New Experimental Searches for Dark Matter

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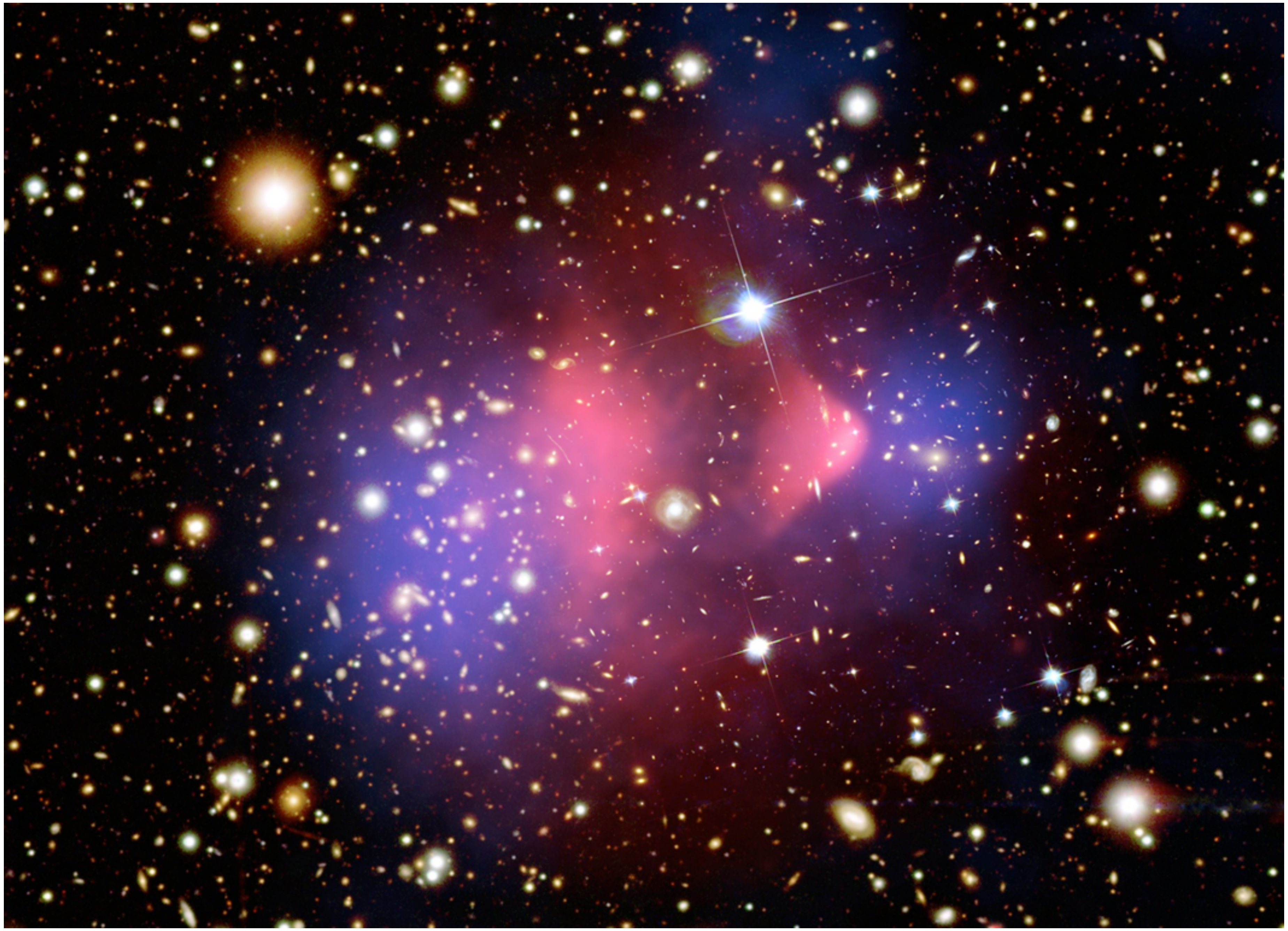
The Johns Hopkins University

Dark Matter



A New Particle

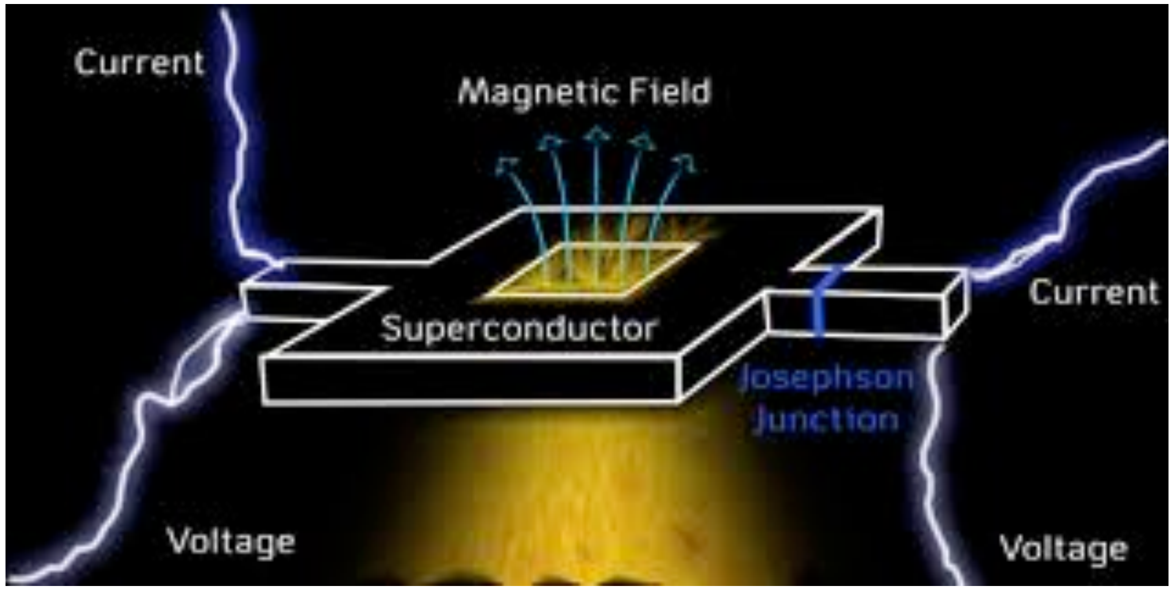
Non gravitational interactions?

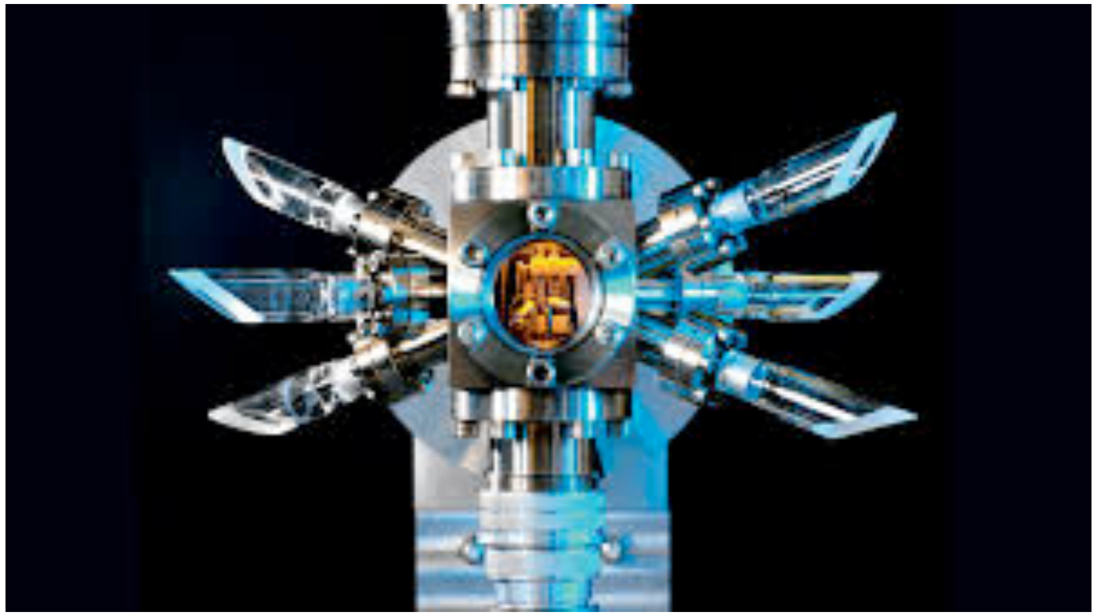
How do we detect them?

Weak effects. Need high precision

Precision Instruments

Impressive developments in the past two decades





Magnetic Field $\lesssim 10^{-16} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$

(SQUIDs, atomic magnetometers)

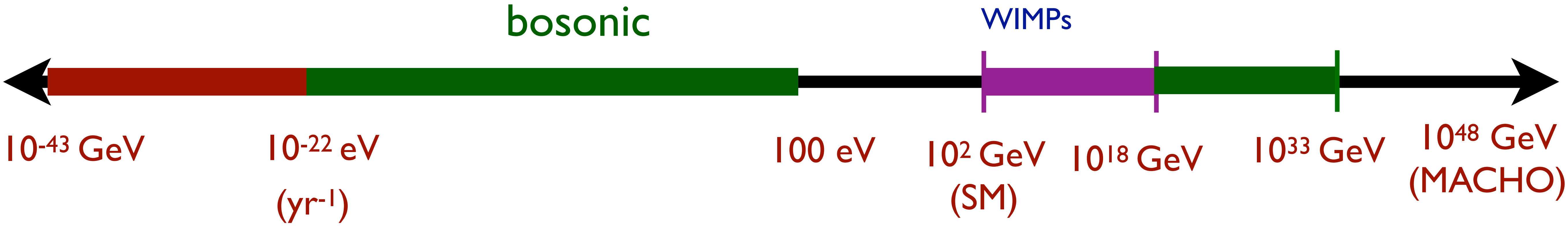
Accelerometers $\lesssim 10^{-13} \frac{\mathrm{g}}{\sqrt{\mathrm{Hz}}}$

(atom and optical interferometers)

Rapid technological advancements

Use to detect new physics?

The Dark Matter Landscape



Fit in galaxy

Standard Model scale ~ 100 GeV

One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)
Soon to hit solar neutrino floor

Axions, Massive Vector Bosons, Dark Blobs?

WIMP Experiments: Sensitive up to 10^{18} GeV

Terrestrial: up to 10^{33} GeV

How do we make progress?

Outline

1. Ultra-light Dark Matter (10^{-22} eV - 10^{-5} eV)

2. Directional Detection of Dark Matter

3. Magnetic Bubble Chambers

4. Conclusions

Bosonic Dark Matter

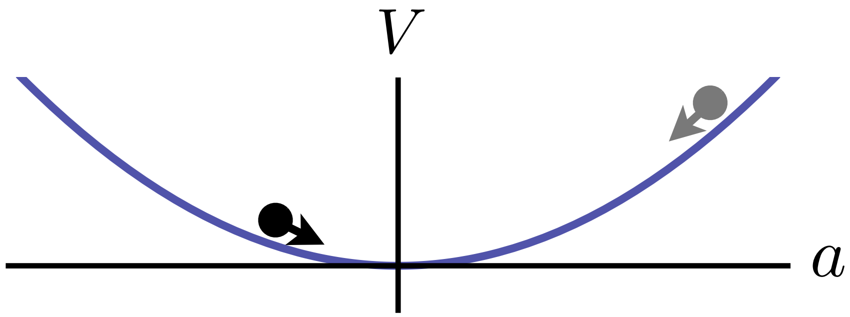
Photons

$$\vec{E} = E_0 \cos\left(\omega t - \omega x\right)$$

Detect Photon by measuring time varying field

Dark Bosons

Early Universe: Misalignment Mechanism

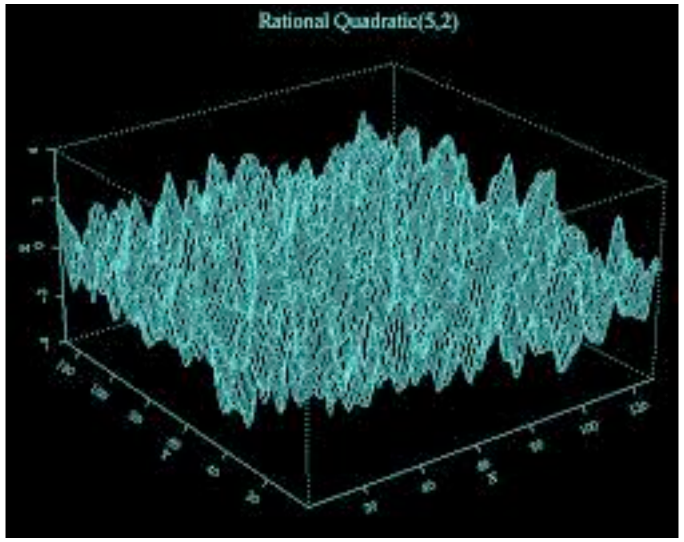


$$a(t) \sim a_0 \cos\left(m_a t\right)$$

Spatially uniform, oscillating field

$$m_a^2 a_0^2 \sim \rho_{DM}$$

Today: Random Field



Correlation length
$\sim 1/(m_a v)$

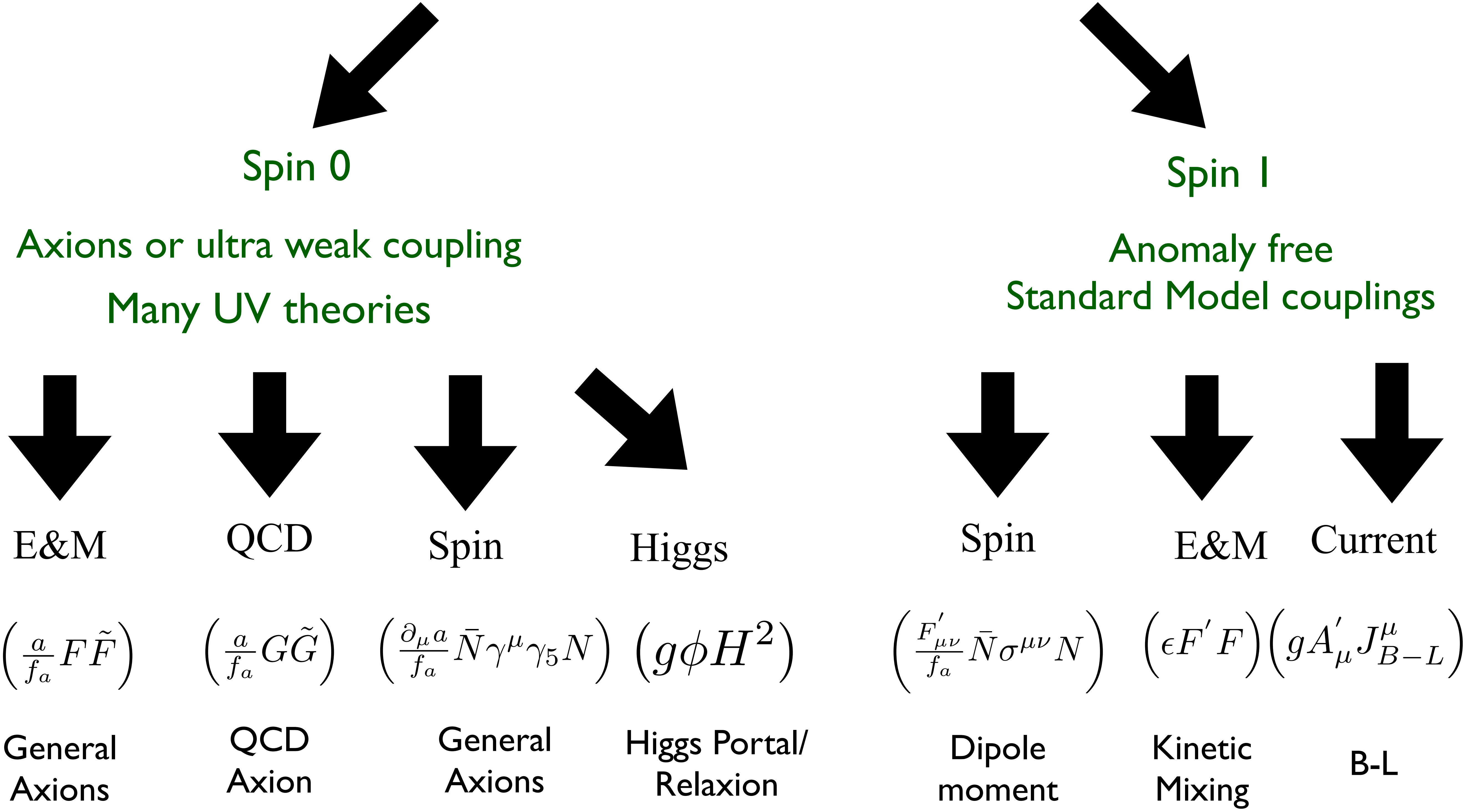
Coherence Time
$\sim 1/(m_a v^2)$
$\sim$ 1 s (MHz/m_a)

Detect effects of oscillating dark matter field

Resonance possible. Q ~ 10^6 (set by v ~ 10^{-3})

What kind of Bosons?

Naturalness. Structure set by symmetries.



Spin 0

Axions or ultra weak coupling

Many UV theories

Spin 1

Anomaly free

Standard Model couplings

E&M

$\left(\frac{a}{f_a} F \tilde{F}\right)$

General Axions

QCD

$\left(\frac{a}{f_a} G \tilde{G}\right)$

QCD Axion

Spin

$\left(\frac{\partial_\mu a}{f_a} \bar{N} \gamma^\mu \gamma_5 N\right)$

General Axions

Higgs

$\left(g \phi H^2\right)$

Higgs Portal/ Relaxion

Spin

$\left(\frac{F^{'}_{\mu\nu}}{f_a} \bar{N} \sigma^{\mu\nu} N\right)$

Dipole moment

E&M

$\left(\epsilon F^{'} F\right)$

Kinetic Mixing

Current

$\left(g A^{'}_\mu J^\mu_{B-L}\right)$

B-L

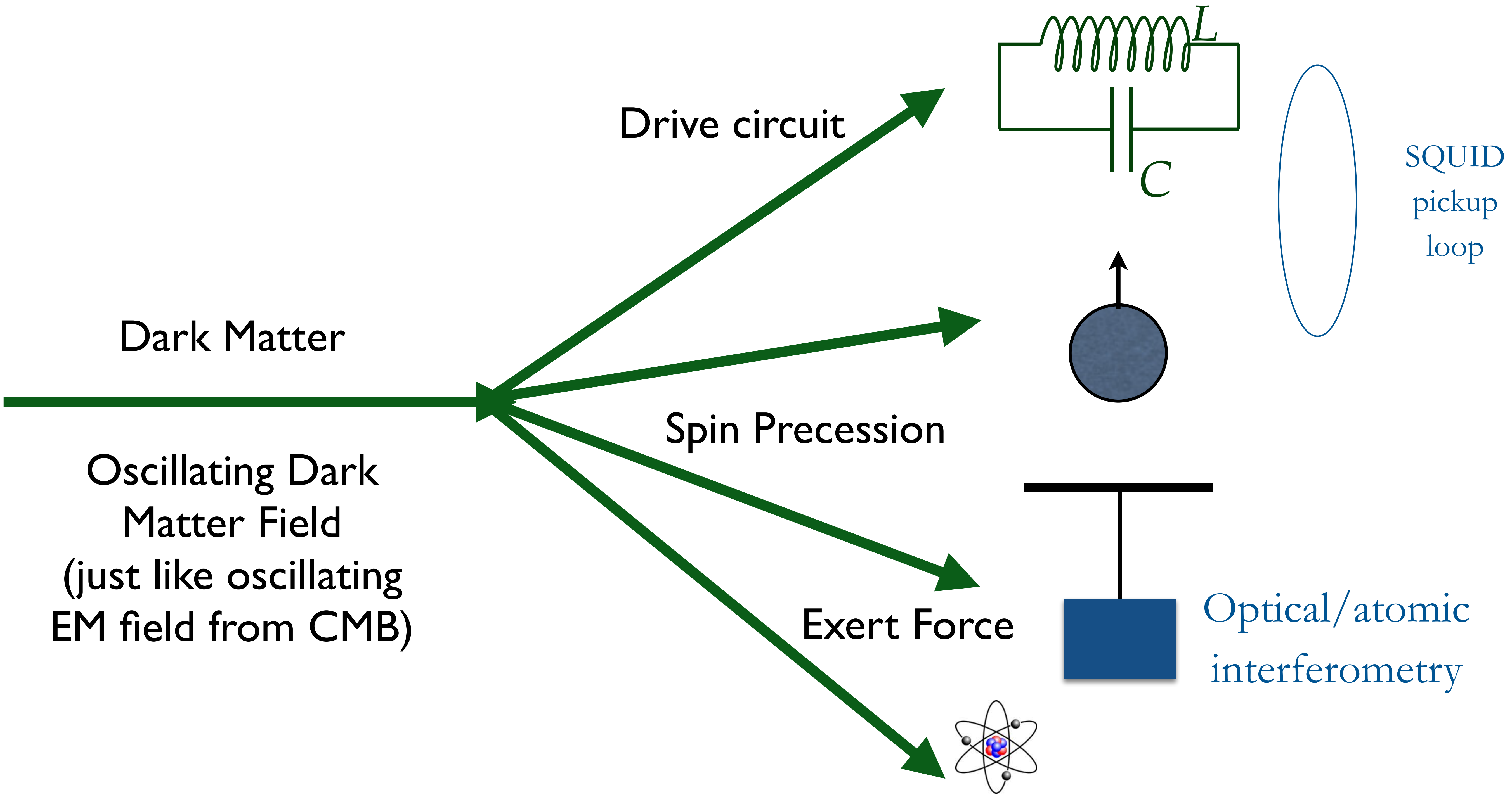
$$\text{Dark Matter} \quad \Longrightarrow \quad a = a_0 \cos\left(m_a t\right)$$

a/c signal between 10^{-7} Hz - 10 GHz

Observable Effects

What can the dark matter wind do?

What can a classical field do?



Drive circuit

Dark Matter

Spin Precession

Oscillating Dark Matter Field (just like oscillating EM field from CMB)

Exert Force

Change Fundamental Constants

a/c effect, narrow bandwidth around dark matter mass

Cosmic Axion Spin Precession Experiment (CASPEr)

with

Dmitry Budker
Peter Graham
Micah Ledbetter
Alex Sushkov

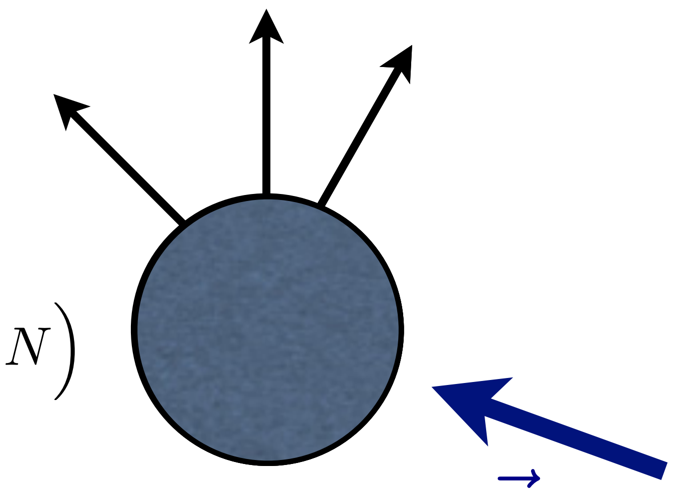
PRX **4** (2014) arXiv: 1306.6089
PRD **88** (2013) arXiv: 1306.6088
PRD **84** (2011) arXiv: 1101.2691

CASPEr: Axion Effects on Spin

General Axions

Neutron in
Neutron
Axion Wind

$\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$



$\vec{v}$

$$H_N \supset \frac{a}{f_a}\vec{v_a}.\vec{S}_N$$

Spin rotates about
dark matter velocity

Effective time varying
magnetic field

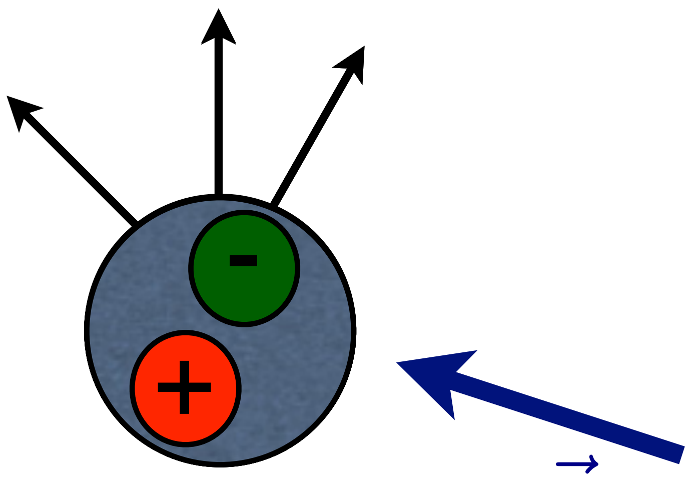
$$B_{eff} \lessapprox 10^{-16}\,\cos\left(m_a t\right)\;\mathrm{T}$$

Other light dark matter (e.g. dark photons) also
induce similar spin precession

Measure Spin
Rotation,
detect Axion

QCD Axion

Neutron in
Neutron
QCD Axion Dark Matter



$\vec{E}$

$\left(\frac{a}{f_a}G\tilde{G}\right)$

QCD axion induces electric dipole moment
for neutron and proton

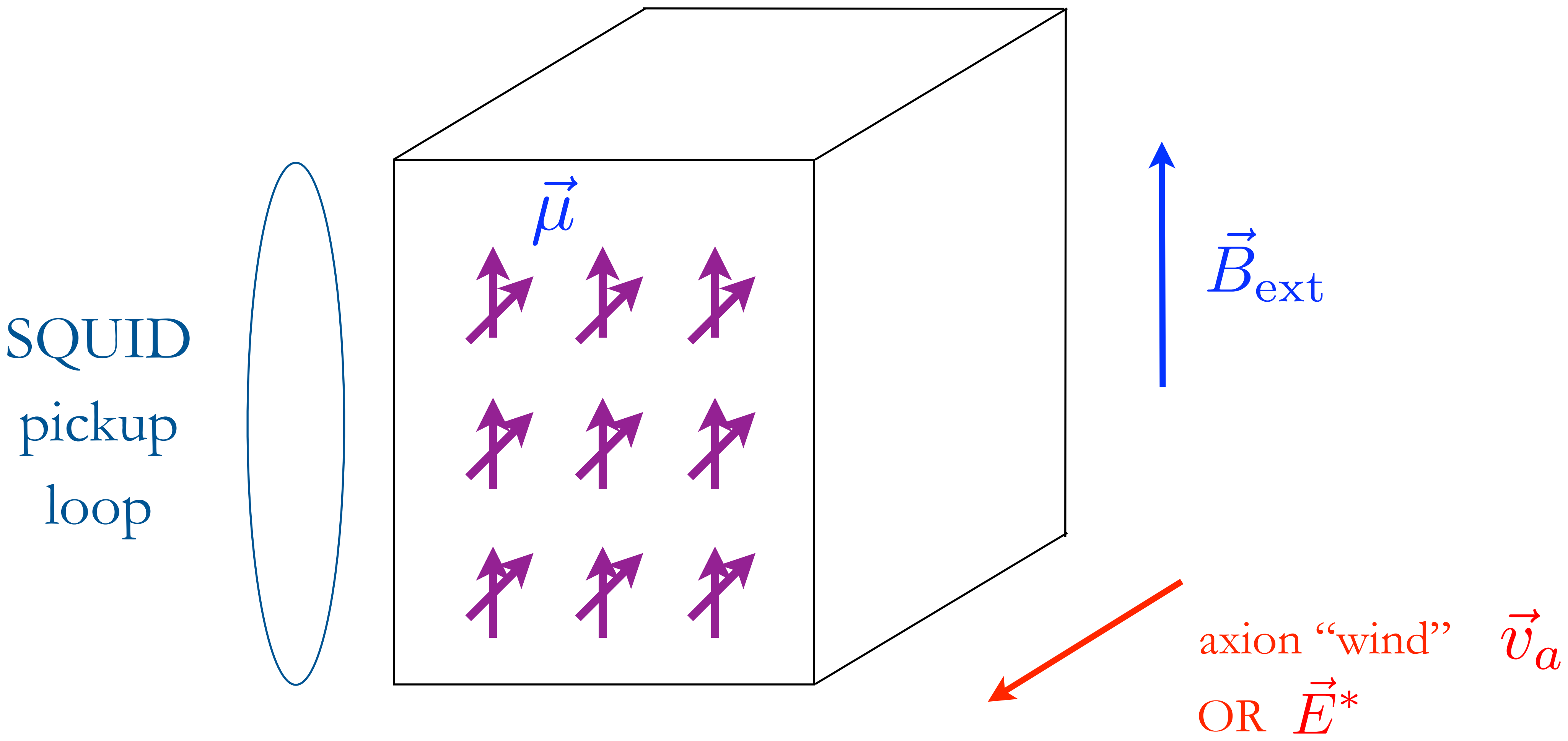
Dipole moment
along nuclear spin

Oscillating dipole: $d \sim 3\times10^{-34}\,\cos\left(m_a t\right)\,e\,\mathrm{cm}$

Apply electric field, spin rotates

CASPEr

Axion affects physics of nucleus, NMR is sensitive probe



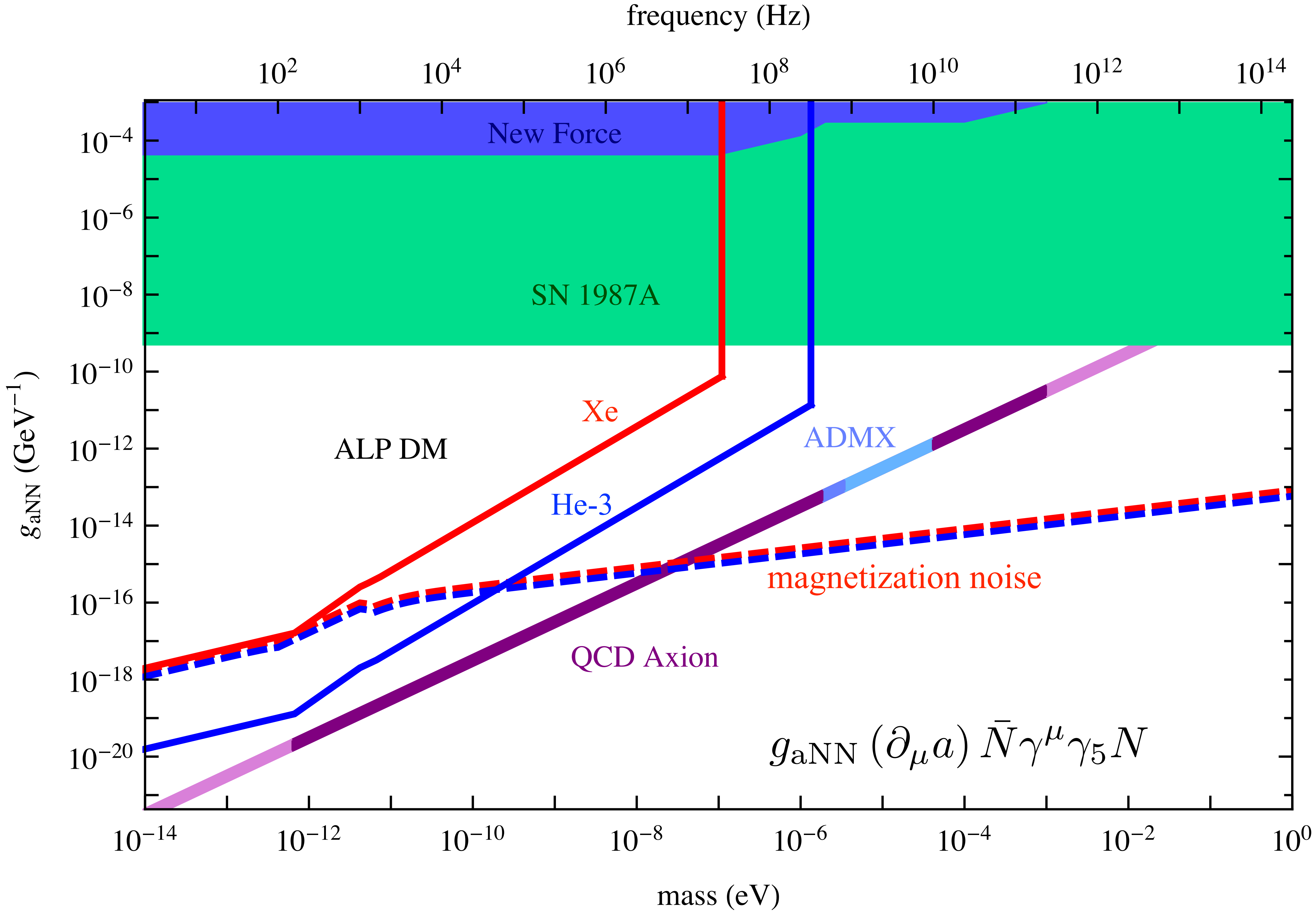
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

NMR well established technology, noise understood, similar setup to previous experiments

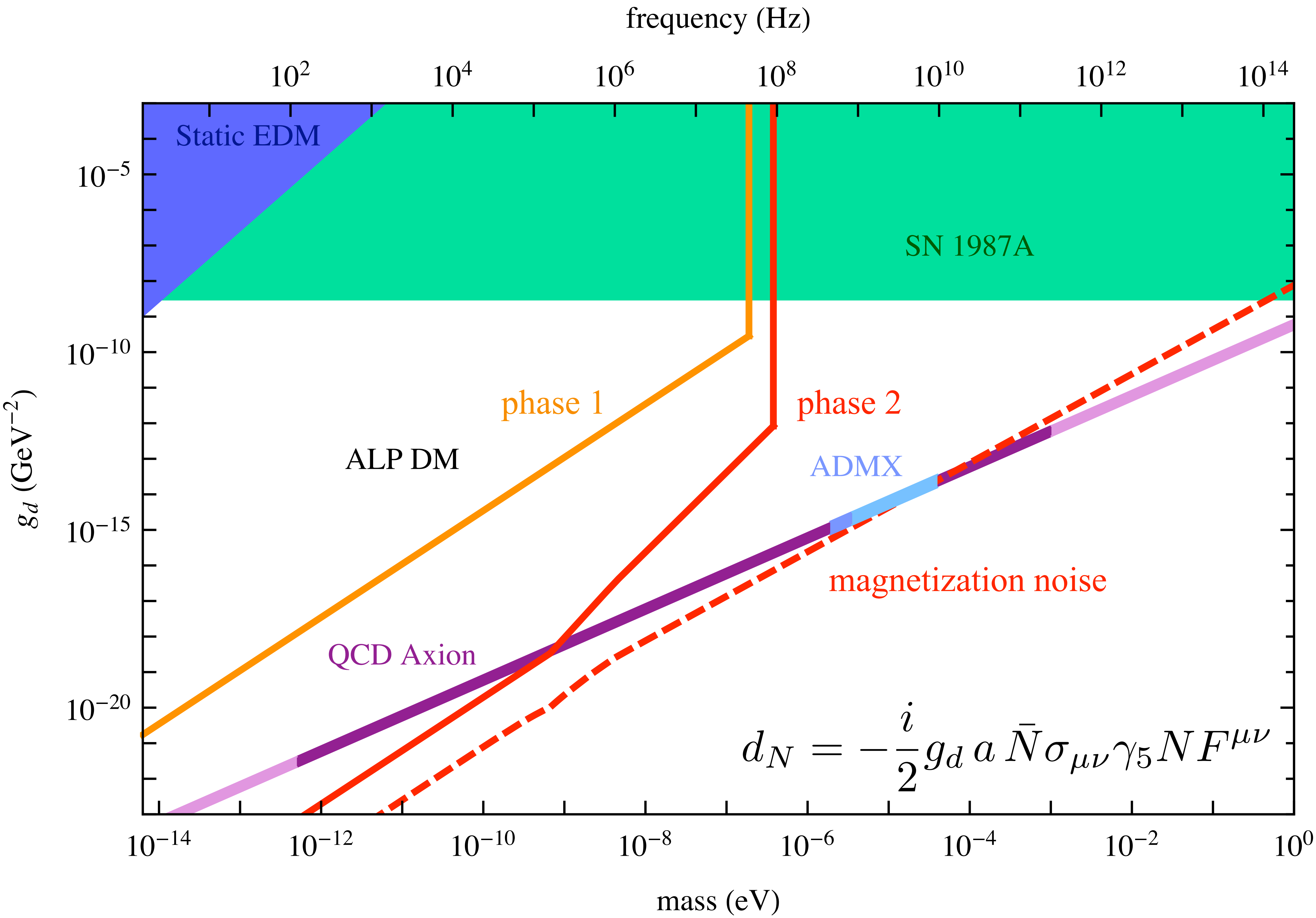
Example materials: LXe, ferroelectric $PbTiO_3$, many others

CASPEr-General Axions



~ year to scan one decade of frequency

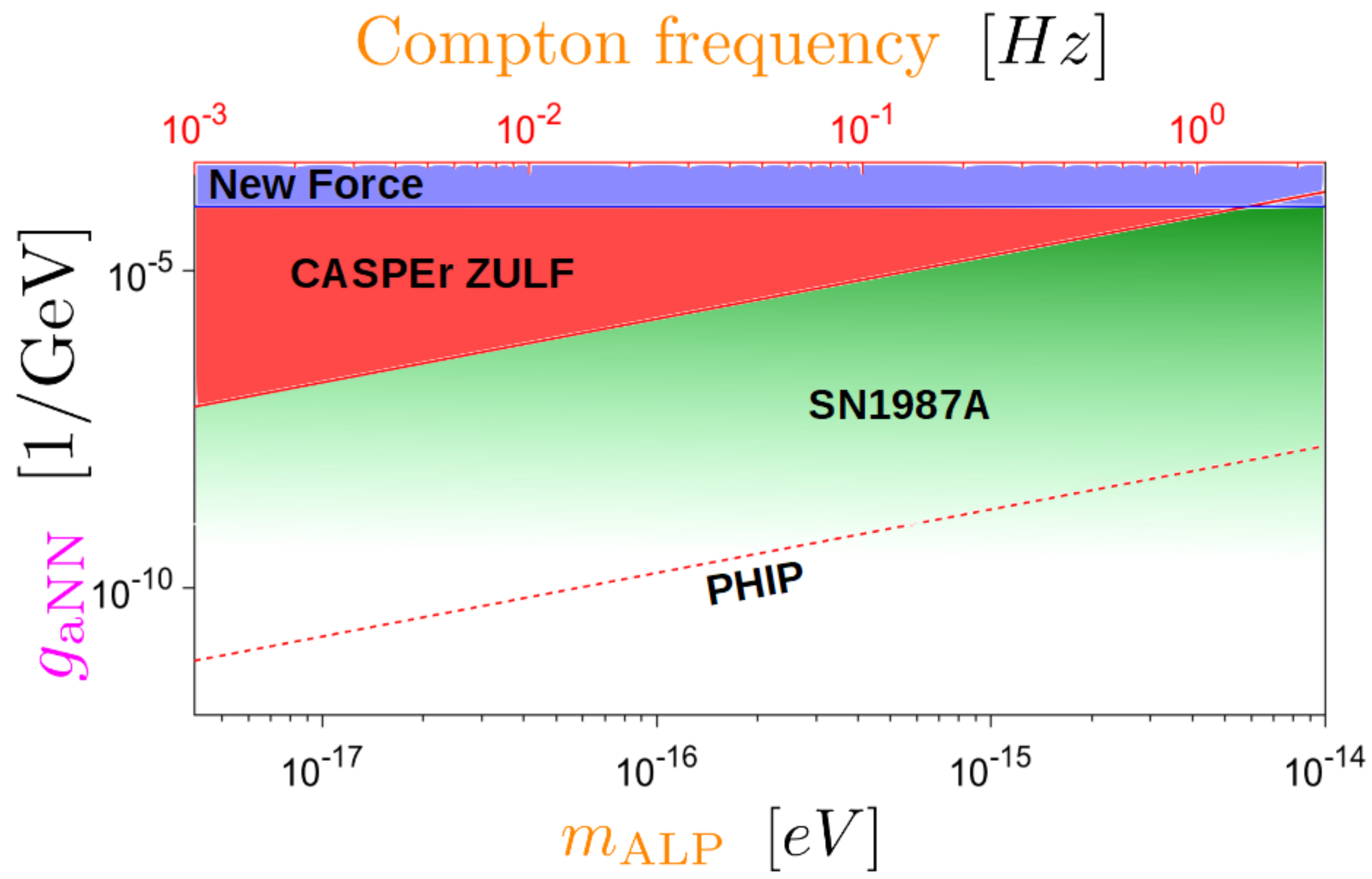
CASPEr-QCD Axion



Verify signal with spatial coherence of axion field

CASPEr-ZULF Results

$$\vec{B}_{\mathrm{ALP}} \propto g_{\mathrm{aNN}} \cos(m_{\mathrm{ALP}} t)\vec{v}$$



10^{-4} nuclear polarization, 24 hr integration time

Dark Photon Detection with a Radio

with

Peter Graham
Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Yue Zhao

arXiv: 1411.7382

Dark Photon Dark Matter

Many theories/vacua have additional, decoupled sectors, new U(1)'s

Natural coupling (dim. 4 operator): $\mathcal{L} \supset \varepsilon F F'$

mass basis:

$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - eJ^\mu_{EM}\left(A_\mu + \varepsilon\, A'_\mu\right)$$

photon with small mass and suppressed couplings to all charged particles

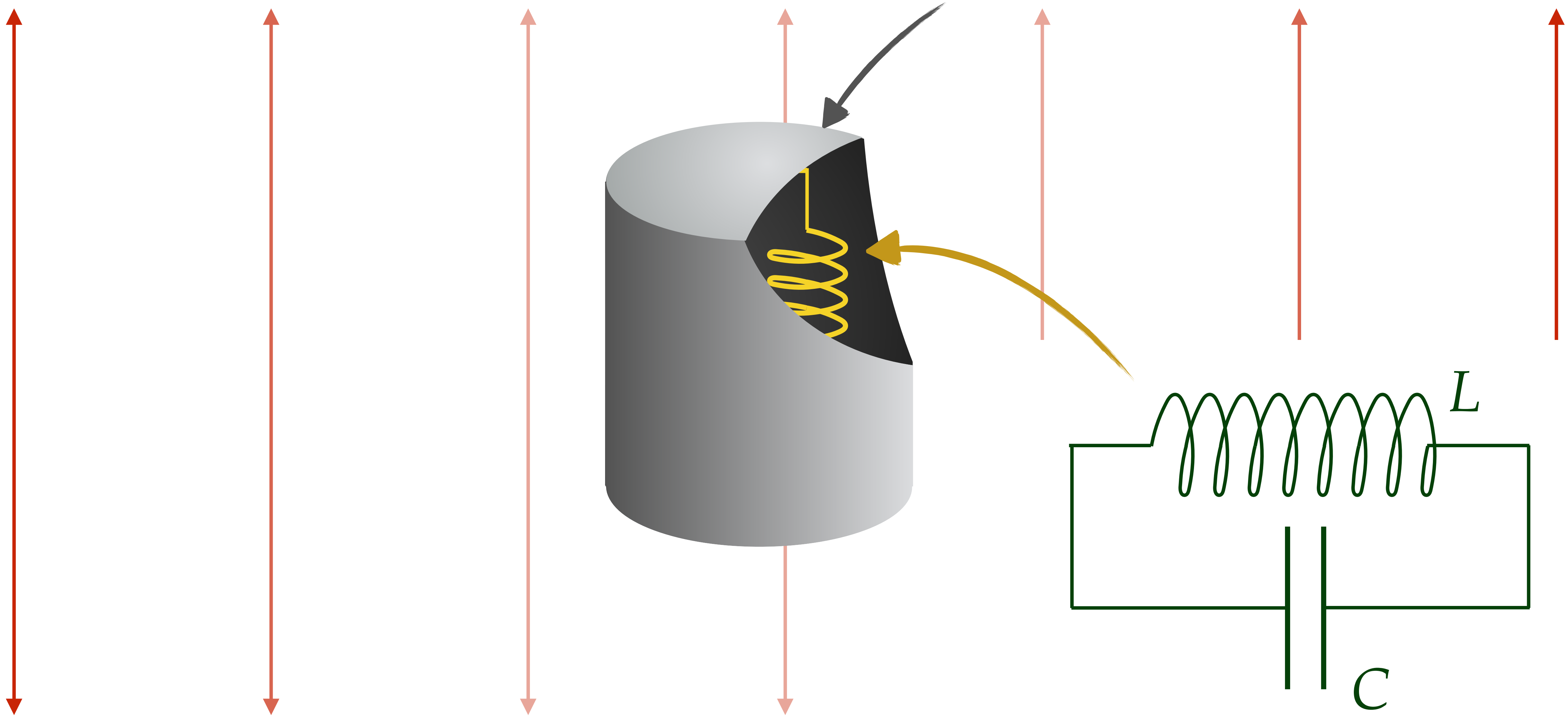
oscillating E' field
(dark matter)

can drive current
behind EM shield

Dark Matter Radio Station

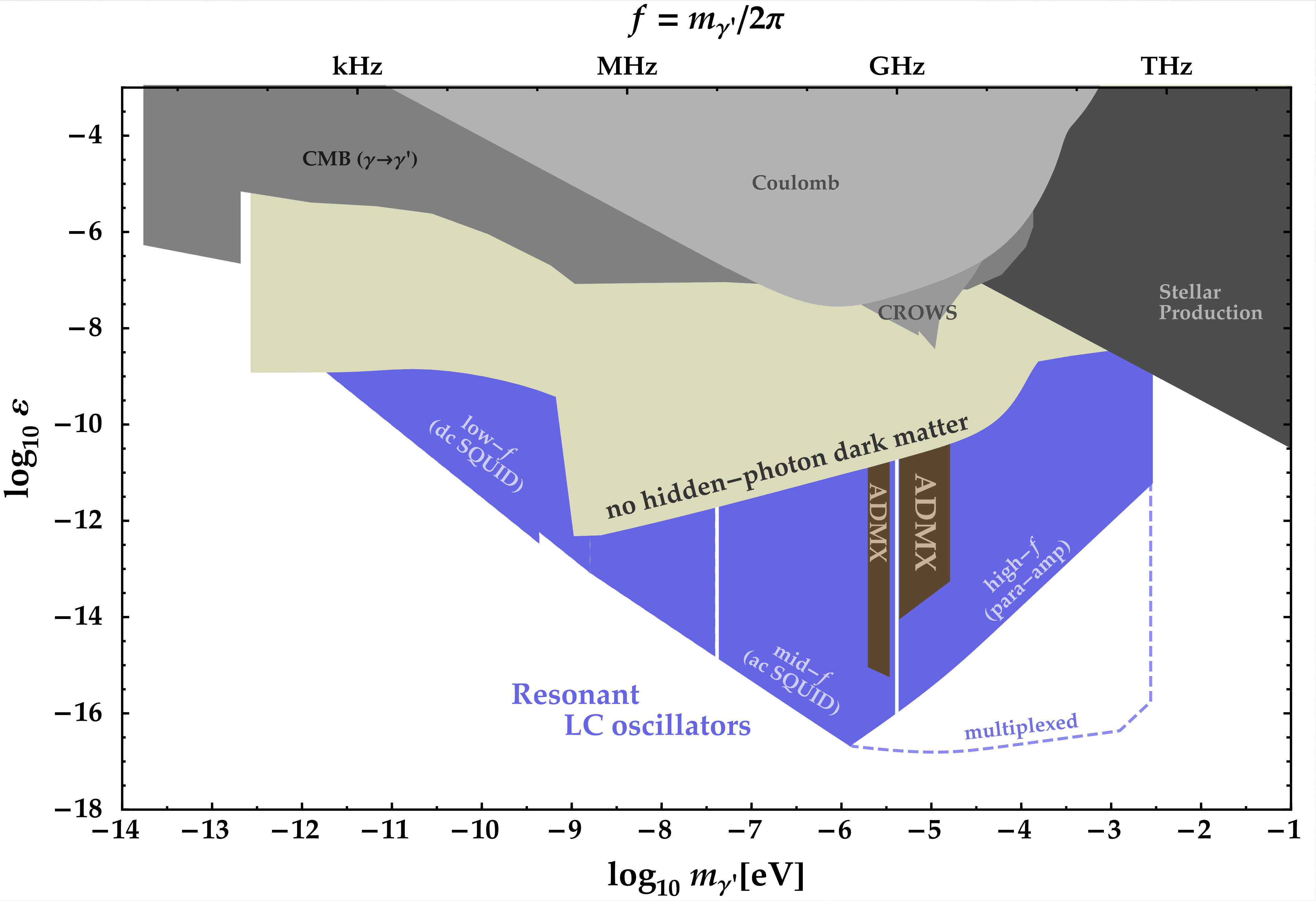
oscillating E' field
(dark matter)

shield



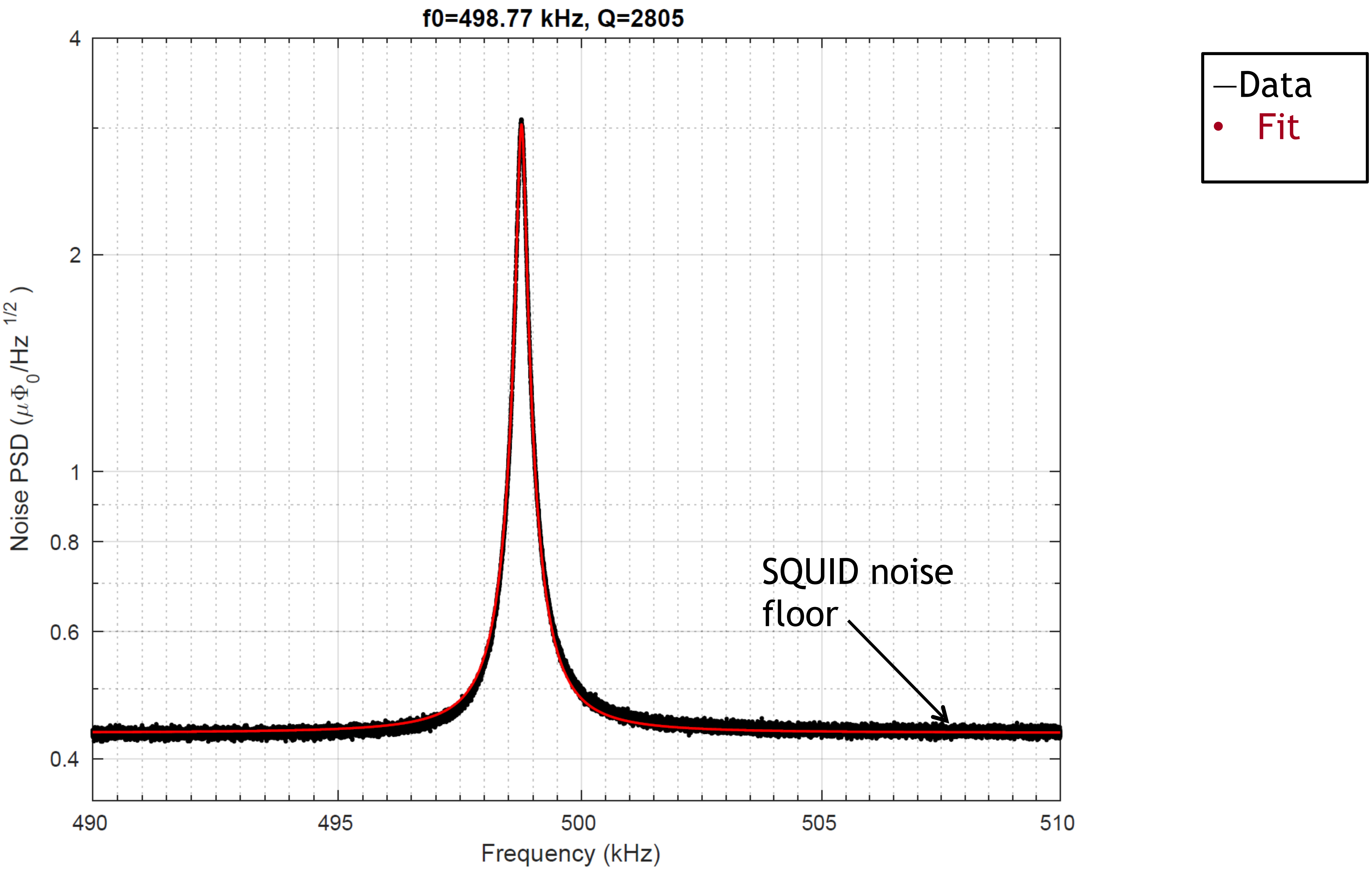
Tunable resonant LC circuit
(a radio)

EXPECTED REACH



Parameters: volume ~0.1 m^3, T= 100mK, $Q=10^6$, 1

DM Radio first data!



SQUID noise floor

9 hr integration time

Q limited by aluminum wire bonds - replace with niobium. Use new SQUID

Dark Matter Detection with Accelerometers

with

Peter Graham
David Kaplan
Jeremy Mardon
William Terrano

B-L Dark Matter

Other than electromagnetism, only other anomaly free standard model current

$$\mathcal{L} = -\frac{1}{4}\left(F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - g J^\mu_{B-L} A'_\mu$$

Protons, Neutrons, Electrons and Neutrinos are all charged

Electrically neutral atoms are charged under B-L

Force experiments constrain $g < 10^{-21}$

oscillating E' field (dark matter)

can accelerate atoms

Force depends on net neutron number - violates equivalence principle. Dark matter exerts time dependent equivalence principle violating force!

The Relaxion

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

Hierarchy problem solved through cosmic evolution - does not require any new physics at the LHC

ϕ is a light scalar coupled to higgs with small coupling g

$$\implies \frac{g\phi}{v} m_q \bar{q} q$$

$$\text{Dark matter } \phi \implies \phi = \phi_0 \cos\left(m_\phi \left(t - \vec{\mathrm{v}}.\vec{x}\right)\right)$$

Time variation of masses of fundamental particles

$$\implies \text{force on atoms } \frac{g\nabla\phi}{v} m_q \sim \frac{g m_\phi \vec{\mathrm{v}}}{v} m_q$$

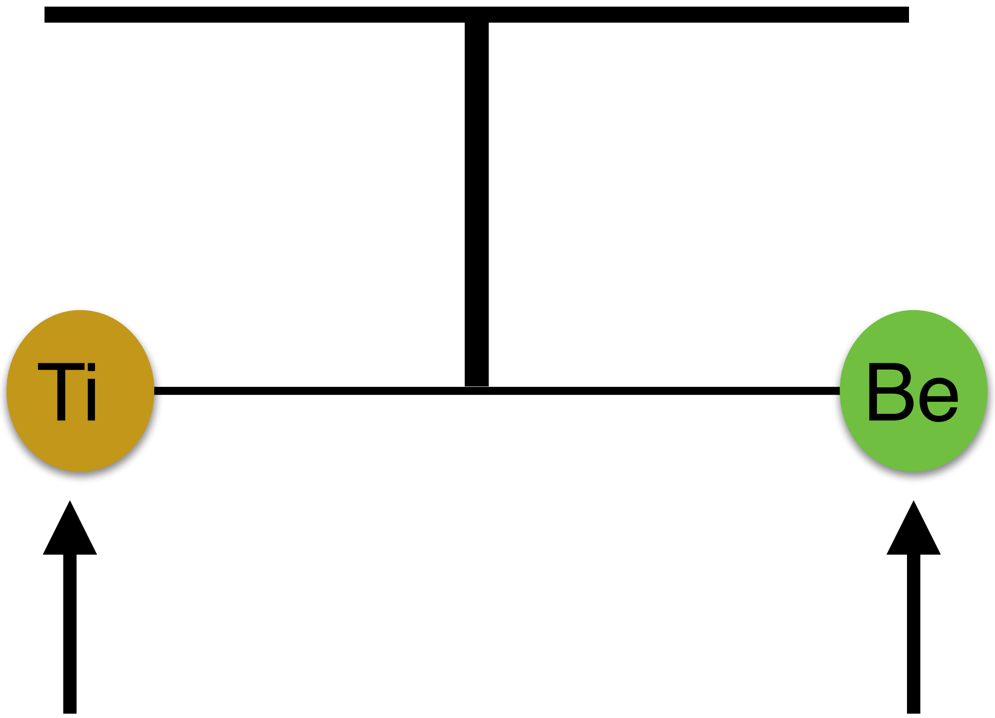
Force violates equivalence principle. Time dependent equivalence principle violation!

Detection Options

Measure relative acceleration between different elements/isotopes.

Leverage existing EP violation searches and work done for gravitational wave detection

Torsion Balance

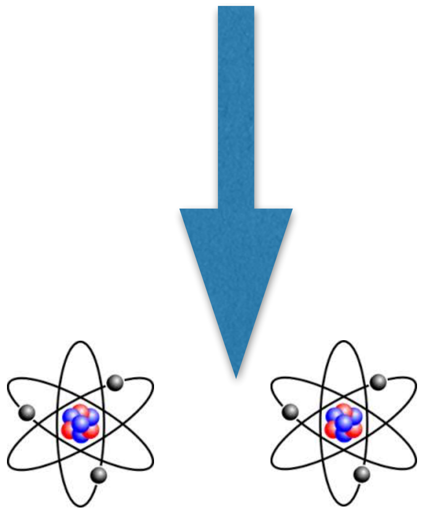


Force from dark matter causes torsion balance to rotate

Measure angle, optical lever arm enhancement

Atom Interferometer

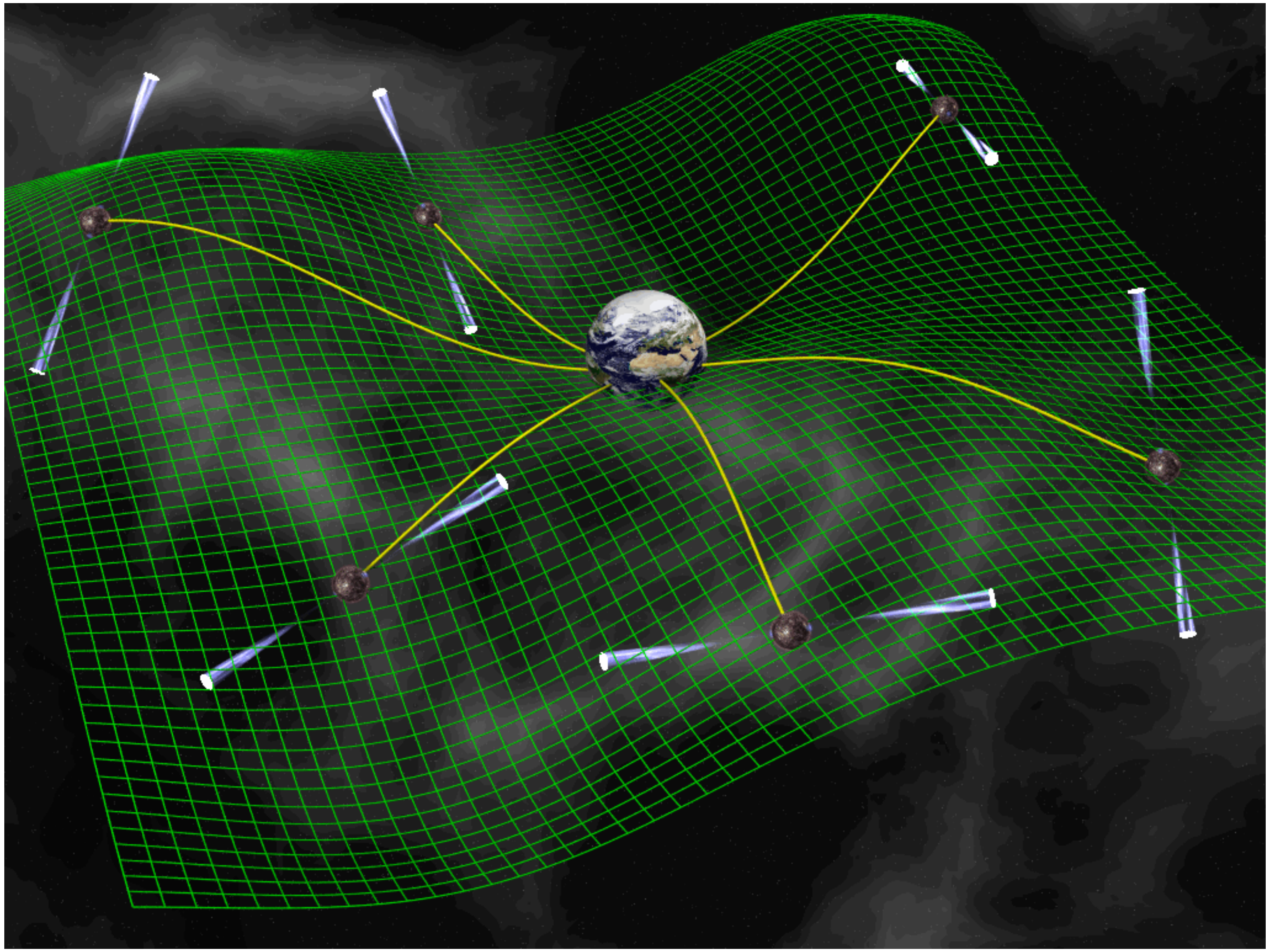
Dark Matter



Differential free fall acceleration

Stanford Facility

Pulsar Timing Arrays



Pulsars are known to have stable rotation - can be used as clocks

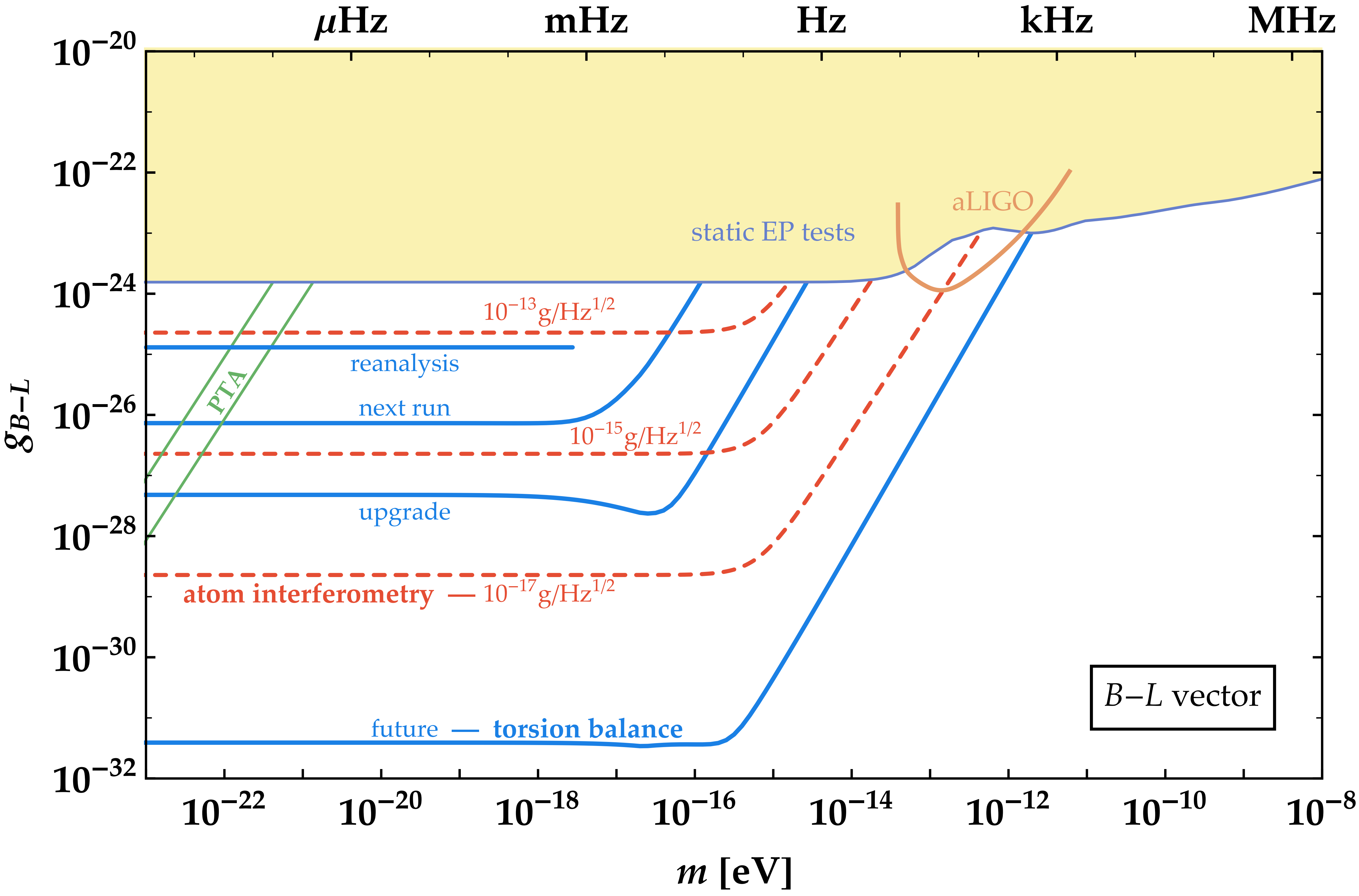
Presently used to search for low frequency (100 nHz) gravitational waves.

Pulsar signal modulates due to gravitational wave passing between earth and the pulsar

Force by dark matter causes relative acceleration between Earth and Pulsar, leading to modulation of signal

Relaxion changes electron mass at location of Earth - changes clock comparison

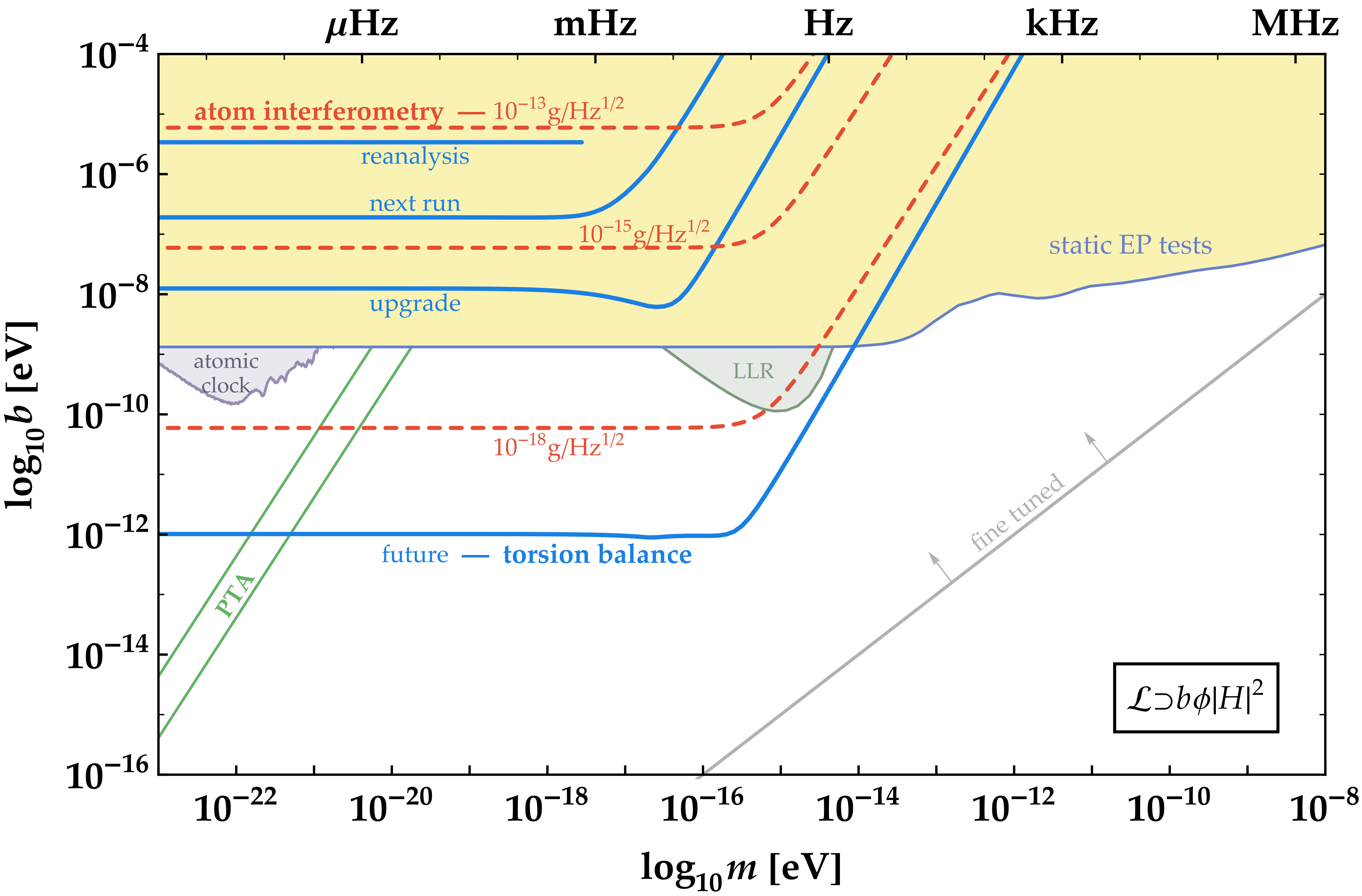
Projected Sensitivities



Torsion Balance limited by fiber thermal noise

Atom interferometers by shot noise

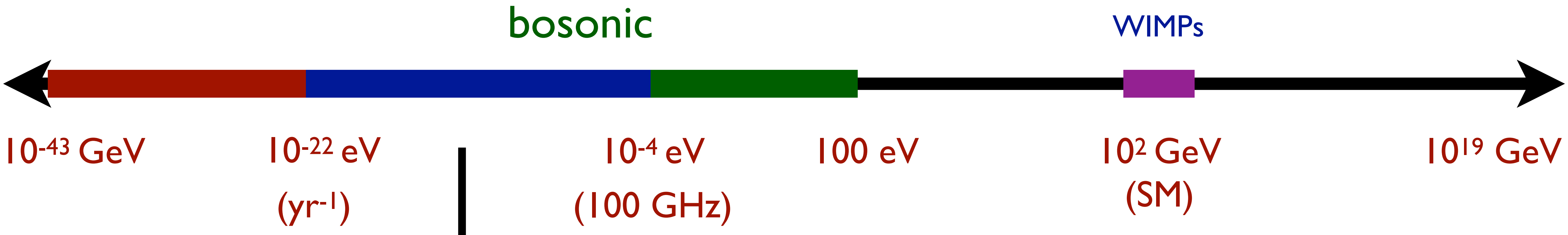
Projected Sensitivities



Torsion Balance limited by fiber thermal noise

Atom interferometers by shot noise

The Dark Matter Landscape



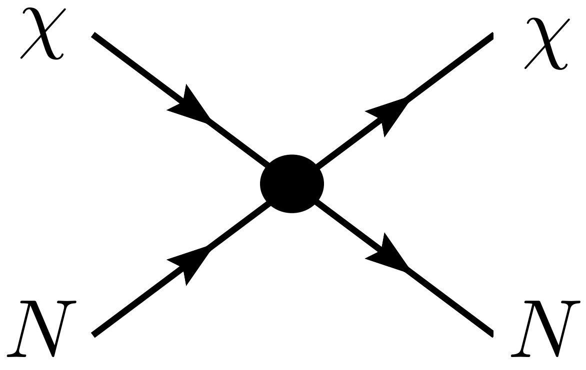
Fit in galaxy

Axions, Hidden photons etc.
Classical Field Dark Matter

Coherent over T~ μs - 10^6 years.
Enough time to build phase ~ (δE) T.
ADMX, CASPEr, DM-Radio

What about 10^{-4} eV - GeV?

Close tie to Weak Scale Physics,
Thermal Freeze-out



Hard scattering, 10 - 100 keV energy
deposition, probing higgs exchange

Beyond solar neutrinos?

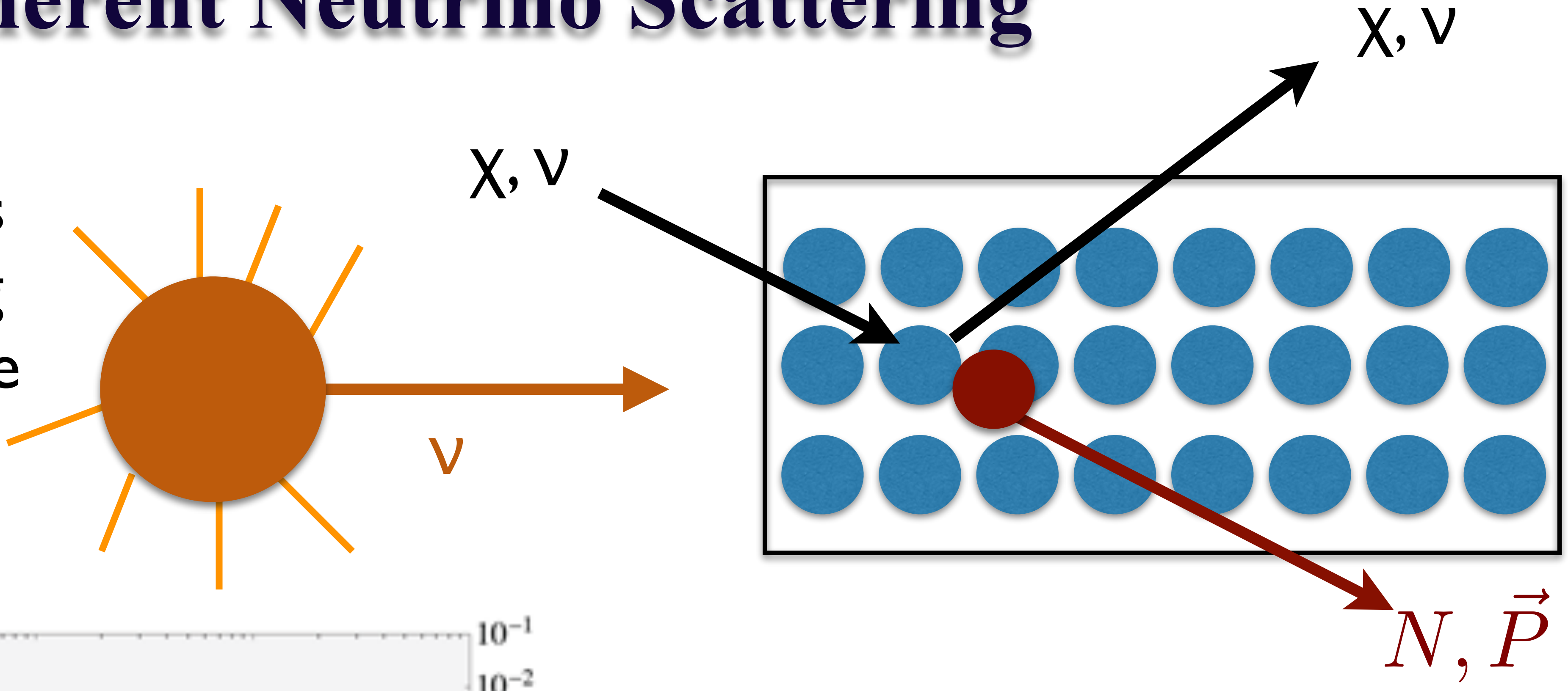
This Talk

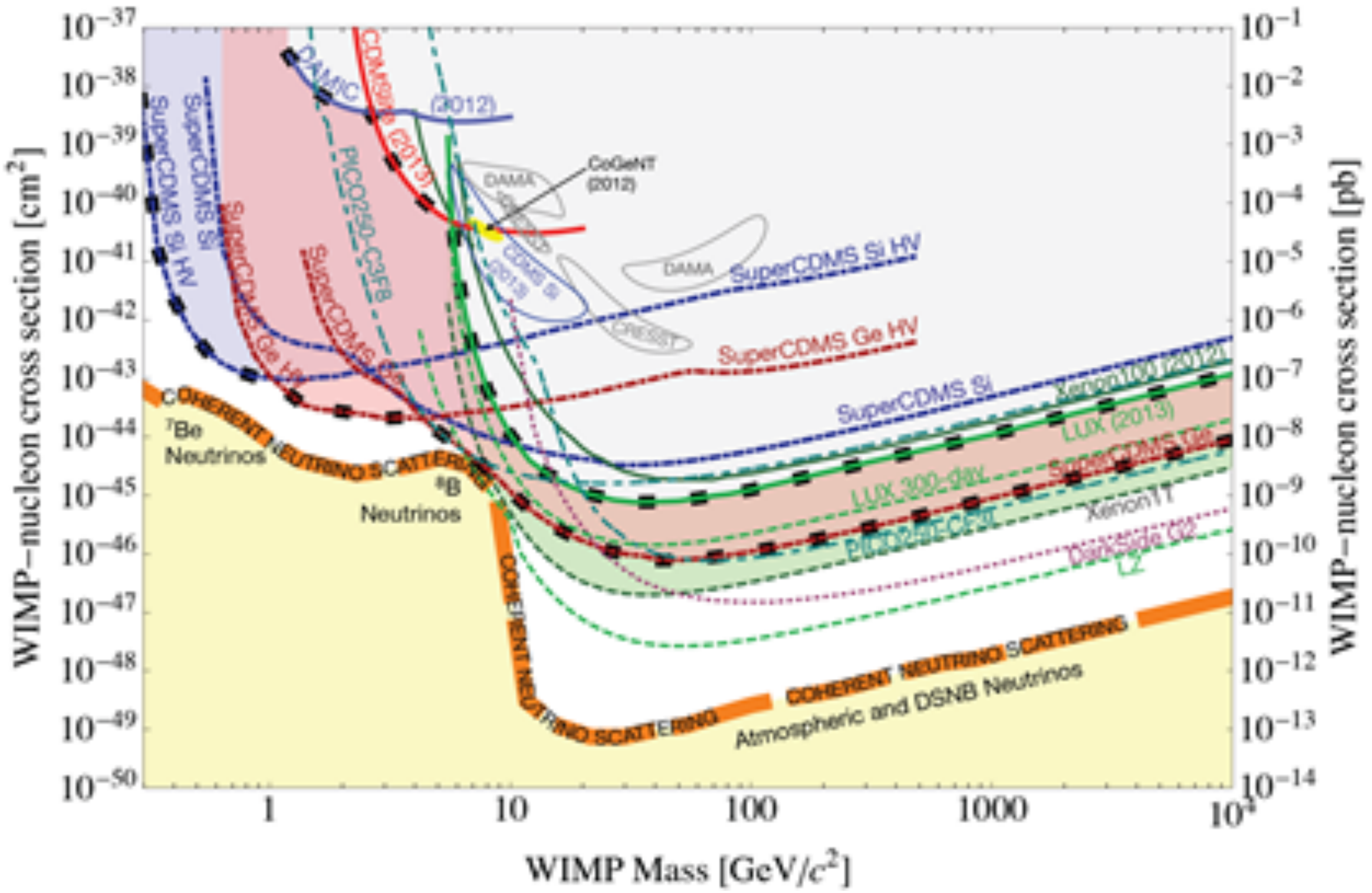
Directional Detection of Dark Matter with Crystal Defects

with
Misha Lukin, Alex Sushkov, Ron Walsworth and Nicholas Zobrist

Coherent Neutrino Scattering

Neutrinos and WIMPs have similar scattering topologies - rare, single particle collision with detector





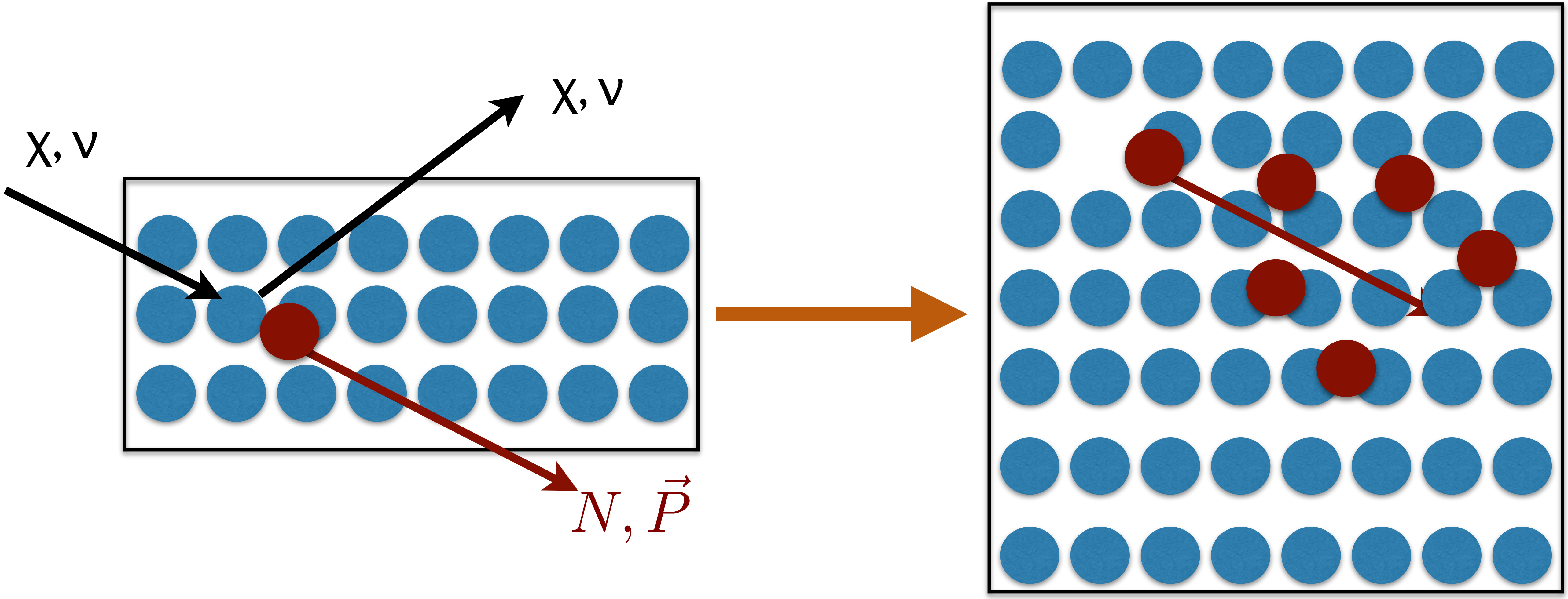
Sun produces neutrinos. Irreducible background.

Go beyond next generation?

Isotropic Dark Matter. Know location of Sun. Veto nuclear recoils coming from Sun's direction

Challenge: Big Target Mass. Need directional detection at solid state density.

Collision Aftermath



Tell-tale damage cluster well correlated with direction of initial ion, localized within ~ 50 nm

Collision Aftermath

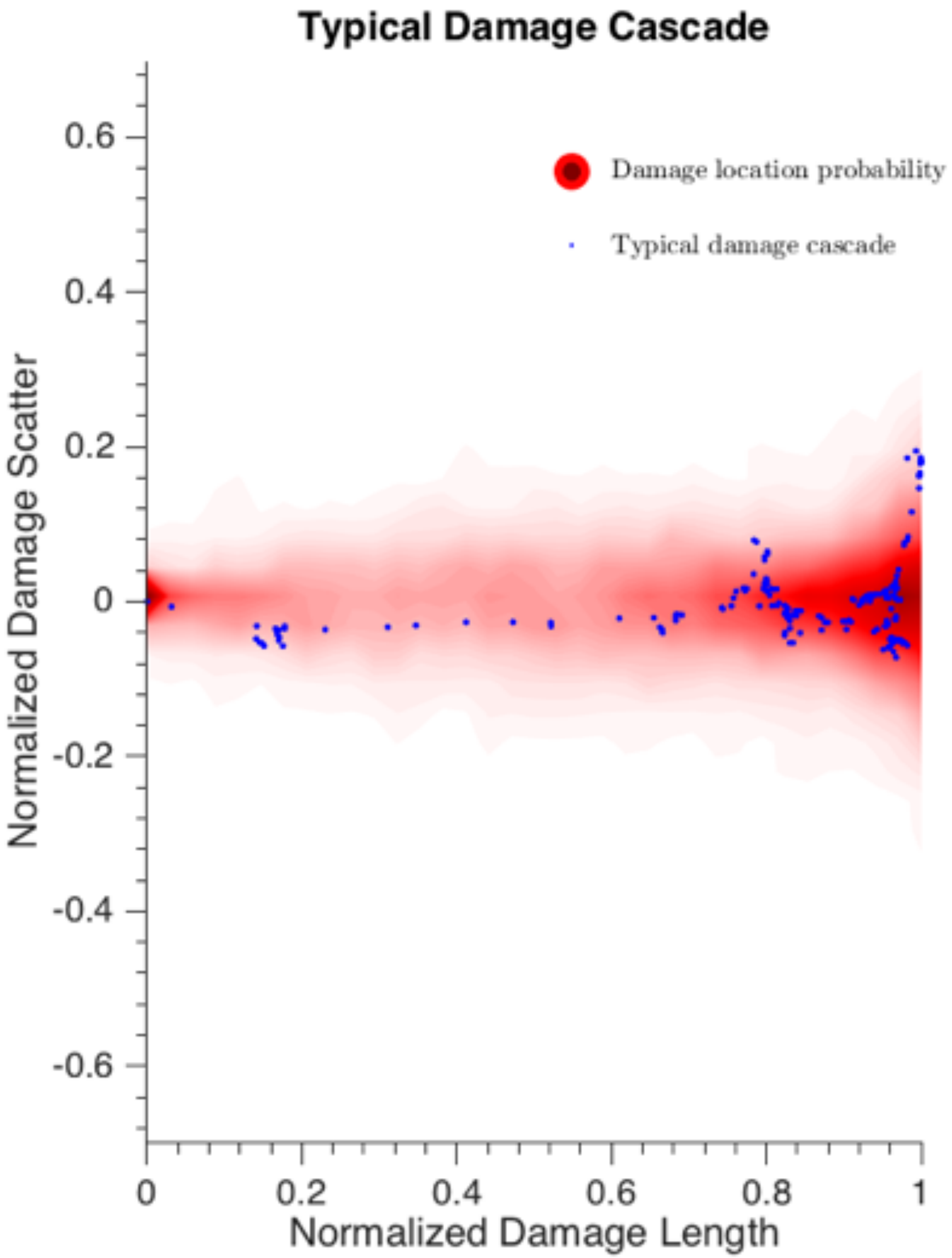
Tell-tale damage cluster well correlated with direction of initial ion, localized within ~ 50 nm

Results of TRIM simulation, 30 keV initial ion

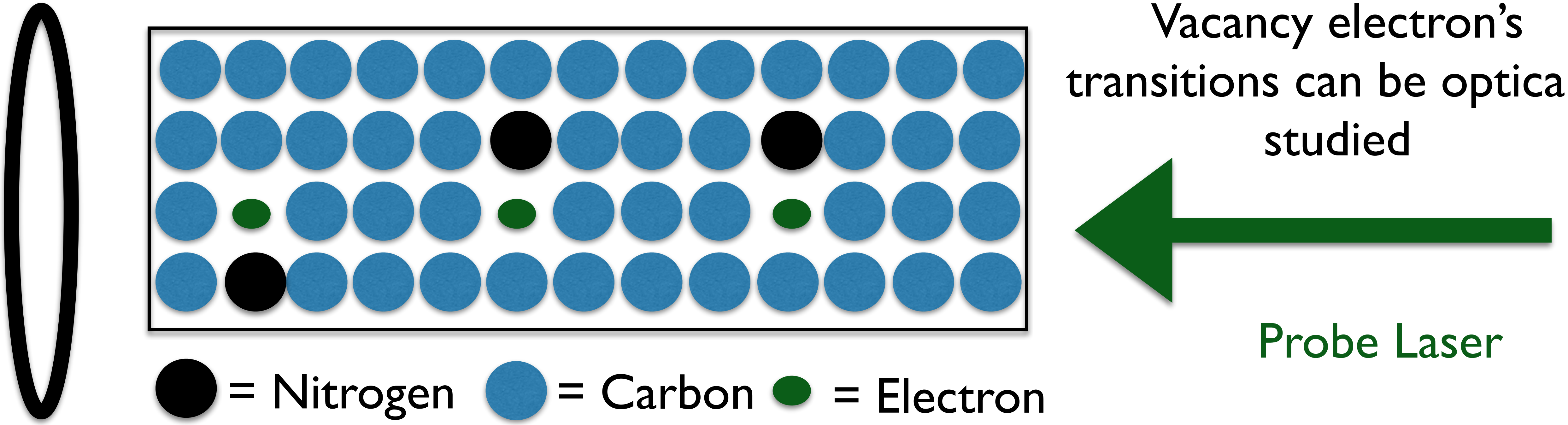
O(200 - 300) vacancies and interstitials, lattice potential ~ 30 eV

Damage cascade well correlated with direction of input ion

Need nano-scale measurement of damage cascade



Nitrogen Vacancy Center in Diamond



Vacancy electron's transitions can be optically studied

Probe Laser

⚫ = Nitrogen 🔵 = Carbon 🟢 = Electron

Collect light

Electronic levels sensitive to crystal environment ~ 50 nm scale

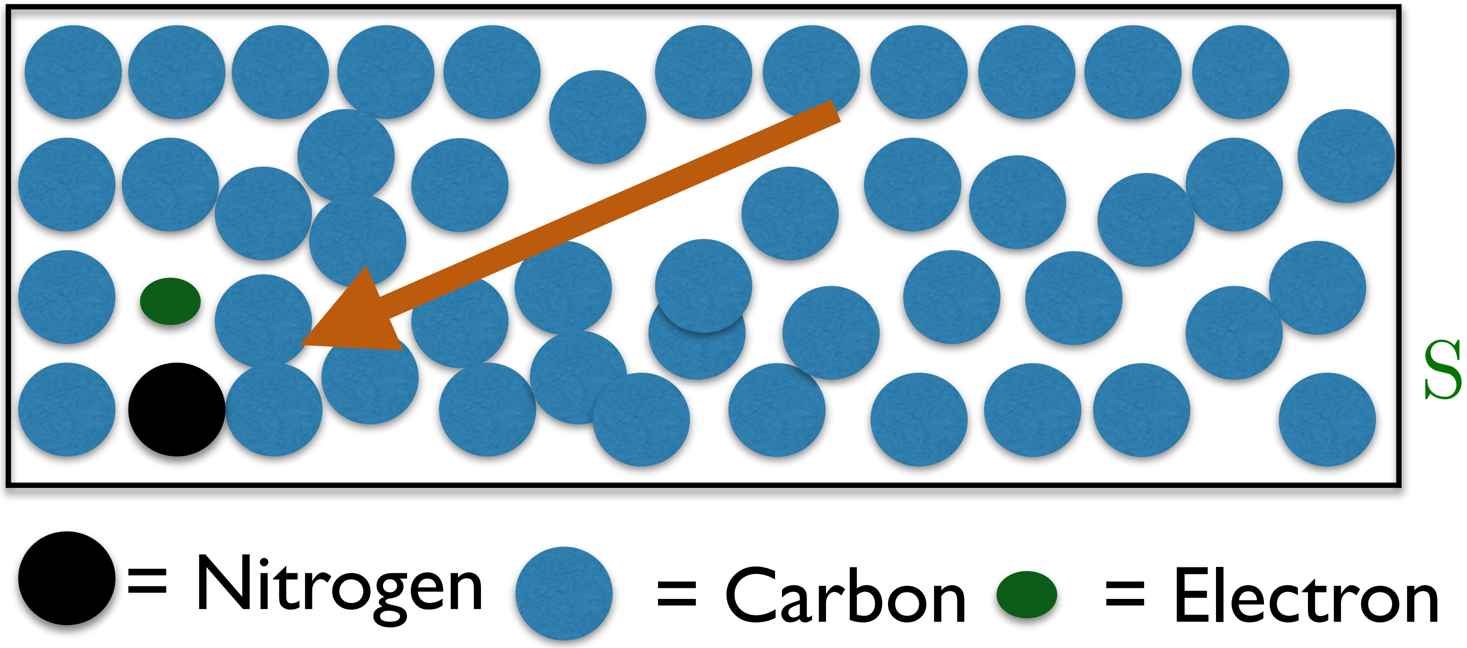
~ 1 per (30 nm)^3 of NV centers in bulk diamond demonstrated

Nano-scale measurements experimentally demonstrated. Active development of sensors by many groups around the world.

Can this be used for directional detection? What is the effect of the damage cascade on a NV center?

Note: similar phenomenology applies to F-centers of Metal Halides

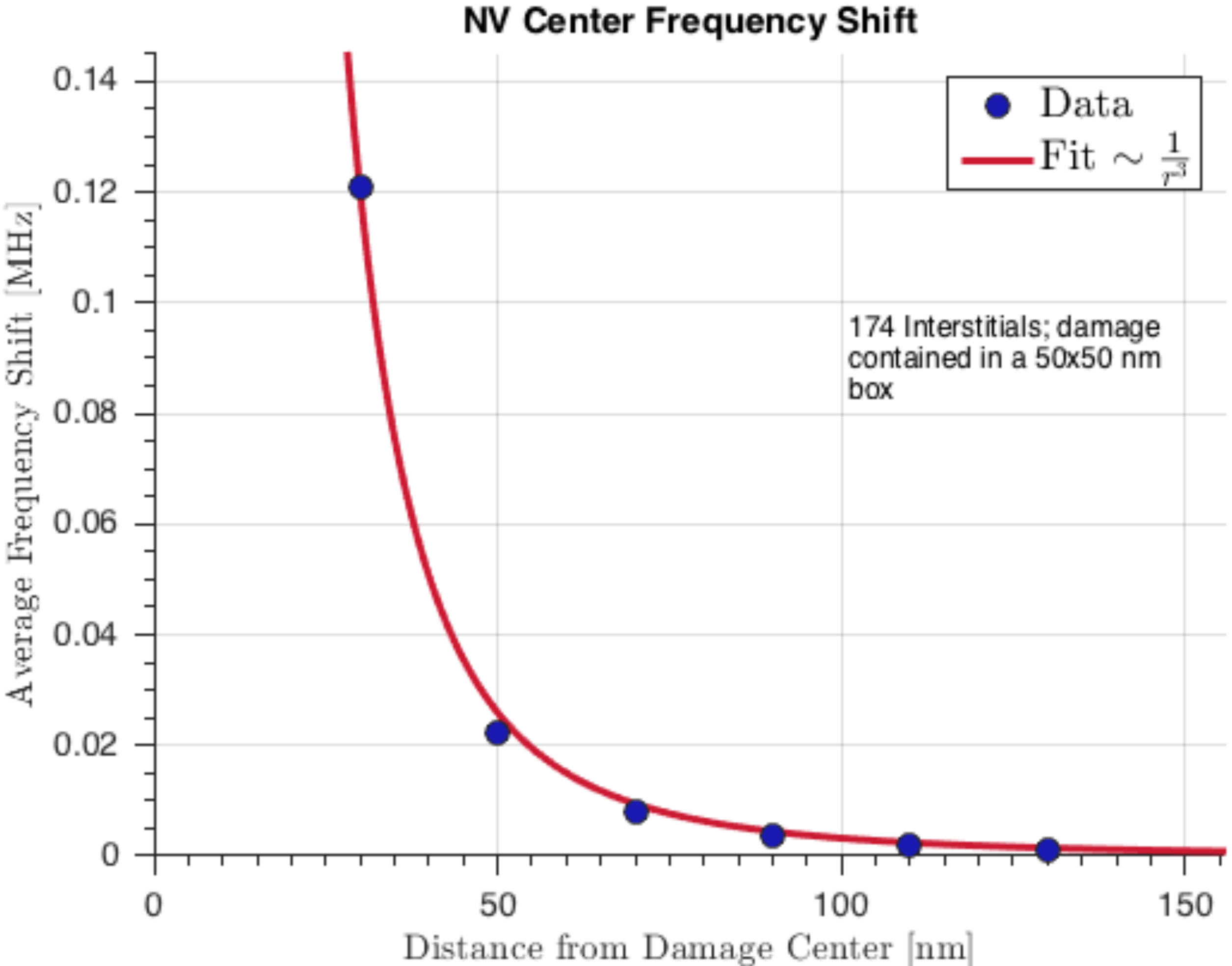
Damage Cascade and NV Centers



Damage leads to strain in crystal.
Strain shifts transition line

$$\text{Strain: } \nabla u \propto \frac{1}{r^3} \times \mathcal{O}\,(100-300)$$

(Hooke's Law)



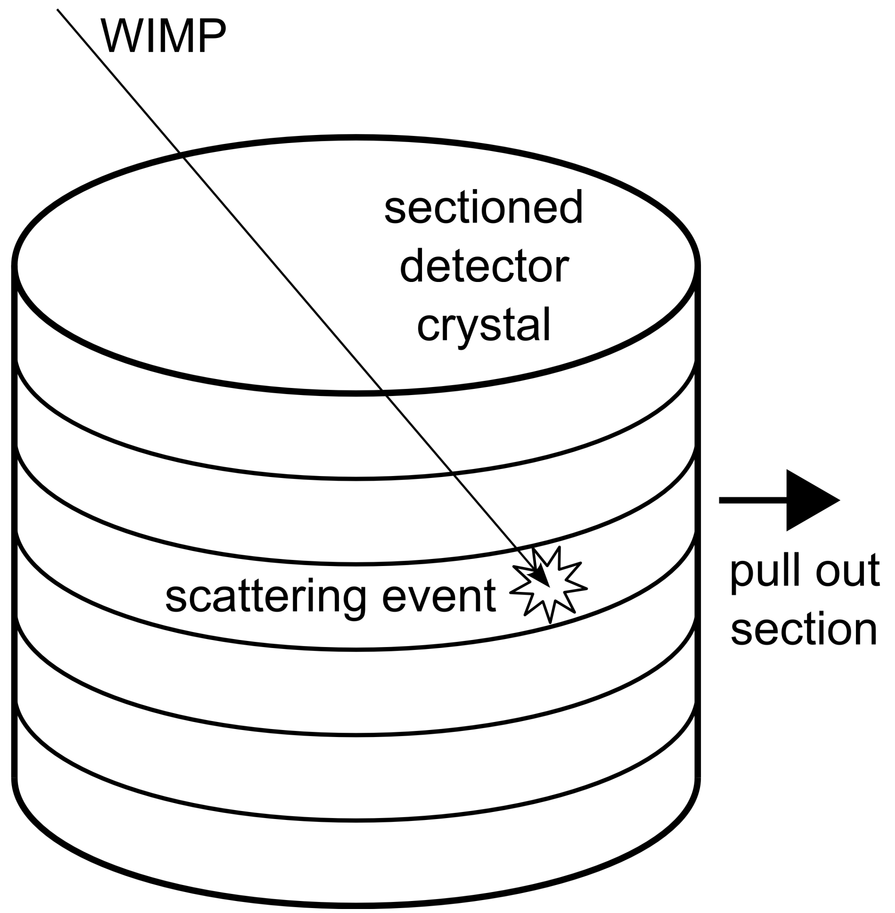
174 Interstitials; damage contained in a 50x50 nm box

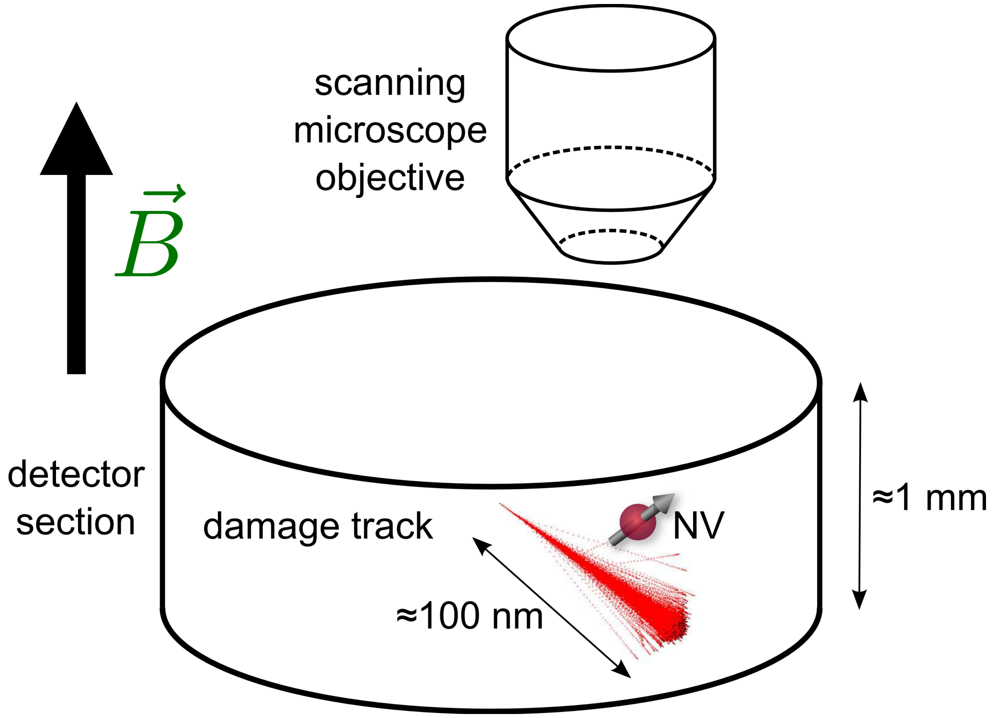
TRIM simulation of damage cascade - calculate strain using Hooke's law

NV center shift ~ 100 kHz @ 30 nm
Natural line width ~ kHz

Single NV center has sensitivity to cascade!

Detector Concept





Large detector, segments of thickness ~ mm

NV center density ~ 1 per (30 nm)^3

Conventional WIMP scattering ideas (scintillation, ionization etc.) to localize interesting events

Expect few events/year that could be WIMP or neutrinos

Pull out segments of interest. Conventional schemes localize events to within mm

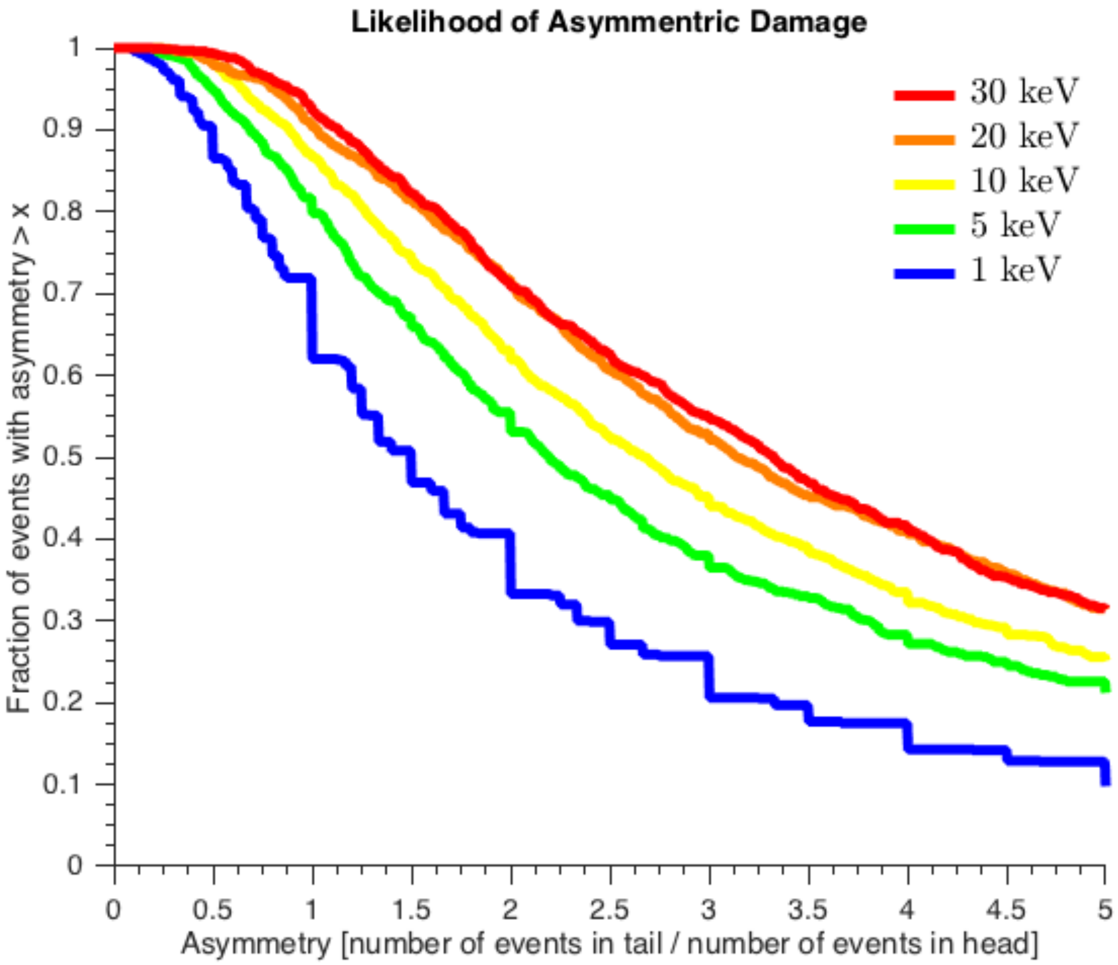
Micron-scale localization by simply shining light - damaged area will have measurable frequency shifts

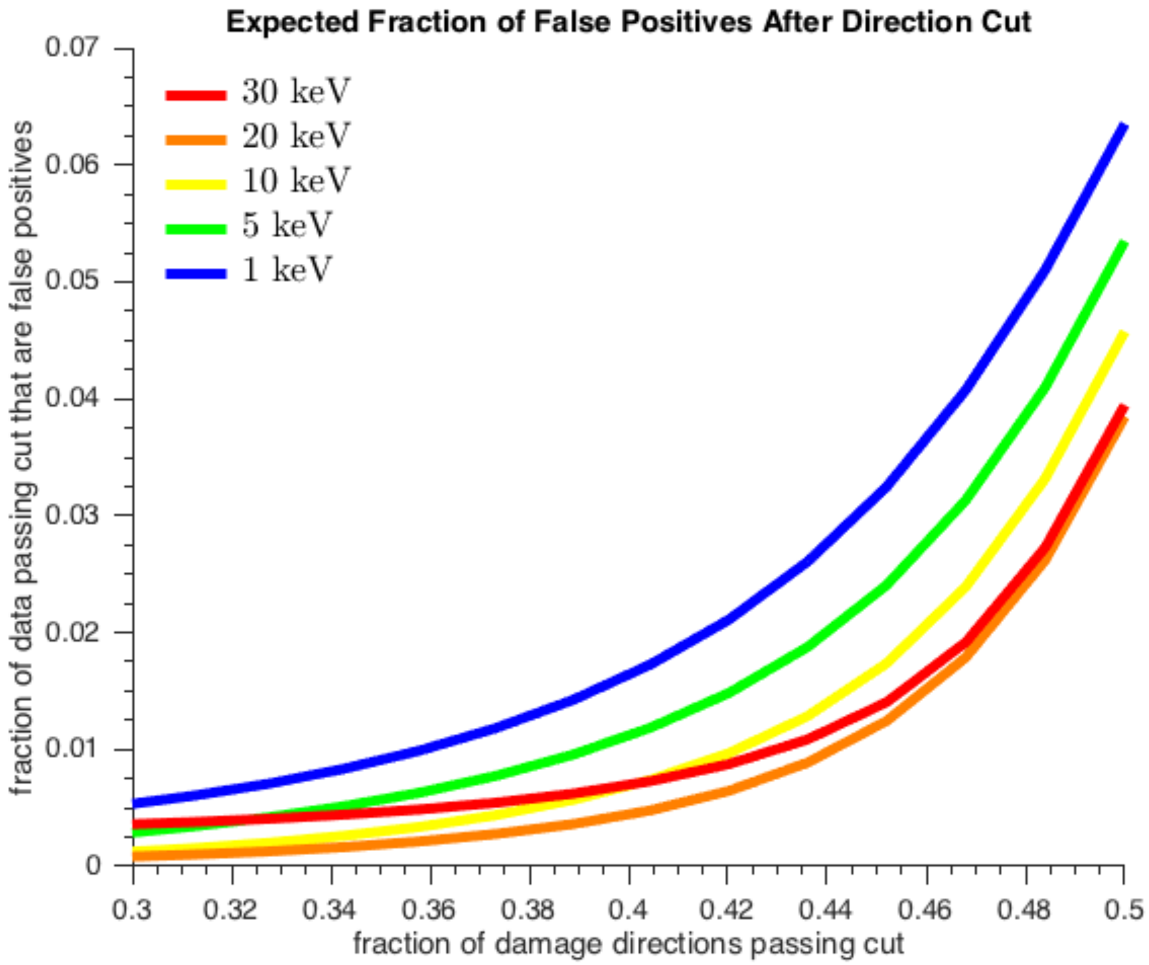
For nano-scale resolution, apply external magnetic field gradient - hence need segmentation

Results

Take crystal. Grid of NV centers with density 1 per (30 nm)^3

Run ~ 1000 TRIM simulations, get cascade for each. Can grid distinguish direction (including head vs tail)?





More damage in tail vs head used for discrimination. Above 10 keV, efficiency > 80%, false positive < 4%

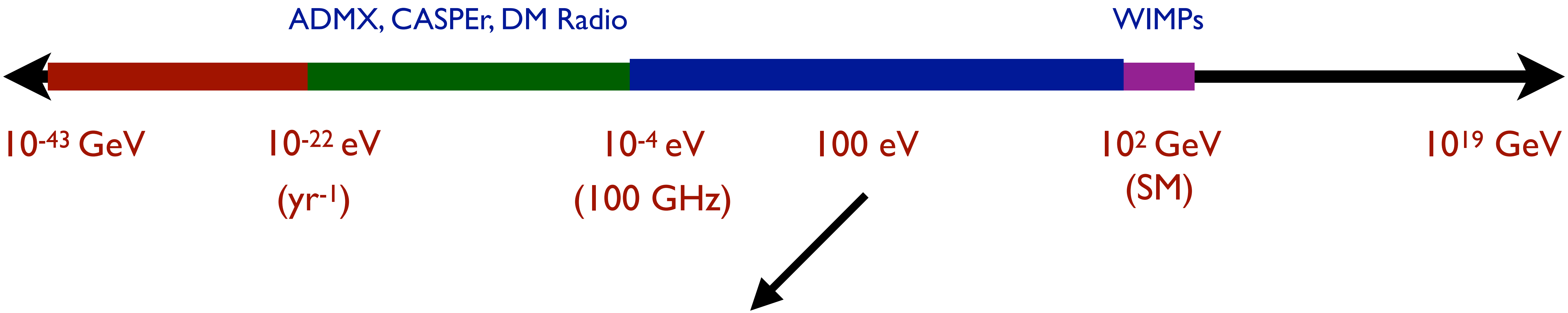
5 σ detection with few events!

Magnetic Bubble Chambers

with

Phil Bunting, Hao Chen, Giorgio Gratta, Michael Nippe, Jeffrey Long, Rupak Mahapatra and Tom Melia

The Dark Matter Landscape



ADMX, CASPEr, DM Radio

WIMPs

10^{-43} GeV

10^{-22} eV

(yr^{-1})

10^{-4} eV

(100 GHz)

100 eV

10^{2} GeV

(SM)

10^{19} GeV

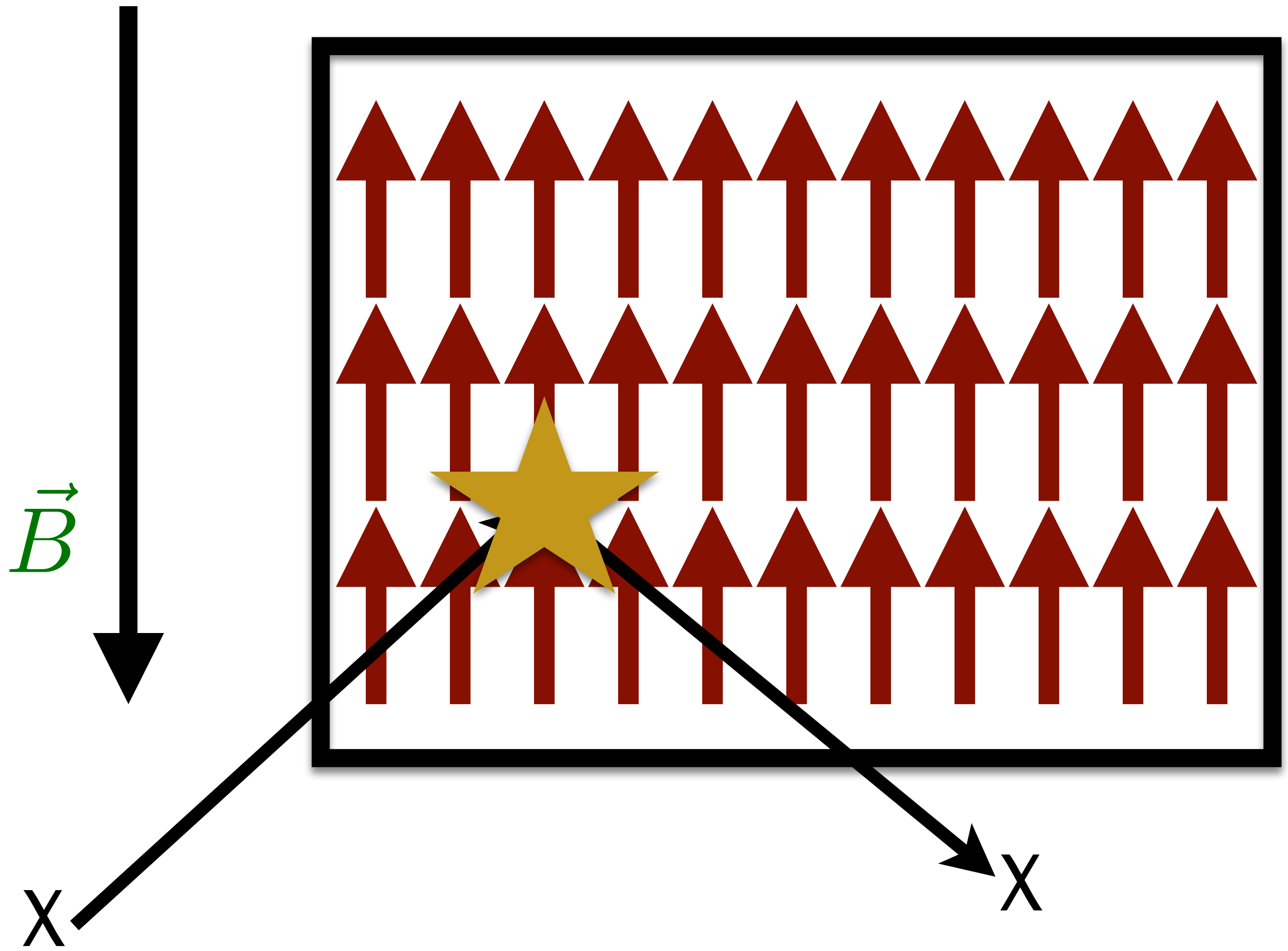
What about this range?

Coherence time of signal too short for phase measurement to work. Energy deposition too small to be been using conventional WIMP calorimeters

Need amplification of deposited energy (meV - keV)

Challenge: Need large target mass. Rare dark matter event. Requires amplifier stability > years

Concept

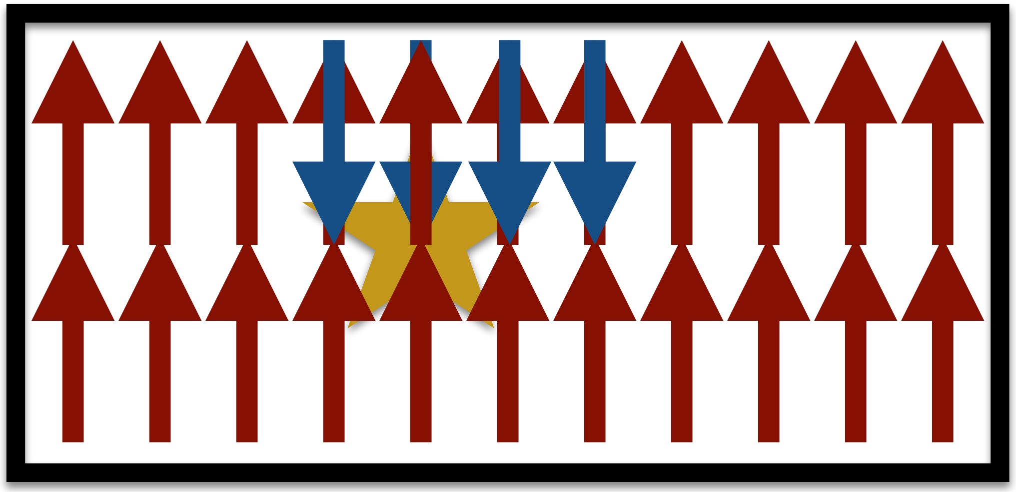


Consider magnet with all spins aligned

Spins now in metastable excited state with energy $\sim g \mu B$

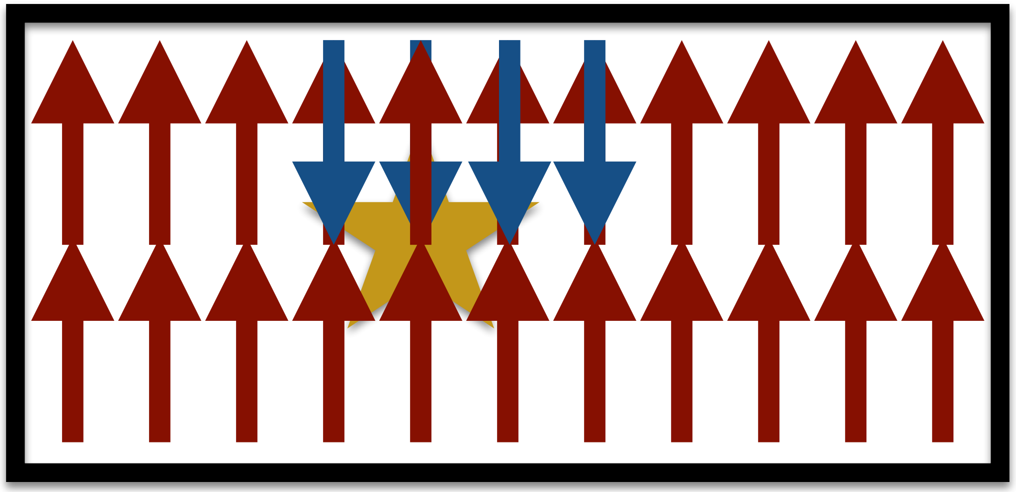
Dark Matter collides, deposits heat. Causes meta-stable spin to flip

Spin flip releases stored Zeeman energy (exothermic). Released energy causes other spins to flip, leading to magnetic deflagration (burning) of material.



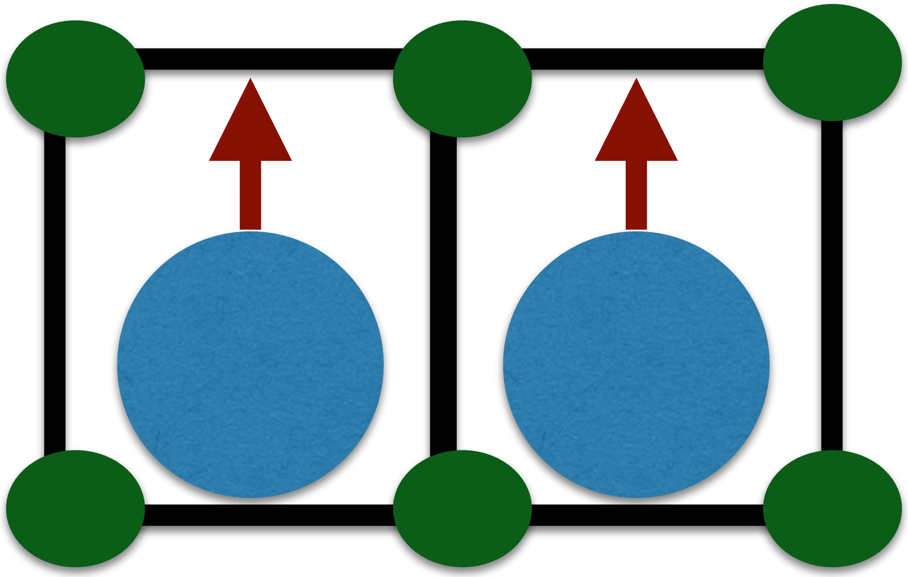
Amplifies deposited energy. Like a bubble chamber. Is this possible? Stability?

Single Molecular Magnets



Will not happen in a ferromagnet - spins are strongly coupled.

Need weak spin-spin coupling. But need large density - necessary for heat conduction. Can't use gas.



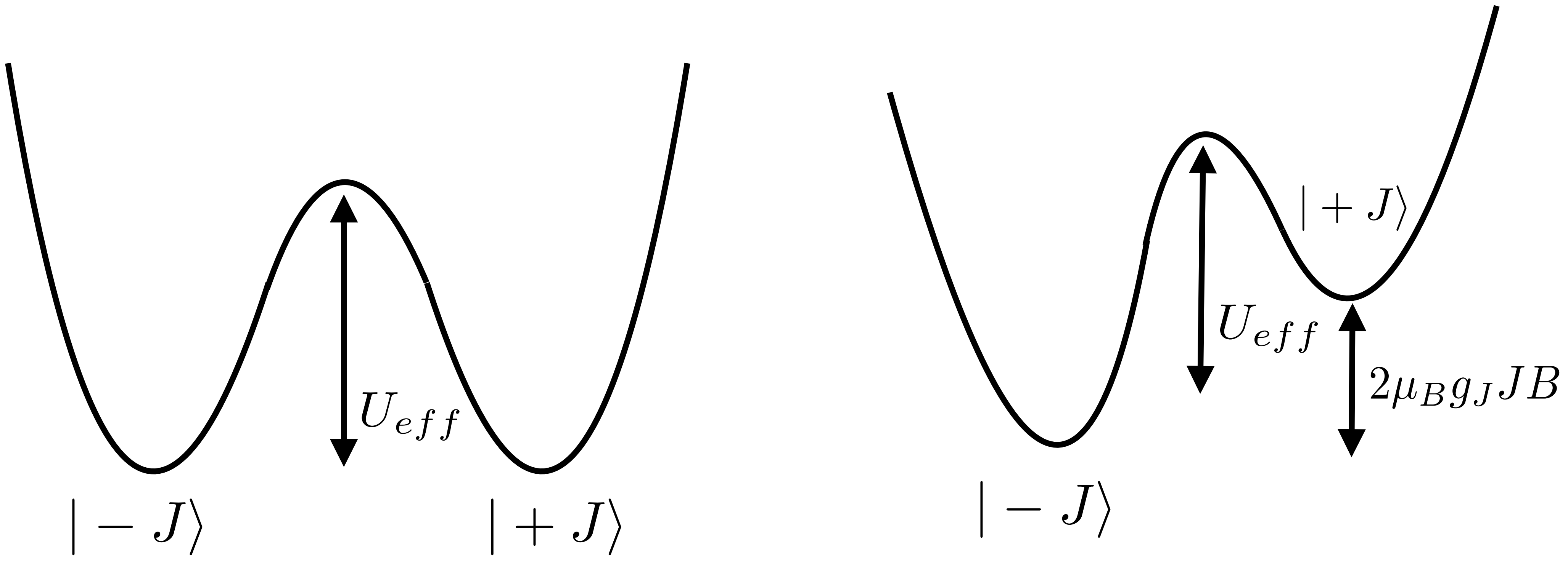
Organo-Metallic complexes. Central metal complex surrounded by organic material.

Weak coupling between adjacent metal complexes - but still large density

Each molecule acts as an independent magnet

Recently discovered systems. Few 100 known examples. Can make large samples. Magnetic deflagration experimentally observed and well studied in Manganese Acetate complexes

Magnetic Deflagration



System well described by 2 level Hamiltonian.
Two states separated by energy barrier.

Turn on magnetic field, metastable state decays to ground state through tunneling

$$\tau \propto \tau_0 \exp\left(U_{\text{eff}}/T\right)$$

Ultra-long lived state at low temperature - localized heating
rapidly decreases life-time, decay results in more energy release

Condition for Deflagration

Initially heat region of size λ to T

Thermal Diffusion, lowers T

$$\tau_{\mathrm{D}} \propto \lambda^2$$

Spin flips, releases energy, increases T

$$\tau \propto \tau_0 \, \exp\left(U_{\mathrm{eff}}/T\right)$$

Deflagration occurs as long as we heat a sufficiently large region

U_{eff} and τ_0 sets the detector threshold. Short τ_0 and small U_{eff} means tiny energy deposit will sufficiently heat up material to trigger deflagration. Low threshold

Known examples with $\tau_0 \sim 10^{-13}$ s, $U_{\mathrm{eff}} \sim 70$ K, enabling 0.01 eV thresholds

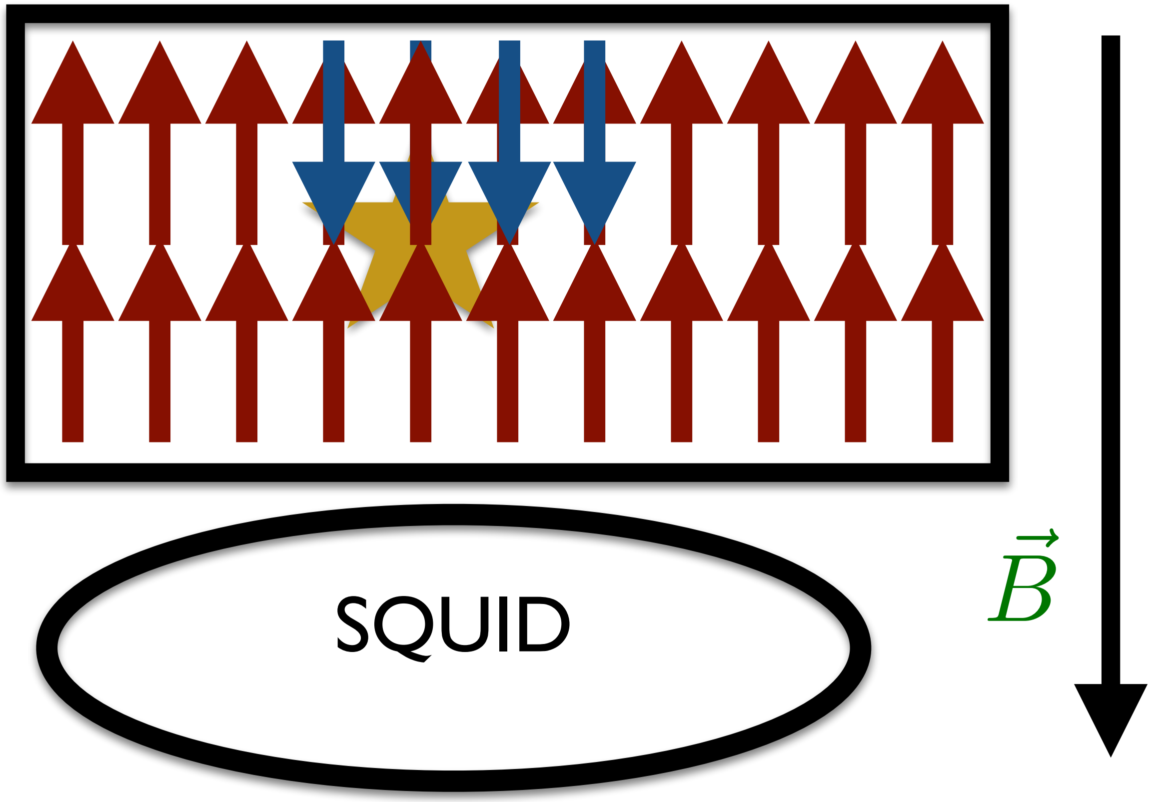
Detector Stability

High energy (> MeV) background from radio-active decays.

Detect MeV events using conventional means. Actual background at low energy very low - forward scattering of compton events

Problem: MeV events will constantly set off detector. Reset time vs operation time? Big problem for bubble chambers like COUPP

Expected background ~ 1/(m^2 s). Initial detector size ~ (10 cm)^3 (kg mass), 1 background event ~ 100 s



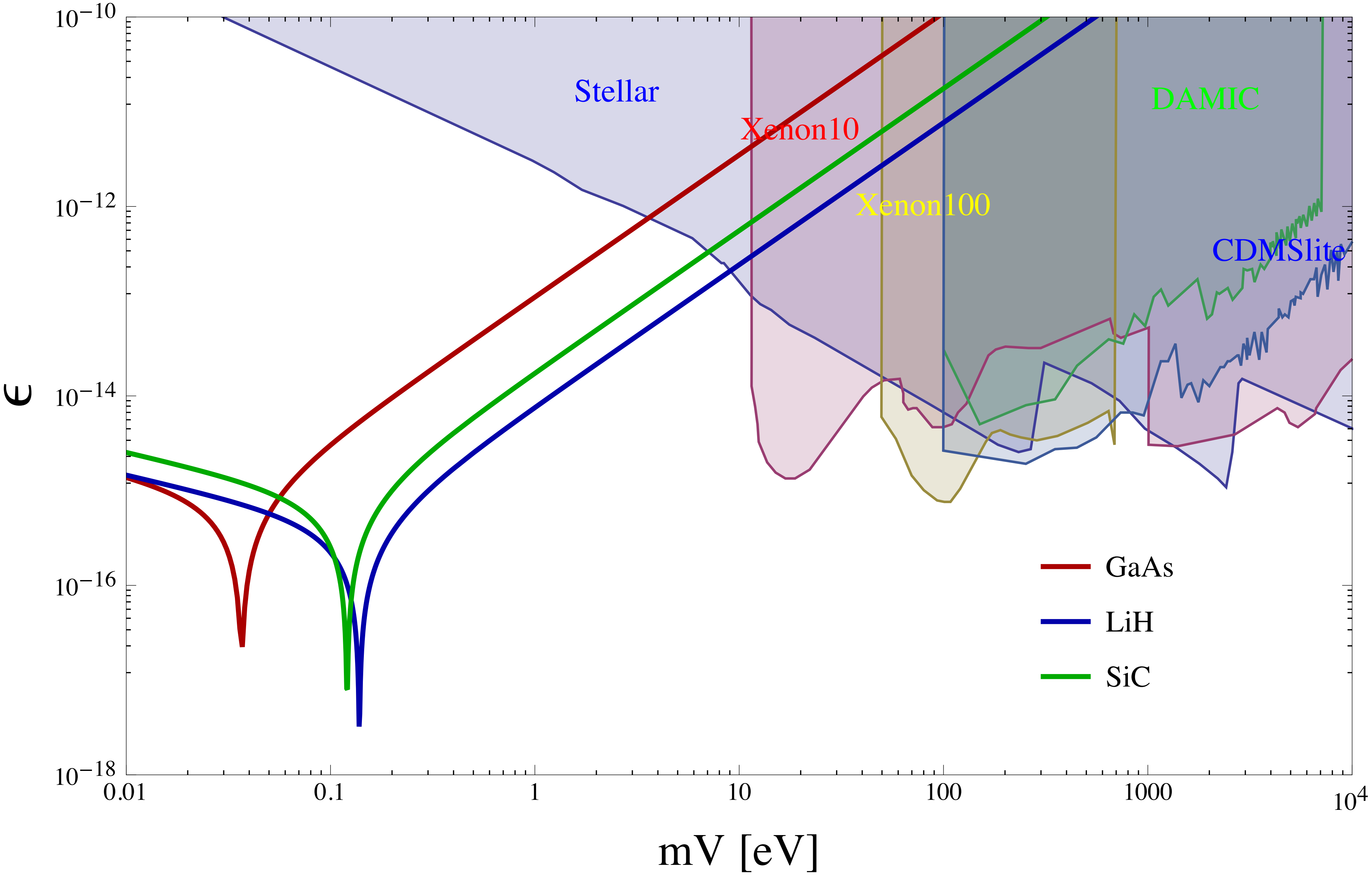
With precision magnetometers, don't need entire crystal to flip

Within ~ 10 μs, flame ~ 10 - 100 μm. Visible with SQUID.

Shut off B, turn off fuel. Deflagration stops. Lose ~ (10 - 100 μm)^3 of volume every 100 s.

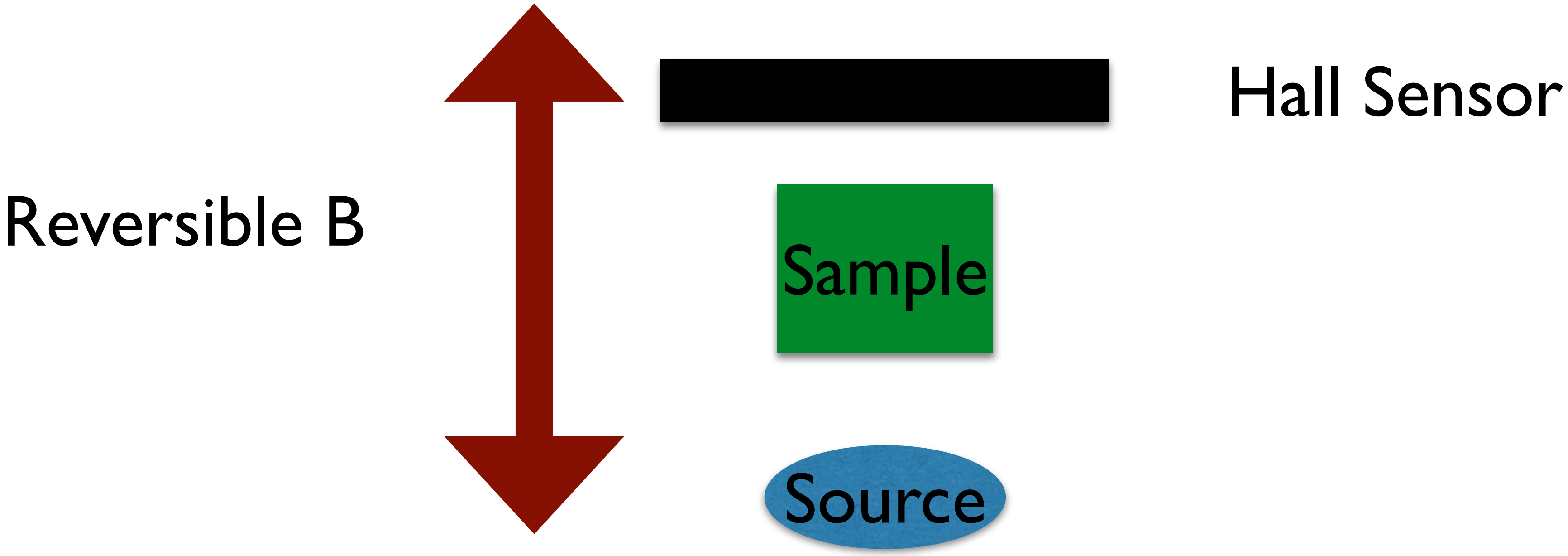
Potential Reach

$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - eJ^\mu_{EM}\left(A_\mu + \varepsilon\, A'_\mu\right)$$



Absorption obtained from photoabsorption. Exposure of 1 kg-year

Trial using Mn-Ac

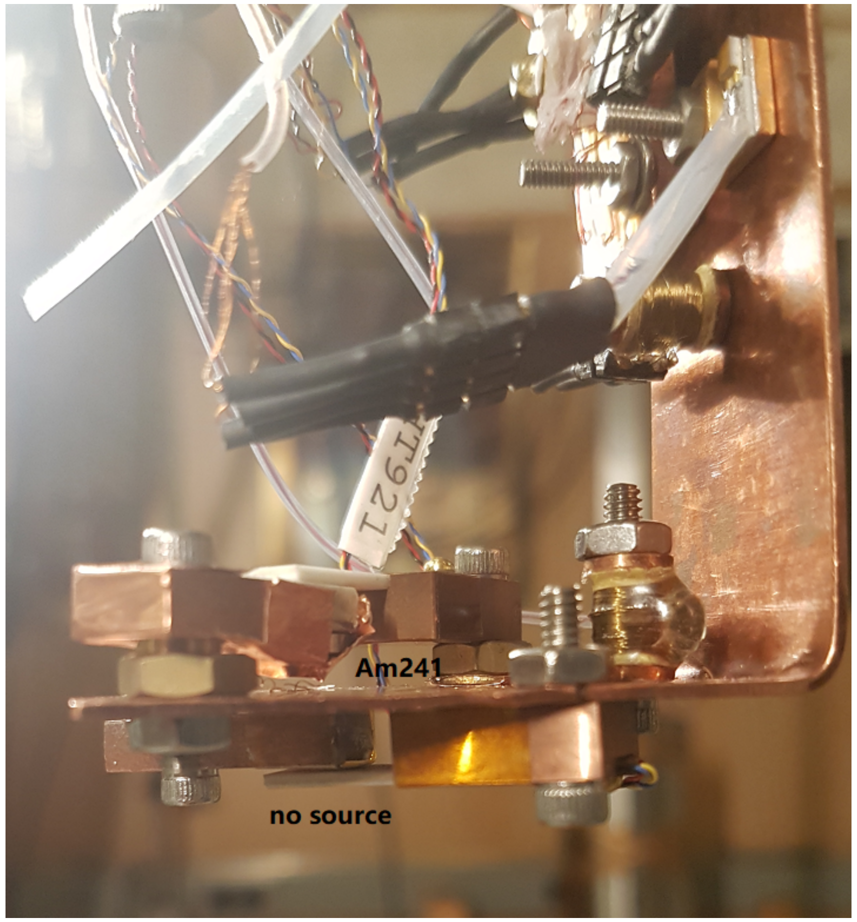


Reversible B

Hall Sensor

Sample

Source

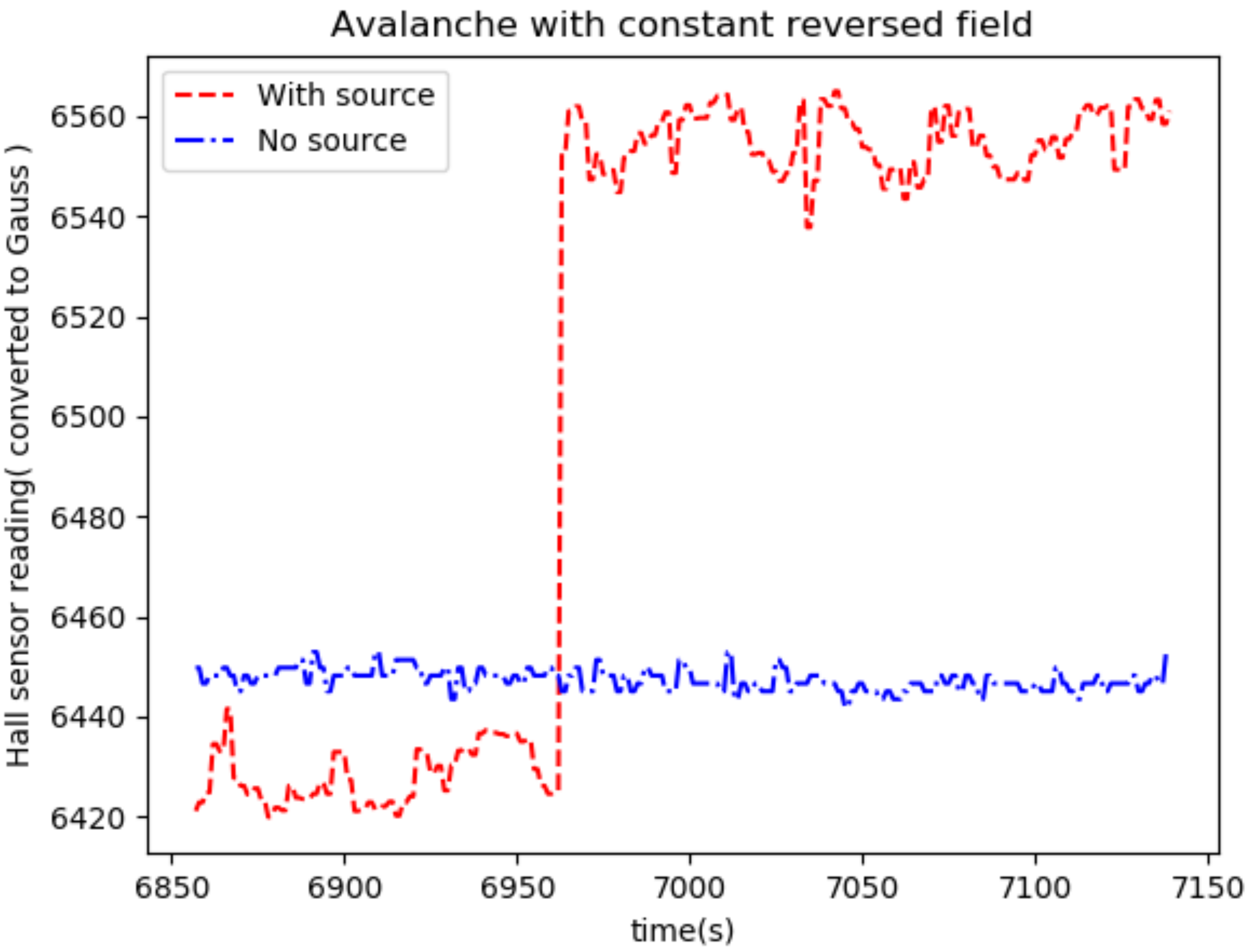


Two sets of Mn12-Ac and Hall sensors

One with μCi Am 241 α source
One without source

Metastability? Deflagration?

Results

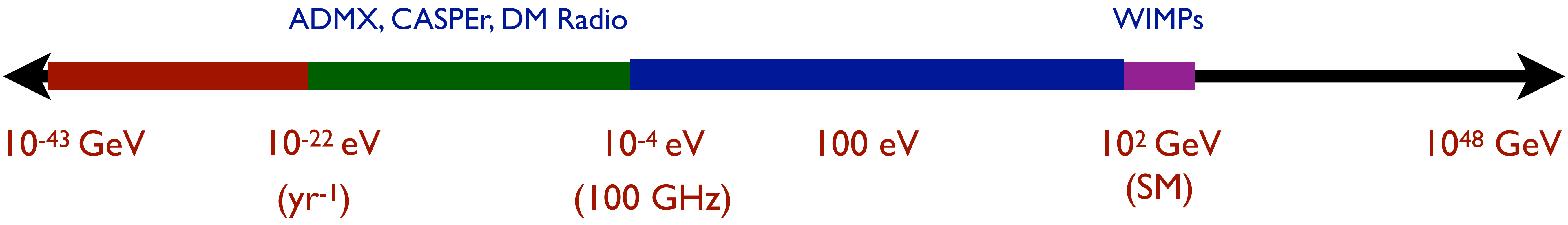


Avalanche only observed with source

Mn12-Ac has high threshold (~ few MeV) - using new materials now

Conclusions

The Dark Matter Landscape



ADMX, CASPEr, DM Radio

WIMPs

10^{-43} GeV

10^{-22} eV

(yr^{-1})

10^{-4} eV

(100 GHz)

100 eV

10^{2} GeV

(SM)

10^{48} GeV

Poor observational constraints on dark matter

Experiments under development can now search for dark matter particles with mass between 10^{-22} eV - 10^{-6} eV, using a variety of precision measurement tools

Explored concepts for WIMP directional detection in solid state densities and single molecular magnets for dark matter in the range 10^{-4} eV - GeV

Need to develop tools to cover full range of possibilities