Quantum electromagnetic sensors

and the search for axion dark matter below 1 μeV

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SLAC

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DM Radio supported by Heising Simons Foundation Gordon and Betty Moore Foundation

QuantISED sub-μeV axion sensor team

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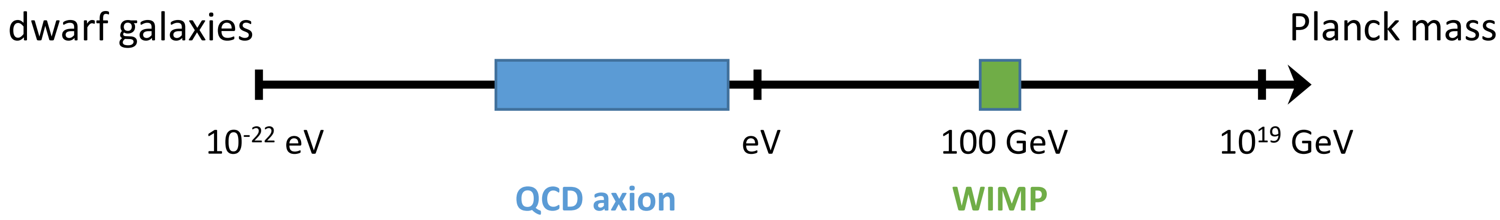
Surjeet Rajendran
Jyotirmai Singh
Cady van Assendelft
Kevin Wells
Betty Young
Cyndia Yu

+ DM Radio Team (including ABRACADABRA)

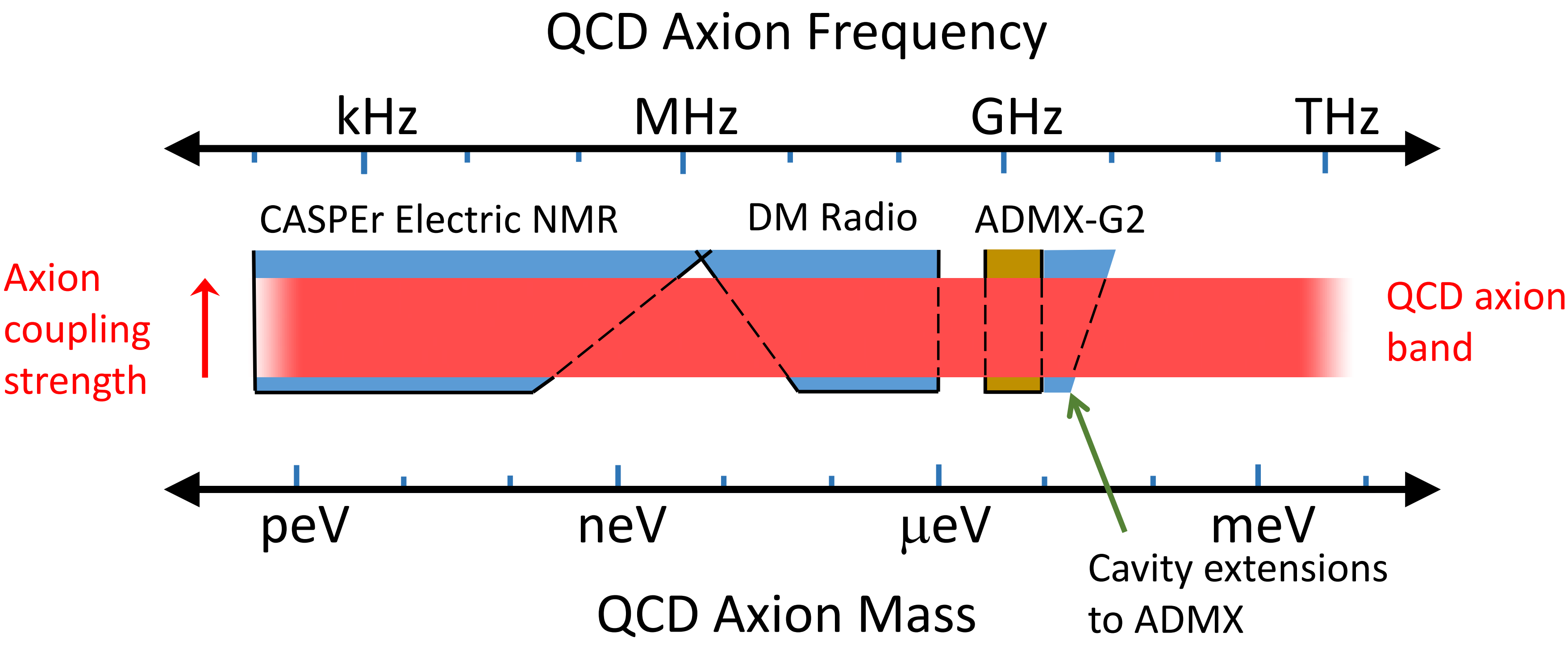
Two “strongly motivated” dark-matter candidates



- **Weakly Interacting Massive Particle (WIMP)**
  - Motivated by 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.
- **QCD axion**
  - Fixes the standard model: motivated as solution to strong CP problem in QCD and hierarchy problem.
  - Naturalness: misalignment production of observed abundances over full mass range, peV-meV
  - Largely unexplored parameter space.

QCD axion: the need for quantum sensors

- Projected science reach at SQL shown in blue
- Assumptions made about experimental parameters (volume, magnetic field strength) may change—only approximate!



QCD axion: the need for quantum sensors

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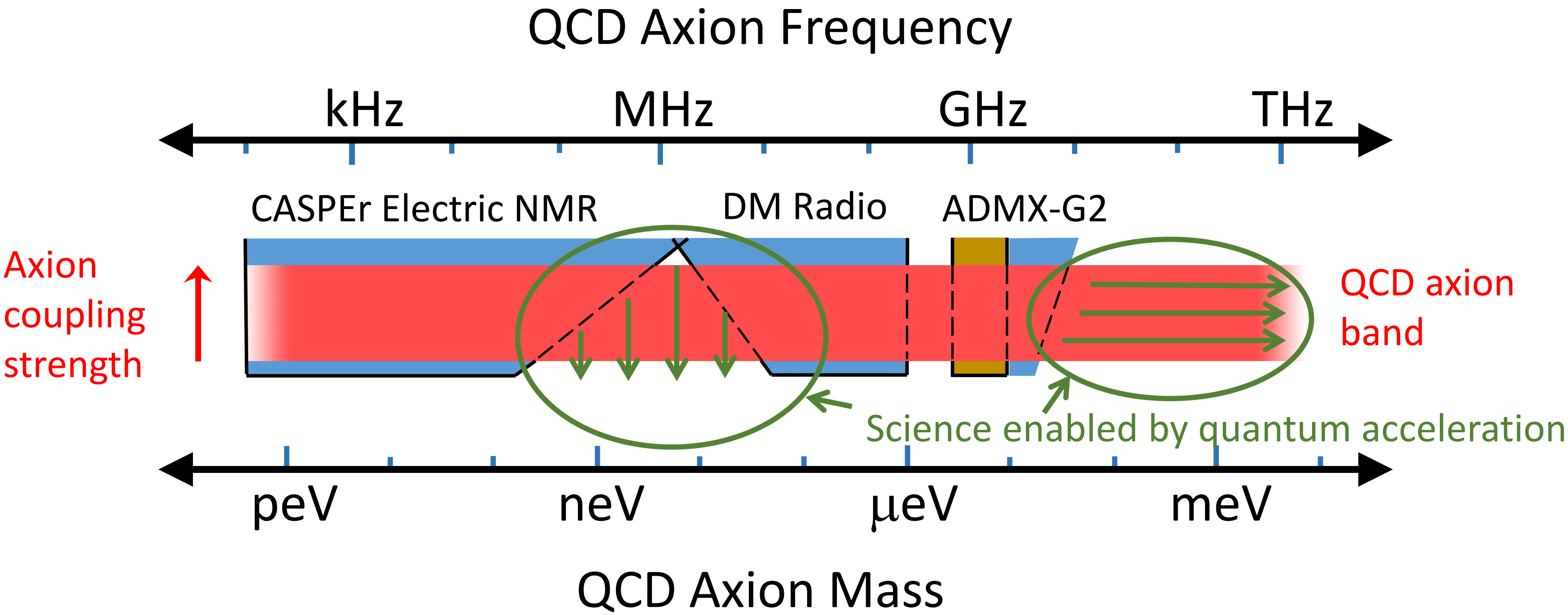
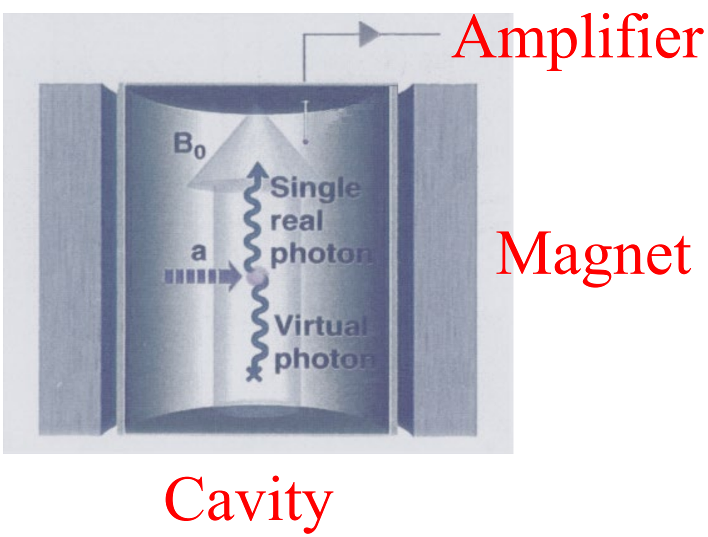


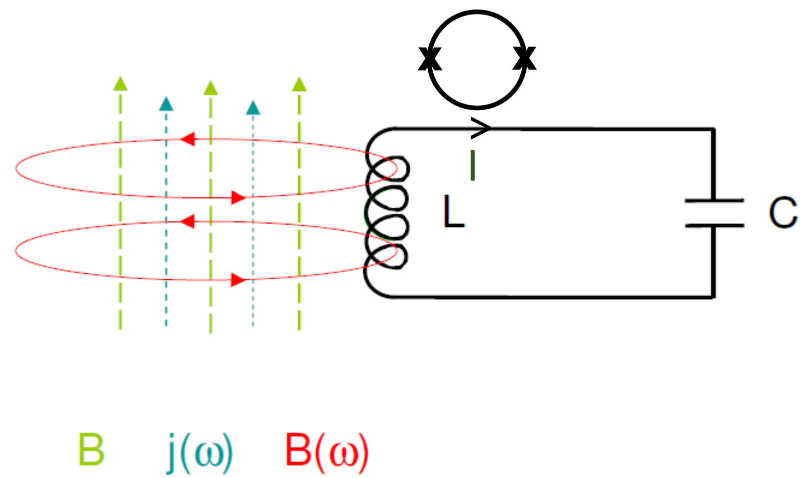
- Quantum acceleration required to cover full QCD band

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)
ν>300 MHz:
Cavity-based searches
(ADMX, HAYSTAC)



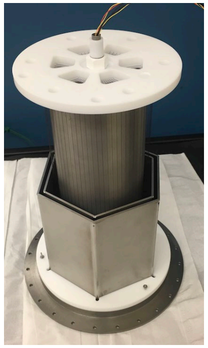
Proposal: Cabrera, Thomas (2010)
ν<300 MHz:
Lumped-element searches
(DM Radio, ABRACADABRA, Florida LC)

DM Radio Experiment Family

DM Radio Pathfinder

Status: In testing / operation

- 0.67 L, no magnet
- Q~200,000 now
- 4 K
- Hidden photon science
- DC SQUID



DM Radio-Quantum
DM Radio-50L

Status: In construction

- ~0.5 T, 50 L magnet
- Dilution refrigerator
- ALP science
- Platform for quantum sensors

Dark Matter Radio Cubic Meter (DMRadio-m^3)

Status: R&D funded under DOE Dark Matter New Initiatives call
See Lindley Winslow talk, Thursday 20 Feb 2020, 17:30

- Brings together both DM Radio and ABRACADABRA teams
- QCD axion over 5 MHz – 200 MHz (20neV-0.8 μeV)
- ~4T, ~m^3 magnet
- Dilution refrigerator

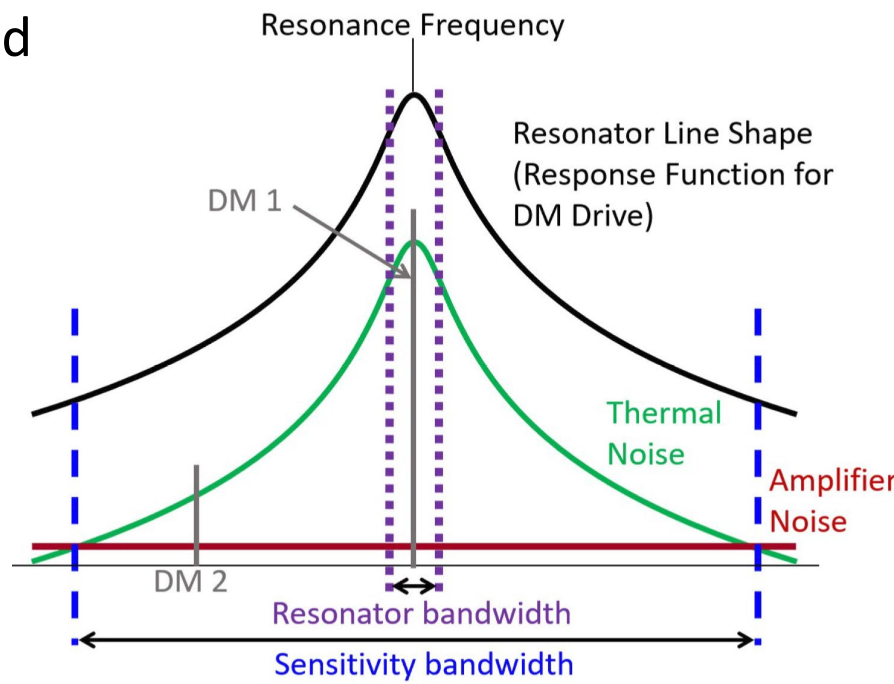
Integrated sensitivity: the figure of merit

- Science reach determined by integrated sensitivity across search band
- Figure of merit with quantum-limited amplifier:

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

- $|S_{21}(\nu)|^2$: transmission from dark-matter signal source to amplifier (entry in scattering matrix $S(\nu)$)
- n(ν)= signal source thermal occupation number
- "+1" is standard quantum limit

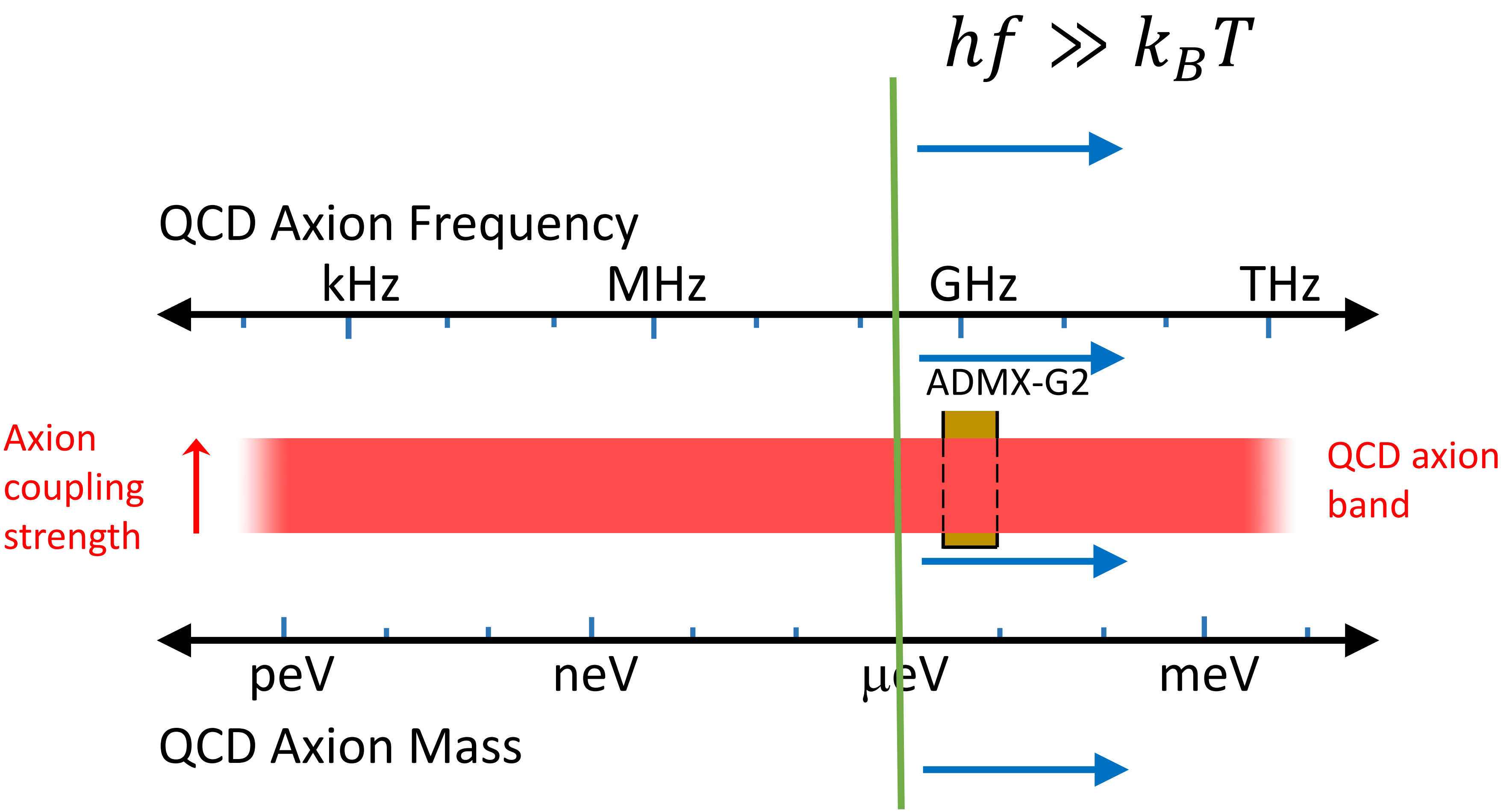
Example: single-pole resonator



S. Chaudhuri et al., arXiv:1904.05806 (2019).

- A single-pole resonator has nearly ideal integrated sensitivity
- Substantial sensitivity available outside of resonator bandwidth.

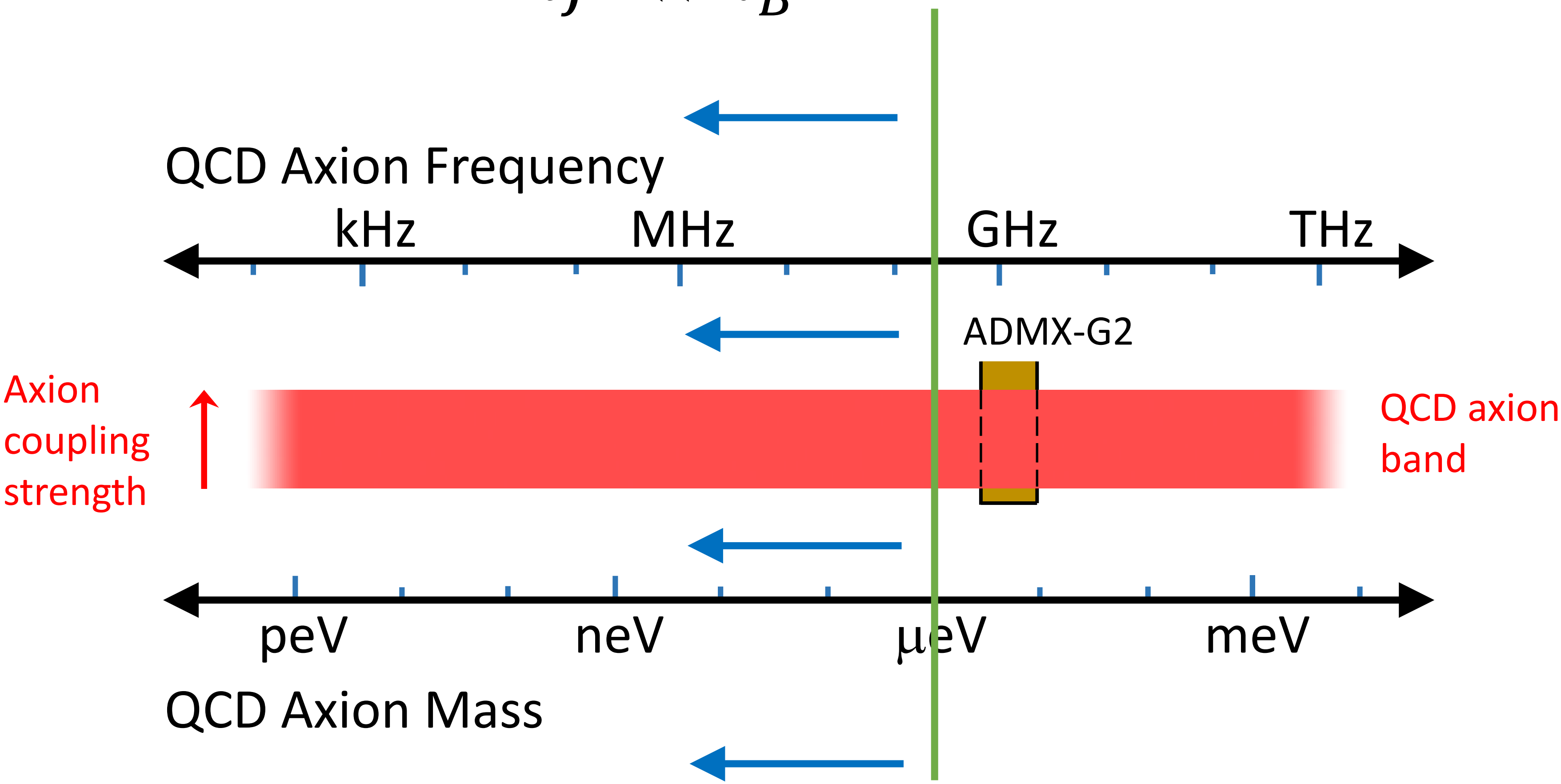
>~ μeV: Ground State



- Ground state
- Cavity resonators (experimental scale of order of Compton wavelength)
- Scattering-mode amplifiers

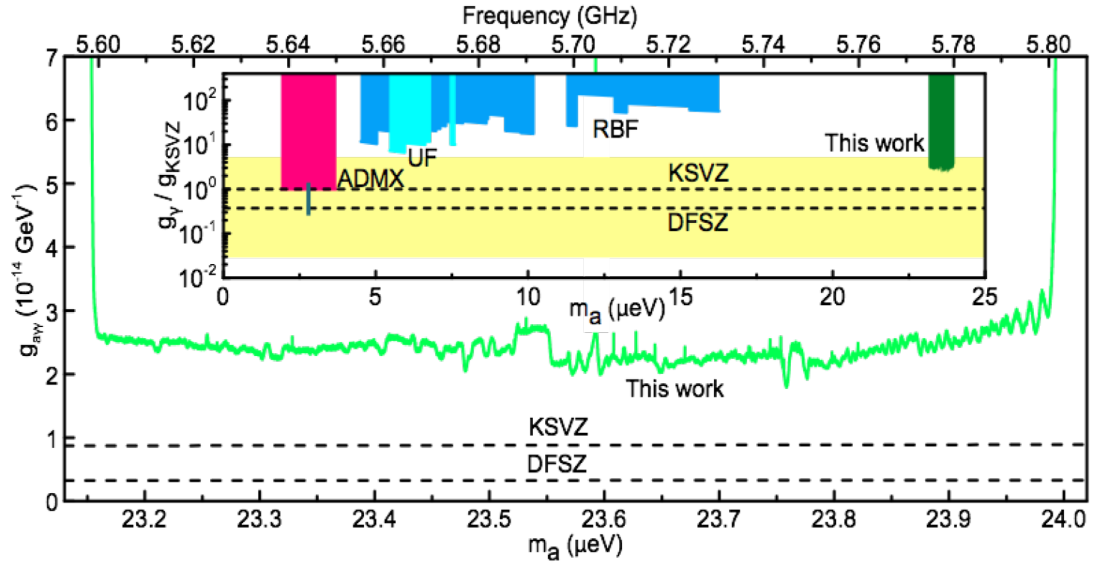
<~ μeV : High Occupation

$$hf \ll k_B T$$

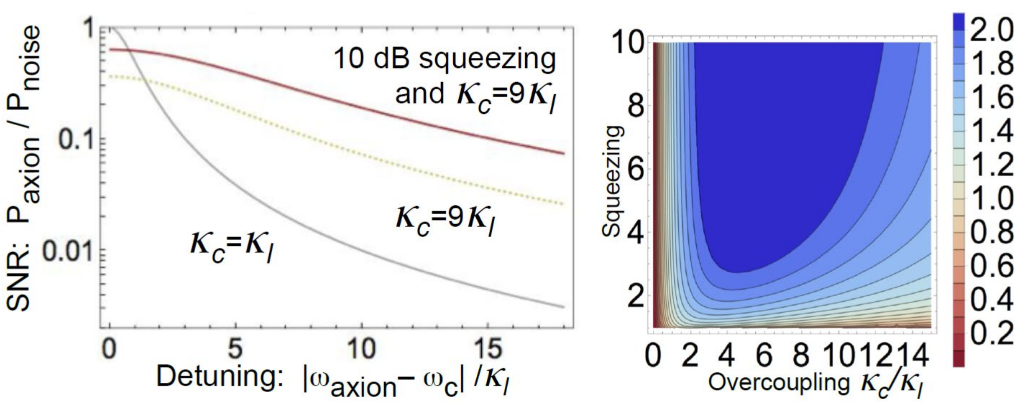


- Thermal state
- Lumped LC resonators (experimental scale << Compton wavelength)
- Op amp-mode amplifiers

HAYSTAC: Acceleration through squeezing



HAYSTAC run 1 & 2 combined exclusion plot

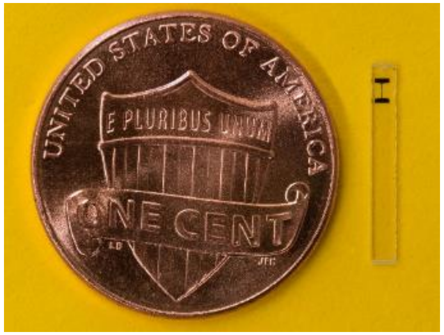


HAYSTAC Phase II squeezed state receiver projected acceleration

Droster, Alex G., and Karl van Bibber. "HAYSTAC Status, Results, and Plans." *arXiv preprint arXiv:1901.01668* (2019).

See: Reina Maruyama talk?

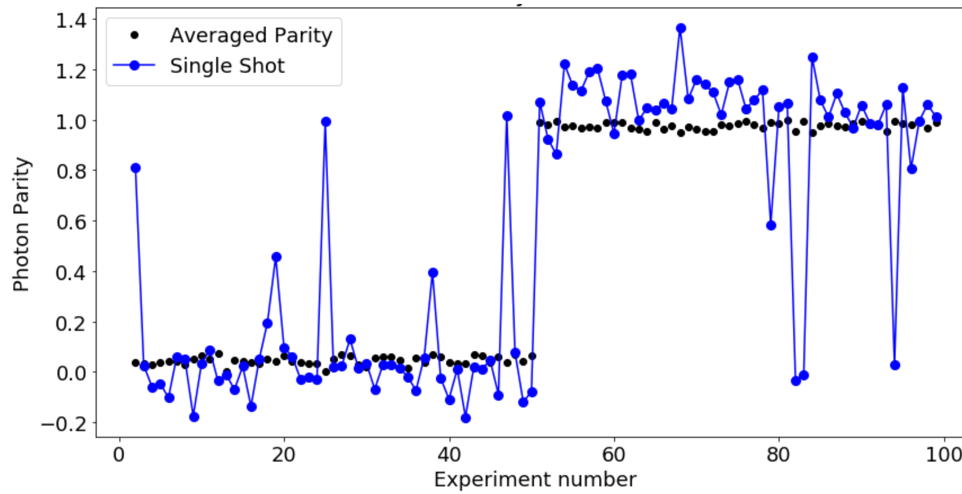
Ground state measurement: QND photon counting



Akash Dixit, Aaron Chou, David Schuster

Use qubit as an atomic clock whose frequency depends on the number of photons in the cavity. The electric field of even a **single photon** will exercise the non-linearity of the qubit oscillator and shift its frequency.

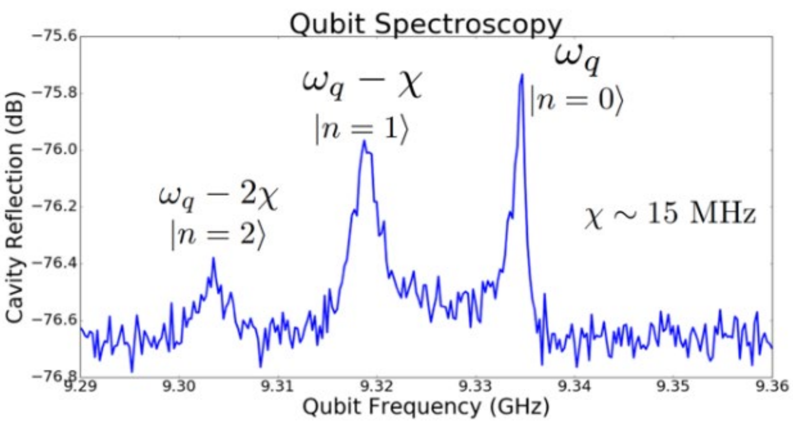
Repeatedly measure the clock frequency to determine whether the cavity contains 0 or 1 photon:



Many QND measurements agree that the cold cavity contains 0 photons

Many QND measurements of the single photon **without absorbing it.**

Inject 1 photon



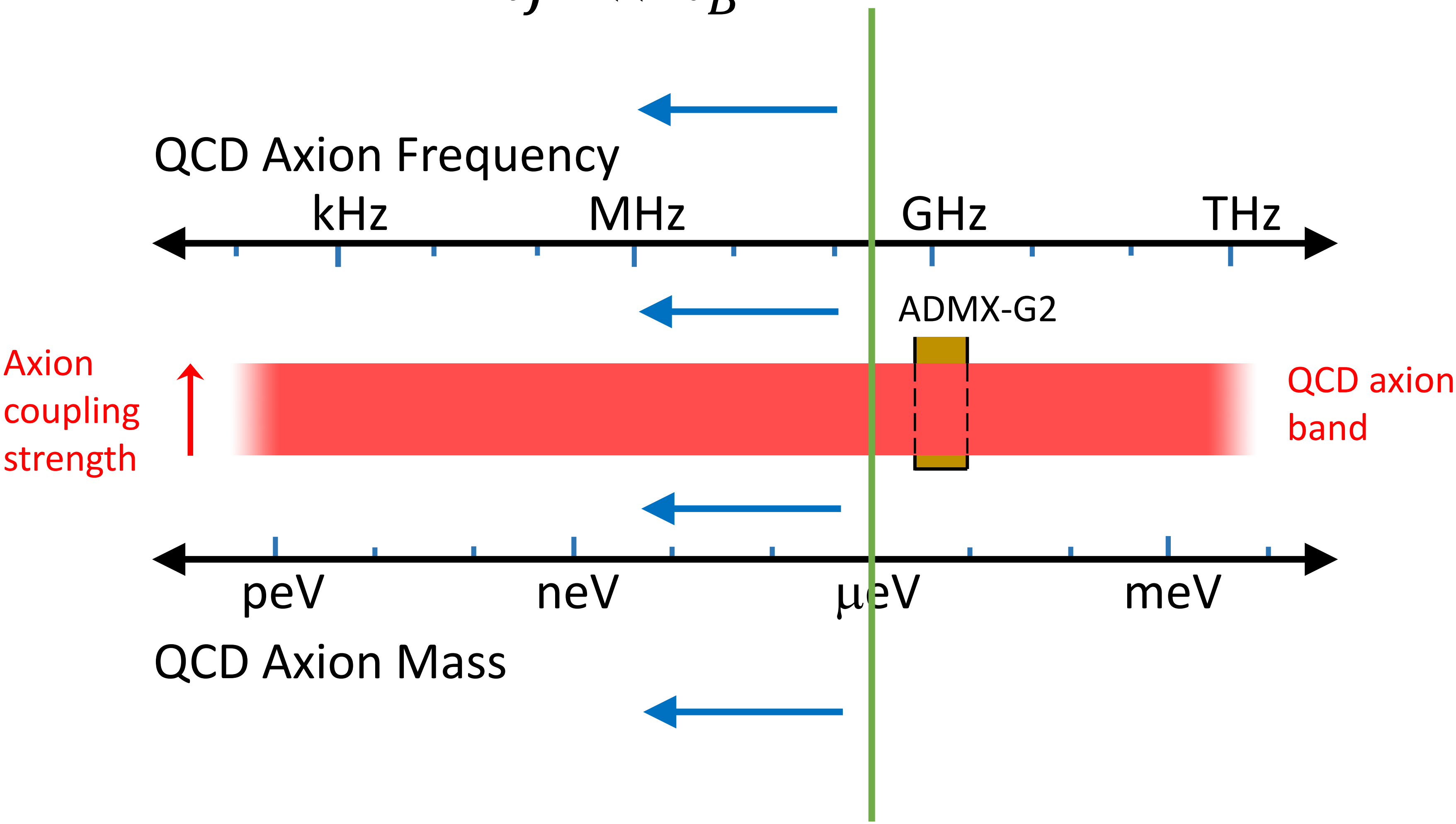
Count # of photons by measuring the quantized frequency shift of the qubit.

Figure Credit: Aaron Chou, FNAL

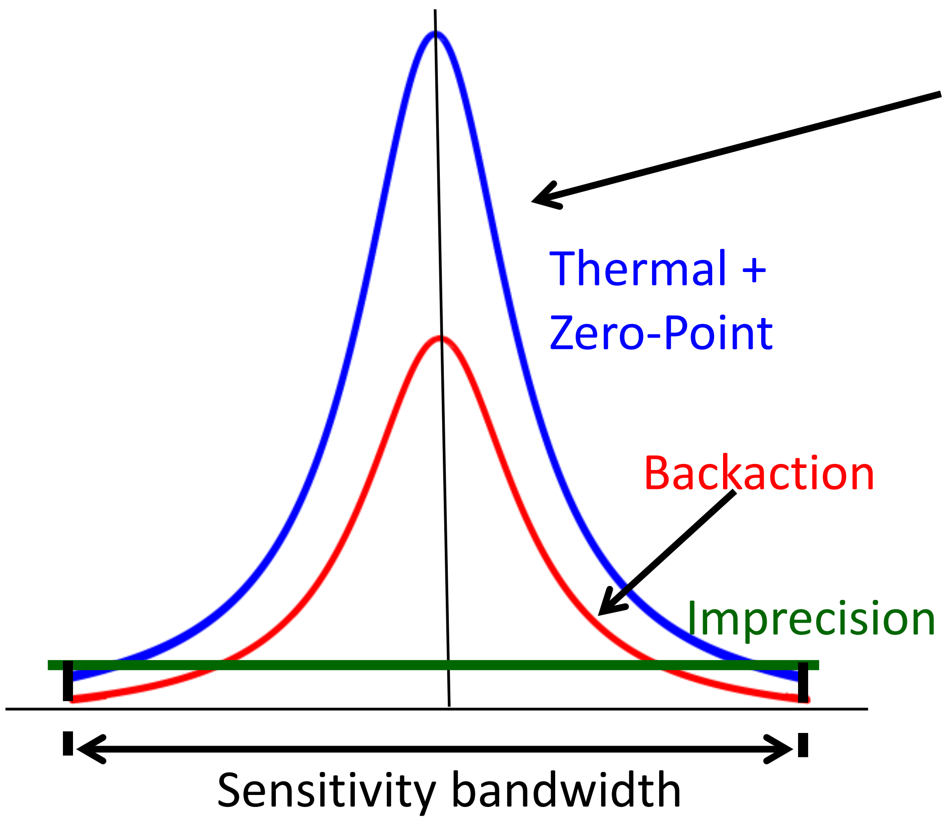
Fermilab THE UNIVERSITY OF CHICAGO HEISING-SIMONS FOUNDATION

Second regime: High Occupation

$$hf \ll k_B T$$



Photon counting is useless when $hf \ll k_B T$



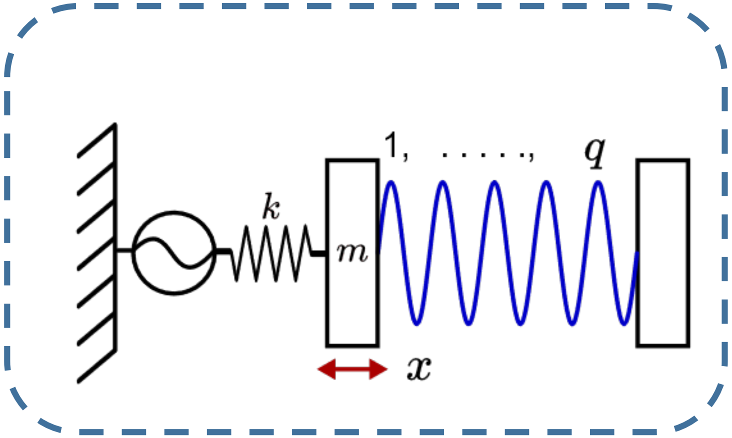
- $\sqrt{N}$ thermal fluctuations in the number of resonator photons
- Sensitivity not improved by photon counting

$\rightarrow$ **Backaction evasion**

Implement ***backaction evasion*** to reduce both imprecision and backaction noise below the standard quantum limit, increasing the sensitivity bandwidth

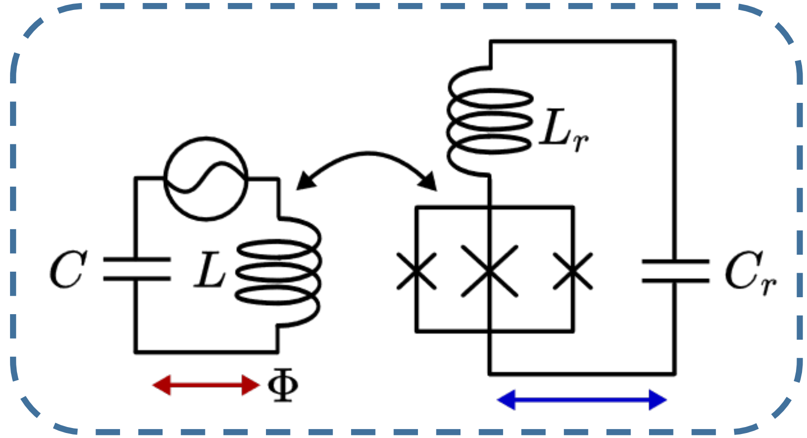
Radio-Frequency Quantum Upconverters: Analagous to Optomechanical Systems

LIGO:



$$\omega_a = \sqrt{\frac{k}{m}} \qquad \omega_b = \frac{2\pi q c}{l(x)}$$

Axion detector with RQU:



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

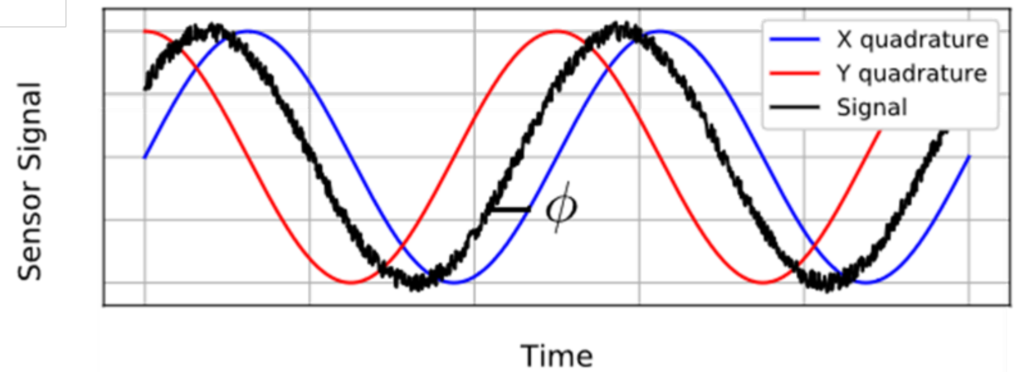
Same Hamiltonian for both systems (to first order in coupling)

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

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

Low Frequency LC Circuit Quadratures

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



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

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

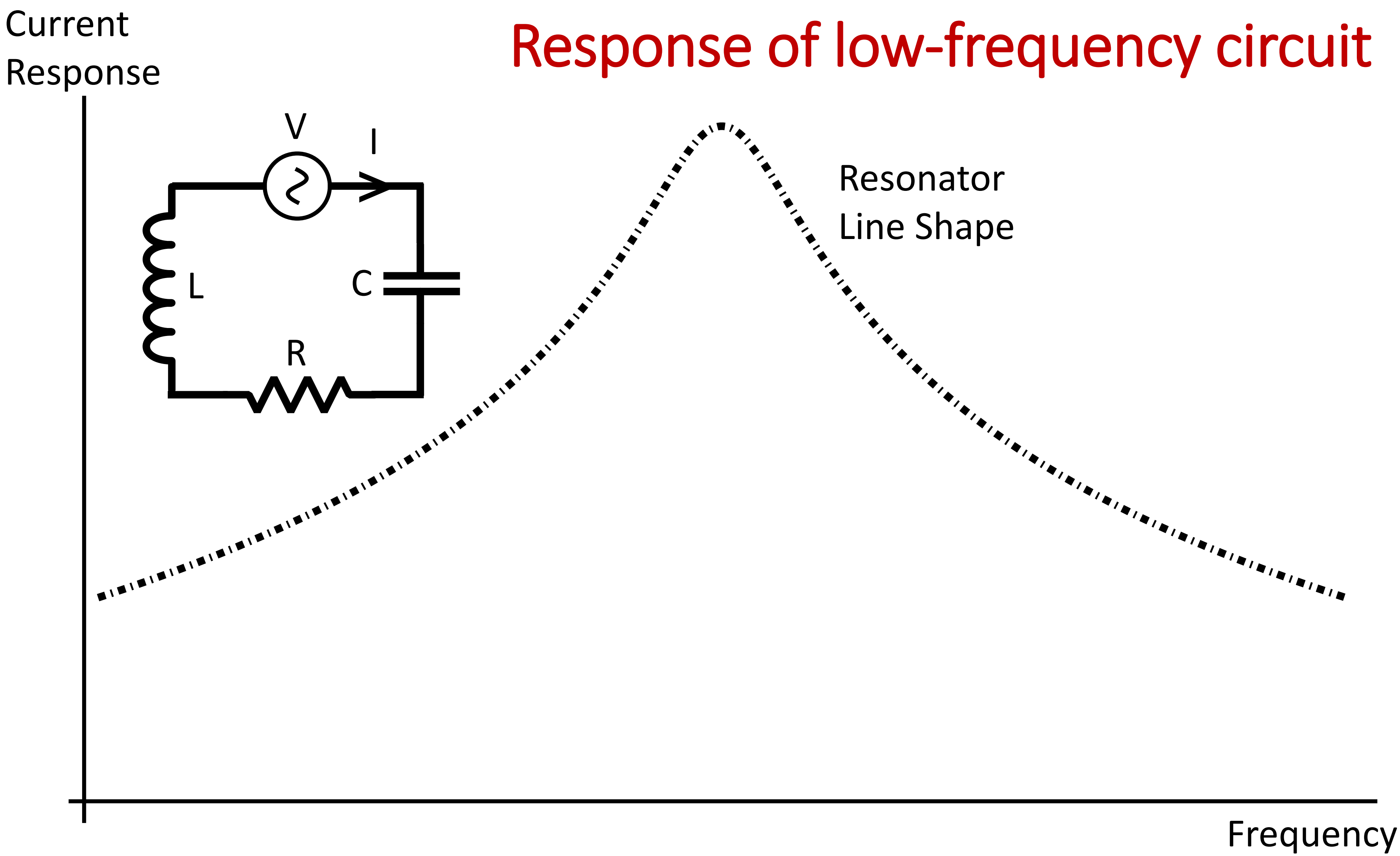
$$\hat{Y} = \frac{1}{\sqrt{2}}\left(\hat{a}\, e^{i\omega_a t} - \hat{a}^{\dagger} e^{-i\omega_a t}\right)$$

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

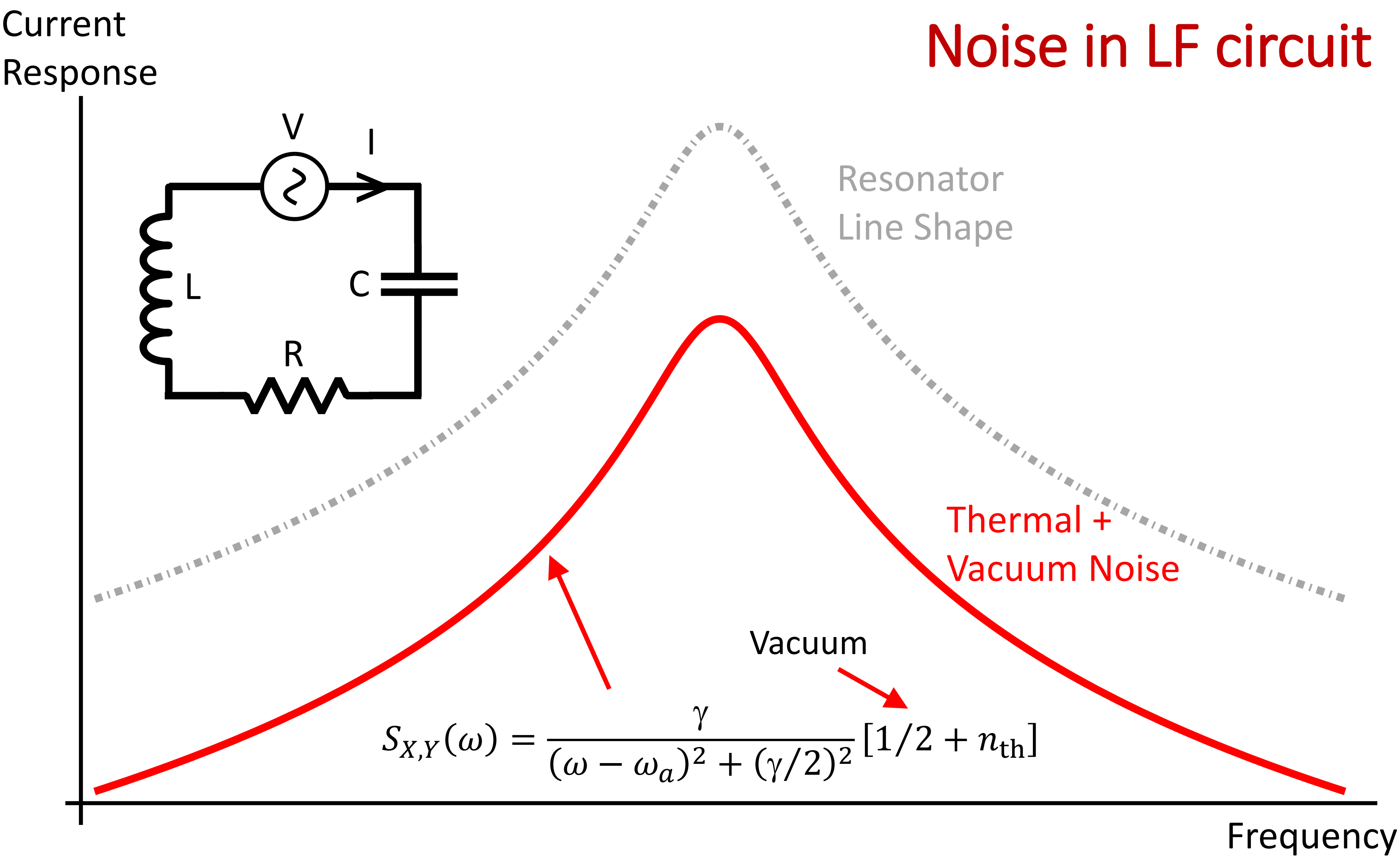
See optomechanical analogue, e.g.
AA Clerk, F. Marquardt, and K. Jacobs, *New Journ. Phys.* **10,** 095010 (2008).

One key difference: optimization for integrated sensitivity

Response of low-frequency circuit

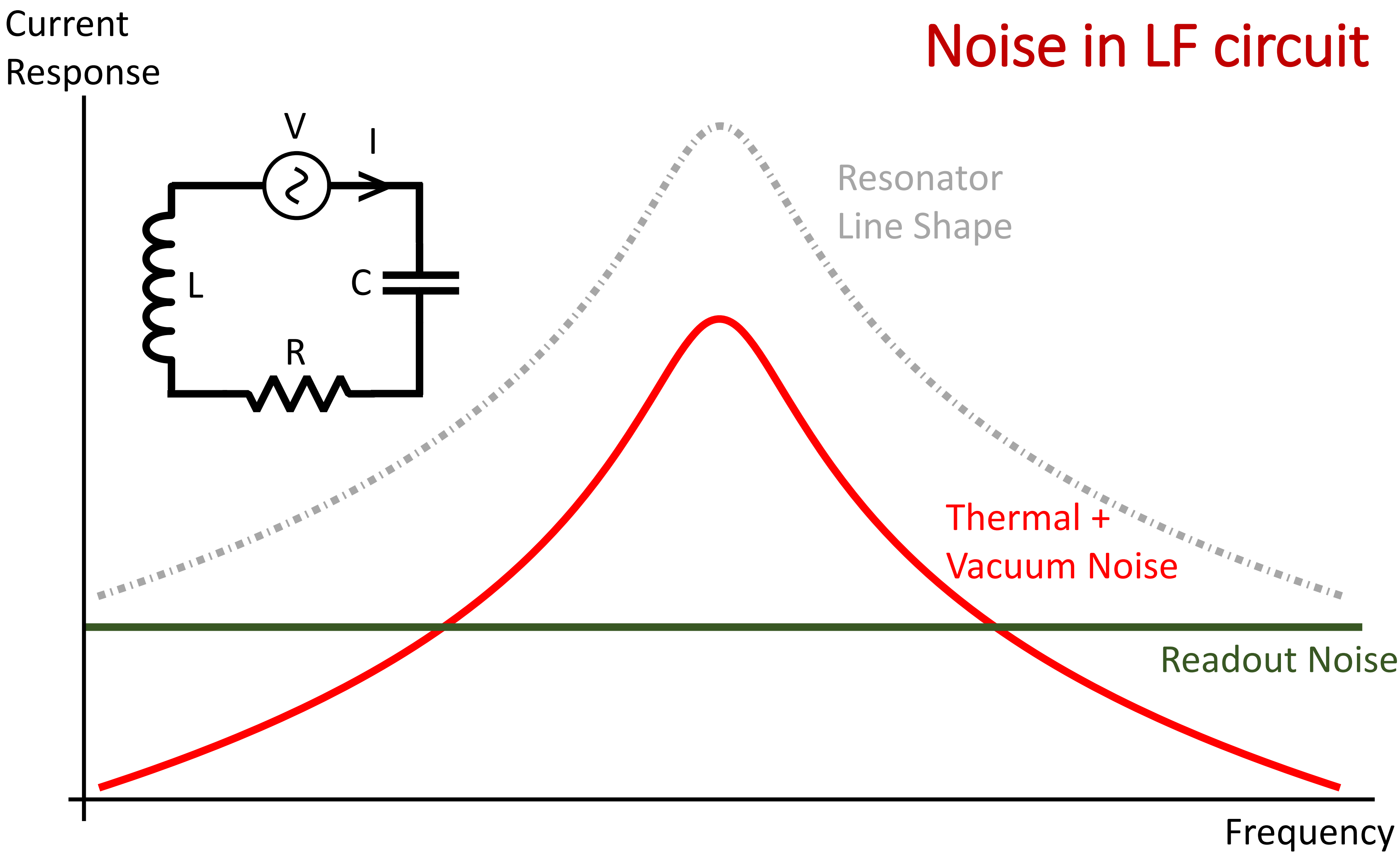


Noise in LF circuit

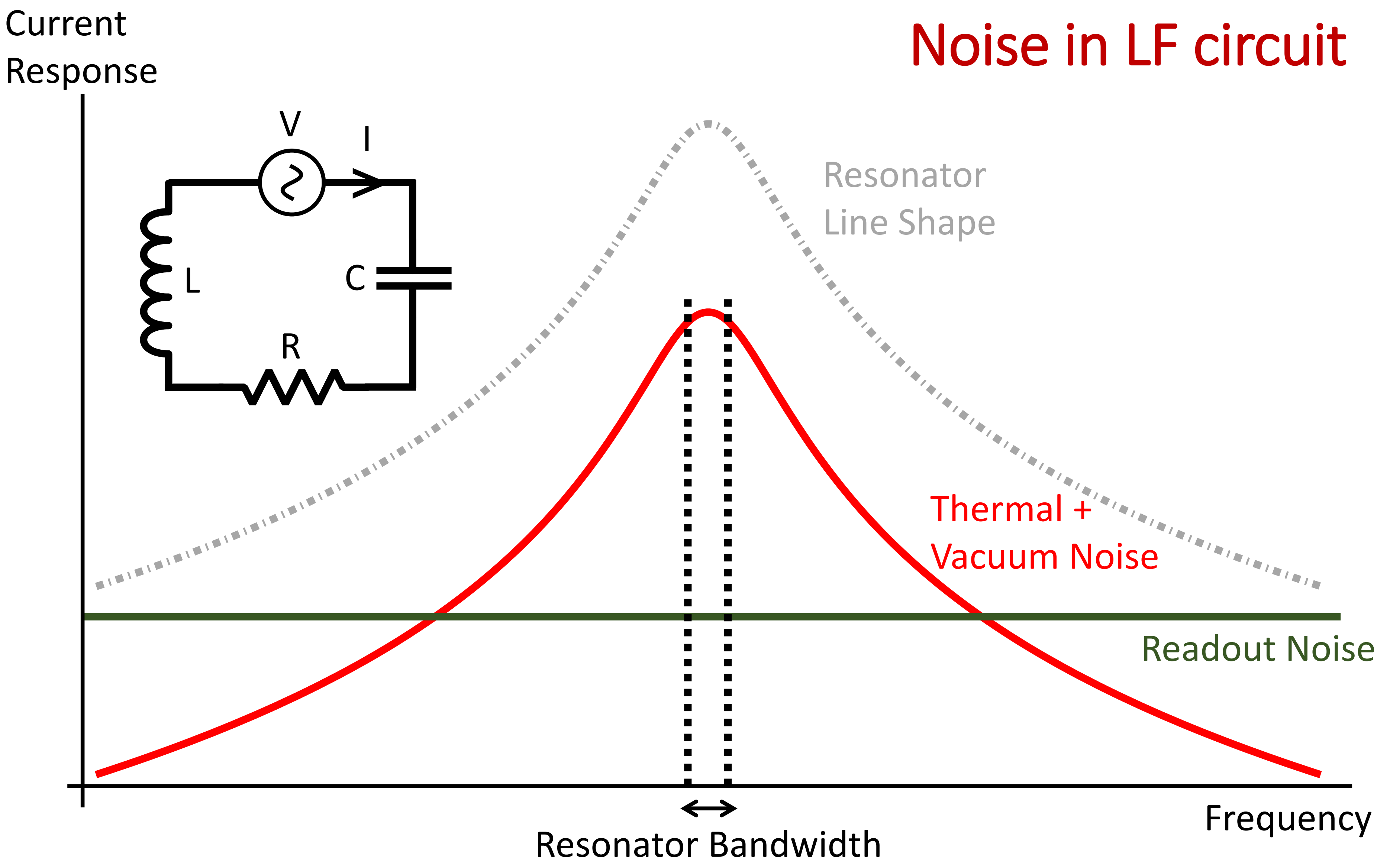


Thermal occupation $\quad n_{\mathrm{th}} = \left(\exp\left[\frac{\hbar\omega_a}{k_{\mathrm{B}}T}\right] - 1\right)^{-1}$

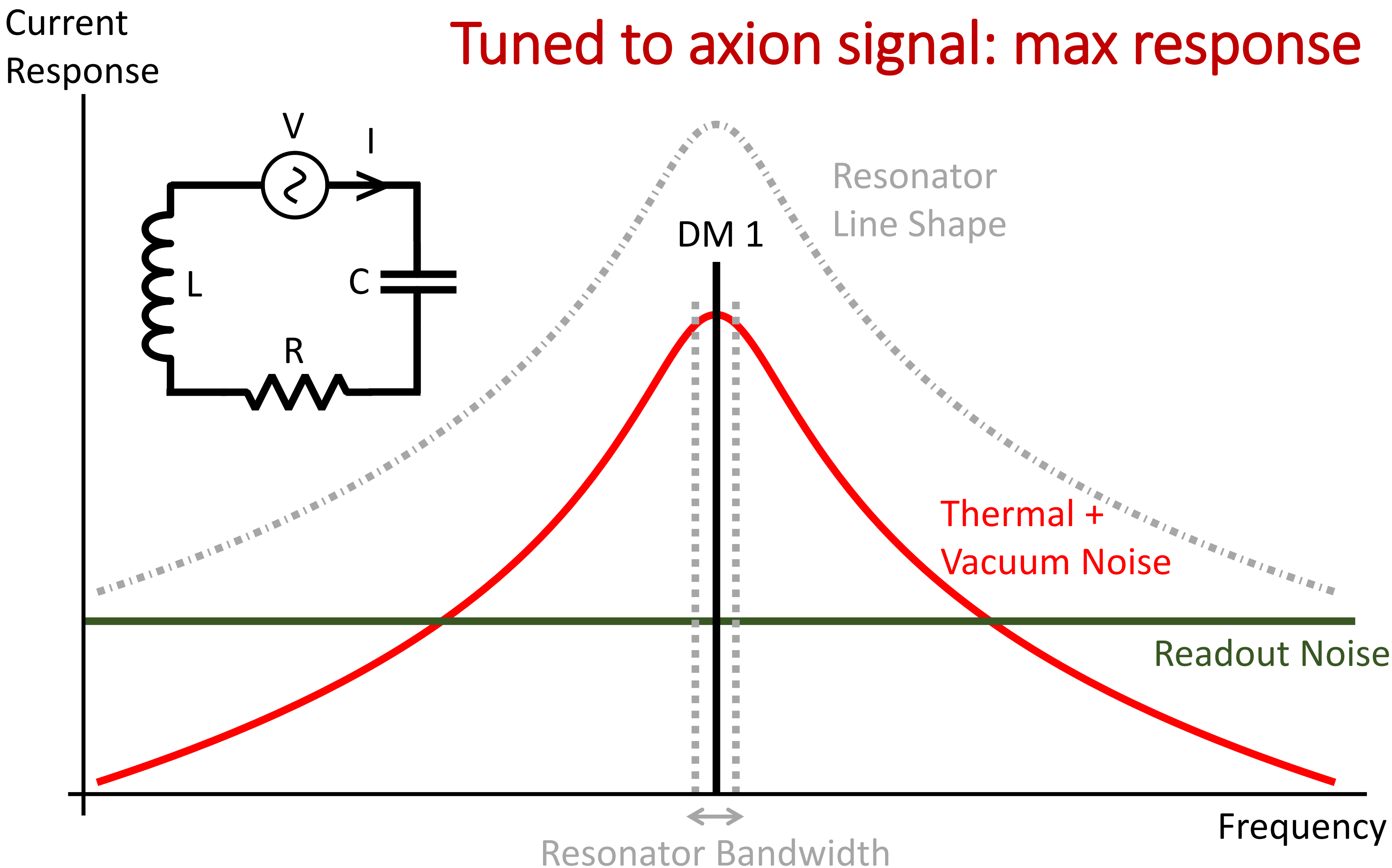
Noise in LF circuit



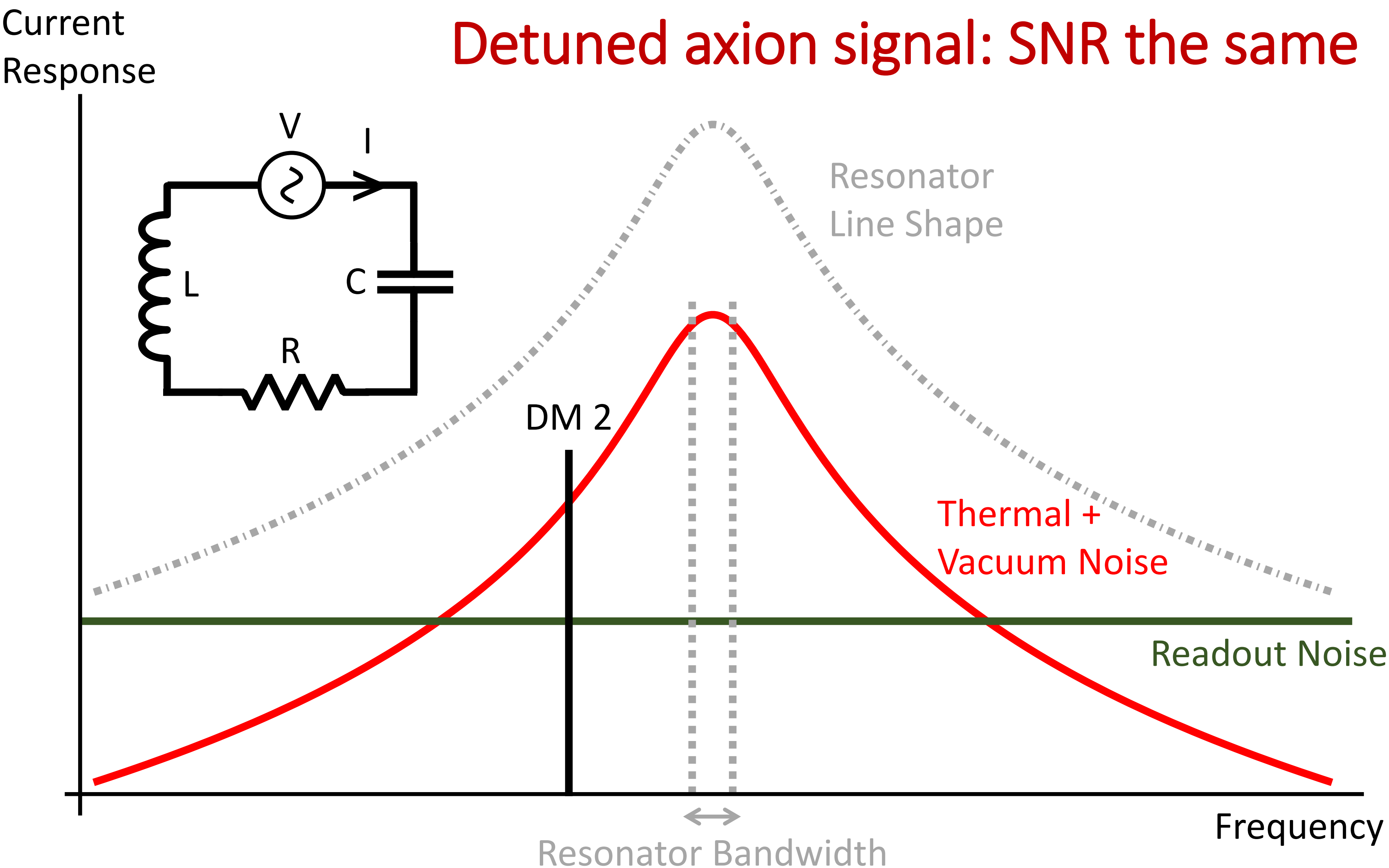
Noise in LF circuit



Tuned to axion signal: max response

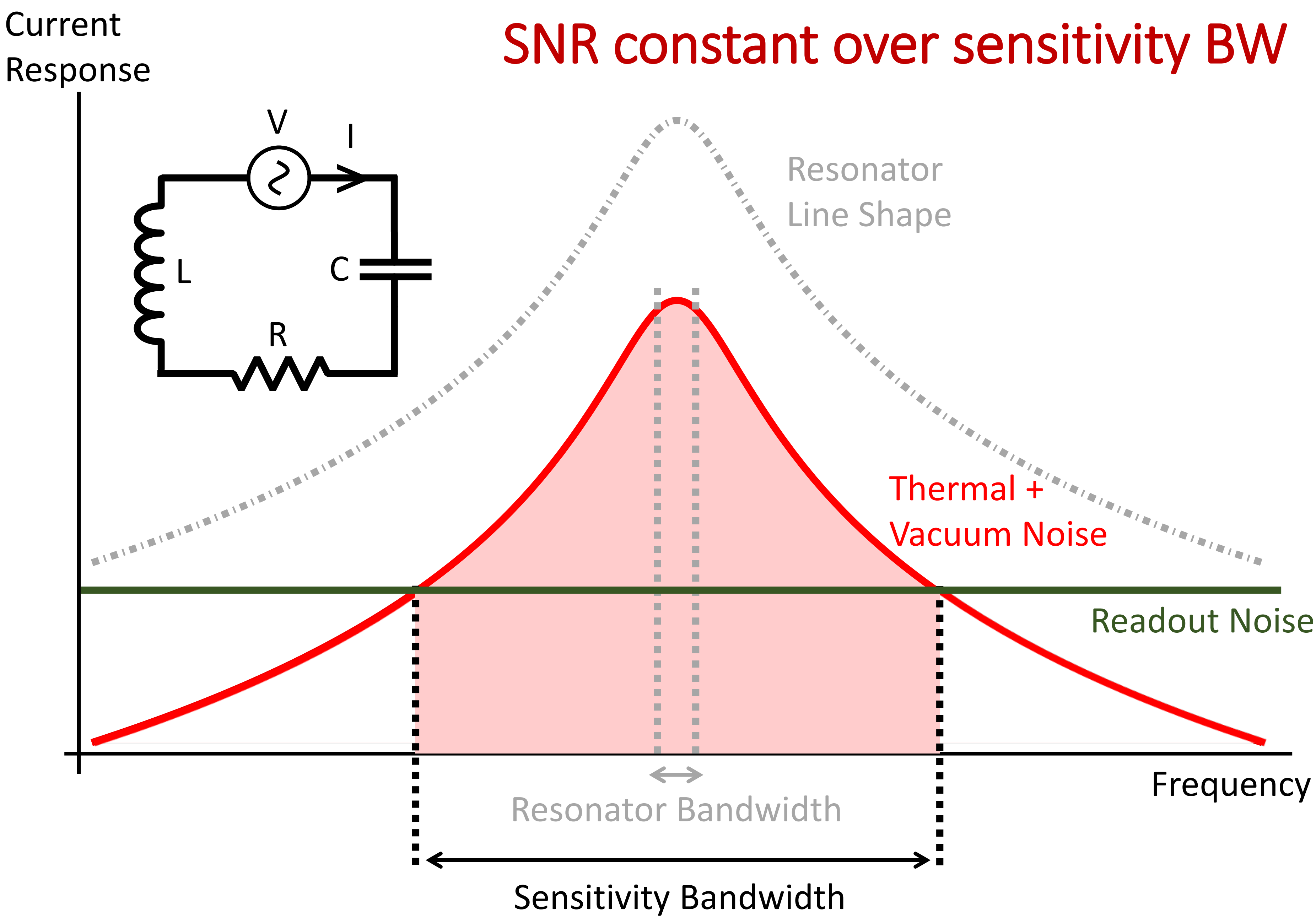


Detuned axion signal: SNR the same

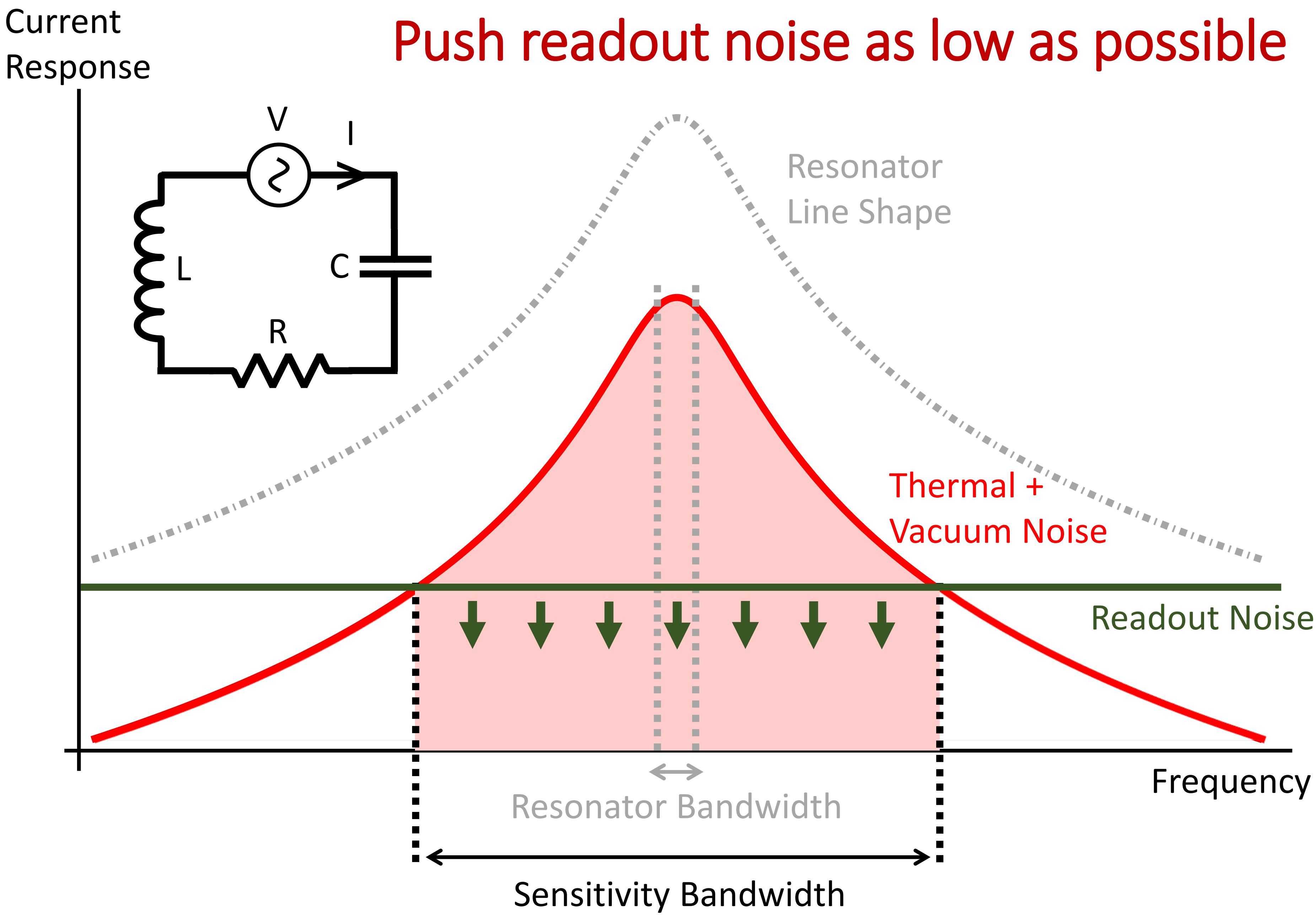


- SNR not degraded when readout subdominant to thermal noise

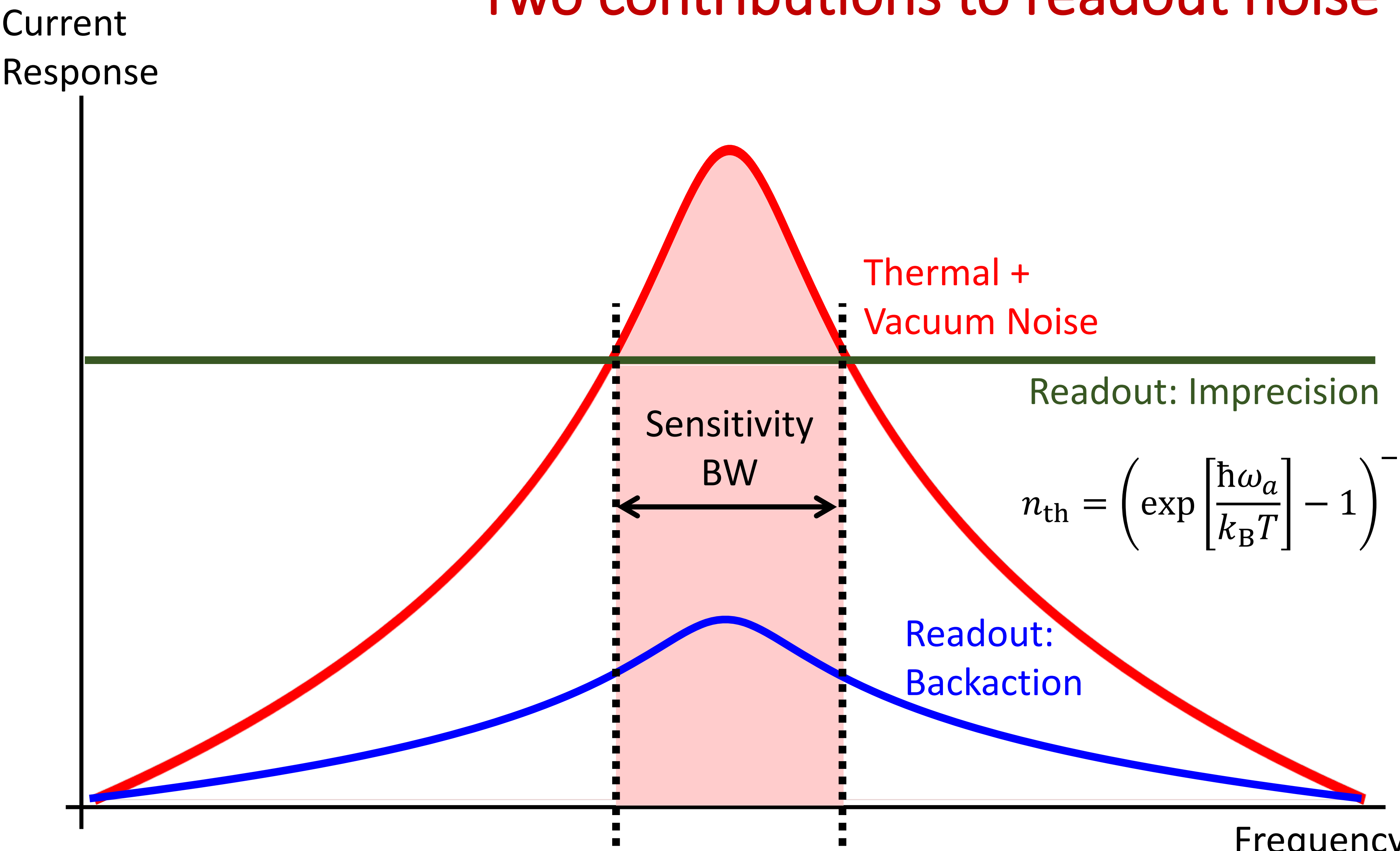
SNR constant over sensitivity BW



Push readout noise as low as possible



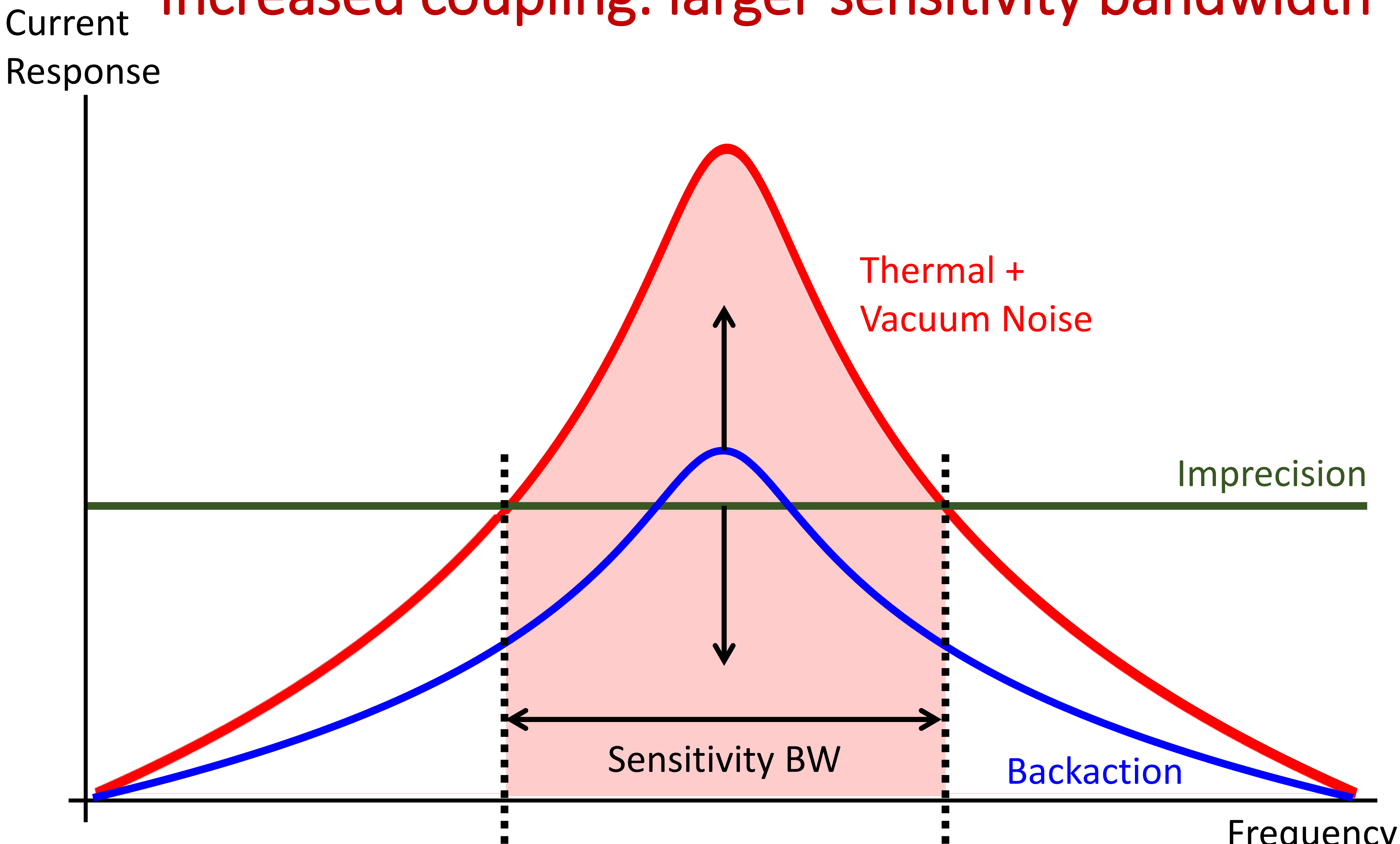
Two contributions to readout noise



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

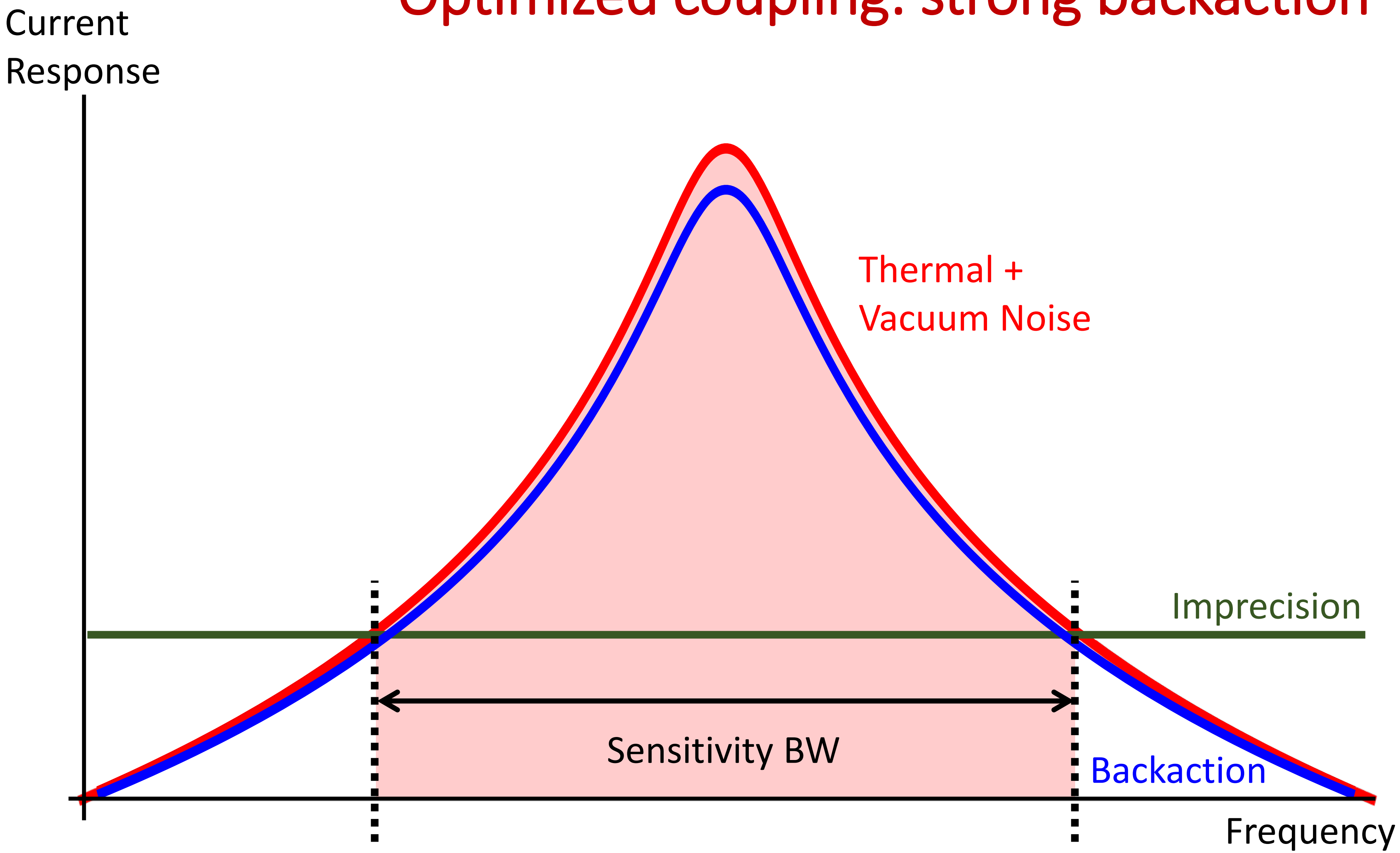
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}\left[1/2 + n_{\mathrm{th}} + n_{\mathrm{BA}}\right] + S_{\mathrm{IMP}}(\omega)$$

Increased coupling: larger sensitivity bandwidth



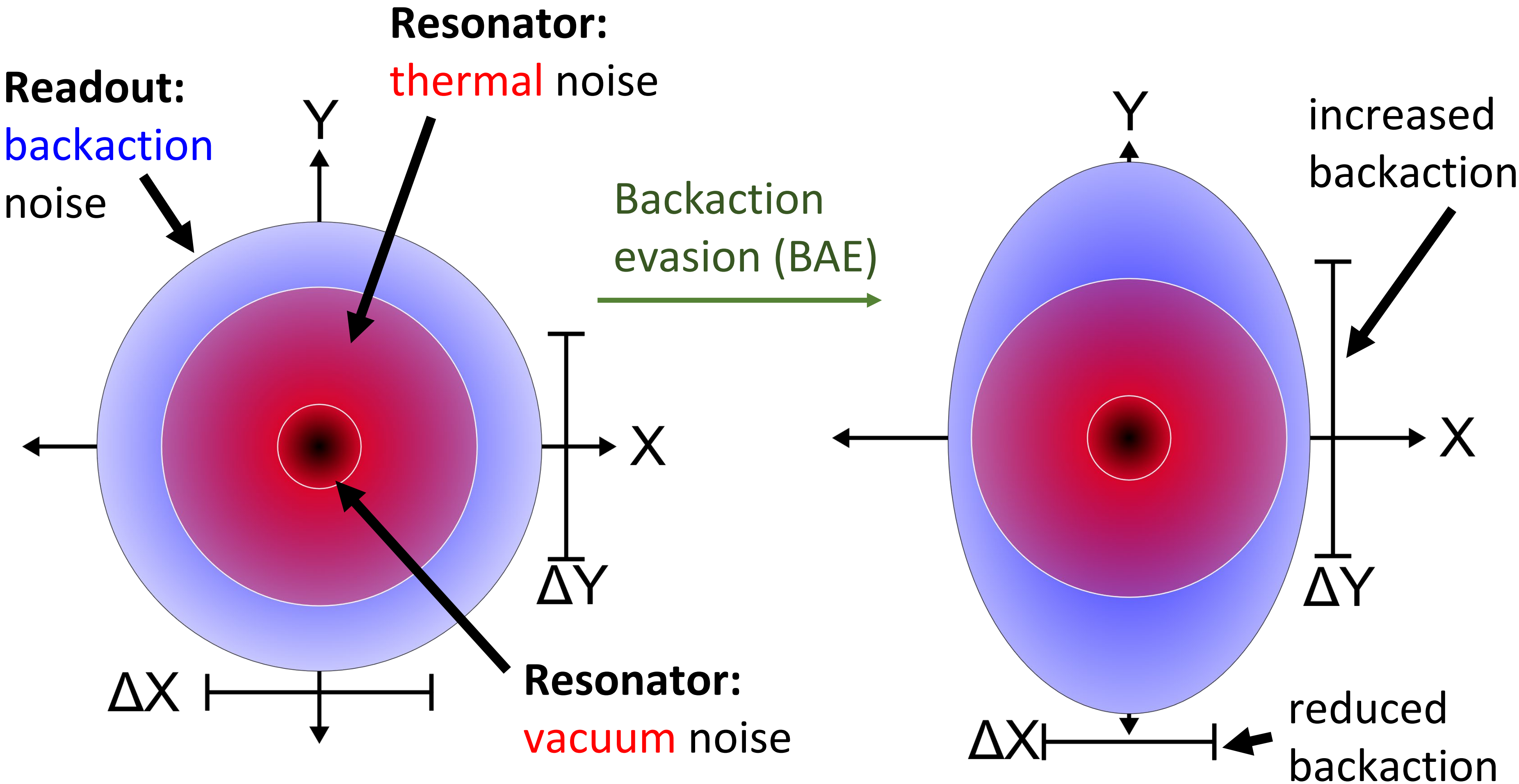
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}\left[1/2 + n_{\mathrm{th}} + n_{BA}\right] + S_{\mathrm{IMP}}(\omega)$$

Optimized coupling: strong backaction



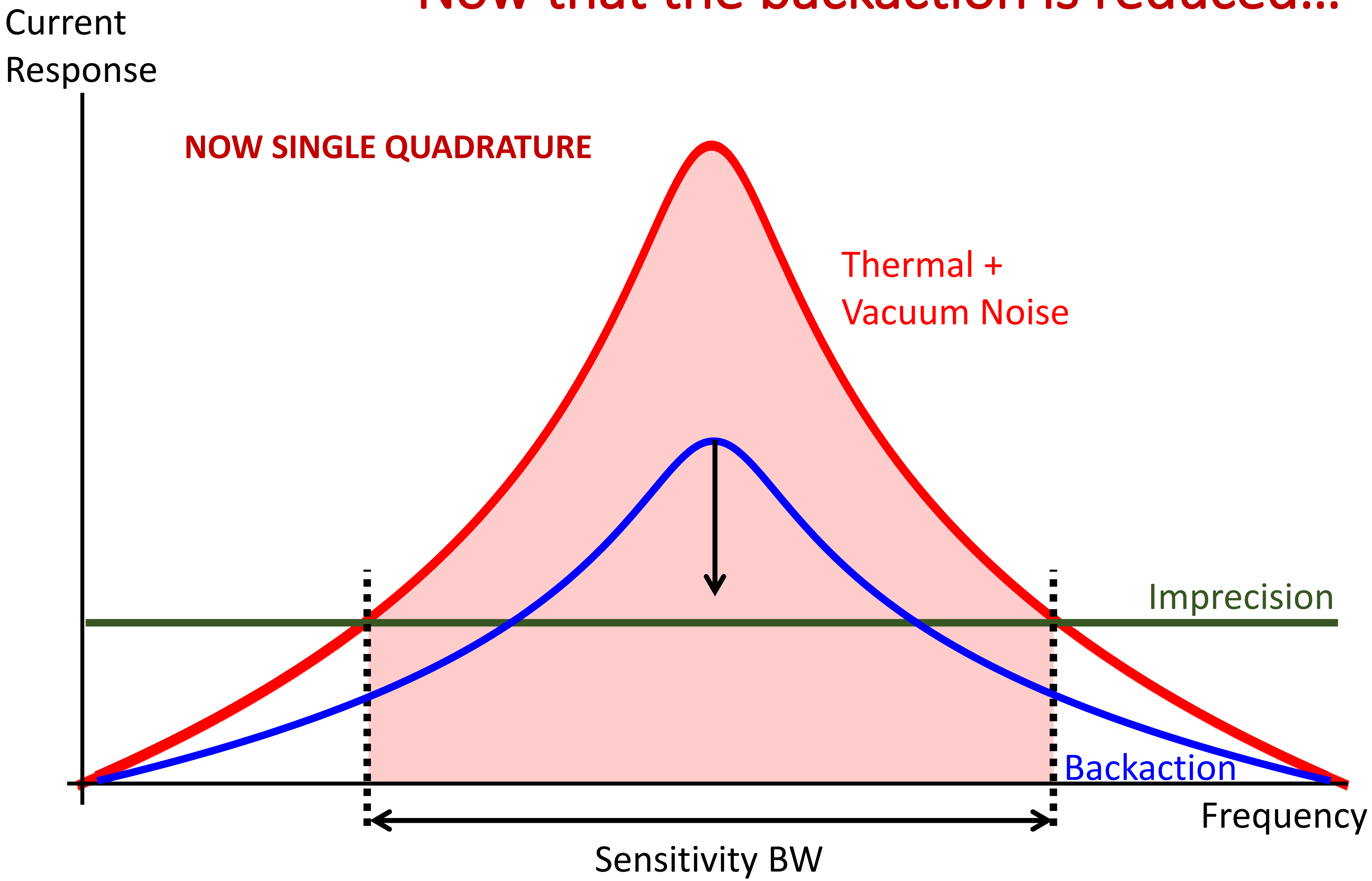
$$S_{X,Y}(\omega) = \frac{\gamma}{(\omega - \omega_a)^2 + (\gamma/2)^2}\left[1/2 + n_{\text{th}} + n_{BA}\right] + S_{\text{IMP}}(\omega)$$

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

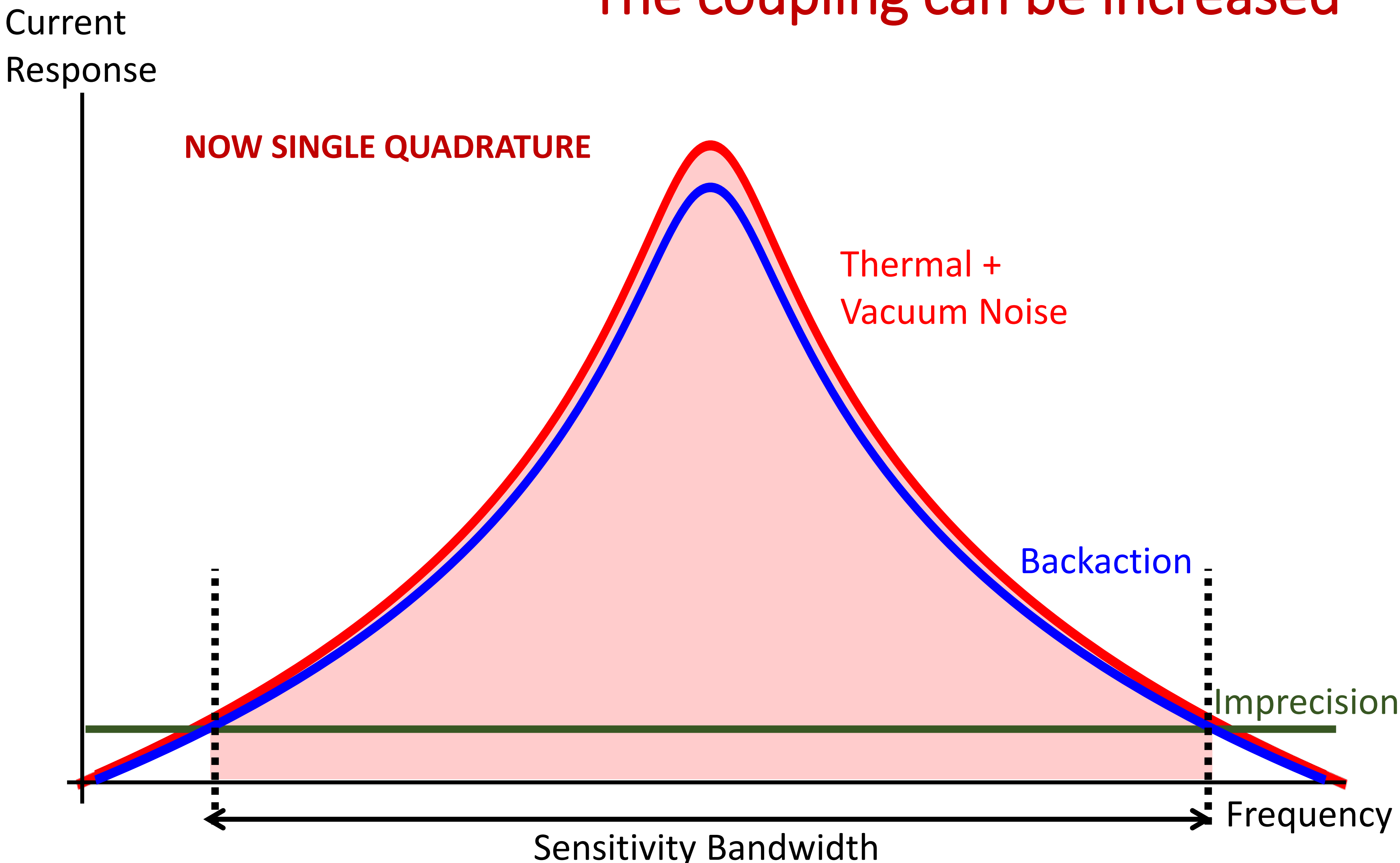


The reduction in the total X-quadrature noise appears unimpressive

Now that the backaction is reduced…



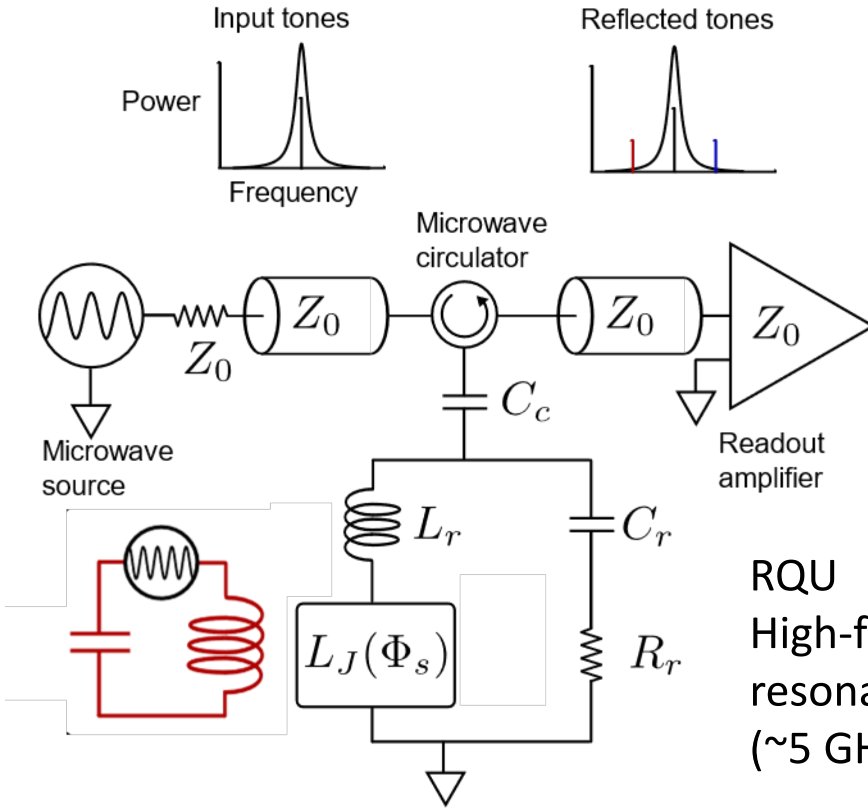
The coupling can be increased



Sensitivity BW can be greatly increased

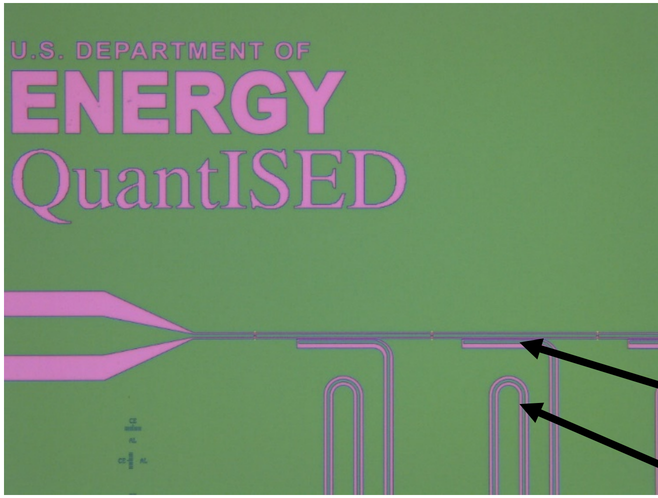
RF Quantum Upconverters

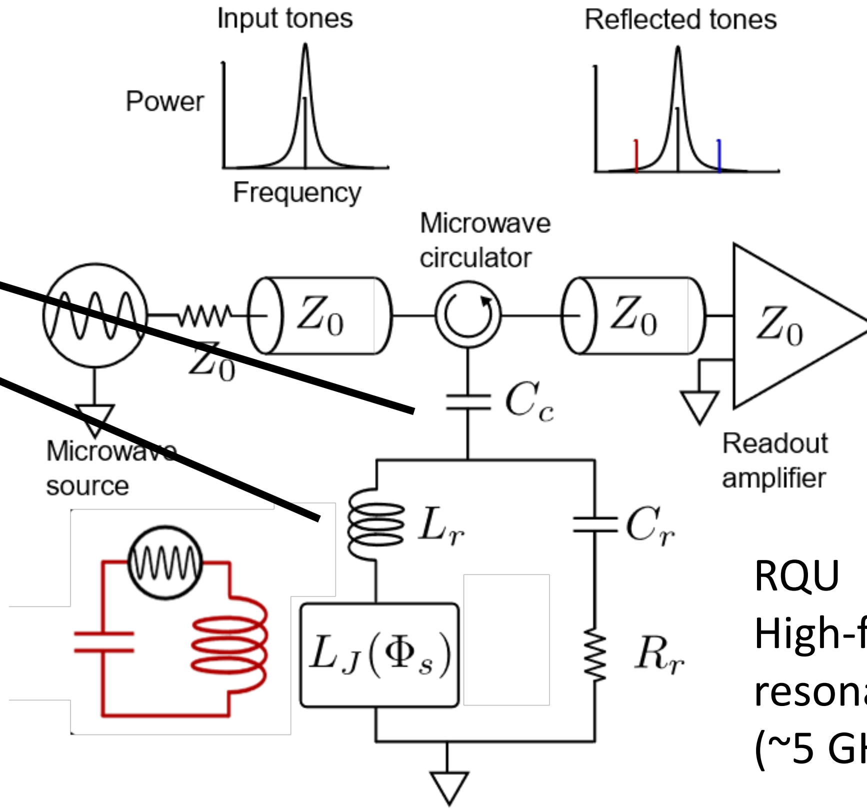
- Electromagnetic sub-μeV axion searches presently use dc SQUIDs in frequency range kHz – 100 MHz.
- The best dc SQUIDs in this frequency range, coupled to macroscopic resonant circuits, are 20 times worse than the SQL, and they couple loss to the resonant circuit.
- A dissipationless sensor is needed that can achieve SQL, and conduct phase-sensitive operations like backaction evasion with electromagnetic signals at audio-RF frequencies.



RQU
High-frequency resonator
(~5 GHz)

RF Quantum Upconverters





RQU
High-frequency resonator
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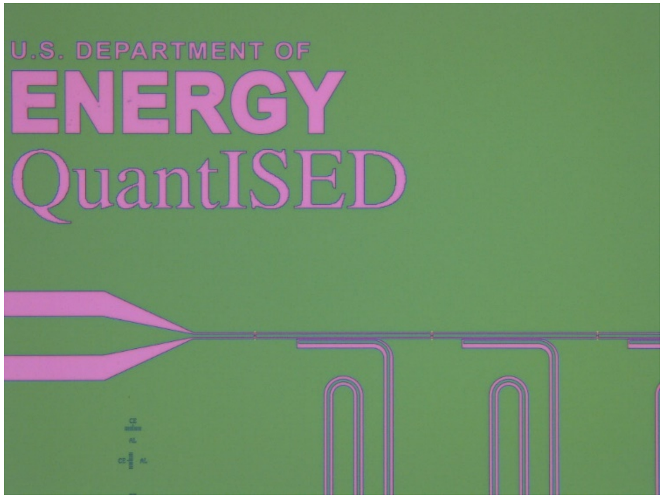
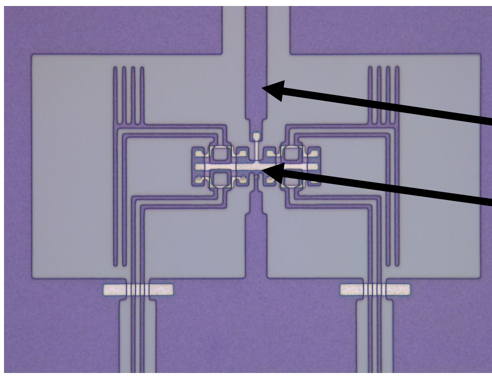
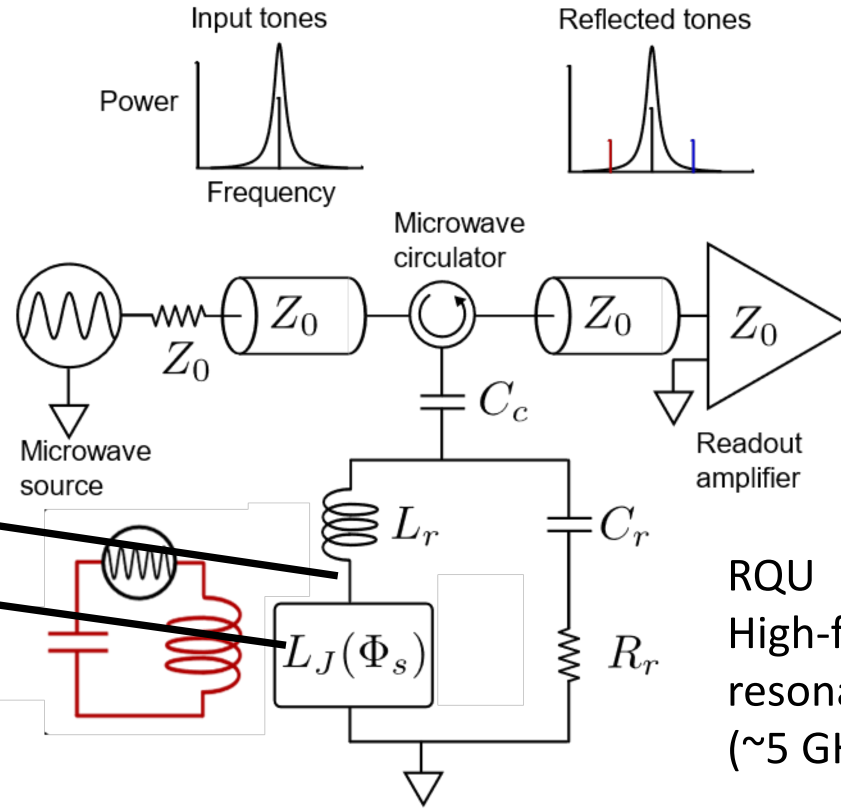
RF Quantum Upconverters



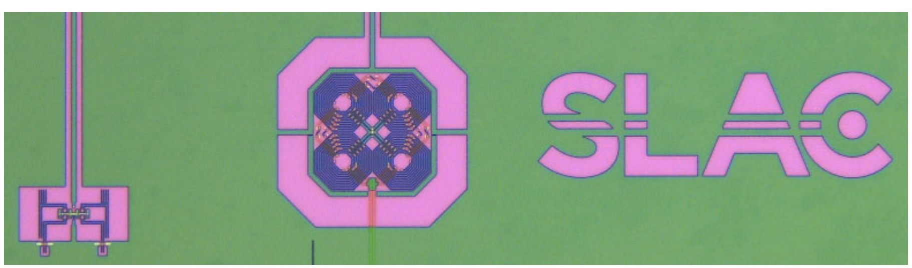




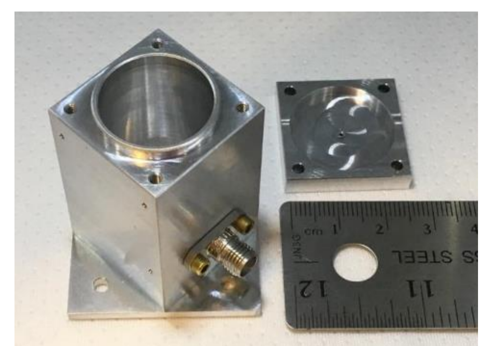
RQU
High-frequency
resonator
(~5 GHz)

Lithographic resonator RQUs:

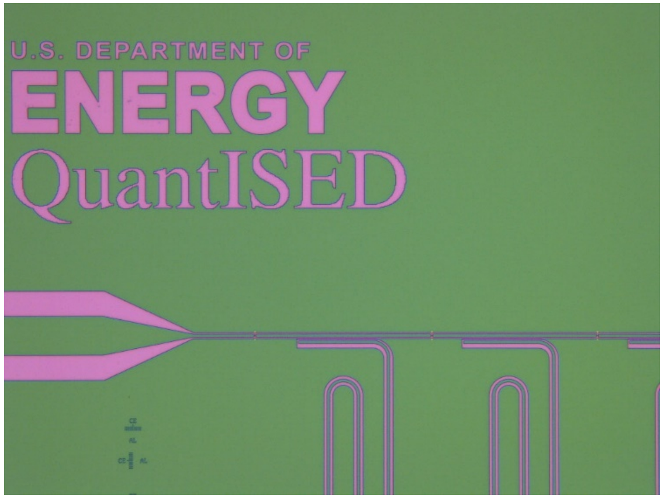
3-junction RQU 1-junction RQU

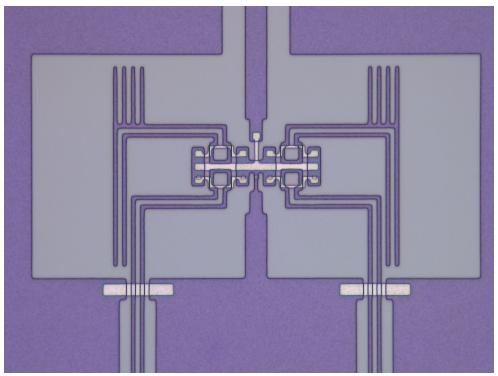


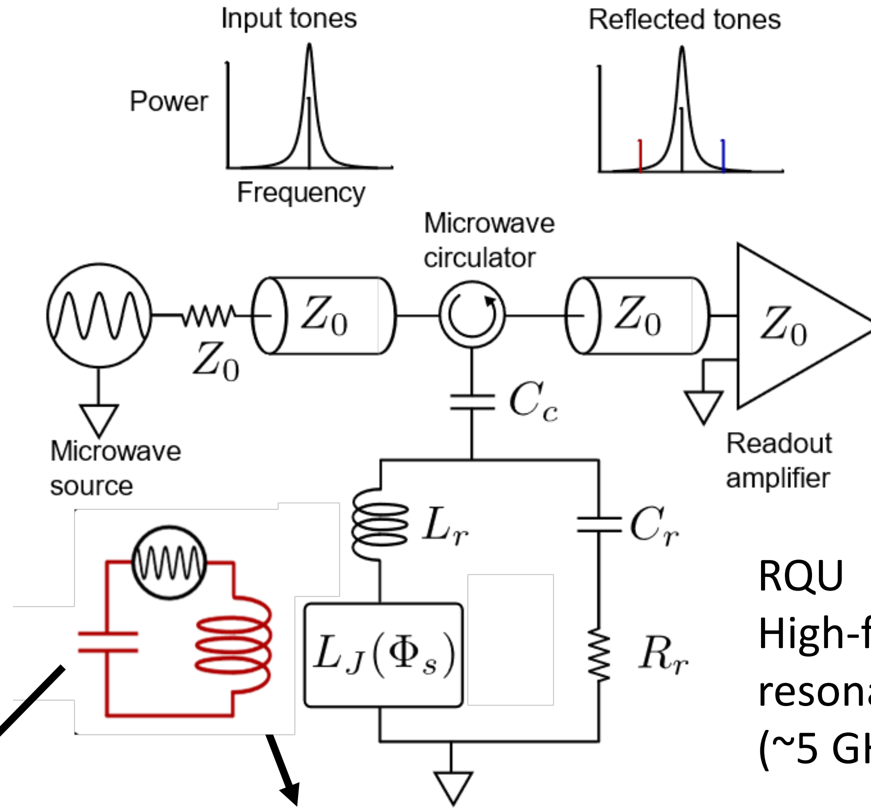
Cavity resonator RQUs:



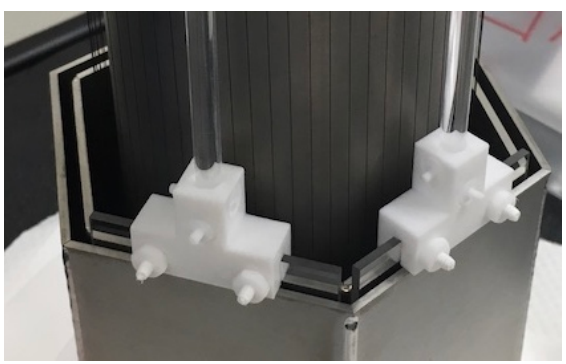
RF Quantum Upconverters







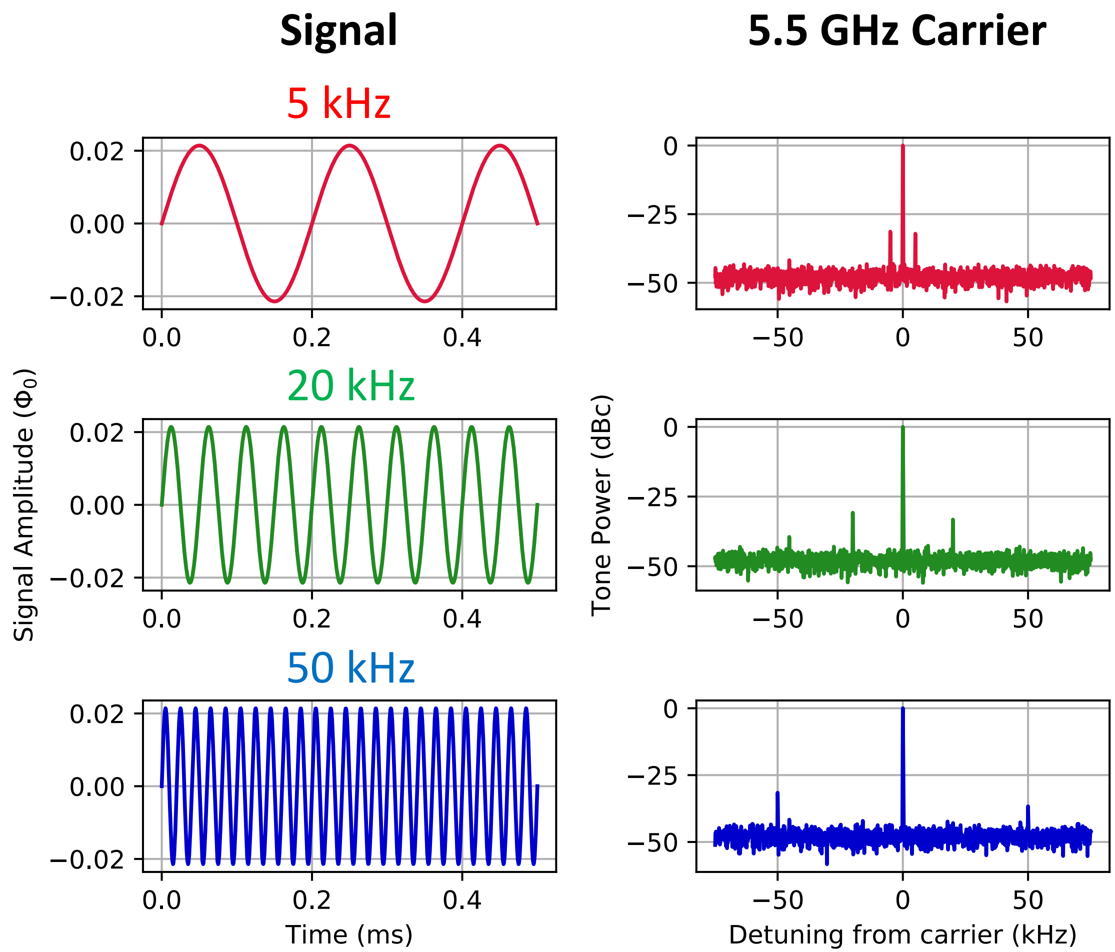
RQU
High-frequency
resonator
(~5 GHz)



DM Radio Pathfinder
Low-frequency
resonator
(~MHz)

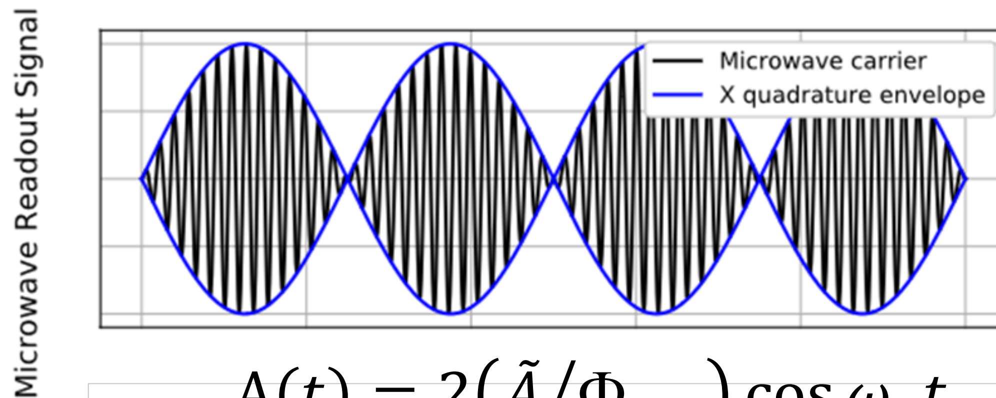
Data illustrating RF Upconversion

- Data illustrating upconversion in single-junction RQUs
- Single-junction RQU excited on resonance
- 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.



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

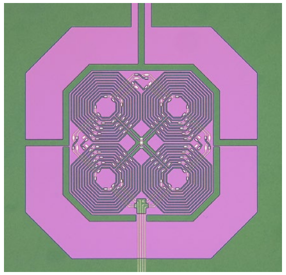
Clerk, *New Journ. Phys.* **10,** 095010 (2008).

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

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

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.

Phase-Sensitive Upconversion Data

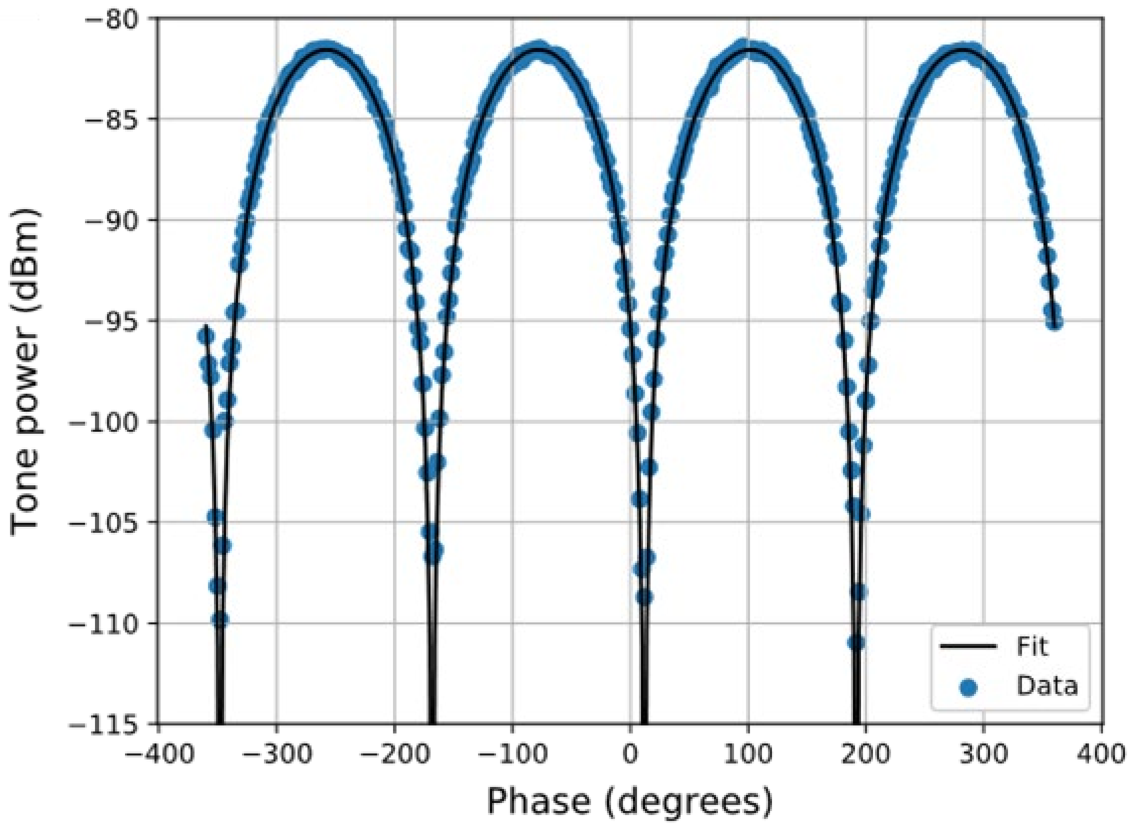


Single-junction RQU

Input: 50 kHz flux signal into single-junction RQU

Carrier: 5.5 GHz sinewave amplitude modulated at 50 KHz

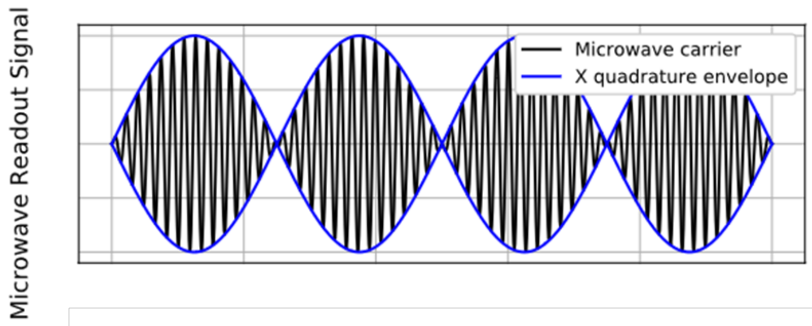
Measure: output tone power as a function of phase shift between input sinewave and AM modulation



29.6 dB of phase-sensitive gain contrast

- Necessary step towards full backaction evasion

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 $\hat{\mathrm{X}}$ quadrature is measured, the backaction is injected preferentially into the $\hat{\mathrm{Y}}$ 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

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

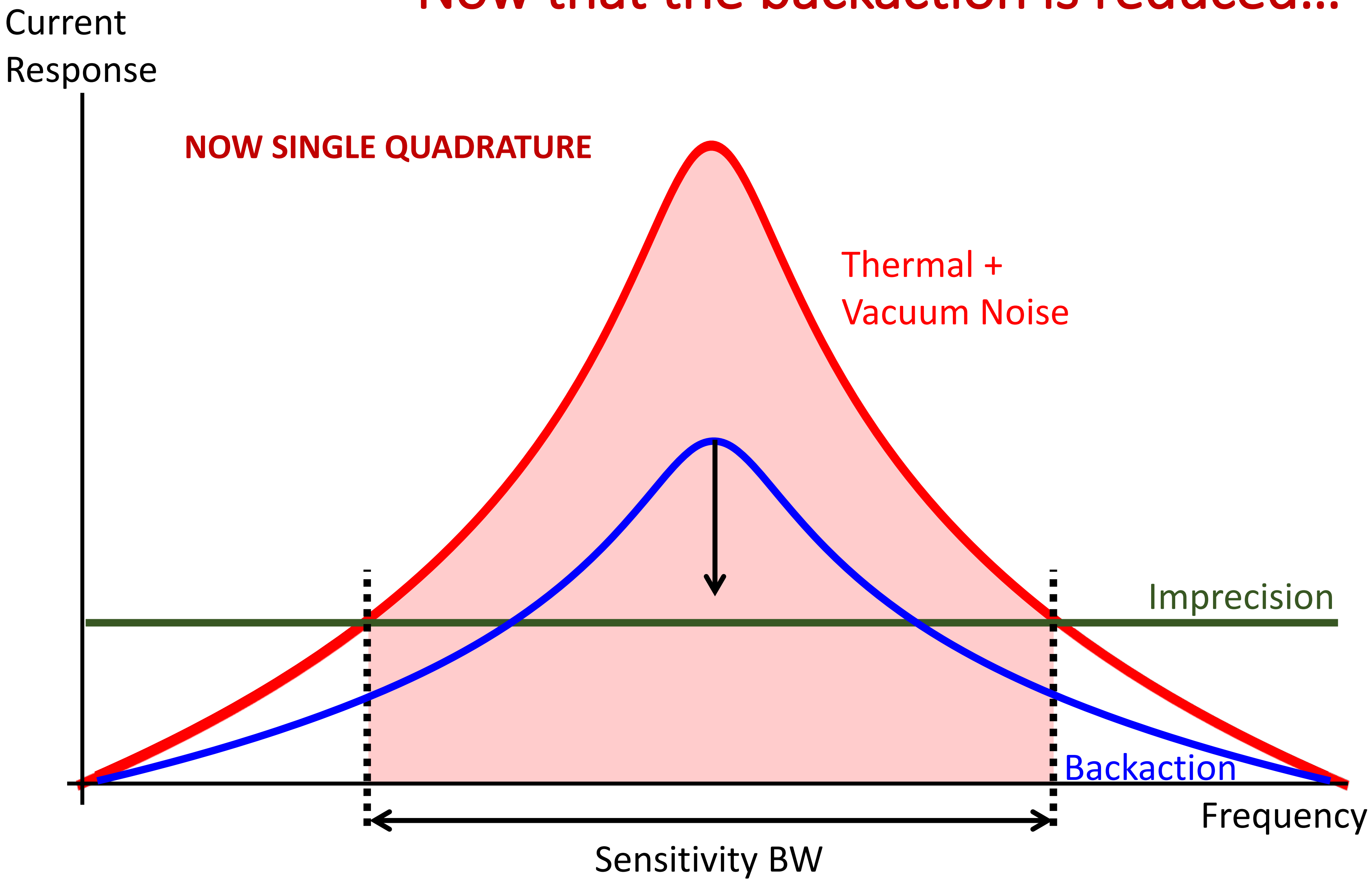
$$S_Y(\omega) = \frac{\gamma}{(\omega-\omega_a)^2 + (\gamma/2)^2}\left[1/2 + n_{\mathrm{th}} + n_{\mathrm{BA}}\right] + S_{\mathrm{IMP}}(\omega)$$

Microwave resonator linewidth

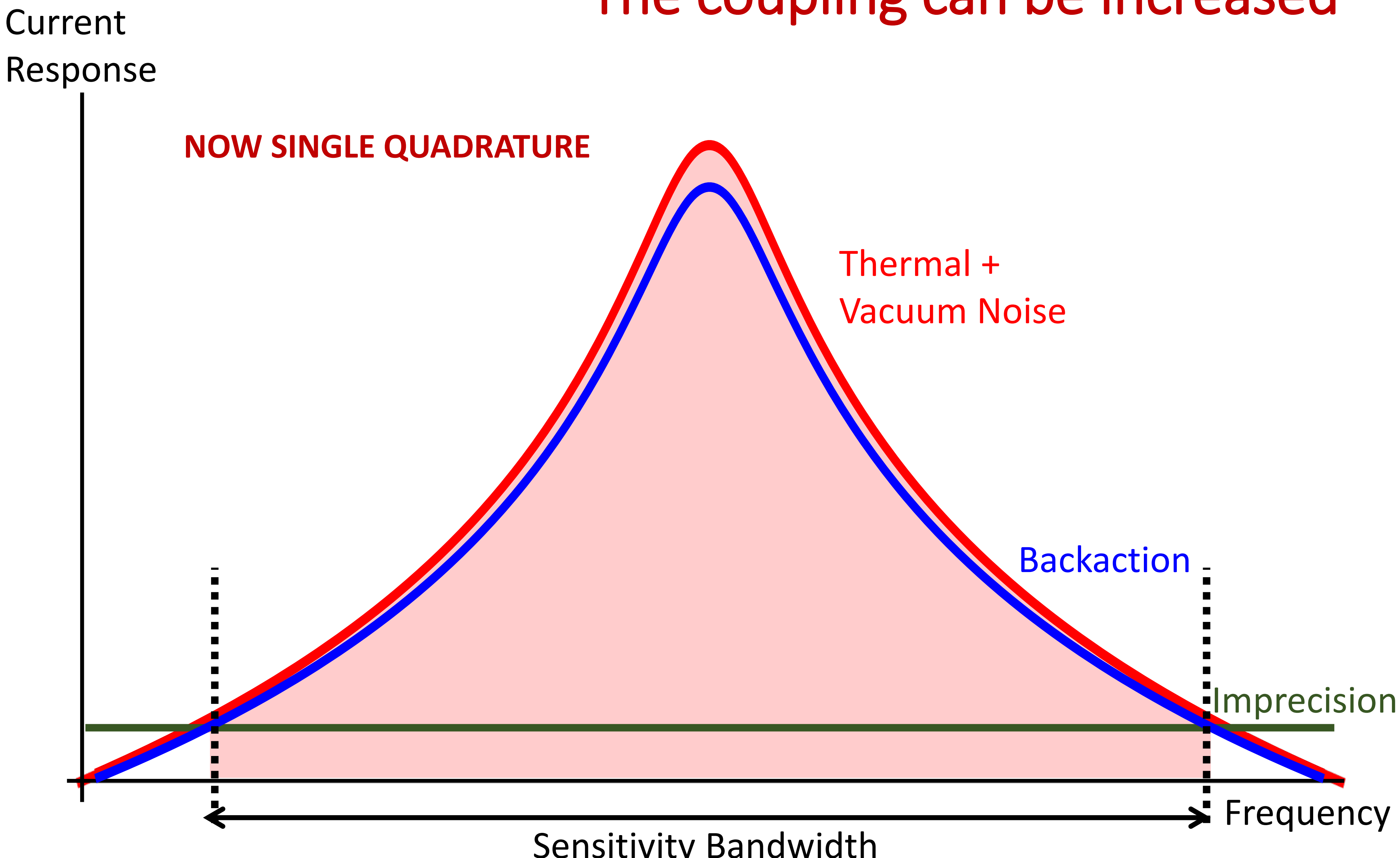
$$n_{\mathrm{leak}} = \frac{n_{\mathrm{BA}}}{32}\left(\frac{\kappa}{\omega_a}\right)^2$$

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

Now that the backaction is reduced…



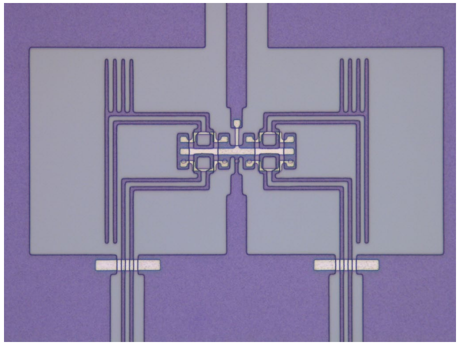
The coupling can be increased

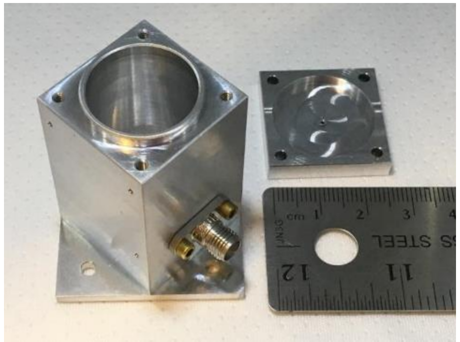


Sensitivity BW can be greatly increased

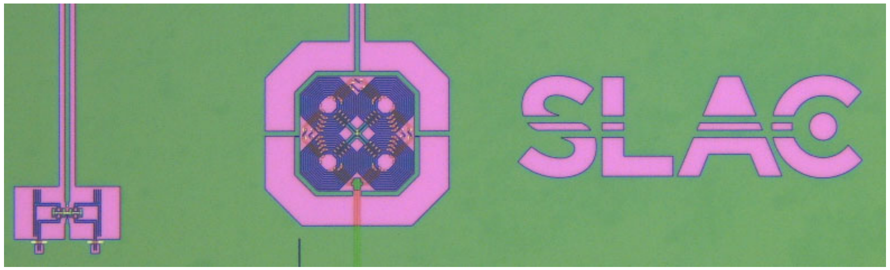
Next steps

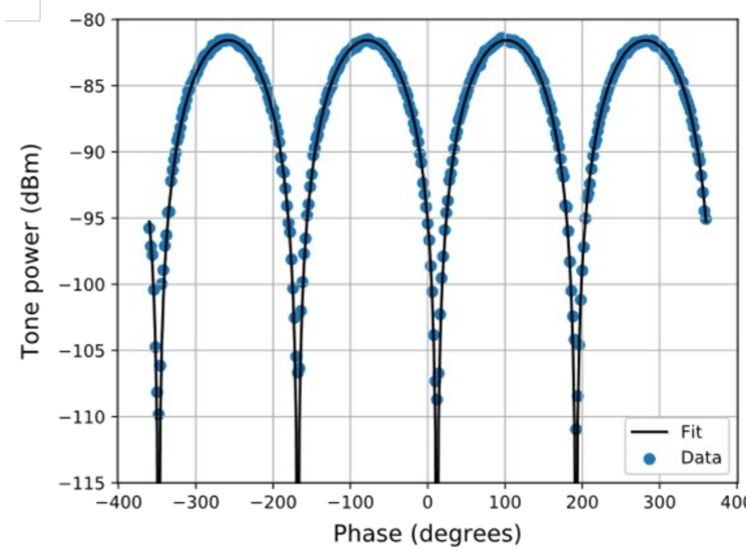
- 29.6 dB of phase-sensitive gain contrast achieved with 1-junction RQU.
- 1-junction RQUs couple to uncontrolled microwave modes in the low-frequency resonator. Implement 3-junction design that cleanly isolates the microwave and low-frequency circuits by symmetry / bias.
- To get >~ 3 dB of BAE, need to improve dynamic range by better parameter optimization, incorporating series arrays of junctions and/or 9-junction circuits designed to null the first-order Kerr nonlinearity.
- Implement cavity resonators to improve the Q of the microwave circuit / reduce backaction leakage





Summary

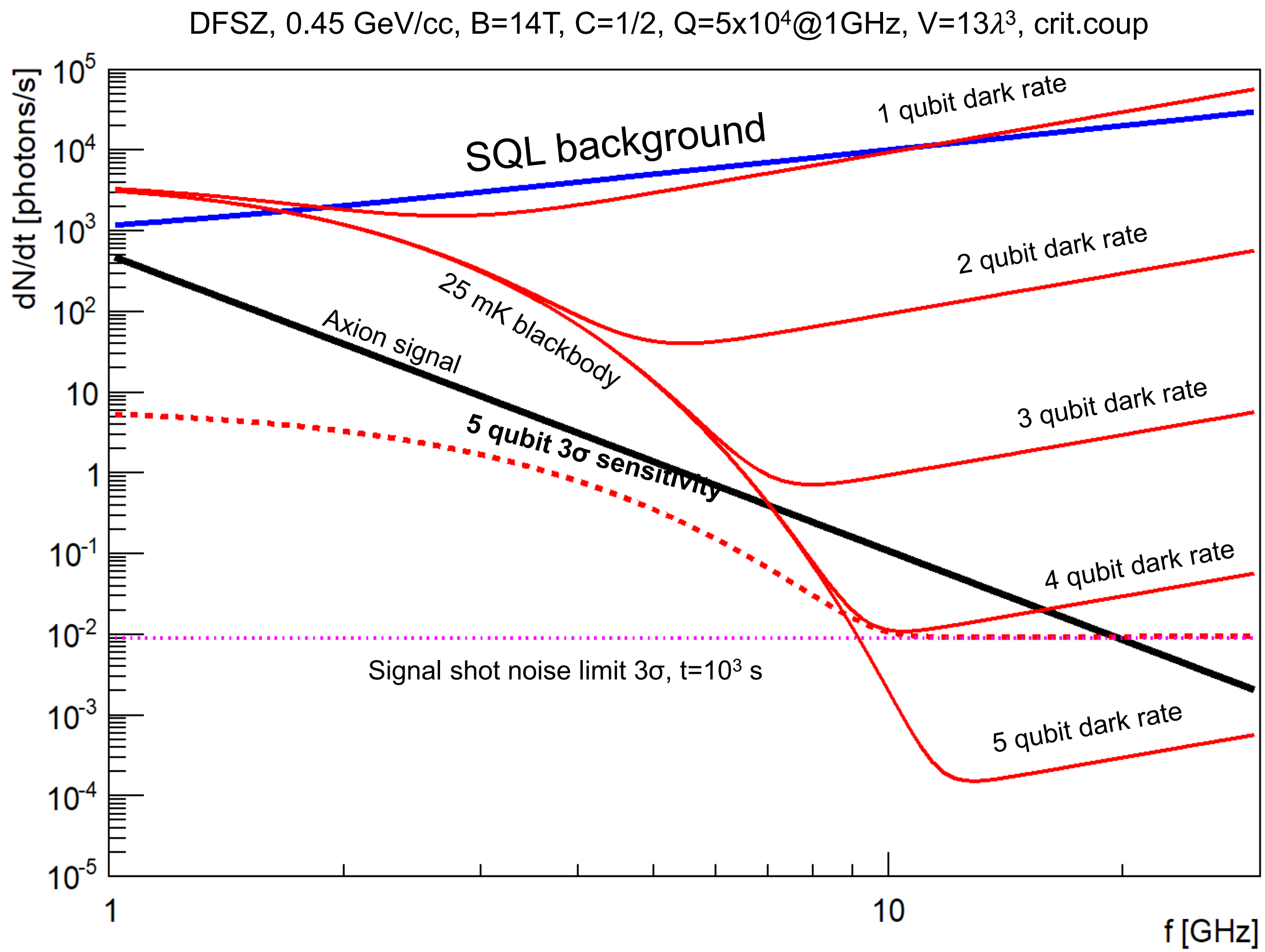




- There is a compelling need for quantum sensors for fundamental physics
- It will not be possible to fully probe the QCD axion band without quantum acceleration
- Radio-frequency quantum upconverters can enable measurement better than the SQL below for axion mass below 1 μeV
- 29.6 dB of phase-sensitive gain contrast in an RF Quantum Upconverter achieved – a first step


STOP

Ground state measurement: QND photon counting



Sensitivity limited only by signal photon shot noise.

See: David Schuster talk?

Figure Credit: Aaron Chou, FNAL

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Weak coupling to electromagnetism

The Axion Lagrangian Density:

The axion can also couple to nuclear spins, but let's focus on electromagnetic searches.

$$\mathcal{L} = \boxed{\frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2} - \boxed{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + \boxed{\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\widetilde{F}^{\mu\nu}}$$

Axion dynamics

Standard E&M

Weak coupling to axions

Modified Maxwell's Equations

$$\boldsymbol{\nabla} \cdot \mathbf{E} = g_{a\gamma\gamma}\mathbf{B} \cdot \boldsymbol{\nabla} a$$

$$\boldsymbol{\nabla} \times \mathbf{B} - \partial_t \mathbf{E} = g_{a\gamma\gamma}\left(\mathbf{E} \times \boldsymbol{\nabla} a - \mathbf{B}\partial_t a\right)$$

$$\boldsymbol{\nabla} \times \mathbf{E} + \partial_t \mathbf{B} = 0$$

$$\boldsymbol{\nabla} \cdot \mathbf{B} = 0$$

This looks like an effective current density parallel to a background B-field