Coherent quantum measurement for low-temperature detectors

Kent Irwin
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SLAC
• 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 2.0 and low-temperature detectors

QCD axions: a coherent quantum playground
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Speculative future: quantum enhancement of classical multiplexing?
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 (\( \phi \)) of an electromagnetic signal in an LC resonator perfectly at the same time.

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

- 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

What if I don’t care about phase???

See review: Clerk et al, RMP 82, 1155 (2010)
Quantum 2.0: Evade the SQL for better measurement

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


What if I don’t care about phase???
• 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.
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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.
It was previously believed that overproduction of dark matter and isocurvature constrains the preferred axion mass to be above a threshold of order $\mu$eV.

• “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)


There is no significant preference for axions to be above $\mu$eV. The full QCD axion band should be searched.
QCD Axions: strongly motivated over whole range

QCD Axions: strongly motivated over whole range

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

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.


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THE LANDSCAPE

Dark Sector Candidates, Anomalies, and Search Techniques

- QCD Axion
- Ultralight Dark Matter
  - Pre-Inflationary Axion
  - Post-Inflationary Axion
- Hidden Sector Dark Matter
  - Hidden Thermal Relics / WIMPless DM
  - Asymmetric DM
  - Freeze-In DM
- SIMPs / ELDERS
  - Beryllium-8
  - Muon g-2
- Small-Scale Structure

Status

Low temperature dark matter detectors

22 July 2019
THE LANDSCAPE

Goal

Dark Sector Candidates, Anomalies, and Search Techniques

- QCD Axion
- Ultra-light Dark Matter
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Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

- Microlensing

Low temperature dark matter detectors

22 July 2019
Among the most well motivated dark matter candidates are QCD axions in the $\text{peV} - \mu\text{eV}$ mass range (including PQ symmetry breaking at GUT and Planck scales).
Quest for the QCD axion: G2 science reach

QCD Axion Frequency

kHz MHz GHz THz

QCD Axion Mass

peV neV µeV meV

Axion coupling strength

ADMX-G2

QCD axion band
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 \(S(\nu)\)).
- \(n(\nu)\): signal source thermal occupation number.
- “+1” is standard quantum limit.

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

Resonator measurement at Standard Quantum Limit

- **Noise-matched on resonance**
- **Noise-mismatched on resonance**

- Increased coupling: reduced imprecision, increased backaction
- 50% on-resonance noise penalty. Much larger sensitivity bandwidth
Two regimes: (1) Ground State

\[ hf \gg k_B T \]

- **QCD Axion Frequency**
  - kHz
  - MHz
  - GHz
  - THz

- **QCD Axion Mass**
  - peV
  - neV
  - µeV
  - meV

Axion coupling strength

- **CASPER Electric NMR**
- **DM Radio**
- **ADMX-G2**

QCD axion band
Two regimes: (2) High Occupation

\[ hf \ll k_B T \]

QCD Axion Frequency

- kHz
- MHz
- GHz
- THz

QCD Axion Mass

- peV
- neV
- µeV
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Axion coupling strength

CASPER Electric NMR, DM Radio, ADMX-G2

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\( hf \ll k_B T \)
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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 without absorbing it.

Inject 1 photon

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

Figure Credit: Aaron Chou, FNAL
Ground state measurement: QND photon counting

DFSZ, 0.45 GeV/cc, B=14T, C=1/2, Q=5x10^4@1GHz, V=13\lambda^3, crit.coup

Sensitivity limited only by signal photon shot noise.

Figure Credit: Aaron Chou, FNAL
See Aaron Chou’s talk, this session: 15:45
• Quantum 2.0 and low-temperature detectors

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HAYSTAC: Acceleration through squeezing

HAYSTAC run 1 & 2 combined exclusion plot


HAYSTAC Phase II squeezed state receiver projected acceleration
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Two regimes: (2) High Occupation

\[ hf \ll k_B T \]

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Axion coupling strength

2. High Occupation
 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

See Dale Li talk, 16:00, this session

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

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

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

- CASPEr Electric NMR
- DM Radio
- ADMX-G2

Axion coupling strength

QCD axion band

Cavity extensions to ADMX
QCD axion: the need for quantum sensors

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- Quantum acceleration required to cover full QCD band
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• 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.

\[ \Delta X \Delta Y \geq \frac{h \omega}{2} \]

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