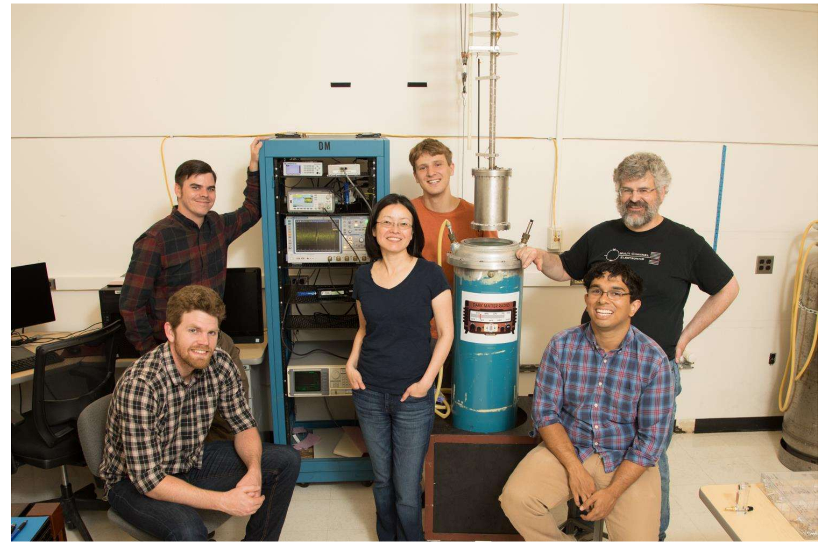



# DM Radio: An Optimized Resonant Search For Axion and Hidden-Photon Dark Matter, 100 Hz-300 MHz

**DM Radio DJs:**

**Stanford:** **Saptarshi Chaudhuri,** Hsiao-Mei Cho, Carl Dawson, Peter Graham, Kent Irwin, Stephen Kuenstner, Dale Li, Arran Phipps

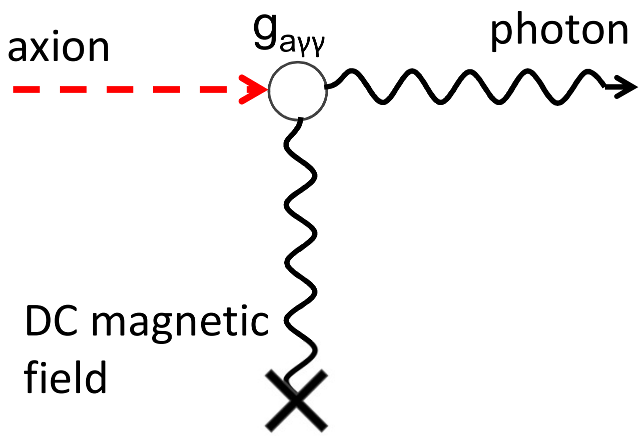
**Berkeley:** Surjeet Rajendran

**Collaborators on DM Radio extensions:**

Tony Tyson, UC Davis, Lyman Page, Princeton

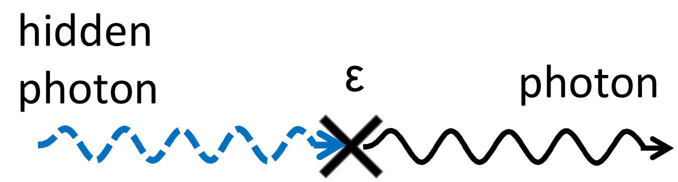
HEISING-SIMONS FOUNDATION KIPAC SLAC Cal UC DAVIS UNIVERSITY OF CALIFORNIA PRINCETON UNIVERSITY

## Axions (spin 0)




- Solves strong CP problem
- Converts to photon via inverse Primakoff effect- requires background EM field
- Photon frequency gives mass, $hf=mc^2$
- ~$10^{-6}$ bandwidth set by DM virial velocity

## Hidden Photons (spin 1)

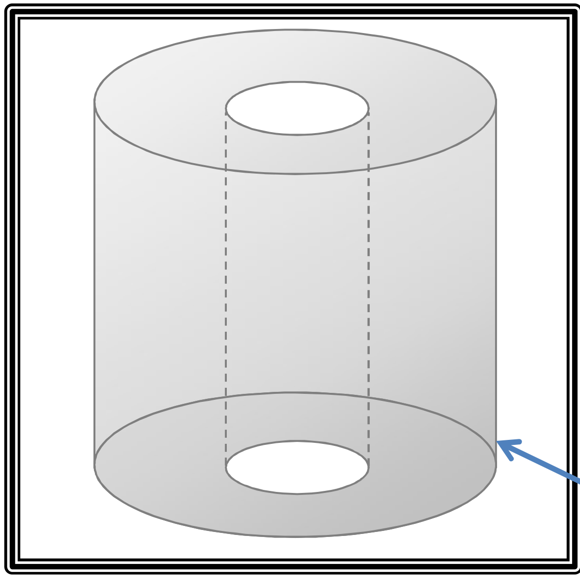


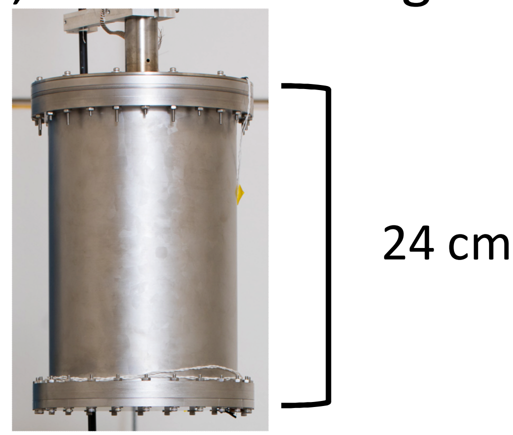

- Appears in generic extensions of Standard Model, may be produced by cosmic inflation
- Converts via kinetic mixing
- Photon frequency gives mass, $hf=mc^2$
- ~$10^{-6}$ bandwidth set by DM virial velocity

DM behaves as effective EM current density →
Look for oscillating, quasi-static magnetic field

# Detection scheme

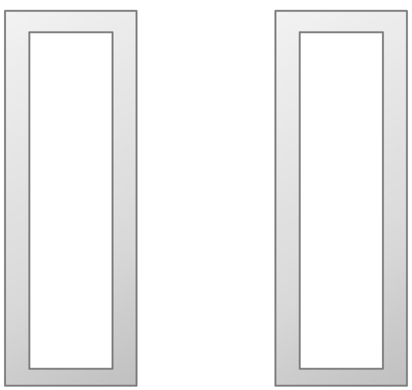
Superconducting shield- blocks photons, lets DM through

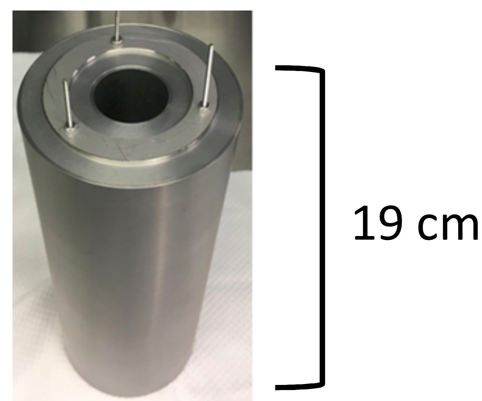





Hollow, superconducting sheath (like a long, hollow donut)

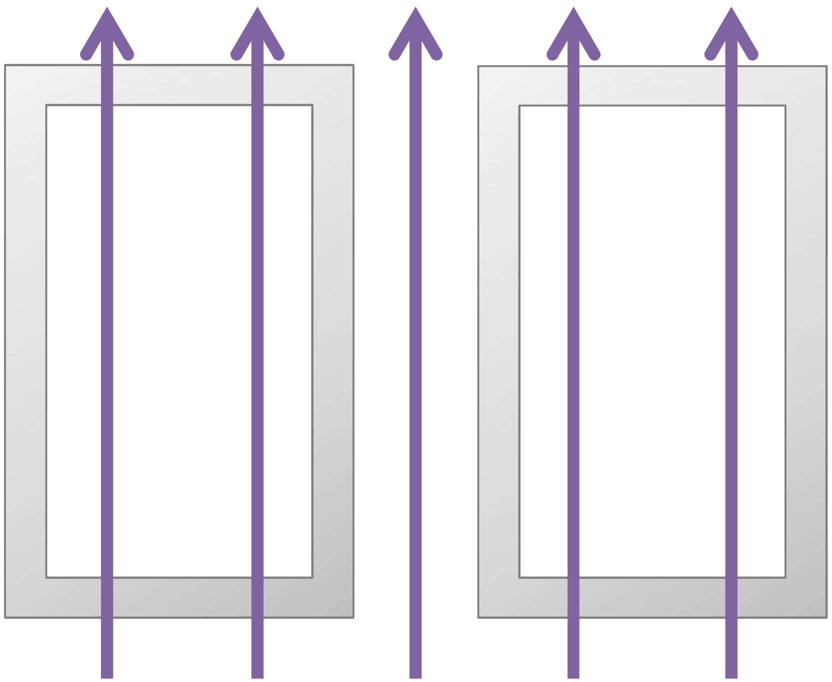
Cross-section



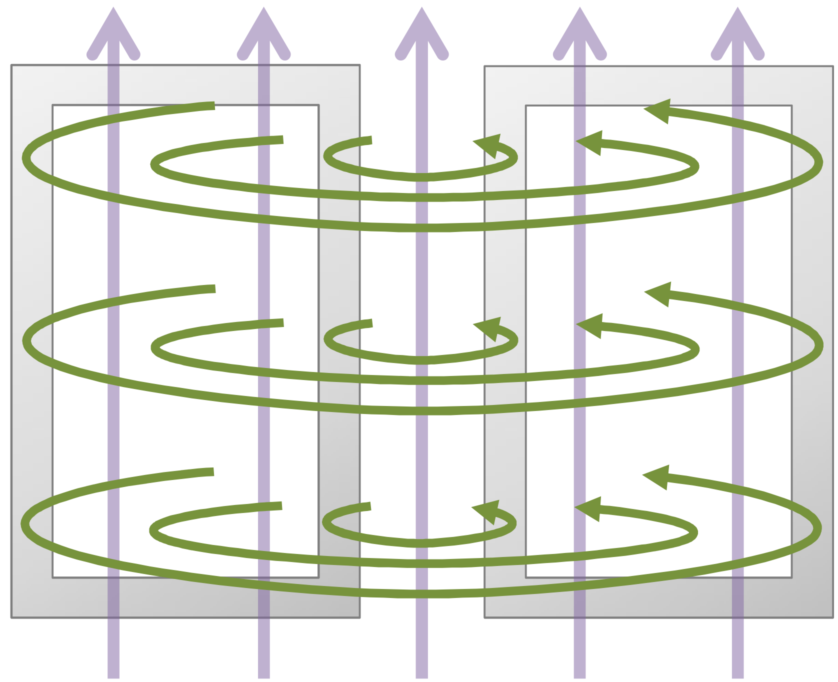


# Hidden photon detection

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

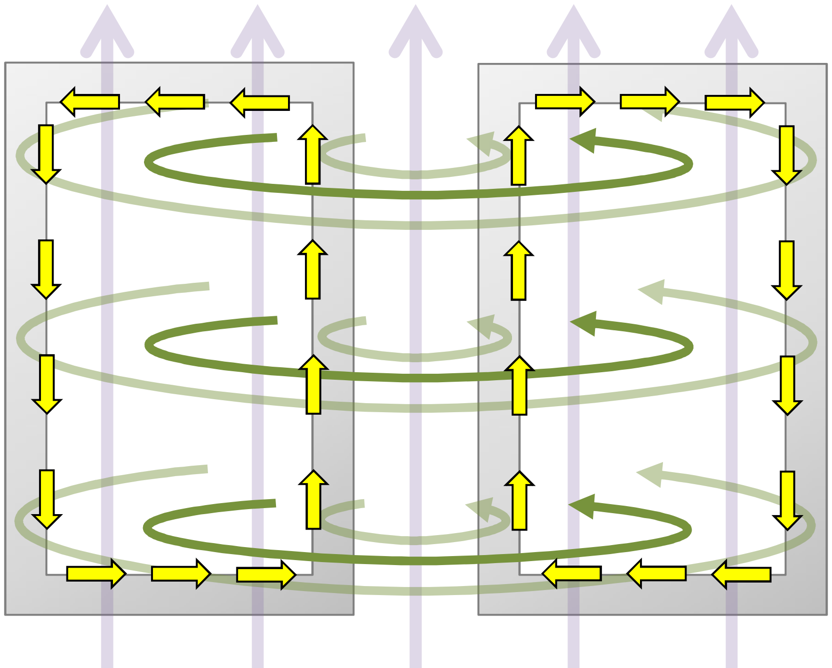


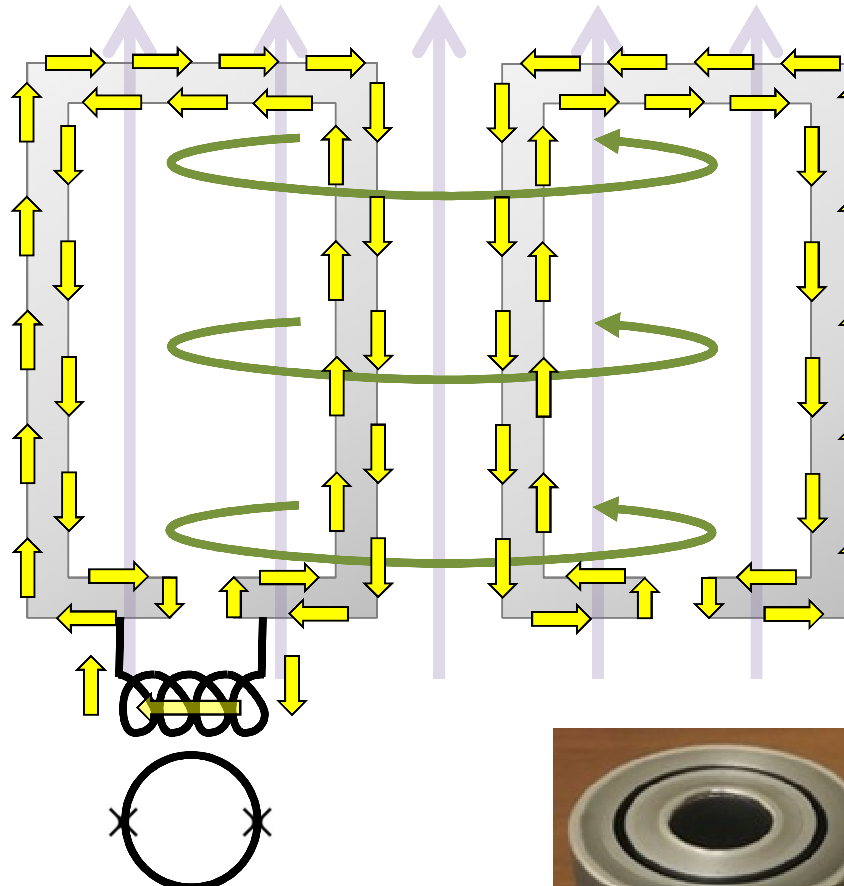
$$\vec{B}_{\mathrm{HP}}(t) = |\vec{B}_{\mathrm{HP}}(t)|\,\hat{\phi}$$

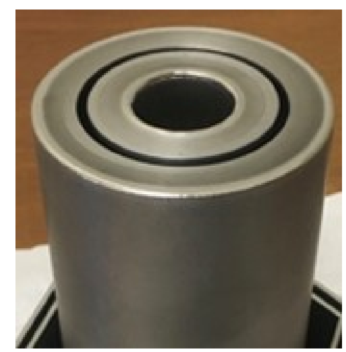


1. Hidden photon field acts as effective AC current.
2. Current generates circumferential, quasi-static B-field.

# Hidden photon detection



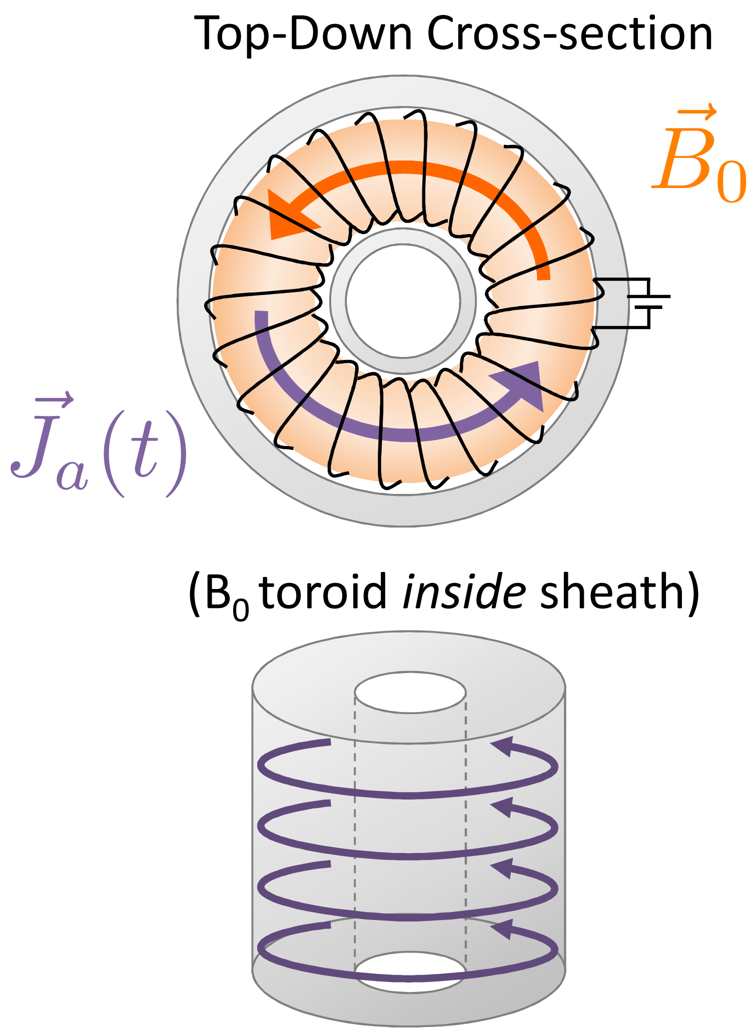


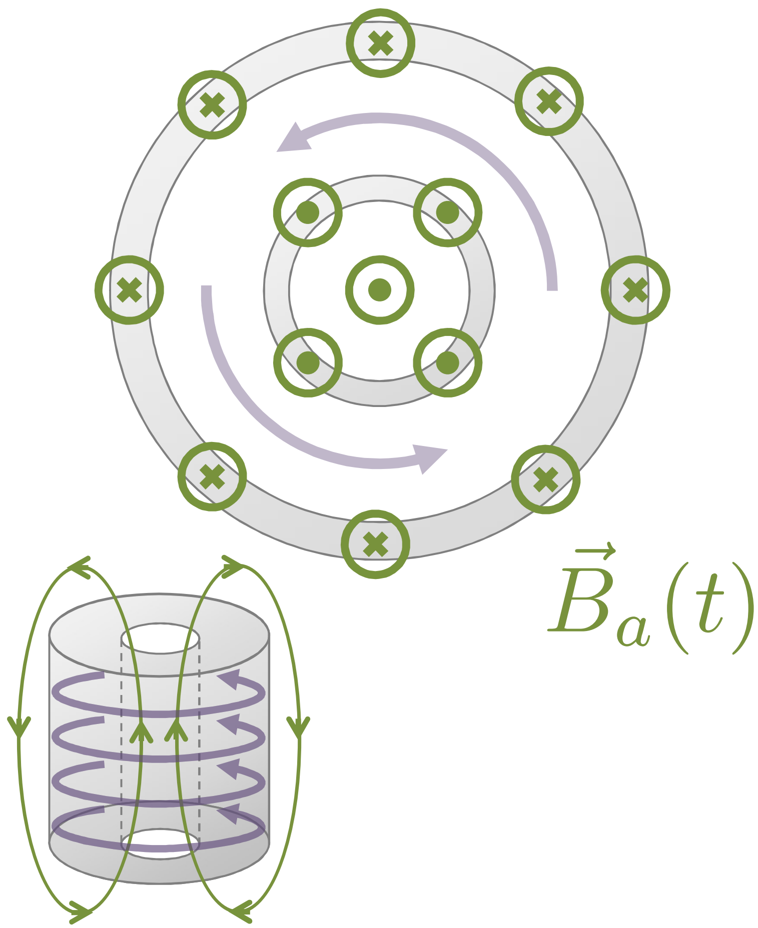


3. Screening currents (yellow) flow to cancel field in bulk.

4. Cut slit in sheath, detect currents with SQUID.

# Axion detection

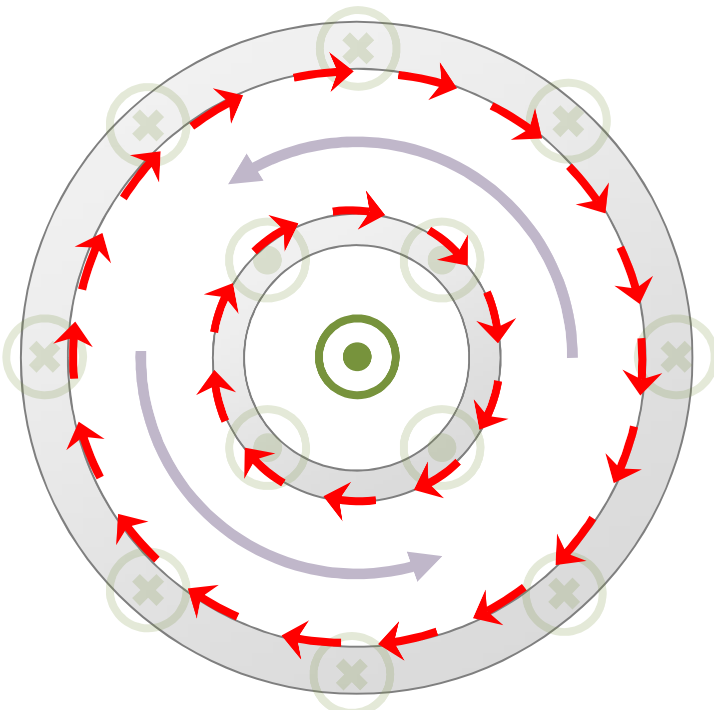


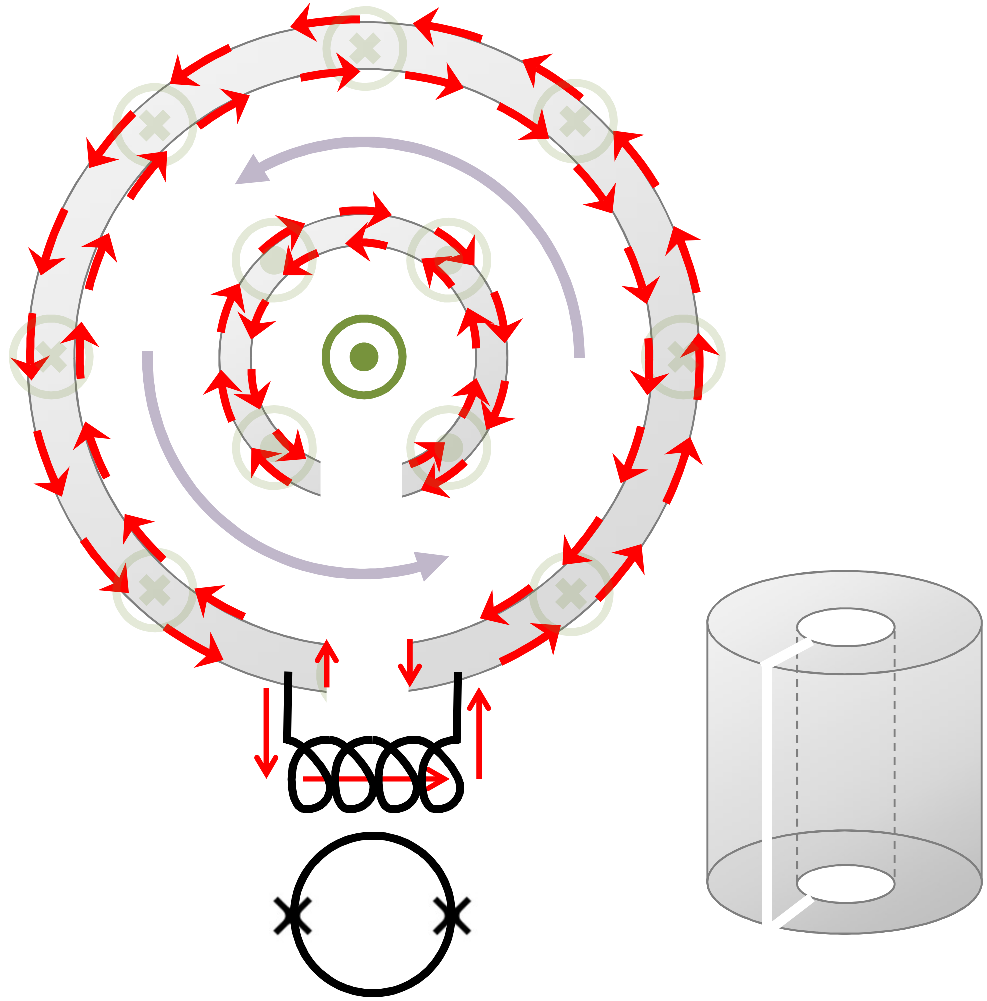




1. Toroidal coil produces DC magnetic field inside sheath. Axions behave as AC current.

2. Current generates oscillating, quasi-static B-field.

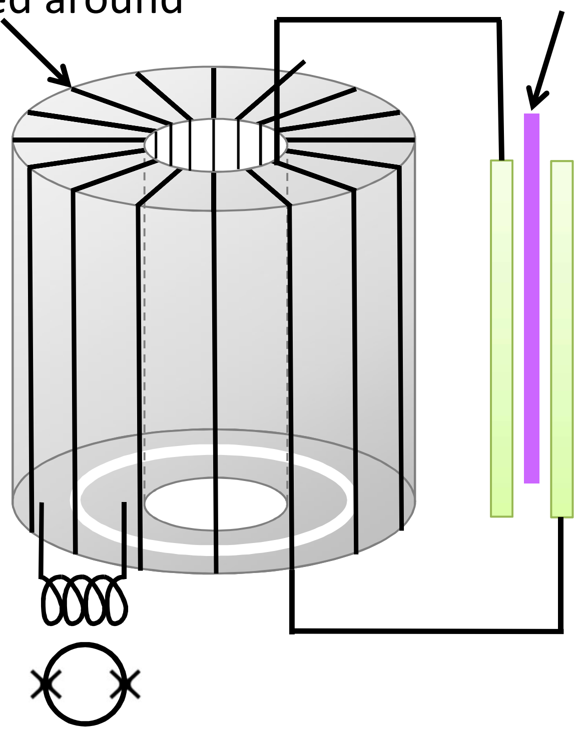
# Axion detection



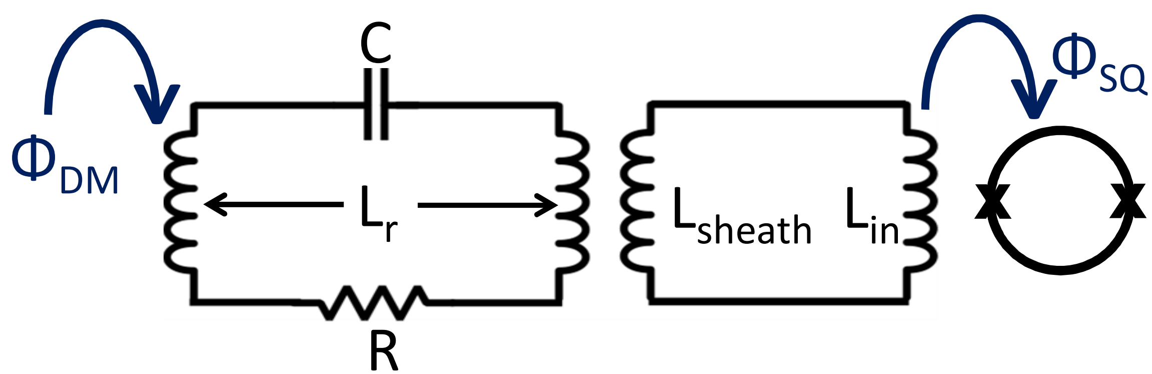


3. Screening currents (red) flow to cancel field in bulk.
4. Cut side slit in sheath, detect currents with SQUID.

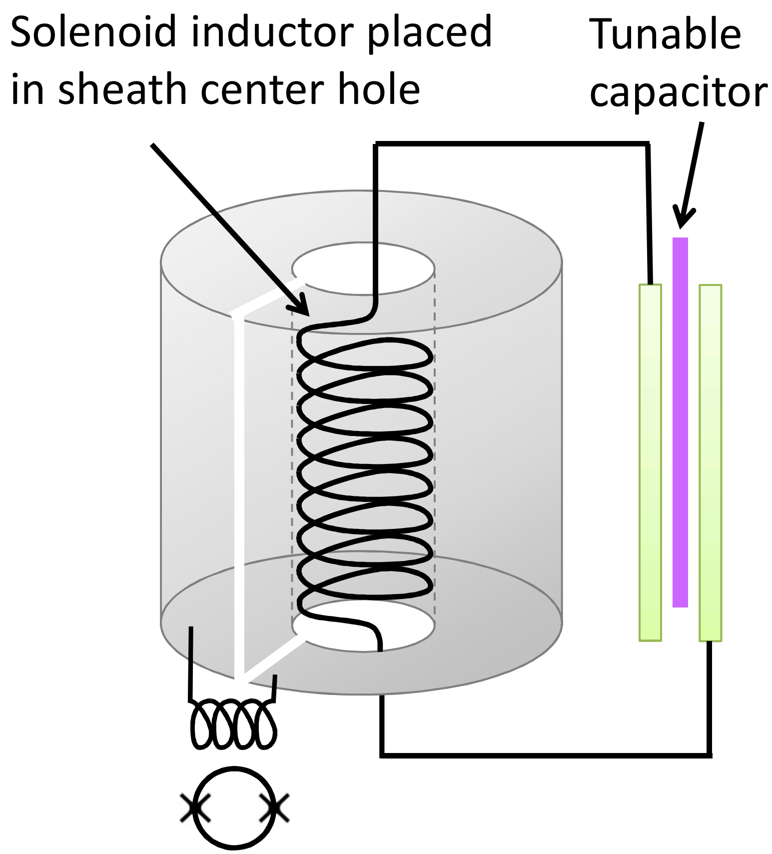
# Resonant enhancement for hidden photons




- Add 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
- S. Chaudhuri et al, PRD **92**, 075012 (2015)
- M. Silva-Feaver et al, IEEE Trans. On Appl. Superc. **27**, 1 (2016)



# Resonant enhancement for axions

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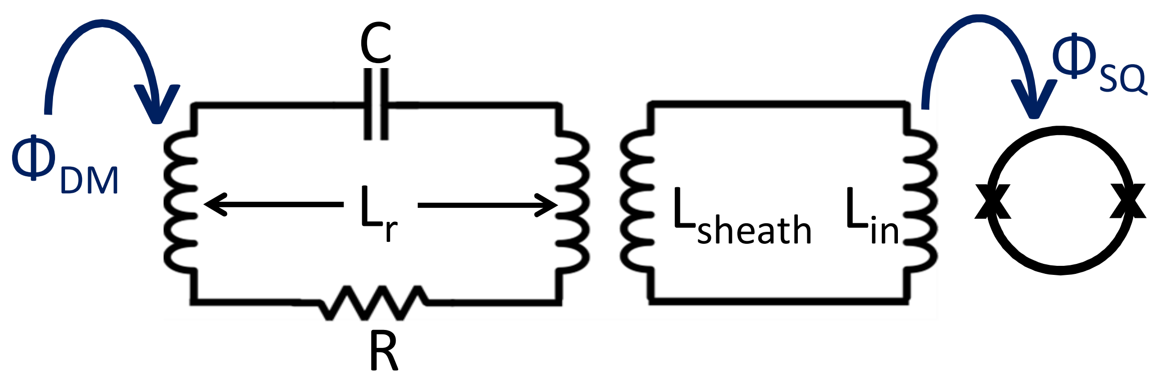
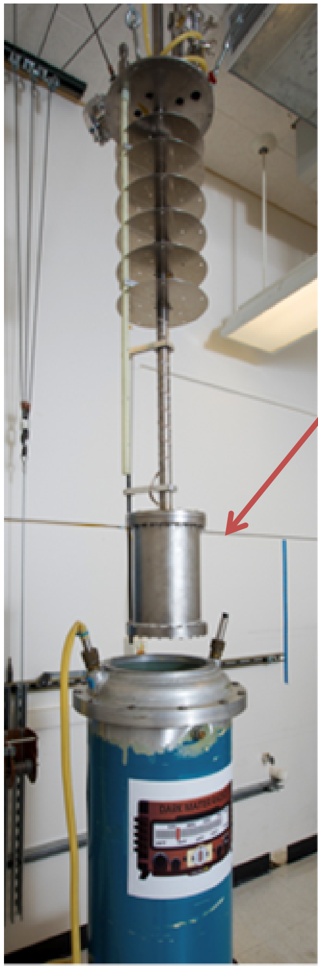


# DM Radio Pilot

**4K Dip Probe**



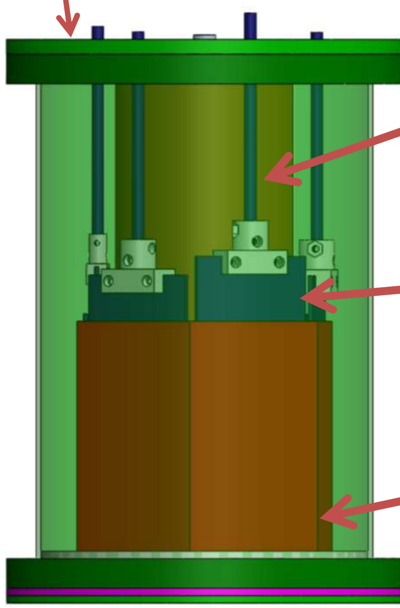
Cryoperm-lined
LHe dewar

## 750 mL Pilot funded through SLAC LDRD

- Focus on hidden photons
- T=4K (Helium Dip Probe)
- Frequency/Mass Range:
  - 100 kHz – 10 MHz / 500 peV – 50 neV
- 2-3 month scan time

**Science scans begin this year!**

Nb shield



Nb slitted sheath

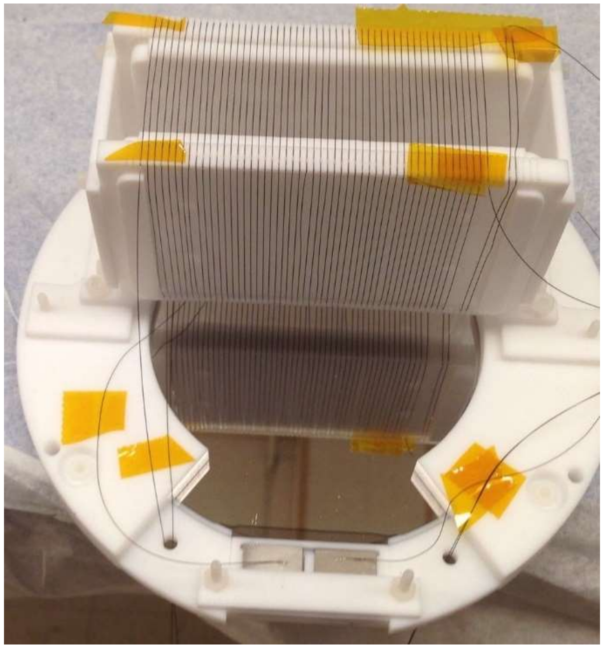
Movable
sapphire dielectrics

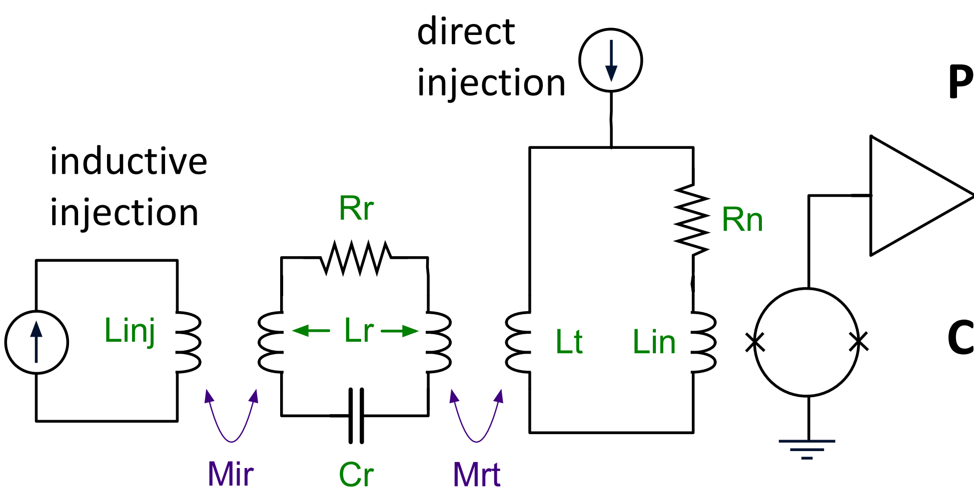
Nb hex capacitor

7.5 cm

19 cm

# DM Radio fixed resonator






**Goals**

- Demonstrate high Q~$10^6$
- Understand material properties
- Characterize SQUID amplifiers
- Establish calibration and data analysis procedures

**Resonator**

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

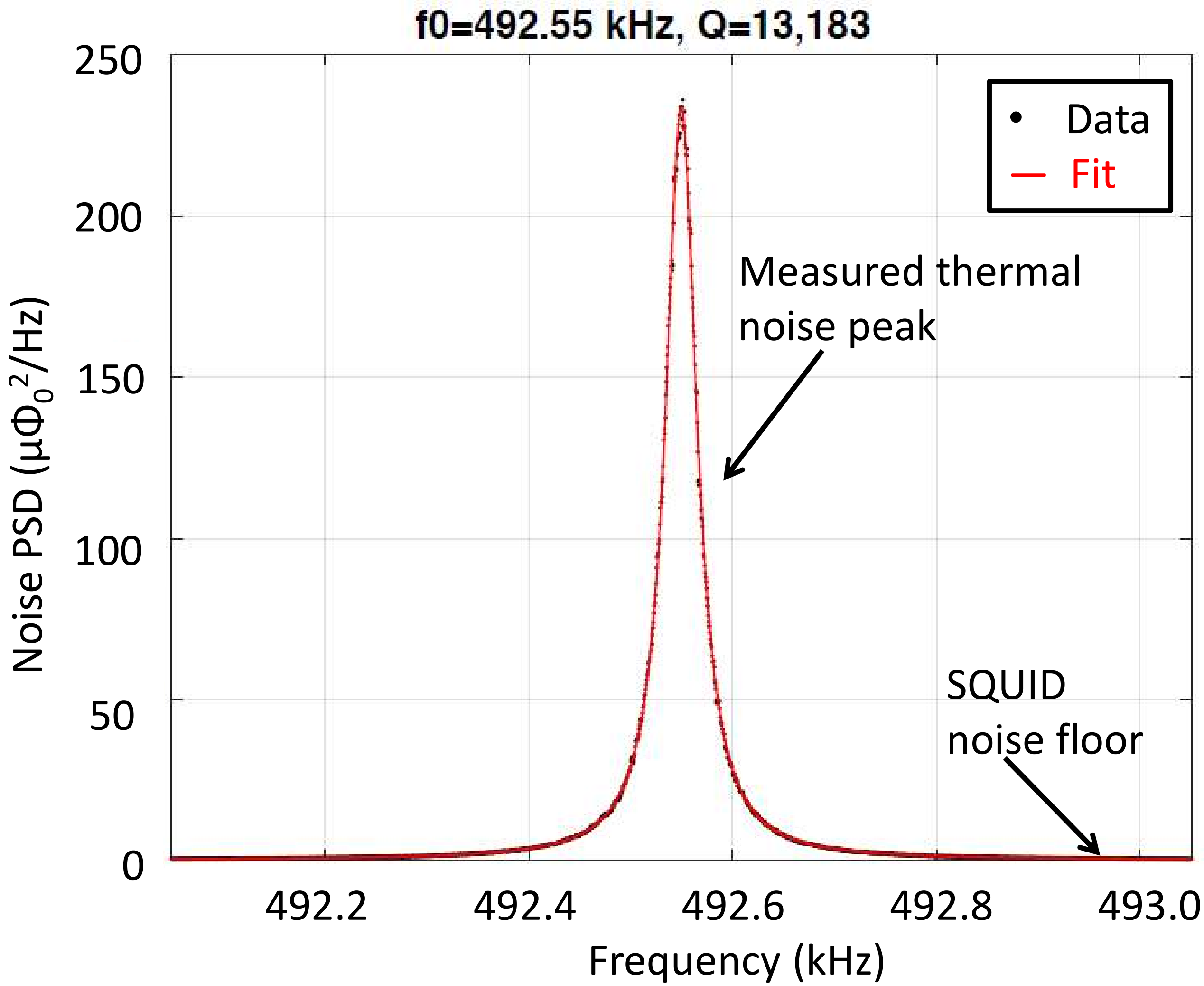
**Pickup Transformer**

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

**Calibration**

- Single-turn injection coil (~750 nH)
- Direct current injection into transformer coil

# DM Radio fixed resonator: Q=13,183




- Q likely limited by loss in support structure- will replace with different materials
- Several hours of integration to test calibration/analysis protocols

# Next steps

- Continue work on increasing Q factor, SQUID optimization
- Pilot detector: all parts (niobium, sapphire, PTFE) fabricated. Characterization of tuning system.
    - Pilot science scans begin this year!
- Dil fridge for Phases 1 and 2 to be delivered in November.
    - Phase 1: 30L, 10 mK
    - Phase 2: 1000L, 10 mK
- Begin magnet R&D for axion detection soon after!
- Q, volume, temperature, applied B-field…What other knobs can we turn to improve sensitivity?

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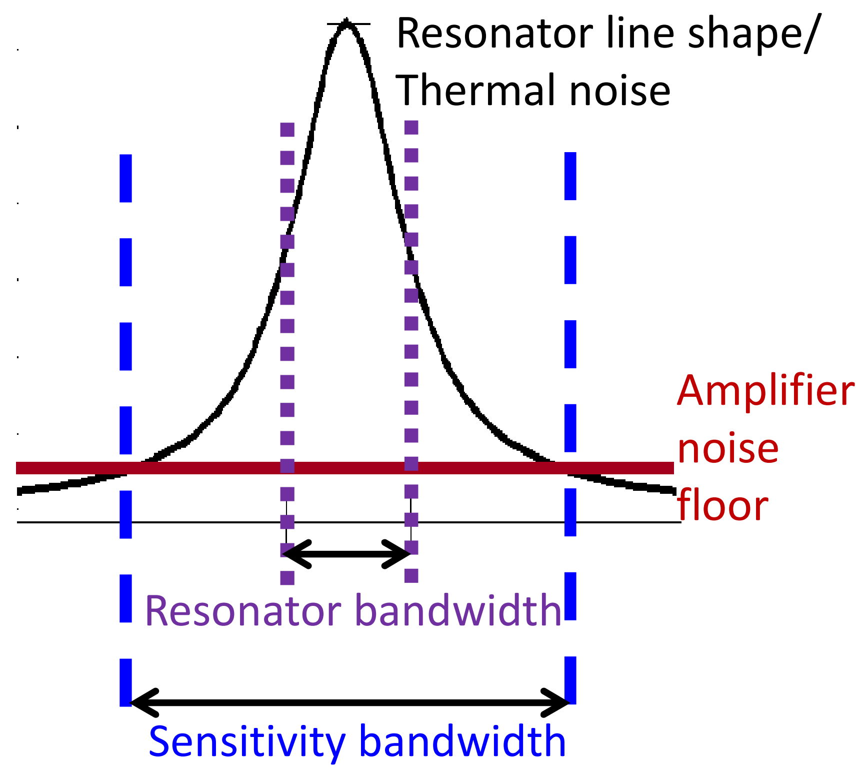
Knobs informed by fundamental limitations on electromagnetic DM searches.

"Fundamental Limits of Electromagnetic Searches for Axions and Hidden Photons: Part I-The Quantum Limit"
S. Chaudhuri, K. Irwin, P. Graham, J. Mardon, arxiv:1803.01627

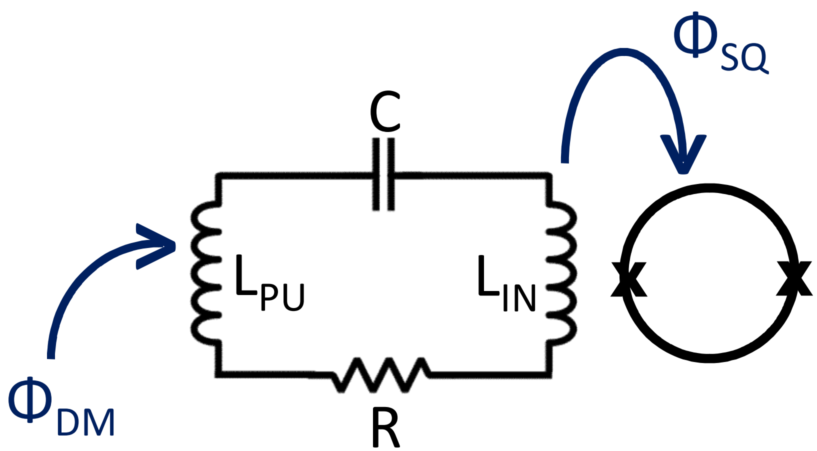
# Utilizing sensitivity outside resonator bandwidth

- SNR not degraded as long as thermal noise > amplifier noise
- Enhancement from using all information in sensitivity BW
- DM Radio fixed resonator:
  - Resonator BW: 37 Hz
  - Sensitivity BW: 1.16 kHz
- Now: optimizing Pilot SQUIDs to improve science reach

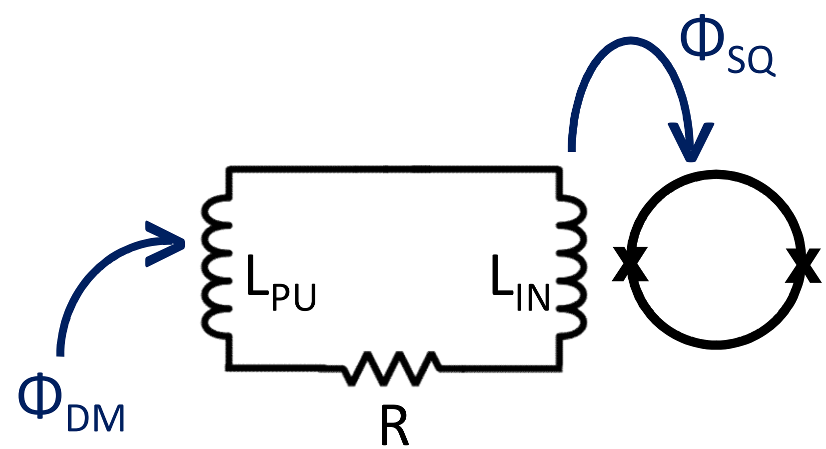



- Receiver figure of merit is not sensitivity at peak response, but *integrated sensitivity*.
- Quantum-limited amplifiers desirable for thermal states hf<kT.

# Resonator beats broadband




(e.g. DM Radio, Chaudhuri et al, PRD **92**, 075012 (2015) )

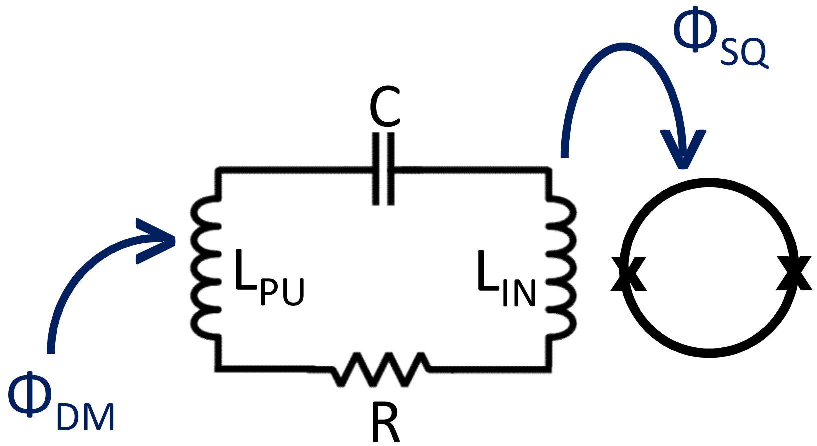



(ABRACADABRA, Kahn et al, PRL **117**, 141801 (2016) )

- Near resonance:
  - Resonator: thermal noise rung up, above amplifier noise
  - Broadband: thermal noise rolled off by LR pole, degraded by amplifier
- Far above resonance: capacitance shorts out, same sensitivity
- Resonator fixed at lowest search frequency beats broadband
- When scanned, resonator integration times a couple orders of magnitude lower than broadband

One-pole resonator is better at all frequencies where a resonator can be practically constructed (>~100 Hz)

# Resonator beats broadband

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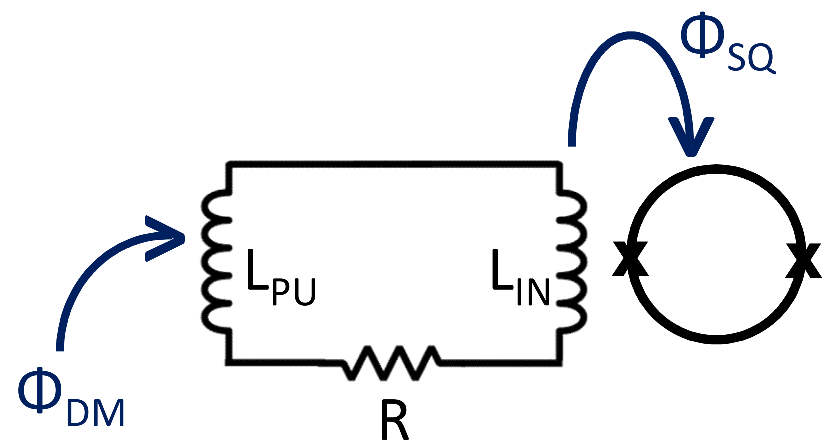


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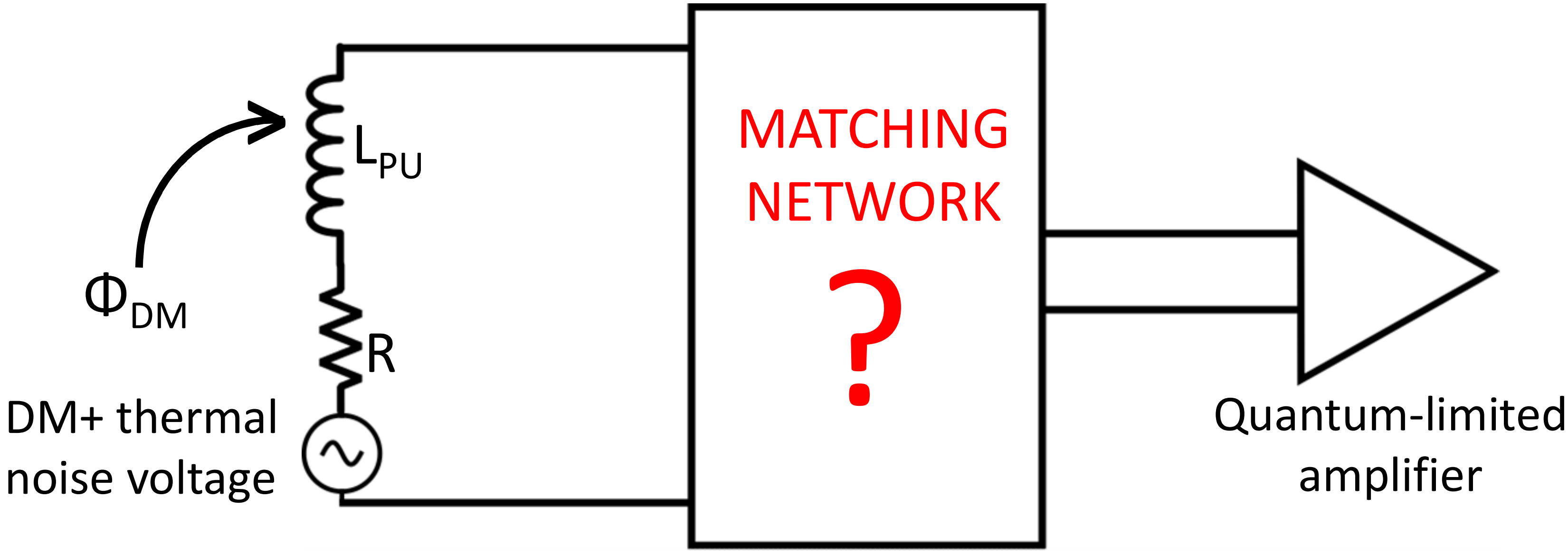
Resonant is better than broadband. *But what is best?*

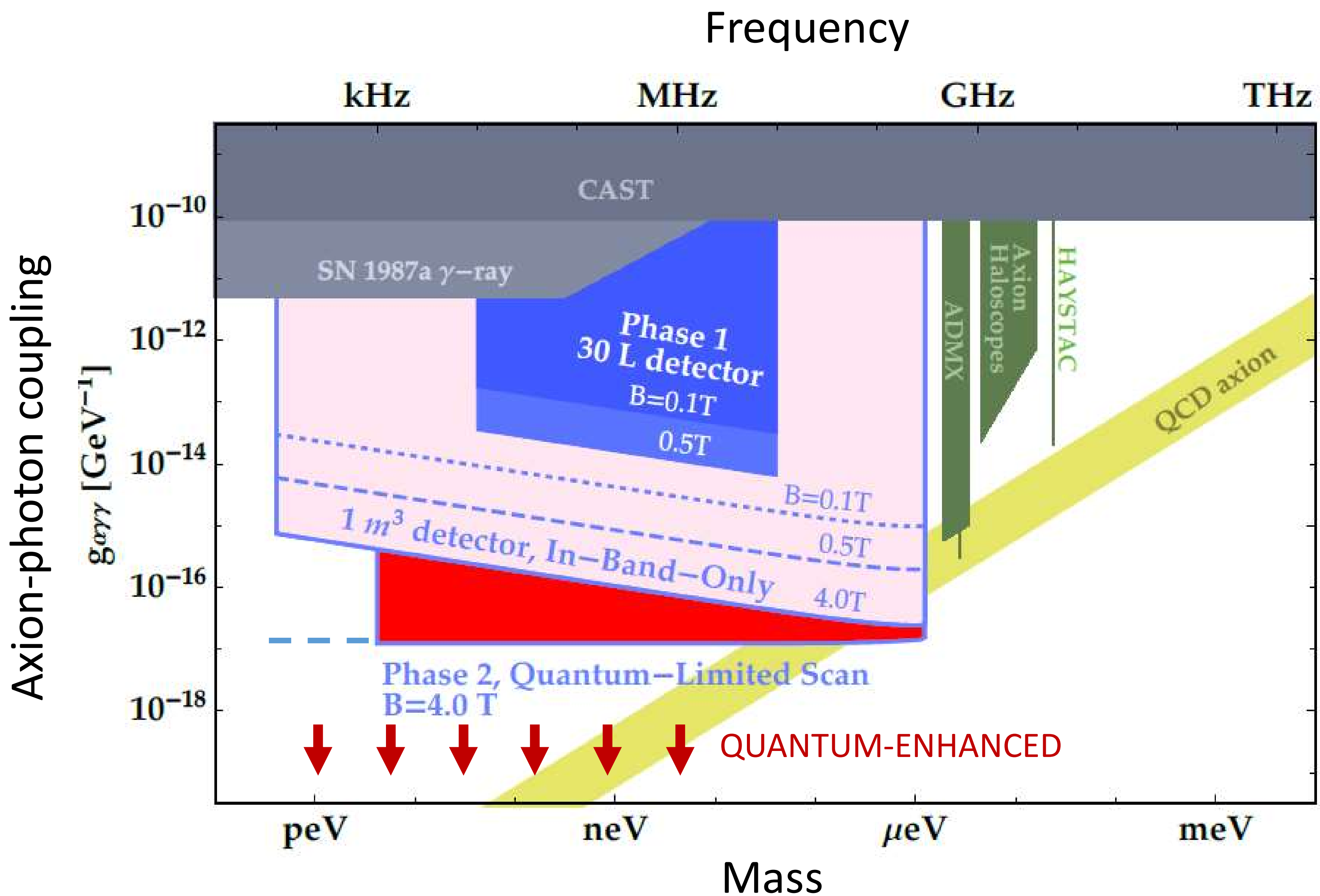
# Integrated sensitivity limited by Bode-Fano



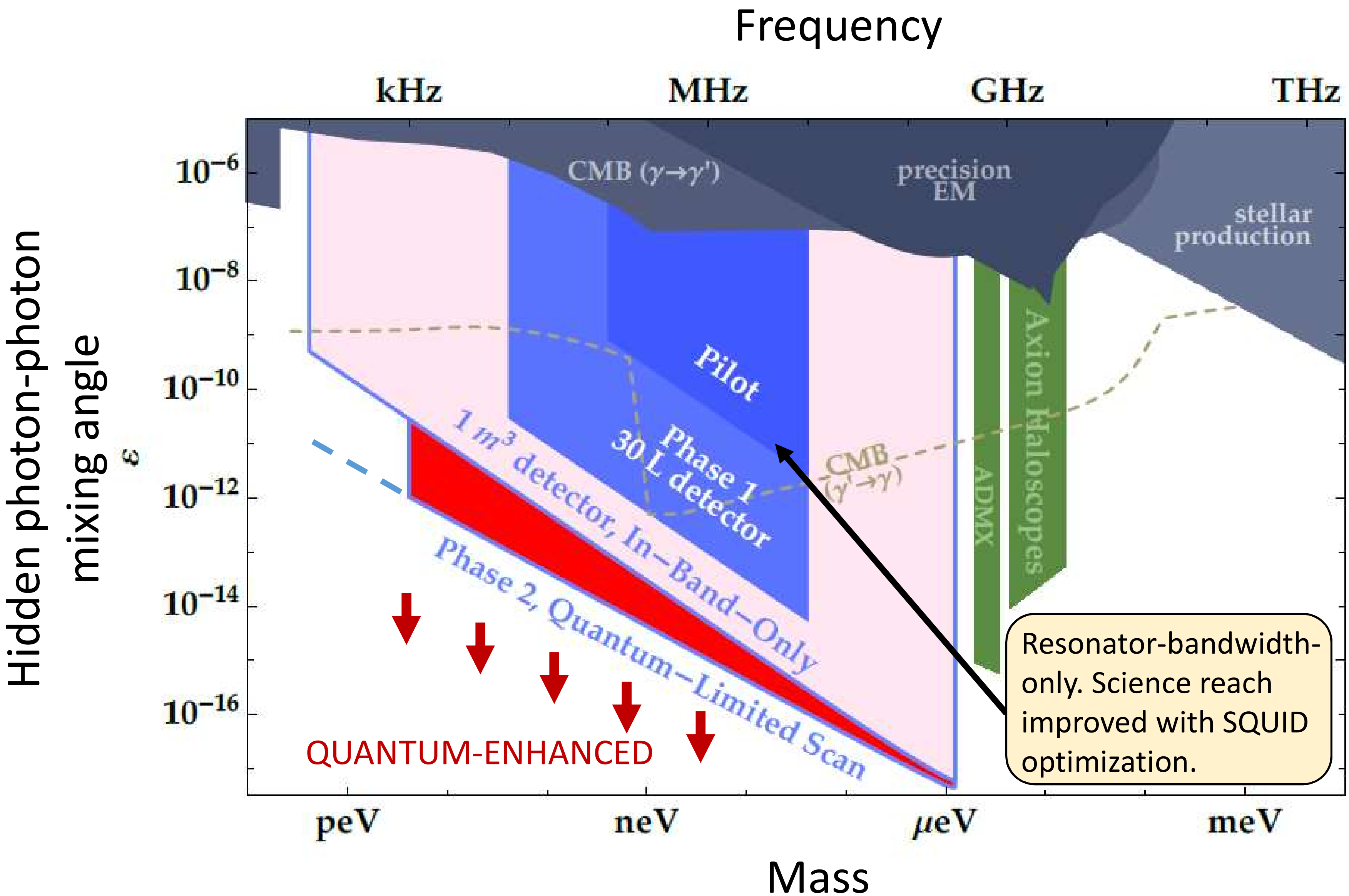

- Inductive coupling is optimal
- Matching reactance to real amplifier noise impedance
- For fixed inductor quality + pickup volume, integrated sensitivity constrained by Bode-Fano criterion
  - H.W. Bode, ``Network Analysis and Feedback Amplifier Design" (1946)
  - R.M. Fano, *Journal of the Franklin Institute* (1950)
- Single-pole resonator is ≈75% of maximum integrated sensitivity

***Resonators are fundamentally near-ideal.***

# Dark Matter Radio science: axions



# Dark Matter Radio science: hidden photons



# Summary

- DM Radio: optimized resonant search for axion and hidden photon dark-matter, 100 Hz-300 MHz
- Hidden photon measurements underway, improving Q
- Usable sensitivity outside resonator bandwidth
  - SQUID optimization underway for Pilot
- Resonant approach always beats broadband approach
- Bode-Fano: resonator searches fundamentally near-optimal
- Fundamental limits: strong motivator for quantum-limited amplifiers, measurements evading the Standard Quantum Limit

# Extras

# Fundamental limits: strong motivator for quantum sensors

- How do we get around these limits?
- Build bigger, higher quality receivers
  - $Q>10^6$ optimal
- Nonlinear, active matching circuits to evade Bode-Fano
- Evade Standard Quantum Limit on amplification using squeezing, entanglement, photon counting, backaction evasion, etc.
  - Development already under way!
  - HAYSTAC: squeezing
  - ADMX: photon counting
  - DM Radio: backaction evasion
  - More soon!