



富嶽三十六景 神奈川沖  
浪裏

# Axion Experiment and Theory

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Science and  
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# Axion Dark Matter

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

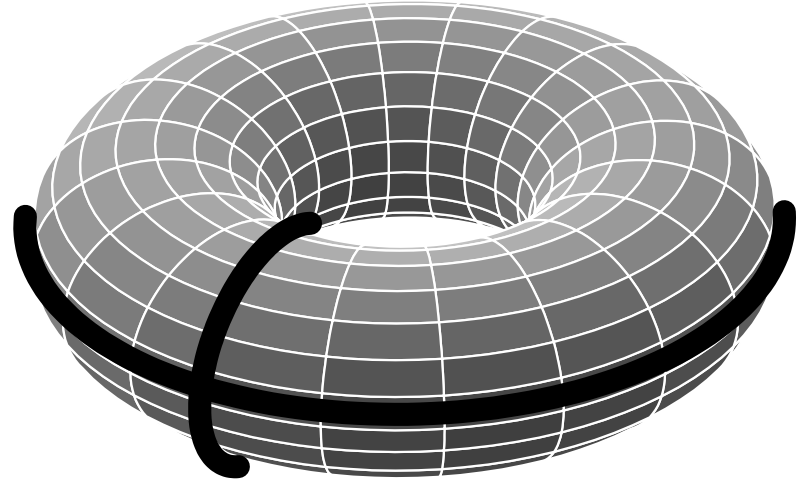
# Axion Theories



Neutron observed to have EDM  $\sim 0$ . This can be explained by the QCD axion.

$$m_a f_a = m_\pi f_\pi \Rightarrow m_a = 5.7 \mu\text{eV} (10^{12} \text{ GeV} / f_a)$$

One parameter DM model valid since 1980's  
High scale SSB  $\rightarrow$  low mass particle.



Extra dims. of string theory wrapped by gauge fields  $\rightarrow$  axion-like particles.

**Number of axions given by topological invariants.**

**Masses spread over log scale: “the string axiverse”.**

# Axion Relic Density

Relic density from solving the Klein-Gordon equation for a massive scalar field:

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

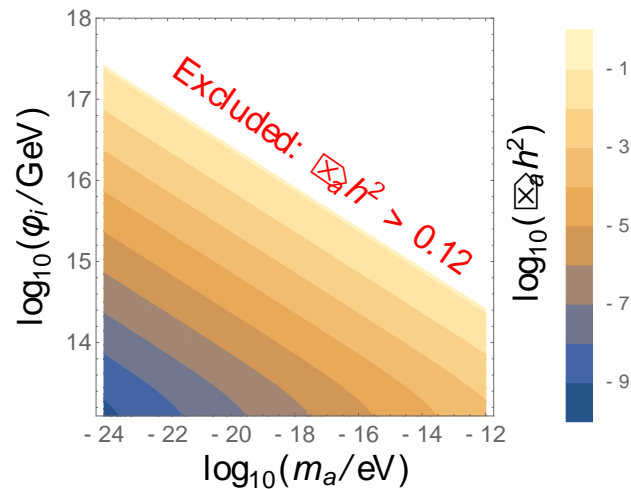
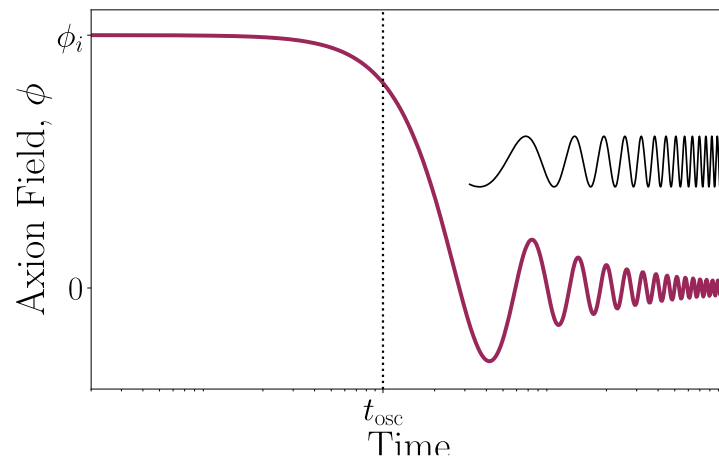
Damped SHM with time dependent “friction”.

Oscillates and decays when  $H < m$ .

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2.$$

$H \sim 1/t \rightarrow \rho \sim a^{-3}$ . Harmonically oscillating scalar behaves like pressureless dust.

$$\Omega_a h^2 = 0.12 \left( \frac{\phi_i}{1.5 \times 10^{15} \text{GeV}} \right)^2 \left( \frac{m}{10^{-15} \text{eV}} \right)^{\frac{1}{2}}$$



# Axion Dark Matter

Axions can be modeled as an **oscillating classical field**:

$$\phi = \phi_0 \cos \omega_a t$$
$$\omega_a = m_a + \frac{1}{2} m_a v^2 = m_a [1 + \mathcal{O}(10^{-6})]$$

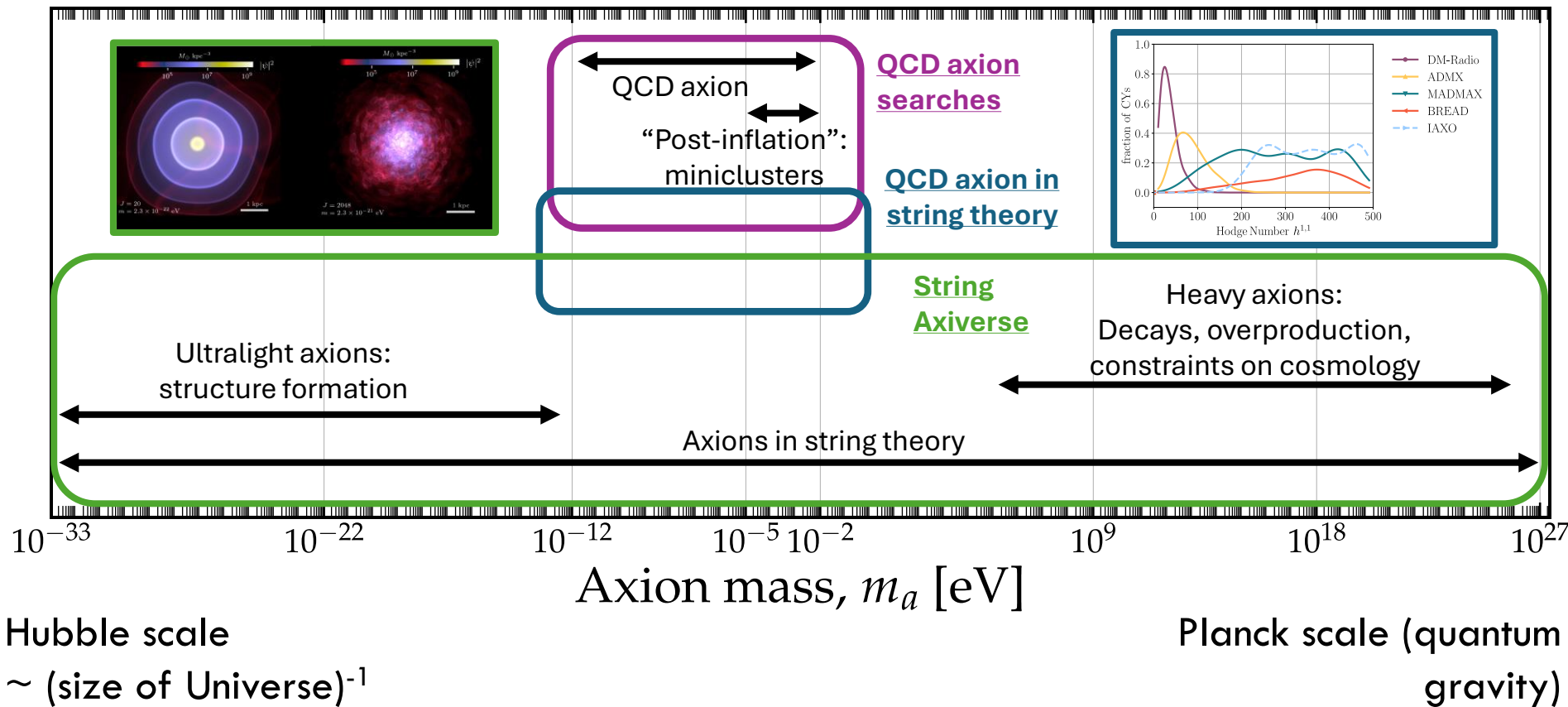
$$\nu_a \approx 1 \text{ GHz} \times \left( \frac{m_a}{6 \mu\text{eV}} \right)$$

From galactic  
rotation curve

Local DM density given as a harmonic oscillator:

$$\rho_{\text{DM}} = \frac{1}{2} m_a^2 \phi_0^2 \quad = 0.3\text{-}0.4 \text{ GeV cm}^{-3}$$

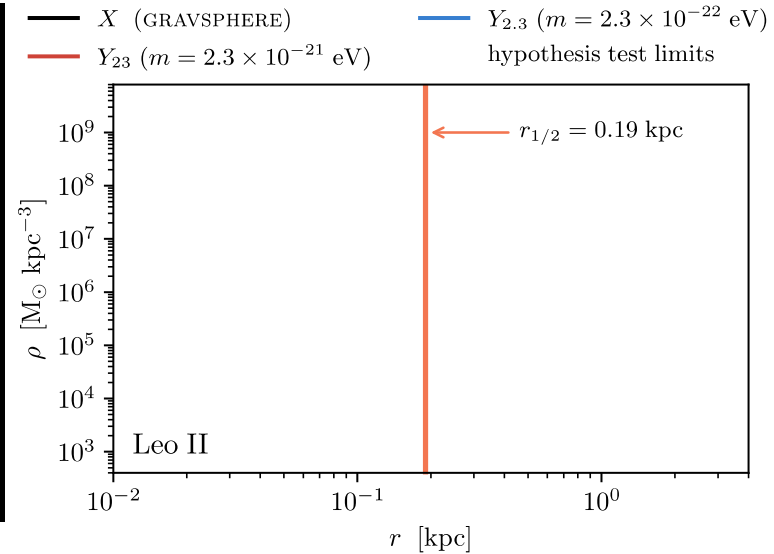
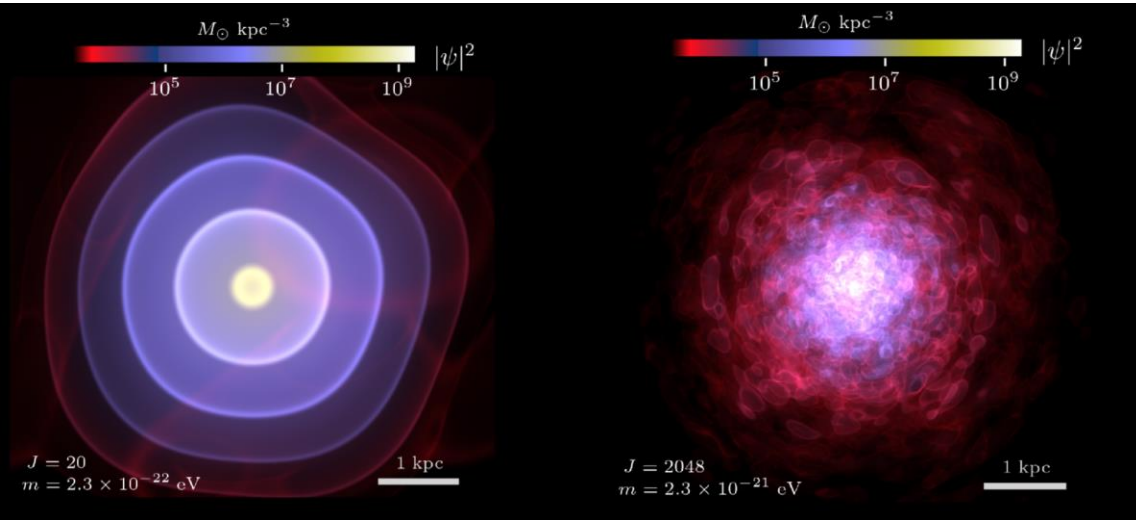
→ if we know  $m_a$  we  
know field amplitude &  
frequency



# DM lower limit: $2 \cdot 10^{-21}$ eV

Zimmermann, DJEM et al (PRL)

Folk wisdom: de Broglie wavelength must be smaller than dwarf galaxy radius.  
“Bosonic Tremaine-Gunn bound”. Extremely difficult to compute precisely.



Leo-II is cuspy. Waves give cores. Compare self-consistent wavefunction to model-independent reconstruction of density + rigorous stats  $\rightarrow$  strong limit.

# RECENT THEORY HIGHLIGHTS

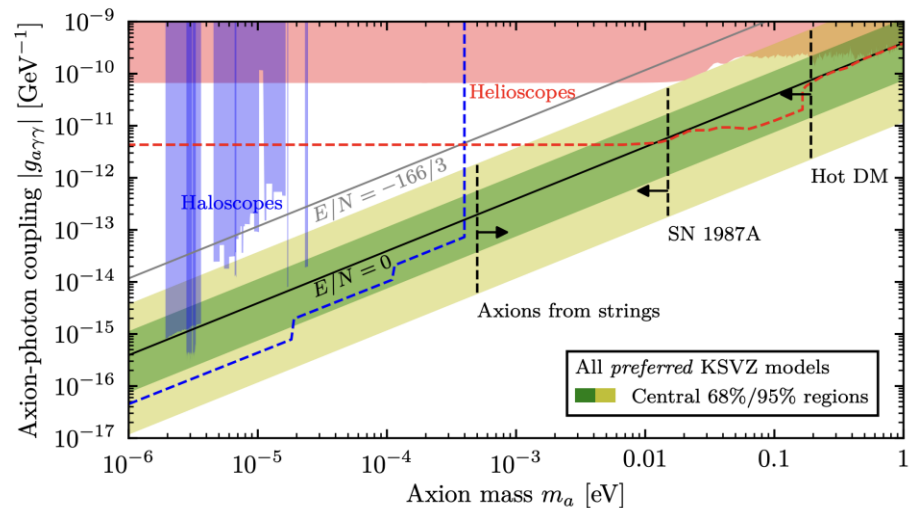


# The QCD Axion

**Recent highlight 1:** the landscape of QCD axion models.

e.g. Di Luzio+ (2016+); Plakkot & Hoof (2021)

$$g_{a\gamma} = 2 \times 10^{-16} \text{ GeV}^{-1} (m_a / \mu\text{eV}) \left( \frac{E}{N} - 1.92 \right)$$

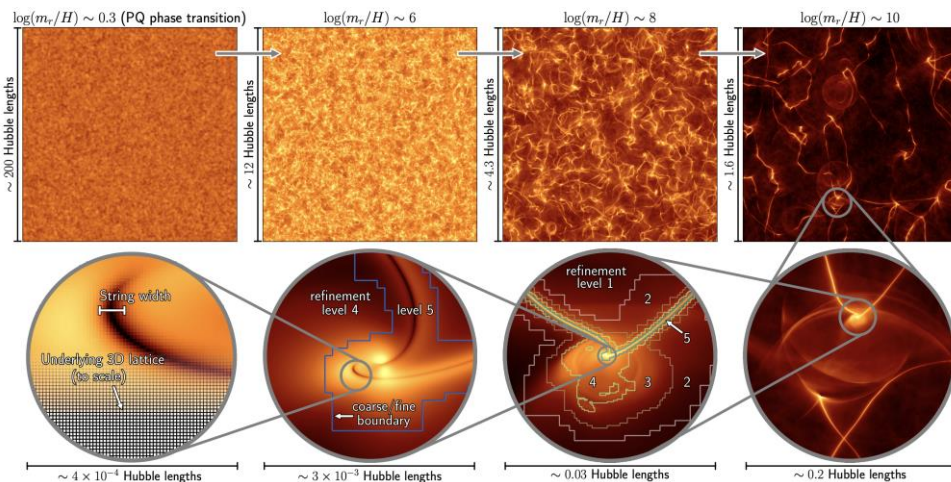


**Recent highlight 2:** predicting the axion mass in the “post-inflation” scenario.

e.g. Gorghetto et al (2018+);

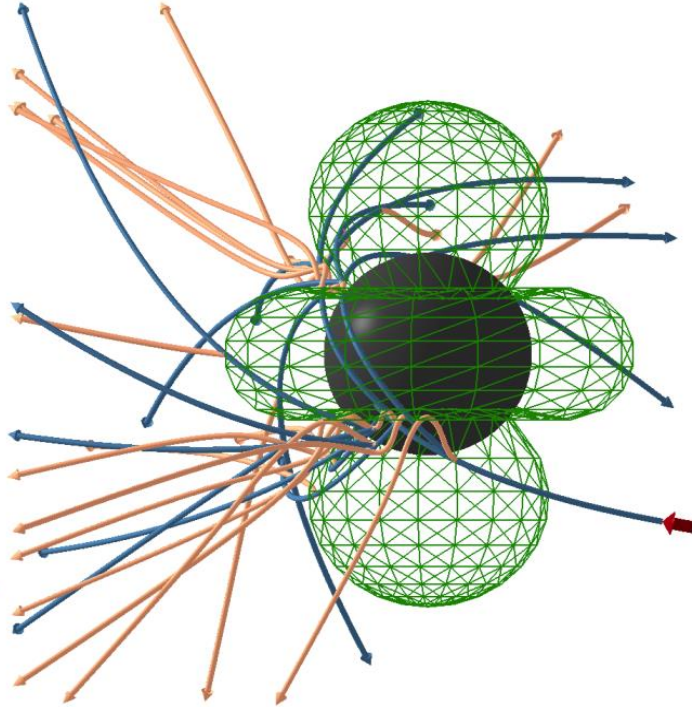
Saikawa et al (2024); Buschmann et al (2018+)

$$m_a \approx 50 - 500 \mu\text{eV}$$



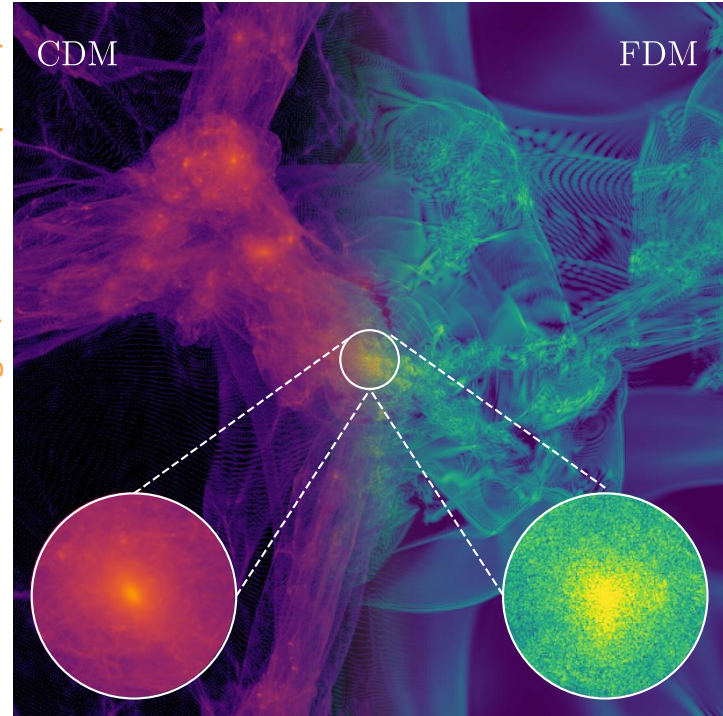
# Astrophysics & Cosmology

MacDonald et al (2023)



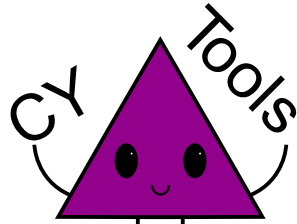
Neutron star magnetospheres convert axions in radio waves.

Lägue, DJEM et al (2024)

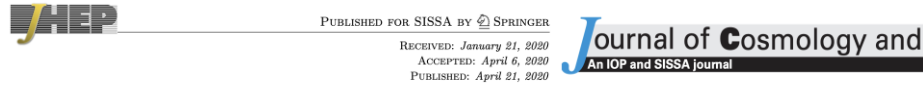


Simulations allow modeling of wavelike effects on cosmic structure.

# Type IIB String Theory



Rapid progress in understanding explicit Calabi-Yau compactifications and constructing large ensembles. Characterised by “Hodge numbers” ( $h_{1,1}, h_{2,1}$ ).



The Kreuzer-Skarke axiverse

## Superradiance in strings

Viraf M. Mehta,<sup>a</sup> Mehmet Demirtas,<sup>b</sup>  
David J.E. Marsh,<sup>a</sup> Liam McAllister<sup>b, c</sup>

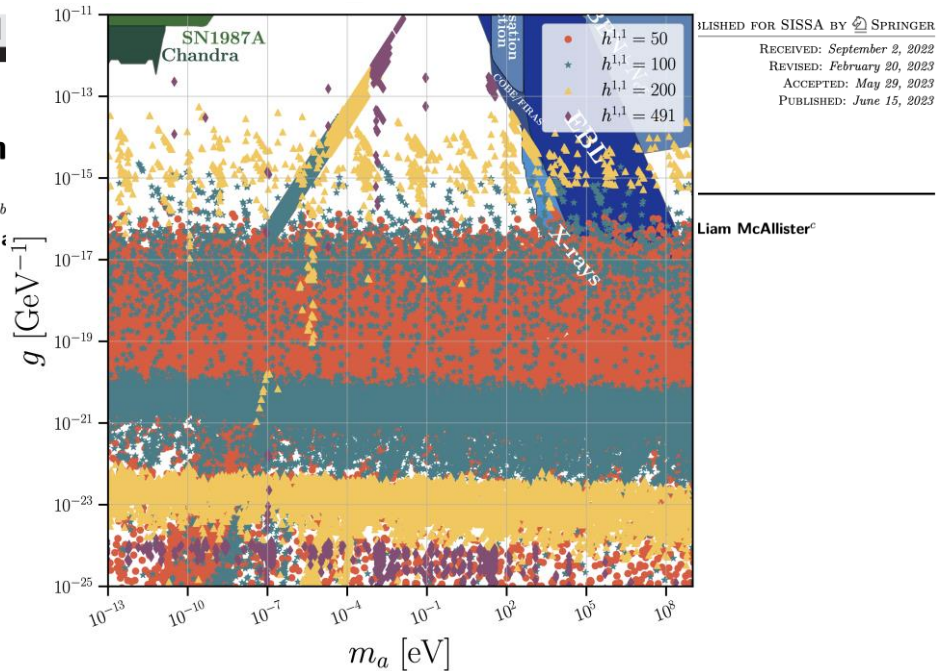
Mehmet Demirtas,<sup>a</sup> Cody Long,<sup>b</sup> Liam McAllister<sup>d</sup> and Mike Stillman<sup>e</sup>



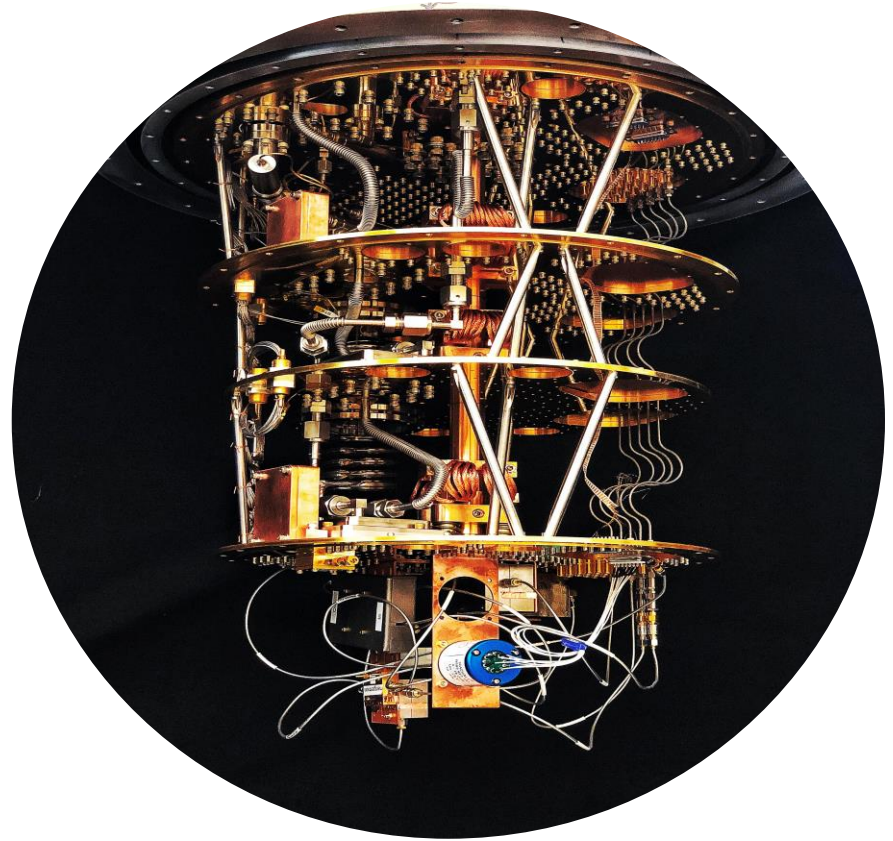
RECEIVED: March 5, 2024  
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Glimmers from the axiverse

Naomi Gendler<sup>g, a, c</sup> David J.E. Marsh,<sup>b</sup> Liam McAllister<sup>c</sup> and Jakob Moritz<sup>c</sup>



# Direct detection: “Haloscopes”



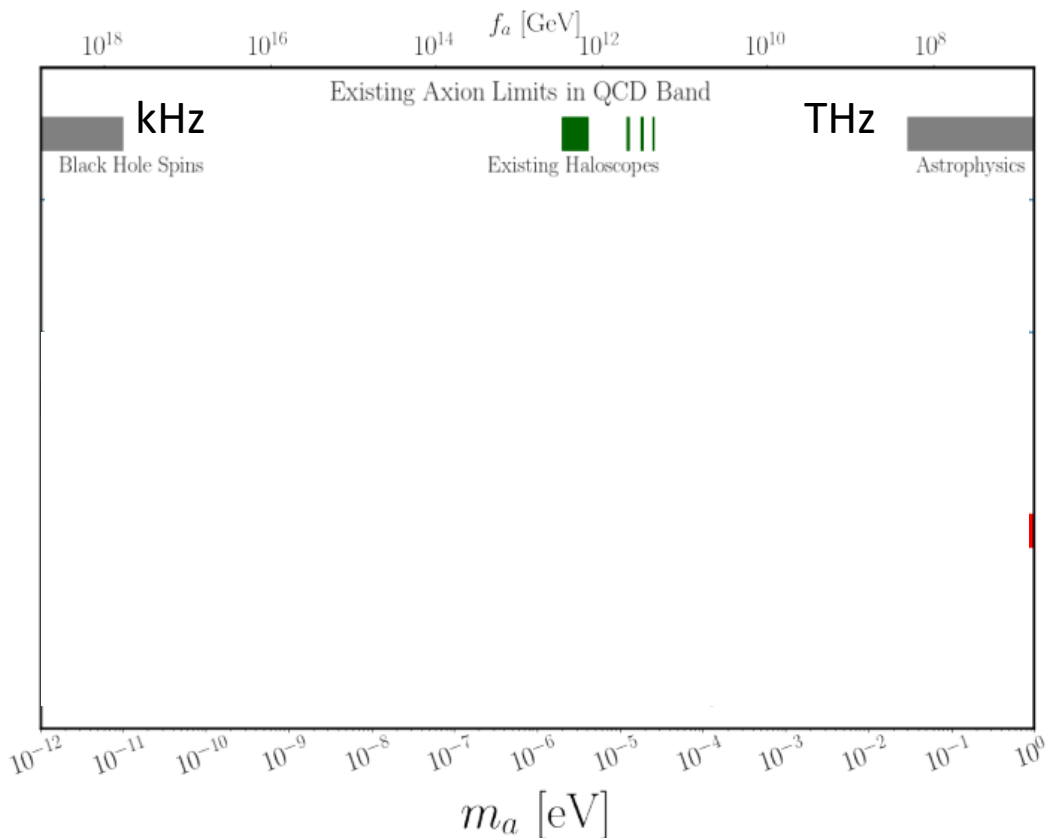
# The QCD axion will be found

QCD axion mass:

$$m_a = 5.7 \mu\text{eV} \left( \frac{10^{12} \text{ GeV}}{f_a} \right)$$

Bounded from above by  
SN1987A  $\nu$  burst duration.  
Bounded from below by black  
hole superradiance.

Axion DM is an oscillating  
classical field in kHz to THz.



# Resonant Cavities

Sikivie (1983); ADMX collab.  
“Dark Matter” (DJEM et al)

Axions interact with electromagnetism via:

$$\mathcal{L}_{\text{int}} = -\frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = g\phi\vec{E}\cdot\vec{B}$$

→ axions source Maxwell’s equations:

$$\nabla\cdot\vec{E} = \rho_e - g\vec{B}\cdot\nabla\phi,$$

$$\vec{\nabla}\times\vec{E} - \dot{\vec{B}} = -\vec{J}_e - g(\vec{B}\cdot\dot{\phi} - \vec{E}\times\nabla\phi)$$

B source → linearise for E wave equation:

$$\ddot{\vec{E}} - \nabla^2\vec{E} = \frac{\omega^2}{m}\sqrt{2\rho_a}g\vec{B}\cos\omega t.$$

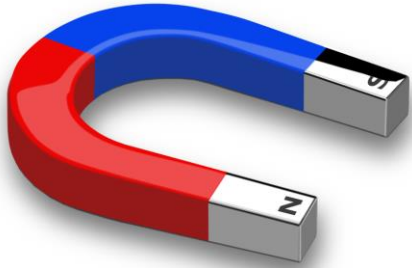
→ resonance via boundary conditions.

$$P = \frac{g^2 B^2 V \rho_{\text{DM}}}{m} Q.$$

Power  $10^{-22}$  W in  
typical experiment



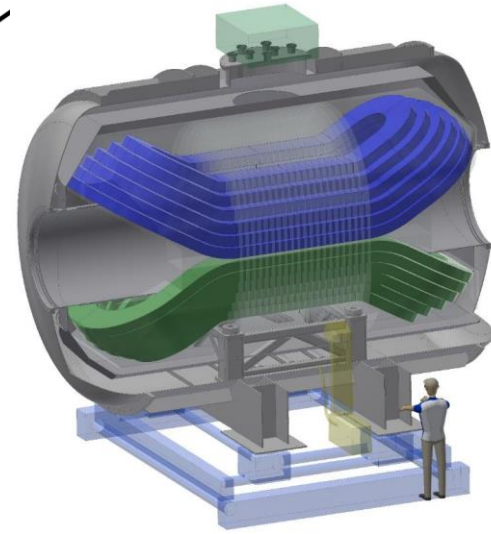
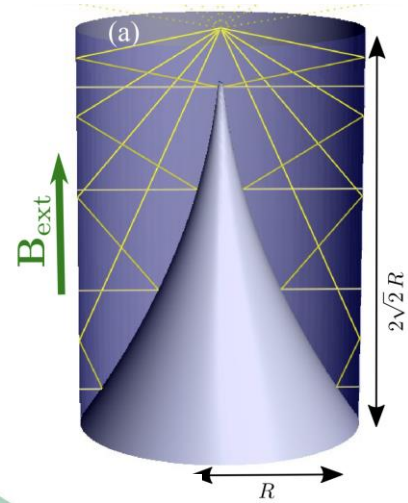
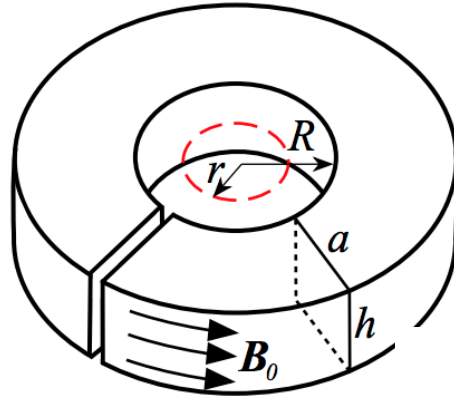
# How to Detect Axions



# Haloscopes beyond GHz

Technology doesn't scale well.  
Many new ideas since ~2012.

- Low frequency: DMRadio ABRA resonant circuits.
- Mid: MADMAX dielectrics, ALPHA wire metamaterial.
- High: BREAD dish antenna, quasiparticles (see later).



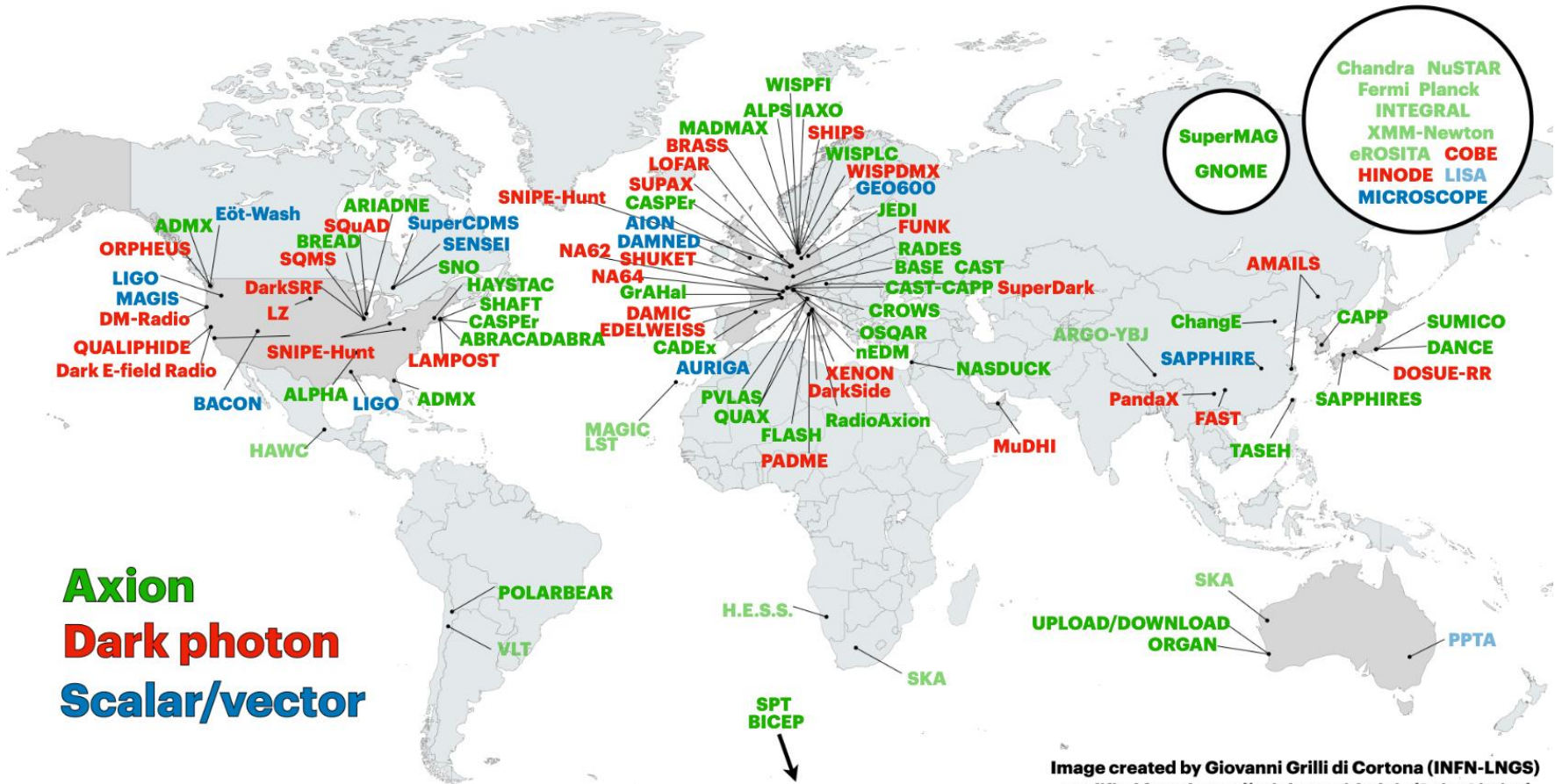
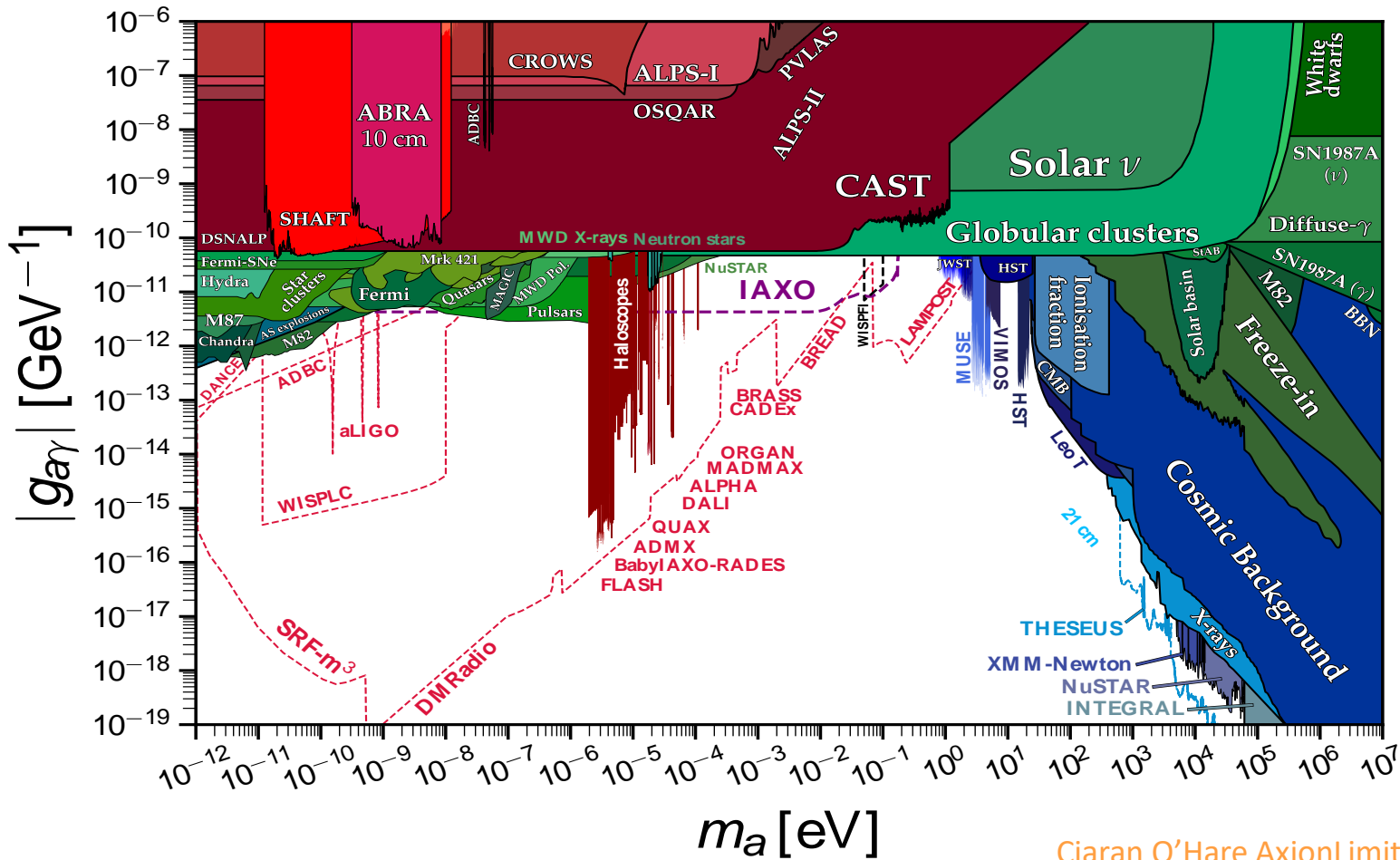


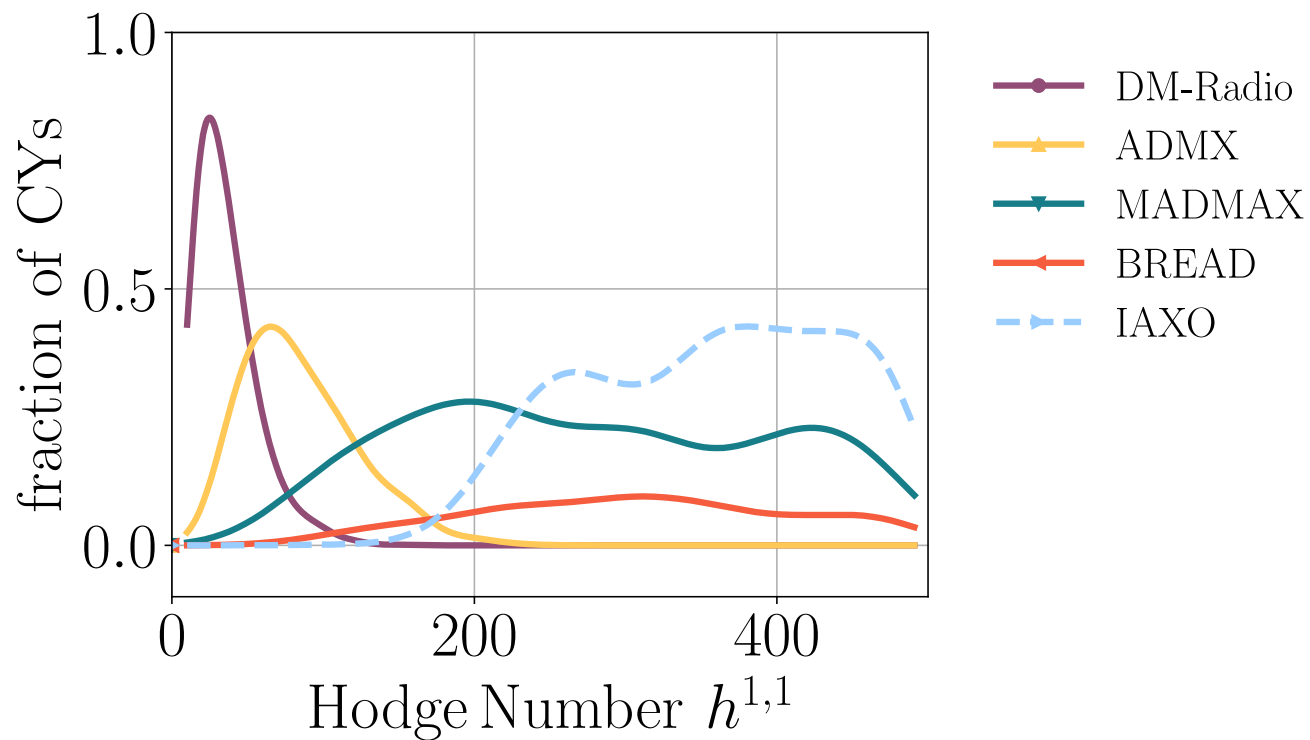
Image created by Giovanni Grilli di Cortona (INFN-LNGS) modified from <https://cajohare.github.io/AxionLimits/>



Ciaran O'Hare AxionLimits Github

Note: other couplings also probed.

# CY topology in the lab



# DISCOVERY OF THE AXION QUASIPARTICLE

Qiu, DJEM et al, to appear in Nature



# Axion Quasiparticles

Review: Sekine & Nomura (2021)

ARTICLES

PUBLISHED ONLINE: 7 MARCH 2010 | DOI: 10.1038/NPHYS1534

nature  
physics

## Dynamical axion field in topological magnetic insulators

Rundong Li<sup>1</sup>, Jing Wang<sup>1,2</sup>, Xiao-Liang Qi<sup>1</sup> and Shou-Cheng Zhang<sup>1\*</sup>

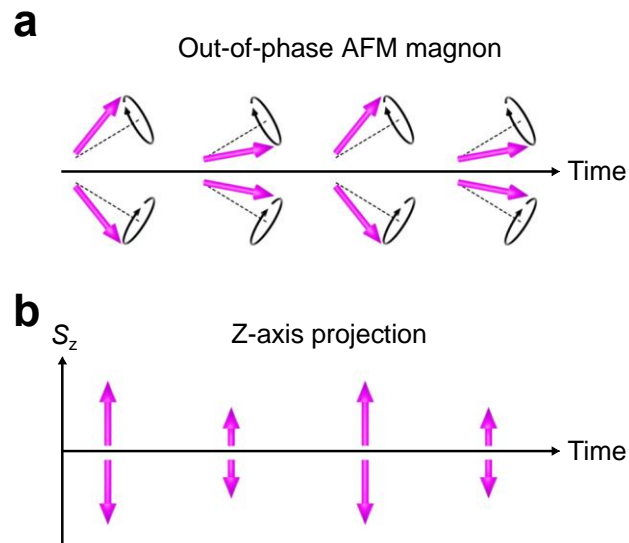
Fluctuating antiferromagnetic order can couple to E.B → axion quasiparticle.

Axion  $\sim$  magnetoelectric coupling  $\alpha_{ij}$ . Static value  $\pi$  in topological insulators.

Until now, candidate materials included  $\text{Mn}_2\text{Bi}_2\text{Te}_5$  using antiferromagnetic amplitude mode. Difficult to excite, materials unstable.

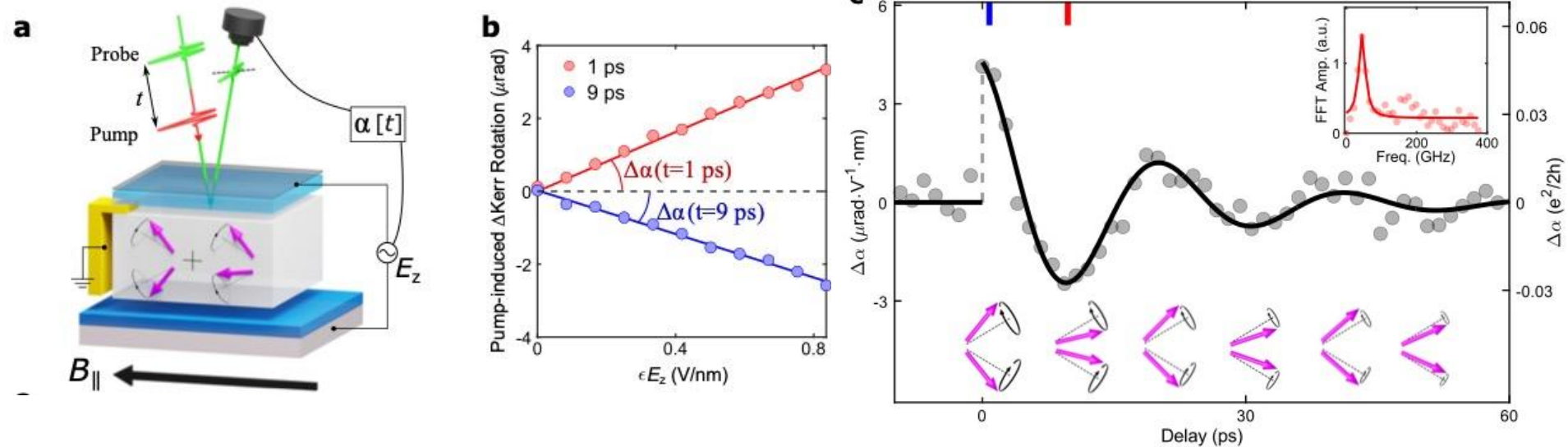
**New insight:** in-plane B tilts spins → order parameter fluctuation.

This can be achieved in more well understood “axion insulator”  $\text{MnBi}_2\text{Te}_4$ .



# Measuring the Quasiparticle

Qiu, DJEM et al (2025)



Axion-photon coupling causes probe laser polarization angle to oscillate at frequency  $\sim$  axion mass. Measured frequency 44 GHz  $\sim$  0.2 meV.

Exciting laboratories for analogue physics, e.g. gravitational Chern-Simons.

*Axion quasiparticle polaritons* provide a tunable axion DM detector in difficult THz.

