Quantum-Limited Scan Strategies: Fundamental Limits on Axion and Hidden Photon Detection


PREPRINT IN PREPARATION! Email scaudh2@stanford.edu for details and requests.

INTRODUCTION

• Axion and hidden photon: two promising candidates for cold dark matter
• Axion and hidden photon manifest as effective current density, produce detectable AC electromagnetic fields
• Frequency: \( v_{ax} = \frac{mc^2}{\hbar} \), Bandwidth: \( \Delta v_{ax} \sim 10^{-6}v_{ax} \)
• Three parts to dark matter detector (Fig. 1), e.g. scanning resonator (Fig. 2, 4a)
• If thermal noise dominates readout noise (Fig. 3), SNR independent of matching network - not considered previously

What is optimal resonator? What is optimal scan strategy?

Fig. 1. Schematic of a light-field dark matter detector.

Fig. 2. Equivalent circuit model for resonant detector in scattering mode. Resonator tuned by changing capacitance. Used in ADMX/HAYSTAC.

EXAMPLE: RESONANT BETTER THAN BROADBAND LR

(a) Resonant RLC input circuit read out by SQUID. (b) Broadband LR circuit.

• Kahn et al, PRL 117, 141801 (2016) claim broadband better than \( Q \approx 10^6 \) for frequencies below \( \sim 100 \) kHz in presence of only imprecision noise
• Considered only info within resonator bandwidth
• Considering sensitivity bandwidth, resonant is much better than broadband at all frequencies at which a resonator can practically be made

Fig. 4. (a) Resonant RLC input circuit read out by SQUID. (b) Broadband LR circuit.

Fig. 5. Ratio of minimum detectable coupling for resonant (R) and broadband (B) plotted vs rest mass frequency.

WHY A RESONATOR? CLOSE TO BODE-FANO LIMIT

• Maximize integrated sensitivity across search band, between \( \nu_s \) and \( \nu_b \)
• Figure of merit for scattering system with quantum-limited amplifier:
  \[ U = \int_0^{\nu_b} dv \left[ \frac{1}{R_{SNR}(v)} \right] \]
  \[ n(\nu) = \text{cavity thermal occupation number, } "1" \text{ is standard quantum limit} \]
• Constraint provided by Bode-Fano criterion for matching LR to real impedance:
  \[ \int_0^{\nu_b} dv \ln \left[ \frac{1}{R_{SNR}(v)} \right] \leq \frac{R}{2} \]
  \[ n(\nu) \gg 1 \]

• Optimal resonator is within ~75% of fundamental limit!

Fig. 6. Integrands of \( U \) plotted for noise matching and optimal mismatching for \( n(\nu) = 50 \).

Fig. 7. Current noise normalized to \( h/\nu \) vs resonator detuning normalized to resonator half width. Thermal occupation \( n(\nu) = 50 \).

OPTIMIZING RESONATOR SENSITIVITY: QUANTUM-LIMITED AND BACKACTION-DOMINATED

• Optimize resonator at frequency \( \nu_b \) with respect to coupling factor
  \[ G_{ax} = \frac{\text{Amplifier Noise Impedance}}{\text{Resonator Impedance}} \]
• Optimal ratio for maximizing \( U \)
  \[ y = \frac{G_{ax}}{\frac{1}{\nu_b} - R} \]

• Same optimization result for quantum-limited SQUID amplifier
• Imprecision and backaction noise inversely proportional on-resonance
  \[ S_{TH} = \frac{\nu_b}{\nu} \]
• Gives tradeoff between on-resonance SNR and sensitivity bandwidth
• In optimal resonator readout, amplifier noise is dominated by backaction.

Fig. 8. Top: Axion exclusion plot. Bottom: Hidden photon exclusion plot.

DM Radio Quantum-Limited Scan: Four order of magnitude improvement in scan speed at 100 kHz!

• COMING SOON: Extension to nonclassical methods: squeezing/photon counting
• Implementation in DM Radio experiment
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IMPROVED SCIENCE REACH WITH OPTIMAL SCAN

• Optimal time distribution is equal time per decade, maximizes exclusion area
• Should aim for as high Q as possible, even above "dark matter \( Q = 10^6 \)"

FREQUENCY kHz MHz GHz THz

AXION PHOTON COUPLING

MID-PLANE PHOTON-MIXING ANGLE

HIDDEN PHOTON-MIXING

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