Title: Quantum Limits of Electromagnetic Axion and Hidden-Photon Dark Matter Searches

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Abstract: <p>We present fundamental limits of axion and hidden-photon dark matter searches probing the electromagnetic coupling. These limits are informed by constraints on noise in phase-insensitive amplifiers, as well as constraints on impedance matching. We motivate the use of quantum-limited amplifiers for dark matter searches, in particular at low masses/frequencies, where they provide a substantial enhancement due to sensitivity outside of the detector bandwidth. We discuss the role of priors, e.g. direct detection and astrophysical constraints, in optimizing scan strategies and comparing receiver architectures. We show that the figure of merit for wideband dark matter searches is the integrated sensitivity of the receiver circuit, and that the integrated sensitivity is constrained by the Bode-Fano criterion. The optimized single-pole resonator read out by a quantum-limited amplifier is close to the Bode-Fano limit, establishing such a search technique as a fundamentally near-ideal setup for dark matter measurement. We discuss the implications of these broad optimization statements for DM Radio, a lumped-element search for axion and hidden-photon dark matter operating in the 100 Hz (~0.5 peV)- 300 MHz (~1 ueV) range. Our results strongly motivate the use of quantum measurement techniques (e.g. squeezing, entanglement, photon counting, backaction evasion), which evade the limits, in future dark matter searches.</p>

Quantum Limits of Electromagnetic Axion and Hidden-Photon Dark Matter Searches

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06/05/2018

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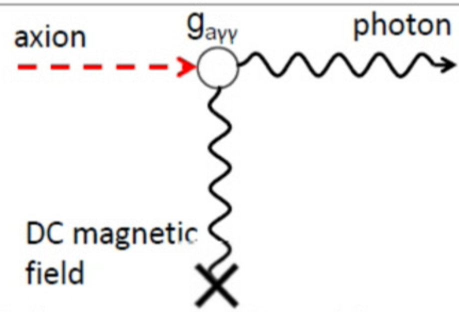
Outline

- Axion- and hidden-photon dark matter
- Fundamental limits on searches using coupling to photons
  - S. Chaudhuri, K. Irwin, P. Graham, J. Mardon, arXiv:1803.01627
  - DM detection as informed by circuit models!
- DM Radio: An Optimized Resonant Search for Axion and Hidden Photon Dark Matter, 100 Hz-300 MHz
- Future prospects for ultralight DM searches
  - Evading the limits with quantum measurement techniques

Axions (spin 0)



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

Ultralight, high number density → Look for classical, oscillating EM field

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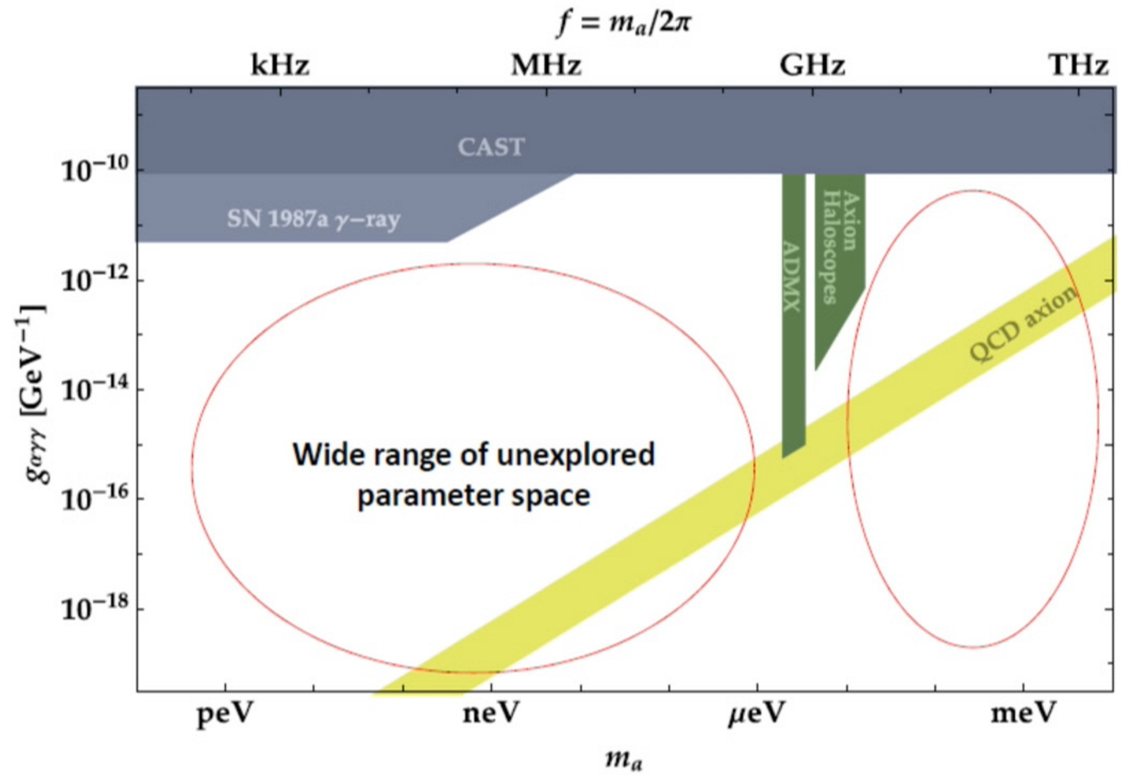
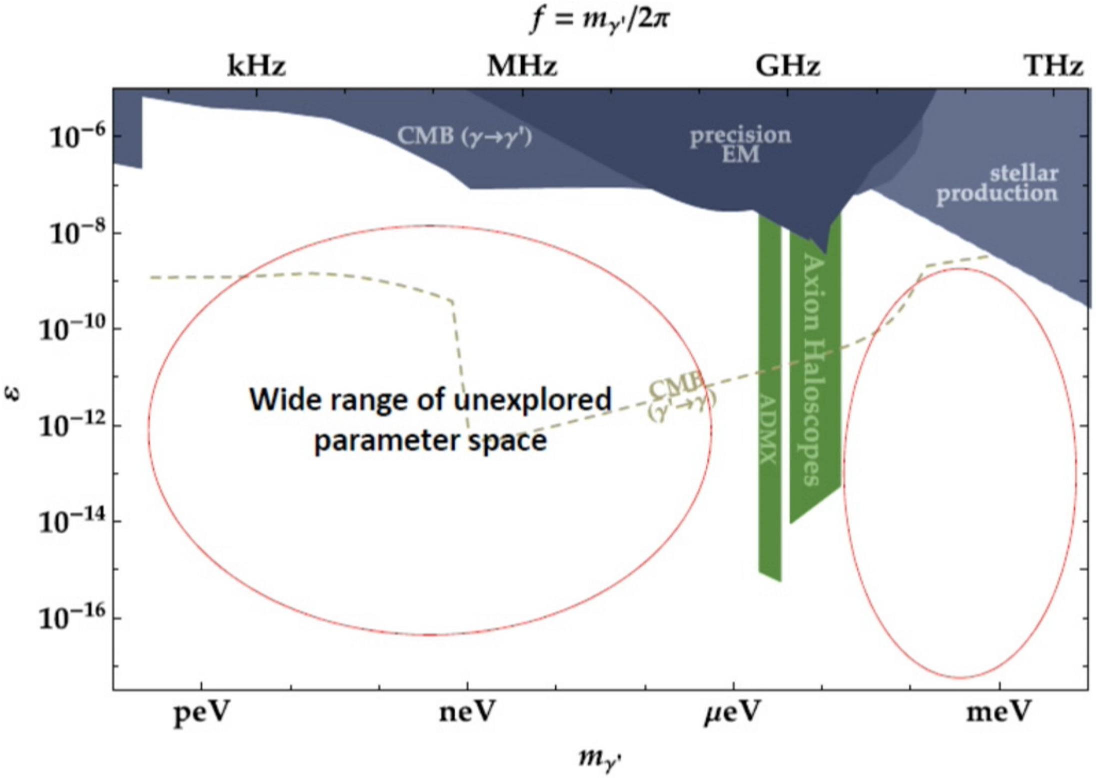
Axions: wide unexplored parameter space



Hidden photons: wide unexplored parameter space



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Many searches! How do we determine which technique is best?

- Many search techniques:
  - Resonant (ADMX, HAYSTAC, LC search, DM Radio)
  - Reactive broadband (ABRACADABRA)
  - Free-space antenna (Dish antenna, e.g. BRASS)
  - …
- Fundamentally, what technique is best? How do we perform apples-to-apples comparisons?
- What are the limitations on the sensitivity of ANY technique?
- To answer these questions, need a unified framework for modeling electromagnetic receivers:

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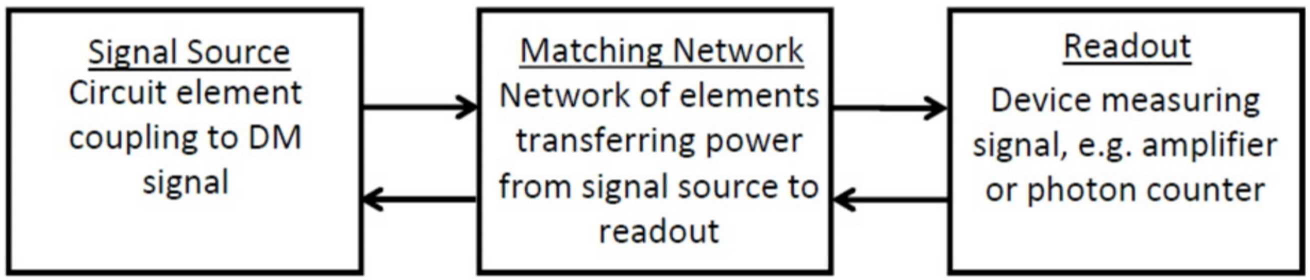
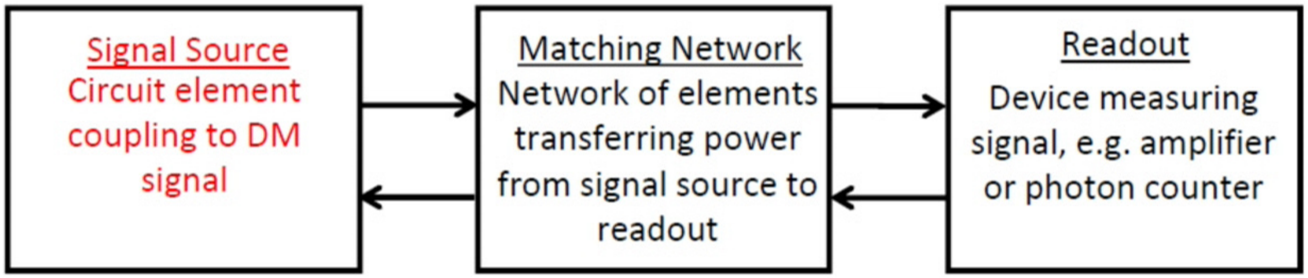
Circuit Models!

Receiver circuit model: schematic



To arrive at fundamental limits, optimize each block and interactions across blocks.

Receiver circuit model: schematic



To arrive at fundamental limits, optimize each block and interactions across blocks.

Inductive coupling is optimal

- Coupling element is inductive, capacitive, or resistive
- Experiment size sub-Compton-wavelength:
  - DM effect can be treated as effective AC current density (e.g. interaction basis for hidden photon)
  - Dominant effect is magnetic field, so inductive coupling optimal
- Experiment size Compton wavelength or larger:
  - Magnetic and electric field effects comparable, so inductive and capacitive couplings yield comparable excitations
  - Analogous interactions across blocks

Why not resistive coupling?

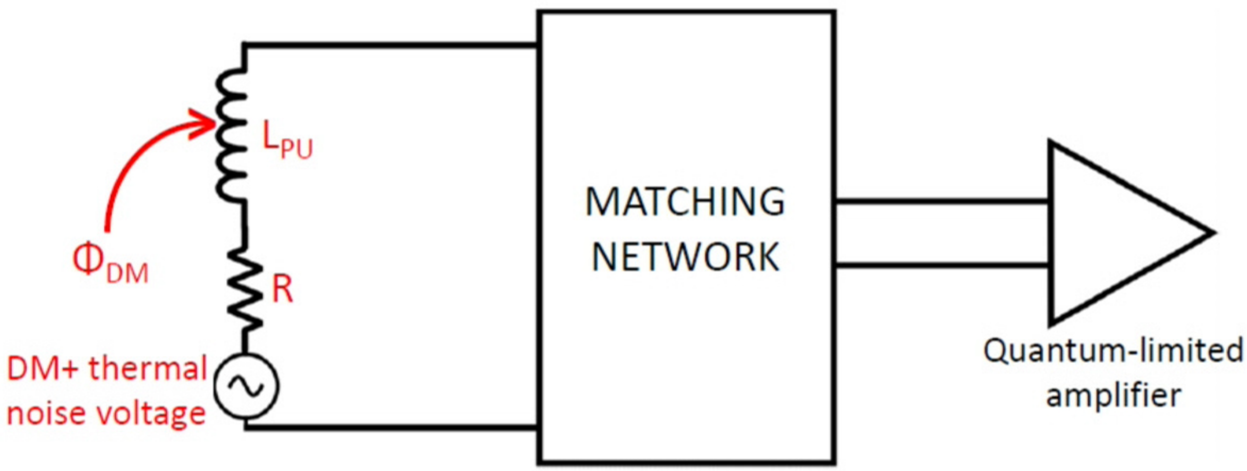
- Why not resistive coupling, e.g. free space antenna?
  - For regular vacuum electromagnetic waves, broadband resistive absorber can absorb 50% of available power at all frequencies!
- Half-wave resonant cavity better at coupling power from DM than broadband resistive absorber (Sec. II)
- Resistive coupling: power absorption limited by radiation of visible photons
- Begs the question: What does it take to impedance match to (couple maximum power from) dark matter?
  - See Sec. II-III of arXiv paper and Kent's talk about impedance matching to dark matter
  - S. Chaudhuri, in preparation

Model for axion / hidden photon detection through electromagnetism

Signal Source
1) Inductive coupling to DM signal is optimal
2) Residual loss and associated thermal noise

Matching Network
Examples:
1) Single-pole LC resonator
2) Broadband inductive
3) Multi-pole resonator

Readout
1) Phase-insensitive amplifier
2) Quantum limit on performance
3) Imprecision and backaction noise



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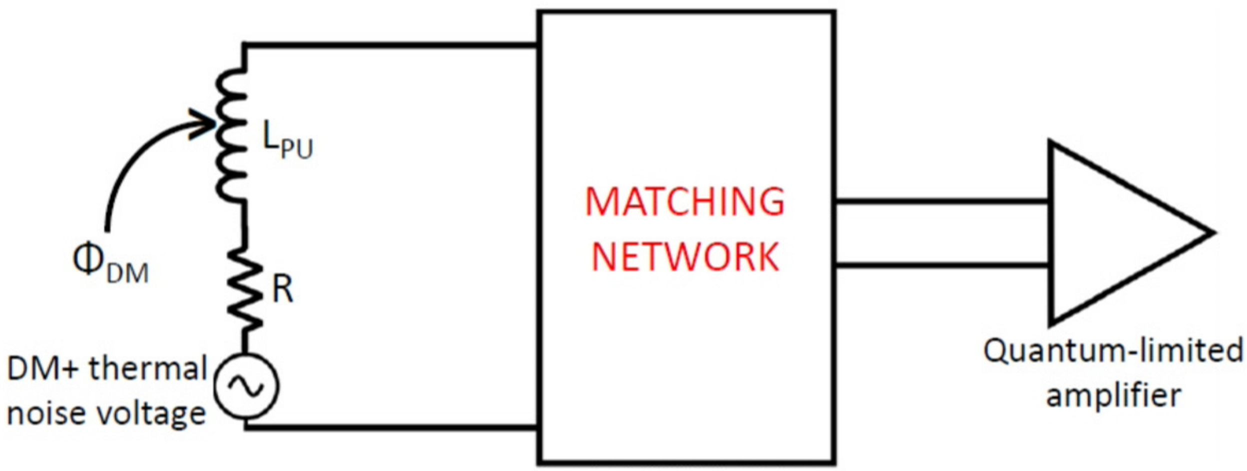

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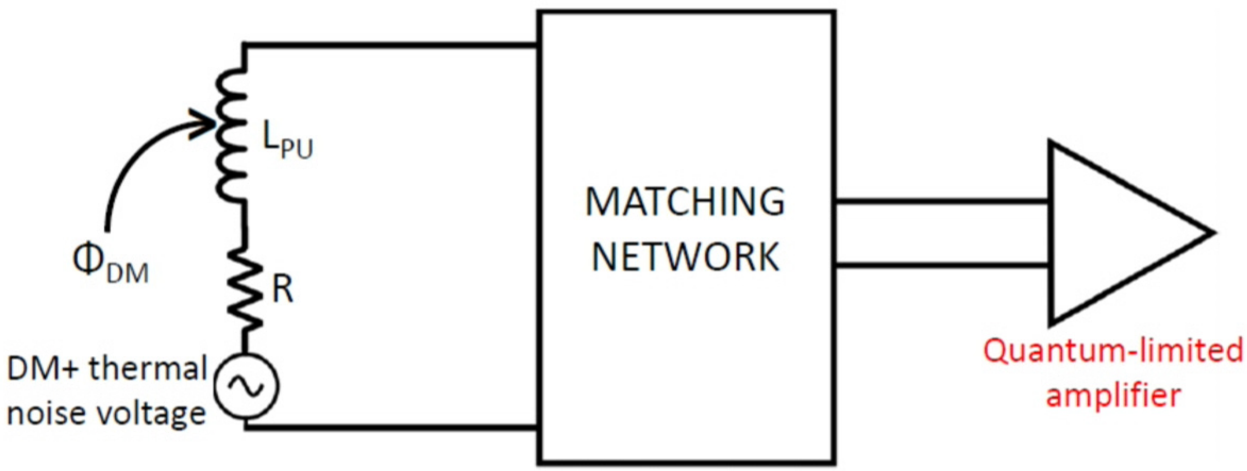

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Standard Quantum Limit (SQL) on amplification

- Phase-insensitive amplifier: both sine and cosine components of signal ("quadratures") are amplified equally
- Subject to Standard Quantum Limit: Heisenberg uncertainty on noise performance
  - H.A. Haus and J.A. Mullen, Phys. Rev. **128**, 407 (1962)
  - Caves, PRL **26**, 1817 (1982)
  - Modern review: Clerk et al, RMP **82**, 1155 (2010)
- SQL=1 photon of noise added by the measurement
  - 1 photon= increase required in thermal occupation number of circuit for change in thermal noise to equal amplifier noise
- SQL has two components:

Standard Quantum Limit (SQL) on amplification

SQL=1 photon

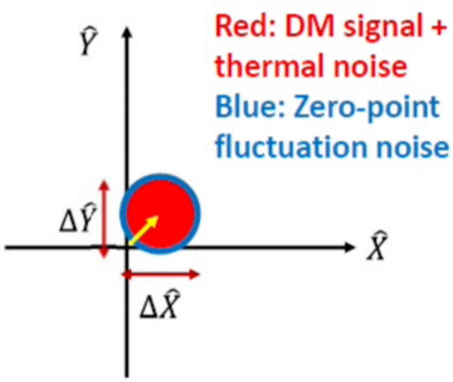
Zero-point fluctuation noise (1/2)

- Quadrature measurements $\hat{X}$ (cosine) and $\hat{Y}$ (sine) applied to vacuum have nonzero variance →noise

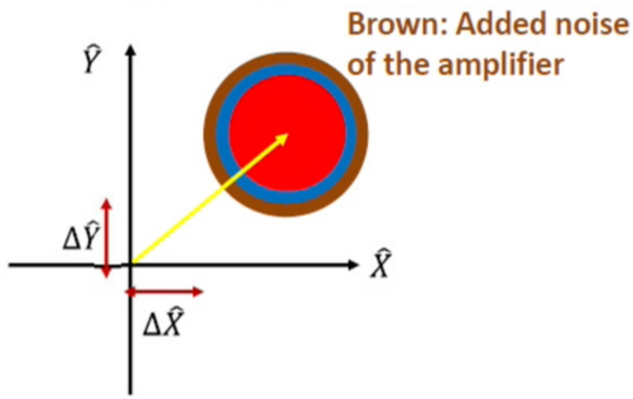
Amplifier noise (1/2)

- Noise added upon amplification from simultaneously measuring two noncommuting operators, $[\hat{X}, \hat{Y}] = i$

Amplifier Input



Amplifier Output

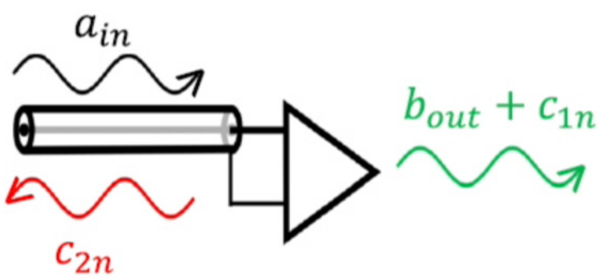


Amplifier noise = imprecision + backaction

- Amplifier has two effective noise modes
- Imprecision noise: independent of input circuit
- Backaction noise: dependent on input circuit

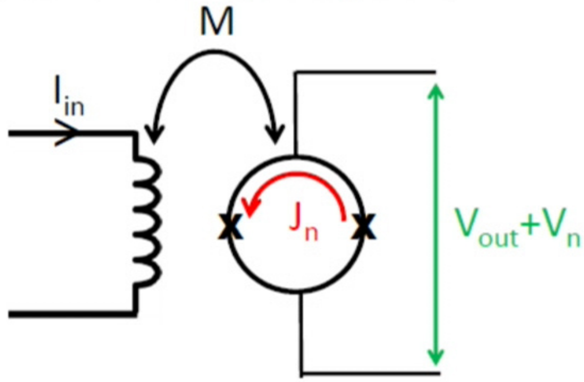
Amplifier noise = imprecision + backaction

Scattering-mode Amplifier



- E.g. JPAs, used in ADMX, HAYSTAC
- Incoming wave a_{in} amplified, giving output wave b_{out}
- Imprecision noise: intrinsic noise wave c_{1n} at output
- Backaction noise: noise wave c_{2n} injected into input circuit
- Reflects off input circuit, appears as more noise at output

Flux-to-Voltage Amplifier



- E.g. SQUIDs, used in DM Radio
- Input current I_{in} feeds flux into loop, giving output voltage V_{out}
- Imprecision noise: intrinsic voltage fluctuations V_n at output
- Backaction noise: circulating noise currents J_n couple voltage to input
- Creates noise currents in input, appears as more noise at output

Noise matching needed to achieve SQL

- Couple too weakly: signal-to-imprecision-noise ratio high
- Couple too strongly: high backaction noise
- Want to vary coupling to amplifier and other circuit parameters to minimize total noise
- *Noise matched to amplifier*: imprecision and backaction balanced to minimize total noise
- *Noise impedance*: circuit impedance when noise matched
- Achieving SQL of one photon: don't need just quantum-limited amplifier, need noise matching as well

How do we optimize matching network?

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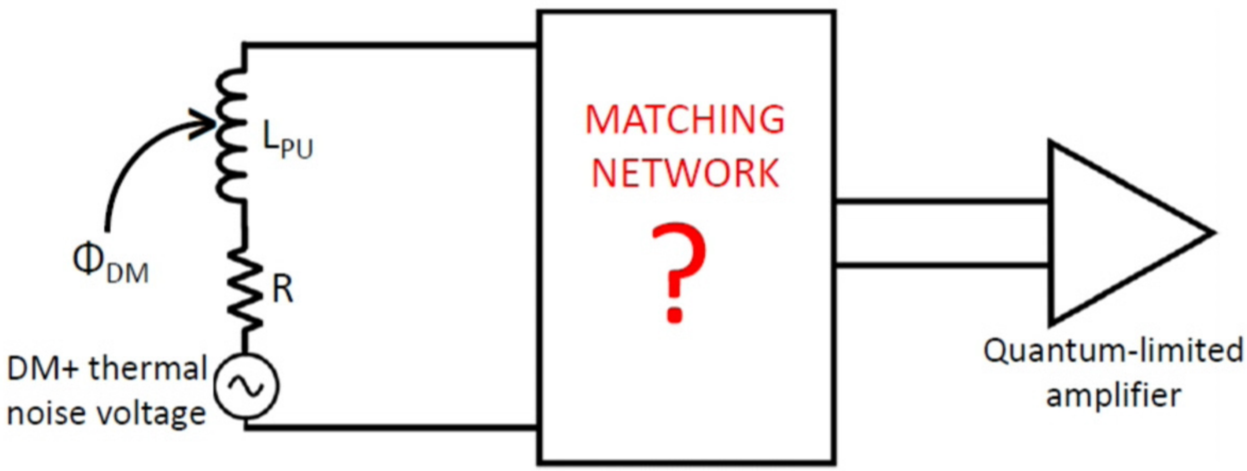

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Value function for matching optimization

- Value function needs to reflect:
  - Signal-to-noise ratio (SNR)
  - Priors- Favored mass or coupling range? Candidate signal to validate?
- Value function is expectation value of SNR squared:

$$U[S(\nu)] = E[SNR^2\,[S(\nu)]]$$

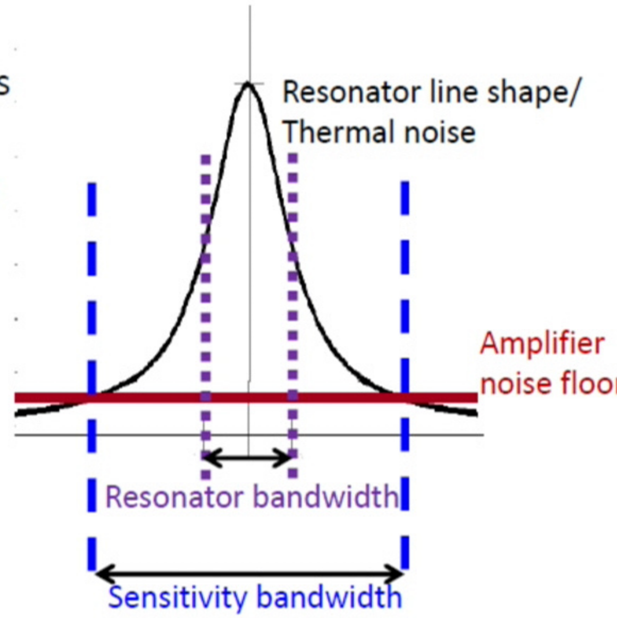
- $S(\nu)$=scattering matrix for the network
- Expectation is evaluated with user-defined preference functions for DM properties, e.g. mass
- *Log-uniform search*
  - Uninformative priors on DM
  - DM mass uniformly likely in log space
  - Want sensitivity as large as possible over as wide a bandwidth as possible

Log-uniform search: optimize integrated sensitivity

- Maximize integrated sensitivity across search band, between ν_l and ν_h
- Figure of merit with quantum-limited amplifier:

$$U[S(\nu)] = \int_{\nu_l}^{\nu_h} d\nu \left(\frac{|S_{21}(\nu)|^2}{|S_{21}(\nu)|^2 n(\nu) + 1} \right)^2$$

- $n(\nu)$= signal source thermal occupation number
- "+1" is standard quantum limit



Substantial sensitivity available outside of resonator bandwidth for thermal resonator states. Scan rate enhancement!

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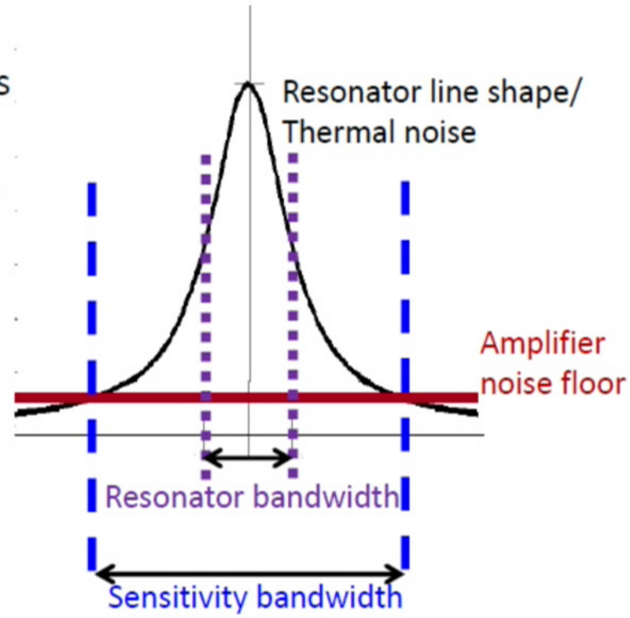


Substantial sensitivity available outside of resonator bandwidth for thermal resonator states. Scan rate enhancement!

Quantum-limited amplifiers highly desirable for thermal states hf<kT.

How large can sensitivity U be? Bode-Fano limit

- Constraint provided by Bode-Fano criterion for matching LR to a quantum-limited amplifier with a real noise impedance:
  - H.W. Bode, ``Network Analysis and Feedback Amplifier Design" (1946)
  - R.M. Fano, *Journal of the Franklin Institute* (1950)
- *Assume matching network is linear, passive, and reciprocal.*

Bode-Fano

$$\int_{\nu_l}^{\nu_h} d\nu \, ln\left(\frac{1}{|S_{22}(\nu)|}\right) \leq \frac{R}{2L_{PU}} \quad \Rightarrow$$

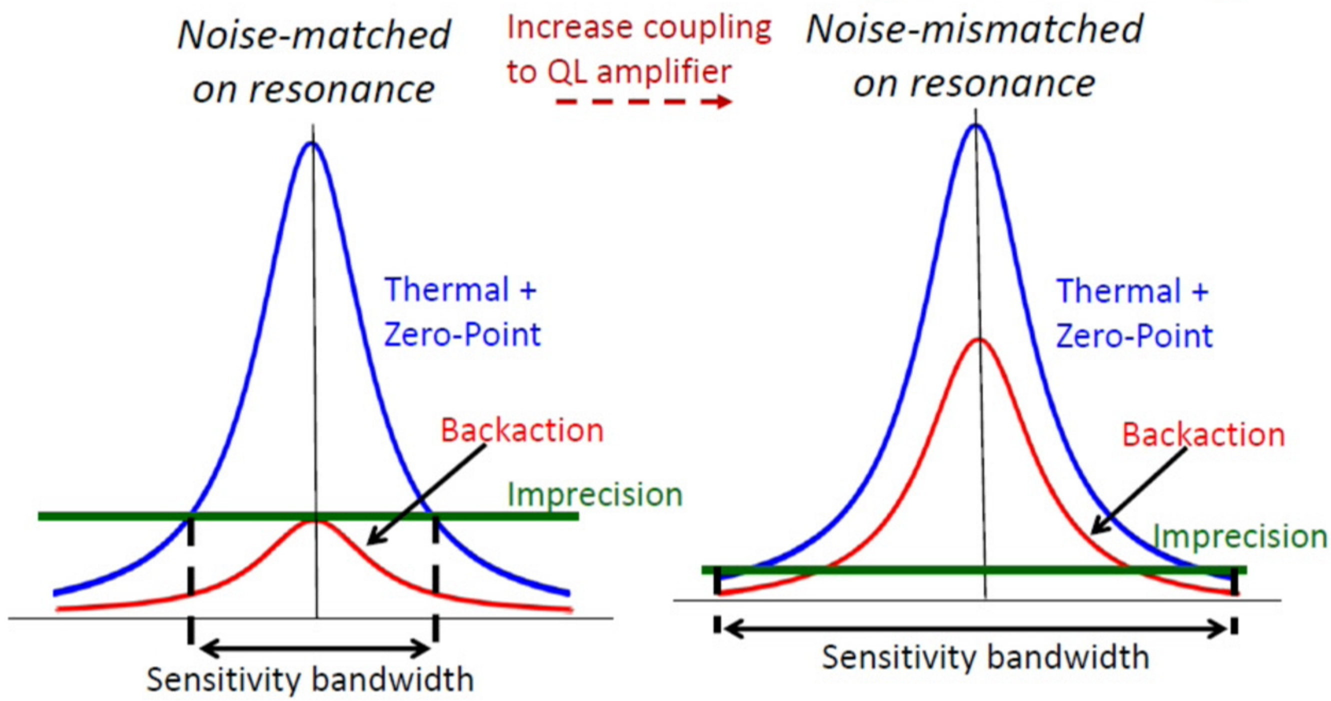
Bode-Fano-limited U

$$U[S(\nu)] \leq \begin{cases} \frac{1}{4n(\nu_h)} \frac{R}{L_{PU}}, & n(\nu_h) \gg 1 \\ 0.41 \frac{R}{L_{PU}}, & n(\nu_h) \ll 1 \end{cases}$$

- Analogous constraint for RC signal source

An ***optimal*** single-pole resonator can have a figure of merit U that is ~75% of the fundamental limit (pretty good!)

Optimize coupling strength with respect to integrated sensitivity



- Increased coupling: reduced imprecision, increased backaction
- 50% on-resonance noise penalty. Much larger sensitivity bandwidth!

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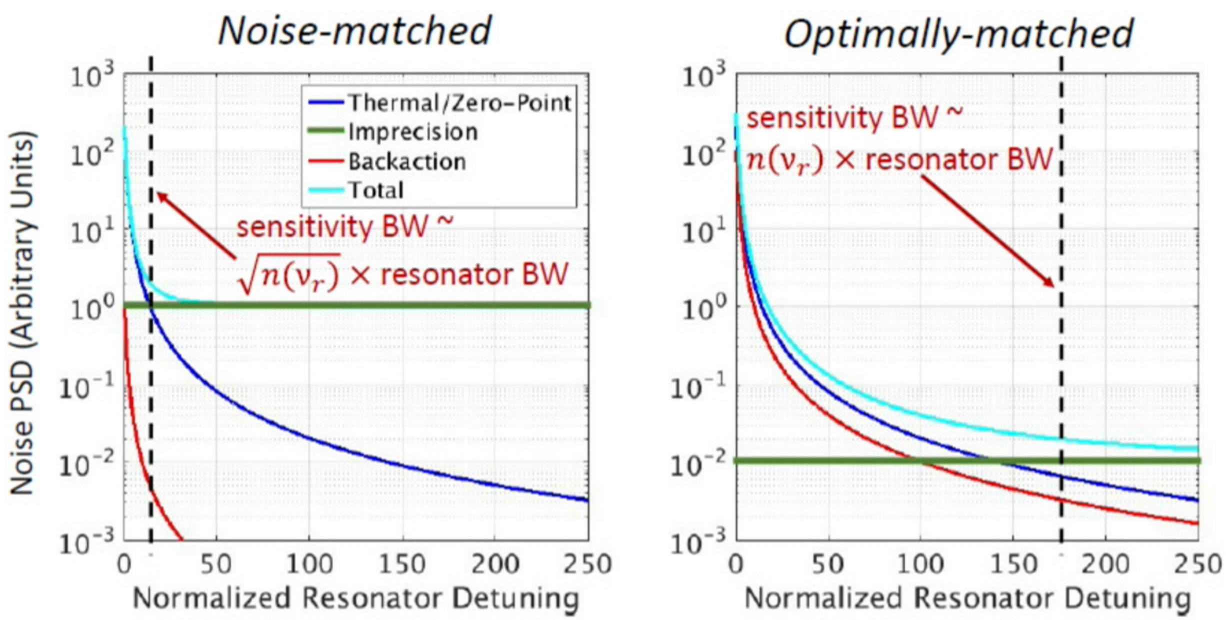
Optimal resonator readout: quantum-limited, noise-mismatched, backaction-dominated



- $n(\nu_r)$=50: 14 resonator BW vs. 173 resonator BW
- Order of magnitude enhancement in scan rate!

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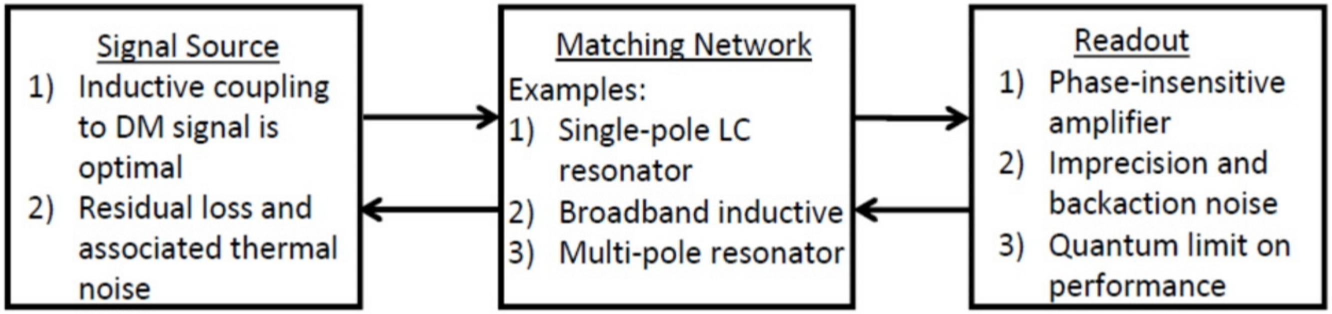
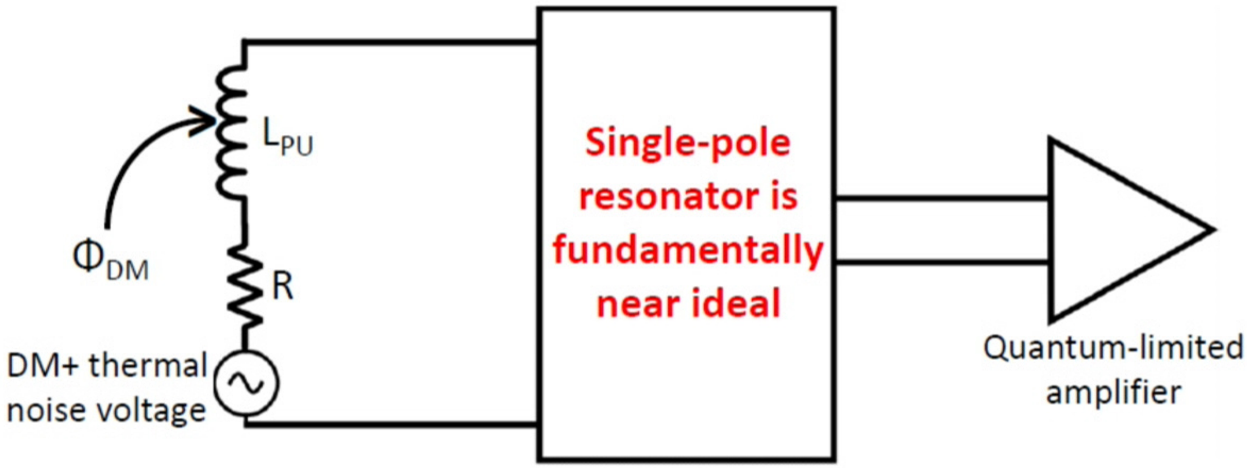
Completing our optimal detector!





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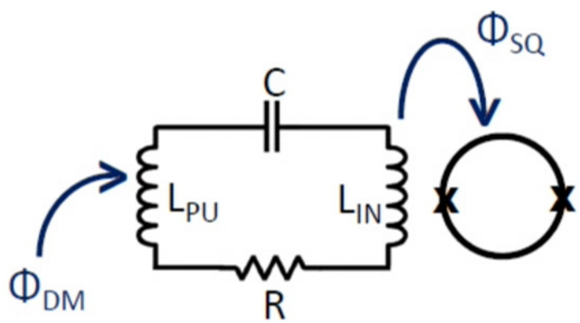
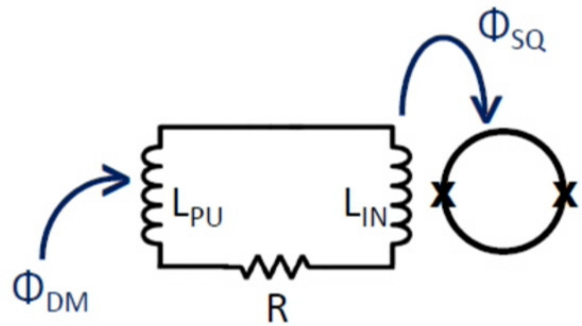
Tunable single-pole resonator vs broadband



Capacitively-tuned, resonant RLC input circuit read out by SQUID. (e.g. DM Radio, Chaudhuri et al, PRD 92, 075012 (2015))

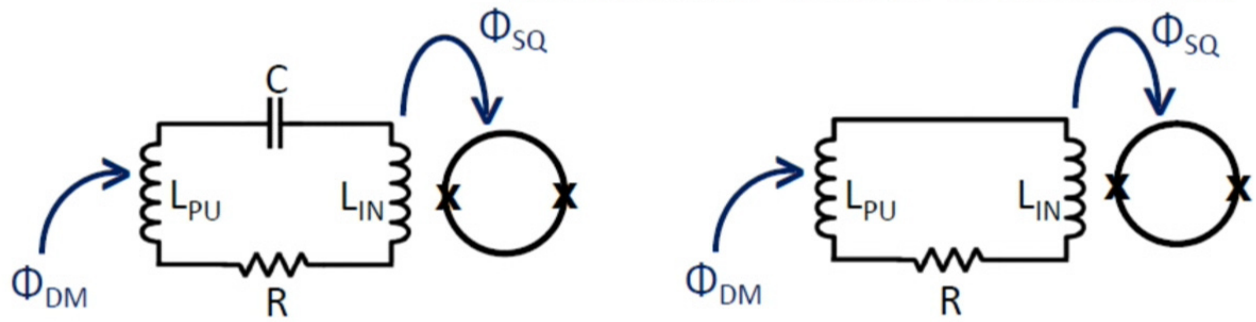


Broadband LR circuit. (ABRACADABRA, Kahn et al, PRL 117, 141801 (2016))

Is resonant or broadband better?

See Appendix G, pg. 141-153 for more details.

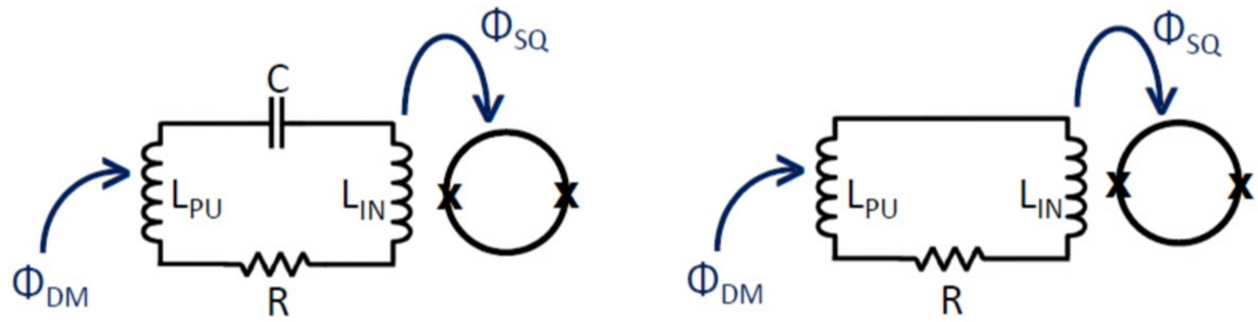
Resonator beats broadband



- 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

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

Resonator beats broadband



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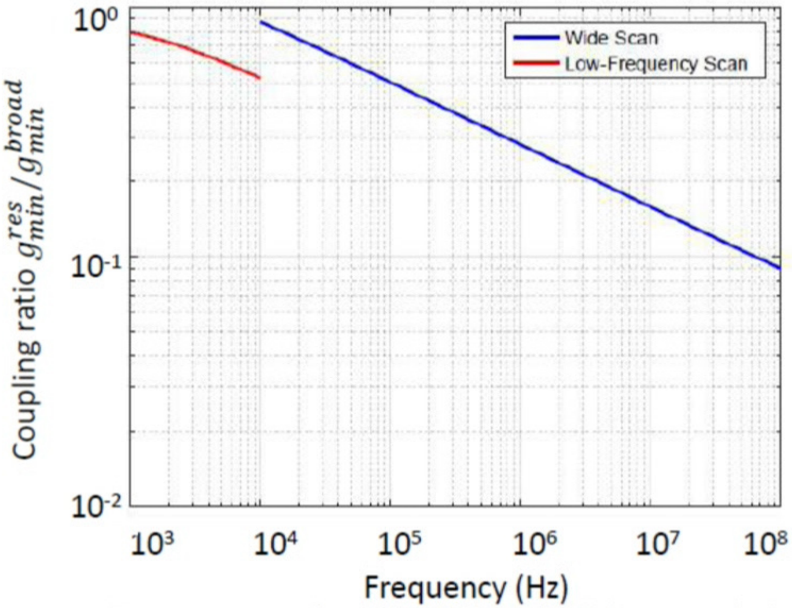
- Resonator fixed at lowest search frequency beats broadband
- **How much better? Let's do an apples-to-apples comparison…**

Apples-to-apples comparison of resonant and broadband

- Assumes same volume, same loss ($Q=10^6$), detector temperature of 10 mK.
- Assumes optimally matched amplifier at standard quantum limit.
- Assumes equal time per e-folding for resonant scan and same total integration time.
- Assumes same fixed search range
  - Lowest possible search frequency: ~1 kHz
  - Mathematical approximations for resonator optimization break down at lower frequencies
  - Highest possible search frequency: ~100 MHz
  - Parasitics make broadband amplification challenging

One-pole scanned resonator vs. broadband



Ratio of minimum detectable coupling for one-pole resonant and broadband plotted vs rest mass frequency.

Value < 1 implies resonator limit stronger than broadband limit

- Two scans: log-uniform (wide scan), low-masses-preferred (low-frequency scan)
- Must be careful about extrapolating!
- For wide scan, looks like resonant is worse below ~6 kHz only because of log-uniform priors above 10 kHz
- If interested in low frequencies, choose a prior favoring those

Summary of fundamental limits

- Circuit models highly informative in optimizing dark matter detectors
- Inductive coupling is optimal
- Figure of merit for receiver in wideband search is not sensitivity at peak response, but integrated sensitivity
- Quantum-limited amplifiers desirable for maximizing integrated sensitivity
- Must pay attention to measurement backaction to fully optimize
- Bode-Fano: single-pole resonators are fundamentally ideal
- Resonant detector beats reactive broadband under any prior

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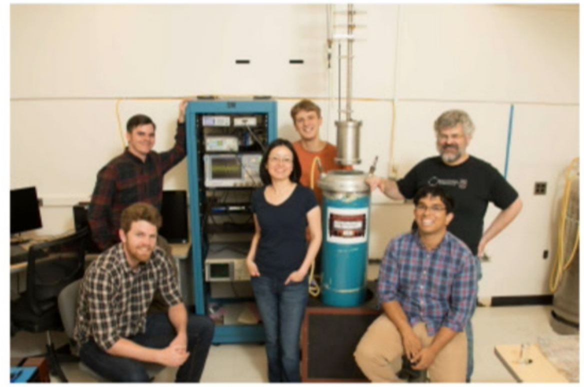


DM Radio: An Optimized Resonant Search For Axion and Hidden-Photon Dark Matter, 100 Hz-300 MHz

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:

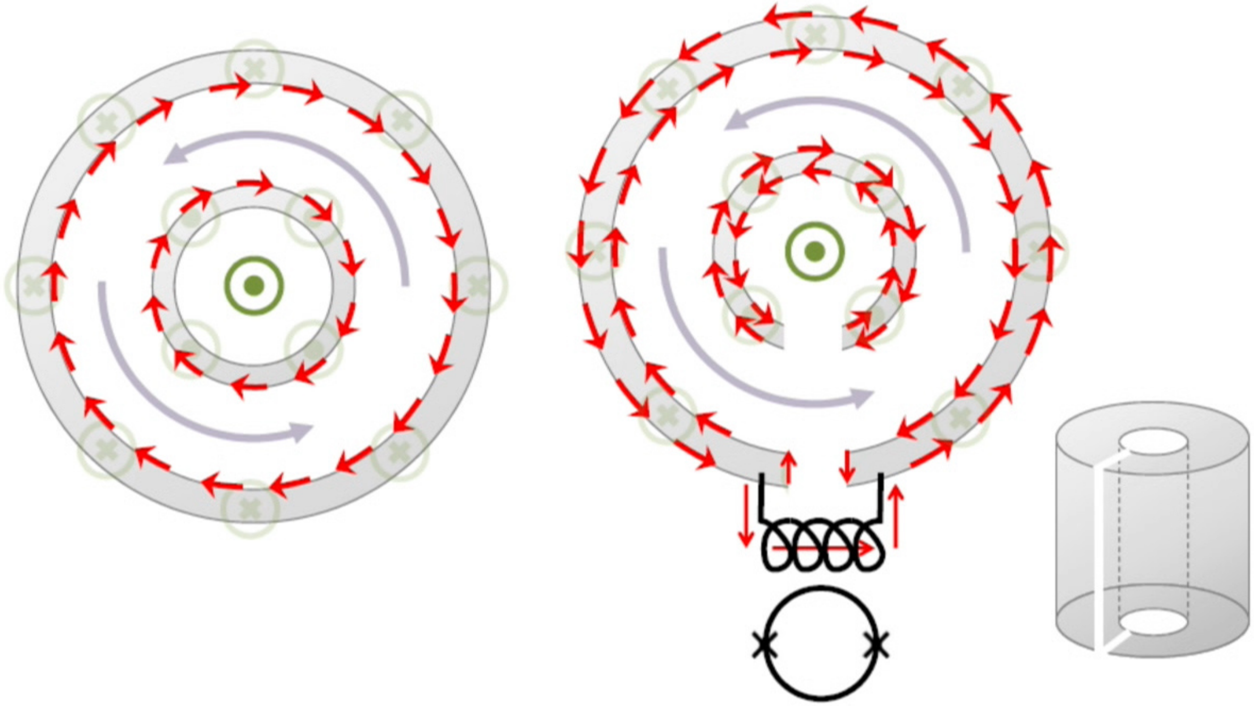
Tony Tyson, UC Davis, Lyman Page, Princeton

HEISING-SIMONS FOUNDATION KIPAC SLAC Cal UCDAVIS UNIVERSITY OF CALIFORNIA PRINCETON UNIVERSITY

From fundamental limits to practical searches

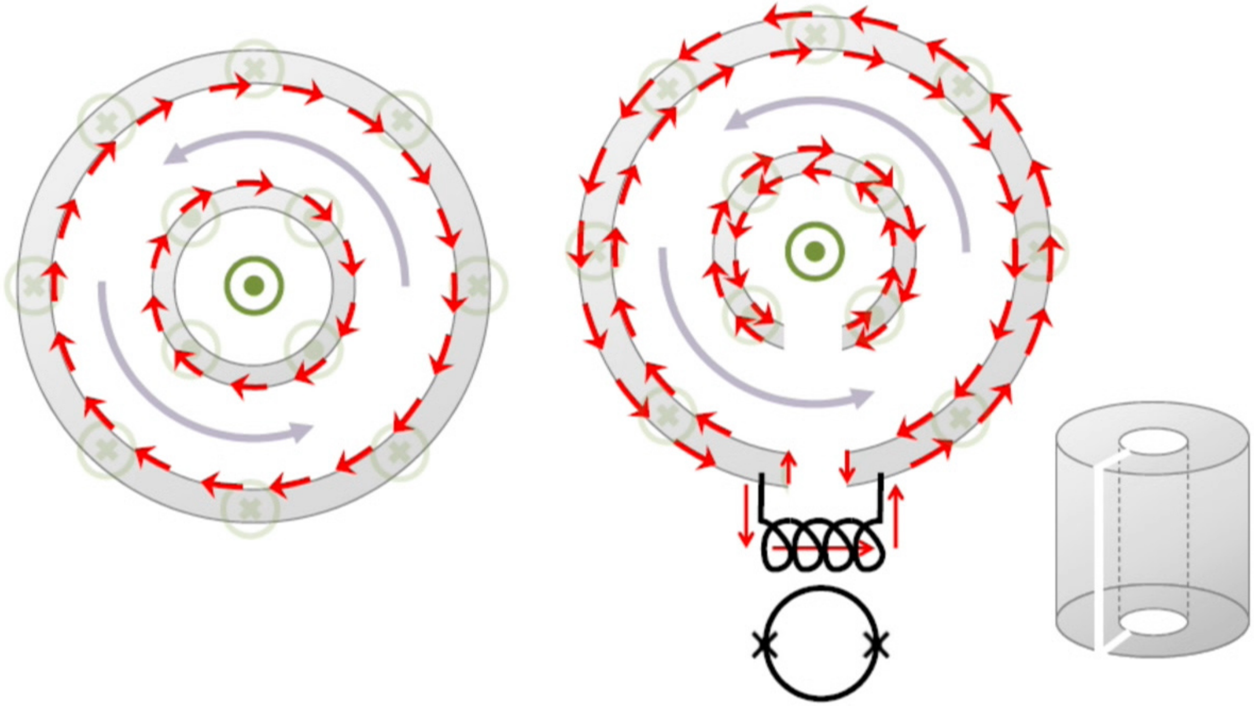
Optimization statement	Design conclusion
Inductive coupling optimal	Use inductive pickup
Bode-Fano: single-pole resonator near-optimal	Build a single-pole resonator.
Quantum-limited amplifier optimal for maximizing integrated sensitivity	Use a low-noise amplifier, preferably quantum-limited.
Achieve as low thermal noise as possible	Conduct experiment cryogenically.
Achieve as high quality factor as possible	Use superconducting components and low-loss dielectrics.

Axion detection



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

Axion detection



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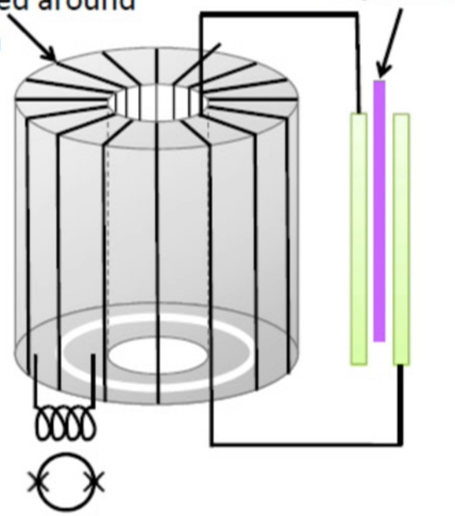
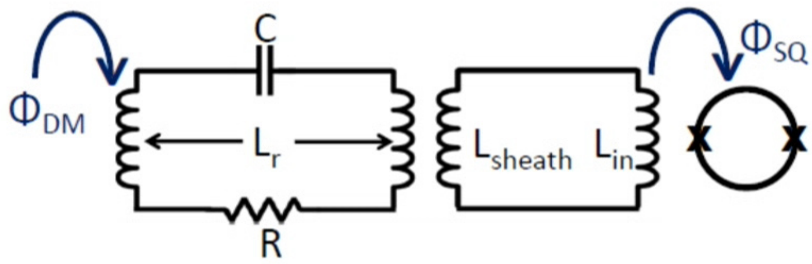
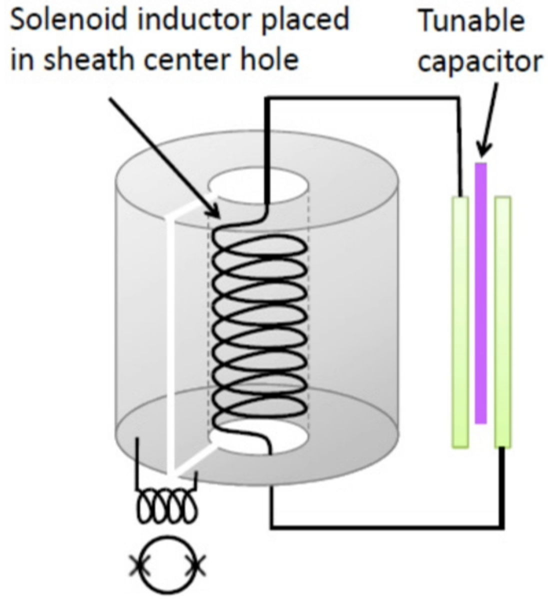
Resonant enhancement for hidden photons



- 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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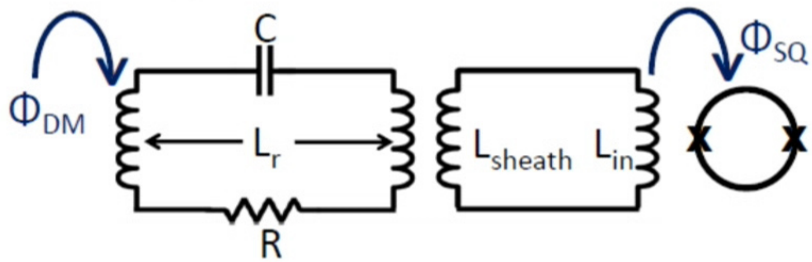

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DM Radio Pilot

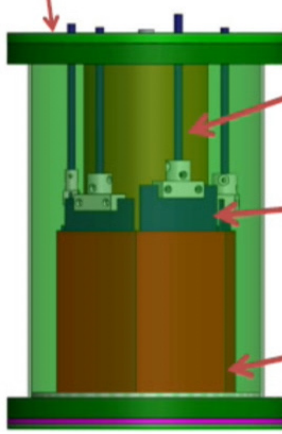
4K Dip Probe

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!



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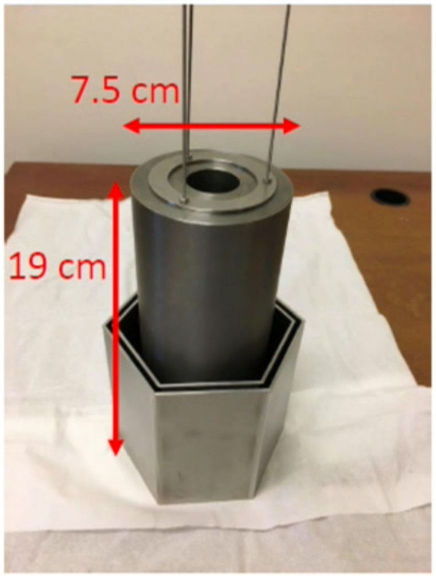
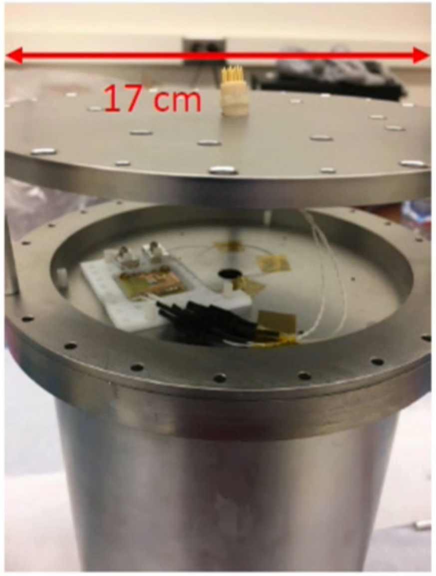
DM Radio Pilot

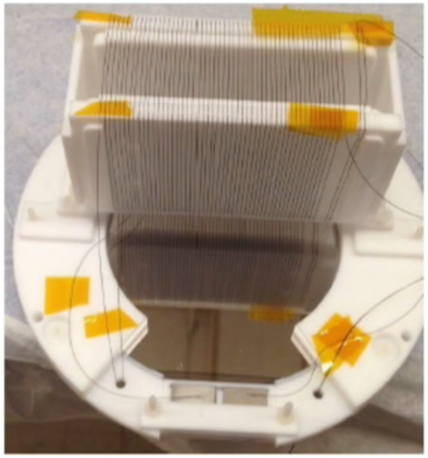


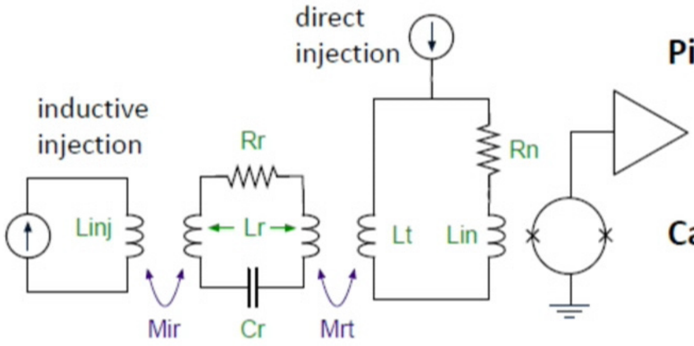


Toroidal form for inductor + hexagonal parallel-plate capacitor

SQUID inside shielded annex

DM Radio fixed resonator





Goals

- Demonstrate high Q~10^6
- Understand material properties
- Characterize dc 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

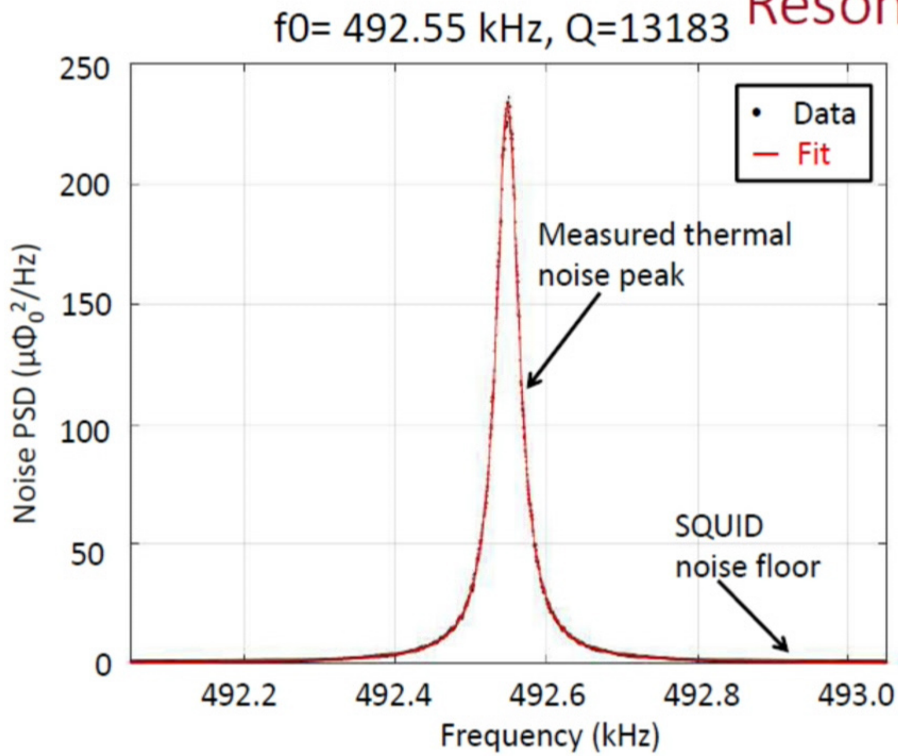
Pickup Transformer

- 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

Resonator data

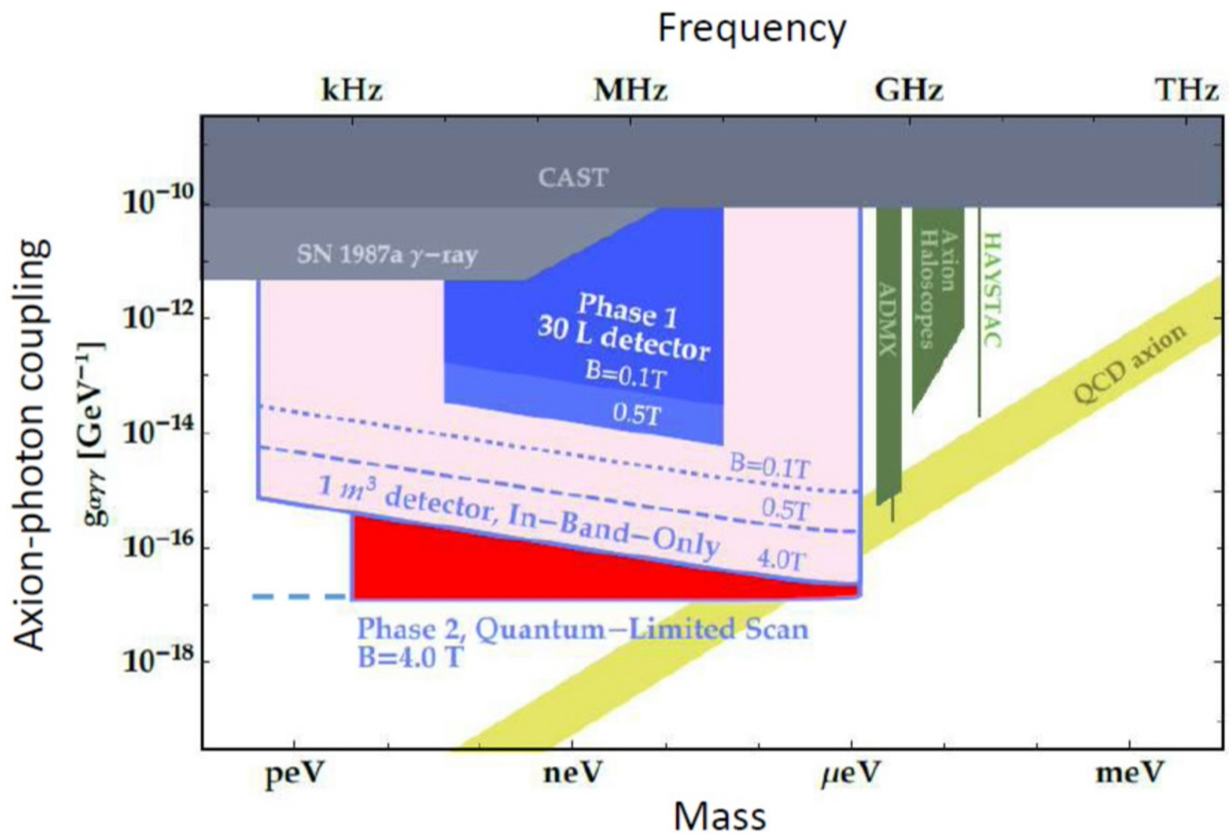


- Resonator BW: 37 Hz, sensitivity BW: 1.16 kHz
- SQUIDs being optimized to increase sensitivity BW
- Q likely limited by loss in support structure- replace with different materials
- Several hours of integration to test calibration/analysis protocols

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!
- Starting now: quantum-limited amplifier development based on microwave SQUID technology

Dark Matter Radio science: axions



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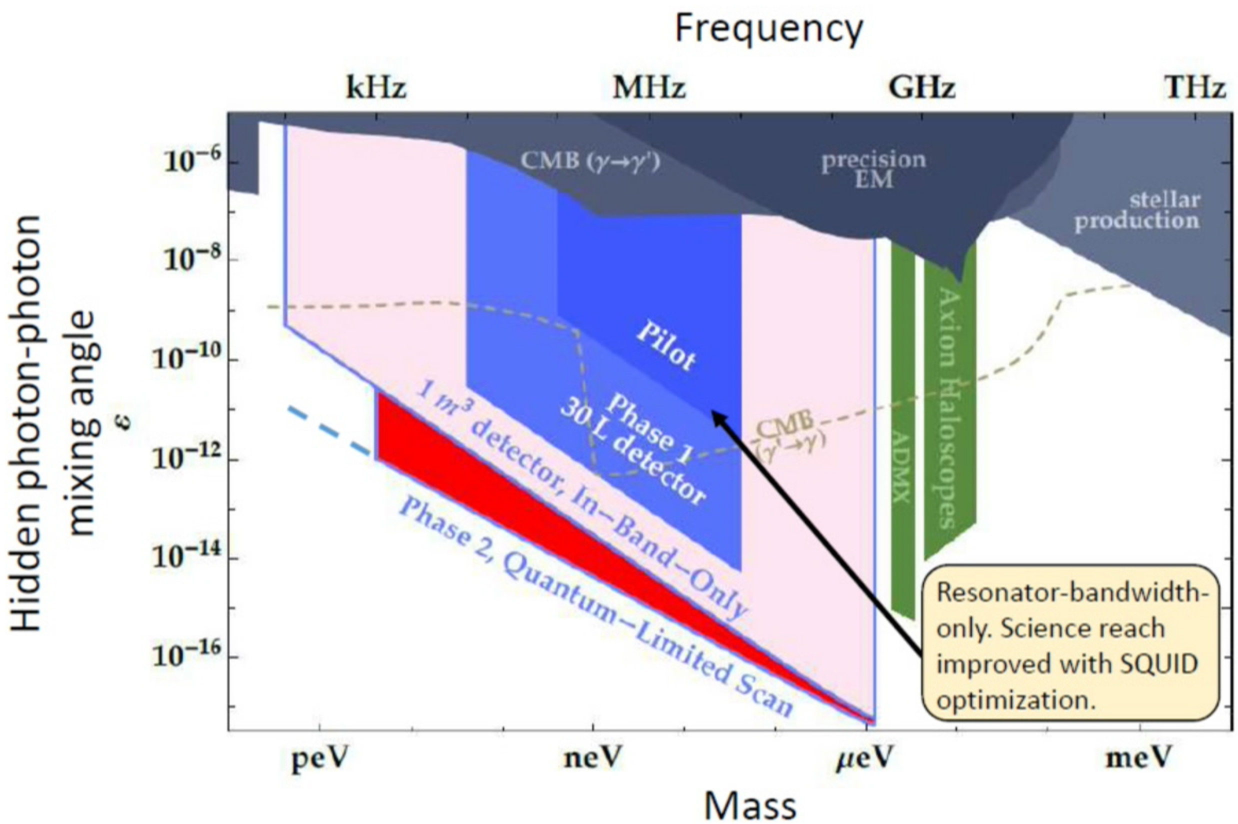
Dark Matter Radio science: hidden photons



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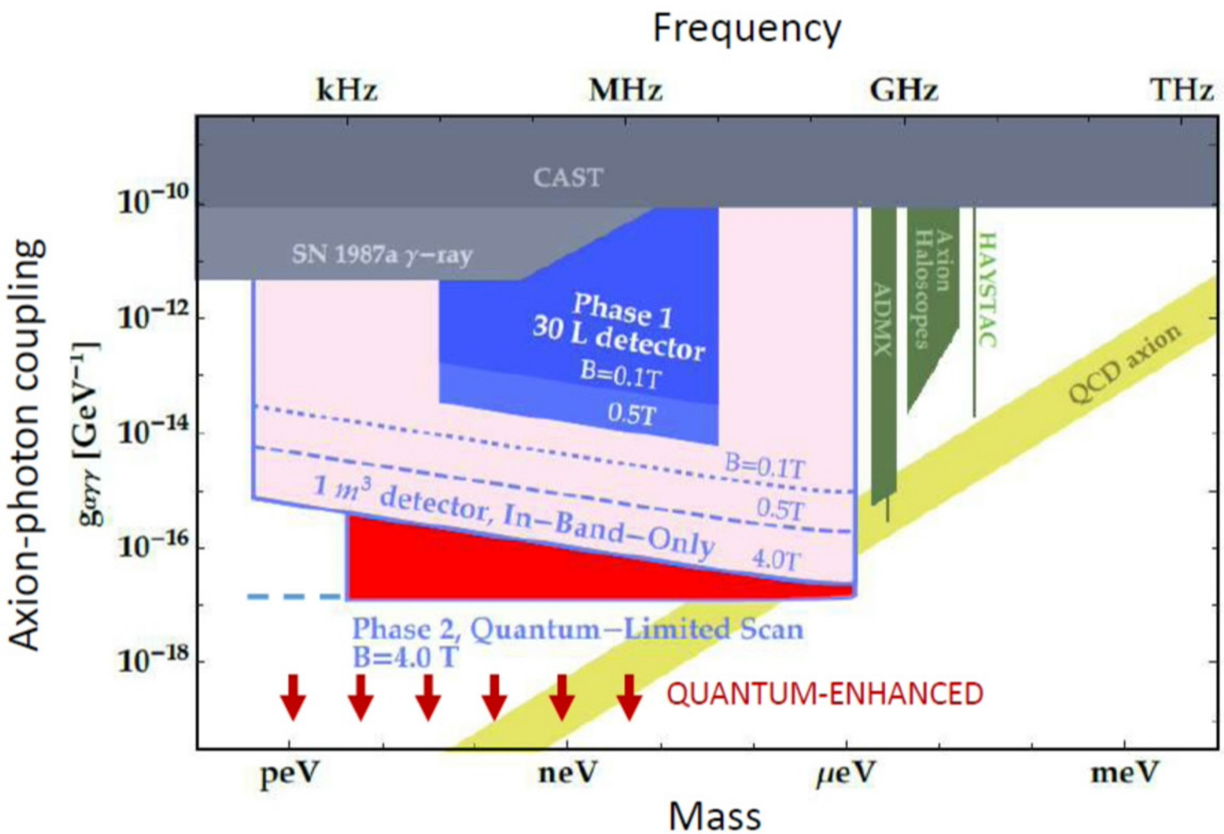
Fundamental limits: strong motivator for quantum sensors

- How do we get around these limits?
- Build bigger, higher quality receivers
  - $Q>10^6$ optimal
- Evade Bode-Fano
  - Nonlinear or active matching circuit
  - Multi-port circuit with multiple elements excited by DM
  - Calibration, stability a significant challenge
- 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!

Dark Matter Radio science: axions



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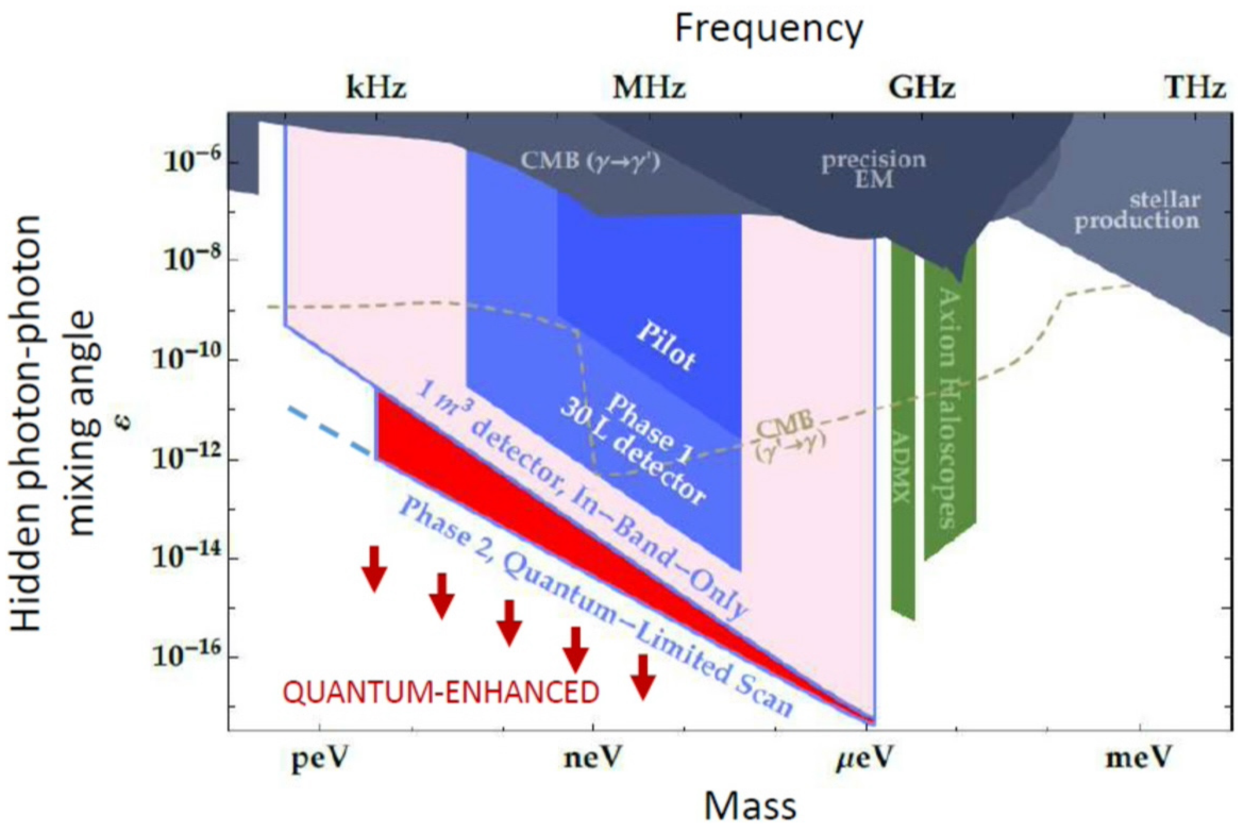
Dark Matter Radio science: hidden photons



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Conclusions

- Established a quantum limit on axion and hidden-photon dark matter detection using circuit models
- Single-pole resonators fundamentally near-ideal, subject to SQL on amplification
- Used optimization statements to inform DM Radio design
- Pilot scan to begin this year, building towards Stages 1 and 2
- Fundamental limits: strong motivate for the broad use of quantum measurement technology in ultralight DM searches

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