
THE ORIGINAL TASTE OF
OLD GOLD. DARK CHOCOLATE
WITH 70% COCOA
200g
NET
Get to know your
10%
SEE BACK OF PACK
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Axions

Basic Theory and Suggestions for Experiments

Semi-popular introduction:
quantamagazine.org/how-axions-may-explain-times-arrow-20160107/

Big recent review, with *many* references:
arxiv.org/pdf/1801.08127.pdf

Axion-plasmon converter: arxiv.org/pdf/1904.11872.pdf

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.

[BTW: A key ingredient of topological insulators!]

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.

⇒ 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, electric dipole moments of nuclei would be far larger than experiments allow.)

Fundamental Theorem of the Standard Model

$$SU(3) \times SU(2) \times U(1)$$

$$U_R^a \ : \ (3,\ 1,\ \frac{2}{3})$$

$$D_R^a \ : \ (3,\ 1,\ -\frac{1}{3})$$

$$Q_L^a \ : \ (3,\ 2,\ \frac{1}{6})$$

$$E_R^a \ : \ (1,\ 1,\ -1)$$

$$L_L^a \ : \ (1,\ 2,\ -\frac{1}{2})$$

$$\phi : \ (1,\ 2,\ -\frac{1}{2})$$

$$Q_L \equiv \begin{pmatrix} U_L \\ D_L \end{pmatrix}$$

Coupling Types

Maxwell / Yang-Mills

$$\frac{1}{4g^2}\,\mathrm{Tr}\,G_{\mu\nu}G^{\mu\nu}$$

Fermion kinetic

$$Z^a_b\;\bar{Q}_a\gamma^\mu\,(i\partial_\mu+\frac{\lambda^\rho}{2}A^\rho_\mu+\frac{\tau^\sigma}{2}B^\sigma_\mu+\frac{1}{6}C_\mu)Q^b$$

Higgs

$$Y\,\partial^\mu\phi^\dagger\,\partial_\mu\phi-m^2\phi^\dagger\phi+\lambda(\phi^\dagger\phi)^2$$

Up-type mass

$$M^a_b\;\bar{Q}_a\,\phi\,U^b\;+\;\mathrm{h.c.}$$

Down-type mass

$$N^a_b\;\bar{Q}_a\,\tilde{\phi}\,D^b\;+\;\mathrm{h.c.}$$

(similarly, leptons)

Theta terms

$$\frac{\theta}{32\pi^2}\,\mathrm{Tr}\;\epsilon_{\alpha\beta\gamma\delta}\,G^{\alpha\beta}\,G^{\gamma\delta}$$

Y can be absorbed into normalization of ϕ

Z and its relatives can be diagonalized and absorbed into normalizations.

M and N can be diagonalized using independent unitary transformations on Q, U, D -

Note, however, that the unitary transformations on Q required to diagonalize M and N may be different.

Kobayashi-Maskawa Theory

Note, however, that the unitary transformations on Q required to diagonalize M and N may be different.

Their relative orientation introduces structure into the covariant derivates connecting U_L and D_L -

or, in more physical terms, a “mixing angles” for W boson couplings.

$$\begin{array}{cc} & U_L \\ D_L & \begin{pmatrix} v^1_1 & v^1_2 & v^1_3 \\ v^2_1 & v^2_2 & v^2_3 \\ v^3_1 & v^3_2 & v^3_3 \end{pmatrix} \end{array}$$

Without upsetting the preceding steps, we can still make phase re-definitions of the Us and Ds.

Using that freedom, we can make the top row and leftmost column real.

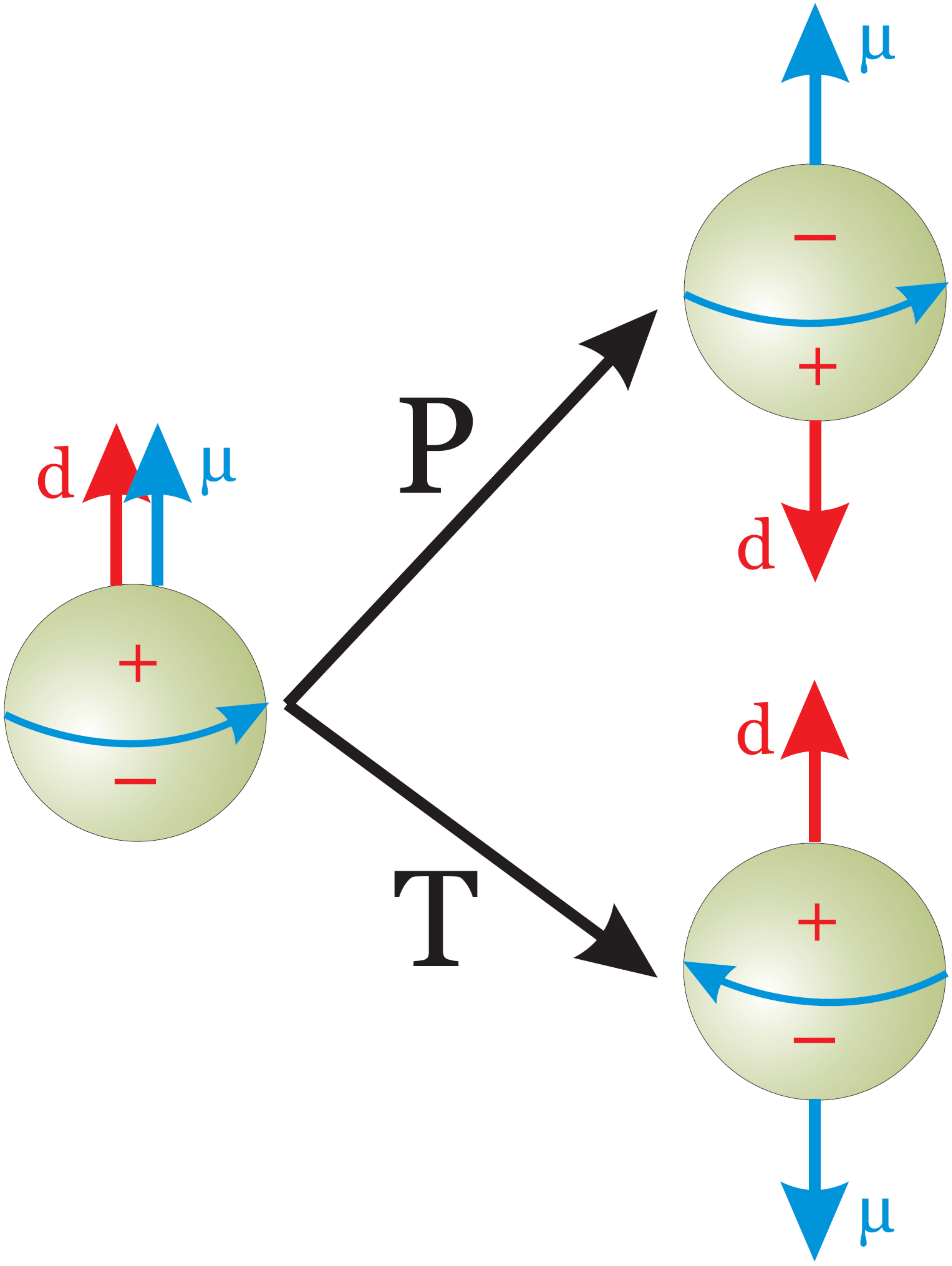
Then unitarity leaves us with exactly one non-trivial (& T violating) phase.

With only two families, we would not have T violation at all. Kobayashi and Maskawa actually predicted the third family, in advance of its experimental discovery.

Their theory of weak mixing angles now describes a wealth of phenomena successfully.

BUT …

There is still the $\boldsymbol{\theta}$ term!


d
μ
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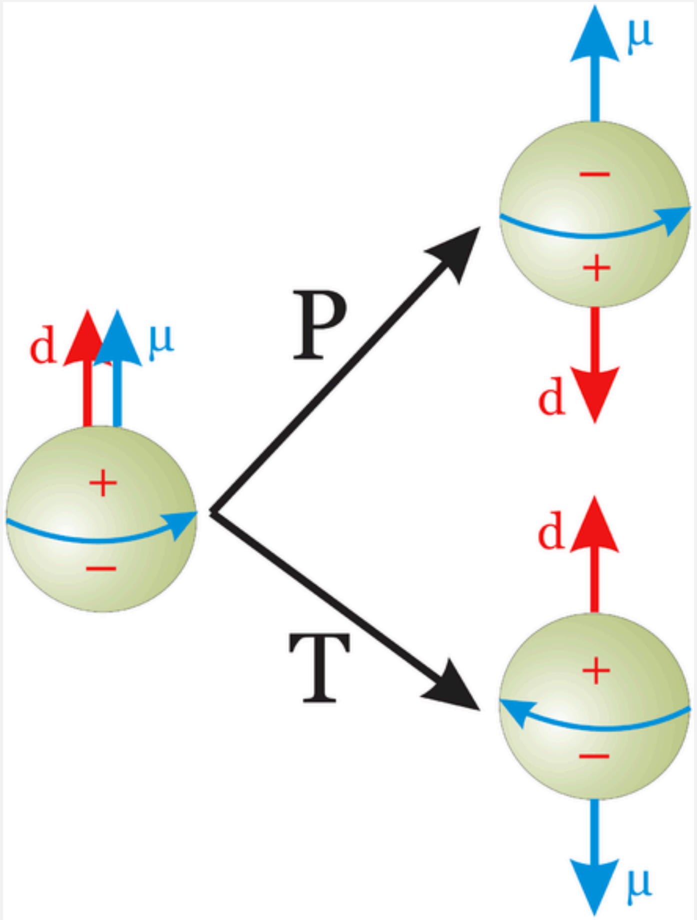
+
d
d
+
−
μ

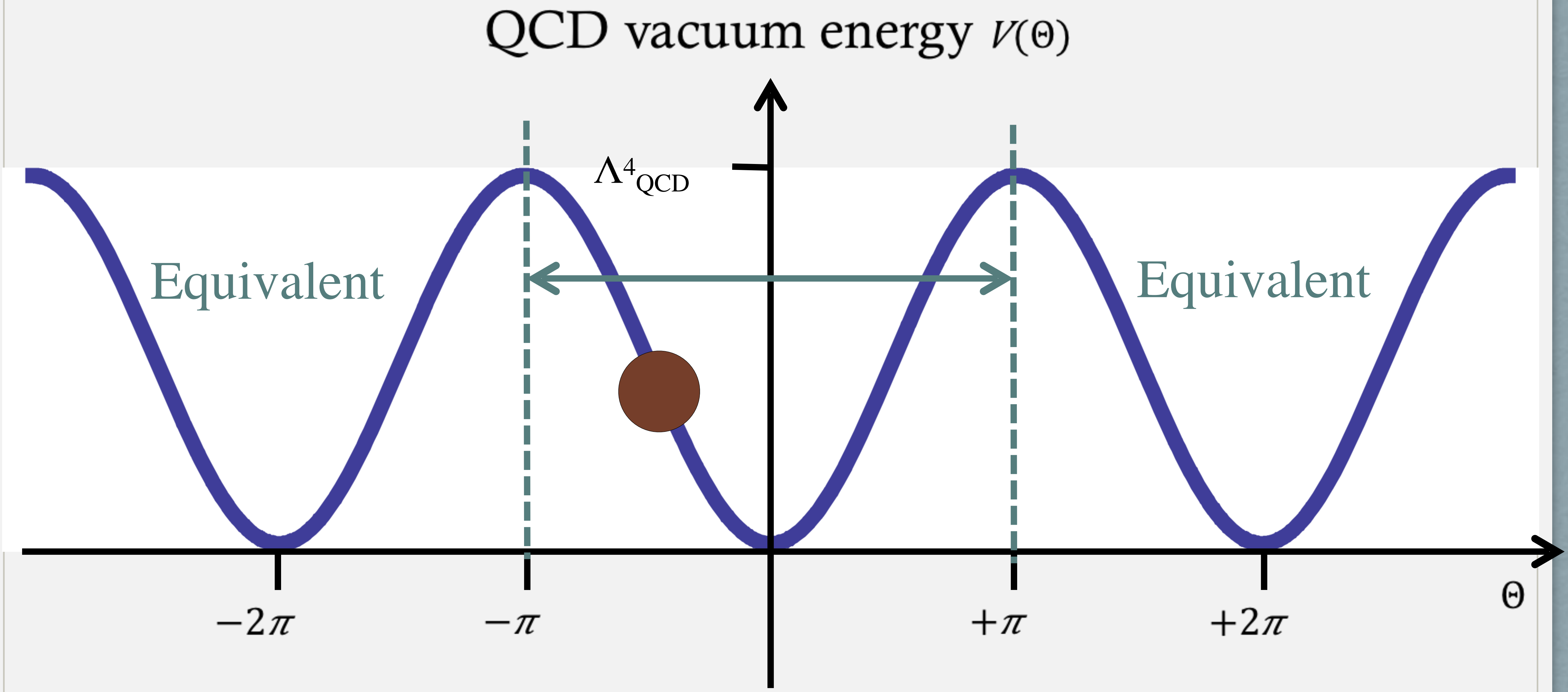
Strong CP problem

- QCD potentially has a CP violating term
- Measurement of neutron EDM (which requires T violation) gives $\theta<10^{-10}$
- Why is θ so ridiculously small?
- “Anthropic” arguments won’t cut it here.

$$\theta \frac{g^2}{32\pi^2} G\widetilde{G}$$



Strong CP problem



- θ=0 minimizes the vacuum energy, but θ is not a dynamical term

Alex Millar

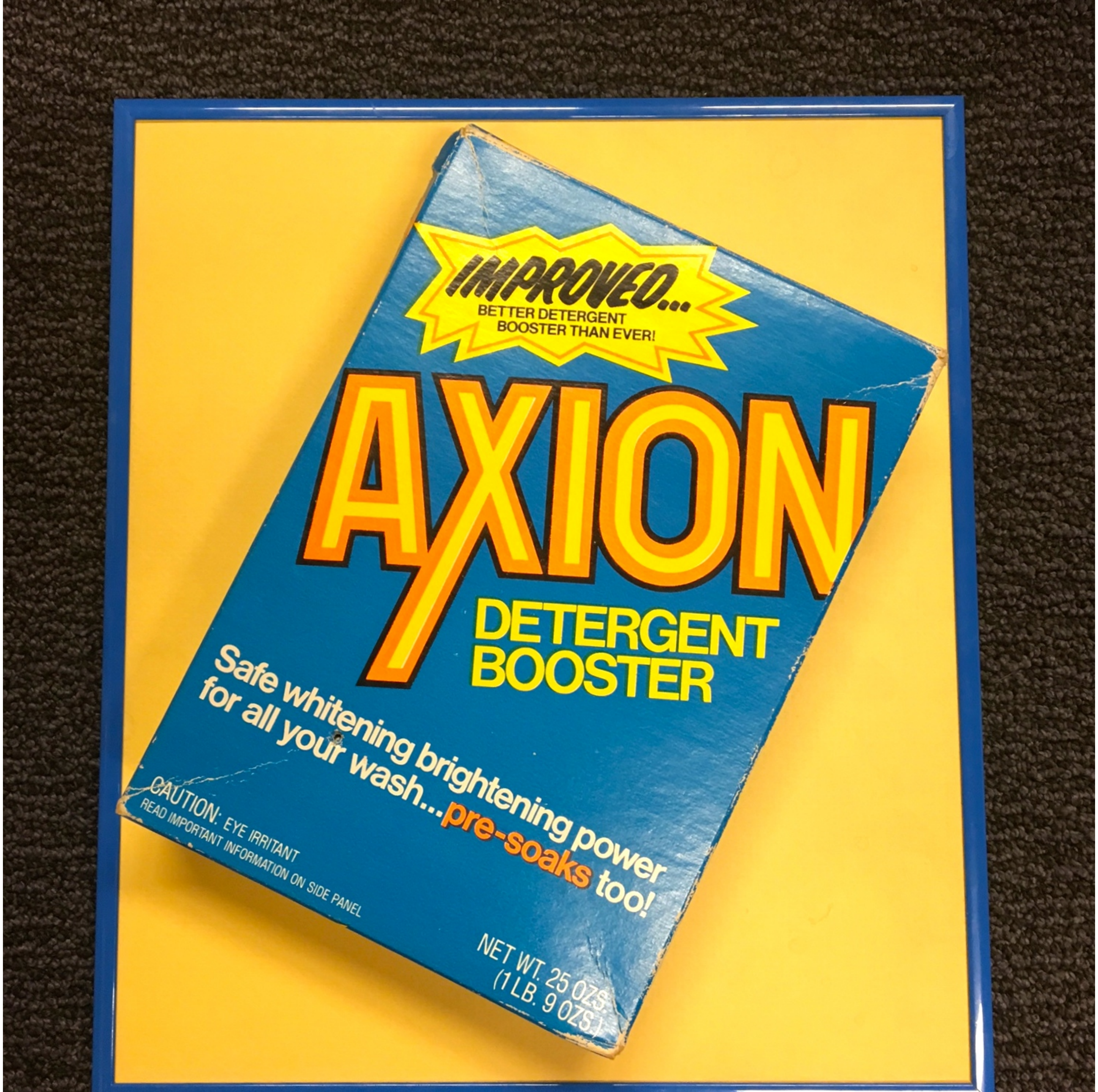
Why?

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.)

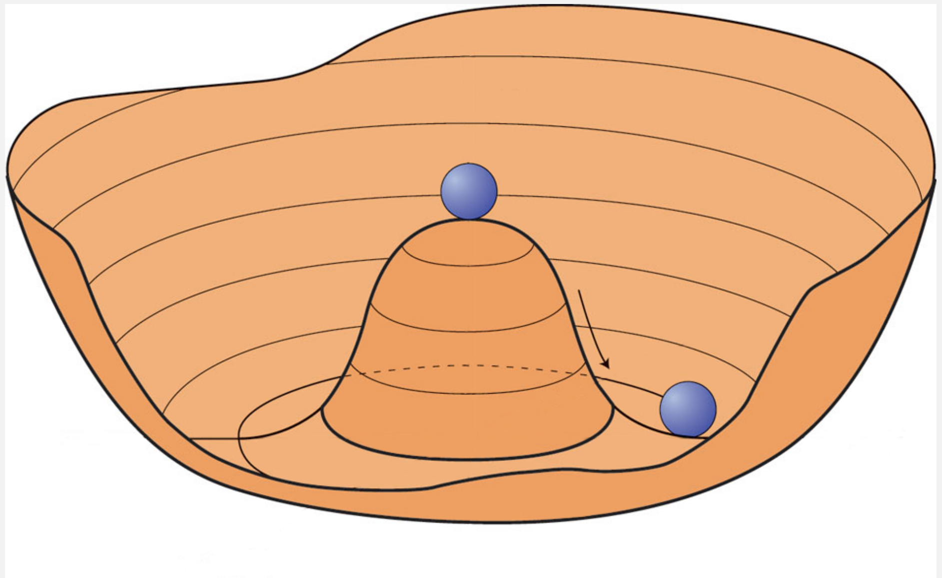
Axion Intuition

What are Axions?

- Solution to the Strong CP problem: make θ a dynamical field so it can minimize the energy and send θ to zero

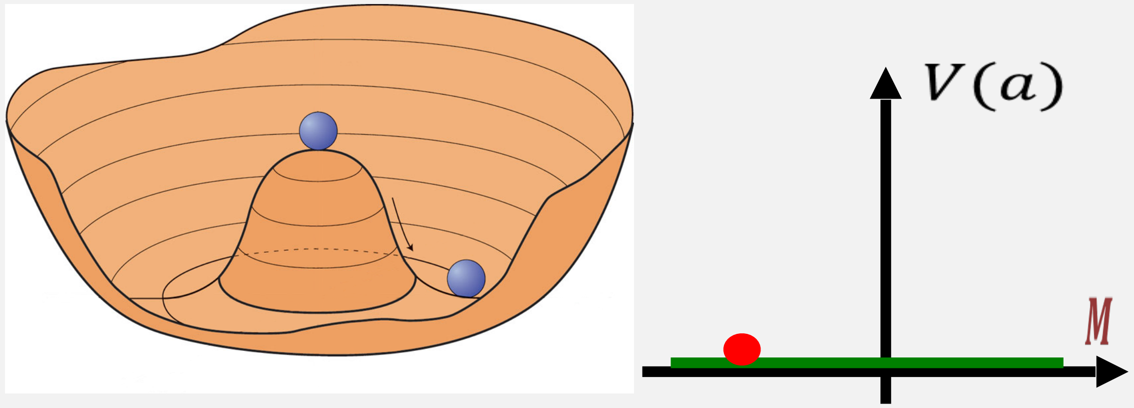
$$\mathscr{L}_{\text{stand mod + axion}} = \ldots + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- We need a new anomalous U(1) chiral symmetry (Peccei-Quinn), which is broken at high temperature ~f_a (around 10^{12} GeV)

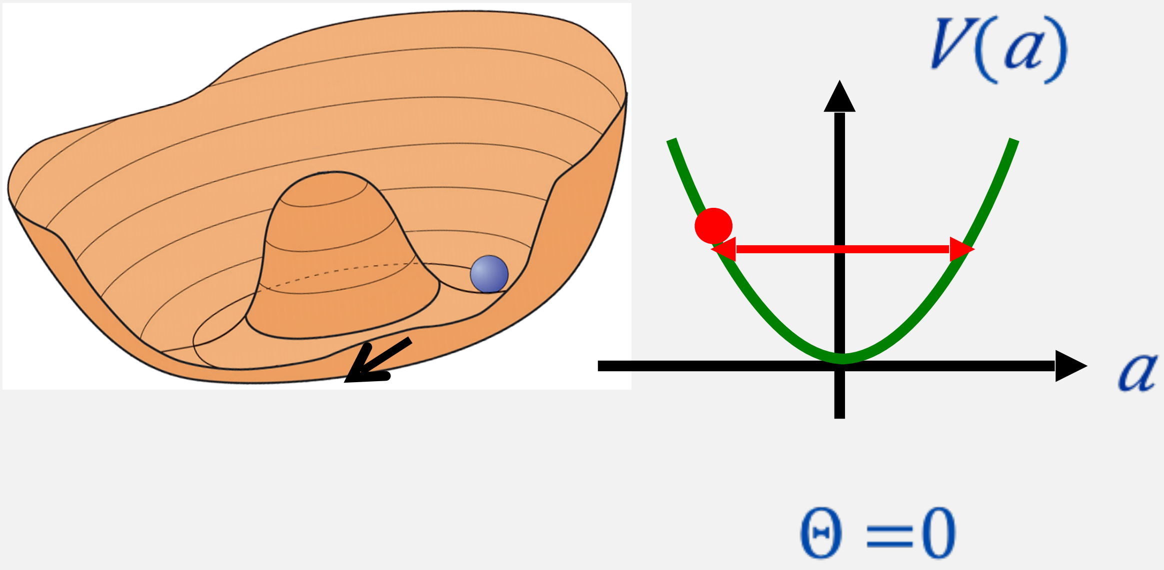


What are Axions?

- The axion is the angular degree of freedom



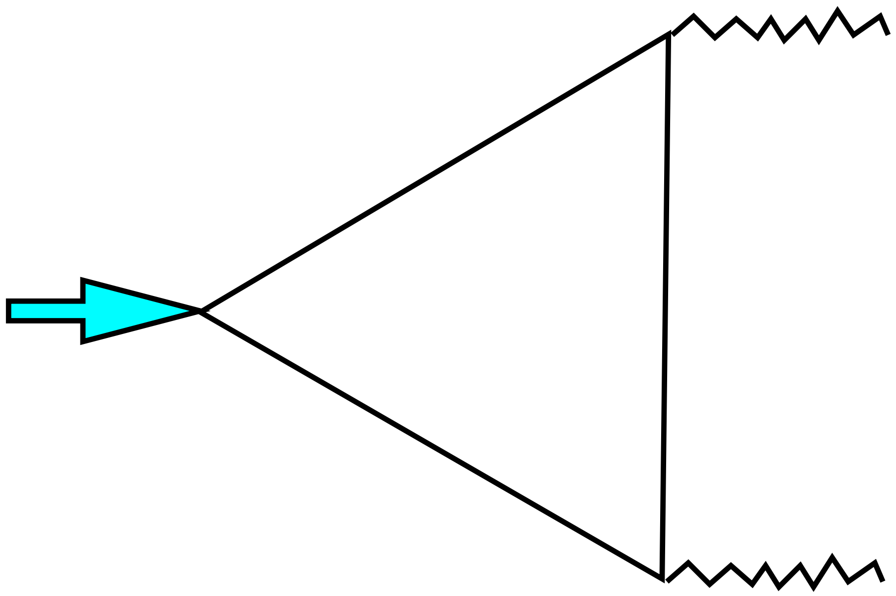
- It is energetically negligible at intermediate temperatures
- At the QCD scale the potential tilts as the axion acquires a mass
- The axion rolls down to a CP conserving minimum



Axion Deep Theory

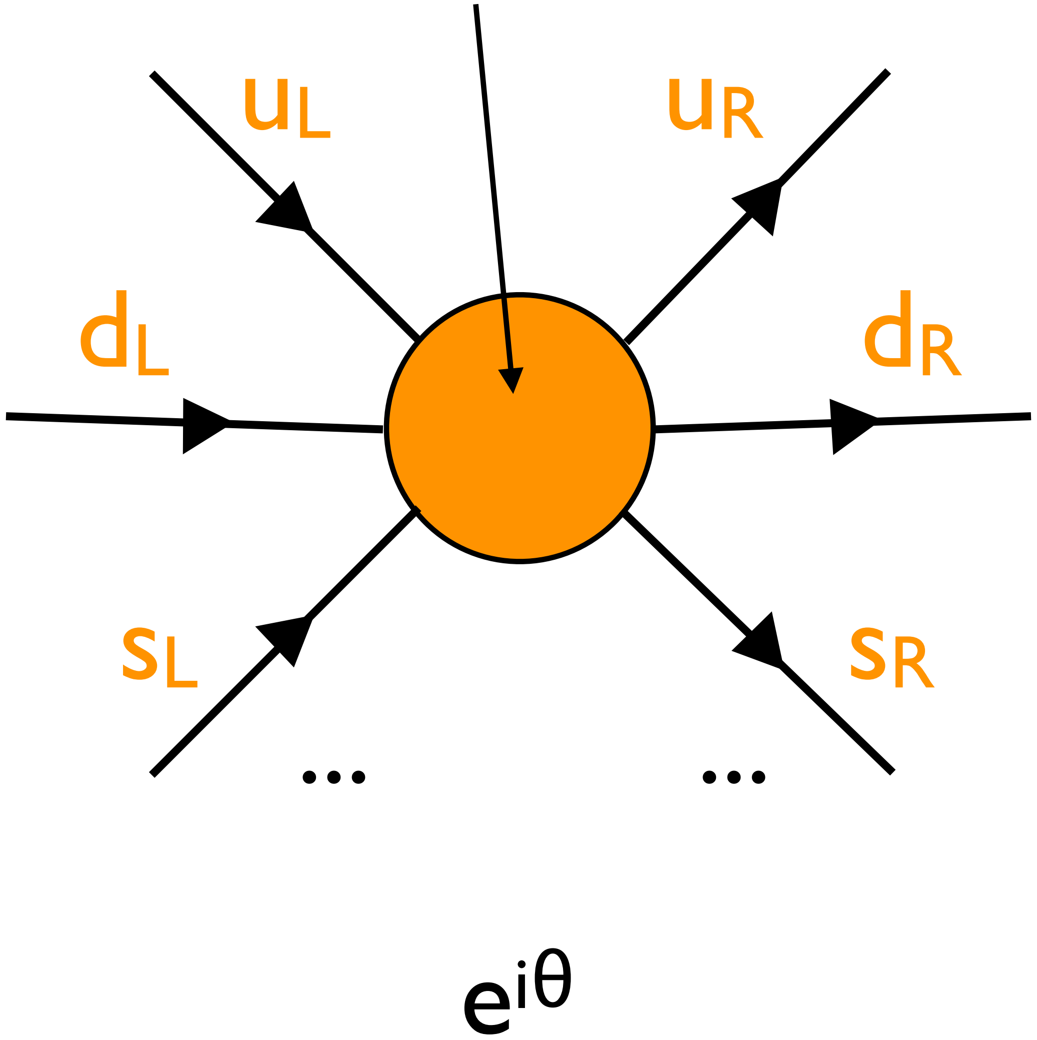
The anomaly equation + Noether’s theorem shows us that some transformations induce θ terms.

We can visualize this using an “ ’t Hooft vertex” that displays the zero modes which accompany a topologically non-trivial gauge field.



$$\partial_\mu(\bar{u}\gamma_5\gamma^\mu u + \bar{d}\gamma_5\gamma^\mu d) \equiv \partial_\mu j^{5\mu} \propto \mathrm{Tr}\ \epsilon^{\alpha\beta\gamma\delta} G_{\alpha\beta} G_{\gamma\delta}$$

Unit second Chern class, or “instanton number 1”



Integrated anomaly equation: fields with topology induce changes in fermion number, implemented by zero modes. [2 side comments]

θ occurs (only) in coefficient of this process.

Peccei-Quinn transformation

$$\begin{aligned} \phi_j \quad &\rightarrow \quad e^{iq_{\phi_j}\lambda} \\ f_k \quad &\rightarrow \quad e^{iq_{f_j}\lambda} \\ \theta \quad &\rightarrow \quad \theta + \sum_{0\,\mathrm{modes}} q_{f_k}\lambda \end{aligned}$$

We would like $\mathcal{L}_{\mathrm{without}\ \theta}$ to be invariant, so that θ becomes an autonomous dynamical variable.

(We would like $\mathcal{L}_{\text{without } \theta}$ to be invariant, so that θ becomes an autonomous dynamical variable.)

In QCD, this possibility is blocked by mass terms. If we are to keep the mass terms fixed, then we must choose equal phases for left- and right-handed quarks - so there is no net change in $\boldsymbol{\theta}$.

In the complete SM, it is still blocked. We can throw the phases of individual quark fields onto ϕ, but then we get the total phase change from $\phi^3 \phi^{*3}$ - i.e., no net change.

One way to get a successful PQ transformation, is to have a new “quark” Q, which is the only thing to transform, with $q_{QL} \neq q_{QR}$ †.

When Q condenses, we get an axion field:

$$\langle \bar{Q}_L Q_R \rangle = F e^{ia/F} \neq 0$$

Variations in a induce proportional variations in $\boldsymbol{\theta}$.

†(Of course, there are many other ways.)

Axion Properties

Because axions are so closely tied to a 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.

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

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

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

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

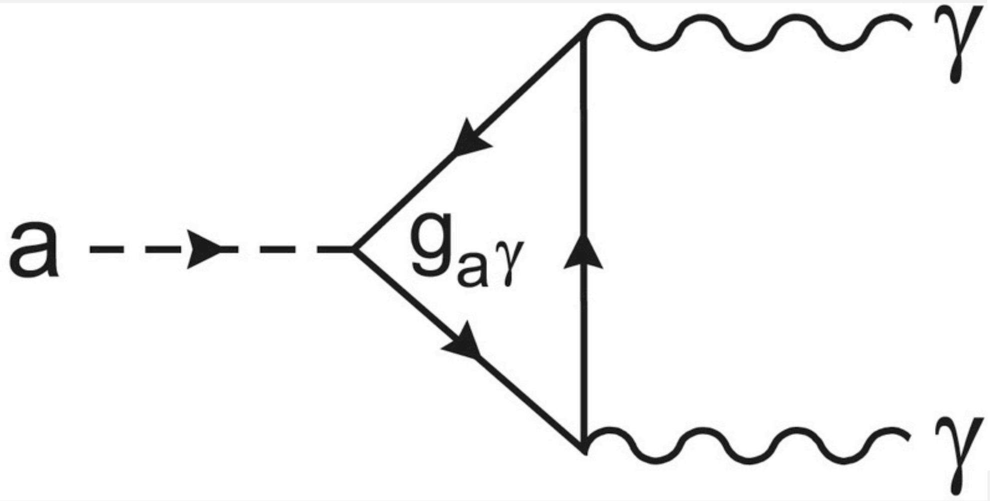
It also arises, with “emergent” axions, in condensed matter physics, as the effective theory of topological insulators.

Axion-electrodynamics

- Axions and ALPs interact with photons through an anomaly term

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2a^2 - \boxed{\frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a,}$$

- This coupling is tiny, but still important



$$m_a = 5.70(7)\,\mu\text{eV}\,\frac{10^{12}\text{GeV}}{f_a}\,,$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}C_{a\gamma} = 2.04(3)\times 10^{-16}\ \text{GeV}^{-1}\,\frac{m_a}{\mu\text{eV}}\,C_{a\gamma}\,,$$

$$C_{a\gamma} = \frac{E}{N} - 1.92(4)\,,$$

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

B induces charge

$$\begin{aligned}
\nabla\cdot E &= -\,\kappa\,\nabla a\cdot B \\
\nabla\times E &= -\,\frac{\partial B}{\partial t} \\
\nabla\cdot B &= 0 \\
\nabla\times B &= \frac{\partial E}{\partial t} + \kappa\,(\dot{a}B + \nabla a\times E)
\end{aligned}$$

ADMX, abracadabra, (MADMAX)

E induces current (surface Hall effect)

Plasmon drive

In the presence of a background magnetic field, the axion field:

mixes with the photon, and

pumps electromagnetic excitations.

One can add materials (including “boundaries”) to encourage the pumping.

We may also get axion couplings from the fermion terms

$$c\,m\,a\,\bar{f}\gamma_5 f \;\approx\; \frac{c}{2}\,\partial_\mu a\;\bar{f}\gamma_5\gamma^\mu f$$

Non-relativistic limits:

$$\dot{a}\,\vec{p}\cdot\vec{\sigma}$$

$$\nabla a\;\cdot\;\vec{\sigma}$$

Thus axions induce electric dipole moments in nuclei, and possibly electrons.

Axion fields that vary in time and space will induce oscillatory electric dipole moments.

Axion Cosmology

Dark Matter

- Strong experimental evidence that General Relativity cannot describe the cosmos when the known baryonic matter is used.
- Modifications to gravity both have significant theoretical problems, and fail to explain the full suite of cosmological observations.
- Need a new massive particle to explain observations (or at least something that behaves like one)

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.

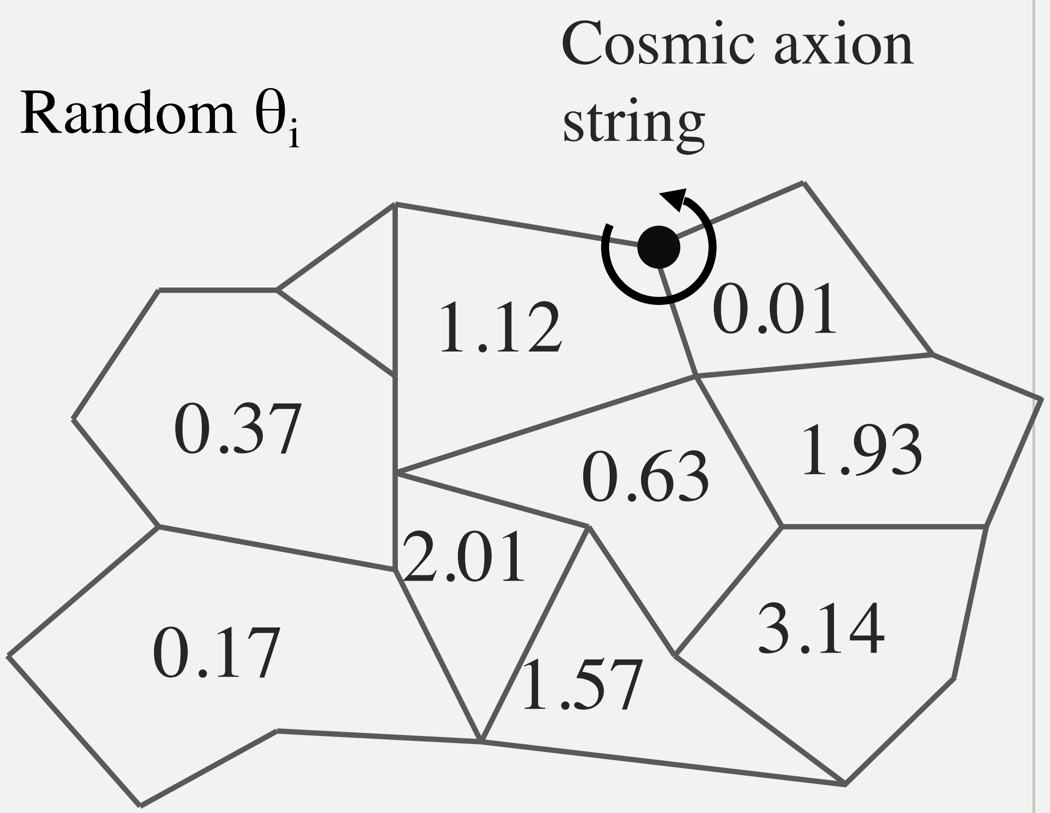
The axion fluid is a source of cold dark matter. It may well be the dominant source.

There are two basic scenarios for axion cosmology.

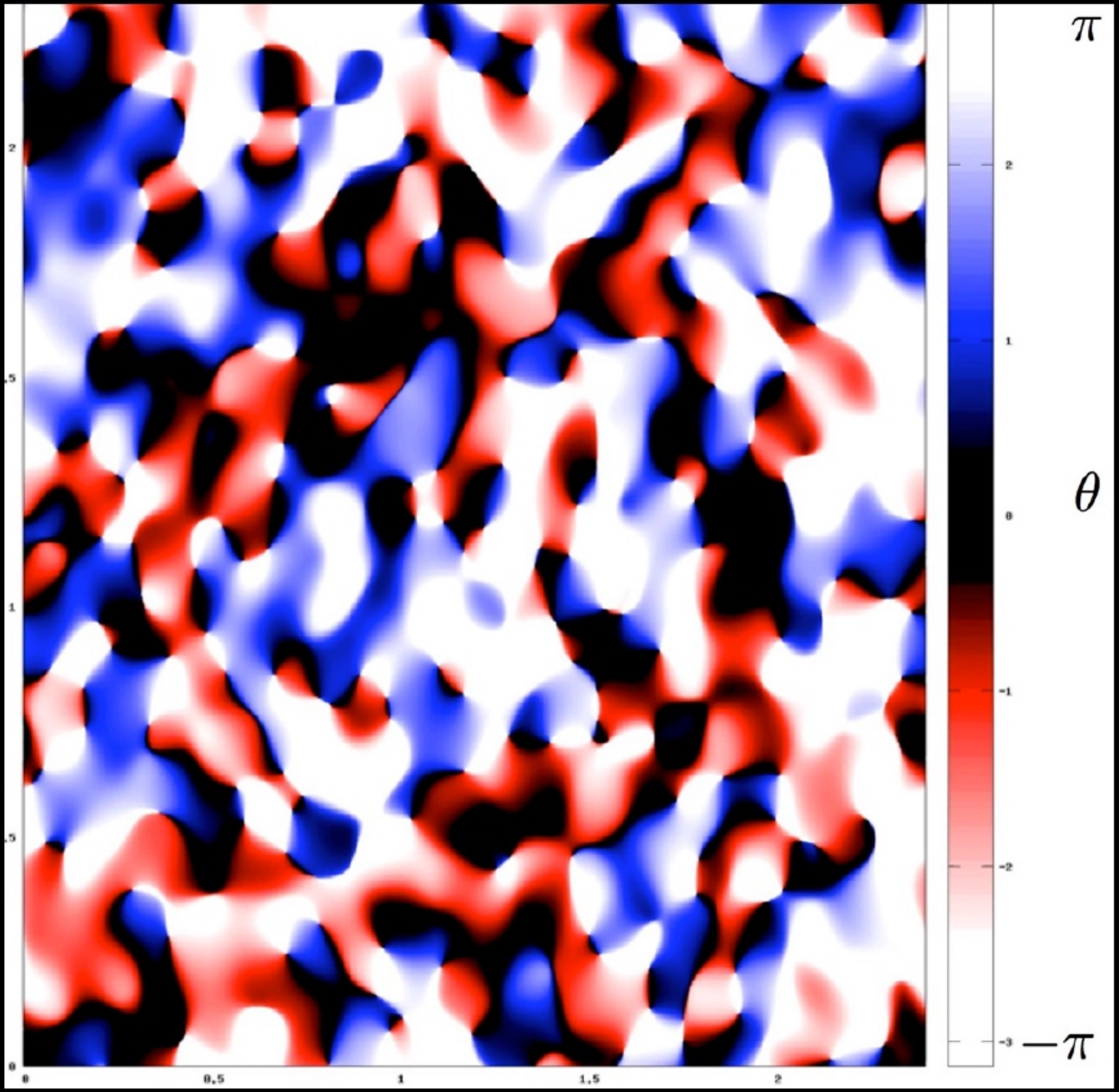
post-inflationary scenario

Axion DM: scenario 1

- Scenario 1: PQ broken after inflation
- θ_i has random values in every casual region, with the dark matter density determined by the average
- Topological defects such as strings and domain walls exist in the early universe



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 $m_a = 26.2 \pm 3.4\,\mu\text{eV}$.

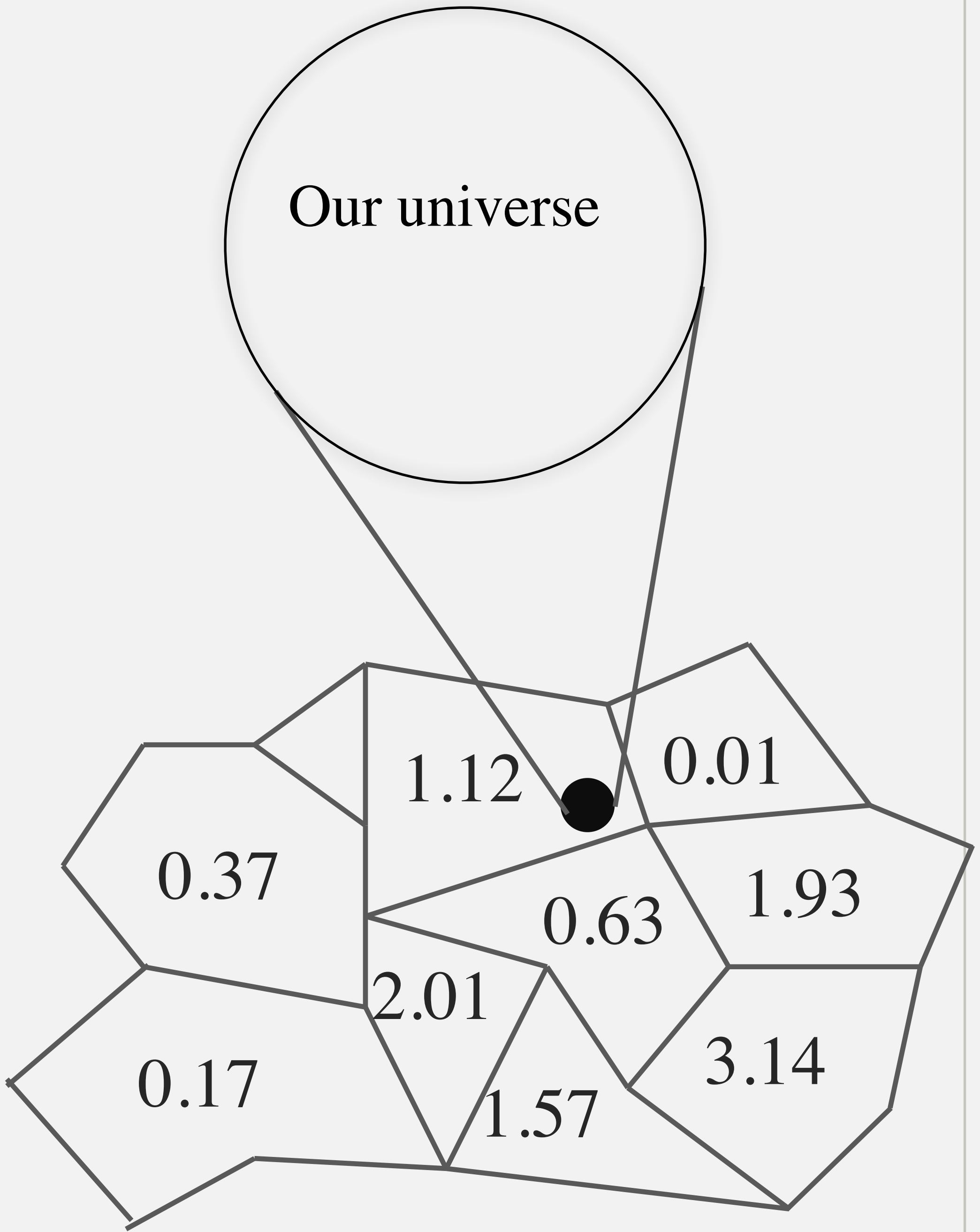
Keywords: axions, dark matter, cosmic strings, global strings

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

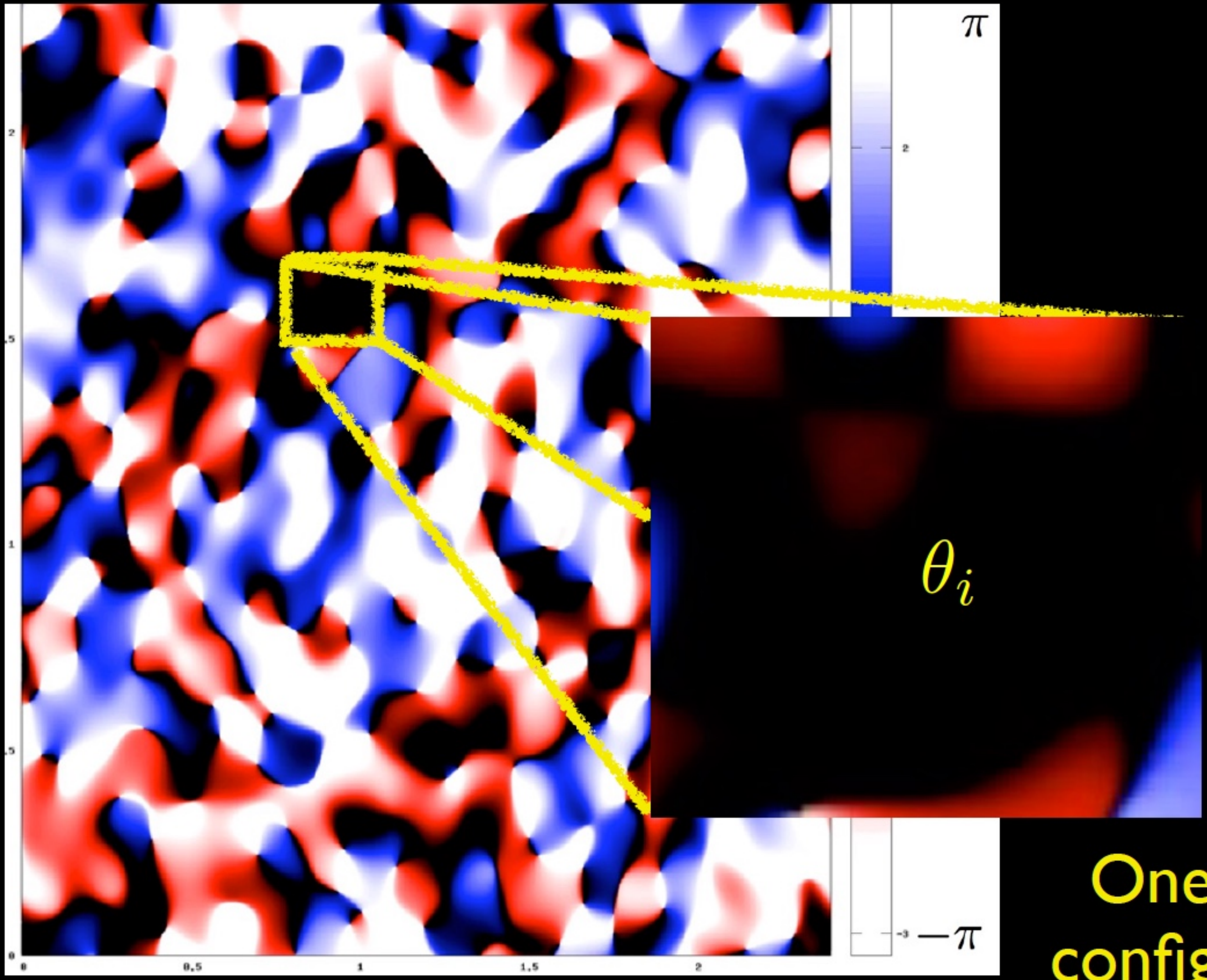
pre-inflationary scenario

Axion DM: scenario 2

- Scenario 2: PQ broken before inflation
- θ_i has a single random value which determines the dark matter density
- No topological defects



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 $\theta_{0.}$

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:

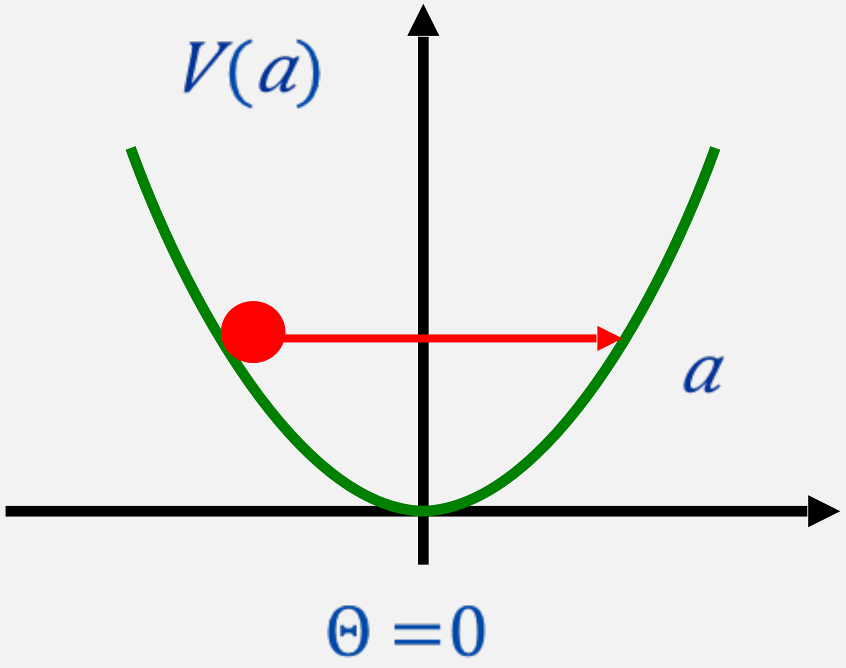
One can associate F with unification scales, i.e. $F \backsimeq 10^{16}$ GeV.

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

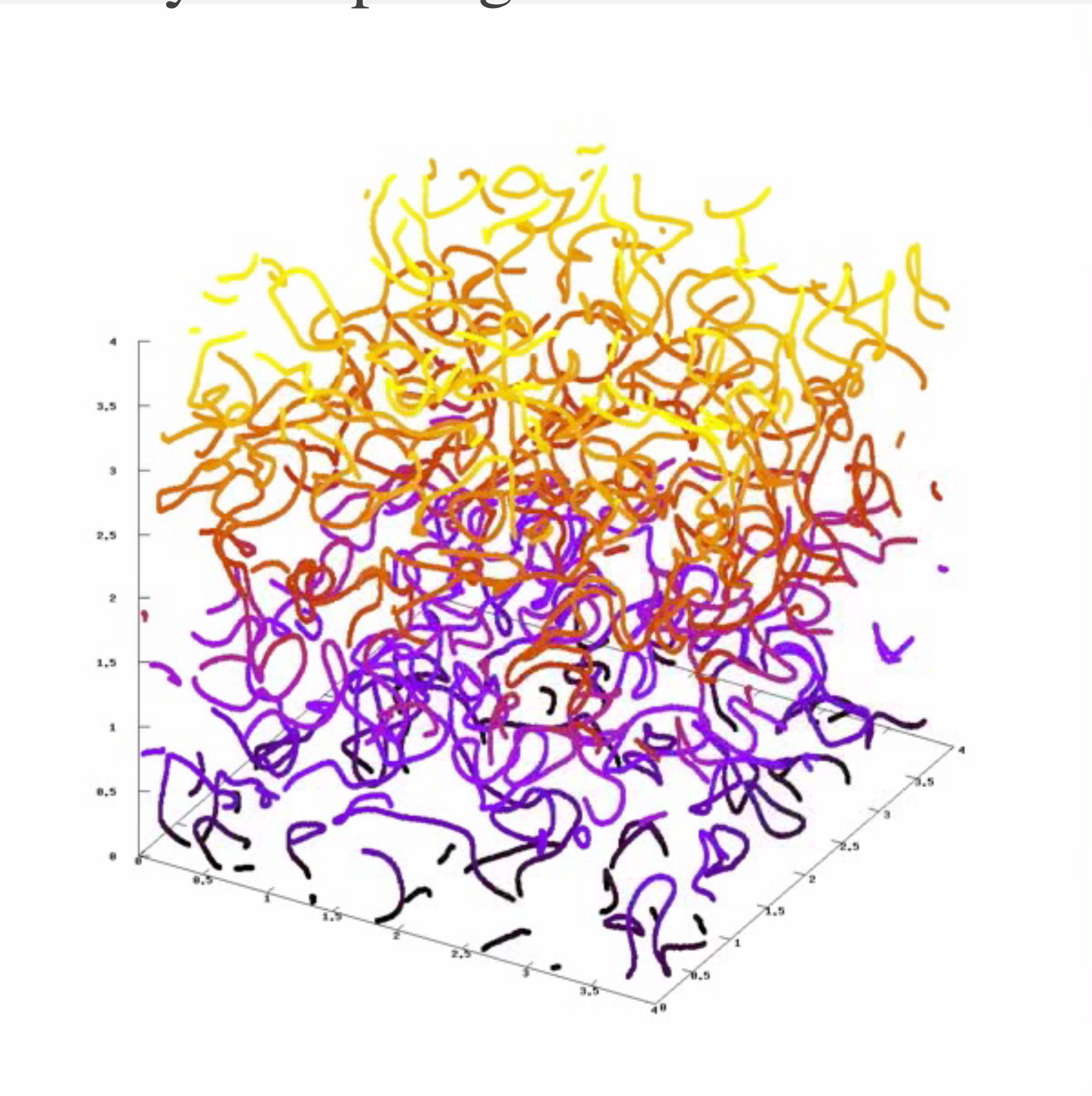
One finds a plausible explanation of the ratio of dark to baryonic matter.

Axion production mechanisms

Vacuum Misalignment

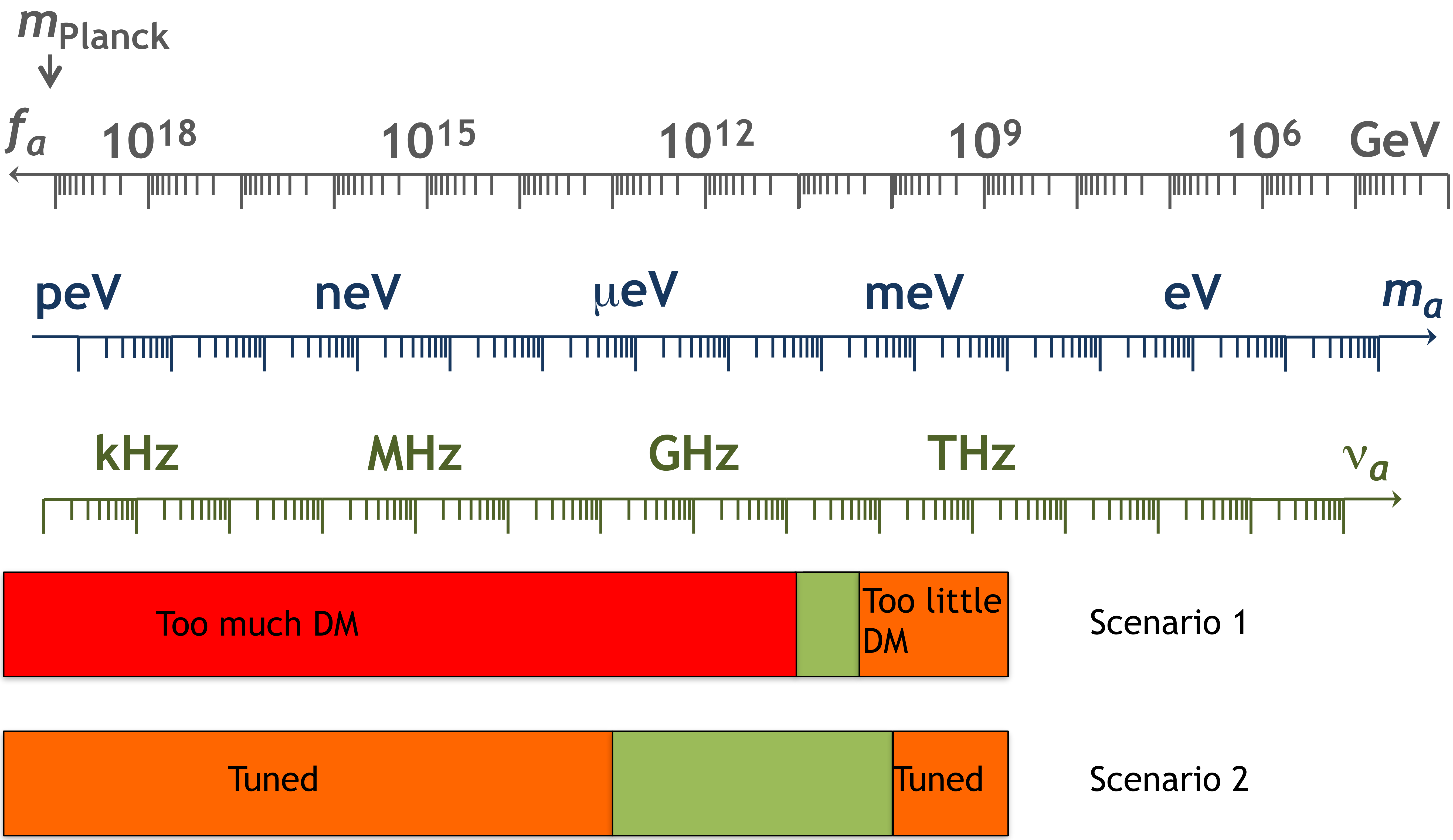


Decay of topological defects

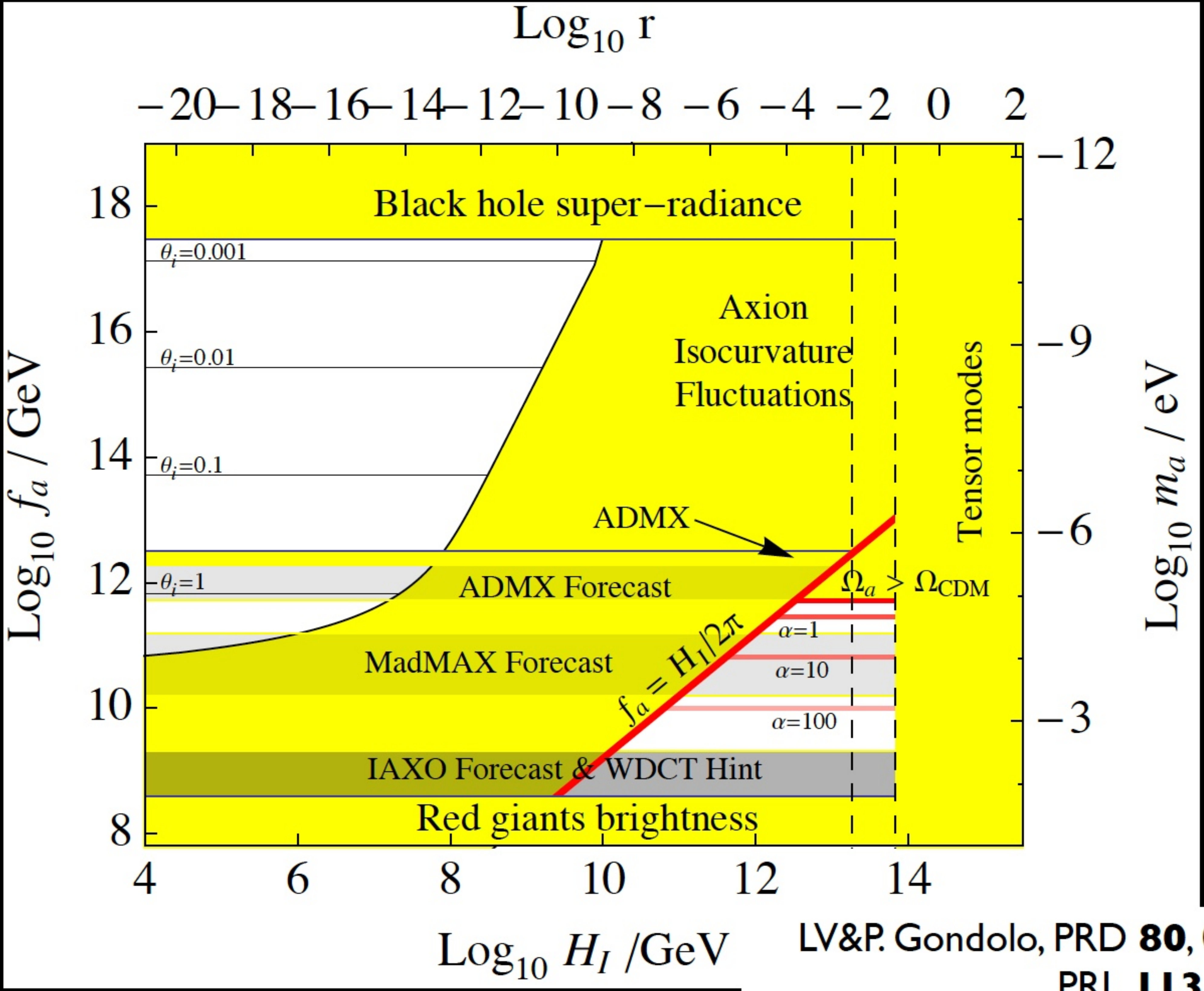


Animation credit: Javier Redondo

Constraints


m_{Planck}
f_a
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
GeV
peV
neV
μeV
meV
eV
m_a
kHz
MHz
GHz
THz
ν_a
Too much DM
Too little DM
Scenario 1
Tuned
Tuned
Scenario 2

Axion parameter space



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

Forces from Axions:
ARIADNE and QUAX

Effective coupling types

scalar (P, T violating) : $a\bar{\psi}\psi$

pseudoscalar (P, T conserving) : $a\bar{\psi}\gamma_5\psi$

$$V_{\mathrm{mm}} \;\sim\; \int d^3k\, e^{i\vec{k}\cdot\vec{r}}\, \frac{1}{k^2+m_a^2} \sim \frac{e^{-m_a r}}{r}$$

$$V_{\mathrm{md}} \;\sim\; \int d^3k\, e^{i\vec{k}\cdot\vec{r}}\, \frac{\vec{\sigma}\cdot\vec{k}}{k^2+m_a^2} \sim \vec{\sigma}\cdot\vec{\nabla}_r V_{mm}(r)$$

PRL **113,** 161801 (2014) PHYSICAL REVIEW LETTERS week ending 17 OCTOBER 2014

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

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(Received 5 March 2014; revised manuscript received 27 August 2014; published 14 October 2014)

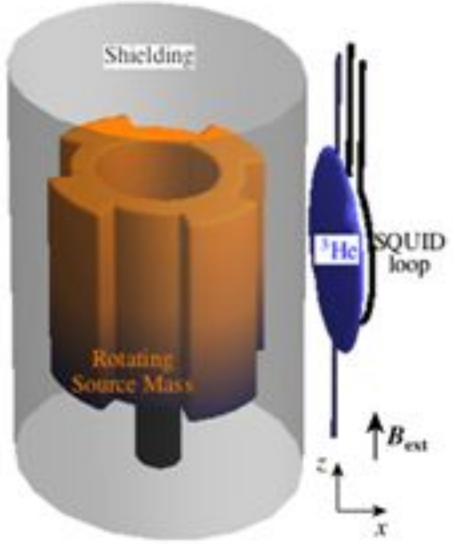


FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N \cdot \vec{B}_{ext}/\hbar$ of the NMR sample. Superconducting cylinders screen the NMR sample from the source mass and (not shown) the setup from the environment.

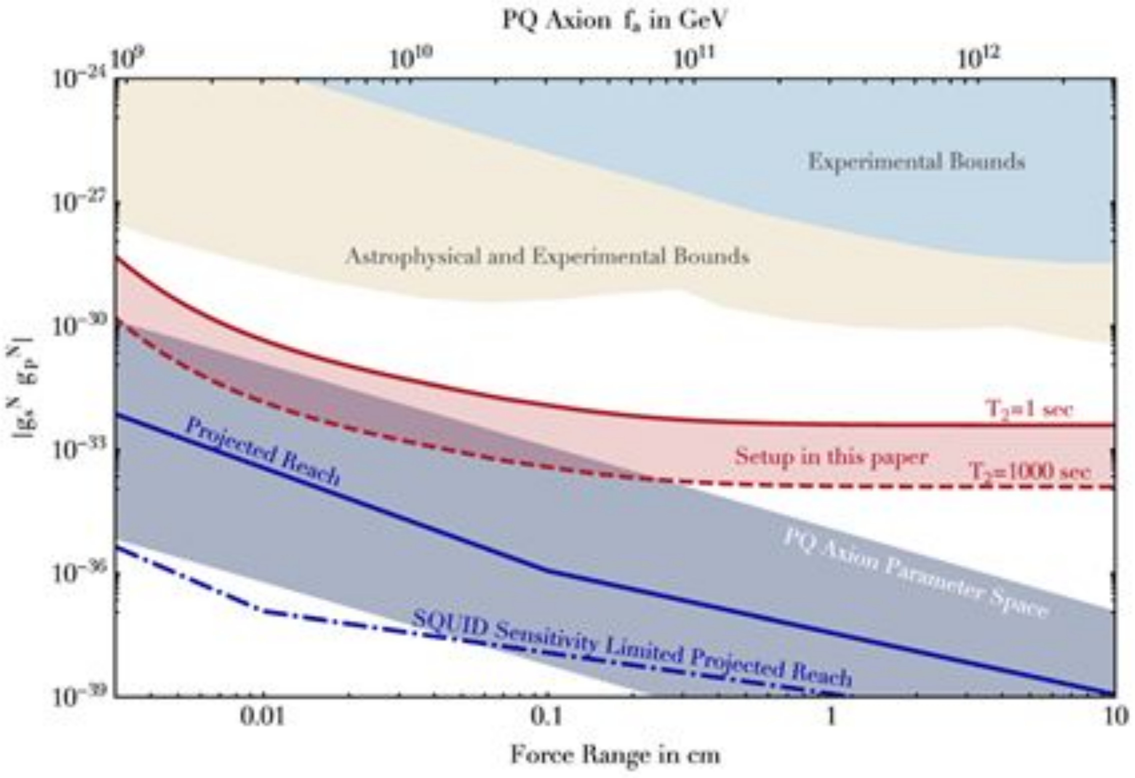
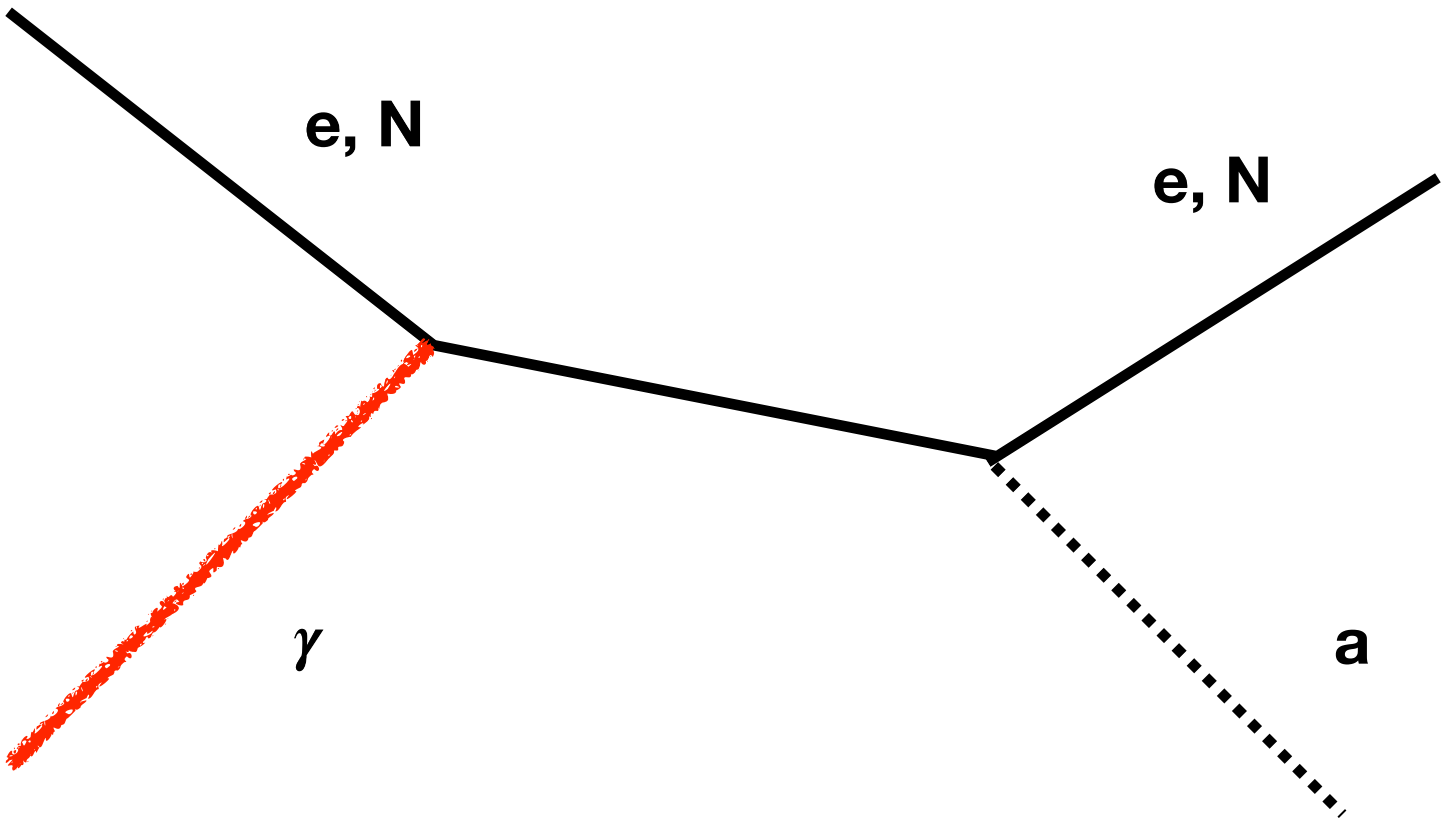


FIG. 2 (color online). Projected reach for monopole-dipole axion mediated interactions.

ARIADNE: Axion Resonant InterAction DetectioN Experiment

A.Geraci, A.Arvanitaki, A.Kapitulnik, Chen-Yu Liu, J.Long, Y.Semertzidis, M.Snow
(to be supported by NSF and/or DoE?)

Stellar Cooling



stellar axion emission processes

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).

Detailed calculations of super-radiance in Kerr black holes are quite complex, but the qualitative mechanism is closely related to Cerenkov radiation, as I'll now indicate.

$$(E, k) \;\rightarrow\; (E', k') + (\omega, q)$$

$$\begin{aligned}
E^2 - v^2 k^2 &= m^2 \\
{E'}^2 - v^2 {k'}^2 &= m^2 \\
\omega^2 - q^2 &= 0 \\
E &= E' + \omega \\
k &= k' + q
\end{aligned}$$

$$\begin{aligned} \omega^2(v^2-1) &= 2(\omega E' - v^2 q\cdot k') \\ &= 2(v^2 q\cdot k - \omega E) \end{aligned}$$

We must demand **ω** > 0. Then there are no solutions to the first equation if $v^2 < 1$, but for $v^2 > 1$ we can solve both.

The algebra gets messy in general, but simplifies for E, E′ >> m. Then we have:

$$\hat{q}\cdot\hat{k} > \frac{1}{v} > \hat{q}\cdot\hat{k}'$$

The solutions lie close to the "Mach cone".

Intuition: k is expensive, and we can gain energy by trading it in.

Super-radiance is a similar phenomenon with momentum replaced by angular momentum, and velocity by angular velocity (of frame dragging).

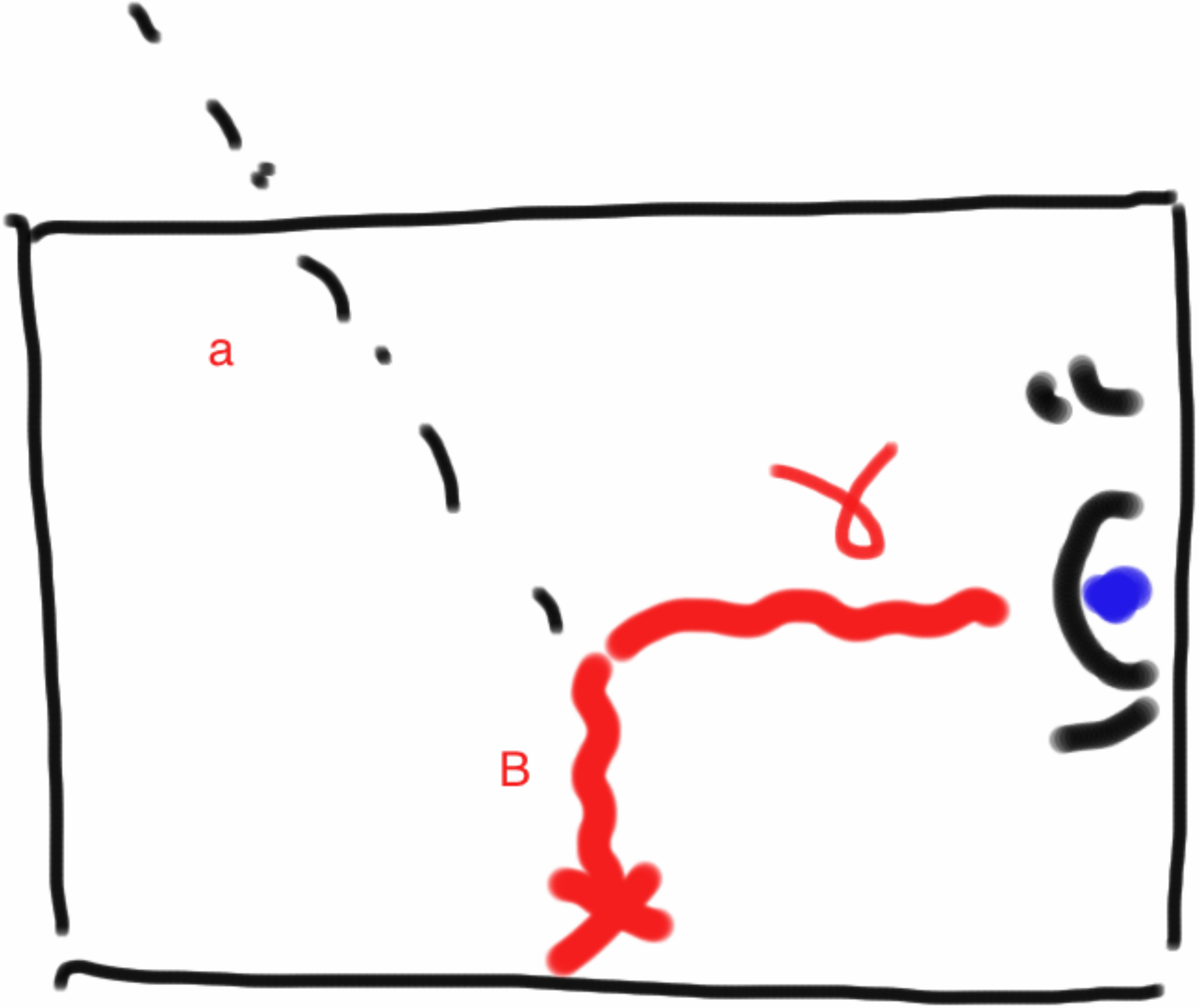
This effect could de-populate some regions of the (M, J) plane, and also affect gravitational wave signals.

It is a window into a range of ultra-light axion masses.

Helioscopes: CAST and IAXO

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

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


a
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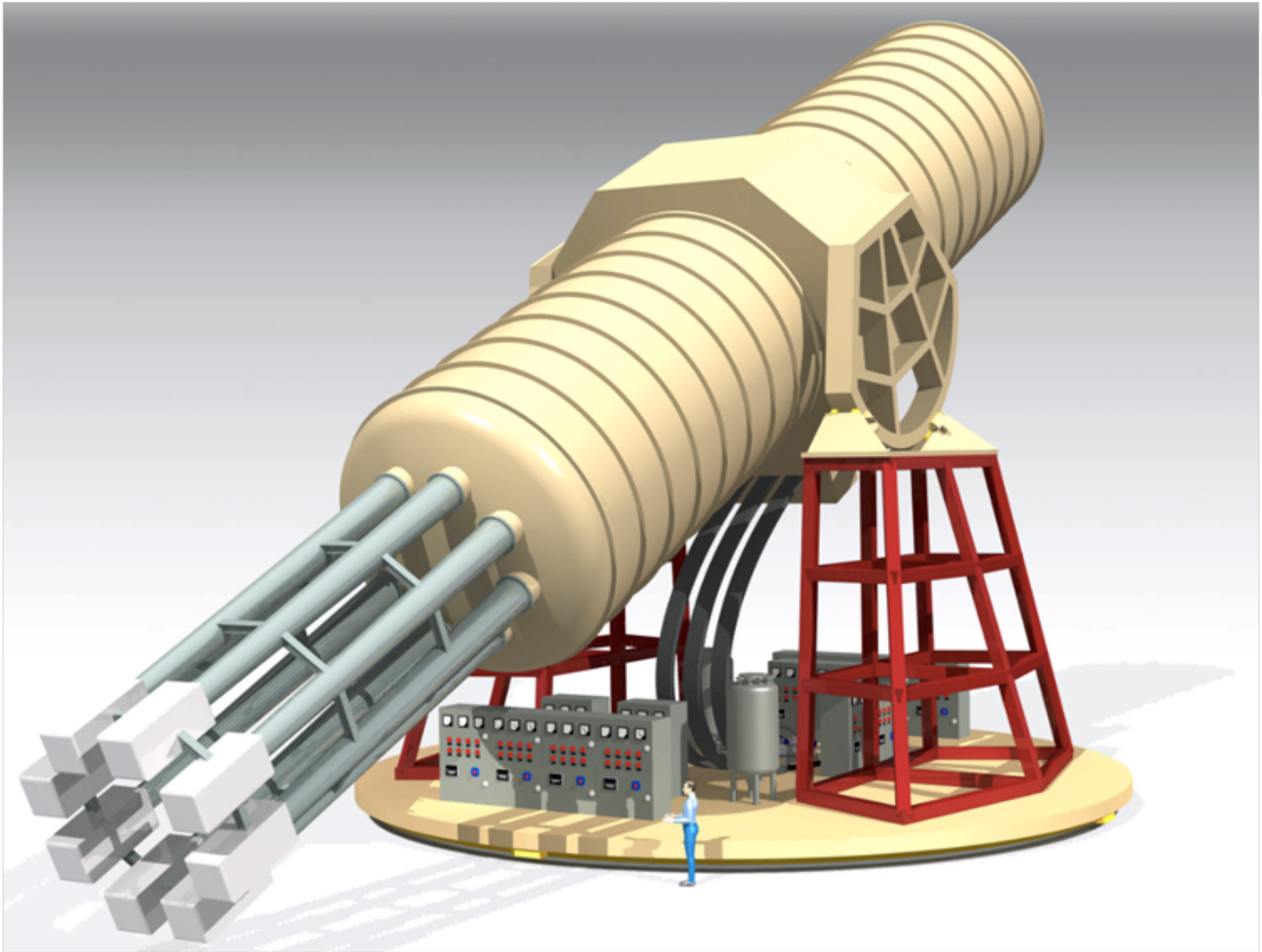
B



One might also hope to see photons from conversion of cosmic background axions in the magnetic fields around neutron stars (or conceivably elsewhere).

Haloscopes

Axion DM is a classical field

- Two classical limits of QFT: point particles and classical fields
- Wimps are an example of the first: heavy (~100 GeV) and low in number – direct detection looks for scatterings
- Axions are light (~10^{15} times lighter) and highly degenerate ($n_a \sim 10^{25}$)
- Totally different phenomenology

Axion-photon conversion

- Lowest order QFT→Fermi's golden rule

$$\Gamma_{a\to\gamma} = 2\pi \sum_{\mathbf{k}} |\mathcal{M}|^2 \, \delta(\omega_a - \omega_{\mathbf{k}}) \, .$$

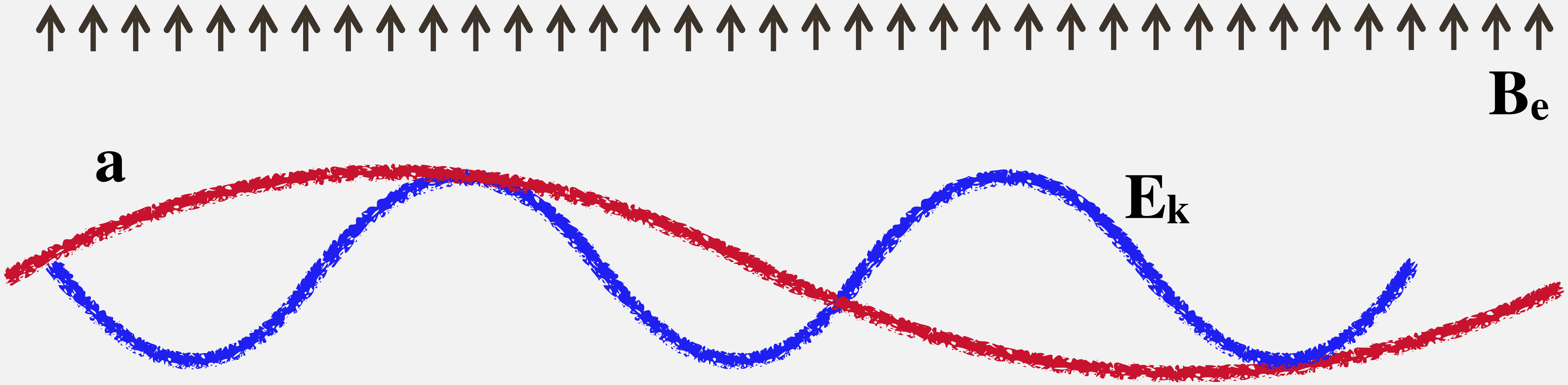
- Matrix element is given by the overlap of the axion and photon wave functions

$$\mathcal{M} = \frac{g_{a\gamma}}{2\omega V} \int d^3\mathbf{r} \, e^{i\mathbf{p}\cdot\mathbf{r}} \, \mathbf{B}_{\mathrm{e}}(\mathbf{r}) \cdot \mathbf{E}^*_{\mathbf{k}}(\mathbf{r})$$

- Experimental goal: how do we make this non-zero?

Axion-photon conversion

- In vacuum and constant B_e this oscillatory integral vanishes

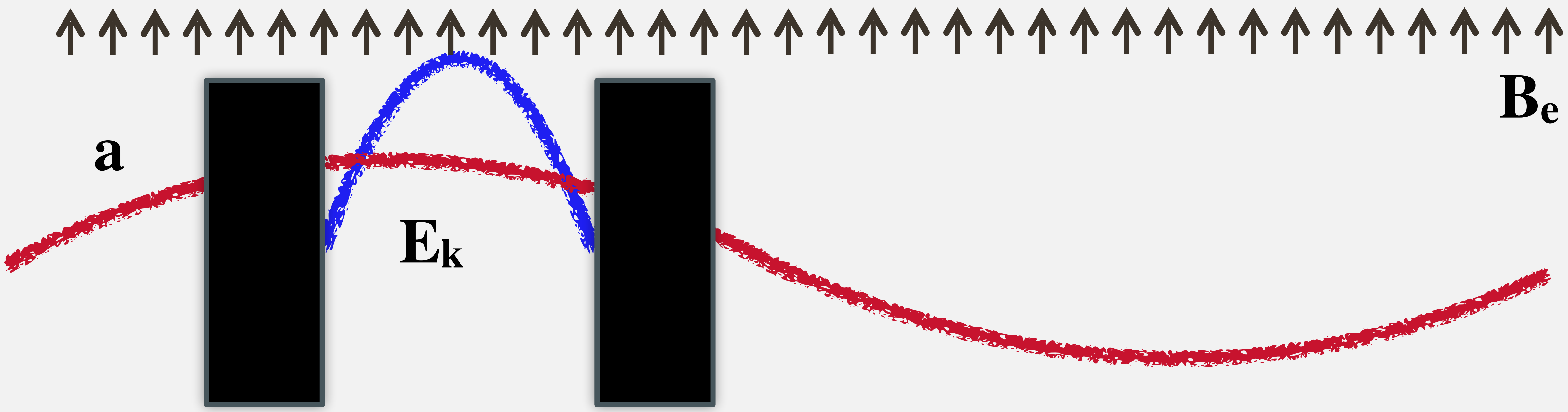


- Modify the free photon wave function!

ADMX and Haystack

Cavity haloscopes

- Inside a cavity E_k becomes the cavity modes

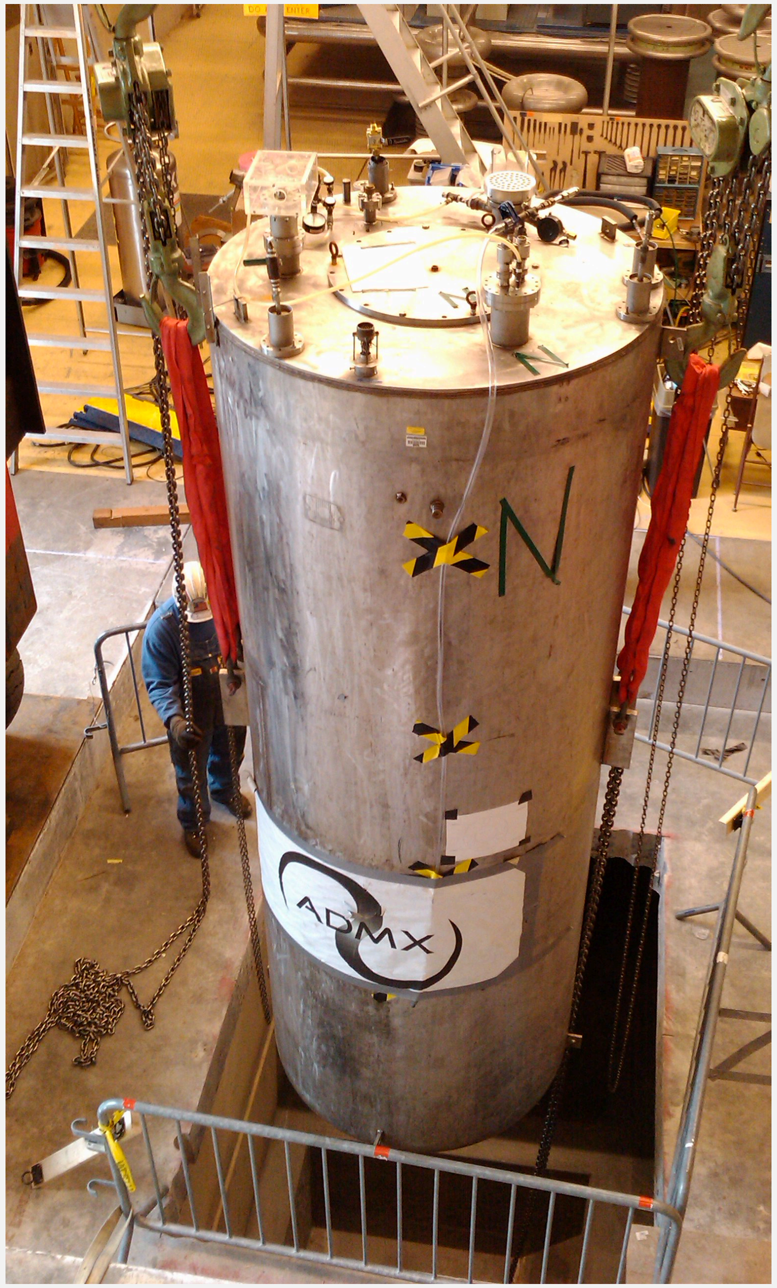


- Normalisation is given by the “quality factor” of the cavity


N
ADMX
WIZSCIENCE.COM

Cavity Haloscopes

- Build a cavity at the same scale as the axion's Compton wavelength – resonant enhancement
- Hugely increases signal, but only in a very narrow range
- Power and bandwidth inversely related
- Requires large volume – hard to do for large axions masses (small wavelengths)



Cavity detectors aim to detect cosmic axion background axions.

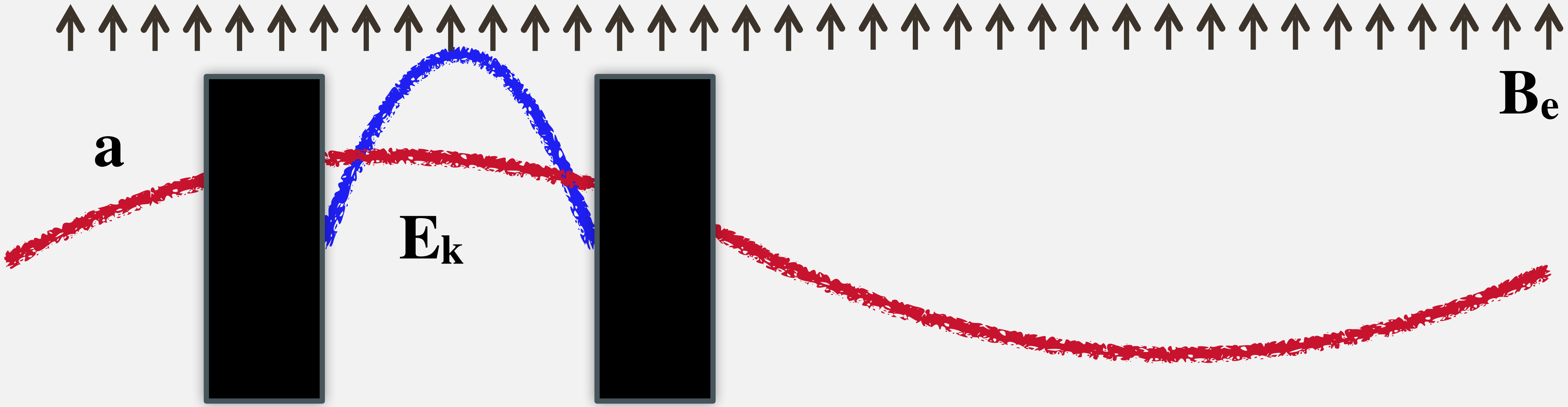
A large magnetic field induces their conversion into (observable) photons.

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

MadMAX

Cavity haloscopes

- Inside a cavity E_k becomes the cavity modes



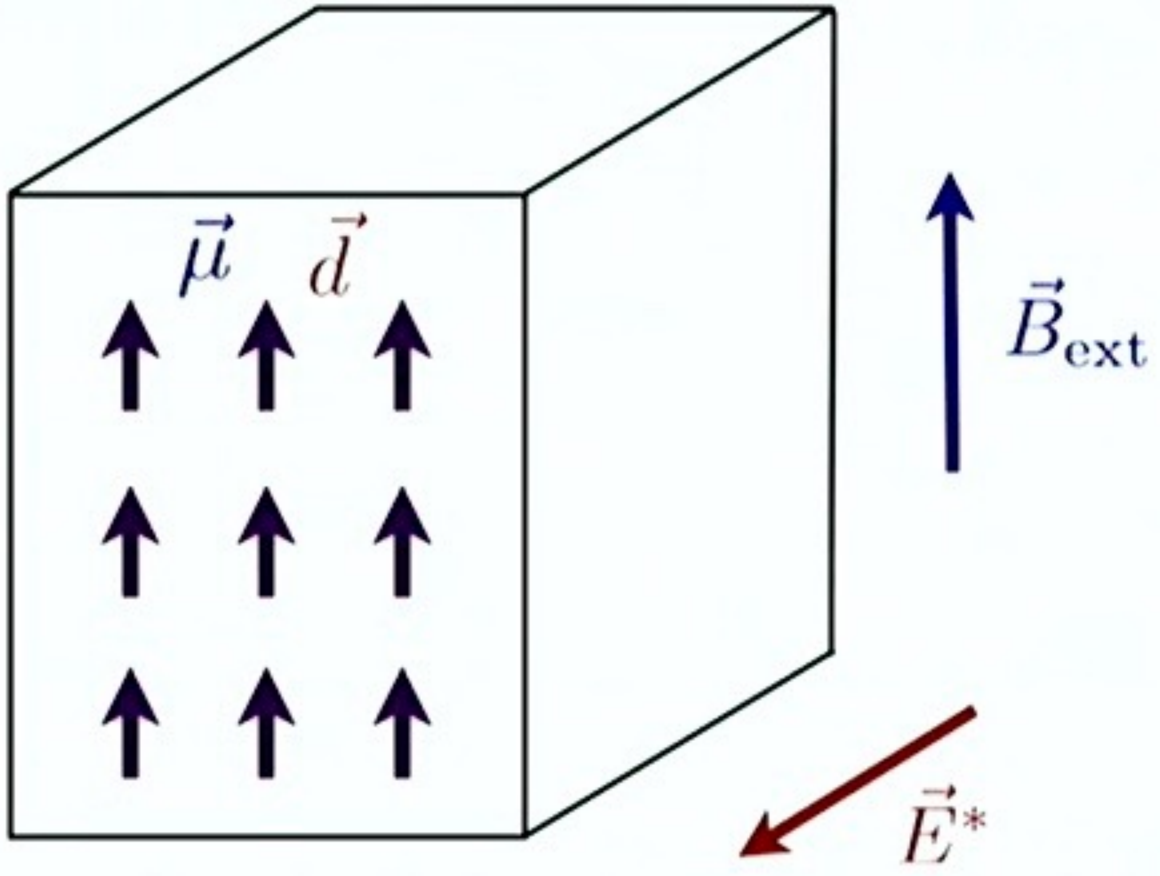
- Normalisation is given by the “quality factor” of the cavity

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

Spin Haloscope:
CASPEr

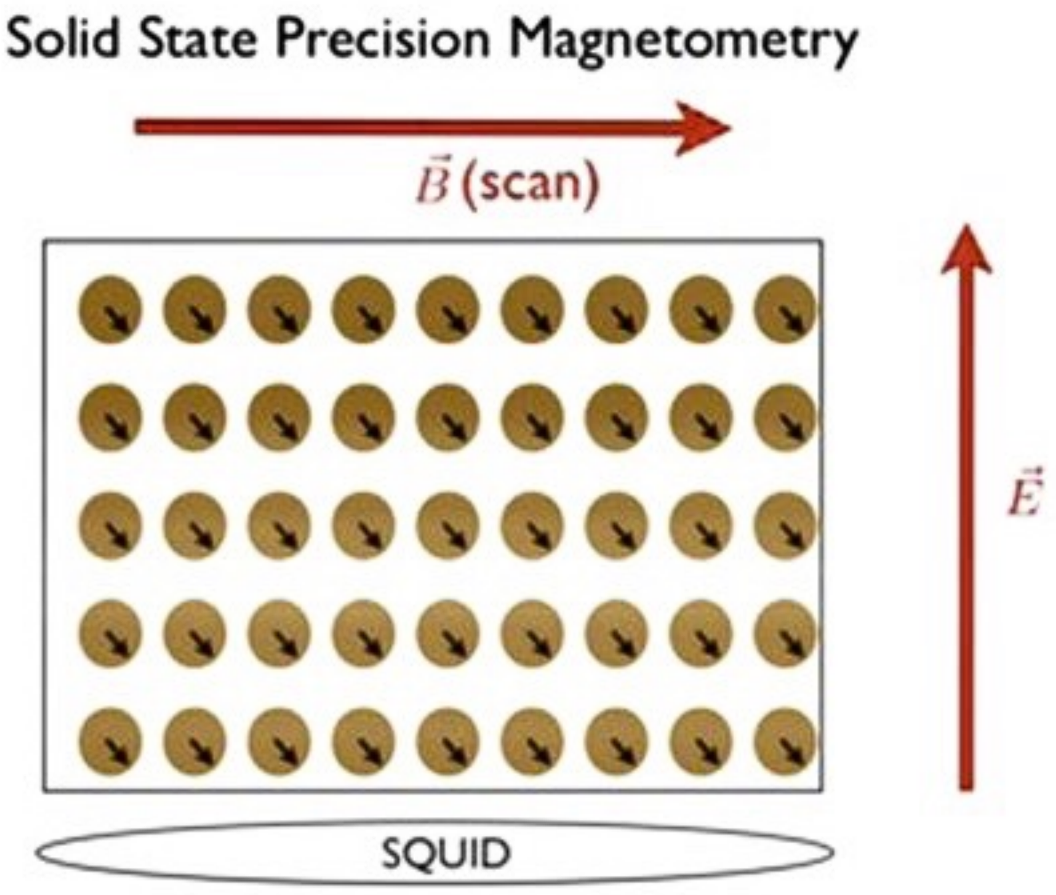
Cosmic Axion Spin Precession Experiment (CASPEr)

NMR techniques + high precision magnetometry

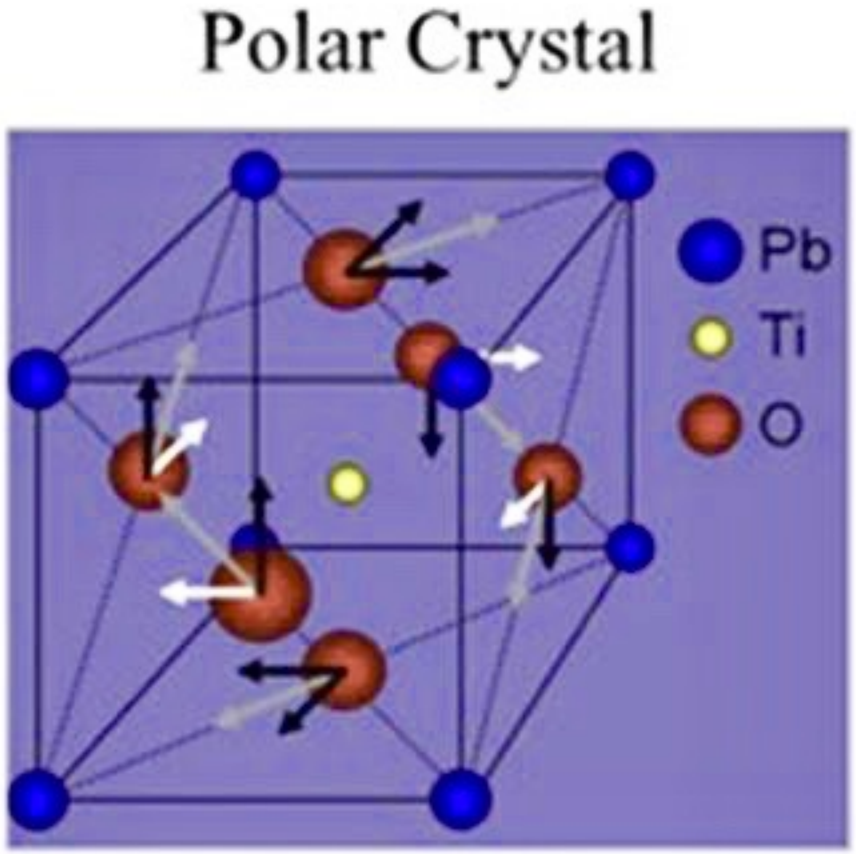


Larmor frequency = axion mass ➔ resonant enhancement

Searching for Axions in the Anthropic Window



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

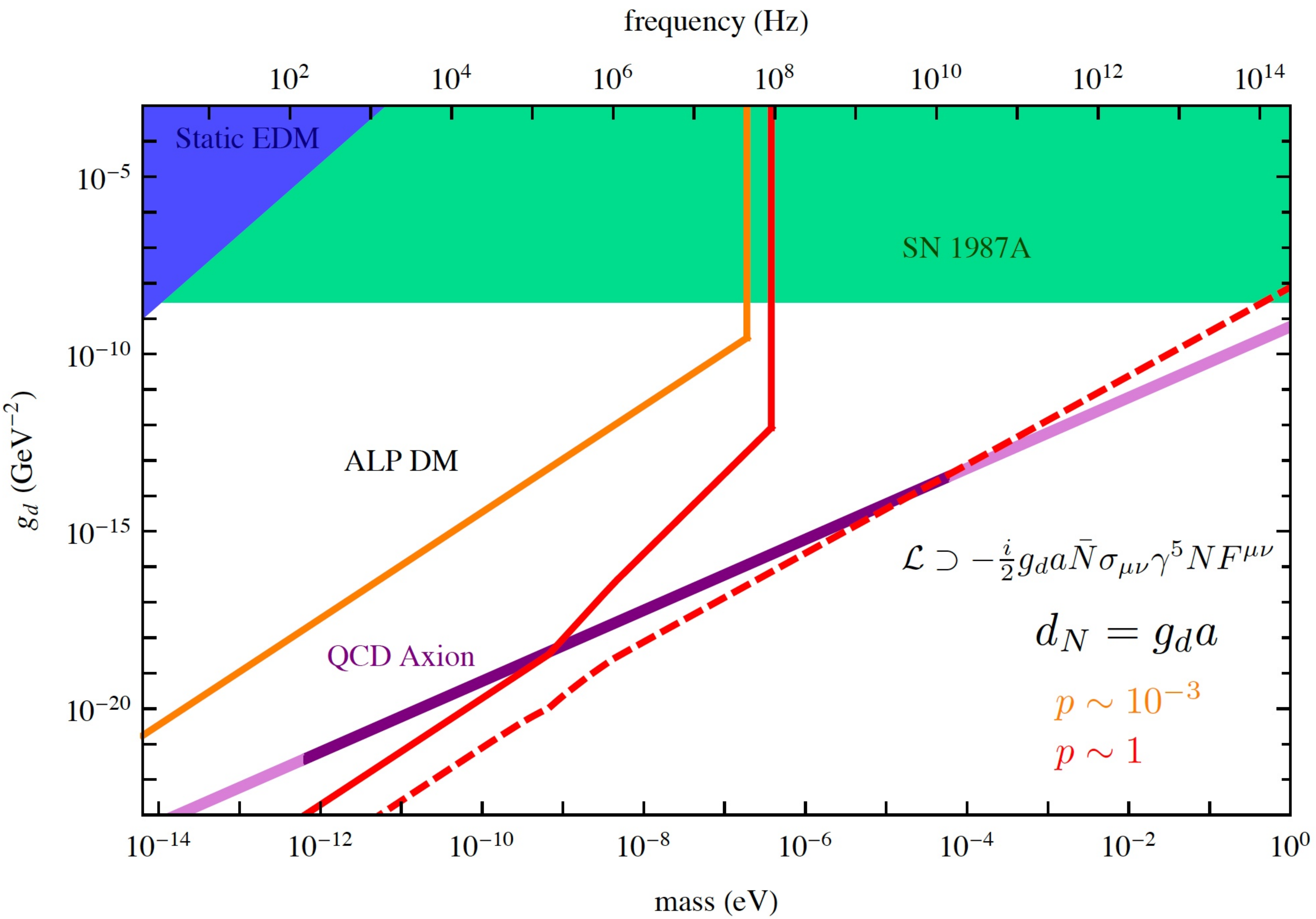


Lead Titanate

CASPEr experiment
Precise magnetometry to measure
tiny deviations from Larmor frequency

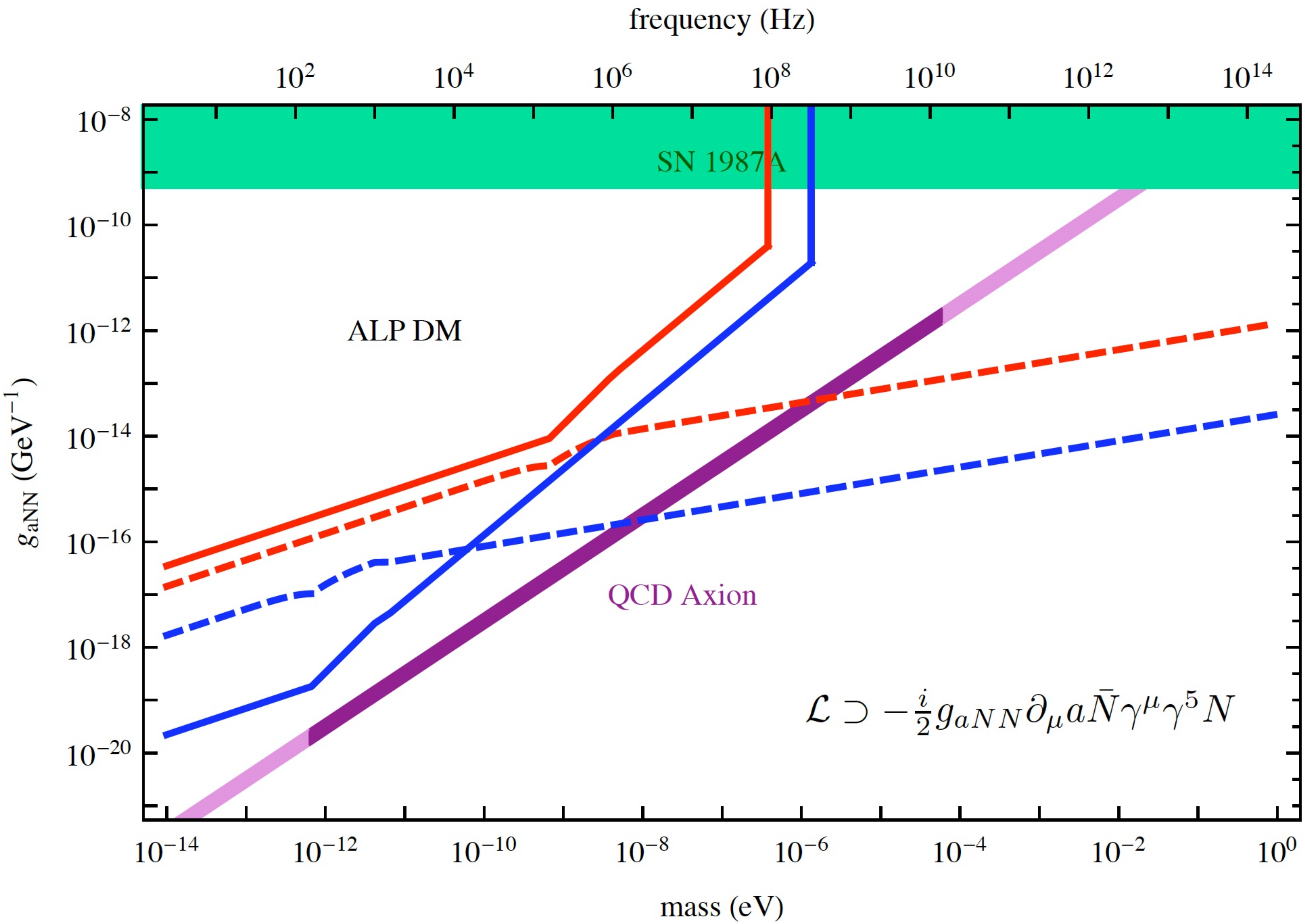
Graham & Rajendran, arXiv:1101.2691
Budker, Graham, Ledbetter, Rajendran & Sushkov, arXiv:1306.6089

Projected Sensitivity in Lead Titanate



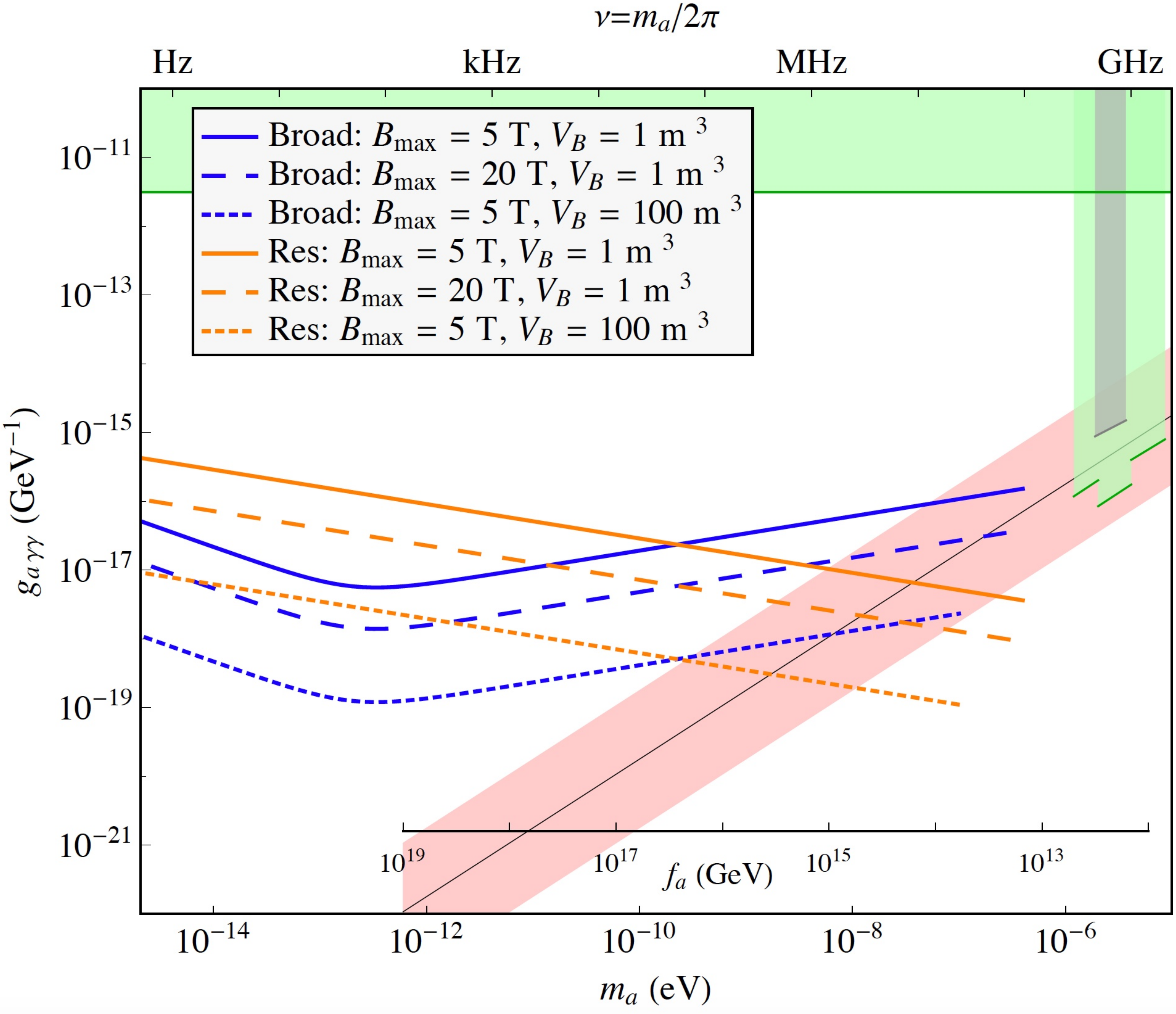
$$\delta B = 0.1 \frac{\mathrm{fT}}{\sqrt{\mathrm{Hz}}},\ n = \frac{10^{22}}{\mathrm{cm}^3},\ V = 1000\ \mathrm{cm}^3,\ T_2 = 1\ \mathrm{s}$$

Projected Sensitivity



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

Field haloscope: 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
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{19}
10^{17}
10^{15}
10^{13}
f_a (GeV)
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
m_a (eV)

Plasma Haloscope

Searching for axion dark matter with tuneable plasma haloscopes

Matthew Lawson, Alex Millar, Matteo Pancaldi, Edoardo Vitagliano, Frank Wilczek

M. Lawson et al arXiv:1904.11872

Oskar Klein
centre

The $a\vec{E} \cdot \vec{B}$ coupling allows the cosmic axion field to drive electromagnetic radiation.

Since the coupling is weak, and the axion line is narrow, we should take advantage of resonance.

Also, the axion field is quite homogeneous, spatially. In particle language: Its deBroglie wavelength is much larger than its Compton wavelength.

It would be helpful if the photon mass matched the axion mass. Then a uniform magnetic field would allow axions to convert to photons resonantly in a large volume.

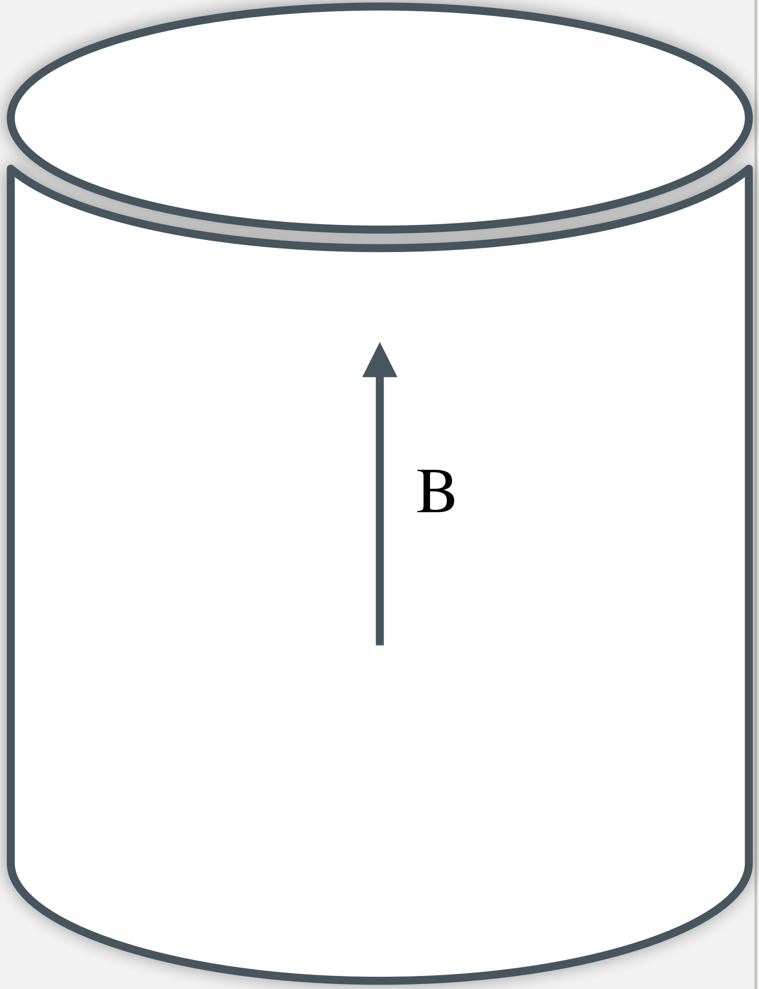
Photons acquire mass in superconductors and in gaseous plasmas, but are not suitable.

The cold plasmas inside metals are closer to what we want, but for bulk metals the plasma frequency is too large (and not easily tunable).

Bright idea: Don't fill all space with metals; instead, use an array of wires, aligned along the $\vec{B}_0$ field

Finite media

- Finite experiment needs finite plasma
- Easiest case: plasma cylinder



$$\mathbf{B} = \mathbf{B}_t + B_z\hat{\mathbf{z}}\,; \quad \mathbf{E} = \mathbf{E}_t + E_z\hat{\mathbf{z}}\,; \quad \mathbf{B}_{\mathrm{e}} = B_{\mathrm{e}}\hat{\mathbf{z}}\,,$$

$$\left(\boldsymbol{\nabla}_t + \frac{\partial}{\partial z}\hat{\mathbf{z}}\right) \times (\mathbf{B}_t + B_z\hat{\mathbf{z}}) = -i\omega\left(\mathbf{E}_t + \epsilon_z E_z\hat{\mathbf{z}}\right) - i\omega g_{a\gamma} a B_{\mathrm{e}}\hat{\mathbf{z}}\,,$$

$$\left(\boldsymbol{\nabla}_t + \frac{\partial}{\partial z}\hat{\mathbf{z}}\right) \times (\mathbf{E}_t + E_z\hat{\mathbf{z}}) = i\omega\left(\mathbf{B}_t + B_z\hat{\mathbf{z}}\right)\,.$$

Finite media

- Symmetry separates the transverse and axial fields

$$\mathbf{E}_t = \frac{1}{\omega^2 - k^2}\left(\nabla \frac{\partial \mathbf{E}_z}{\partial z} + i\omega \nabla_t B_z \times \hat{\mathbf{z}}\right) ,$$

$$\mathbf{B}_t = \frac{1}{\omega^2 - k^2}\left(\nabla \frac{\partial \mathbf{B}_z}{\partial z} - i\omega \nabla_t E_z \times \hat{\mathbf{z}}\right) .$$

$$\frac{\omega^2}{\omega^2 - k^2}\left(r^2 \frac{\partial^2 E_z}{\partial^2 r} + r \frac{\partial E_z}{\partial r}\right) + r^2\omega^2\epsilon_z E_z + r^2\omega^2 g_{a\gamma} B_{\mathrm{e}} a = 0 \,,$$

Finite media

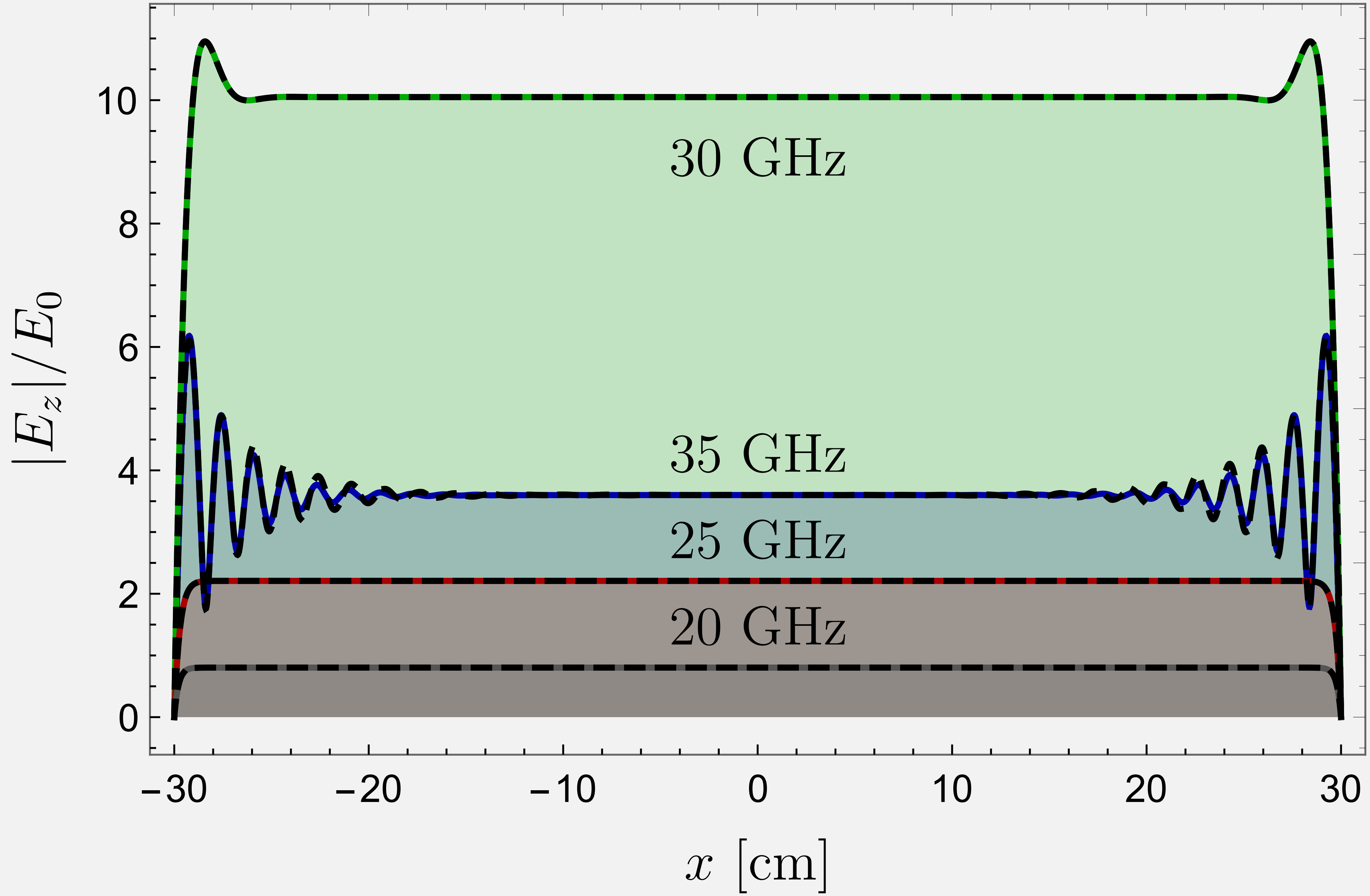
- Plasma must be in B-field (solenoid) so assume conductive walls

$$E_z = -\frac{a g_{a\gamma} B_{\mathrm{e}}}{\epsilon_z} + \frac{a g_{a\gamma} B_{\mathrm{e}}}{\epsilon_z} \frac{J_0(\sqrt{\epsilon_z} r\omega)}{J_0(\sqrt{\epsilon_z} R\omega)} ,$$

$$\mathbf{B}_t = -\frac{a g_{a\gamma} B_{\mathrm{e}}}{\sqrt{\epsilon_z}} \frac{J_1(\sqrt{\epsilon_z} r\omega)}{J_0(\sqrt{\epsilon_z} R\omega)} \hat{\theta} .$$

$$\epsilon_z = 1 - \frac{\omega_p^2}{\omega^2 - i\gamma\omega}$$

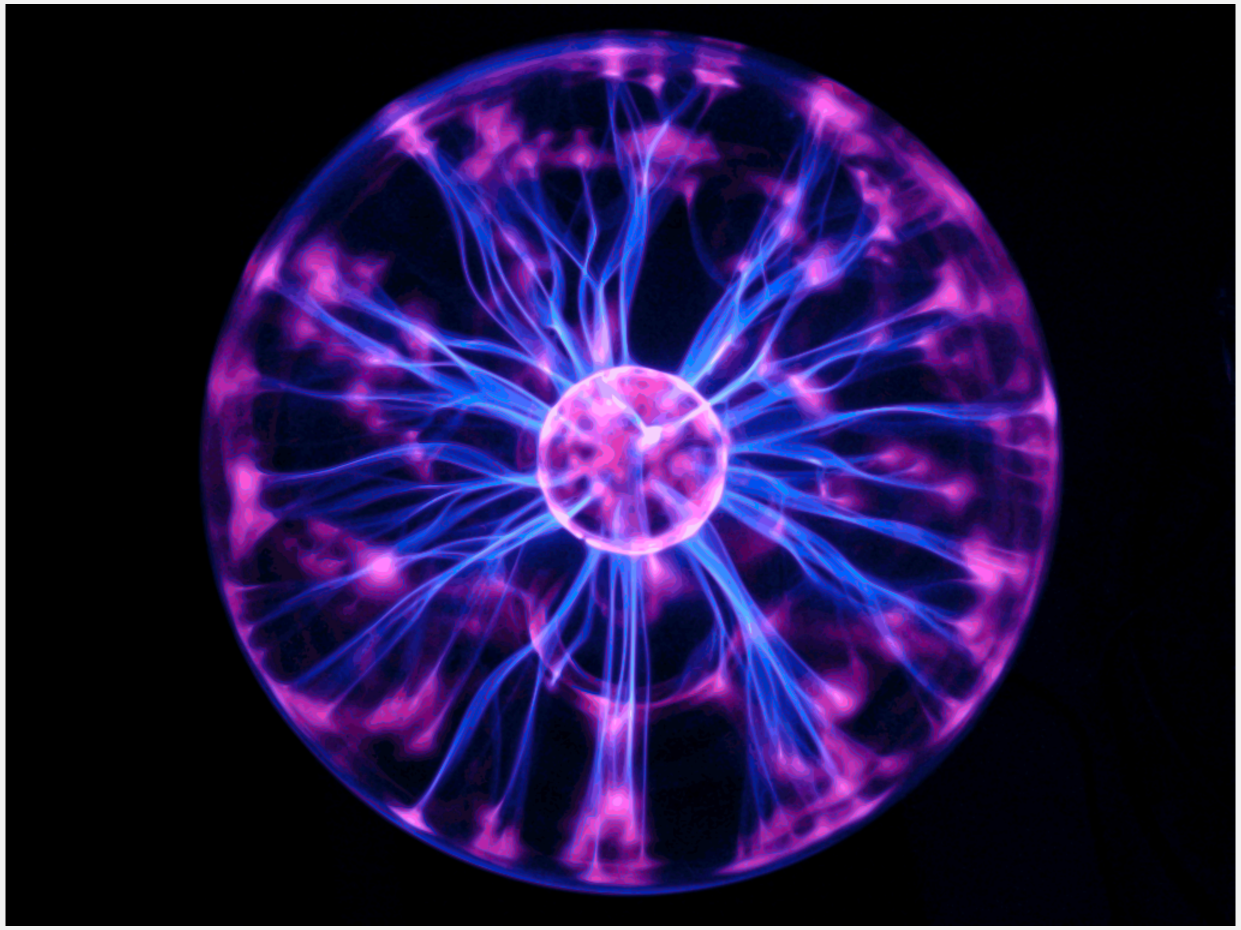
Finite media



What do you want in a material?

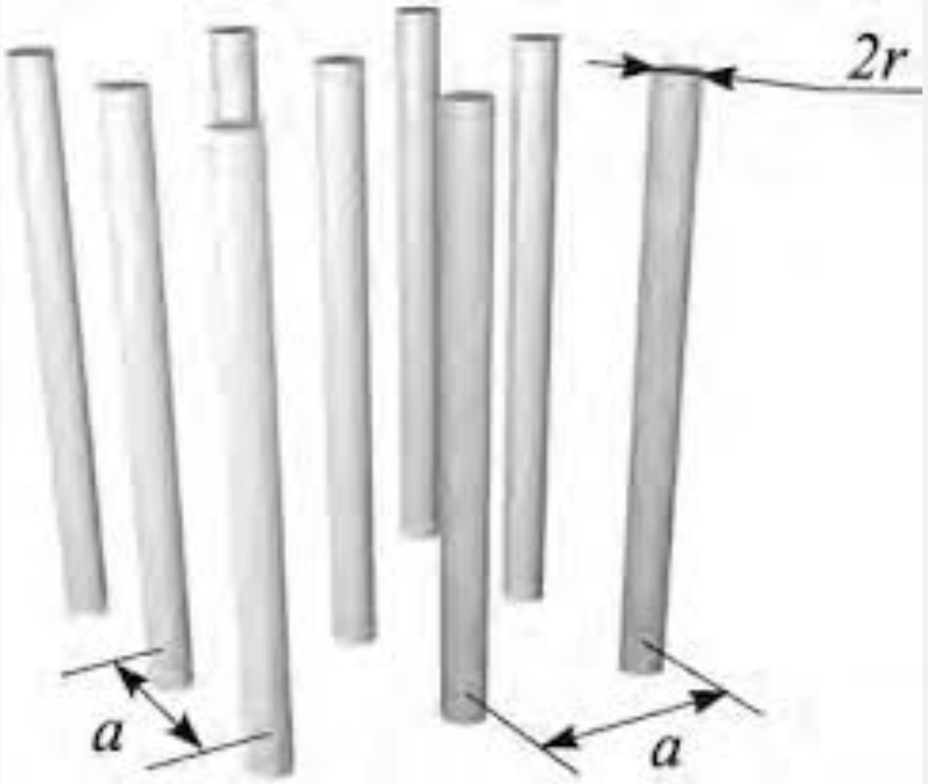
- Cryogenic temperatures
- Tuneable plasma frequency
- Large volume
- “Low” plasma frequency
- Low loss

$$\epsilon_z = 1 - \frac{\omega_p^2}{\omega^2 - k_z^2 + i\omega\Gamma}$$



Thin wire metamaterials

- One of the first metamaterials
- Plasma frequency determined by two factors: effective electron number density and mass
- Wires mutually induct, changing the plasma frequency



Thin wire metamaterials

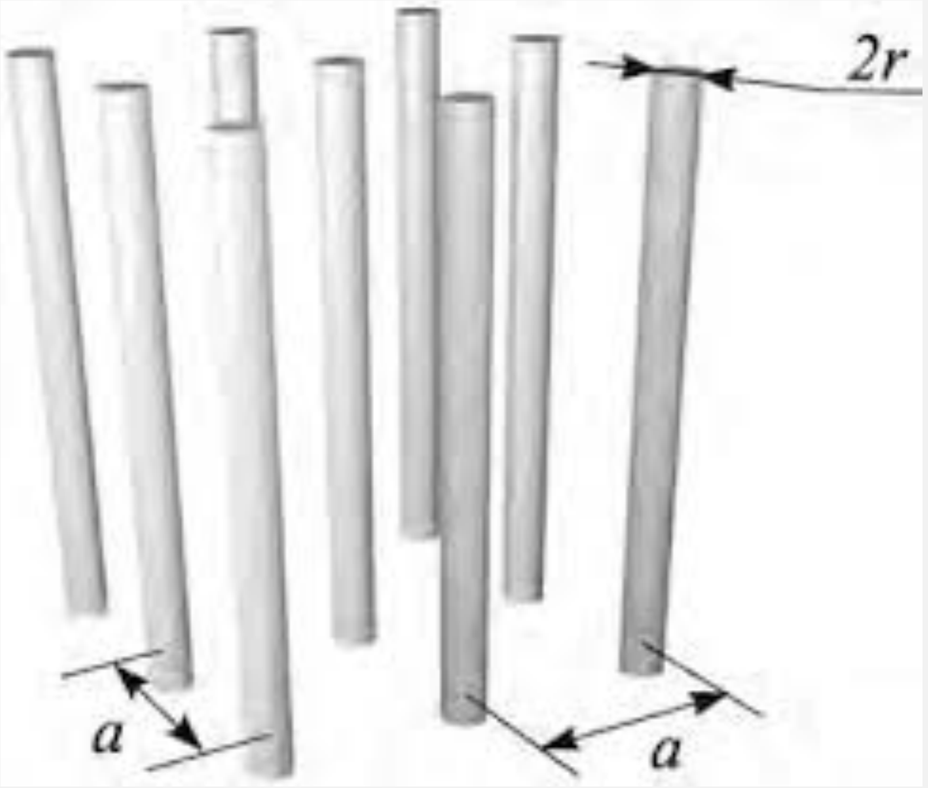
- Together

$$n_e = n\frac{\pi r^2}{a^2} \quad ; \quad m_{eff} = \frac{e^2 \pi r^2 n}{2\pi} \log\frac{a}{r} \, ,$$

- Actual electron density of wires cancels

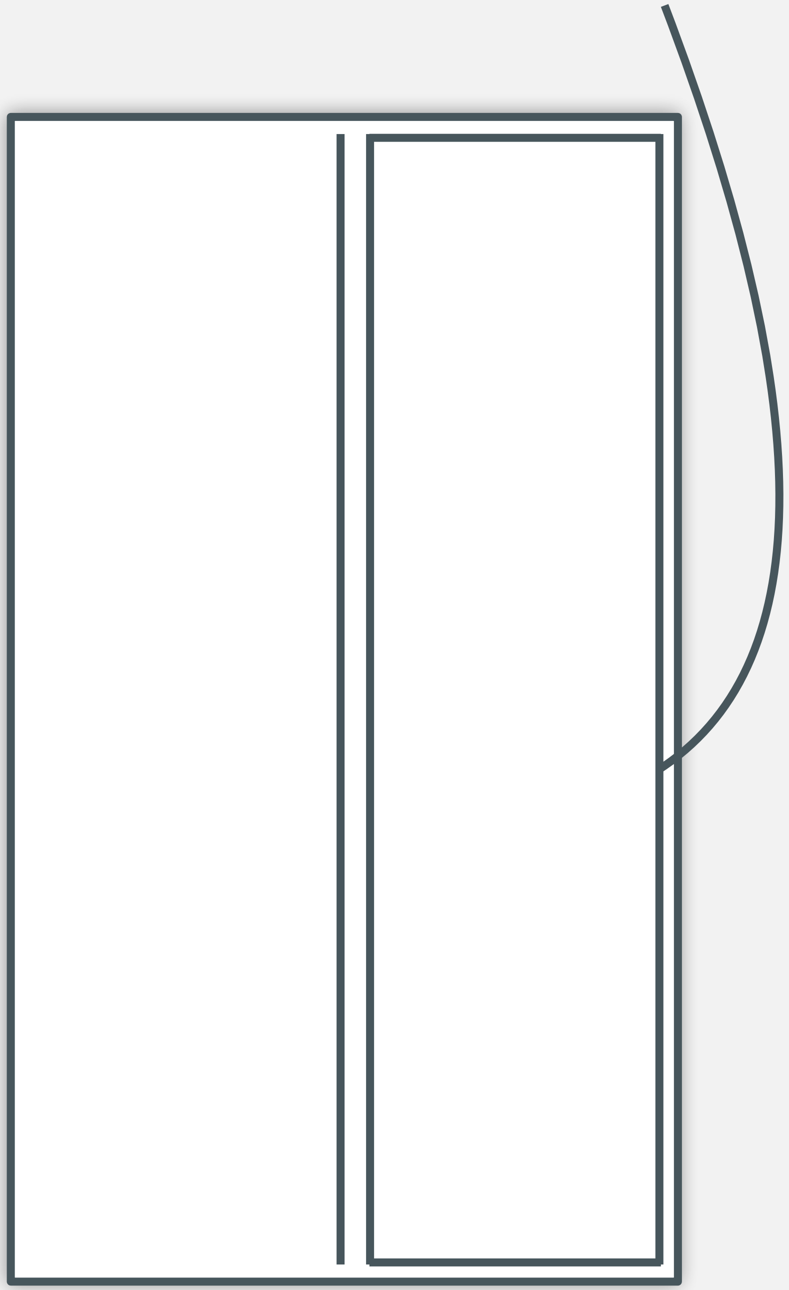
$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{a^2 \log(a/r)} \, .$$

- ~cm spacing gives ~GHz plasma frequency
- Tuneable with spacing!

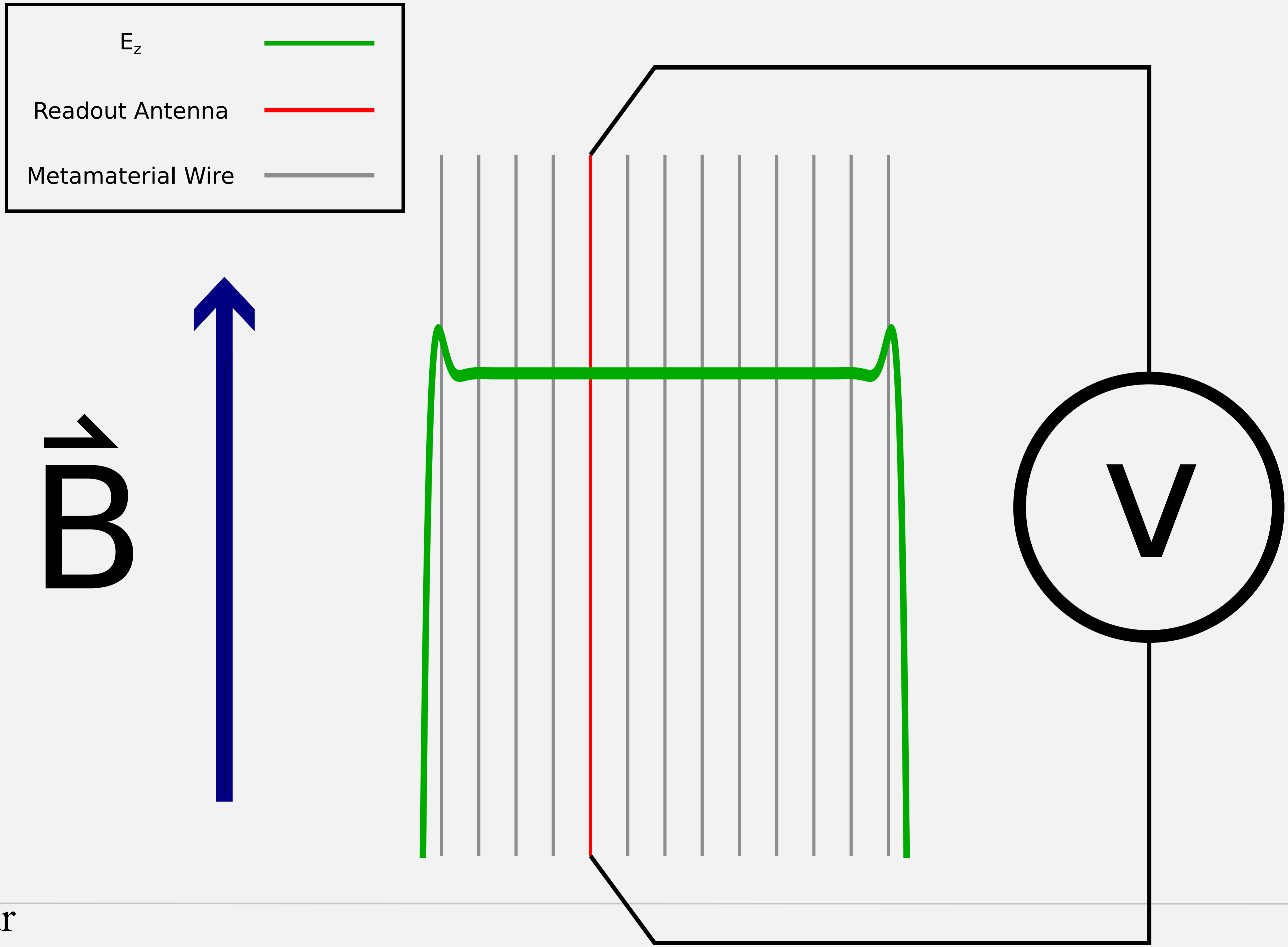


Signal readout

- So we have an E-field…
  but what's the signal?
- Two obvious options
- Read out the wire voltages
- Run an inductive loop



Setup



Potential reach

- E-fields and dielectric constant give the produced power

$$P = \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B_{\rm e}^2$$

- "Geometry factor" almost constant for large devices (opposite to cavity haloscope)

$$\mathcal{G} = \frac{\epsilon_z^2}{a_0^2 g_{a\gamma}^2 B_{\rm e}^2 V} \frac{1}{2} \int \frac{\partial(\epsilon_z \omega)}{\partial \omega} |\mathbf{E}|^2 + |\mathbf{B}|^2 dV .$$

- Quality factor is given by the loss term

$$Q = \omega/\Gamma$$

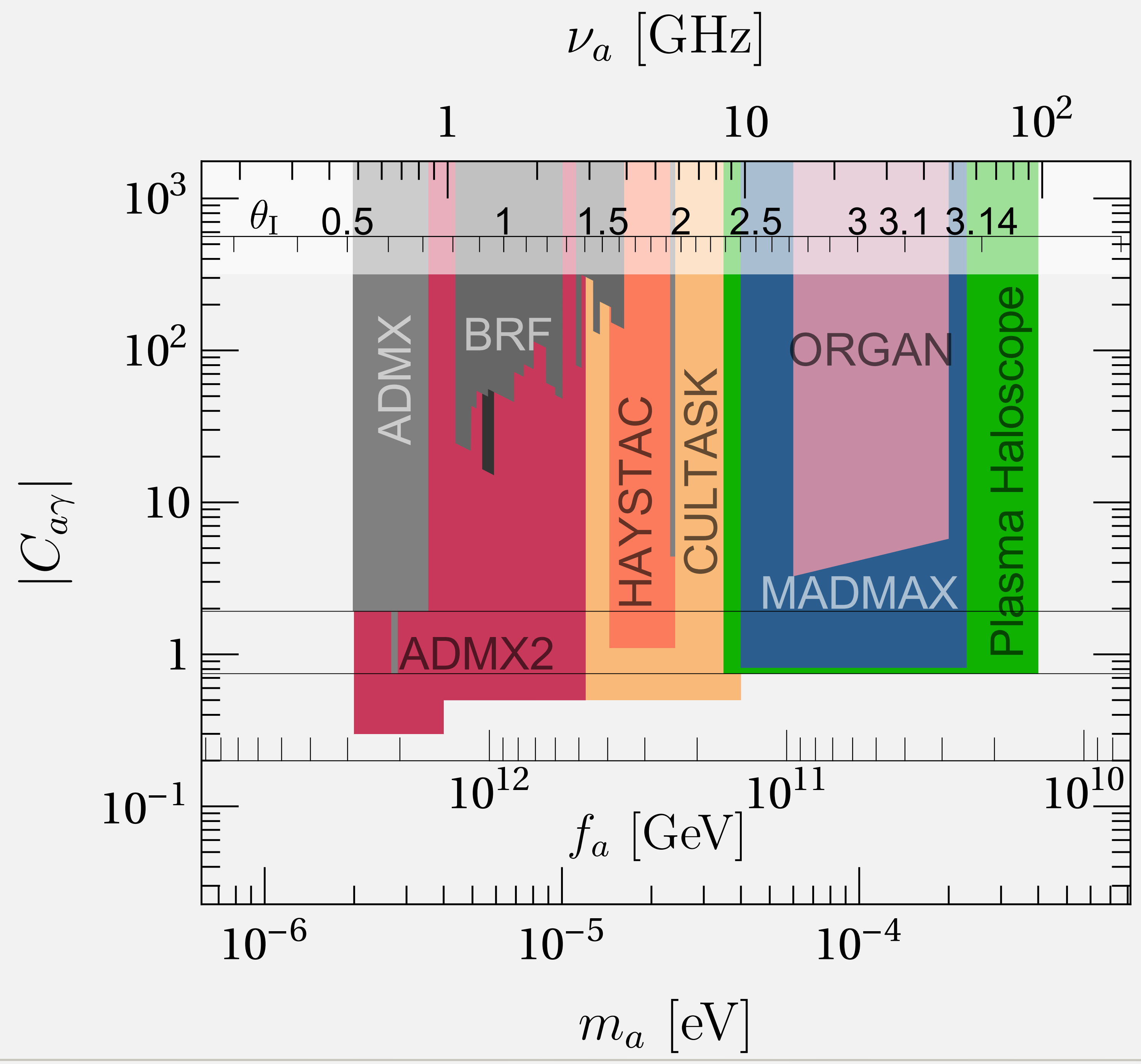
Potential reach

- Dicke's formulae

$$\Delta t = \left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2 \left(\frac{T_{\mathrm{sys}}}{P_\gamma}\right)^2 \Delta\nu_a$$

- High power gives fast scanning
- Assume 10 T B-field, V=0.8m^3 with a conservative Q=100 using quantum limited detection

Discovery Potential



Advantages over a cavity

- Much larger volumes: effective “geometry factor” is constant in the infinite volume limit
- Different media may allow for non-mechanical tuning
- Still can be made resonant to hopefully match quality factors
- Less good for very low frequencies ($\varepsilon\omega R>\pi$)

Vs dielectric haloscopes

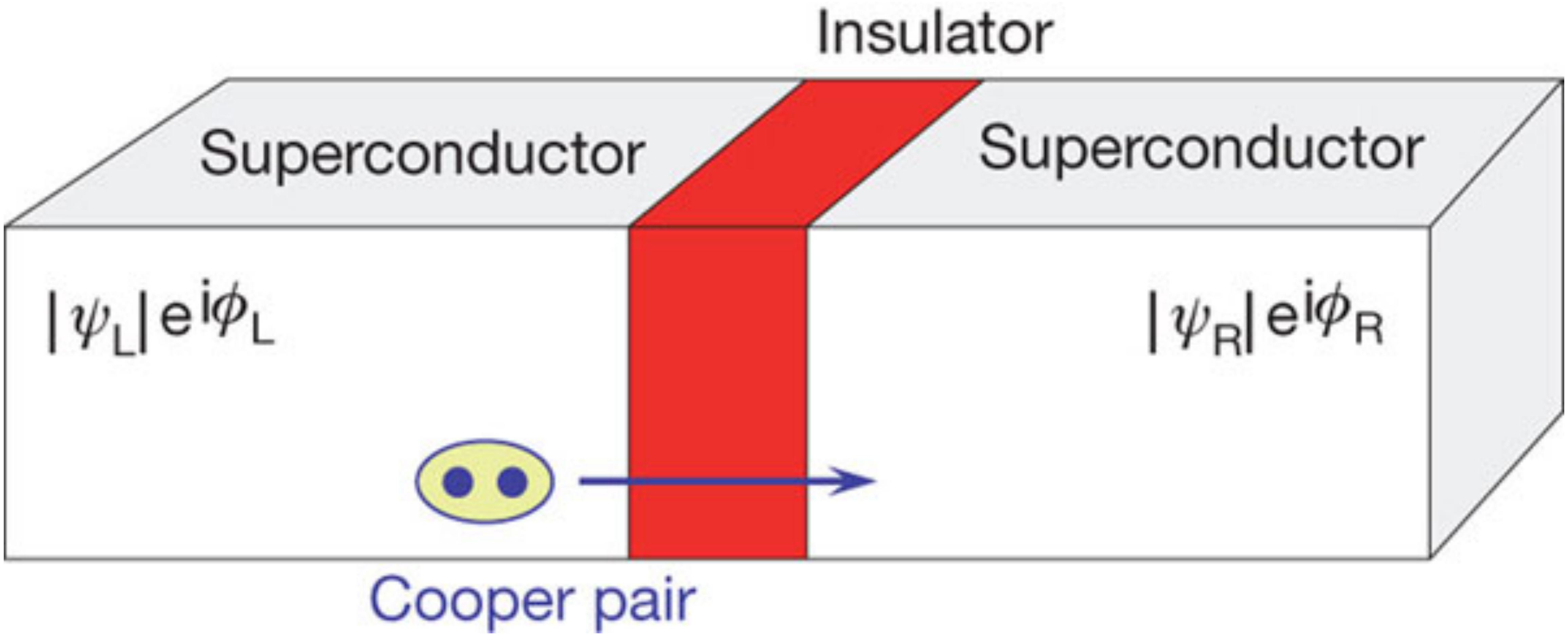
- **Pros:**
- Solenoidal magnet
- Works for any frequency you can find a good medium
- Might also work with say semi-conductors
- May allow for non-mechanical tuning
- **Cons:**
- Must be resonant (potentially harder tuning)
- Behind on R&D

Plasmascope Conclusions

- Axions are a highly well motivated dark matter candidate with a unique phenomenology
- Axion plasma mixing a promising new avenue for axion detection
- Provides an alternative detection mechanism for high-mass axions
- Very competitive sensitivity

SNIPS

Superconducting Nitpicking Systems


Insulator
Superconductor
Superconductor
$|\psi_L|e^{i\phi_L}$
$|\psi_R|e^{i\phi_R}$
Cooper pair

$$L \;=\; \hbar n\,\dot{\delta} - \frac{\hbar j_0}{2e}\,\cos\delta - 2neV$$

phase/number conjugacy

misalignment energy

electric potential energy

$$j \;=\; j_0\,\sin\delta$$

DC Josephson

$$\frac{d\delta}{dt} \;=\; \frac{2eV}{\hbar}$$

“Schrödinger”

$$j(t) \;=\; j_0\,\sin\big(\frac{2eV}{\hbar}t + \delta_0\big)$$

$\boldsymbol{\tau}$ breaking

NG mode

$$j(t) \;=\; j_0 \,\sin\,(\frac{2eV}{\hbar}t + \delta_0)$$

$$V(t) = V_0 + \epsilon \cos m_a t$$

$$\Delta j(t) \;\approx\; j_0 \,\cos(\frac{2eV}{\hbar}t + \delta_0)\,\frac{2e\epsilon}{\hbar}\cos m_a t$$

Thus we get sidebands, split by $\pm m_a$.

T odd response!

Homework problem: Compute some epsilons.

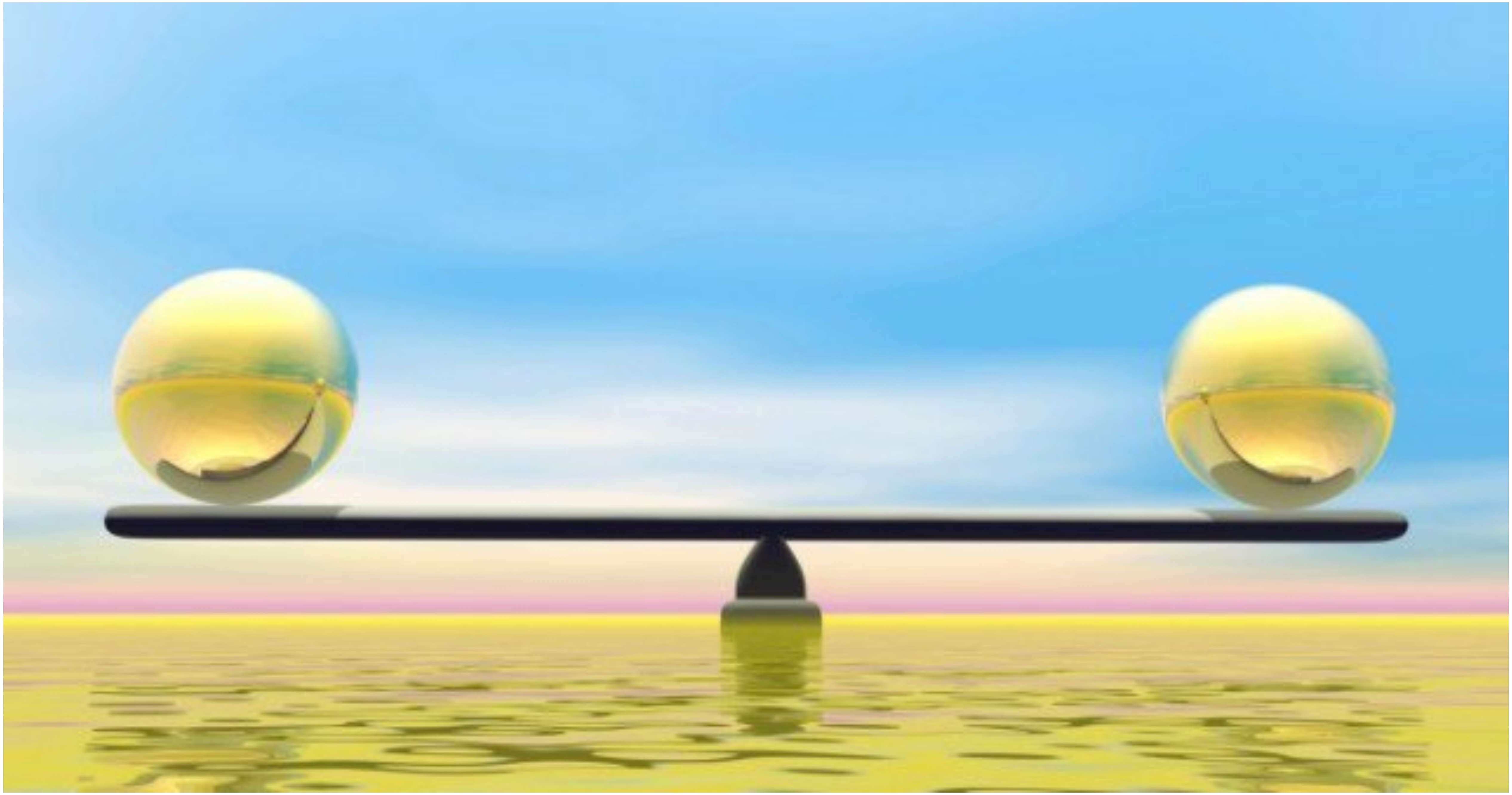
Possibly important remark: SNIPS can be driven by other things, besides cosmic axion background.

Summary and Prospects

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

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

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



Balancing past and future