Planetary Defense & Space Quantum Technologies for Fundamental Physics

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with **Josh Eby, Marianna Safronova**
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Burt, J. Prestage, R. Tjoelker, D. Enzer, D. Kuang, D. Murphy et al., Nature 595 (2021) 43.
Page Editor: NASA Administrator
NASA Official: Brian Dunbar

- https://arxiv.org/abs/2112.07674
- https://arxiv.org/abs/2107.04038

Under review by Nature Astronomy

Big questions

- How much dark matter are there in the solar system? Do we really know?

- Can planetary data set meaningful dark matter constraints? General Relativity? 5th forces?

- Can we use current or future space Quantum Technology to study fundamental physics?

Answers

- How much dark matter are there in the solar system? **We don’t really know!**

- Can planetary data set meaningful dark matter constraints? General Relativity? 5th forces? **Yes!**

- Can we use current or future space Quantum Technology to study fundamental physics? **Yes, I will show you an example today.**

Theme of this talk:

Bridging **Planetary Date, Space (Quantum) Technologies**, and **Fundamental Physics**

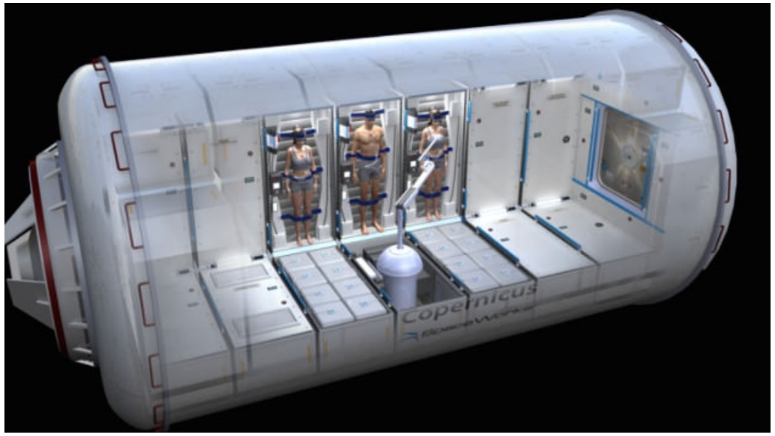
This talk may have real-life consequences!

Anteaters - Starship

~~Don't~~ Please Look Up

Why Space Quantum Clocks?
Auto-Navigating Spacecraft & Space Travel

NASA Kennedy Space Center's Visitor Complex (Public Domain)



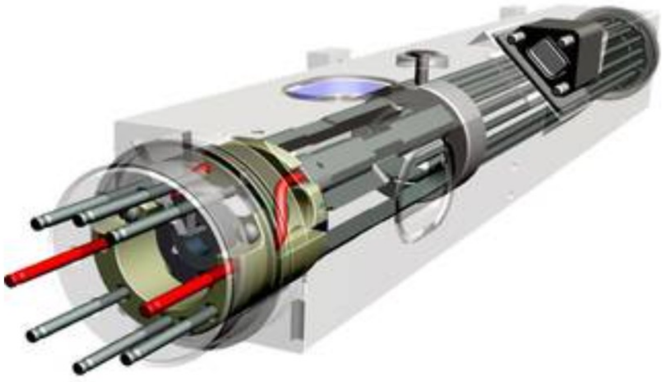
Artist's concept for Mars-ready habitat. Image Credit: SpaceWorks Torpor/NASA collaboration

Exploring the deep space: **auto-driving Spacecraft; needs precision timing!!!**

NASA Deep Space Atomic Clocks (current technology!) & Deep space and global navigation satellite system (GNSS)

Can we use the technology to study fundamental physics?

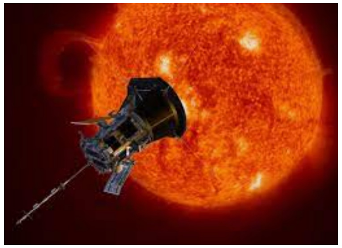
NASA DSAC as a major motivation



Up to 50 times more stable than the atomic clocks on GPS satellites, the **mercury-ion Deep Space Atomic Clock loses one second every 10 million years**, as proven in controlled tests on Earth.

- Launched in 2019, the clock has operated for more than **12 months in space and demonstrated there a long-term stability of 3×10^{-15} at 23 days**
  Burt, Prestage, Tjoelker, Enzer, Kuang, Murphy et al., Nature 595 (2021) 43.

- Exceeds previous space clock performance by up to an order of magnitude



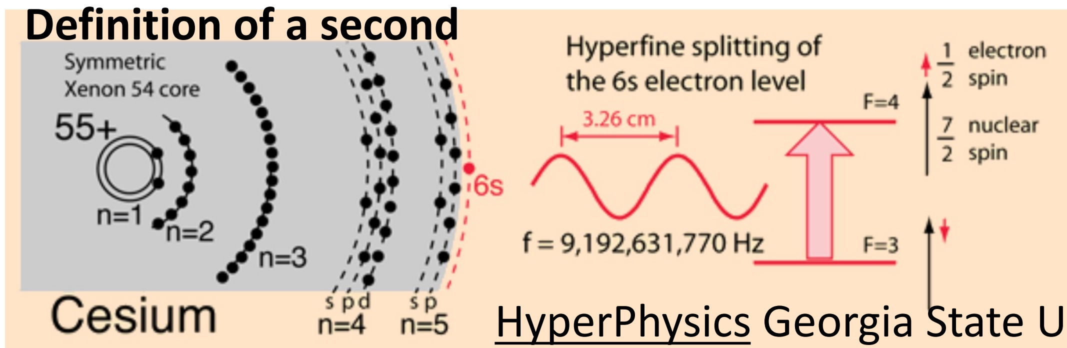
Parker Solar Probe: billion-dollar mission
Kasper, Klein, Lichko, Huang, Chen, Badman et al., Parker solar probe enters the magnetically dominated solar corona, Phys. Rev. Lett. (2021)

Caesium Standard and Atomic Clock

- Atomic clocks: used to measure the distance between objects by timing how long it takes a signal to travel from A to B.

- For space exploration, clocks must be extremely precise:

- **An error of even one second can mean the difference between landing on Mars or missing it by hundreds of thousands of miles.**



Definition of a second

HyperPhysics Georgia State U

http://hyperphysics.phy-astr.gsu.edu/hbase/acloc.html

Reference: U.S. Naval Observatory, Cesium Clocks

Outline

- Ultralight Dark Matter
- Solar Bound-State Halo
- Sensitivity of (Space-based) Clocks

Dark Matter Coupling

$$\mathcal{L} \supset \kappa\phi \left(d_{m_e} m_e \bar{e}e + \frac{d_\alpha}{4} F_{\mu\nu}F^{\mu\nu} + \frac{d_g\,\beta_3}{2g_s} G^A_{\mu\nu}G^{A\mu\nu} \right), \tag{1}$$

where e is the electron field, $F^{\mu\nu}$ $(G^{A\mu\nu})$ is the electromagnetic (QCD) field strength, g_s and β_3 are the strong interaction coupling constant and beta function (respectively), and $\kappa = \sqrt{4\pi}/M_P$ with $M_P = 1.2 \times 10^{19}$ GeV.

Oscillation of Massive Scalars

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{3}a_\phi\phi^3 + \frac{1}{4}\lambda_\phi\phi^4.$$

$$\phi(t,\vec{x}) = \phi_0 \cos(m_\phi t - \vec{k}_\phi \cdot \vec{x} + \dots).$$

$$\omega \simeq m_\phi.$$

DM energy density $\rho_\phi = \frac{1}{2}m_\phi^2\phi_0^2$

Atomic Physics Probe

$$\mathcal{L} \supset \kappa\phi \left(d_{m_e} m_e \bar{e} e + \frac{d_\alpha}{4} F_{\mu\nu} F^{\mu\nu} + \frac{d_g\, \beta_3}{2g_s} G^A_{\mu\nu} G^{A\mu\nu} \right), \tag{1}$$

$$\mu(\phi) \simeq \mu_0 \left(1 + d_{m_e} \kappa\phi\right), \quad \alpha(\phi) \simeq \alpha_0 \left(1 - d_\alpha \kappa\phi\right)$$

$$\alpha_s(\phi) \simeq \alpha_{s,0} \left(1 - \frac{2 d_g \beta_3}{g_s} \kappa\phi\right), \tag{2}$$

where $\mu = m_e/m_p$ is the electron-proton mass ratio, and the subscript $_0$ denotes the central (time-independent) value of μ, α, and α_s.

Atomic Probe Basics

$$\mathcal{L} \supset \kappa\phi\left(d_{m_e} m_e \bar{e}e + \frac{d_\alpha}{4} F_{\mu\nu}F^{\mu\nu} + \frac{d_g\,\beta_3}{2g_s} G^A_{\mu\nu}G^{A\mu\nu}\right), \tag{1}$$

Turning off d_{m_e} and d_g for demonstrations,

$$f_A \propto \alpha^{\xi_A+2},$$

$$\alpha = \alpha_0(1 + d_\alpha \kappa\phi(t)).$$

$$\frac{\delta(f_A/f_B)}{f_A/f_B} \simeq (\xi_A - \xi_B) d_\alpha \kappa\phi(t).$$

Experimental observable! There are other observables, which Marianna may cover

- For example, if **A is a hyperfine microwave transition and B is an electronic optical transition, ζA = 1 and ζB = 0.**
- For details, see 1405.2925, Arvanitaki, Huang, Tilburg, PRD 15

Solar Bound-State Halo or Solar Halo

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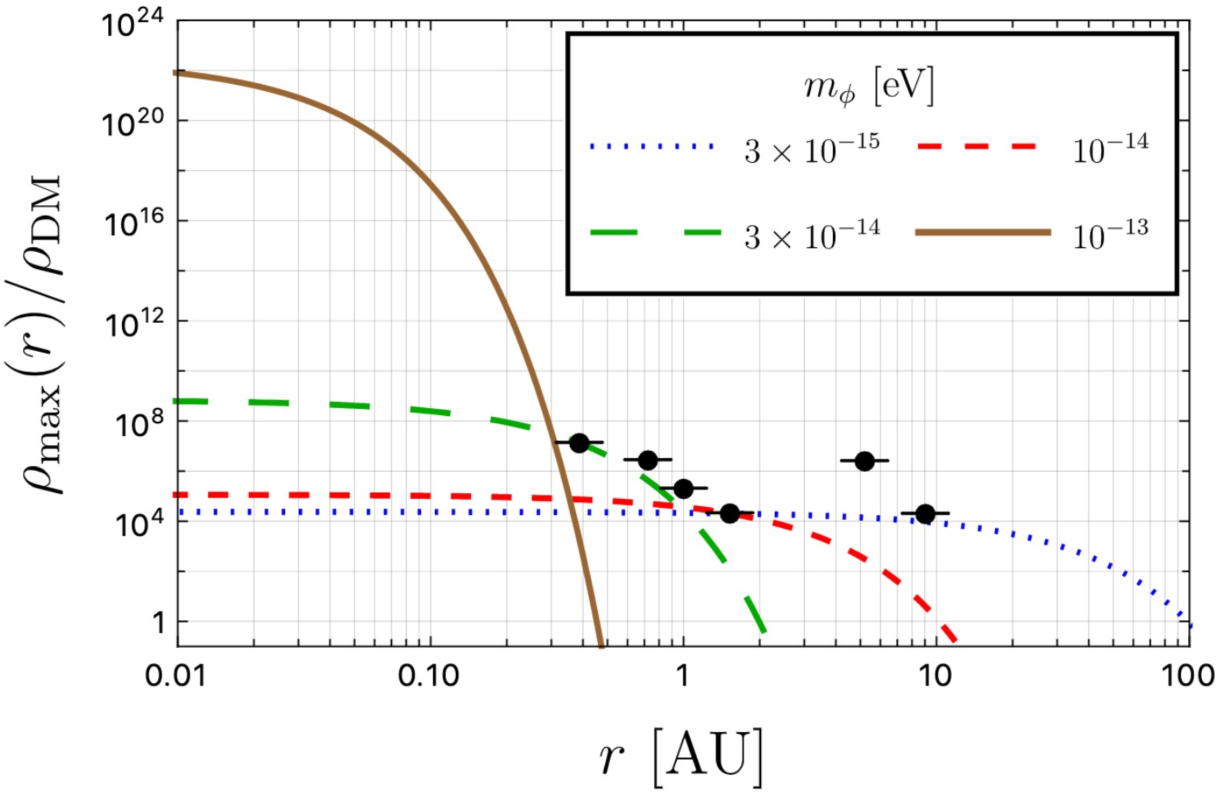
Dark matter in solar system? **Planetary constraint!**



Mercury, Venus, Earth, Mars, Jupiter, Saturn

Pitjev, Pitjeva, 1306.5534, Astronomy Letters ’13

Tsai, Eby, Safronova, 2112.07674

Scalar DM Halo

Stable solution supported by external potential

$$V_{\rm ext} = \begin{cases} -\dfrac{G\, m_\phi\, M_{\rm ext}}{r} & \text{for } R_\star > R_{\rm ext}\,, \\ -\dfrac{3\, G\, m_\phi\, M_{\rm ext}}{2\, R_{\rm ext}} \left[1 - \dfrac{1}{3}\left(\dfrac{r}{R_{\rm ext}}\right)^2\right] & \text{for } R_\star \le R_{\rm ext}\,, \end{cases}$$

$$\rho(r) \simeq \rho_\star \exp\left(-2r/R_\star\right), \quad \text{for } R_\star > R_{\rm ext}$$

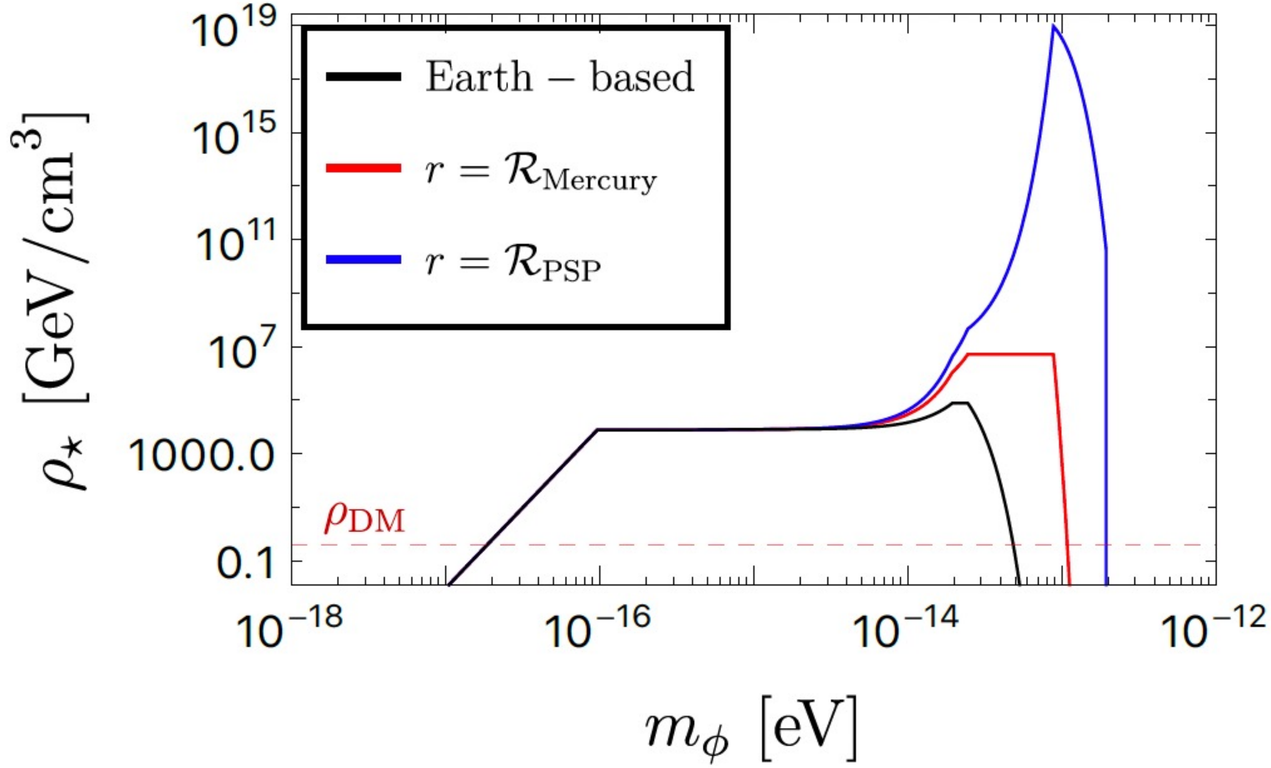
$$R_\star \simeq \frac{M_P^2}{M_{\rm ext}\, m_\phi^2},$$

where $M_{\rm ext} = M_\odot$ is the mass of the external host body; note that $R_\star$ is independent of the total mass in the halo

$$v_\star = (m_\phi\, R_\star)^{-1},$$

Banerjee, Budker, Eby, Flambaum, Kim, Matsedonskyi, and Perez, 1912.04295

Enhancement of the density



Tsai, Eby, Safronova, 2112.07674

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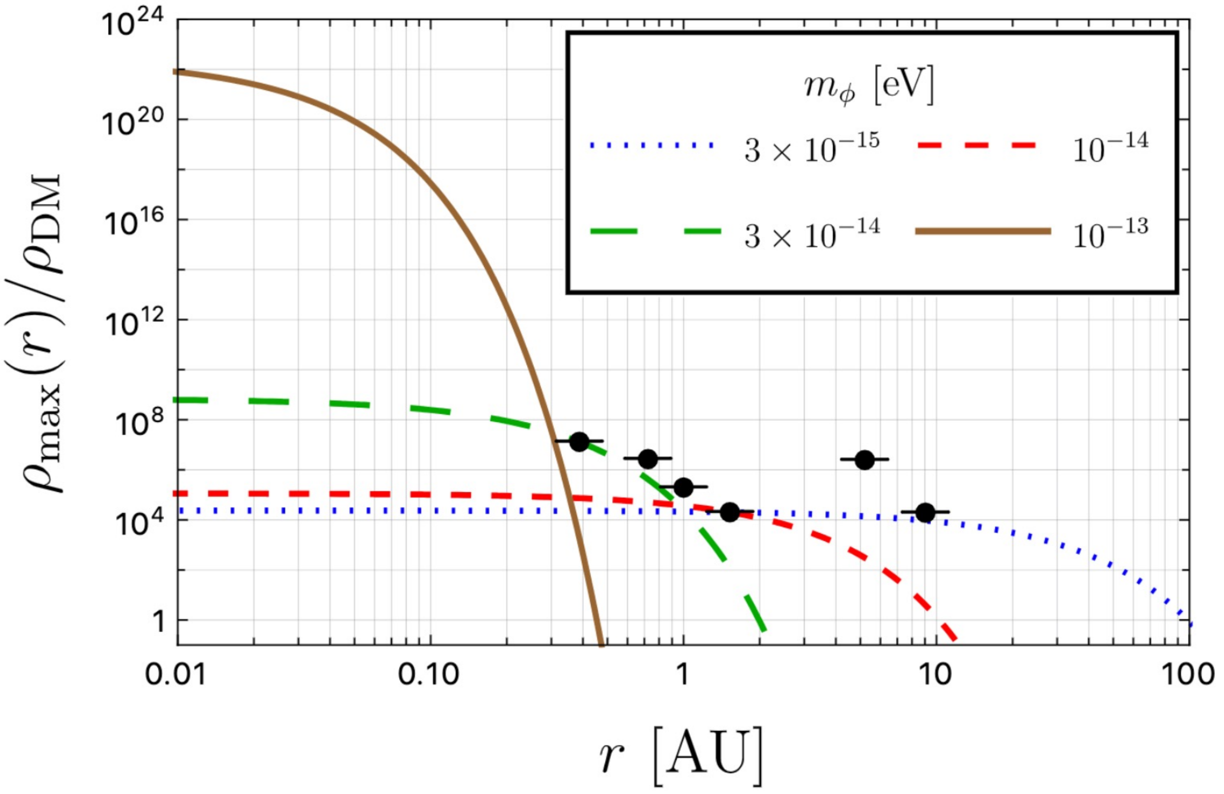
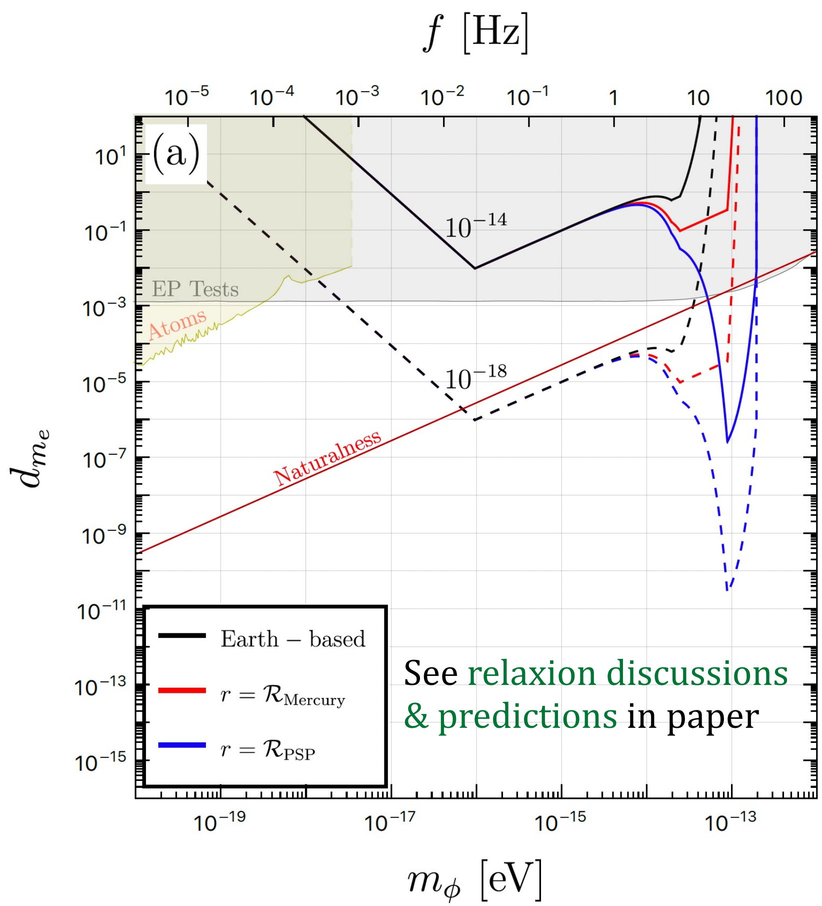
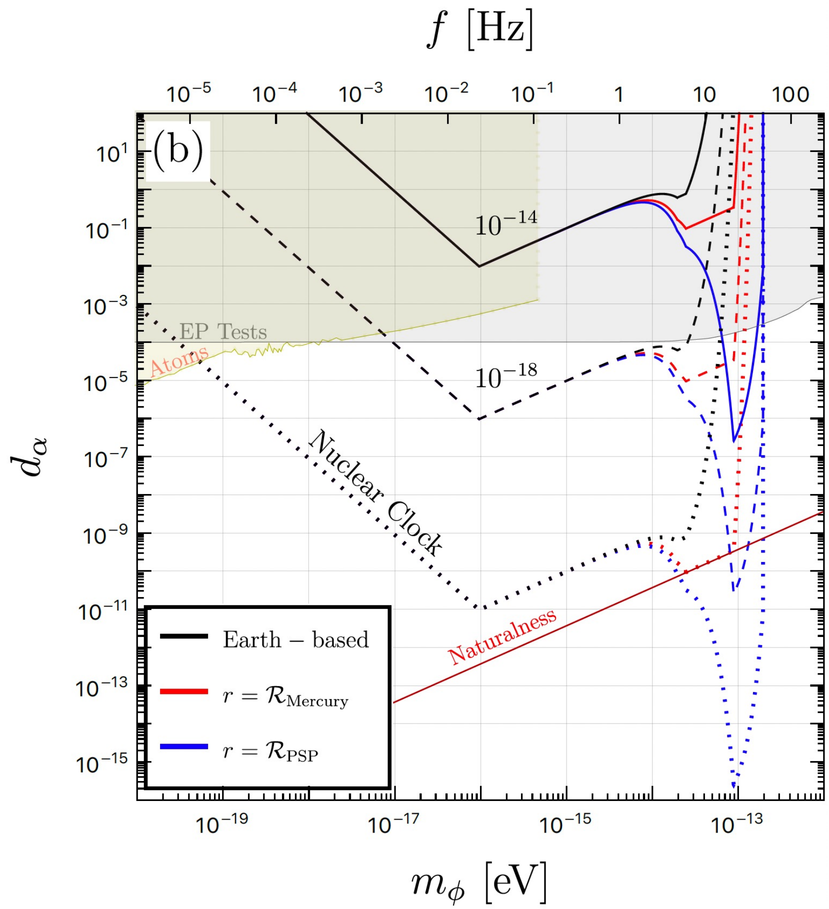


New project!
Improve the constraint with asteroid data! Model independent!
Tsai +, to improve Pitjev, Pitjeva, 1306.5534, *Astronomy Letters '13*

Results





$$\mathcal{L} \supset \kappa\phi \left(d_{m_e} m_e \bar{e} e + \frac{d_\alpha}{4} F_{\mu\nu} F^{\mu\nu} + \frac{d_g \, \beta_3}{2 g_s} G^A_{\mu\nu} G^{A\mu\nu} \right), \quad (1)$$

$$\frac{g_e^2 \Lambda^2}{(4\pi)^2} \lesssim m_\phi^2, \quad \Lambda = 4\pi v_{EW} \simeq 3 \text{ TeV}.$$

Naturalness condition

- Motivate **Specific Frequency Region!**
- Motivate **Nuclear Clocks!**
- **Tsai, Eby, Safronova, 2112.07674**

More on the Planetary Constraints: Ultralight Dark Sector

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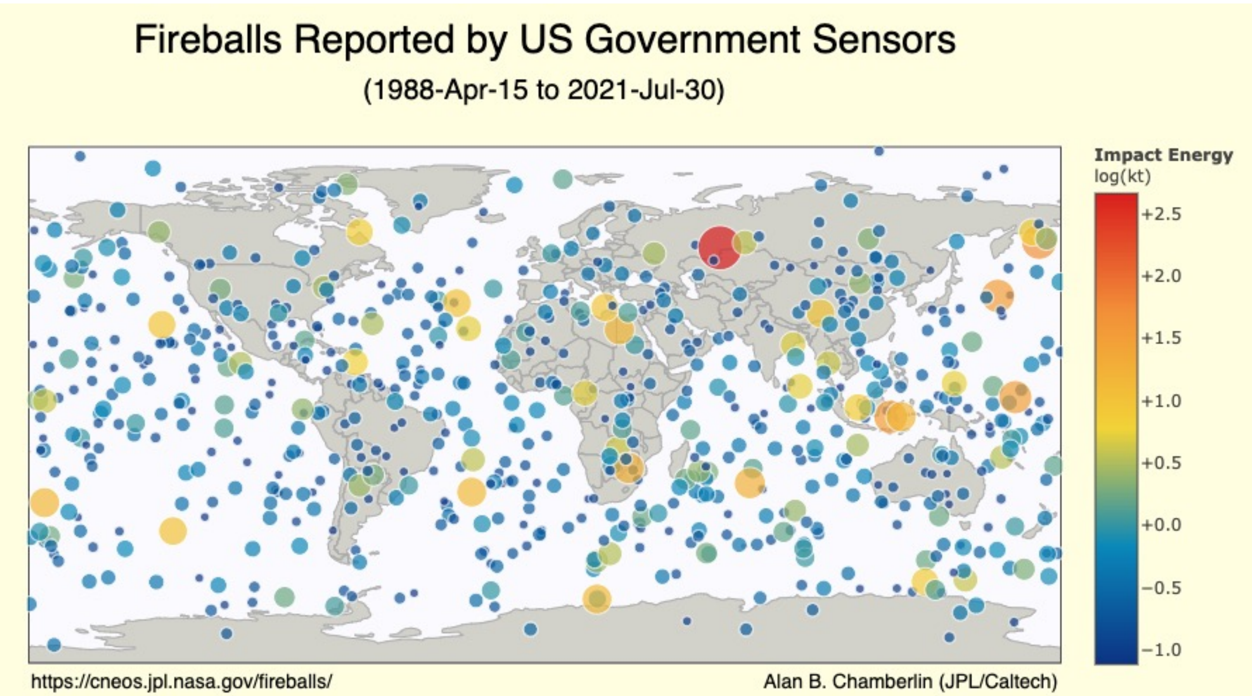
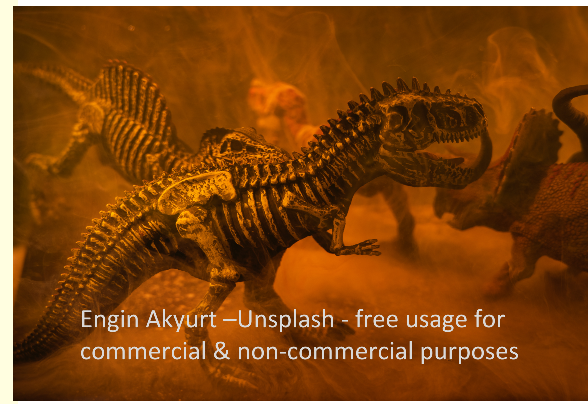
Asteroids hitting the earth





~ 65 million years ago

Tracking asteroids is extremely important

e.g., unexpected 2013 Chelyabinsk meteor injured >1500 people

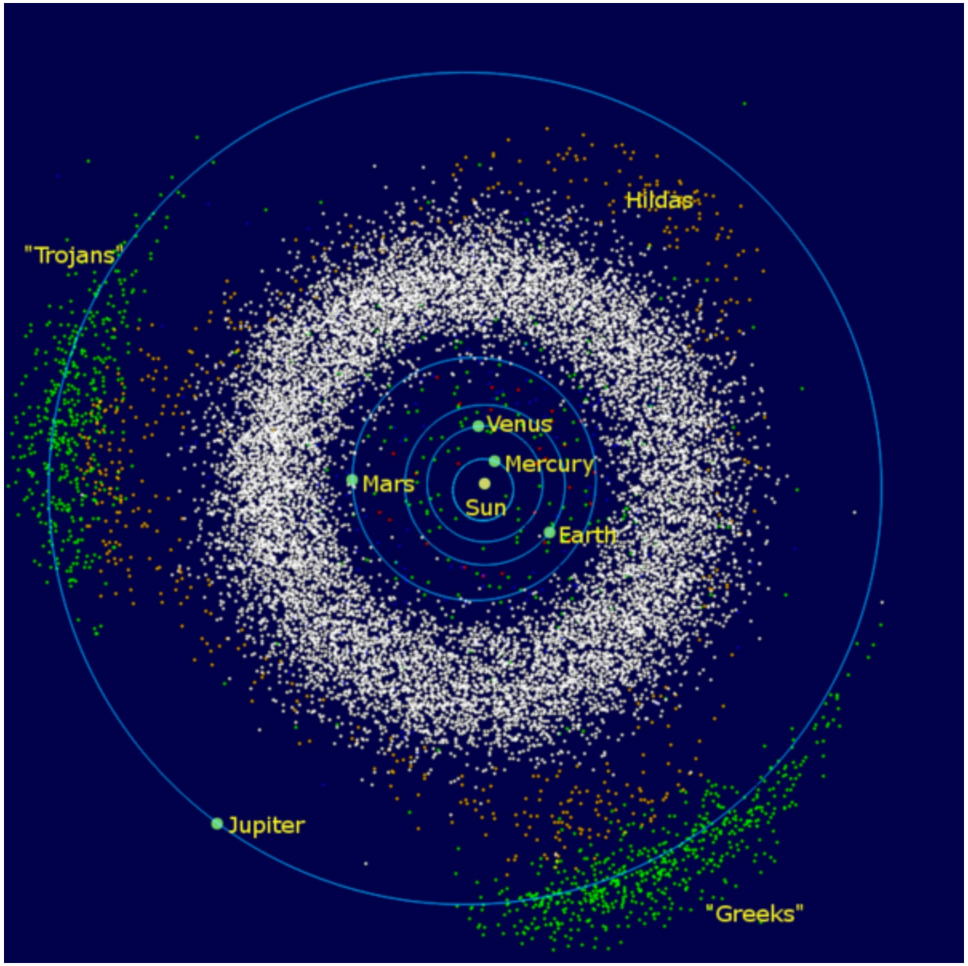
Also, near-Earth asteroid search accidentally found ‘Oumuamua

Asteroids

By Sidney Paget

"Professor Moriarty stood before me"

"Is he not the celebrated author of *The Dynamics of an Asteroid*, a book which ascends to such rarefied heights of pure mathematics that it is said that there was no man in the scientific press capable of criticizing it?
— Sherlock Holmes, The Valley of Fear



https://commons.wikimedia.org/wiki/File:InnerSolarSystem-en.png, public domain, granted usage for any purposes

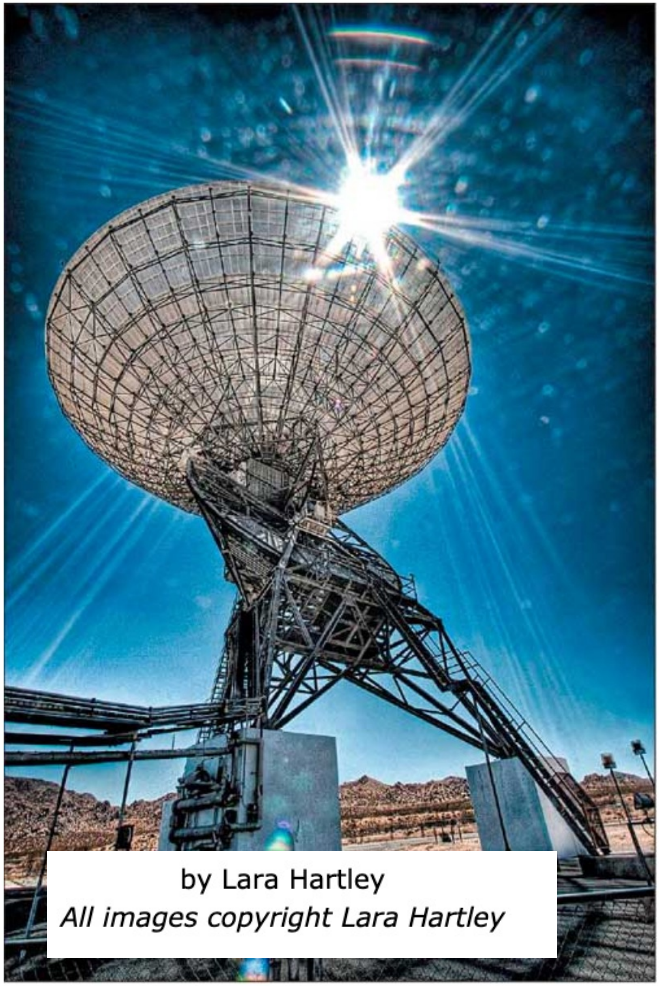
Radar Observations

- Radar – **Goldstone Observatory**: Provide very precise location and velocity information of the asteroids

- **Radar astronomy:** observing nearby astronomical objects by reflecting microwaves off target objects and analyzing the reflections.

- **Round-trip light time (RTLT):** The elapsed time taken by a signal travelling from the Earth to a spacecraft or other celestial body

- **Doppler shift:**



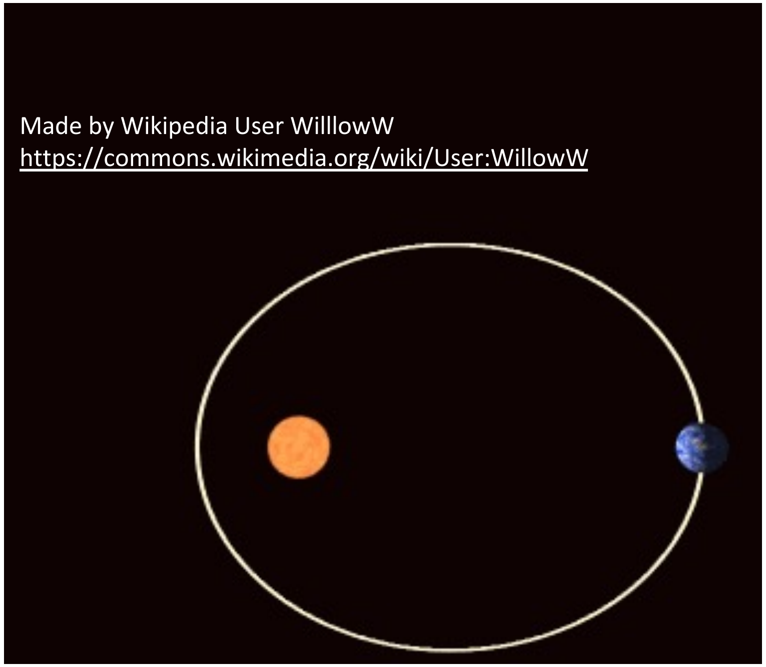
Students can control the huge Echo radio telescope to collect data from objects in the universe at which the antenna is pointed.

https://www.desertusa.com/desert-california/goldstone-deep-space.html

By Charly Whisky, CC BY-SA 3.0
https://en.wikipedia.org/wiki/Doppler_effect#/media/File:Dopplerfrequenz.gif

Perihelion Precession: Einstein's Success

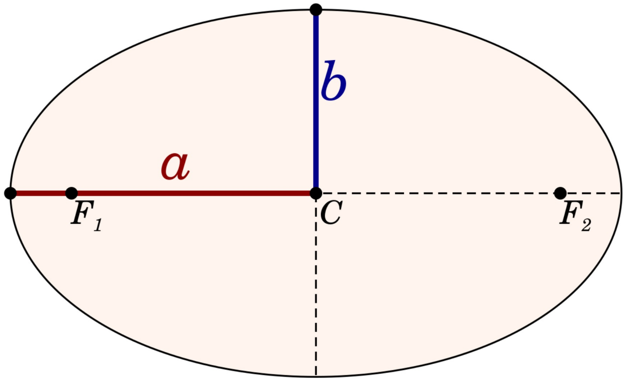
Precession of Mercury's perihelion (closest point to the Sun)



https://en.wikipedia.org/wiki/Apsidal_precession#/media/File:Precessing_Kepler_orbit_280frames_e0.6_smaller.gif under CC BY 3.0

$$\frac{\mathrm{d}^2u}{\mathrm{d}\varphi^2} + u - \frac{GM_\odot}{L^2} = \boxed{\frac{3GM_\odot}{c^2}u^2.}$$ **(GR)**

- Consider planar motion and fix θ = π/2.
- Define inverse radius variable u ≡ 1/r = u(φ)
- $a = \frac{L^2}{M_\odot(1-e^2)}$, a is the semi-major axis



M. W. Toews (CC0)

5^{th} force and Yukawa Potential

$$V(r) = \widetilde{\alpha}\frac{GM_\odot M_*}{r}\exp\left(-\frac{r}{\lambda}\right),$$

$$V(r) = \mp\frac{g^2}{4\pi}\frac{Q_\odot Q_*}{r}\exp\left(-\frac{mc^2}{\hbar c}r\right),$$

$$\frac{d^2u}{d\varphi^2} + u - \frac{GM_\odot}{L^2} = \frac{3GM_\odot}{c^2}u^2 + \boxed{\widetilde{\alpha}\frac{GM_\odot}{L^2}\left(1+\frac{1}{\lambda u}\right)e^{-\frac{1}{\lambda u}}},$$

(fifth force)

- Gauge boson, dark photon of $U(1)_B$ or scalar coupled to baryon number
- g is new physics coupling constant, and m is the mediator mass
- See, e.g., Poddar et al, https://arxiv.org/abs/2002.02935

Ultralight Bosons

1. **Spin 0: ultralight scalars coupled to Standard Model particles**

$$\mathcal{L}_\phi \subset (g_{\phi,p}\bar{p}p + g_{\phi,n}\bar{n}n + g_{\phi,e}\bar{e}e)\phi$$

2. **Spin 1: Dark photon of gauged $U(1)_B$,**
   with coupling g_A, charging all baryons equally
   charge: $q_p = q_n = 1$

$U(1)_B$ has chiral anomaly, so extra heavy particle is needed,
and there may be additional constraints & model building needed for those constraints
(Constraints: Dror, Lasenby, Pospelov, arXiv:1705.06726, arXiv:1707.01503)
(Models to alleviate bounds: Green, Schwarzy, PLB 87, Kaplan, NPB 91)

3. Our study can also be applied to $U(1)_{B-L}$, $L_e - L_{\mu,\tau}$, etc. ,
   Need to understand the asteroid compositions for these.

Precession (Analytical) at Low-Mass Limit

$$|\Delta\varphi_{\phi,A'}| \simeq \frac{2\pi}{1+\frac{g^2}{4\pi G m_p^2}} \frac{g^2}{4\pi G m_p^2} \left(\frac{amc}{\hbar}\right)^2 (1-\mathrm{e}) \,.$$

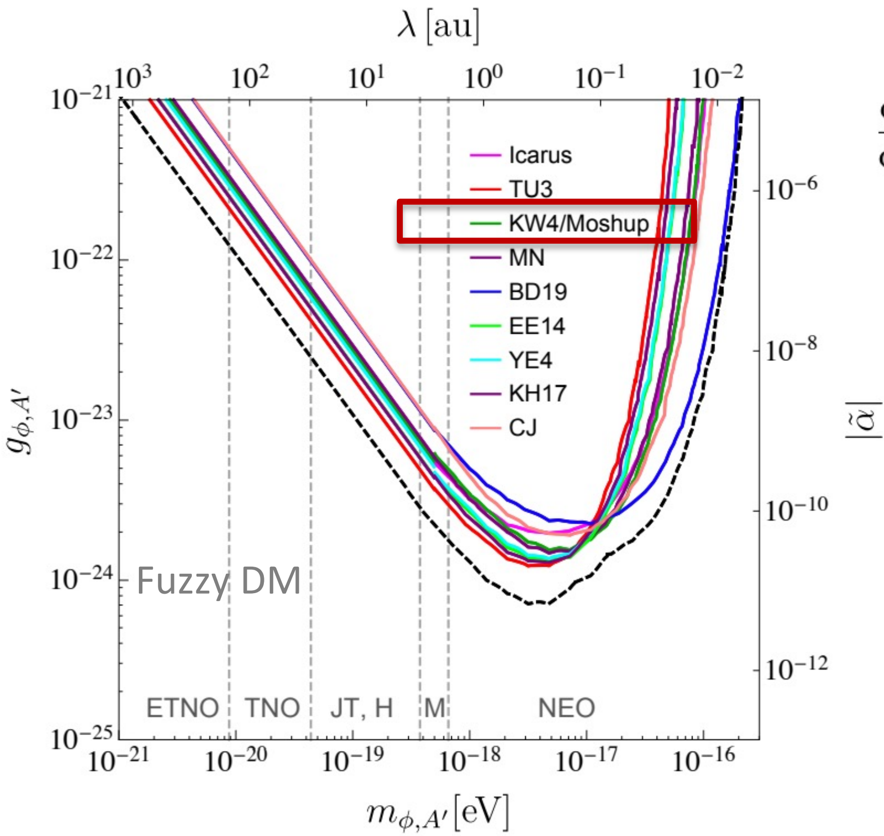
(fifth force)

$$\Delta\varphi_0 = \frac{6\pi G M_\odot}{a(1-\mathrm{e}^2)c^2}\left[\frac{2-\beta+2\gamma}{3}\right]$$

(GR)

- **m_p is proton mass**
- **for low mass, m << 1/ a (Natural Unit)**
- **The term gets larger with a**
- That's why we should explore **objects further away from the Sun:** not just Mercury or other planets
- **Not depending on target celestial bodies' mass**

Results for the new physics



$$\frac{\mathrm{d}^2u}{\mathrm{d}\varphi^2}+u-\frac{GM_\odot}{L^2}=\frac{3GM_\odot}{c^2}u^2+\tilde{\alpha}\frac{GM_\odot}{L^2}\left(1+\frac{1}{\lambda u}\right)e^{-\frac{1}{\lambda u}}, \quad (3)$$

Recast

$$\sigma_\beta = 5.6\times 10^{-4},$$

Verma, Margot, Greenberg, APJ '17

Optimal 2022 results,

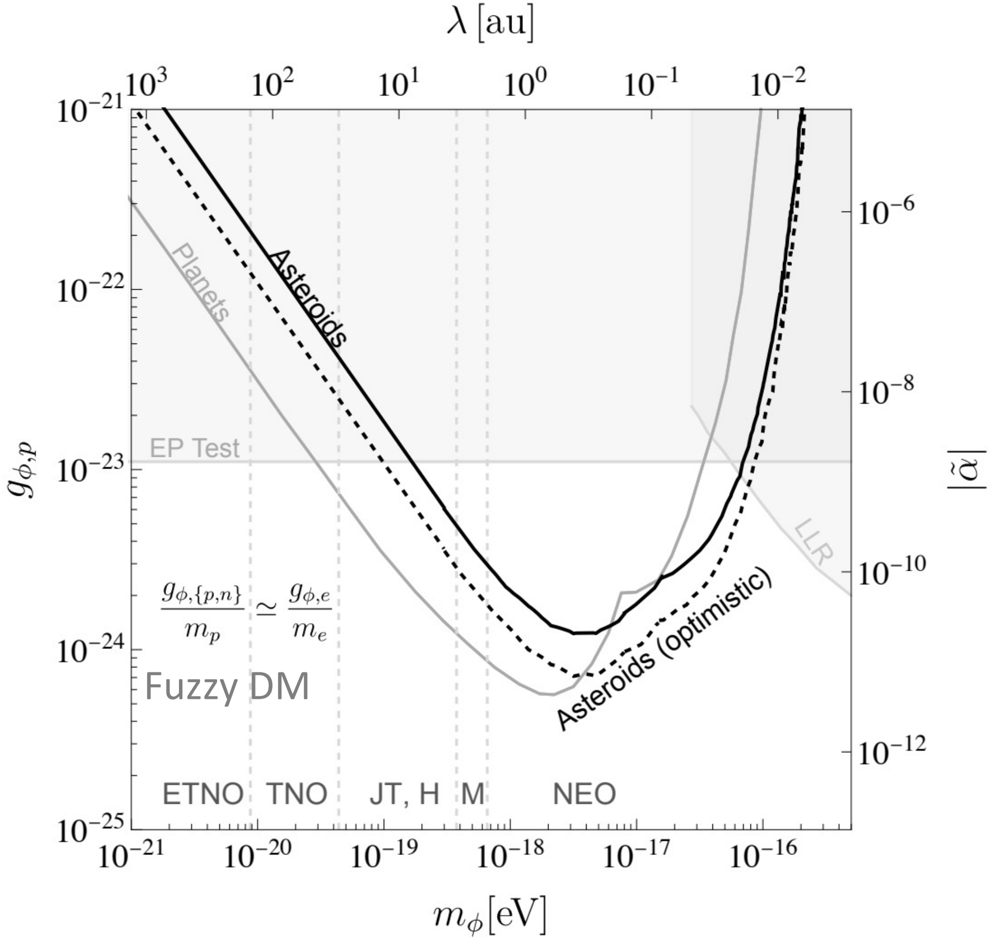
$$\sigma_\beta \sim 2\times 10^{-4},$$

Best reach:
TU3, MN, BD19

$$\Delta\varphi^2_{\phi,A'} < \left|\frac{\partial\Delta\varphi_0}{\partial\beta}\right|^2\sigma_\beta^2+\left|\frac{\partial\Delta\varphi_0}{\partial J_2}\right|^2\sigma_{J_2}^2+2\rho\left|\frac{\partial\Delta\varphi_0}{\partial\beta}\,\frac{\partial\Delta\varphi_0}{\partial J_2}\right|\sigma_{J_2}\sigma_\beta\,.$$

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

Asteroid Constrain EP Conserving 5th forces

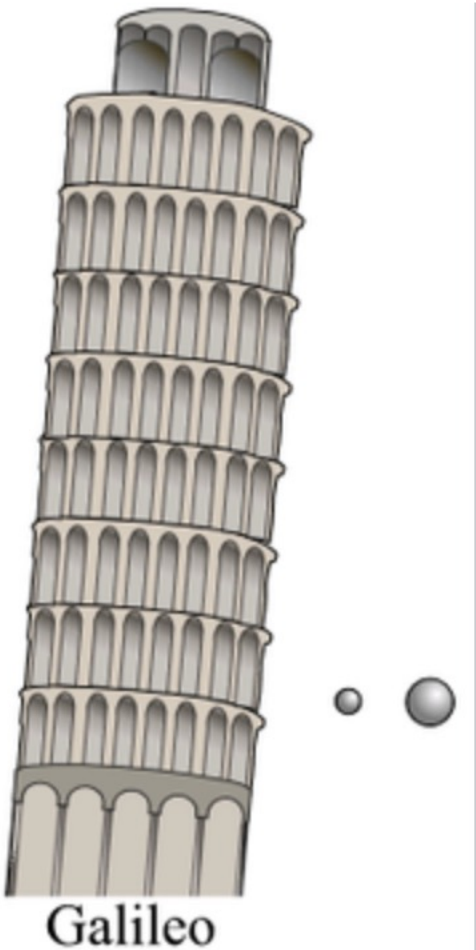


- **LLR: Lunar Laser Ranging**
  Williams, Turyshev, Boggs, PRL 04
- **Planets:**
  Poddar, Mohanty, Jana, EPJC 21
- **Asteroidal / Planetary / Lunar Probes are the strongest for equivalence principle conserving fifth forces.**

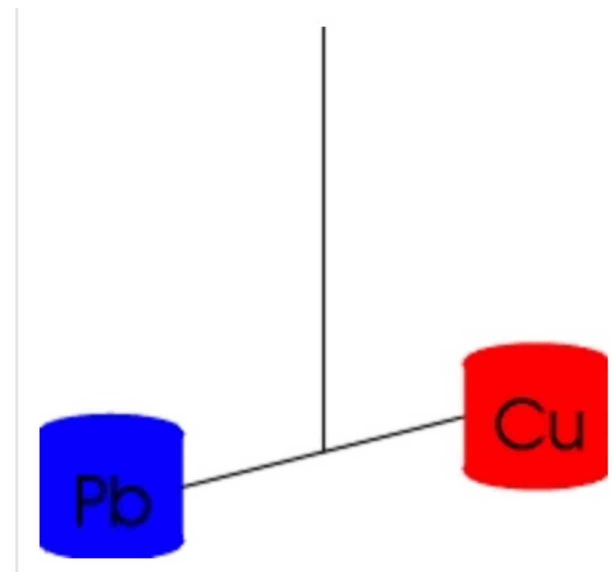
Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

We are conducting a **detailed study** using **MONTE** with people from **JPL & ESA**

Torsion Balance: Modern-Day Tower of Pisa experiment

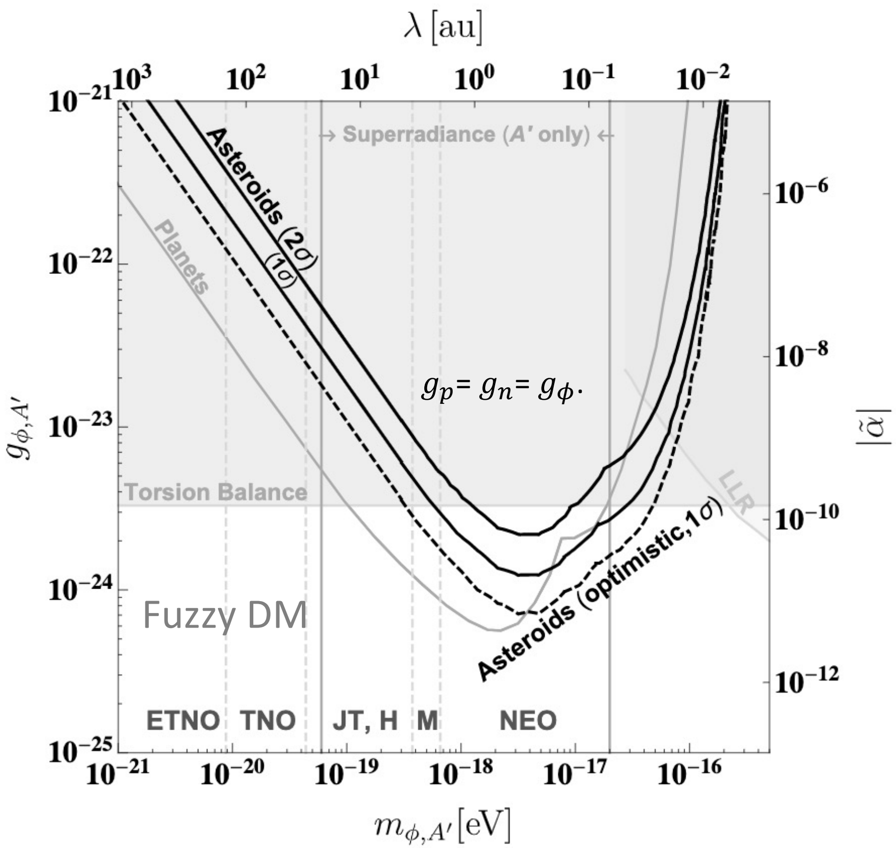


Wikipedia



The Eöt-Wash Group, University of Washington
https://www.npl.washington.edu/eotwash/torsion-balances

Equivalence Principle-Breaking Fifth Forces



- **Best reach: TU3, MN, BD19**
- **Torsion Balance Exp:** Schlamminger, Choi, Wagner, Gundlach, Adelberger, PRL 08
- **Superradiance:** Baryakhtar, Galanis, Lasenby, and Simon, PRD 21
- **LLR: Lunar Laser Ranging** Williams, Turyshev, Boggs, PRL 04
- **Planets:** Poddar, Mohanty, Jana, EPJC 21

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

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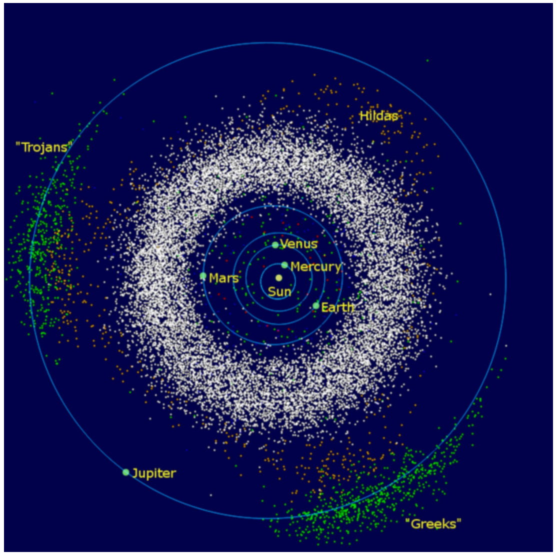
Future objects of interest

Minor Planets	a [au]	$\sim$ Numbers
Near-Earth Object (NEO)	$< 1.3^*$	> 25000
Main-Belt Asteroid (M)	$\sim 2 - 3$	$\sim$ 1 million
Hilda (H)	3.7 - 4.2	> 4000
Jupiter Trojan (JT)	5.2	> 9800
Trans-Neptunian Object (TNO)	> 30	2700
Extreme TNO (ETNO)	> 150	12

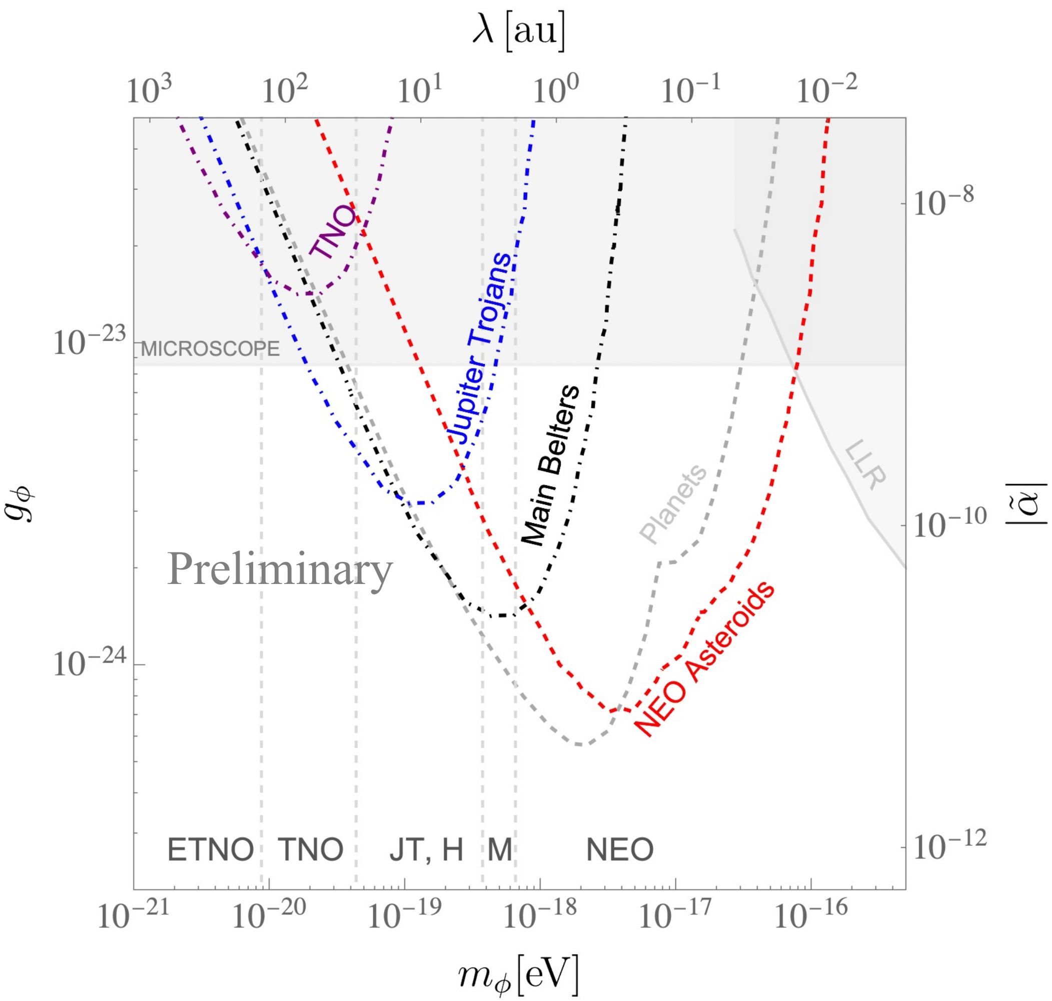
TABLE I. Targets for our future studies, for which exciting opportunities are provided by sheer numbers and observational programs, classified roughly based on their typical semi-major axes.
*NEOs are defined as having perihelia $a(1 - \mathrm{e}) < 1.3\,\mathrm{au}$.



$$|\Delta\varphi_{\phi,A'}| \simeq \frac{2\pi}{1 + \frac{g^2}{4\pi G m_p^2}} \frac{g^2}{4\pi G m_p^2} \left(\frac{amc}{\hbar}\right)^2 (1 - \mathrm{e})\,.$$

- Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038
- ***Can also probe dark matter, primordial black hole, etc***

Compilations of Various Probes



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Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

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Other Exciting Research Directions

- **Asteroidal/Planetary Tracking Array;** develop a tracking array to study bosonic ultralight dark matter (possible) and gravitational wave (difficult)
- **Model independent DM constraint**

- **Lunar Laser + Radar Ranging**
  LLR + **transponder**; **multi-messenger localization!**
  exploring ideas with Tim on probing lunar physics; with Asantha about LISA+
  Also, more collaborations with UCSD regarding LLR!

- **Q-SEnSE + SpaceQ informal meeting:**

Dan Scheeres, daniel.scheeres@colorado.edu
Hani Zaheer, hani@udel.edu
Jay McMahon, jay.mcmahon@colorado.edu
Marianna Safronova, msafrono@udel.edu
Penny Axelrad, penina.axelrad@colorado.edu
Yu-Dai Tsai, yt444@cornell.edu

Thank you.
Happy to discuss more!

Thank Josh, Marianna, Luca, Sunny, Youjia for comments

Outreach/Interview: https://www.youtube.com/watch?v=xDX9XwLHBuM (~58K views!)

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