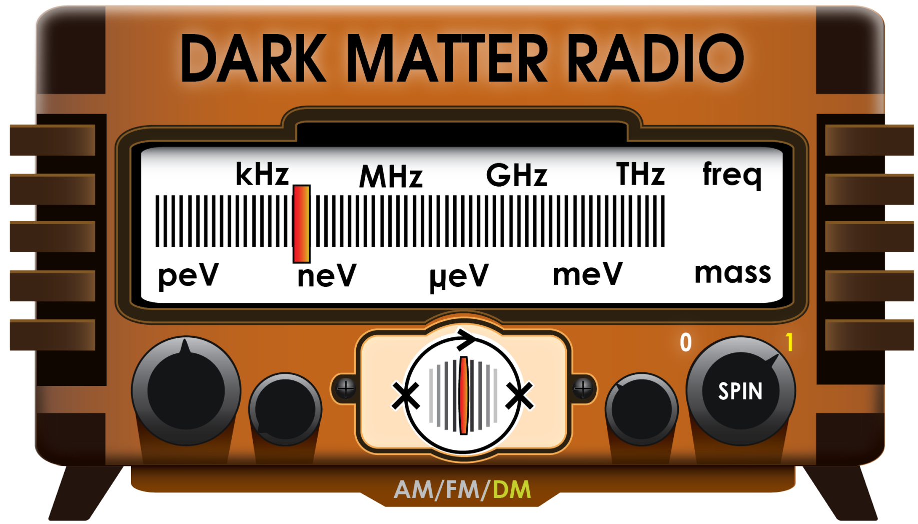
DM Radio

Searching for Ultra-Light-Field Dark Matter

Arran Phipps
Stanford University
Irwin Group



SLAC

KIPAC

HEISING-SIMONS FOUNDATION

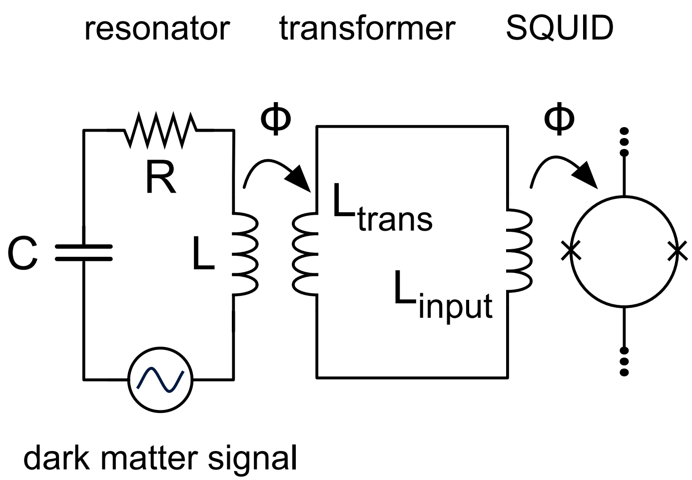
QuantISED

DM Radio DJs

Arran Phipps, Saptarshi Chaudhuri, Stephen Kuenstner, Carl Dawson, Dale Li, Hsiao-Mei (Sherry) Cho, Betty Young, Connor Fitzgerald, Kevin Wells, Henry Froland, Peter Graham, Kent Irwin

What is DM Radio?

- A superconducting, tunable lumped-element LC resonator
- Initially read out by a DC SQUID, will be replaced by an optimized quantum sensor we are developing through a separate project

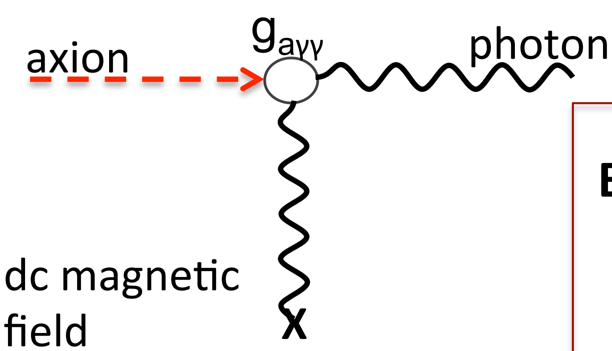


- Searching for axion/hidden photon dark matter from peV to μeV
  - Compton wavelength >> dimensions of experiment
  - Dark matter signal has simple cos(ωt) dependence

Possible Candidates

Axions

- Spin-0 pseudoscalars
- Possible solution to strong-CP problem
- Many other axion-like particles (ALPs)
- Detection via inverse Primakoff effect, requires DC B-field



Hidden Photons

- Massive spin-1 vector bosons
- Non-thermal production via misalignment mechanism, inflationary fluctuations
- Interacts with photons through kinetic mixing

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

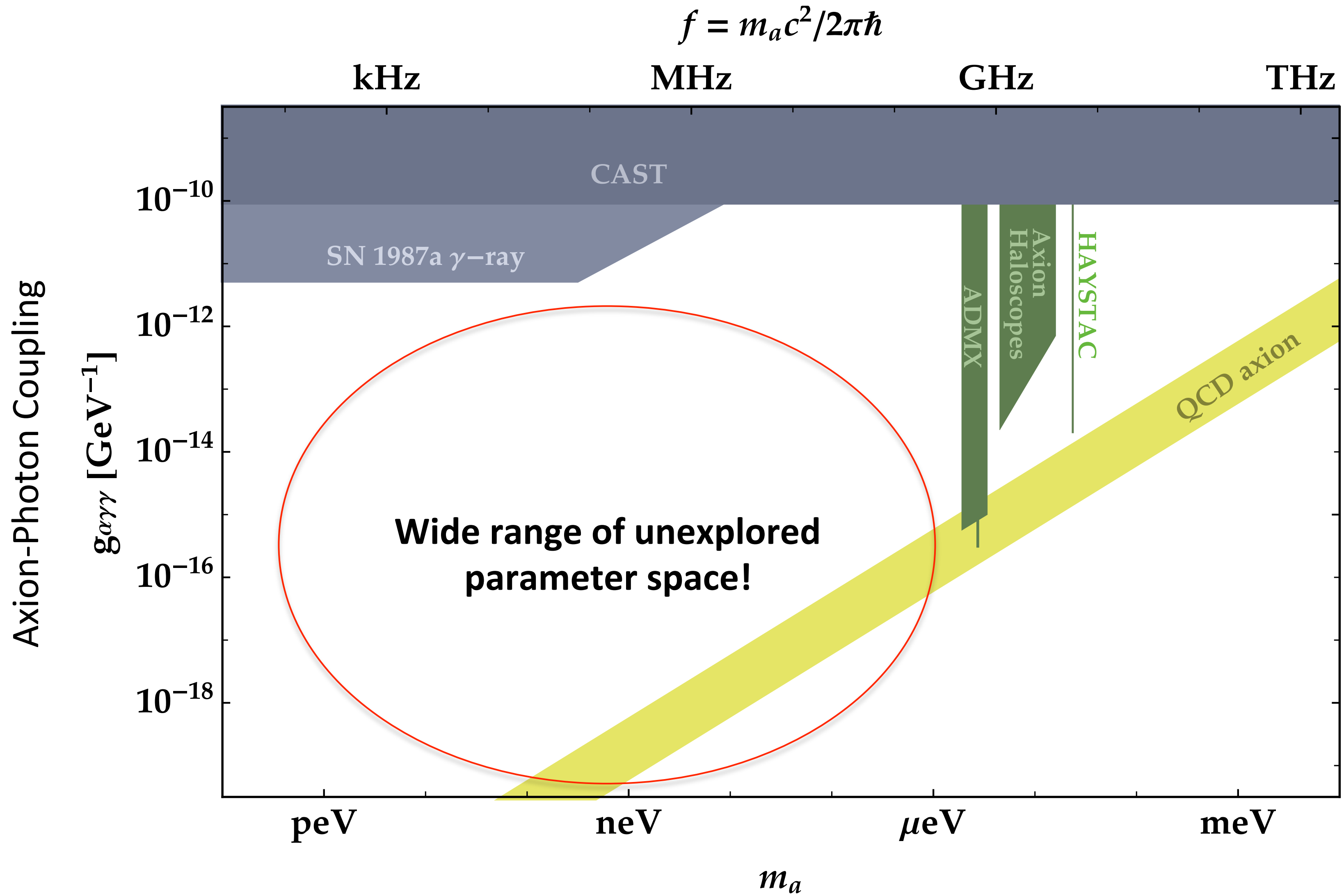
- No DC B-field required

Not a real current! Does not carry charge

Both candidates appear as an *effective* source term in Maxwell's equations

$$\nabla \times \vec{B} \propto \vec{J}_{\mathrm{DM}}$$

Axions – plenty of room at the bottom!



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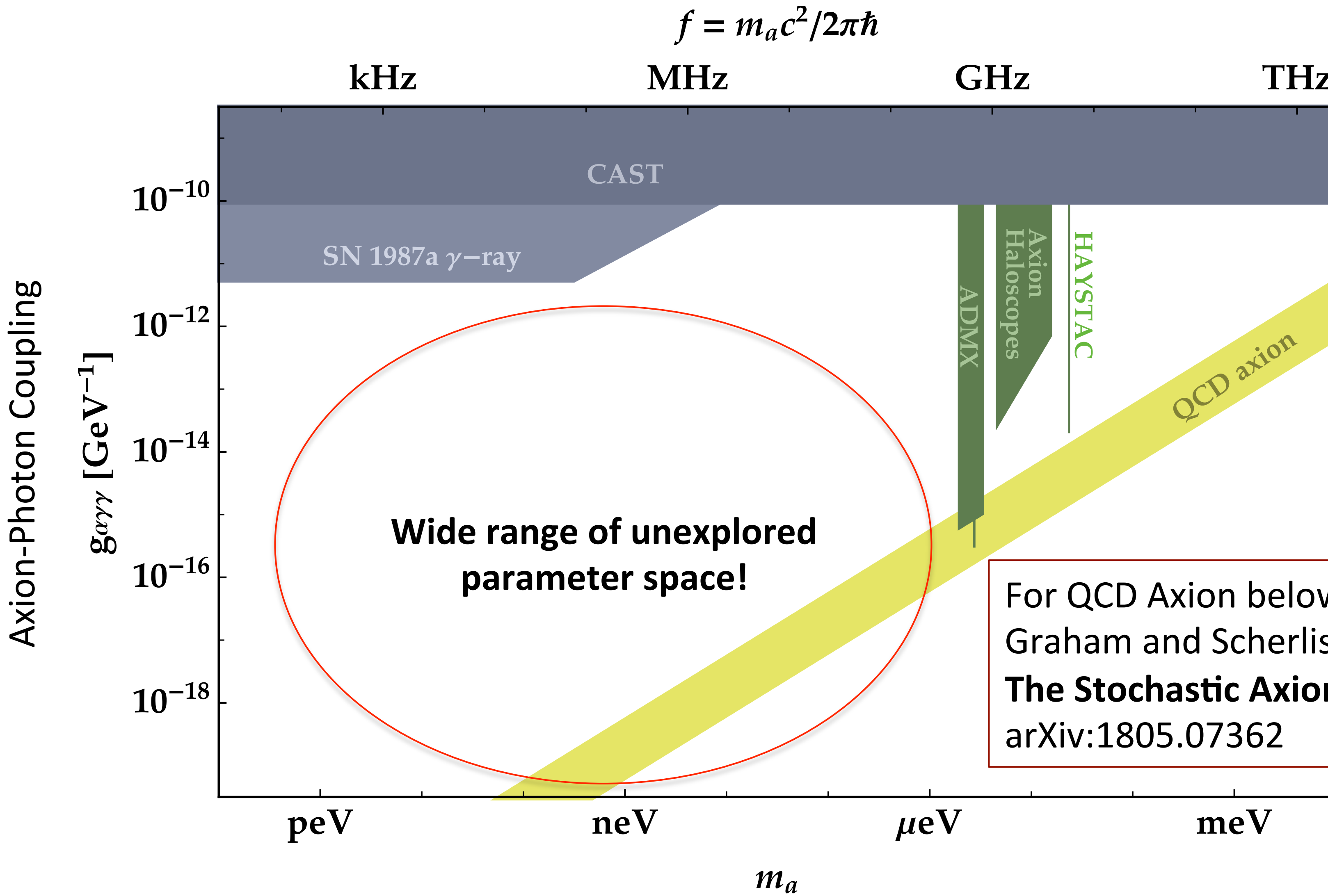
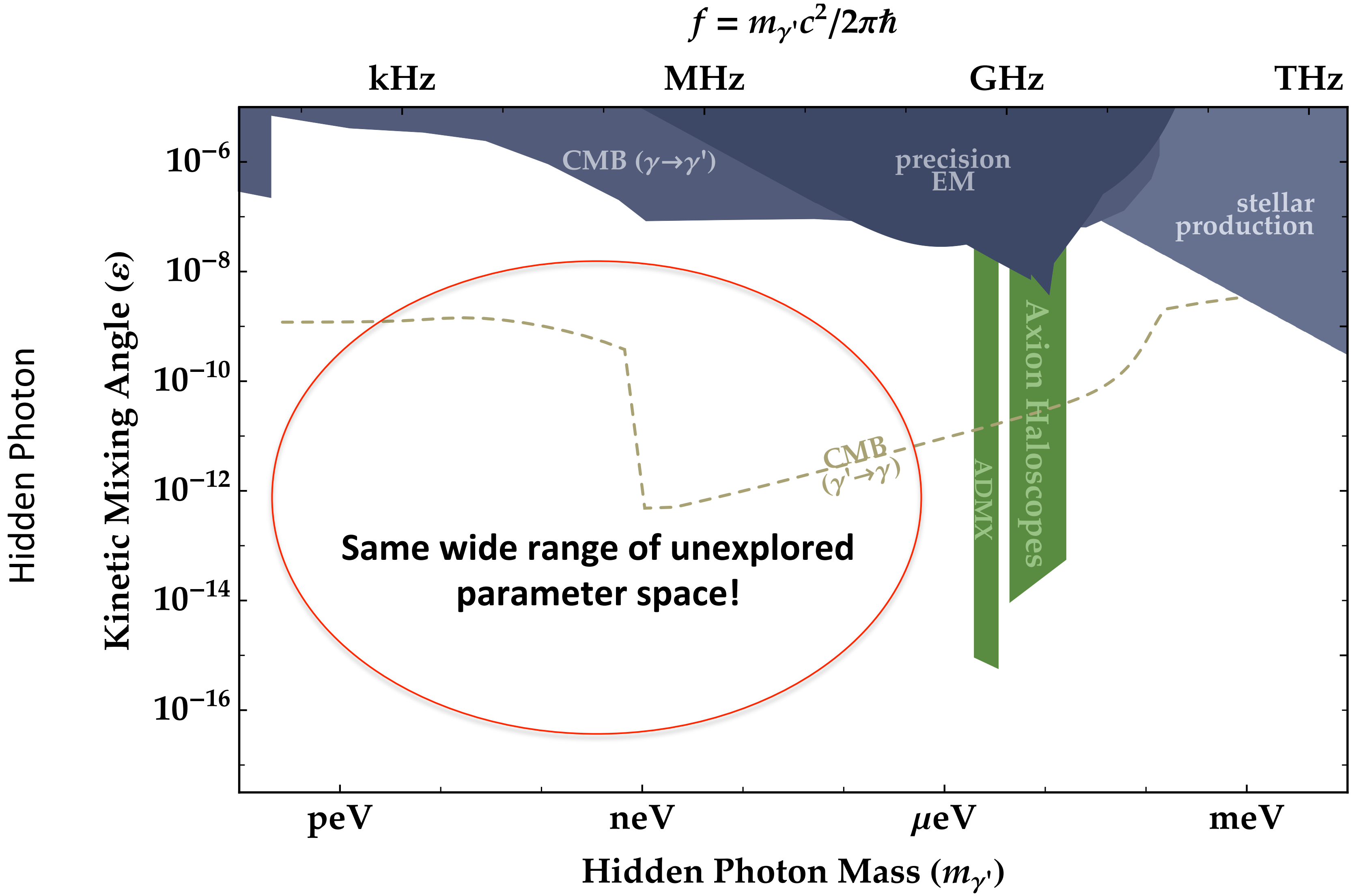
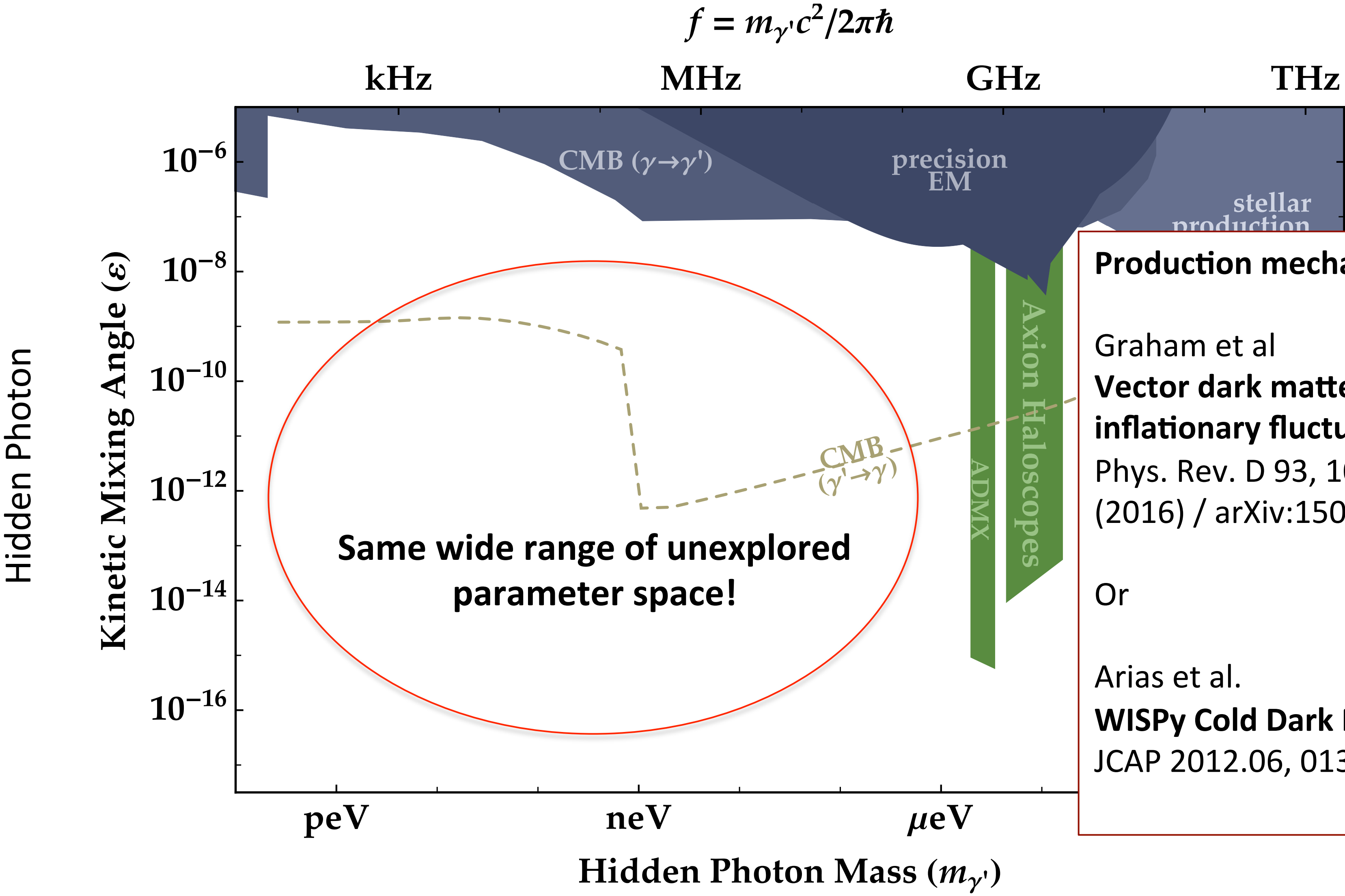


For QCD Axion below μeV see Graham and Scherlis
The Stochastic Axion Scenario
arXiv:1805.07362

Hidden Photons – plenty of room at the bottom!



Hidden Photons – plenty of room at the bottom!



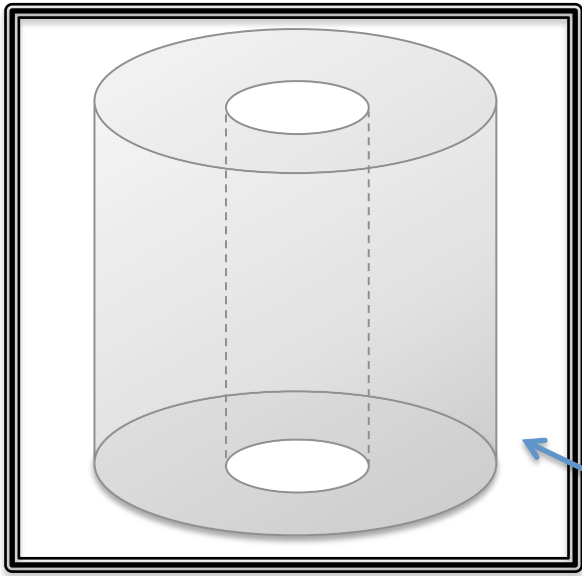
Production mechanisms:

Graham et al
Vector dark matter from inflationary fluctuations
Phys. Rev. D 93, 103520 (2016) / arXiv:1504.02102

Or

Arias et al.
WISPy Cold Dark Matter
JCAP 2012.06, 013 (2012)

Hidden Photon Detection

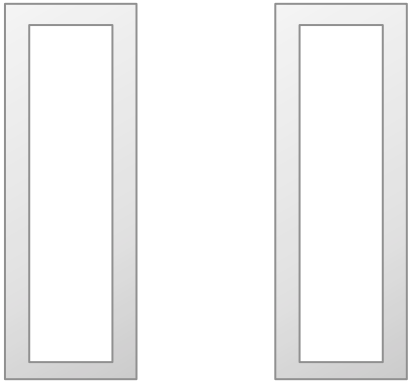


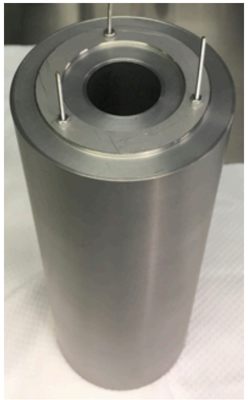
Superconducting shield

9.5 inches

Hollow, superconducting sheath (toroid)

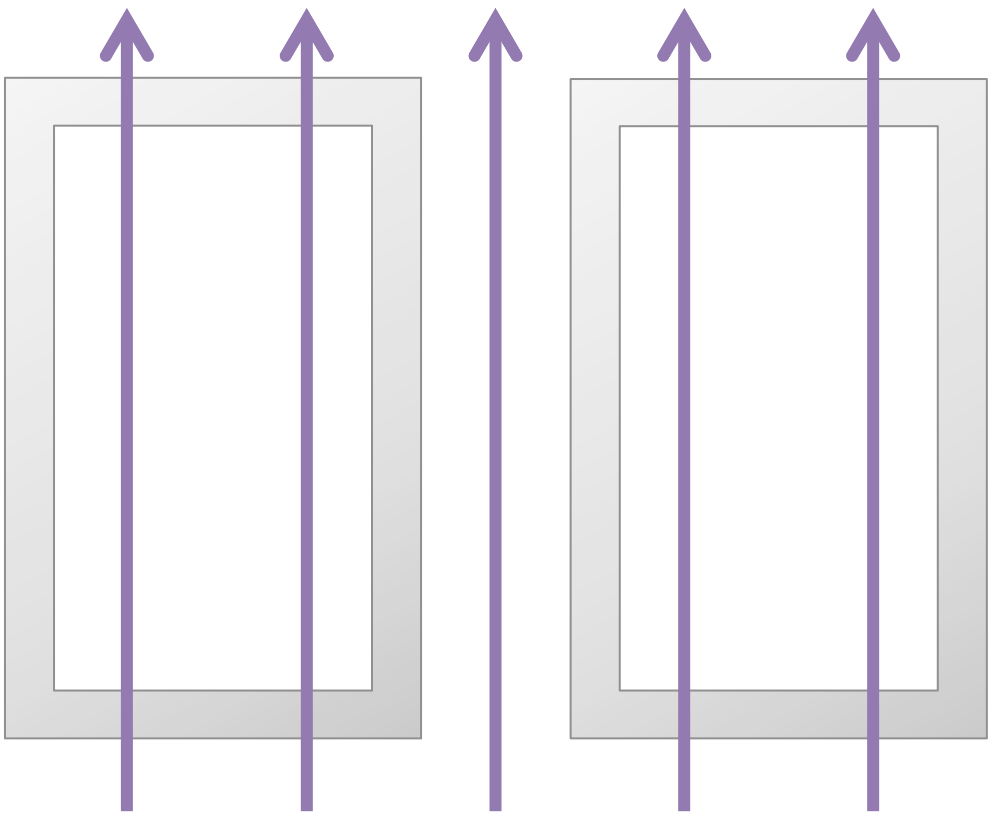
Cross-section





7.5 inches

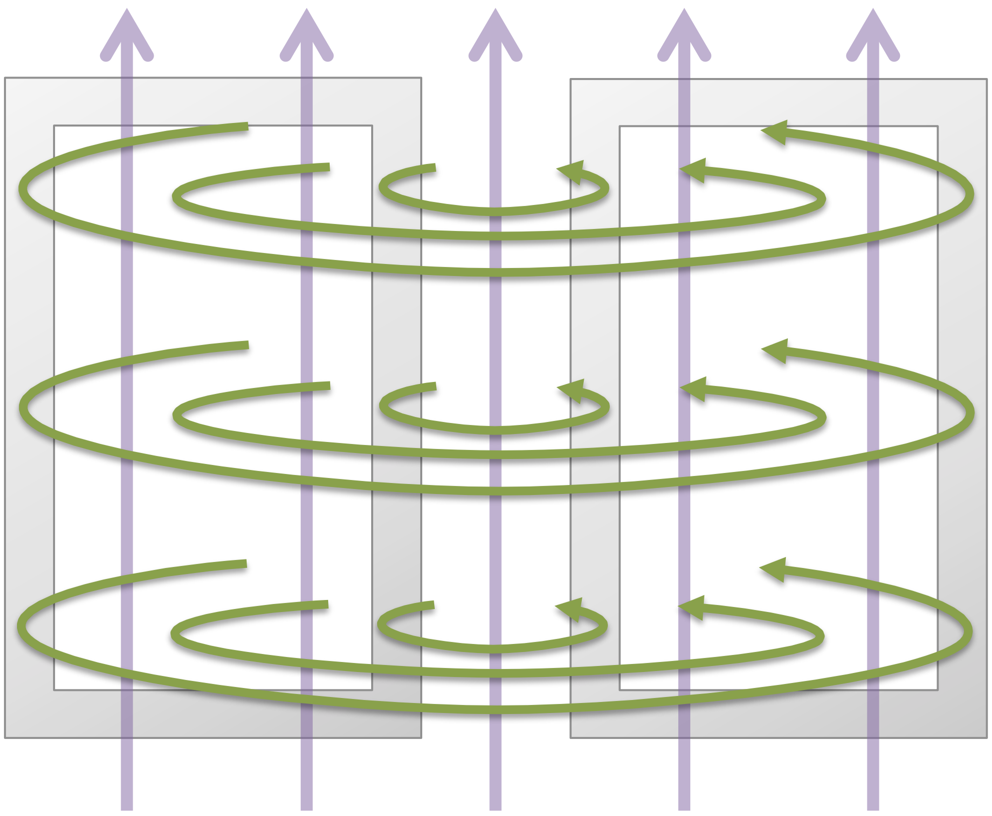
Hidden Photon Detection



$$\vec{J}_{\mathrm{HP}}(t)$$

- Hidden photons penetrate superconductors, acts as an effective AC current

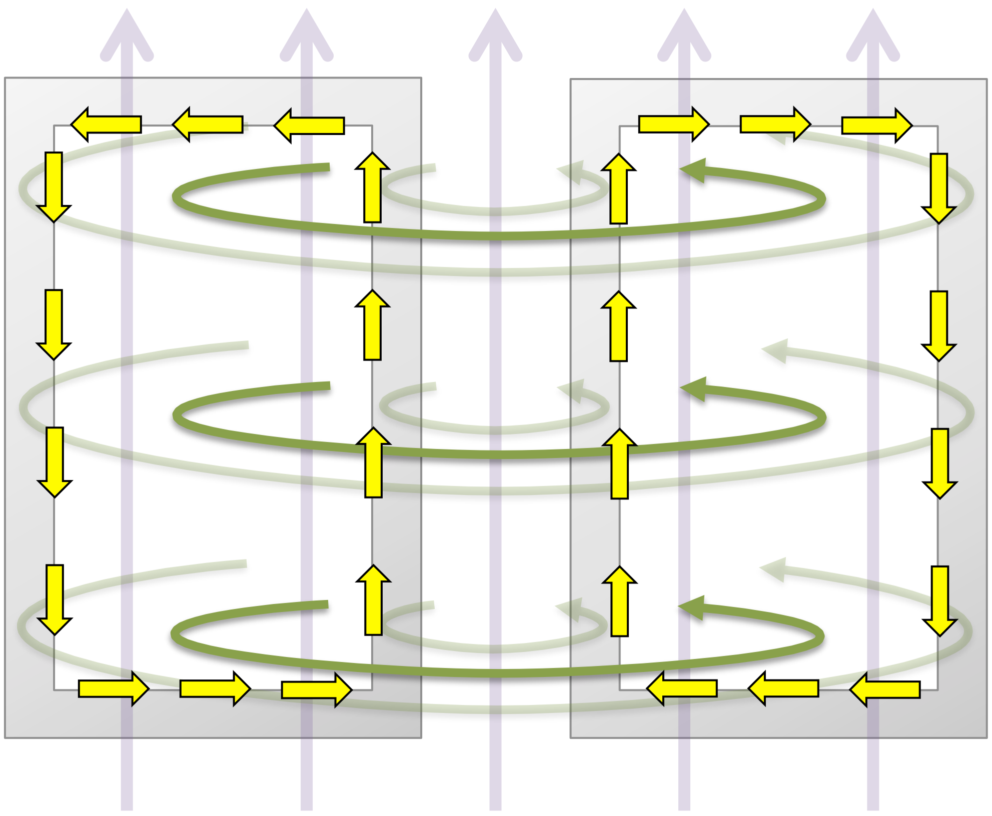
Hidden Photon Detection



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

- Hidden photons penetrate superconductors, acts as an effective AC current
- Generates a REAL circumferential, quasi-static B-field

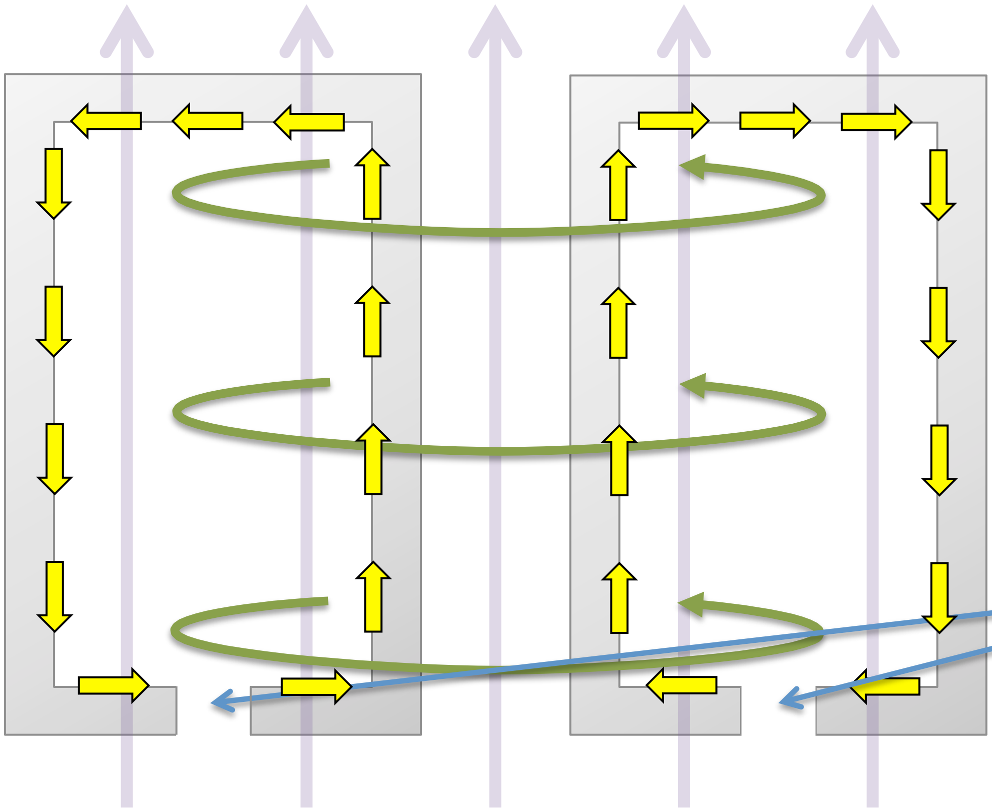
Hidden Photon Detection



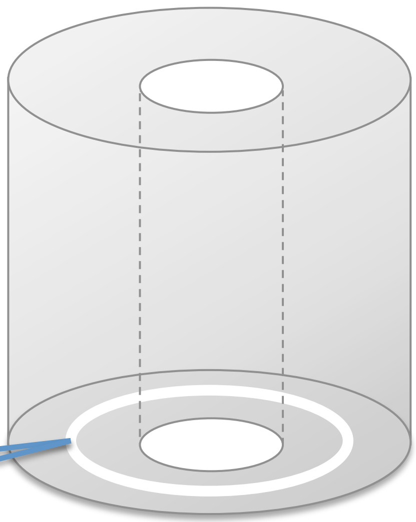
Meissner Effect

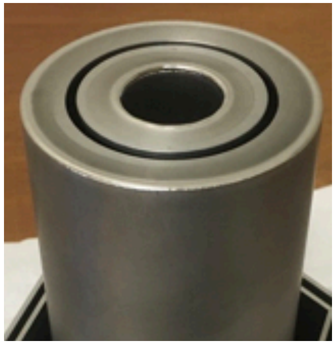
- Hidden photons penetrate superconductors, acts as an effective AC current
- Generates a REAL circumferential, quasi-static B-field
- Screening currents in superconductor flow to cancel field in bulk

Hidden Photon Detection

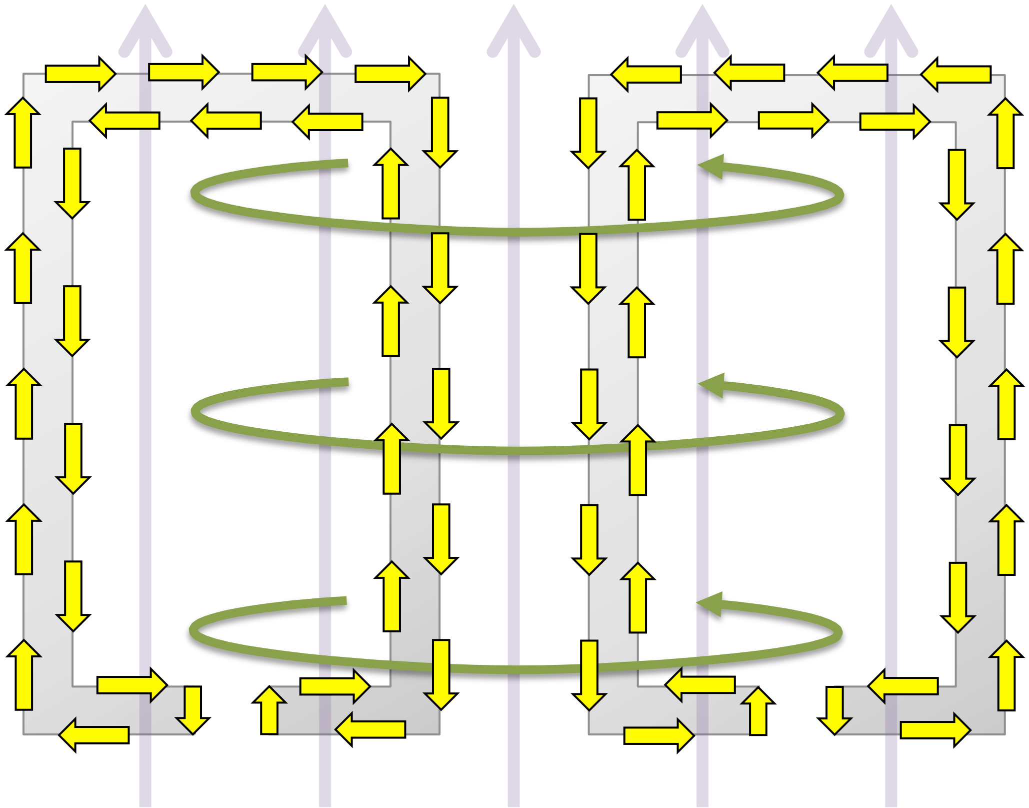


- Cut concentric slit at bottom of sheath



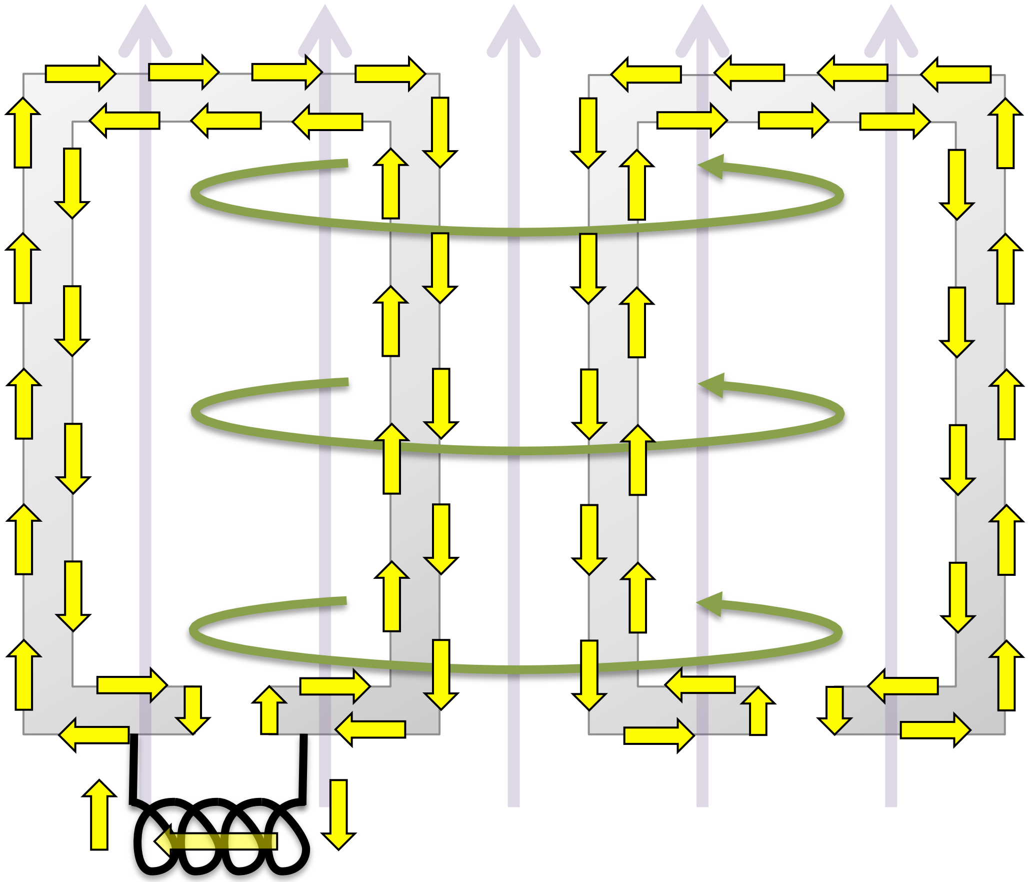


Hidden Photon Detection



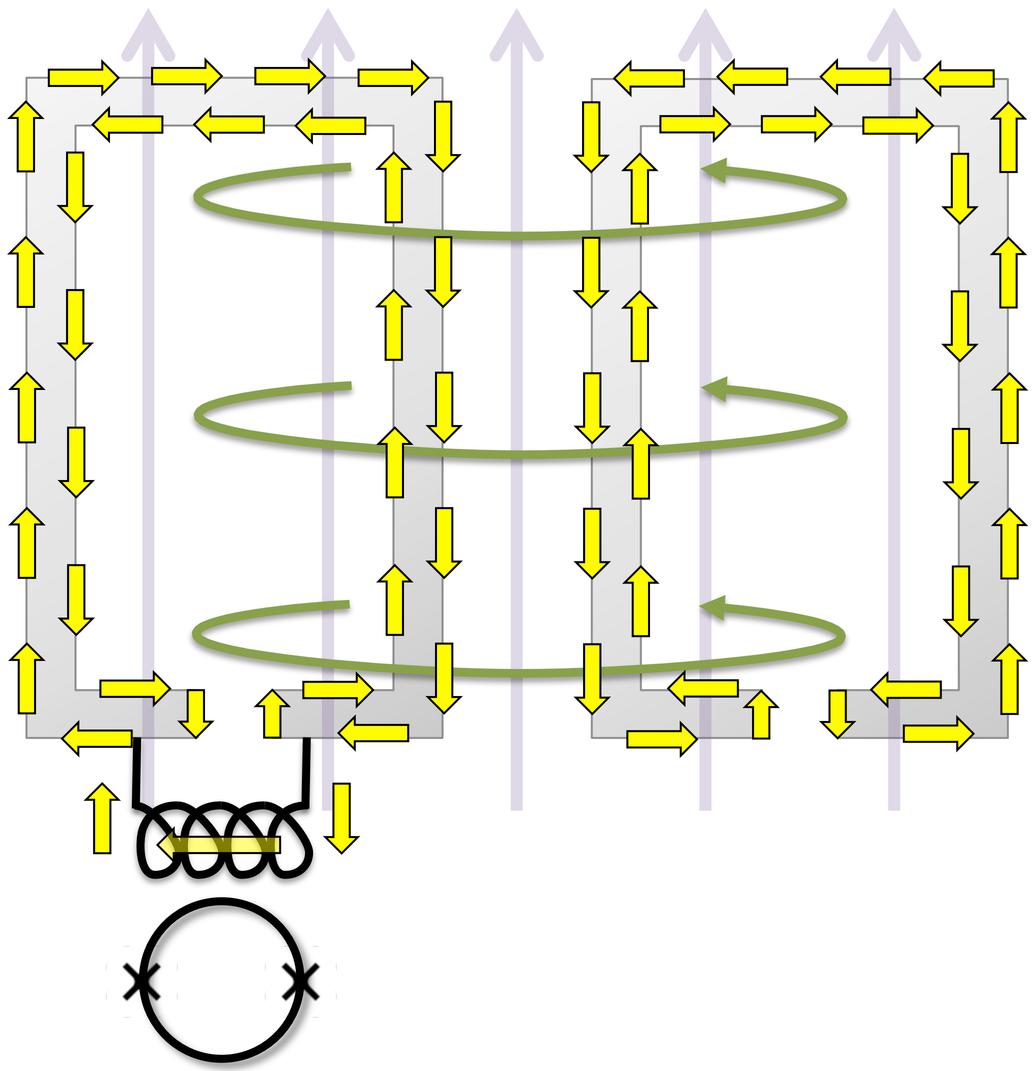
- Cut concentric slit at bottom of sheath
- Screening currents continue to flow along outer surface

Hidden Photon Detection



- Cut concentric slit at bottom of sheath
- Screening currents continue to flow along outer surface
- Add an inductive loop to siphon some of the screening current

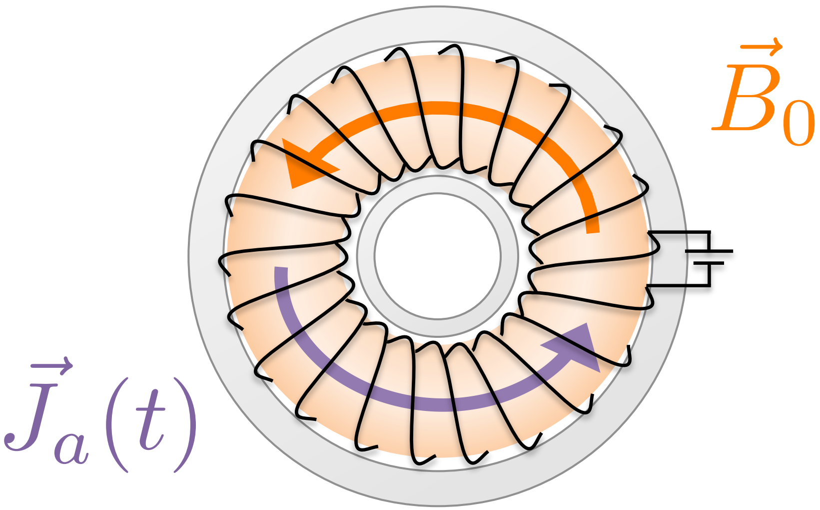
Hidden Photon Detection



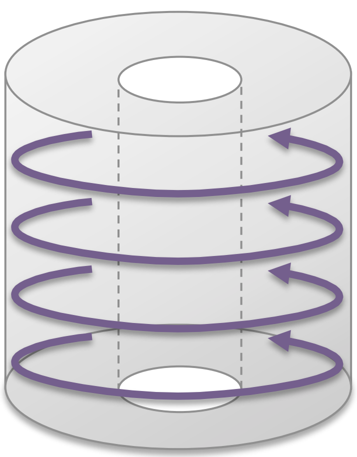
- Cut concentric slit at bottom of sheath
- Screening currents continue to flow along outer surface
- Add an inductive loop to siphon some of the screening current
- Sense with SQUID or quantum sensor

Axion Detection

Top-Down Cross-section



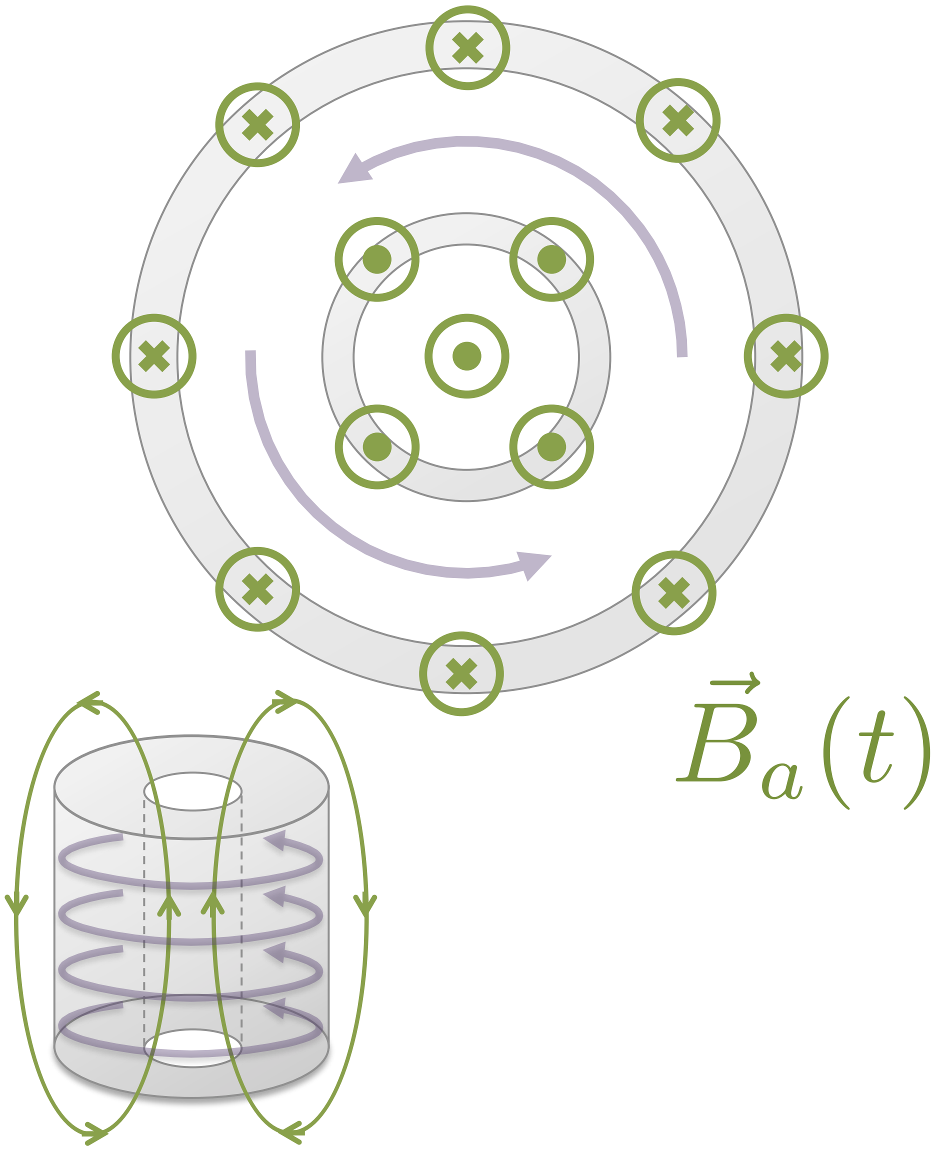
(B_0 toroid *inside* sheath)



- Toroidal coil produces DC magnetic field inside superconducting sheath
- Axions interact with DC field, acts as an effective AC current along direction of applied field

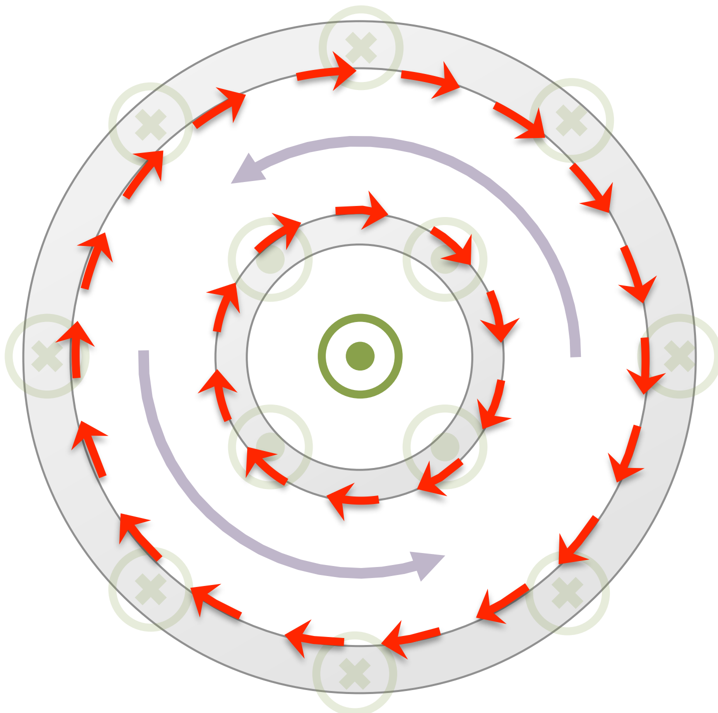
$$\vec{J}_a = |\vec{J}_a|\,\hat{\phi}$$

Axion Detection



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

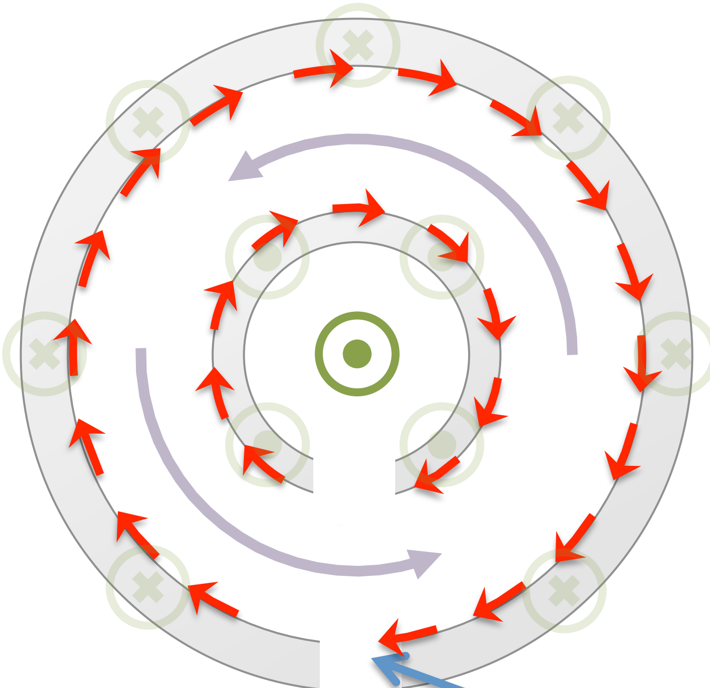
Axion Detection



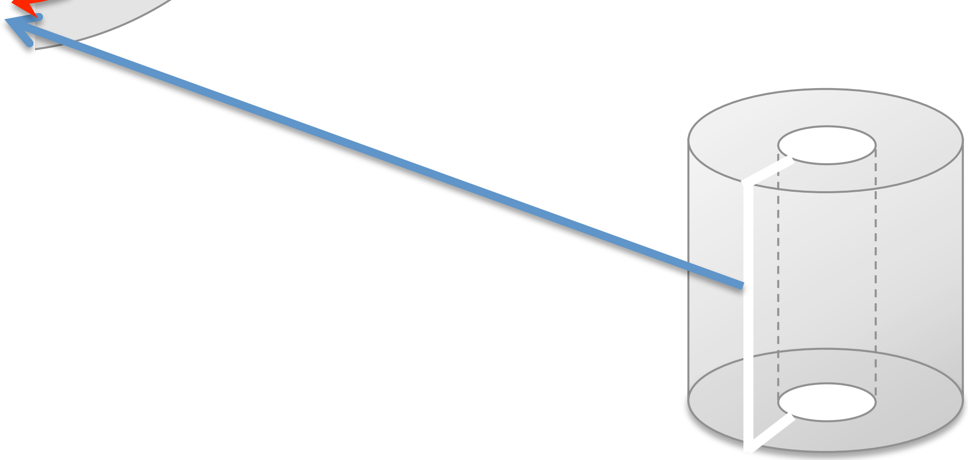
Meissner Effect

- Screening currents in superconductor flow to cancel field in bulk

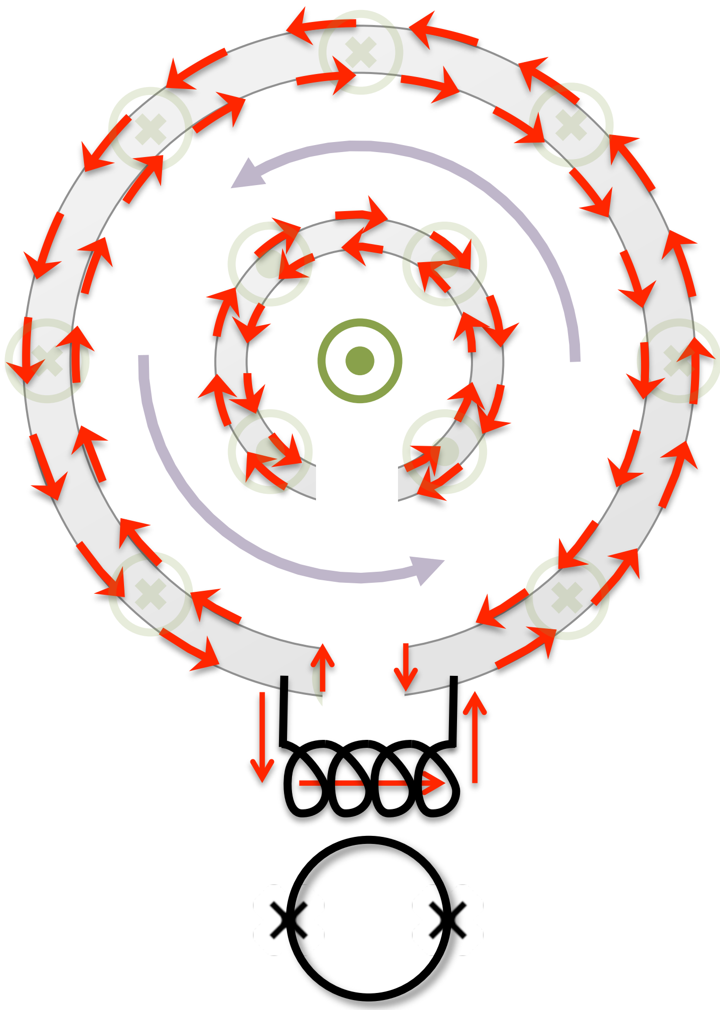
Axion Detection



- Screening currents in superconductor flow to cancel field in bulk
- Cut a slit from top to bottom of the superconducting sheath



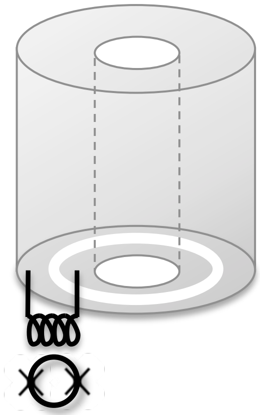
Axion Detection



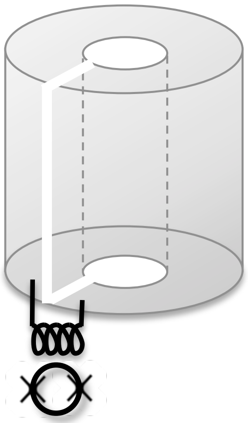
- Screening currents continue along outer surface
- Use inductive loop to siphon some of the screening current
- Readout with SQUID or quantum sensor

Broadband Detectors

Broadband Hidden Photon Detector

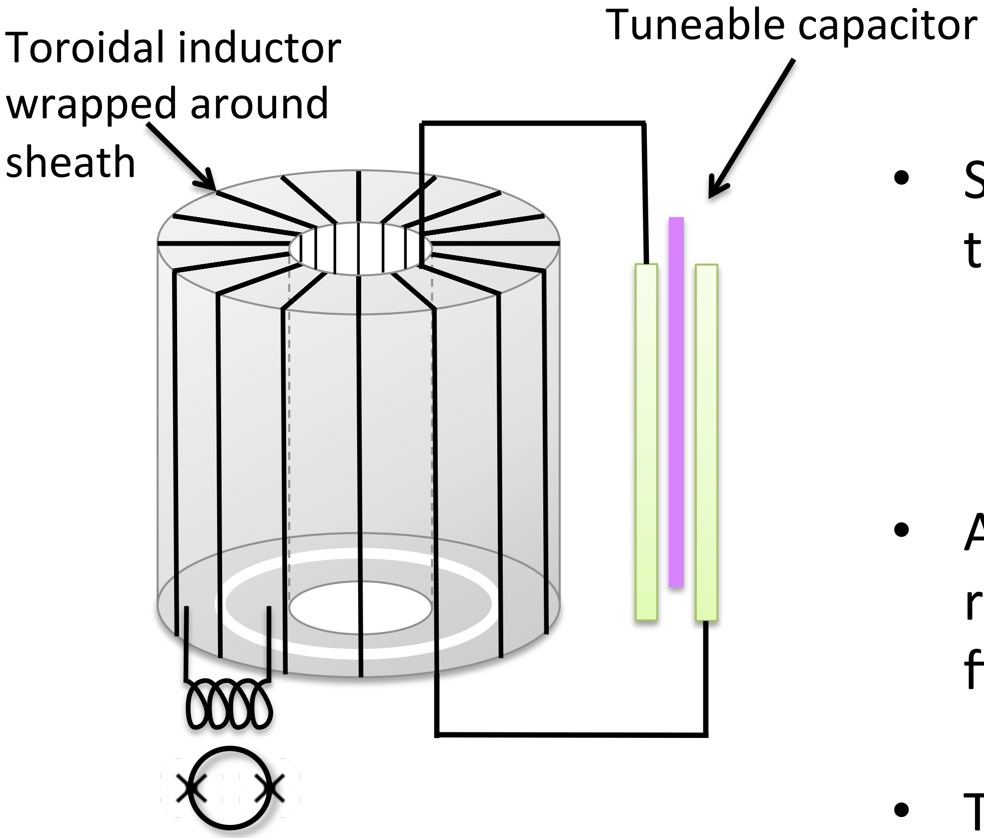


Broadband Axion Detector



- Can operate broadband – no need to scan over frequency
- Weak signal
- Long integration times

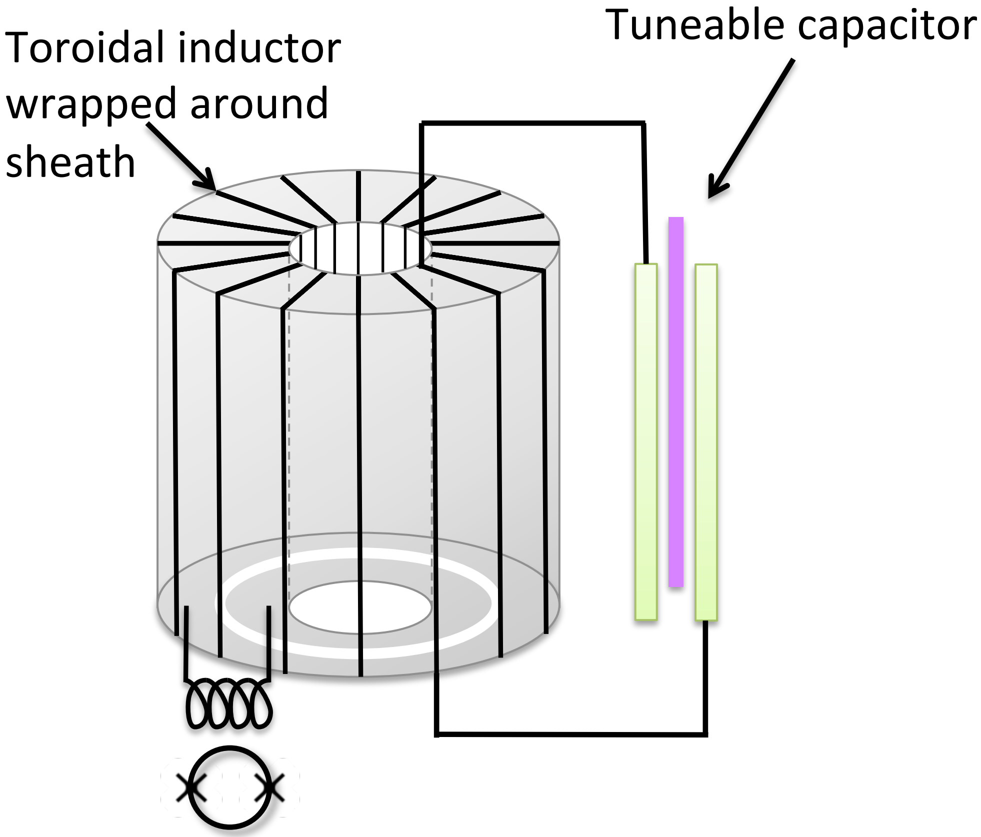
Resonant Enhancement



LC Oscillator Hidden Photon Configuration

- Signal can be enhanced through the use of a resonator
  - Near-optimal method, see Kent Irwin's talk
- 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
  - Short integration at each step

Resonant Enhancement



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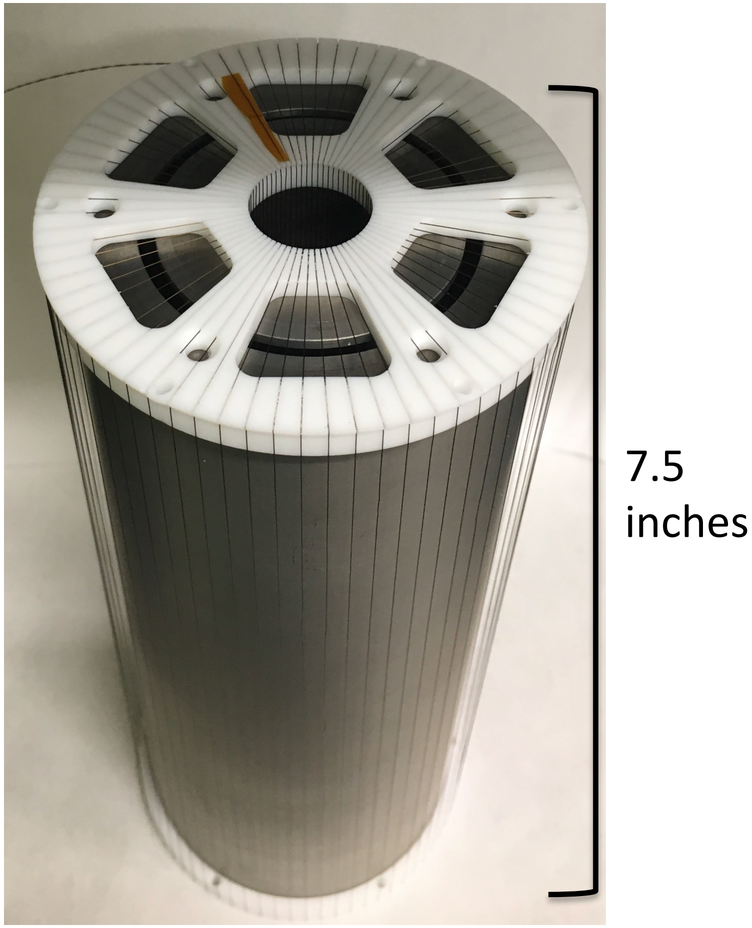
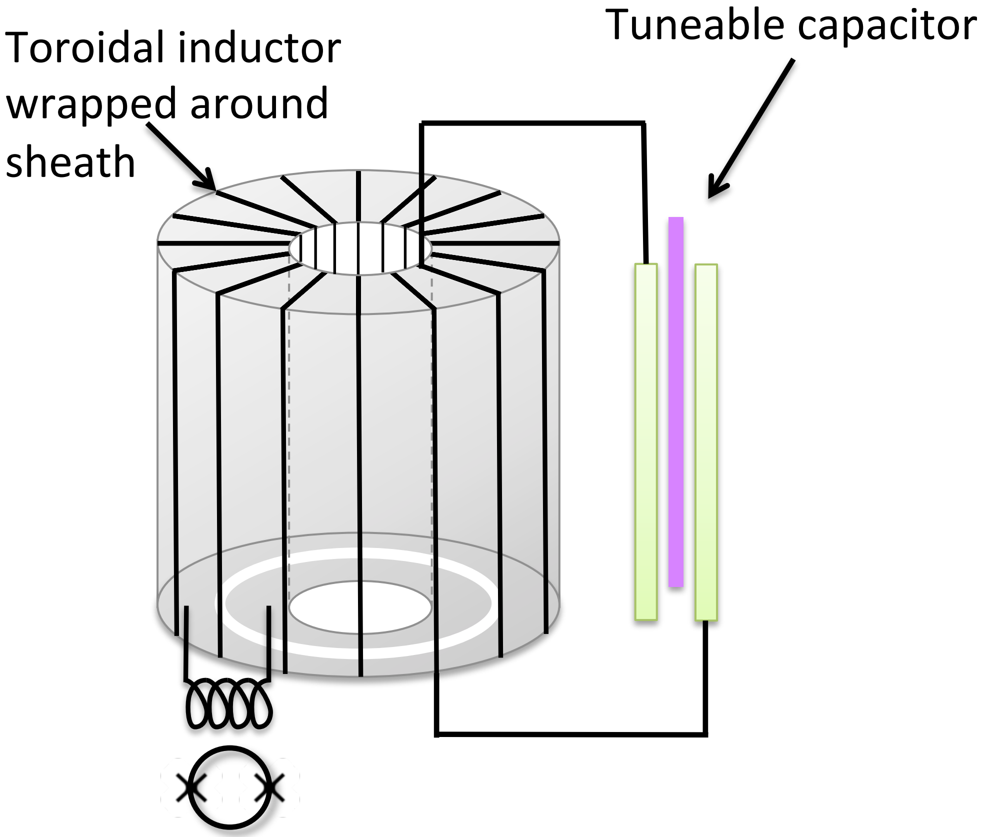


72-turn NbTi Toroidal Coil

Resonant Enhancement



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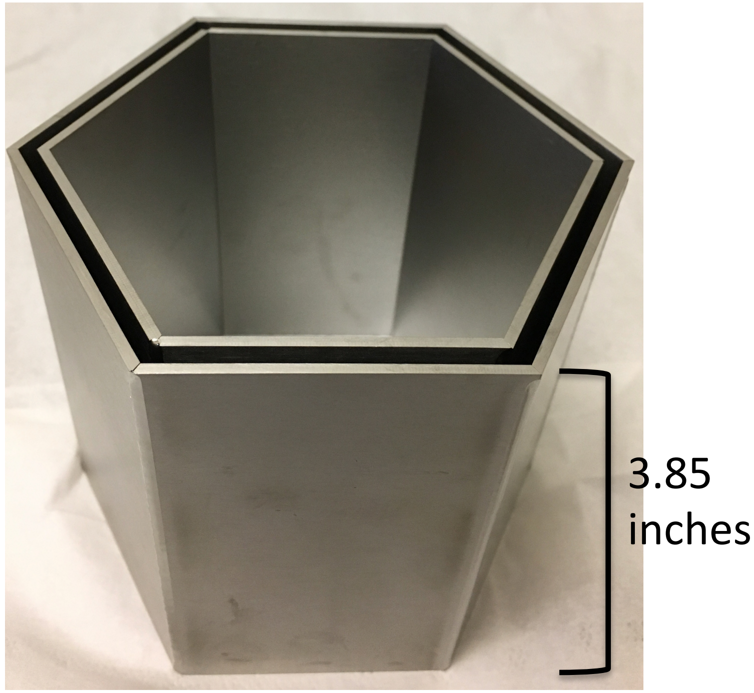
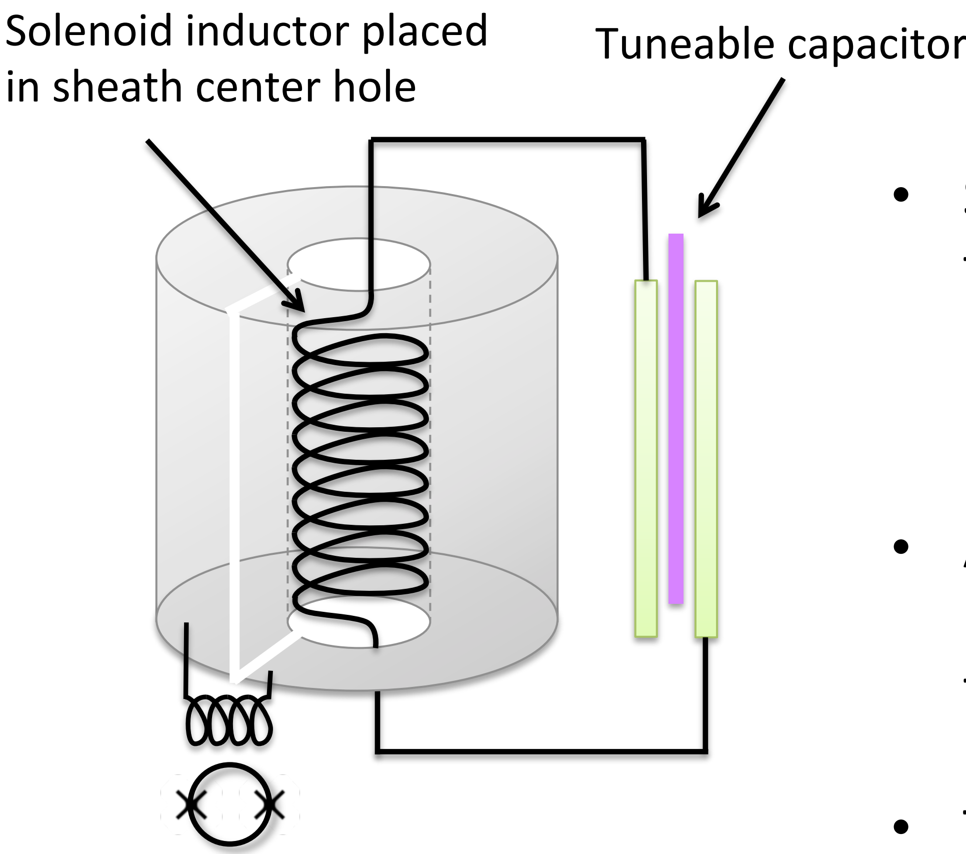


Nb Hex Capacitor

Sapphire plates (not shown) used to tune

Resonant Enhancement



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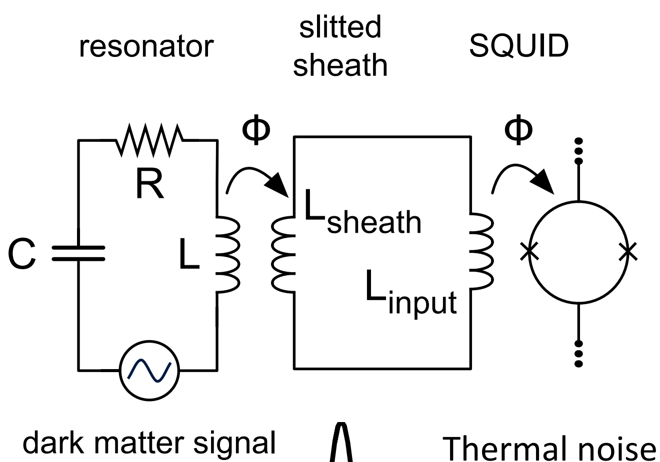
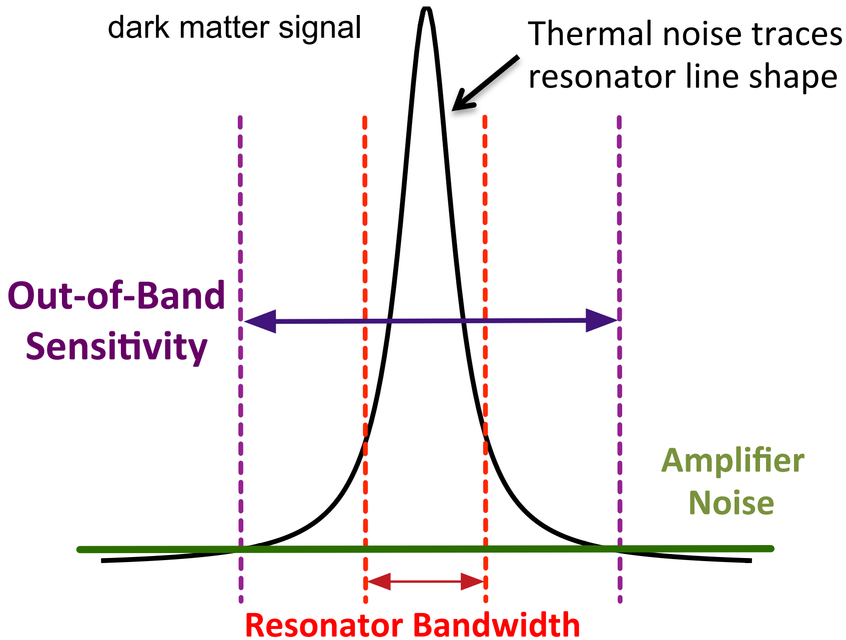
Resonant Enhancement

Equivalent Circuit Model





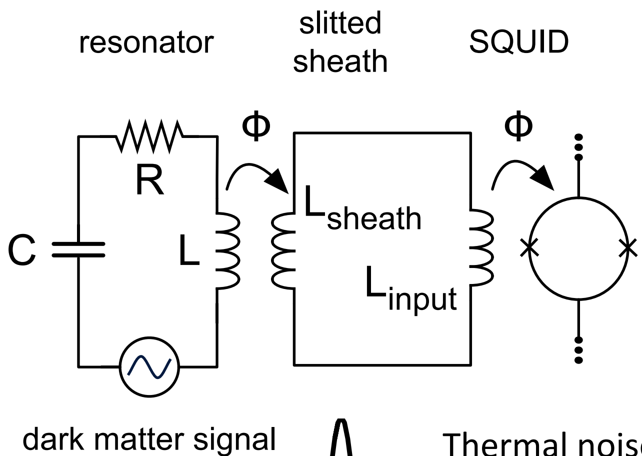
Looking for excess power above thermal noise

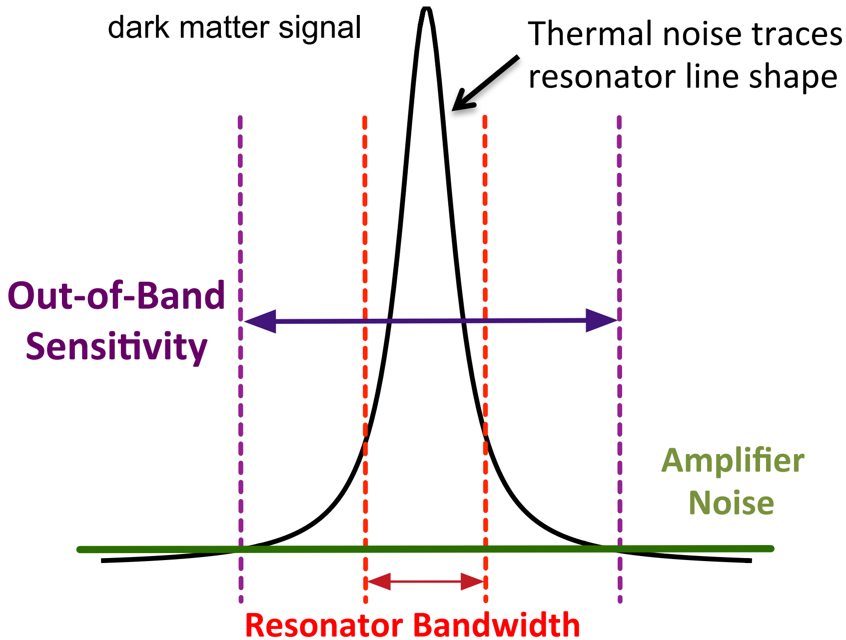
To maximize signal-to-noise…

- Large volume: $\mathrm{SNR} \propto V^{5/6}$ (in amplitude)
- Minimize R (sets Q): $\propto Q^{1/4}$
  - Goal: $Q \sim Q_{\mathrm{DM}} \sim 10^6$
- Decrease temperature: $\propto T^{-1/2}$
- Minimize readout noise
  - Determines scan depth/time
  - Still want quantum-limited amps!

Resonant Enhancement

Equivalent Circuit Model





Looking for excess power above thermal noise

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More details: See Kent Irwin's talk or Chaudhuri et al
Fundamental limits of electromagnetic axion and hidden-photon dark matter searches
arXiv:1803.01627

- Minimize readout noise
  - Determines scan depth/time
  - Still want quantum-limited amps!

DM Radio Pilot

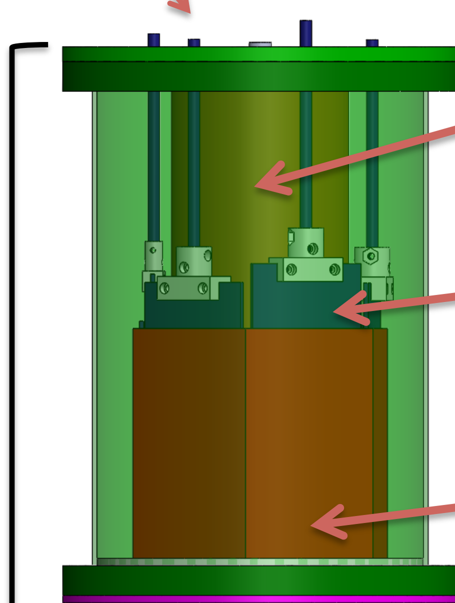
4K Dip Probe

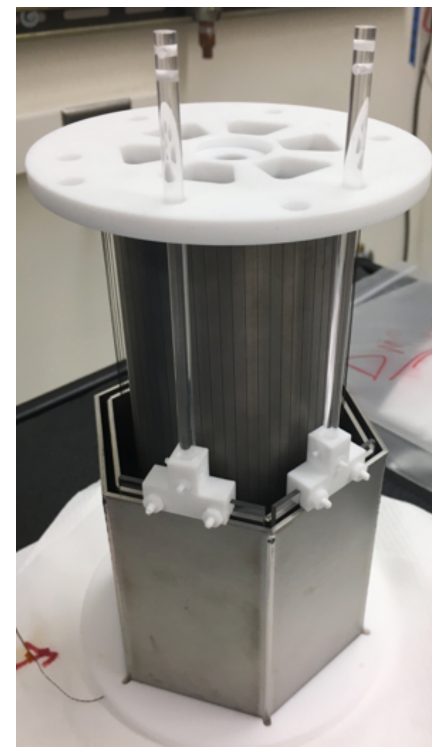
Cryoperm-lined LHe dewar

700 mL Pilot construction through SLAC LDRD

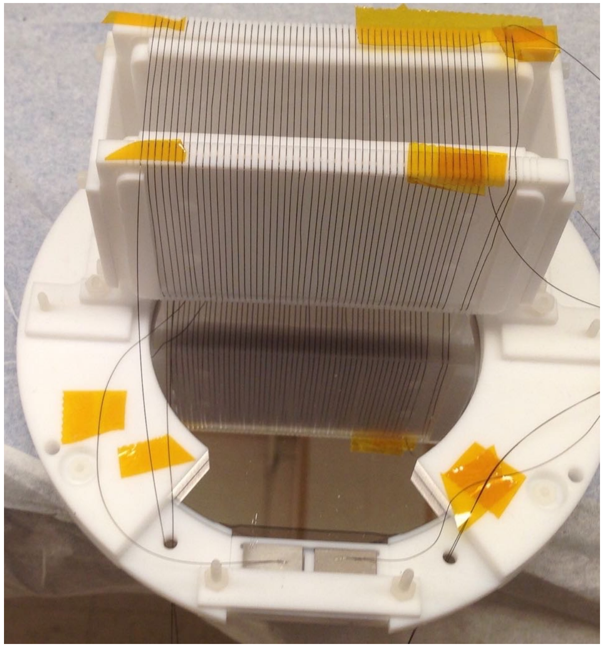
- Focus on hidden photons
- T=4K (Helium Dip Probe)
- Frequency/Mass Range:
  - 100 kHz – 10 MHz / 500 peV – 50 neV

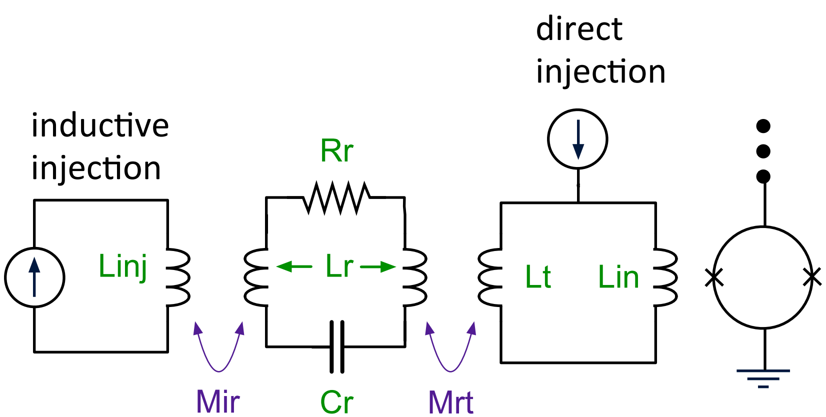
Science scans begin Fall 2018!





DM Radio Fixed Resonator





Resonator

- 40-turn NbTi coil (~53 uH)
- 2 nF sapphire capacitor
- Resonance at ~500 kHz
- 100 mL detection volume

Pickup Transformer

- Equivalent to "slitted sheath"
- Single-turn coil (~750 nH)
- Connected to SQUID input coil

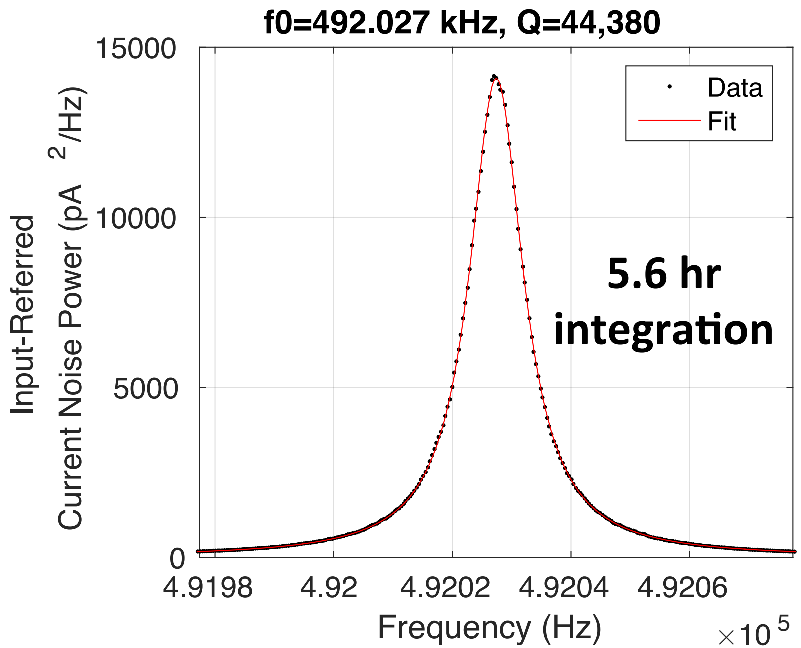
Readout

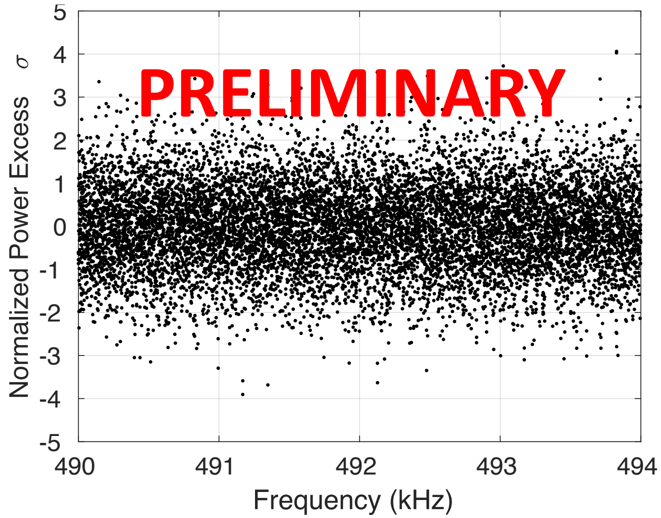
- Re-purposed SQUID we designed for TES readout
- Nb wirebonds to input coil

Calibration

- Single-turn injection coil
- Direct injection into transformer coil

DM Radio Fixed Resonator





Q-factor improvement from 2,800 → 44,380

- Switch to Nb wirebonds
- Remove or solder-coat all normal-metal hardware
- Clean up amplifier noise

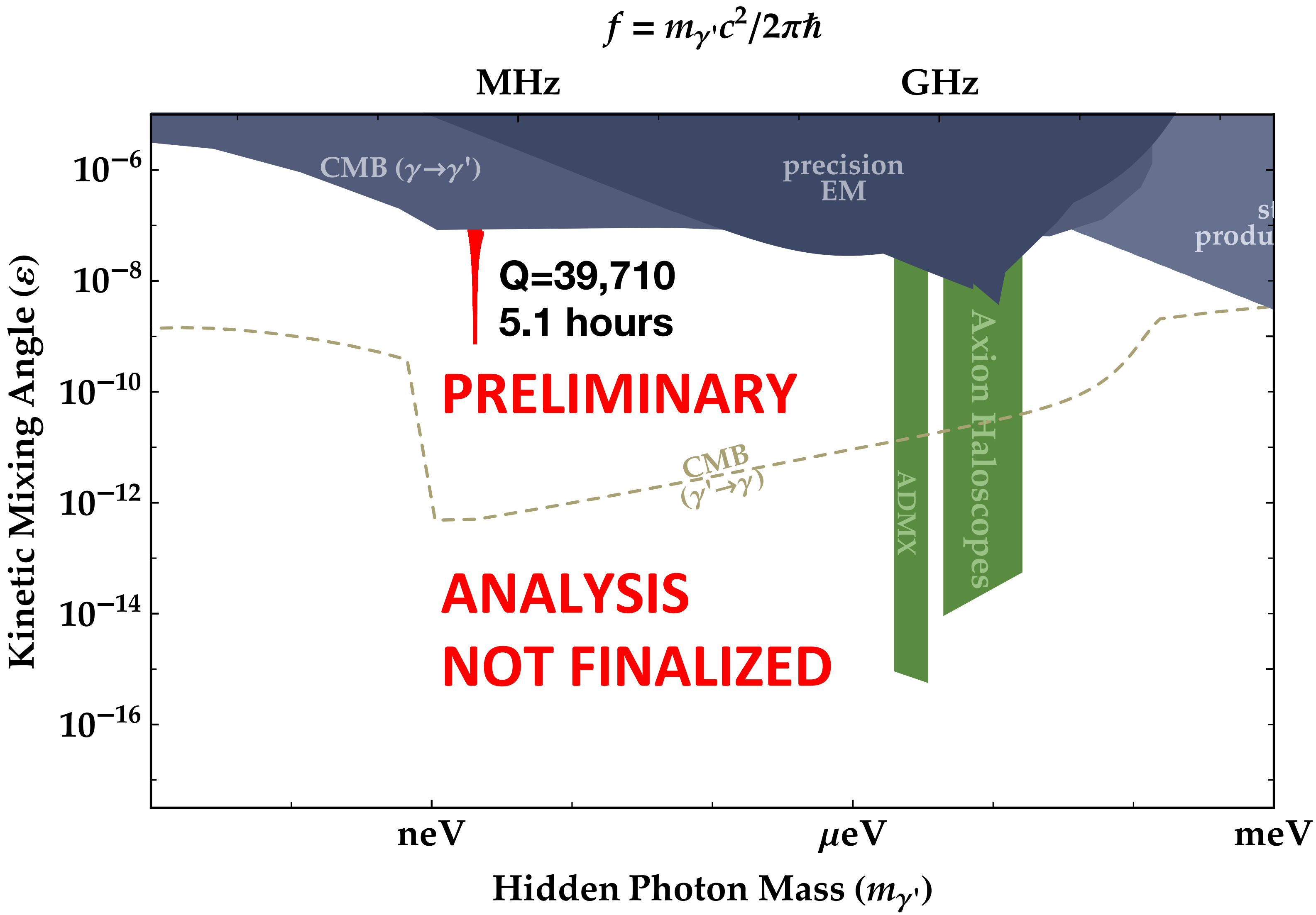
About 30 bandwidths of out-of-band sensitivity!

Preliminary check:
No 5σ power excess

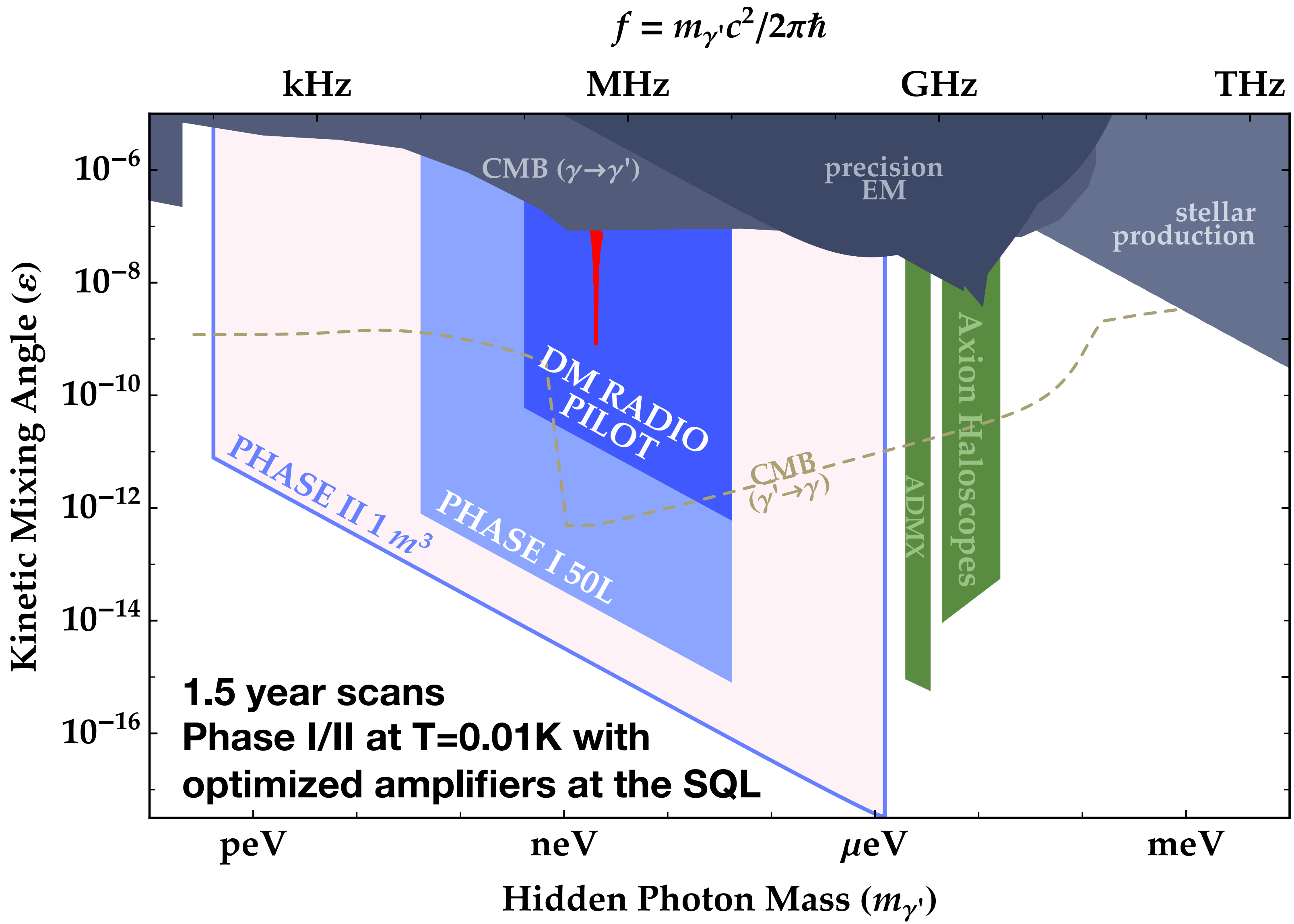
Higher Q expected from Pilot

- 10x higher characteristic impedance
- Vacuum-gap Nb capacitor
- Better B-field containment

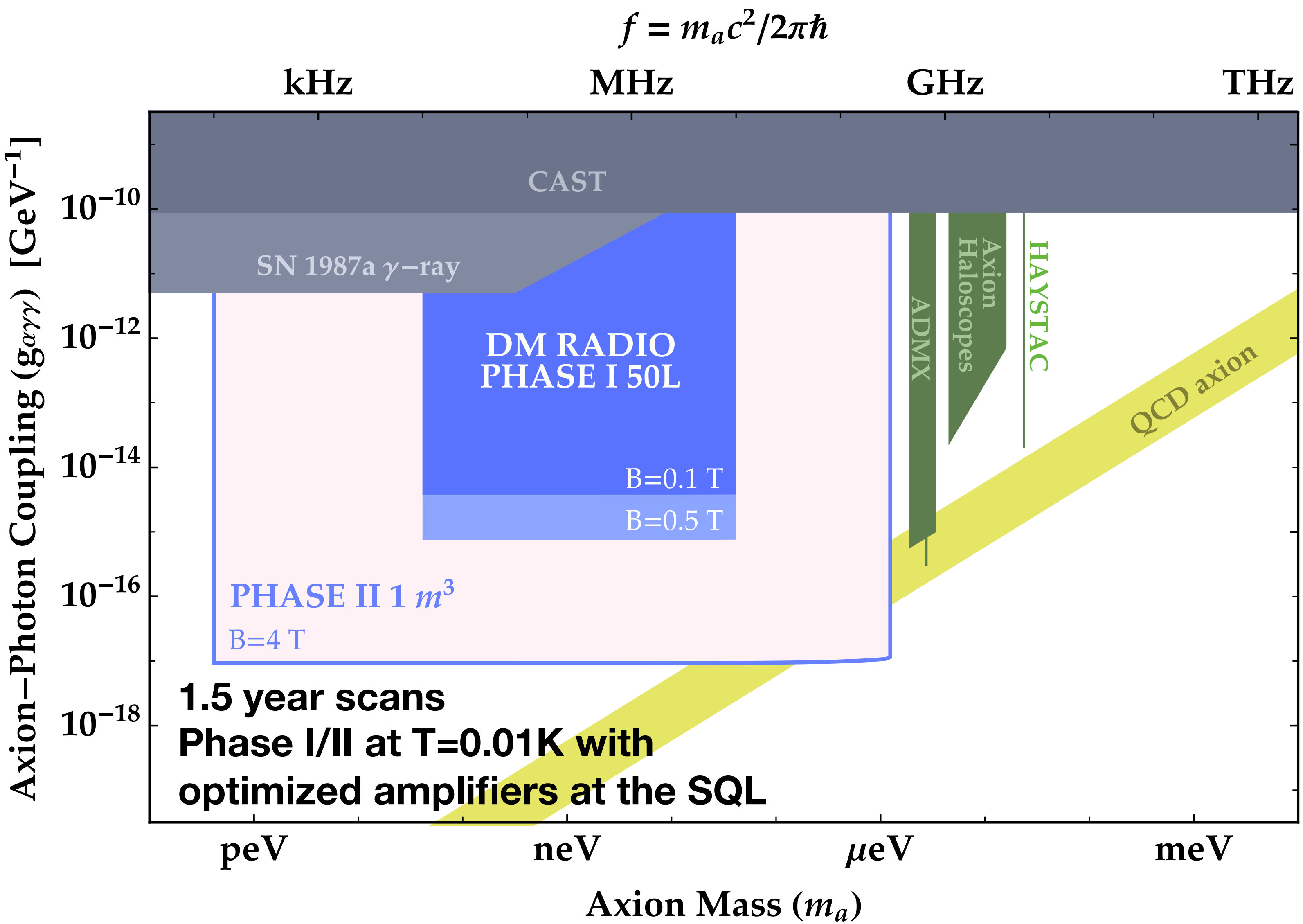
DM Radio Fixed Resonator



Hidden Photon Sensitivity



Axion Sensitivity



Program Status

Detector	Detector Volume	Target Candidates	Operating Temp	Frequency/Mass Range	Status
Fixed Resonator	100 mL	Hidden photons	4.2 K	500 kHz 1 neV	Analysis
Pilot	700 mL	Hidden photons	4.2 K	100 kHz – 10 MHz 500 peV – 50 neV	Science scans begin Fall 2018
Phase I	50 L	Hidden photons and axions	10 mK	10 kHz – 10 MHz 50 peV – 50 neV	Dil. fridge arrives Nov. 2018
Phase II	1 m^3	Hidden photons and axions	10 mK	100 Hz – 300 MHz ~1 peV – ~1 μeV	Planning

With a dilution refrigerator…

- Use aluminum instead of Nb
- Add magnetic field for axions
- Quantum-limited amplifiers

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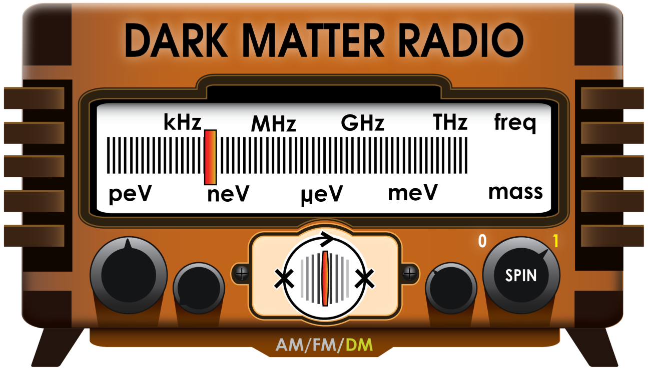
Conclusions



DM Radio:
A Superconducting Lumped-Element
Dark Matter Detector
For Axions and Hidden Photons

QuantISED

Publications

Chaudhuri et al., **Radio for hidden-photon dark matter detection**
Phys. Rev. D 92, 075012 (2015) / arXiv:1411.7382

Chaudhuri et al., **Fundamental limits of electromagnetic axion and hidden-photon dark matter searches**
arXiv:1803.01627

Silva-Feaver et al., **Design Overview of the DM Radio Pathfinder Experiment**
IEEE Transactions on Superconductivity 27, no. 4 (2017) / arXiv:1610.09344

Graham and Scherlis, **The Stochastic Axion Scenario**
arXiv:1805.07362

Graham, Mardon, and Rajendran, **Vector dark matter from inflationary fluctuations**
Phys. Rev. D 93, 103520 (2016) / arXiv:1504.02102