Quantum Sensors for Ultra-light Dark Matter Detection

Hsiao-Mei Sherry Cho

SLAC National Accelerator Laboratory

Thursday August 1st, 2019

ISEC2019
International Superconductive Electronics Conference
July 28 - August 1, 2019
The Riverside Convention Center
Riverside, CA

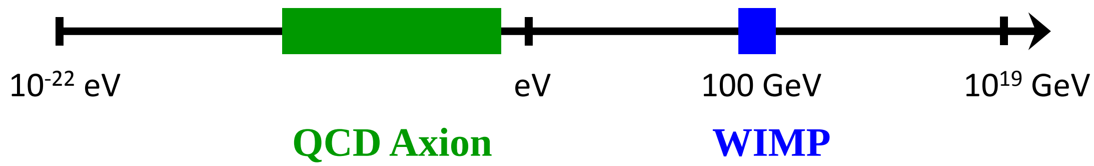
Team and supports

Stanford/SLAC/Santa Clara
Prof. K. Irwin
Prof. P. Graham
Prof. B. Young
D. Li
A. Ames
S. Carman
S. Chaudhuri
C. Dawson
C. FitzGerald
R. Gruenke
A. Phipps
S. Kuenstner
C. Yu

UC-Berkeley
Prof. Karl A. van Bibber
A. Droster
A. Leder
S. Rajendran

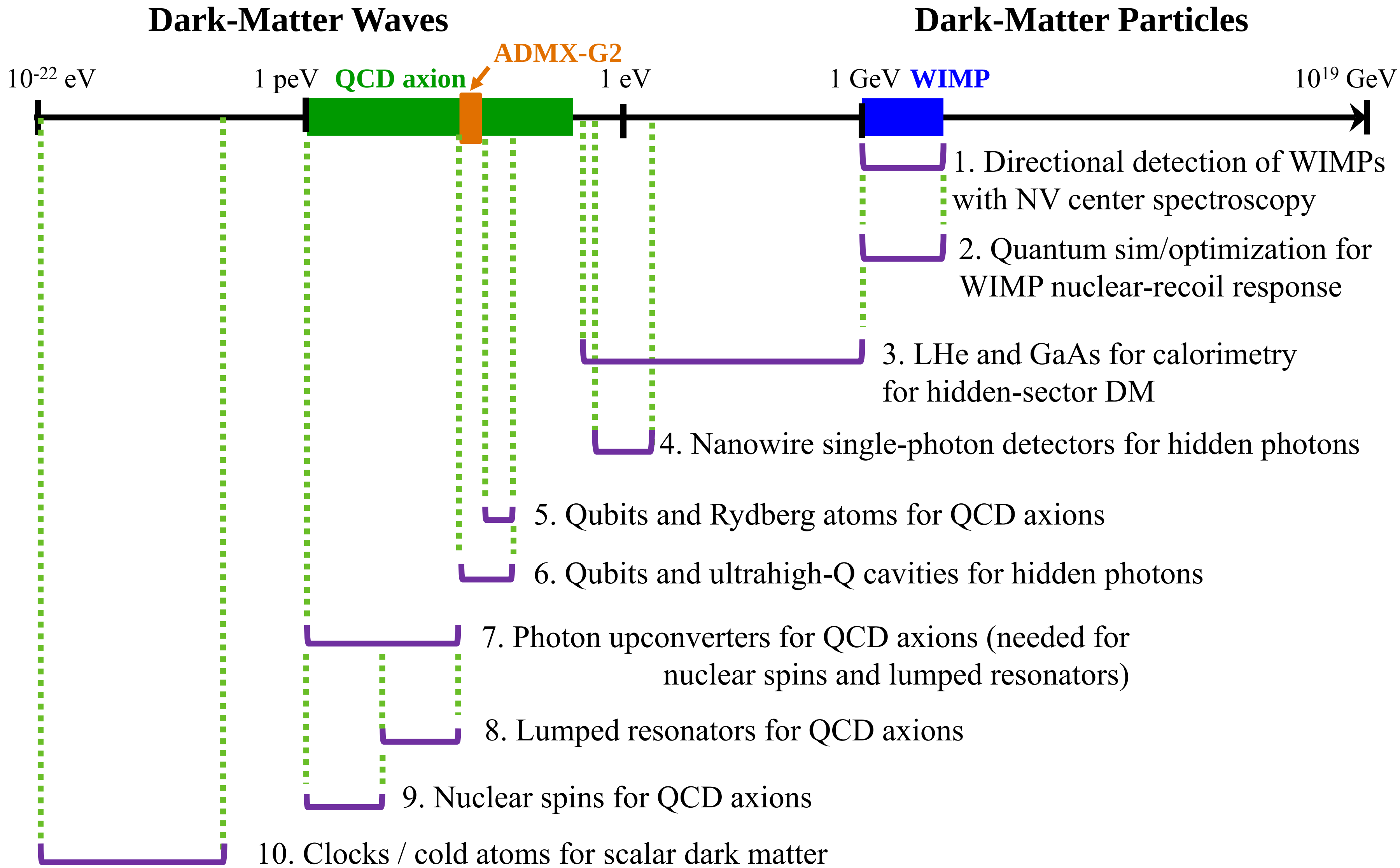
Boston University
Prof. A. Sushkov
D. Aybas

Two "strongly motivated" dark-matter candidates

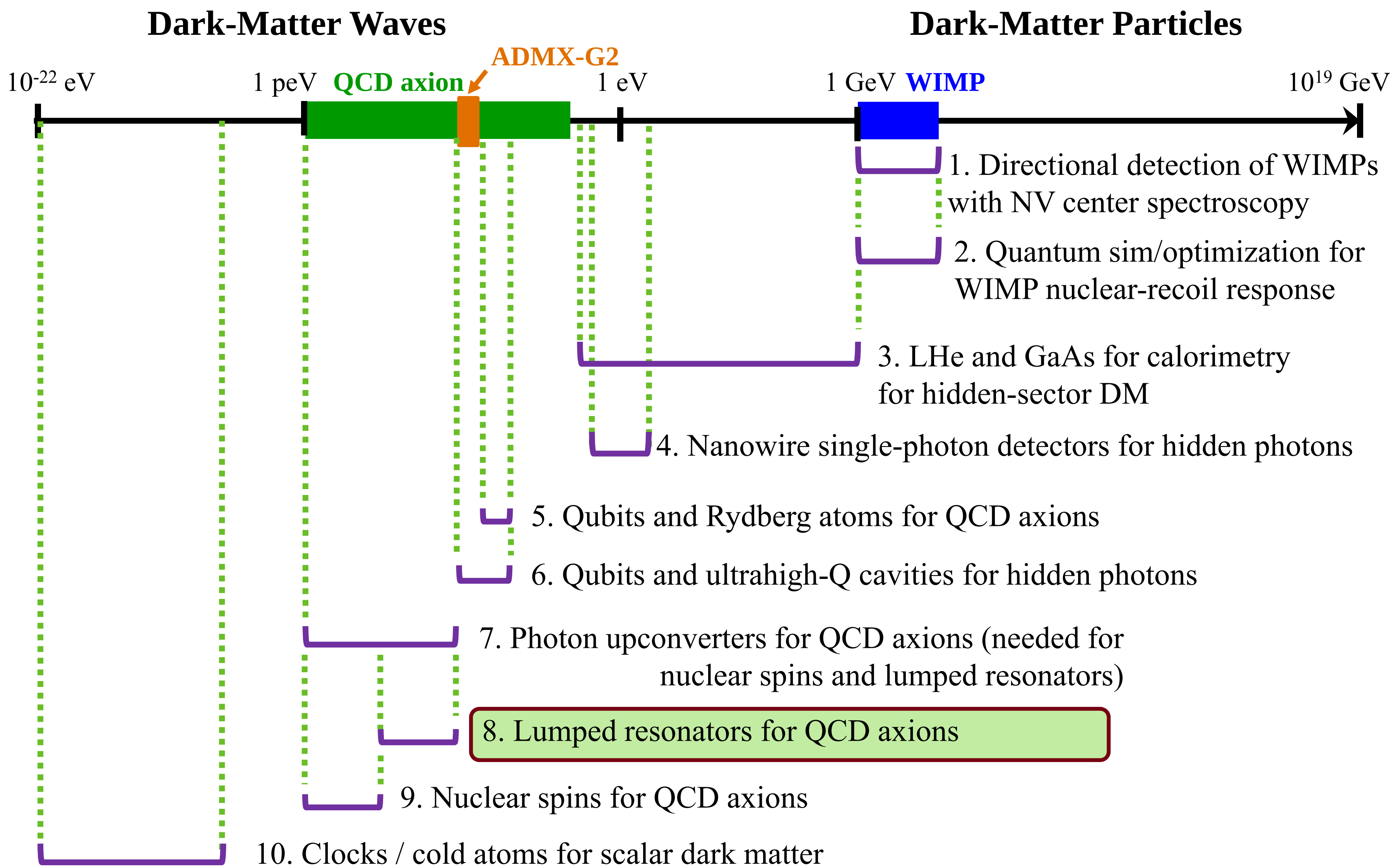


- **Weakly Interacting Massive Particle (WIMP)**
  - Motivated by supersymmetry
  - Naturalness: thermal production of observed abundances for WIMPs near 100 GeV.
  - Ongoing, 30-year effort to produce (supersymmetry at LHC) and detect (direct dark-matter searches). Much interesting phase space has already been ruled out. (LHC= Large Hadron Collider)
- **QCD Axion**
  - Motivated as solution to strong CP problem and hierarchy problem.
  - Naturalness: misalignment production of observed abundances over full mass range, peV-meV
  - Largely unexplored parameter space.

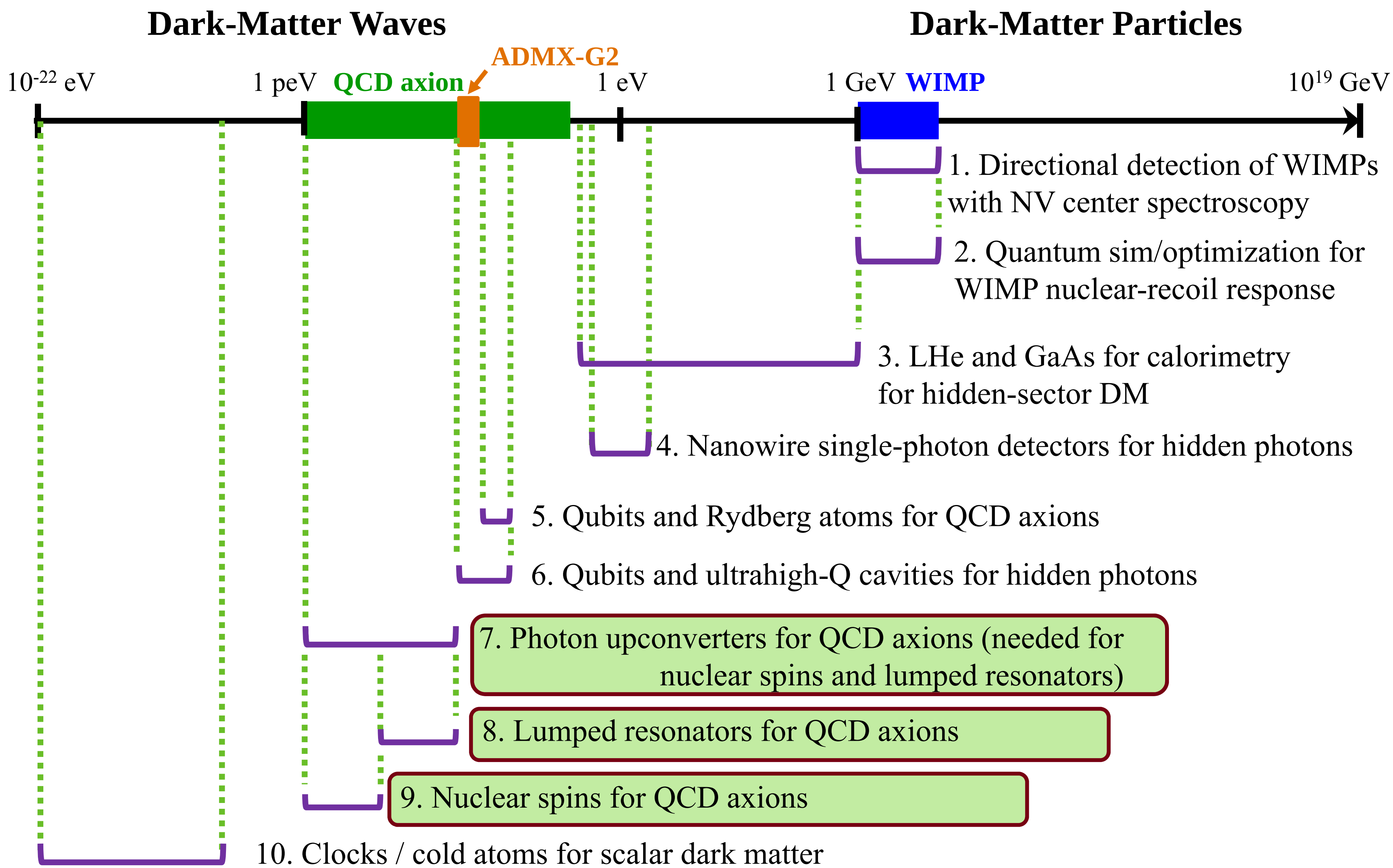
QuantISED in the Dark-Matter Landscape



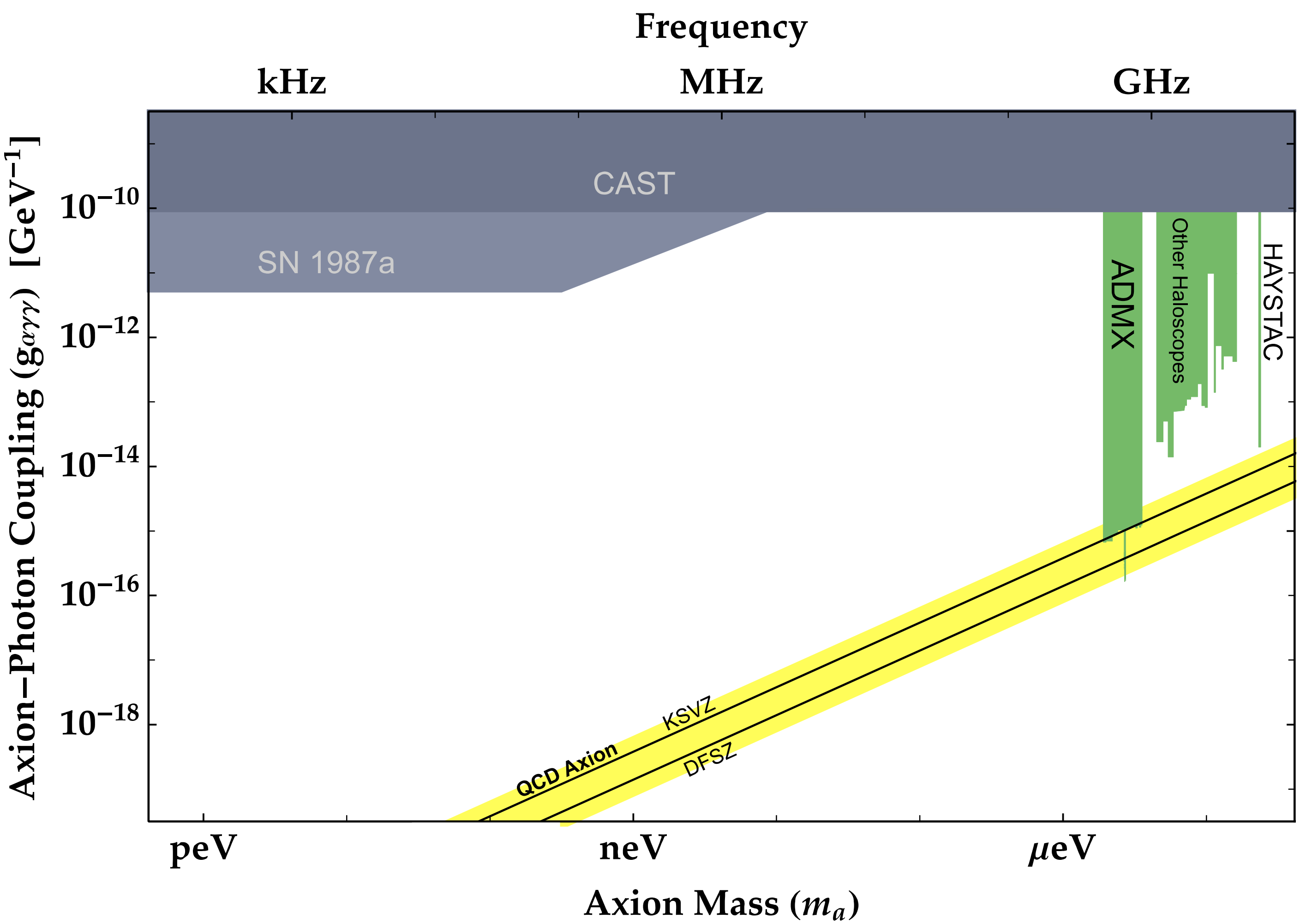
QuantISED in the Dark-Matter Landscape



QuantISED in the Dark-Matter Landscape

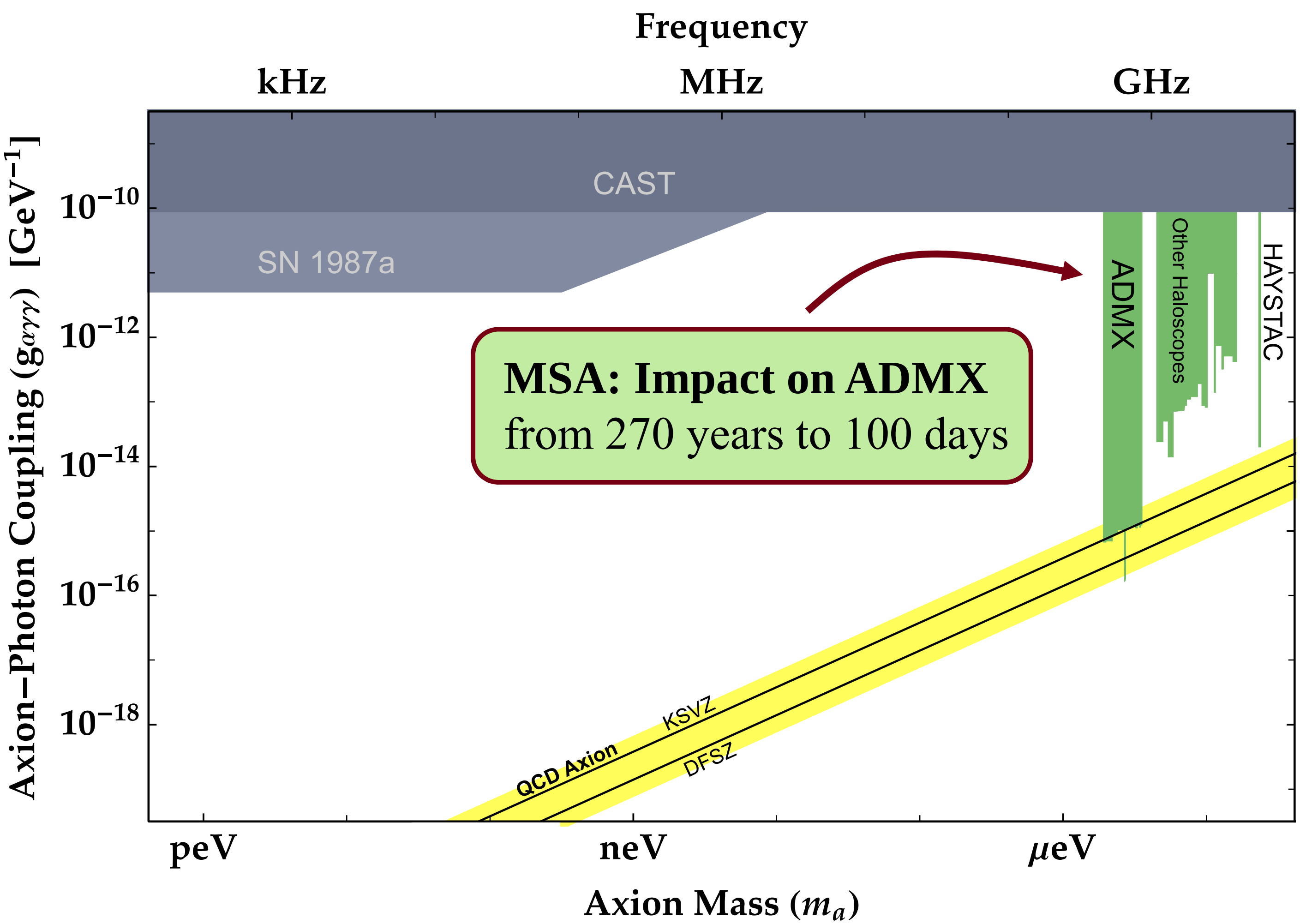


QCD Axions: strongly motivated over whole range



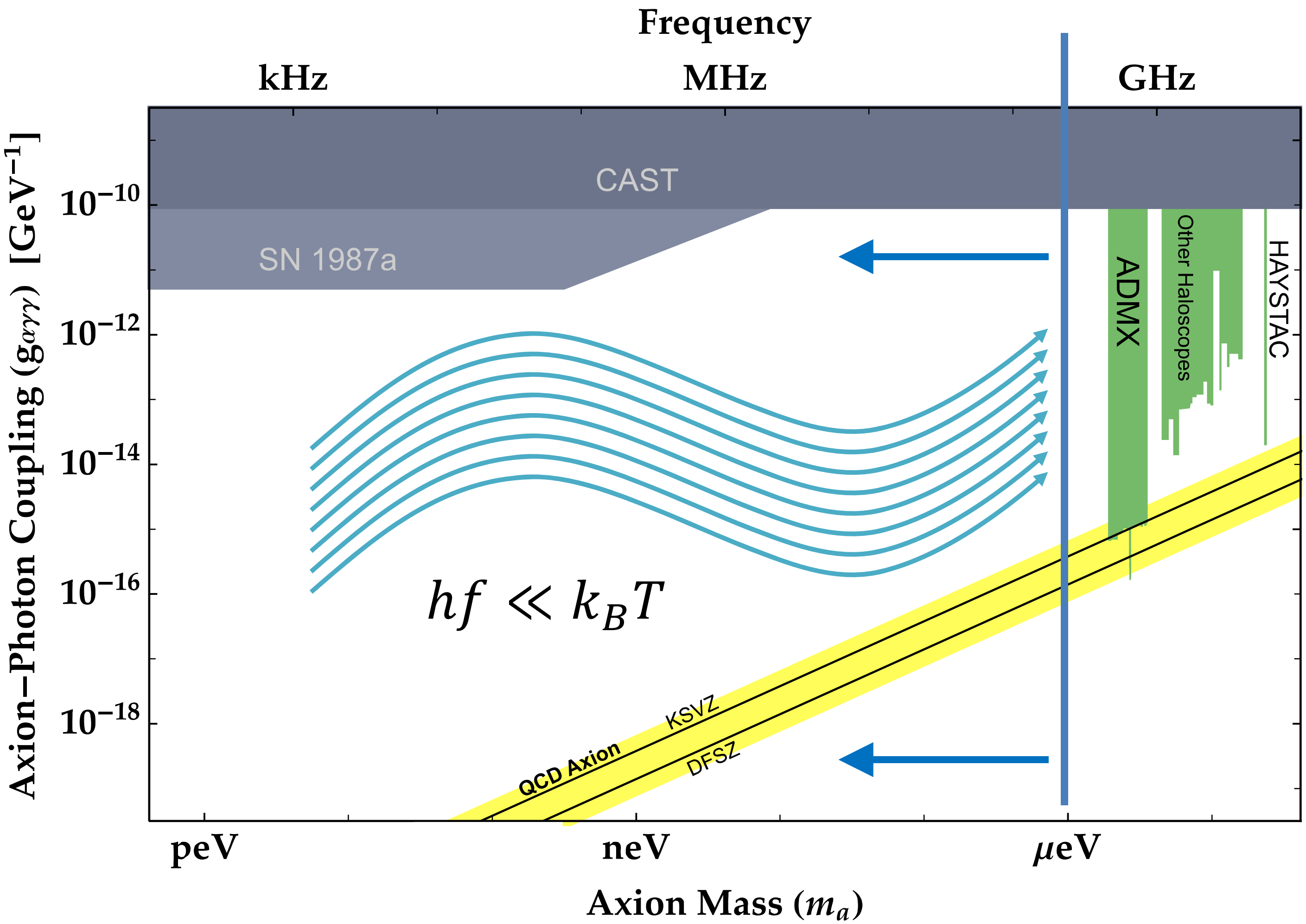
KSVZ: Kim-Shifman-Vainshtein-Zakharov model
DFSZ: Dine-Fischler-Srednicki-Zhitnitskii model

QCD Axions: strongly motivated over whole range



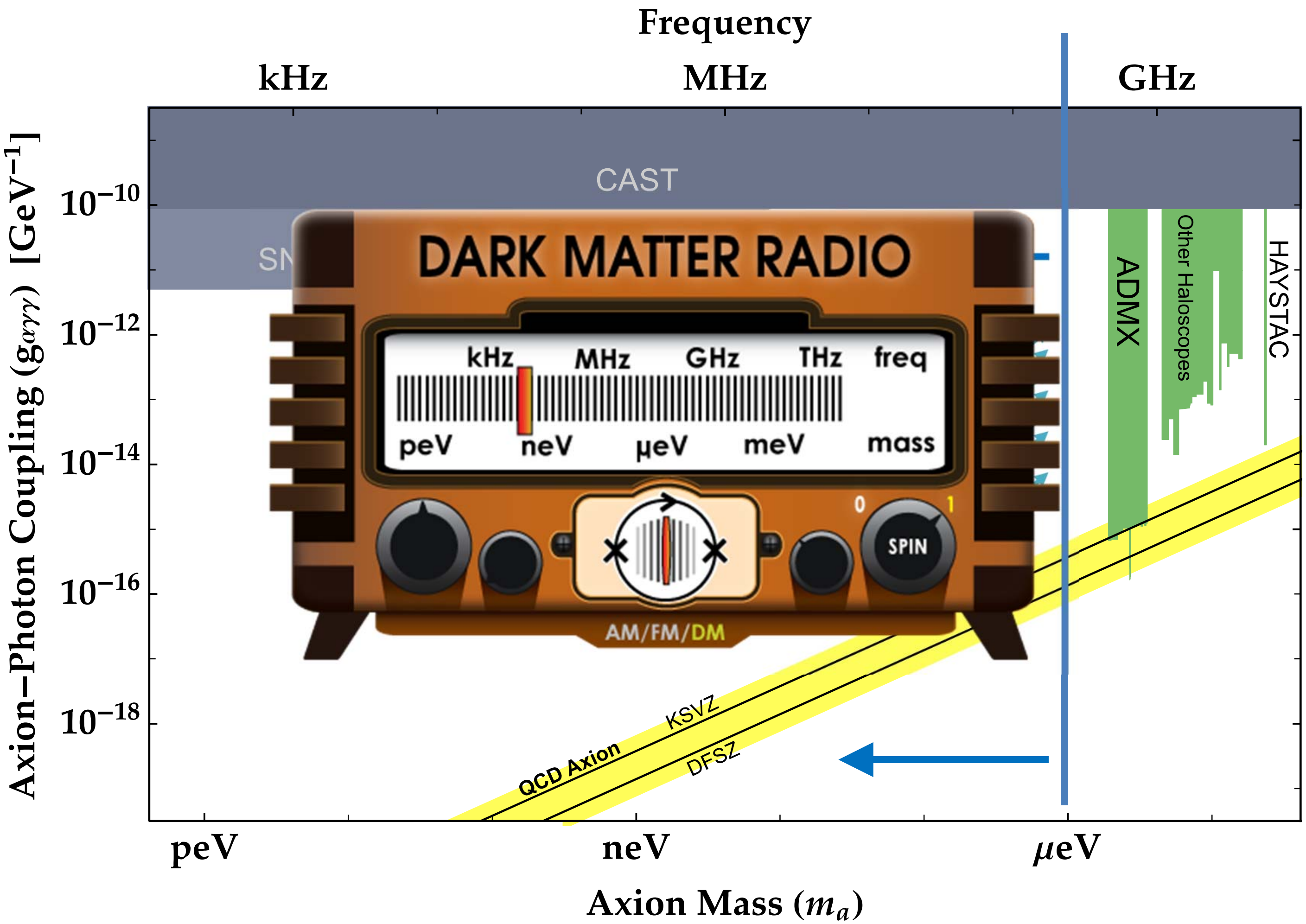
KSVZ: Kim-Shifman-Vainshtein-Zakharov model
DFSZ: Dine-Fischler-Srednicki-Zhitnitskii model

QCD Axions: strongly motivated over whole range



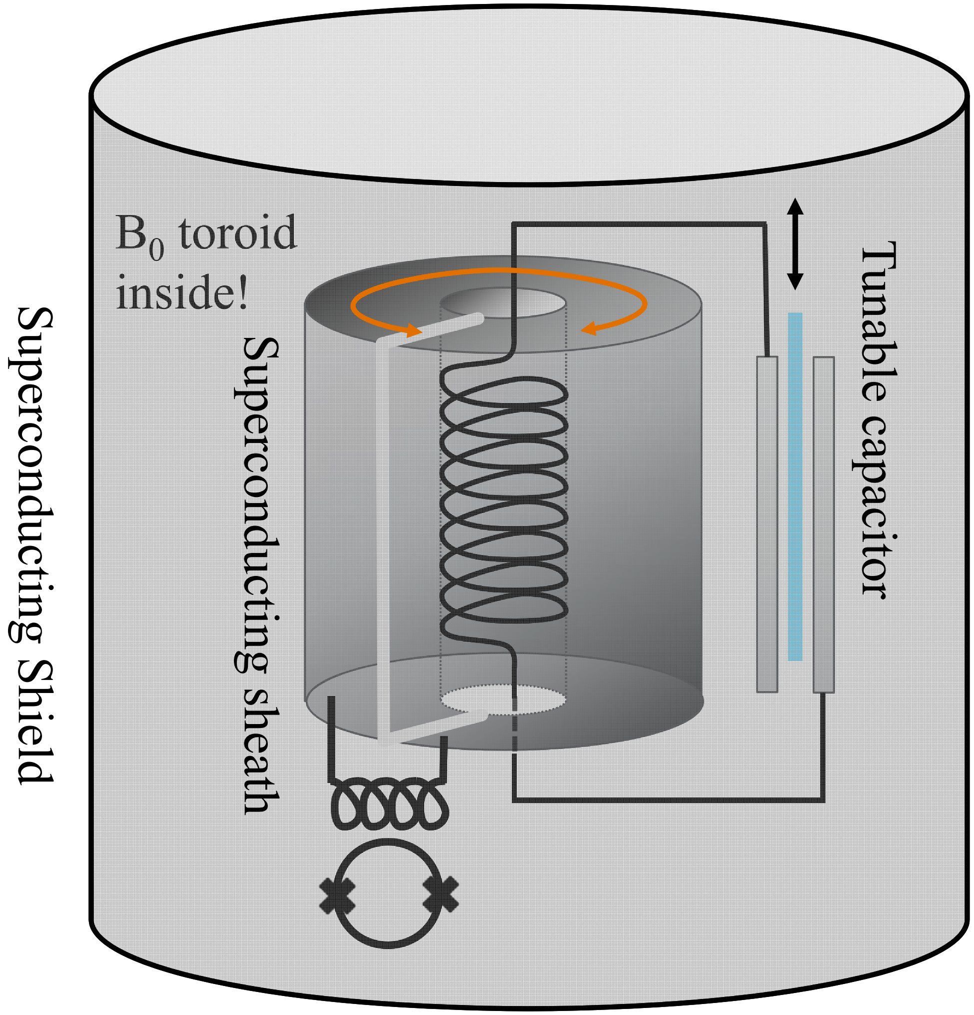
Below 1 μeV wavelengths $\lambda_{\text{coherence}} \approx 100\,\text{km} \times (10^{-8}\text{eV}/m)$

QCD Axions: strongly motivated over whole range



Below 1 μeV wavelengths $\lambda_{\mathrm{coherence}} \approx 100\,\mathrm{km} \times (10^{-8}\mathrm{eV}/m)$

DM Radio is a lumped-element Axion detector



Axions convert to oscillating EM signal in background DC magnetic field B_0

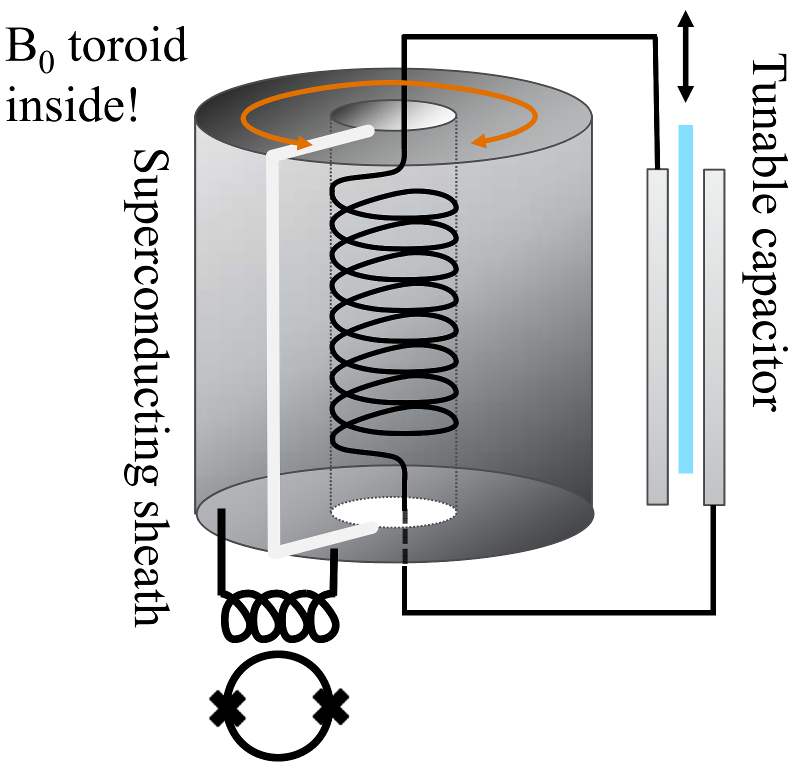
$$\vec{J}_a(t)$$

Supercurrent induced by Axion oscillating current is detected by SQUIDs

Signal enhancement when resonance frequency matches rest-mass frequency f_{DM}=mc2/h

S. Chaudhuri et al, PRD **92**, 070512 (2015)

DM Radio is a lumped-element Axion detector



Axions convert to oscillating EM signal in background DC magnetic field B_0

$$\vec{J}_a(t)$$

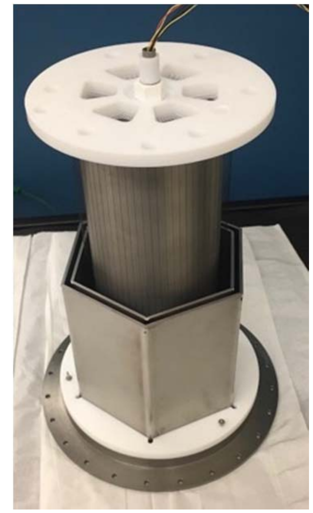
Supercurrent induced by Axion oscillating current is detected by SQUIDs

Signal enhancement when resonance frequency matches rest-mass frequency f_{DM}=mc2/h

S. Chaudhuri et al, PRD **92**, 070512 (2015)

DM Radio Pathfinder

- Shield+detector mounted to end of probe
- Probe inserted into cryoperm-lined dewar
- Readout cable runs up center tube



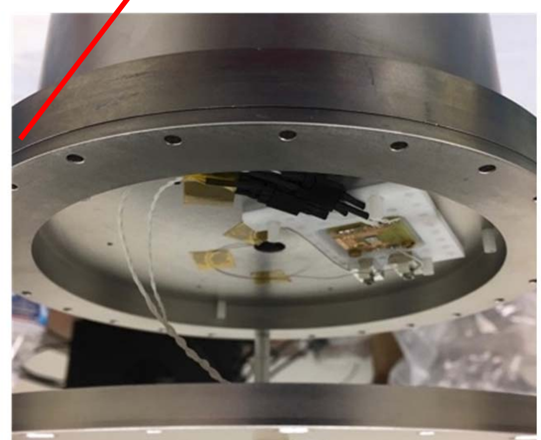
Nb hex capacitor

Superconducting shield
2mm thick Nb

9.5 inches

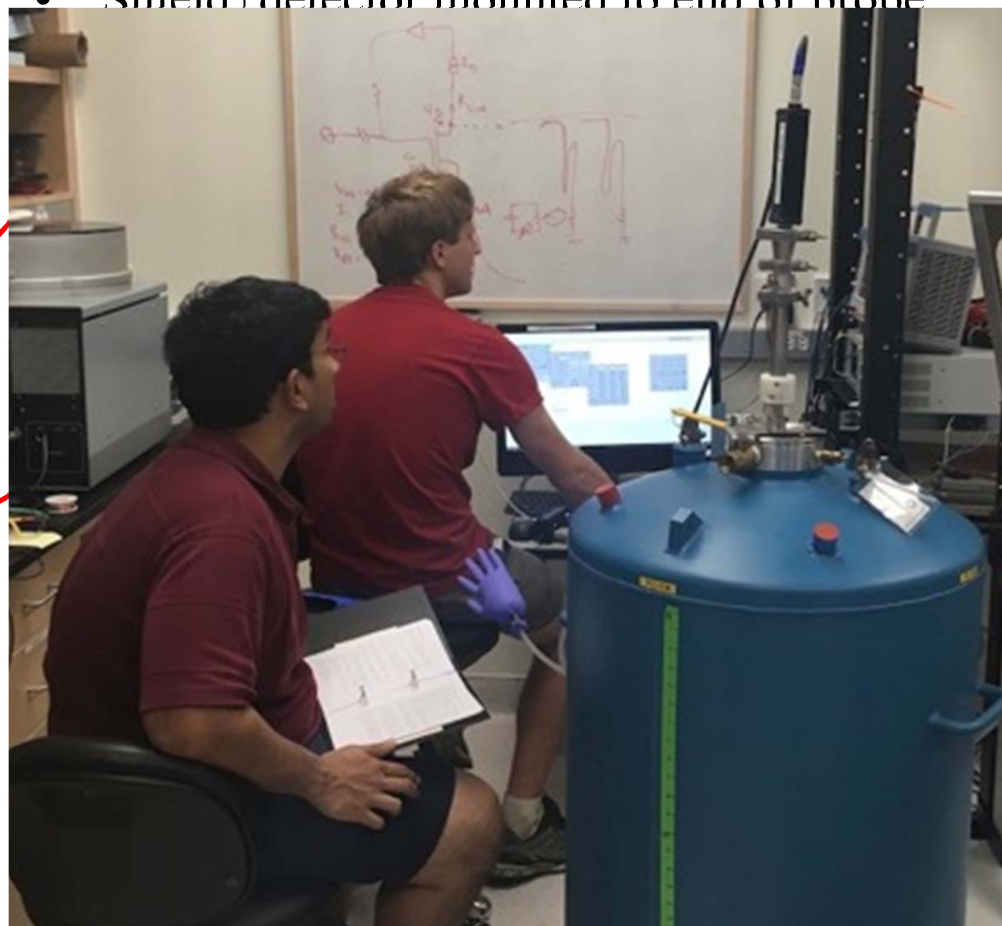
5.7 inches

SQUID Annex

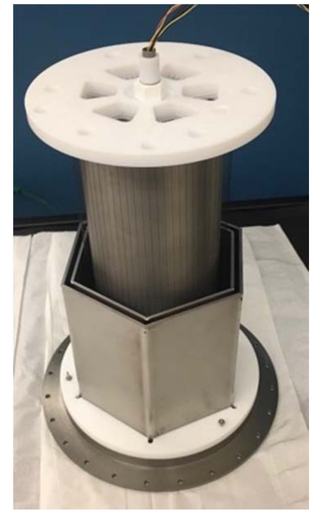


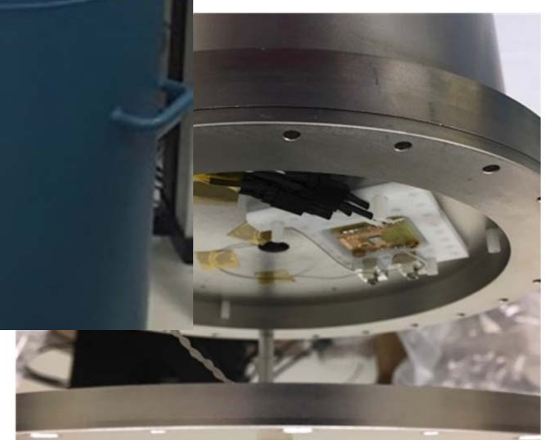
DM Radio Pathfinder

- Shield+detector mounted to end of probe



tor

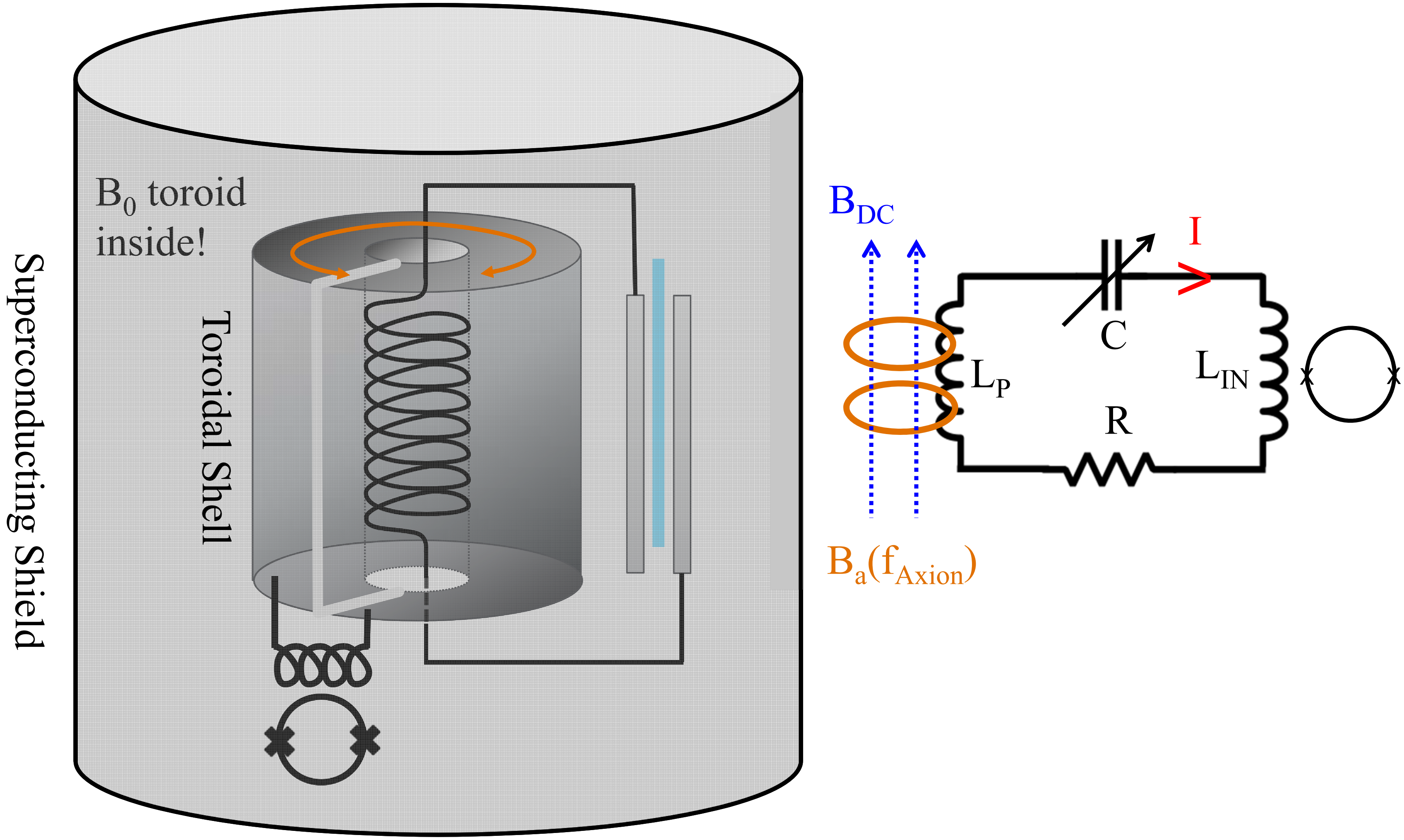




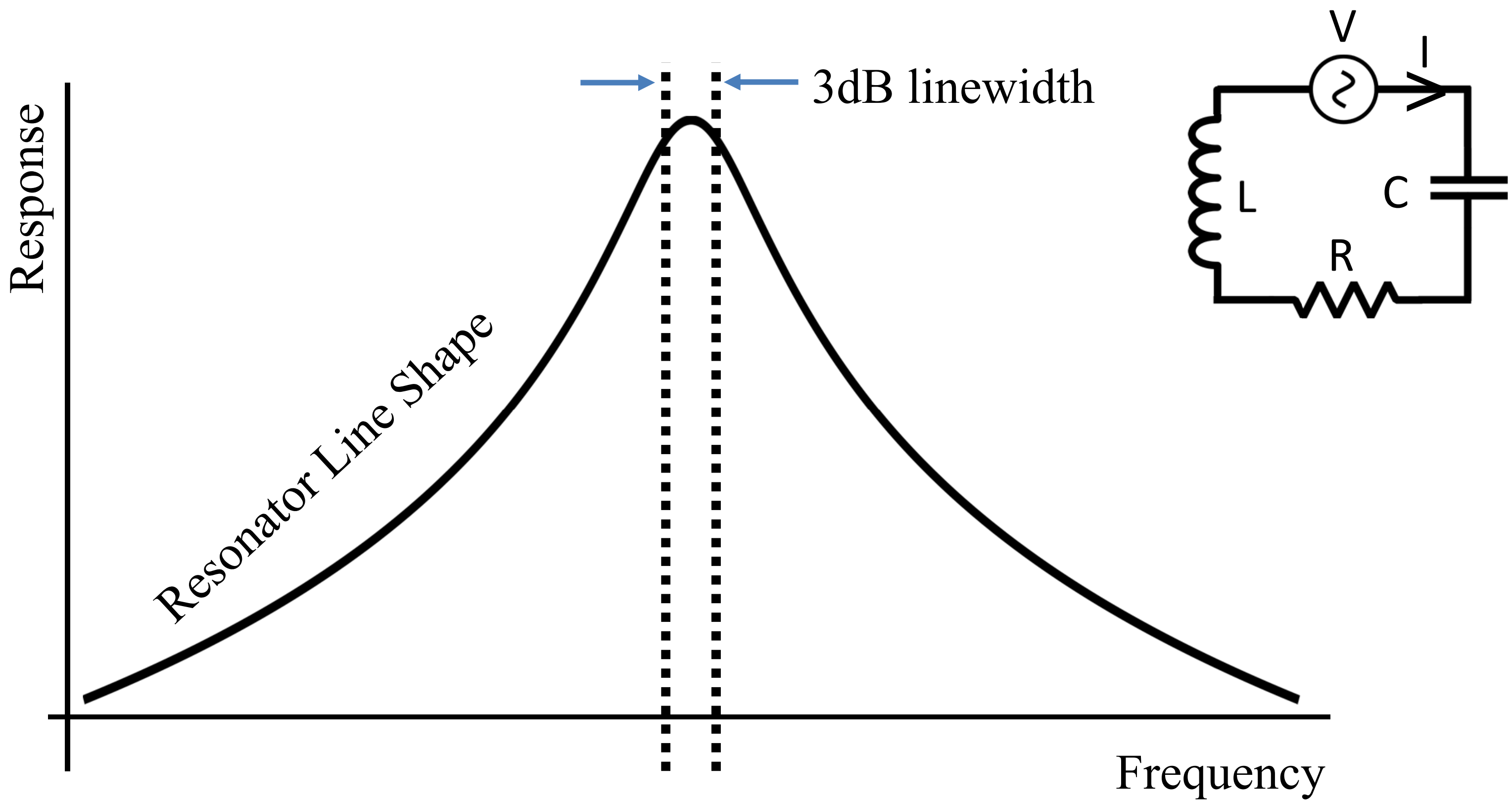
5.7 inches

14

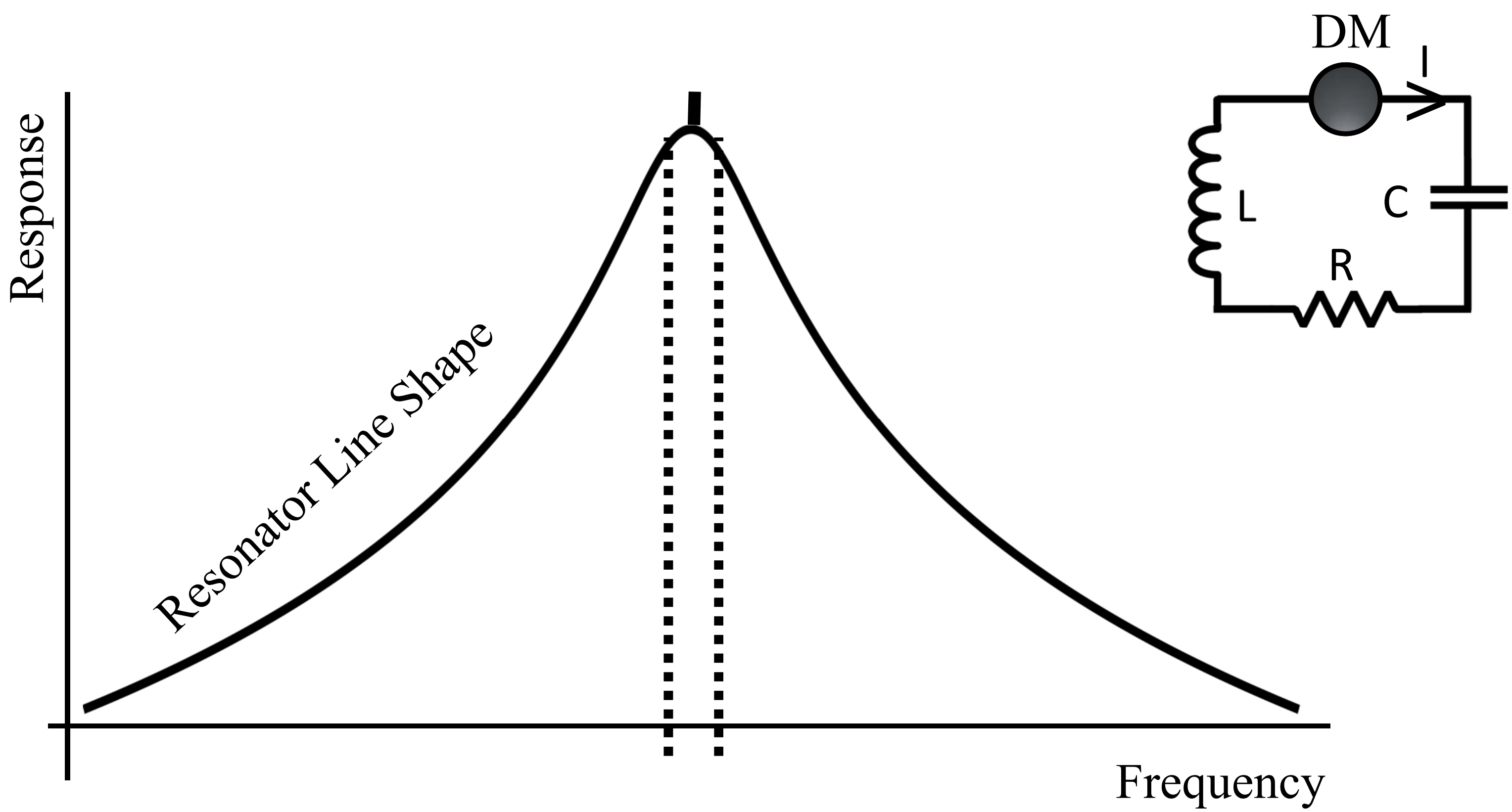
DM Radio is a lumped-element dark matter detector



Output: single-pole resonator



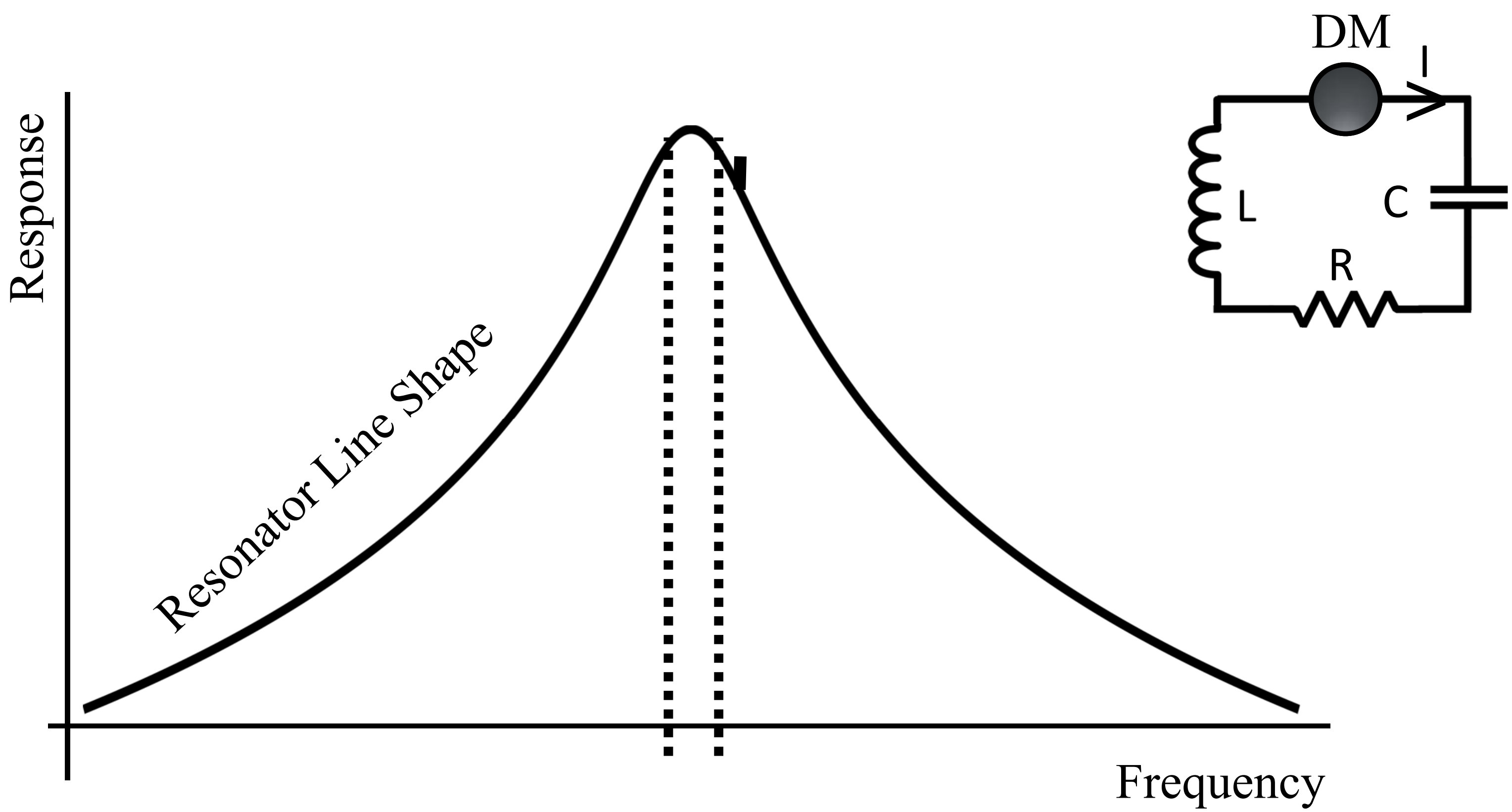
The Signal exists far out from the linewidth



SNR does not degraded when readout subdominant to thermal noise

$hf \ll k_B T$: high thermal occupation

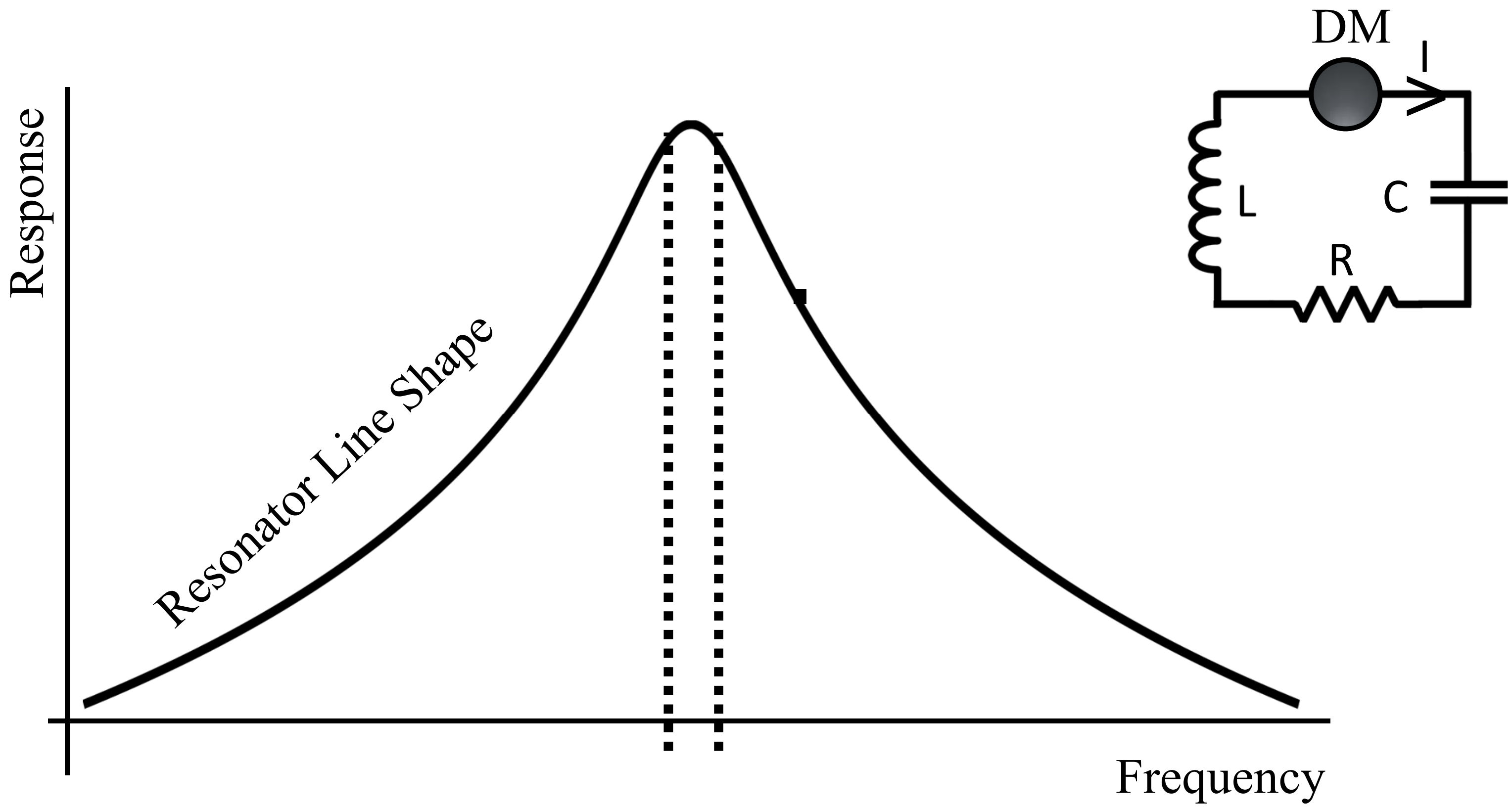
The Signal exists far out from the linewidth



SNR does not degraded when readout subdominant to thermal noise

$hf \ll k_B T$: high thermal occupation

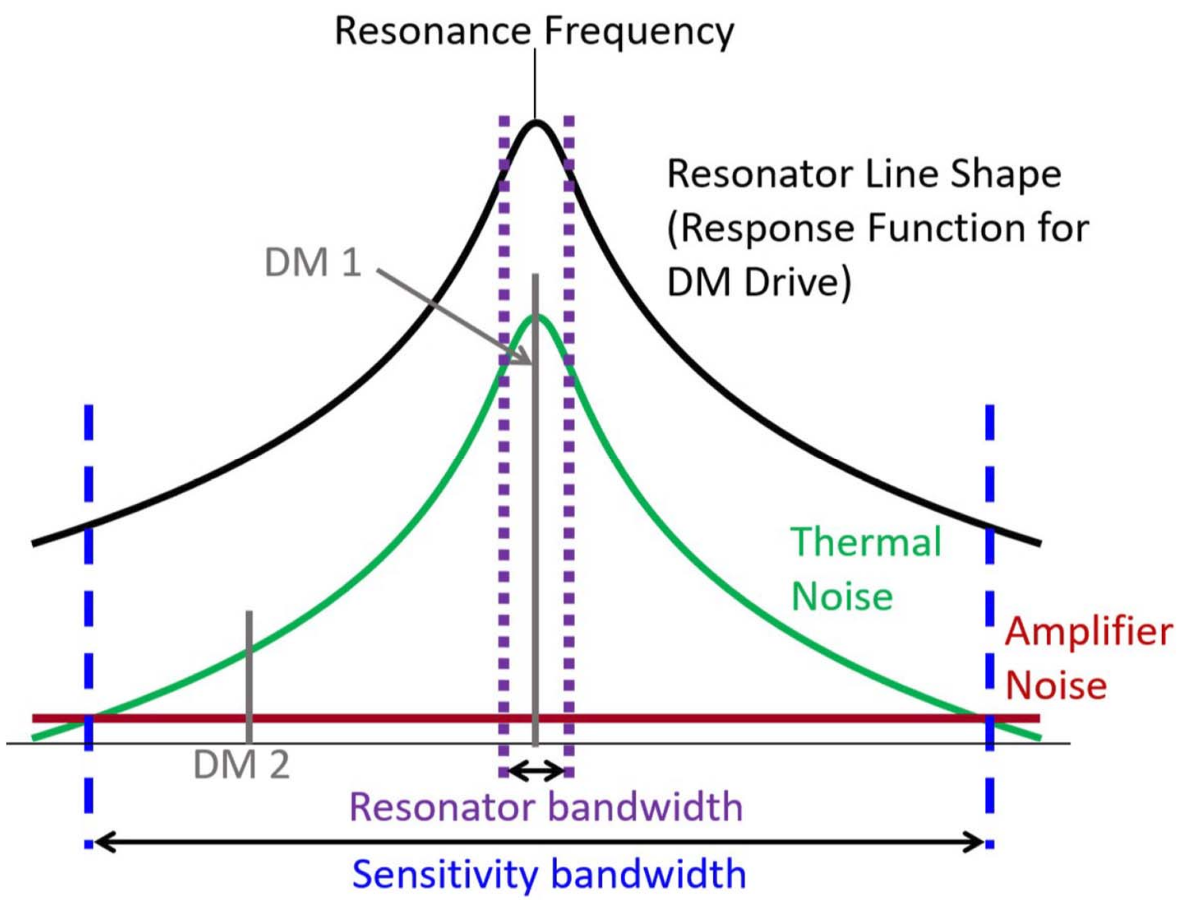
The Signal exists far out from the linewidth



SNR does not degraded when readout subdominant to thermal noise

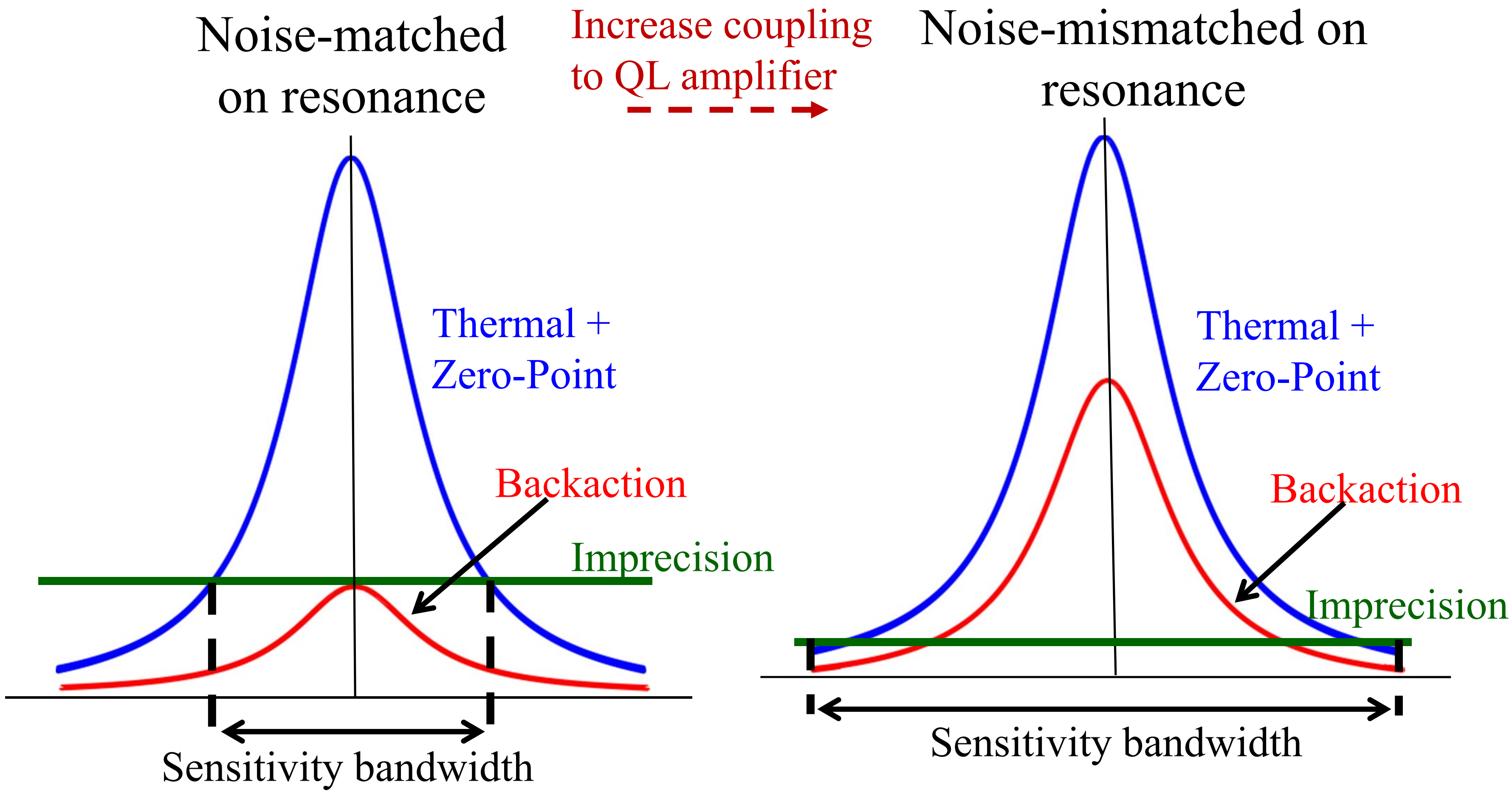
$hf \ll k_B T$: high thermal occupation

Electromagnetic coupling: integrated sensitivity



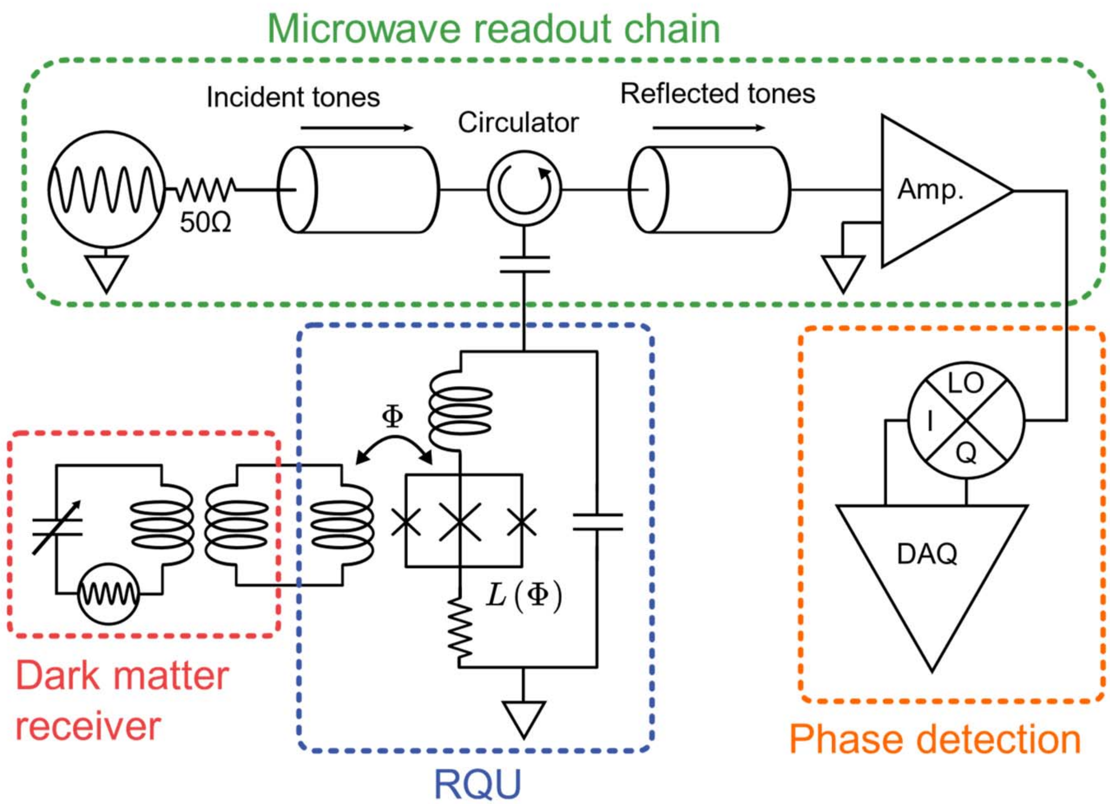
Science reach determined by integrated sensitivity across search band

Resonator measurement at Standard Quantum Limit



- Increased coupling: reduced imprecision, increased backaction
- 50% on-resonance noise penalty. Much larger sensitivity bandwidth

The RF Quantum Upconverter (RQU)



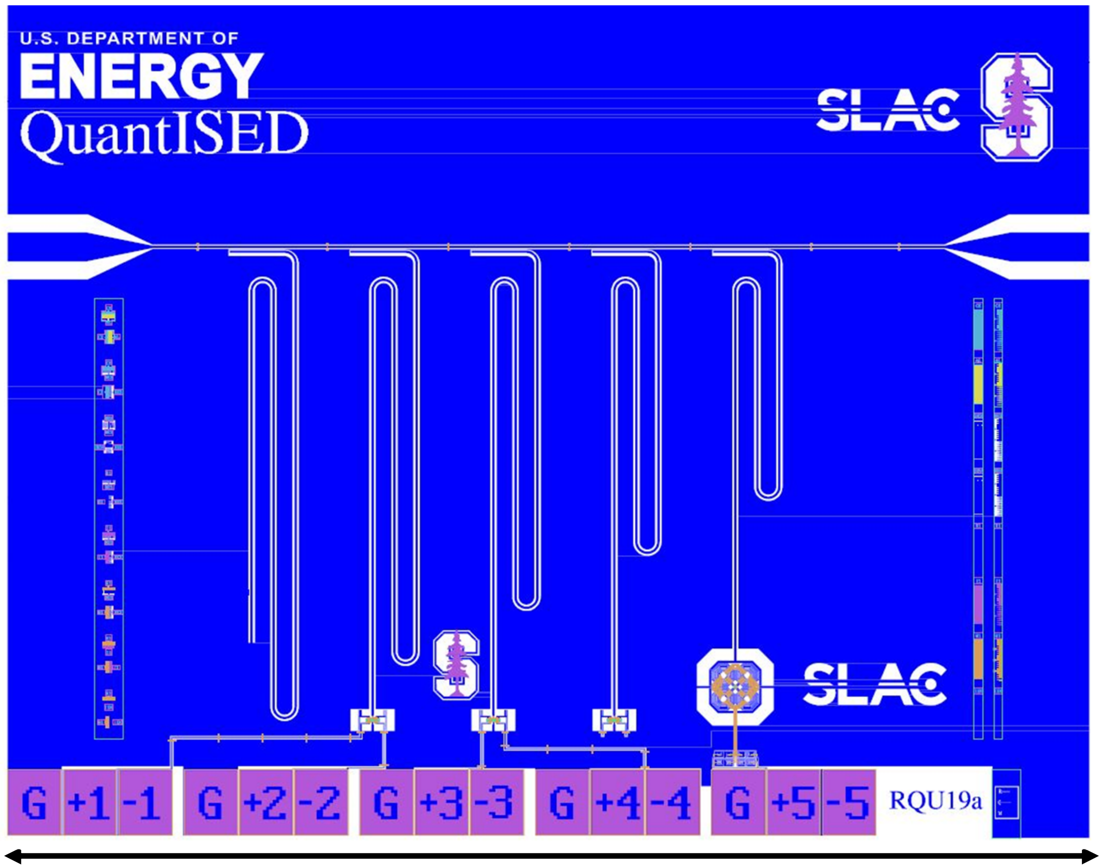
→ A three junction interferometer acts as a flux-variable inductance, upconverting RF signals to microwave frequencies

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

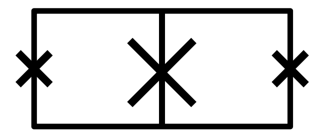
→ RQU evades backaction with quantum protocol (cavity optomechanics)

Aspelmeyer, Markus, et al. "Cavity optomechanics." Reviews of Modern Physics (2014)

The RF Quantum Upconverter (RQU)

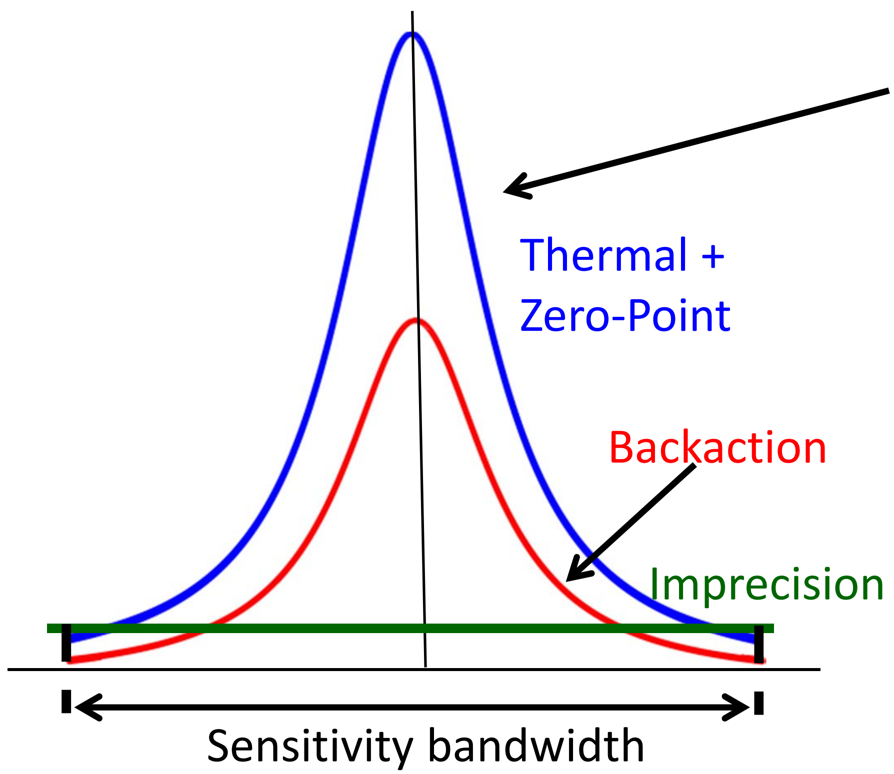


5 mm



- 1/2/1; 1/3/1, 1/4/1
- Nb/AlOx/Nb junctions
  Ic ~ 2 uA

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

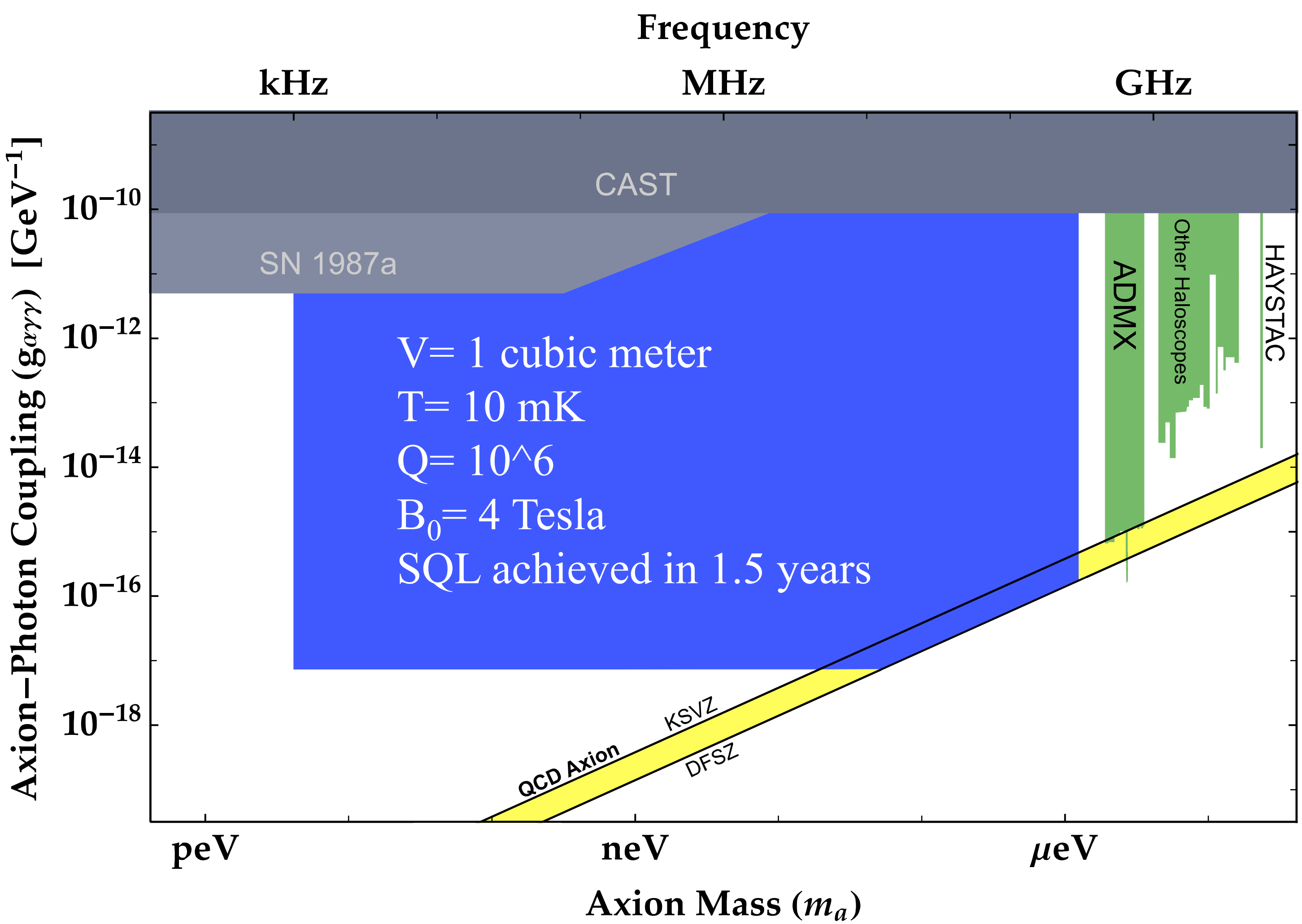


- $\sqrt{N}$ thermal fluctuations in the number of resonator photons
- Sensitivity not improved by photon counting
- Goal: reduce backaction & imprecision noise to widen sensitivity bandwidth

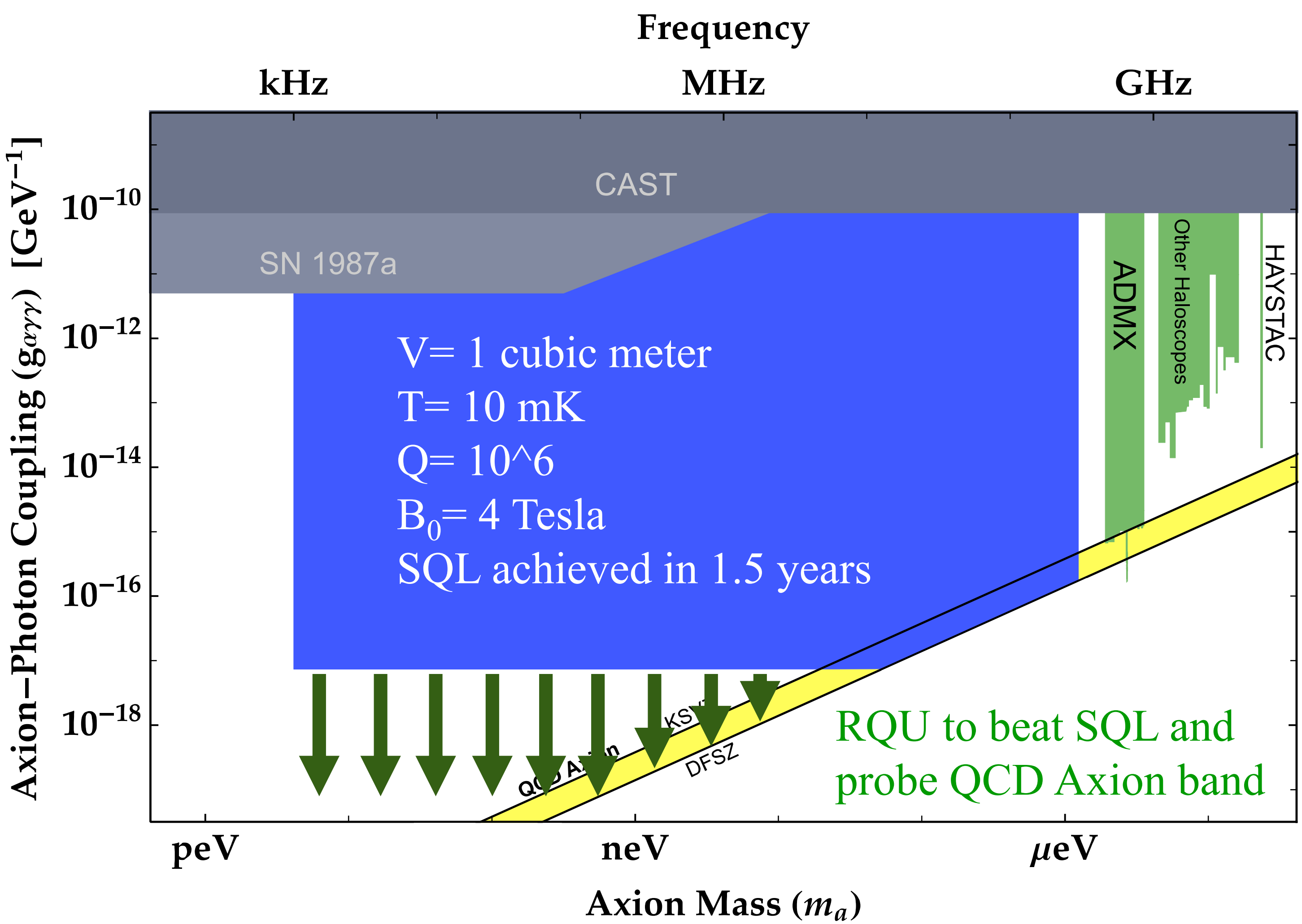
→ **Backaction evasion**

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

DM Radio will detect or rule-out Axions in big area



DM Radio will detect or rule-out Axions in big area



Team

Stanford/SLAC/Santa Clara
Prof. K. Irwin
Prof. P. Graham
Prof. B. Young
D. Li
A. Ames
S. Carman
S. Chaudhuri
C. Dawson
C. FitzGerald
R. Gruenke
A. Phipps
S. Kuenstner
C. Yu