Ultralight Dark Matter and the Precision Frontier of Particle Physics

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Stanford

Precision Experiments

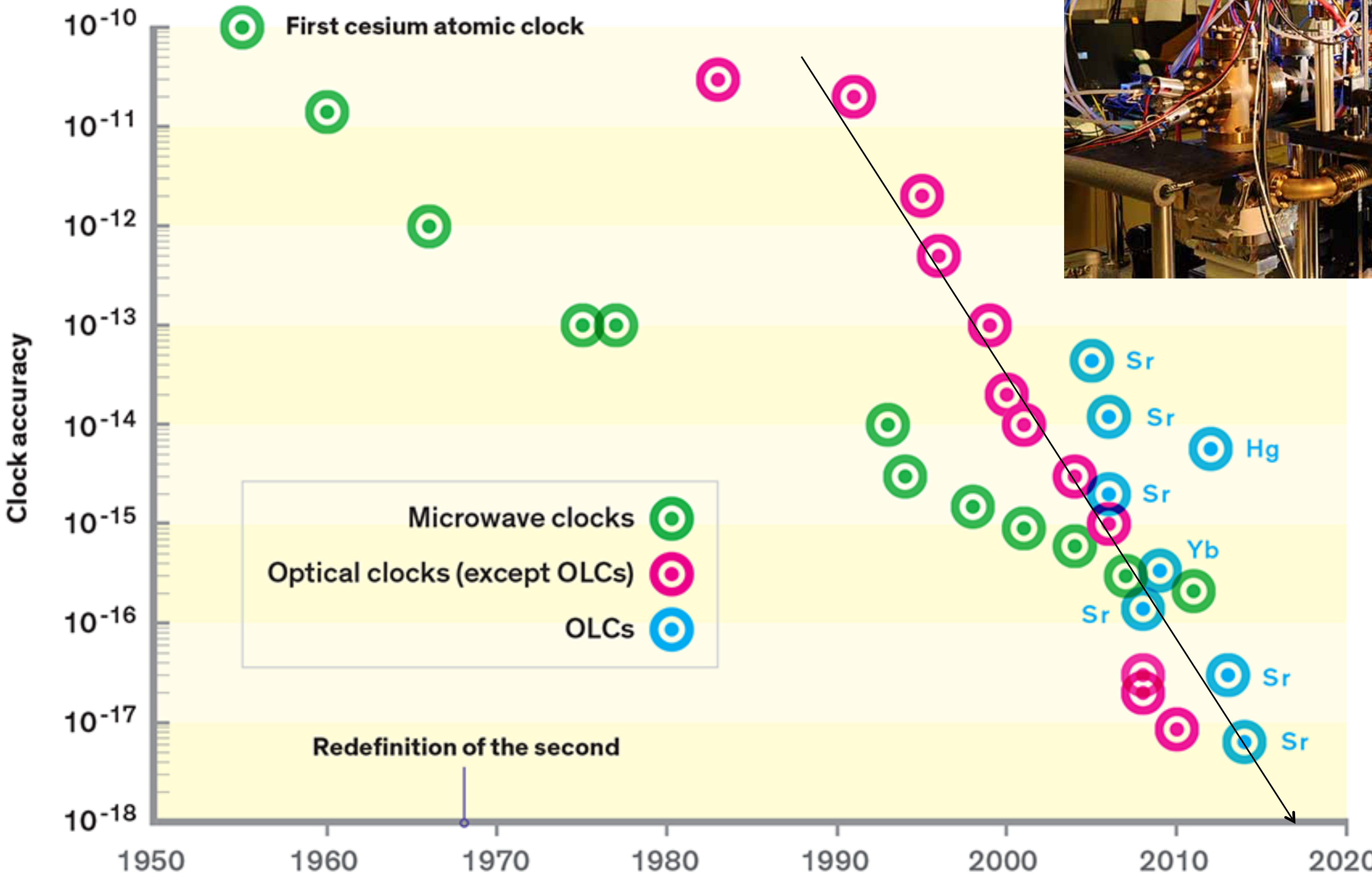
Precision measurement offers a powerful new approach for particle physics beyond conventional particle colliders/detectors

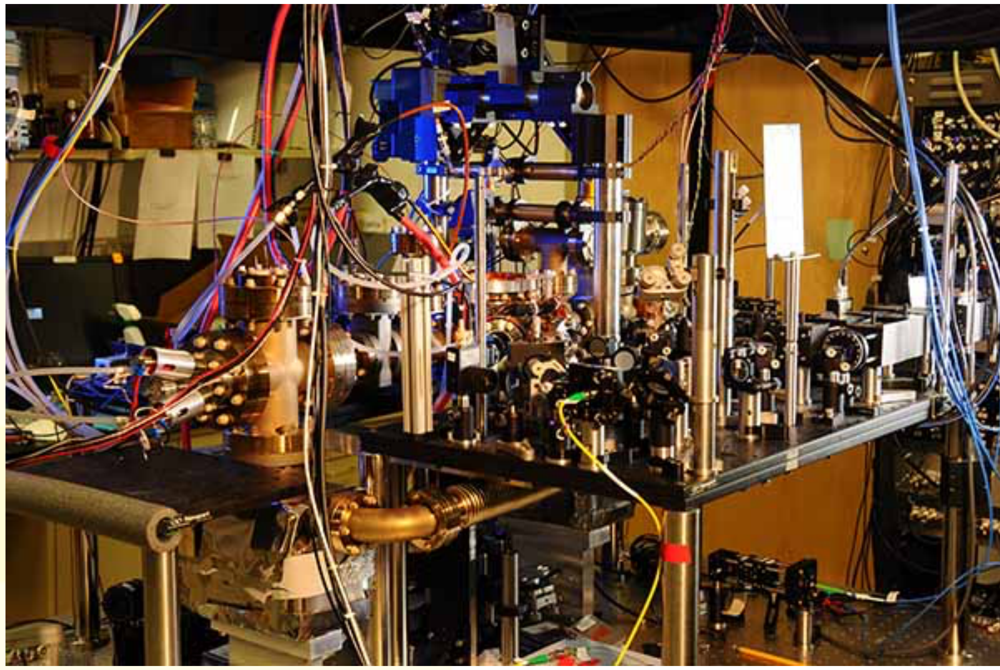
not completely new (e.g. EDMs, new forces, etc.),
but small compared to traditional particle detection

- New technologies rapidly pushing precision measurement
  - e.g. atomic clocks have 18 digit precision
- Required for axions, gravitational waves…
  - critical questions such as hierarchy problem or nature of dark matter may not be answered at weak scale

Many promising, unexplored directions

Atomic Clock Sensitivity





current technology already allows many new searches, and will improve by orders of magnitude

Outline

1. Dark Matter Detection

2. Axion Dark Matter
   1. Cosmic Axion Spin Precession Experiment (CASPEr) (D. Budker + A. Sushkov)
   2. DM Radio (K. Irwin)

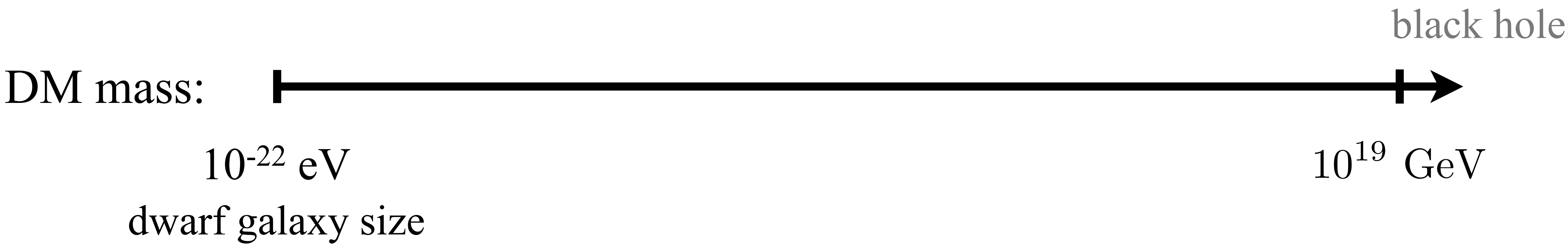
3. Other techniques

4. Gravitational waves and dark matter with atom interferometry
   (M. Kasevich + J. Hogan)

Dark Matter Detection

Dark Matter Candidates

What do we know about dark matter?



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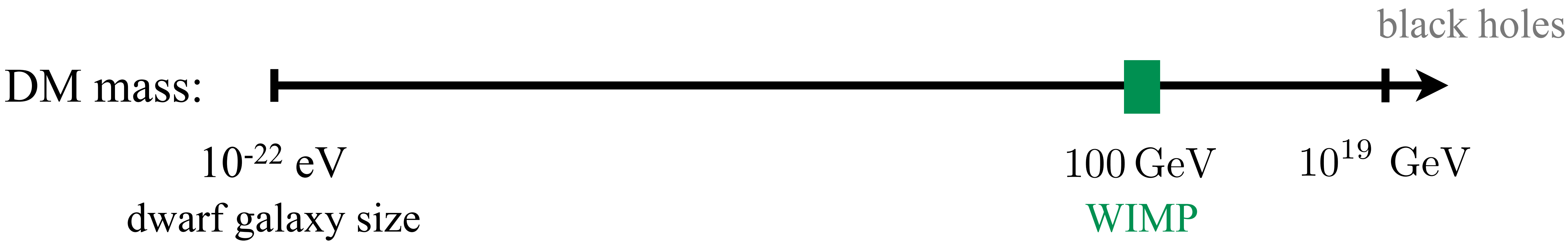

WIMP is well-motivated, significant direct detection effort focused on WIMPs

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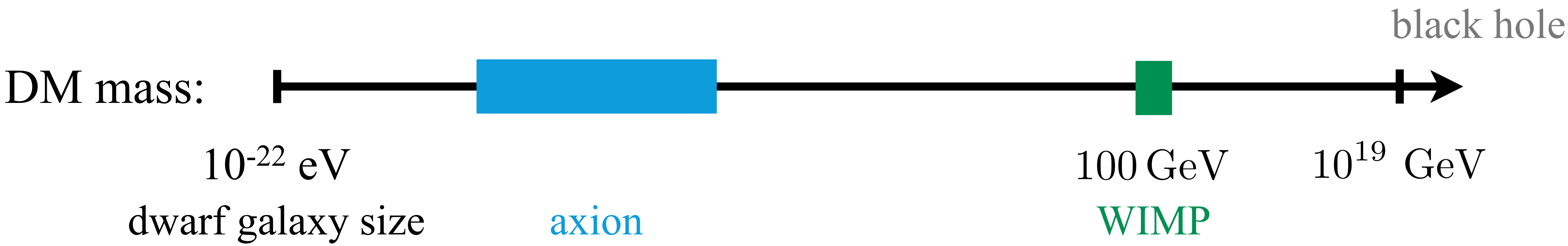

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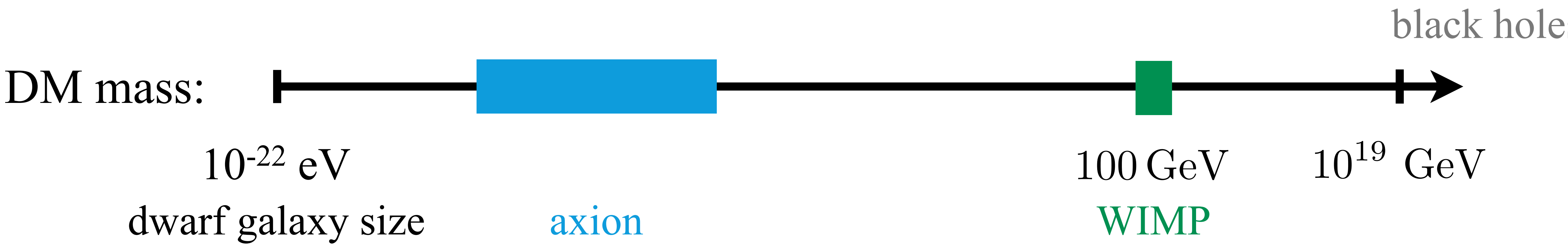

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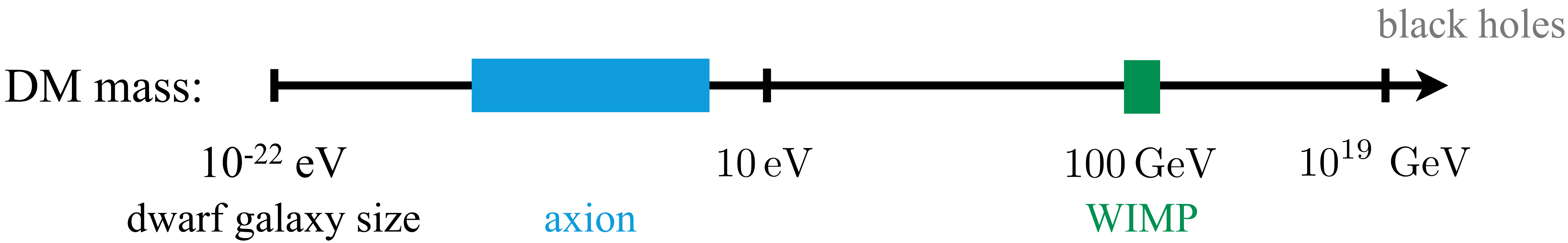
Axion is other best-motivated candidate, only a small fraction of parameter space covered

Huge DM parameter space currently unexplored!

Direct Detection

How can we detect DM?



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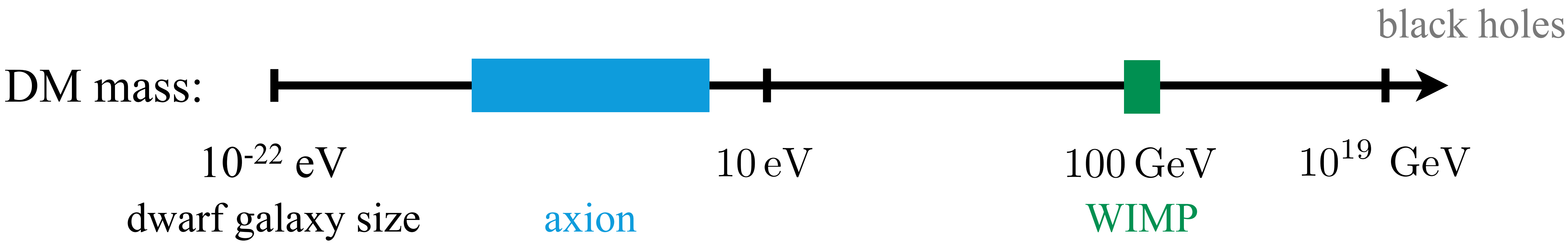

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field-like (e.g. axion)
new detectors required

particle-like (e.g. WIMP)
particle detectors best

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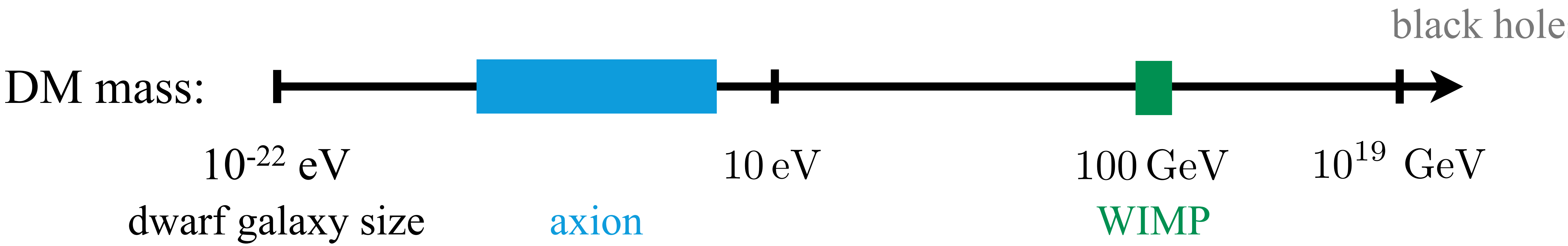

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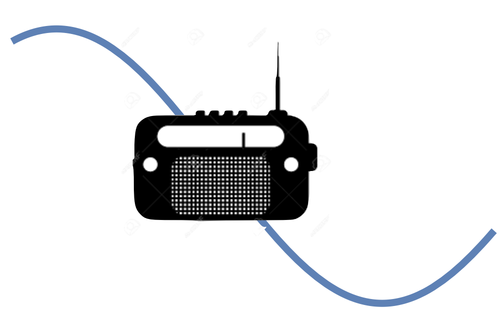

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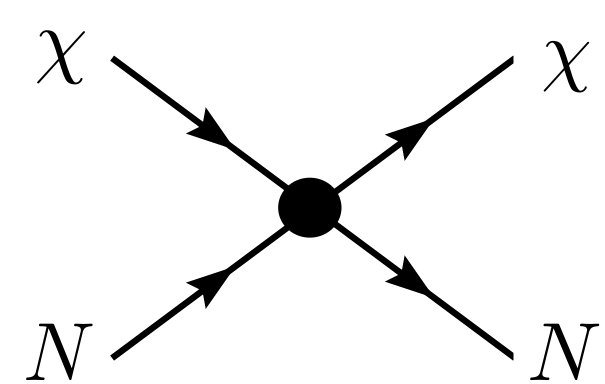
Search for single, hard particle scattering



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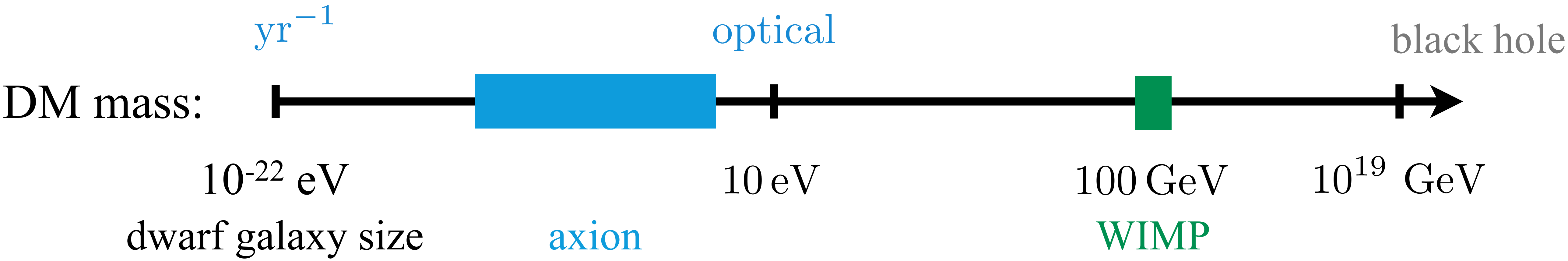

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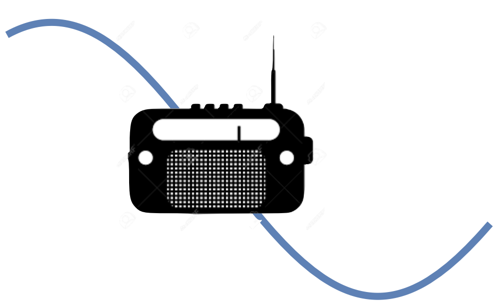

Frequency range accessible!

particle-like (e.g. WIMP)

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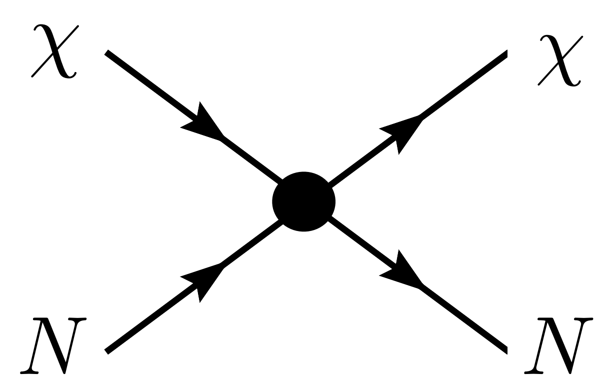
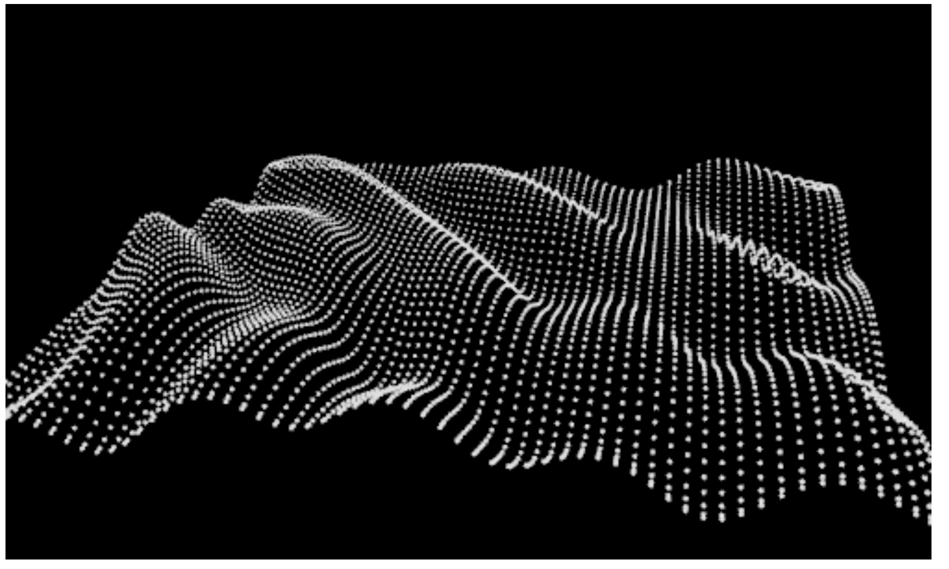
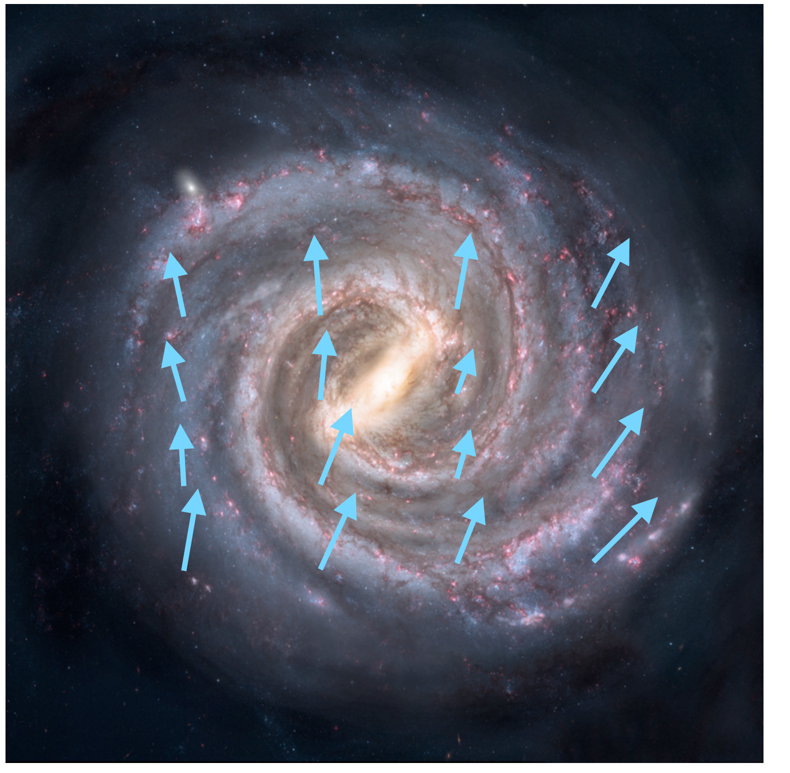


“Field” Dark Matter

particle DM

DM at long deBroglie wavelength
useful to picture as a “coherent” field:





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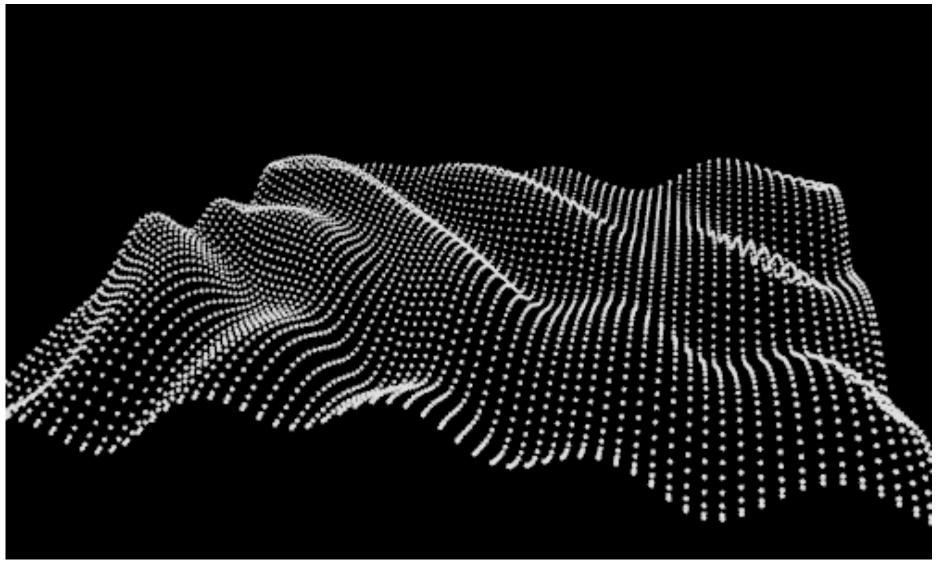

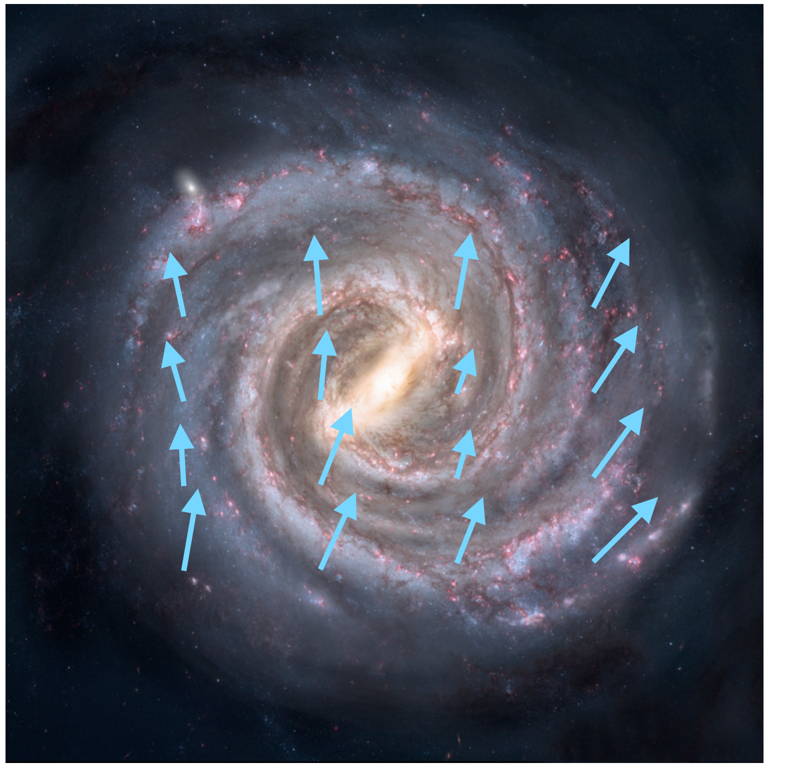

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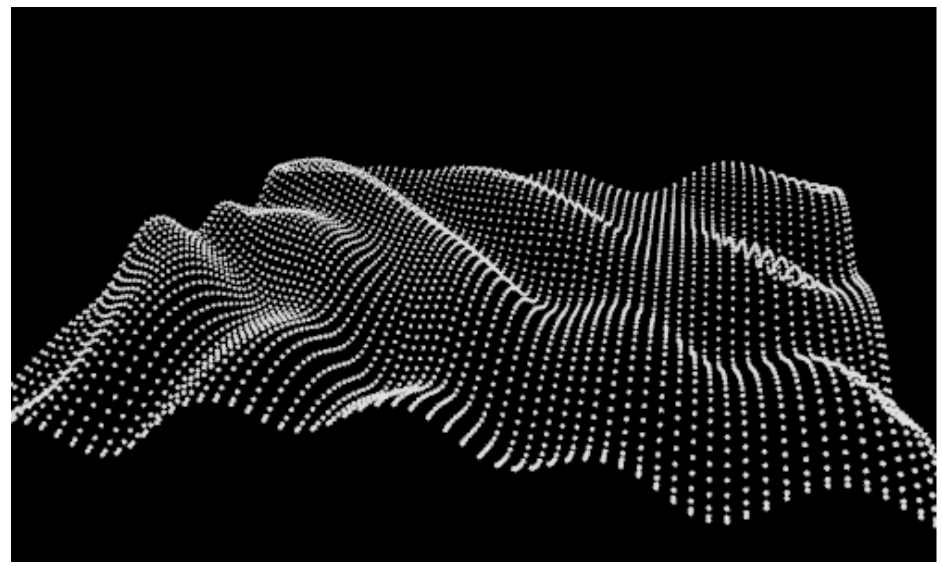

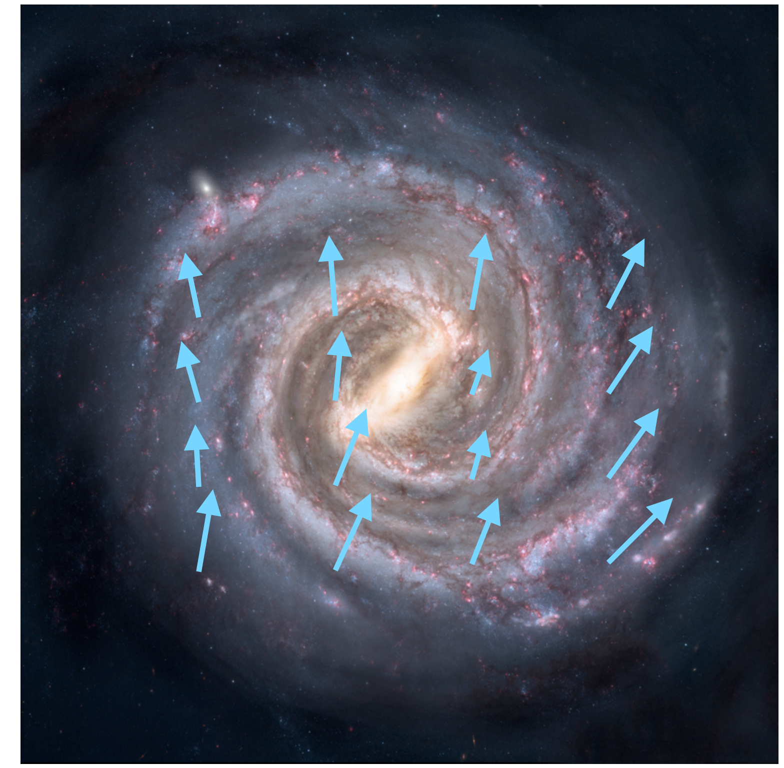

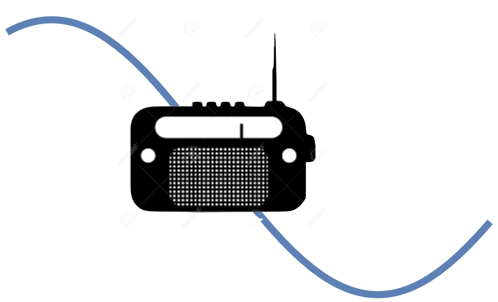

signal frequency = DM mass = m

spread by DM kinetic energy $\sim mv^2$

galactic virial velocity $v \sim 10^{-3}$ ➜ line width $\sim 10^{-6}m$

➜ coherence time, $Q \sim 10^6$ periods

Possibilities for Light Dark Matter

Effective field theory ➜ only a few possible couplings to us
four types of experiments:

light DM

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano arXiv:1512.06165

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E&M - drive currents

$a\,F\tilde{F}$

QCD - change nuclear properties

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spin - cause precession

$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$

scalar - new force/SM properties

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  all current axion searches (e.g. ADMX)

- QCD - change nuclear properties
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- scalar - new force/SM properties
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e.g. aids axion detection

Can cover all these possibilities

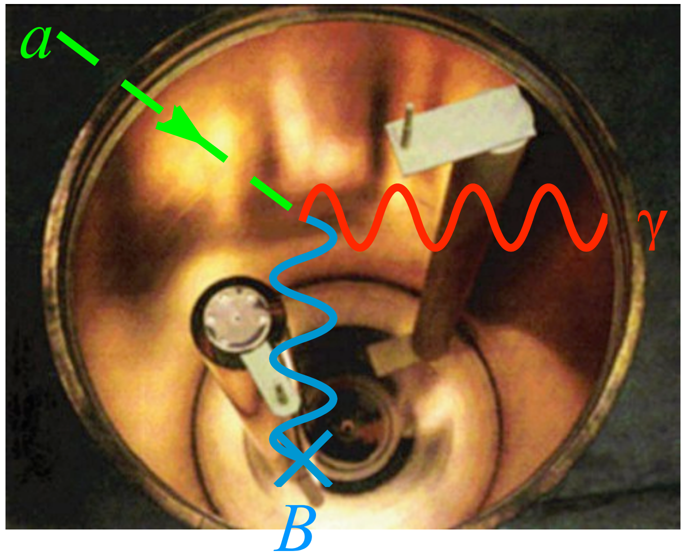
with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano arXiv:1512.06165

Axion Detection

Existing Axion Searches

all existing experiments rely on axion coupling to E&M (photons): $\mathcal{L} \supset a\, F\tilde{F} = a\, \vec{E} \cdot \vec{B}$

drives cavity at frequency m_a



ADMX focuses on axions ~ 0.5 - 10 GHz

axion Compton wavelength ~ size of cavity

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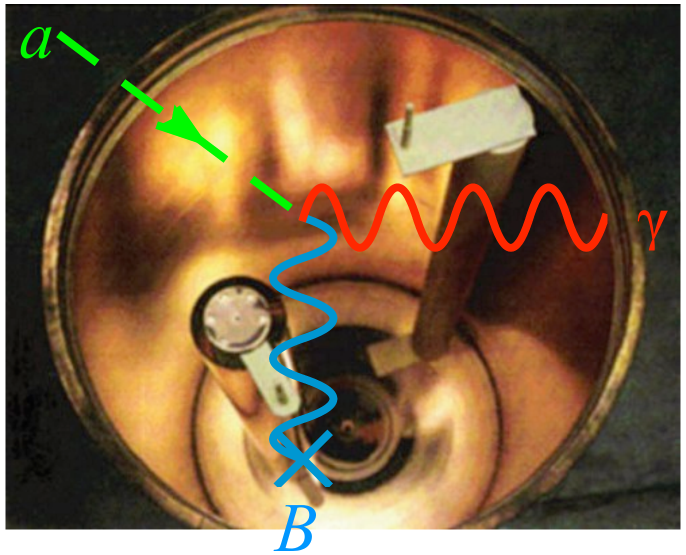


$a\,F\tilde{F} \sim a\,\partial\,(A\,\partial A)$ is a derivative operator

integrate by parts ➜ all effects depend on derivative of axion field

all effects suppressed by $\sim \dfrac{\text{experiment size}}{\text{axion wavelength}}$

at lower masses, axion wavelength ➜ 300 km

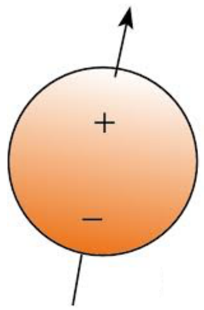
(axions from fundamental scales near Planck scale)

how cover the full axion mass range? a different operator

The Axion

Strong CP problem:

$\mathcal{L} \supset \theta\, G\widetilde{G}$ creates nucleon EDM $d \sim 3 \times 10^{-16}\, \theta\, e\, \mathrm{cm}$ measurements ➜ $\theta \lesssim 10^{-9}$



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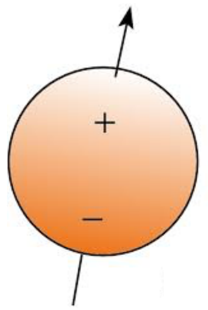
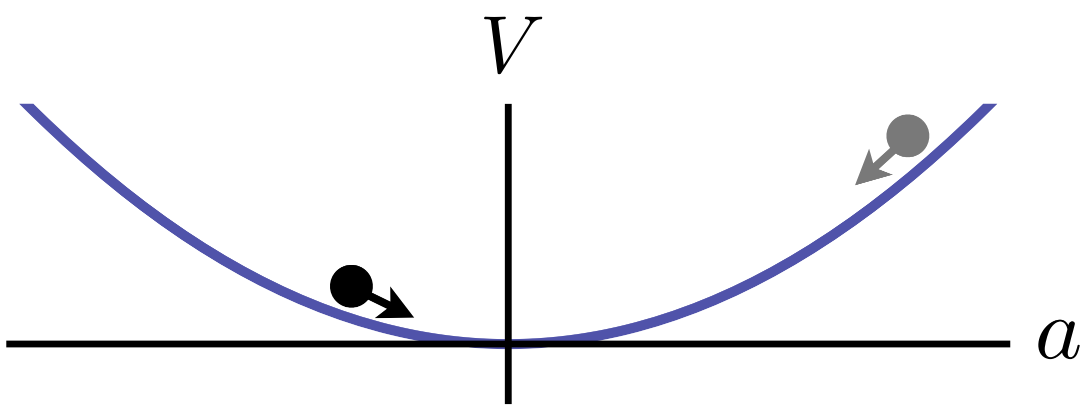


Axion solution:

make it dynamical $\mathcal{L} \supset \dfrac{a}{f_a} G\widetilde{G}$ so damps down towards zero



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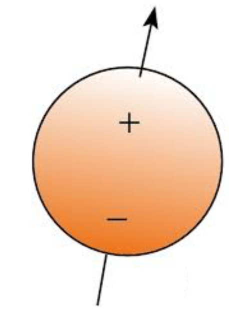

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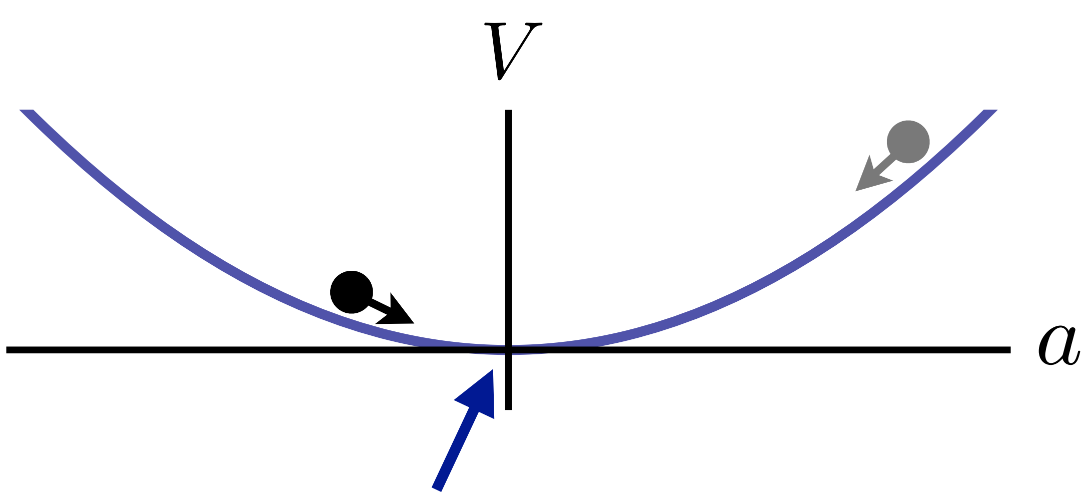

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calculate a_0:

$$m_a^2\, a_0^2 \sim \rho_{\mathrm{DM}} \sim 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

still has small residual oscillations today ➜ Axion is a natural dark matter candidate

Preskill, Wise & Wilczek; Abott & Sikivie; Dine & Fischler (1983)

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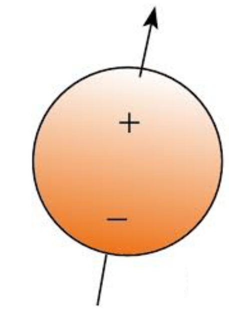

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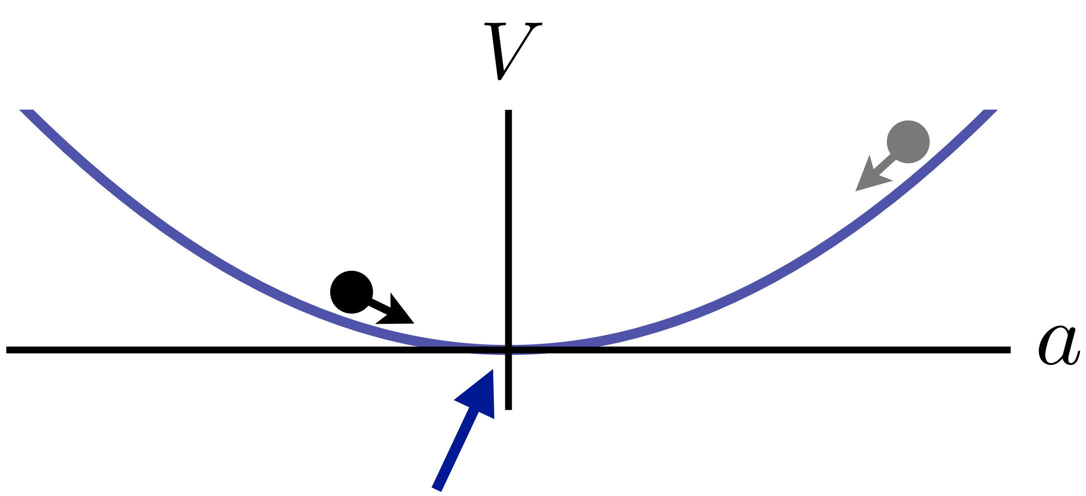

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adiabatic approximation ➜ $d \sim 3 \times 10^{-16}\, \dfrac{a}{f_a}\, e\,\mathrm{cm}$

Axion DM causes oscillating nucleon EDM today, not a derivative effect!

completely changes axion detection

generally light bosonic DM causes oscillating fundamental “constants”

Cosmic Axion Spin Precession Experiment (CASPEr)

with

Dmitry Budker
Micah Ledbetter
Surjeet Rajendran
Alex Sushkov

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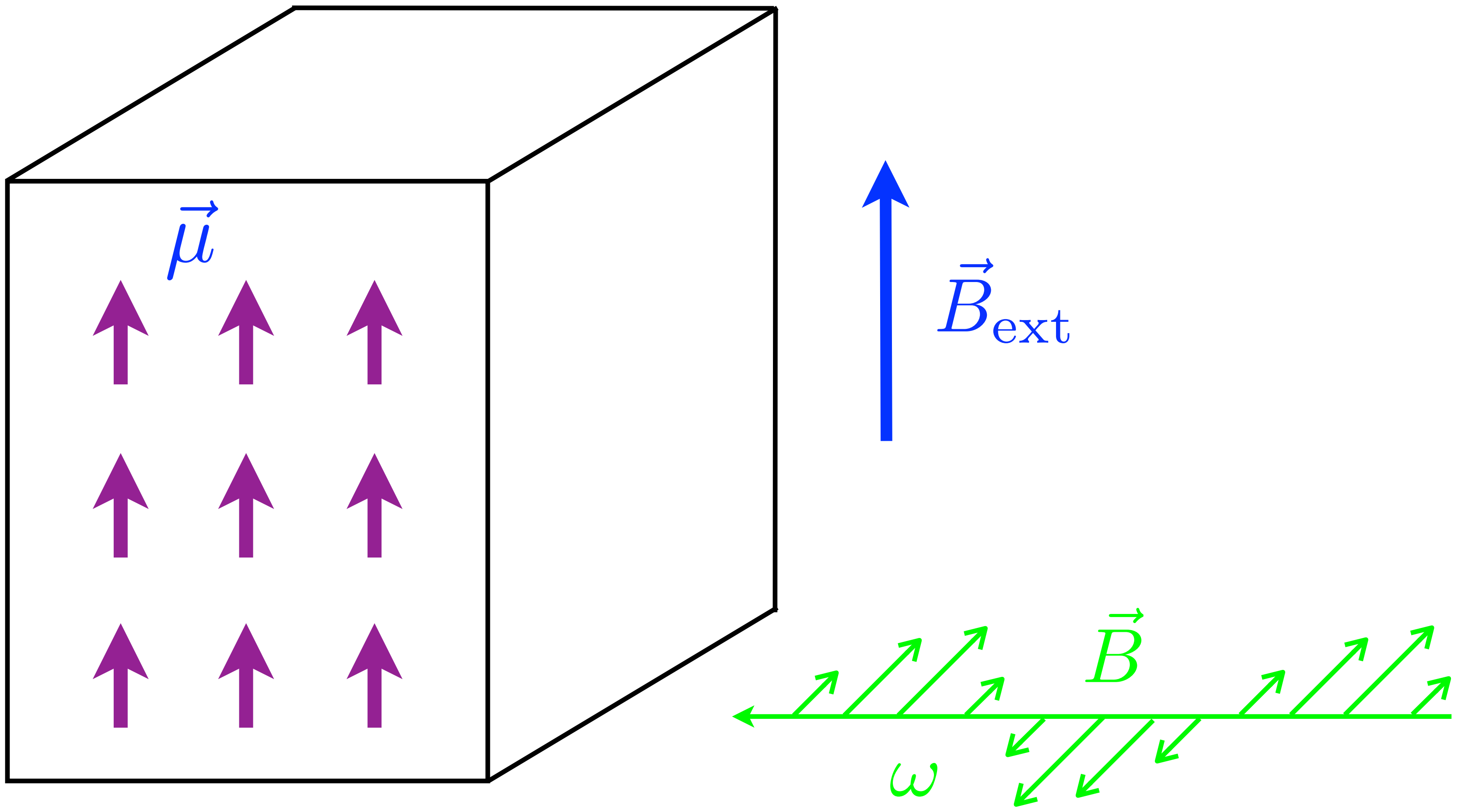
DFG Deutsche Forschungsgemeinschaft

PRX **4** (2014) arXiv:1306.6089
PRD **88** (2013) arXiv:1306.6088
PRD **84** (2011) arXiv:1101.2691

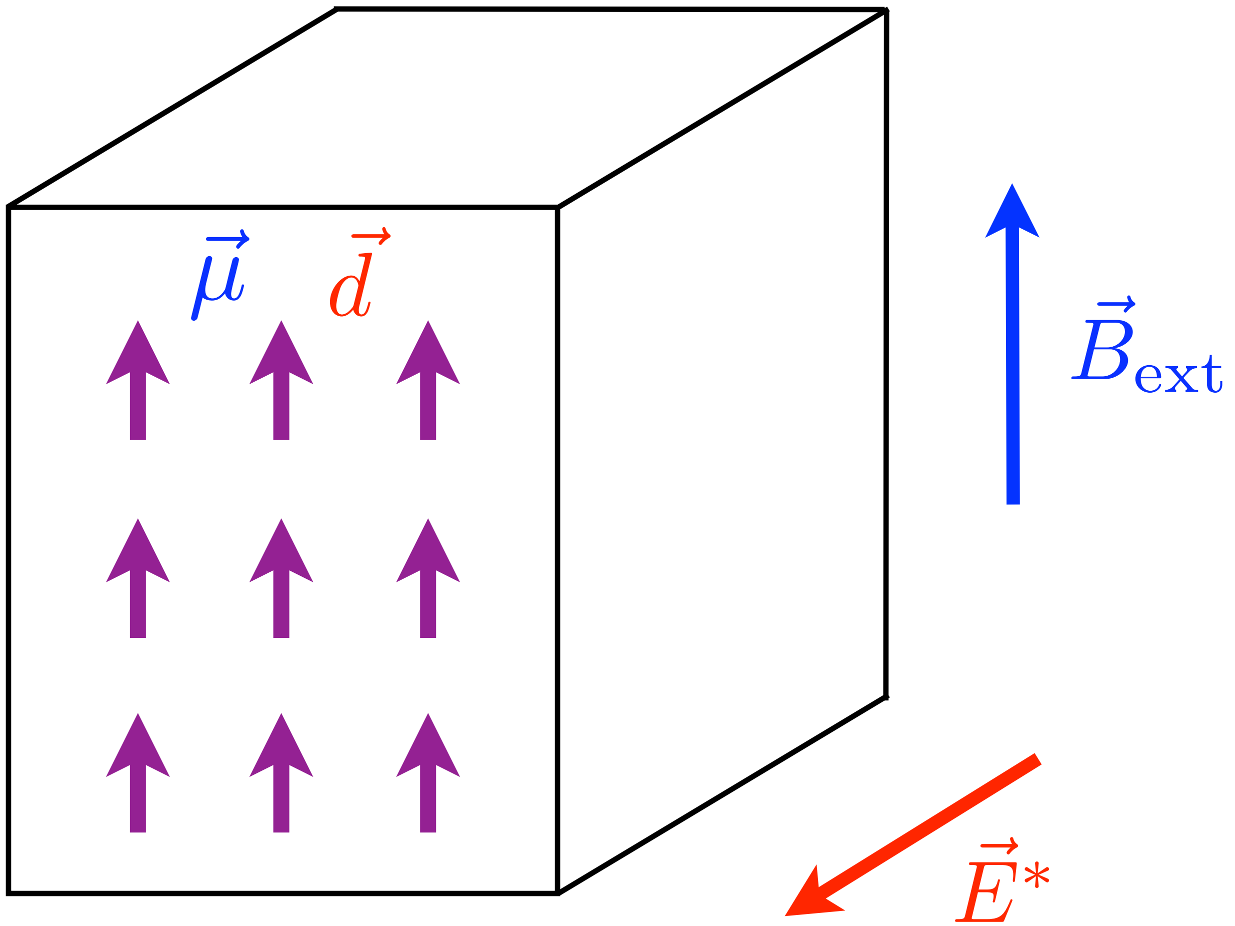
Axions with NMR



NMR resonant spin flip when Larmor frequency $\quad 2\mu B_{\text{ext}} = \omega$

Cosmic Axion Spin Precession Experiment (CASPEr)

NMR techniques + high precision magnetometry



Larmor frequency = axion mass ➔ resonant enhancement

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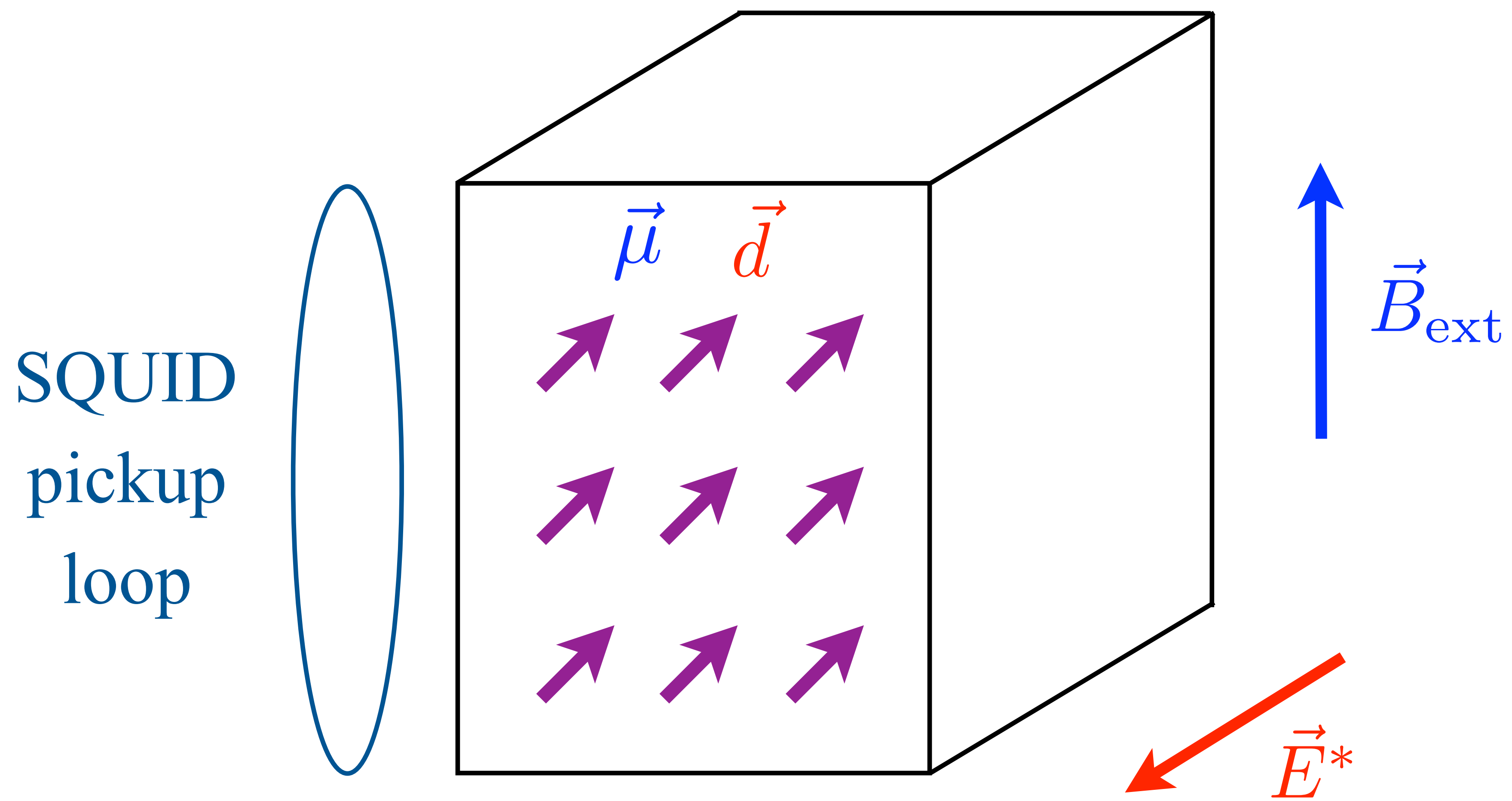
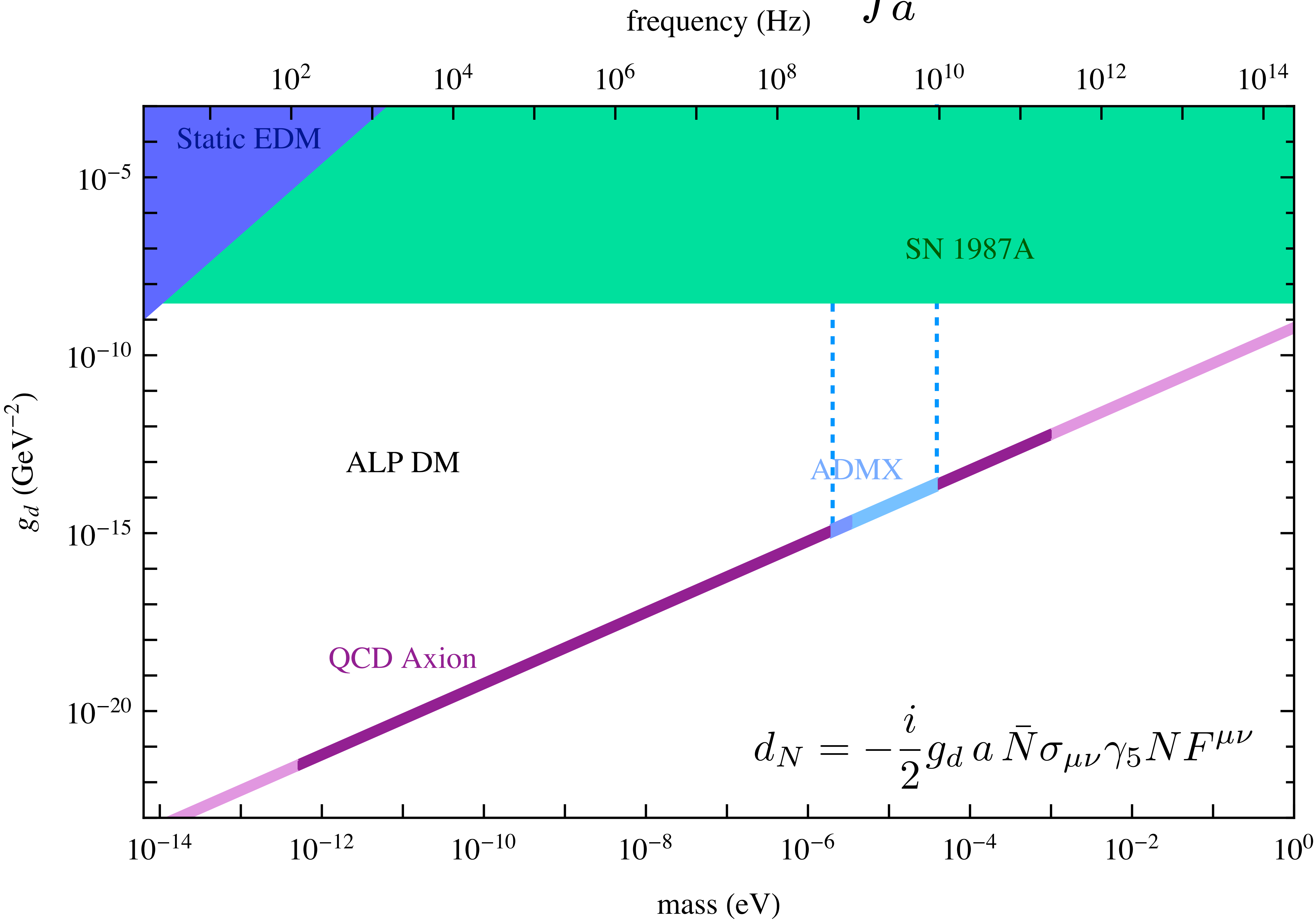


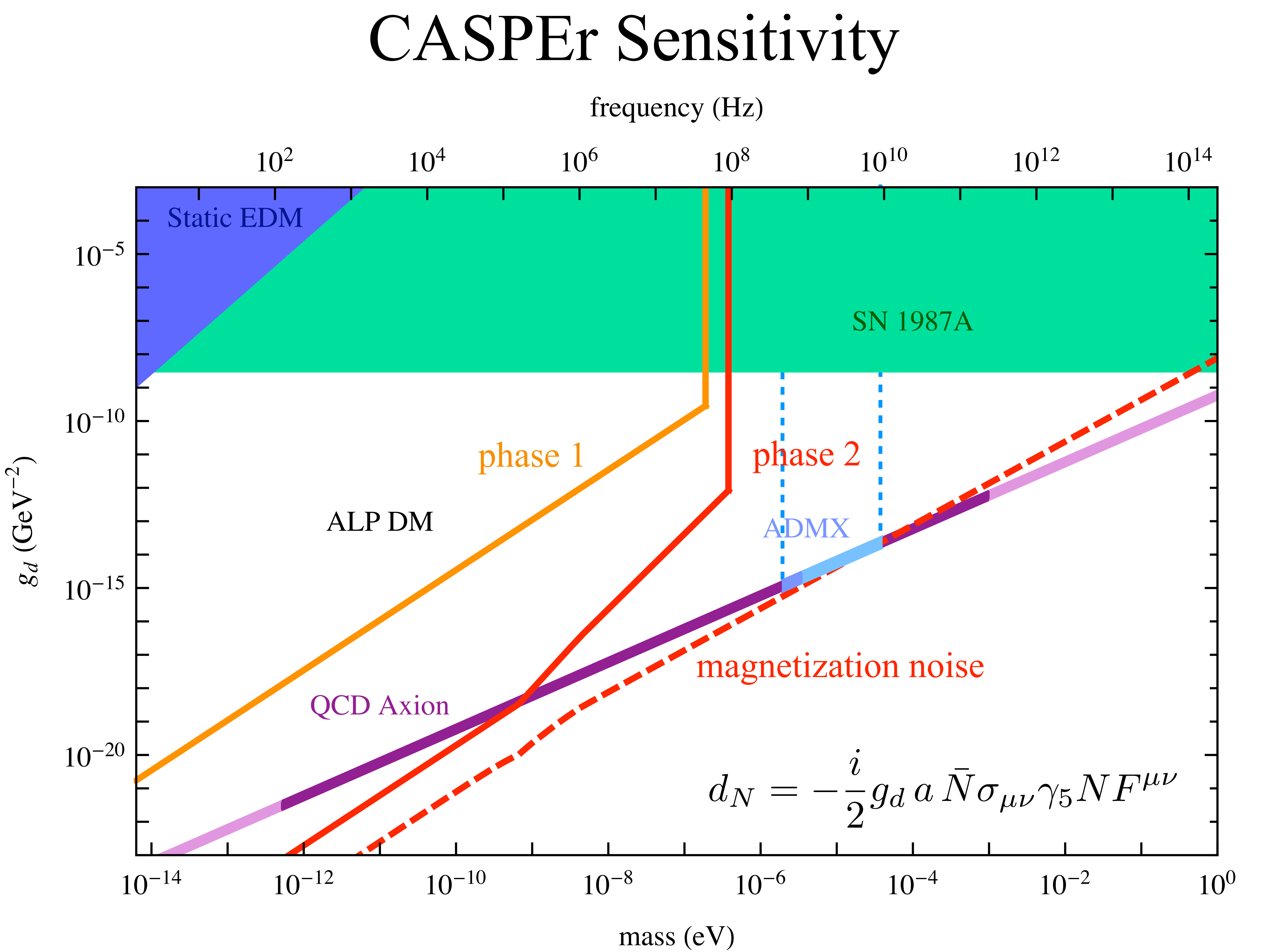
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

ferroelectric (e.g. $PbTiO_3$), NMR pulse sequences (spin-echo,…),…
quantum spin projection (magnetization) noise small enough

Axion Limits on $\frac{a}{f_a} G\widetilde{G}$





CASPEr Sensitivity
frequency (Hz)
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Static EDM
SN 1987A
phase 1
phase 2
ALP DM
ADMX
magnetization noise
QCD Axion
$d_N = -\frac{i}{2} g_d\, a\, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$
g_d (GeV^{-2})
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
mass (eV)

Cosmic Axion Spin Precession Experiment (CASPEr)

New field of axion direct detection, similar to early stages of WIMP direct detection

No other way to search for light axions

Would be the discovery of dark matter and glimpse into physics at high energies ~ 10^{16} - 10^{19} GeV

BOSTON UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

Stanford

CALIFORNIA STATE UNIVERSITY EAST BAY

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Peter W. Graham
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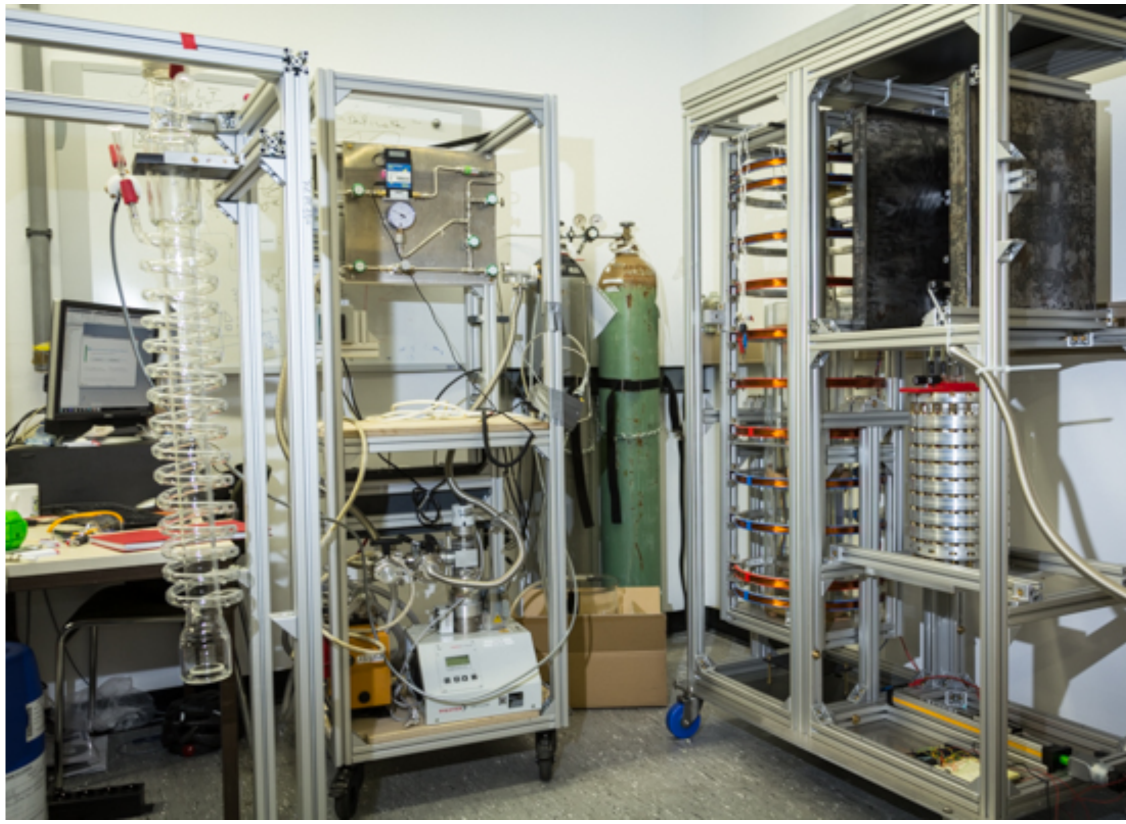
Arne Wickenbrock
John Blanchard
Marina Gil Sendra
Gary Centers
Nataniel Figueroa
Deniz Aybas
Adam Pearson
Hannah Mekbib
Tao Wang

under construction at Mainz and BU



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DM Radio

with

Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Surjeet Rajendran
Yue Zhao

+ collaborating with Tony Tyson + Mani Tripathi's groups (Davis)

PRD **92** (2015) arXiv:1411.7382

DM Radio

open axion frequency range below ADMX and above CASPEr

use LC circuit S. Thomas, B. Cabrera, P. Sikivie

want to cover wide DM frequency (mass) range, and all possible candidates (scalar and vector)

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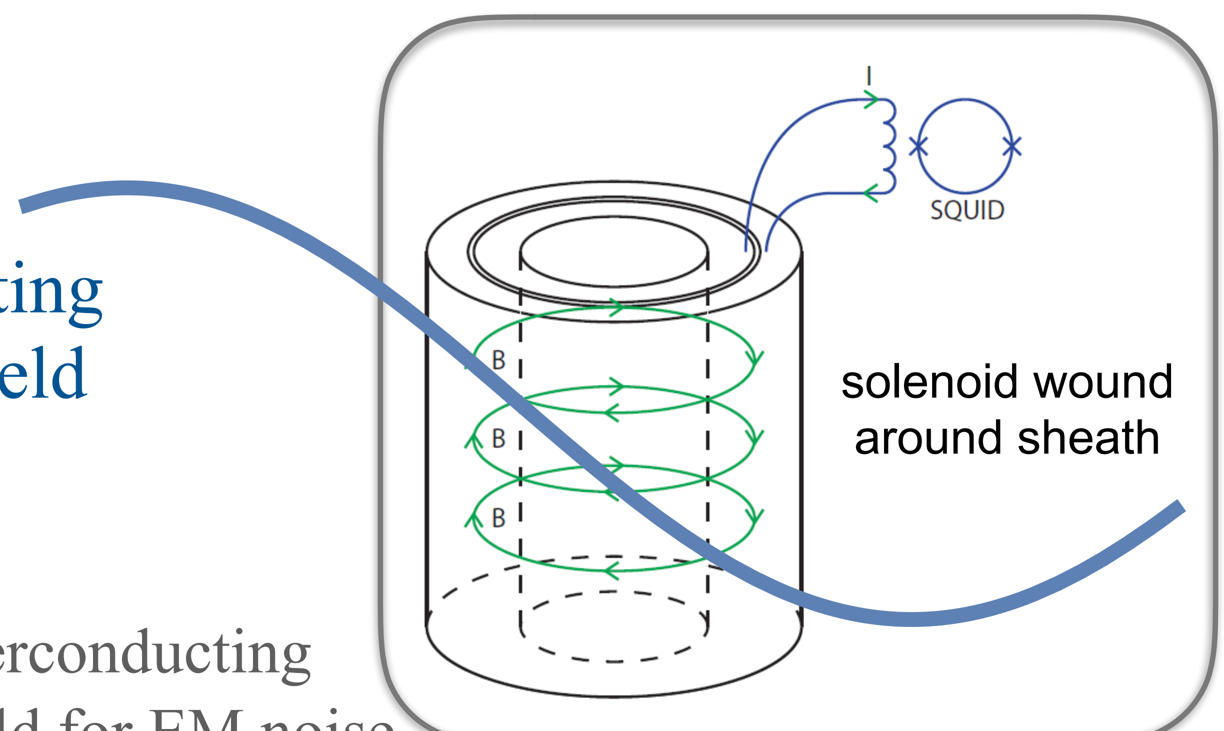
DM Radio:

oscillating
DM field



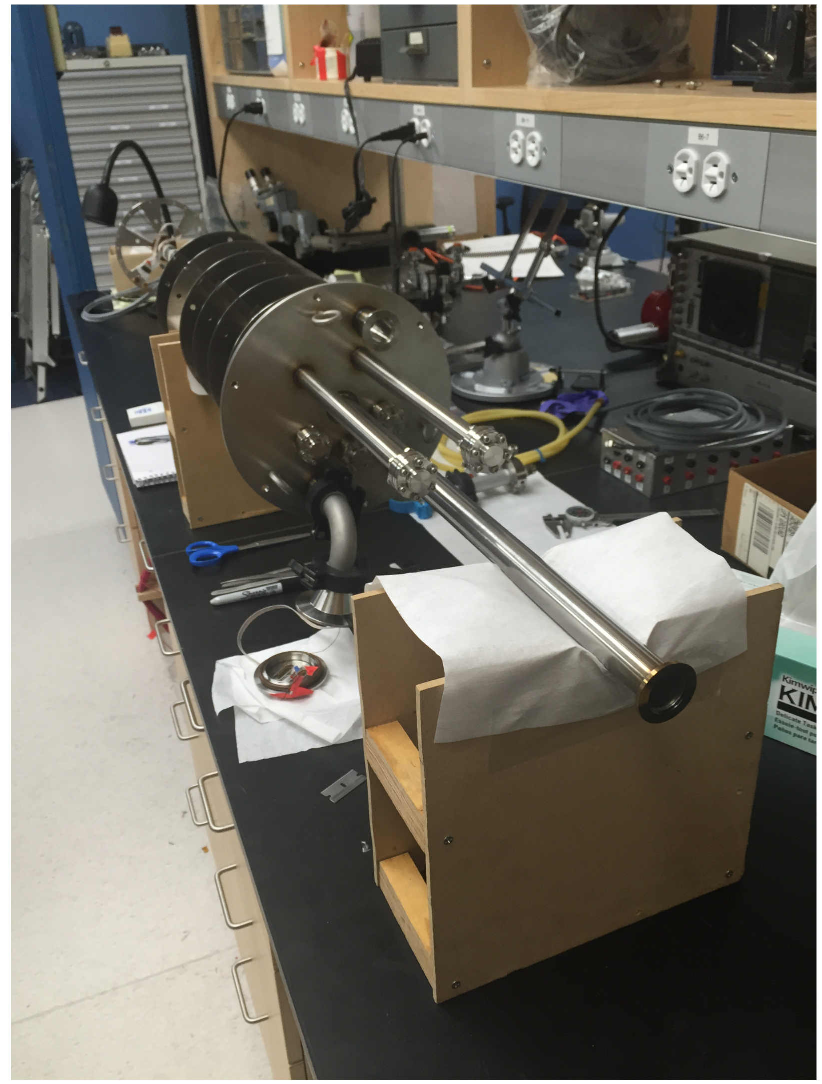
superconducting
shield for EM noise

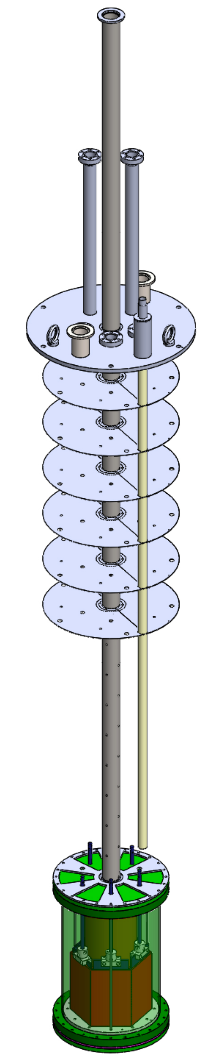
this geometry necessary for DM signal

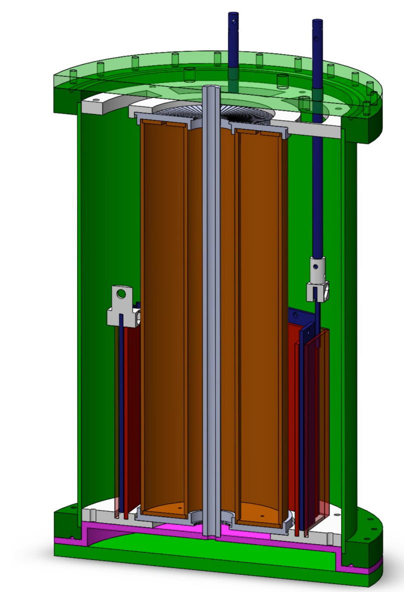
DM Radio Experiment

Widely tunable, lumped element resonator $Q \sim 10^6$

Kent Irwin
Peter W. Graham
Surjeet Rajendran
Jeremy Mardon
Saptarshi Chaudhuri
Arran Phipps
Dale Li
Sherry Cho
Betty Young
Stephen Kuenstner
Harvey Mosley
Richard Mule
Max Silva-Feaver
Zach Steffen
Sarah Stokes Kernasovskiy







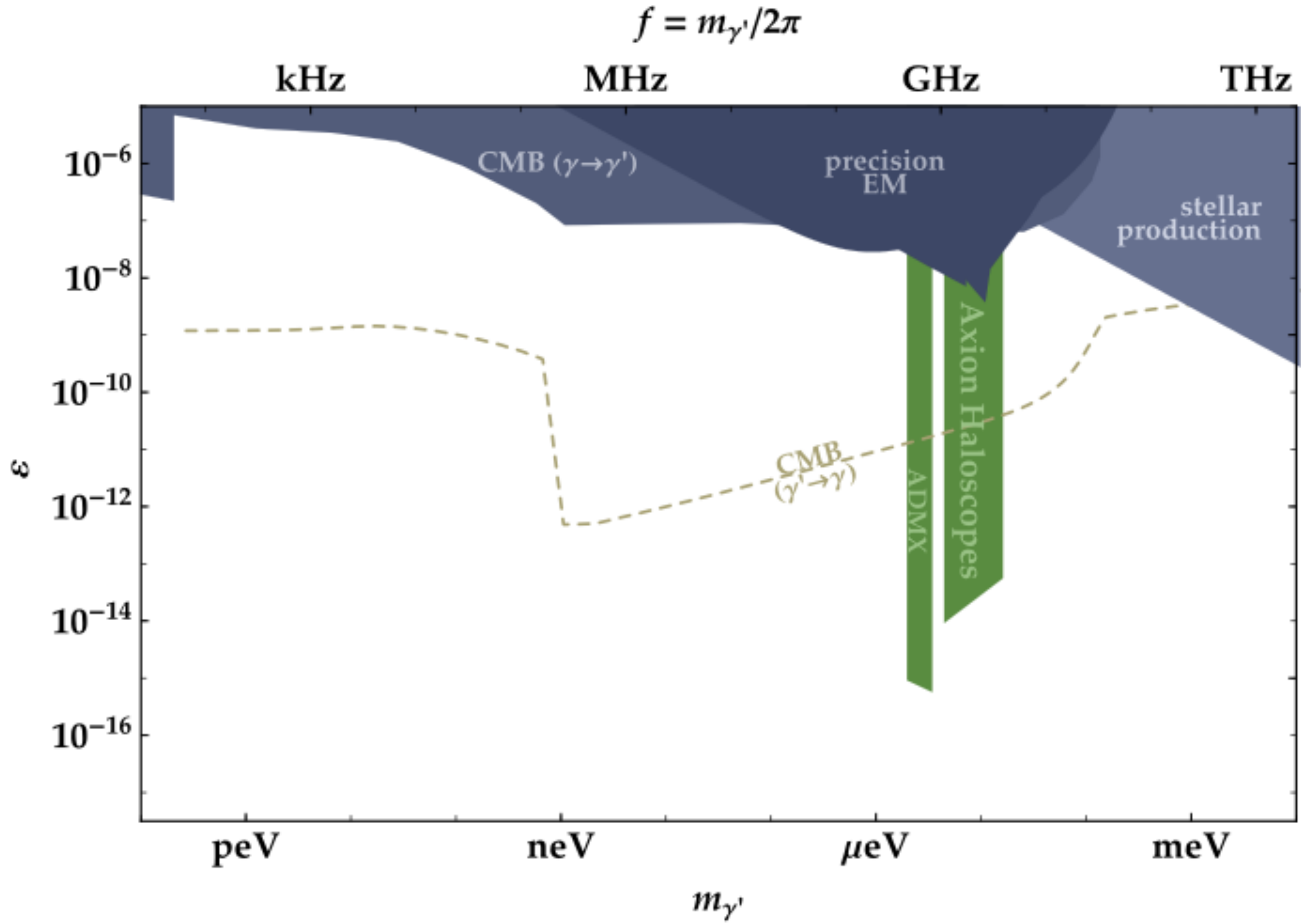
Pathfinder: 4 K 300 cm^3 under construction, initial results ~ 2017

start with hidden photon (vector) detection, later add B field for axion detection

complementary to accelerator searches for heavier hidden photons (e.g. HPS)

DM Radio Sensitivity to Hidden Photons

coupling
to E&M



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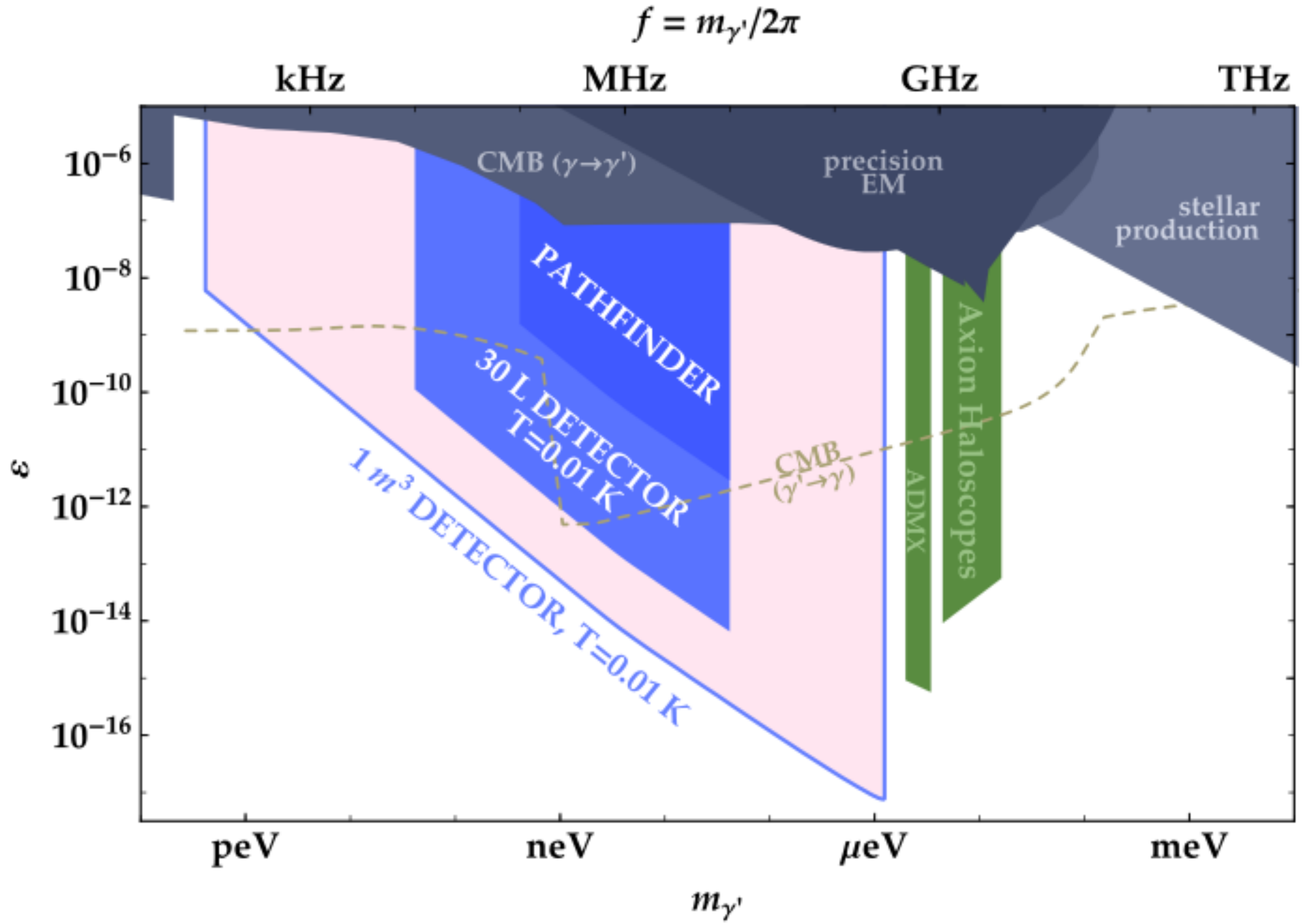
coupling
to E&M



we found hidden photon DM is produced by inflation, and in this frequency range

PWG, Mardon, Rajendran PRD **93** (2016)

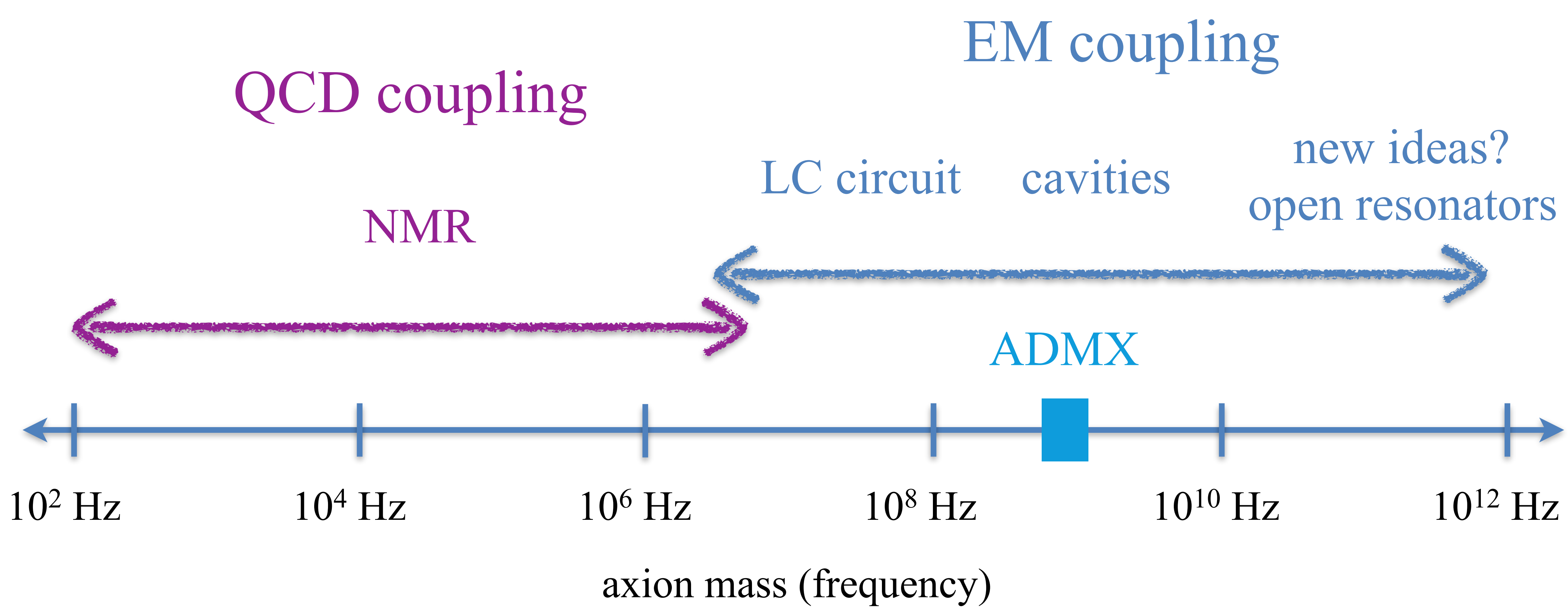
a discovery allows measurement of DM power spectrum:
verify quantum fluctuation production
and measure scale of inflation

SLAC

KIPAC

QCD Axion Dark Matter

May be able to cover all of QCD axion dark matter:

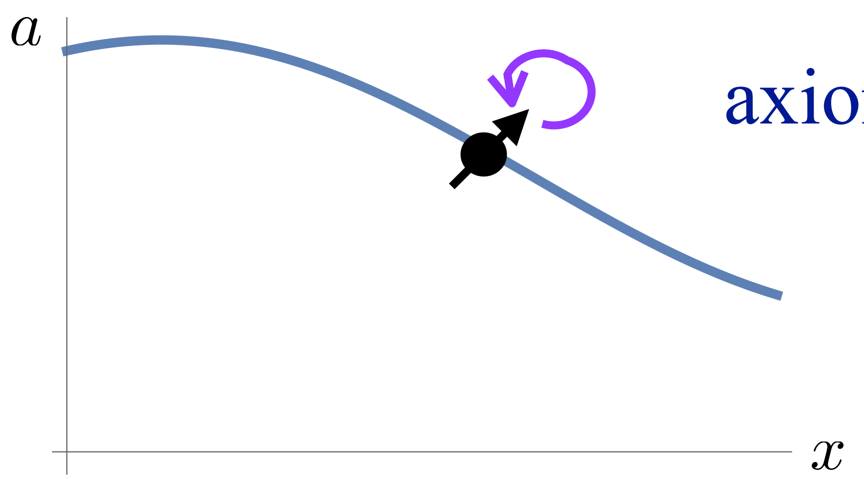


many more new ideas beyond these for axion detection in general!

Other Couplings & Techniques

Axion DM Effects

spin coupling: $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ ➜ $H \ni \nabla a \cdot \vec{\sigma}_N$



axion DM field gradient torques electron and nucleon spins

oscillates with axion frequency

proportional to axion momentum (“wind”)

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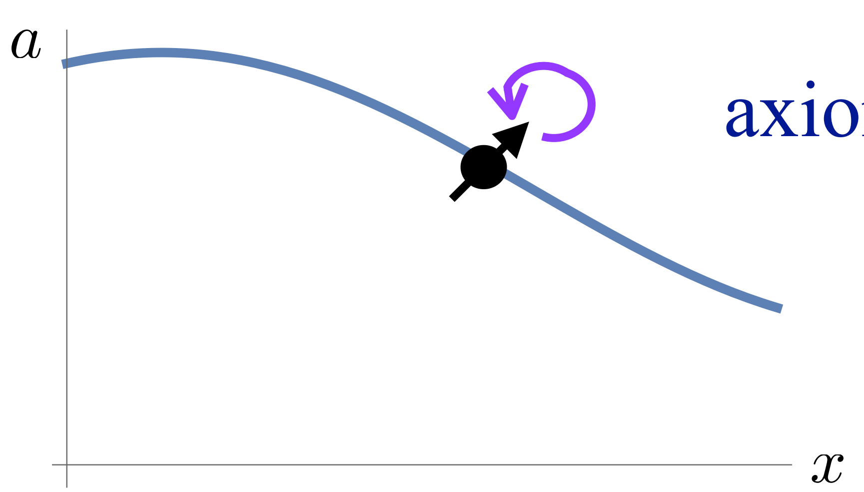
spin coupling: $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ ➜ $H \ni \nabla a \cdot \vec{\sigma}_N$

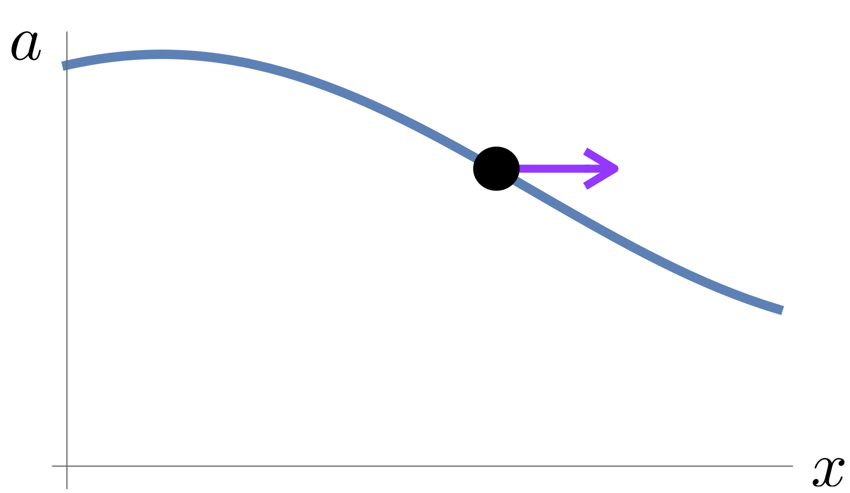


axion DM field gradient torques electron and nucleon spins

oscillates with axion frequency

proportional to axion momentum ("wind")

scalar coupling: $aH^\dagger H$ e.g. change electron mass



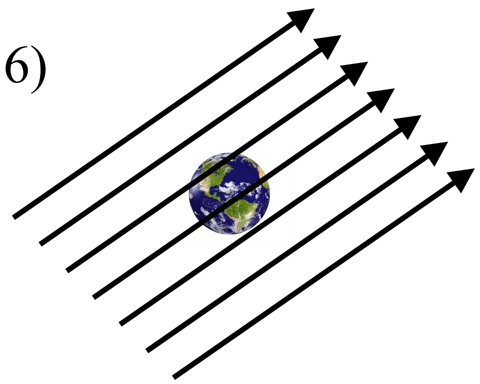
axion DM field gradient can exert a force

oscillatory and violates equivalence principle

same effects allow searches for hidden photons

Force/Torque from Dark Matter

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano PRD **93** (2016)

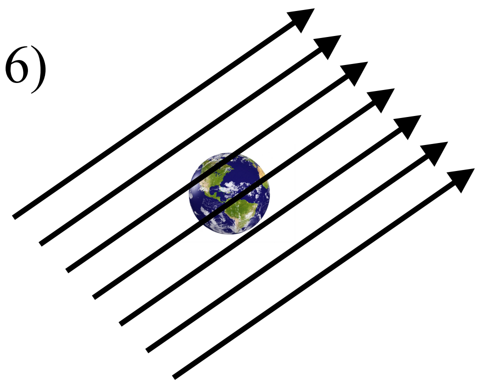


New oscillatory force/torque from dark matter

New Direct Detection Experiments:

Force/Torque from Dark Matter

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano PRD **93** (2016)



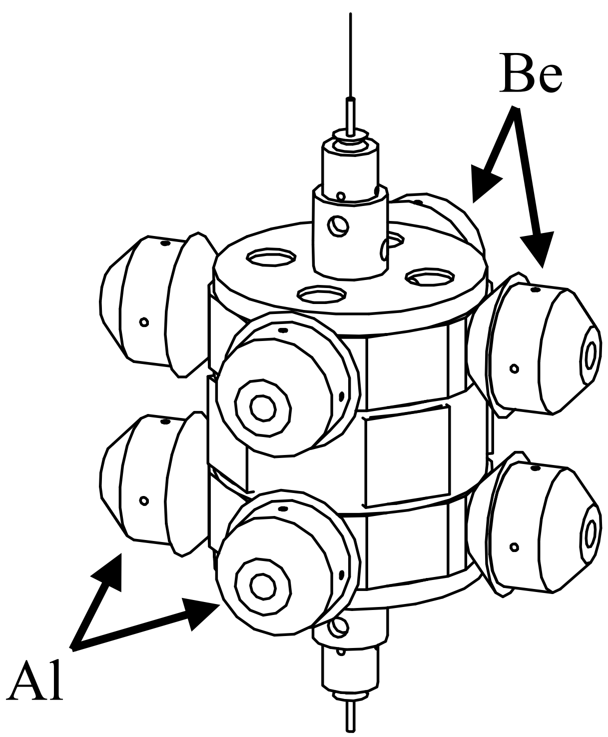
New oscillatory force/torque from dark matter

New Direct Detection Experiments:

Torsion Balances

scalar balance for force

spin-polarized for torque



Eot-Wash analysis underway

with Will Terrano

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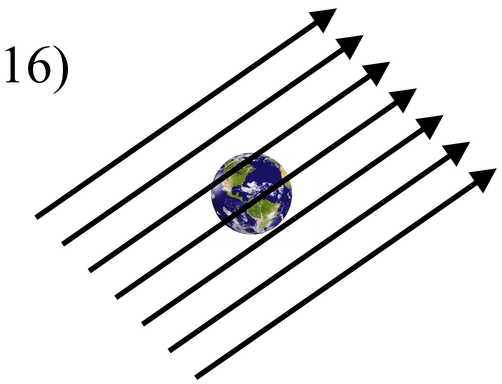

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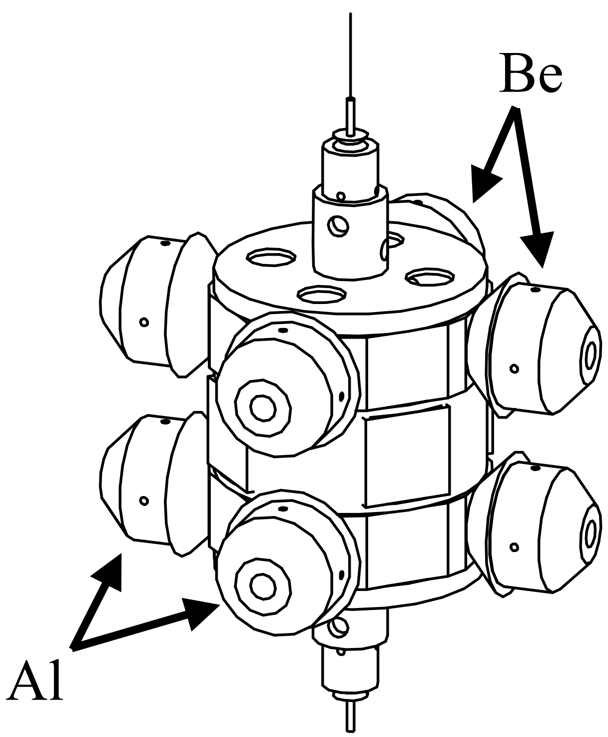

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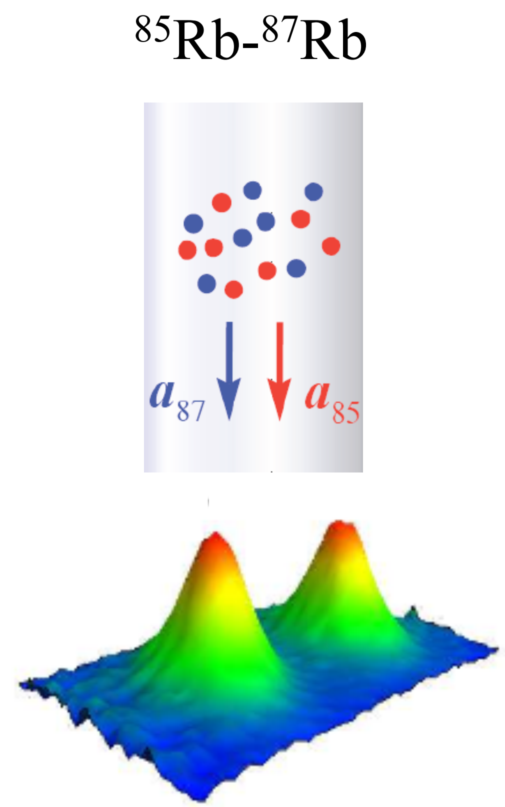
with Will Terrano

Atom Interferometers

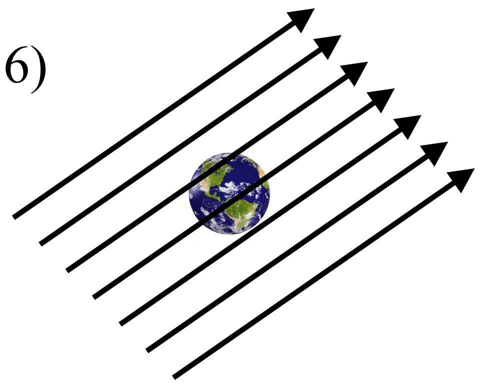
split + recombine atom wavefunction
measure atom spin and acceleration



In construction Kasevich/Hogan groups

Force/Torque from Dark Matter

with D.E.Kaplan, J.Mardon, S.Rajendran, & W.A.Terrano PRD **93** (2016)



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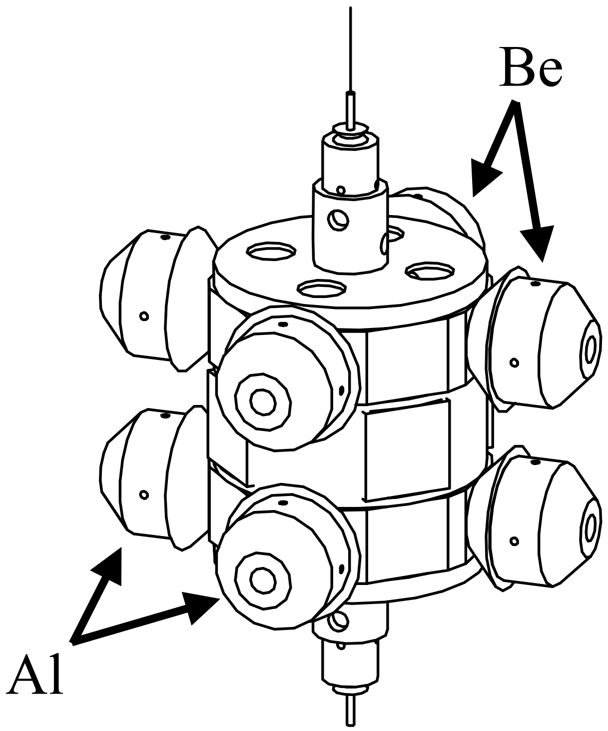

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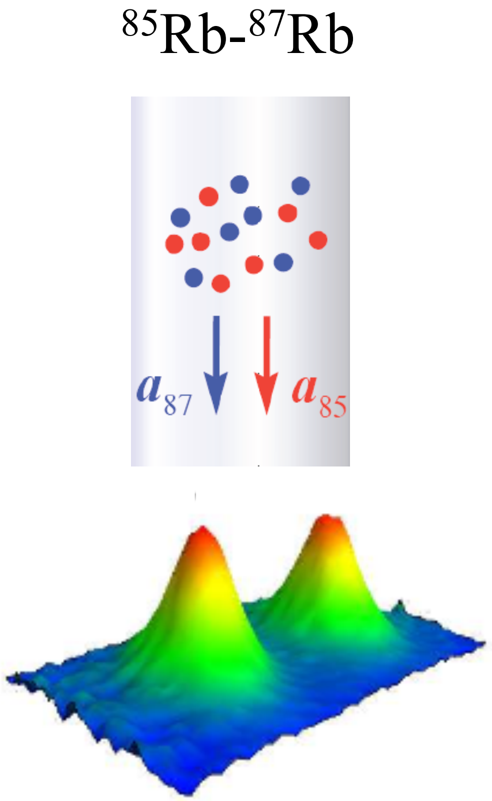
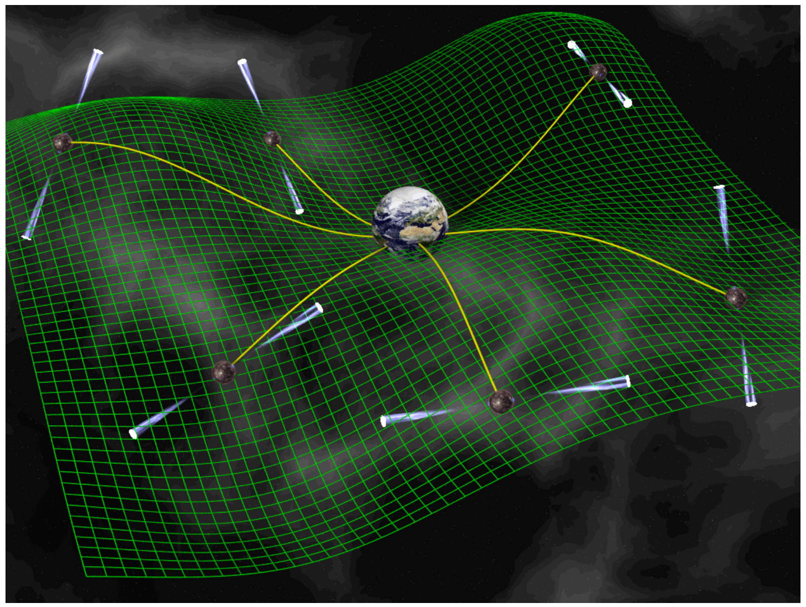
split + recombine atom wavefunction
measure atom spin and acceleration



In construction Kasevich/Hogan groups

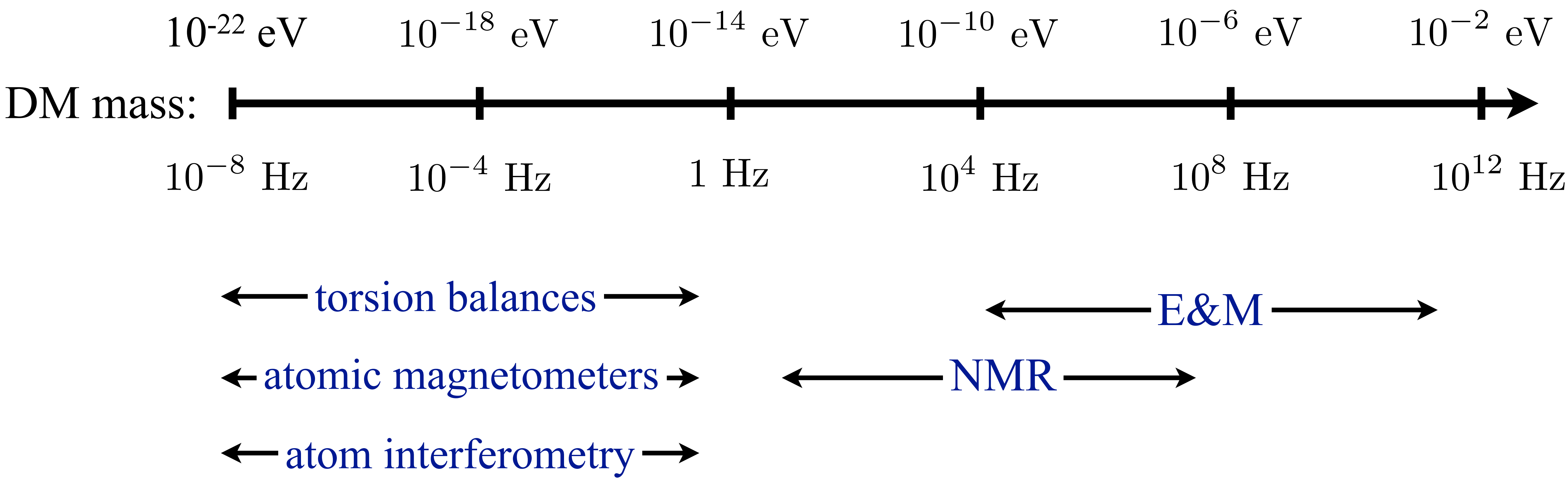
Pulsar Timing Arrays

DM and gravitational wave
detection similar



covers frequency range ~10 Hz down to yr^{-1}

DM Direct Detection



DM Direct Detection

DM mass:

10^{-22} eV | 10^{-18} eV | 10^{-14} eV | 10^{-10} eV | 10^{-6} eV | 10^{-2} eV

10^{-8} Hz | 10^{-4} Hz | 1 Hz | 10^{4} Hz | 10^{8} Hz | 10^{12} Hz

torsion balances

atomic magnetometers

atom interferometry

E&M

NMR

Coupling:

E&M

QCD

Spin

Scalar

Eot-Wash (spin)

Eot-Wash (scalar)

Atom Interferometry (spin)

Atom Interferometry (scalar)

CASPEr-Electric

CASPEr-Wind

ADMX

HAYSTAC

LC Circuit

DM Radio

ABRACADABRA

Gravitational Wave Detection with Atom Interferometry

with

Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

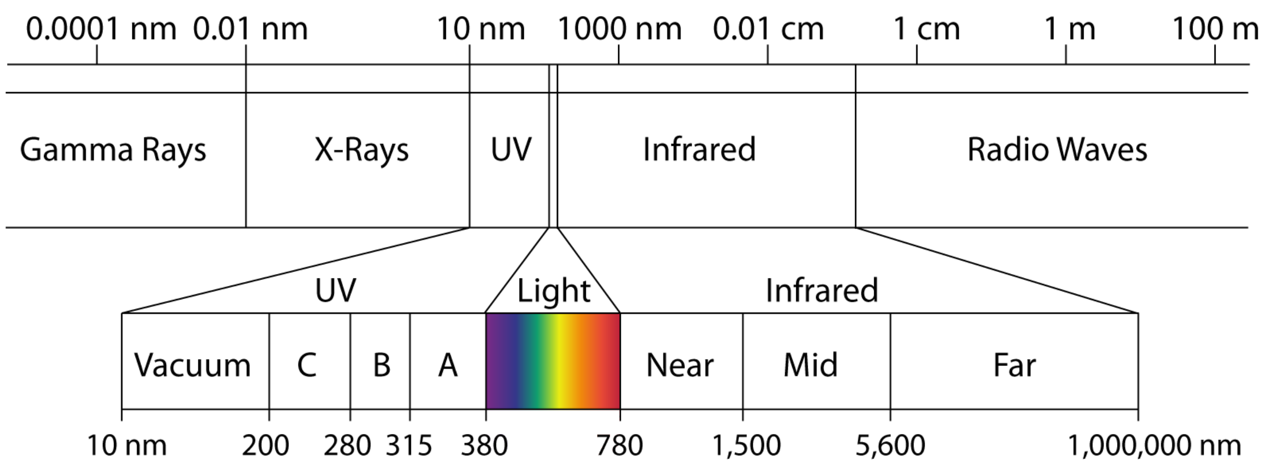
W.M. KECK FOUNDATION

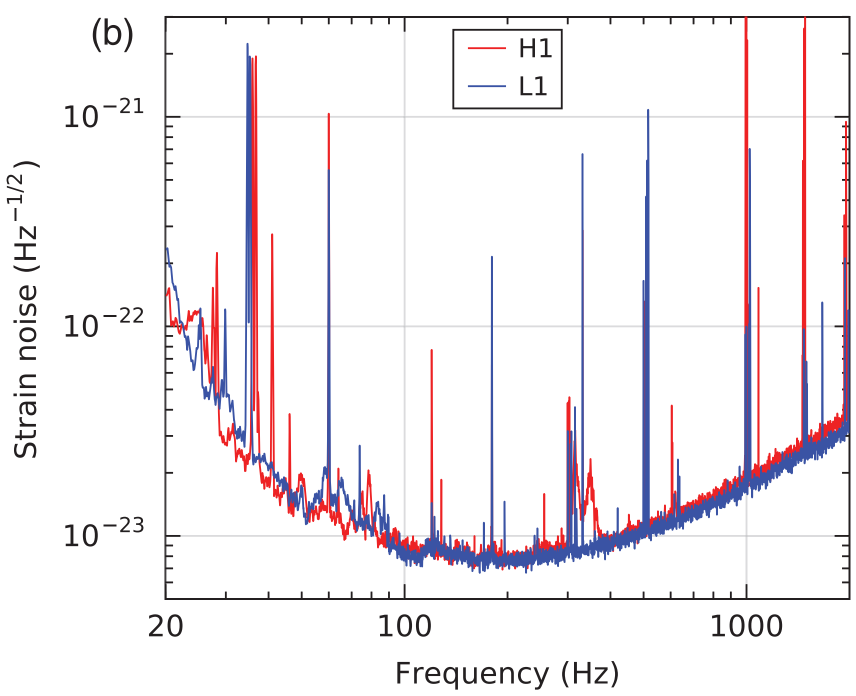
PRD **94** (2016) arXiv:1606.01860
PRL **110** (2013) arXiv:1206.0818
GRG **43** (2011) arXiv:1009.2702
PLB **678** (2009) arXiv:0712.1250
PRD **78** (2008) arXiv:0806.2125

Gravitational Spectrum

Gravitational waves open a new window to the universe

Every new EM band opened has revealed unexpected discoveries, gravitational waves give a new spectrum





Advanced LIGO can only detect GW's > 10 Hz ➜ How look at lower spectrum?

New detectors?

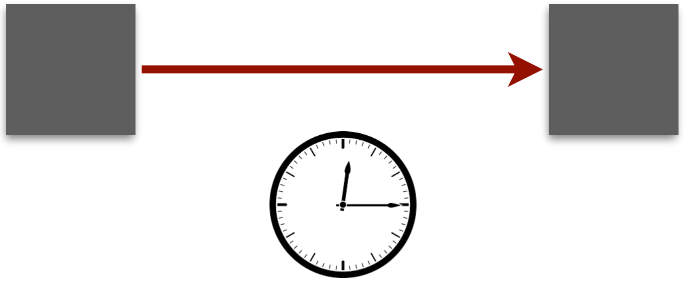
Gravitational Wave Detection

Gravitation Wave Detector

inertial test masses

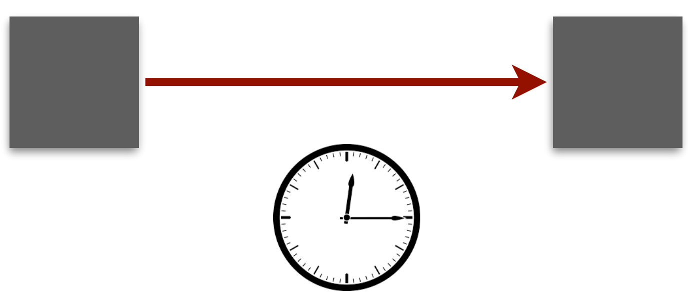
baseline

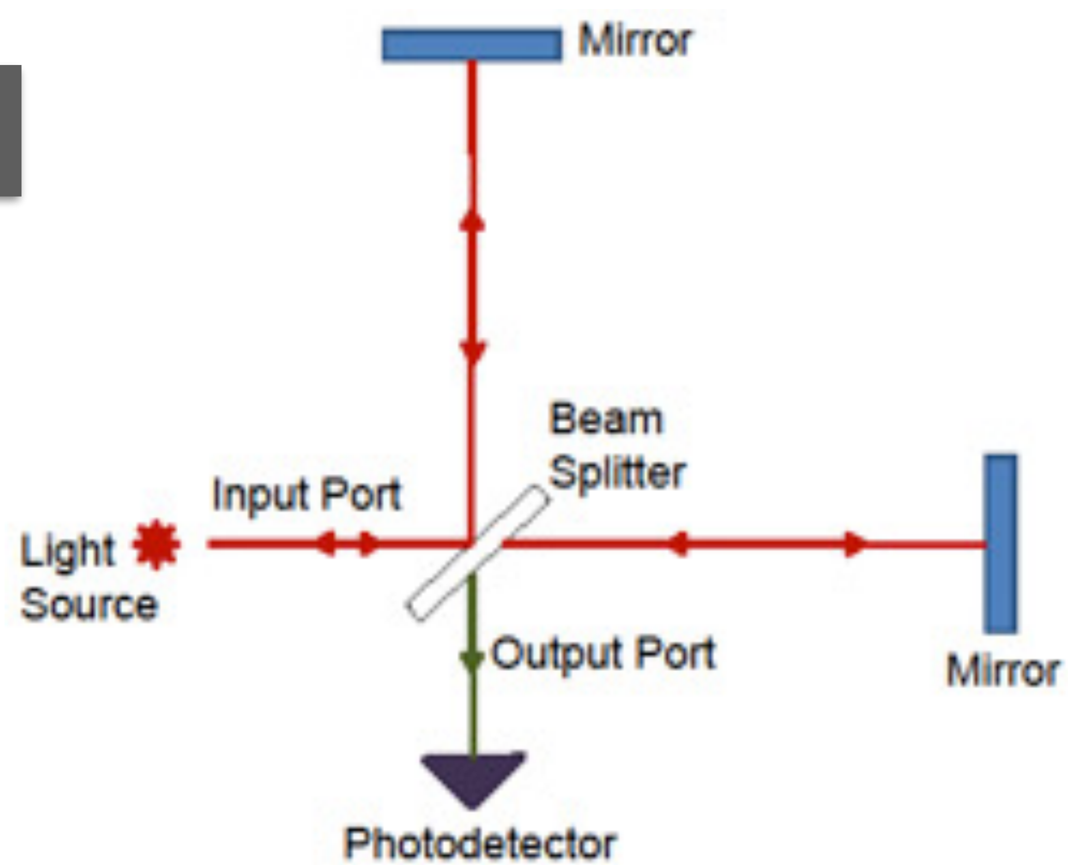
good clock



Gravitational Wave Detection

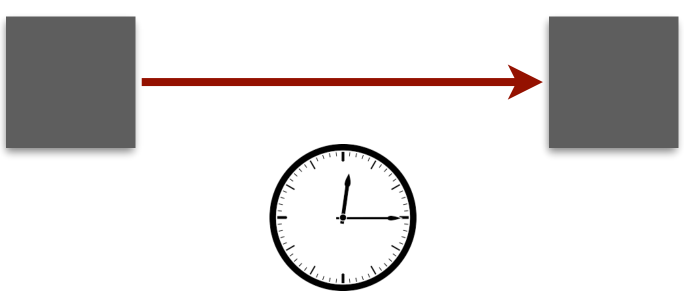
Gravitation Wave Detector	LIGO
inertial test masses	mirrors
baseline	laser
good clock	second arm

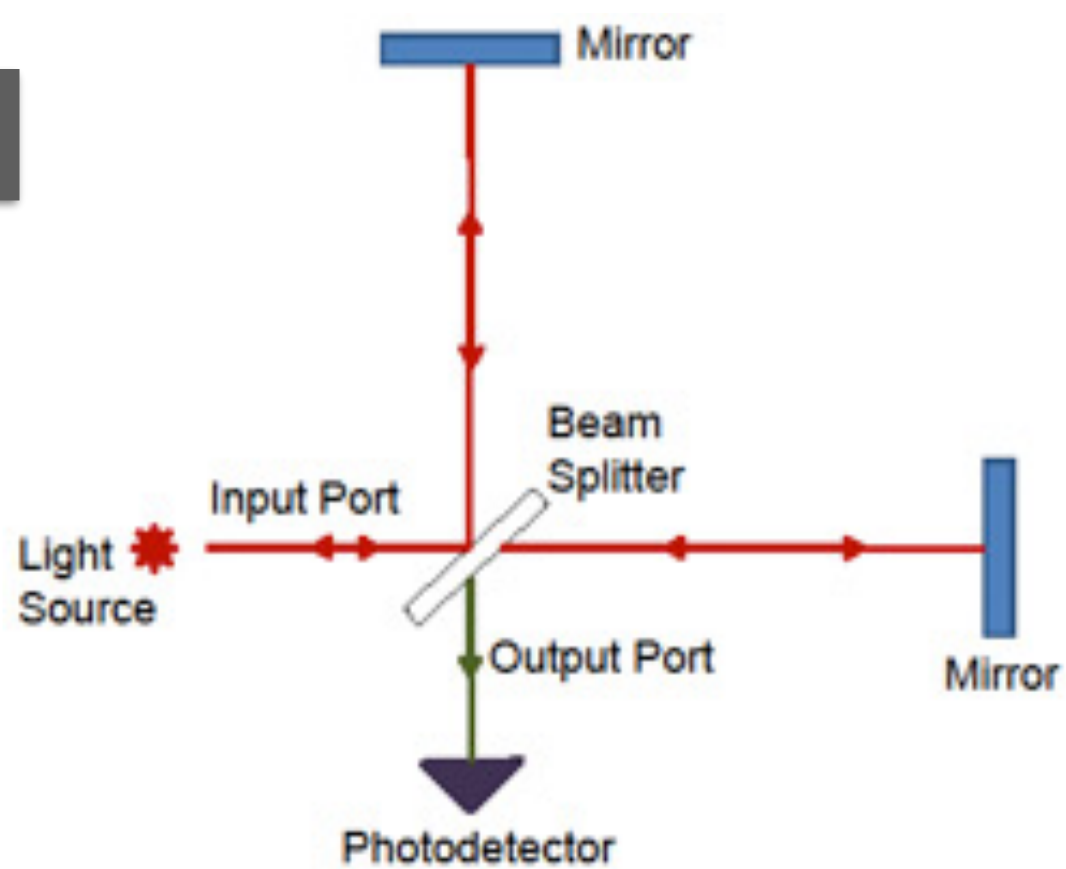


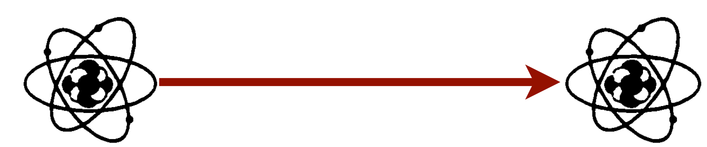


Gravitational Wave Detection

Gravitation Wave Detector	LIGO	Atom Interferometry
inertial test masses	mirrors	atoms
baseline	laser	laser
good clock	second arm	atoms







Gravitational Wave Detection

Gravitation Wave Detector	LIGO	Atom Interferometry
inertial test masses	mirrors	atoms
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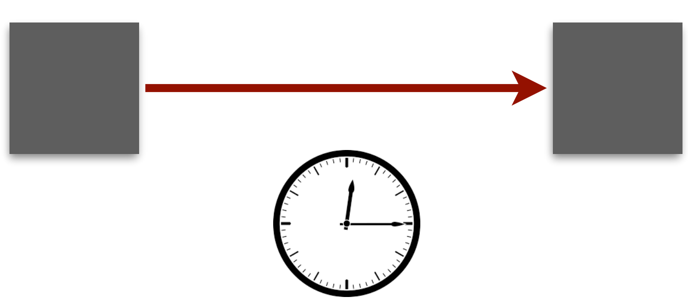
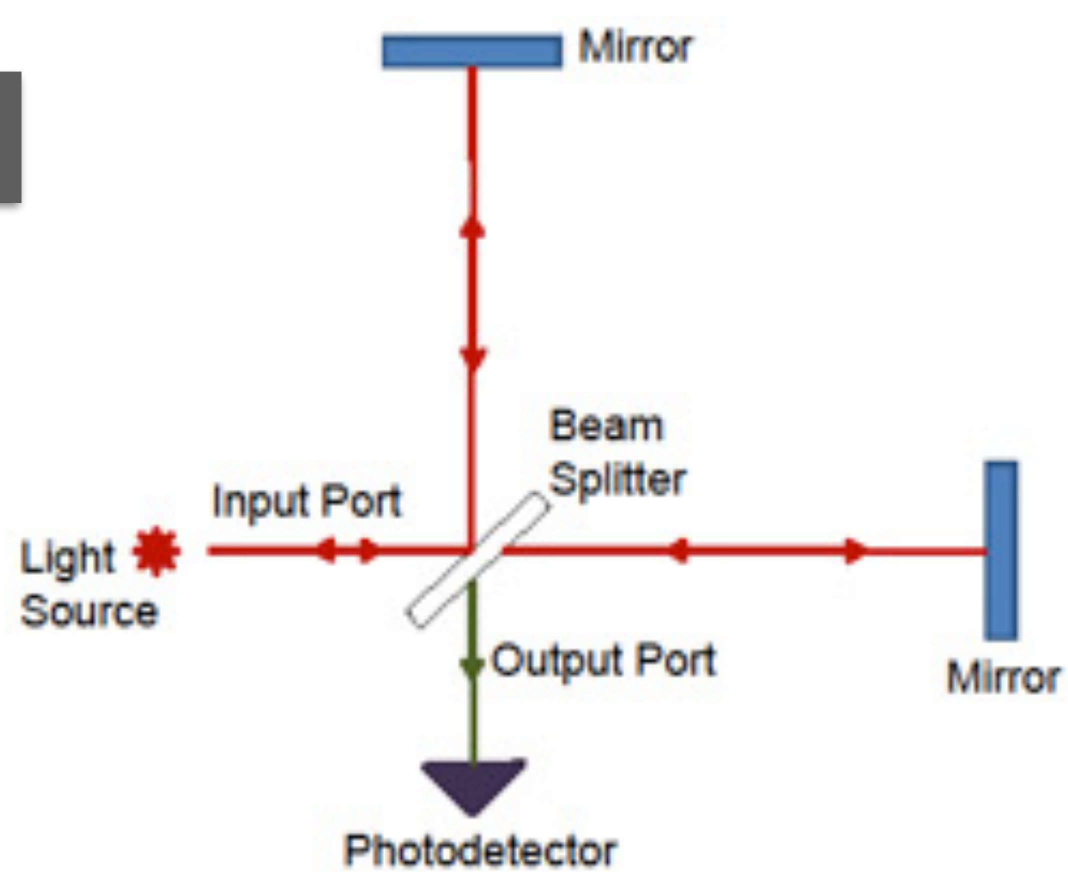
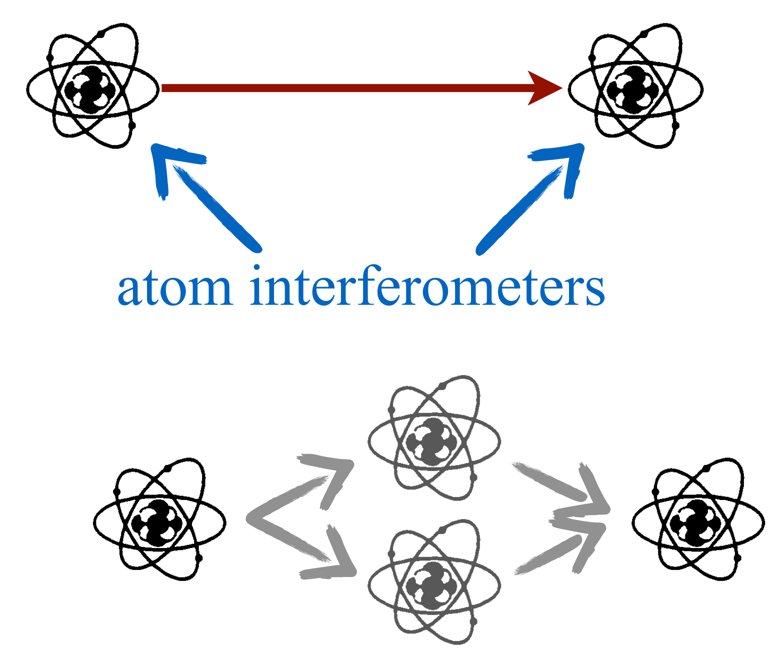






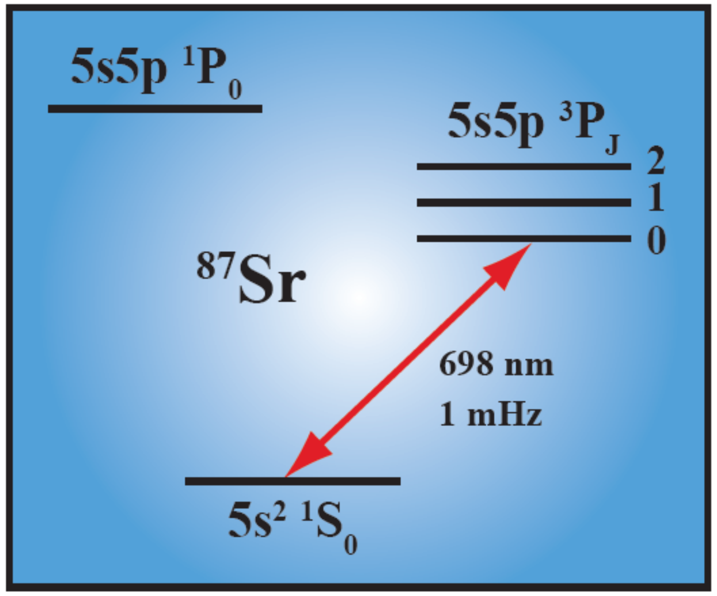
Atom Interferometry for Gravitational Waves

run atom interferometer as hybrid clock/accelerometer

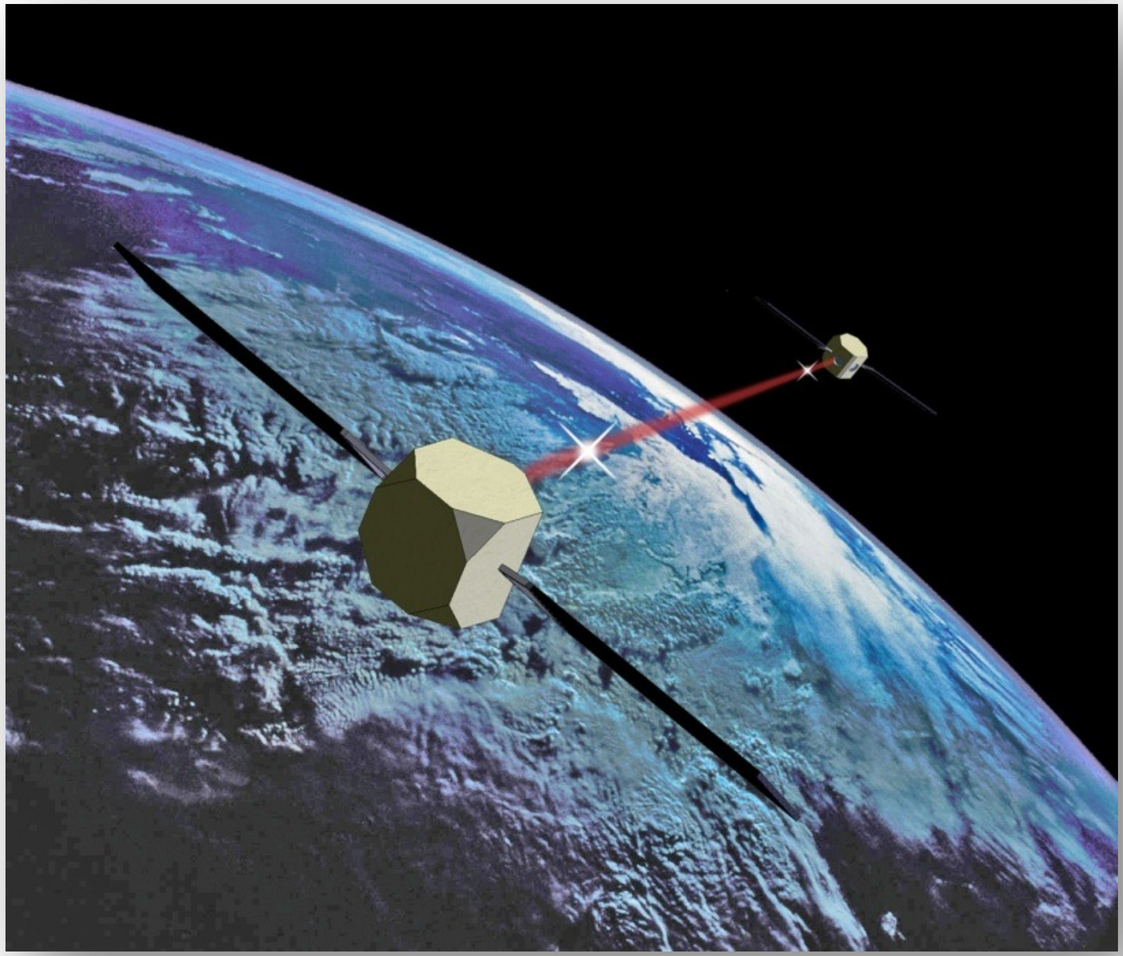
PWG, Hogan, Kasevich, Rajendran PRL **110** (2013)

atoms act as clocks, measure light travel time

remove laser noise with single baseline



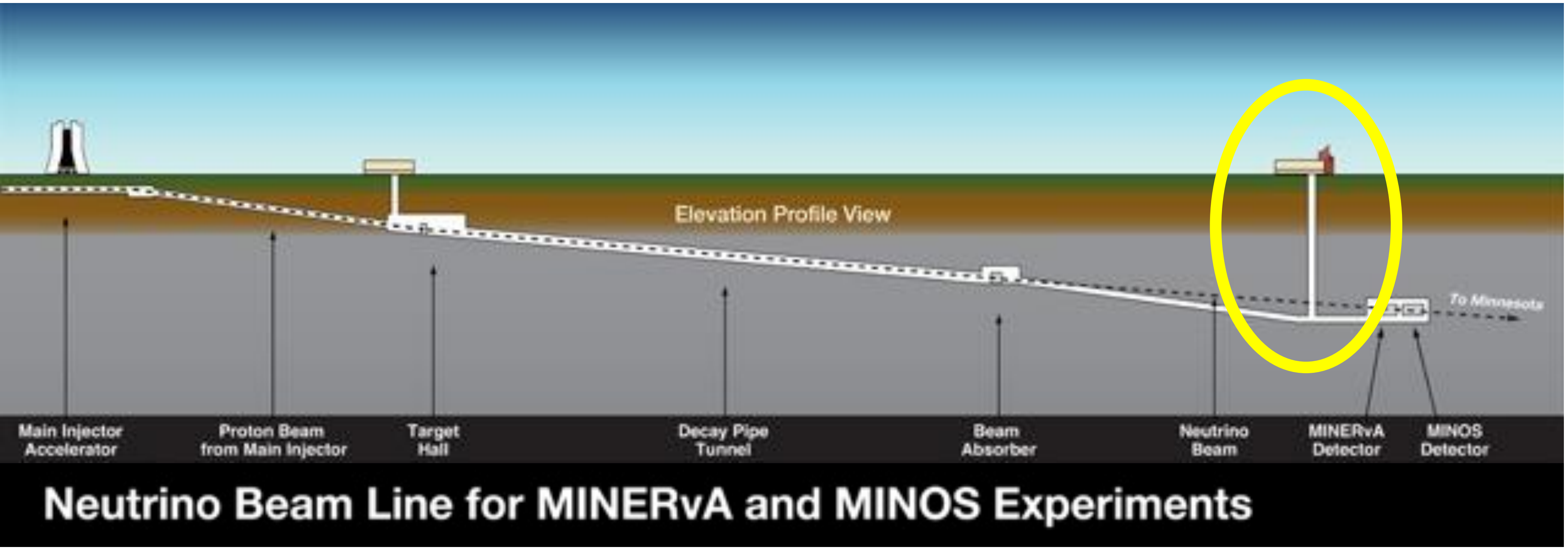
Clock transition in candidate atom ^{87}Sr

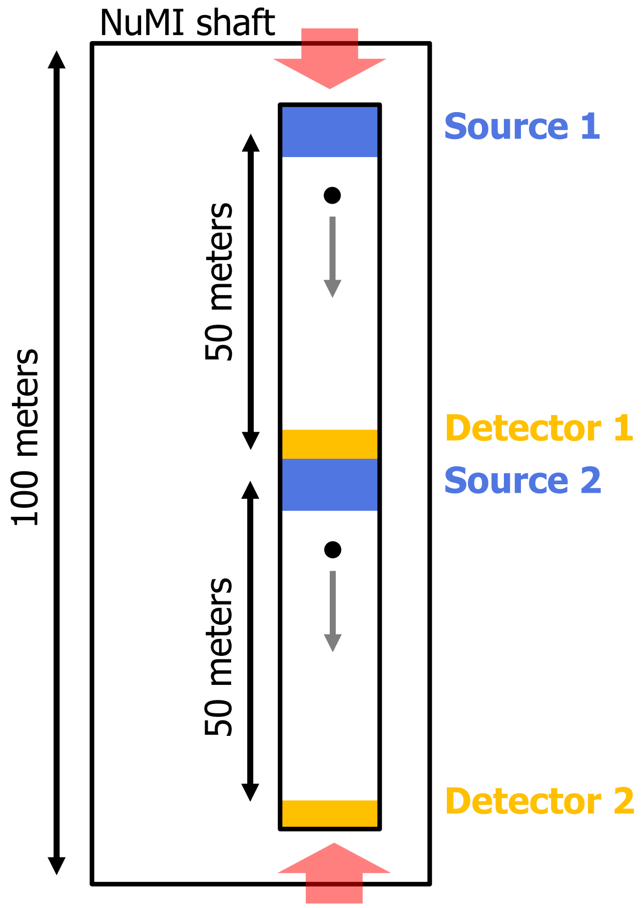


accelerometer ➜ atoms are good inertial test masses

terrestrial? seismic noise automatically removed

100 m Detector Proposal at Fermilab

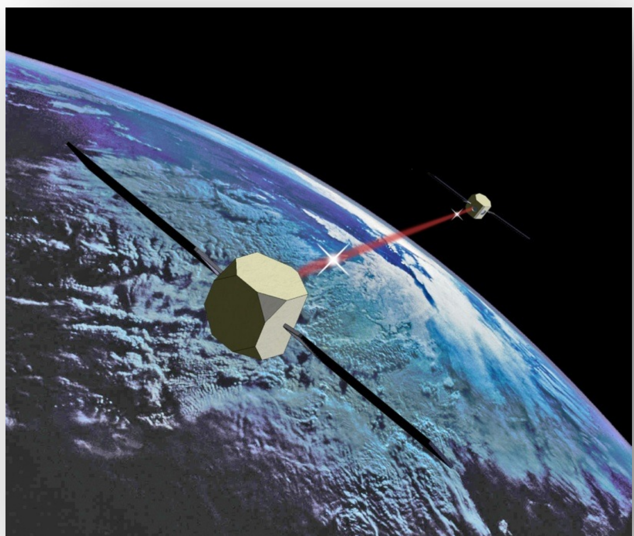




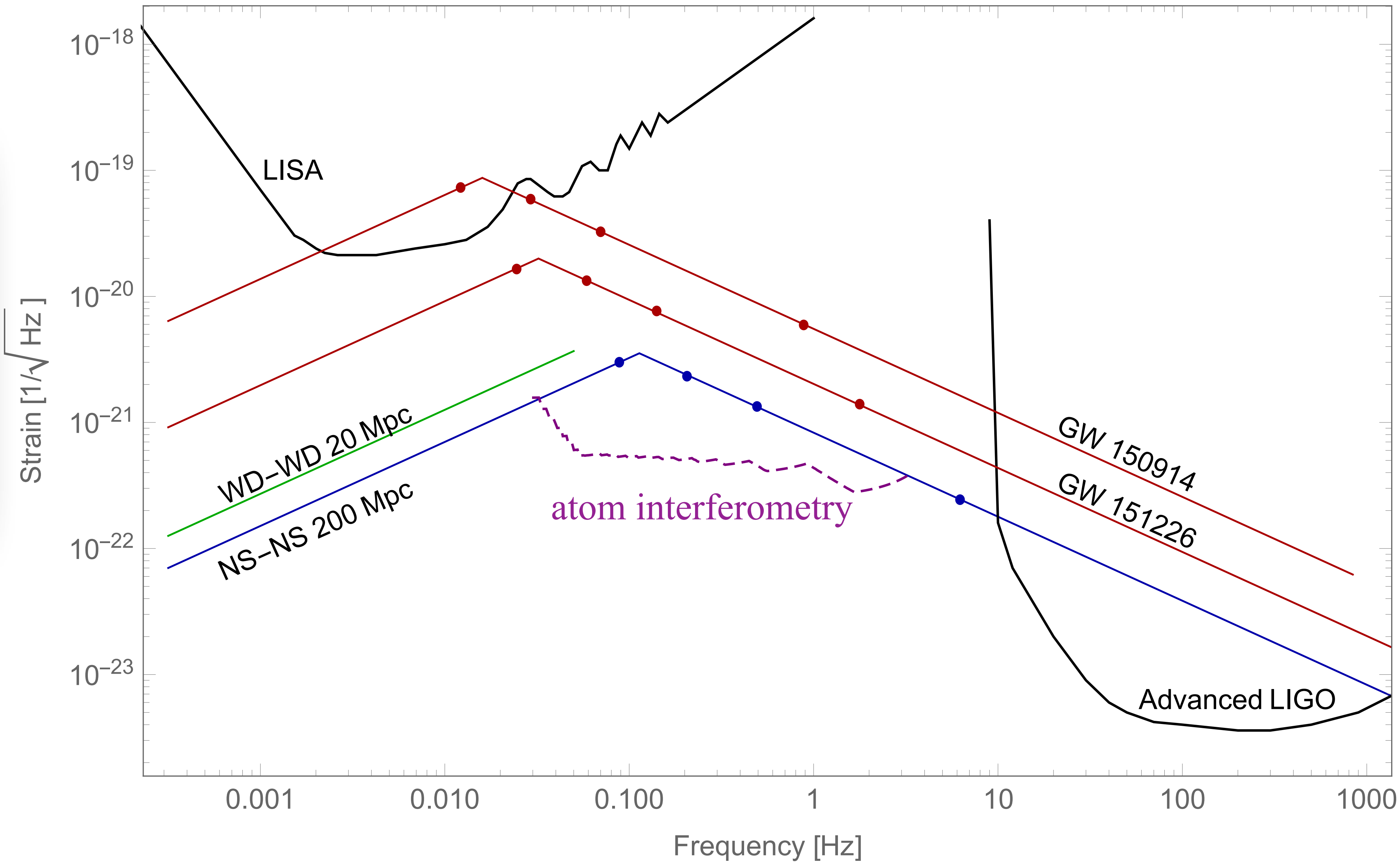
- 100 m atom interferometer (accelerometer) drop tower
- >3 s drop time to split and recombine atomic wavefunctions
- Detect dark matter through oscillatory force
- Also gravitational waves from unknown sources
- Lead to ~km scale detector for GW's (e.g. BH mergers) and DM, opens band below LIGO and above LISA (~ 0.1 - 10 Hz)

Atom Interferometry for Gravitational Waves

Atoms could access mid-frequency band



earth orbit allows polarization measurement with single detector



for example this band allows:

localize sources on the sky (e.g. sub-degree accuracy) and predict BH and NS binary mergers for other telescopes to observe

with Sunghoon Jung

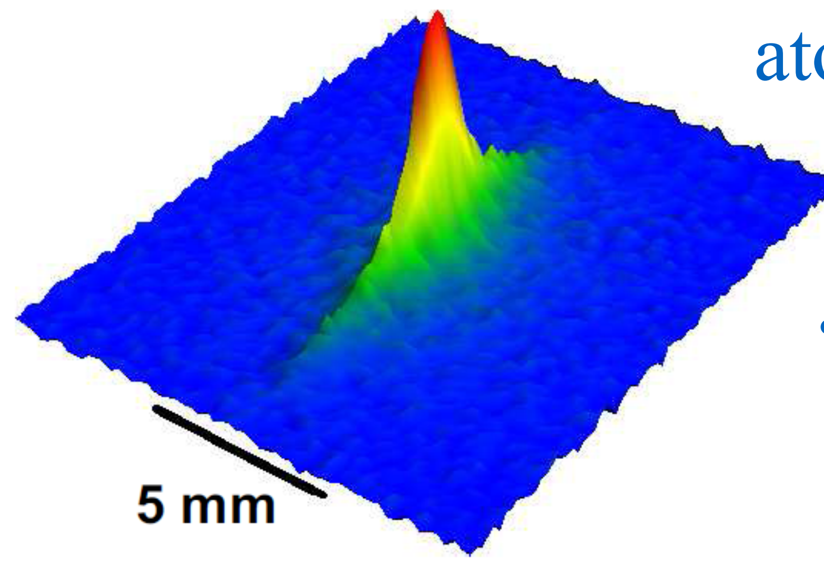
may measure initial BH spins and orbital eccentricity

Recent Experimental Results

(Kasevich and Hogan groups)

Stanford Test Facility

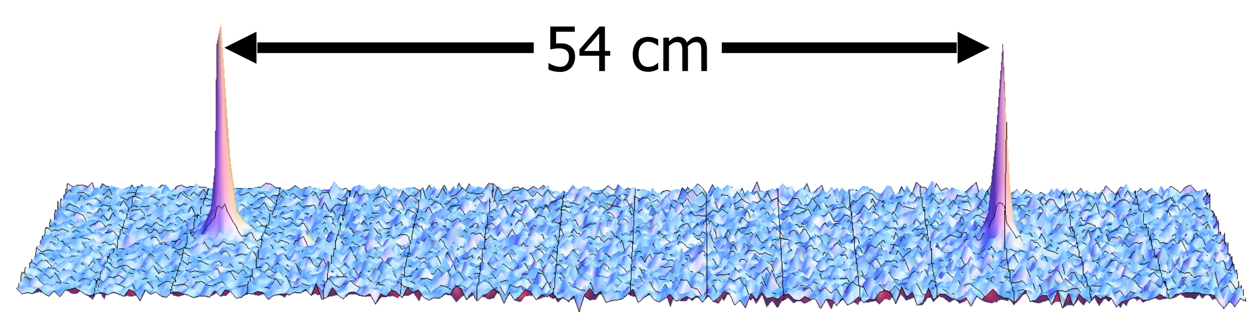
demonstrate necessary technologies:



atom cooling

➜ 50 pK

Macroscopic splitting of atomic wavefunction:



Kovachy et. al, *Nature* (2015)

Summary

Precision measurement is a powerful tool for particle physics and cosmology

new technologies beyond traditional particle detectors

e.g. combination of several experiments will cover QCD axion dark matter fully

Light dark matter (axions) and gravitational wave detection similar:

detect coherent effects of entire field, not single particles

- laser interferometry
- atom interferometry (clocks)
- NMR
- high-precision magnetometry (SQUIDs, atomic systems)
- torsion pendulums
- optically-levitated dielectric spheres
- …

Many more possibilities we haven’t thought of yet…

Backup Slides

Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

scalar

vector

arXiv:1512.06165

Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

scalar → pseudo-scalar (axion)
scalar → scalar

vector → vector
vector → axial-vector

arXiv:1512.06165

Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

scalar → pseudo-scalar (axion)

$a\,F\tilde{F}$	E&M
$a\,G\tilde{G}$	QCD
$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)

scalar → scalar

vector → vector

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arXiv:1512.06165

Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

scalar

- pseudo-scalar (axion)
  - $a\,F\tilde{F}$ — E&M
  - $a\,G\tilde{G}$ — QCD
  - $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ — matter (spin)
- scalar
  - $\phi\,h^\dagger h,\ \phi\,\mathcal{O}_{\rm SM}$ — SM properties (electron mass)

vector

- vector
- axial-vector

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Possibilities for Light Dark Matter

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  - scalar
    - $\phi\,h^\dagger h,\ \phi\,\mathcal{O}_{\rm SM}$ — SM properties (electron mass)
- vector
  - vector
    - $A'_\mu\bar{\psi}\gamma^\mu\psi$ — charged
    - $F'_{\mu\nu}F^{\mu\nu}$ — DM-photon mixing
    - $F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$ — dipole moment
  - axial-vector
    - $A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$ — spin

arXiv:1512.06165

Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities
(symmetry, effective field theory):

scalar	pseudo-scalar (axion)	$a\,F\tilde{F}$	E&M	current searches (e.g ADMX)
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		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)	
	scalar	$\phi\,h^\dagger h,\ \phi\,\mathcal{O}_{\rm SM}$	SM properties (electron mass)	
vector	vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	charged	
		$F'_{\mu\nu}F^{\mu\nu}$	DM-photon mixing	
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole moment	
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arXiv:1512.06165

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		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)	
	scalar	$\phi\, h^\dagger h,\ \phi\, \mathcal{O}_{\rm SM}$	SM properties (electron mass)	use other couplings
vector	vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	charged	e.g. can reach axion parameter space considered impossible
		$F'_{\mu\nu}F^{\mu\nu}$	DM-photon mixing	
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole moment	
	axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	spin	

arXiv:1512.06165

Possibilities for Light Dark Matter

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current searches
(e.g ADMX)

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	axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	spin

use other couplings

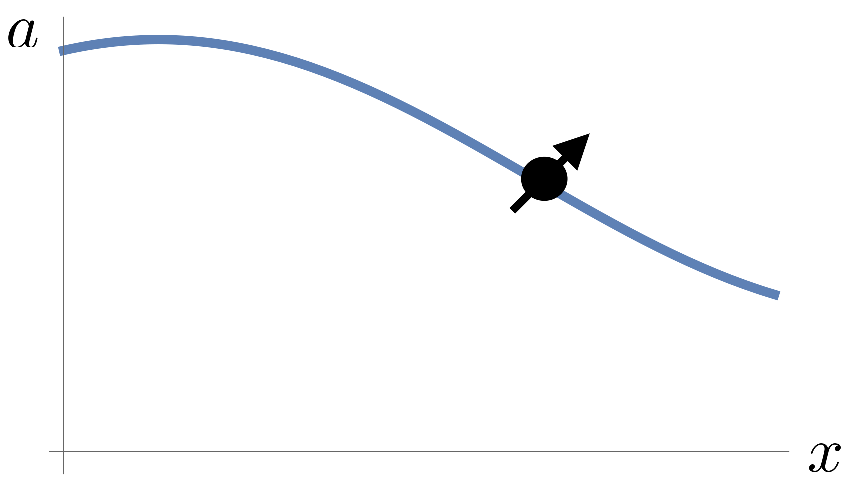
e.g. can reach axion parameter space considered impossible

Can cover all these possibilities!

arXiv:1512.06165

CASPEr-Wind

can also use direct coupling of axion to nucleons: $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ ➜ $H \ni \nabla a \cdot \vec{\sigma}_N$

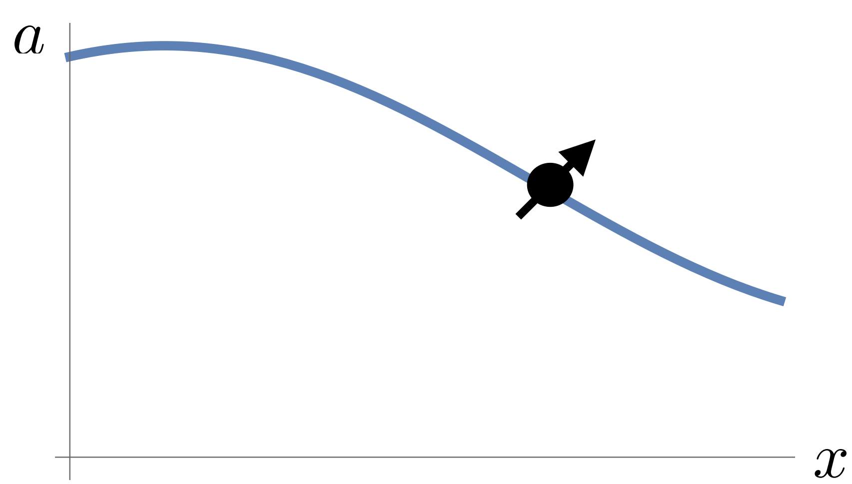


nuclear spins precess in DM axion field

proportional to axion momentum (“wind”)

CASPEr-Wind

can also use direct coupling of axion to nucleons: $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ ➜ $H \ni \nabla a \cdot \vec{\sigma}_N$



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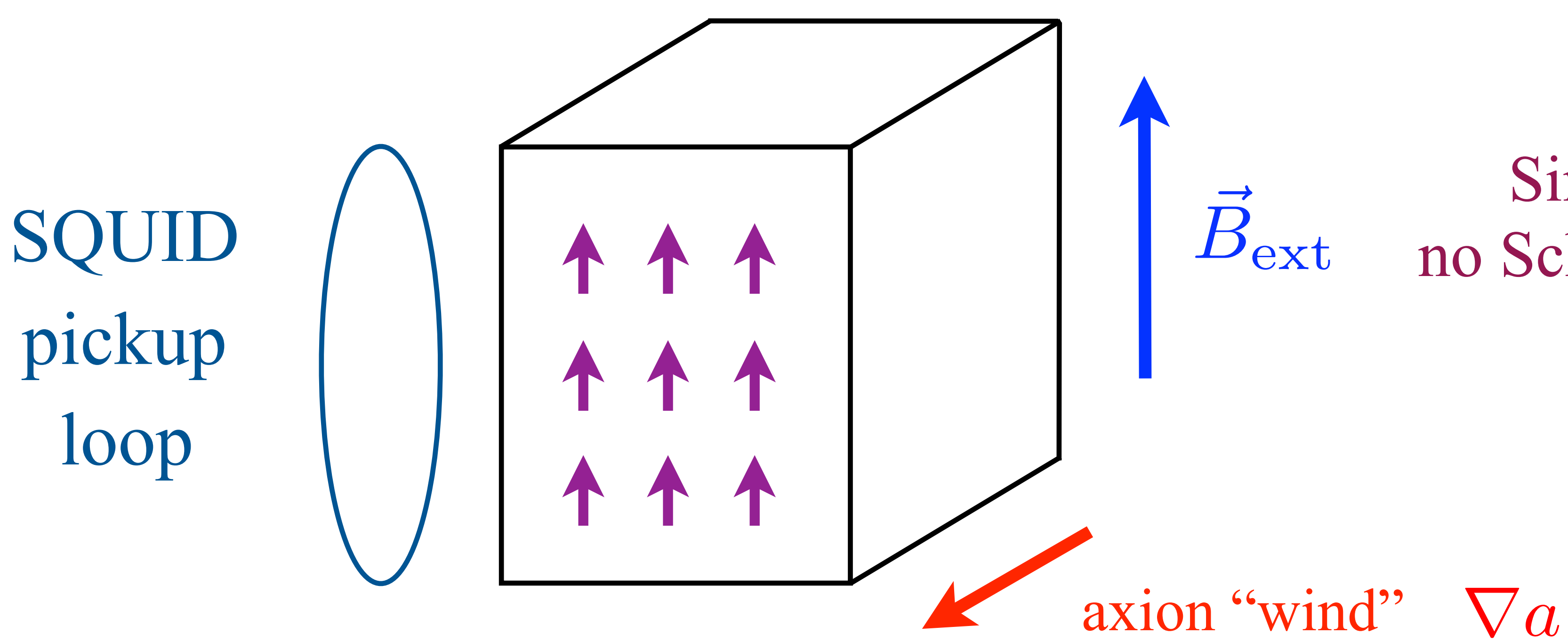
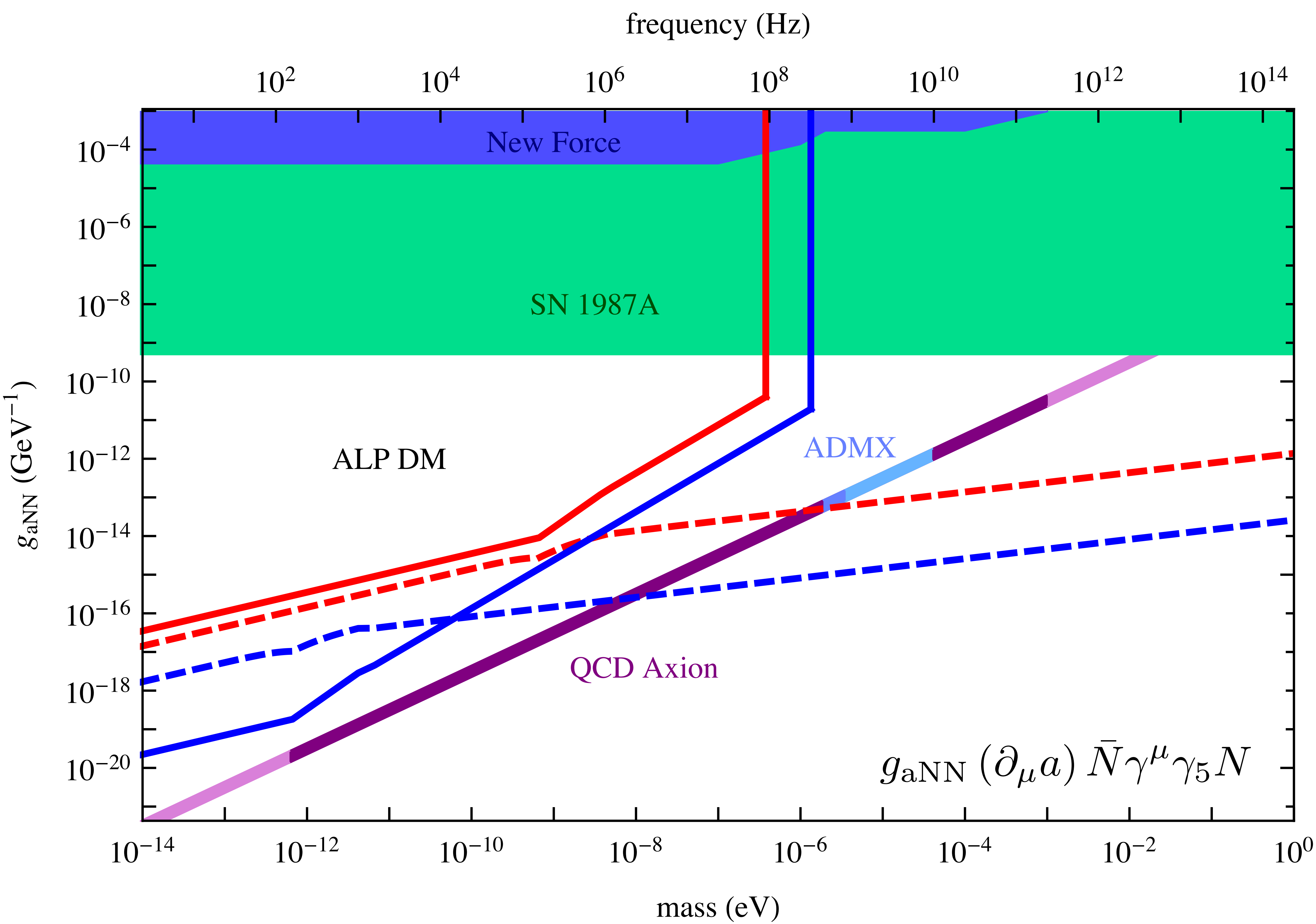


Similar to CASPEr-Electric but
no Schiff suppression, no polar crystal
➜ can use LXe or ^{3}He

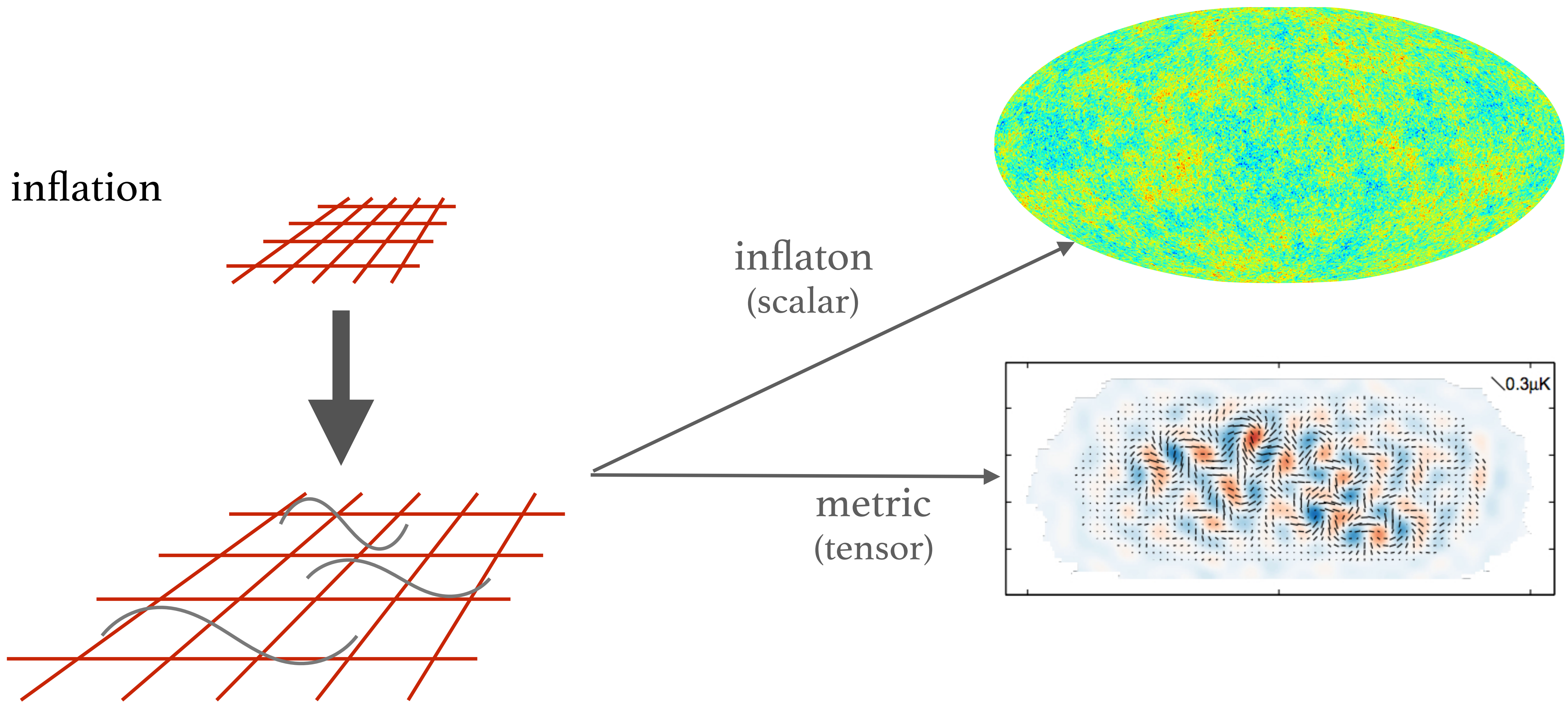
makes a directional detector for axions (and gives annual modulation)

Limits on Axion-Nucleon Coupling



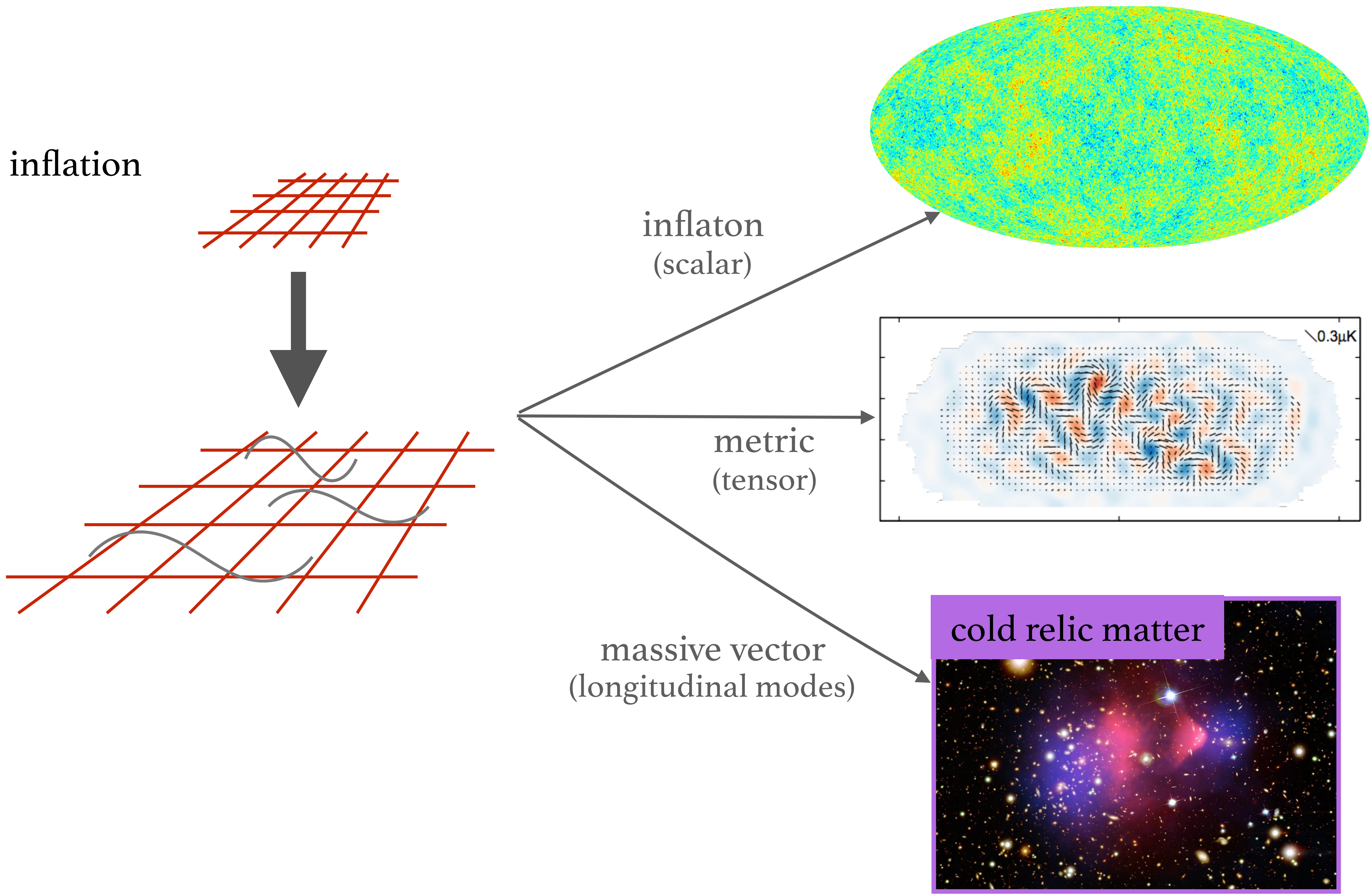
Vectors

Inflationary Production of Massive Vector



PWG, J. Mardon, & S. Rajendran 1504.02102

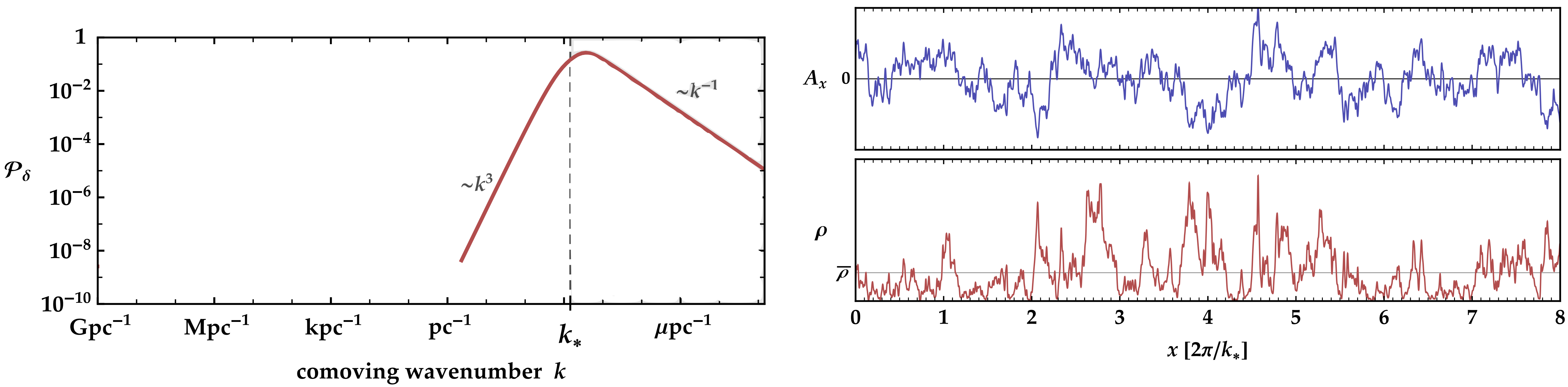
Inflationary Production of Massive Vector



PWG, J. Mardon, & S. Rajendran 1504.02102

Relic vector matter

Power spectrum   Large short-scale fluctuations



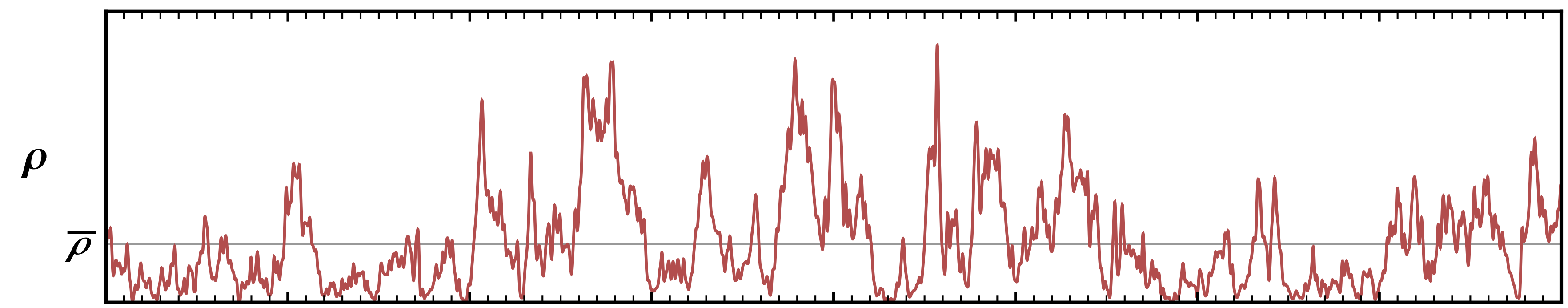
scalar: scale-invariant on long scales ⟶ isocurvature problem
vector: suppressed power on long scales ⟶ NO isocurvature problem

Abundance set by H_I and m:

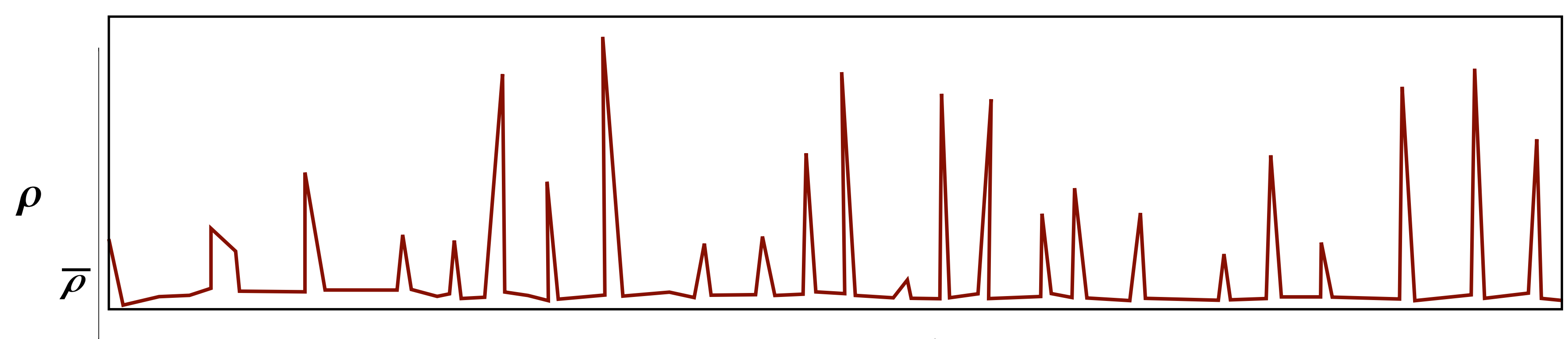
$$\boxed{\frac{\Omega_A}{\Omega_{\rm cdm}} \approx \sqrt{\frac{m}{6\times 10^{-6}\,\mathrm{eV}}}\left(\frac{H_I}{10^{14}\,\mathrm{GeV}}\right)^2}$$

Substructure (best guess)

Primordial fluctuations (pre m.r.e.)



Self-bound clumps (post m.r.e.)



time

small clumps

density $\sim \varrho_{\mathrm{mre}}$ (10^6 overdense)

size $\sim L_{\mathrm{mre}} \ll 1$A.U.

spacing $\sim (a_0/a_{\mathrm{mre}})L_{\mathrm{mre}} \lesssim 1$A.U.

Implication for Searches?

- Large small-scale clumping is a general possibility
- ρ in lab varies over time
- $\rho \longrightarrow \sim 10^6 \rho$ when in clump (or more?)
- $\longrightarrow$ signal is HUGE and easy to see…
  …IF at right frequency
- Best strategy: scan range fast and repeat (maximizes chance of hitting frequency when in clump)