Pre-Inflationary Axions: Quantum Sensing and the Search for QCD axion dark matter below 1 ueV

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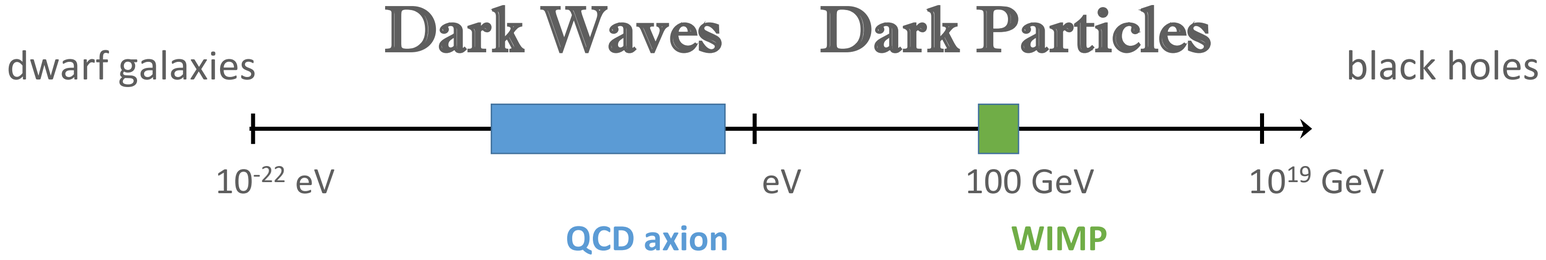
Two “strongly motivated” dark-matter candidates

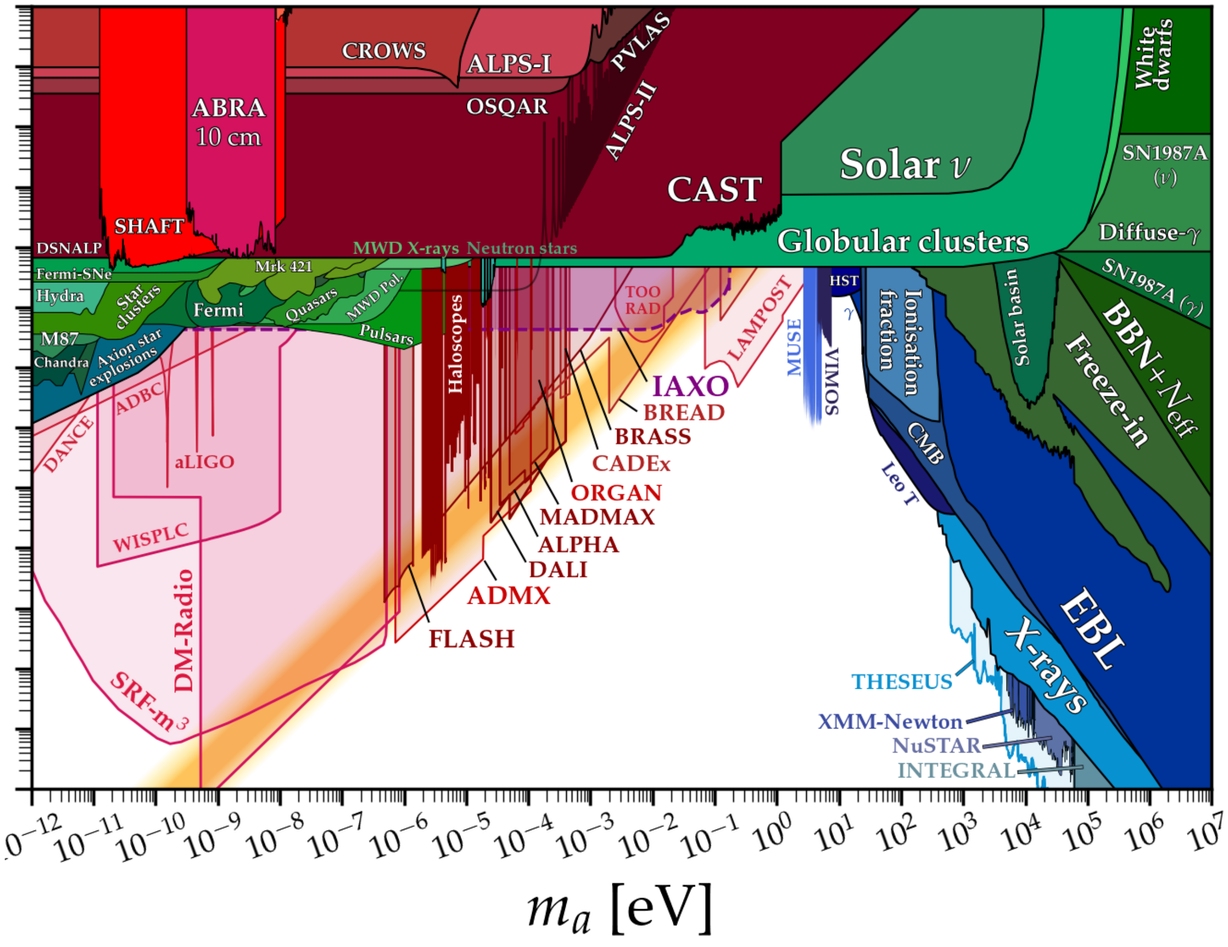


- **Weakly Interacting Massive Particle (WIMP)**
  - *Motivated* by the theory of supersymmetry.
  - *Naturalness*: thermal production of observed abundances for WIMPs near 100 GeV.
  - Ongoing, 30-year effort to produce (supersymmetry at LHC) and detect (direct dark-matter searches). Much interesting phase space has already been ruled out.
- **Axion**
  - *Motivated* as solution to a major problem with the standard model: the “strong CP problem.” Resolves a major issue with theory of Quantum chromodynamics (QCD).
  - *Naturalness*: misalignment production of observed abundances of dark matter.
  - Largely unexplored parameter space

Technology is emerging to fully search for QCD axion dark matter

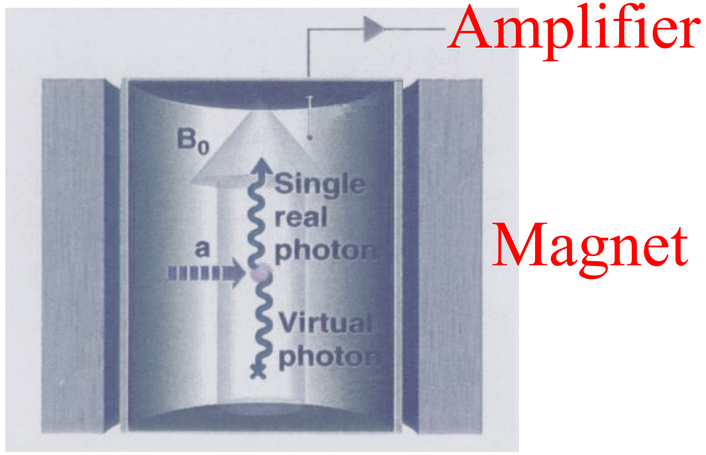
Natural axion dark matter mass space

- It was previously believed that axions below ~300 MHz (~ μeV) mass would be overproduced relative to the observed dark matter abundance.
- In 2018, a theoretical breakthrough (Peter Graham & Alan Guth) showed that pre-inflationary sub-μeV axions can naturally produce the observed dark matter abundance.
- Only a tiny fraction of the natural axion dark matter mass range (from peV to ~10 meV) has been searched to the best DSFZ model
- Many quantum techniques and a community effort is required to fully search the natural axion dark matter mass range

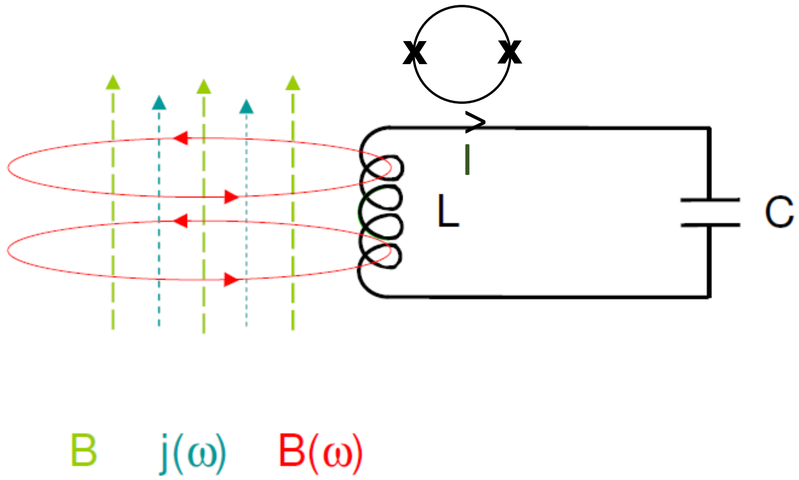


Probing QCD axion through electromagnetism

- Axion field converts to oscillating electromagnetic signal in background DC magnetic field (inverse Primakoff effect)
- Detect using a tunable resonator (an AM radio)



Proposal: Sikivie (1983)
v>300 MHz:
Cavity-based searches
(ADMX, HAYSTAC, CAPP, …)
Tune the resonant frequency with tuning rods & cavity sets



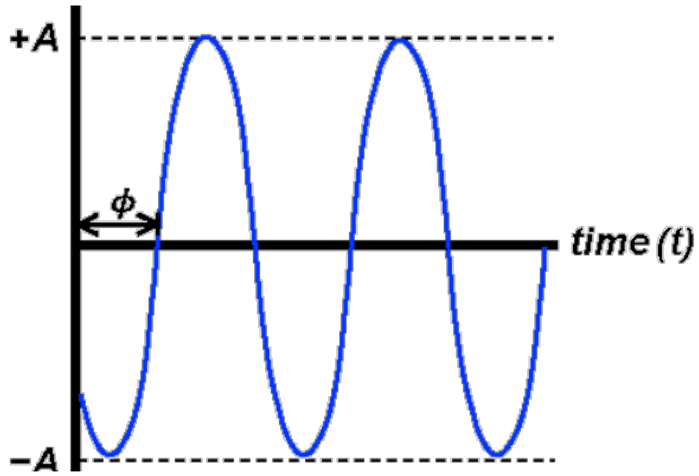
v<300 MHz:
Lumped-element searches
(DM Radio, ABRACADABRA, ADMX-SLIC)
Tune the resonant frequency with variable capacitor or inductor

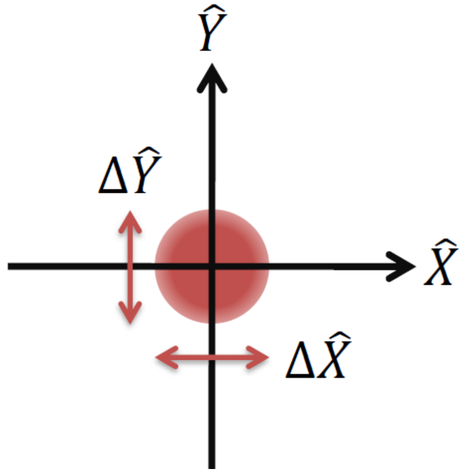
You can't know both amplitude and phase of an electromagnetic signal perfectly

Heisenberg tells us that you can't know the position and momentum of a particle perfectly at the same time:

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$A\cos(\omega t + \phi) = X\cos(\omega t) + Y\sin(\omega t)$$





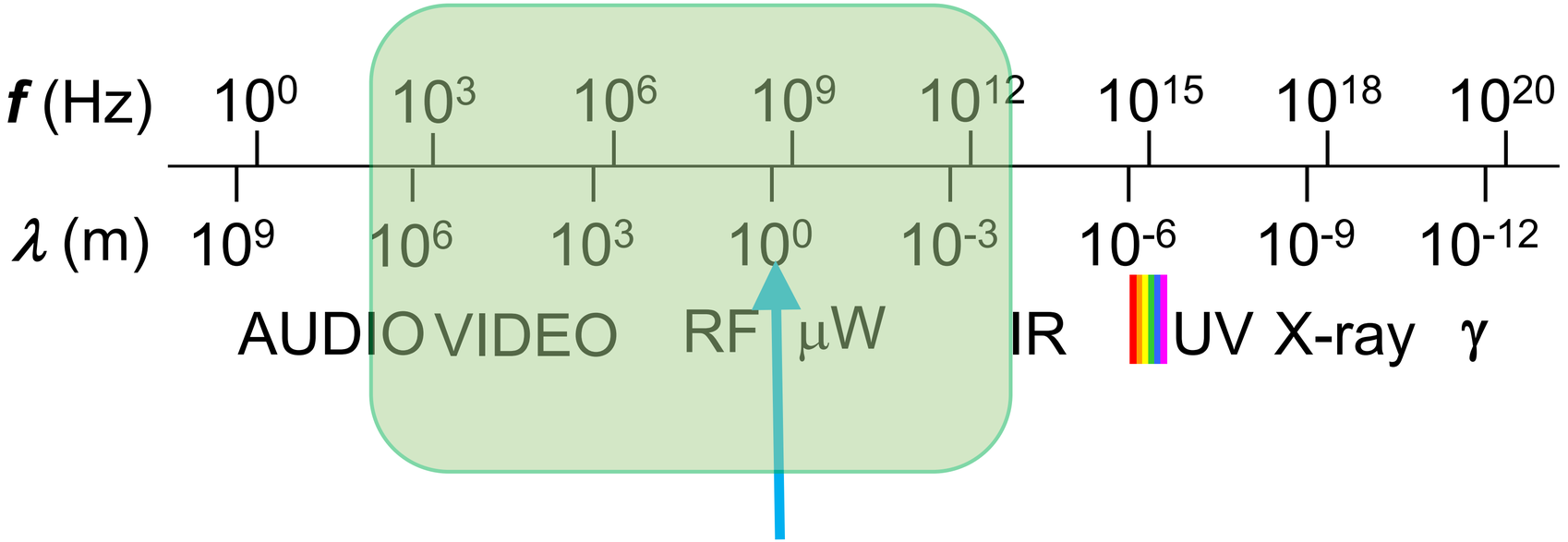
"Vacuum noise" or "zero-point noise"

A "classical" sensor measures both amplitude and phase with equal sensitivity, limited by the Standard Quantum Limit of $\hbar\omega$

What if I don't care about phase???

Axions span two distinct regions of quantum technology:

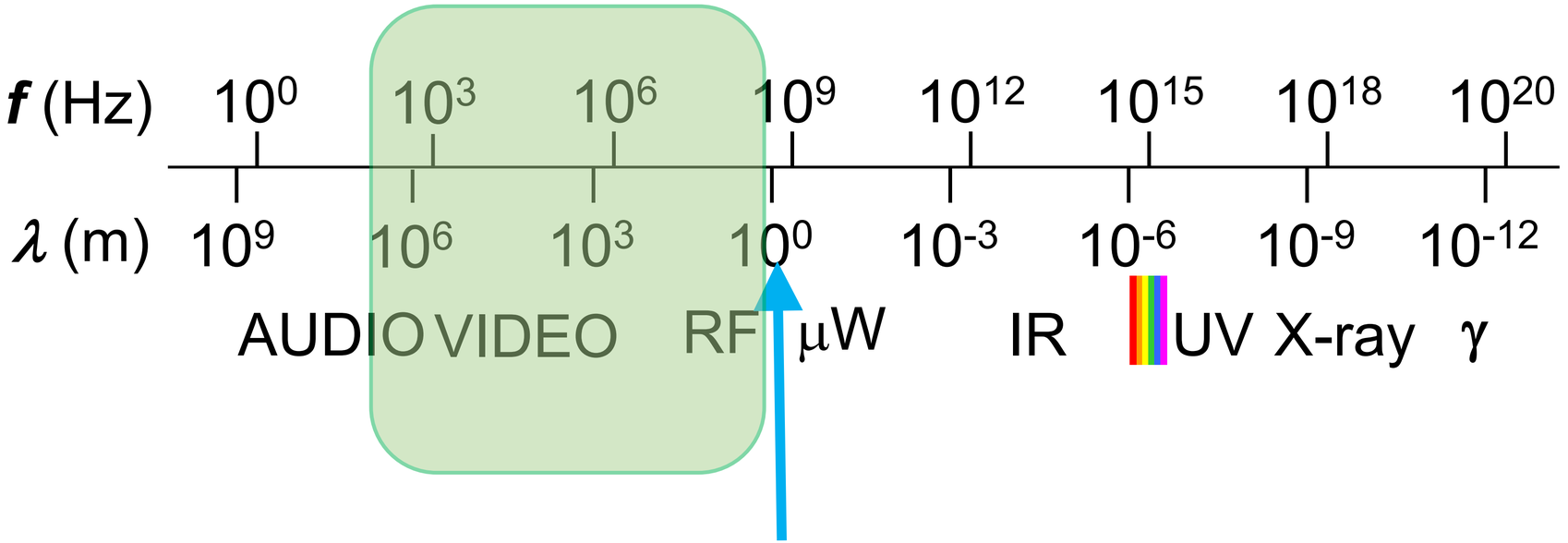
Smaller-than-human and larger-than-human scale



300 MHz ~ 0.015 Kelvin ~ 1 m

300 MHz ~ human scale ~ dilution refrigerator temperature

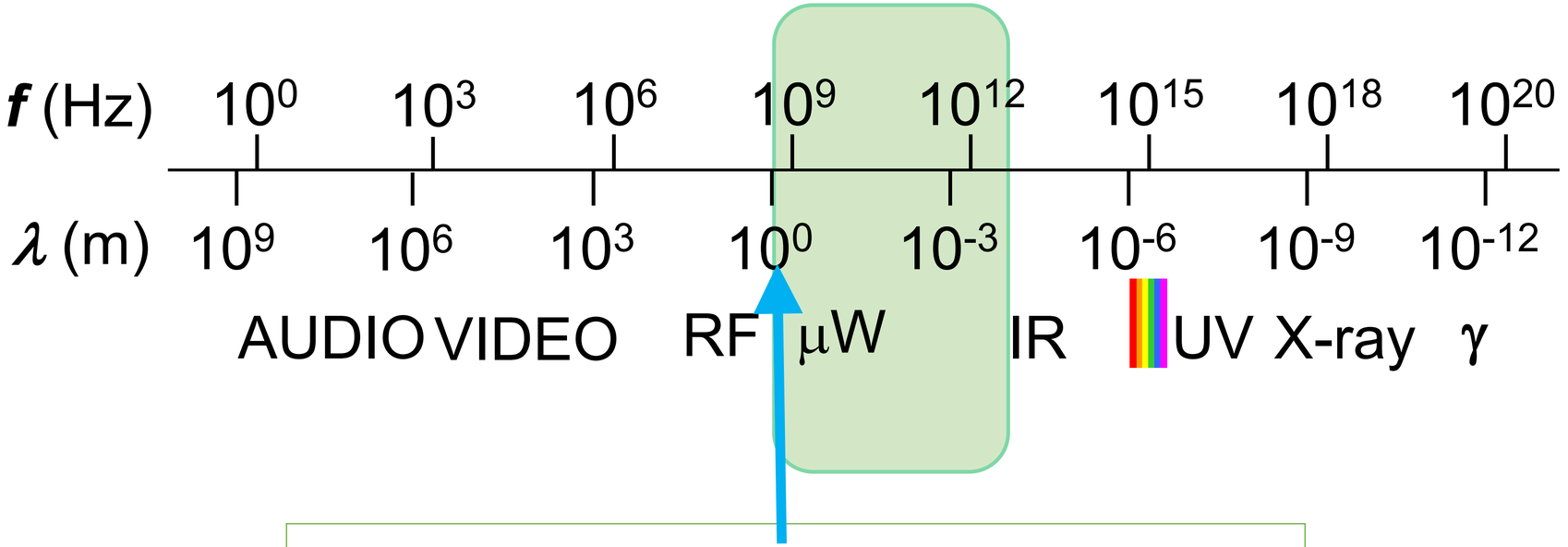
Larger than humans



300 MHz ~ 0.015 Kelvin ~ 1 m

Bottom ~60% of QCD axion band

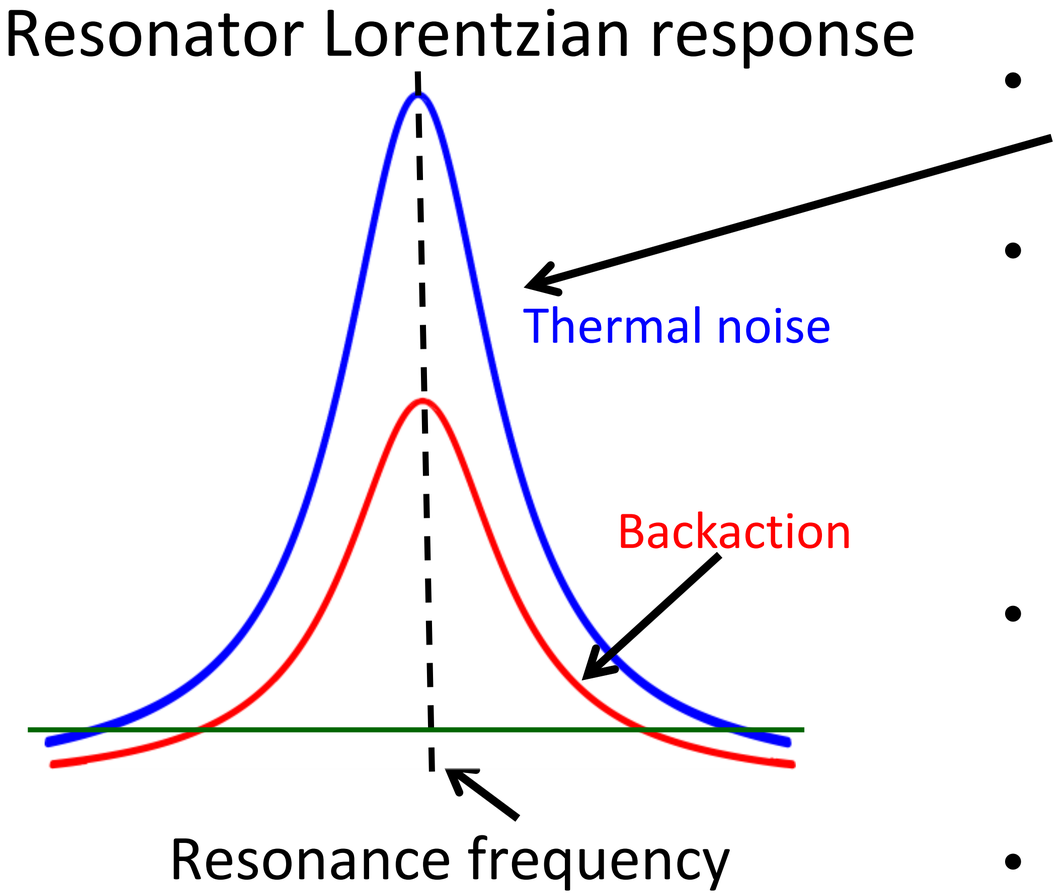
Smaller than humans



300 MHz ~ 0.015 Kelvin ~ 1 m

Top ~40% of QCD axion band

Photon counting is NOT useful when $hf \ll k_B T$



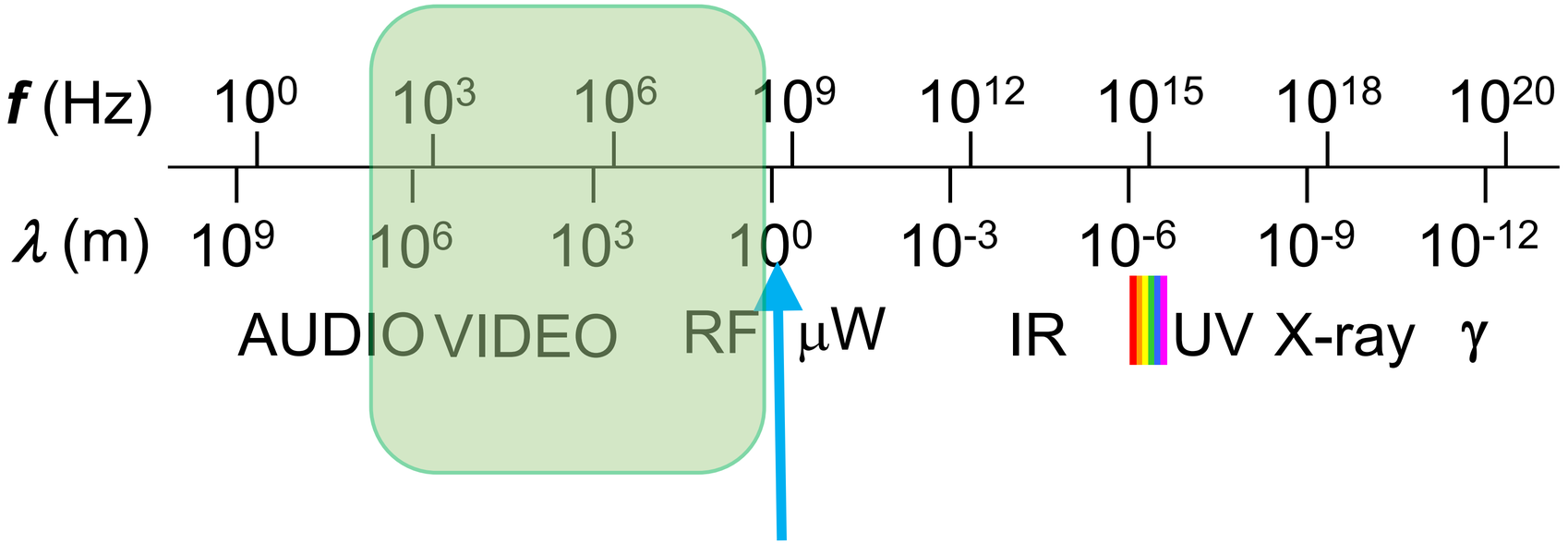
- $\sqrt{N}$ thermal fluctuations in the number of resonator photons
- Example: 10 MHz resonator with Q ~ 10^6. Resonator lifetime ~1 s. SQL is one photon per ~second. Operation at 50 mK:

$$\left.k_B T\right/_{hf} \approx 1000$$

- Every ~ 1 ms, a thermal photon transits (enters or leaves) the resonator. This is the "thermal photon transit time".
- There is no way to tell thermal photons from axions if you don't measure phase!

Photon counting doesn't help if $hf < k_B T$ and you average for more than the thermal photon transit time

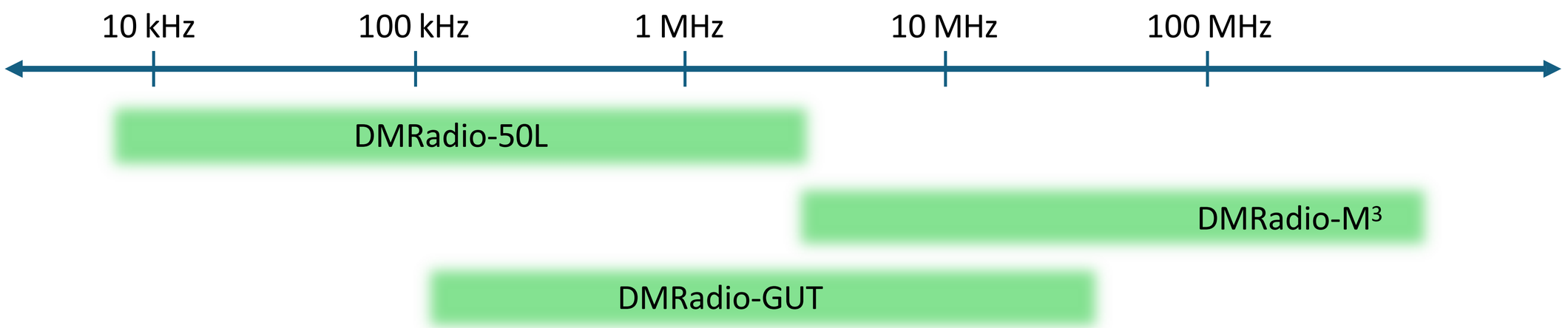
Larger than humans



300 MHz ~ 0.015 Kelvin ~ 1 m

Bottom ~60% of QCD axion band

DMRadio suite of experiments



- Axion wavelength ≫ detector size: **lumped element regime**.
- Large thermal occupation even at cryogenic temperatures.
- DC SQUIDs are “standard” readout technology and will be used in DMRadio-M3.
- DMRadio-50L is a quantum testbed to demonstrate enhancement with quantum sensors
- For DMRadio-GUT, quantum enhancement necessary to meet science goals.

DMRadio Collaboration

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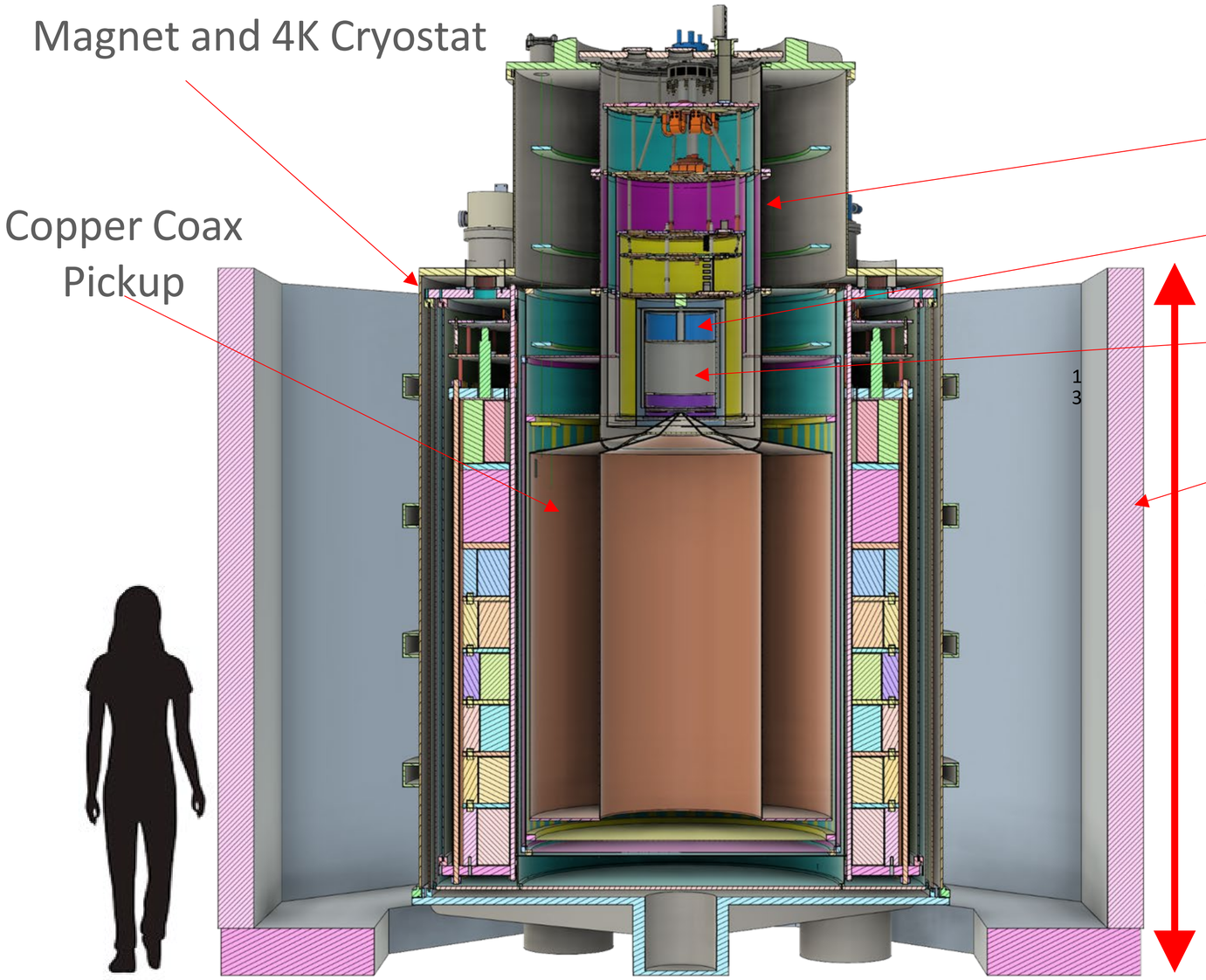
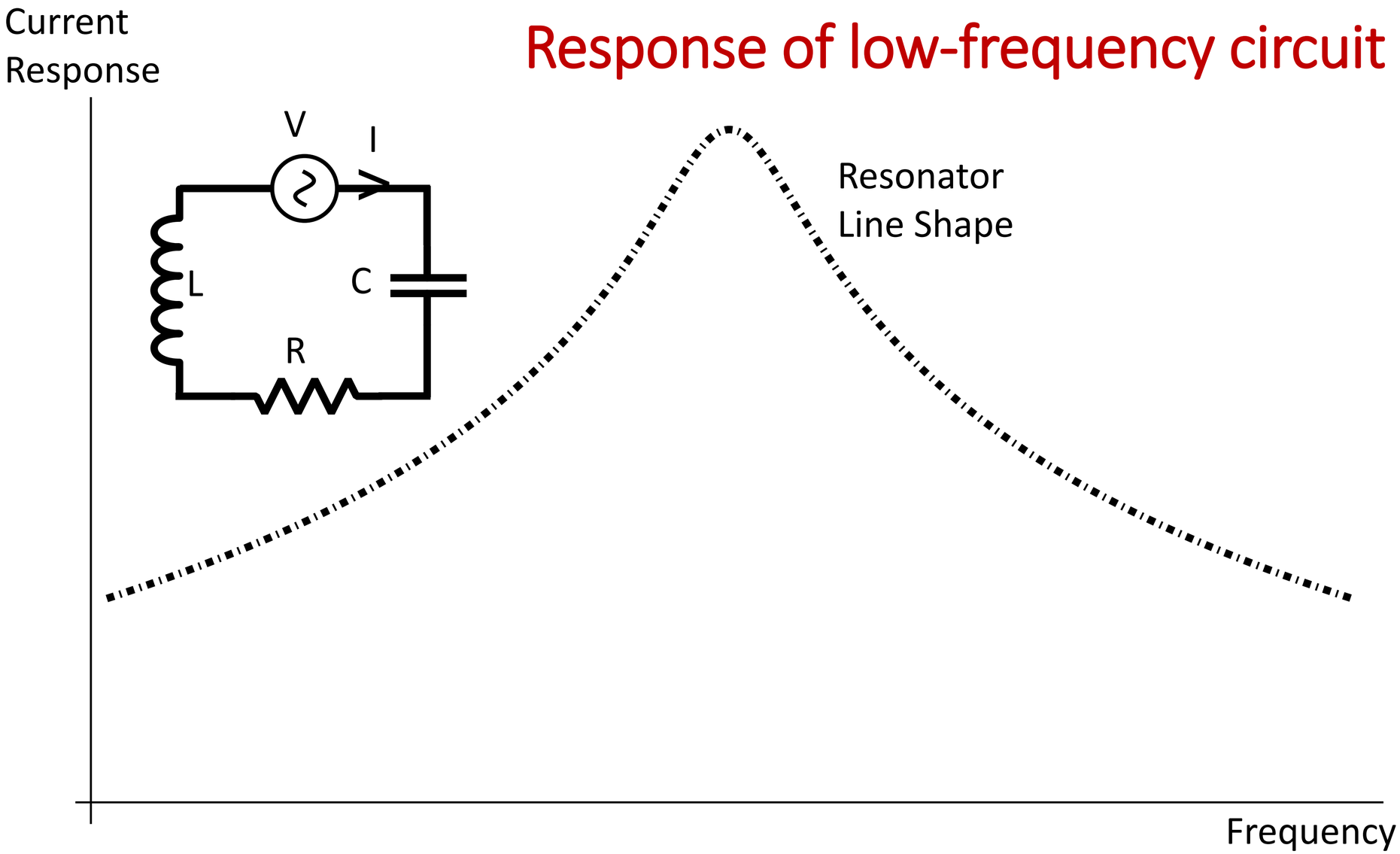
DMRadio Meter Cubed

Part of the Dark Matter New Initiatives Program

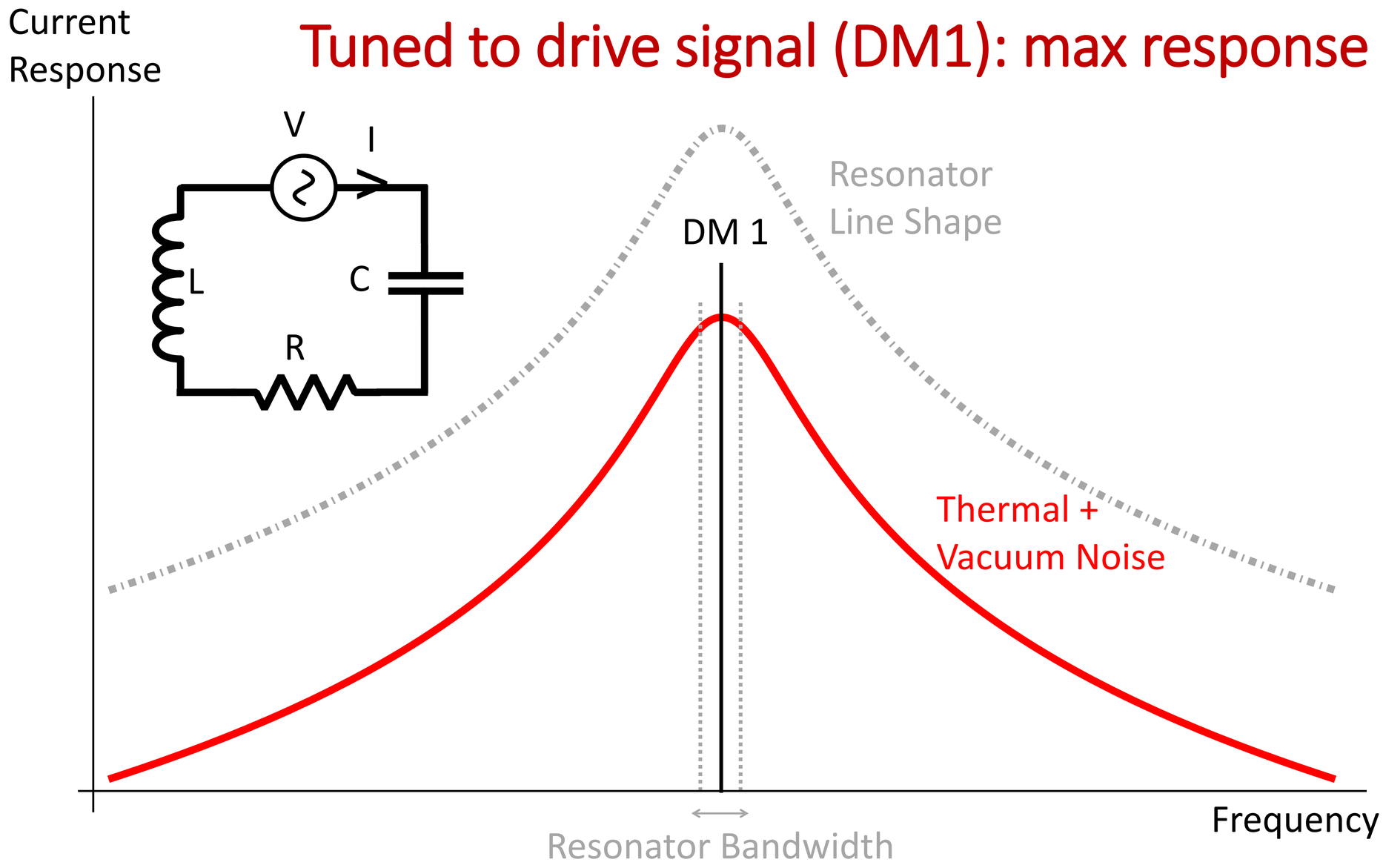


- Phys Rev. D, 106, 103008 (2022)
- High-frequency modeling, arXiv: 2302.14084
- Goal: DFSZ sensitivity 30-200 MHz

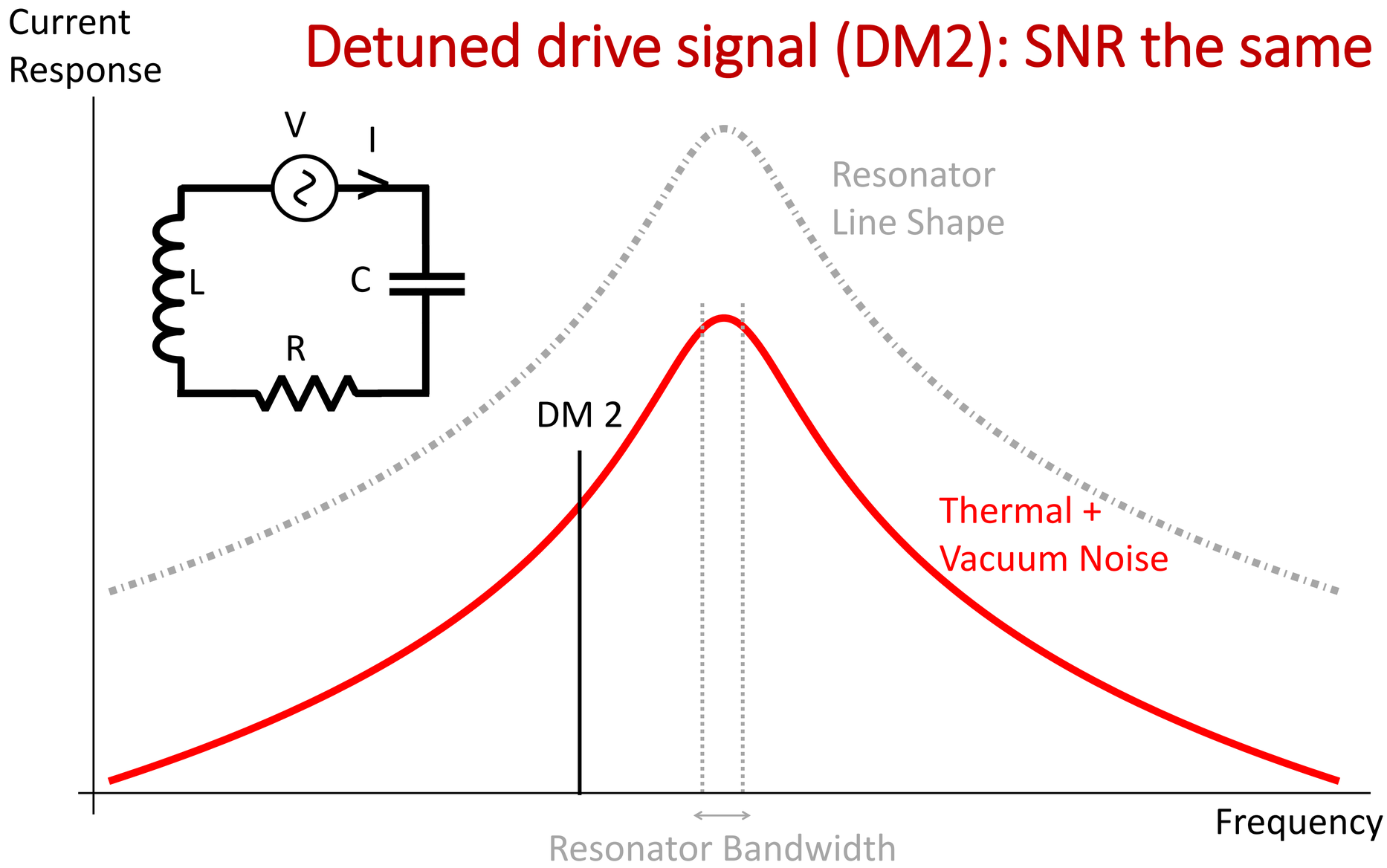
Response of low-frequency circuit



Tuned to drive signal (DM1): max response

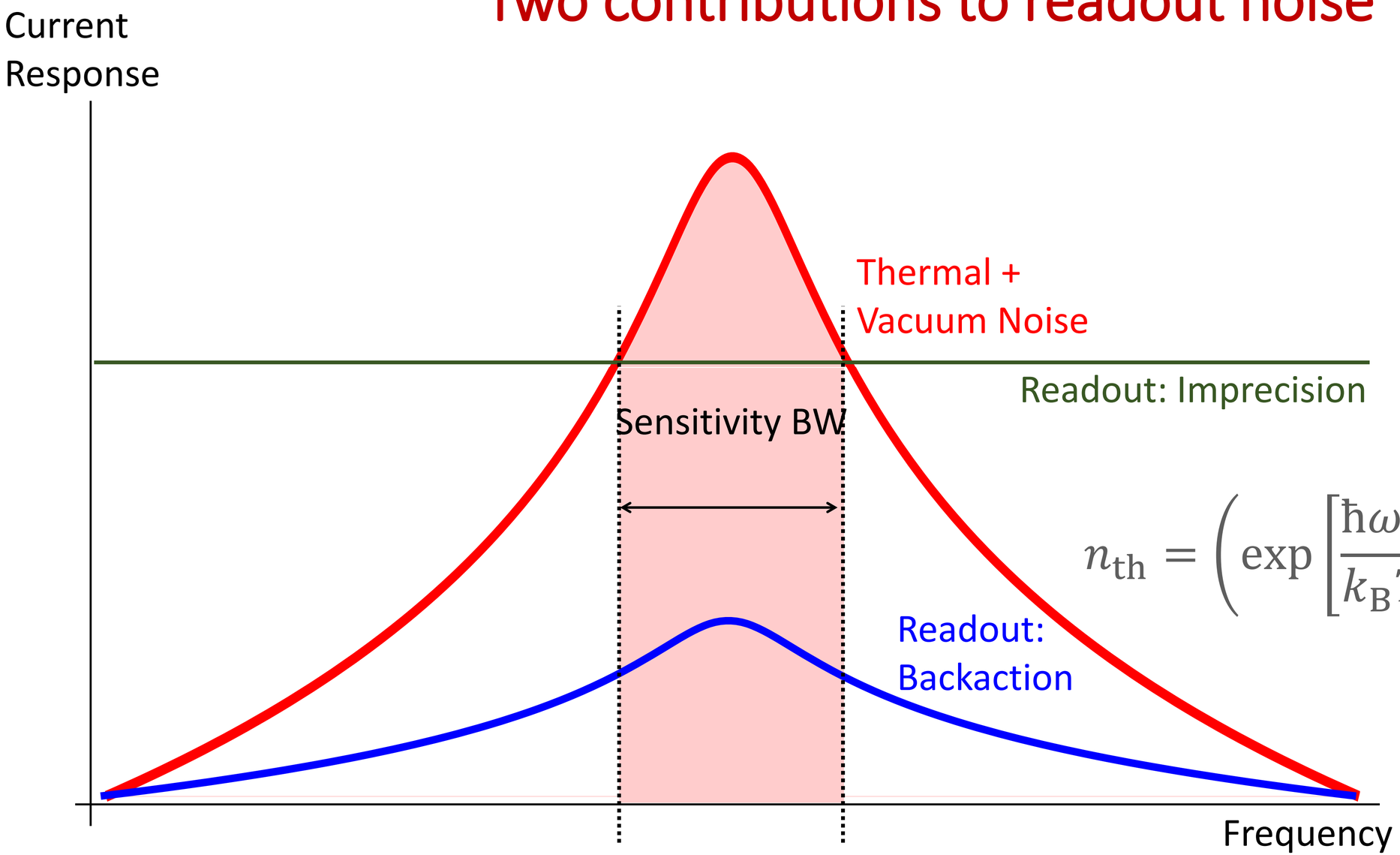


Detuned drive signal (DM2): SNR the same



- SNR not degraded when readout subdominant to thermal noise

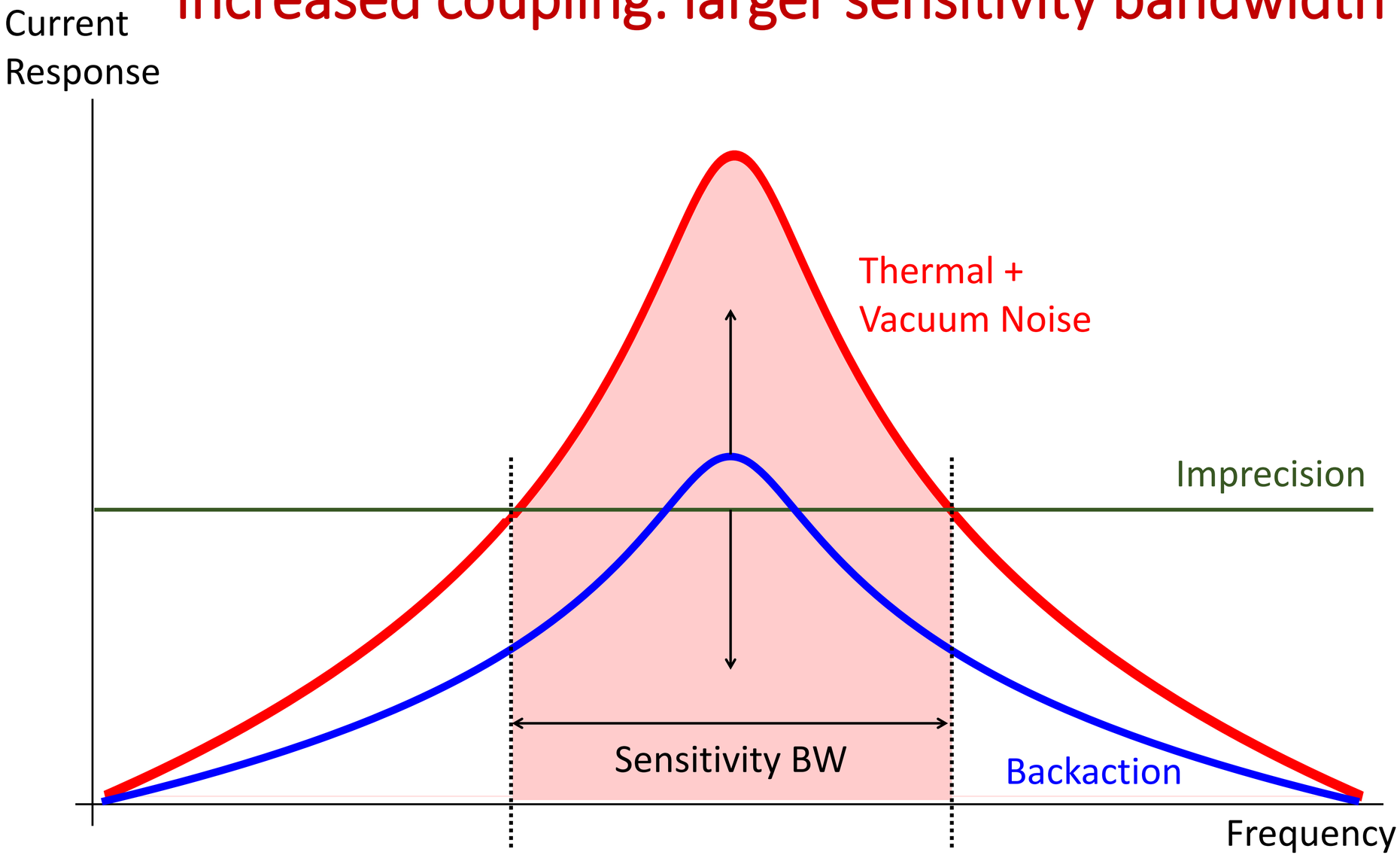
Two contributions to readout noise



$$n_{\mathrm{th}} = \left(\exp\left[\frac{\hbar \omega_a}{k_{\mathrm{B}} T} \right] - 1 \right)^{-1}$$

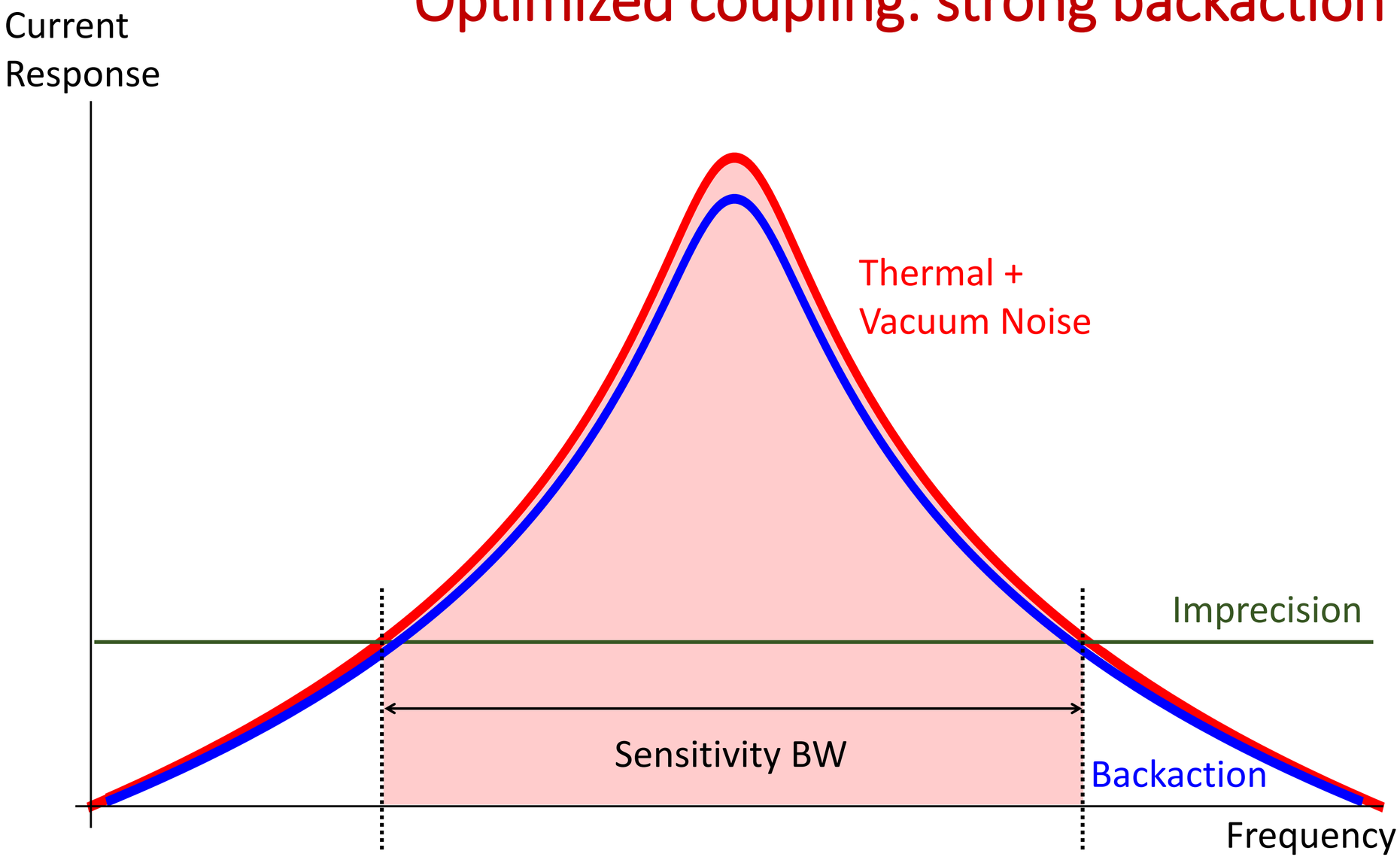
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2} [1/2 + n_{\mathrm{th}} + n_{\mathrm{BA}}] + S_{\mathrm{IMP}}(\omega)$$

Increased coupling: larger sensitivity bandwidth



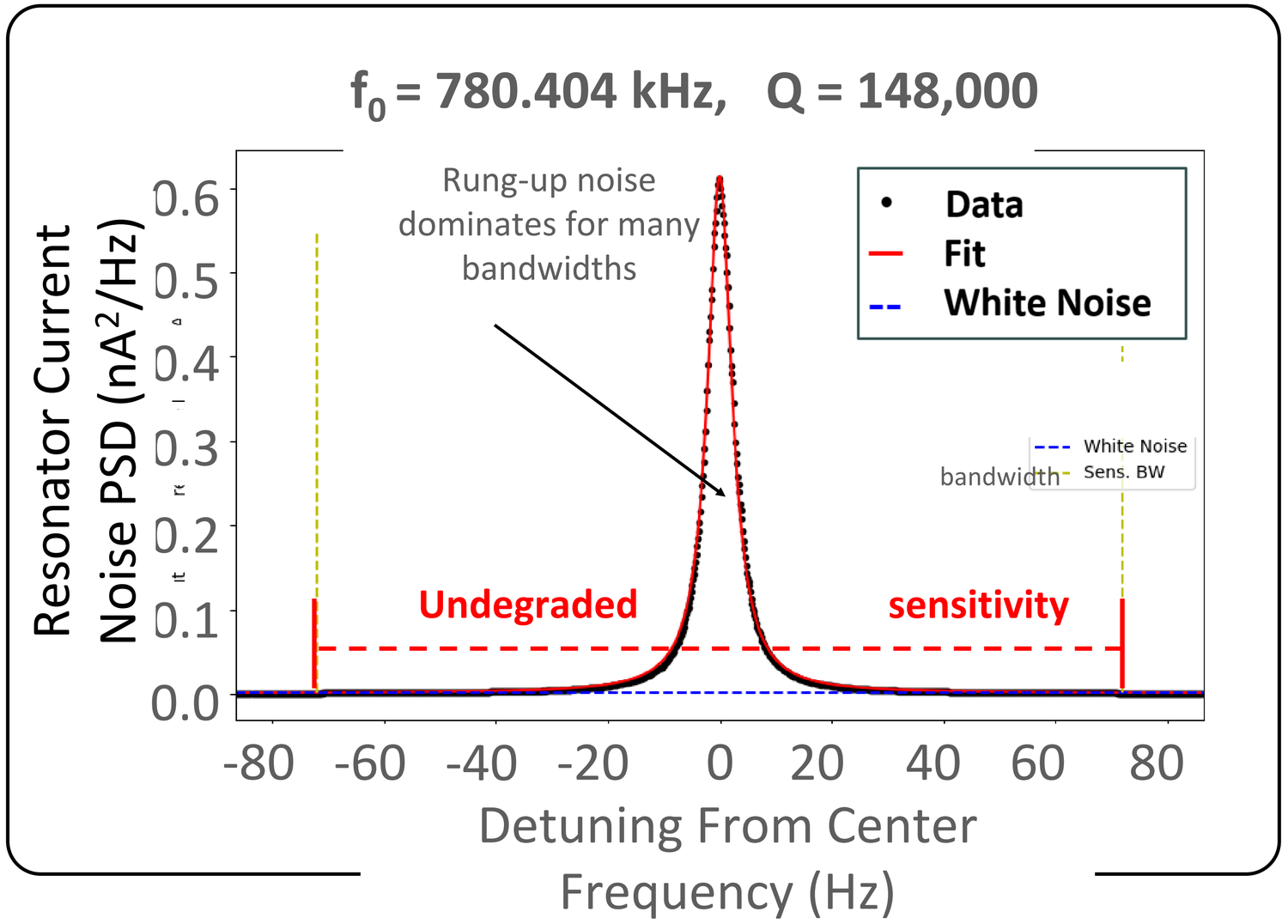
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}[1/2 + n_{\mathrm{th}} + n_{BA}] + S_{\mathrm{IMP}}(\omega)$$

Optimized coupling: strong backaction



$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}[1/2 + n_{\mathrm{th}} + n_{BA}] + S_{\mathrm{IMP}}(\omega)$$

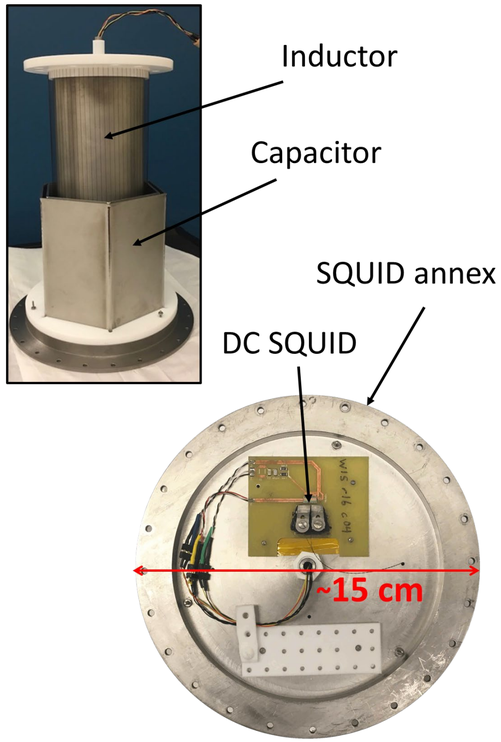
Example of optimizing noise match for bandwidth with a dc SQUID



Resonator bandwidth: ~5 Hz

Sensitivity bandwidth: ~150 Hz

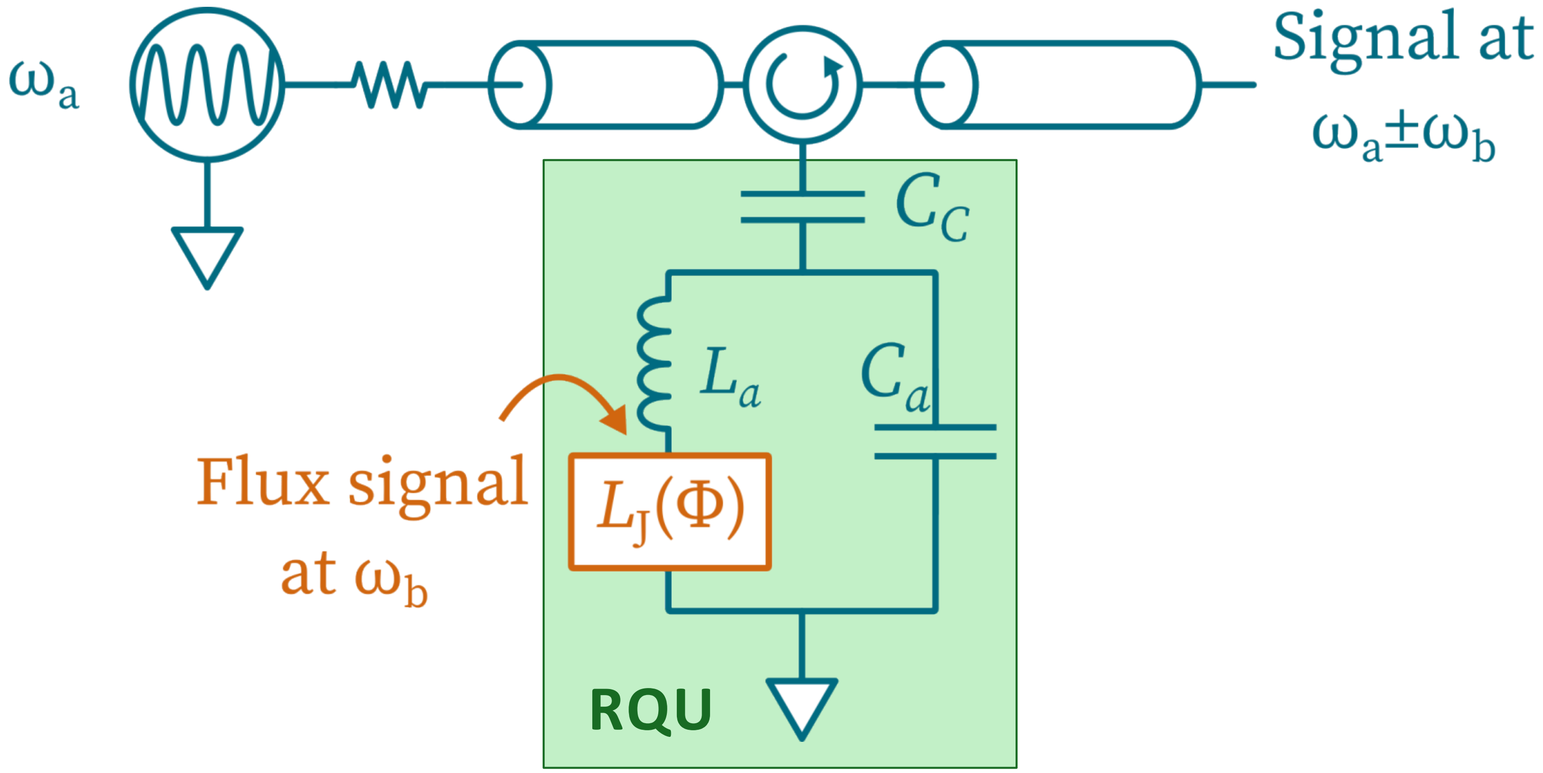
DMRadio Pathfinder

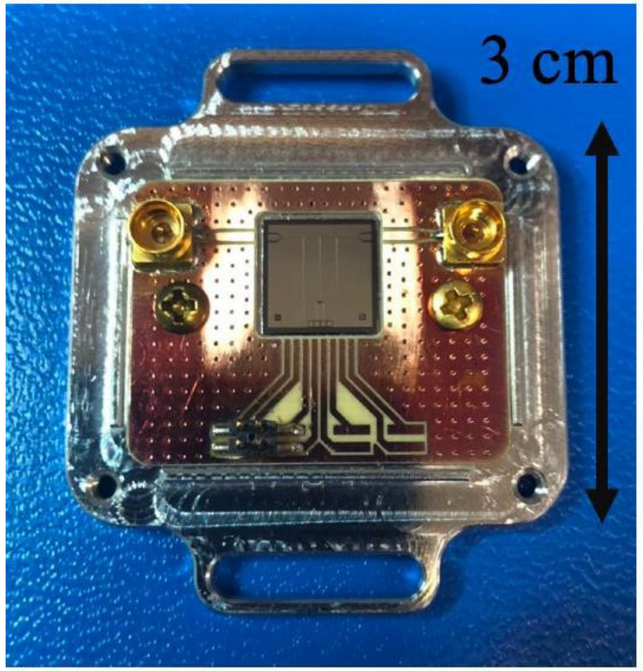


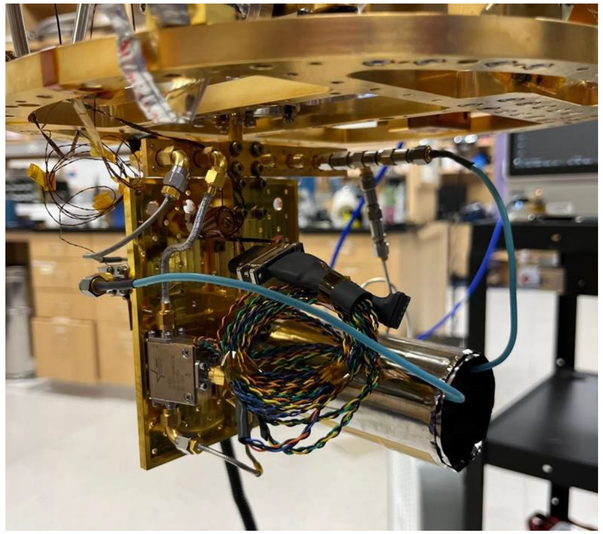
With optimized noise match, sensitivity bandwidth 30x larger than resonator bandwidth, with negligible degradation on resonance

Radio-frequency Quantum Upconverter (RQU) circuit model

- Tunable inductance modifies electrical length of GHz resonator.
- Three-wave mixing upconverts signal mode to sidebands around microwave drive tone.



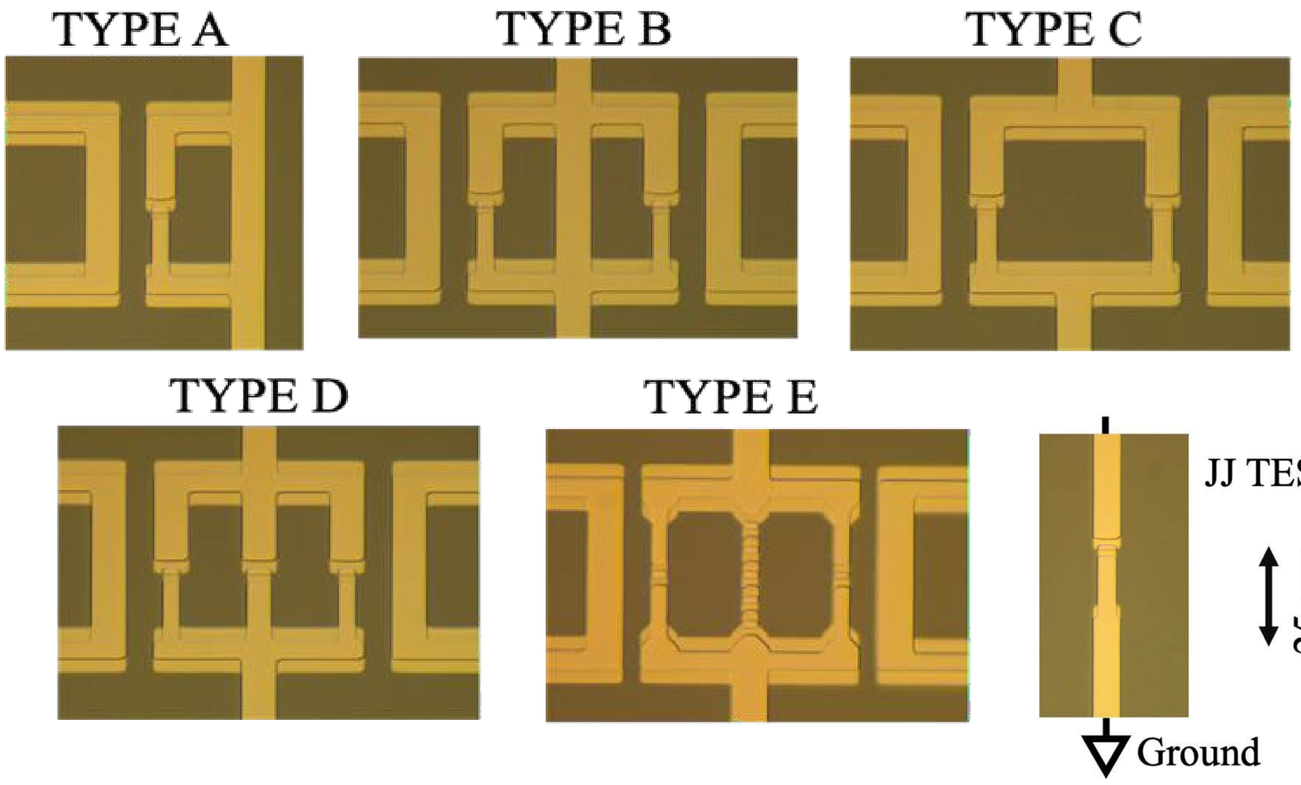




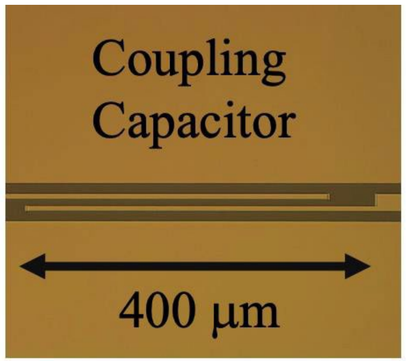
RQU fabrication

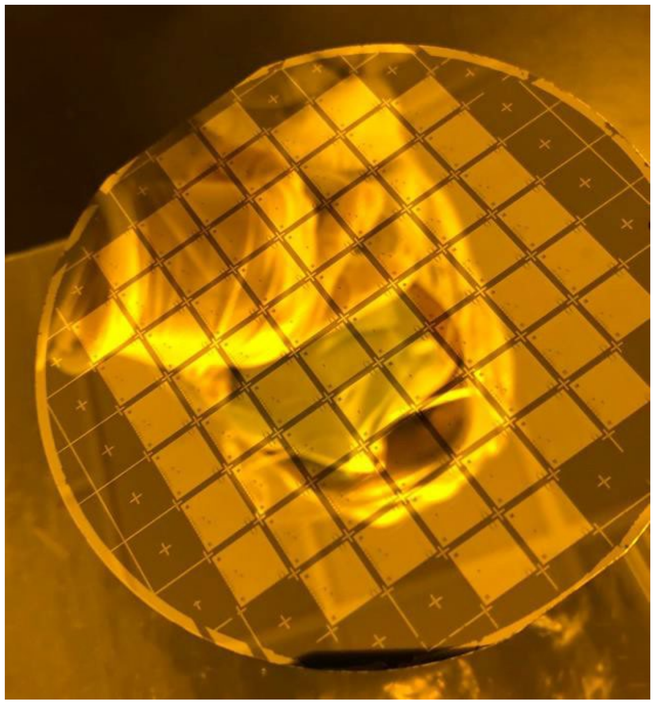
- Fab process is fast and flexible, enabling a range of designs.

Tunable inductance design



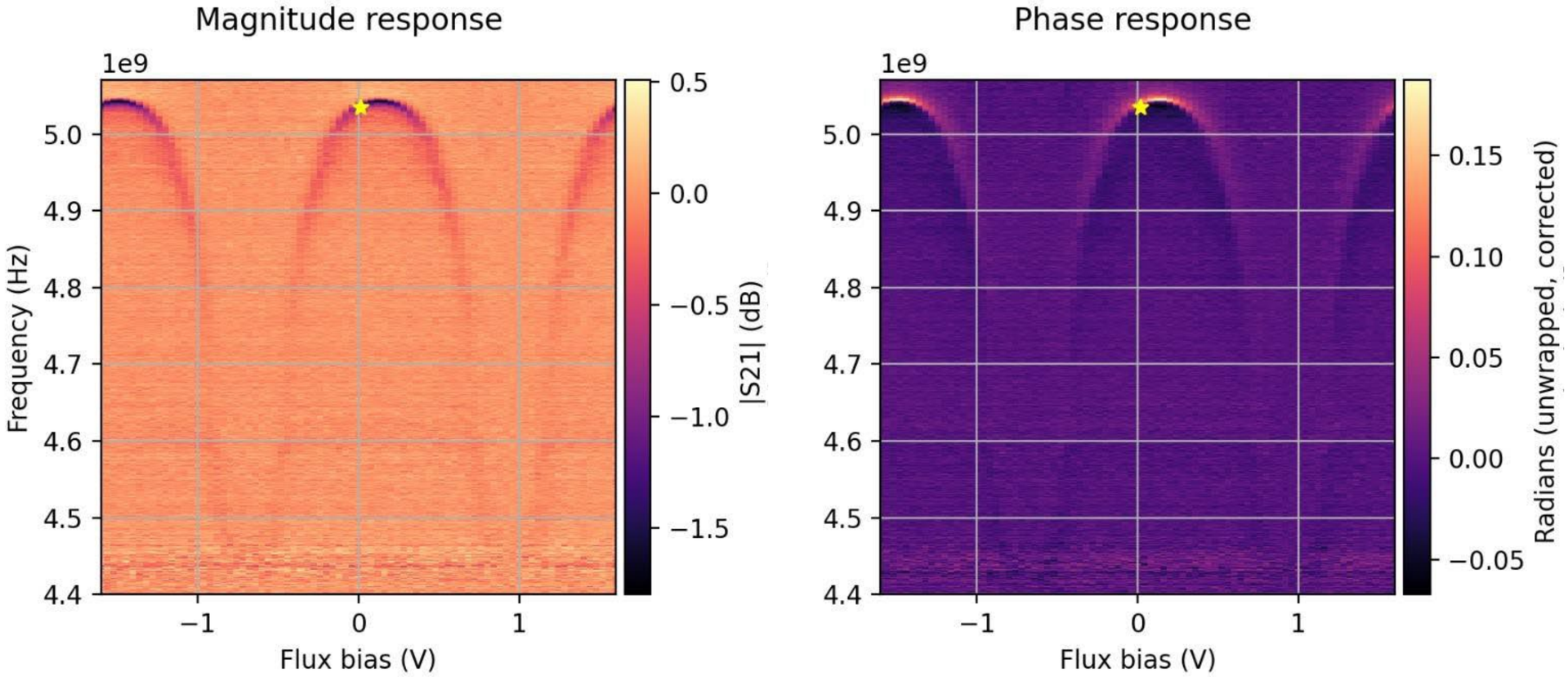
Microwave components



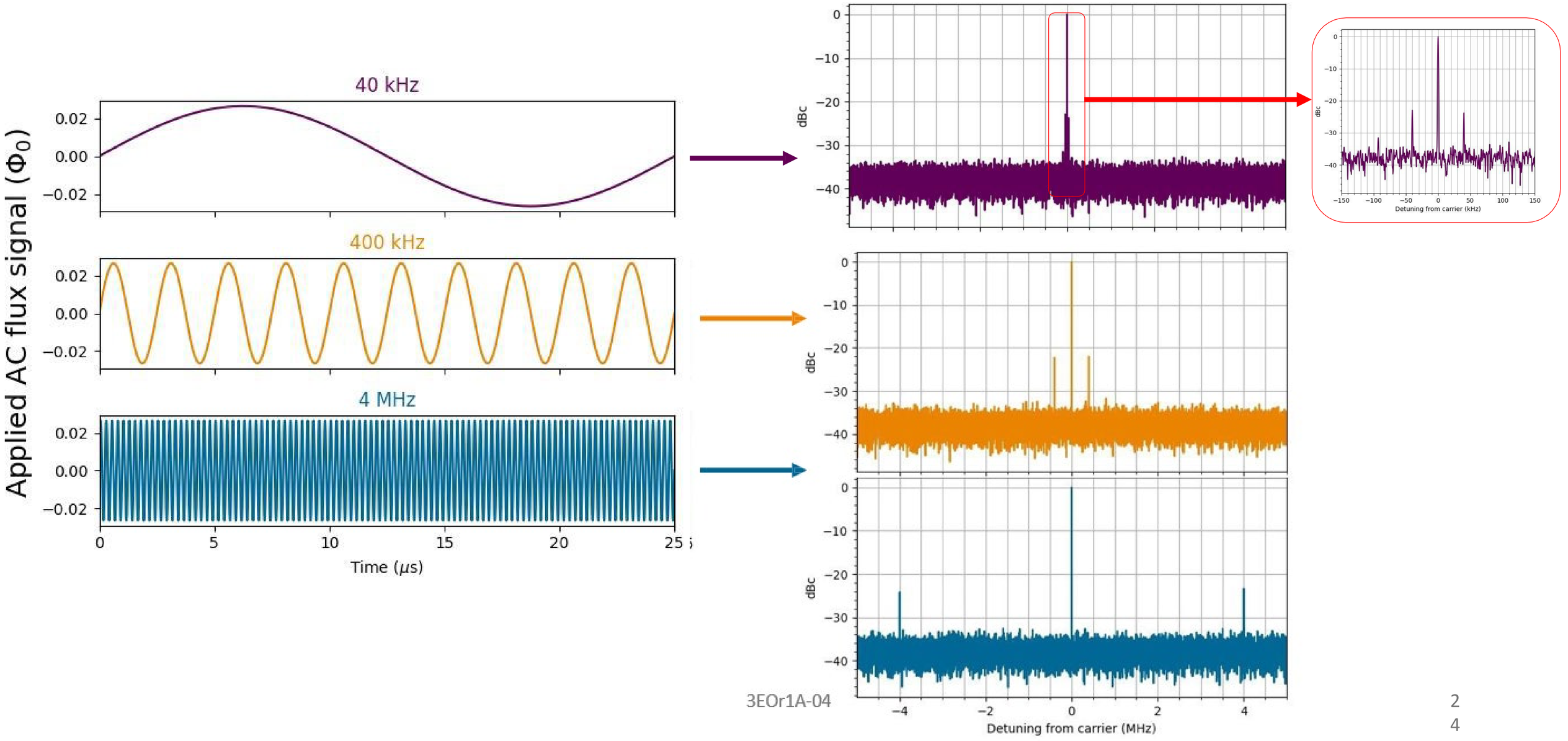


RQU operating point

- Type D (3JJ) devices tuning of ~600MHz with applied DC flux.
- Microwave resonator centered in 4.5-5GHz, in C-Band frequency.

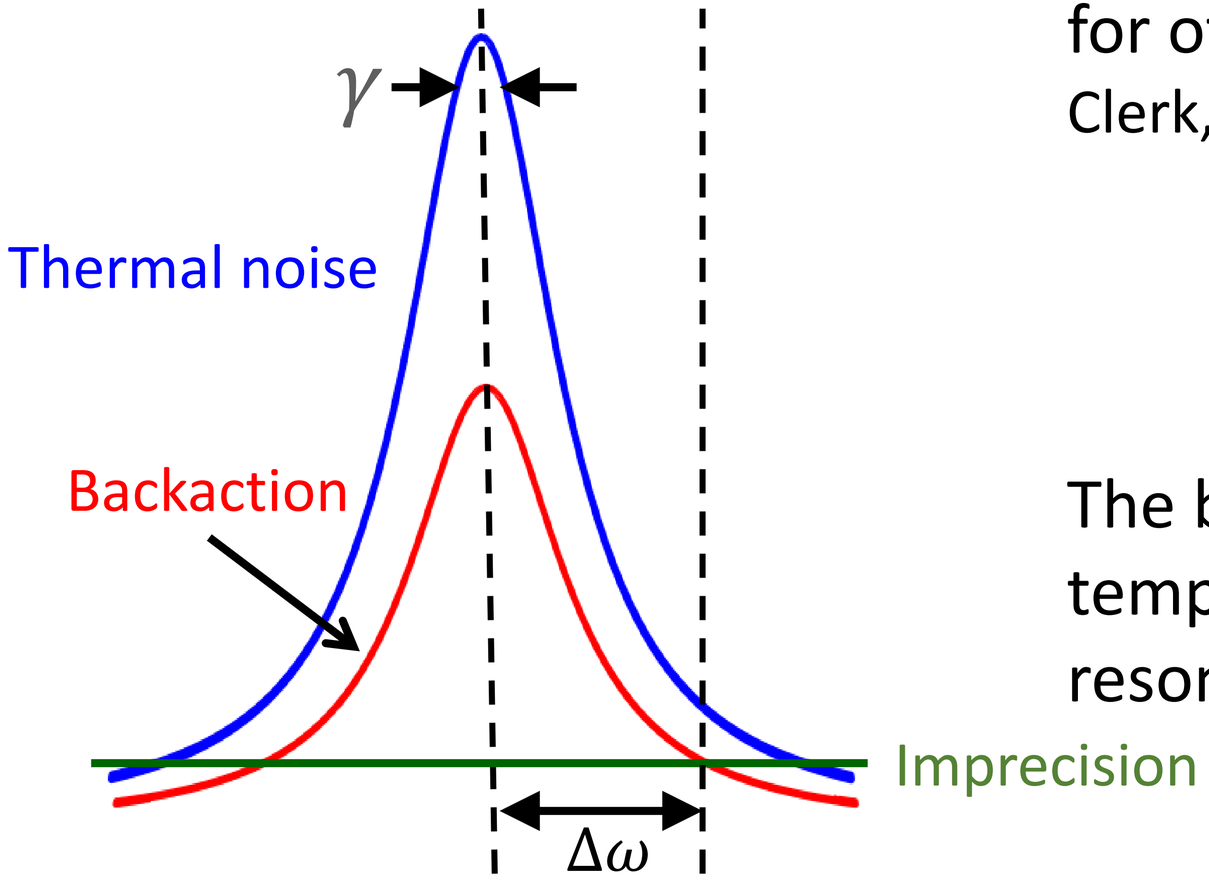


Frequency upconversion



Standard quantum limit off visibility bandwidth in a thermal state

A linear amplifier operated at the SQL with no imprecision-backaction correlations ($S_{IV} = 0$)



When $\Delta\omega \gg \gamma$, the standard quantum limit for off-resonance noise temperature is (A. Clerk, RMP **82**, 1155 (2010)

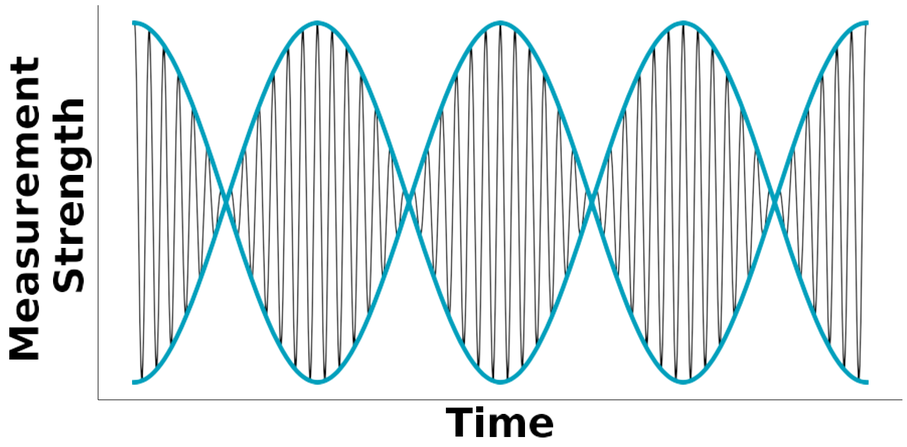
$$kT_N = \hbar\omega\left(n_{therm} + 1 + \frac{\Delta\omega}{\gamma}\right)$$

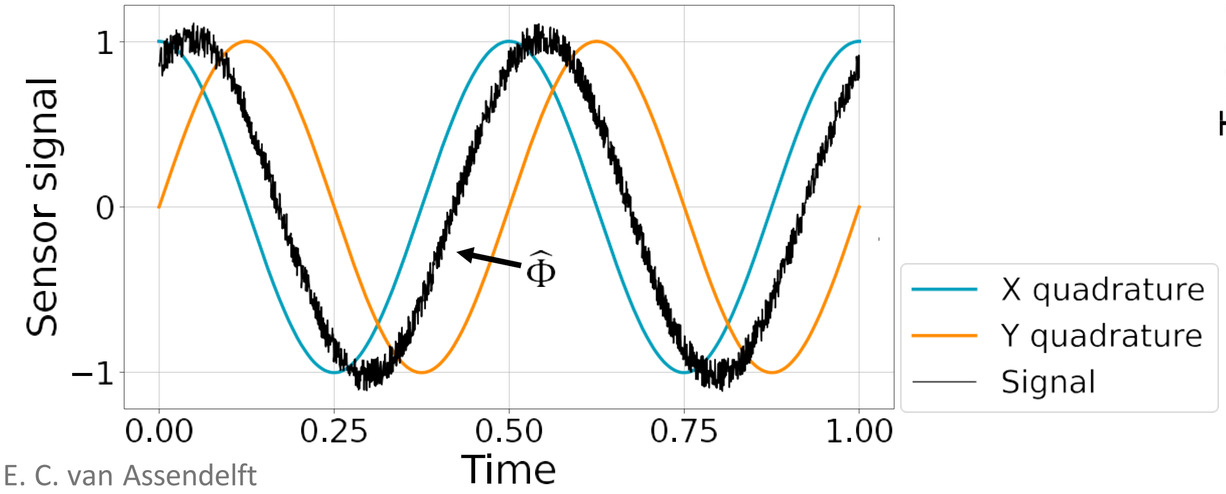
The bandwidth at which the noise temperature is degraded by 2 from the on-resonance value at SQL is

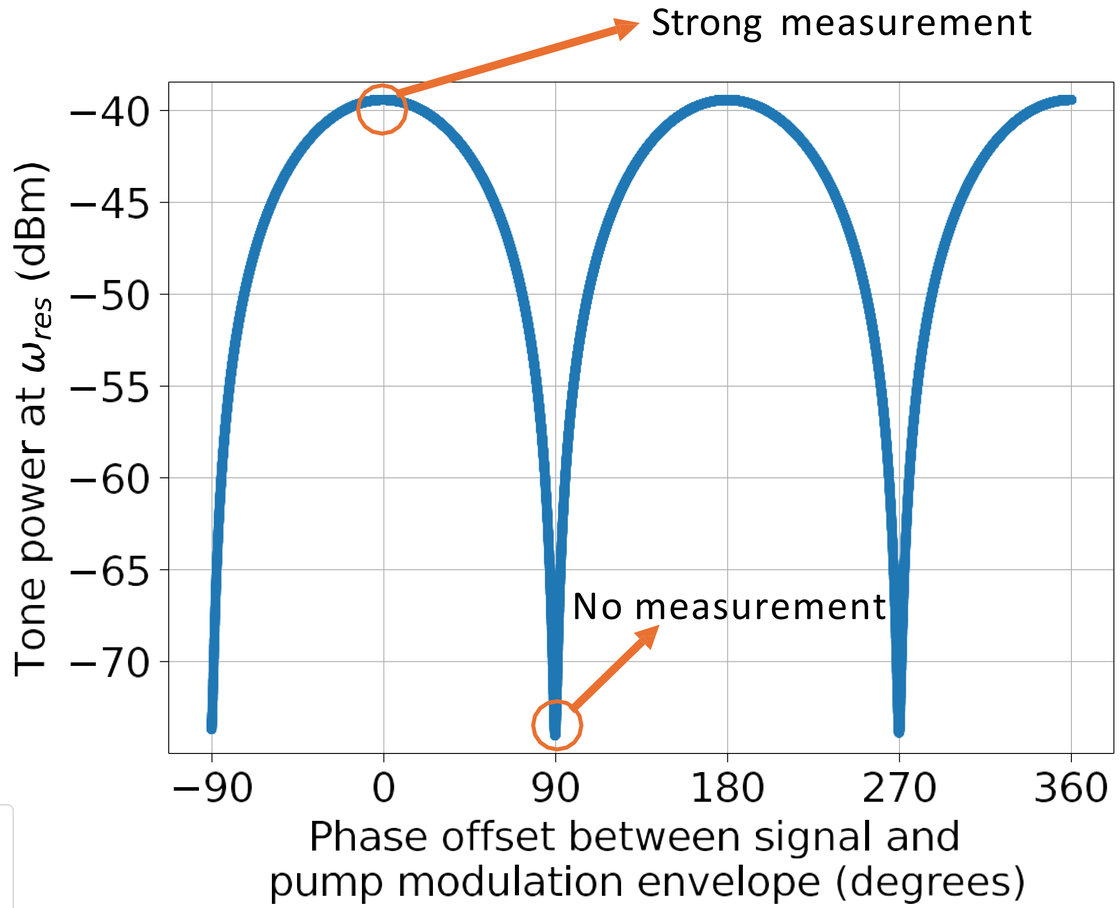
$$\Delta\omega_{SQL} = \gamma(n_{therm} + 1)$$

Demonstration of Phase-Sensitive Gain

An amplitude-modulated readout with an envelope that matches the MHz flux signal selectively amplifies one quadrature.



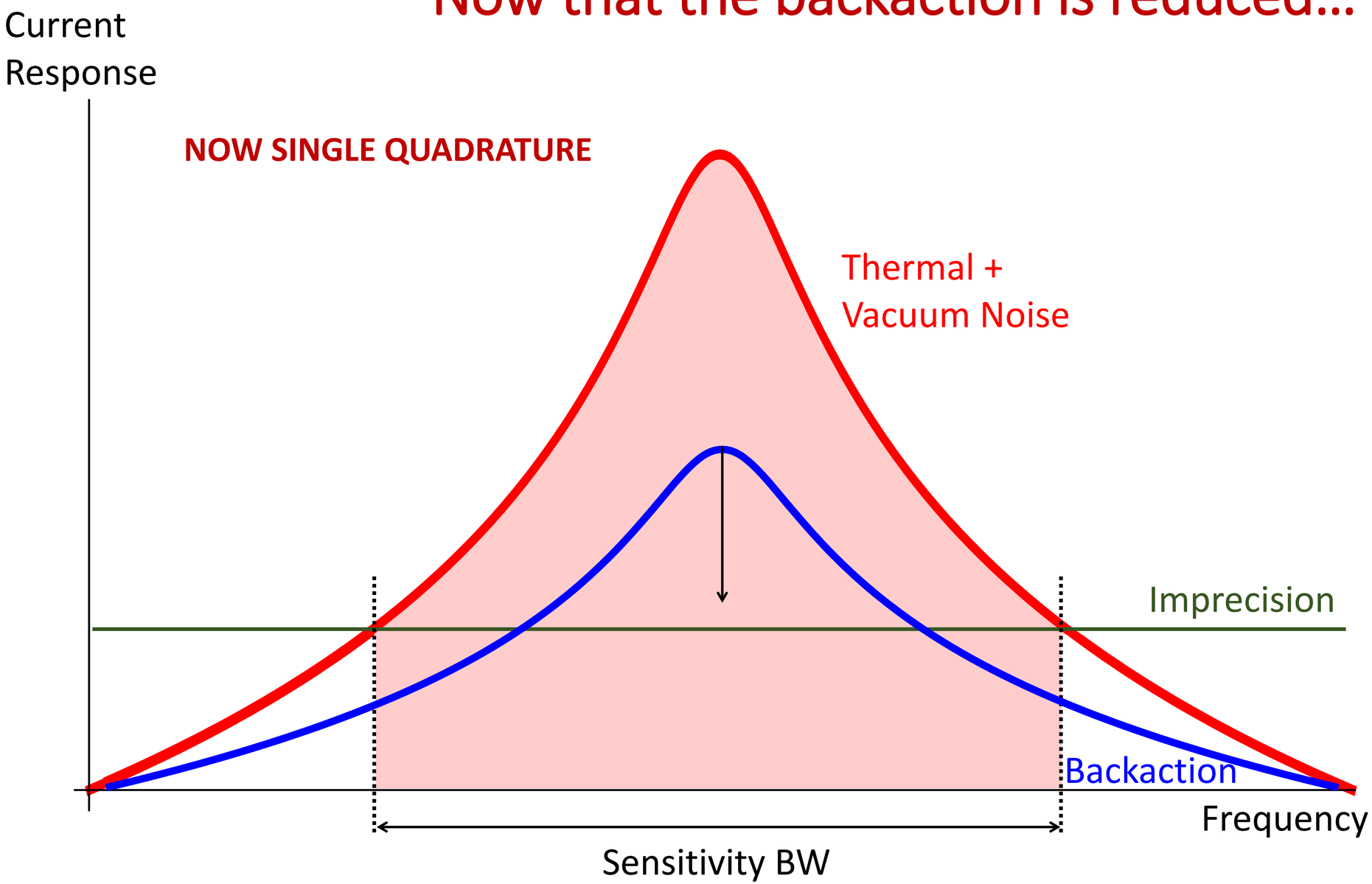




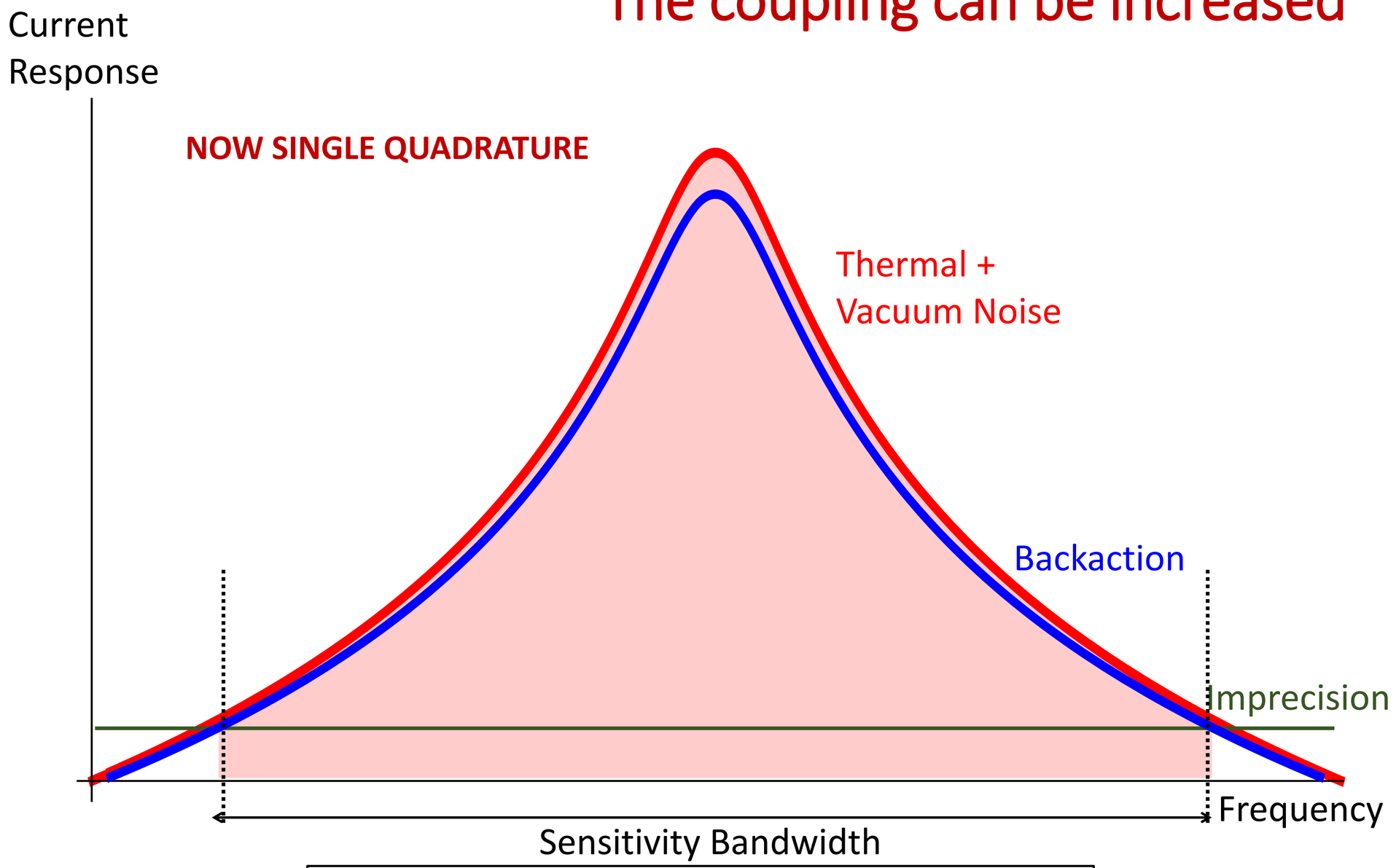
>30 dB Extinction Ratio

E. C. van Assendelft

Now that the backaction is reduced…

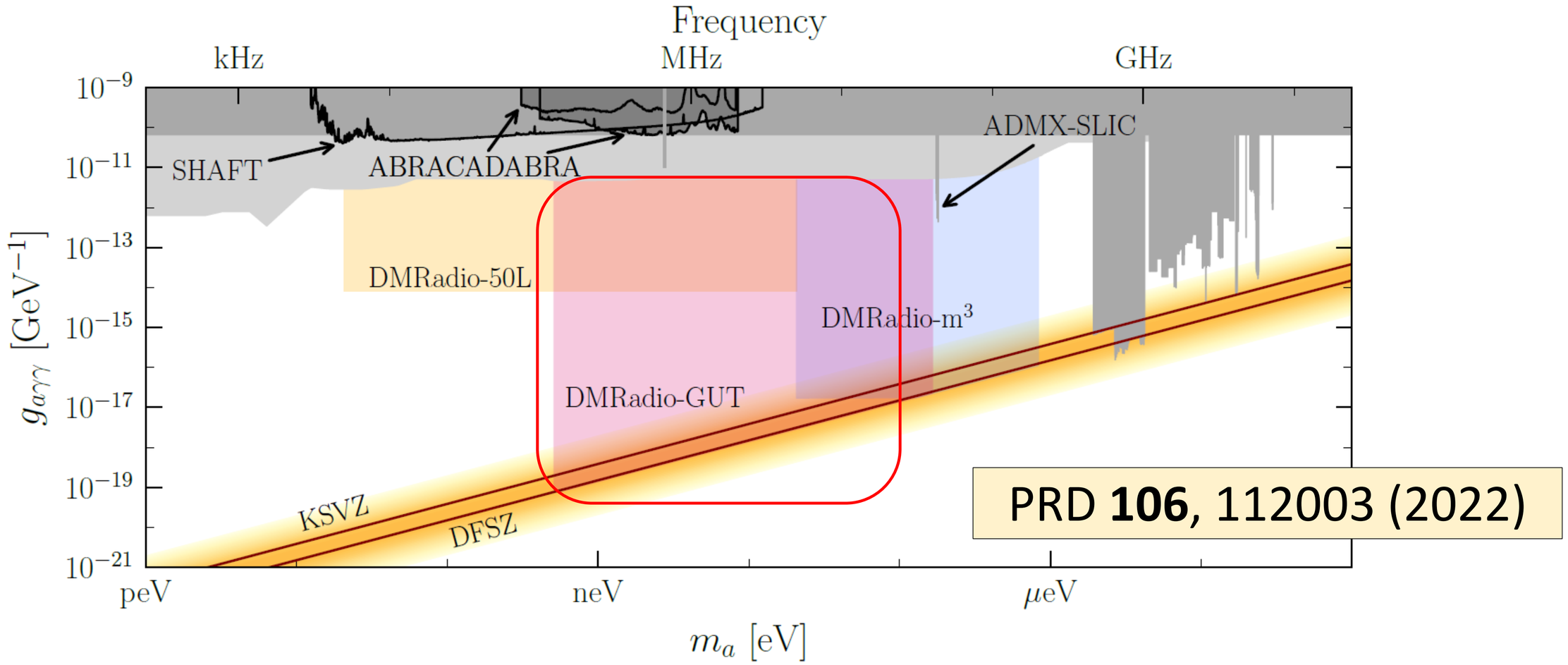


The coupling can be increased



Sensitivity BW can be greatly increased

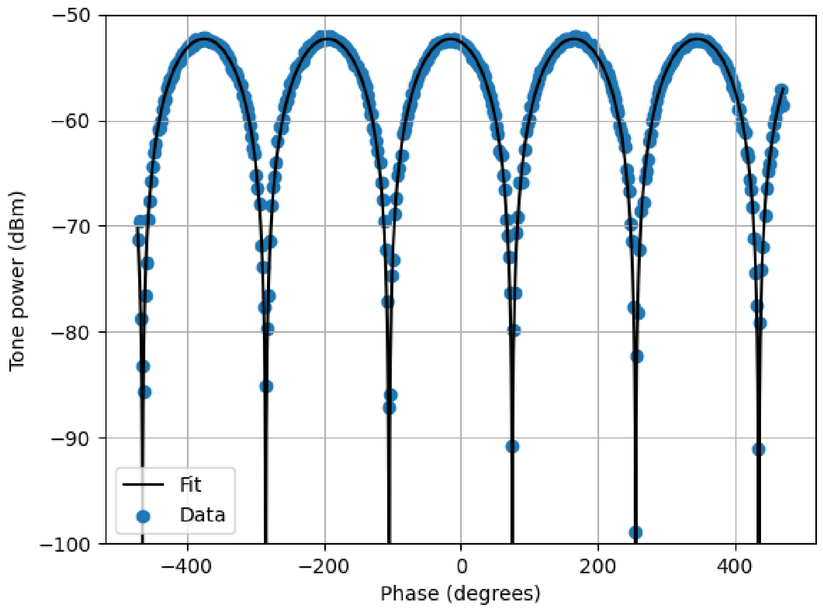
DMRadio-GUT: ambitious, long-term search

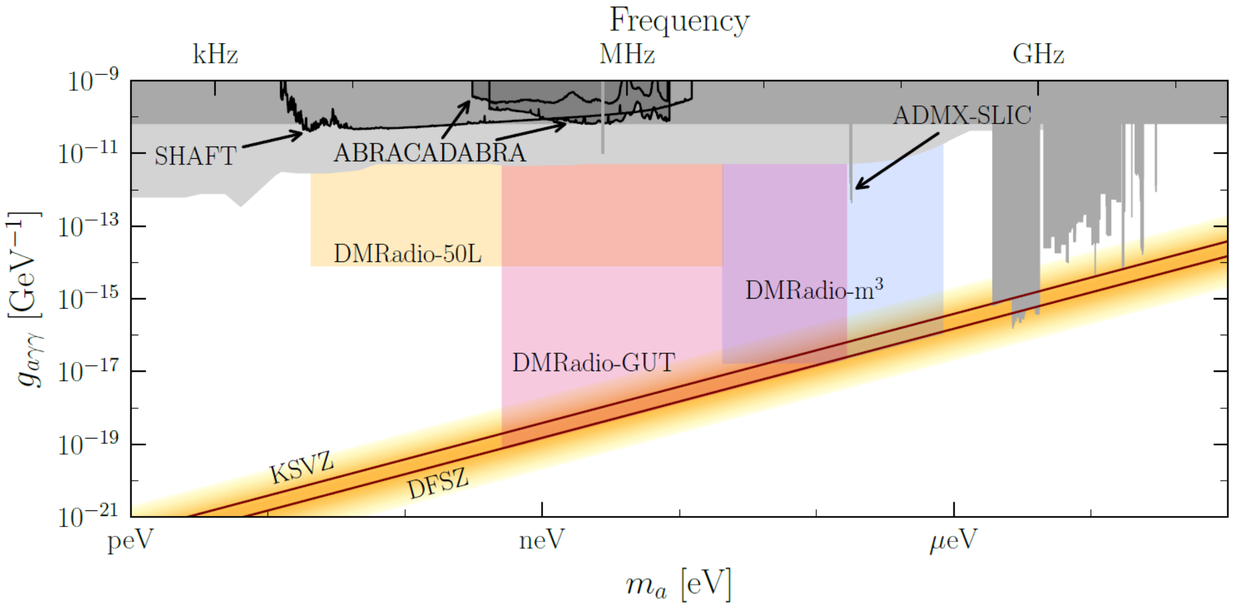


PRD **106**, 112003 (2022)

- Sensitivity to axion PQ scales near GUT (~1 neV)
- Requires evasion of the Standard Quantum Limit

Conclusion





The implementation of full SQL evasion will open a door for the first time to *electromagnetic* measurement of QCD axion masses at the GUT scale