Quantum sensors for the QCD axion

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Santa Clara: Connor Fitzgerald, Betty Young
Berkeley: Alexander Droster, Alexander Leder, Surjeet Rajendran
Boston University: Alex Sushkov, and the CASPEr collaboration

Outline

- The quest for the QCD axion
- QCD axion searches beyond the Standard Quantum Limit
- Axions from peV - μeV
- Fundamental noise limits
- Photon upconverters
- Backaction evasion

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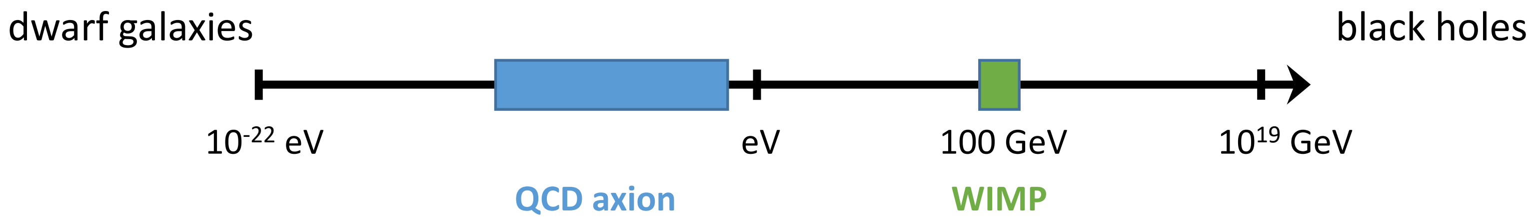
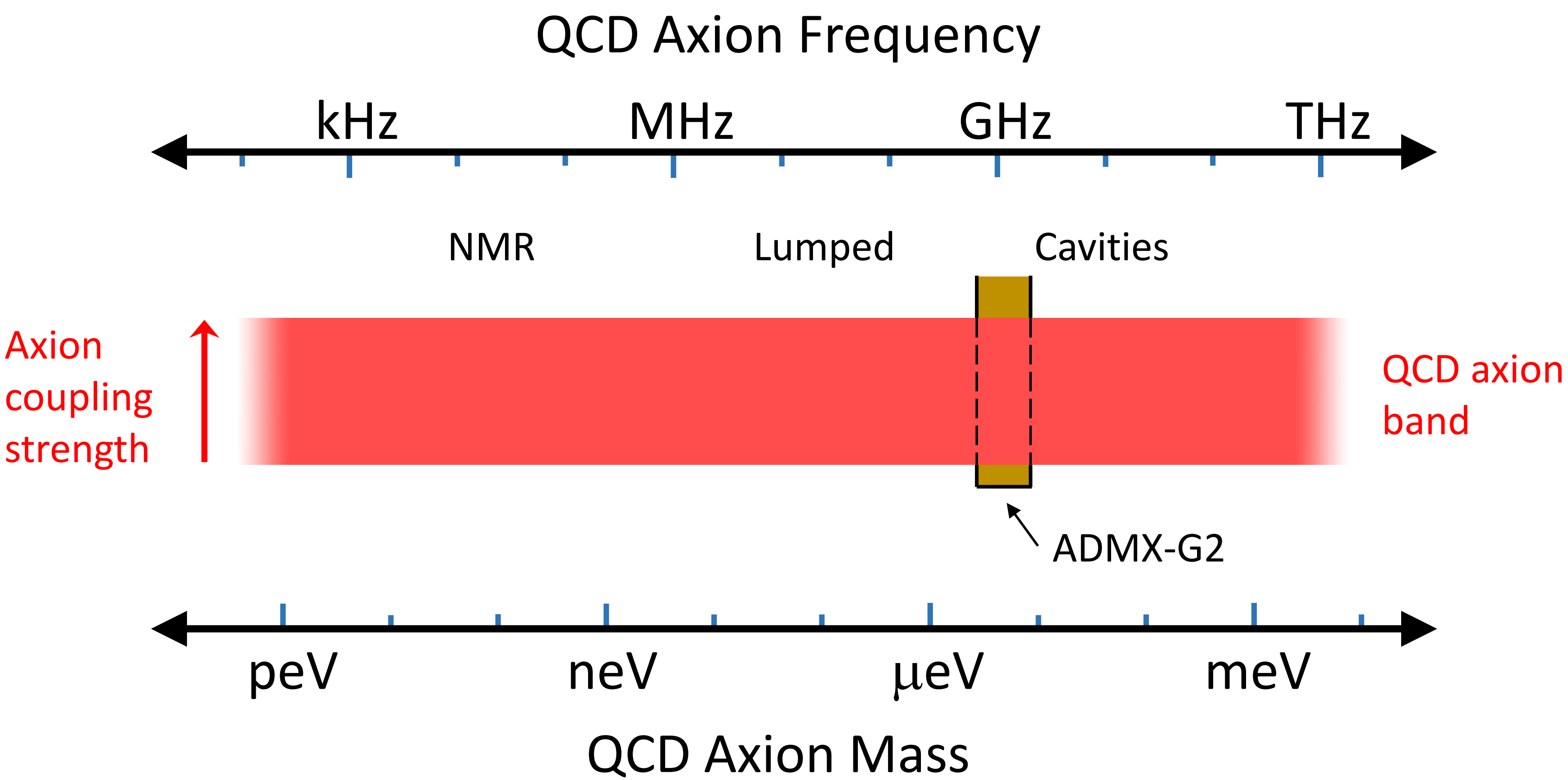
Two “strongly motivated” dark-matter candidates



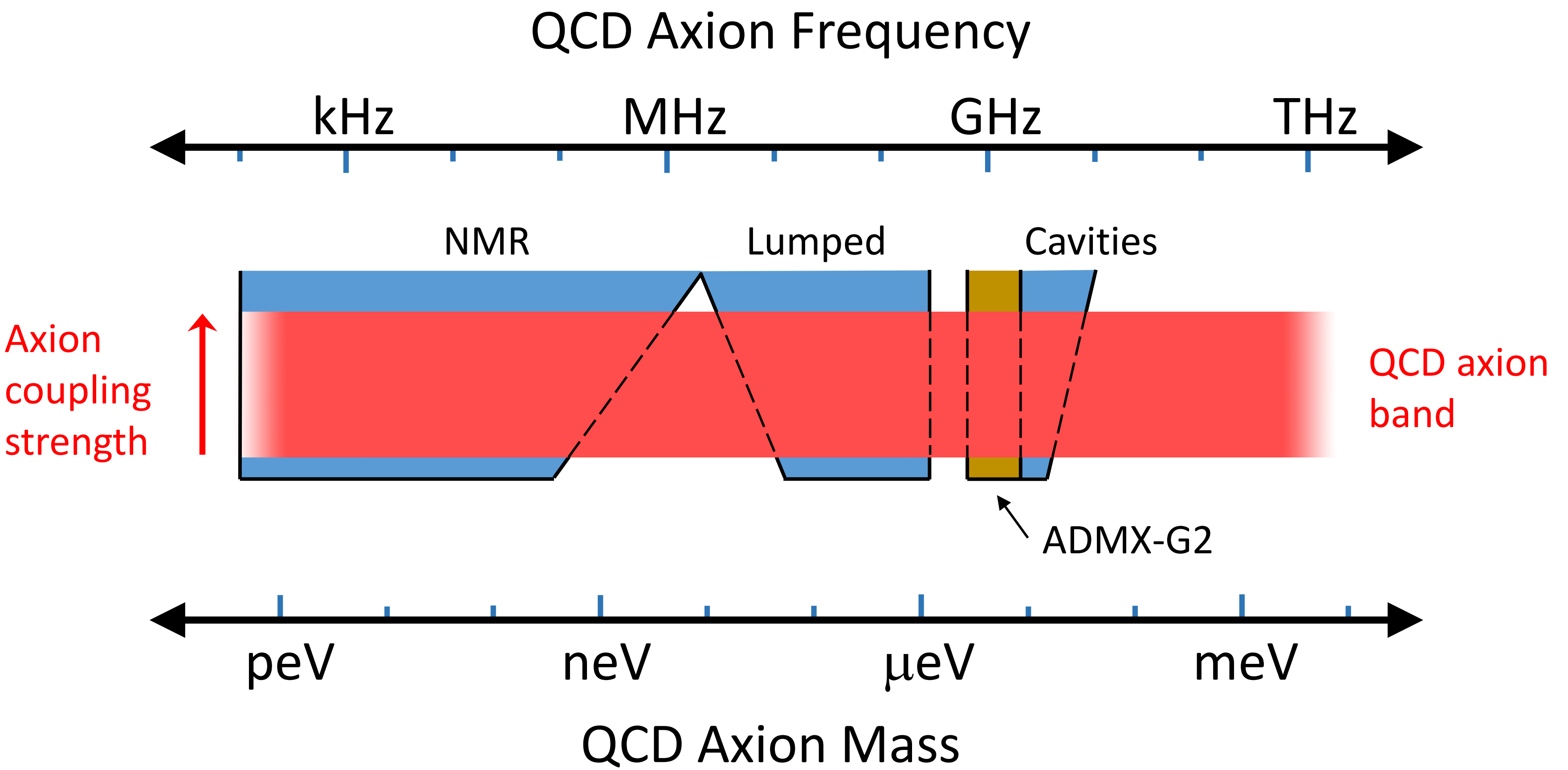
- **Weakly Interacting Massive Particle (WIMP)**
  - Occam’s razor: candidates from supersymmetry
  - Naturalness: thermal production of observed abundances for WIMPs near 100 GeV
- **QCD axion**
  - Occam’s razor: axion solves strong CP problem in QCD
  - Naturalness: misalignment production of observed abundances both pre- and post-inflationary scenarios

Quest for the QCD axion – G2 science reach



QCD axion searches at the Standard Quantum Limit

- Projected science reach of experiments at the SQL are in **blue**.
- Assumptions made about experimental parameters (volume, field strength…) may change – this is approximate!



It will not be possible to probe the full QCD axion band without quantum sensors

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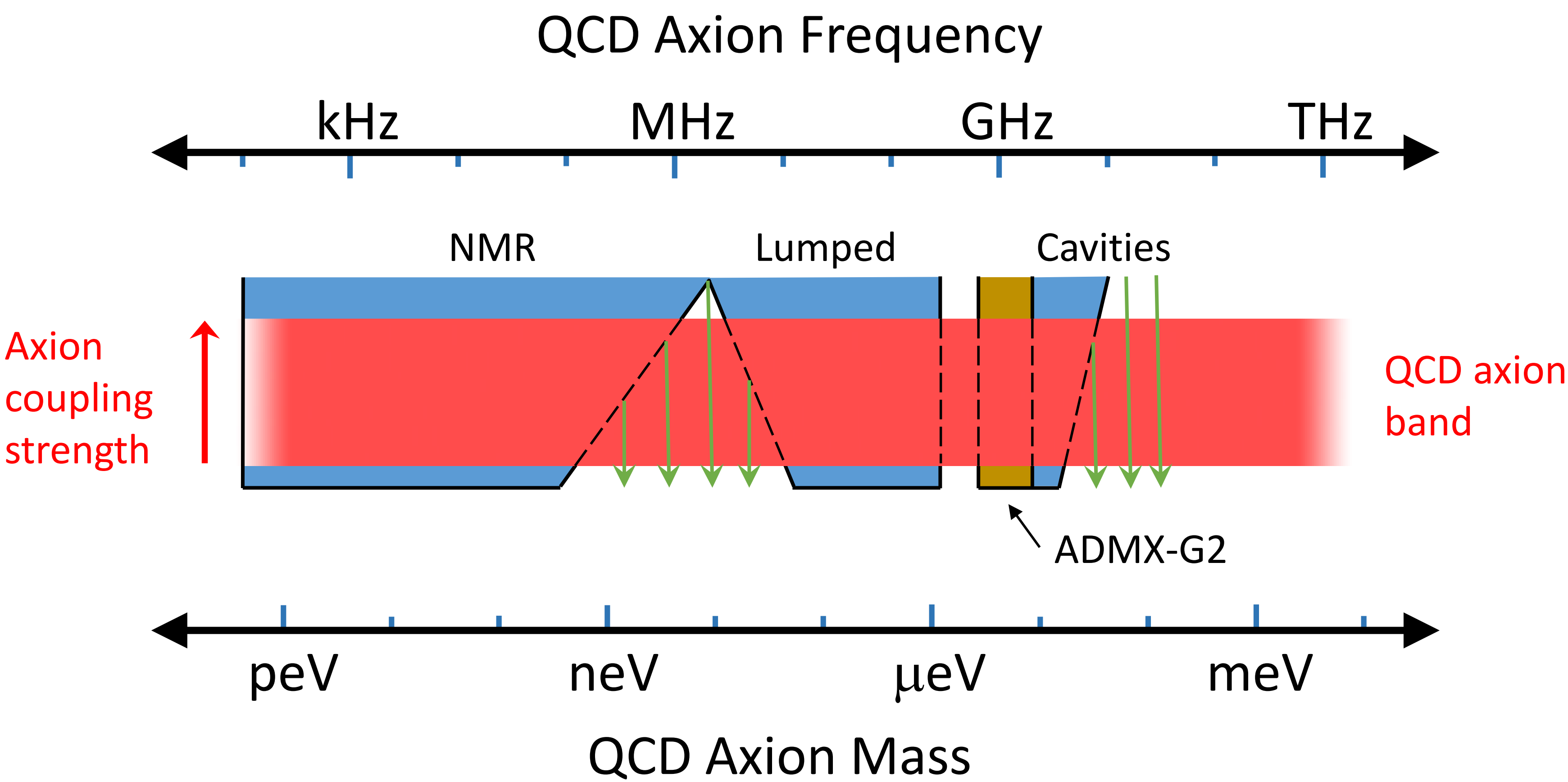
QCD axion searches beyond the Standard Quantum Limit

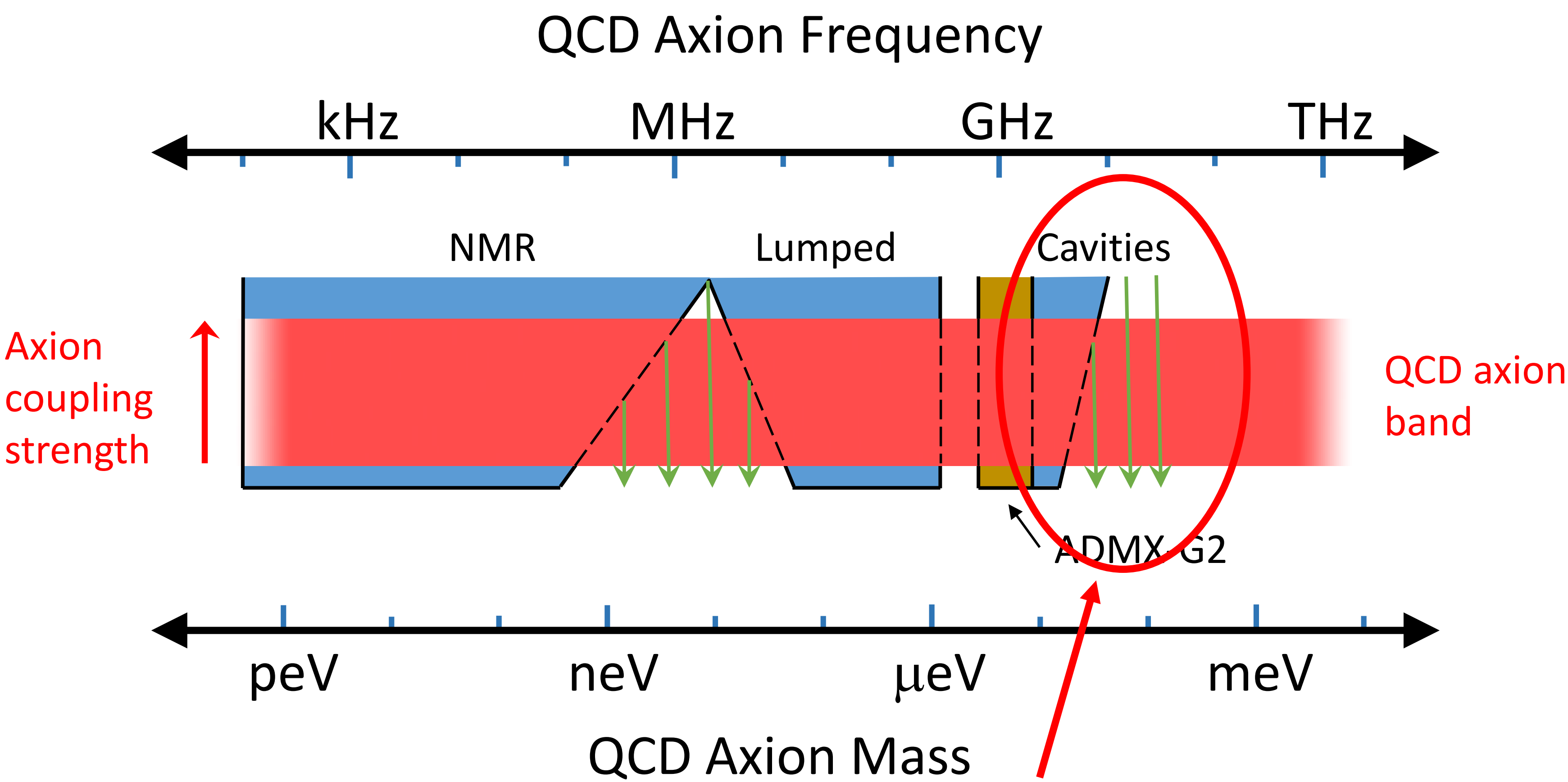
Green arrows: searches beyond the SQL



It will not be possible to probe the full QCD axion band without quantum sensors

Accelerating cavity searches

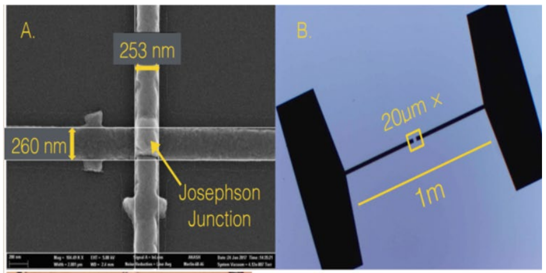
Green arrows: searches beyond the SQL

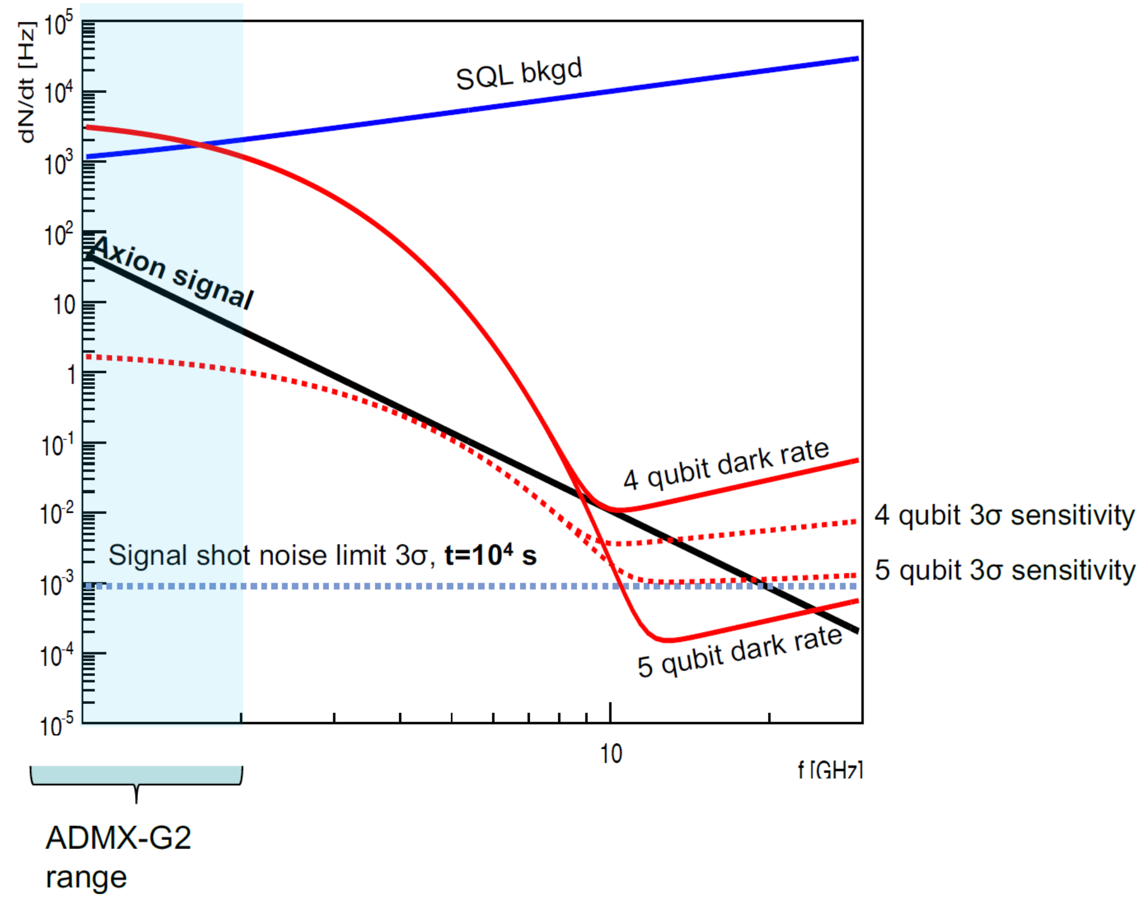


Cavities can be enhanced by squeezers and photon counters based on Josephson parametric amplifiers (see HAYSTAC) and qubits.

Qubit-based photon counters: great at high frequency

Figure from Fermilab





Sensitivity enhancement over the SQL when $hf \gg k_B T$

Not useful when $hf < k_B T$ (photon counting just resolves the thermal distribution). Most useful above 10 μeV.

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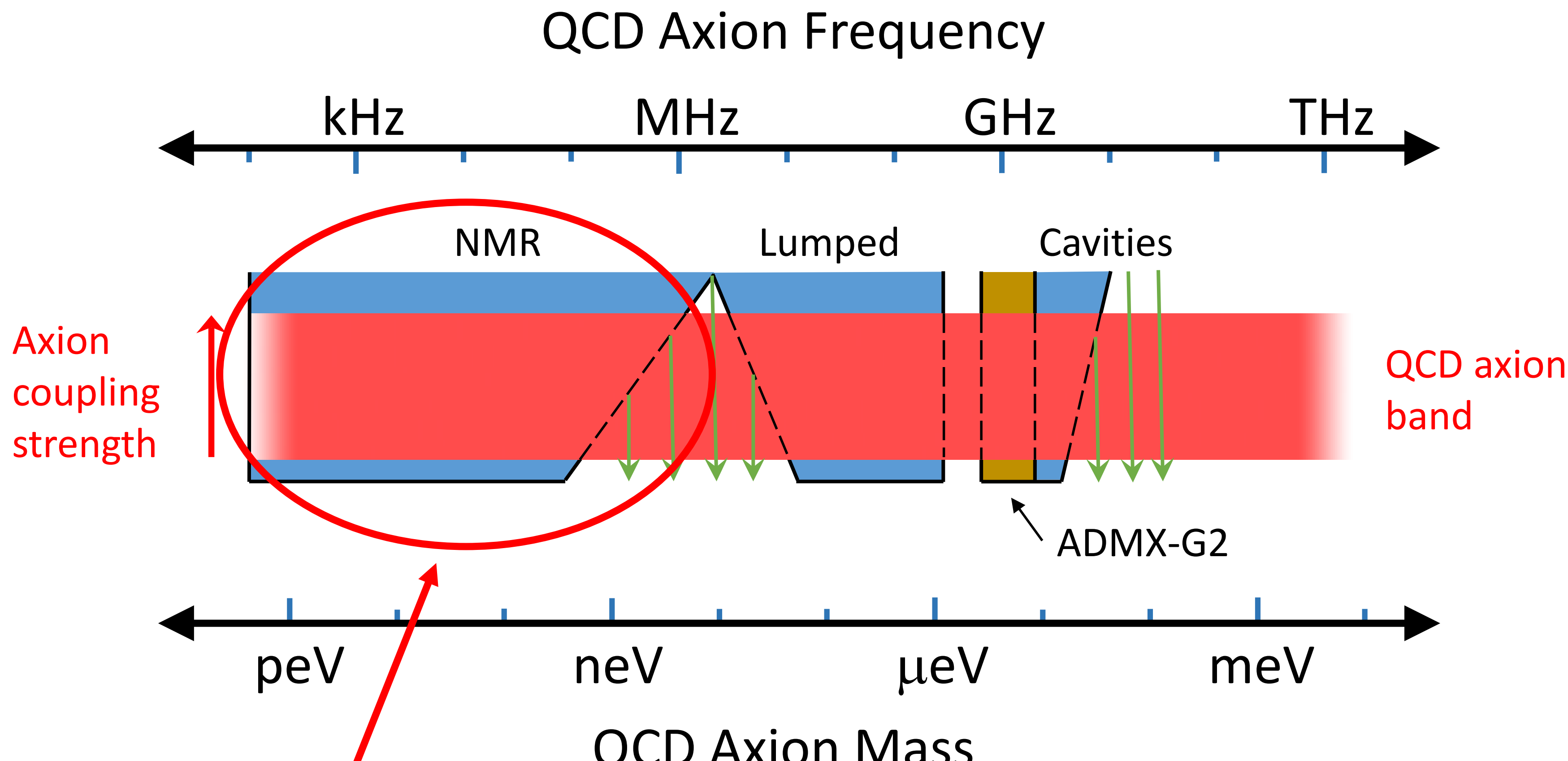
Accelerating searches < 300 MHz (1 μeV)

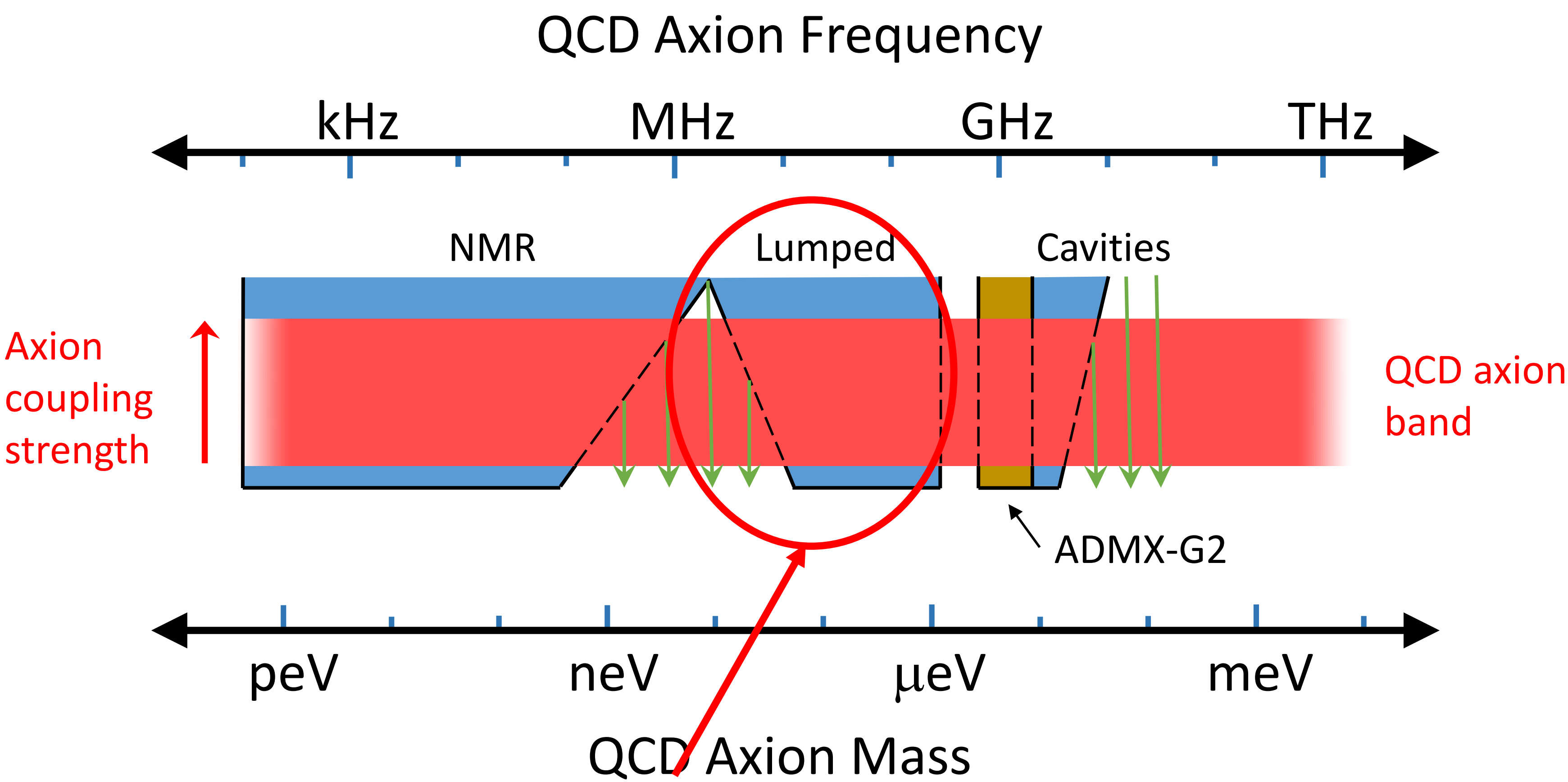
Green arrows: searches beyond the SQL



1. NMR searches can be accelerated using photon upconverters (the subject of this talk)

Accelerating searches < 300 MHz (1 μeV)

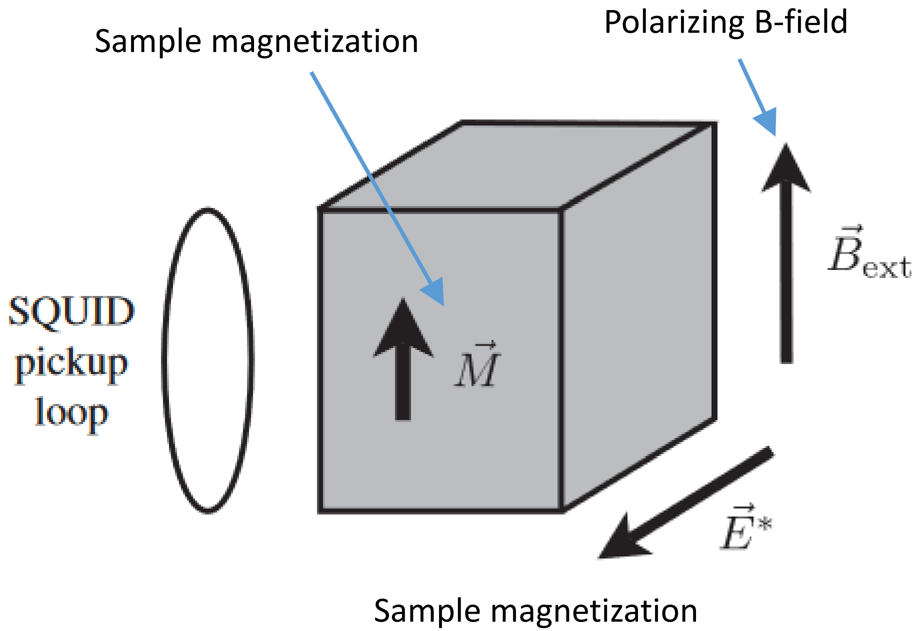
Green arrows: searches beyond the SQL



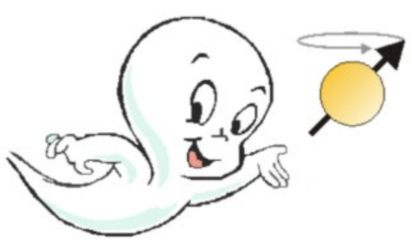
1. Lumped-element searches like DM Radio can be accelerated using photon upconverters (the subject of this talk)

Searching for axions with NMR

- Axions couple to nuclear spins through the strong force, inducing an effective nuclear electric dipole moment which oscillates at f_{ax}.
- A spin-polarized sample of nuclear spins will resonantly precess if f_{ax} matches their Larmor frequency.
- The precessing magnetization can be detected with a SQUID magnetometer or quantum sensor.

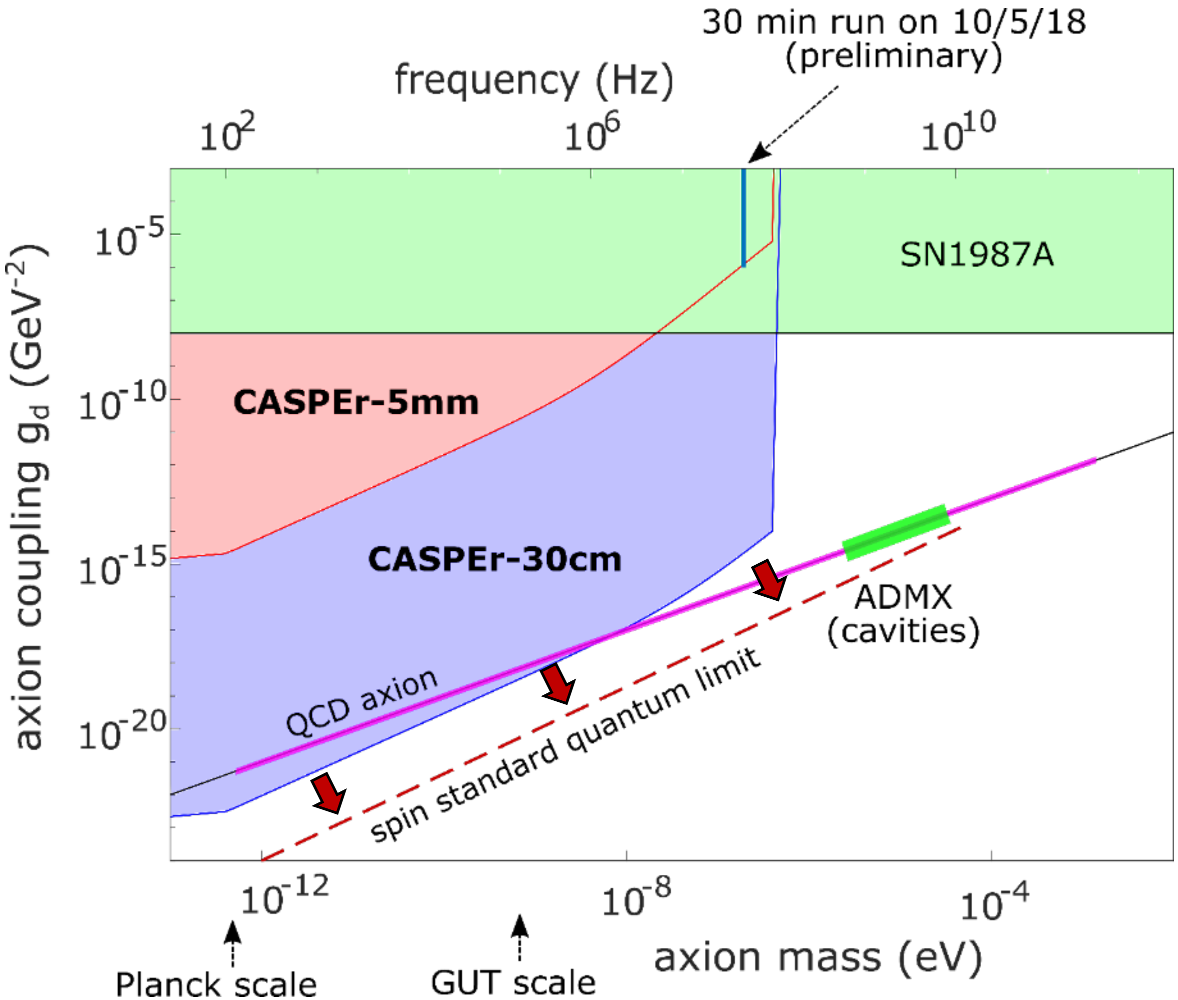


CASPEr-electric



See Alex Sushkov's talk for CASPEr collaboration list

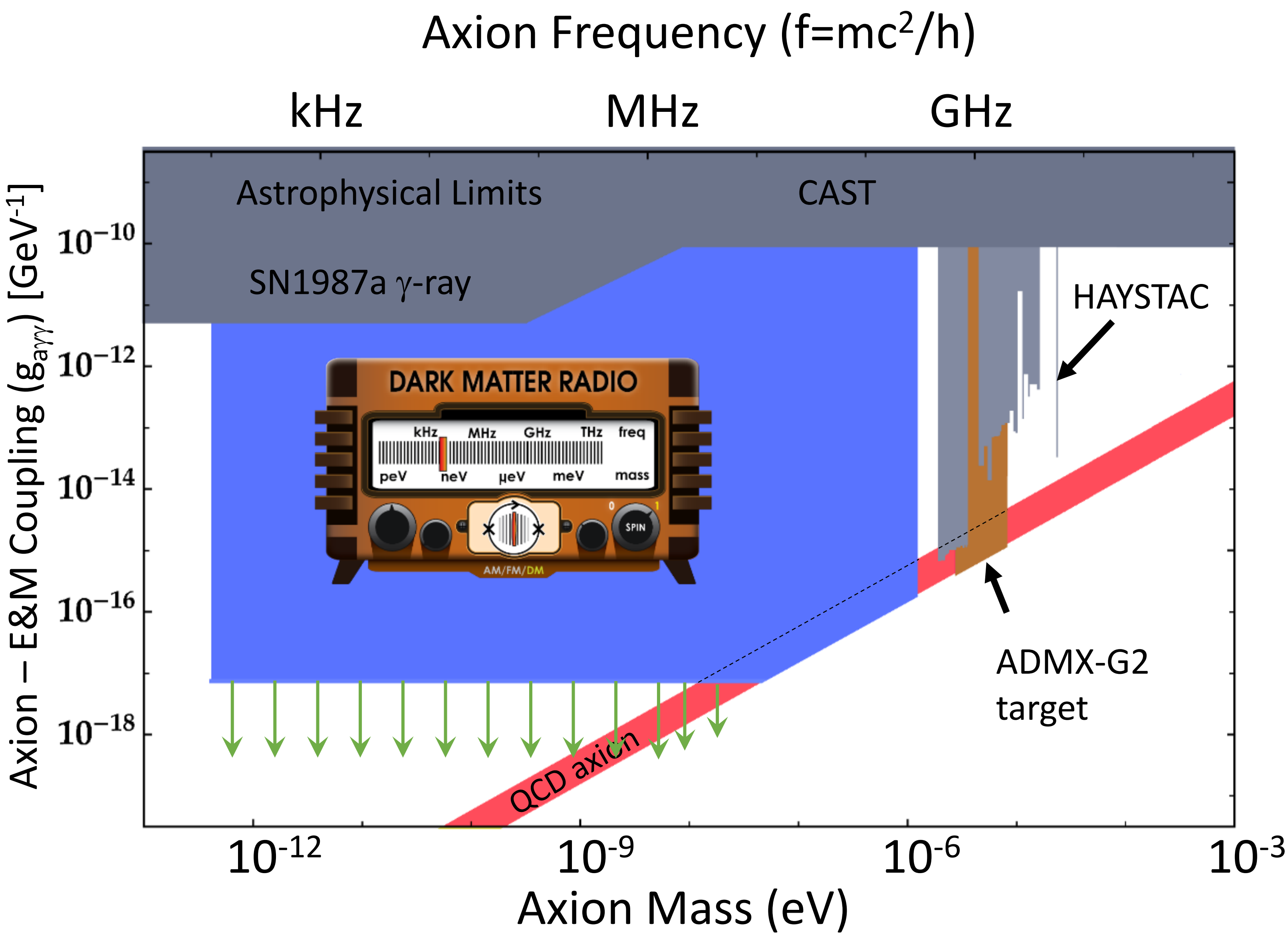
Accelerating NMR search: CASPEr-e



See Alex Sushkov's talk for source of this figure, and CASPEr collaboration list

- Quantum electromagnetic sensors can help CASPEr's science reach to extend to the spin projection noise SQL
- Spin squeezing can extend below the spin projection SQL

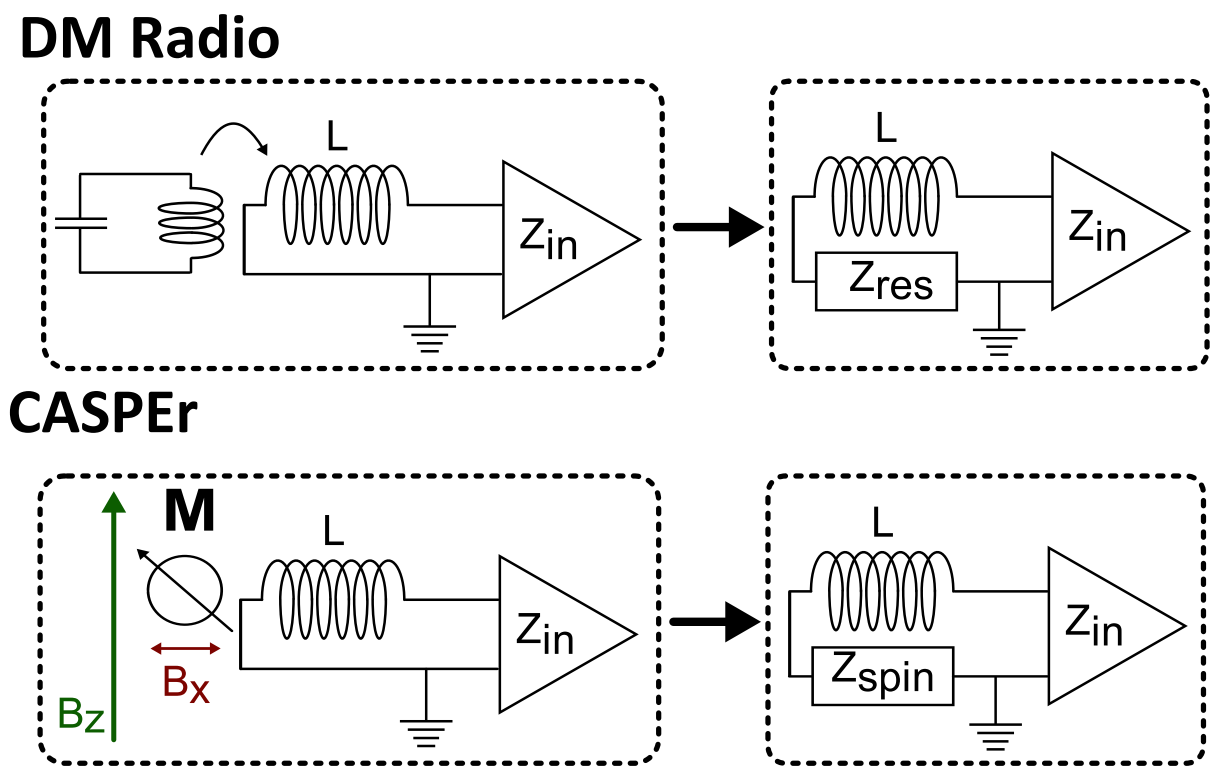
Accelerating lumped element search: DM Radio



Shared Quantum Sensor Needs < 300 MHz

NMR and electromagnetic axion experiments both need quantum sensors.

The circuit models for interaction are related, and both experiments benefit from similar quantum sensors: photon upconverters.



For the balance of this talk, we provide more details on DM Radio in particular

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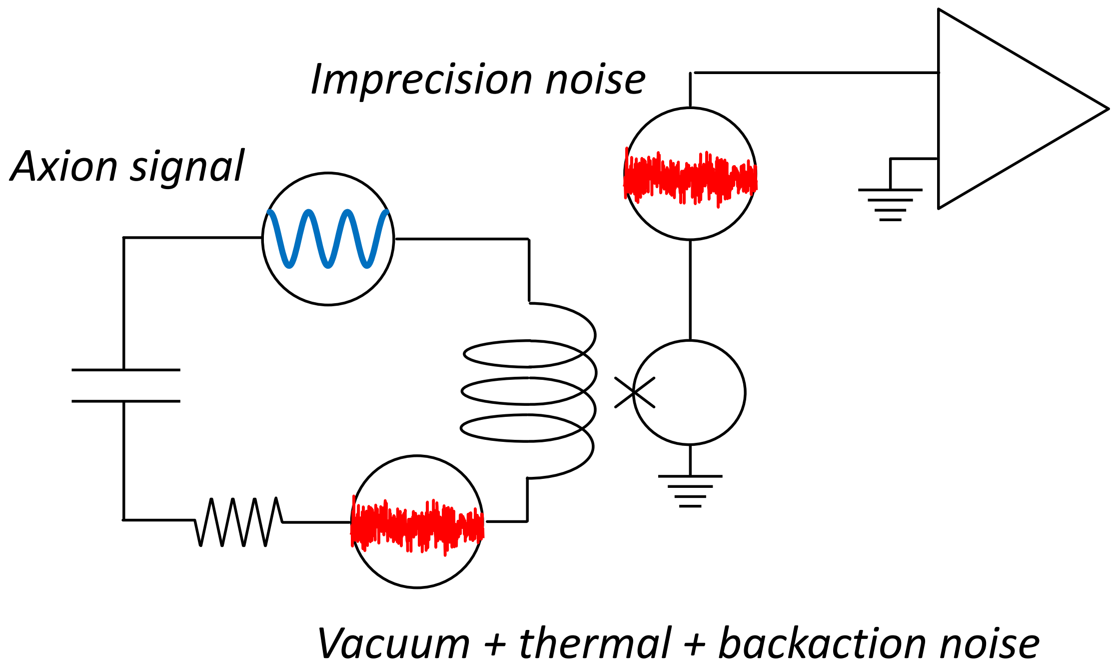
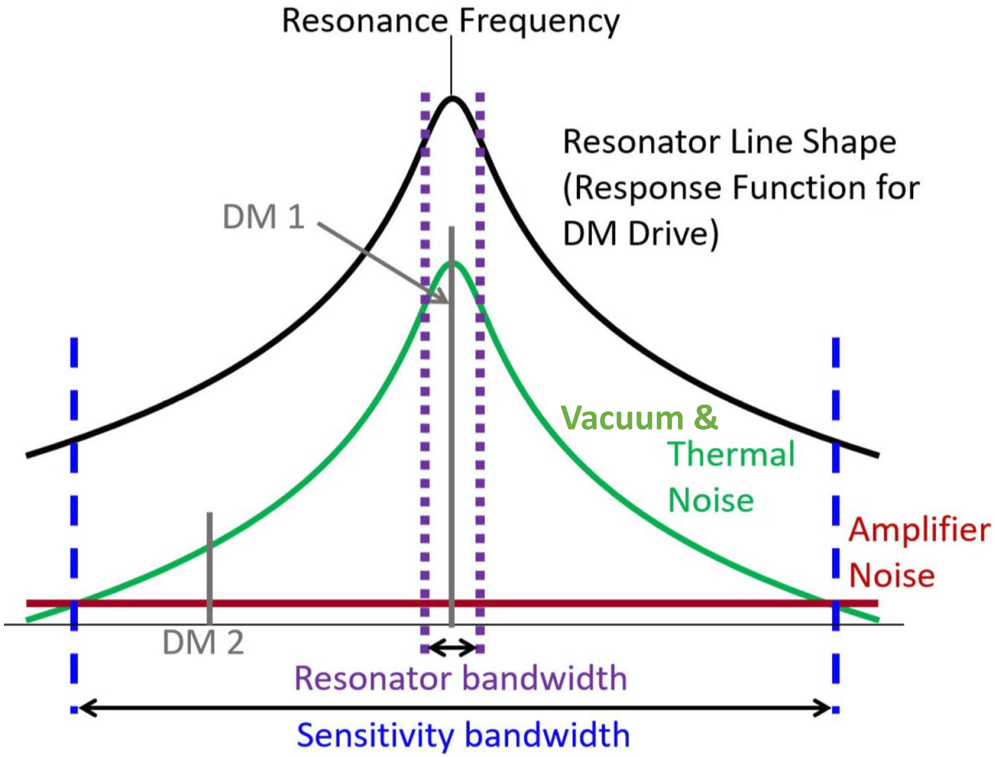
Fundamental noise sources



1. **Thermal Noise:** set by the resonator's thermal occupation.
2. **Vacuum Noise:** required by quantum mechanics.
3. **Amplifier Noise:** composed of *imprecision* and *backaction* noise, and subject to a Standard Quantum Limit.
4. **(NMR only:** also consider spin-projection noise.)

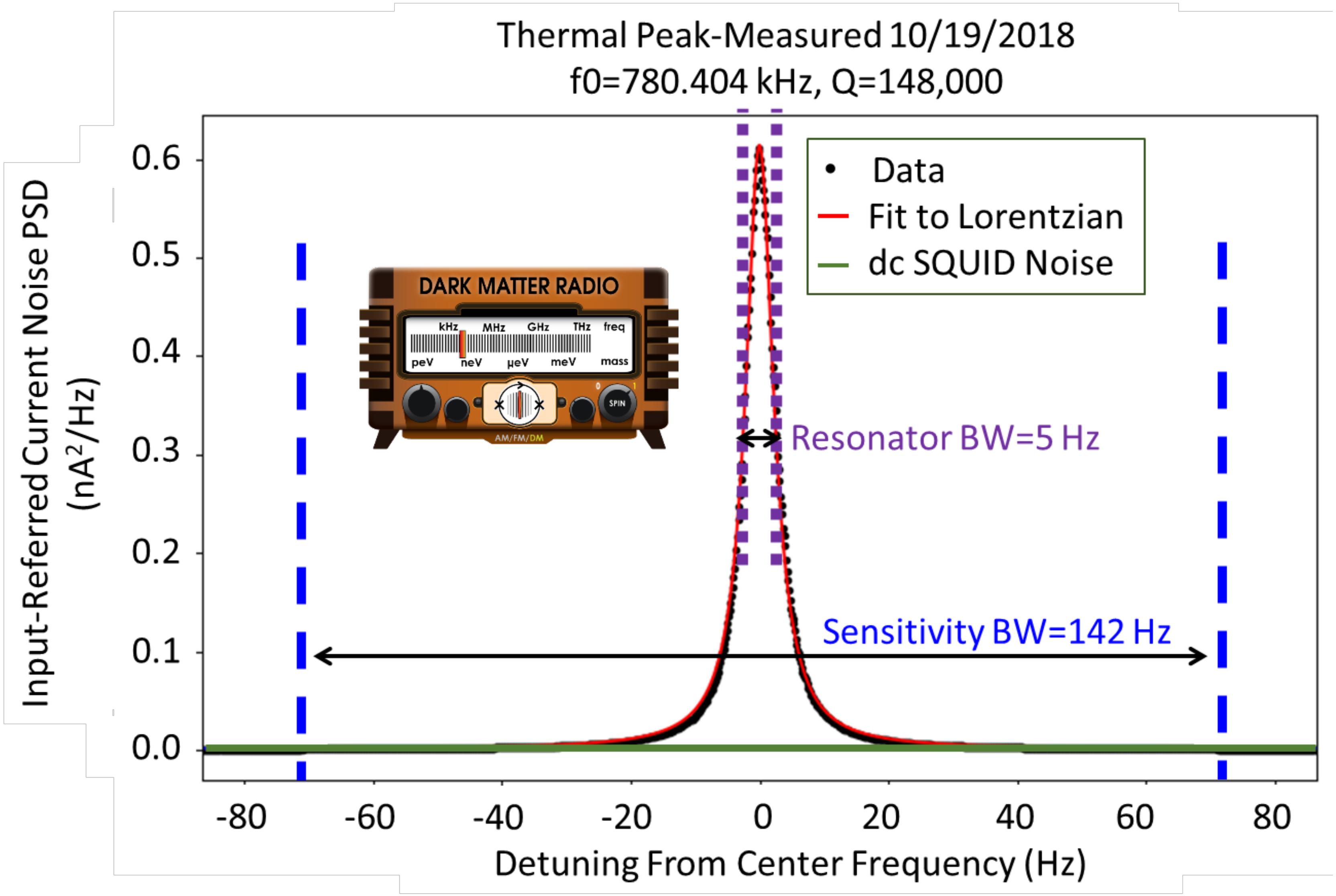
Noise spectrum in resonator

- Dark matter signal appears as "bump" on top of noise
- Thermal noise, vacuum noise, and amplifier backaction roll off outside of Lorentzian resonator bandwidth.
- SNR is independent of detuning long as thermal noise > amplifier noise: defines the "sensitivity bandwidth"



Sensing below the SQL increases the sensitivity bandwidth, and accelerates the search, even when $hf \ll k_B T$

Sensitivity bandwidth determined by amplifier noise



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 ($\hat{Y}$)

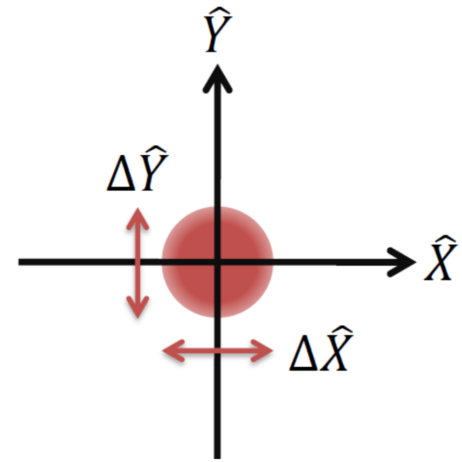
$$\hat{H} = \frac{\hbar\omega}{2}\left(\hat{X}^2 + \hat{Y}^2\right)$$

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

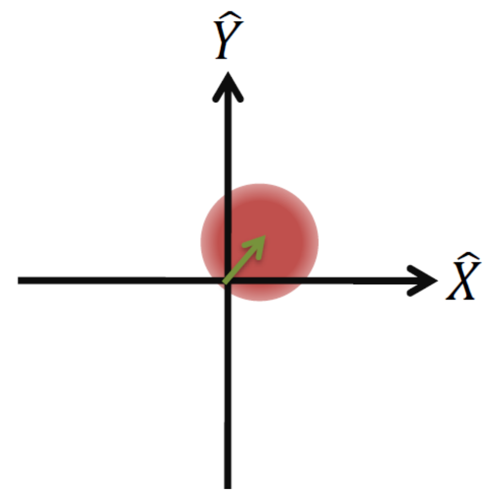
$$\Delta\hat{X}\Delta\hat{Y} \geq \frac{1}{2}$$ vacuum noise

When amplified, add one more ½ quantum

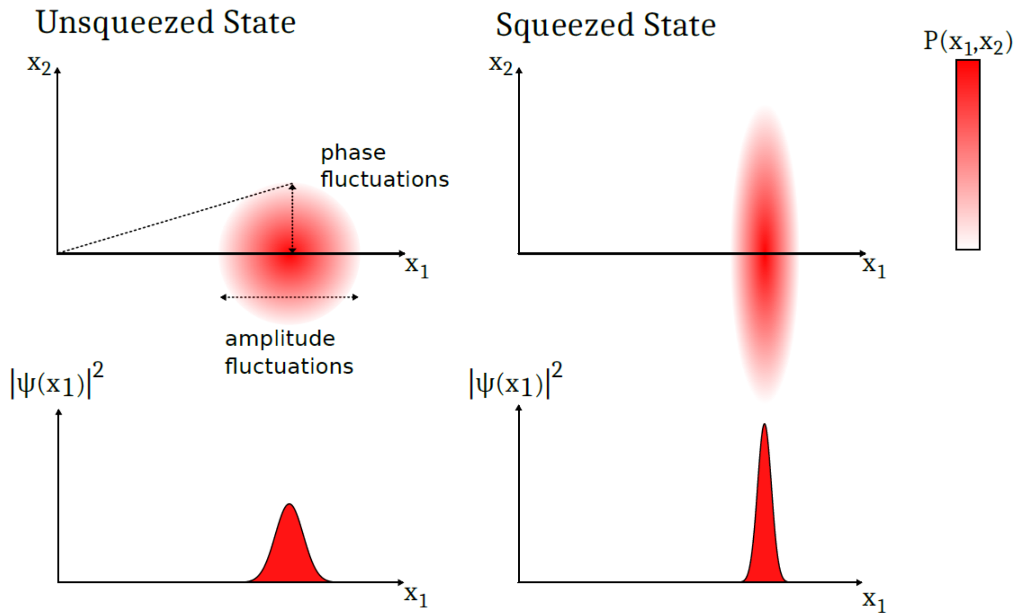
$$N_{add} \geq \frac{1}{2}$$

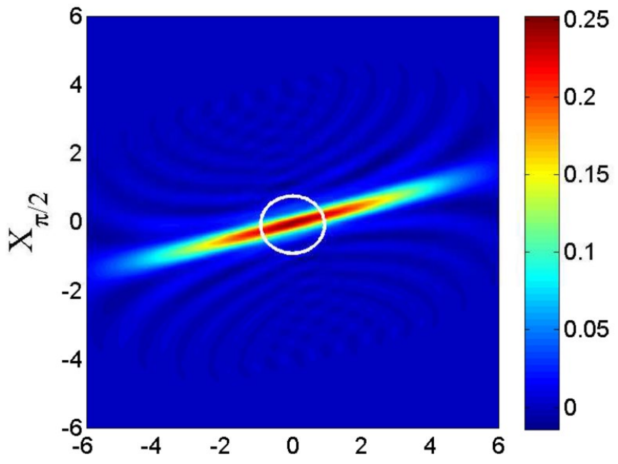


With nonzero expectation value



How to measure better than the SQL

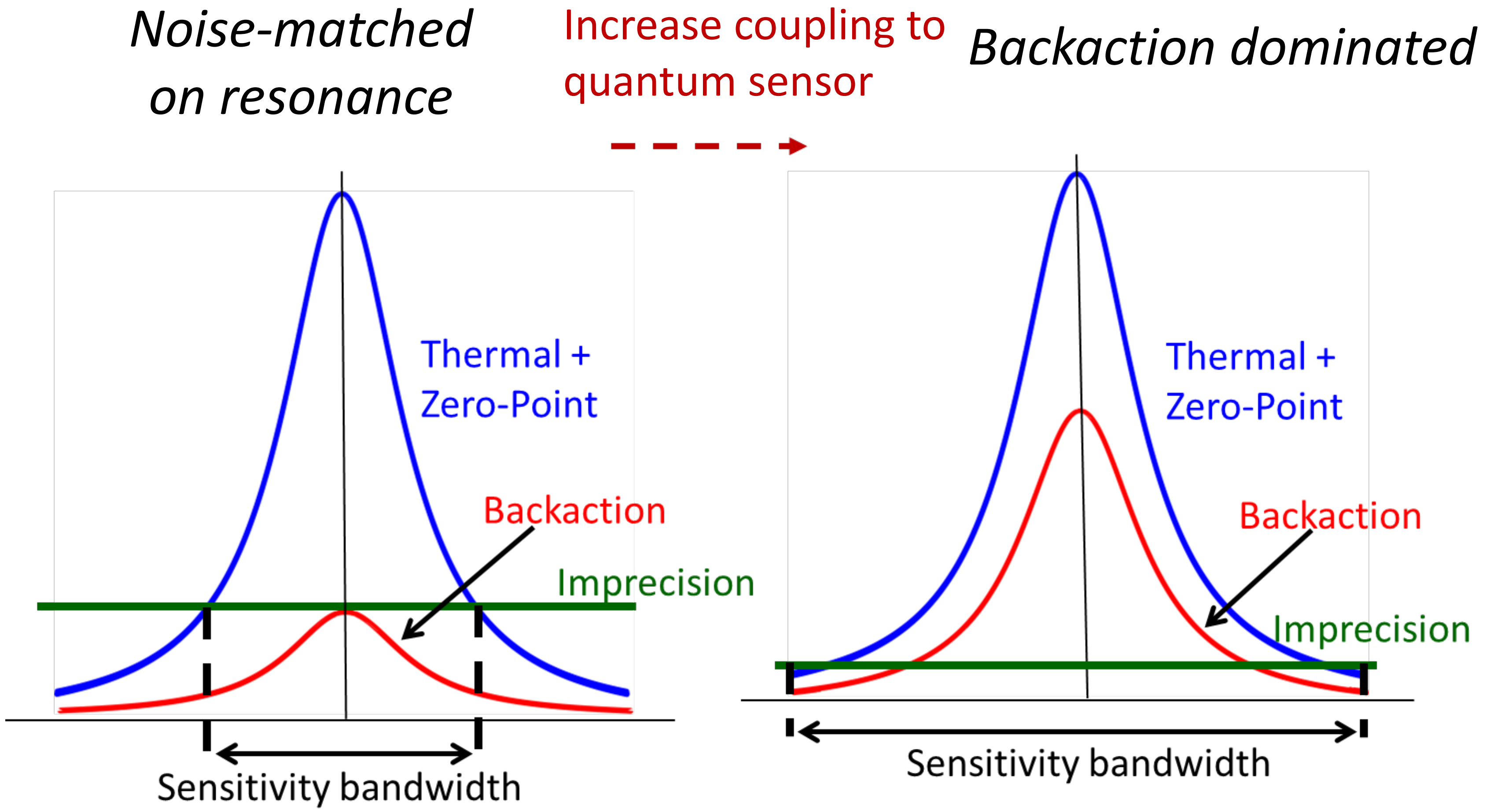




F. Mallet et al. *Phys. Rev. Lett.* **106**, 220502 (2011).

- Principle: measure one quadrature and put the uncertainty into the other quadrature (e.g. squeezing). If we can do this, single-quadrature precision is not limited by Heisenberg.
- There are several ways to achieve this outcome. They are deeply inter-related (and involve entanglement), and all obey the Uncertainty Principle.
- We'll focus on Back-Action Evasion (BAE), which is particularly interesting for axions with mass < 1 μeV.

Backaction evasion increases sensitivity bandwidth



- Increased coupling: better imprecision, worse backaction
- **Backaction Evasion:** Put backaction in one quadrature, measure the other to increase sensitivity bandwidth.

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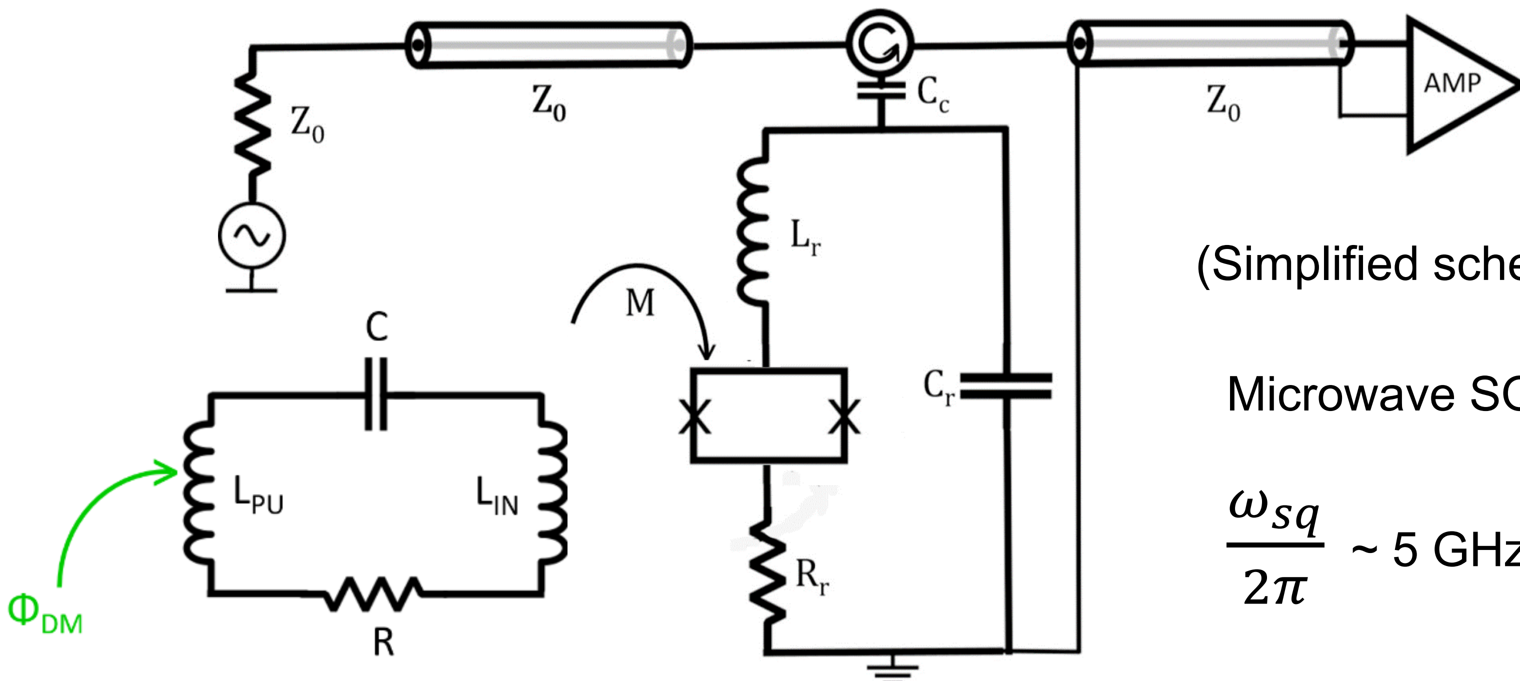
Measuring a resonator with a microwave SQUID

KD Irwin and KW Lehnert. *Appl. Phys. Lett.* **85**, 2107 (2004).
JAB Mates., et al. *Appl. Phys. Lett.* **92,** 023514 (2008).

Dissipationless microwave SQUID photon upconverter



(Simplified schematic)

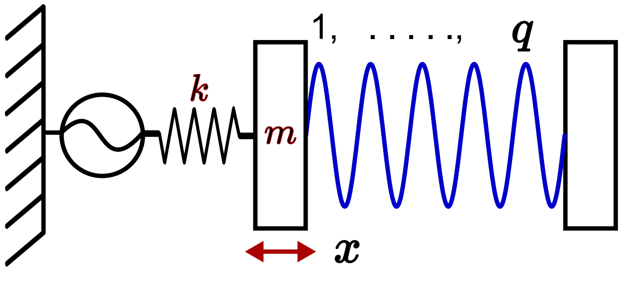
Microwave SQUID:

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

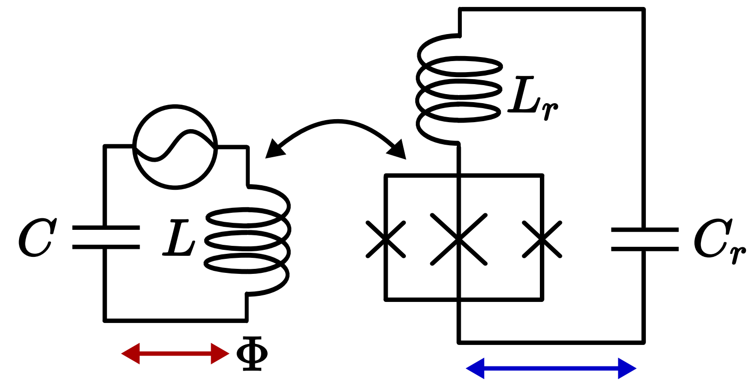
DM Radio: $\frac{\omega_r}{2\pi}$ = 1 kHz – 100 MHz

the Zappe Photon Upconverter (ZPU)

Optomechanics



Zappe Photon Upconverter



$$\hat{H} = \hbar\omega_a(\hat{a}^\dagger\hat{a} + 1/2) + \hbar\omega_b(\hat{b}^\dagger\hat{b} + 1/2) + \hbar g(\hat{b}^\dagger + \hat{b})\hat{a}^\dagger\hat{a}$$

- Uses a three-junction interferometer (Zappe) rather than a single junction (as does a microwave squid photon upconverter)
- Better symmetry, and clean implementation of Optomechanical Hamiltonian (same as LIGO)

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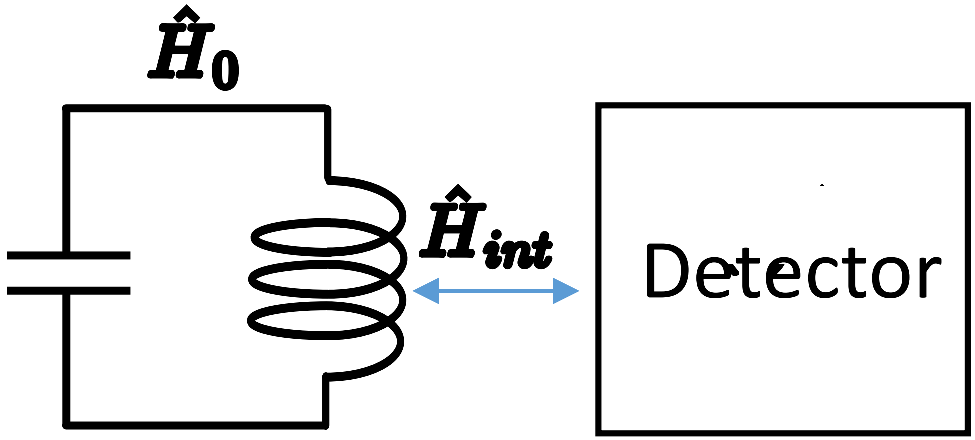
Backaction evasion with ZPU



$$\hat{H}_0 = \hbar\omega_b \hat{b}^\dagger \hat{b} \qquad \hat{H}_{int} = A(t)(\hat{b} + \hat{b}^\dagger)\hat{D}$$

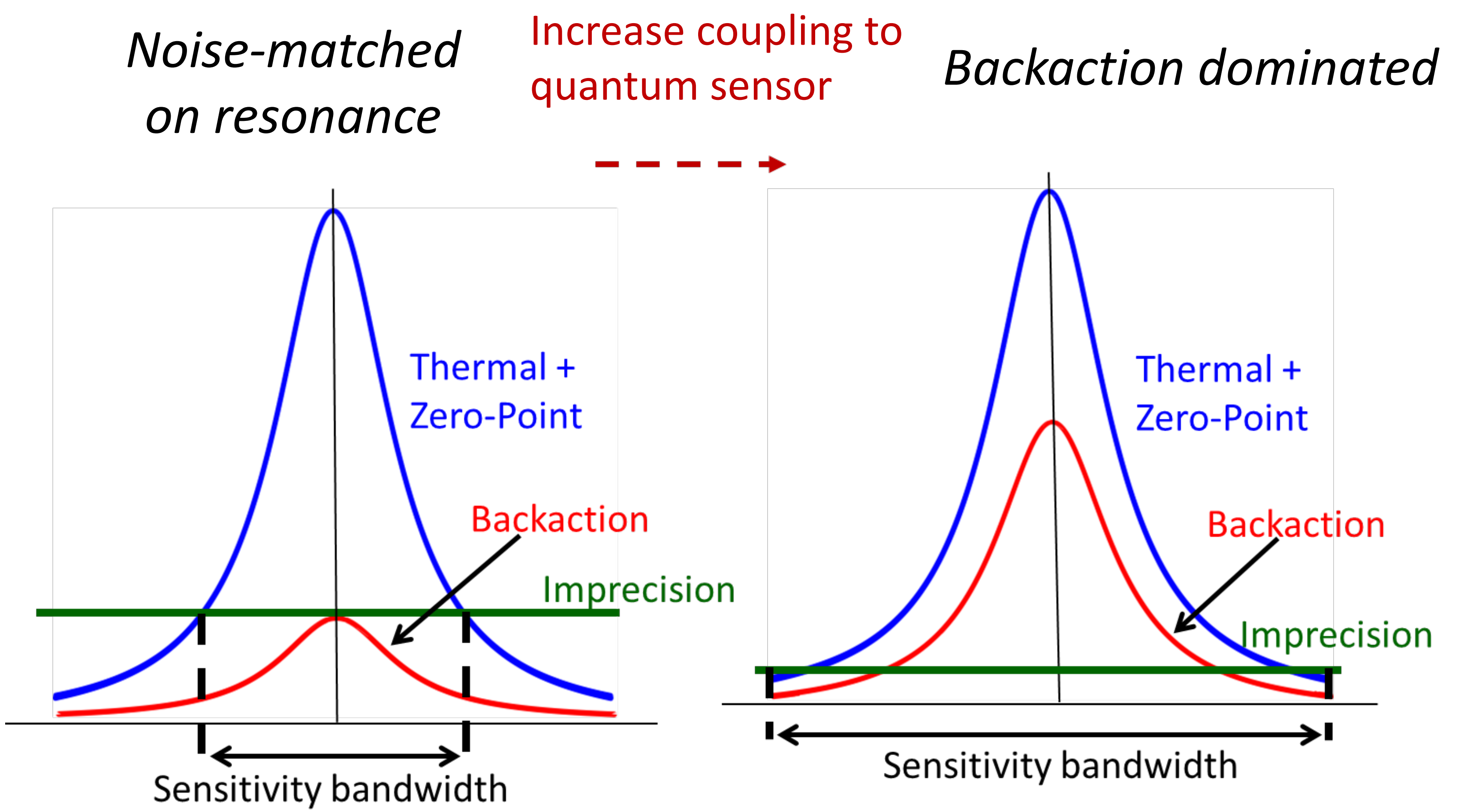
- Originally proposed by Braginsky (1980) for gravitational wave detectors: use a detector that only couples backaction to a single quadrature.
- Amplitude-modulate the coupling at the resonator's frequency

$$A(t) \propto \cos(\omega_b t)$$

- Averaged over time, only couples to a single quadrature:

$$\hat{H}_{int} \propto \hat{X}\,(1 + \cos(2\omega_b t)) + \hat{Y}\sin(2\omega_b t)$$

Backaction evasion increases sensitivity bandwidth



- Increased coupling: better imprecision, worse backaction
- **Backaction Evasion:** Put backaction in one quadrature, measure the other to increase sensitivity bandwidth.

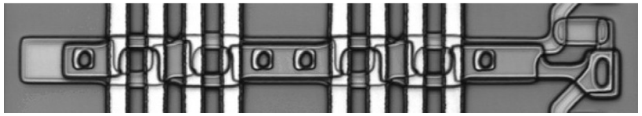
ZPU implementations

Photon upconverters with lithographic GHz resonators

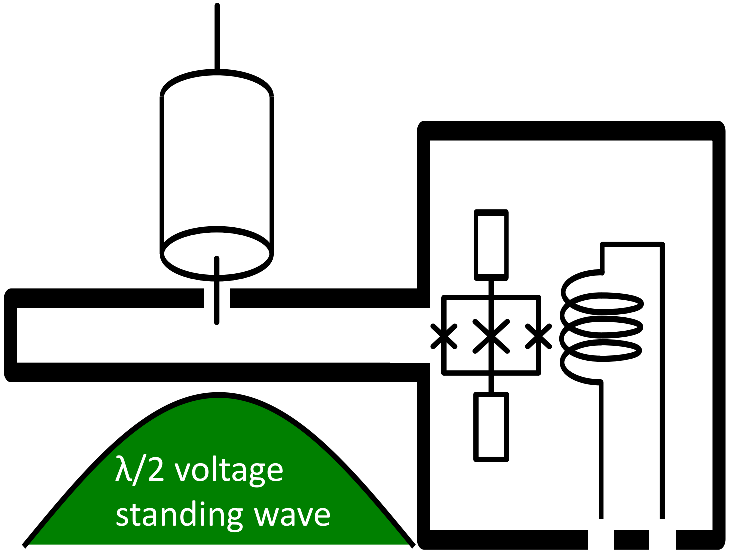
- Photon upconverters (microwave SQUIDs) are mature with lithographic resonators

JAB Mates., et al. *Appl. Phys. Lett.* **92,** 023514 (2008).

- Devices with Zappe symmetry are in design / fabrication
- Zappe symmetry demonstrated in switches



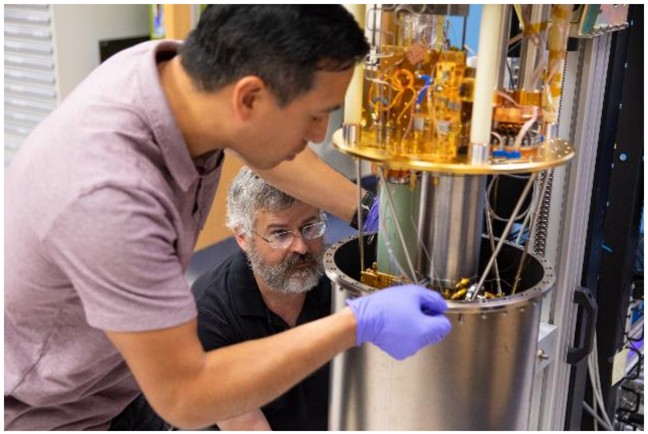
Photon upconverters with 3D cavity resonators



- 3D cavity implementations are in prototyping.
- Similar idea to 3D transmon qubits, but much higher participation ratio.
- Higher Q than lithographic resonators: should provide more dB of backaction evasion.

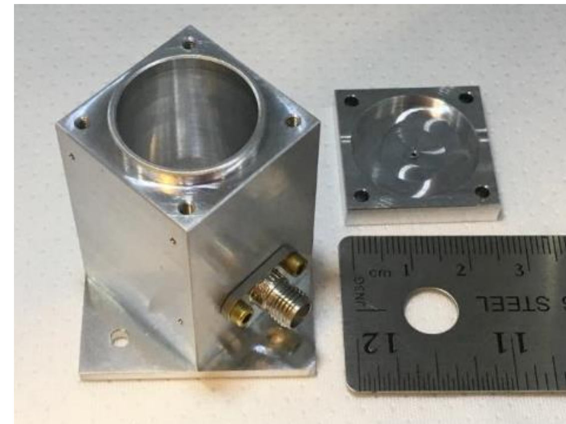
ZPU cryogenic testing

HPD He3-backed ADR



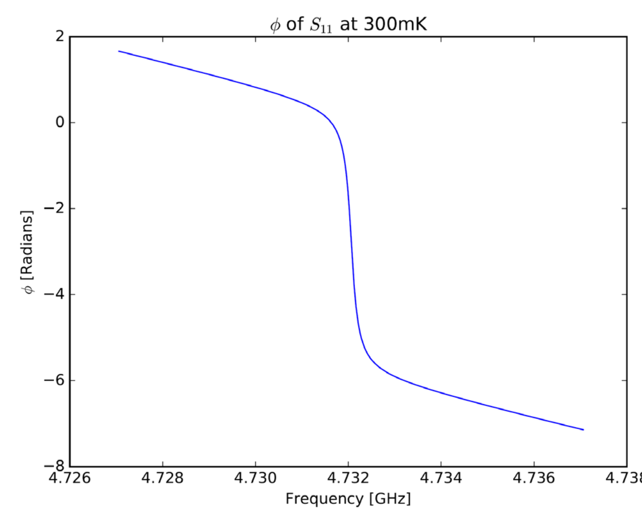
Blufors dilution refrigerator

ZPU 4.7 GHz 3D Cavity

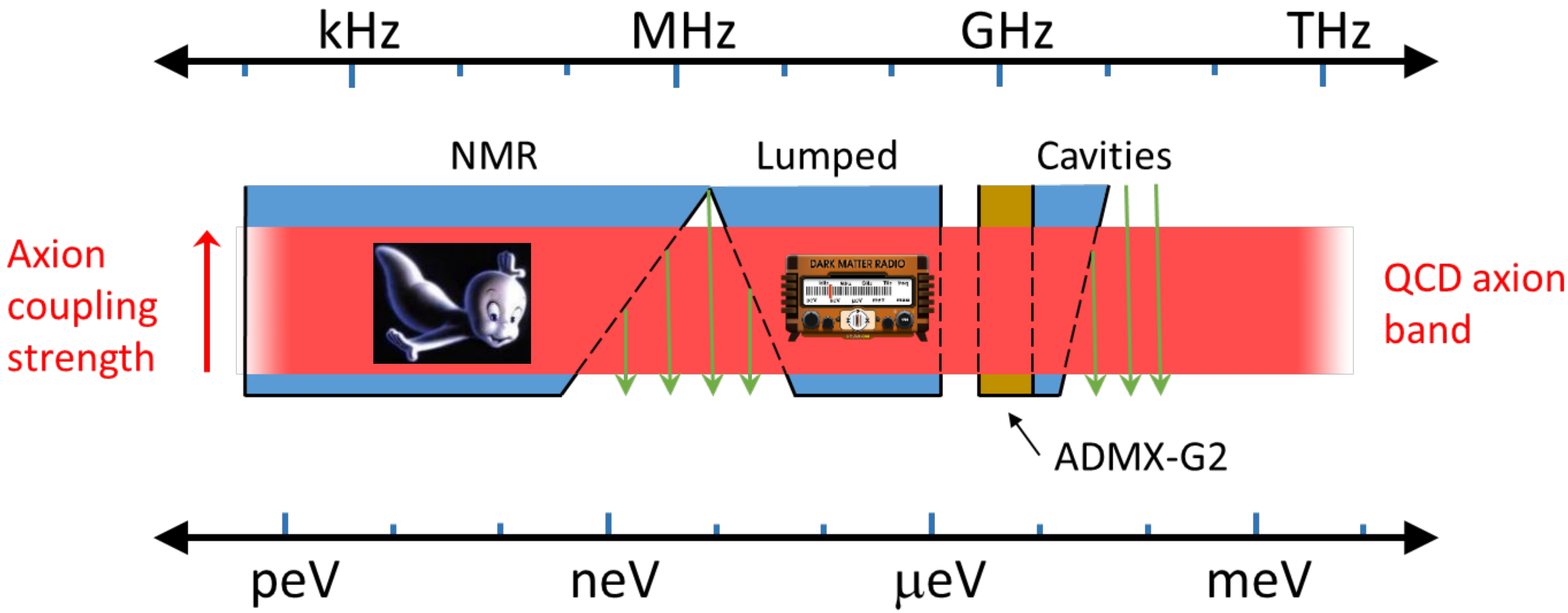


- Measurements presently done in HPD He3-backed ADR
- 25 mK base temperature
- Full suite of microwave wiring and test equipment
- Bluefors dilution refrigerator will be delivered in January
- Simon Chase He-3 refrigerator will be used for CASPEr ~300 mK

ZPU 4.7 GHz 3D Cavity Measurement



Summary

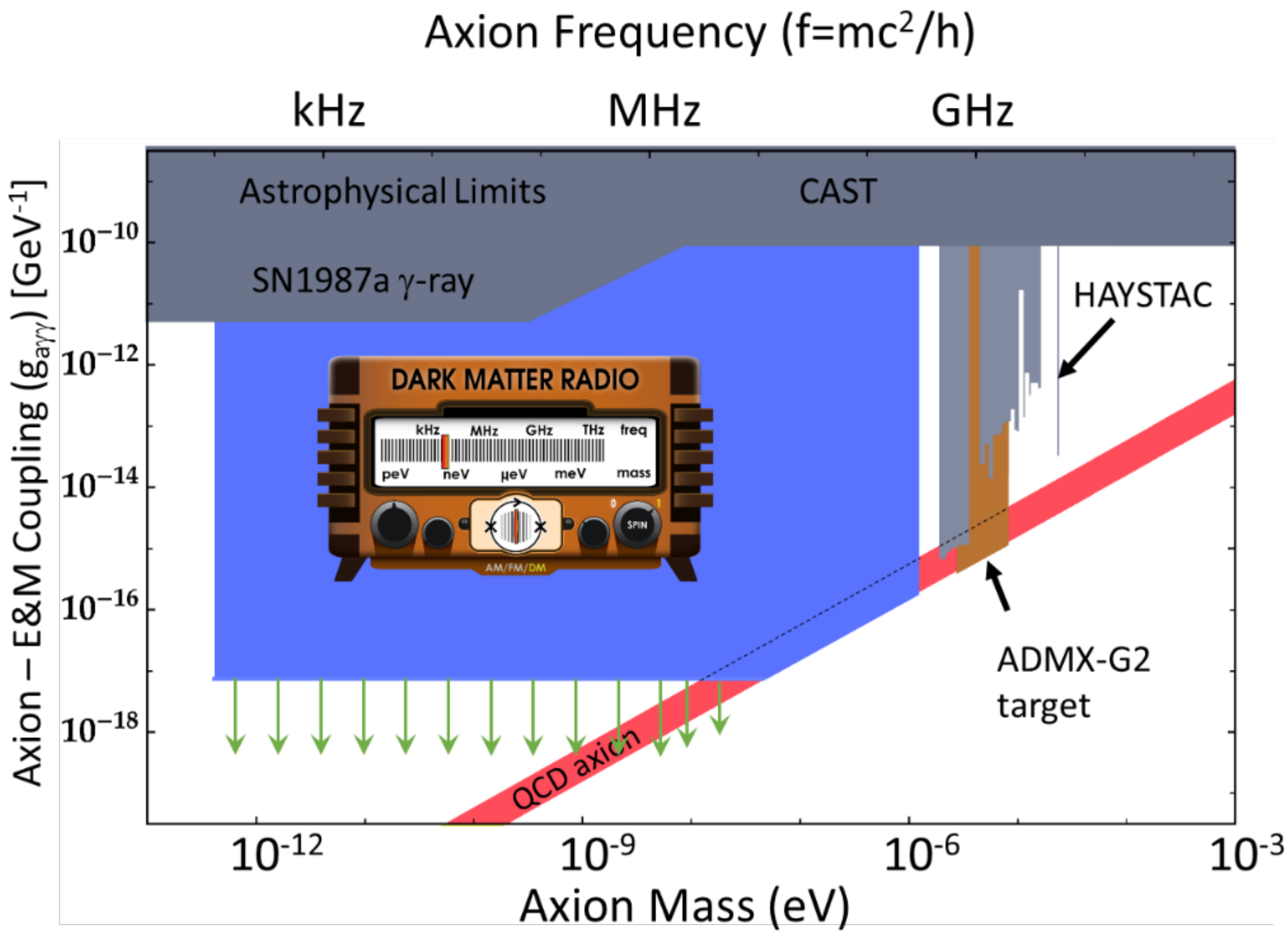


- It will not be possible to fully probe the QCD axion band without quantum sensors. *Like LIGO, our back is against the wall.*

- Zappe Photon Upconverters for both DM Radio and CASPER-e enable a full probe of the QCD axion band below ~ 1 μeV (about 60% of the allowed QCD axion mass range).


STOP

DM Radio Cubic Meter

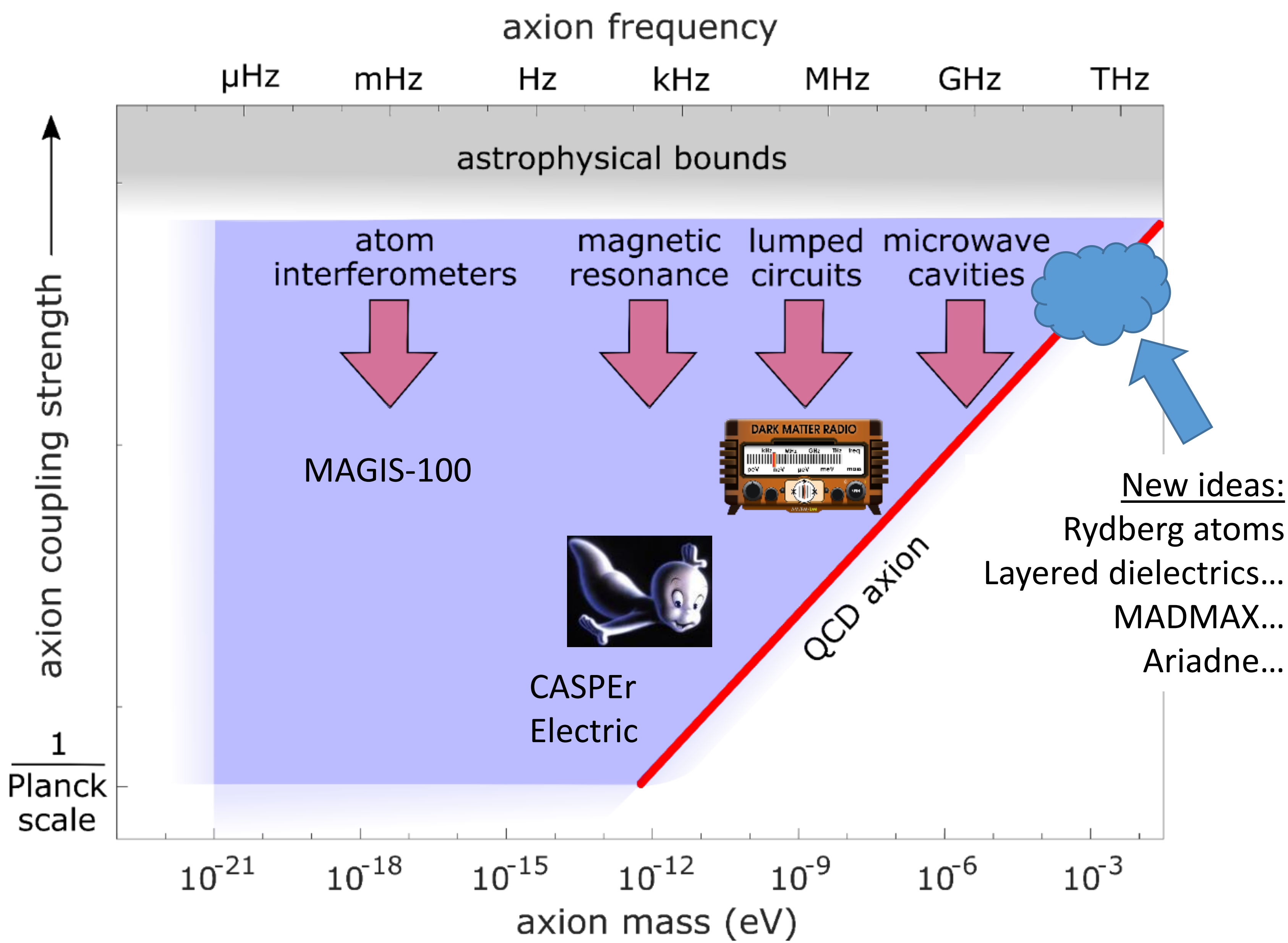


Source: "Optimal Electromagnetic Searches for Axion and Hidden-Photon Dark Matter," S. Chaudhuri, K.D. Irwin, P.W. Graham, and J. Mardon, submitted to PRL

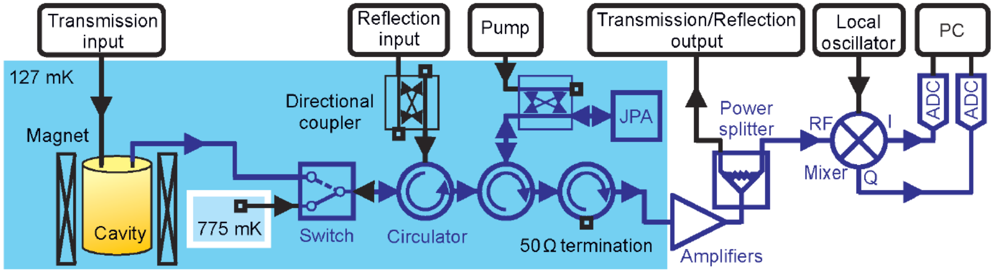
Assumptions:

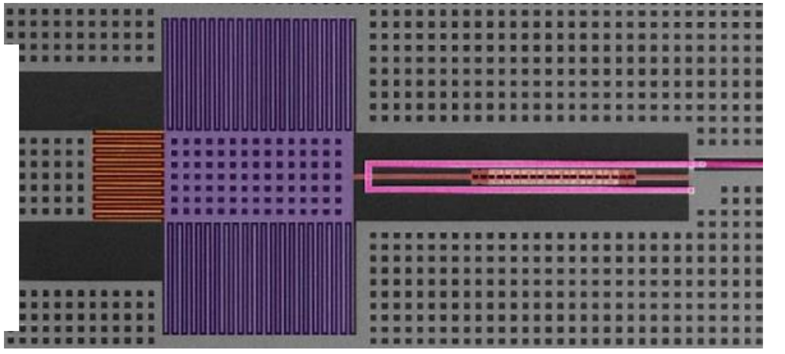
- 4 T solenoidal toroidal magnet with cubic meter volume *inside* superconducting sheath
- Coupling to quantum-limited amplifier optimized for scan sensitivity
- Optimal scan for log uniform priors (could instead use QCD priors)
- 3.5 years total scan time (100 days per e-folding)

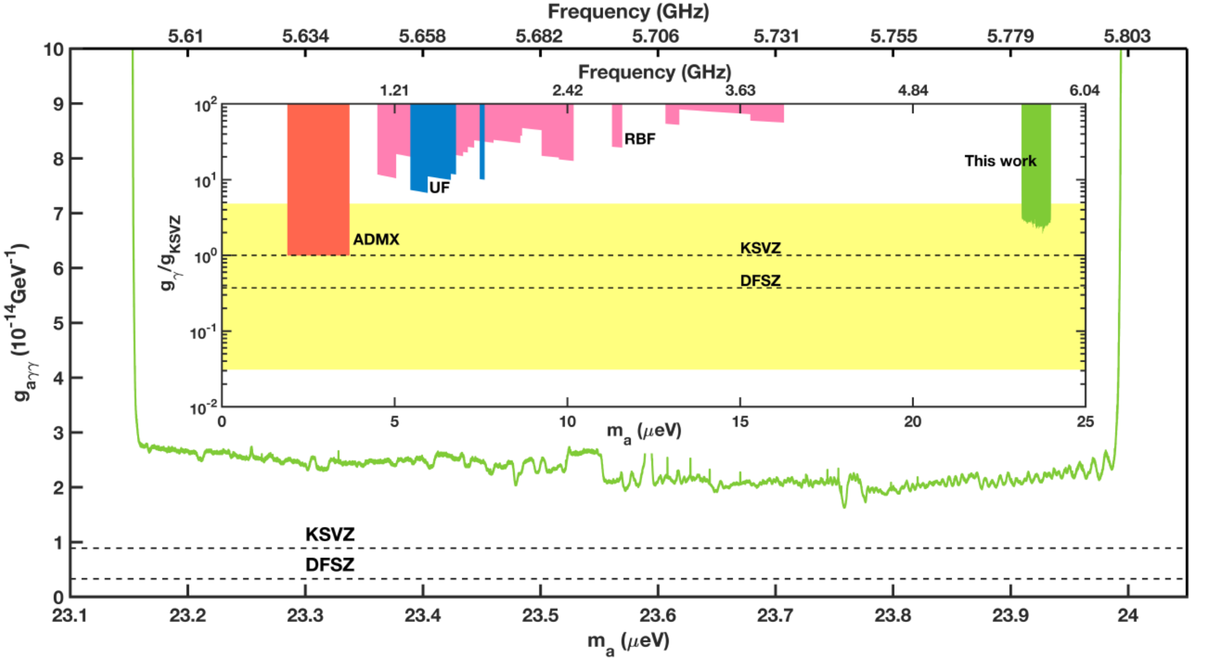
How to detect dark-matter waves



Squeezing: HAYSTAC







arXiv:1803.03690