Quantum Measurement Protocols for Upconverting Sensors

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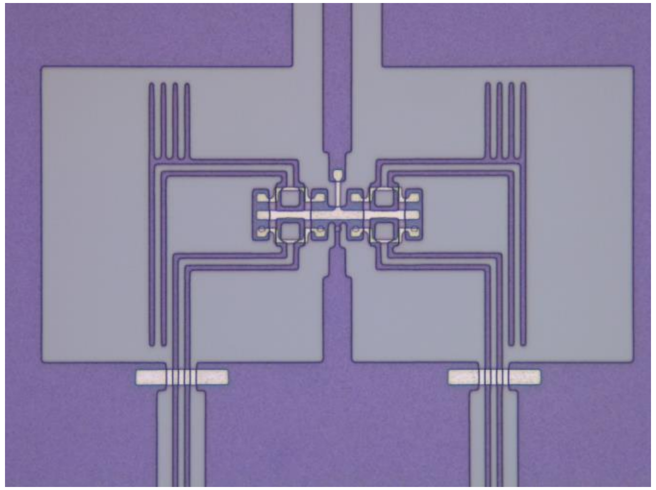
Introduction

1. Quantum sensing from DC to 300 MHz (VHF), in the thermal regime.

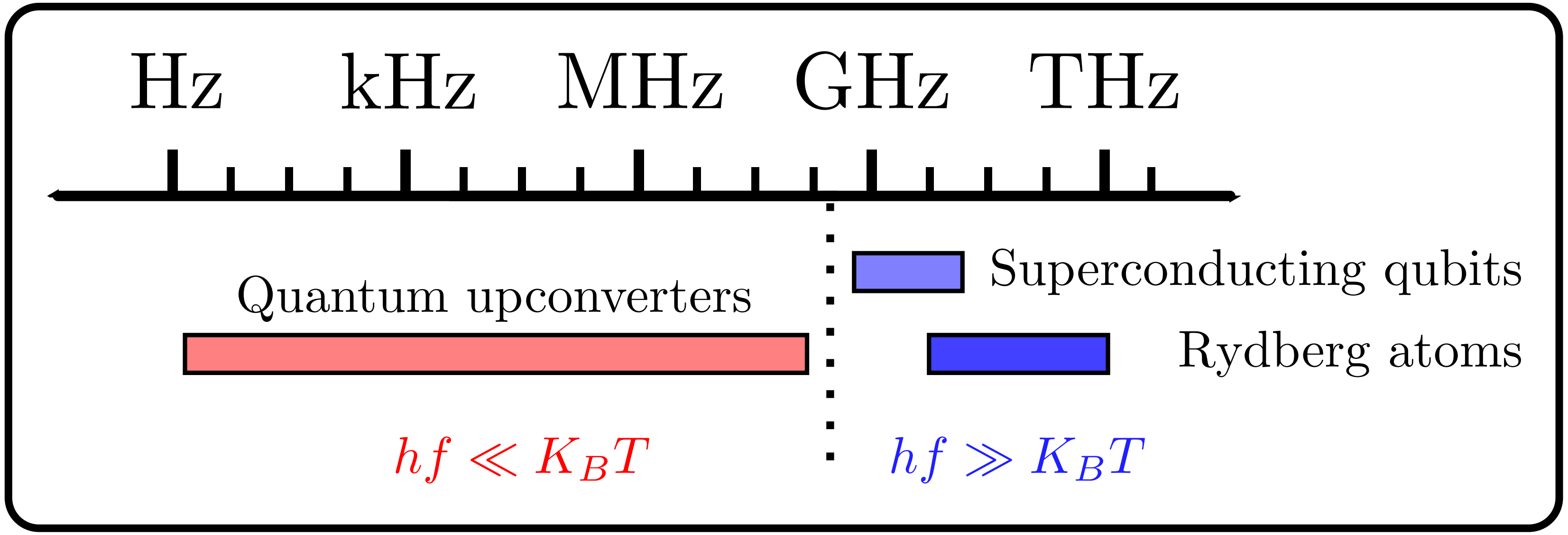
2. Reaching the Standard Quantum Limit (SQL) by upconverting DC-VHF signals to microwave frequencies.

3. Evading the SQL using phase coherence between the DC-VHF and microwave frequency bands.



Regimes of quantum optics

- It is impractical to directly cool electromagnetic sensors far below ~10mK.
- This leaves our sensor with residual thermal excitations, so we require different measurement protocols than experiments above ~1GHz.



Why we need quantum sensors

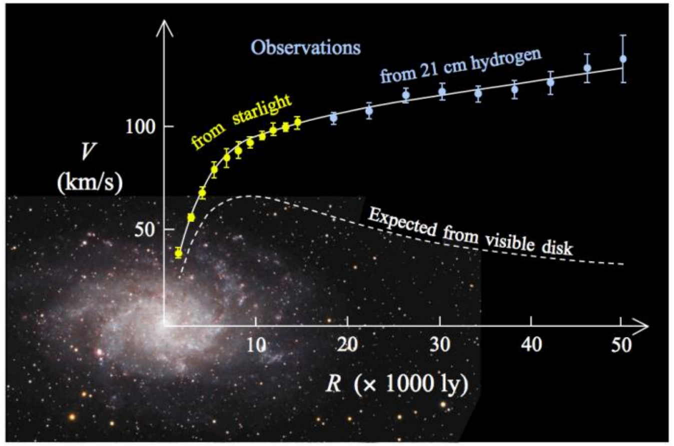
- Experiments searching for extremely weak DC-VHF signals are important, since they can:
  - detect or rule out well-motivated dark matter candidates,
  - measure on nuclear magnetic resonance samples in very weak magnetic fields,
  - perform sensitive magnetometry, e.g. in a scanning SQUID system.
- **In many cases, overall experimental sensitivity is limited by noise added in the measurement/amplification process**

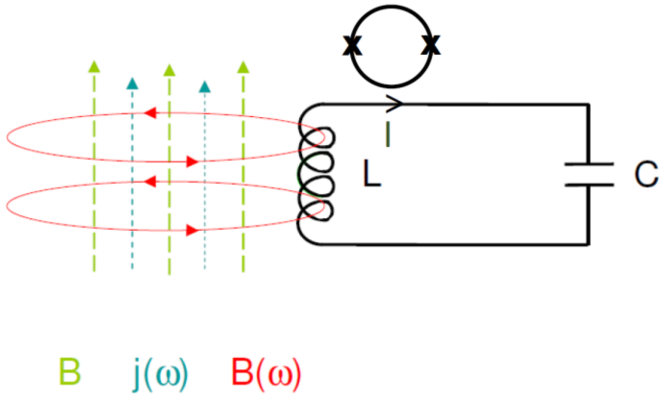
Quantum sensors for dark matter

- The QCD axion is a hypothetical particle that would account for our indirect observations of dark matter.

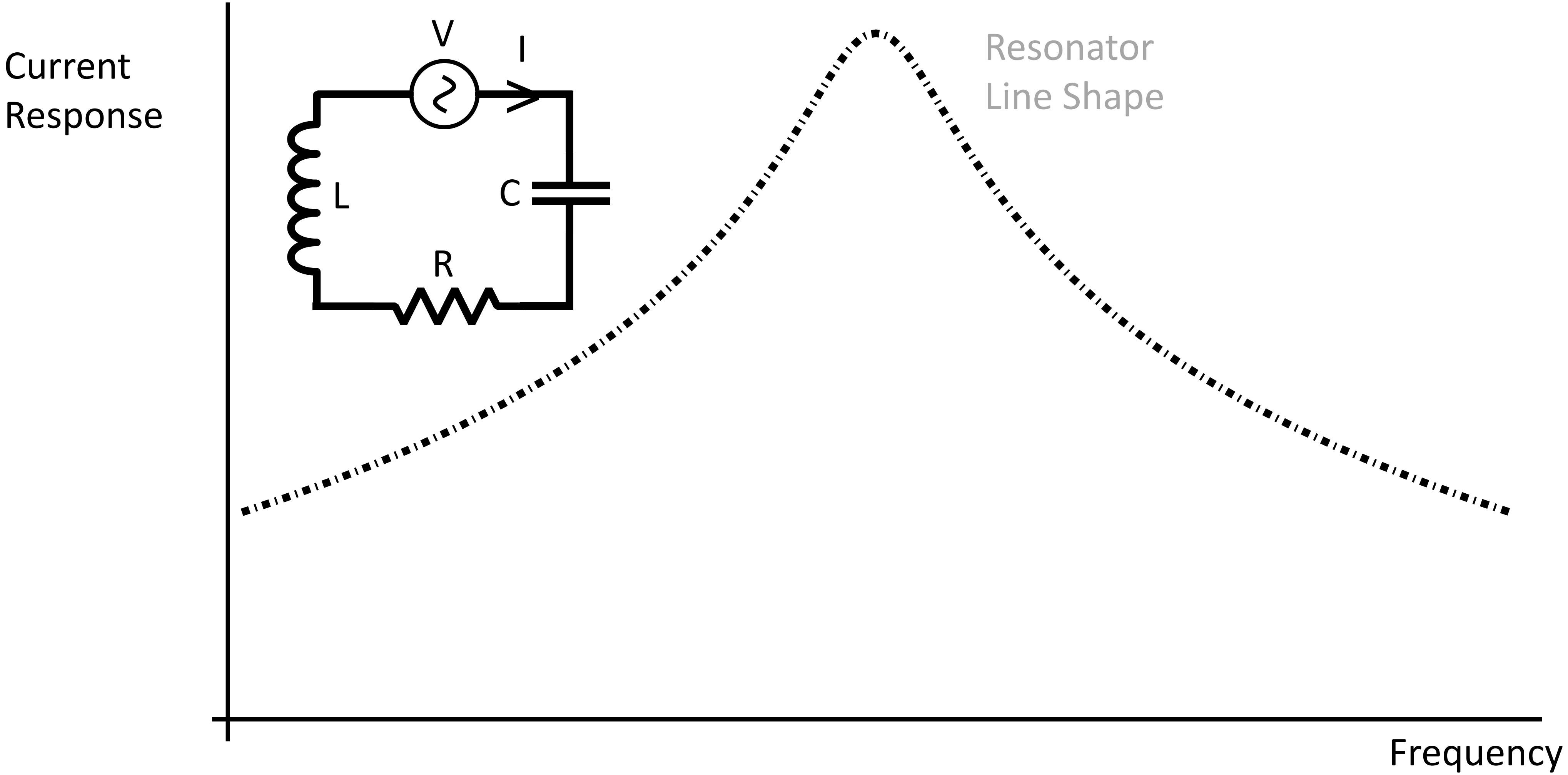
- It converts to a weak AC magnetic field in the presence of a strong DC magnetic field.

- The signal appears in a narrow (but unknown) frequency band, with a total power of order **10^{-24} Watts.**

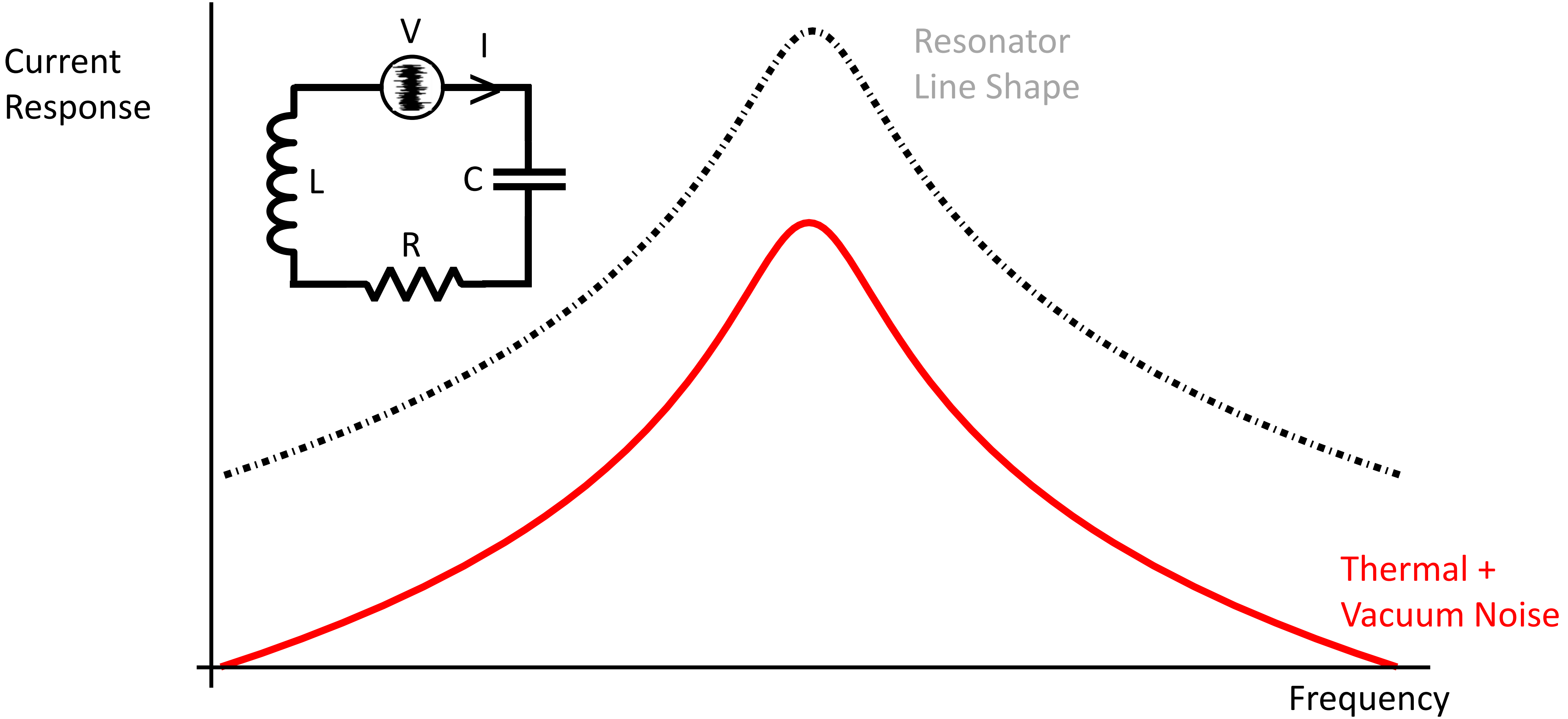




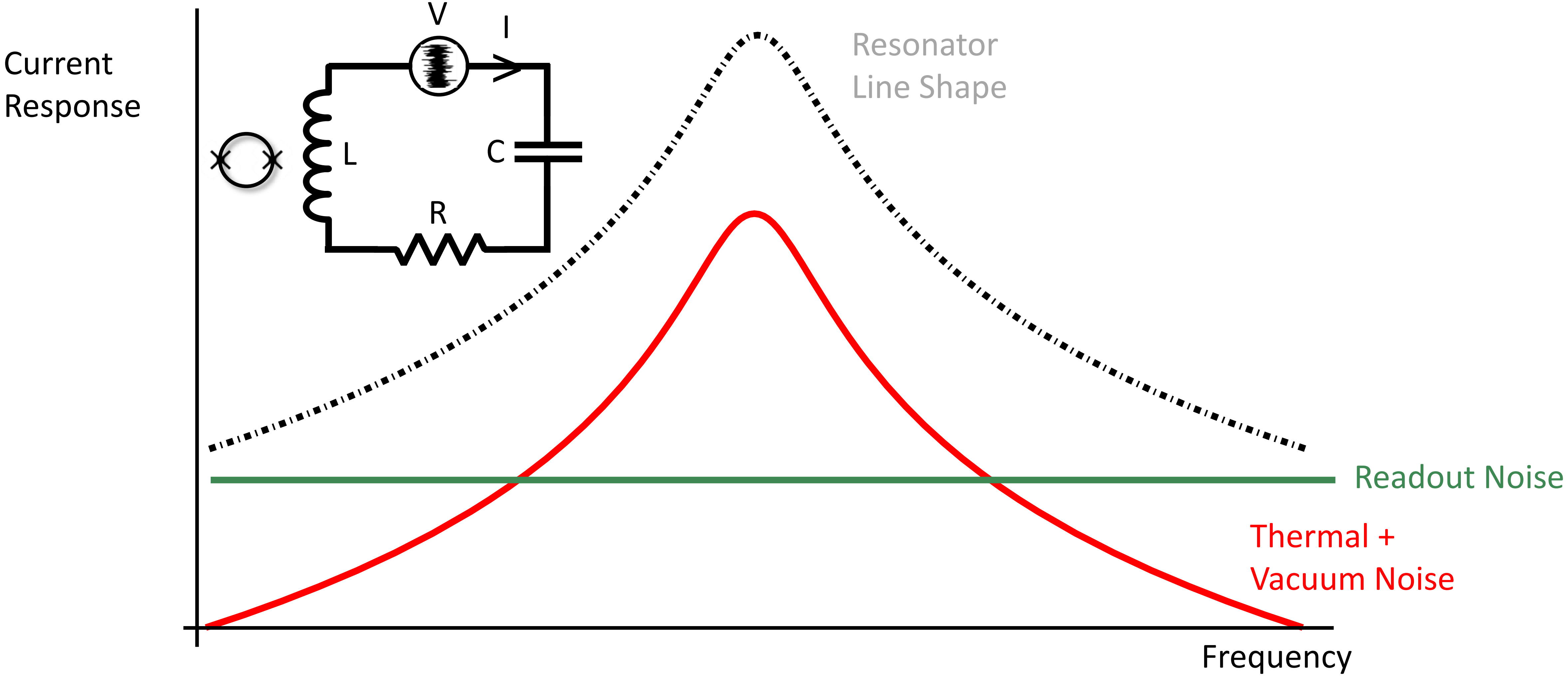
Resonant circuit response



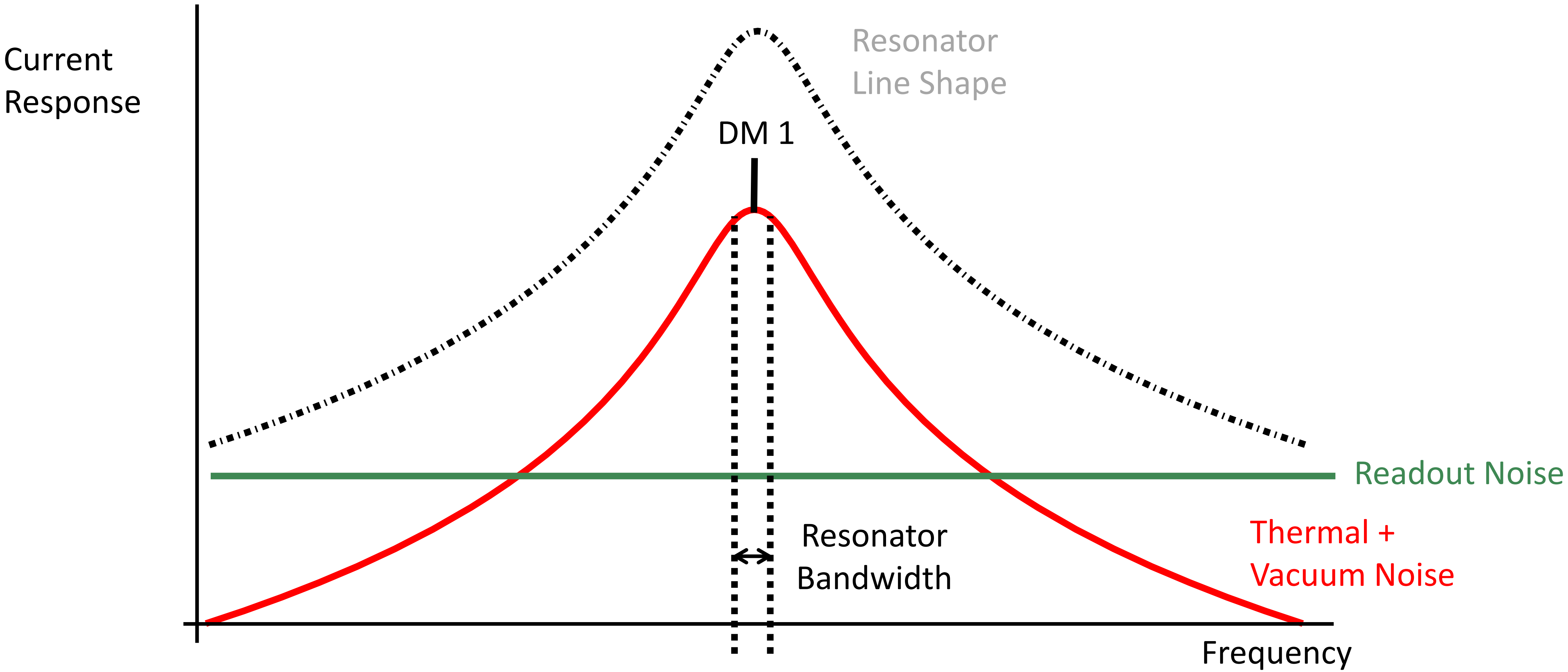
Thermal noise in resonator



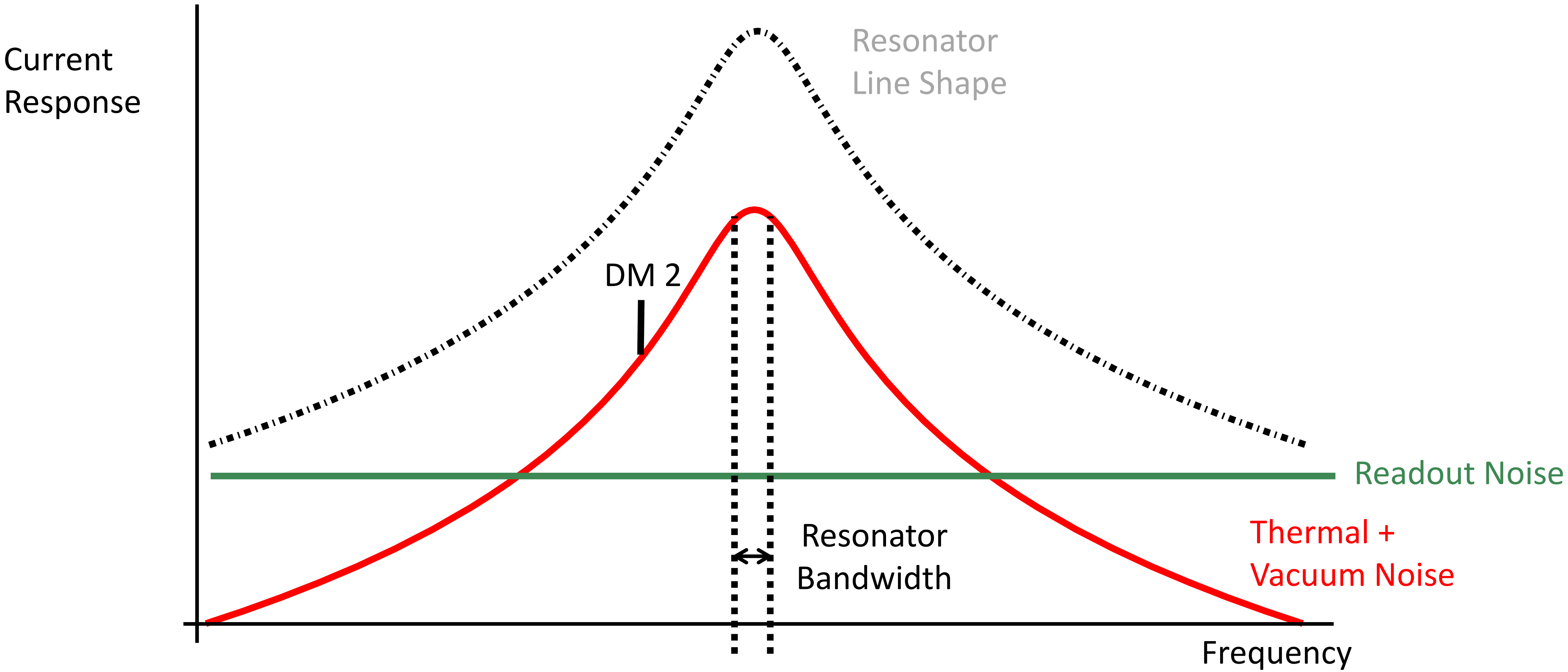
Added noise due to amplification



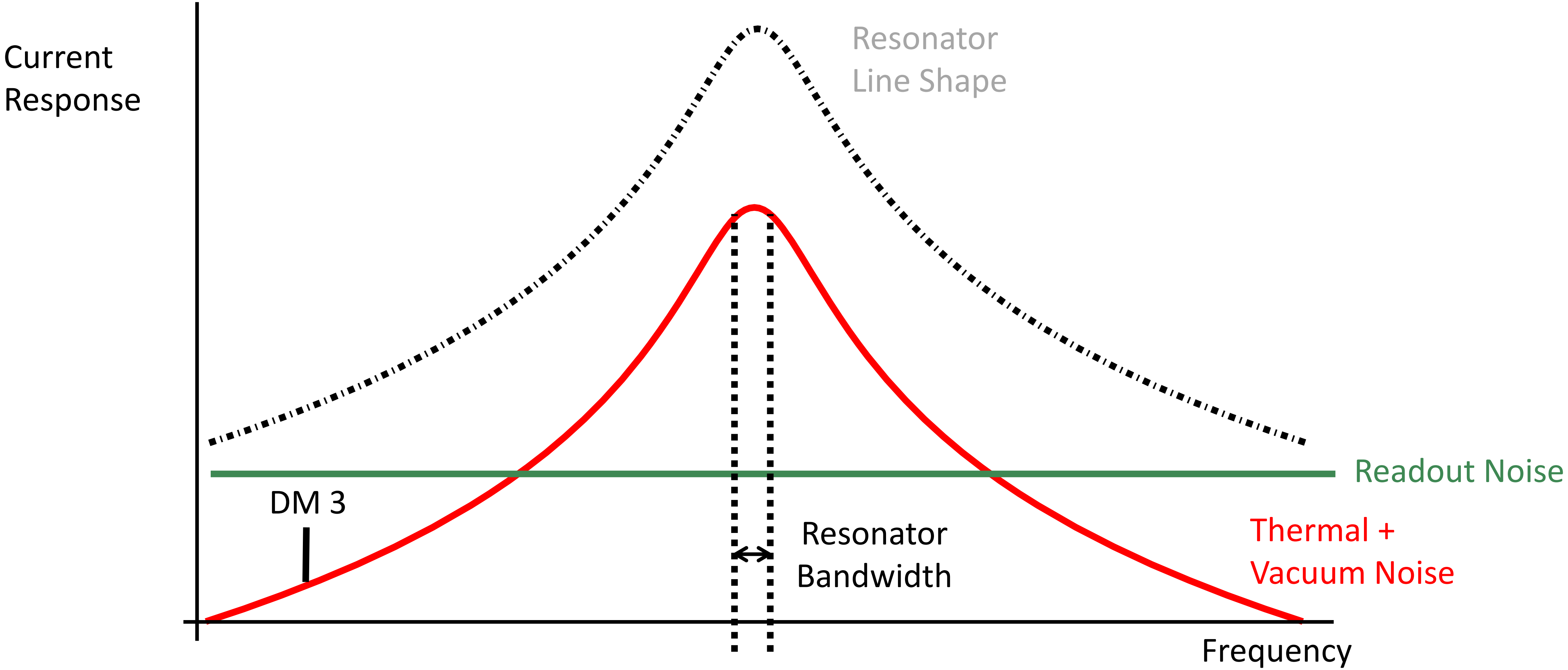
Tune exactly to DM frequency



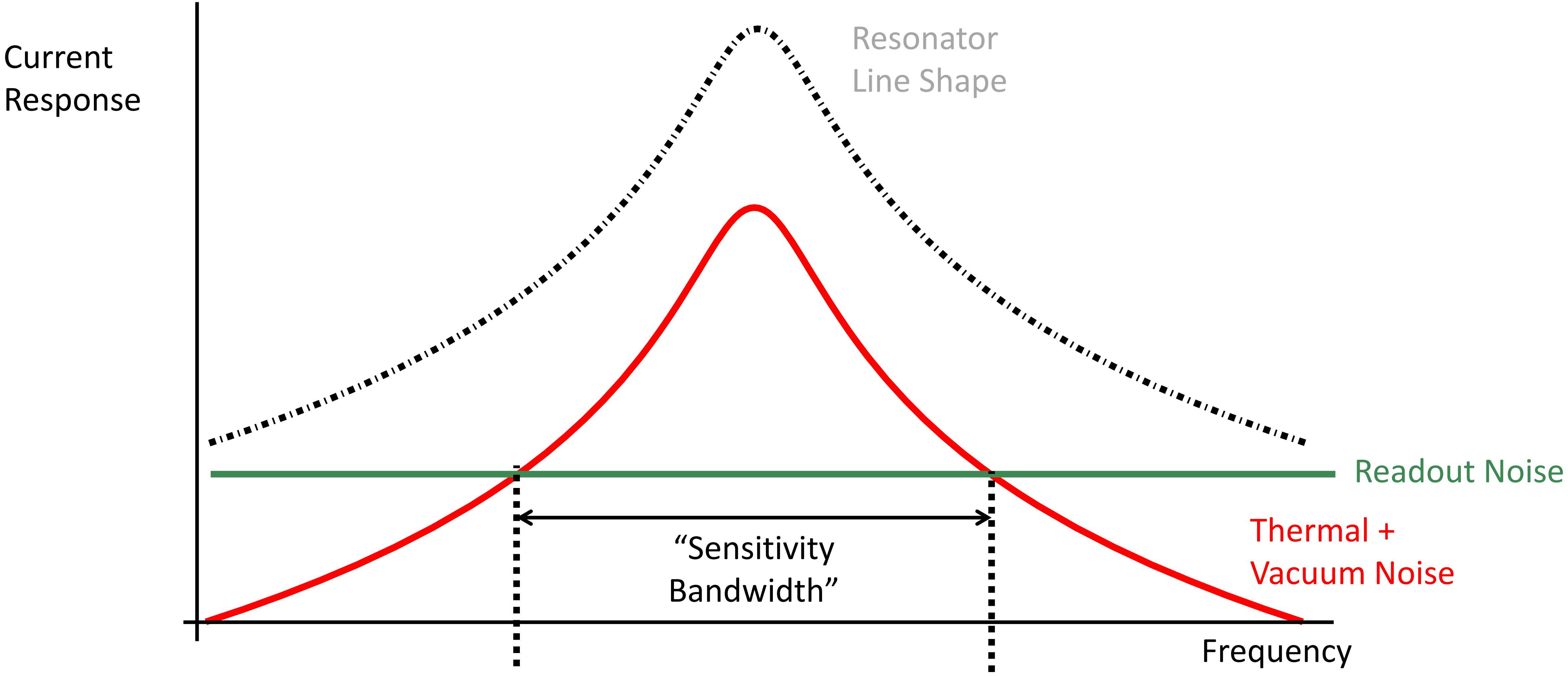
Detune slightly from DM frequency



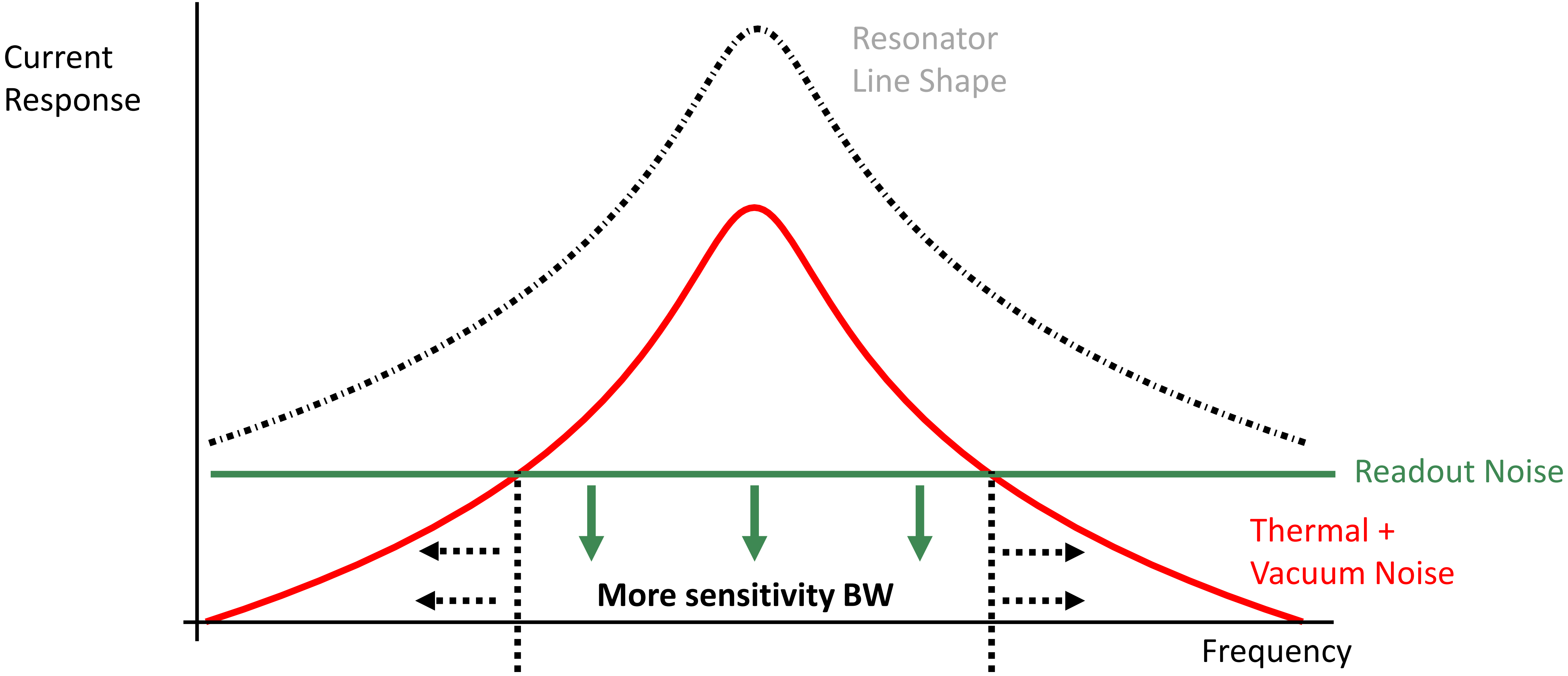
Detune too far from DM frequency



Use all available information!

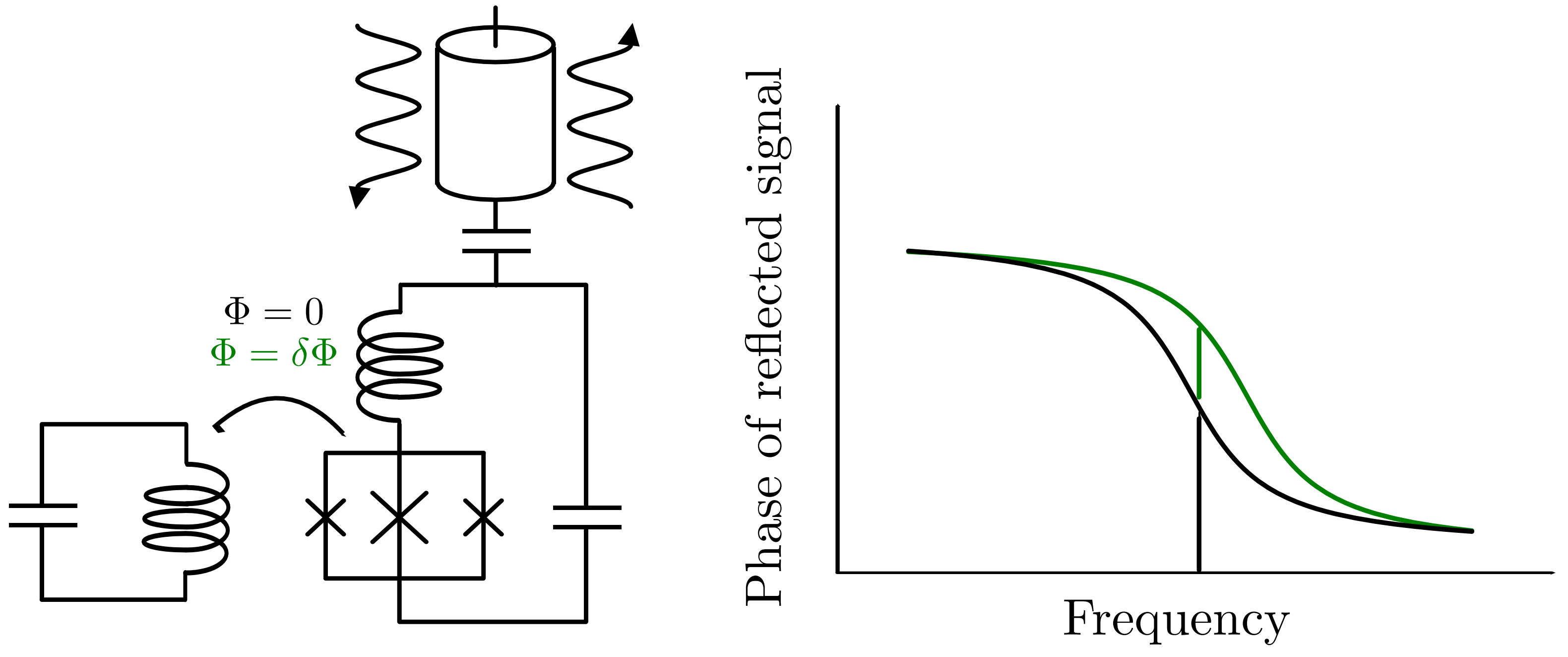


Minimize readout noise



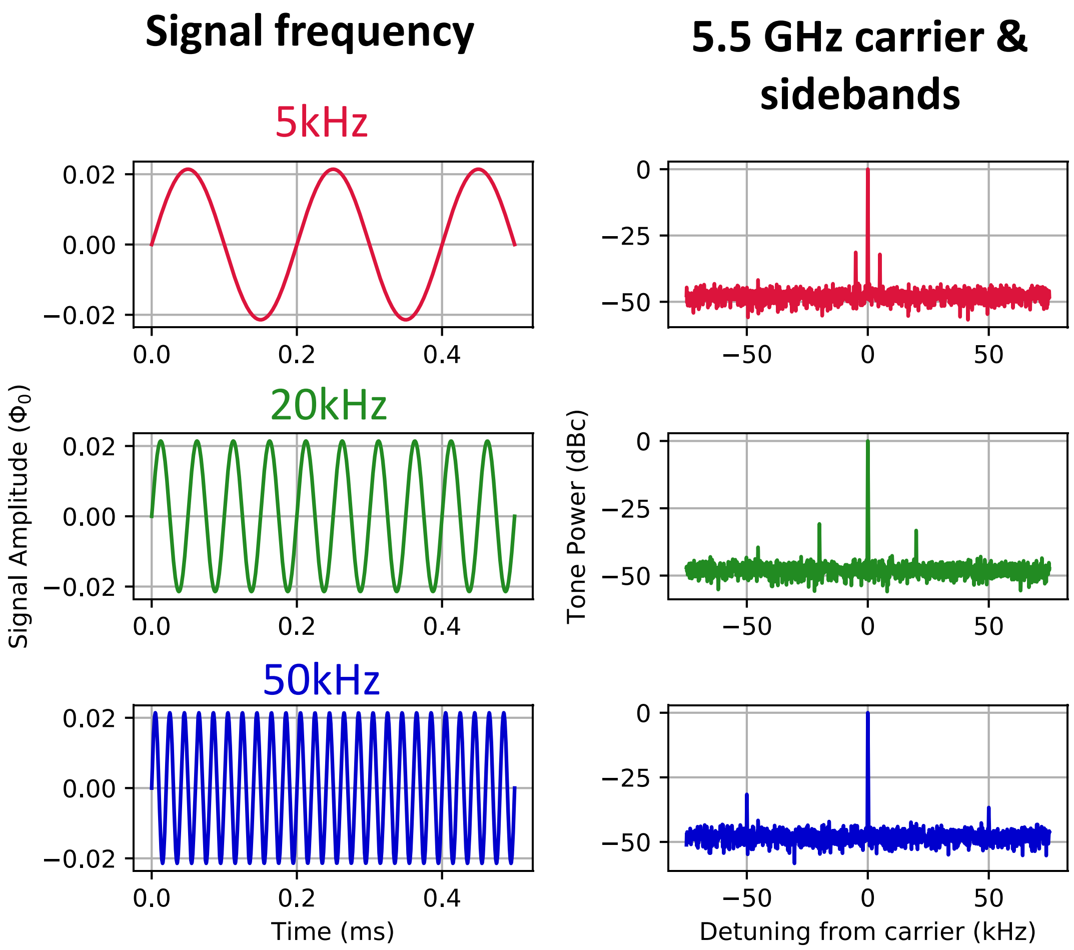
Upconverting to reach the SQL

- We can use an RF Quantum Upconverter (RQU) to read out our resonator.
- The DC-VHF signal from the resonator modulates the phase of the reflected microwave tone.



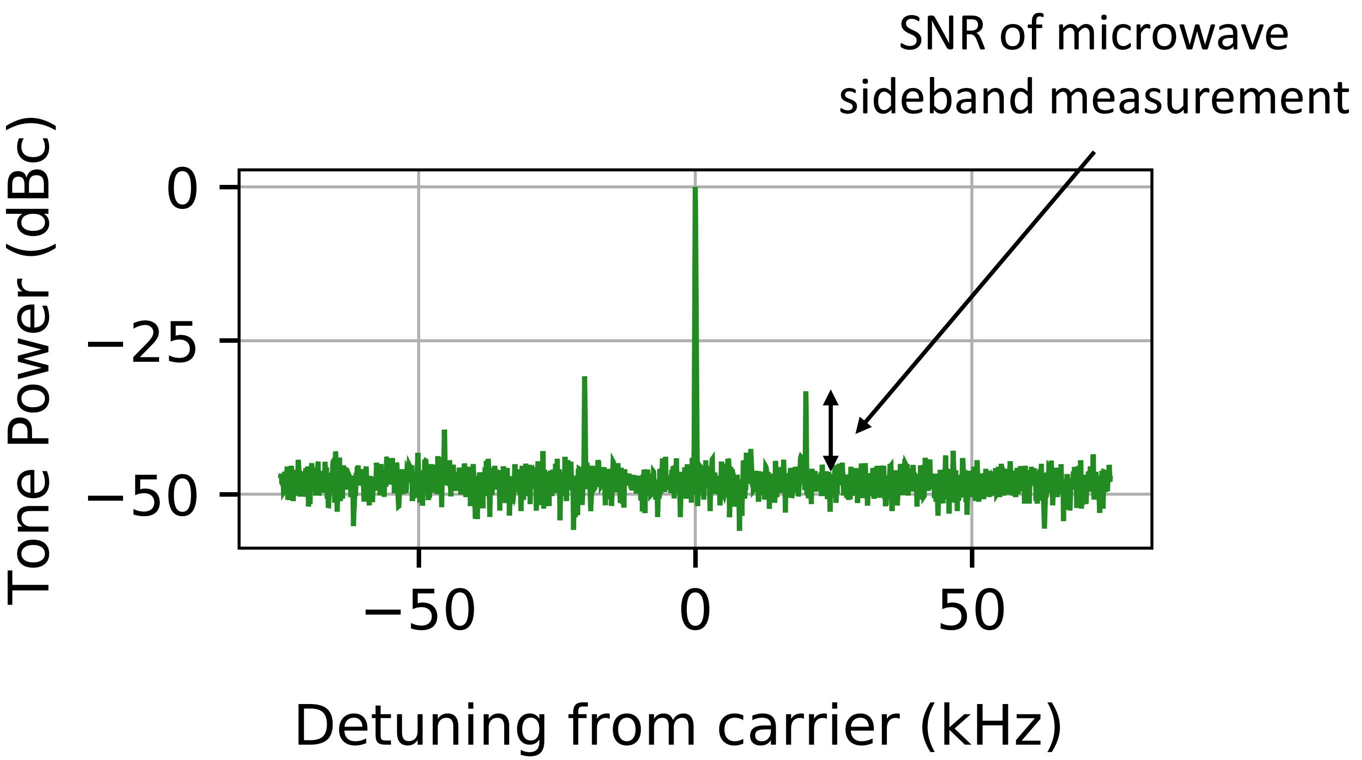
Data showing upconversion

- Signal information appears as symmetric sidebands on the microwave carrier.
- We can demodulate the microwave carrier at room temperature to recover the original signal.



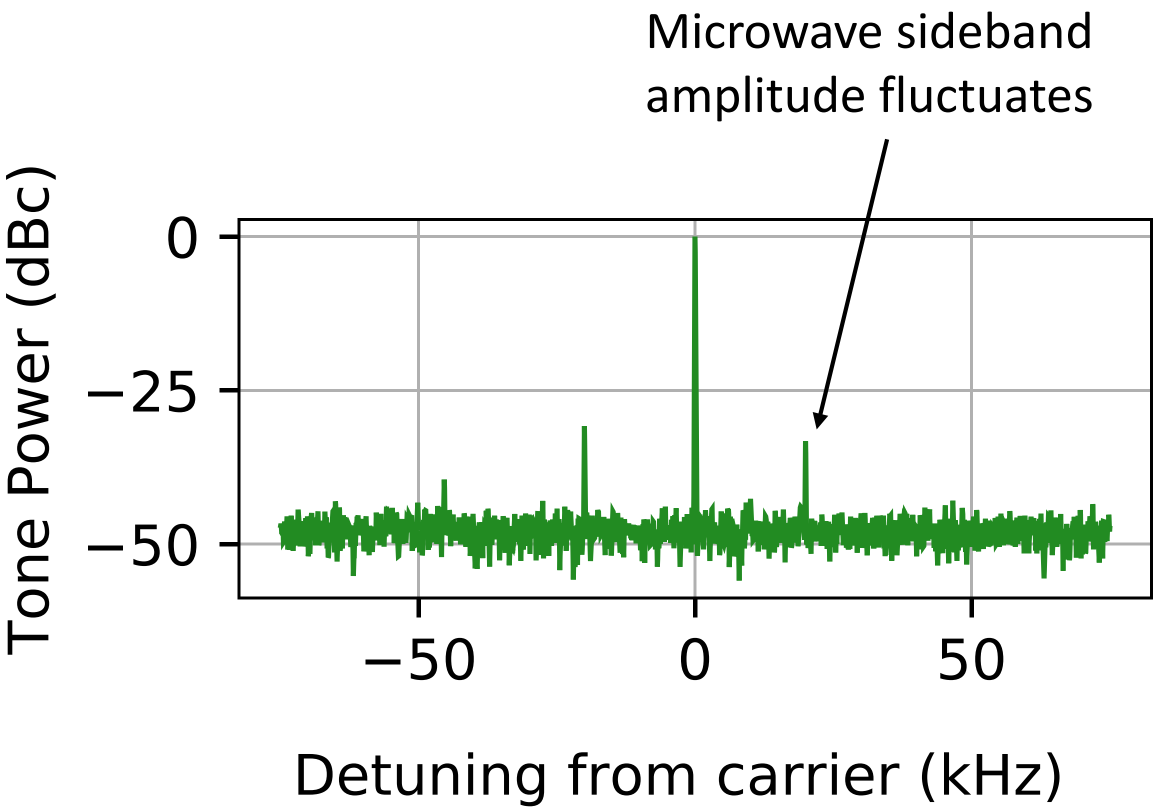
RQU Noise Sources: Imprecision

- ‘Imprecision noise’ comes from imperfect knowledge of the microwave sidebands.
- Due to quantum fluctuations in the **phase** of the microwave tone, we have limited SNR on the signal sidebands.

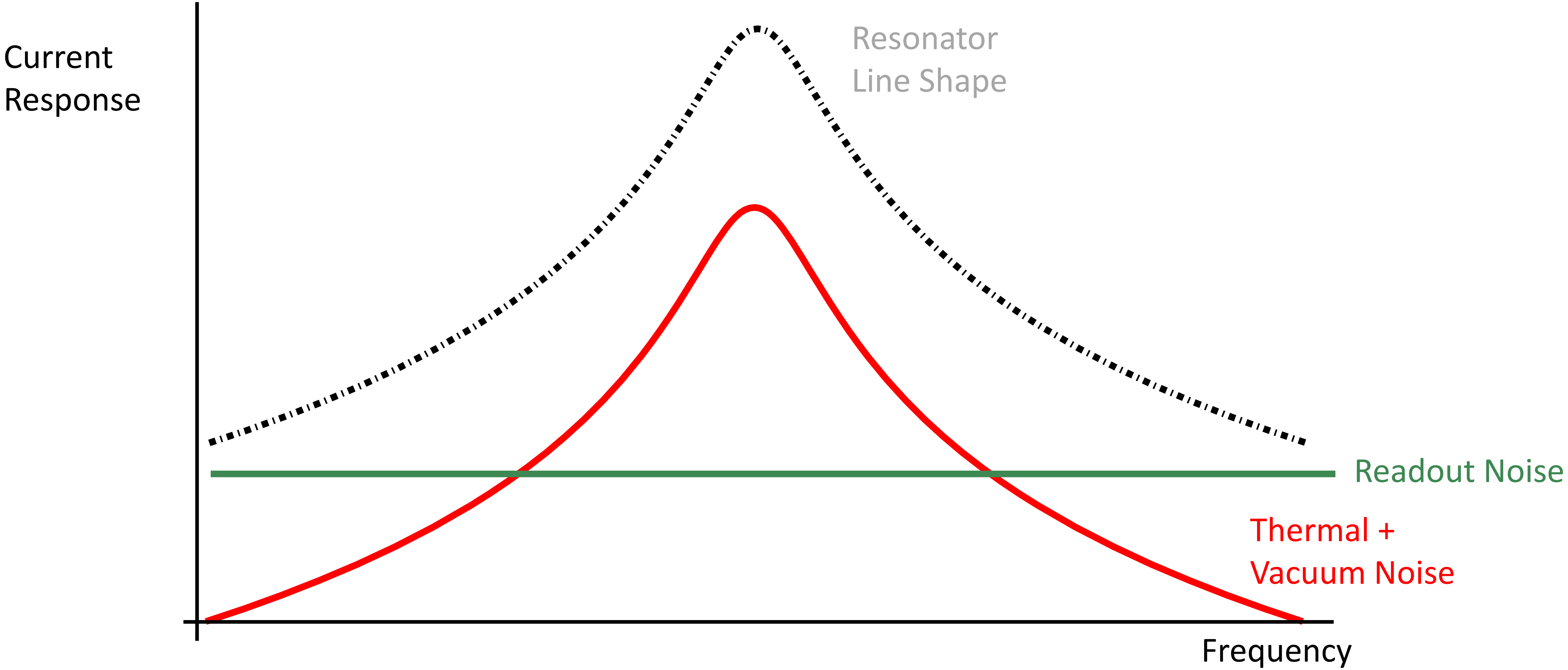


RQU Noise Sources: Backaction

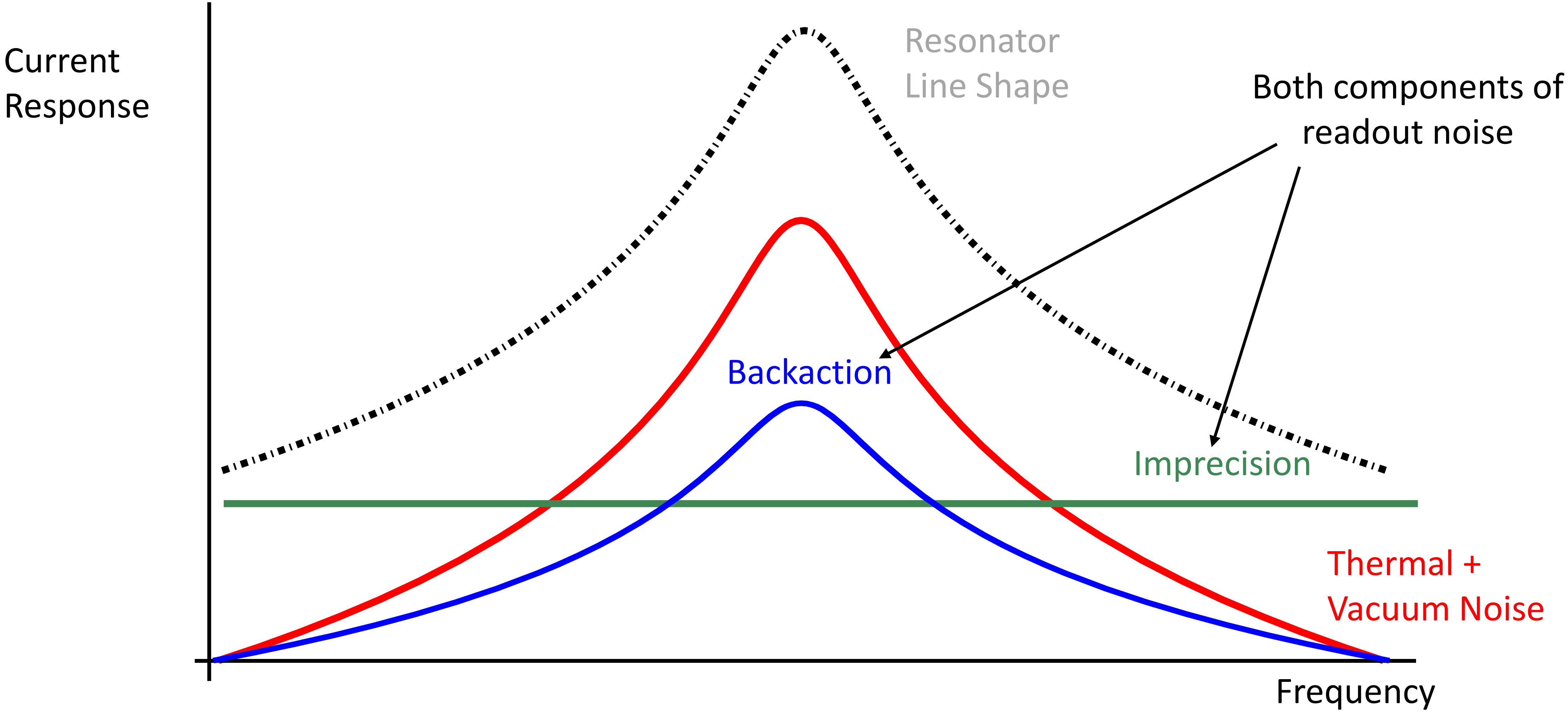
- ‘Backaction noise’ comes from quantum fluctuations in the **amplitude** of the microwave tone.
- These fluctuations drive noise voltage back into the input circuit.
- Imprecision and backaction noise are always in tension, so we need to optimize tone power for each particular application.



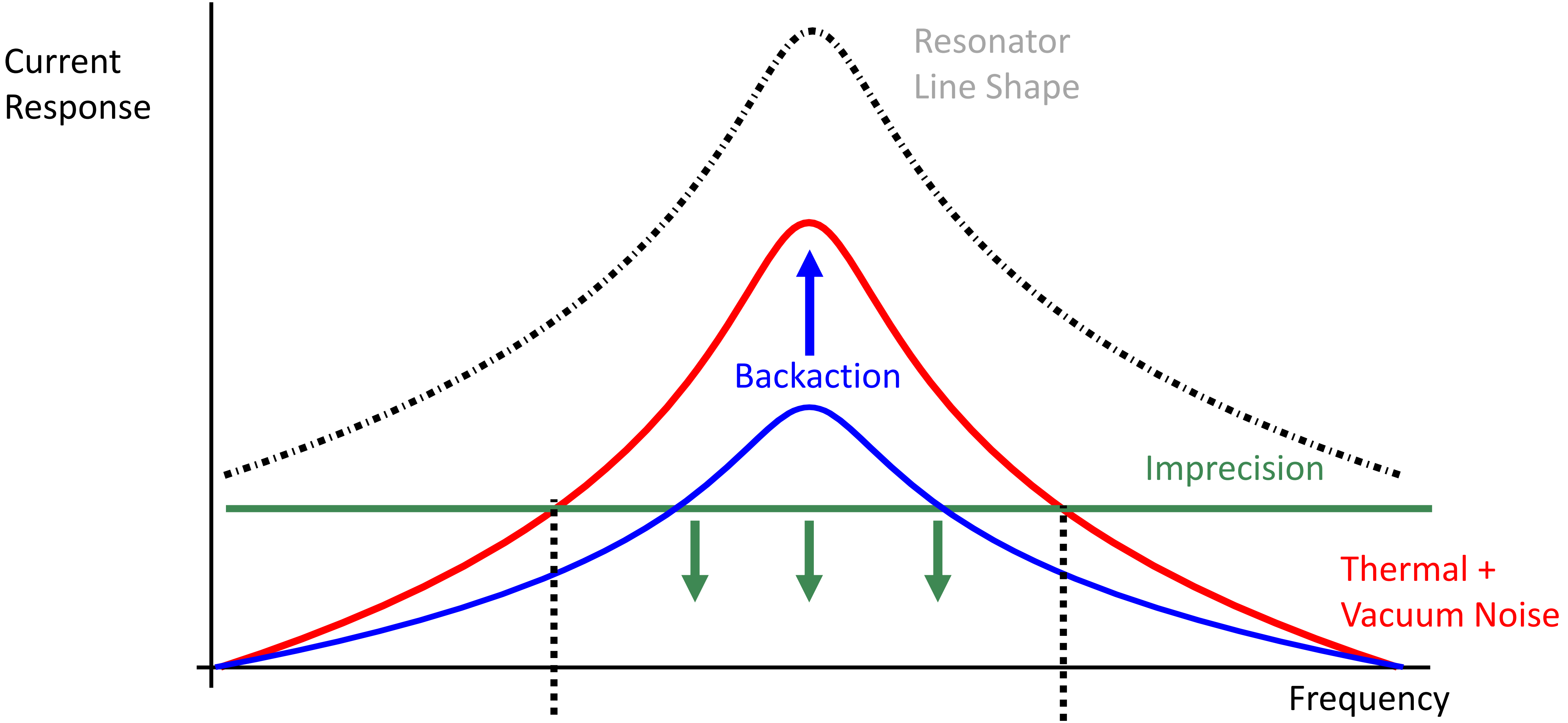
Readout = Imprecision + Backaction



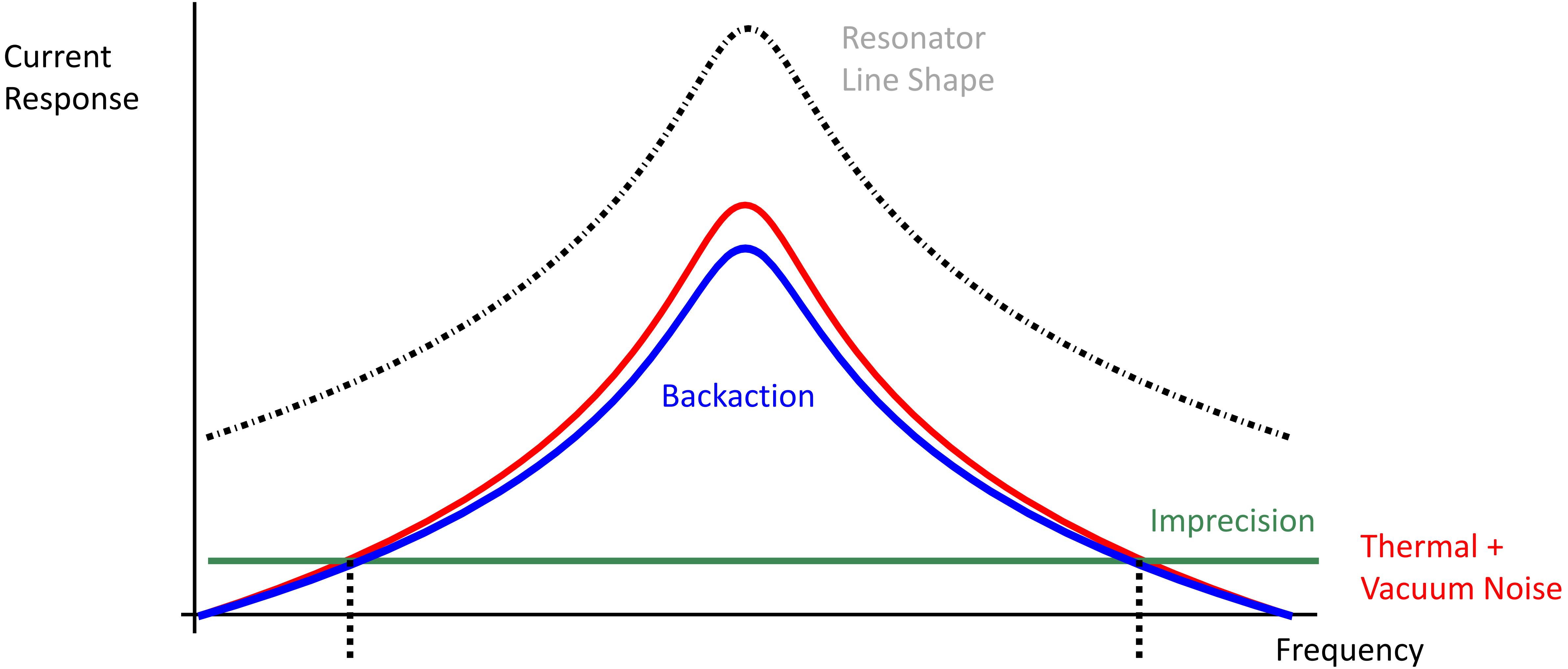
Readout = Imprecision + Backaction



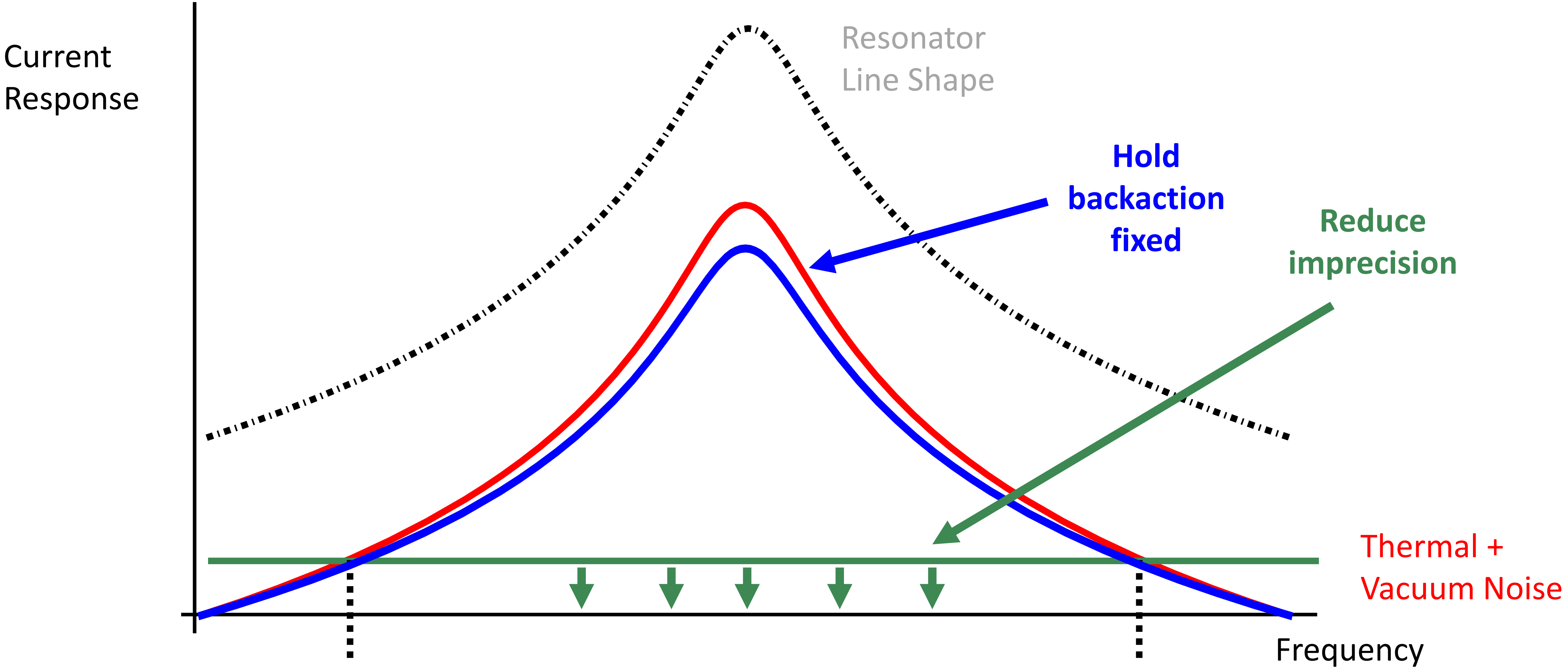
Lowering imprecision increases backaction



Optimize by having strong backaction

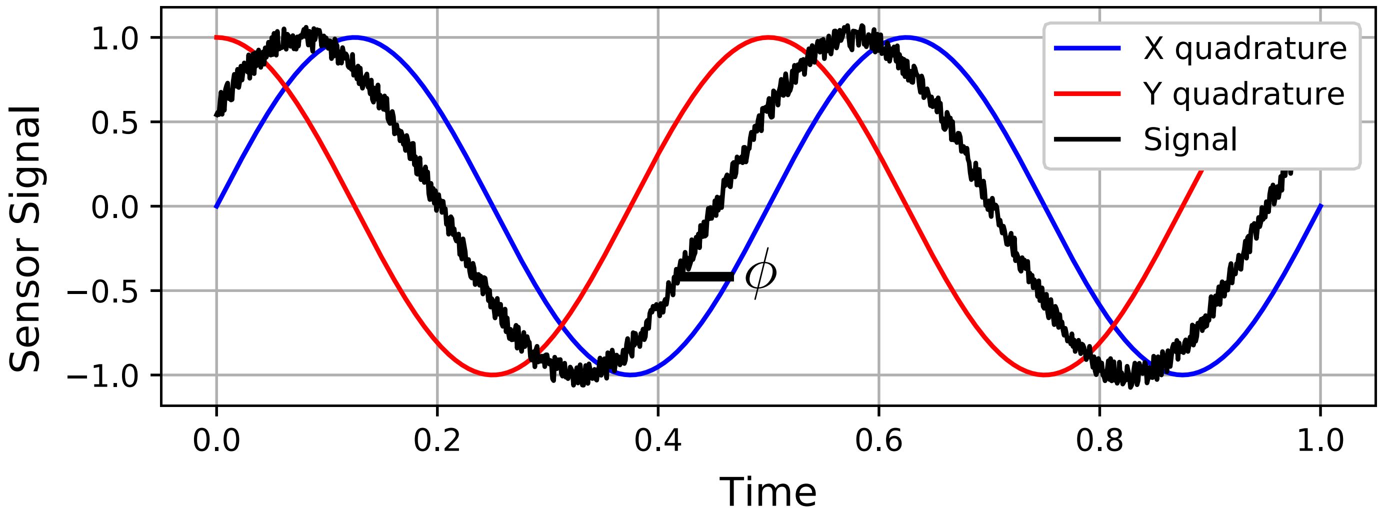


Evading backaction: motivation



Signal quadratures

- A generic signal at a fixed frequency has ‘sine’ and ‘cosine’ components, or X and Y quadrature amplitudes.
- When written as quantum operators, these quadratures do not commute.
- The Heisenberg uncertainty principle applies!

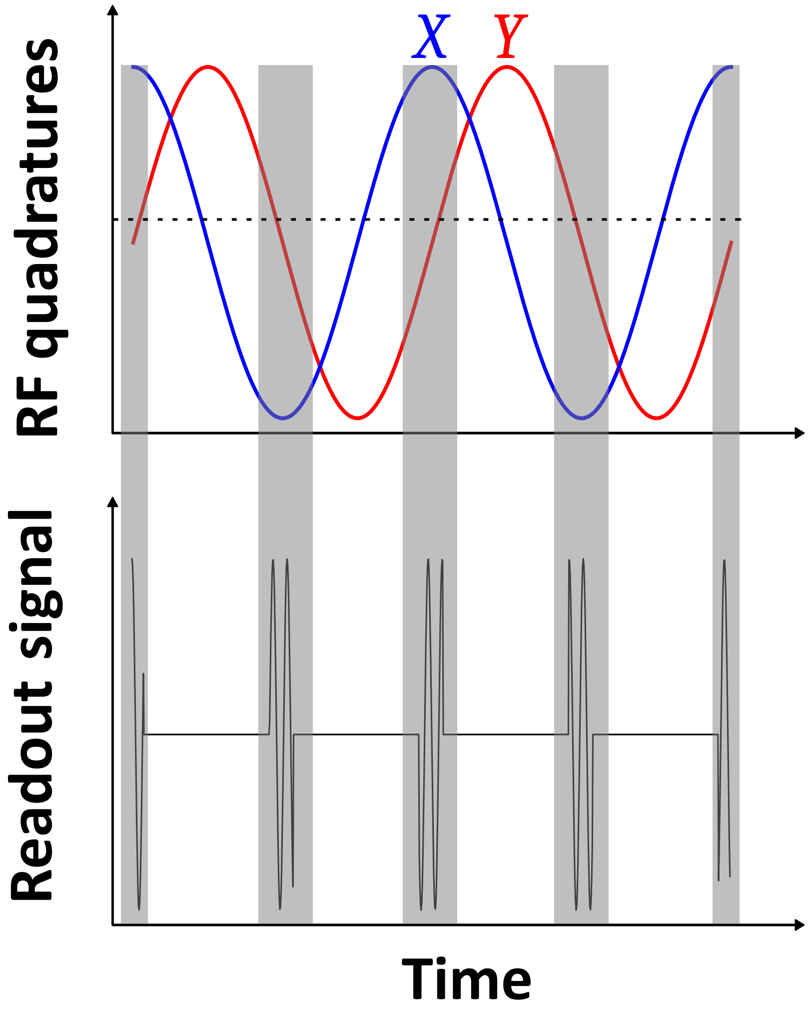


$$[\hat{X}, \hat{Y}] = i$$

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

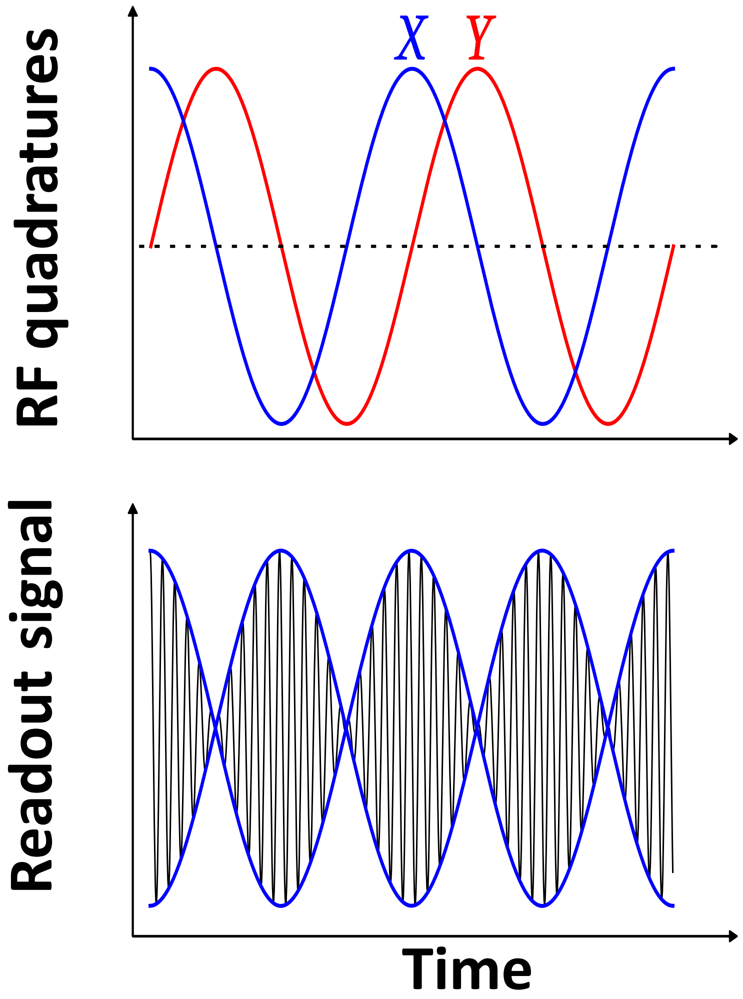
Stroboscopic readout

- If we forgo all information about the Y quadrature, in principle we can measure the X quadrature arbitrarily well.
- One scheme for doing this is to pulse the microwave readout tone, with the phase of the pulse matched to the X quadrature.

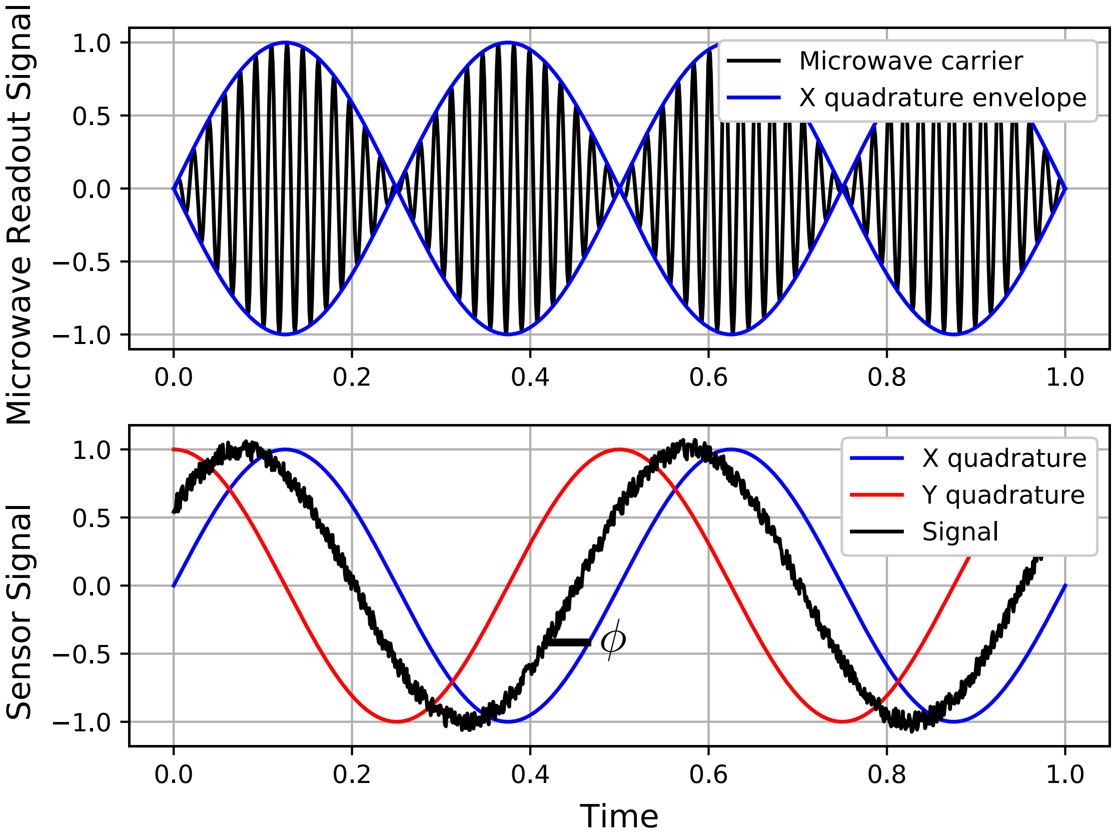


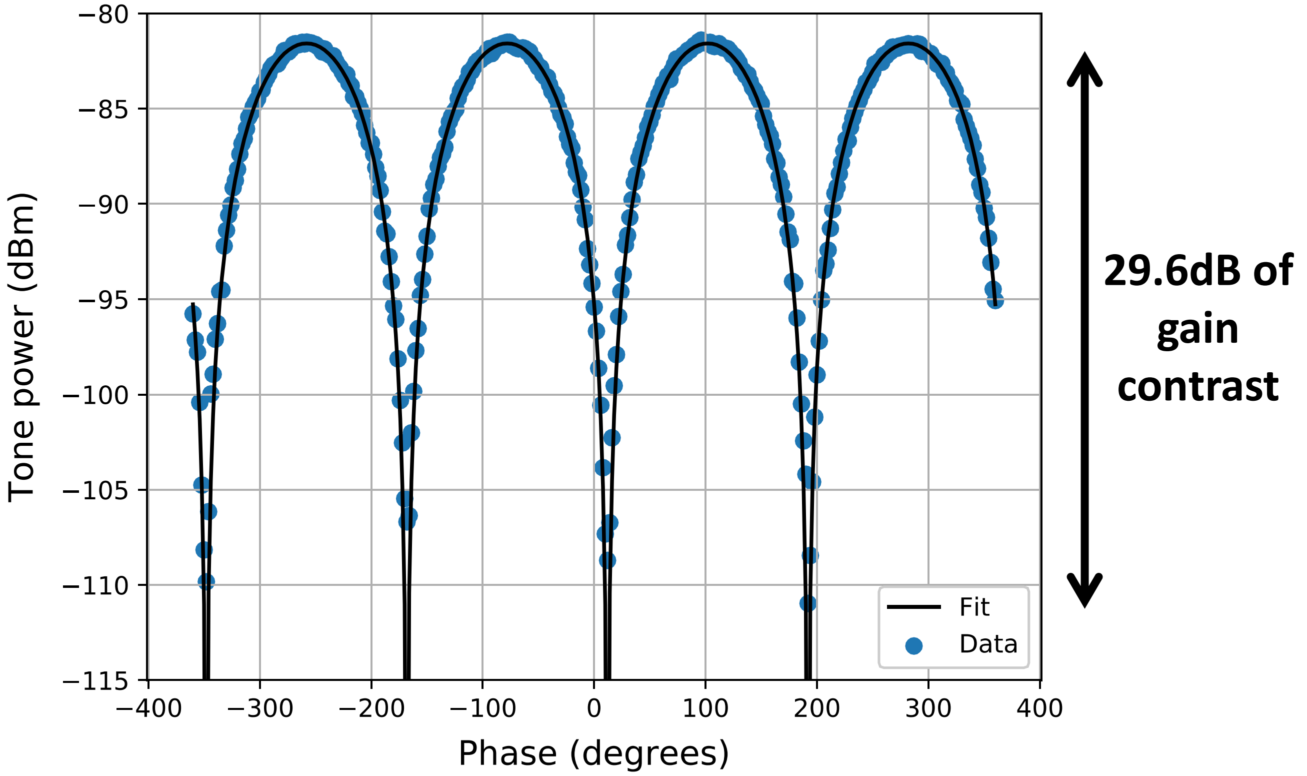
Backaction evading readout

- A pulse train is potentially inconvenient due to its harmonic content.
- Instead, we can use a smoothly varying amplitude modulation envelope.
- When the phase of the AM envelope lines up with the X quadrature, we do not backact on that quadrature.



Proof of concept: RQU data





Conclusions

1. Quantum sensing in the thermal regime is a powerful tool to improve the science reach of precision electromagnetic measurements
2. The upconversion scheme is very flexible: the user can choose a readout protocol by setting the frequencies, phases, and amplitudes of microwave tones.
3. Initial measurements show successful upconversion and high gain contrast.