Quantum enhanced methods for ultralight dark matter searches

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Haystac

U.S. DEPARTMENT OF
ENERGY
Office of Science

DOE-HEP QuantISED program
search for ultralight dark matter: a quantum metrology problem

quantum squeezing is already speeding up the search for axionic dark matter

quantum technology development may dramatically accelerate an axion search
Particle nature of dark matter remains unknown

ordinary matter 15%

dark matter 85%

dark matter:

- 85% of the matter in the universe
- detected only gravitationally
- cold (gravitationally bound)
- mean density: $\sim 0.4 \text{ GeV/cm}^3$
Ultralight dark matter must be bosonic

ultralight dark matter (e.g. axions):

quantum degenerate Bose gas

more wave-like than particle-like

tone: feeble, persistent, unknown frequency
Laboratory based searches for ultralight dark matter

classical signal acting on a quantum harmonic oscillator

microwave cavities

spin ensembles

ADMX, HAYSTAC, CASPEr, DMradio

dark matter

high-Q tunable oscillator

decoherence

evolution in rotating frame

null hypothesis

dark matter hypothesis

\[ \hat{H}_r = 0 \]
\[ \hat{H}_r = F_y(t) \hat{X} + F_x(t) \hat{Y} \]
Quantum noise pollutes inference of classical force

null hypothesis

\[
\begin{bmatrix}
\hat{X}, \hat{Y}
\end{bmatrix} = i
\]

\[
\delta \hat{X} \delta \hat{Y} \geq \frac{1}{2}
\]

ground state

dark matter hypothesis

\[
\hat{Y}
\]

\[
\hat{X}
\]

displaced ground state

“quantum limit”--- coherent state limit (CSL)

prepare in ground state, evolve, measure $X$ noiselessly
null hypothesis

\[ [\hat{X}, \hat{Y}] = i \]

\[ \delta \hat{X} \delta \hat{Y} \geq \frac{1}{2} \]

squeezed state

null hypothesis dark matter hypothesis

\[ [\hat{X}, \hat{Y}] = i \]

\[ \delta \hat{X} \delta \hat{Y} \geq \frac{1}{2} \]

displaced squeezed state

beat the quantum limit

prepare in squeezed state, evolve, measure \( X \) noiselessly
quantum enhanced axion search
Hypothetical QCD axion: a light particle that is cold and dense enough to contribute to dark matter

mechanism to resolve strong-CP problem (Peccei and Quinn)
Why is CP symmetry well-preserved in QCD?
Why is the neutron so round?

axion mass range
2 \, \mu \text{eV} < m_a c^2 < 2000 \, \mu \text{eV}

as a frequency
500 \, \text{MHz}^* < m_a c^2 / h < 500 \, \text{GHz}

*post-inflation scenario
Axion field couples to electromagnetism

modified QCD Lagrangian \[ \Rightarrow g_{A\gamma\gamma} A \left( \vec{E} \cdot \vec{B} \right) \]

linearize coupling around static \( \vec{B} \)-field

\[ A \xrightarrow{\gamma} E_A = E_{\gamma} \]

dark matter axions create microwave photons
Scan cavity to search for resonant axion to photon conversion

1 L volume
$Q = 10^4$
$\omega_{cav} \sim 2\pi \times 5 \text{ GHz}$

Josephson parametric amplifier (JPA) measure $\hat{X}$ noiselessly

haloscope (Sikivie 1983) at the quantum limit (HAYSTAC 2017)
Average noise to resolve tiny excess axion power

\[ \hat{X}(t) \]

spectrum analyzer

\[ S_{XX}(\omega) \]

\[ \Delta \omega_a \approx \Delta \omega_{cav} \approx 100 \]

10^{-3} noise precision \( \Rightarrow \) 10^6 measurements

tune \( \rightarrow \) wait and average \( \rightarrow \) tune

100 axion bands per cavity tuning

scan rate proportional to bandwidth

\[ \omega_a = m_a c^2 / \hbar \]

quantum noise

\[ 1 + 10^{-3} \]
Measurement backaction limits haloscope bandwidth

- Optimum on-resonance axion sensitivity
-背action
- Decoherence
- Axion signal

- \( \kappa_{\text{meas}} \) measurement rate
- \( \kappa_{\text{loss}} \) decoherence rate

- Optimum on-resonance axion sensitivity

- \( \kappa_{\text{meas}} = \kappa_{\text{loss}} \)

- Bandwidth

\( 2\kappa_{\text{loss}} \)
Squeezing yields larger bandwidth through backaction evasion

\[ \kappa_{\text{meas}} \] measurement rate
\[ \kappa_{\text{loss}} \] decoherence rate
squeezing preserves sensitivity with
\[ \kappa_{\text{meas}} > \kappa_{\text{loss}} \]
bandwidth \( > 2\kappa_{\text{loss}} \)
JPAs measure one quadrature noiselessly

\[
\hat{Y} \rightarrow \hat{X}
\]

\[
\text{pump} \quad \rightarrow \quad \hat{Y} / \sqrt{G} \rightarrow \sqrt{G} \hat{X}
\]

100 µm

capacitor

signal

in

out

flux tunable inductor

pump

flux line
JPAs prepare microwave squeezed states

\[ \delta^2 \hat{Y} = \frac{G}{2} \]
\[ \delta^2 \hat{X} = \frac{1}{2G} \]

squeezed quadrature: quantum noise suppressed
Demonstration of squeezing and determination of loss: second JPA analyzes squeezed state created by first

Phase $\theta$ chooses measured quadrature relative to squeezed quadrature.


Loss $\eta$: 1.63 dB
First quantum enhanced dark matter search

double the CSL scan rate

A quantum enhanced search for dark matter axions
Prohibitive resources required to scan one decade at CSL

1 – 10 GHz at CSL for DFSZ

1 x 9T magnet \quad \text{or} \quad 16 \times 30T \text{ magnets}

\sim 20,000 \text{ yrs} \quad \text{or} \quad \sim 10 \text{ yrs} + 1.2 \text{ B}$
engineering more quantum enhancement
Squeezing diminished by circulator and cascaded signal path

\[ \hat{X} \text{ information} \]

ferrite circulator loss
absorption
reflection

1 cm
A better approach to backaction evading measurements

<table>
<thead>
<tr>
<th>axion cavity</th>
<th>readout cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_A$</td>
<td>$\omega_R$</td>
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</tbody>
</table>

engineering QND interaction between two cavities

$\hat{H}_I = \hbar G \hat{X}_R \hat{X}_A$

\[
\frac{d}{dt} \hat{Y}_R = -G \hat{X}_A
\]

monitor $\hat{Y}_R$ infer $\hat{X}_A$

backaction deposited in unmonitored quadrature

no ferrite circulators
no loss from reflection
Two mode squeezing, state swapping yield QND Hamiltonian

\[ g = G \left[ \cos(\omega_\Delta t) + \cos(\omega_\Sigma t + \phi) \right] \]

\[ \omega_\Delta = \omega_A - \omega_R \]

\[ \omega_\Sigma = \omega_A + \omega_R \]

15 times speedup over CSL

CEASEFIRE: Cavity Entanglement And Swapping Experiment For Improving Readout Efficiency
Tunable coupler from an inductor bridge

Conclusions

superconducting quantum technology accelerates the search for dark matter

quantum squeezing doubles search rate in HAYSTAC apparatus

greater speedup possible with circulator-less concepts

Yale, August 2018, SSR commissioning