A New Operator for Axion Dark Matter Detection

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with

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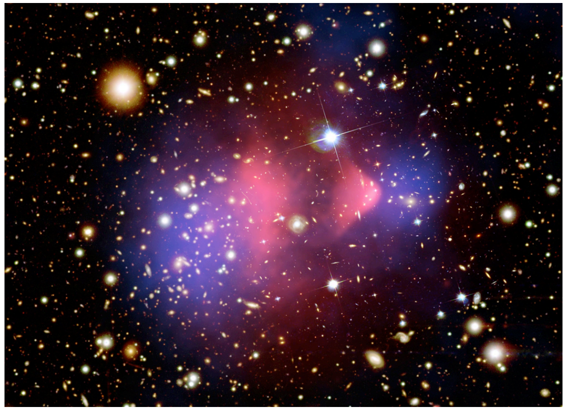
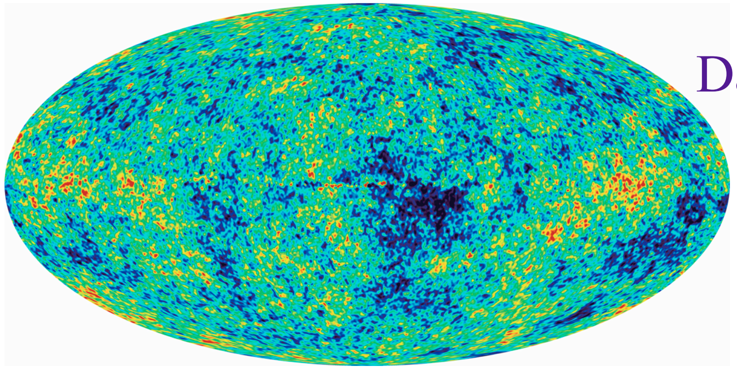
PRD **84** (2011) arXiv:1101.2691
+ to appear

Dark Matter Motivation



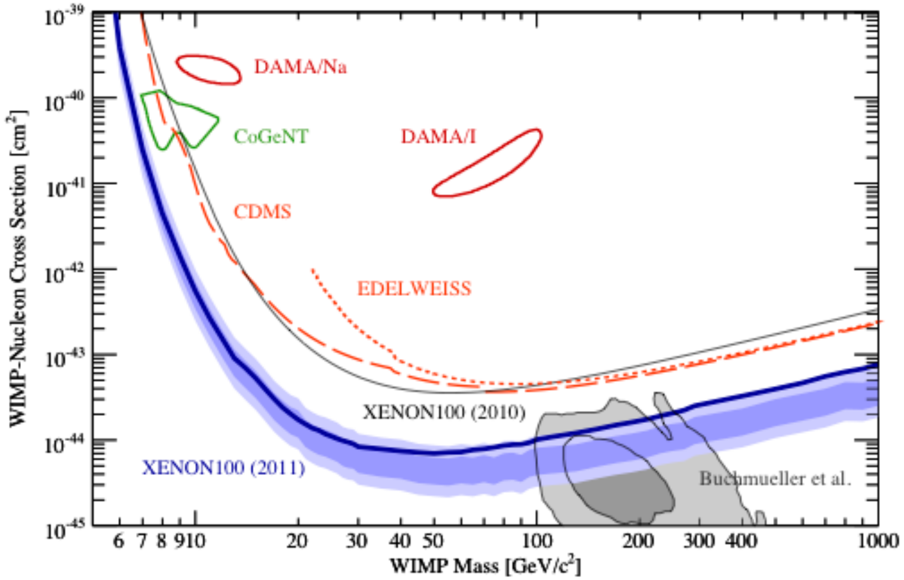


Dark Matter requires physics beyond the Standard Model

and

it's almost the only such proof

two best candidates: WIMPs and Axions



many experiments search for WIMPs

currently challenging to discover axions in most of parameter space

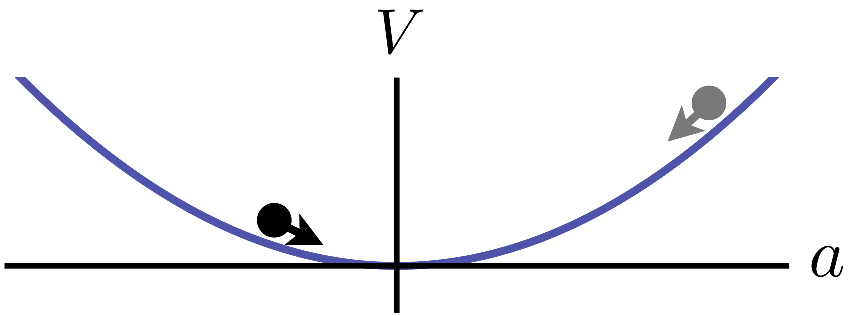
Important to find new ways to detect axions

Cosmic Axions

$$\mathcal{L} \supset m_a^2 a^2 \quad \text{with} \quad m_a \sim \frac{(200\ \text{MeV})^2}{f_a} \sim \text{MHz}\left(\frac{10^{16}\ \text{GeV}}{f_a}\right)$$

misalignment production:

after inflation axion is a constant field, mass turns on at $T \sim \Lambda_{QCD}$ then axion oscillates



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

Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

the axion is a good cold dark matter candidate

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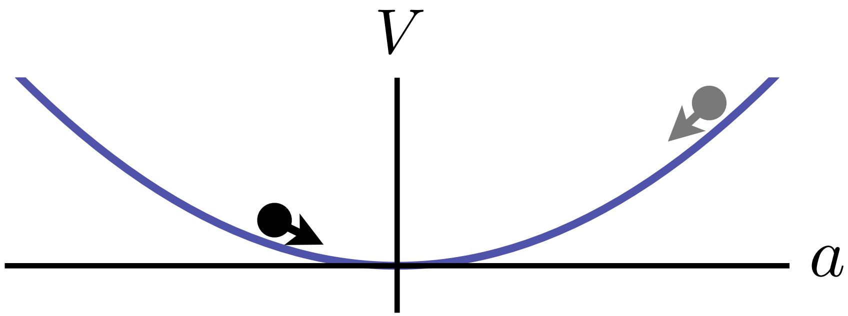

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axion easily produces correct abundance $\rho = \rho_{\text{DM}}$

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

we assume:

1. PQ transition does not occur after inflation (or axion strings decay to axions)
2. gravitational waves not observed in CMB (axions ⇒ isocurvature or non-gaussian)

Fox, Pierce, & Thomas (2006)

Axions From High Energy Physics

Easy to generate axions from high energy theories

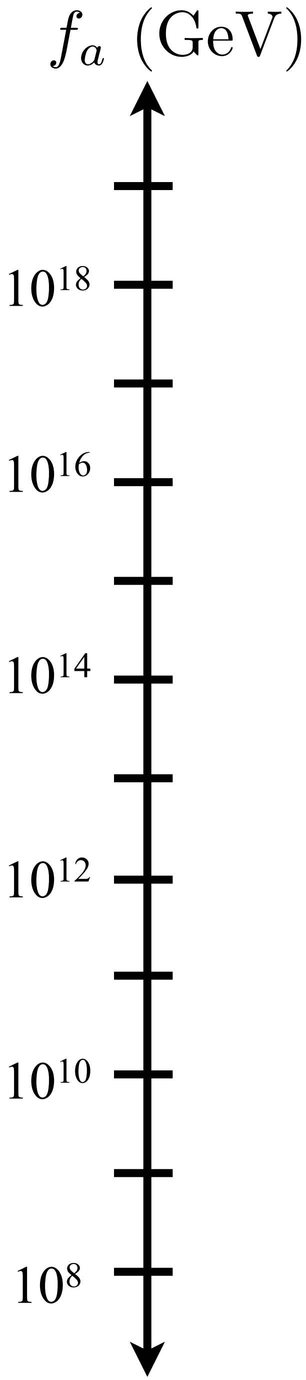
have a global PQ symmetry broken at a high scale f_a

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

Svrcek & Witten (2006)

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

Constraints and Searches



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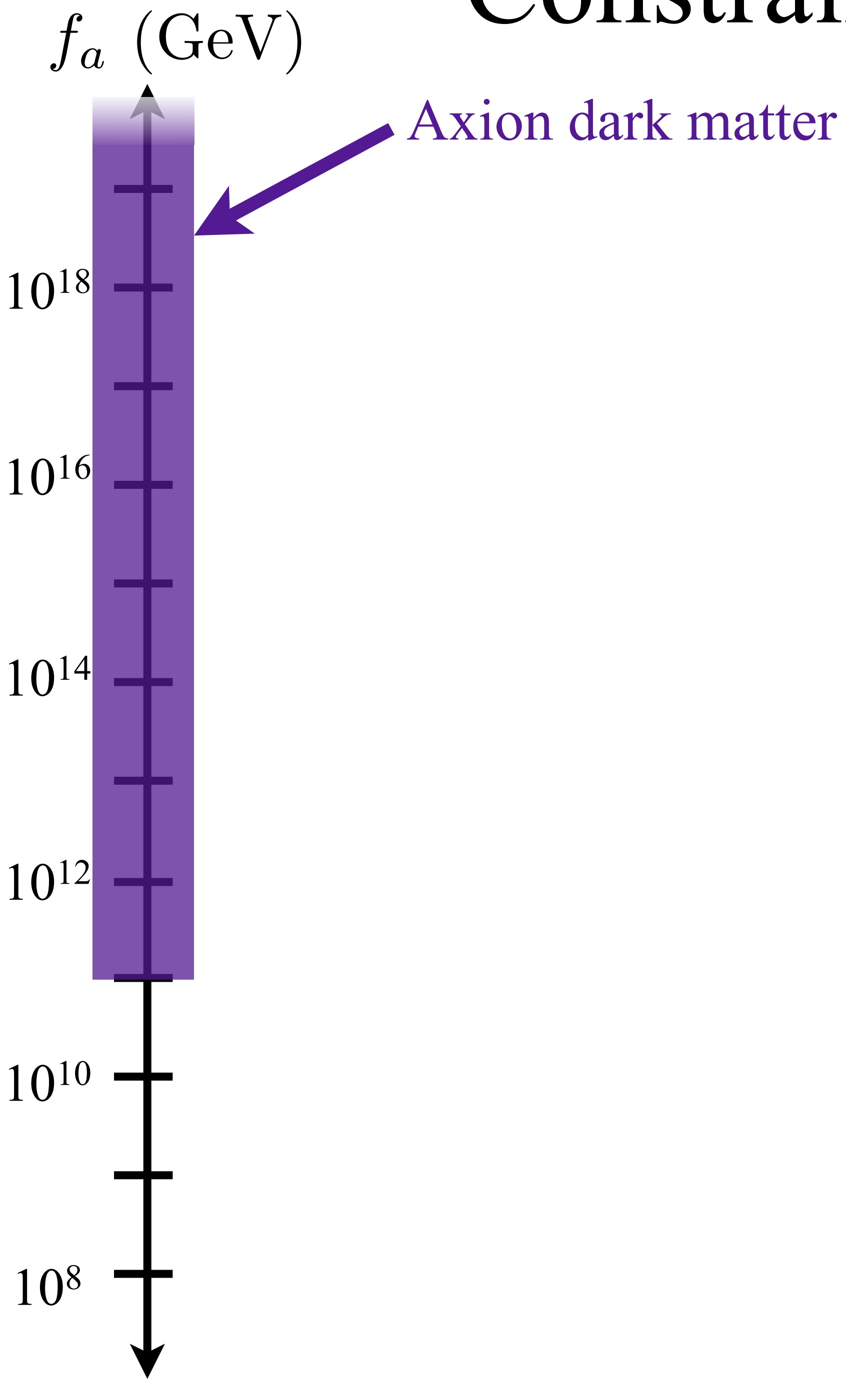

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axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

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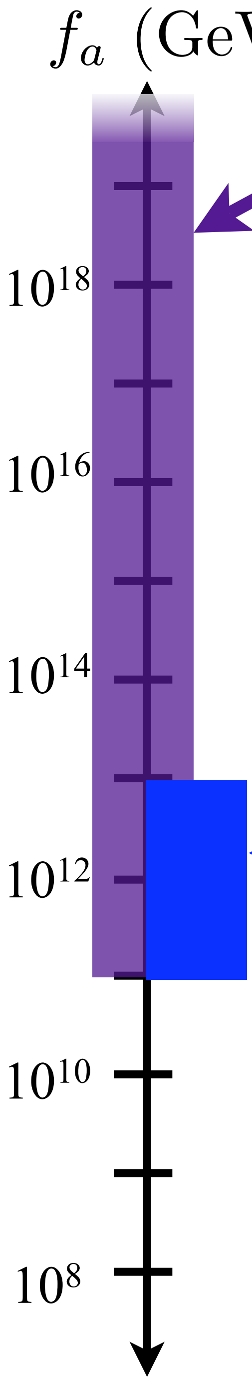

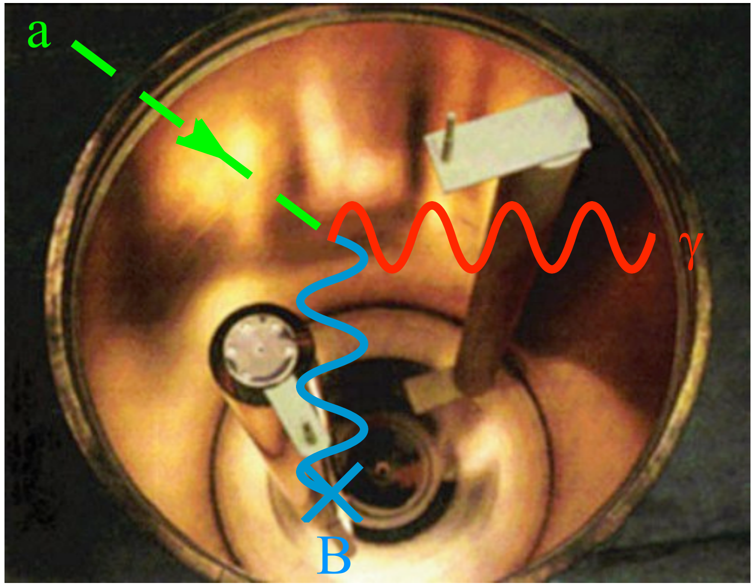

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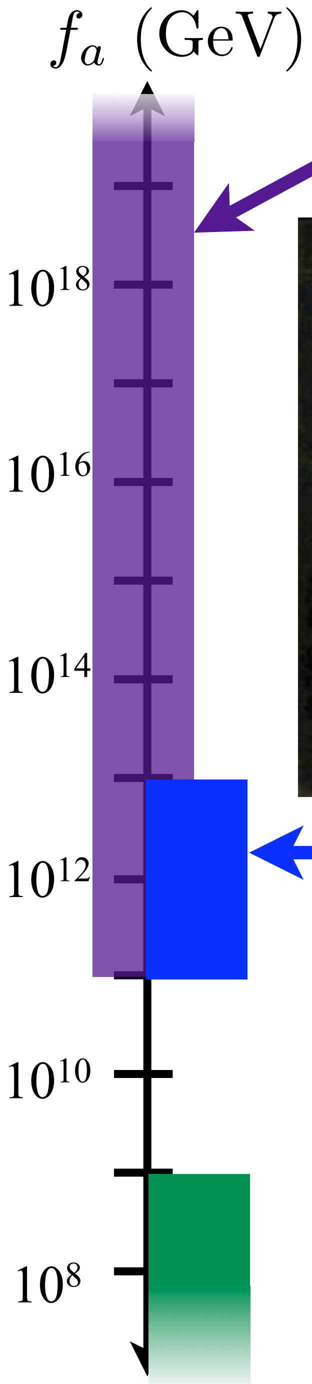

Axion dark matter

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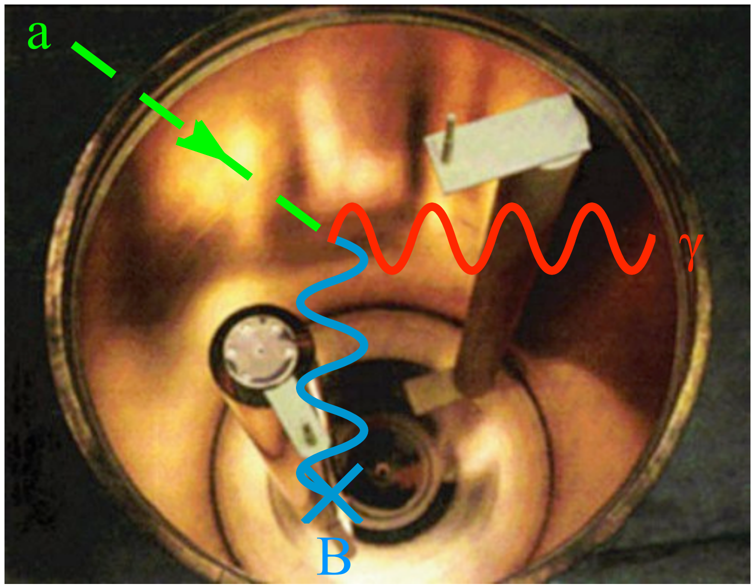

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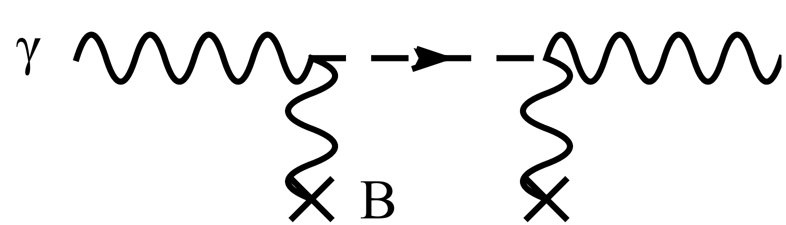
laser experiments:



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

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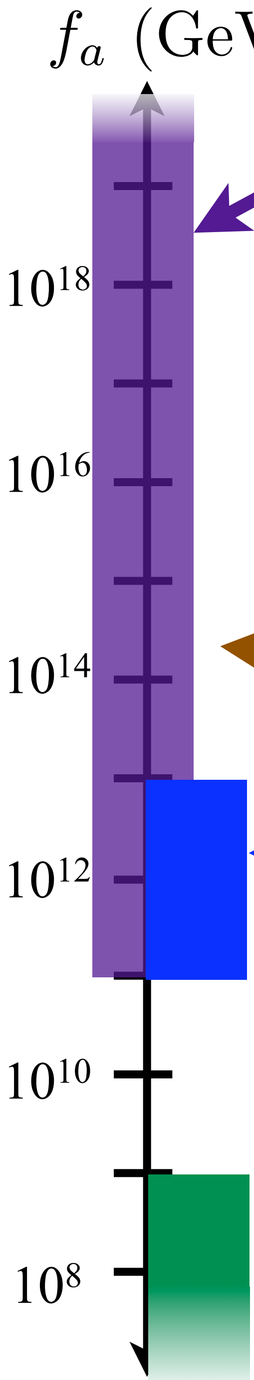

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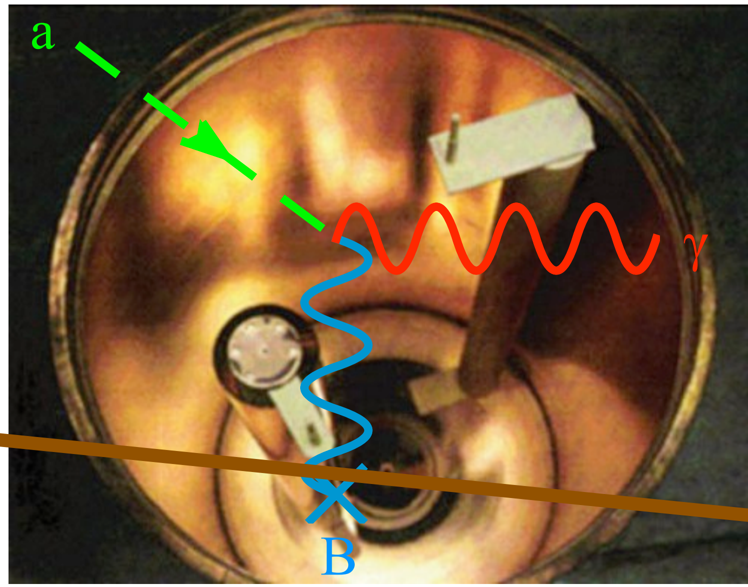

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S. Thomas

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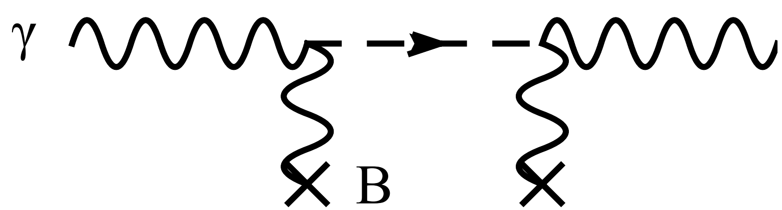

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Other ways to search for high f_a axions?

A Different Operator For Axion Detection

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: $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G} + m_a^2 a^2$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \frac{a}{f_a} \, e \, \mathrm{cm}$

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

the axion gives all nucleons a rapidly oscillating EDM independent of f_a

A Different Operator For Axion Detection

the axion gives all nucleons a rapidly oscillating EDM

thus all (free) nucleons radiate

standard EDM searches are not sensitive to oscillating EDM

We’ve considered two methods for axion detection:

1. EDM affects atomic energy levels (significantly different from standard EDM searches)

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2. collective effects of the EDM in condensed matter systems (Preliminary)

“Atomic Clock” Setup

Unlike a normal EDM search, can look directly for the axion, without external EM fields to modulate the signal

PWG & S. Rajendran PRD **84** (2011)

instead use internal fields, much larger: $$E_{\text{int}} \sim \frac{e}{\text{Å}^2} \sim 10^{12}\,\frac{\text{V}}{\text{m}}$$

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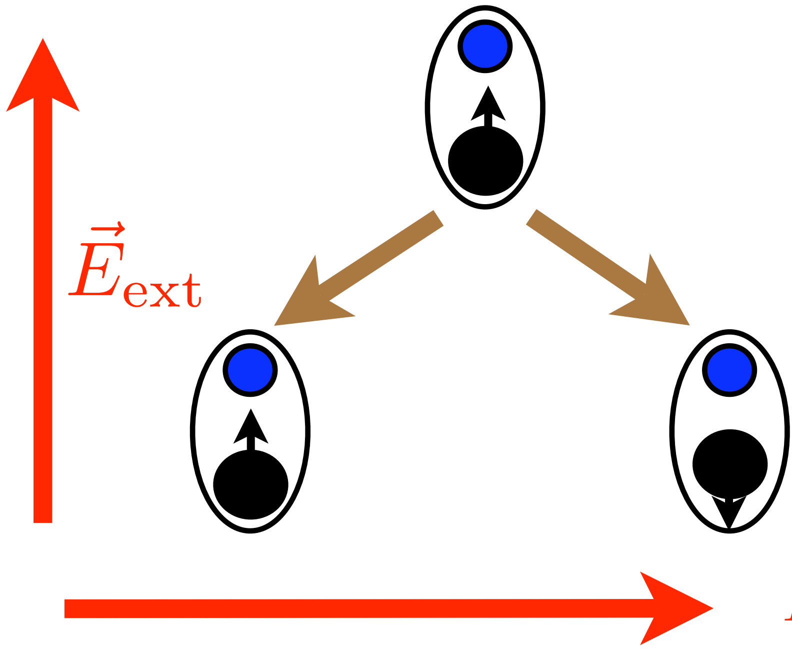

There are two important caveats:
Parity: requires molecules
Schiff’s Theorem: requires Actinides

$$\vec{B}_{\text{ext}} \sim 0.1\text{T}\left(\frac{10^{16}\ \text{GeV}}{f_a}\right)$$

NMR spin precession ⇒ coherent phase addition at frequency m_a

Scan frequency by changing B: up to ~1 MHz (10 MHz?) achievable

cross-correlate between two different experiments

Molecular Axion Searches

differential measurement cancels backgrounds, preserves signal since axion effects different between the two species

induces a shift to the energy levels: $\delta\omega \sim \vec{E}_{\text{int}} \cdot \vec{d}_n \sim 10^{-24}\ \text{eV}$

shot noise limit is $\delta\omega \sim \left(1\ \text{s} \cdot \sqrt{10^{14}\ \text{atoms}}\right)^{-1} \sim 7 \times 10^{-23}\ \text{eV}$

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Possible Future Improvements:

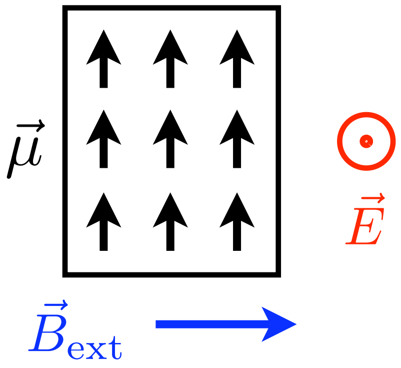
- cool more molecules? steadily improving...
- better traps: O(10-100) improvement from longer interrogation times
- O(10) from using ^{229}Pa
- Squeezed atom states?

$$\text{Shot Noise} \sim \frac{1}{N} \text{ instead of } \frac{1}{\sqrt{N}}$$

Vuletic group at MIT demonstrated O(5)

Condensed Matter Techniques (Preliminary)

high nuclear spin alignment achieved in several systems



applied E field causes precession of nucleus

SQUID measures resulting B field change

builds on e^- EDM experiments Lamoreaux (2002)

resonant enhancement: $\propto \dfrac{nEd}{|\mu B_{\text{ext}} - m_a|}$

signal scales with large density of nuclei:

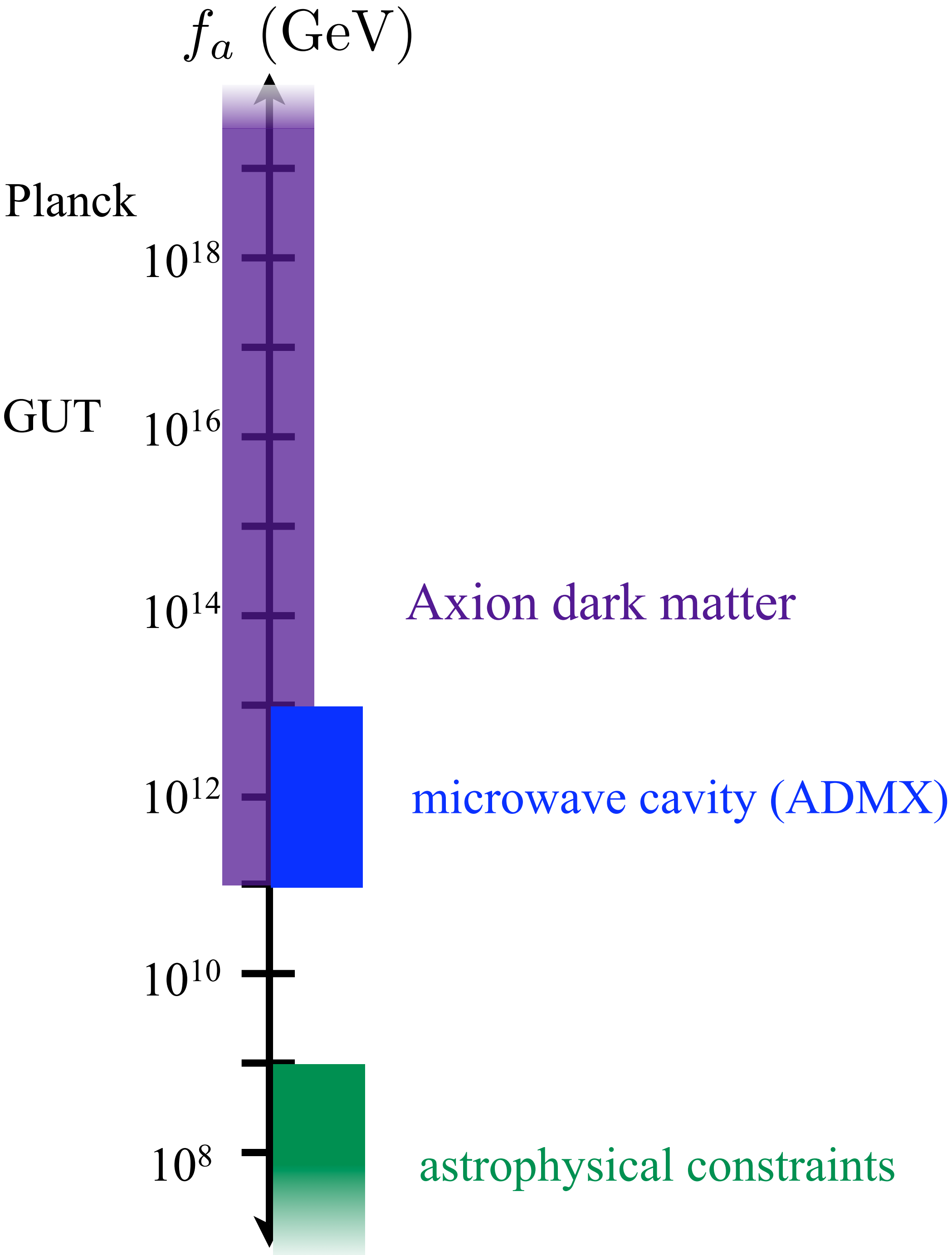
non-resonant experiment also possible

measure correlations between two independent experiments

differential measurement removes backgrounds, requires uniform B-field

sensitivity and backgrounds appear promising

Axion Searches with Gluon Coupling



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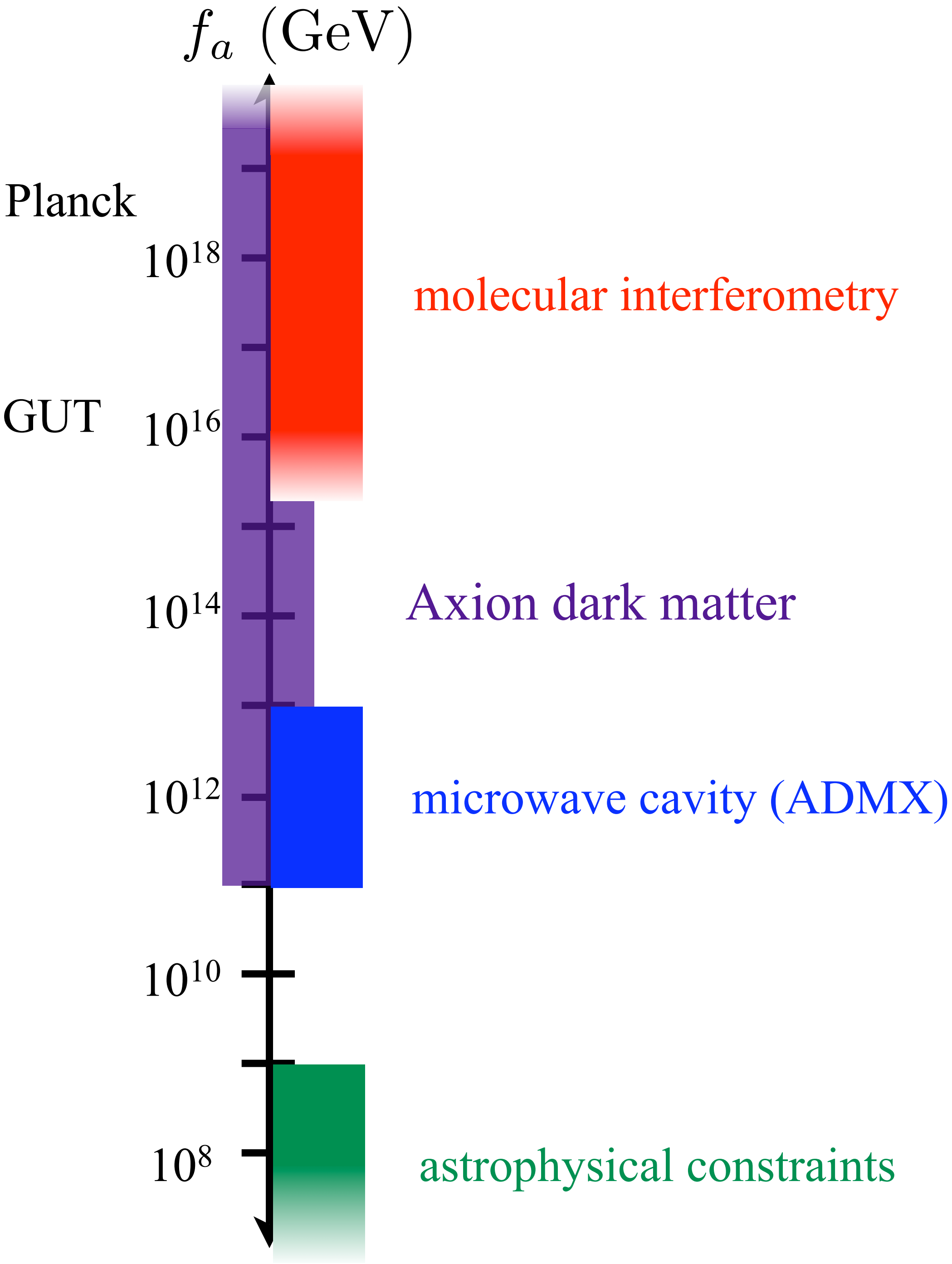

can most easily search in kHz - GHz frequencies ➞ high f_a

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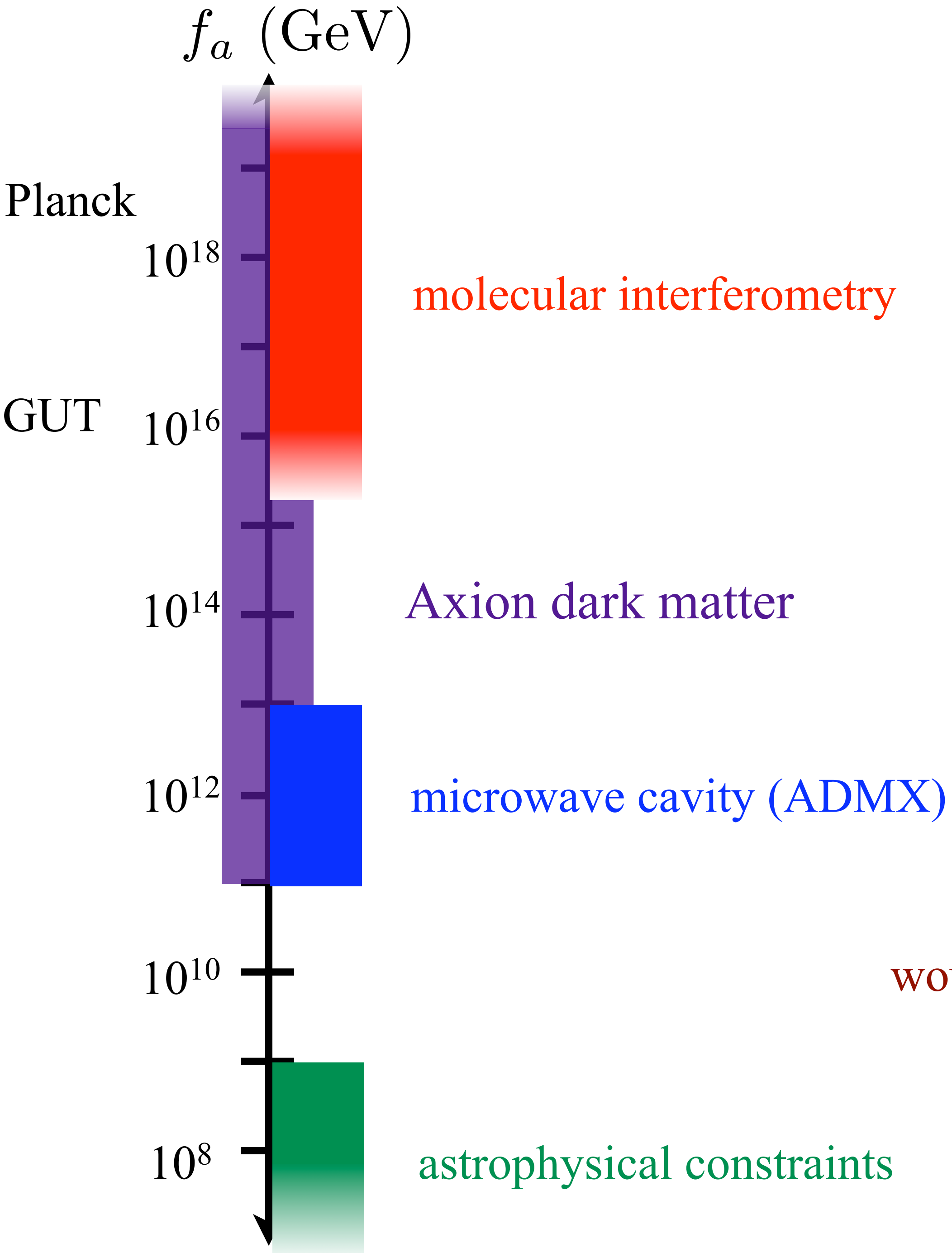


can most easily search in kHz - GHz frequencies ➙ high f_a

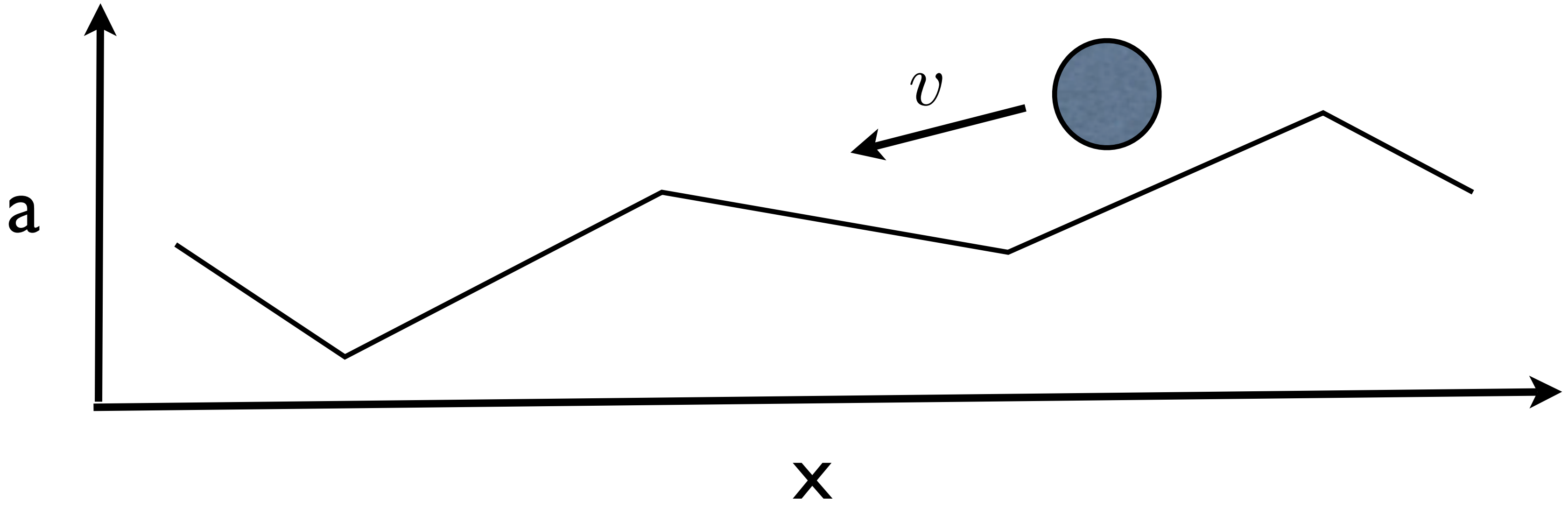
difficult technological challenges, similar to early stages of WIMP detection

axion dark matter is very well-motivated, no other way to search for at high f_a

would be both the discovery of dark matter and a glimpse into physics at very high energies

Axion Coherence

How large can T be?



Spatial homogeneity of the field?

$$\text{Classical field a(x) with velocity v} \sim 10^{-3} \Longrightarrow \frac{\nabla a}{a} \sim \frac{1}{m_a\, v}$$

spread in frequency (energy) of axion = $\frac{\Delta\omega}{\omega} \sim \frac{\frac{1}{2} m_a v^2}{m_a} \sim 10^{-6}$

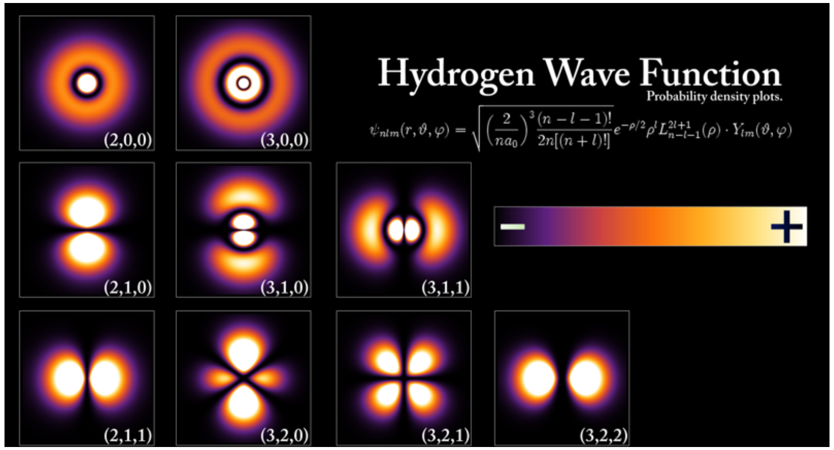
$$T \sim \frac{1}{m_a\, v^2} = 1\ \text{s} \left(\frac{f_a}{10^{16}\ \text{GeV}}\right)$$

Parity Breaking

Axion breaks parity (CP)

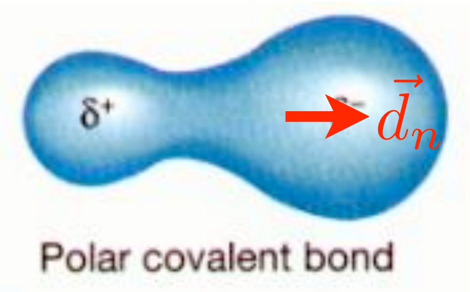
Atomic states have very little parity breaking

thus $\vec{E}_{\rm int} \cdot \vec{d}_n \approx 0$



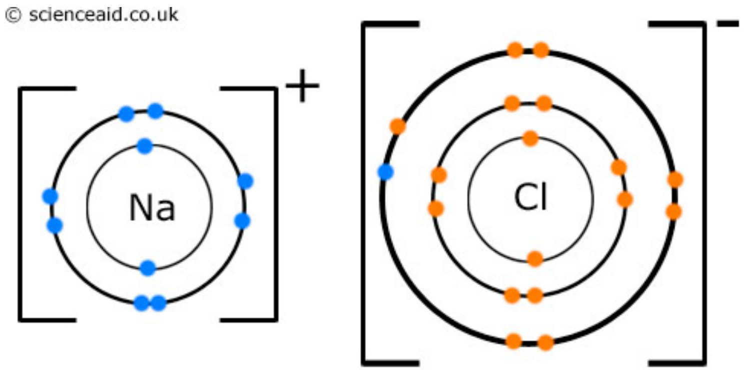
One possible solution:

molecules can naturally break parity at O(1), though more difficult to work with due to low-lying modes



Must control molecular rotation with applied E field (~ 10^6 V/m)

Use applied B field (< 0.1 T) to rotate nuclear spin with axion's frequency (easily scanned)



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higher moments take into account corrections to this (e.g. finite size of nucleus...)

Schiff moment: $\delta\omega \sim E_{\rm int}\, d_S \sim \left(10^{-9}\, Z^3\right) E_{\rm int}\, d_n$

often use Hg or Tl $\delta\omega \sim 10^{-3}\, E_{\rm int}\, d_n \sim 10^{-27}\ {\rm eV}$

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^{225}Ra	0.2	2×10^{-25} eV
^{239}Pu	0.3	3×10^{-25} eV
^{223}Fr	0.4	4×10^{-25} eV
^{225}Ac	0.6	6×10^{-25} eV
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NIST cooled polar ^{40}K^{87}Rb to < μK