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

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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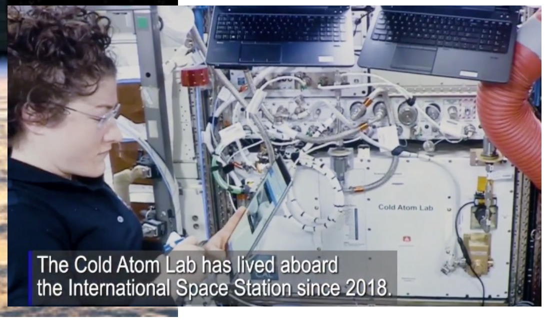
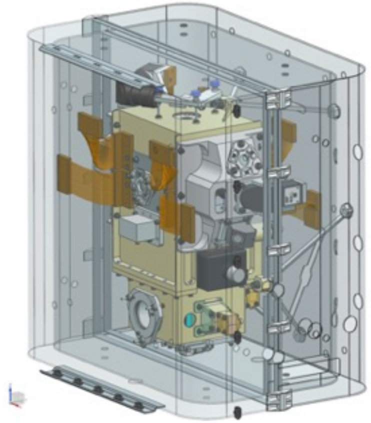
Cold Atom Laboratory Orbiting Earth on ISS

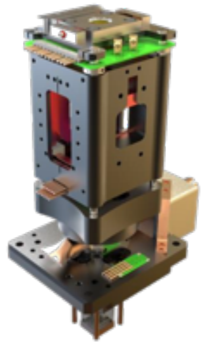
NASA/JPL Cold Atom Laboratory (CAL) on ISS

(Launched in May 2018, has been operating in space since)



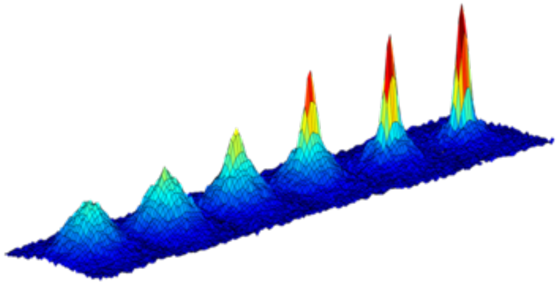
CAL Science module



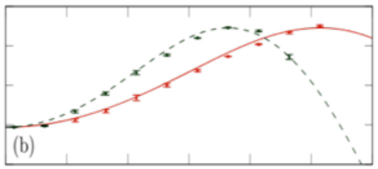


Aveline, et al. Nature 582, 193–197 (2020).

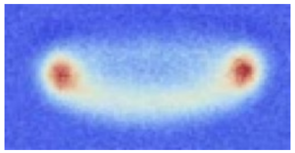
Bose-Einstein condensate quantum gas on orbit (CAL).

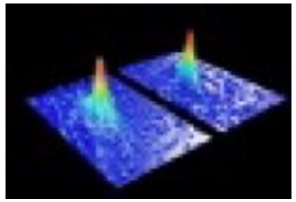


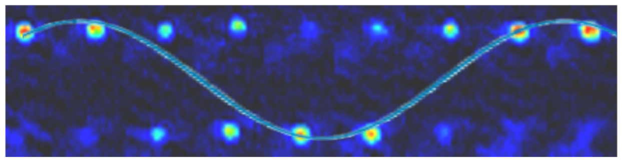
Adiabatic expansion (Sackett)



BEC bubble-geometry (Lundblad)



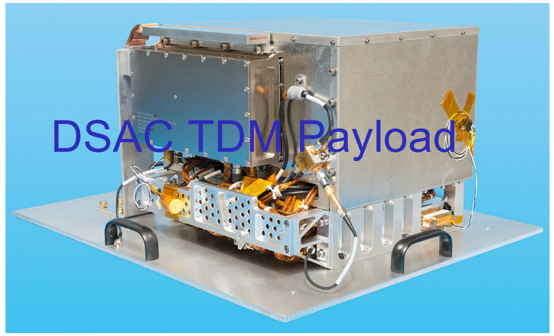


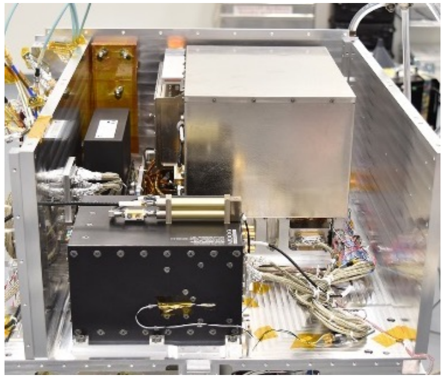


Atom interferometers (Bigelow, Williams)

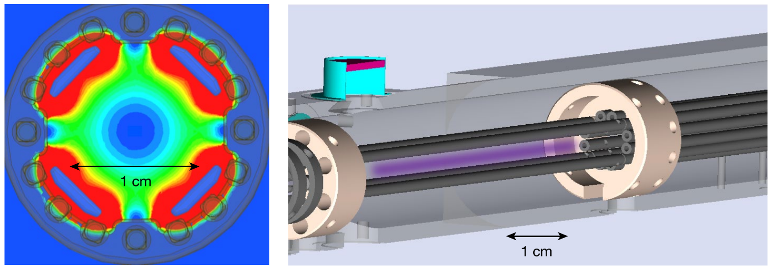
Deep Space Atomic Clock (DSAC)

44 | Nature | Vol 595 | 1 July 2021

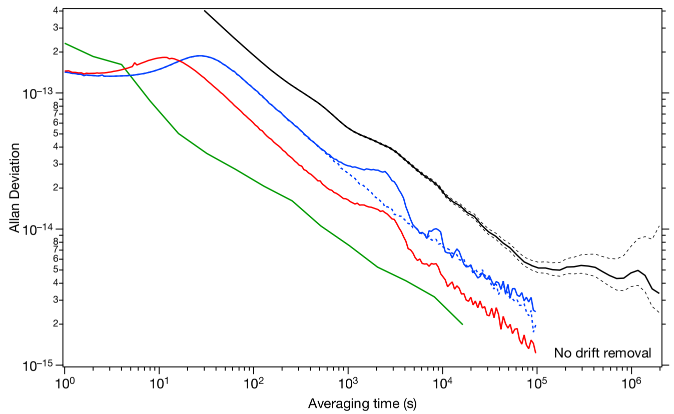




DSAC Demo Unit (DU)
Atomic Resonator (JPL)
V: 285 x 265 x 228 mm
M: 16 kg
Physics Pkg – 6.6 kg
P: 50 W
Physics Pkg – 17 W



Reproposed trap configuration for the clock experiments

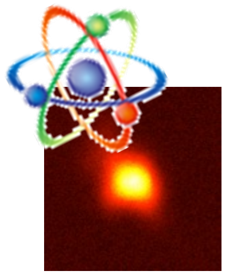


DSAC on-orbit performance (red line)

Atomic Clocks and Quantum Sensors

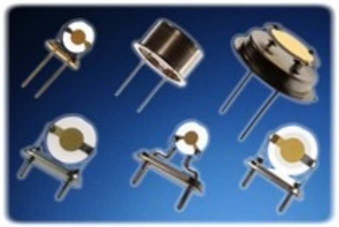
Precision measurements rely on stable frequency references and clocks.

Quartz clocks

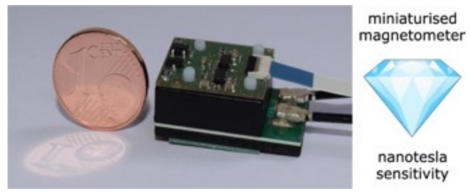


Clocks

Sensors



quartz microbalance (mass sensor)

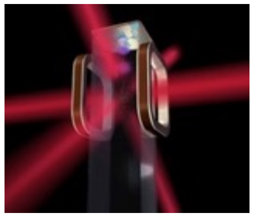


Diamond based magnetometer
(Sciencedirect.com)

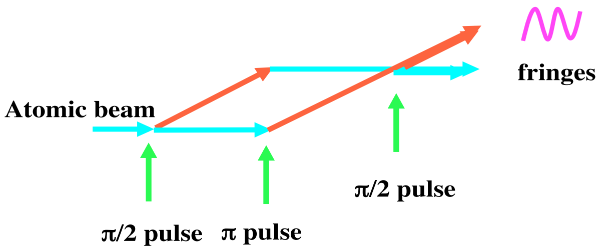
Atomic Test Mass Quantum Sensor (ATMQS)

General Approach: Atom interferometer-based Atomic Test Mass Quantum Sensor

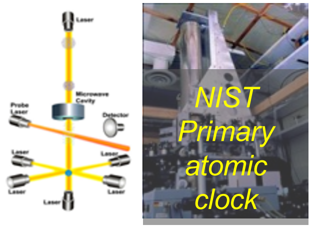
Ideal atomic particle test mass + **Displacement Detection** + **Atomic system stability** => **New capabilities**



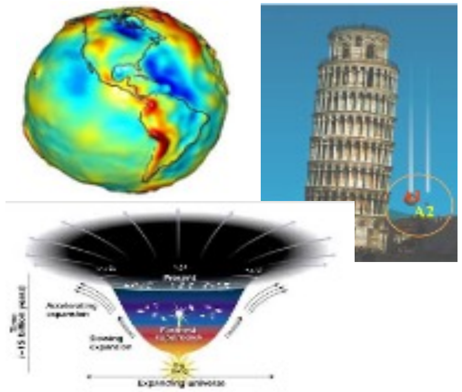
Laser-cooled atom cloud at μK to pK



Quantum duality matter wave and superposition



Atomic properties and laser precision (Atomic clock approach)



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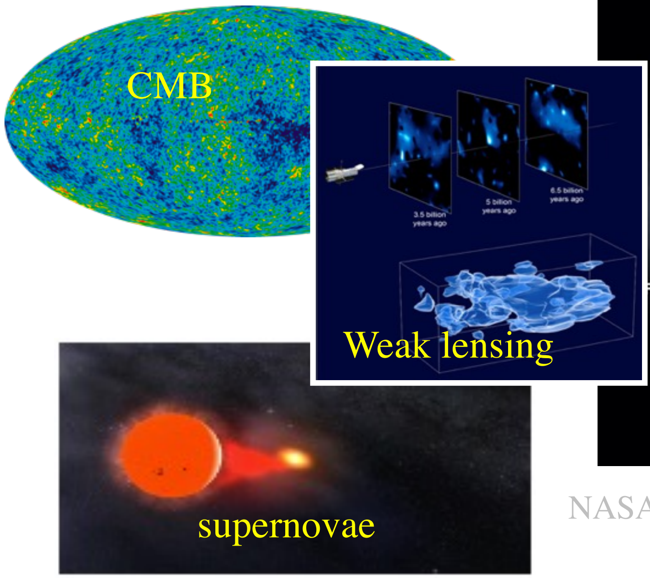
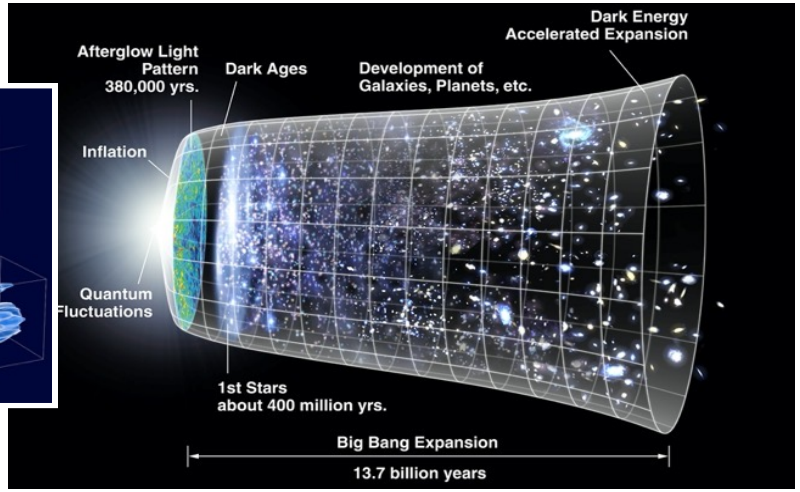
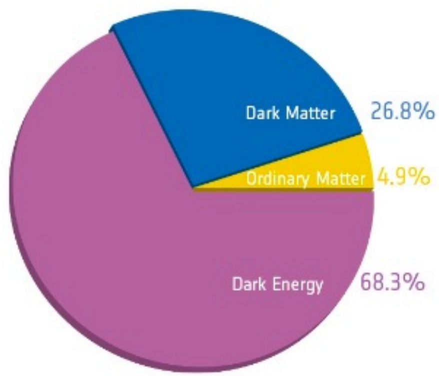
The Universe and Dark Energy

Why must dark energy exist?





NASA/JPL



Dark Energy (DE) affects:

- Expansion history of the Universe
  - How fast did the Universe expand?
  - Also called the geometry of the Universe
- Growth of structures
  - How do structures (which are mostly dark matter) evolve and grow over time?
  - Attractive gravity competes with repulsive dark energy force?

What's the Nature of Dark Energy?

What are the effects of dark energy?

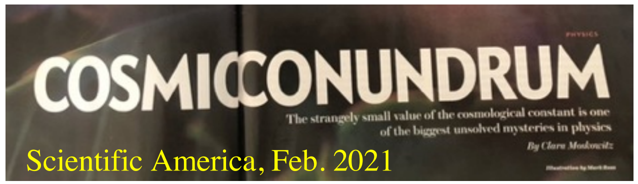
LSST — Legacy Survey of Space and Time — Vera C. Rubin Observatory | Euclid | Nancy Grace Roman Space Telescope

Joining DES, HSC, KiDS, HetDEX, DESI… and others

Proposed lifetime	2022 - 2032	2022 - 2029	2025 - 2031
Mirror size (m)	6.5 (effective diameter)	1.2	2.4
Survey size (sq deg)	~20,000	15,000	2,227
Median z (WL)	0.9	0.9	1.2
Depth (5σ AB mag point source)	~27	~24 (NIR) ~26 (Vis)	~27
FoV (sq deg)	9.6	0.5 (Vis) 0.5 (NIR)	0.28
Filters	u-g-r-i-z-y	Y-J-H-Vis	Y-J-H-F184
PSF Size	~0.7"	~0.2" (Vis)	~0.2" (NIR)
Mode	Photometry	Photometry/Grism	Photometry/Grism

J. Rhodes

- *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 which provides the opportunity for a direct detection !!*

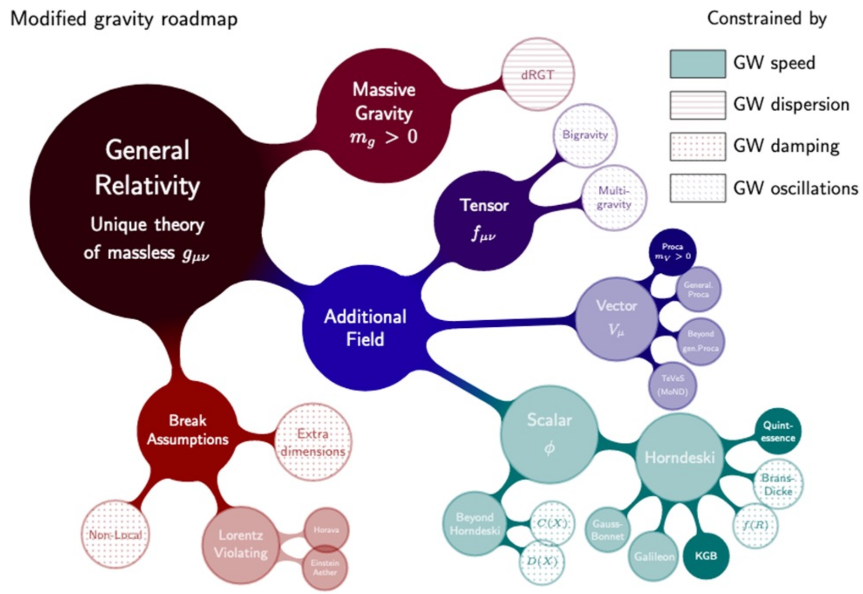


Modified Gravity Models

What is the nature of the dark energy force?

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



Source: Ezquiaga & Zumalacárregui (2018)

Self-interaction, source of screening

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \partial^2\phi, \dots)\partial_\mu\phi\partial^\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

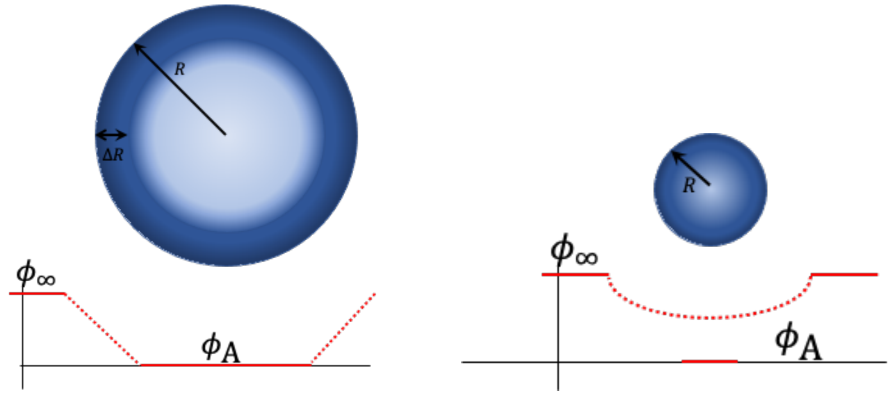
Chameleon ϕ Symmetron ϕ	• **Thin-shell model** • Atoms are less screened than bulk. • Constrained by lab/atomic tests.
Galileon $\partial^2\phi$ (Vainshtein)	• Length scale is very large, less likely measurable in lab experiments.

The scientific motivation and significance for a direction detection of dark energy is similar to that of the direct detection of gravitational waves.

Thin Shell Model Laboratory Measurements

$$V_{\text{eff}}(\phi) = \frac{\Lambda^n}{\phi} + \frac{\phi}{M}\rho$$

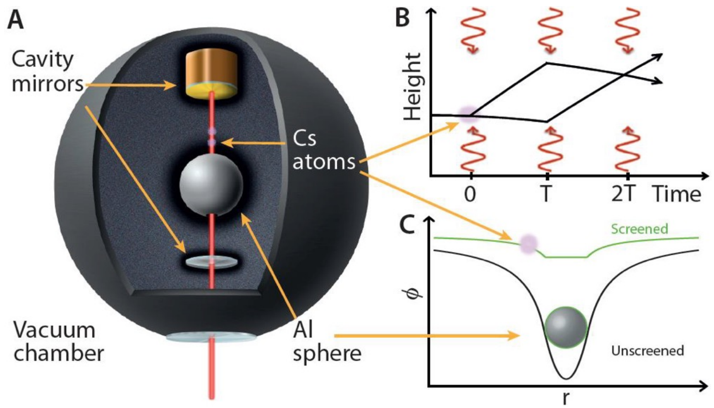
A scalar field ϕ with potential V including non-linear self- and matter interactions



large mass screening

atomic particle unscreened

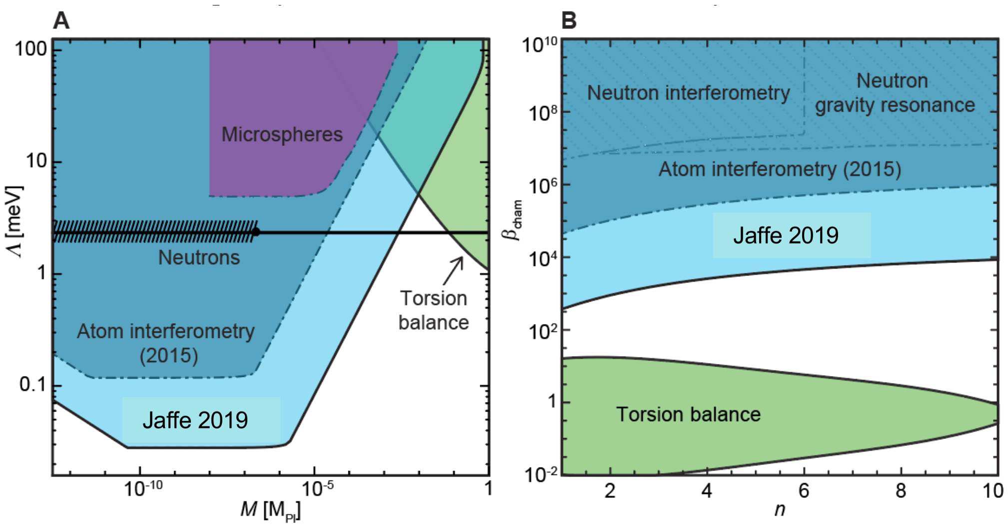
C. Burrage, E. J. Copeland, E. A. Hinds, JCAP 1503 (2015) 03, 042



Atom-interferometry constraints on dark energy.
Hamilton et al. Science, 349, 849 (2015)

Jaffe et al. *Nature Physics* **volume 13**, pages 938–942 (2017)

Sabulsky et al., *Physical Review Letters*, 2019.

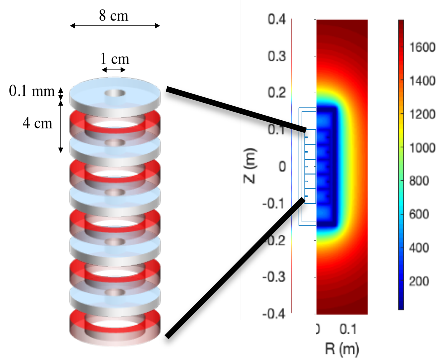


Constraints on Chameleon Model

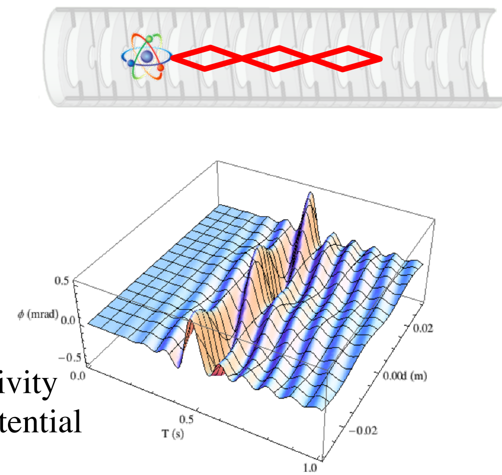
Dark Energy Direction in Microgravity

DESYRE Project – Dark energy Search by interferometry in the Einstein Elevator

Einstein Elevator Facility, HITech, LUH

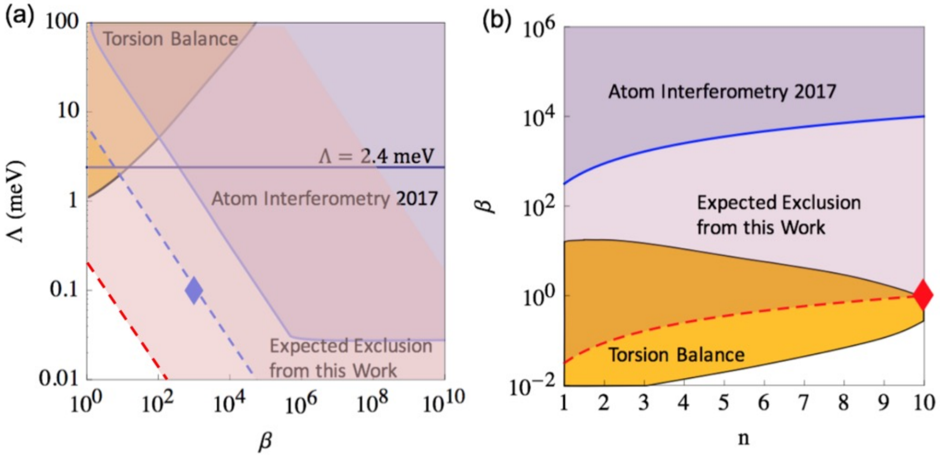


Multi-loop AIs, periodic potential

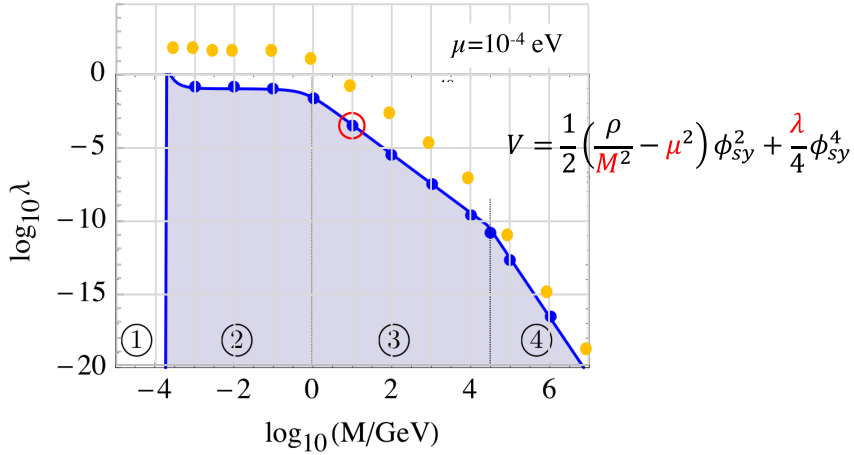


- Long interrogation time for higher sensitivity
- Designed dark energy periodical field potential
- Multi-loop atom interferometry

Chiow and Yu, Phys Rev D, **97,** 044043 (2018).



Expected Chameleon Constraints



Expected Symmetron Constraints

Chiow and Yu, Phys Rev D, **101,** 083501 (2020).

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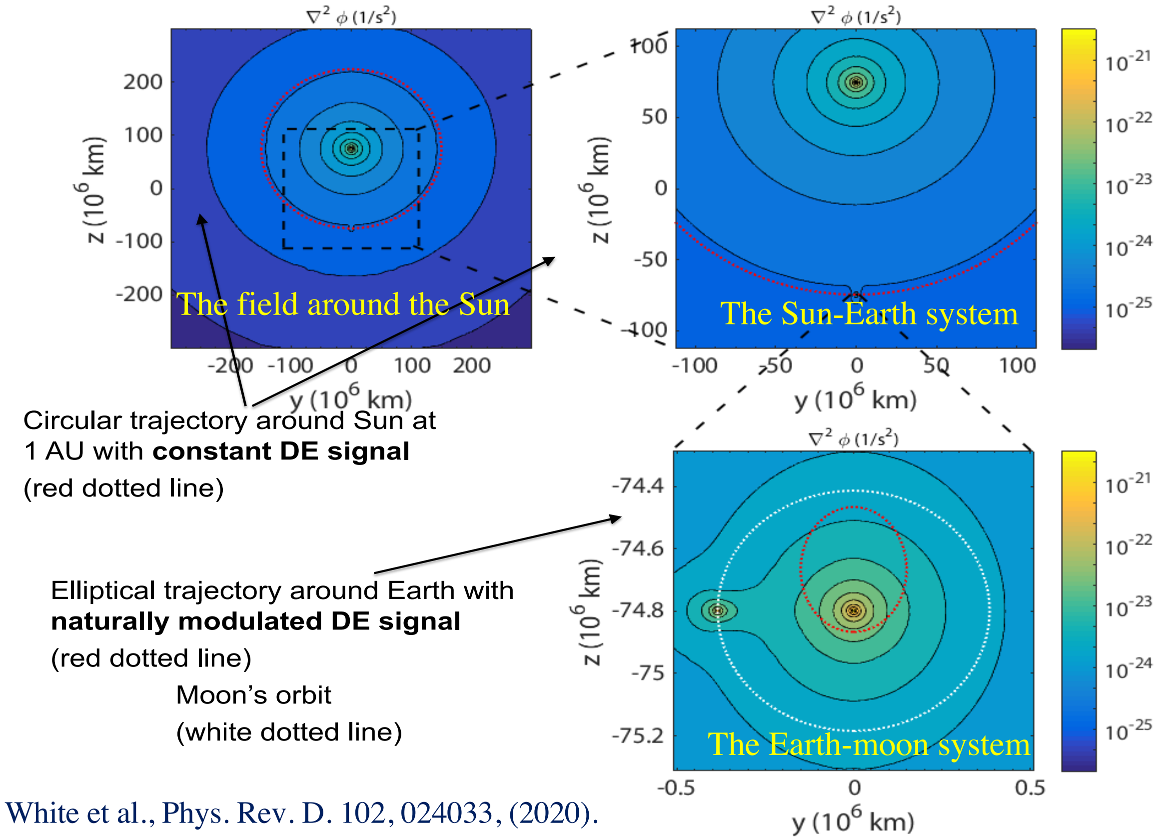
Vainshtein Model as a Benchmark

Simulated cubic galileon field with Vainshtein screening in the solar system

$$\nabla^2\phi + \frac{r_c^2}{3}\left[(\nabla^2\phi)^2 - (\nabla_{ij}\phi)^2\right] = 8\pi G\rho, r_c \sim 6000\ Mpc$$



White et al., Phys. Rev. D. 102, 024033, (2020).

@1 AU from the Sun, the gravity strength $6\times10^{-3}\ m/s^2$, Galileon dark energy force, $\sim 10^{-13}\ m/s^2$

Key points

- "Screening" properties of the new field suppresses the DE force significantly in the solar system (near masses), making it ten (10) orders of magnitude smaller than the gravity force.
- So far, it has evaded the gravity measurements in the solar system – Einstein's gravity theory still holds, for now.
- The signal strength is detectable and has strong dependence on mass and distance.

Main technical challenges in the detect detection

1. Sensitivity
2. Gravity interference
3. Spacecraft self-gradient/drag force
4. Near DC (low frequency) measurements

Measurement Approach

Choice of measurables for suppressing the large Gravity force

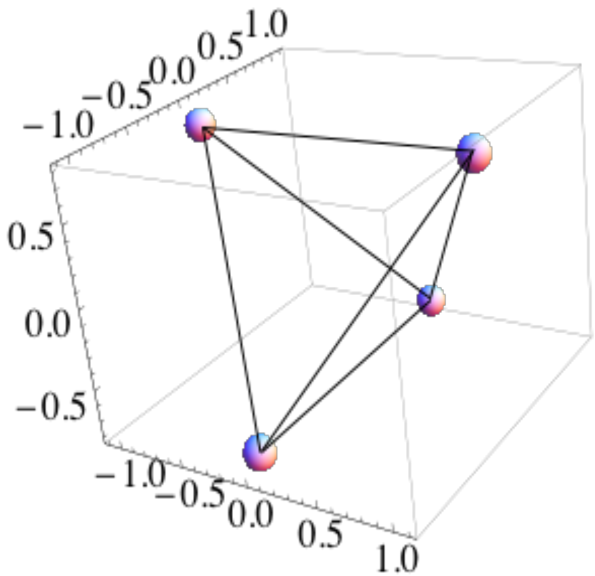
Challenge: measuring a dark energy force directly on top of the 10^{10} x larger gravity.

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

- Measure the force gradient tensor

$$\overleftrightarrow{\gamma} = \begin{pmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} \\ \gamma_{21} & \gamma_{22} & \gamma_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{pmatrix}$$

- For gravitational forces, the trace of the tensor vanishes $\gamma_{11} + \gamma_{22} + \gamma_{33} = 0$, and *it does not vanish for DE fields*, greatly suppressing the major systematic effect.
- Using a smart constellation with orientation independent measurements – measure differential accelerations, , between each pair of the four satellites.



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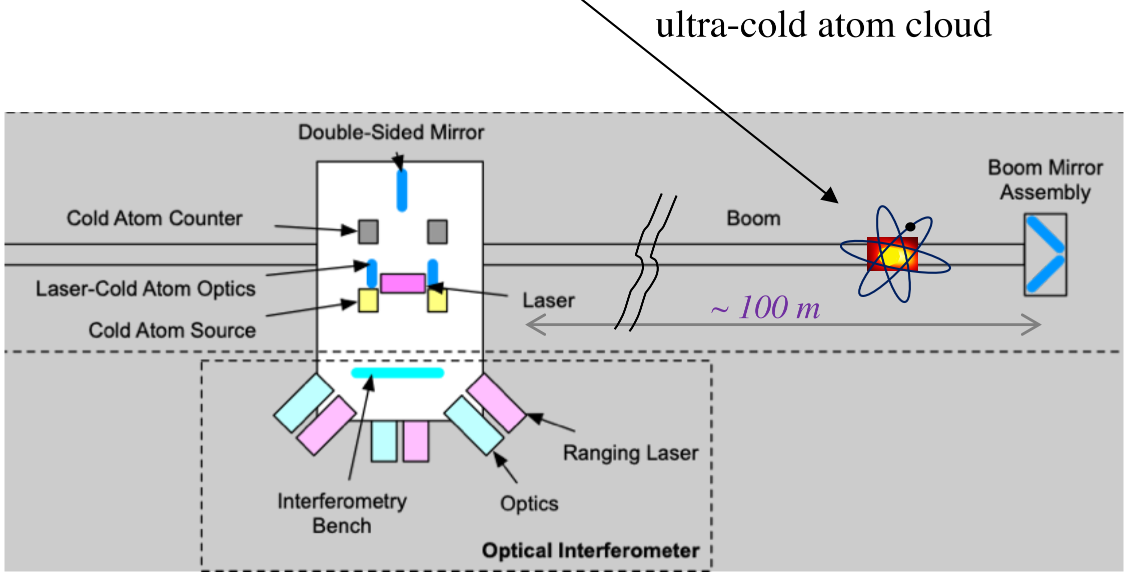
Drag Force Reduction

Achieve drag-free measurements without flying drag-free satellites

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.

Conventional drag force reduction



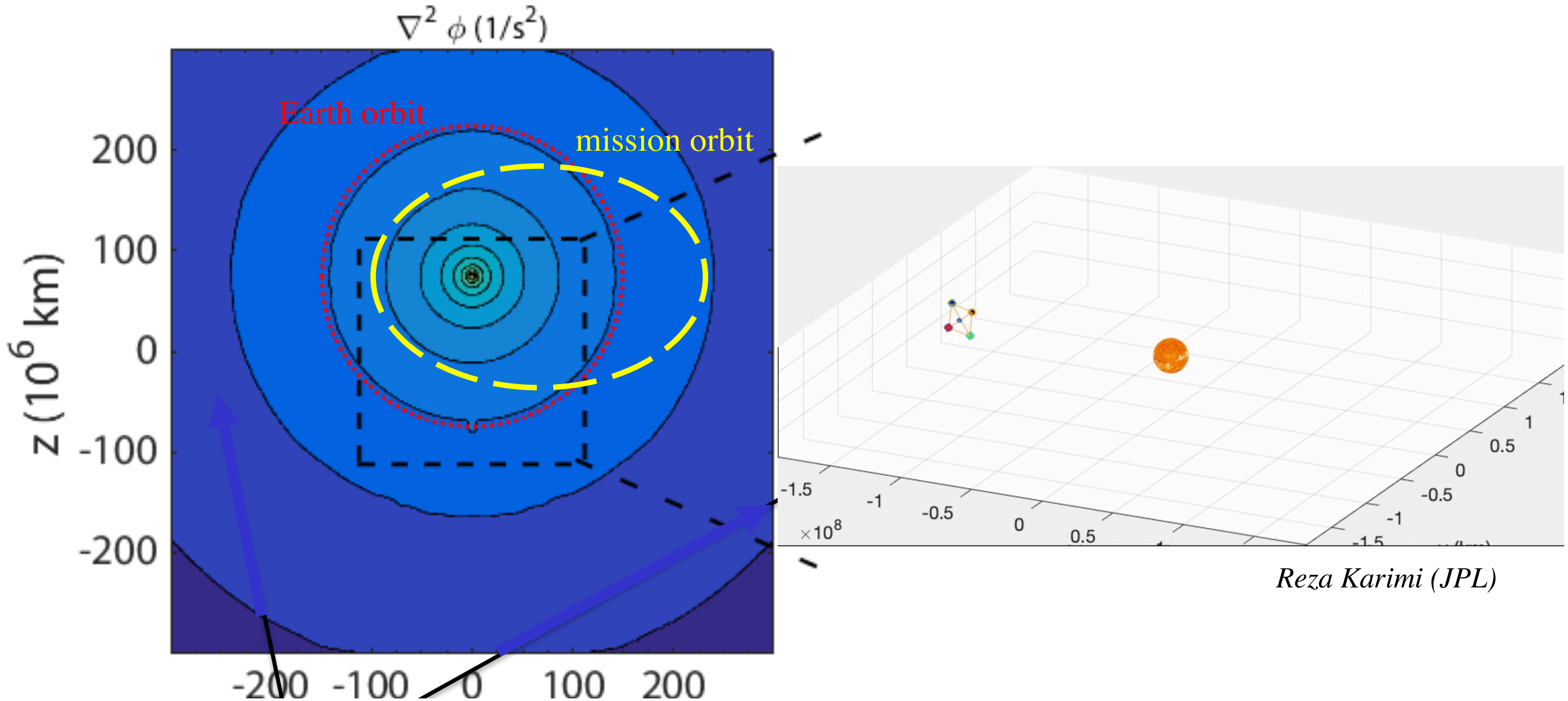
spacecraft

Orbit Choice

Choice of the measurement orbit trajectory for time and spatial dependence

Challenge: combating 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.
(This is in addition to the expected measurement stability of atomic sensors)



Reza Karimi (JPL)

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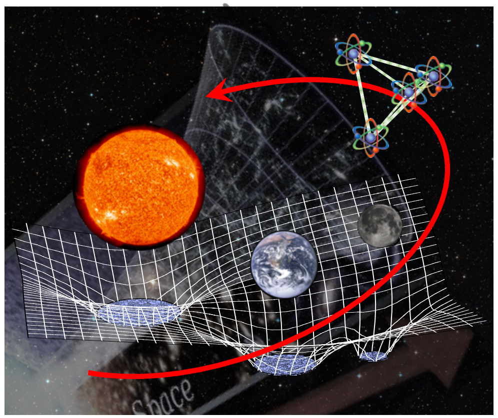
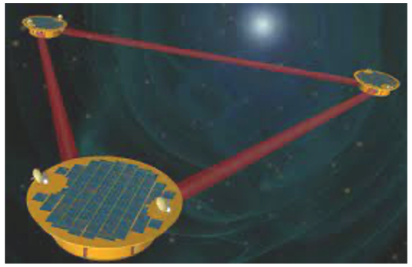
More Gravity Exploration Opportunities



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 fields.*

Enabling technology: *quantum sensor of atom interferometers using atomic particles as test masses and matter-wave interferometric measurements for weak forces.*



- DE mission effectively has multiple LISA-like 2-arm interferometers in a non-planar geometry.
- 100,000 km armlength desired happens to make the detection band fall between LISA and LIGO, ~0.03 Hz – 1 Hz.
- DE mission with its 4 arms allows us to use cross-correlation to dig out the stochastic background (not just excess power).
- The nonplanar antennas also allow determinations of polarizations of stochastic GW signals.

Opportunities for other gravity measurements.

- Detection of dark matter ultra-light fields
- Testing the nature of quantum gravity by exploring interactive quantum information sensing and non-Gaussianity of the atomic quantum system
- Precision gravity measurements in solar system and possible detection of unknown objects in the solar system.

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