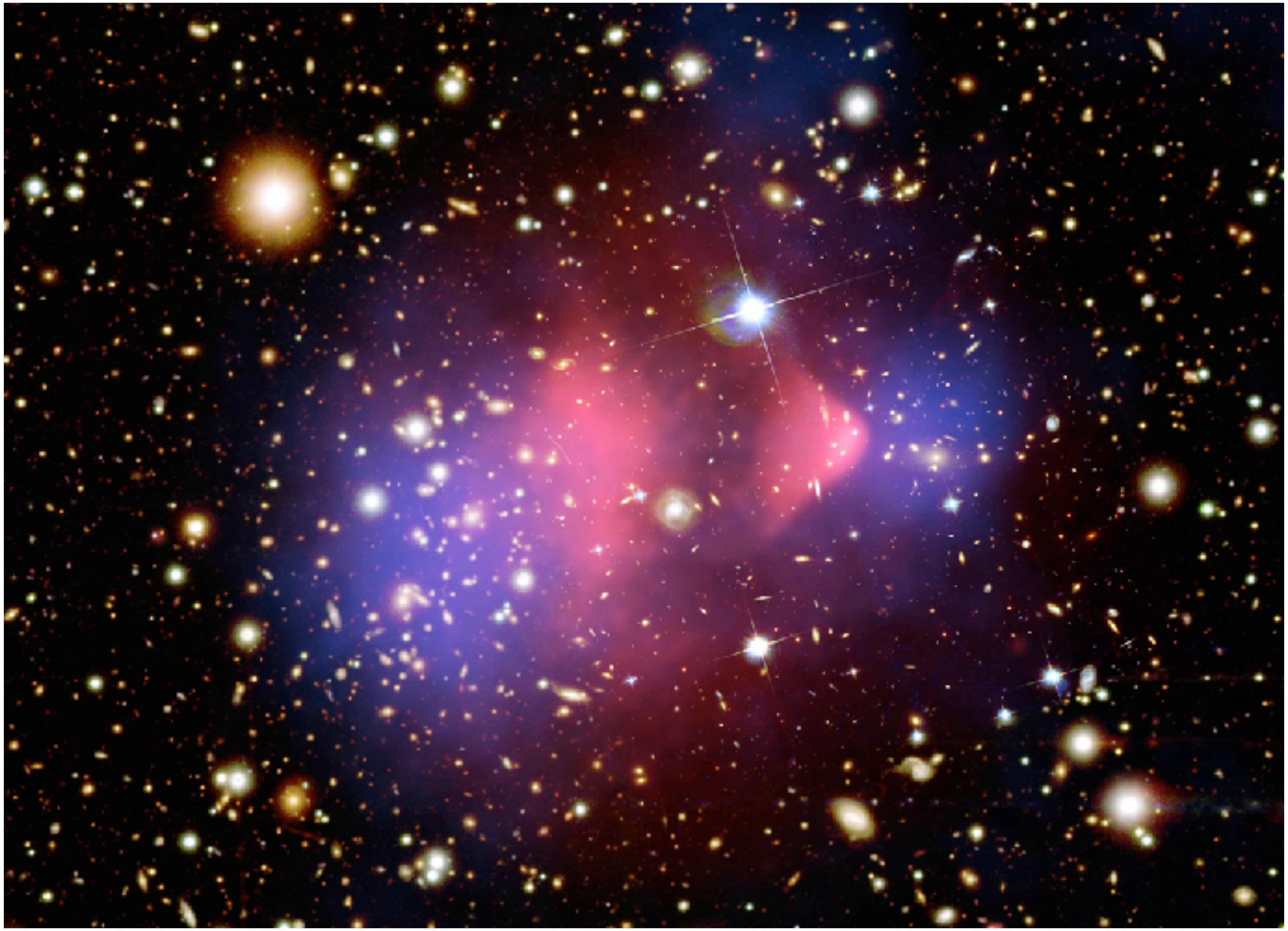
New Experimental Searches for Dark Matter

Surjeet Rajendran,
UC Berkeley

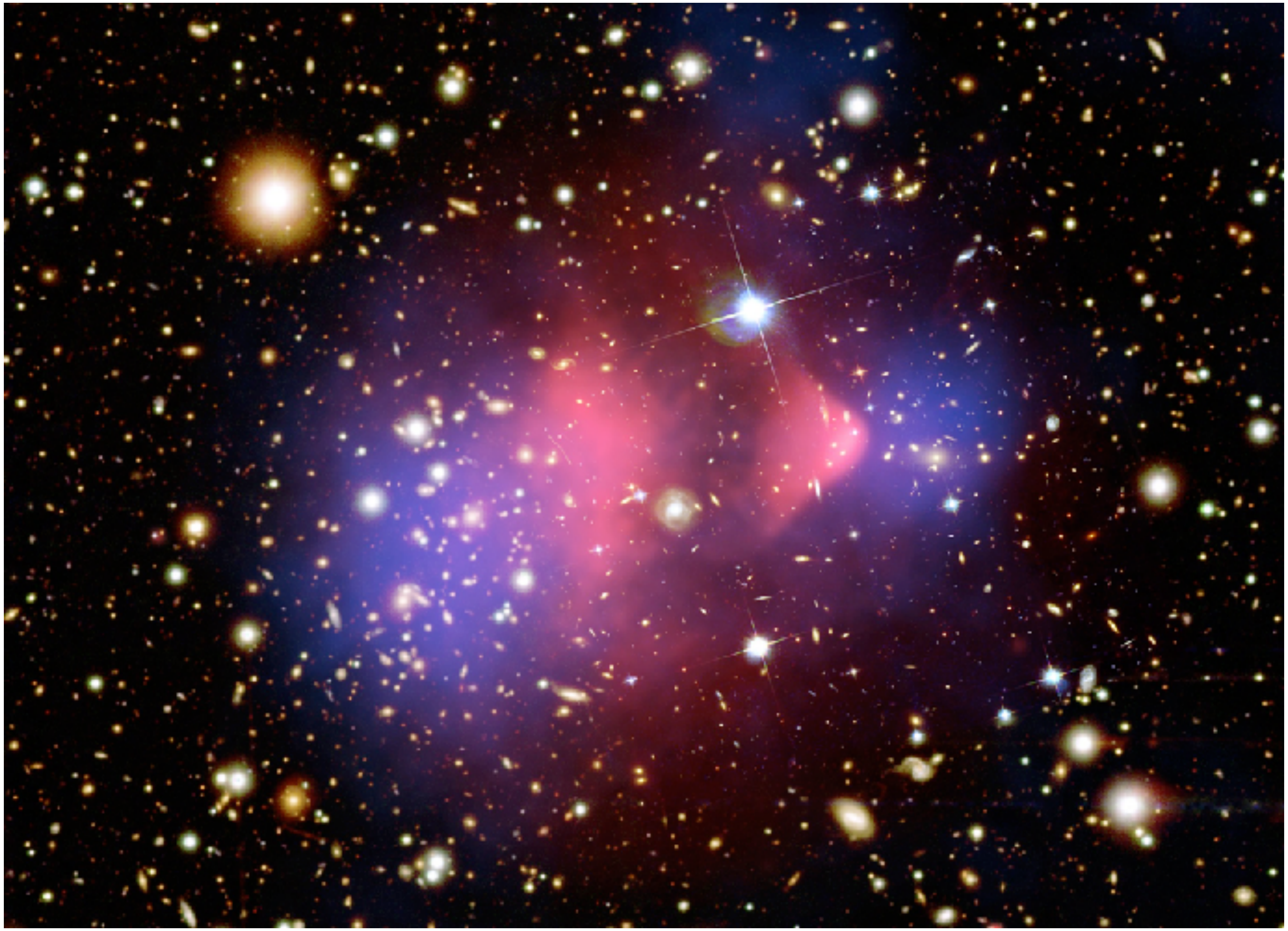
Dark Matter



A New Particle

Non gravitational interactions?

Dark Matter



A New Particle

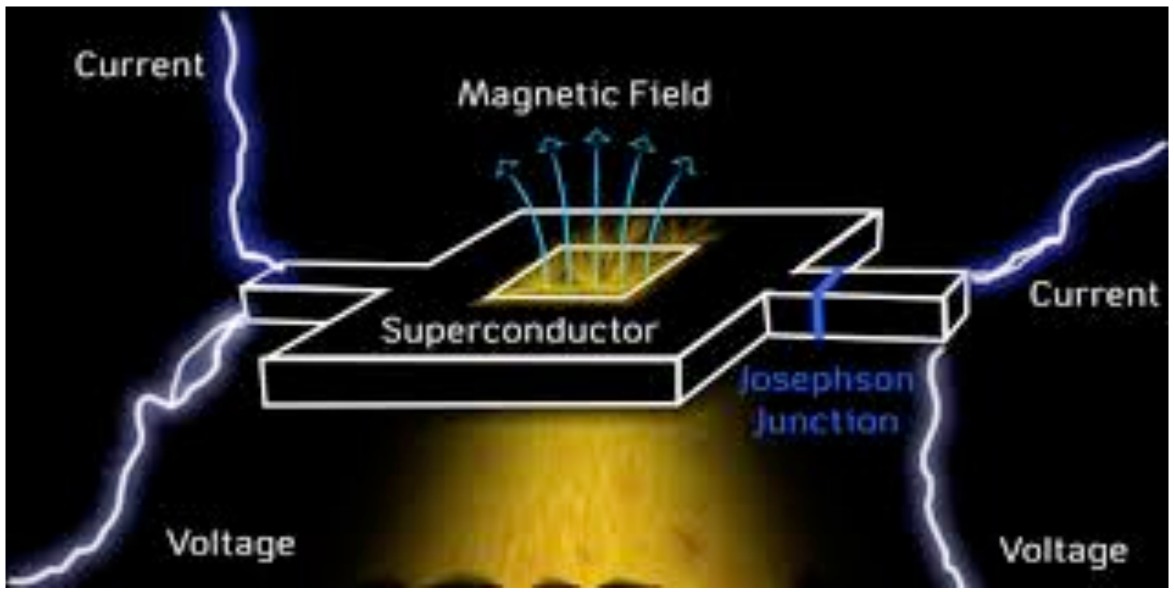
Non gravitational interactions?

How do we detect them?

Weak effects. Need high precision

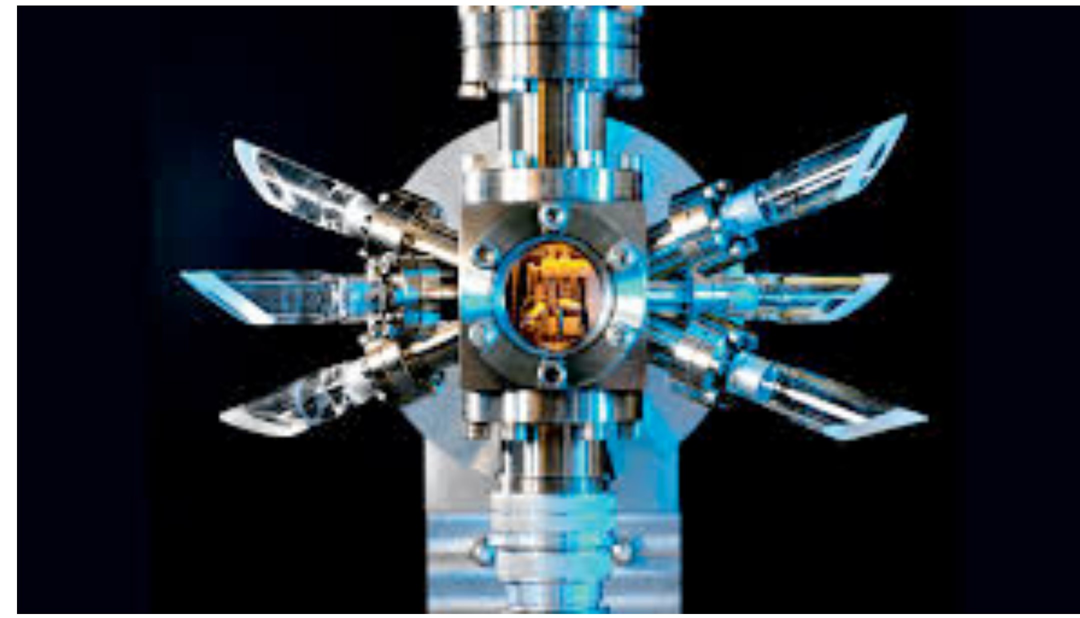
Precision Instruments

Impressive developments in the past two decades



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

(SQUIDs, atomic magnetometers)



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(atom and optical
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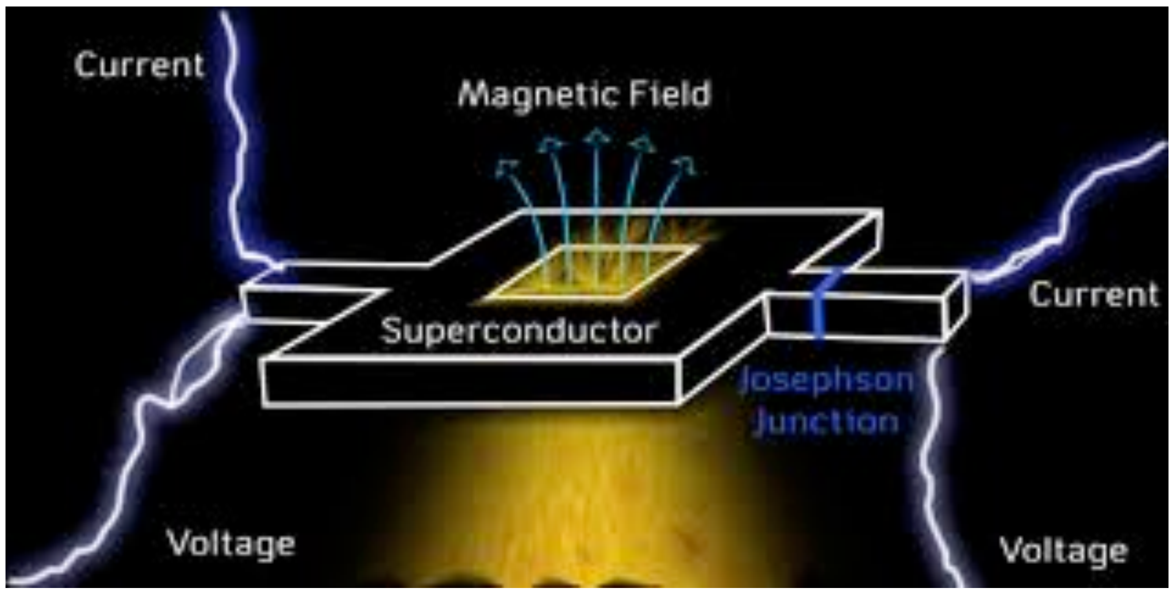

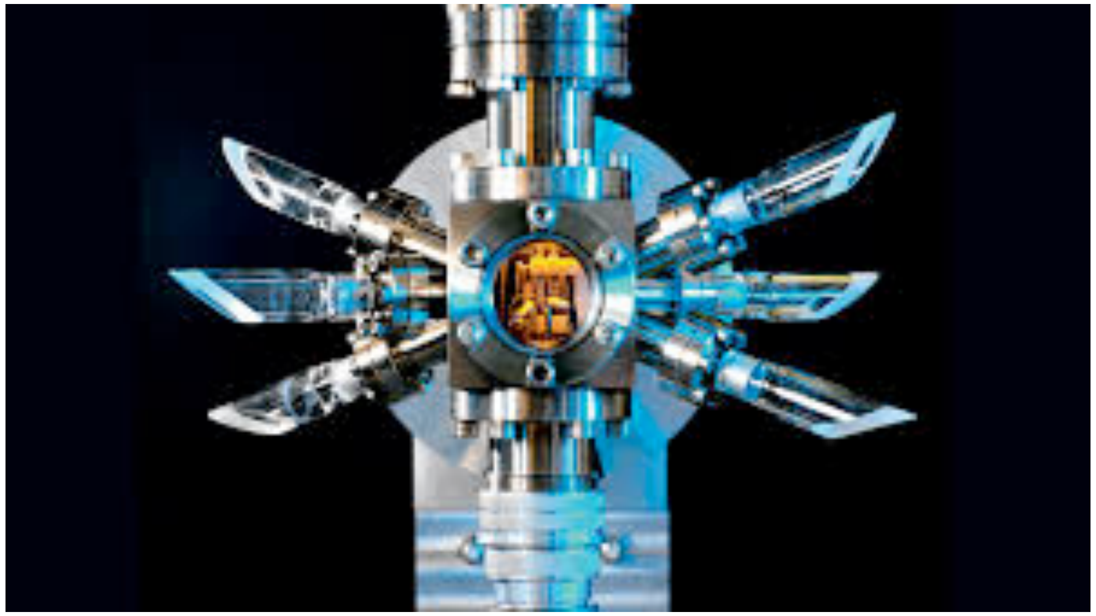

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Rapid technological advancements

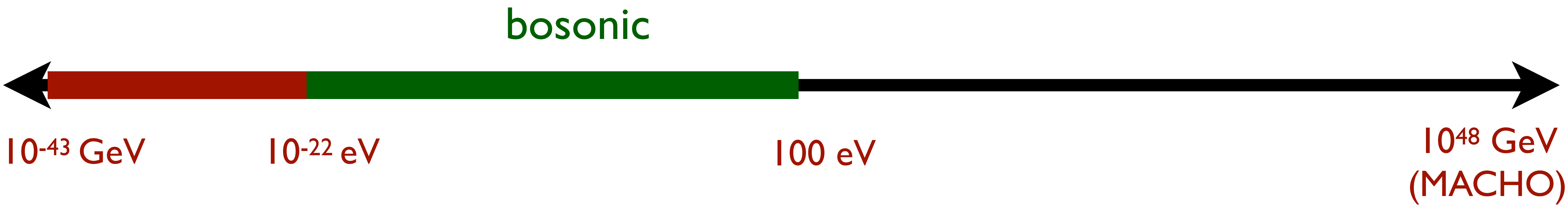
Use to detect new physics?

The Dark Matter Landscape

10^{-43} GeV

10^{48} GeV
(MACHO)

The Dark Matter Landscape



Fit in galaxy

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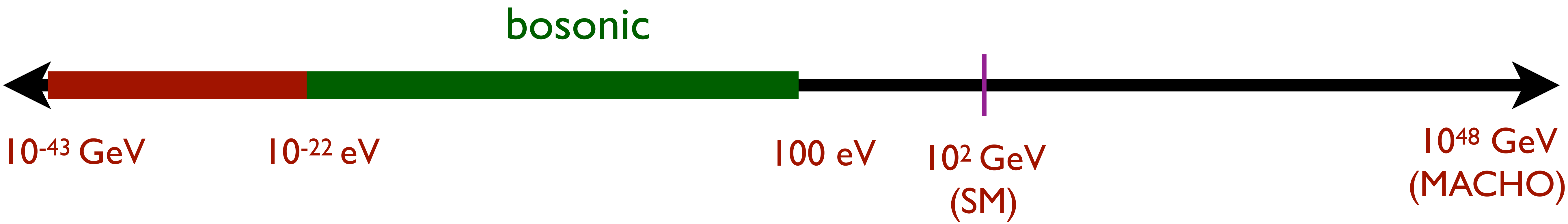

Fit in galaxy

Standard Model scale ~ 100 GeV

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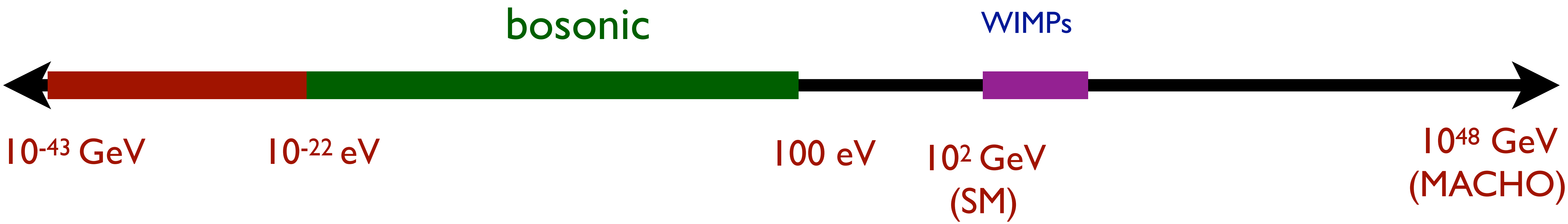

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One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)
Soon to hit solar neutrino floor

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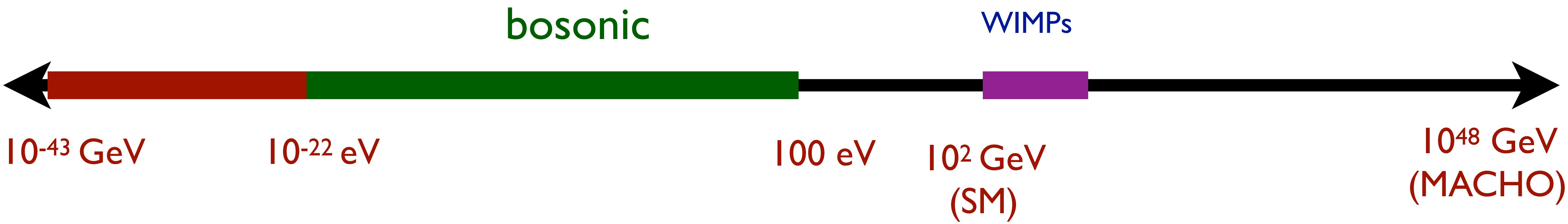

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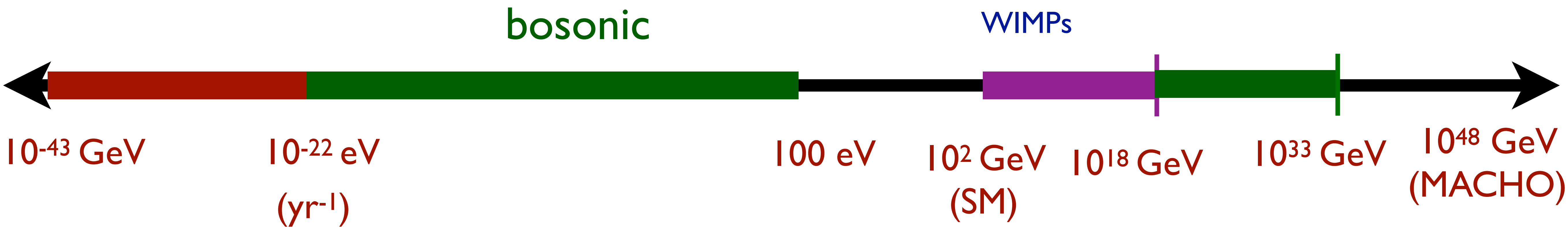

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WIMP Experiments: Sensitive up to 10^{18} GeV

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. Ultra-heavy Dark Matter (10^{16} GeV - 10^{33} GeV)

5. Conclusions

Bosonic Dark Matter

Photons

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

Detect Photon by measuring time varying field

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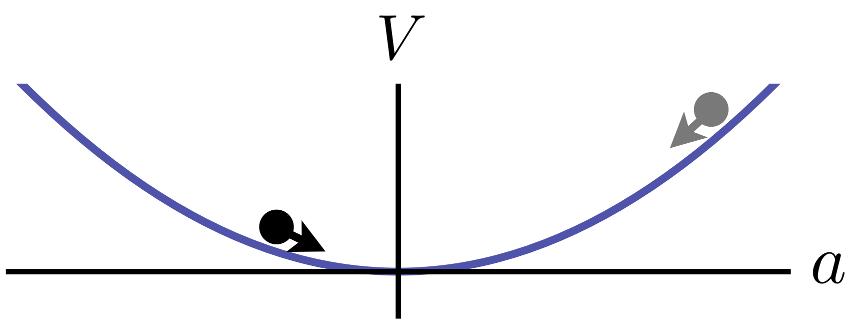
Dark Bosons

Early Universe:
Misalignment Mechanism



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

Spatially uniform, oscillating field

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

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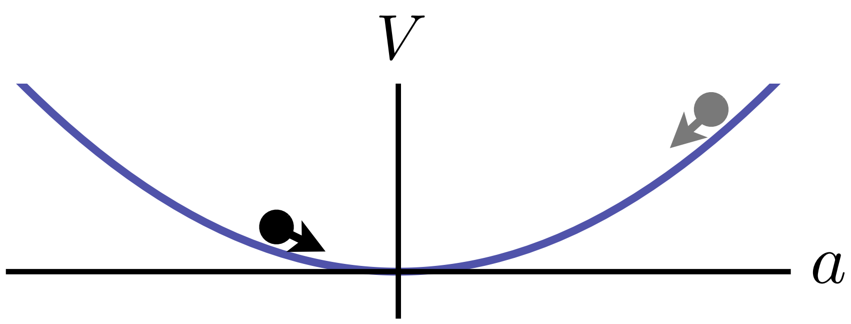

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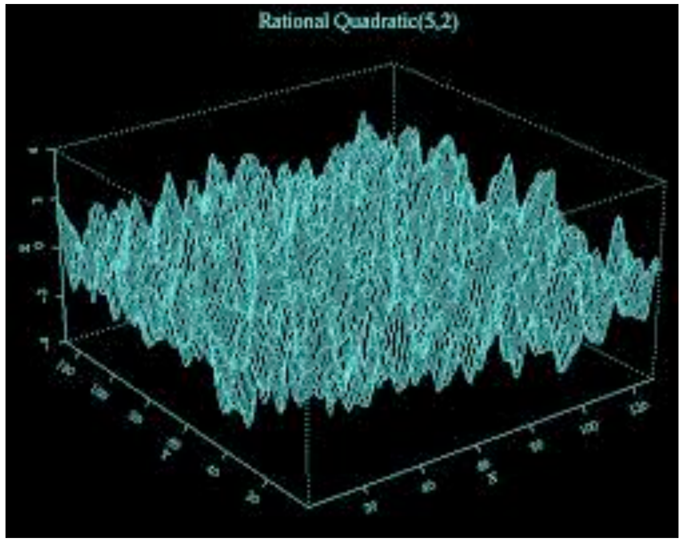

Correlation length
$\sim 1/(m_a v)$

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

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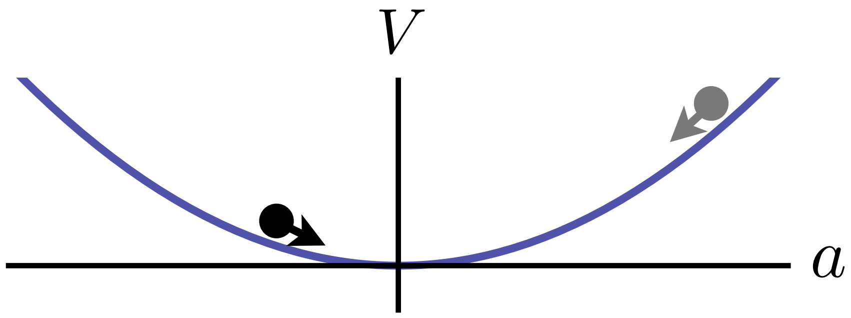

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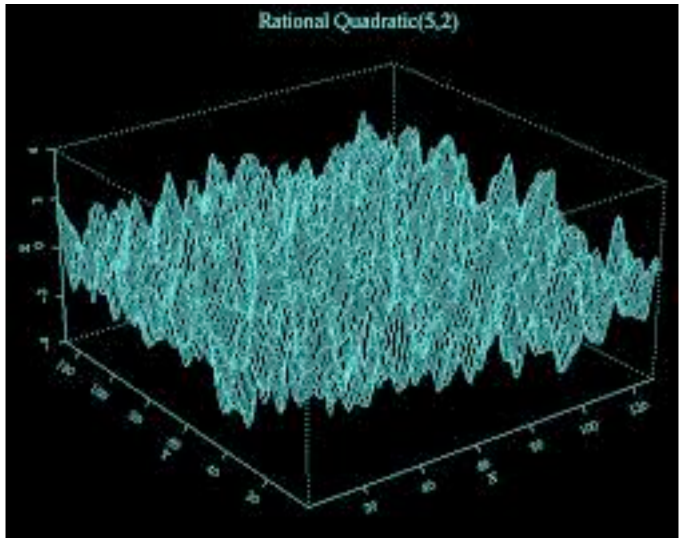

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Coherence Time $\sim 1/(m_a v^2)$ ~ 1 s (MHz/m_a)

Detect effects of oscillating dark matter field

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

What kind of Bosons?

Naturalness. Structure set by symmetries.

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Spin 0

Axions or ultra weak coupling

Many UV theories

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Many UV theories

E&M	QCD	Spin	Higgs
$\left(\frac{a}{f_a} F\tilde{F}\right)$	$\left(\frac{a}{f_a} G\tilde{G}\right)$	$\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma_5 N\right)$	$\left(g\phi H^2\right)$
General Axions	QCD Axion	General Axions	Higgs Portal/ Relaxion

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Standard Model couplings

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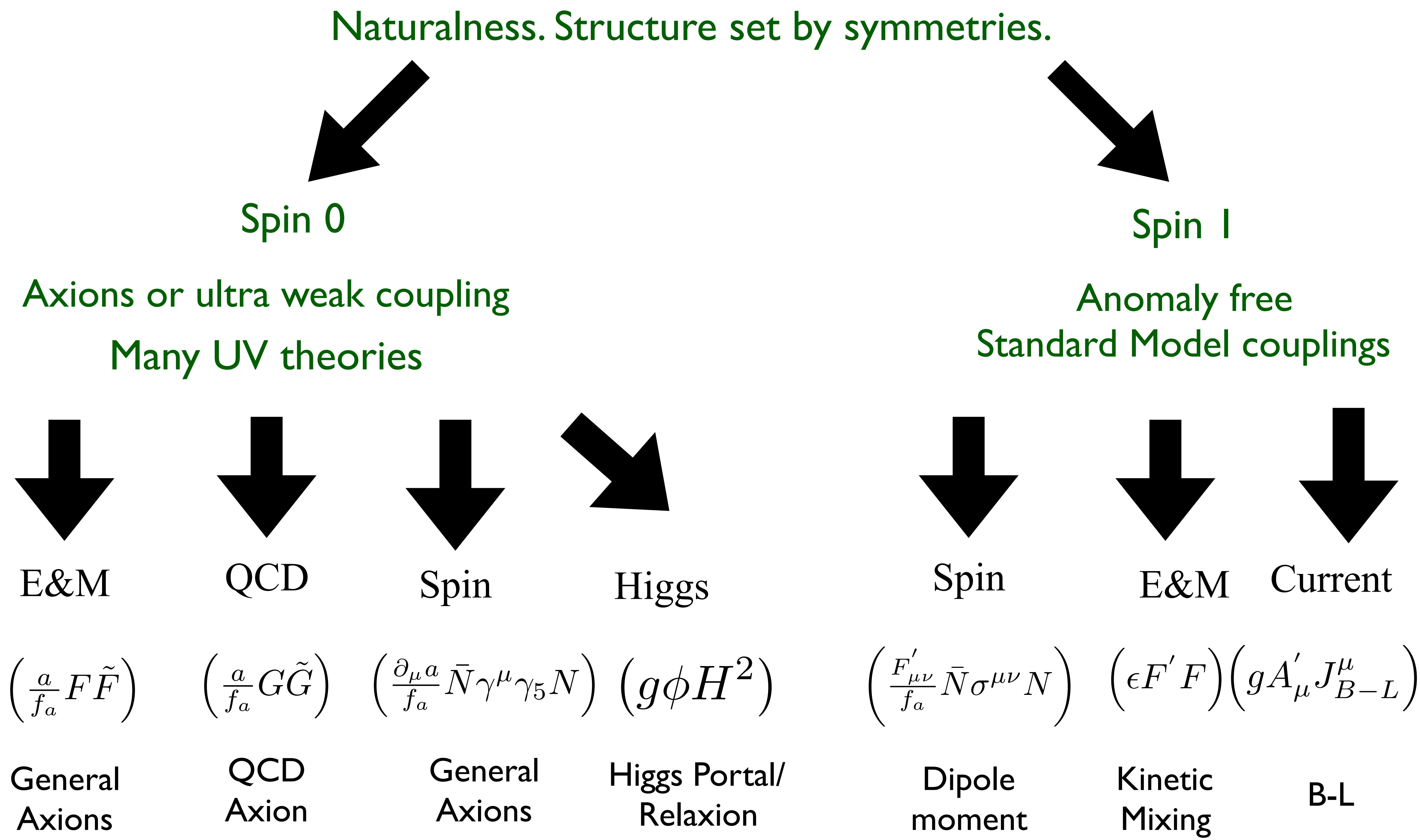

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Standard Model couplings

Spin	E&M	Current
$\left(\frac{F'_{\mu\nu}}{f_a}\bar{N}\sigma^{\mu\nu}N\right)$	$\left(\epsilon F' F\right)$	$\left(g A'_\mu J^\mu_{B-L}\right)$
Dipole moment	Kinetic Mixing	B-L

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

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

Observable Effects

What can the dark matter wind do?

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What can the dark matter wind do?

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Dark Matter

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

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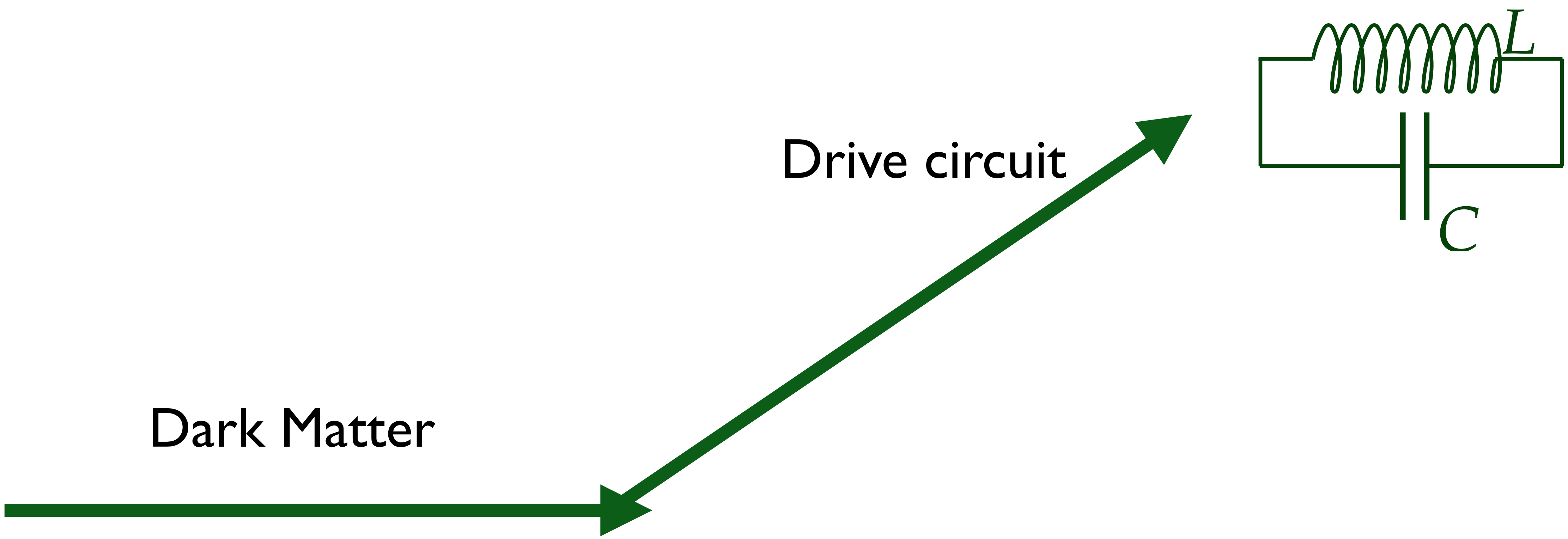

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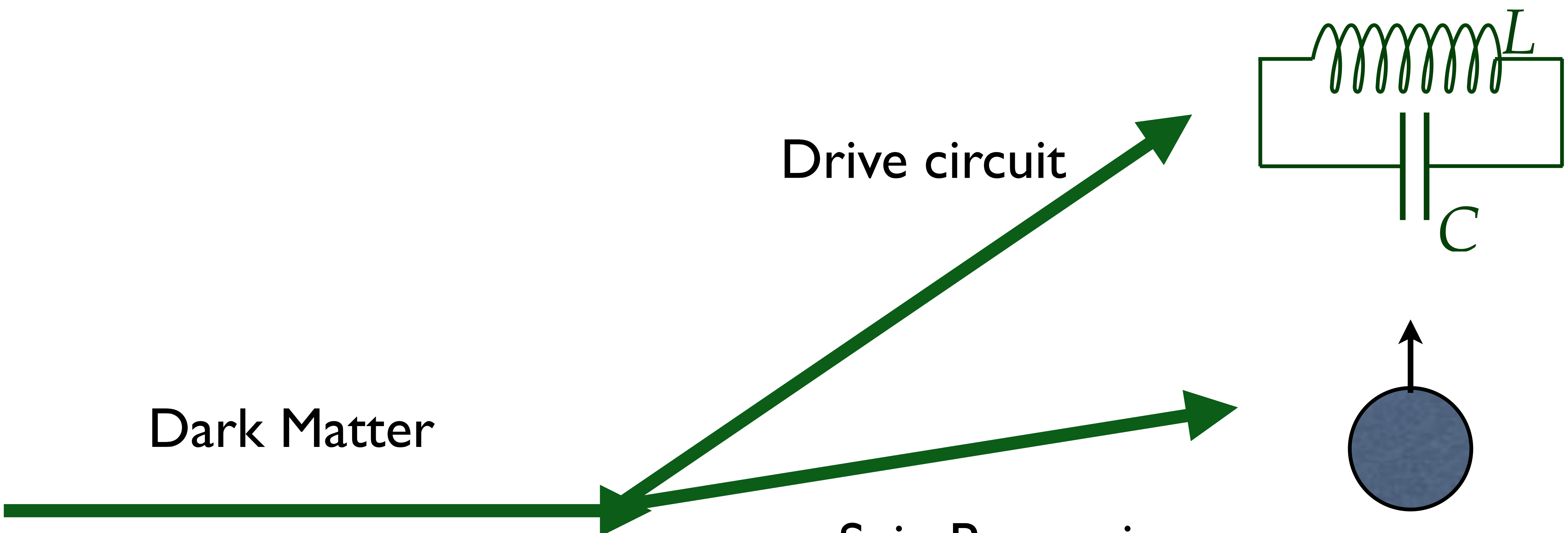

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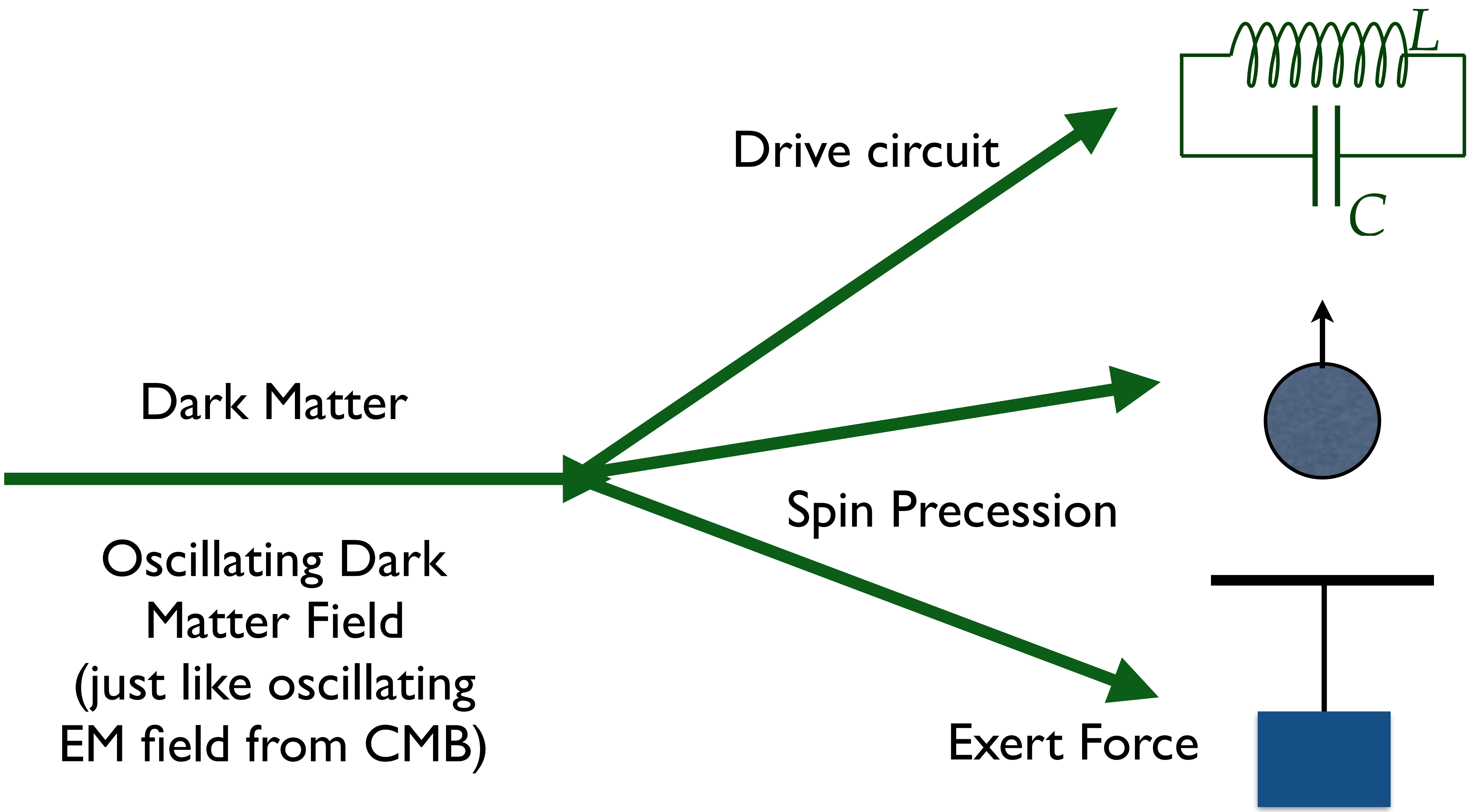

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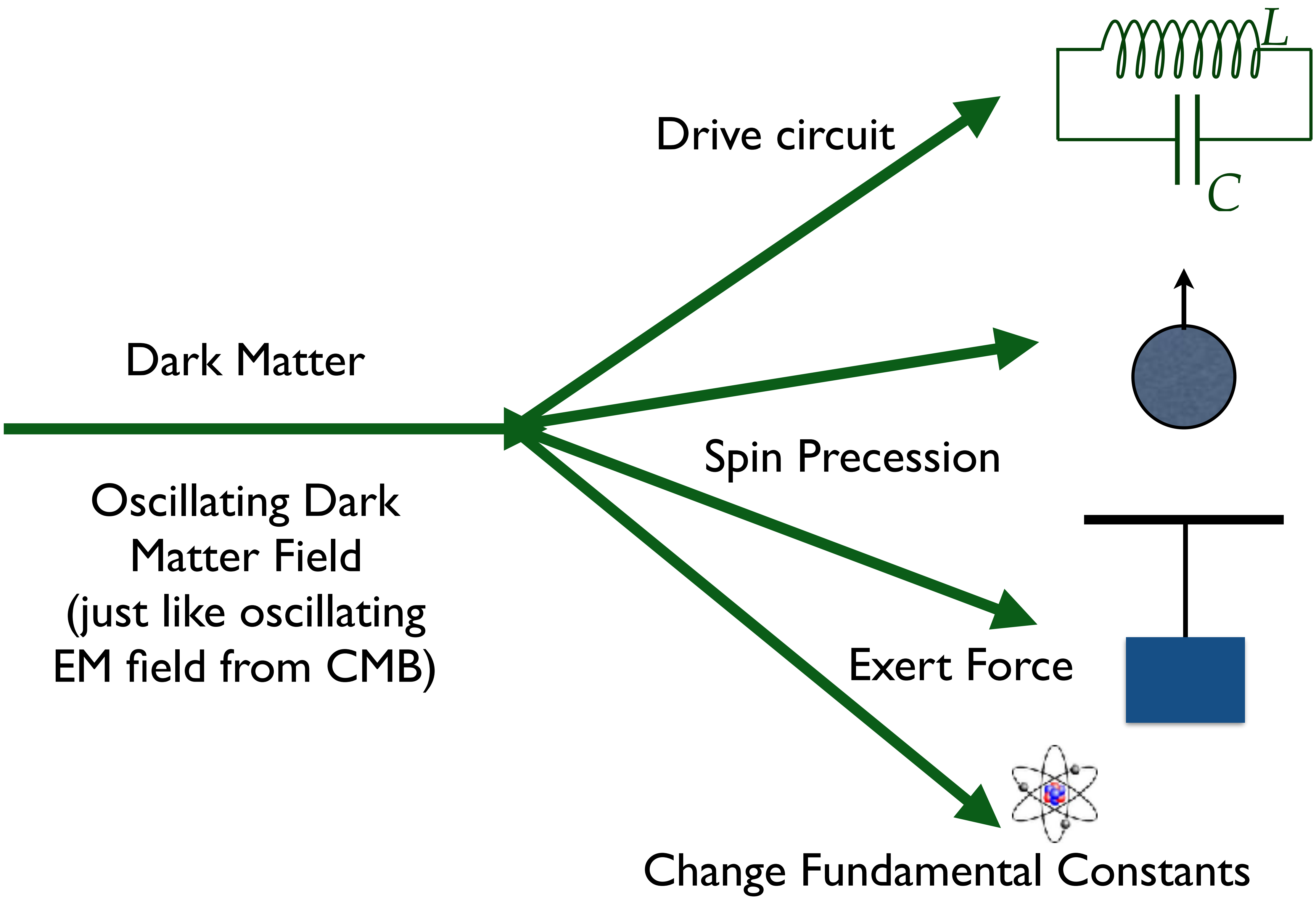

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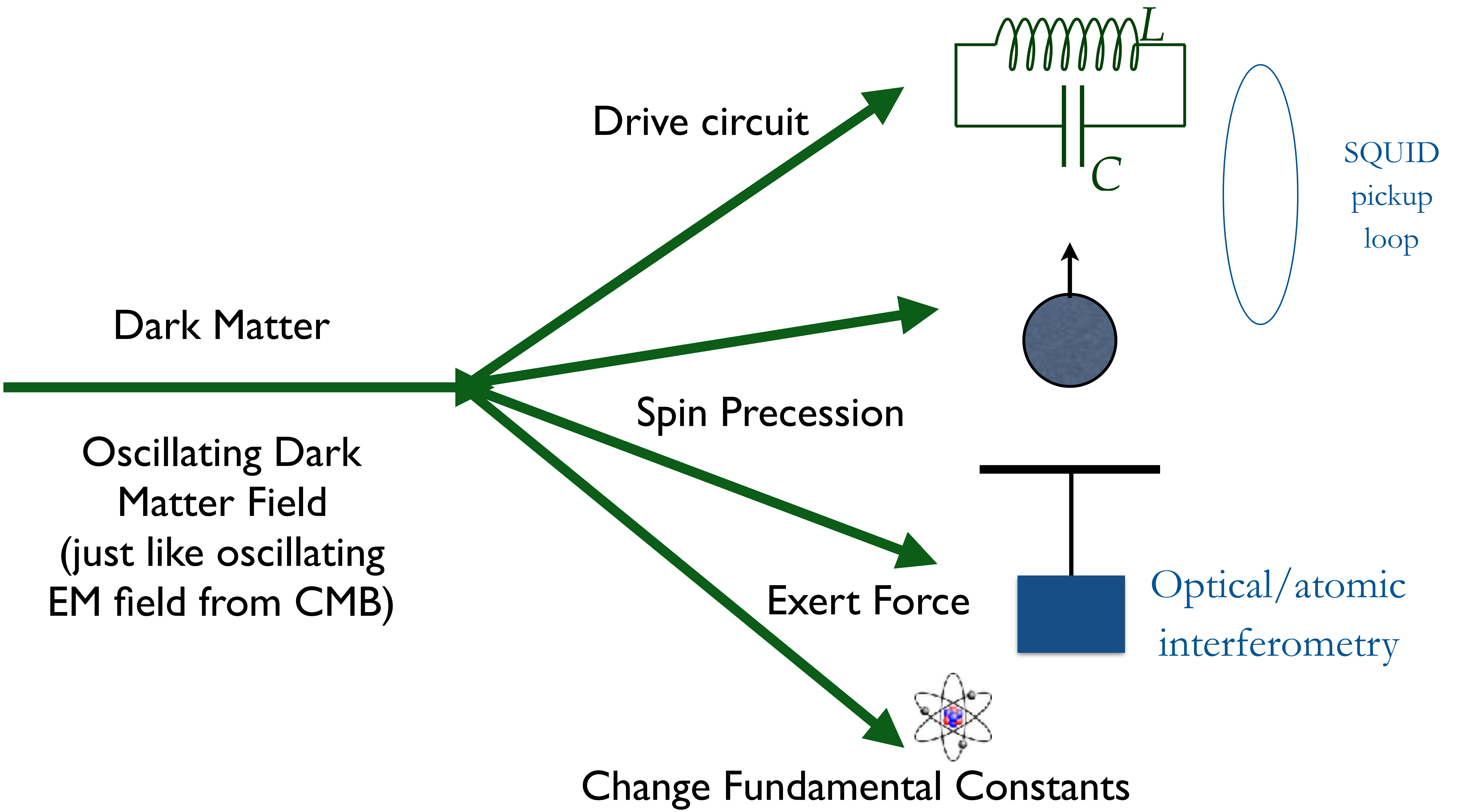

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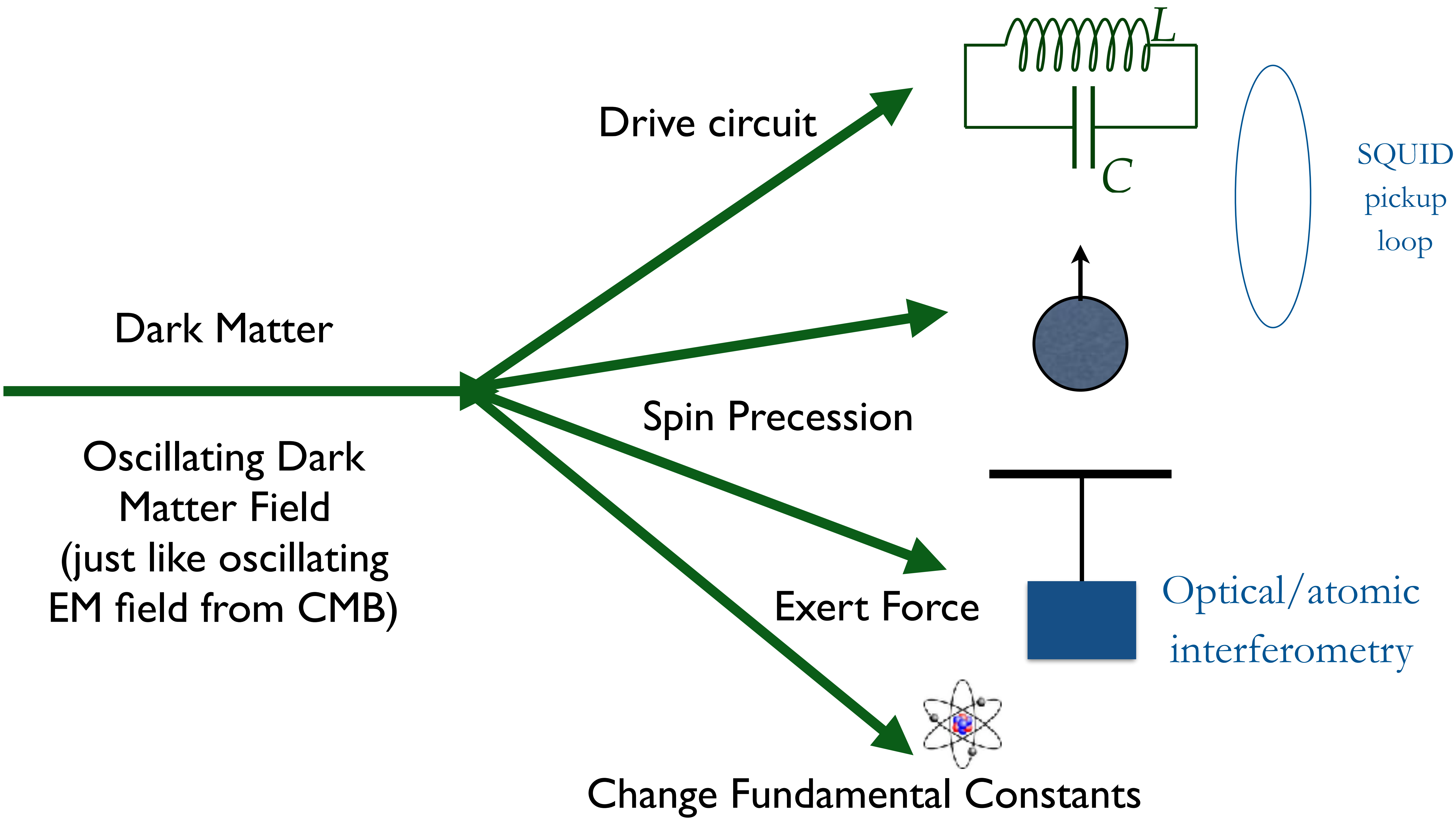

a/c effect, narrow bandwidth around dark matter mass

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

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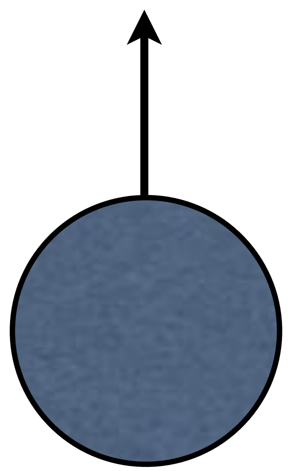
General Axions

Neutron



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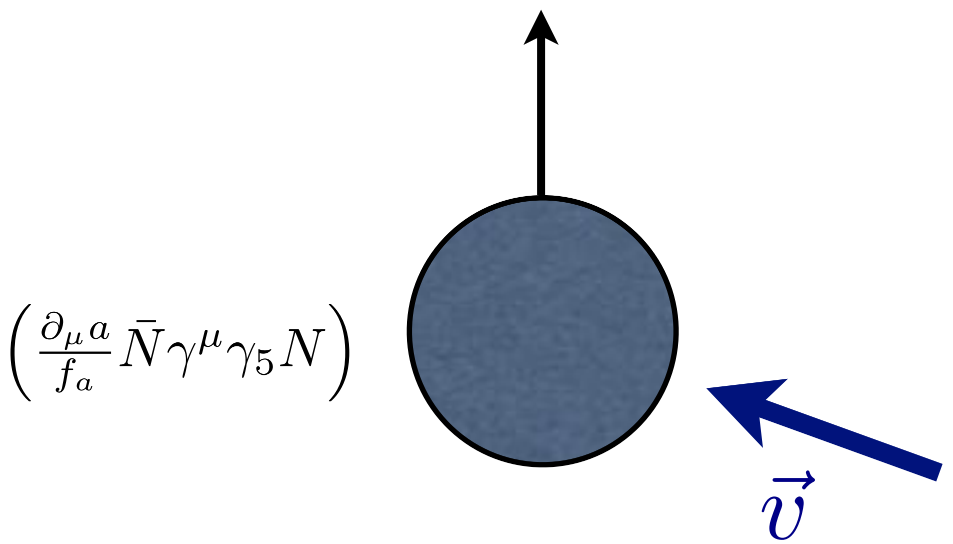
General Axions

Neutron in
Axion Wind



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

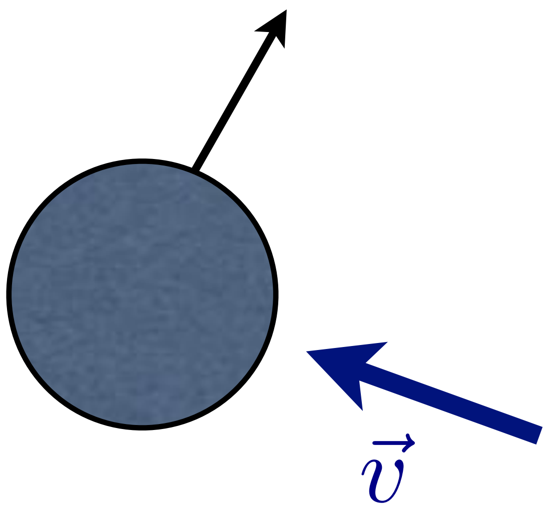
Spin rotates about
dark matter velocity

CASPEr: Axion Effects on Spin

General Axions

Neutron in Axion Wind

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



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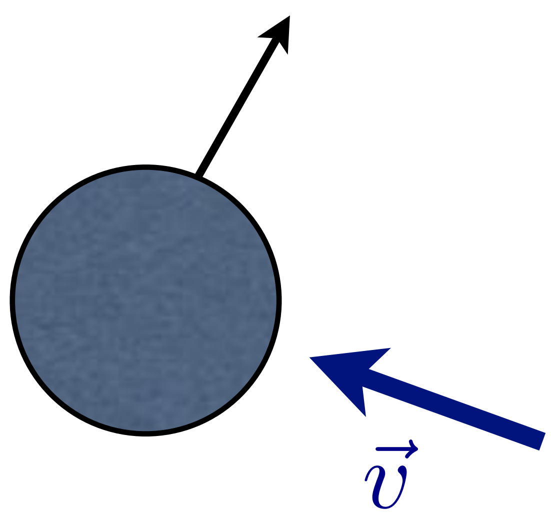

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Effective time varying magnetic field

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

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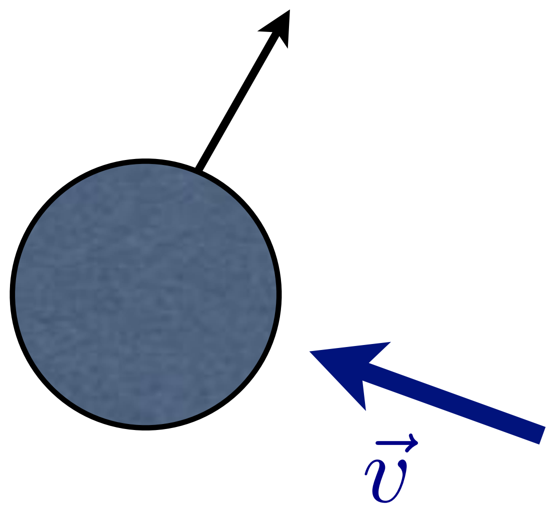

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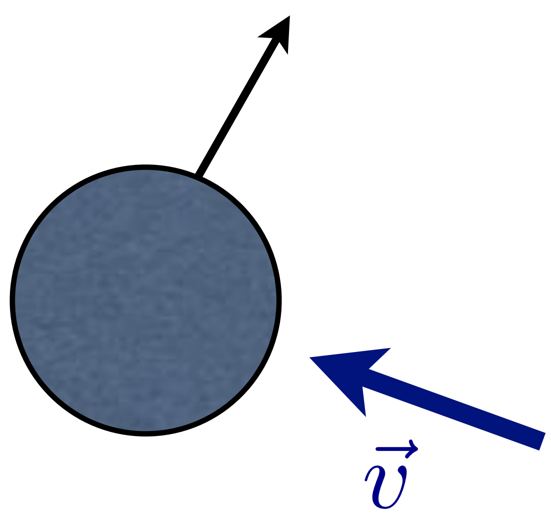

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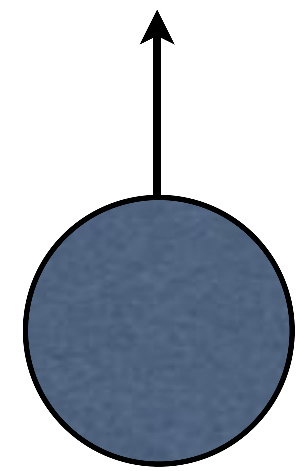

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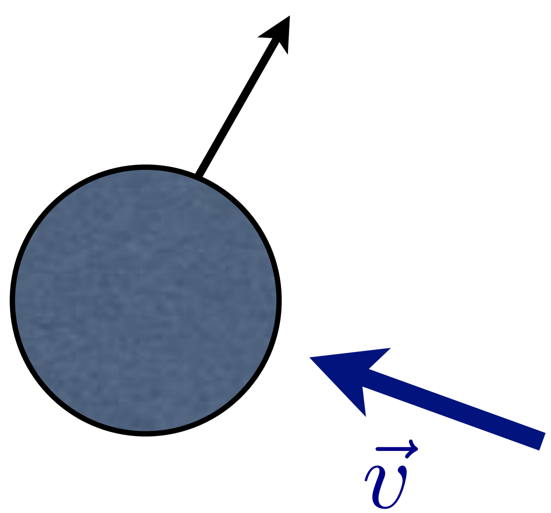

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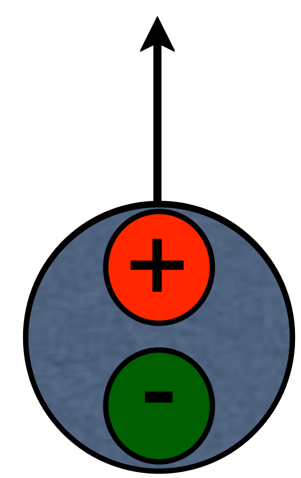

$\left(\frac{a}{f_a}G\tilde{G}\right)$

QCD axion induces electric dipole moment for neutron and proton

Dipole moment along nuclear spin

Oscillating dipole: $d \sim 3\times 10^{-34}\cos(m_a t)\ e\,\mathrm{cm}$

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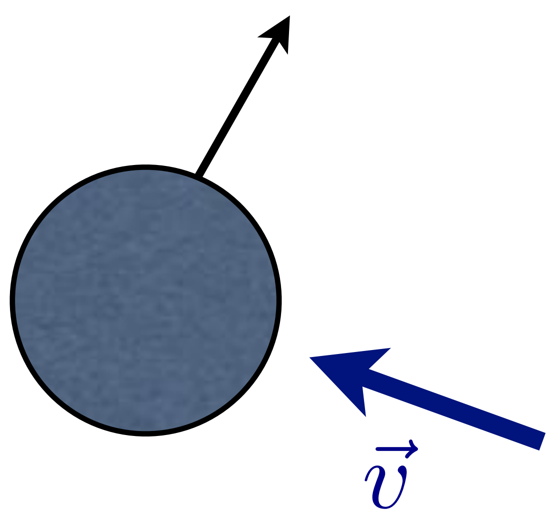

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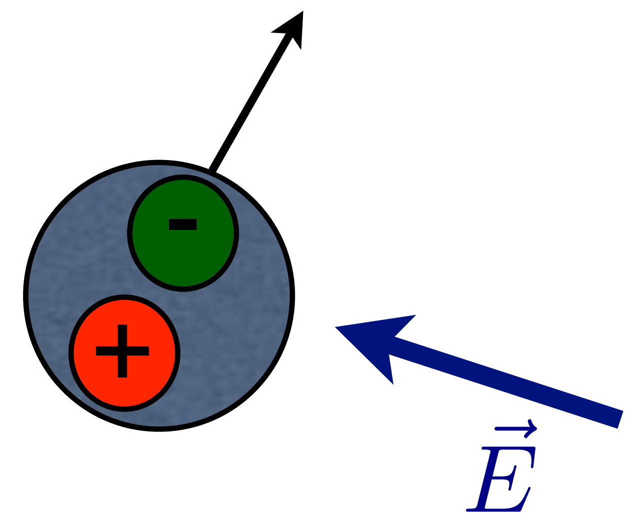

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Apply electric field, spin rotates

CASPEr: Axion Effects on Spin

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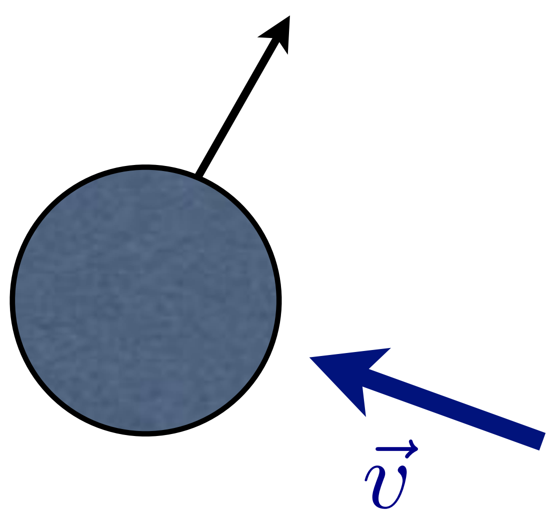

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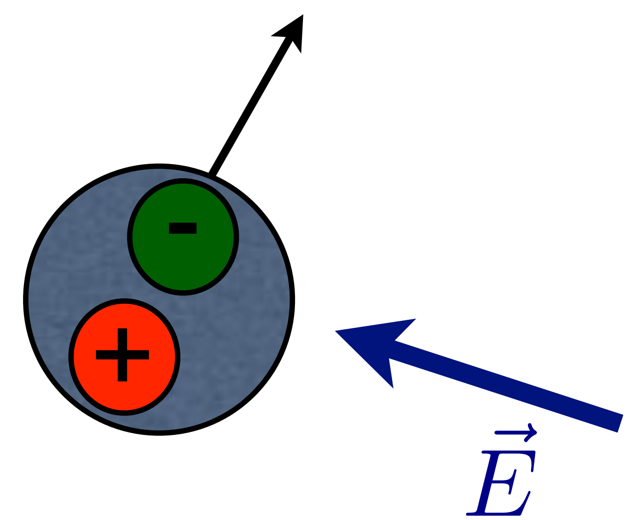

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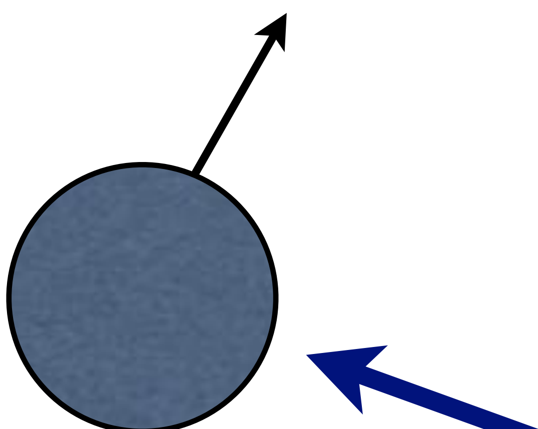

$\vec{v}$

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Measure Spin Rotation, detect Axion

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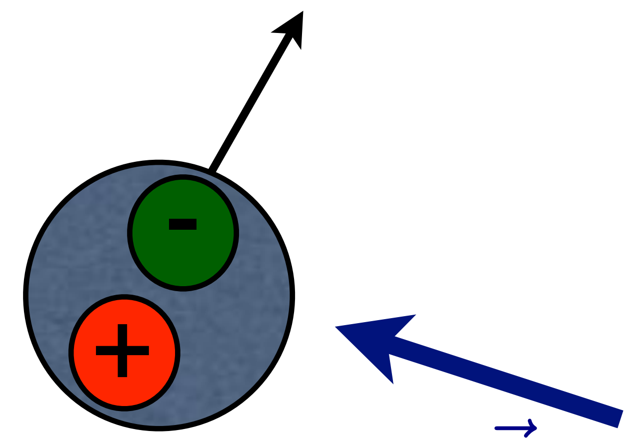

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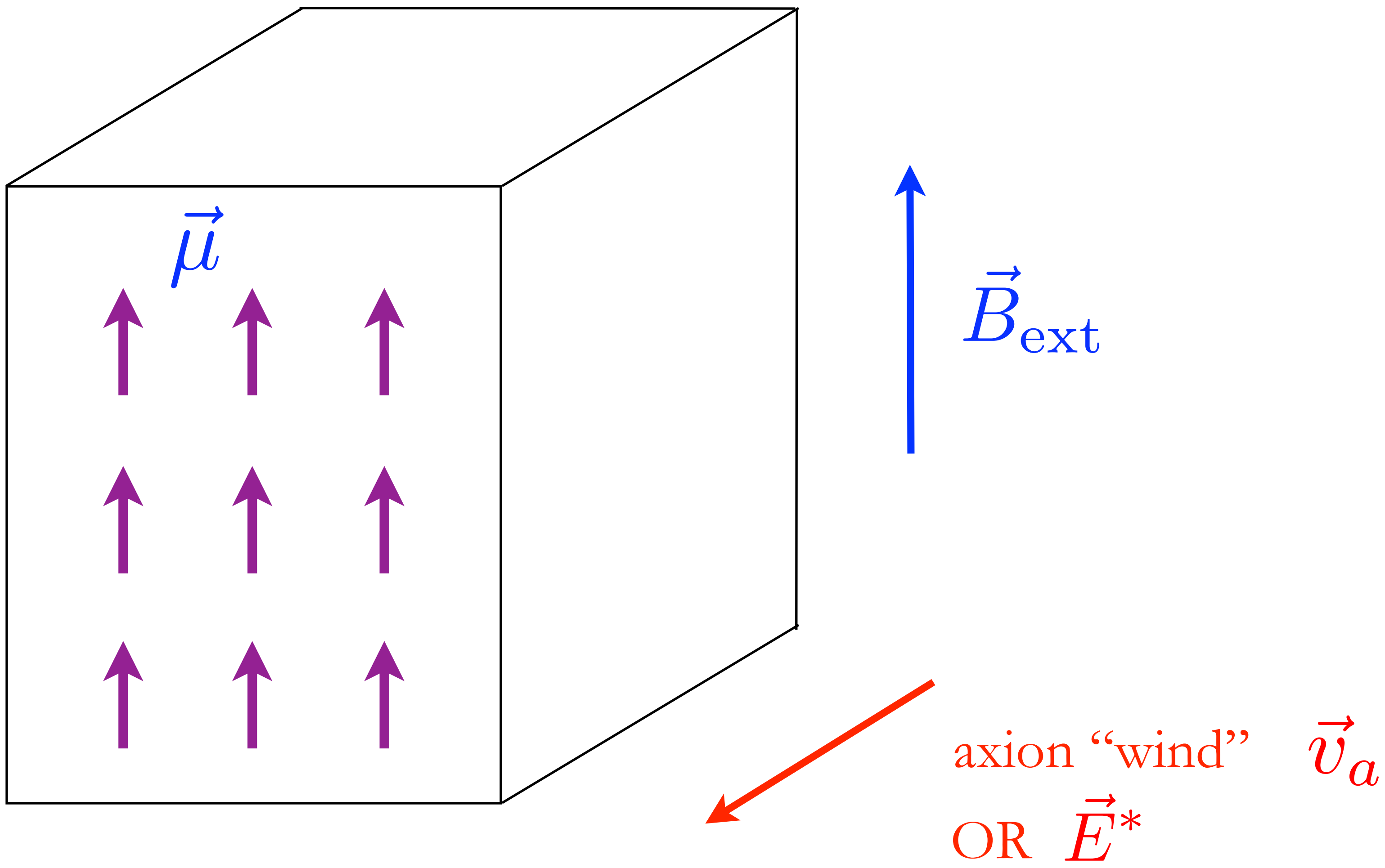
CASPEr

Axion affects physics of nucleus, NMR is sensitive probe



Larmor frequency = axion mass ➔ resonant enhancement

CASPEr

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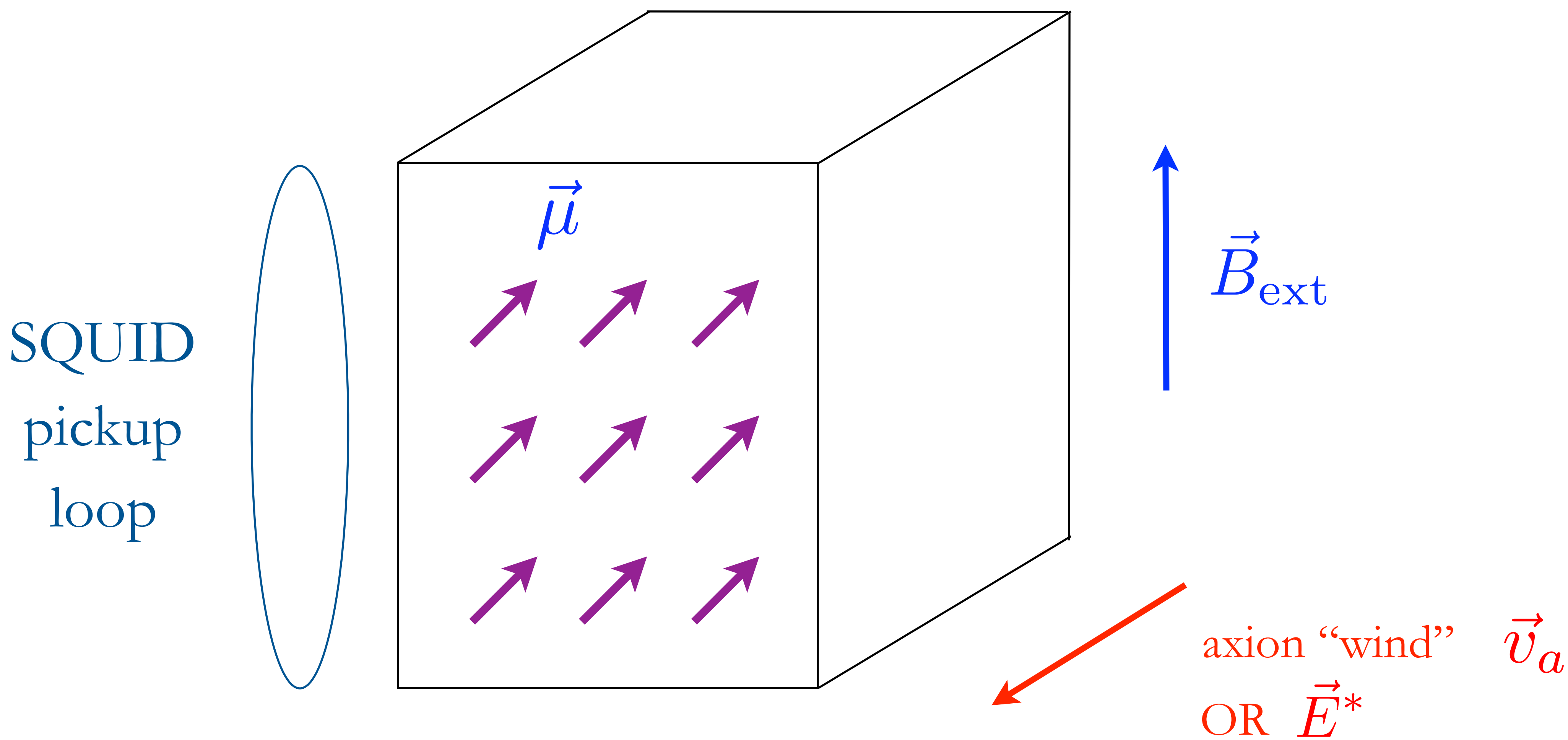


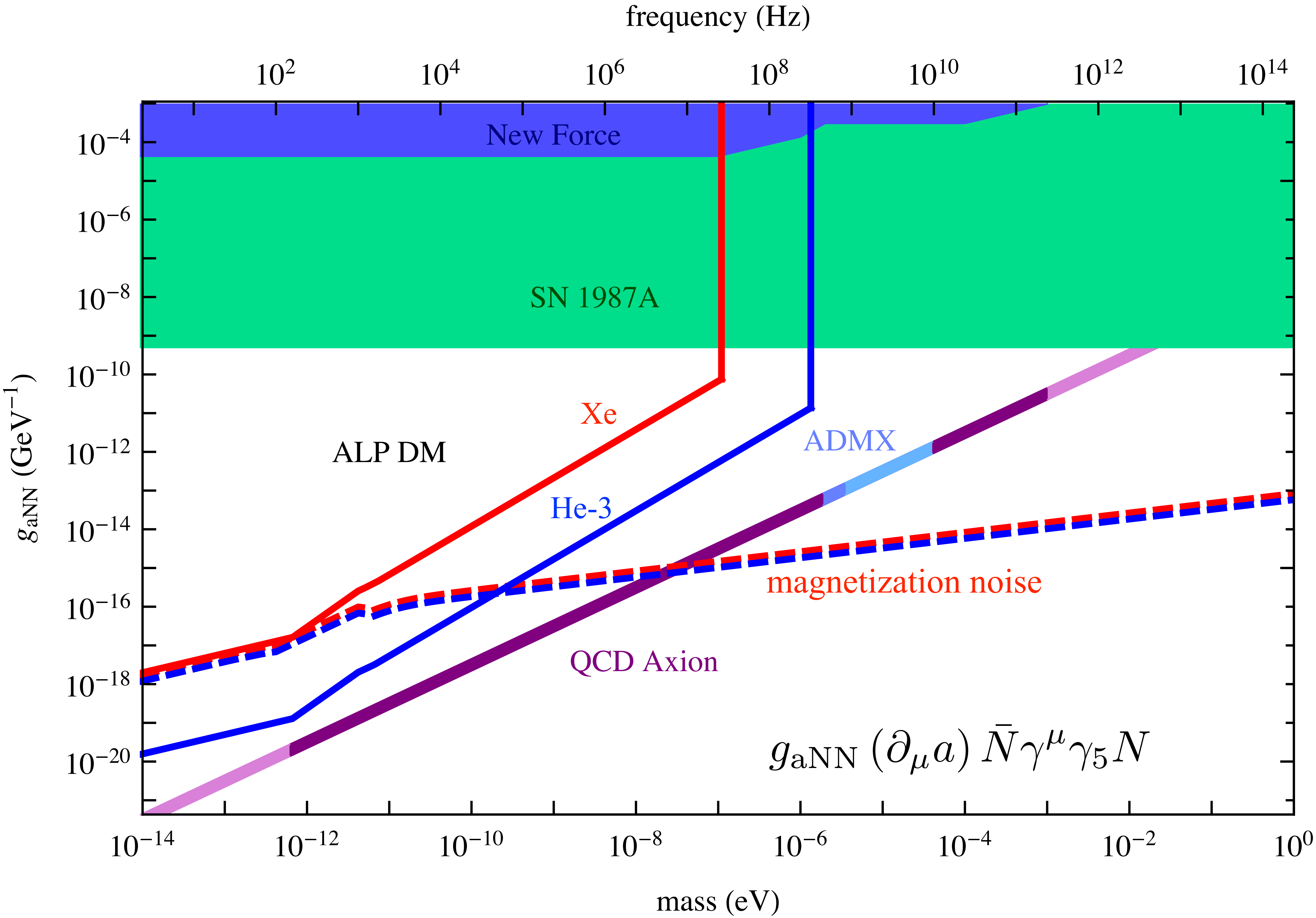
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

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

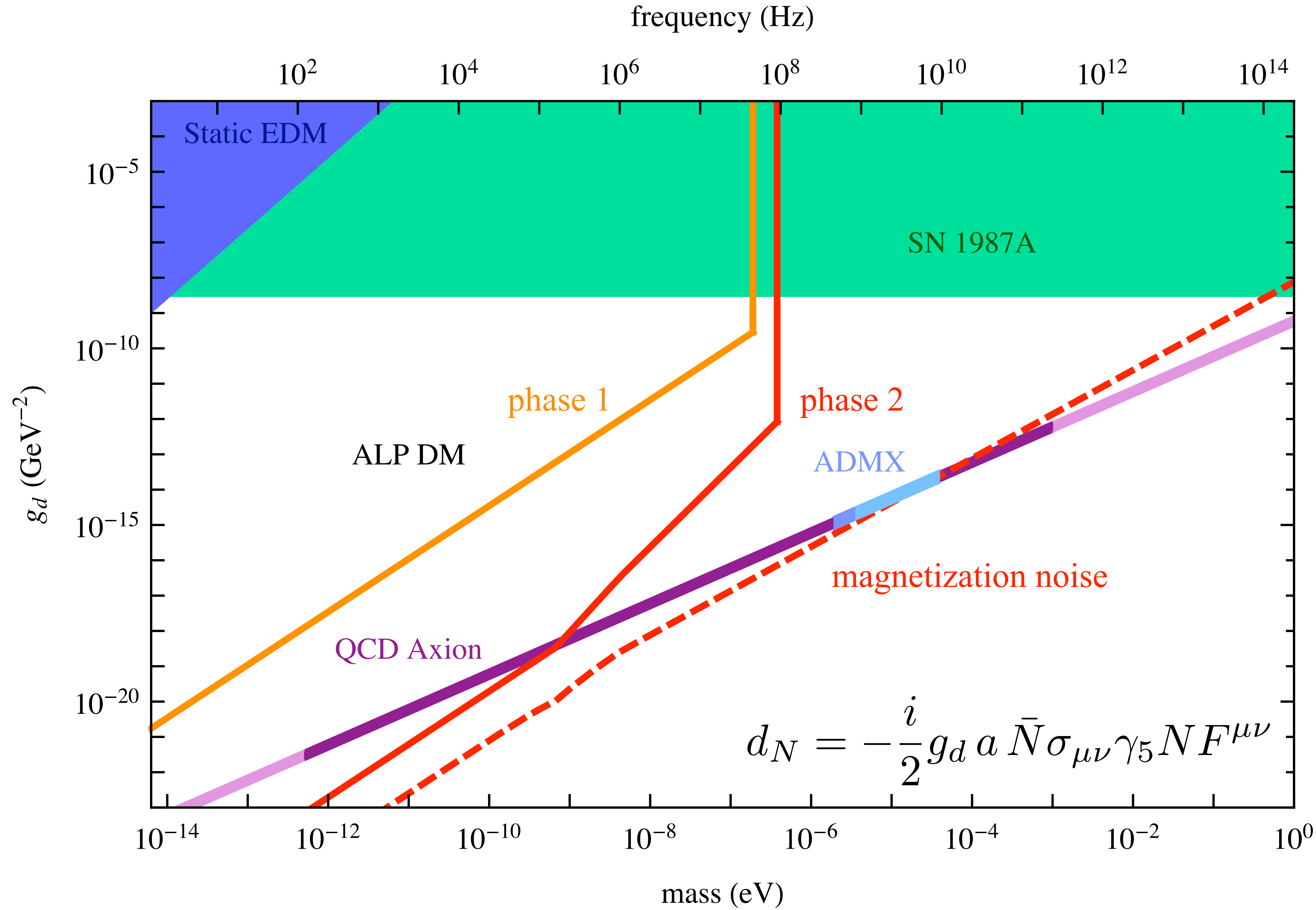
Example materials: LXe, ferroelectric $PbTiO_3$, many others

CASPEr-General Axions



~ year to scan one decade of frequency

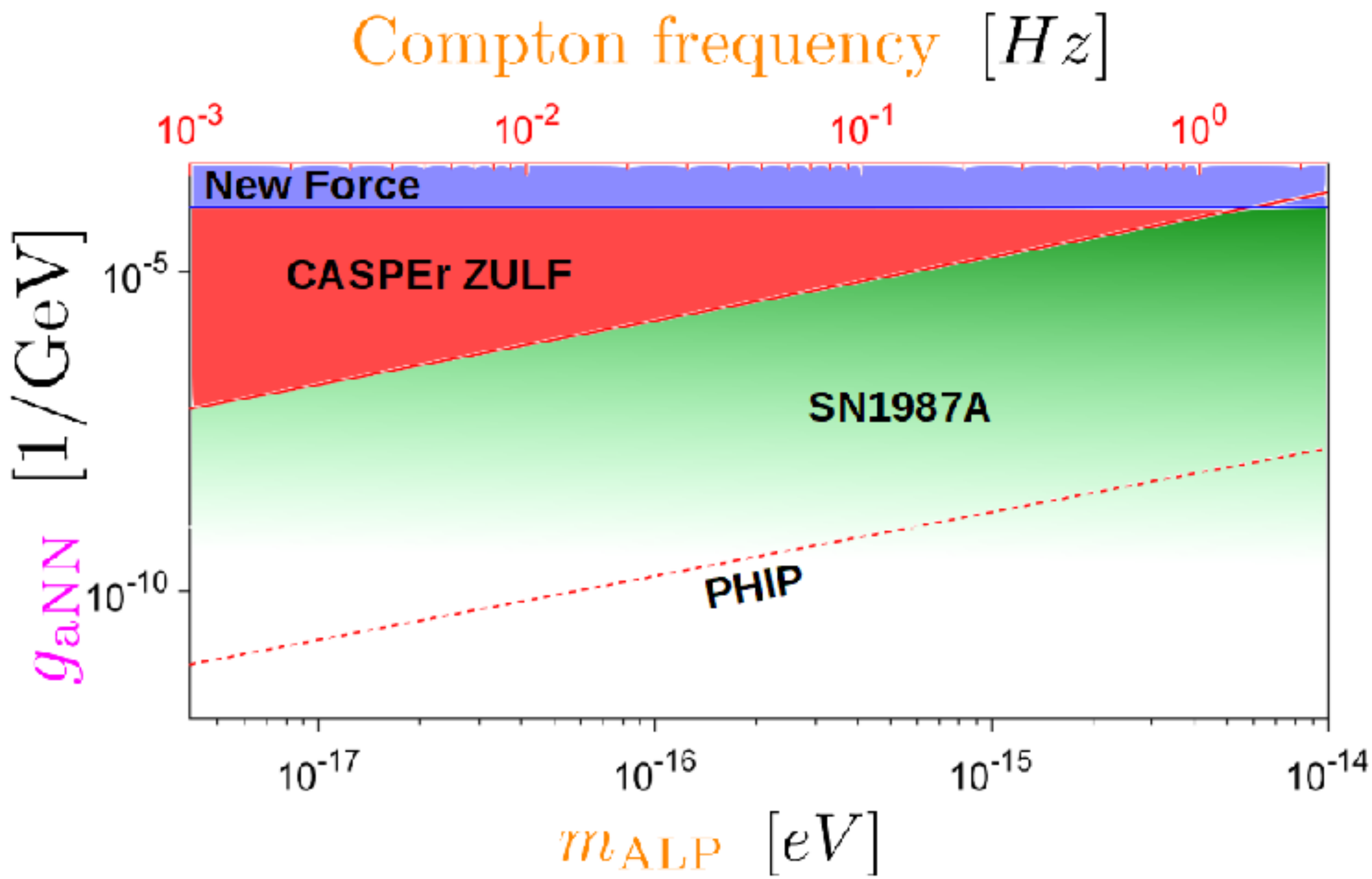
CASPEr-QCD Axion



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

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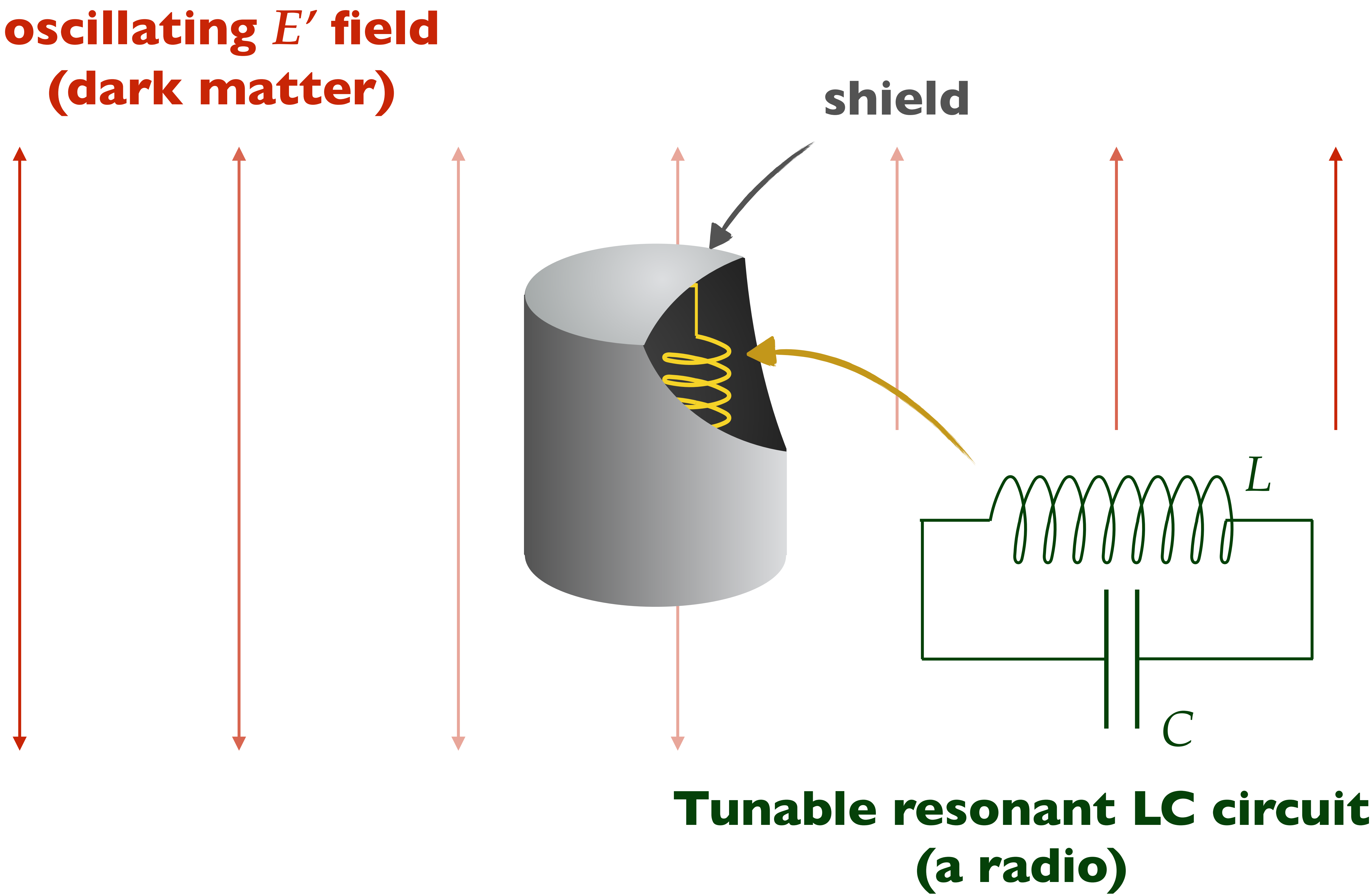
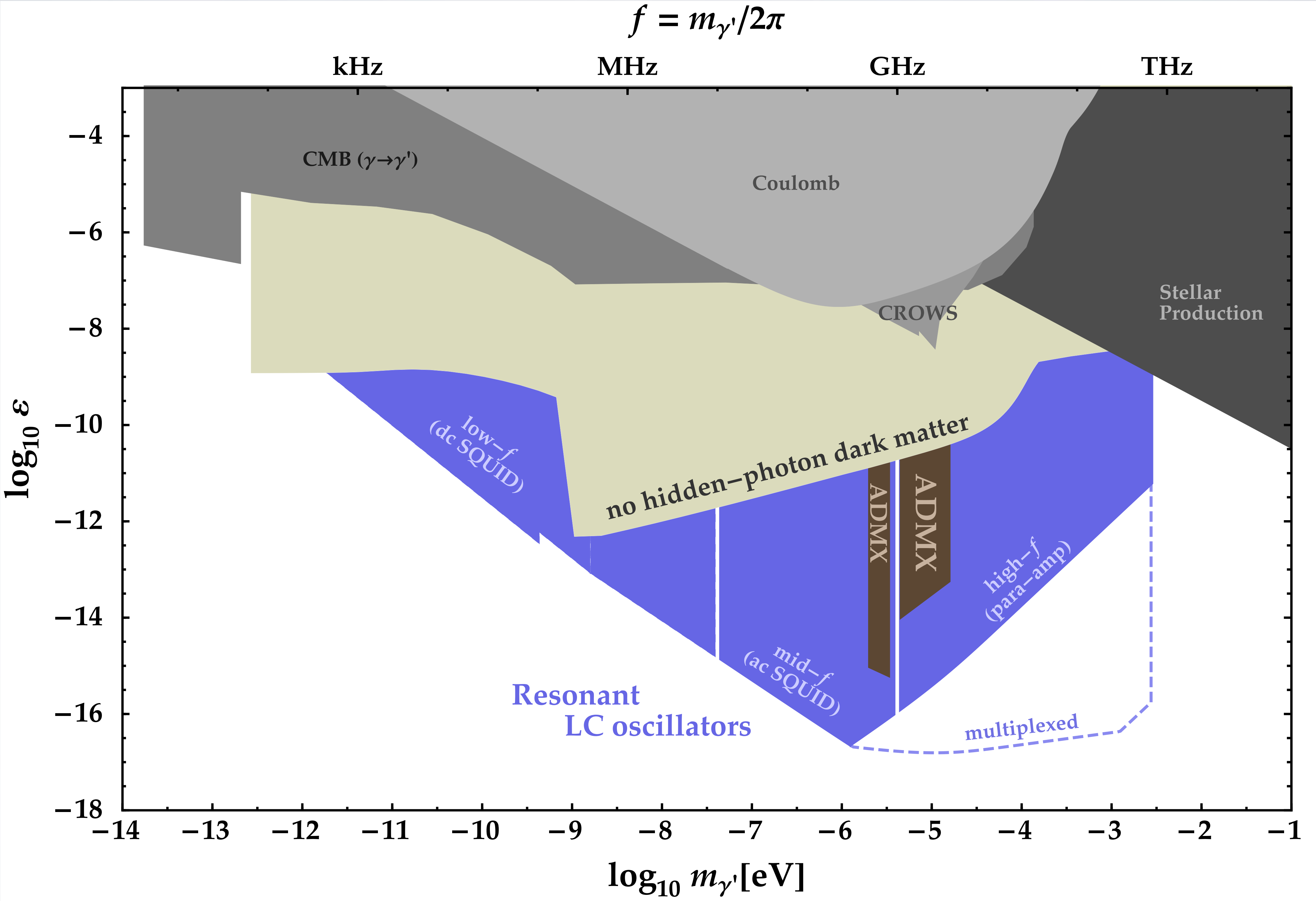
oscillating E' field (dark matter)

can drive current behind EM shield

Dark Matter Radio Station

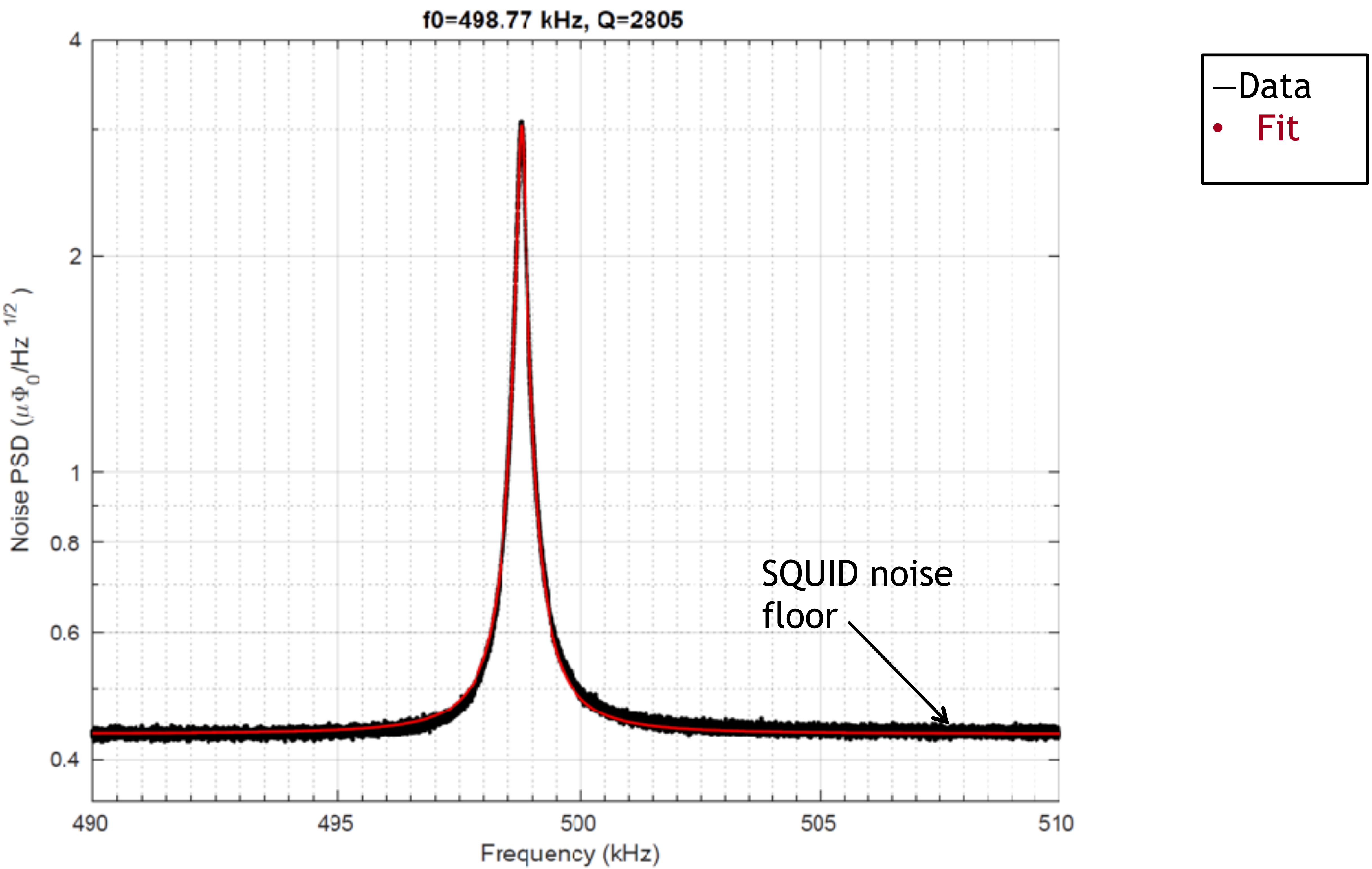


Expected reach



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

DM Radio first data!



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 $g < 10^{-21}$

B-L Dark Matter

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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

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

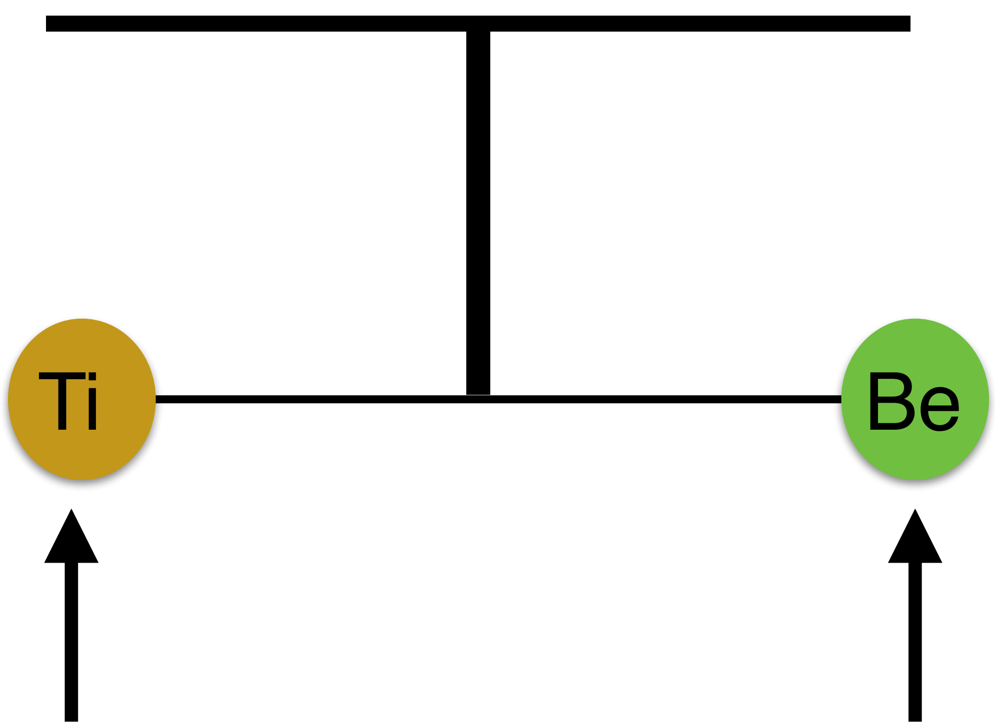
Force violates equivalence principle. Time dependent equivalence principle violation!

Detection Options

Measure relative acceleration between different elements/isotopes.

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

Torsion Balance

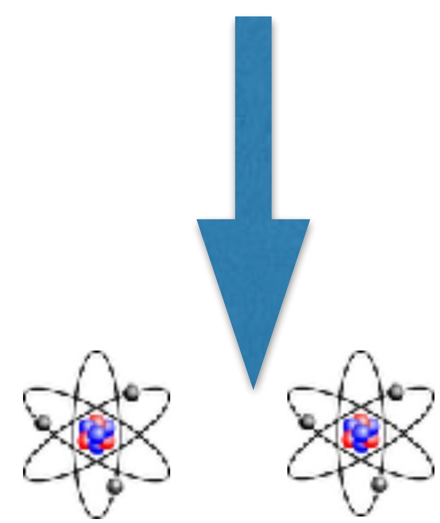


Force from dark matter causes torsion balance to rotate

Measure angle, optical lever arm enhancement

Atom Interferometer

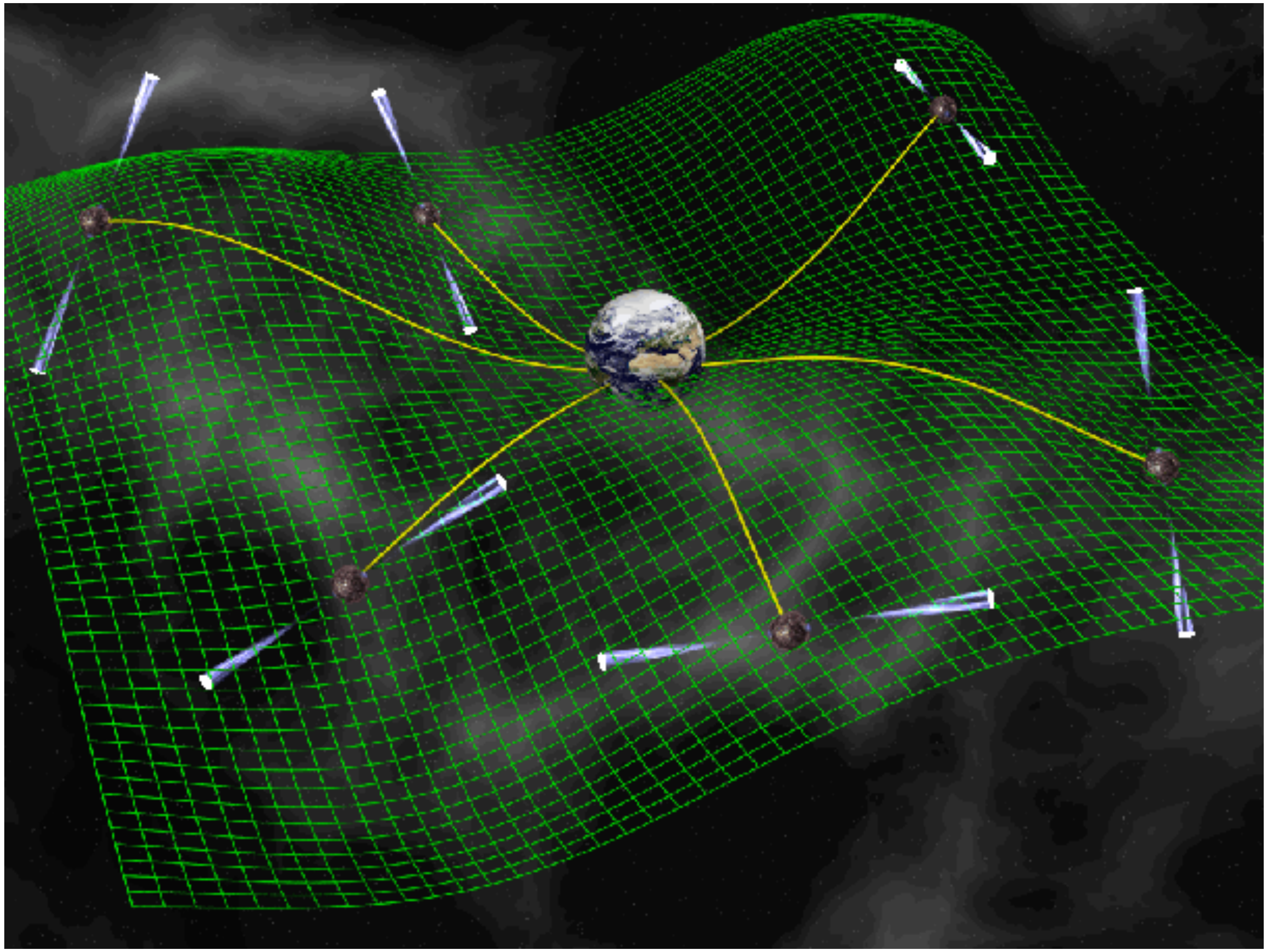
Dark Matter



Differential free fall acceleration

Stanford Facility

Pulsar Timing Arrays

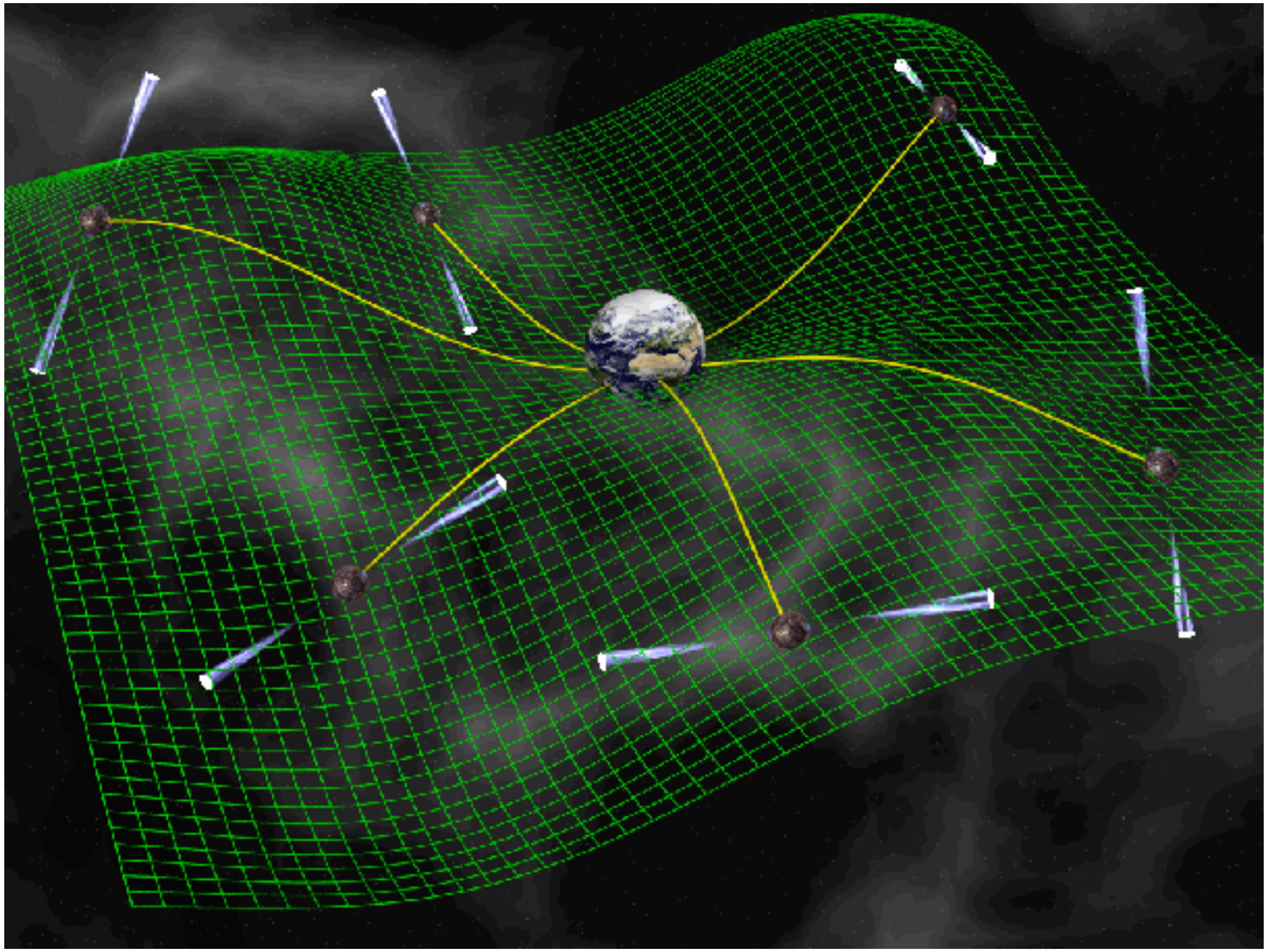


Pulsars are known to have stable rotation - can be used as clocks

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

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

Pulsar Timing Arrays



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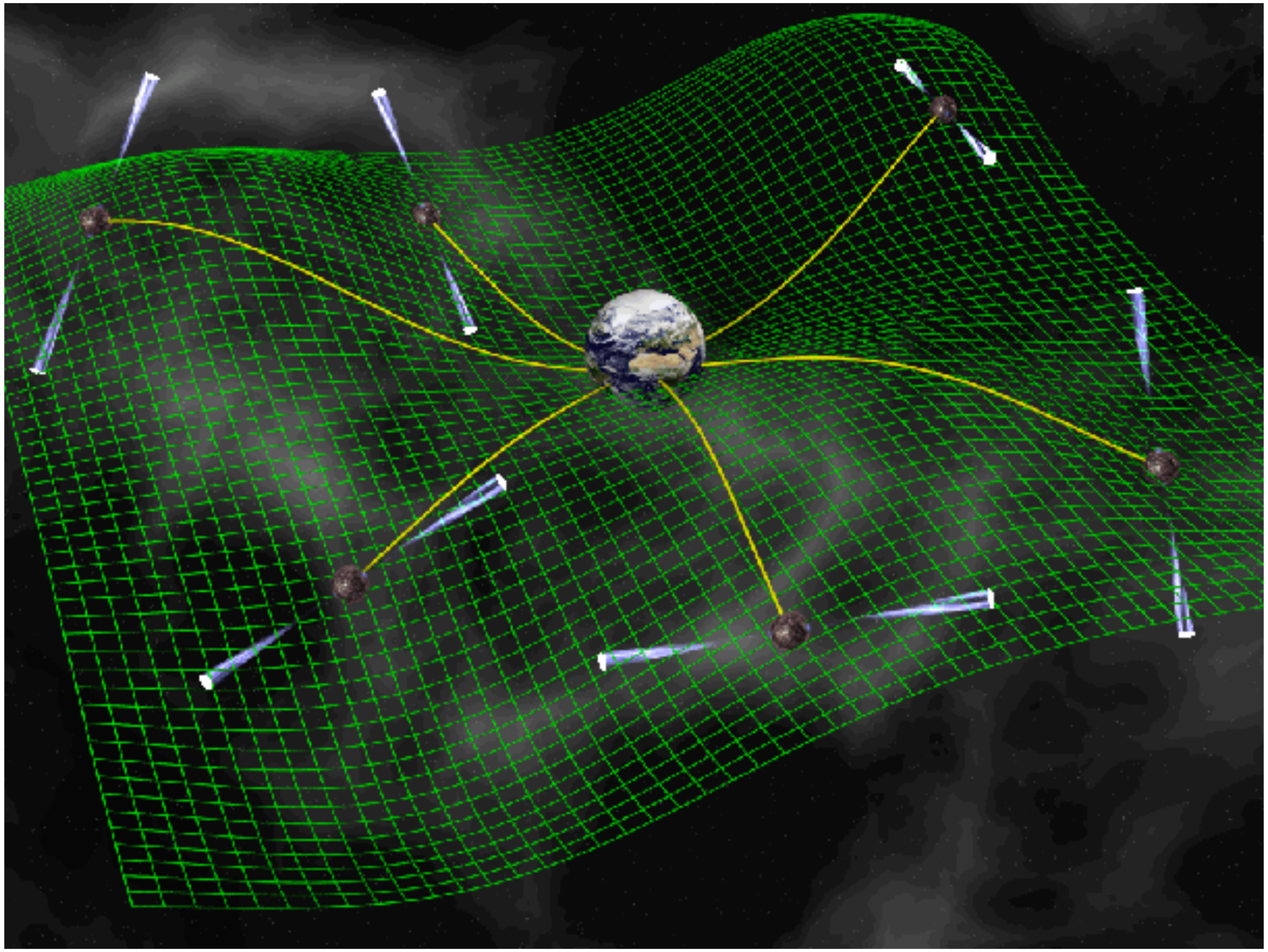

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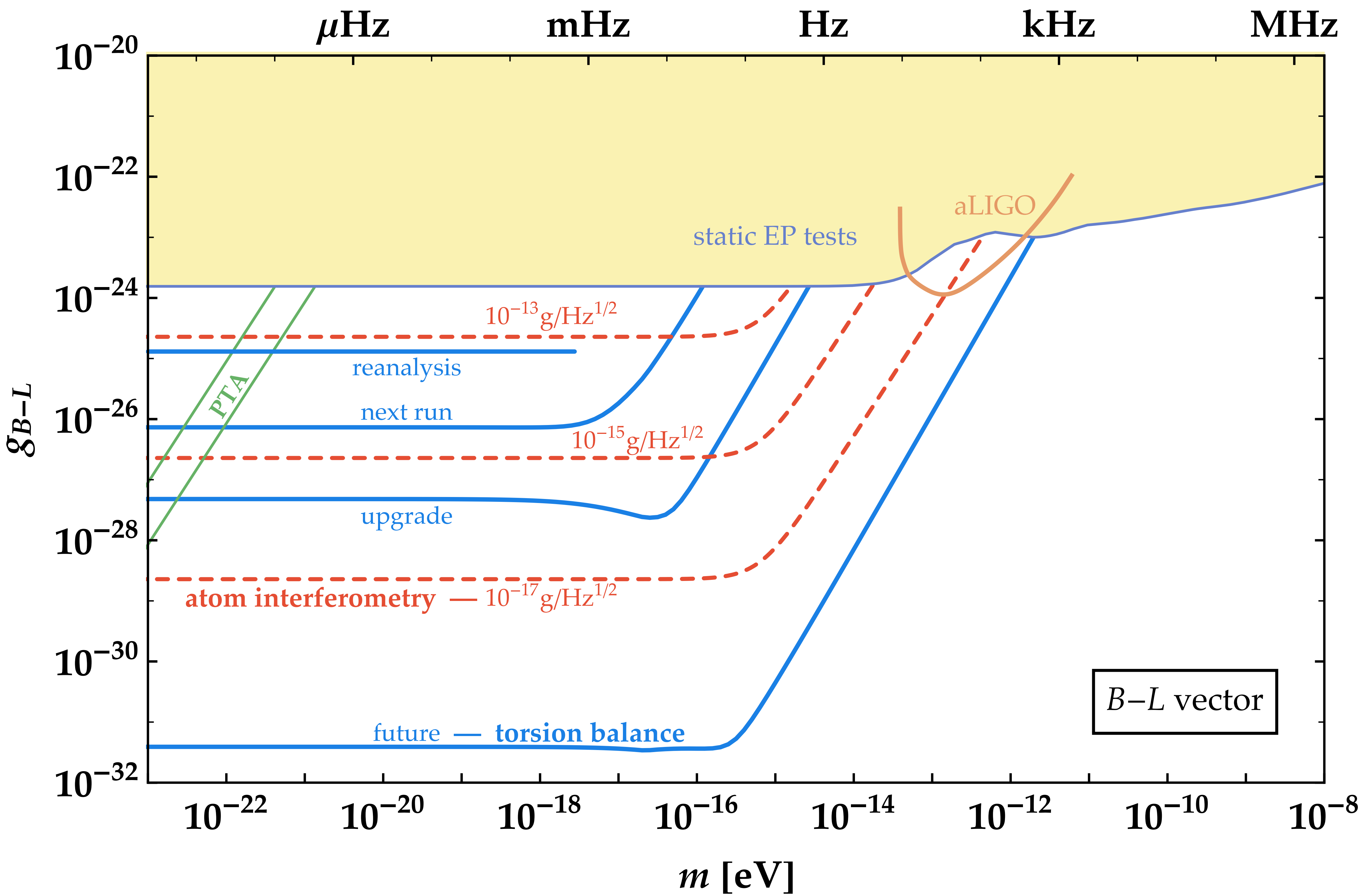
Relaxion changes electron mass at location of Earth - changes clock comparison

Projected Sensitivities



Torsion Balance limited by fiber thermal noise

Atom interferometers by shot noise

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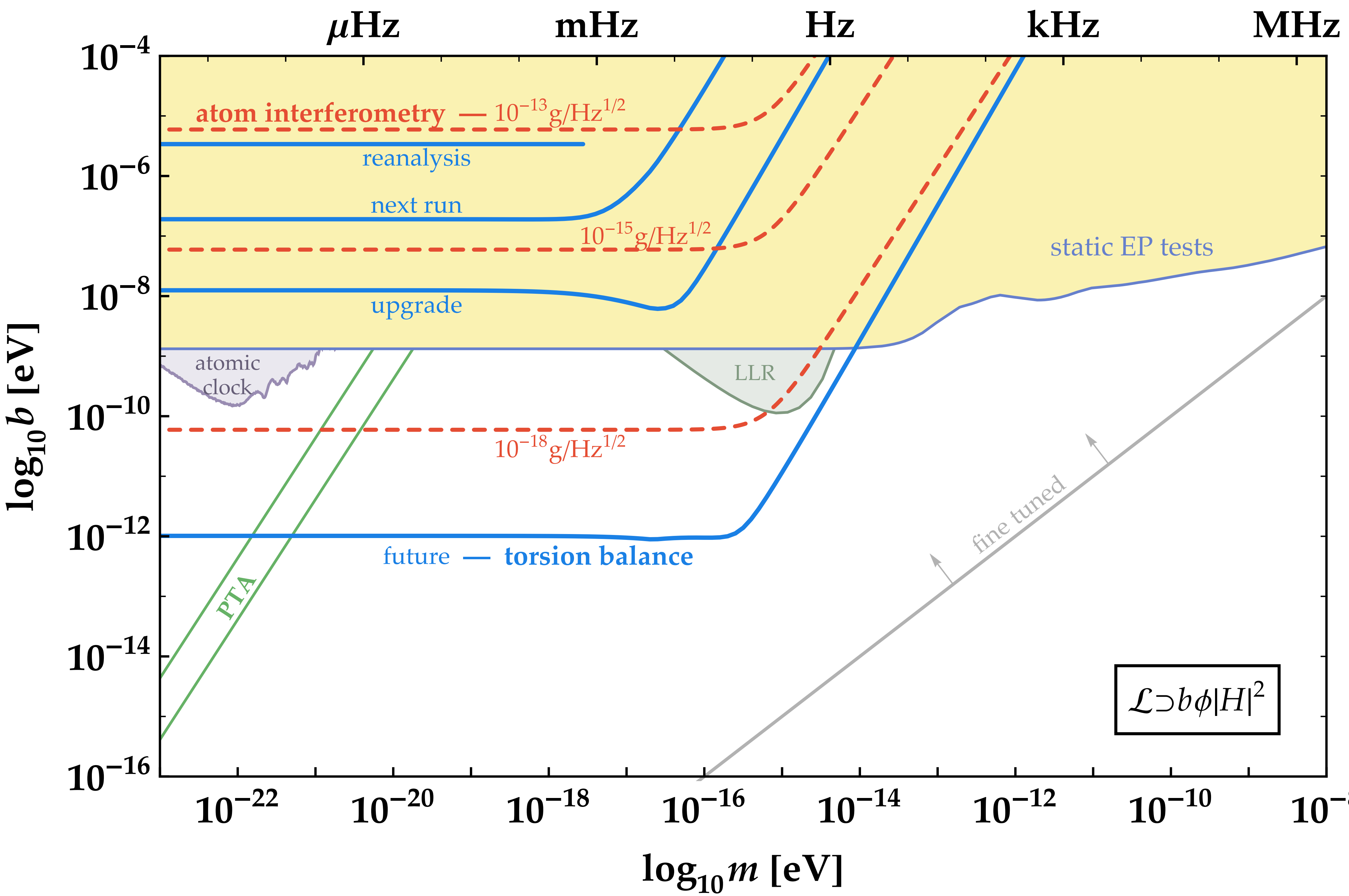

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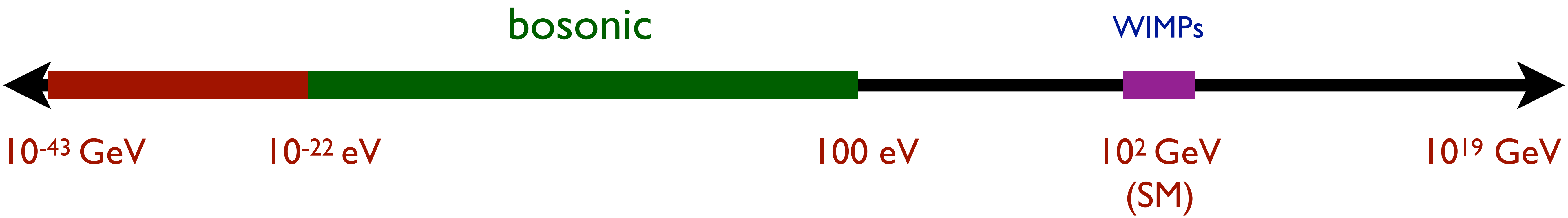
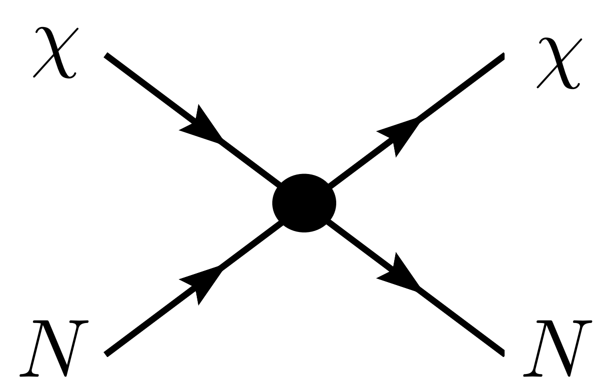
The Dark Matter Landscape



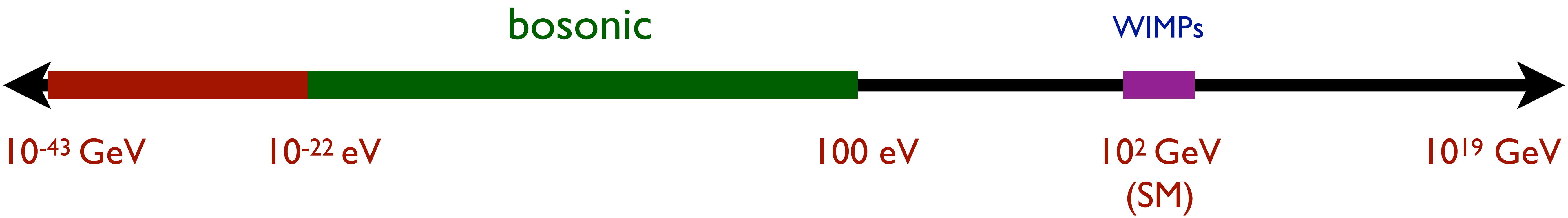
Fit in galaxy

Close tie to Weak Scale Physics,
Thermal Freeze-out



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

The Dark Matter Landscape



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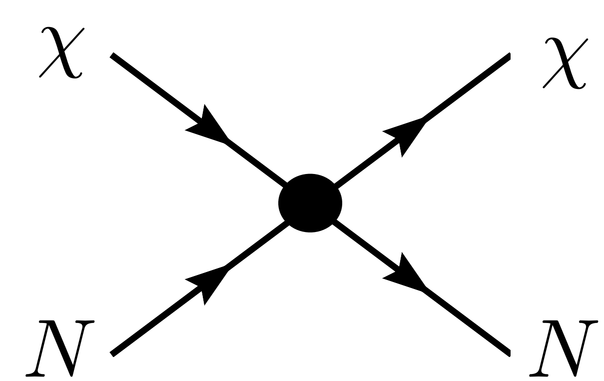

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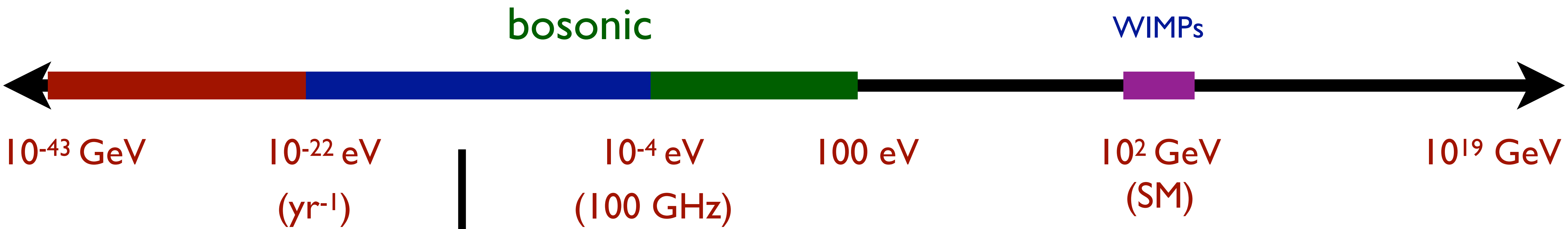
Beyond solar neutrinos?

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

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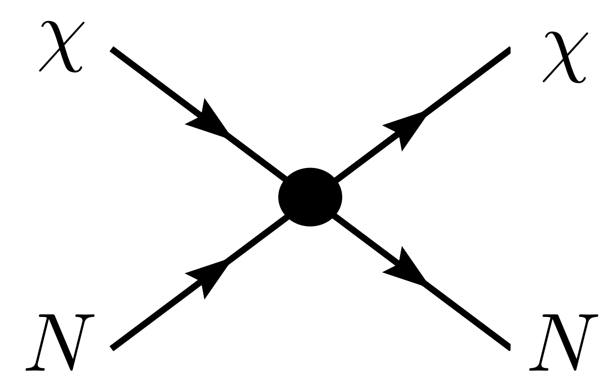

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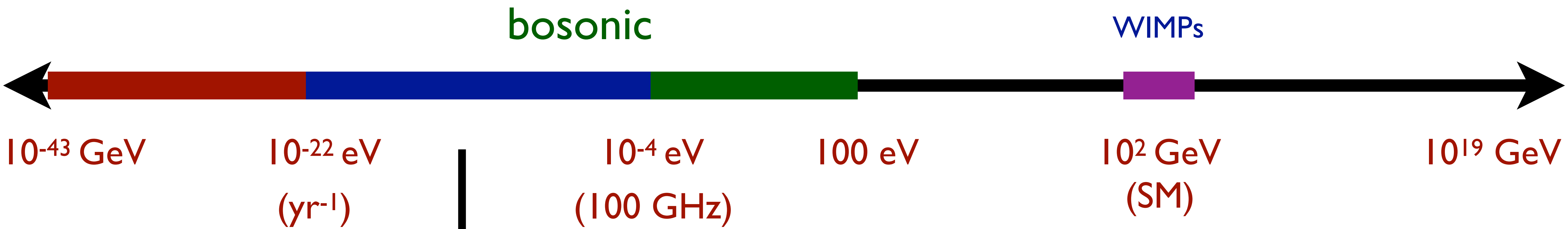

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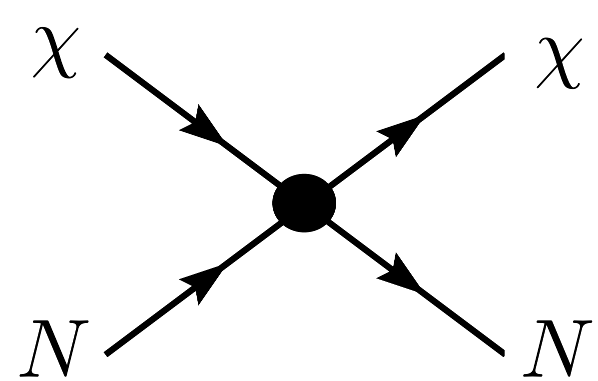

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The Dark Matter Landscape

bosonic — WIMPs

10^{-43} GeV | 10^{-22} eV (yr^{-1}) | 10^{-4} eV (100 GHz) | 100 eV | 10^{2} GeV (SM) | 10^{19} GeV

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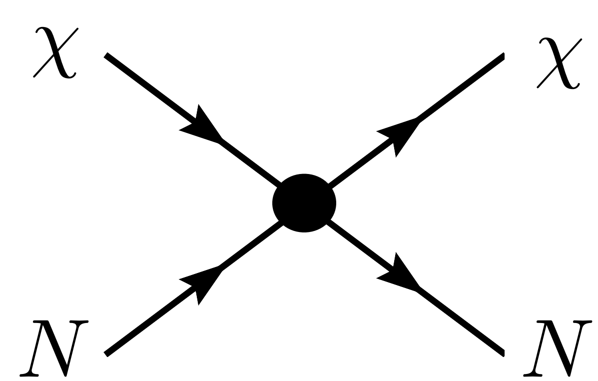


Hard scattering, 10 - 100 keV energy deposition, probing higgs exchange

Beyond solar neutrinos?

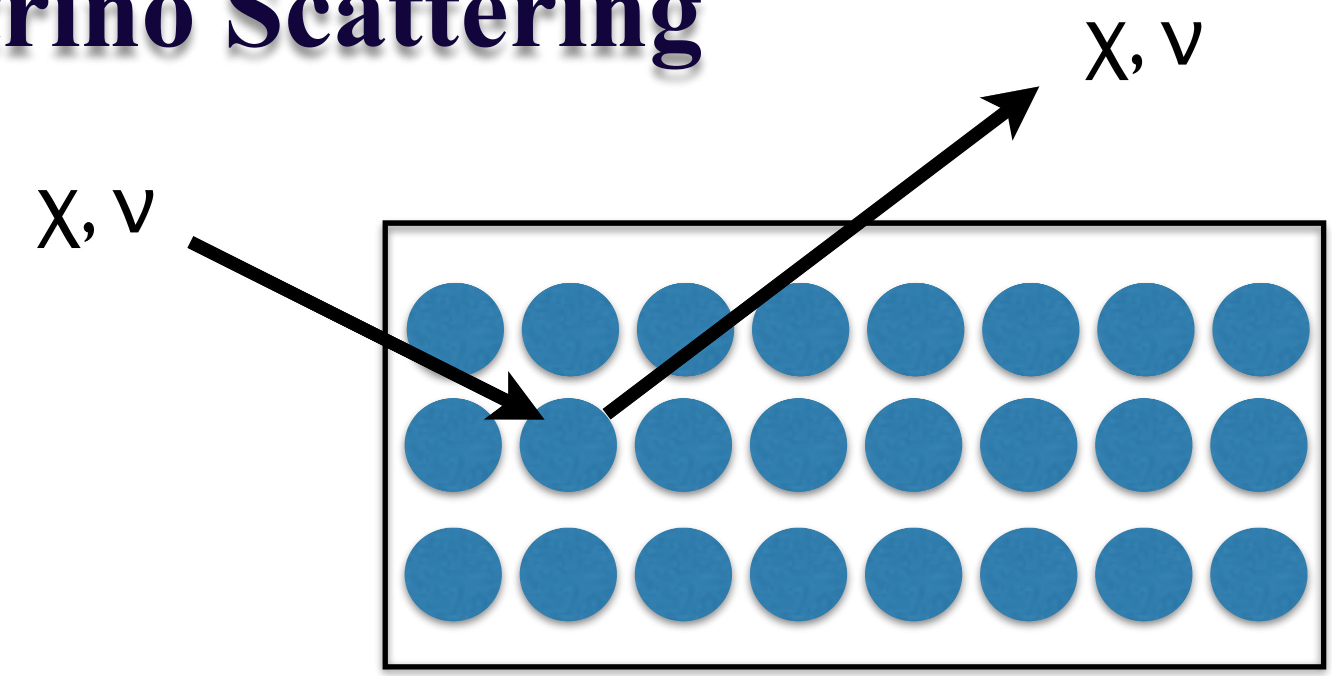
This Talk

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



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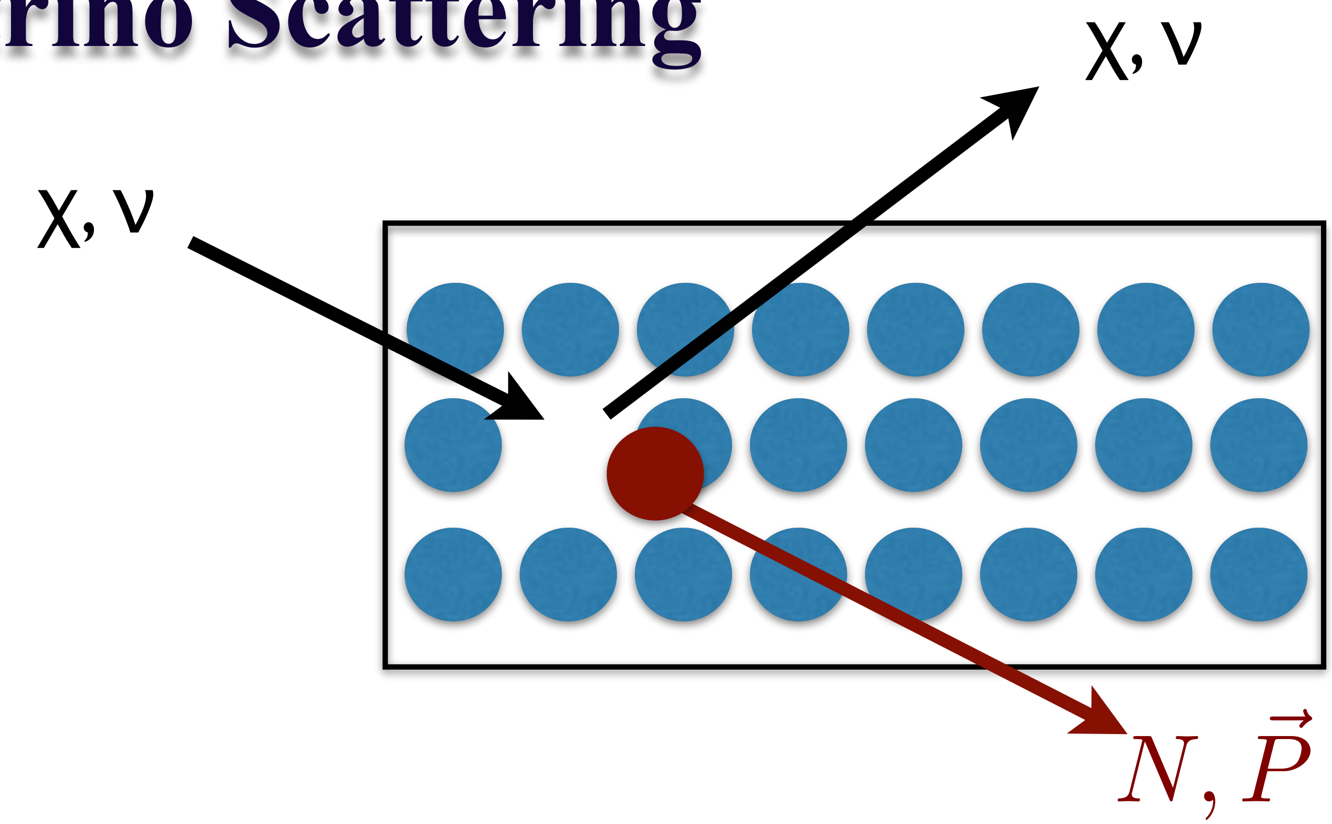

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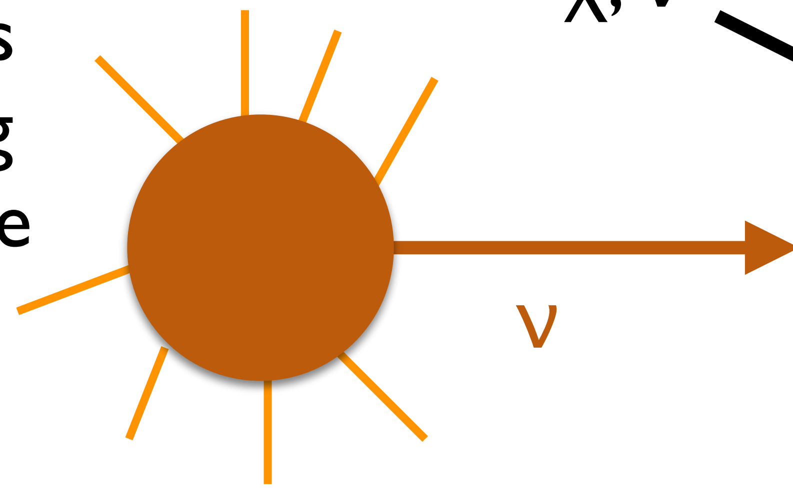
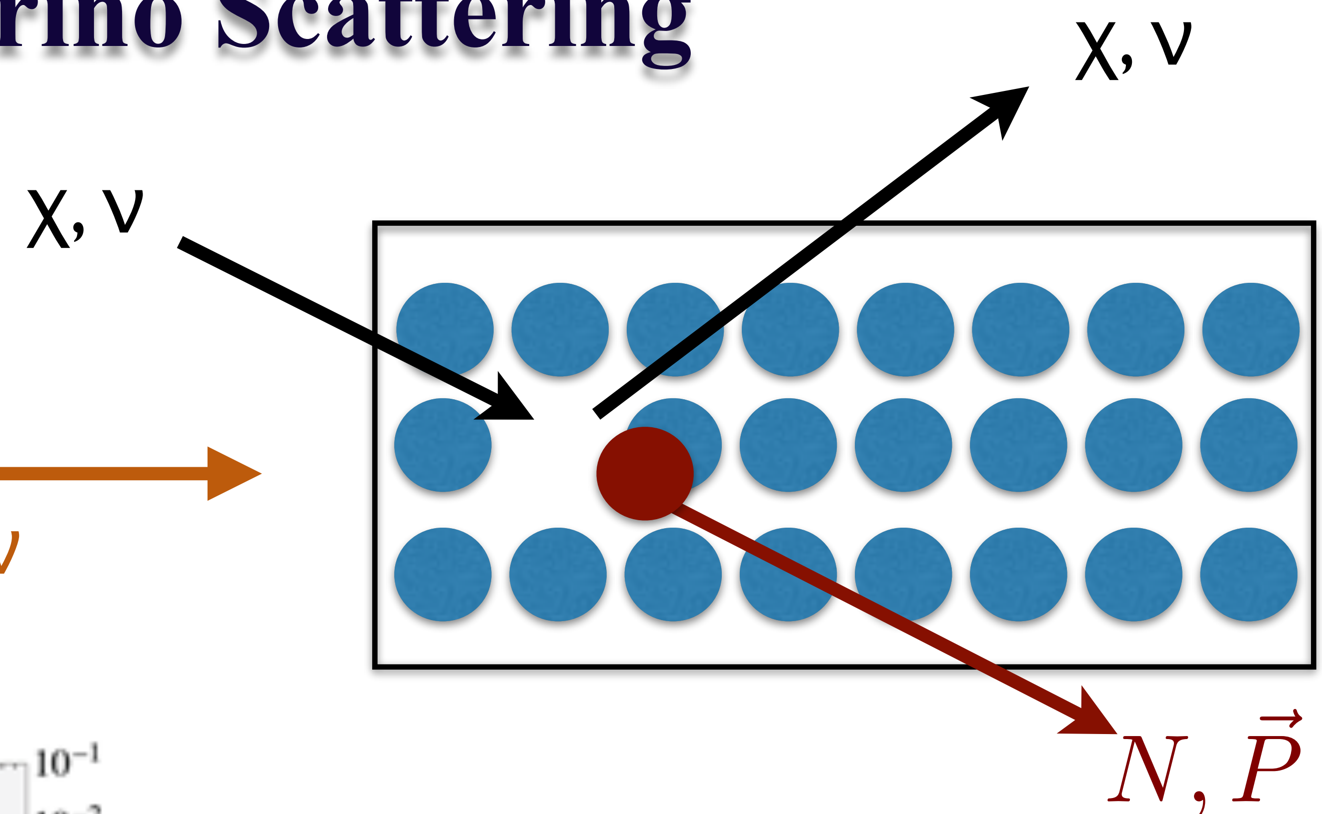
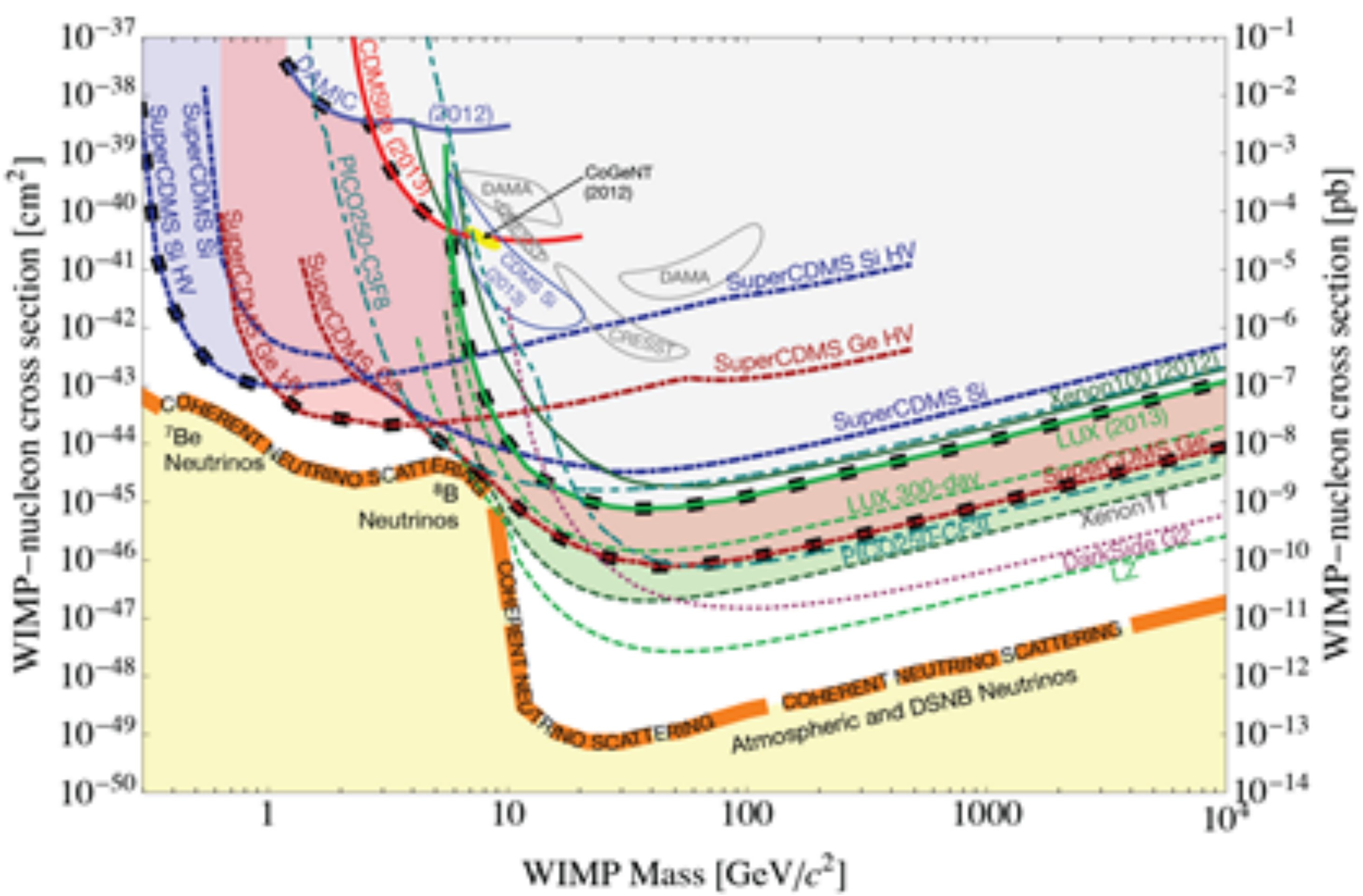




Sun produces neutrinos. Irreducible background.

Go beyond next generation?



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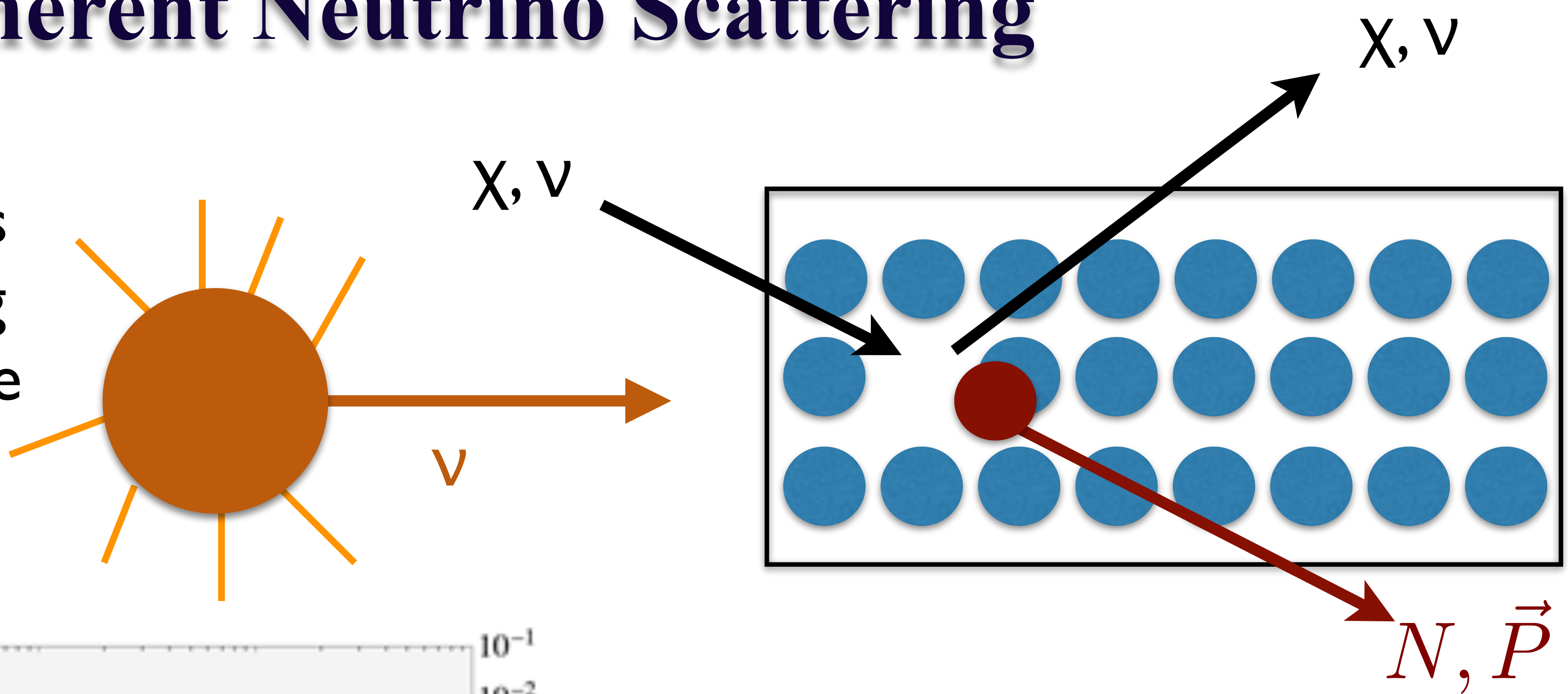

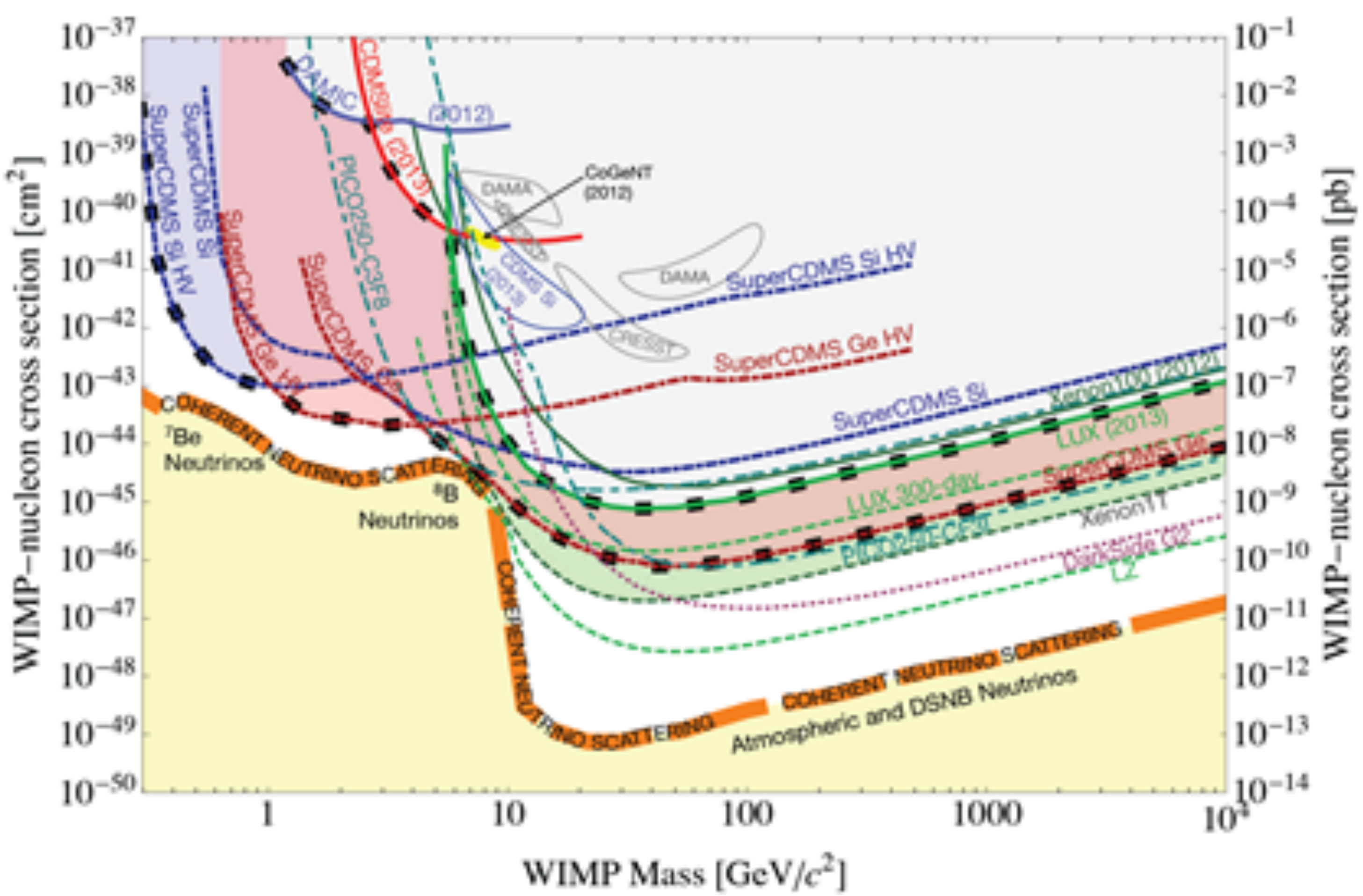

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Go beyond next generation?

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

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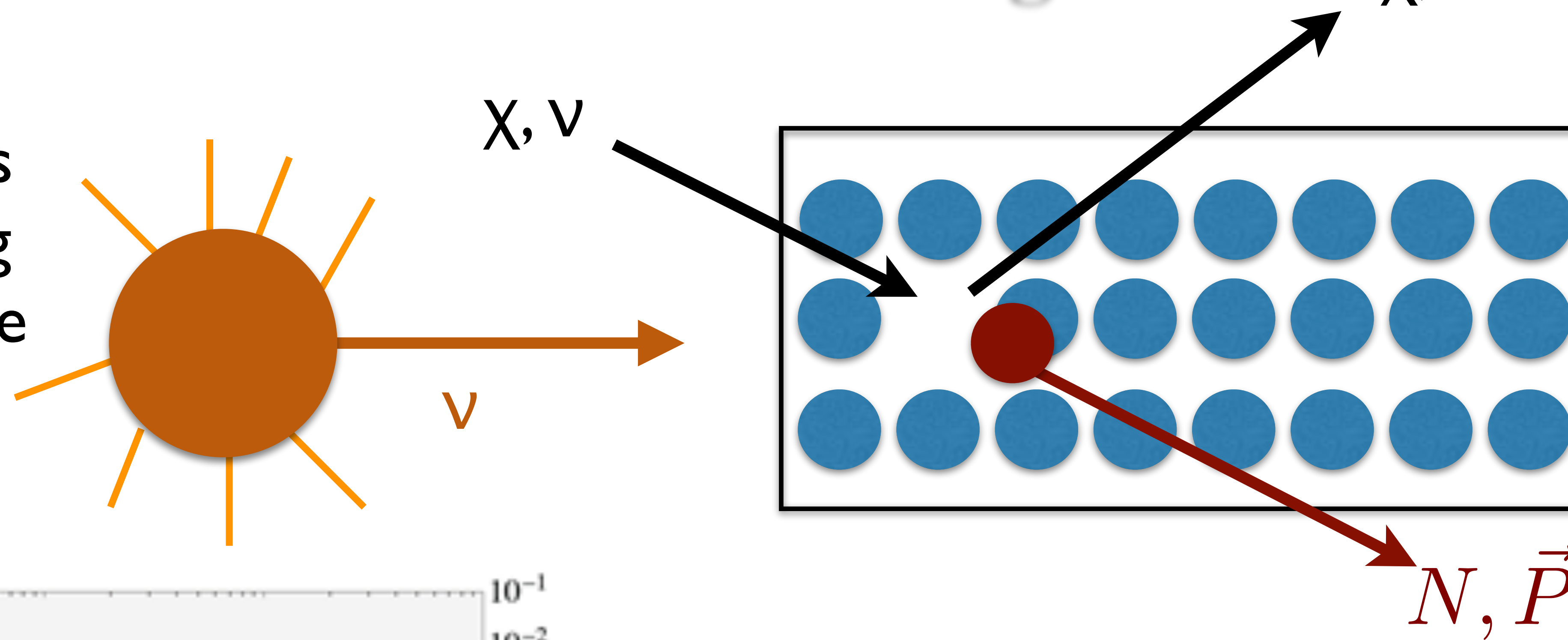

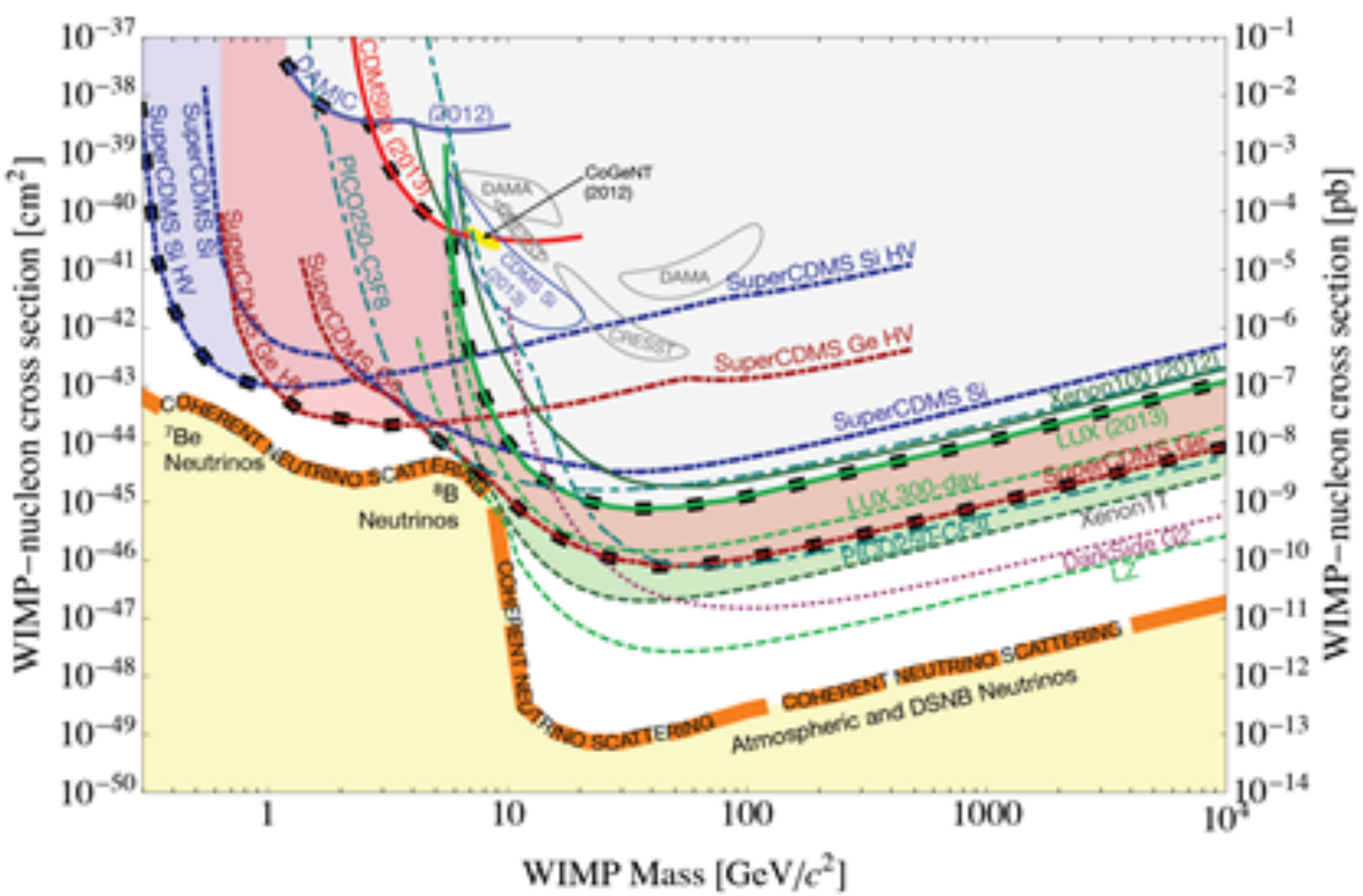

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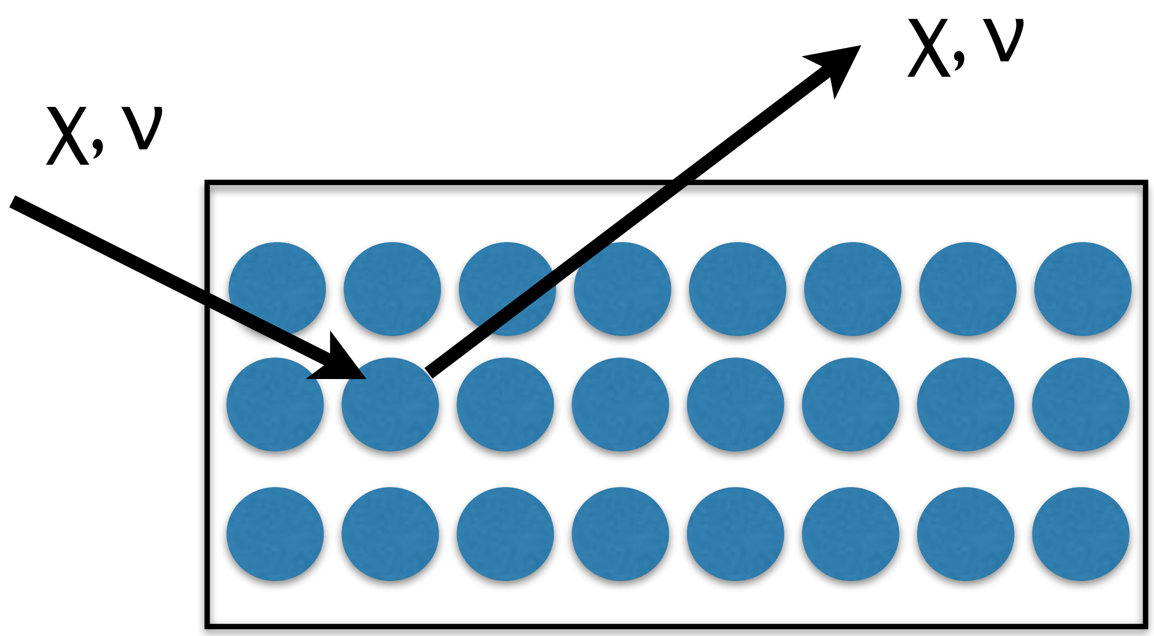
Isotropic Dark Matter. Know location of Sun. Veto nuclear recoils coming from Sun's direction

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

Collision Aftermath



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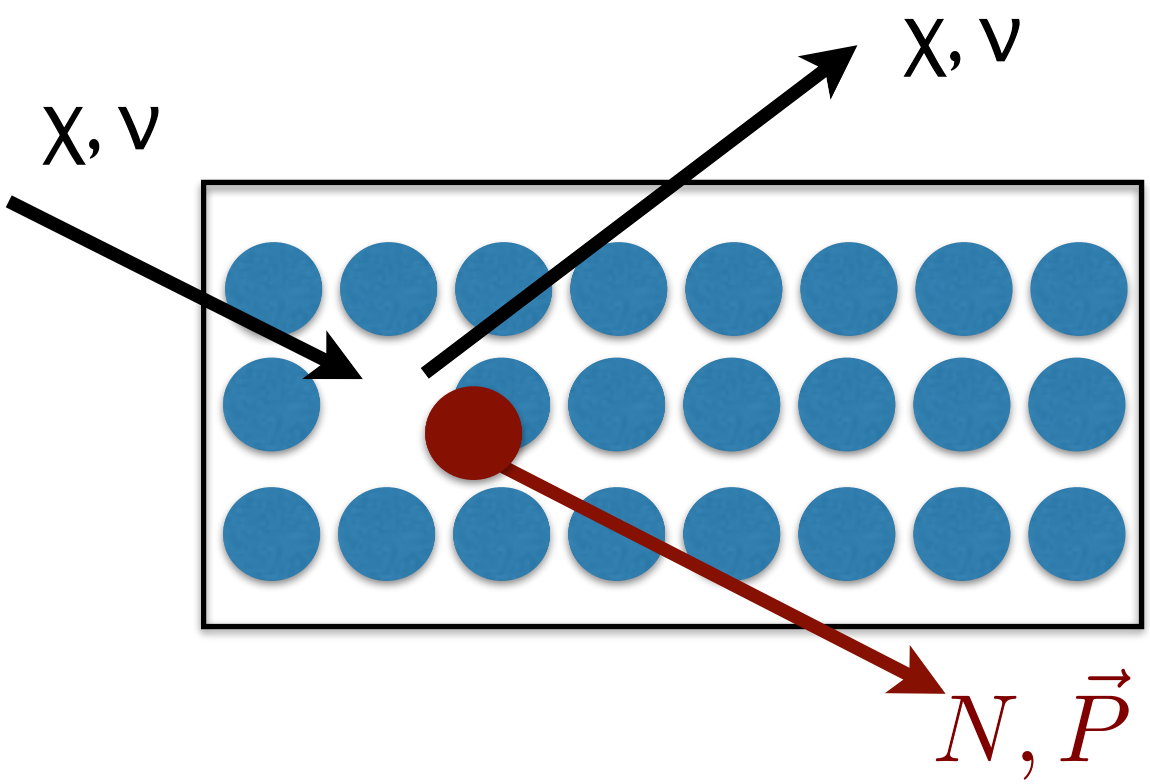

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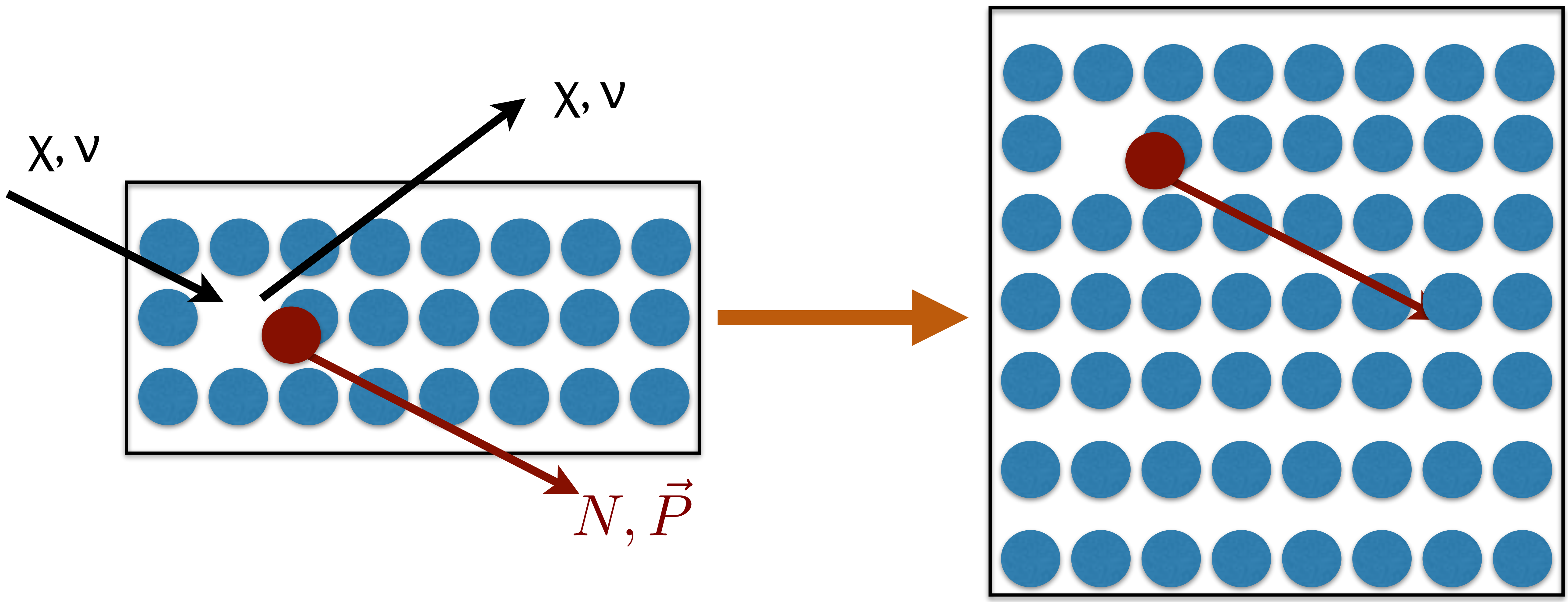

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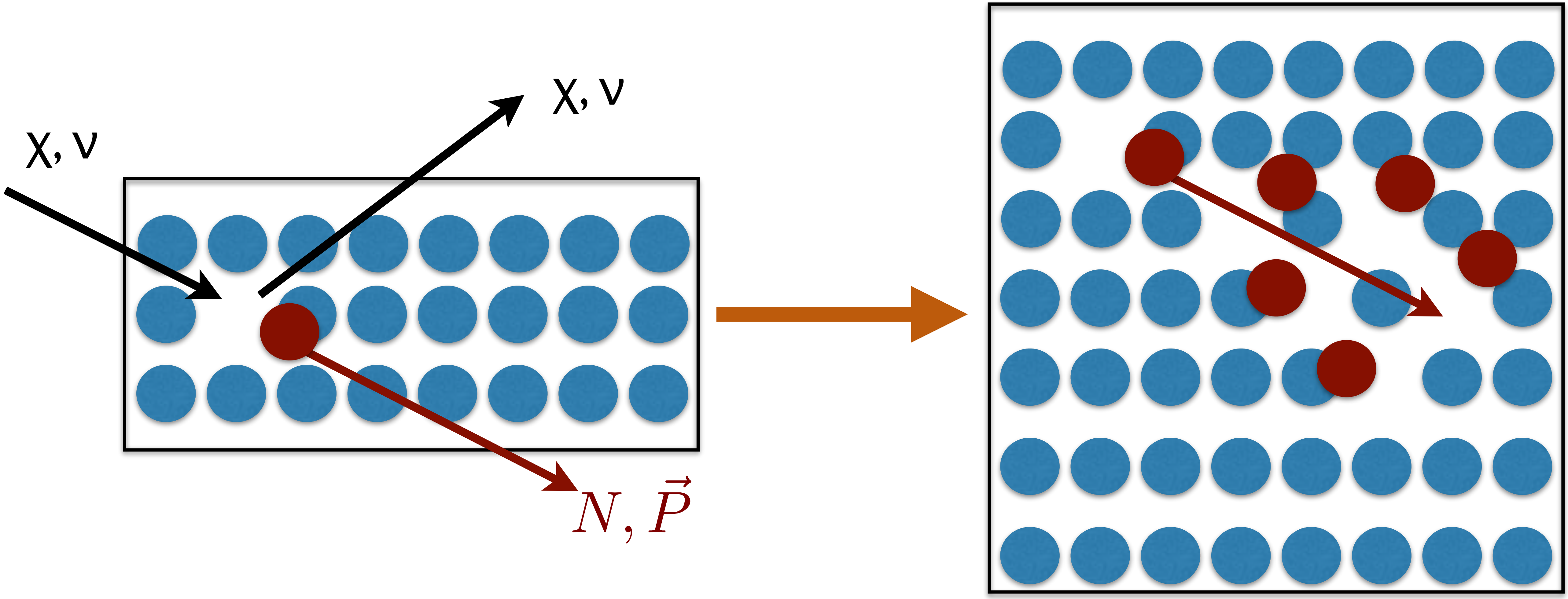

Tell-tale damage cluster well correlated with direction of initial ion, localized within ~ 50 nm

Collision Aftermath

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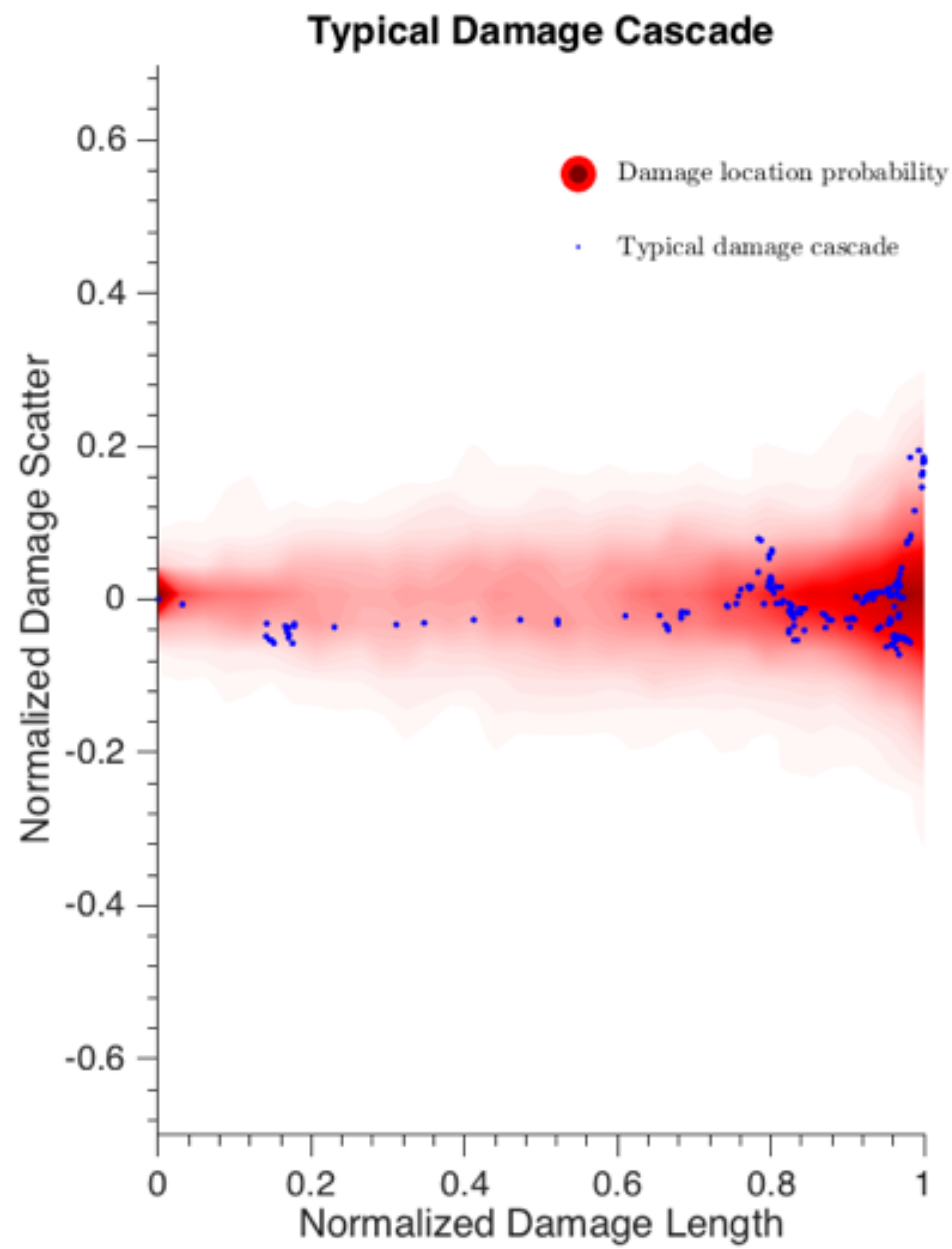
Results of TRIM simulation, 30 keV initial ion

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

Damage cascade well correlated with direction of input ion



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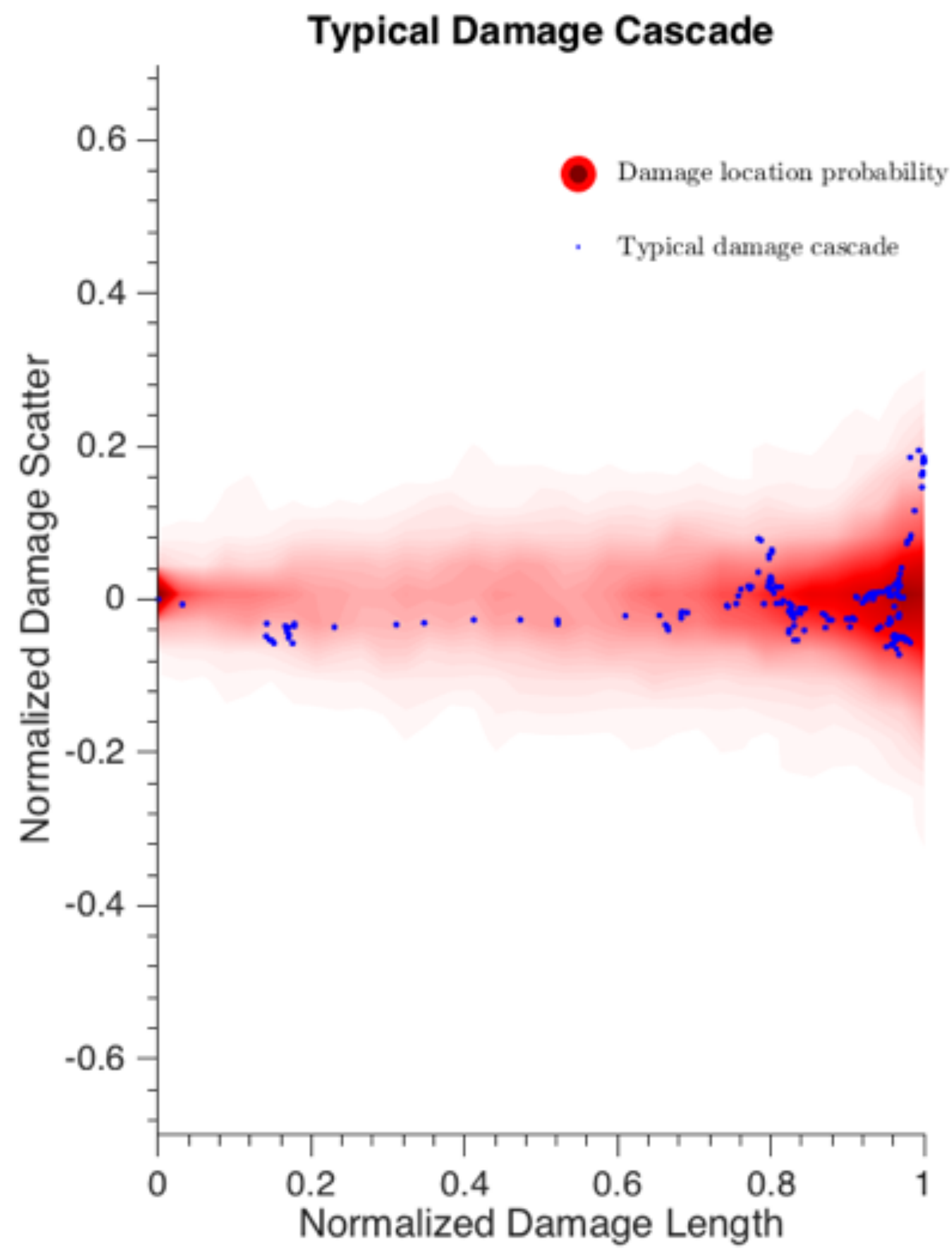
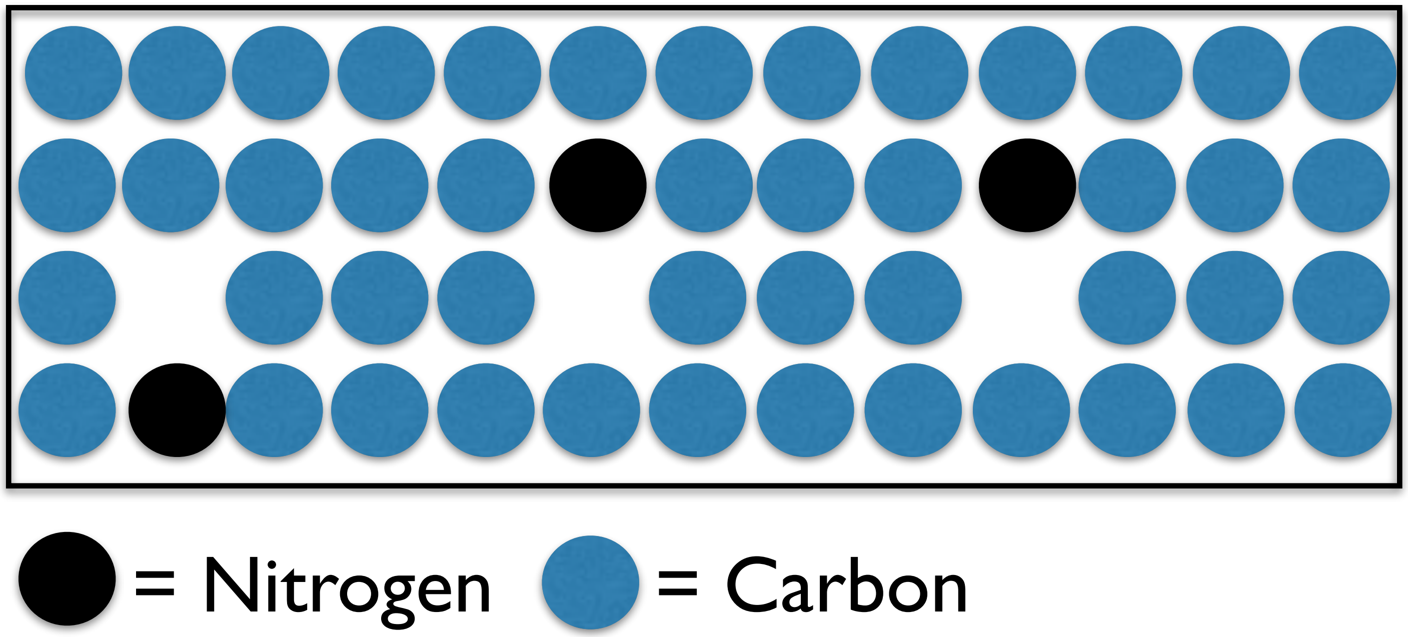
Need nano-scale measurement of damage cascade



Nitrogen Vacancy Center in Diamond



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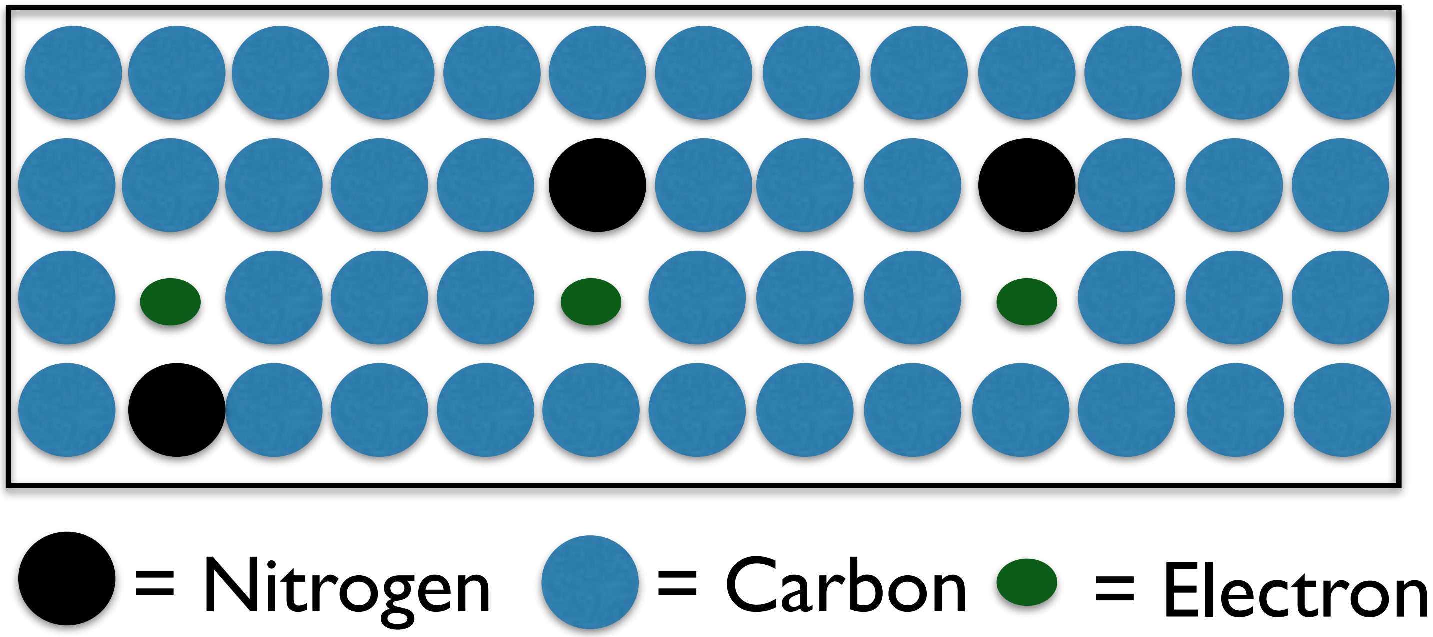

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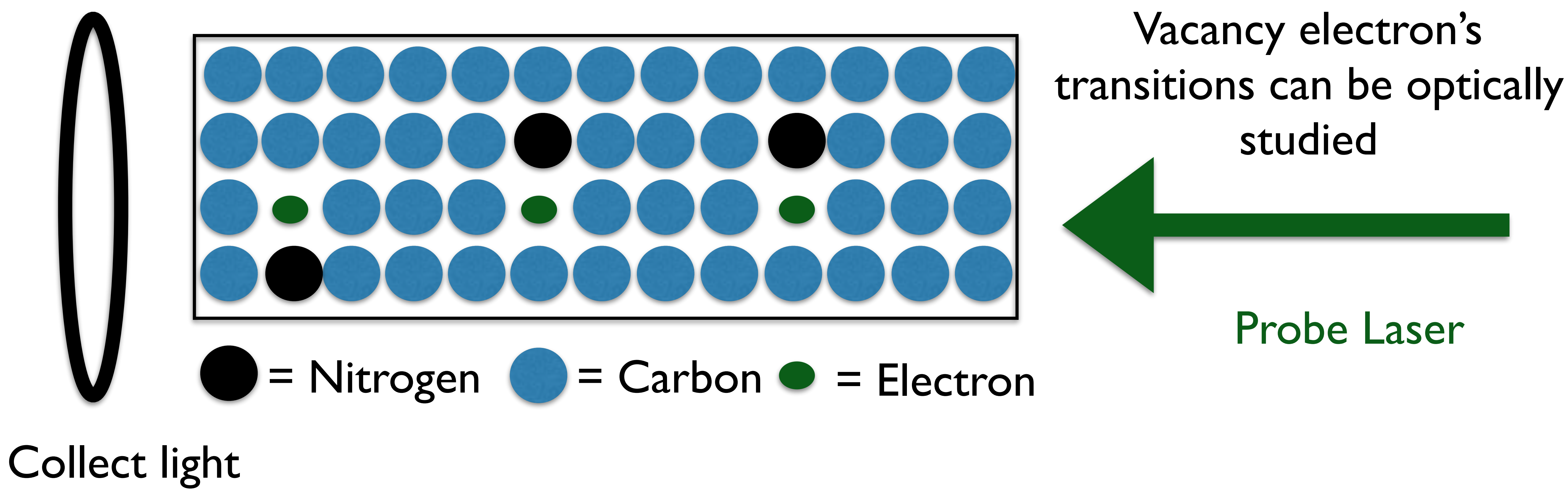

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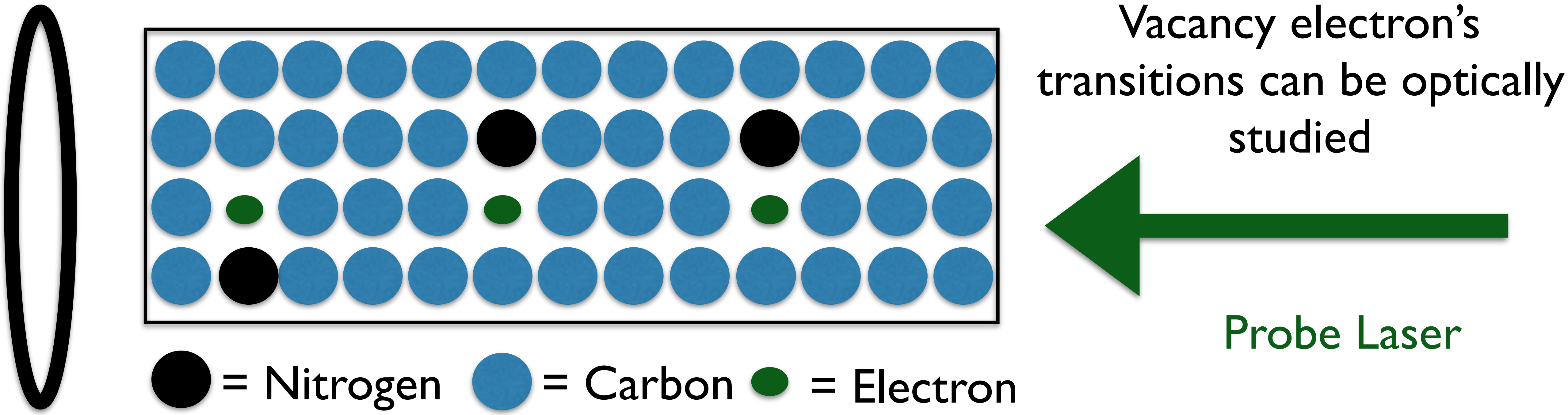
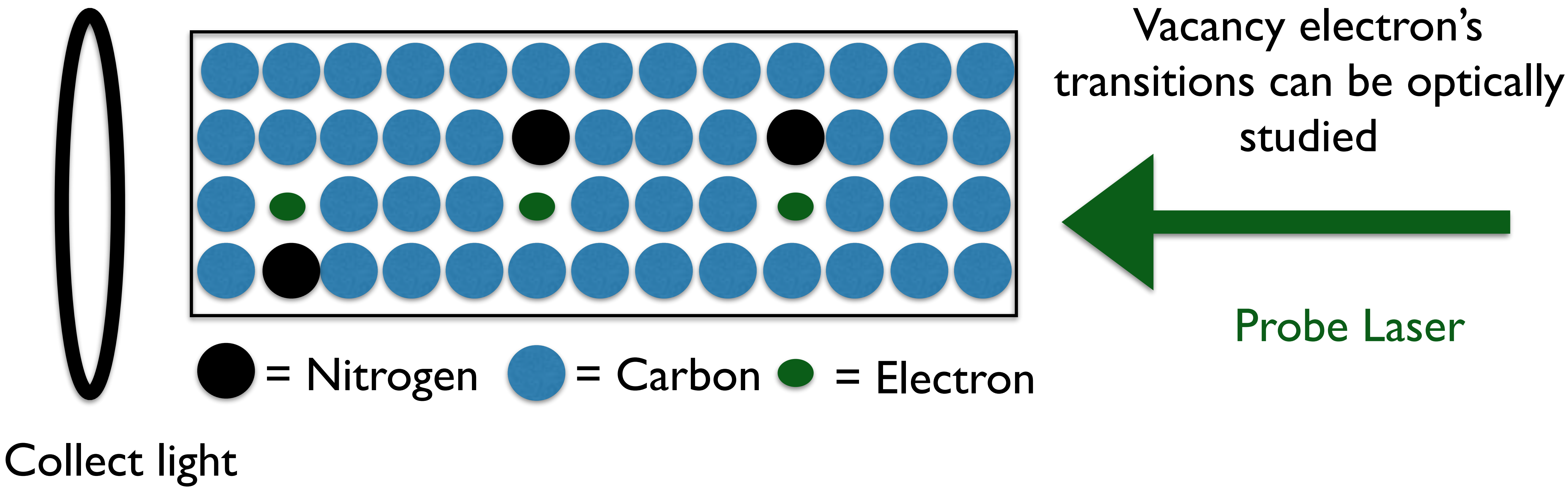


Collect light

Electronic levels sensitive to crystal environment ~ 50 nm scale

Nitrogen Vacancy Center in Diamond



Electronic levels sensitive to crystal environment ~ 50 nm scale

~ 1 per $(30\ \text{nm})^3$ of NV centers in bulk diamond demonstrated

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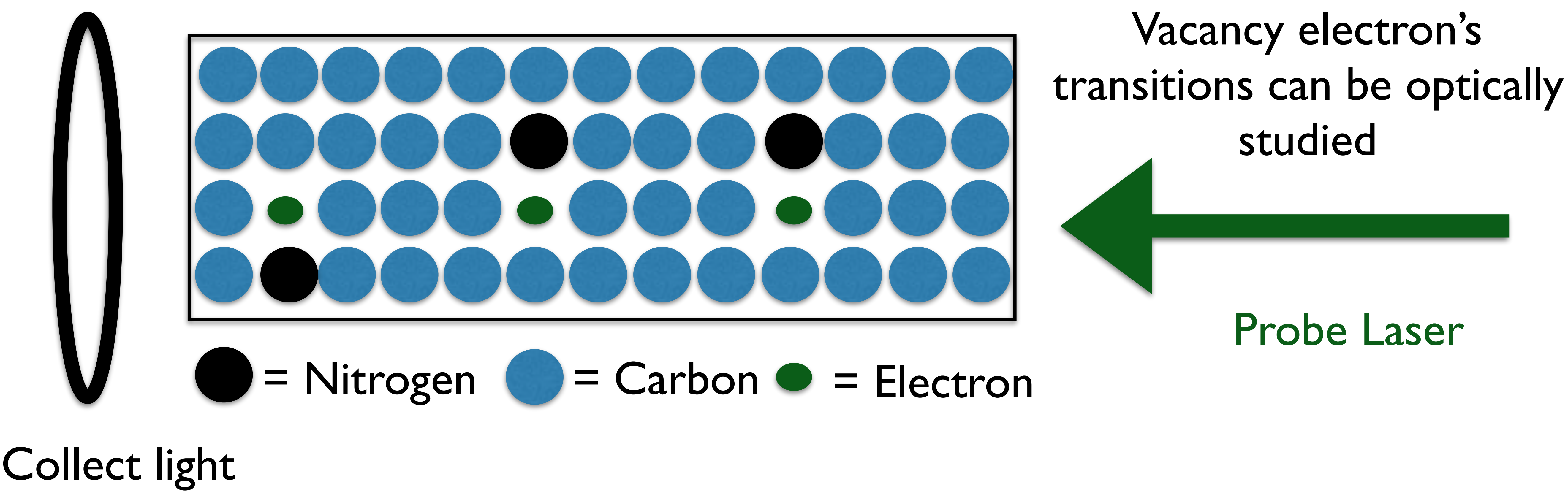

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Nano-scale measurements experimentally demonstrated. Active development of sensors by many groups around the world.

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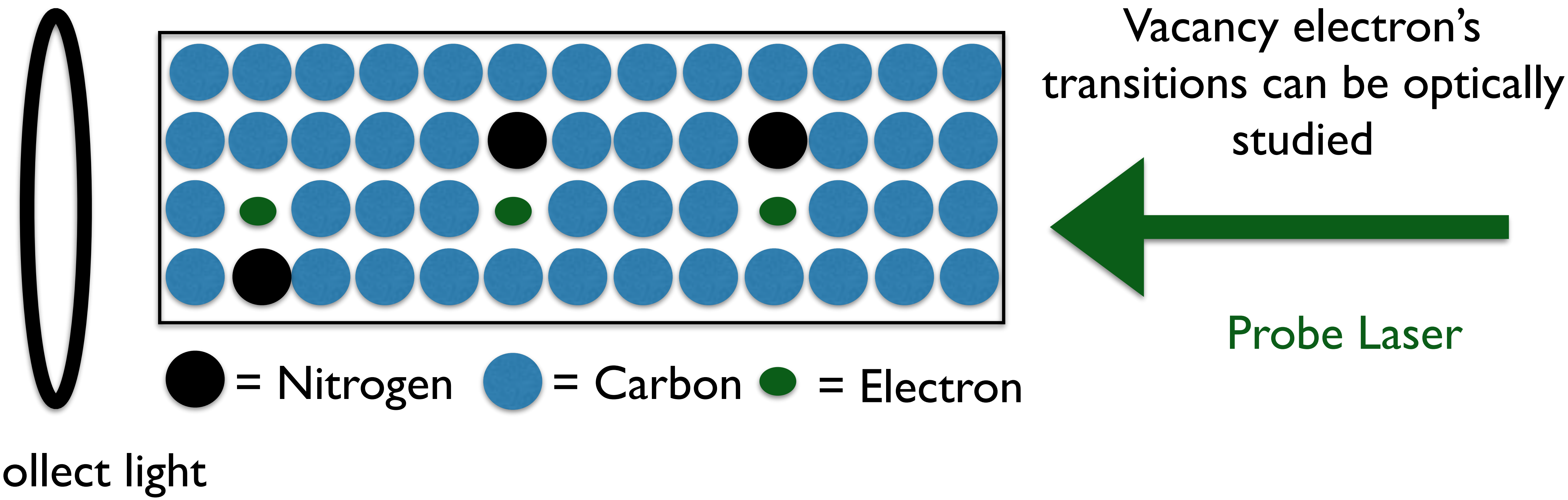

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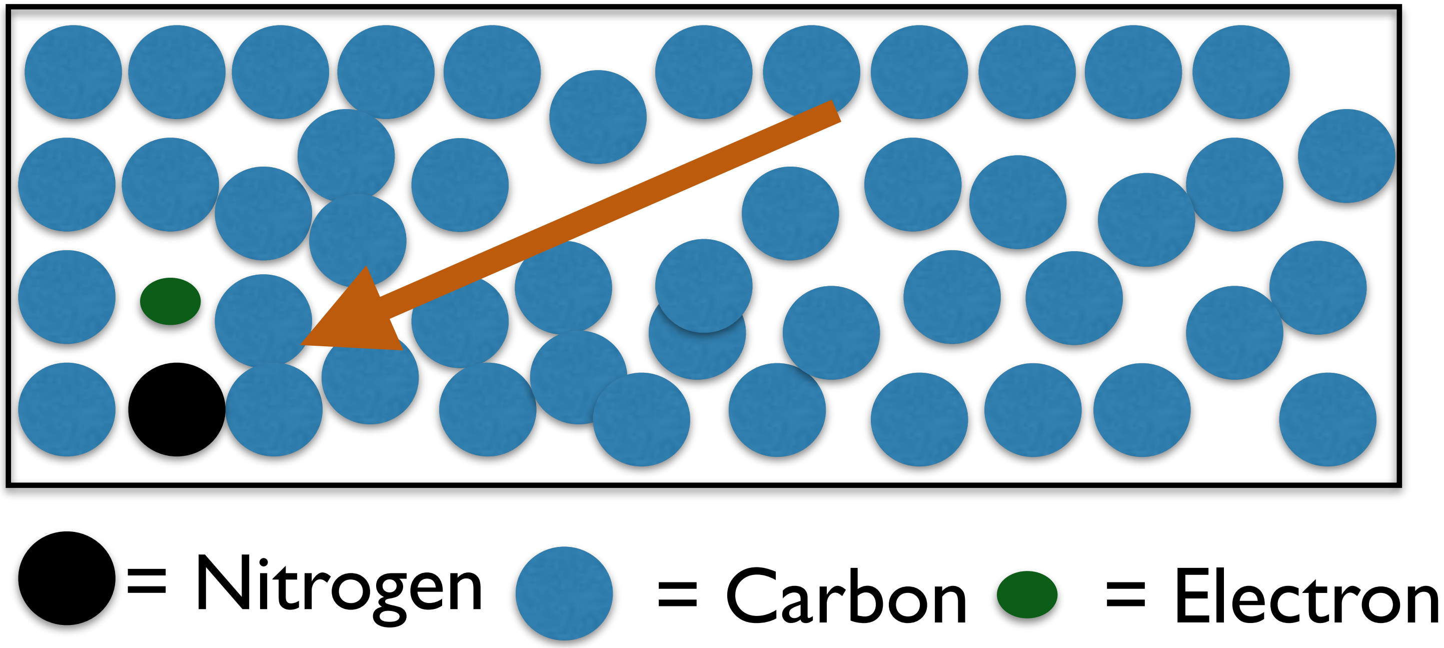
Can this be used for directional detection? What is the effect of the damage cascade on a NV center?

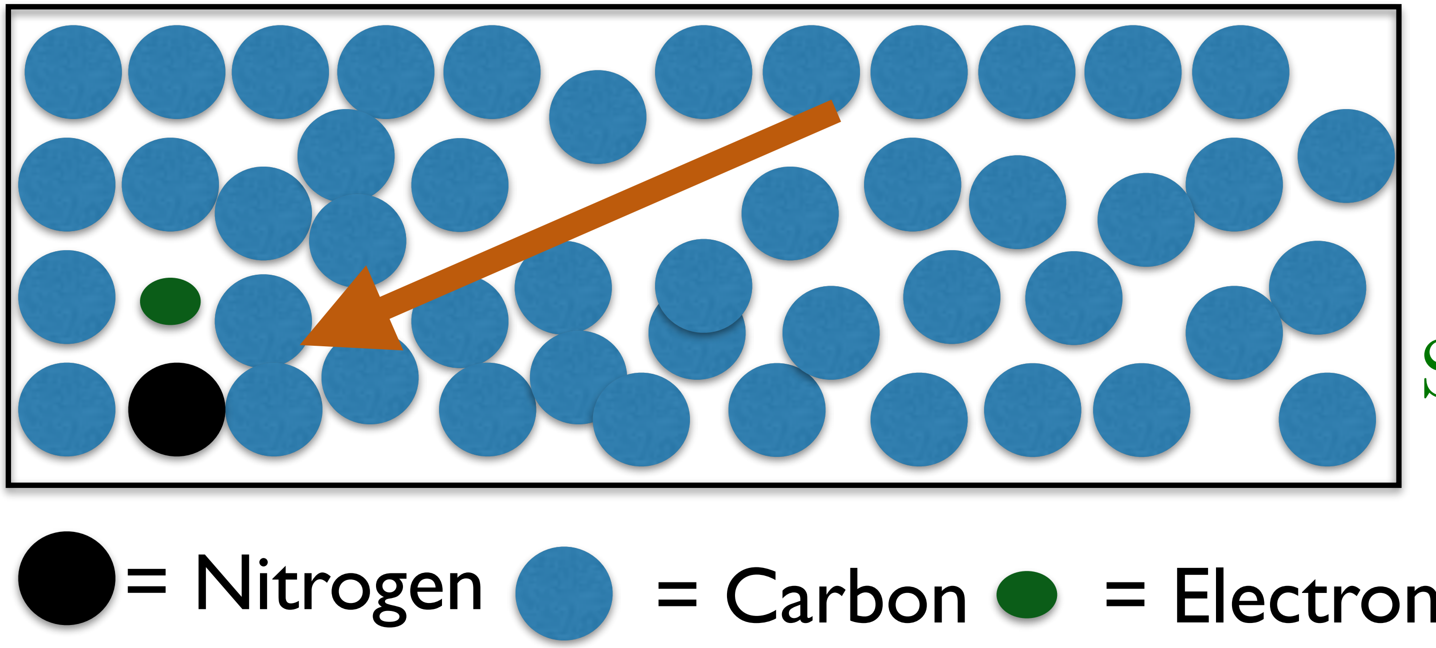
Note: similar phenomenology applies to F-centers of Metal Halides

Damage Cascade and NV Centers



Damage leads to strain in crystal.
Strain shifts transition line

Damage Cascade and NV Centers



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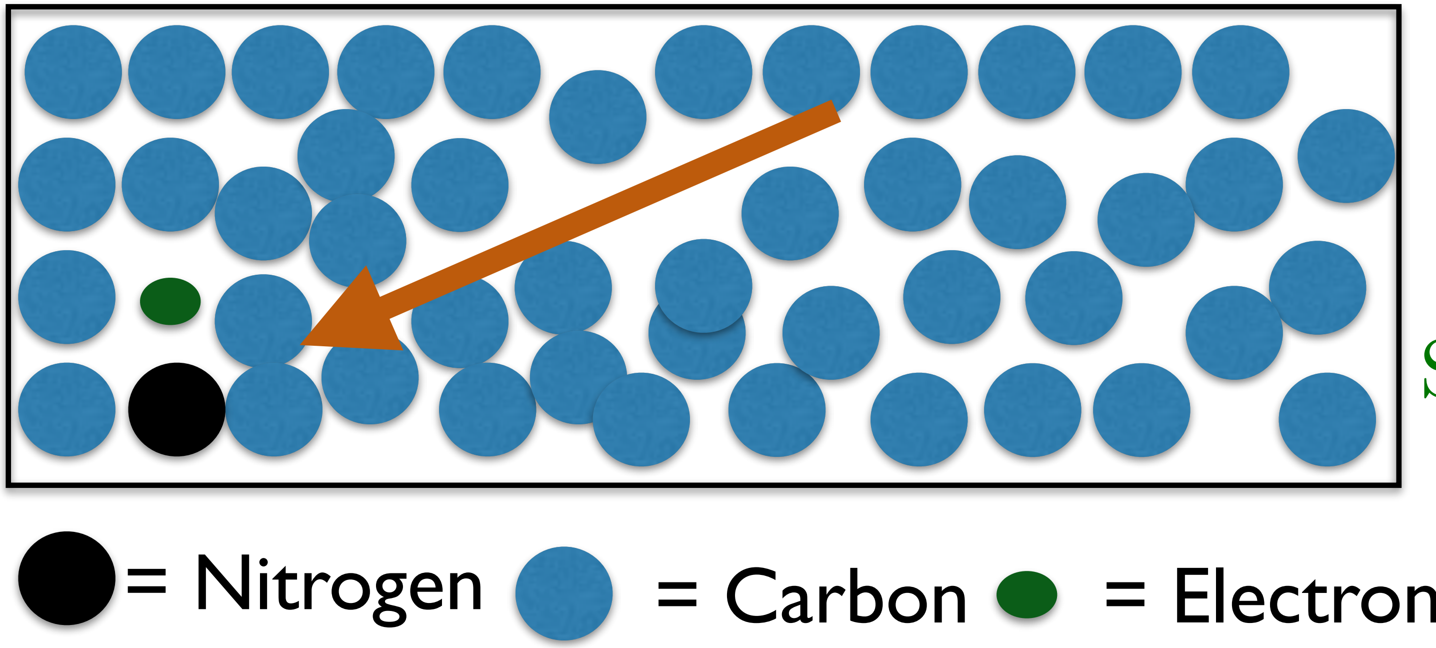
Strain: $\nabla u \propto \frac{1}{r^3}$

(Hooke's Law)

Damage Cascade and NV Centers



Damage leads to strain in crystal.
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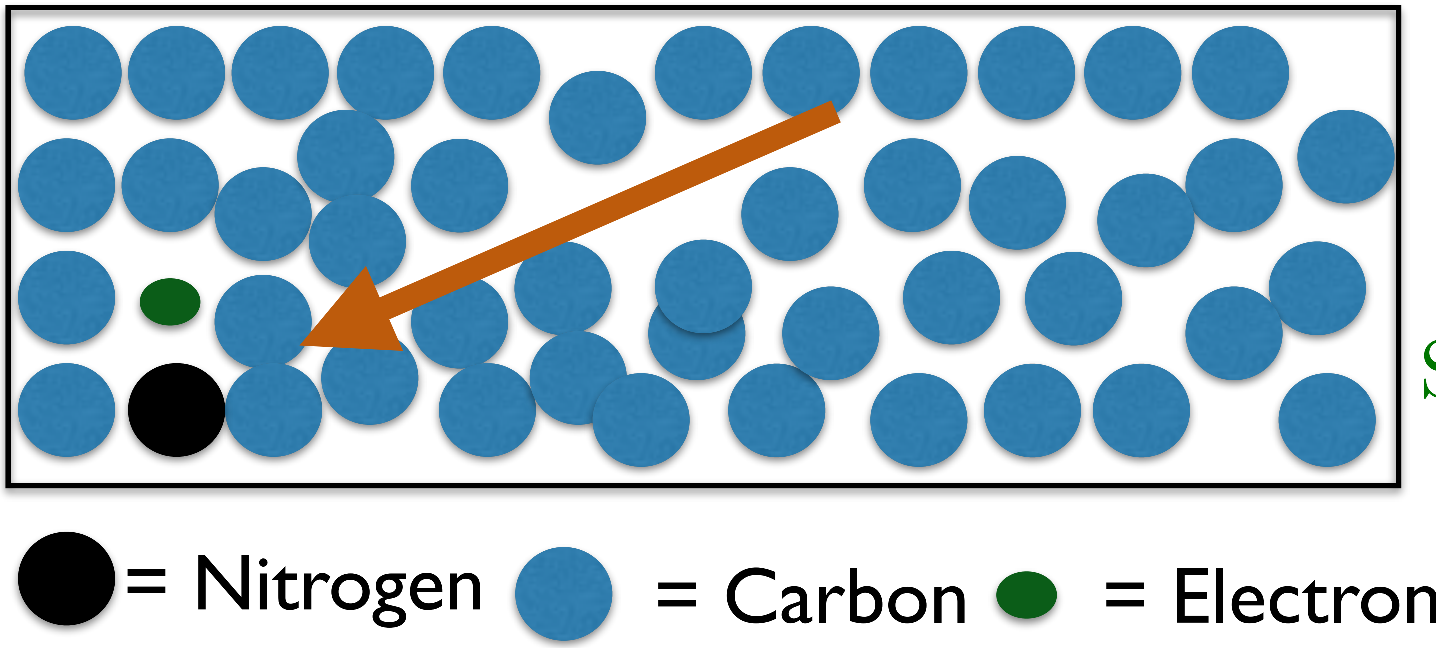
Strain: $\nabla u \propto \frac{1}{r^3} \times \mathcal{O}\,(100 - 300)$

(Hooke's Law)

Damage Cascade and NV Centers



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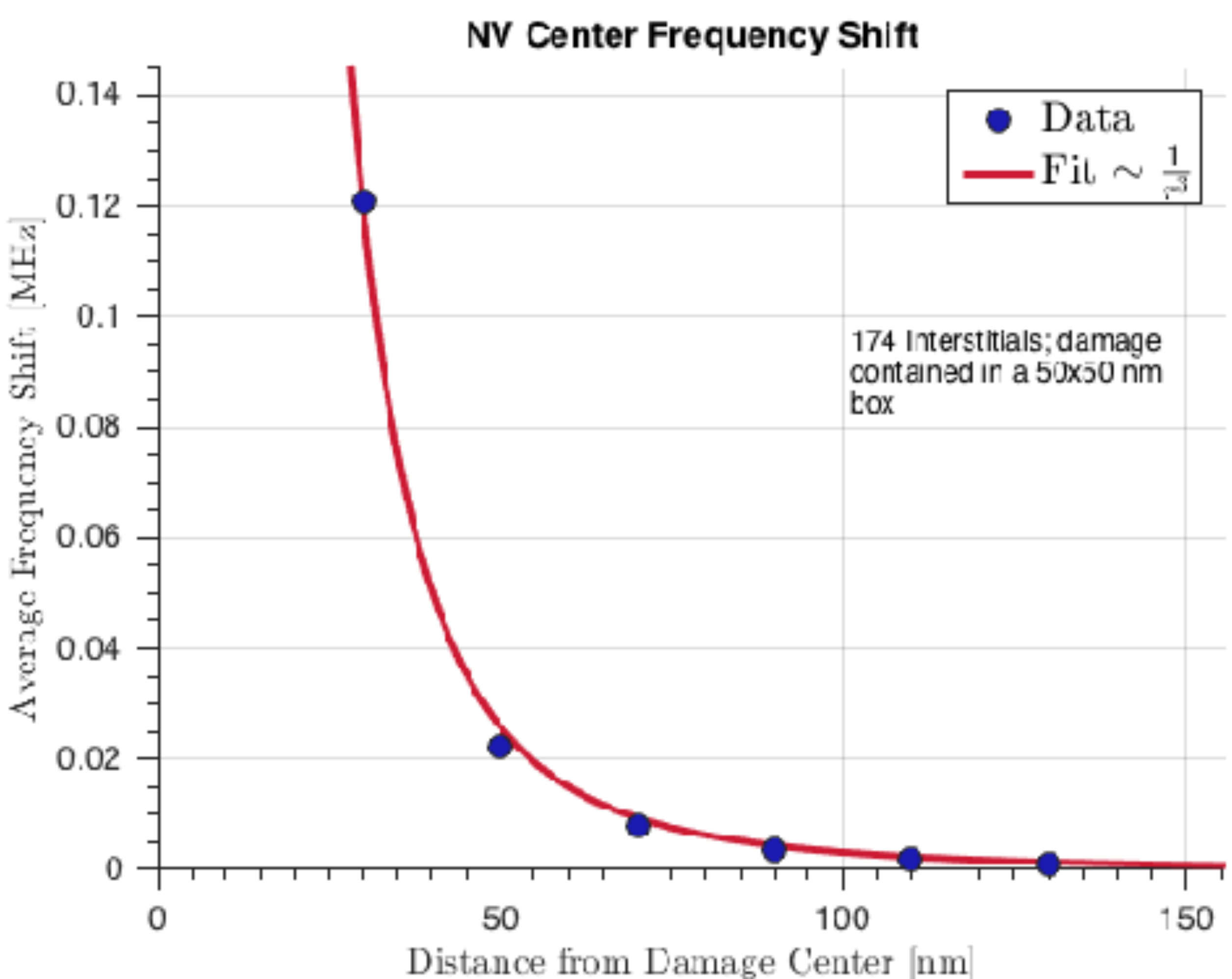
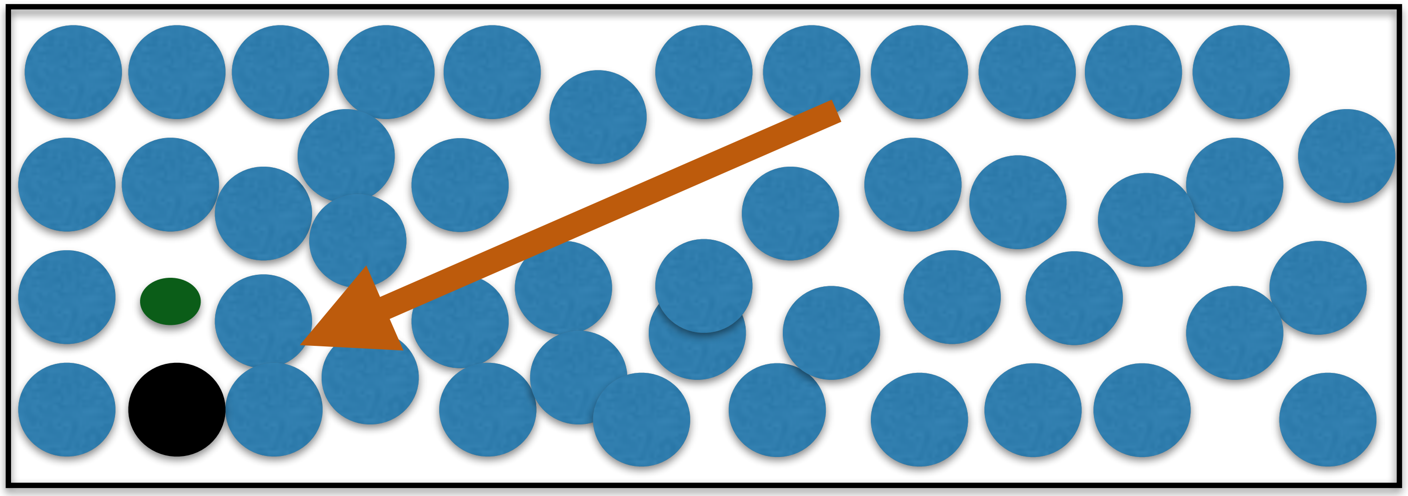


TRIM simulation of damage cascade - calculate strain using Hooke's law

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

Damage Cascade and NV Centers



= Nitrogen = Carbon = Electron

Damage leads to strain in crystal.
Strain shifts transition line

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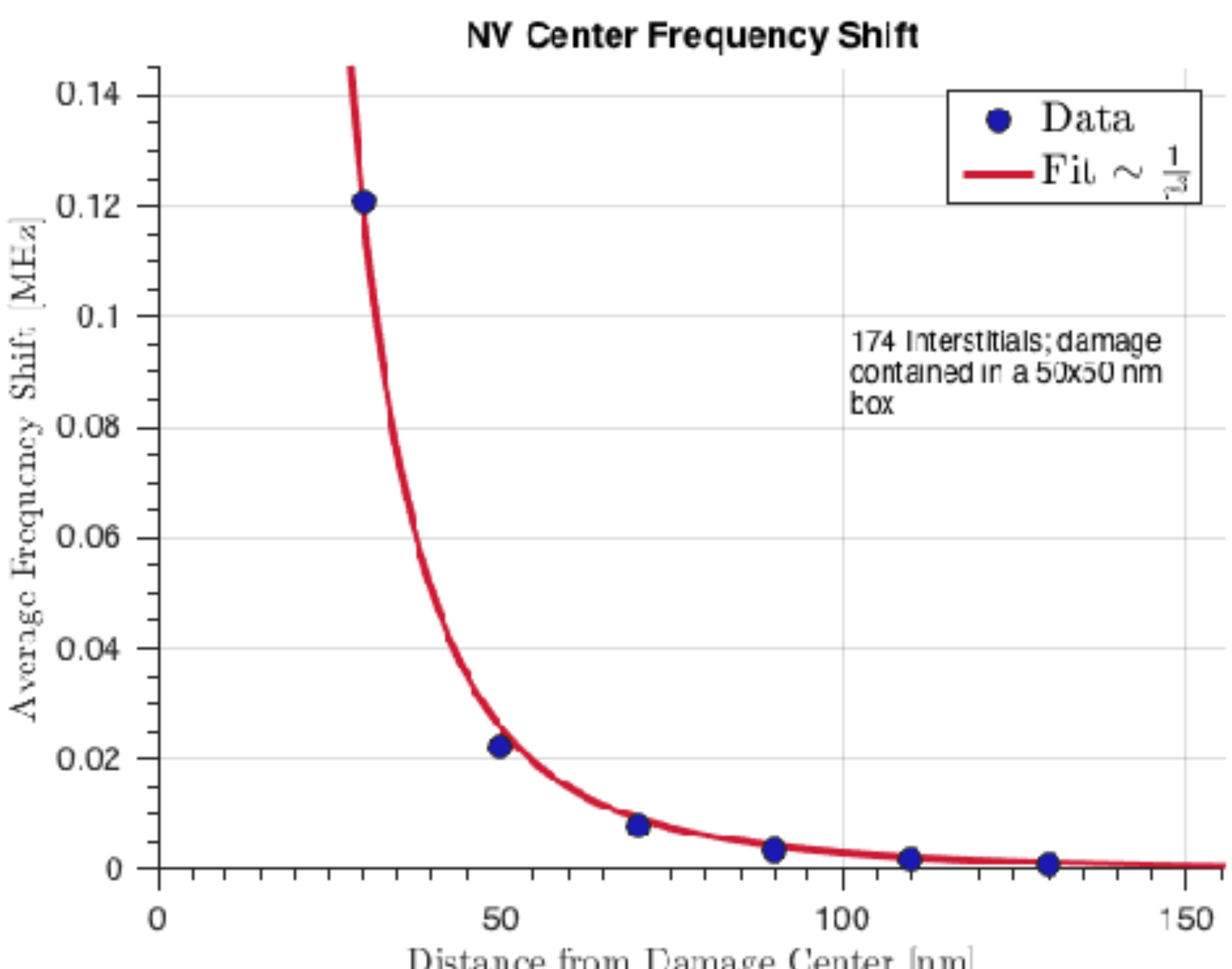

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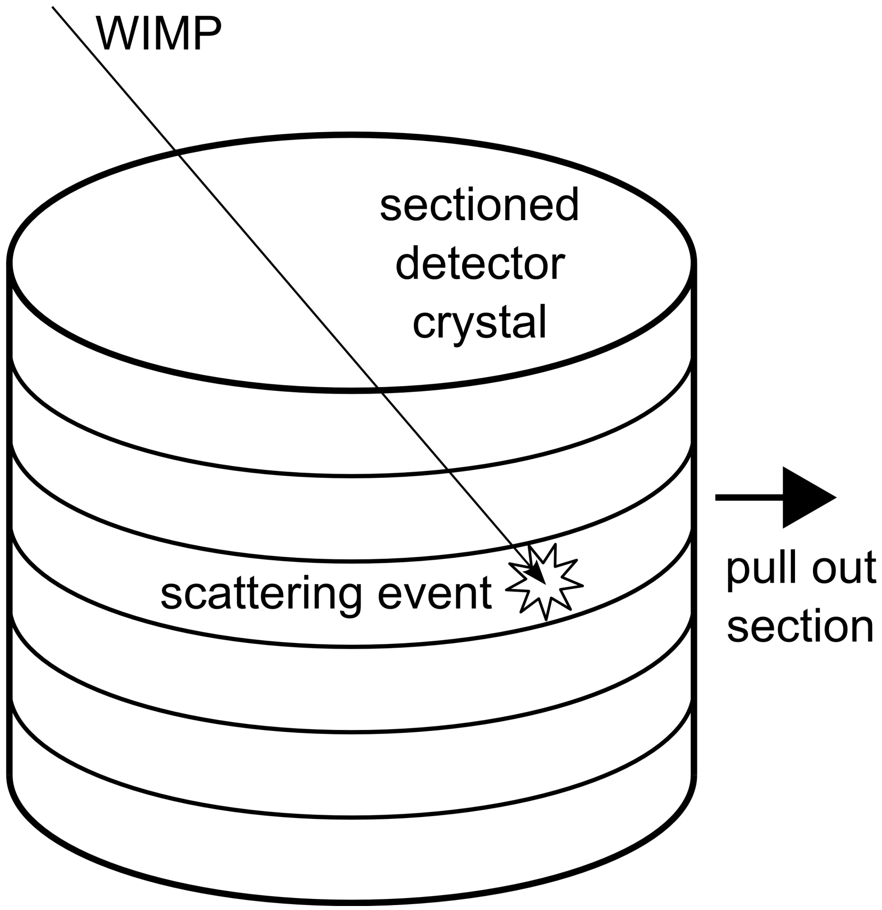
Single NV center has sensitivity to cascade!

Detector Concept



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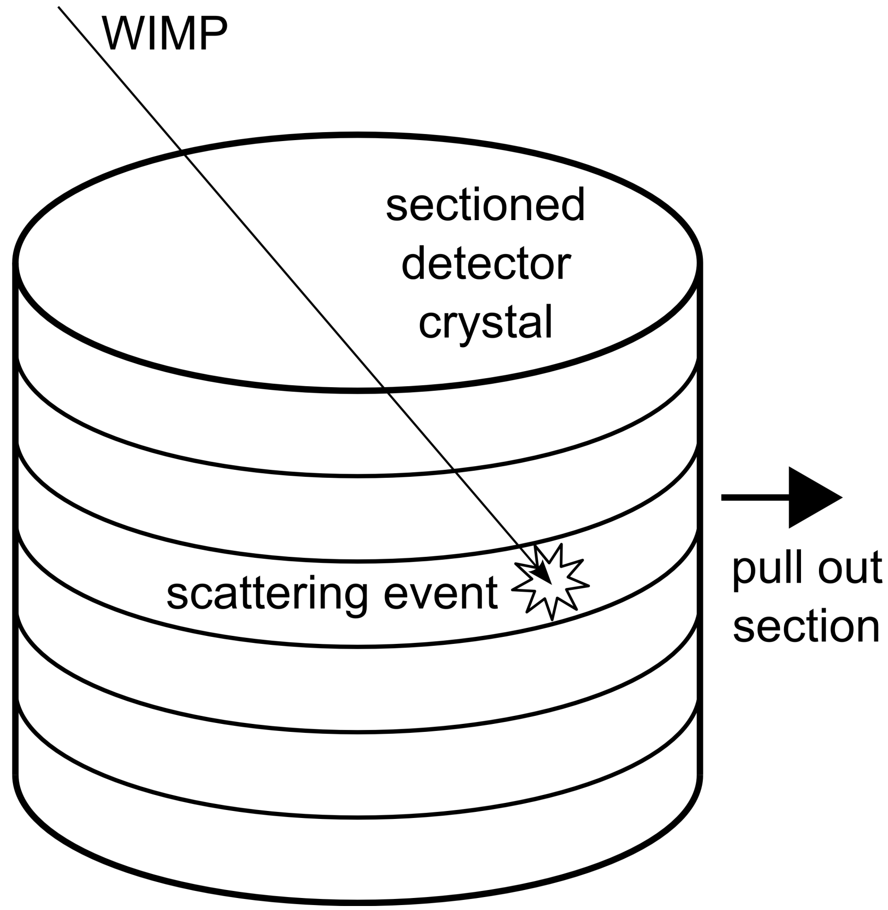

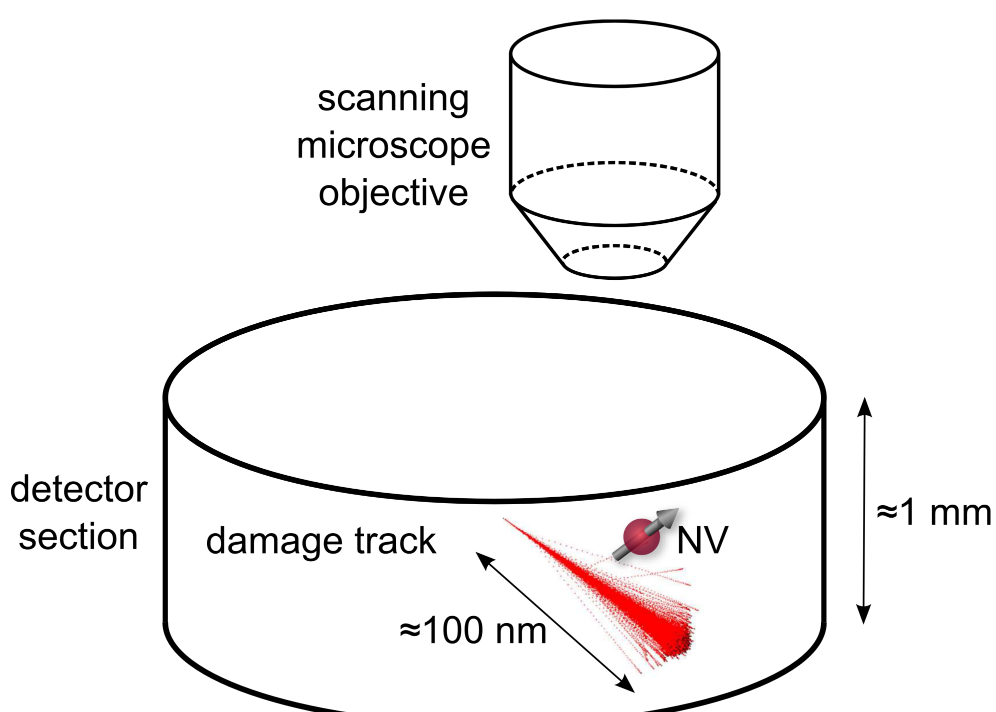

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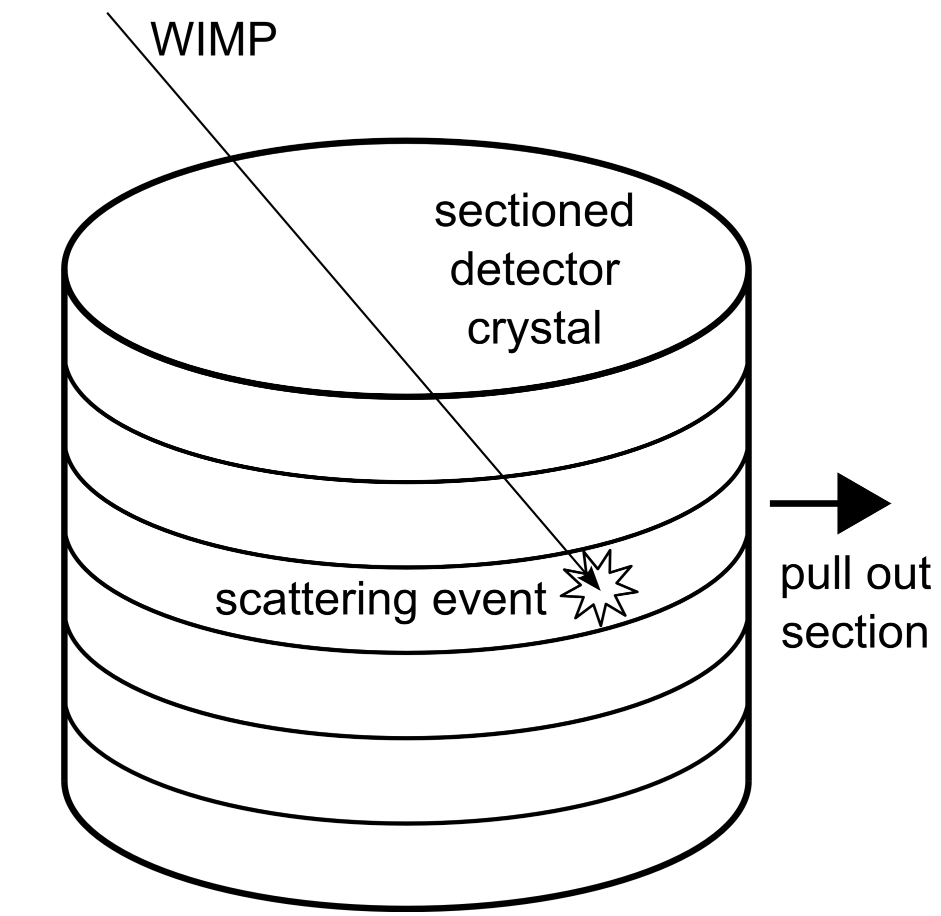

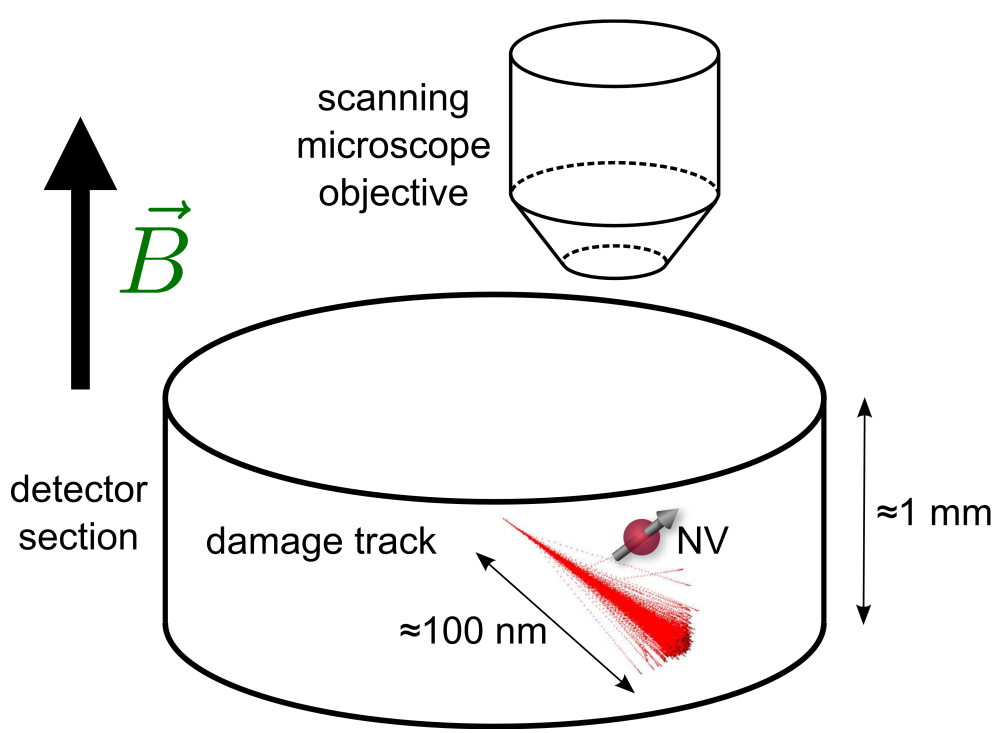

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For nano-scale resolution, apply external magnetic field gradient - hence need segmentation

Results

Take crystal. Grid of NV centers with density 1 per $(30\ \text{nm})^3$

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

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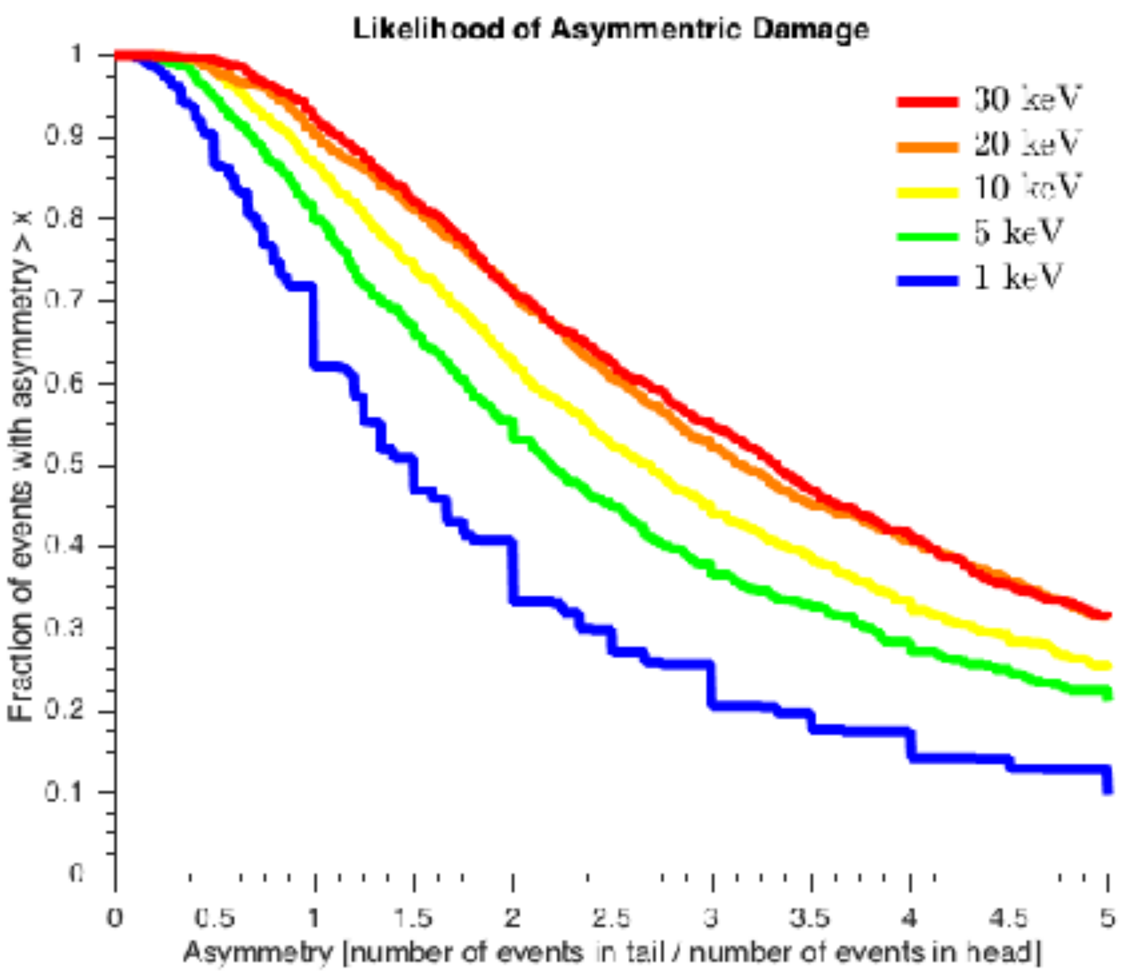

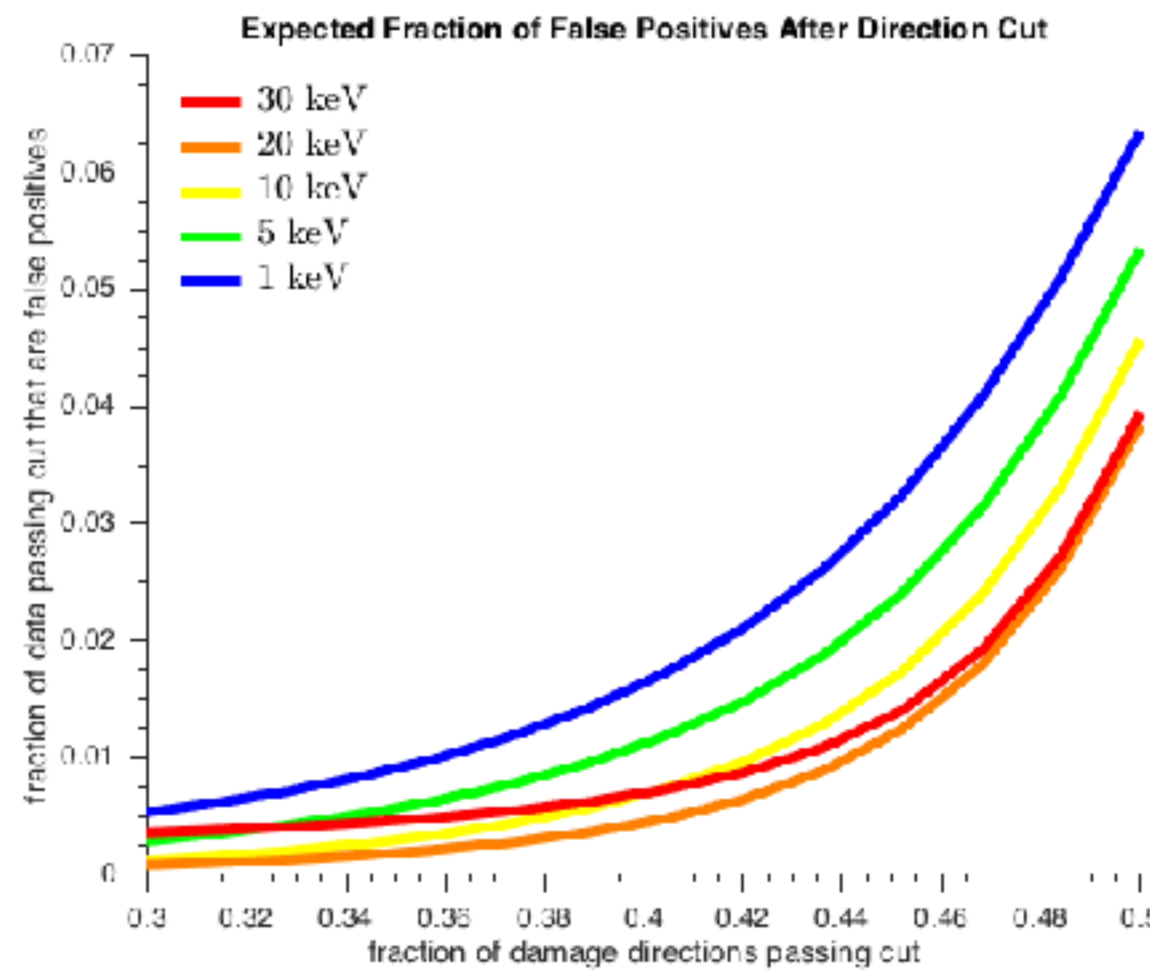

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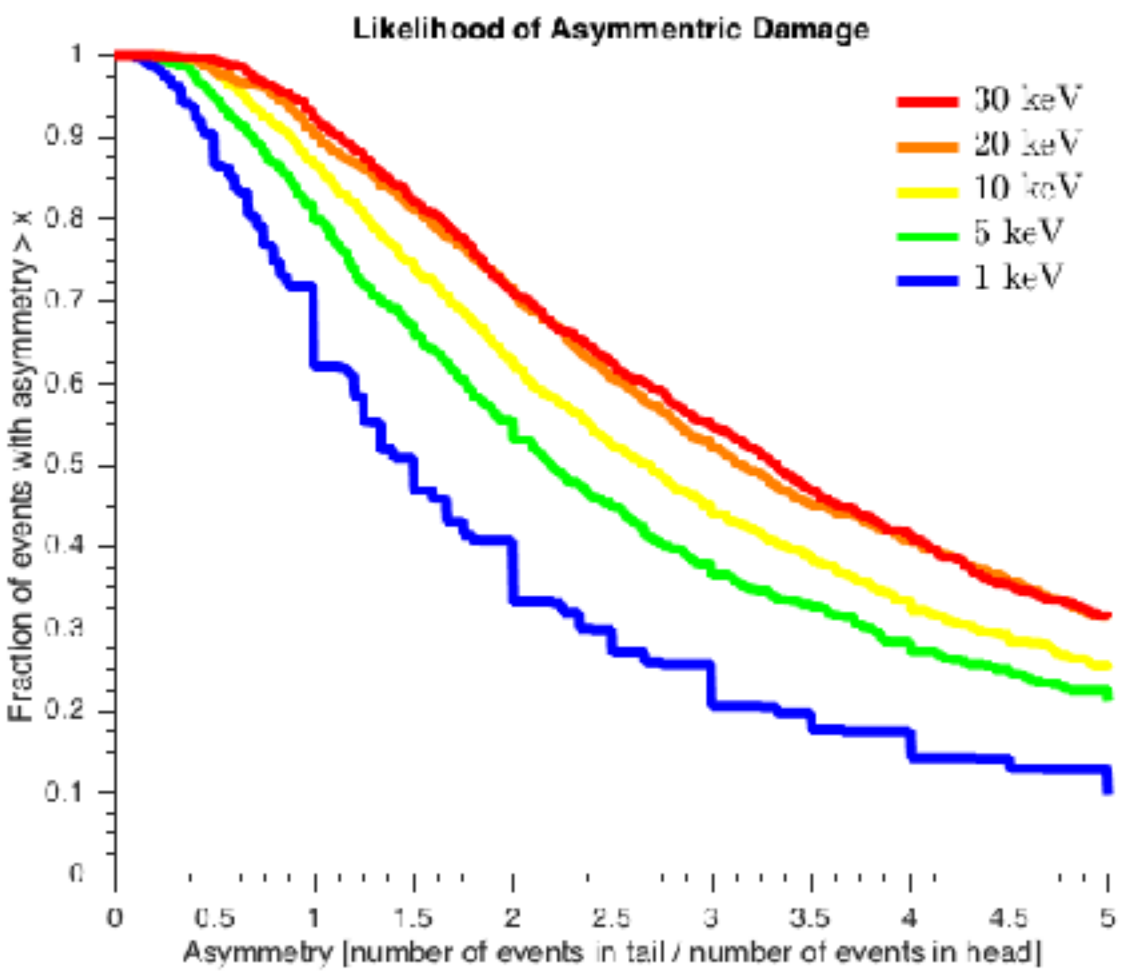

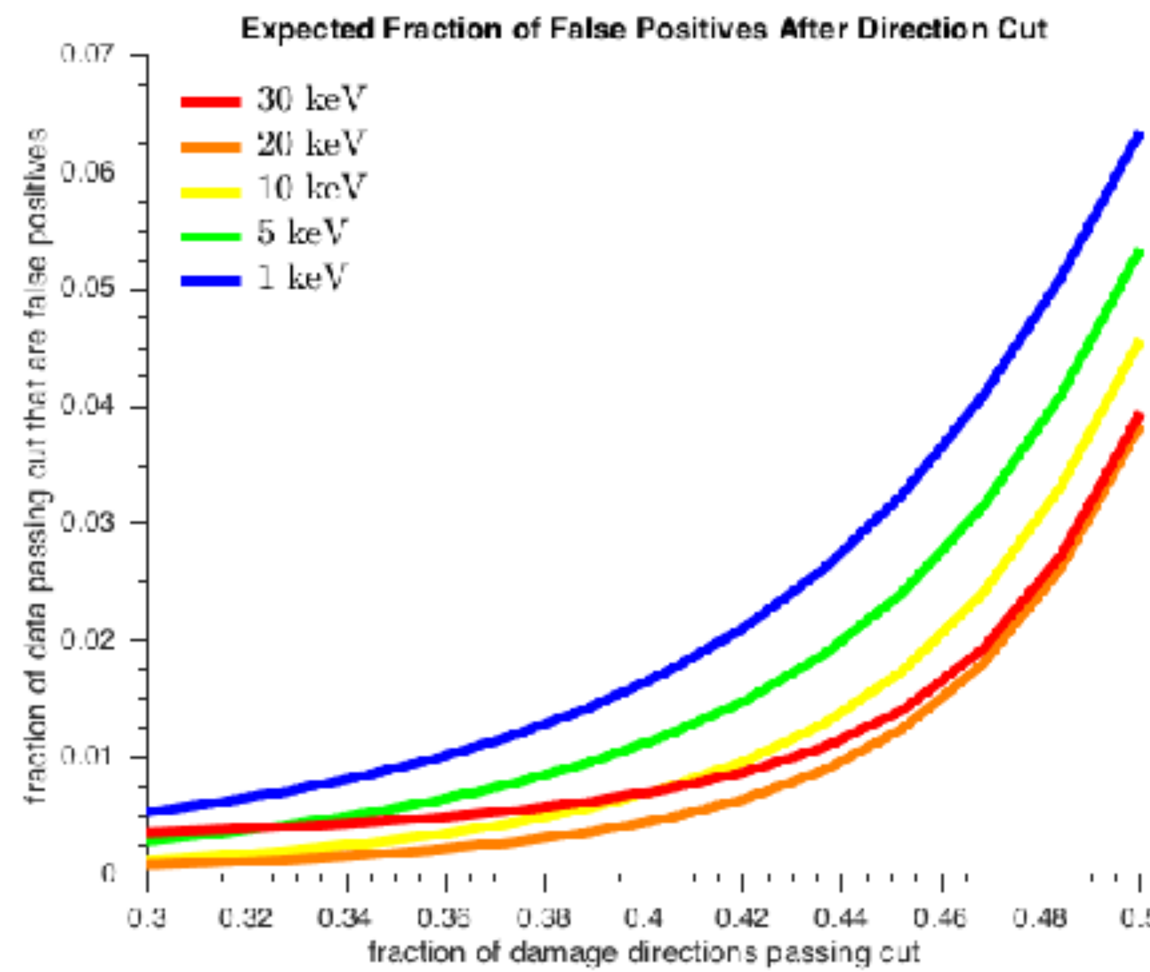

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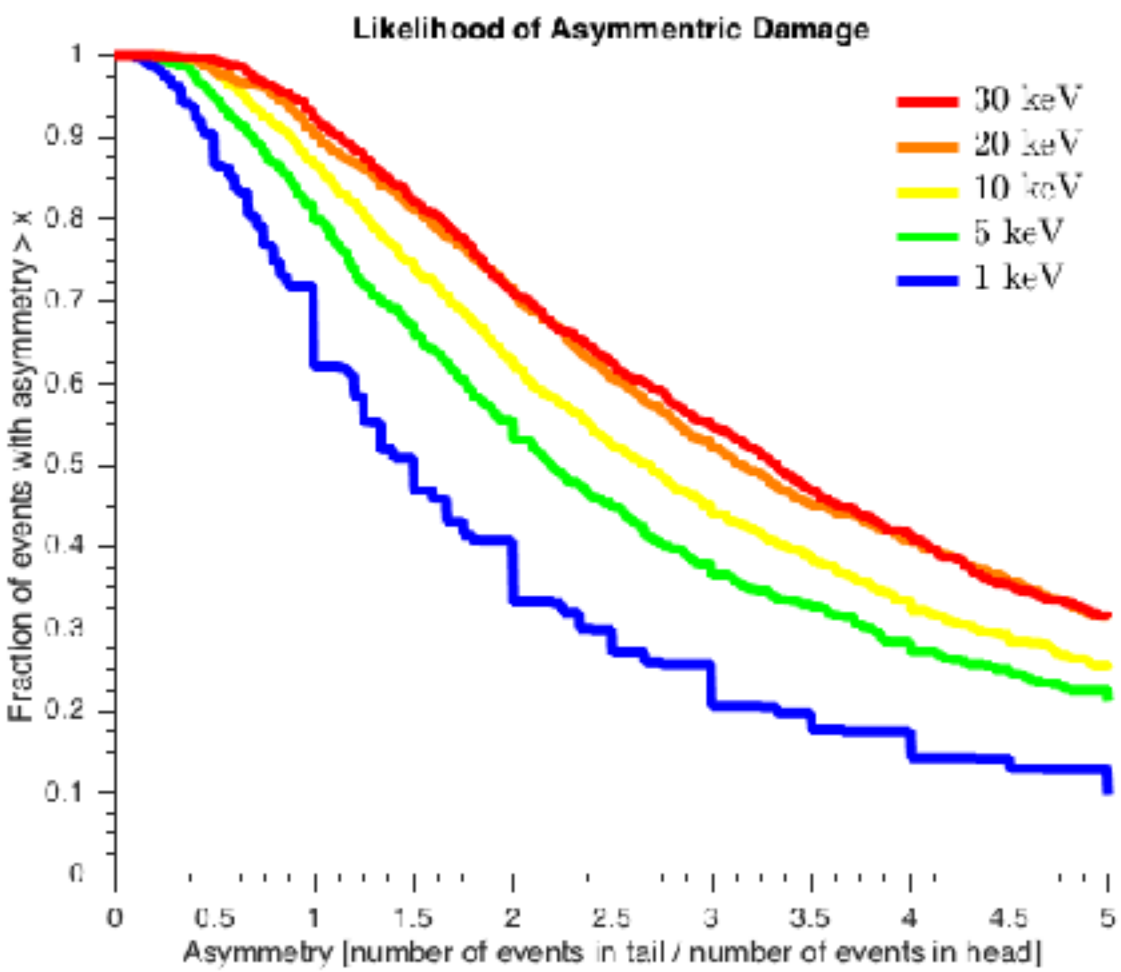

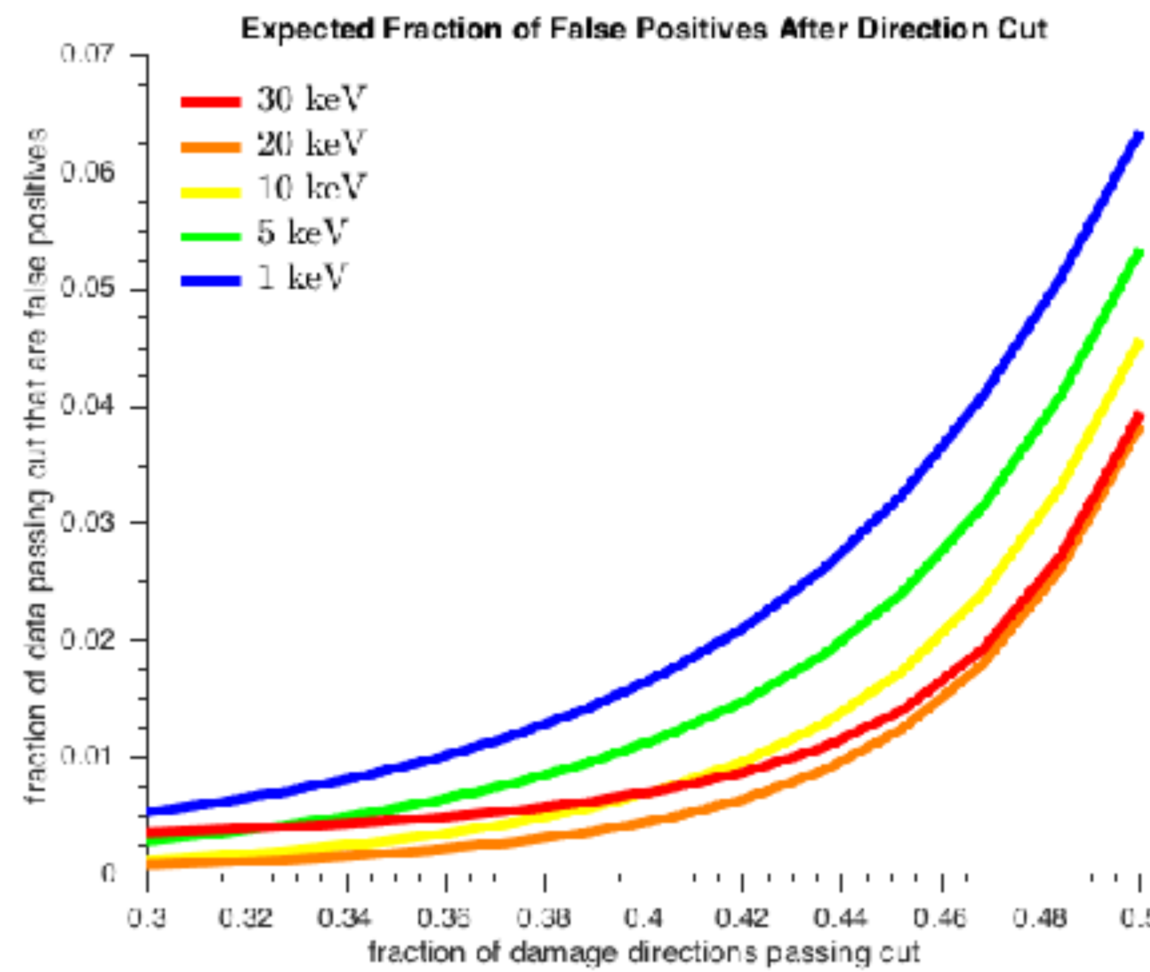

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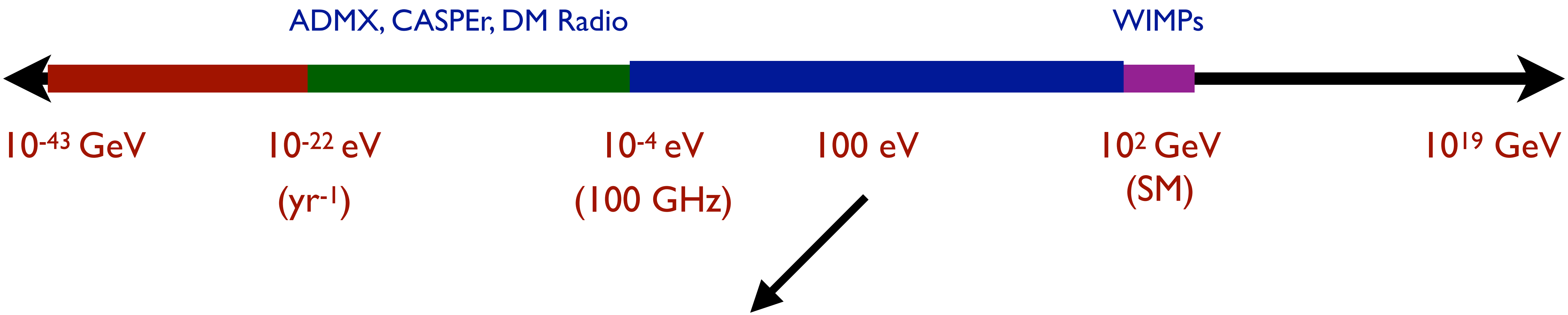
5 σ detection with few events!

Magnetic Bubble Chambers

with

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

The Dark Matter Landscape



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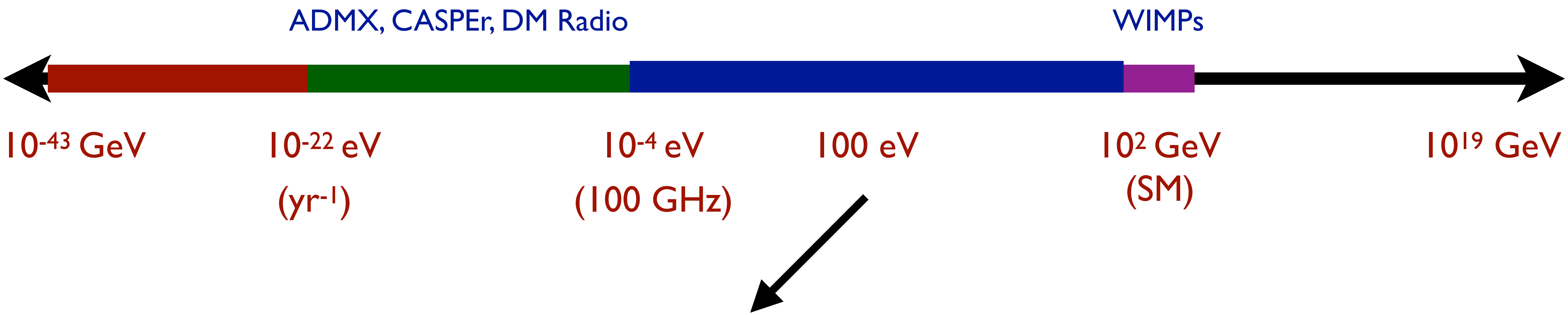

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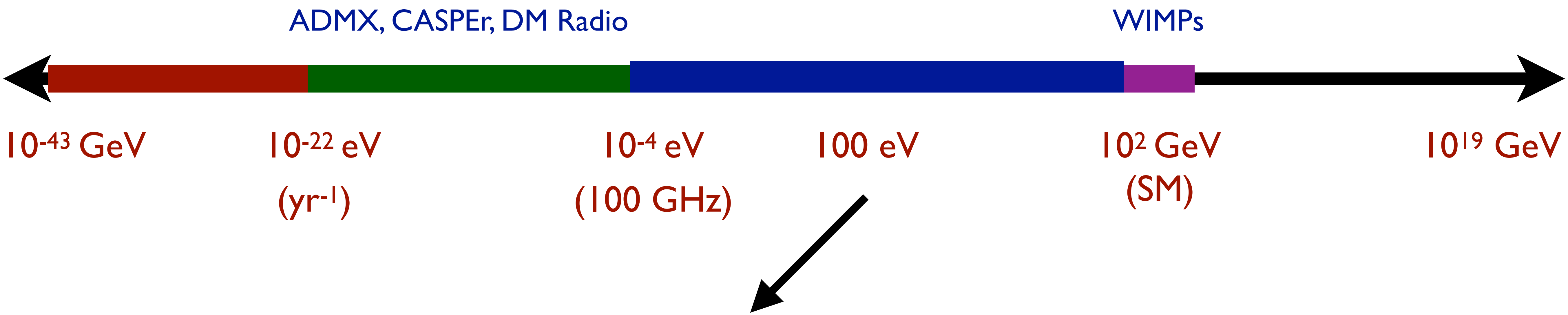

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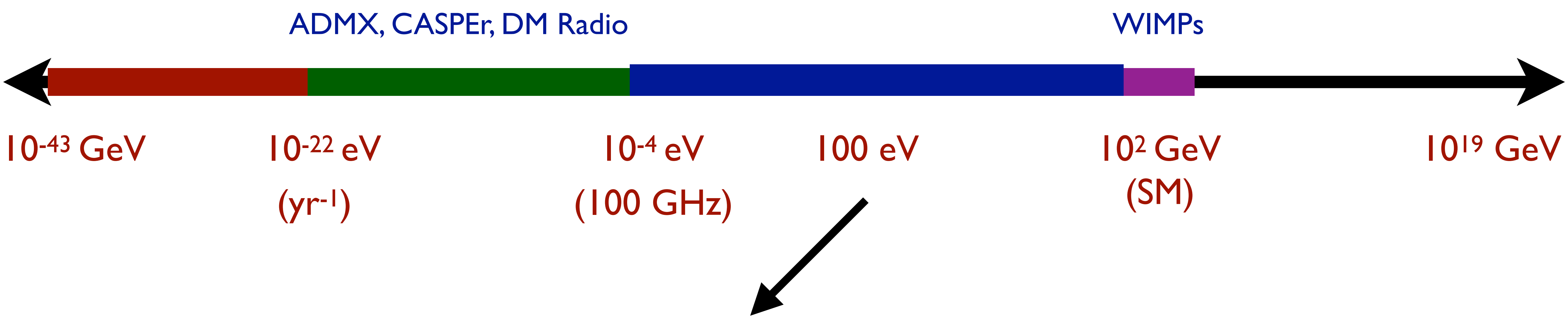

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Challenge: Need large target mass. Rare dark matter event. Requires amplifier stability > years

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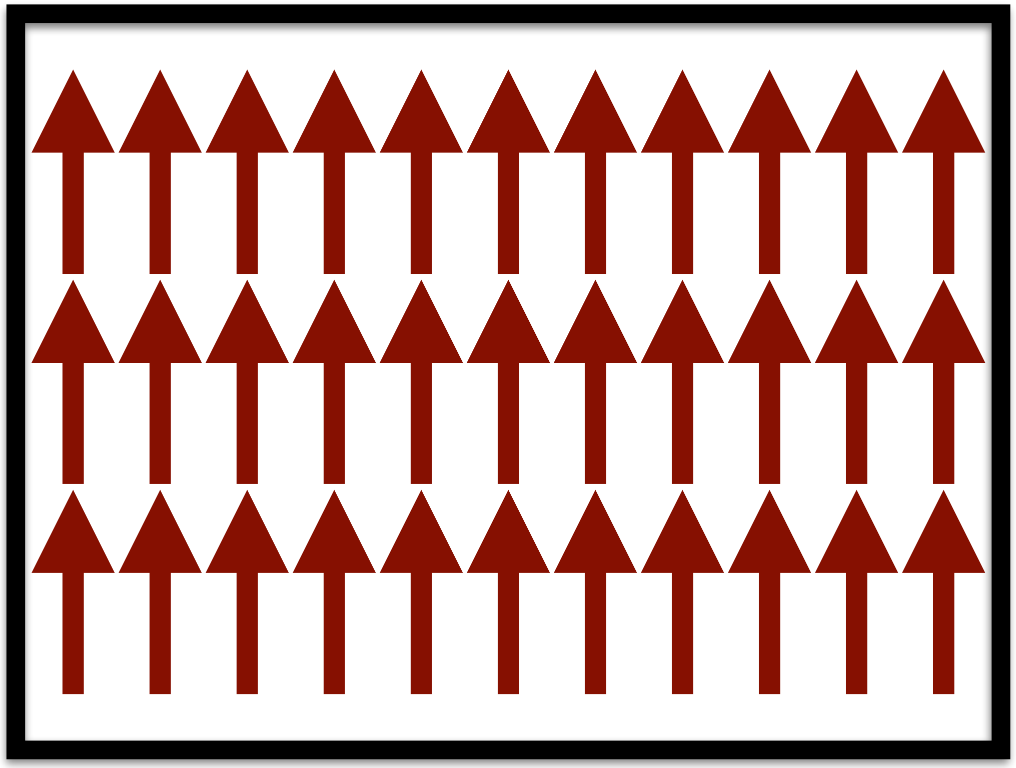

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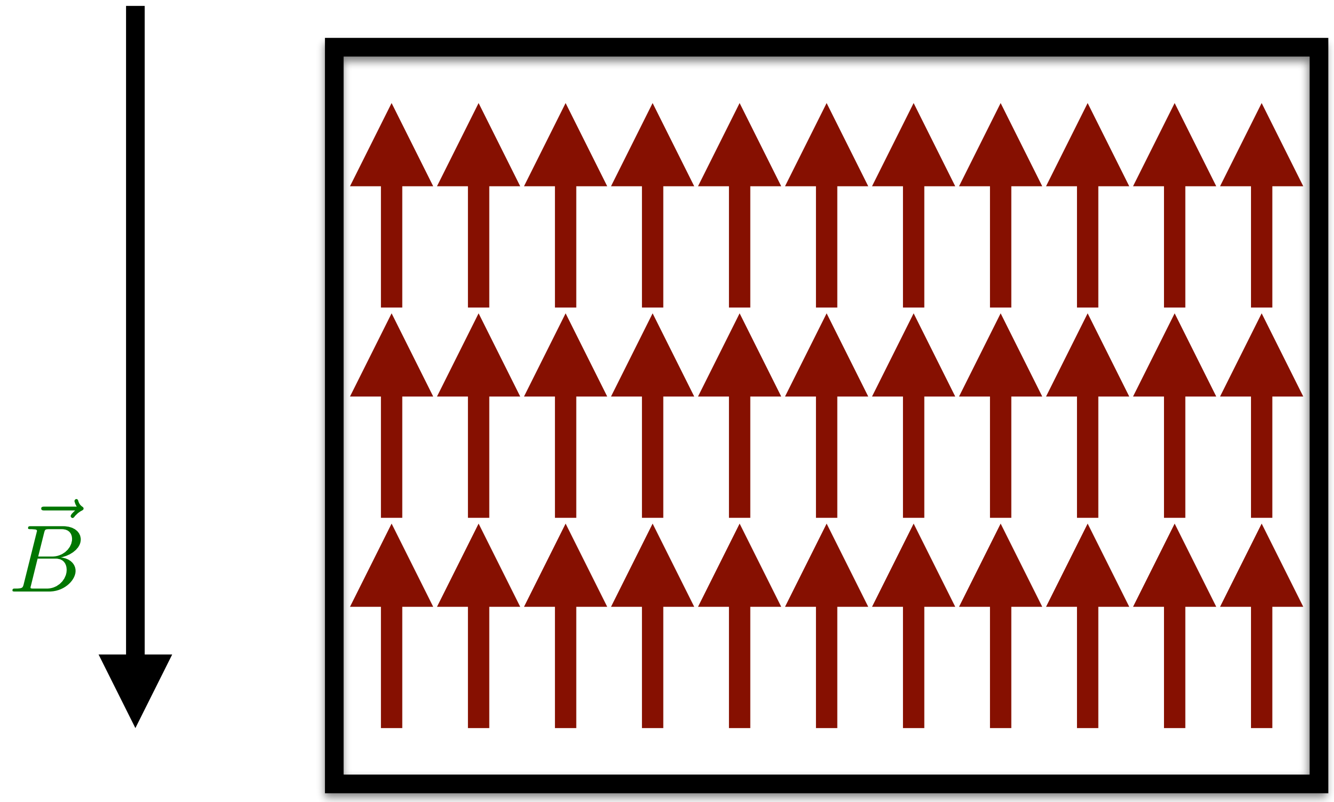

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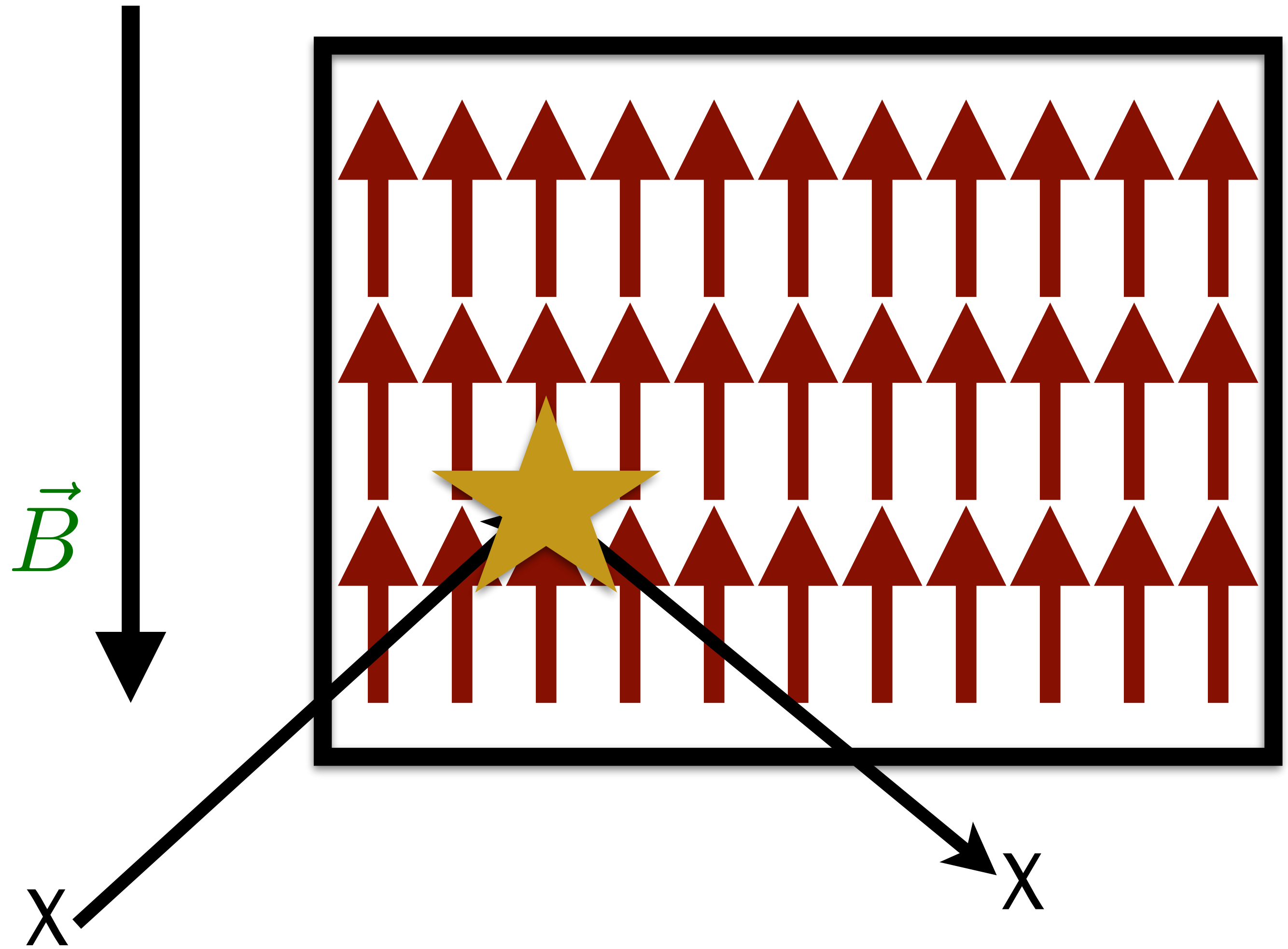

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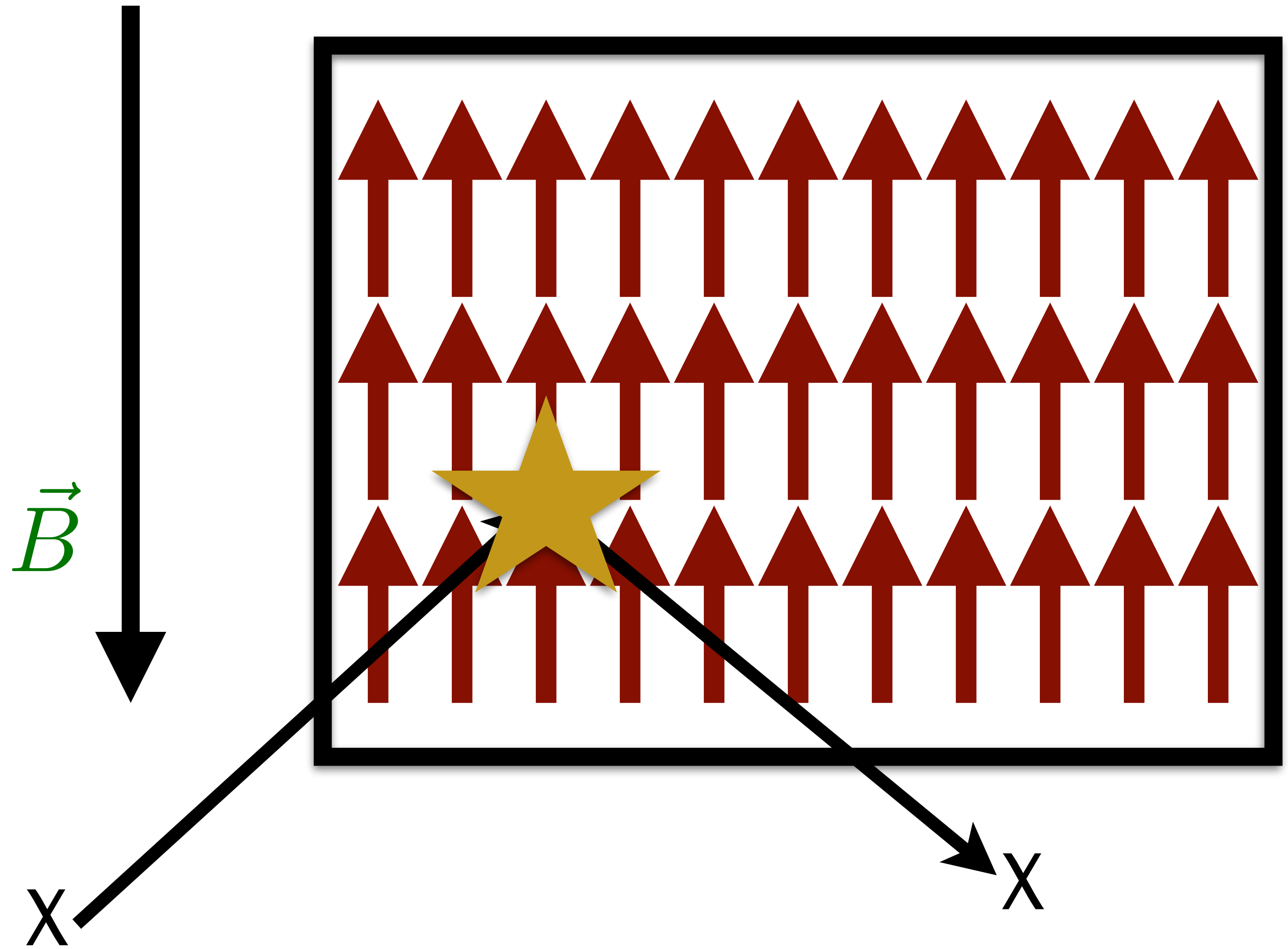

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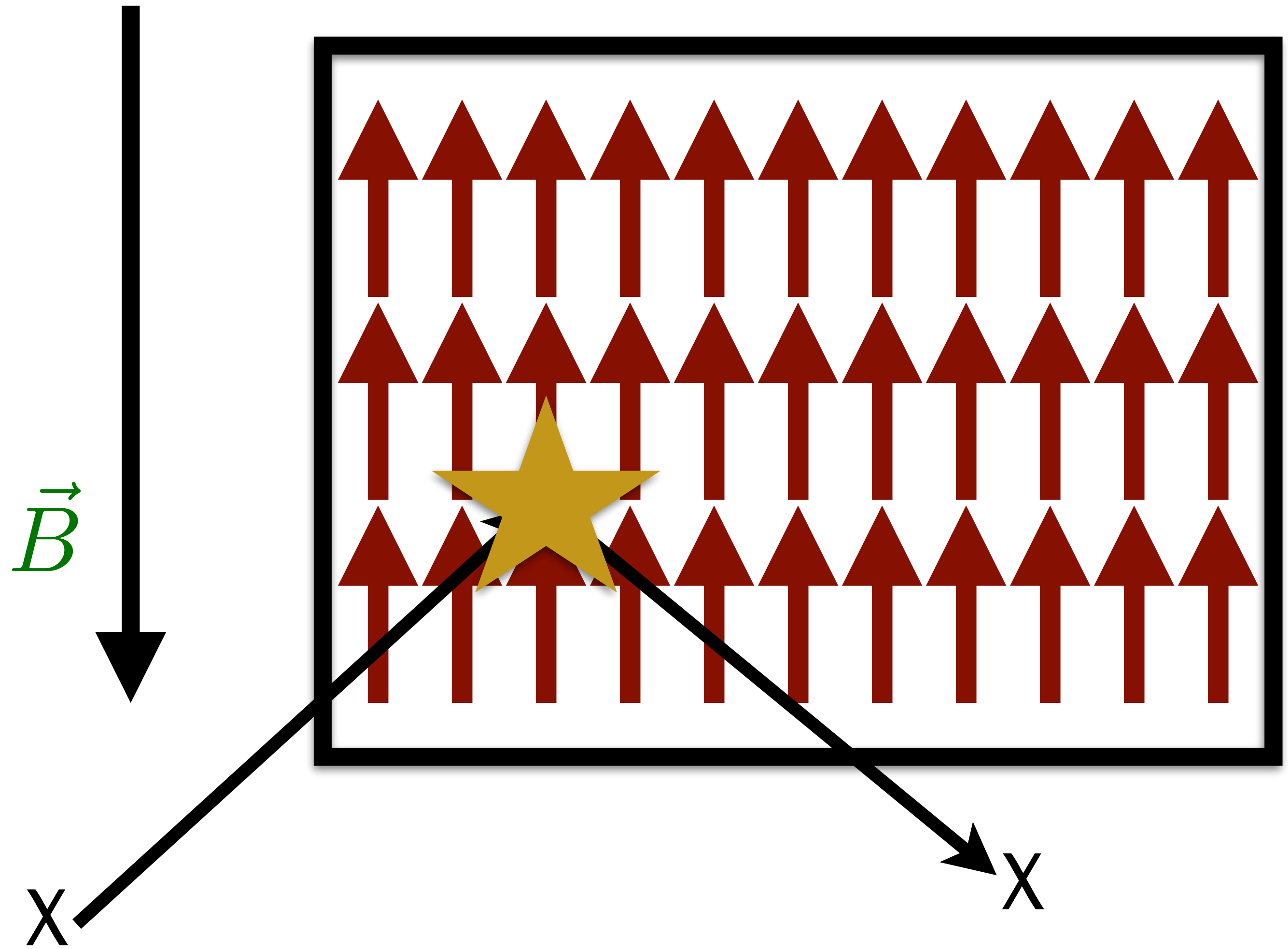

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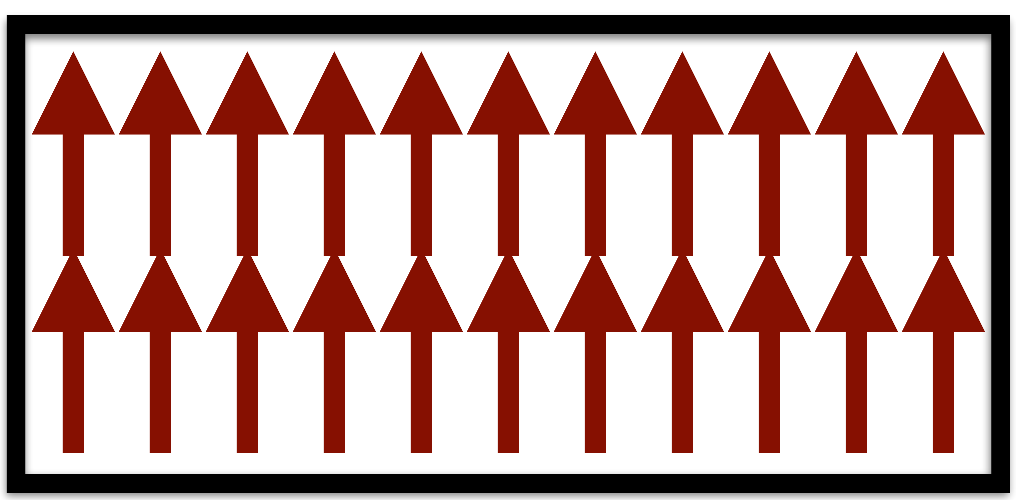

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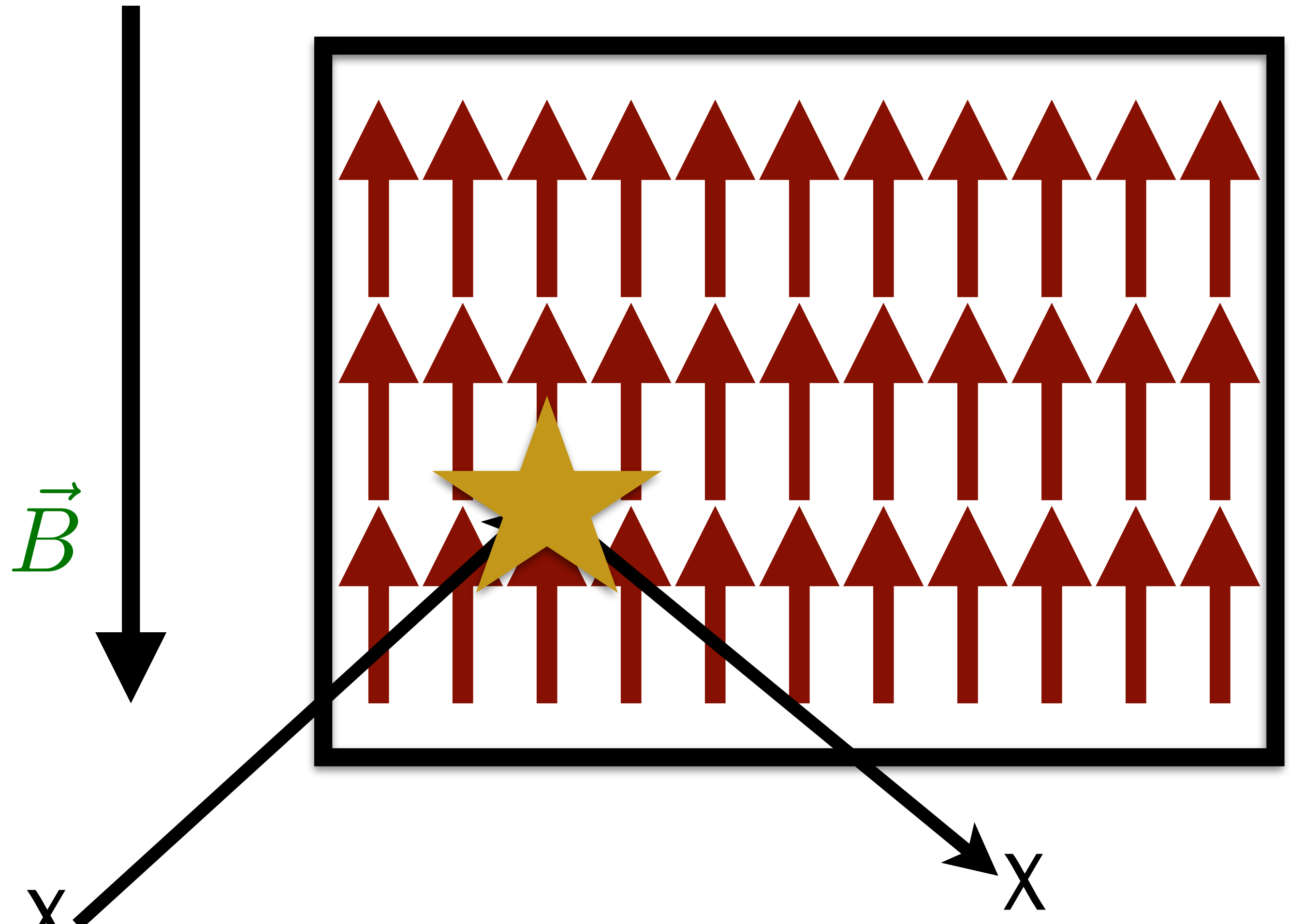

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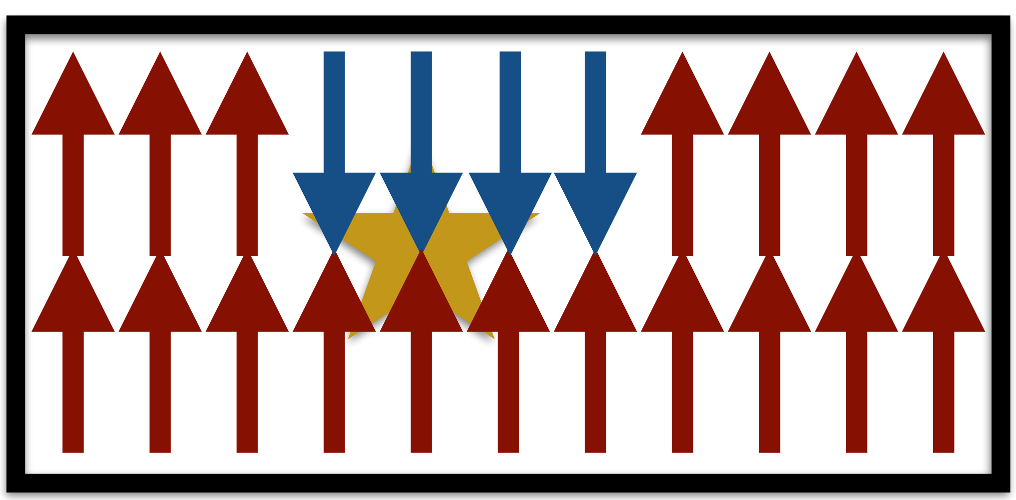

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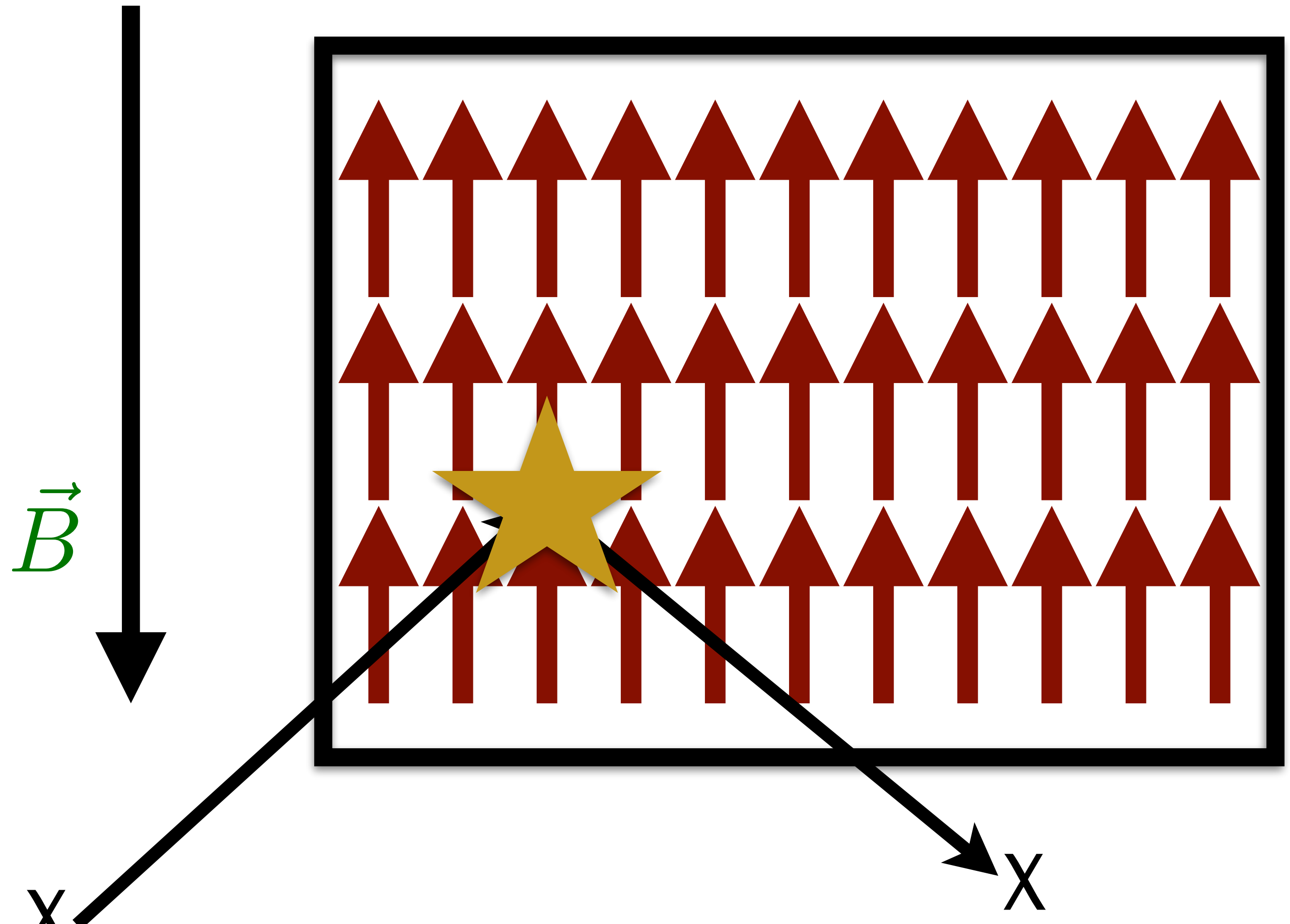

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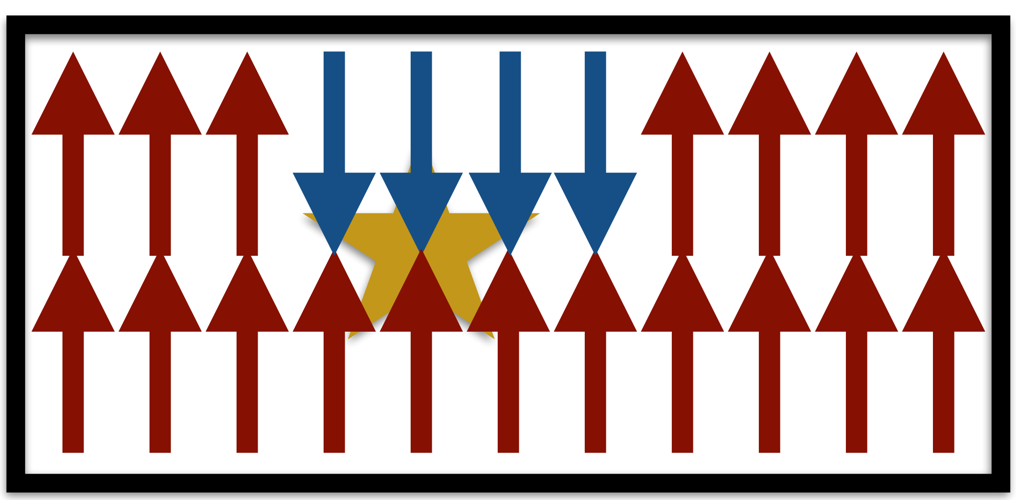

Amplifies deposited energy. Like a bubble chamber. Is this possible? Stability?

Single Molecular Magnets

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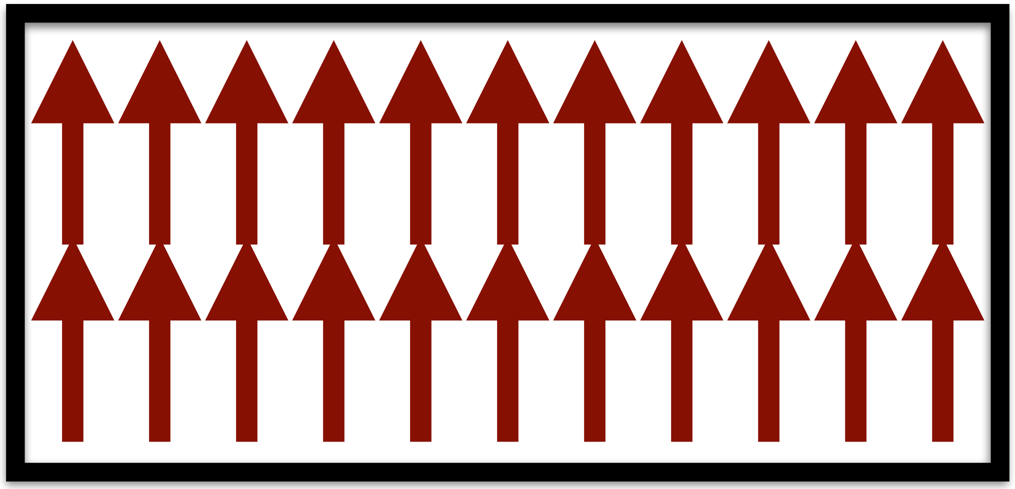

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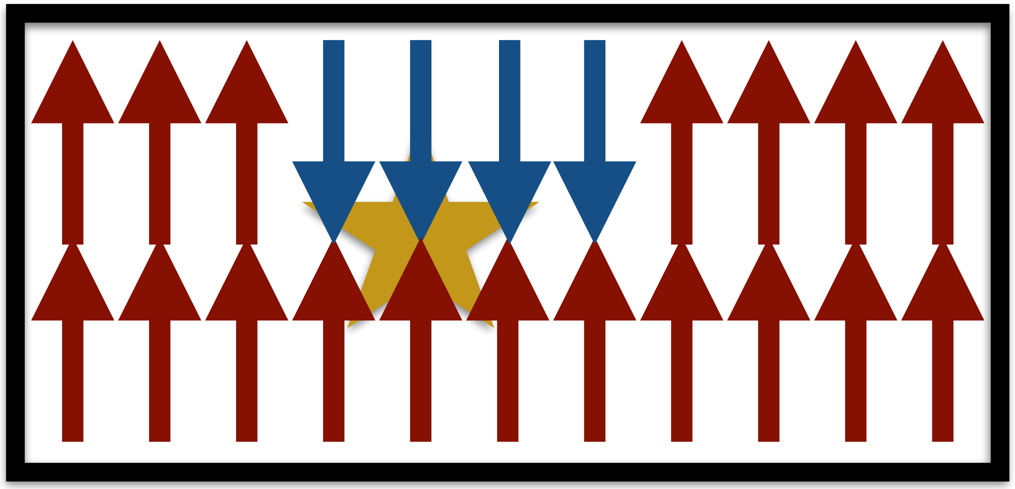

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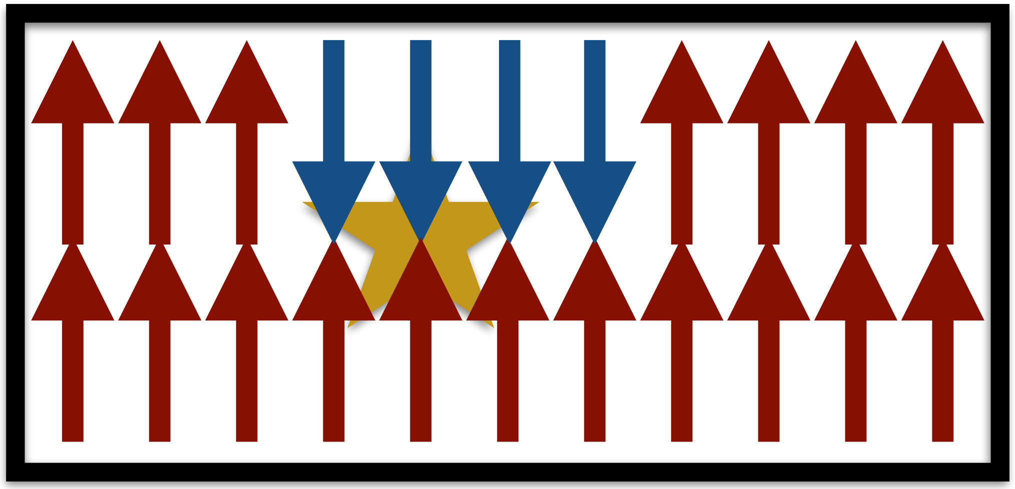

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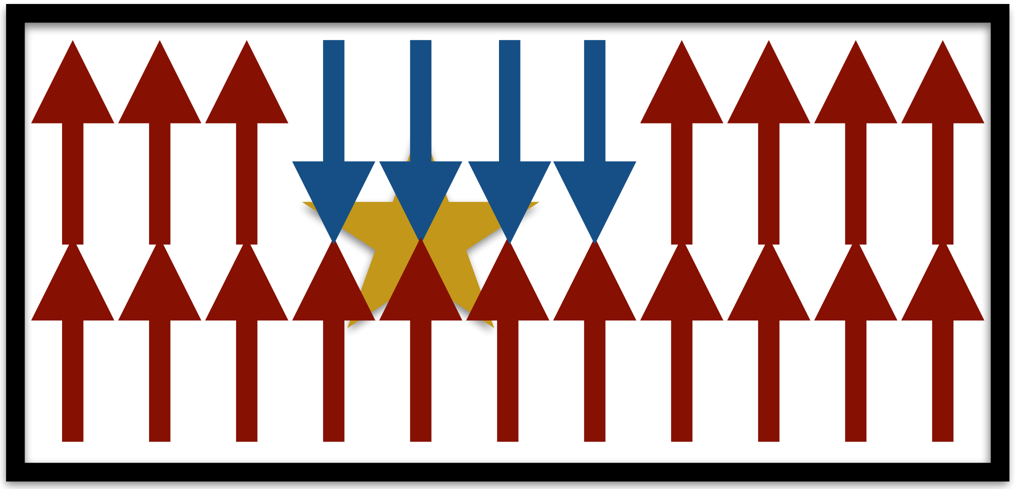

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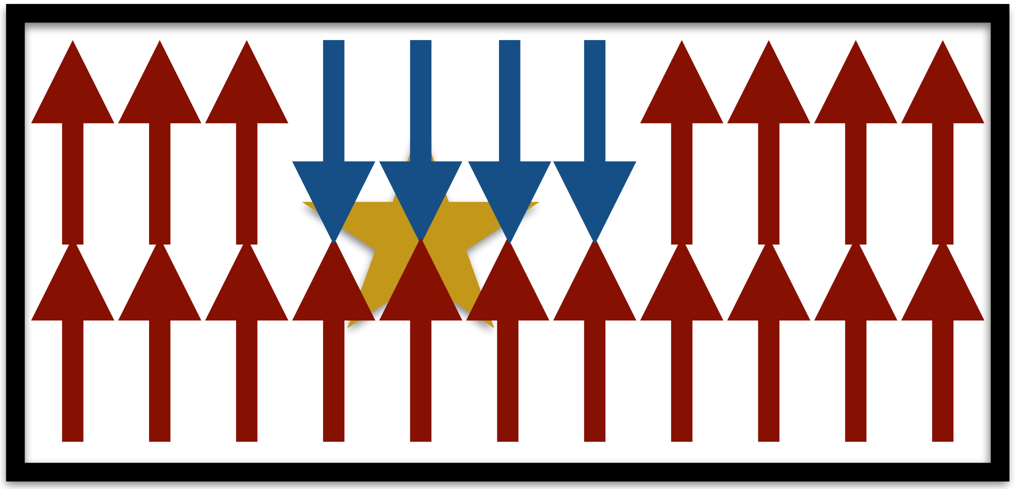

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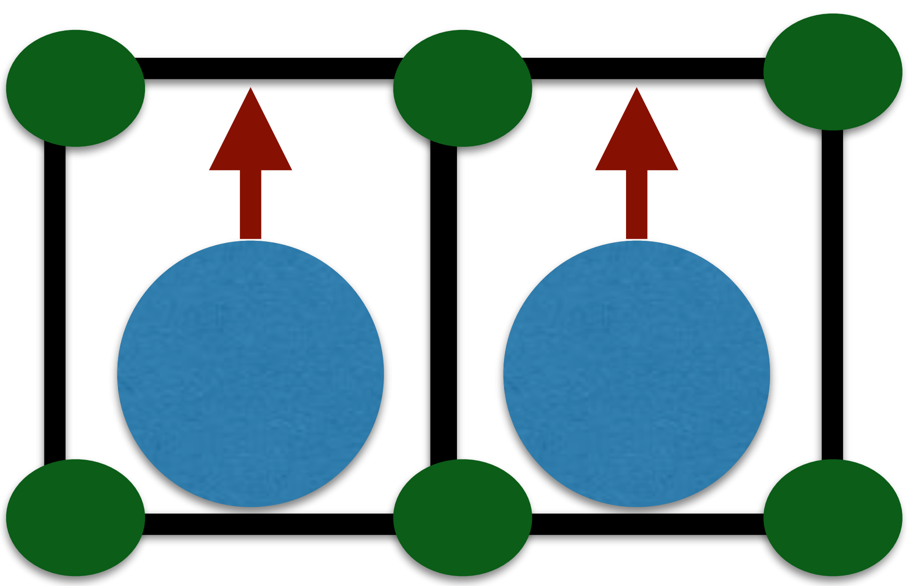

Organo-Metallic complexes. Central metal complex surrounded by organic material.

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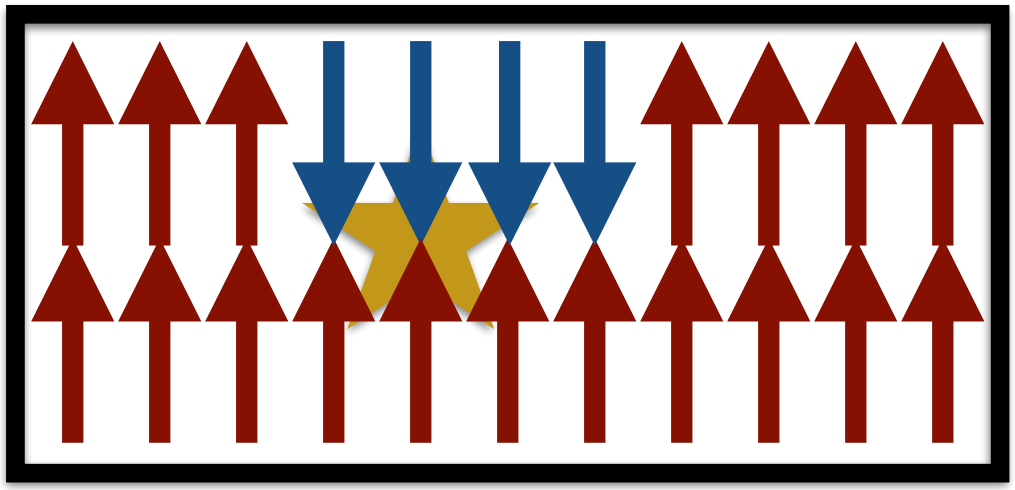

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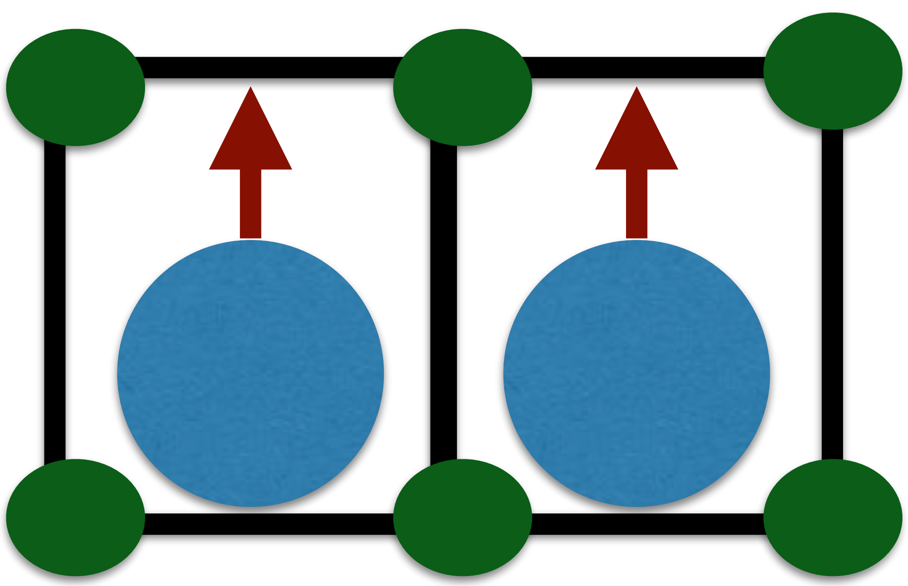

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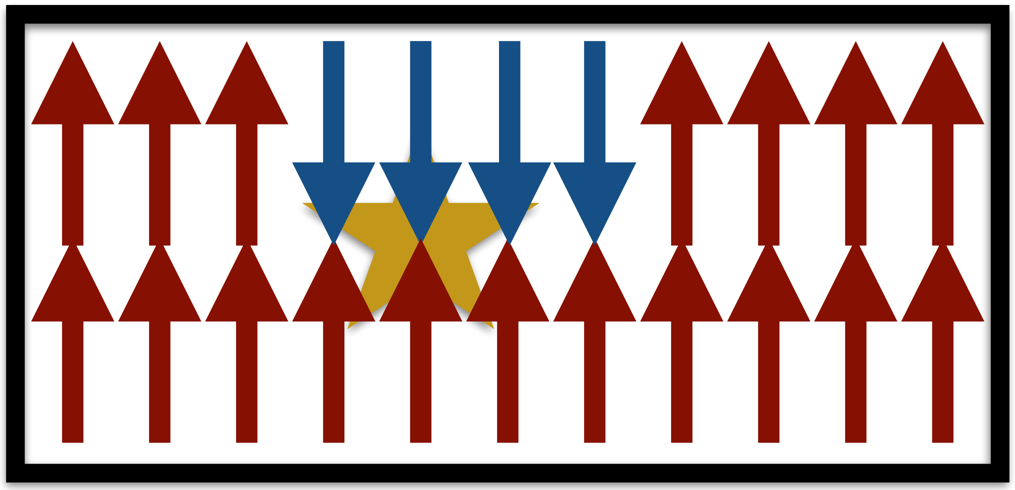

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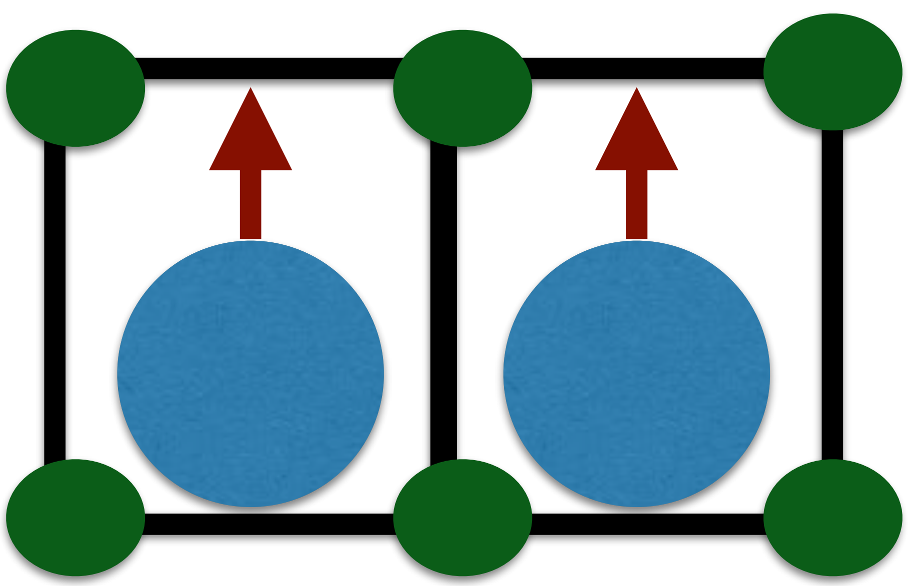

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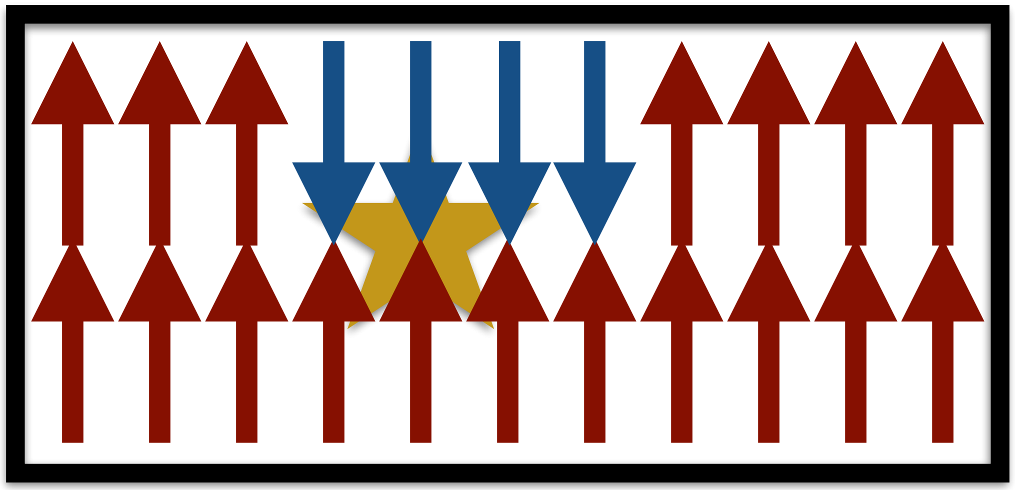

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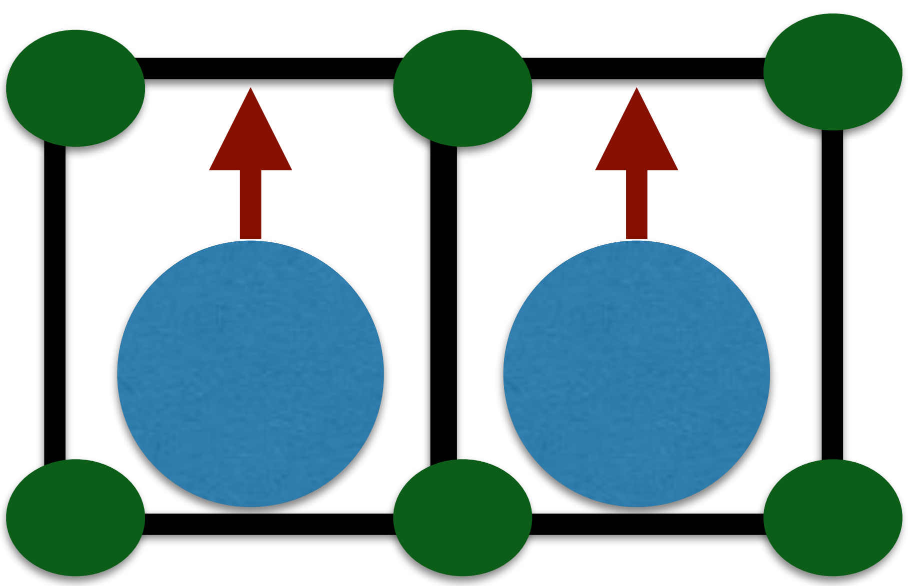

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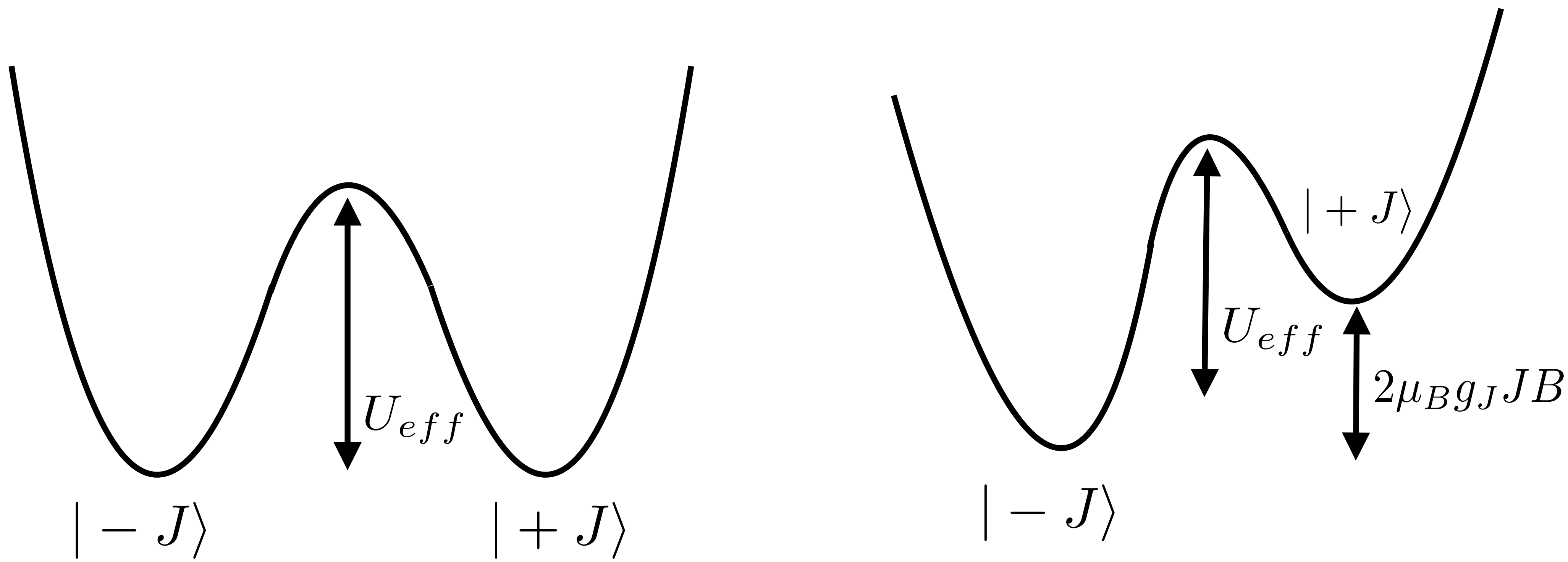
Recently discovered systems. Few 100 known examples. Can make large samples. Magnetic deflagration experimentally observed and well studied in Manganese Acetate complexes

Magnetic Deflagration



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Two states separated by energy barrier.

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

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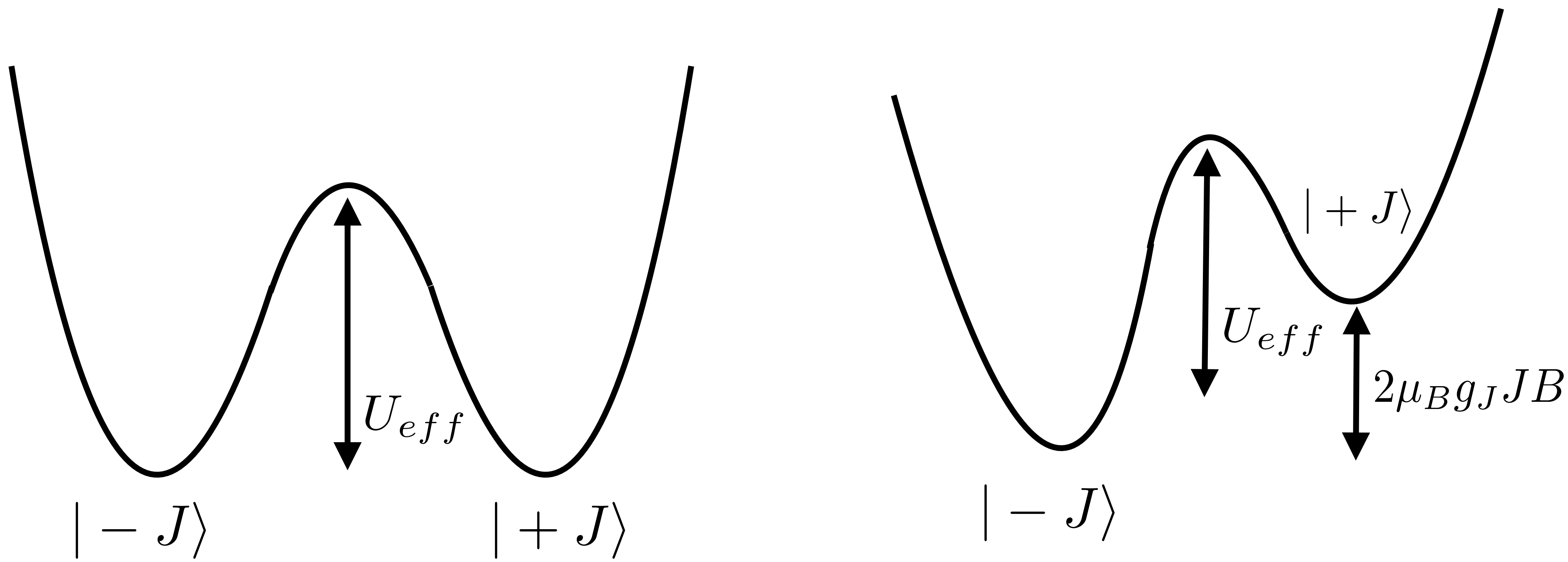

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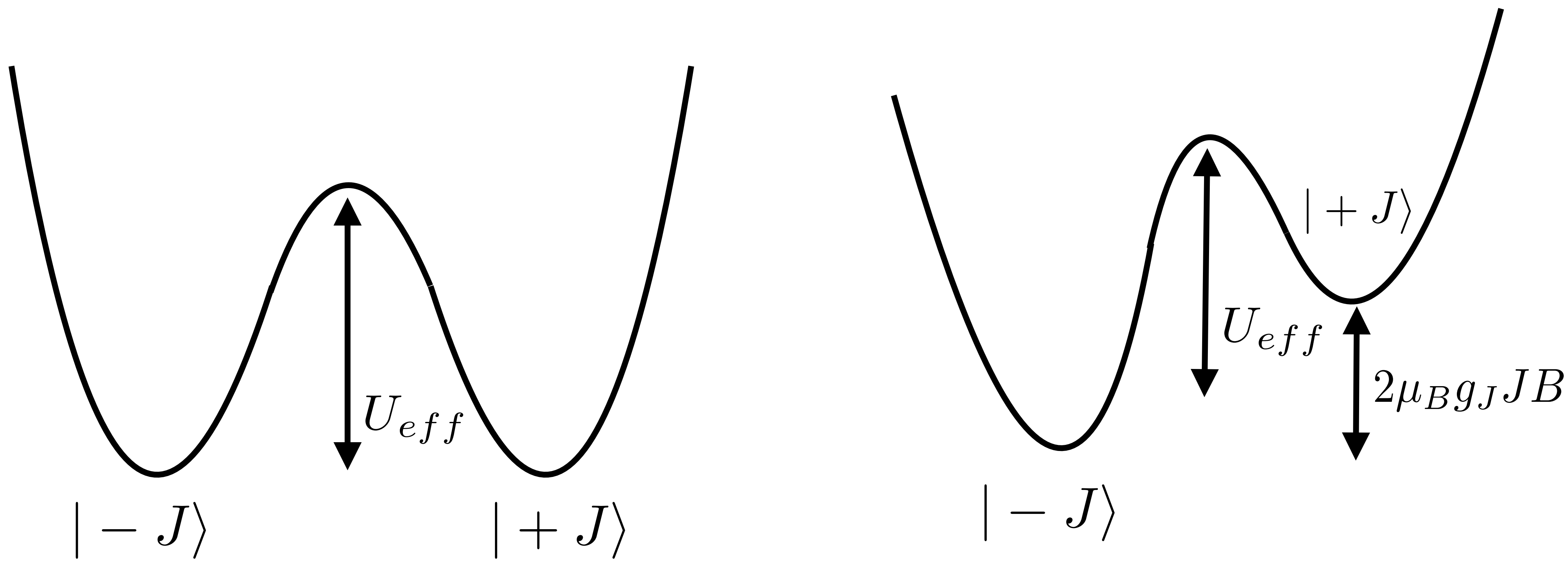

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Ultra-long lived state at low temperature - localized heating rapidly decreases life-time, decay results in more energy release

Condition for Deflagration

Initially heat region of size λ to T

Thermal Diffusion, lowers T

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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

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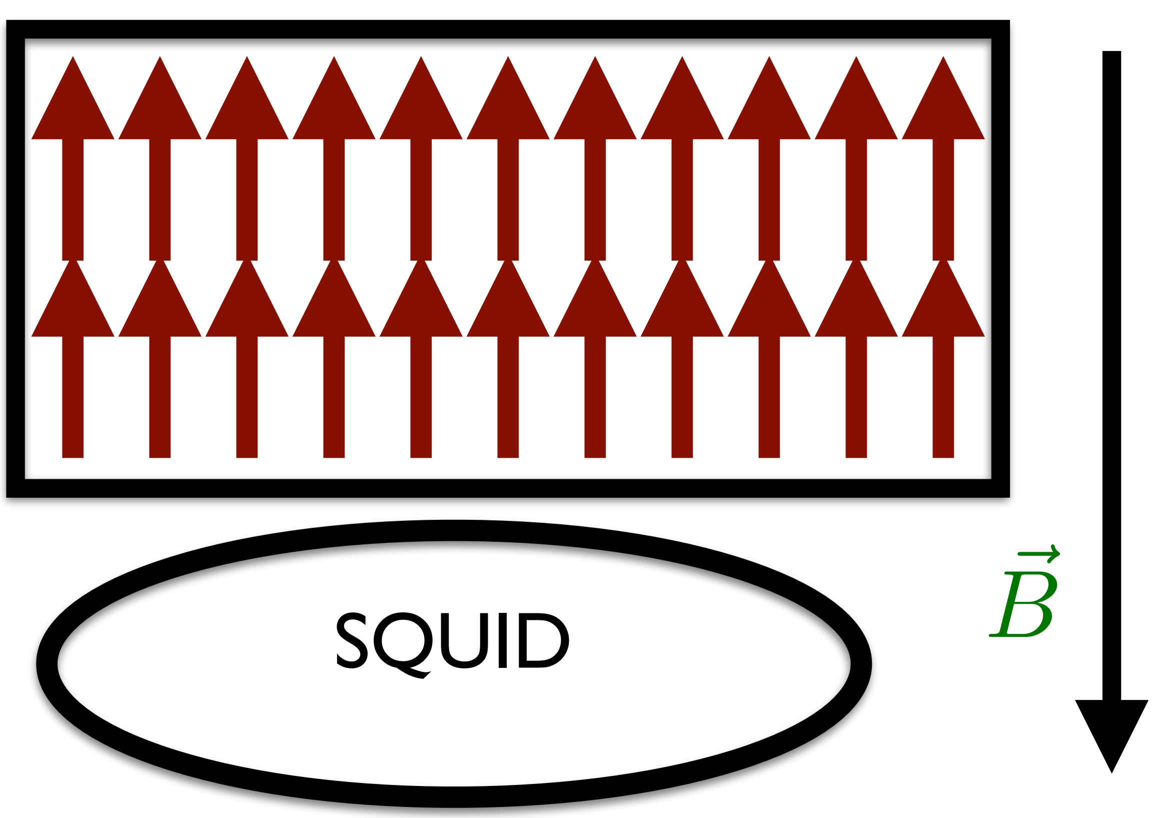

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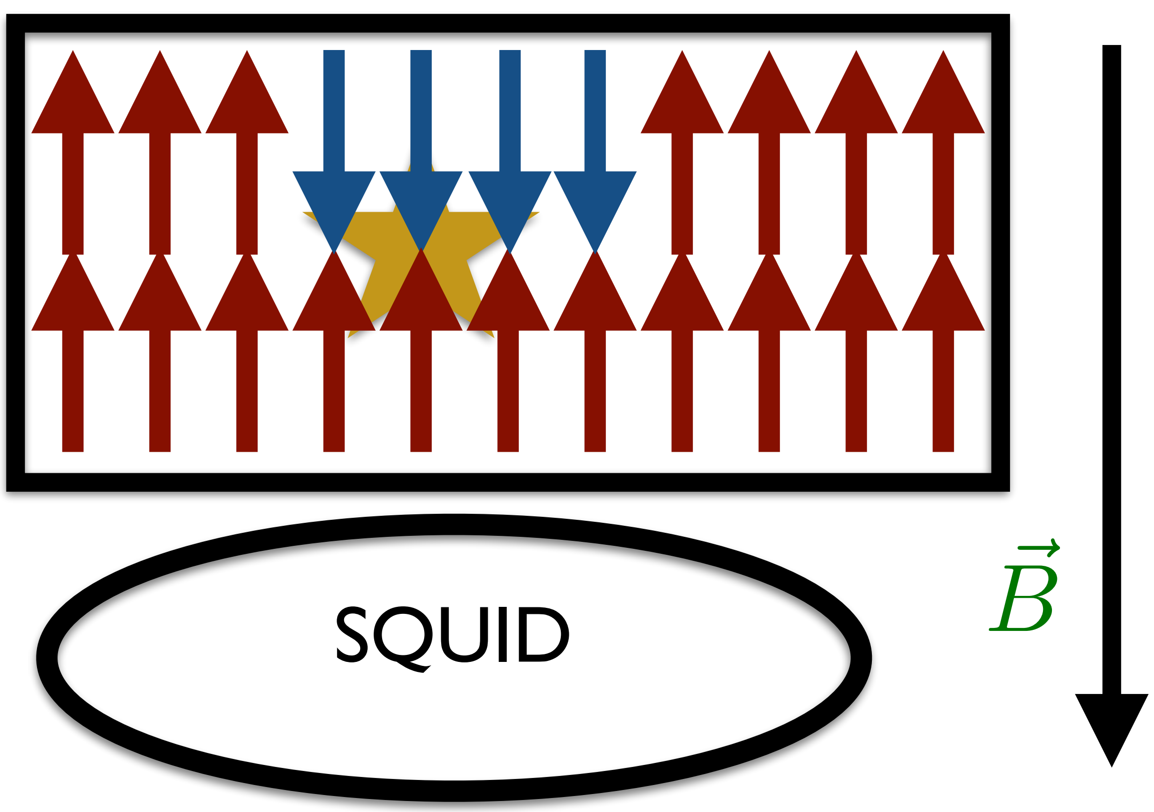

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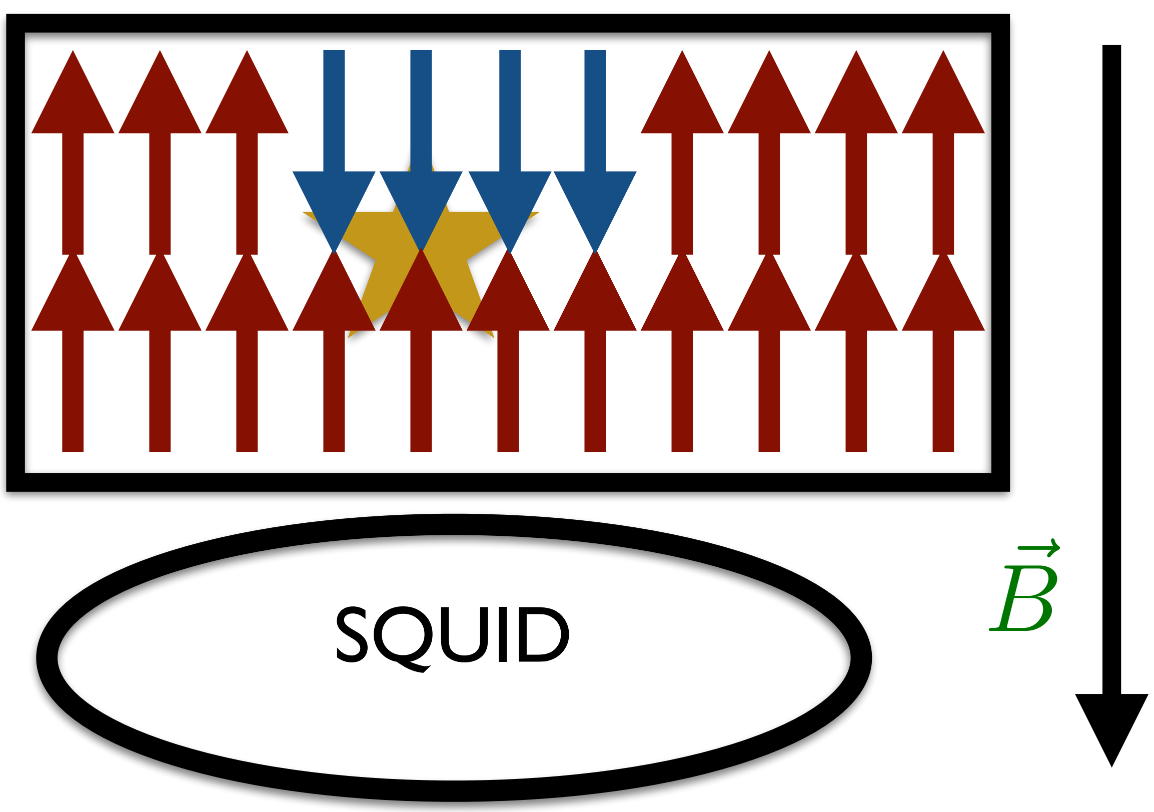

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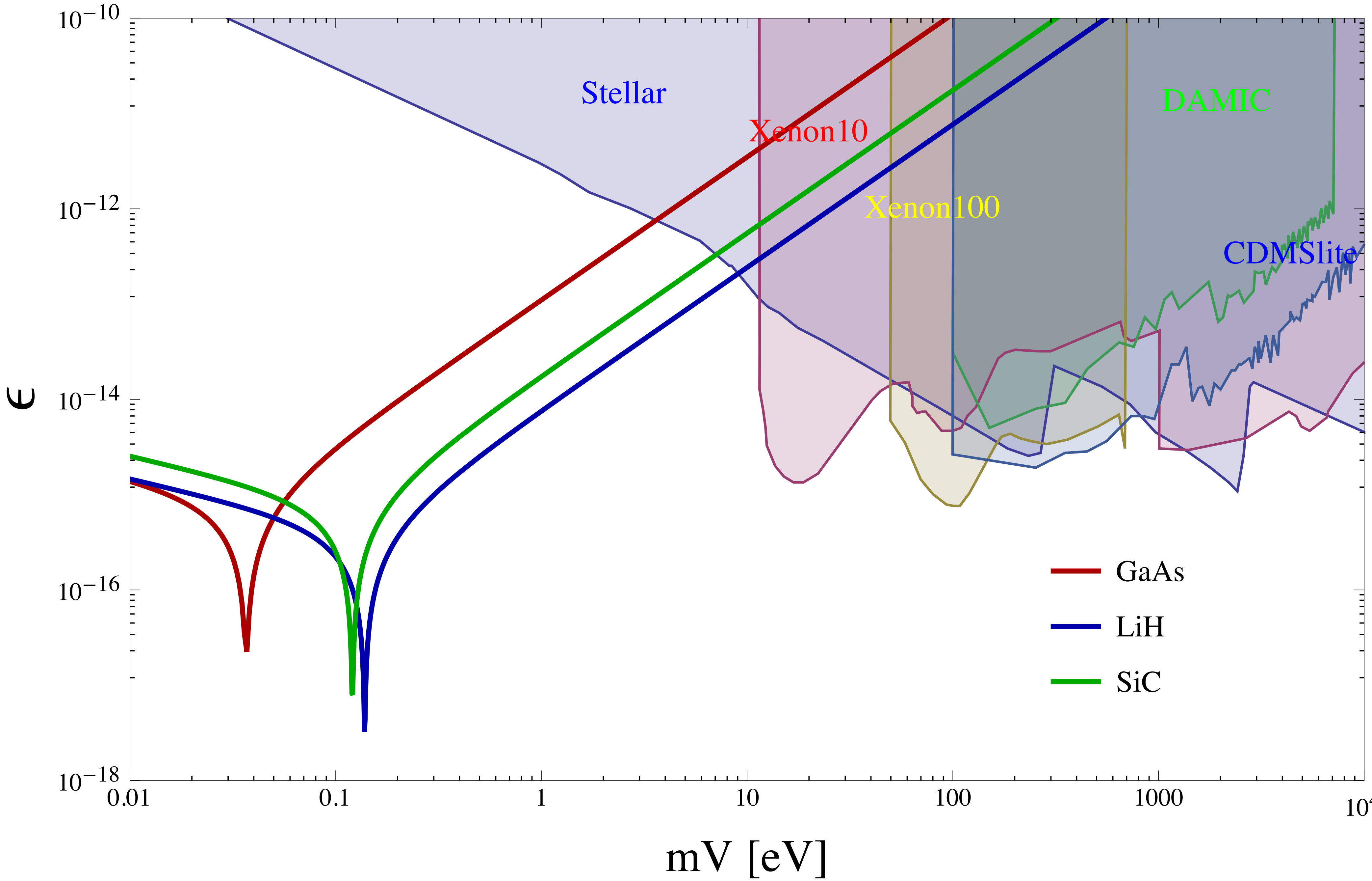
Shut off B, turn off fuel. Deflagration stops. Lose ~ (10 - 100 µm)^3 of volume every 100 s.

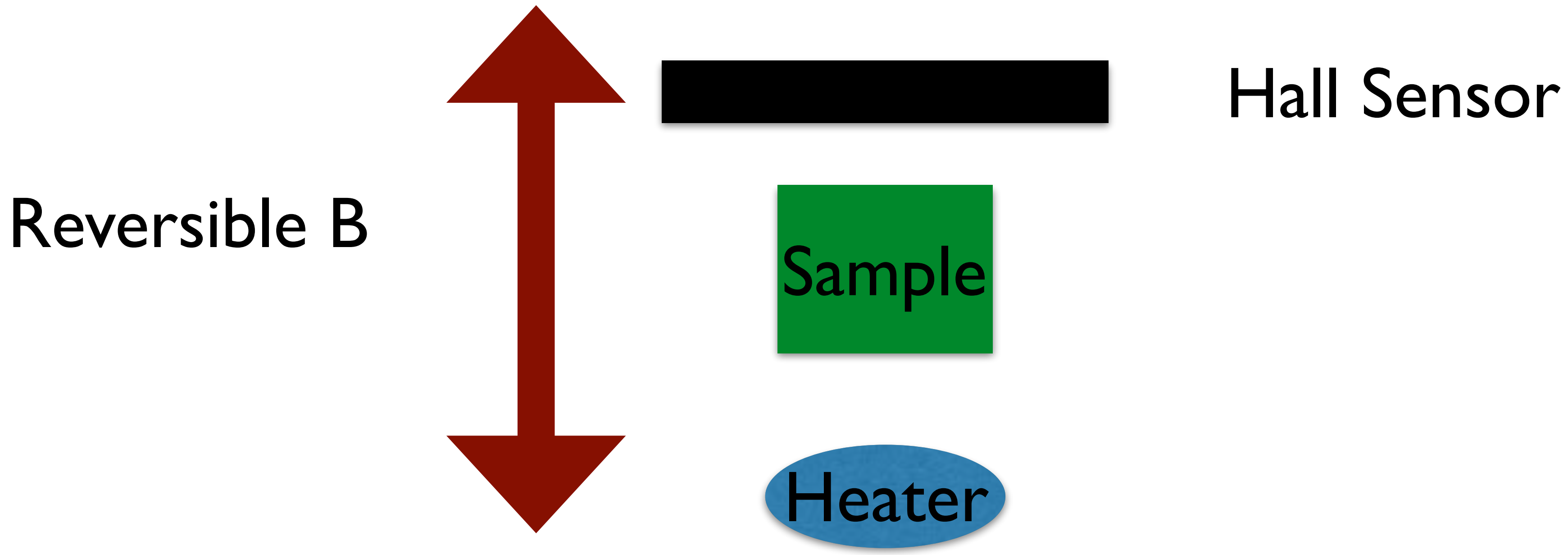
Potential Reach

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

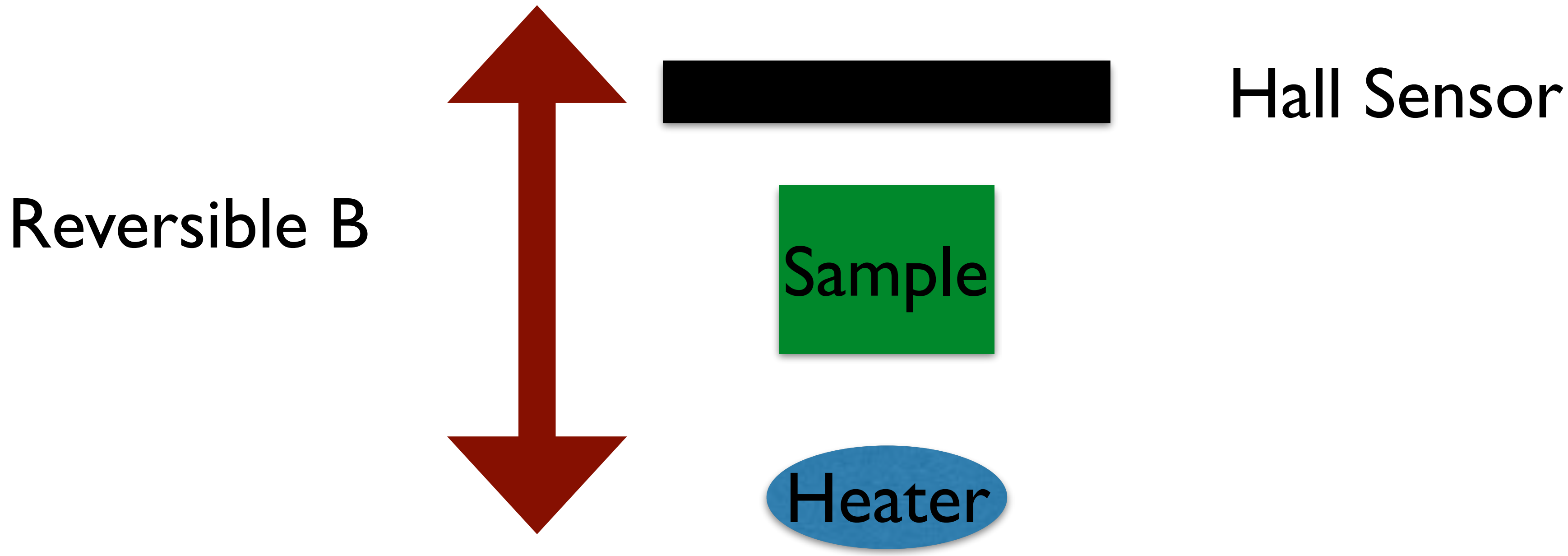


Absorption obtained from photoabsorption. Exposure of 1 kg-year

Trial using Mn-Ac

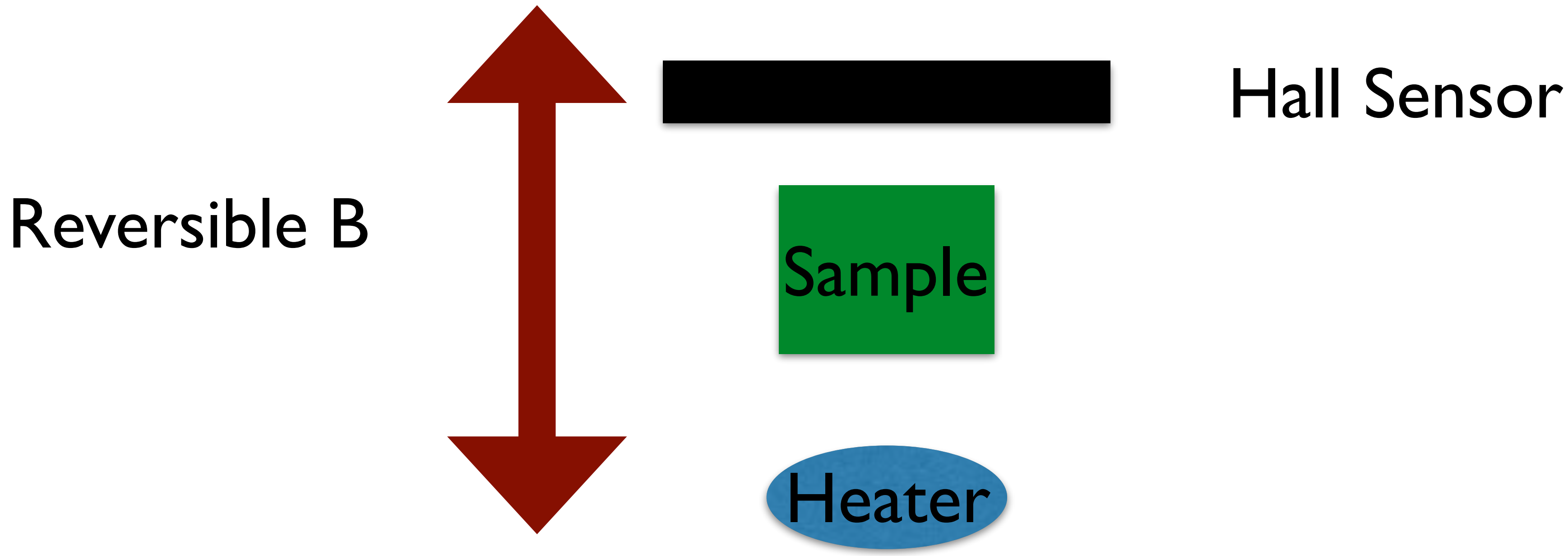


Trial using Mn-Ac



Metastability? Deflagration?

Trial using Mn-Ac



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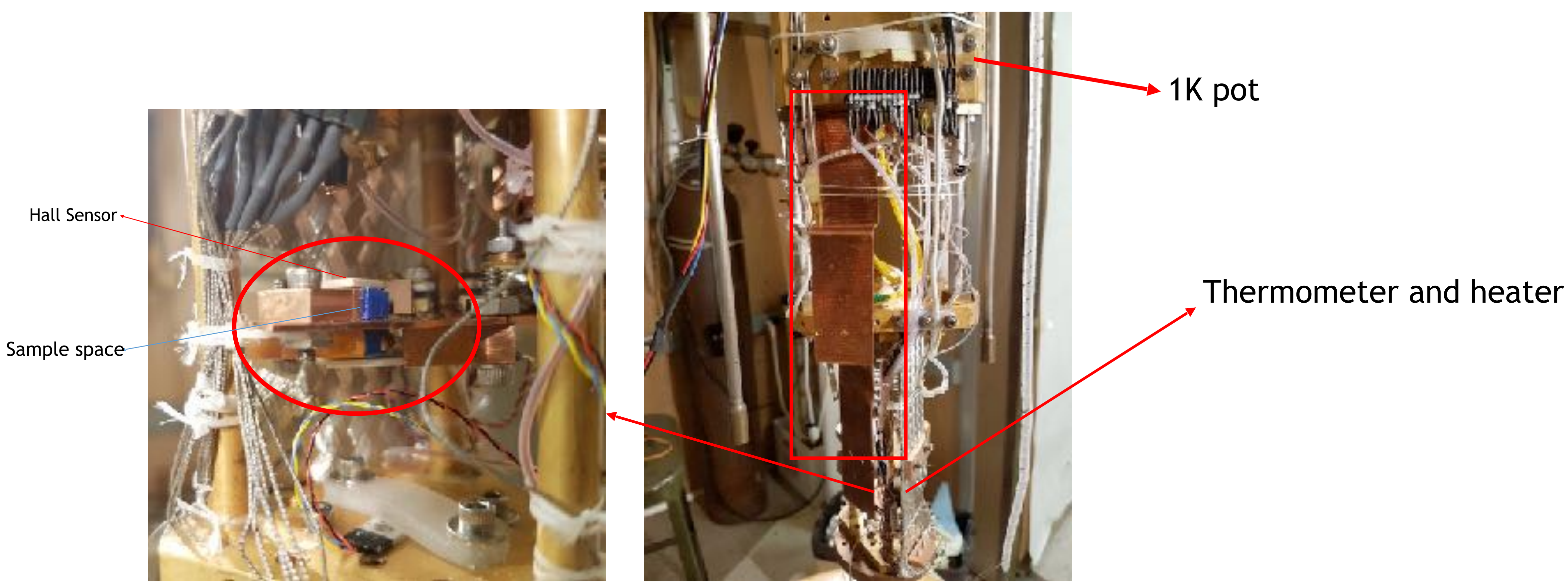
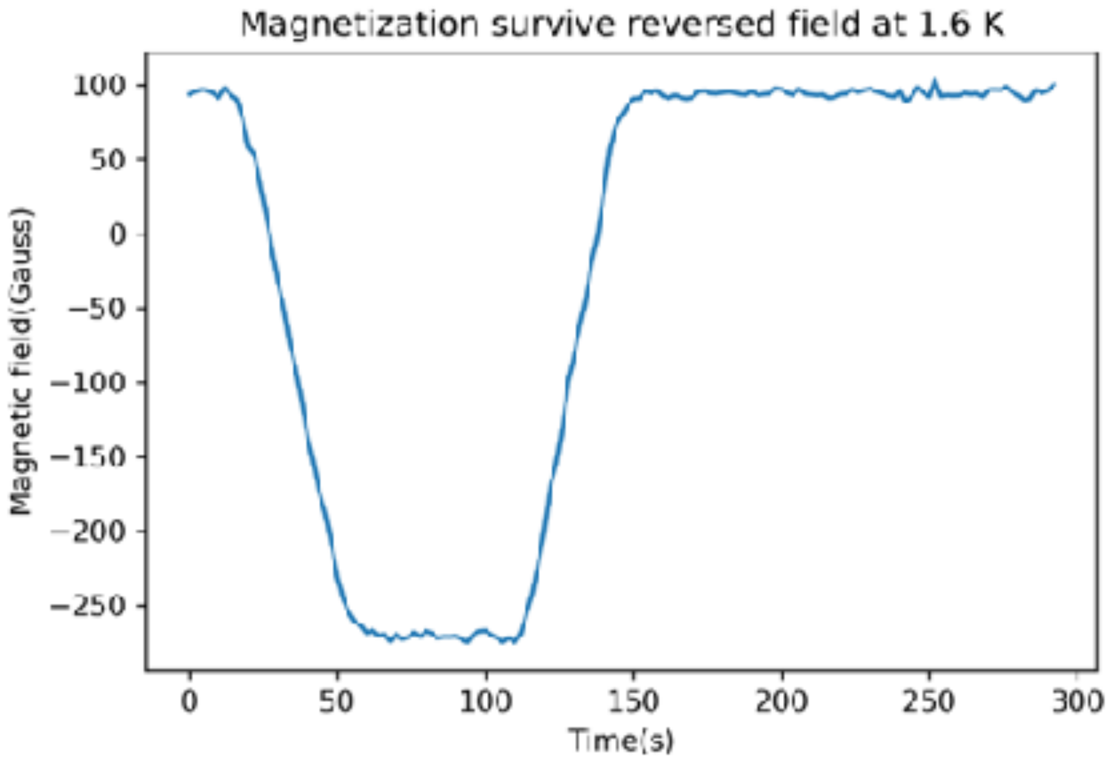
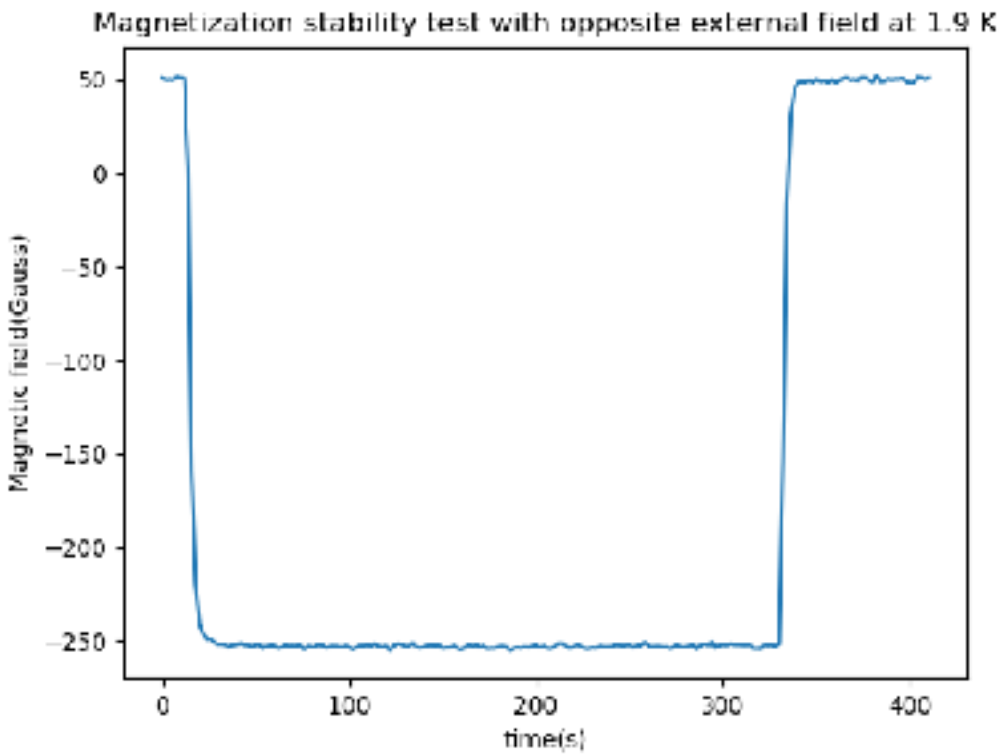


Data from Trial Run

Metastability





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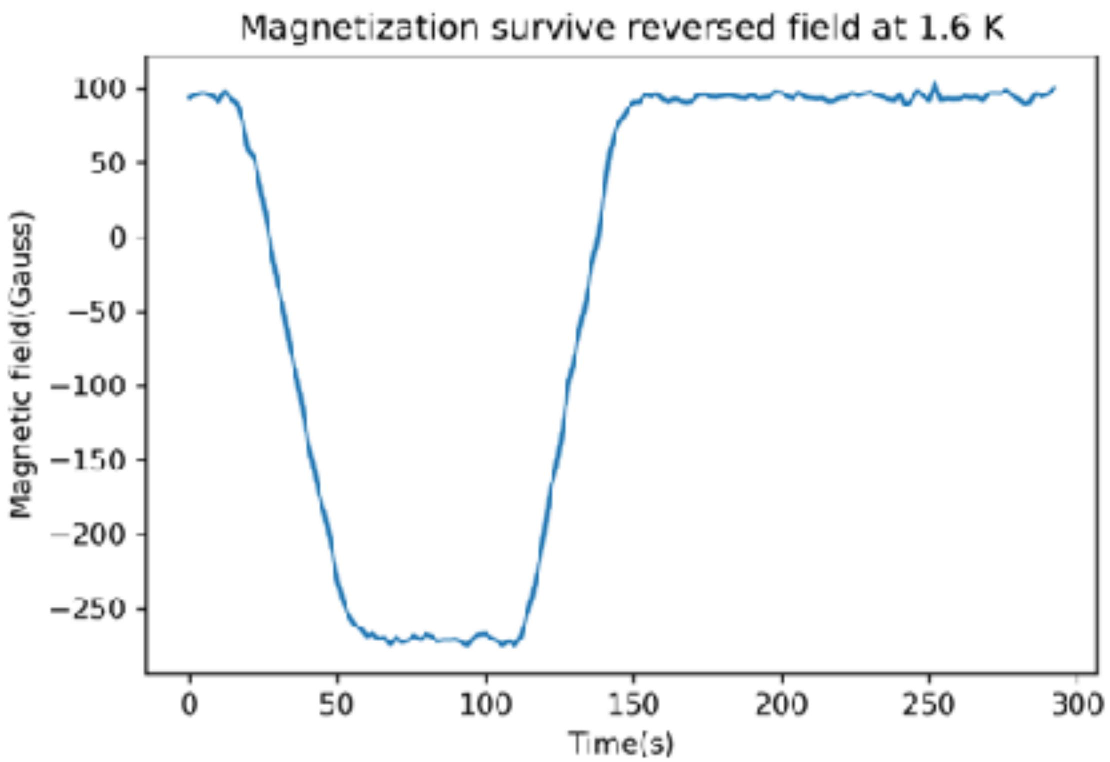
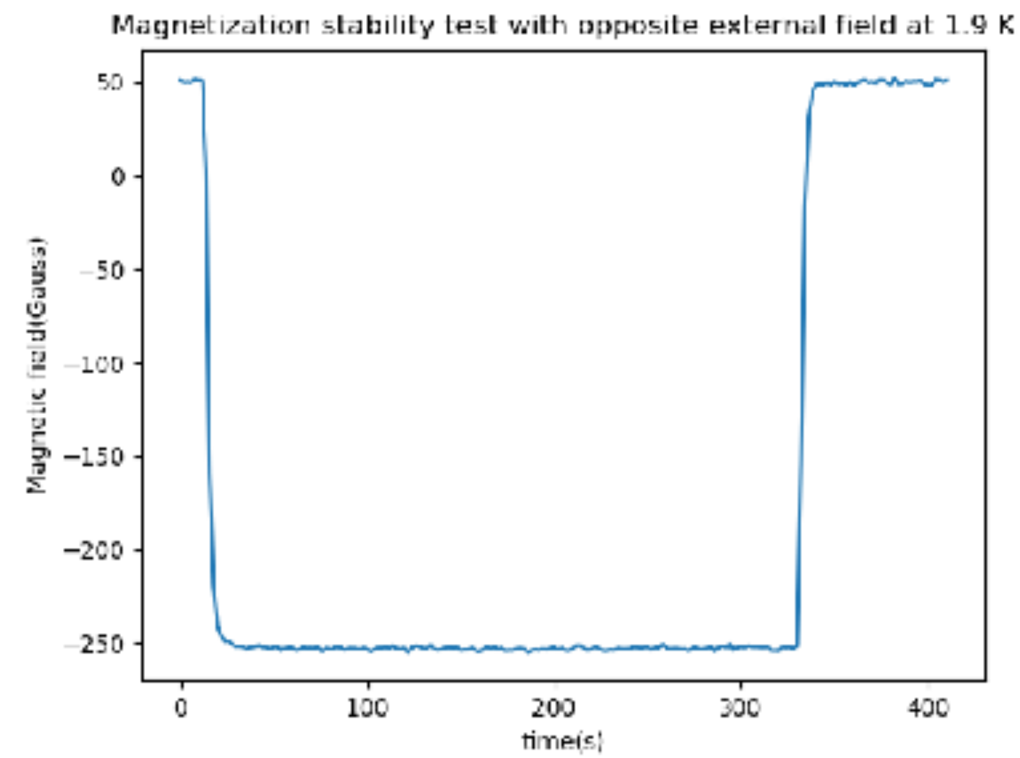
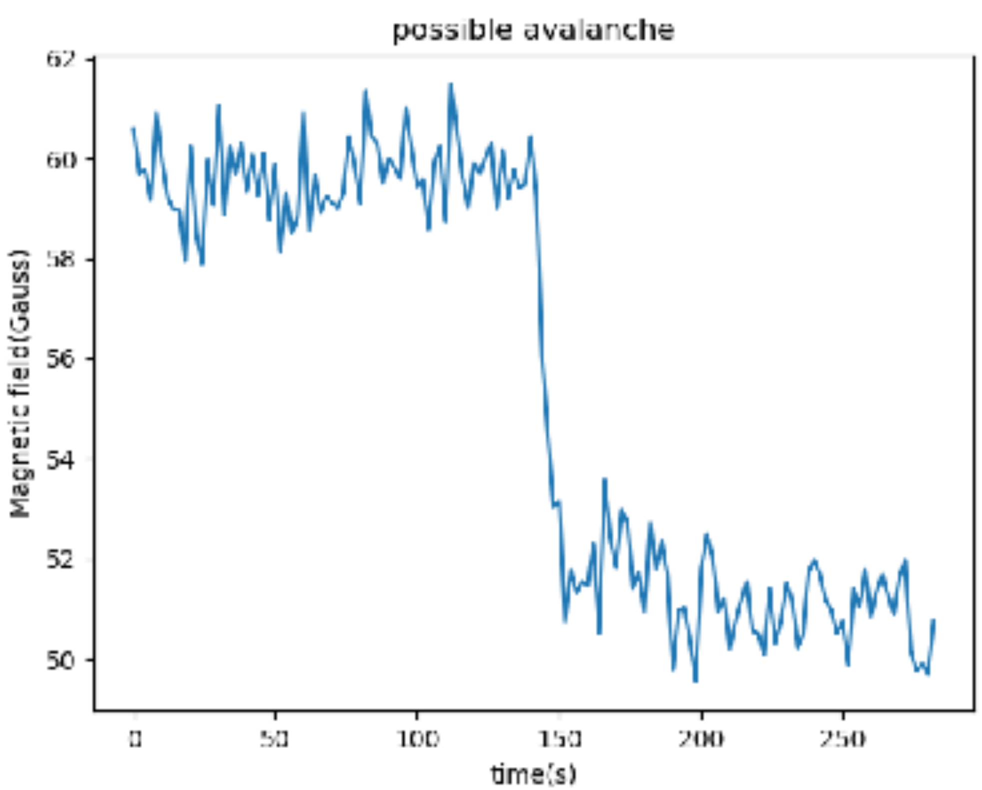




Avalanche?



Sharp Drop observed at 2 K.

Consistent with avalanche.

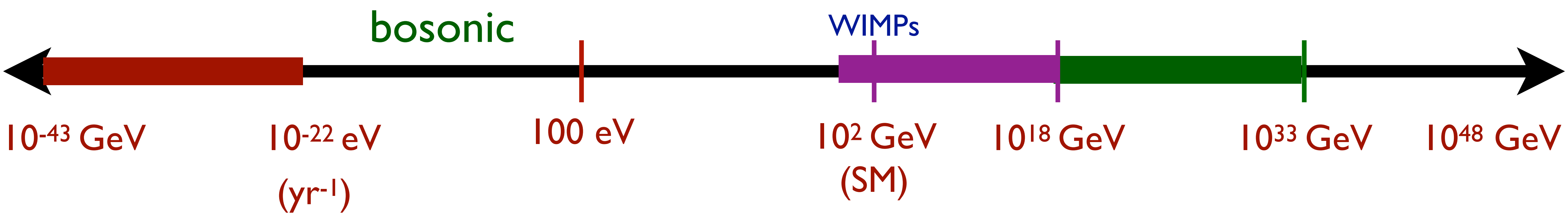
But observed near end of run when out of Helium.

Searching for Ultra-Heavy Dark Matter

Surjeet Rajendran,
UC Berkeley

(with Dorota Grabowska and Tom Melia)

The Dark Matter Landscape



Fit in galaxy

Standard Model scale ~ 100 GeV

Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)

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

What if dark matter is super heavy?

Low number density - need large detectors.

Terrestrial: up to 10^{33} GeV

Outline

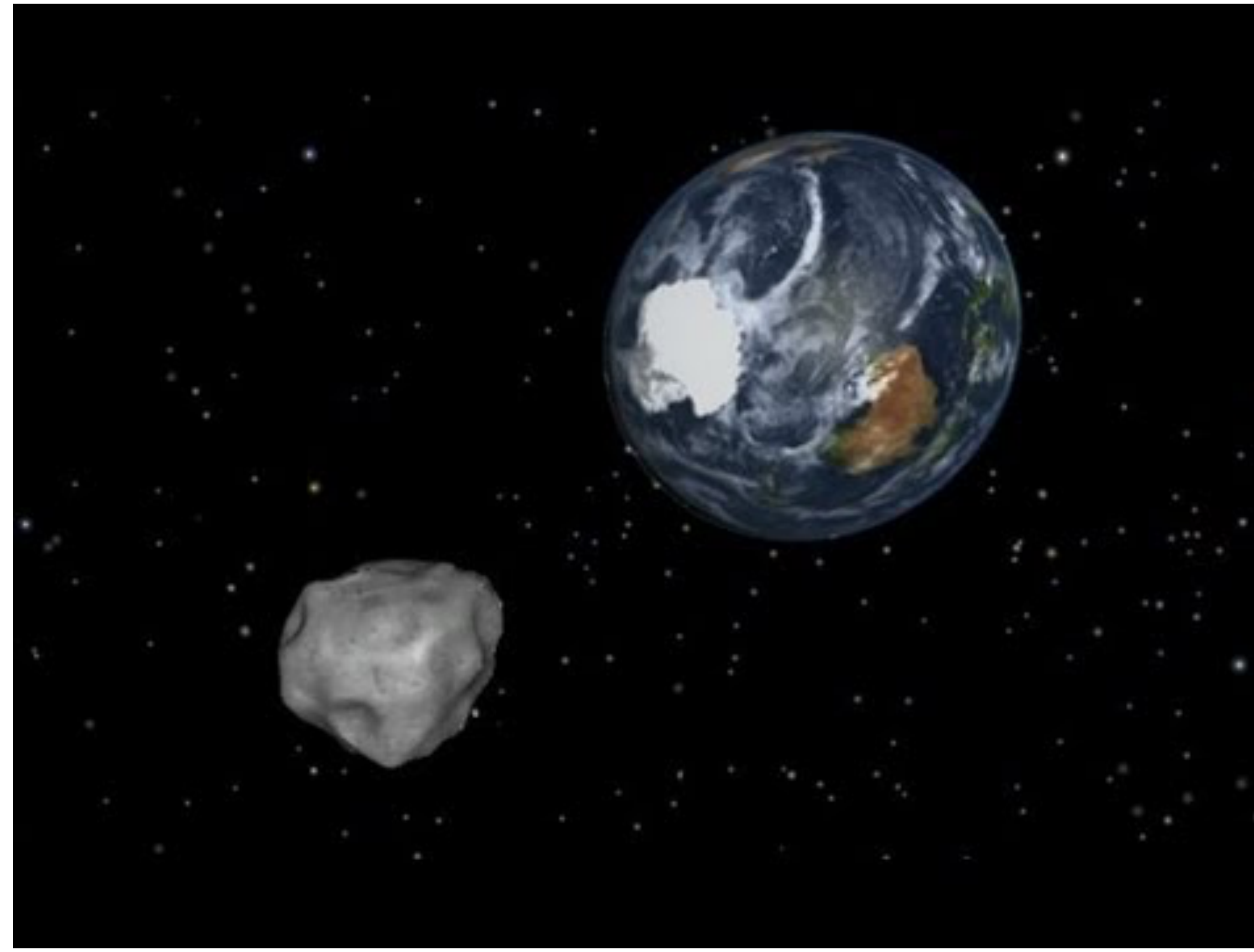
1. Theory and Phenomenology

2. Constraints

3. Detection

Ultra-heavy Dark Matter?

Large composite blob

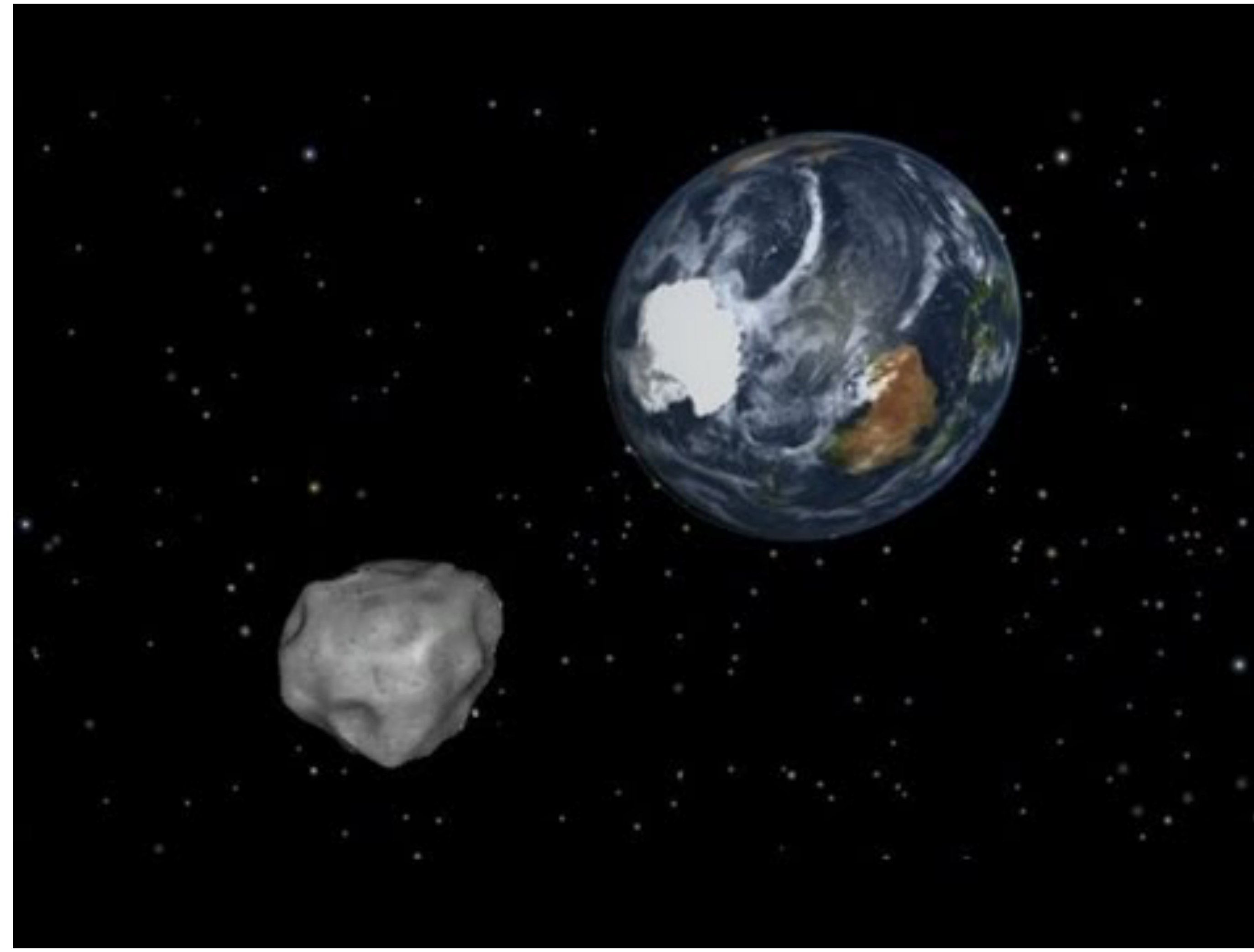


Weak constraints on self-interactions of dark matter

Strong self-interactions in dark sector

Ultra-heavy Dark Matter?

Large composite blob



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Efficient nucleosynthesis? Primordial production? Galactic evolution?

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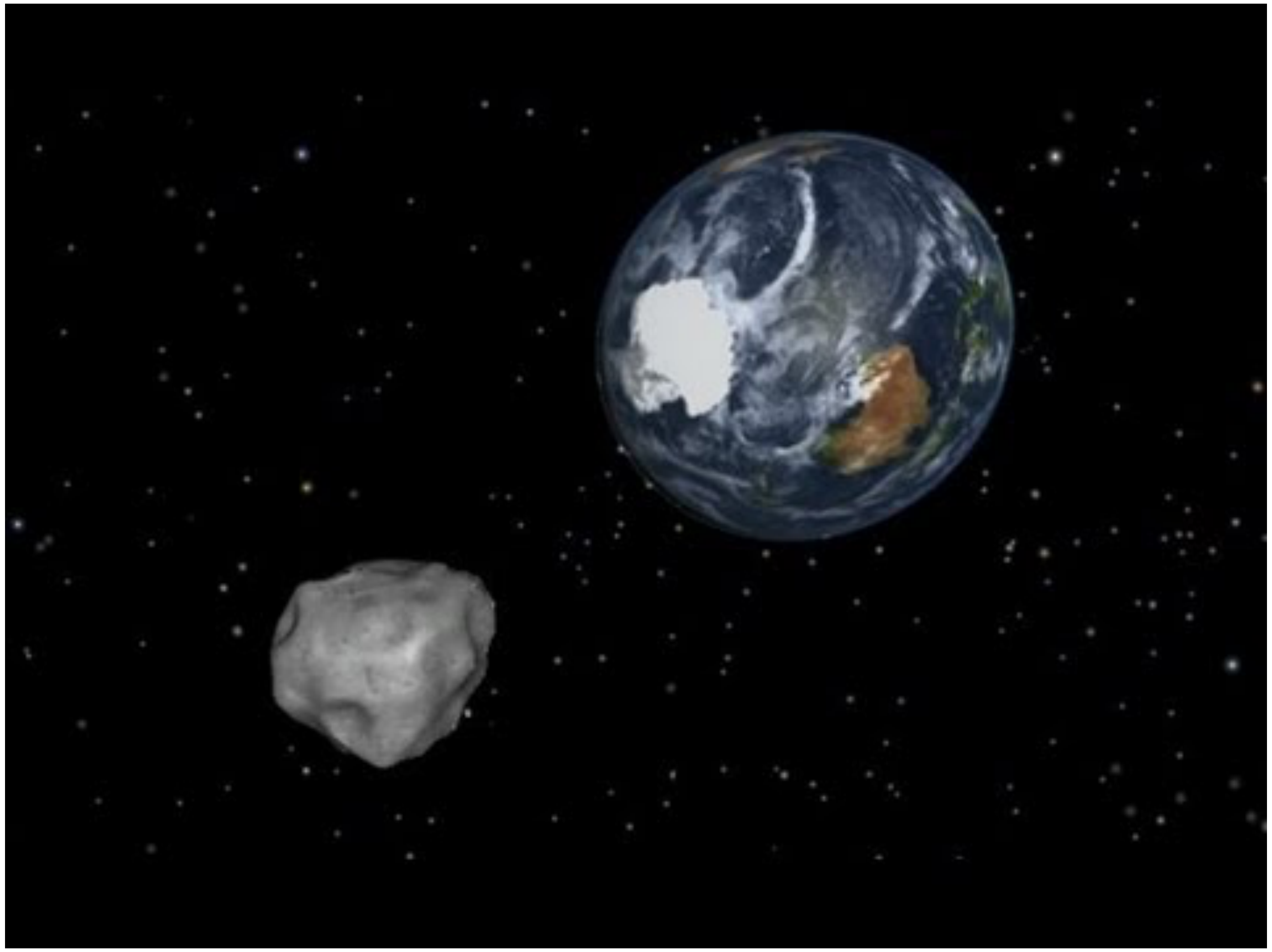

Weak constraints on self-interactions of dark matter

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Observational Effects?

Ultra-heavy Dark Matter?

Large composite blob

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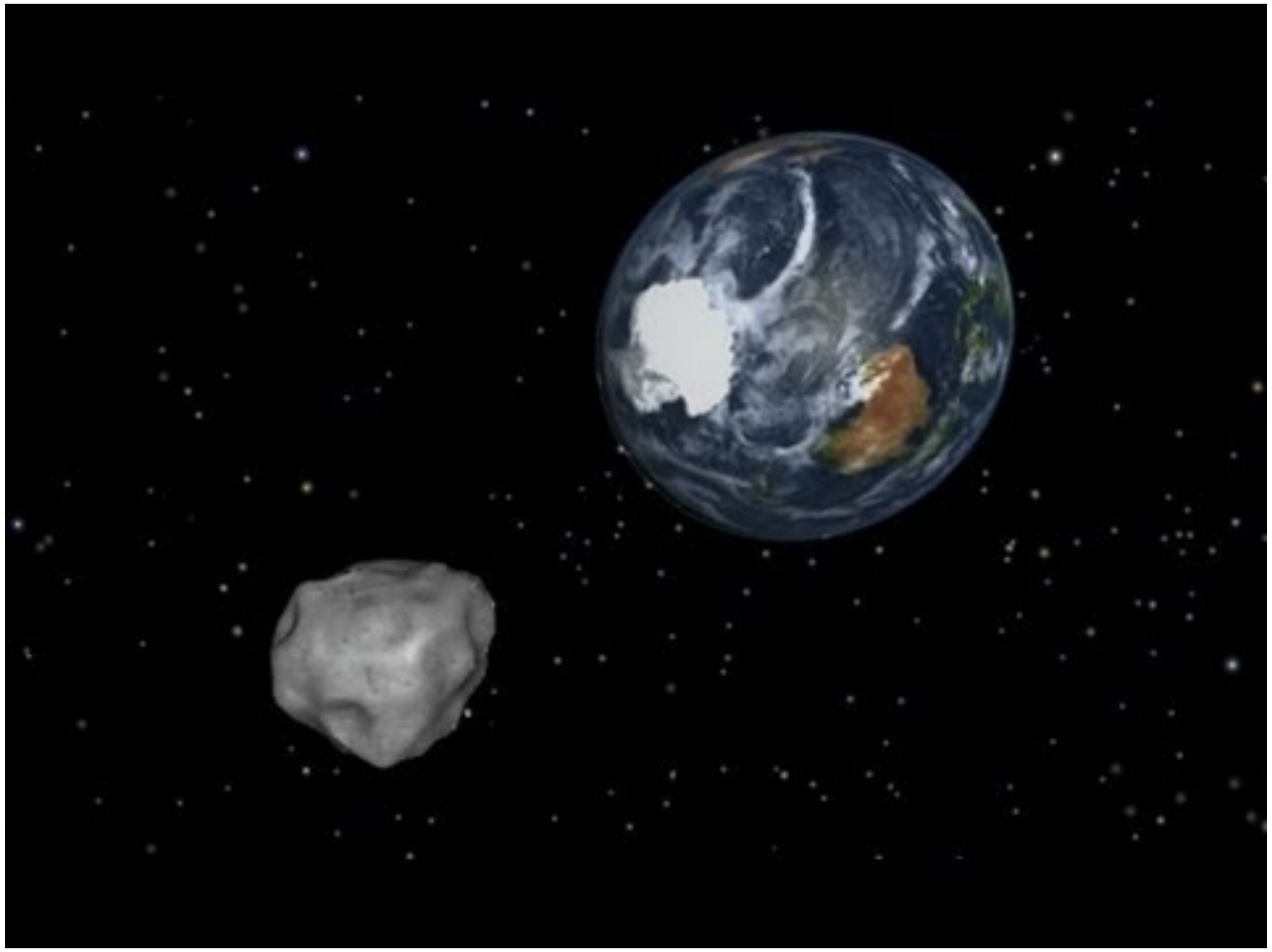

Efficient nucleosynthesis? Primordial production? Galactic evolution?

Observational Effects?

Key Point: Lots of dark matter partons packed into single blob

Rare but potentially spectacular transit

What does the blob look like?

Self-Interaction Scale Λ, Parton Mass $\sim \Lambda$

What does the blob look like?

Self-Interaction Scale Λ, Parton Mass ~ Λ

Fermionic

Bosonic

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Self-Interaction Scale Λ, Parton Mass ~ Λ

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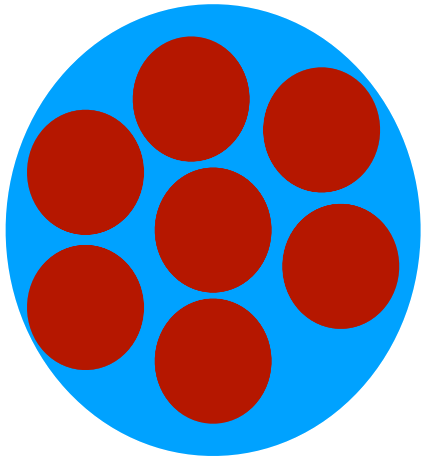

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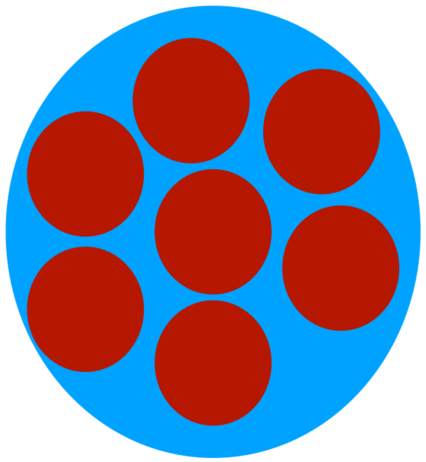

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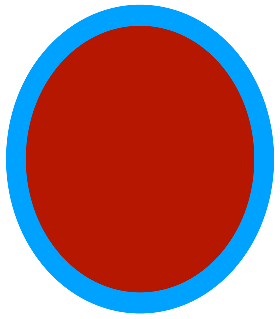

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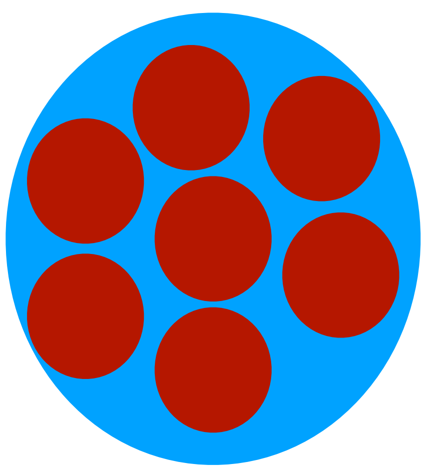

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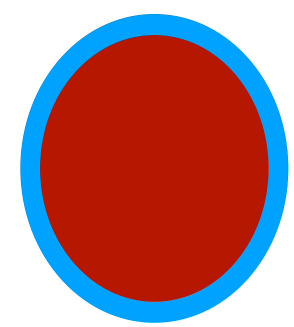
$$\mathcal{L} \supset g_\chi \phi \bar{\chi} \chi$$

Bosonic



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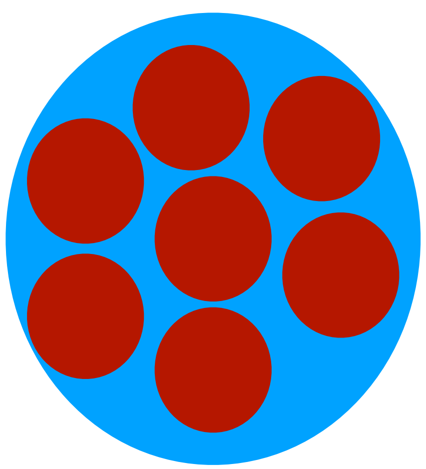

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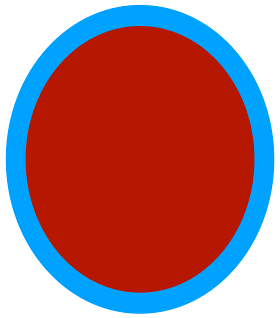

$$R \sim \frac{1}{\Lambda}$$

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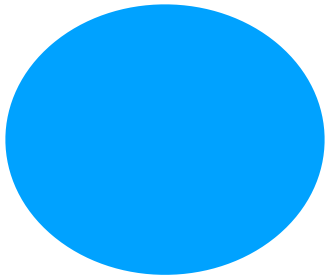
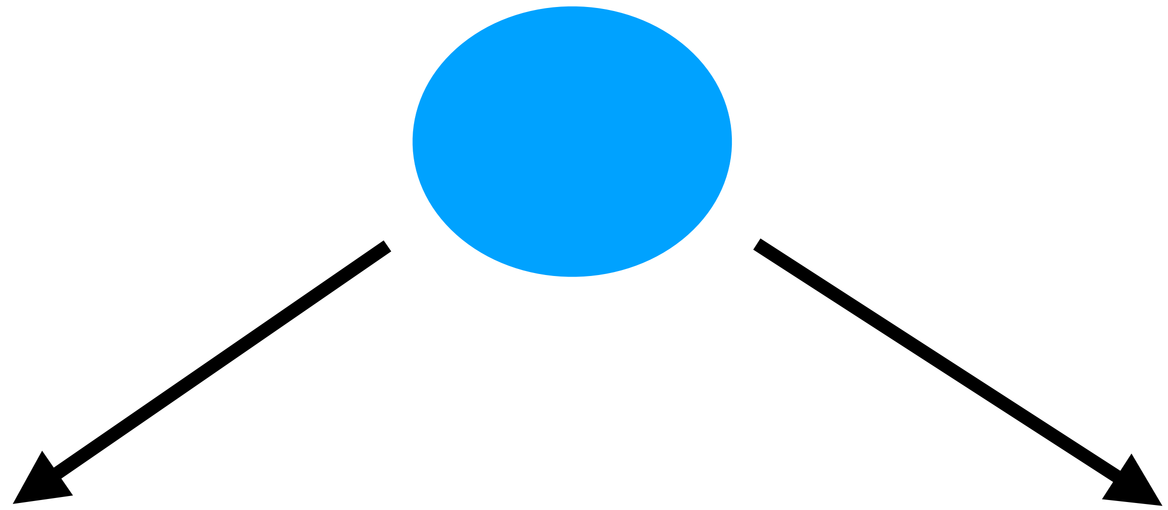
Standard Model Interactions

$$+\mu^2 \phi^2 + g_N \phi \bar{N} N + \frac{1}{f_a} \partial_\nu \phi \bar{N} \gamma^\nu \gamma_5 N + \frac{\phi}{\alpha M} F_{\mu\nu} F^{\mu\nu}$$

Observational Effects



Observational Effects



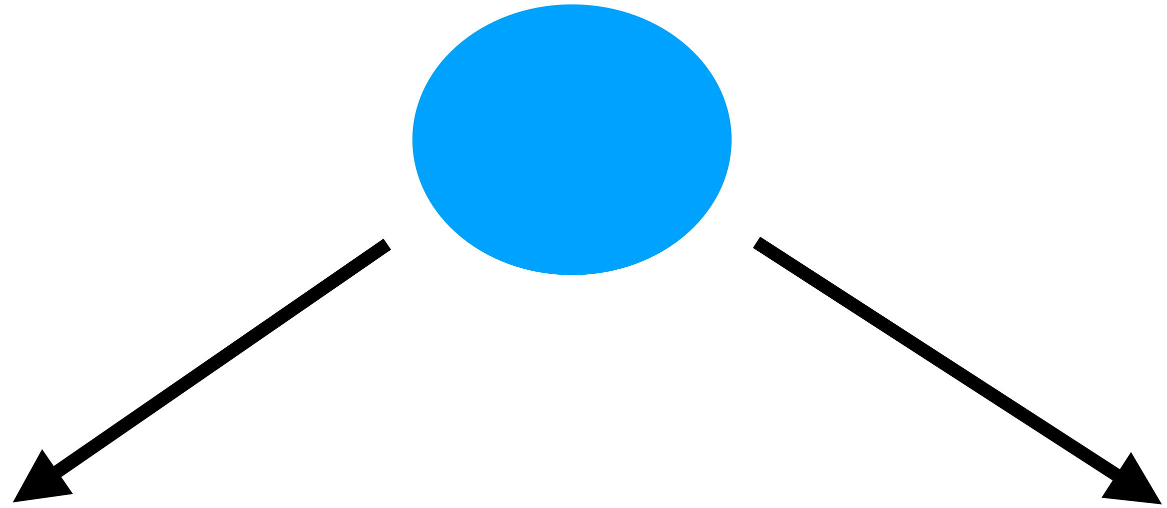
Short Range

$\mu^{-1} < \lambda_p$

Long Range

$\mu^{-1} > \lambda_p$

Observational Effects



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Dark Matter scatters, deposits energy. Calorimetry

Compositeness could enable multiple scattering

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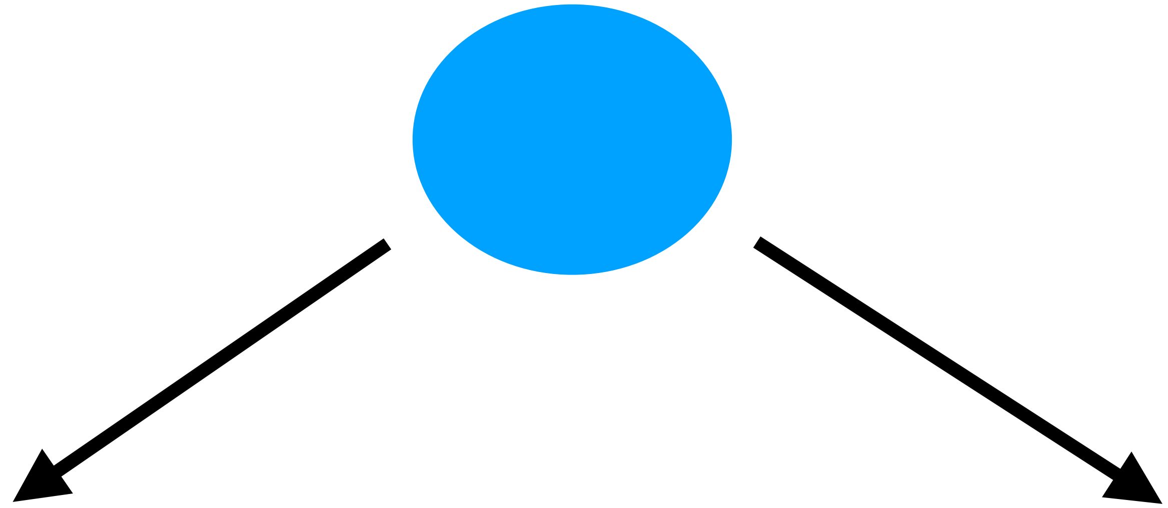
$\mu^{-1} > \lambda_p$

Observational Effects



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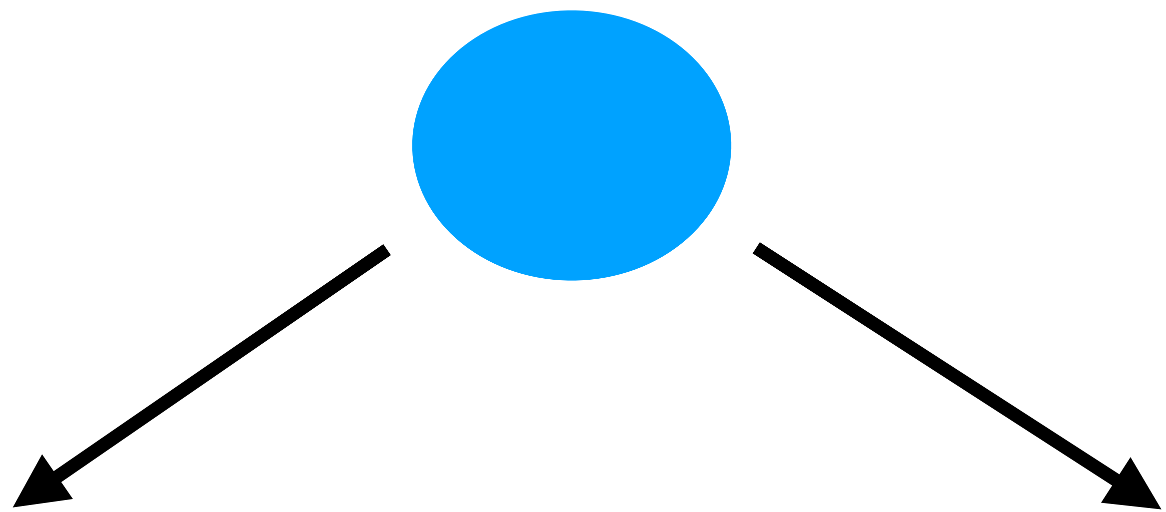
Blob sources classical field

Use detectors of ultra-light dark matter

Observational Effects



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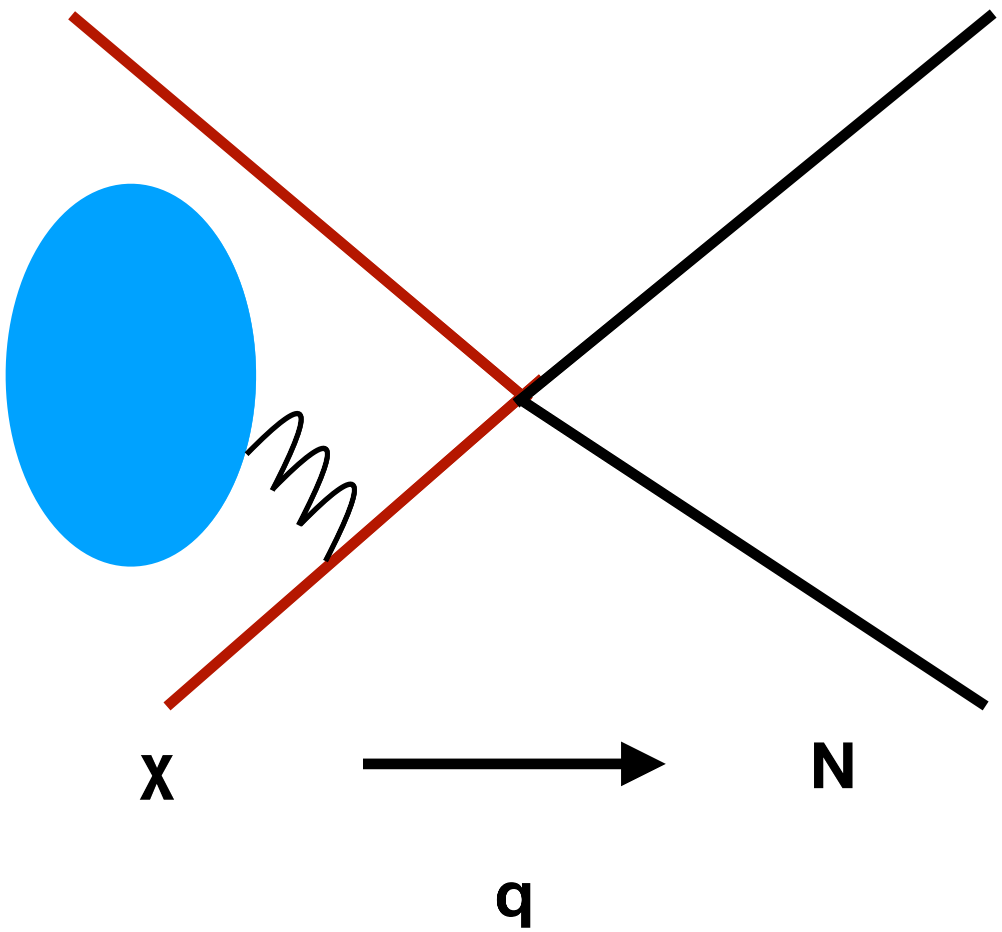
Use detectors of ultra-light dark matter

Leverage: $c > v_{dm} > v_{human}$

Constraints?

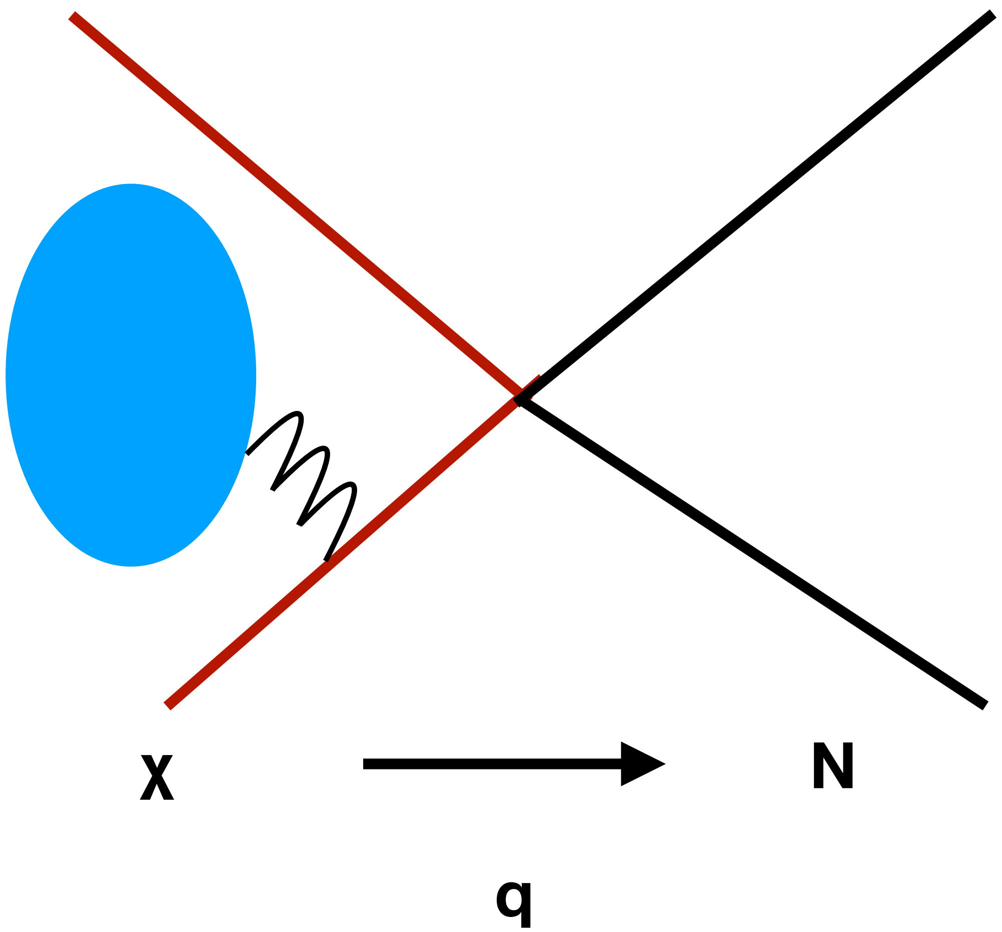
Short Range



Scattering at the partonic level

Parton transfers momentum to blob

Short Range



Scattering at the partonic level

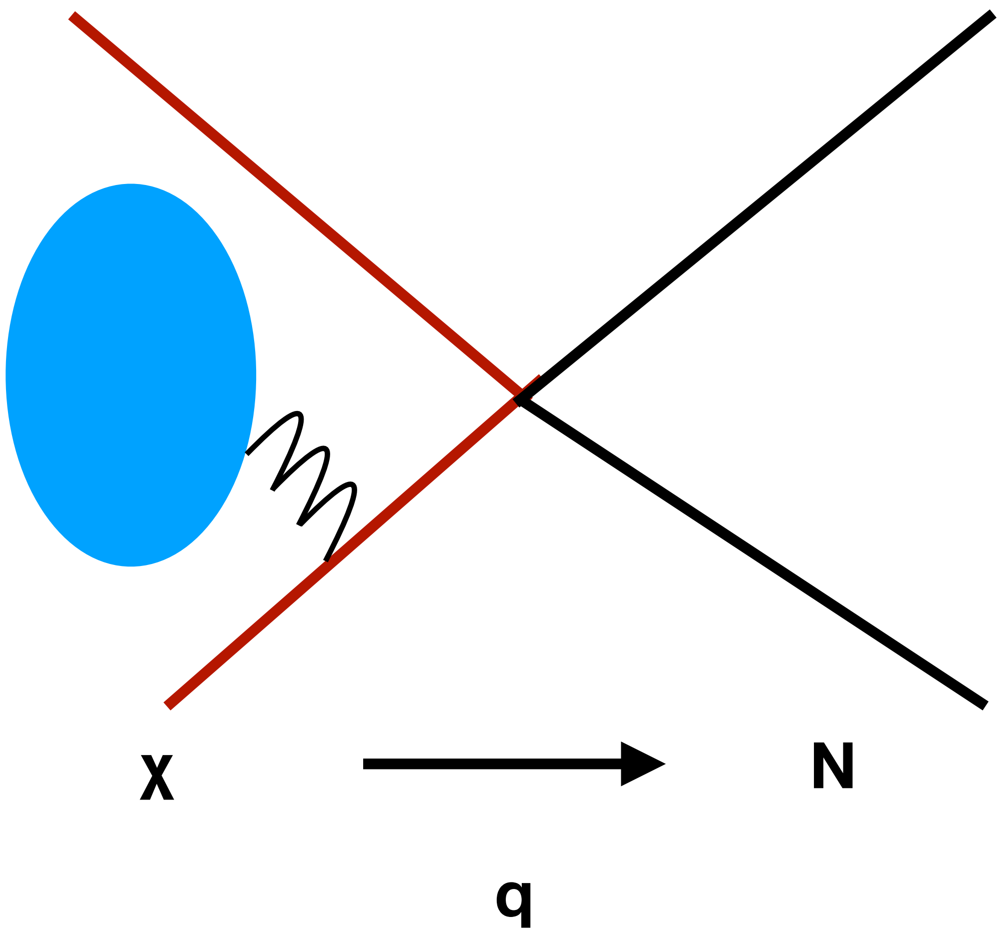
Parton transfers momentum to blob

Form factor for q >> $1/r_\chi \sim \Lambda$

M >> m_N, kinematics set by m_N

q = Min[m_N v, Λ]

Short Range



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Key Point: $\Lambda < 300$ keV => soft energy transfer, no ionization

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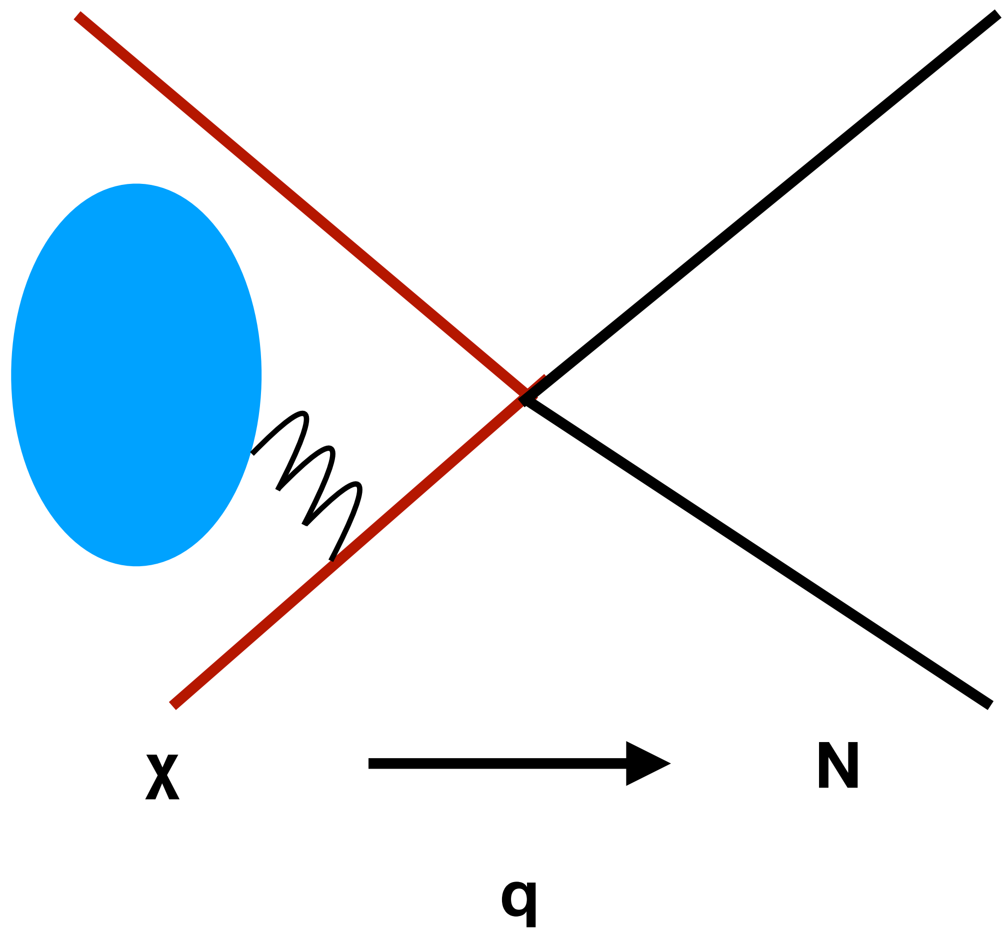

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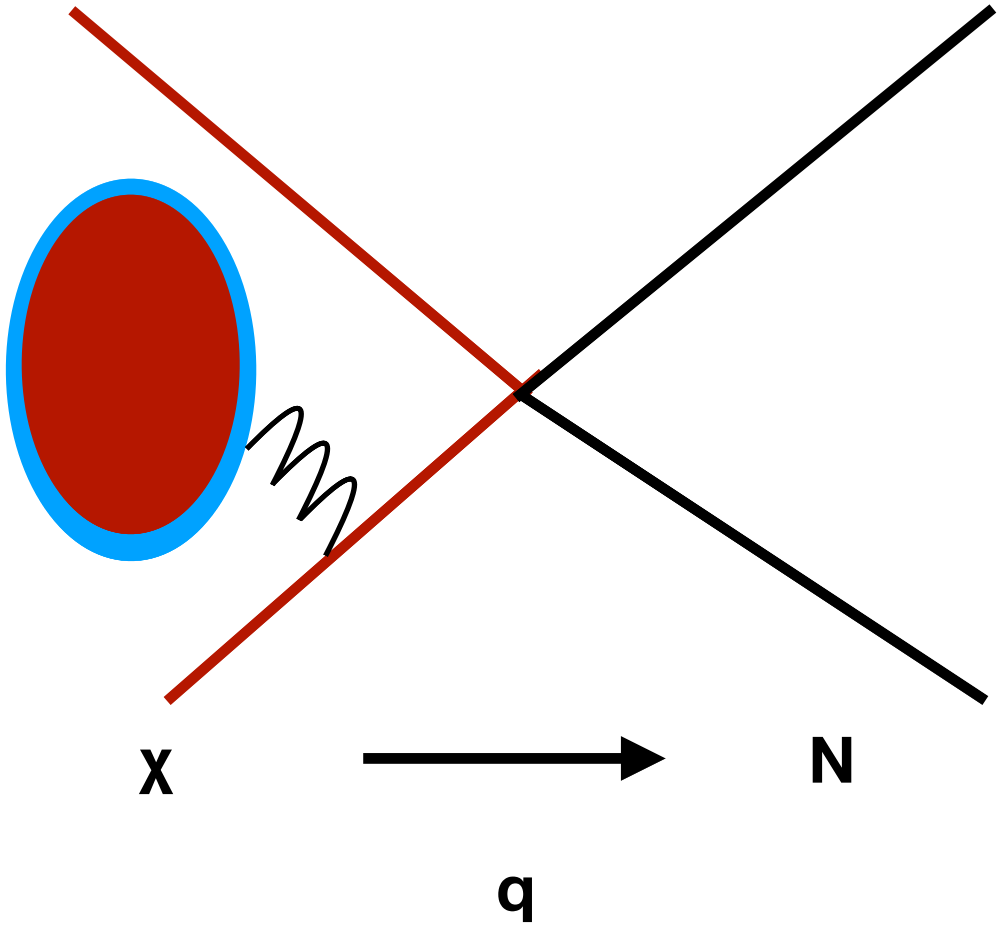
Key Point: $\Lambda < 300$ keV => soft energy transfer, no ionization

This Work: 10 keV < Λ < 10 MeV

Goal: Robust parameter space, targeted experimental signals

Short Range: Bosonic Blob



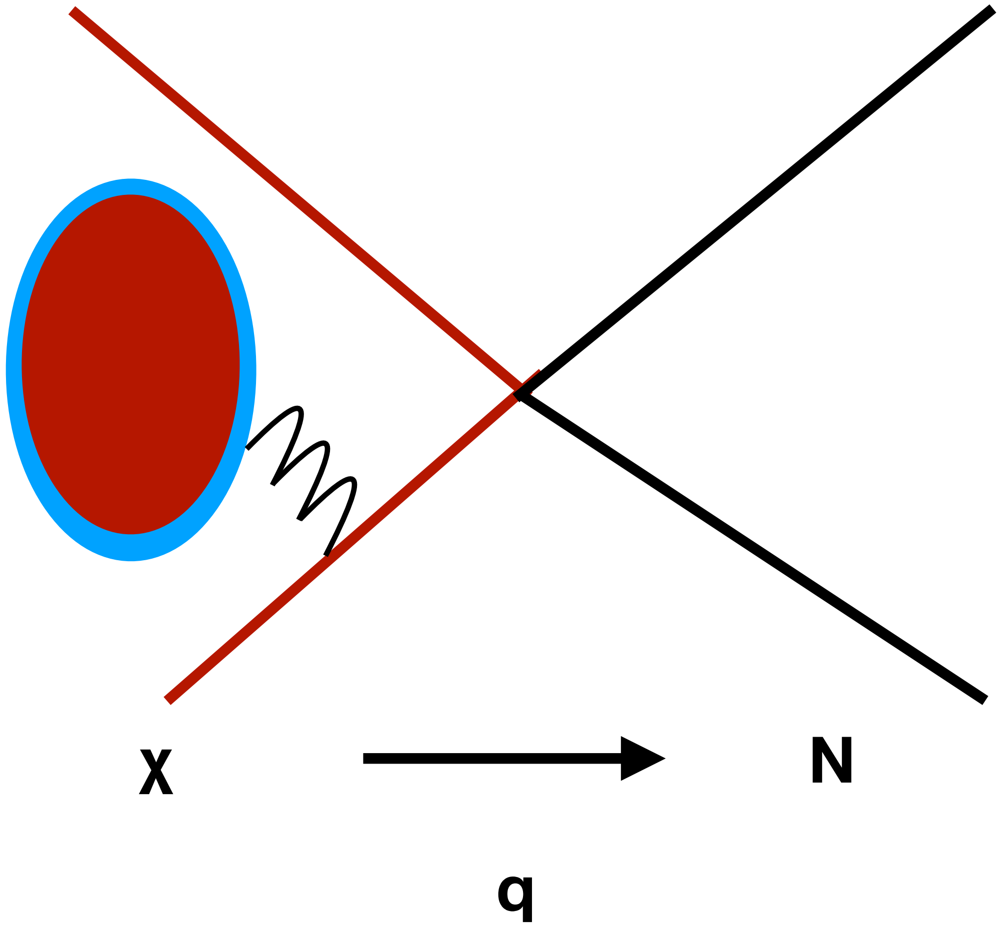
R ~ 1/Λ

10 keV < Λ < 10 MeV => q ~ 1/R

Cross-section Coherently Enhanced

Easily geometric $\sigma = 1/\Lambda^2$

Short Range: Bosonic Blob



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$$\frac{dE}{dx} = \eta_m \left(\frac{\Lambda^2}{m_N}\right)\frac{1}{\Lambda^2} = \frac{\eta_m}{m_N} \sim \mathrm{keV/cm}$$

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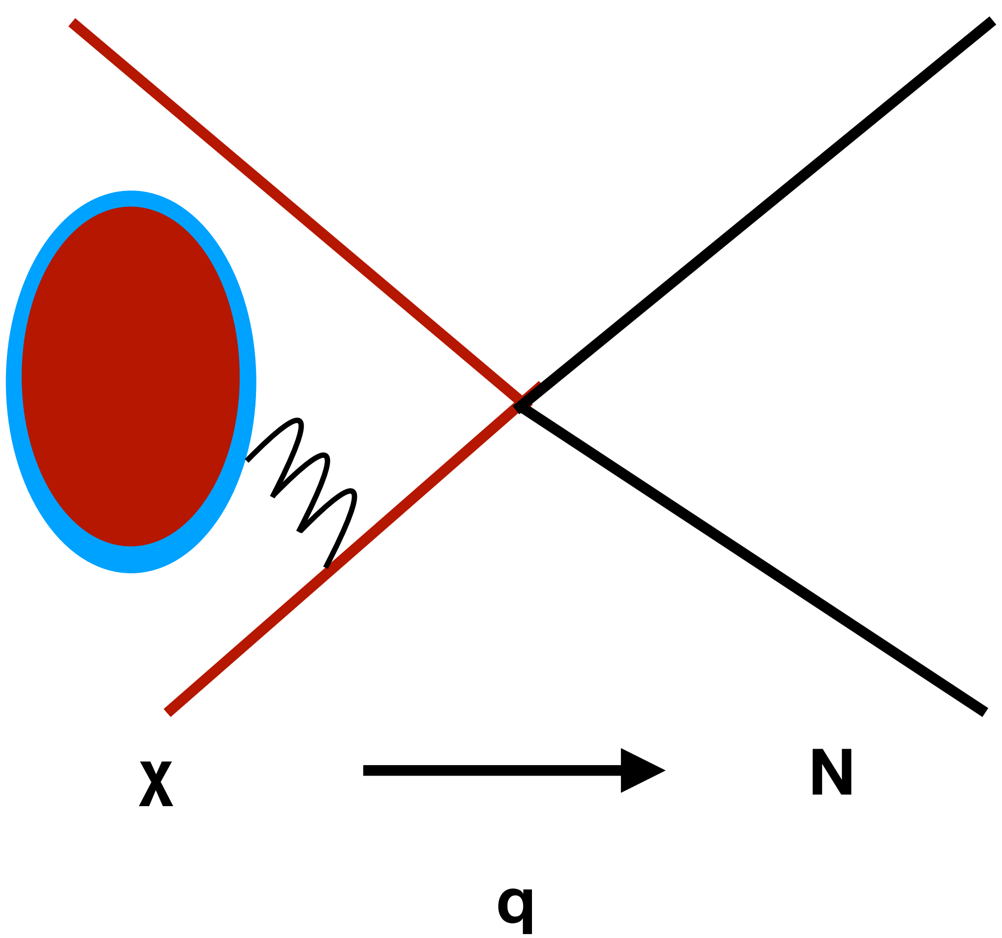

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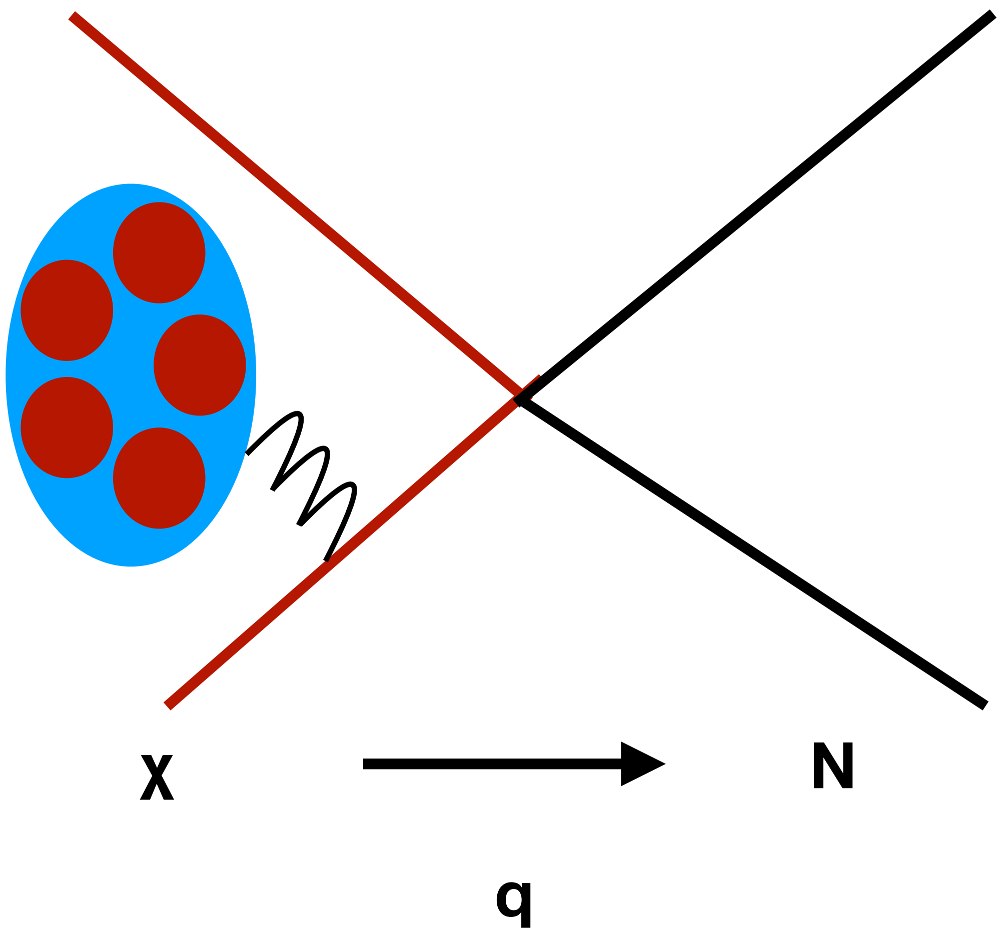
Form depends on Λ - ionize for Λ > 300 keV, heat below that

Short Range: Fermionic Blob

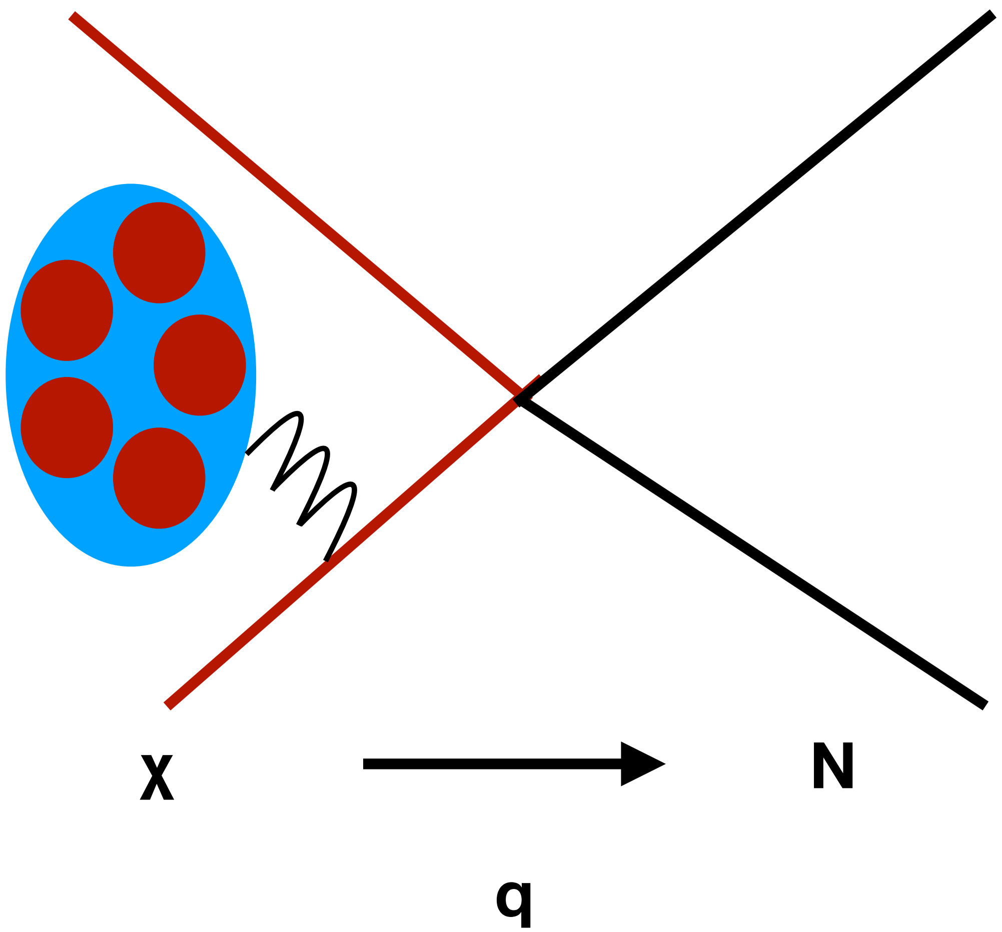


$R \sim N^{1/3}/\Lambda$

Coherent enhancement only for soft scattering => low energy deposition

Lots of partons => multiple scattering possible

Short Range: Fermionic Blob



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$$\frac{dE}{dx} = \eta_m \left(\frac{M}{\Lambda}\right) \left(\frac{g_\chi^2 g_N^2 m_N^2}{\mu^4}\right) \left(\frac{\Lambda^2}{m_N^2 v_x^2}\right) \left(\frac{\Lambda^2}{m_N}\right)$$

Form depends on Λ - ionize for Λ > 300 keV, heat below that

Long Range

Take Range $1/\mu$ >> Blob size R

Blob sources classical field $g_\chi N/r$

Long Range

Take Range 1/μ >> Blob size R

Blob sources classical field g_χ N/r

$$g_N \phi \bar{N} N$$

Exerts Force

Energy Loss in Medium due to dynamical friction

$$\frac{dE}{dx} \sim 2\pi \int_0^{\frac{1}{\mu}} dr r \eta_m m_N \left(\frac{F(r)}{m_N} \frac{r}{v} \right)^2$$

Long Range

Take Range 1/μ >> Blob size R

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(when adiabatic)

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$$\frac{1}{f_a} \partial_\nu \phi \bar{N} \gamma^\nu \gamma_5 N$$

Causes Spin Precession

$$\delta\theta \sim \frac{g_\chi N}{f_a r v}$$

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(when adiabatic)

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Causes Spin Precession

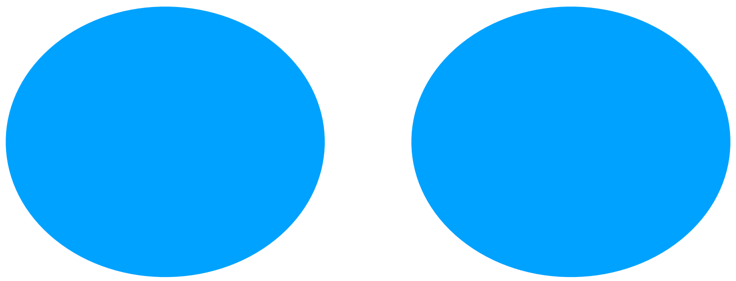
$$\delta\theta \sim \frac{g_\chi N}{f_a r v}$$

$$\frac{\phi}{\alpha M} F_{\mu\nu} F^{\mu\nu}$$

Induces Strain

$$h \sim \frac{g_\chi N}{r M}$$

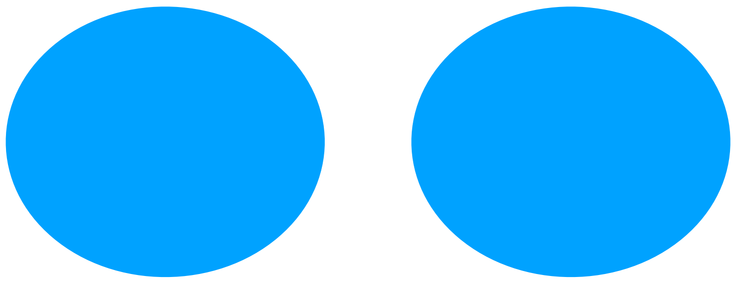
Constraints



Bullet Cluster Bounds.
For short range, no constraints on bosons.

Not relevant if blob < 10 percent of dark matter

Constraints



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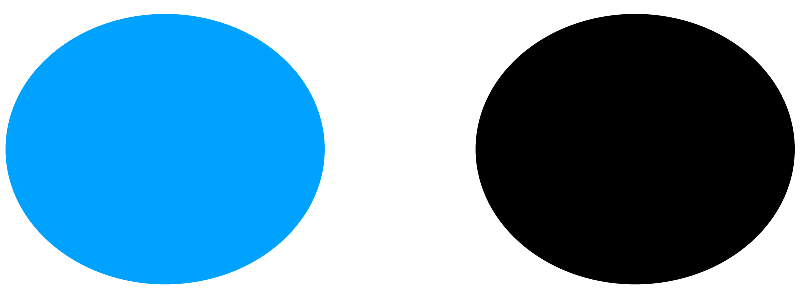
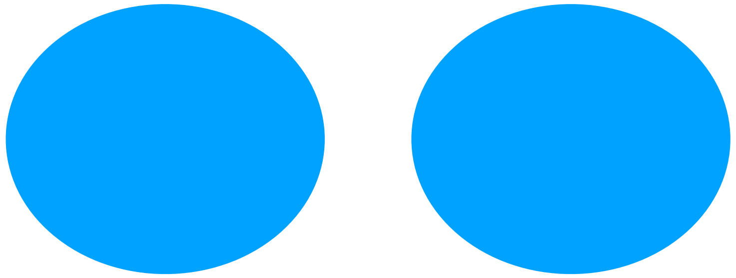


Blob - baryon friction bounded by BAO. Not a significant constraint.

Constraints



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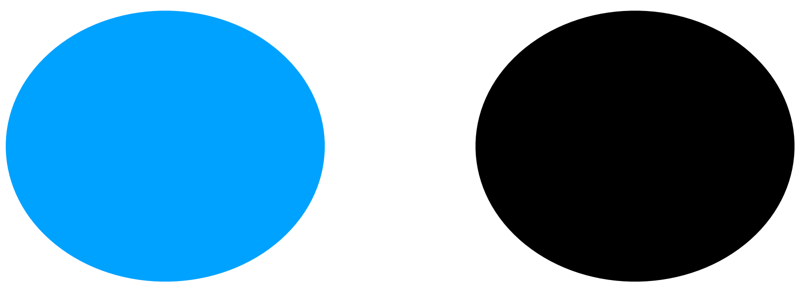

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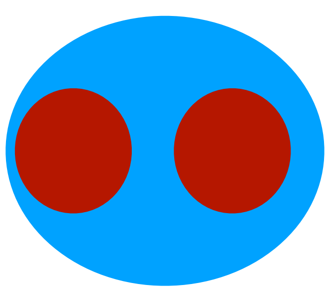


No instability from ϕ

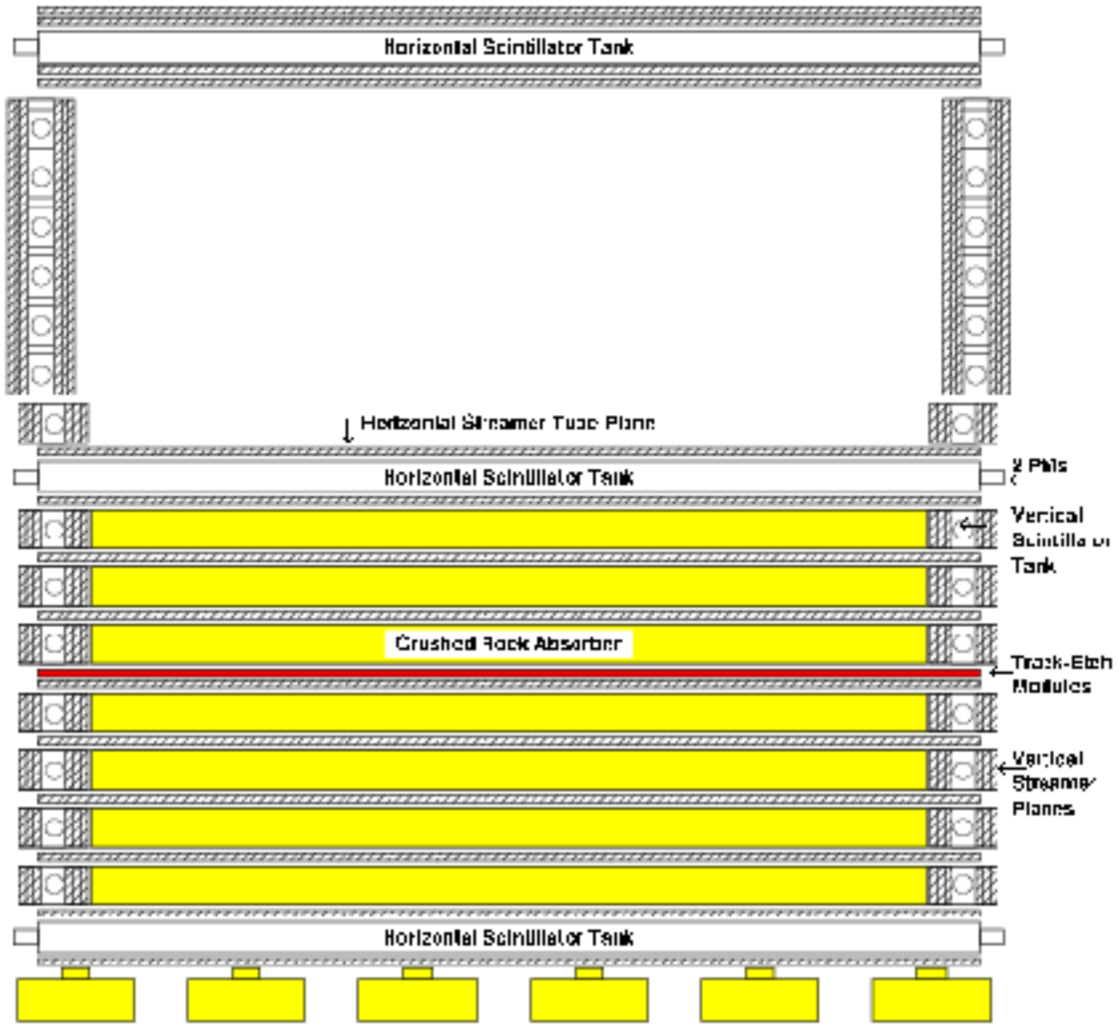
$$g_\chi \lessapprox \frac{1}{\sqrt{N}}$$

(bosonic)

$$g_\chi \lessapprox \frac{1}{N^{\frac{1}{3}}}$$

(fermionic)

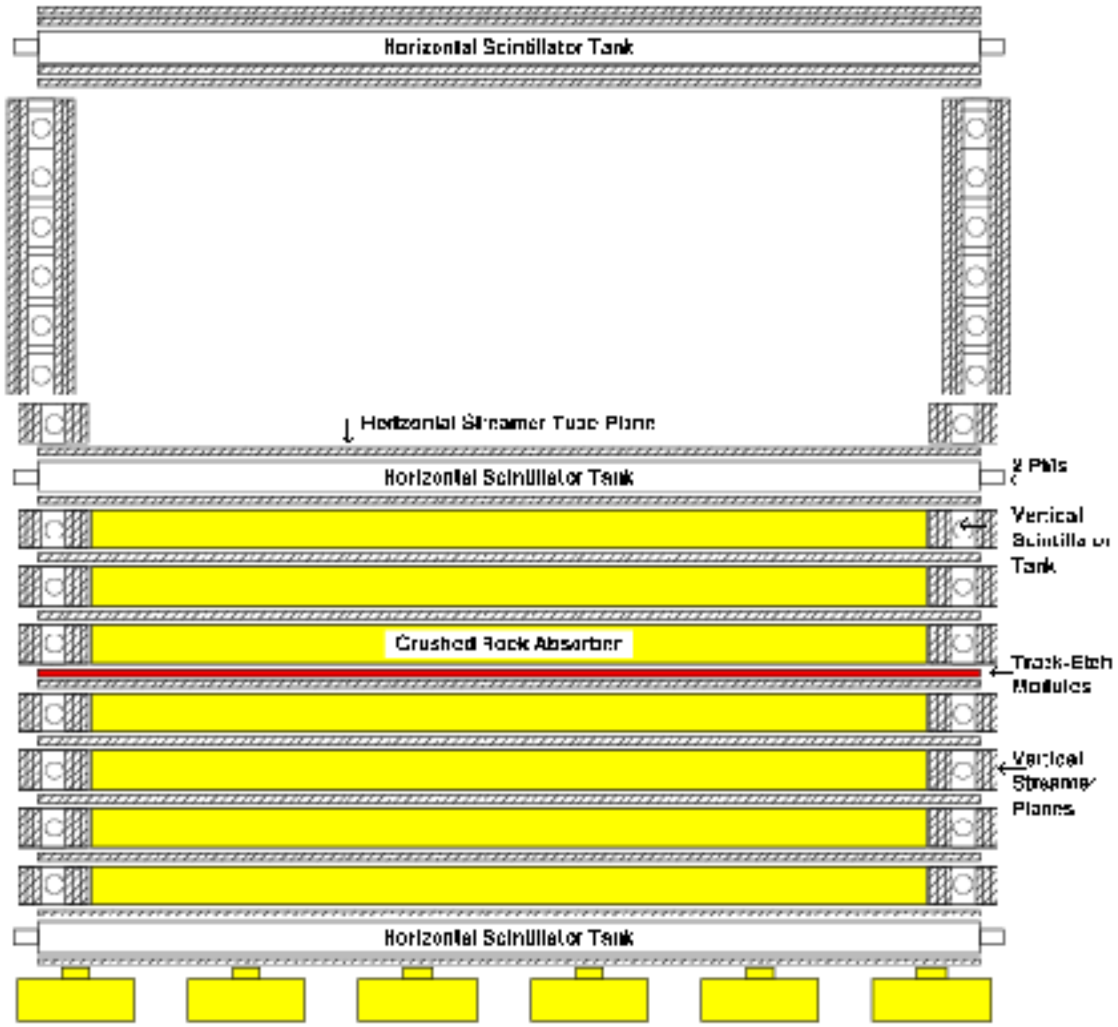
Constraints



MACRO Monopole Search
(~ 80 x 10 x 10 m^3)

Energy Threshold: 6 MeV/cm
+
Scintillation

Constraints



MACRO Monopole Search
(~ 80 x 10 x 10 m^3)

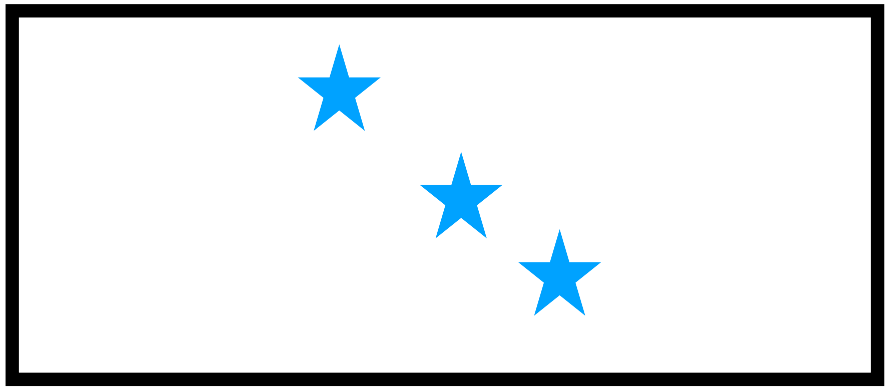
Energy Threshold: 6 MeV/cm
+
Scintillation

Mediator coupling to Standard Model constrained by new force searches, astrophysical bounds on light particles, collider limits

Detection

Short Range

Ionization
($\Lambda > 300$ keV)



MACRO=> $dE/dx < 6$ MeV/cm

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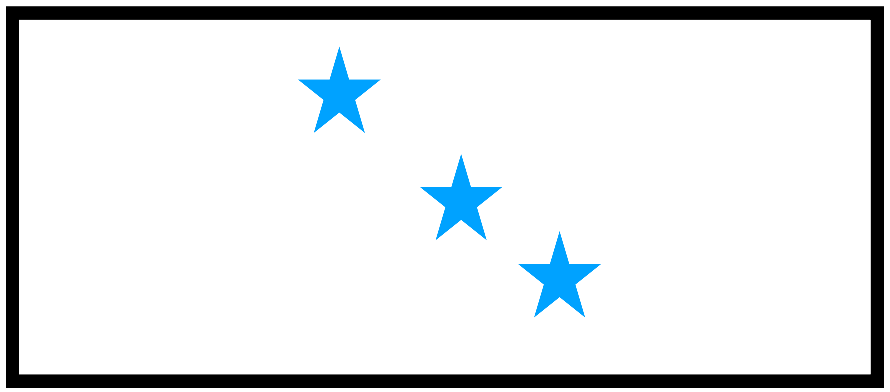
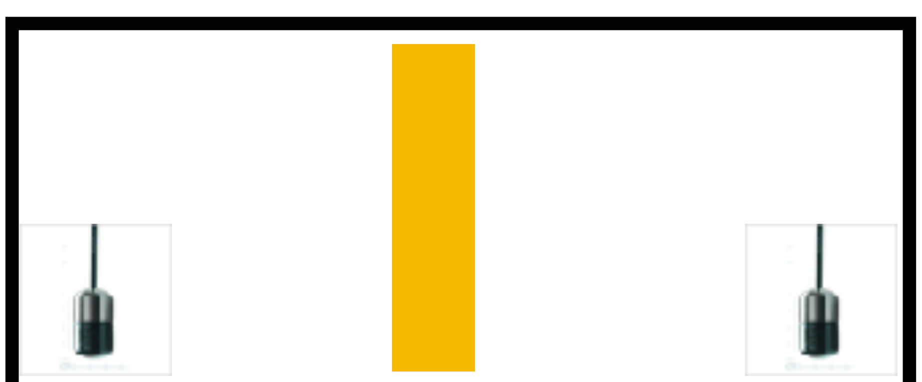


MACRO=> dE/dx < 6 MeV/cm

Huge Volume?

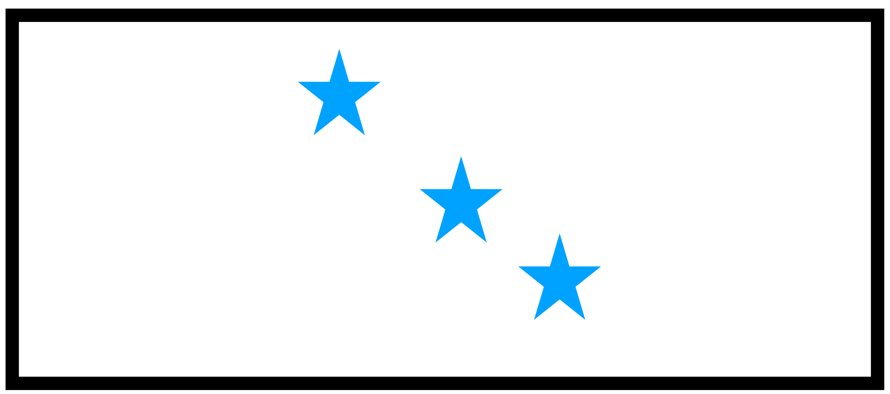


Hydrophones: dE/dx ~ keV/A

Detection

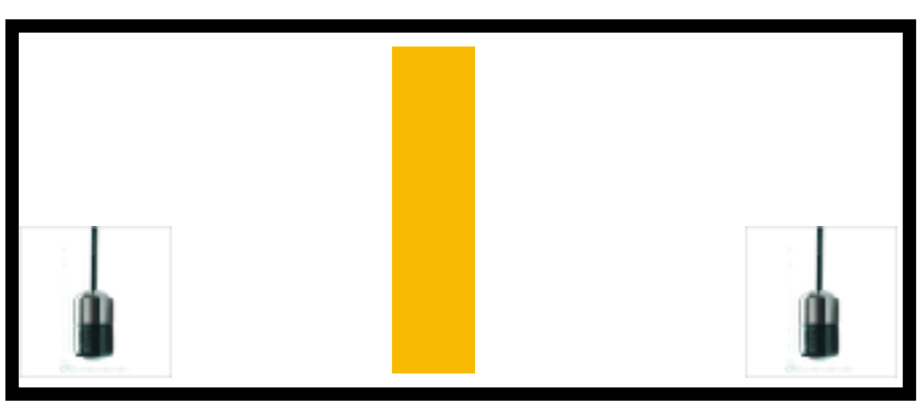
Short Range

Ionization
(Λ > 300 keV)



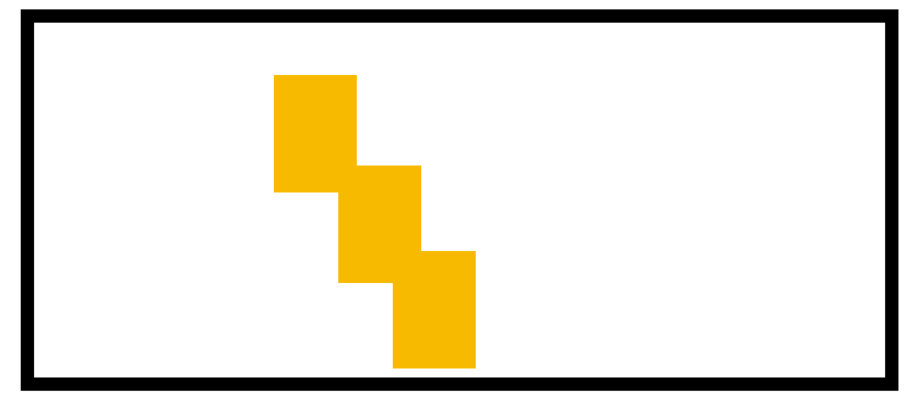
MACRO=> dE/dx < 6 MeV/cm

Huge Volume?



Hydrophones: dE/dx ~ keV/A

Acoustic
(Λ < 300 keV)



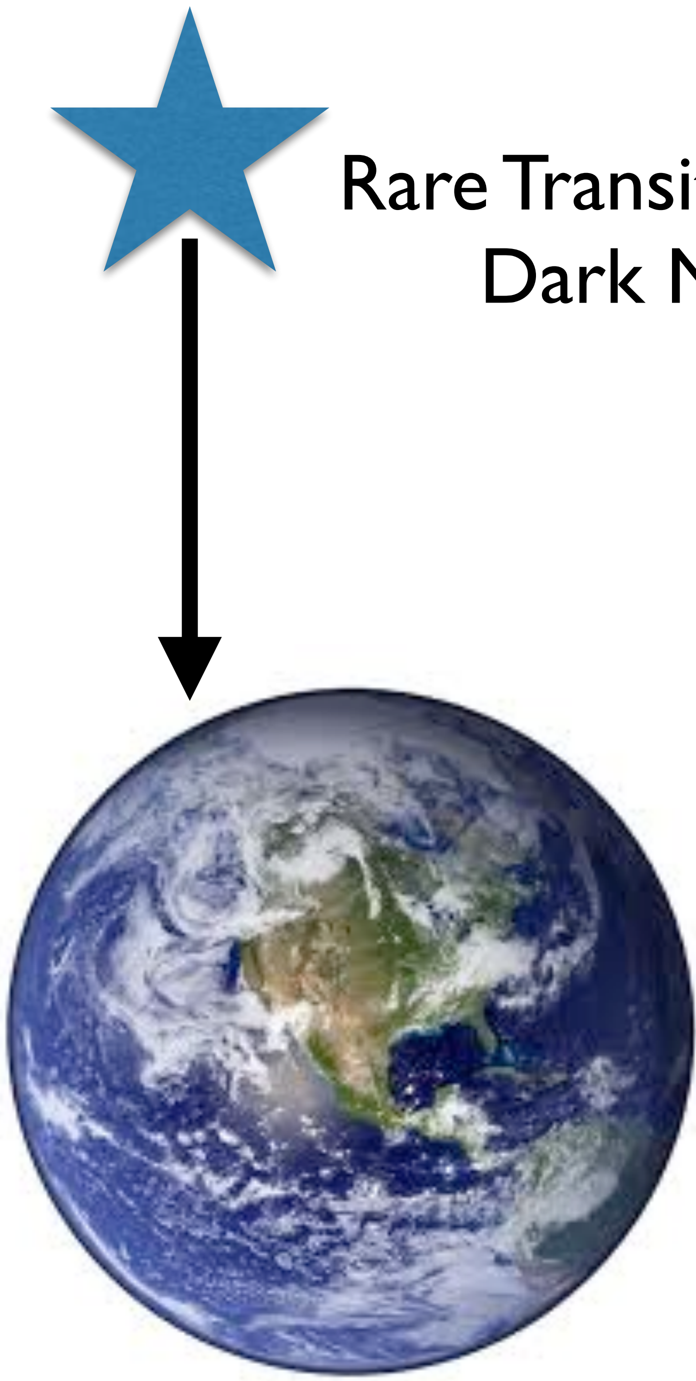
Low threshold calorimeter like CDMS

Line of hot cells

Energy depositions ~ keV/cm

Detection

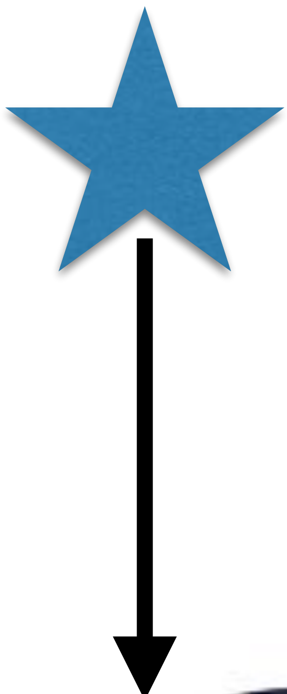
Long Range



Rare Transit of Heavy
Dark Matter

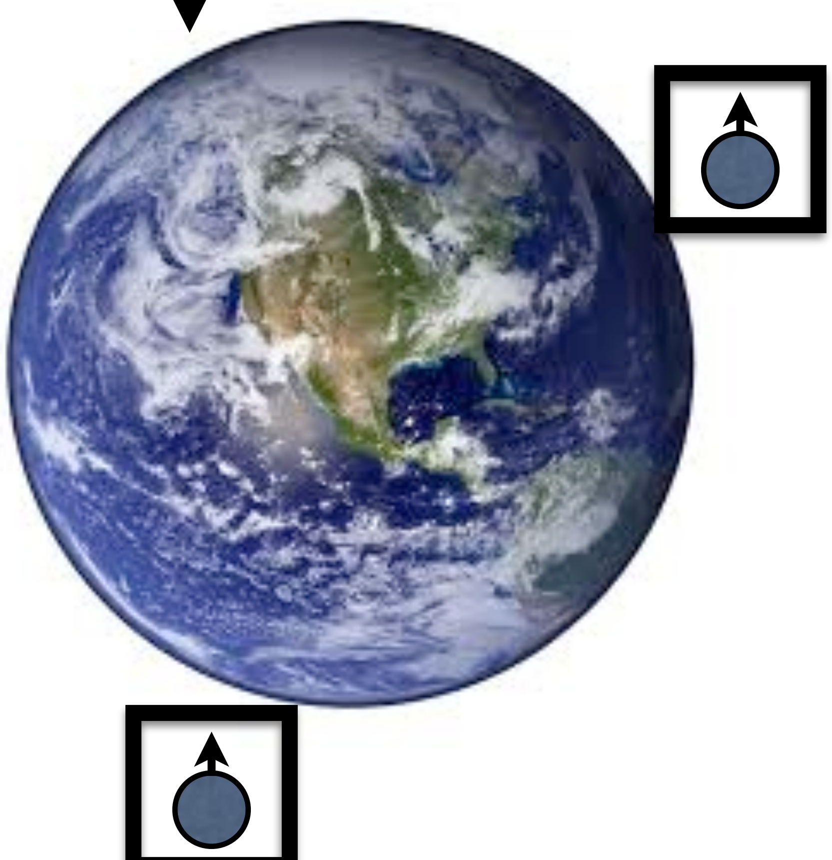
Detection

Long Range



Rare Transit of Heavy Dark Matter

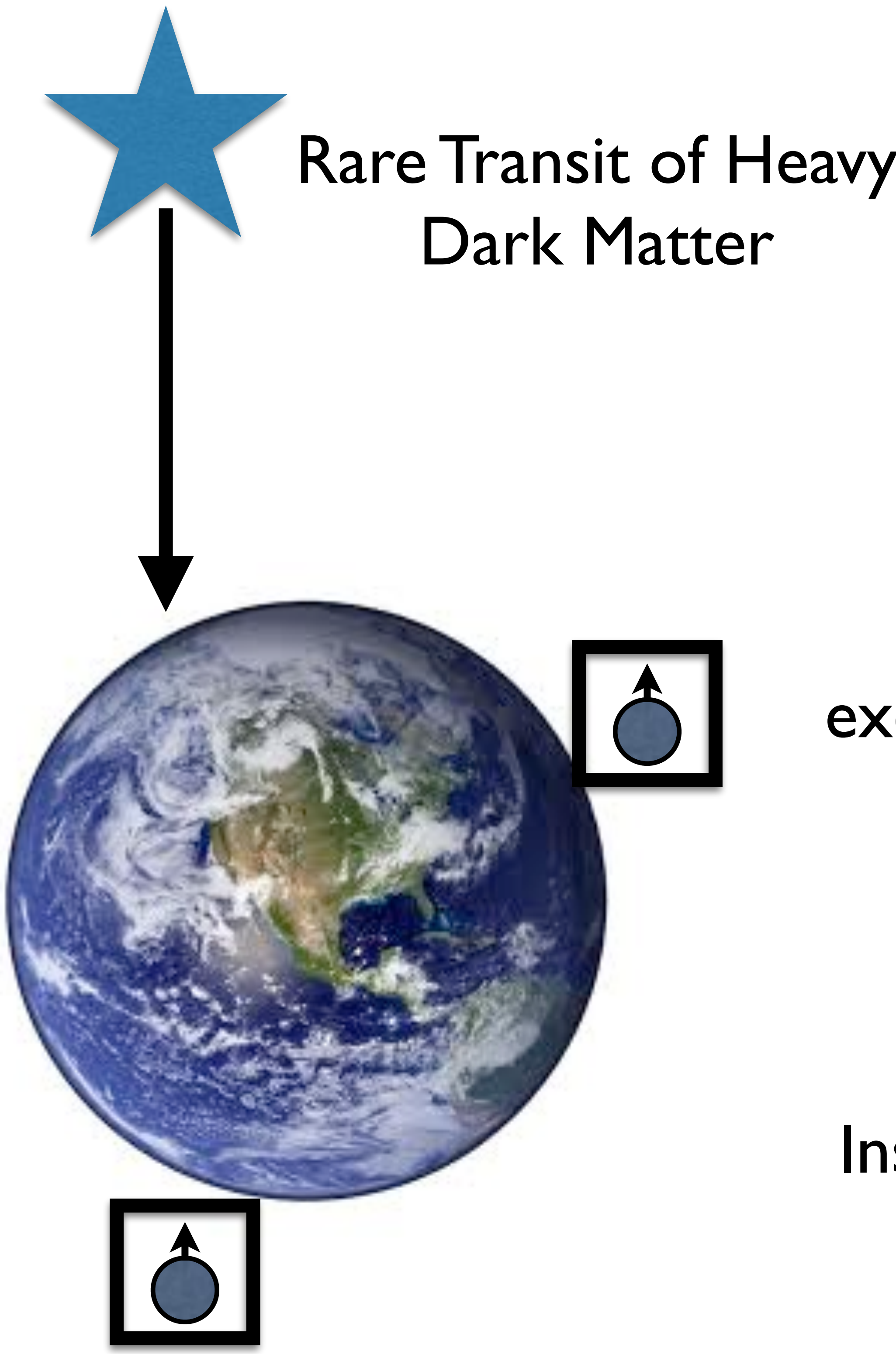
Classical field created by dark matter - correlated excitation of multiple detectors



Same class of effects as light dark matter - excitation of currents, spin precession, acceleration, variation of fundamental constants

Detection

Long Range



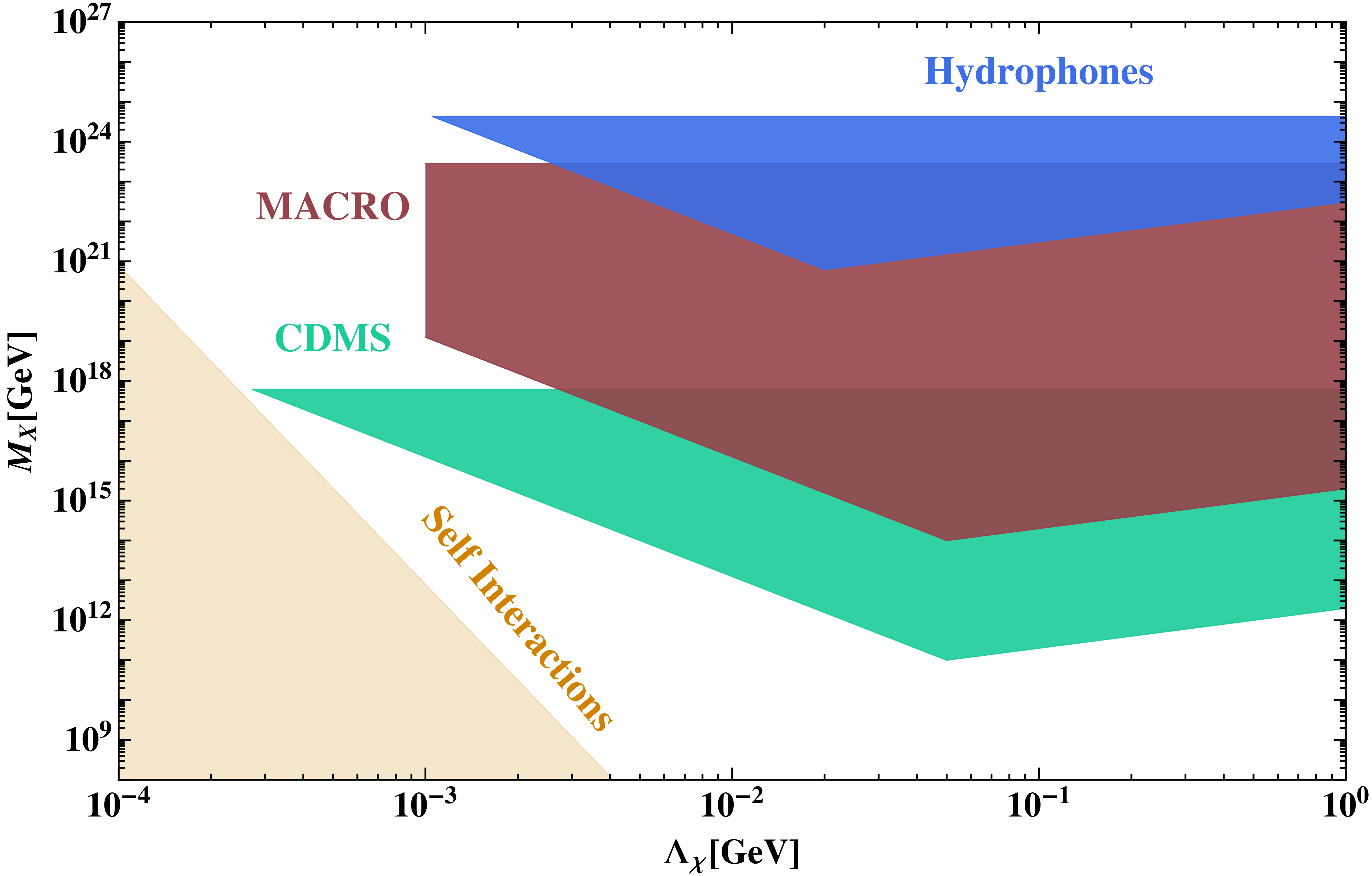
Classical field created by dark matter - correlated excitation of multiple detectors

Same class of effects as light dark matter - excitation of currents, spin precession, acceleration, variation of fundamental constants

Instead of continuous, coherent a/c effect, look for correlated transients in network

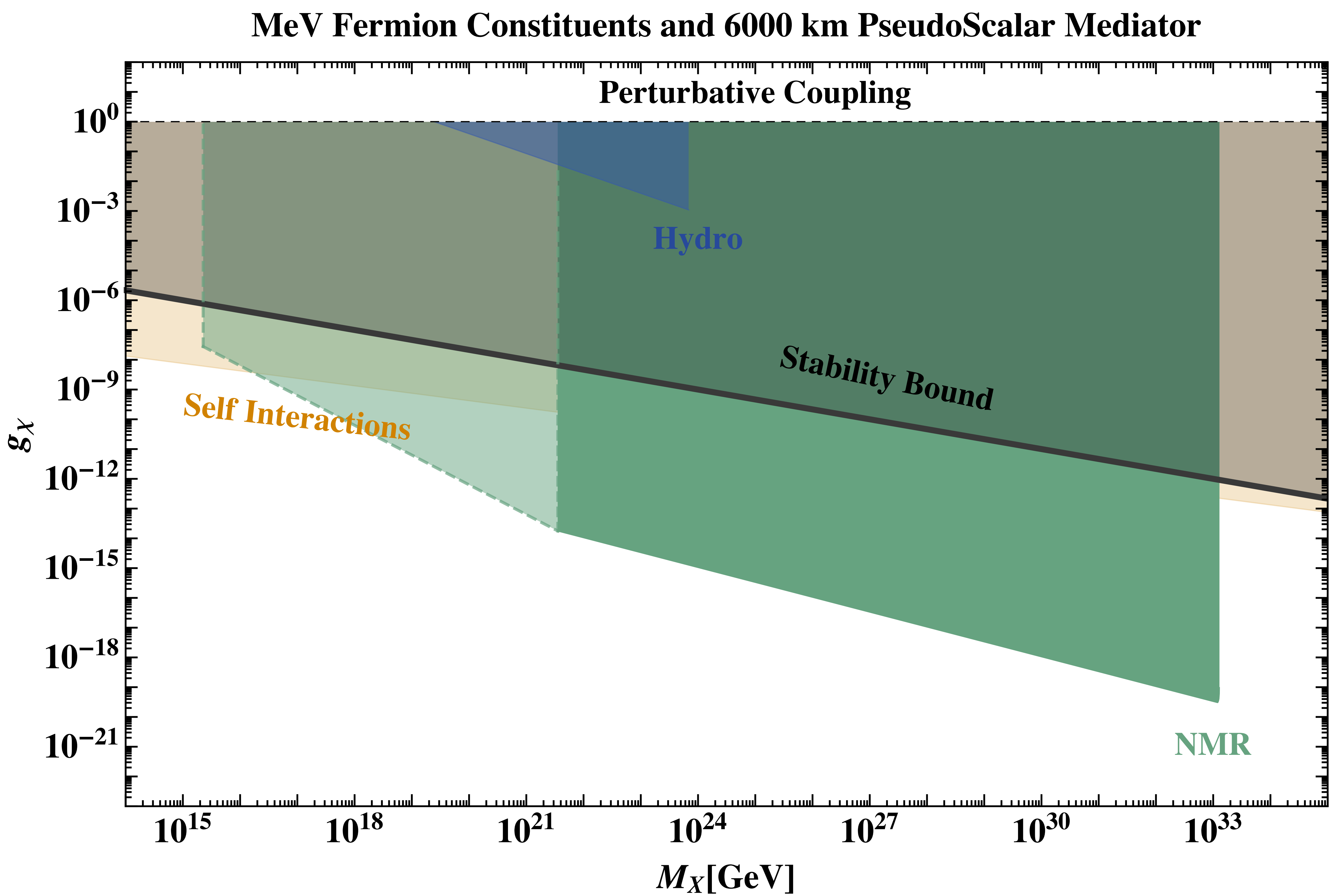
Up to dark matter mass ~ 10^8 gm

Reach



Hydrophones
MACRO
CDMS
Self Interactions
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
M_X[GeV]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Λ_χ[GeV]

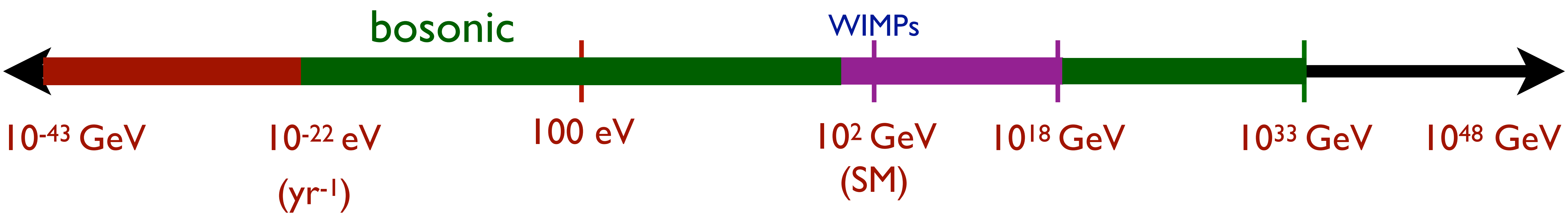
Reach



MeV Fermion Constituents and 6000 km PseudoScalar Mediator
Perturbative Coupling
Hydro
Stability Bound
Self Interactions
NMR
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
g_χ
10^{15}
10^{18}
10^{21}
10^{24}
10^{27}
10^{30}
10^{33}
M_X[GeV]

Conclusions

The Dark Matter Landscape



Poor observational constraints on dark matter

Significant opportunity to probe dark matter from 10^{-22} eV - 10^{33} GeV

Possible to probe above 10^{33} GeV using astrophysical systems - particularly white dwarfs