Wave dark matter: Quantum Enabled Opportunities for Discovery

Chelsea Bartram
Snowmass
CF02-Wave-like Dark Matter
06/17/2022

Rubin's Galaxy - NASA, ESA, B. Holwerda

Gravitationally-interacting

Non-Baryonic

Very stable

Cold (non-relativistic)

Feebly-interacting

Wave-like ?

Rubin's Galaxy - NASA, ESA, B. Holwerda

What do we mean by wave-like?

Wave-like Definition: Mass < 1 eV

Broad Candidate Categories:

- Pseudo-scalar*
- Scalar
- Vector

Cosmological Production: Athermal (misalignment).

Detection: Coherent interaction of the wave with the detector. Resonant amplification often key.

**The most famous candidate in this group is the QCD axion.*

Wave-like dark matter

$$a(\vec{x},t) = \frac{\sqrt{(2\rho_{DM})}}{m_a}\cos\left(m_a t + \mathcal{O}(\nu_{DM})\vec{x}\right)$$

ρ_{DM} = 0.45 GeV/cm^3

De Broglie Wavelength $\lambda_{\rm dB} \approx \frac{2\pi}{mv}$

Occupancy Number $N \approx \frac{\rho_{\rm DM}}{m}\lambda_{dB}^3$

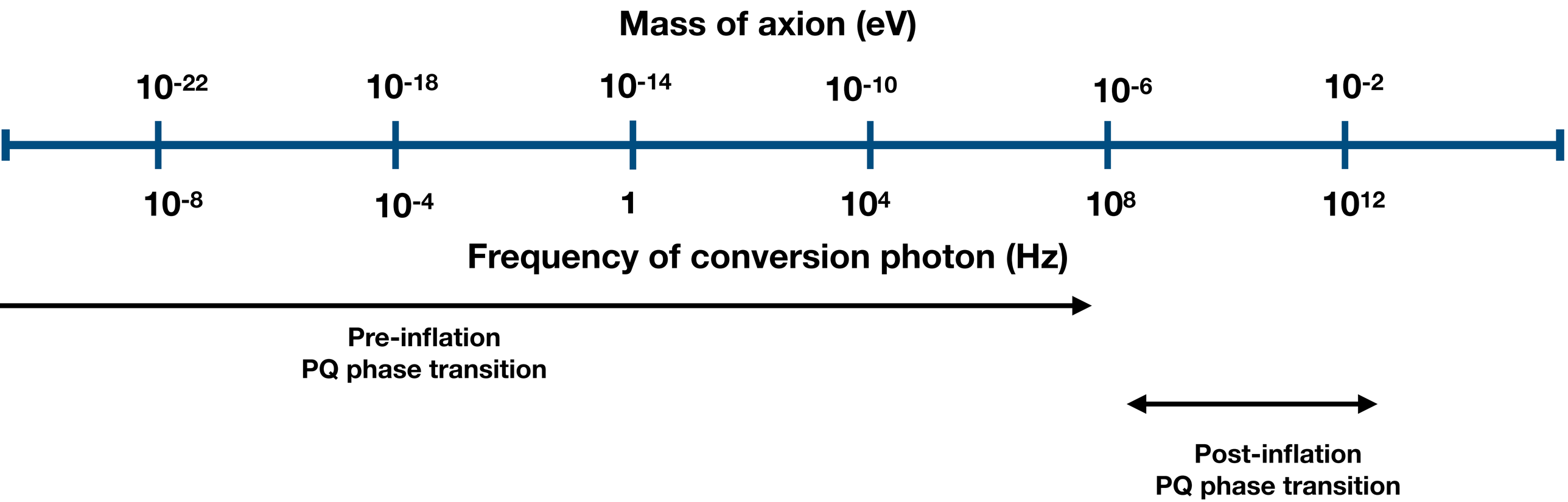
WIMP dark matter (m ~ 100 GeV): λ_{dB} ~ 10^{-13} m with N ~ 10^{-36}

Axion dark matter (m ~ 10^{-6} eV): λ_{dB} ~ 100 m with N ~ 10^{44}

Theoretical Constraints

Lower bound set by size of dark matter halo size of dwarf galaxies

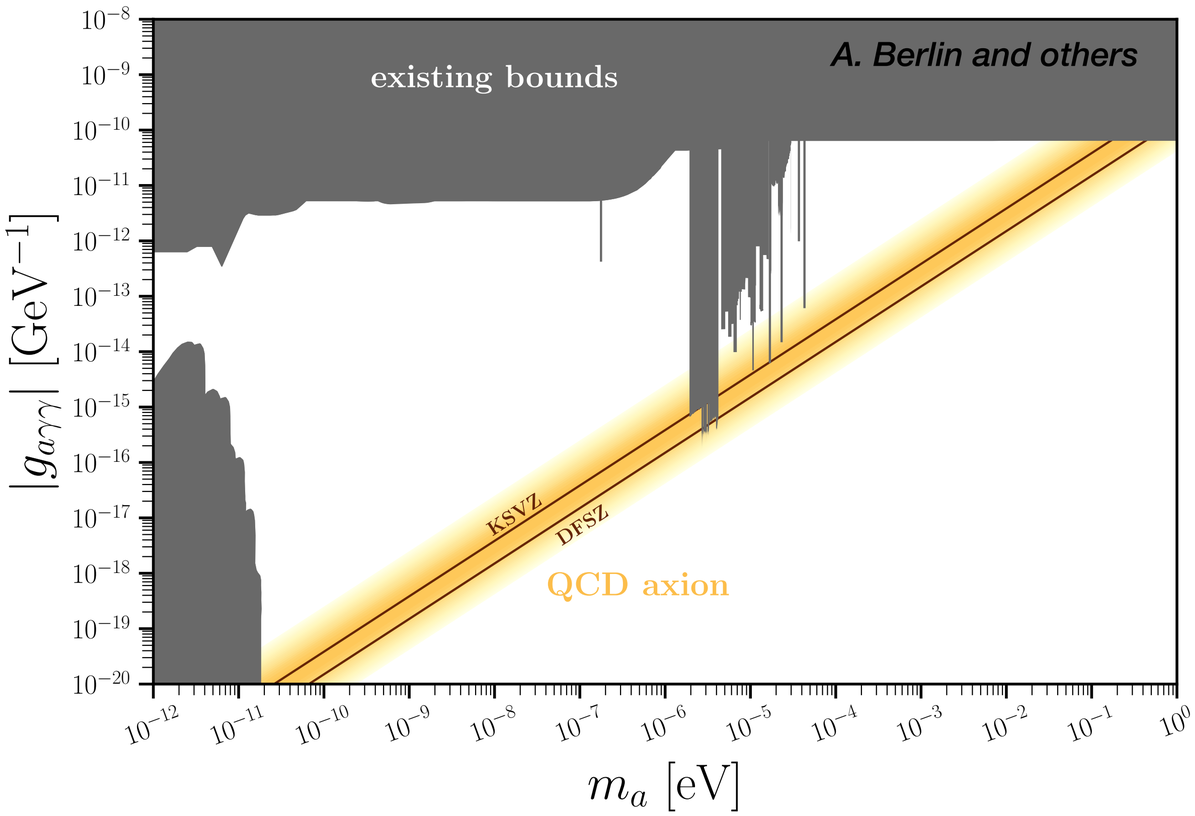
Upper bound set by SN1987A and white dwarf cooling time



Adaptation of L. Winslow DPF Slide

The QCD Axion

- $U(1)_{PQ}$ introduced to preserve CP symmetry in the Strong Interaction.
- The QCD axion is a psuedo-Nambu-Goldstone boson produced by the breaking of $U(1)_{PQ}$.
- Couples to **photons**, nucleons, electrons.
- Broad Categories of models:
  - **KSVZ** introduces heavy quarks.
  - **DFSZ** introduces additional Higgs fields.*

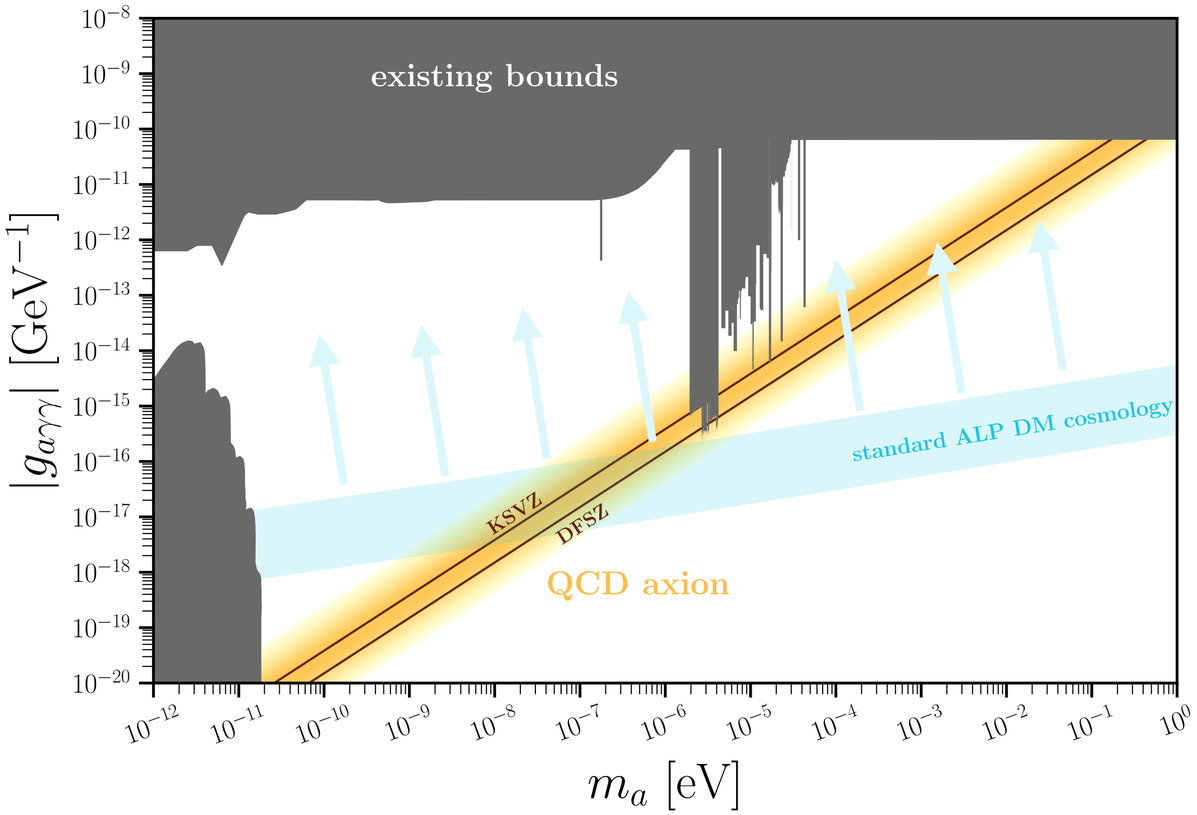


** DFSZ is the benchmark for the field.*

Axion-Like Particles (ALPs)

- Similar particles produced in many higher order theories.
- Depending on the details of the theory and the cosmology, discovery possible in many intermediate scale experiments.
- We are lazy and often refer to the QCD axion and ALPs as just axions.

A. Berlin and others



In summary, roughly need to cover 10^{-12} eV to 1eV

Axion Detection

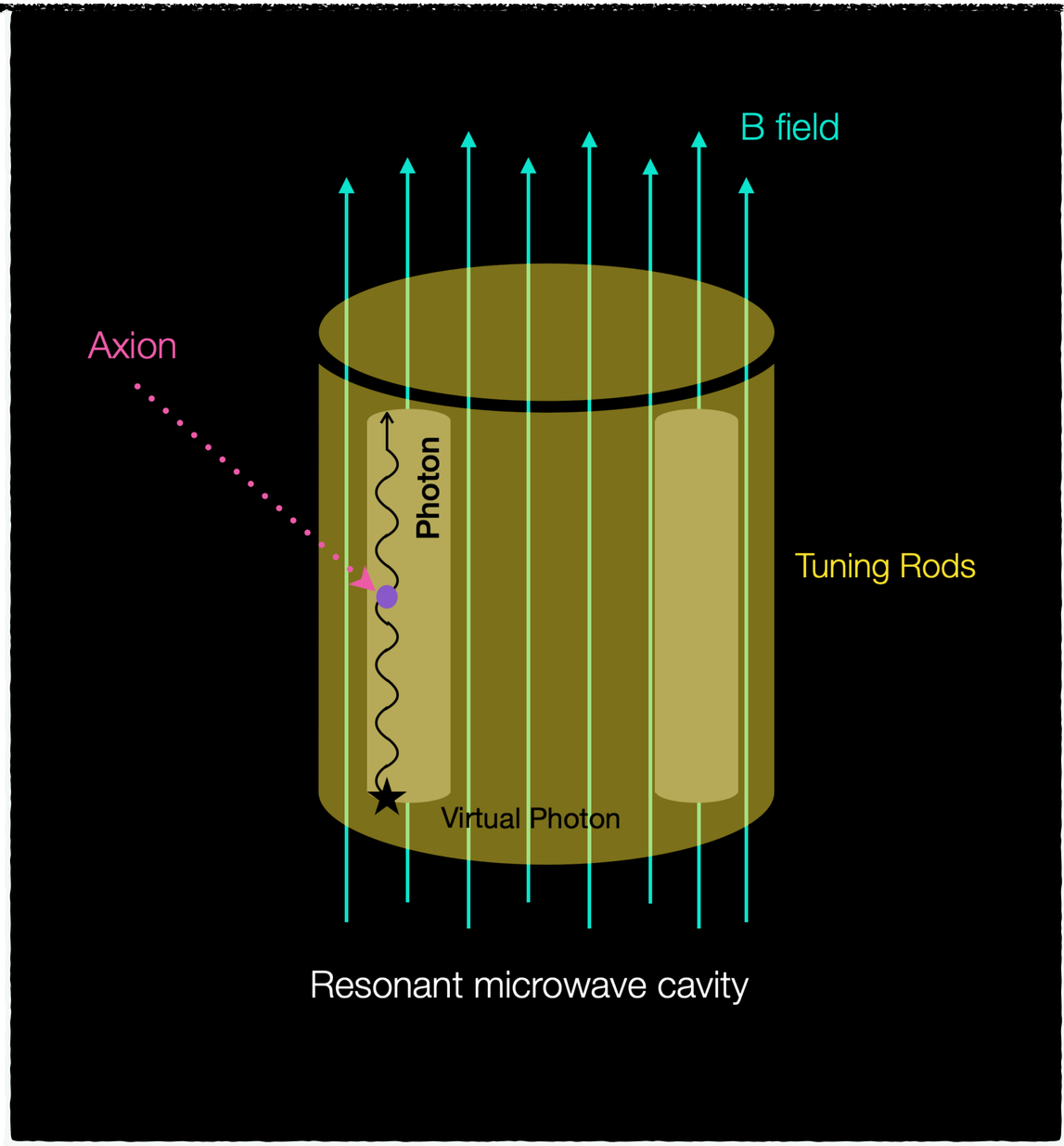
- Photon detection: cleanest channel for discovery

- Inverse Primakoff Effect: Axion converts to photon in magnetic field

- Dealing with microwave frequencies

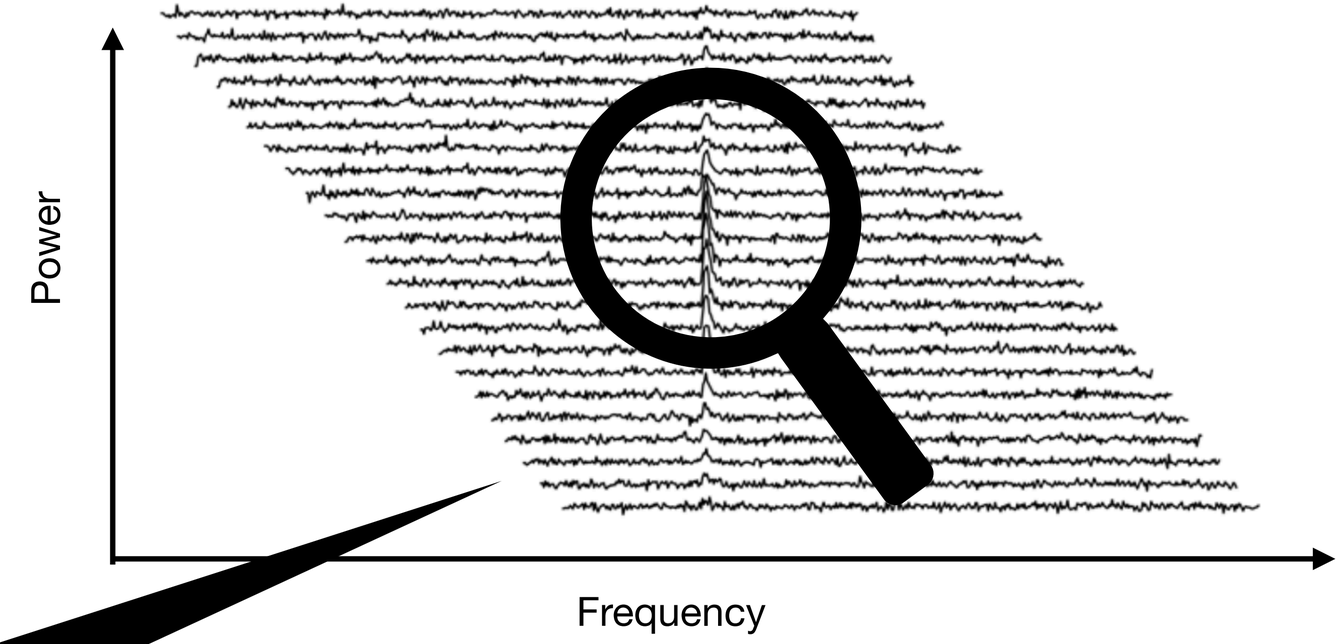
- Sensitive to axion photon coupling ($g_{a\gamma\gamma}$)

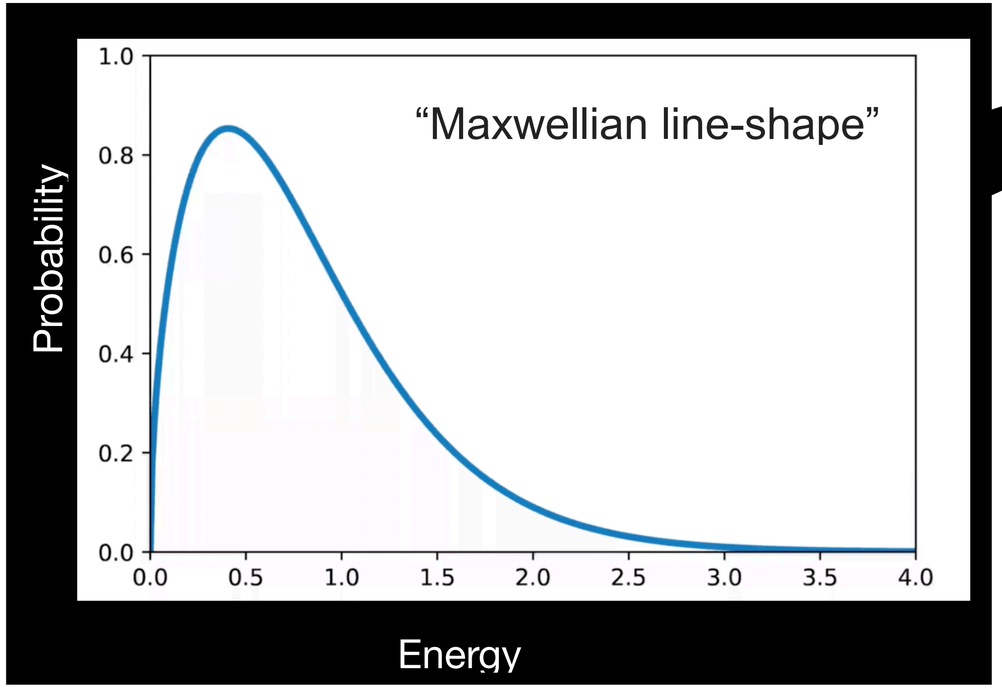
- Other couplings exist and can be leveraged for detection as well (more later).



Photon searches

- Look for peak in power spectrum
- Frequency proportional to the mass of the dark matter
- Line-shape or velocity distribution characteristic of dark matter halo



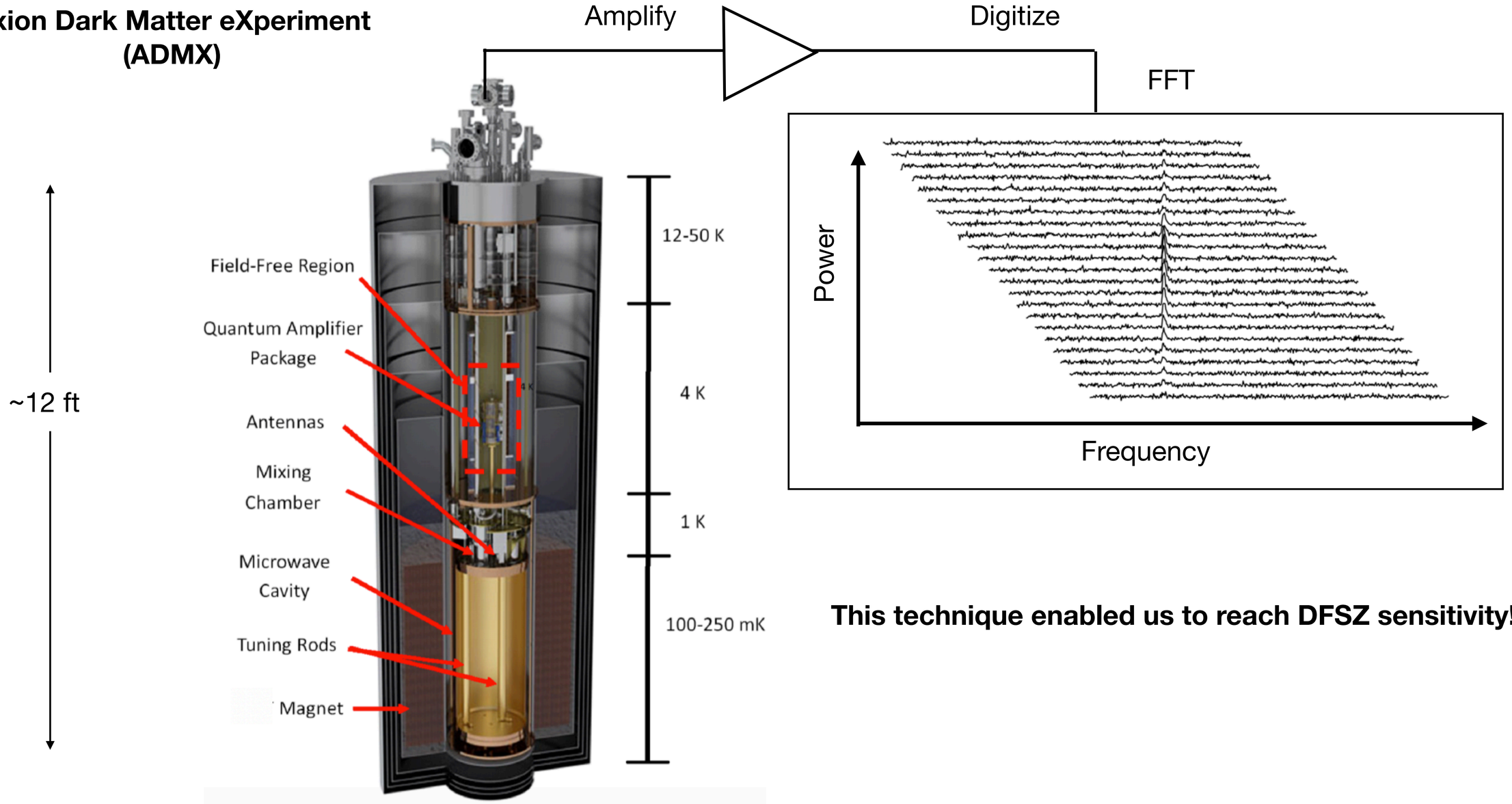


Signal on order of 10^{-23} Watts!

How to achieve adequate signal-to-noise for DFSZ sensitivity?

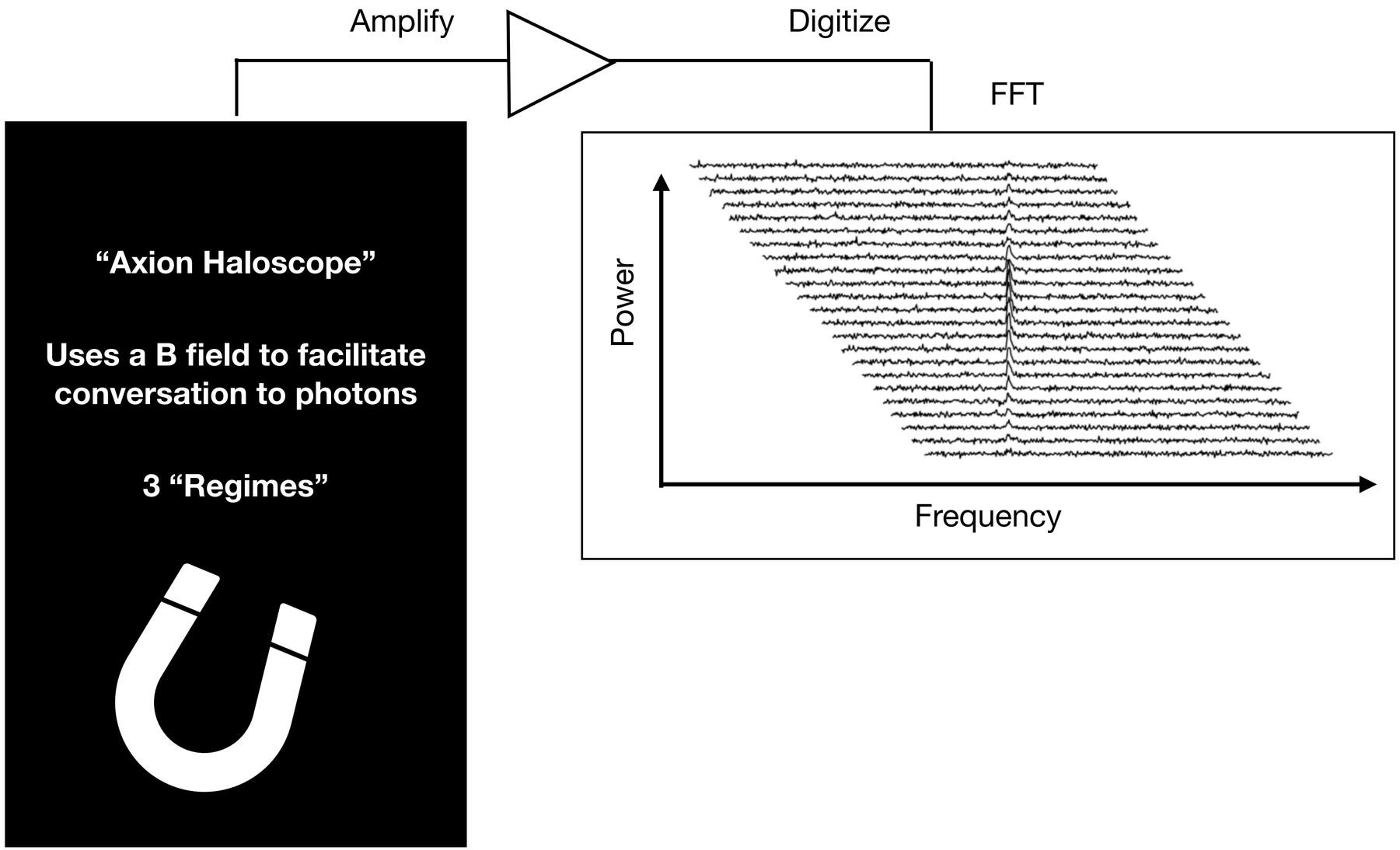
Resonant Haloscope

Axion Dark Matter eXperiment (ADMX)



This technique enabled us to reach DFSZ sensitivity!

Resonant Haloscope



Modified Maxwell's Equations

$$\vec{\nabla}\cdot\vec{E} = -g_{a\gamma\gamma}\vec{B}\cdot\vec{\nabla}a$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

Modified Source-free Maxwell's Equations

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

$$\vec{\nabla}\times\vec{B} = -\frac{\partial\vec{E}}{\partial t} - g_{a\gamma\gamma}(\vec{E}\times\vec{\nabla}a - \frac{\partial a}{\partial t}\vec{B})$$

Modified Maxwell's Equations

$$\vec{\nabla}\cdot\vec{E} = -g_{a\gamma\gamma}\vec{B}\cdot\cancel{\vec{\nabla}a}$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

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

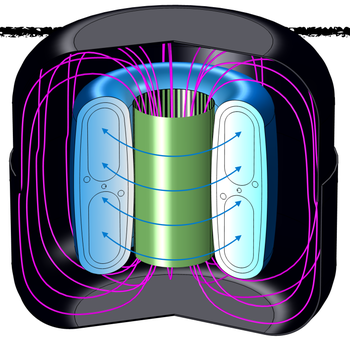
$$\vec{\nabla}\times\vec{B} = -\frac{\partial\vec{E}}{\partial t} - g_{a\gamma\gamma}(\vec{E}\times\cancel{\vec{\nabla}a} - \frac{\partial a}{\partial t}\vec{B})$$

These terms are assumed to be small.

Detection Regimes

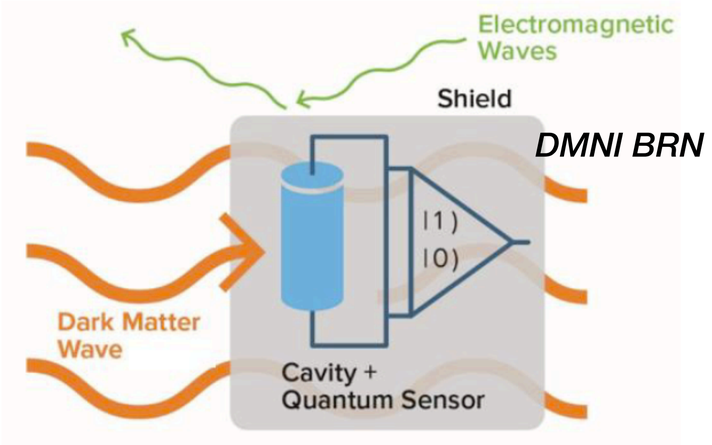
$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\rm eff}}$$

Quasistatic regime: $\lambda_{\rm Comp} \gg R_{\rm exp}$



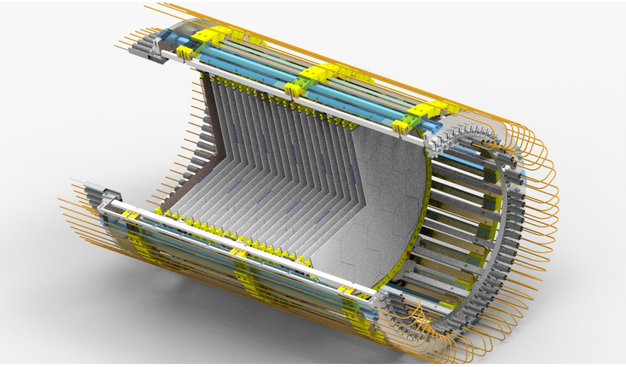
$$\underbrace{\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t}} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\rm Comp} \sim R_{\rm exp}$



$$\cancel{\nabla \times \mathbf{B}_r} = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Radiation regime: $\lambda_{\rm Comp} \ll R_{\rm exp}$

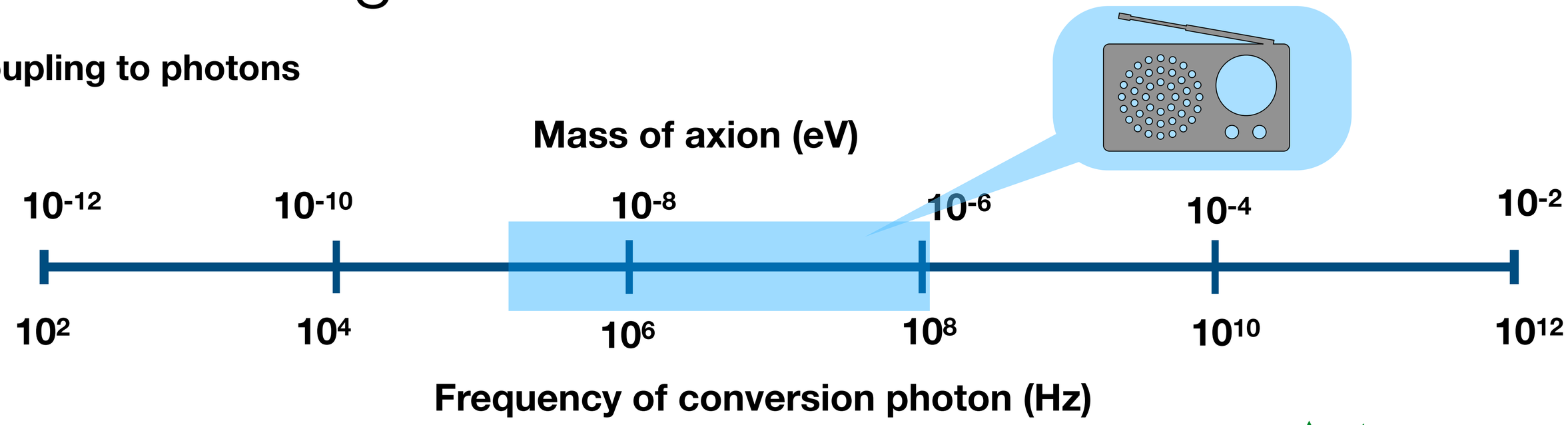


Y. Kahn

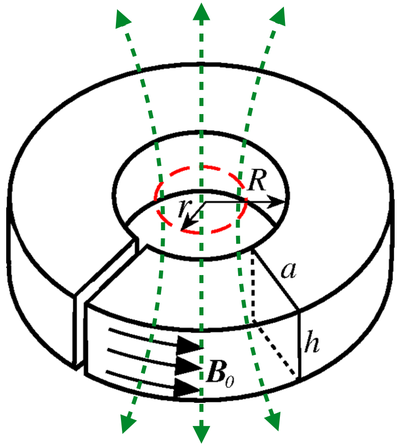
Detection Regimes

DM Radio/ABRA/LC Circuit

Coupling to photons



$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0}_{\mathbf{J}_{\rm eff}}\frac{\partial a}{\partial t}$$



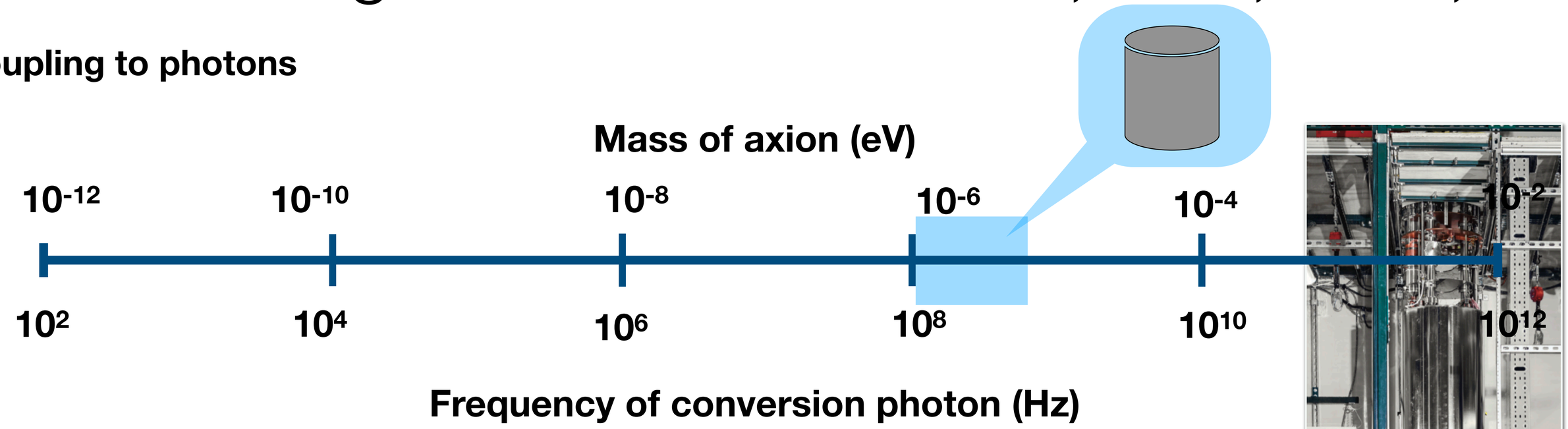
- **Effective axion current sources magnetic field**
- **Sourced B field detected by pickup loop**
- **SQUIDs used in readout**

Quasistatic regime: $\lambda_{\rm Comp} \gg R_{\rm exp}$

Detection Regimes

Cavity Haloscopes:
ADMX, HAYSTAC, CAPP-8TB, TASEH

Coupling to photons



$$\nabla \times \mathbf{B}_r = \underbrace{\frac{\partial \mathbf{E}_r}{\partial t}} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

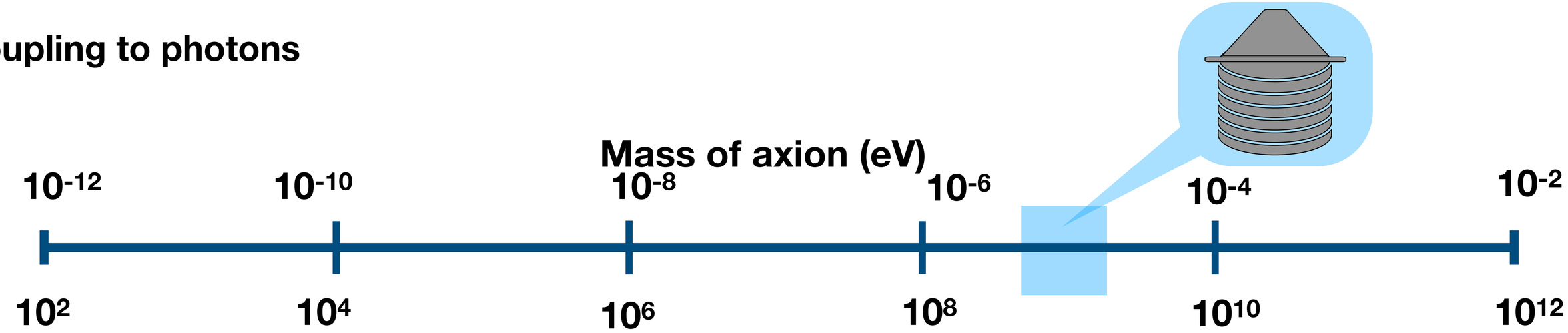
Cavity regime: $\lambda_{\mathrm{Comp}} \sim R_{\mathrm{exp}}$

- **Axion conversion to photon generates E field in cavity**
- **Cavity volume similar in scale to photon wavelength**
- **Excess power picked up via antenna**
- **Quantum amplifiers used in receiver chain**

Detection Regimes

Dielectric haloscopes: MADMAX, Orpheus

Coupling to photons

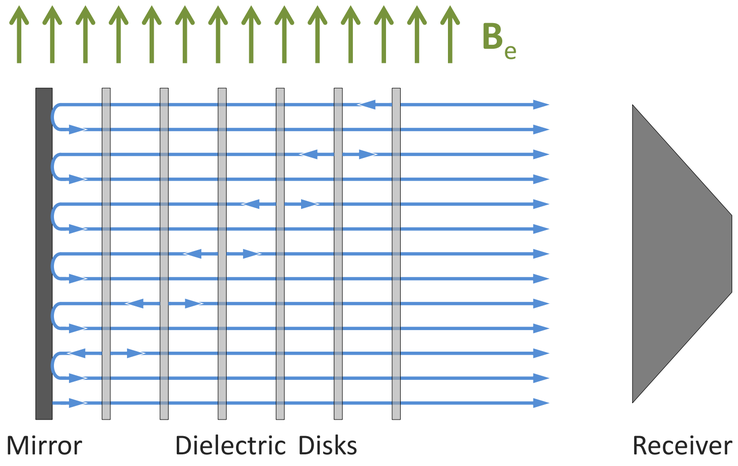


Frequency of conversion photon (Hz)

$$\cancel{\nabla \times \mathbf{B}_r} = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma}\mathbf{B}_0\frac{\partial a}{\partial t}$$

Radiation regime:

$$\lambda_{\mathrm{Comp}} \ll R_{\mathrm{exp}}$$

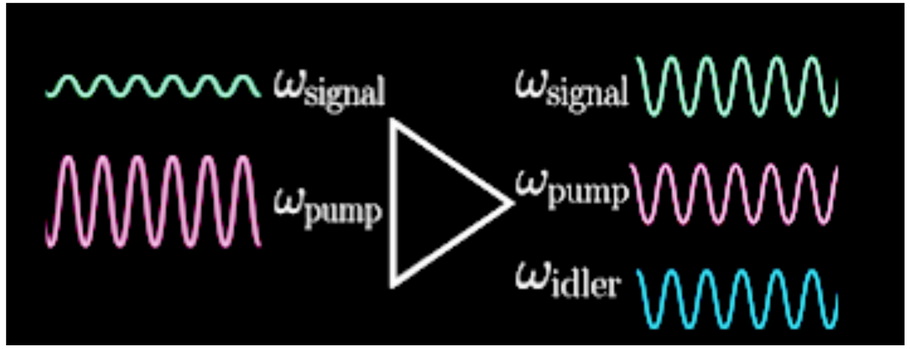


Boundary conditions enable higher frequency photon detection

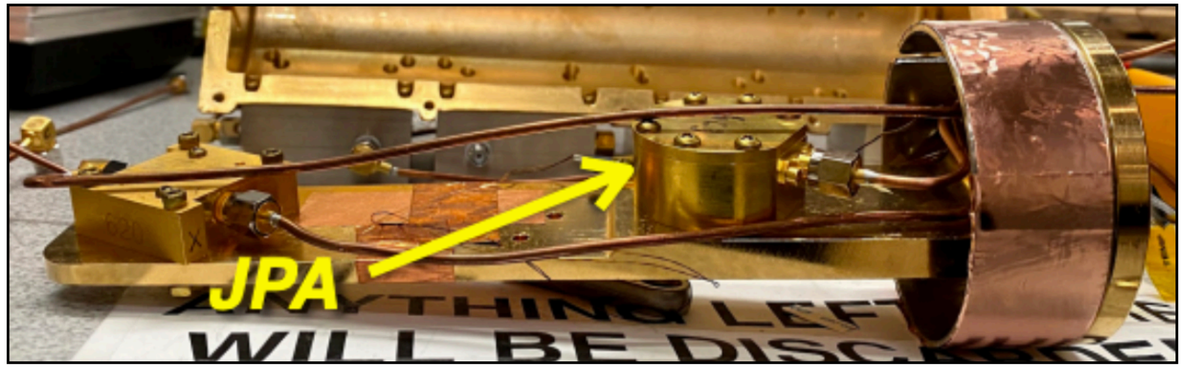
Enabling technologies: amplifiers

Quantum amplifiers allow for noise levels close to the Standard Quantum Limit

- Microstrip SQUID Amplifiers (MSAs) and SQUIDs
  - Better option for lower frequency range searches
  - Narrowband gain
- Josephson Parametric Amplifiers (JPAs)
  - Ideal for higher frequency range searches
  - Narrowband gain
- Josephson Traveling Wave Parametric Amplifiers (JTWPAs)
  - Ideal for higher frequency range searches
  - Broadband gain



Figures courtesy of Shahid Jawas

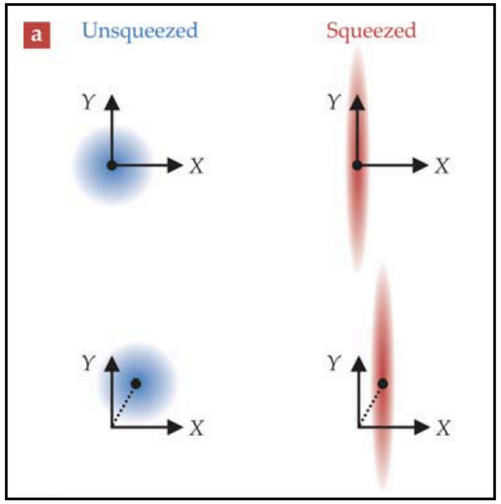


ADMX JPA and JTWPA

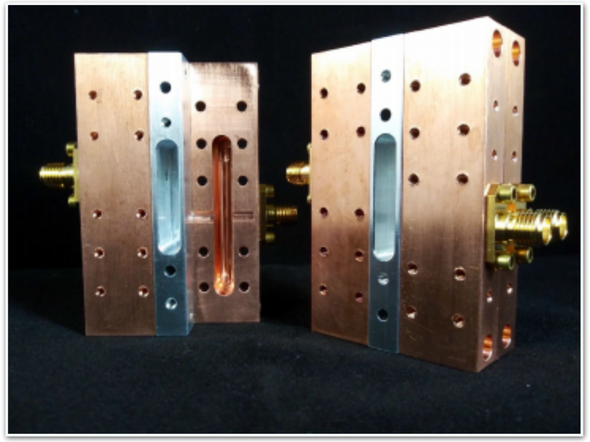
Enabling technologies: quantum protocols

- Quantum non-demolition photon counting
- Squeezing
- Backaction evasion
- Resolved sideband cooling
- Entangled states

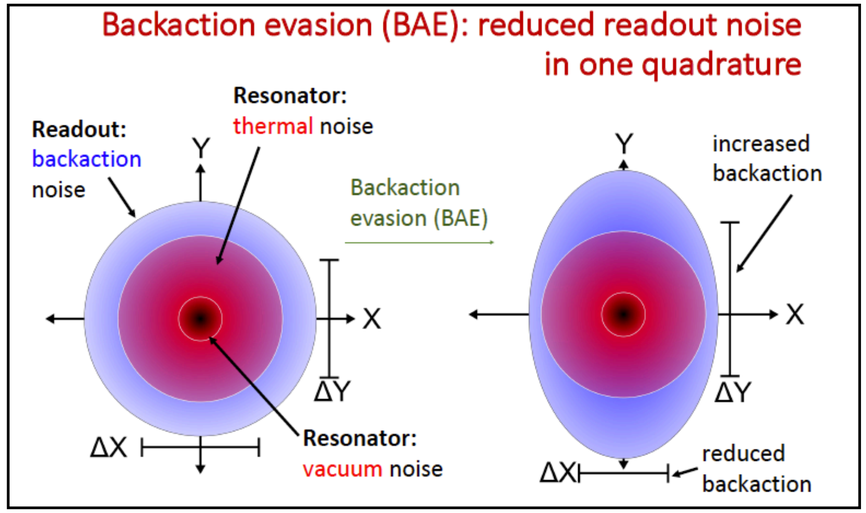
K. Irwin



HAYSTAC
Physics Today 72, 6, 48 (2019);



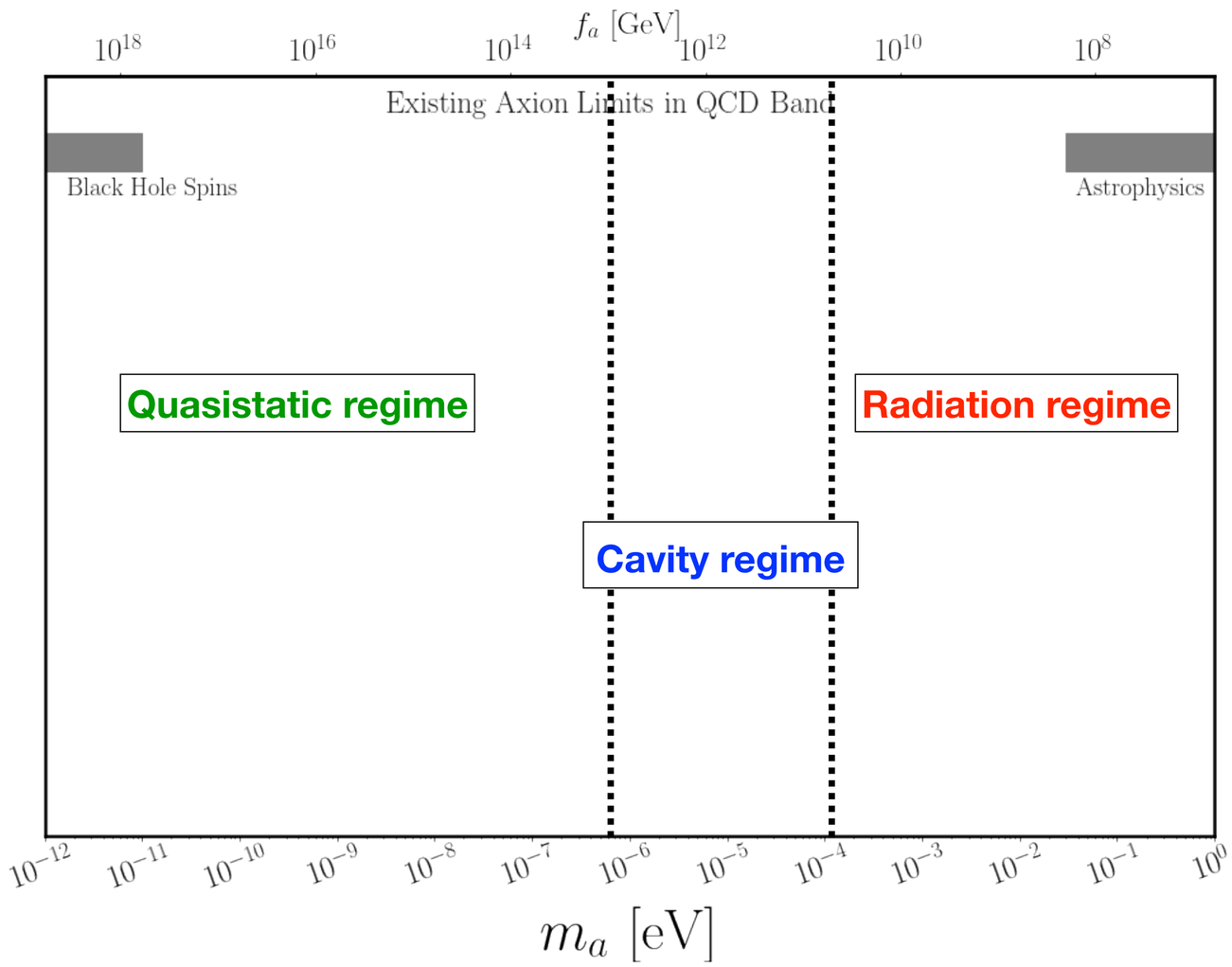
Hidden photon qubit search
Akash Dixit and Aaron Chou



Status: Previous Decade

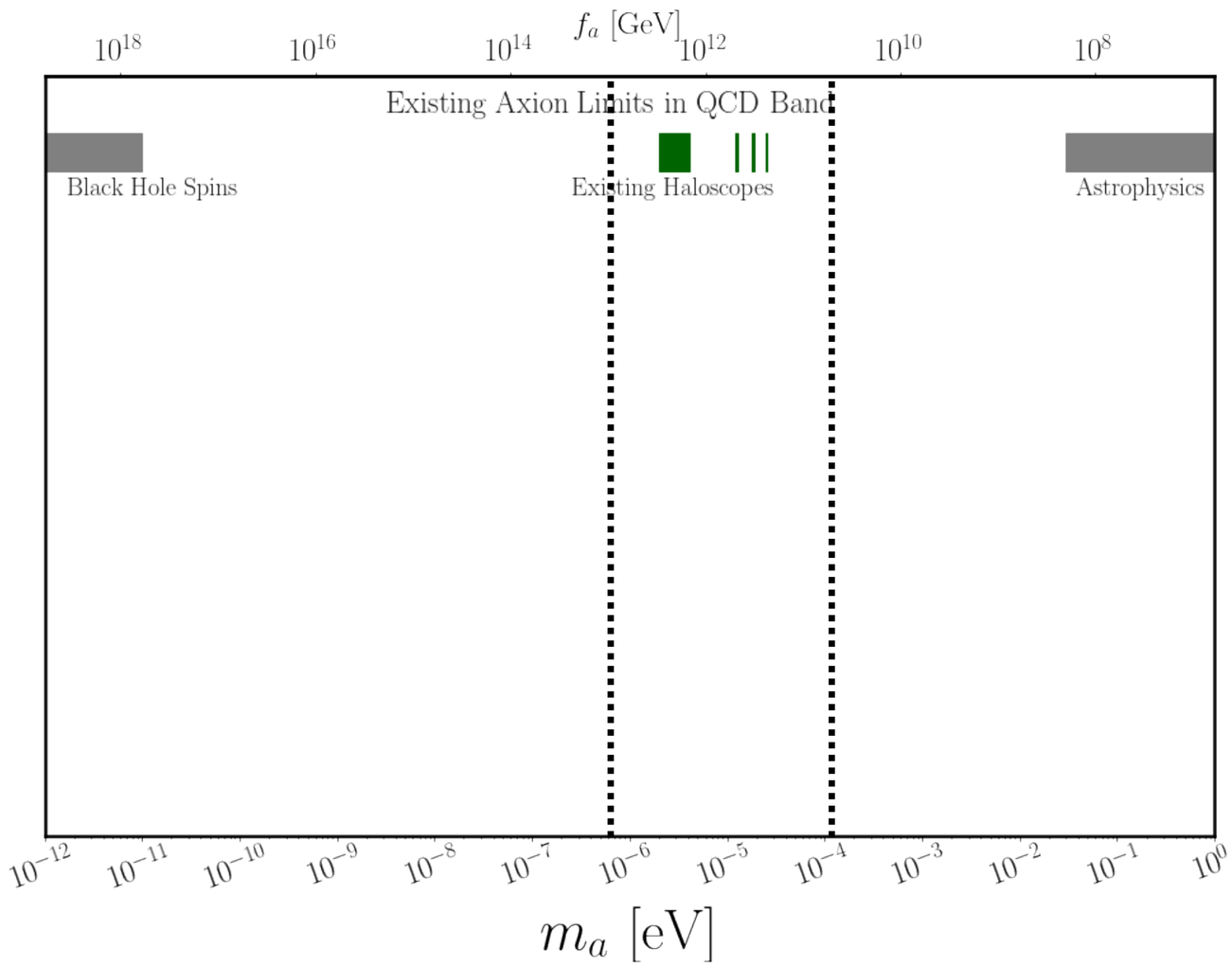
- No Experiments had probed the QCD band.

Note: Astrophysical probes provide key constraints at high and low masses.



Status: Current

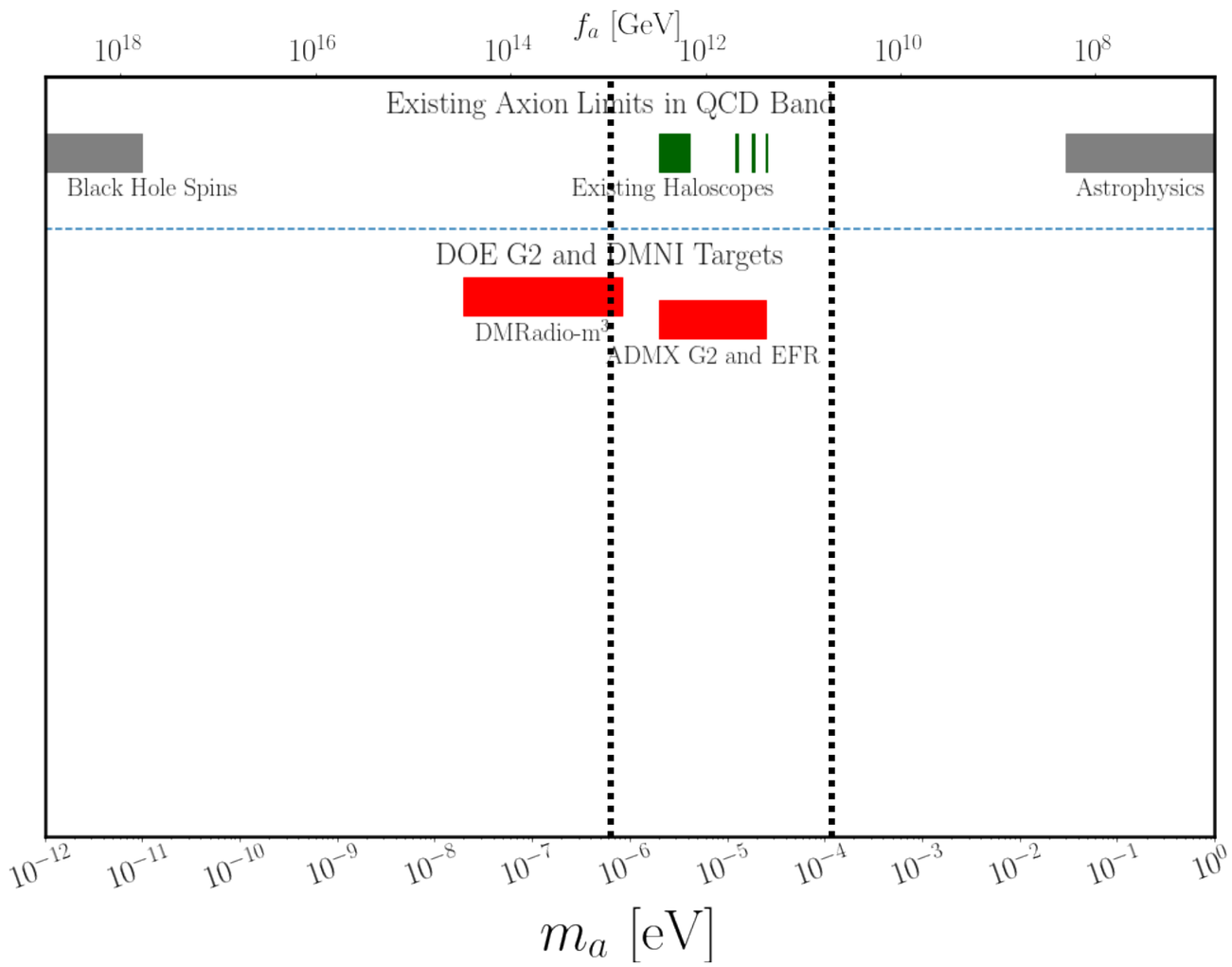
- ADMX G2 has reached DFSZ in some parameter space.
- HAYSTAC and CAPP are exploring the QCD band.



Dark Matter New Initiatives (DMNI)

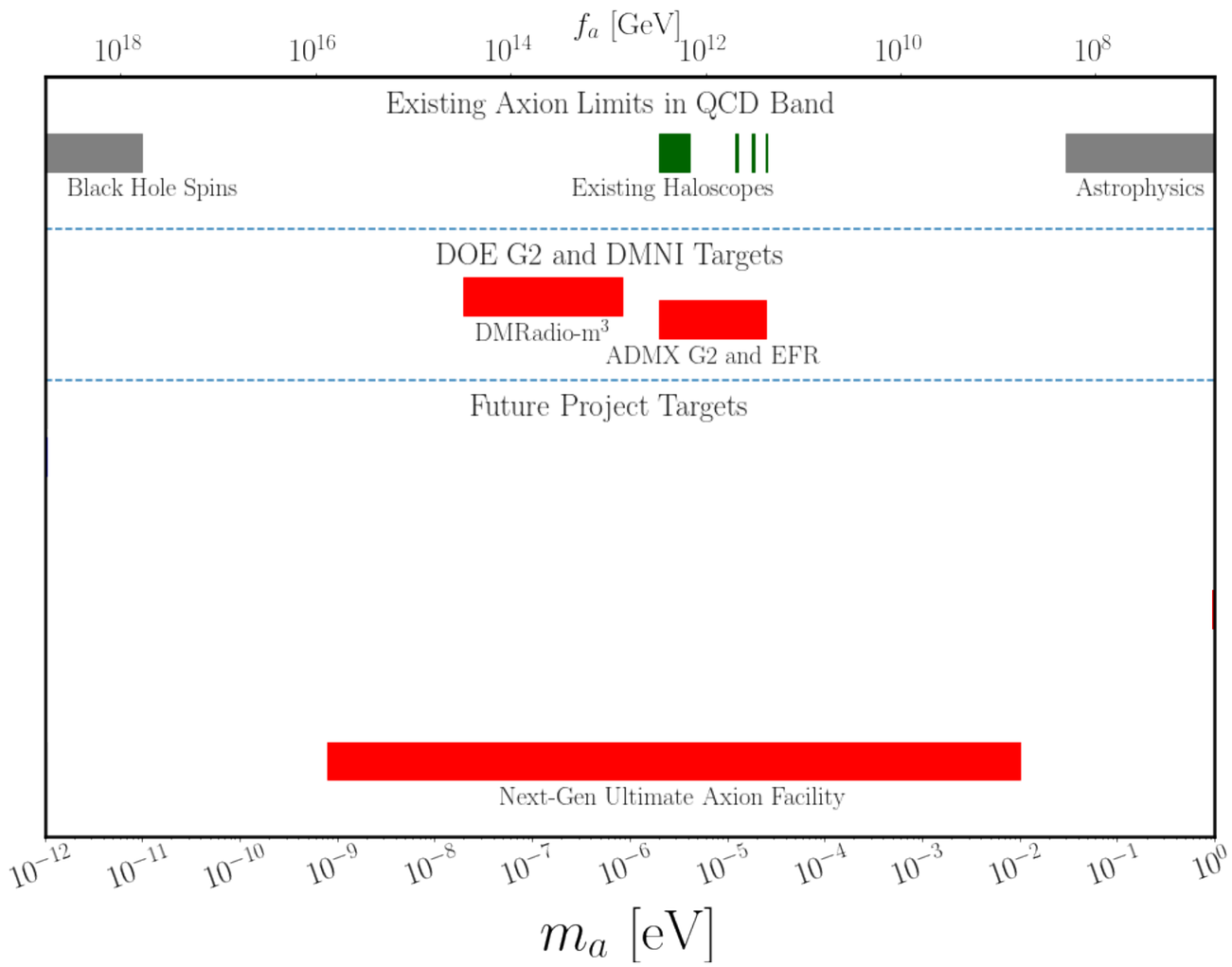
- The BRN for Dark Matter New Initiatives and subsequent call for proposals was very successful.

- DMRadio-m^3 and ADMX-EFR are preparing project execution plans and are poised to make significant inroads into the QCD axion parameter space.



The Ultimate Experiment

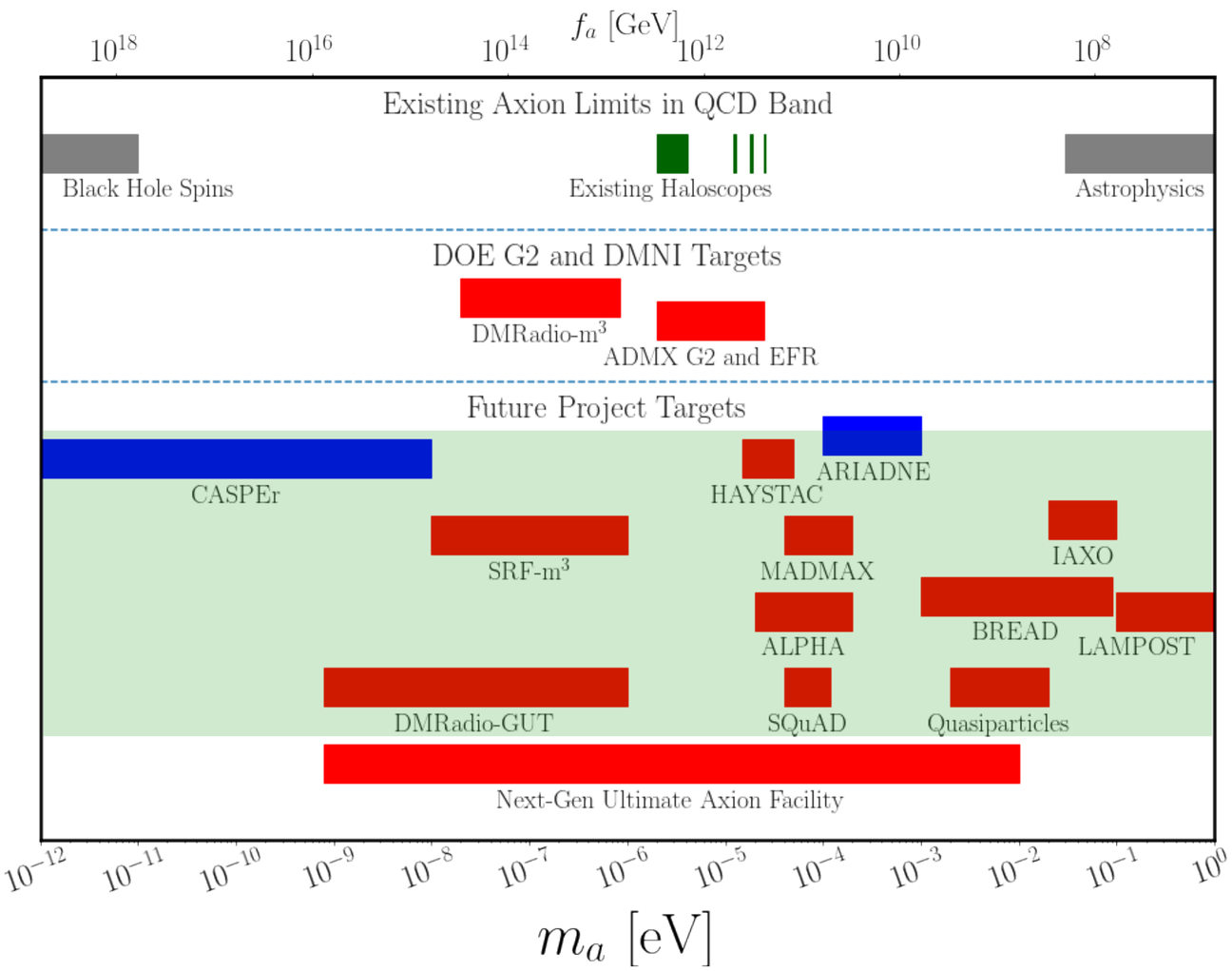
- Cryogenic infrastructure at 4K and Dilution refrigerator temperatures (10-100mK).
- Large High Field Magnets, likely making uses of high-temperature superconducting magnets developed for other applications including fusion.
- High Q Cavities.
- **Beyond the Standard Quantum Limit (BSQL) Enabled Readout**



Demonstrator and R&D Programs

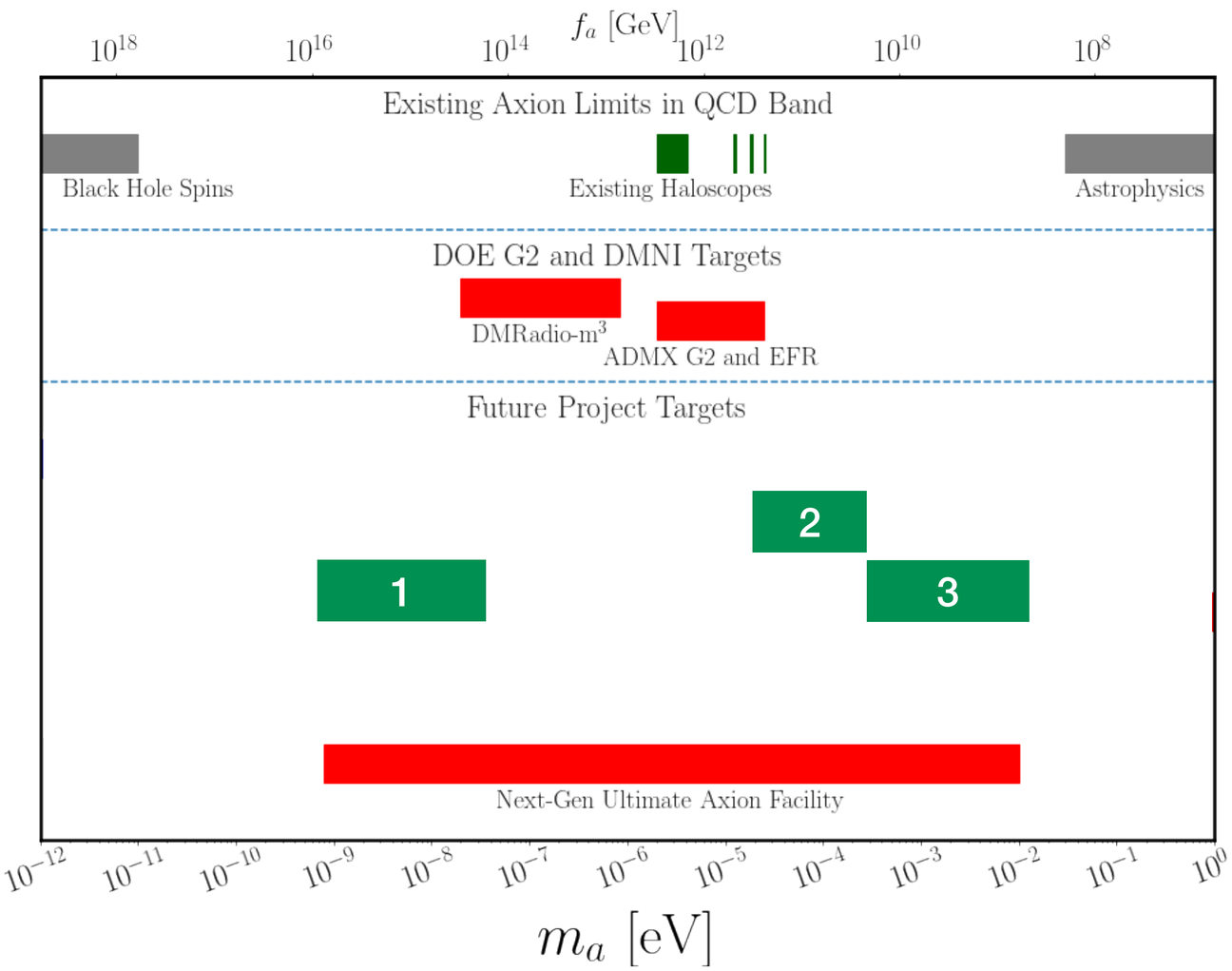
Many efforts focused on:

- Cavity geometry
- Beyond the Standard Quantum Limit (BSQL) Enabled Readout



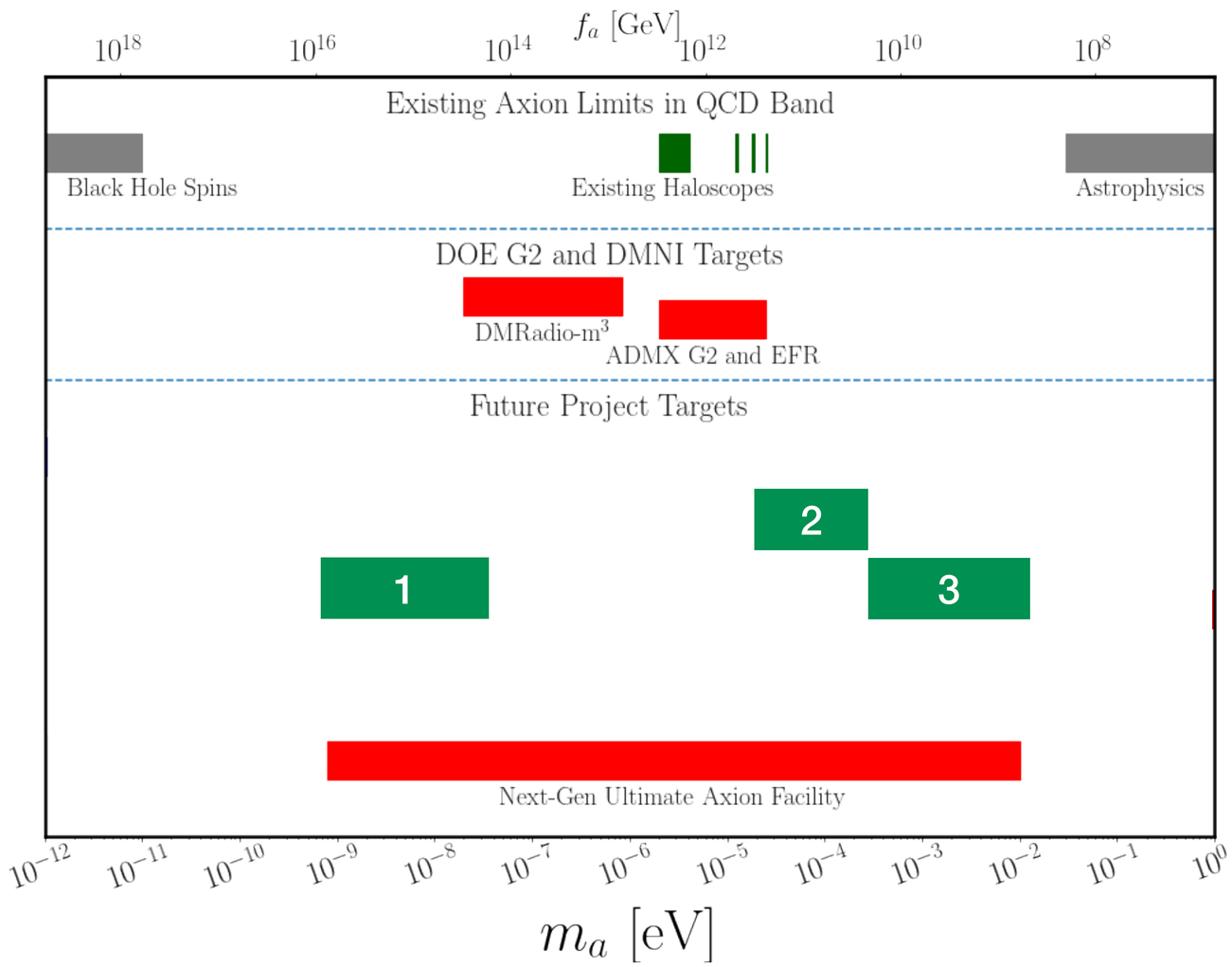
Summary:

- 2 Cosmologies
  - Pre-Inflation below 1μeV
  - Post-Inflation above 1μeV
- 3 Frequency Regimes
- 3 Noise Regimes



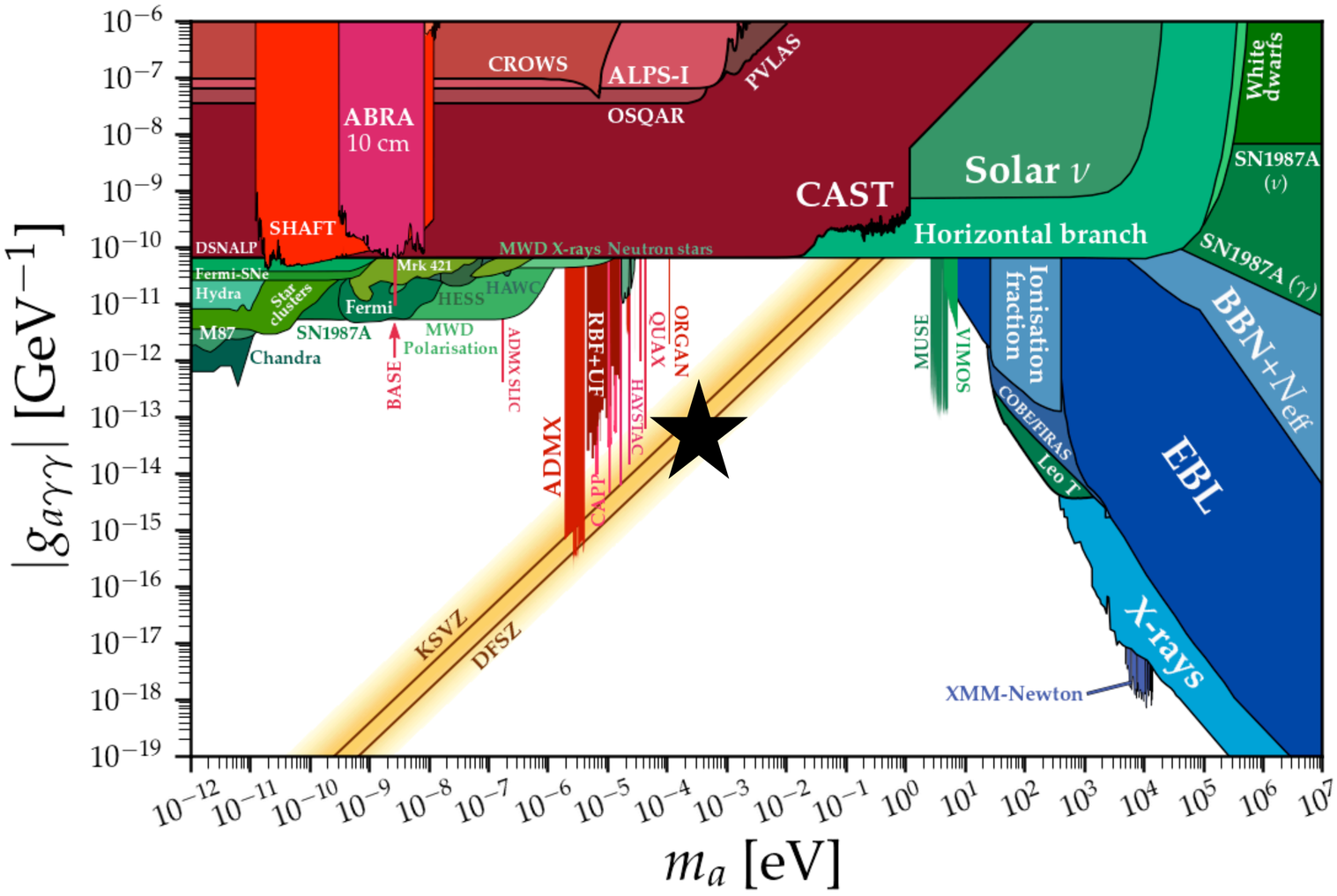
Summary:

***3** additional small/medium experiments to cover the full axion dark matter parameter space.*



Consequence of Discovery:

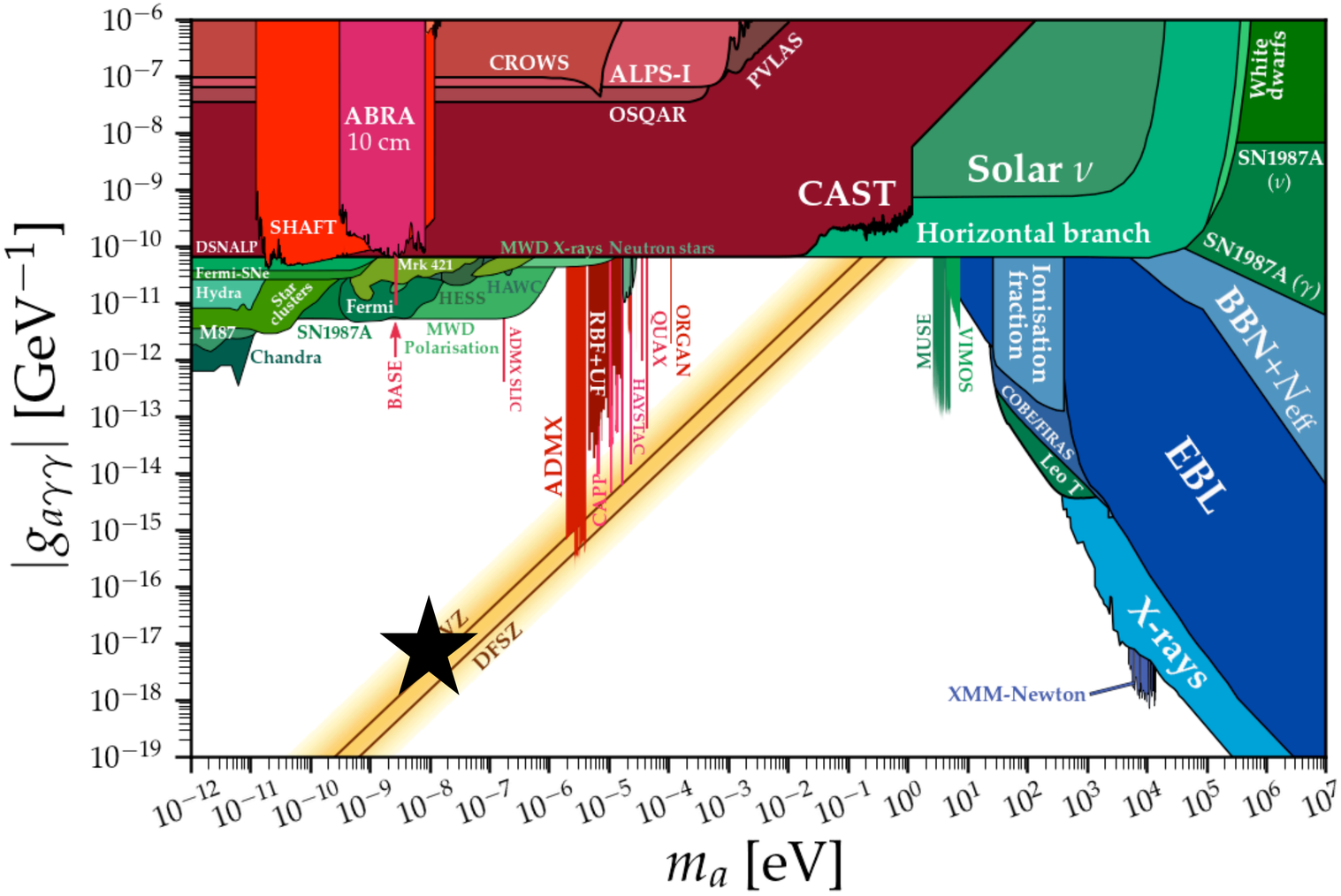
- This is a QCD axion that was created <u>after inflation</u>.
- Expanded Higgs sector or additional quarks.



https://cajohare.github.io/AxionLimits/docs/ap.html

Consequence of Discovery:

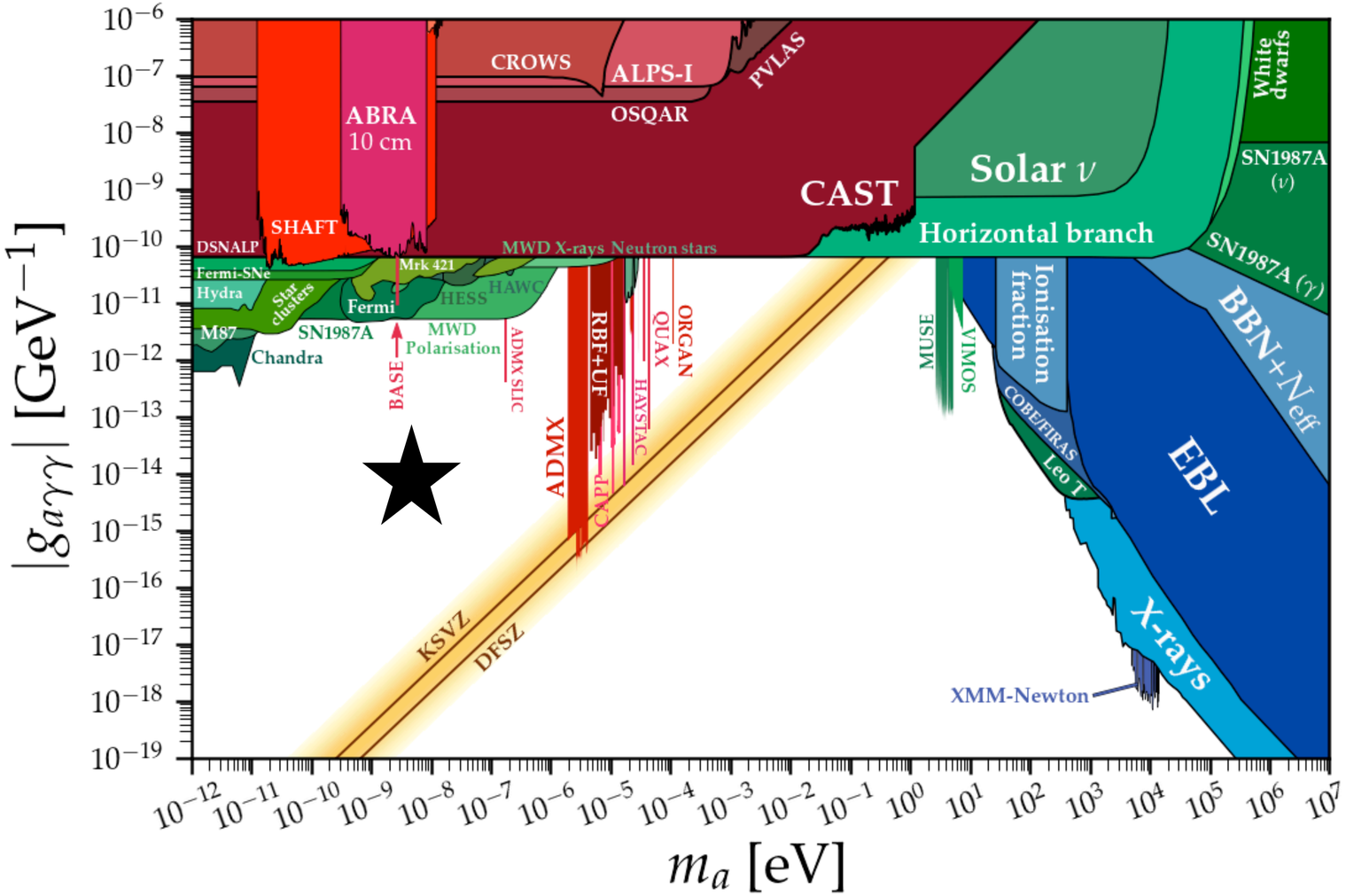
- This is a QCD axion that was created <u>before inflation</u>.
- GUT-scale axion clear proof of new physics at this scale.
- Expanded Higgs sector or additional quarks.
- Connected to CMB signatures.



https://cajohare.github.io/AxionLimits/docs/ap.html

Consequence of Discovery:

- This is an axion-like particle (ALP)
- Proof of higher order theory.
- Possible signatures in accelerator-based experiments.



https://cajohare.github.io/AxionLimits/docs/ap.html

Next steps…

$$L = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F_{mu\nu} + g_{aNN} (\partial_\mu) \bar{N} \gamma^\mu \gamma_5 N + g_{aie} (\partial_\mu) \bar{e} \gamma^\mu \gamma_5 e$$

Coupling to photons

Coupling to nucleon EDM

Causes electric dipole moments (EDMs) in nuclei/atoms/molecules

Coupling to axion nuclear moment

Creates spin-dependent energy shifts/spin precession in fermions

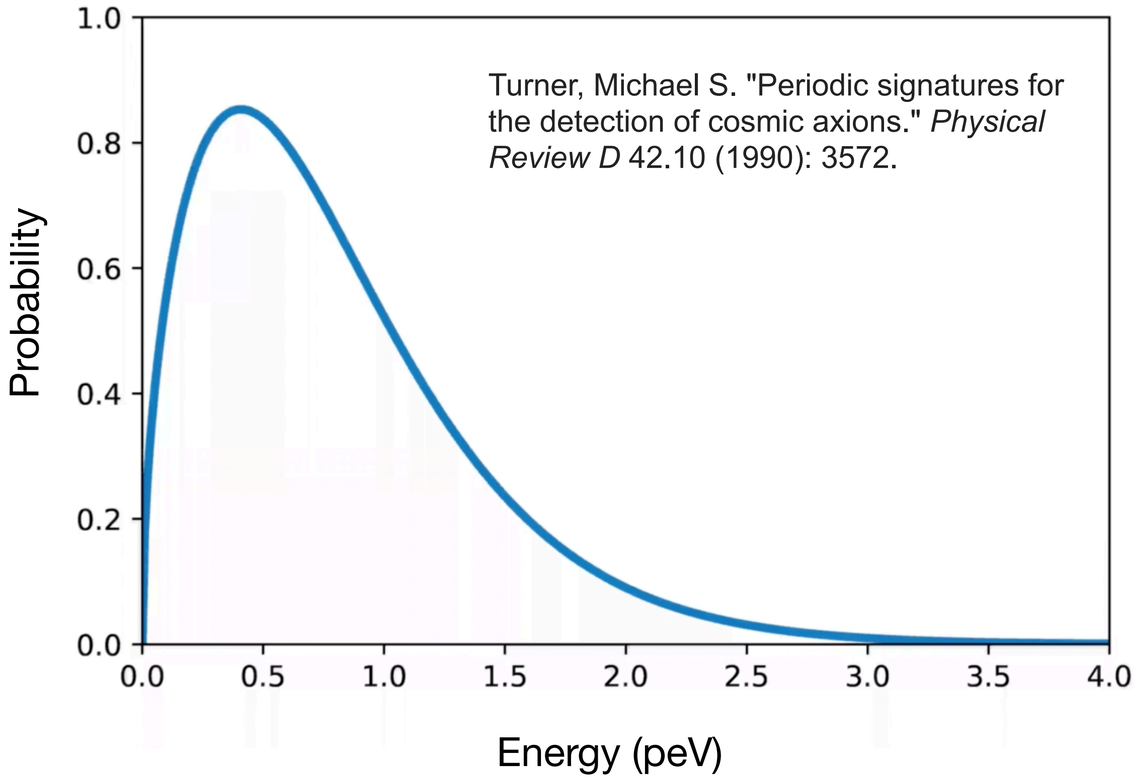
Coupling to axial electron moment

Axioelectric effect, Analogous to photoelectric effect

Adapted from L. Winslow DPF slide and Y. Kahn, See Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Studying the wave-like dark matter

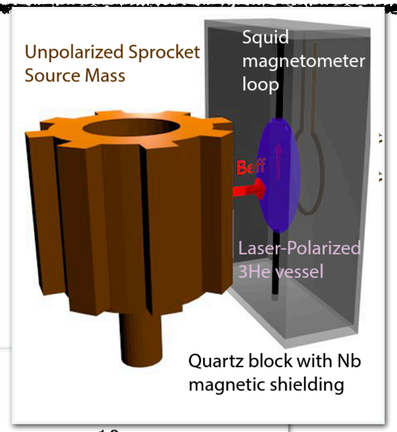
Dark Matter Halo velocity distribution and doppler shift

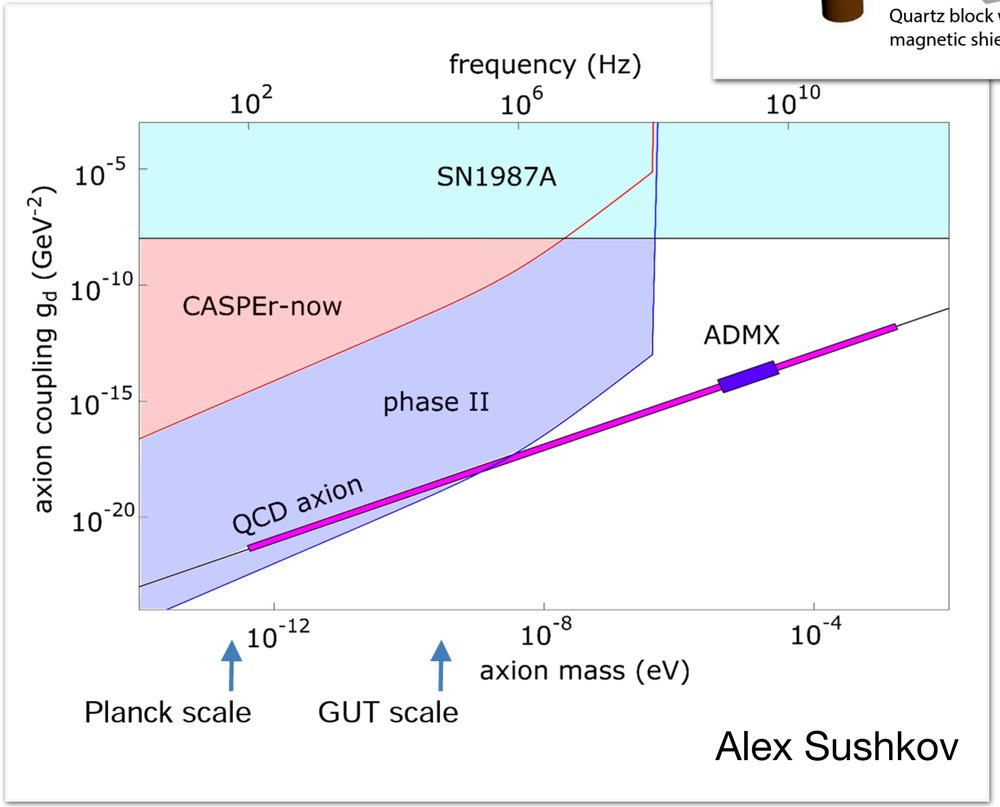


Turner, Michael S. "Periodic signatures for the detection of cosmic axions." *Physical Review D* 42.10 (1990): 3572.

Measure other axion couplings: CASPEr, ARIADNE, etc

Geraci, A. A., et al. "Progress on the ARIADNE axion experiment." *arXiv preprint arXiv:1710.05413* (2017).





Alex Sushkov

Photon channel: High-resolution studies of the axion signal

Use tools from AMO to measure other couplings →

What if we find wave-like dark matter?

Scalar:

- Connected to origin of Fundamental constants (masses, couplings)
- Possible connection to hierarchy problem (e.g. relaxion)
- Often Sensitivity to Planck suppressed couplings ➔ Probing gravity connection

Vector:

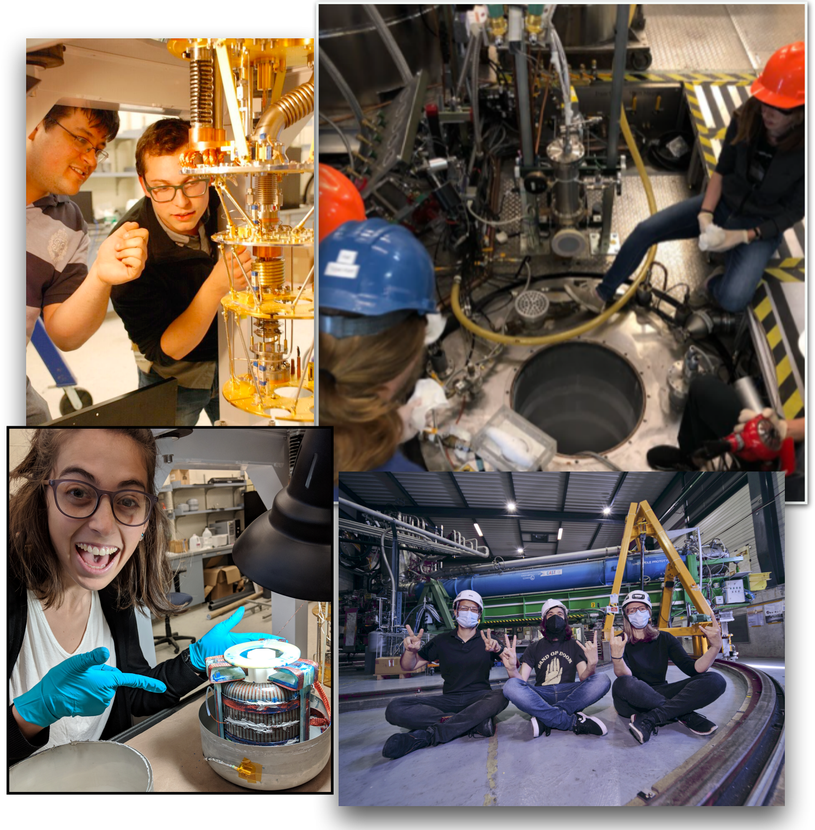
- New Fundamental gauge group
- May originate from earliest times, e.g. inflation

- Precision information: Experiments typically can precisely measure mass and other properties
- Astrophysical information: High prevision dark matter velocity (squared) distribution can be determined shortly after discovery ➔ insights into structure formation

Conclusions

…if you catch out drift…

- The parameter space for wave-like dark matter is largely unexplored.
- Definitive search for QCD axions is possible.
- Quantum devices are key to real progress.
- Real possibility of discovery around the corner!



Thank you!