Quantum Sensors for New Physics

Asher Berlin - Fermilab

Seattle Snowmass Summer Meeting
July 23, 2022

See also:
arXiv:2203.12714, ...
New technology opens windows into new physics.
There is an opportunity to explore new physics at previously inaccessible scales with developing technology.

How can developments in quantum sensing be steered to make the biggest impact on fundamental physics?

What is the nature of dark matter?
What Have We Learned?

*dark matter resides in galaxies (including our own)*

![Galaxy Image]

**velocity:** $v_{\text{DM}} \sim 100 \text{ km/s} \sim 10^{-3} \text{ c}$

**mass density:** $m_{\text{DM}} n_{\text{DM}} \sim \text{GeV/cm}^3$

Few heavy particles or many light particles?
What is the dark matter mass?
What Have We Learned?

\begin{center}
\begin{tabular}{cccccc}
10^{-22} \text{ eV} & eV & GeV & \(M_{\text{pl}}\) & 10^{-10} \(M_{\odot}\) & DM mass \\
\hline
\end{tabular}
\end{center}
What Have We Learned?

The search for WIMPs has been an incredible success.

What now?
What Have We Learned?

<table>
<thead>
<tr>
<th>10^{-22} \text{eV}</th>
<th>\text{eV}</th>
<th>\text{GeV}</th>
<th>M_{pl}</th>
<th>10^{-10} \text{M}_\odot</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{feeble-coupled}</td>
<td>\text{WIMP}</td>
<td></td>
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</table>

Quantum/precision detectors

Quiet and coherent enough to build up a detectable signal.

*We can now explore a wide range of previously inaccessible scales.*

Maybe the dark matter and hierarchy problem are not solved together.

\[
\downarrow
\]

If so, the space of motivated signals is dramatically enlarged.

\[
\downarrow
\]

This motivates a strong diversification of the experimental program.
Going Further

QIS for BSM physics

a single catch-all experiment $\rightarrow$ multitude of bang-for-buck experiments

NMR

KIDs

SRF cavities

atomic clocks/interferometers

$< $ SQL

SC qubit

SNSPDs

nonlinear optics

optically levitated dielectrics

skipper CCDs

LC circuits

ion traps

See also:


arXiv:2203.12714, ...
Going Further

**QIS for BSM physics**

a single catch-all experiment $\rightarrow$ multitude of bang-for-buck experiments

**What is the role of a theorist?**

Creative repurposing of existing detectors.

Motivating/conceiving/designing new small-scale experiments.

This is especially crucial in emerging fields.

see arXiv:2203.10089
Quantum Manipulation

I.

- atomic clocks
- atomic interferometers
- < SQL for axions
- ion traps, ...

Detecting Individual Quanta

II.

- skipper CCDs
- supercond. nanowires
- supercond. qubits, ...

Supercond. RF cavities

III.

- axions
- dark photons
- photon mass
- millicharged particles
- gravitational waves, ...

*some of these boundaries are blurry*
I. Quantum Manipulation

atomic clocks
atomic interferometers
< SQL for axions
ion traps, ...

II. Detecting Individual Quanta

skipper CCDs
supercond. nanowires
supercond. qubits, ...

III. Supercond. RF cavities

axions
dark photons
photon mass
millicharged particles
gravitational waves, ...

I. Quantum Manipulation
Atomic Clocks

oscillation of fundamental constants

\[ \mathcal{L} \sim \frac{\phi}{M_{\text{pl}}} \left( d_c F_{\mu \nu} F^{\mu \nu} + d_m m_e \bar{e}e \right) \]

- improvement of existing clocks
- nuclear clocks, molecular clocks
- quantum-entangled clocks, < SQL

future

Oscillation of fundamental constants in the Standard Model, as shown by the graph, has potential implications for the future of atomic clocks. The graph illustrates the oscillation in frequency uncertainty over the years, highlighting advancements in atomic clock technology.

The future of atomic clocks promises significant improvements in precision, with applications in areas such as nuclear clocks, molecular clocks, and quantum-entangled clocks. These advancements are expected to push the limits of precision and accuracy even further, with implications for fundamental physics and cosmology.
Atomic Interferometers

+ gravitational waves

future

- MAGIS-100 at Fermilab
- MAGIS-km, space-based, ...
Role of Theorists

Hunting for topological dark matter with atomic clocks

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Searching for dilaton dark matter with atomic clocks

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Junwu Huang† and Ken Van Tilburg‡
Stanford Institute for Theoretical Physics, Department of Physics,
Stanford University, Stanford, CA 94305, USA
(Dated: February 3, 2015)

Searching for dark matter and variation of fundamental constants with laser and maser interferometry

Y. V. Stadnik* and V. V. Flambaum†

School of Physics, University of New South Wales, Sydney 2052, Australia
(Dated: March 24, 2015)

Testing General Relativity with Atom Interferometry

Savas Dimopoulos, Peter W. Graham, Jason M. Hogan, and Mark A. Kasevich

Department of Physics, Stanford University, Stanford, California 94305
(Dated: February 6, 2008)

Gravitational Wave Detection with Atom Interferometry

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(Dated: October 22, 2018)
Beyond the Standard Quantum Limit

< SQL

measure $x$ not $y$

measure amplitude not phase
Beyond the Standard Quantum Limit

**Axion Dark Matter Detection**

**superconducting qubits**


non-destructive photon counting

(search rate $\times 10^3$)

**HAYSTAC**


vacuum squeezing

(search rate $\times 2$)
II. Detecting Individual Quanta

skipper CCDs
supercond. nanowires
supercond. qubits, ...

I. Atomic clocks
atomic interferometers
< SQL for axions
ion traps, ...

III. Axions
dark photons
photon mass
millicharged particles
gravitational waves, ...

Outline

Quantum Manipulation

Detecting Individual Quanta

Supercond. RF cavities
Detecting Individual Quanta

**low-energy quanta, low dark counts**

skipper CCDs, SENSEI

arXiv:1706.00028

\[ E_{th} \sim 1 \text{ eV} \]

non-destructive repeated charge counting, dark count \(< 10^{-3} \text{ e/pix/day} \)

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**Single-electron and single-photon sensitivity with a silicon Skipper CCD**

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(Dated: June 2, 2017)
Detecting Individual Quanta

*low-energy quanta, low dark counts*

superconducting nanowires

MeV-scale dark matter scattering
arXiv:1903.05101

Detecting Dark Matter with Superconducting Nanowires
Yoav Hochberg,† Ilya Charaev,‡ Sae-Woo Nam,§ Varun Verma,∥ Marco Colangelo,¶ and Karl K. Berggren

LAMPOST (axions)
arXiv:2110.01582

New Constraints on Dark Photon Dark Matter with Superconducting Nanowire Detectors in an Optical Haloscope
Jeff Chiles,† Ilya Charaev,‡-§ Robert Lasenby,∥ Masha Baryakhtar,∥ Junwu Huang,∥ Alexna Roshko,† George Burton,∥ Marco Colangelo,¶ Ken Van Tilburg,‡-§ Asimina Arvanitaki,∥ Sae Woo Nam,† and Karl K. Berggren

(E_{th} \sim 1\ eV)

infrared/optical photon counting, dark count \sim 1\ per\ day
Detecting Individual Quanta

Future Developments

Single-Phonon Detectors
arXiv:1512.04533

Exotic Narrow-Gap Semiconductors
SPLENDOR collaboration

Transition-edge sensor:
(single optical phonons, $E_{th} \sim 50$ meV)
III. SRF Cavities

Developing even a single technology opens up a versatile array of new physics opportunities.

Outline

I. Quantum Manipulation
   - atomic clocks
   - atomic interferometers
   - ion traps, ...

II. Detecting Individual Quanta
    - skipper CCDs
    - supercond. nanowires
    - supercond. qubits, ...

III. Supercond. RF cavities
    - axions
    - dark photons
    - photon mass
    - millicharged particles
    - gravitational waves, ...

III. SRF Cavities
SRF Cavities

Why superconducting RF cavities?

1. most efficient engineered oscillators
   \[ Q \sim 10^{12} \]
   long coherence for quantum computation

2. large oscillating fields
   \((0.2 \, \text{T}, \sim \text{GHz})\)

3. precisely manufactured and operated
   \((\text{nm-precision})\)

4. already used for new physics searches
   \((\text{experimentalists})\)
SRF Cavities

- sub-Hz frequency wobble
- resolved thermal noise
- plan for a week run

A Parametrically Enhanced Hidden Photon Search

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DarkSRF (Fermilab)
Debye' (eq) can be used to estimate the experimental sensitivity to decays of long-lived particles, such as dark photons.

Table 1: A summary of relevant features of upcoming high-intensity proton fixed-target experiments. Using Eqs. (222) and (223), meter keV

\[ m q v \gg \text{Debye} \]

\[ \text{SRF cavity} A \]

\[ \text{shield} \]

\[ \text{emitter} \]

\[ \text{receiver} \]

\[ \gamma \epsilon A' \]
New Physics for Free at DarkSRF

\[ E_{em} e^{i\omega t} \quad \text{emitter} \]

\[ E_{rec} e^{i\omega t} \quad \text{receiver} \]

shield

\[ A'_L \]

longitudinal dark photon

\[ \gamma \quad \epsilon \quad A' \]

\[ \epsilon m_{A'} \lesssim 6 \times 10^{-16} \text{ eV} \approx 10^{-48} \text{ g} \]
New Physics for Free at DarkSRF: SM Photon Mass

A longitudinal mode is a longitudinal mode

\[ m_\gamma \lesssim 6 \times 10^{-16} \text{ eV} \approx 10^{-48} \text{ g} \]

(best direct laboratory bound on the SM photon mass in 50 years)

A. Berlin, A. Hook
Schwinger pair-production of millicharged particles

\[ E_{cr} \sim 50 \text{ MV m}^{-1} \times \left( \frac{m_\chi}{\text{meV}} \right)^2 \left( \frac{q_\chi}{10^{-7}} \right)^{-1} \]

(best laboratory sensitivity to light millicharges by > five orders of magnitude)

**Heterodyne Frequency Conversion**

**Axion Dark Matter**


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Axion transfers power from driven mode to quiet mode.

Enhanced signal for light axions: \( \text{GHz} / m_a \gg 1 \) and \( Q \sim 10^{12} \)
**Heterodyne Frequency Conversion**

**High-Frequency Gravitational Waves (MAGO)**

Gravitational wave transfers power from driven mode to quiet mode.

strain sensitivity $\sim 10^{-20}$ for kHz - MHz frequencies
Many Other Applications

Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities

arXiv:2203.12714
Role of Theorists

Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion
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Institut de Physique Théorique, Université Paris Saclay, CEA, F-91191 Gif-sur-Yvette, France

Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson,
Philip Schuster, Sami Tantawi, Natalia Toro, and Kevin Zhou

Microwave cavity searches for low-frequency axion dark matter
Robert Lasenby

Heterodyne Broadband Detection of Axion Dark Matter
Asher Berlin, Raffaele Tito D’Agnolo, Sebastian A. R. Ellis, and Kevin Zhou

On the operation of a tunable electromagnetic detector for gravitational waves
F Pegoraro†, E Picasso‡ and L A Radicati‡‡
†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Microwave Apparatus for Gravitational Waves Observation
R. Ballantini, A. Chincarini, S. Cuneo, G. Gemme,* R. Parodi, A. Podestà, and R. Vaccarone
INFN and Università degli Studi di Genova, Genova, Italy

Ph. Bernard, S. Calatroni, E. Chiaveri, and R. Losito
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R.P. Croce, V. Galdi, V. Pierro, and I.M. Pinto
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E. Picasso
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CERN, Geneva, Switzerland
Outlook

+... many more
Outlook

*Now is an important time*

We are now beginning to explore physics beyond the Standard Model at scales currently inaccessible with previous technology.

How can technologies coming online be steered to make the biggest impact on fundamental physics?

A shift in our priors has motivated a larger set of signals. Many bang-for-buck experiments > single catch-all experiment.

Theory and experiment are evolving together in this effort. The role of theorists is crucial in emerging fields.

see “Snowmass2021 Theory Frontier: Theory Meets the Lab”

arXiv:2203.10089