Quantum Sensing for Dark Matter and Gravitational Waves

Peter Graham
Stanford
Open Questions

The Standard Model of Particle Physics and Cosmology is remarkably successful

but this success deepens the remaining mysteries

e.g. we’d like to understand the nature of dark matter and dark energy and the earliest moments of our universe
Quantum Technologies?

Quantum sensors achieved incredible sensitivities!

*e.g.* atomic clocks have improved **rapidly**

complementary to more traditional particle colliders/detectors

theorist/experimentalist collaboration led to many new directions

likely many more still undiscovered!
Examples of Quantum Technologies for Fundamental Physics

I can’t overview entire field, will choose a few examples I can discuss:

1. Millicharged Particles and Trapped Ions (in progress)

2. Atomic Interferometry for Gravitational Waves $\sim$ Hz

3. Atomic Clocks and Gravitational Waves at $\sim \mu$Hz (in progress)

Of course community is pursuing MANY more, I’m excited to hear all the talks!
Millicharged Particle Detection with Trapped Ions

with
Dmitry Budker
Harikrishnan Ramani
Ferdinand Schmidt-Kaler
Christian Smorra
Stefan Ulmer

to appear
significant interest recently in “millicharged” particles (charge = $\varepsilon e$)
- mystery of charge quantization, dark matter candidate, EDGES anomaly...

direct detection (underground and surface)

$F_{DM} = (\alpha m_d/q)^2$

generally weakly coupled particles penetrate Earth

$\sigma_x [\text{cm}^2]$
Detection of Millicharged Particles

significant interest recently in “millicharged” particles (charge = εe)
- mystery of charge quantization, dark matter candidate, EDGES anomaly...

millicharged particles can have large couplings

can get stopped + thermalize to 300 K ~ 25 meV

most direct detection expts have thresholds ~ keV maybe down to ~ eV

still diffuse downwards “traffic jam” → very large number densities!

1907.00011 M. Pospelov, S. Rajendran, H. Ramani
2012.03957 M. Pospelov & H. Ramani

1905.06348 Emken et al

Detection of Millicharged Particles

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A New Kind of Dark Matter Detector

So have low energy millicharged particles, but with large density and large cross section!

How can we detect this?

Need a sensitive low threshold detector
Low target mass acceptable
Maximize charged particle scattering

Trapped ion

Ambient millicharged particles scatter off trapped ion, heating it

\[
\dot{H} = \sqrt{\frac{2}{\pi}} \frac{n_{mcp} m_{mcp} m_{ion}(T_{mcp} - T_{ion})}{(m_{ion} + m_{mcp})^2} \frac{\sigma_0}{u_{th}^3}
\]

\[
u_{th}^2 = \frac{T_{ion}}{m_{ion}} + \frac{T_{mcp}}{m_{mcp}}
\]

only the ion needs to be cooled

if whole trap is cryogenic the millicharges cool in walls
\rightarrow Enhances number density inside trap

long-range Coulomb scattering \rightarrow larger cross section at lower velocities
Ion Traps as Detectors

Ion traps excellent at isolation, can detect very low energy depositions!
Much recent progress motivated by quantum computing

BASE experiment, CERN

Measurement of Ultralow Heating Rates of a Single Antiproton in a Cryogenic Penning Trap

M. J. Borchert,1,2,4 P. E. Blessing,1,3 J. A. Devlin,1 J. A. Harrington,1,4 T. Higuchi,1,5 J. Morgner,1,2 C. Smorra,1 E. Wursten,1,7 M. Bohman,1,4 M. Wiesinger,1,4 A. Mooser,1 K. Blaum,4 Y. Matsuda,5 C. Ospelkaus,2,8 W. Quint,3,9 J. Walz,6,10 Y. Yamazaki,11 and S. Ulmer1

sensitive to collisions depositing ~ neV in overall heating rate

e.g. $^{40}$Ca ions sensitive to $\sim 10^{-9}$ eV sec
with individual collisions ~ few neV

1409.6572 M. Brownnutt, M. Kumph, P. Rabl & R. Blatt
New Limits From Ion Traps

We choose 3 experiments to set new limits but many more ion trap experiments have achieved low noise and could extend reach

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Ion</th>
<th>$V_z$</th>
<th>$T_{wall}$</th>
<th>$\omega_p$ [neV]</th>
<th>$T_{trap}$ [neV]</th>
<th>Heat Rate [neV/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hite et al, 2012 [3]</td>
<td>Paul</td>
<td>$^9$Be</td>
<td>0.1 V</td>
<td>300 K</td>
<td>$\omega_z = 14.8$</td>
<td>14.8</td>
<td>640</td>
</tr>
<tr>
<td>Goodwin et al, 2016 [4]</td>
<td>Penning</td>
<td>$^{40}$Ca</td>
<td>175 V</td>
<td>300 K</td>
<td>$\omega_z = 1.24$</td>
<td>1.24</td>
<td>0.37</td>
</tr>
<tr>
<td>Borchert et al, 2019 [5]</td>
<td>Penning</td>
<td>$p^-$</td>
<td>0.6 V</td>
<td>5.6 K</td>
<td>$\omega_+ = 73.8$</td>
<td>7380</td>
<td>0.002</td>
</tr>
</tbody>
</table>

room temp, cryogenic

detector threshold

cooled ions

sensitivity

Penning Trap

Paul Trap (Hite et al)
New Limits From Ion Traps

Different experiments have very complementary reach!

Significant differences between traps
- threshold
- target mass
- heating rate
- temperature
New Limits From Ion Traps

existing ion traps already reach well past previous bounds
Future Prospects

past measurements not made for dark matter detection already place strong constraints significant improvement possible in future with experiments designed to search for millicharges

- observing individual events reduces heating background, requires continuous monitoring of ion (already employed in some experiments)

- highly charged ion boosts signal

- lower threshold boosts event rate

- collective excitations in ion crystals could also reduce backgrounds

\(n_{\text{lab}} = 10^3 \text{ cm}^{-3}\)
Gravitational Waves
Gravitational waves will be major part of future of astronomy, astrophysics and cosmology. Crucial to observe as many bands as possible! Many observatories operating or planned from ~ nHz to kHz.

Important to consider all possible detection techniques to cover the entire spectrum.
Mid-band (~Hz) Gravitational Waves with Atom Interferometry
International Efforts in Gravitational Wave Detection with Atom Interferometry

Terrestrial Detectors under construction now:

<table>
<thead>
<tr>
<th>Project</th>
<th>Baseline Length</th>
<th>Number of Baselines</th>
<th>Orientation</th>
<th>Atom</th>
<th>Atom Optics</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAGIS-100</td>
<td>100 m</td>
<td>1</td>
<td>Vertical</td>
<td>Sr</td>
<td>Clock AI, Bragg</td>
<td>USA</td>
</tr>
<tr>
<td>AION [10]</td>
<td>100 m</td>
<td>1</td>
<td>Vertical</td>
<td>Sr</td>
<td>Clock AI</td>
<td>UK</td>
</tr>
<tr>
<td>MIGA [5]</td>
<td>200 m</td>
<td>2</td>
<td>Horizontal</td>
<td>Rb</td>
<td>Bragg</td>
<td>France</td>
</tr>
<tr>
<td>ZAIGA [8]</td>
<td>300 m</td>
<td>3</td>
<td>Vertical</td>
<td>Rb, Sr</td>
<td>Raman, Bragg, OLC</td>
<td>China</td>
</tr>
</tbody>
</table>

Plans (only) for satellite detectors, e.g. MAGIS and AEDGE leverage technology developed in these terrestrial detectors. Rest of talk I'll focus on science with these, use MAGIS as example.
Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:

![Graph showing frequency vs. strain with labels for Advanced LIGO, LISA, MAGIS-4k, MAGIS-Space, GGN, and MAGIS-Space.]

Figure 13: MAGIS-100 detector conceptual CAD model. The side view (a) shows a cross section of the existing ≥90 m underground NuMI shaft, with the MAGIS-100 vacuum tube installed. The three atom sources are attached at the (b) top, (c) middle, and (d) bottom of the detector. A laser hutch at the top of the shaft contains the interferometry lasers. The laser light enters the vacuum system at the top of the shaft through a vacuum viewport and then propagates downwards inside the vacuum tube.
Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:

mid-frequency band is ideal for angular localization
predict merger time and location on sky (sub-degree)

PWG & S. Jung PRD 97 (2018)
Neutron Star Mergers would allow EM telescopes to observe merger as it happens

e.g. learn more about NS mergers, kilonovae, origin of r-process elements, etc.
White Dwarf Mergers

What do we learn?
- What does a WD-WD collision look like? (Some of) Type Ia SN?
- measure rate, double degenerate vs single degenerate model of type Ia

- mergers only detectable in mid-band
- may be localized and predicted in advance ➔ multi-messenger astronomy
Dark Matter Detection with MAGIS

MAGIS can also detect ultralight dark matter (e.g. axions) with 3 complementary searches:

1. single-baseline “gravitational wave” search
   Arvanitaki, PWG, Hogan, Rajendran, Tilburg, PRD 97 (2018)

2. equivalence principle violation search
   PWG, Kaplan, Mardon, Rajendran, Terrano, PRD 93 (2016)

3. spin torque search
   PWG, Kaplan, Mardon, Rajendran, Terrano, Trahms, Wilkason, PRD 97 (2018)
Gravitational waves will be major part of future of astrophysics and cosmology must observe in all possible bands

Mid-band GW Science

Complementary to LIGO and LISA, observing with atoms in the mid-band may allow:

• Excellent angular resolution

• Identify upcoming NS (and BH) mergers allowing EM telescopes to observe event

• Standard siren measurements for cosmology: measure Hubble, dark energy EOS...

• Study WD mergers, type Ia supernovae, double degenerate vs single degenerate, etc.

• Measure BH spins and orbital eccentricities, learn about formation, heavier BH’s

• Possibly early universe sources of GW’s (inflation/reheating, cosmic strings, etc.)

• ... Likely surprises too!

Gravitational waves will be major part of future of astrophysics and cosmology must observe in all possible bands

These atomic detectors can also directly detect axion and dark photon dark matter
Atomic Clocks and Gravitational Waves at ~ 1-10 µHz

(PRELIMINARY)

with

Michael Fedderke

Surjeet Rajendran
Why the “µHz Gap”?  

Why doesn’t LISA reach lower frequencies?  

- proof mass acceleration noise  
- rises at low frequency  
- measured:

How could you reach lower frequencies?  

- Decrease acceleration noise (e.g. µAres concept)  
- Extend arm length (µAres)  
- Use astrophysical proof mass, e.g. pulsar timing or lunar laser ranging approach
μAres concept a LISA-like configuration with L ~ 1 AU arm lengths

assumes acceleration noise flat at low frequencies, not rising as 1/f

Other ways to observe this band?

Many sources in ~ $10^{-7}$ Hz - $10^{-4}$ Hz band!
Astrophysical Proof Masses

Why doesn’t Pulsar Timing reach higher frequencies?

Pulsars very heavy so excellent inertial proof masses (and clocks)

Baseline is “too long” or really insufficient timing of pulses for higher frequency band

want: shorter baseline for good SNR of pulses, man-made clock + pulses

Lunar laser ranging uses Earth-Moon system

but Earth has atmosphere + seismic noise (plate tectonics...)

what can we use?
So what can we use?

Bigger than a satellite, smaller than the Earth so no atmosphere or plate tectonics: can we use asteroids?

Will evaluate asteroids as inertial proof masses for gravitational wave detection

in particular will evaluate acceleration noise for asteroids will argue it can naturally be much lower than human-made proof masses in this frequency band

toy concept for a full GW experiment (others possible too):

433 Eros

focus on ~ 10 km asteroids orbiting ~ 2 AU with baseline ~ AU
Some Example Asteroids
from NASA asteroid database:

<table>
<thead>
<tr>
<th>full_name</th>
<th>a (AU)</th>
<th>e</th>
<th>per_y</th>
<th>n_dop_obs_used</th>
<th>H</th>
<th>diameter (km)</th>
<th>albedo</th>
<th>rot_per</th>
</tr>
</thead>
<tbody>
<tr>
<td>433 Eros (A898 PA)</td>
<td>1.458045729</td>
<td>0.222951265</td>
<td>1.760617117</td>
<td>2</td>
<td>10.4</td>
<td>16.84</td>
<td>0.25</td>
<td>5.27</td>
</tr>
<tr>
<td>1627 Ivar (1929 SH)</td>
<td>1.863272945</td>
<td>0.396783058</td>
<td>2.543448329</td>
<td>1</td>
<td>12.7</td>
<td>9.12</td>
<td>0.15</td>
<td>4.795</td>
</tr>
<tr>
<td>2064 Thomsen (1942 RQ)</td>
<td>2.178626927</td>
<td>0.329840411</td>
<td>3.215751662</td>
<td>12.6</td>
<td>13.61</td>
<td>0.0549</td>
<td>4.233</td>
<td></td>
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<tr>
<td>3353 Jarvis (1981 YC)</td>
<td>1.863022742</td>
<td>0.084636421</td>
<td>2.54293604</td>
<td>13.7</td>
<td>10.528</td>
<td>0.049</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>6618 Jimsimons (1936 SO)</td>
<td>1.874978569</td>
<td>0.044348412</td>
<td>2.56745396</td>
<td>13.4</td>
<td>11.506</td>
<td>0.07</td>
<td>4.142</td>
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</tbody>
</table>
Human Exploration of Asteroids

Have landed on asteroids many times:

<table>
<thead>
<tr>
<th>Body</th>
<th>Mission</th>
<th>Country/Agency</th>
<th>Date of landing/impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eros</td>
<td>NEAR Shoemaker</td>
<td>USA</td>
<td>12 February 2001</td>
</tr>
<tr>
<td>Itokawa</td>
<td>Hayabusa</td>
<td>Japan</td>
<td>19 November 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25 November 2005</td>
</tr>
<tr>
<td>Ryugu</td>
<td>Hayabusa2</td>
<td>Japan</td>
<td>21 September 2018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>France / Germany</td>
<td>3 October 2018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Japan</td>
<td>21 February 2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 April 2019</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>April 2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11 July 2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>October 2019</td>
</tr>
<tr>
<td>Bennu</td>
<td>OSIRIS-REx</td>
<td>USA</td>
<td>20 October 2020</td>
</tr>
</tbody>
</table>

Much ongoing interest in landing on asteroids

I’ll mainly focus on evaluating asteroids as proof masses, not on (challenging) engineering aspects of rest of mission
**Asteroid Acceleration Noise**

Gravitational perturbations from planets etc. are low frequency (and well-known) reduced by larger and farther asteroid albedo/area fluctuations at rotation period (out of band)

Solar intensity fluctuations measured at relevant frequencies

A major remaining, fluctuating, force is radiation pressure from sun. To estimate:

\[
a \sim \frac{A_{\text{ast}}}{M_{\text{ast}}} \frac{P_{\oplus}}{P_{\ast}} \left( \frac{r_{\oplus}}{r_{\ast}} \right)^2
\]

\[
\text{strain ASD: } \sqrt{S_h(f)} = \left( \frac{3\epsilon\bar{P}_{\oplus}}{4\rho_{\ast}R_c \cdot (2\pi f)^2 L} \left( \frac{r_{\oplus}}{r_{\ast}} \right)^2 \right) \sqrt{S_{\bar{P}}(f)}
\]

albedo/area fluctuations at rotation period (out of band)

diameters > 1 km give sufficient noise suppression
Unexplored GW Band

Asteroid radius: 8.00 km. Asteroid mass: $5.36 \times 10^{15}$ kg. Baseline: 1.00 AU.

- LISA [1702.00706]
- NANOGrav 15-yr [1812.11595]
- Nancy Roman EML (Full) [2610.00216]
- Nancy Roman (2010.00221)
- Gaia [2010.00216]
Solar Intensity Acceleration Noise

Measured solar intensity fluctuations, applied to example asteroid

\[ \sqrt{S_h(f)} = \left( \frac{3\epsilon \bar{P}_\oplus}{4\rho_{\text{ast}} R_c \cdot (2\pi f)^2 L} \left( \frac{r_\oplus}{r_{\text{ast}}} \right)^2 \right) \sqrt{S_P(f)} \]

strain ASD:

measured solar intensity PSD

Fröhlich & Lean (2004)

solar wind has smaller average force but larger in-band variation,

estimate similarly:
Solar Wind Acceleration Noise

Measured solar wind fluctuations, applied to example asteroid

\[
\sqrt{S_h(f)} = \frac{3\epsilon m_p}{4R\rho_{\text{ast}}(2\pi f)^2 L} \sqrt{S_\Omega(f)}
\]

strain ASD:

measured solar wind PSD

\[
\Omega = n_p v_p^2
\]
Thermal Noise

Solar intensity fluctuations cause variable heating → thermal expansion noise

day-night variation huge but at rotation frequency (see next)

relevant noise is solar fluctuations at our frequencies

over these time-scales average temperature fluctuates in roughly 1 m surface layer of asteroid

surface height fluctuation is noise
Rotation Noise

Asteroid rotation periods generally ~ few hours

removes higher frequency bands

many other acceleration noise sources (e.g. collisions, tidal heating, seismic noise, etc) appear sufficiently small for asteroid diameters > 1 km

asteroid as inertial proof mass allows significant improvement at low frequencies
Clock Noise

Asteroid is good inertial proof mass, quickly estimate other noise sources

translated current atomic clock

existing (terrestrial) clocks already sufficient for great GW sensitivity!
will assume this can be improved sufficiently that it is not limiting
Radio/Optical Link Noise

Estimate radar-ranging accuracy

Asteroids have significant, uncontrollable relative motion

Laser pulsing

Radio interferometry

Possibly allows a link system with significantly reduced technical complications relative to optical interferometry
Asteroid Gravity Gradient Noise

predominantly around orbital period (of detector) \( \sim \) few years

Fedderke, PWG, Rajendran, PRD (2021)

dedicated simulation using NASA JPL asteroid catalog, supplemented with estimate for higher frequency “close pass” noise of unmodeled asteroids using e.g. lunar crater data

cuts off any inner solar system experiment for GW’s at frequencies \(<\) few \( \times 10^{-7} \) Hz
Asteroids as proof masses with atomic clocks appear capable of observing $\sim 10^{-6}$ Hz - $10^{-4}$ Hz band hopefully encourages further study!

motivates trials of space-qualified atomic clocks

also motivates asteroid tests including seismic measurements (mars and moon measurements encouraging)

"just" placing atomic clock and laser (or radio) link on two asteroids will have sensitivity:
Examples of Quantum Technologies for Fundamental Physics

1. Millicharged Particles and Trapped Ions (in progress)

2. Atomic Interferometry for Gravitational Waves ~ Hz

3. Asteroids and Atomic Clocks for Gravitational Waves at ~ µHz (in progress)

Many exciting talks to come!
Backup Slides
Dark Matter Detection

Bounds as a fraction of dark matter:

\[ f_Q = \frac{\rho_Q}{\rho_{DM}} \]

\[ f_Q = 10^{-12}, 10^{-9}, 10^{-6}, 10^{-3} \]

\[ \epsilon > 1 \text{m Thermalization} \]

\[ \epsilon > 1 \text{km Thermalization} \]