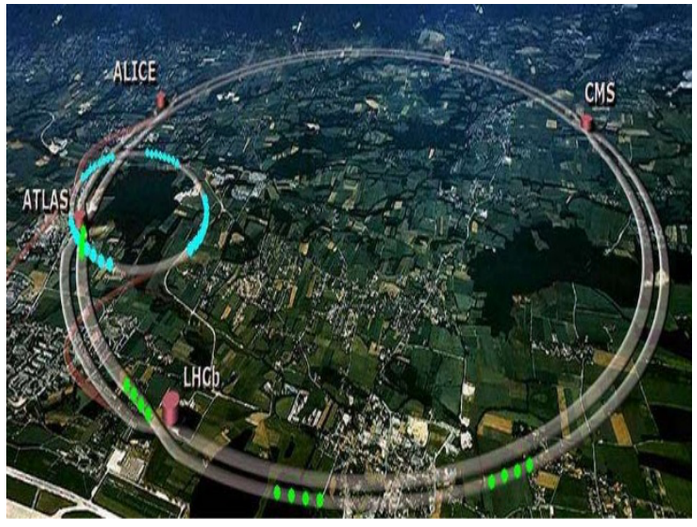
Axions: Phenomenology and Detection

Surjeet Rajendran,
The Johns Hopkins University

Grand Challenge of High Energy Physics

Standard Model experimentally established



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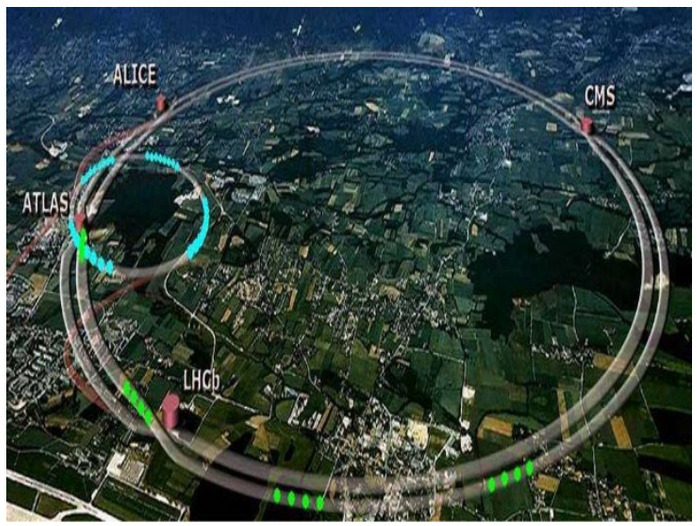
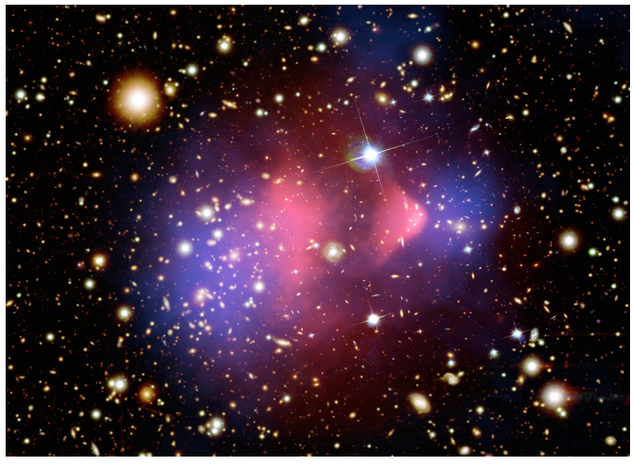
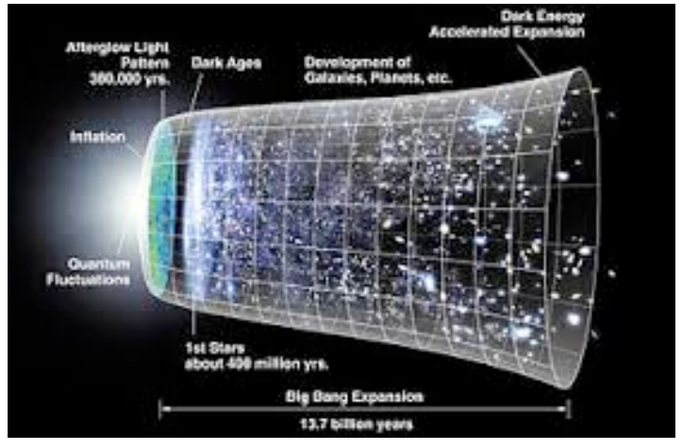


We know there is new physics out there

Matter?
Universe?



Dark Matter



Dark Energy

Hierarchy

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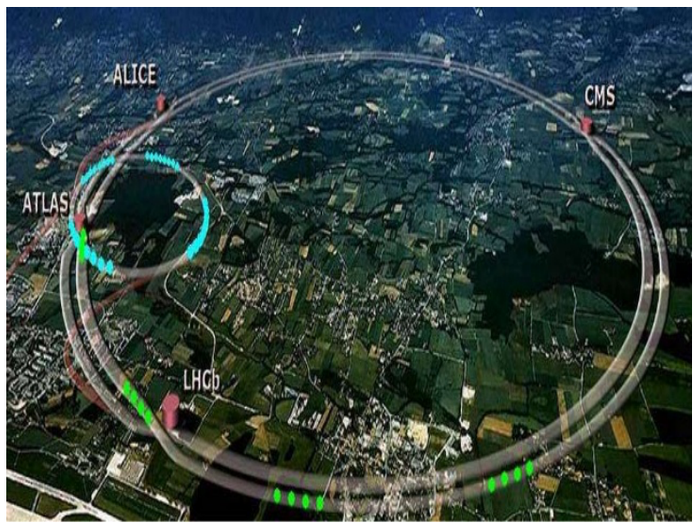

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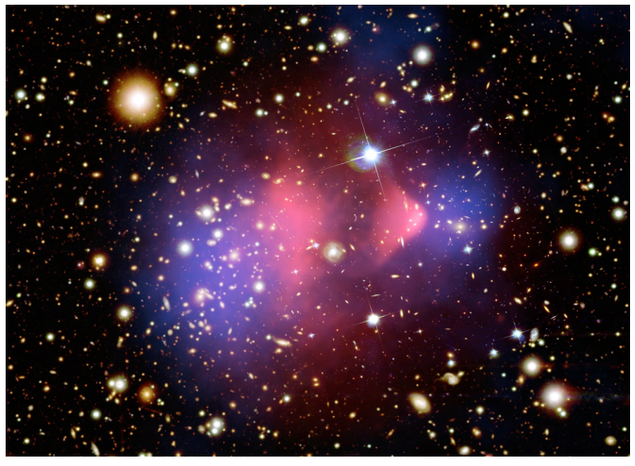

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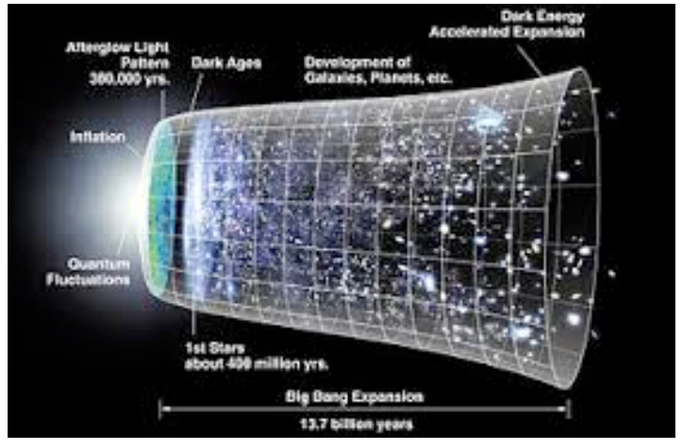

Dark Energy

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Where is this new physics?

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Mass? Strength?

0 **Mass** **10^{19} GeV (Quantum Gravity)**

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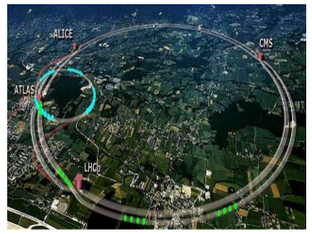
S t r e n g t h

Colliders



Gravity

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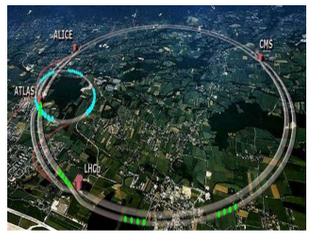

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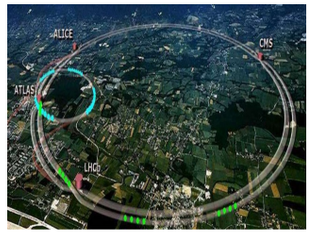

Gravitational Waves, Dark Matter, Dark Energy

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Strength

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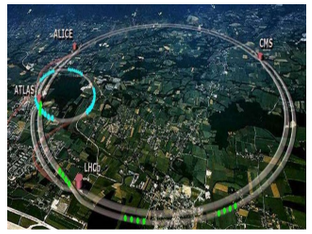

Gravity

Gravitational Waves, Dark Matter, Dark Energy

Strong Physics Case

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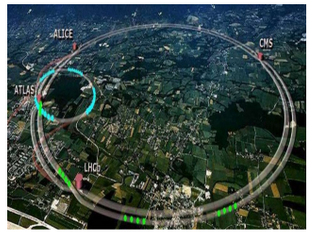

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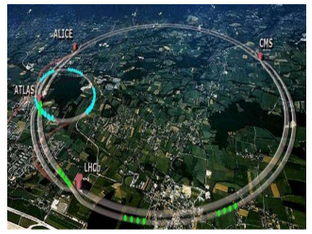

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Magnetic Field ~ 10^{-20} T

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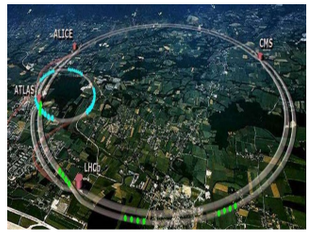

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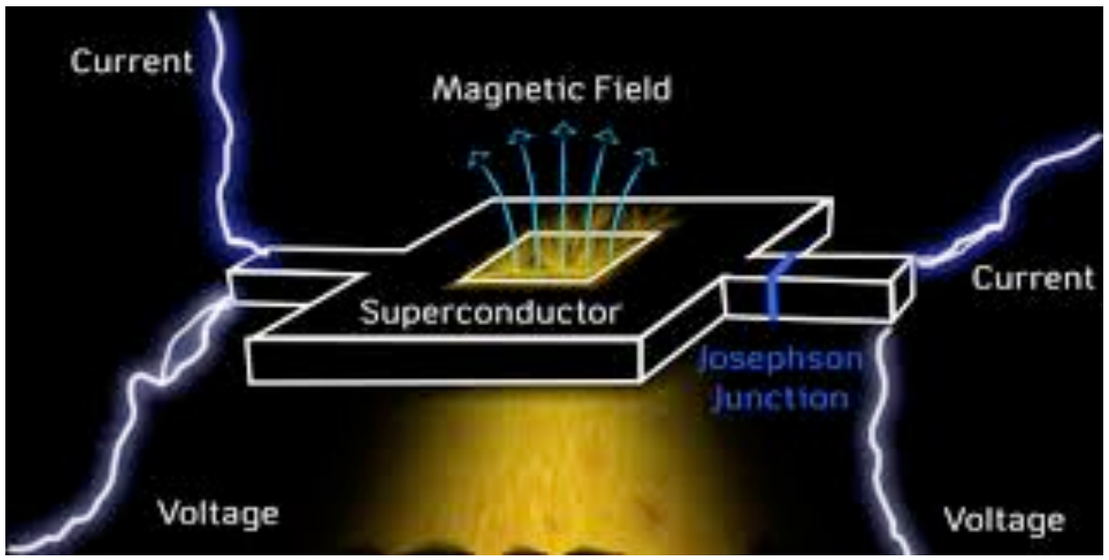
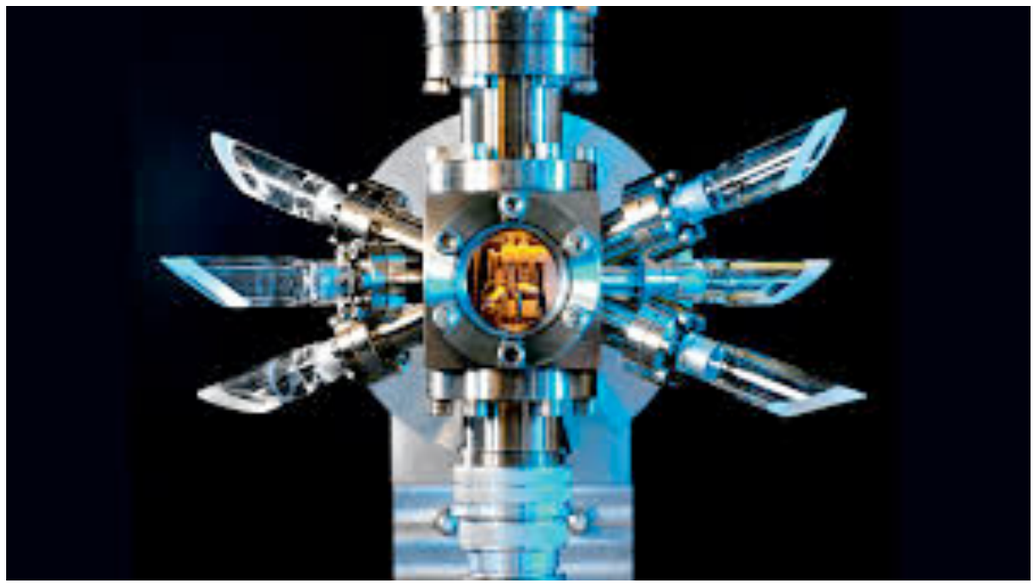
Gravity

How?

Quantum Sensors

Impressive developments in quantum sensors in the past two decades





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

(SQUIDs, atomic magnetometers)

$$\text{Accelerometers} \lessapprox 10^{-13} \frac{\text{g}}{\sqrt{\text{Hz}}}$$

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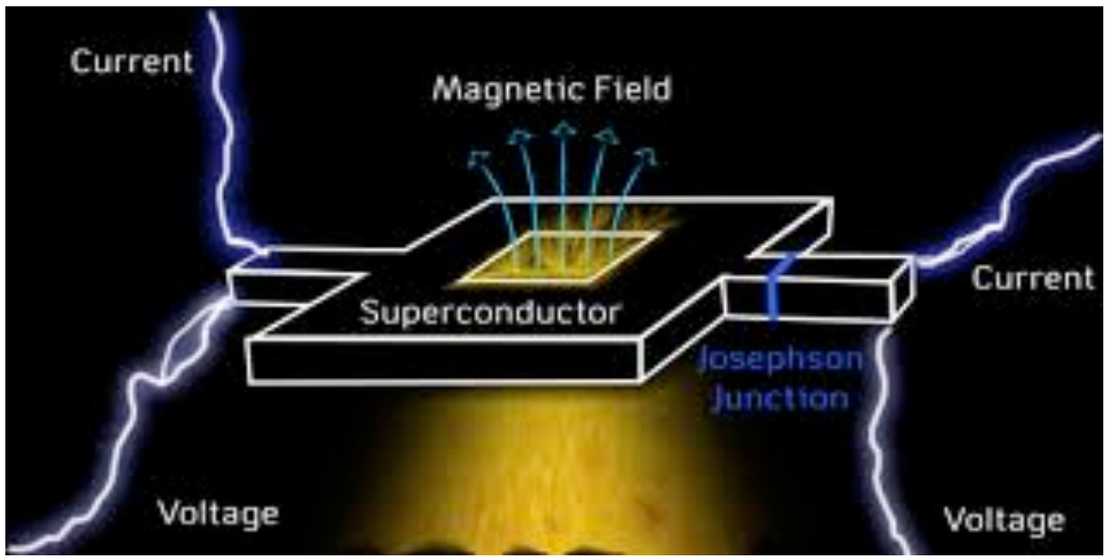

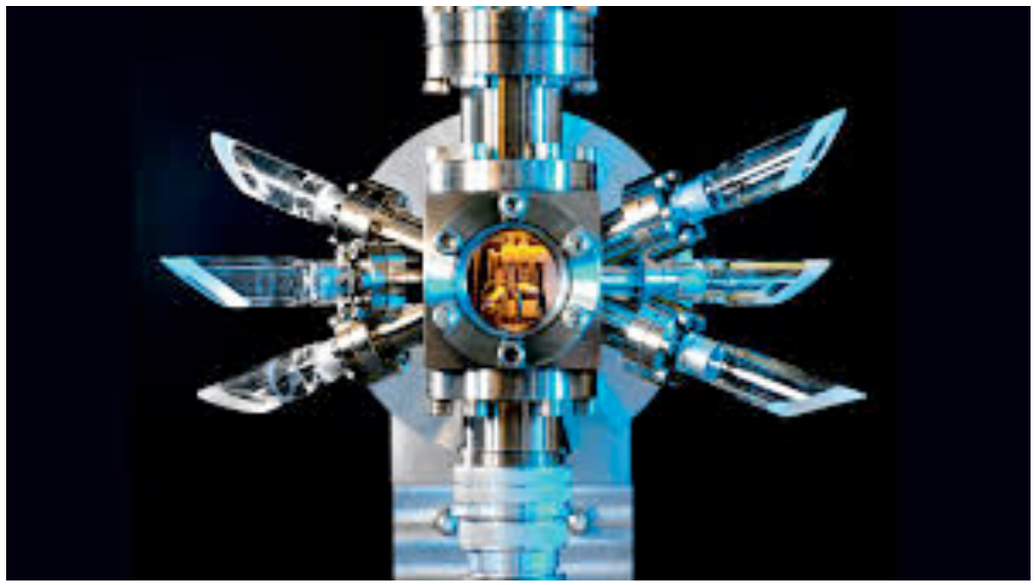

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Rapid technological advancements

Time to find gravitational waves, dark matter, maybe even dark energy?

Outline

1. Theory Overview

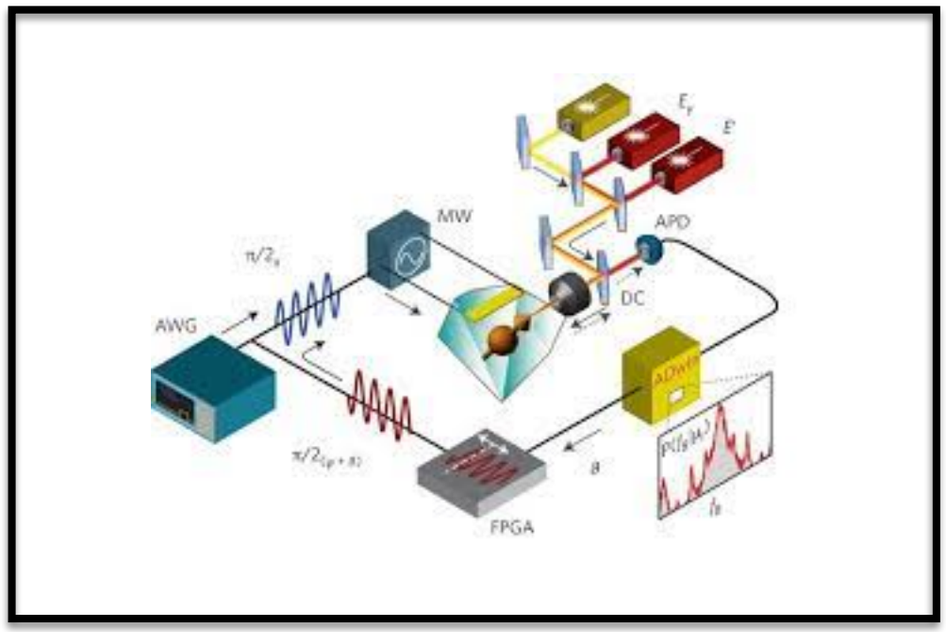
2. Experimental Landscape

3. Conclusions

Theory Overview

Light Boson Detection

(1) Local Source



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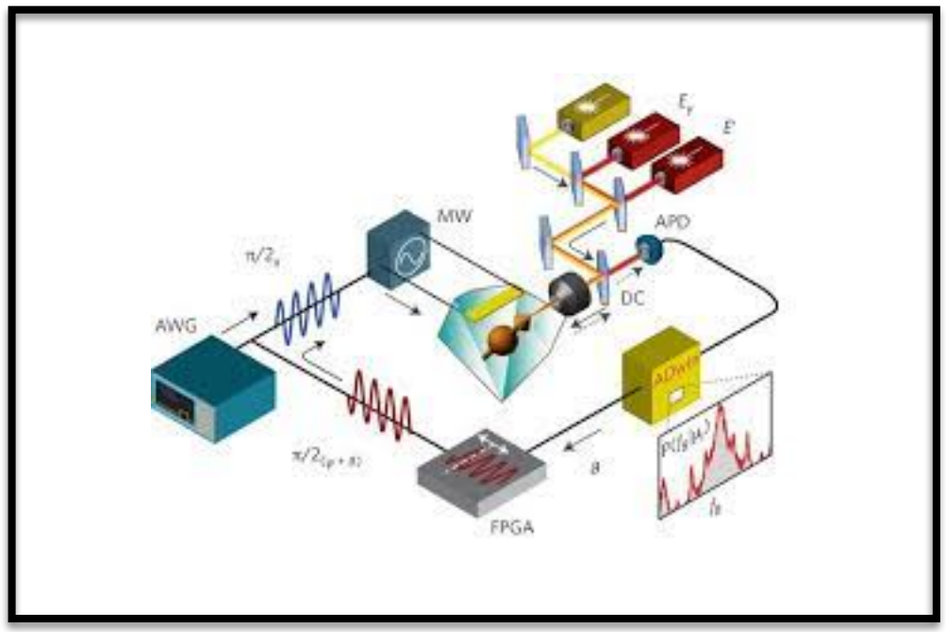

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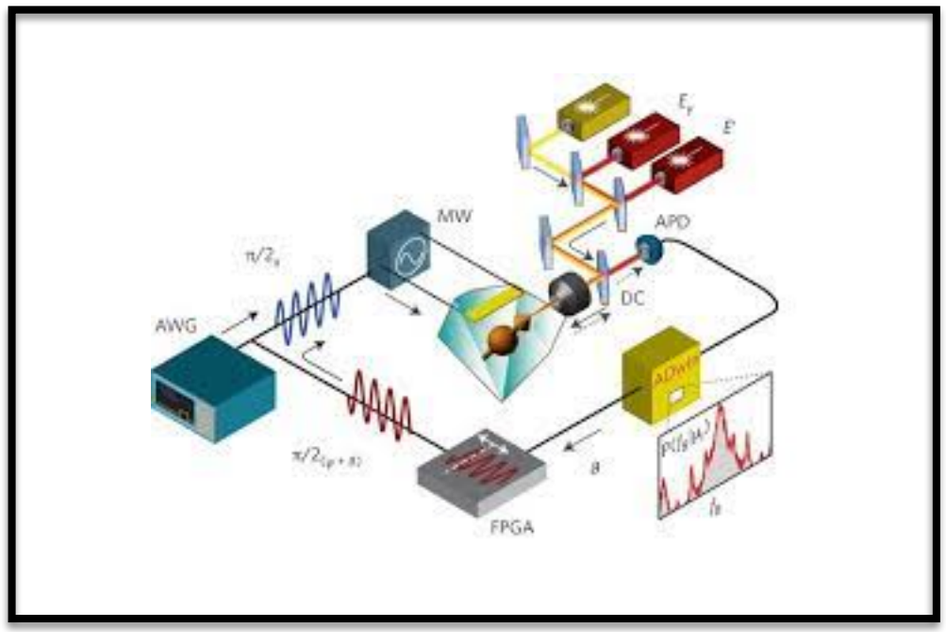

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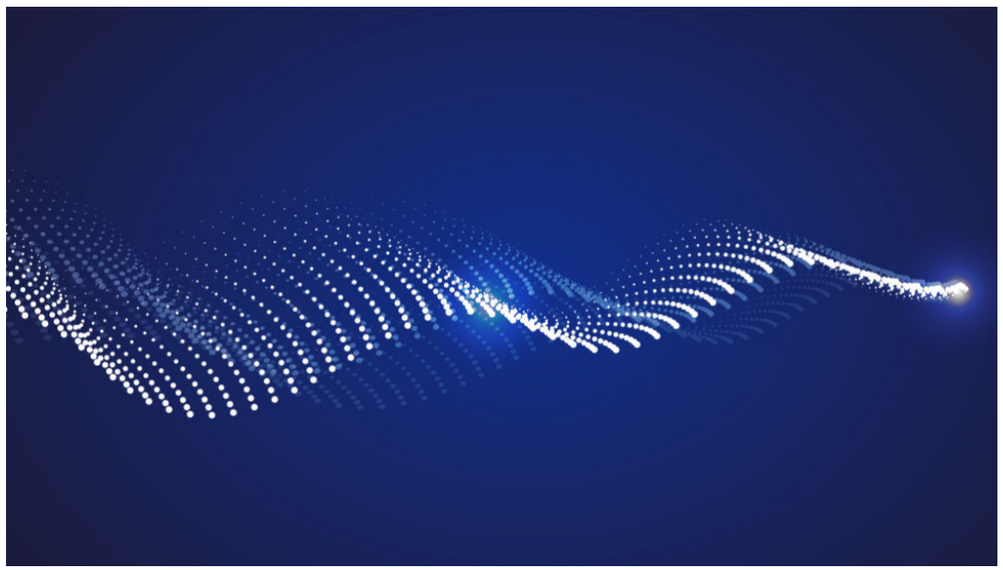
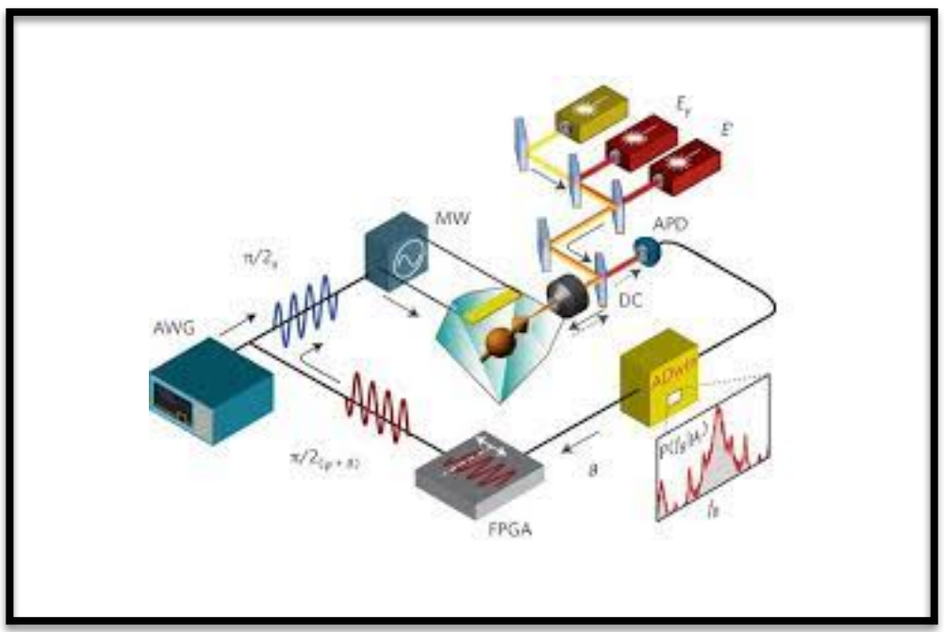
(2) Cosmic Source

Ultra-light dark matter (<< 1 eV)





Bosonic Dark Matter

Photons

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

Detect Photon by measuring time varying field

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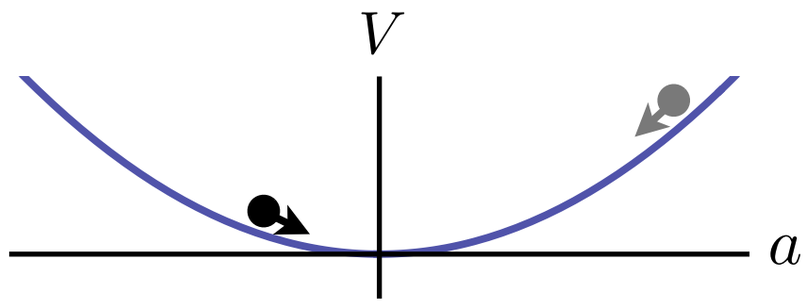
Dark Bosons

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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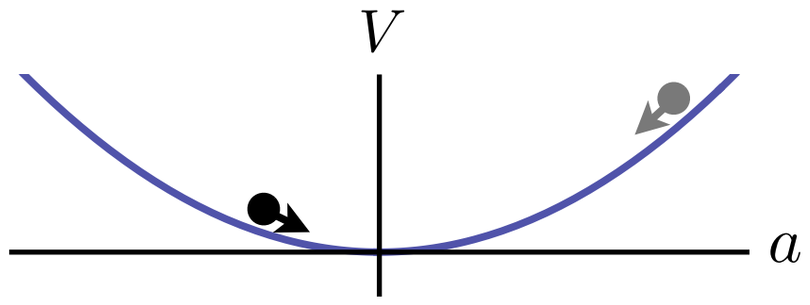

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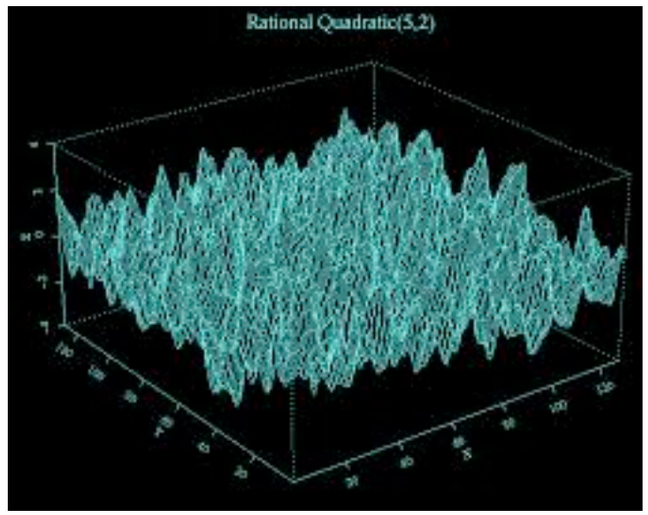

Correlation length
~ 1/(m_a v)

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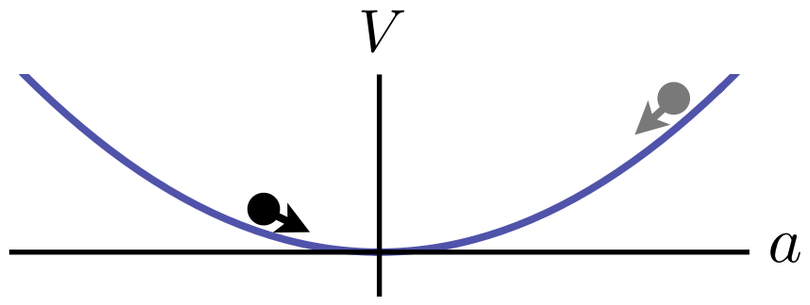

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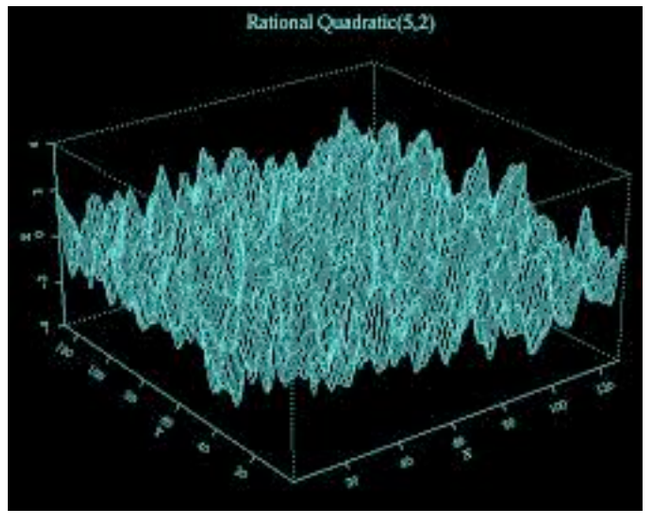

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Detect effects of oscillating dark matter field

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

Light Bosonic Fields

Radiative corrections?

Look for symmetry structures

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Spin 0

Axions or ultra weak coupling

Many UV theories

E&M

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

Axion-Like Particle

QCD

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QCD Axion

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Higgs Portal/ Relaxion

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Dipole moment

E&M

$\left(\epsilon F' F\right)$

Kinetic Mixing

Current

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

B-L

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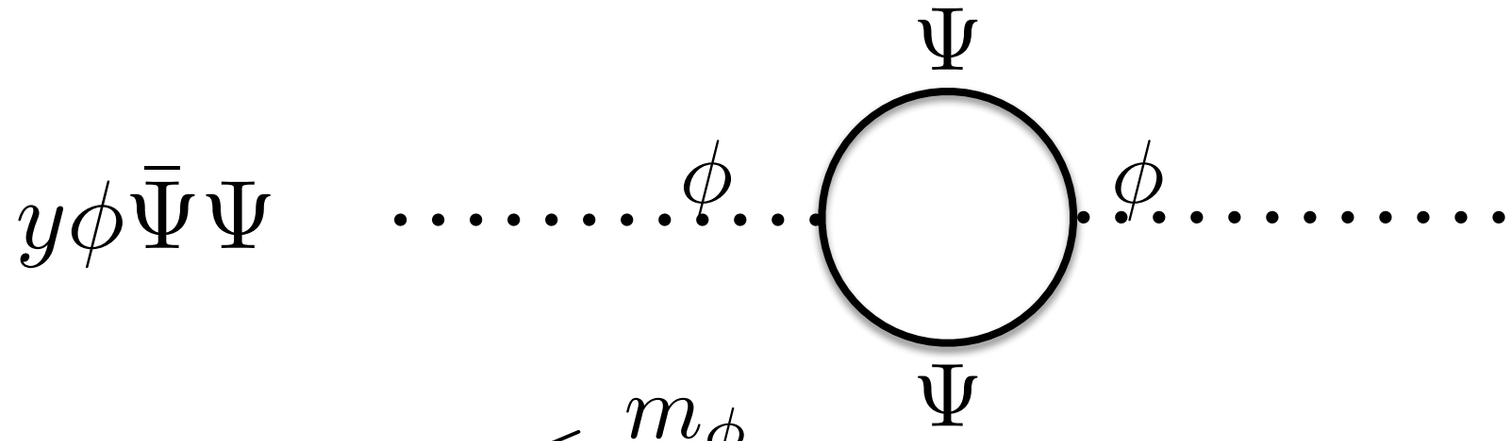
Maybe no symmetries - just weak couplings?



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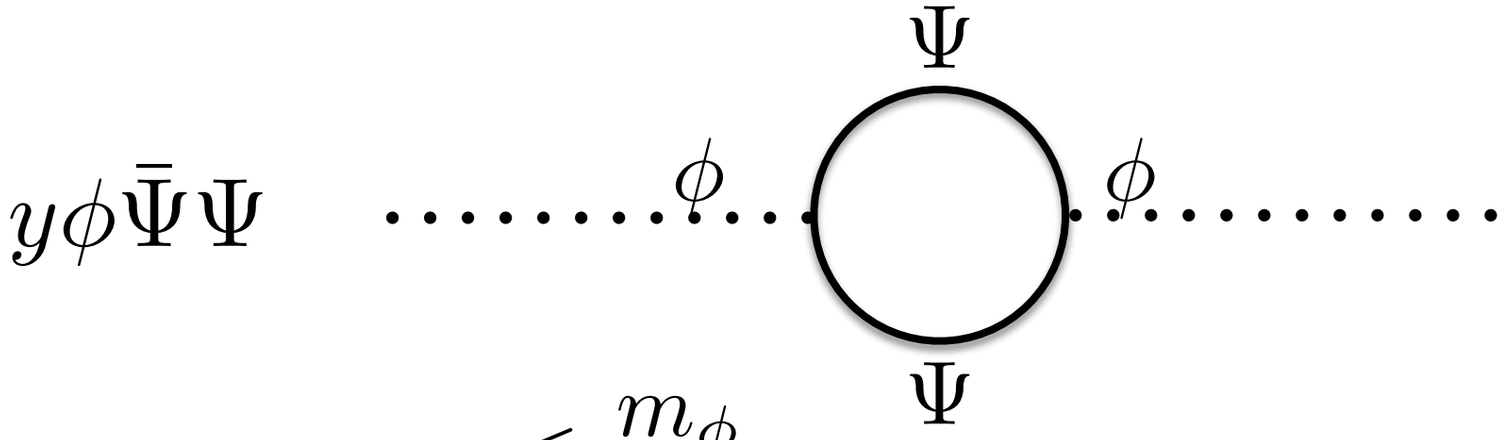

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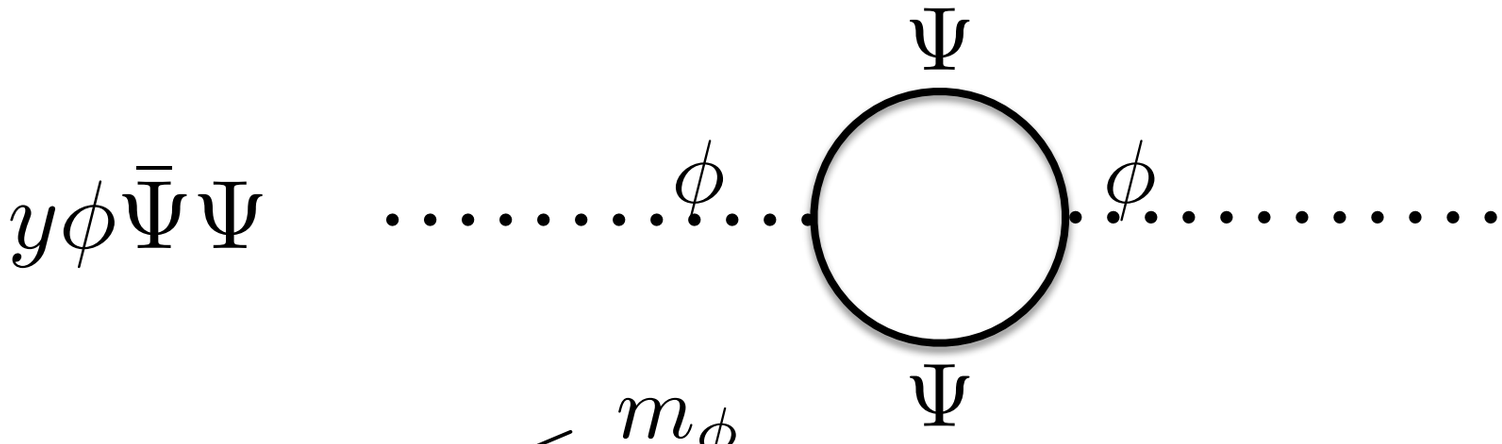

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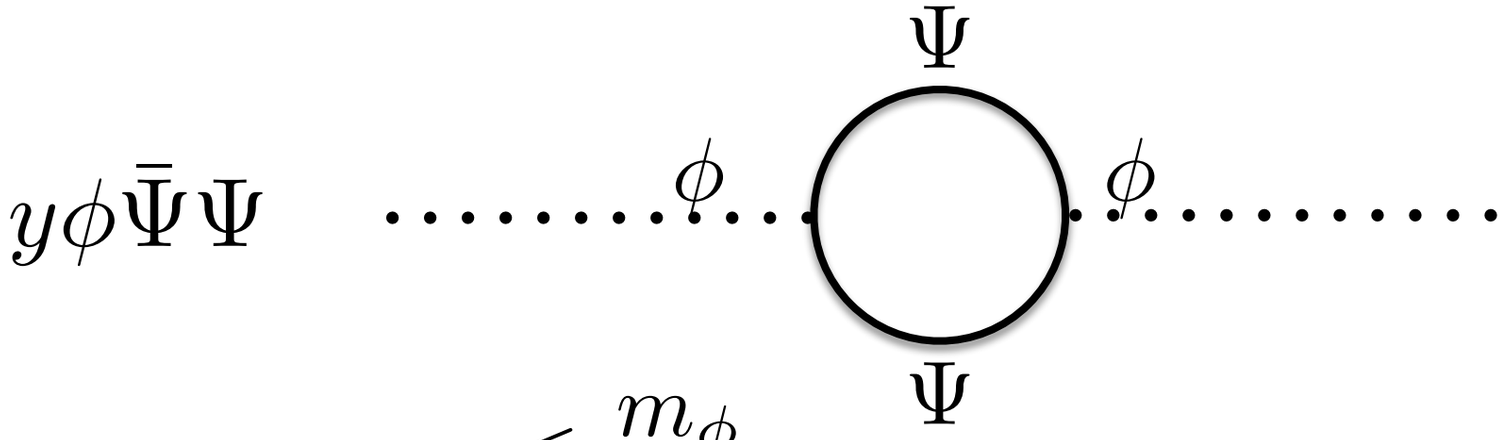

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How to search?

Observable Effects

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What can a classical field do?

Dark Oscillating Field

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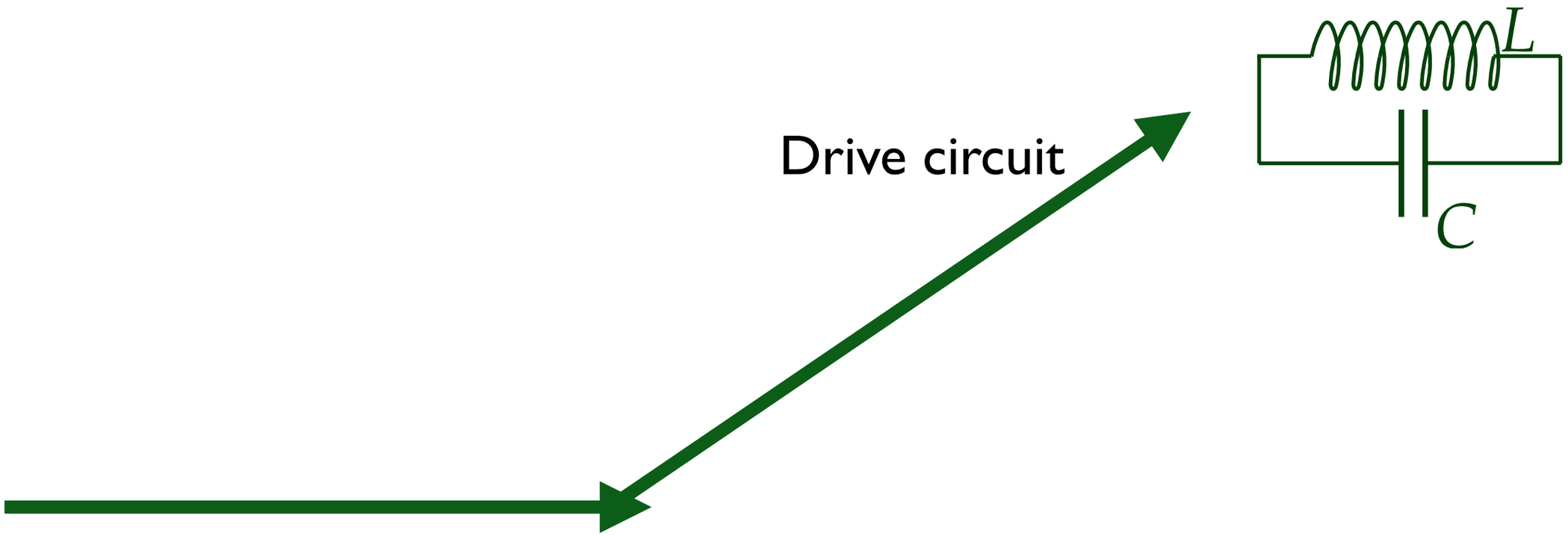

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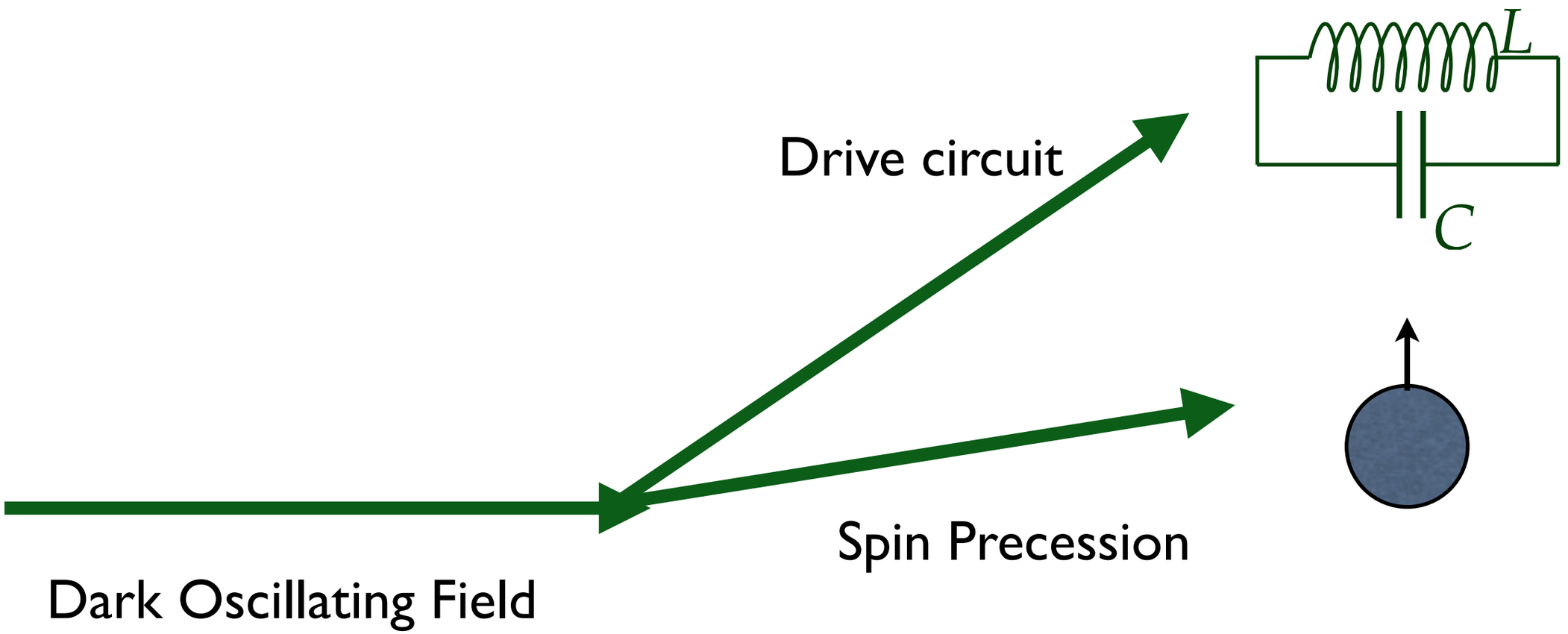

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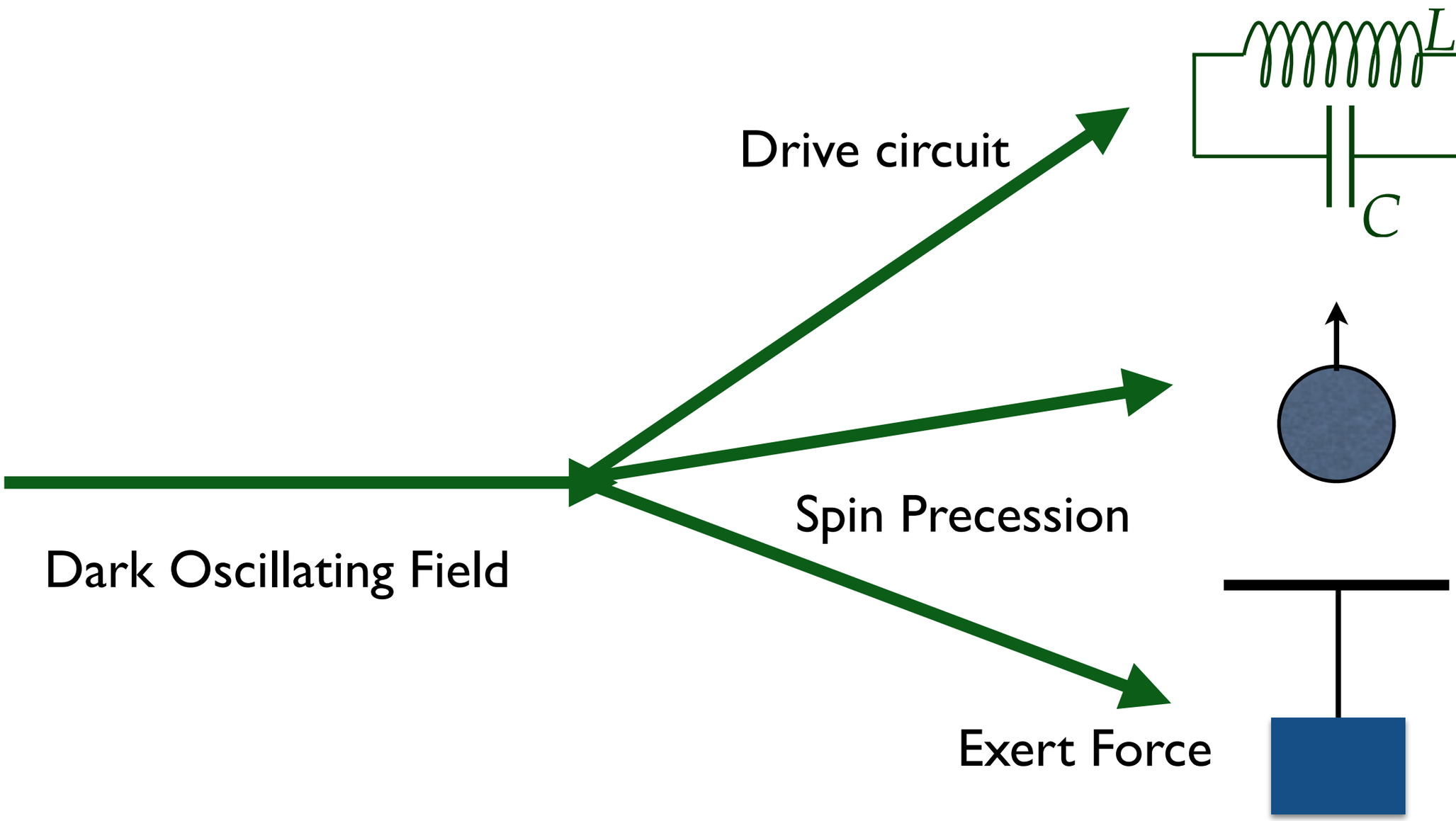

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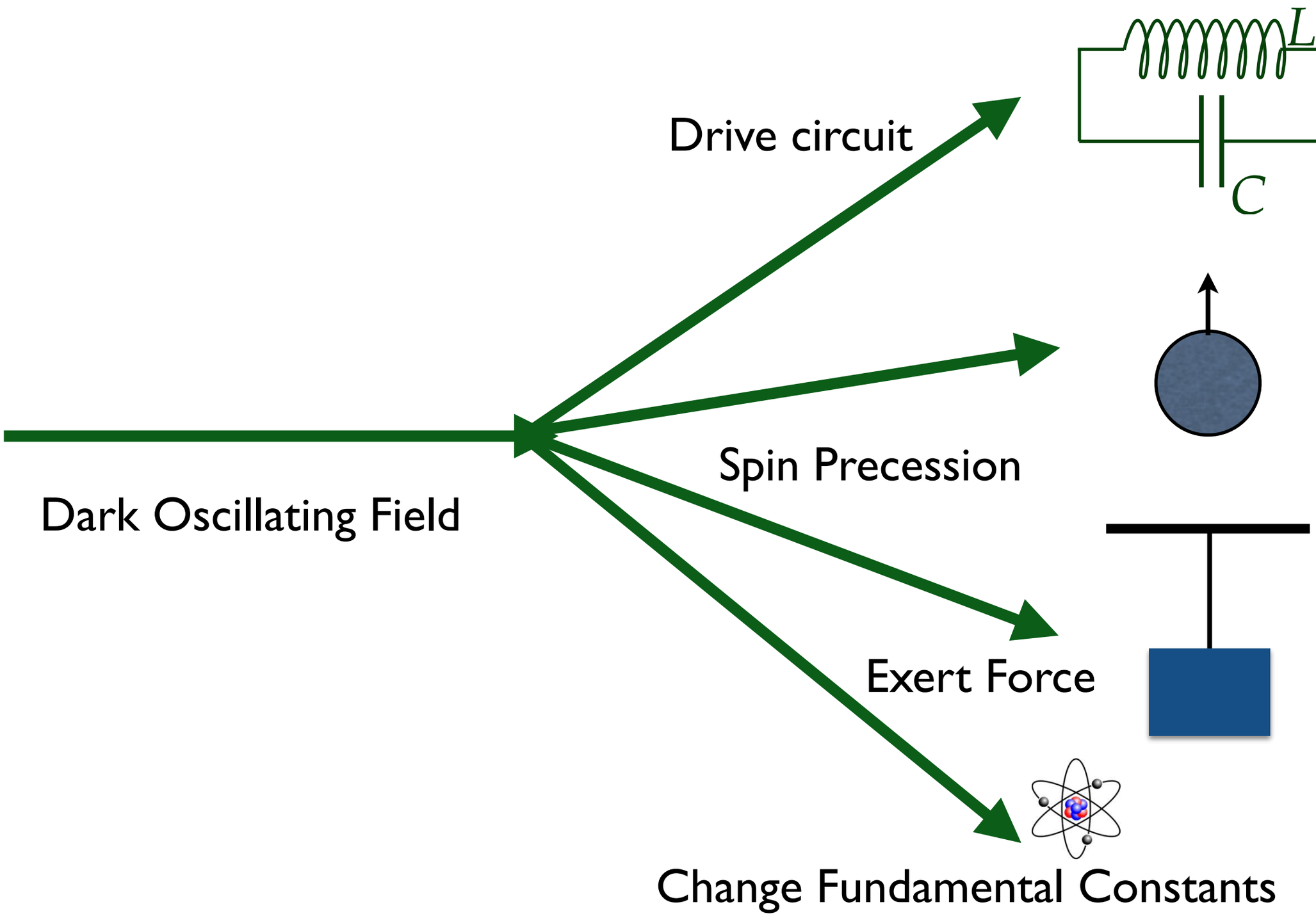

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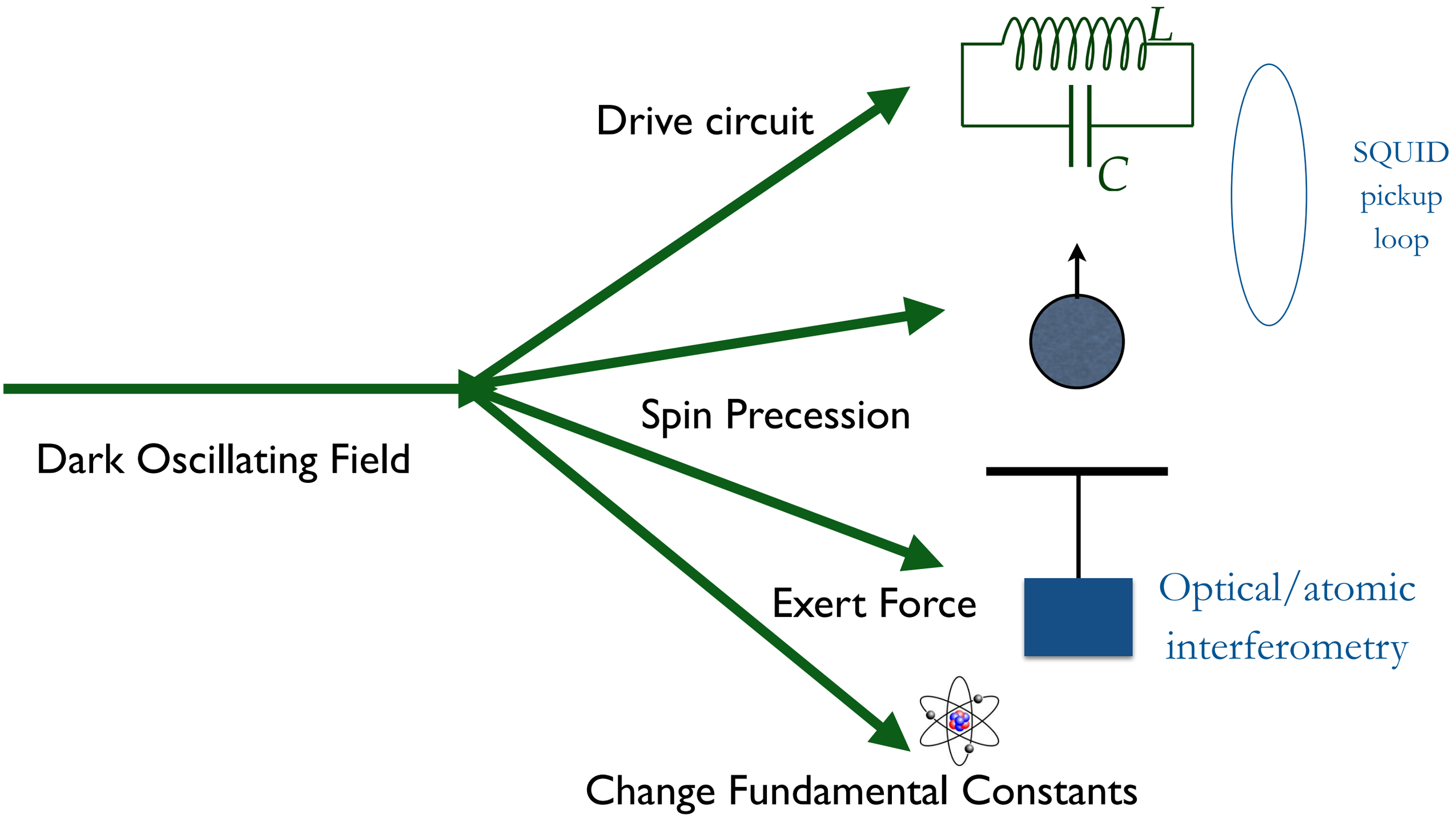

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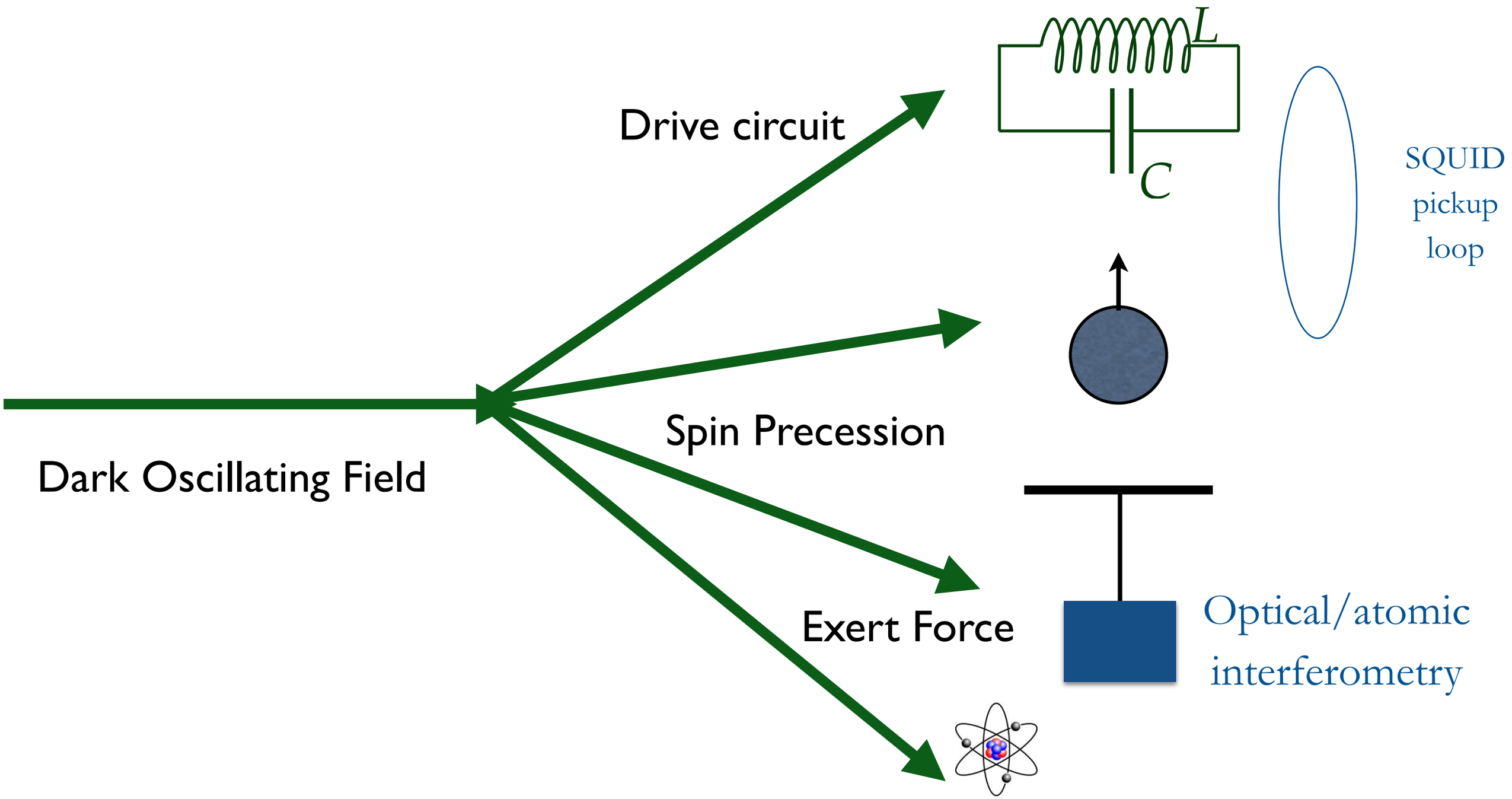

a/c effect, narrow bandwidth around dark matter mass

Experimental Landscape

Electromagnetic Resonators

Axion Dark Matter

Spontaneously Broken Global Symmetry

Goldstone Boson: $\mathcal{L} \supset \dfrac{a}{f_a} F\tilde{F}$

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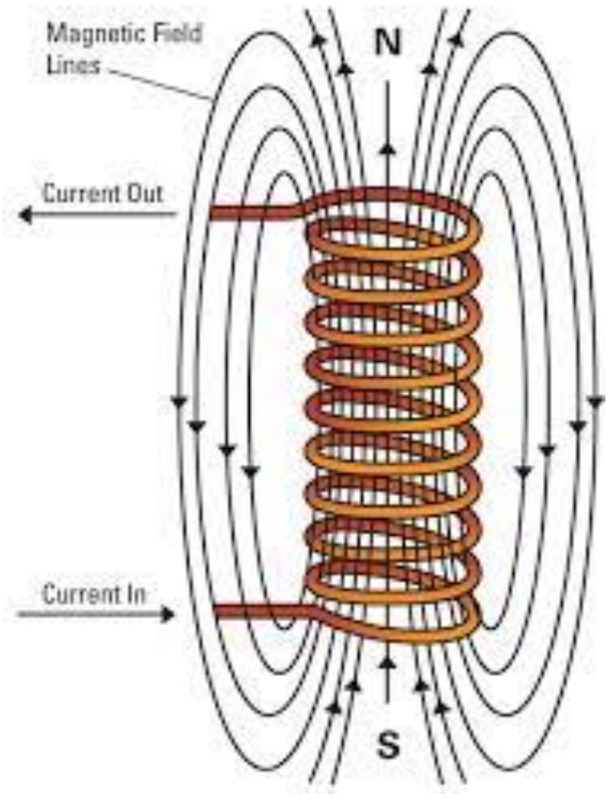
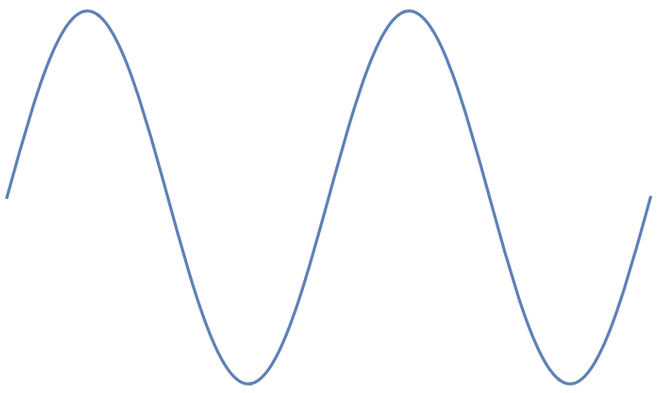
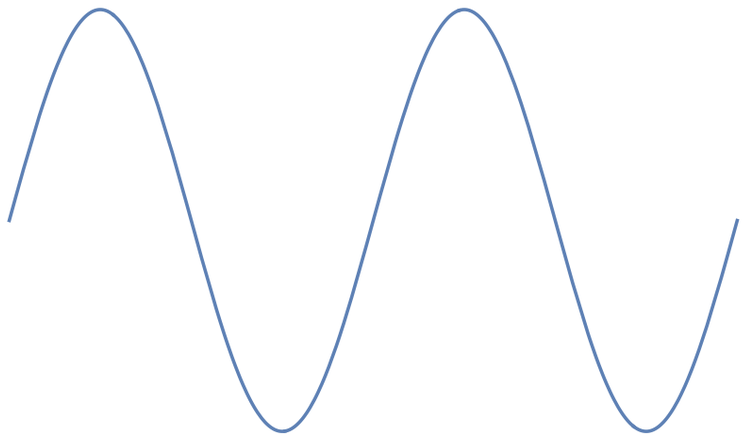




oscillating axion field



oscillating electric field

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:

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

photon with small mass and suppressed couplings to all charged particles

Dark Photon Dark Matter

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

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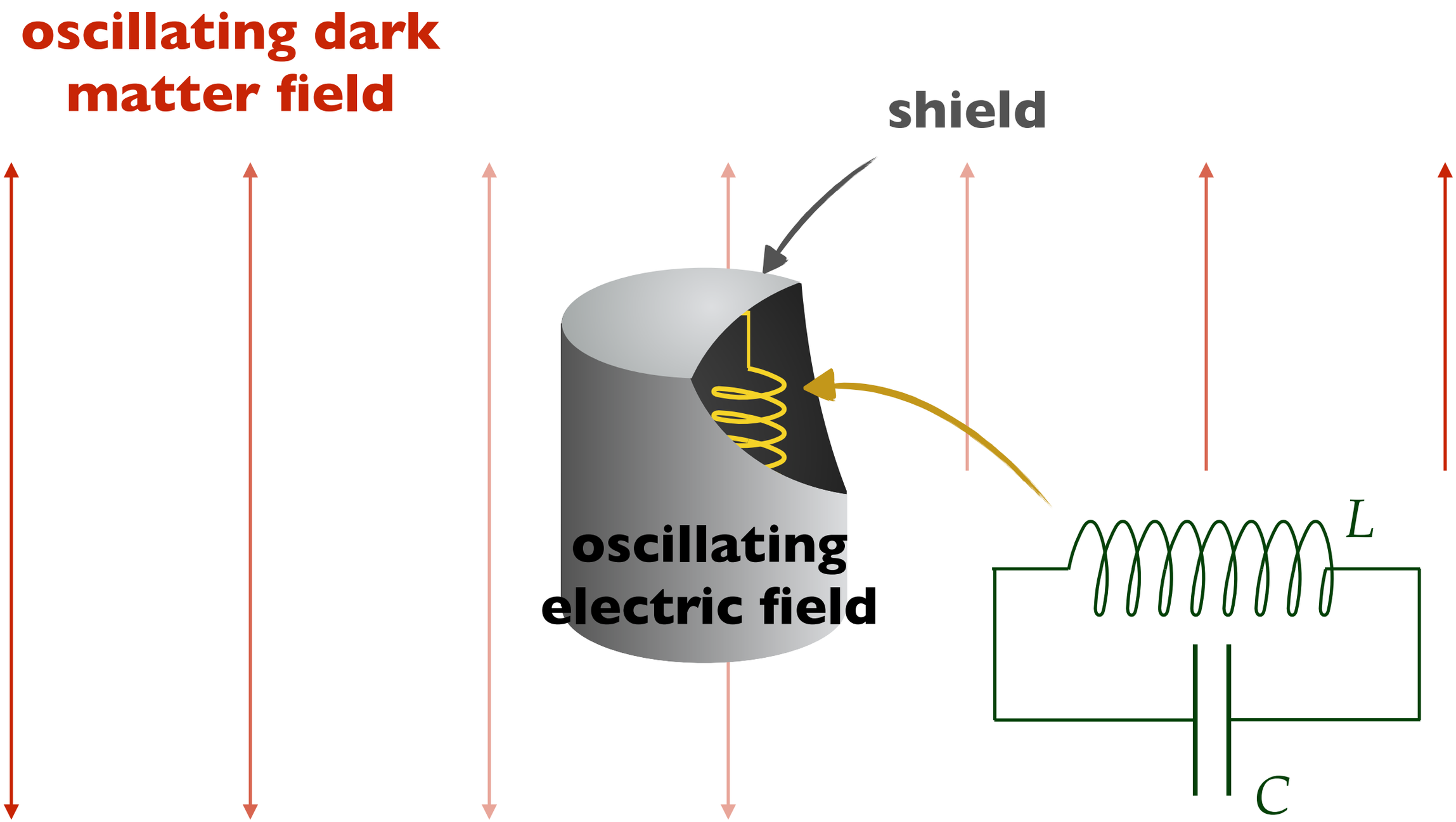
Charge sees small oscillating electric field

Dark Matter Radio Station



Tunable resonant circuit (a radio)

Spin Precession

CASPEr: Axion Effects on Nuclear Spin

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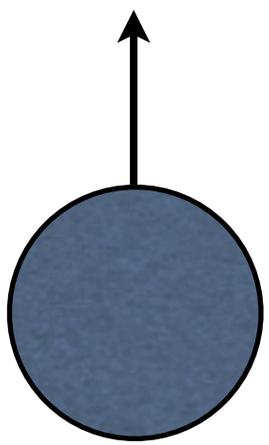
General Axions

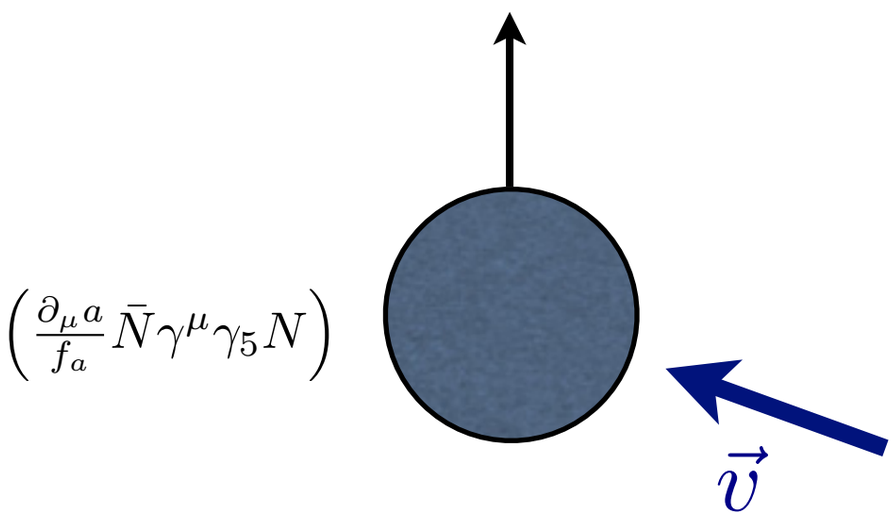
Neutron



CASPEr: Axion Effects on Nuclear Spin

General Axions

Neutron in
Axion Wind



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Spin rotates about
dark matter velocity

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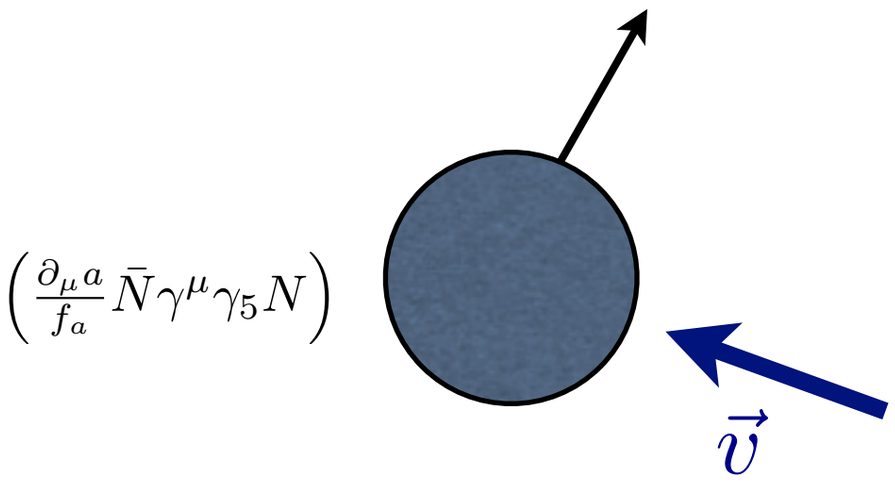

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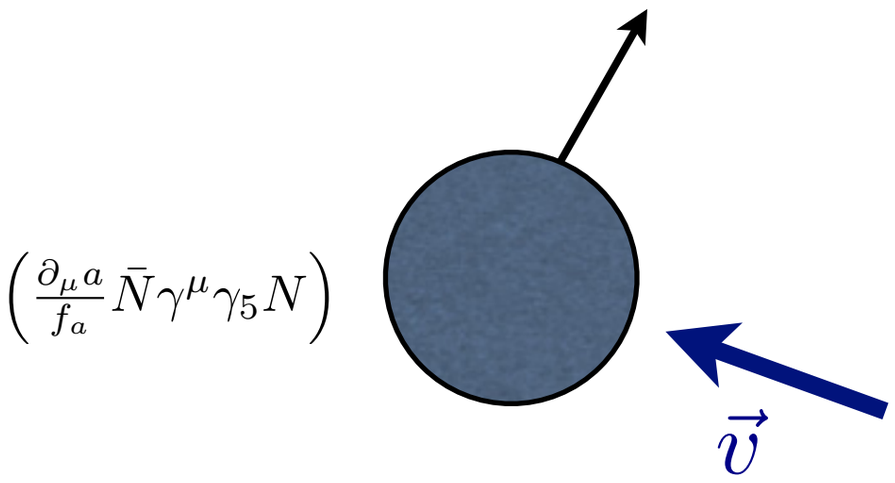

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Effective time varying
magnetic field

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

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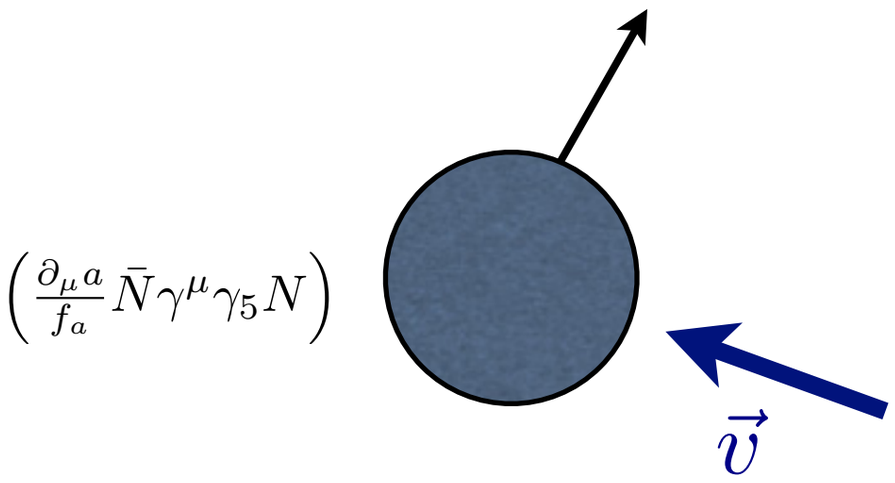

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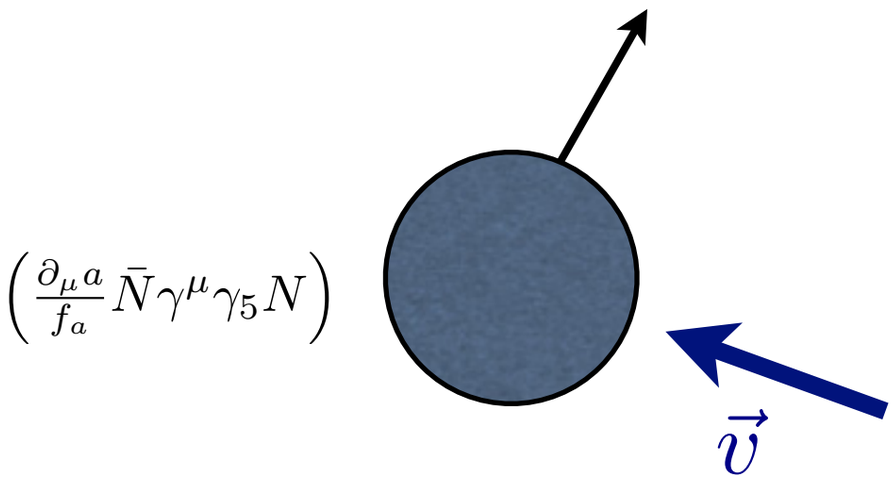

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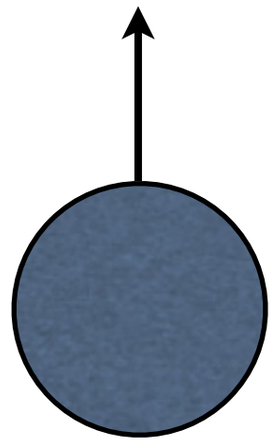
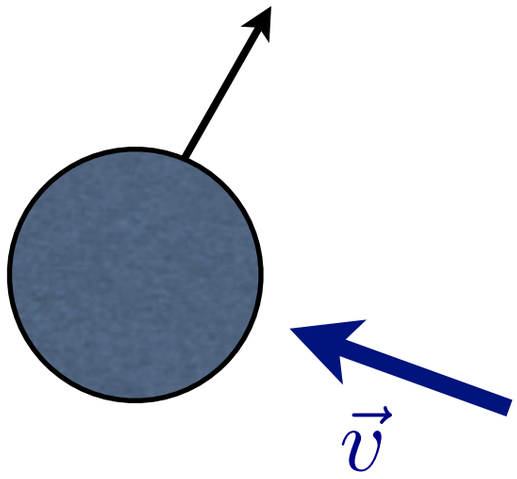


CASPEr: Axion Effects on Nuclear Spin

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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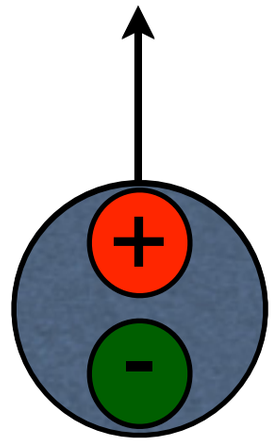
QCD Axion Dark Matter



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

QCD axion induces electric dipole moment
for neutron and proton

Dipole moment
along nuclear spin

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

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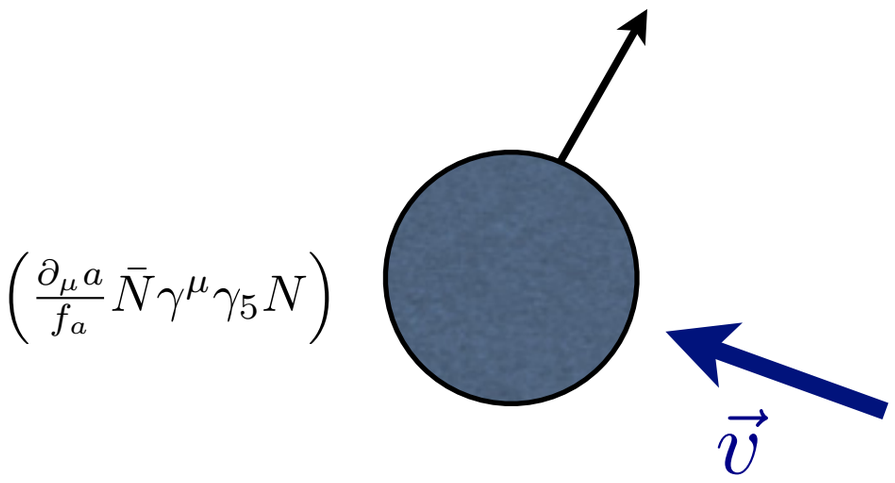

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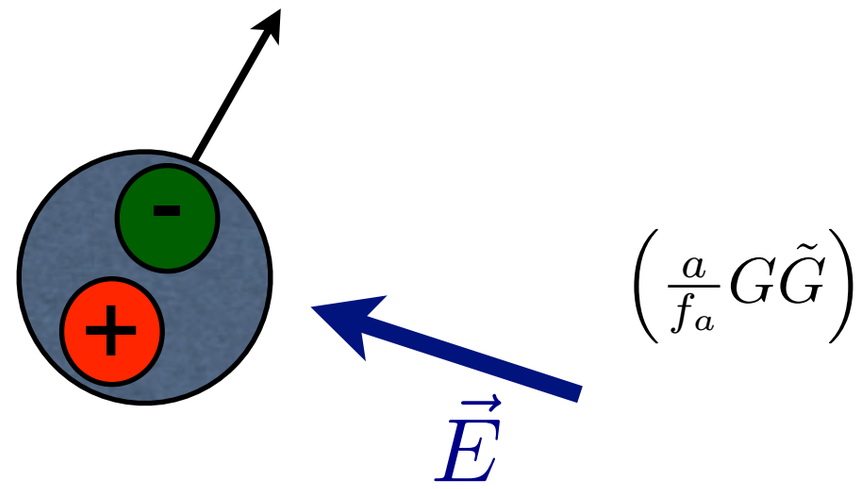

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Apply electric field, spin rotates

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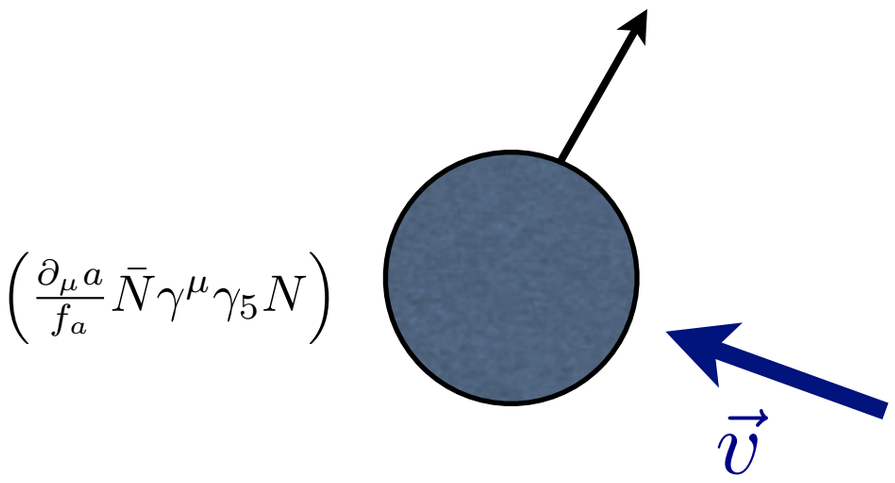

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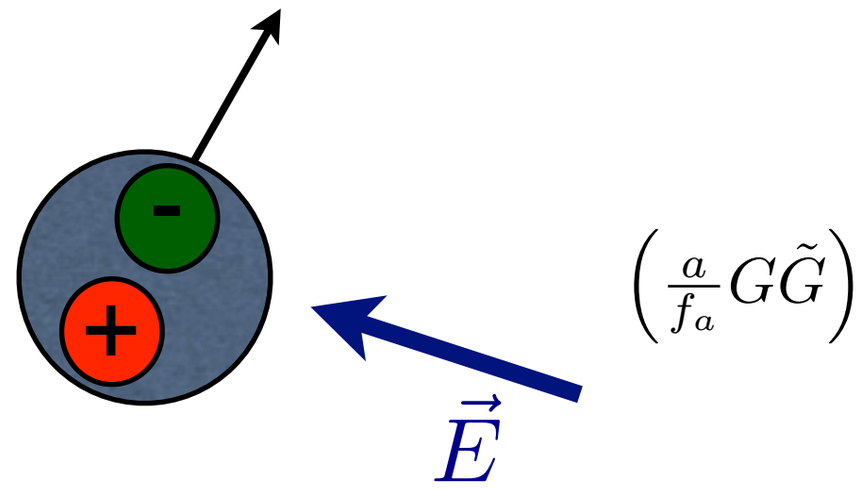

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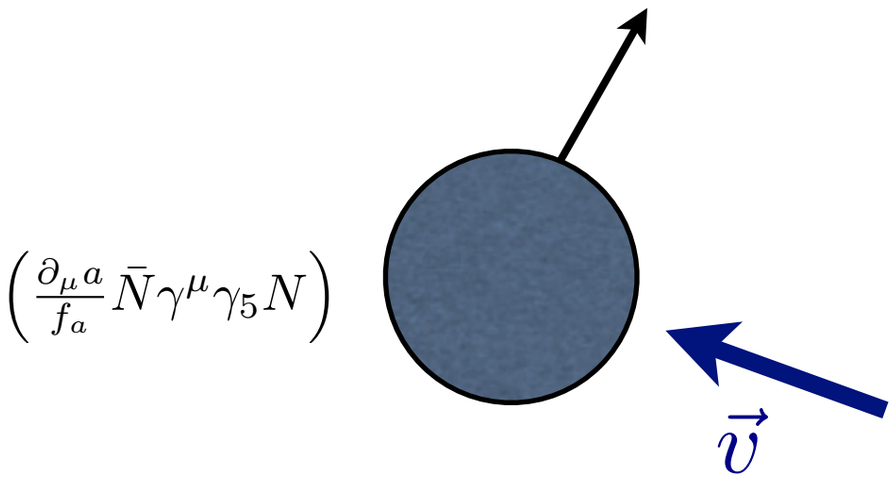

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Measure Spin
Rotation,
detect Axion

QCD Axion

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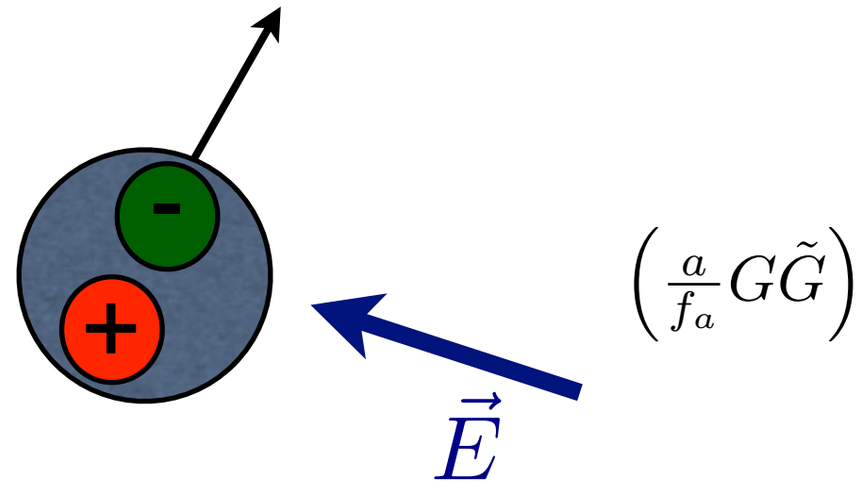
QCD Axion Dark Matter



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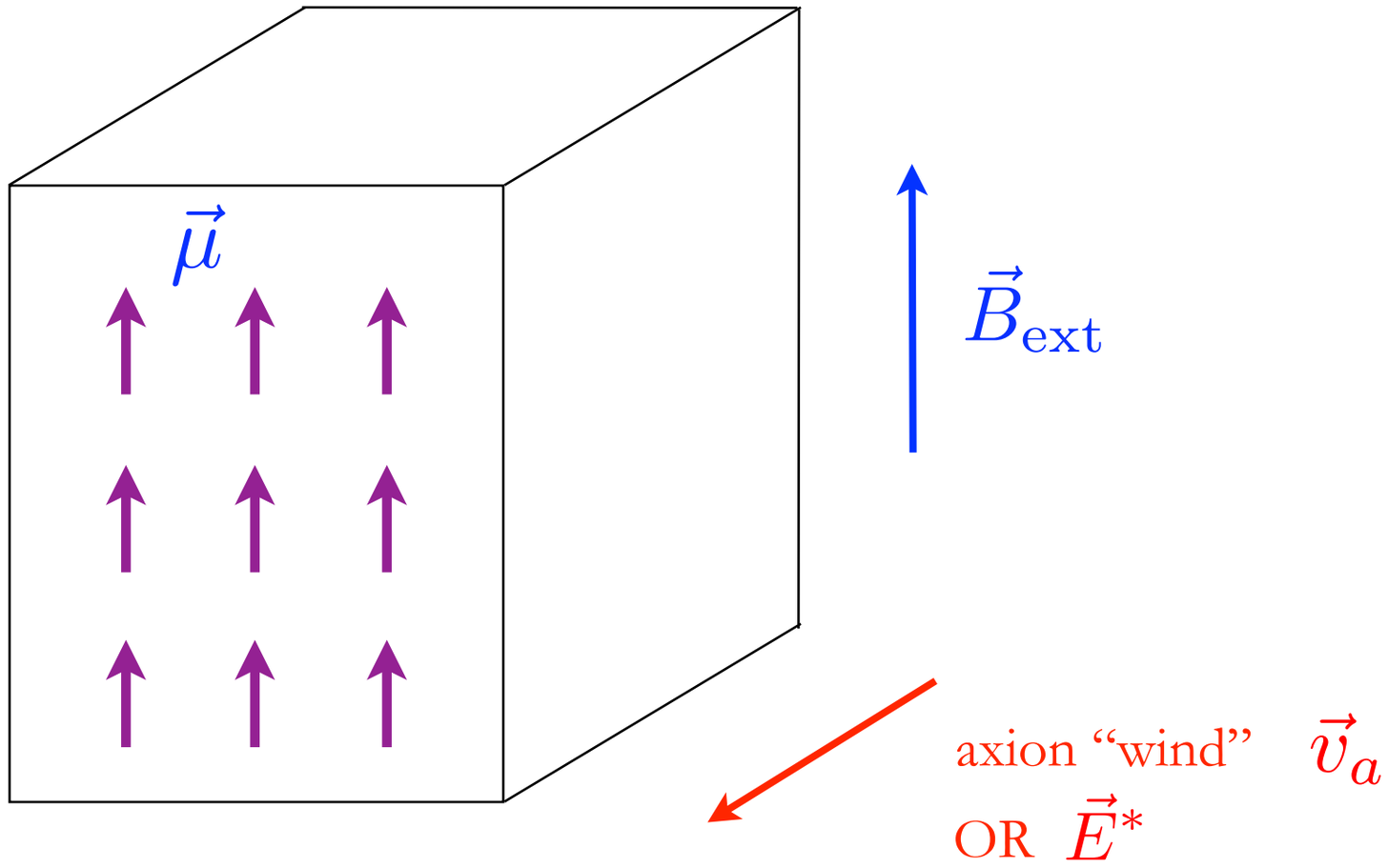
CASPEr

Axion affects physics of nucleus, NMR is sensitive probe



Larmor frequency = axion mass ➔ resonant enhancement

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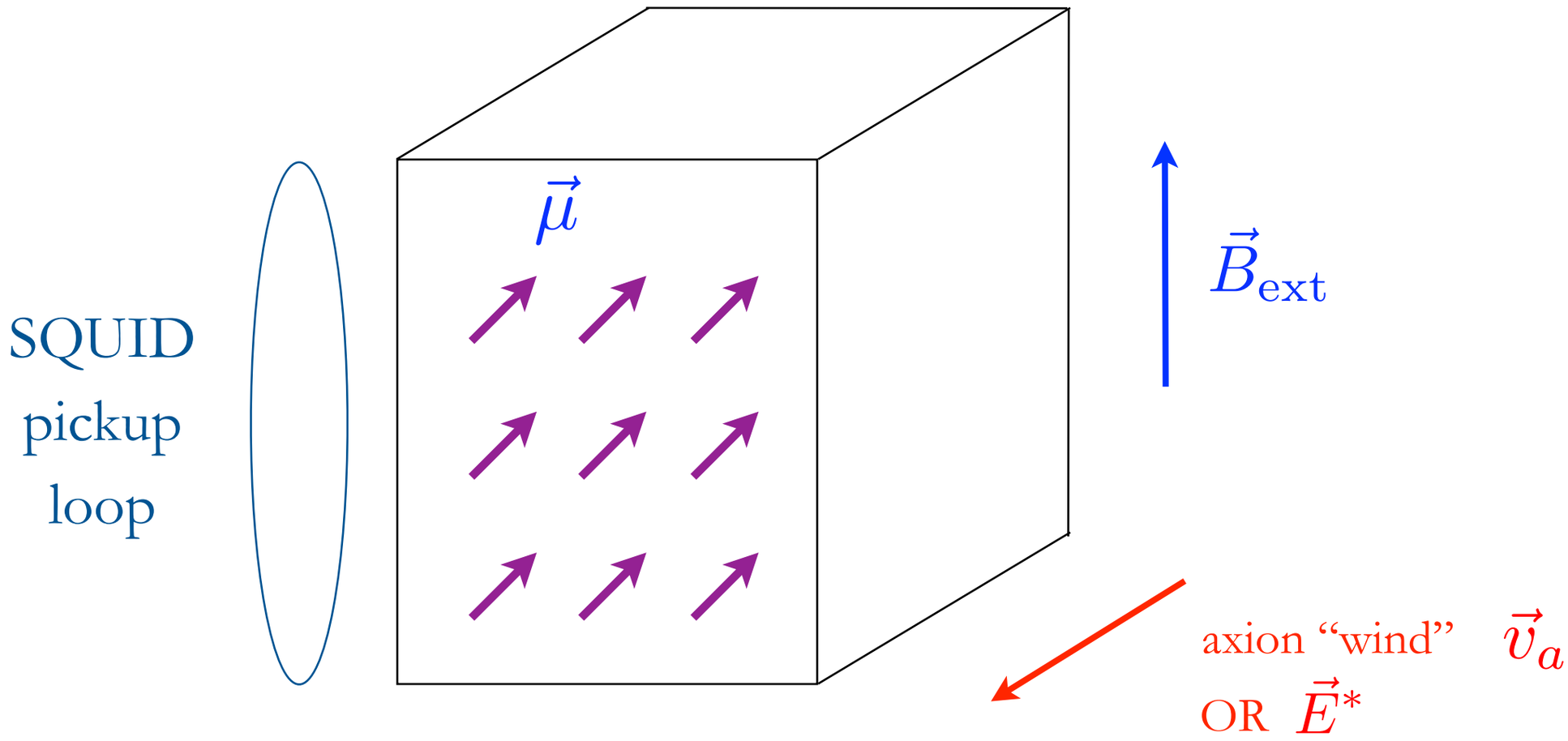


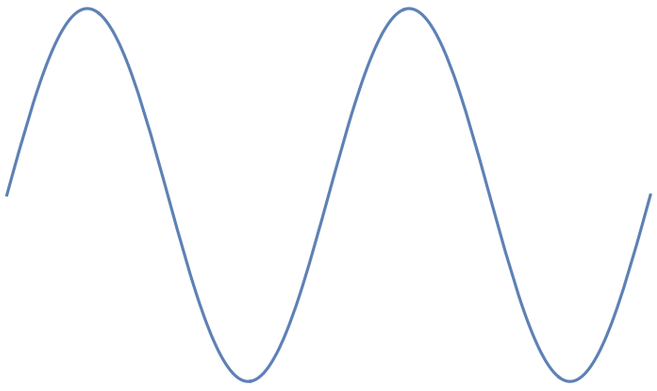
Larmor frequency = axion mass ➔ resonant enhancement

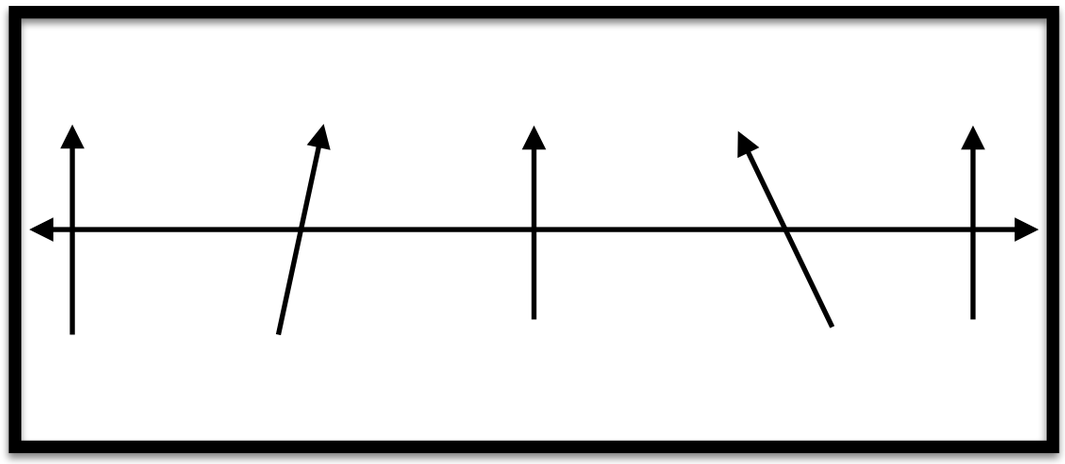
SQUID measures resulting transverse magnetization

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

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

Axion Effects on Photon Spin





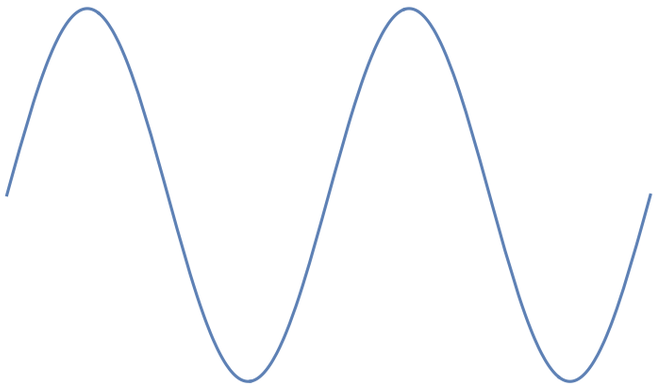
oscillating axion field

Photon Polarization Rotation

Left and Right Circularly Polarized light have different phase velocity

Detect Interferometrically

Axion Effects on Photon Spin



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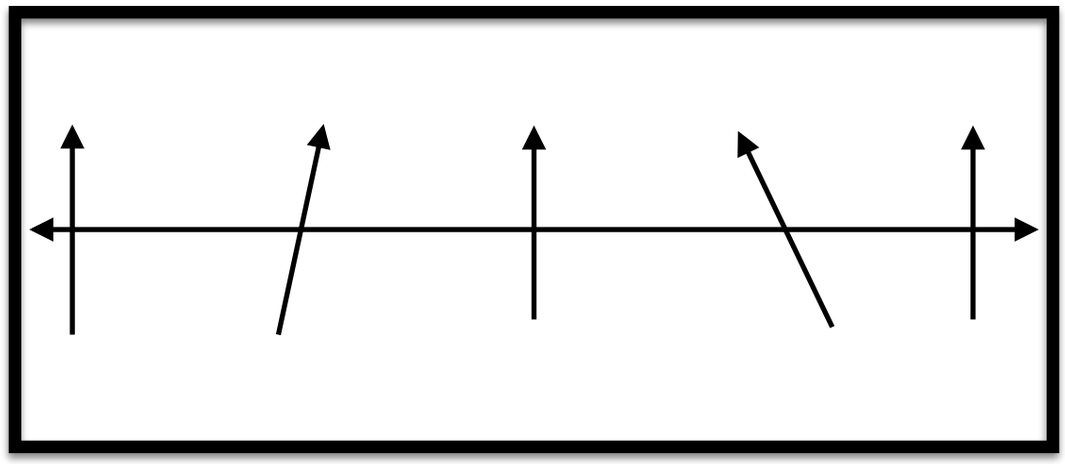

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Electron Spin?

Accelerations

B-L Dark Matter

Anomaly Free Standard Model Current

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

Protons, Neutrons, Electrons and Neutrinos are all charged

Electrically neutral atoms are charged under B-L

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

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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

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

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

Time variation of masses of fundamental particles

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

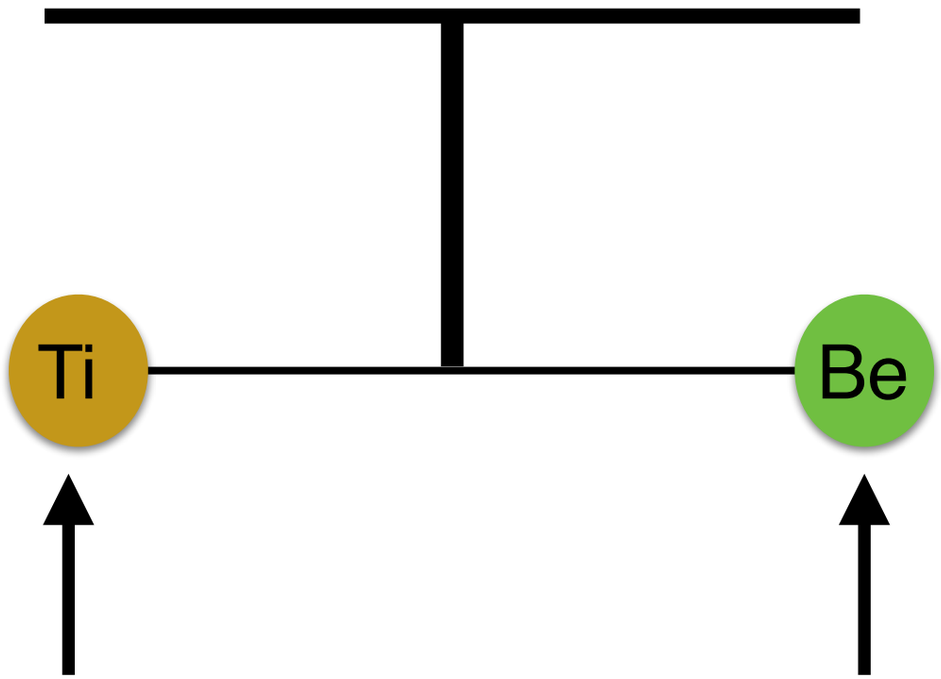
Force violates equivalence principle. Time dependent equivalence principle violation!

Detection Options

Measure relative acceleration between different elements/isotopes.

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

Torsion Balance

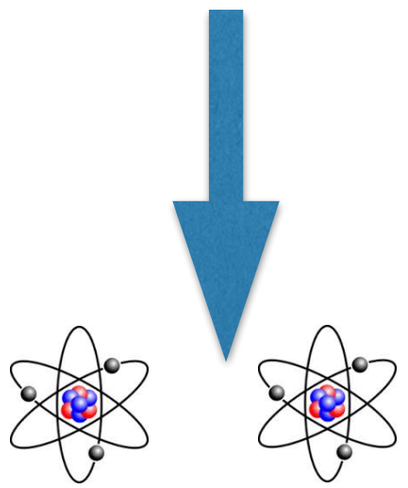


Force from dark matter causes torsion balance to rotate

Measure angle, optical lever arm enhancement

Atom Interferometer

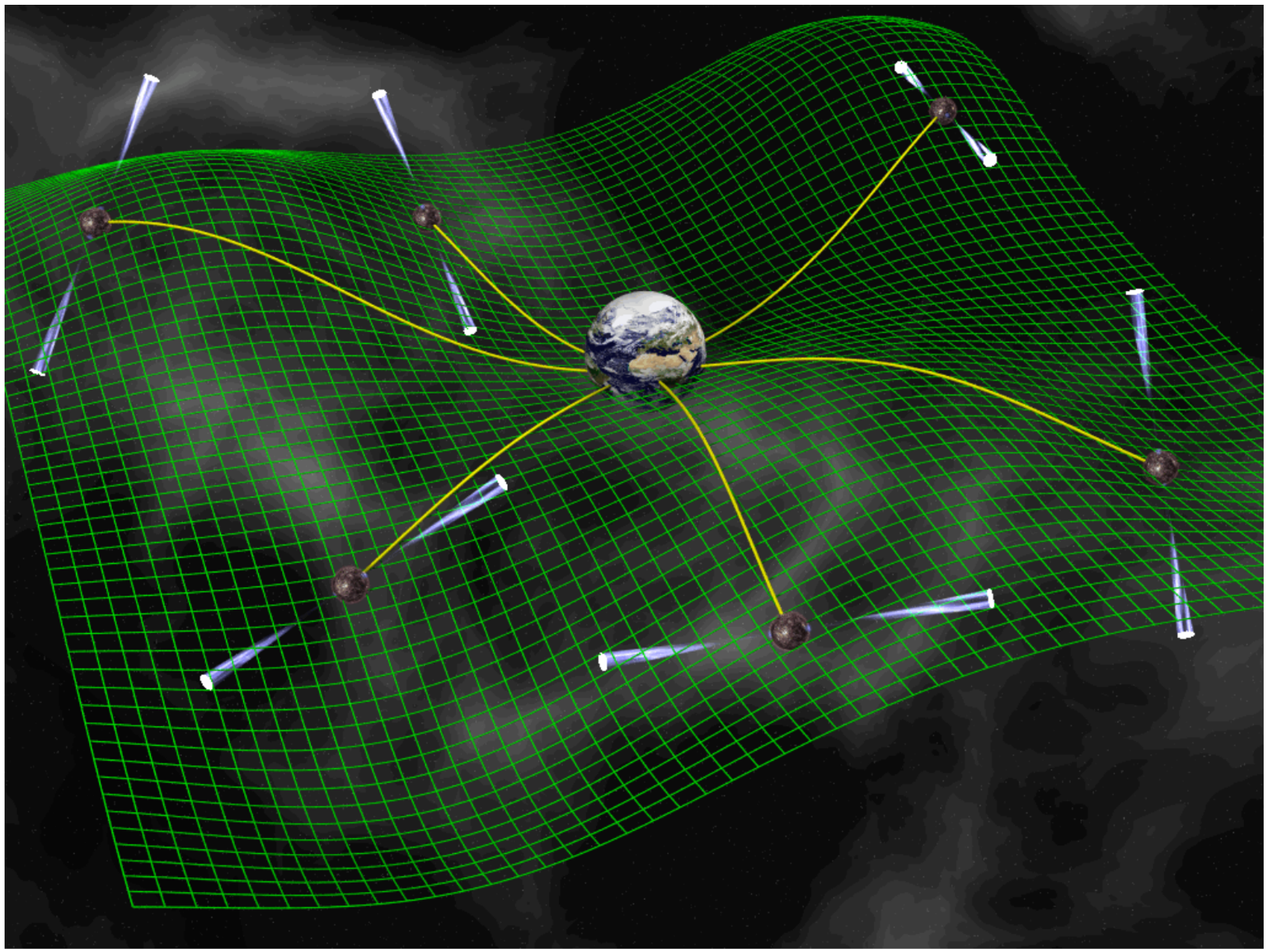
Dark Matter



Differential free fall acceleration

Stanford Facility

Pulsar Timing Arrays

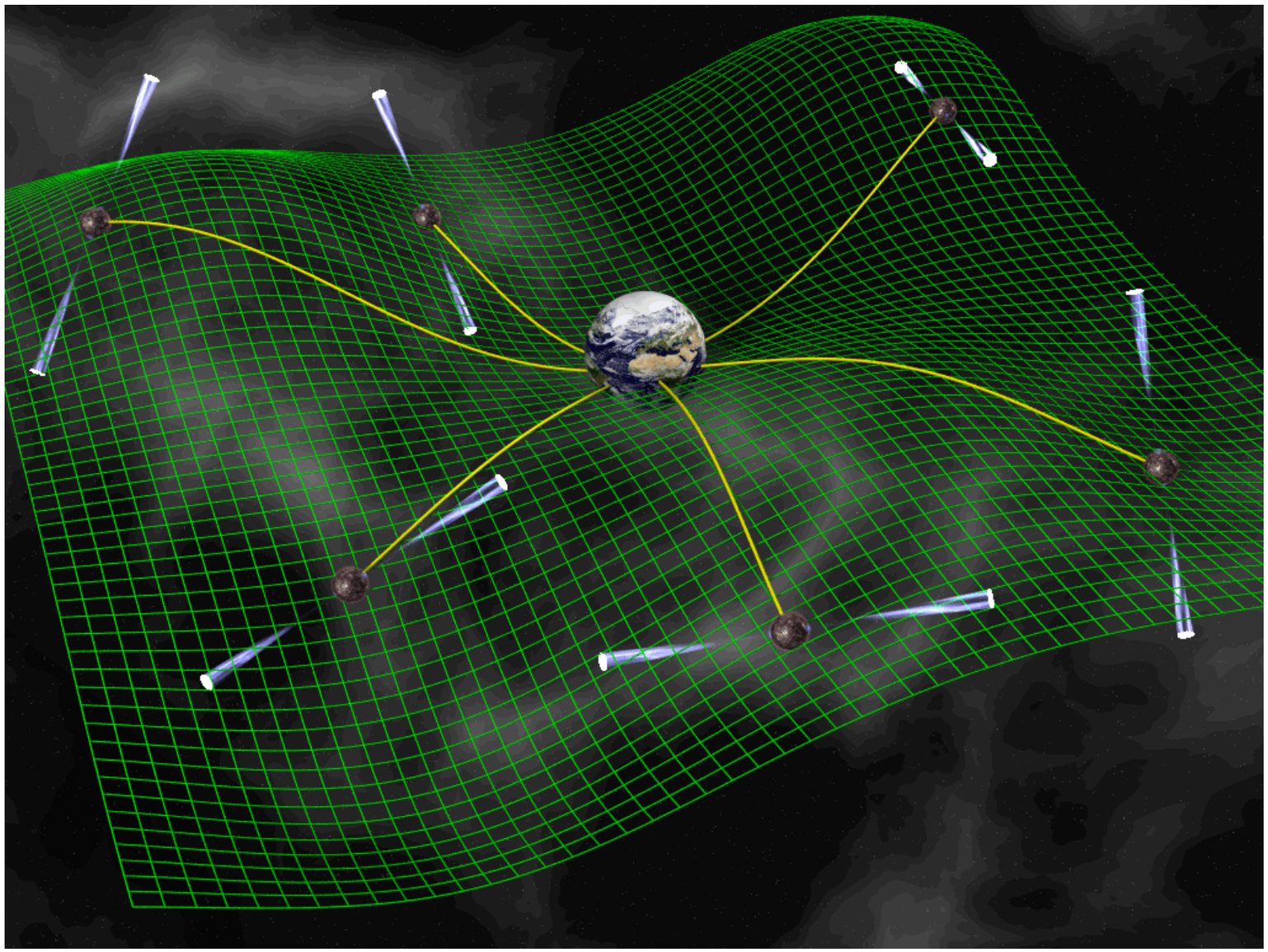


Pulsars are known to have stable rotation - can be used as clocks

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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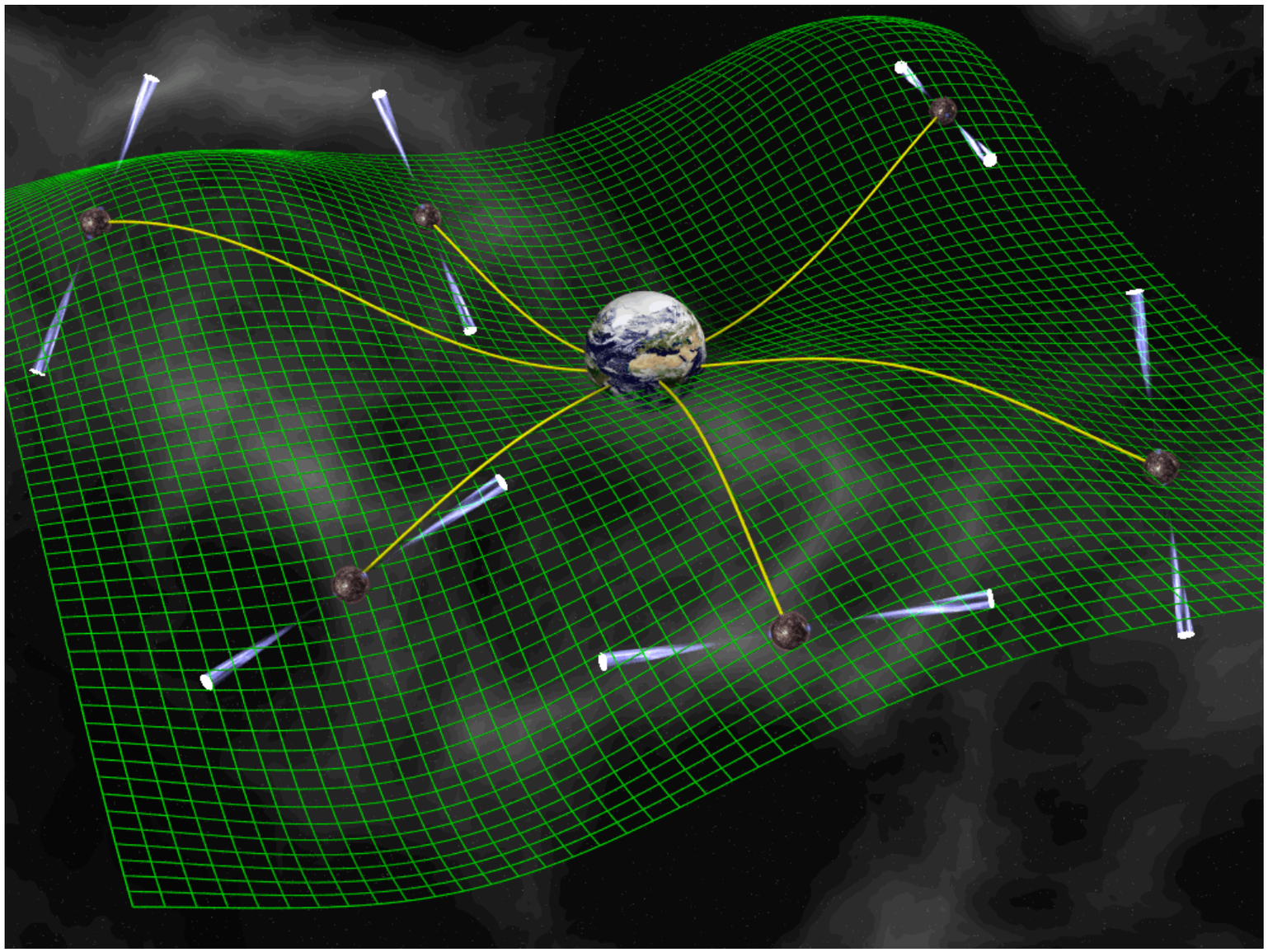

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Relaxion changes electron mass at location of Earth - changes clock comparison

Conclusions

WIMPs

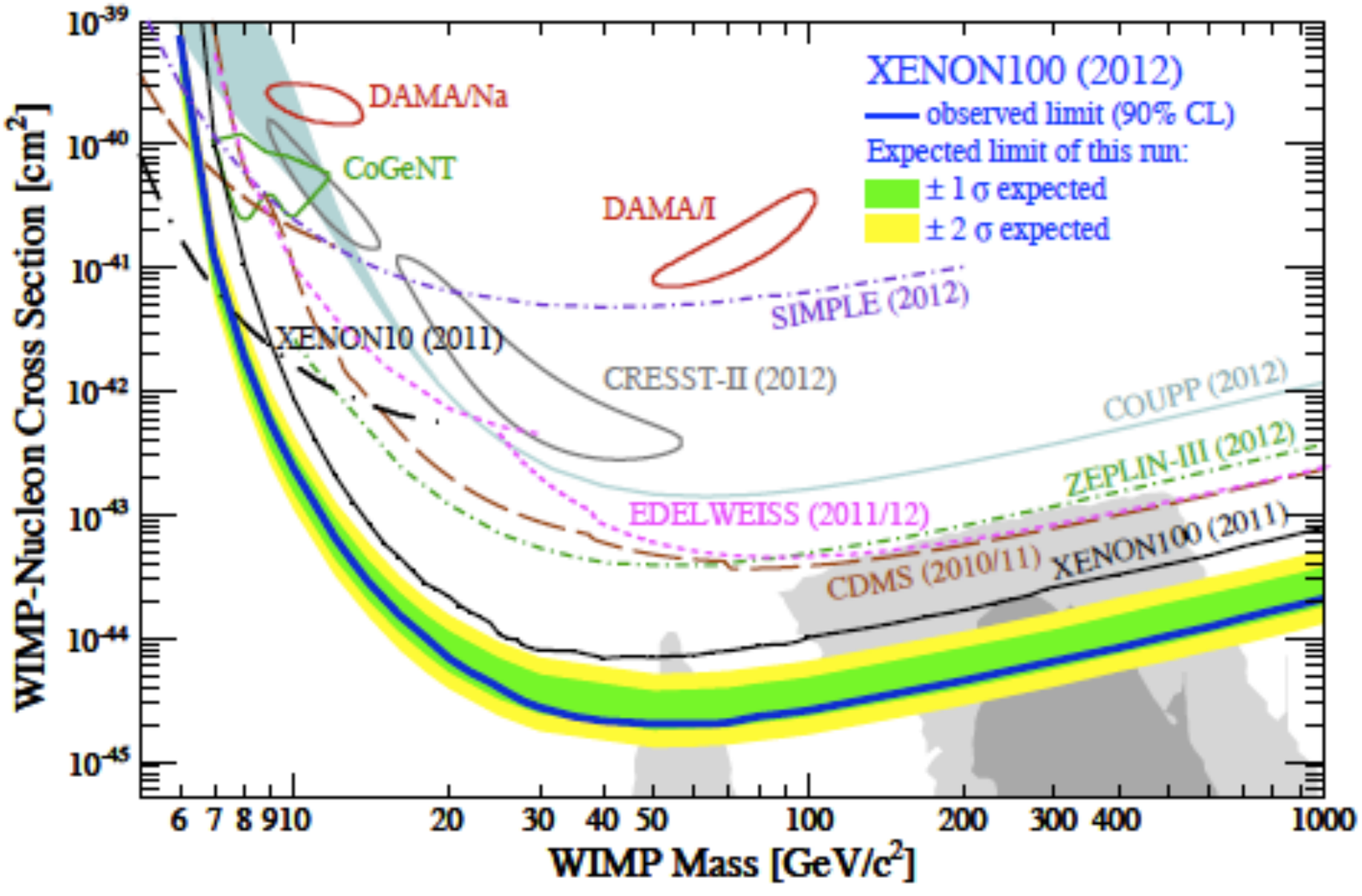
Scalable

Goodman & Witten (1985): $\sigma \sim 10^{-38}\,\mathrm{cm}^2$

Z

h

W



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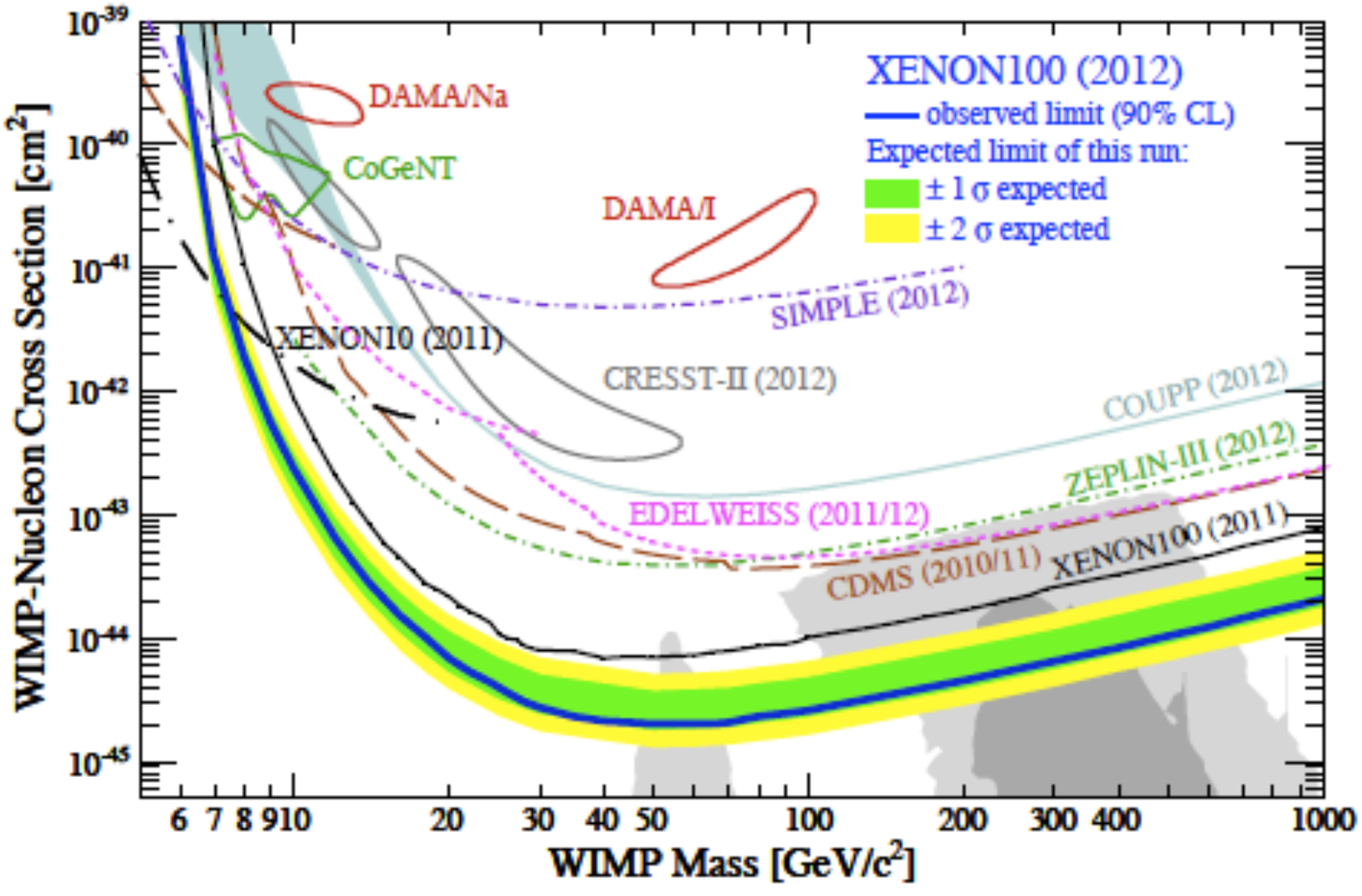
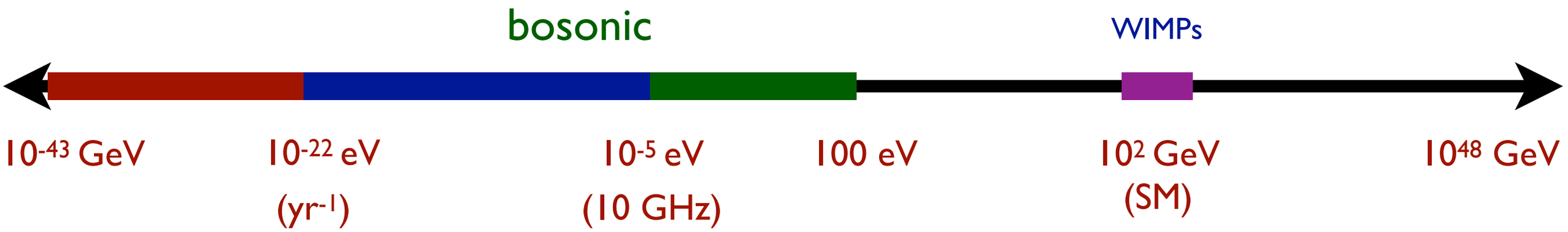


Similar approach seems possible in searching for oscillating fields

The Dark Matter Landscape



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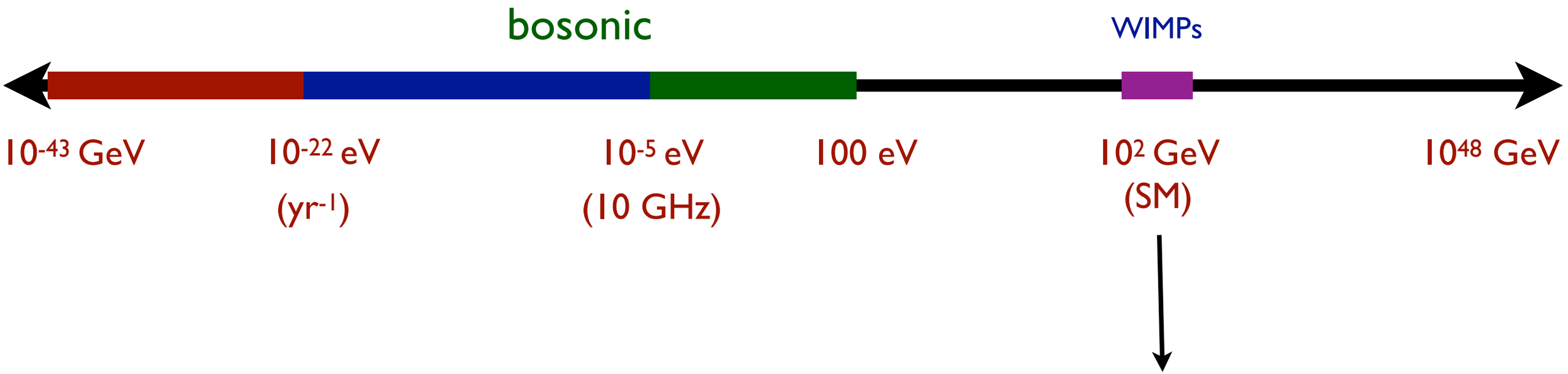
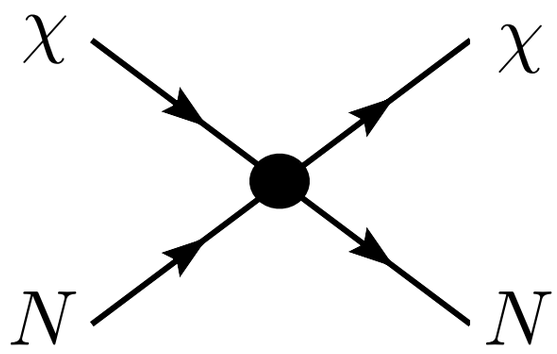


Search for single, hard particle scattering



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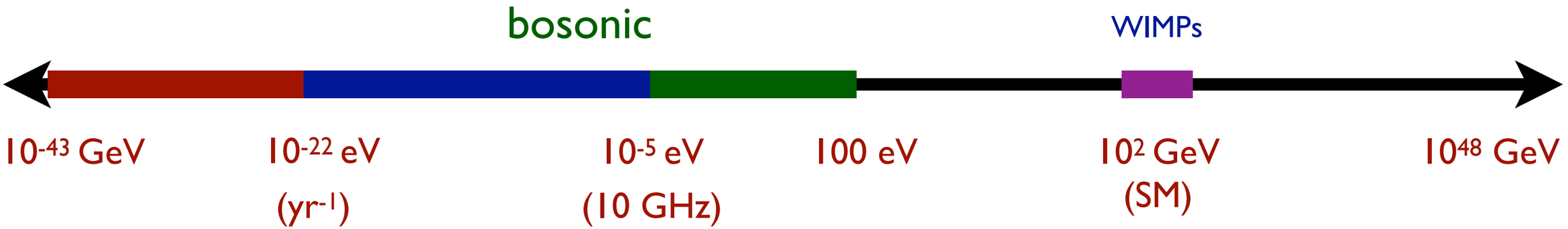


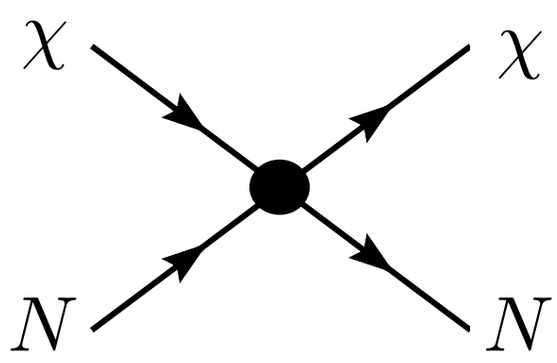
Time dependent moments of coherent classical field

Interactions restricted by symmetry

Frequencies can naturally be lab accessible (nHz - 10 GHz)

Lab-scale experiments

Search for single, hard particle scattering



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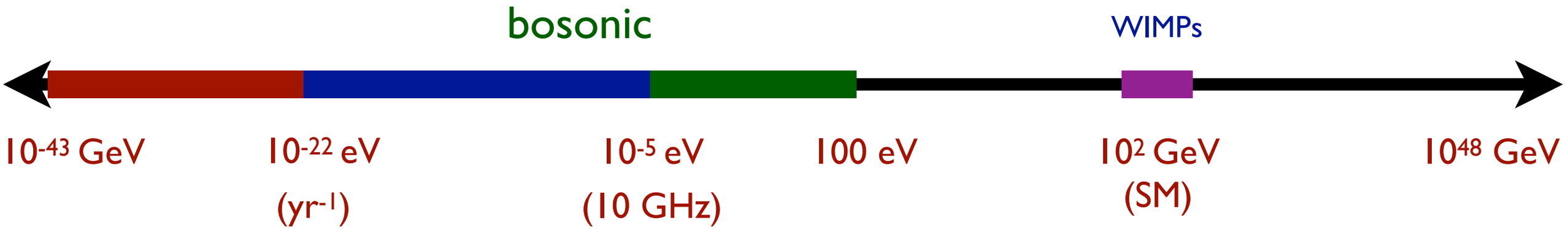

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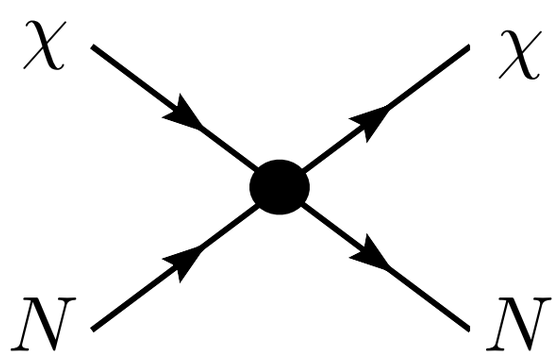

How do we cover full range?
What about Dark Energy?