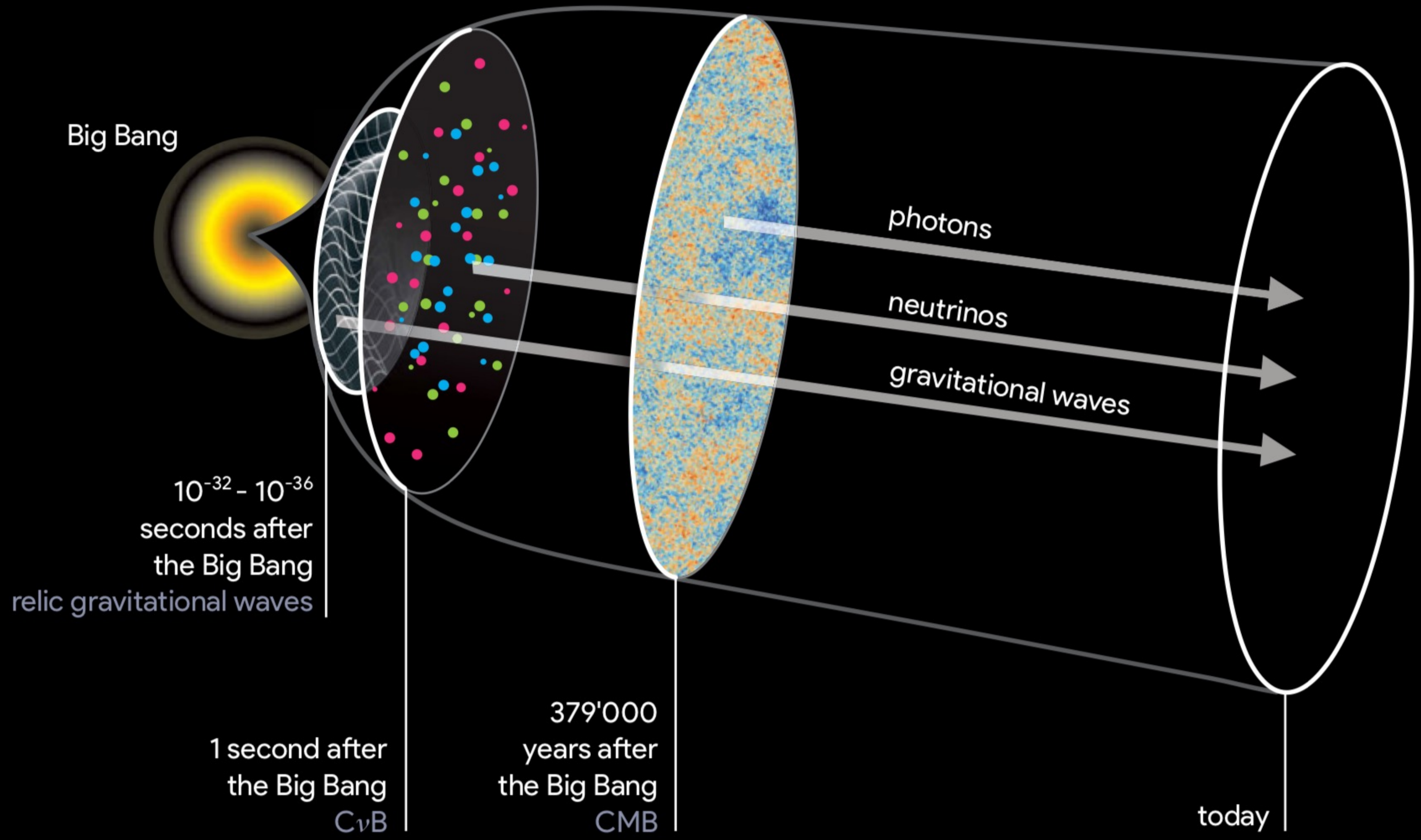


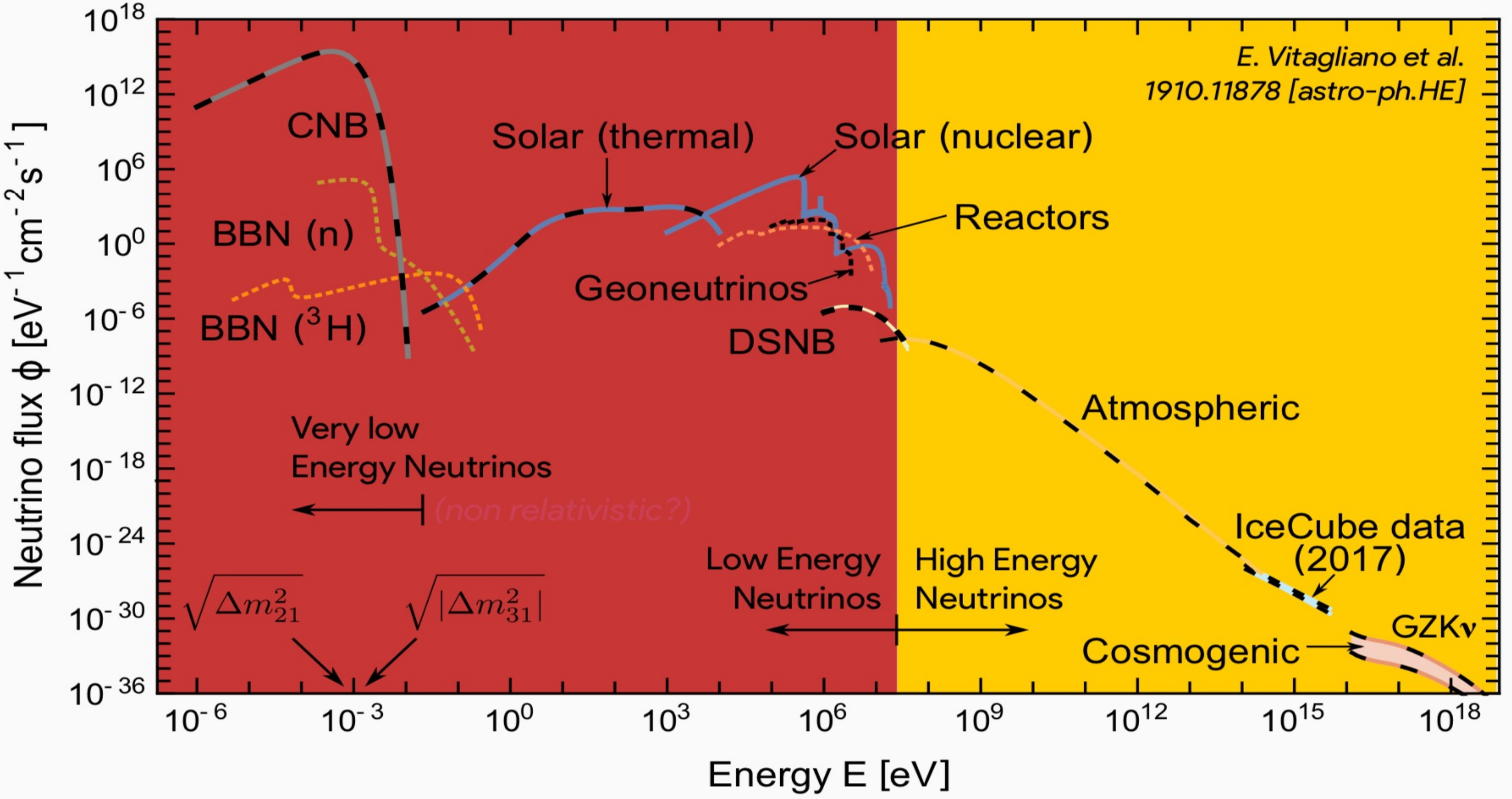
Astrophysical accelerators
E_ν ~ TeV - PeV
Detected ✔

Terrestrial radioactivity
E_ν up to 1 MeV
Detected ✔



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

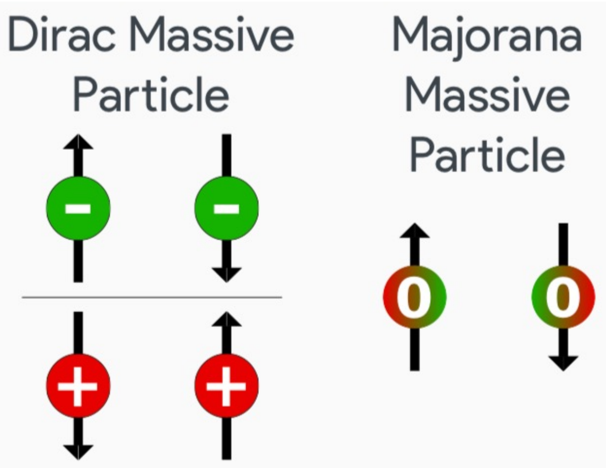

Big Bang
photons
neutrinos
gravitational waves
10^{-32} - 10^{-36}
seconds after
the Big Bang
relic gravitational waves
1 second after
the Big Bang
CνB
379'000
years after
the Big Bang
CMB
today



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

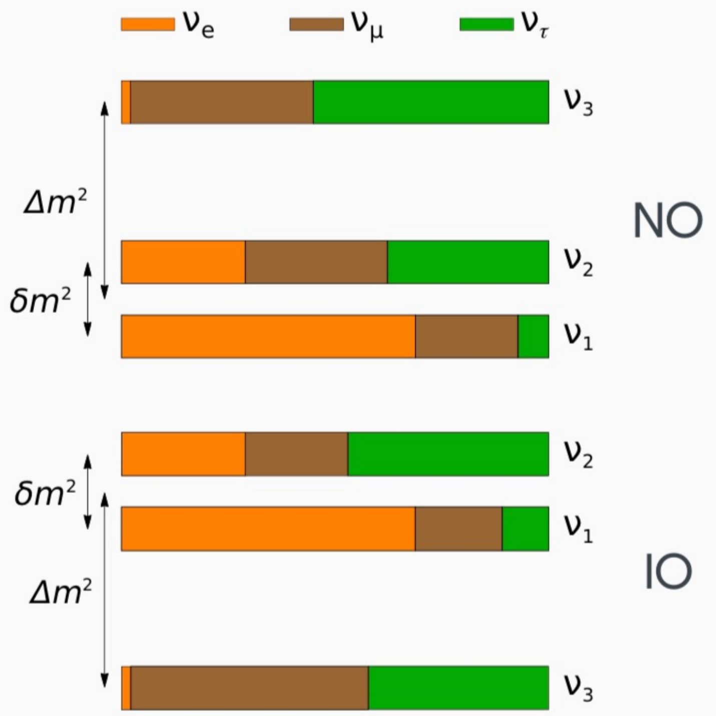
CνB is the largest neutrino density at Earth but yet it has never been measured;

- 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);

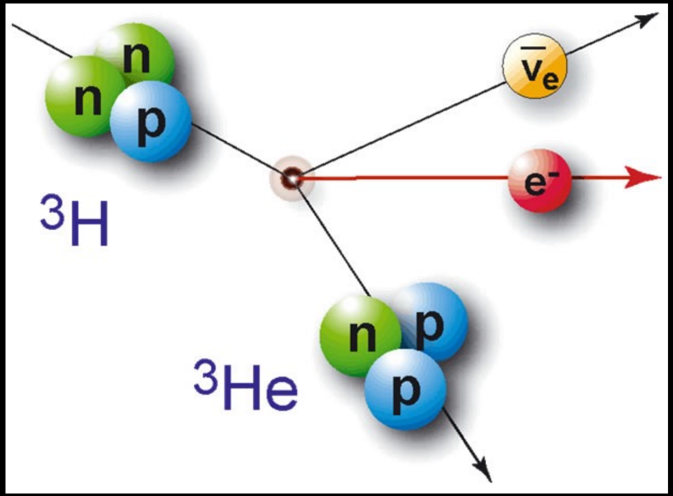


In particular

- 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)

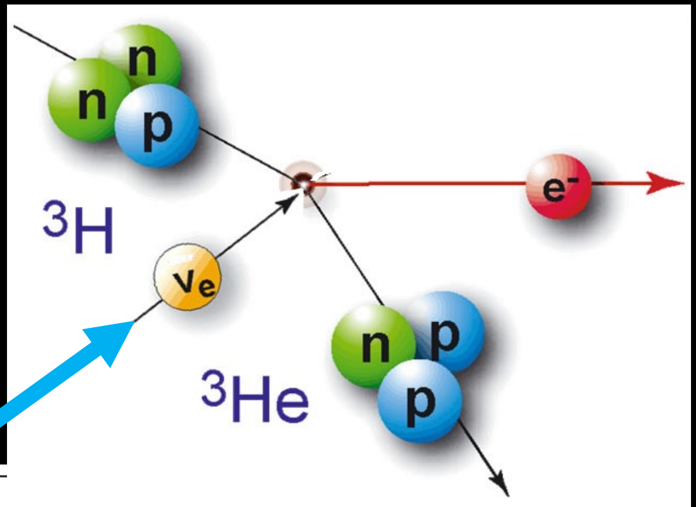


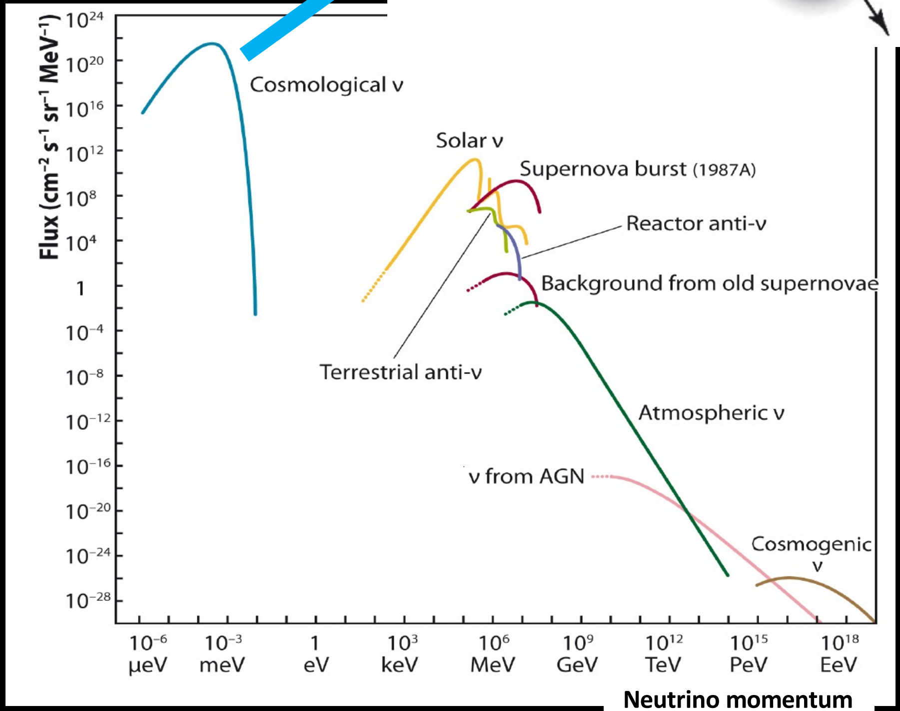
How can we directly detect relic neutrinos today?



Tritium β-decay
(12.3 yr half-life)

Neutrino capture on Tritium





Neutrino momentum ~ 0.17 meV

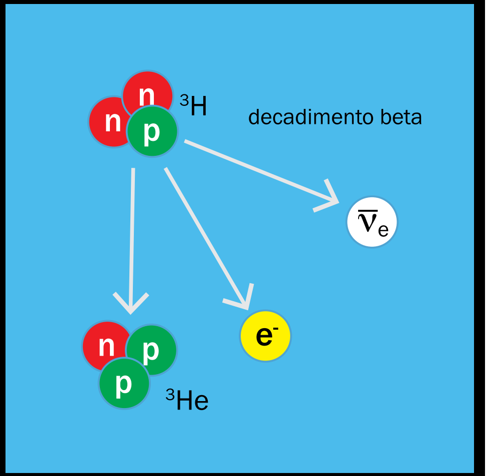
For m_ν = 50 meV,
KE = $p^2/2m$
= 0.17 meV (0.17 meV/100 meV)
= 0.3 μeV

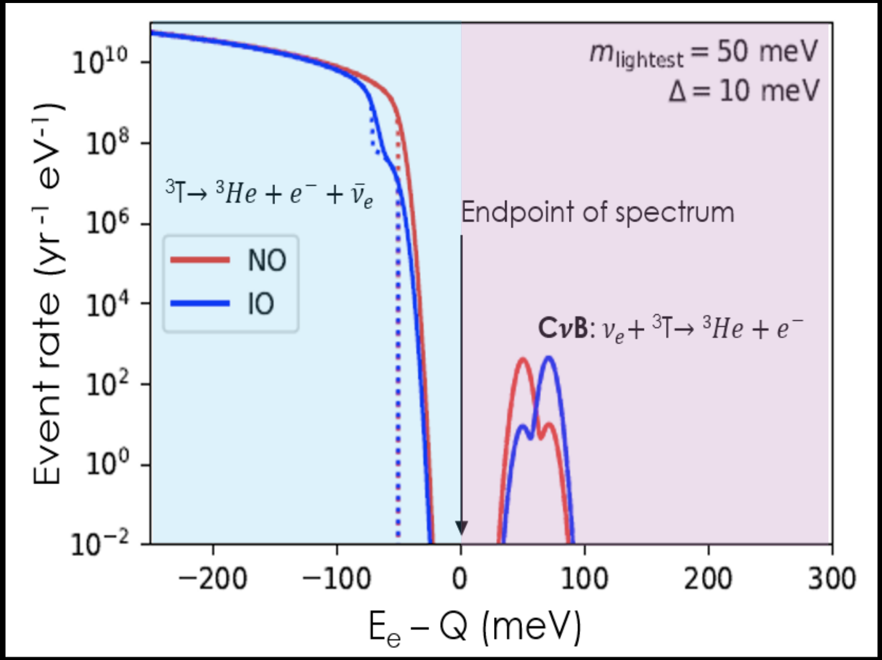
Ultra-Cold!

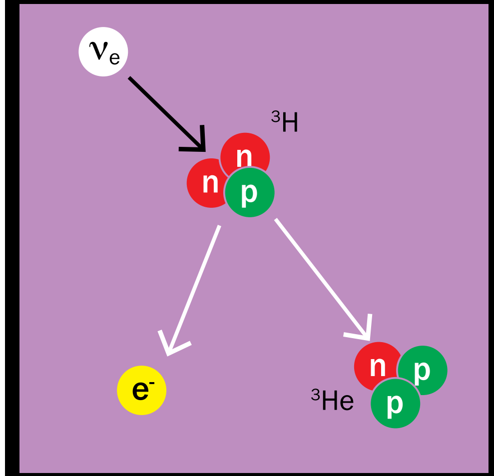
Slide credit: Tully

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]







What do we know?

Electron flavor expected with

m > ~50meV

from neutrino oscillations

Gap (2m) constrained to

m < ~200meV

from Cosmology

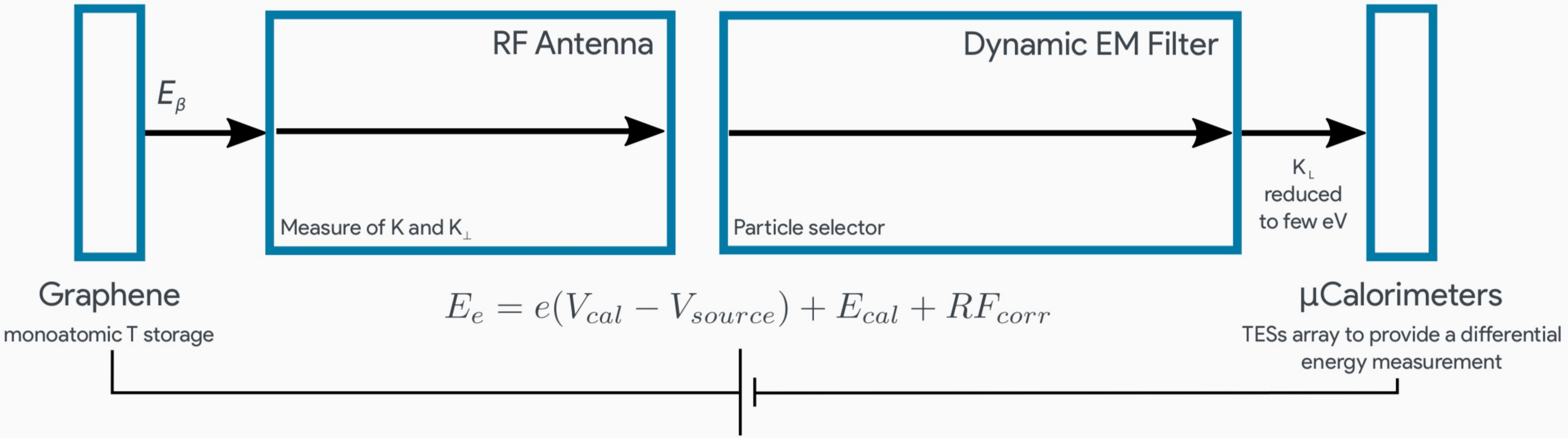
Slide credit: Tully

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

Slide credit: Tully

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 (summer 2021)

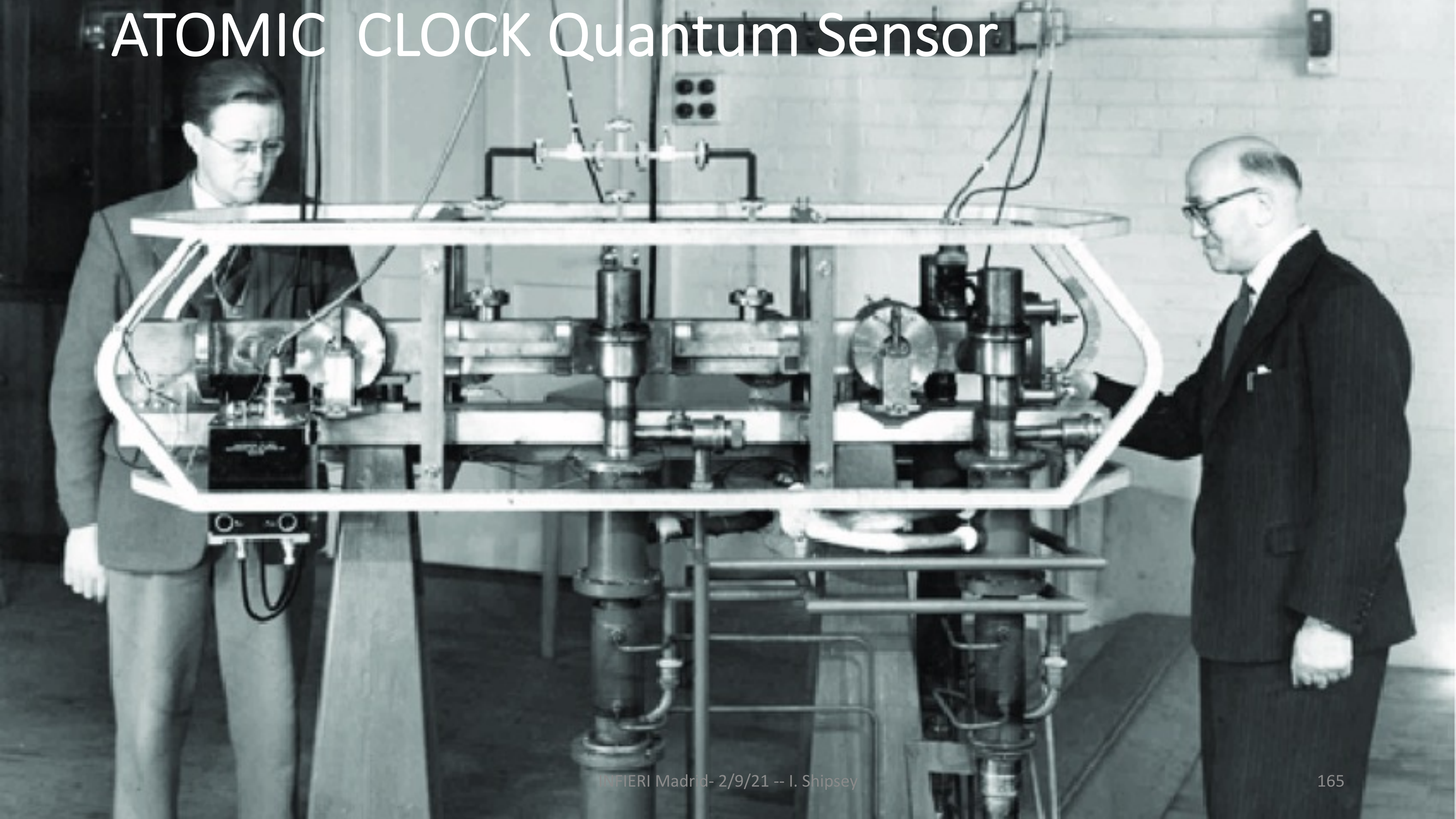
CNB direct detection is at a much more advanced phase than it was 6 years ago

- 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

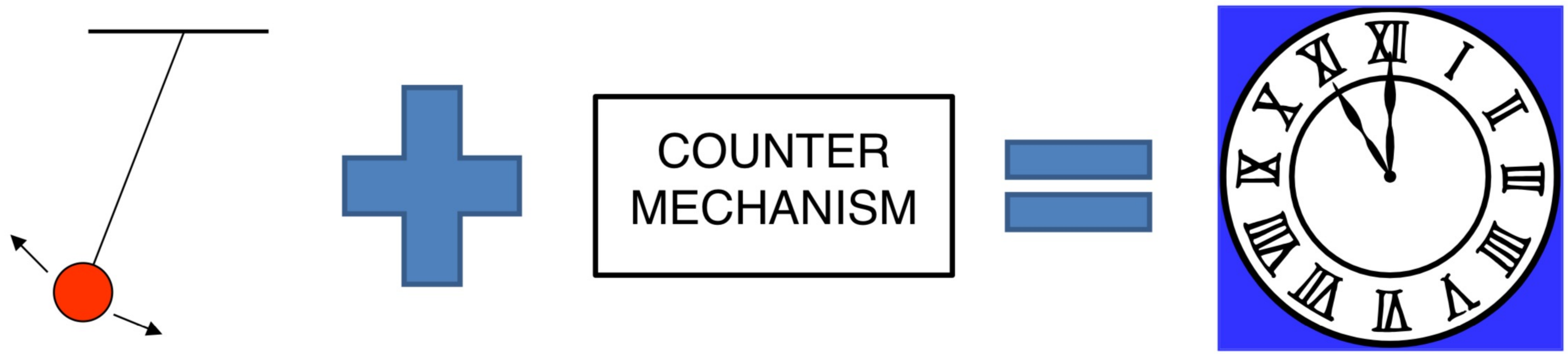
We hope to enter an exciting new phase with PTOLEMY this year with a rich experimental program focused on achieving CNB detection

Slide credit: Tully

ATOMIC CLOCK Quantum Sensor

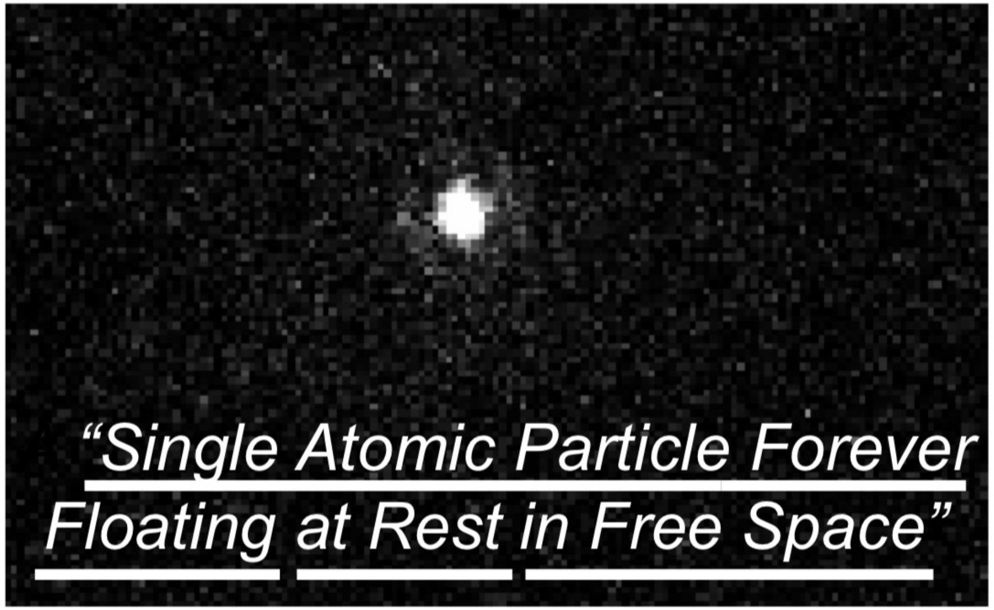


Clocks and oscillators



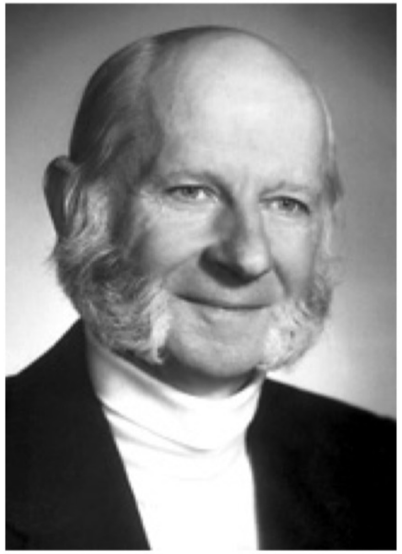
OSCILLATOR	COUNTER MECHANISM
Earth rotation	Sundial
Pendulum Swing	Clock Gears and Hands
Quartz Crystal Vibration	Electronic Counter
Cesium Atomic Vibration	Microwave Counter

Trapped Atomic Ions



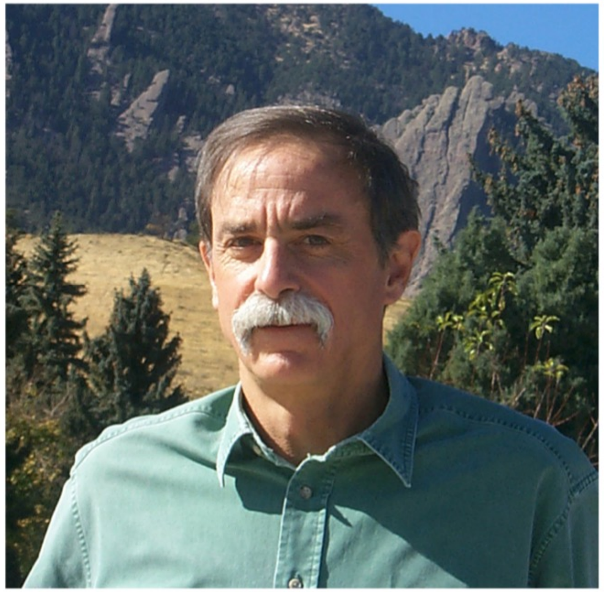
- Quantum-limited experiments
- Long interaction times
- Small relativistic shifts
- Small perturbation from EM fields

Predicted resolution of 1×10^{-18}



Hans Dehmelt

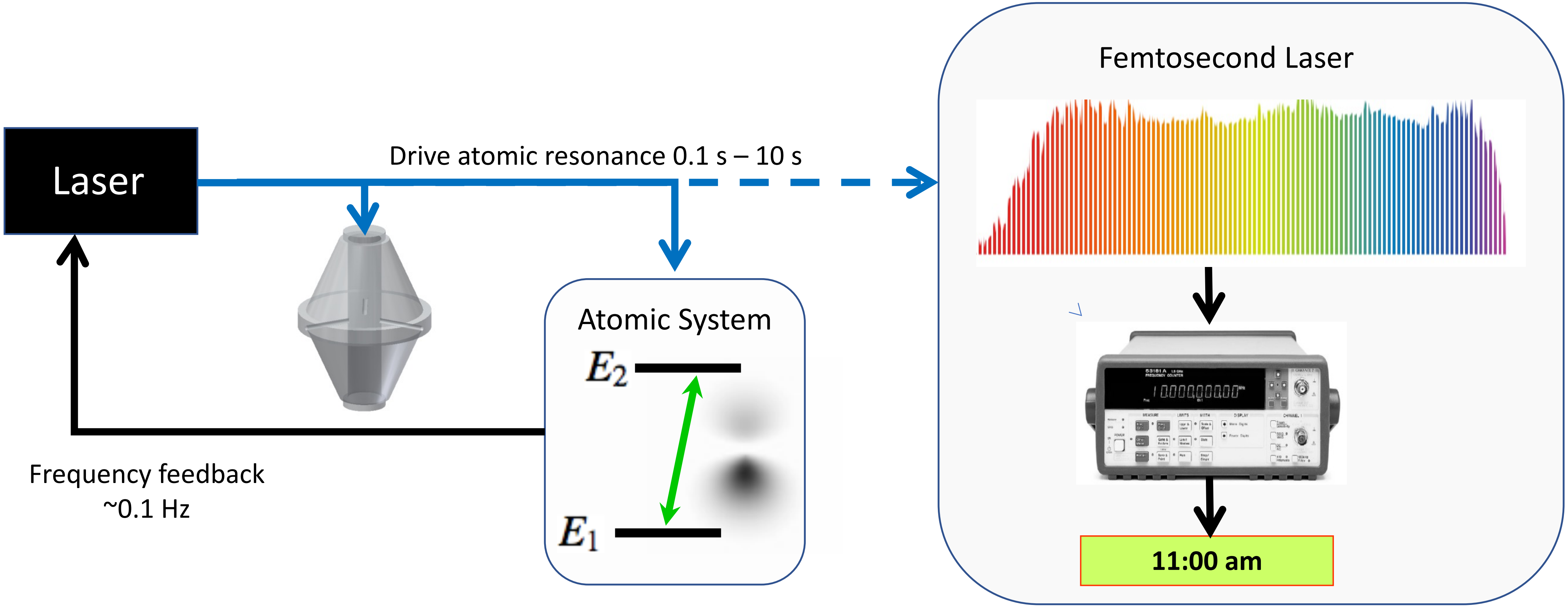
Hans Dehmelt 1988 *Phys. Scr.* **1988** 102



+ Strong, controllable interactions between ions

Slide credit: David Hume

Principle of Optical Clocks



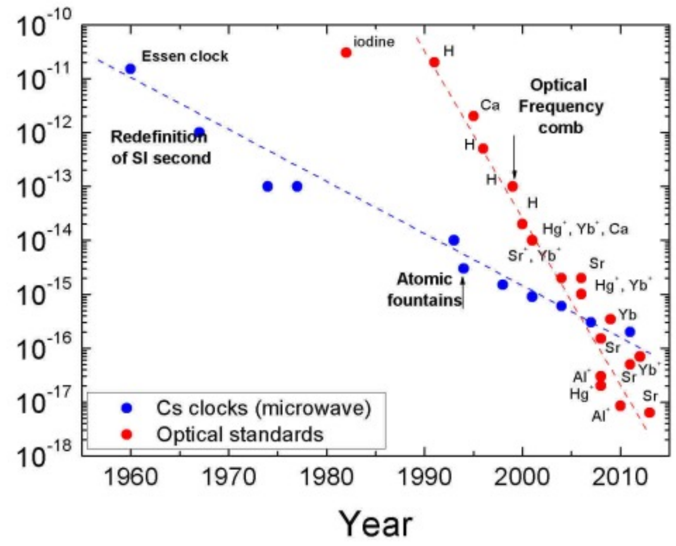
Clock frequency: $f_0 = \frac{E_2 - E_1}{h}$ ≈10^{15} Hz

Slide credit: David Hume

Trends in Precision Frequency Metrology

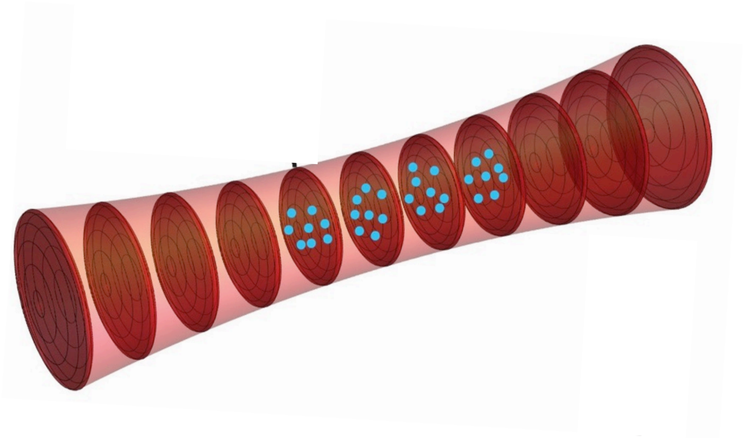
In recent years, optical frequency measurements have. . .

…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

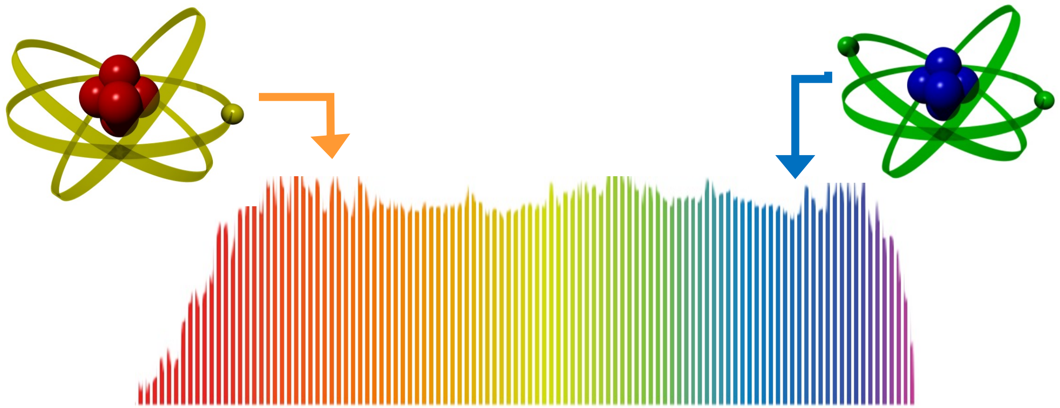
More atoms = higher stability

- 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



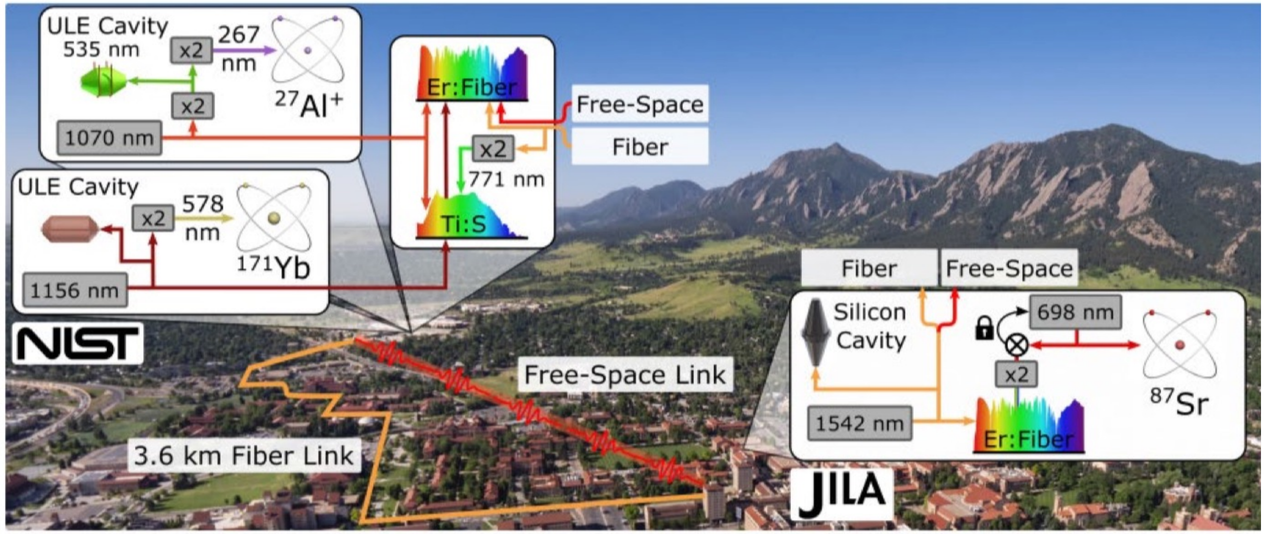
$$R(t) = \frac{\omega_1(t)}{\omega_2(t)}$$

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

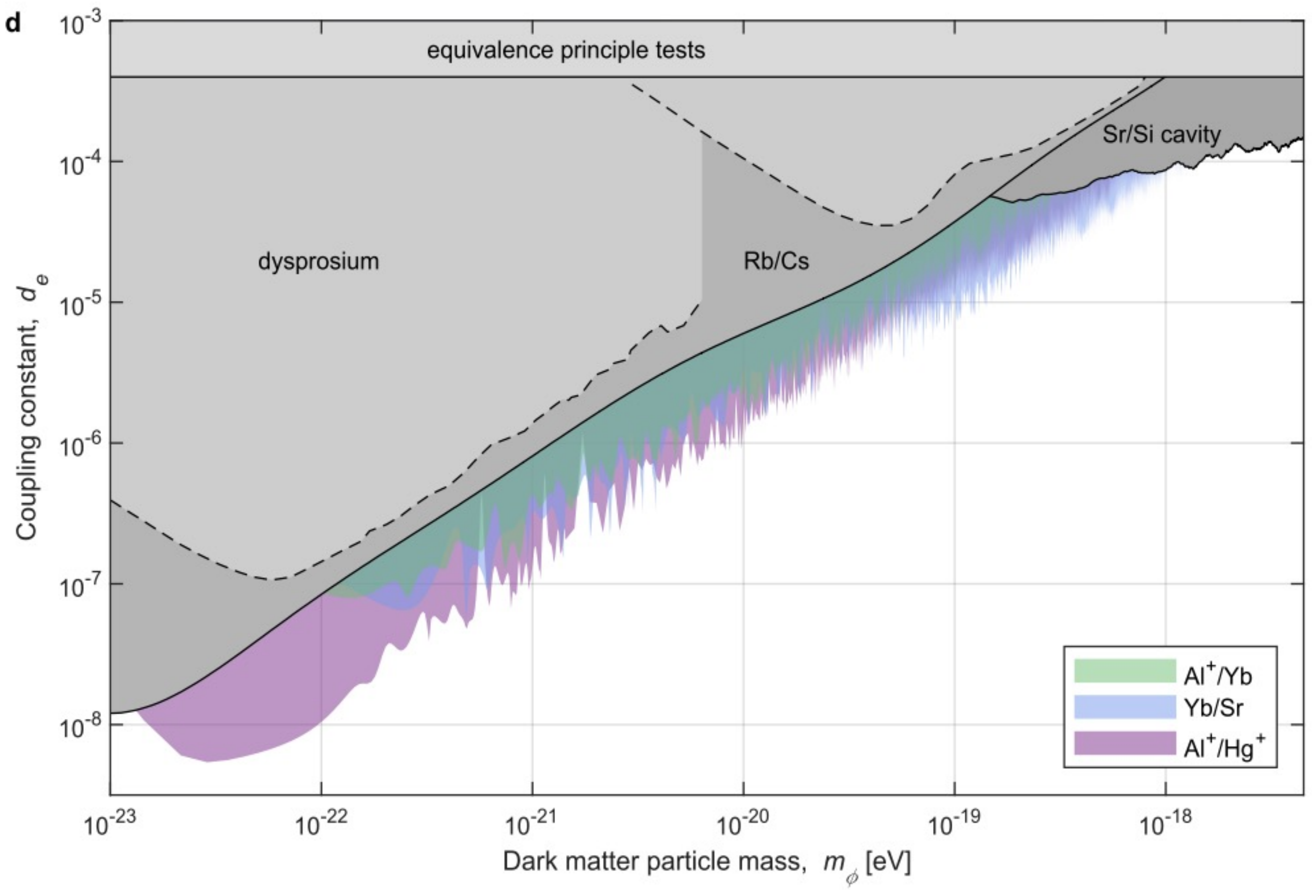
Searches for oscillations in the frequency ratio

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

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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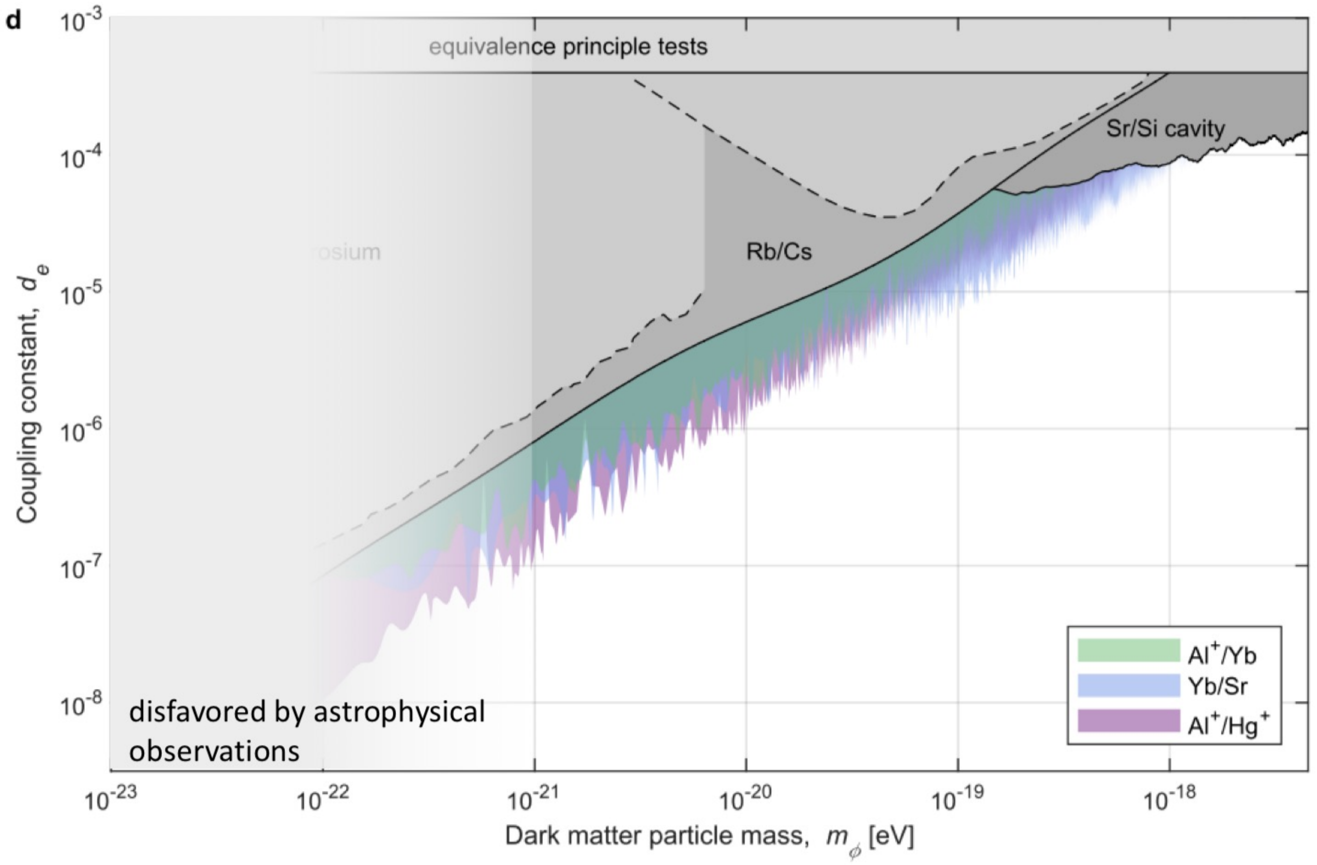
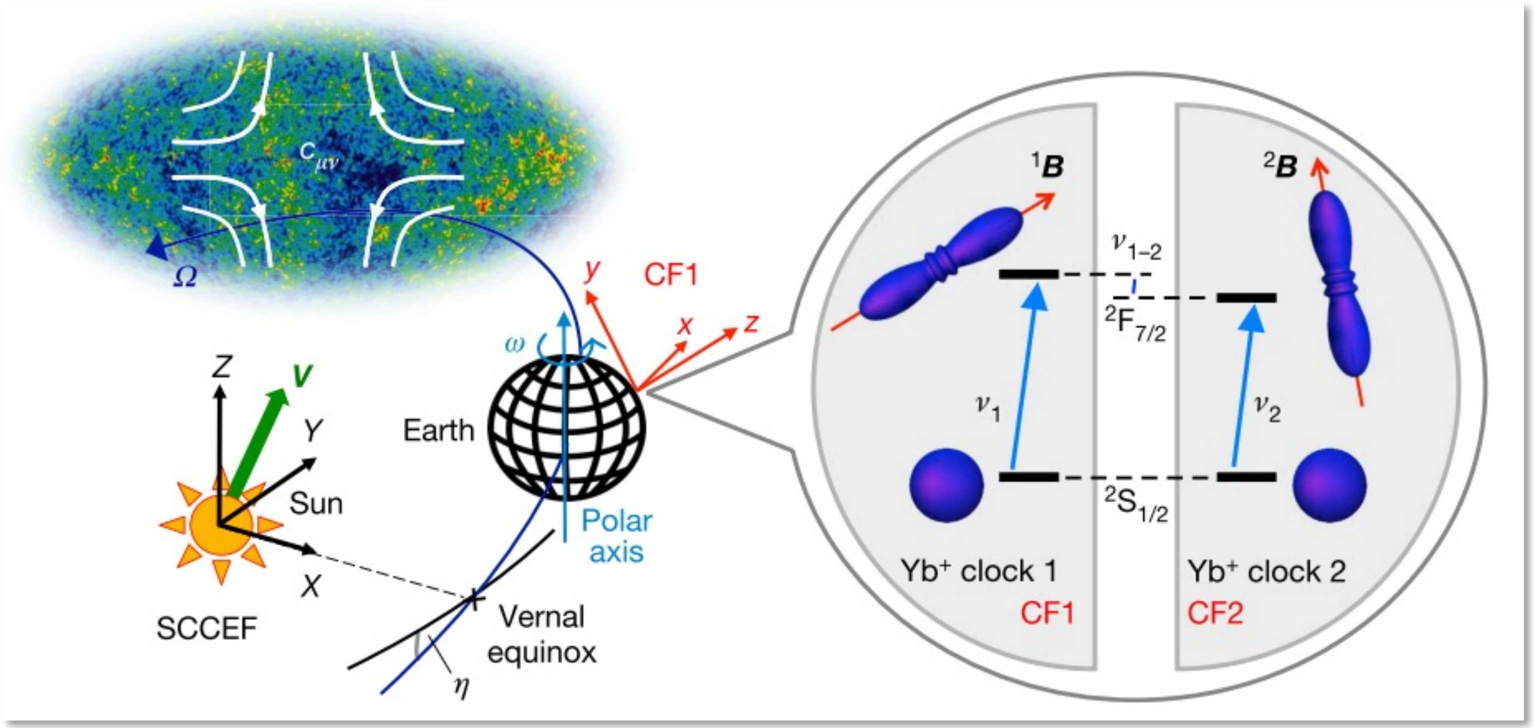


~ 10X improvement over several orders of magnitude in mass

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

Testing Lorentz Symmetry

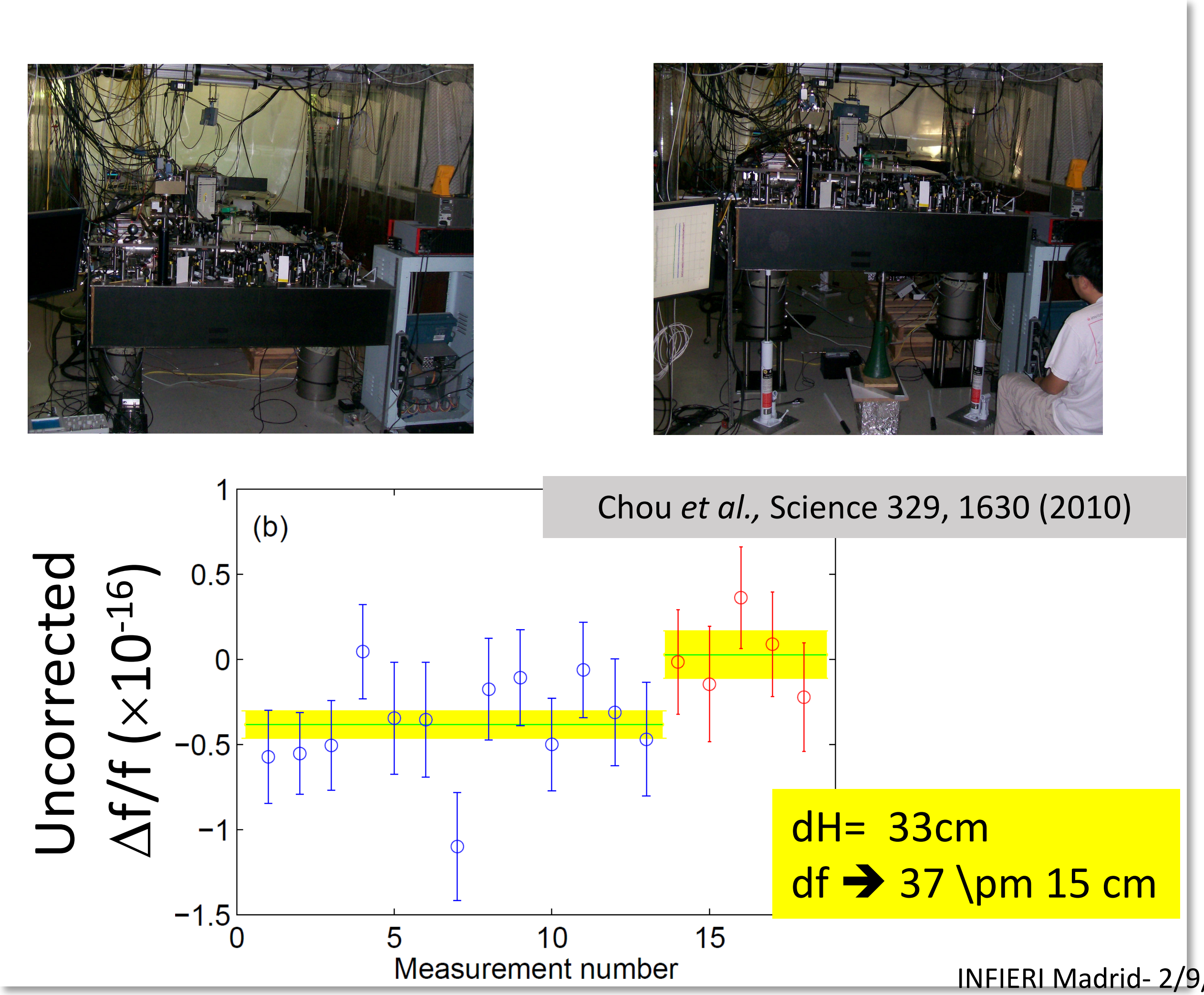


Sanner *et al.*, Nature 567, 204 (2019)

Slide credit: David Hume

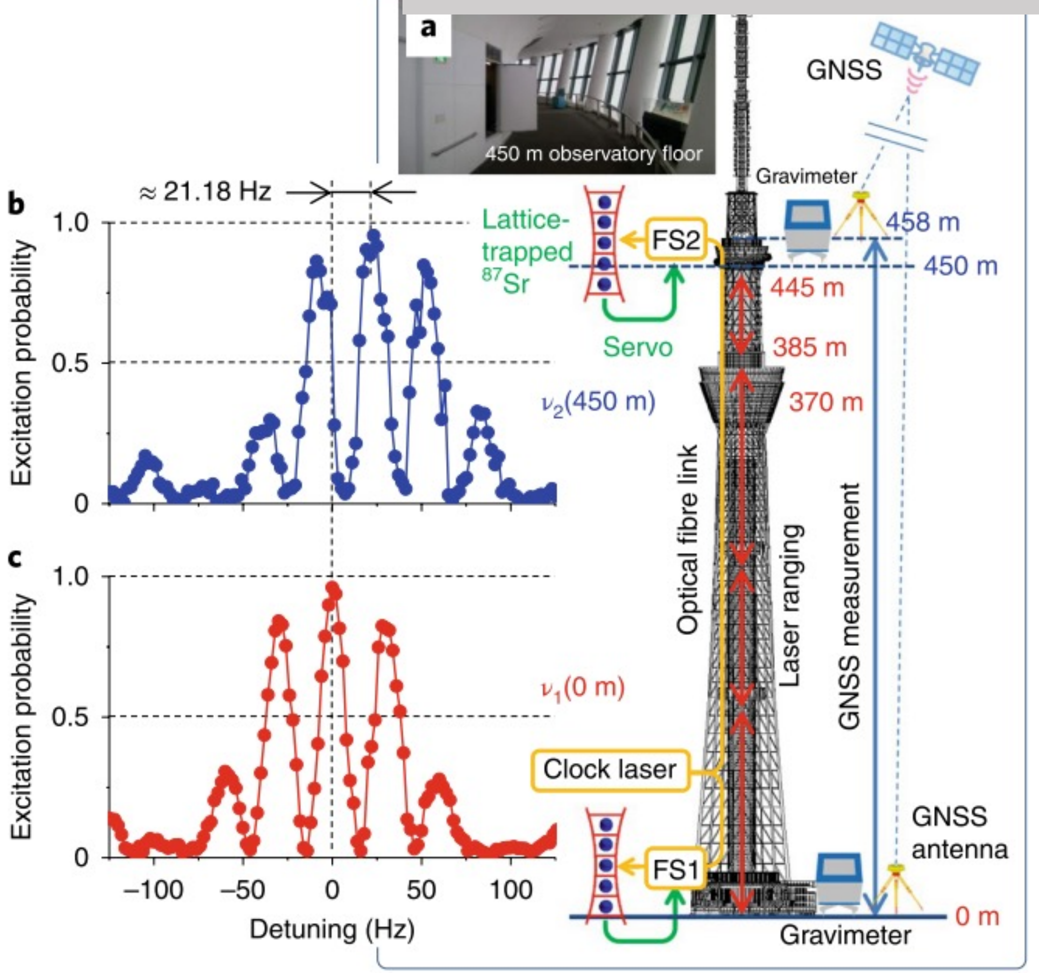
Measuring the Gravitational Redshift

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



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

dH= 33cm
df ➔ 37 \pm 15 cm



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

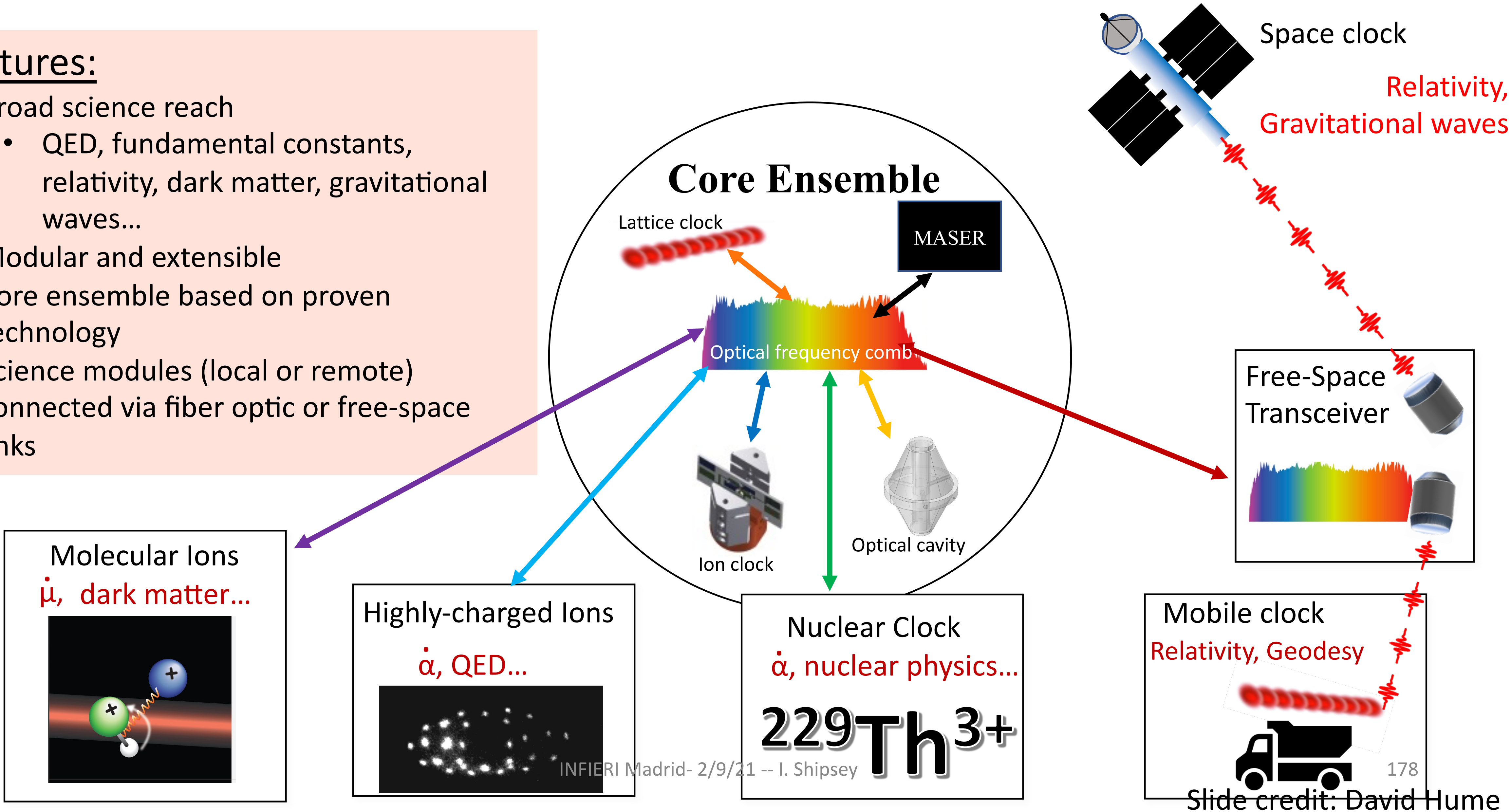
$$\Delta\nu/\nu_1 = (49{,}337.8 \pm 4.3)\times 10^{-18}$$
$$\bar{g}\Delta h/c^2 = (49{,}337.1 \pm 1.4)\times 10^{-18}.$$

Most stringent test of GR on Earth's surface

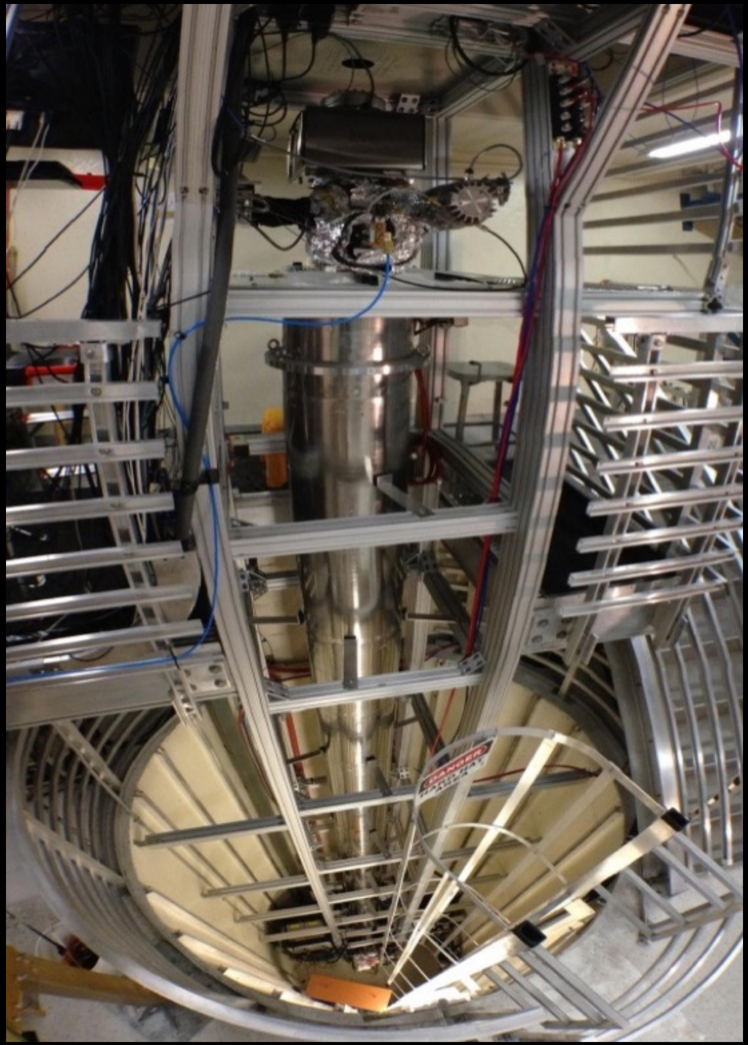
An Atomic Observatory for Fundamental Physics

Features:

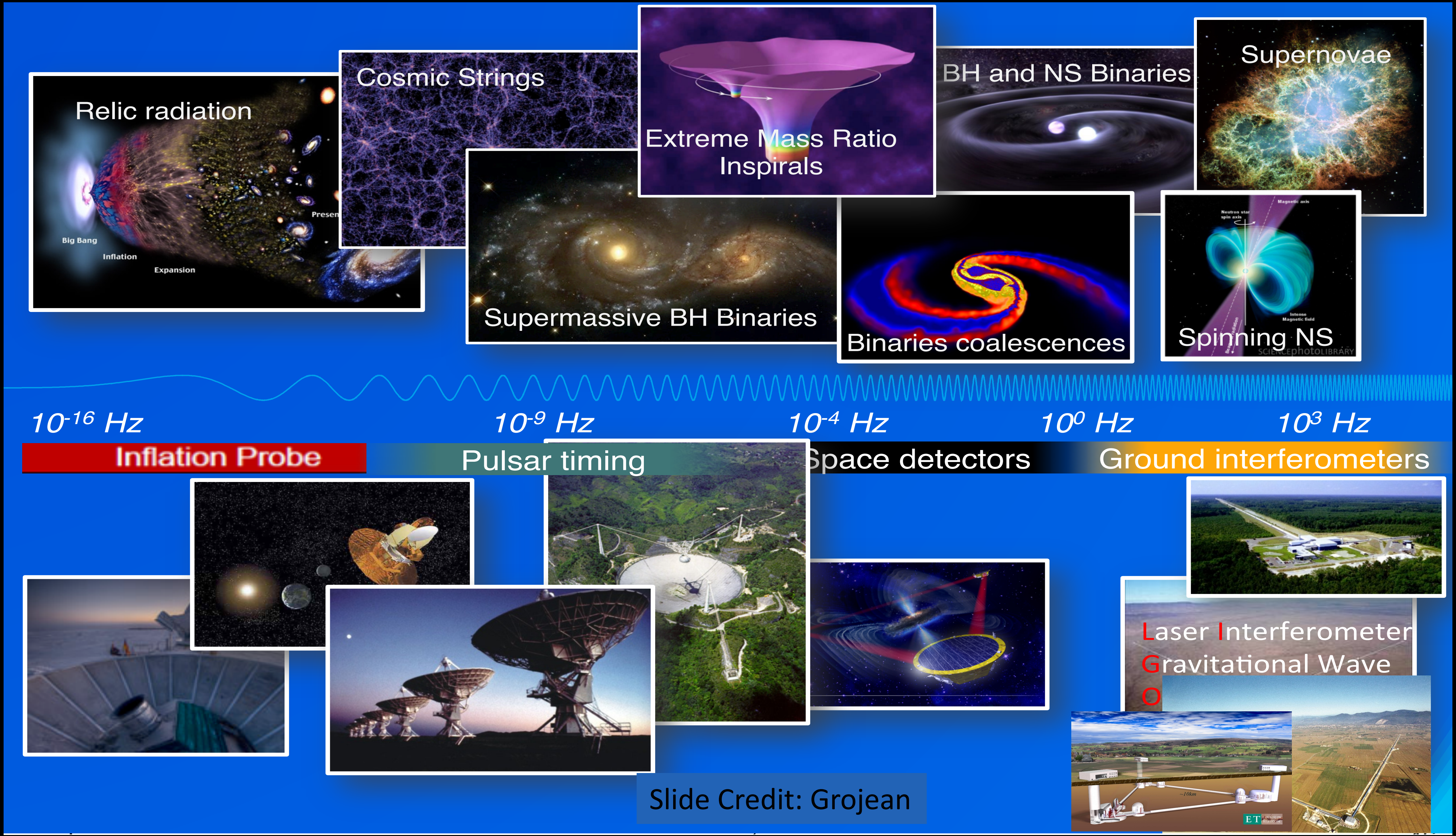
- Broad science reach
    - QED, fundamental constants, relativity, dark matter, gravitational waves…
- Modular and extensible
- Core ensemble based on proven technology
- Science modules (local or remote) connected via fiber optic or free-space links



Atom Interferometry

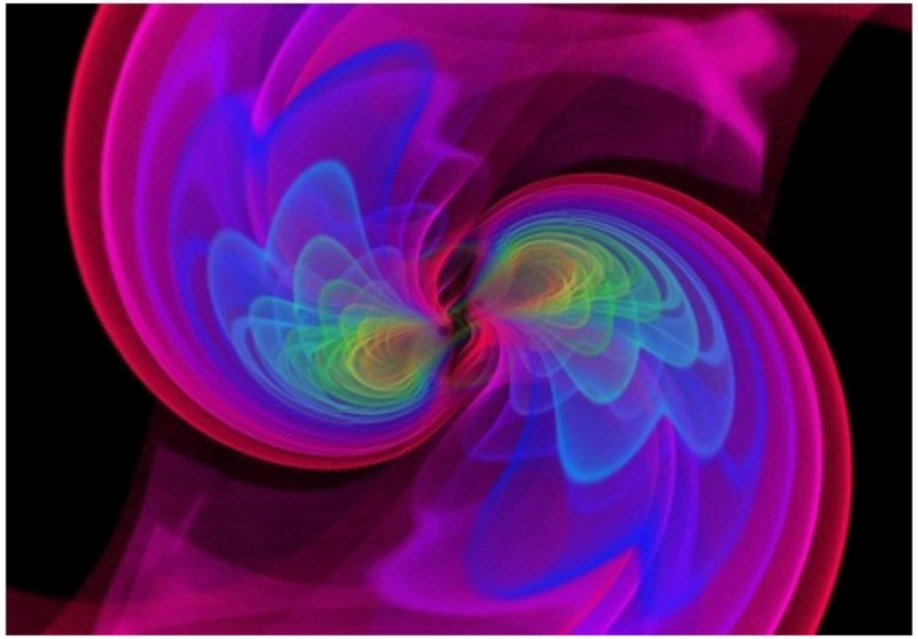


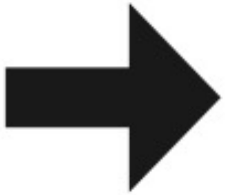
Gravitational Waves: Cosmology and Astrophysics



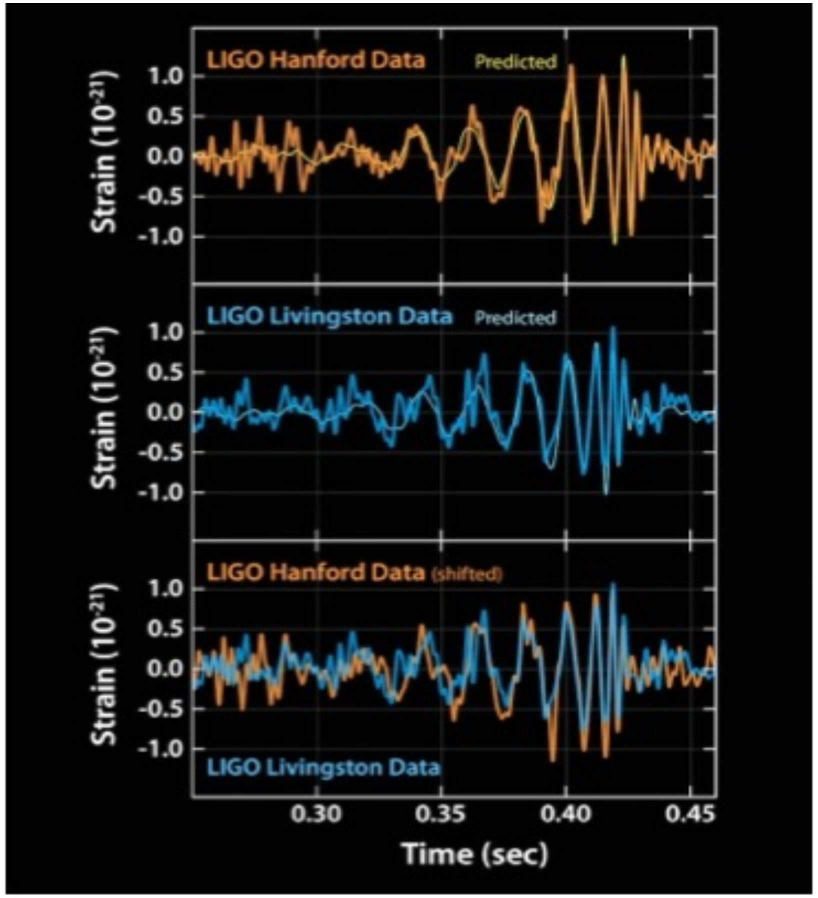
The pictures that shook the world

GW150914





1.3 billion years later on earth

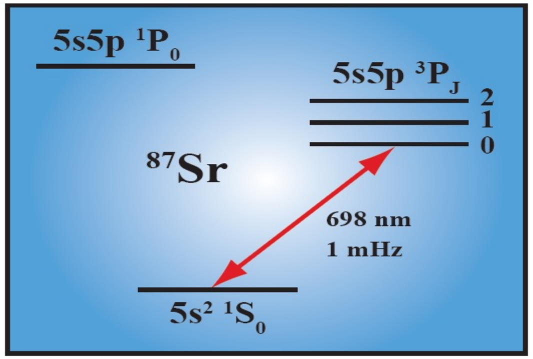


Slide Credit: Grojean

what did it teach us?

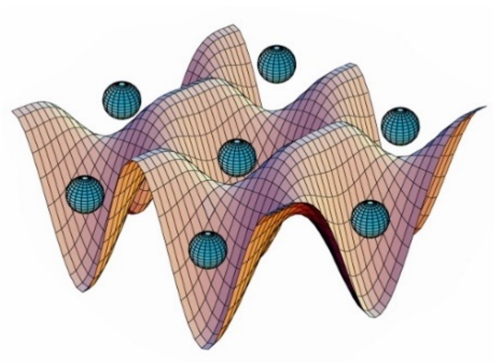
- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV ($c_g - c_\gamma < 10^{-17}$ GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity > 100 keV

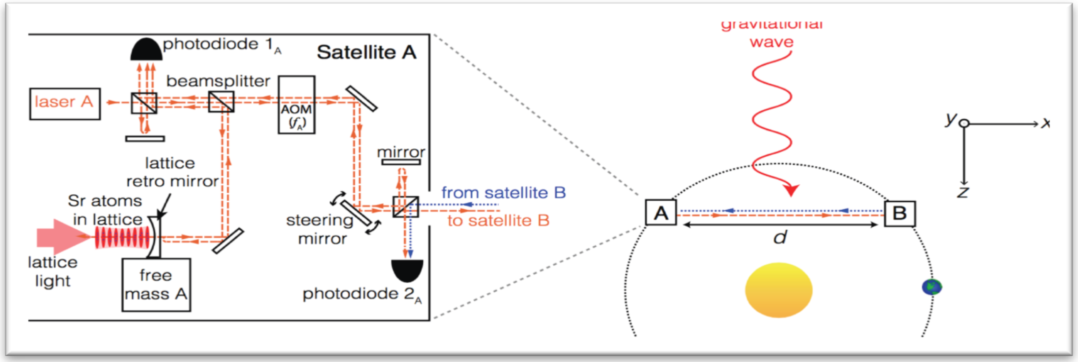
Atomic clocks and atom interferometers



- 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

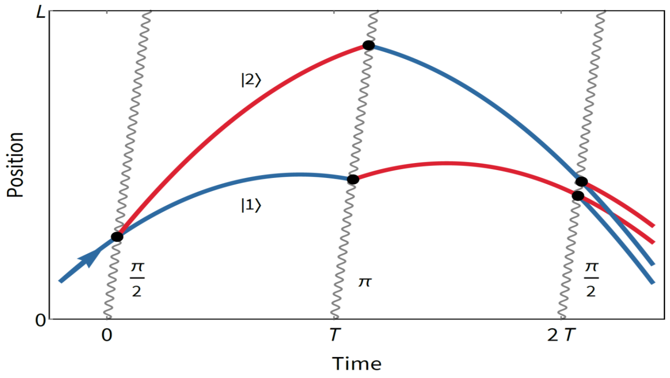
Optical lattice clocks

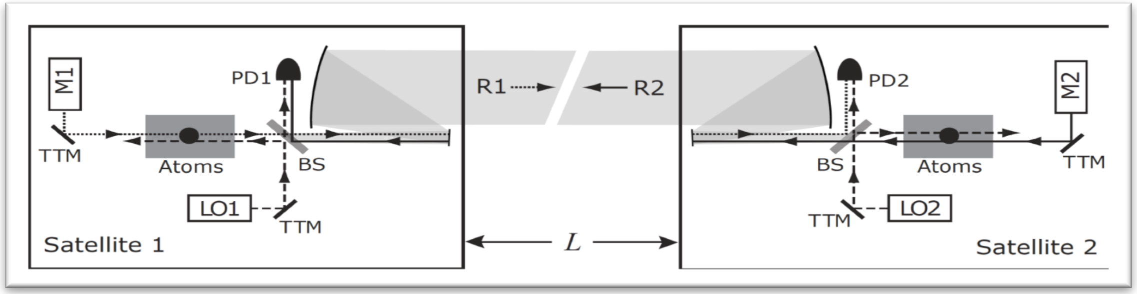




Kolkowitz et al., PRD 2016

Atom interferometers





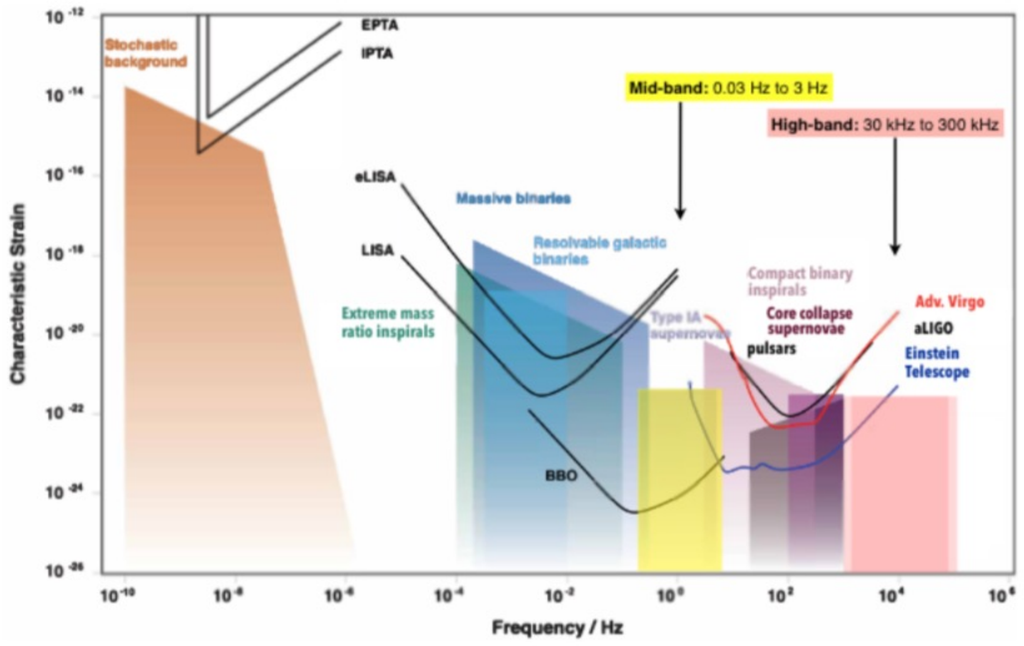
Hogan et al., PRA 2016

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

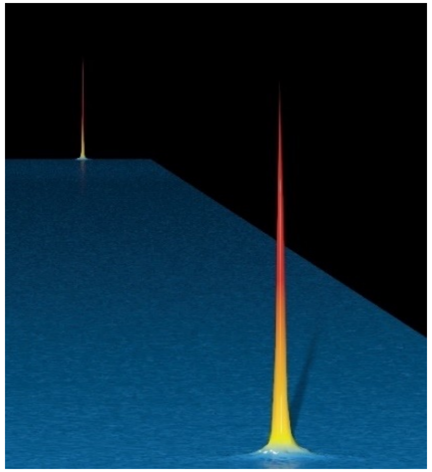


Ultralight wave-like dark matter probe

- 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

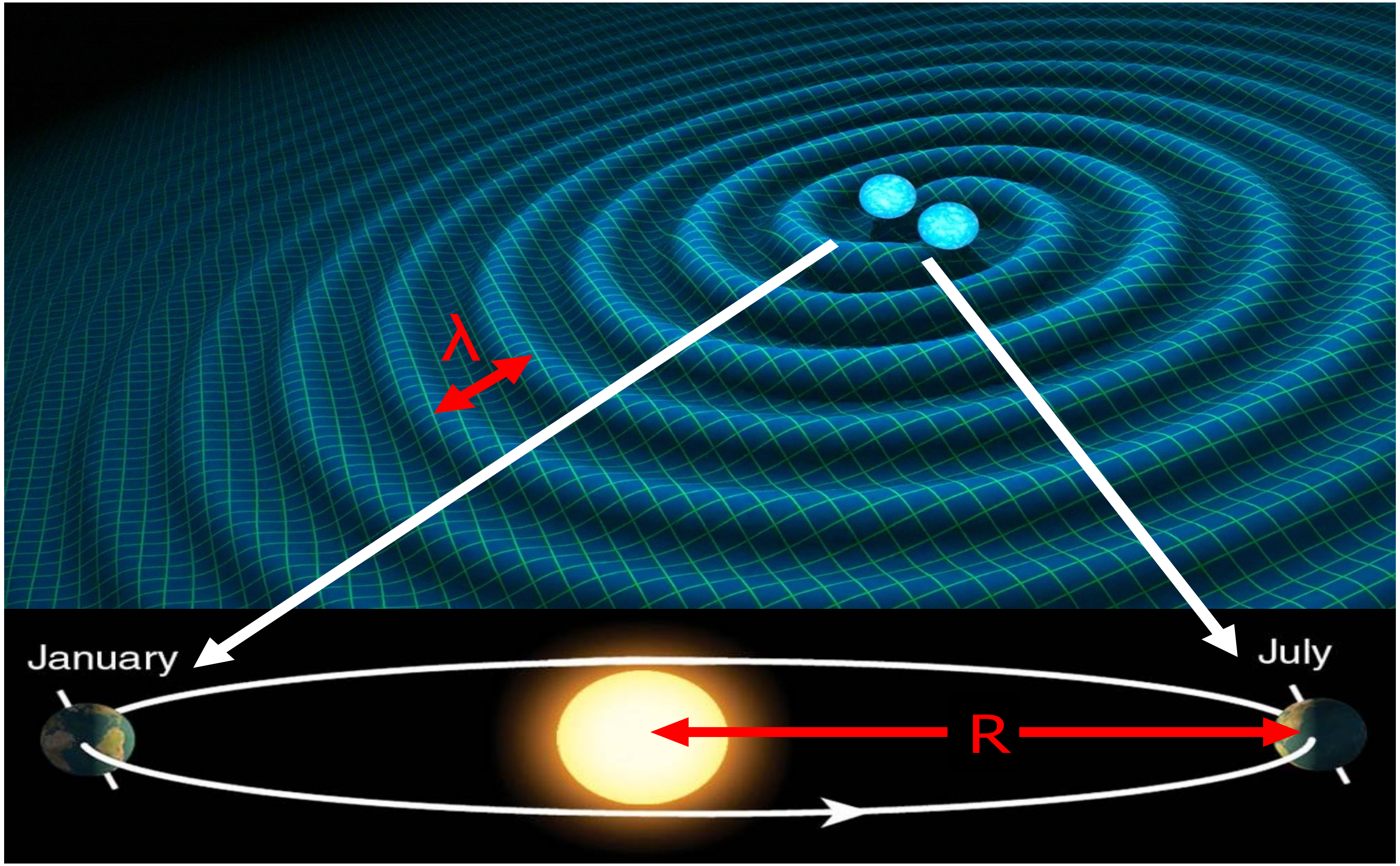
Sky localization precision:

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

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



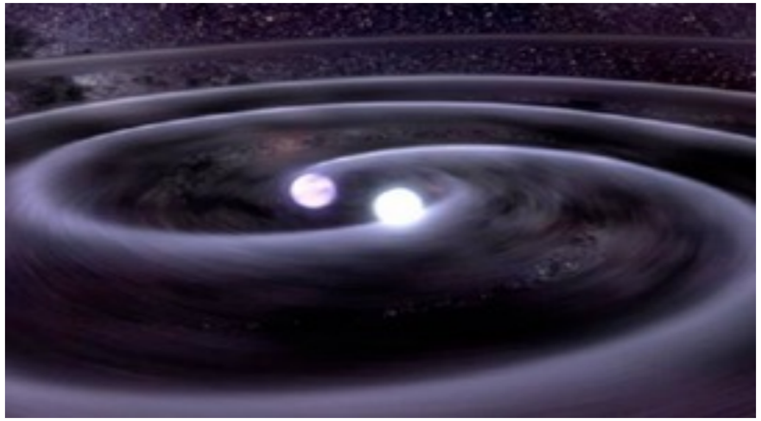
Slide credit: Jason Hogan

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

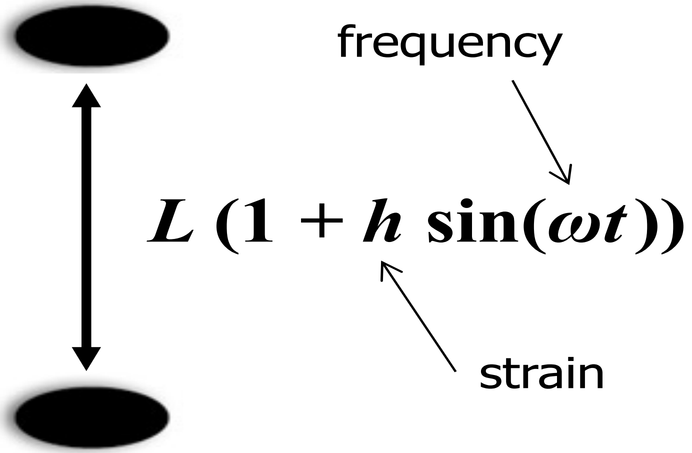
Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

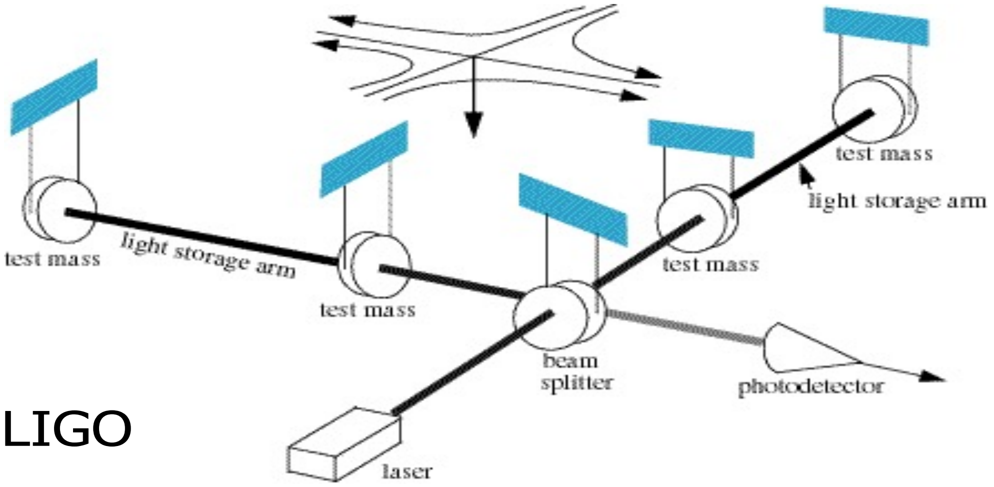
Gravitational Wave Detection

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



Megaparsecs…





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).

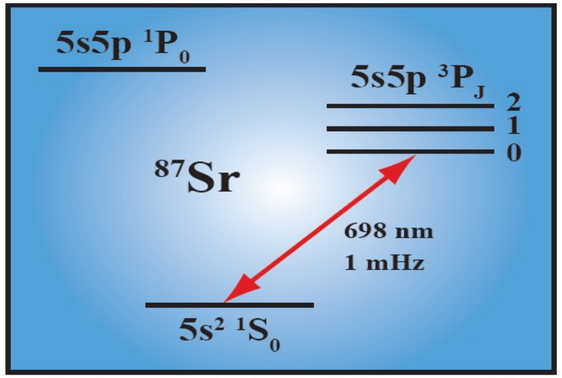
In MAGIS, atoms play both roles.

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

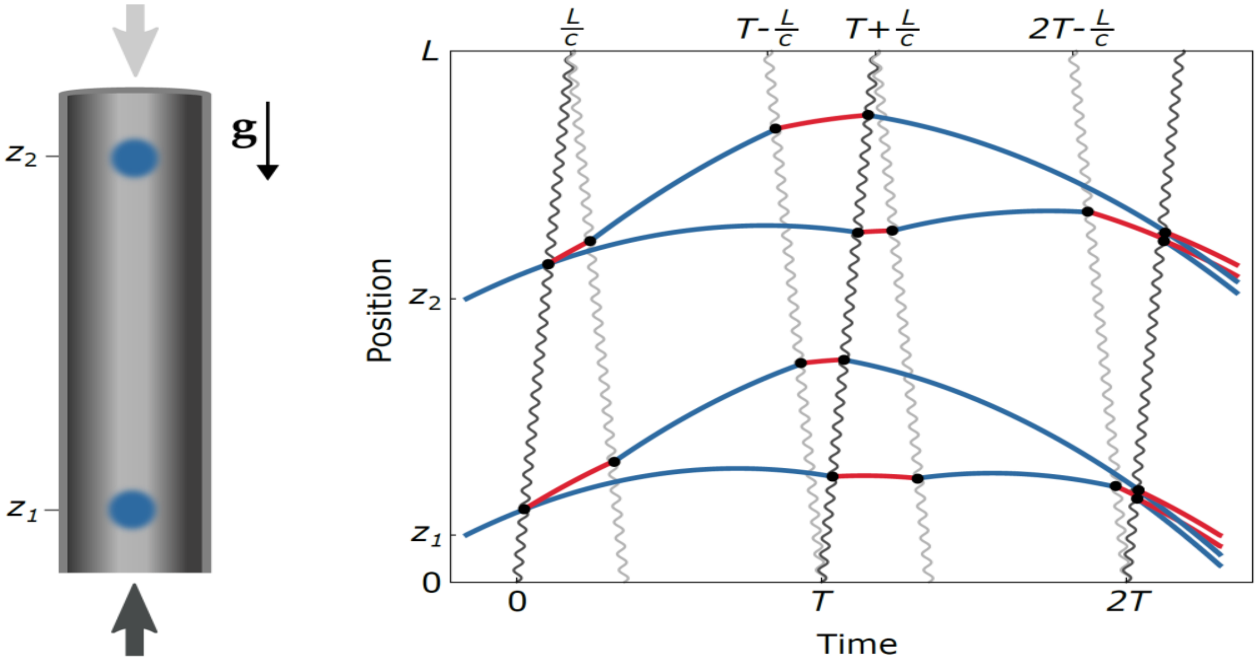
Clock atom interferometry

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:

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

(variations over time T)

Two ways for phase to vary:

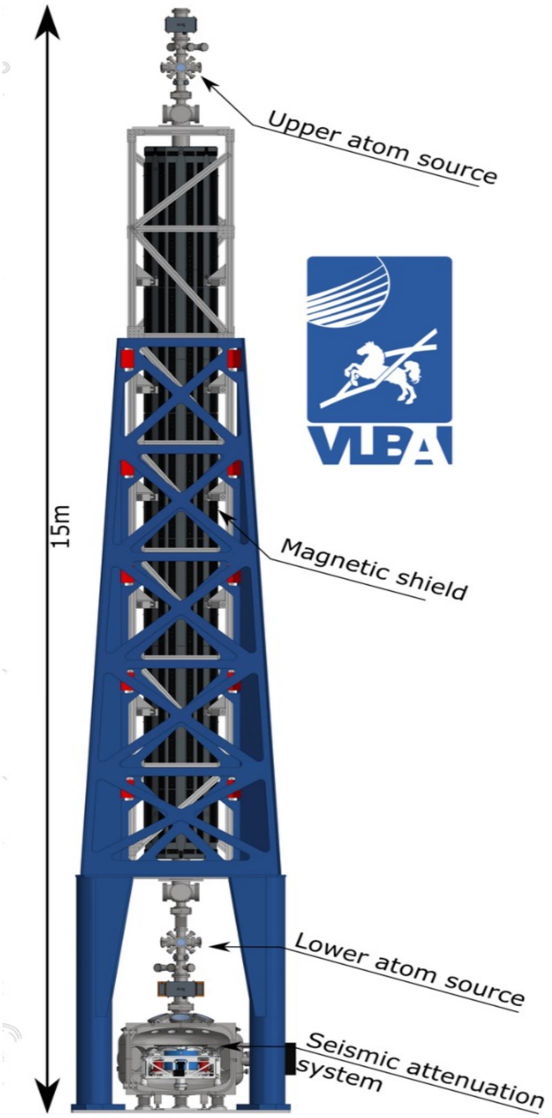
$\delta\omega_A$ *Dark matter*

$\delta L = hL$ *Gravitational wave*

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

Slide credit: Jason Hogan

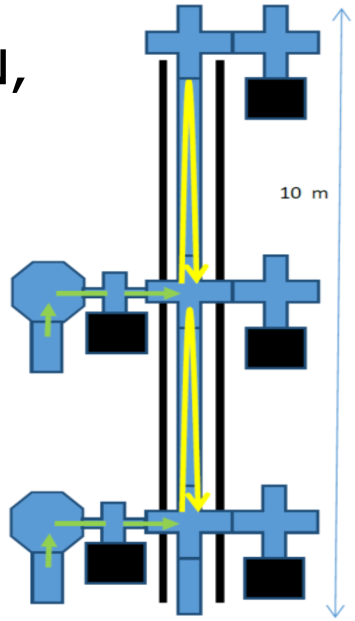
10-meter scale atom drop towers



Hannover, Germany

Wuhan, China

AION, UK

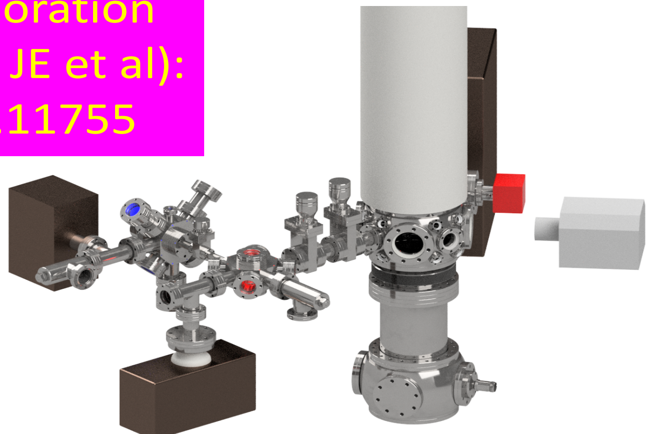


Stanford University

Planned Site for AION 10m

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

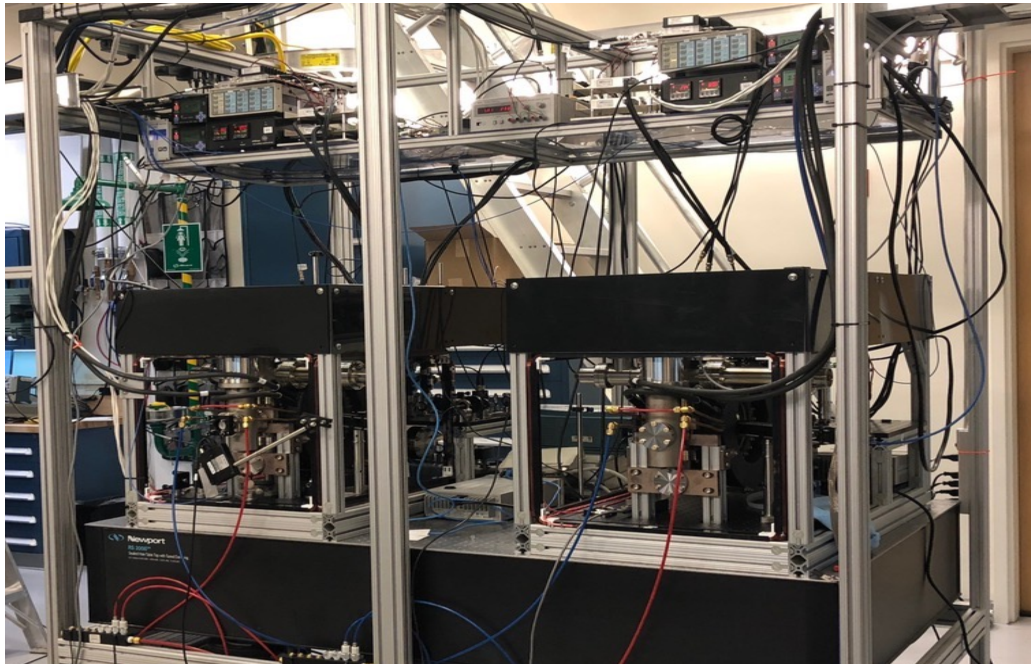
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

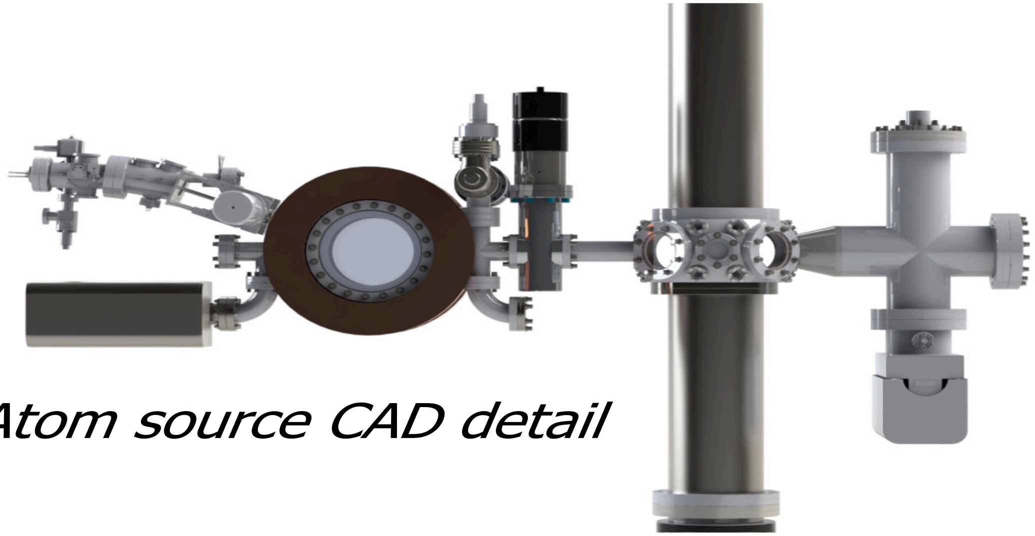


Stanford 10-meter Sr prototype

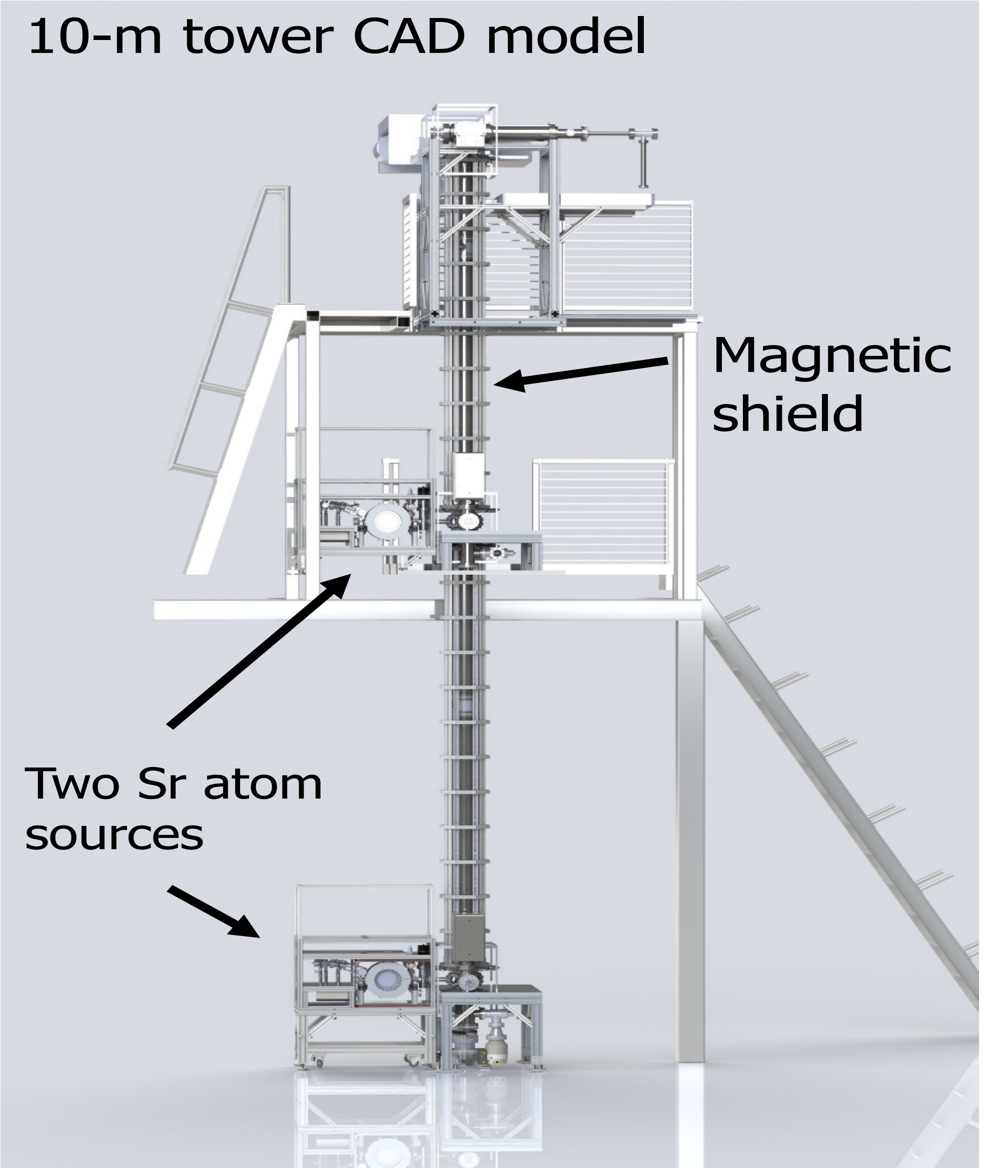
(MAGIS prototype)

Two assembled Sr atom sources





Atom source CAD detail

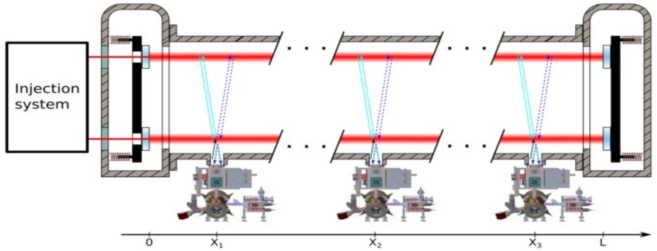


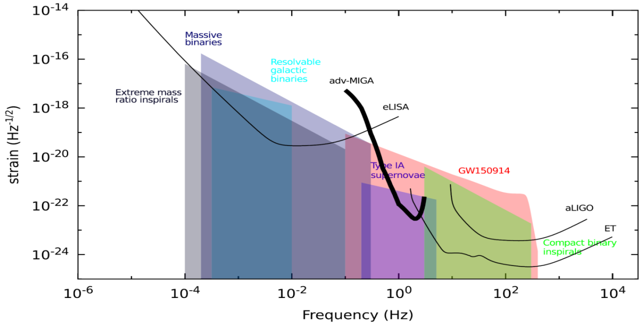
Slide credit: Jason Hogan

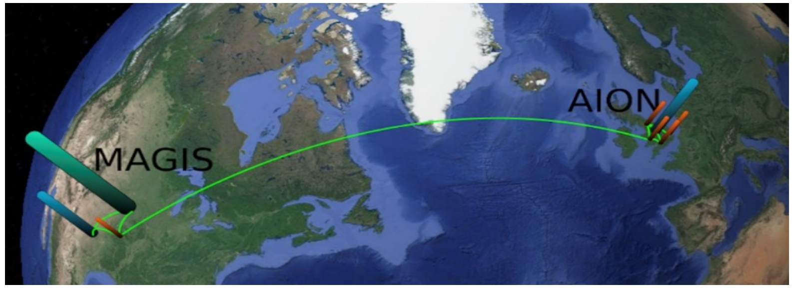
International efforts in long baseline atomic sensors

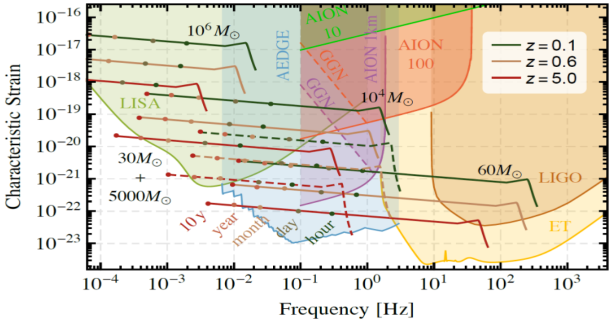
Project	Baseline Length	Number of Baselines	Orientation	Atom	Atom Optics	Location
MAGIS-100	100 m	1	Vertical	Sr	Clock AI, Bragg	USA
AION	100 m	1	Vertical	Sr	Clock AI	UK
MIGA	200 m	2	Horizontal	Rb	Bragg	France
ZAIGA	300 m	3	Vertical	Rb, Sr	Raman, Bragg, OLC	China

MIGA: Matter Wave laser Interferometric Gravitation Antenna (France)



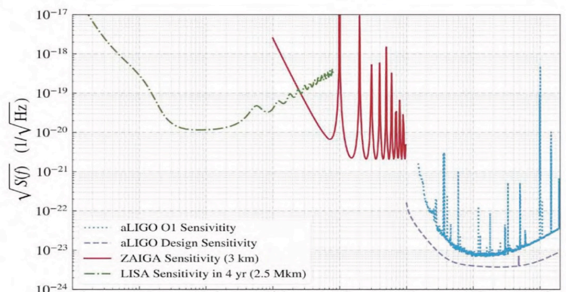






AION: Atom Interferometer Observatory and Network (UK)

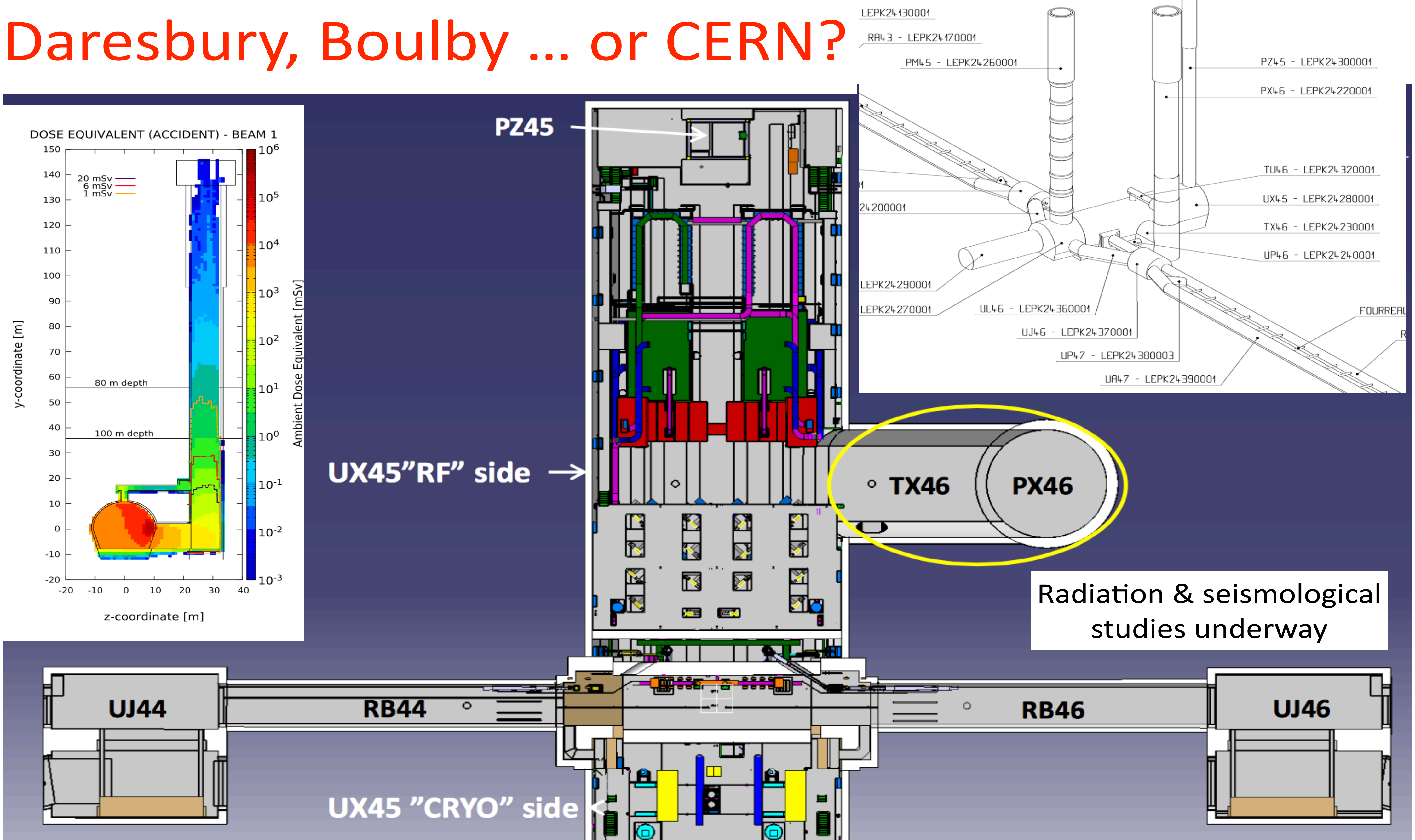
ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna (China)



Slide credit: Jason Hogan

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

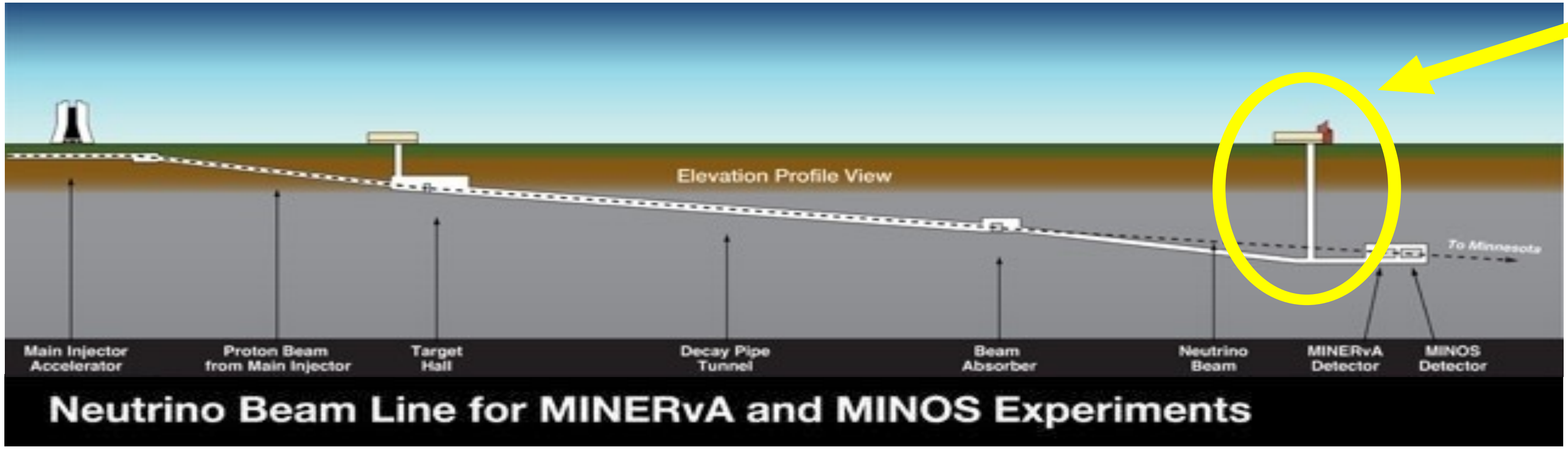
Possible Sites for AION 100m: Daresbury, Boulby … or CERN?

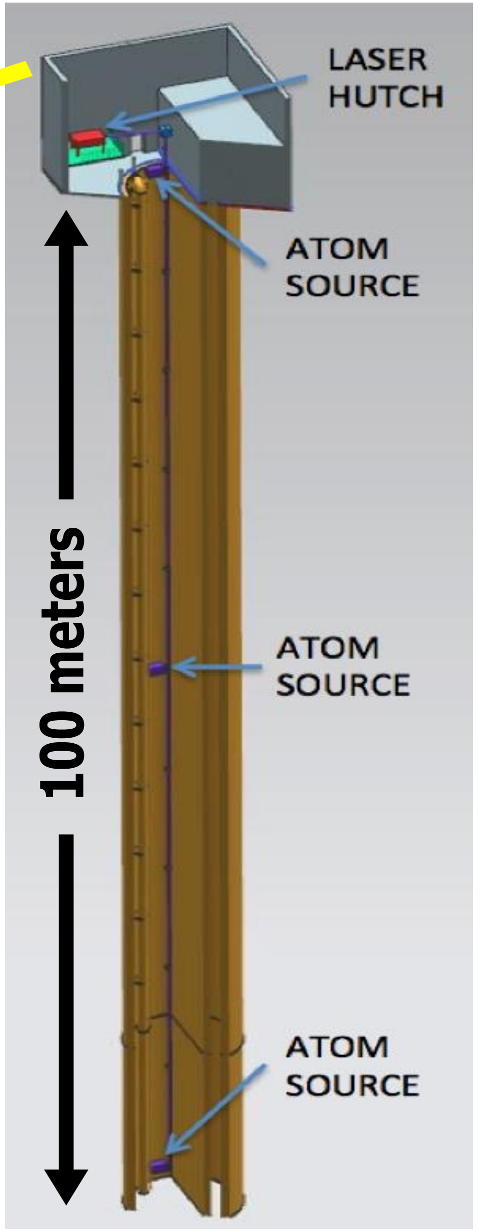


Radiation & seismological studies underway

MAGIS-100: Detector prototype at Fermilab

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





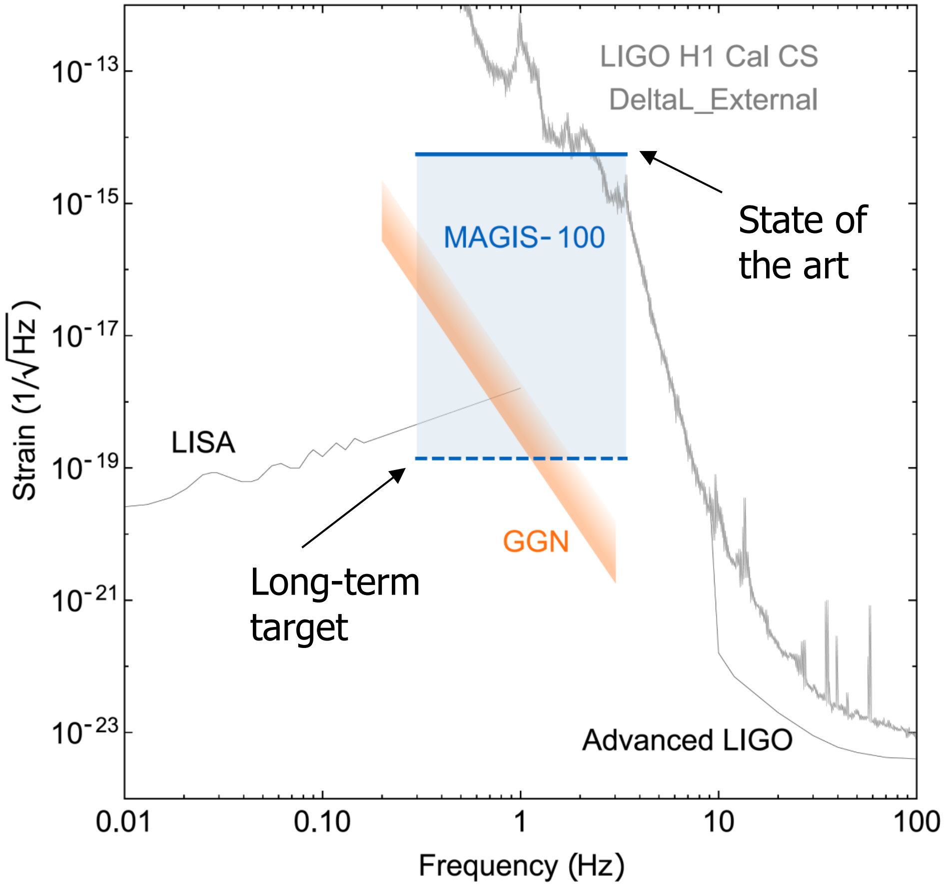
- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

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

Slide credit: Jason Hogan

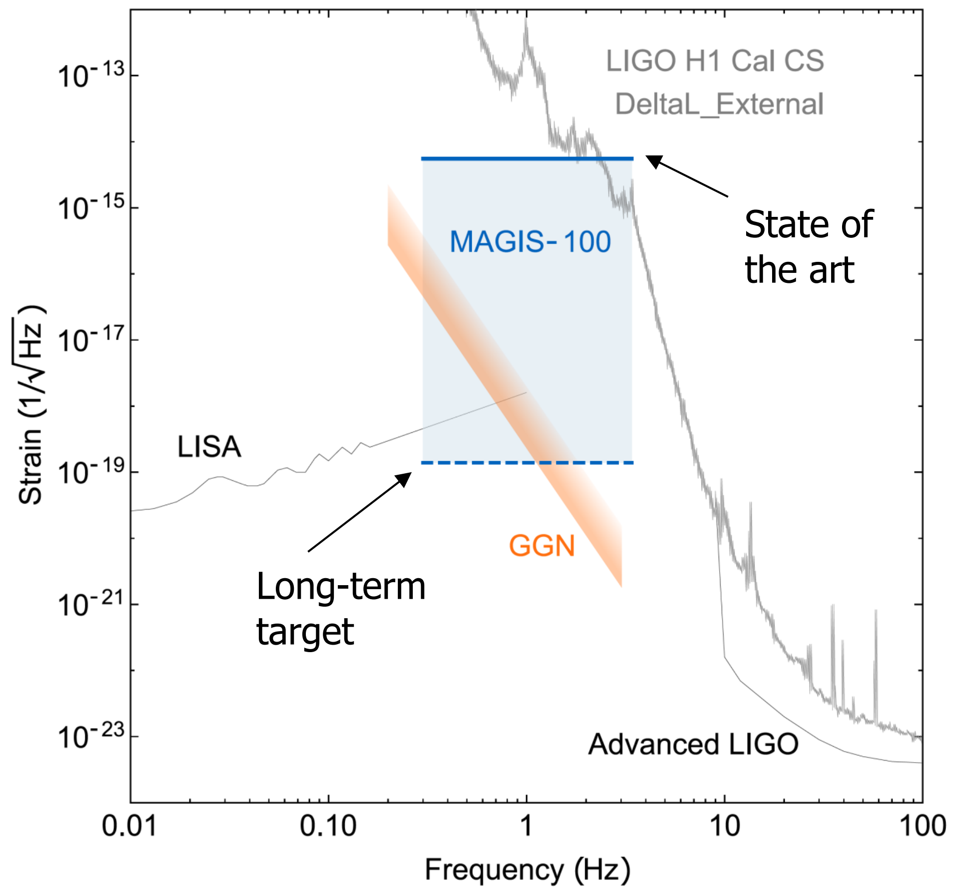
MAGIS-100 projected sensitivity

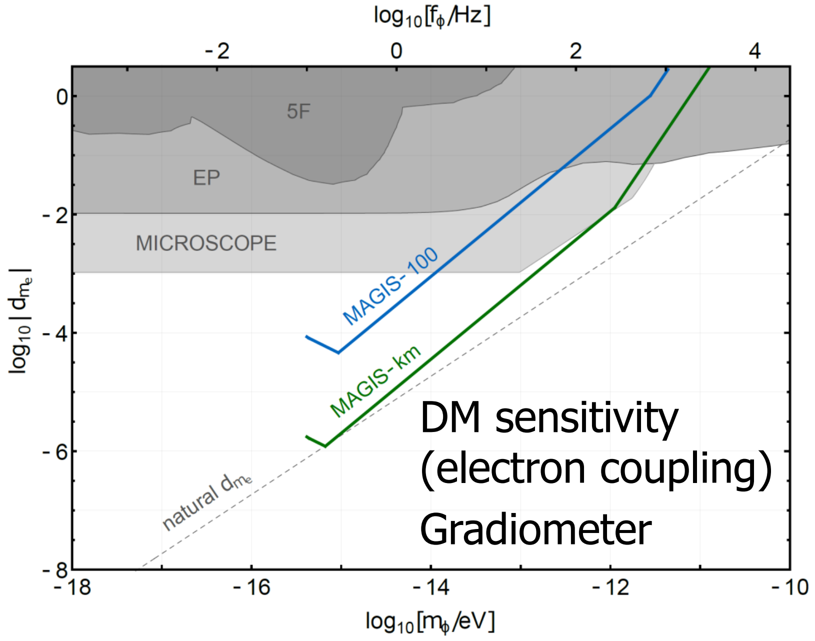
Gravitational wave sensitivity

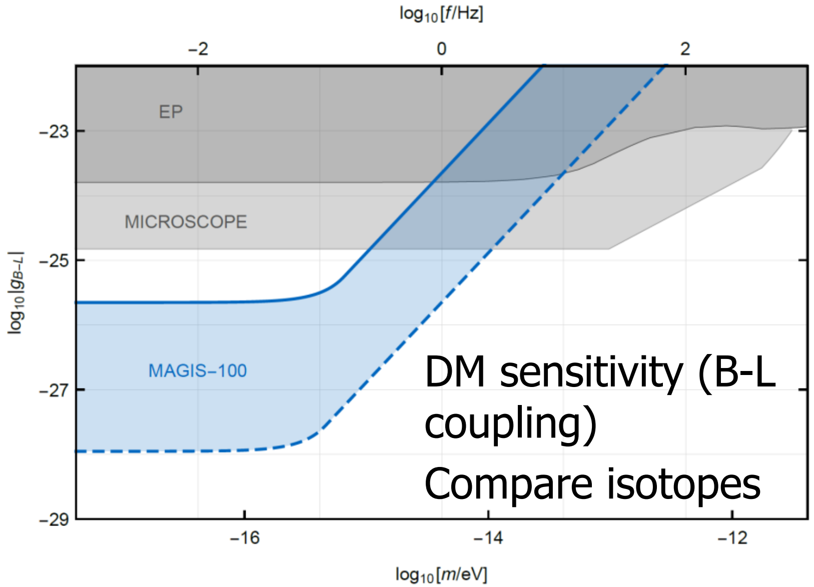


MAGIS-100 projected sensitivity

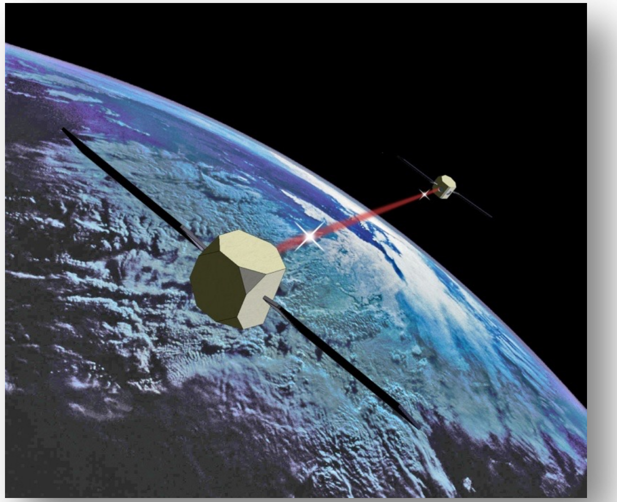
Gravitational wave sensitivity







MAGIS-style satellite detector



Satellite detector concept

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

Example design

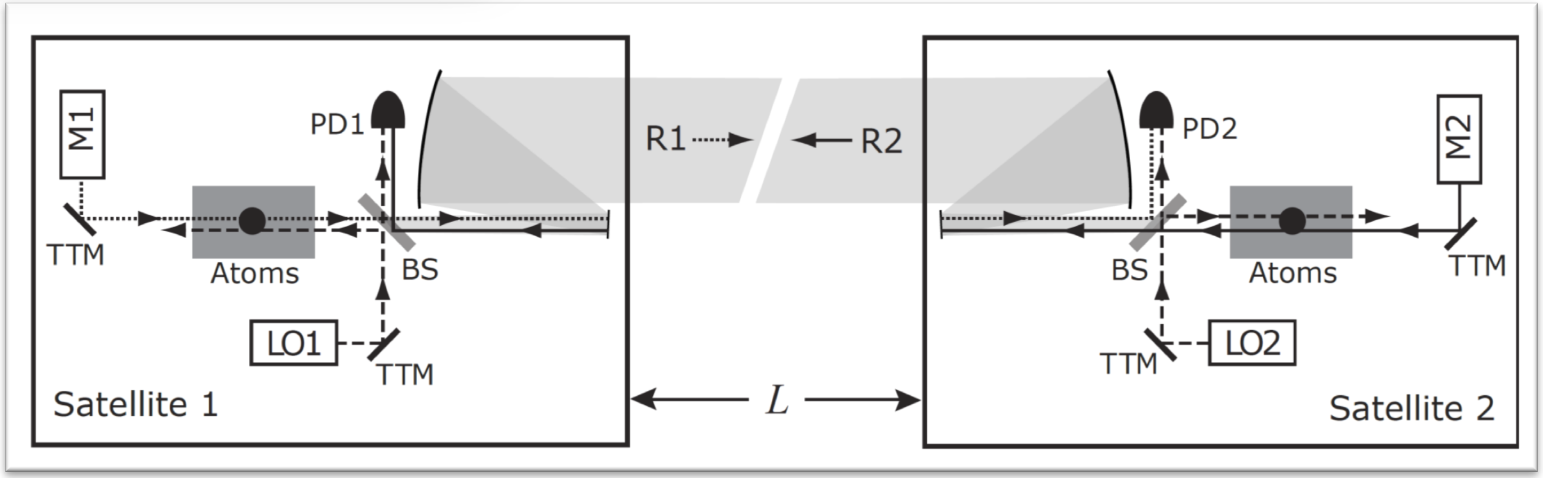
$$L = 4 \times 10^7 \text{ meters}$$

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

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

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

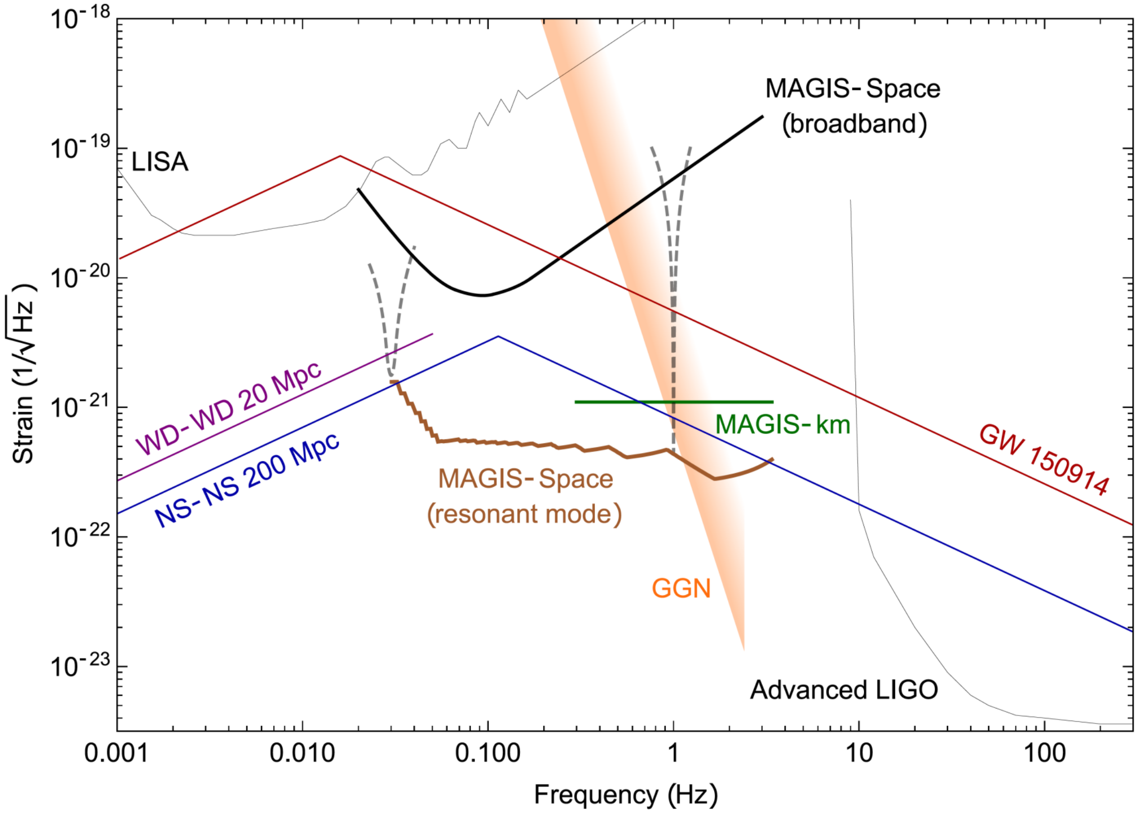
$$n_p < 10^3$$



- 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

@ CERN: PBC, large low energy physics community…

https://indico.cern.ch/event/1002356/ PBC technology annual workshop 2021 (focus on quantum sensing)
https://indico.cern.ch/event/1057715/ PBC technology mini workshop: superconducting RF (Sep. 2021)

Initial experiments with quantum sensors world-wide
→ rapid investigation of new phase space

→ scaling up to larger systems, improved devices
→ expanding explored phase space

⟶ particles, atoms, ions, nuclei:	tests of QED, symmetries
⟶ atomic interferometers:	DM searches
⟶ RF cavities:	axion searches

typically not obvious, given that most detectors rely on detecting the product of many interactions between a particle and the detector (ionization, scintillation, Cerenkov photons, …)

handful of ideas that rely on quantum devices, or are inspired by them, but do not necessarily use them as quantum detectors per se, but rather their properties to enhance / permit measurements that are more difficult to achieve otherwise

main focus on tracking / calorimetry / timing

closely related: nanostructured materials
→ Frontiers of Physics, M. Doser et al., 2022

these are not developed concepts, but rather the kind of approaches one might contemplate working towards

Michael Doser
EP Seminar
13/5/2022

very speculative!

Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) **5.3.6** *

GEMs (graphene)

Atoms, molecules, ions

5.3.5 *

Rydberg TPC's

Spin-based sensors

5.3.3 *

helicity detectors

* https://cds.cern.ch/record/2784893

Michael Doser
EP Seminar
13/5/2022

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
- 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

Most recent European Strategies

the large …

weblink

2017-2026 European Astroparticle Physics Strategy

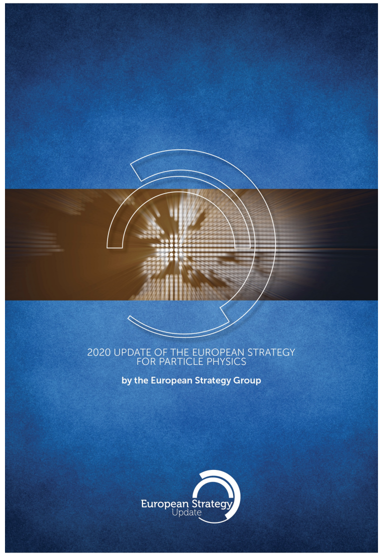
… the connection …

weblink

Long Range Plan 2017 Perspectives in Nuclear Physics

… the small

weblink



2020 Update of the European Particle Physics Strategy

Are community driven strategies outlining our ambition to address compelling open questions

Guidance for funding authorities to develop resource-loaded research programmes

Most recent European Strategies

the large …

weblink

2017-2026 European Astroparticle Physics Strategy

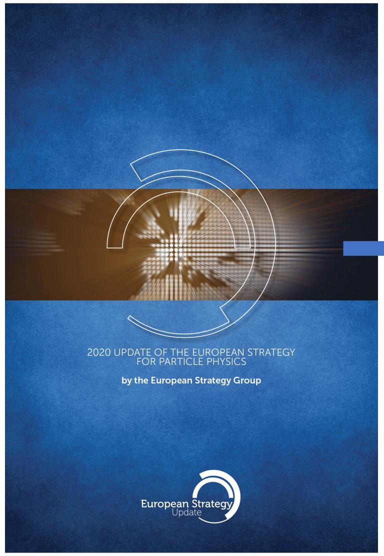
… the connection …

weblink

Long Range Plan 2017 Perspectives in Nuclear Physics

… the small

weblink



2020 Update of the European Particle Physics Strategy

ECFA Detector R&D Roadmap

ECFA Detector R&D Roadmap

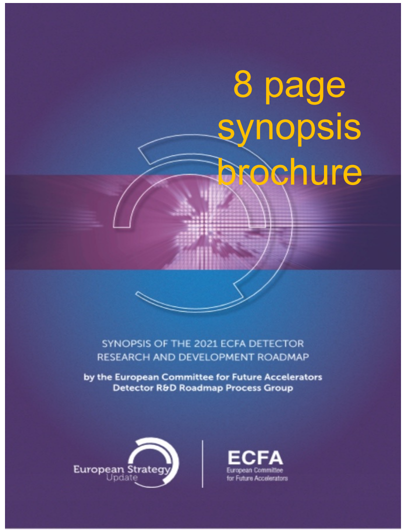
- Given the future physics programme, identify **the main technology R&D to be met so that detectors ar not the limiting factor for the timeline.**
- Detector context considered:

- Full exploitation of LHC
- Long baseline neutrinos
- Detectors for future Higgs-EW-Top factories (in all manifestations)
- Long term vision for 100 TeV hadron collider

- Future muon colliders
- Accelerator setup for rare decays/dark matter
- Experiments for precision QCD
- Non accelerator experiments (reactor neutrinos, double beta decay, dark matter)

Process organised by Panel and nine Task Forces with input sessions and open symposia with wide community consultation (1359 registrants)

Main Document published (approval by RECFA at 19/11/21) and 8 page synopsis brochure prepared for less specialised audience

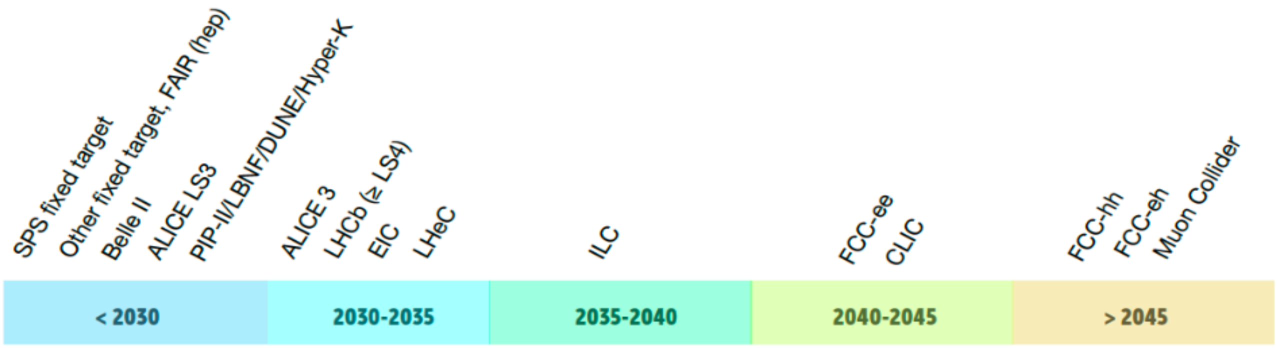


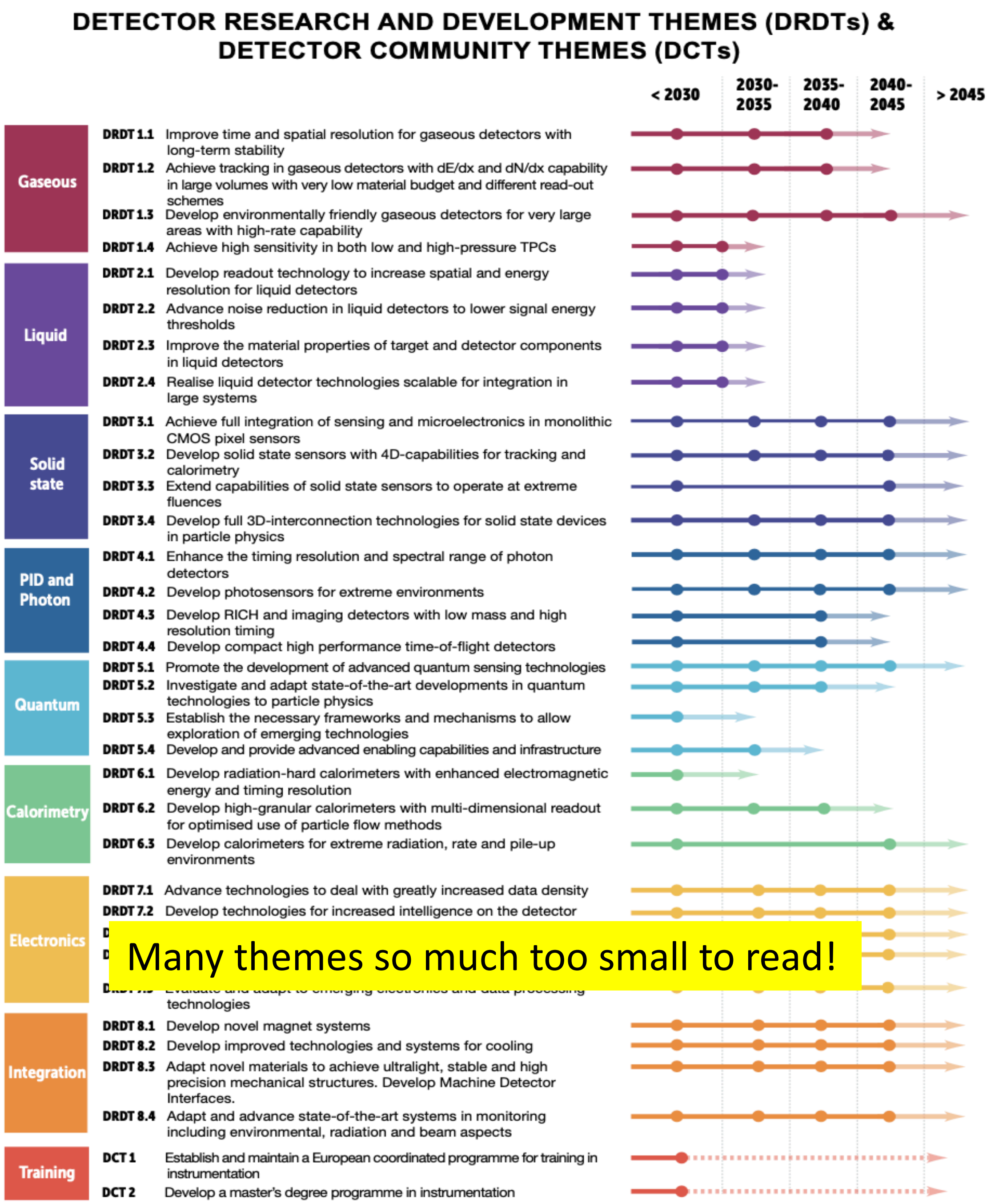
ECFA Detector R&D Roadmap Panel web pages at: https://indico.cern.ch/e/ECFADetectorRDRoadmap

Documents CERN-ESU-017: 10.17181/CERN.XDPL.W2EX

Roadmap Document Structure

Within each Task Force (one for each technology area + training) the aim is to propose a time ordered detector R&D programme by Detector Research and Development Themes (DRDT) in terms of **capabilities not currently achievable**.





Many themes so much too small to read!

Roadmap Document Structure

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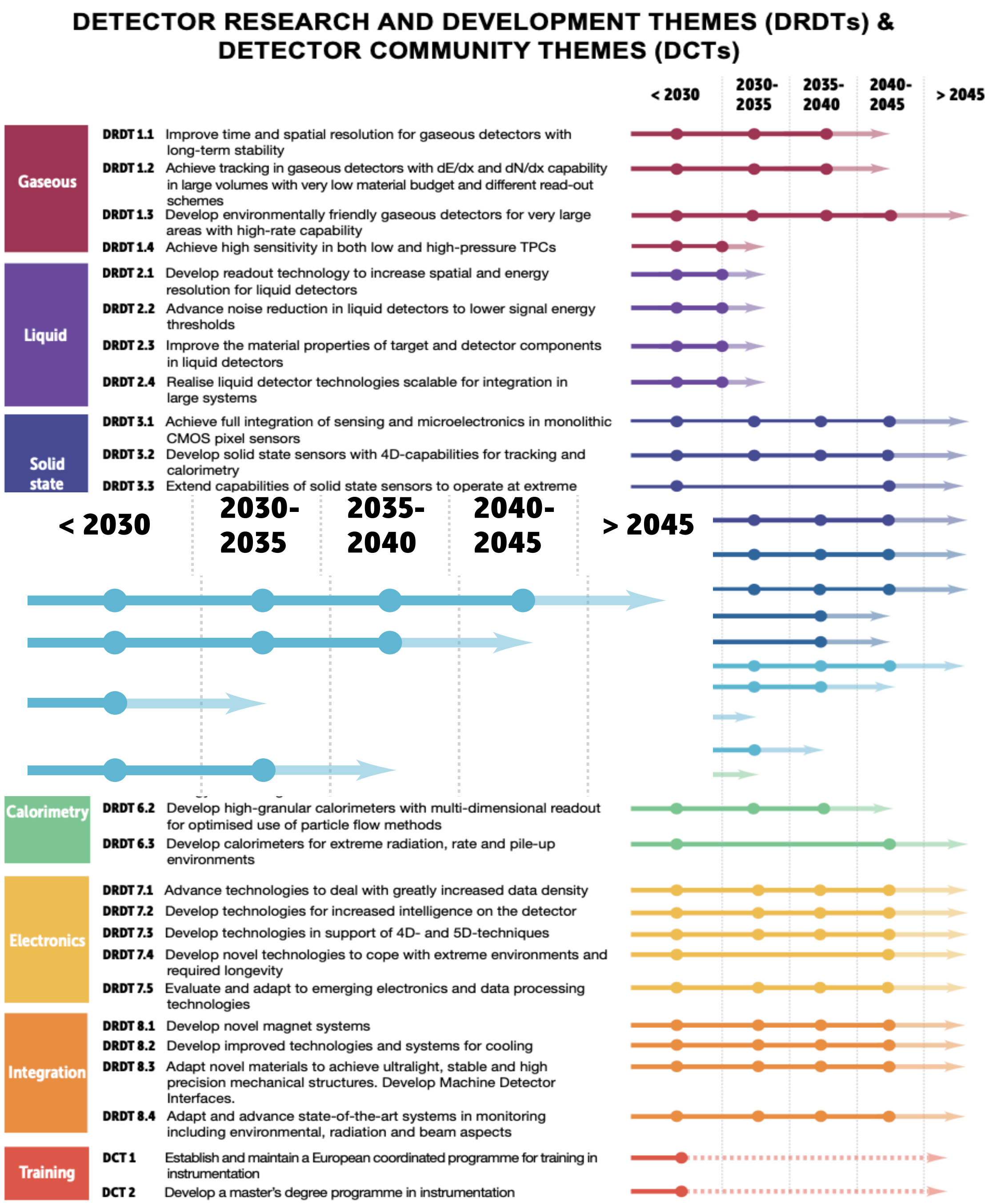
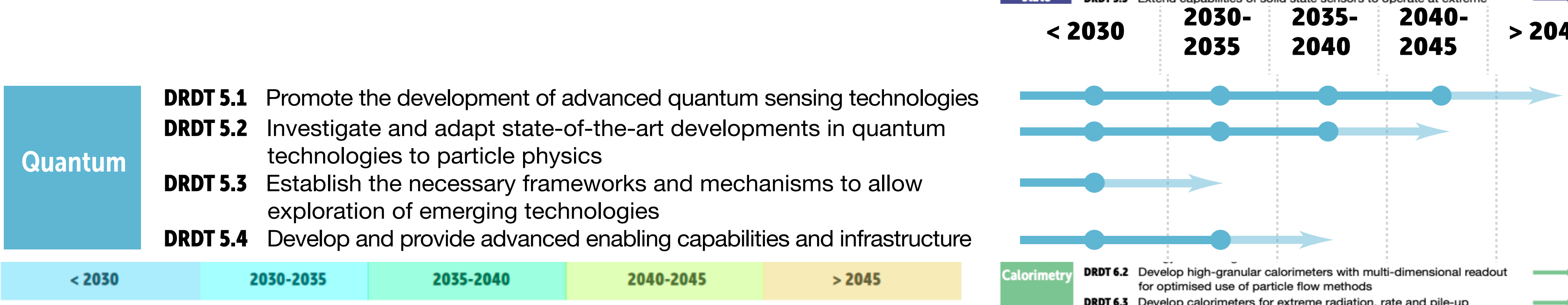
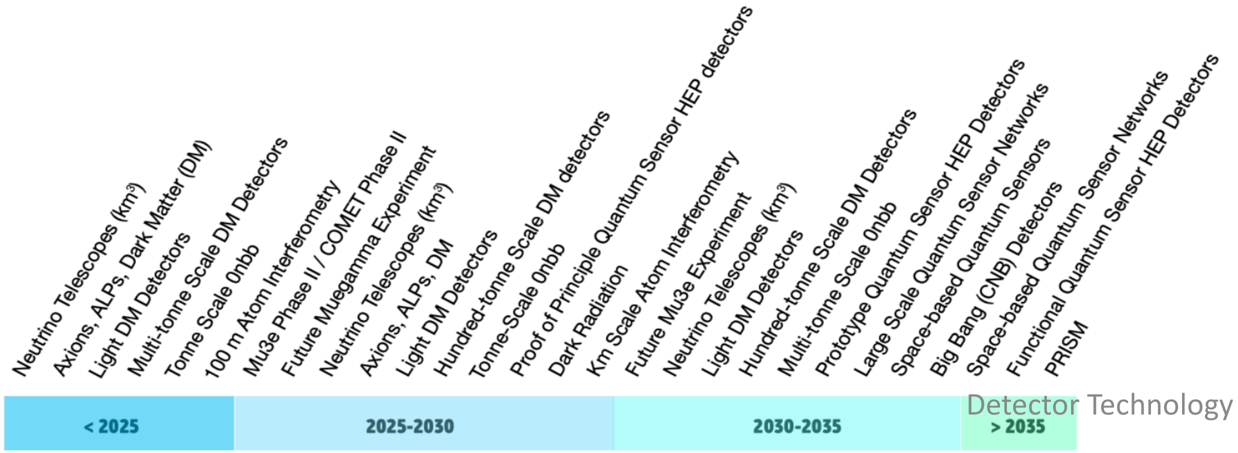


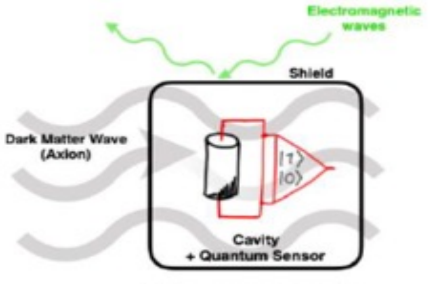




Quantum and emerging technologies

- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated**: clocks and clock networks, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, atom interferometry, …
- Several initiatives started at CERN, DESY, FNAL, US, UK, …

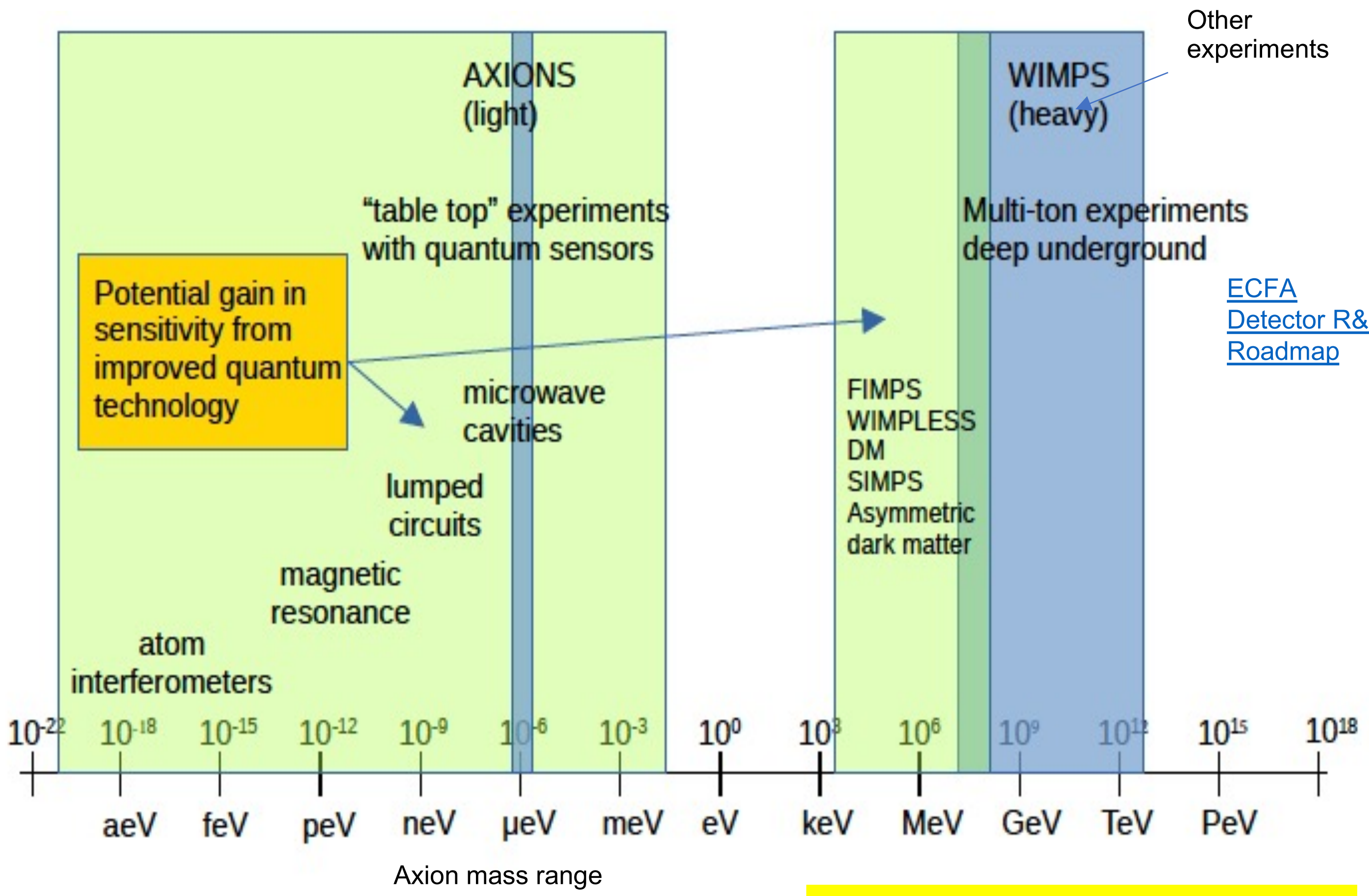
QUANTUM TECHNOLOGY INITIATIVE



Microwave Cavity

S. Golawa

Example: potential mass ranges that quantum sensing approaches open up for Axion searches



ECFA Detector R&D Roadmap

Blue: now
Light green: with quantum

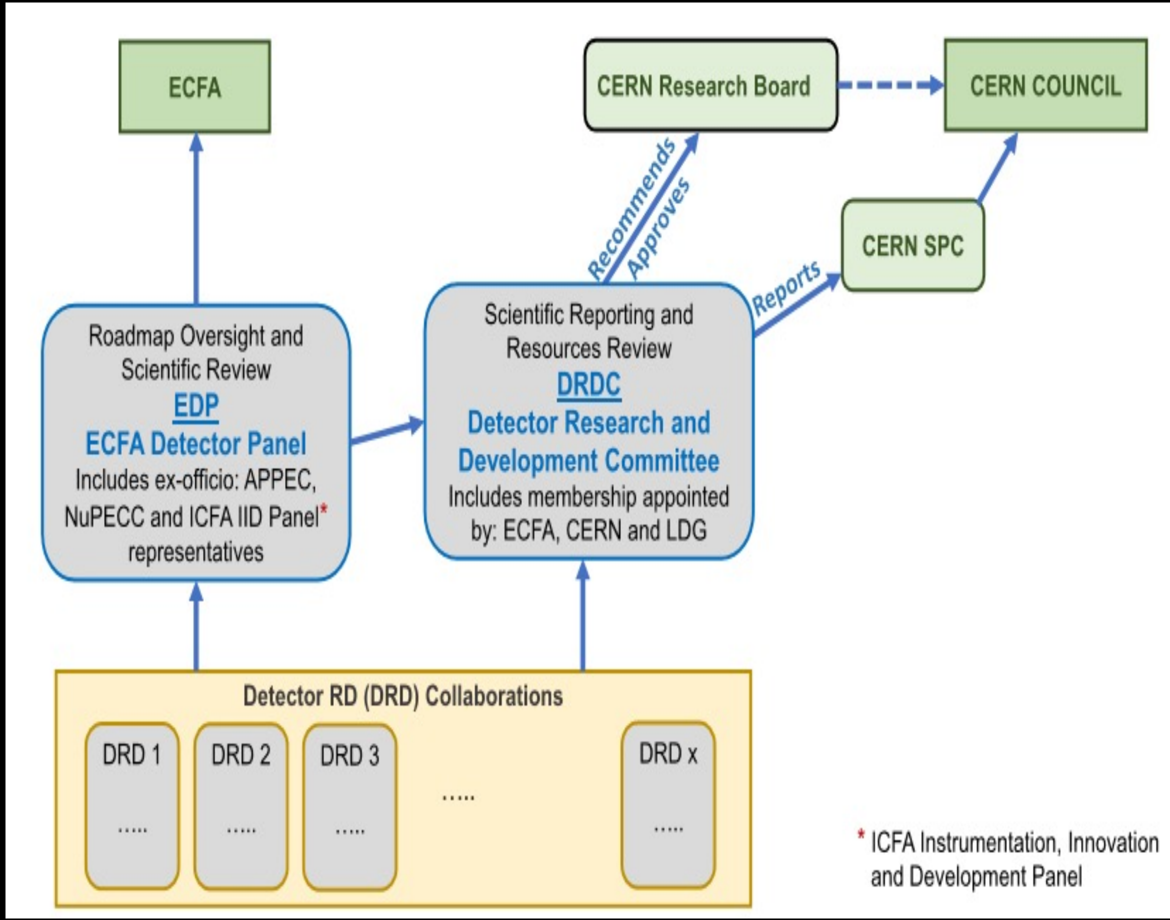
Roadmap Implementation Plan

- Next step: ECFA was mandated by Council in December 2021 to work out an implementation plan (*in close collaboration with the SPC, funding agencies & relevant research organisations in Europe and beyond)*

- Work ongoing

  - First implementation plan proposed

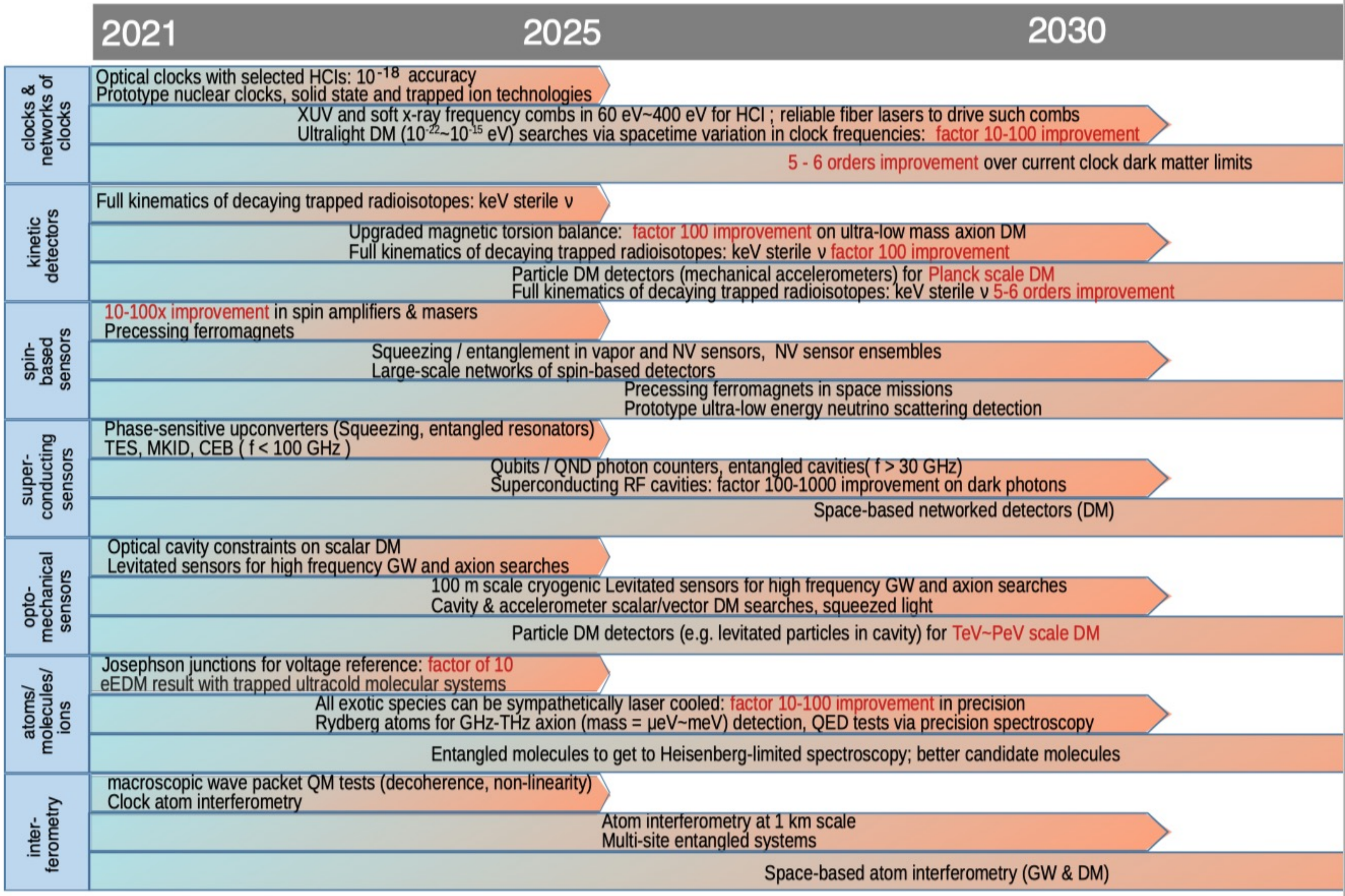
  - Discussions with CERN Council and Funding Agencies have started



Proposed structure:
- Establish new Detector R&D (DRD) Collaborations at CERN (one for each detector technology)
- Oversight and reviews by ECFA and CERN Committees

In line with the RECFA R&D roadmap, it makes sense to consider a quantum-sensing R&D program that brings together the following strands:

- Clocks and clock networks 5.3.1
- Kinetic detectors 5.3.2
- Spin-based sensors 5.3.3
  Superconducting sensors 5.3.3
- Optomechanical sensors 5.3.4
- Atoms/molecules/ions 5.3.5
  Atom interferometry 5.3.5
- Metamaterials, 0/1/2D-materials !
  Quantum materials 5.3.6



also for HEP!

"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark" *(Michelangelo)*

Aim high or we will not realize the potential of our field, discovery will be stalled and we betray ourselves and the next generation.

Photo credit: Michael Hoch/CERN

Acknowledgements

Many thanks to my ECFA Detector R&D Panel co-coordinator colleagues:

Phil Allport, Jorgen d'Hondt, Karl Jakobs, Silvia dal la Torre, Manfred Krammer, Susanne Kuehn, Felix Sefkow

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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