Quantum Sensing of Low-Frequency Electromagnetic Signals

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US QIS Summer School
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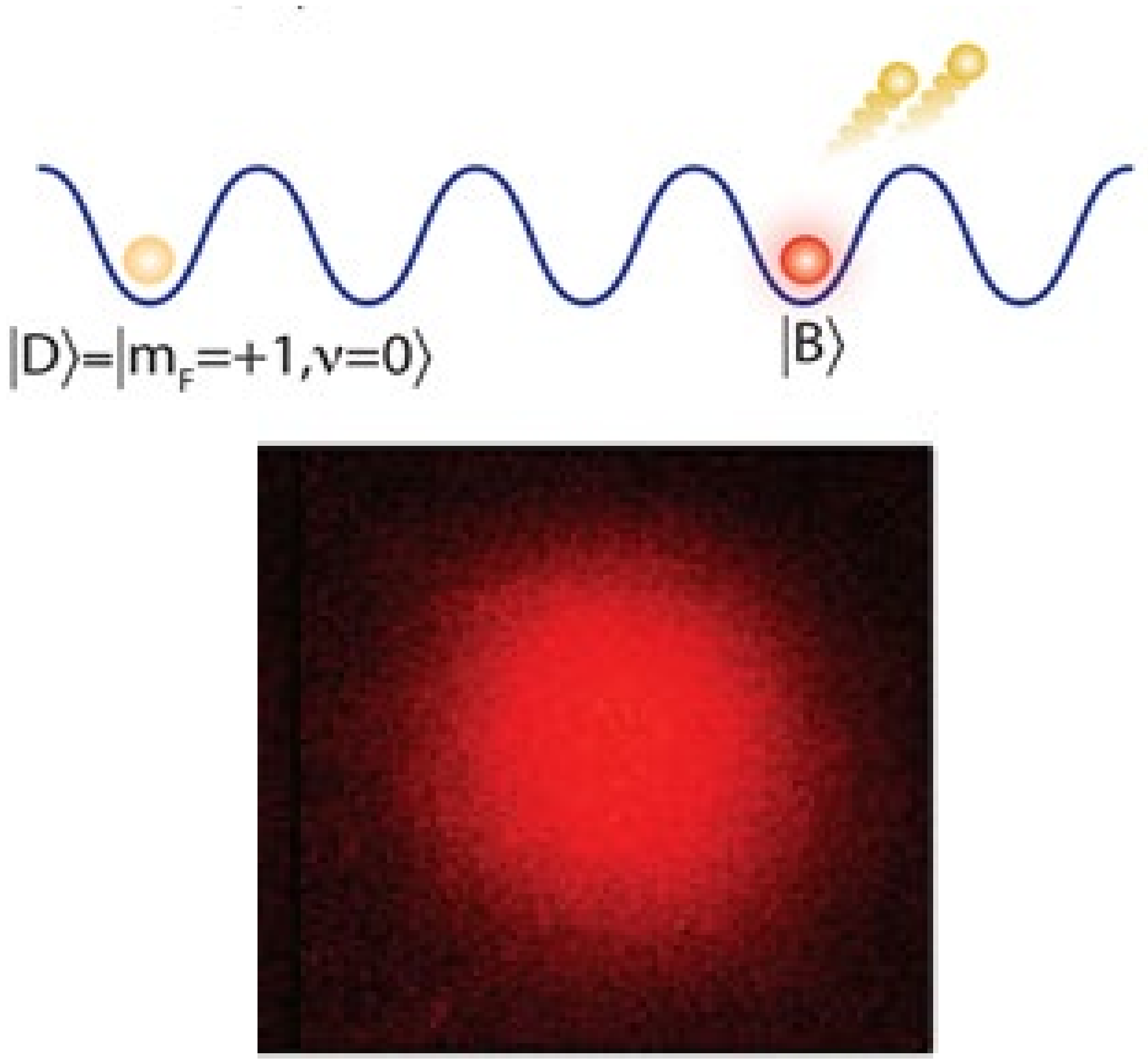
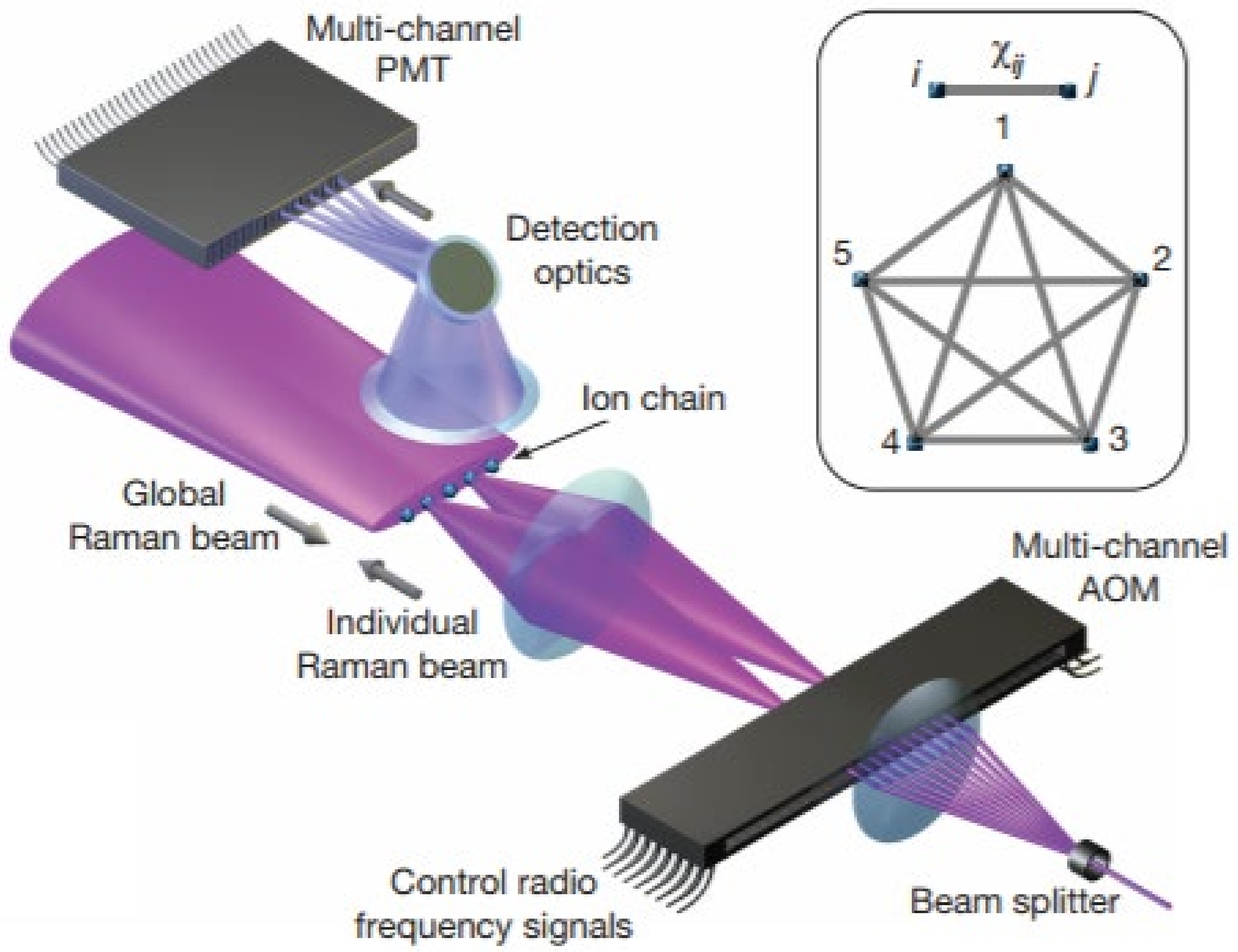
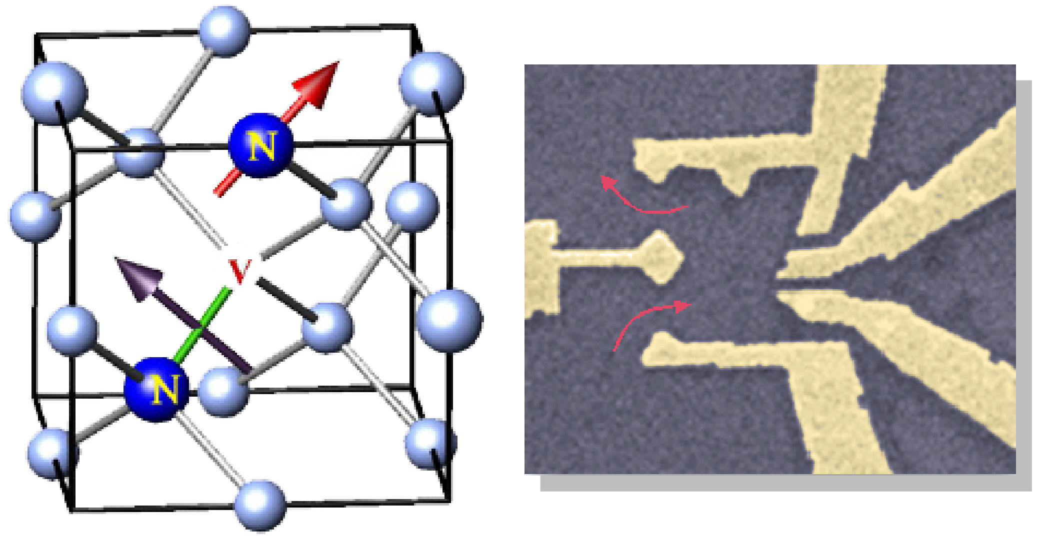
Quantum sensing modalities



Cold atoms

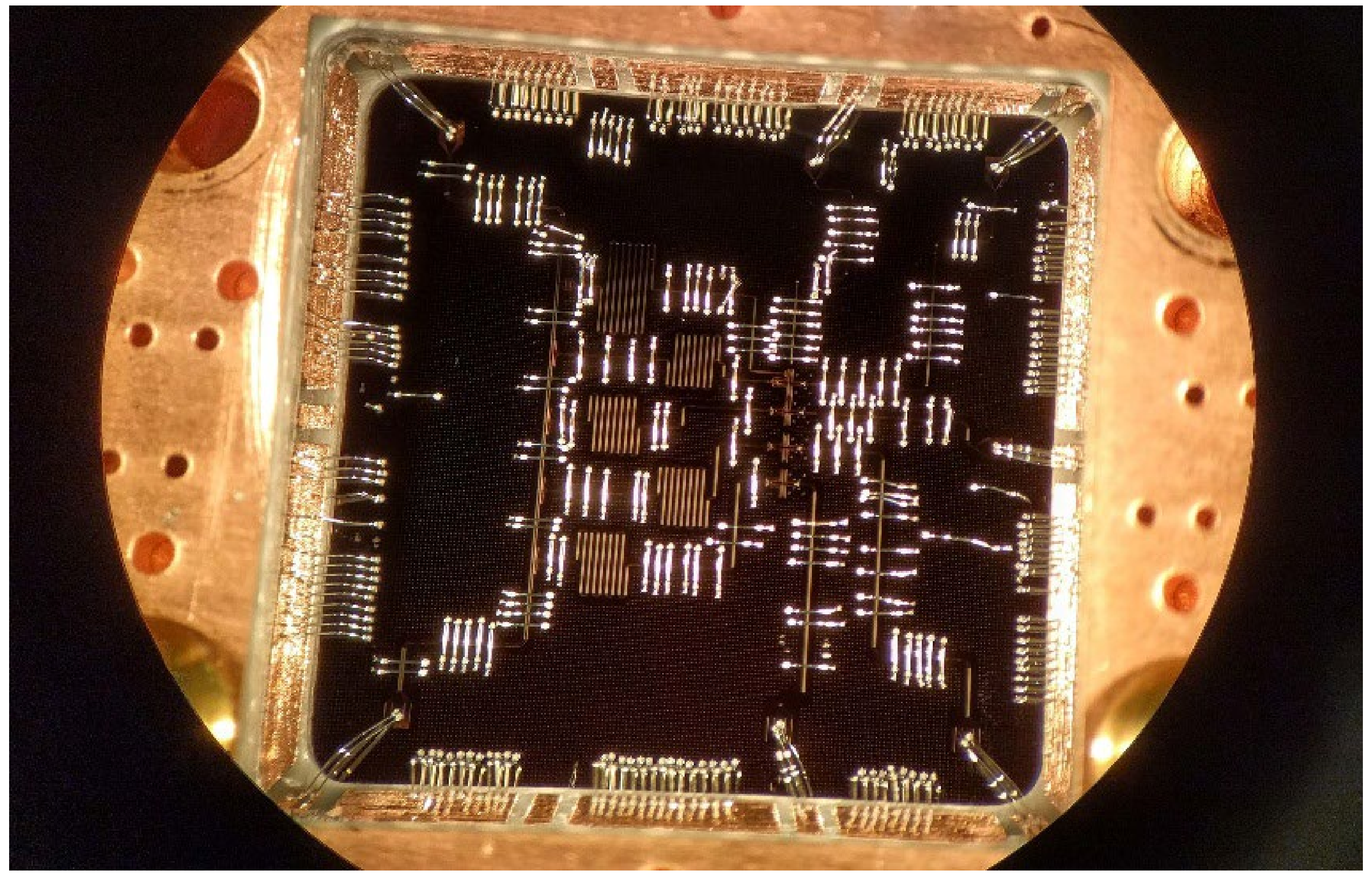


Trapped ions

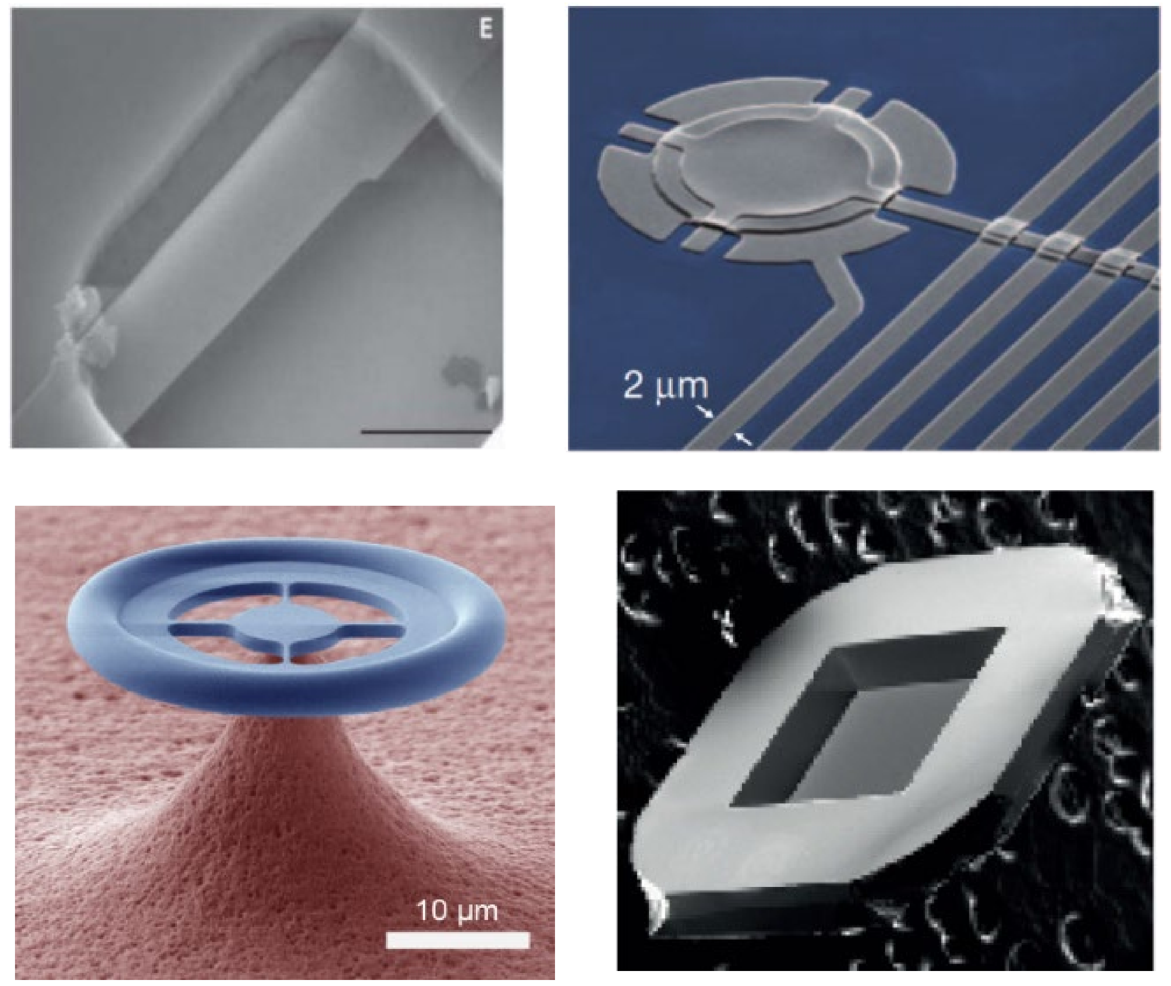


Spins (electron / nuclear)

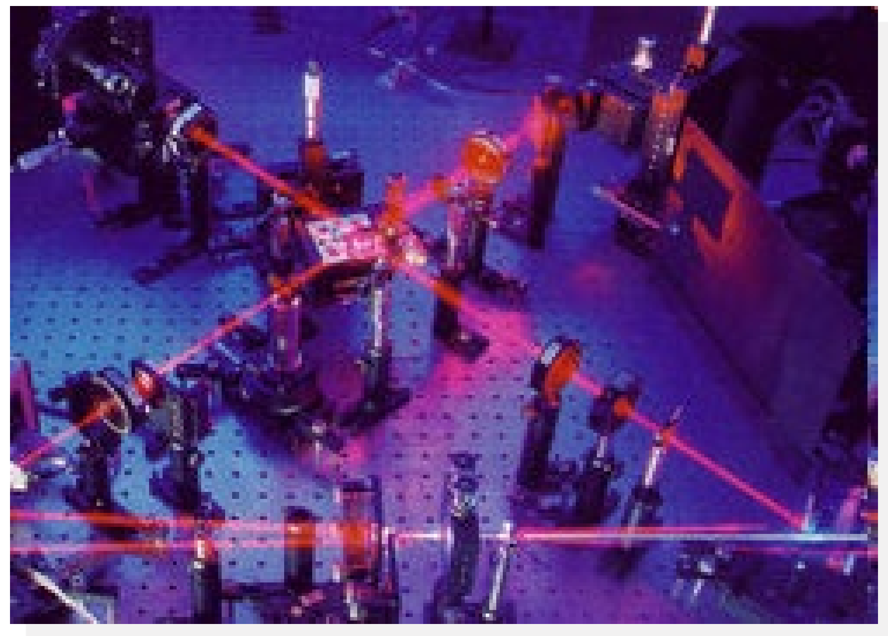
. . .



Superconducting



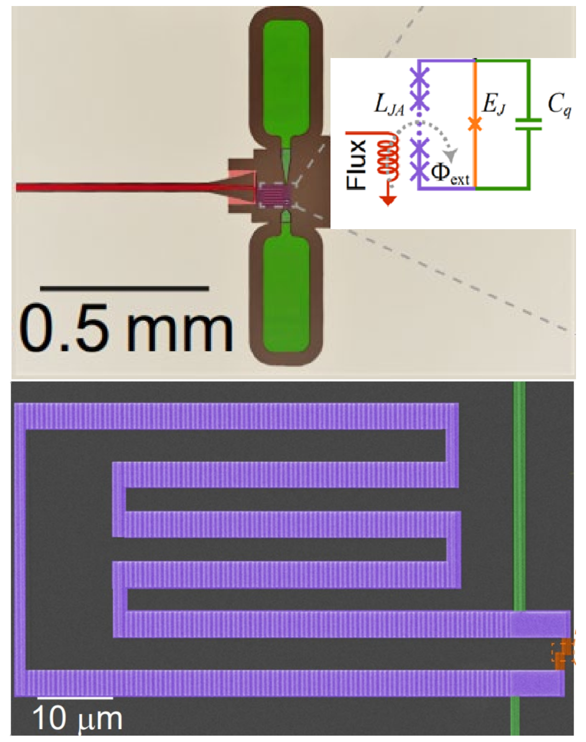
Optomechanical



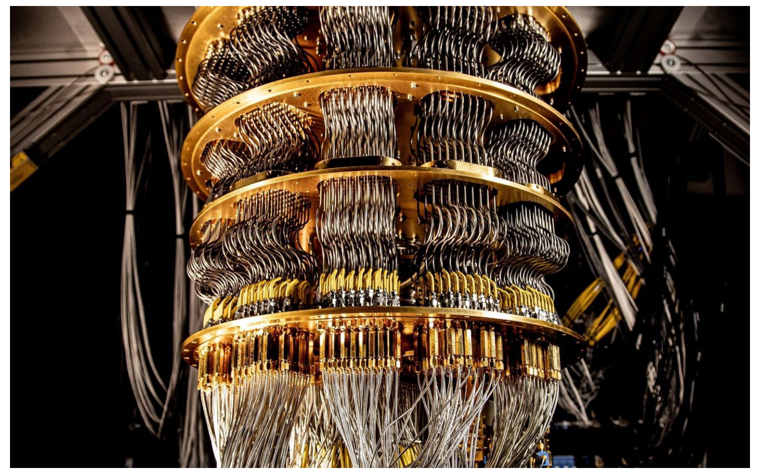
Optical

One Motivation: A Golden Age for QIS and Dark Matter

The Quantum Information Revolution



Qubit (Schuster)

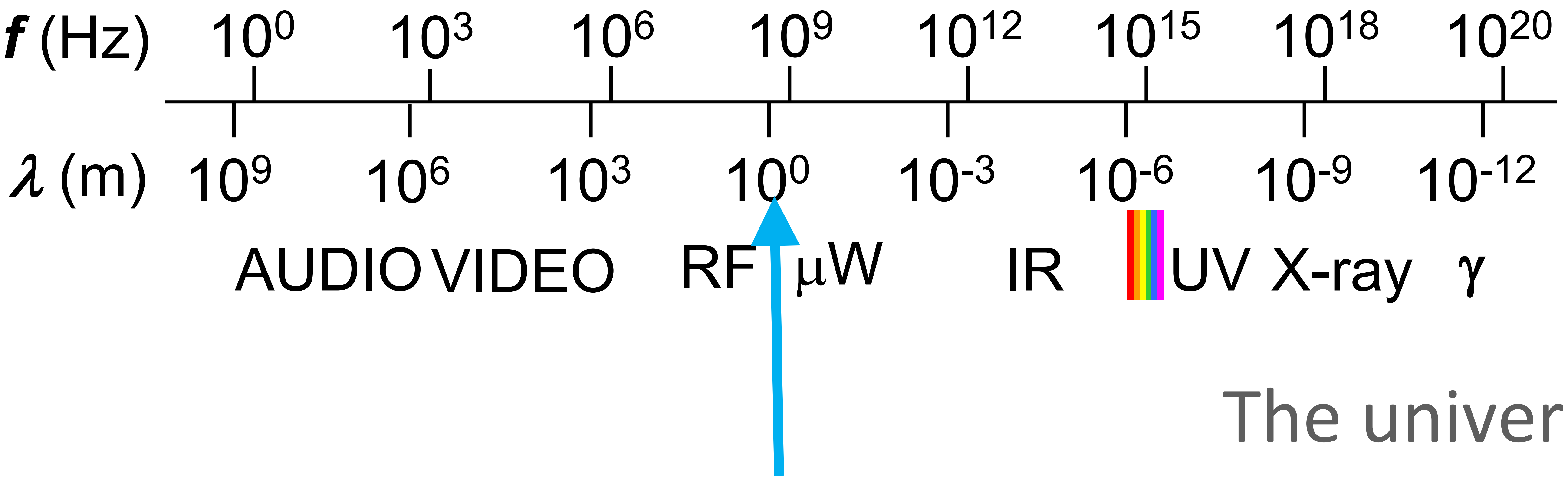

Quantum computer (Google)

- Advances in quantum control
  ⇒ Major governmental, industrial, and academic investment in new quantum technologies
- Near-term opportunities for leveraging quantum advantage:
  - Sensing beyond the standard quantum limit
  - Quantum simulations of physical phenomena intractable to classical computers

The Dark Matter Revolution

- Progress in theoretical understanding of:
  - Diverse range of dark-matter candidates
  - QCD axion: uniquely motivated for resolving the Strong CP problem
- Searching for diverse range of dark-matter candidates requires diverse new quantum sensor technologies (photon detectors, atomic clocks, spins, superconducting qubits, ...)
- Searching for QCD axion requires quantum sensitivity enhancement: reduce time to fully measure QCD axion band from millennia to years

Focus on electromagnetic signal wavelength >= human scale

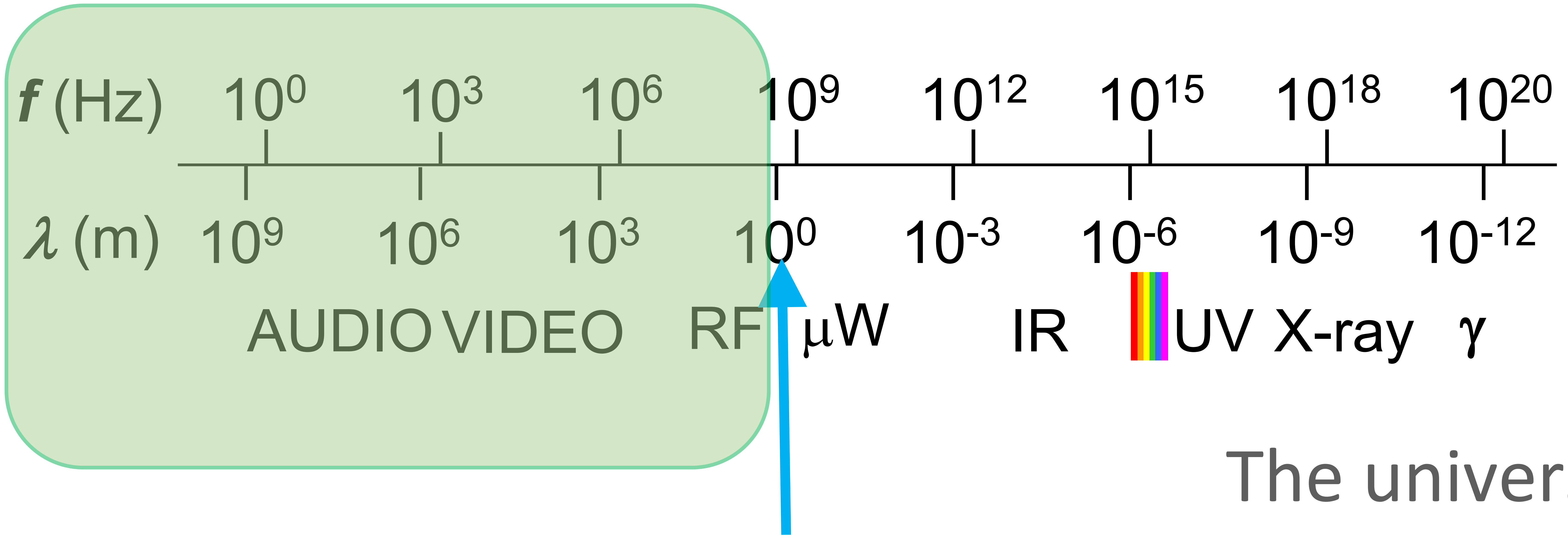


The universe ~ 2.7 K

300 MHz ~ 0.015 Kelvin ~ 1 m

300 MHz ~ human scale ~ dilution refrigerator temperature

This lecture will address techniques to measure frequencies < 300 MHz (including upconverting them to higher frequencies)



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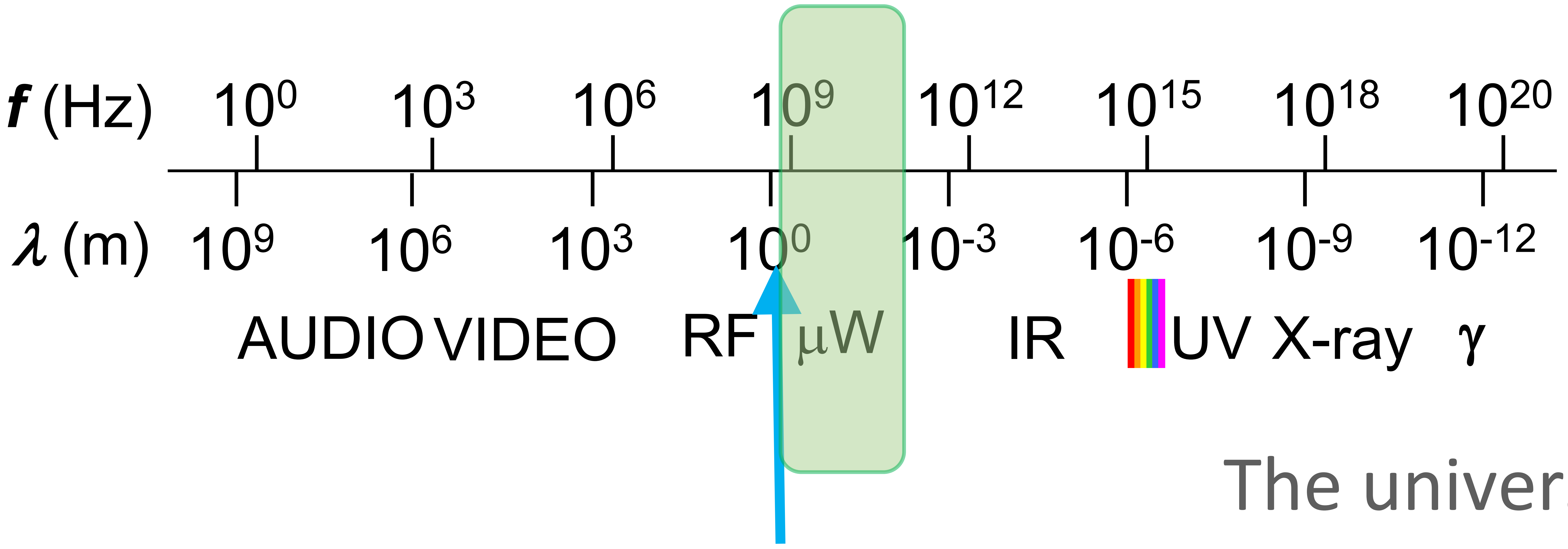
Aaron Chou's lecture (next) will address microwave-frequency techniques with qubits



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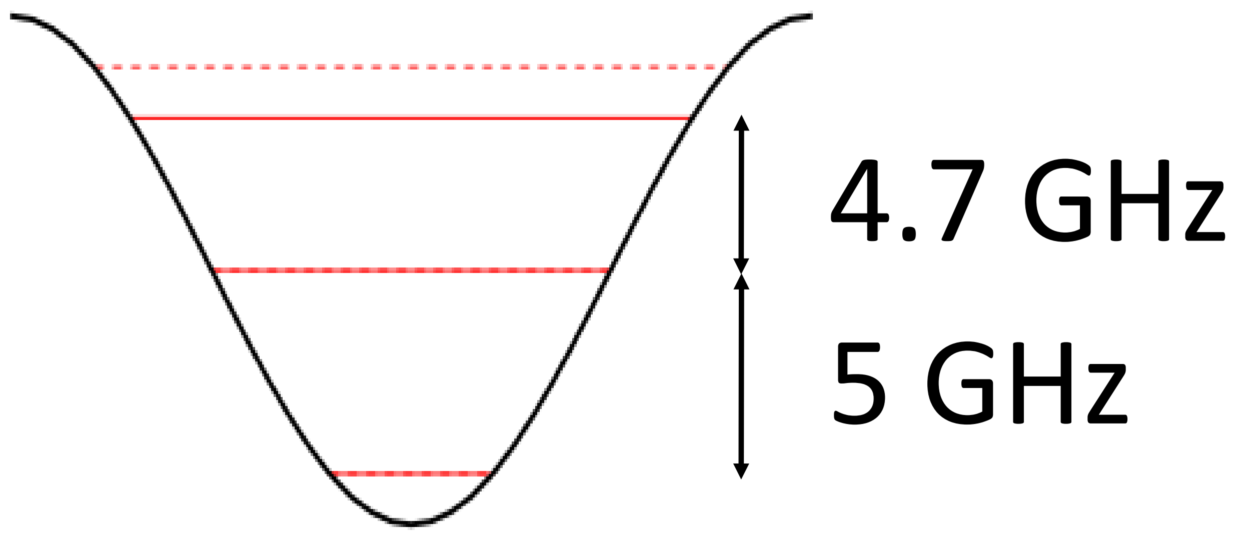
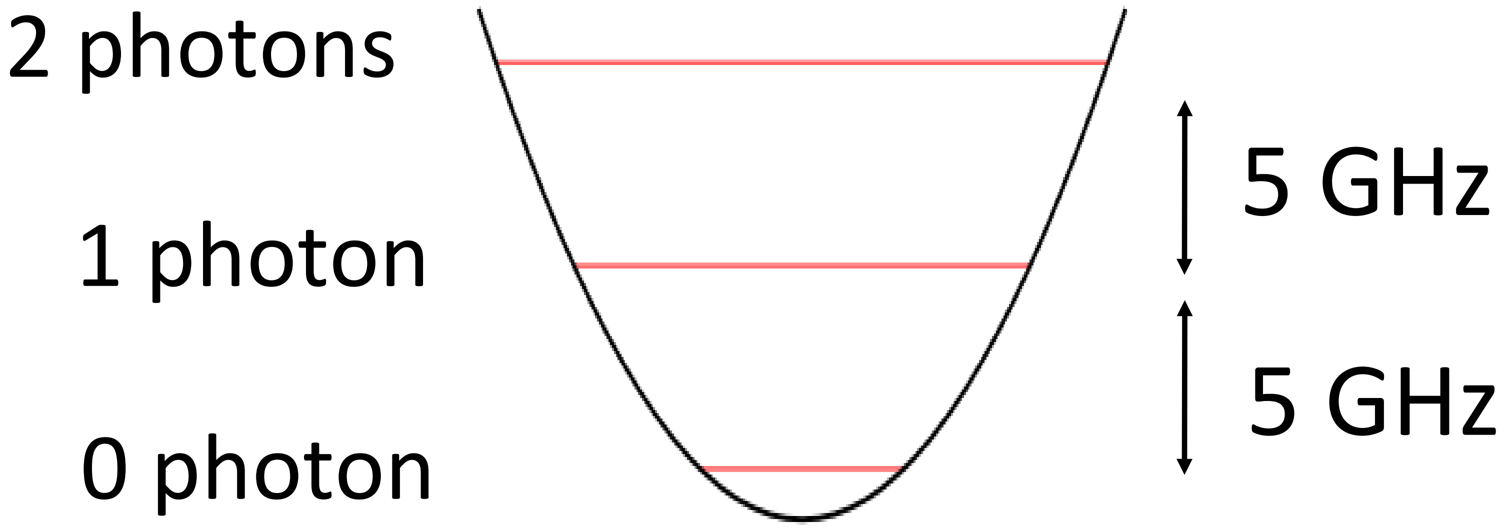
Continuous variables quantum information

- A qubit, or two-level system, is in some superposition of two states, |0> and |1>. It is "digital"-like.
- Physical observables (e.g. the strength of an electromagnetic field) have continuous intervals. They are "analog"-like.
- Often, continuous variables signals are sensed in a weak, continuous measurement, rather than a single projection. (the realized quantum limits are similar in either case).
- *The quantum optics approach to continuous variables*: model each mode of an electromagnetic field as a harmonic oscillator with annihilation & creation operators
- The state of the harmonic oscillator can be expressed as a phasor diagram, with $\hat{X}$ and $\hat{Y}$ quadrature components



Qubit with nonlinear level spacing

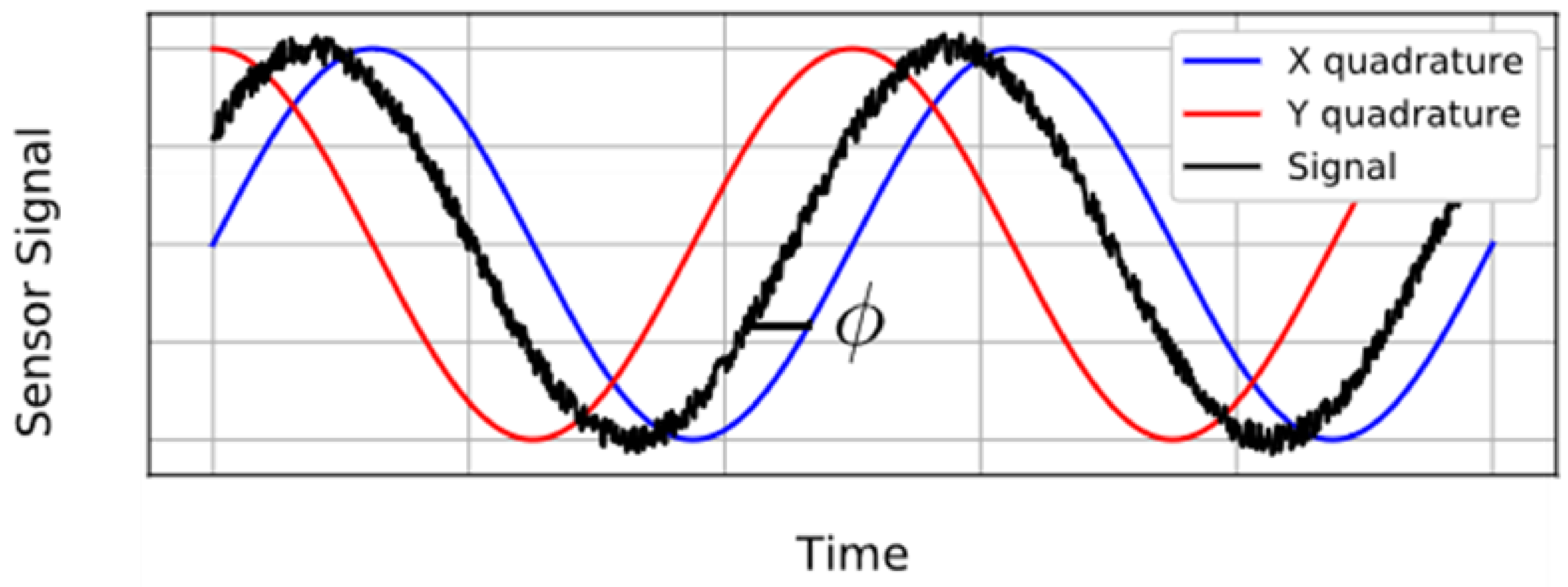


SHO with linear level spacing

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

Low Frequency LC Circuit Quadratures of a single mode

Low-frequency signal (black) has components in the X-quadrature (blue) and in the Y-quadrature (red)



$$\hat{X} = \frac{1}{\sqrt{2}}\left(\hat{a}\, e^{i\omega_a t} + \hat{a}^{\dagger} e^{-i\omega_a t}\right)$$

$$\hat{Y} = \frac{1}{\sqrt{2}}\left(\hat{a}\, e^{i\omega_a t} - \hat{a}^{\dagger} e^{-i\omega_a t}\right)$$

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

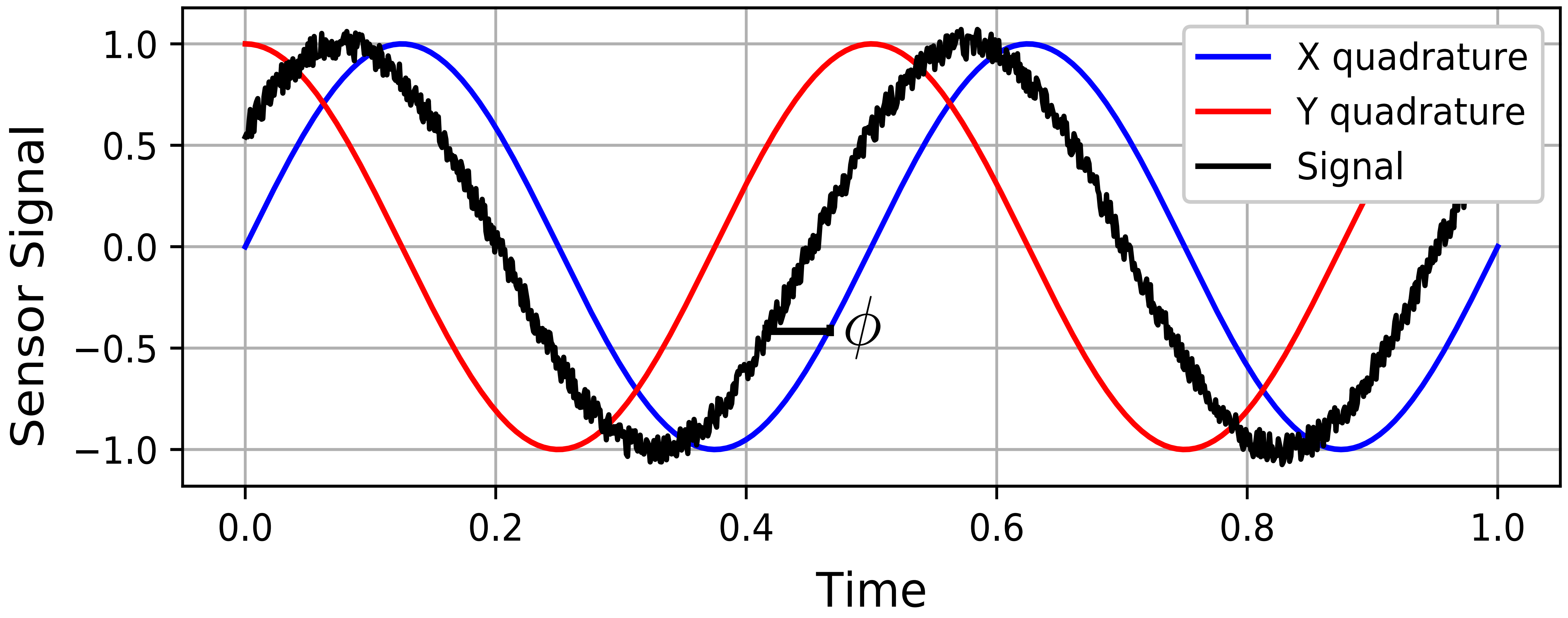
Consider a magnetic flux signal $\hat{\Phi}(t)$

$$\hat{\Phi}(t) = \sqrt{2}\Phi_{zpt}\left(\hat{X}(t)\cos\omega_a t + \hat{Y}(t)\sin\omega_a t\right)$$

See review: Clerk et al, RMP **82**, 1155 (2010)

The Standard Quantum Limit for Electromagnetism

- A generic E&M signal has ‘sine’ and ‘cosine’ components, which do not commute.
- The Heisenberg uncertainty principle says we cannot measure both perfectly, so an amplifier must add noise.
- The “standard quantum limit” is achieved when both components are measured as well as possible, saturating the Heisenberg Uncertainty Relation
- Equivalent to one photon of noise



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

Commutator

$$\Delta X \Delta Y \geq \frac{1}{4}$$

Heisenberg Uncertainty Relation

The Standard Quantum Limit (SQL) 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 ($\hat{Y}$)

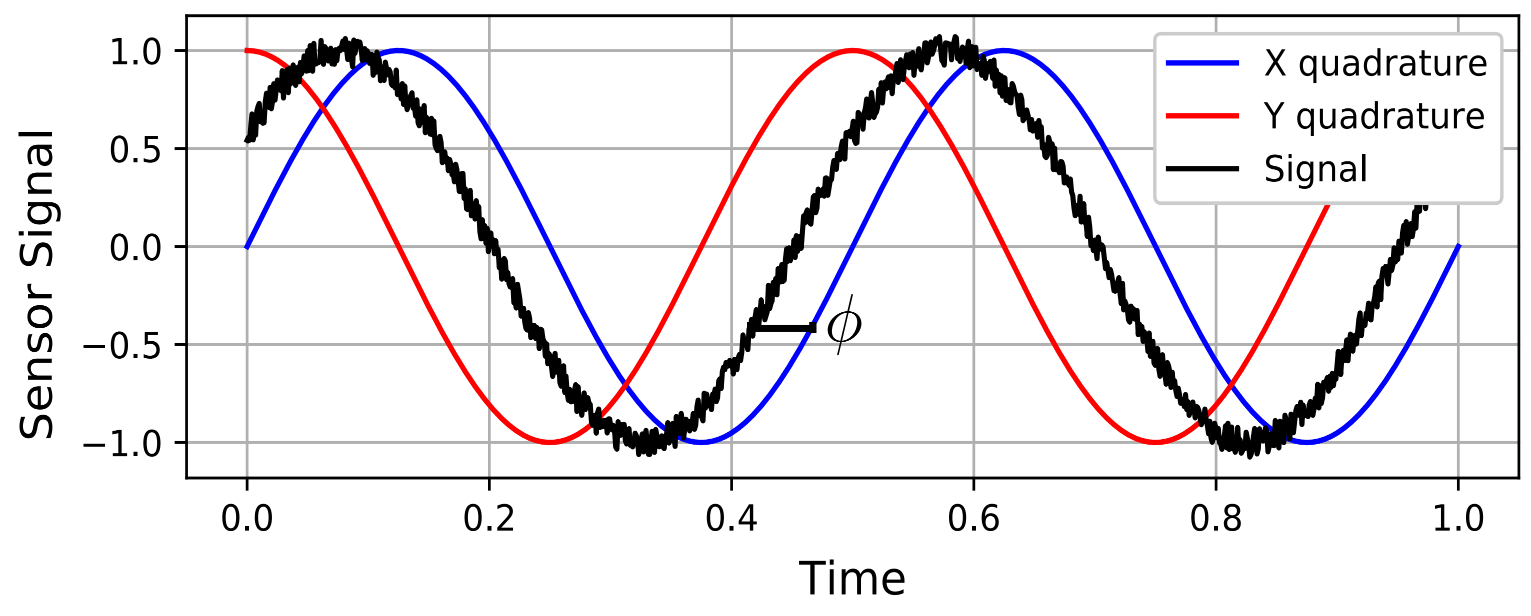
$$\hat{H} = \frac{\hbar\omega}{2}\left(\hat{X}^2 + \hat{Y}^2\right)$$

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

vacuum noise

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

Time representation



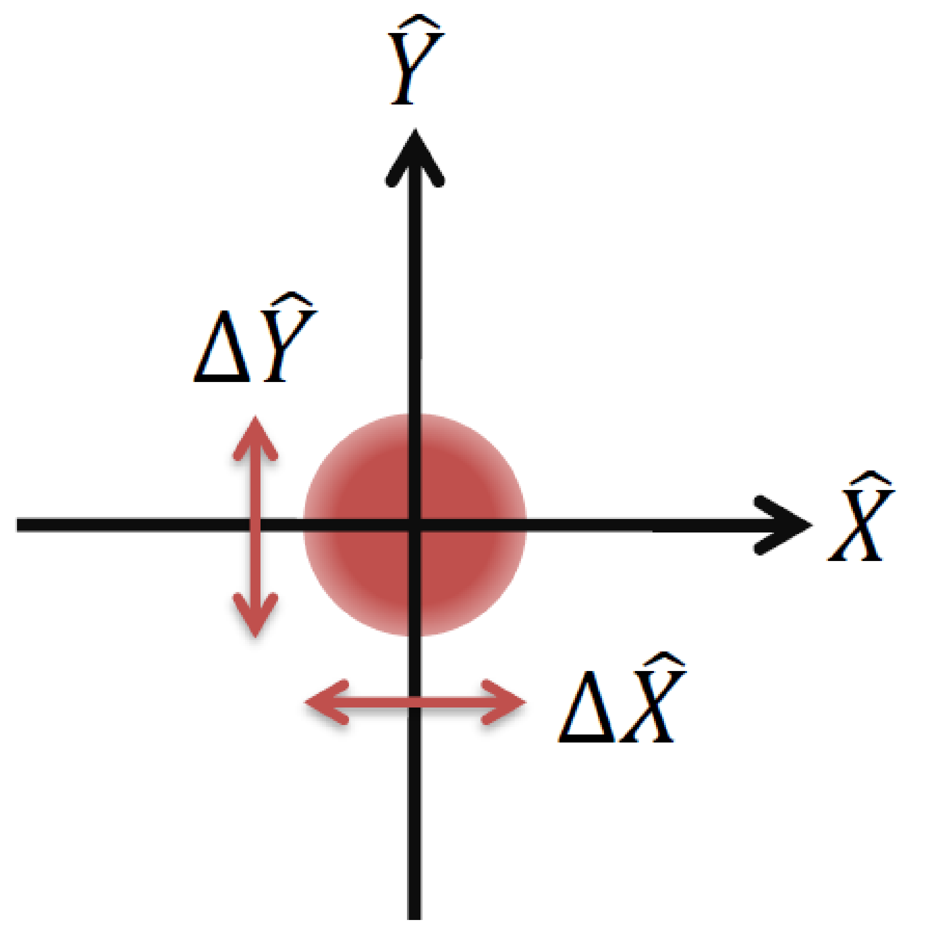
When amplified, add one more ½ quantum

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

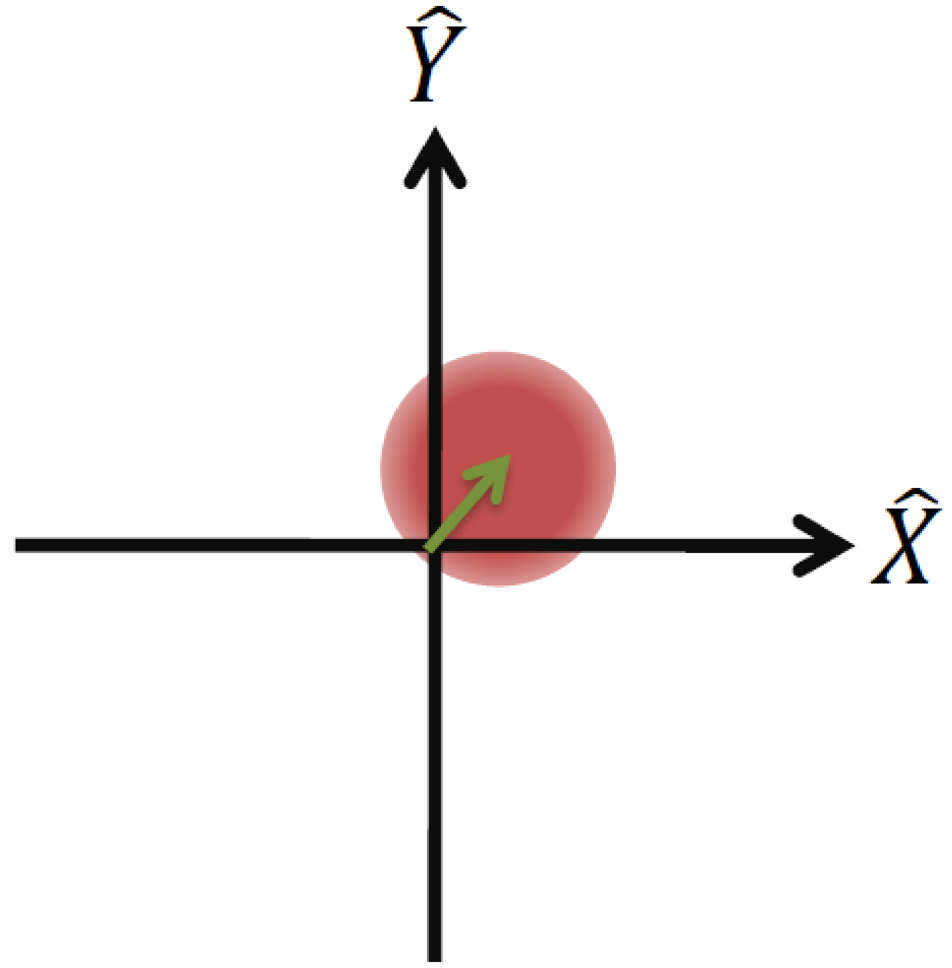
"SQL": 1 photon of noise

- Per measurement
- Measure ~ once per resonator coherence time

Phasor representation



With nonzero expectation value

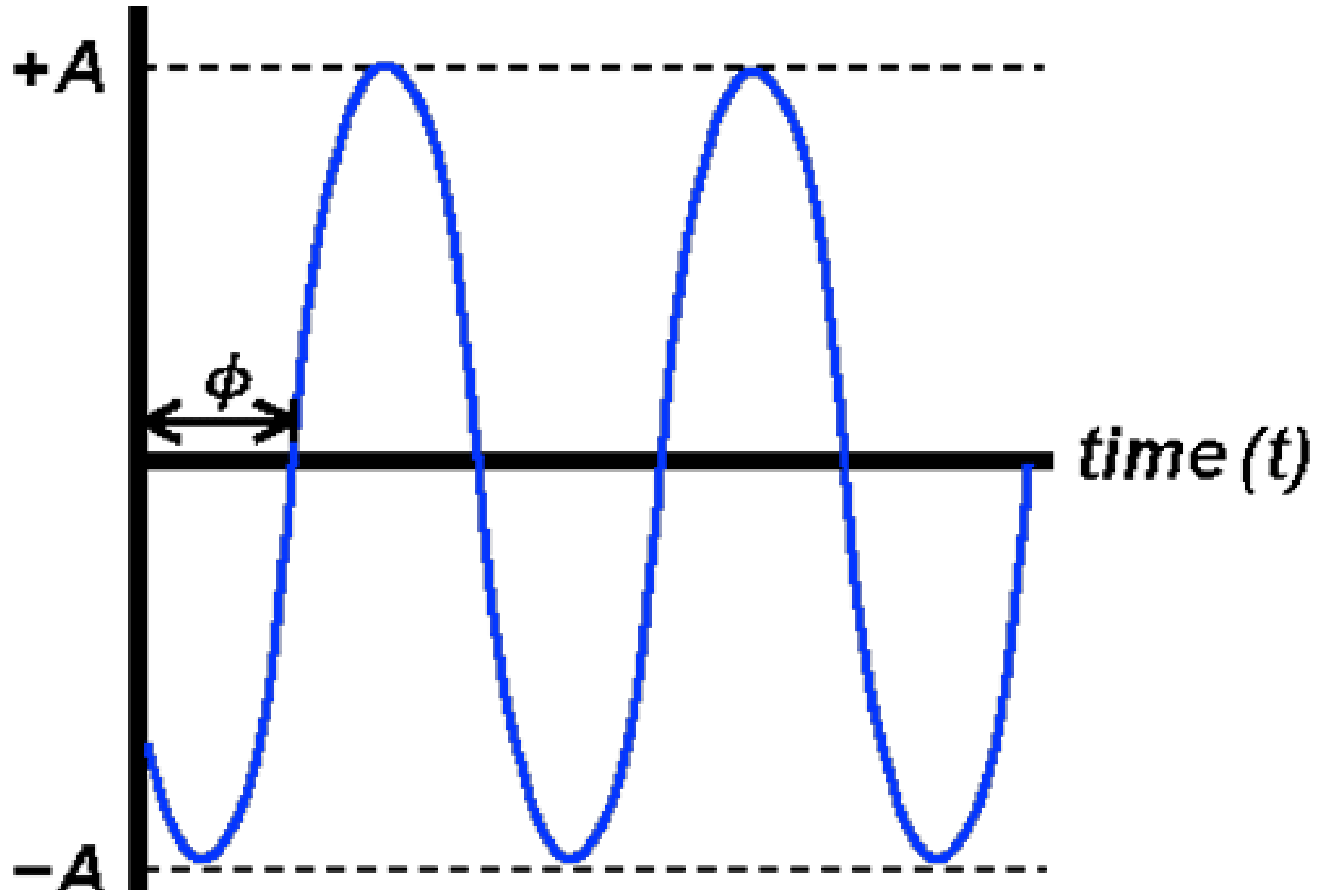


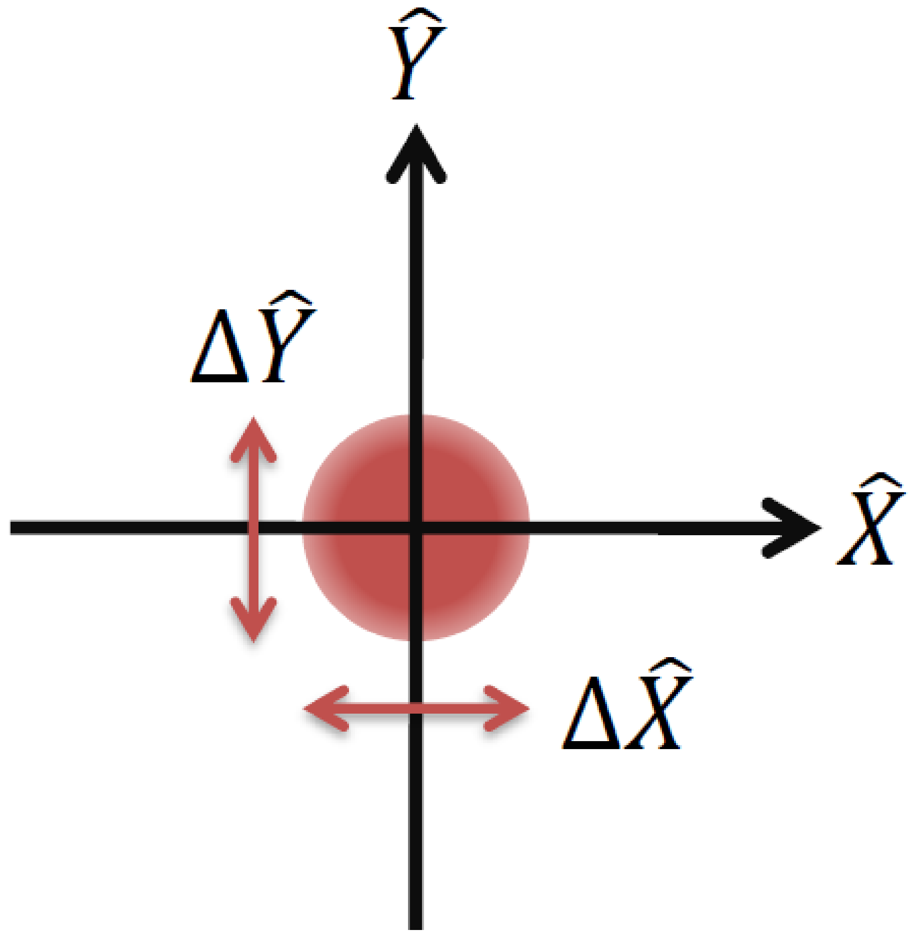
You can't know both amplitude and phase perfectly

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

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

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

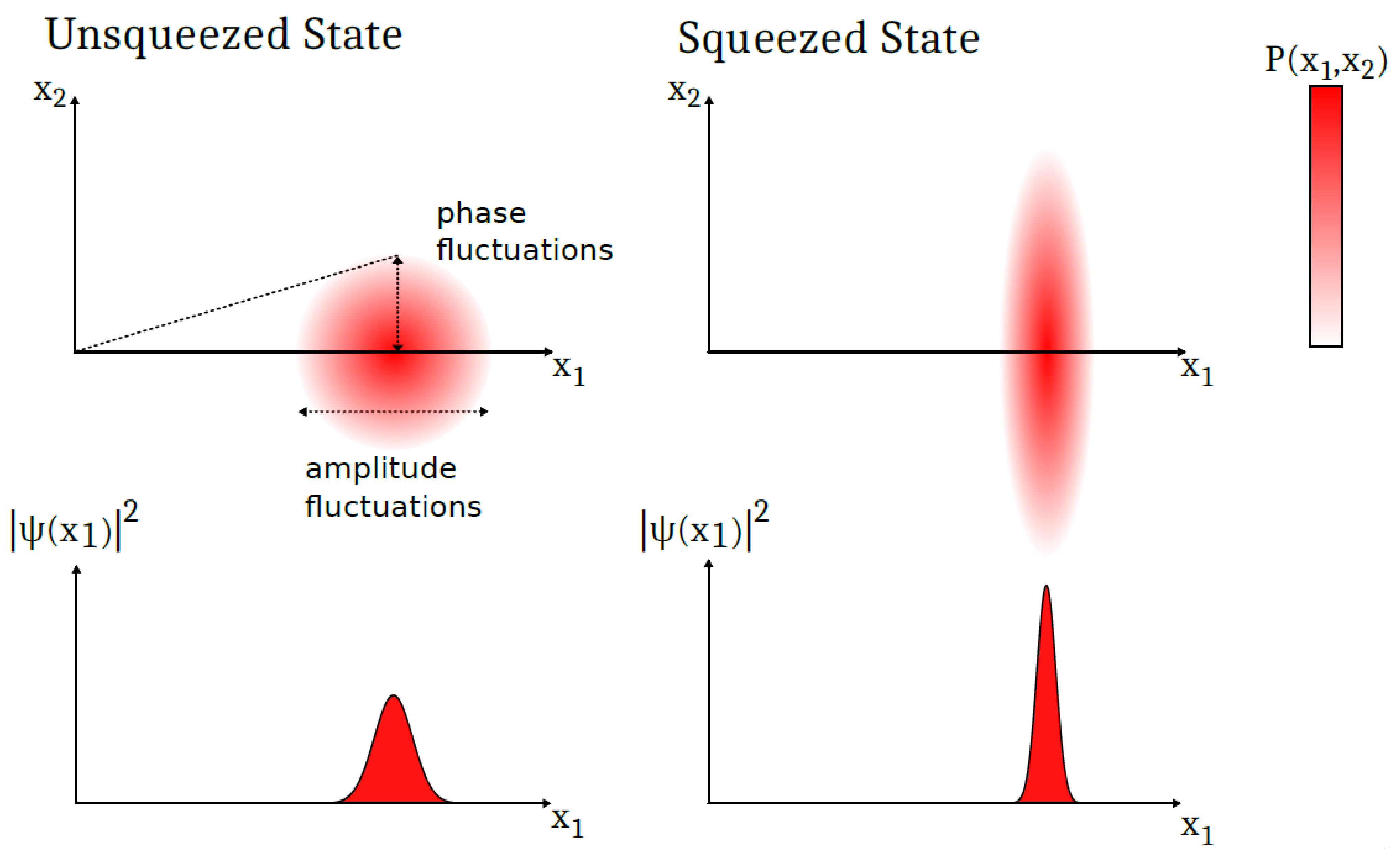


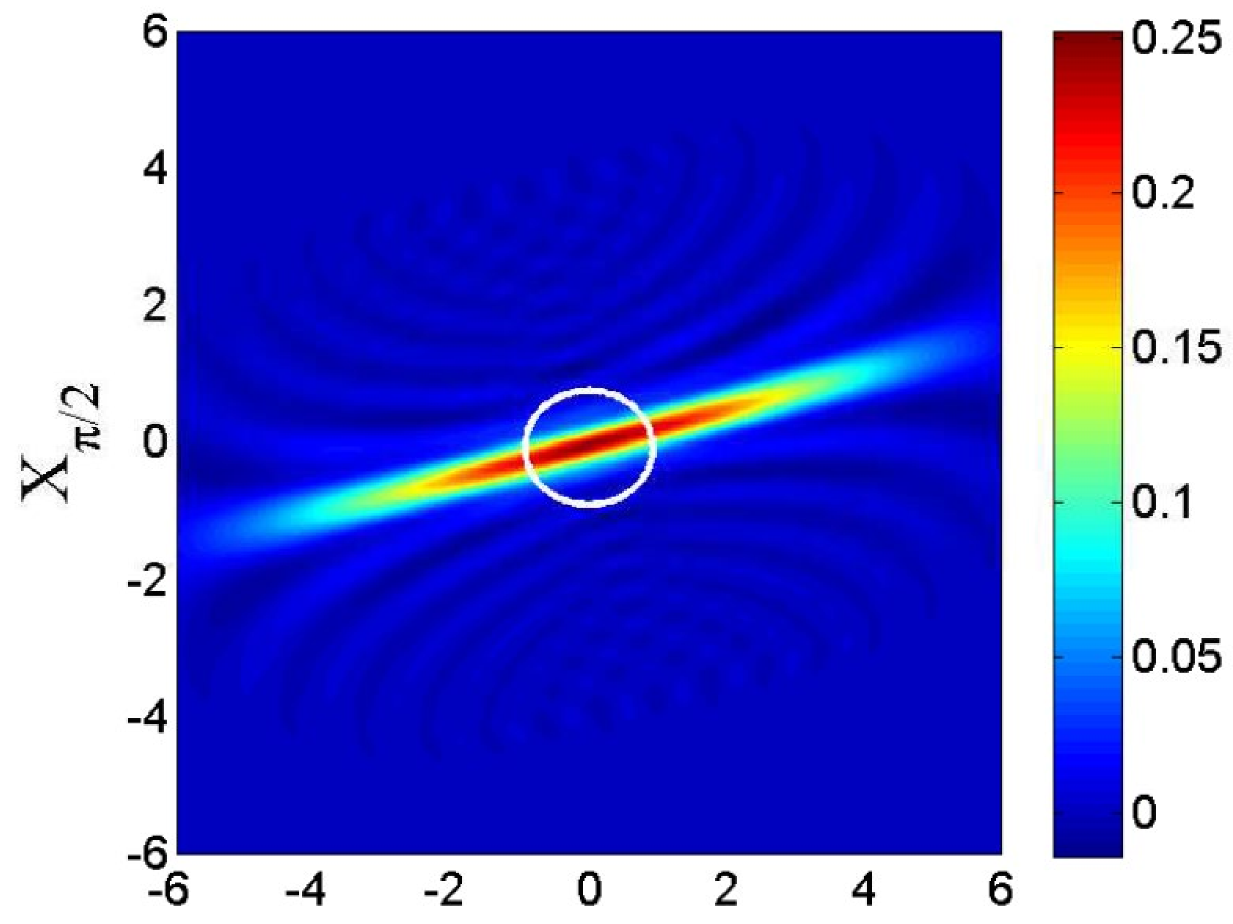


A "classical" sensor measures both amplitude and phase with equal sensitivity, limited by the Standard Quantum Limit of $\hbar\omega$

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

One way to evade the SQL - squeezing





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

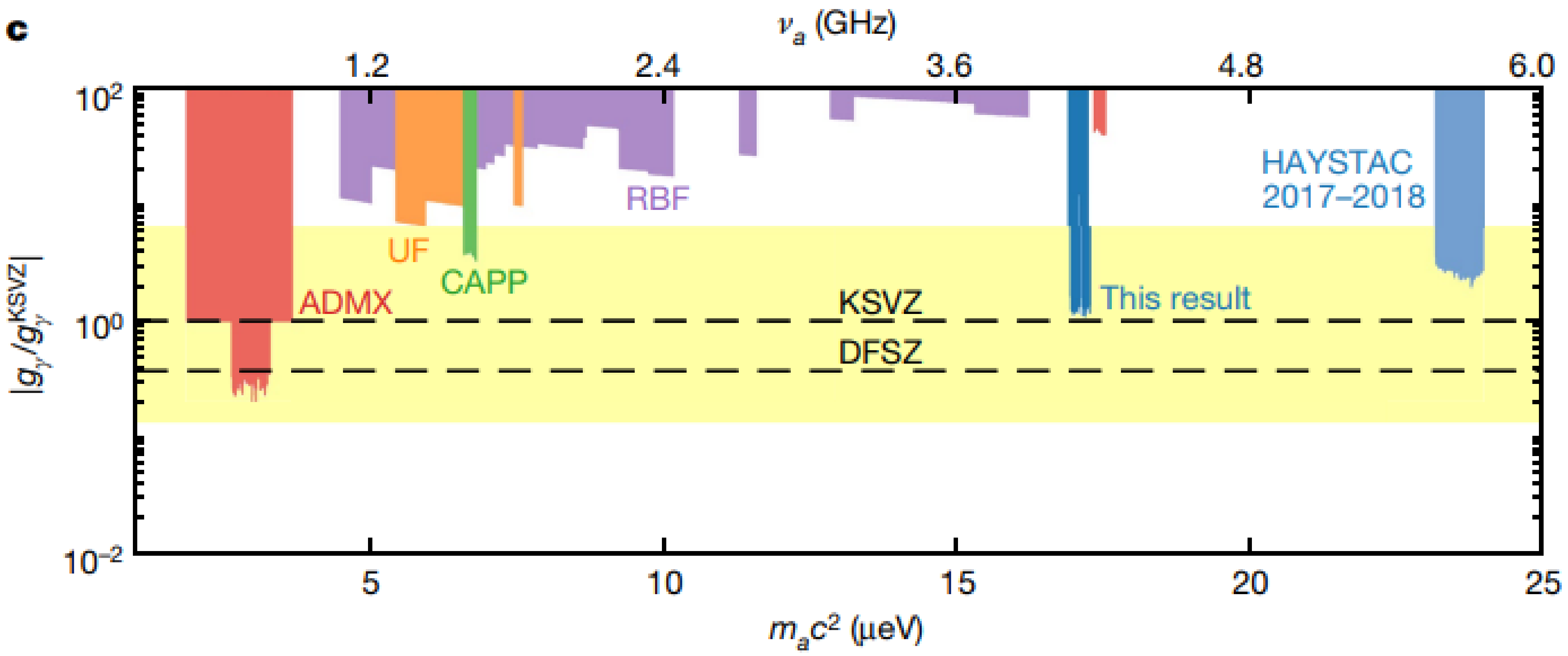
- Don't measure both amplitude and phase. (Equivalently, don't measure both sine and cosine quadratures)
- There are several ways to achieve this outcome. They are deeply inter-related (and involve entanglement), and all obey the Uncertainty Principle.

Better science thru evading the Standard Quantum Limit

LIGO Livingston

- LIGO performs quantum measurements at better than the SQL to measure gravitational waves more sensitively
- LIGO uses squeezing to improve interferometry, but it could also utilize backaction evasion (BAE).

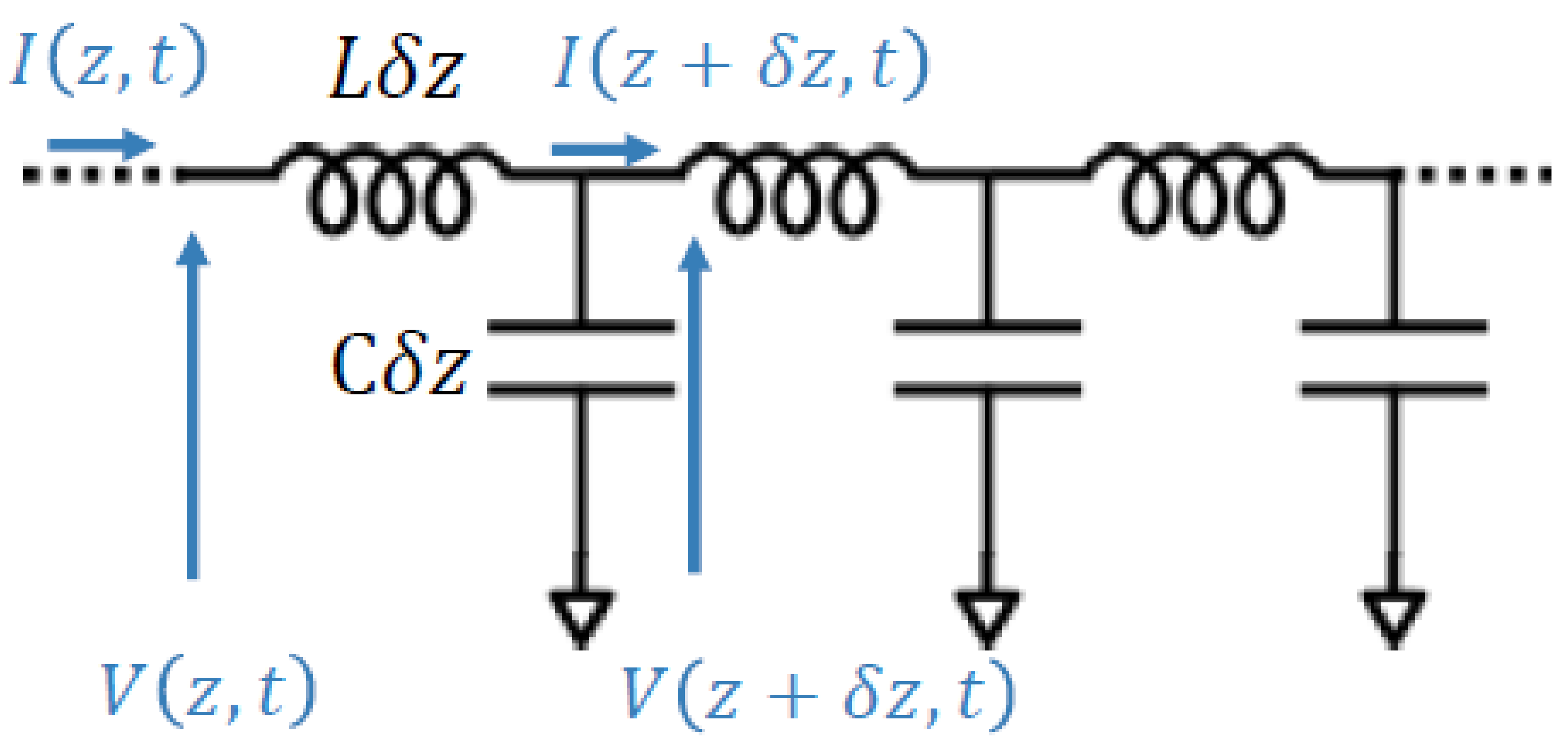
HAYSTAC: Faster science through squeezing



HAYSTAC quantum accelerated science reach

Backes, Kelly M., et al. "A quantum enhanced search for dark matter axions."
Nature 590.7845 (2021): 238-242.

Primer to TWPA: telegrapher equations



From Florent's lecture:

Consider the single propagating mode limit

$$\begin{cases} -\dfrac{\partial V(z,t)}{\partial z} = L\dfrac{\partial I(z,t)}{\partial t} \\ -\dfrac{\partial I(z,t)}{\partial z} = C\dfrac{\partial V(z,t)}{\partial t} \end{cases}$$

generic

$$\begin{cases} \dfrac{\partial^2 V(z,t)}{\partial z^2} - LC\dfrac{\partial^2 V(z,t)}{\partial t^2} = 0 \\ \dfrac{\partial^2 I(z,t)}{\partial z^2} - LC\dfrac{\partial^2 I(z,t)}{\partial t^2} = 0 \end{cases}$$

$$\begin{cases} V(z,t) = V^+ e^{i[\omega t - kz]} + V^- e^{-i[\omega t - kz]} \\ I(z,t) = \dfrac{V^+}{Z_0} e^{i[\omega t - kz]} - \dfrac{V^-}{Z_0} e^{-i[\omega t - kz]} \end{cases}$$

$$Z_0 = \sqrt{\frac{L}{C}}$$

$$v_p = \frac{\omega}{k} = \frac{1}{\sqrt{LC}}$$

Single-mode, waves vs. IV

- In a single-moded signal, at any point in the transmission line, ***four numbers*** are required to describe the electromagnetic signal.
- Propagating wave:

Re{V+}, Im{V+} for the right-propagating wave

Re{V-}, Im{V-} for the left-propagating wave

- Equivalently, you can use the voltage and current at each point in space for the sum of the left- and right- propagating waves:

Re{V}, Im{V}

Re{I}, Im{I}

$$V(z,t) = V^+ e^{i[\omega t - kz]} + V^- e^{-i[\omega t - kz]}$$

$$I(z,t) = \frac{V^+}{Z_0} e^{i[\omega t - kz]} - \frac{V^-}{Z_0} e^{-i[\omega t - kz]}$$

- Good for scattering calculations
- Microwave engineering
- Scattering-mode amplifiers

- Useful for Ohm’s Law /
- Circuit diagrams
- “Op-amp” mode amplifiers

Scattering mode / opamp mode

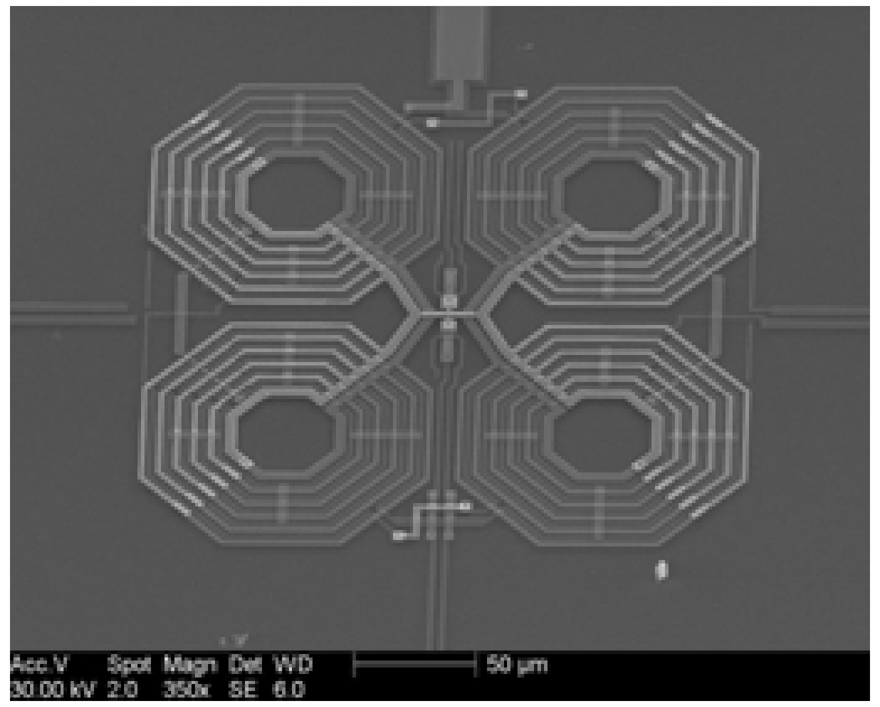
Scattering-mode amplifiers

- Amplification of waveforms
- Typical when length scale > lambda
- Input described by incoming and outgoing waves
- RF amplifiers and HEMTs, Parametric amplifiers

"Op-amp"-mode amplifiers

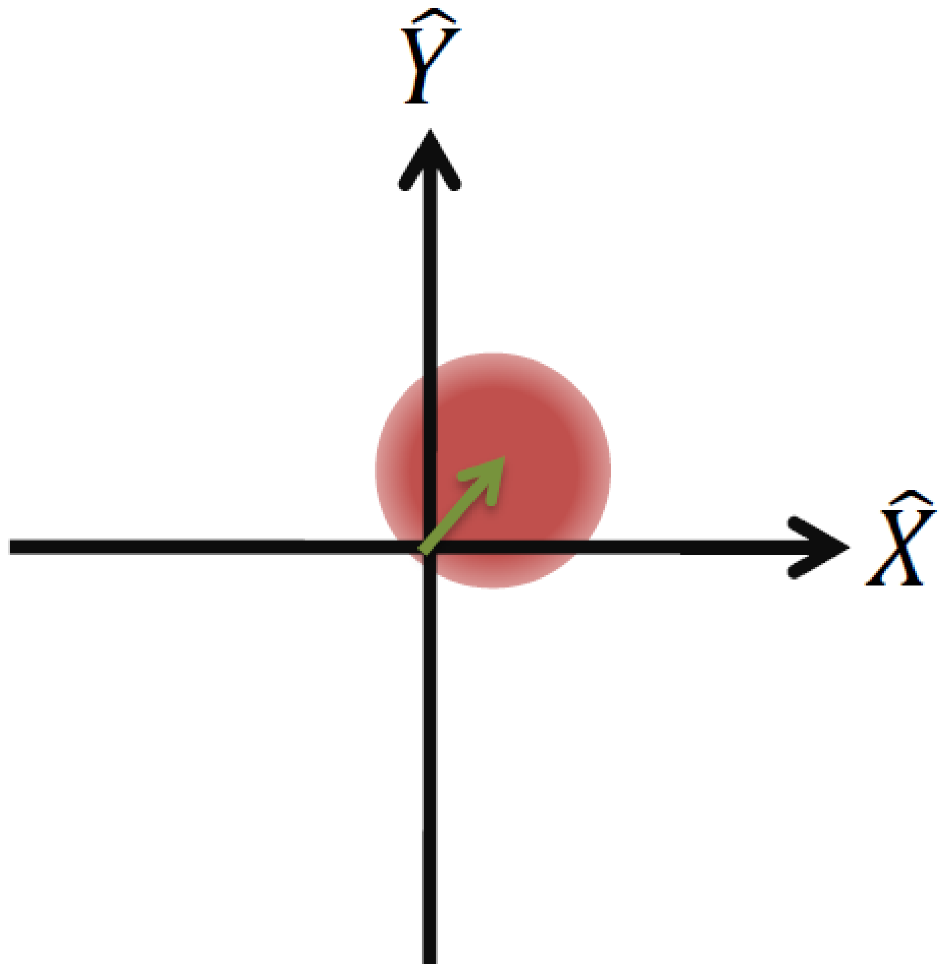
- Amplification of state variable (voltage, current, flux)
- Typical when length scale < lambda
- Input described by state variable and backaction on input, and tuning coupling
- FETs, bipolar transistors
- dc SQUIDs

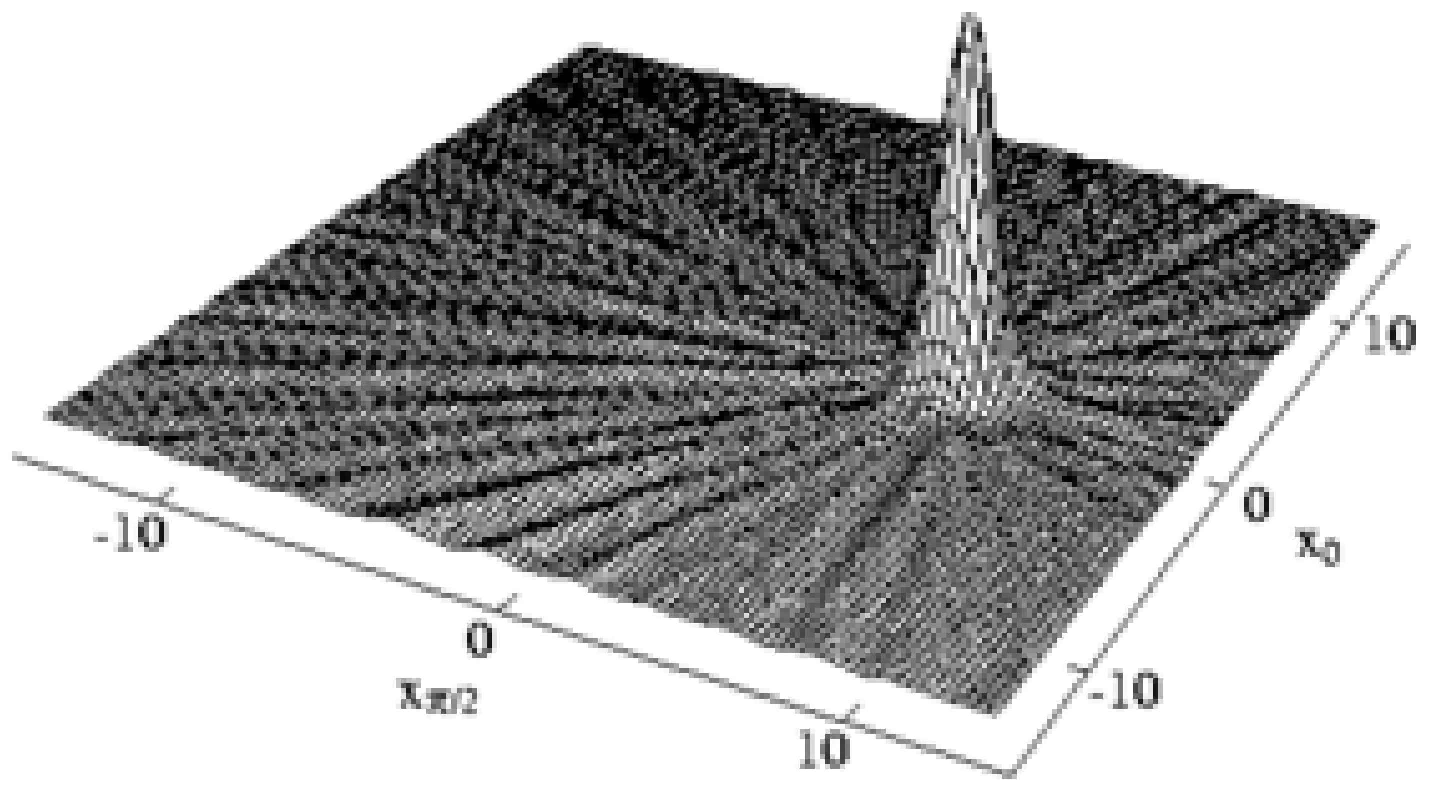
Quantum limits are analogous, but take different treatment

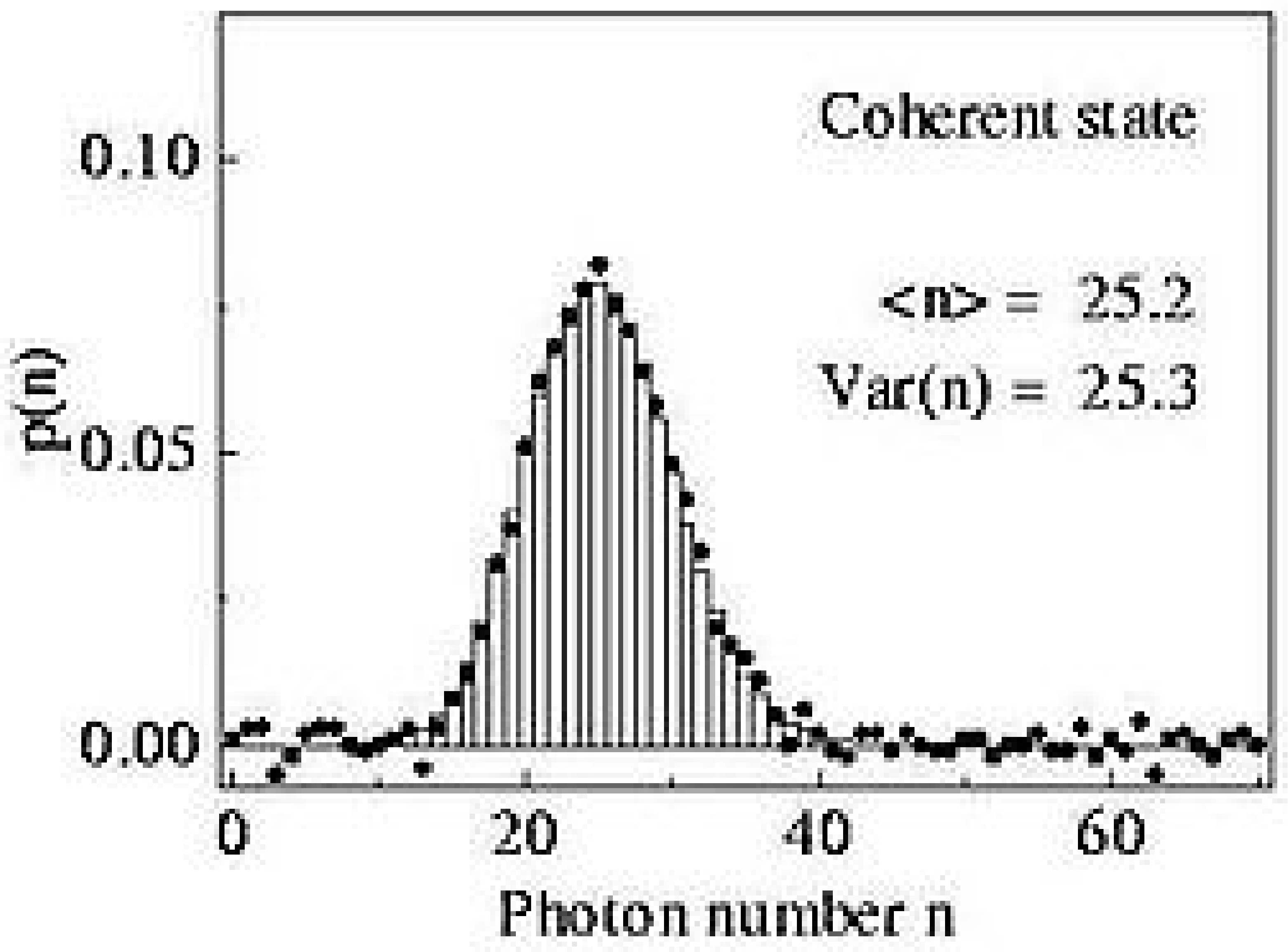


Coherent states

- A "best approximation" of a sinewave.
- Eigenstate of the annihilation operator
- Uncertainty balanced between $\hat{X}$ and $\hat{Y}$

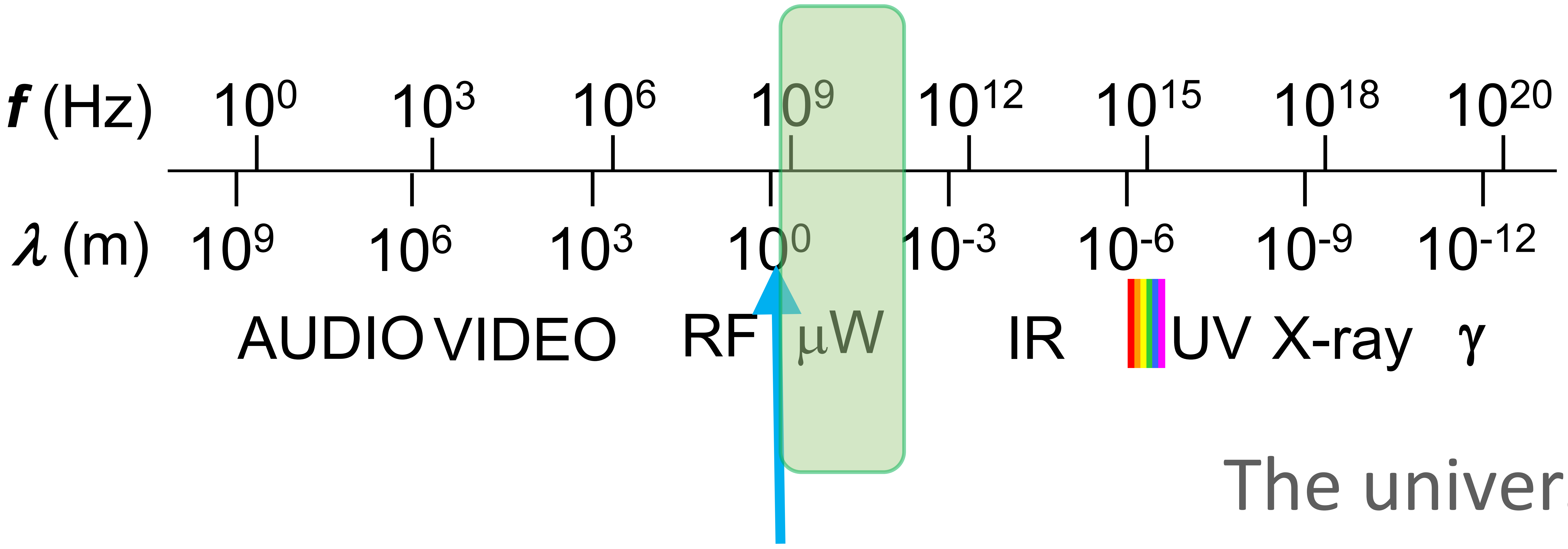






- Coherent state is a superposition of many different photon-number states.
- Eigenstate of photon number is "Fock" state
- Projection noise of coherent onto Fock state -> "shot" noise (another SQL)

Aaron Chou's lecture will address microwave-frequency techniques with qubits, including Fock state preparation



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Sensing electromagnetic signals at low frequency

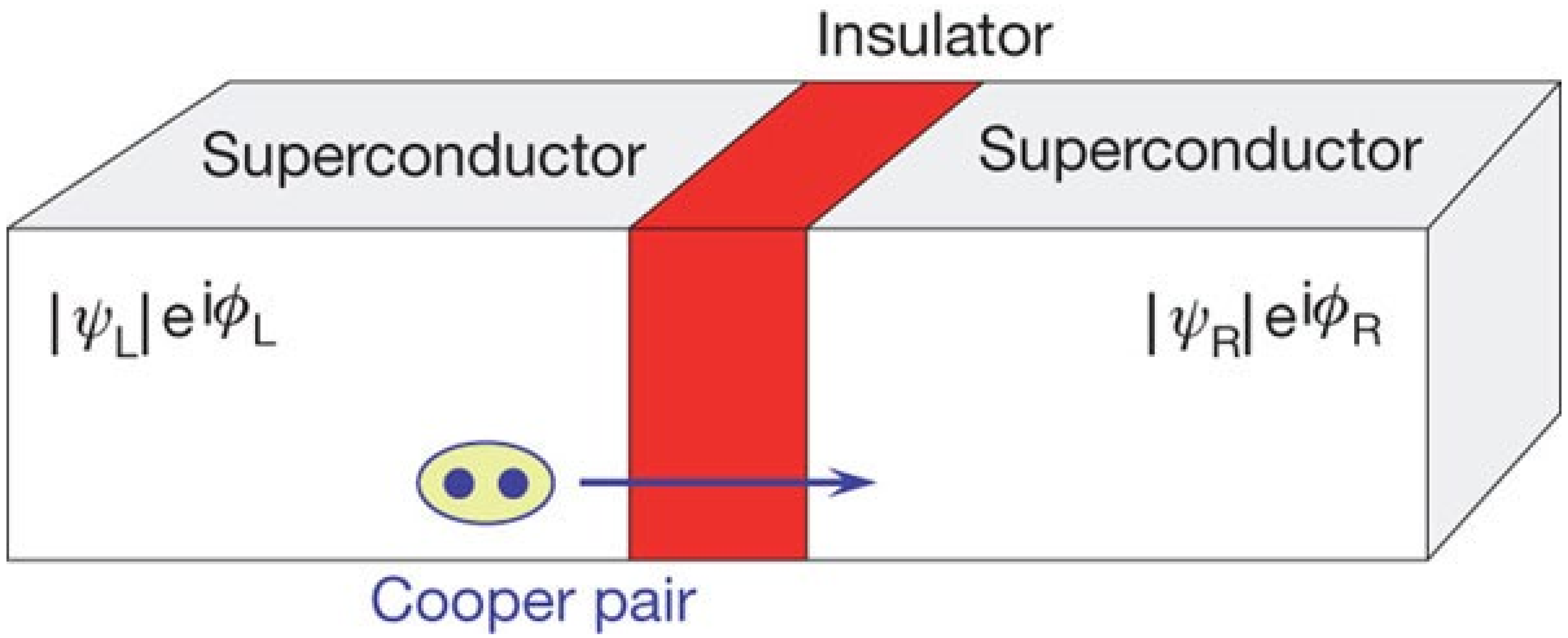
- Preparing Fock states difficult because of thermal photons
- Op-amp mode amplifiers used because length >> lambda
- Many types of amplifiers are traditionally available: FETs, bipolar transistors, SET electrometers. Most are far from any Standard Quantum Limit
- The more traditional amplifier that is often considered “quantum limited” is the dc SQUID, an op-amp mode amplifier
- Mode: flux-to-voltage amplifier (current can be transduced to flux, so can be a current-to-voltage amplifier).

Let’s work through the problem of understanding quantum limits in a quantum-limited flux amplifier. *Noise matching and backaction are more central in an op-amp-mode measurement than in a scattering-mode measurement*

Then we consider newer alternatives to the dc SQUID

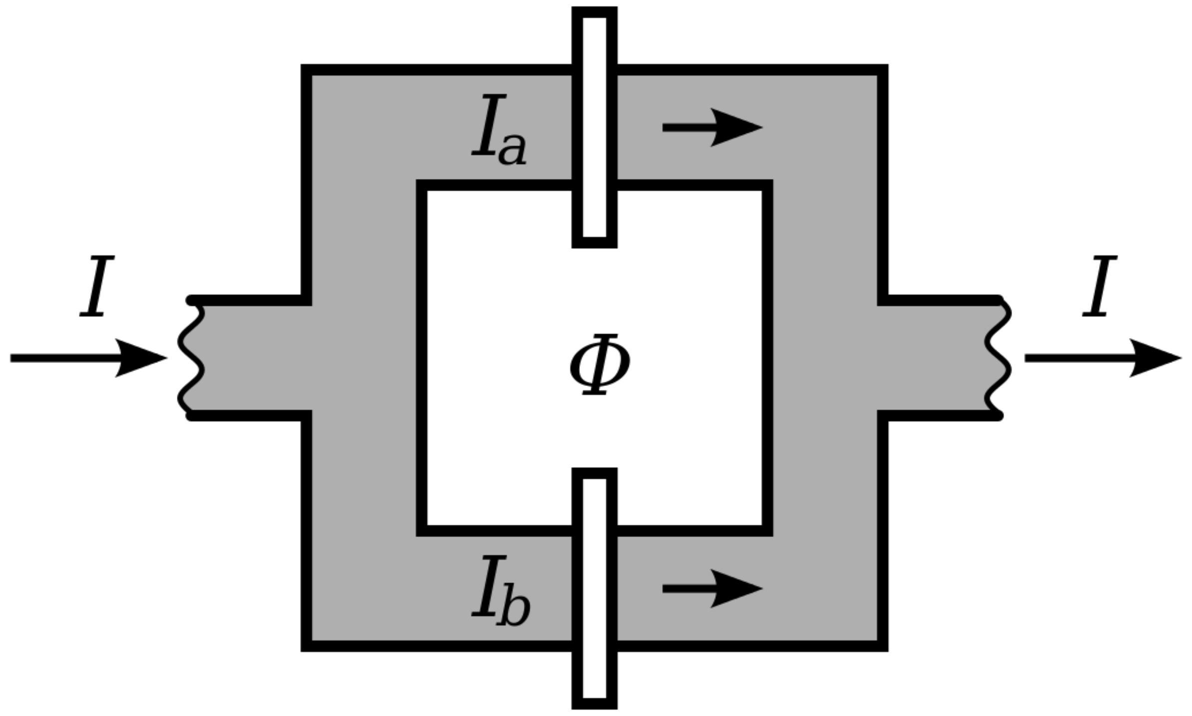
Josephson Junctions

Brian Josephson
Nobel Prize, 1973



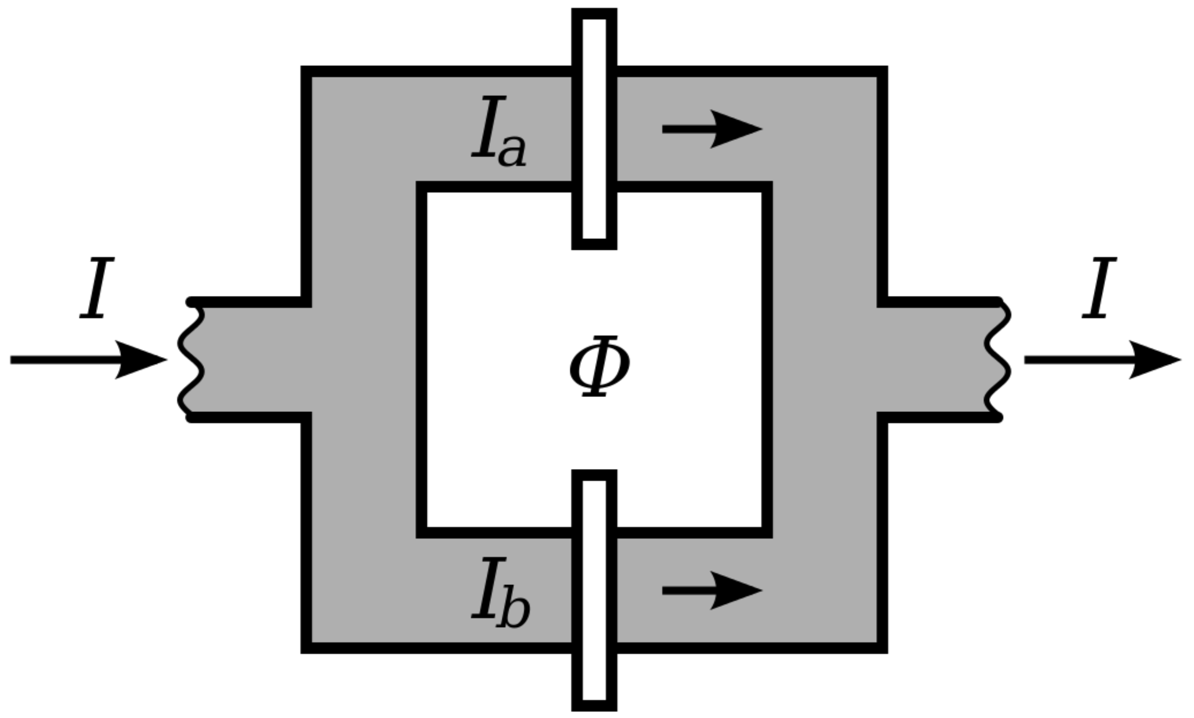
$$I = I_c \sin(\phi_R - \phi_L)$$

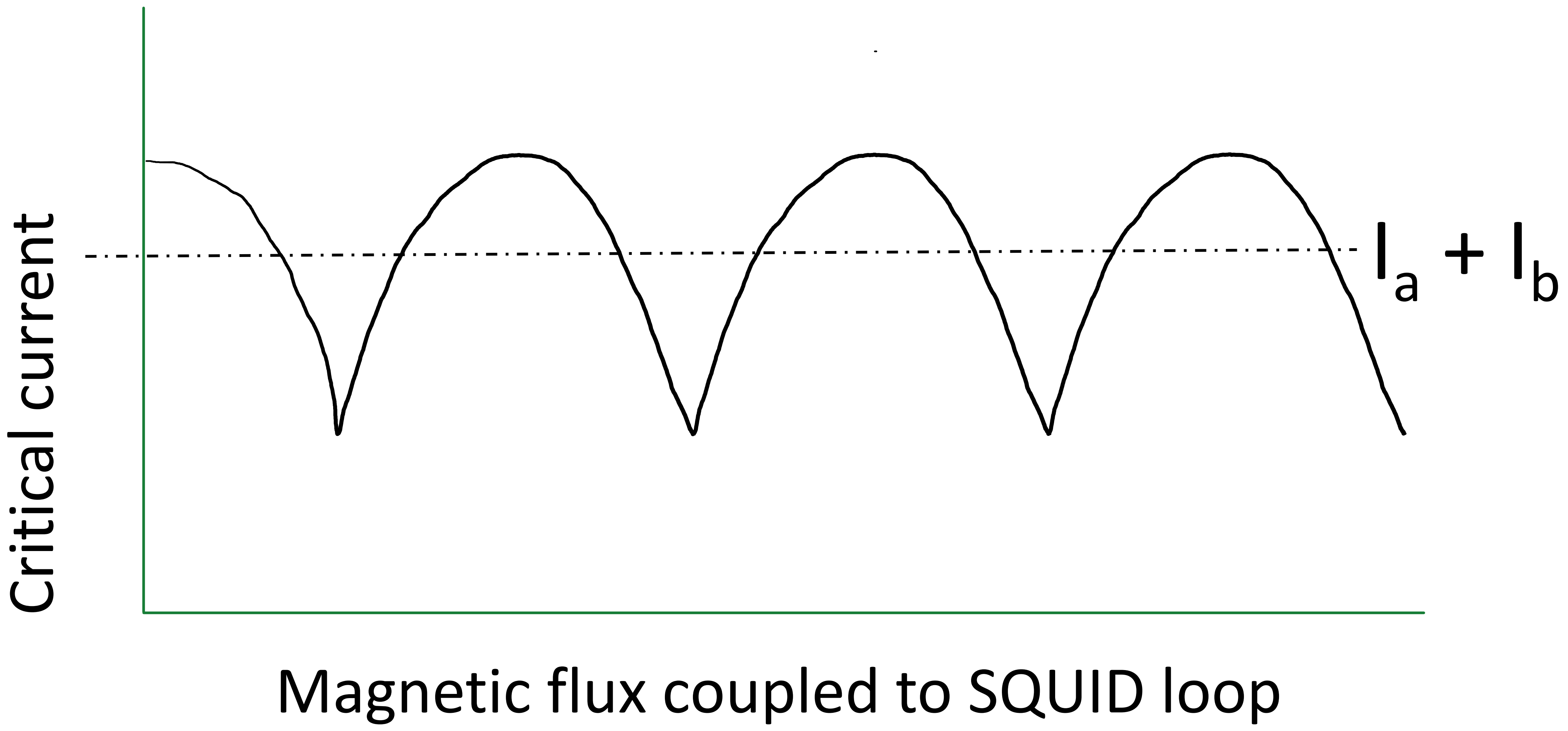
It gets more interesting when you make a loop:
The magnetic flux modulates the superconducting phase



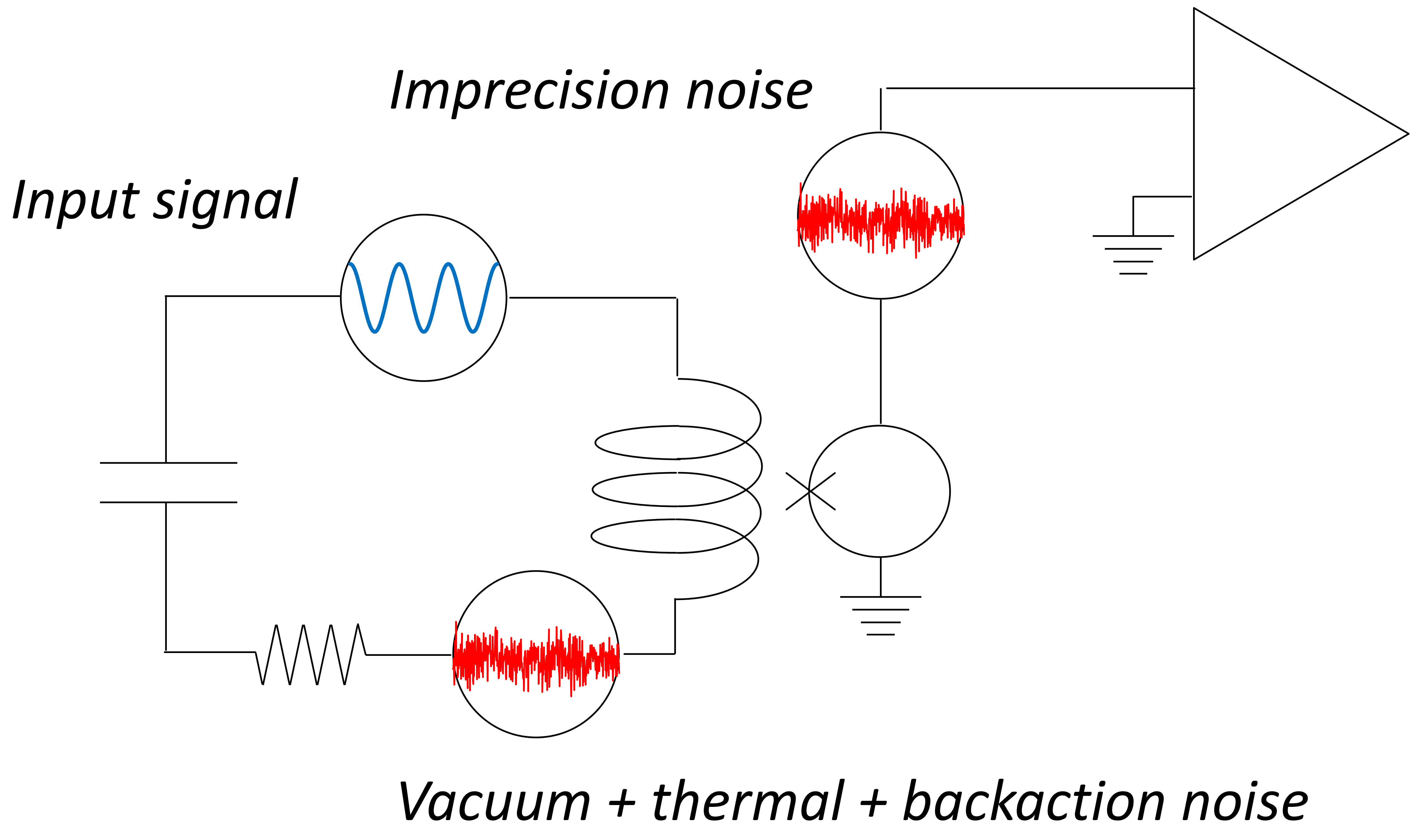
SQUIDs

- Superconducting Quantum Interference Device (SQUID)
- Invented by Arnold Silver, Ford
- Quantum interference pattern analogous to a two-slit interferometer



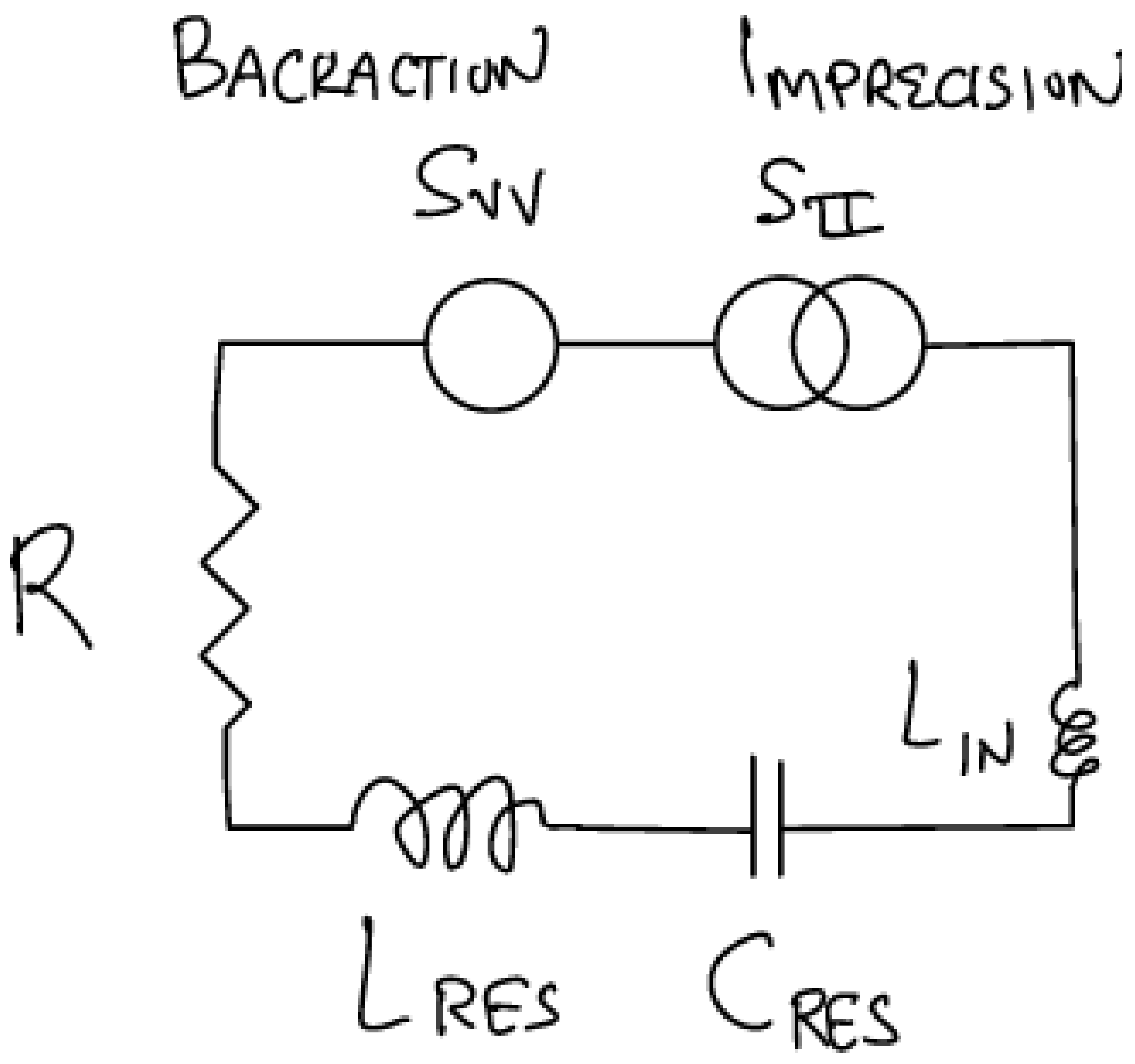


Noise sources in op-amp mode electrical measurement



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, can be subject to a Standard Quantum Limit.

How do you noise match an op-amp mode amplifier?



$$\omega_0 = \frac{1}{\sqrt{L_{\rm tot} C_{\rm res}}}$$

Our classical noise temperature definition:

$$4 k_{\rm B} T_{\rm n} \, {\rm Re}\{Z_{\rm res}\} = \mathcal{S}_{VV} + |Z_{\rm res}|^2 \mathcal{S}_{II} - 2\,{\rm Re}\{Z^*_{\rm res} \mathcal{S}_{IV}\}$$

On resonance $Z_{\rm res}(\omega_0) = R.$

$$4 k_{\rm B} T_{\rm n}(\omega_0) R = \mathcal{S}_{VV} + R^2 \mathcal{S}_{II} - 2R\,{\rm Re}\{\mathcal{S}_{IV}\}.$$

There are other definitions of noise temperature! (e.g. Caves) -> including vacuum noise in zero-temperature source. This is just the amplifier added noise.

See review: Clerk et al, RMP **82**, 1155 (2010)

Quantum limit on the added noise of an op-amp mode amplifier

$$\mathrm{Re}\{\mathcal{S}_{IV}\} = 0$$

Consider the special case of an amplifier without real correlations. This is generally true of a dc SQUID flux amplifier.

$$4k_B T_{\mathrm{n}}(\omega_0)R = \mathcal{S}_{VV} + R^2\mathcal{S}_{II}$$

Noise match

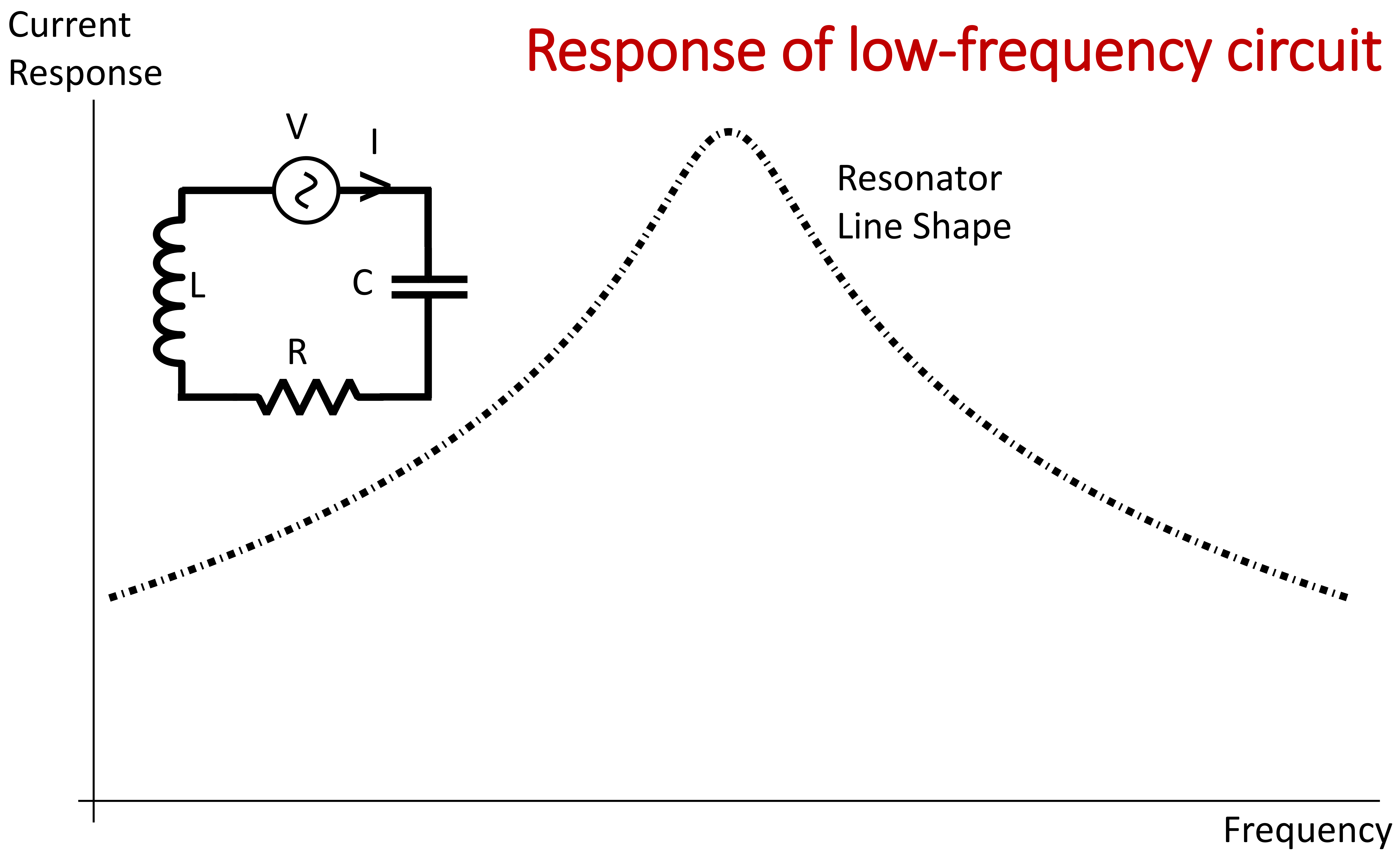
$$k_{\mathrm{B}}T_{\mathrm{min}} = \frac{1}{2}\sqrt{\mathcal{S}_{VV}\mathcal{S}_{II}}$$

Noise matched -> minimum noise temperature

$$k_{\mathrm{B}}T_{\mathrm{min}} = \hbar\omega_0/2$$

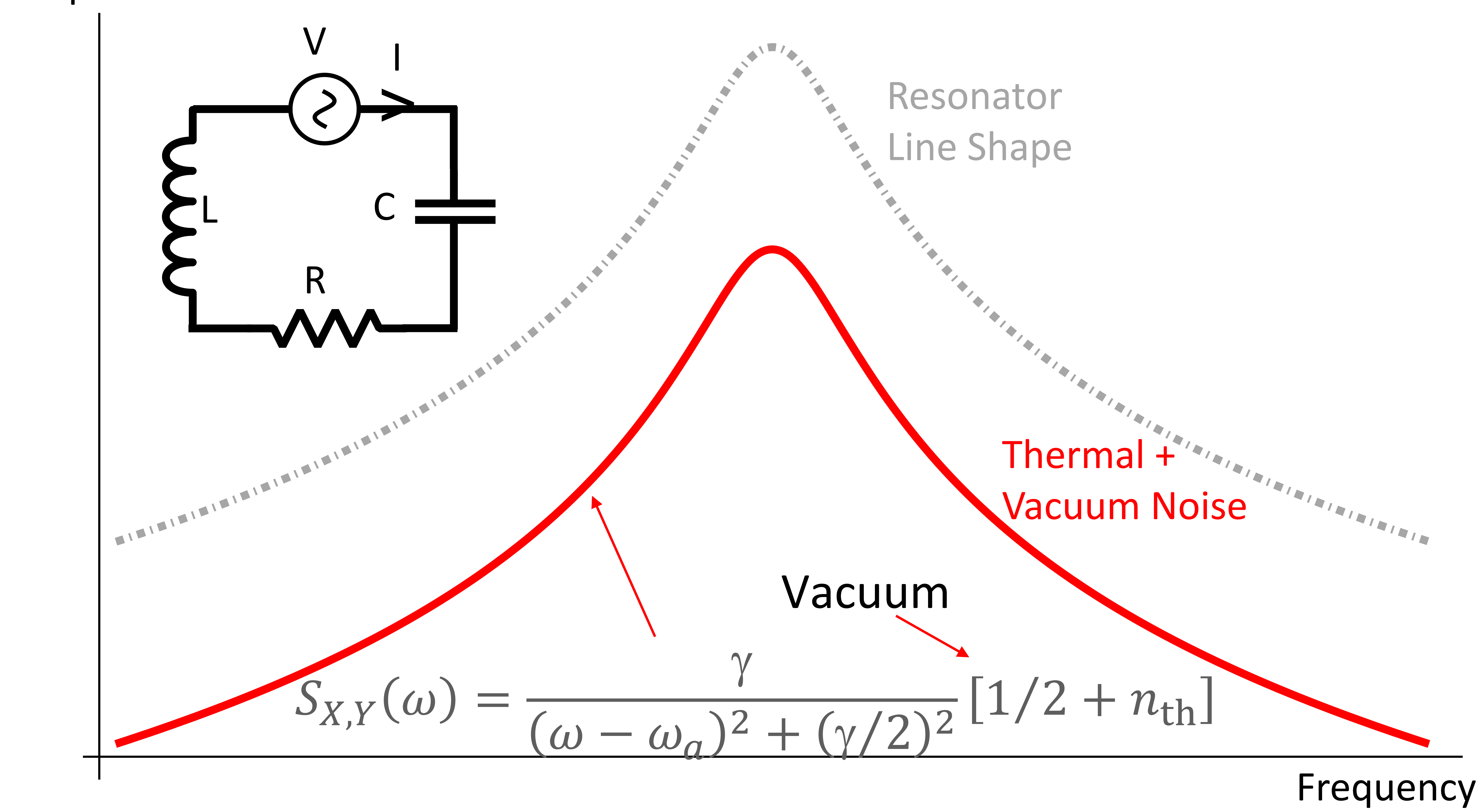
Quantum limit on noise temperature (Devoret / Schoelkopf, not Caves' definition).

Response of low-frequency circuit



There is more to noise matching than on-resonance noise!

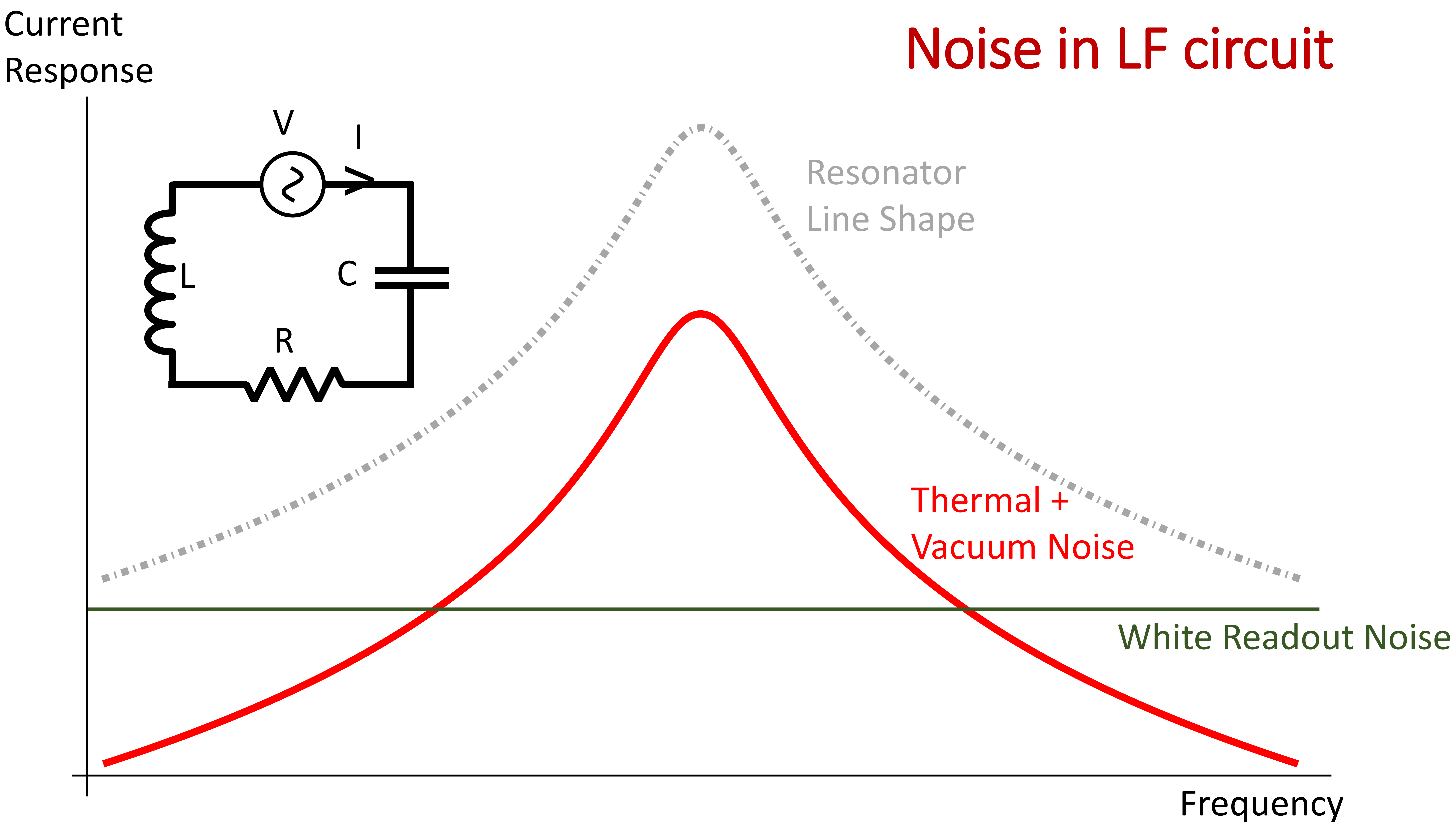
Noise in LF circuit



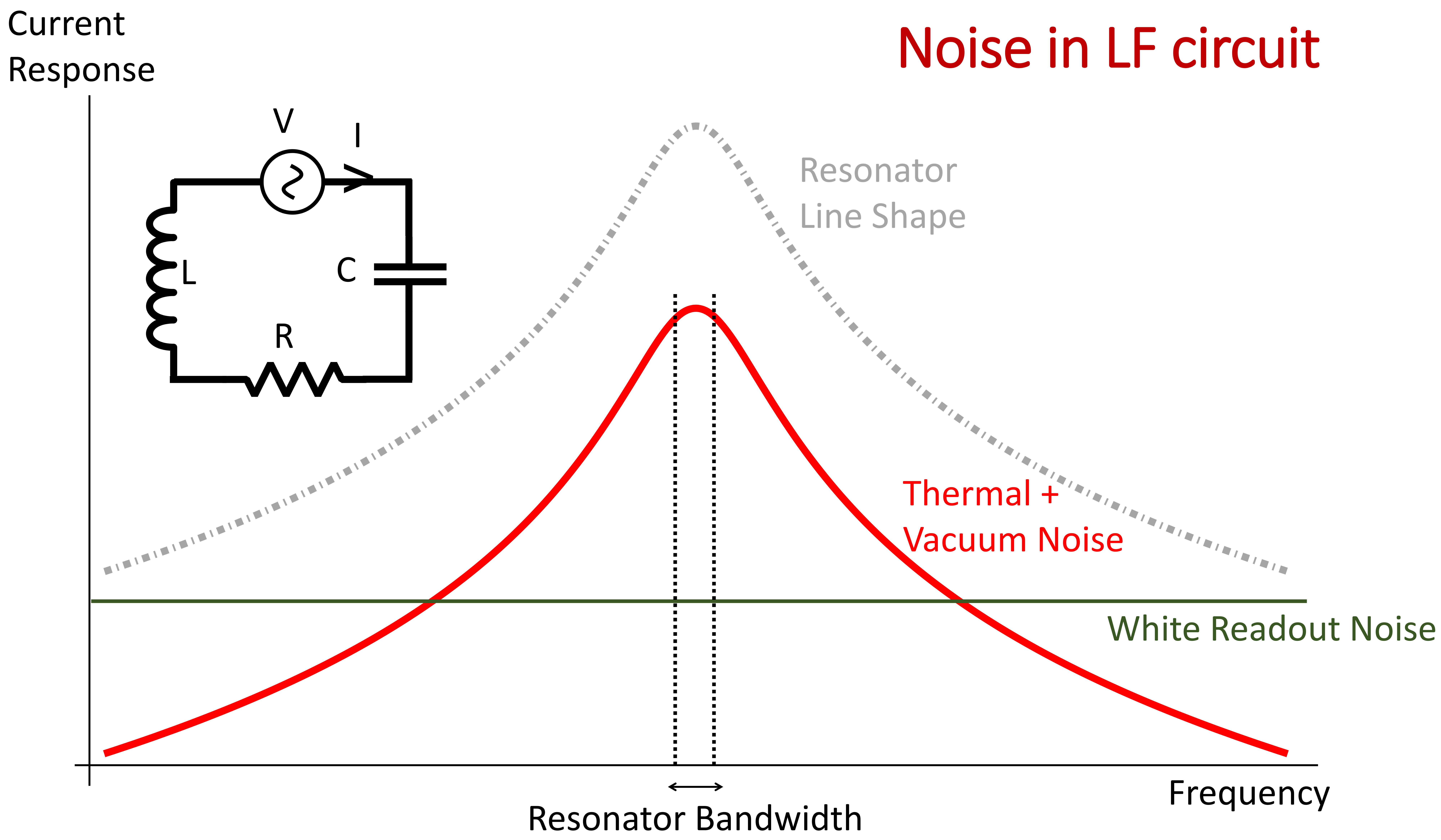
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}\left[1/2 + n_{\text{th}}\right]$$

Thermal occupation $$n_{\text{th}} = \left(\exp\left[\frac{\hbar\omega_a}{k_B T}\right] - 1\right)^{-1}$$

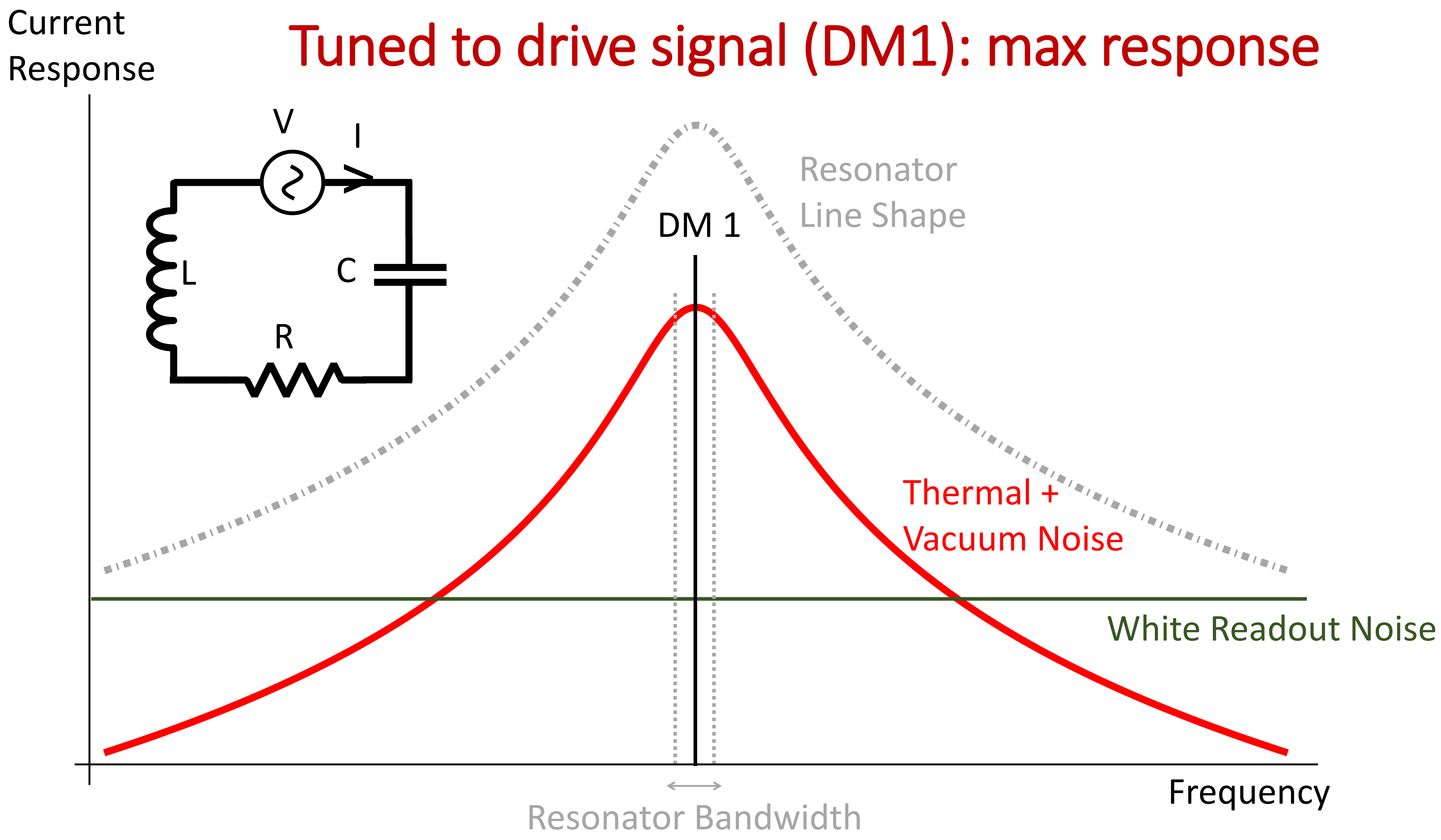
Noise in LF circuit



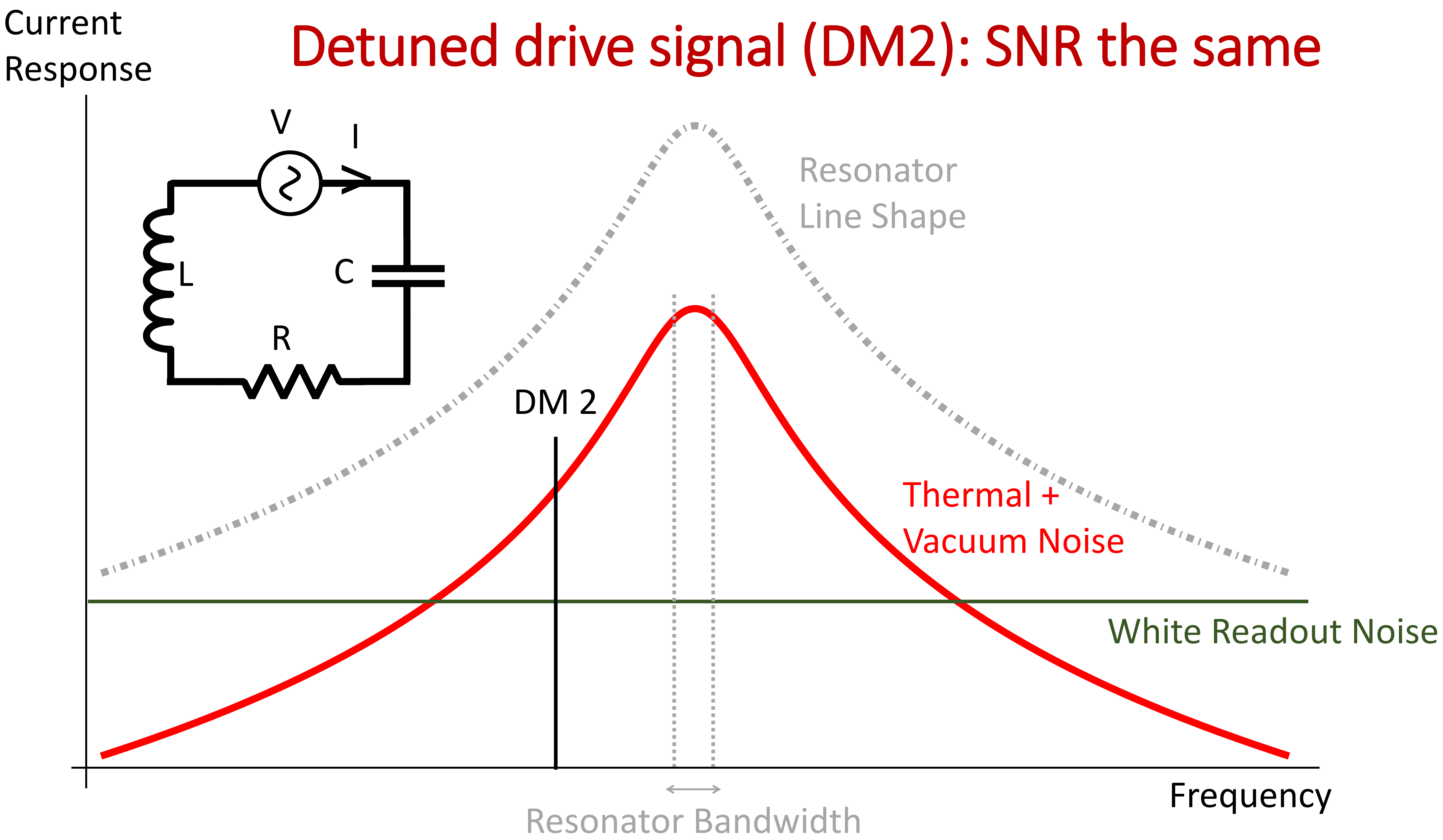
Noise in LF circuit



Tuned to drive signal (DM1): max response

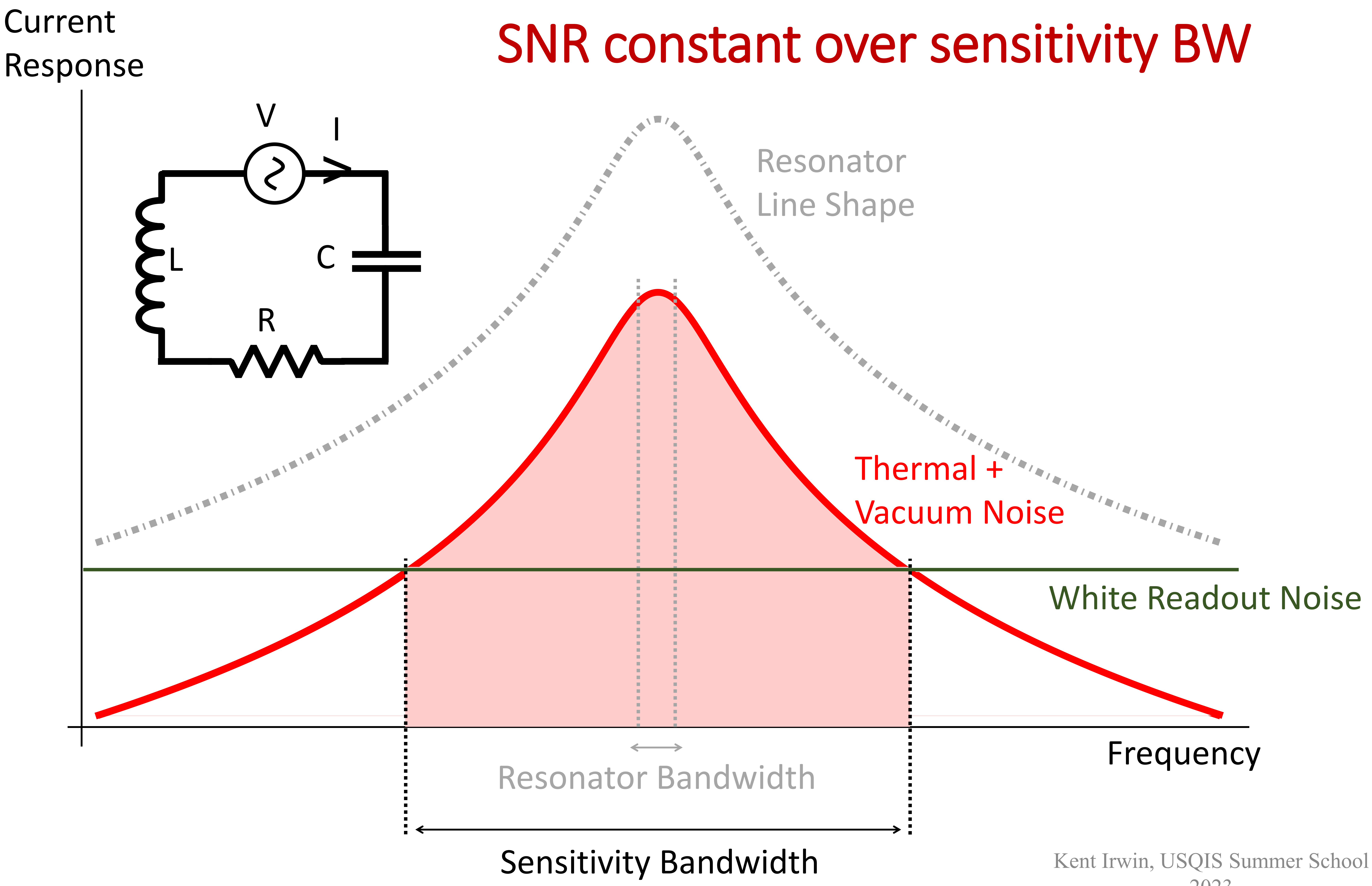


Detuned drive signal (DM2): SNR the same

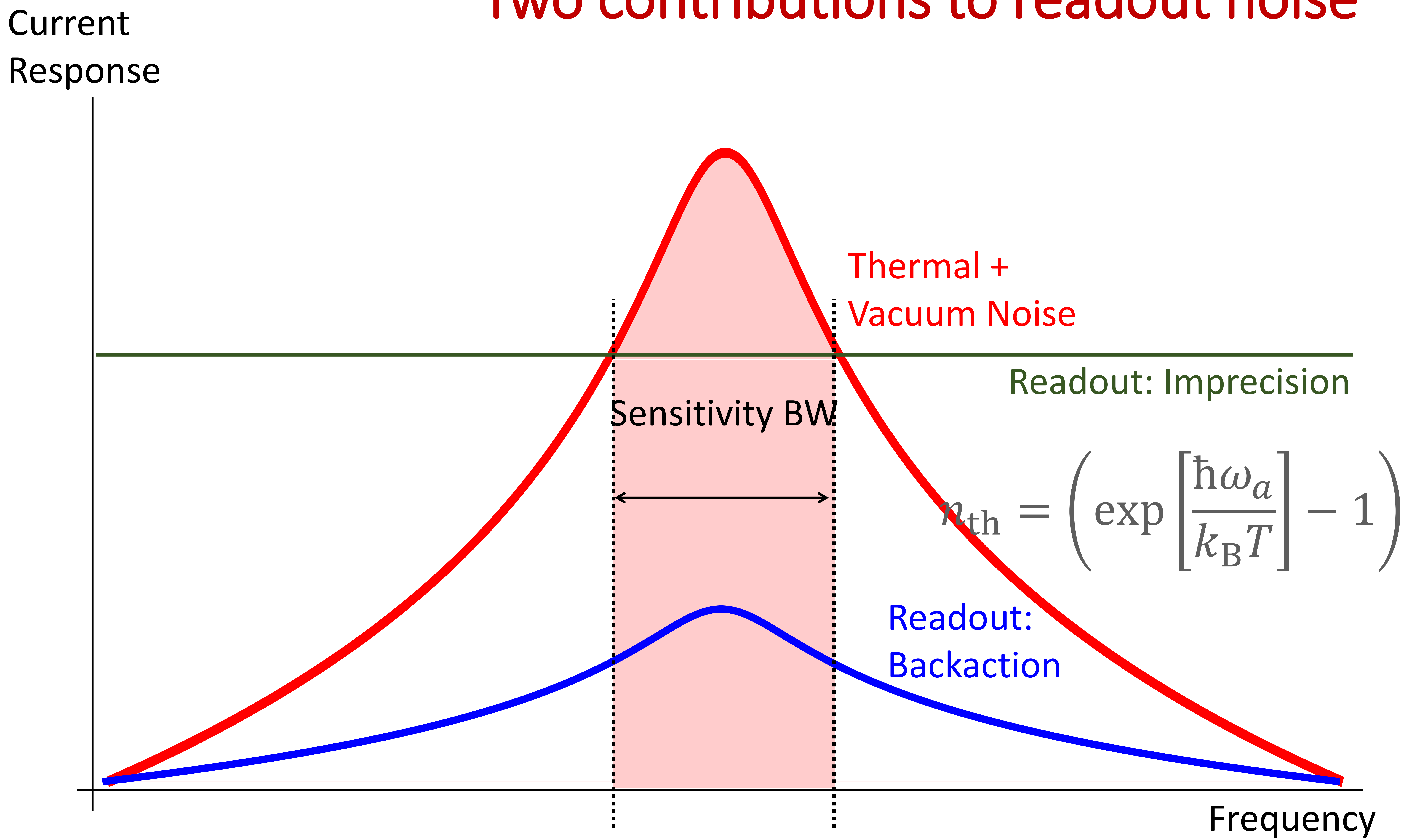


- SNR not degraded when readout subdominant to thermal noise

SNR constant over sensitivity BW



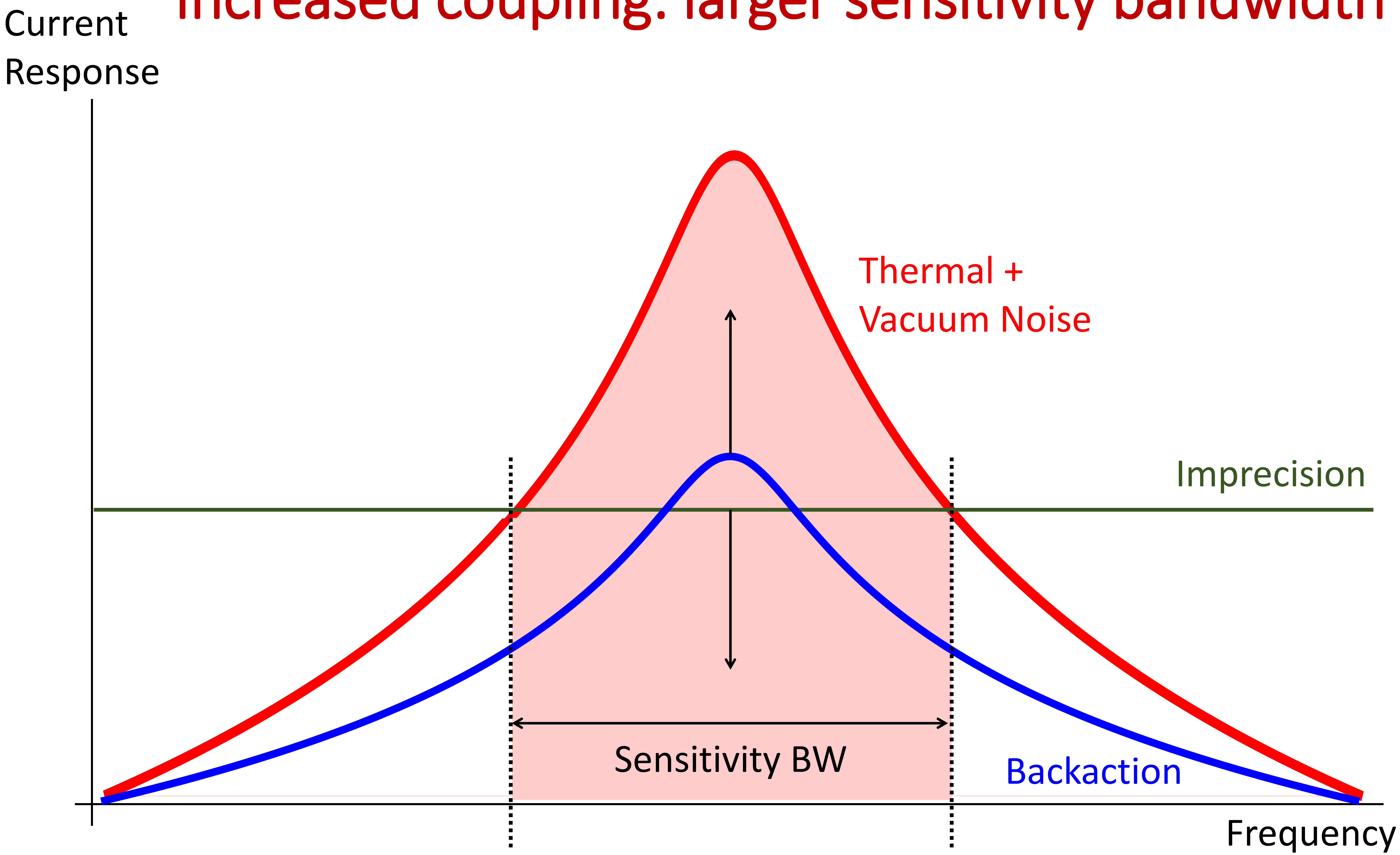
Two contributions to readout noise



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

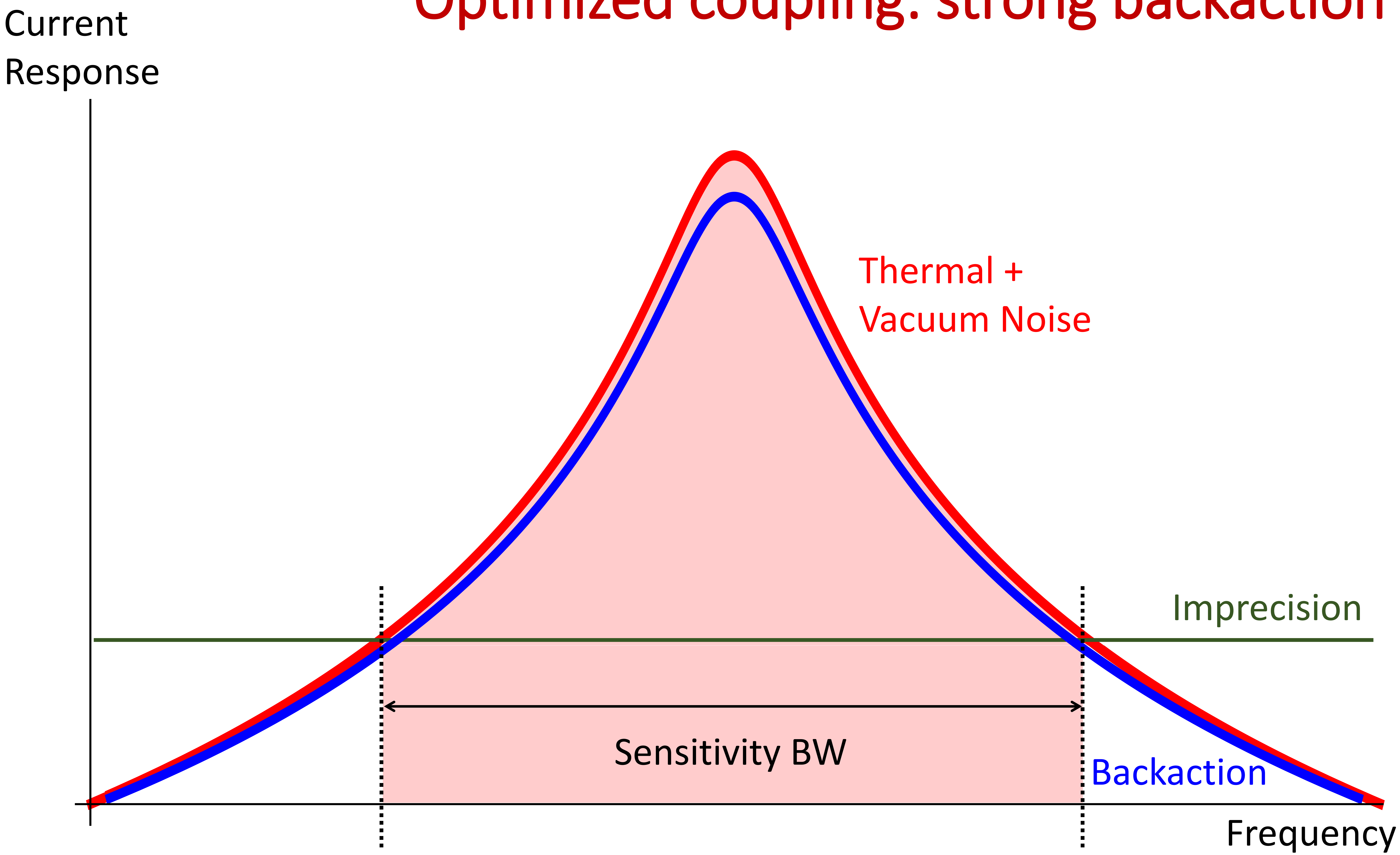
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}\left[1/2 + n_{\mathrm{th}} + n_{\mathrm{BA}}\right] + S_{\mathrm{IMP}}(\omega)$$

Increased coupling: larger sensitivity bandwidth



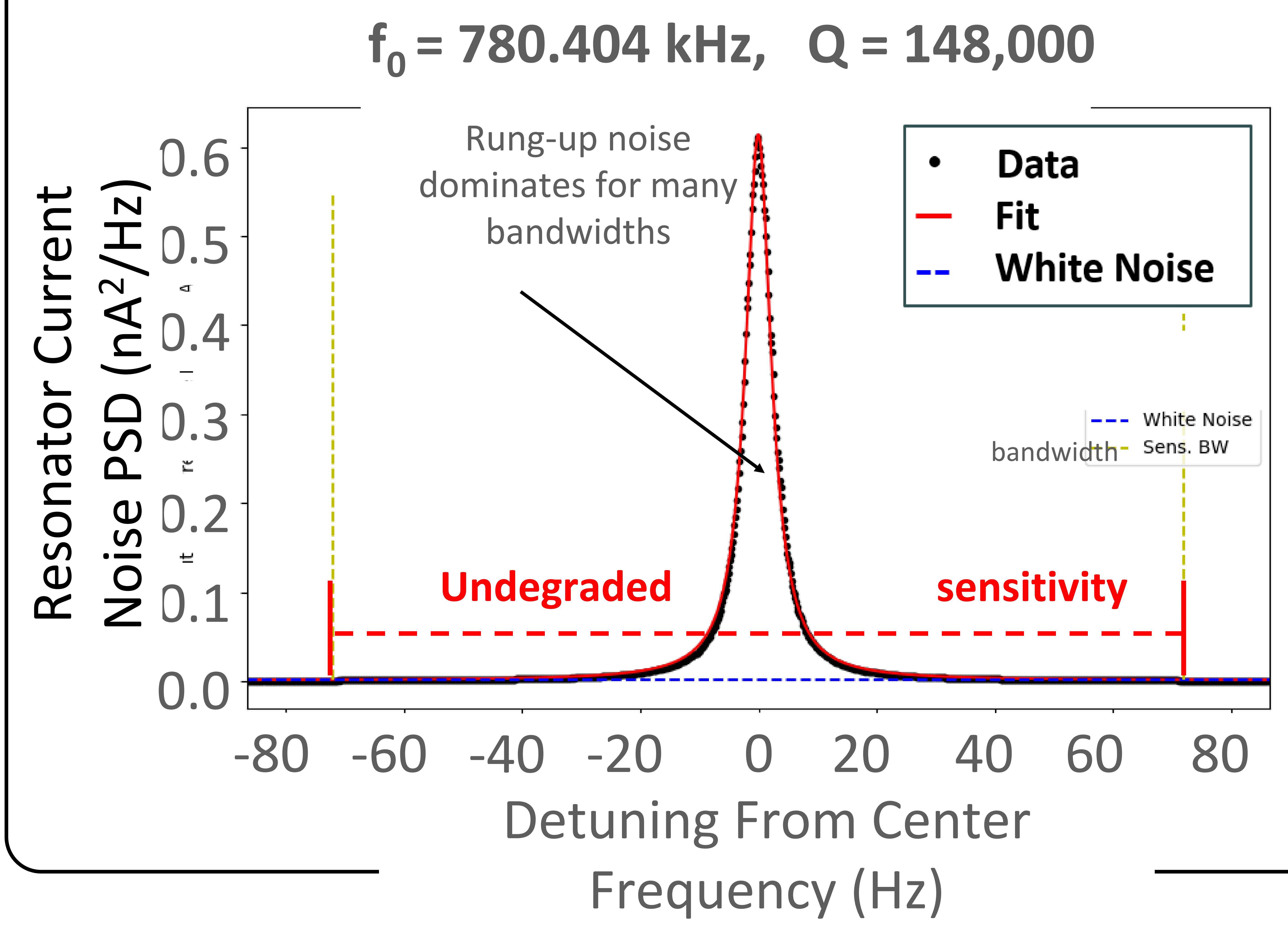
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}\left[1/2 + n_{\text{th}} + n_{BA}\right] + S_{\text{IMP}}(\omega)$$

Optimized coupling: strong backaction



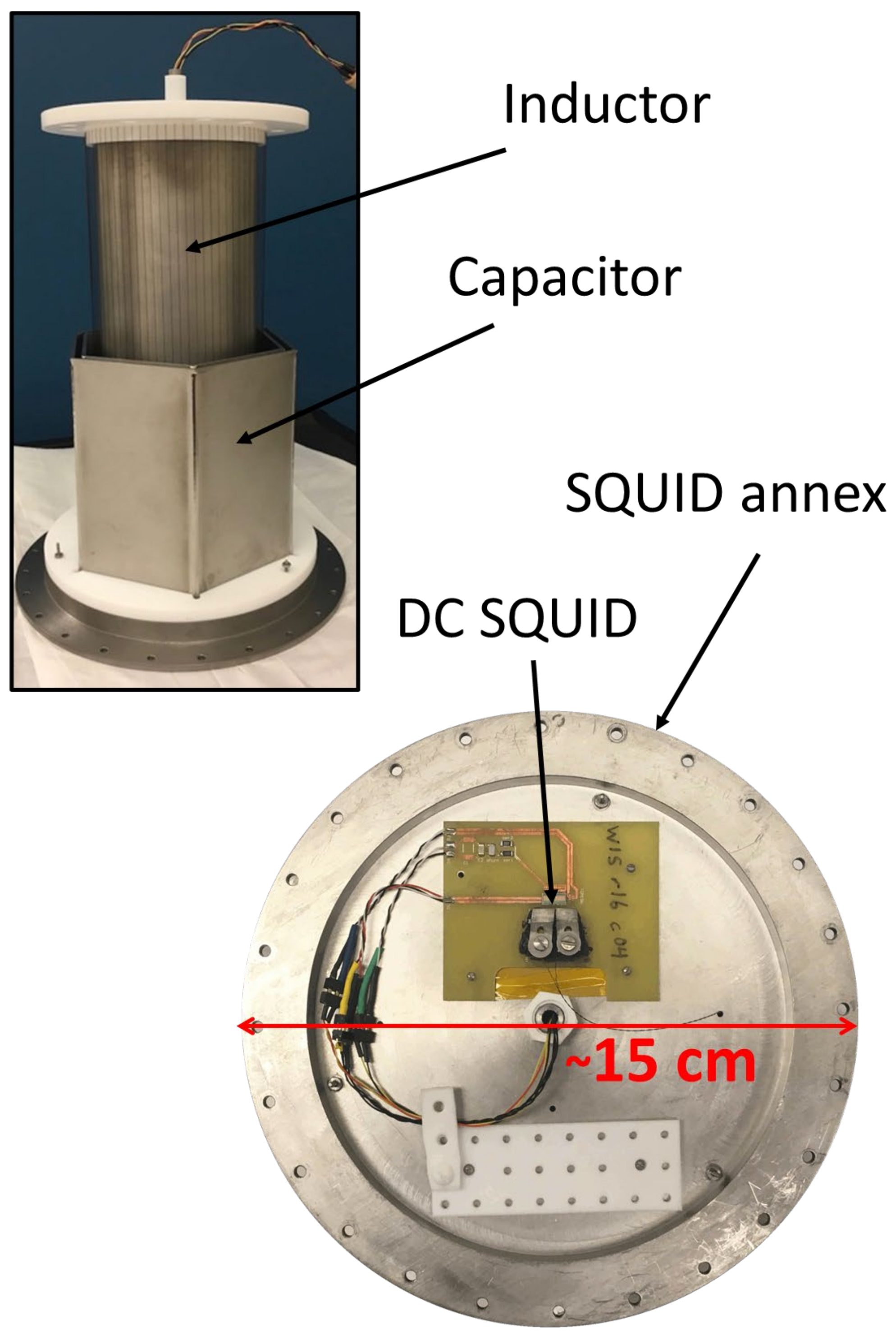
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}\left[1/2 + n_{\mathrm{th}} + n_{BA}\right] + S_{\mathrm{IMP}}(\omega)$$

Example of optimizing noise match for bandwidth with a dc SQUID



Resonator bandwidth: ~5 Hz
Sensitivity bandwidth: ~150 Hz

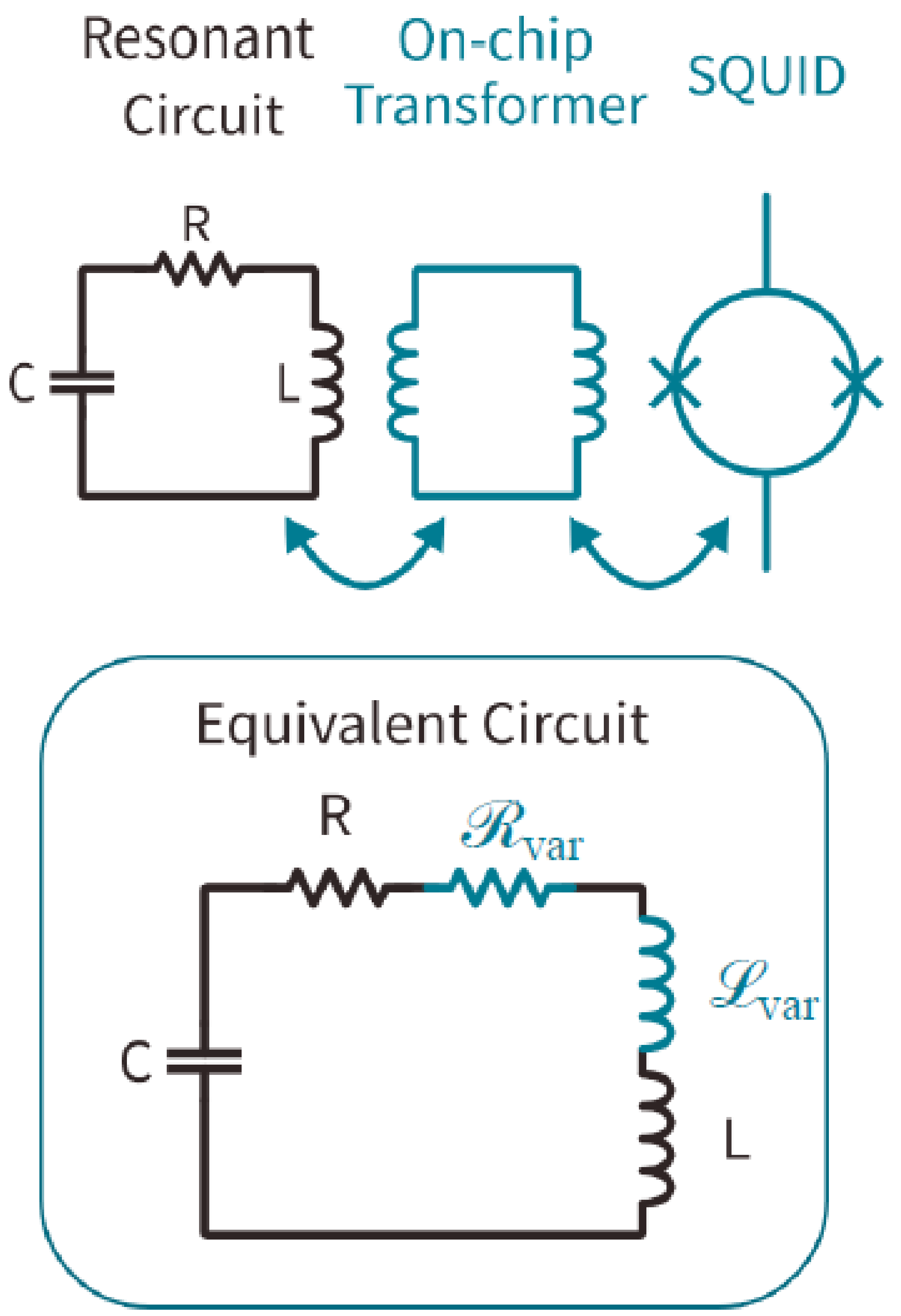
DMRadio Pathfinder

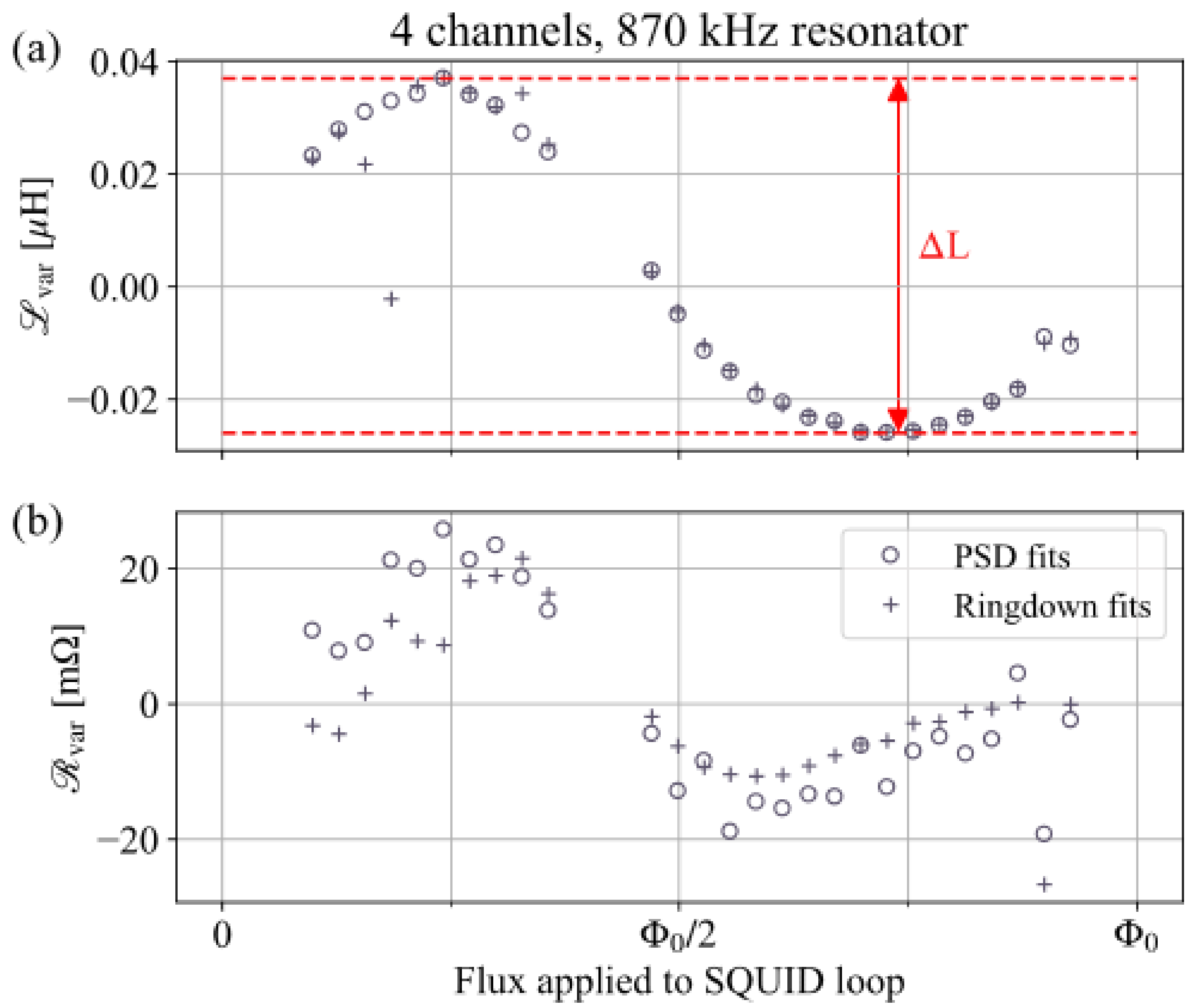


With optimized noise match, sensitivity bandwidth 30x larger than resonator bandwidth, with negligible degradation on resonance

Other dc SQUID issues

- Resistive shunts mean that significant power can be dissipated.
- Significant damping shifts frequency, degrades Q of input circuit.
- Energy sensitivity is limited by design, noise impedance is fixed.
- Challenging to truly thermalize below ~100mK.

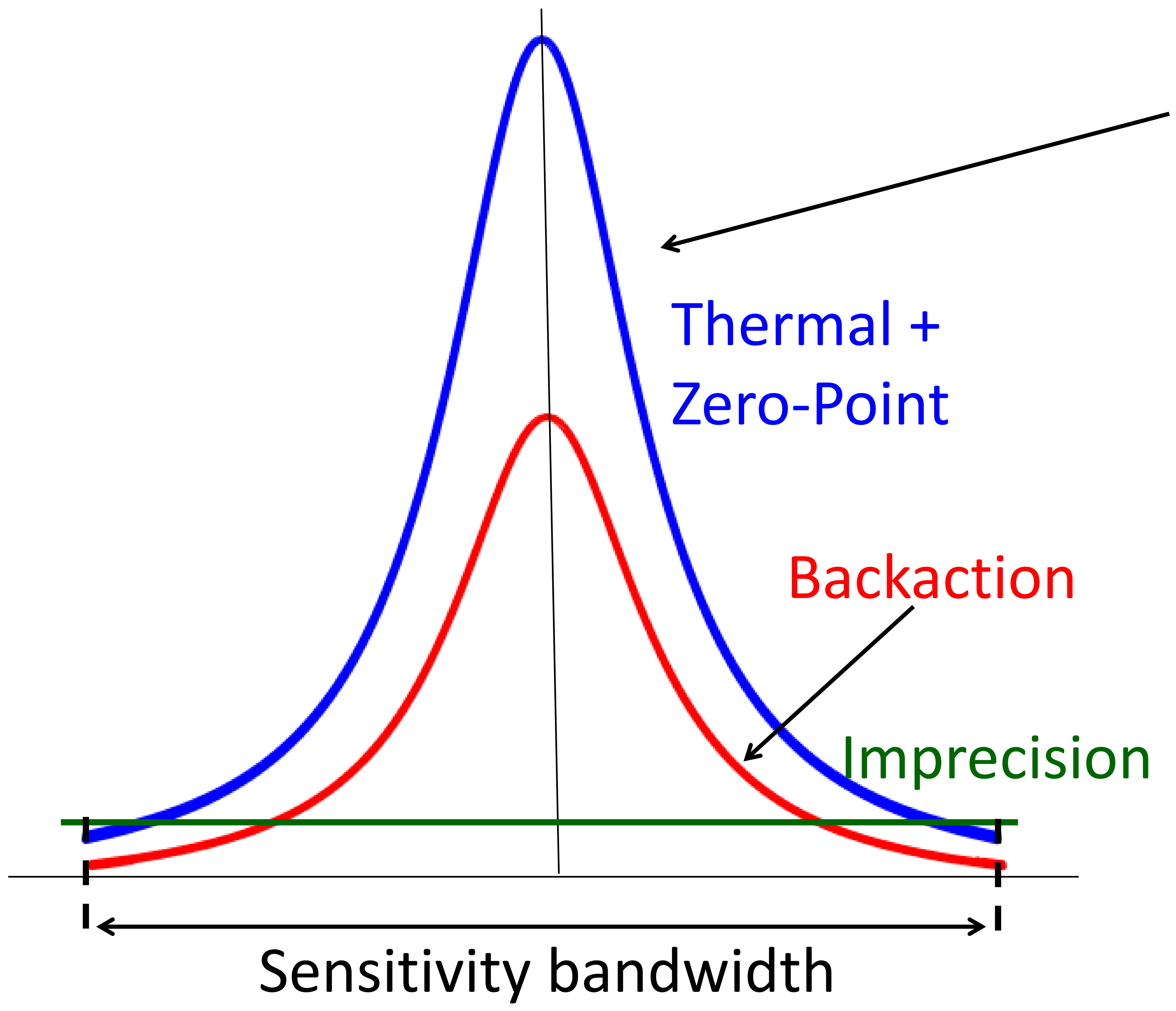




	ΔL	ΔR
870 kHz resonator		
1 channel	14.4 nH	48.9 mΩ
4 channels	63.0 nH	44.9 mΩ
630 kHz resonator		
2 channels	42.9 nH	25.4 mΩ
4 channels	63.1 nH	17.8 mΩ

E. C. van Assendelft, *et al.* IEEE Transactions on Applied Superconductivity (2023).

“Click” photon counting is not useful when $hf \ll k_B T$



- $\sqrt{N}$ thermal fluctuations in the number of resonator photons
- Sensitivity not improved by photon “click” counting
- Preparing a high-N Fock state difficult

$\rightarrow$ **Need other techniques**

- ***Backaction evasion*** to reduce both imprecision and backaction noise to below the standard quantum limit
- Or squeeze thermal noise

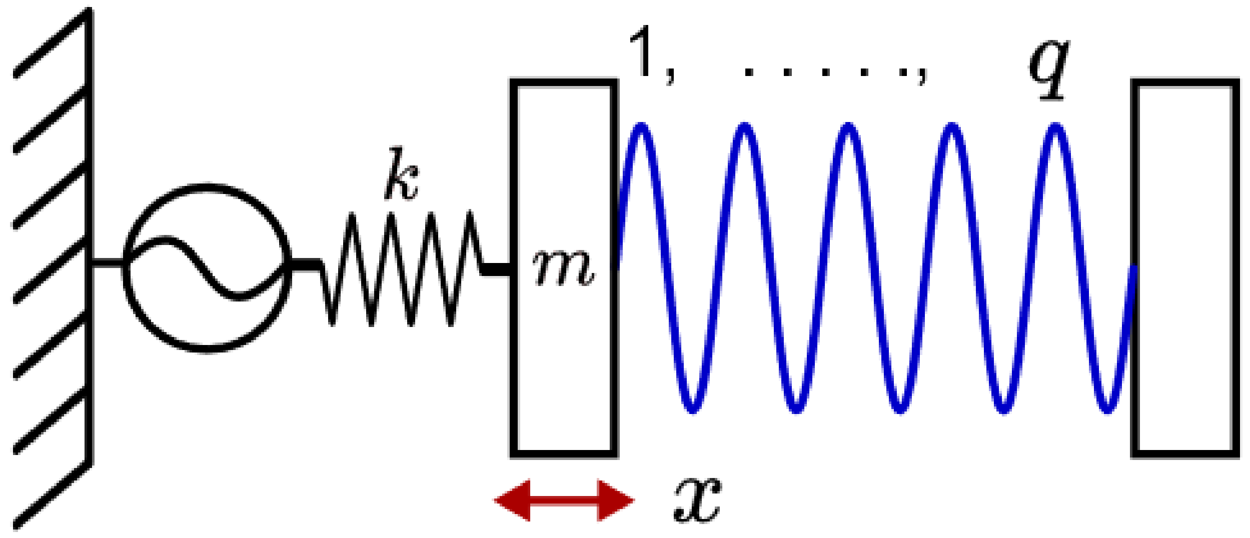
Better science thru evading the Standard Quantum Limit

LIGO Livingston

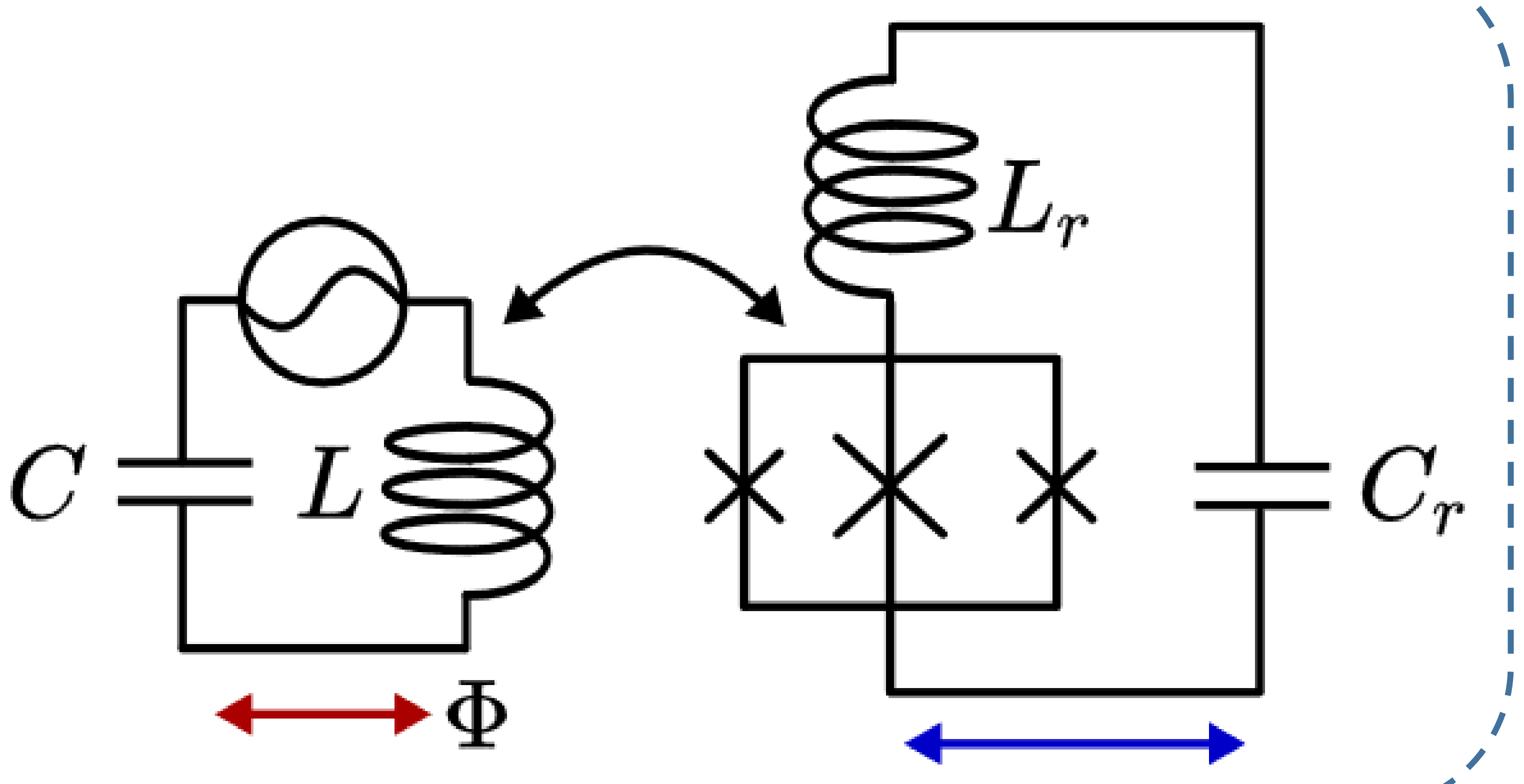
- LIGO performs quantum measurements at better than the SQL to measure gravitational waves more sensitively
- LIGO uses squeezing to improve interferometry, but it could also utilize backaction evasion (BAE).

Radio-Frequency Quantum Upconverters: Analogous to Optomechanical Systems

LIGO:



Axion detector with RQU:



$$\omega_a = \sqrt{\frac{k}{m}} \quad \omega_b = \frac{2\pi qc}{l(x)}$$

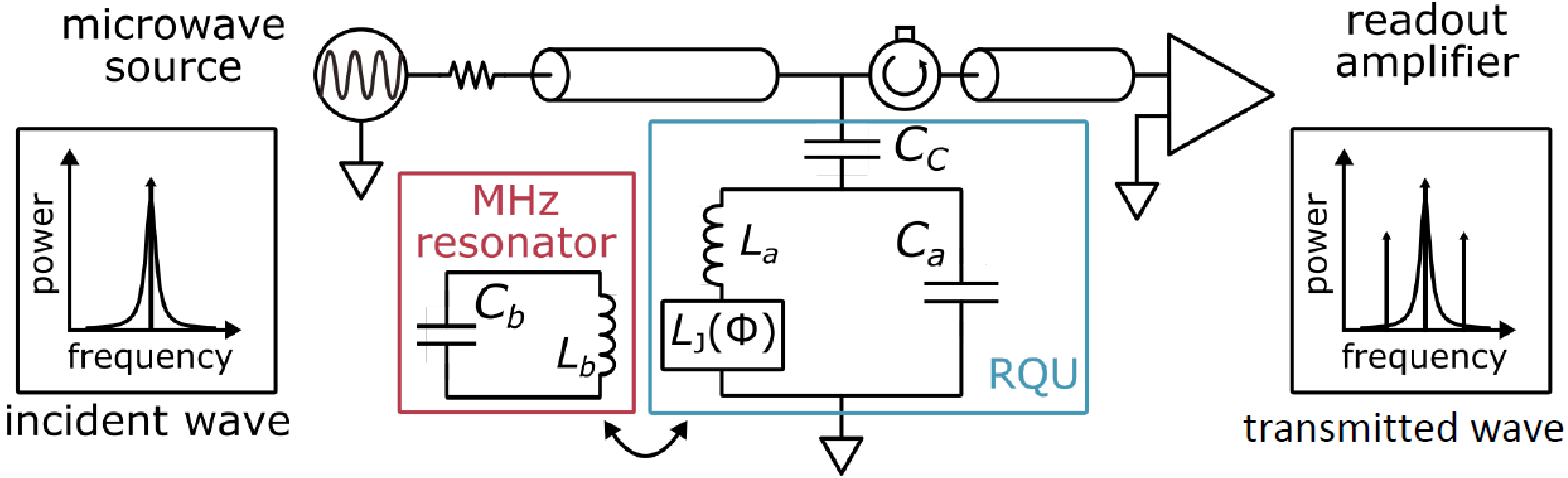
$$\omega_a = \sqrt{\frac{1}{LC}} \quad \omega_b = \sqrt{\frac{1}{L_r(\Phi)C_r}}$$

Optomechanical Hamiltonian

$$\widehat{\mathrm{H}} = \hbar\omega_a\left(\hat{a}^\dagger\hat{a} + 1/2\right) + \hbar\omega_b\left(\hat{b}^\dagger\hat{b} + 1/2\right) + \widehat{\mathrm{H}}_{\mathrm{INT}}$$

$$\widehat{\mathrm{H}}_{\mathrm{INT}} = -\hbar\hat{F}\hat{b}^\dagger\hat{b}\left(\hat{a}^\dagger + \hat{a}\right)/\sqrt{2}$$

RF-to-Microwave Quantum Upconversion



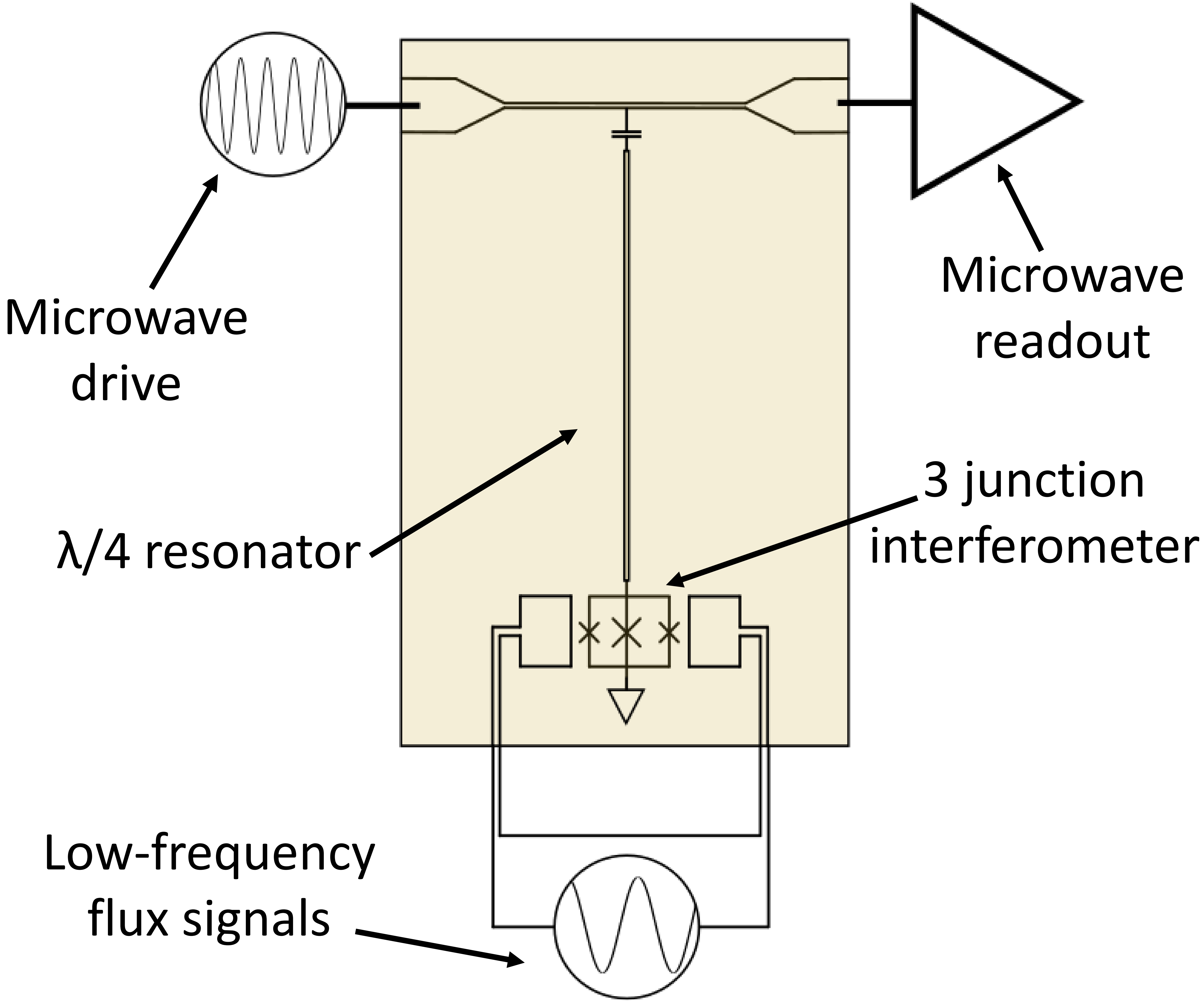
Optomechanical Hamiltonian

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

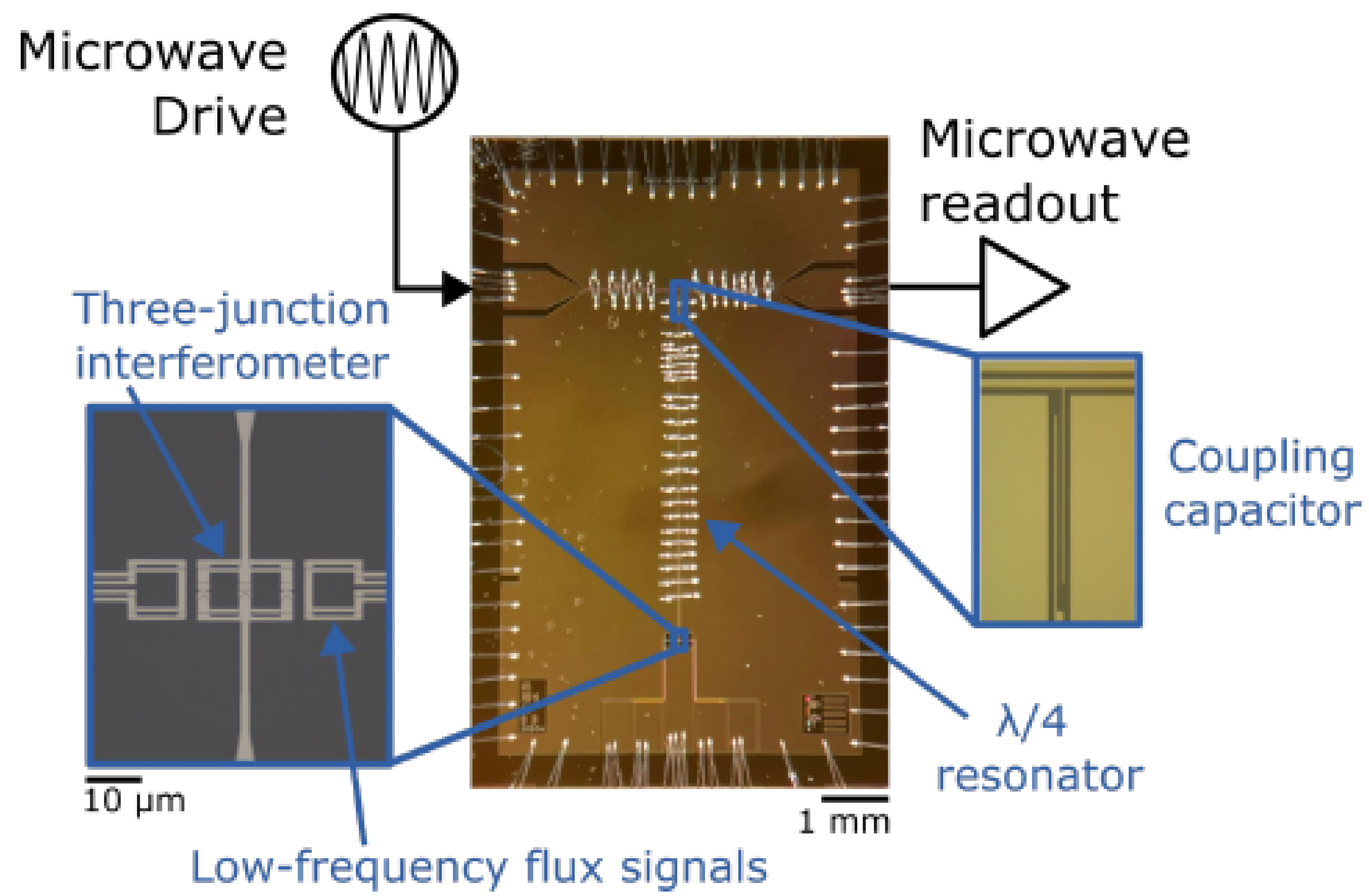
$$\hat{H}_{INT} = -\hbar\hat{F}\hat{b}^\dagger\hat{b}\left(\hat{a}^\dagger + \hat{a}\right)/\sqrt{2}$$

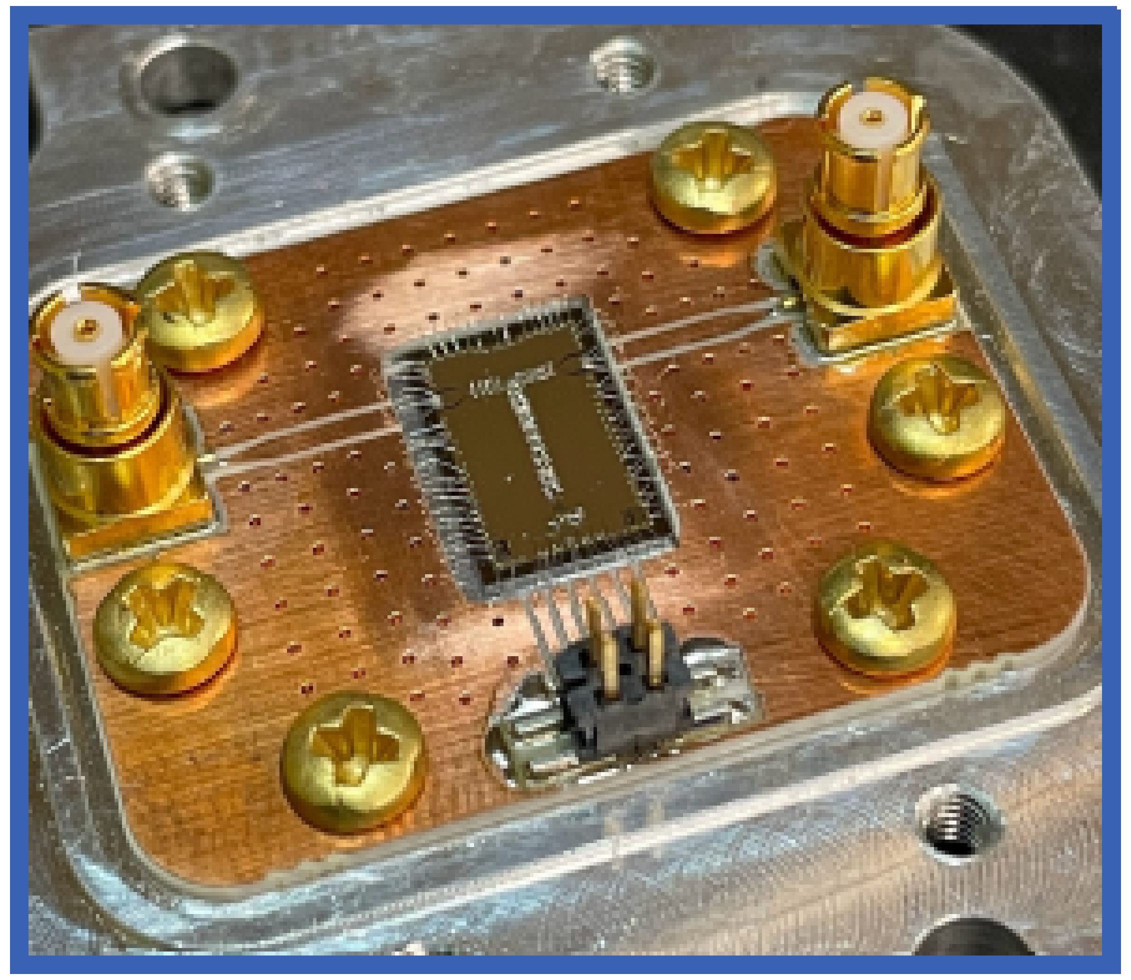
Implementing the RQU

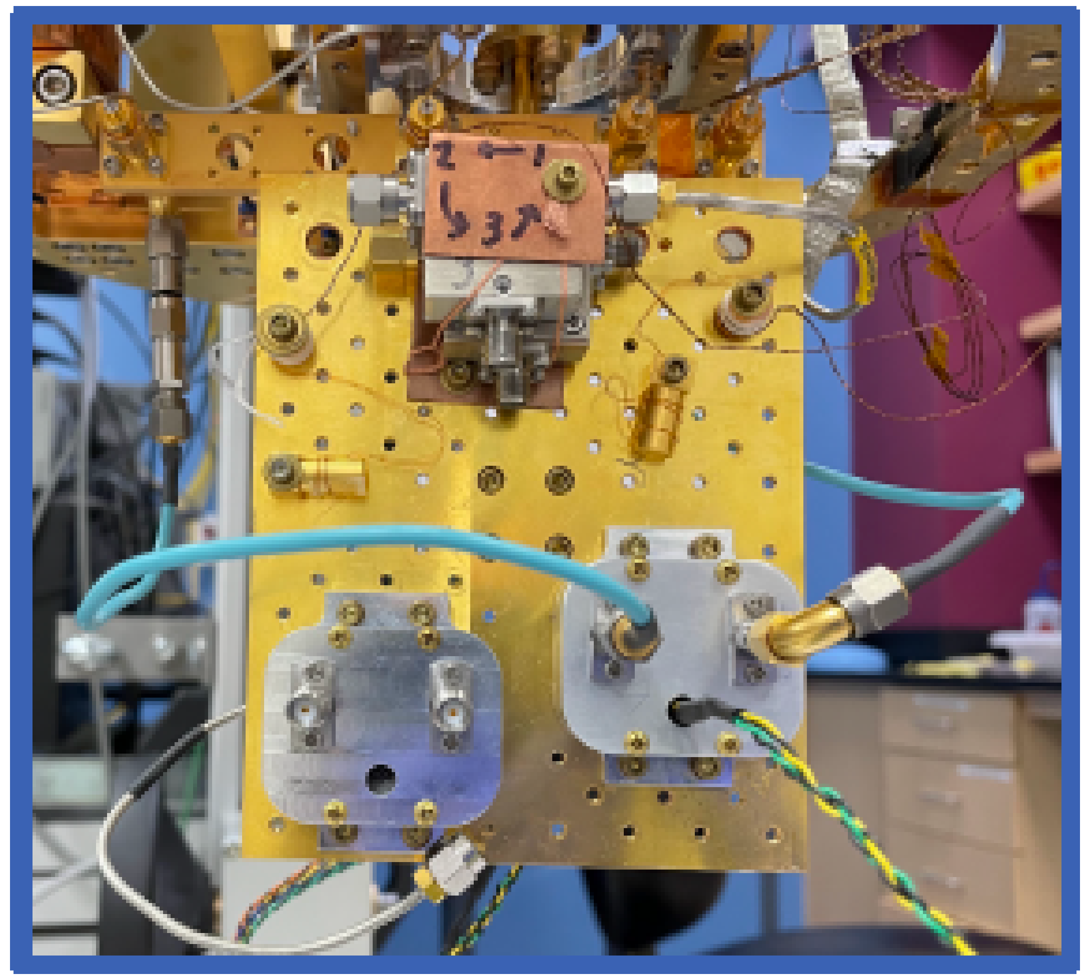
- A tunable inductor is made of an interferometer with three Josephson junctions and two loops.
- The microwave resonator is a quarter wave stub of coplanar waveguide.
- Flux inputs couple a low-frequency input signal into the interferometer.
- Low-frequency (~MHz) signal is converted to microwave signal (~6 GHz)



Implementing the RQU

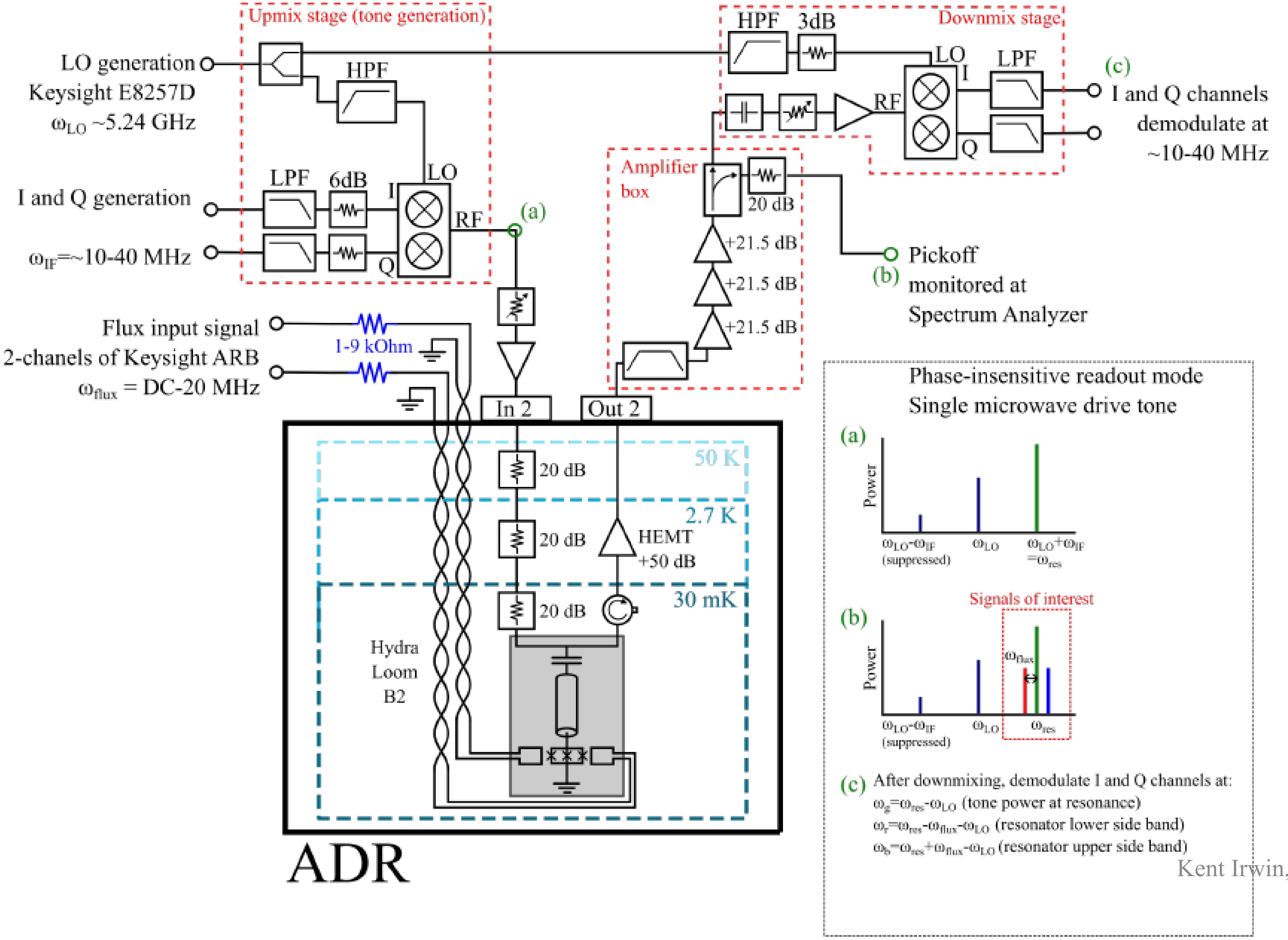




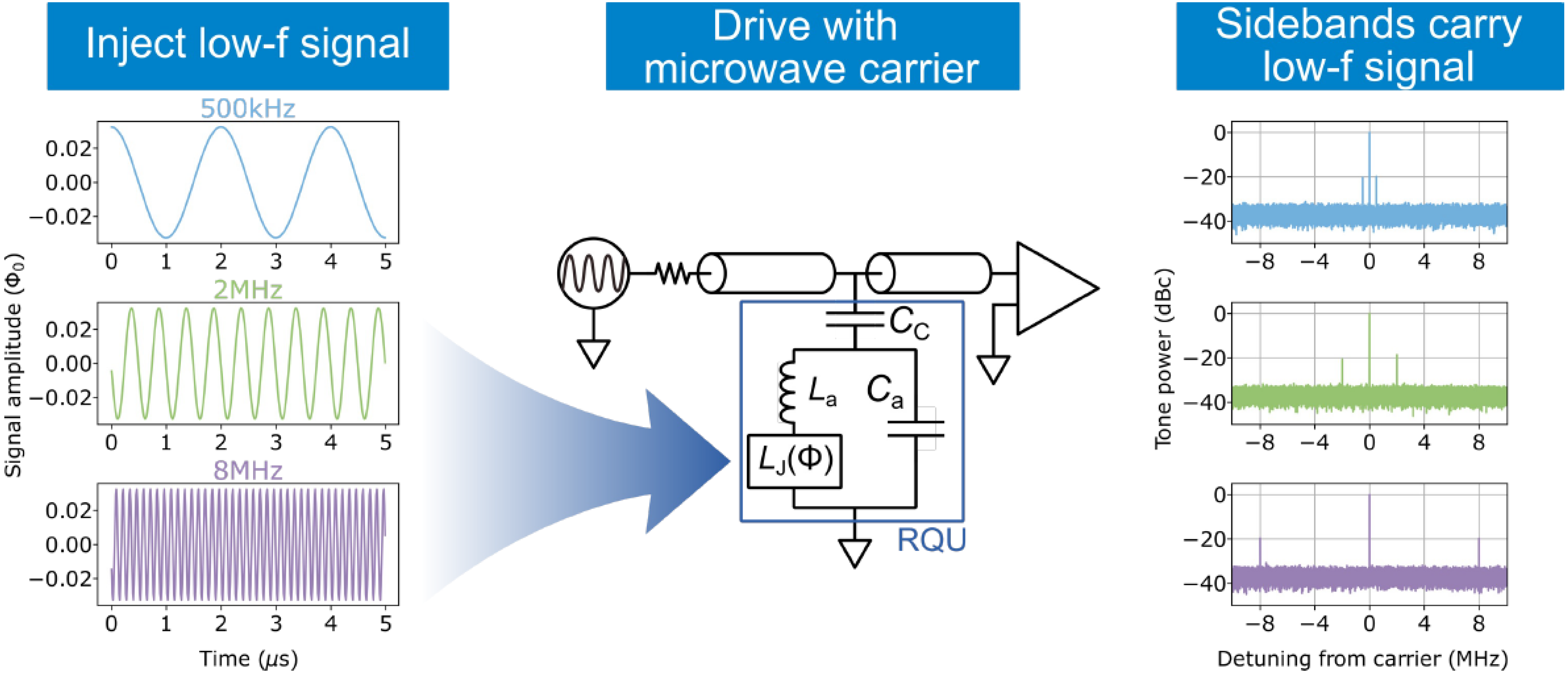


- Al-AlOx-Al on silicon substrate.
- Single deposition process using shadow evap.
- Symmetric 3-junction interferometer with larger central junction inductance.
- Single-turn flux signal input loops next to interferometer.
- Coplanar waveguide quarter-wave resonator.
- Capacitor couples the resonator to the transmission line.

RQU Readout Chain



Data Illustrating RF Upconversion

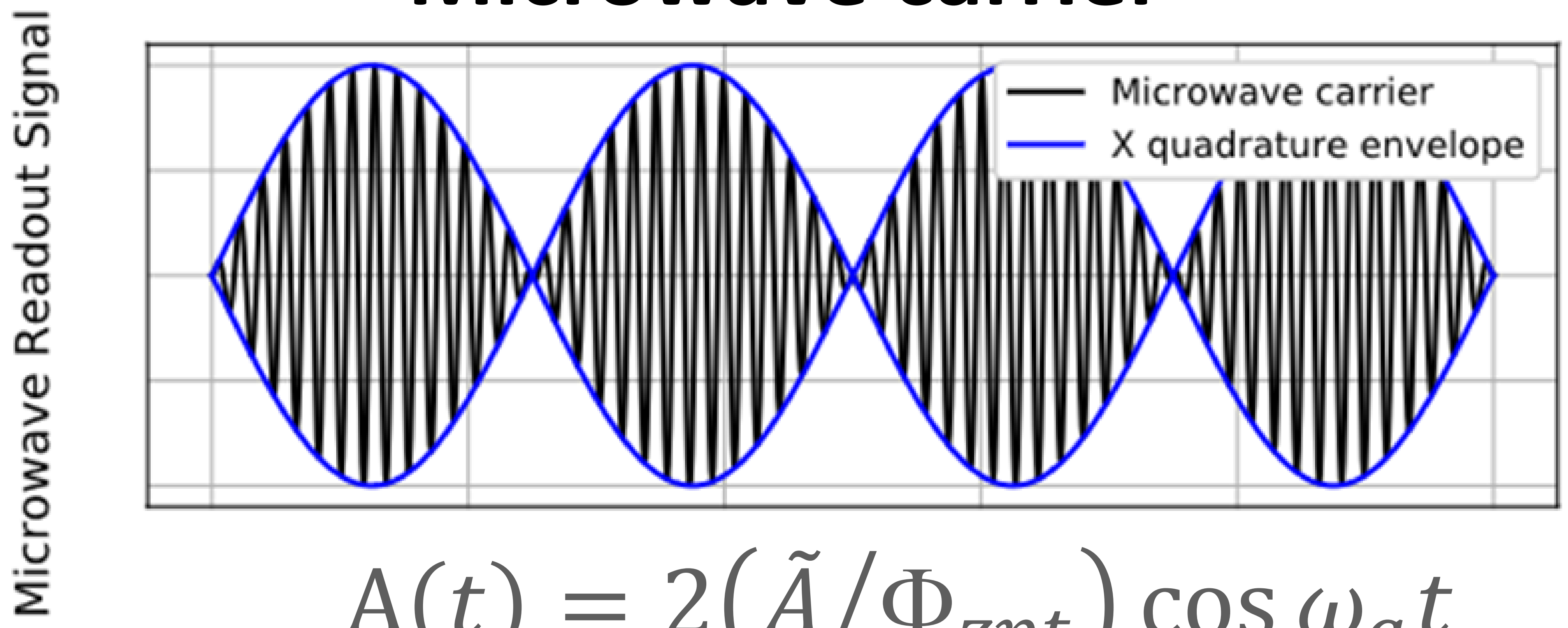


- Data illustrating upconversion in RQU
- The signal information is upconverted to symmetric sidebands on the microwave carrier tone.

Phase-Sensitive Upconversion

If the carrier tone is amplitude modulated in phase with the X-quadrature of the input signal, phase-sensitive amplification of only the X-quadrature is achieved.

Microwave carrier



$$A(t) = 2\left(\tilde{A}/\Phi_{zpt}\right)\cos\omega_a t$$

Clerk, *New Journ. Phys.* **10,** 095010 (2008).

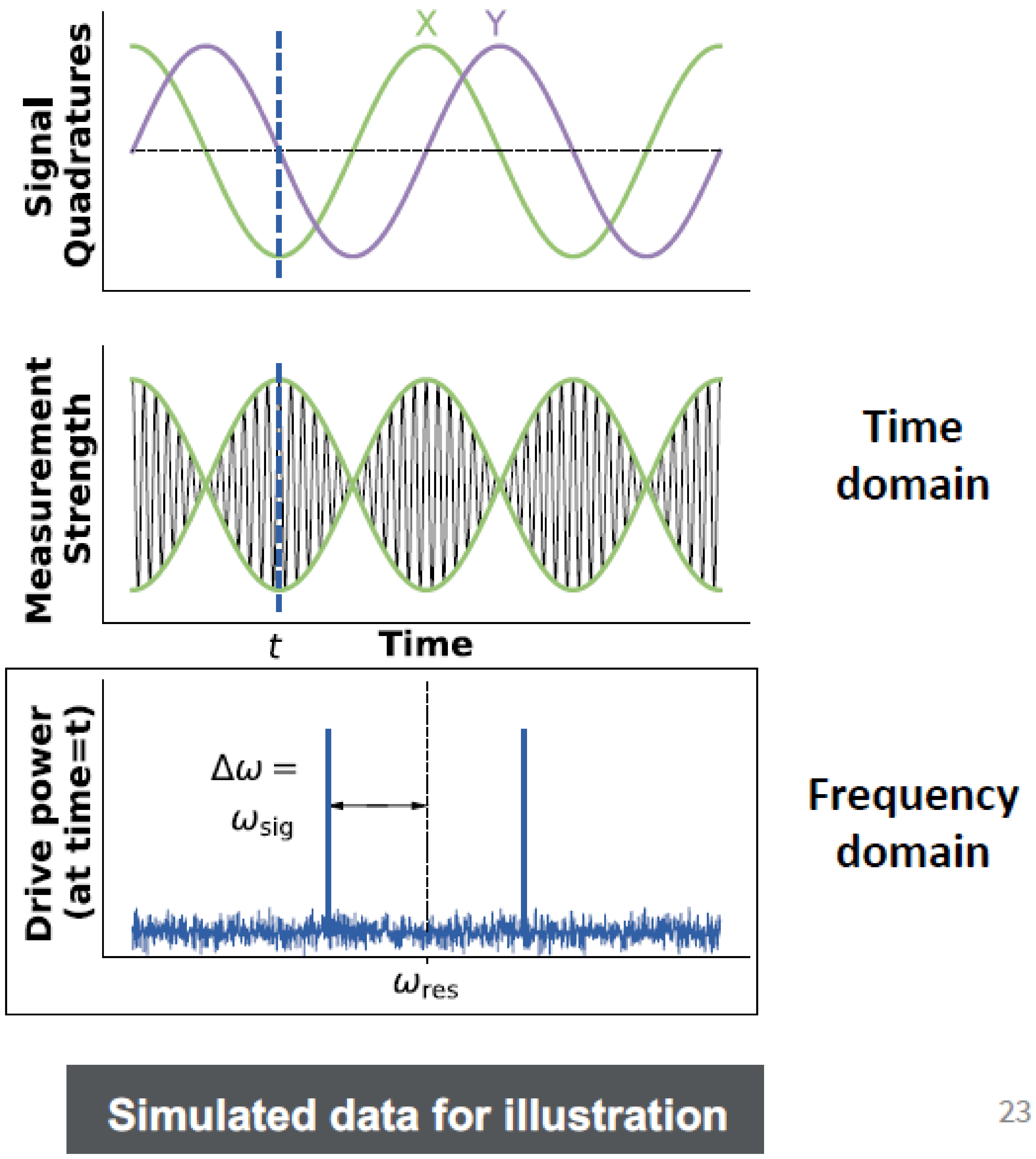
$$\hat{H} = \hbar\omega_a\left(\hat{a}^\dagger\hat{a} + 1/2\right) + \hbar\omega_b\left(\hat{b}^\dagger\hat{b} + 1/2\right) + \hat{H}_{INT}$$

$$\hat{H}_{INT} = -\hbar A\hat{F}\hat{\Phi} = -\sqrt{2}\hbar\tilde{A}\hat{F}\left[\hat{X}(1 + \cos(2\omega_a t)) + \hat{Y}\sin(2\omega_a t)\right]$$

If the carrier tone is amplitude modulated in phase with the X-quadrature of the input signal, phase-sensitive upconversion of only the X-quadrature is achieved (averaged over multiple cycles).

How to achieve amplitude modulation

- Measurement strength depends on microwave drive amplitude.
- A smooth amplitude modulation envelope, averaged over time, will contain no information about the Y quadrature.
- Create the amplitude modulated drive by injecting two microwave tones detuned from the resonant frequency by $\pm\omega_{sig}$



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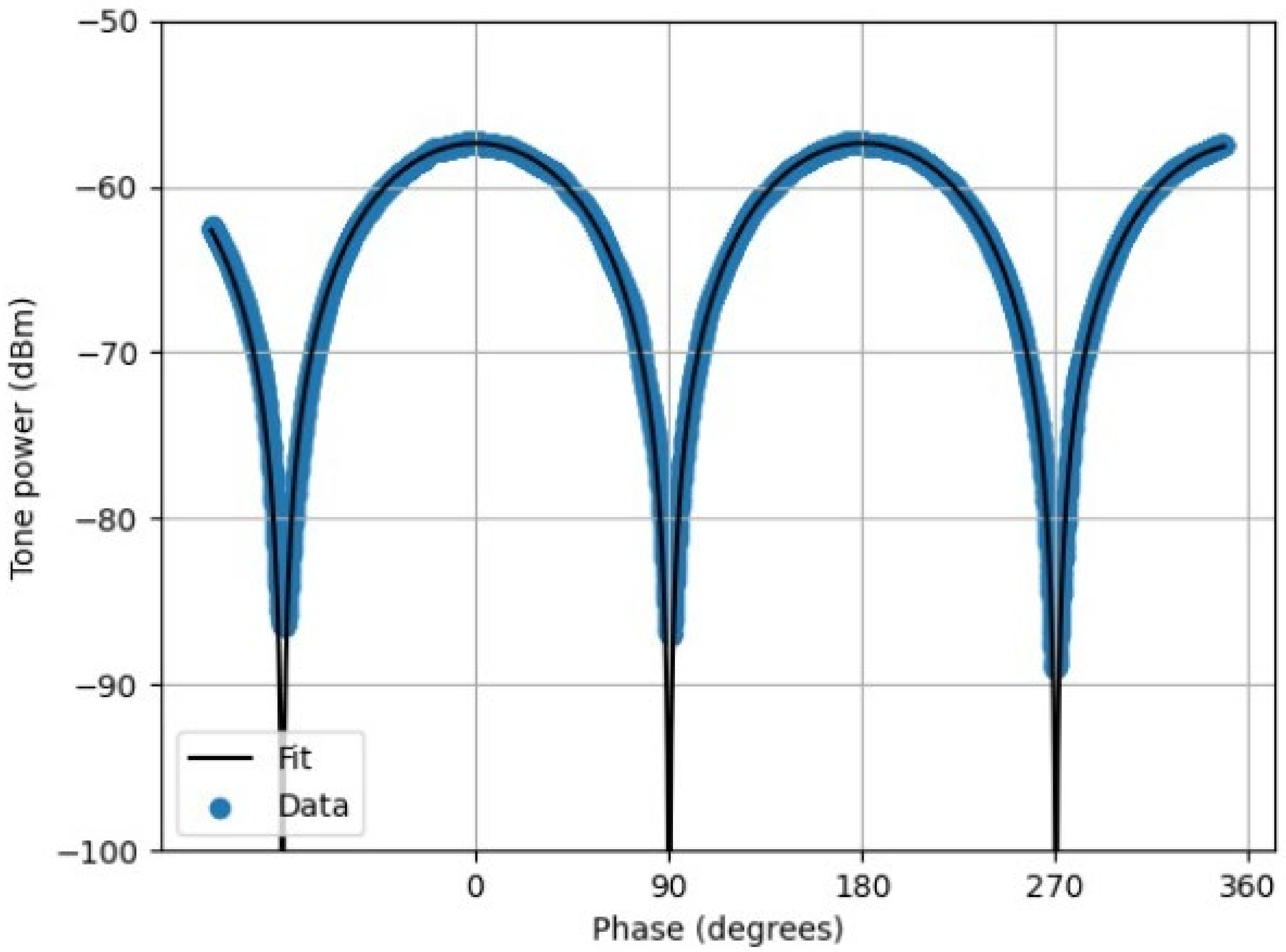
Demonstrated RQU phase-sensitive gain

Input: 5 MHz flux signal into an RQU

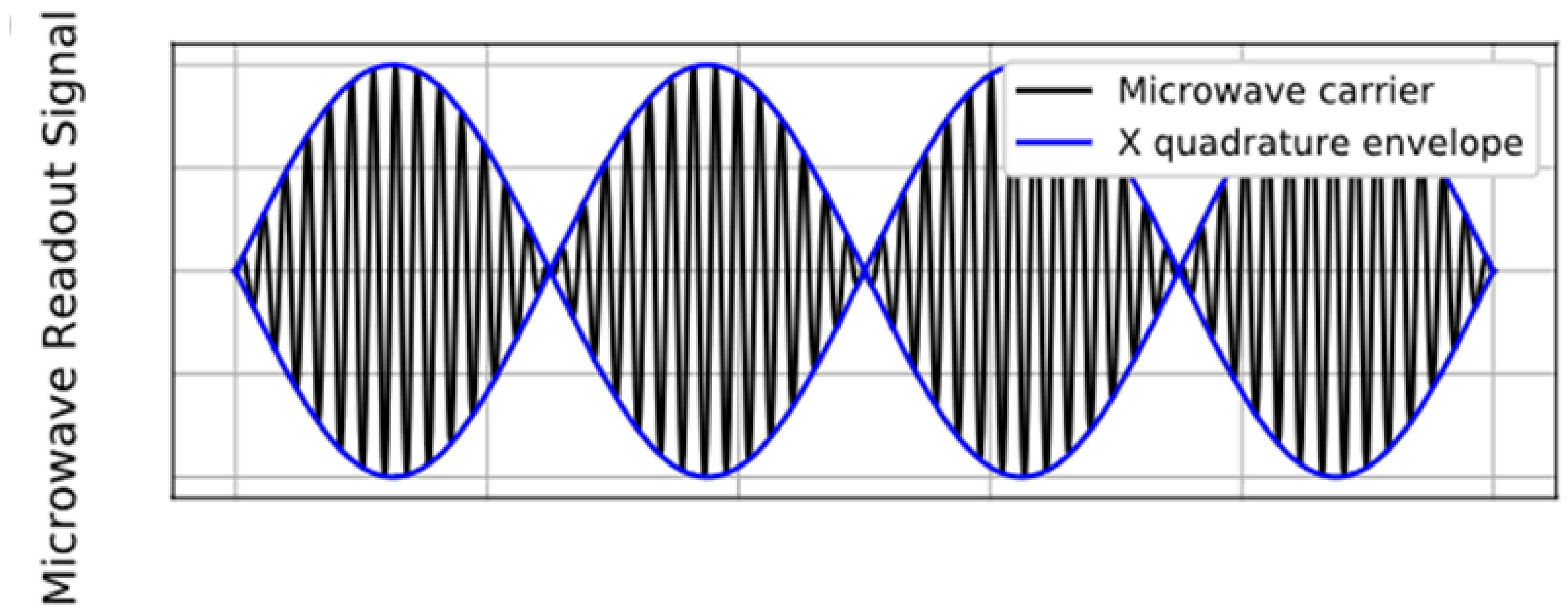
Carrier: 5.26 GHz sinewave amplitude modulated at 5.26 GHz

Measure: output tone power as a function of phase shift between input sinewave and AM modulation

Extinction ratio: ratio of maximum gain to minimum gain:
Curve fit to > 50 dB
Always measured to > 30 dB



Full Backaction Evasion



Carrier tone modulated to measure only X quadrature

- A backaction signal from the microwave resonator only does work on an LC resonator quadrature, on average, if it is 90 degrees out of phase.
- In this limit, if only the $\hat{X}$ quadrature is measured, the backaction is injected preferentially into the $\hat{Y}$ quadrature (which is not measured) - BAE
- If the Q of the microwave resonator is high enough (the "good cavity" limit), the sidebands are fully resolved

Microwave resonator linewidth

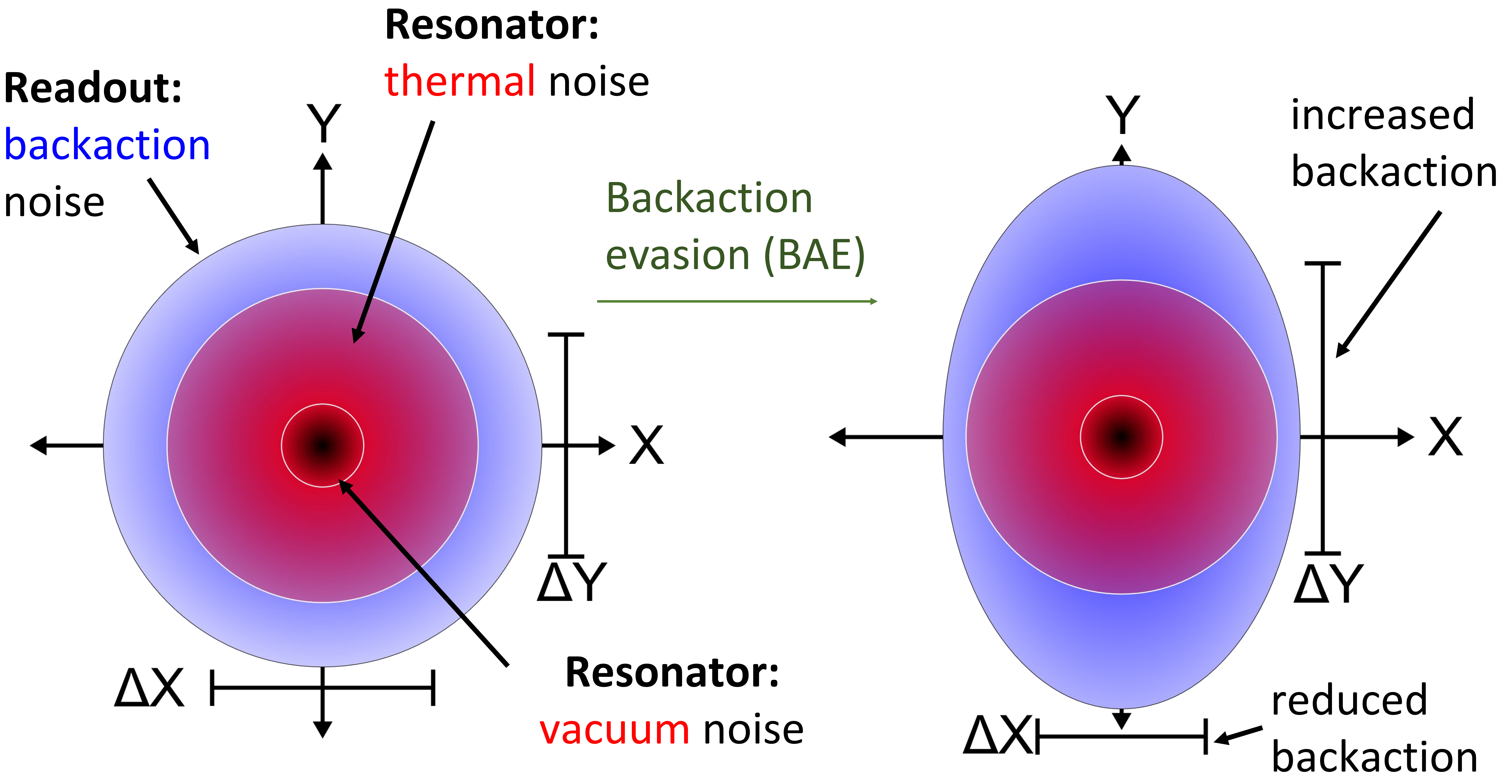
$$S_X(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}[1/2 + n_{\text{th}} + n_{\text{leak}}] + S_{\text{IMP-X}}(\omega)$$

$$n_{\text{leak}} = \frac{n_{\text{BA}}}{32}\left(\frac{\kappa}{\omega_a}\right)^2$$

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

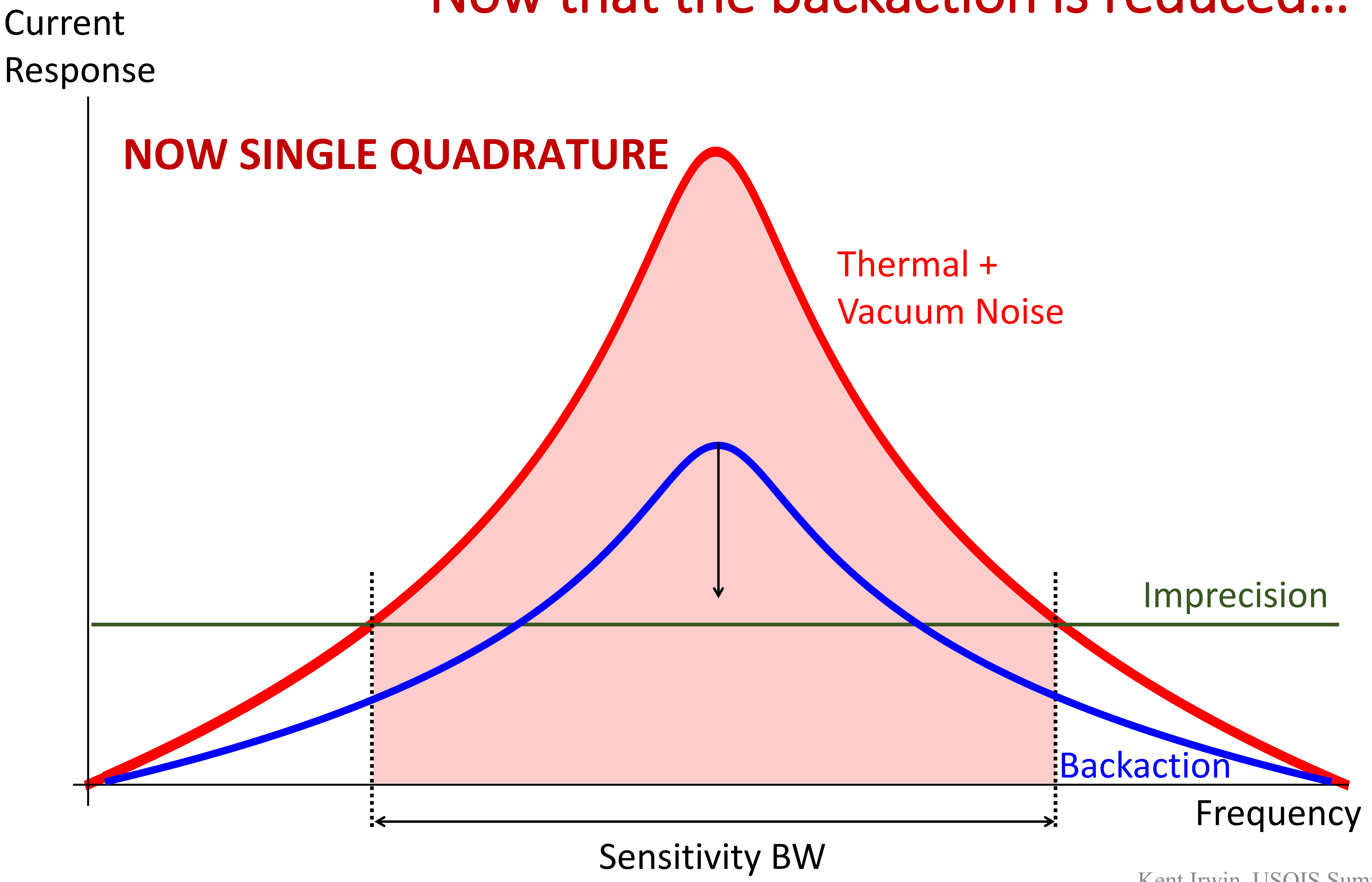
Braginsky, Vorontsov, and Thorne. *Science* **209,** 547 (1980).
AA Clerk, F. Marquardt, and K. Jacobs, *New Journ. Phys.* **10,** 095010 (2008).

Backaction evasion (BAE): reduced readout noise in one quadrature

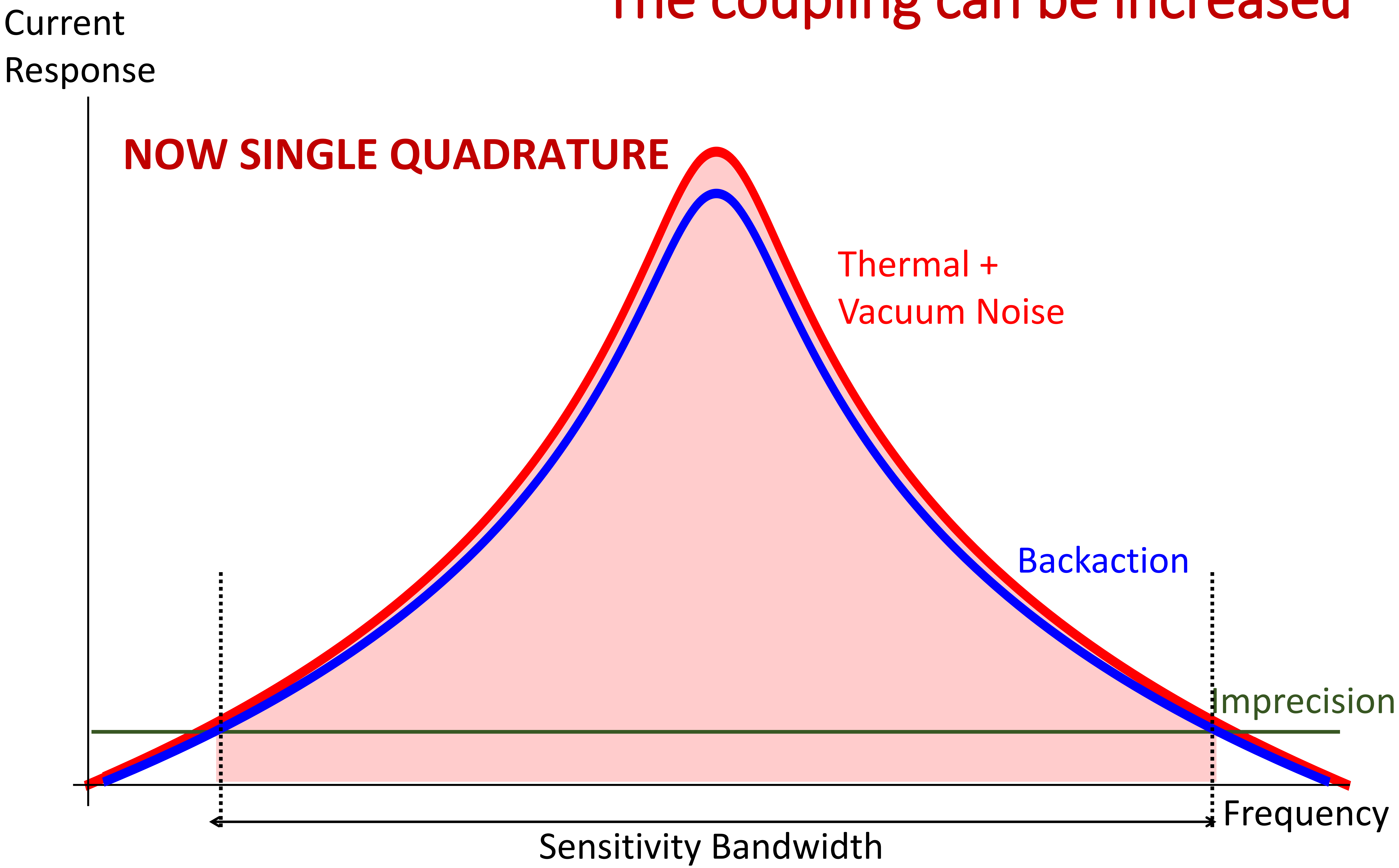


The reduction in the total X-quadrature noise appears unimpressive on resonance

Now that the backaction is reduced…

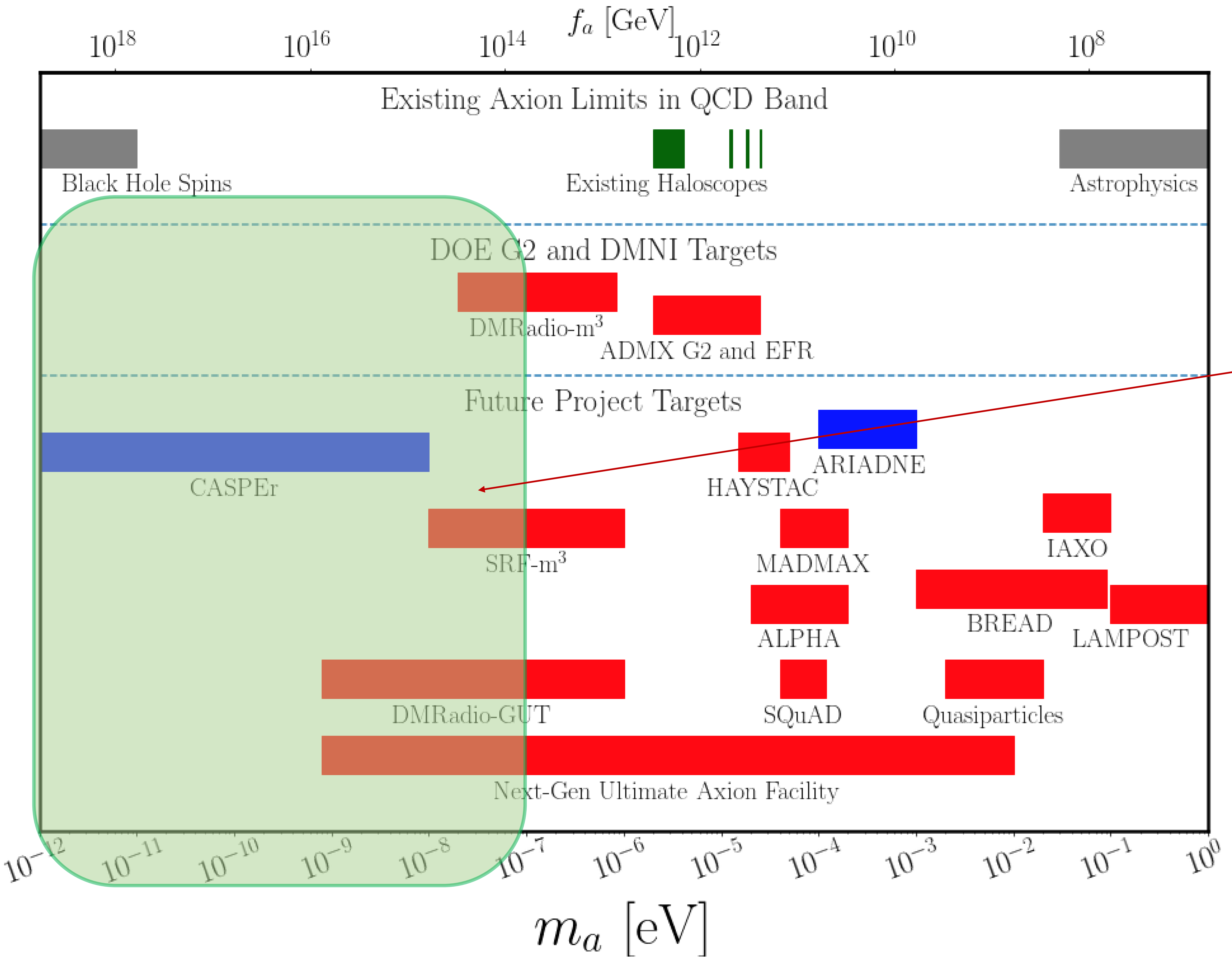


The coupling can be increased



Sensitivity BW can be greatly increased

SNOWMASS: a comprehensive search for QCD axions



QCD axions here: provably requires measurement below the SQL to probe the best models

Figure 3 of Snowmass CF2 summary
https://snowmass21.org/_media/cosmic/repv1_cf2.pdf

SNOWMASS: a comprehensive search for QCD axions

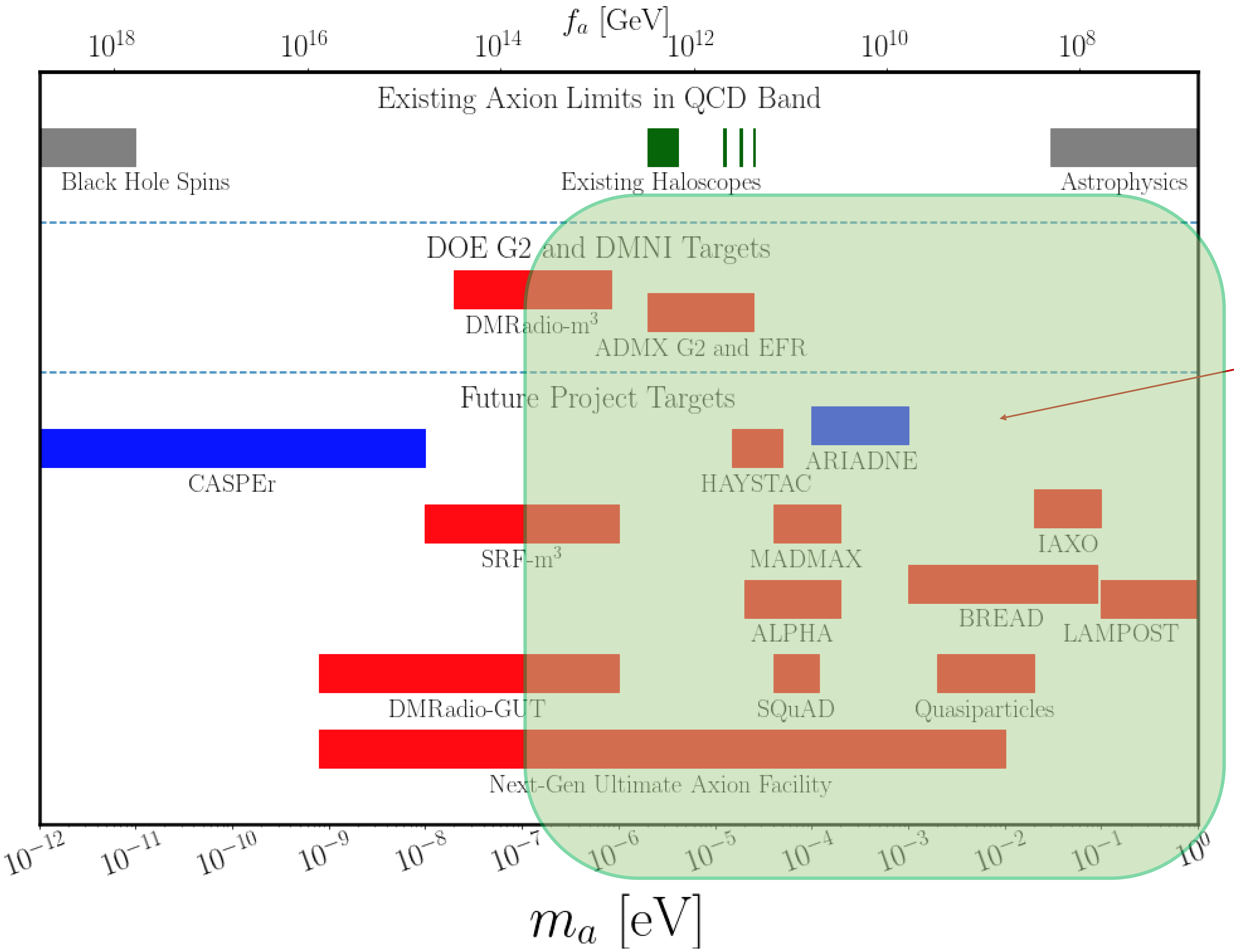
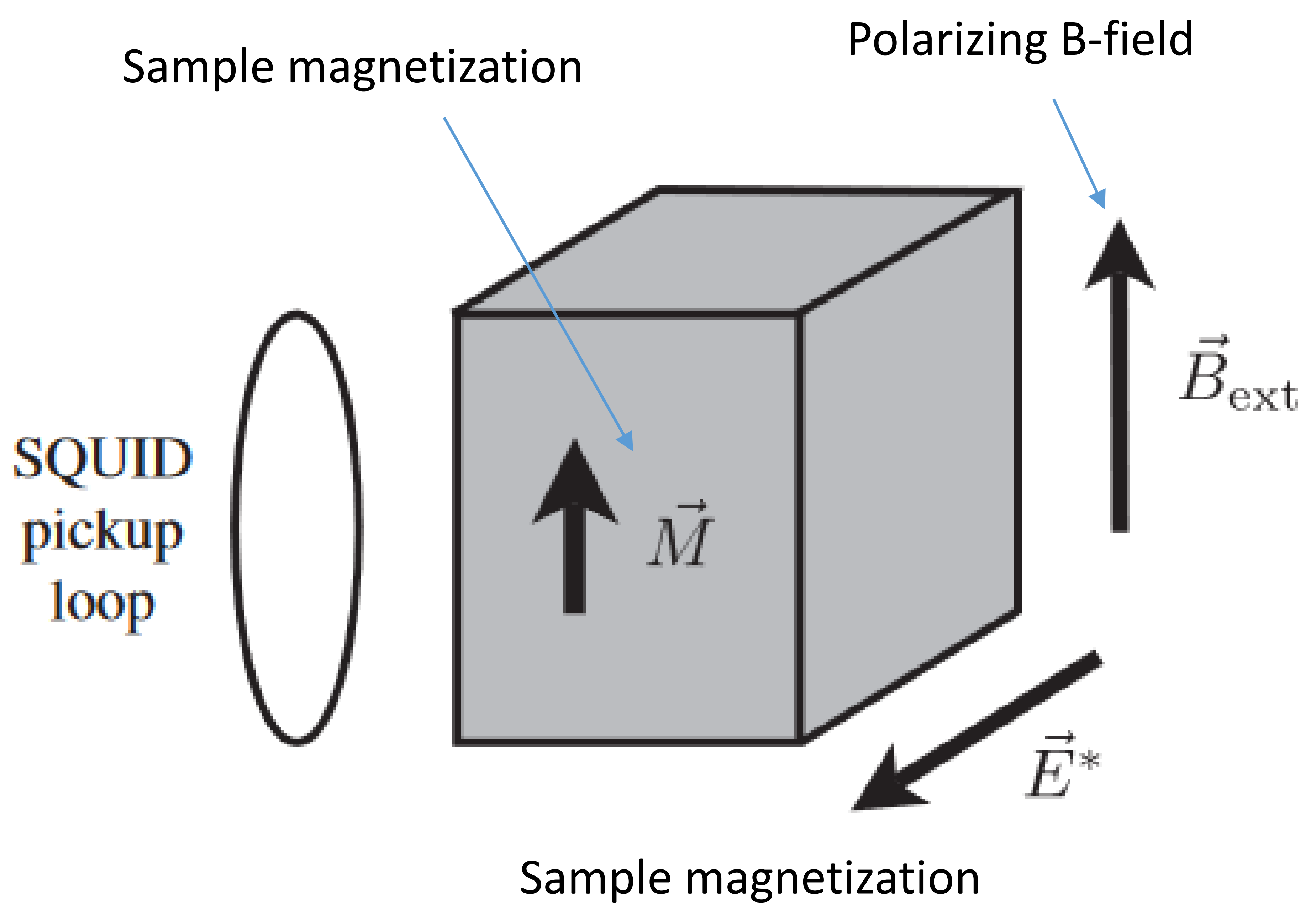


Figure 3 of Snowmass CF2 summary
https://snowmass21.org/_media/cosmic/repv1_cf2.pdf

QCD axions here: New quantum sensing modalities required to cover all frequency space

Searching for axions with NMR

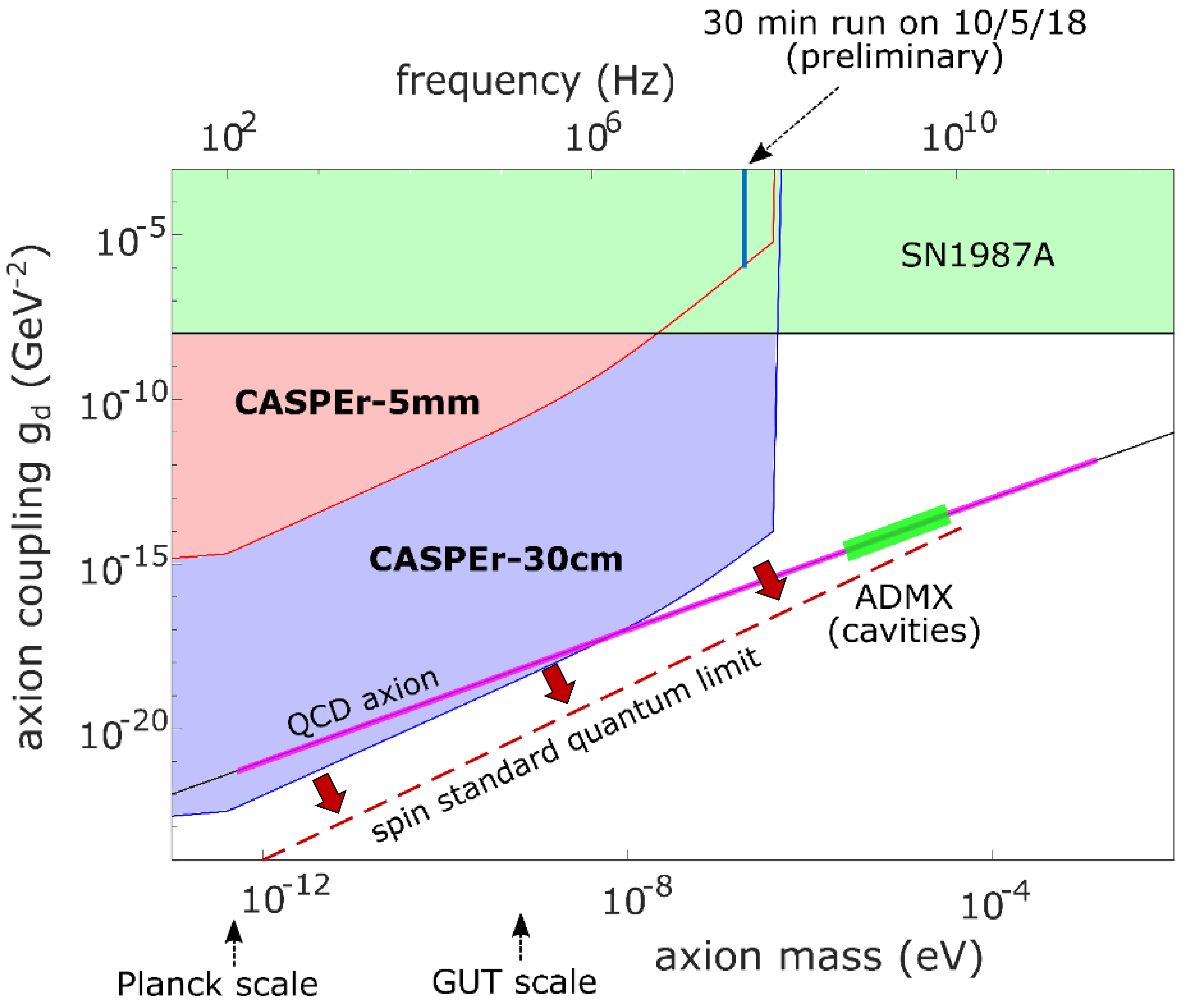
- Axions couple to nuclear spins through the strong force, inducing an effective nuclear electric dipole moment which oscillates at f_{ax}.
- A spin-polarized sample of nuclear spins will resonantly precess if f_{ax} matches their Larmor frequency.
- The precessing magnetization can be detected with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



CASPEr-electric

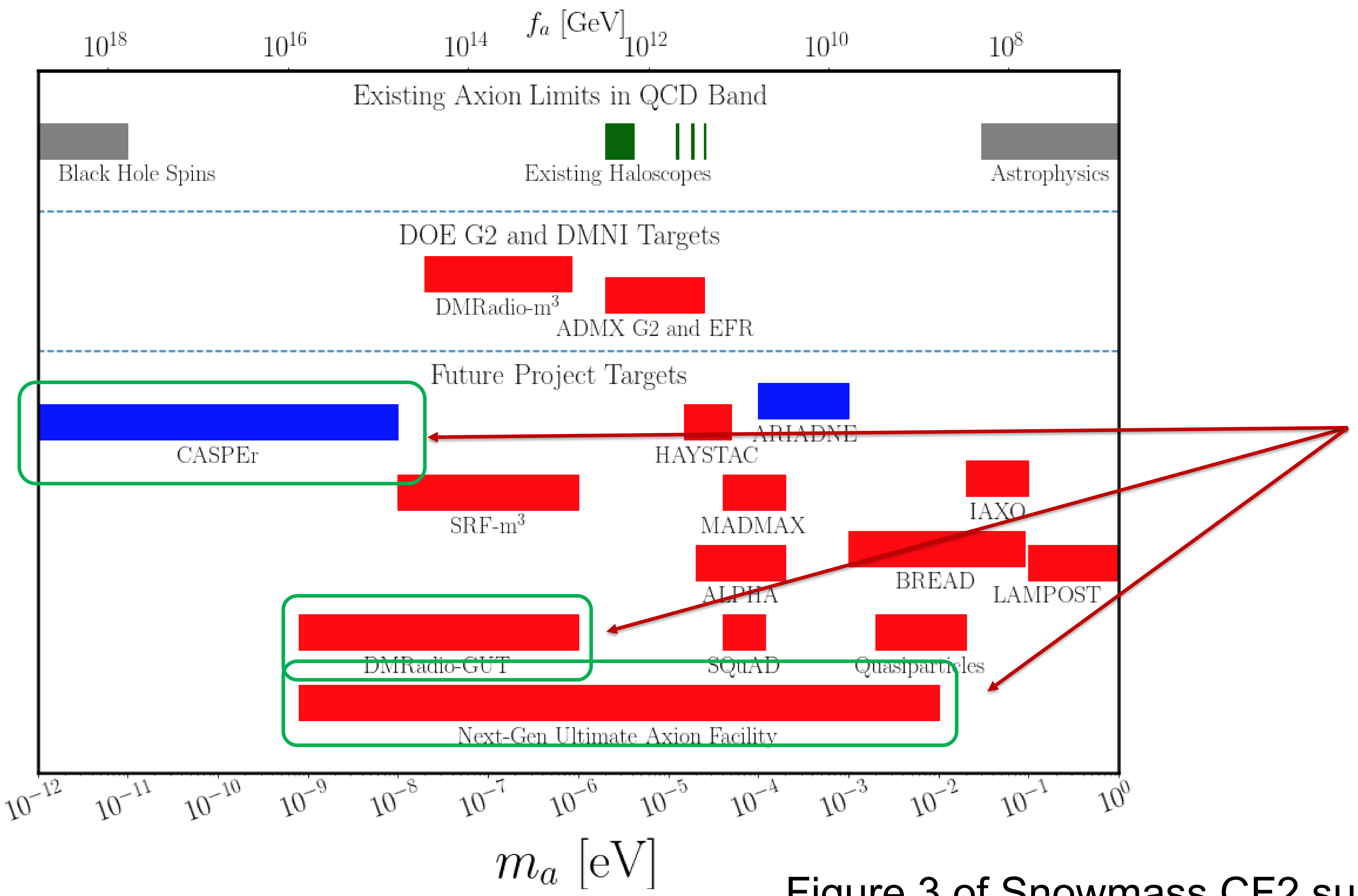
Garcon, Antoine, et al. "The Cosmic Axion Spin Precession Experiment (CASPEr): a dark-matter search with nuclear magnetic resonance." *Quantum Science and Technology* 3.1 (2017): 014008.

Accelerating NMR search: CASPEr-e



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

Snowmass Graph: Axions and SLAC Quantum



BAE with RQU could enable these experiments

Figure 3 of Snowmass CF2 summary
https://snowmass21.org/_media/cosmic/repv1_cf2.pdf

Conclusions

- New breakthroughs in QIS are leading to a revolution in measurement.
- Compelling applications in fundamental physics, including dark matter, require measurement better than Standard Quantum Limits so that we can achieve results in ***years*** instead of ***millennia***.
- Quantum measurement varies at different frequencies, and for different sources -> one size does not fit all, but the same principles underly all of them.
- Next lecture: Aaron Chou will talk about the quantum toolbox at microwave frequencies with qubits