From T to Axions, Dark Matter, and an Experiment

1. Why fundamental physics needs axions

2. Axions as particles

2a. Axion electrodynamics

3. Why cosmology needs dark matter

4. How axions make dark matter

5. (Axions and astrophysics)

6. (Axions and laboratory physics)

7. (Axion haloscopes)

7a. Plasma haloscope

8. (Emergent "Axions")

for more details (and hundreds of references) see e.g.
https://pdg.lbl.gov/2020/reviews/rpp2020-rev-axions.pdf

(1) Why Fundamental Physics Needs Axions

A Series of “Why?”s

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. They constrain possible interactions.

Exactly two possible sources of T symmetry violation are consistent with those principles.

One of them* beautifully explains what Cronin and Fitch observed (and a lot more).

The other** doesn't happen.

* The particles with definite mass are not the same as the particles the W boson couples to. There is a unitary matrix - the so-called CKM mixing matrix - that describes who decays to who and how much.

The CKM matrix governs flavor-changing weak decays.

Inside the CKM matrix there is one non-trivial phase factor $e^{i\delta}$.

The T (or CP) violating effects due to $e^{i\delta}$ are subtle asymmetries between channels involving particles and antiparticles in flavor-changing weak decays, e.g. $\Gamma(X \to AB) \;\neq\; \Gamma(\bar{X} \to \bar{A}\bar{B})$

** The so-called θ term $\Delta L \propto \theta E^a \cdot B^a$ modifies the self-interactions of color gluons - i.e., QCD.

θ is odd under T, i.e. $\theta \rightarrow -\theta$.

One can calculate that a non-zero value of θ will induce an electric dipole moment d_n for the neutron.

Experimental limits on d_n constrain $|\theta| \leq 10^{-10}$.

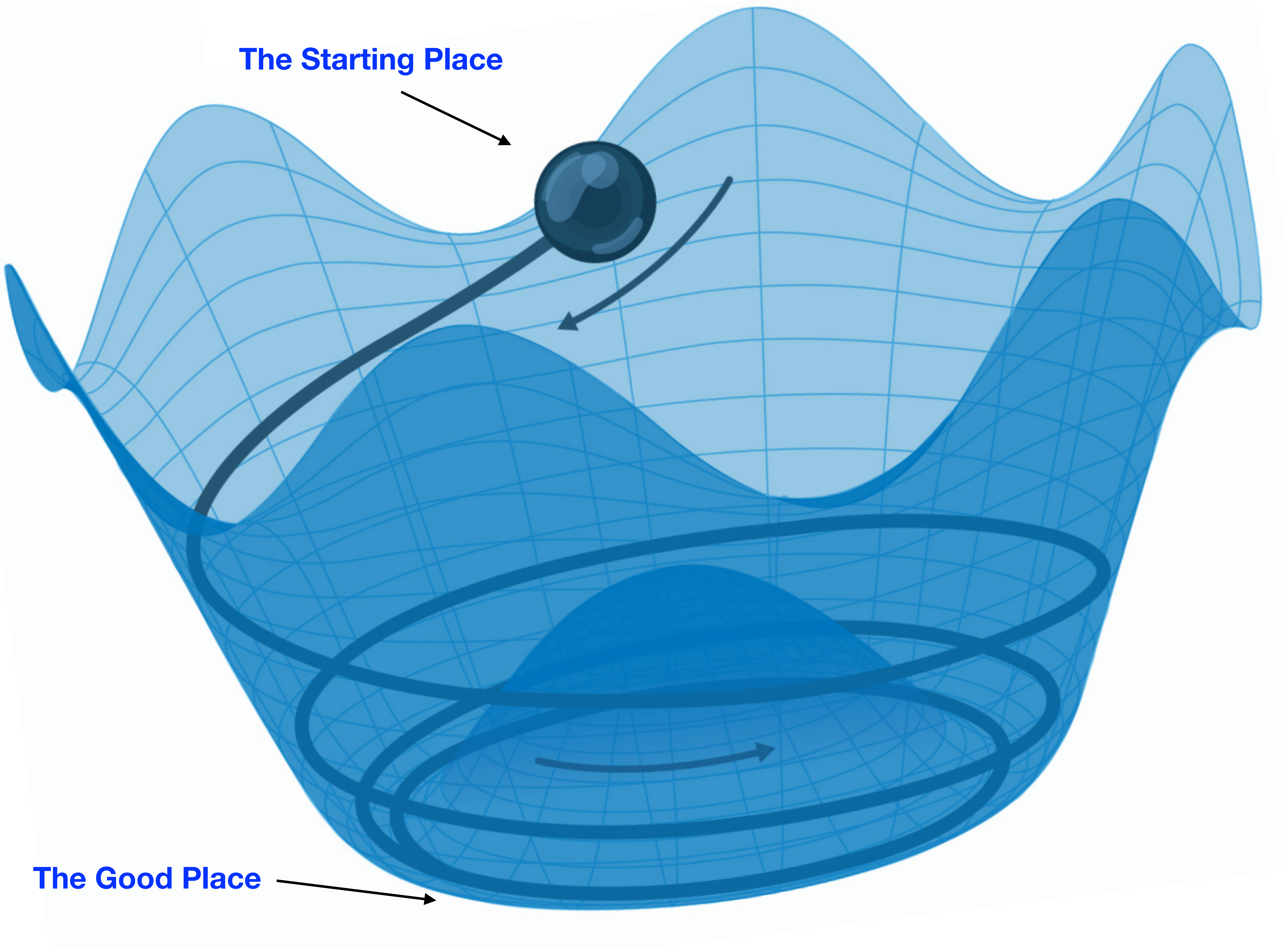
Why?

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

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

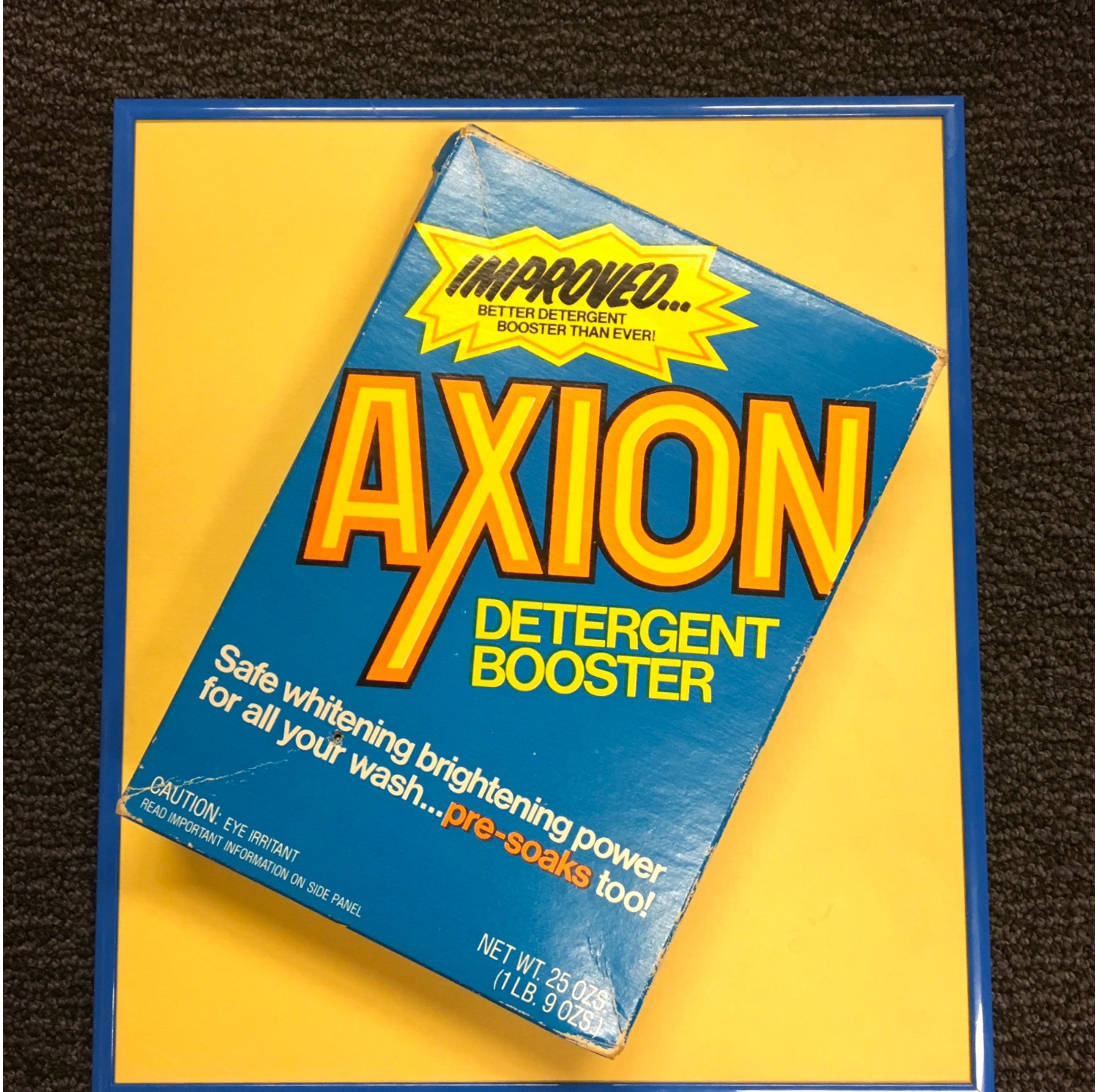
An otherwise mysterious coincidence gets explained dynamically.

It is a theory of evolution - for a fundamental “constant”!


The Starting Place
The Good Place

Oscillations in the new field make 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.)

A bit more technically:

The Strong P, T Problem

The standard model divides into two sectors: the gauge sector and the flavor, or Higgs, sector.

The gauge sector is tightly principled and brilliantly successful.

The flavor sector is looser. It has had considerable success in correlating data, but it requires many phenomenological input parameters.

Its most striking success, I think, is the KM theory of T violation.

But there's a serpent in the garden:

The overall phase of quark mass matrix physically meaningful.

In the minimal standard model, this phase is a free parameter, theoretically.

Experimentally, it is very small: $|\theta| < 10^{-10}$.

This is the most striking *unnaturality* of the standard model, aside from the cosmological term.

It does not seem susceptible of anthropic "explanation".

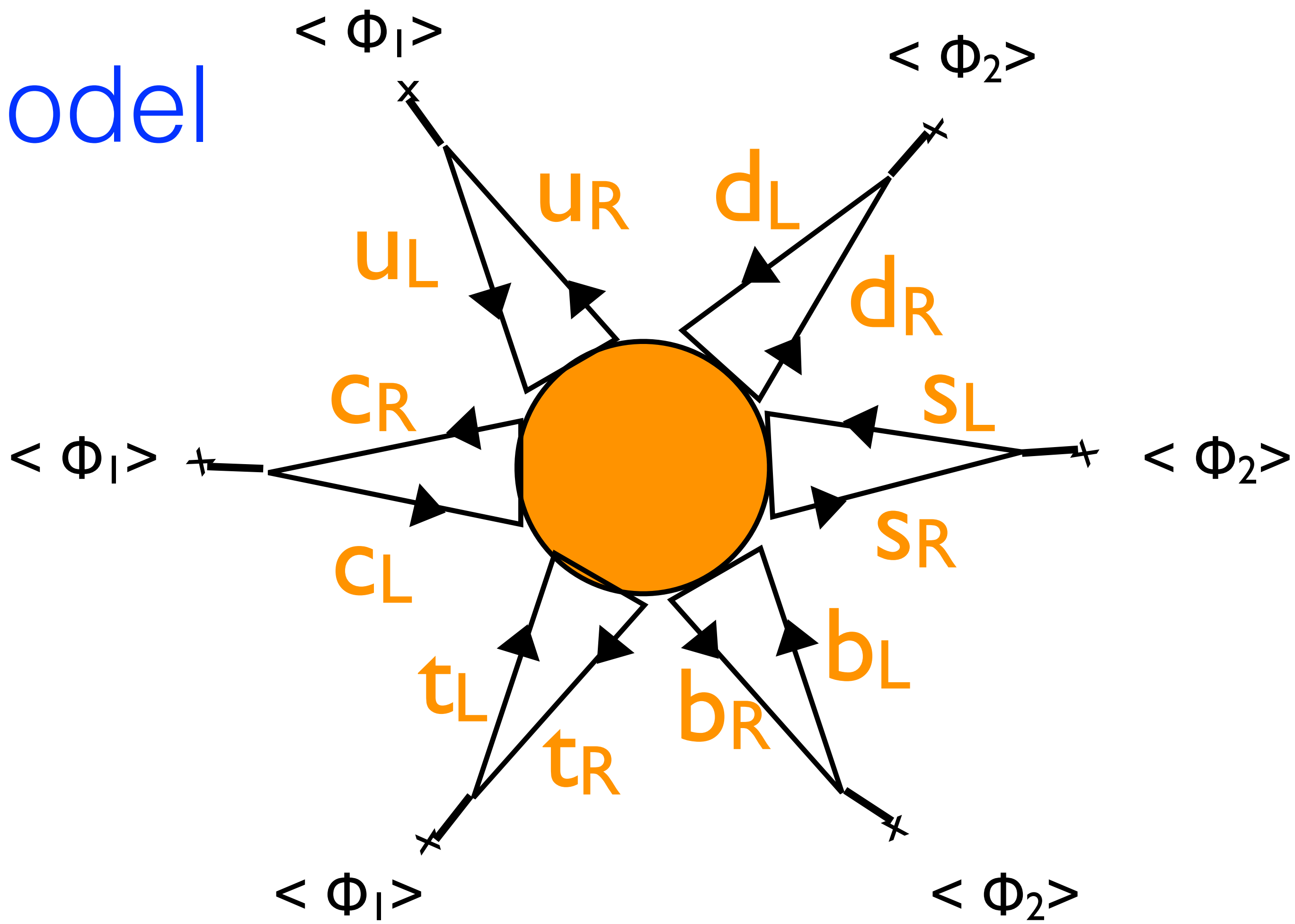
PQ Quasi-Symmetry

The most convincing response to this challenge: PQ “symmetry”

More precisely: We postulate an asymptotic or classical symmetry (perhaps accidental or approximate) under translations of θ, that is violated by QCD non-perturbatively, through instantons.

Small θ will be favored dynamically.

minimal PQ model



$e^{i\theta}$

$$V(\alpha) \sim -\cos\alpha\,\Lambda_{\rm QCD}^4$$

$$m_a^2 \sim \frac{1}{F^2}\frac{d^2V(\alpha)}{d\alpha^2} \sim \frac{\Lambda_{\rm QCD}^4}{F^2}$$

Axions Defined

We can implement the general mechanism with a complex scalar order parameter field ϕ, and PQ charge assignments.

The axion field is established at the PQ transition, $\langle\phi\rangle = F e^{i\theta} = F e^{ia/F}$.

F parametrizes the stiffness of the axion field.

a is an approximate Nambu-Goldstone boson.

It has a non-vanishing potential, and mass, as indicated previously.

Its main couplings are dictated by the broken symmetry, following standard NG-ology.

(2) Properties of Axions

Mass, Spin, and Interactions

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 stiffness of the axion field.

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

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

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

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

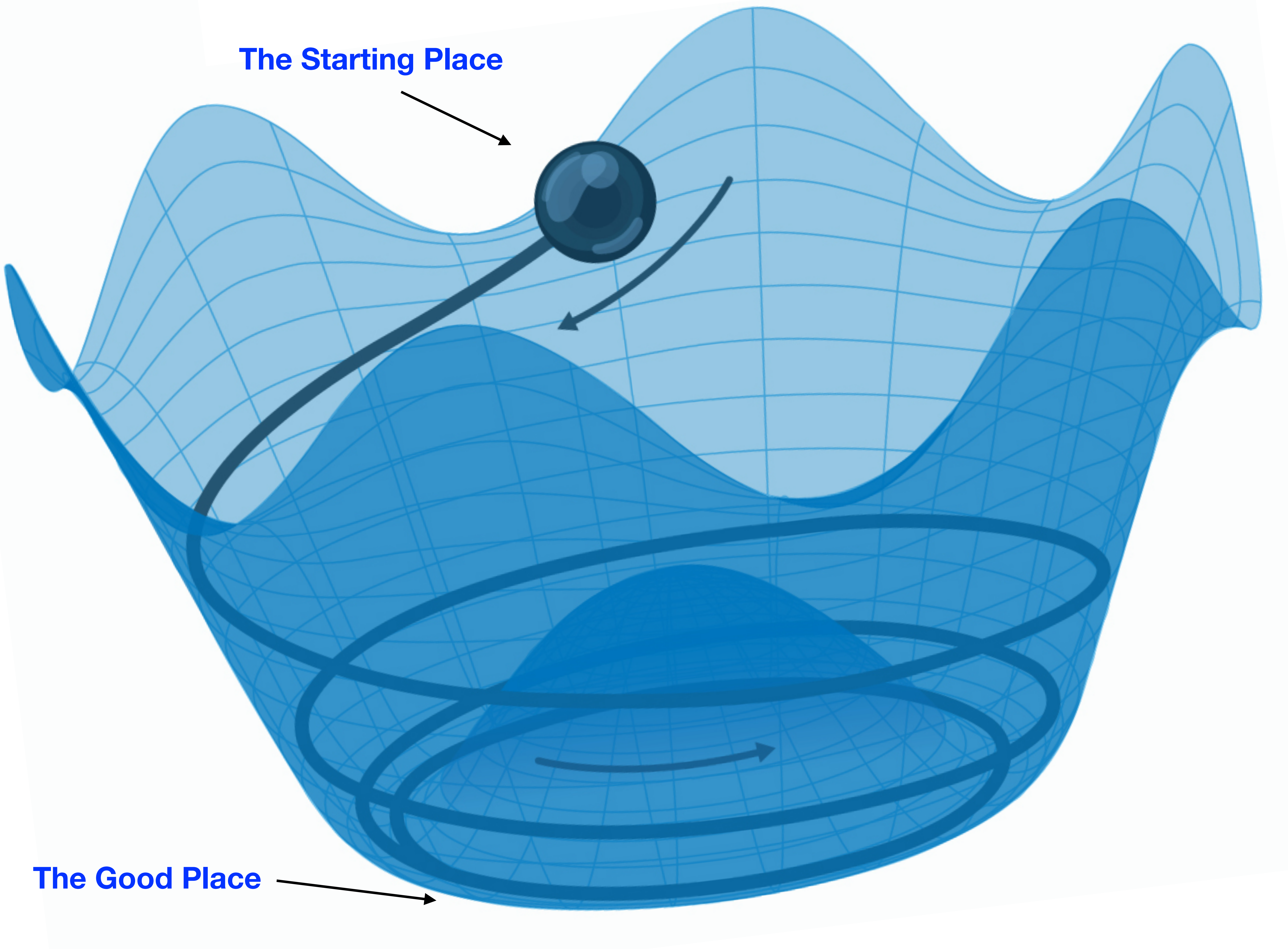
$$\begin{aligned}
\nabla \cdot E &= -\kappa\, \nabla a \cdot B \\
\nabla \times E &= -\frac{\partial B}{\partial t} \\
\nabla \cdot B &= 0 \\
\nabla \times B &= \frac{\partial E}{\partial t} + \kappa\, (\dot{a} B + \nabla a \times E)
\end{aligned}$$

ADMX, abracadabra, MADMAX, ALPHA

E induces current (surface Hall effect)

(4) How Axions Make Dark Matter

Production and Processing


The Starting Place
The Good Place

A space-filling condensate forms at a high temperature ($\sim F$).

It remains frozen in place until a much lower temperature ($\sim$ 1 GeV).

The axion field settles down close to the bottom of the well, but there are small residual oscillations.

The residual oscillations can also be considered as a collection of particles, quanta. This is the cosmic axion background.

For the residual density, one finds: $\rho_{\rm axion} \propto \sim F$

Scenario A: conventional cosmology

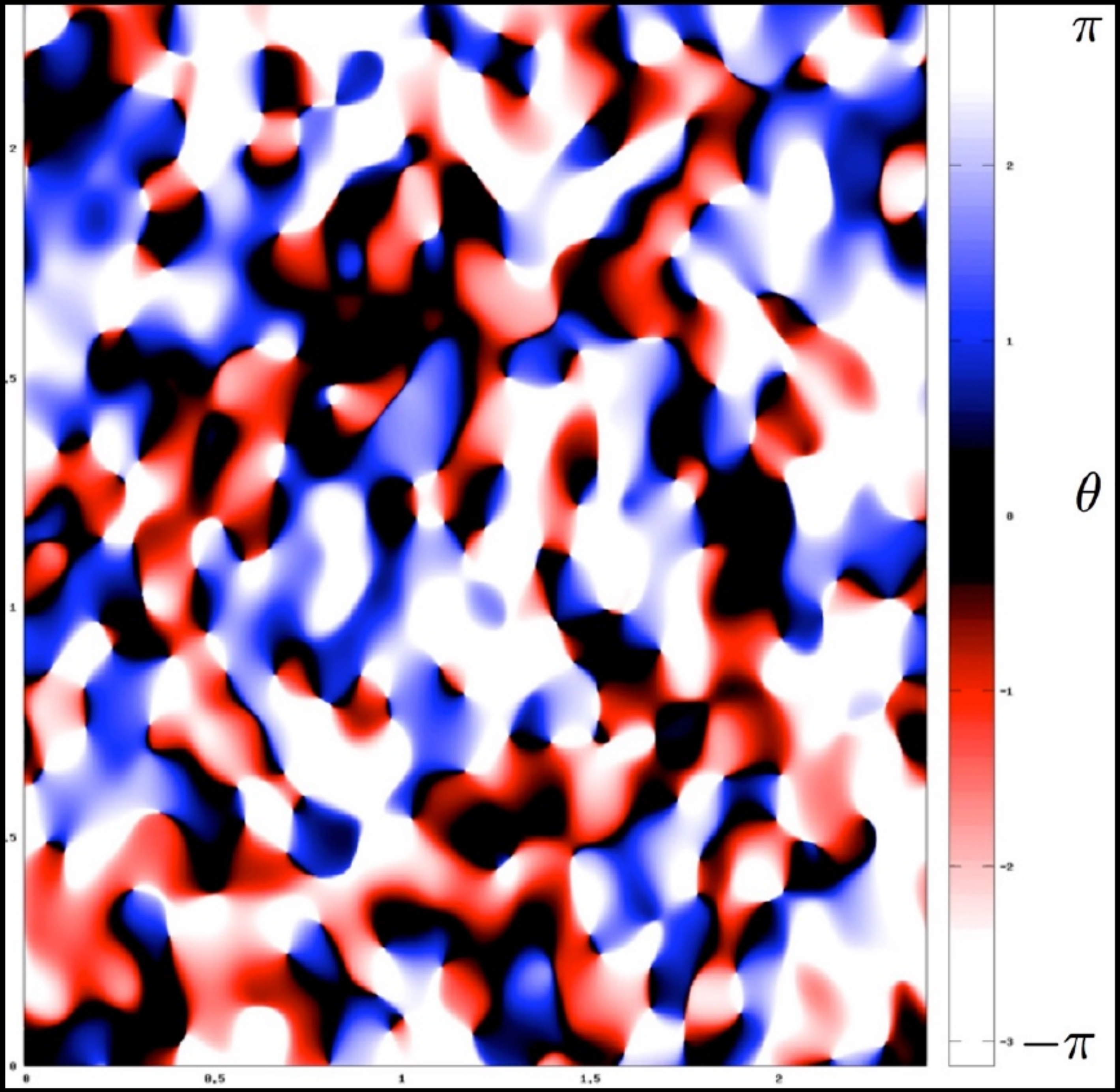
In the conventional Big Bang cosmology, today's universe samples many past "universes". Thus we must average over the initial displacement θ_0.

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

Note that since observations constrain $F \gtrsim 10^{10}$ GeV, based on accelerator and astrophysical limits, *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. (See below.)

Scenario A: PQ breaks after inflation



Dark Matter from Axion Strings with Adaptive Mesh Refinement

Malte Buschmann,[1,*] Joshua W. Foster,[2,3,4,†] Anson Hook,[5] Adam Peterson,[6] Don E. Willcox,[6] Weiqun Zhang,[6] and Benjamin R. Safdi[3,4,‡]

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[2]*Leinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109*
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(Dated: August 13, 2021)

Axions are hypothetical particles that may explain the observed dark matter (DM) density and the non-observation of a neutron electric dipole moment. An increasing number of axion laboratory searches are underway worldwide, but these efforts are made difficult by the fact that the axion mass is largely unconstrained. If the axion is generated after inflation there is a unique mass that gives rise to the observed DM abundance; due to nonlinearities and topological defects known as strings, computing this mass accurately has been a challenge for four decades. Recent works, making use of large static lattice simulations, have led to largely disparate predictions for the axion mass, spanning the range from 25 microelectronvolts to over 500 microelectronvolts. In this work we show that adaptive mesh refinement (AMR) simulations are better suited for axion cosmology than the previously-used static lattice simulations because only the string cores require high spatial resolution. Using dedicated AMR simulations we obtain an over three order of magnitude leap in dynamic range and provide evidence that axion strings radiate their energy with a scale-invariant spectrum, to within ~5% precision, leading to a mass prediction in the range (40,180) microelectronvolts.

40-180 μeV ≈ 10-45 GHz

Scenario B: inflation after condensation

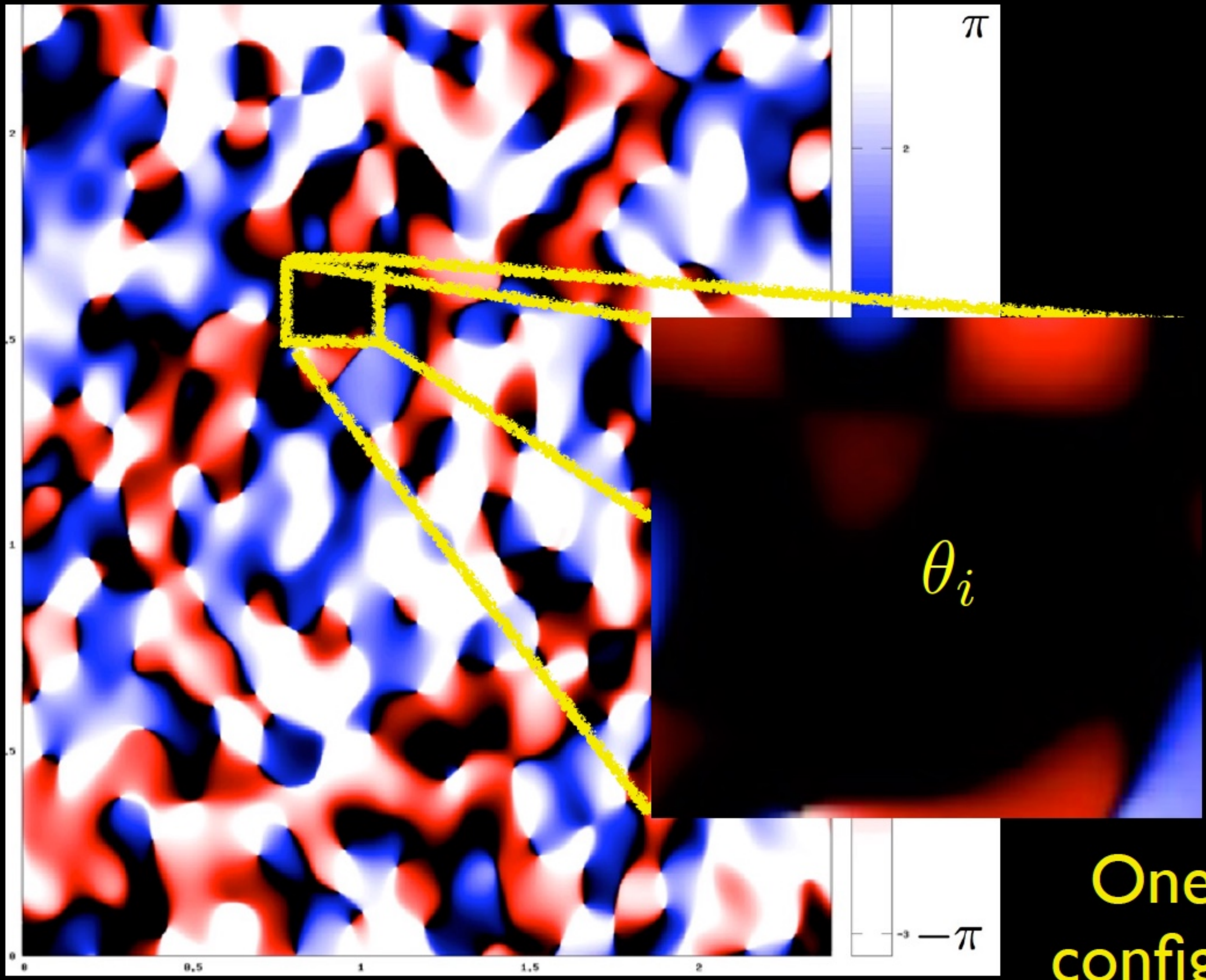
If inflation intervenes, then today's universe samples a small patch of past "universes". We should *not* average over θ_0.

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

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

In either scenario, *it is hard to avoid significant axion dark matter, if axions exist at all.*

Scenario B: PQ breaks during inflation



One initial configuration is singled out

In either scenario, *it is hard to avoid significant axion dark matter, if axions exist at all.*

(7a) Plasma Haloscope

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

B induces charge

$$\begin{aligned}
\nabla\cdot E &= -\,\kappa\,\nabla a\cdot B \\
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\end{aligned}$$

ADMX, abracadabra, MADMAX, ALPHA

E induces current (surface Hall effect)

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

mixes with the photon, and

pumps energy into electromagnetic fields.

One can add materials (including “boundaries”) to encourage the pumping, by exploiting *resonance*.

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

Previous experiments are based on giving axions momentum.

A different approach: Give the photon a mass!

Photon mass situations:

~~Superconductor~~

Plasma

~~Hot gas~~

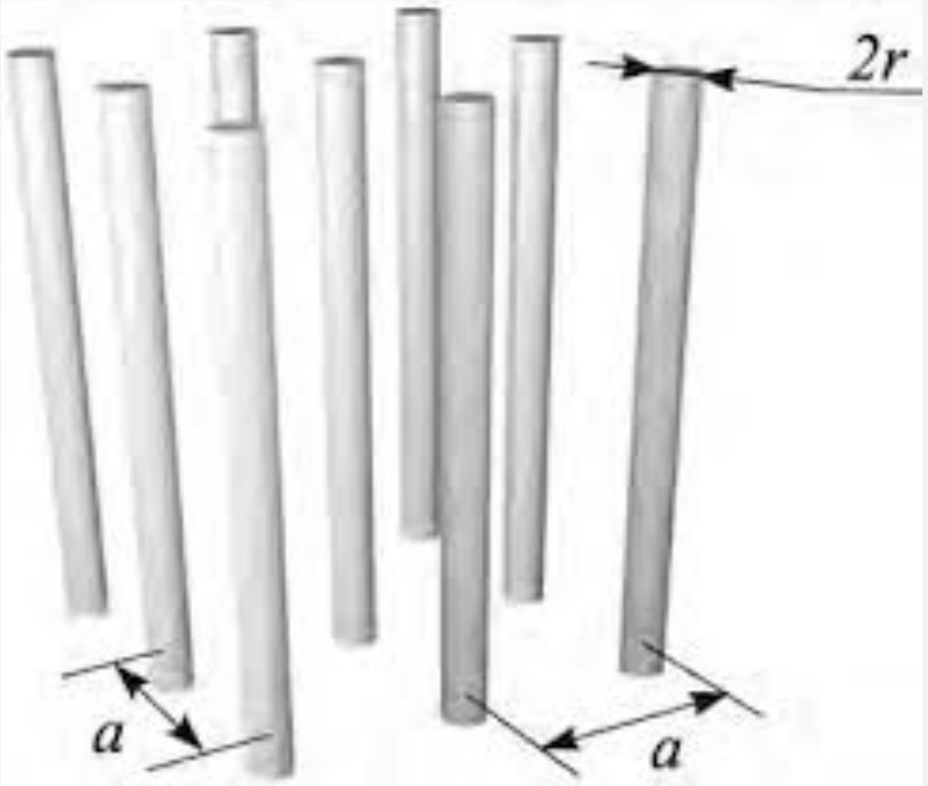
~~Metal~~

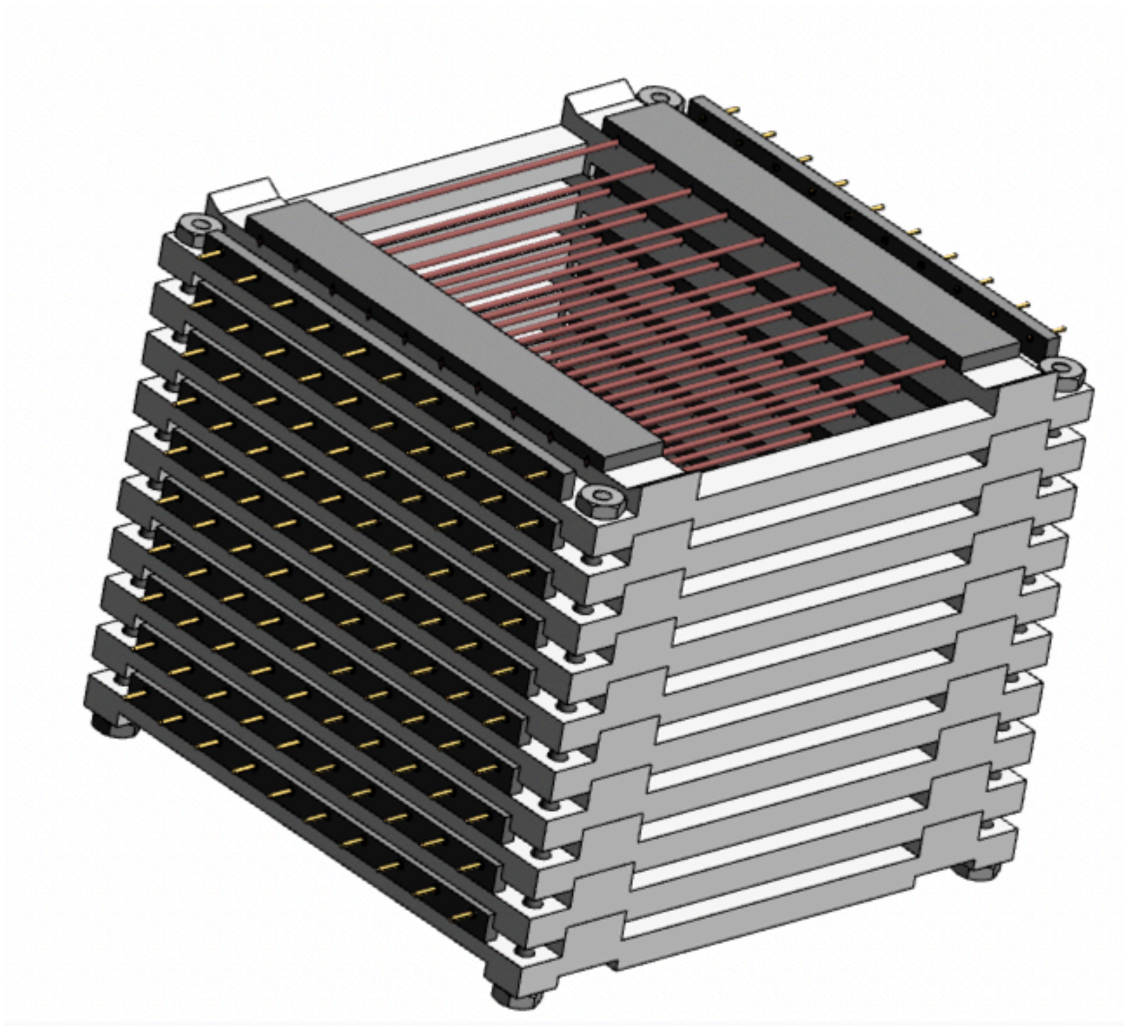
Semiconductor?

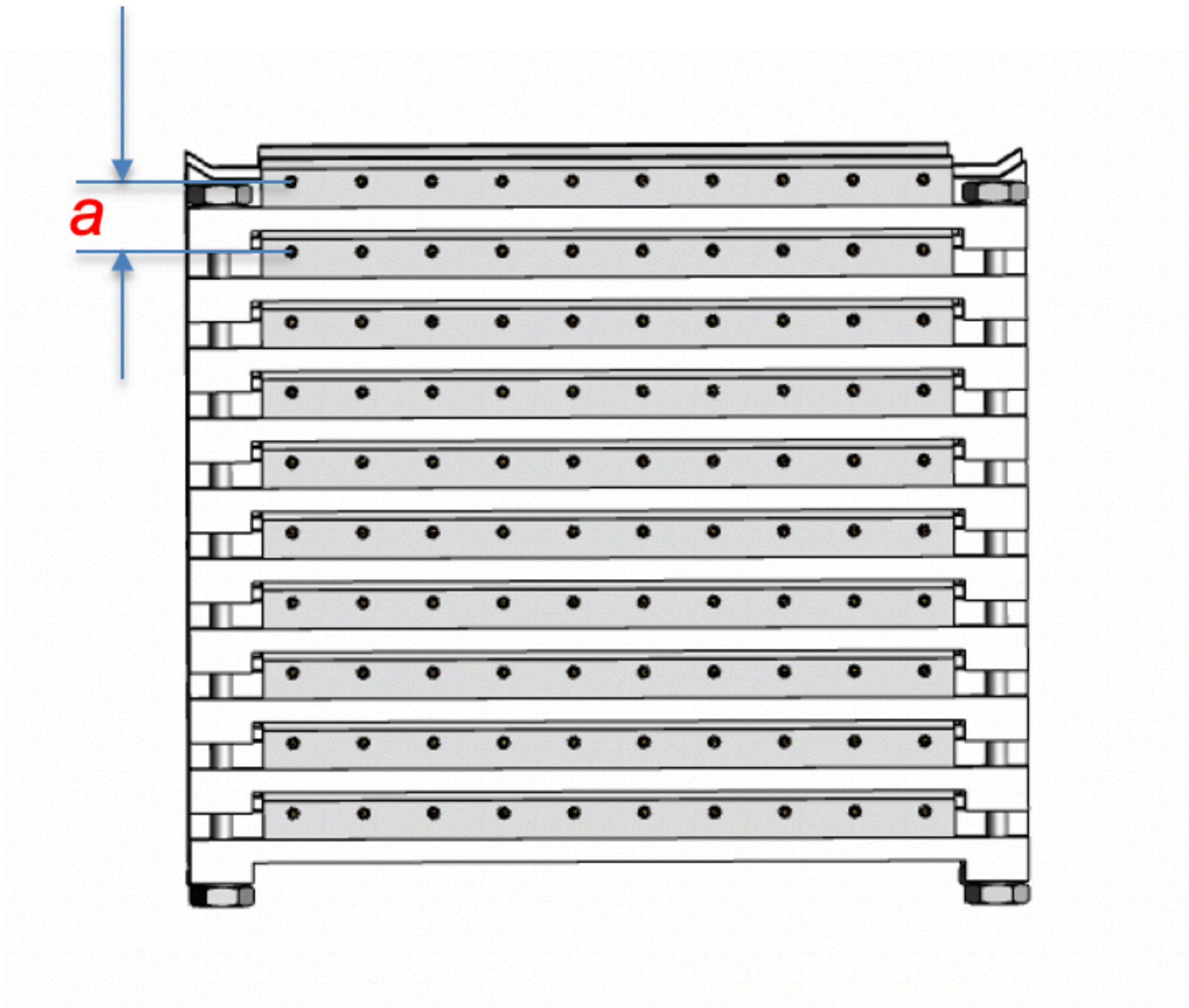
Metamaterial

Thin wire metamaterials

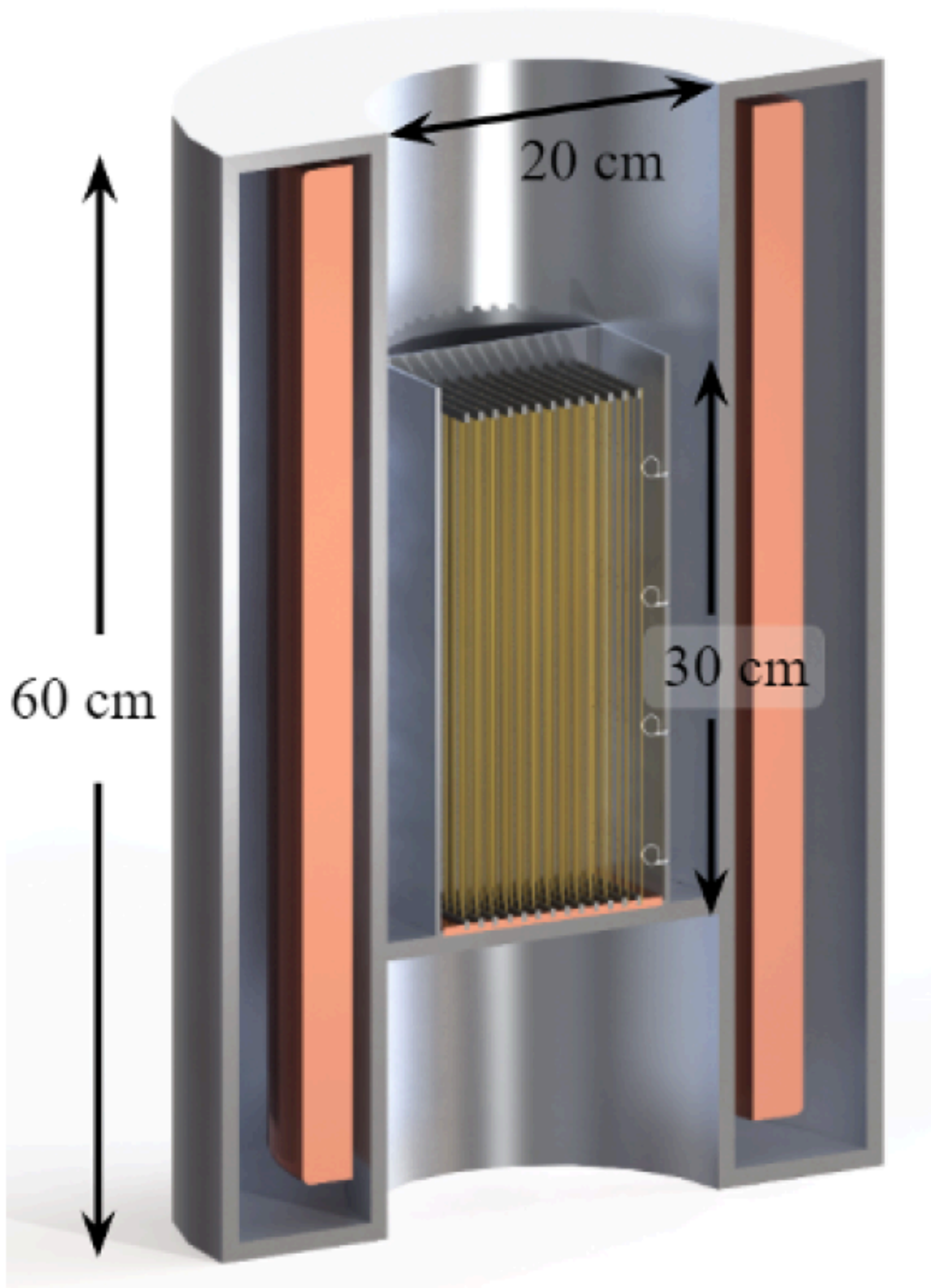
- One of the first metamaterials
- Plasma frequency determined by two factors: effective electron number density and mass
- Wires mutually induct, changing the plasma frequency







Concept and Prototype



Pathfinder Proposal

[Submitted on 11 Aug 2021]

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Malte Buschmann, Joshua W. Foster, Anson Hook, Adam Peterson, Don E. Willcox, Weiqun Zhang, Benjamin R. Safdi

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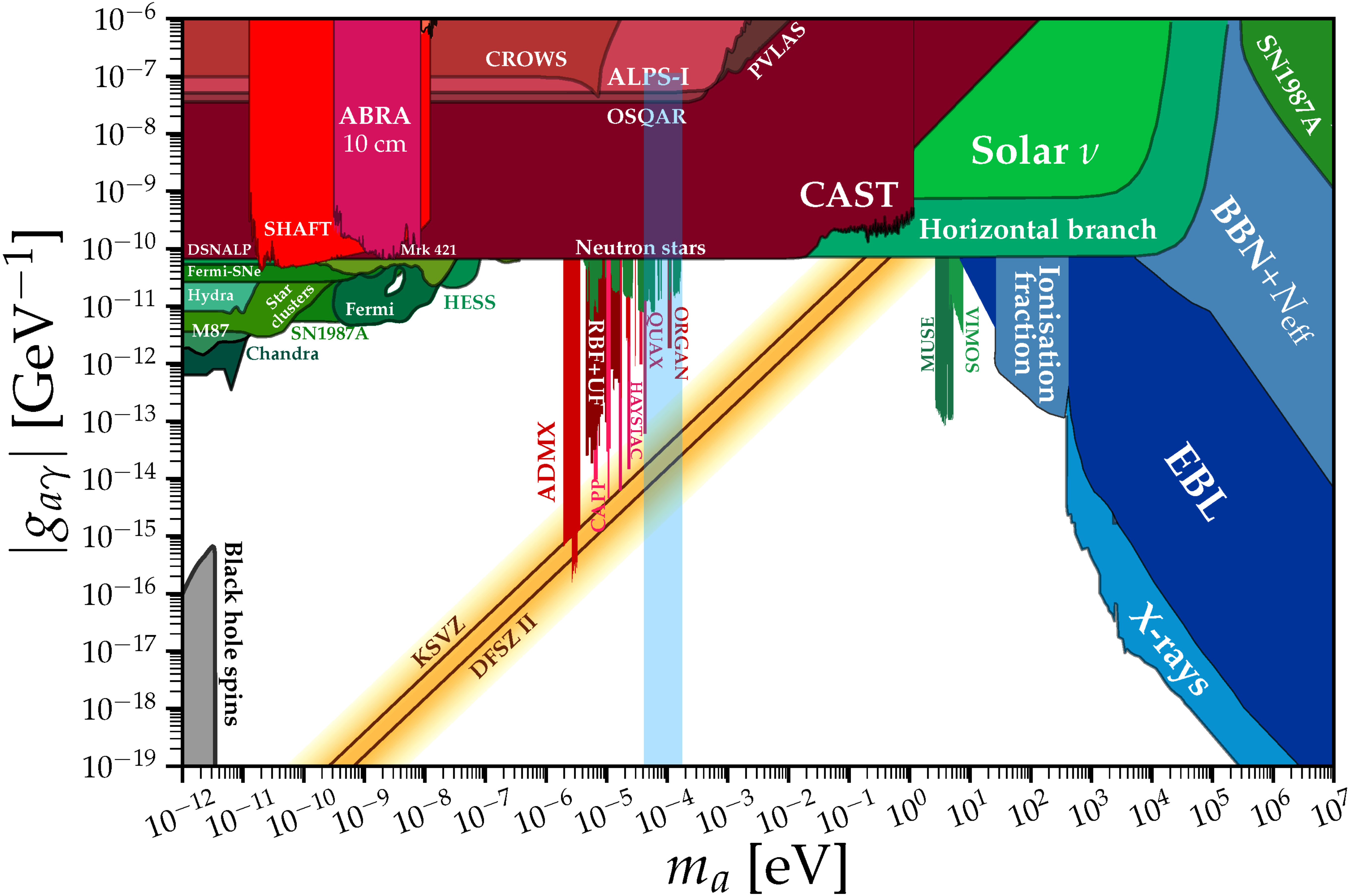
Comments: 7+11 pages, 4 + 10 figures, Supplementary Animations at this https URL
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy Physics - Theory (hep-th)
Cite as: arXiv:2108.05368 **[hep-ph]**
(or arXiv:2108.05368v1 **[hep-ph]** for this version)



CROWS
ALPS-I
PVLAS
ABRA
10 cm
OSQAR
SN1987A
Solar ν
CAST
Horizontal branch
SHAFT
DSNALP
Mrk 421
Neutron stars
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
RBF+UF
QUAX
ORGAN
HAYSTAC
ADMX
CAPP
MUSE
VIMOS
Ionisation fraction
BBN+$N_{\rm eff}$
EBL
X-rays
Black hole spins
KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
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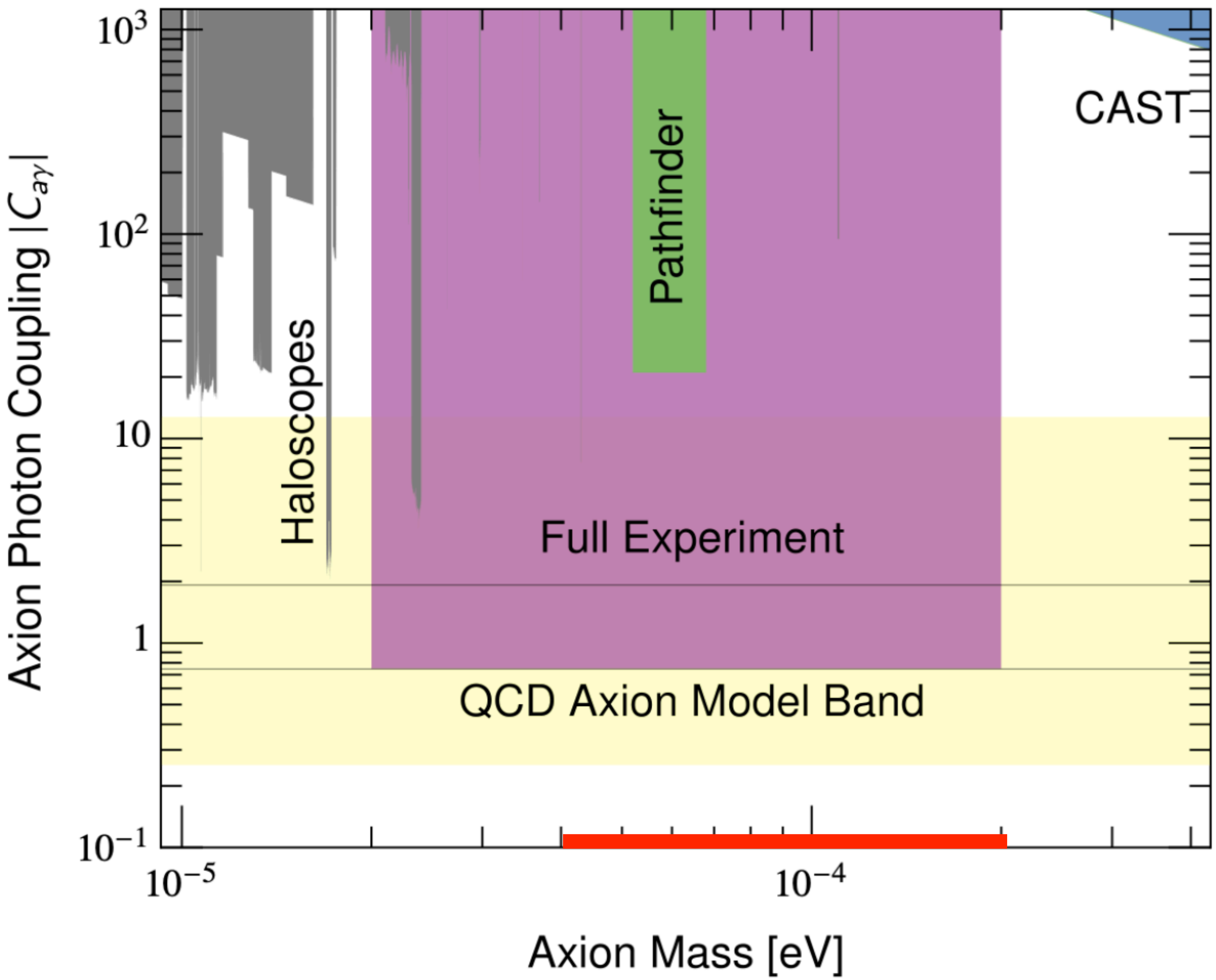


Axion Photon Coupling $|C_{a\gamma}|$
10^3
10^2
10
1
10^{-1}
10^{-5}
10^{-4}
Axion Mass [eV]
Haloscopes
Pathfinder
CAST
Full Experiment
QCD Axion Model Band

[unused slides follow]

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

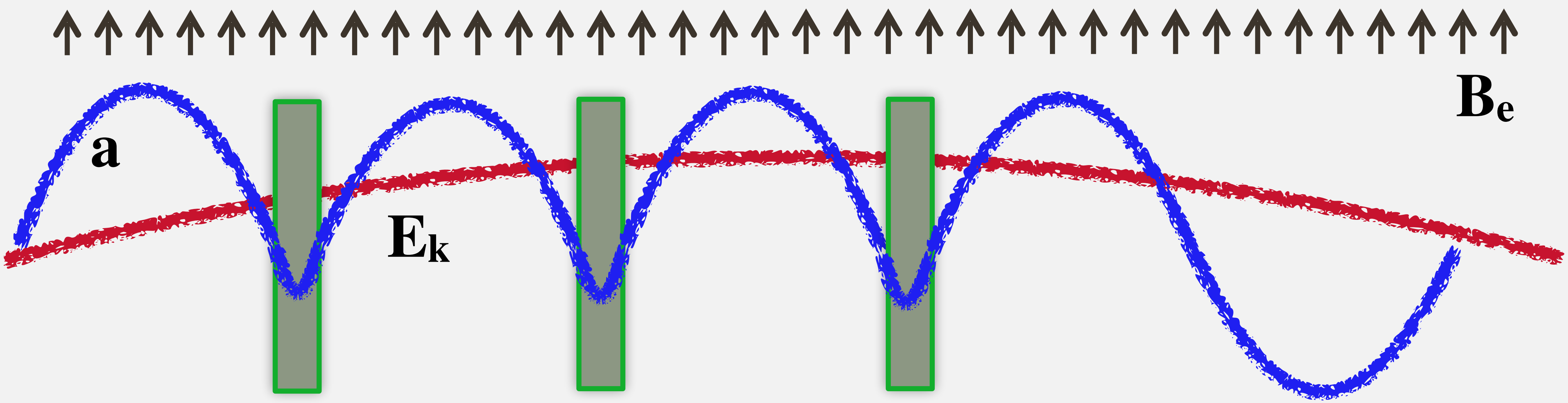
If you run a movie of everyday life backwards, it does not look like everyday life.


STOP

MadMAX

Dielectric haloscopes

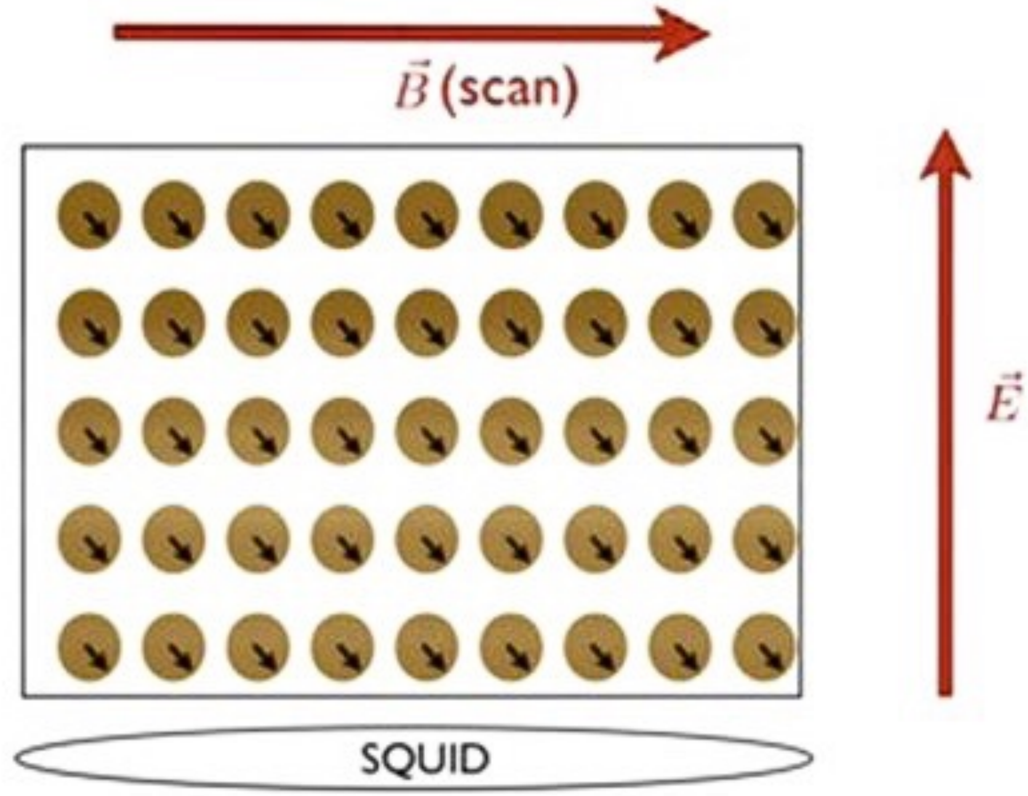
- Introduce a series of dielectric layers



- Dielectric layers distort the free photon wave function, giving a non-zero overlap

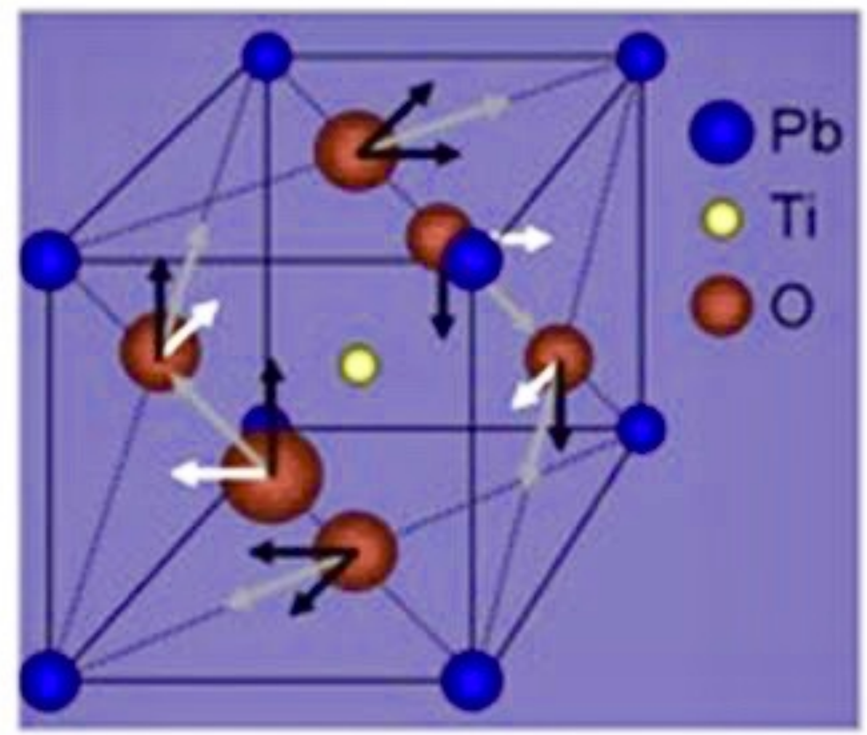
Searching for Axions in the Anthropic Window

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

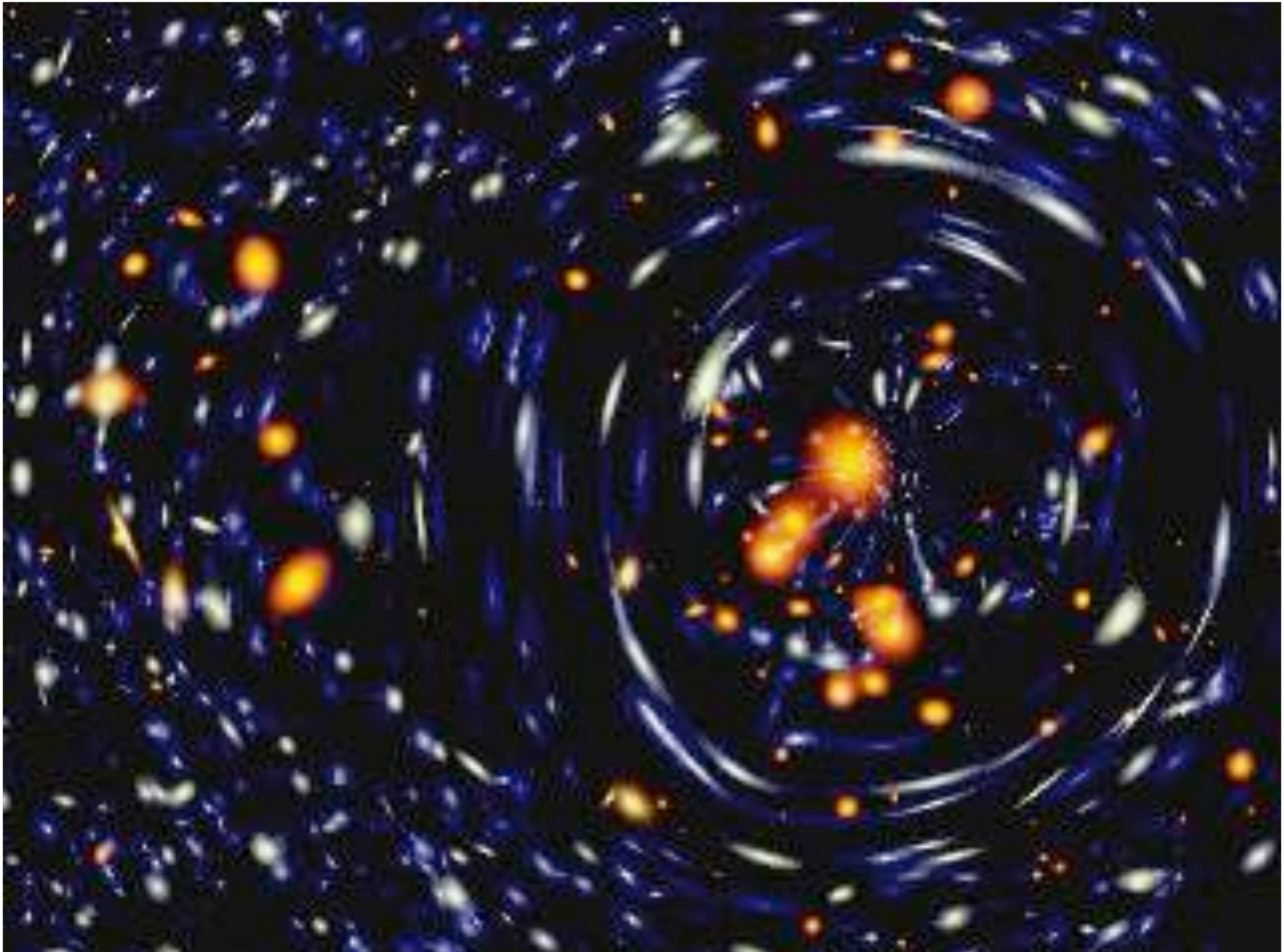
Graham & Rajendran, arXiv:1101.2691
Budker, Graham, Ledbetter, Rajendran & Sushkov, arXiv:1306.6089

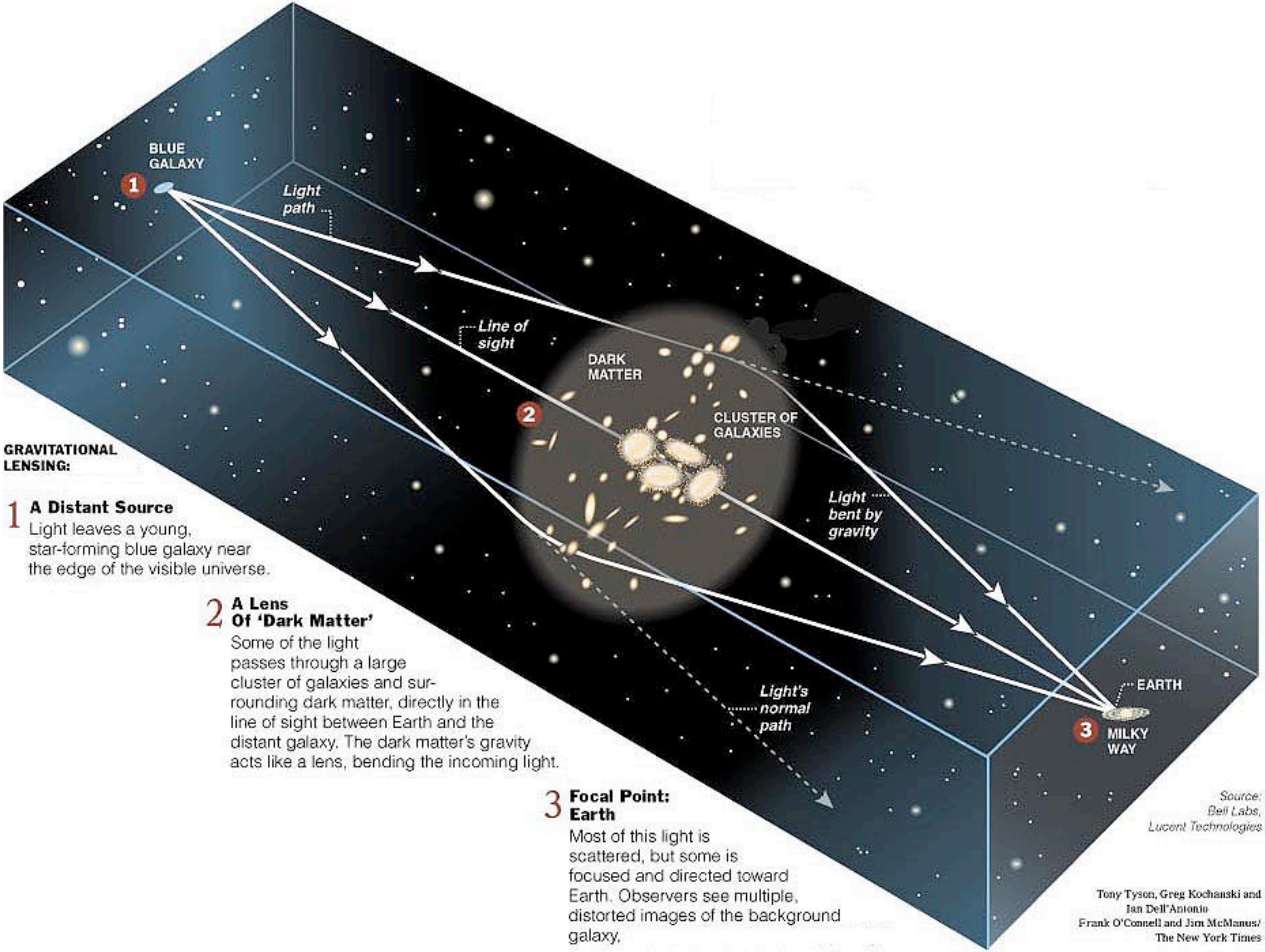
(3) Why Cosmology Needs Dark Matter

Mysterious Accelerations

Many astronomical and cosmological observations point toward the existence of *dark matter*.

So far, we “see” dark matter only through its gravity.





GRAVITATIONAL LENSING:

1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 Focal Point: Earth
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

Dark matter provides a large fraction of the mass of the universe - much more than “normal” matter!

We know what it *weighs*, but we’d like to find out what it *is*.

We have important information about what it *isn't*:

- anything in the standard model (e.g., neutrinos)
- primordial black holes
- WIMPs, in much of their parameter space

And important clues about what it *is*:

very feeble interactions

cold when it decouples

(5) Axions and Astrophysics

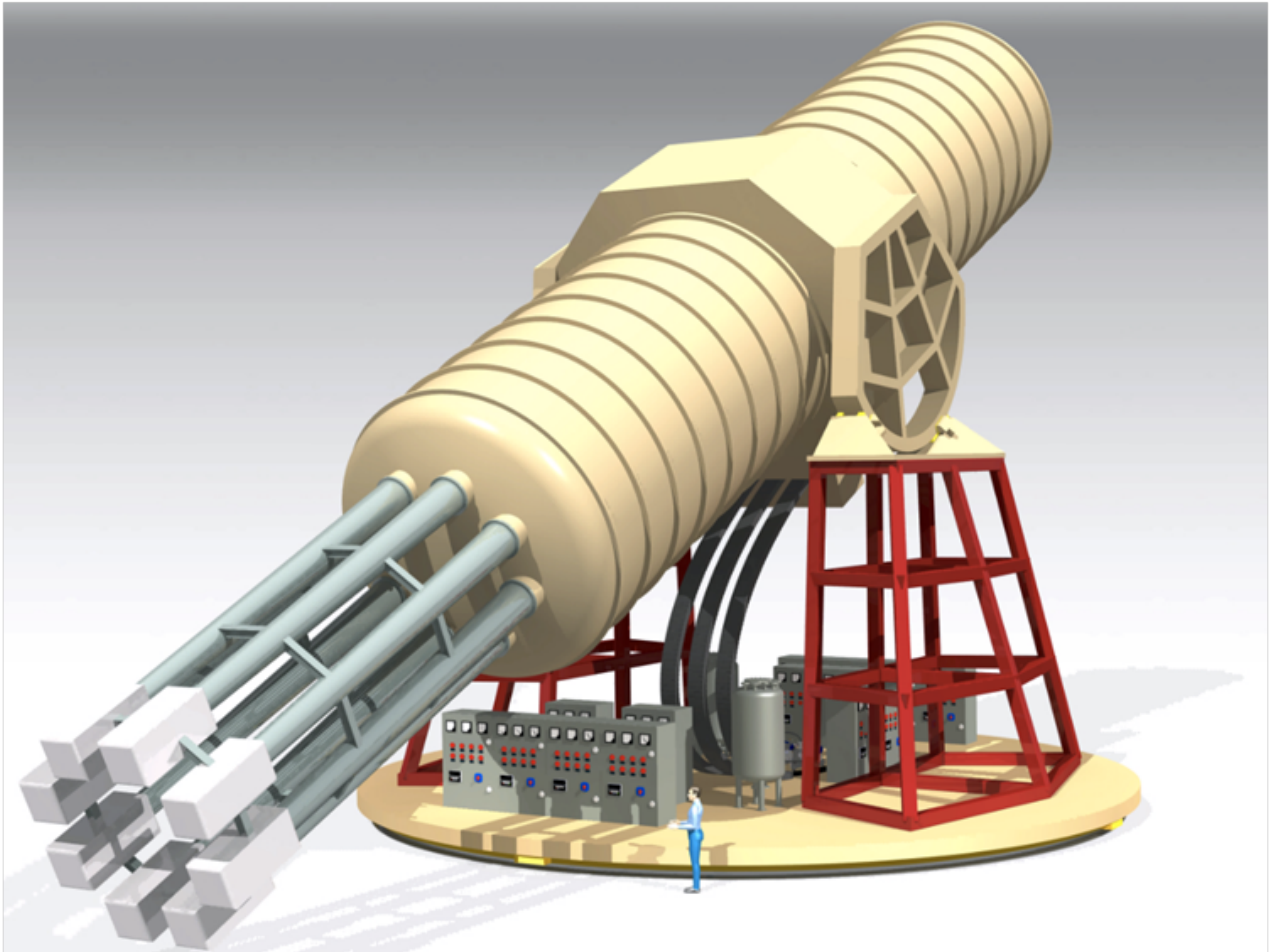
Constraints and Opportunities

Axions can be produced and emitted in astrophysical environments.

This introduces a new mechanism of stellar cooling.

Observations of red giant, neutron star and white dwarf evolution constrain $F \geq 10^9\ \text{GeV}$.

We can also look for axions emitted from the Sun.



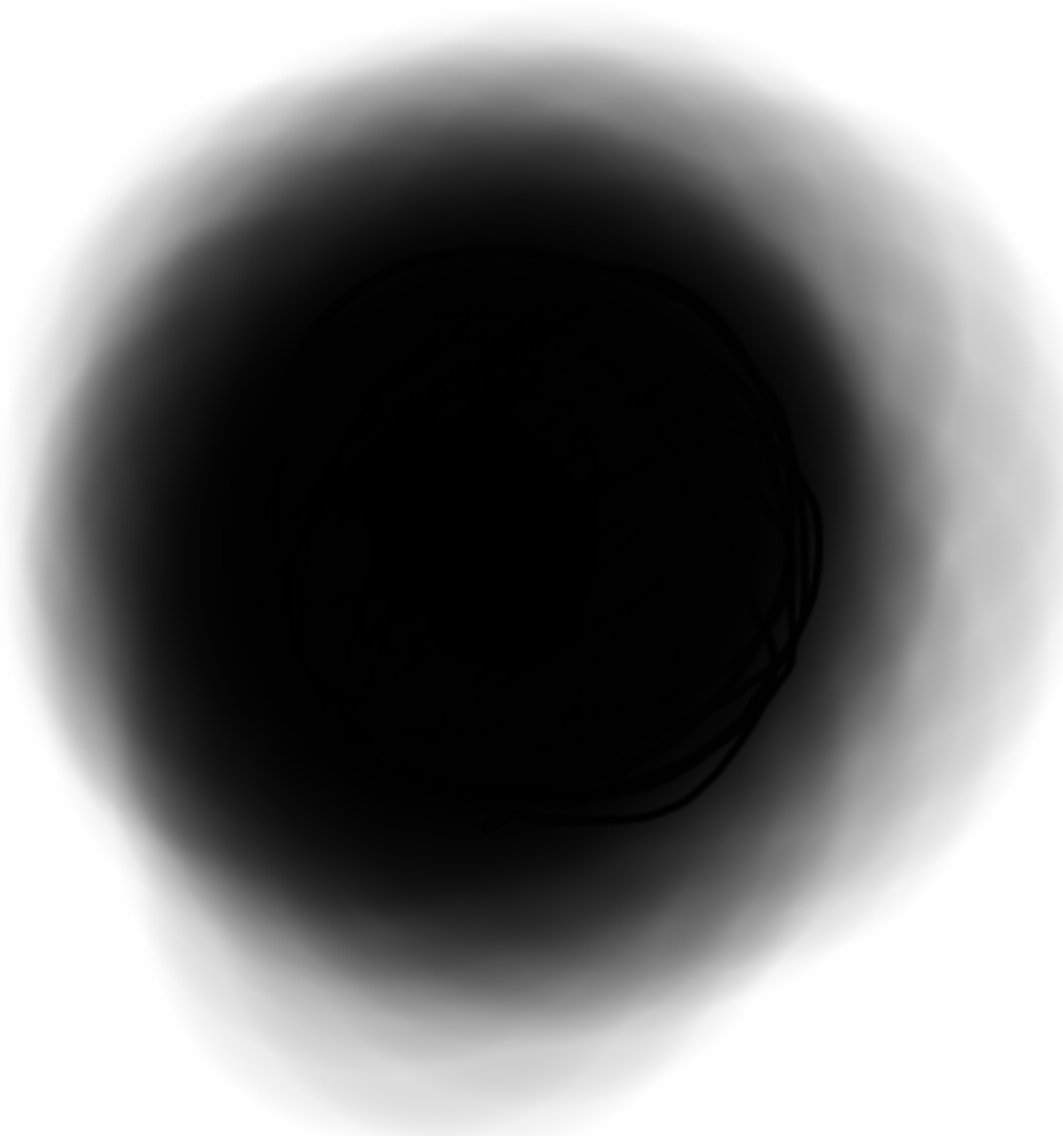
Axions can convert into photons in the presence of a magnetic field, and neutron stars have very big magnetic fields.

We can look for unexplained emission of x-rays.

(There is an interesting claim of positive indications …)

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 (super-radiance) builds up an atmosphere.



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

(6) Axions and Laboratory Physics

Effects and Searches

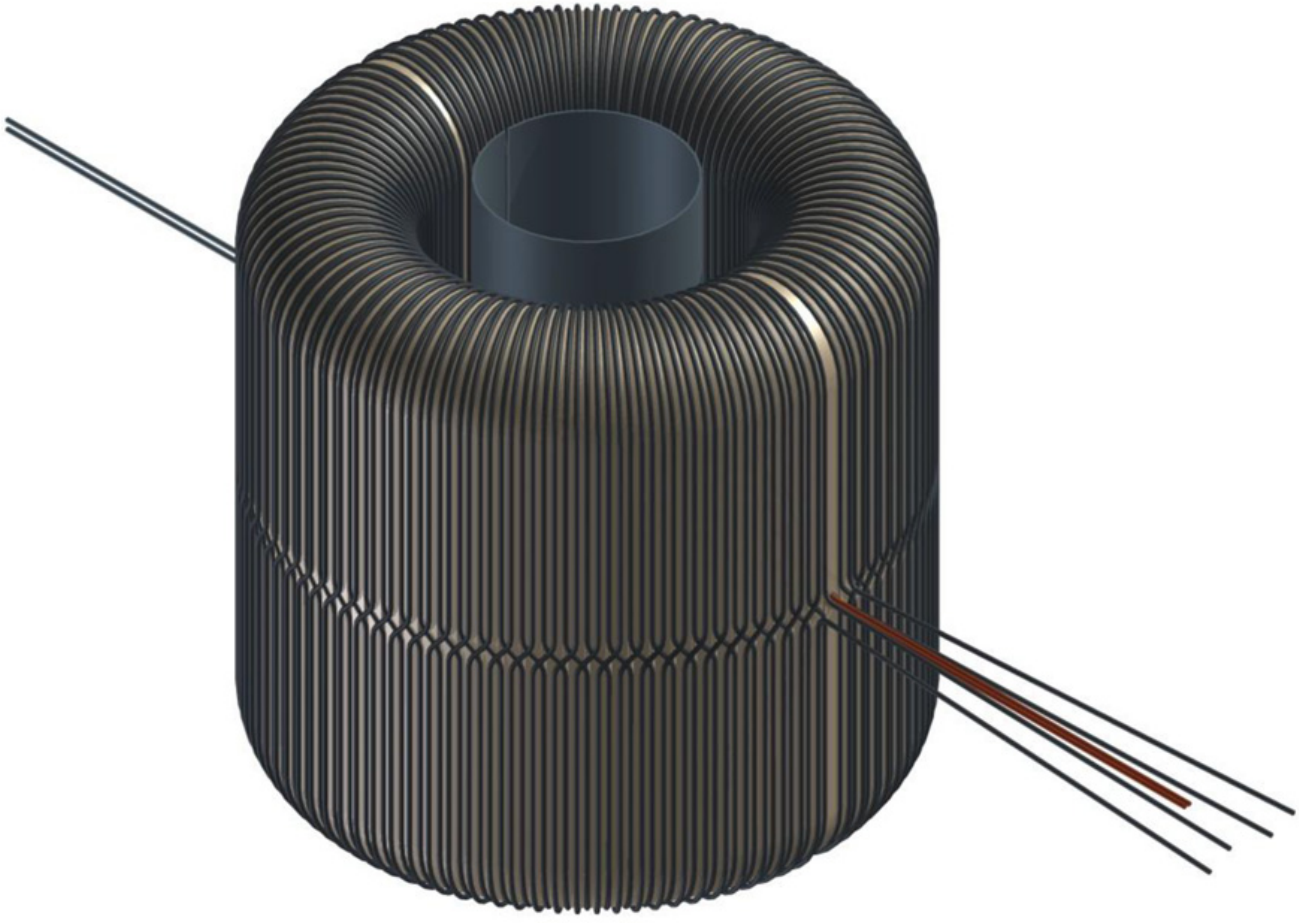
Exchange of axions leads to new macroscopic forces. These could show up in Cavendish-style experiments.

Another interesting effect is “light shining through walls” by $\gamma \to a \to \gamma$.

(7) Axion Haloscopes

Results and Promise

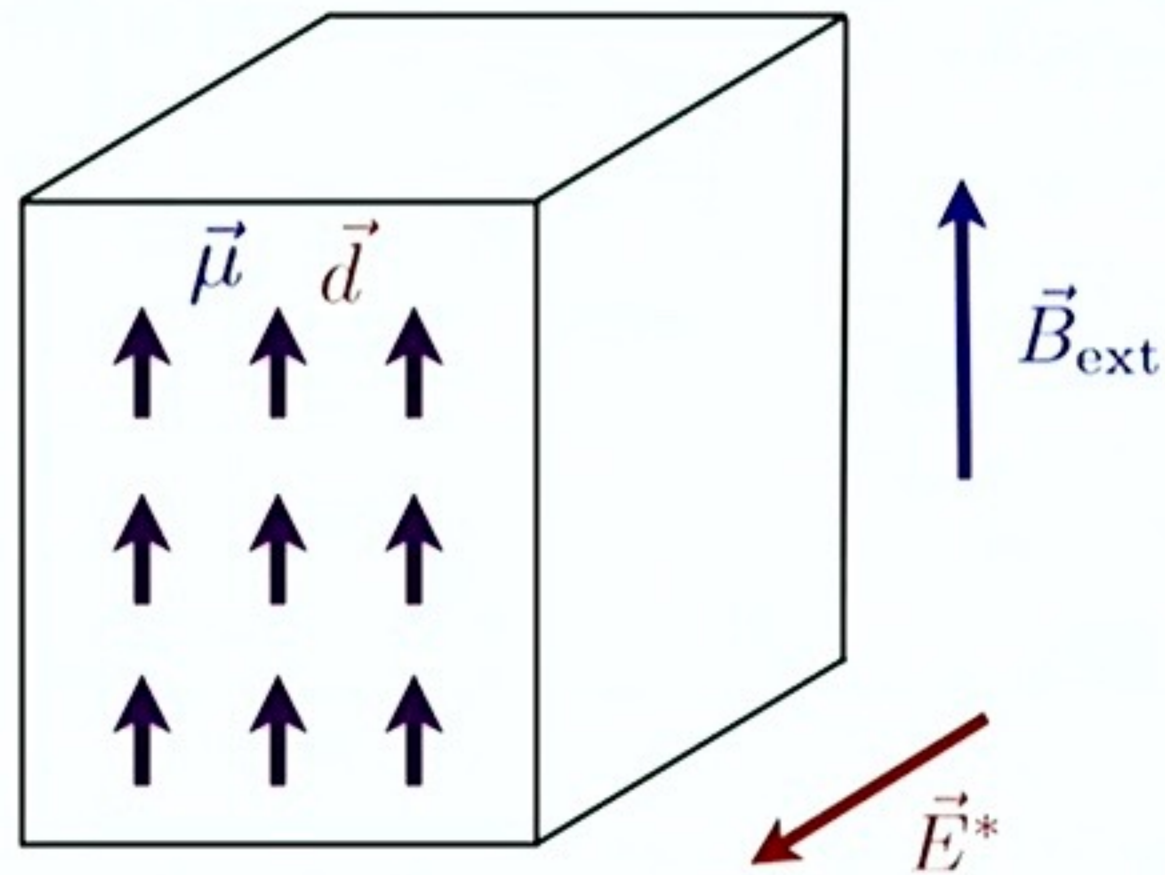
abracadabra



CASPEr

Cosmic Axion Spin Precession Experiment (CASPEr)

NMR techniques + high precision magnetometry



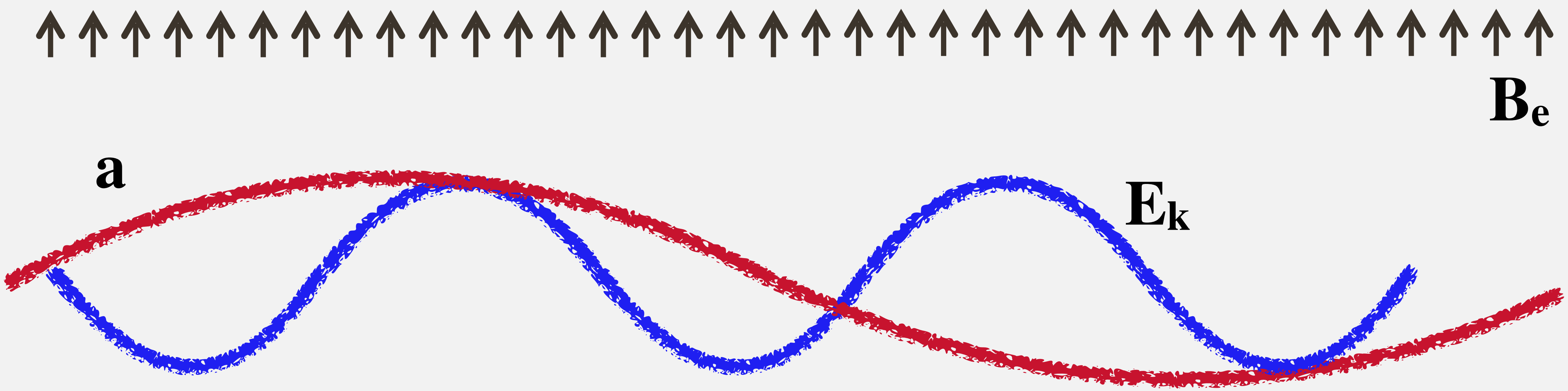
Larmor frequency = axion mass ➔ resonant enhancement

Electromagnetic Converters

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

Axion-photon conversion

- In vacuum and constant B_e this oscillatory integral vanishes

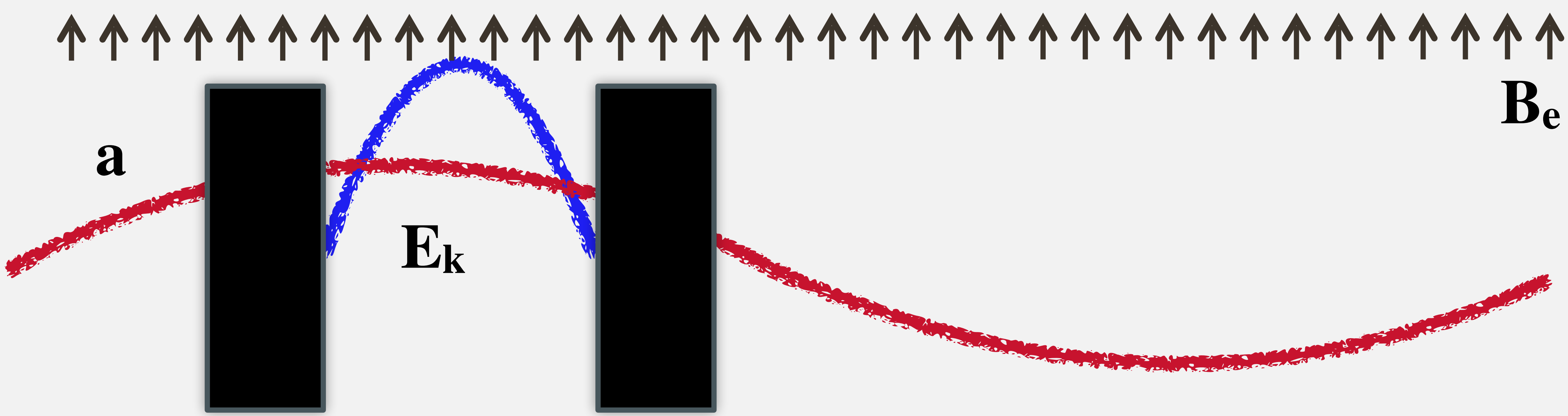


- Modify the free photon wave function!

ADMX / Haystack

Cavity haloscopes

- Inside a cavity E_k becomes the cavity modes



- Normalisation is given by the "quality factor" of the cavity


ADMX
WIZSCIENCE.COM

(8) Emergent “Axions”

Same Equations, Different Realizations

The ideas and equations of axion physics have suggested, and continue to suggest, new effects in advanced materials.

In these applications, the “axions” are *emergent* particles. They follow the same (or similar) equations as fundamental axions, but are much more easily accessible.

PHYSICAL REVIEW LETTERS

VOLUME 58 4 MAY 1987 NUMBER 18

Two Applications of Axion Electrodynamics

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(Received 27 January 1987)

The equations of axion electrodynamics are studied. Variations in the axion field can give rise to peculiar distributions of charge and current. These effects provide a simple understanding of the fractional electric charge on dyons and of some recently discovered oddities in the electrodynamics of antiphase boundaries in PbTe. Some speculations regarding the possible occurrence of related phenomena in other solids are presented.

PACS numbers: 14.80.Gt, 05.30.Fk, 14.80.Hv, 71.50.+t

Whether or not axions[1] have any physical reality, their study can be a useful intellectual exercise. For by having a field which modulates the effects of anomalies and instantons and calculating the consequences of its variation in space and time, we can get some intuitive feeling for these important, but often subtle and obscure, things. Also, it is (I shall argue) not beyond the realm of possibility that fields whose properties partially mimic those of axion fields can be realized in condensed-matter systems. In this spirit, I will consider in this paper two situations where the equations of axion electrodynamics seem to illuminate otherwise surprising phenomena, and then speculate briefly on potential generalizations.

To begin, let us recall the equations of axion electrodynamics. They are generated by adding to the ordinary Maxwell Lagrangean an additional term

$$\Delta\mathcal{L} = \kappa a \mathbf{E}\cdot\mathbf{B}, \qquad (1)$$

where κ is a coupling constant. The resulting equations are

$$\nabla\cdot\mathbf{E} = \tilde{\rho} - \kappa\nabla a\cdot\mathbf{B}, \qquad (2)$$

$$\nabla\times\mathbf{E} = -\partial\mathbf{B}/\partial t, \qquad (3)$$

$$\nabla\cdot\mathbf{B} = 0, \qquad (4)$$

$$\nabla\times\mathbf{B} = \partial\mathbf{E}/\partial t + \tilde{\mathbf{j}} + \kappa(\dot{a}\mathbf{B} + \nabla a\times\mathbf{E}), \qquad (5)$$

where $\tilde{\rho},\tilde{j}$ are the ordinary (nonaxion) charge and current. We see that there is an extra charge density proportional to $-\nabla a\cdot\mathbf{B}$, and current density proportional $\nabla a\times\mathbf{E} + \dot{a}\mathbf{B}$. The form of these terms reflects the discrete symmetries of a: a is P and T odd. Also, these terms depend only on space-time *gradients* of the axion field. This is because with $a=$const, $\Delta\mathcal{L}$ in Eq. (1) becomes a perfect derivative, and does not affect the equations of motion.

Dyon charge.—Consider a magnetic monopole surrounded by a spherical ball in which $a=0$, modulating within a thin shell into $a=\theta$ at large distances (Fig. 1). Now because of the axion term in (2) one finds that the domain wall carries electric charge density $-\kappa\nabla a\cdot\mathbf{B}$, or charge/unit length $-\kappa\nabla a\Phi$ when integrated over direction, where Φ is the magnetic flux. The total charge seen by observers far from the monopole is

$$q = -\kappa\theta\Phi. \qquad (6)$$

The Witten effect,[2] that in a θ vacuum magnetic monopoles become dyons with fractional charge to their magnetic charge and to θ, is essentially contained in (6). By our introducing axions, and allowing θ to become a

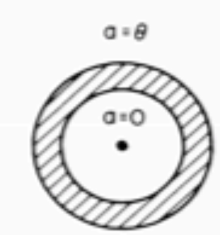
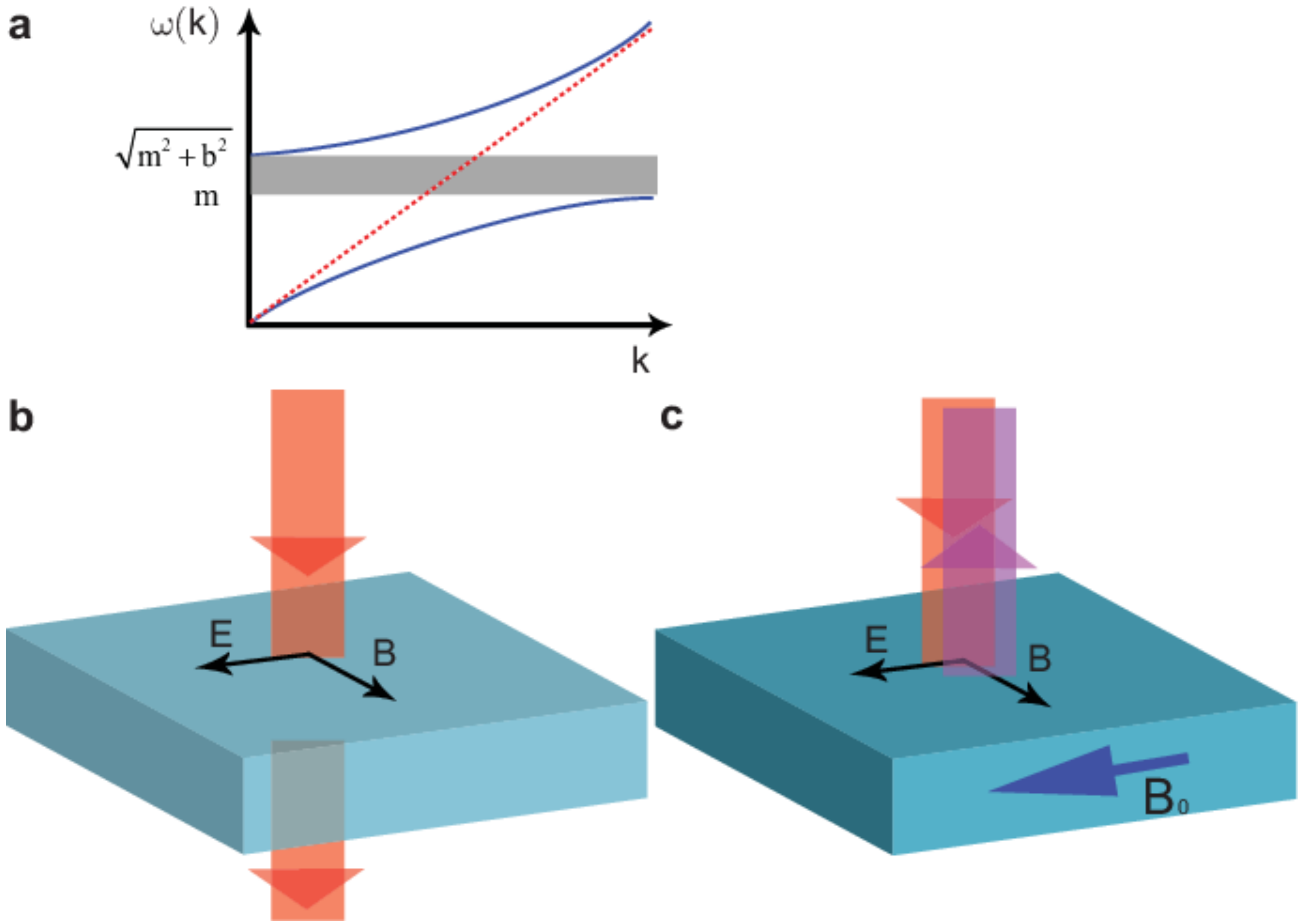


FIG. 1. Monopole surrounded by a shell of axion domain wall.



“Topological Insulators” Embody Axion Electrodynamics

Quantized Faraday and Kerr rotation and axion electrodynamics of a 3D topological insulator

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See all authors and affiliations
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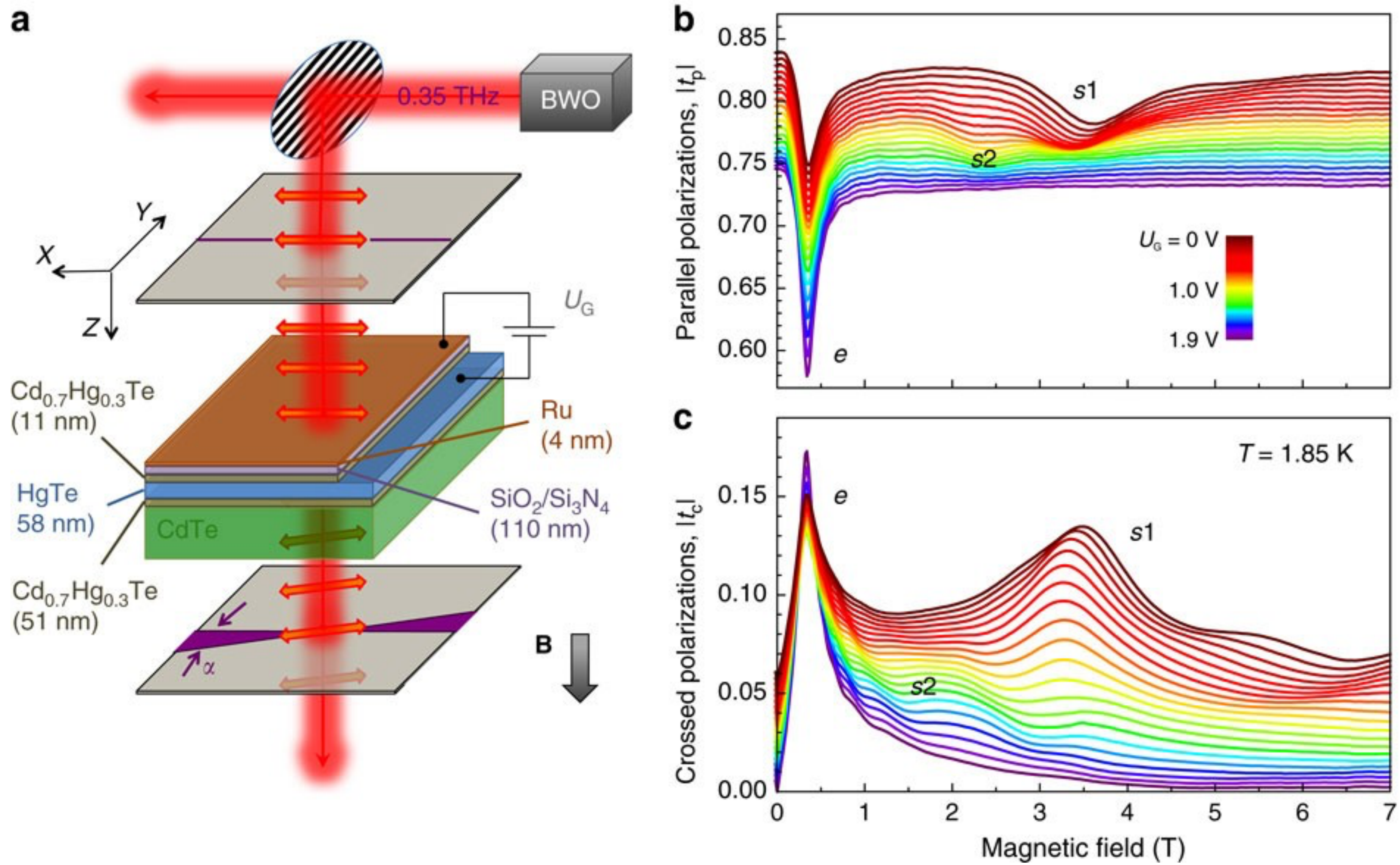
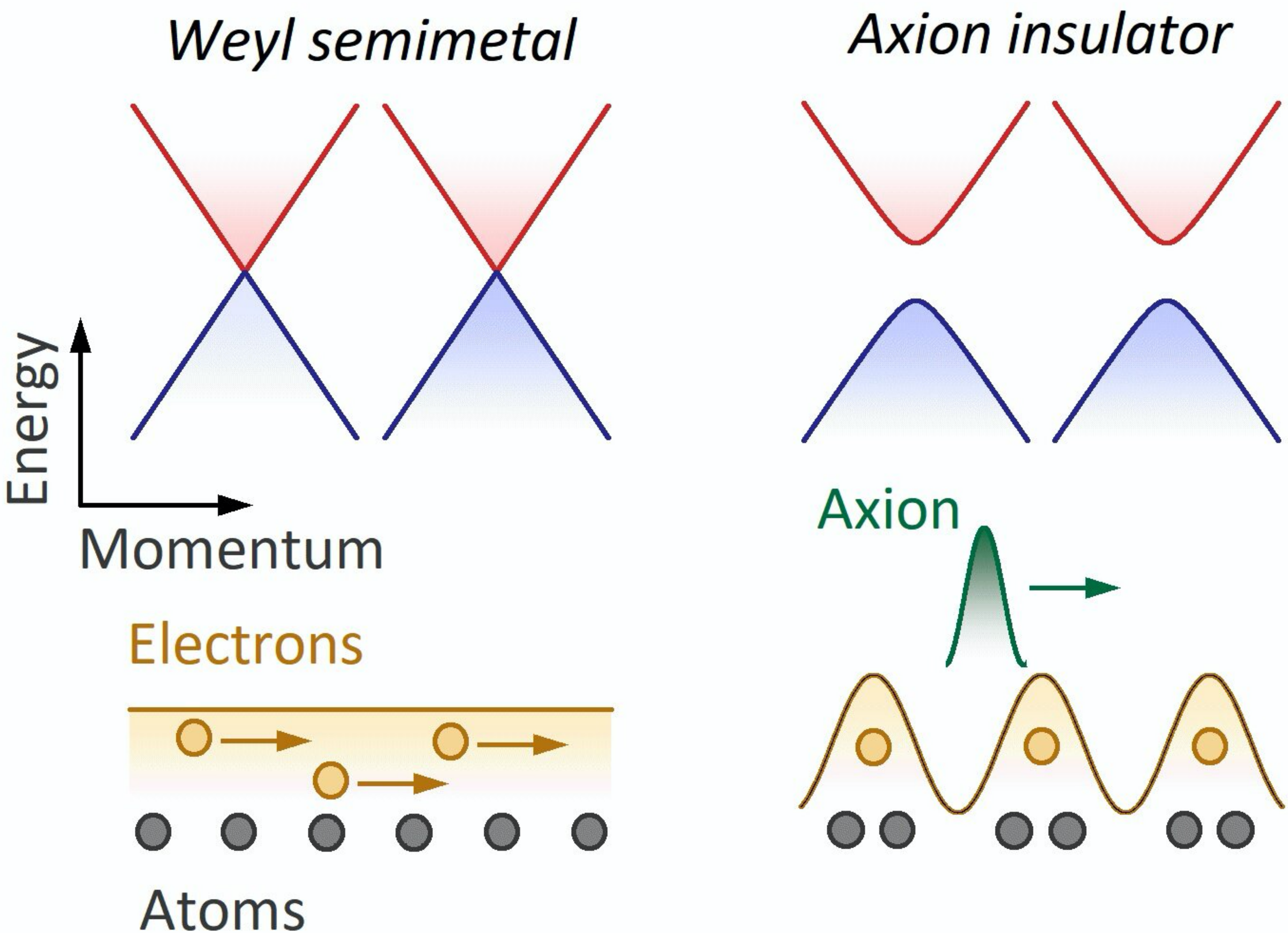




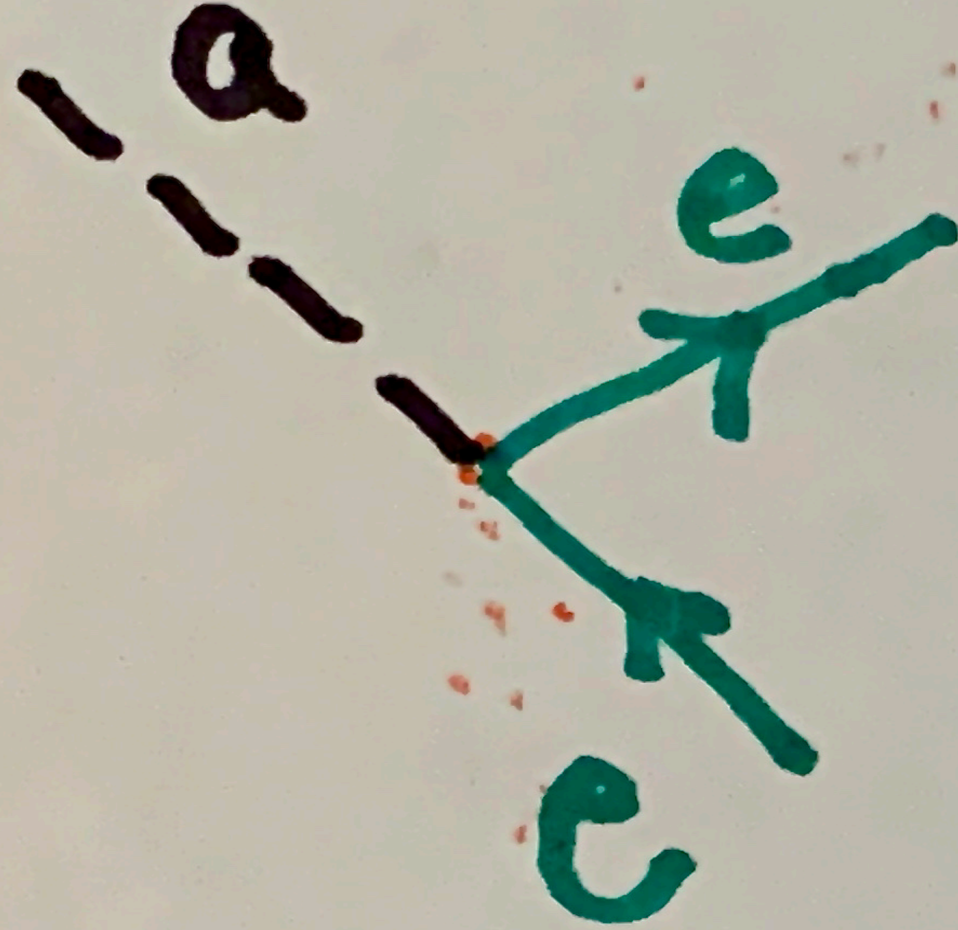
Weyl semimetal
Axion insulator
Energy
Momentum
Axion
Electrons
Atoms

Final Words

“One cannot escape the feeling that these mathematical formulae have an independent existence and an intelligence of their own, that they are wiser than we are, wiser even than their discoverers, that we get more out of them than was originally put into them.”

People are exploring possibilities for converting axions directly into quasiparticles.

This requires identifying quasiparticles with the right quantum numbers in appropriate materials.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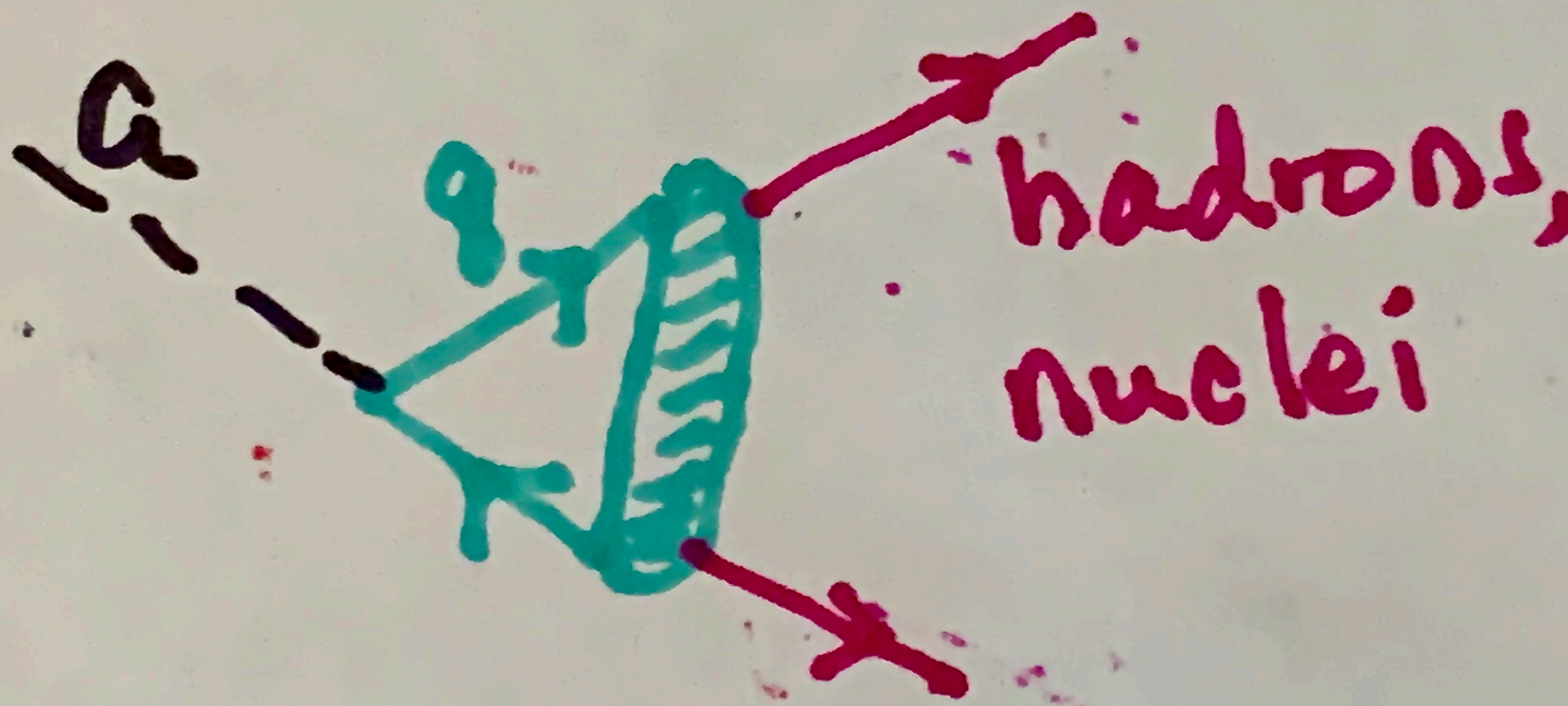
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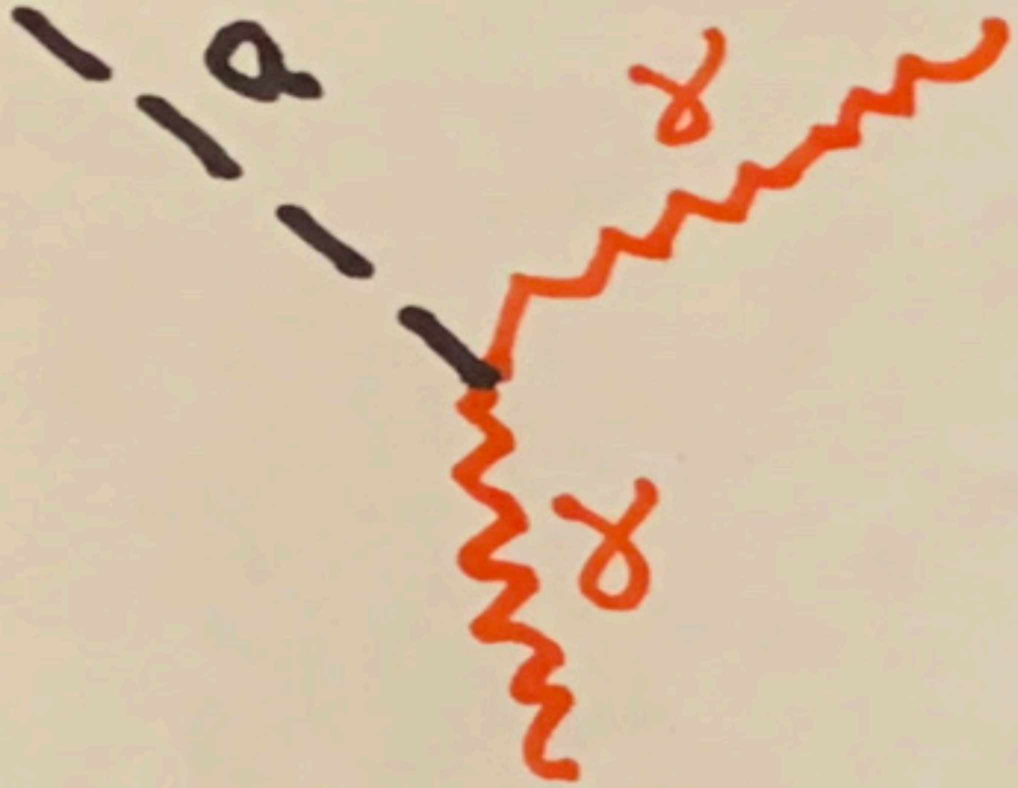
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Axions also induce electric dipole moments in nuclei, and possibly electrons.

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