Coherent quantum measurement for low-temperature detectors

Kent Irwin
Stanford University
SLAC

22-26 JULY 2019
MILANO
LTD 18
LOW TEMPERATURE DETECTORS

Outline

- Quantum 2.0 and low-temperature detectors

- QCD axions: a coherent quantum playground

  > 30 GHz: Early stage R&D; more ideas needed!

  5-30 GHz: Quantum non-demolition photon counting

  300 MHz - 10 GHz: Quantum-limited amplifiers / squeezing

  100 Hz – 300 MHz: Backaction evasion in LC resonator

  100 Hz – 100 MHz: Quantum magnetometry of NMR spins

- Speculative future: quantum enhancement of classical multiplexing?

Outline

- Quantum 2.0 and low-temperature detectors

- QCD axions: a coherent quantum playground

  > 30 GHz: Early stage R&D; more ideas needed!

  5-30 GHz: Quantum non-demolition photon counting

  300 MHz - 10 GHz: Quantum-limited amplifiers / squeezing

  100 Hz – 300 MHz: Backaction evasion in LC resonator

  100 Hz – 100 MHz: Quantum magnetometry of NMR spins

- Speculative future: quantum enhancement of classical multiplexing?

Quantum 1.0 and low-temperature detectors

Quantum Mechanics has long played a central role in LTDs: Quantum 1.0

- Energy gaps in semiconductor absorbers / thermistors
- Macroscopic quantum phase transitions in TESs
- Superconducting energy gaps in MKIDs
- Superconducting energy gaps in nanowire detectors / SSPDs
- Quantum interference in SQUIDs
- etc. etc.

Quantum 2.0: coherent quantum measurement

The new quantum revolution is bringing new tools that will broadly impact LTDs

Characteristics

1. Evasion of “quantum limits” that apply to classical circuits
   - Vacuum noise, backaction, projection noise…
2. Control and manipulation of coherent quantum states
   - Superconducting qubit phase
   - Nuclear spins
   - Superconducting phase in other Josephson devices

     (Parametric amplifiers, quantum upconverters, Josephson PMTs)

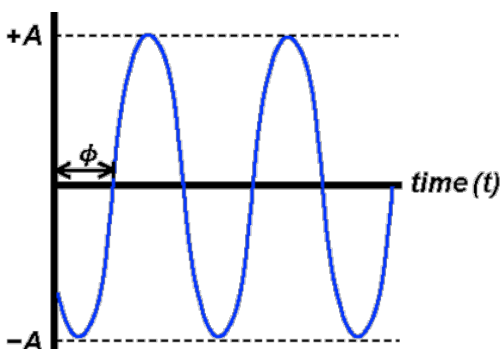
Heisenberg and the Standard Quantum Limit (SQL)

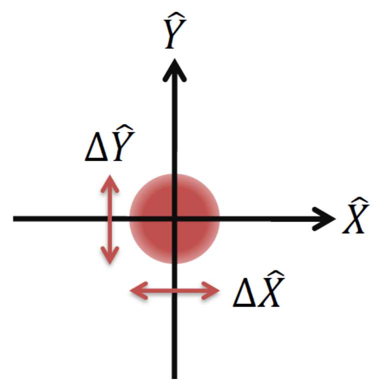
- Heisenberg tells us that you can't know the position and momentum of a particle perfectly at the same time:

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

- Heisenberg also tells us that you can't know both the amplitude (A) and phase (ϕ) of an electromagnetic signal in an LC resonator perfectly at the same time.

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





$$\boxed{\Delta X \Delta Y \geq \frac{\hbar\omega}{2}}$$

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

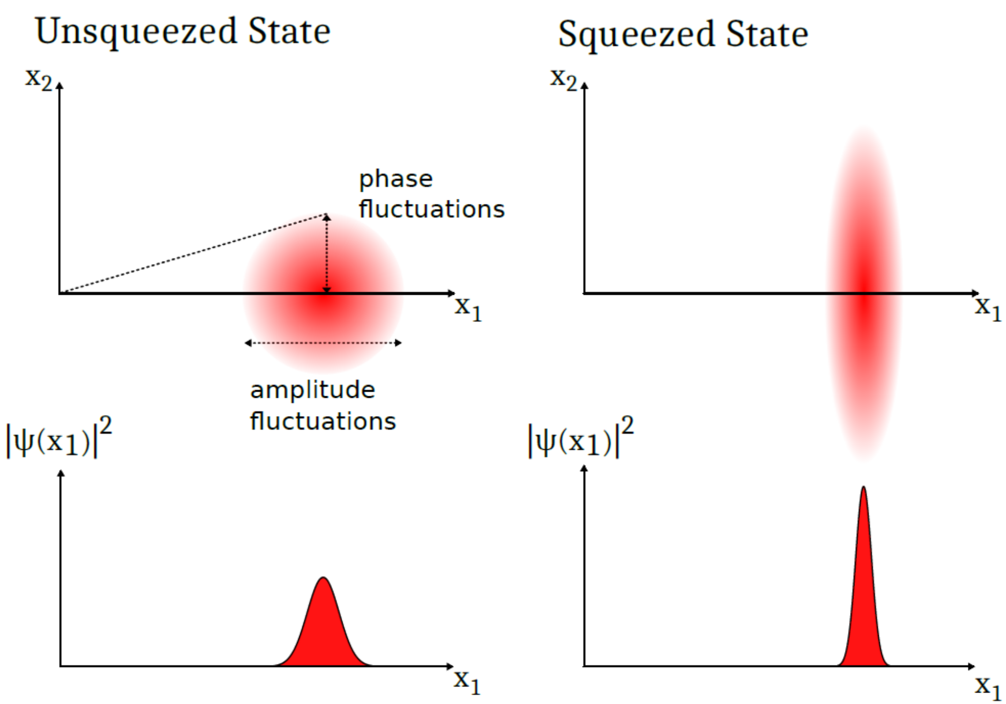
- A Quantum 1.0 (classical) sensor measures both amplitude and phase with equal sensitivity, limited by the Standard Quantum Limit of $\hbar\omega/2$ (a "half a photon")
- An additional $\hbar\omega/2$ is added by amplification

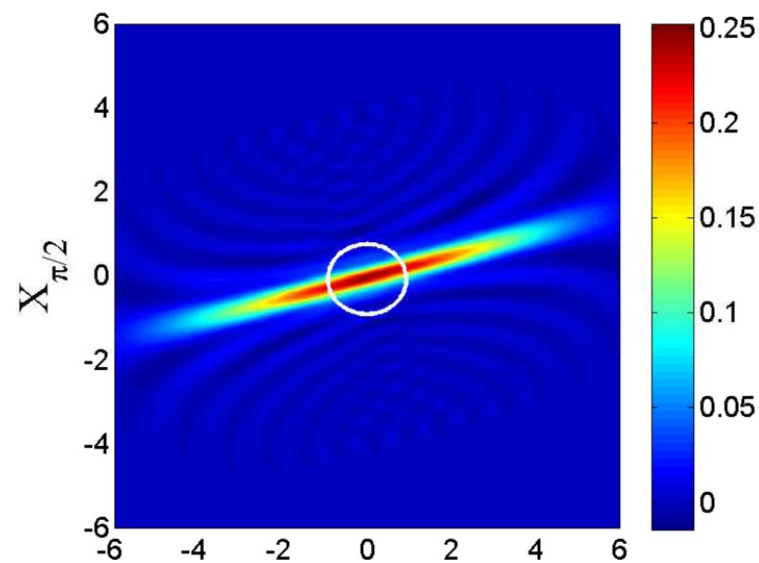
See review: Clerk et al, RMP **82**, 1155 (2010)

Quantum 2.0: Evade the SQL for better measurement

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

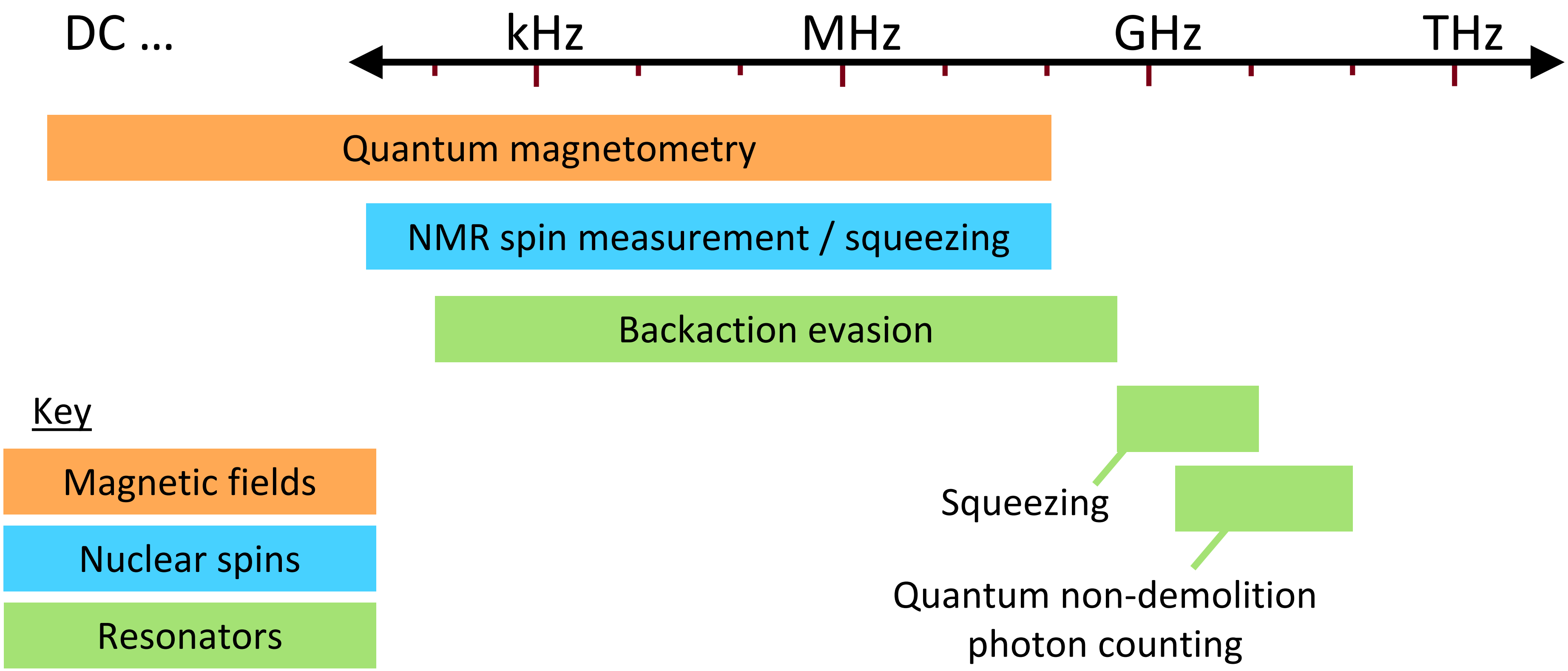
Squeeze the uncertainty into phase, and measure amplitude better than the Standard Quantum Limit!





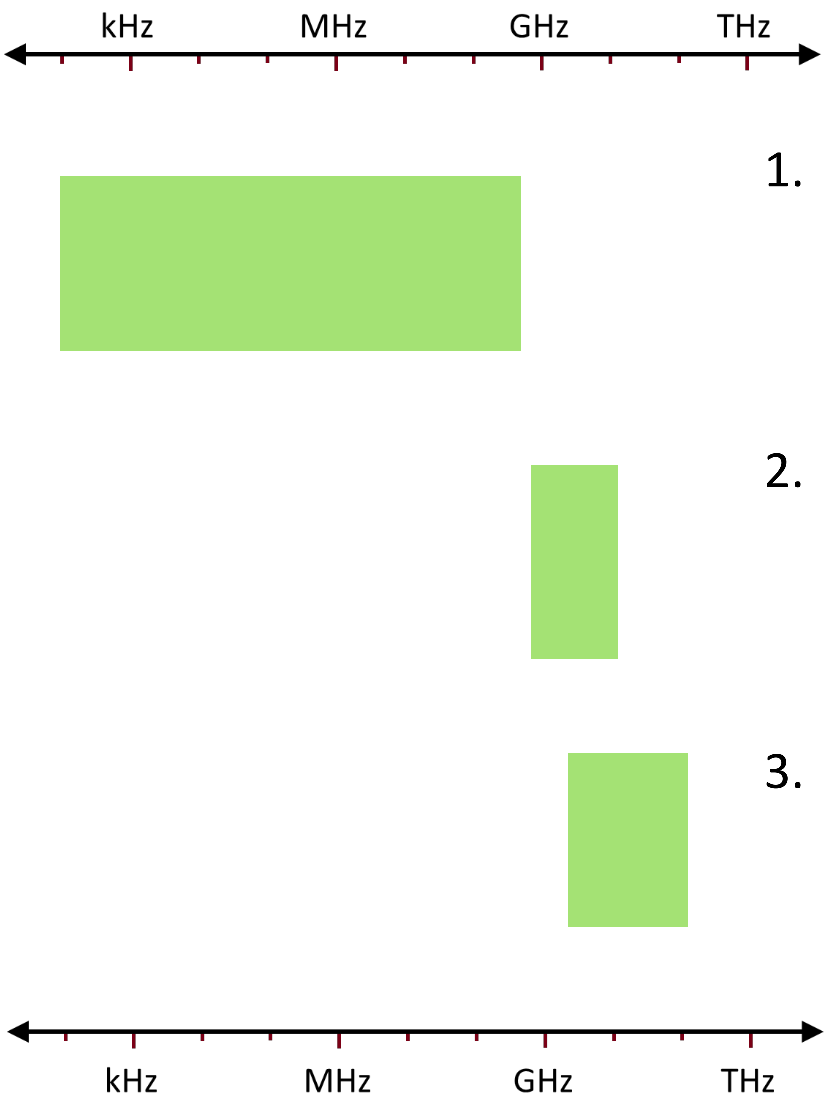
Mallet et al. *Phys. Rev. Lett.* **106**, 220502 (2011)

Quantum 2.0 in electromagnetic LTDs

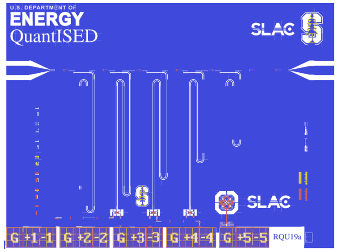


- Superconducting quantum sensors can be *provably superior* to classical sensors in practical use from DC to THz.
- Enhanced sensitivity by exploitation of quantum correlations, including squeezing, entanglement, backaction evasion.

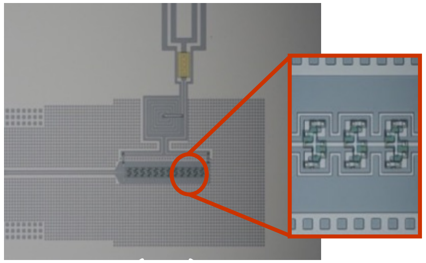
Quantum 2.0 in electromagnetic resonators



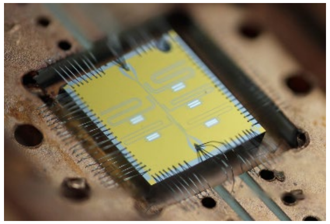
1. Below 300 MHz – *radio-frequency quantum upconverter (RQU)*
2. From ~300 MHz to ~10 GHz, squeezing with *Josephson parametric amplifiers (JPAs)*
3. Above ~ GHz, Quantum Non-Demolition photon counting - *qubits*.



Quantum upconverters, Irwin group / Stanford



JPA, Lehnert / JILA

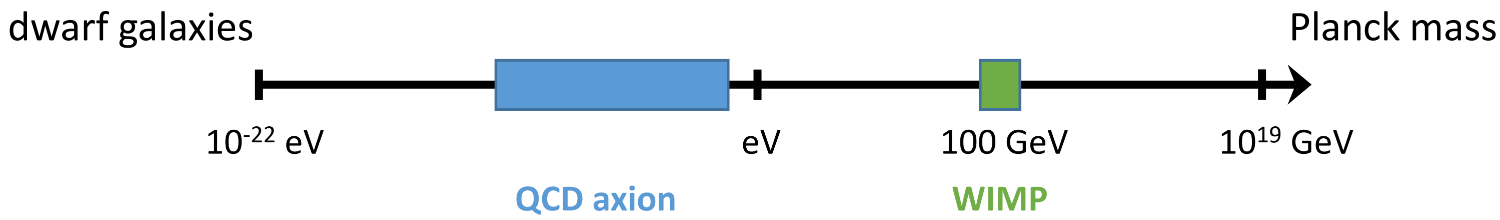


Qubits, Siddiqi / UCB

Outline

- Quantum 2.0 and low-temperature detectors
- QCD axions: a coherent quantum playground
  - **> 30 GHz:** Early stage R&D; more ideas needed!
  - **5-30 GHz:** Quantum non-demolition photon counting
  - **300 MHz - 10 GHz:** Quantum-limited amplifiers / squeezing
  - **100 Hz – 300 MHz:** Backaction evasion in LC resonator
  - **100 Hz – 100 MHz:** Quantum magnetometry of NMR spins
- Speculative future: quantum enhancement of classical multiplexing?

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**
  - 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.

QCD Axions: strongly motivated below 1 μeV

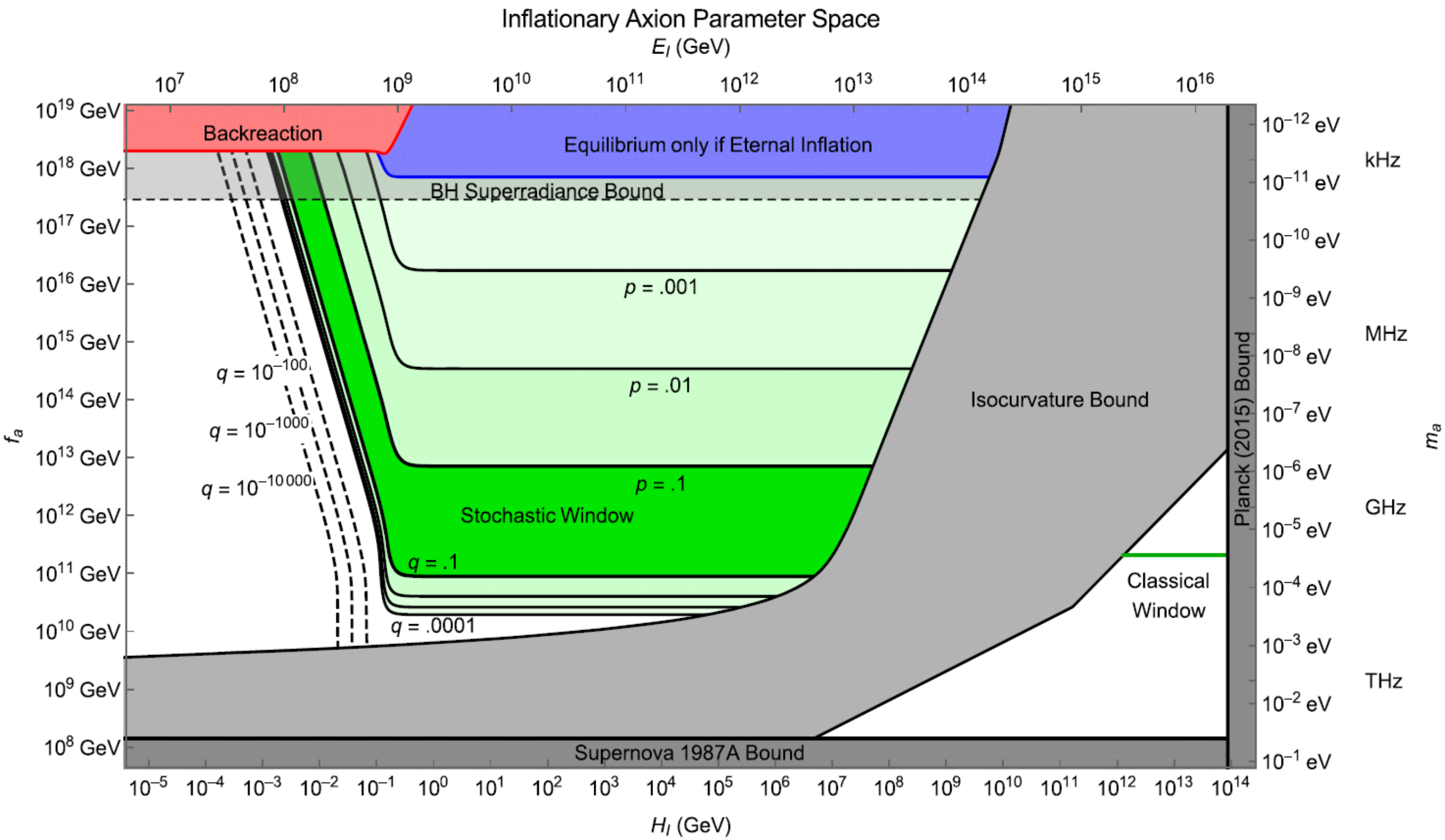
- It was previously believed that overproduction of dark matter and isocurvature constrains the preferred axion mass to be above a threshold of order μeV.

- **"Recent theoretical advances have significantly expanded the phenomenology of the QCD axion, resulting in the realization that QCD axion dark matter can exist over a wide range of masses from 100 Hz to 1 THz"** (peV – meV)

DOE Report on Basic Research Needs for Dark Matter Small Projects, 2018-19
https://science.osti.gov/~/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

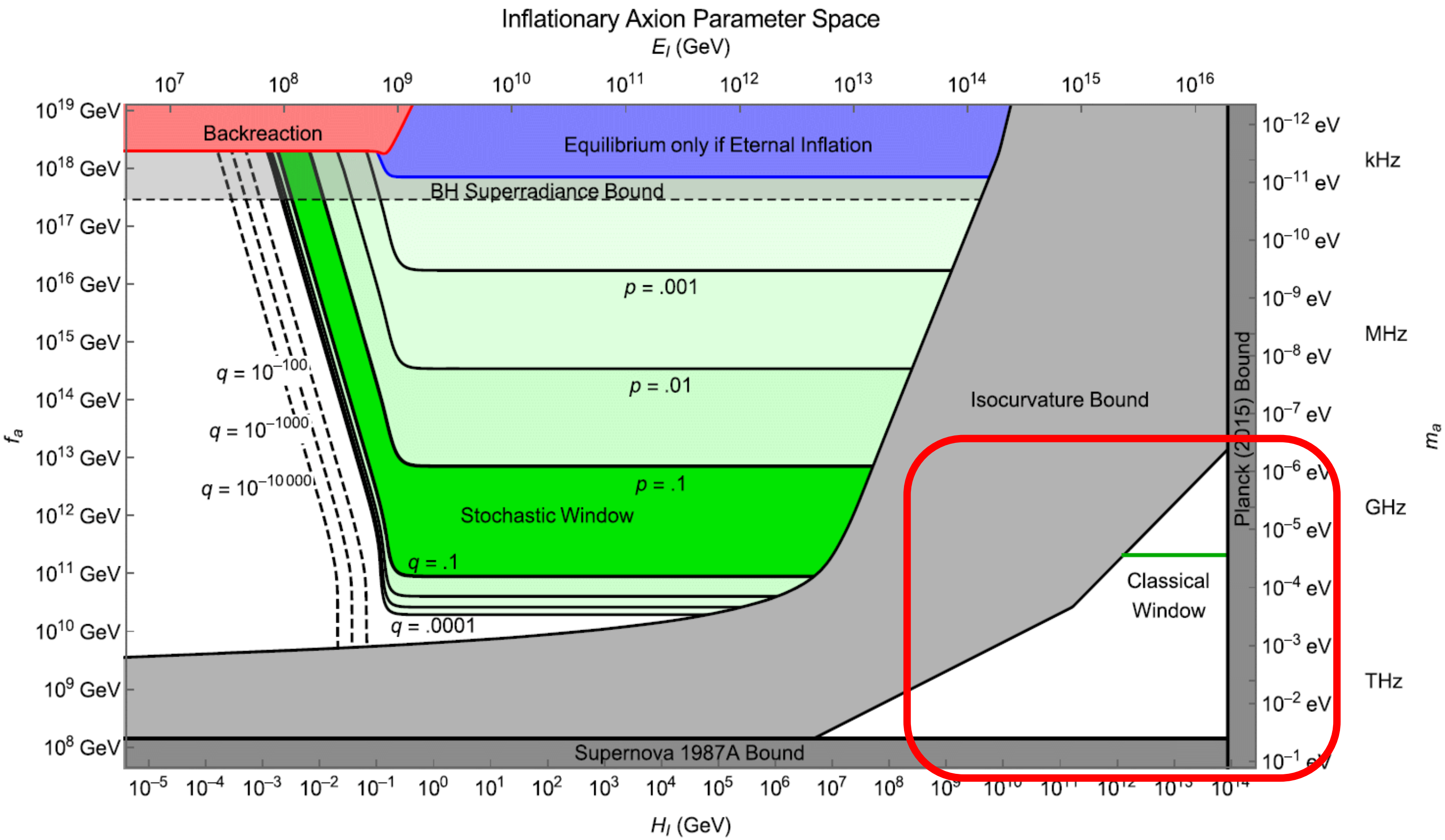
There is no significant preference for axions to be above μeV. The full QCD axion band should be searched.

QCD Axions: strongly motivated over whole range



P.W. Graham and A. Scherlis. *Physical Review D* 98.3 (2018): 035017.

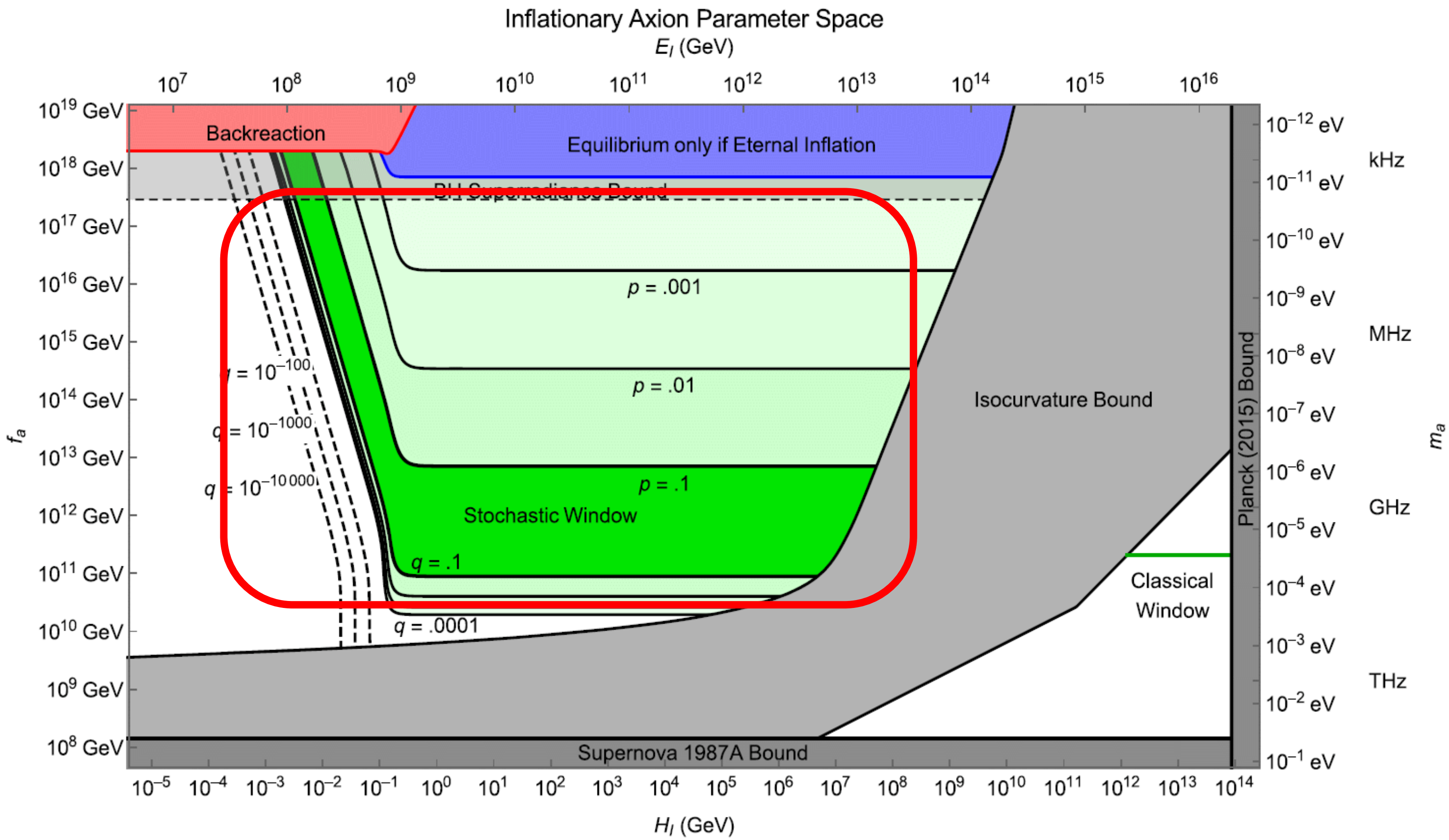
QCD Axions: strongly motivated over whole range



P.W. Graham and A. Scherlis. *Physical Review D* 98.3 (2018): 035017.

- Post-inflationary axions favored with mass > μeV
- Masses < μeV tend to over-produce and generate too much isocurvature
- This is the “classical” axion window

QCD Axions: strongly motivated over whole range



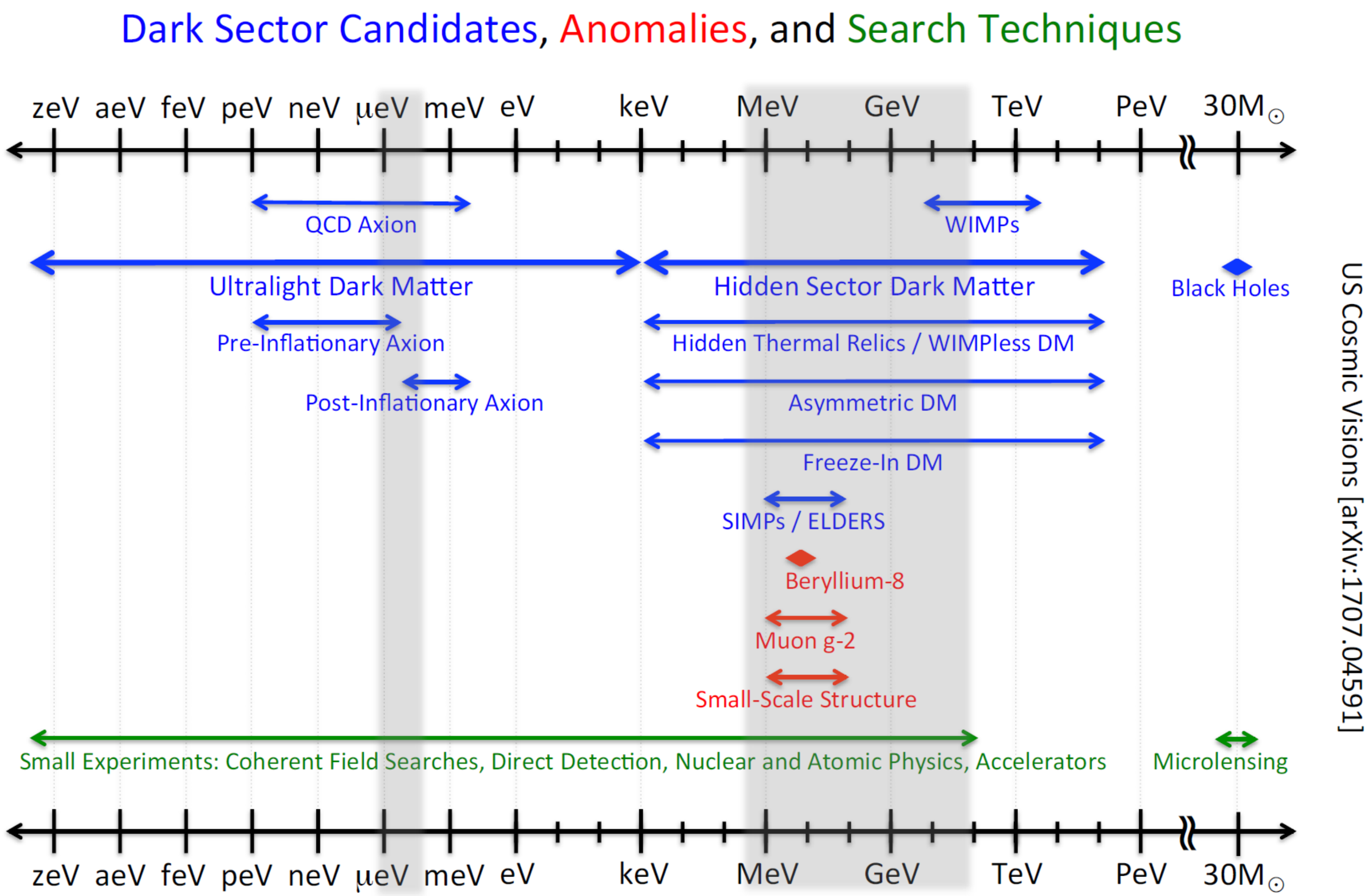
P.W. Graham and A. Scherlis. *Physical Review D* 98.3 (2018): 035017.

- Axion abundance can be generated by stochastic quantum fluctuations during inflation.
- During inflation the axion tends toward an equilibrium, assuming the Hubble scale is low and inflation lasts sufficiently long, generating dark matter with negligible isocurvature.
- This is the “stochastic” axion window, which generates QCD axion dark matter over a broad mass range.

Federica Petricca, Monday, 7/22, 16:40
Low Temperature Dark-Matter Detectors

THE LANDSCAPE

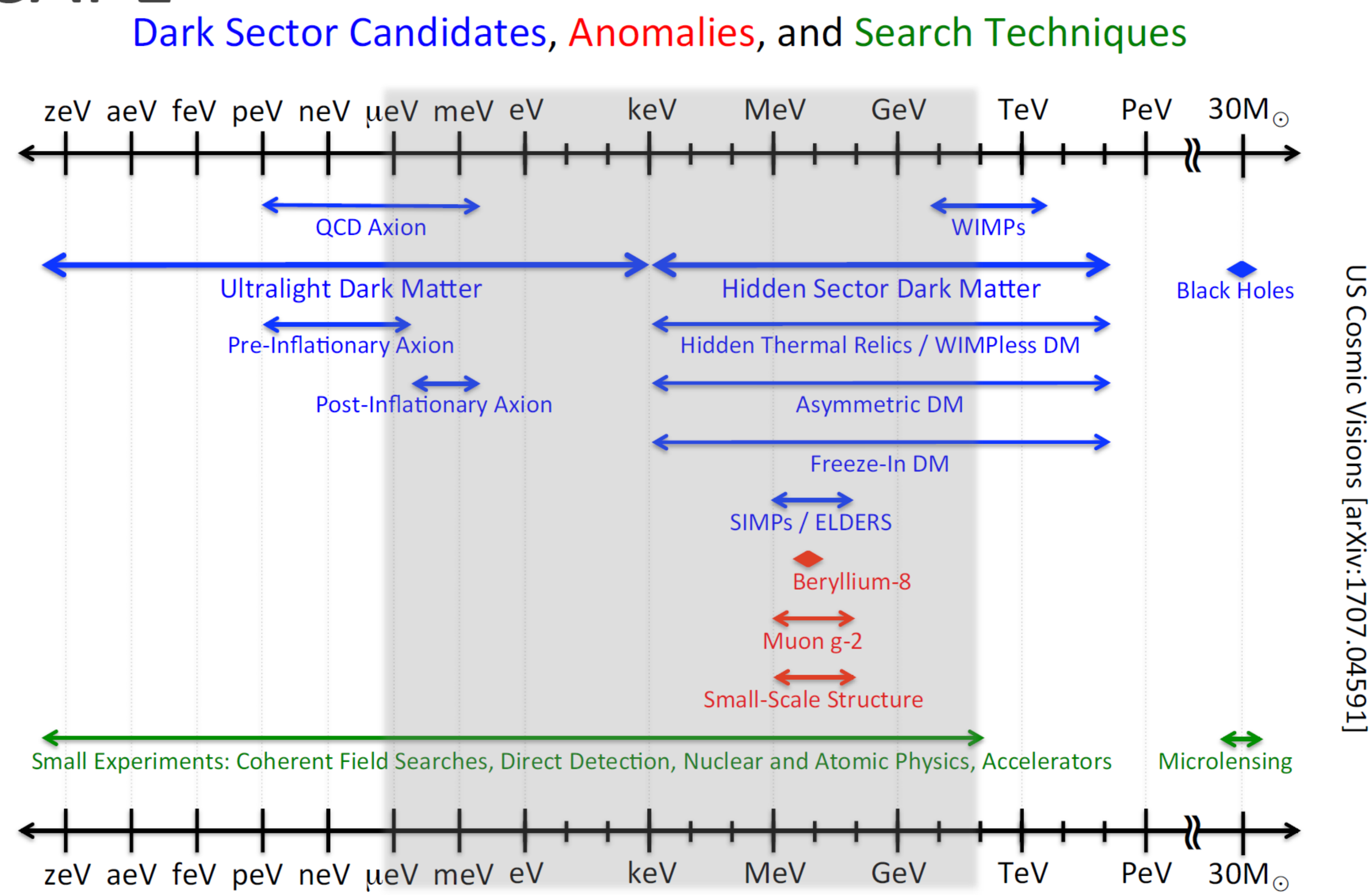
Status



Federica Petricca, Monday, 7/22, 16:40
Low Temperature Dark-Matter Detectors

THE LANDSCAPE

Goal



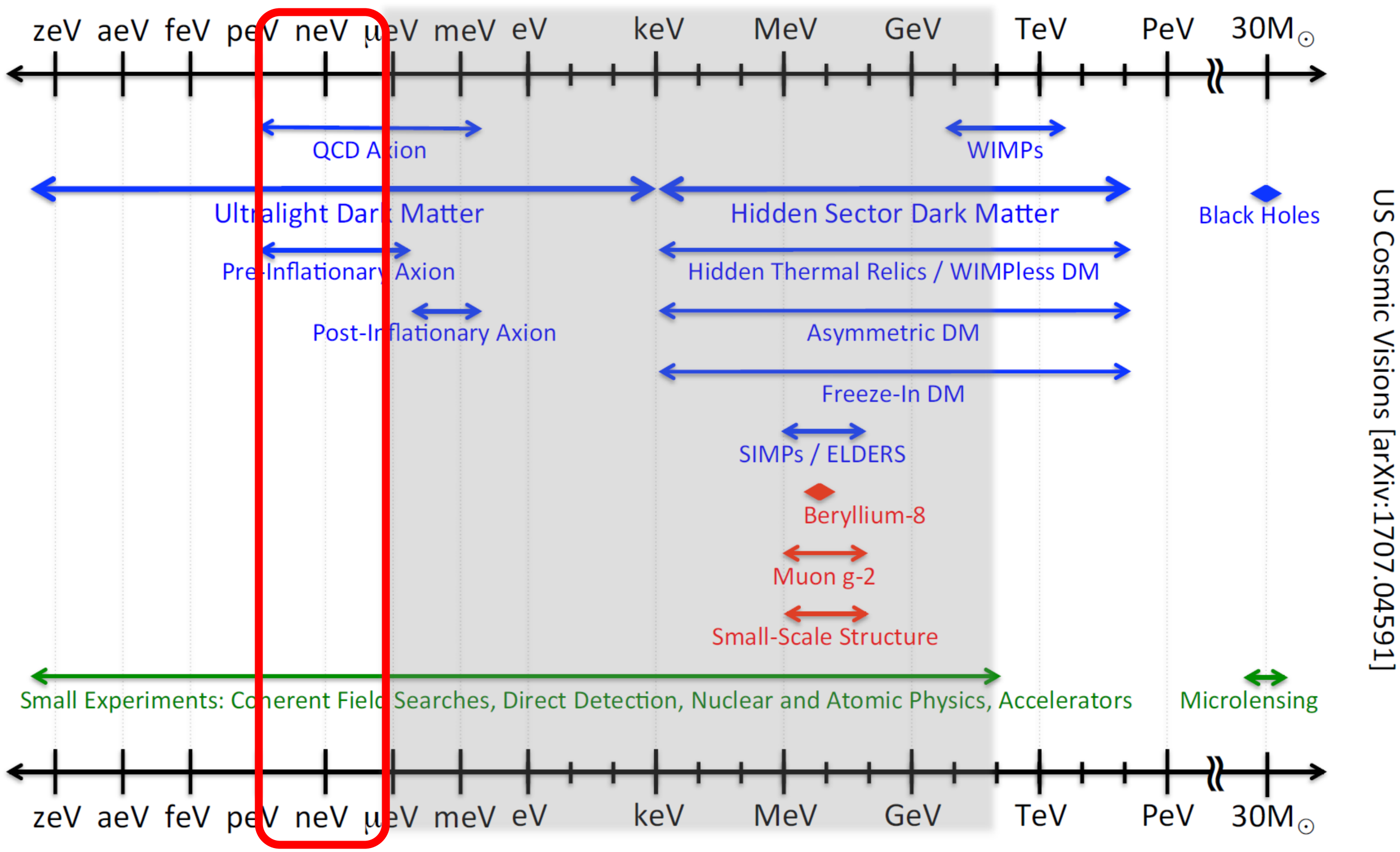
Federica Petricca, Monday, 7/22, 16:40
Low Temperature Dark-Matter Detectors

THE LANDSCAPE

Goal

Enhanced Goal
includes peV-μeV

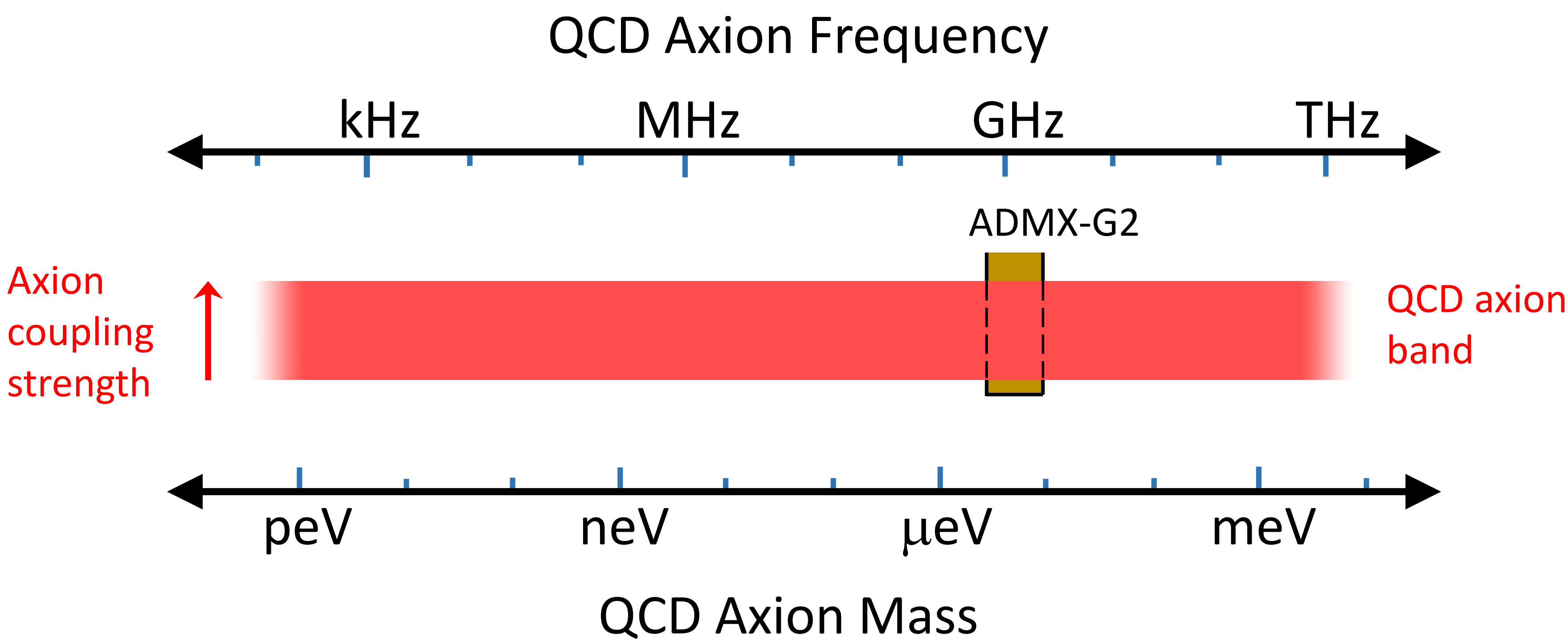
Dark Sector Candidates, Anomalies, and Search Techniques



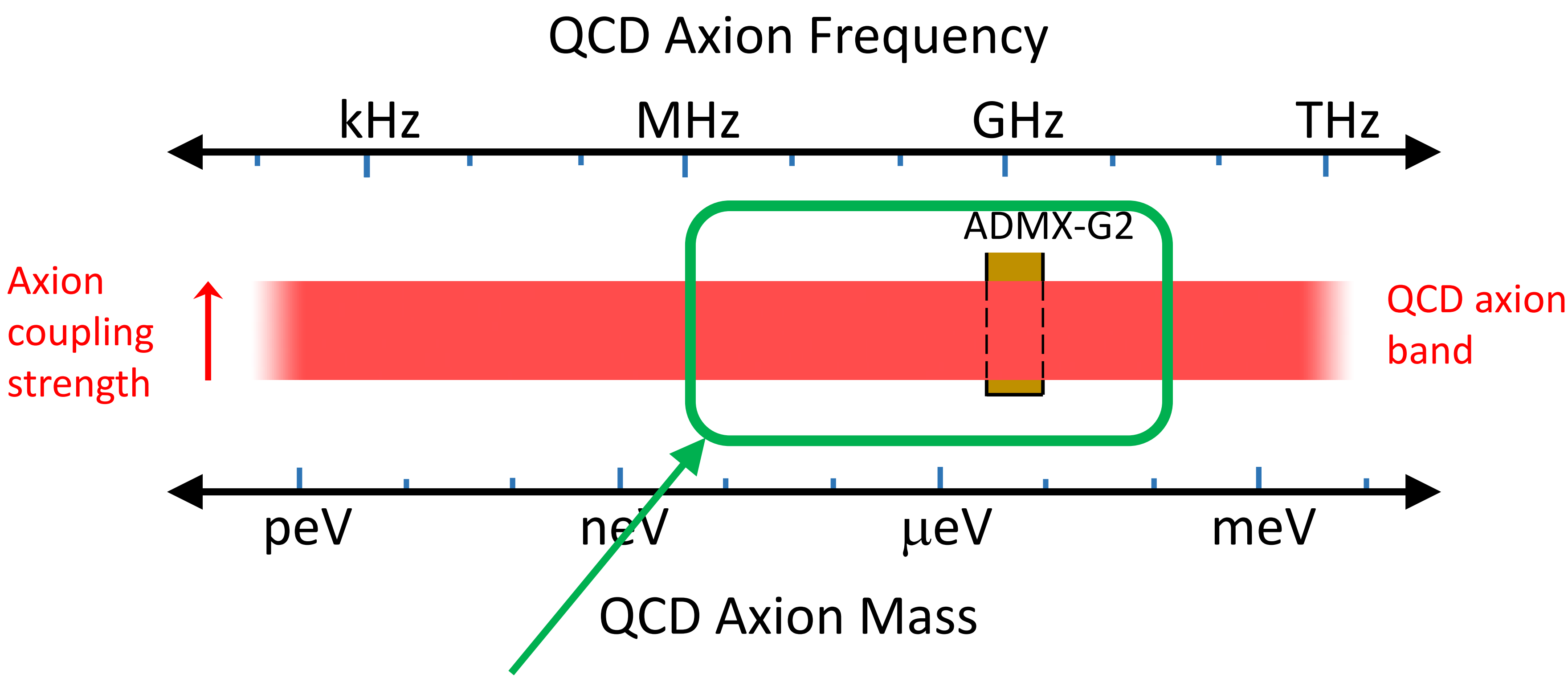
22 July 2019 Low temperature dark matter detectors 30

Among the most well motivated dark matter candidates are QCD axions in the peV – μeV mass range (including PQ symmetry breaking at GUT and Planck scales)

Quest for the QCD axion: G2 science reach



QCD axion: electromagnetic coupling



Mass range where search is best done through axion coupling to photons

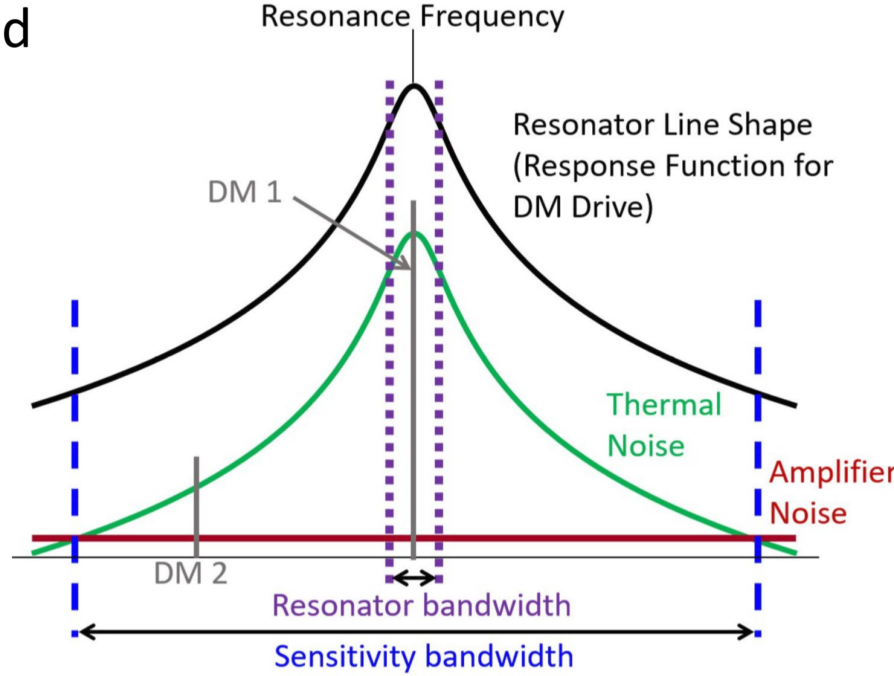
Electromagnetic coupling: integrated sensitivity

- 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

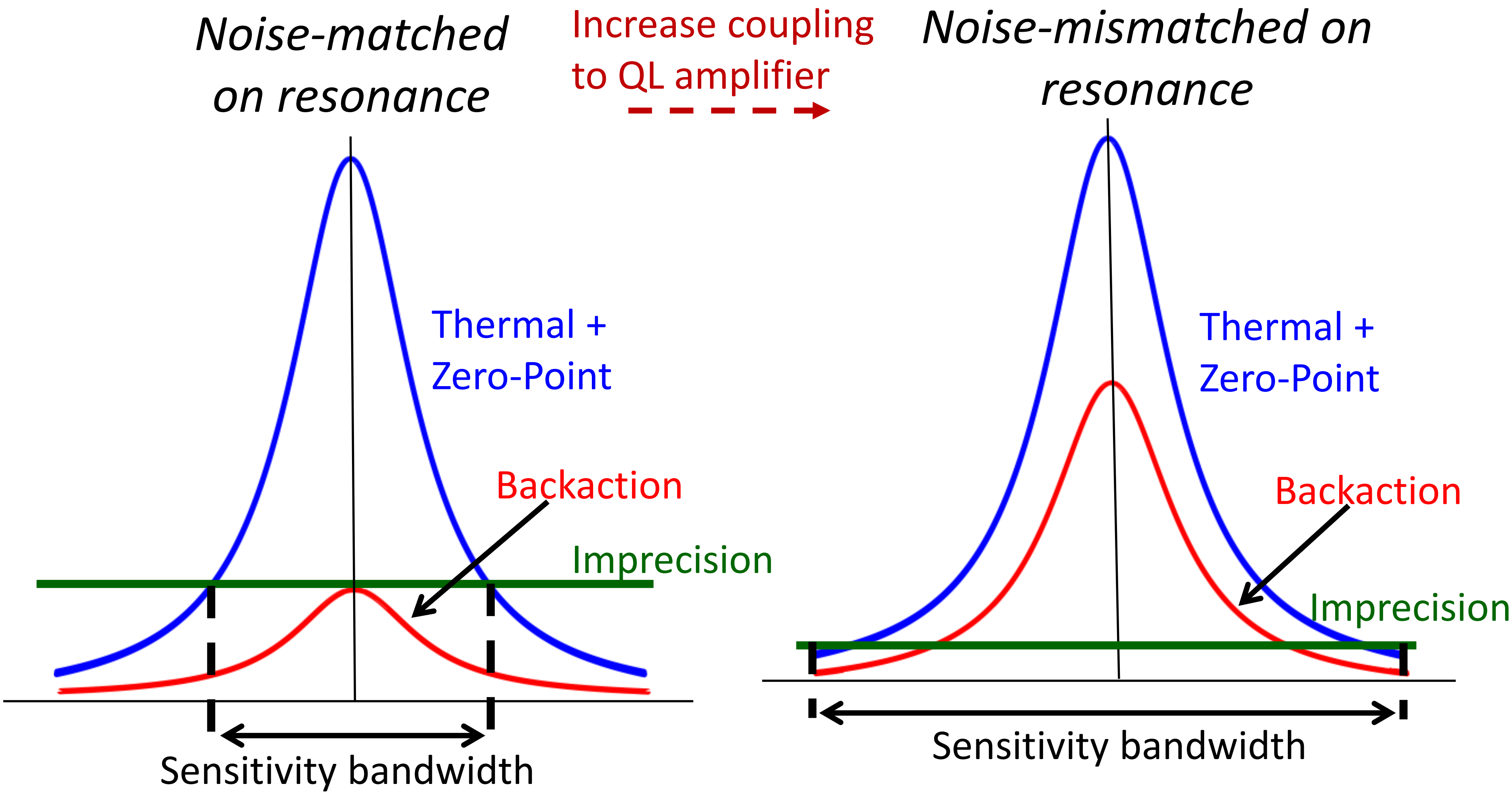
Example: single-pole resonator



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

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

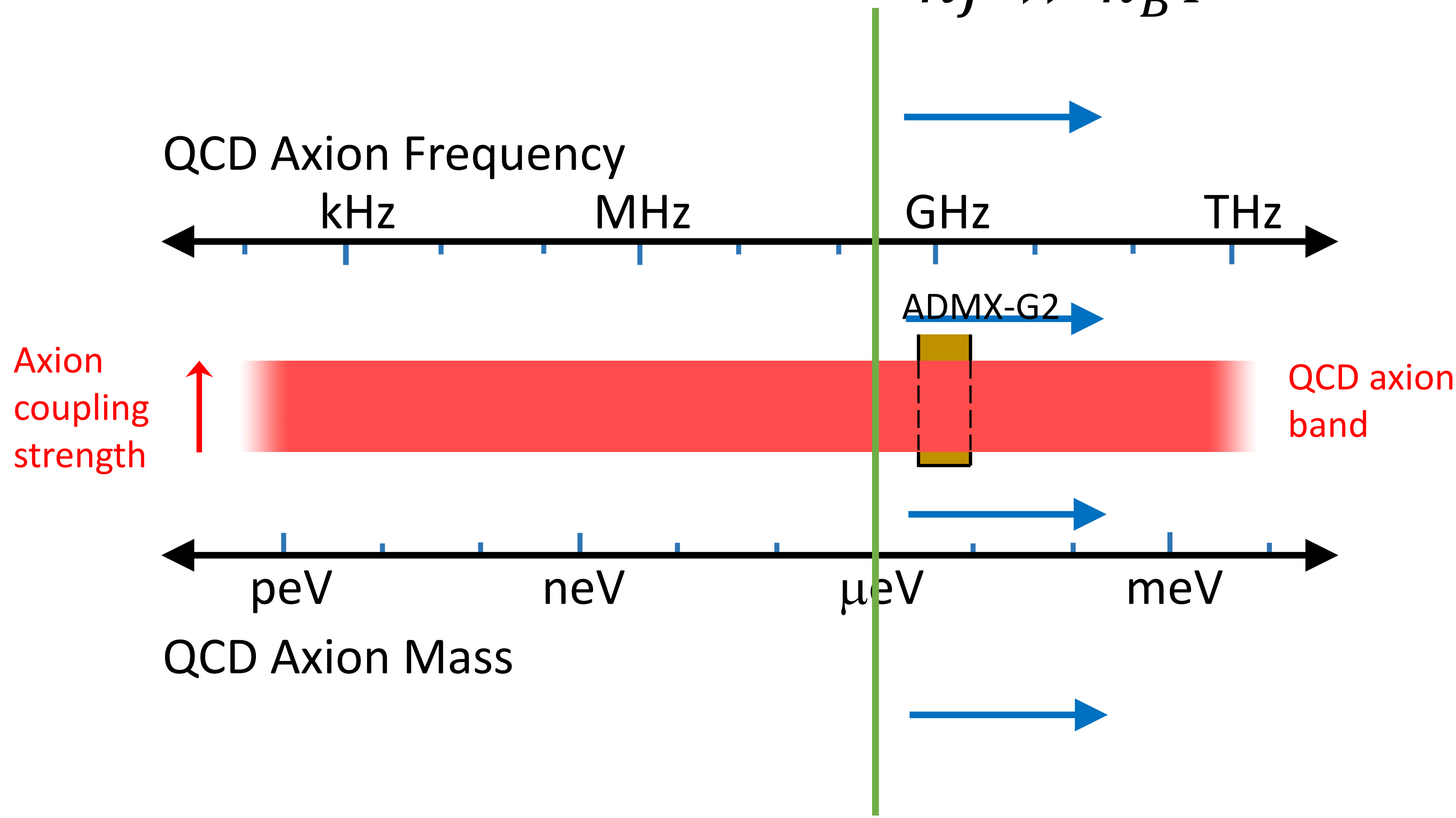
Resonator measurement at Standard Quantum Limit



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

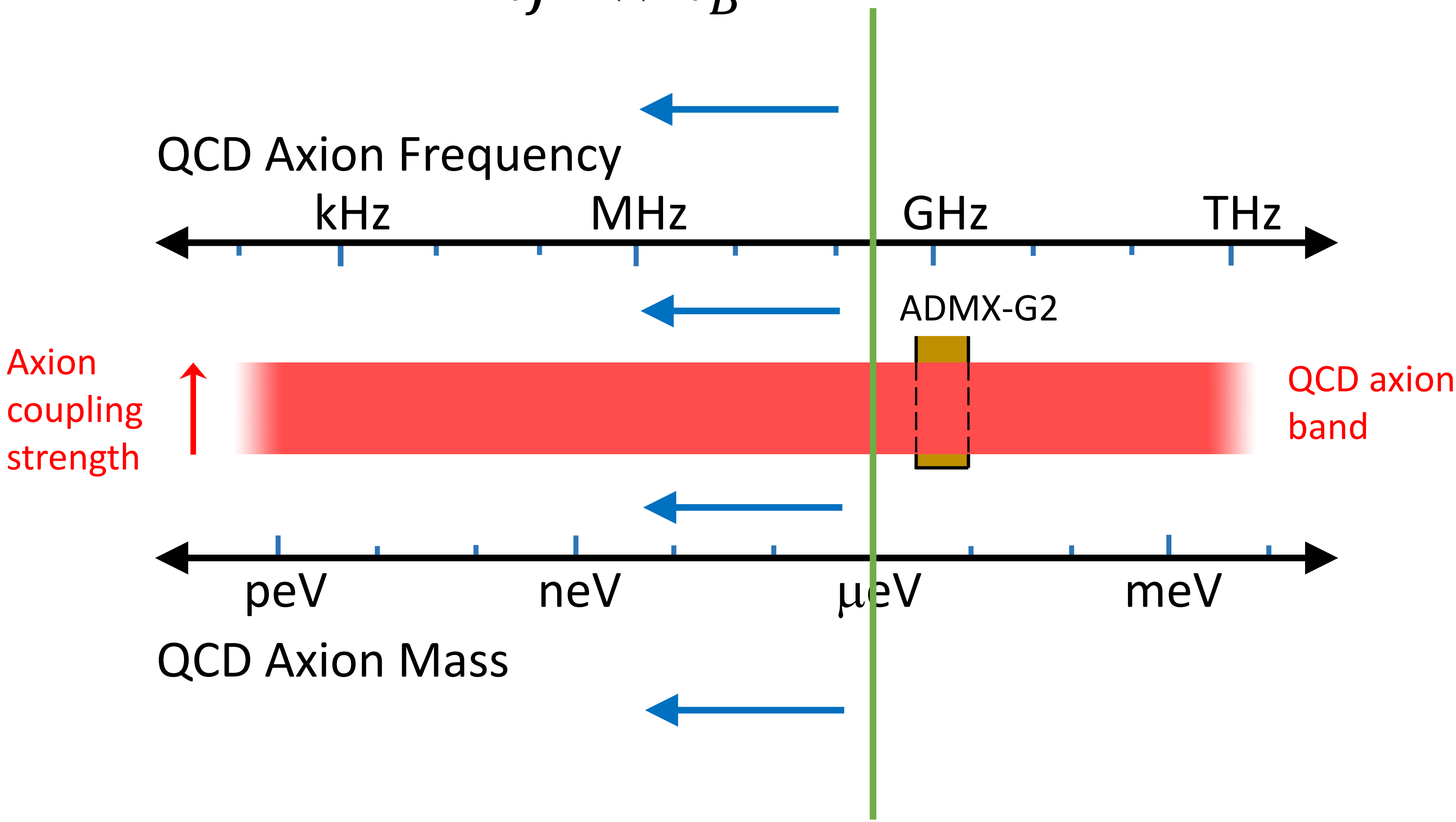
Two regimes: (1) Ground State

$$hf \gg k_B T$$



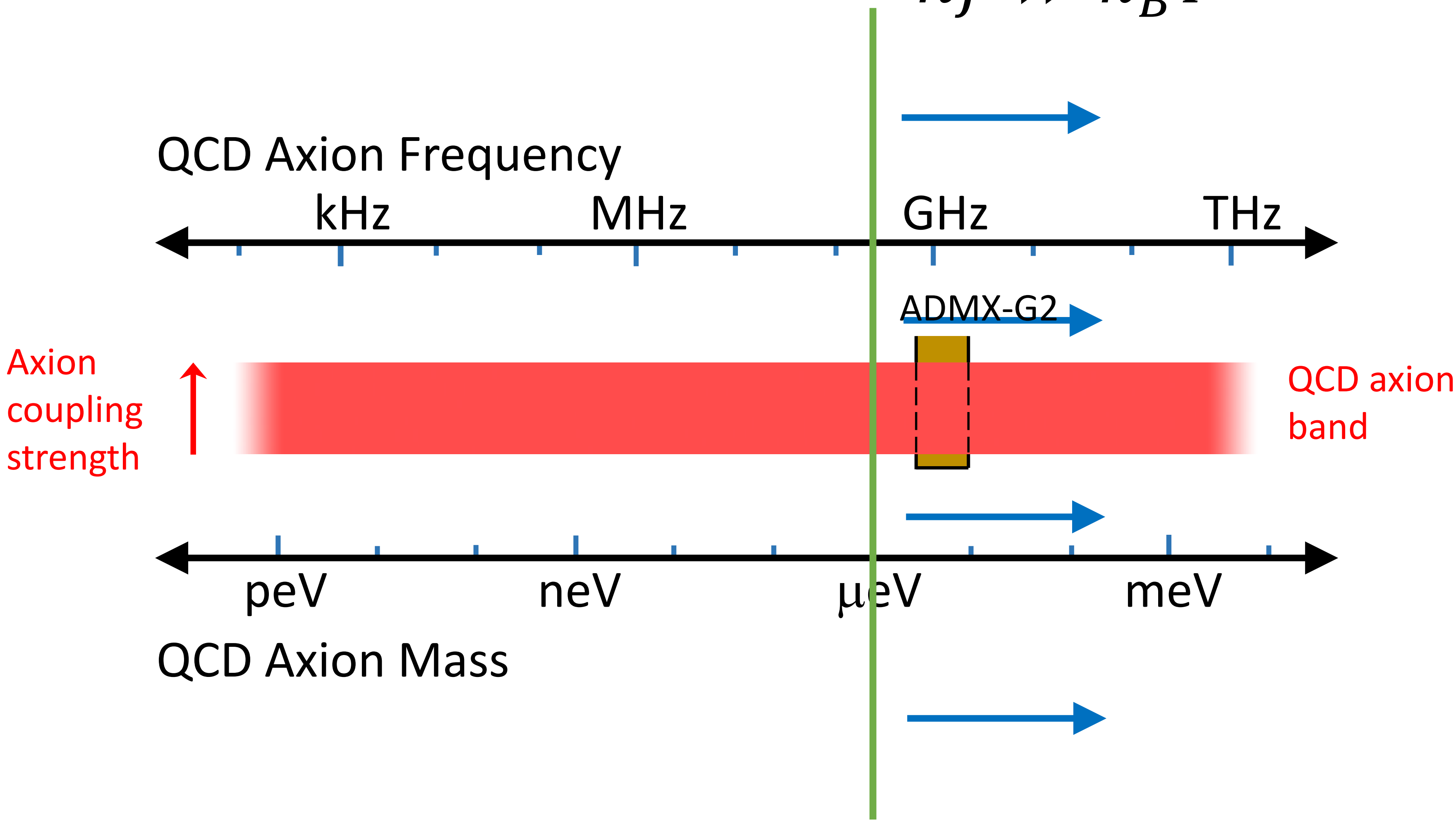
Two regimes: (2) High Occupation

$$hf \ll k_B T$$



Two regimes: (1) Ground State

$$hf \gg k_B T$$



Outline

- Quantum 2.0 and low-temperature detectors
- QCD axions: a coherent quantum playground

  > 30 GHz: Early stage R&D; more ideas needed!

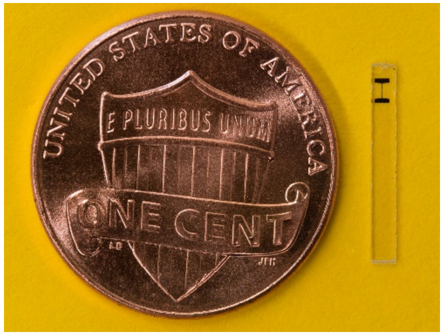
  5-30 GHz: Quantum non-demolition photon counting

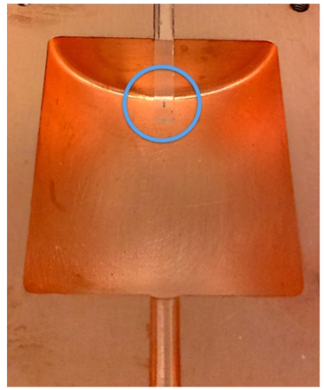
  300 MHz - 10 GHz: Quantum-limited amplifiers / squeezing

  100 Hz – 300 MHz: Backaction evasion in LC resonator

  100 Hz – 100 MHz: Quantum magnetometry of NMR spins
- Speculative future: quantum enhancement of classical multiplexing?

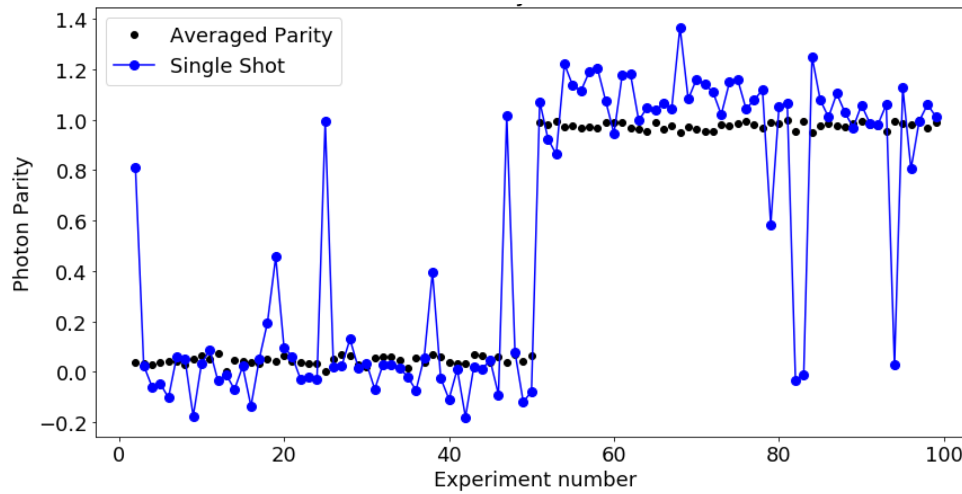
Ground state measurement: QND photon counting



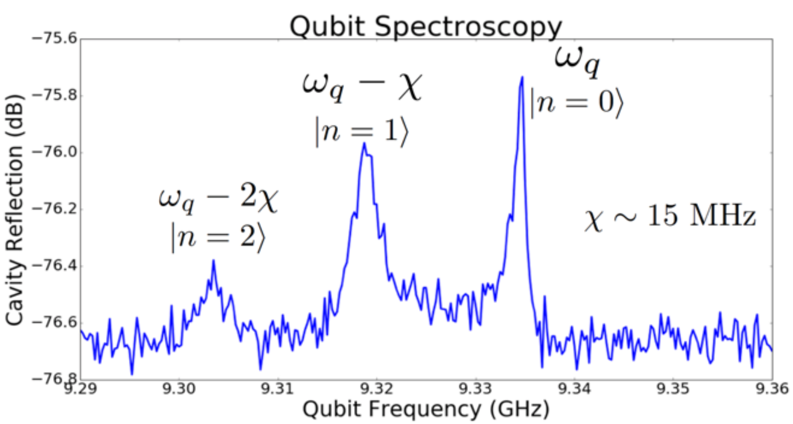


Akash Dixit, Aaron Chou, David Schuster

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



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.



Many QND measurements agree that the cold cavity contains 0 photons

Inject 1 photon

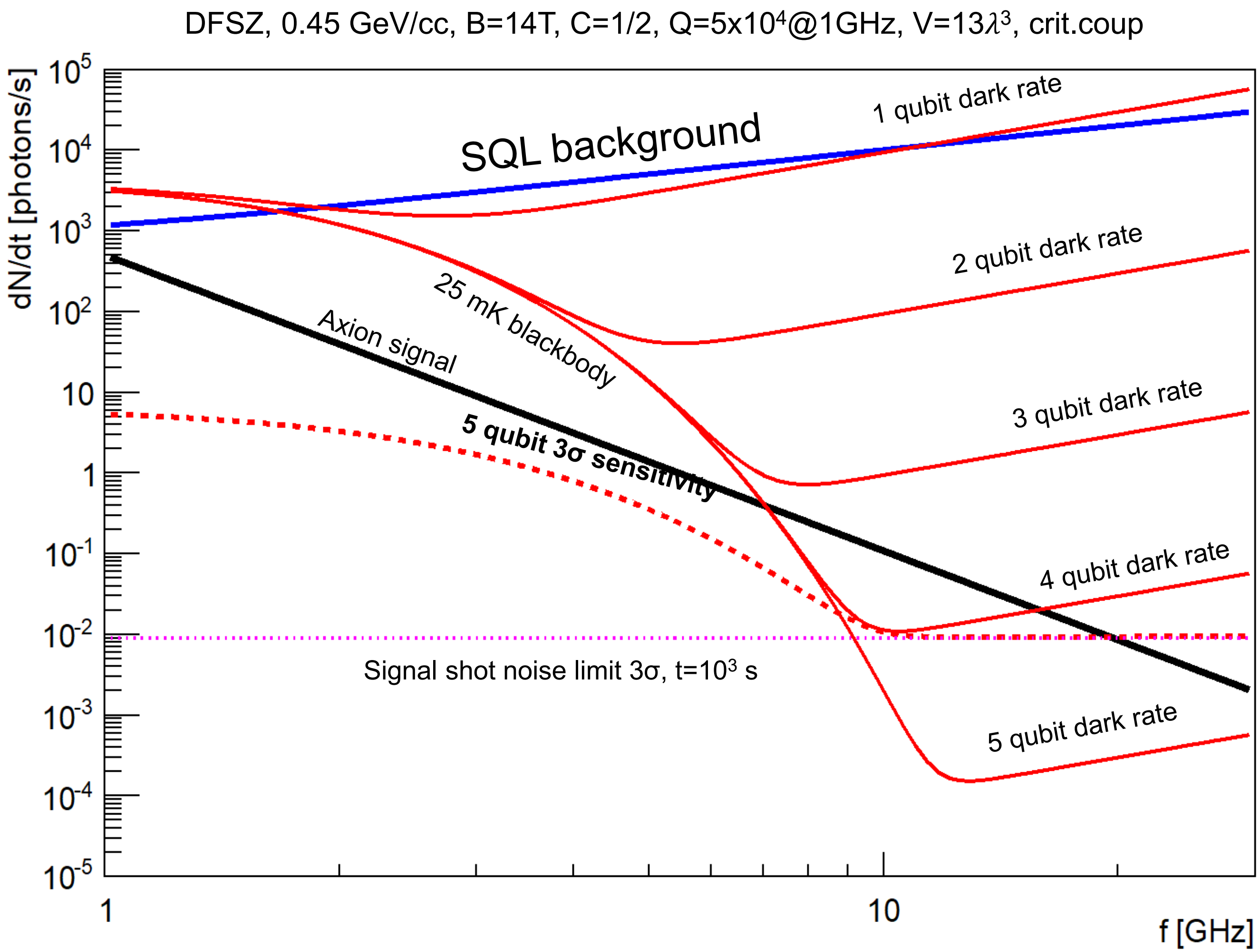
Many QND measurements of the single photon **without absorbing it.**

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

Ground state measurement: QND photon counting



Sensitivity limited only by signal photon shot noise.

Figure Credit: Aaron Chou, FNAL

See Aaron Chou's talk, this session: 15:45

Outline

- Quantum 2.0 and low-temperature detectors
- QCD axions: a coherent quantum playground

  > 30 GHz: Early stage R&D; more ideas needed!

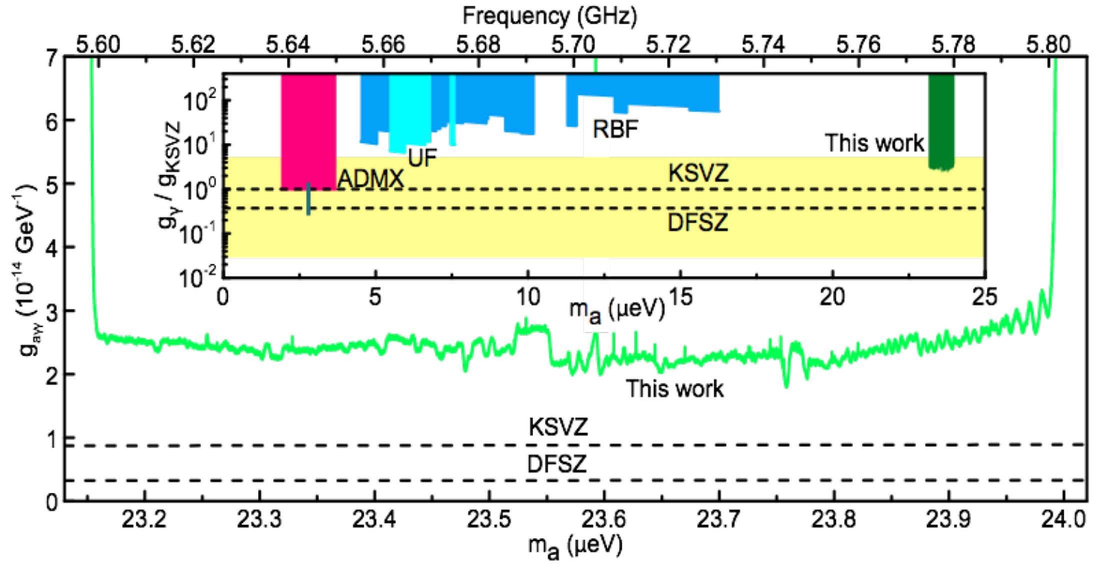
  5-30 GHz: Quantum non-demolition photon counting

  300 MHz - 10 GHz: Quantum-limited amplifiers / squeezing

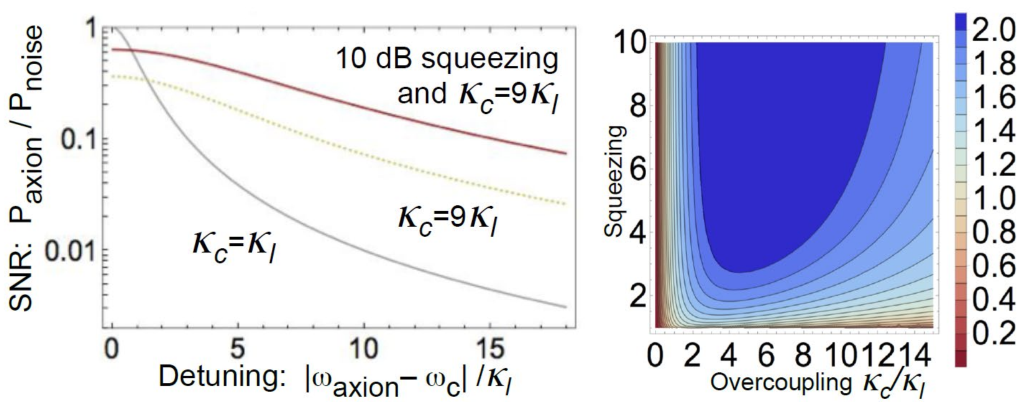
  100 Hz – 300 MHz: Backaction evasion in LC resonator

  100 Hz – 100 MHz: Quantum magnetometry of NMR spins
- Speculative future: quantum enhancement of classical multiplexing?

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).

Outline

- Quantum 2.0 and low-temperature detectors

- QCD axions: a coherent quantum playground

  > 30 GHz: Early stage R&D; more ideas needed!

  5-30 GHz: Quantum non-demolition photon counting

  300 MHz - 10 GHz: Quantum-limited amplifiers / squeezing

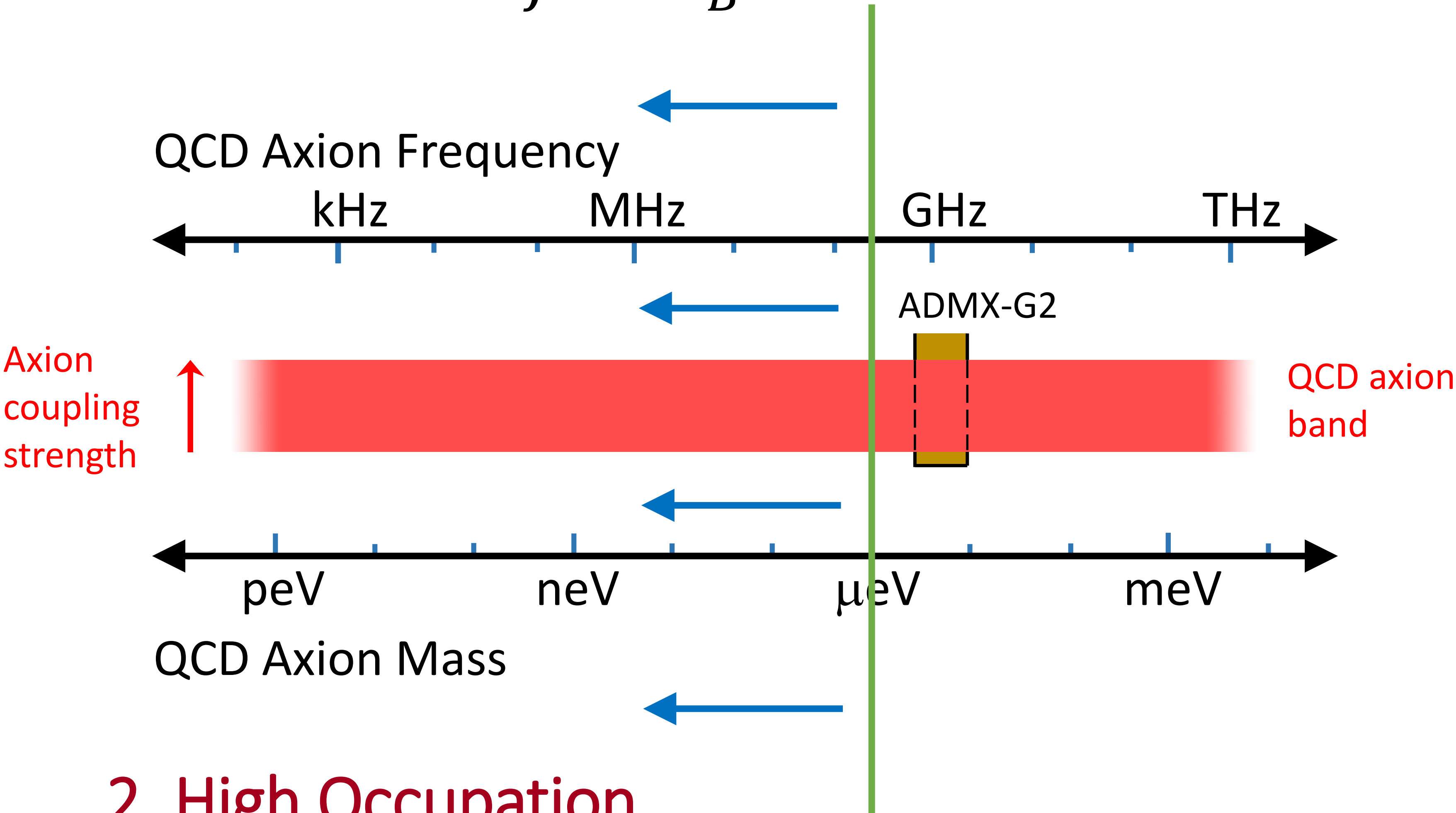
  100 Hz – 300 MHz: Backaction evasion in LC resonator

  100 Hz – 100 MHz: Quantum magnetometry of NMR spins

- Speculative future: quantum enhancement of classical multiplexing?

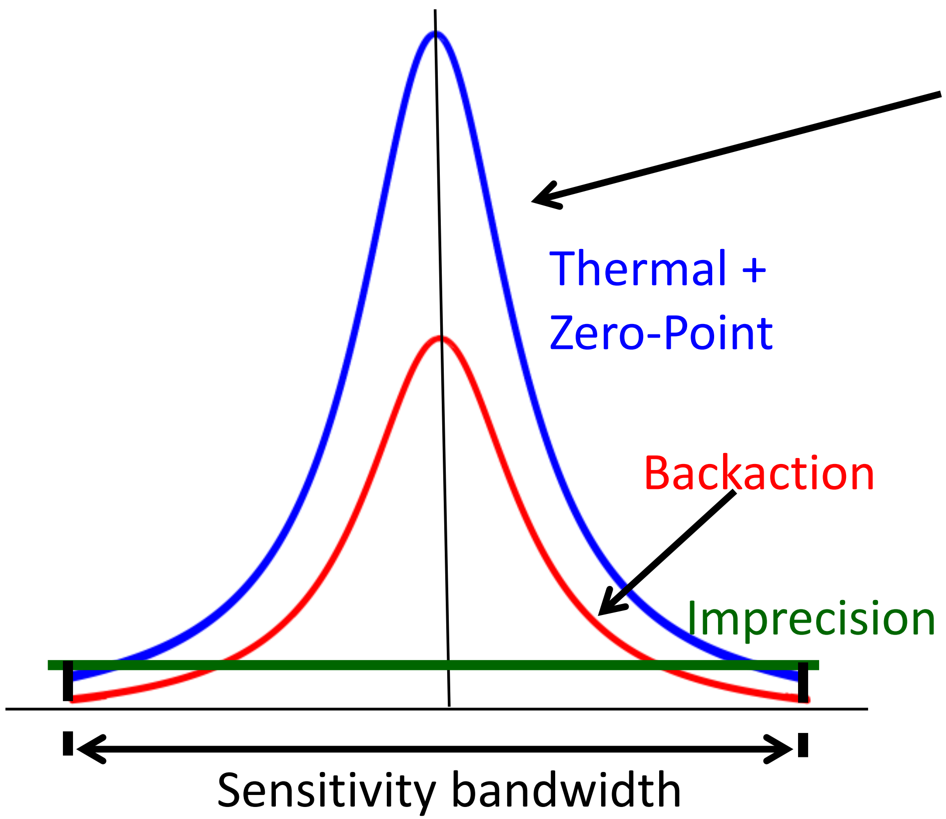
Two regimes: (2) High Occupation

$$hf \ll k_B T$$



2. High Occupation

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



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

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

$\rightarrow$ **Backaction evasion**

See Dale Li talk, 16:00, this session

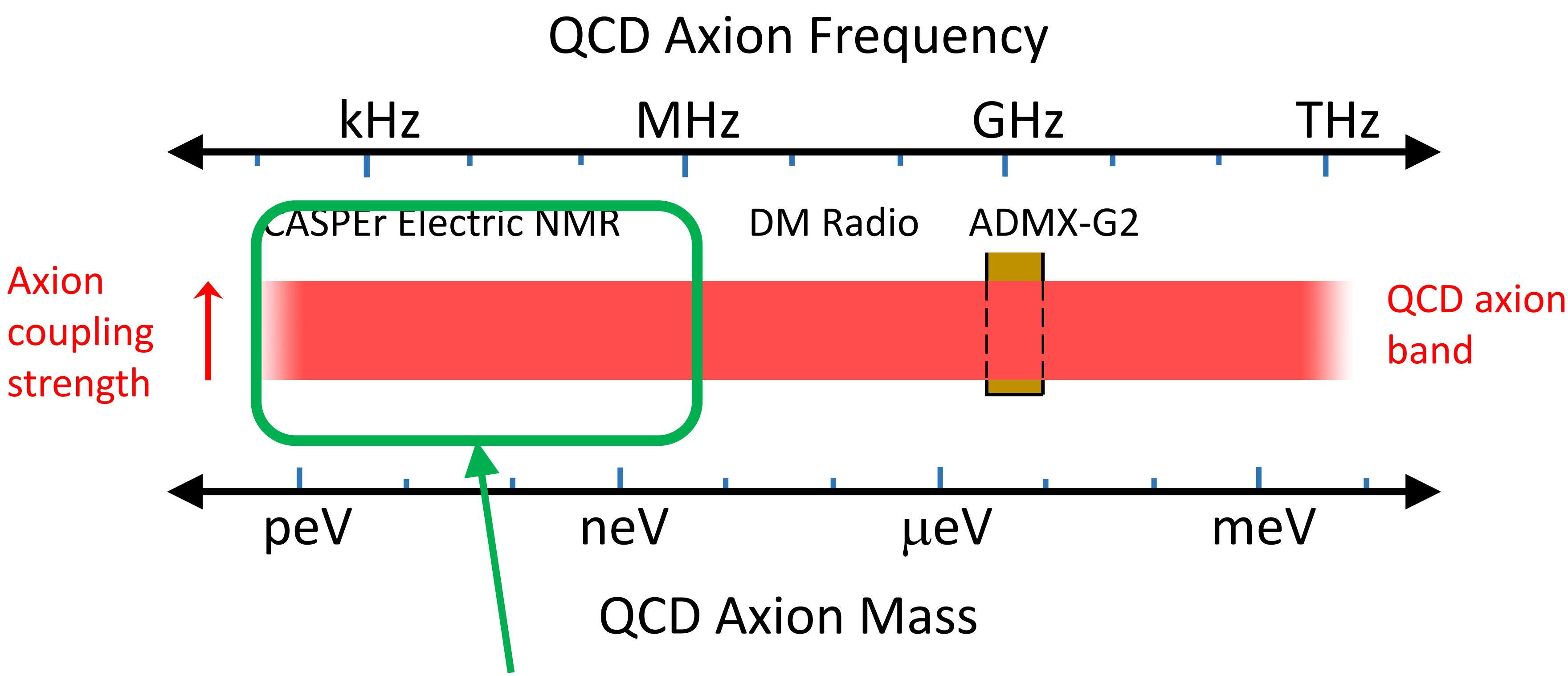
Poster 305. Quantum Sensors for Quantum Coherent Dark Matter Detectors
Stephen Kuenstner (Stanford University)
25/07/2019, 17:45

Outline

- Quantum 2.0 and low-temperature detectors

- QCD axions: a coherent quantum playground
  - **> 30 GHz:** Early stage R&D; more ideas needed!
  - **5-30 GHz:** Quantum non-demolition photon counting
  - **300 MHz - 10 GHz:** Quantum-limited amplifiers / squeezing
  - **100 Hz – 300 MHz:** Backaction evasion in LC resonator
  - **100 Hz – 100 MHz:** Quantum magnetometry of NMR spins
- Speculative future: quantum enhancement of classical multiplexing?

QCD axion: coupling to nuclear spins

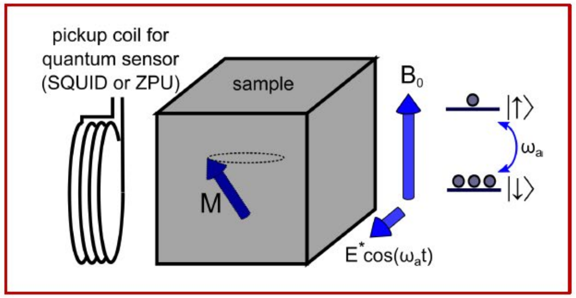


Mass range where search is best done through axion coupling to nuclear spins through strong force

CASPEr-electric: measuring QCD axions through spins

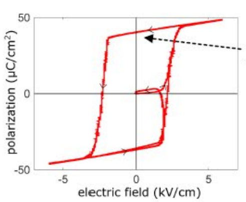
QCD axions → Nuclear spin precession → Electromagnetic signal

Status (PI: A. Sushkov, BU)

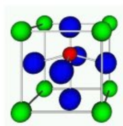


sample → ferroelectric PMN-PT: spin → ^{207}Pb

$(1-x)[Pb(Mg_{1/3}Nb_{2/3})O_3]/x[PbTiO_3]$



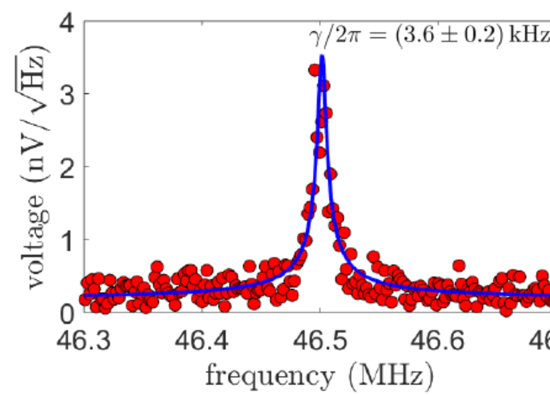
$E^* = 3 \times 10^8\ \mathrm{V/cm}$



CASPEr-electric-5mm at Boston University

Initial Results

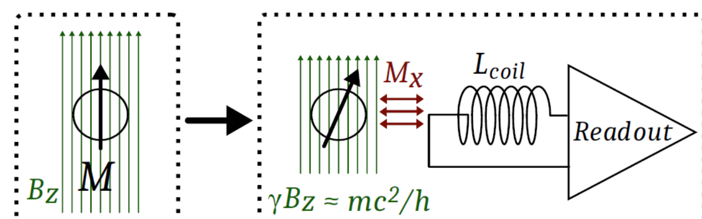
measurements of ^{207}Pb spin ensemble magnetic resonance in PMN-PT at 4.2 K:



Enhancement with low-temperature quantum sensors

- Implement quantum upconverters to improve sensitivity of spin measurement over dc SQUID

See Poster 303. Optimizing Readout for Nuclear Magnetic Resonance Axion Searches
Stephen Kuenstner (Stanford University)

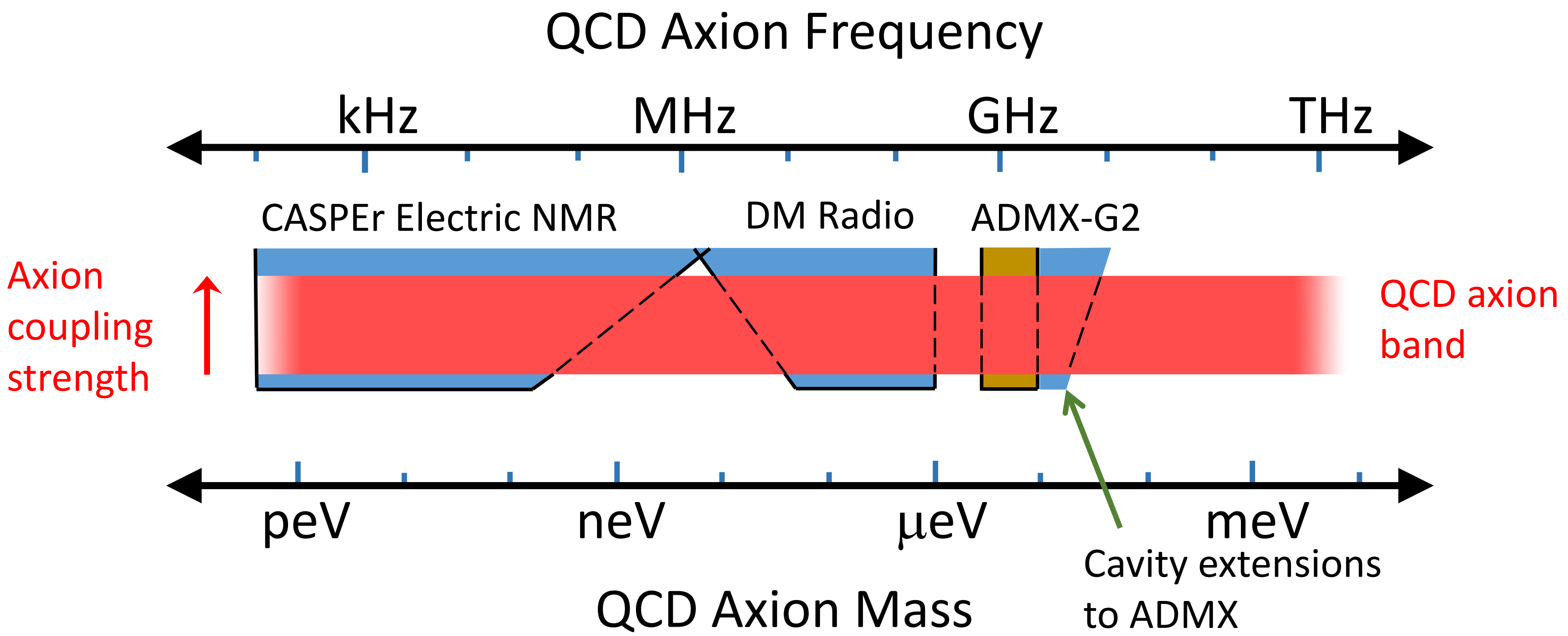


Polarize spins in a strong magnetic field

Detect axion-induced torques on spins by transverse magnetization

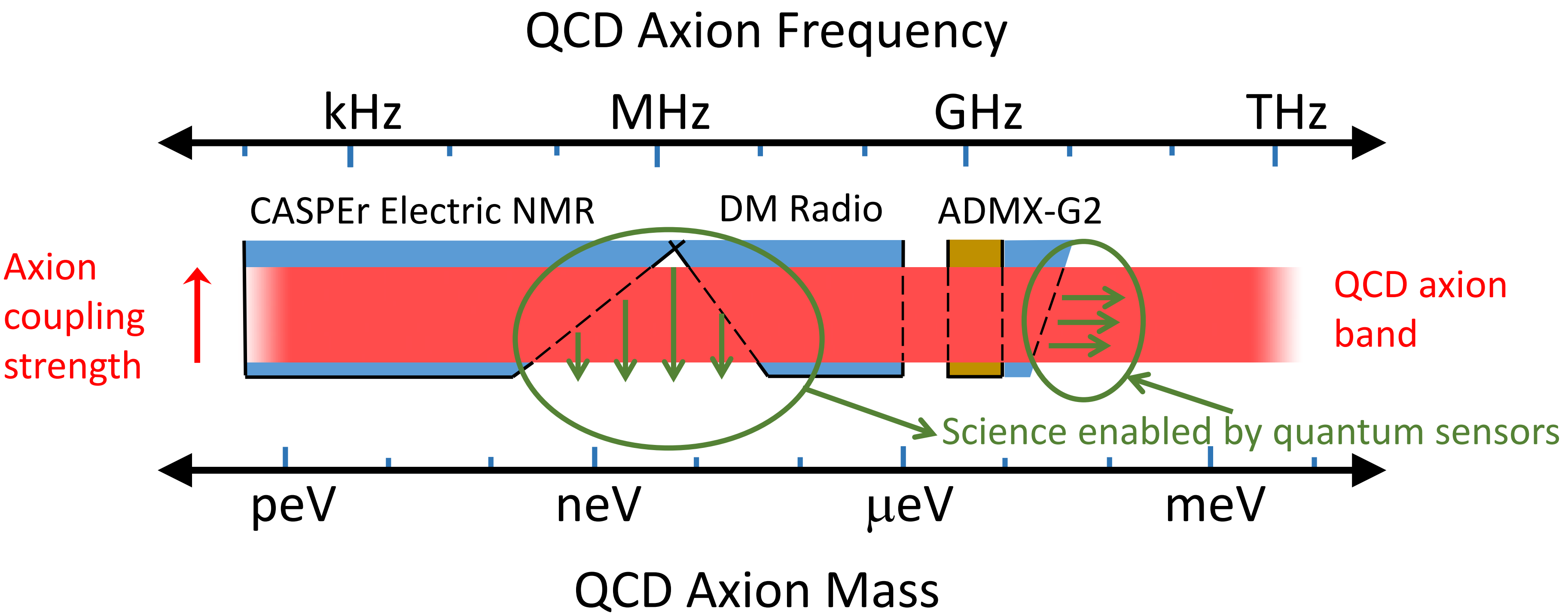
QCD axion: the need for quantum sensors

- 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

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



- Quantum acceleration required to cover full QCD band

Outline

- Quantum 2.0 and low-temperature detectors

- QCD axions: a coherent quantum playground

  > 30 GHz: Early stage R&D; more ideas needed!

  5-30 GHz: Quantum non-demolition photon counting

  300 MHz - 10 GHz: Quantum-limited amplifiers / squeezing

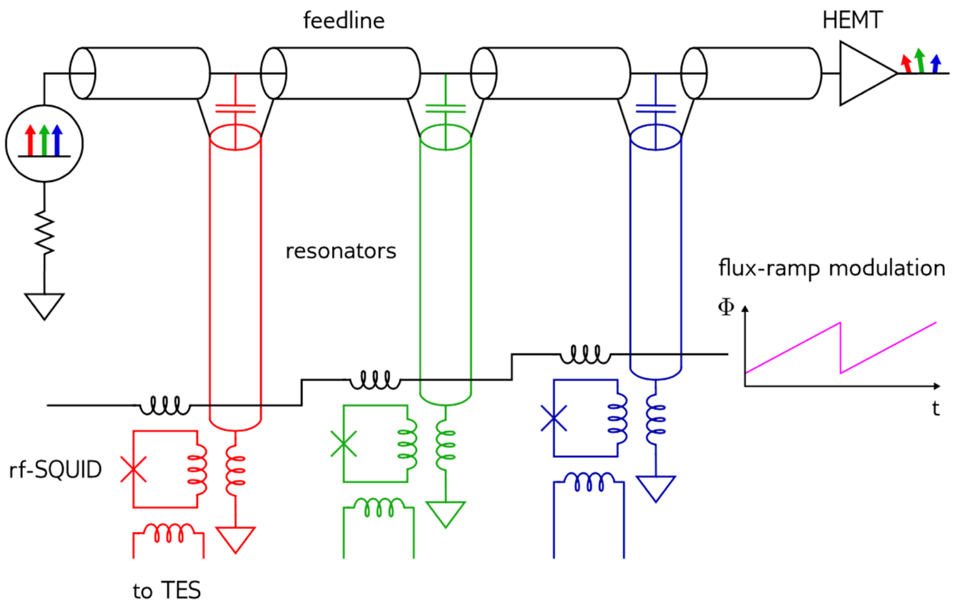
  100 Hz – 300 MHz: Backaction evasion in LC resonator

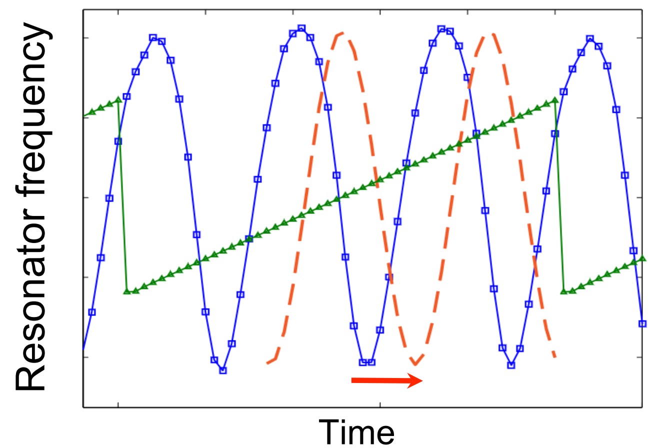
  100 Hz – 100 MHz: Quantum magnetometry of NMR spins

- Speculative future: quantum enhancement of classical multiplexing?

Speculative: quantum mux of classical signals

- The mux factor of some sensors (e.g. microwave SQUIDs with x-ray TESs) is limited by the dynamic range.
- It may eventually be possible to maximize the dynamic range by measuring the strength of the microwave resonator to the SQL.





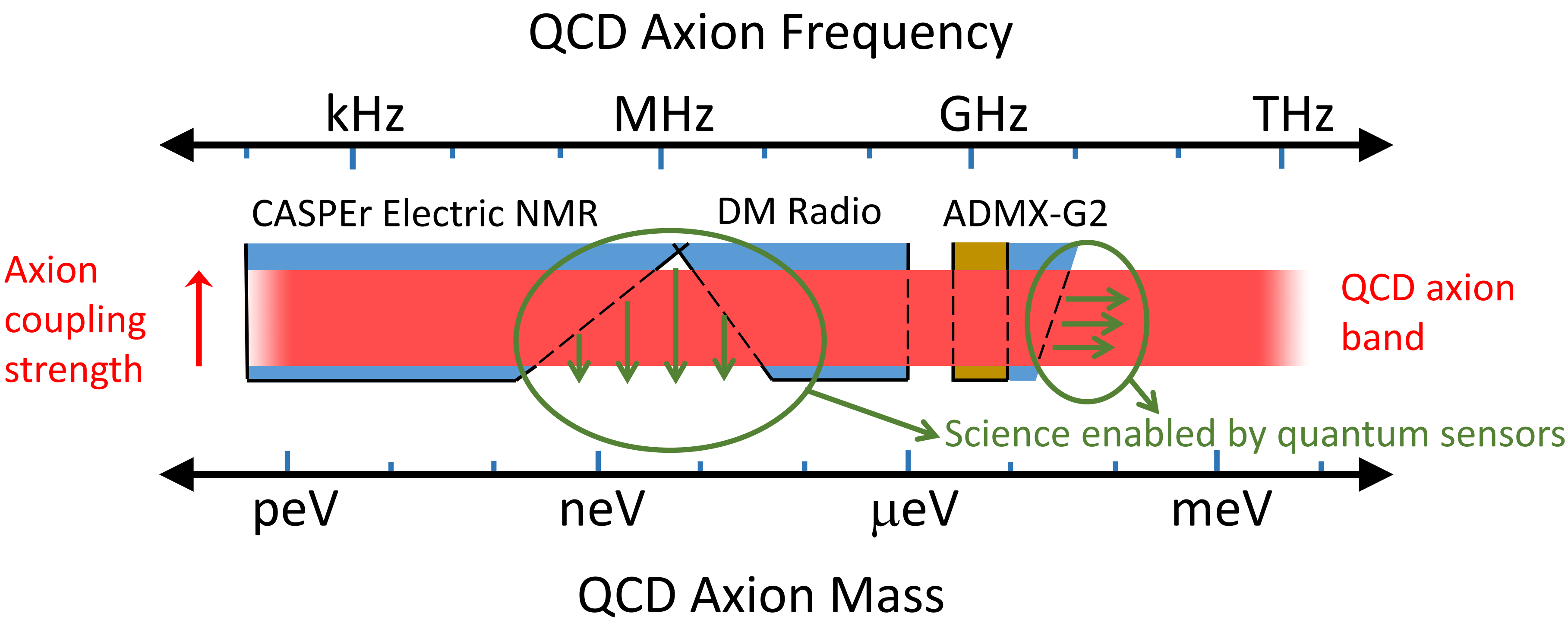
SQL

$$\Delta X \Delta Y \geq \frac{\hbar\omega}{2}$$

What if I don't care about amplitude??

- The TES signal is encoded in the resonator in its phase
- Squeezing noise into amplitude could enable greater dynamic range, and higher MUX factors.

Conclusions



- The QCD axion band is a playground for demonstrating emerging Quantum 2.0 sensors
- The full QCD axion band requires quantum acceleration to be covered
- We are only at the beginning of applying coherent quantum techniques to LTDs