New Ideas in Axion Searches

Axion Motivation

A Series of “Why?”s

Few aspects of experience are as striking as the asymmetry between past and future.

If you run a movie of everyday life backwards, it does not look like everyday life.


STOP

Yet time-reversal symmetry (T) was a notable property of the fundamental laws of physics for several centuries, starting with Newtonian mechanics, and continuing through general relativity and quantum electrodynamics.

Why?

As long as T symmetry appeared to be an exact, fundamental feature of physical law, it was unclear that asking “Why?” would be fruitful.

T symmetry might be rock bottom.

In 1964, James Cronin and Val Fitch discovered a subtle effect in K meson decays that slightly violates T symmetry.

$\Rightarrow$ T symmetry is **not** rock bottom.

It's not even quite true - just very nearly so.

Why?

We've *almost* nailed it.

The basic, sacred* principles of modern physics - relativity + quantum mechanics + local symmetry - are very powerful.

There are exactly two possible sources of T symmetry violation, that are consistent with those principles.

One of them beautifully explains what Cronin and Fitch observed, and a lot more.

The other doesn’t happen.

> (If it did, we would observe electric dipole moments of nuclei which are far larger than experiments allow.)

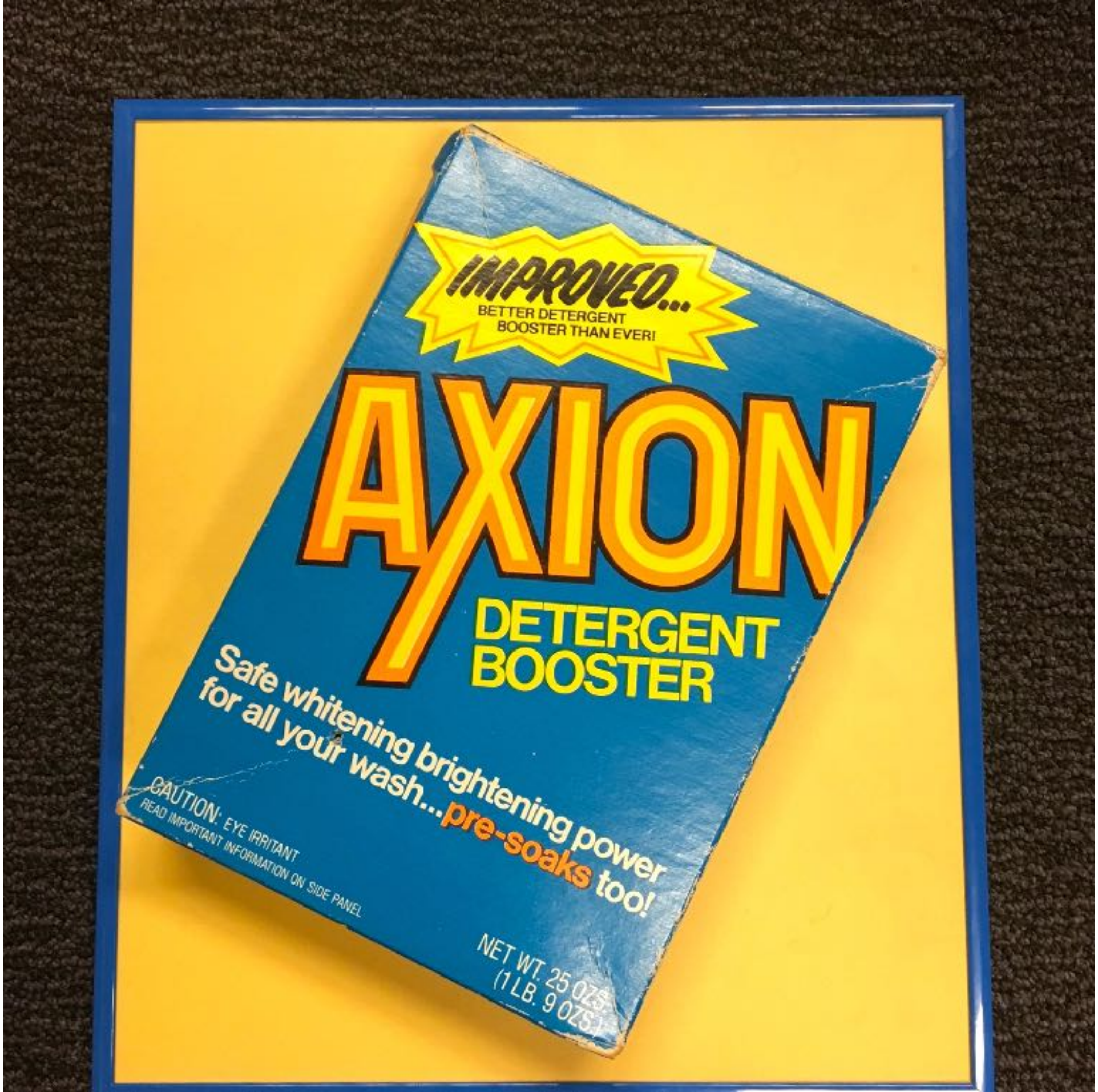
Why?

Over the past 40+ years, there have been several attempts to explain why, but only one has stood the test of time.

We promote the unwanted term to a *dynamical* entity - a “field”, which *evolves* to zero.

The new field is made of a new kind of particle.

I named it the *axion,* in homage to a laundry detergent:


IMPROVED...
BETTER DETERGENT
BOOSTER THAN EVER!
AXION
DETERGENT
BOOSTER
Safe whitening brightening power
for all your wash...pre-soaks too!
CAUTION: EYE IRRITANT
READ IMPORTANT INFORMATION ON SIDE PANEL
NET WT. 25 OZS.
(1 LB. 9 OZS.)

Axion Properties

Because axions are so closely tied to symmetry and its breaking, we can say a lot about their properties.

For most practical purposes, we arrive at a one-parameter theory.

The parameter, usually denoted F (or f), has dimensions of mass.

It is associated with the mass scale at which potential T-violating effects first arise.

$$\mathcal{L}_{\mathrm{kin}} = \frac{1}{2}\left(g^{\mu\nu}\partial_\mu a \partial_\nu a + m^2 a^2\right)$$

$$m_a^2 \sim \frac{(\Lambda_{QCD})^4}{F^2}$$

$$\mathcal{L}_{\mathrm{int}} \sim -\frac{a}{F}\left(c_G\, \alpha_s G_{\mu\nu}\tilde{G}^{\mu\nu} + c_\gamma\, \alpha F_{\mu\nu}\tilde{F}^{\mu\nu} + d_q \sum_q m_q\, \bar{q}\gamma_5 q + d_l \sum_l m_l\, \bar{l}\gamma_5 l + \ldots\right)$$

The electromagnetic part is especially elegant, and it is central to several search strategies.

It also arises, with “emergent” axions, in condensed matter physics, as the effective theory of topological insulators.

$$\mathcal{L} = \kappa\, a\, \vec{E} \cdot \vec{B} = \frac{\kappa}{2}\, a\, \epsilon^{\alpha\beta\gamma\delta} F_{\alpha\beta} F_{\gamma\delta}$$

B induces charge

$$\nabla \cdot E = -\kappa\, \nabla a \cdot B$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

ADMX, abracadabra

$$\nabla \cdot B = 0$$

$$\nabla \times B = \frac{\partial E}{\partial t} + \kappa\, (\dot{a} B + \nabla a \times E)$$

E induces current (surface Hall effect)

Axions also induce electric dipole moments in nuclei, and possibly electrons.

Axion fields that vary in time and space will induce oscillatory effective EDMs.

Axion Cosmology

The axion field is established at the symmetry* breaking transition, according to $<\phi> = Fe^{i\theta} = Fe^{ia/F}$.

At the transition the energy associated with varying θ is negligible, and differences from the minimum $\theta \cong 0$ can be imprinted.

The stored field energy eventually materializes. Its energy density today is roughly proportional to $F \sin^2\theta_0$.

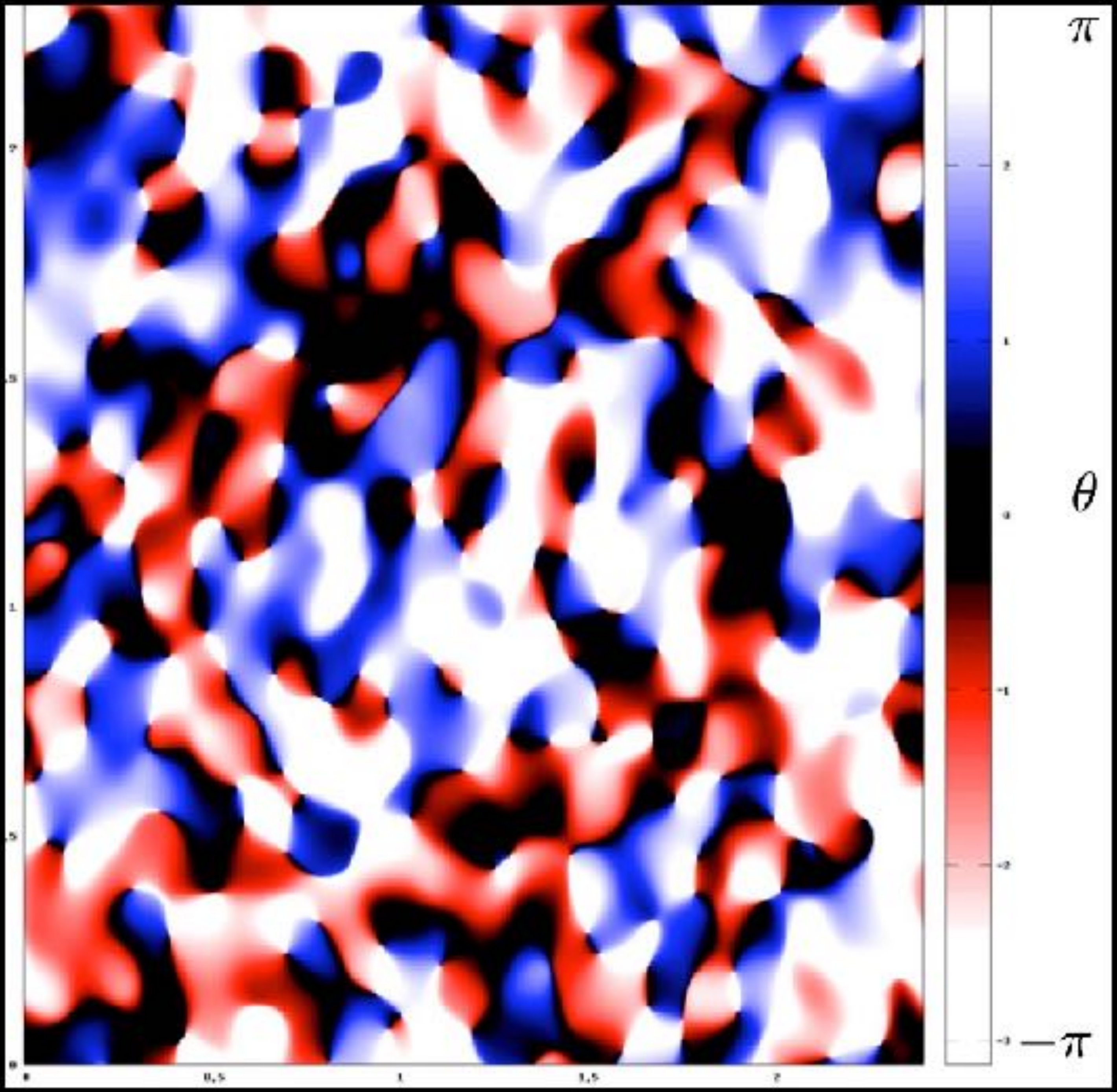
The energy is embodied in a cold Bose-Einstein condensate of axions.

The axion fluid is a source of cold dark matter. It may well be the dominant source.

There are two basic scenarios for axion cosmology.

post-inflationary scenario

Scenario A: PQ breaks after inflation



If no episode of inflation intervenes, then today's universe samples many past "universes". Thus we must average over θ_0.

We find that something close to $F \backsimeq 10^{12}$ GeV corresponds to the observed dark matter density.

(Note that since observations constrain $F \gtrsim 10^{10}$ GeV , it is hard to avoid significant axion dark matter, if axions exist at all.)

In recent work, estimates of the QCD parameters and of the axion field evolution have become considerably tighter.

The dark-matter axion mass

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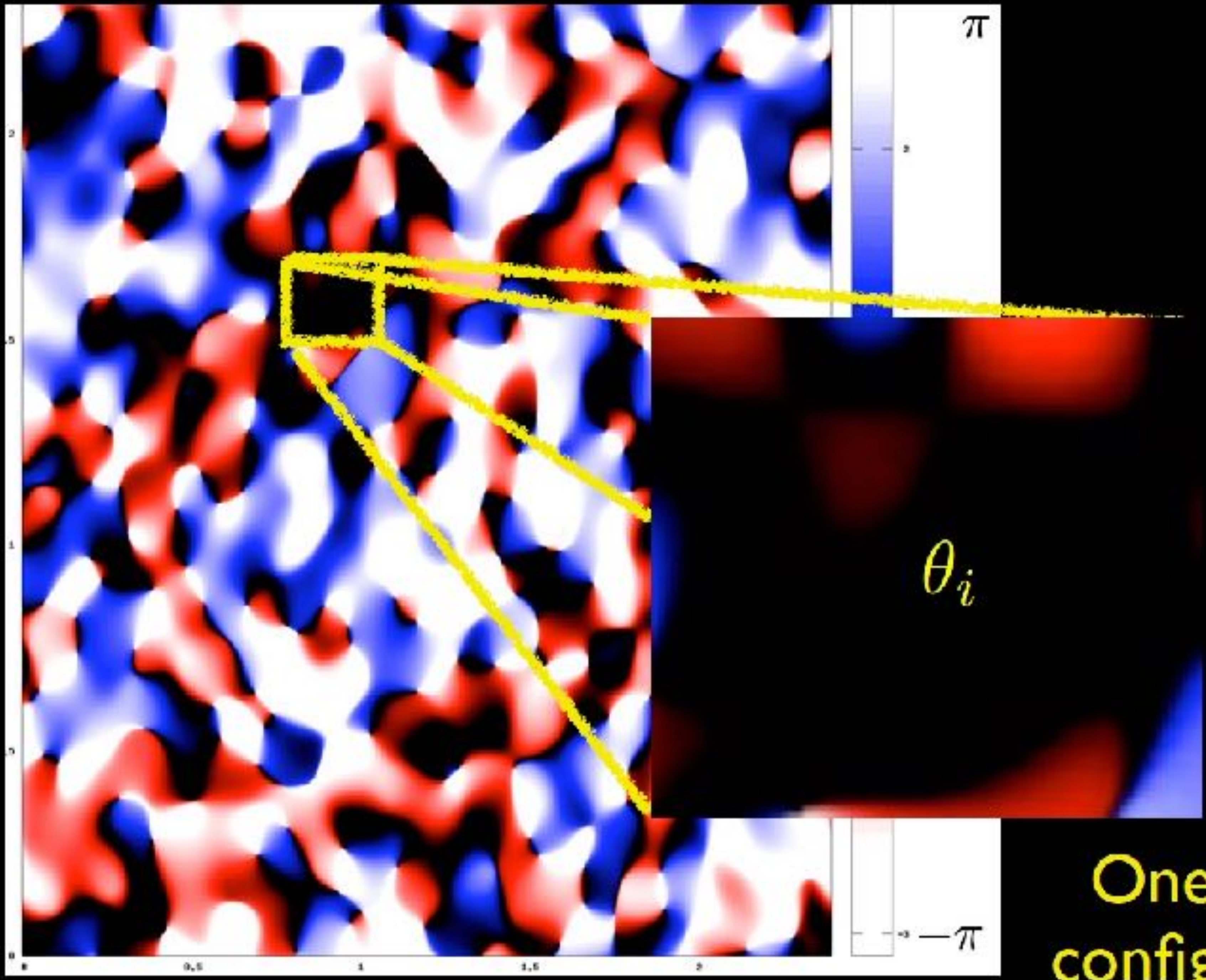
ABSTRACT: We evaluate the efficiency of axion production from spatially random initial conditions in the axion field, so a network of axionic strings is present. For the first time, we perform numerical simulations which fully account for the large short-distance contributions to the axionic string tension, and the resulting dense network of high-tension axionic strings. We find nevertheless that the total axion production is somewhat *less* efficient than in the angle-averaged misalignment case. Combining our results with a recent determination of the hot QCD topological susceptibility [1], we find that if the axion makes up all of the dark matter, then the axion mass is $m_a = 26.2 \pm 3.4\,\mu\mathrm{eV}$.

KEYWORDS: axions, dark matter, cosmic strings, global strings

If this holds up, we’ve got a bullseye to shoot at!

pre-inflationary scenario

Scenario B: PQ breaks during inflation



One initial configuration is singled out

If inflation does intervene, then today's universe samples a small patch of past "universes". We should *not* average over θ_0.

It is possible to have $F > 10^{12}$ GeV, compensated by a small value of θ_0.

In this case, selection arguments suggest that the most likely result is that axions dominate the dark matter.

The.pre-inflationary scenario has some desirable features, which may compensate for its reliance on selection:

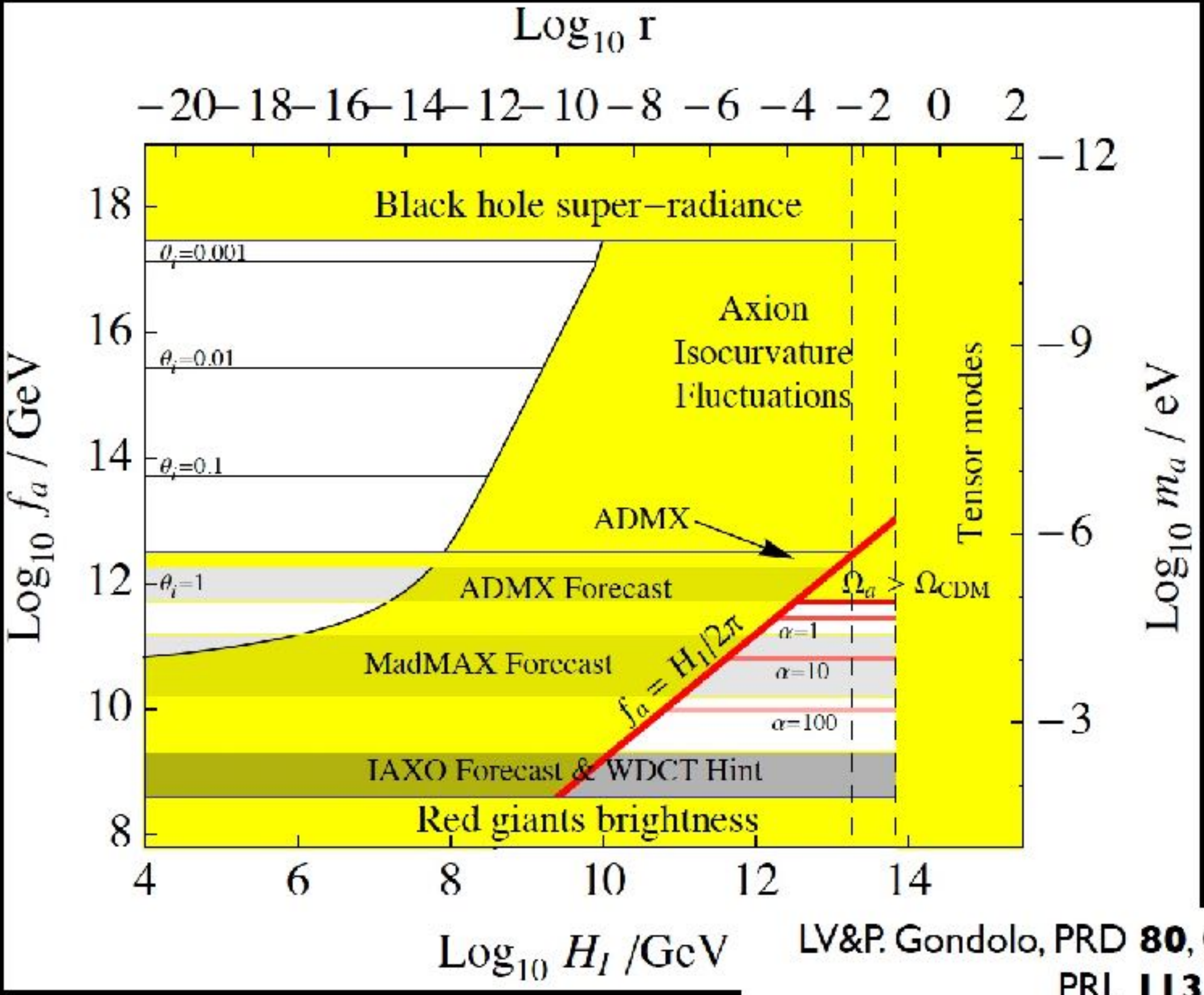
One can associate F with unification scales, i.e. $F \simeq 10^{16}$ GeV.

Possible complications with axion strings or domain walls get inflated away.

One finds a plausible explanation of the ratio of dark to baryonic matter.

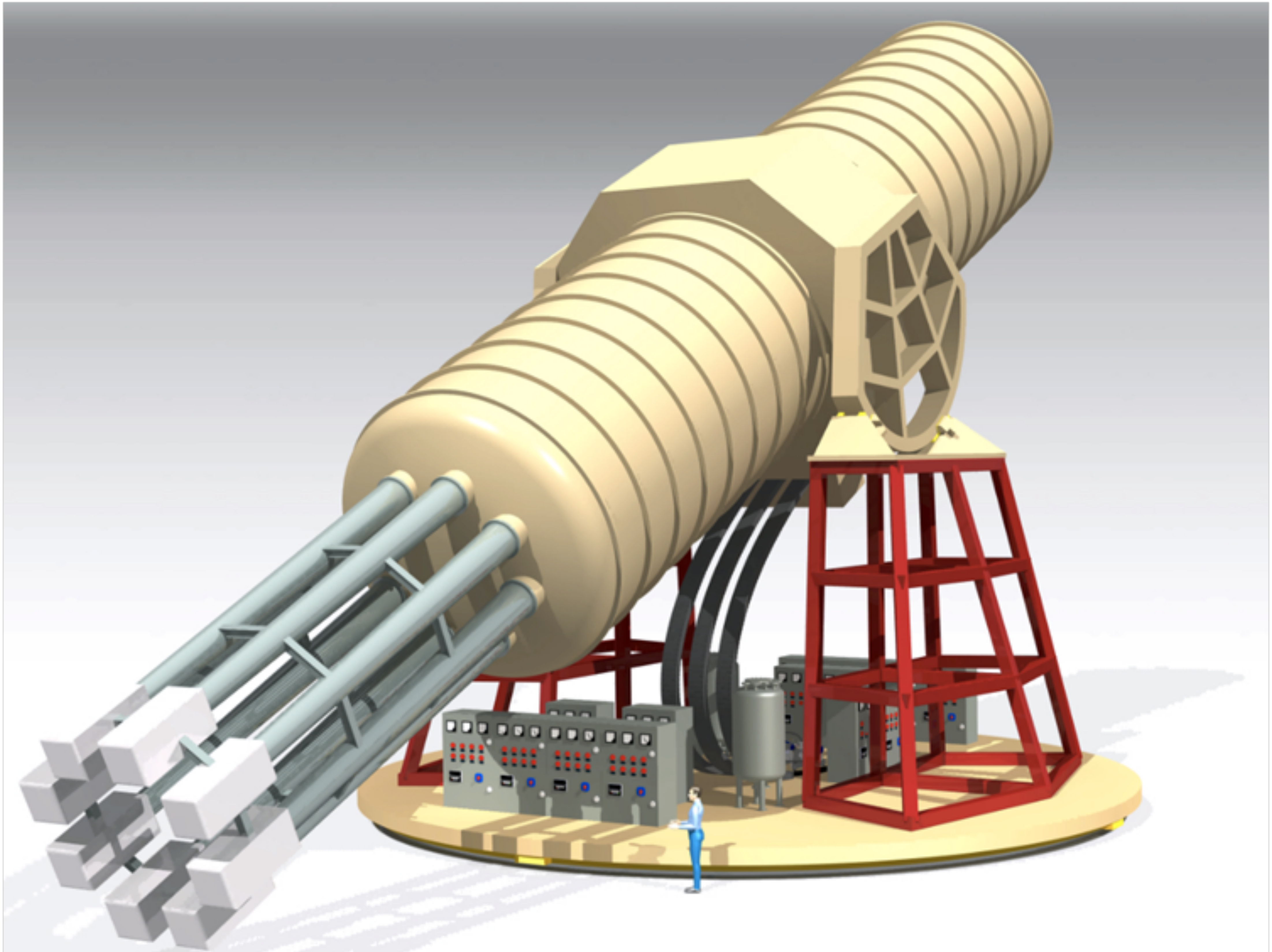
Constraints

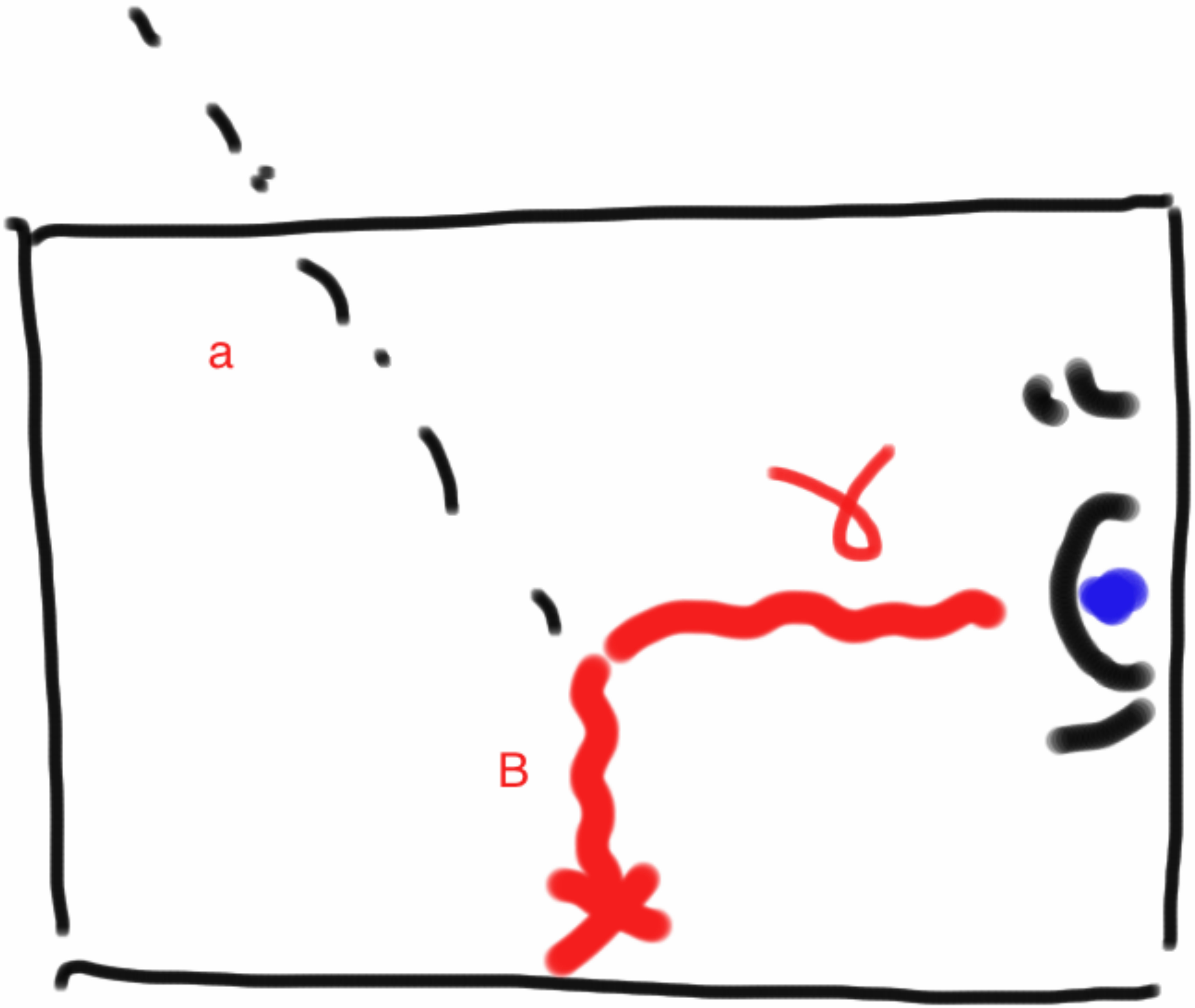
Axion parameter space



LV&P. Gondolo, PRD **80**, 035024 (2009); PRL **113**, 011802 (2014)

CAST and IAXO




a
B
γ

“Axion helioscopes” aim to detect axions emitted by the Sun.

A large magnetic field induces their conversion into (observable) photons.

ADMX


N
ADMX
WIZSCIENCE.COM

Cavity detectors aim to detect cosmic axion background axions.

A large magnetic field induces their conversion into (observable) photons.

Note: (m, 0) -> (m, m) doesn't go, so we need to do some electrical engineering, introducing appropriate inhomogeneities.

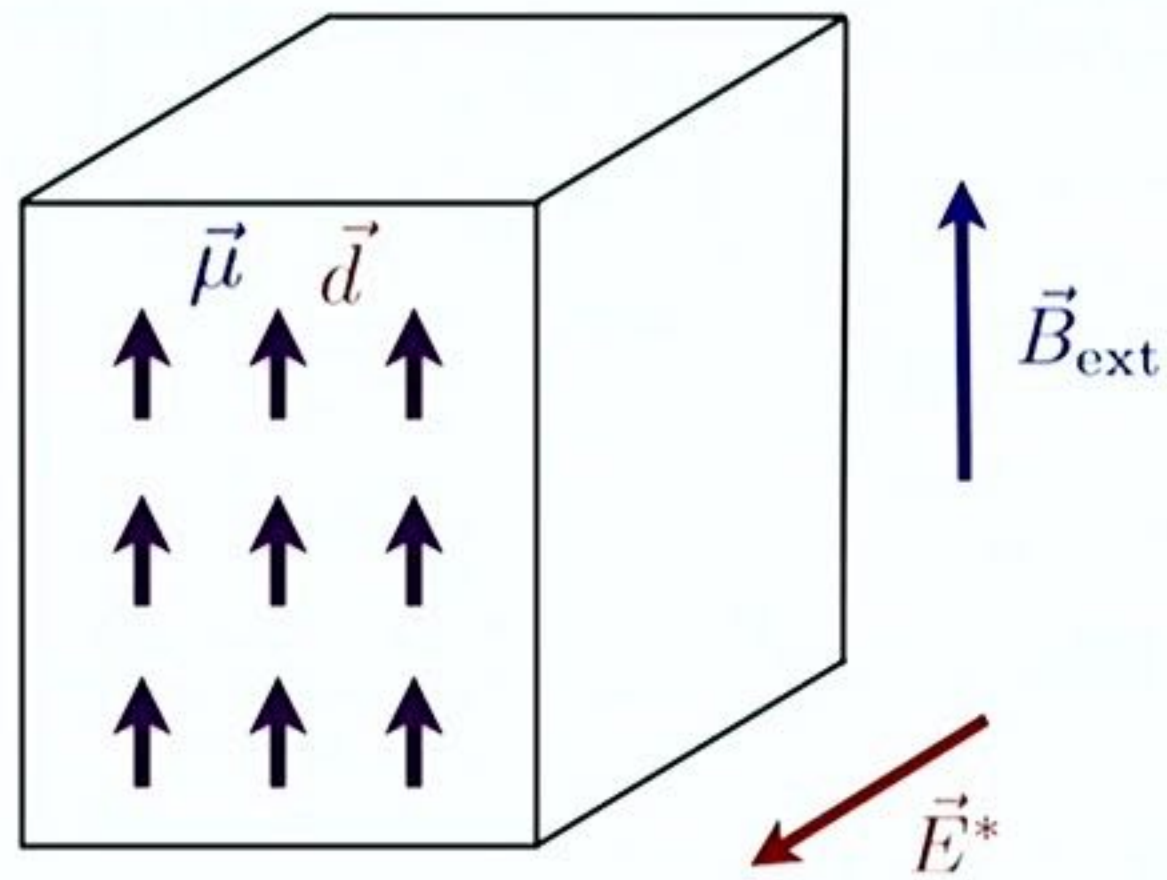
MadMAX

More fine-grained antennas can be tuned to higher frequencies.

CASPEr

Cosmic Axion Spin Precession Experiment (CASPEr)

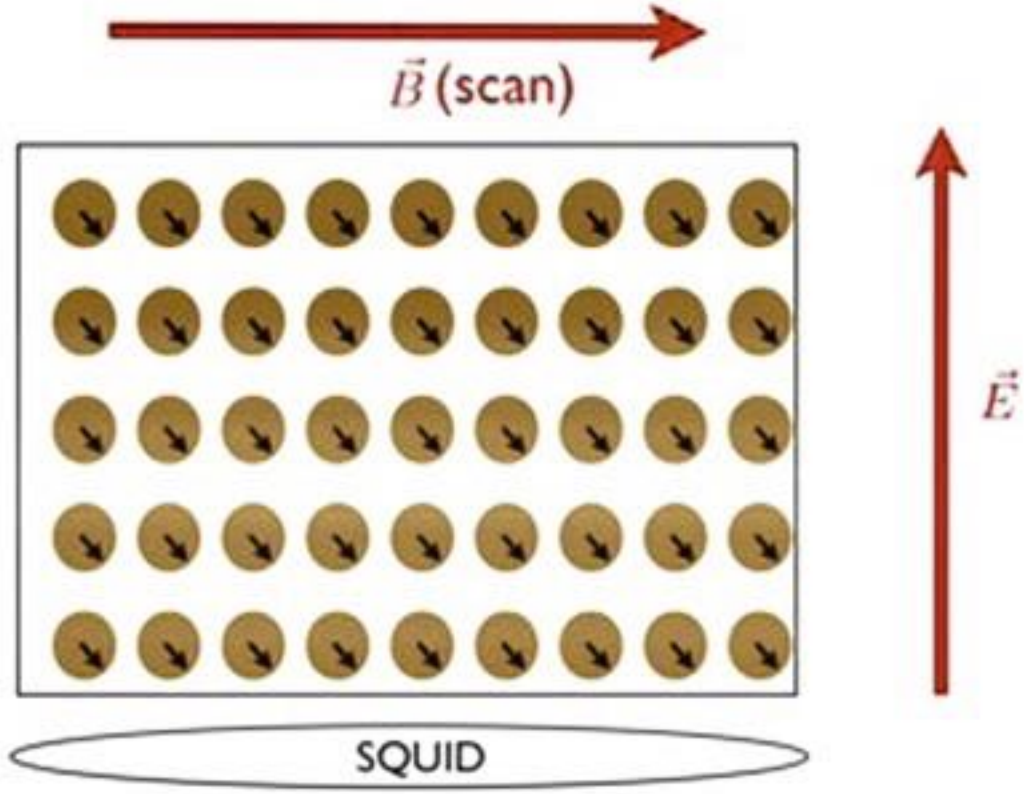
NMR techniques + high precision magnetometry



Larmor frequency = axion mass ➔ resonant enhancement

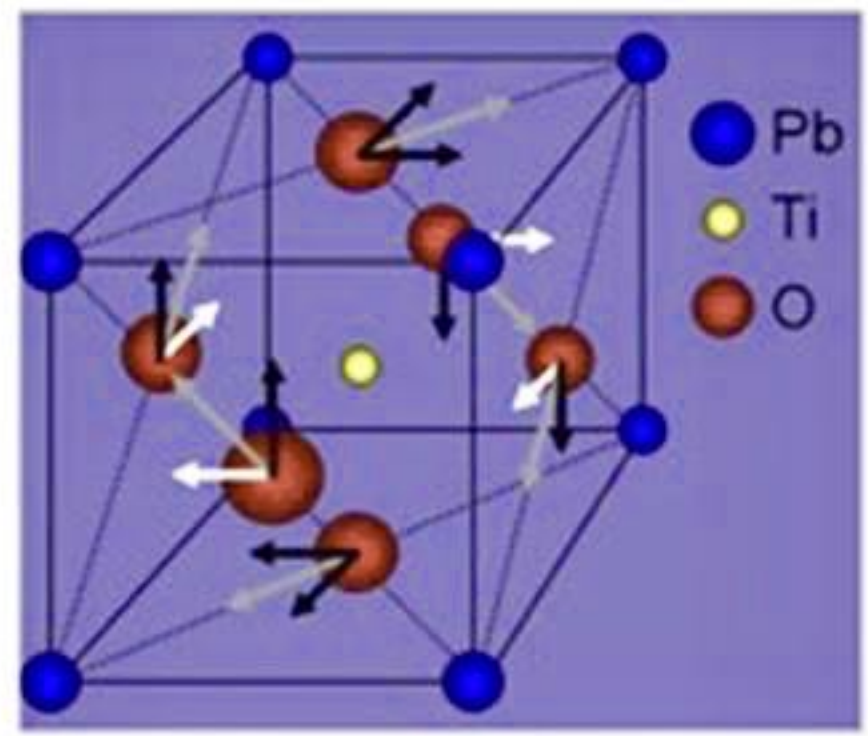
Searching for Axions in the Anthropic Window

Solid State Precision Magnetometry



$$\delta B \sim n\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left((2\mu_N B - m_a)t\right) \sin\left(2\mu_N B t\right)$$

Polar Crystal

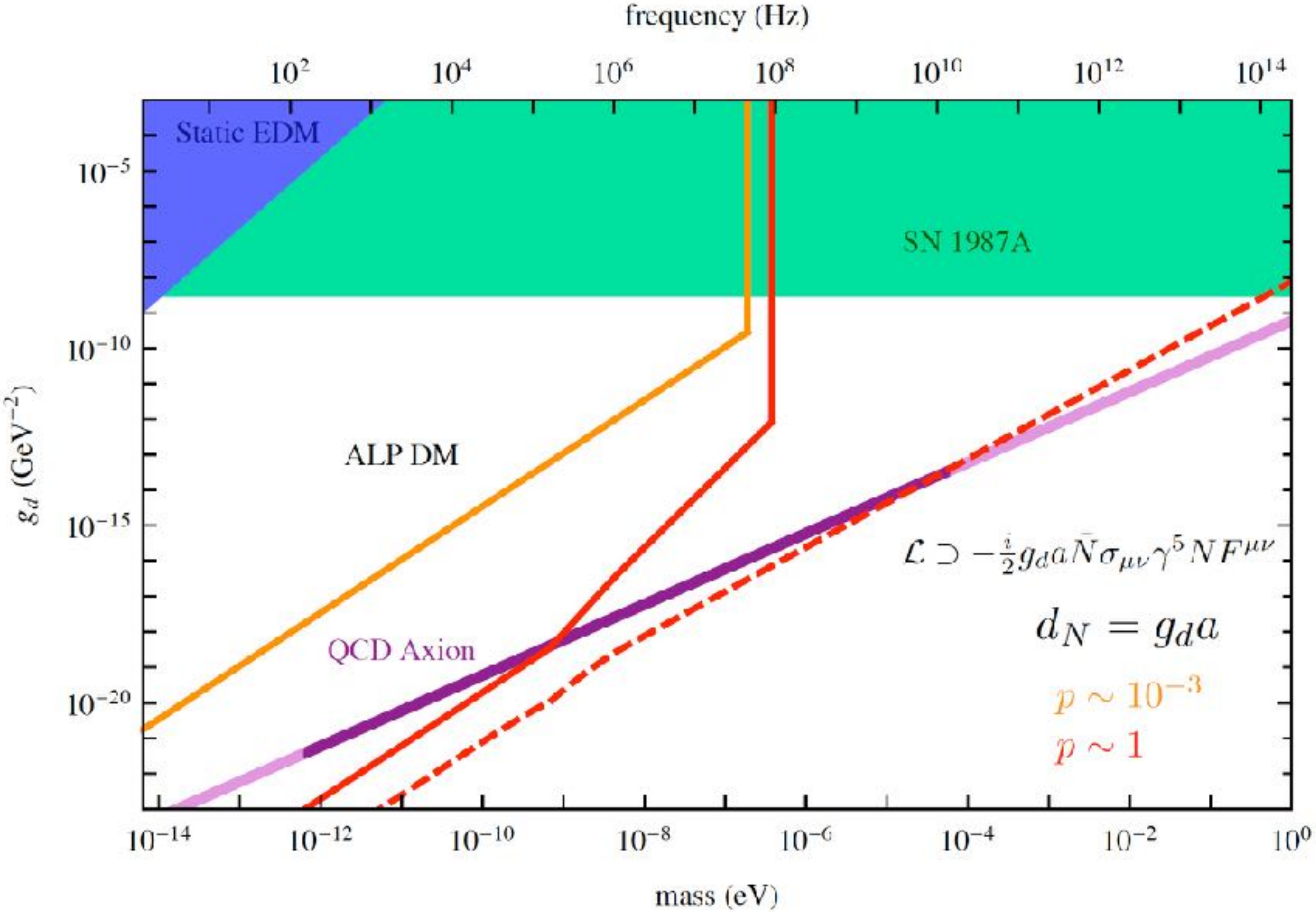


Lead Titanate

CASPEr experiment
Precise magnetometry to measure
tiny deviations from Larmor frequency

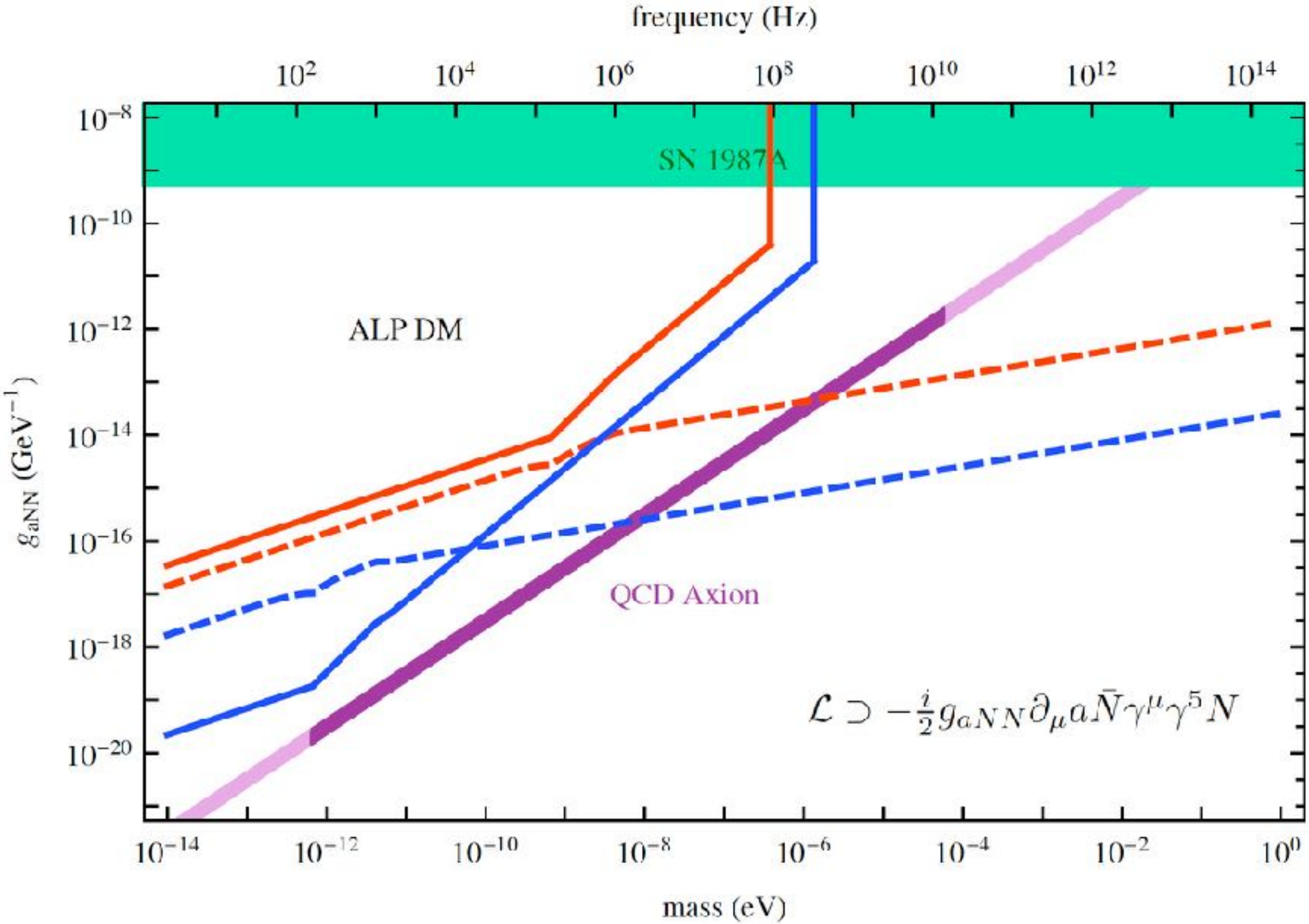
Graham & Rajendran, arXiv:1101.2691
Budker, Graham, Ledbetter, Rajendran & Sushkov, arXiv:1306.6089

Projected Sensitivity in Lead Titanate



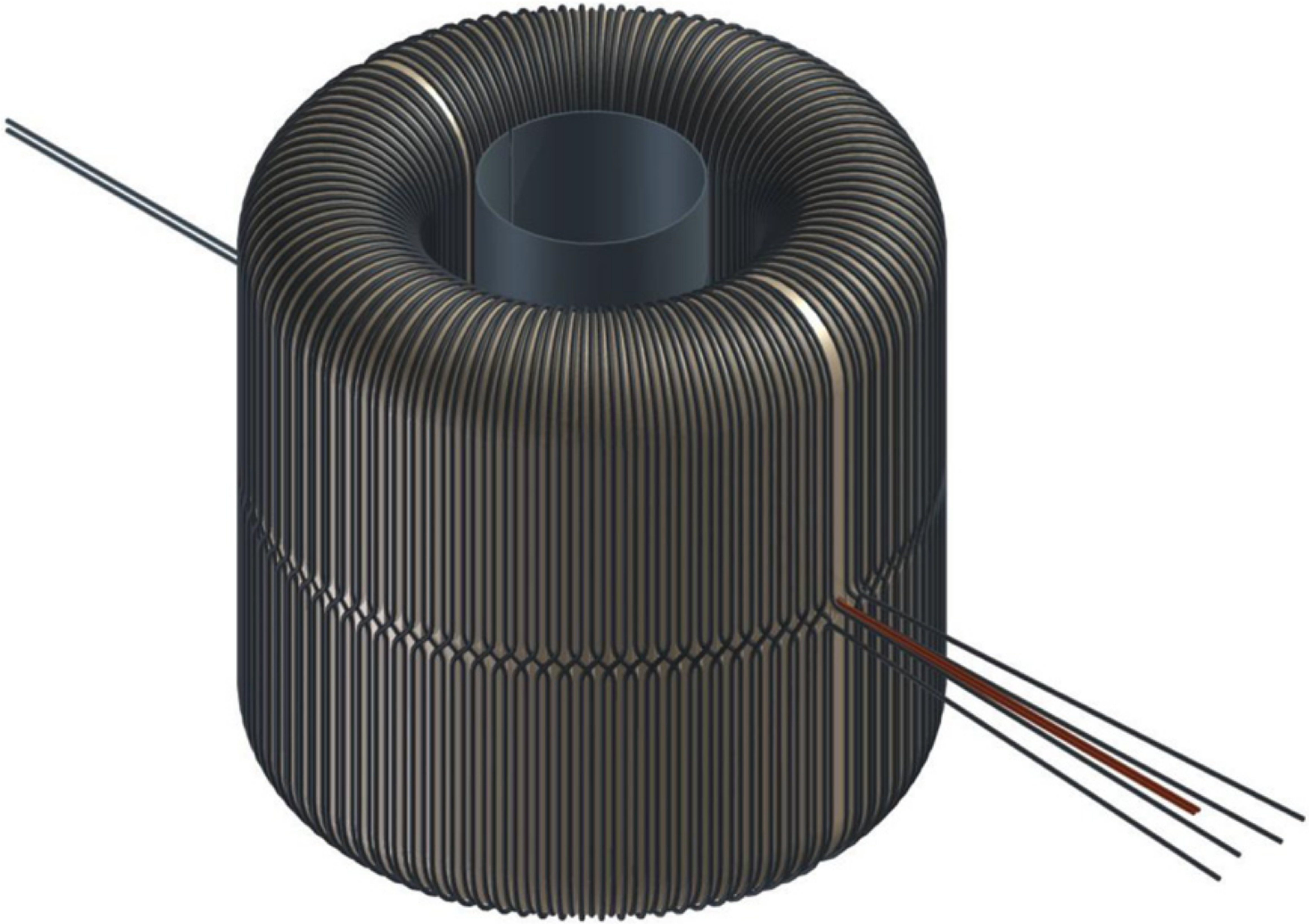
$$\delta B = 0.1 \frac{\text{fT}}{\sqrt{\text{Hz}}},\ n = \frac{10^{22}}{\text{cm}^3},\ V = 1000\ \text{cm}^3,\ T_2 = 1\ \text{s}$$

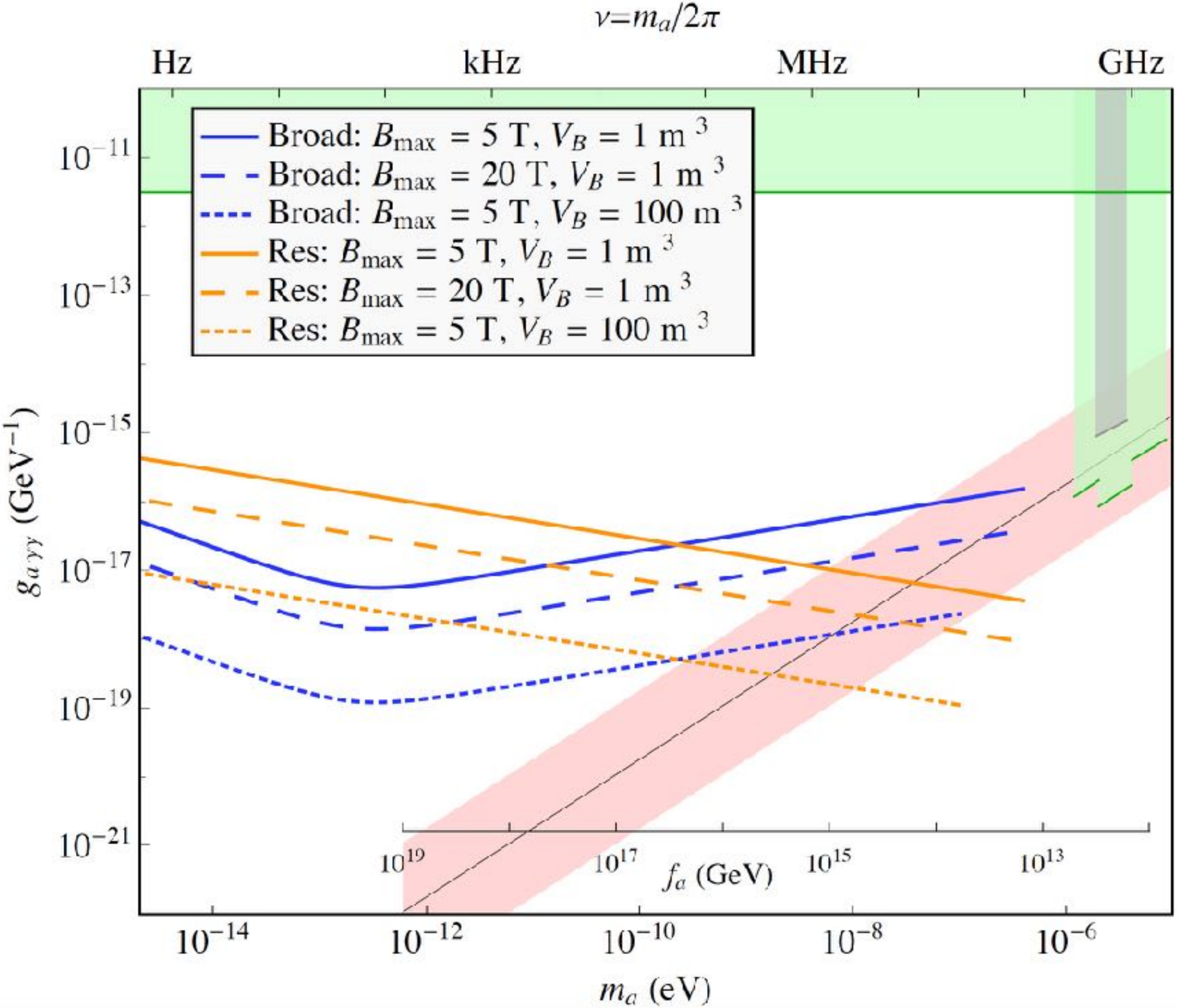
Projected Sensitivity



$$\delta B = 0.1 \frac{\text{fT}}{\sqrt{\text{Hz}}},\ n = \frac{10^{22}}{\text{cm}^3},\ V = 1000\ \text{cm}^3,\ T_2 = 1\ \text{s}$$

abracadabra



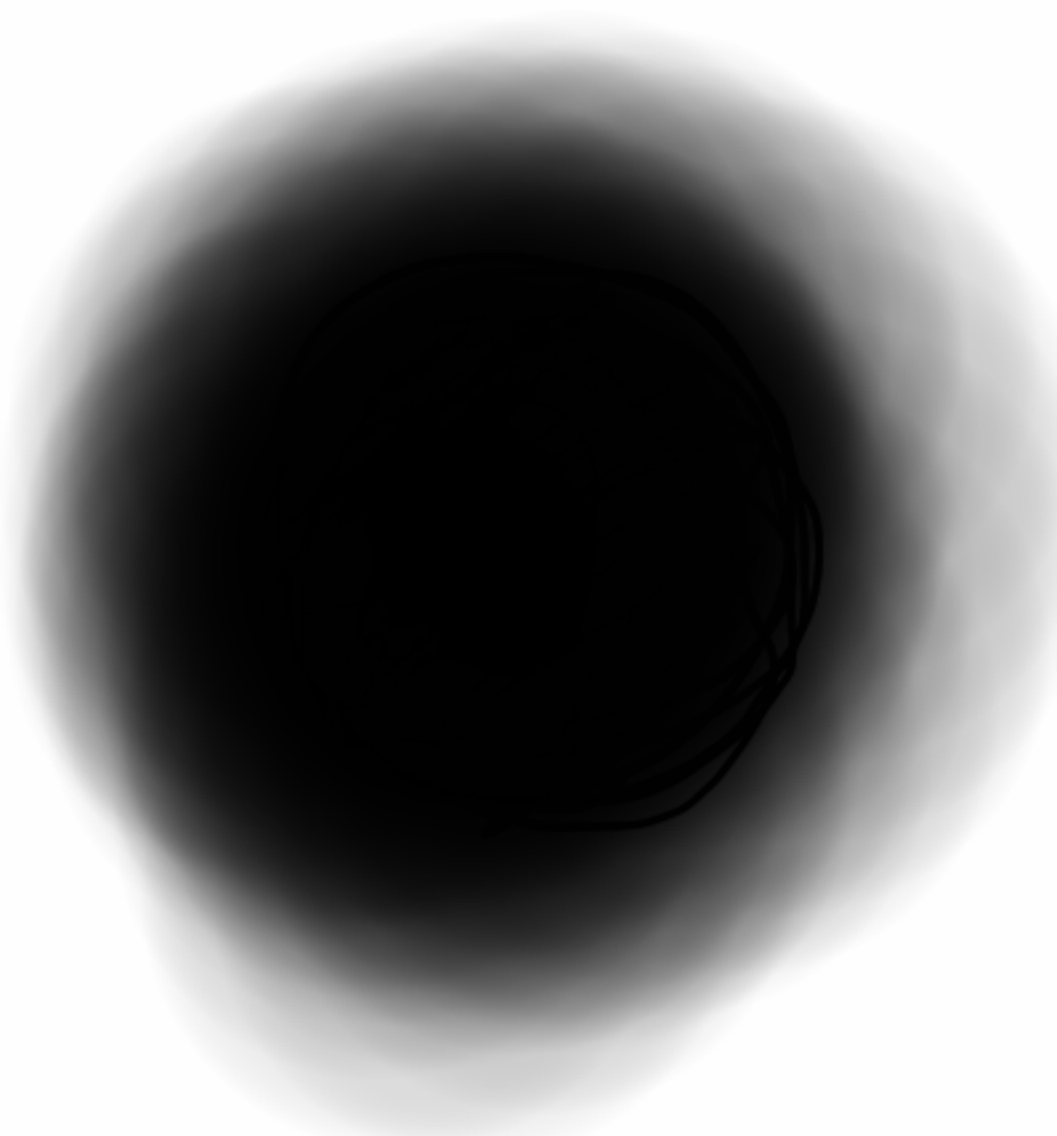


$\nu = m_a/2\pi$
Hz
kHz
MHz
GHz
Broad: B_{max} = 5 T, V_B = 1 m^3
Broad: B_{max} = 20 T, V_B = 1 m^3
Broad: B_{max} = 5 T, V_B = 100 m^3
Res: B_{max} = 5 T, V_B = 1 m^3
Res: B_{max} = 20 T, V_B = 1 m^3
Res: B_{max} = 5 T, V_B = 100 m^3
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{19}
10^{17}
10^{15}
10^{13}
f_a (GeV)
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
m_a (eV)

Black Holes

Spinning black holes can lower their energy by radiating light particles, thus reducing their angular momentum.

If the Compton wavelength of the particles is comparable to the radius of the black hole, they can get trapped. Then induced emission builds up an atmosphere (superradiance).



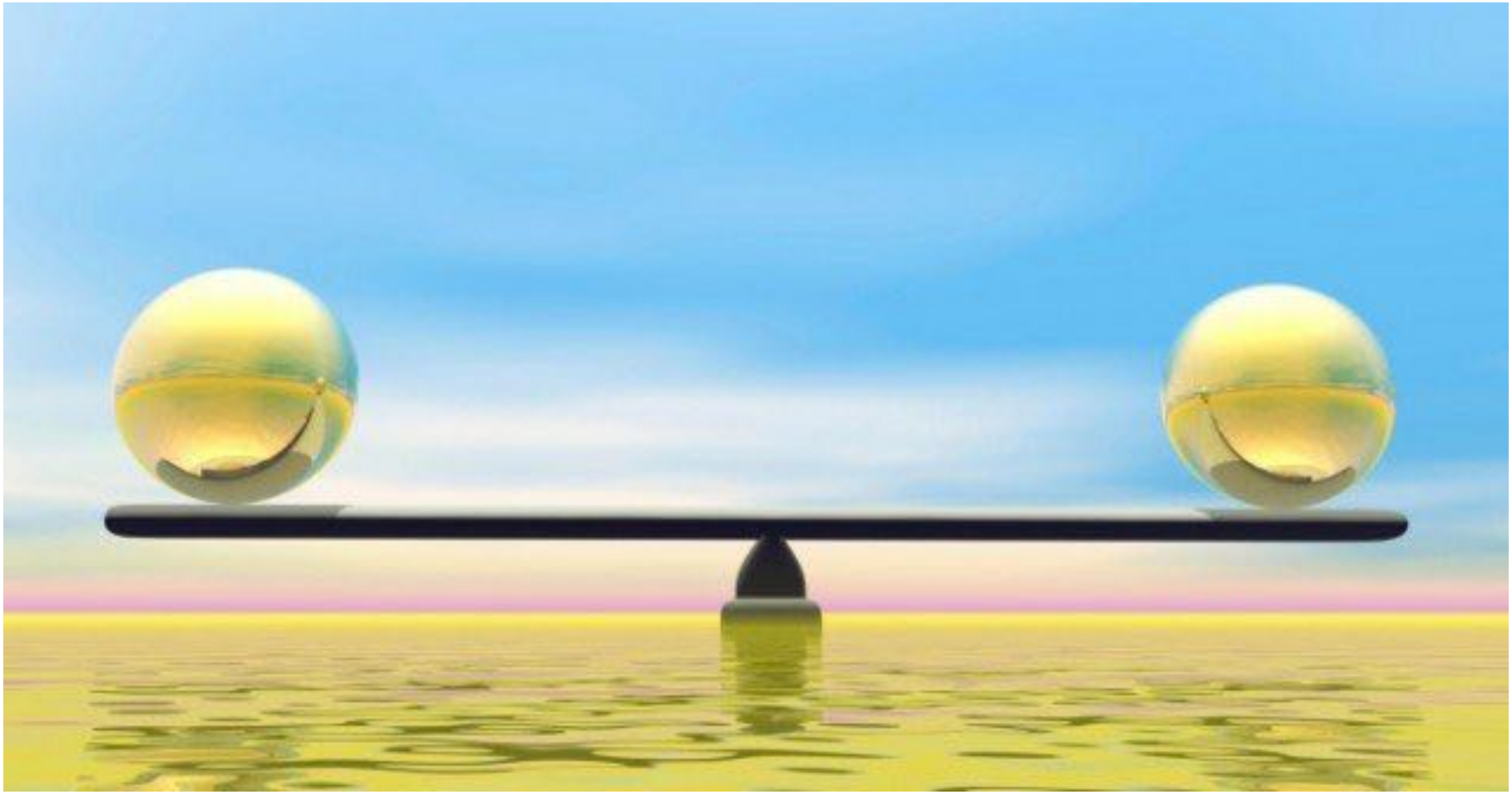
This effect could de-populate some regions of the (M, J) plane, and also affect gravitational wave signals.

Summary and Prospects

Axions are a uniquely attractive solution to a deep conceptual issue - Why T?

If they exist at all, straightforward implementation of big bang cosmology suggests that axions contribute significantly to, and plausibly dominate, the astronomical dark matter.

Ingenious ideas and heroic engineering can bring that cosmic axion background within our field of view.



Balancing past and future