Title: Electromagnetic searches for axions and hidden photons

Date: Feb 07, 2018 02:00 PM

URL: http://pirsa.org/18020080

Abstract: <p>One of the most enduring mysteries in particle physics is the nature of the non-baryonic dark matter that makes up 85% of the matter in the universe. For several decades, most searches for this mysterious substance have focused on Weakly Interacting Massive Particles (WIMPs). Recently, there has been a surge in theoretical interest in ultra-light-field dark matter candidates, including QCD axions (spin 0 bosons) and hidden photons (spin 1 bosons), which can be probed through their coupling to electromagnetism or nuclear spin. I will discuss general principles of efficiently searching for the direct detection of the electromagnetic coupling of these candidates, how the sensitivity of these experiments can be improved by the exploitation of quantum correlations in the electromagnetic signals that they produce, and describe the Dark Matter Radio, and experiment searching for axions and hidden photons in the frequency range of 1 kHz through 100 MHz.</p>

Electromagnetic searches for axions and hidden photons

Kent Irwin
Stanford University

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Waterloo, Ontario
February 7, 2018

Stanford University

HEISING-SIMONS FOUNDATION

SLAC

KIPAC

Cal

UCDAVIS
UNIVERSITY OF CALIFORNIA

PRINCETON UNIVERSITY

DM Radio DJs

Stanford: Arran Phipps, Dale Li, Saptarshi Chaudhuri, Peter Graham, Jeremy Mardon, Hsiao-Mei Cho, Stephen Kuenstner, Carl Dawson, 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

Many of the results here will be published in paper late Feb., "Fundamental Limits on Electromagnetic Searches for Axions and Hidden Photons"
S. Chaudhuri, K. Irwin, P. Graham, J. Mardon

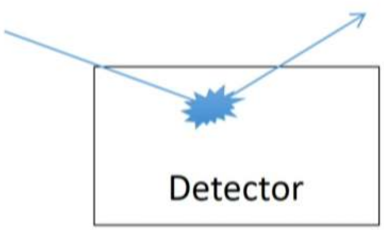
Outline

- Field-like dark matter: axions and hidden photons
- Coupling electrons to light-field dark matter
  - Impedance matching
  - Quantum noise and integrated scan sensitivity
  - Bode-Fano limit on coupling
  - Quantum-limited science reach
- Measuring below the standard quantum limit
  - Quantum sensing protocols
  - Measuring a thermal state with quantum sensors
  - Squeezing, backaction evasion
- The Dark Matter Radio (DM Radio)

Particle-like and field-like dark matter

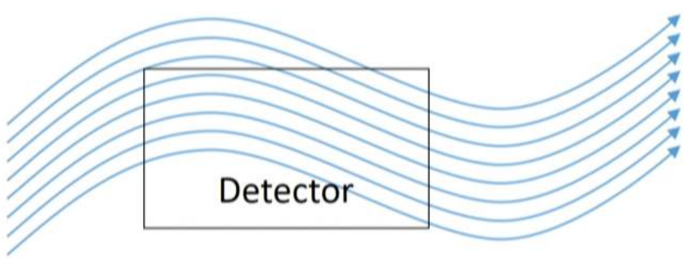
Heavy Particles

- Number density is small (small occupation)
- Tiny wavelength
- No detector-scale coherence
- Look for scattering of individual particles



Light Fields

- Number density is large (must be bosons)
- Long wavelength
- Coherent within detector
- Look for classical, oscillating background field



5

Dark matter candidate: axion (spin 0)

- Strong CP Problem

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

Neutron Electric Dipole Moment

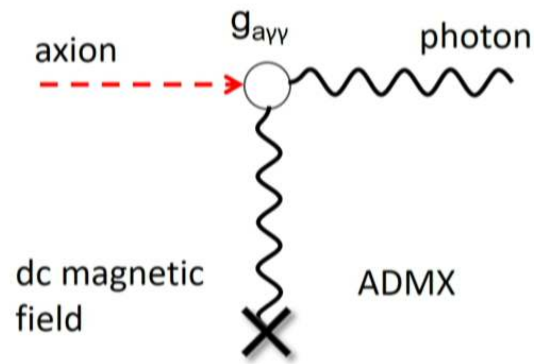
$$\theta_{\mathrm{QCD}} < 10^{-10}$$

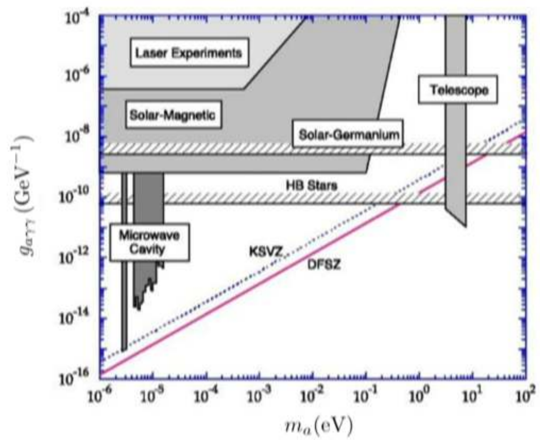
Why is it so small?

Solution: θ_{QCD} is a dynamical field

(Peccei-Quinn solution, the axion)

- Can be detected via inverse Primakoff effect – coupling to electromagnetism
- Frequency: $\nu_{DM} = \frac{mc^2}{h}$
- Virialized Bandwidth: $\Delta\nu_{DM} \sim 10^{-6}\nu_{DM}$





Leslie J Rosenberg PNAS 2015;112:12278-12281

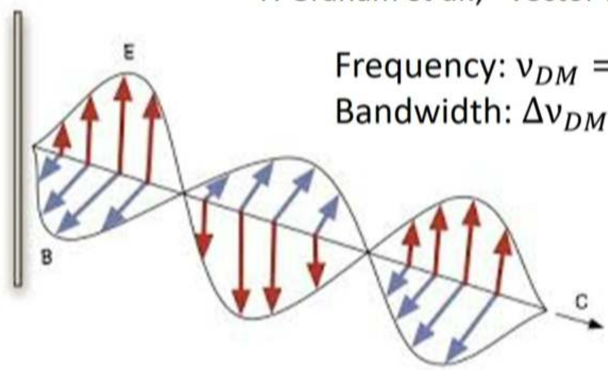
Hidden photon: vector boson (spin 1)

- Couples to ordinary electromagnetism via kinetic mixing

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

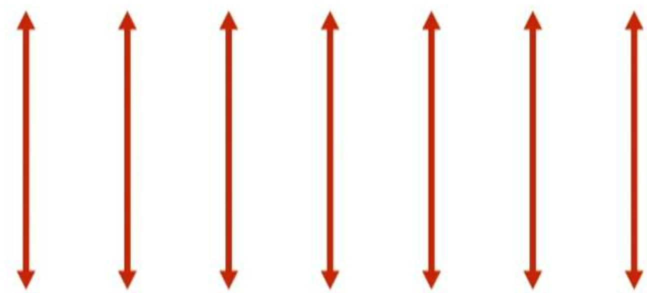
- Vector dark matter can be generated in observed dark matter abundance by inflationary fluctuations

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



Frequency: $\nu_{DM} = mc^2/h$
Bandwidth: $\Delta\nu_{DM} \sim 10^{-6}\nu_{DM}$

(oscillating E' field)

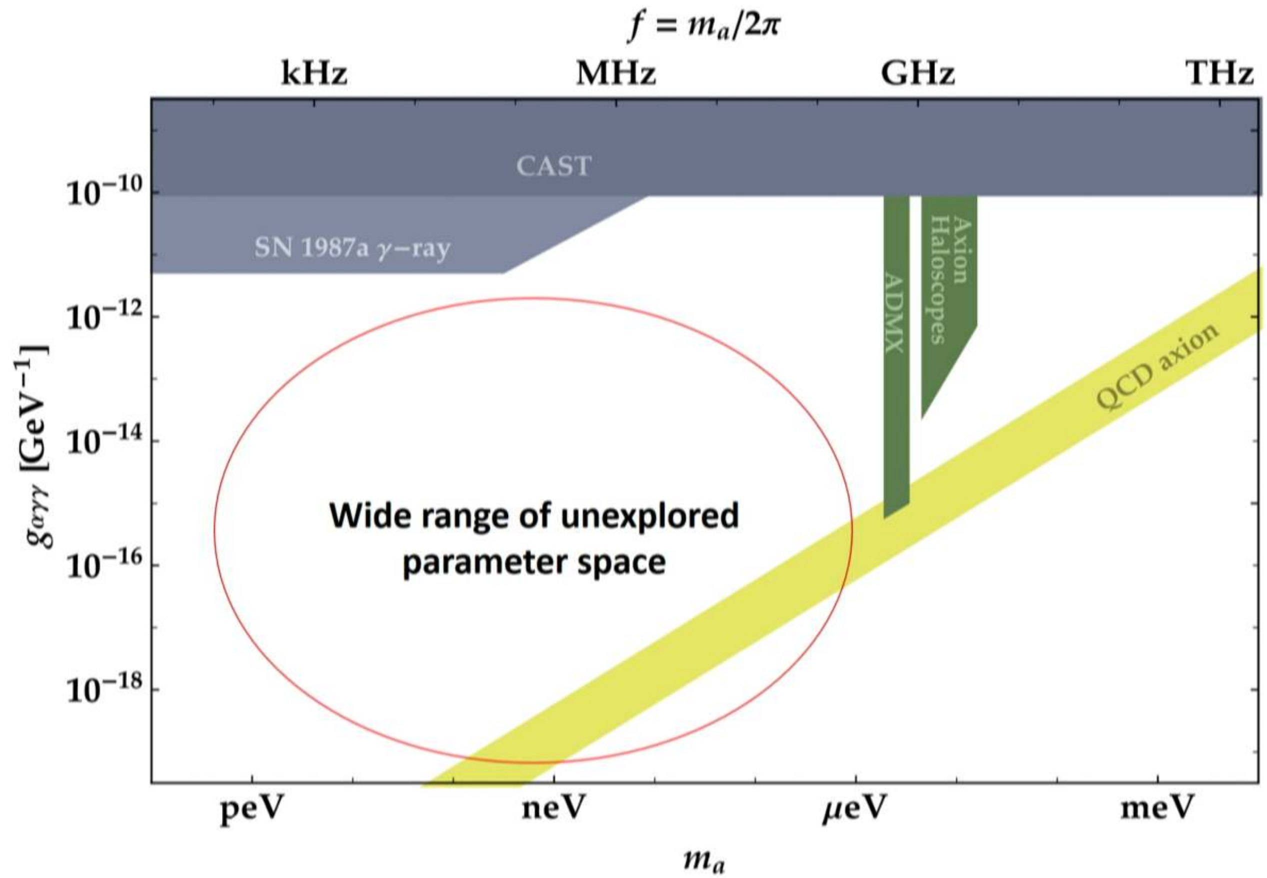


CMB photon

Hidden Photon DM

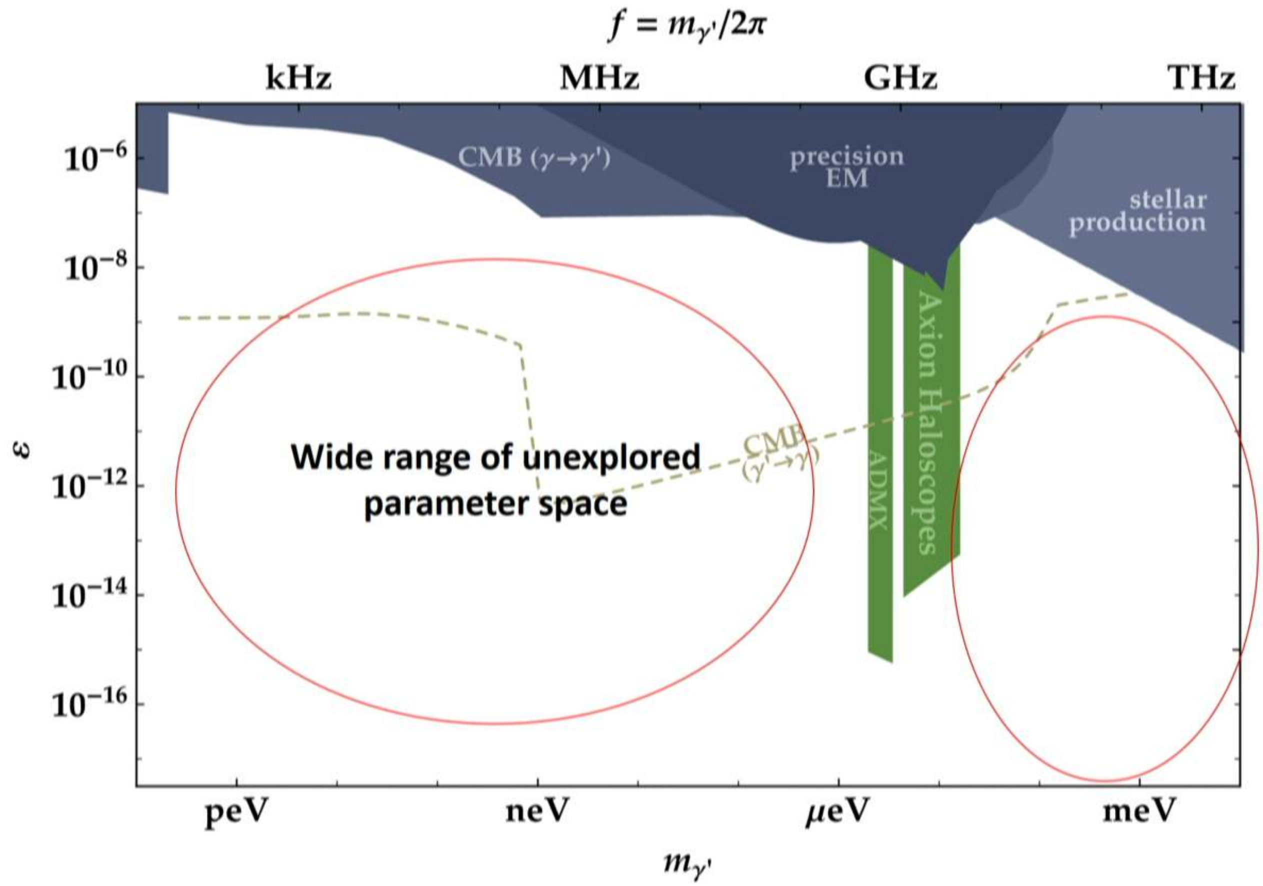
Hidden photon DM drives EM currents

Axions: wide unexplored parameter space



8

Hidden photons: wide unexplored parameter space



9

Outline

- Field-like dark matter: axions and hidden photons
- Coupling electrons to light-field dark matter
  - Impedance matching
  - Quantum noise and integrated scan sensitivity
  - Bode-Fano limit on coupling
  - Quantum-limited science reach
- Measuring below the standard quantum limit
  - Quantum sensing protocols
  - Measuring a thermal state with quantum sensors
  - Squeezing, backaction evasion
- The Dark Matter Radio (DM Radio)

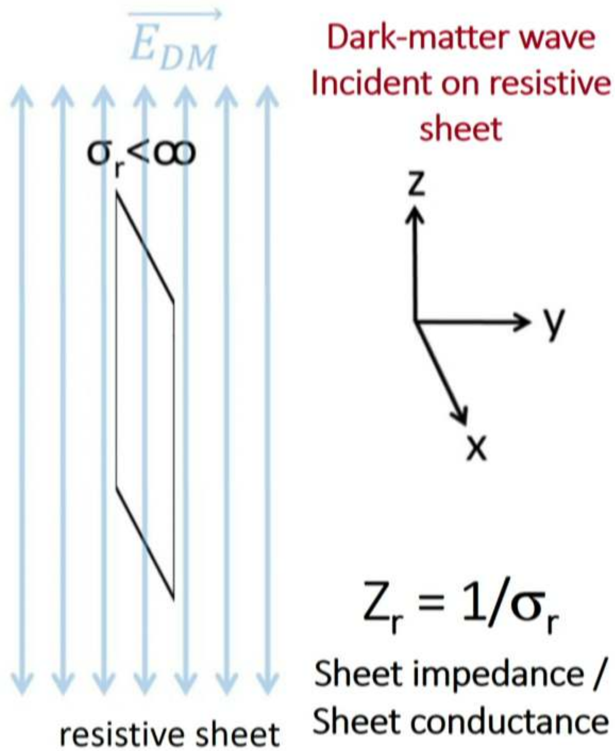
How do you couple DM power to electrons?

- Consider a DM field propagating in free space as a plane wave (to keep it simple)
- Consider an effective induced electric field from the DM, E_{DM}. This can arise from kinetic mixing, or Primakoff.
- Initially consider E_{DM} as a stiff field, with zero source impedance.
- Is that all we need to know? We would make a resistive sheet of arbitrarily low resistance, and the DM would dissipate arbitrarily high power: clean renewable energy! (No)

Impedance matching to the DM source field is tricky

Power coupled from dark matter to a resistive sheet

$P = \frac{{E_{DM}}^2 \sigma}{2}$? No, not that simple



$Z_r = 1/\sigma_r$

Sheet impedance / Sheet conductance

- Electrons driven by dark-matter electric fields radiate visible photon plane waves into free space in both directions
- Power coupled to sheet:

$$\frac{P}{A} = \frac{|E_{DM}|^2}{Z_{fs}} \frac{Z_{fs}/2Z_r}{\left(1 + Z_{fs}/2Z_r\right)^2}$$

- Maximum power coupled to electrons is limited by "drag" from photon emission

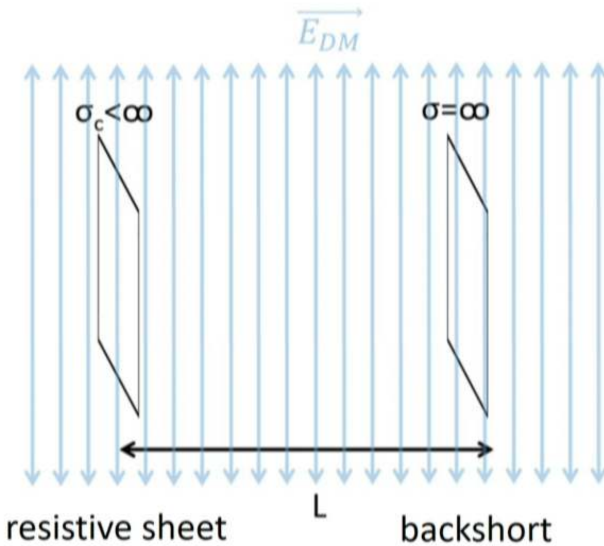
$$\frac{P}{A} \leq \frac{1}{4} \frac{|E_{DM}|^2}{Z_{fs}}$$

- Maximum power at

$$Z_r = \frac{Z_{fs}}{2}$$

A broadband resistive absorber is a bad impedance match to dark matter

Decoupling from photons with a backshort



- L < de Broglie, so induced currents on two sheets are coherent.
- Assume perfectly on resonance

$$L = \lambda_{compton}/2$$

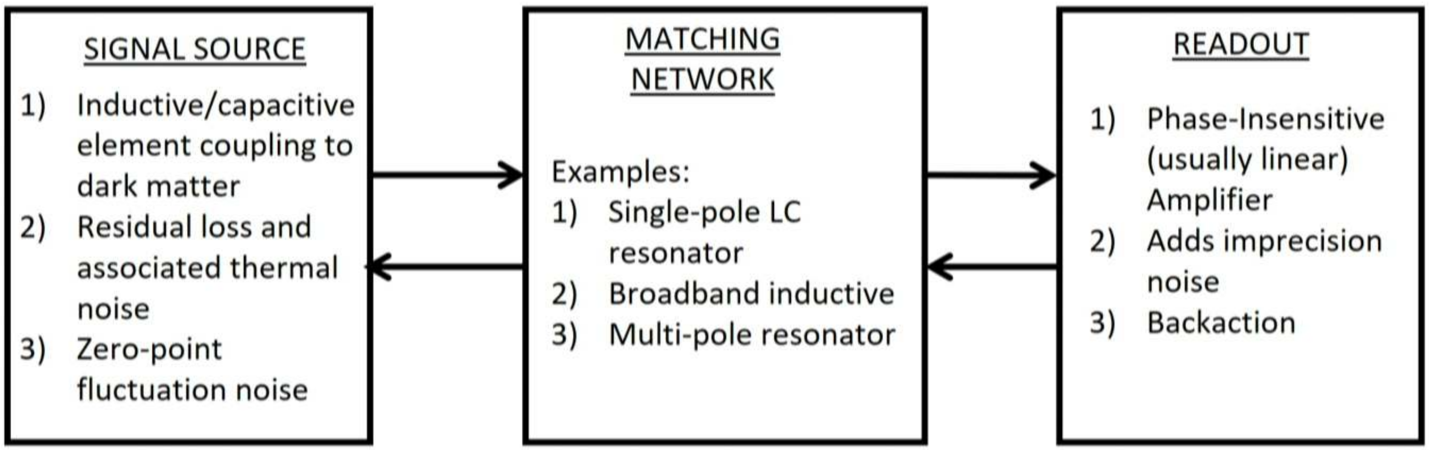
$$\frac{P}{A} = 2|E_{DM}|^2\sigma_c$$

- Radiated visible wave from the backshort destructively interferes with visible wave from conductive sheet
- Can we couple to infinite power as $\sigma_c \to \infty$?

No: (1) virialization (2) backaction on dark matter

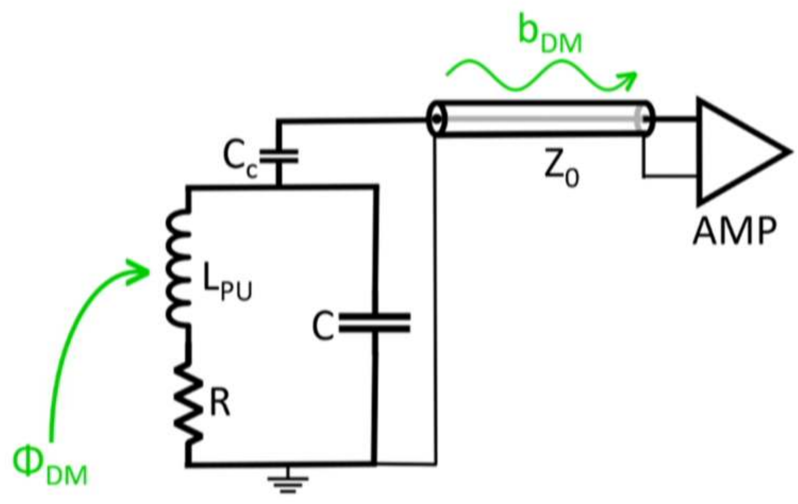
When visible photons decoupled, better impedance match is possible to DM field

Model for electromagnetic axion / hidden photon detection through electromagnetism



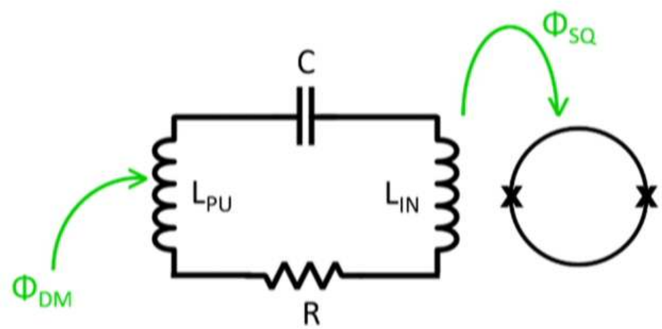
- We must couple with a reactance in order to decouple from photons, or we are poorly impedance matched to the dark matter
- Standard Quantum Limit (SQL): Heisenberg uncertainty when both quadratures of the field are measured.
- At least 1 photon of noise from zero-point vacuum noise, imprecision, and backaction.
- Also non-ideal noise sources (thermal, EMI, etc.)

Scattering mode impedance matching

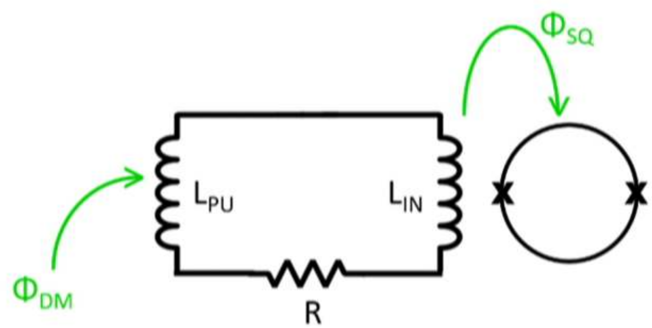


- Equivalent circuit model for resonant detector in scattering mode.
- Resonator tuned by changing capacitance.

Op-amp mode impedance matching



Scanned, one-pole resonant RLC input circuit read out by SQUID. (e.g. DM Radio)



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

1. Is resonant or broadband better?
2. Can we do better with a more complex (multi-pole) matching structure?

Quantum noise in a harmonic oscillator

The Hamiltonian of a harmonic oscillator is

$$\hat{H} = \hbar\omega\left(a^{\dagger}a + 1/2\right)$$

The Hamiltonian can be written in the cosine component ($\hat{X}$) and the sine component ($\hat{Y}$)

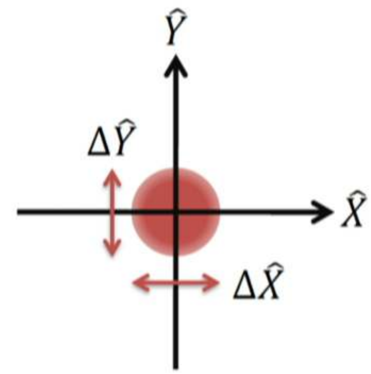
$$\hat{H} = \frac{\hbar\omega}{2}\left(\hat{X}^2 + \hat{Y}^2\right)$$

$$\left[\hat{X}, \hat{Y}\right] = i$$

$$\Delta\hat{X}\Delta\hat{Y} \geq \frac{1}{2}$$ vacuum noise

When amplified, add one more ½ quantum

$$N_{add} \geq \frac{1}{2}$$



With nonzero expectation value

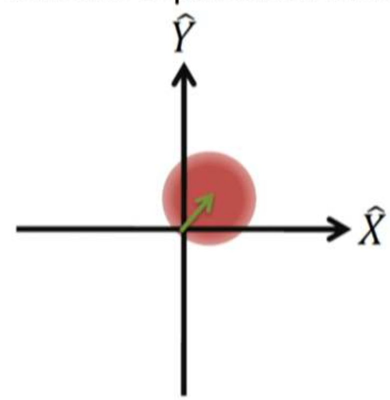


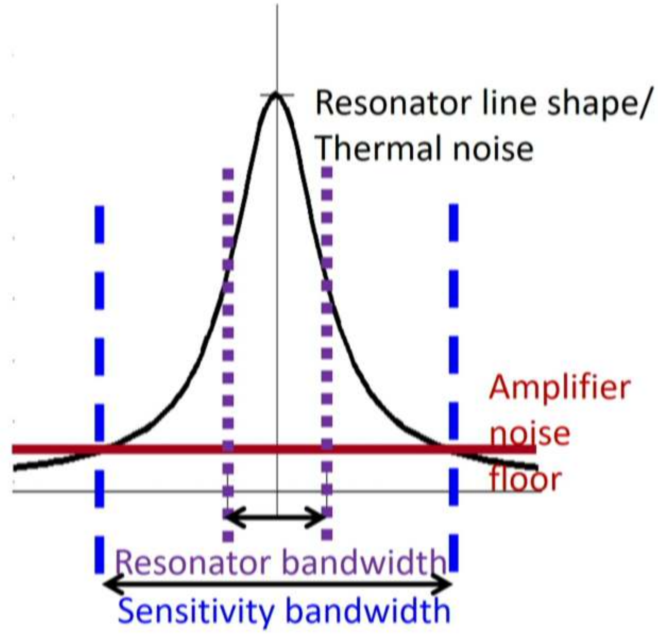
Figure of merit for integrated sensitivity

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

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

$n(\nu)$= cavity thermal occupation number, "1" is standard quantum limit.

- Includes vacuum noise, amplifier imprecision noise and backaction
- Similar calculation for op-amp mode



Example: One-pole LC resonator output noise spectrum. Figure of merit integrates sensitivity at all relevant frequencies. There is significant information outside of the resonator bandwidth, depending on amplifier noise floor.

Bode-Fano Limit on Impedance Match

A one-pole resonator is always more sensitive than a broadband measurement when it can be built. But a multi-pole resonator can be better still. How much better? *Assume the transformer is linear, passive, and reciprocal.*

- Constraint provided by Bode-Fano criterion for matching LR to a quantum-limited amplifier with a real noise impedance:

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

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

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

Bode-Fano Limit on Impedance Match

A one-pole resonator is always more sensitive than a broadband measurement when it can be built. But a multi-pole resonator can be better still. How much better? *Assume the transformer is linear, passive, and reciprocal.*

- Constraint provided by Bode-Fano criterion for matching LR to a quantum-limited amplifier with a real noise impedance:

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

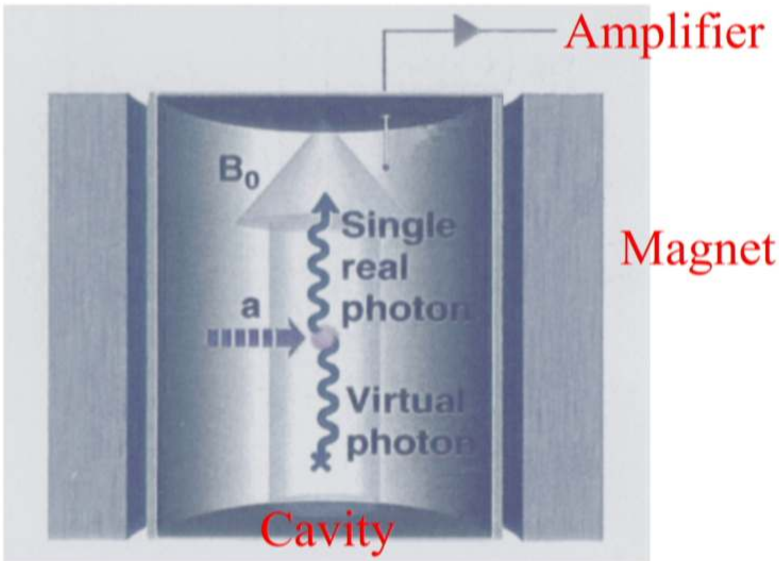
$$U \leq \begin{cases} \frac{1}{4n(\nu_h)} \frac{R}{L_{PU}}, & n(\nu_h) \gg 1 \\ 0.41 \frac{R}{L_{PU}}, & n(\nu_h) \ll 1 \end{cases}$$

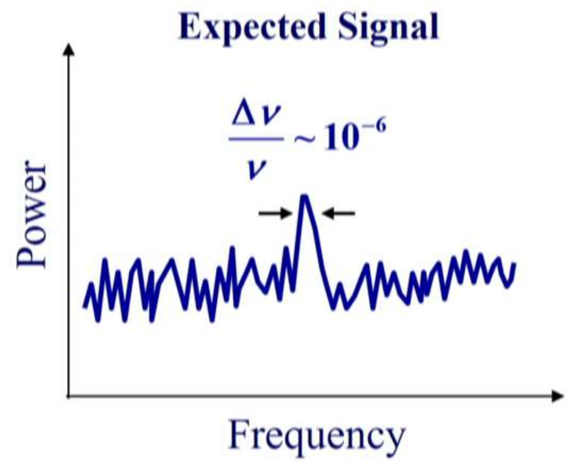
- An optimal single-pole resonator can have a figure of merit U that is ~75% of the fundamental limit of a multi-pole circuit (pretty good!)

Resonant conversion of axions into photons

Pierre Sikivie (1983)

Primakoff Conversion





ADMX experiment

Thanks to John Clarke

Idea for subwavelength, lumped-element experiment

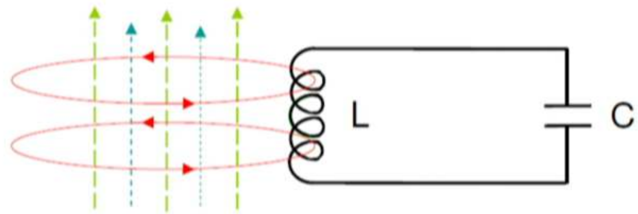
Detecting String-Scale QCD Axion Dark Matter

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(ω) B(ω)

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

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

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

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

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

Workshop Axions 2010, U. Florida, 2010

DM Radio DJs

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

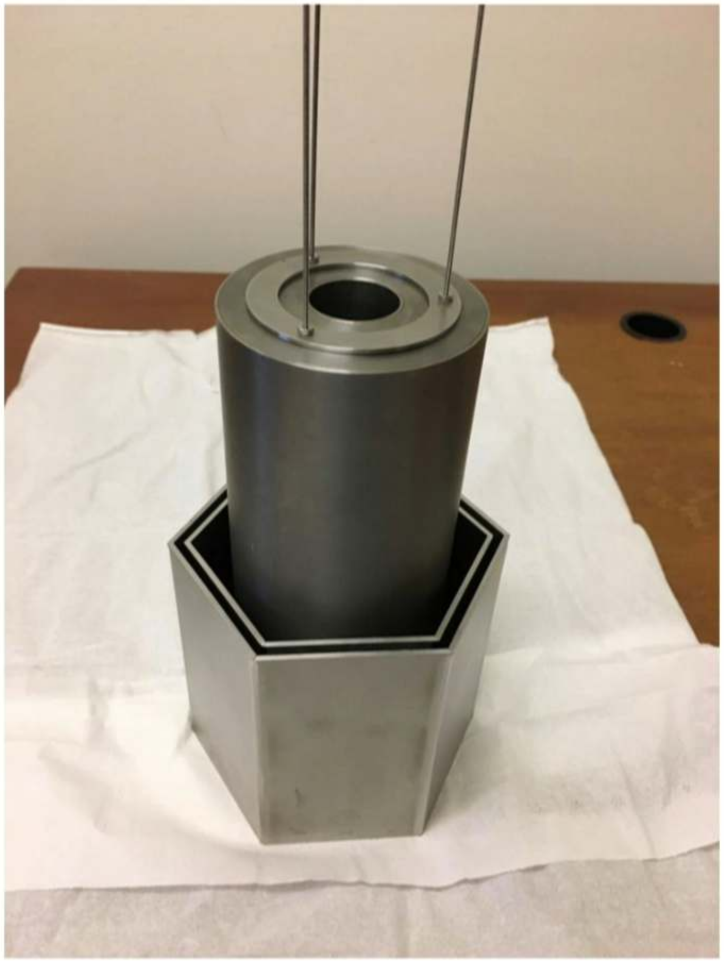
Berkeley: Surjeet Rajendran

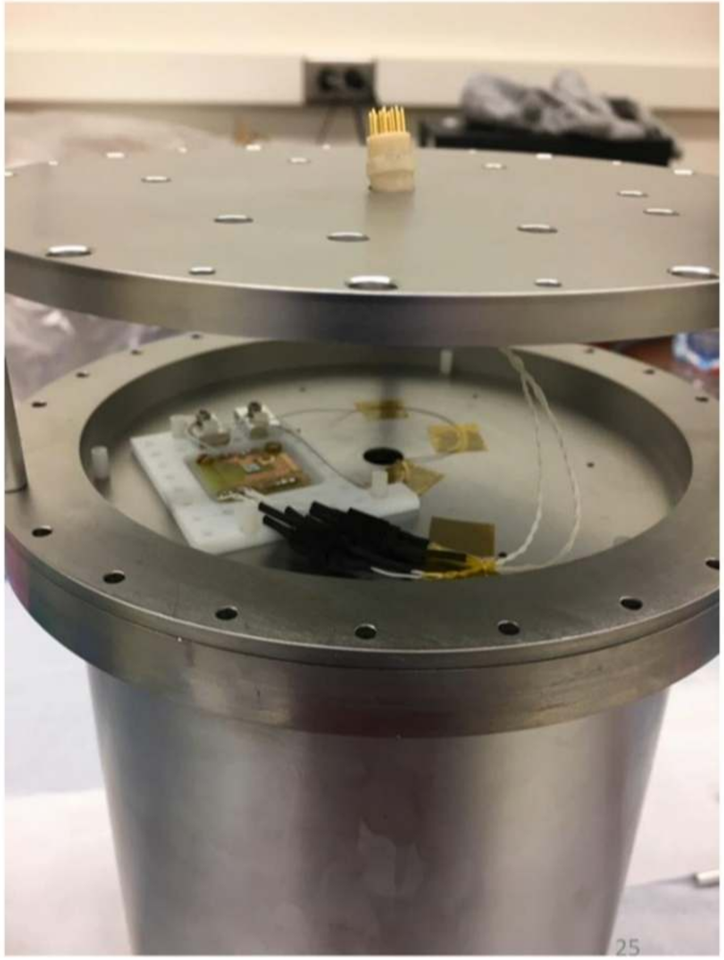
Collaborators on DM Radio extensions:

Tony Tyson, UC Davis

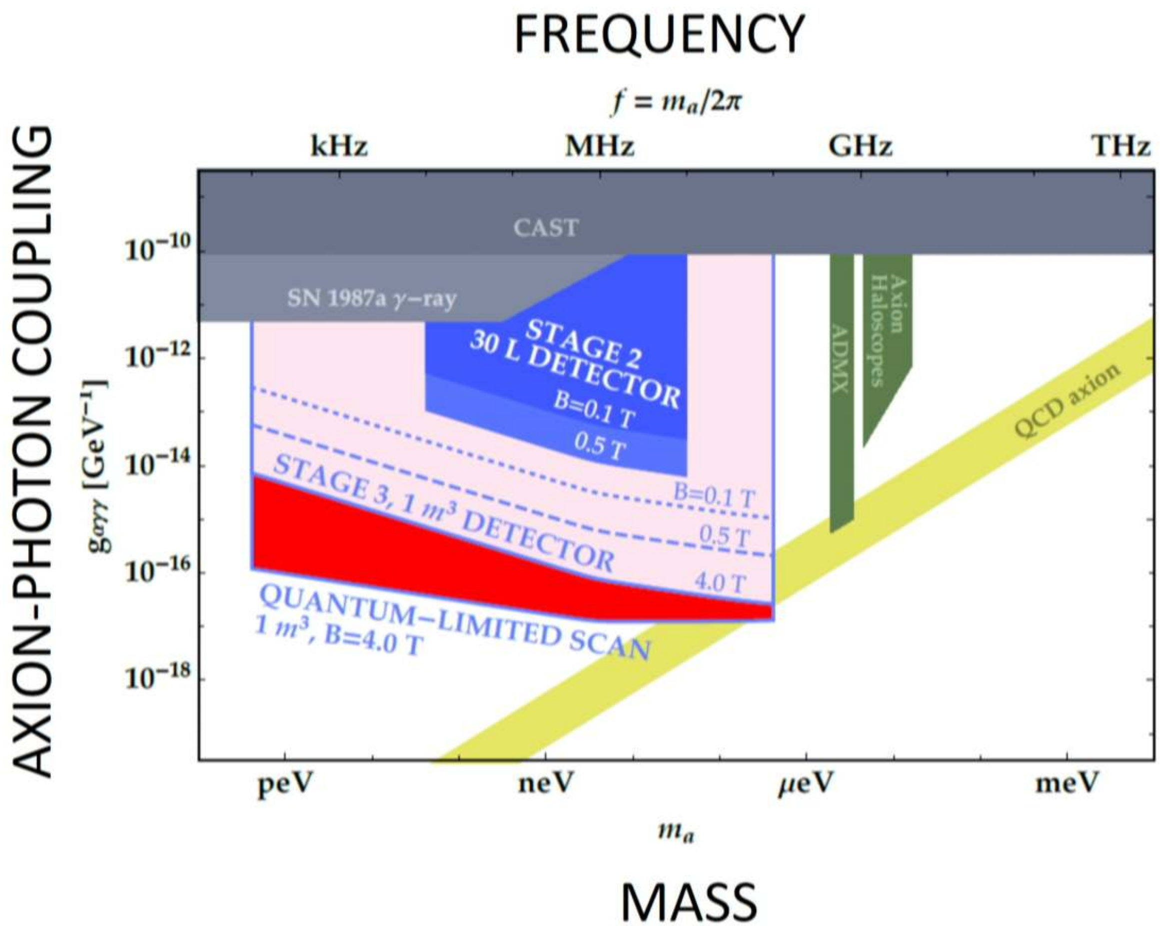
Lyman Page, Princeton

DM Radio Pathfinder

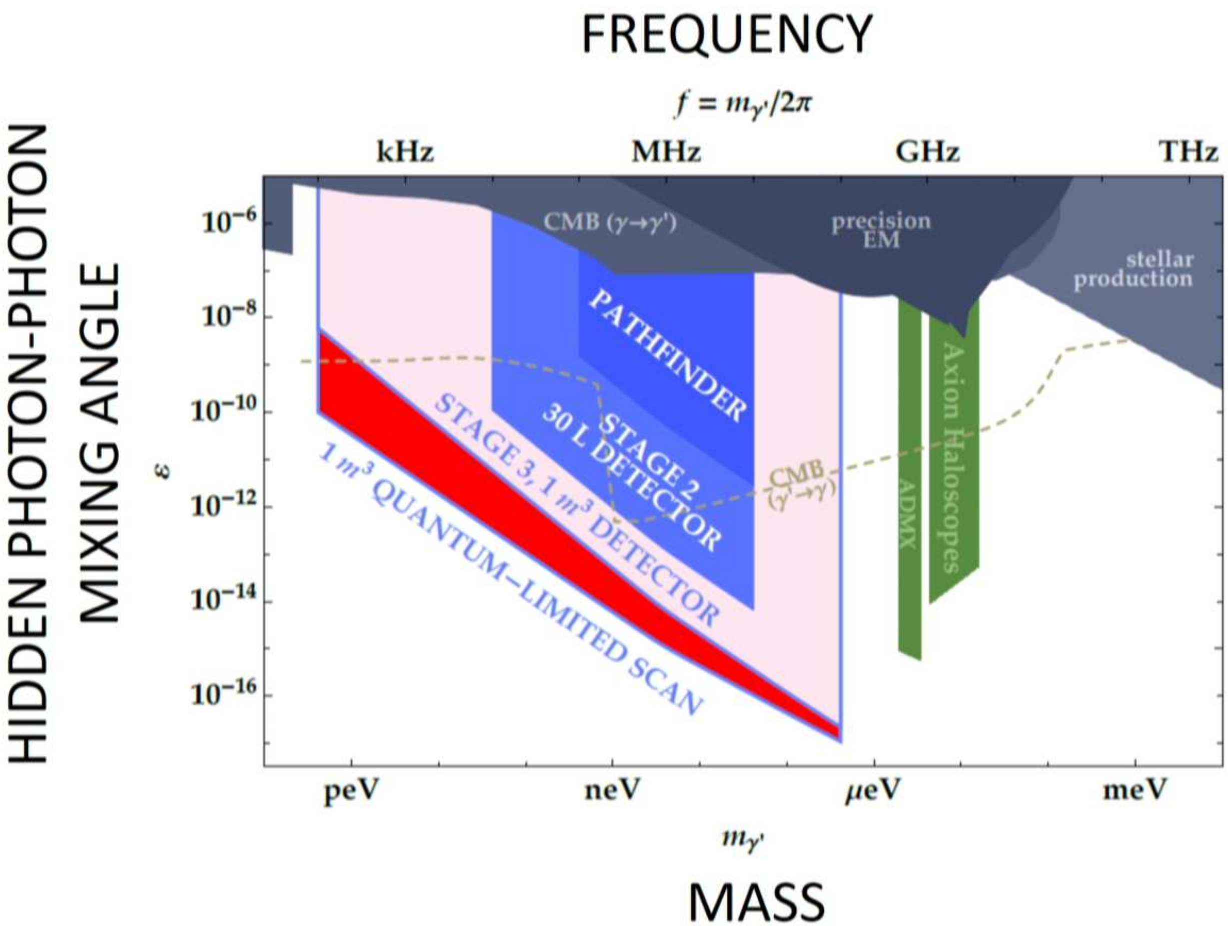




Dark Matter Radio science: axions



Dark Matter Radio science: hidden photons



Outline

- Field-like dark matter: axions and hidden photons
- Coupling electrons to light-field dark matter
  - Impedance matching
  - Quantum noise and integrated scan sensitivity
  - Bode-Fano limit on coupling
  - Quantum-limited science reach
- Measuring below the standard quantum limit
  - Quantum sensing protocols
  - Measuring a thermal state with quantum sensors
  - Squeezing, backaction evasion
- The Dark Matter Radio (DM Radio)

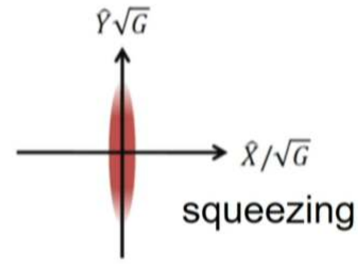
Quantum sensing

- If we don't need to measure both quadratures of a field, we don't have to be limited by the standard quantum limit.

- The standard quantum limit can be evaded using quantum correlations. These techniques are deeply related:

  - Photon counting
  - Squeezing
  - Backaction evasion
  - Entanglement
  - Cooling
  - Quantum nondemolition

$$\hat{H} = \hbar\omega\left(a^\dagger a + 1/2\right)$$



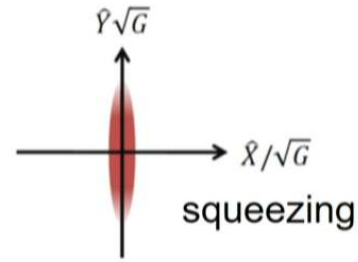
Quantum sensing

- If we don't need to measure both quadratures of a field, we don't have to be limited by the standard quantum limit.

- The standard quantum limit can be evaded using quantum correlations. These techniques are deeply related:

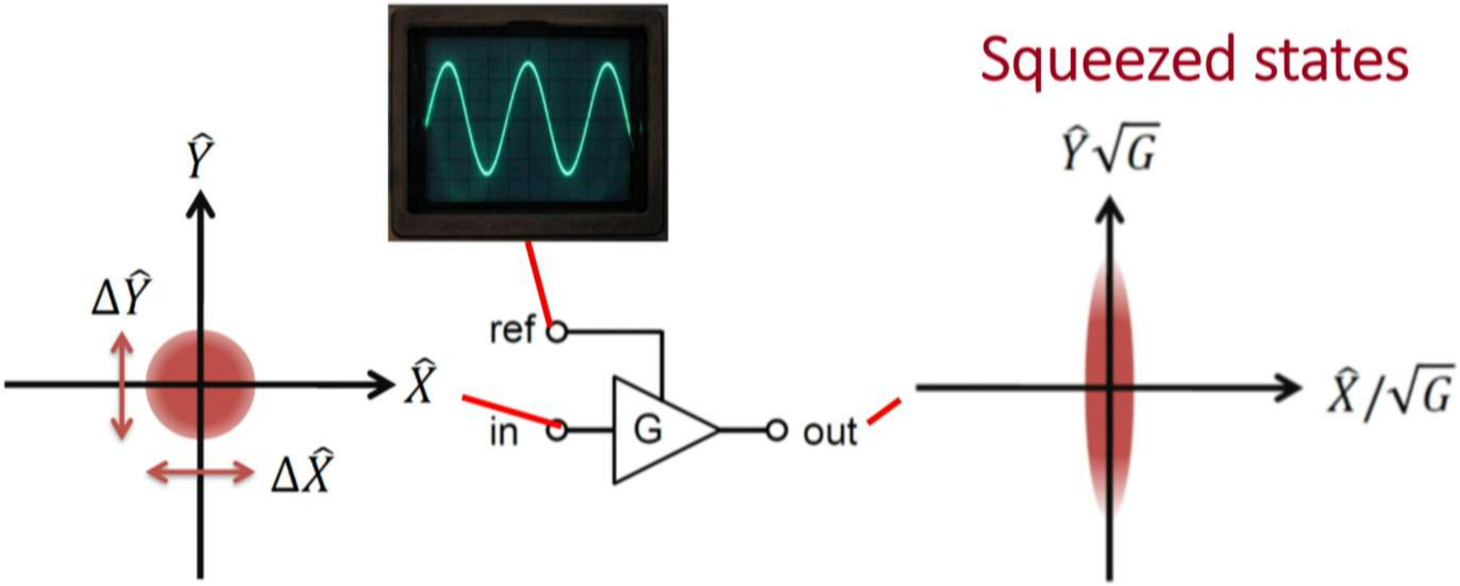
  - Photon counting
  - Squeezing
  - Backaction evasion
  - Entanglement
  - Cooling
  - Quantum nondemolition

$$\hat{H} = \hbar\omega\left(a^{\dagger}a + 1/2\right)$$



29

Squeezed states



Still true:

$$\Delta\hat{X}\Delta\hat{Y} \geq \frac{1}{2}$$

But concentrated in one quadrature, $\Delta\hat{Y}$.

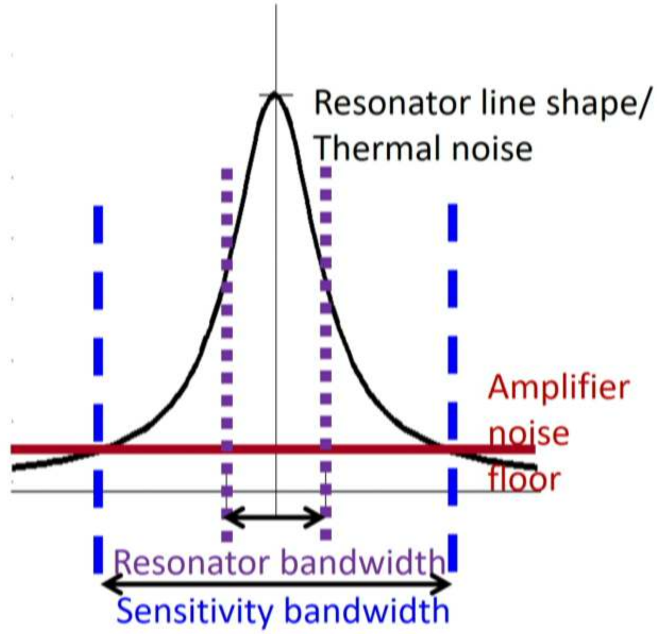
This enables signal in the other quadrature, $\Delta\hat{X}$, to be measured with precision below the Standard Quantum Limit.

Quantum sensing of thermal states

$\hbar\omega < k_B T$ Thermal state

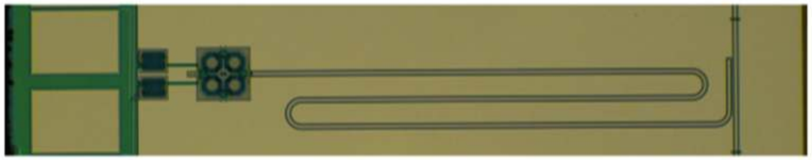
Why would we use a quantum sensor for a thermal state?

- The signal to noise within the resonator bandwidth is not helped by a better amplifier.
- The sensitivity of the amplifier determines the *sensitivity bandwidth*, and thus the sensitivity of a search for an unknown signal frequency.
- Very large speedup possible for a sensor operating below the standard limit even if $\hbar\omega < k_B T$

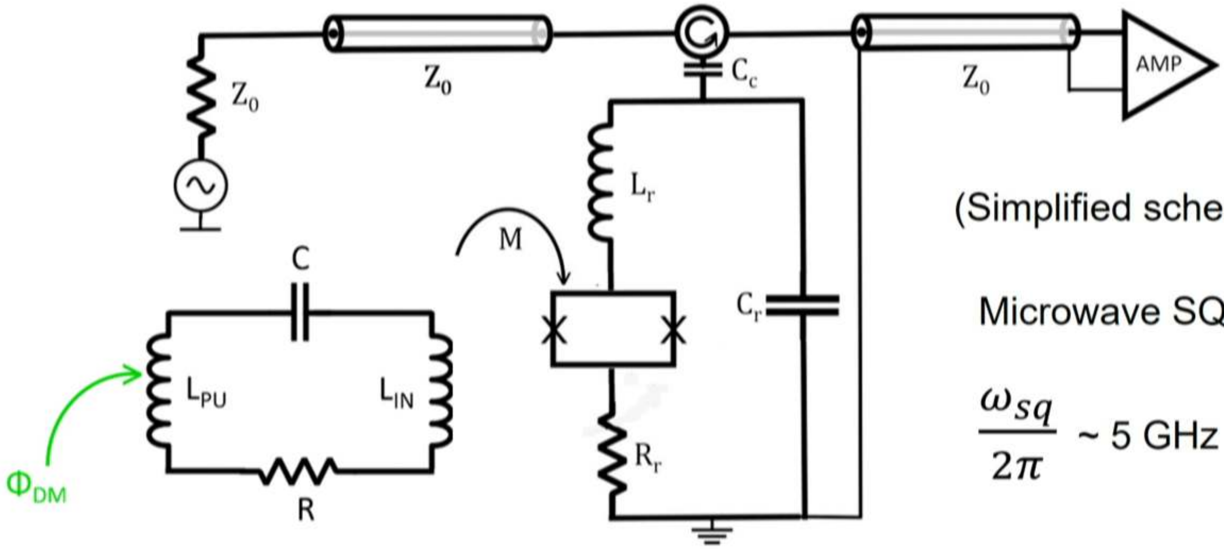


Quantum sensors are needed for low-frequency thermal states too

Measuring a resonator with a dissipationless microwave SQUID frequency upconverter



Dissipationless microwave SQUID flux amplifier



(Simplified schematic)

Microwave SQUID:

$$\frac{\omega_{sq}}{2\pi} \sim 5\text{ GHz}$$

DM Radio: $\frac{\omega_r}{2\pi} = $ 1 kHz – 100 MHz

Hamiltonian maps onto optomechanical system

DM Radio: $\frac{\omega_r}{2\pi}$ = 1 kHz – 100 MHz   Microwave SQUID: $\frac{\omega_{sq}}{2\pi}$ ~ 5 GHz

Uncoupled Hamiltonian: $\hat{H}_0 = \hbar\omega_{sq}\hat{a}^{\dagger}\hat{a} + \hbar\omega_r\hat{b}^{\dagger}\hat{b}$

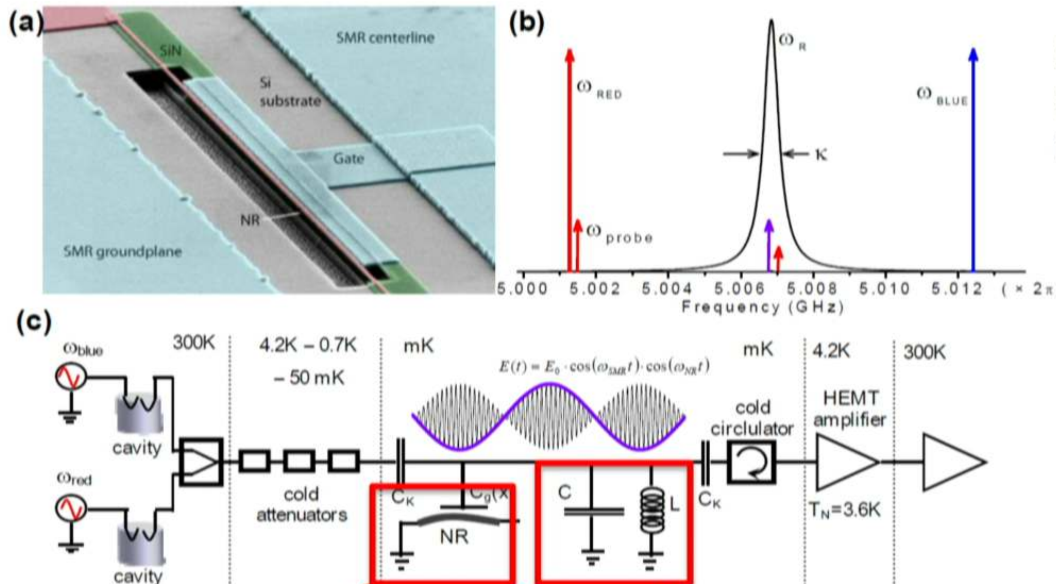
Interaction Hamiltonian: $\hat{H}_{int} = -\hbar G\hat{\Phi}_{in}\hat{a}^{\dagger}\hat{a} = -\hbar g_0\hat{a}^{\dagger}\hat{a}\left(\hat{b} + \hat{b}^{\dagger}\right)$

This maps onto the Hamiltonian of on optomechanical resonator with:

Displacement r	⟷	Flux Φ
Momentum p	⟷	Charge Q
Inverse spring constant 1/k	⟷	Inductance L
Mass m	⟷	Capacitance C

Nonlinear interaction upconverts photons from the DM Radio resonator to the uwave SQUID, downconverts uwave SQUID photons to the DM Radio, leading to backaction

Hamiltonian maps onto optomechanical system



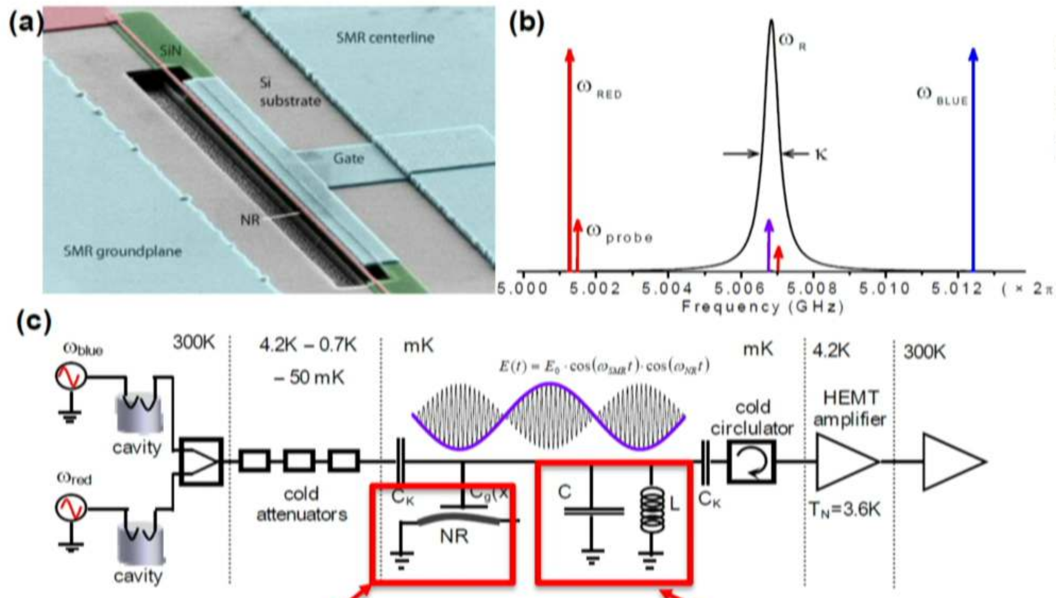
See Clerk, Schwab talks

Low-frequency mechanical resonance
(Maps onto DM radio Hamiltonian)

High-frequency LC resonance
(Maps onto uwave SQUID Hamiltonian)

Hertzberg, J. B., Rocheleau, T., Ndukum, T., Savva, M., Clerk, A. A., & Schwab, K. C. (2010). Back-action-evading measurements of nanomechanical motion. *Nature Physics*, *6*(3), 213-217.

Hamiltonian maps onto optomechanical system



See Clerk, Schwab talks

Low-frequency mechanical resonance
(Maps onto DM radio Hamiltonian)

High-frequency LC resonance
(Maps onto uwave SQUID Hamiltonian)

Hertzberg, J. B., Rocheleau, T., Ndukum, T., Savva, M., Clerk, A. A., & Schwab, K. C. (2010). Back-action-evading measurements of nanomechanical motion. *Nature Physics*, *6*(3), 213-217.

Hamiltonian maps onto optomechanical system

DM Radio: $\frac{\omega_r}{2\pi}$ = 1 kHz – 100 MHz   Microwave SQUID: $\frac{\omega_{sq}}{2\pi}$ ~ 5 GHz

Uncoupled Hamiltonian: $\hat{H}_0 = \hbar\omega_{sq}\hat{a}^\dagger\hat{a} + \hbar\omega_r\hat{b}^\dagger\hat{b}$

Interaction Hamiltonian: $\hat{H}_{int} = -\hbar G\hat{\Phi}_{in}\hat{a}^\dagger\hat{a} = -\hbar g_0\hat{a}^\dagger\hat{a}\left(\hat{b} + \hat{b}^\dagger\right)$

This maps onto the Hamiltonian of on optomechanical resonator with:

Displacement r	↔	Flux Φ
Momentum p	↔	Charge Q
Inverse spring constant 1/k	↔	Inductance L
Mass m	↔	Capacitance C

Nonlinear interaction upconverts photons from the DM Radio resonator to the uwave SQUID, downconverts uwave SQUID photons to the DM Radio, leading to backaction

Hamiltonian maps onto optomechanical system

DM Radio: $\frac{\omega_r}{2\pi}$ = 1 kHz – 100 MHz   Microwave SQUID: $\frac{\omega_{sq}}{2\pi}$ ~ 5 GHz

Uncoupled Hamiltonian: $\hat{H}_0 = \hbar\omega_{sq}\hat{a}^\dagger\hat{a} + \hbar\omega_r\hat{b}^\dagger\hat{b}$

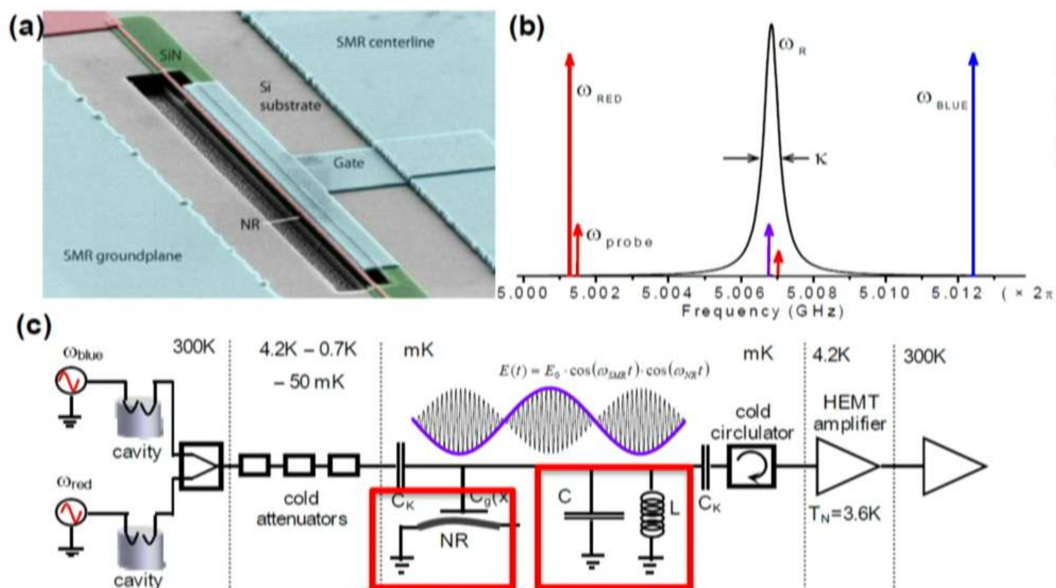
Interaction Hamiltonian: $\hat{H}_{int} = -\hbar G\hat{\Phi}_{in}\hat{a}^\dagger\hat{a} = -\hbar g_0\hat{a}^\dagger\hat{a}\left(\hat{b} + \hat{b}^\dagger\right)$

This maps onto the Hamiltonian of on optomechanical resonator with:

Displacement r	⟷	Flux Φ
Momentum p	⟷	Charge Q
Inverse spring constant 1/k	⟷	Inductance L
Mass m	⟷	Capacitance C

Nonlinear interaction upconverts photons from the DM Radio resonator to the uwave SQUID, downconverts uwave SQUID photons to the DM Radio, leading to backaction

Hamiltonian maps onto optomechanical system



See Clerk, Schwab talks

Low-frequency mechanical resonance
(Maps onto DM radio Hamiltonian)

High-frequency LC resonance
(Maps onto uwave SQUID Hamiltonian)

Hertzberg, J. B., Rocheleau, T., Ndukum, T., Savva, M., Clerk, A. A., & Schwab, K. C. (2010). Back-action-evading measurements of nanomechanical motion. *Nature Physics*, *6*(3), 213-217.

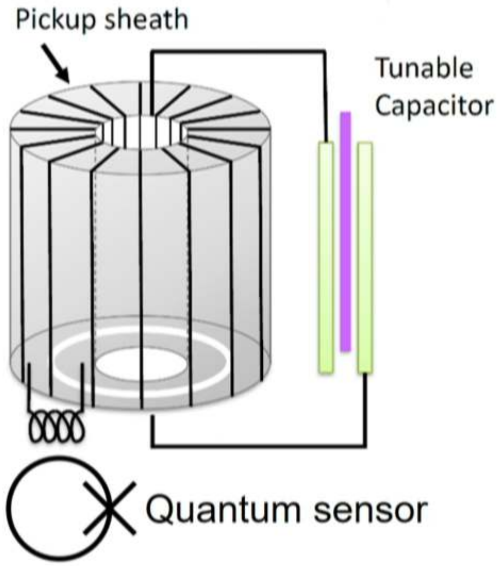
Outline

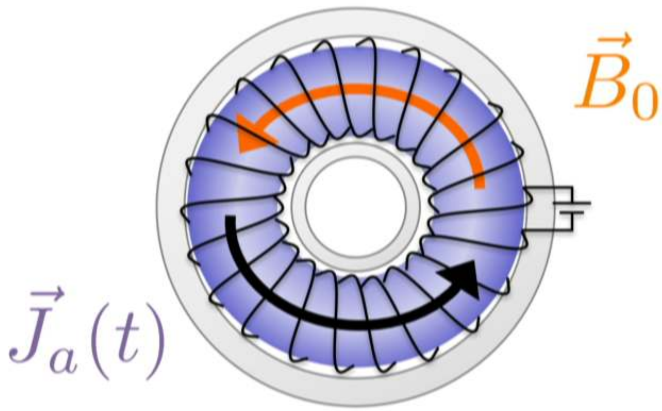
* Field-like dark matter: axions and hidden photons
* Coupling electrons to light-field dark matter
  - Impedance matching
  - Quantum noise and integrated scan sensitivity
  - Bode-Fano limit on coupling
  - Quantum-limited science reach
* Measuring below the standard quantum limit
  - Quantum sensing protocols
  - Measuring a thermal state with quantum sensors
  - Squeezing, backaction evasion
* The Dark Matter Radio (DM Radio)

The Dark Matter Radio

HEISING-SIMONS FOUNDATION

SLAC KIPAC Cal



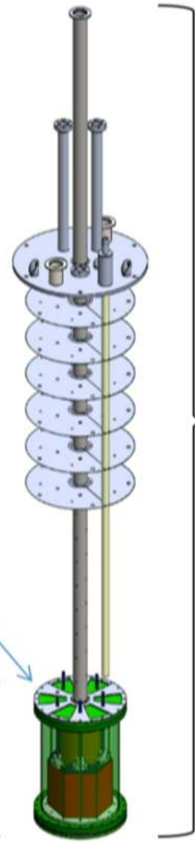


38

DM Radio pathfinder experiment

4K Dip Probe

Inserts into Cryoperm-lined helium dewar

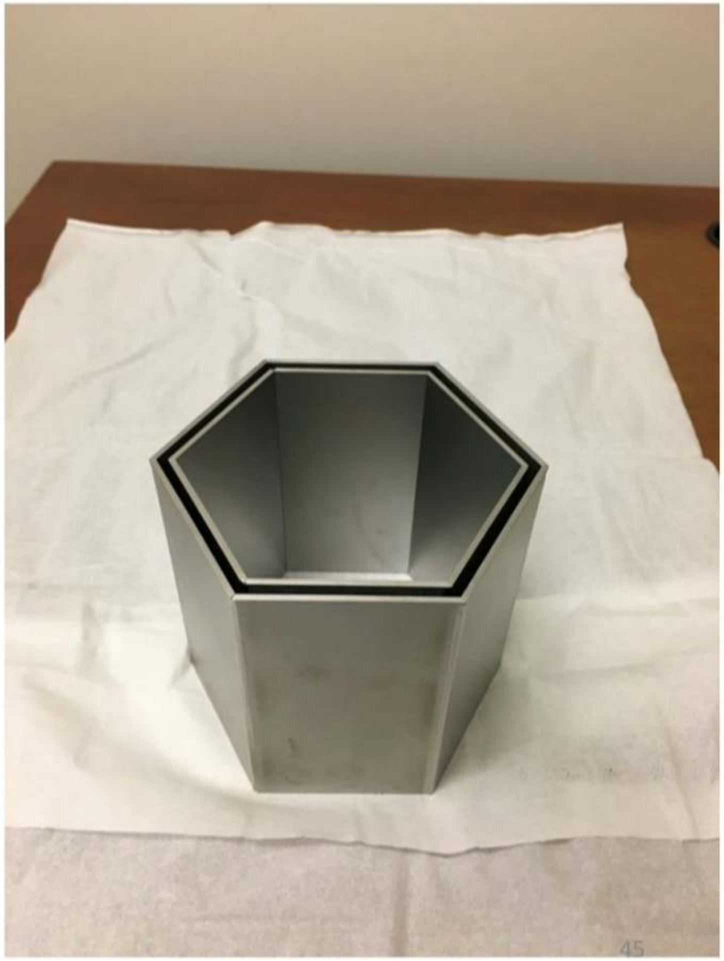


750 mL Pathfinder now being tested

- 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

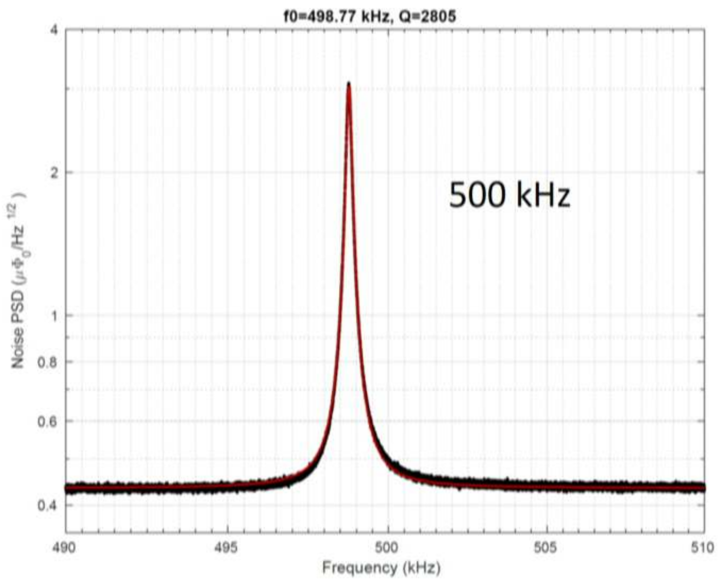
Design Overview of the DM Radio Pathfinder Experiment
M. Silva, arXiv:1610.09344, 2016

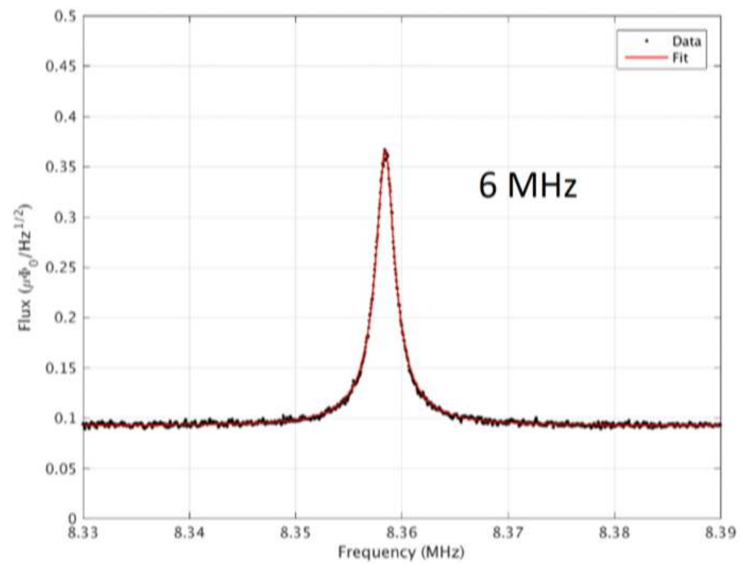
Toroidal Nb sheath and parallel-plate capacitors



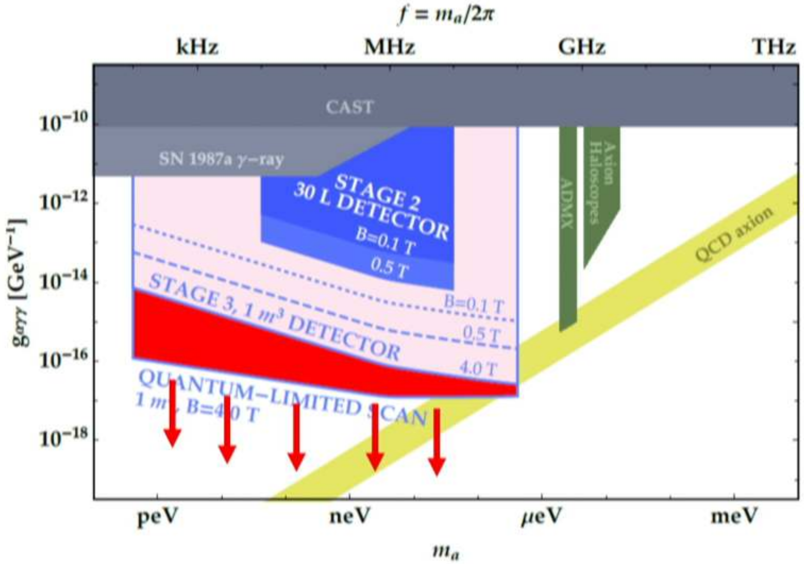
DM Radio Pathfinder

DM Radio first data





- Measured signal from thermal state at 4 K
- Data shown for two tuning frequencies: 500 kHz and 6 MHz
- Q limited by normal (aluminum) wirebonds. Will now replacing with niobium, with a target Q of 10^6



Conclusions

- We have derived scan sensitivity limits on detection of axions and hidden photons with electromagnetic coupling.
- Quantum sensing will enable science reach better than the standard quantum limit.
- The DM Radio Pathfinder is in engineering shakeout, dilution refrigerator for next stage has been ordered.