Dark Matter Radio (DM Radio)

Kent Irwin for the DM Radio Collaboration

DM Radio Pathfinder

Particle-like and field-like dark matter

Heavy Particles

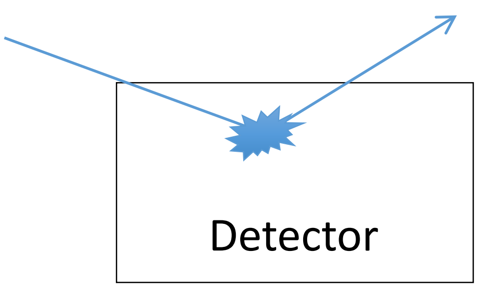
- Number density is small (small occupation)
- Tiny wavelength
- No detector-scale coherence

Light Fields

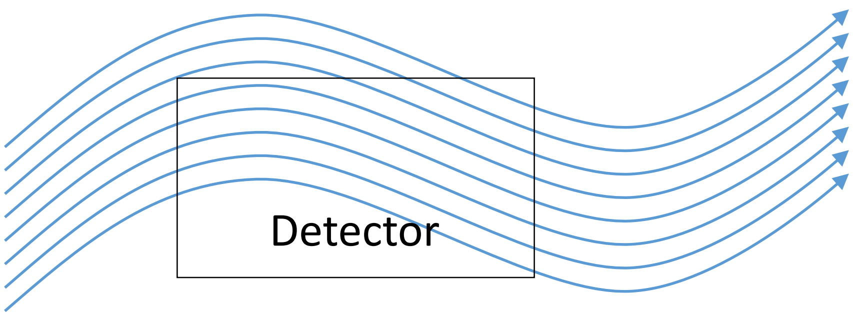
- Number density is large (must be bosons)
- Long wavelength
- Coherent within detector

$$\lambda_{\text{coherence}} \approx 100\,\text{km} \times (10^{-8}\text{eV}/m)$$

- Look for scattering of individual particles

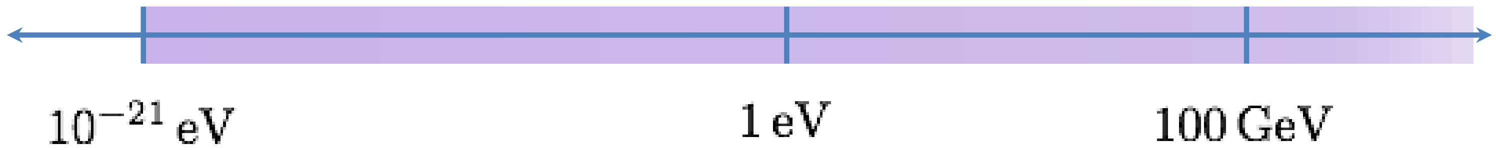


- Look for classical, oscillating background field



The light-field dark matter zoo

DM mass:



Light (field) DM
- Spin-0 scalar
- Spin-1 vector
- Higher spin (tensor) disfavored

Heavy (particle) DM
- WIMPs
- Etc. etc.

Light-field dark matter is a boson

1. Scalar field (spin-0)
2. Pseudoscalar (spin-0, but changes sign under parity inversion) “axion”
3. Vector (spin-1): “hidden photon”
4. Pseudovector (spin-1, but changes sign on parity inversion)

About those priors…

- Naturalness

  Thermal production of ~100 GeV particles (WIMPs) at the electroweak energy scale produces ~ observed abundances of dark matter.

  ➡ "**WIMP miracle**."

- Occam's Razor

  ➡ Supersymmetry suggests particles with WIMP-like properties.

  ➡ Axion: solves strong CP problem in QCD.

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P. Graham *et al*., "Vector Dark Matter from Inflationary Fluctuations," arxiv:1504.02102

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- Occam's Razor

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But the universe doesn't seem so "natural"… and Occam so rarely seems to apply in normal life.

Possible dark matter candidate: axion (spin 0)

- Strong CP Problem

$$\mathcal{L} \sim \frac{g_s^2}{32\pi^2}\theta_{\rm QCD} G\tilde{G}$$

Neutron Electric Dipole Moment

$$\theta_{\rm QCD} < 10^{-10}$$

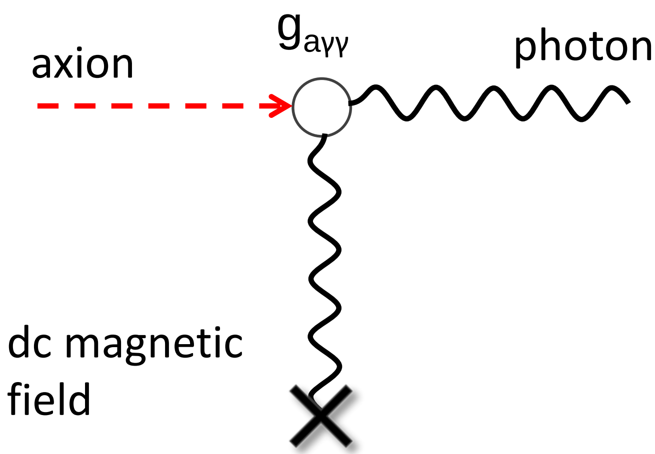
Why is it so small?

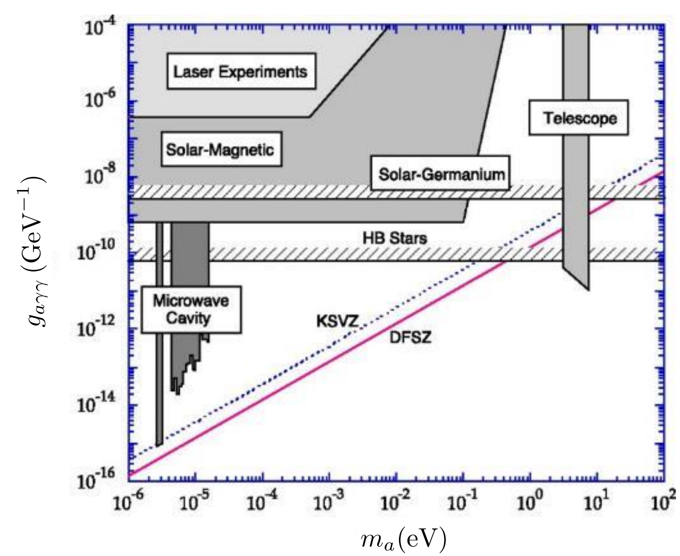
Solution: $\theta_{\rm QCD}$ is a dynamical field

(Peccei-Quinn solution, the axion)

- Spin-0 boson

- Can be detected via inverse Primakoff effect



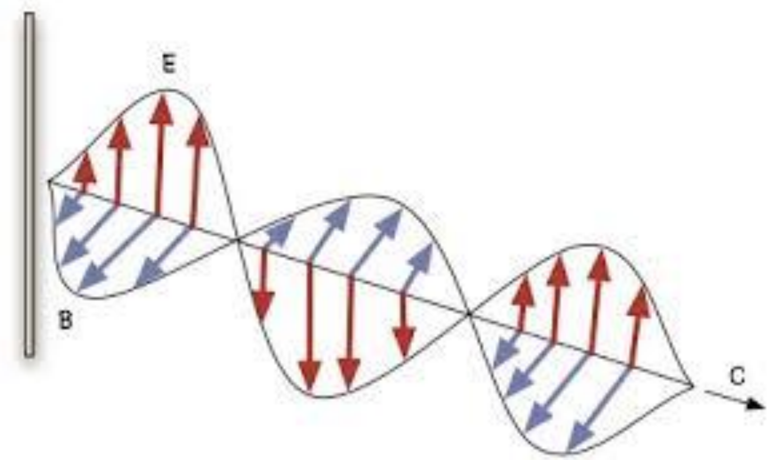


Leslie J Rosenberg PNAS 2015;112:12278-12281

“Hidden” photon: generic vector boson (spin 1)

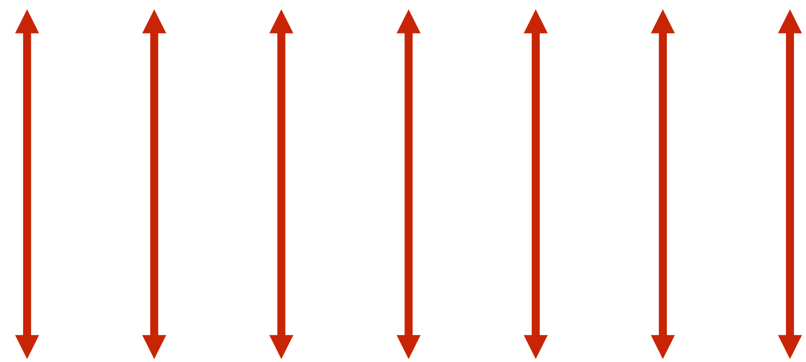
- A new photon, but with a mass, and weak coupling
- Couples to ordinary electromagnetism via kinetic mixing

$$\mathcal{L} \sim -2\varepsilon F^{\mu\nu} F'_{\mu\nu}$$



CMB photon

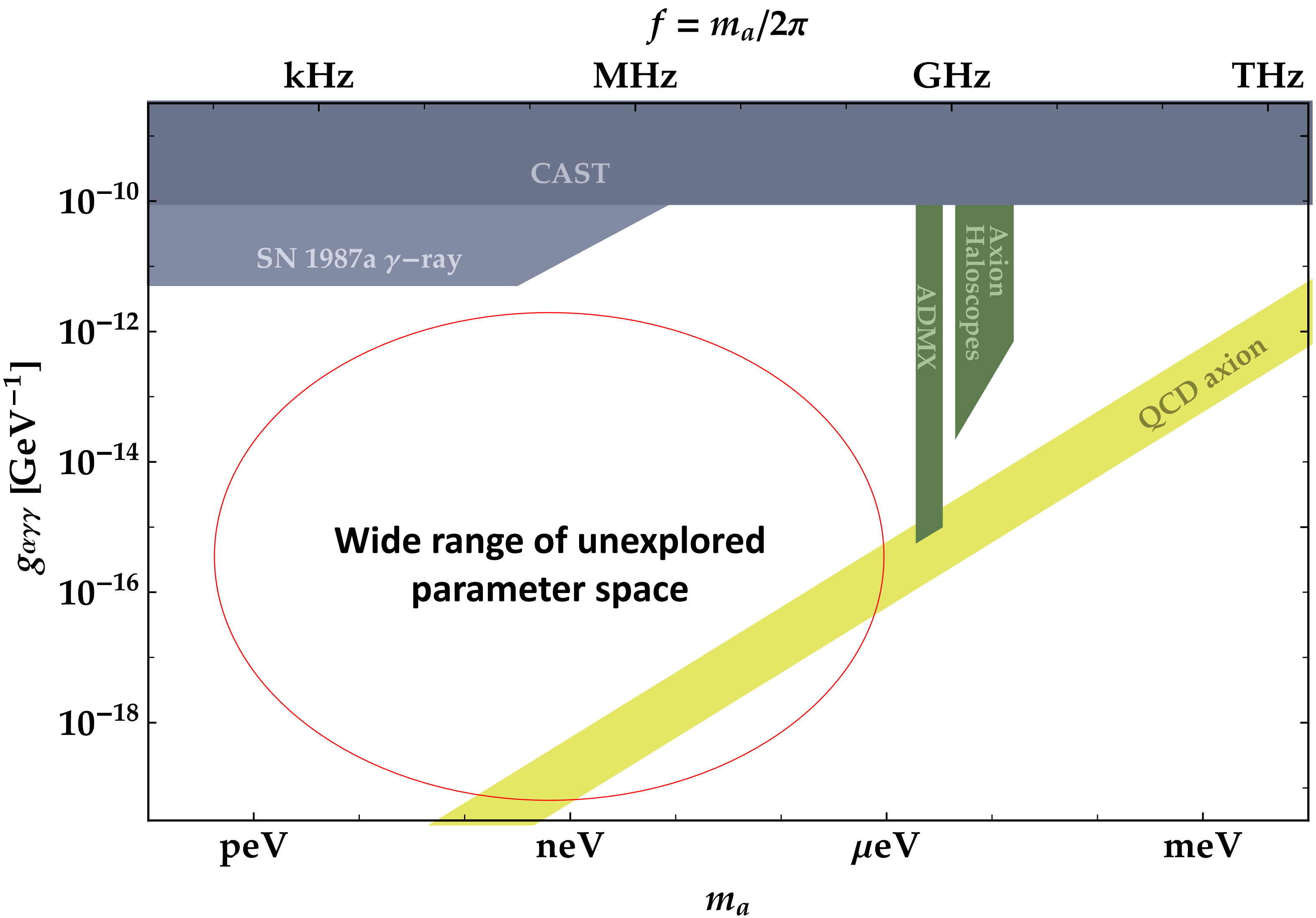
(oscillating E’ field)



Hidden Photon DM

Hidden photon DM drives EM currents

Axions: plenty of room at the bottom



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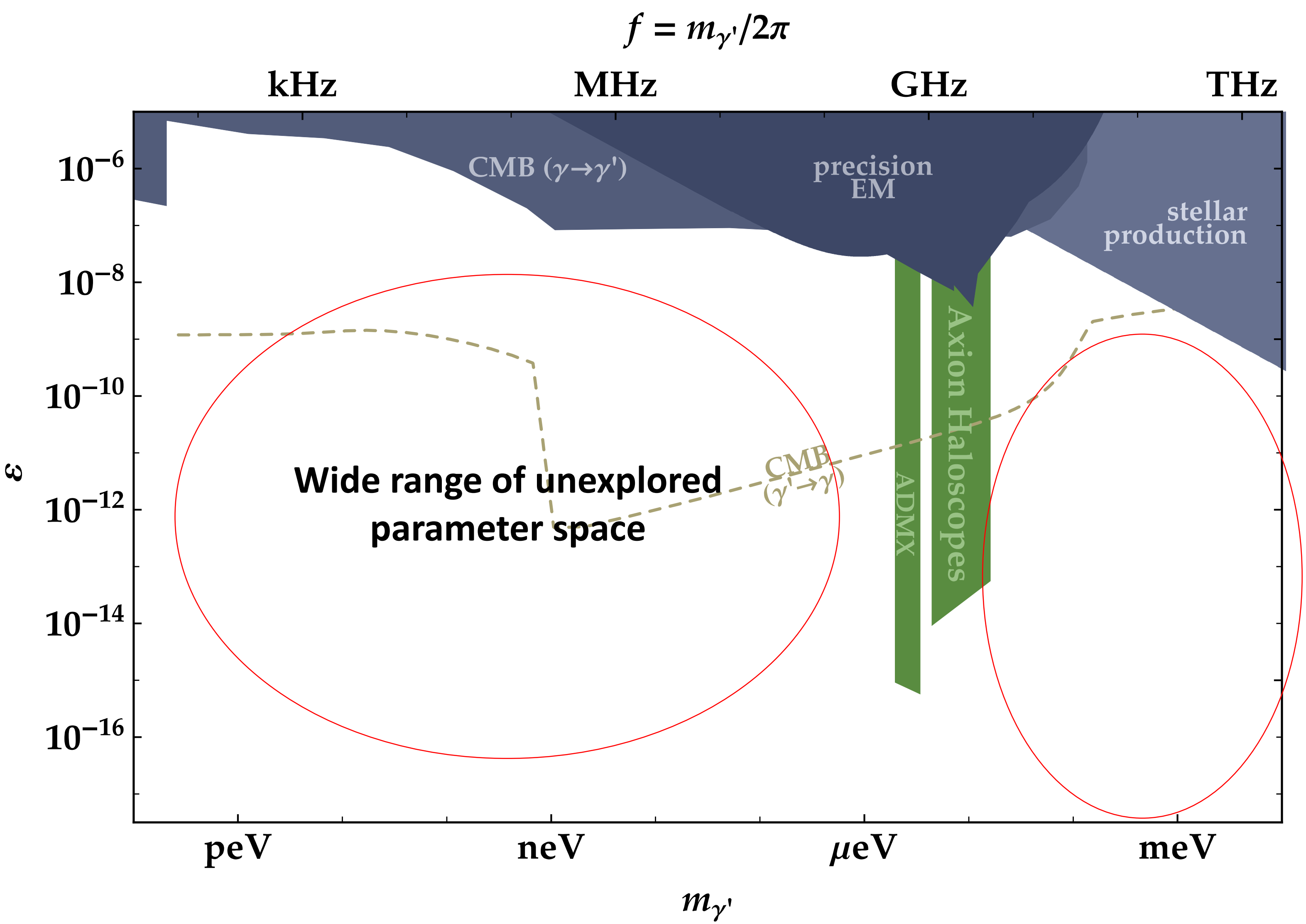
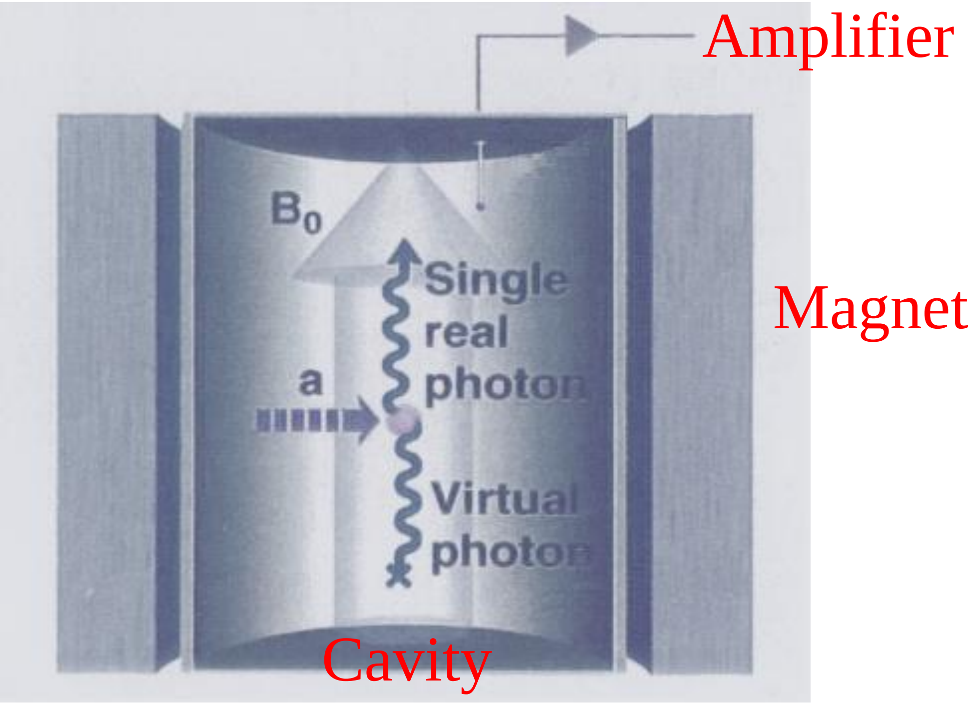


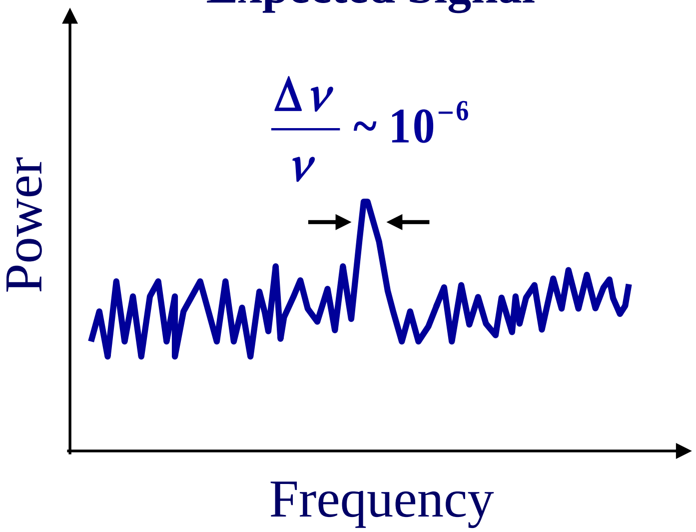
Resonant conversion of axions into photons

Pierre Sikivie (1983)

Primakoff Conversion



Expected Signal



ADMX experiment

Thanks to John Clarke

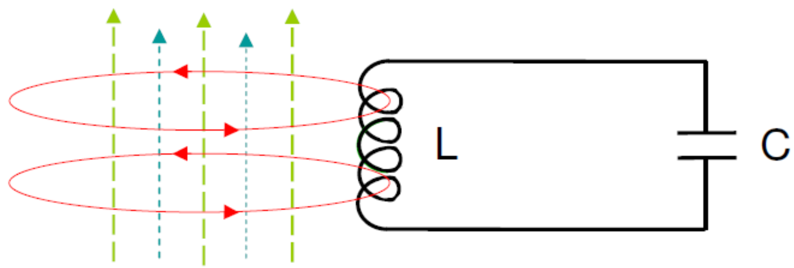
Detecting String-Scale QCD Axion Dark Matter


Blas Cabrera
Scott Thomas

Workshop Axions 2010, U. Florida, 2010

Dark Matter Axion Detection – Large f_a/N :

- Resonant LC Circuit



$$\omega_0^2 = 1 / LC$$

$$\gamma = R/L = \omega_0/Q$$

B $j(\omega)$ $B(\omega)$

$$\left(-\omega^2 L - i\omega R + \frac{1}{C}\right) q = \mathcal{E}$$

$$I = \frac{i\omega\mathcal{E}/L}{\omega_0^2 - \omega^2 - i\gamma\omega}$$

On Resonance
$$U = \frac{1}{2}L|I|^2 = \frac{1}{2}Q^2\frac{M^2}{L}|I_a|^2$$

Also: Sikivie, P., N. Sullivan, and D. B. Tanner. "*Physical review letters* 112.13 (2014): 131301.

Also useful for hidden photons:
Arias et al., arxiv:1411.4986
Chaudhuri et al., arxiv: 1411.7382v2

Workshop Axions 2010, U. Florida, 2010

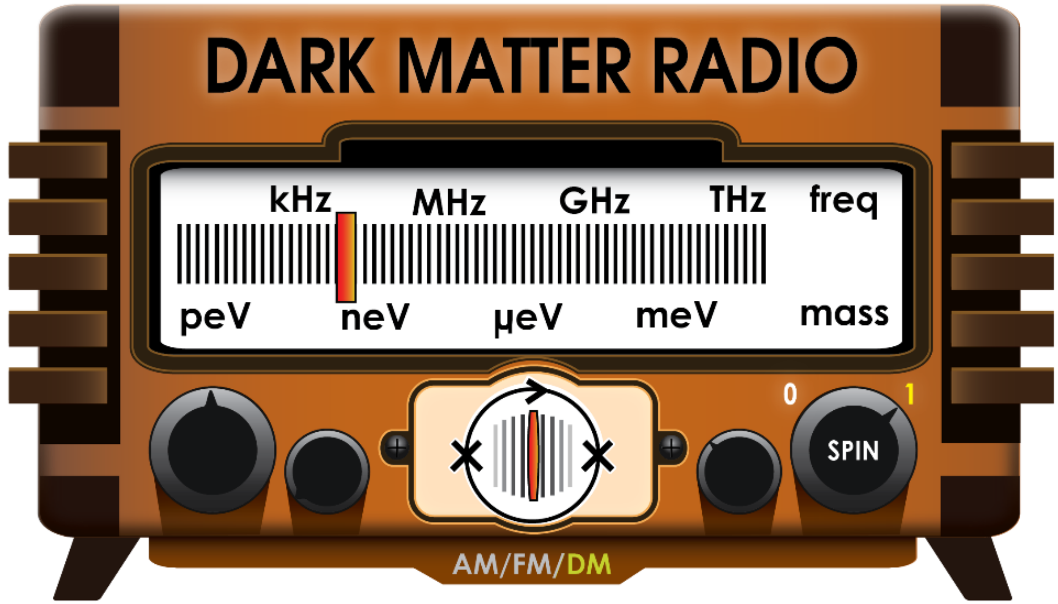
SLAC

KIPAC

Cal

UC DAVIS
UNIVERSITY OF CALIFORNIA

PRINCETON UNIVERSITY



DM Radio DJs

Stanford: Arran Phipps, Dale Li, Saptarshi Chaudhuri, Peter Graham, Jeremy Mardon, Hsiao-Mei Cho, Stephen Kuenstner, Harvey Moseley, Richard Mule, Max Silva-Feaver, Zach Steffen, Betty Young, Sarah Church, Kent Irwin

Berkeley: Surjeet Rajendran

Collaborators on DM Radio extensions:

Tony Tyson, UC Davis

Lyman Page, Princeton

	Distance	Coherence E	Coherence f
SLAC	0 km		
Stanford / KIPAC	3 km	300 neV	70 MHz
Cal	40 km	20 neV	5 MHz
UC DAVIS UNIVERSITY OF CALIFORNIA	120 km	7 neV	2 MHz
PRINCETON UNIVERSITY	5,000 km	0.2 neV	40 kHz

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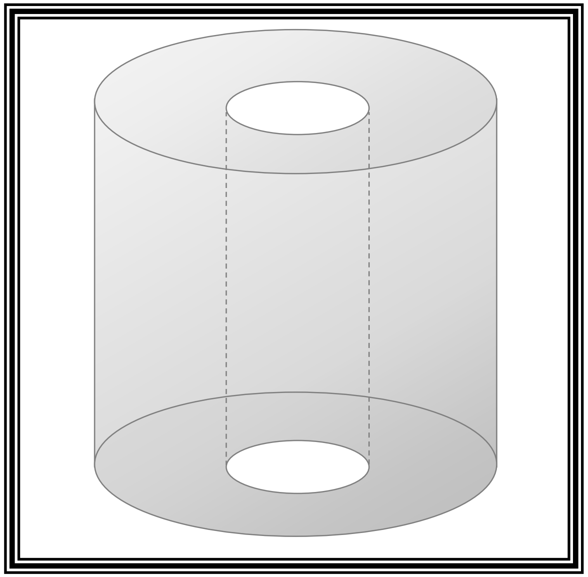
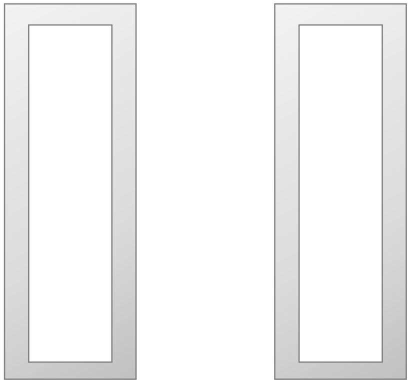
Block EMI background with a superconducting shield

Superconducting shield



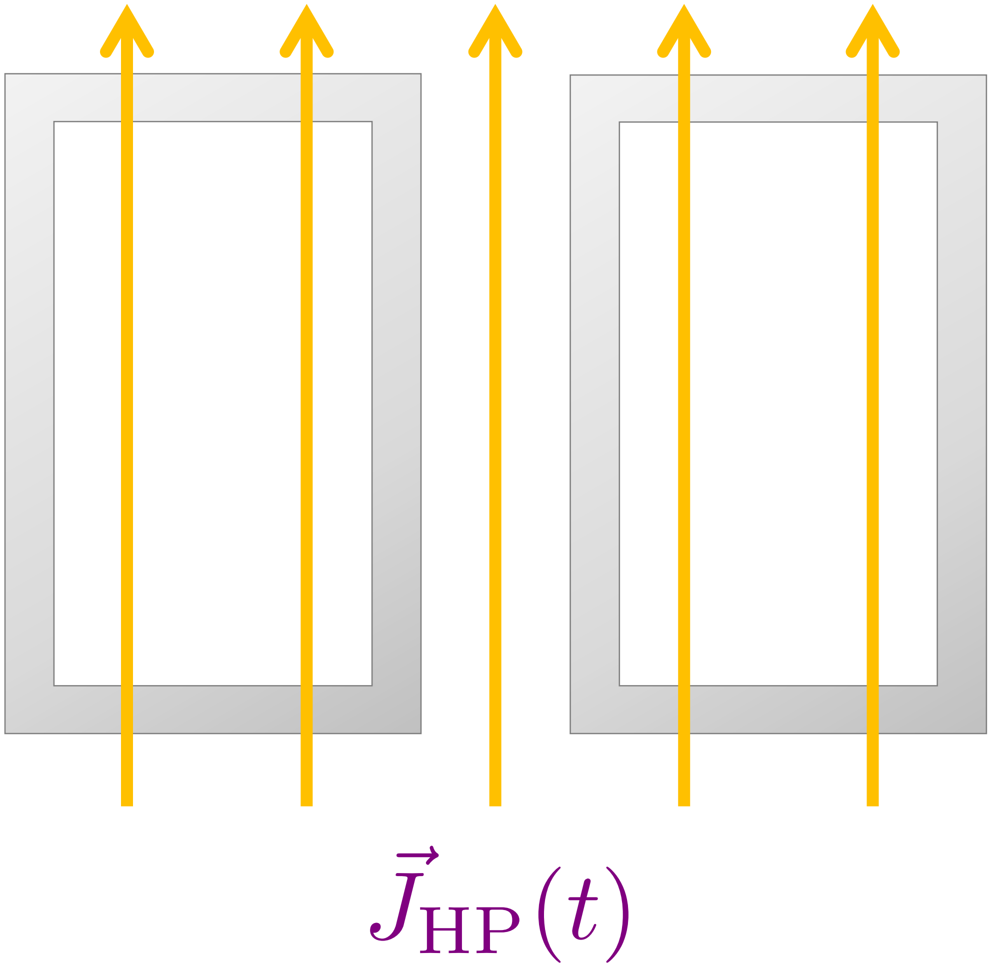
Cross-section



- In the subwavelength limit of DM Radio, you can approximate the signal from axions and hidden photons as an effective stiff ac current filling all space, with frequency $f = mc^2/h$ (the "interaction basis")
- To detect this signal, we need to block out ordinary photons with a superconducting shield

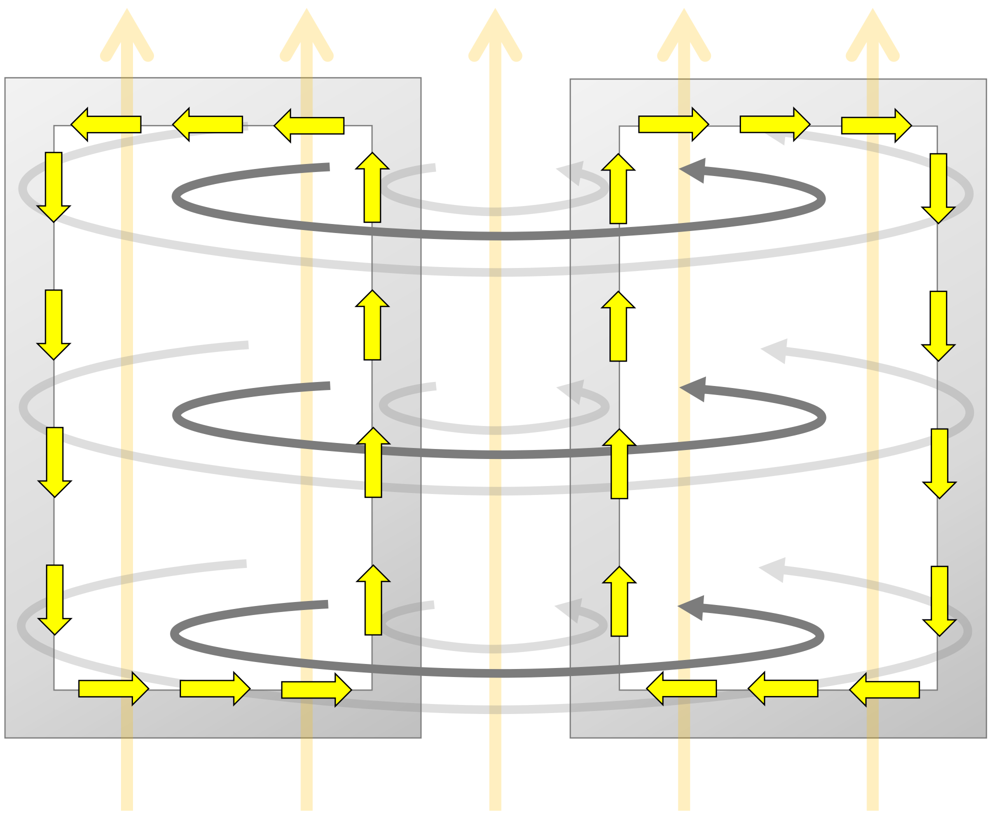
Hollow, superconducting sheath (like a hollow donut)

How to measure effective hidden photon current



- Hidden photon effective ac current penetrates superconductors

How to measure effective hidden photon current

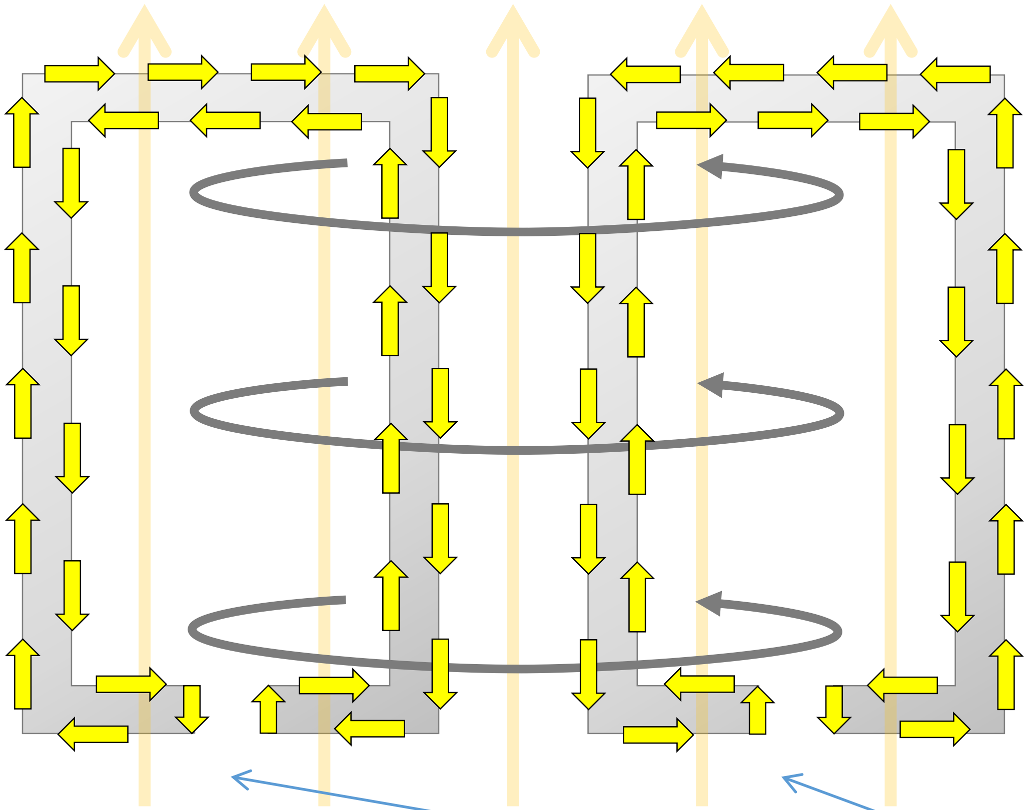


$$\vec{B}_{\mathrm{HP}}(t) = |\vec{B}_{\mathrm{HP}}(t)|\,\hat{\phi}$$

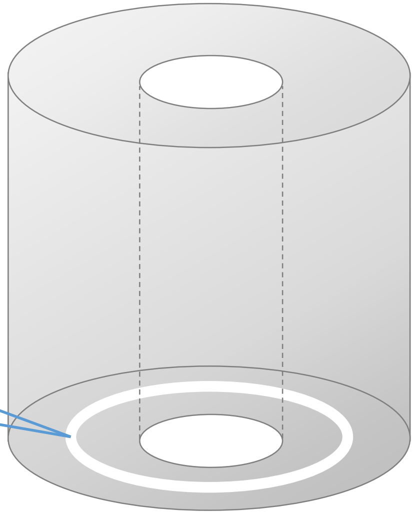
Meissner Effect

- Hidden photon effective ac current penetrates superconductors
- Generates a REAL circumferential, quasi-static B-field
- Screening currents on superconductor surface flow to cancel field in bulk

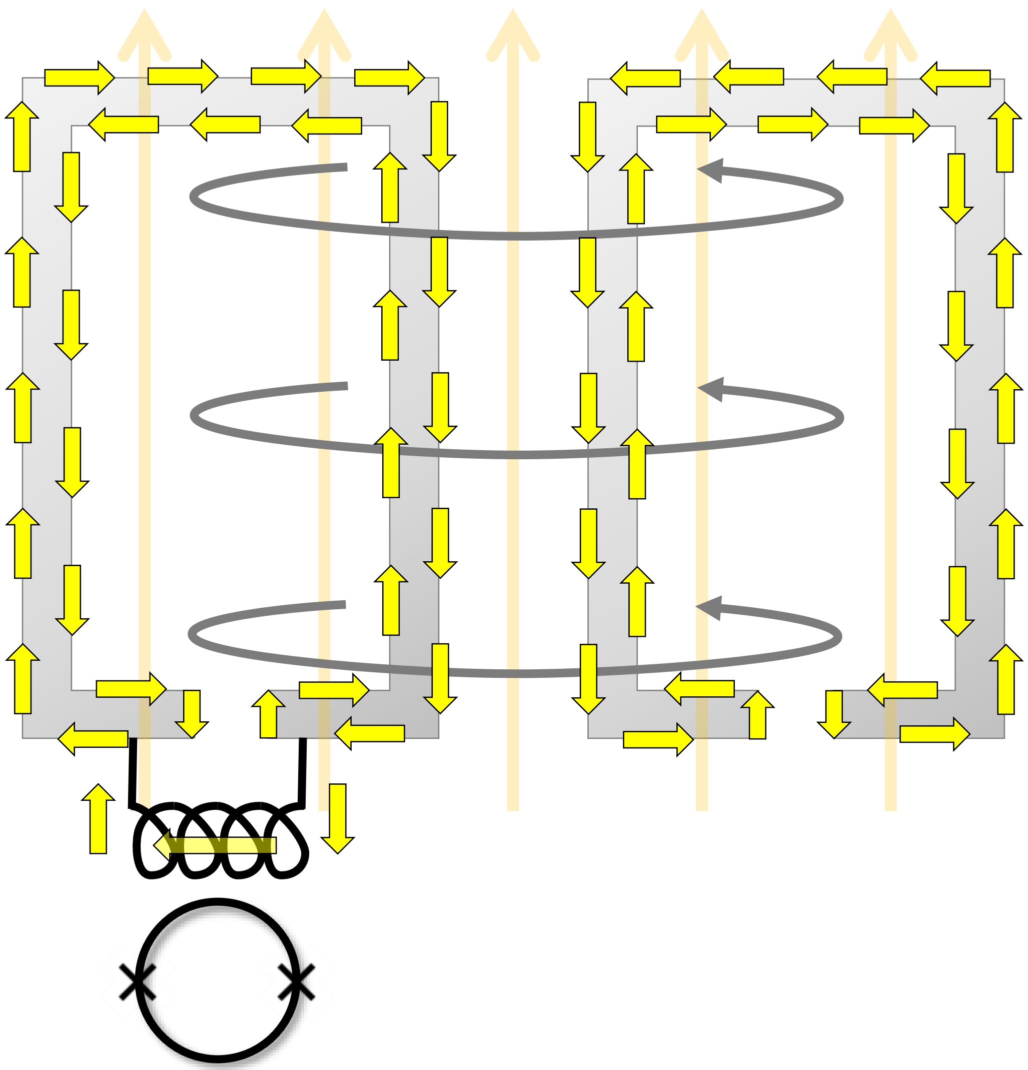
How to measure effective hidden photon current



- Cut concentric slit at bottom of cylinder
- Screening currents return on outer surface



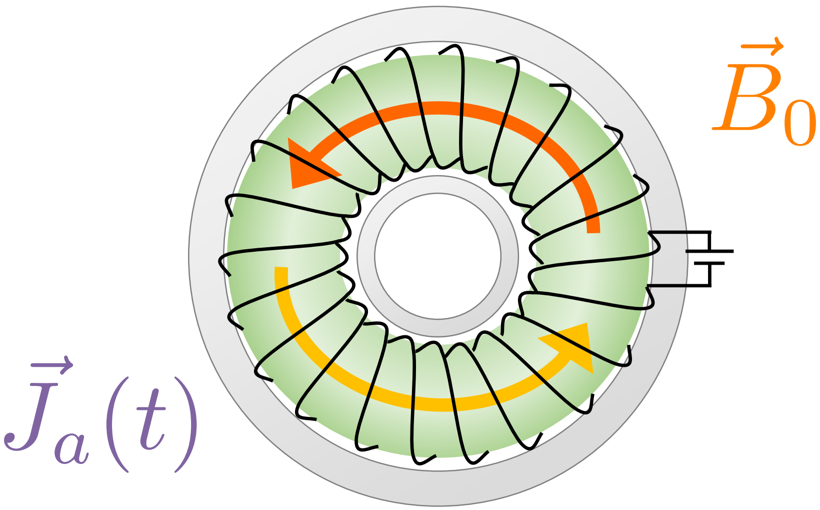
How to measure effective hidden photon current



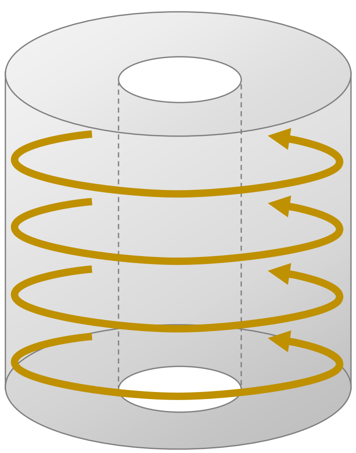
- Cut concentric slit at bottom of cylinder
- Screening currents return on outer surface
- Add an inductive loop to couple some of the screening current to SQUID

How to measure effective axion current

Top-Down Cross-section



(B_0 toroid *inside* cylinder)

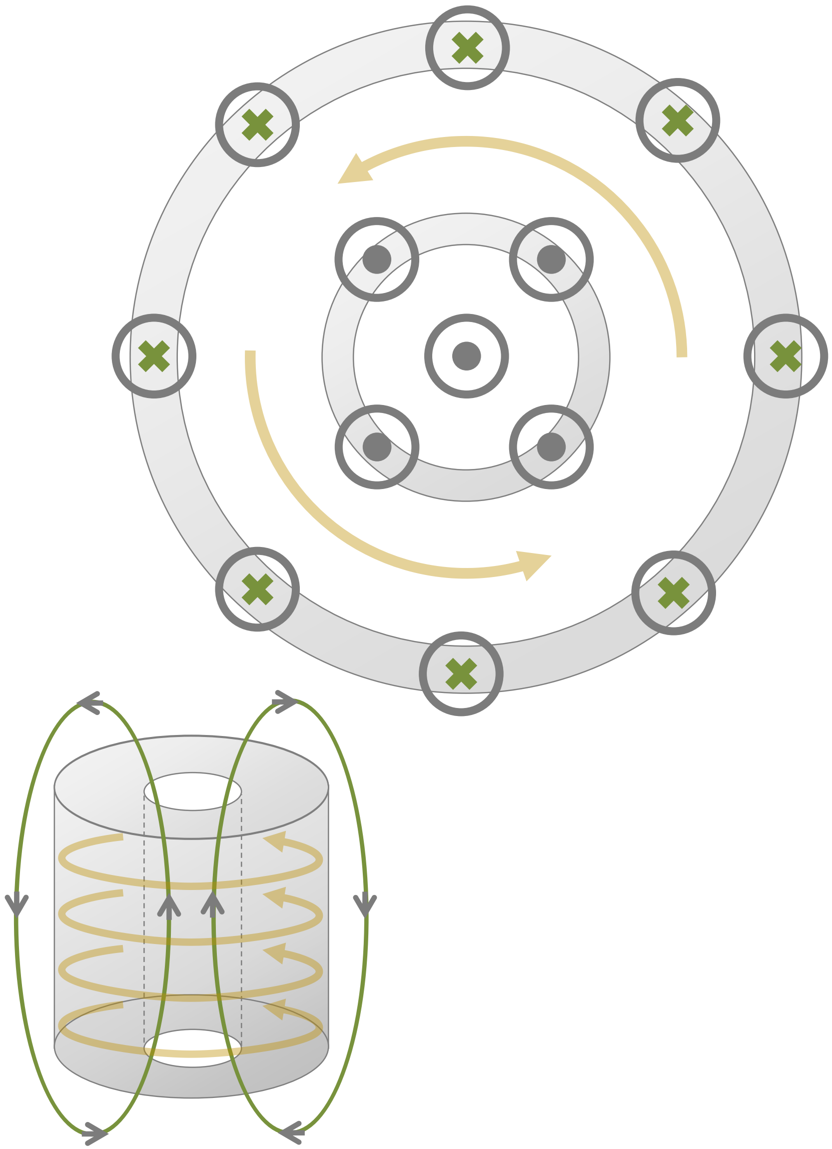


- Toroidal coil produces DC magnetic field inside superconducting cylinder

- Axions interact with DC field, generates effective AC current along direction of applied field

$$\vec{J}_a = |\vec{J}_a|\,\hat{\phi}$$

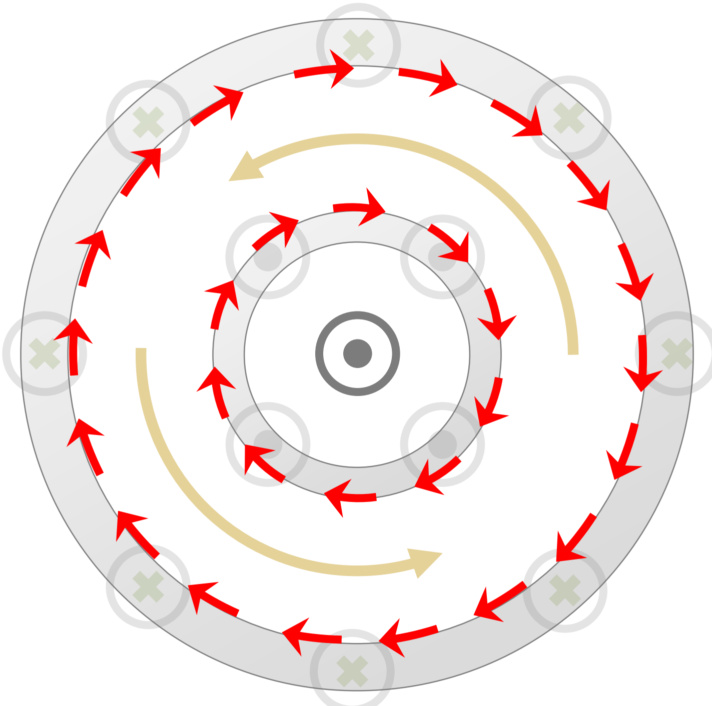
How to measure effective axion current



- Toroidal coil produces DC magnetic field inside superconducting cylinder
- Axions interact with DC field, generates effective AC current along direction of applied field
- Produces REAL quasi-static AC magnetic field

$$\vec{B}_a(t)$$

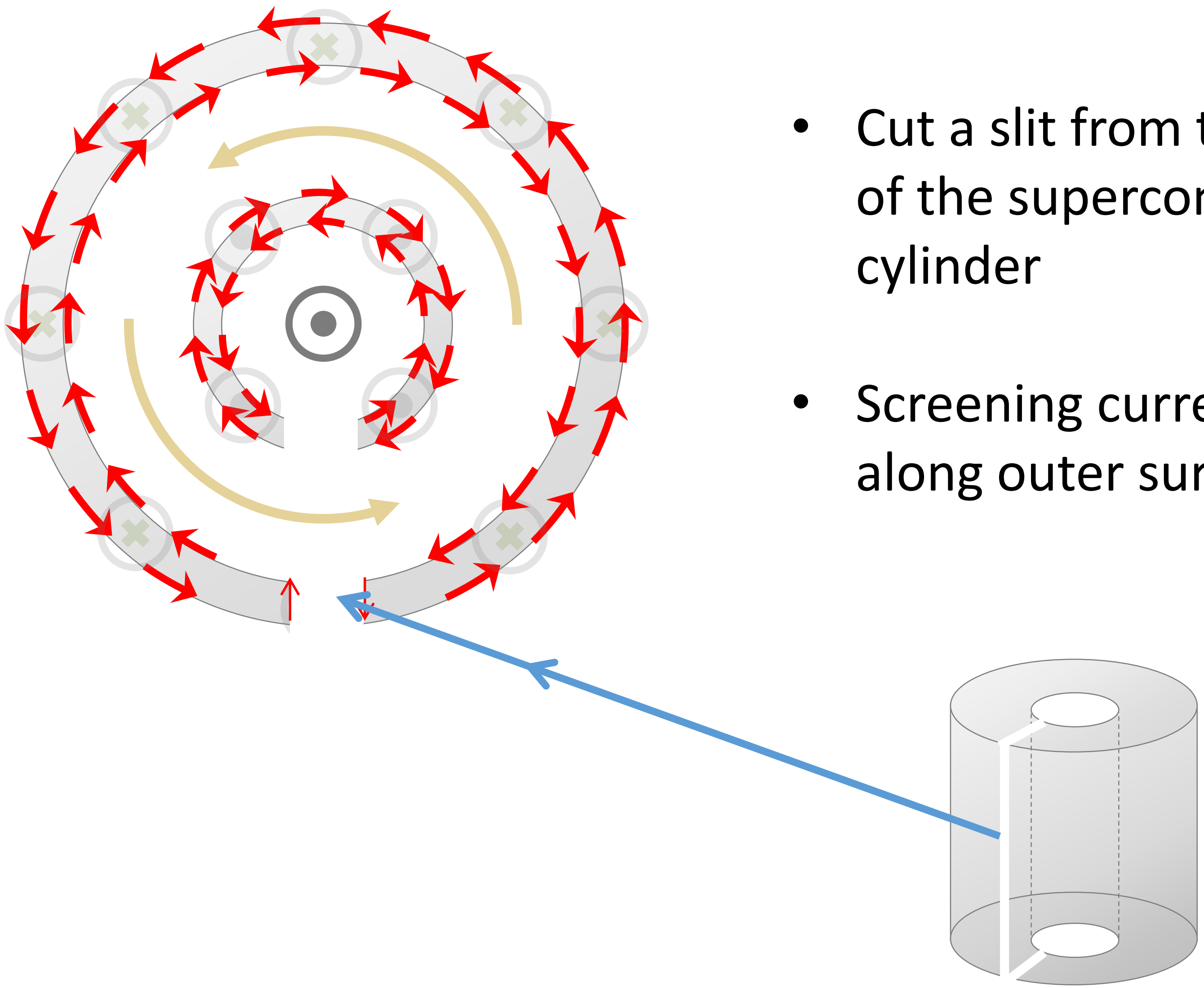
How to measure effective axion current



Meissner Effect

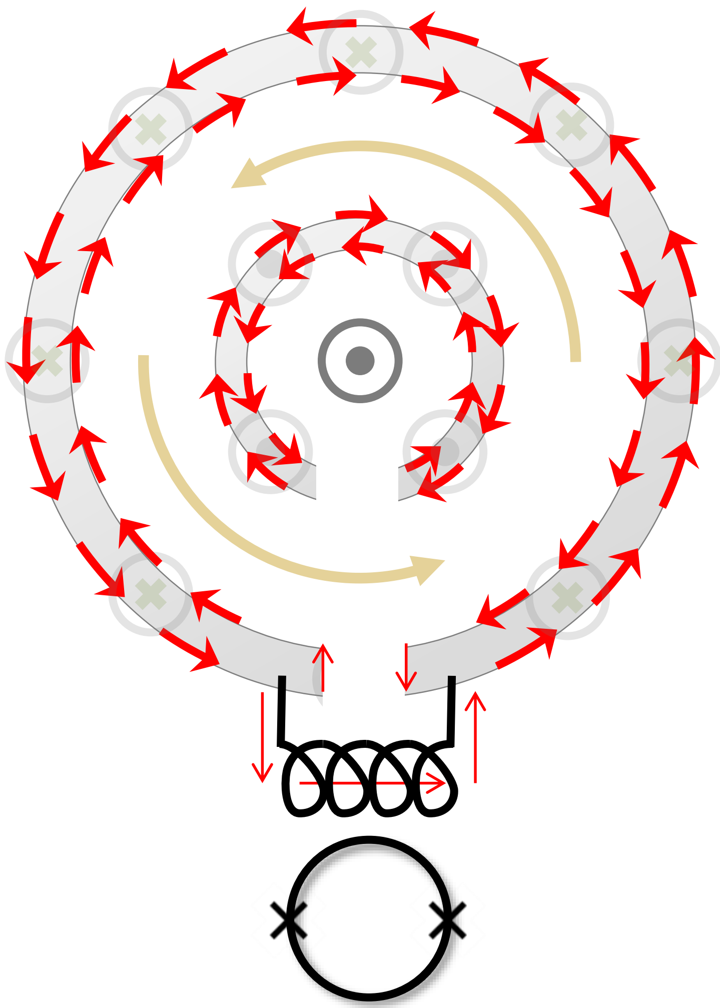
- Screening currents in superconductor flow to cancel field in bulk

How to measure effective axion current



- Cut a slit from top to bottom of the superconducting cylinder
- Screening currents continue along outer surface

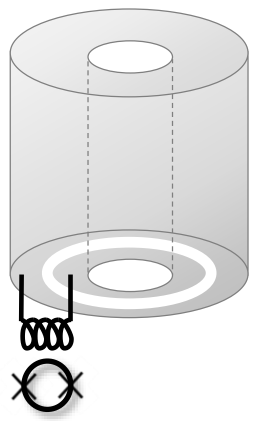
How to measure effective axion current



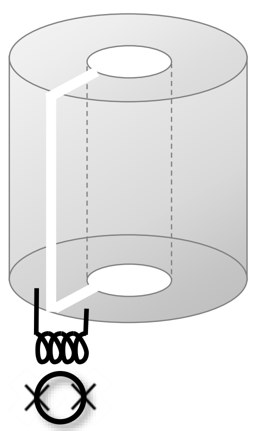
- Cut a slit from top to bottom of the superconducting cylinder
- Screening currents continue along outer surface
- Use inductive loop to couple screening current to SQUID

Broadband detection: limited signal to noise

Hidden Photon Detector



Axion Detector



- Can operate broadband – no need to scan
- Long integration times
- Interfering EMI pickup difficult to manage

ABRACADABRA

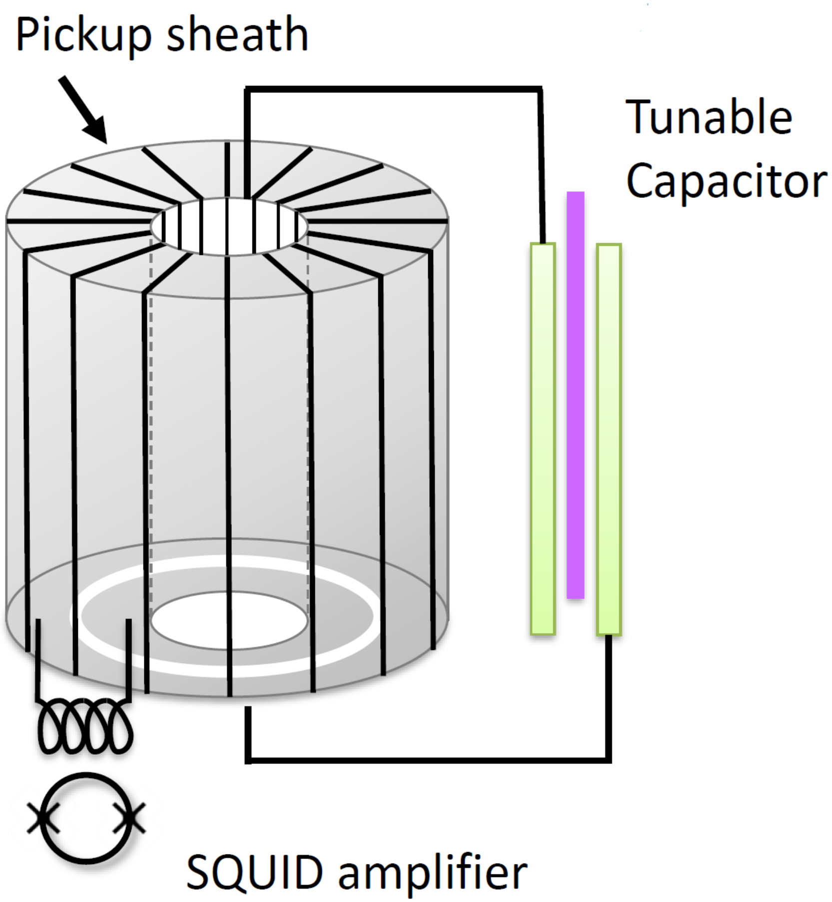
Y. Kahn et al.

arXiv:1602.01086, 2016

If it is possible to build a resonator, signal to noise is improved, even considering the need to scan.

Chaudhuri et al., in preparation, 2017

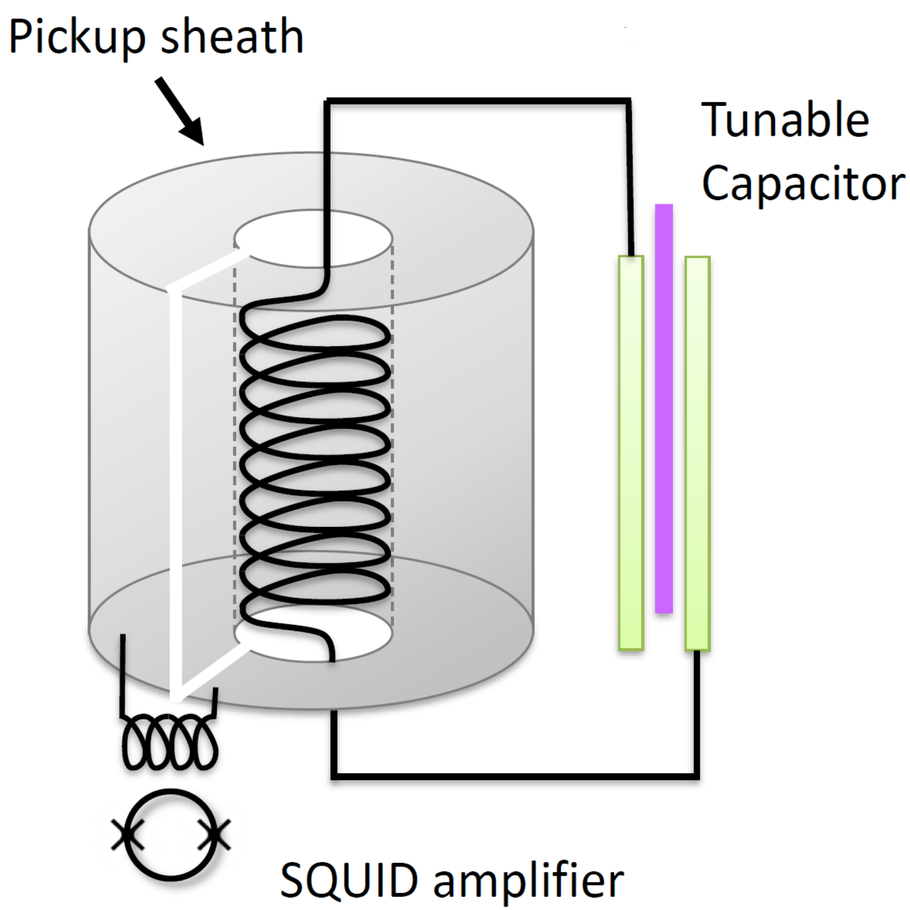
Resonant enhancement



LC Oscillator Hidden-Photon Configuration

- Coherent fields can be enhanced through the use of a resonator
- Add a tunable lumped-element resonator to ring up the magnetic fields sourced by local dark matter
- Tune dark matter radio over frequency span to hunt for signal

Resonant enhancement



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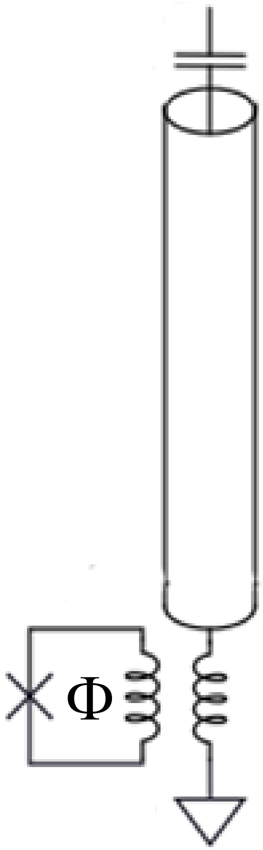
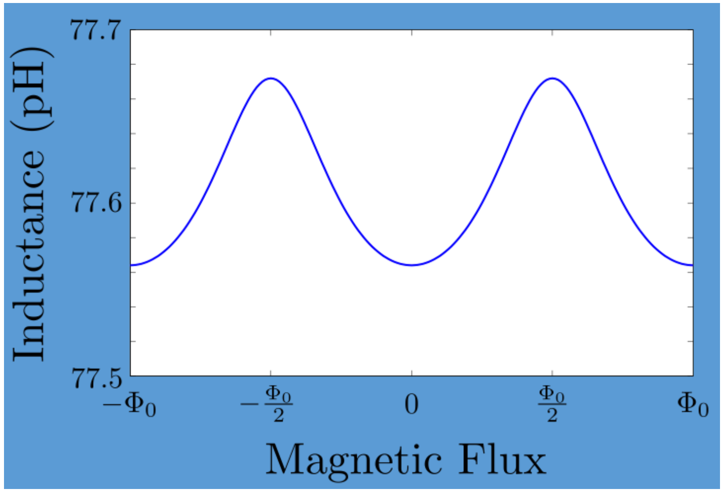
ac SQUIDs

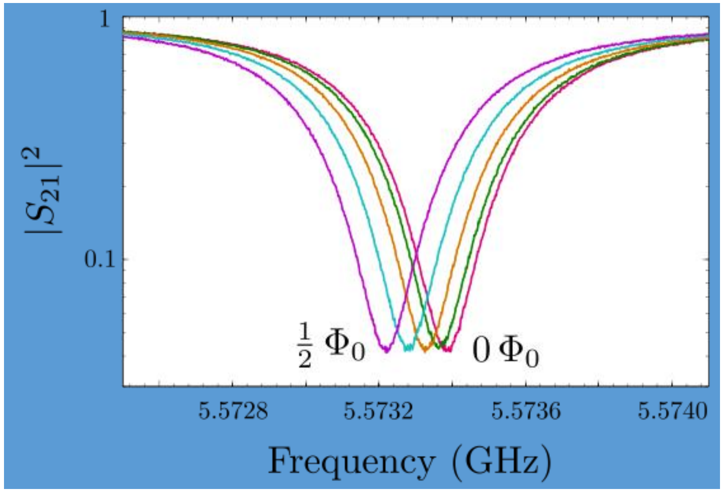


- dc SQUIDs can be used at low frequency, but at >~1 MHz, dissipation in the resistive shunts used in dc SQUIDs degrades the Q of the DM Radio resonator
- At higher frequencies, we are using an "ac SQUID": a reactive device that operates as a flux-variable inductor
- Flux detected by change in frequency of a resonator
- Can be quantum limited

Inductance response



Resonance response

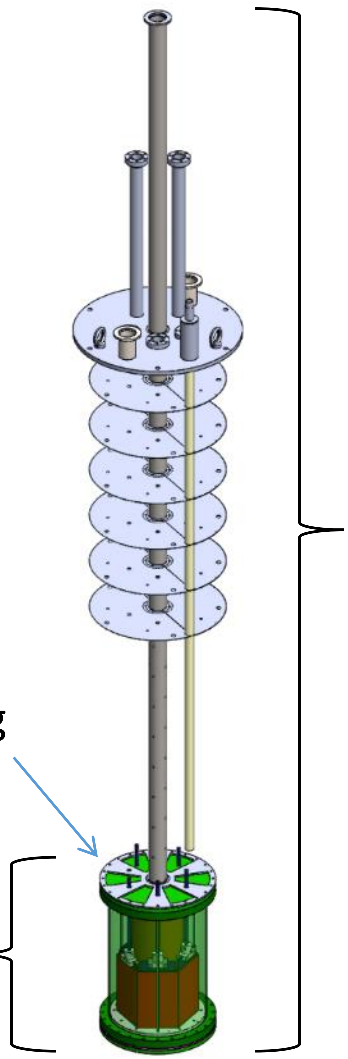


DM Radio pathfinder experiment

<u>4K Dip Probe</u>

Inserts into Cryoperm-lined helium dewar

Detector inside superconducting shield



67 inches

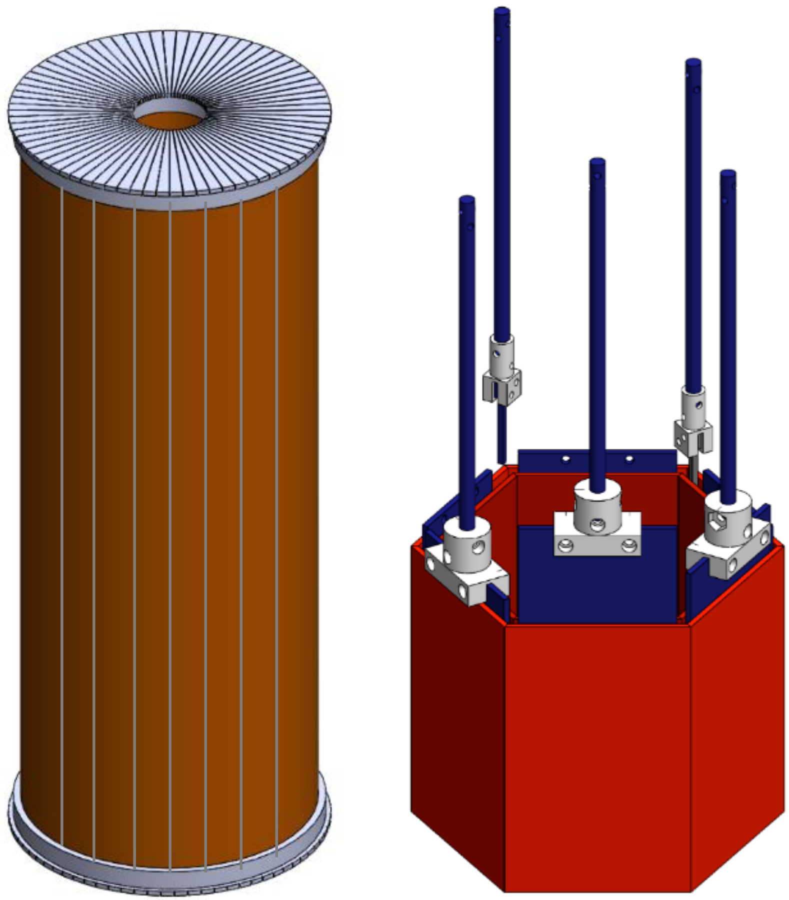
9.5 inches

750 mL Pathfinder now being tested

- Initial focus on hidden photons
- T=4K (Helium Dip Probe)
- Frequency/Mass Range:
  100 kHz – 10 MHz
  500 peV – 50 neV
- Coupling Range
  ε : $10^{-9} – 10^{-11}$
- Readout: DC SQUIDs

Design Overview of the DM Radio Pathfinder Experiment
M. Silva, arXiv:1610.09344, 2016

Resonant frequency tuning



$$\frac{\Delta f}{f} \approx 1 \times 10^{-6}$$ per .001" of motion

Scan time

- 30 days/decade
- 3-6 months total scan

Ultra-coarse tuning

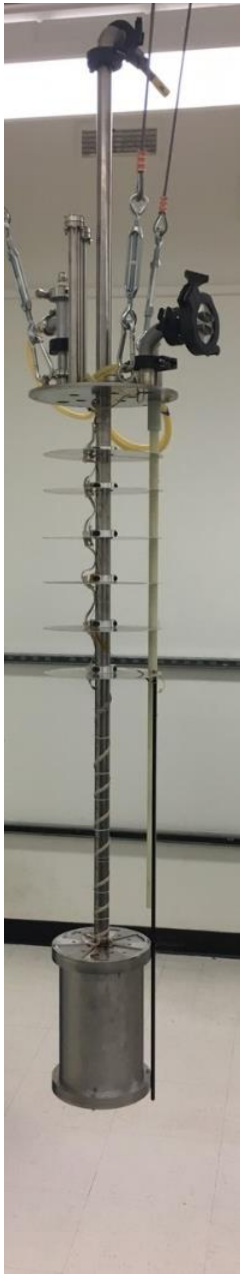
- fixed sapphire plate fully inserted/removed (tune C)
- change number of turns in solenoid coil (tune L)

Coarse tuning

- position of sapphire dielectric plates (3)

Fine tuning

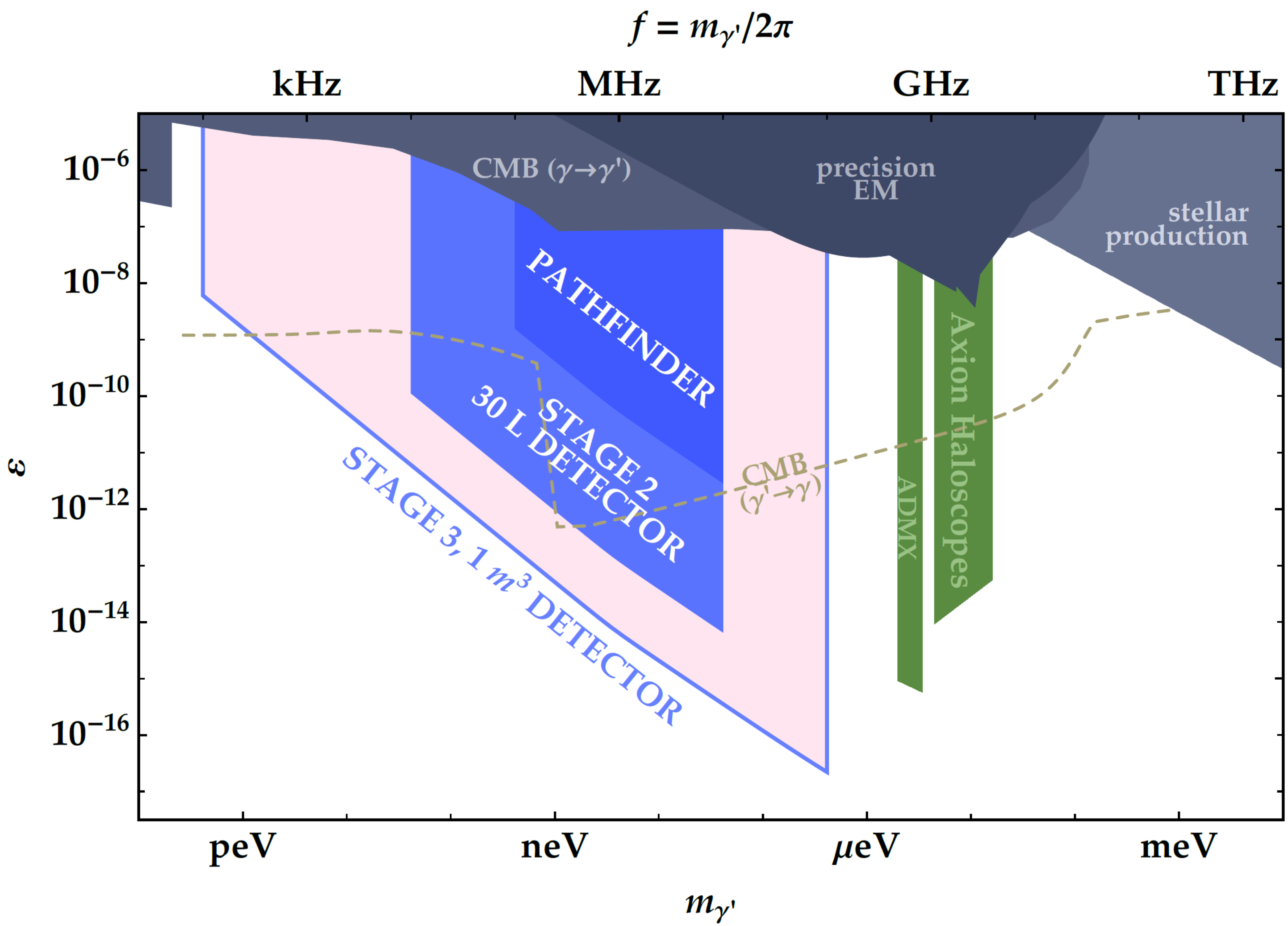
- position of sapphire needle
- position of niobium needle



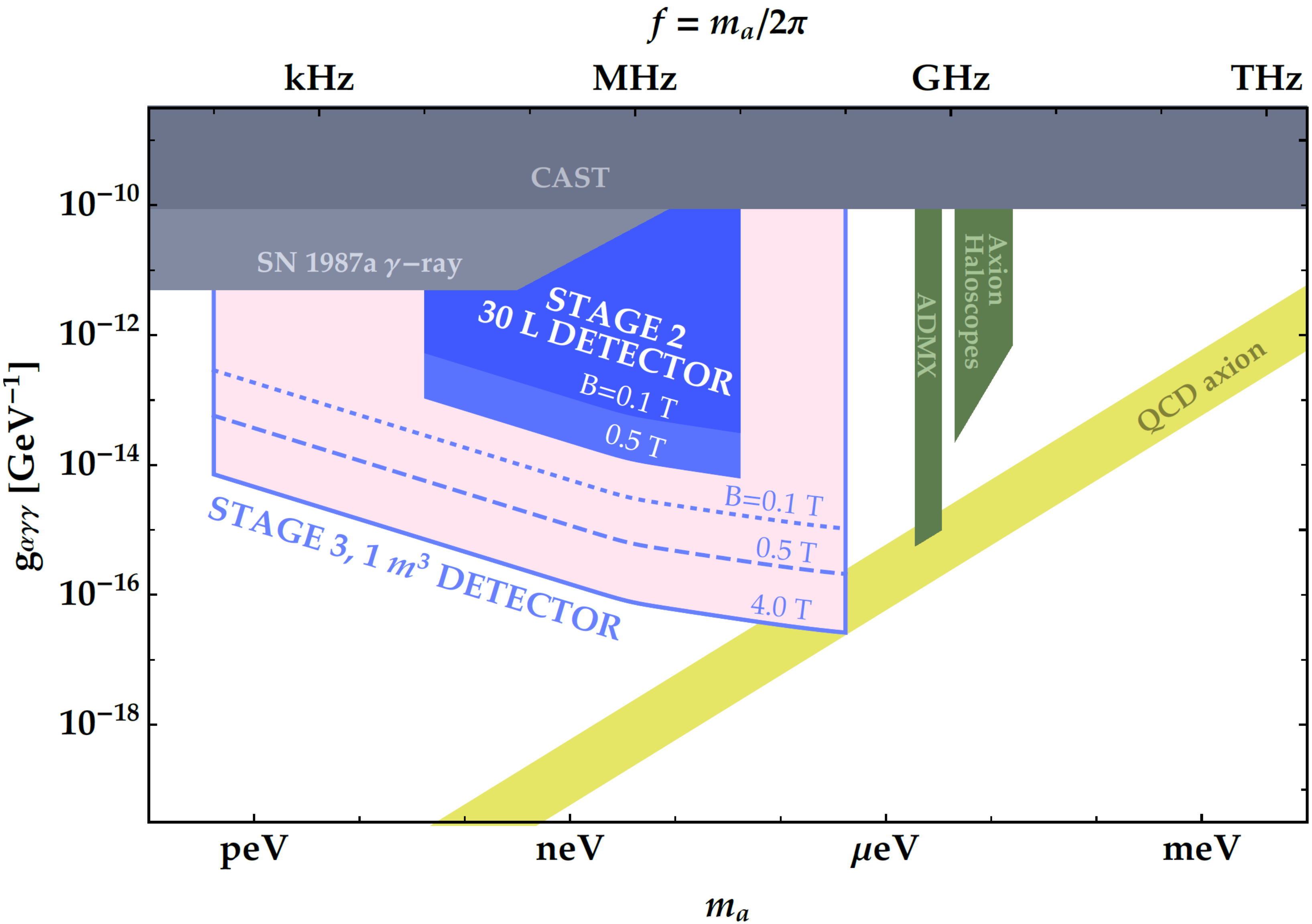
Present status - Pathfinder

- *Pathfinder construction complete*
- SQUIDs and readout electronics tested / working
- Now testing fixed resonators to evaluate Q, material properties, then scan
- **Initial science scans Summer 2017**

DM Radio science reach: hidden photons (lumped-element)



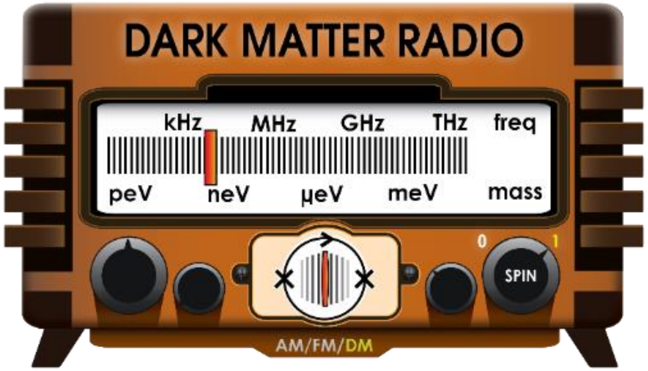
DM Radio science reach: axions



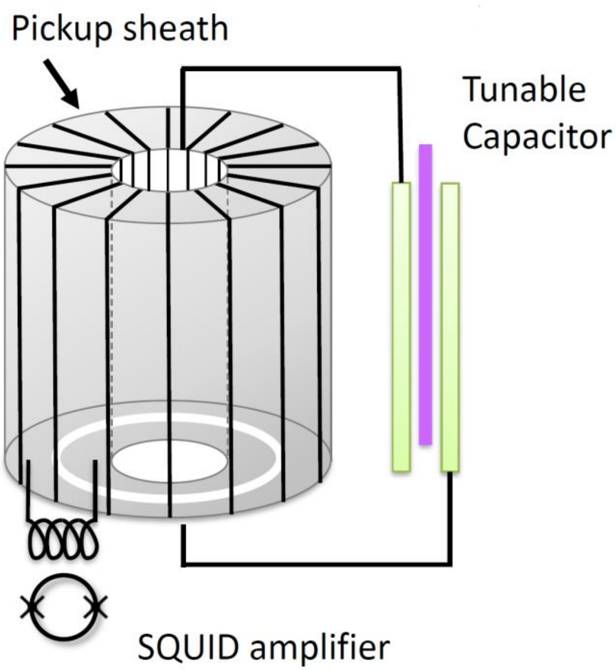
Potential Budget

- Pathfinder is funded and becoming operational
- Stage 2 $\approx$ \$1.3 M
  - With DOE lab overhead & costs (less expensive on campus with students and postdocs)
  - Dilution refrigerator, materials, supplies, equipment, FTEs
- Stages 2+3, One-site ~\$5M
- Stage 2+3 Multi-site, multi-orientation \$5-10M

Conclusions

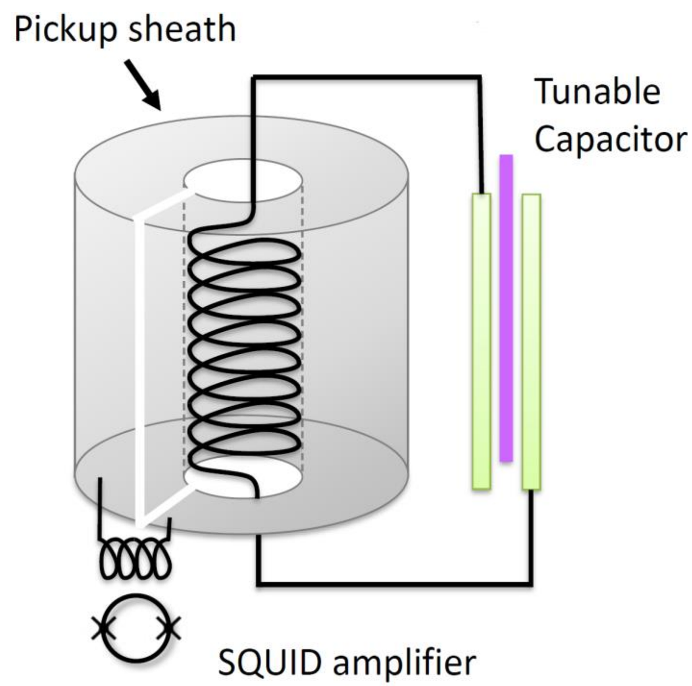


Hidden Photons



LC Oscillator Hidden-Photon Configuration

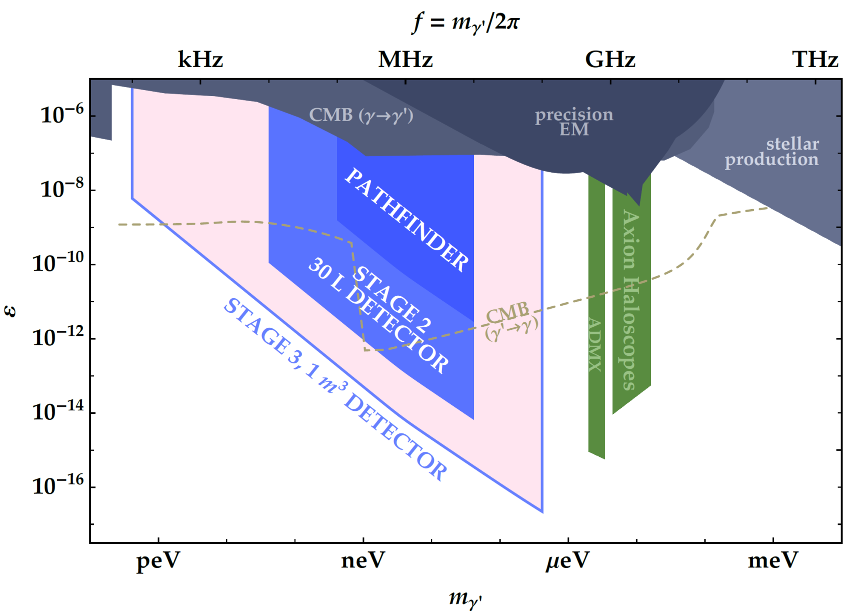
Axions



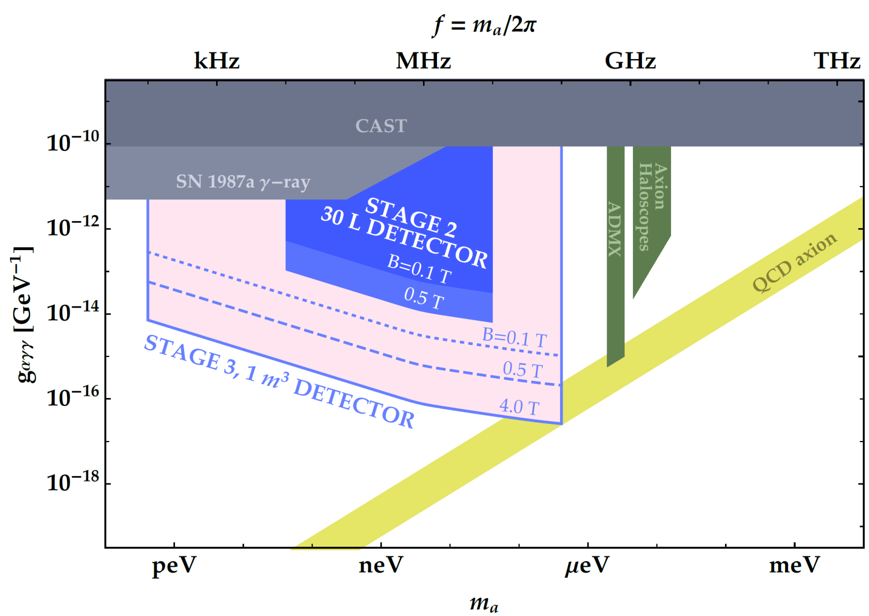
LC Oscillator Axion Configuration

Conclusions

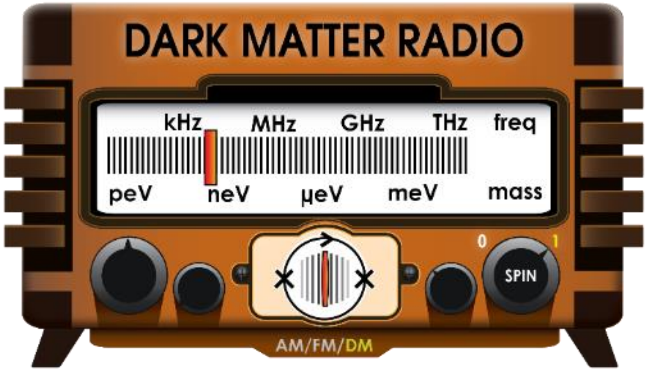
Hidden Photons



Axions



Conclusions



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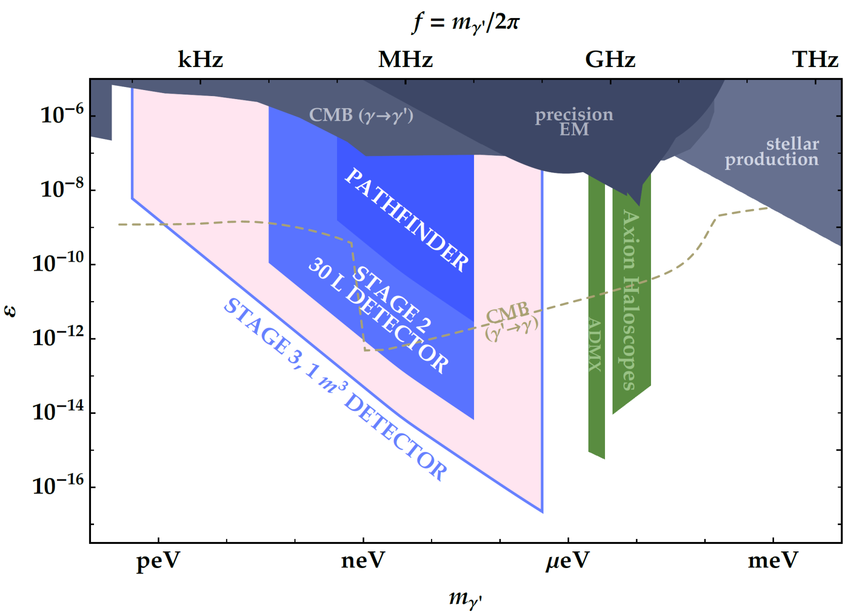

Axions