Quantum computing technology for particle detection

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Detectors for Science Working Group Pre-Meeting 2

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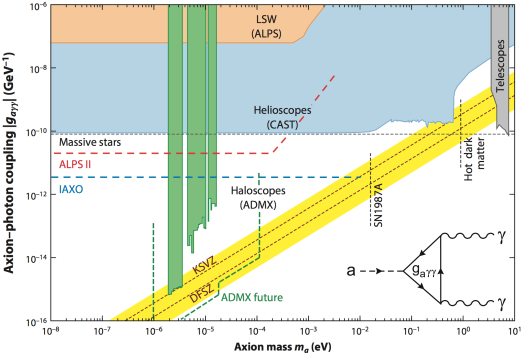
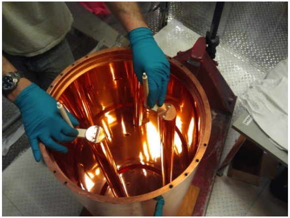
A brief introduction to QCD axions

- Locally coherent oscillation of QCD vacuum angle θ about the CP-conserving minimum.
- $\theta(x, t) = \theta_{\max} e^{i(kx - m_a t)}$, with $\theta_{\max} \sim 10^{-19}$
- While WIMPs are point-like and suited to bolometry, sub-eV axions are field-like and require unique detector strategies.

QCD axions: well-motivated, but the mass is not well-constrained





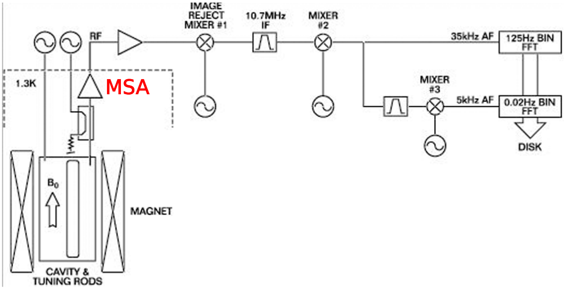
ADMX 500 MHz - 1 GHz "haloscope"

- $\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}$
- $P_{a\gamma\gamma} = g^2_{a\gamma\gamma}\frac{\rho_0}{m_a}B_0^2 V C_{nm\ell} Q_L \sim 10^{-23}$ W
- Current haloscope experiments looking at ≤ 2 GHz and ~ 6 GHz.
- SN1987A give us an upper limit $m_a \sim 250$ GHz...

Signal integration is nontrivial.

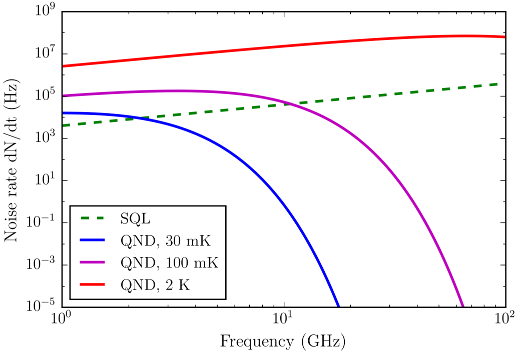
- $P_{a\gamma\gamma} = g^2_{a\gamma\gamma} \frac{\rho_0}{m_a} B_0^2 V C_{nm\ell} Q_L$
- To boost signal power, you can:
  - increase Q_L (but $Q_0 = 10^6$ $\sim$axion linewidth, and superconductors are not easy to use in $B_0 \sim 10$ T)
  - increase $B_0^2 V$
  - increase form factor $C_{nm\ell}$ via clever cavity design
- Alternative approach: lower noise rates!

Axion Dark Matter eXperiment layout



- Cavity operates at O(100) K
- Superconducting electronics package (microstrip squid amplifier) in a field-compensated region
- Warm electronics: heterodyning, etc.
- This approach is ok up to O(10) GHz, beyond which we run into the **single quantum limit**.

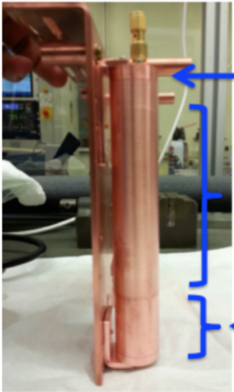
We need qubits to beat noise-limited linear amplifiers.

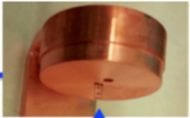


- Linear amplifiers suffer from irreducible zero-point noise (Caves, Phys. Rev. D, 1982).
- Quantum nondemolition measurements possible w/ qubits (Schuster *et al.*, Nature, 2007)

10 GHz band: QND detector with artificial atom based on 3D superconducting qubit

AC, Akash Dixit, D.Schuster (U.Chicago)



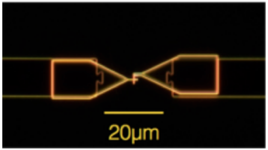


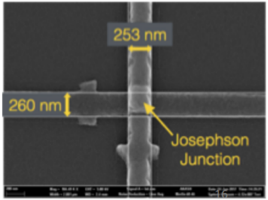
Waveguide coupler

Qubit sensor

Axion cavity
in high B-field

25 mm





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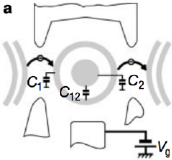
Possible single photon detectors in the 100 GHz band

- **Tiny low heat capacitance TES bolometers** placed inside cavities, reducing threshold from 1 eV down to 10^{-3} eV
  - Unlike WIMP detectors, we do not need large volume since we want quantum efficiency to be tiny to maintain high cavity quality factor.
  - Unlike CMB detectors we do not need to sink 10 pW DC power
  - Possible collaboration with Flavio Gatti (Genova) funded by Marie Curie staff exchange grant
- QND or direct photon absorption using artificial atoms implemented using **quantum dots**
  - Single photon absorption induces transition between Landau levels
  - Transition frequencies are continuously tunable via external magnetic field
  - Single electron transistors become single photon detectors



Komiyama, et.al, Nature (2000)

200 MHz $\lesssim m_a \lesssim$ 200 GHz

Our LDRD supports a mK-class test stand.

- He^3-He^4 dilution refrigerator
- Integrated $\mathcal{O}(10)$ T solenoid
- Siting is in progress.

- We are currently searching at $\mathcal{O}(1)$ GHz.
- Our QC LDRD effort gives us access to $\mathcal{O}(10)$ GHz band.
- We have the beginnings of a plan to reach 100 GHz.
- All this work can be accommodated by our test stand.