Opportunities of Cold Atom Quantum Sensors under Microgravity and in Space

- With focus on direct detection of dark energy

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Dark energy detection discussions are based on collaborations with
• S. Chiow of JPL
• DESYRE team from DLR
• and NIAC investigation team

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Cold Atom Laboratory Orbiting Earth on ISS

BEC bubble-geometry (Lundblad)

Adiabatic expansion (Sackett)


Bose-Einstein condensate quantunm gas on orbit (CAL).

Launchd in May 2018, has been operating in space since.

CAL Science module

CAL/JPL Cold Atom Laboratory (CAL) on ISS

Jet Propulsion Laboratory
National Aeronautics and Space Administration
California Institute of Technology

Cold Atom Laboratory Orbiting Earth on ISS

Approved for unlimited public release.
Deep Space Atomic Clock (DSAC)

DSAC on-orbit performance (red line)

Reproposed trap configuration for the clock experiments

Launched in June 2019

Deep Space Atomic Clock

Launch and First Power up
Precision measurements rely on stable frequency references and clocks.

Atomic Clocks and Quantum Sensors
Atomic Test Mass Quantum Sensor (ATMQS)

General Approach: Atom Interferometer based Atomic Test Mass Quantum Sensor

(Atomic clock approach) Atomic properties and laser precision

Atomic beam

\[ \frac{\pi}{2} \text{ pulse} \]

\[ \text{Atomic cloud at } \mu \text{K to pK} \]

\[ \text{Laser-cooled} \]

\[ \text{Atom cloud at } \text{lik to pk} \]

Ideal atomic particle test mass

Detection

Displacement

\[ \text{New capabilities} \]

Quantum duality matter wave and superposition

\[ \text{NIST Primary atomic clock} \]

\[ + \]

\[ + \]

\[ \Rightarrow \]

\[ \text{Atomic system stability} \]

\[ \text{New capabilities} \]
Dark Energy (DE) affects:

- The expansion history of the Universe
- How fast did the Universe expand?
- Also called the geometry of the Universe
- How do structures (which are mostly growth of structures) evolve and grow over time?

Why must dark energy exist?

- Attractive gravity competes with dark matter (evolve and grow over time)
- How do structures (which are mostly growth of structures) evolve and grow over time?
- Attractive gravity competes with repulsive dark energy force?
What's the Nature of Dark Energy?

- According to Einstein, dark energy could be just the cosmological constant, but the measured energy density is off by 120 orders of magnitude!
- It could be a new scalar field, introducing a new force of the same order of magnitude!

What are the effects of dark energy?

J. Rhodes

### Table: Photometric Data

<table>
<thead>
<tr>
<th>Mode</th>
<th>Filter</th>
<th>Photometry/Genism</th>
<th>Photometry/Genism</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSF Size</td>
<td>F 0.9 ( ≤ 5)</td>
<td>0.9 (5)</td>
<td>0.5 (15)</td>
</tr>
<tr>
<td>Point Source</td>
<td>Depth ( ≤ 5)</td>
<td>0.9 (5)</td>
<td>0.5 (15)</td>
</tr>
<tr>
<td>Median (V)</td>
<td>Survey size ( ≤ 5)</td>
<td>0.9 (5)</td>
<td>0.5 (15)</td>
</tr>
<tr>
<td>Effective diameter</td>
<td>0.5 ( ≤ 5)</td>
<td>0.9 (5)</td>
<td>0.5 (15)</td>
</tr>
</tbody>
</table>

\[ \text{Effective diameter} = \frac{2 \times \text{Survey size}}{0.5 ( \text{Effective diameter})} \]

J. Rhodes

DESI, KIDS, HEDEX, Jointing DES, HSC, ESO.
There are many theories of dark energy with modified gravity:

1) allow extra dimensions
2) add new fields

Some of these models are being constrained by:

- Gravitational waves.
- Cosmological observations.
- Solar system experiments.
- Laboratory experiments.

There are major inroads of dark energy with modified gravity:

What is the nature of the dark energy force?

```
\frac{\partial}{\partial t}(\phi) + (\phi) \Lambda - \phi \phi \phi (\cdots \phi \phi \phi) \cdots Z \frac{2}{\Lambda} = \zeta
```
Constraints on Chameleon Model


A scalar field with potential $\phi$ including non-linear self- and matter interactions gives the coupling strength to normal matter in relation to gravity; $M/\sqrt{\Lambda}$ gives the coupling strength to gravity resonance line) could drive cosmic acceleration today. A comparison is made to previous experiments: neutron interferometry complement those from torsion pendulum experiments and torsion balance measurements of $\mu g$ symmetron fields: Constraints by atom interferometry atomic particle unscreened large mass screening

$$d\frac{W}{\phi} + \frac{\phi}{u V} = (\phi)_{\text{eff}} \Lambda$$

Thin Shell Model Laboratory Measurements


Atom interferometry constraints on dark energy.

Making gravity resonance with Atom Interferometry.
Expected Symmetron Constraints

\[ \frac{\delta \phi}{\bar{\lambda}} + \frac{\phi}{\bar{\lambda}} \left( \frac{\delta \phi}{\bar{\lambda}} - \frac{\phi}{\bar{\lambda}} \right) = \Lambda \]

\[ \Lambda = 10^{10} \text{GeV} \]

Community Workshop on Cold Atoms in Space, Sept. 24, 2021

Expected Chameleon Constraints

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\[ \Lambda = 10^{10} \text{GeV} \]

Chiow

Solid dots represent simulation results. Solid region of large \( \bar{\lambda} \phi \) such that \( \bar{\lambda} = \frac{\bar{\lambda}}{\mu} \sim \phi \nabla^2 \bar{\lambda} \phi \)

This invariance was indeed demonstrated in their \( 083501 (2020) \).

Here we describe a recipe for obtaining an expression of \( \bar{\lambda} \phi \) for a specific experiment, which agrees with simulation results fairly well over several orders of magnitude in all region of large \( \bar{\lambda} \phi \).

While this region was considered unconstrainable for two spheres.

If \( \bar{\lambda} \phi \sim \bar{\lambda} \phi \), the radius of the through hole is adjusted to best match the field profile with a through hole:

- Multi-atom interferometry
- Designed dark energy periodic field potential
- Long interferogram time for higher sensitivity
- Einstein Elevator Facility, HITech, LTH

DESRE Project – Dark Energy Search by Interferometry in the Einstein Elevator

Dark Energy Direction in Micрогavity

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Key points

1. Einstein's gravity theory still holds, so far, it has evaded the gravity field screening properties of the new Vainshtein model, making it ten (10) orders of magnitude smaller than (near mass), significantly in the solar system.

2. The signal strength is detectable, making it ten (10) orders of magnitude smaller than (near mass), significantly in the solar system.

3. Gravity interference

4. Near DC (low frequency) measurements

Main technical challenges in the direct detection

• "Screening" properties of the new Vainshtein model suppresses the DE force significantly in the solar system (near masses), making it ten (10) orders of magnitude smaller than (near mass), significantly in the solar system.

• So far, it has evaded the gravity field screening properties of the new Vainshtein model.

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• Gravity interference

• Near DC (low frequency) measurements

- Simulated cubic galileon field with Vainshtein screening in the solar system

$$Vainshtein \text{screening in the solar system}$$

$$Vainshtein \text{screening in the solar system}$$

$$\nabla^2 \phi = \frac{8 \pi G}{c^4} \rho \left( \frac{\phi_0^4}{\phi^2} - \frac{\phi_0^2}{\phi^2} \right) \frac{3 \phi_0^4}{c^2} + \phi_0^2$$
Measurement Approach

Choice of measurables for suppressing the large Gravity force

Challenge: measuring a dark energy force directly on top of the \(10^{10}\times\) larger gravity.

Solution: Recognizing the special 1/r^2 property of the gravity force—tensor trace is strictly ZERO, a test of Inverse Square Law.

Greedy suppressing the major systematic effect:

For gravitational forces, the trace of the tensor vanishes

\[
\begin{pmatrix}
\gamma_{11} + \gamma_{22} + \gamma_{33} &= 0 \\
\gamma_{12} &= \\
\gamma_{23} &= \\
\gamma_{31} &=
\end{pmatrix}
\]

Measuring the force Gradient tensor

\(\nabla\cdot = \begin{pmatrix}
\gamma_{12} & \gamma_{13} & \gamma_{14} \\
\gamma_{21} & \gamma_{23} & \gamma_{24} \\
\gamma_{31} & \gamma_{32} & \gamma_{34}
\end{pmatrix}\)

Using a smart constellation with orientation independent measurements – measure differential accelerations, between each pair of the four satellites.

Measure the force gradient tensor

Choice of measurables for suppressing the large gravity force
Drag Force Reduction

Conventional drag force reduction challenge: test masses must avoid all non-gravitational forces, including spacecraft self-gradient forces.

Solution: utilize the fact that the atoms are fundamentally identical and can be repeatedly generated, and place the atomic test masses far away from the spacecraft in open-space vacuum.

Achieve drag-free measurements without flying drag-free satellites.
Orbit Choice

Challenge: Combining measurement drifts and low frequency noises are extremely difficult over long average time.

Solution: Fly the constellation in an elliptical orbit around the sun with variable distance from the Sun mass, and hence the dark energy force.

Choice of the measurement orbit trajectory for time and spatial dependence.

Orbit Choice
Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

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DE mission effectively has multiple LISA-like 2-arm interferometers in a non-planar geometry.

- DE mission concept being formulated: to fly a tetrahedral constellation of four satellites traversing the solar system looking for the possible unknown force due to dark energy scalar.
- DE mission with 4 arms allows us to use cross-correlation to dig out the stochastic background (not just excess power). LIGO, ~0.03 Hz – 1 Hz.
- DE mission effectively has multiple LISA-like 2-arm interferometers in a non-planar geometry.
- 100,000 km arm length desired happens to make the detection band fall between LISA and LIGO.
- Economy.
- Detection of dark matter ultra-light fields.
- Precision gravity measurements in solar system and possible detection of unknown objects in the solar system.
- Non-Gaussianity of the atomic quantum system
- Testing the nature of quantum gravity by exploring interferometric quantum information sensing and
- Detection of stochastic GW signals.

The non-planar antennas also allow determinations of polarizations of stochastic GW signals.

Opportunities for other gravity measurements.

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More Gravity Exploration Opportunities

Enabling technology: Quantum sensor of atom interferometers fields.

Using atomic particles as test masses and matter-wave
interferometric measurements for weak forces.

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