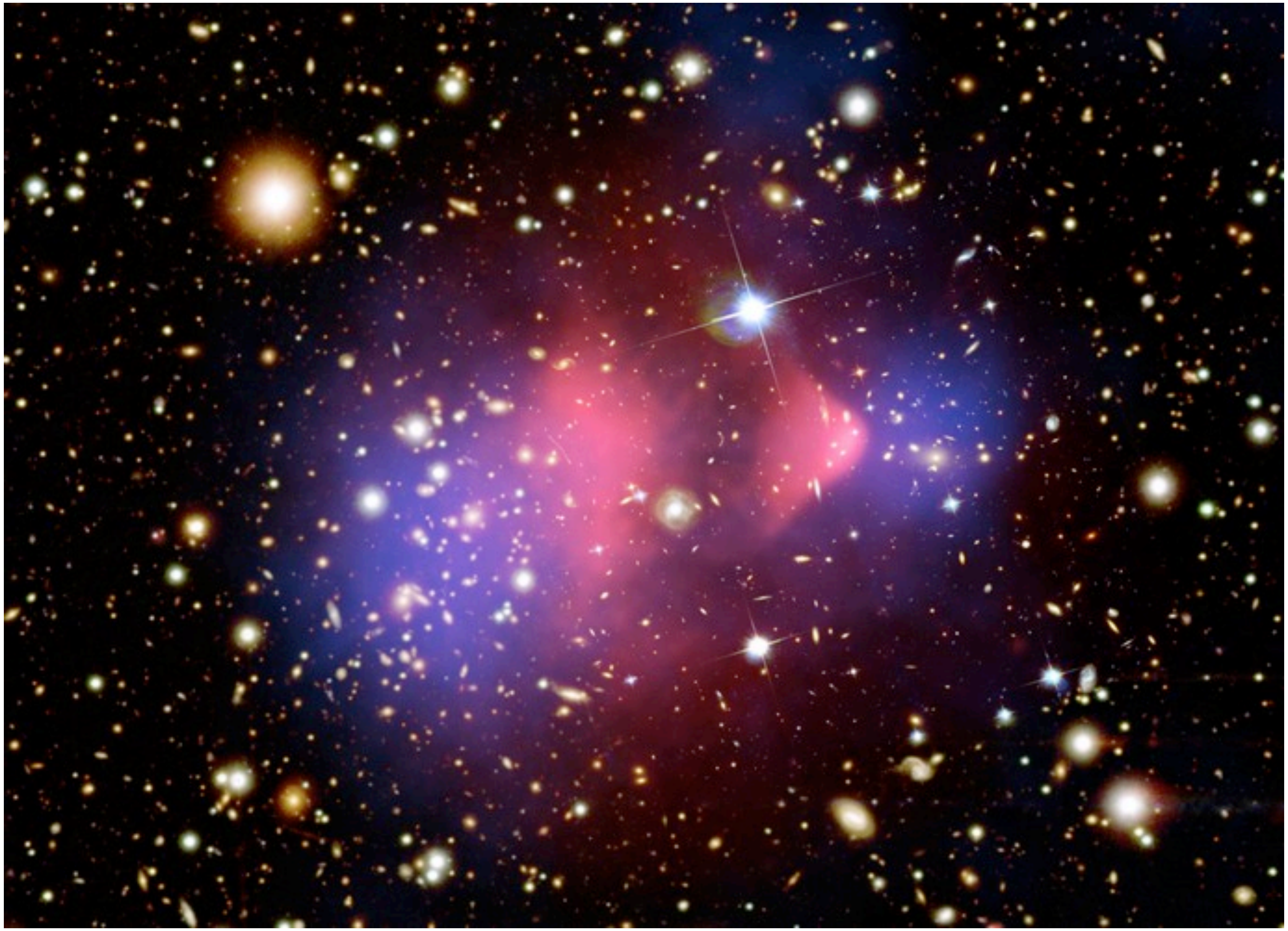
Detecting Ultra-light Dark Matter with Precision Metrology

Surjeet Rajendran,
UC Berkeley

Dark Matter

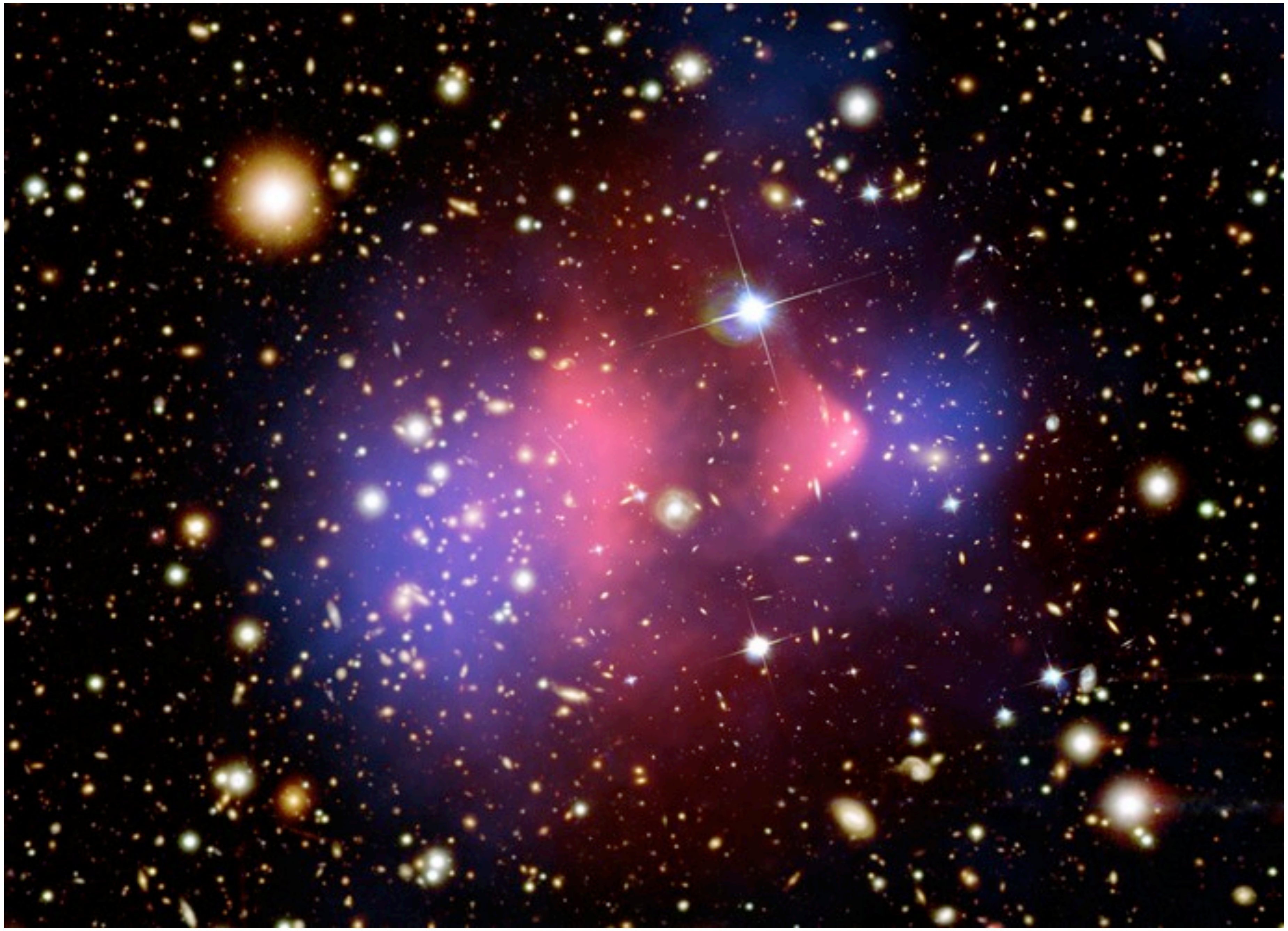
Dark Matter



A New Particle

Non gravitational interactions?

Dark Matter



A New Particle

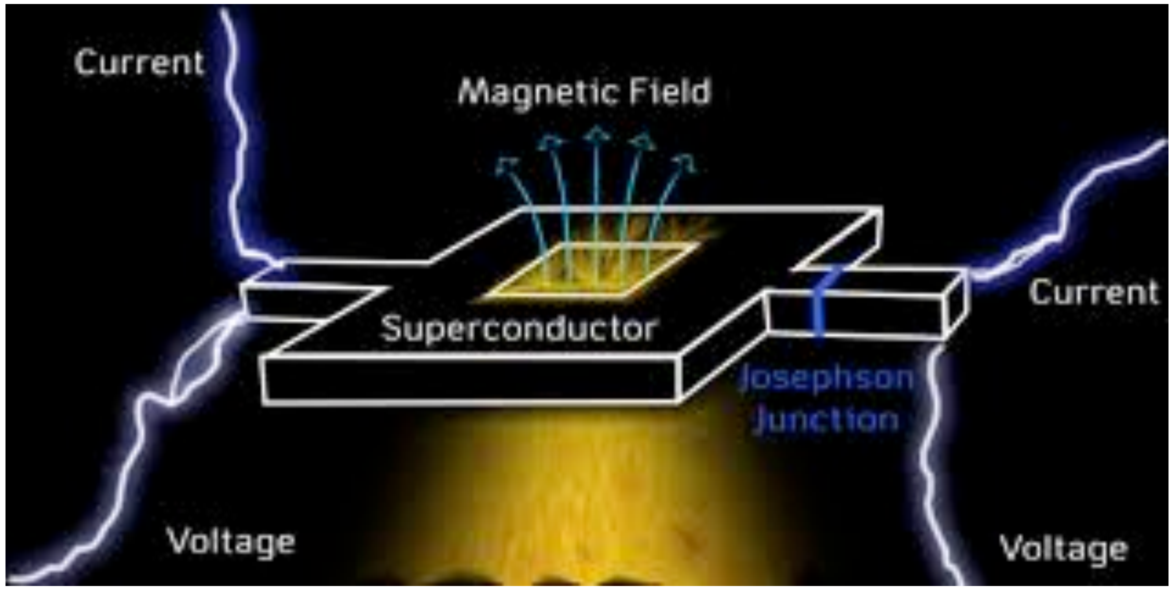
Non gravitational interactions?

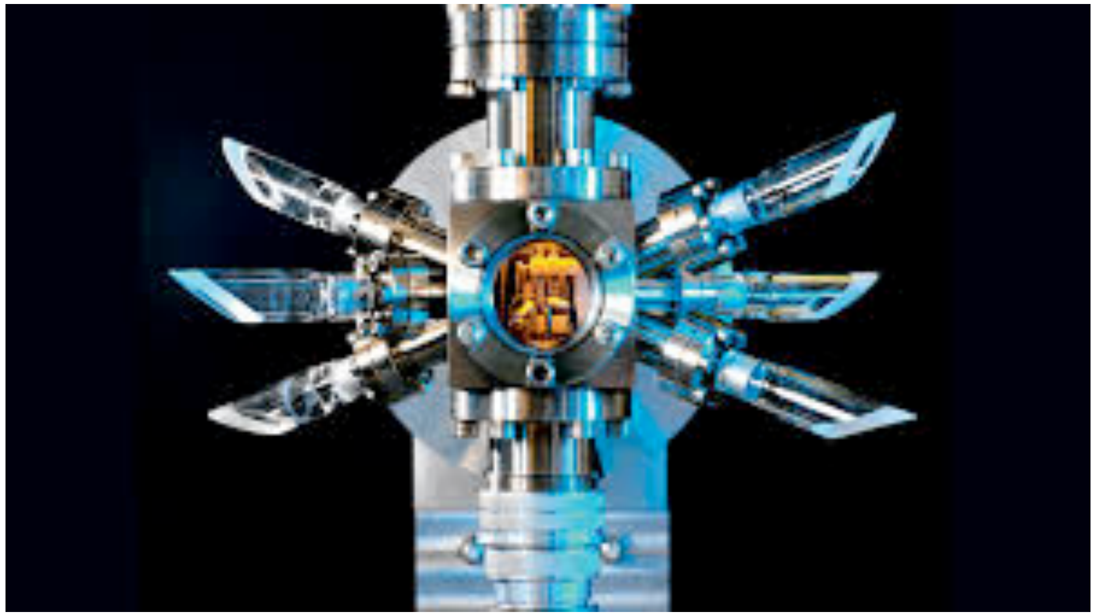
How do we detect them?

Weak effects. Need high precision

Precision Instruments

Impressive developments in the past two decades





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

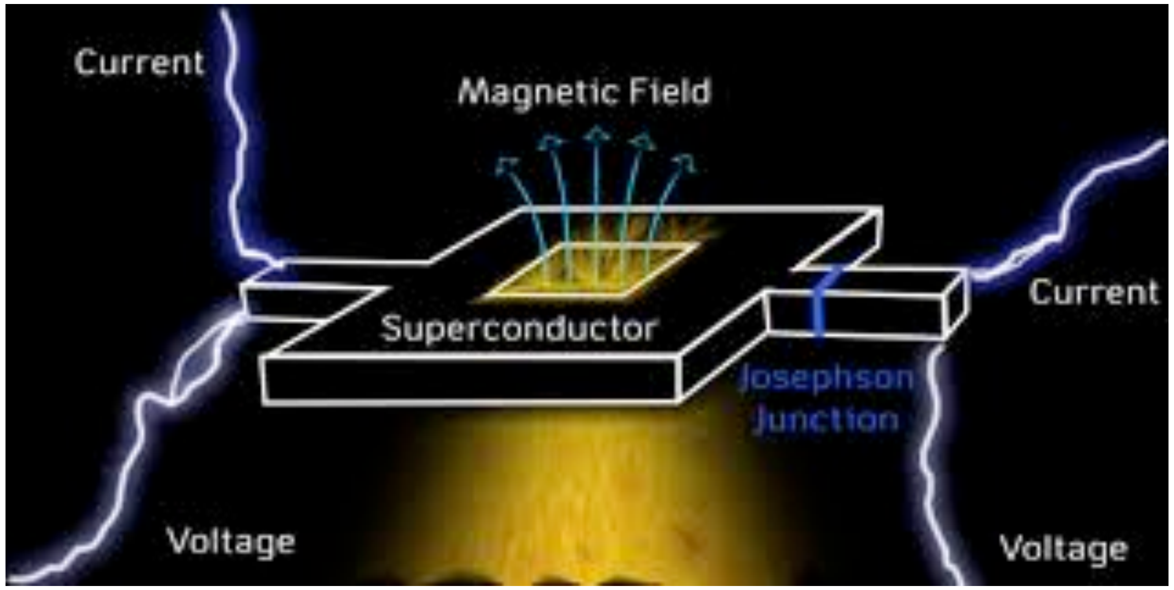
(SQUIDs, atomic magnetometers)

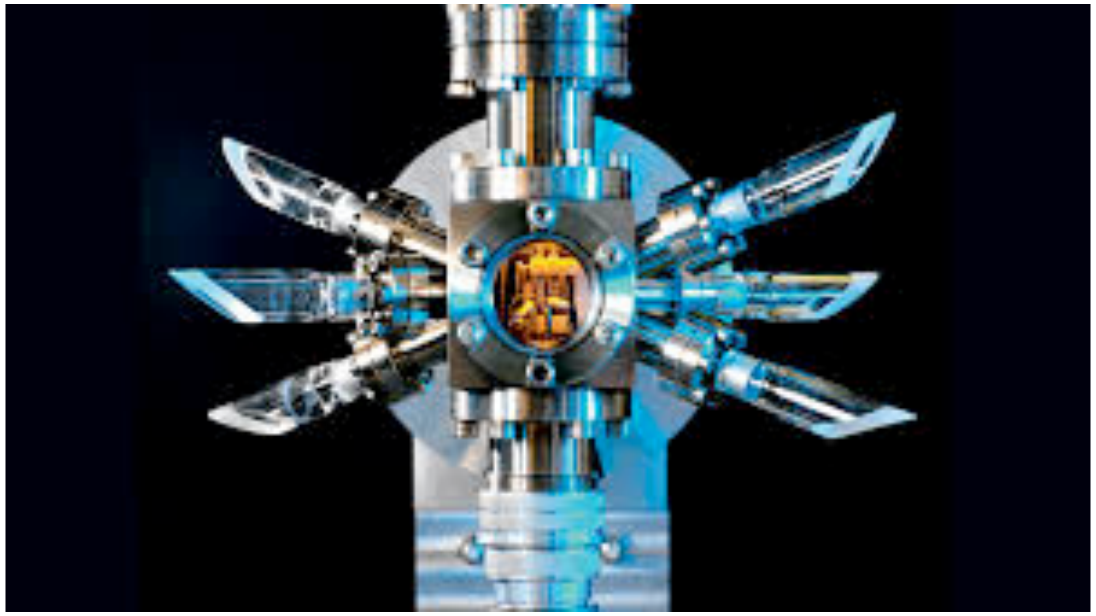
Accelerometers $\lesssim 10^{-13} \frac{\mathrm{g}}{\sqrt{\mathrm{Hz}}}$

(atom and optical interferometers)

Precision Instruments

Impressive developments in the past two decades





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

(SQUIDs, atomic magnetometers)

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

(atom and optical interferometers)

Rapid technological advancements

Use to detect new physics?

Outline

1. Brief Theory Overview

2. Axion Detection with Nuclear Magnetic Resonance

3. Dark Photon Detection with Radios

4. B-L Gauge Boson with Accelerometers

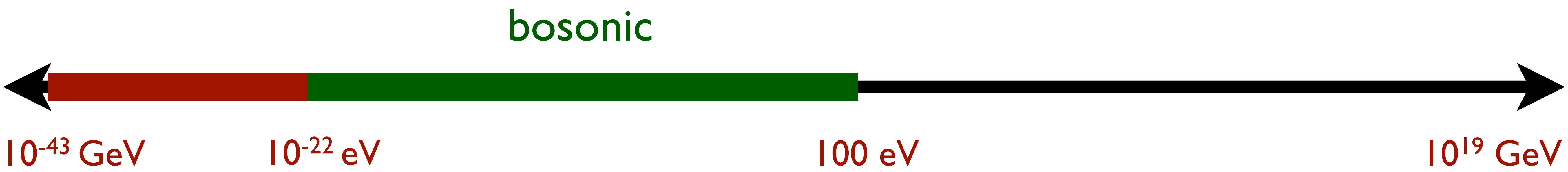
5. Conclusions

The Dark Matter Landscape

10^{-43} GeV

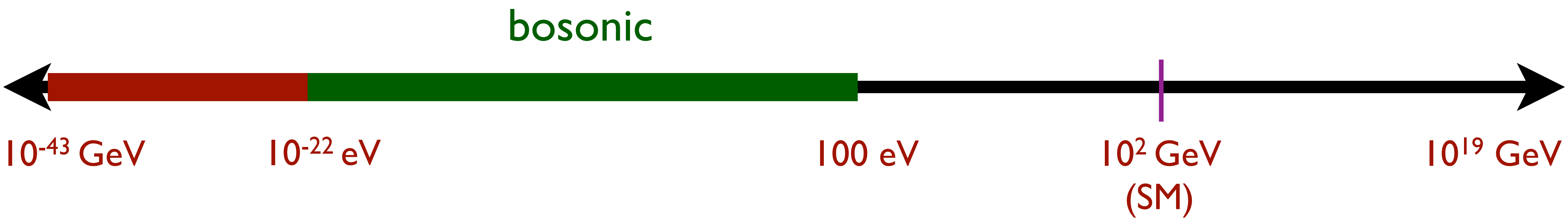
10^{19} GeV

The Dark Matter Landscape



Fit in galaxy

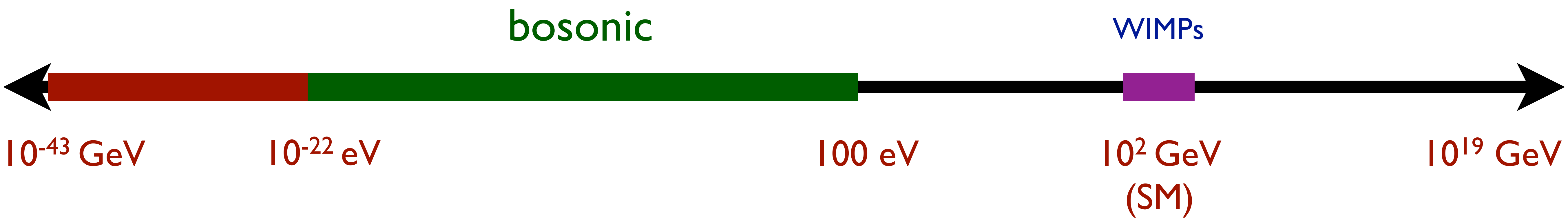
The Dark Matter Landscape



Fit in galaxy

Standard Model scale ~ 100 GeV

The Dark Matter Landscape

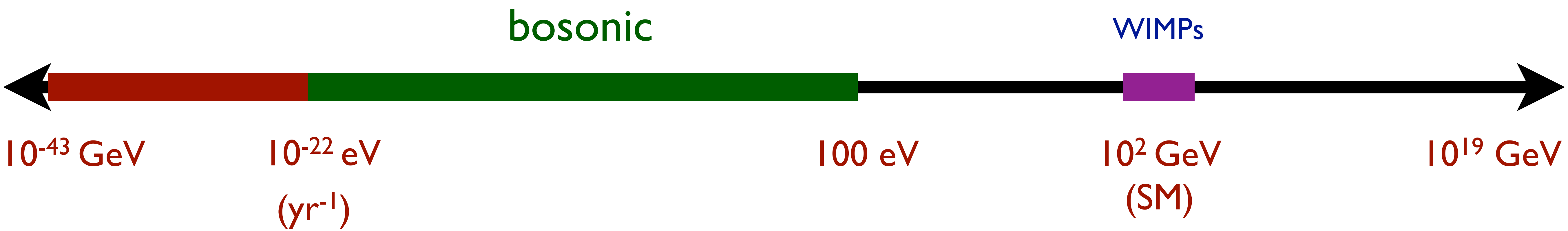


Fit in galaxy

Standard Model scale ~ 100 GeV

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

The Dark Matter Landscape



Fit in galaxy

Standard Model scale ~ 100 GeV

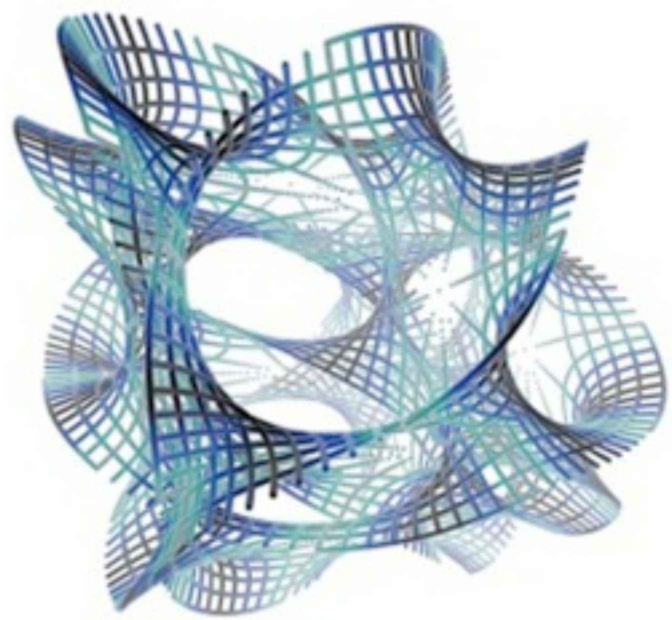
One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)

Other Generic Candidates: Axions, Massive Vector Bosons

Axions From High Energy Physics

Easy to generate axions from high energy theories

have a global symmetry broken at a high scale f_a

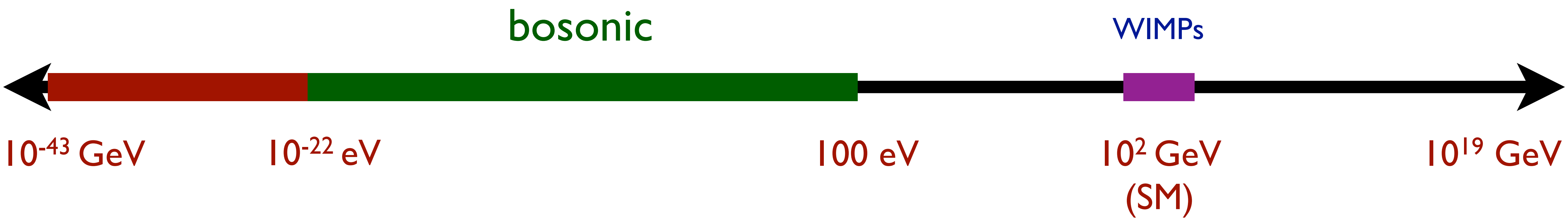


string theory or extra dimensions naturally
create axions from non-trivial topology

naturally gives large $f_a \sim$ GUT (10^{16} GeV) or Planck (10^{19} GeV) scales

Can also similarly get light vector bosons

The Dark Matter Landscape



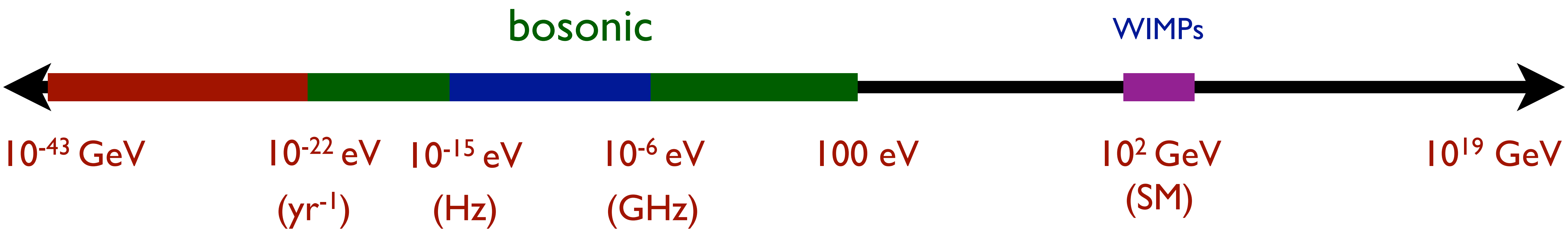
Fit in galaxy

Standard Model scale ~ 100 GeV

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

Other Generic Candidates: Axions, Massive Vector Bosons

The Dark Matter Landscape



Fit in galaxy

Standard Model scale ~ 100 GeV

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

Other Generic Candidates: Axions, Massive Vector Bosons

How do we search for them?
This Talk: Bosons between GHz - Hz
Range includes popular candidates such as the QCD axion

Bosonic Dark Matter

Photons

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

Detect Photon by measuring time varying field

Bosonic Dark Matter

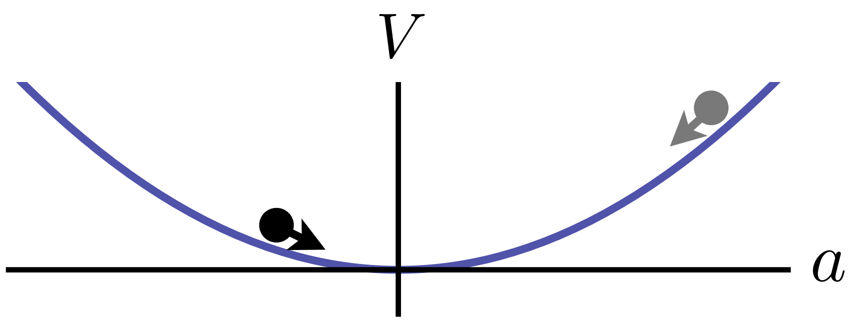
Photons

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

Detect Photon by measuring time varying field

Dark Bosons

Early Universe:
Misalignment Mechanism



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

Spatially uniform, oscillating field

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

Bosonic Dark Matter

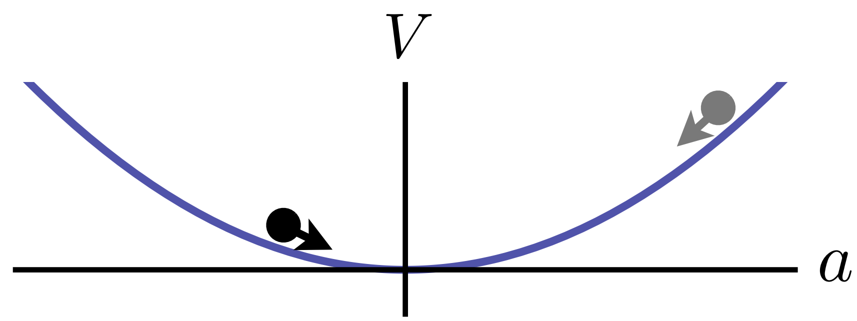
Photons

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

Detect Photon by measuring time varying field

Dark Bosons

Early Universe: Misalignment Mechanism

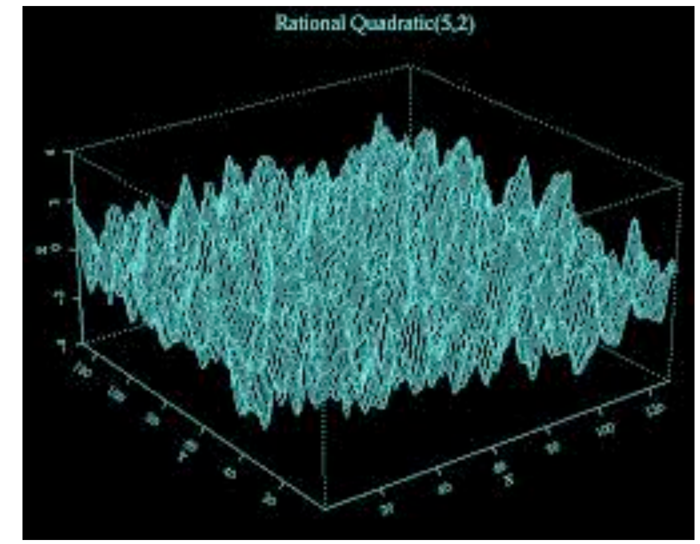


$$a(t) \sim a_0 \cos(m_a t)$$

Spatially uniform, oscillating field

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

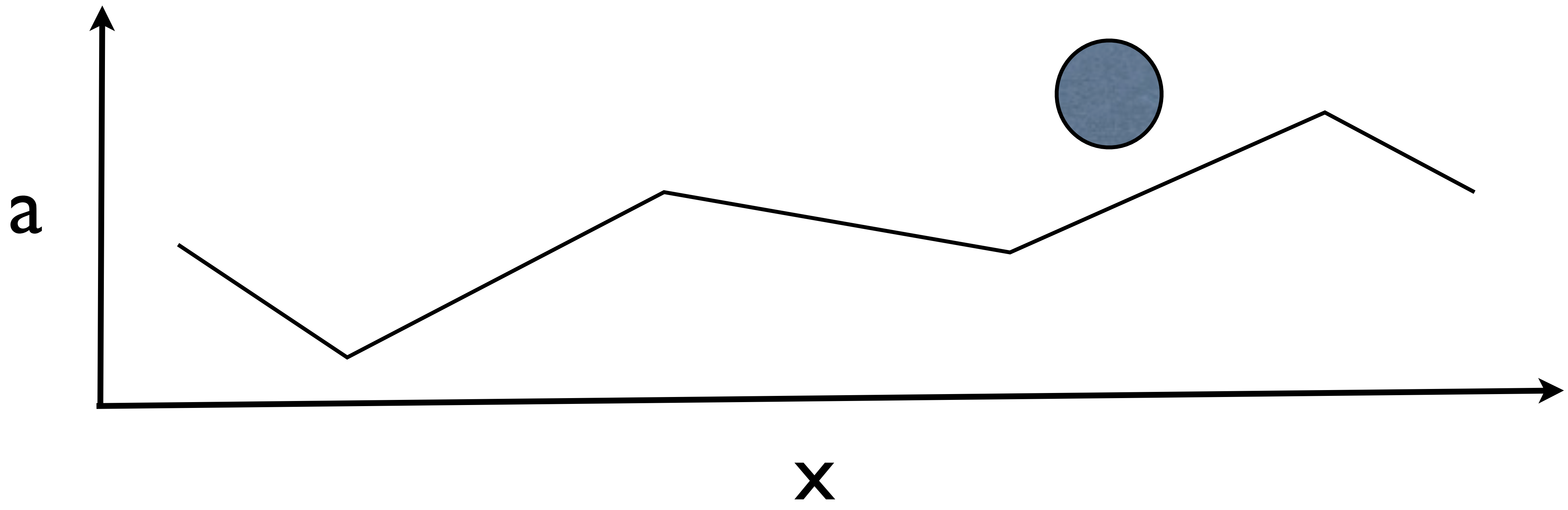
Today: Random Field



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

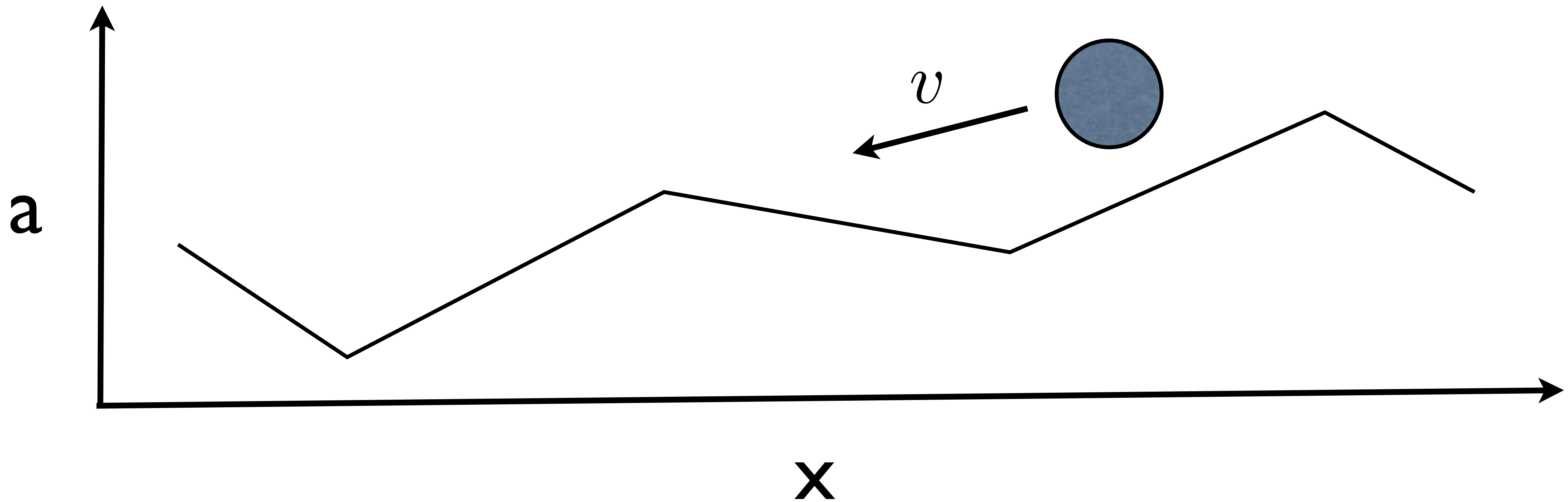
Temporal Coherence

Temporal Coherence



Field Homogenous over ~ $1/(m_a\ v)$

Temporal Coherence



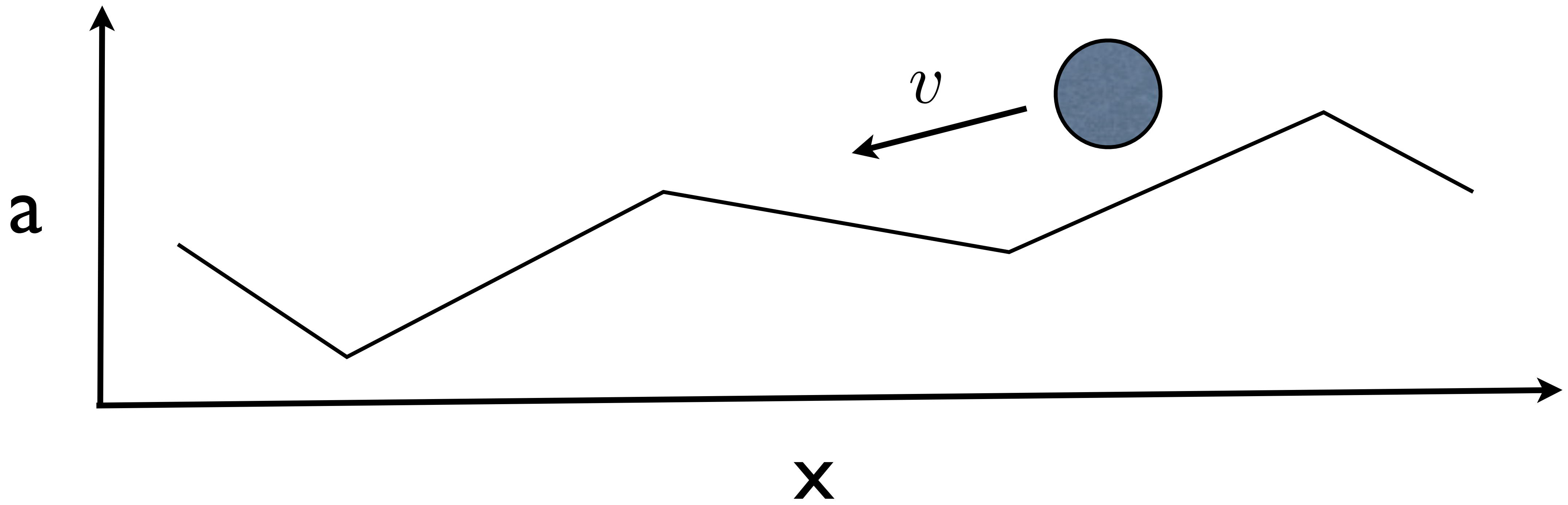
Field Homogenous over ~ $1/(m_a\ v)$

$v \sim 10^{-3}$

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

Random over longer timescales

Temporal Coherence



Field Homogenous over ~ $1/(m_a\, v)$

$v \sim 10^{-3}$

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

Random over longer timescales

Or: power in the field is spread by kinetic energy ~ $m_a v^2$

Bosonic Dark Matter

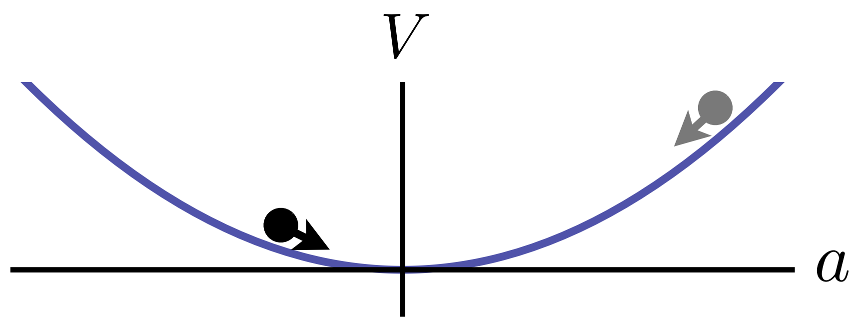
Photons

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

Detect Photon by measuring time varying field

Dark Bosons

Early Universe: Misalignment Mechanism

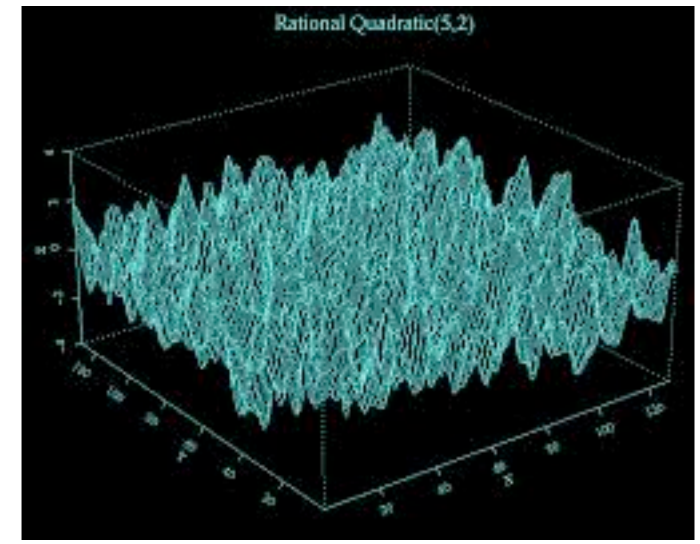


$$a(t) \sim a_0 \cos(m_a t)$$

Spatially uniform, oscillating field

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

Today: Random Field



Correlation length
~ $1/(m_a v)$

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

Bosonic Dark Matter

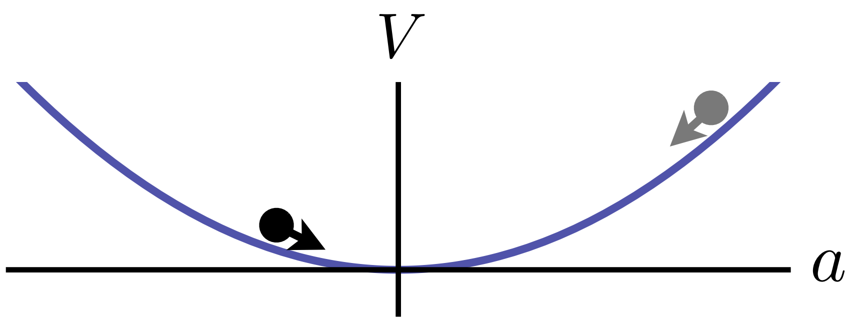
Photons

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

Detect Photon by measuring time varying field

Dark Bosons

Early Universe: Misalignment Mechanism

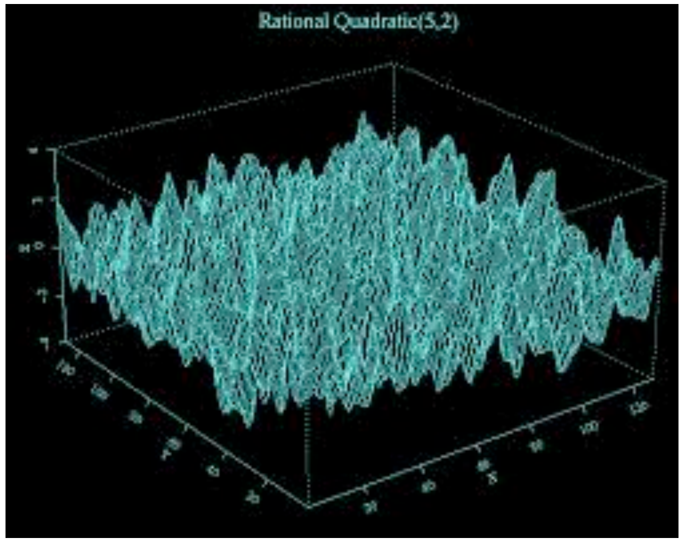


$$a(t) \sim a_0 \cos(m_a t)$$

Spatially uniform, oscillating field

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

Today: Random Field



Correlation length
~ $1/(m_a v)$

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

Detect effects of oscillating dark matter field

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

What kind of Bosons?

Naturalness. Structure set by symmetries.

What kind of Bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

What kind of Bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

Electromagnetism

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

Nuclear Force

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

QCD Axion

Nuclear Spin

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

General Axions

What kind of Bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

Electromagnetism

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

Nuclear Force

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

QCD Axion

Nuclear Spin

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

General Axions

Spin 1

Anomaly free Standard Model couplings

What kind of Bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

Electromagnetism

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

Nuclear Force

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

QCD Axion

Nuclear Spin

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

General Axions

Spin 1

Anomaly free Standard Model couplings

Nuclear Spin

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

Dipole moment

Electro-magnetism

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

Kinetic Mixing

Nucleon Current

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

B-L

What kind of Bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

- Electromagnetism $\left(\frac{a}{f_a} F\tilde{F}\right)$
- Nuclear Force $\left(\frac{a}{f_a} G\tilde{G}\right)$ QCD Axion
- Nuclear Spin $\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu \gamma_5 N\right)$ General Axions

Spin 1

Anomaly free Standard Model couplings

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

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

$$\text{Hz} \lesssim m_a \lesssim \text{GHz}$$

What kind of Bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

Electromagnetism

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

Current Searches

(m_a ~ GHz)

Nuclear Force

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

QCD Axion

Nuclear Spin

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

General Axions

Spin 1

Anomaly free Standard Model couplings

Nuclear Spin

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

Dipole moment

Electro-magnetism

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

Kinetic Mixing

Nucleon Current

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

B-L

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

$$\text{Hz} \lesssim m_a \lesssim \text{GHz}$$

What kind of Bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

Electromagnetism

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

Current Searches

(m_a ~ GHz)

Nuclear Force

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

QCD Axion

Nuclear Spin

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

General Axions

Spin 1

Anomaly free Standard Model couplings

Nuclear Spin

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

Dipole moment

Electro-magnetism

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

Kinetic Mixing

Nucleon Current

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

B-L

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

This Talk

$\boxed{\mathrm{Hz} \lesssim m_a \lesssim \mathrm{GHz}}$

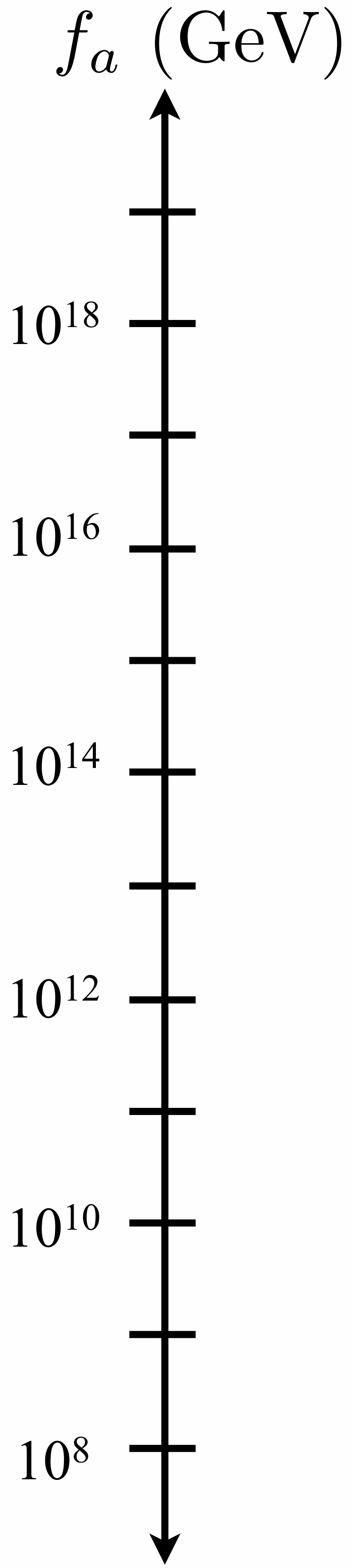
Cosmic Axion Spin Precession Experiment (CASPEr)

with

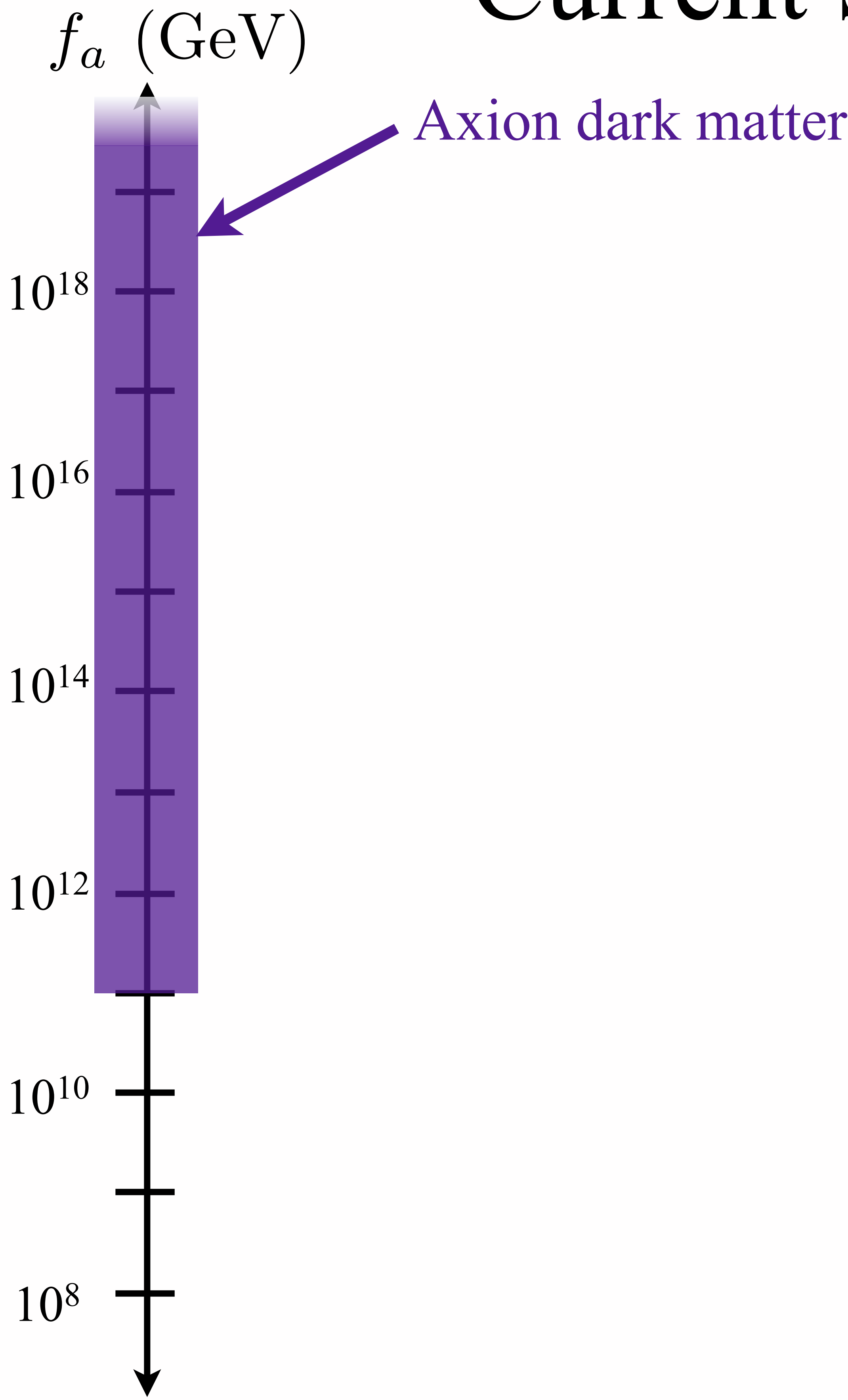
Dmitry Budker
Peter Graham
Micah Ledbetter
Alex Sushkov

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

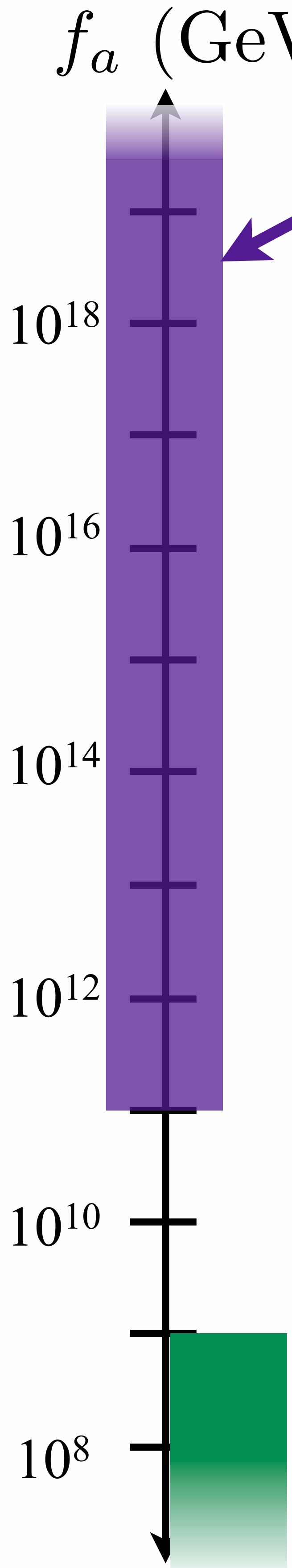
Current Searches: ADMX



Current Searches: ADMX



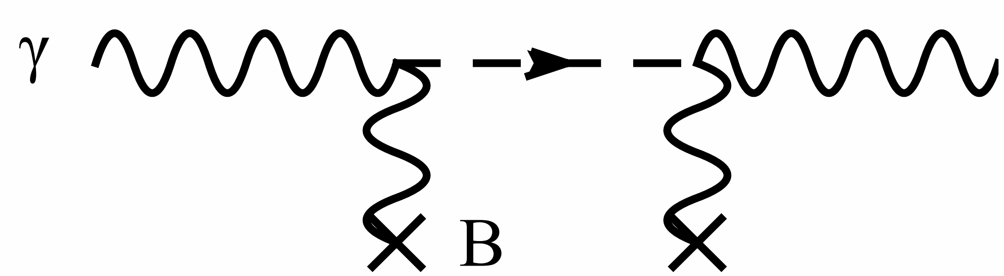
Current Searches: ADMX



Axion dark matter

in most models: $\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a}\vec{E}\cdot\vec{B}$

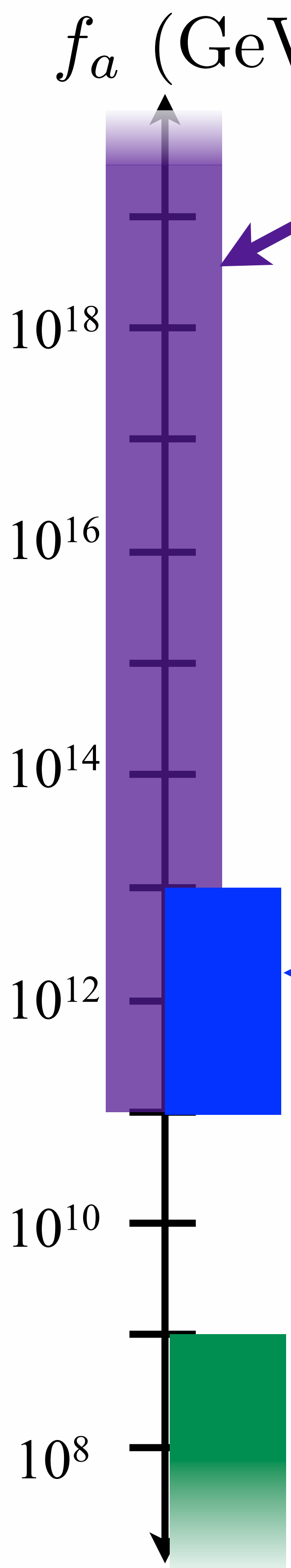
laser experiments:



$\propto \frac{1}{f_a^4}$

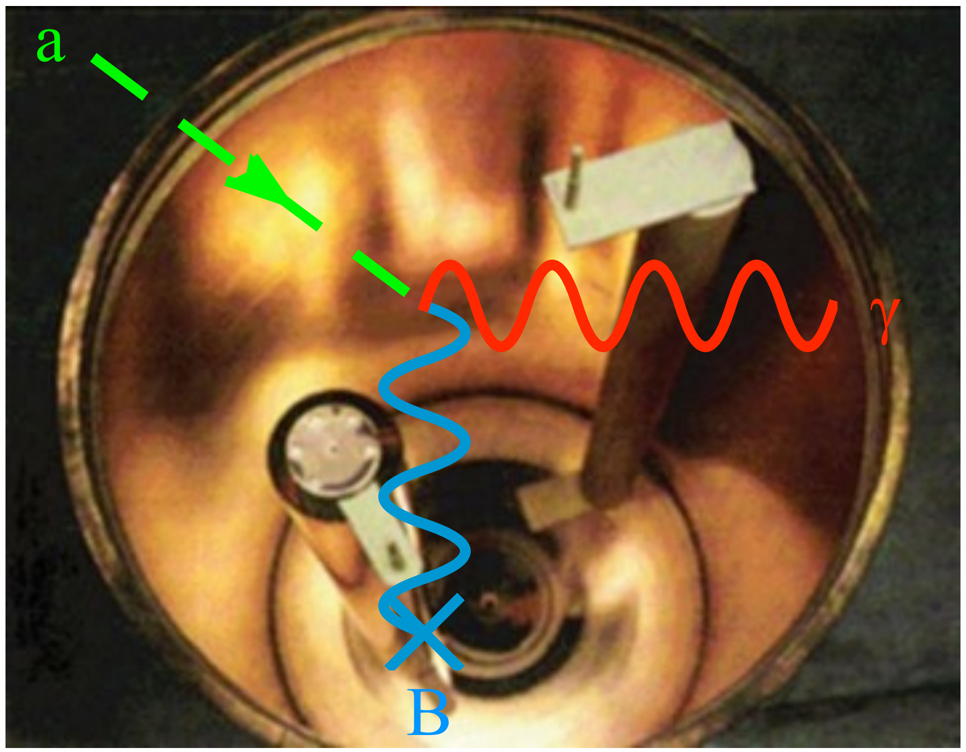
axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments, ALPS, CAST

Current Searches: ADMX



Axion dark matter

in most models: $\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$



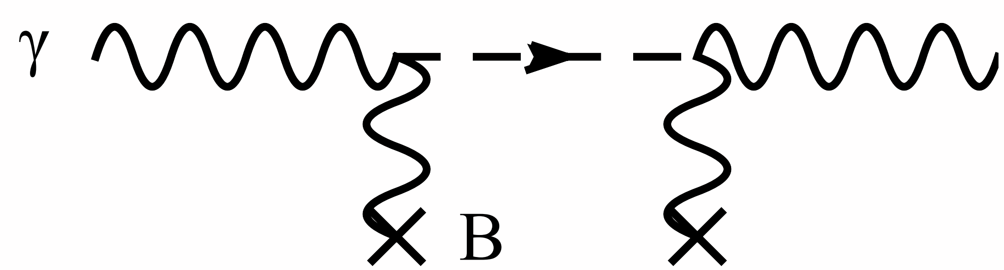
axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

size of cavity increases with f_a

signal $\propto \frac{1}{f_a^3}$

microwave cavity (ADMX)

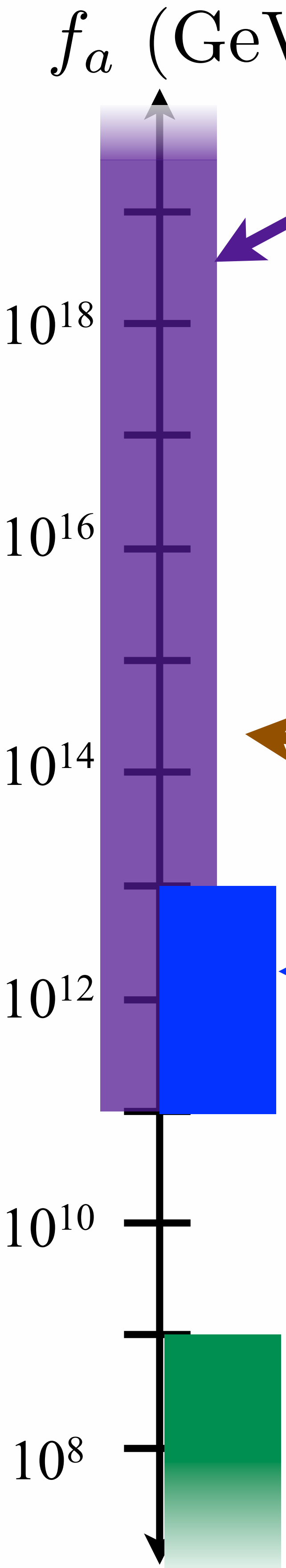
laser experiments:



$\propto \frac{1}{f_a^4}$

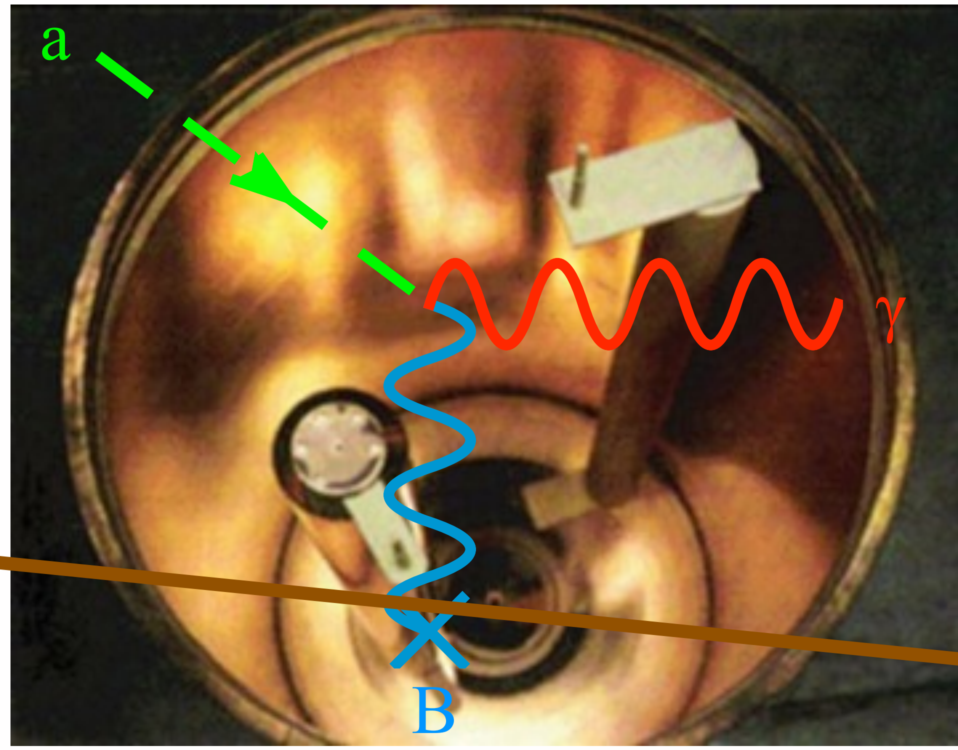
axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments, ALPS, CAST

Current Searches: ADMX



Axion dark matter

in most models: $\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$



axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

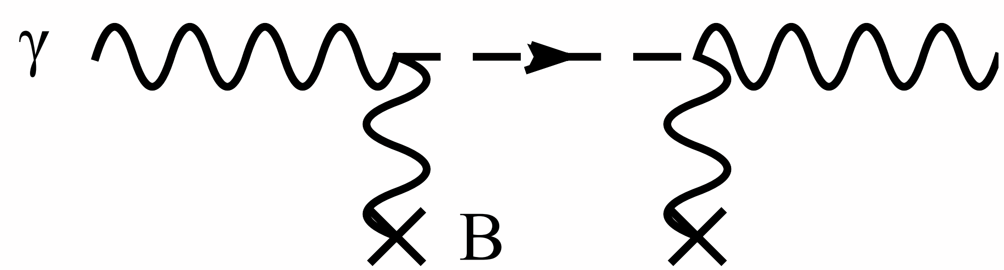
size of cavity increases with f_a

signal $\propto \frac{1}{f_a^3}$

S. Thomas

microwave cavity (ADMX)

laser experiments:



$\propto \frac{1}{f_a^4}$

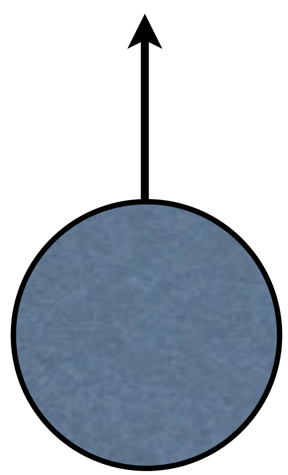
axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments, ALPS, CAST

Other ways to search for light (high f_a) axions?

CASPEr: Axion Effects on Spin

CASPEr: Axion Effects on Spin

General Axions

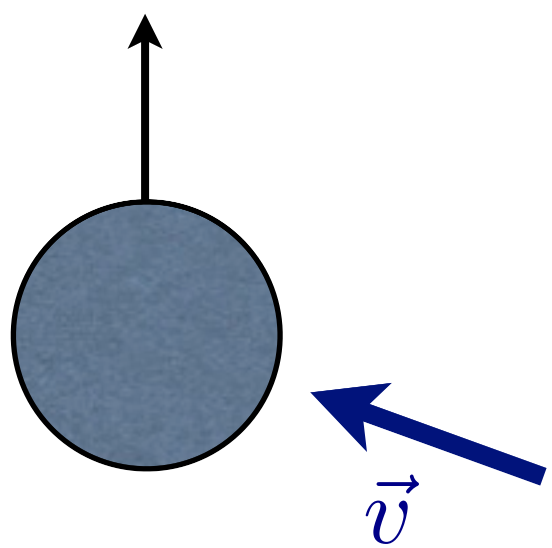


CASPEr: Axion Effects on Spin

General Axions

Neutron in
Axion Wind

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



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

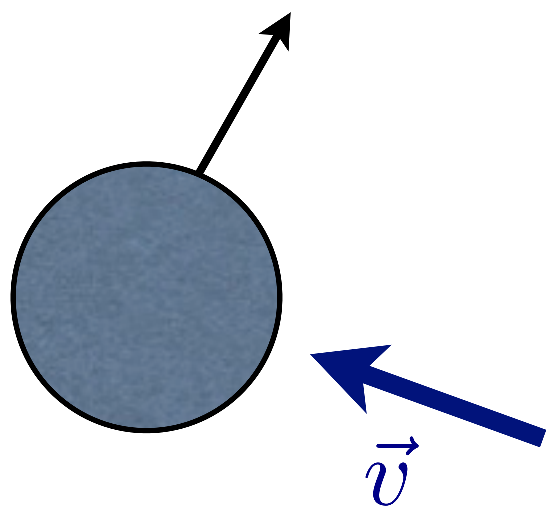
Spin rotates about
dark matter velocity

CASPEr: Axion Effects on Spin

General Axions

Neutron in
Axion Wind

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



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

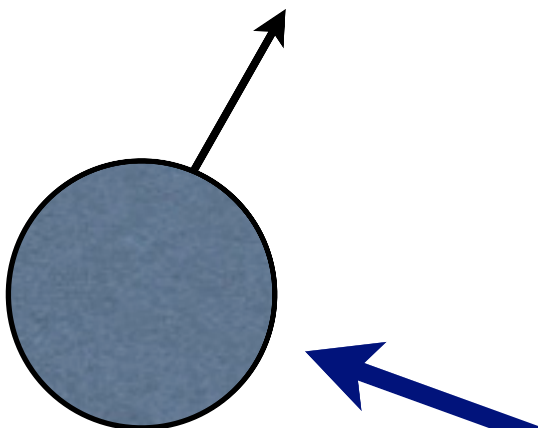
Spin rotates about
dark matter velocity

CASPEr: Axion Effects on Spin

General Axions

Neutron in Axion Wind

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



$\vec{v}$

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

Spin rotates about
dark matter velocity

Effective time varying
magnetic field

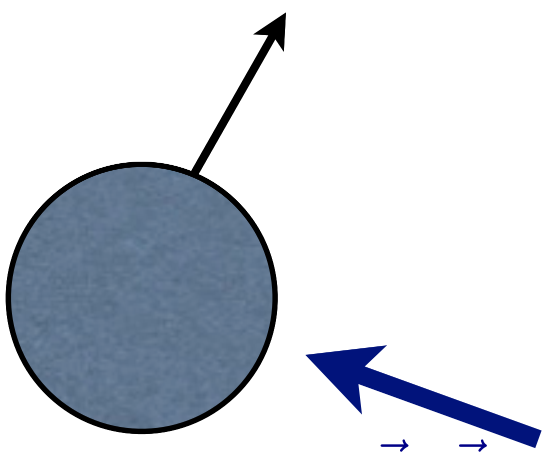
$$B_{eff} \lessapprox 10^{-16}\, \cos\left(m_a t\right)\ \mathrm{T}$$

CASPEr: Axion Effects on Spin

Hidden Photons

Neutron in
Hidden Photon Field

$$\left(\frac{F'_{\mu\nu}}{f_a}\bar{N}\sigma^{\mu\nu}\gamma_5 N\right)$$



$\vec{E}, \vec{B}$

$$H_N \supset \frac{1}{f_a}\,\vec{E}'.\vec{S}_N$$

Spin rotates about
dark matter electric or
magnetic field

Effective time varying
magnetic field

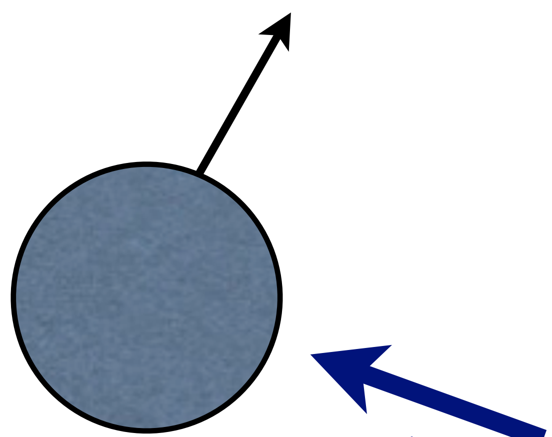
$$B_{eff} \lessapprox 10^{-13}\,\cos\left(m_a t\right)\ \mathrm{T}$$

CASPEr: Axion Effects on Spin

General Axions

Neutron in Axion Wind

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



$\vec{v}$

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

Spin rotates about
dark matter velocity

Effective time varying
magnetic field

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

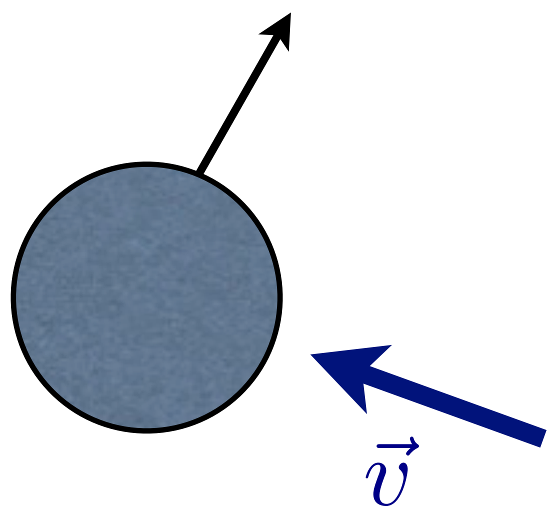
Other light dark matter (e.g. dark photons) also
induce similar spin precession

CASPEr: Axion Effects on Spin

General Axions

Neutron in
Axion Wind

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



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

Spin rotates about
dark matter velocity

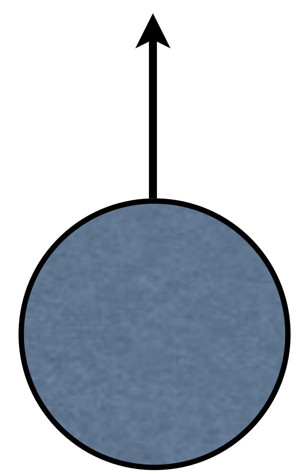
Effective time varying
magnetic field

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

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

QCD Axion

Neutron

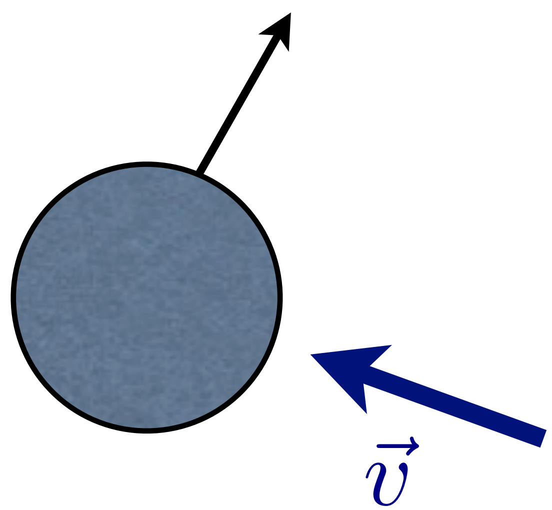


CASPEr: Axion Effects on Spin

General Axions

Neutron in
Axion Wind

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



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

Spin rotates about
dark matter velocity

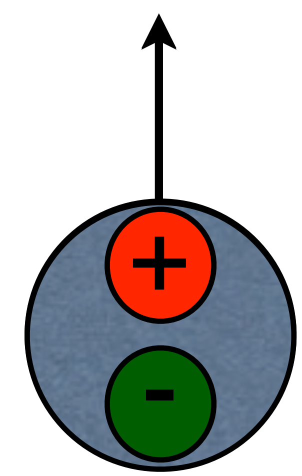
Effective time varying
magnetic field

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

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

QCD Axion

Neutron in
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

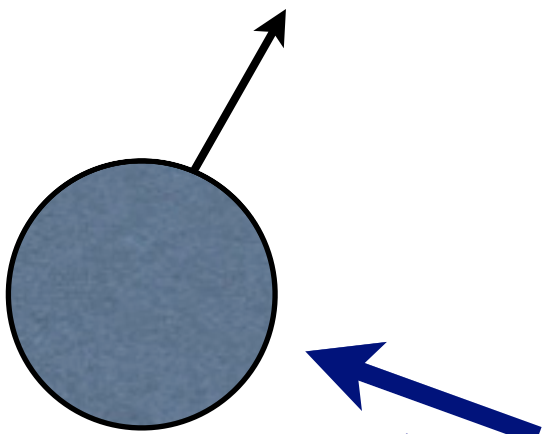
Oscillating dipole: $d \sim 3 \times 10^{-34} \cos\left(m_a t\right)\ e\,\mathrm{cm}$

CASPEr: Axion Effects on Spin

General Axions

Neutron in Axion Wind

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



$\vec{v}$

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

Spin rotates about
dark matter velocity

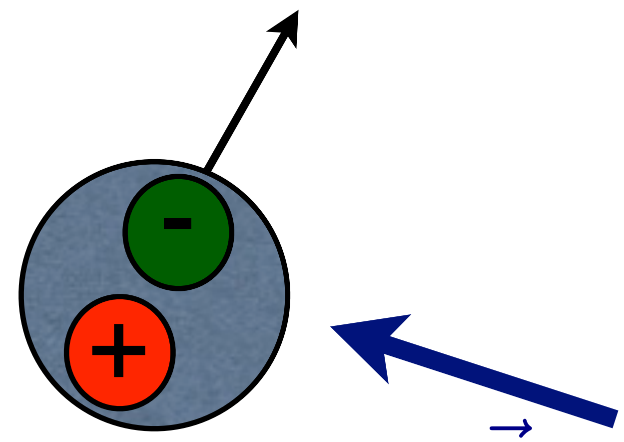
Effective time varying
magnetic field

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

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

QCD Axion

Neutron in QCD Axion Dark Matter



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

$\vec{E}$

QCD axion induces electric dipole moment
for neutron and proton

Dipole moment
along nuclear spin

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

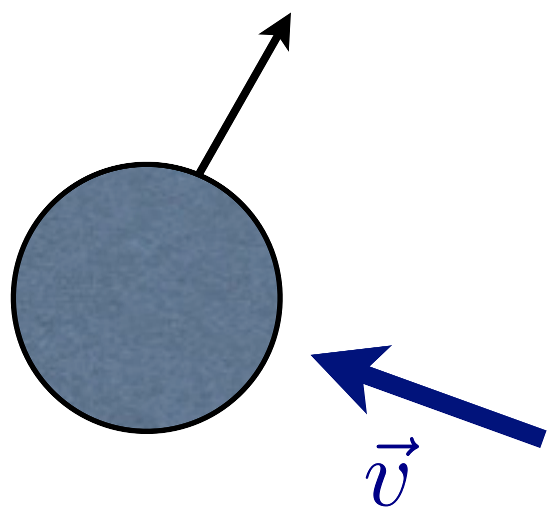
Apply electric field, spin rotates

CASPEr: Axion Effects on Spin

General Axions

Neutron in Axion Wind

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



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

Spin rotates about
dark matter velocity

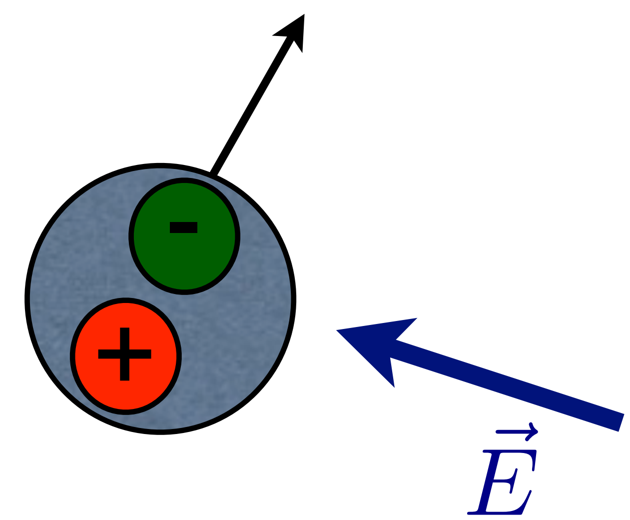
Effective time varying
magnetic field

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

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

QCD Axion

Neutron in 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: $d \sim 3 \times 10^{-34} \cos\left(m_a t\right)\ e\,\text{cm}$

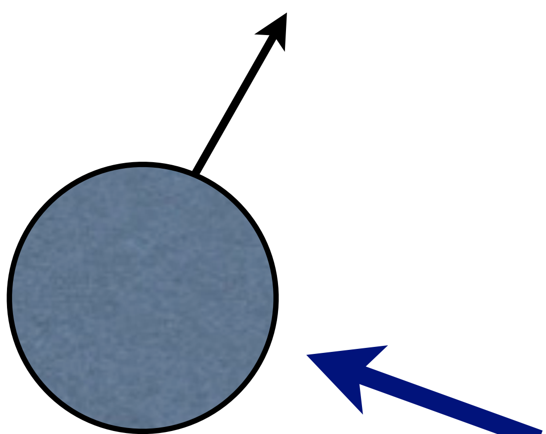
Apply electric field, spin rotates

CASPEr: Axion Effects on Spin

General Axions

Neutron in
Axion Wind

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



$\vec{v}$

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

Spin rotates about
dark matter velocity

Effective time varying
magnetic field

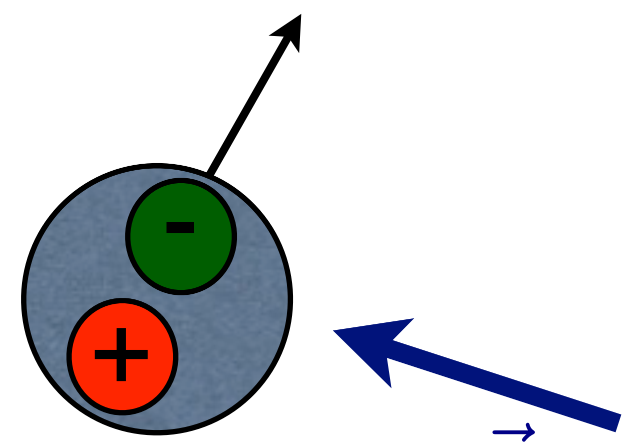
$$B_{eff} \lessapprox 10^{-16} \cos(m_a t) \text{ T}$$

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

Measure Spin Rotation, detect Axion

QCD Axion

Neutron in
QCD Axion Dark Matter



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

$\vec{E}$

QCD axion induces electric dipole moment
for neutron and proton

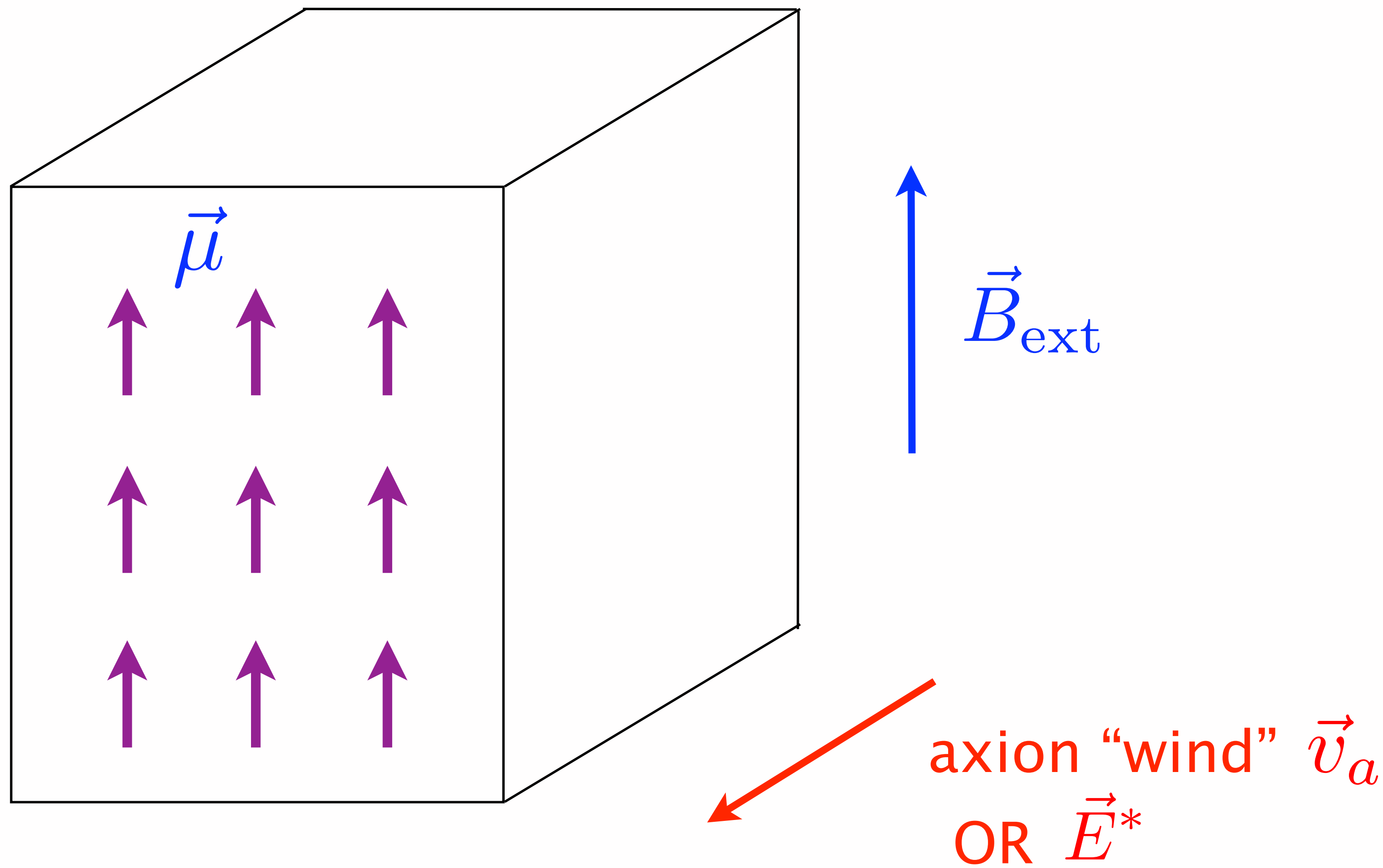
Dipole moment
along nuclear spin

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

Apply electric field, spin rotates

CASPEr

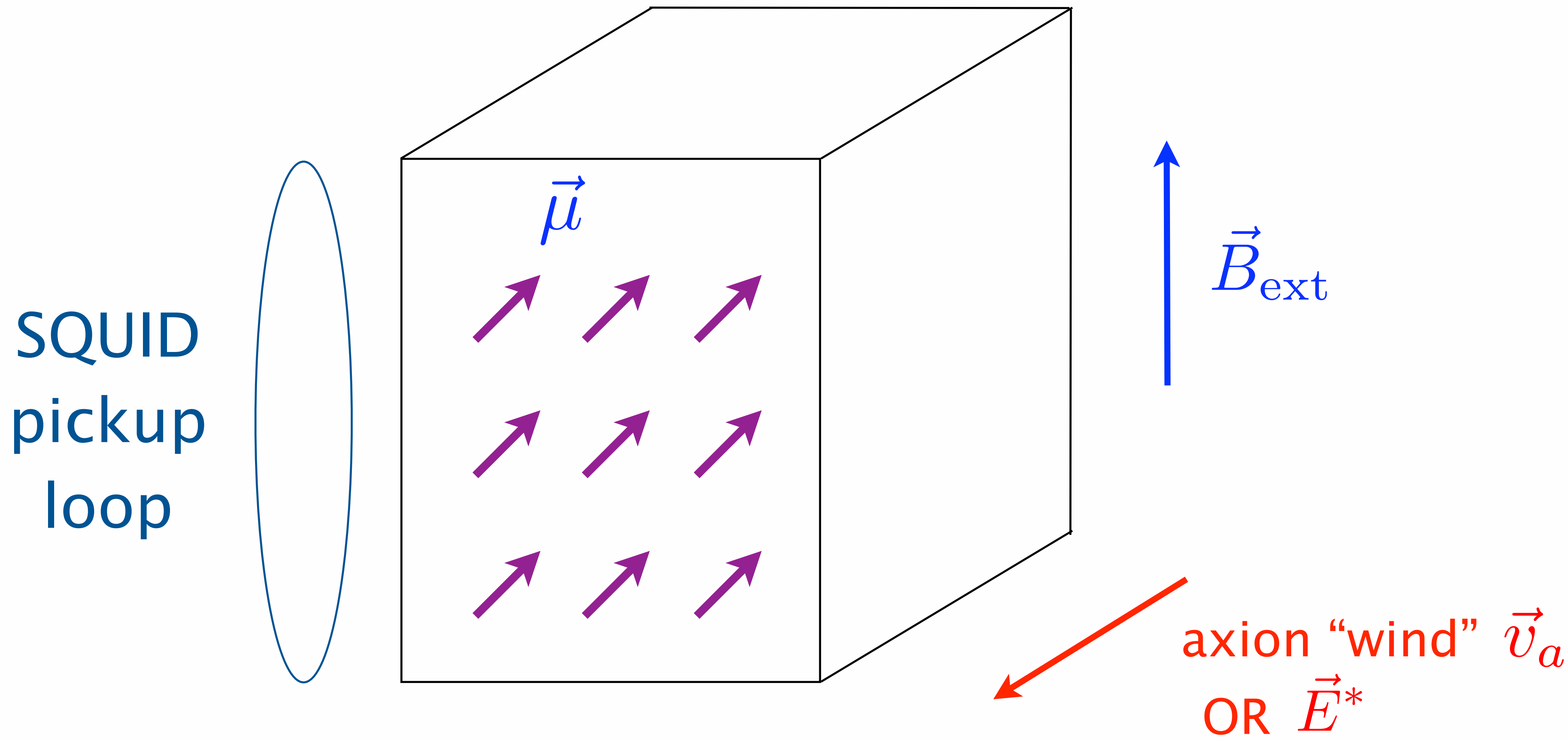
Axion affects physics of nucleus, NMR is sensitive probe



Larmor frequency = axion mass ➔ resonant enhancement

CASPEr

Axion affects physics of nucleus, NMR is sensitive probe



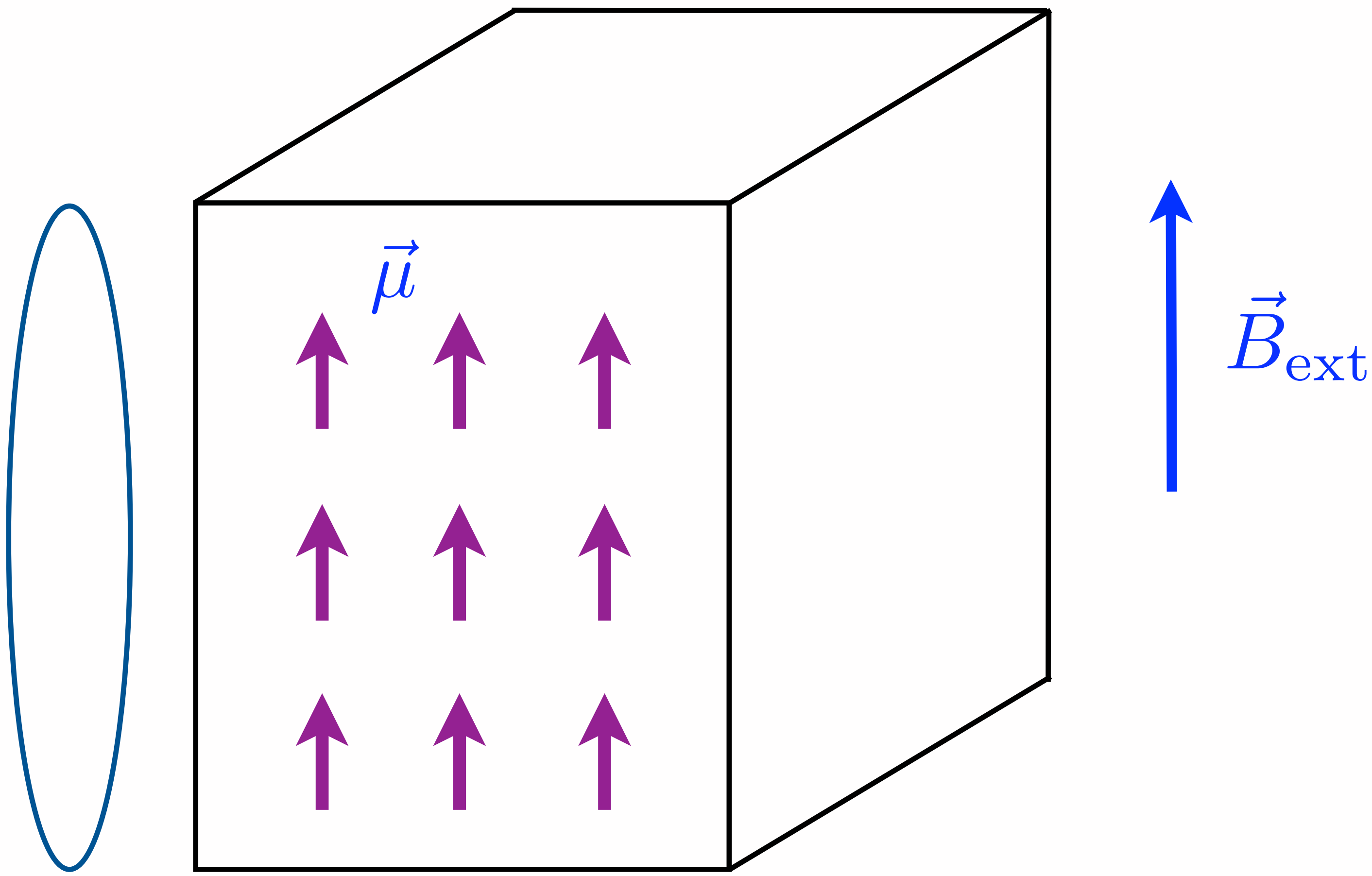
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

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

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

Magnetization Noise



a material sample has magnetization noise

noise arises from quantum spin projection

every spin necessarily has random quantum projection onto transverse direction

$$M_n(\omega) \sim \frac{\mu_N}{r^3}\sqrt{nr^3}\langle S(\omega)\rangle \sim \mu_N\sqrt{\frac{n}{V}}\langle S(\omega)\rangle$$

$S(\omega)$ is Lorentzian, peaked at Larmor frequency, bandwidth ~ $1/T_2$

T. Sleator, E. L. Hahn, C. Hilbert, and J. Clarke, PRL 55, 171742 (1985)

CASPEr-General Axions

for axion wind and other types of DM:

$$M(t) \approx np\mu \left(g_{\mathrm{aNN}} \sqrt{2\rho_{DM}} v \right) \frac{\sin\left(\left(2\mu B_{\mathrm{ext}} - m_a\right)t\right)}{2\mu B_{\mathrm{ext}} - m_a} \sin\left(2\mu B_{\mathrm{ext}} t\right)$$

	Element	Density (n)	Magnetic Moment (μ)	T_2	Max. B	Magnetometer Sensitivity
1.	Xe	$1.3 \times 10^{22} \frac{1}{\mathrm{cm}^3}$	$0.35\, \mu_N$	1300 s	10 T	$10^{-15} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$
2.						$10^{-17} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$

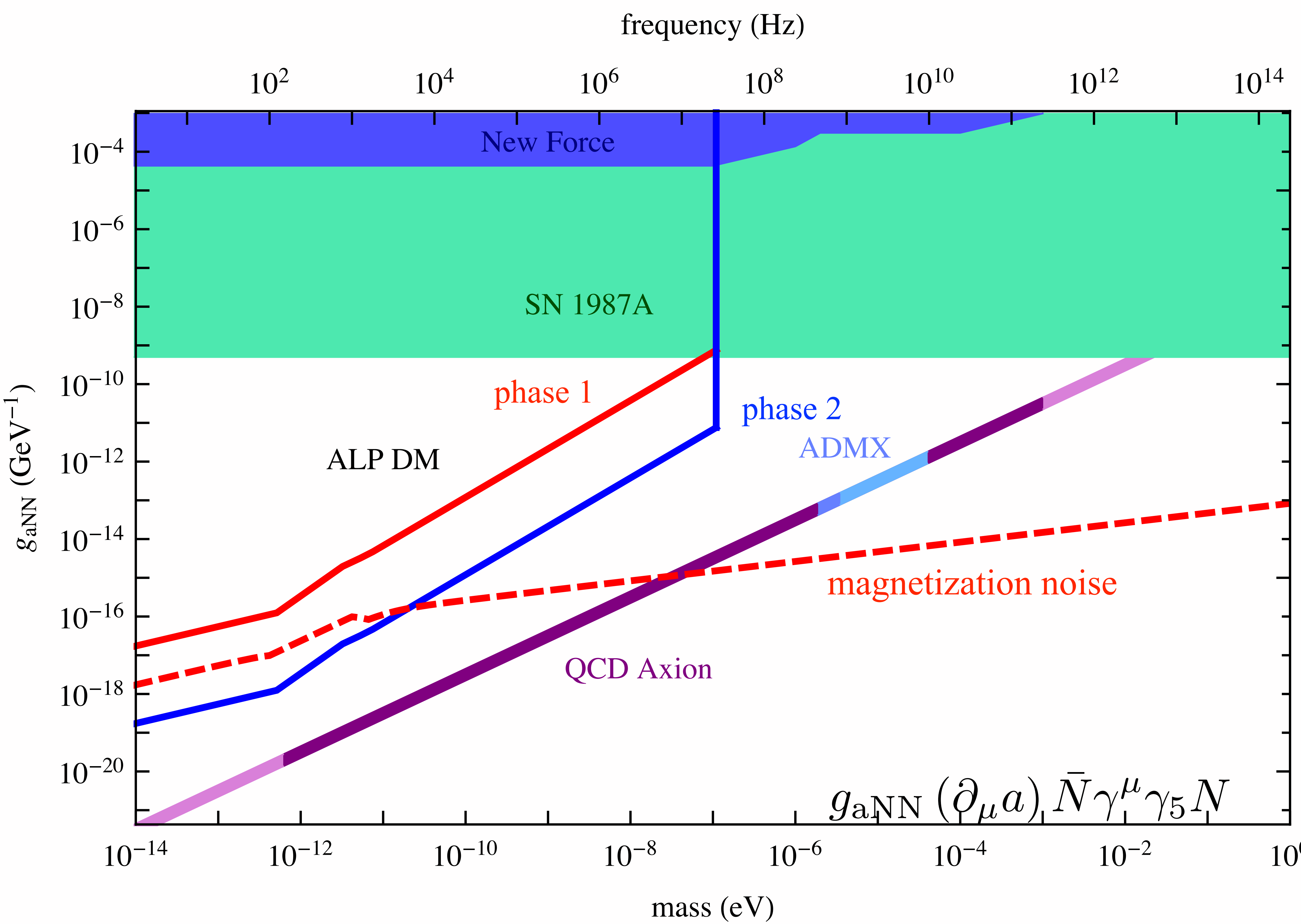
$$p \approx 1$$

take sample size: $L \sim 10$ cm

(or multiple loops over smaller sample)

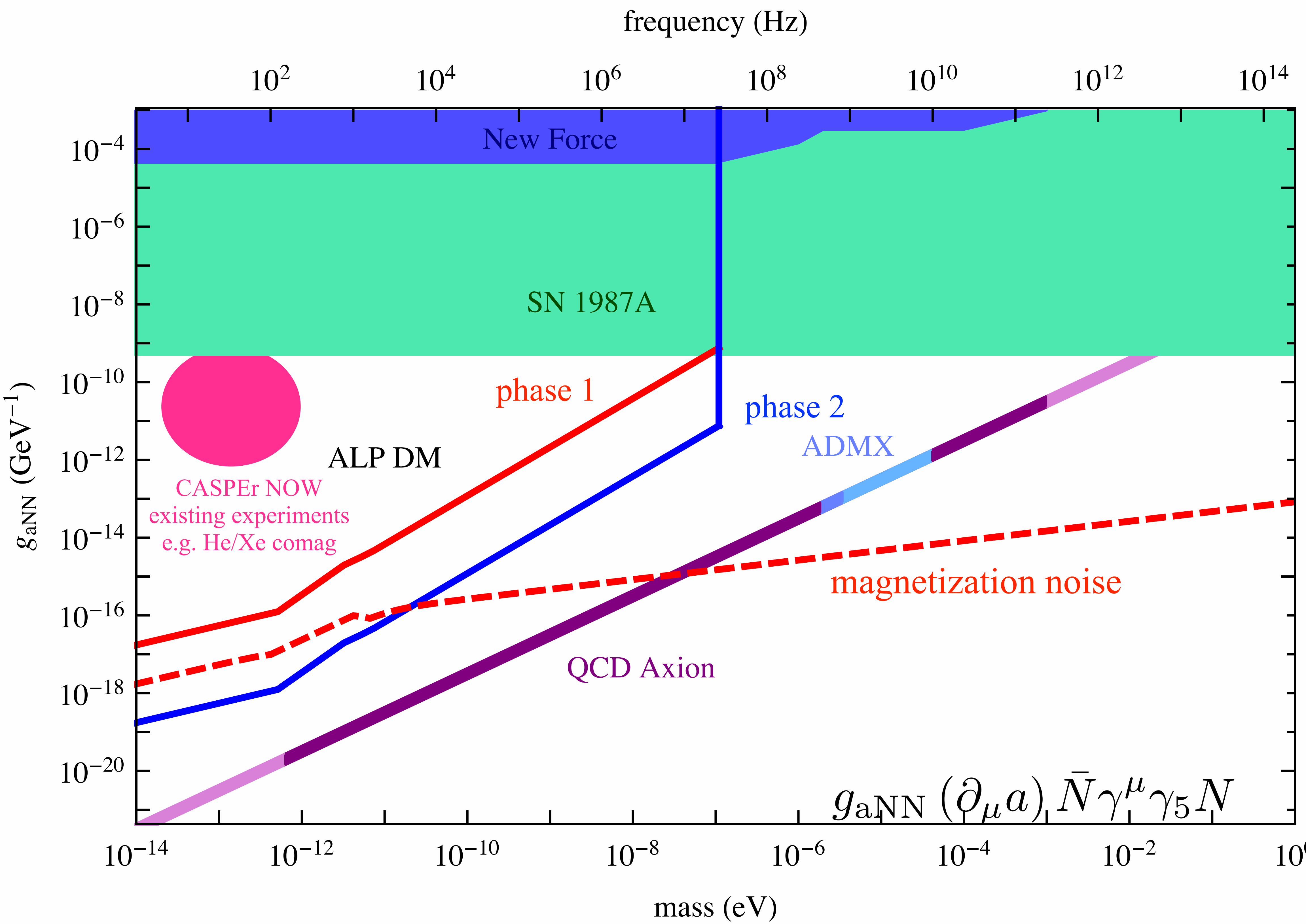
many options for increasing sensitivity

CASPEr–General Axions



~ year to scan one decade of frequency

CASPEr–General Axions



~ year to scan one decade of frequency

CASPEr-QCD Axion

$$M(t) \approx n\mu\epsilon_S d_n E^* p \frac{\sin\left(\left(2\mu B_{\text{ext}} - m_a\right)t\right)}{2\mu B_{\text{ext}} - m_a} \sin\left(2\mu B_{\text{ext}} t\right)$$

	n	E^*	p	T_2	Max. B_{ext}
Phase 1	$10^{22}\,\frac{1}{\text{cm}^3}$	$3\times10^{8}\,\frac{\text{V}}{\text{cm}}$	10^{-3}	1 ms	10 T
Phase 2			1	1 s	20 T

example material: $^{207}\text{Pb} \implies \quad \mu = 0.6\mu_N \quad \epsilon_s \approx 10^{-2}$

take sample size: $L \sim 10$ cm ➜ we take SQUID magnetometer: $10^{-16}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$

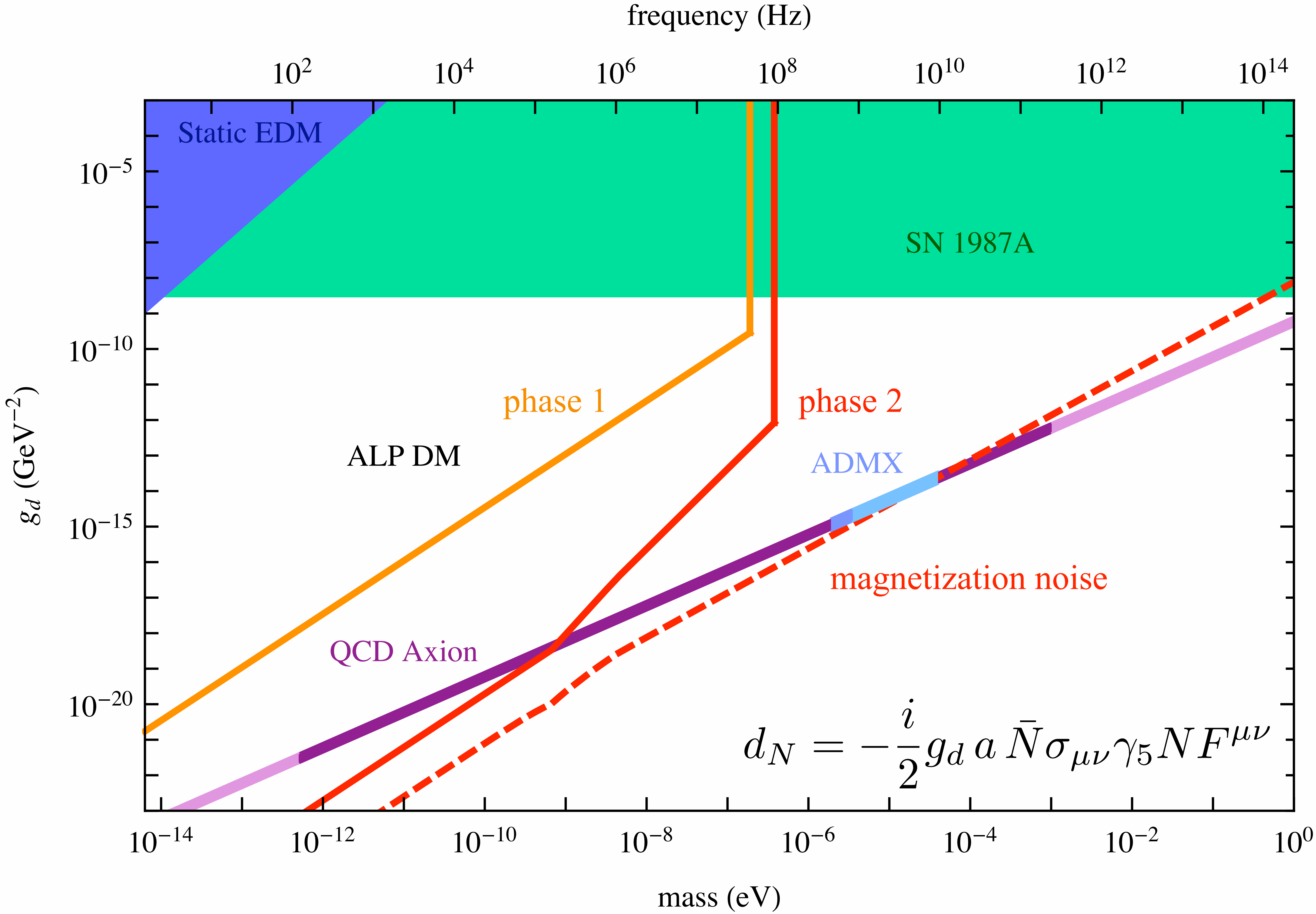
(or multiple loops over smaller sample)

but atomic magnetometers ~ $10^{-17}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$

M.V. Romalis

many options for increasing sensitivity

CASPEr–QCD Axion



Verify signal with spatial coherence of axion field

Dark Photon Detection with a Radio

(to appear)

with

Peter Graham
Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Yue Zhao

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

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

mass basis:

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

photon with small mass and suppressed couplings to all charged particles

oscillating E' field
(dark matter)

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

oscillating E' field (dark matter)

can drive current behind EM shield

Annoying Fact

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

Annoying Fact

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

$$\text{Send } m'_\gamma \to 0$$

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

Annoying Fact

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

$$\text{Send } m_\gamma^{'} \to 0$$

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

Only one linear combination couples to charged particles

Orthogonal component is completely sterile

Annoying Fact

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

$$\text{Send } m'_\gamma \to 0$$

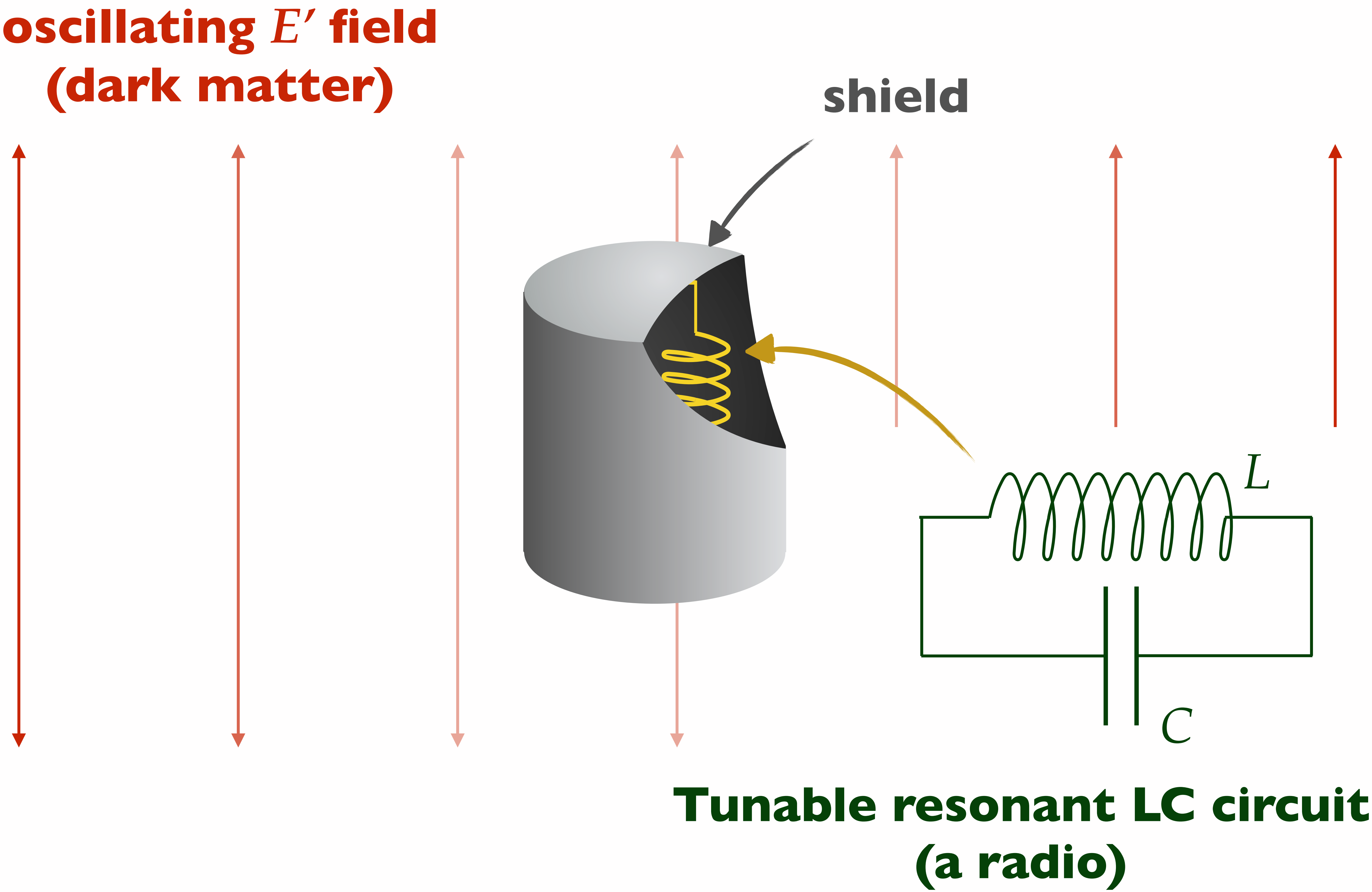
$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) - eJ^\mu_{EM}\left(A_\mu + \varepsilon A'_\mu\right)$$

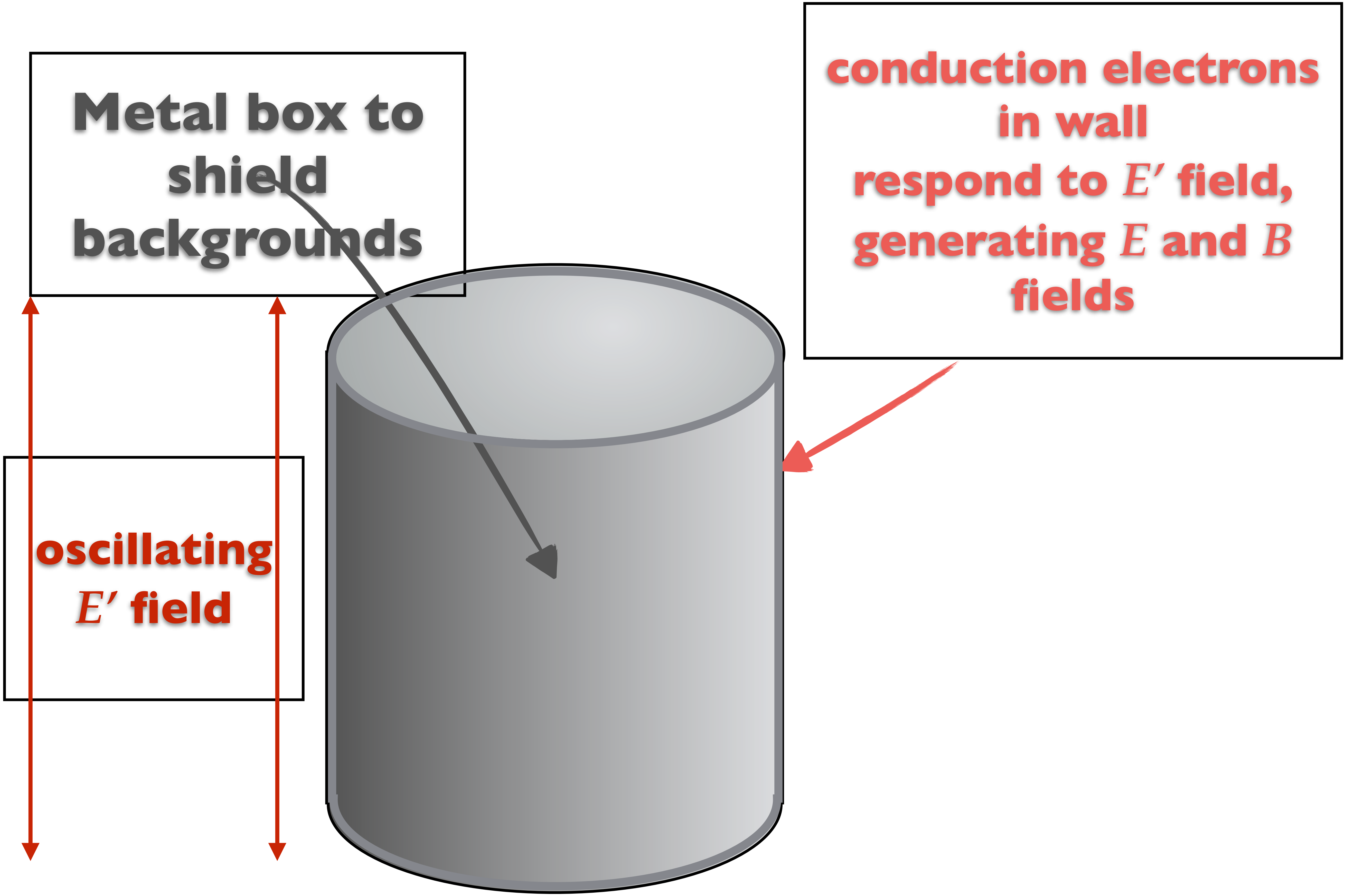
Only one linear combination couples to charged particles

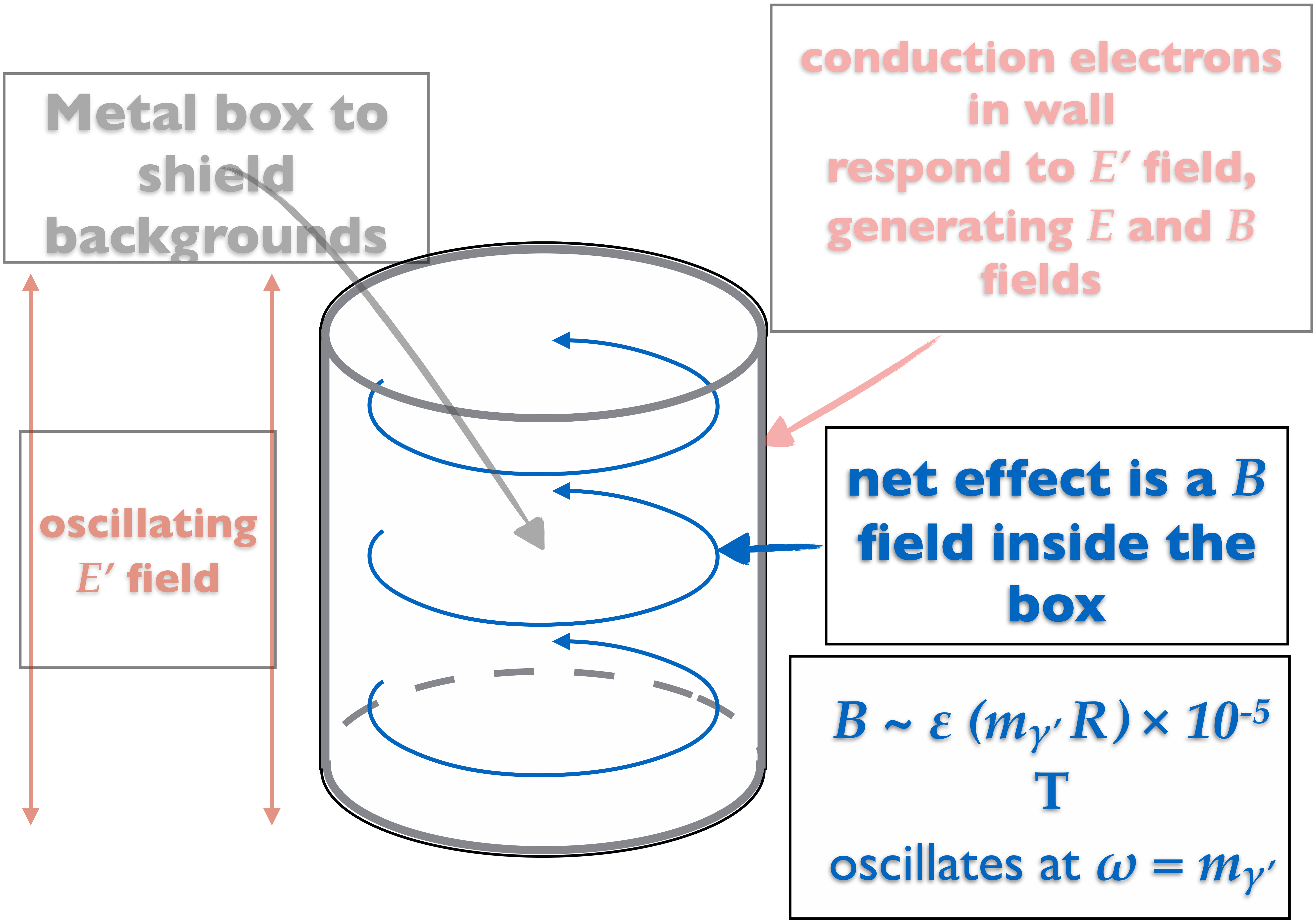
Orthogonal component is completely sterile

$$\text{Physical effects decouple } m'_\gamma \to 0$$

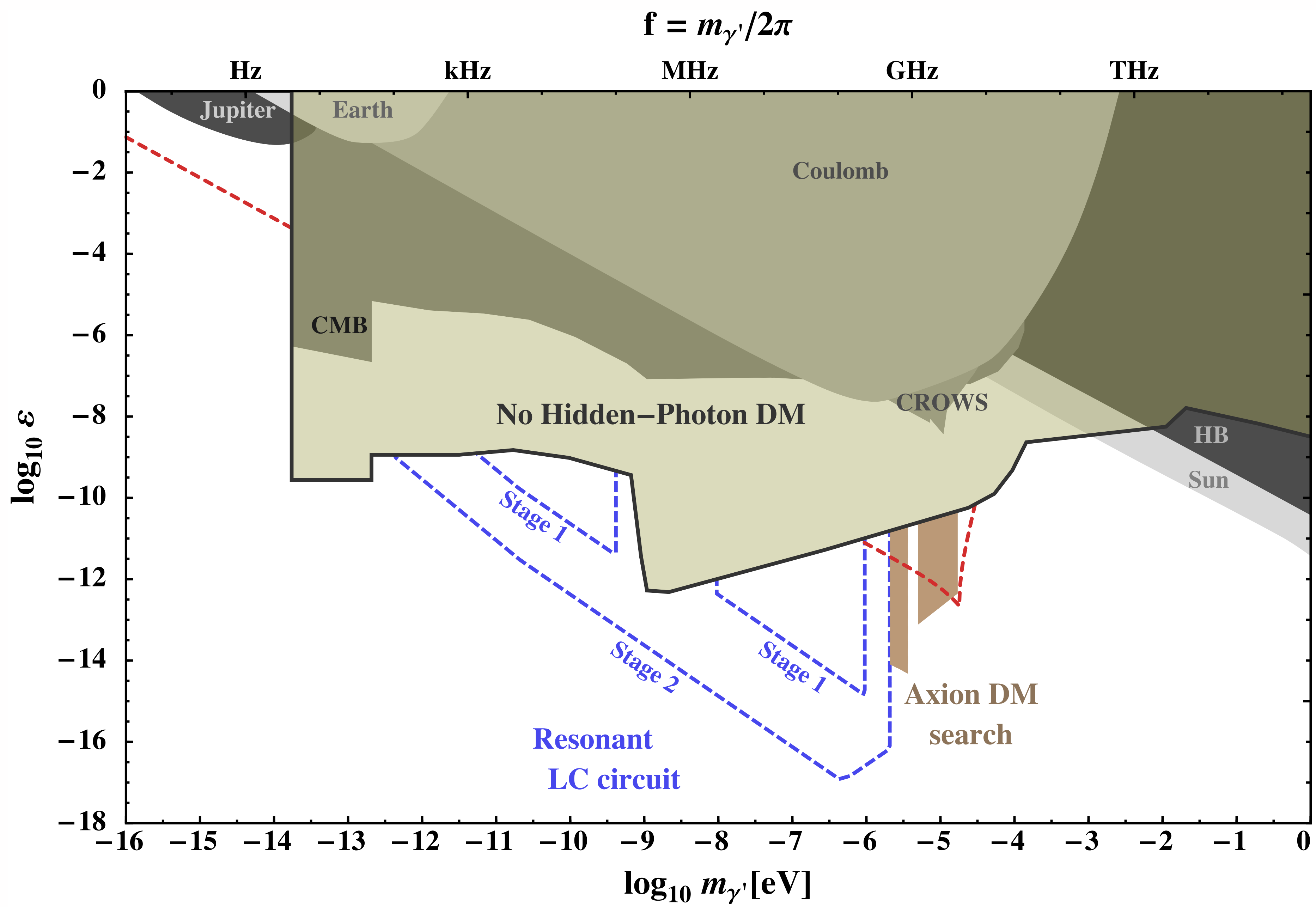
Dark Matter Radio Station




Metal box to shield backgrounds
conduction electrons in wall respond to E' field, generating E and B fields
oscillating E' field


Metal box to shield backgrounds
conduction electrons in wall respond to E' field, generating E and B fields
oscillating E' field
net effect is a B field inside the box
$B \sim \varepsilon\,(m_{\gamma'} R) \times 10^{-5}$ T
oscillates at $\omega = m_{\gamma'}$

Projected Sensitivity (Preliminary)



LC oscillator search: **size ~ 1m** **Q~10^6**

~1 month scan per decade

Stage 1: room temp **Stage 2: T~0.1K**

B-L Dark Matter with Accelerometers

(under development)

with

Peter Graham
Jeremy Mardon
Yue Zhao

B-L Dark Matter

Other than electromagnetism, only other anomaly free standard model current

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

Protons, Neutrons, Electrons and Neutrinos are all charged

Electrically neutral atoms are charged under B-L

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

B-L Dark Matter

Other than electromagnetism, only other anomaly free standard model current

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

Protons, Neutrons, Electrons and Neutrinos are all charged

Electrically neutral atoms are charged under B-L

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

oscillating E' field (dark matter)

can accelerate atoms

B-L Dark Matter

$$\text{Acceleration Per Baryon: } \frac{gE'}{m_n} \sim 10^{-10}\,\frac{\mathrm{m}}{\mathrm{s}^2}\left(\frac{g}{10^{-21}}\right)$$

$$\text{Atomic Accelerometers } \gtrapprox 10^{-12}\,\frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}\ (\text{@ } 1\ \mathrm{Hz})$$

B-L Dark Matter

$$\text{Acceleration Per Baryon: } \frac{gE'}{m_n} \sim 10^{-10}\,\frac{\mathrm{m}}{\mathrm{s}^2}\left(\frac{g}{10^{-21}}\right)$$

$$\text{Atomic Accelerometers } \gtrapprox 10^{-12}\,\frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}\;(@\ 1\ \mathrm{Hz})$$

Dark Matter force depends upon net neutron number
Time dependent equivalence principle violation!

Improvements possible with resonant schemes

Seems promising!

Atomic EP Test

Conclusions

WIMPs

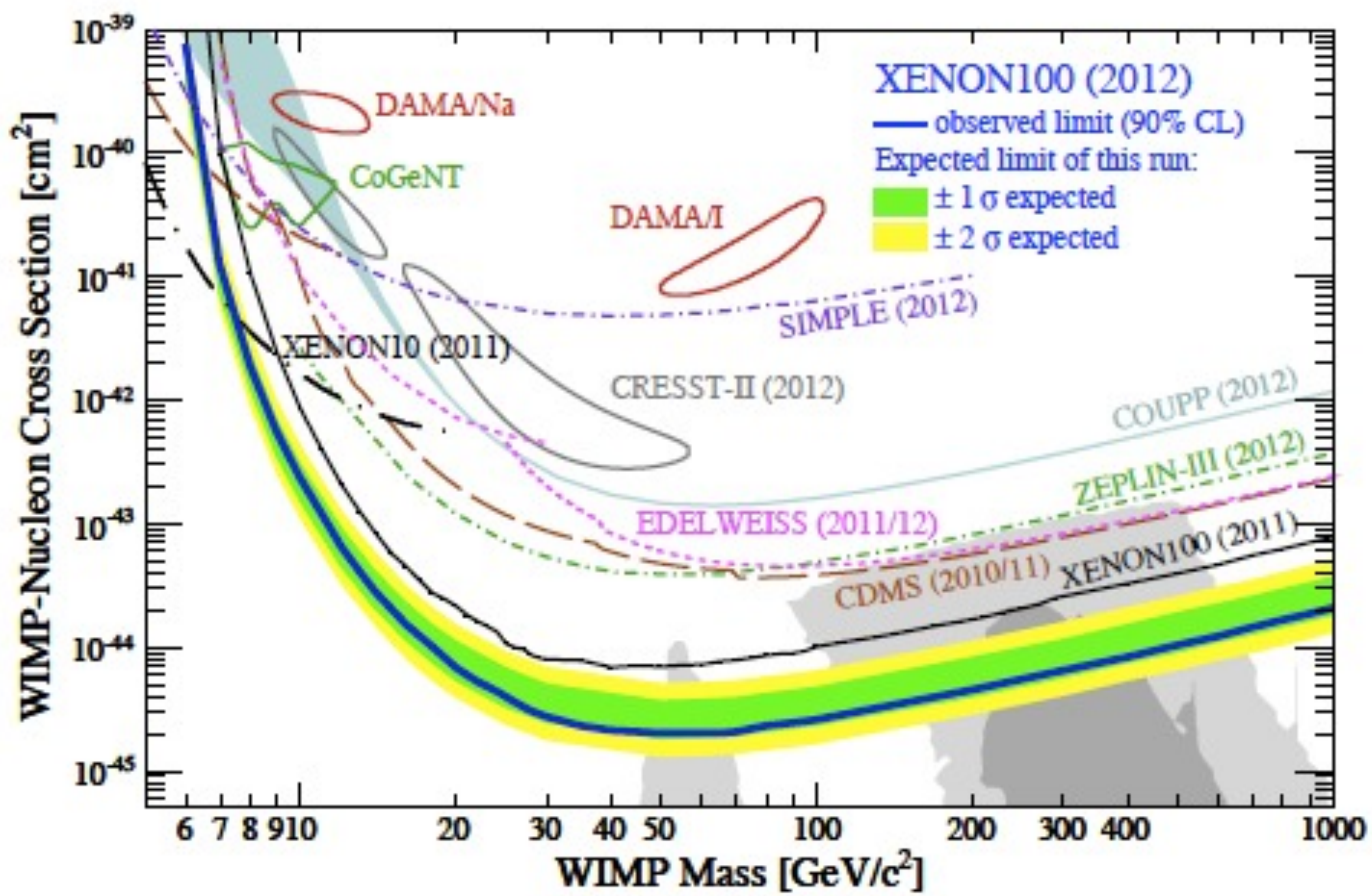
Scalable

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

Z

h

W



WIMPs

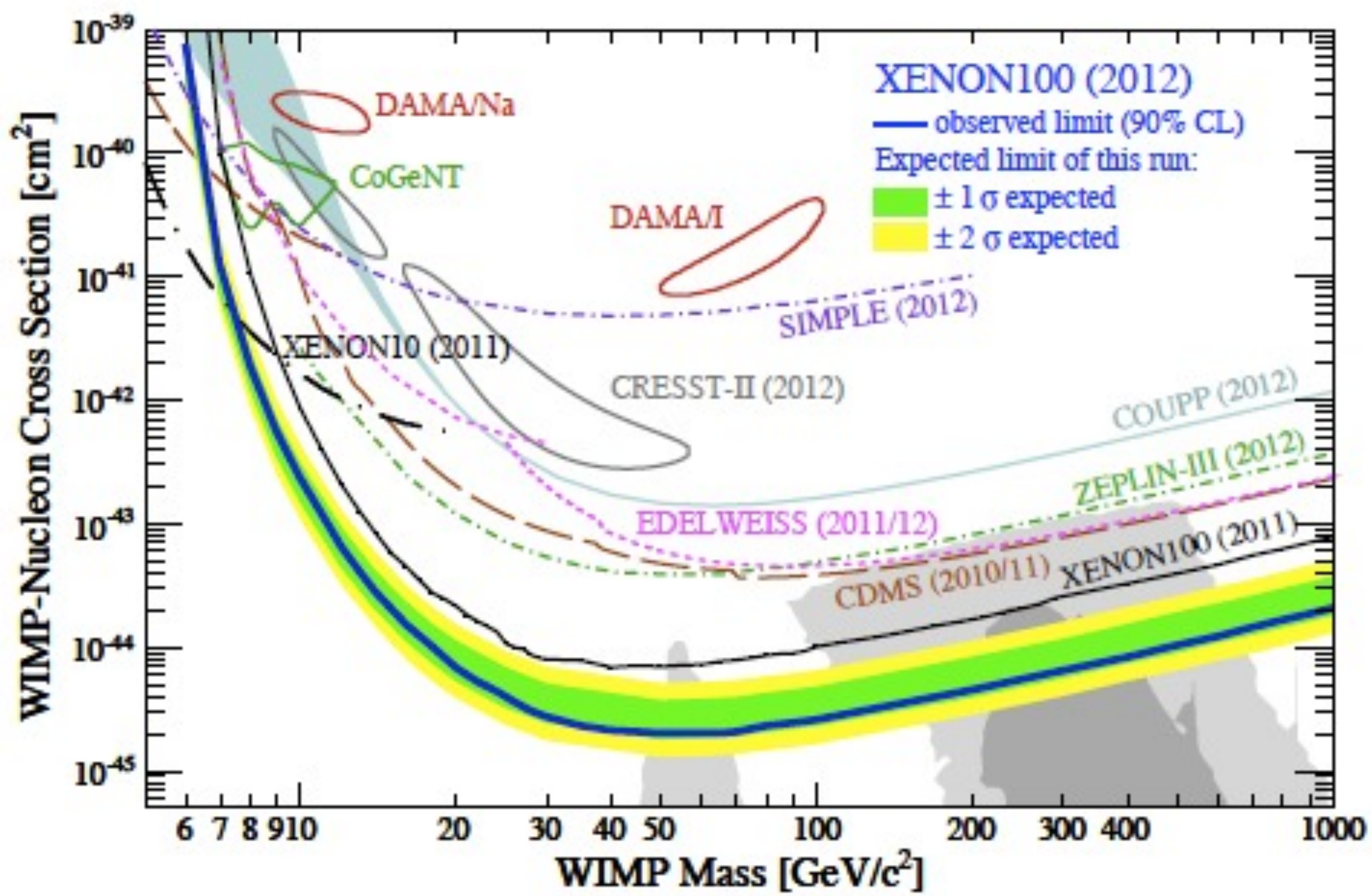
Scalable

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

Z

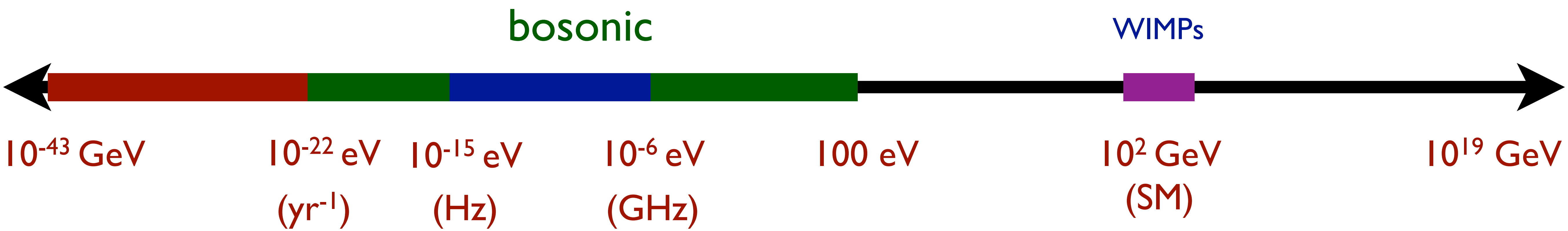
h

W

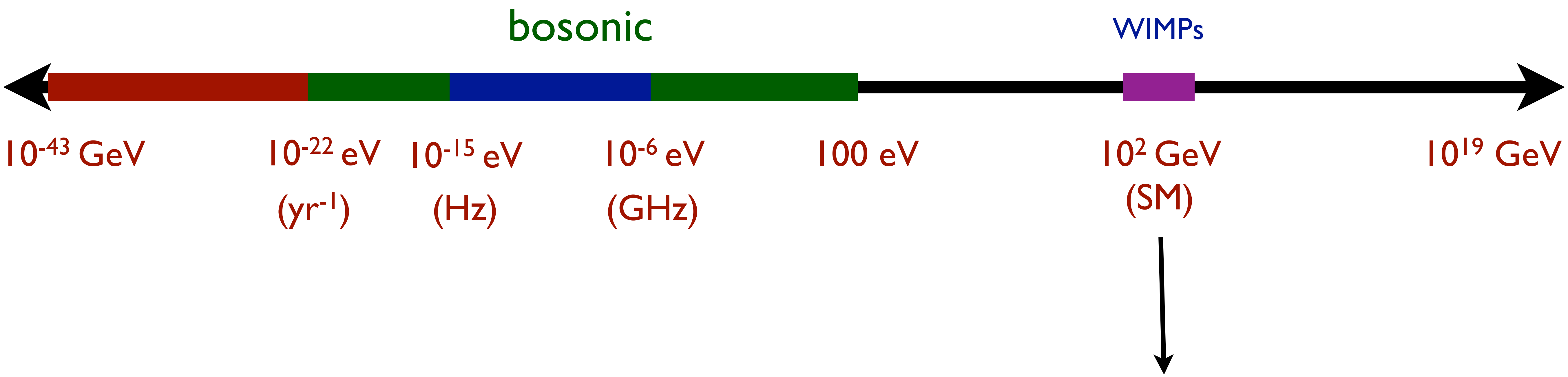


Similar approach seems possible in searching for oscillating fields

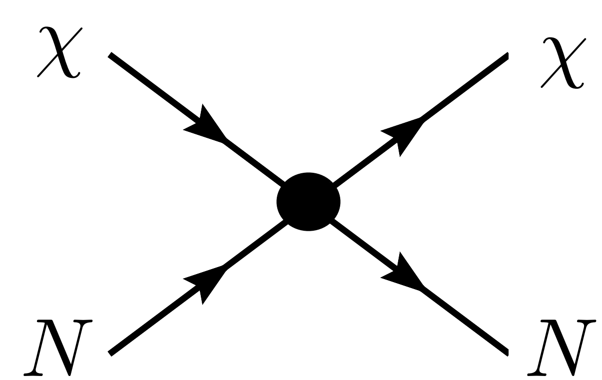
The Dark Matter Landscape



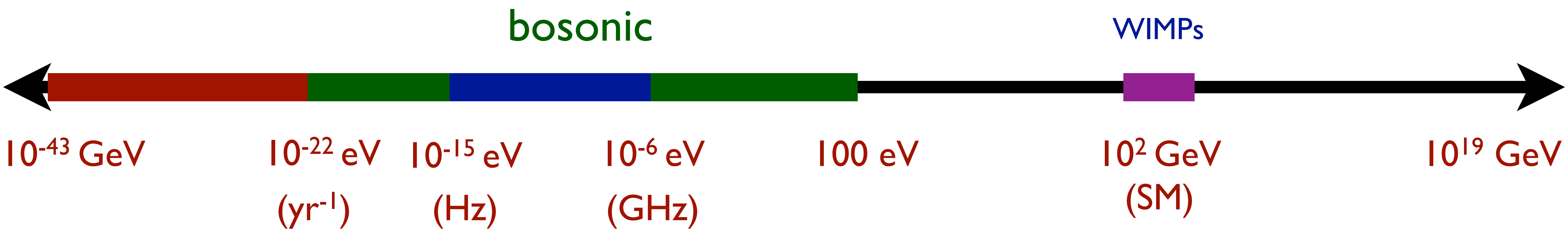
The Dark Matter Landscape



Search for single, hard particle scattering



The Dark Matter Landscape



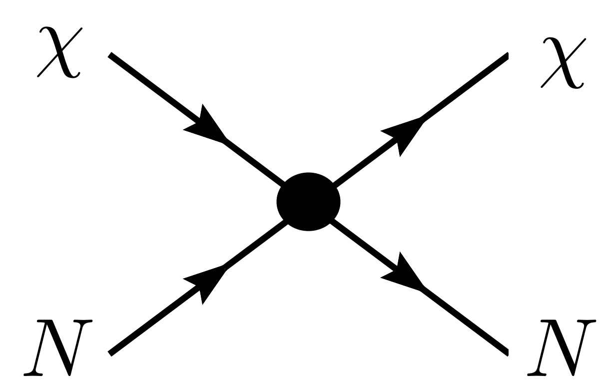
Time dependent moments of coherent classical field

Interactions restricted by symmetry

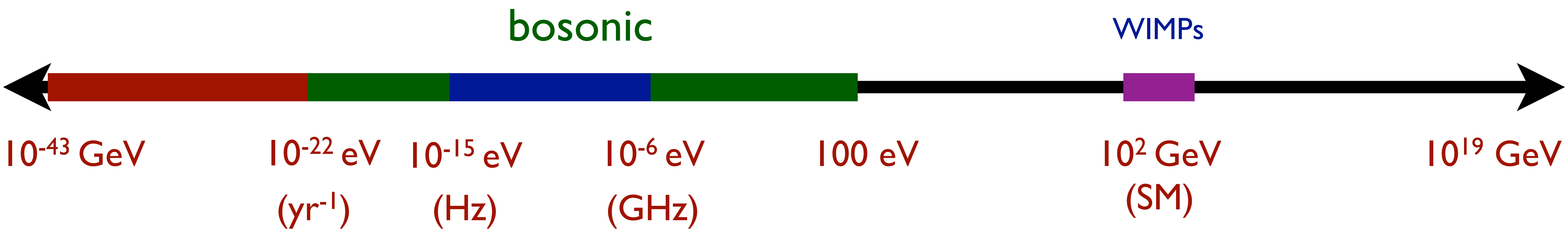
Frequencies can naturally be lab accessible (Hz - GHz)

Lab-scale experiments

Search for single, hard particle scattering



The Dark Matter Landscape



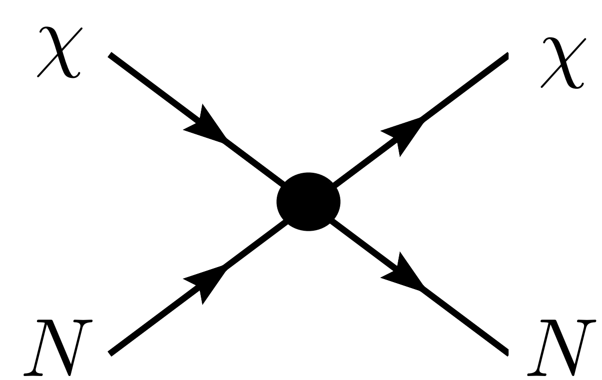
Time dependent moments of coherent classical field

Interactions restricted by symmetry

Frequencies can naturally be lab accessible (Hz - GHz)

Lab-scale experiments

Search for single, hard particle scattering



How do we cover full range?

Backup

A Different Operator For Axion Detection

So how can we detect high f_a axions?

Strong CP problem: $\mathcal{L} \supset \theta\, G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\, \theta\, e\,\mathrm{cm}$

the axion: $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\, \frac{a}{f_a}\, e\,\mathrm{cm}$

A Different Operator For Axion Detection

So how can we detect high f_a axions?

Strong CP problem: $\mathcal{L} \supset \theta\, G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\, \theta\, e\, \mathrm{cm}$

the axion: $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\, \frac{a}{f_a}\, e\, \mathrm{cm}$

$a(t) \sim a_0 \cos\left(m_a t\right)$ with $m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$

axion dark matter $\rho_{\mathrm{DM}} \sim m_a^2 a^2 \sim (200\mathrm{MeV})^4 \left(\frac{a}{f_a}\right)^2 \sim 0.3\, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

so today: $\left(\frac{a}{f_a}\right) \sim 3 \times 10^{-19}$ independent of f_a

axion gives all nucleons an oscillating EDM (kHz-GHz) independent of f_a,
a non-derivative operator

Axions and the CMB

Assuming BICEP detected gravitational waves in the CMB (some tension with Planck):

$$H_{\text{inf}} \sim 10^{14}\ \text{GeV}$$

if symmetry broken after inflation → topological defects (strings + domain walls), constrained by observations

if symmetry broken before inflation → inflation can induce isocurvature perturbations of axion, weak constraint on ALPs probed by CASPEr.

Axions and the CMB

Assuming BICEP detected gravitational waves in the CMB (some tension with Planck):

$$H_{\mathrm{inf}} \sim 10^{14}\ \mathrm{GeV}$$

if symmetry broken after inflation → topological defects (strings + domain walls), constrained by observations

if symmetry broken before inflation → inflation can induce isocurvature perturbations of axion, $\boxed{\text{weak constraint on ALPs probed by CASPEr.}}$

Axions and the CMB

Assuming BICEP detected gravitational waves in the CMB (some tension with Planck):

$$H_{\text{inf}} \sim 10^{14}\ \text{GeV}$$

if symmetry broken after inflation → topological defects (strings + domain walls), constrained by observations

if symmetry broken before inflation → inflation can induce isocurvature perturbations of axion, weak constraint on ALPs probed by CASPEr.

for QCD axion, constrains **one** cosmological history.

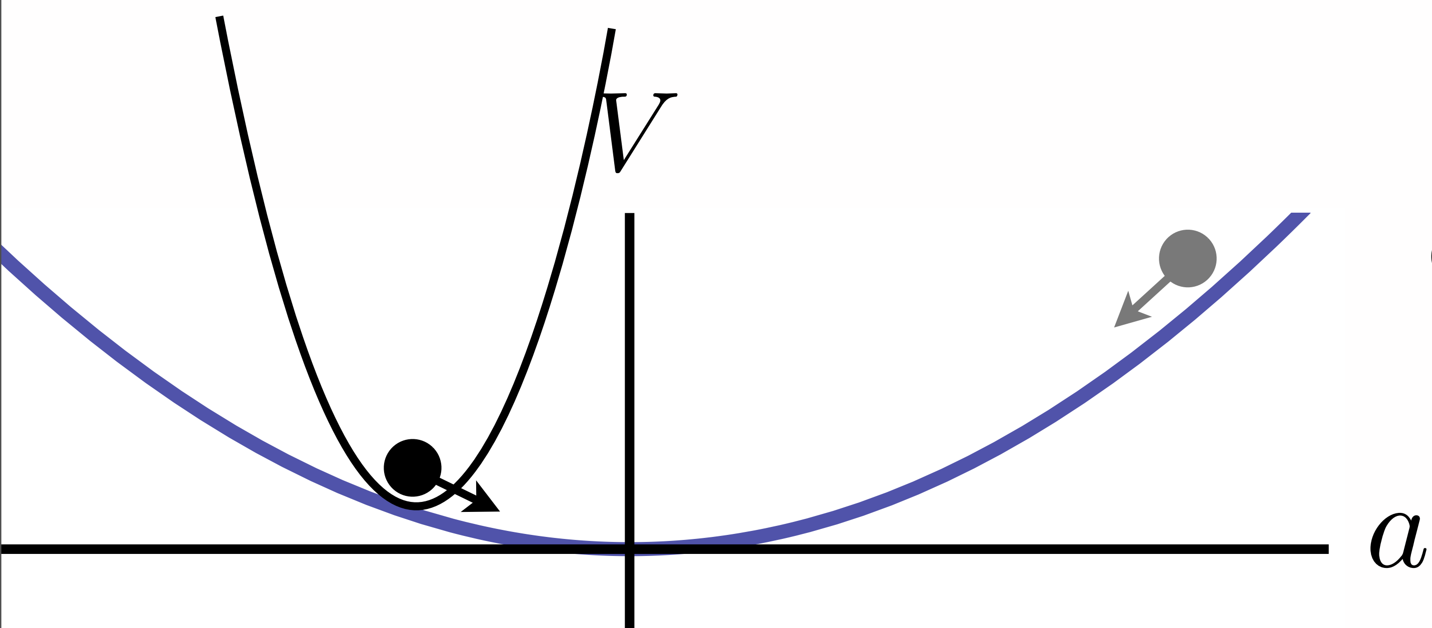
Requires knowing physics all the way up to GUT scale $\sim 10^{16}\ \text{GeV}$

many others possible.

QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.

Need not be on during inflation.



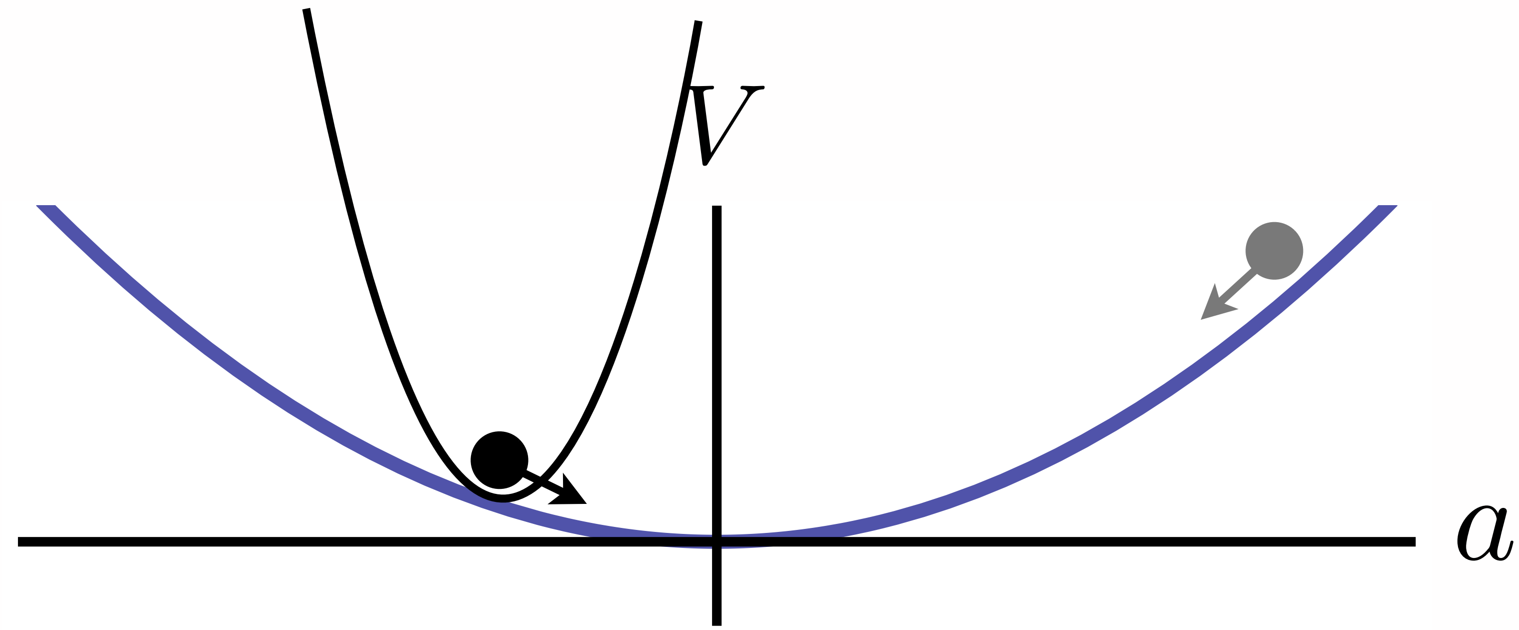
Axion oscillates earlier, damps to high temperature minimum.

Misalignment of minima gives axion dark matter.

Dark matter from choice of parameters instead of initial conditions.

QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.



e.g. thermal monopole density,
high temperature mass,
and many others

Fischler & Preskill (1983)

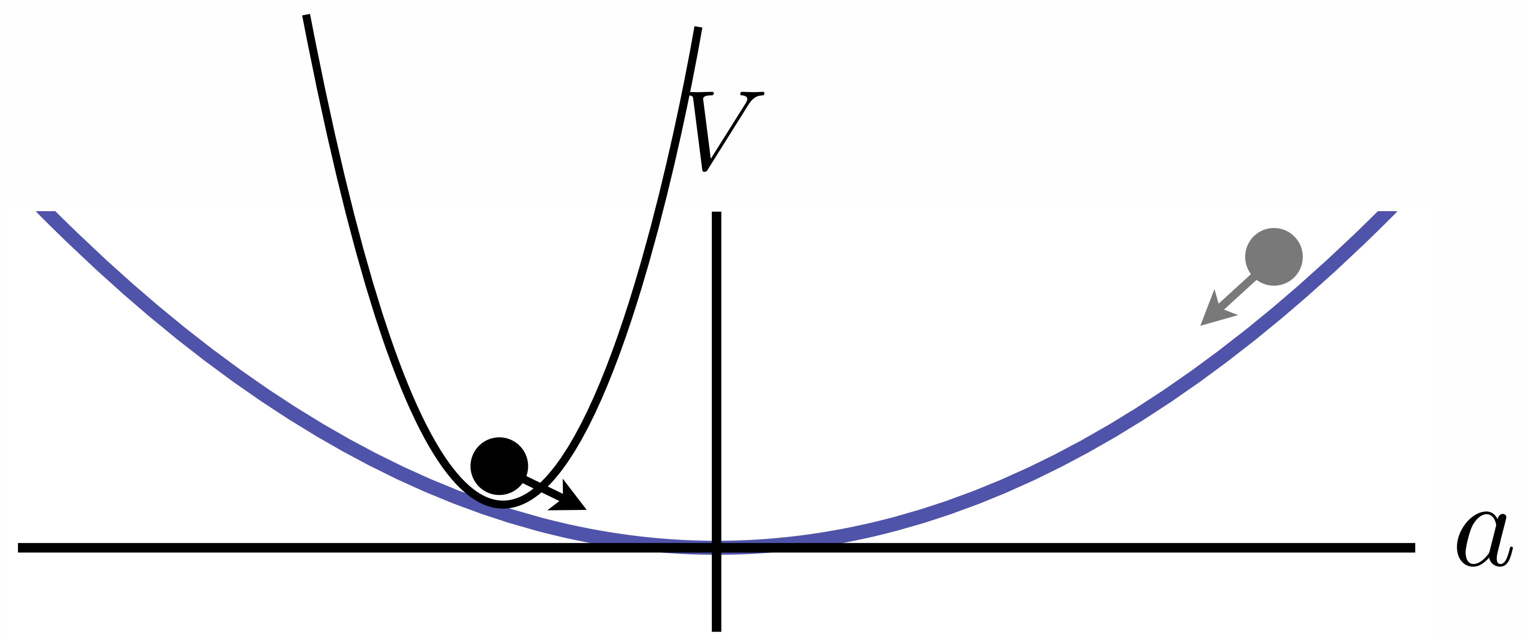
e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

Bound depends upon high energy physics, while strong CP, axion dark matter rely upon low energy physics.

QCD axion offers unique probe of high energy cosmology,
an era difficult even for gravitational wave detectors

QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.



e.g. thermal monopole density, high temperature mass, and many others

Fischler & Preskill (1983)

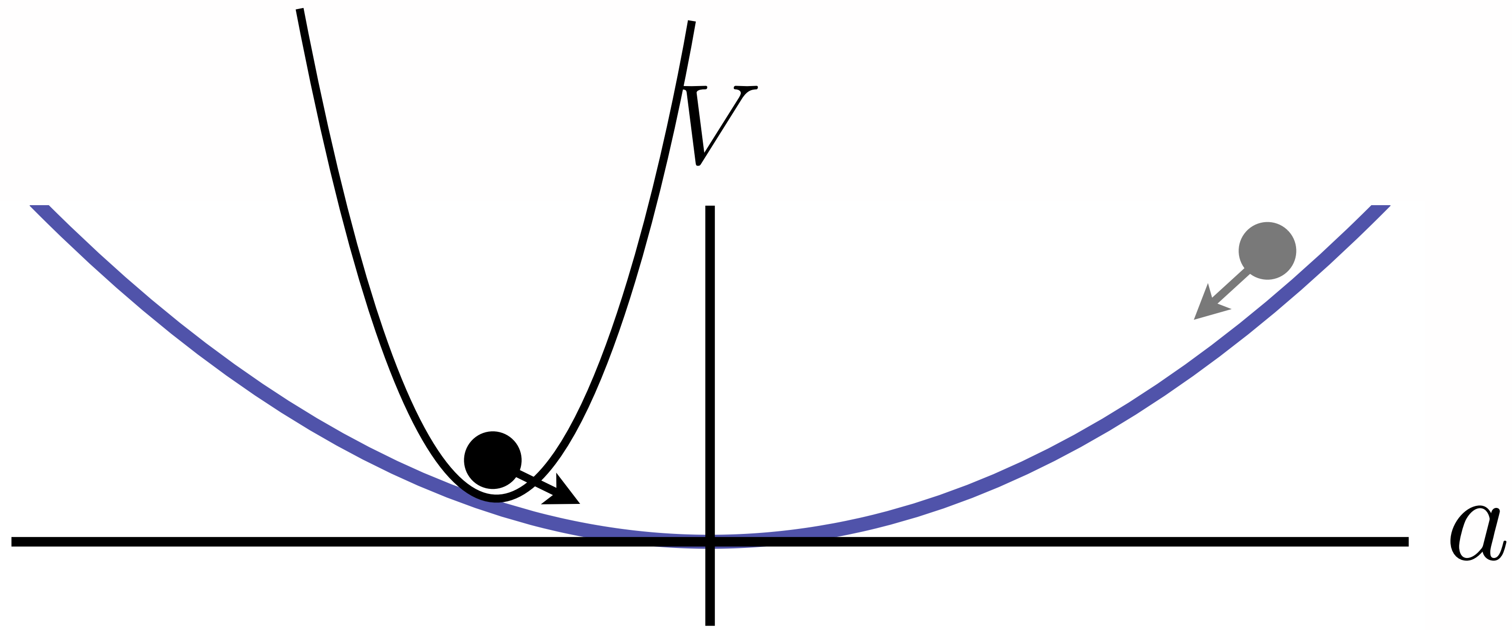
e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

Bound depends upon high energy physics, while strong CP, axion dark matter rely upon low energy physics.

QCD axion offers unique probe of high energy cosmology,
an era difficult even for gravitational wave detectors

QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.



e.g. thermal monopole density, high temperature mass, and many others

Fischler & Preskill (1983)

e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

Bound depends upon high energy physics, while strong CP, axion dark matter rely upon low energy physics.

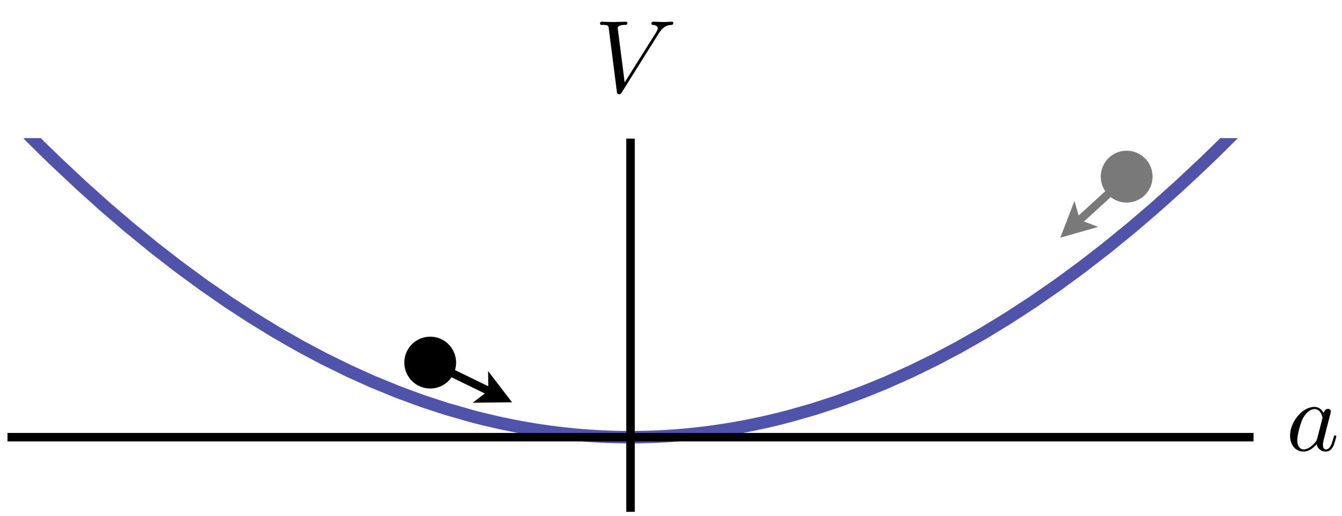
QCD axion offers unique probe of high energy cosmology, an era difficult even for gravitational wave detectors

Two Tenets of Axion Cosmology

1. $m_a << H$: Field is constant as universe expands. Retains energy density.

2. $m_a >> H$: Field oscillates, amplitude damps, energy density decreases like matter.

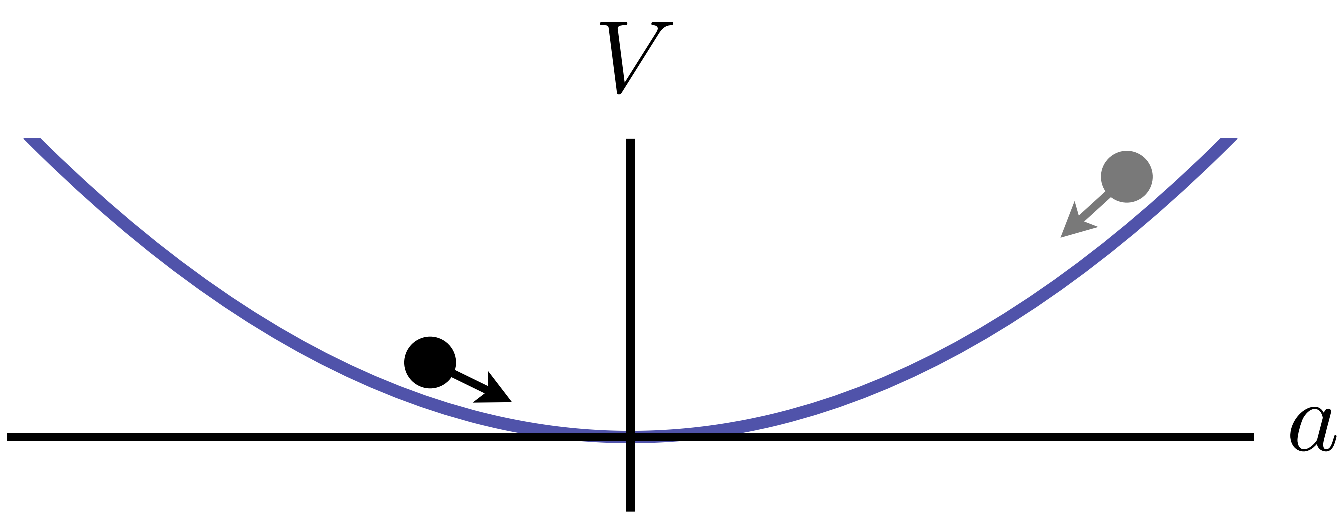
Two Tenets of Axion Cosmology



1. $m_a \ll H$: Field is constant as universe expands. Retains energy density.

2. $m_a \gg H$: Field oscillates, amplitude damps, energy density decreases like matter.

Two Tenets of Axion Cosmology



1. m_a << H: Field is constant as universe expands. Retains energy density.

2. m_a >> H: Field oscillates, amplitude damps, energy density decreases like matter.

m_a can be strongly temperature dependent (e.g. QCD axion)

If m_a is on earlier, there is more damping, fewer overproduction issues

QCD Axion Over-Production

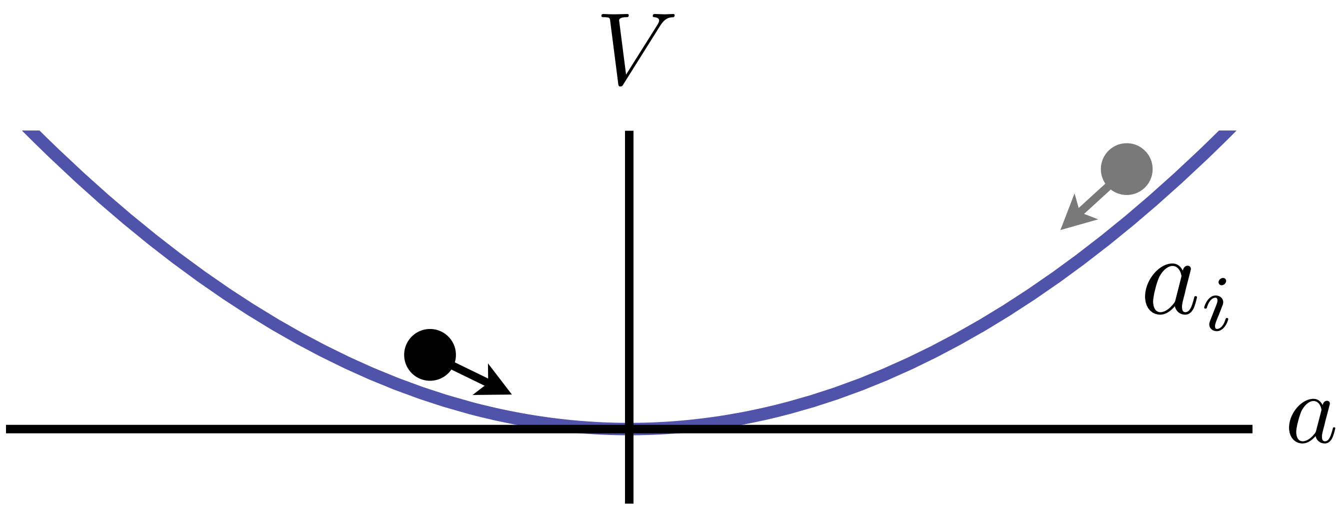
m_a rapidly turns on

a_i

around ~ $\Lambda_{\rm QCD}$

Rate set by f_a and $\Lambda_{\rm QCD}$

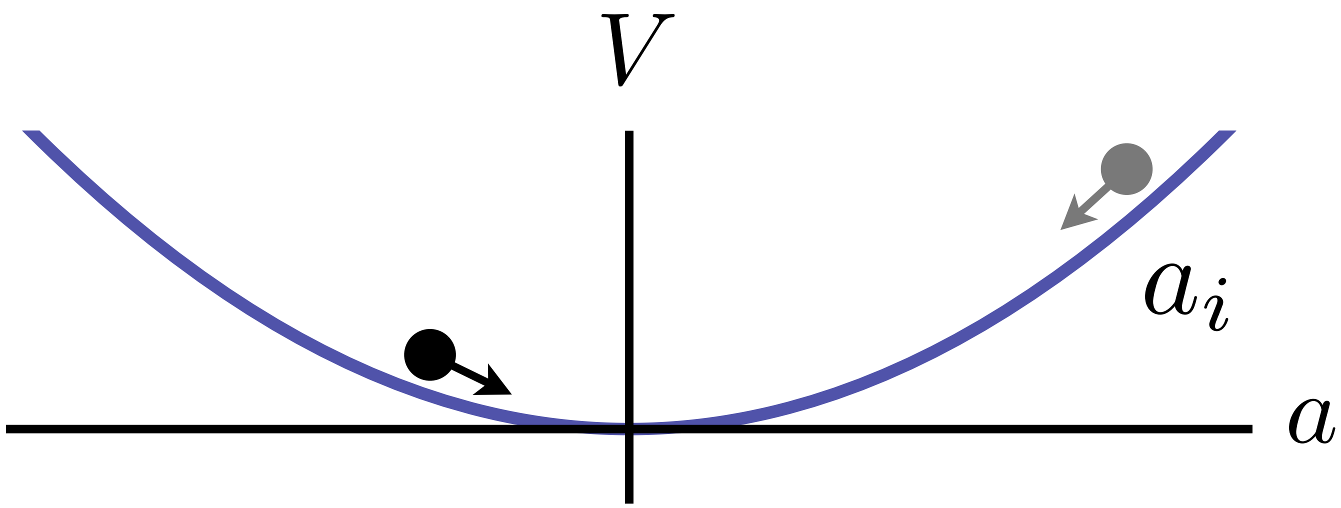
QCD Axion Over-Production



m_a rapidly turns on around ~ $\Lambda_{\rm QCD}$

Rate set by f_a and $\Lambda_{\rm QCD}$

QCD Axion Over-Production



m_a rapidly turns on

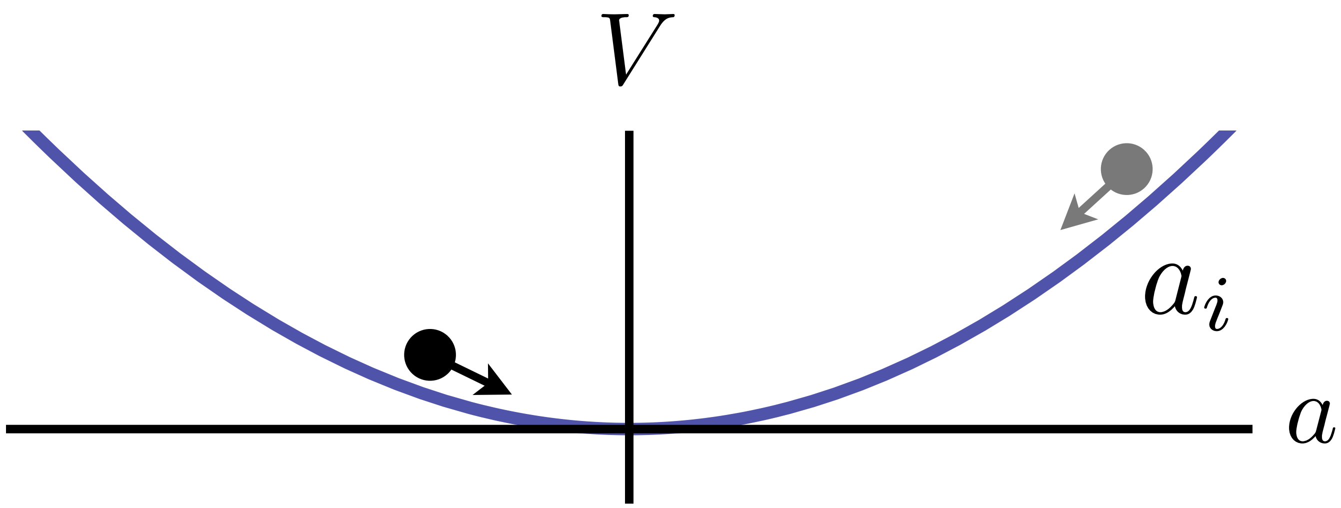
around ~ $\Lambda_{\rm QCD}$

Rate set by f_a and $\Lambda_{\rm QCD}$

requires $\left(\frac{a_i}{f_a}\right)\sqrt{\frac{f_a}{M_{\rm Pl}}} \sim 10^{-3.5}$ late time entropy production eases this

e.g. $\frac{f_a}{M_{\rm Pl}} \sim 10^{-7}$ $\frac{a_i}{f_a} \sim 1$ or $\frac{f_a}{M_{\rm Pl}} \sim 10^{-3}$ $\frac{a_i}{f_a} \sim 10^{-2}$

QCD Axion Over-Production



m_a rapidly turns on around ~ $\Lambda_{\rm QCD}$

Rate set by f_a and $\Lambda_{\rm QCD}$

requires $\left(\frac{a_i}{f_a}\right)\sqrt{\frac{f_a}{M_{\rm Pl}}} \sim 10^{-3.5}$ late time entropy production eases this

e.g. $\frac{f_a}{M_{\rm Pl}} \sim 10^{-7}$ $\frac{a_i}{f_a} \sim 1$ or $\frac{f_a}{M_{\rm Pl}} \sim 10^{-3}$ $\frac{a_i}{f_a} \sim 10^{-2}$

all f_a in DM range (all axion masses ≲ meV) equally reasonable

inflationary cosmology does not prefer flat prior in Θ_i over flat in f_a

Bounds on axion-like-particles are highly model dependent