Quantum Sensing: Superconducting Techniques

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and SLAC National Accelerator Laboratory

Workshop on Quantum Sensing
December 12-14, 2017
Argonne National Laboratory

Superconducting Quantum Sensors

- Using superconducting quantum phase transition / pairbreaking / quantum interference

  HEP Science: Dark Matter, CMB, Dark Energy

1. TES – Roger O'Brient, Zeesh Ahmed, Sae Woo Nam
2. MKID – Roger O'Brient
3. Nanowire – Karl Berggren, Sae Woo Nam
4. SQUIDs – Derek Kimball (CASPEr) – also in TES

- Using quantum correlations to measure below the standard quantum limit

  HEP Science: Dark matter, strong CP, …

1. Josephson parametric amplifier – Konrad Lehnert(HAYSTAC)
2. Microwave SQUID / backaction evasion – this talk (DM Radio), Aashish Clerk – more on backaction evasion

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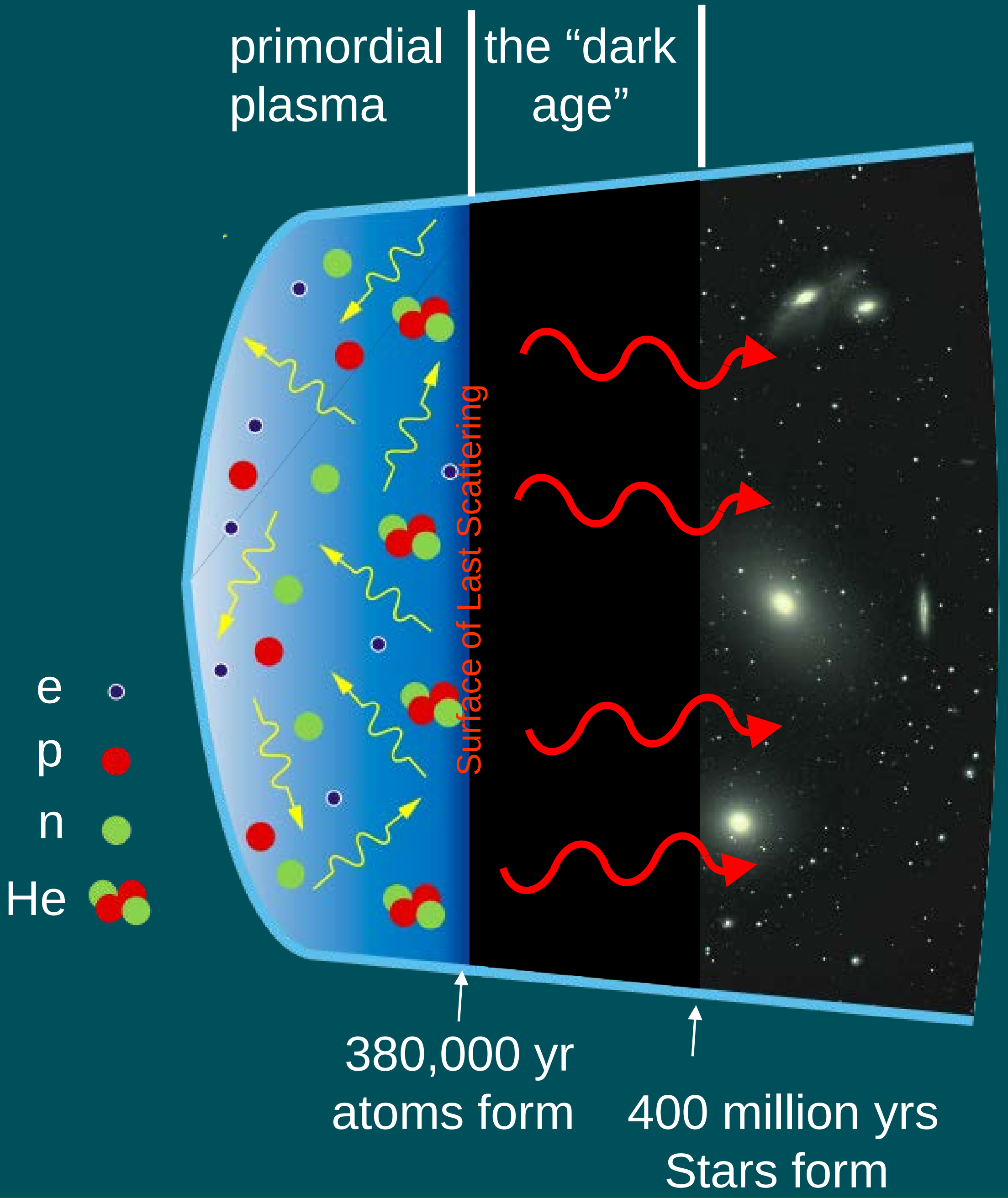
The cosmic microwave background (CMB)

- The early universe was hot, and full of a plasma of photons and baryons

- At 380,000 years after the Big Bang, electrons and protons found each other, and formed neutral hydrogen

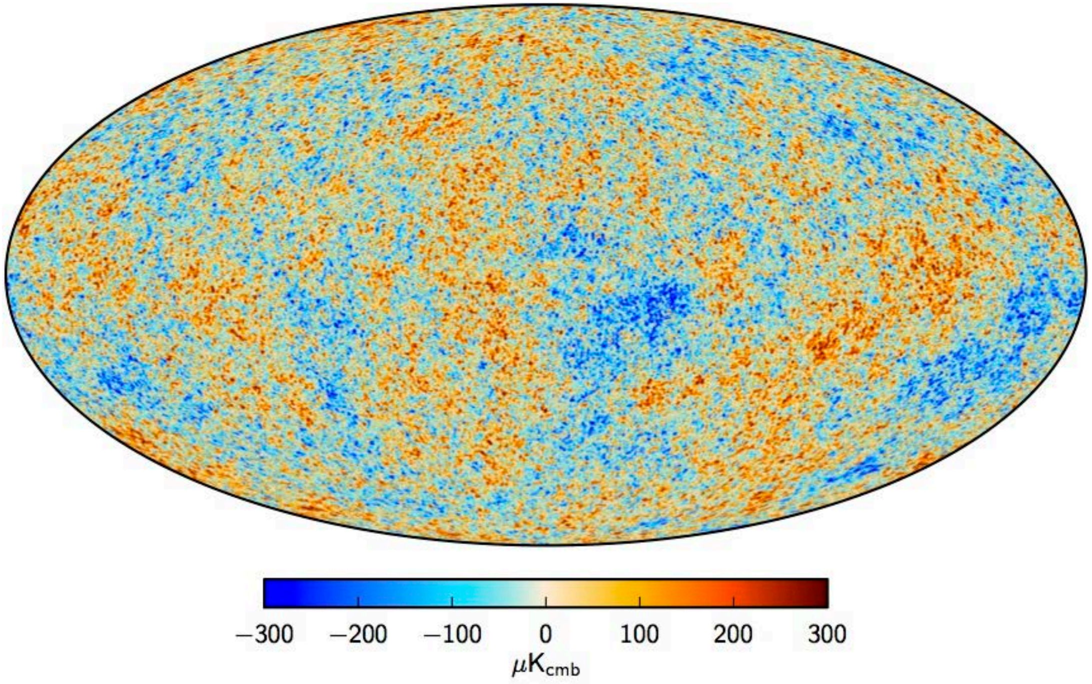
- Since that time, most of the photons haven't scattered

These photons, now cooled to microwave photons, are an image of the early universe



CMB Anisotropies

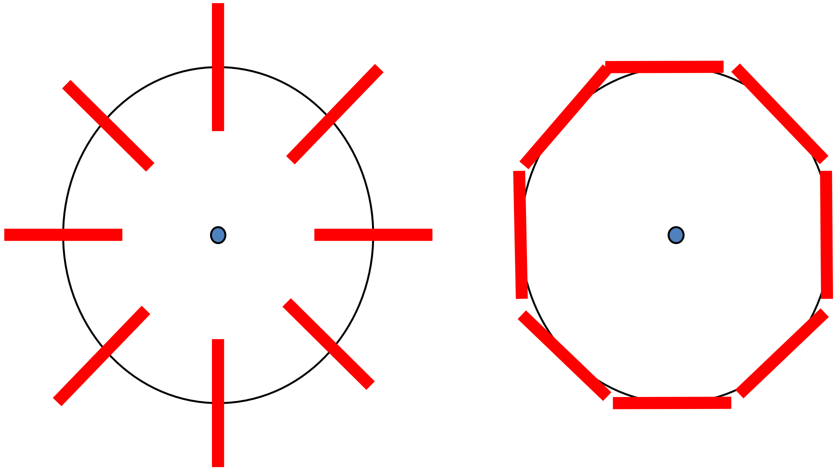
Planck 2015



- Seeds of structure from primordial quantum fluctuations
- Baryon (5%) / Dark Matter (26%) / Dark Energy (69%) today
- Gives age of universe (13.8 Gyr), geometry (flat)
- Precision constraints on L-CDM model

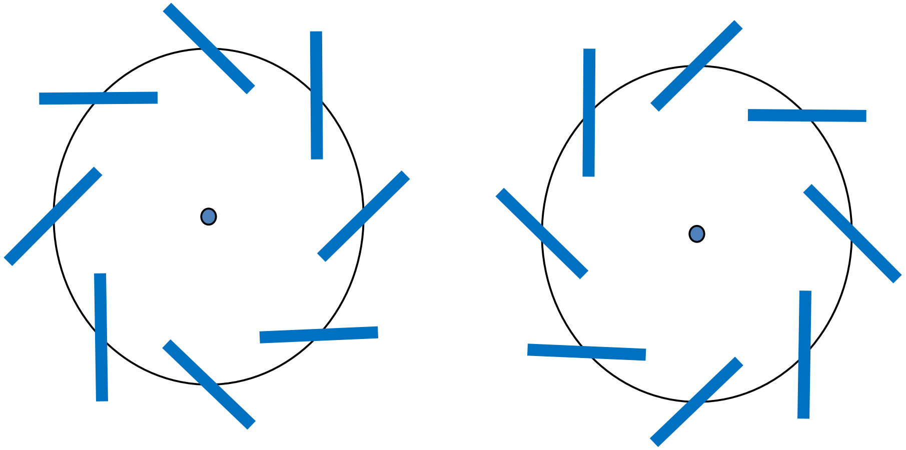
CMB Polarization

Gravitational waves from inflation imprint a polarization signal on the CMB



Acoustic modes: “divergence”, but no “curl”

E-modes

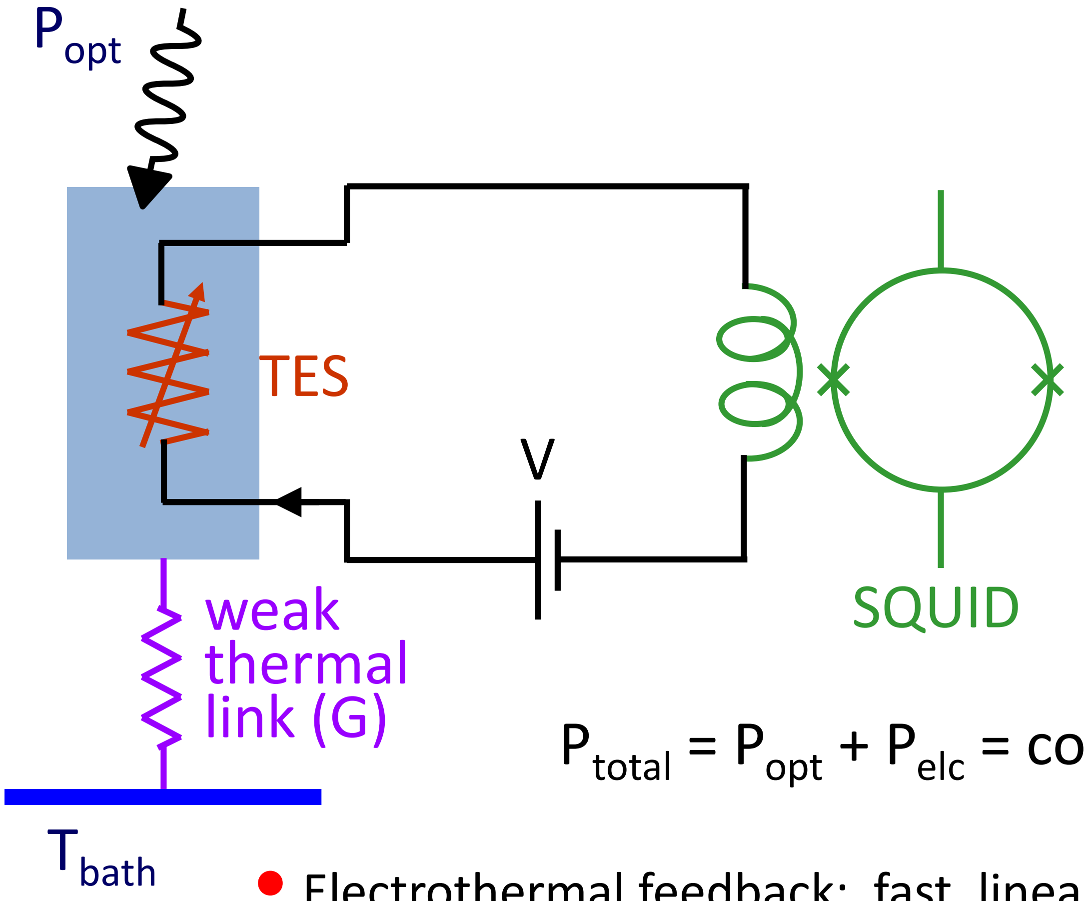


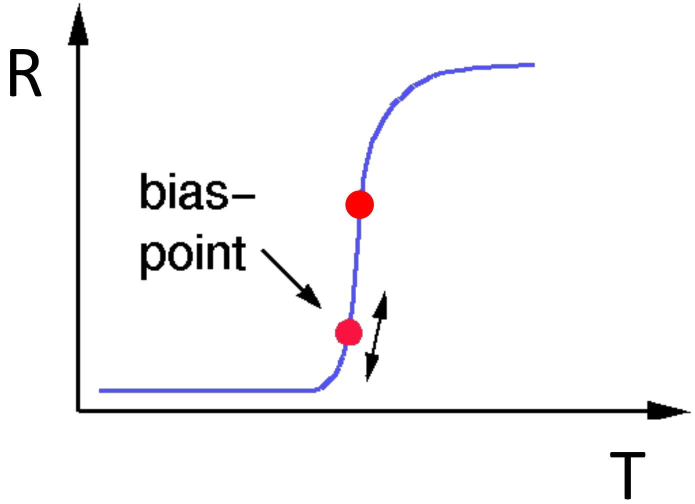
Gravitational modes: “curl” mode

B-modes

- Like the Helmholtz theorem, but for tensors
- Allows the resolution of a tiny (ppb) signal with confidence
- Must be separated from foreground sources of B modes

Voltage-Biased Transition Edge Sensor





$$P_{total} = P_{opt} + P_{elc} = \text{constant}$$

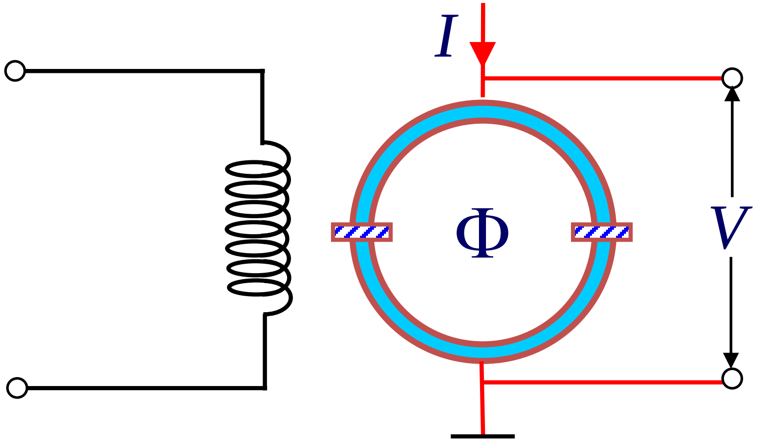
- Electrothermal feedback: fast, linear response

K.D. Irwin, APL 66 (1995)

The dc Superconducting Quantum Interference Device

dc SQUID

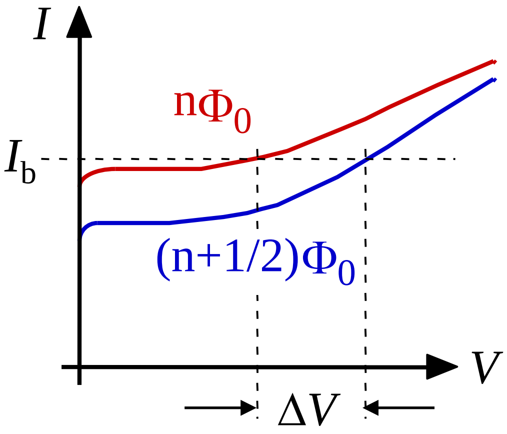
Two Josephson junctions on a superconducting ring

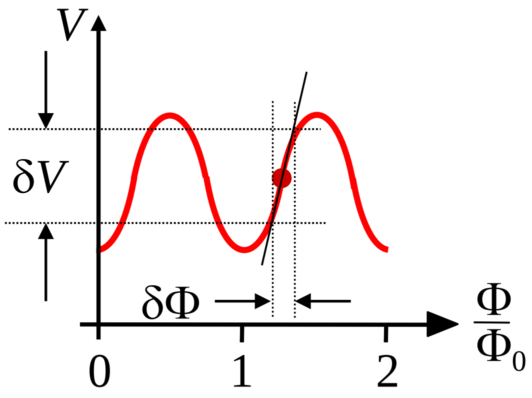


Current-voltage (I-V) characteristic modulated by magnetic flux Φ

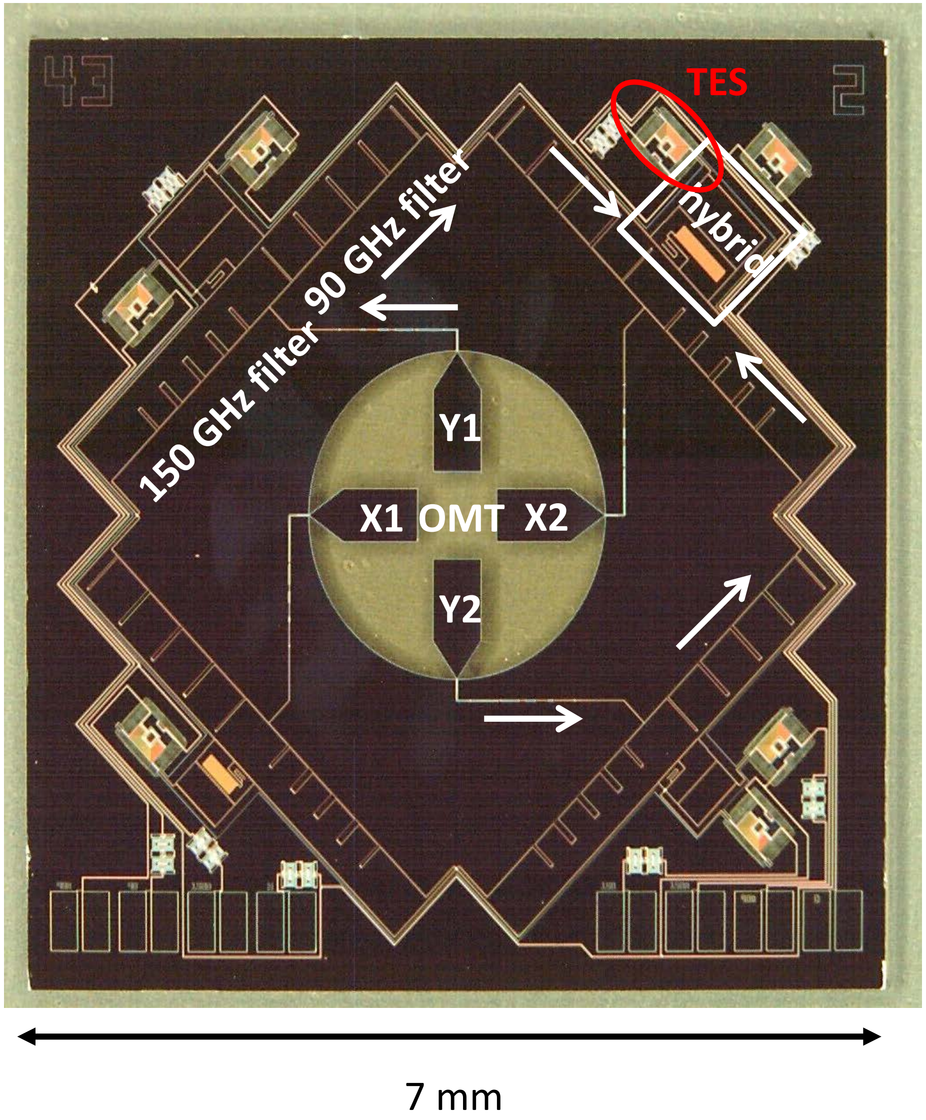
Period one flux quantum

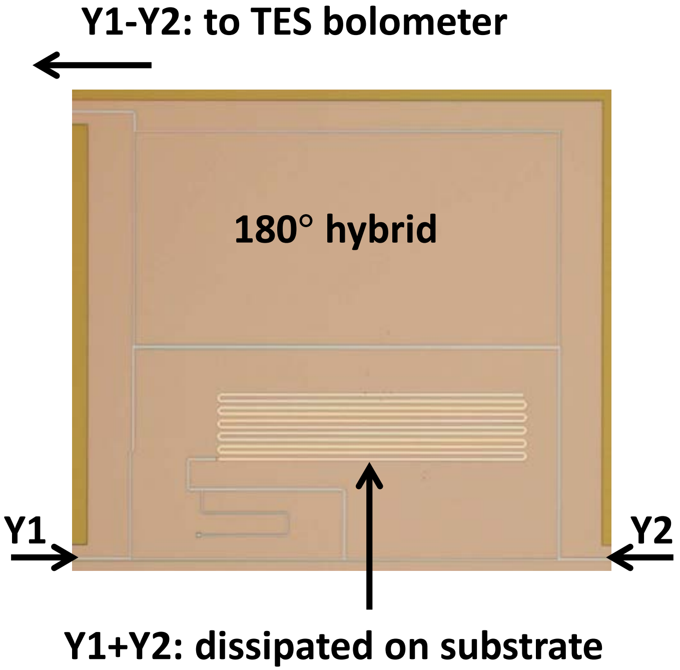
$\Phi_0 = h/2e \approx 2 \times 10^{-15}$ T m^2

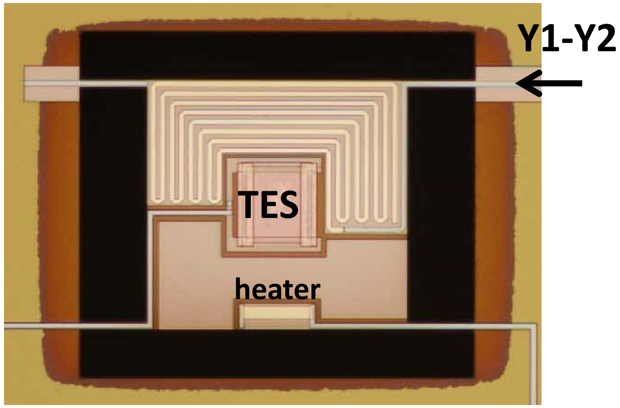




90/150 GHz CMB Polarimeter



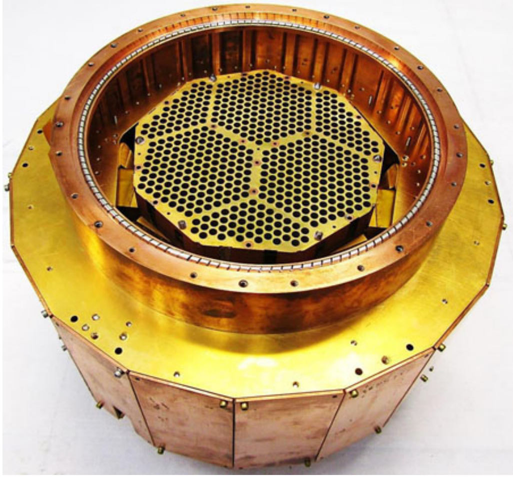




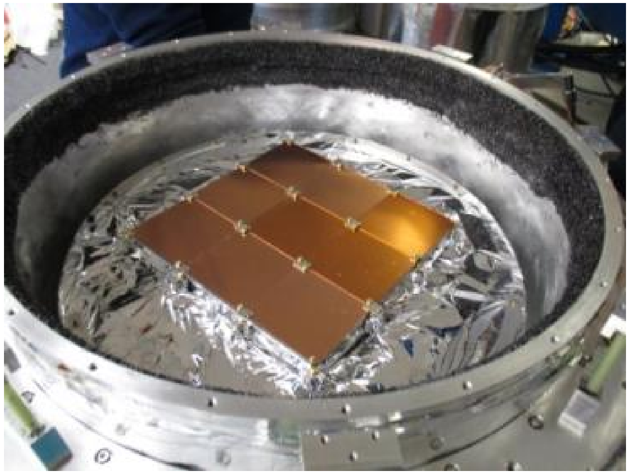
Polarimeter, photo courtesy Hsiao-Mei Cho, SLAC / NIST, ACTPol collaboration

Stage-II CMB instruments producing science

ACTpol

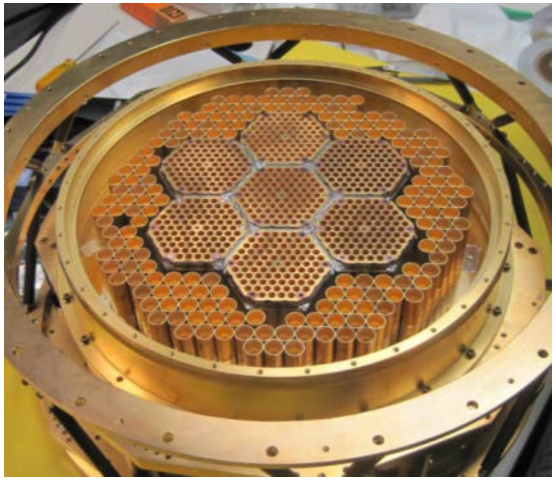


BICEP-3, SPIDER

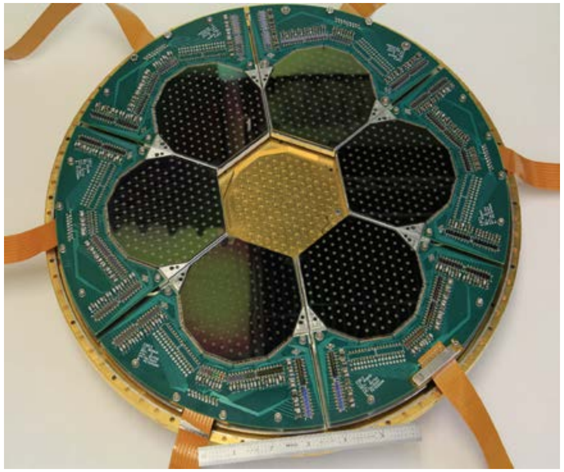


Keck Array

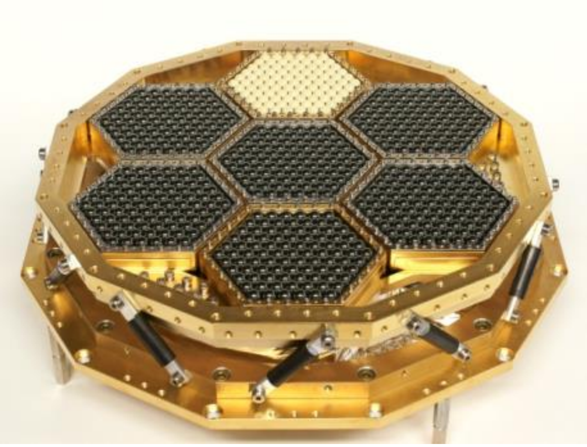
SPTpol



EBEX



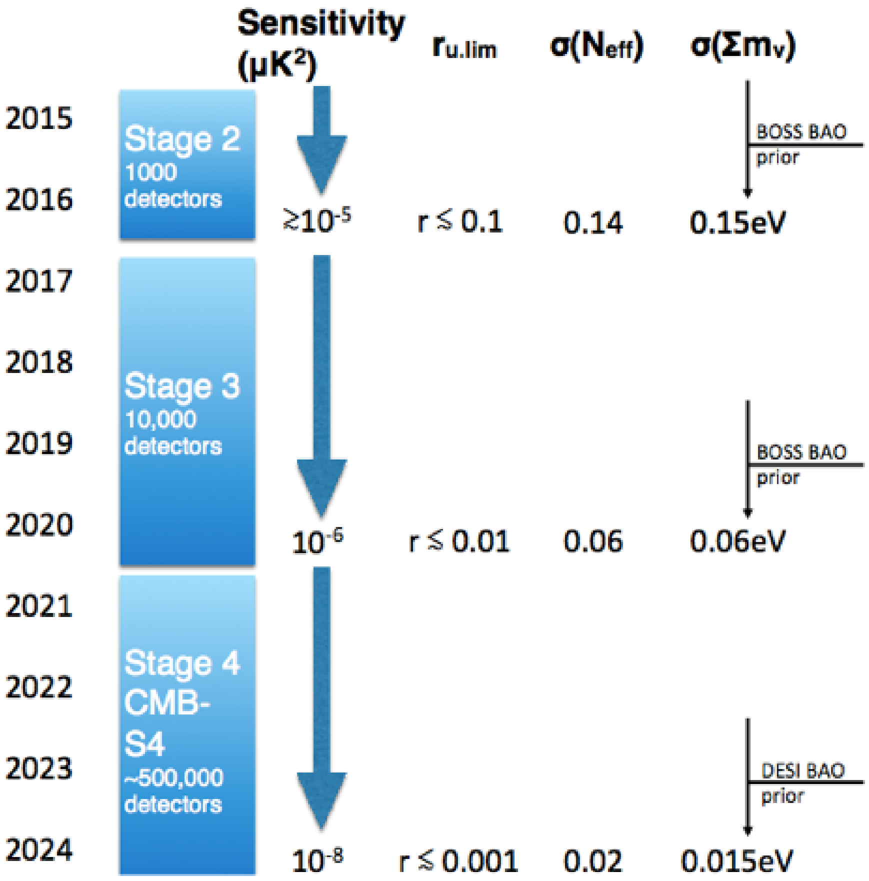
POLARBEAR, Simons



Stage IV CMB experiment: CMB-S4

The future enabled by CMB-S4:

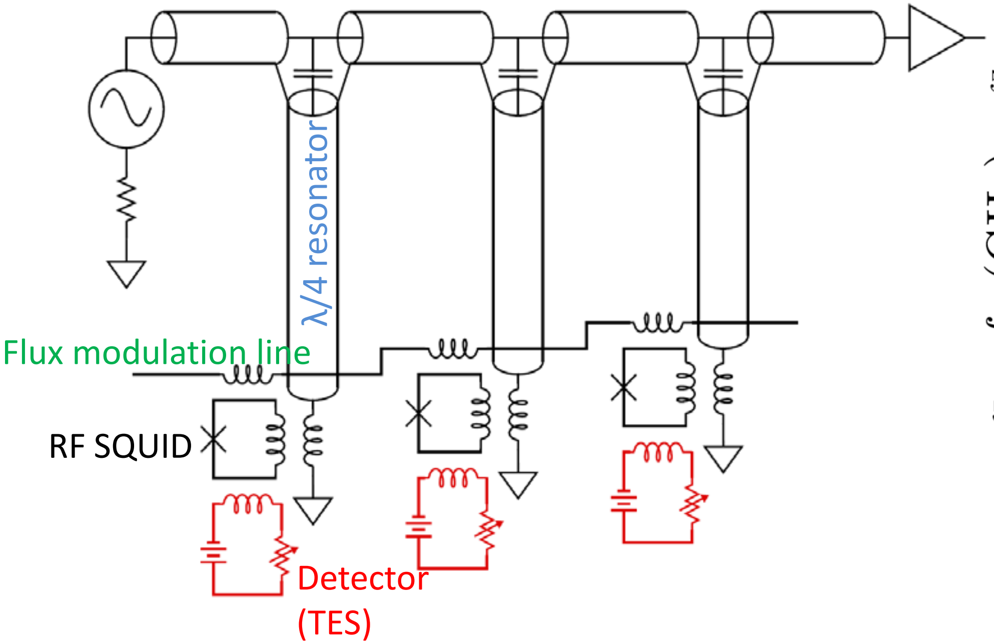
- ***Inflation***: Detect or rule out generic slow roll inflation, E ~ 10^{16} GeV
- ***Dark Radiation:*** Cosmological test of neutrino interactions and additional light species.
- ***Neutrino mass:*** Detection of sum of masses
- ***Dark Energy, Gravity, and Dark Matter:*** Multiple probes constraining structure growth, geometry.
- More fundamental discoveries?

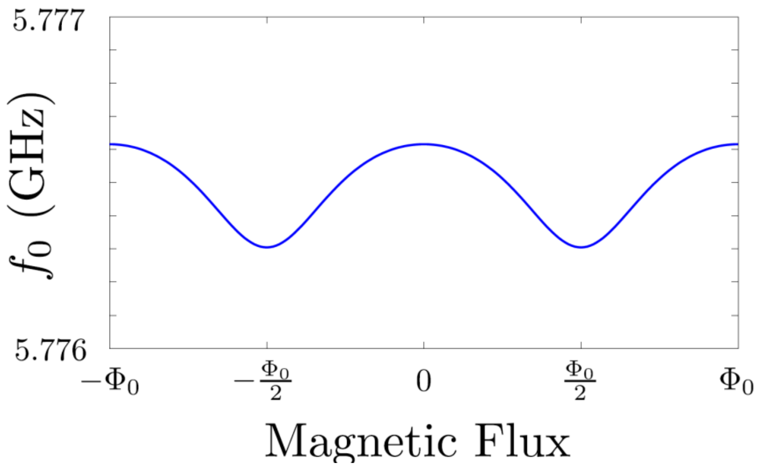


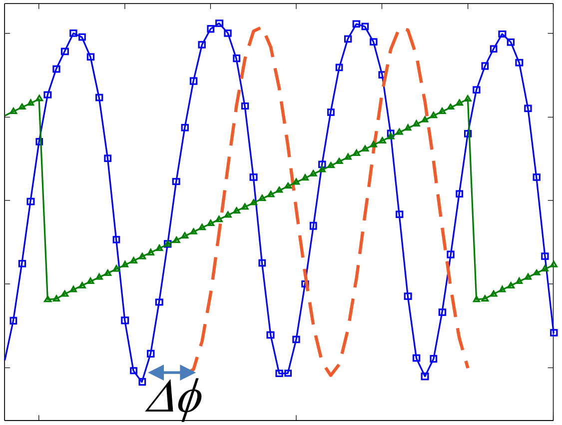
	Sensitivity (μK^2)	$r_{u.lim}$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$
Stage 2 1000 detectors	$\gtrsim 10^{-5}$	$r \lesssim 0.1$	0.14	0.15eV
Stage 3 10,000 detectors	10^{-6}	$r \lesssim 0.01$	0.06	0.06eV
Stage 4 CMB-S4 ~500,000 detectors	10^{-8}	$r \lesssim 0.001$	0.02	0.015eV

Goal 372,000 pixels – higher multiplexing factors needed.

Microwave SQUID multiplexers (μmux)





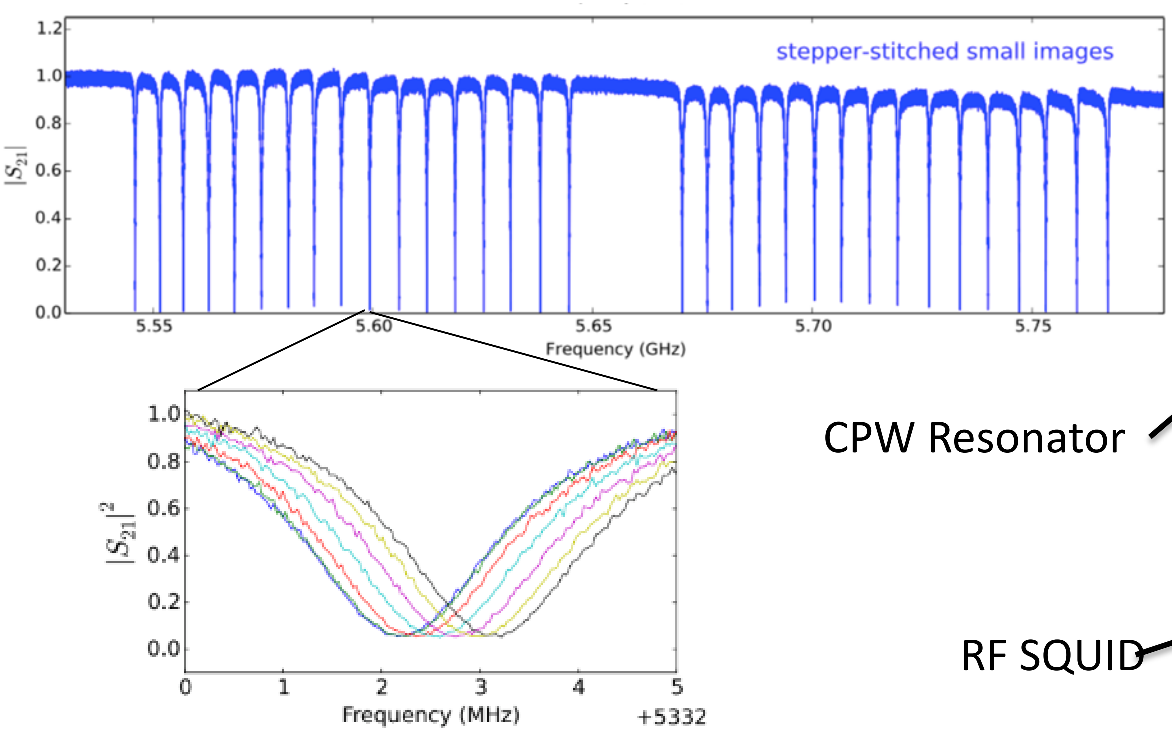


- TES signal is upconverted and amplified through ultra-low noise RF SQUID
- Flux ramp modulation to linearize output in absence of feedback and to avoid low frequency TLS noise.

Provides high multiplexing factors (~4000x) for CMB-S4

Irwin and Lehnert APL 85 (2004)

μmux implementation

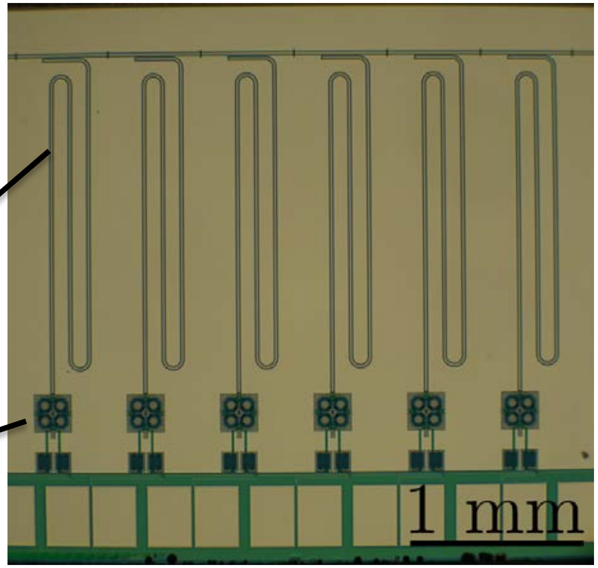


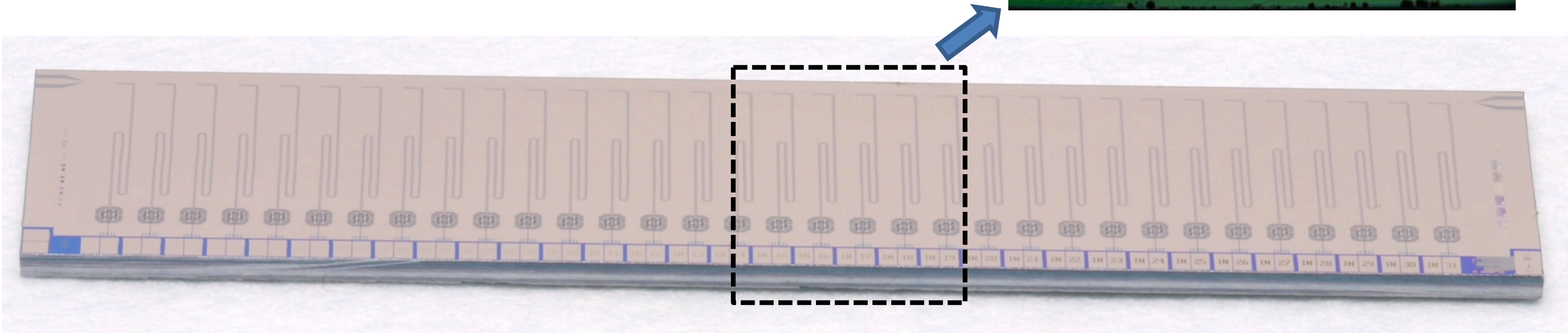
Mates *et al.* APL 92 (2008)

feedline

CPW Resonator

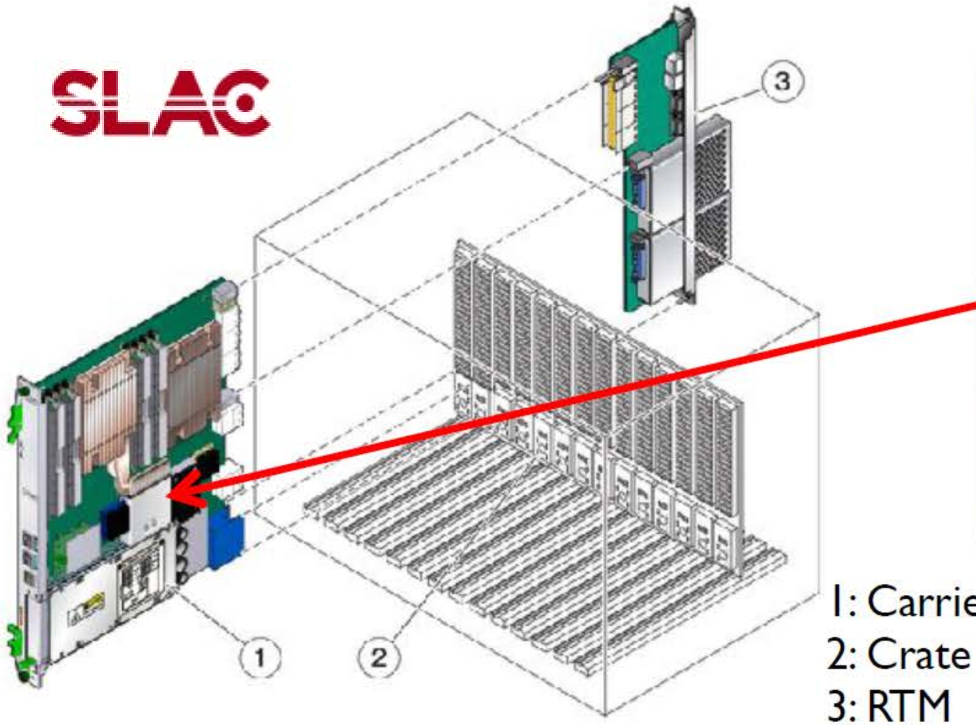
RF SQUID

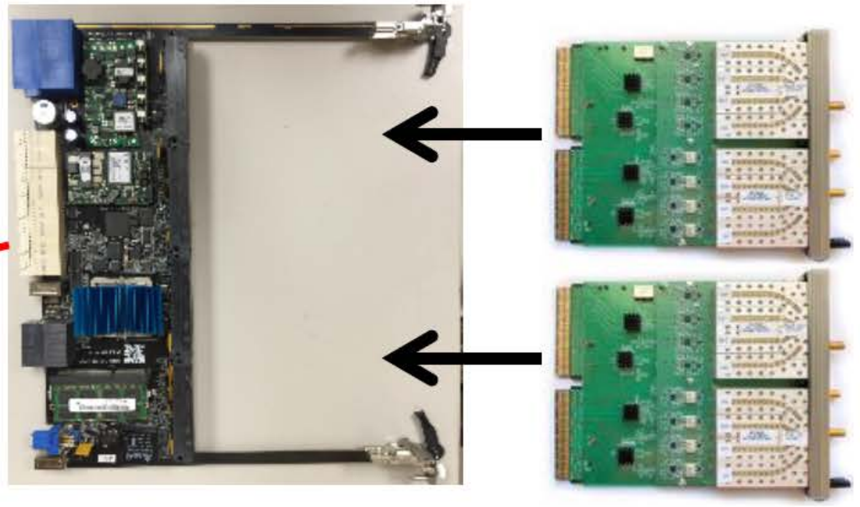




SLAC Microresonator RF Electronics (4 GHz bandwidth)

Zeesh Ahmed talk





1: Carrier Card (Xilinx KU060, 2.7K slices)
2: Crate (ATCA, 1-14 slot available)
3: RTM
Each carrier supports 2 AMC application cards

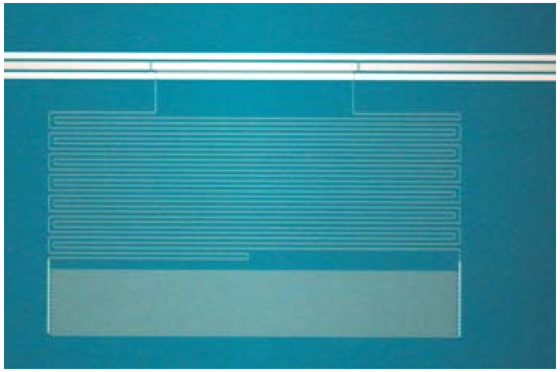
Carrier card: FPGA, memory, backplane connections

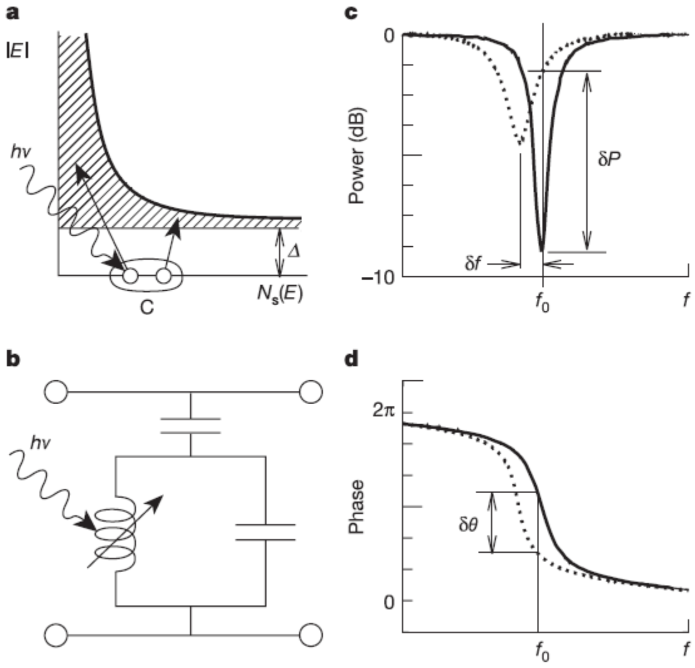
AMC cards: (double-wide full height) ADCs, DACs, high performance front end electronics

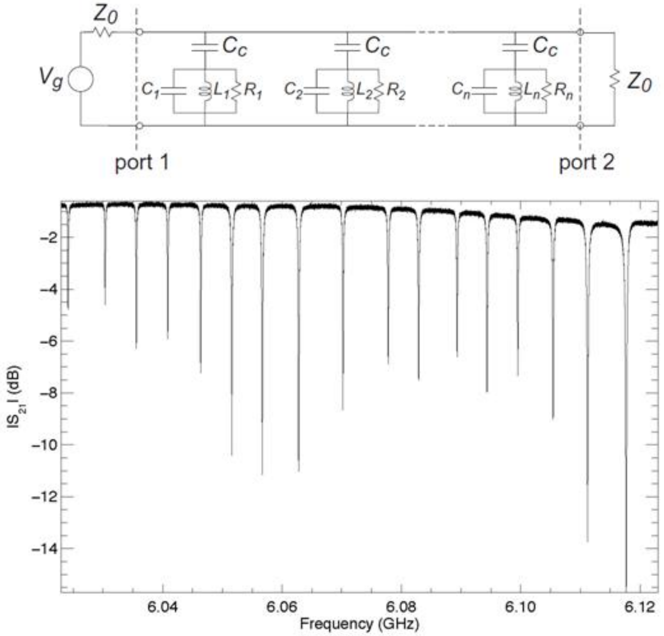
RTM: General purpose IO, extra networks, miscellaneous

Alternative detectors for CMB-S4: MKIDs

Roger O’Brient talk







P. Day *et al.*, Nature (2003).

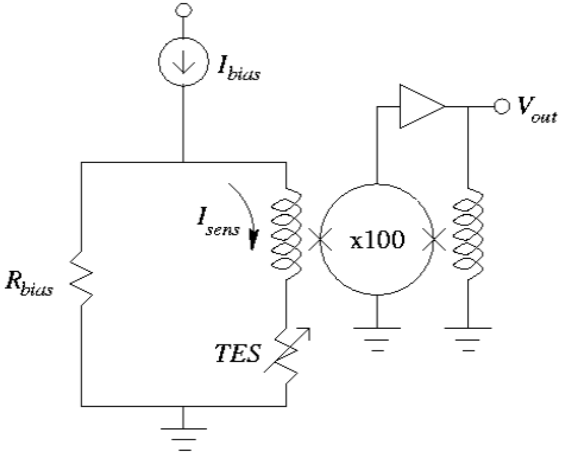
Pros / Cons

+ Integrated RF muxing scales to large formats easily!

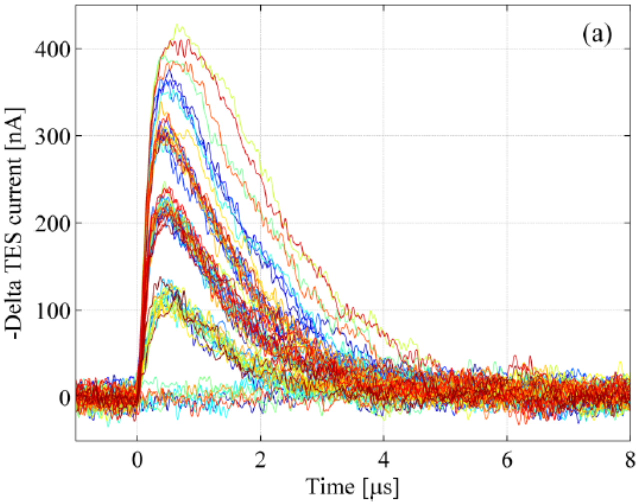
- NEPs in fielded CMB instrument?
- Noise stability?

Sae Woo Nam talk

TES Signal



- Device is voltage biased
- Current through device is pre-amplified using a cryogenic SQUID array amplifier

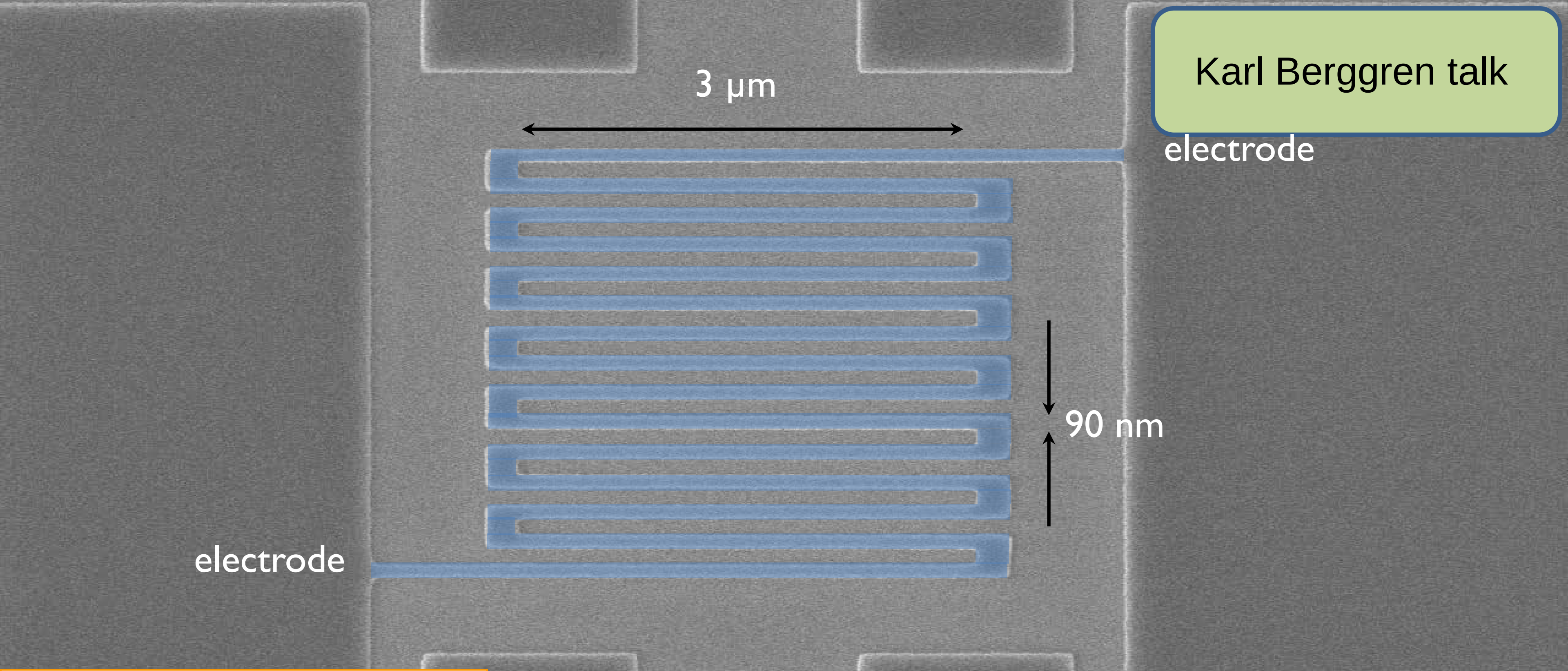


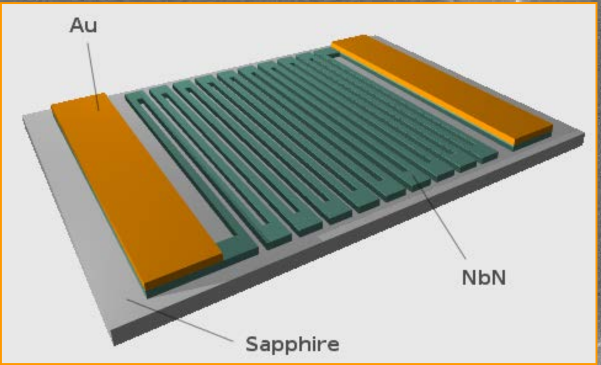
- Absorption events show good distinguishability
- Much slower than APDs

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Superconductive Nanowire Single-Photon Detector

Karl Berggren talk



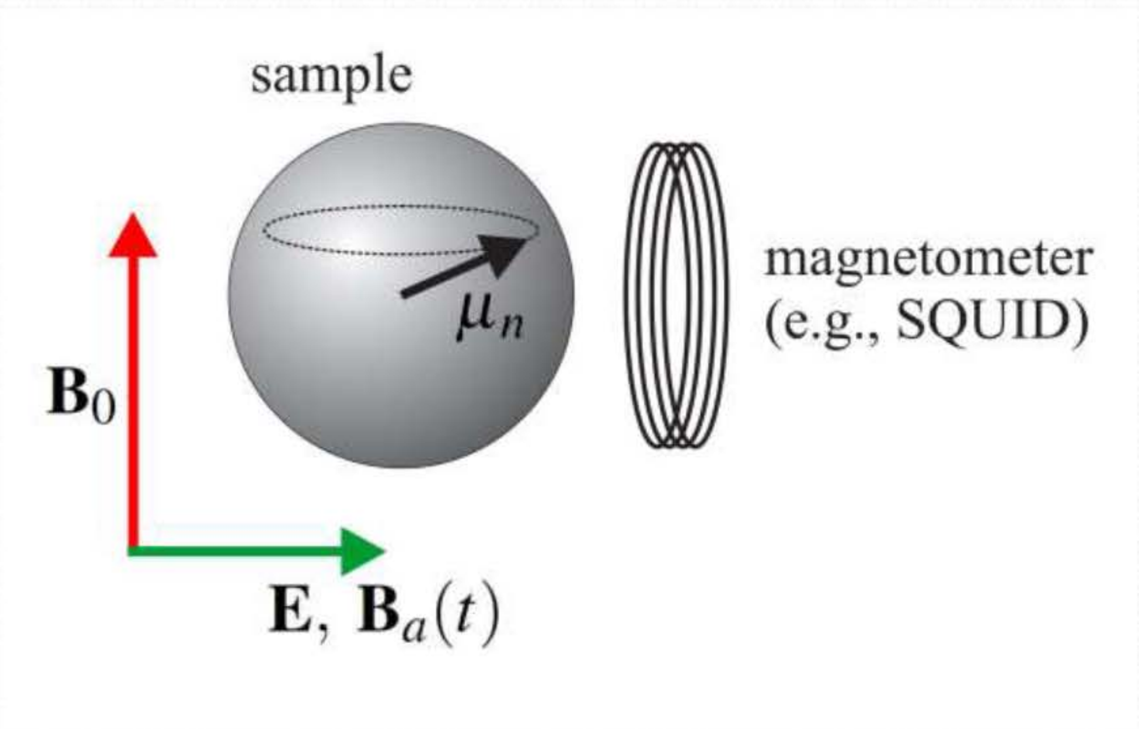


Yang et al., IEEE TAS (2005)

Gol'tsman et al., APL, (2001).

Axion field detection

Derek Kimball talk



Larmor frequency = axion Compton frequency
➔ resonant enhancement.

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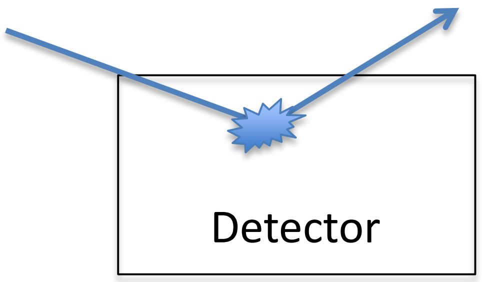
Particle-like and field-like dark matter

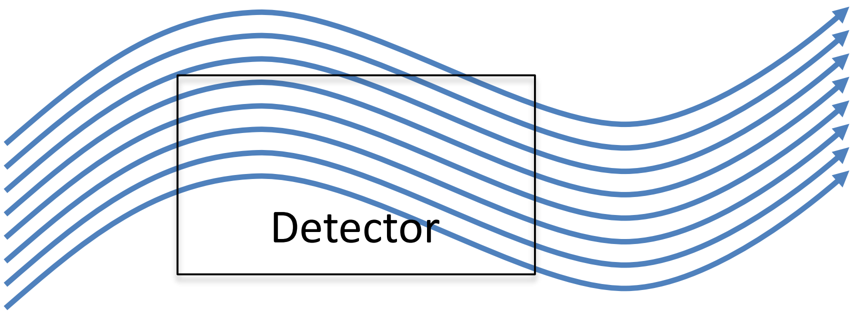
Heavy Particles

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



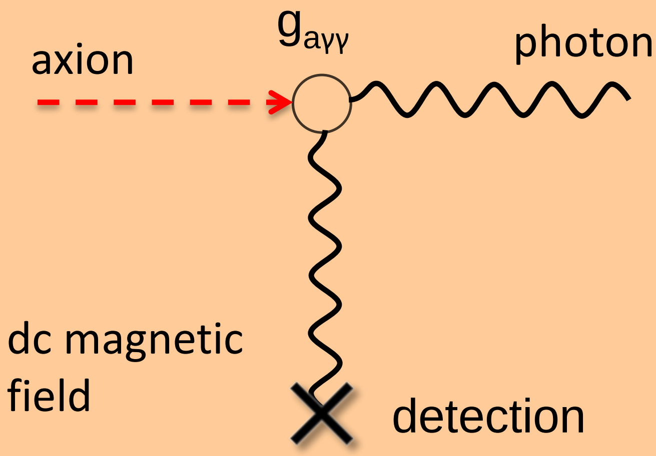
Light Fields

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



Coupling to the dark sector

Axion (spin 0)



axion

$g_{a\gamma\gamma}$

photon

dc magnetic field

detection

- Strong CP Problem

Neutron Electric Dipole Moment

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

Why is it so small?

- Peccei-Quinn solution, the axion, can also be dark matter.

Hidden photon (spin 1)

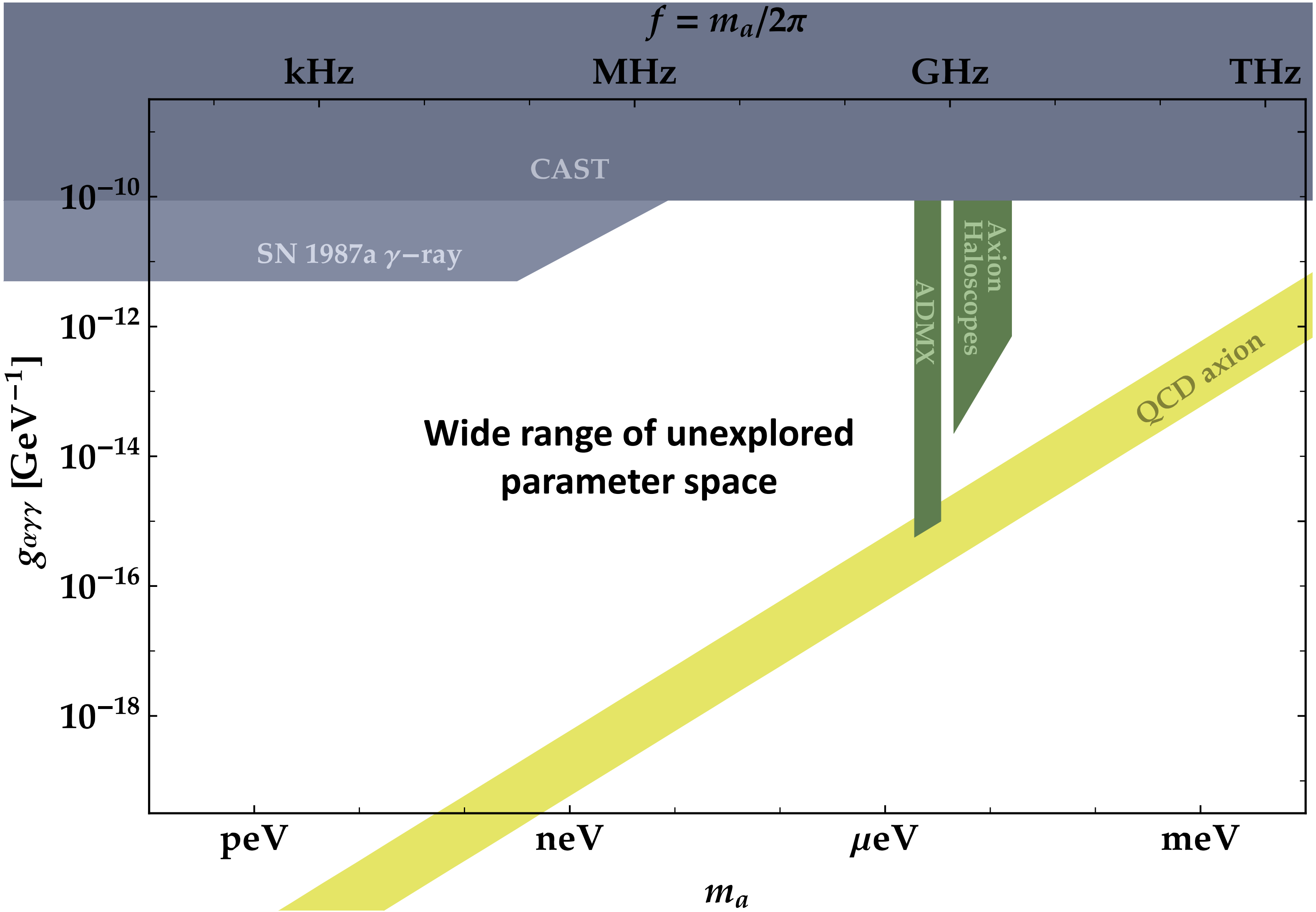
- A new photon, but with a mass, and weak coupling
- Couples to ordinary electromagnetism via kinetic mixing

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

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

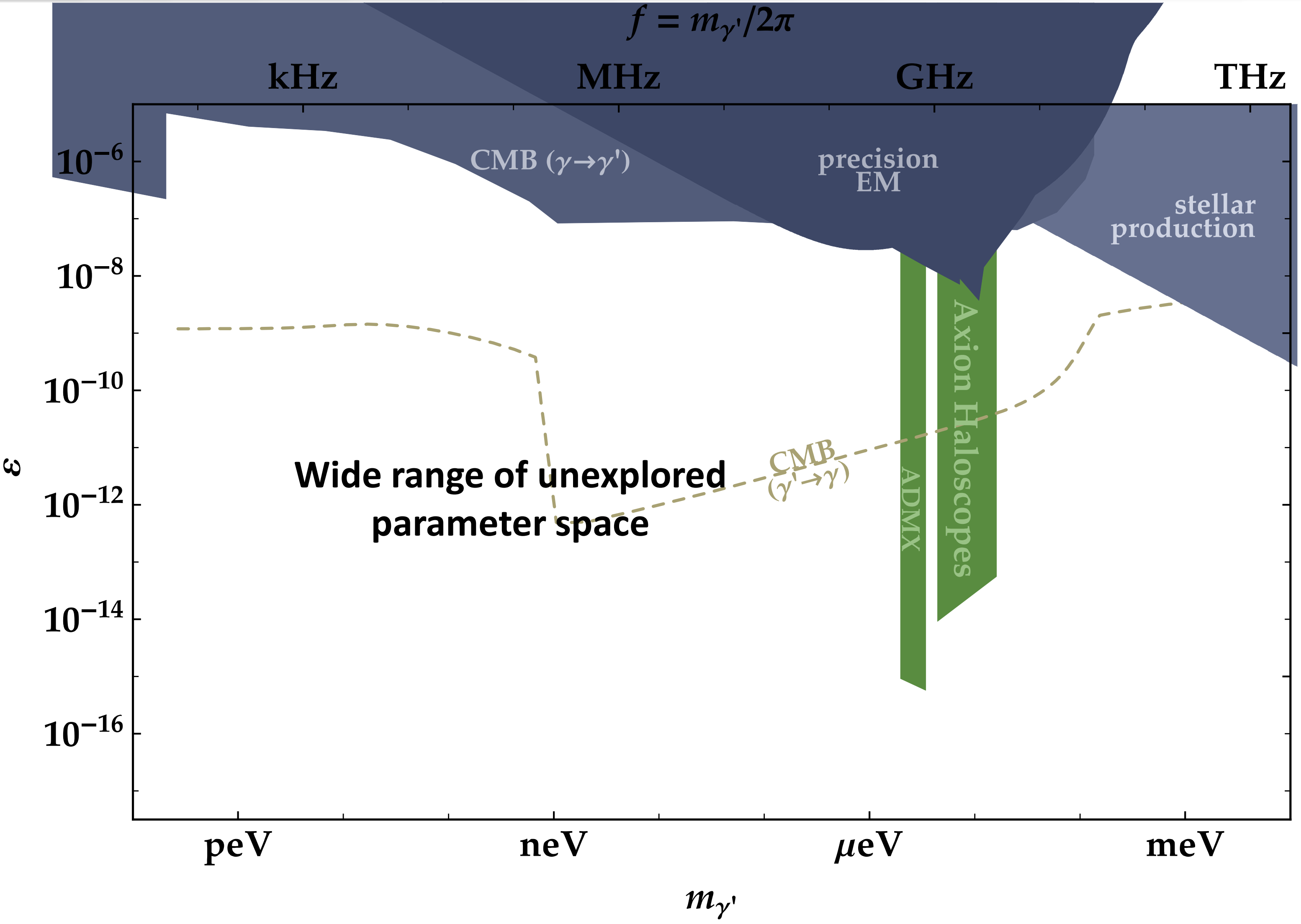
Graham et al., Phys. Rev. D 93, 103520 (2016)

Axions: plenty of room



Wide range of unexplored parameter space

Hidden photons: plenty of room

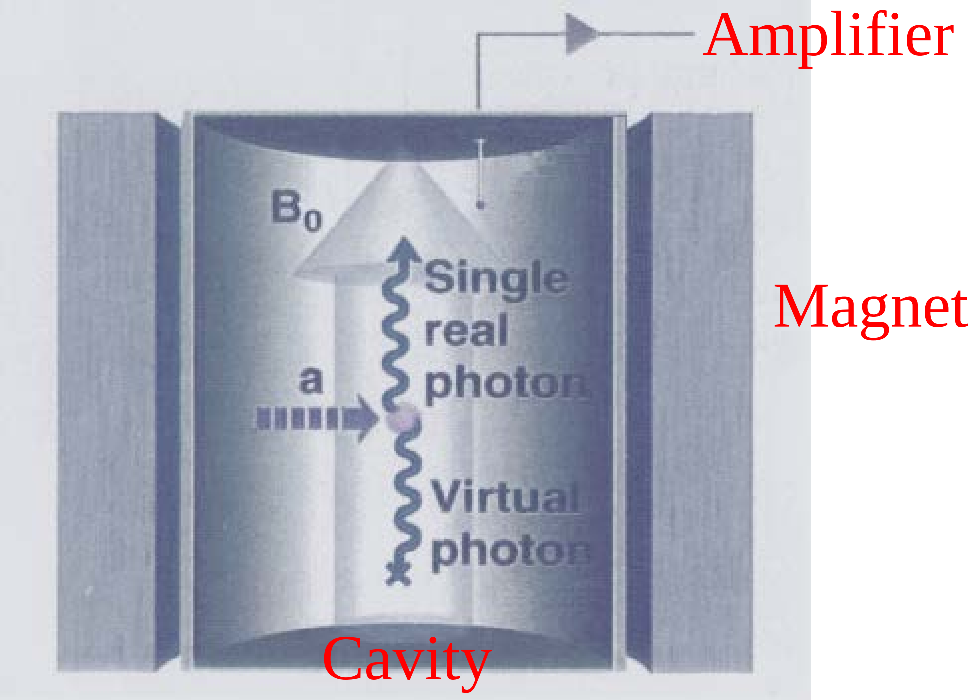


Wide range of unexplored parameter space

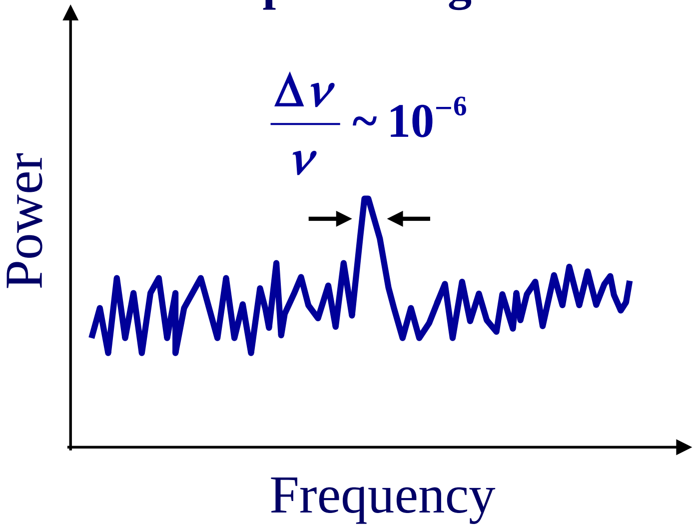
Resonant conversion of axions into photons

Pierre Sikivie (1983)

Primakoff Conversion



Expected Signal



ADMX experiment

Thanks to John Clarke

Idea for subwavelength, lumped-element experiment

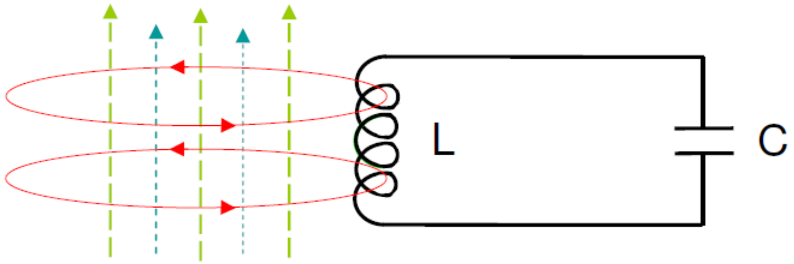
Detecting String-Scale QCD Axion Dark Matter

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)

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

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

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.

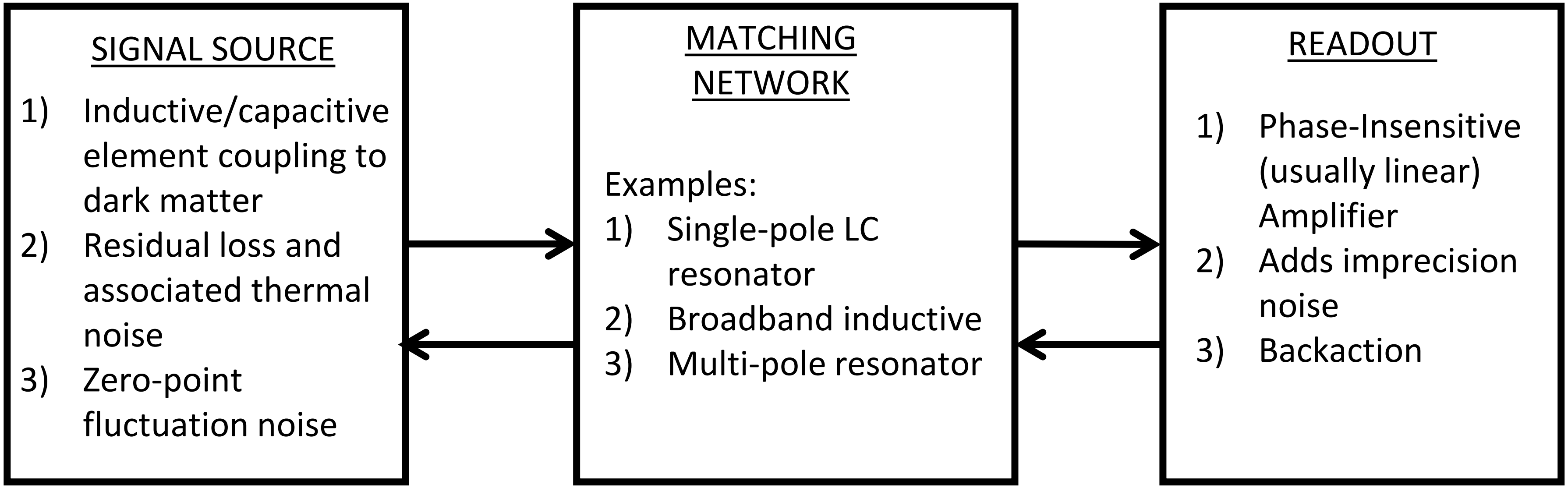
Also can be used for hidden photons:
Arias et al., arxiv:1411.4986
Chaudhuri et al., arxiv: 1411.7382v2

Workshop Axions 2010, U. Florida, 2010

Optimal searches for light-field DM

- Why use a resonant cavity? Why not a broadband search?
- What are the quantum limits on a resonant search with a linear amplifier?
- How can quantum sensors improve these limits?

Model for quantum-limited electromagnectic DM detector



SIGNAL SOURCE

1) Inductive/capacitive element coupling to dark matter
2) Residual loss and associated thermal noise
3) Zero-point fluctuation noise

MATCHING NETWORK

Examples:

1) Single-pole LC resonator
2) Broadband inductive
3) Multi-pole resonator

READOUT

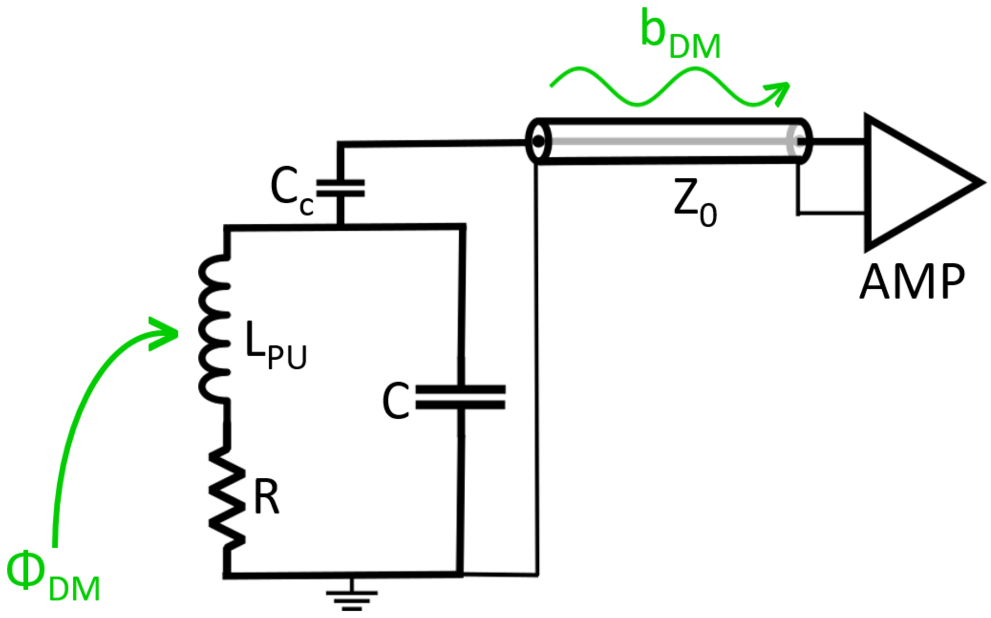
1) Phase-Insensitive (usually linear) Amplifier
2) Adds imprecision noise
3) Backaction

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.

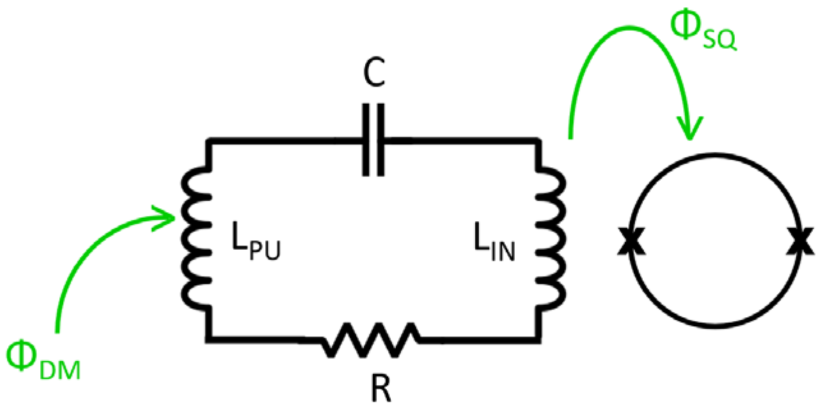
Also non-ideal noise sources (thermal, EMI, etc.)

High Frequency: Scattering mode impedance matching with a single-pole resonator

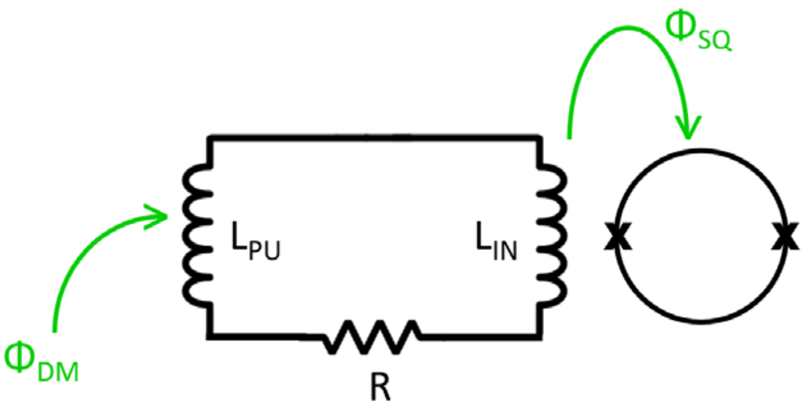


- Equivalent circuit model for resonant detector in scattering mode.
- Resonator tuned by changing capacitance.

Low Frequency: Op-amp mode impedance matching with a single-pole resonator



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



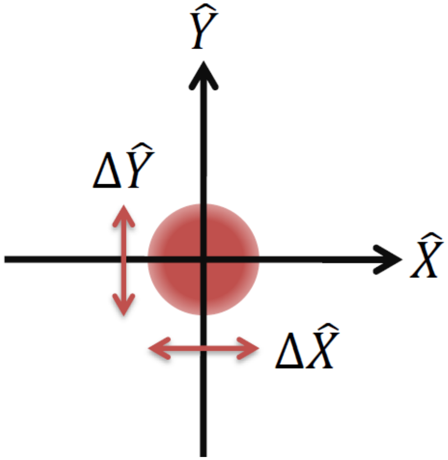
Broadband LR circuit. (Kahn et al, PRL 117, 141801 (2016))

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

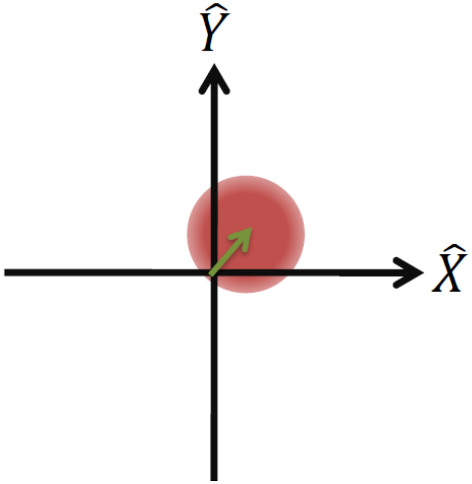


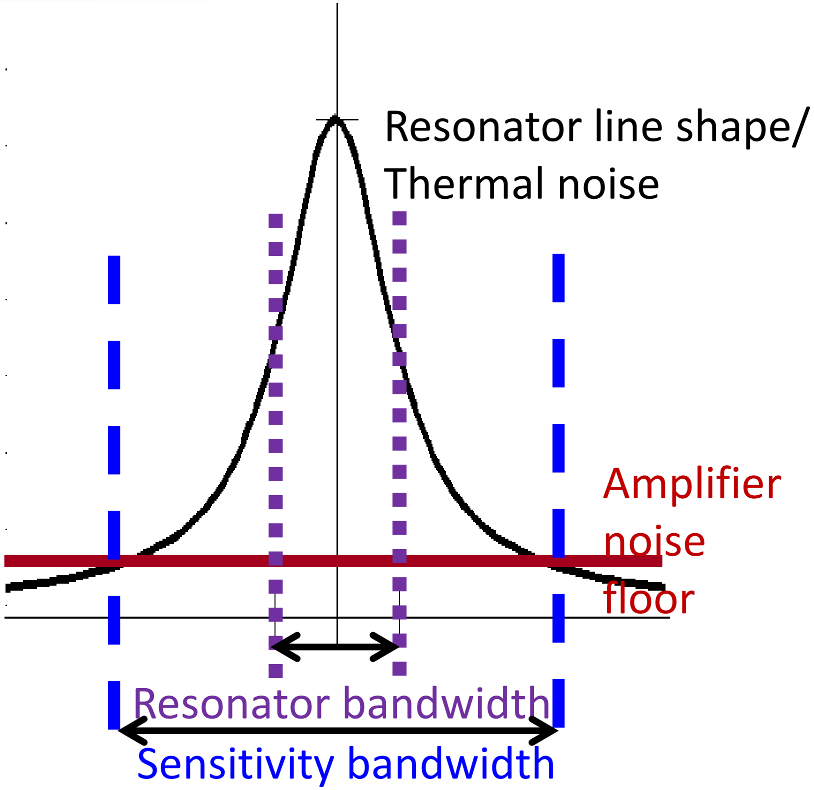
Figure of merit for a scanned search

- 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

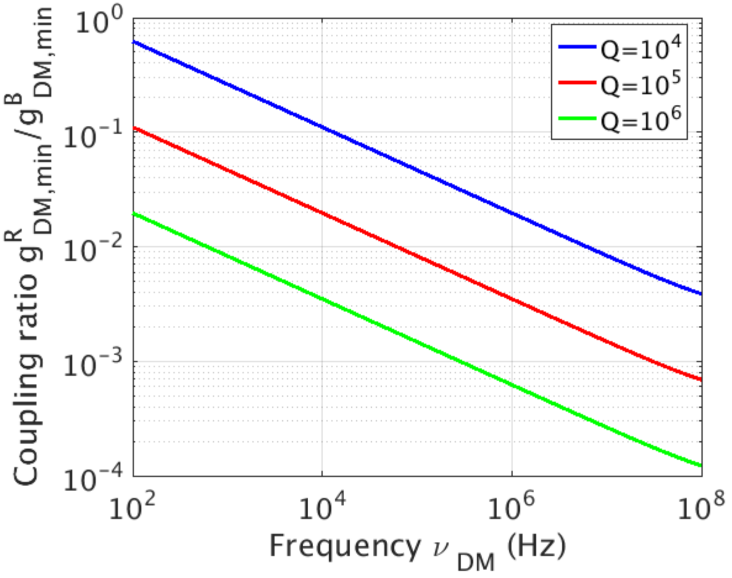
- Includes vacuum noise, amplifier imprecision noise and backaction
- Similar calculation for op-amp mode



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.

Chaudhuri, et al., in preparation

Compare resonant to broadband



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

Value < 1 implies resonator limit stronger than broadband limit

Apples-to-apples

- Assumes same volume, cavity temperature 10 mK.
- Assumes optimally matched amplifier at standard quantum limit.
- Assumes optimal scan strategy.
- Assumes same total integration time over full science bandwidth.

- One-pole resonator is better at all frequencies where a resonator can be practically constructed (>~100 Hz)
- But a one-pole resonator is *not* the best – a multipole circuit is.

Bode-Fano limited 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?

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

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

$$U = \int_{\nu_l}^{\nu_h} d\nu \left(\frac{|S_{21}(\nu)|^2}{|S_{21}(\nu)|^2 n(\nu) + 1}\right)^2 \leq \begin{cases} \frac{1}{4n(\nu_h)} \frac{R}{L_{PU}}, & n(\nu_h) \gg 1 \\ 0.41 \frac{R}{L_{PU}}, & n(\nu_h) \ll 1 \end{cases}$$

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!)

Chaudhuri, et al., in preparation

Optimal searches for light-field DM

- Why use a resonant cavity? Why not a broadband search?
- What are the quantum limits on a resonant search with a linear amplifier?
- How can quantum sensors improve these limits?

Case 1: $hf > k_B T$. Konrad Lehnert

Haystac

Case 2: $hf < k_B T$. This talk.

Quantum sensing in the ground state

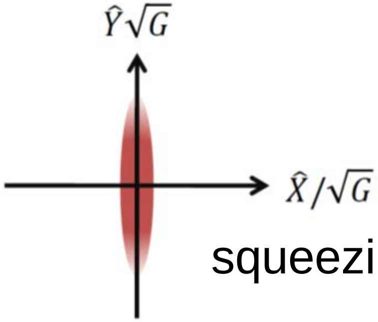
- We usually think of measuring below the standard quantum limit in the thermal ground state:

$\hbar\omega > k_B T$ Thermal ground state

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

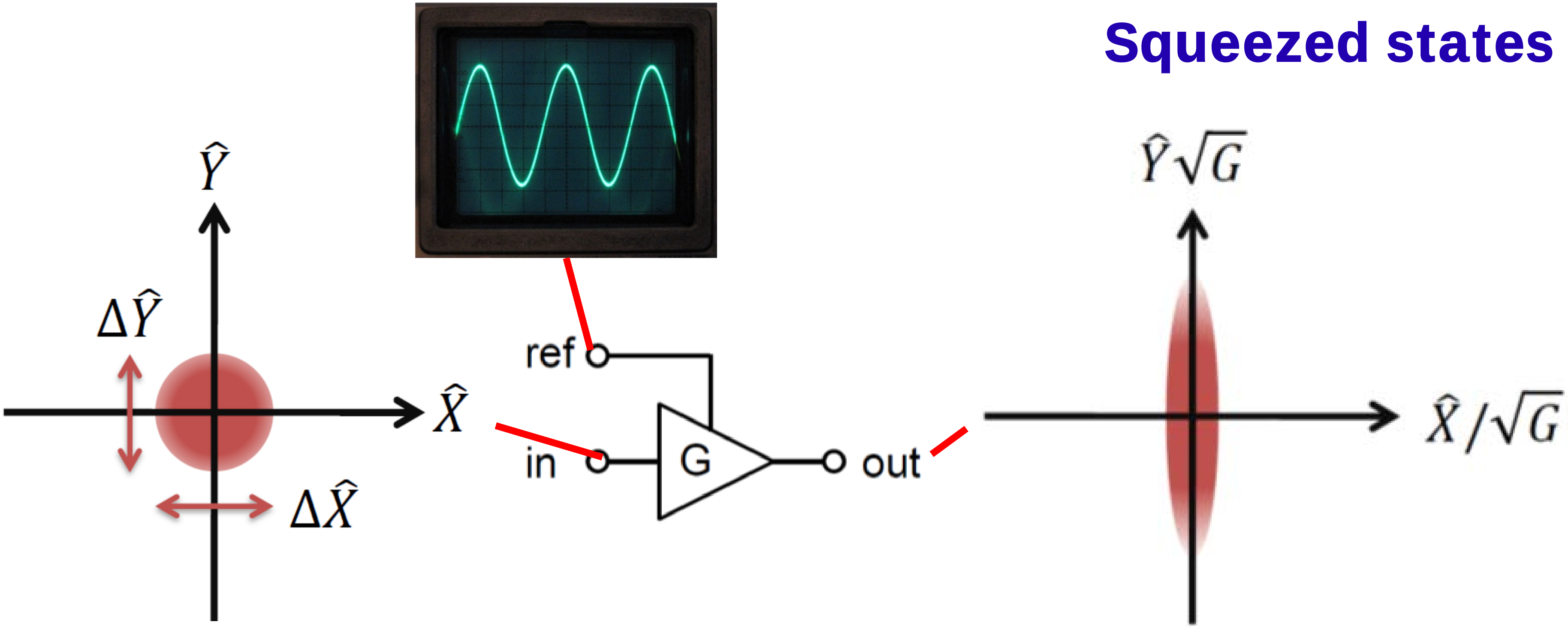
- The standard quantum limit can be evaded using quantum correlations. These techniques are deeply related:
  - Photon counting
  - Squeezing
  - Backaction evasion
  - Entanglement
  - Cooling
  - Quantum nondemolition

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



squeezing

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.

Konrad Lehnert talk

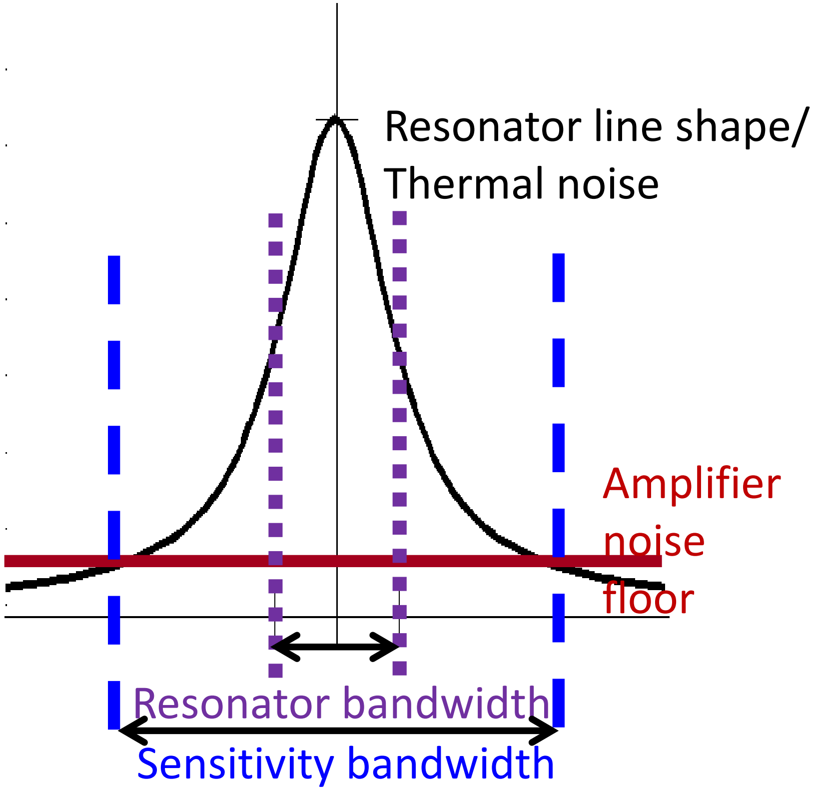
hf >> kT regime with squeezing, entangled cavities, photon-number measurement with qubits, and HAYSTAC experiment

Quantum sensing of thermal states

$\hbar\omega < k_B T$ Thermal state

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

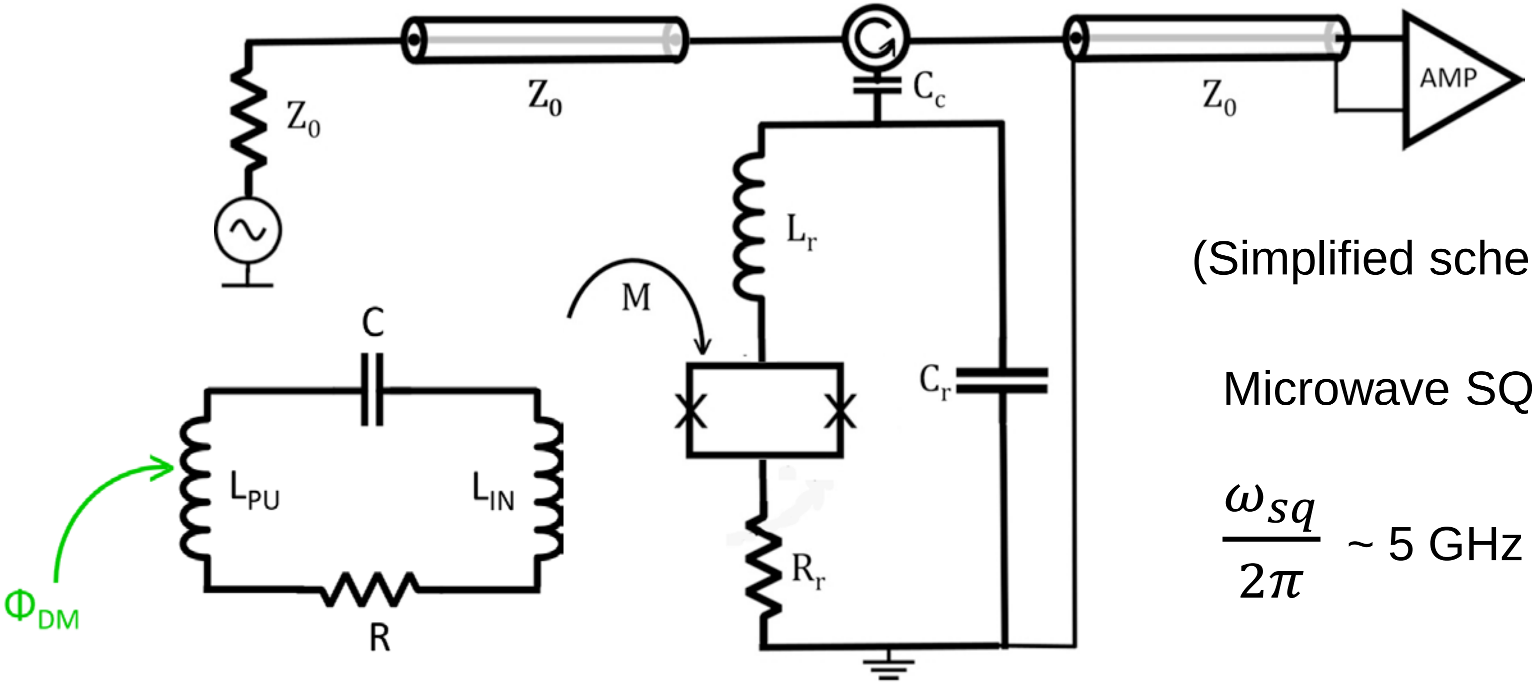
- The signal to noise within the resonator bandwidth is not helped by a better amplifier.
- The sensitivity of the amplifier determines the *sensitivity bandwidth*, and thus the sensitivity of a search for an unknown signal frequency.
- Very large speedup possible for a sensor operating below the standard 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 flux amplifier

Dissipationless microwave SQUID flux amplifier



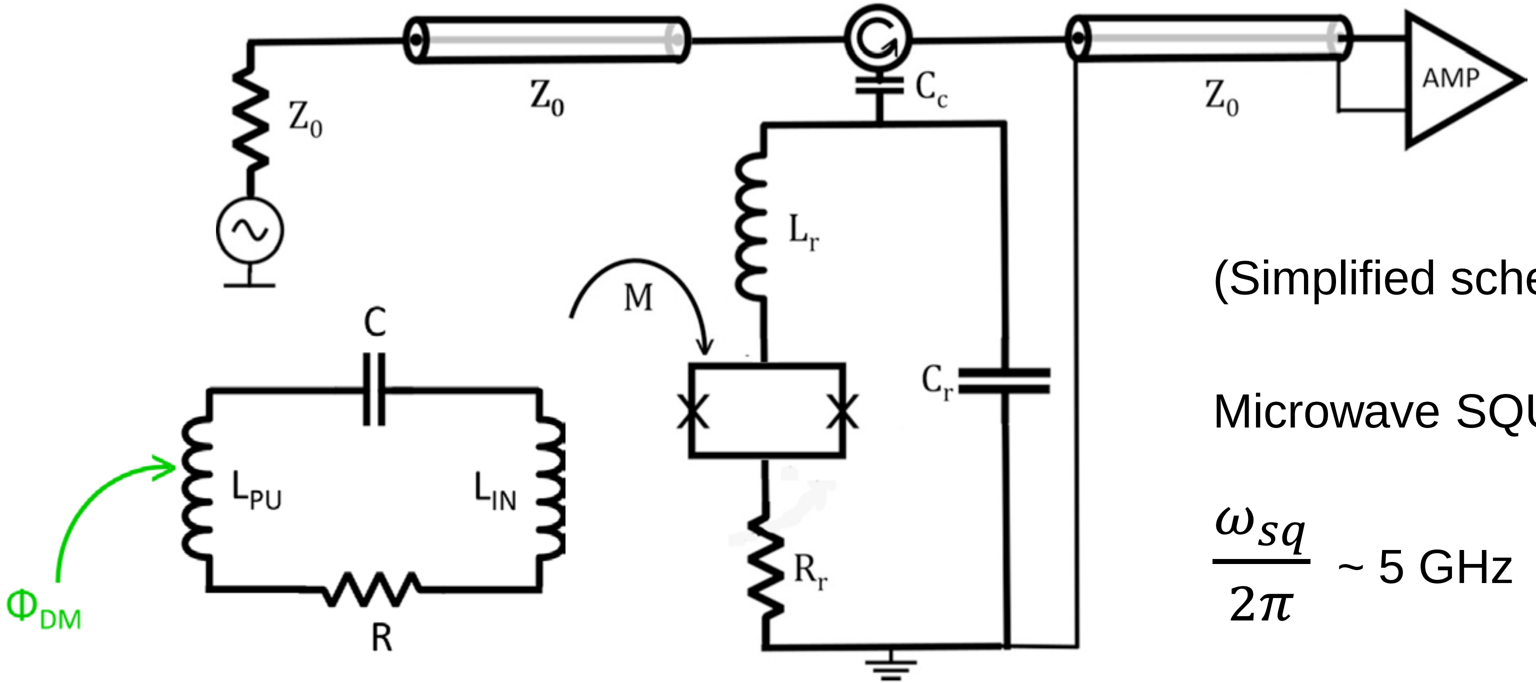
(Simplified schematic)

Microwave SQUID:

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

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

Measuring a resonator with a dissipationless microwave SQUID flux amplifier



(Simplified schematic)

Microwave SQUID:

$\frac{\omega_{sq}}{2\pi}$ ~ 5 GHz

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

Chaudhuri, et al., in preparation

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

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

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

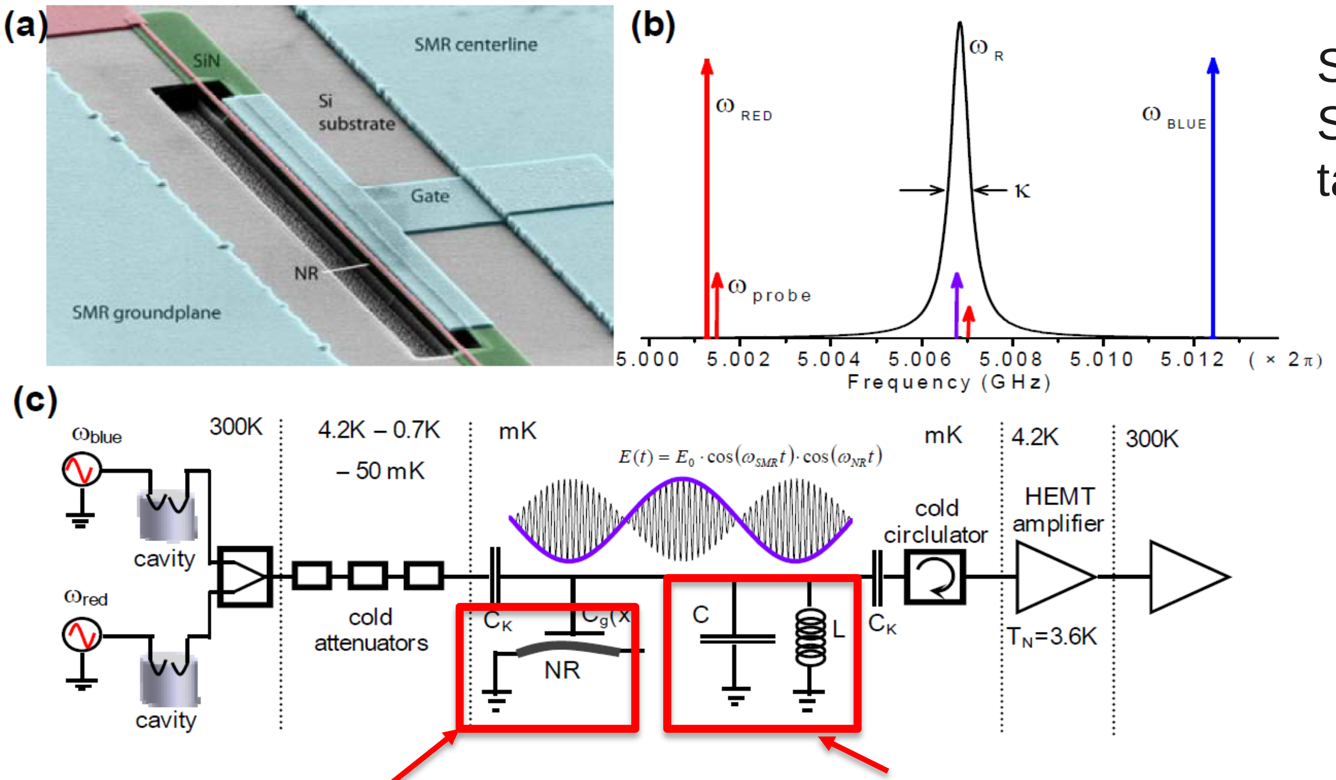
This maps onto the Hamiltonian of on optomechanical resonator with:

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

Chaudhuri, et al., in preparation

Hamiltonian maps onto optomechanical system



See Clerk, Schwab talks

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

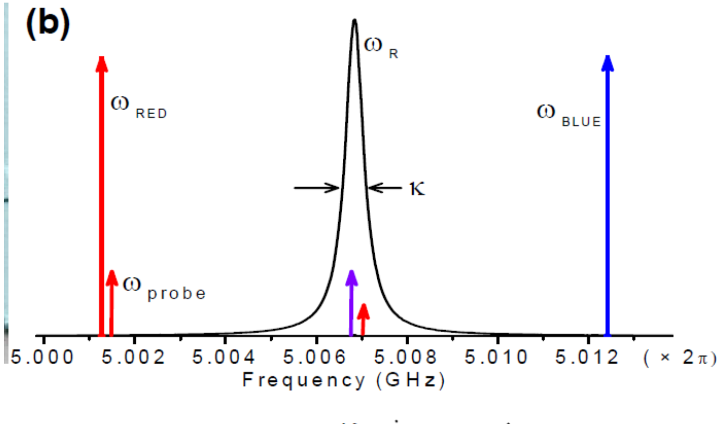
High-frequency LC resonance
(Maps onto uwave SQUID Hamiltonian)

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.

Back-action Evasion

- Originally proposed by Braginsky (1980) for gravitational wave detectors.

- With proper device symmetry, when both sidebands are pumped, the back-action is applied only to the unmeasured quadrature. Allows much stronger coupling, and reduction of both imprecision and back-action noise.

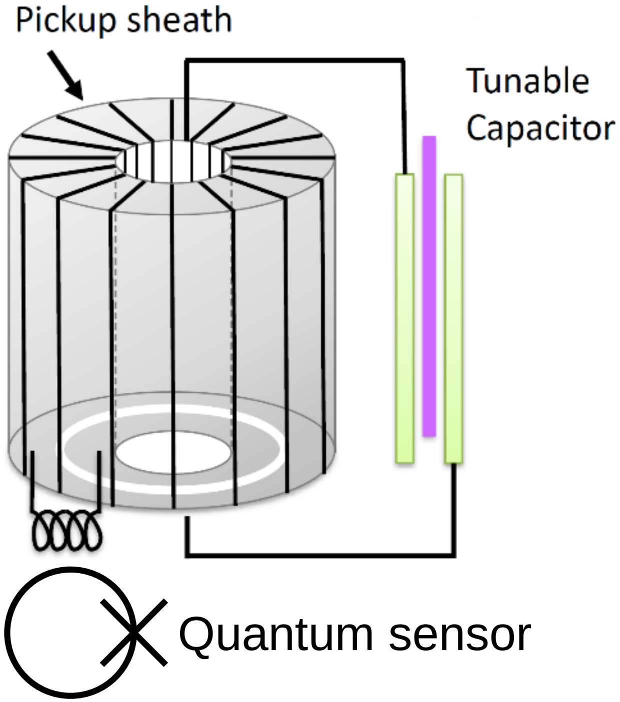


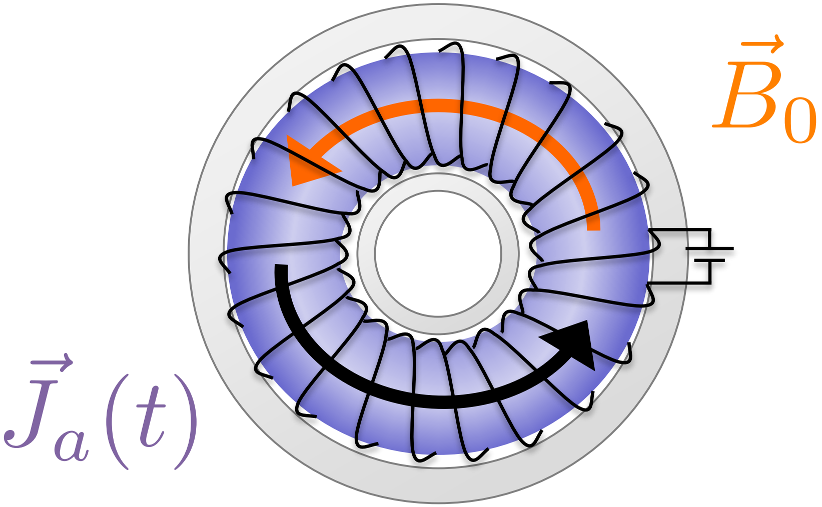
- Squeezing, cooling, other quantum protocols possible

- See Clerk talk for details

Back-action Evasion with microwave SQUIDs is a promising quantum protocol for DM Radio

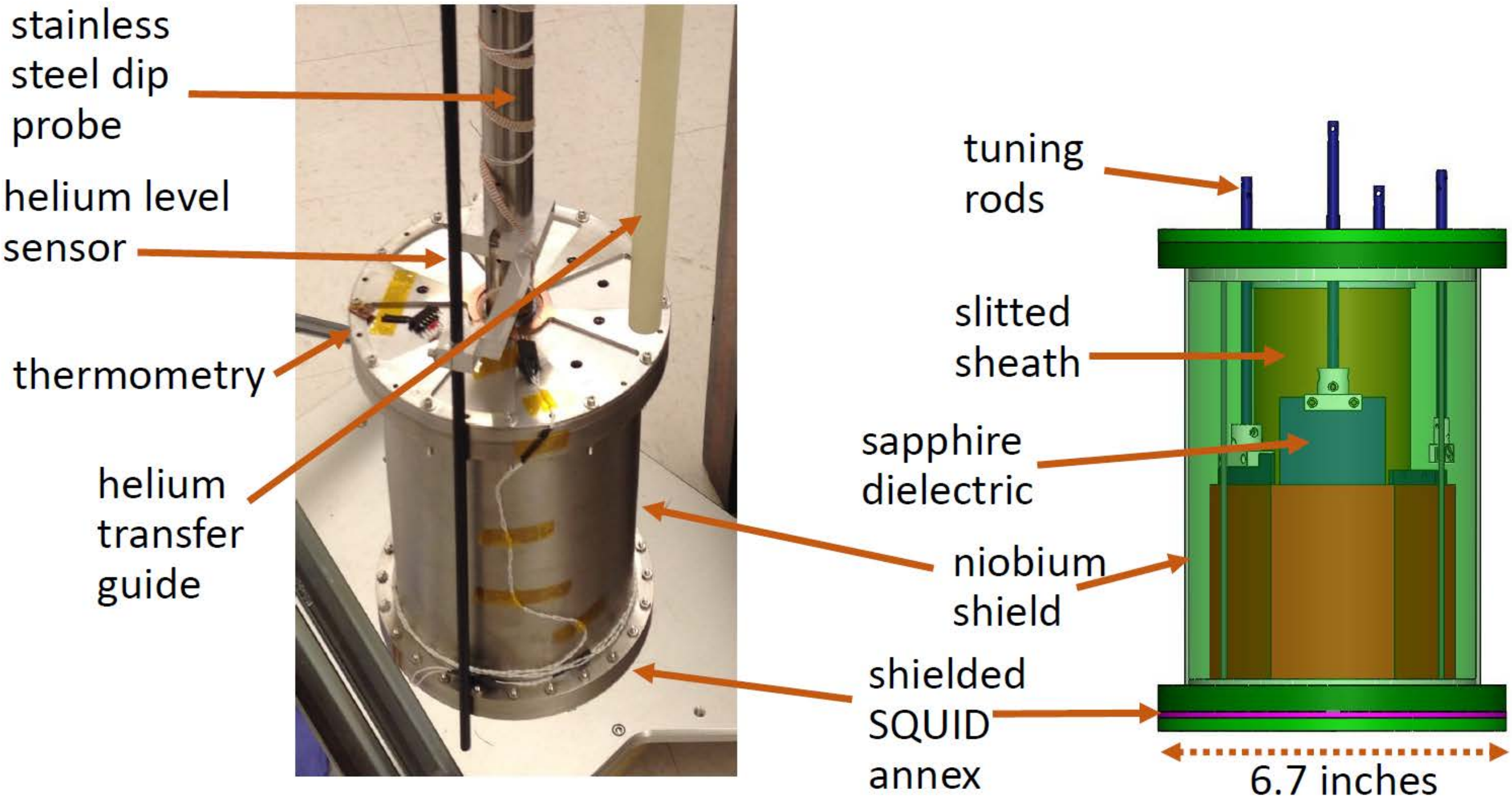
The Dark Matter Radio



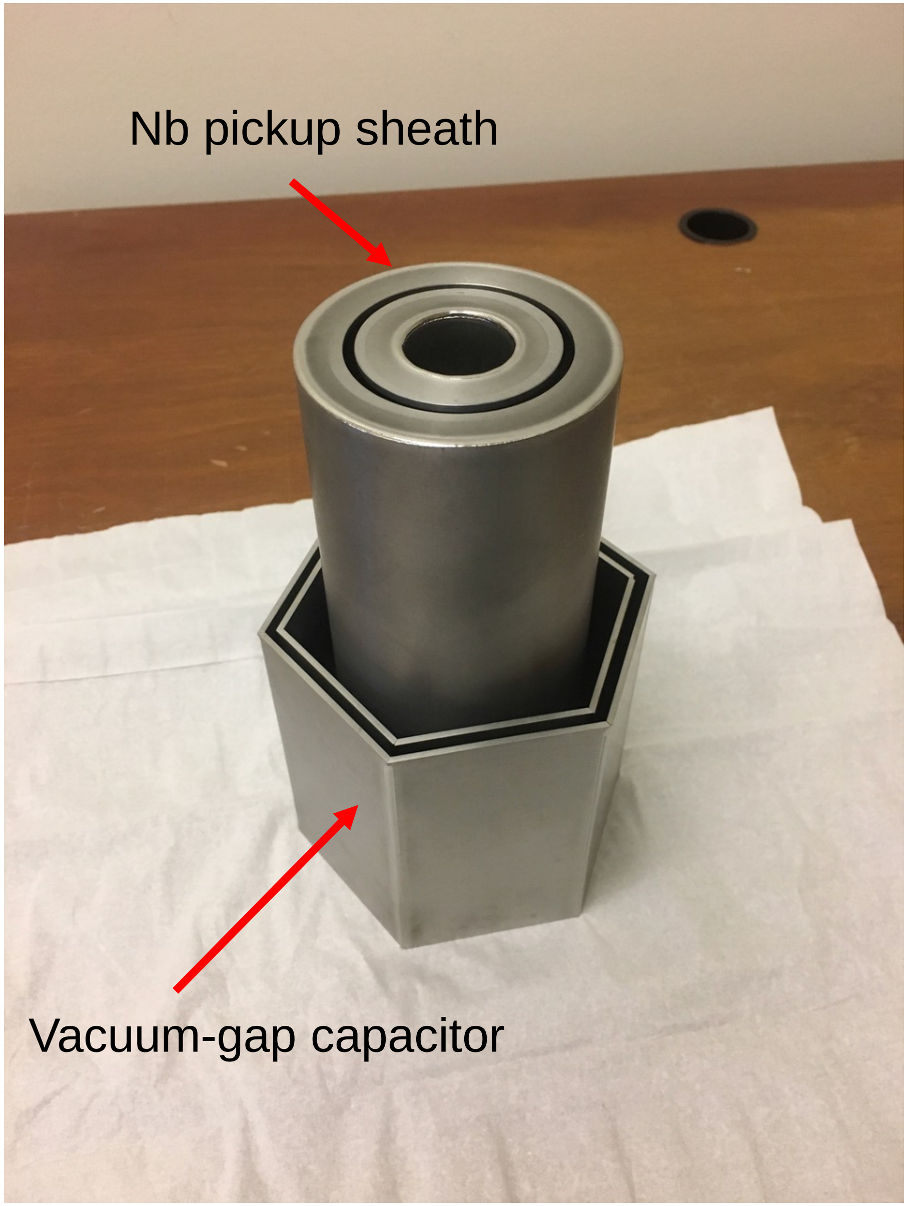


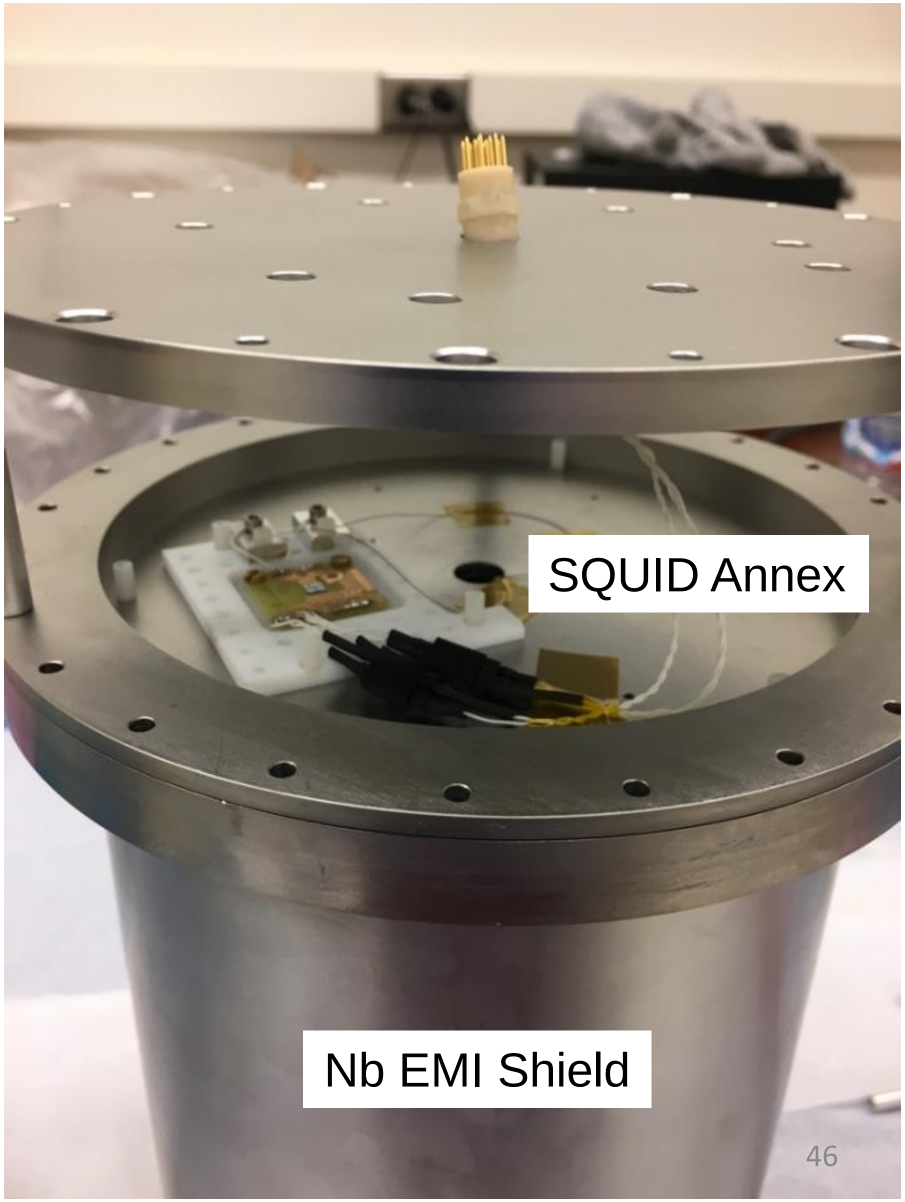
Chaudhuri, Kuenstner, Phipps, Li, Cho, Dawson, Graham, Irwin,…

DM Radio Pathfinder components



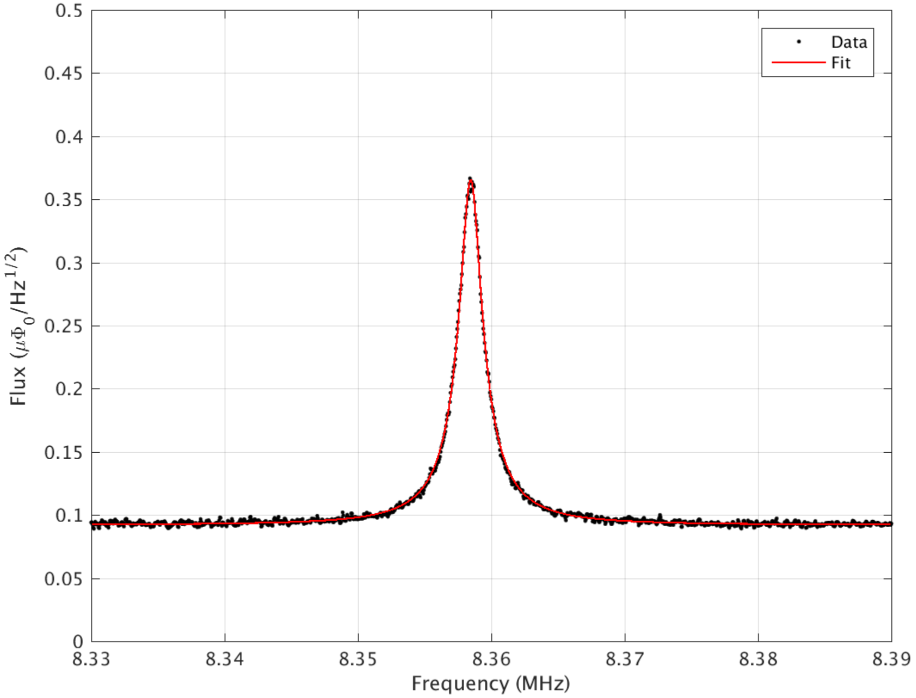
DM Radio Pathfinder components

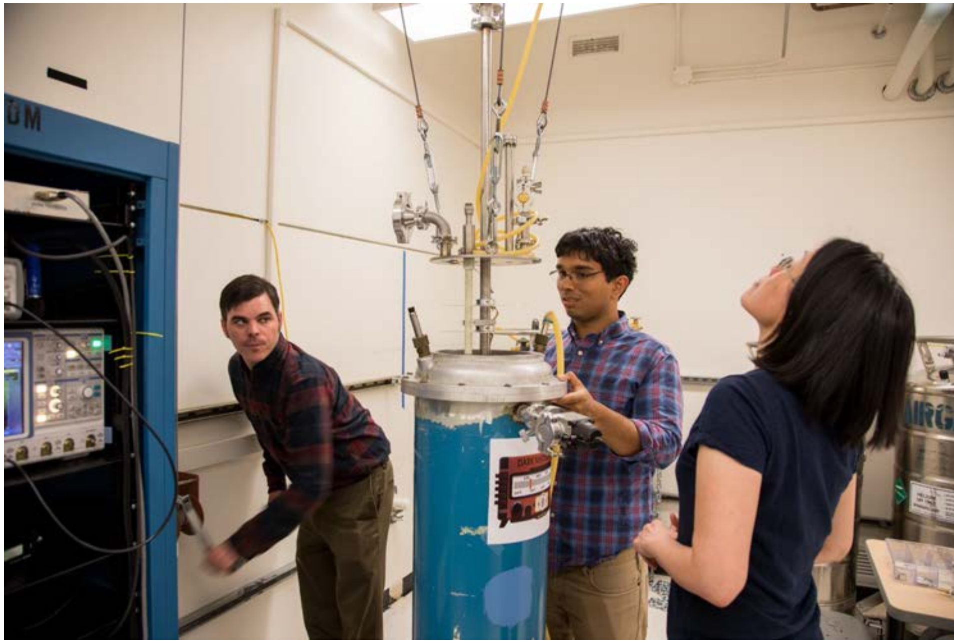




First DM Radio cooldown

First DM Radio resonance



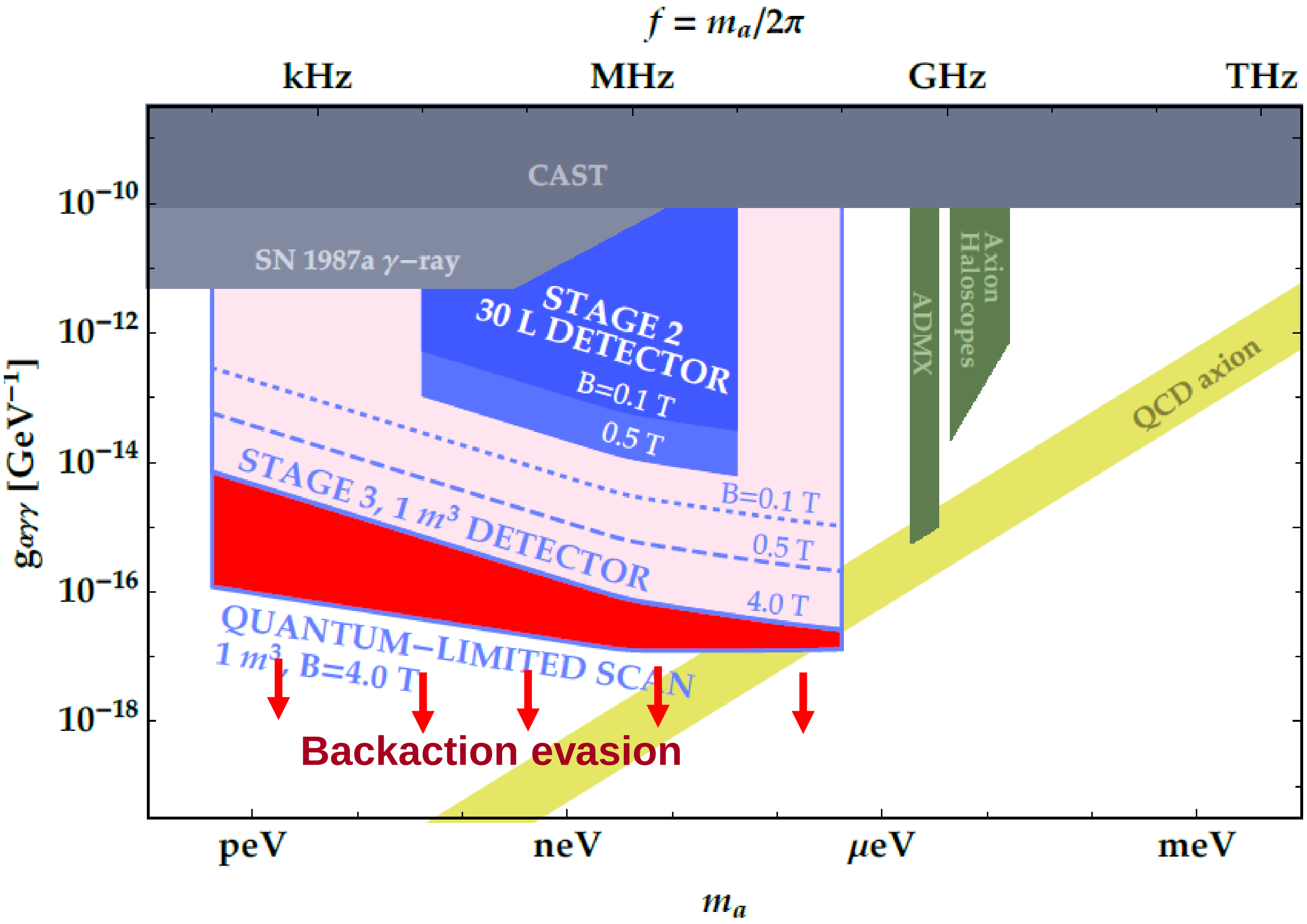


- Low Q=5,027, dominated by normal wirebonds in the first run.
- Measured coupling, fit to circuit model
- Tested major components

DM Radio: Axion science reach

FREQUENCY

AXION-PHOTON COUPLING



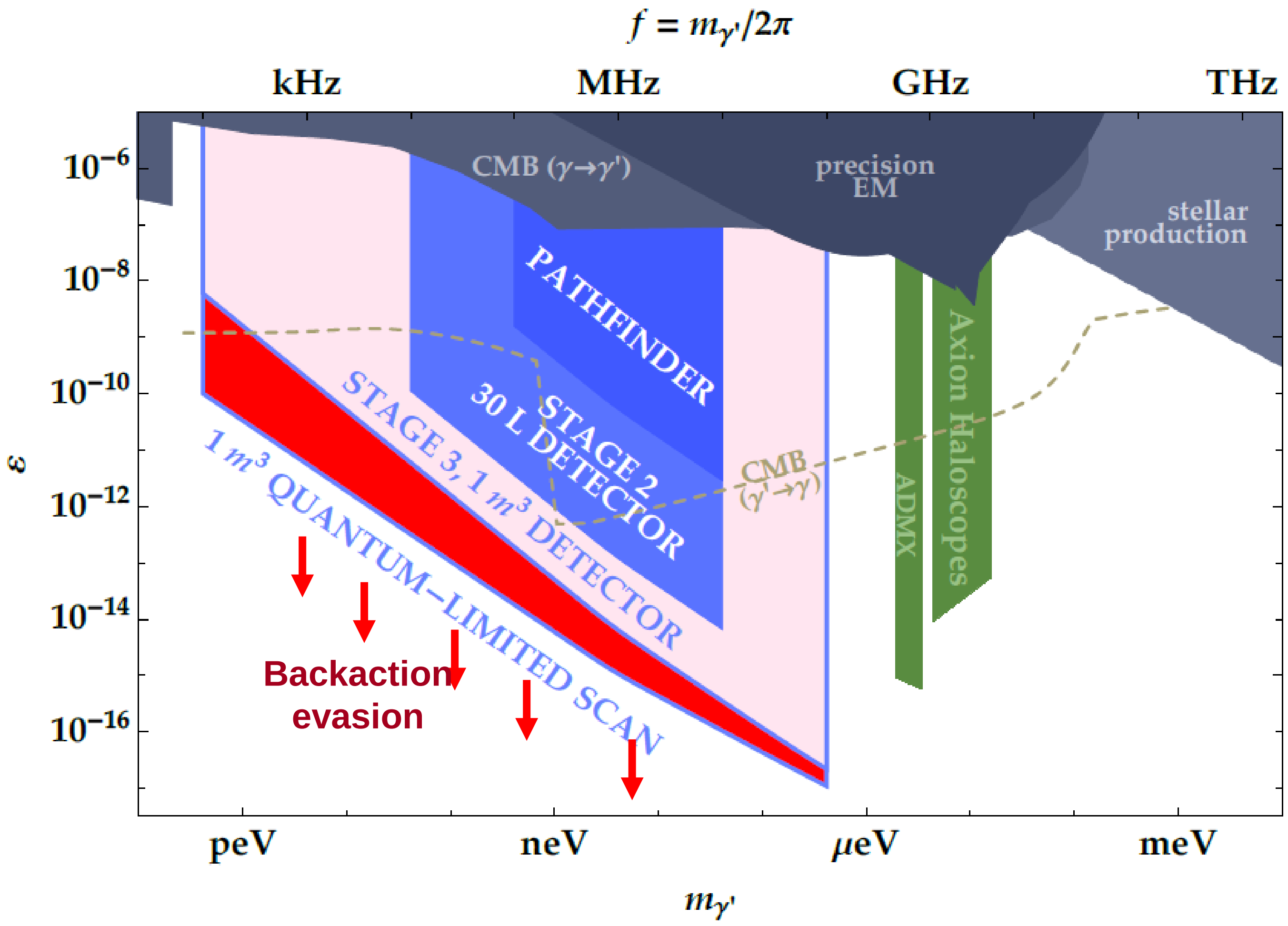
Backaction evasion

MASS

DM Radio: Hidden photon science reach

FREQUENCY

HIDDEN PHOTON-PHOTON MIXING ANGLE



MASS

Summary

- Quantum sensors based on superconductivity are already important in CMB science, dark matter searches, and QIS.
- New HEP science is being enabled by superconducting sensors exploiting quantum correlations to measure below the quantum limit..

$\hbar\omega > k_B T$ (e.g. HAYSTAC, ADMX)
Quantum sensors needed
e.g. JPAs, QUBITs…

$\hbar\omega < k_B T$ (e.g. DM Radio)
Quantum sensors needed
e.g. uwave SQUIDs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