# Ultralight Dark Matter Detection

Peter Graham

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 relatively small

- New technologies rapidly increasing sensitivity
  - e.g. atomic clocks reach 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

# Outline

1. Dark Matter Detection

2. Cosmic Axion Spin Precession Experiment (CASPEr)
   (D. Budker + A. Sushkov)

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

4. DM Radio
   (K. Irwin)

5. Other techniques

# Dark Matter Detection

# Dark Matter Candidates

What do we know about dark matter?

black holes

DM mass:

$10^{-22}$ eV
dwarf galaxy size

$10^{19}$ GeV

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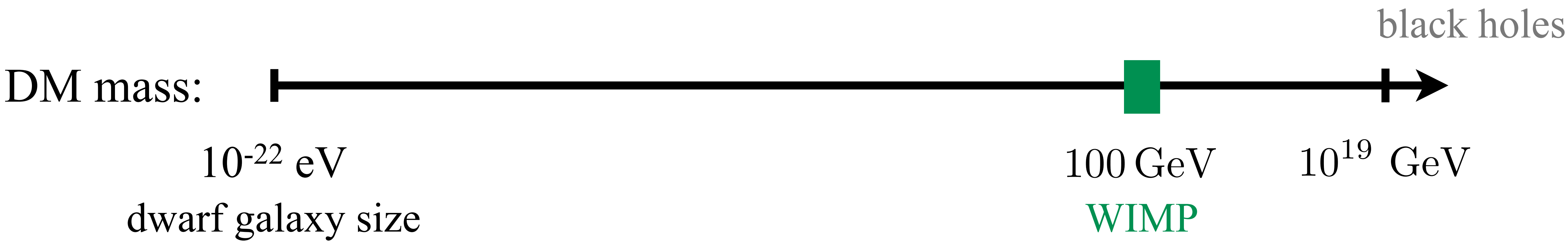


WIMP is well-motivated, significant direct detection effort focused on WIMPs

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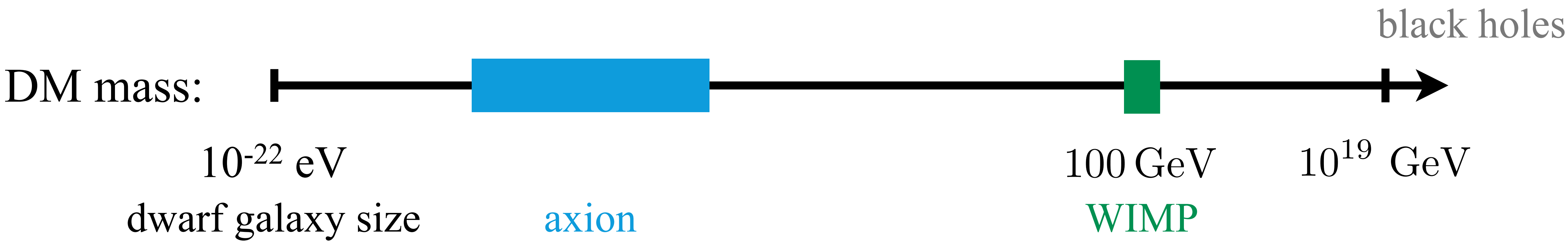


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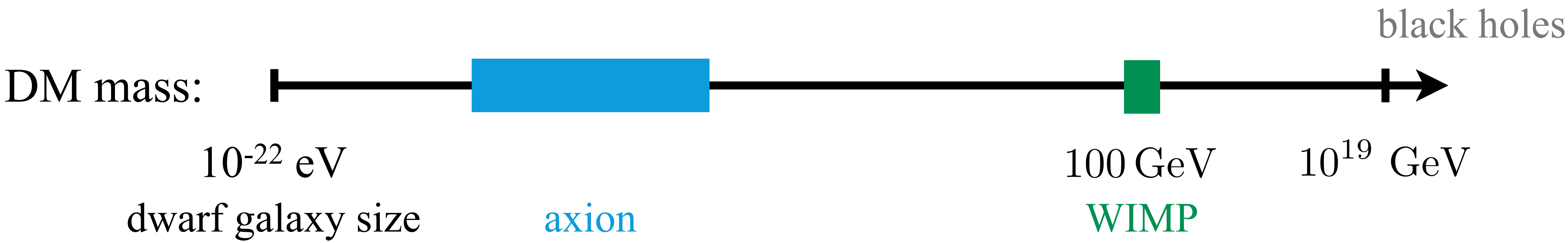


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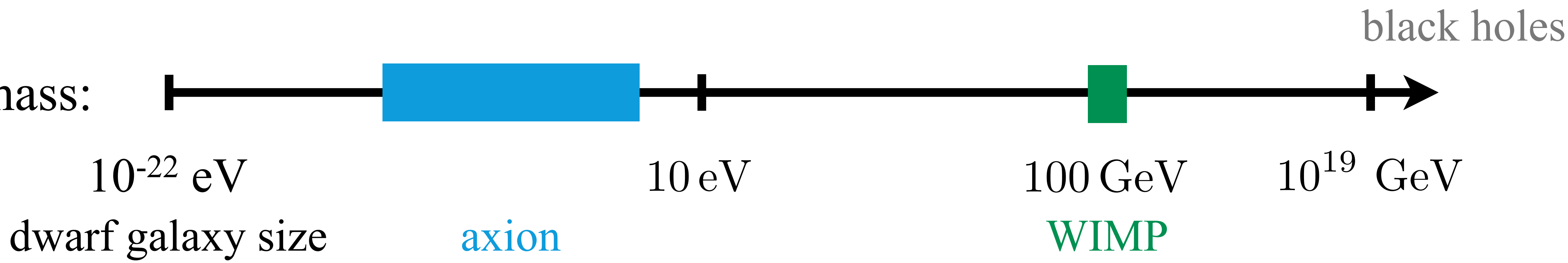
Axion is other best-motivated candidate (can solve strong CP, hierarchy problems), only a small fraction of parameter space covered

Huge DM parameter space currently unexplored!

# Direct Detection

How can we detect DM?

DM mass:




$$\rho_{\rm DM} \approx 0.3\,\frac{\rm GeV}{\rm cm^3} \approx (0.04\,{\rm eV})^4$$ ➔ high phase space density if $m \lesssim 10\,{\rm eV}$

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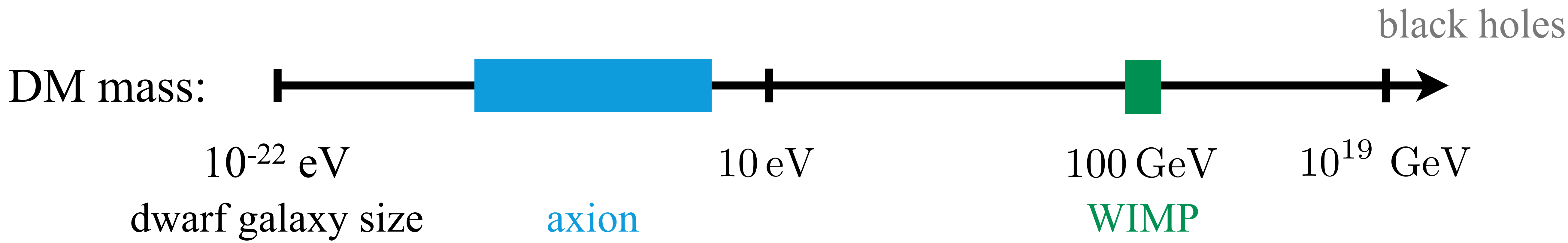


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field-like (e.g. axion)
new detectors required

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

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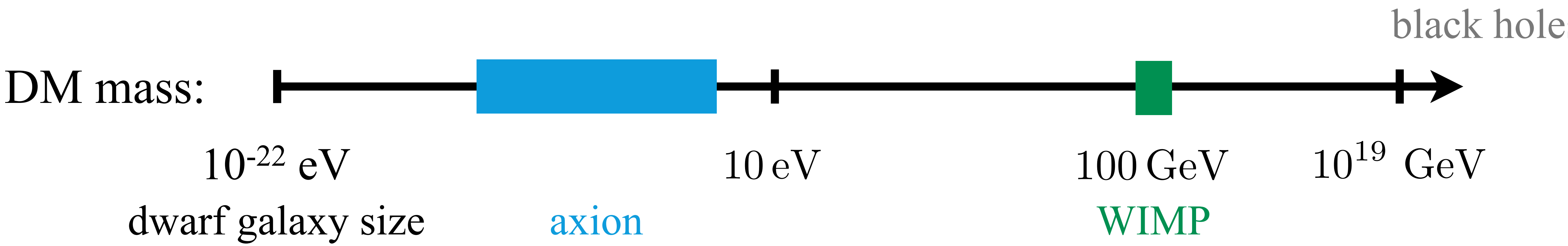


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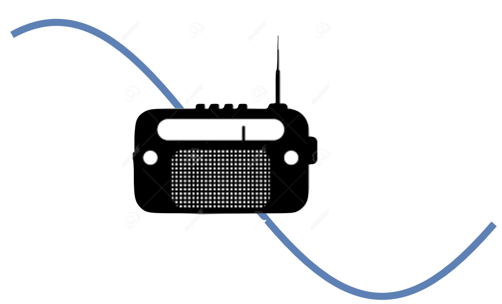

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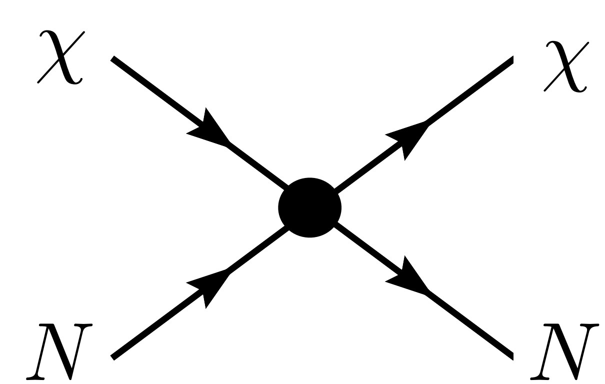
Search for single, hard particle scattering



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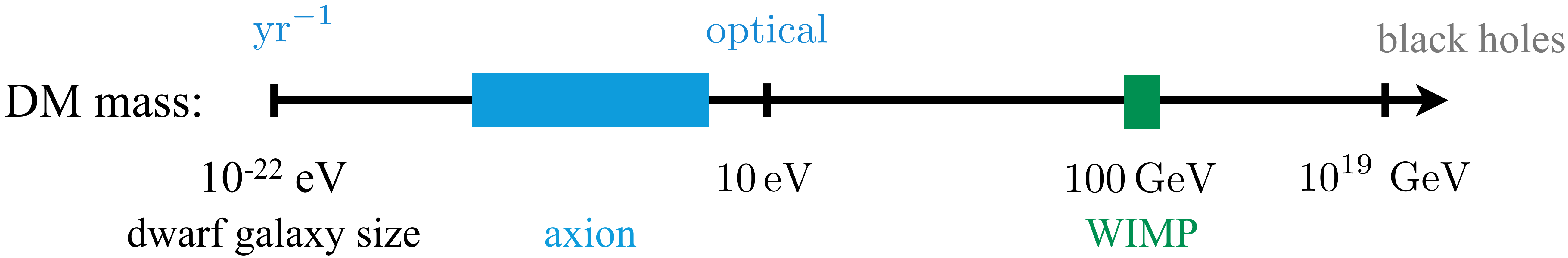


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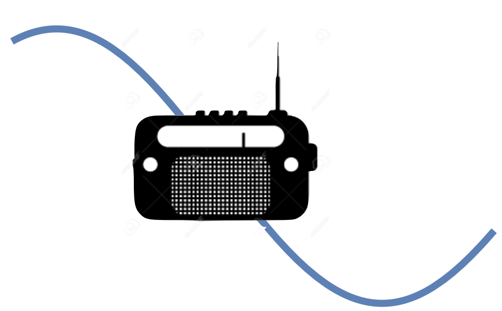

Frequency range accessible!

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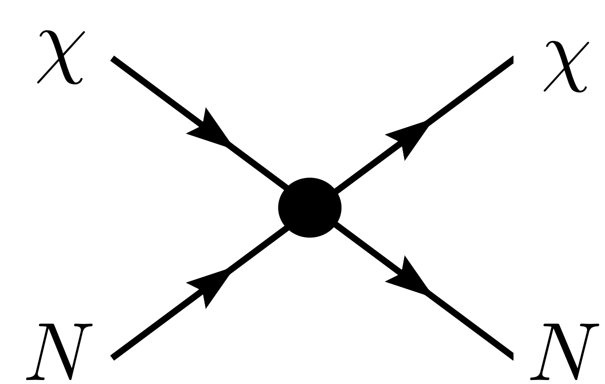

# Possibilities for Light Dark Matter

Effective field theory ➜ only a few possible couplings to us
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light DM

arXiv:1512.06165

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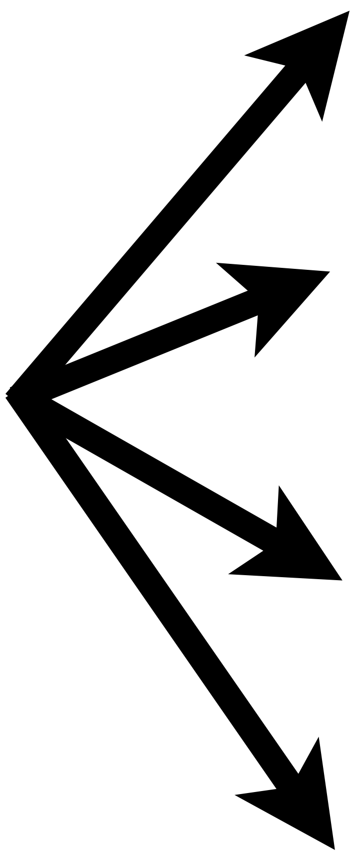

E&M - drive currents

$a\, F\tilde{F}$

QCD - change nuclear properties

$a\, G\tilde{G}$

spin - cause precession

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

scalar - new force/SM properties

$aH^\dagger H$

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Effective field theory ➜ only a few possible couplings to us
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light DM

- E&M - drive currents
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- 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)

arXiv:1512.06165

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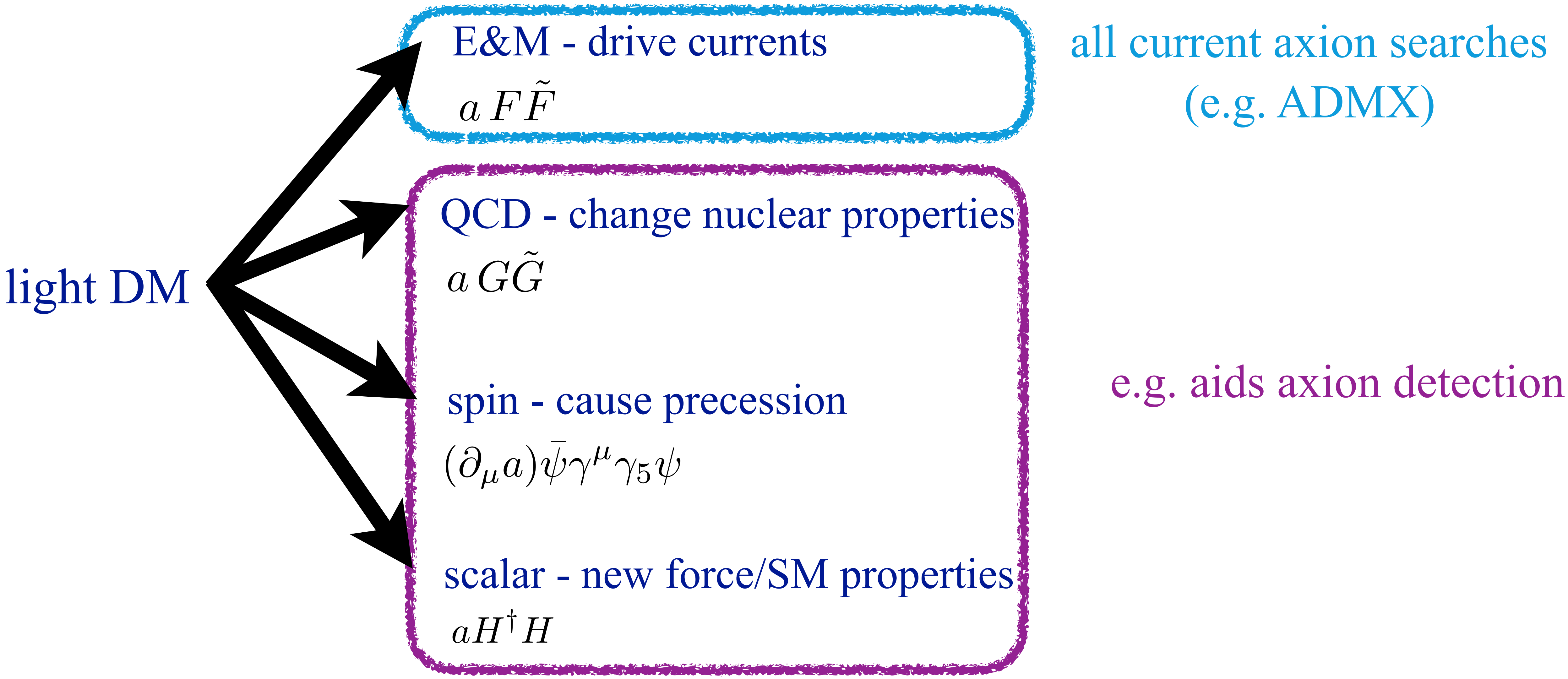
four types of experiments:




Can cover all these possibilities

arXiv:1512.06165

# Cosmic Axion Spin Precession Experiment (CASPEr)

with


Dmitry Budker
Micah Ledbetter
Surjeet Rajendran
Alex Sushkov



HEISING - SIMONS FOUNDATION

SIMONS FOUNDATION

DFG Deutsche Forschungsgemeinschaft



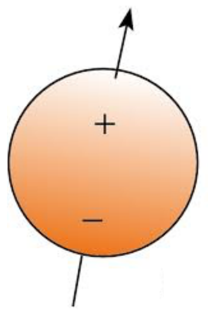
PRX **4** (2014) arXiv:1306.6089
PRD **88** (2013) arXiv:1306.6088
PRD **84** (2011) arXiv:1101.2691

# The Axion

how cover the full axion mass range? a different operator

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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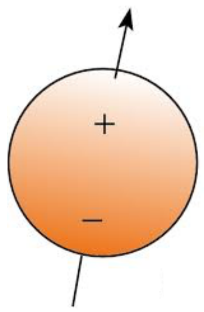


Axion solution:

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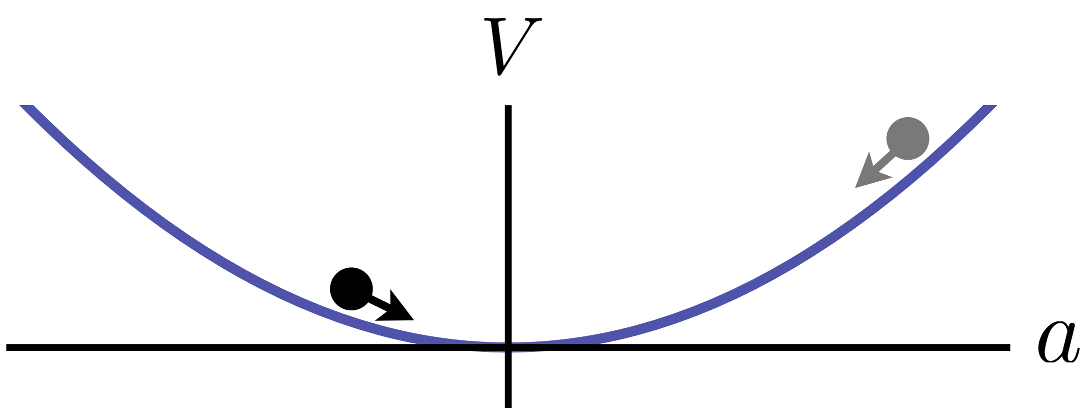


$$a(t) \sim a_0 \cos\left(m_a t\right)$$

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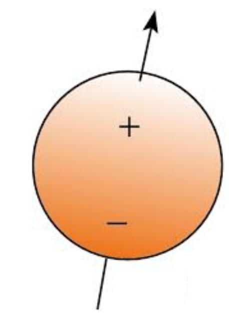


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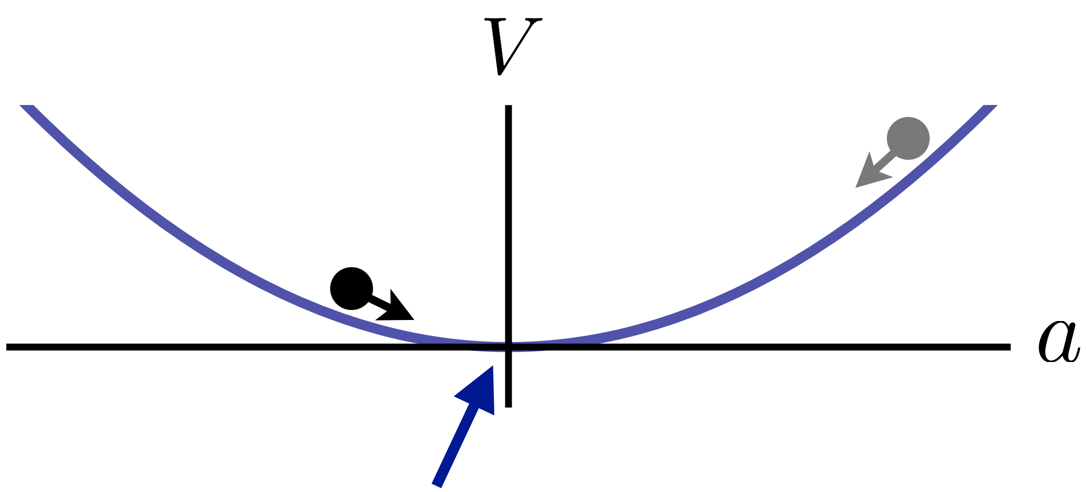


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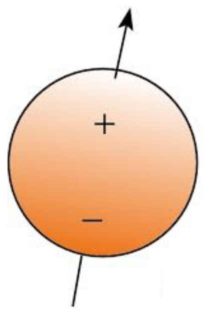


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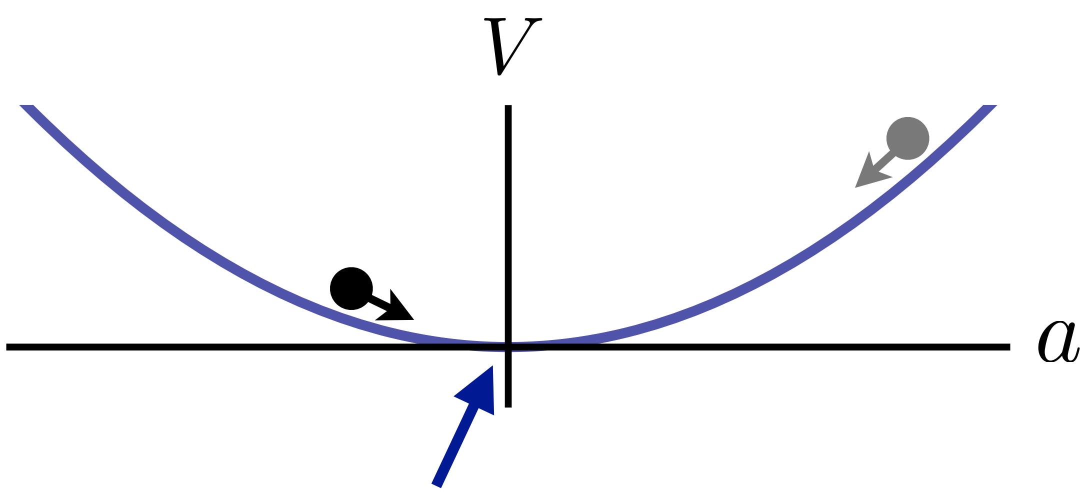


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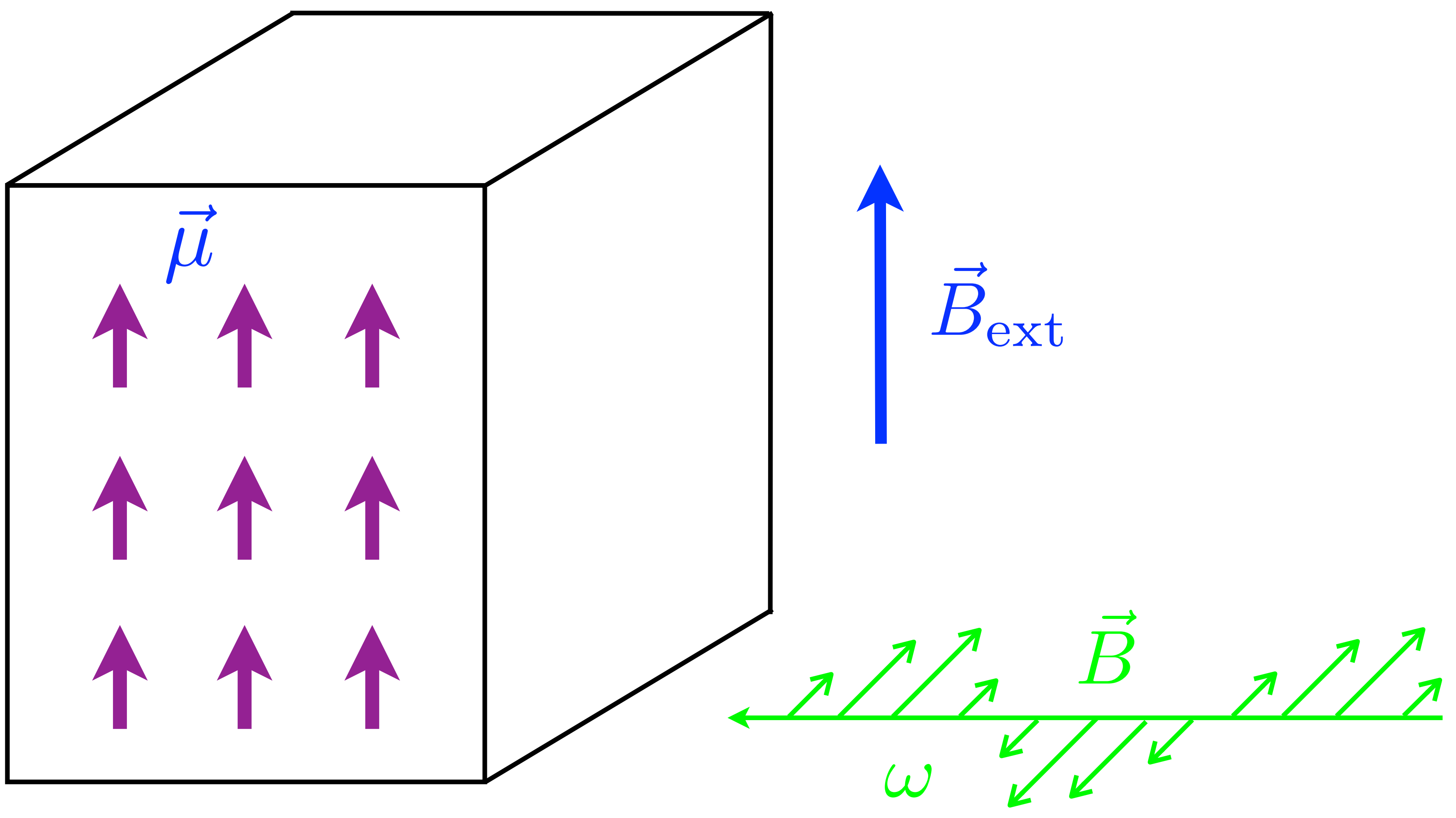
Axion DM causes oscillating nucleon EDM today

completely changes axion detection (a non-derivative effect)

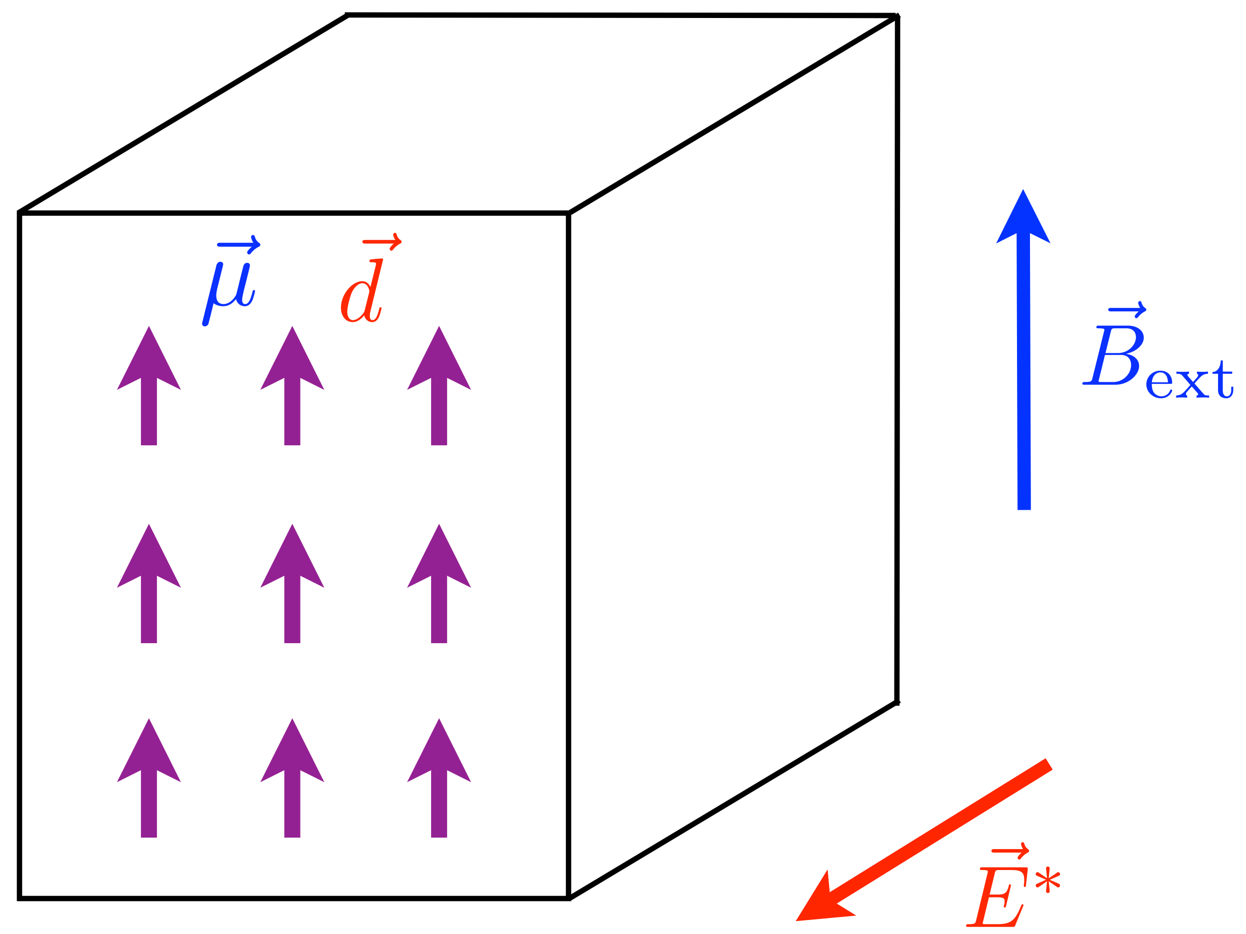
# Axions with NMR




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

# Cosmic Axion Spin Precession Experiment (CASPEr)

NMR techniques + high precision magnetometry




Larmor frequency = axion mass ➔ resonant enhancement

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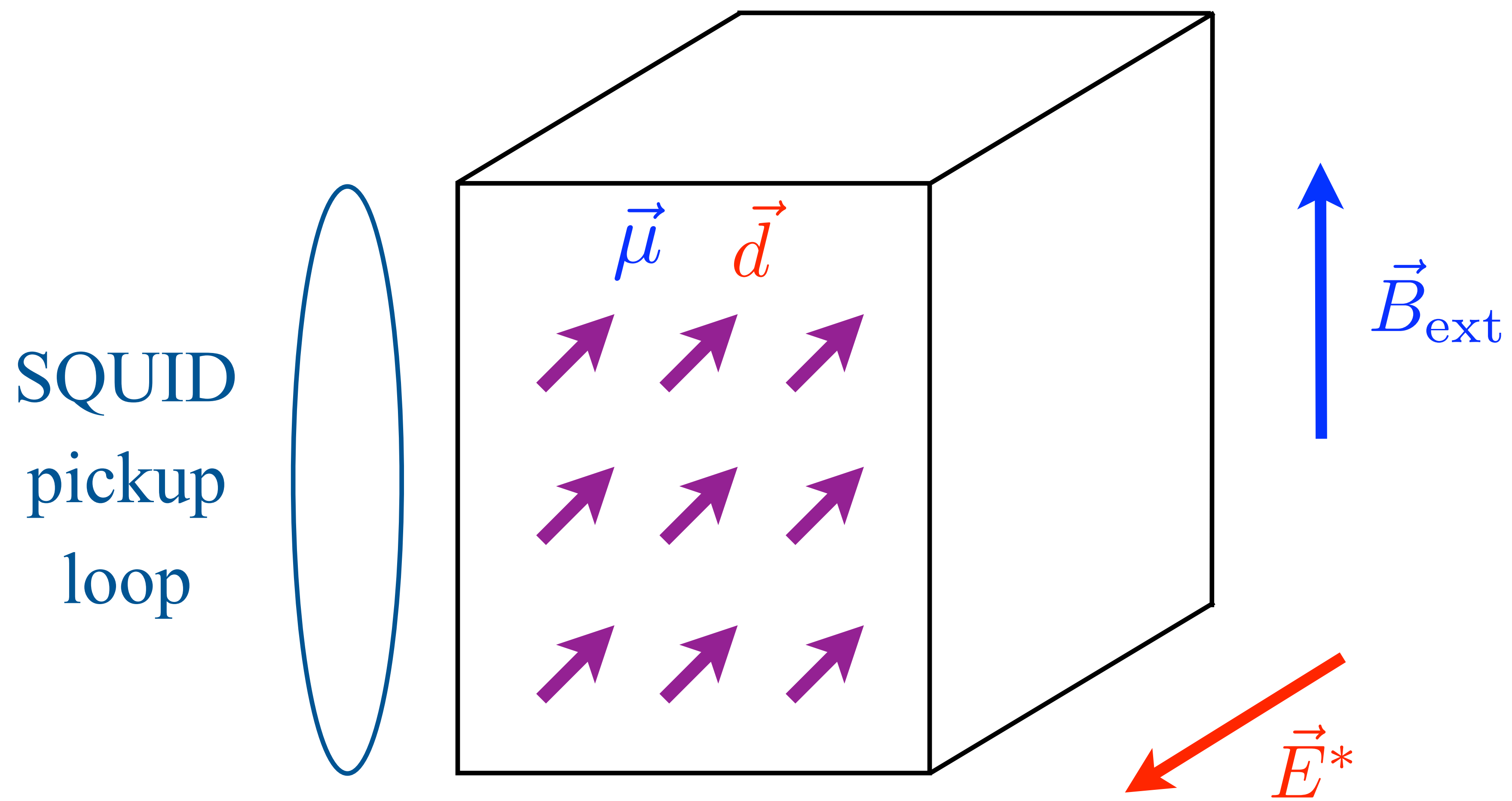
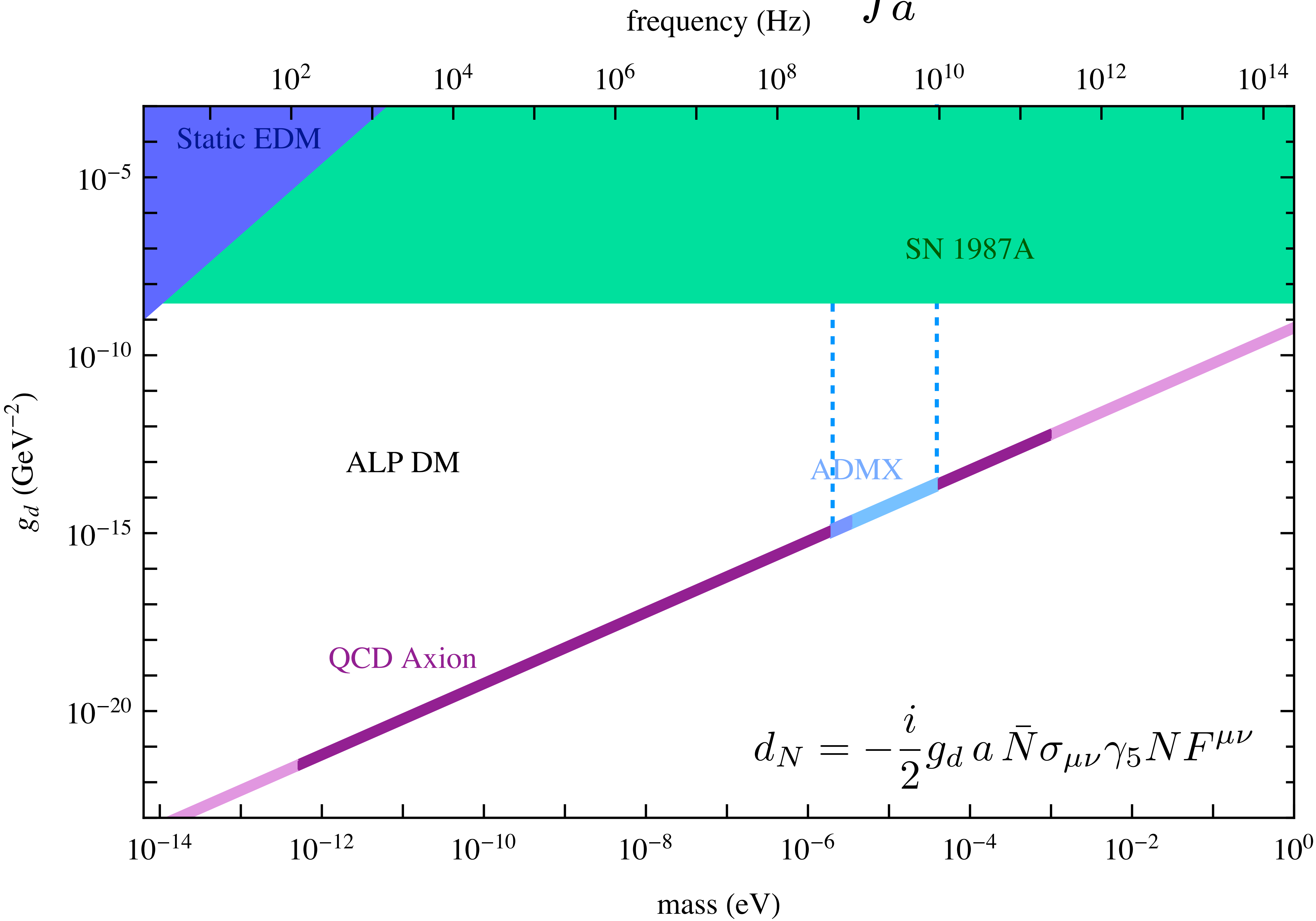



Larmor frequency = axion mass ➔ resonant enhancement

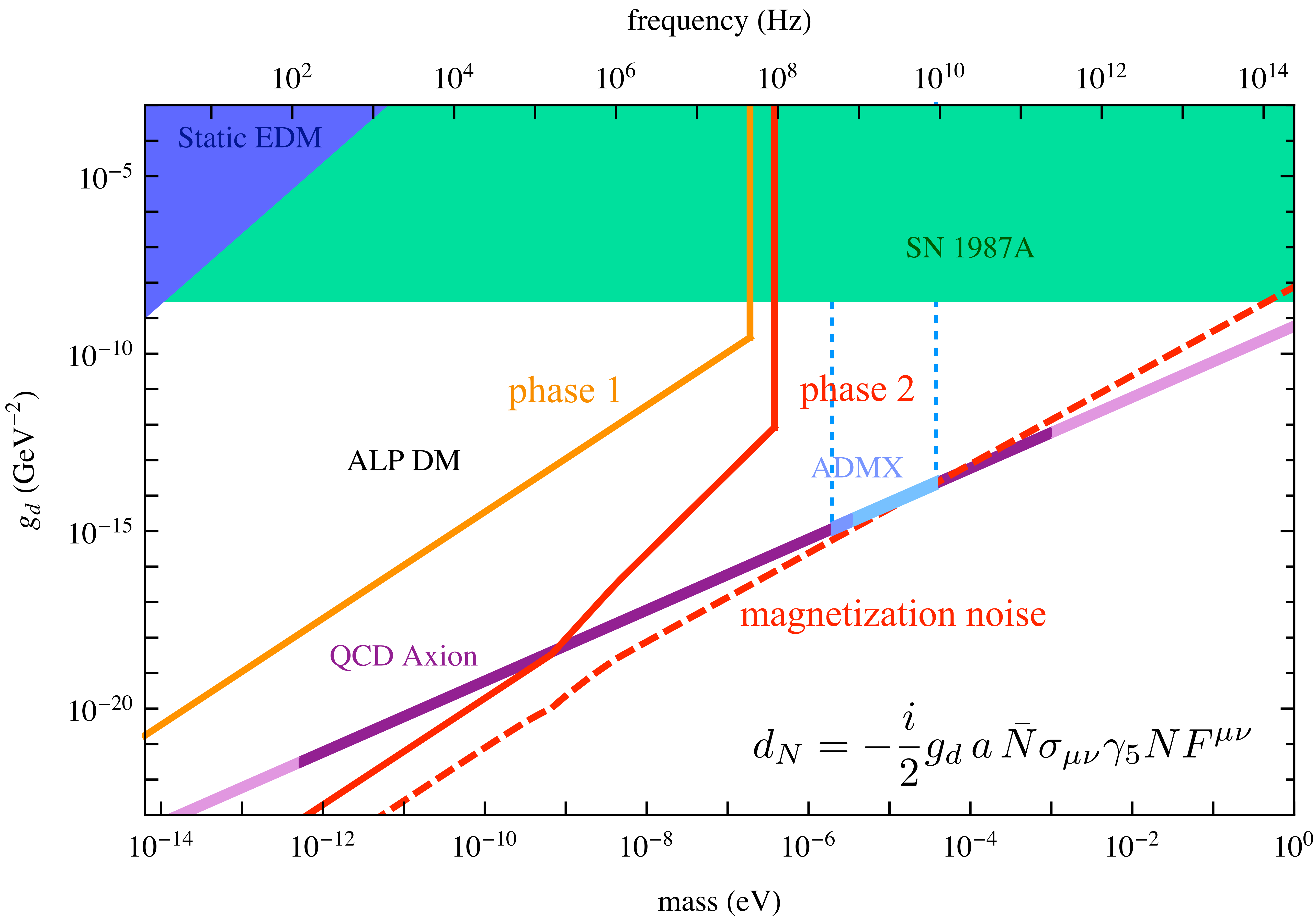
SQUID measures resulting transverse magnetization

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



# 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

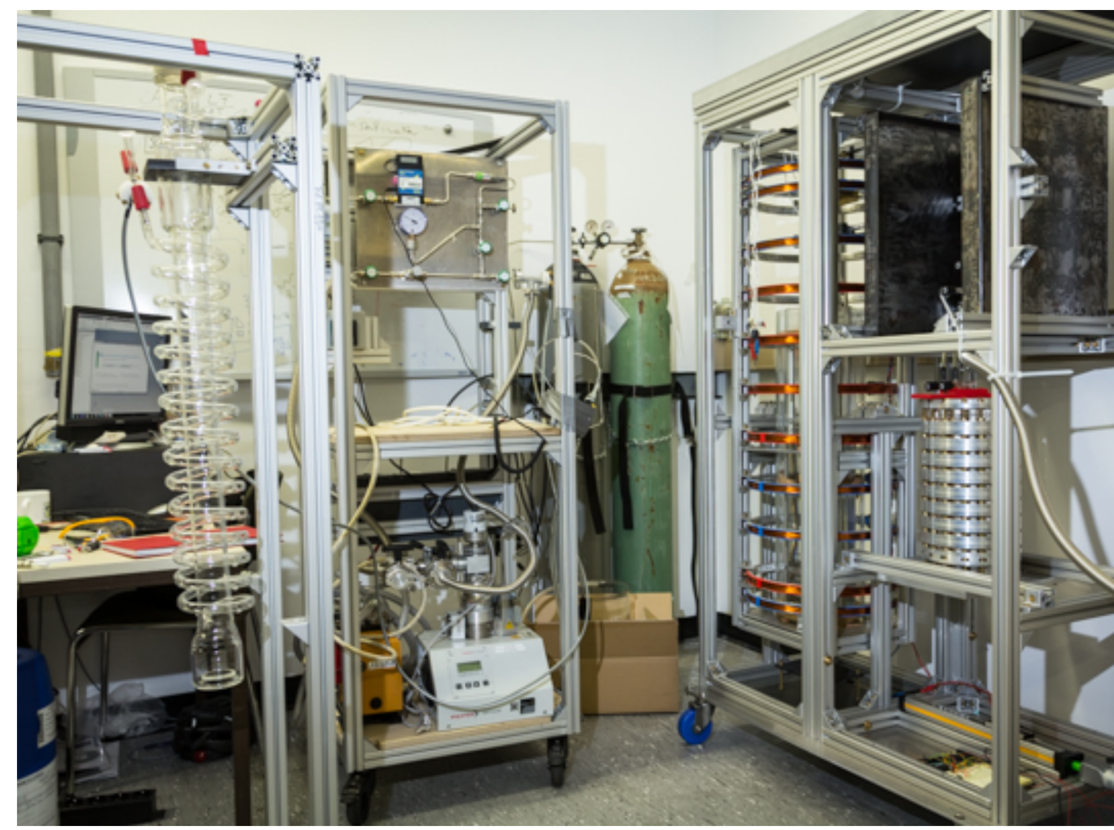
CALIFORNIA STATE UNIVERSITY EAST BAY

HELMHOLTZ GEMEINSCHAFT Helmholtz-Institut Mainz

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ


Dmitry Budker
Alexander Sushkov
Peter W. Graham
Surjeet Rajendran
Derek J. Kimball
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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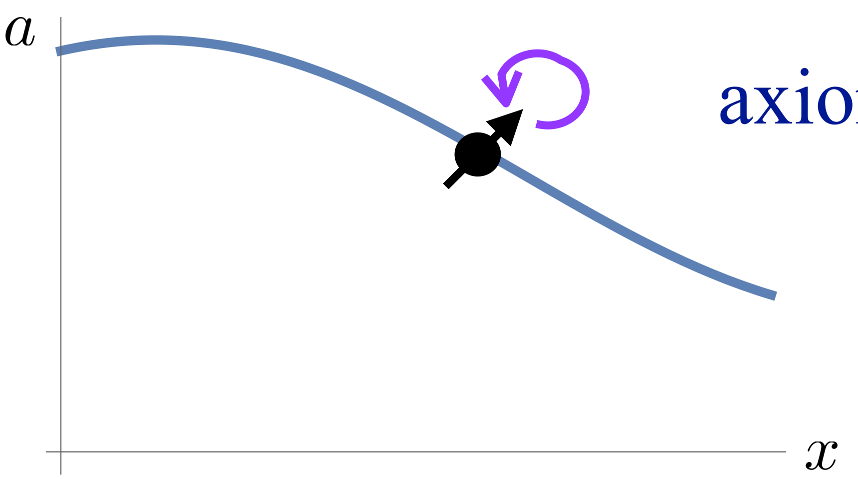
DFG Deutsche Forschungsgemeinschaft

# 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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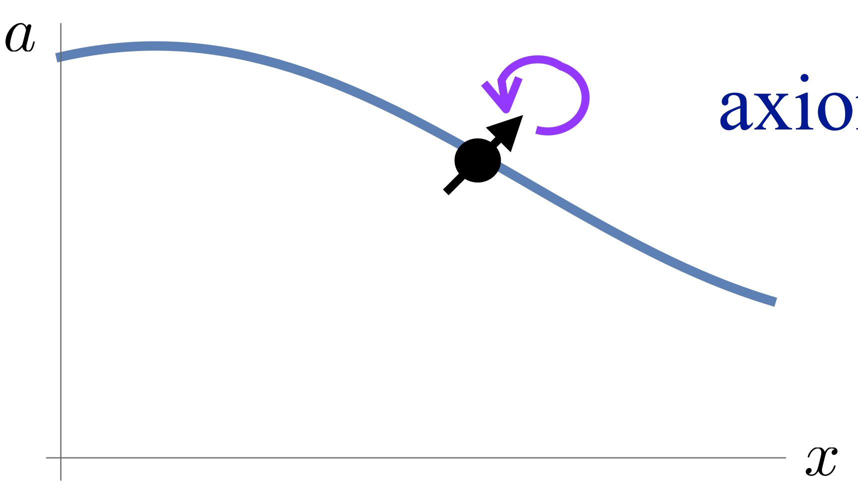


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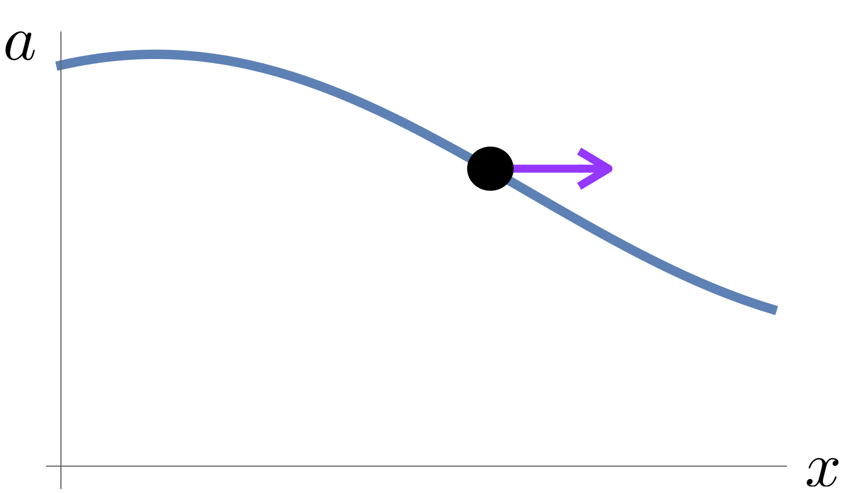
proportional to axion momentum (“wind”)

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



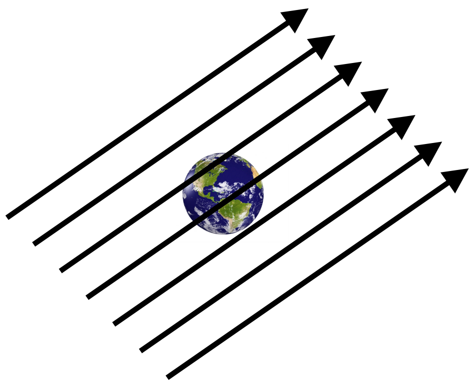

axion DM field gradient can exert a force

oscillatory and violates equivalence principle

same effects allow searches for hidden photons

# Force/Torque from Dark Matter

PRD **93** (2016) arXiv:1512.06165



New oscillatory force/torque from dark matter

New Direct Detection Experiments:

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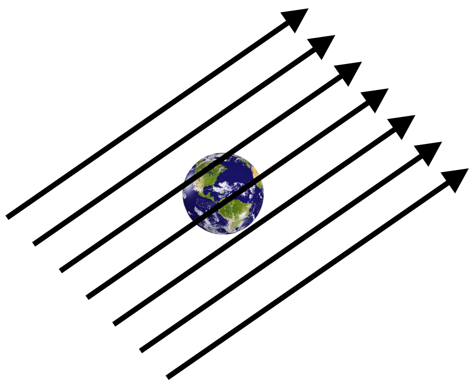

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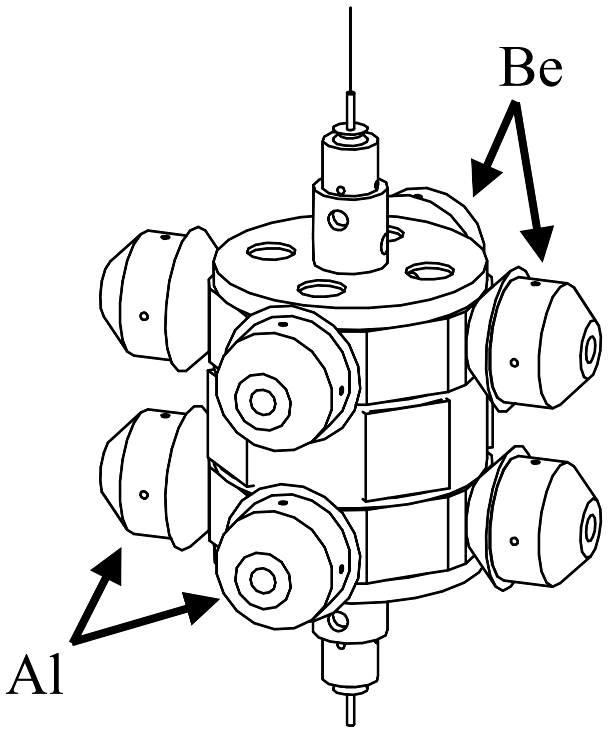
New Direct Detection Experiments:

Torsion Balances

scalar balance for force

spin-polarized for torque




Eot-Wash analysis underway

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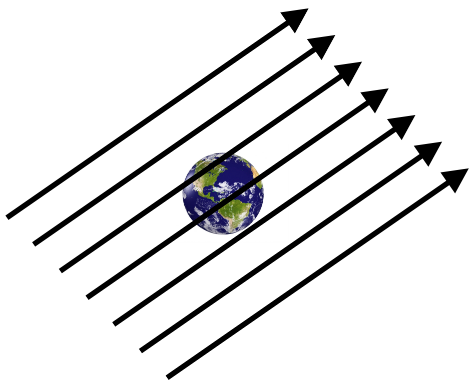

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New Direct Detection Experiments:

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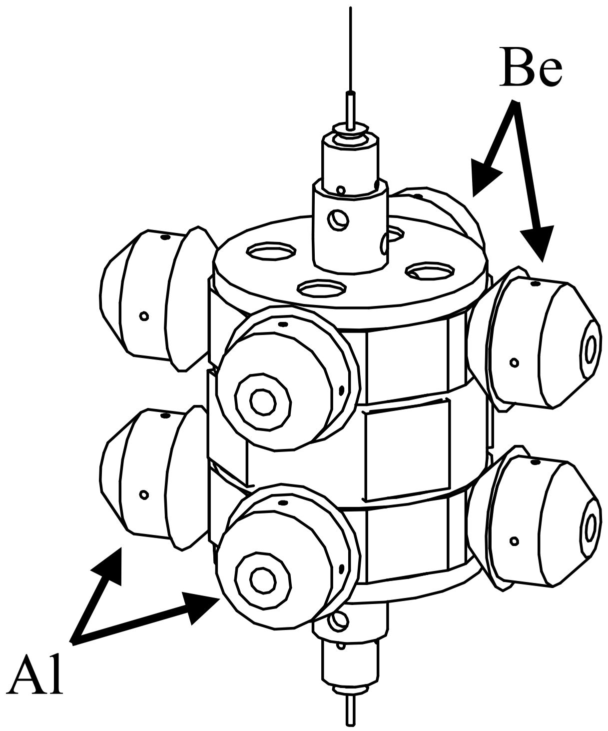
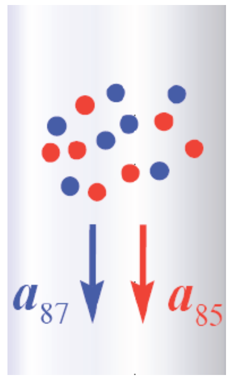
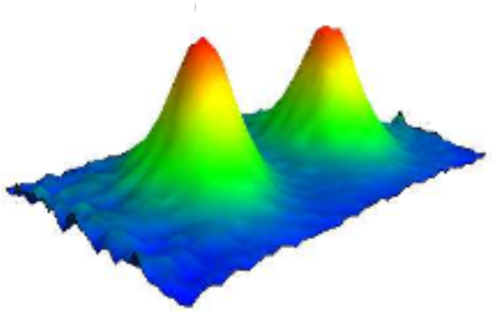
scalar balance for force
spin-polarized for torque

Atom Interferometers

split + recombine atom wavefunction
measure atom spin and acceleration



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In construction Kasevich/Hogan groups

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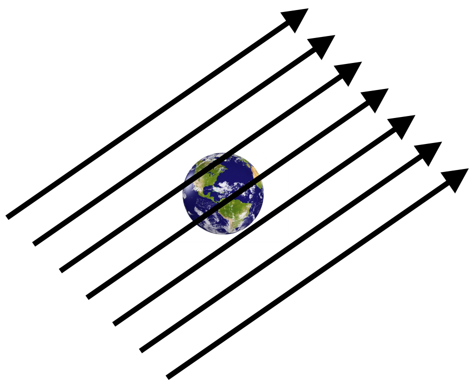
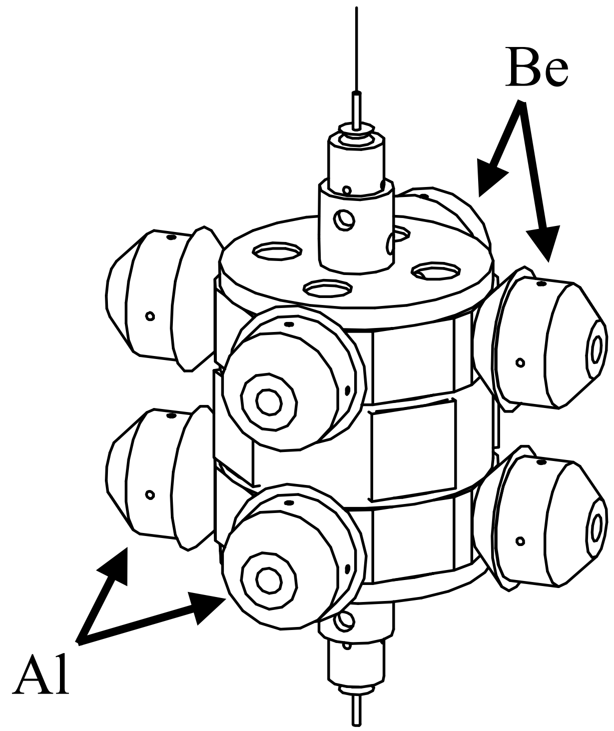
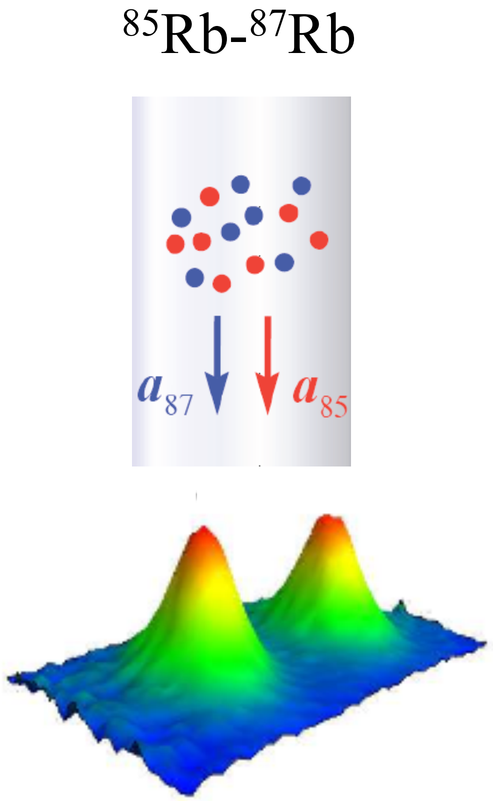
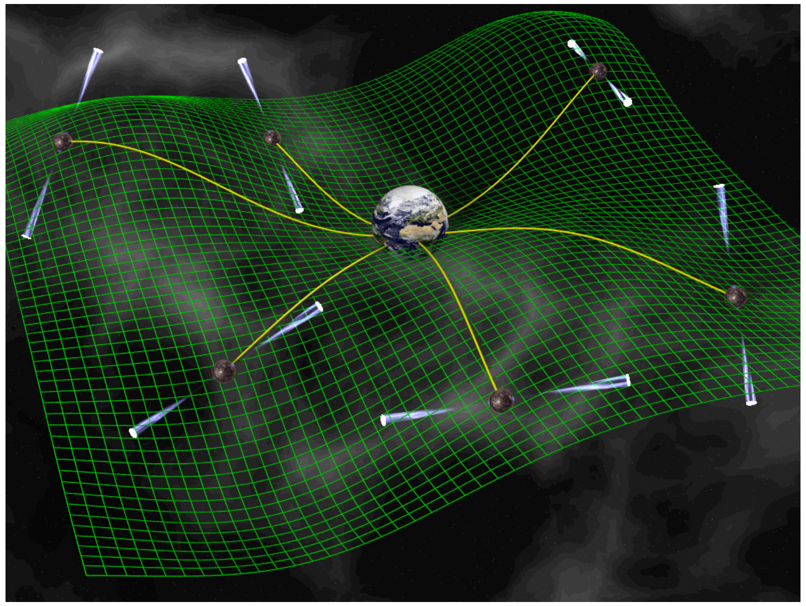


New Direct Detection Experiments:

| Torsion Balances | Atom Interferometers | Pulsar Timing Arrays |
|---|---|---|
| scalar balance for force<br>spin-polarized for torque | split + recombine atom wavefunction<br>measure atom spin and acceleration | DM and gravitational wave<br>detection similar |



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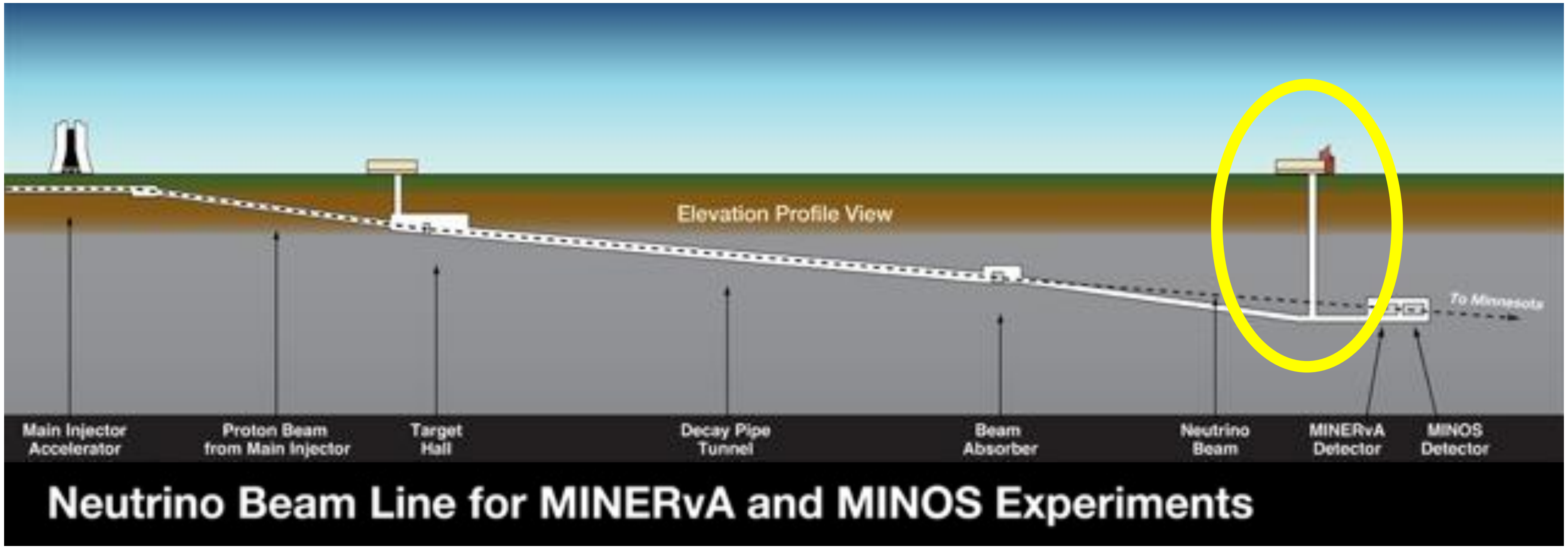
In construction Kasevich/Hogan groups

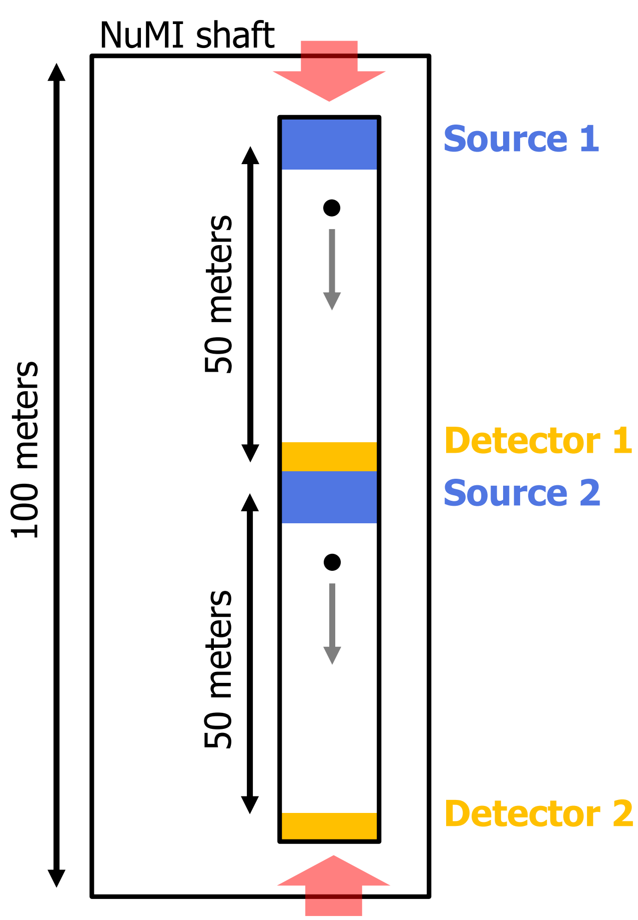
covers frequency range ~10 Hz down to yr$^{-1}$

# Gravitational Waves and Dark Matter with Atom Interferometry

W.M. KECK FOUNDATION

# 100 m Detector Proposal at Fermilab



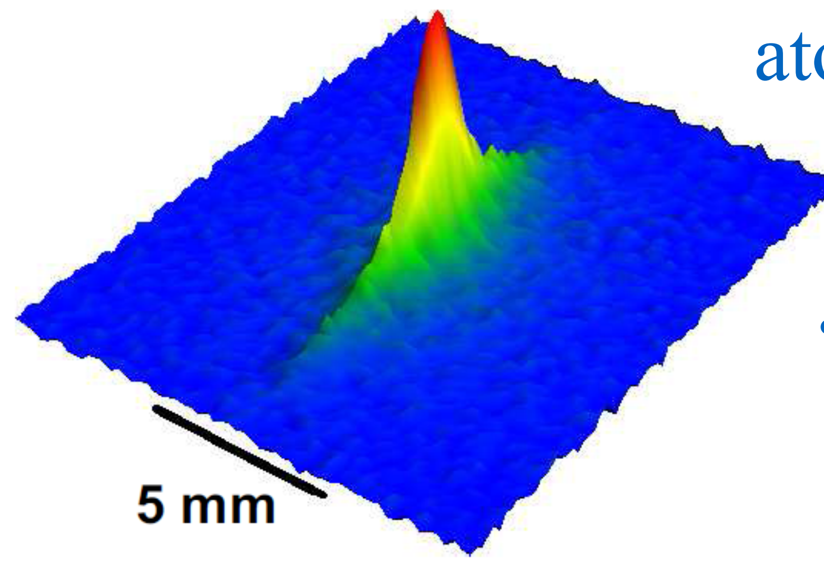

- 100 m atom interferometer (accelerometer) drop tower
- >3 s drop time to split and recombine atomic wavefunctions
- Detect dark matter through oscillatory force
- Also gravitational waves from unknown sources
- Lead to ~km scale detector for GW’s (e.g. BH mergers) and DM, opens band below LIGO and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

# Recent Experimental Results

(Kasevich and Hogan groups)

Stanford Test Facility

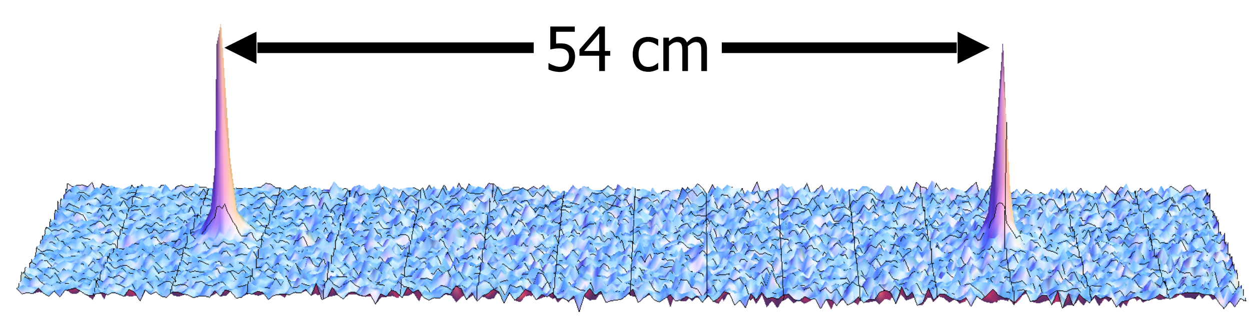
demonstrate necessary technologies:




atom cooling

➜ 50 pK

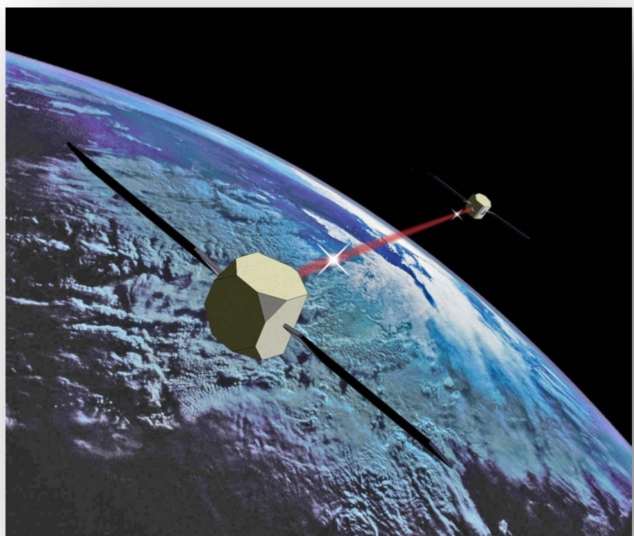
Macroscopic splitting of atomic wavefunction:



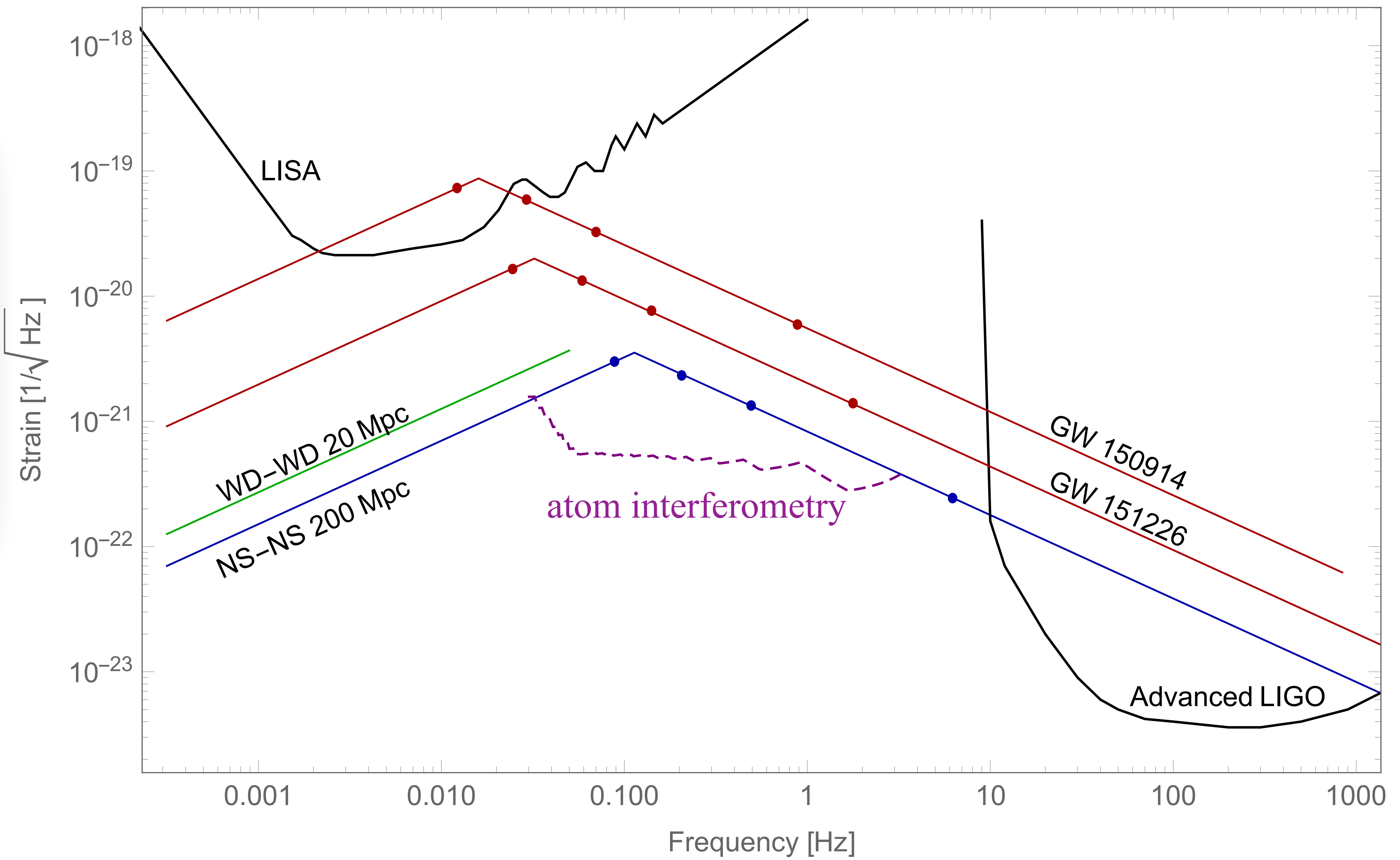

Kovachy et. al, *Nature* (2015)

# 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

# DM Radio

with

Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Surjeet Rajendran
Yue Zhao

SLAC

KIPAC

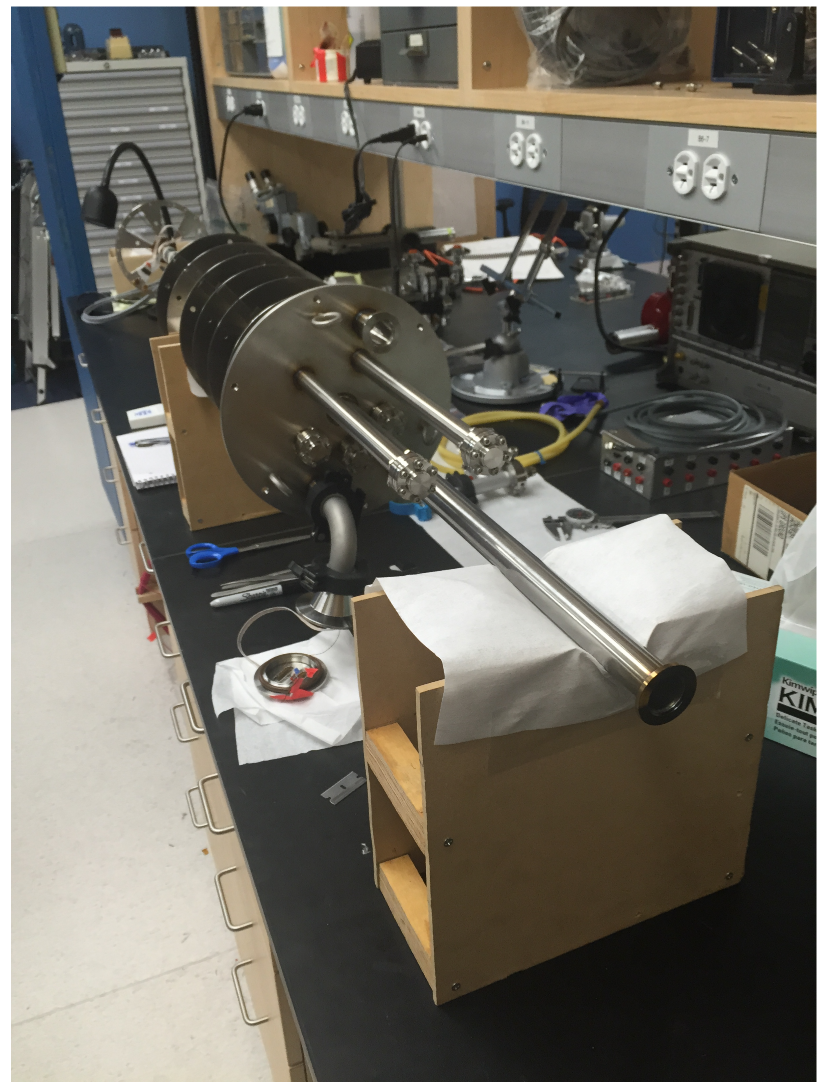
PRD **92** (2015) arXiv:1411.7382

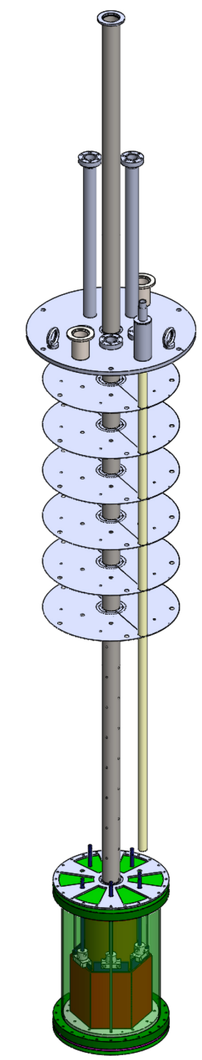
# DM Radio Experiment

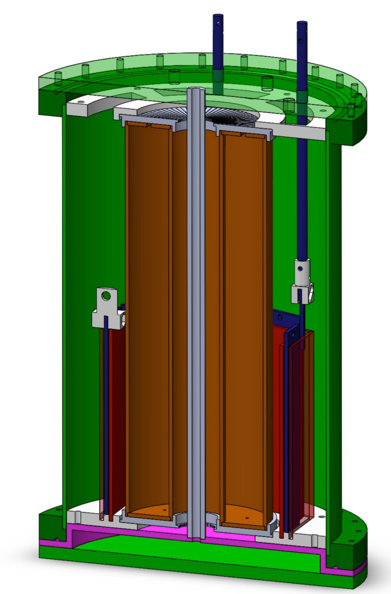
unexplored axion frequency window below ADMX and above CASPEr

Widely tunable, lumped element EM 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







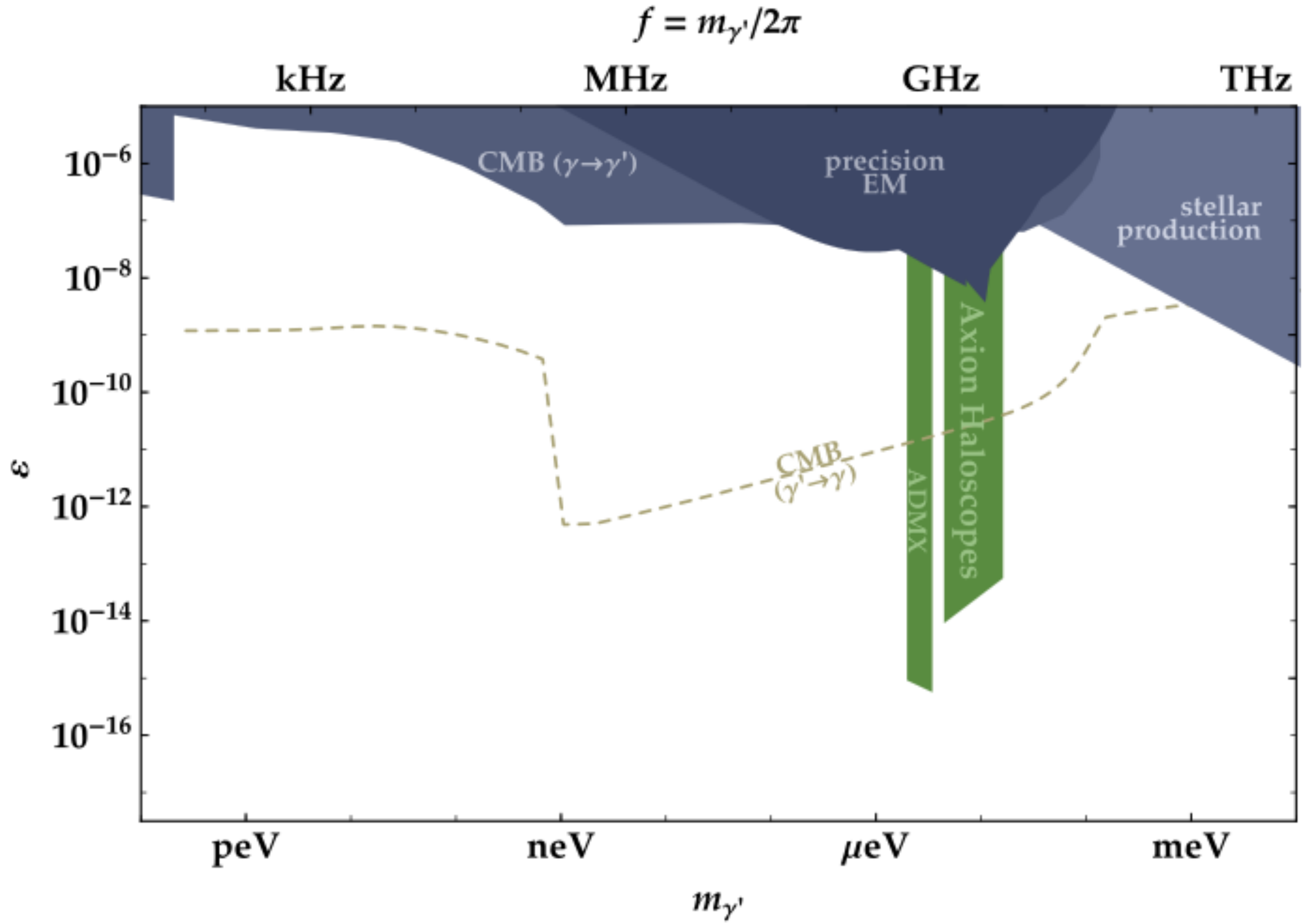
Pathfinder: 4 K  300 $cm^3$   under construction, initial results ~ summer 2017

start with hidden photon 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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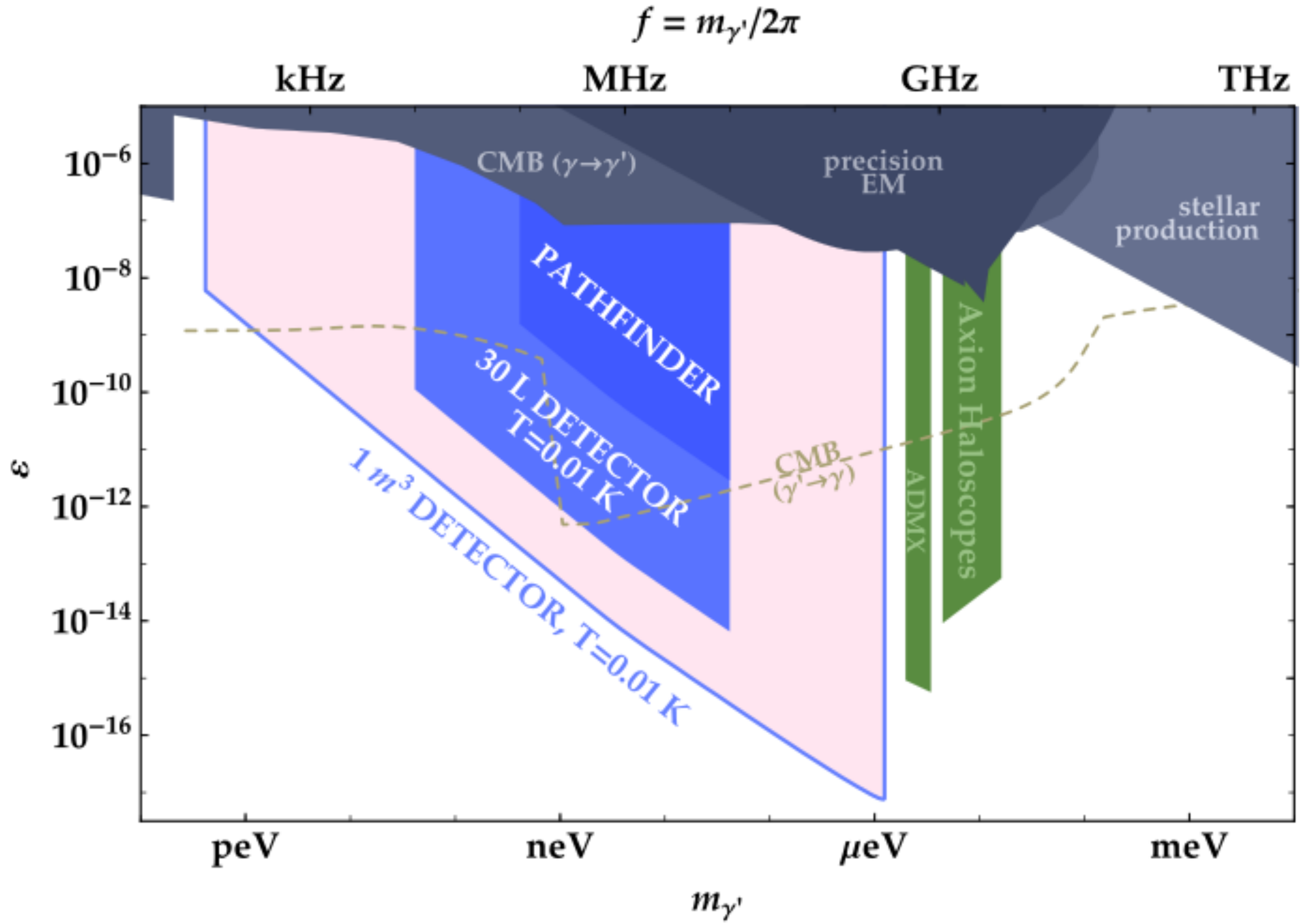


we found hidden photon DM is produced by inflation, and in this frequency range

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

# Dynamical Relaxation for the Hierarchy Problem

with

David E. Kaplan
Surjeet Rajendran

PRL **115** (2015) arXiv:1504.07551

# The Relaxion

All previous solutions (SUSY, extra dimensions…) rely on new physics at weak scale

- tension with LHC results

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new class of solutions: dynamics in early universe    PRL **115** (2015) arXiv:1504.07551

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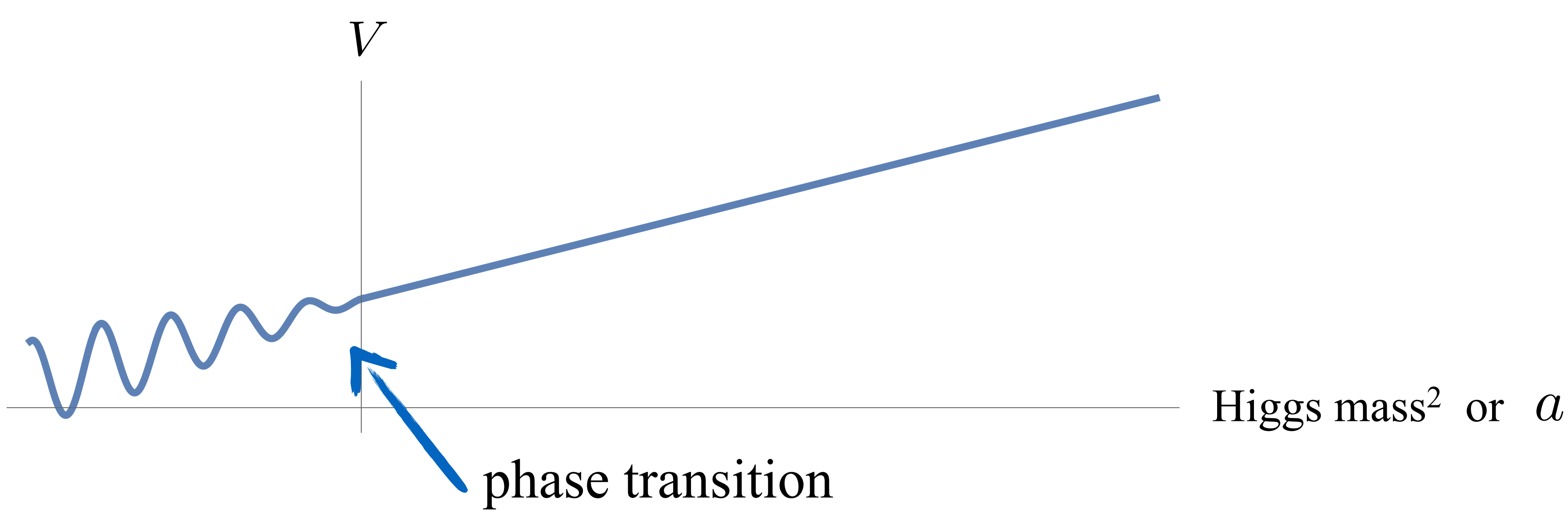
minimal model: SM + QCD axion with softly-broken shift symmetry + inflaton




freezes Higgs mass near critical point in early universe "self-organized criticality"

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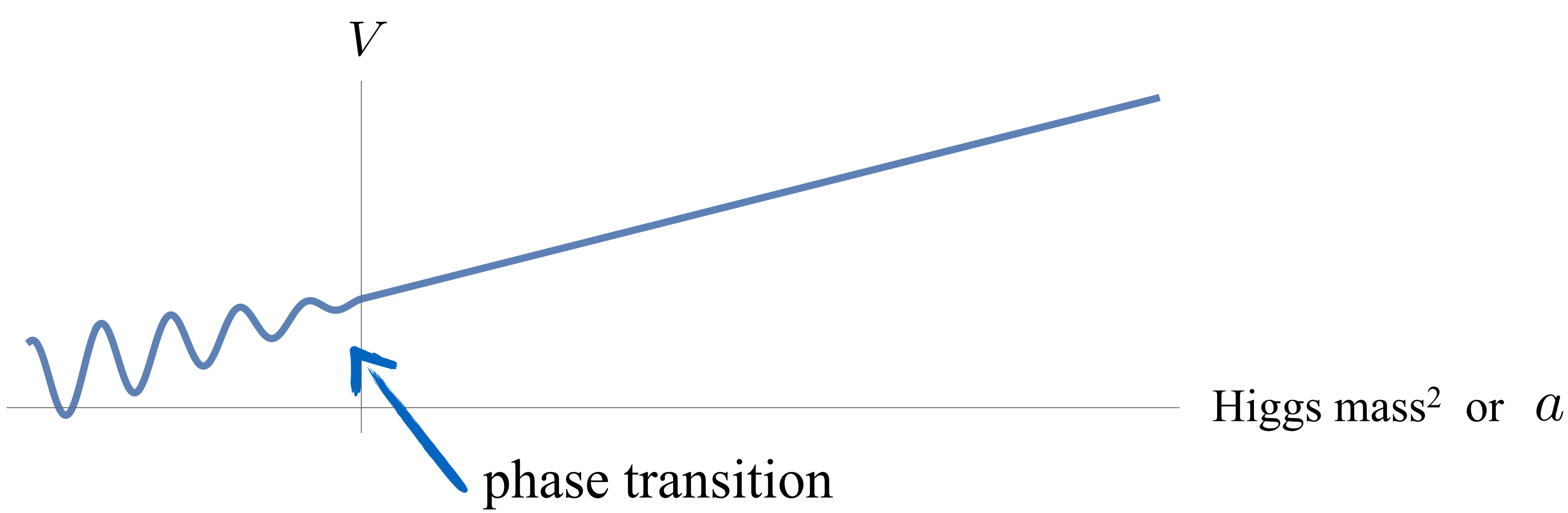


freezes Higgs mass near critical point in early universe "self-organized criticality"

SUSY, extra dimensions… ➜ weak-scale particles (e.g. WIMP)

dynamical relaxation ➜ light particles (e.g. axion)

# Summary

Precision measurement is a powerful tool for particle physics and cosmology

new technologies beyond traditional particle detectors

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

detect coherent effects of entire field, not single particles

1. Cosmic Axion Spin Precession Experiment (CASPEr) - in construction at BU and Mainz
2. Atom Interferometry for DM and gravitational wave detection - demonstrator at Stanford
3. DM Radio - in construction at SLAC/Stanford
4. Torsion balances, atomic magnetometers - analyses happening now

Many more possibilities…