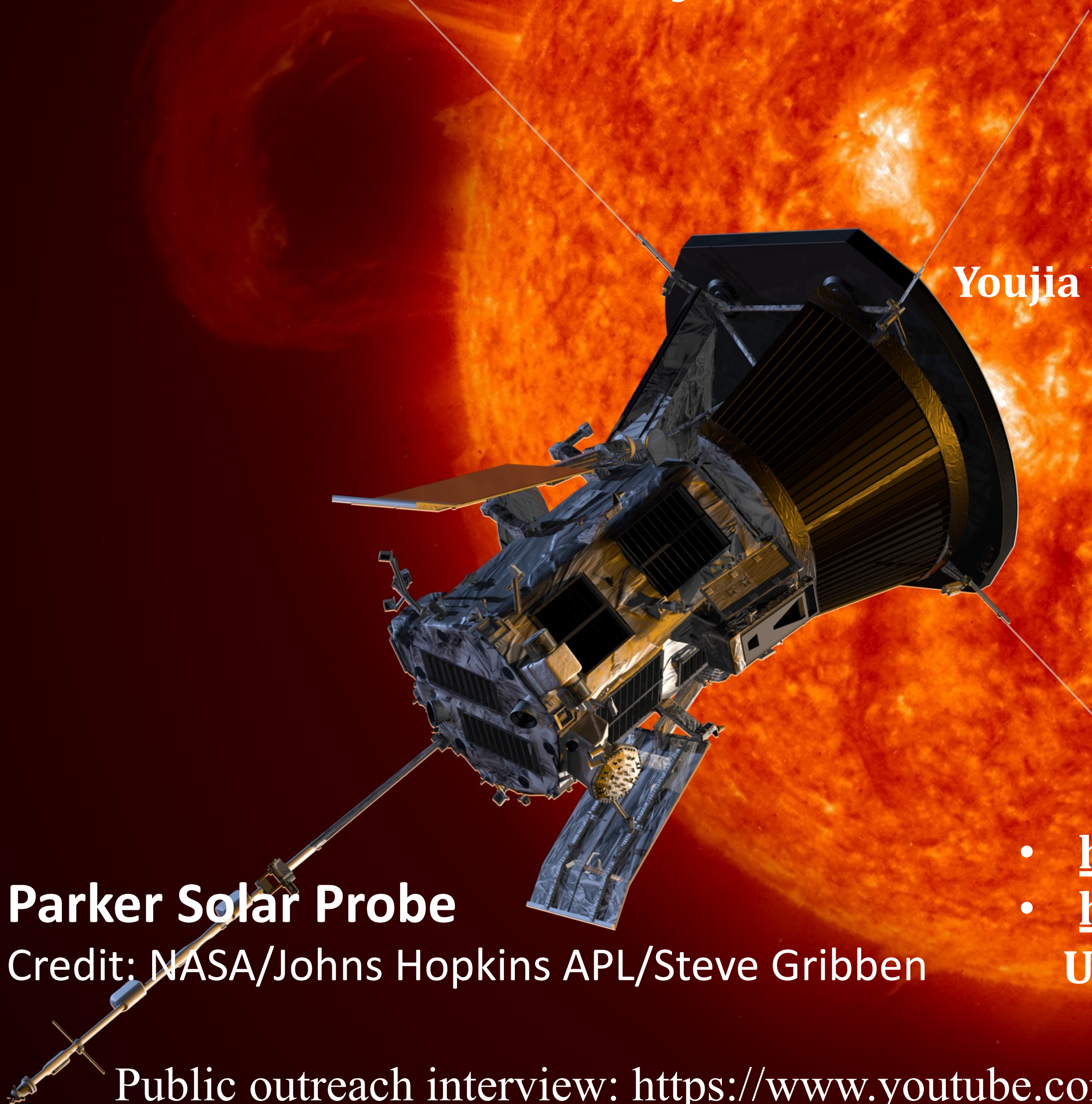
- Sorry, I eventually cannot make it to Pheno this year due to several travel/family complications

- I sincerely thank the organizers for the opportunity to present these works

- I attach my slides for your information.
  The original title is an ongoing work expected to be avaialble on arXiv in coming weeks

Planetary Defense & Space Quantum Technologies for Fundamental Physics

Yu-Dai Tsai
University of California, Irvine
with **Josh Eby, Marianna Safronova**
Youjia Wu, Sunny Vagnozzi, Luca Visinelli
Contact: yudait1@uci.edu &
yt444@cornell.edu



Parker Solar Probe
Credit: NASA/Johns Hopkins APL/Steve Gribben

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

Under review by Nature Astronomy

Public outreach interview: https://www.youtube.com/watch?v=xDX9XwLHBuM

Big Questions

- Can **planetary data** set meaningful constraints on
  Dark matter?
  General Relativity?
  5th forces?

- Can we use current or future **space quantum technologies** to study fundamental physics?

Answers

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

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

- **Robust analyses underway with NASA JPL codes & data**

Outline

- New Technologies & Ultralight Dark Matter
- Space Quantum Clocks & Sensitivity
- Planetary Defense & Fifth Forces
- Model-Independent Probes of **ANY** Dark Matter Candidates
(especially purely gravitational dark matter!)

Theme of this talk:

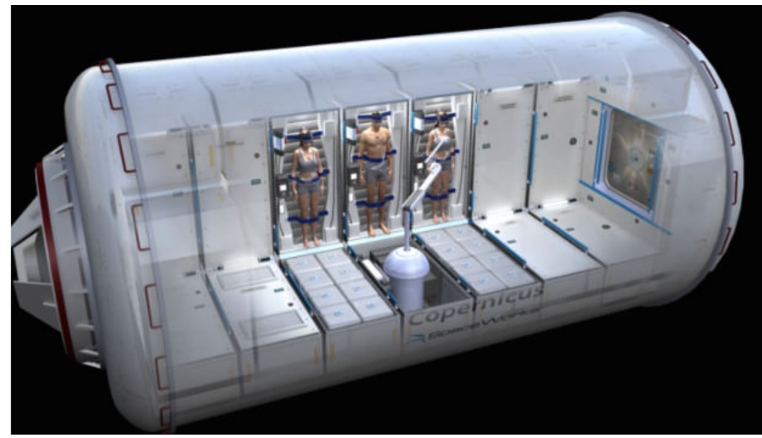
Bridging Planetary Science, Space/Quantum Technologies, and Fundamental Physics

Also, many real-life applications & consequences!

Sun Devils / Anteaters - Starship

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

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



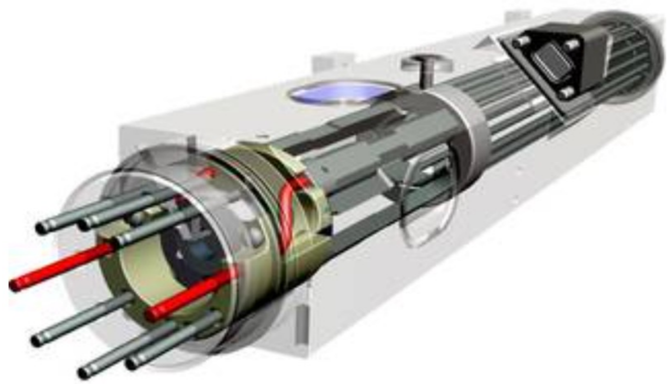
Artist's concept for Mars-ready habitat. Image Credit: SpaceWorks Torpor/NASA collaboration

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)

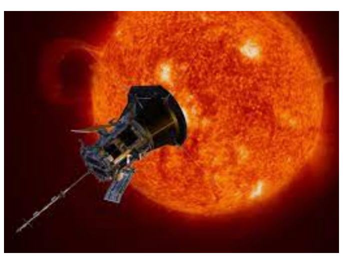
Can we use the technology to study fundamental physics?

NASA DSAC & Parker Solar Probe



- **Deep Space Atomic Clock loses one second every 10 million years**, as proven in controlled tests on Earth.
- The clock has operated for more than **12 months in space; demonstrated long-term fractional frequency stability of 3×10^{-15}**
  Burt, Prestage, Tjoelker, Enzer, Kuang, Murphy et al., Nature 595 (2021) 43.

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



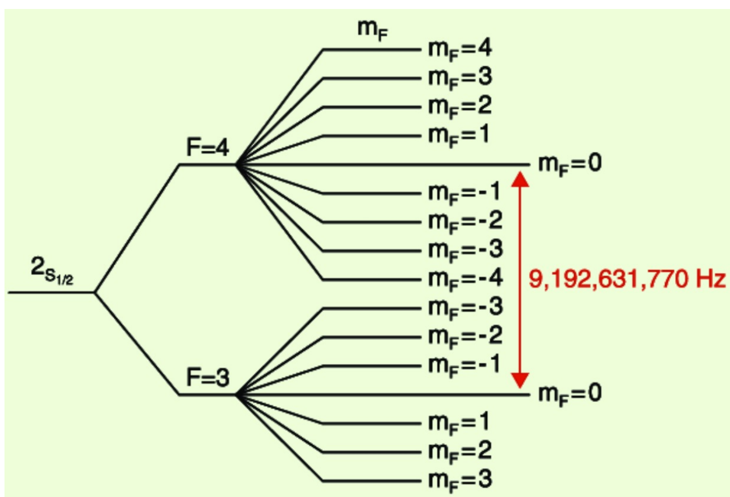
(1.0 m × 3.0 m × 2.3 m)

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

- **Why don’t we put a quantum clock on a solar probe? What can we do with that?**

Atomic Clock & Caesium Standard

- 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!

http://hyperphysics.phy-astr.gsu.edu/hbase/acloc.html
Reference: U.S. Naval Observatory, Cesium Clocks

Will use Natural Units for the talk,

$\hbar = 1$, $c = 1$

but recover the full unit in papers

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Outline

- Ultralight Dark Matter
- Space Quantum Clocks & Sensitivity
- Planetary Defense & Fifth Forces
- Model-Independent Probes of **ANY** Dark Matter Candidates
  (especially purely gravitational dark matter!)

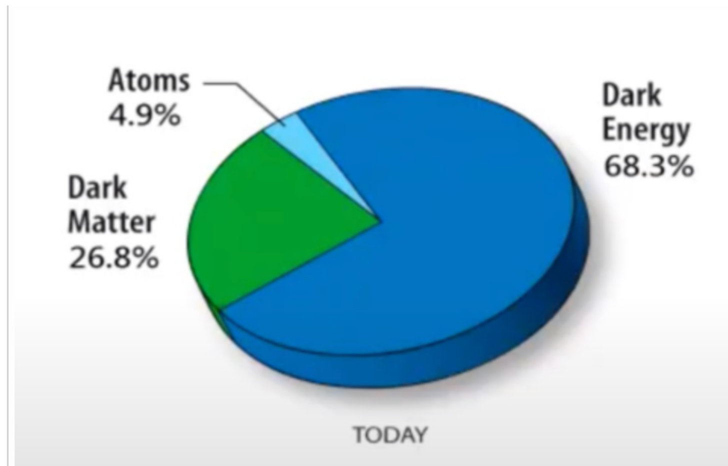
Wave-Like Particles as Dark Matter

$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv}$$

$$N_{\rm dB} \sim \left(\frac{34\,{\rm eV}}{m}\right)^4 \left(\frac{250\,{\rm km/s}}{v}\right)^3 \ {\rm in}\ \ \lambda_{\rm dB}^3$$

- For m << 30 eV, the occupancy NdB is so large that the particles are best described by classical waves
- like electromagnetism, a state with a large number of photons is described by the classical EM fields.

(Fuzzy) Dark Matter Candidate

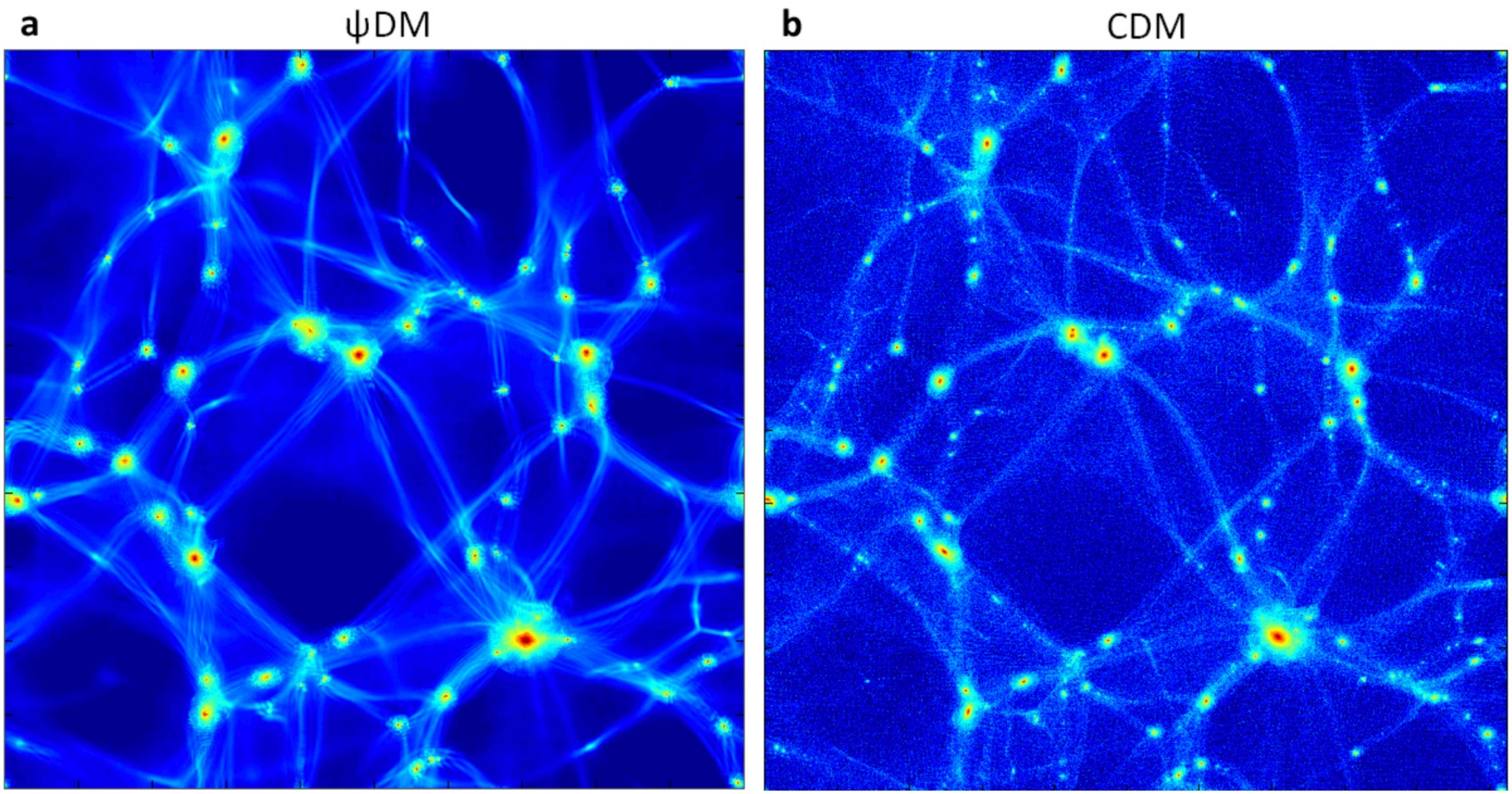


UC Riverside Physics Department
https://physics.ucr.edu/image/dark-matter-dark-energy-pie-chart

- Wave-like fuzzy dark matter candidate: hypothetical form of cold dark matter proposed to solve the cuspy halo problem.

- It would consist of extremely light scalar particles with masses go **as low as 10^{-22} eV (rough lower bound)**:
  de Broglie wavelength λ ∼ 1kpc: affect **structure formation.**

Ultralight Fuzzy Dark Matter



Schive, Chiueh, Broadhurst, Nature Physics '14 arXiv:1406.6586, demonstrated the large-scale structure of this ψDM simulation is indistinguishable from CDM, as desired, but differs radically inside galaxies.

Oscillation of Wave-like Scalars

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

Dark matter potential

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

(Non-relativistic solutions)

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

Oscillation frequency ~ dark matter mass

Dark Matter Coupling

Electrons photons gluons

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

Dark Matter

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.

Atomic Physics Probe

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

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

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

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,

$f_A \propto \alpha^{\xi_A+2}$, f is the frequency of a (clock) transition.

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

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

- **Experimental observable!** See arXiv:1405.2925, Arvanitaki, Huang, Tilburg, PRD 15
- For example, if **A is a hyperfine microwave transition and B is an electronic optical transition, ζA = 1 and ζB = 0.**
- Clock ($\sim$ **10^{-15} for DSAC**) stability translate to how well we can measure $\frac{\delta(f_A/f_B)}{f_A/f_B}$

Solar Bound-State Halo

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Scalar DM Halo

Stable solution can be supported by external potential

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

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

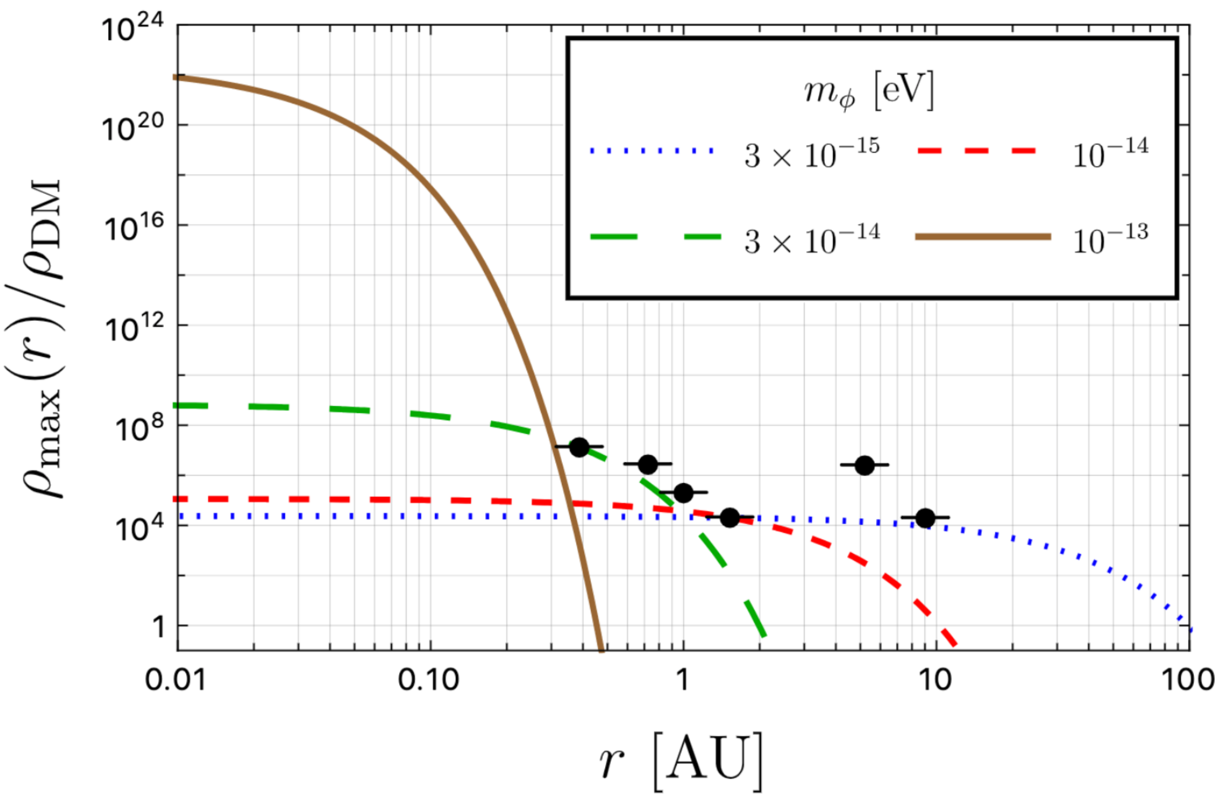
$$R_\star \simeq \frac{M_P^2}{M_{\rm ext}\, m_\phi^2},$$

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

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



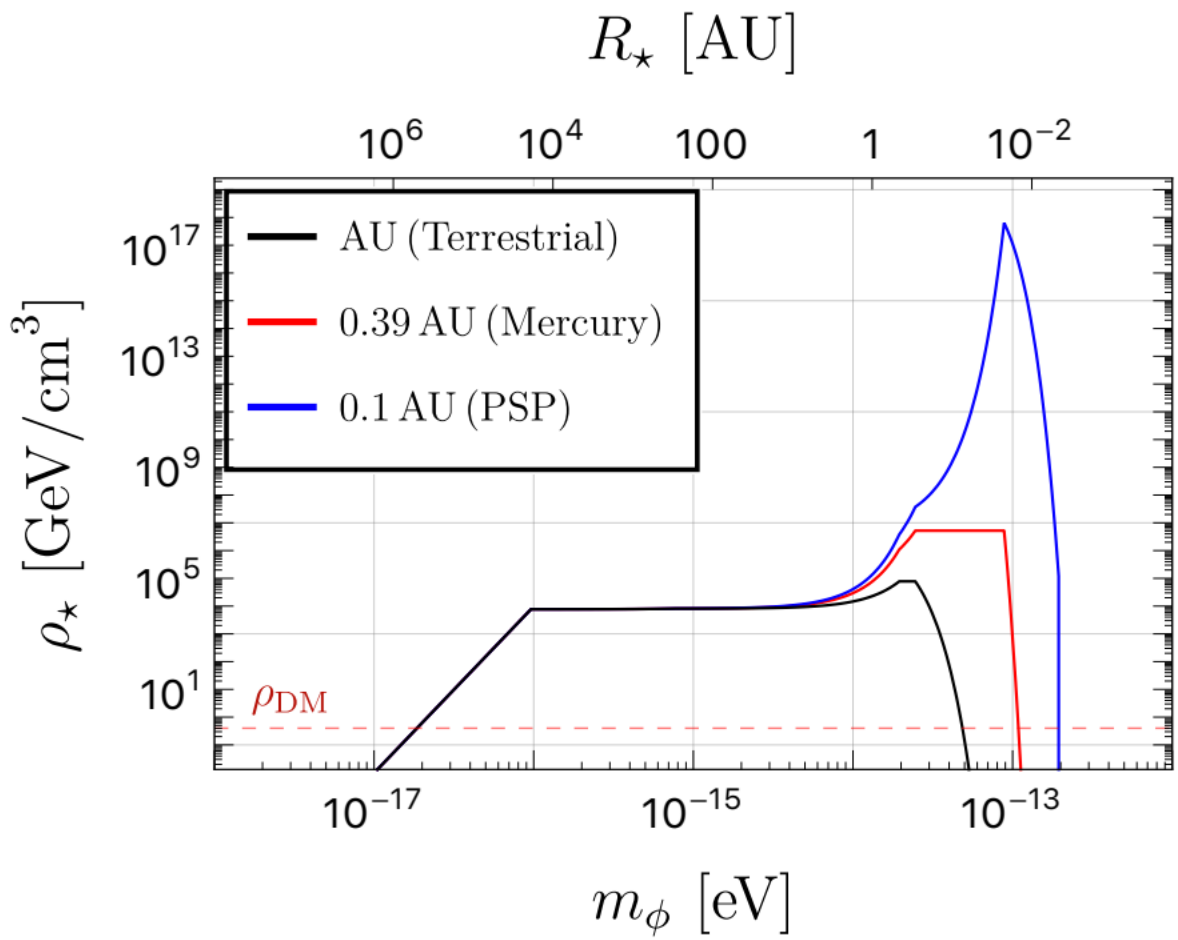
- **Black data points are model-independent constraints!**
- **Dark matter induce precessions to the planets**

Mercury, Venus, Earth, Mars, Jupiter, Saturn

Pitjev, Pitjeva, 1306.5534, Astronomy Letters ’13

Tsai, Eby, Safronova, 2112.07674

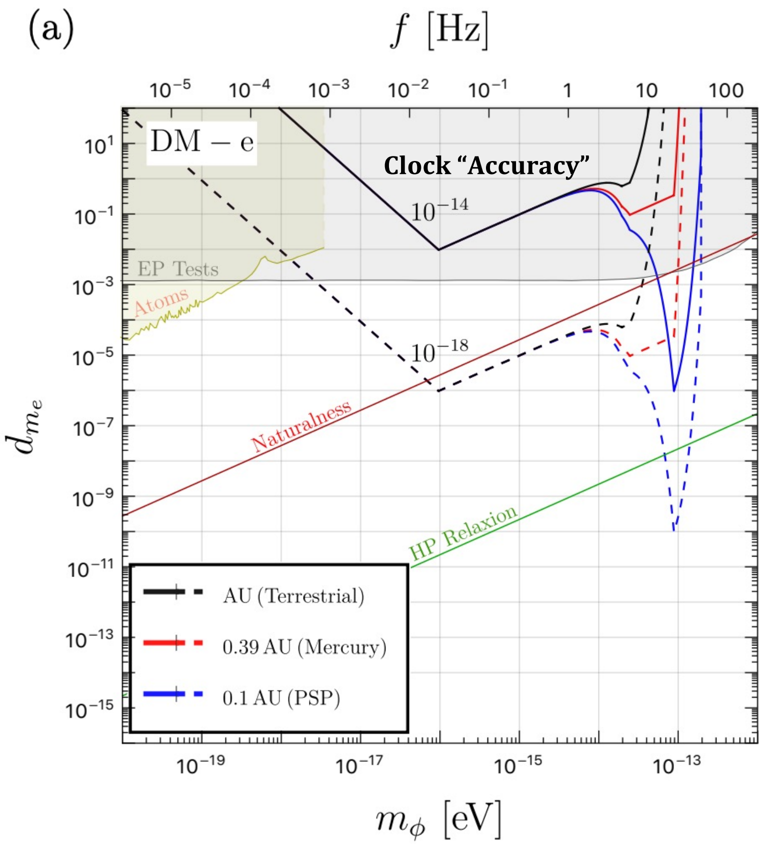
Enhancement of the DM Density

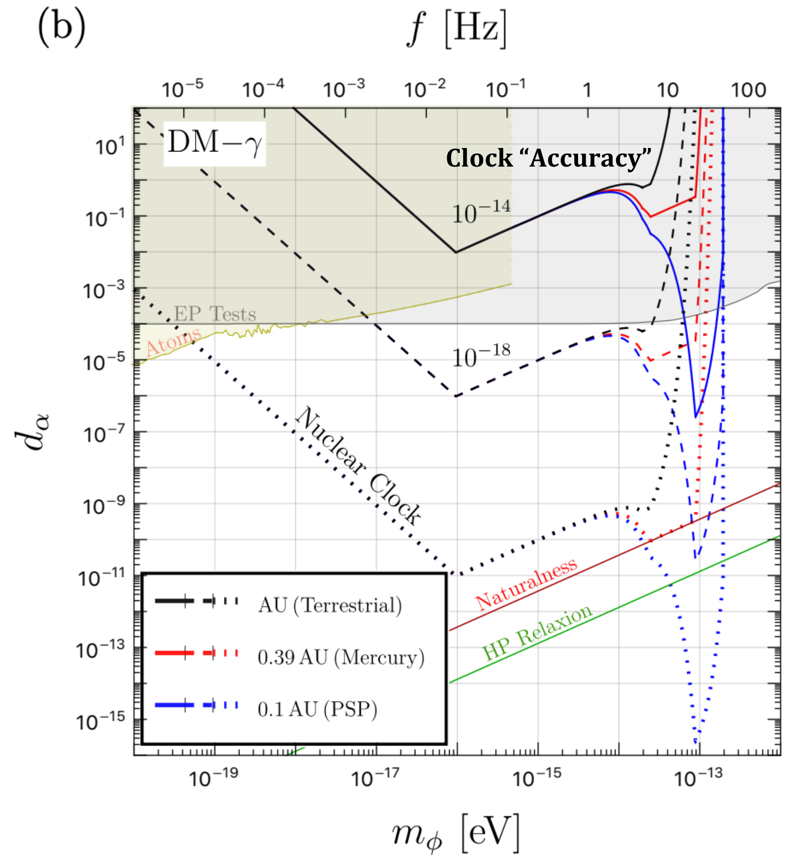


PSP: Parker Solar Probe

Tsai, Eby, Safronova, arXiv:2112.07674

Results





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

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

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

Naturalness condition

Relaxion Line

- For the Higgs portal-like theories, scalar couplings to matter are generated by mixing with the Higgs, and so can be parameterized by a relaxion **$\boldsymbol{\phi}$-higgs mixing angle sinθ;**

- One has g_e= y_e sinθ and $g_\gamma \sim$ (α/4πv) sinθ, where y_e is the Higgs Yukawa coupling to the electron, v is the Electroweak vacuum expectation value (??).

- The green line is assuming maximum relaxion-higgs mixing, which is of order $\boldsymbol{g_e \sim y_e\ (m_\phi/m_H)}$

- see, e.g. , Banerjee, Budker, Eby, Kim, Perez , 1902.08212 for more discussions.

Spatial Variation of Fundamental Constants

$$k_X \equiv c^2 \frac{\delta X}{X\,\delta U}. \quad X = \alpha,\, \mu,\, \text{or } m_q/\Lambda_{QCD}.$$

δU: change in gravitational potential .

$\delta U/c^2 \simeq 3.3 \times 10^{-10}$, Earth variation.

$\delta U/c^2 \sim 9 \times 10^{-8}$, from Earth to Solar probe at 0.1 AU.

- Achieve constraints on k_X that are a factor of $\sim$ 300 stronger!

More on the Planetary Constraints: Ultralight Dark Sector & Fifth Forces

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Extended SM Symmetries & Fifth Forces

Gauged $\boldsymbol{U(1)_{EM}}$ (Standard Model) ⟹ photons

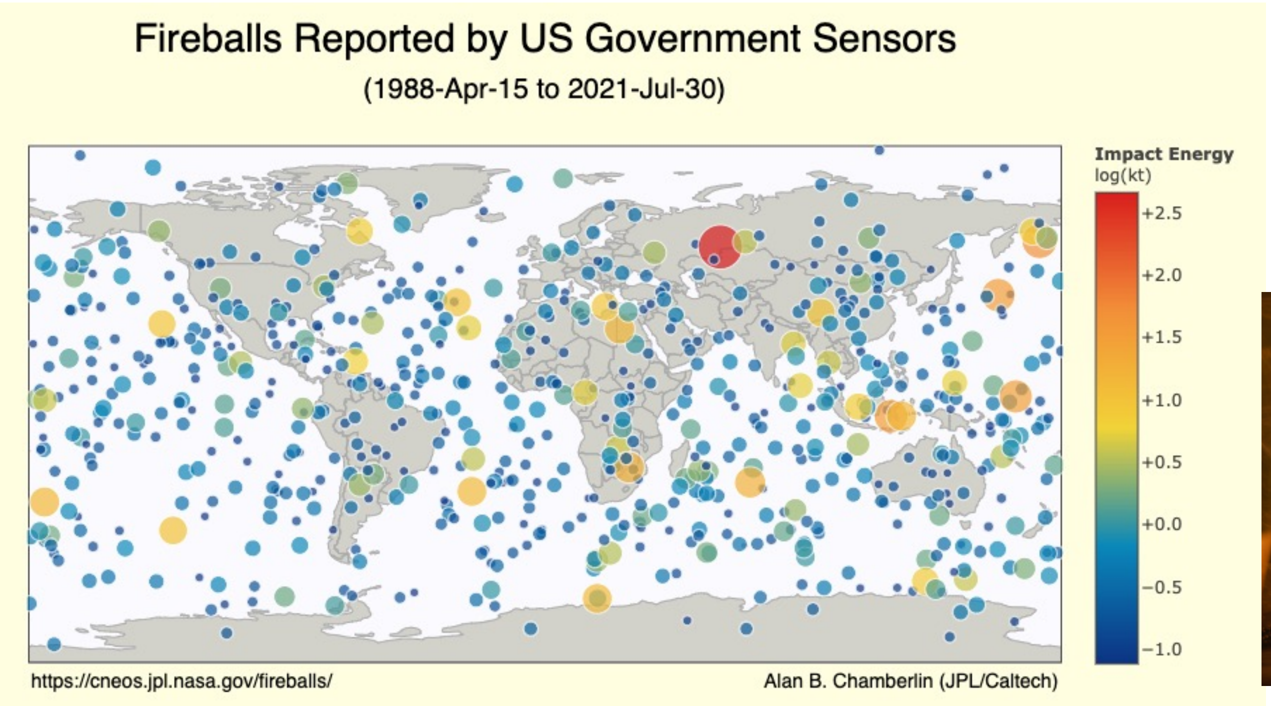
"Gauged" $\boldsymbol{U(1)_{X's}}$ (hypothetical) ⟹ "Dark" photons

- **X can be bayon number, lepton number, etc**:
  Standard Model Global Symmetries

- Motivated by baryogenesis (matter-anti matter asymmetry) & dark matter:

  The ultralight mediators **CAN** but does not have to be dark matter

Asteroids hitting the earth



~~Don't~~ Please Look Up

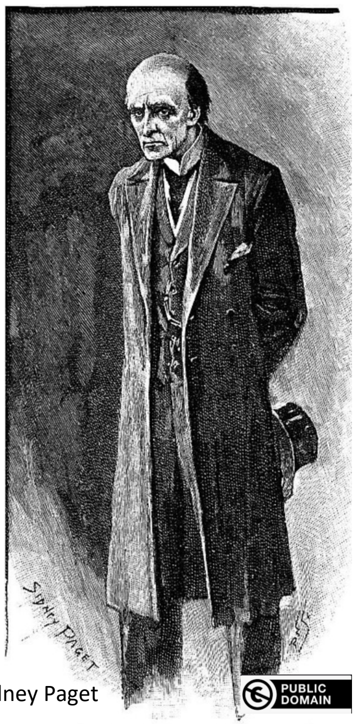
~ 65 million years ago

Tracking asteroids is extremely important

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

Also, near-Earth asteroid search accidentally found 'Oumuamua

Asteroids

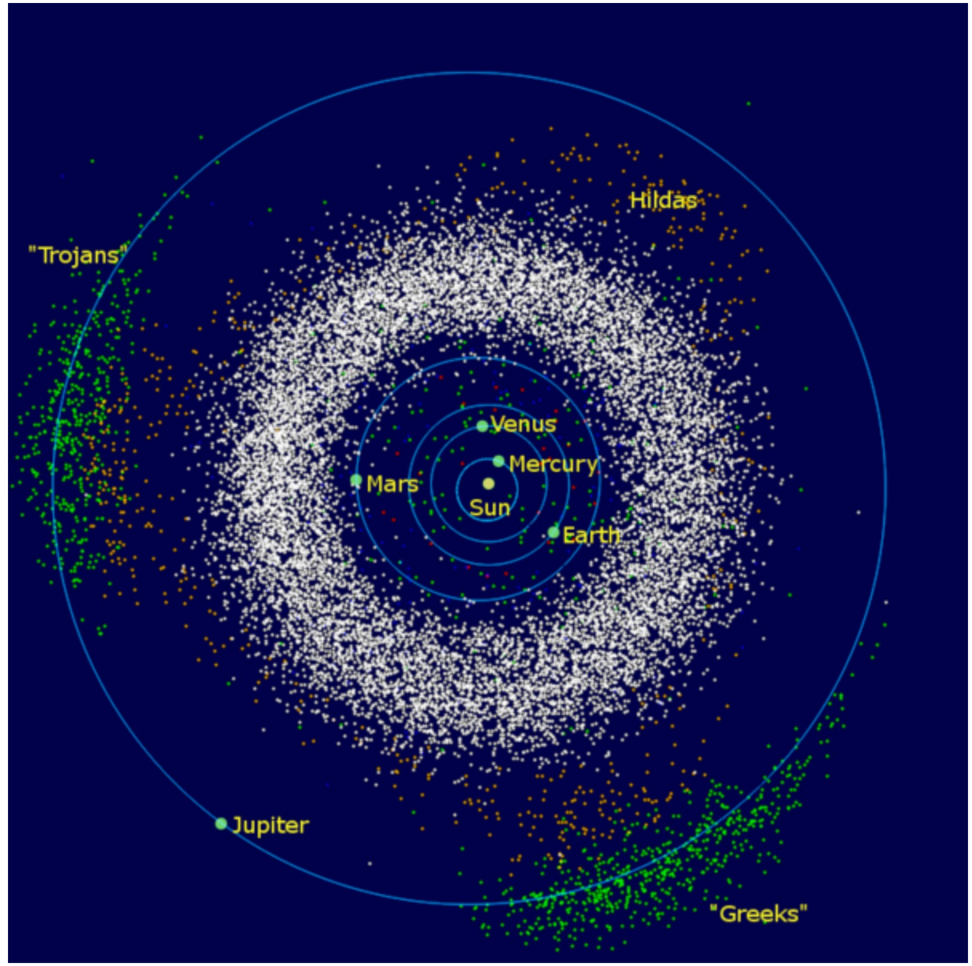


By Sidney Paget

" 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

"The mor hazardous the asteroids, the better for fundamental Physics"
-- Professor Moriarty (maybe)



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

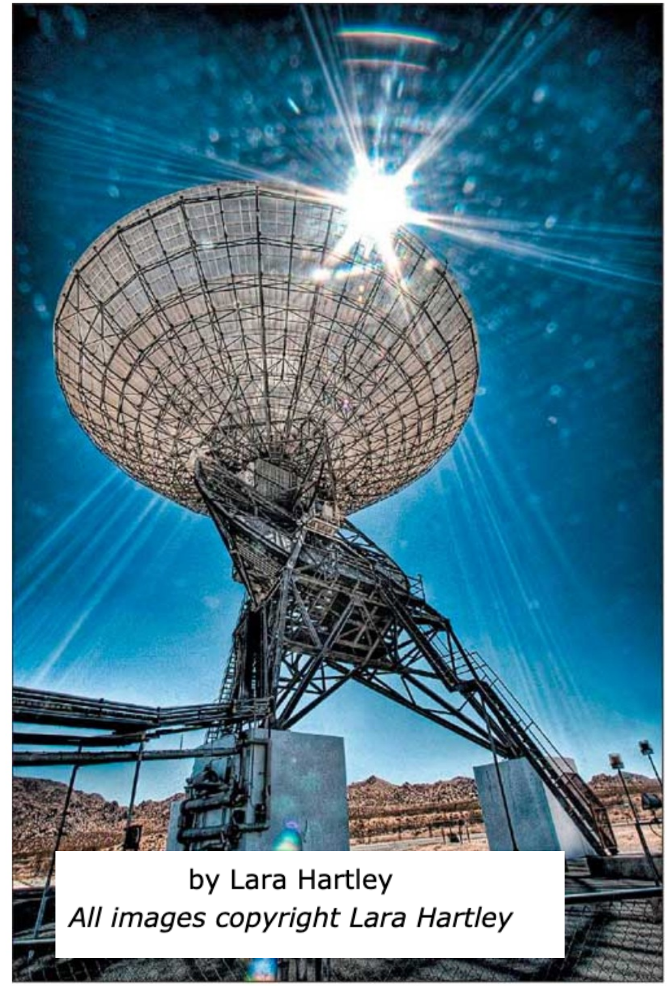
Radar Observations

- 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:**

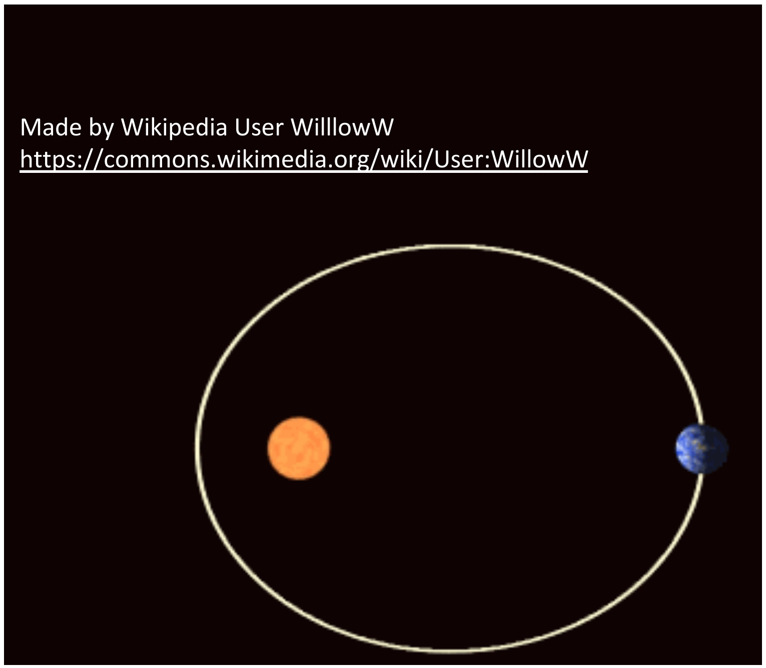


Students can control the huge Echo radio telescope to collect data from objects in the universe at which the antenna is pointed.

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

Perihelion Precession: Einstein's Success

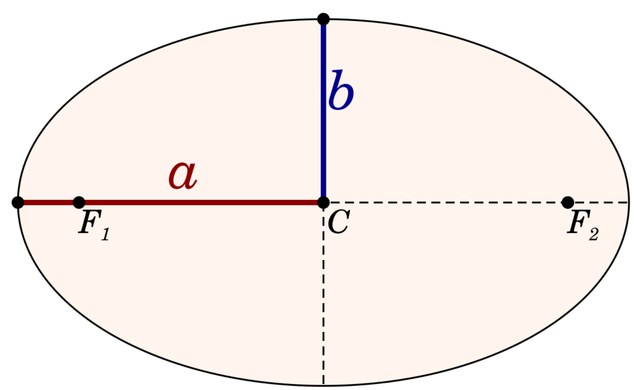
Precession of Mercury's perihelion (closest point to the Sun)



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

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

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

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

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

(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 $\boldsymbol{U(1)_B}$,**
   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 $\boldsymbol{U(1)_{B-L}, L_e - L_{\mu,\tau}}$, etc. ,
   Need to understand the asteroid compositions for these.

Precession (Analytical) at Low-Mass Limit

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

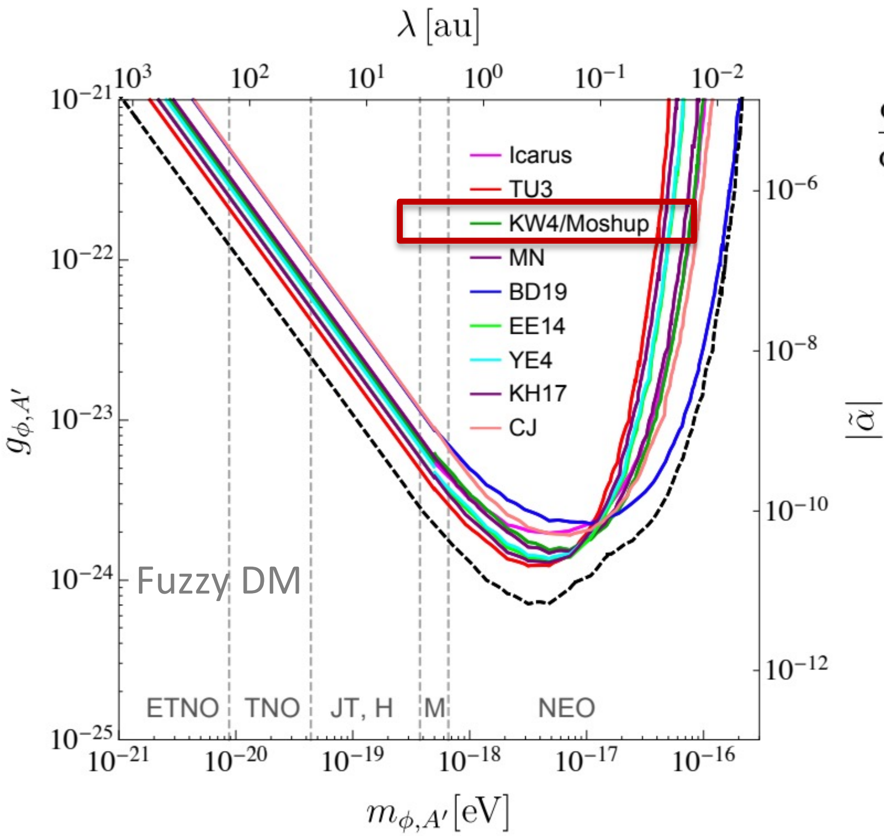
(fifth force)

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

(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



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

Recast

$\sigma_\beta = 5.6 \times 10^{-4}$, Verma, Margot, Greenberg, APJ '17

Optimal 2022 results,

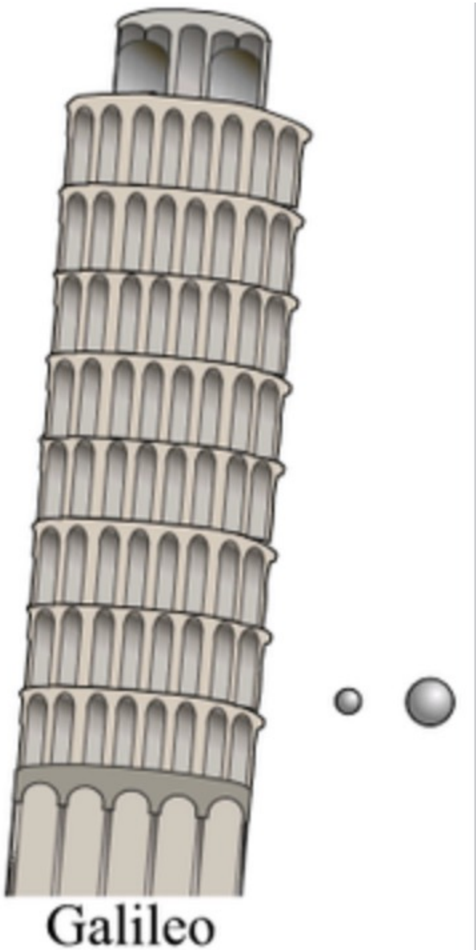
$\sigma_\beta \sim 2 \times 10^{-4}$,

Best reach:
TU3, MN, BD19

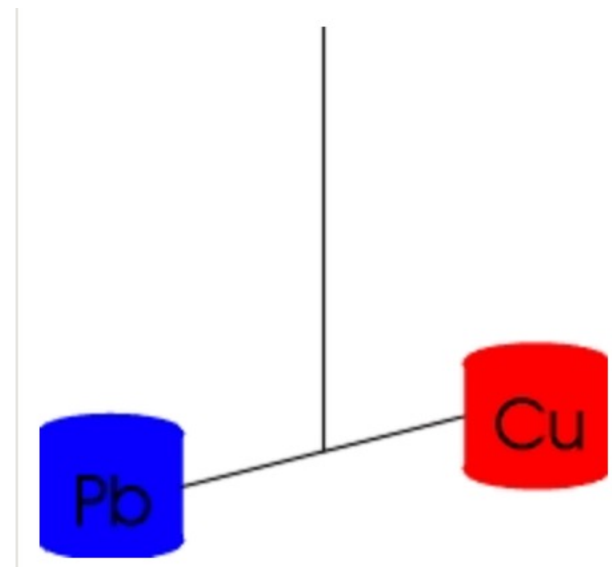
$$\Delta\varphi^2_{\phi,A'} < \left|\frac{\partial\Delta\varphi_0}{\partial\beta}\right|^2 \sigma_\beta^2 + \left|\frac{\partial\Delta\varphi_0}{\partial J_2}\right|^2 \sigma_{J_2}^2 + 2\rho\left|\frac{\partial\Delta\varphi_0}{\partial\beta}\,\frac{\partial\Delta\varphi_0}{\partial J_2}\right|\sigma_{J_2}\sigma_\beta\,.$$

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

Torsion Balance: Modern-Day Tower of Pisa experiment

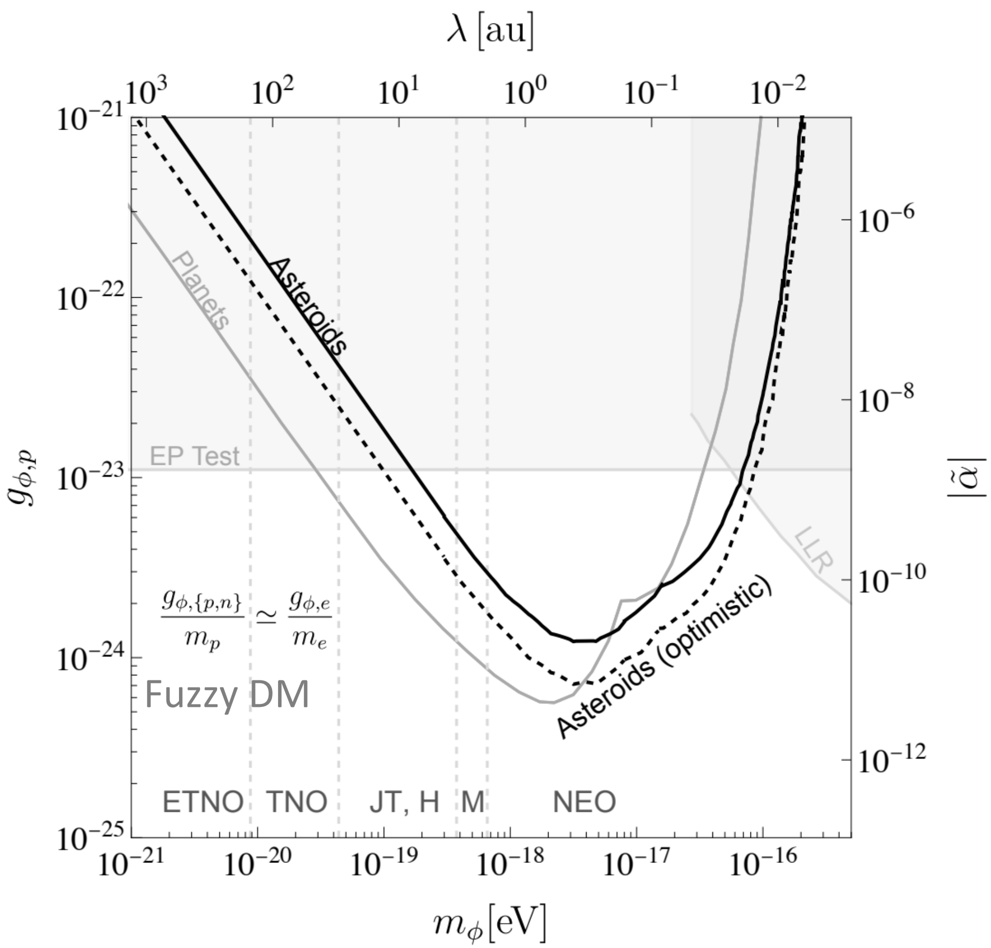


Wikipedia



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

Asteroid Constrain EP Conserving 5^{th} forces

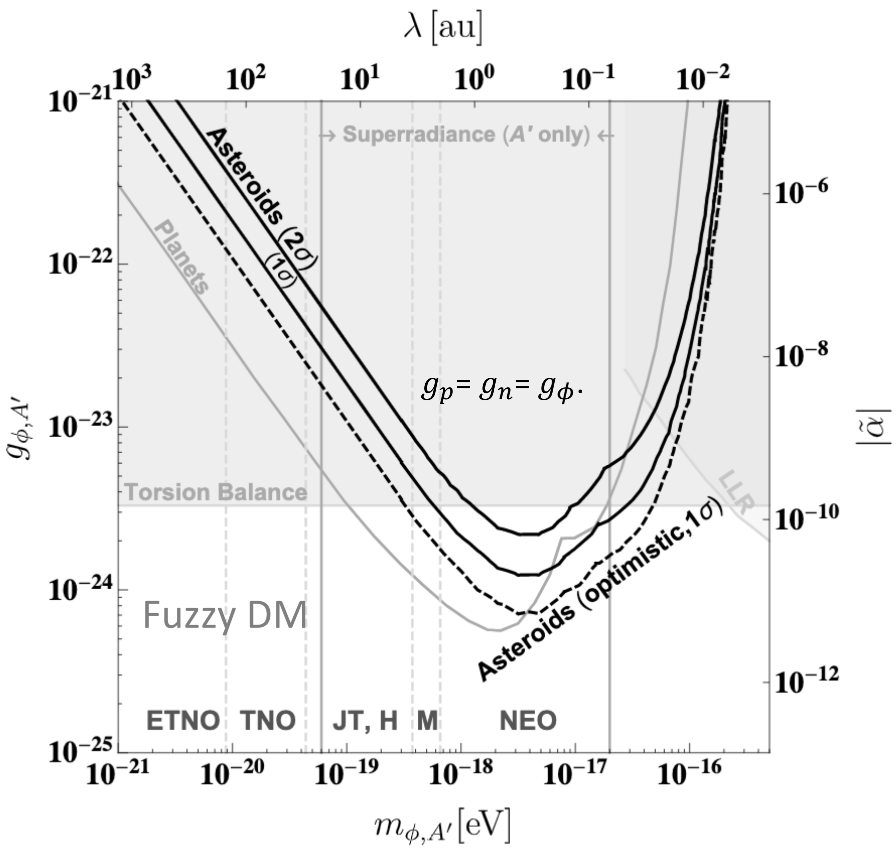


- **LLR: Lunar Laser Ranging**
  Williams, Turyshev, Boggs, PRL 04
- **Planets:**
  Poddar, Mohanty, Jana, EPJC 21
- **Asteroidal / Planetary / Lunar Probes are the strongest for equivalence principle conserving fifth forces.**

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

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

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

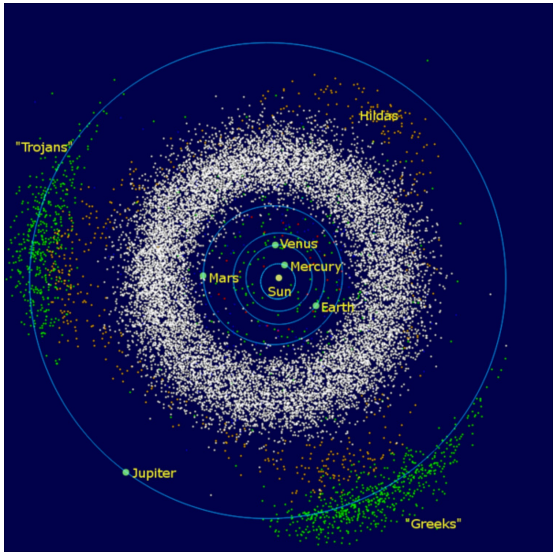
Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

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

Future objects of interest

Minor Planets	a [au]	$\sim$ Numbers
Near-Earth Object (NEO)	$< 1.3^*$	> 25000
Main-Belt Asteroid (M)	$\sim 2 - 3$	~ 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

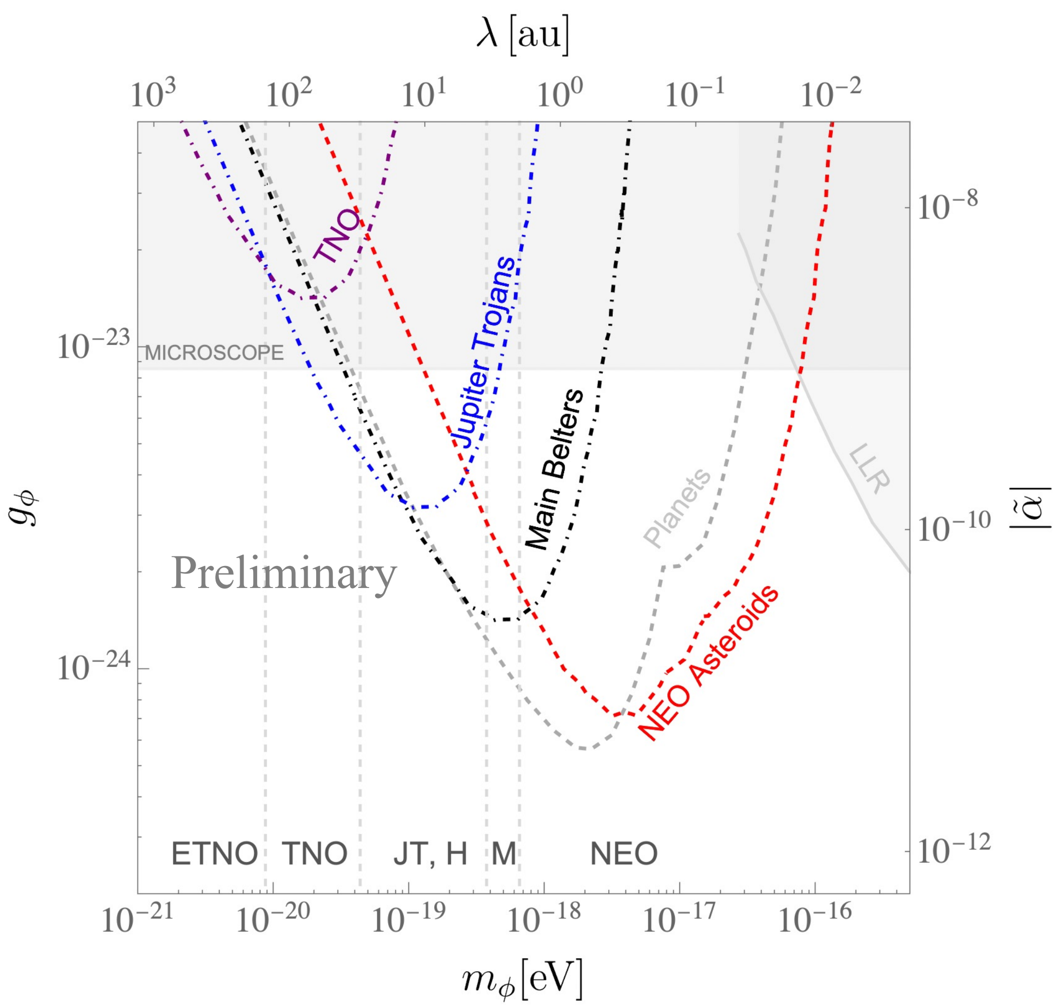
TABLE I. Targets for our future studies, for which exciting opportunities are provided by sheer numbers and observational programs, classified roughly based on their typical semi-major axes.
*NEOs are defined as having perihelia $a(1-\mathrm{e}) < 1.3\,\mathrm{au}$.



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

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

Compilations of Various Probes



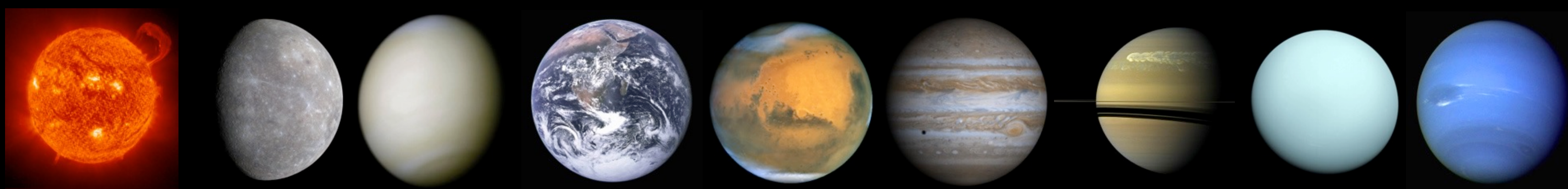
- **LLR: Lunar Laser Ranging**
  Williams, Turyshev, Boggs, PRL 04
- **Planets:**
  Poddar, Mohanty, Jana, EPJC 21
- **Asteroidal / Planetary / Lunar Probes are the strongest for equivalence principle conserving fifth forces.**

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

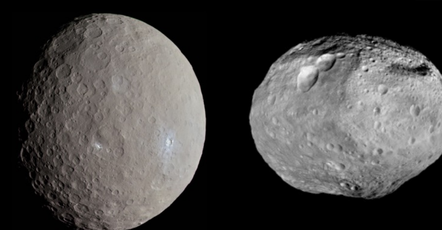
We are conducting a **detailed study** using **MONTE** with people from **JPL & ESA**

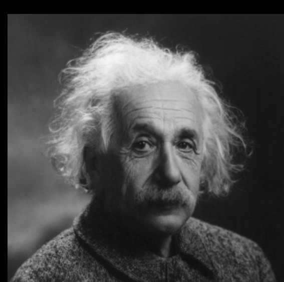
Robust Analysis (NEW): High-fidelity force model

JPL Planetary Ephemerides DE441



Small-body perturbers





PPN formulation for relativity

Oblateness, …

Dr. Davide Farnocchia’s (NASA, JPL) slide

Uncertainties

- Errors in planetary trajectories and masses
- Missing perturbers, errors in perturber masses & trajectories
- Higher order relativistic terms
- Higher order gravity terms
- Poynting-Robertson drag
- Simplifying assumptions in nongravitational force model (non-spherical effects, Yarkovsky, solar torque, physical parameter evolution, etc)
- Solar mass loss and solar wind
- Meteoroid impacts
- Spacecraft interaction
- Whatever else could be missing...

Dr. Davide Farnocchia’s (NASA, JPL) slide

Model-Independent Constraints on Dark Matter

Preliminary Results

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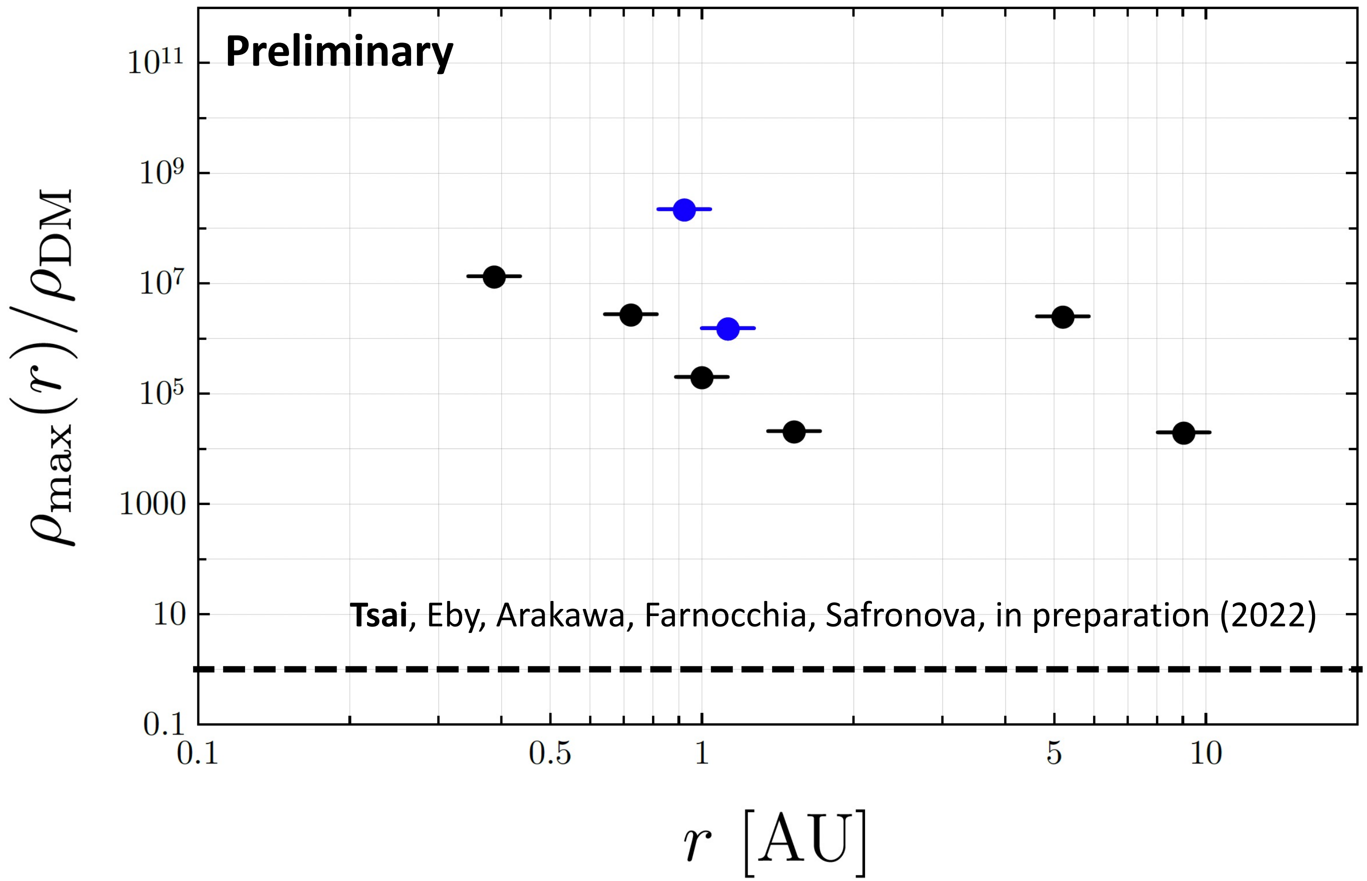
New Project: New Model Independent Constraints!



New project!

Improve the constraint with asteroid data! Model independent!

Tsai, Eby, Arakawa, Farnocchia, Safronova, in preparation

Preliminary results from NASA JPL code & collected data

More References

- Seto, Cooray, arXiv:0405216, PRD 04
- LLR Experiments: Williams, Turyshev, Boggs, PRL 04
  Murphy , Rept. Prog. Phys 13
- Atomic / nuclear clocks for fundamental physics:
  Peik, Schumm, Safronova, Pálffy, Weitenberg, Thirolf, 2012.09304
- GW background, Fedderke, Graham, Rajendran, PRD21
  GW measurement with atomic clocks, Fedderke, Graham, Rajendran, 2112.11431
- Quantum Technologies in Space, Kaltenbaek, Exp Astron 21

Some Upcoming Observations

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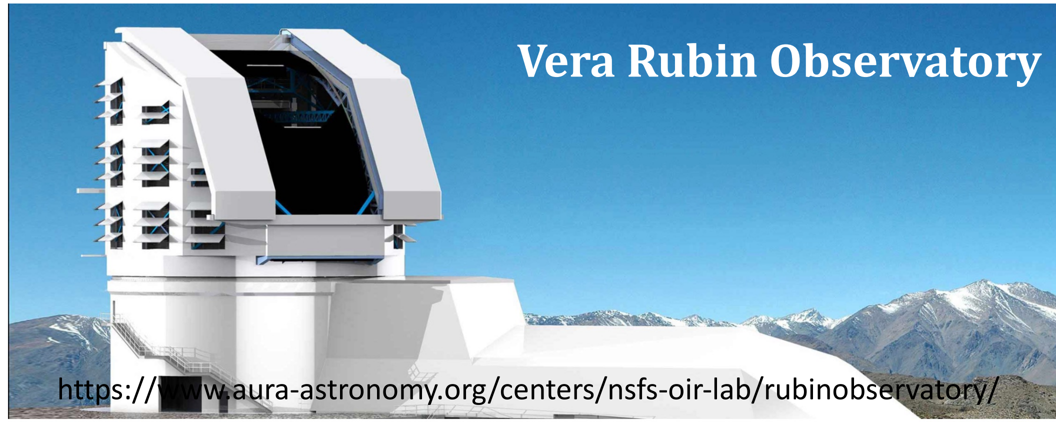
Space Mission & Telescopes

An artist's impression of the Lucy spacecraft performing a flyby of a Jupiter trojan.

NASA/SwRI and SSL/Peter Rubin - https://www.nasa.gov/press-release/nasa-selects-two-missions-to-explore-the-early-solar-system

Lucy is a planned NASA space probe that will complete a 12-year journey to seven different **asteroids. Human landing?**



A photograph and rendering mix of the exterior of the Vera C. Rubin Observatory building on Cerro Pachón in Chile. Image credit: Rubin Obs./NSF/AURA

- Optical – **Vera Rubin Observatory**: increase the **number of solar-system objects by 5 times**.

— Gaia mapping the stars of the Milky Way

Optical – **GAIA** provides stellar reference for asteroid localization

New Ideas for Discussions

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

- **Probing dark energy, f(G) Gauss-Bonett gravity, and other modified gravity theories**

- **Consider non-gravitational dark matter-SM interactions**

Big Picture & Outlook

- Bridging **planetary science, space (quantum) technology, and fundamental physics**

- **Our result is exciting now and has significant potential given the future measurements:**
  radar, **optical**, and **space missions** will bring tremendous progress!

- **Atomic clocks on the moon, spacecraft, satellite,**
  Asteroid Tracking Array, and Advanced Lunar Ranging:
  Many exciting projects forward!
  Collaborating with NIST, NASA, ESA, etc people on proposals

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Exciting Research Directions for Discussions

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

- **Interesting Projects with the Parker Solar Probe or Similar Solar Probes?**

- **Advanced Lunar Laser + Radar Ranging**
  LASER + transponder + quantum technology?

- **Quantum technologies in Space: Q-SEnSE + SpaceQ informal meeting**

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We can also discus & collaborate on …

- LHC Forward Experiments: Forward Physics Facility, FORMOSA (an experiment I proposed), with Feng et al, arXiv:2010.07941 (PRD 21)

- Dark matter model building (Dark sector QCD, Strongly Self-Interacting Dark Matter), arXiv:2008.08608 (PRL 22), arXiv:1512.04545 (PRL 16)

- Dark matter searches using neutron star / compact merger / multi-messenger astronomy, arXiv:2007.03686 (JCAP 21), arXiv:1706.00001 (PRD 18)

- Fixed-target searches for dark matter & long-lived particles (proposed new experiments to search for millicharged particles, i.e., FerMINI), arXiv:1812.03998 (PRD 18)

- Neutrino physics (cosmic neutrino background) & neutrino BSM, arXiv:2007.05513 (PRD 21)

Let’s protect the Earth & find dark matter;
happy to discuss more

Thank you!

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

Public outreach interview:
https://www.youtube.com/watch?v=xDX9XwLHBuM (> 73K views!)

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