New Model Independent Constraints on Dark Matter and Cosmic Neutrinos (while Protecting the Earth)

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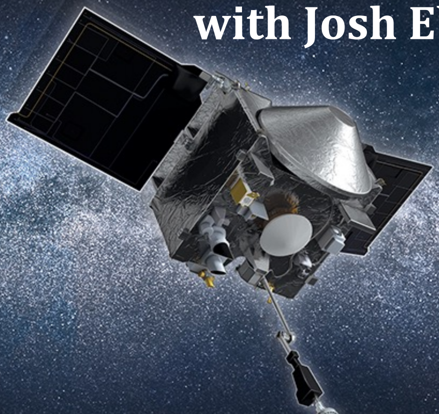
To appear on arXiv next week!



"There is always a possibility that ***dark matter effects can modify the trajectory of an asteroid****, which could wipe out all life on this planet. The only way these people can get on with their happy lives is that* ***they do not know about it****."* – An agent warned me about giving this talk.

NASA's OSIRIS-REx mission readies itself to touch the surface of asteroid Bennu.
Credits: NASA/Goddard/University of Arizona

SpaceQ – Direct Detection of Ultralight Dark Matter with Space Quantum Sensor

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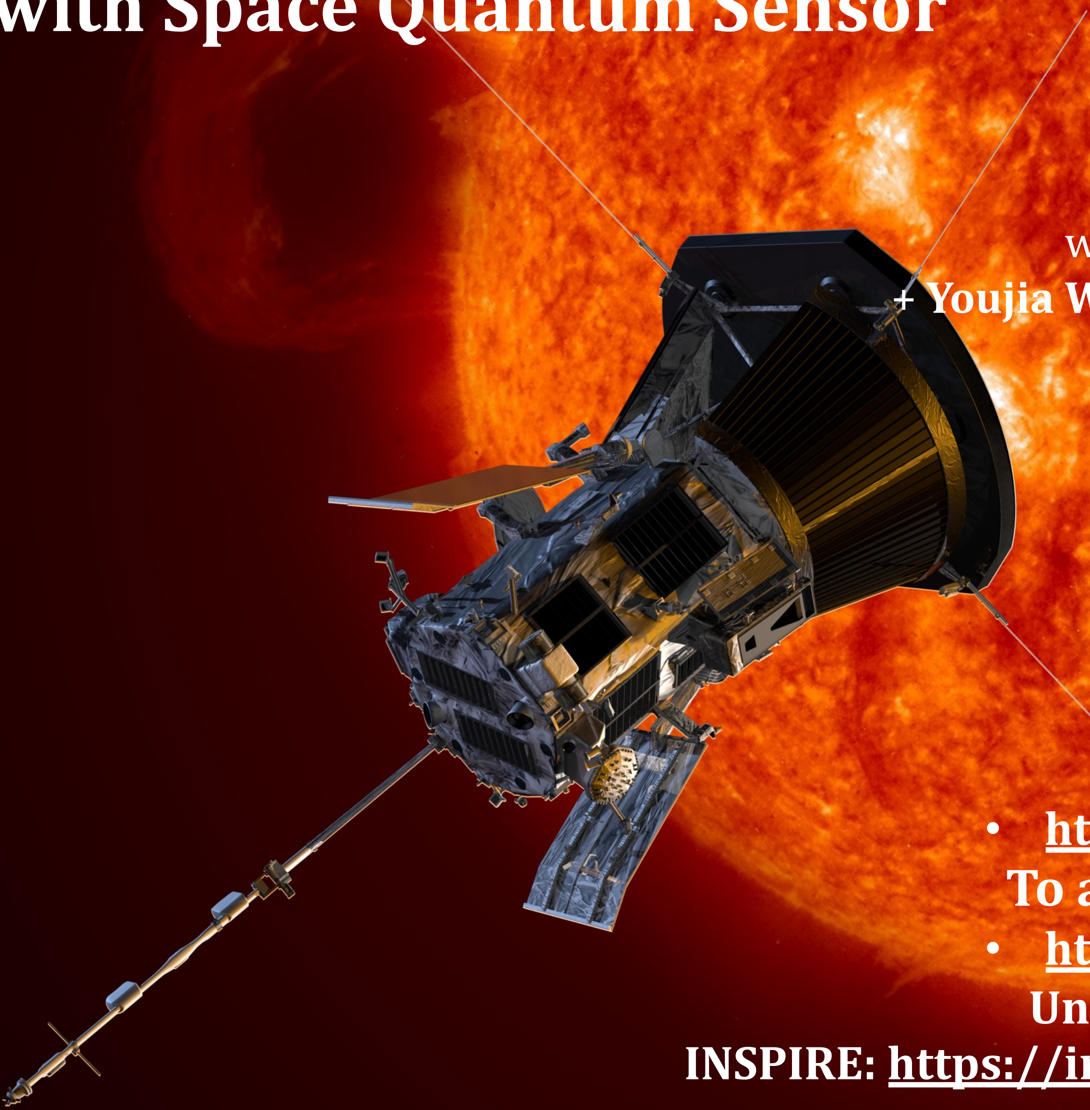


- **https://arxiv.org/abs/2112.07674**
  To appear on Nature Astronomy!
- **https://arxiv.org/abs/2107.04038**
  Under review by Nature Astronomy

INSPIRE: https://inspirehep.net/authors/1274923

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

Collaborations on Various Projects

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

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?

- Clustering mechanisms of purely gravitational dark matter or cosmic neutrinos?

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 utilizing NASA Sentry-II asteroid program & OSIRIS-REx data**

Outline

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

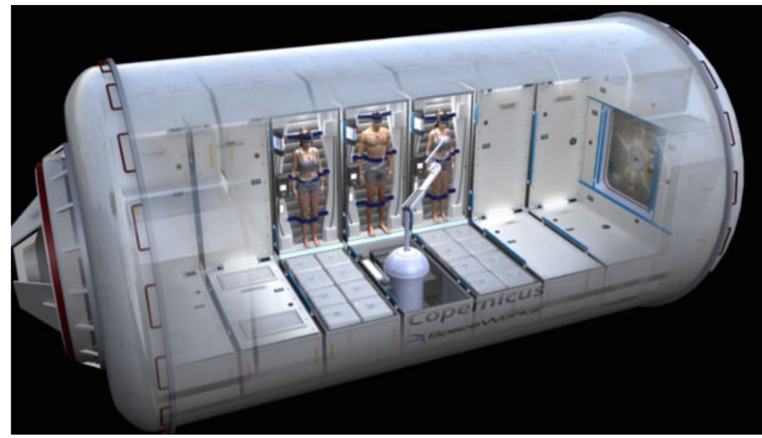
Bridging Planetary Science, Space/Quantum Technologies, and Fundamental Physics

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)

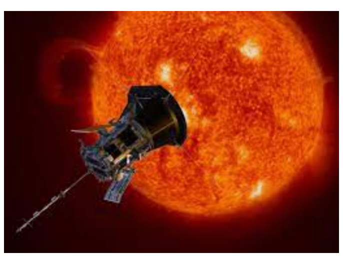
Can we use the technology to study fundamental physics?

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)

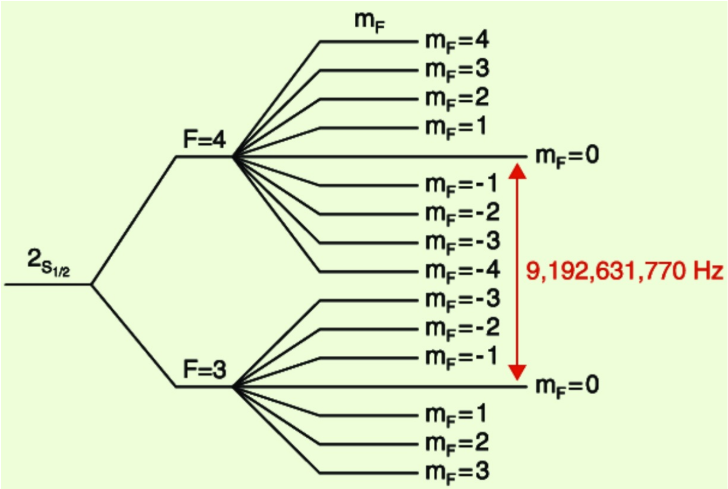
- **Why don't we put a quantum clock on a solar probe? What can we do with that?**

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!

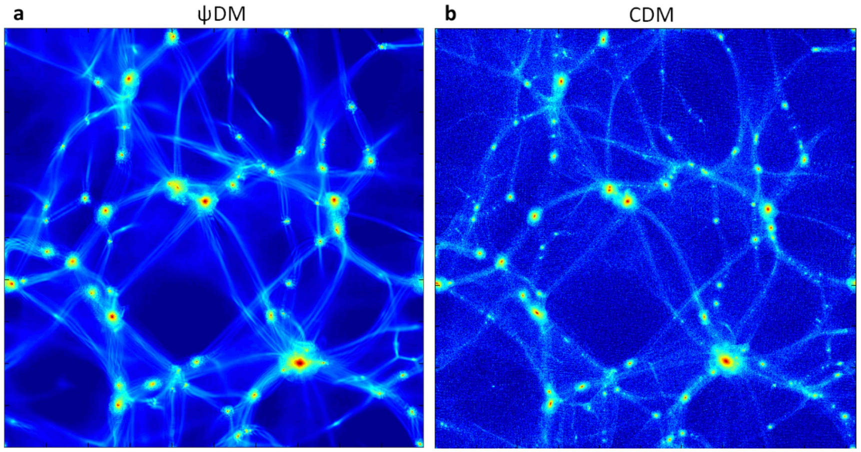
http://hyperphysics.phy-astr.gsu.edu/hbase/acloc.html

Reference: U.S. Naval Observatory, Cesium Clocks

Wave-Like (Fuzzy) Particles as Dark Matter

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

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



Schive, Chiueh, Broadhurst, Nature Physics '14 arXiv:1406.6586,

- For ultralight 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.
- 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.**

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

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

(Non-relativistic solutions)

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

Oscillation frequency ~ dark matter mass

Dark Matter Coupling

Electrons photons gluons

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

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

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

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

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

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

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

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

An example of DM overdensity

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Scalar DM Halo

Stable solution can be supported by external potential

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

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

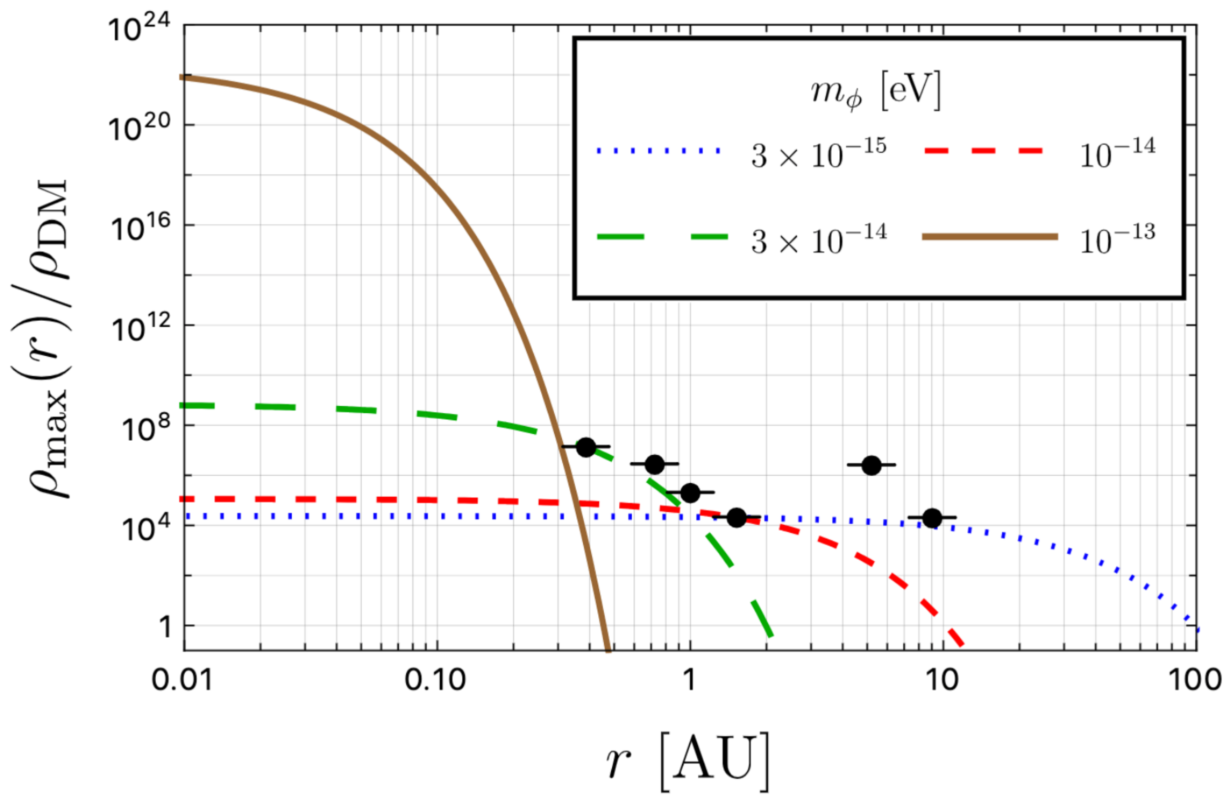
$$R_\star \simeq \frac{M_P^2}{M_{\rm ext}\, m_\phi^2},$$

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

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



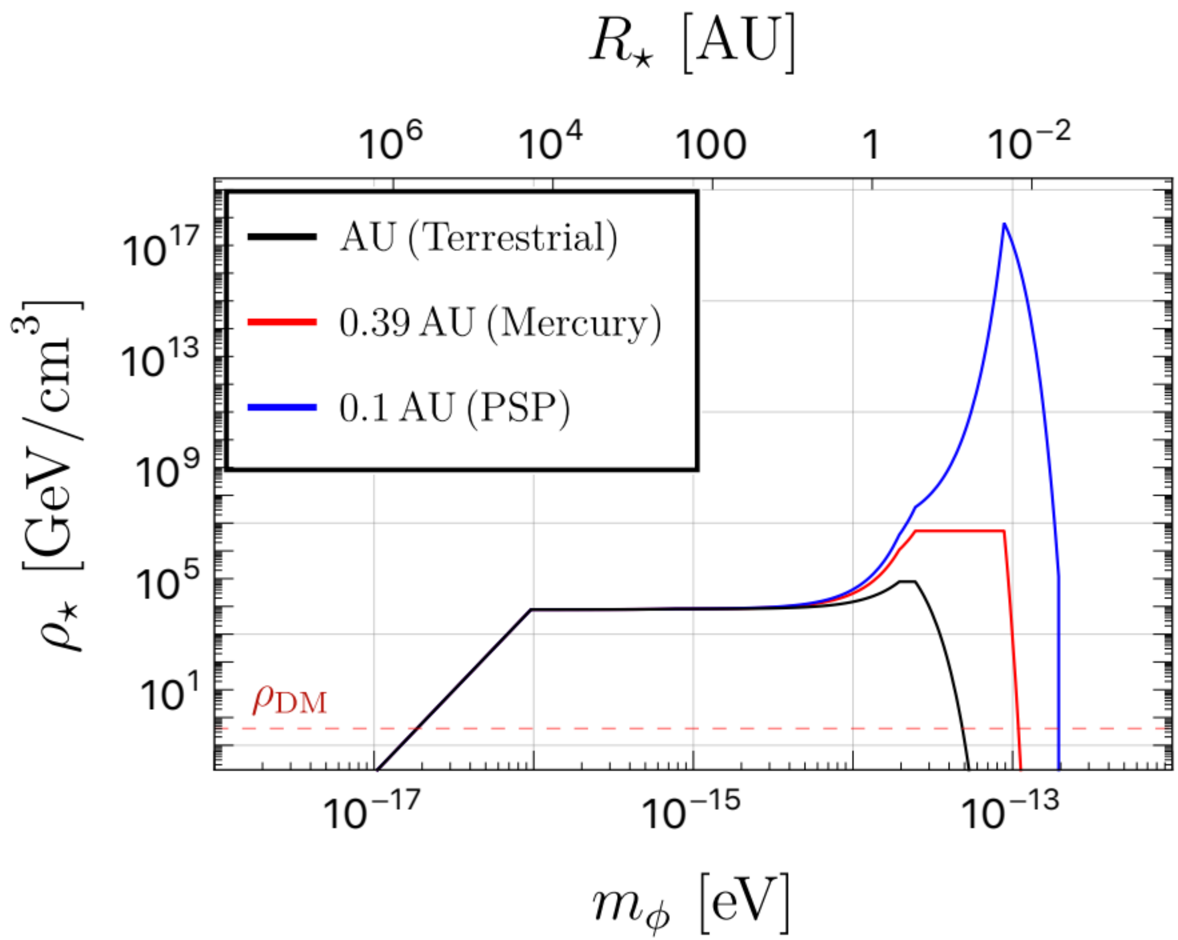
- **Black data points are model-independent constraints!**
- **Dark matter induce precessions to the planets**

Mercury, Venus, Earth, Mars, Jupiter, Saturn

Pitjev, Pitjeva, 1306.5534, Astronomy Letters ’13

Tsai, Eby, Safronova, 2112.07674

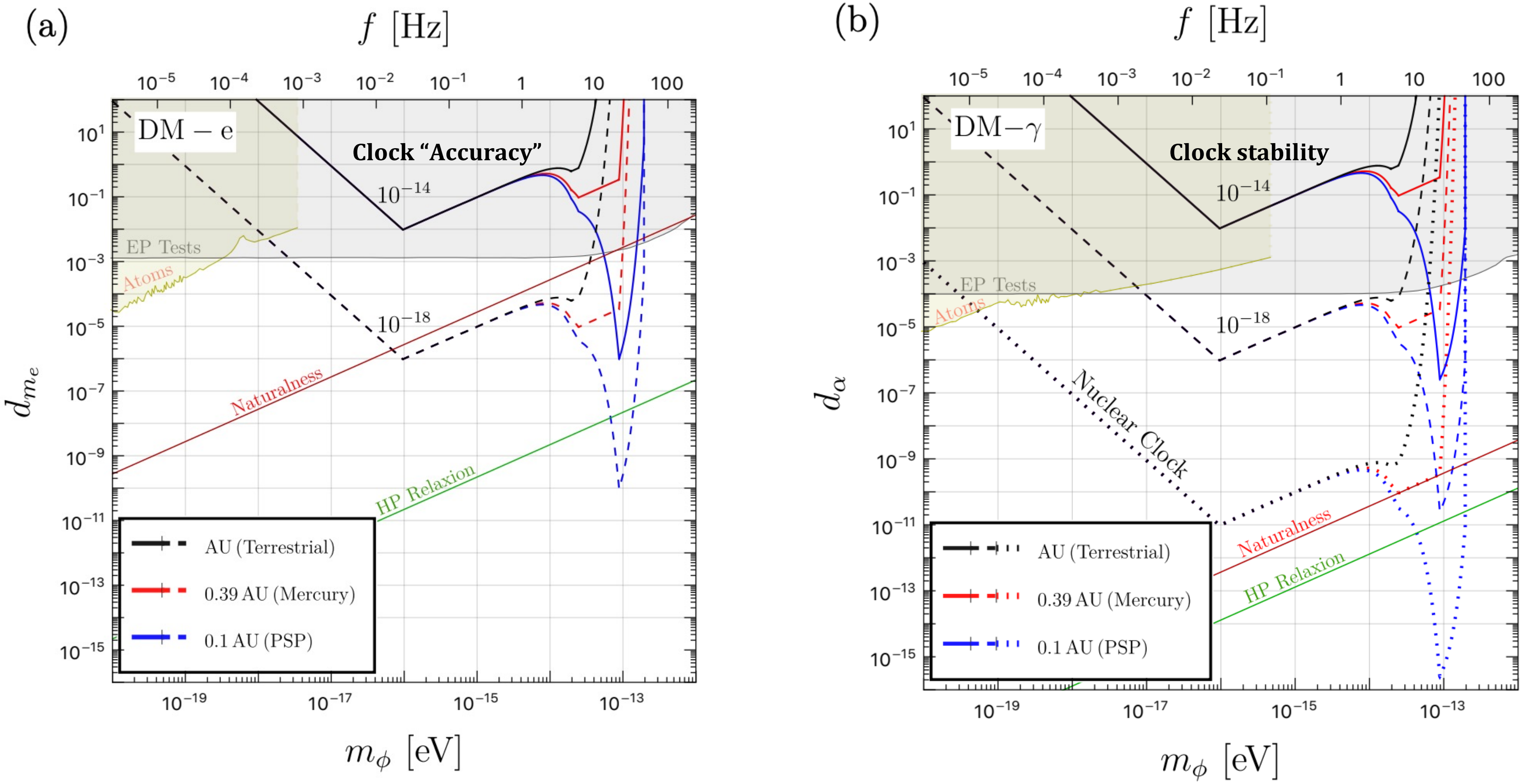
Enhancement of the DM Density



PSP: Parker Solar Probe

Tsai, Eby, Safronova, arXiv:2112.07674

Results



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

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

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

Naturalness condition

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 ~ 300 stronger!

Model-Independent Constraints on Dark Matter

From here on, we only rely on gravitational effects of dark matter, so model independent

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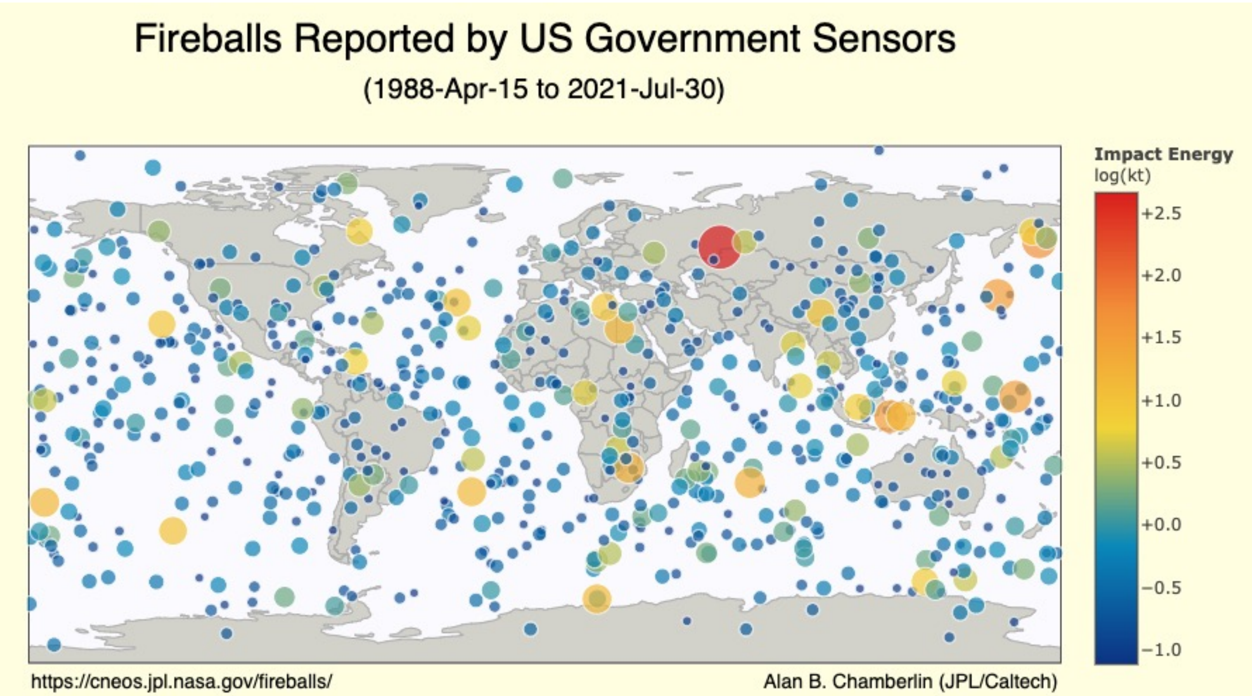
Asteroids hitting the Earth

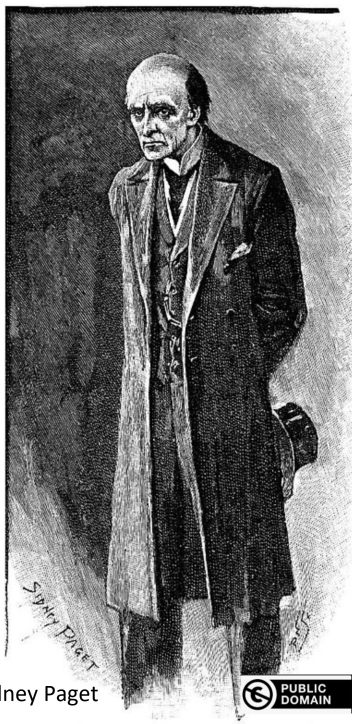


~~Don't~~ Please Look Up

~ 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

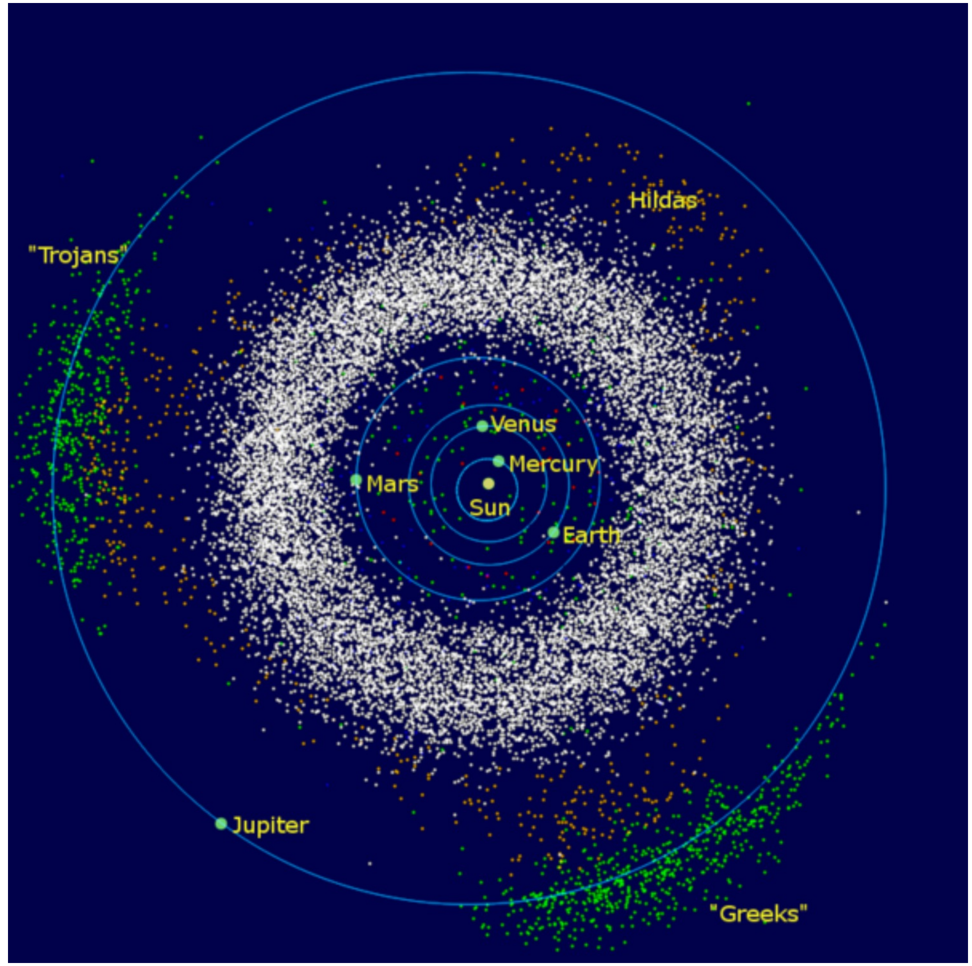


By Sidney Paget

" 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

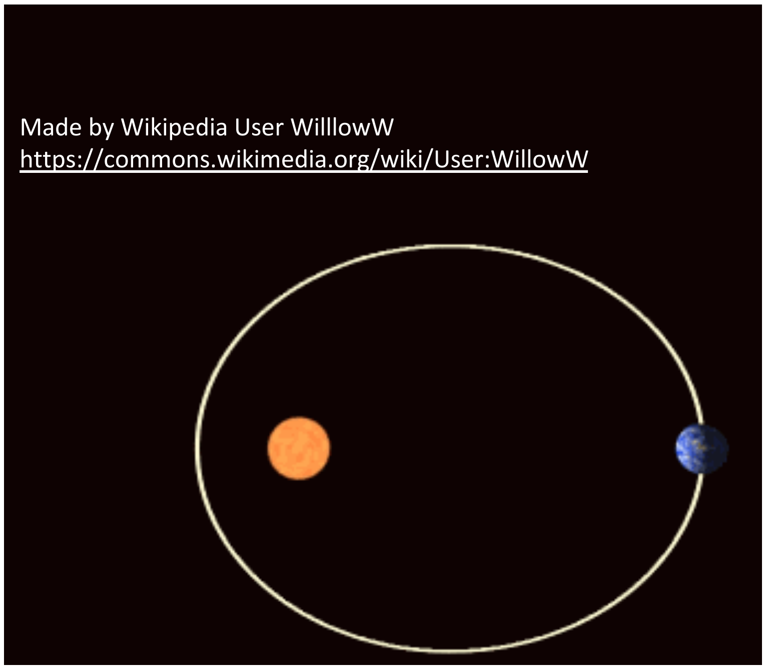
"The mor hazardous the asteroids,
the better for fundamental Physics"
-- Professor Moriarty (maybe)



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

Perihelion Precession: Einstein's Success

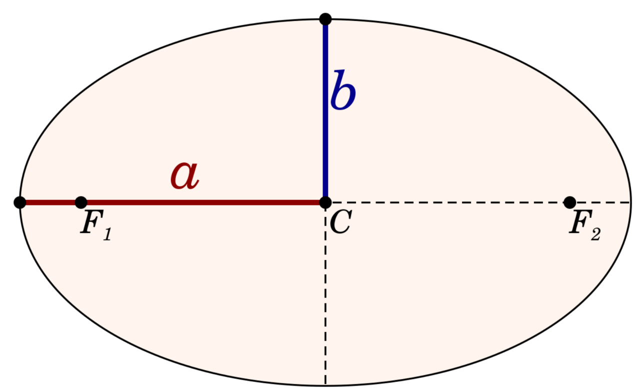
Precession of Mercury's perihelion (closest point to the Sun)



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)

Adding Dark Matter to the Force Model

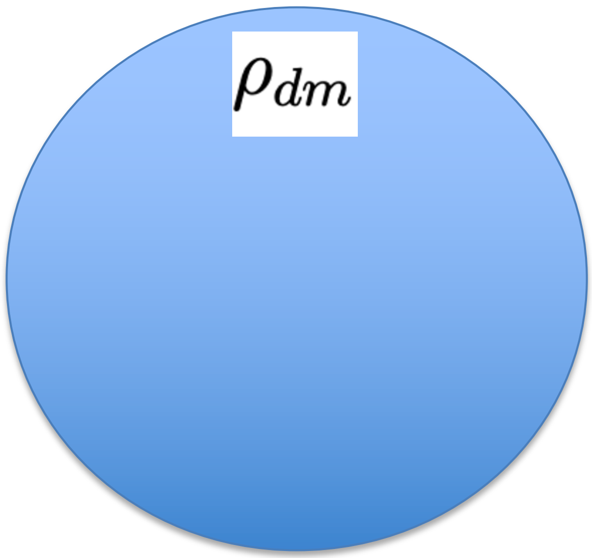
$$
\begin{aligned}
\ddot{\mathbf{r}}_i = \sum_{j \neq i} \frac{\mu_j \left(\mathbf{r}_j - \mathbf{r}_i\right)}{{r_{ij}}^3} \Bigg\{ & 1 - \frac{2(\beta + \gamma)}{c^2} \sum_{l \neq i} \frac{\mu_l}{r_{il}} - \frac{2\beta - 1}{c^2} \sum_{k \neq j} \frac{\mu_k}{r_{jk}} \\
& + \gamma \left(\frac{\dot{s}_i}{c}\right)^2 + (1 + \gamma)\left(\frac{\dot{s}_j}{c}\right)^2 - \frac{2(1+\gamma)}{c^2} \dot{\mathbf{r}}_i \cdot \dot{\mathbf{r}}_j \\
& - \frac{3}{2c^2} \left[\frac{\left(\mathbf{r}_i - \mathbf{r}_j\right) \cdot \dot{\mathbf{r}}_j}{r_{ij}} \right]^2 + \frac{1}{2c^2} \left(\mathbf{r}_j - \mathbf{r}_i\right) \cdot \ddot{\mathbf{r}}_j \Bigg\} \\
& + \frac{1}{c^2} \sum_{j \neq i} \frac{\mu_j}{{r_{ij}}^3} \left\{ \left[\mathbf{r}_i - \mathbf{r}_j\right] \cdot \left[(2 + 2\gamma)\, \dot{\mathbf{r}}_i - (1 + 2\gamma)\, \dot{\mathbf{r}}_j \right] \right\} \left(\dot{\mathbf{r}}_i - \dot{\mathbf{r}}_j\right) \\
& + \frac{3 + 4\gamma}{2c^2} \sum_{j \neq i} \frac{\mu_j \ddot{\mathbf{r}}_j}{r_{ij}}
\end{aligned}
$$

From Dr. Davide Farnocchia's (NASA, JPL) slide

Dark matter

$$
\begin{aligned}
F(r) &= \frac{2\pi}{3} G m \rho_0 \left(\frac{2 r_0^3}{r^2} - 2r \right) \hat{\mathbf{r}} \\
&\simeq -\frac{4\pi}{3} G m \rho_0 r \hat{\mathbf{r}}
\end{aligned}
$$

Dark Matter Profile & Planetary Precession



Dark matter

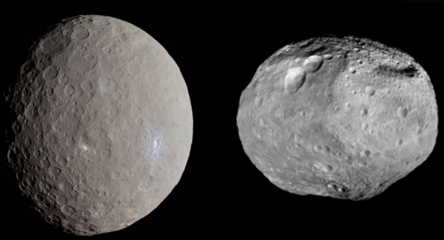
$$F(r) = \frac{2\pi}{3} G m \rho_0 \left(\frac{2 r_0^3}{r^2} - 2r \right) \hat{\mathbf{r}}$$

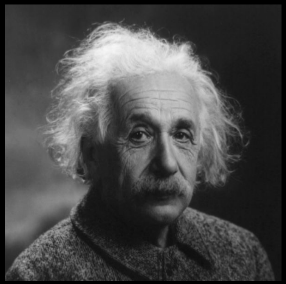
$$\simeq -\frac{4\pi}{3} G m \rho_0 r \hat{\mathbf{r}}$$

Robust Analysis (NEW): High-fidelity force model

JPL Planetary Ephemerides DE441

Small-body perturbers





PPN formulation for relativity

Oblateness, ...

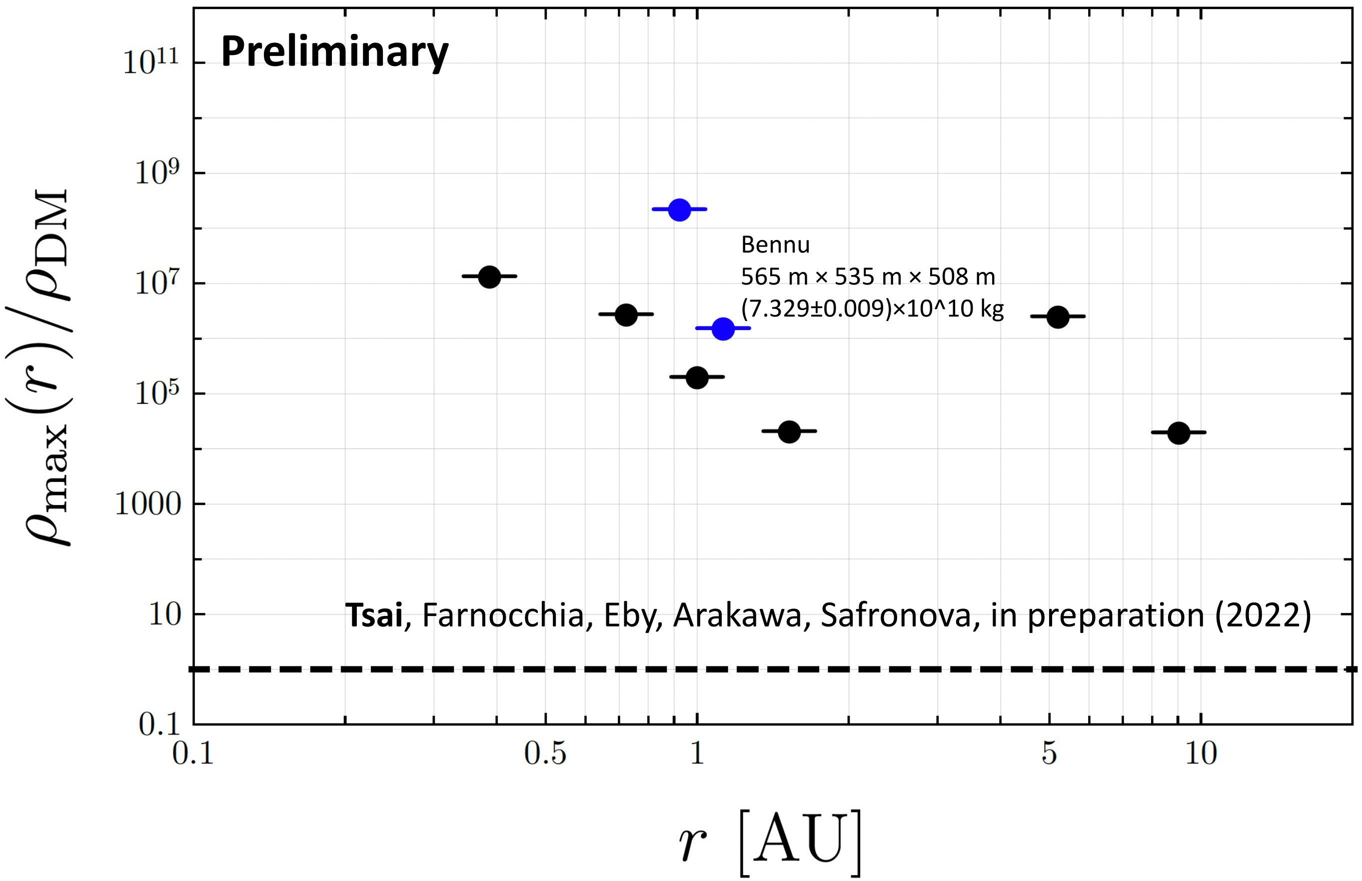
Dr. Davide Farnocchia's (NASA, JPL) slide

Other Sources of Perturbations

- 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

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

New Project: New Model Independent Constraints!

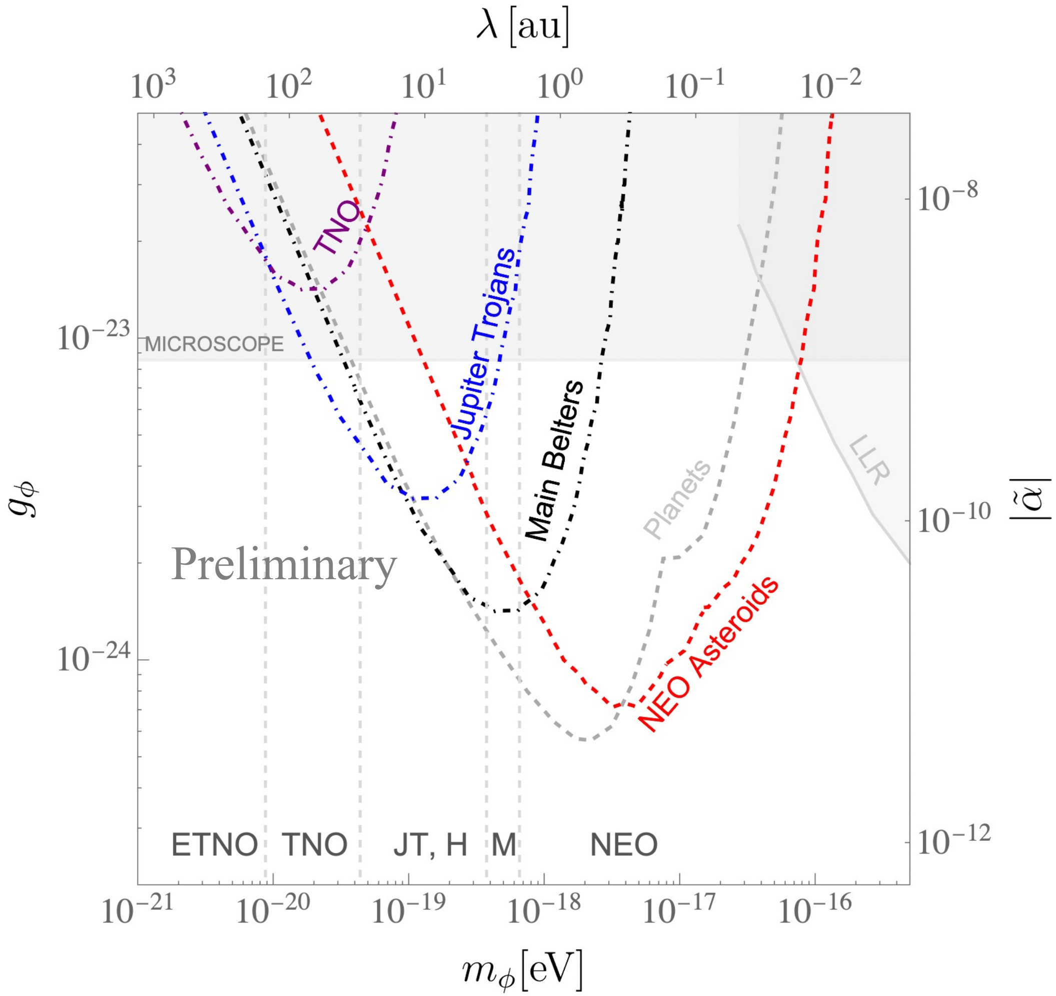


Tsai, Farnocchia, Eby, Arakawa, Safronova, in preparation

Obtained results from NASA JPL Sentry-II code & OSIRIS-Rex+ data

Can be applied to ideas like Solar-Basin & Axion Mini-cluster (more refs in paper)

Probing Fifth Force & Ultralight Mediators



- **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.**
- **More reference & details in the backup slides**

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038, under review by Nature Astronomy
Conducting a **detailed study** collaborating with researchers from **NASA & ESA**

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

Thank you!

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

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

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Backup Slides

I also work on …

- Fixed-target searches for dark matter & long-lived particles (FerMINI & LongQuest) with Pospelov et al.
- LHC Forward Experiments: Forward Physics Facility, FORMOSA (a millicharge experiment I proposed), with Feng et al.
- Dark matter model building (dark sector QCD, Strongly Self-Interacting Dark Matter, SIMP/ELDER), with Murayama, Slatyer, Perelstein et al.
- Dark matter searches using neutron star / compact merger / multi-messenger astronomy, with Profumo, Sathyaprakash et al.
- Neutrino physics (cosmic neutrino background) & neutrino BSM, with Shoemaker et al.
- My works on Inspire HEP & my outreach interview (> 76K views!)

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
- Quantum Technologies in Space, Kaltenbaek, Exp Astron 21

Asteroid g-2 Experiments on Fifth Forces & Ultralight Dark Matter

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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

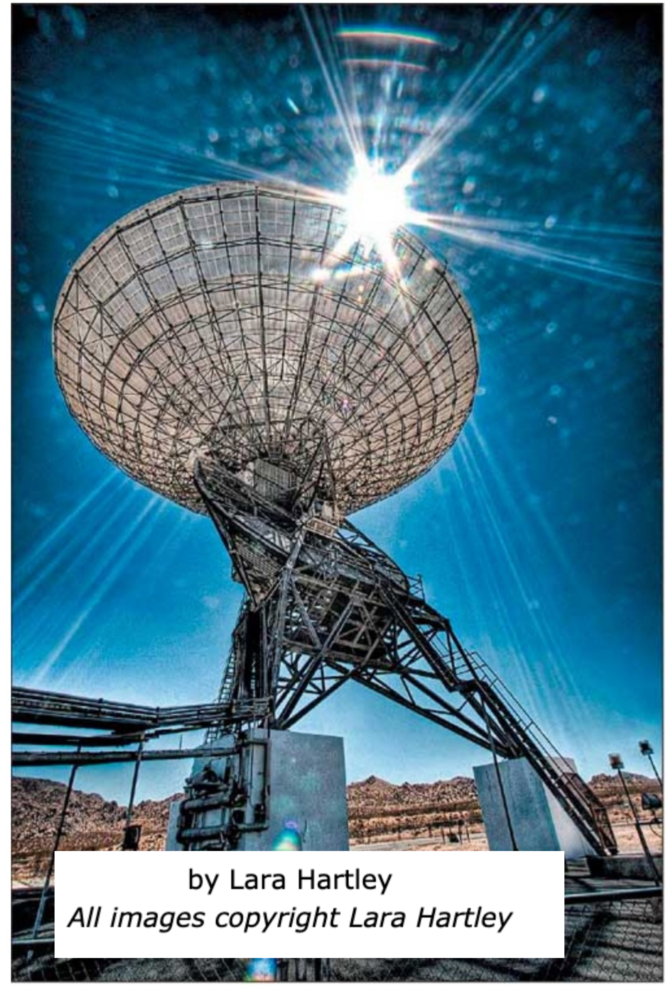
Radar Observations

- 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

5^{th} force and Yukawa Potential

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

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

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

(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

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

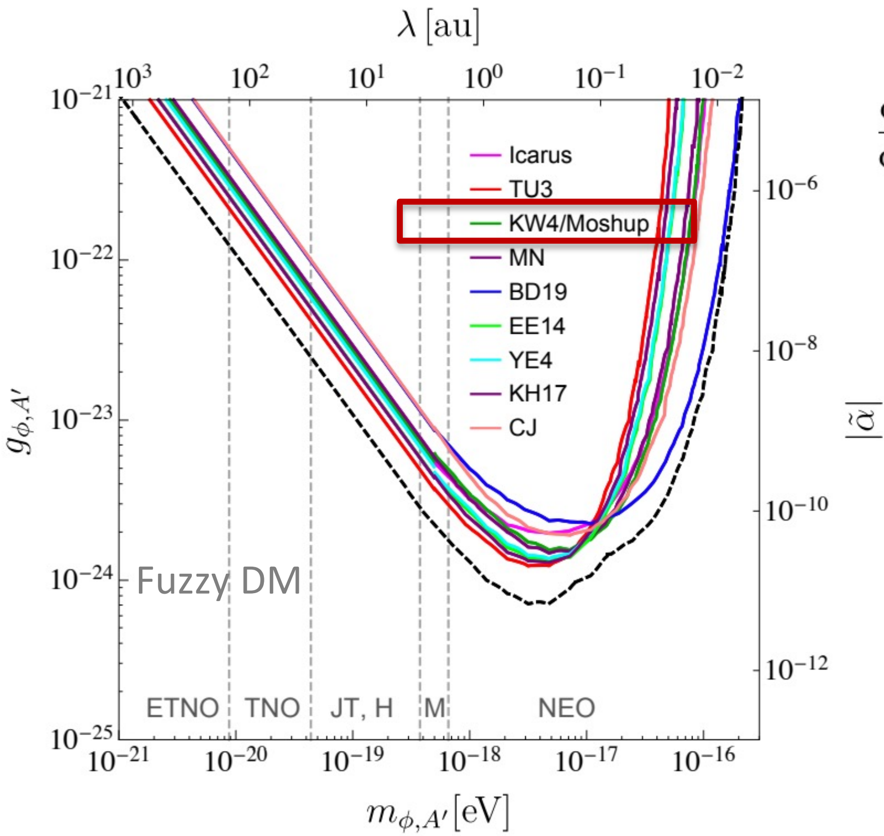
(fifth force)

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

(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



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

Recast

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

Verma, Margot, Greenberg, APJ ‘17

Optimal 2022 results,

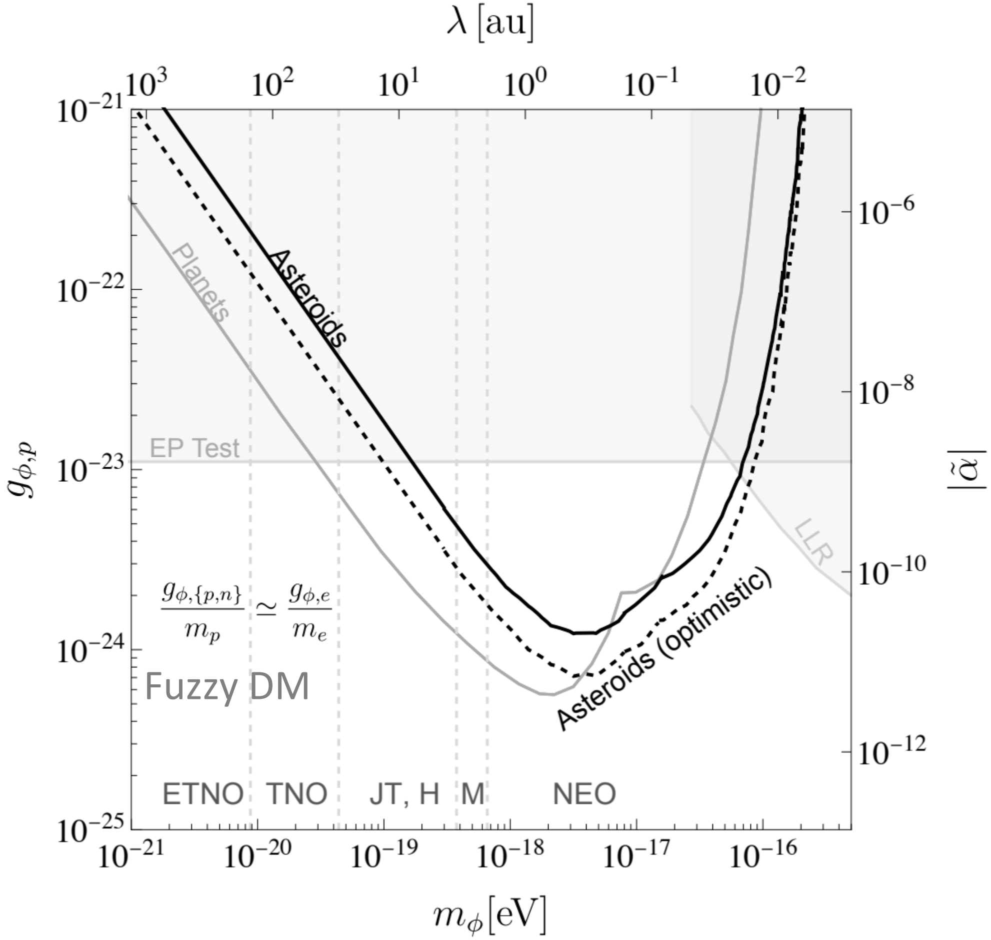
$$\sigma_\beta \sim 2\times 10^{-4},$$

Best reach:
TU3, MN, BD19

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

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

Asteroid Constrain EP Conserving 5th forces

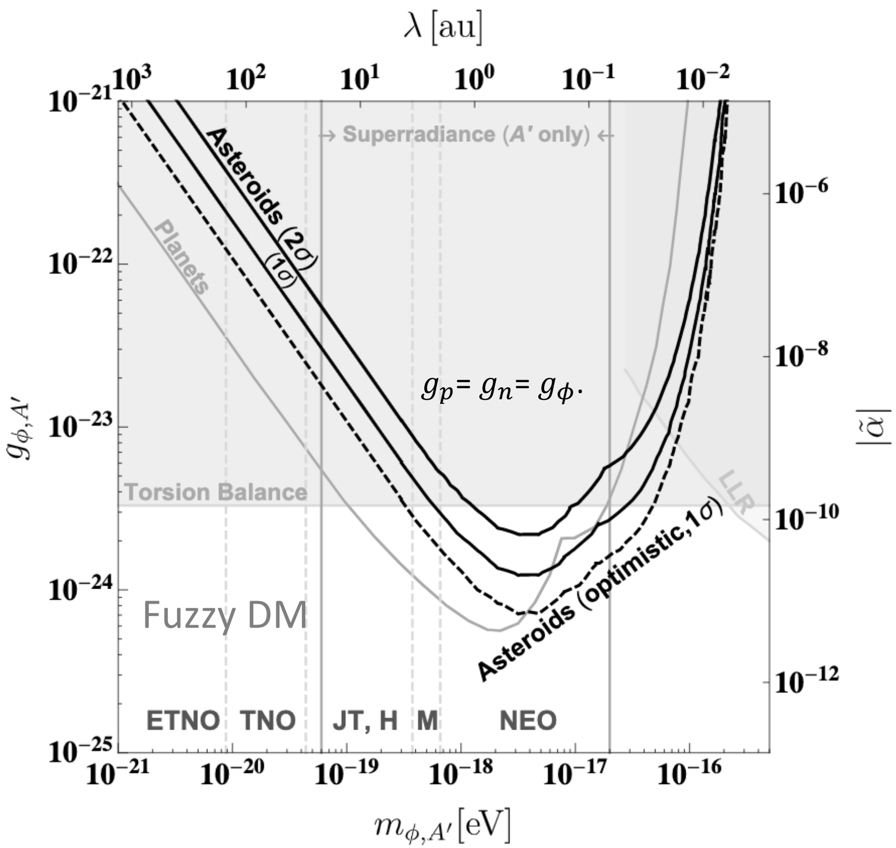


- **LLR: Lunar Laser Ranging**
  Williams, Turyshev, Boggs, PRL 04
- **Planets:**
  Poddar, Mohanty, Jana, EPJC 21
- **Asteroidal / Planetary / Lunar Probes are the strongest for equivalence principle conserving fifth forces.**

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

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

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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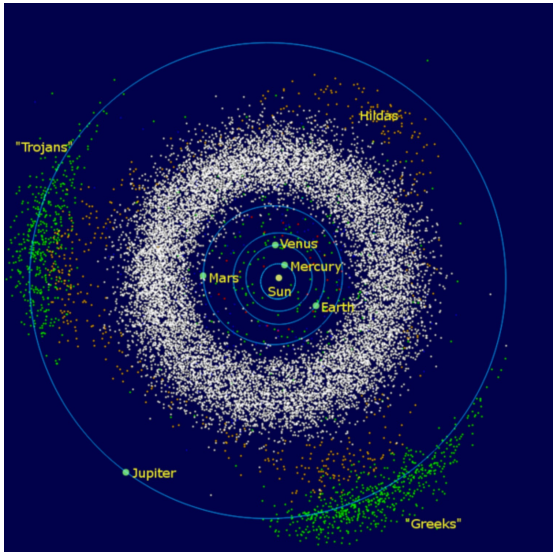
Future objects of interest

Minor Planets	a [au]	$\sim$ Numbers
Near-Earth Object (NEO)	$< 1.3^*$	> 25000
Main-Belt Asteroid (M)	$\sim 2-3$	~ 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 $a(1-\mathrm{e}) < 1.3\,\mathrm{au}$.



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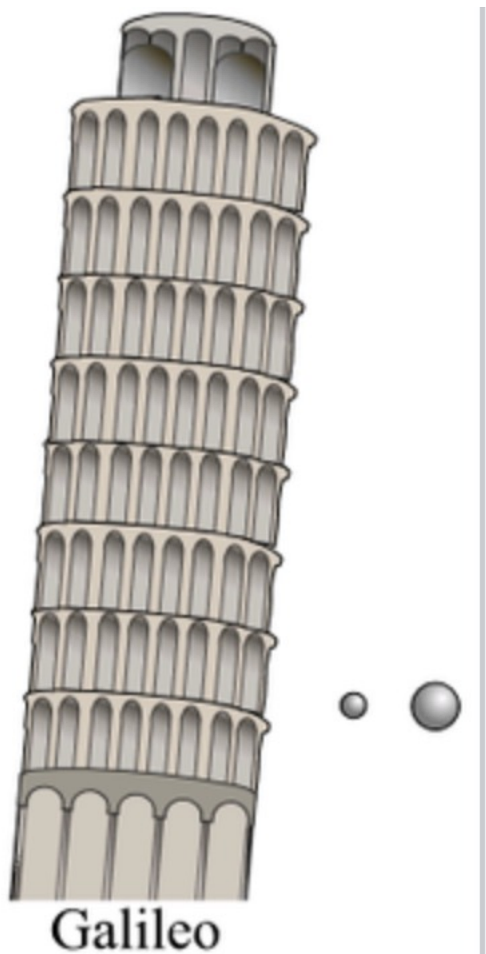
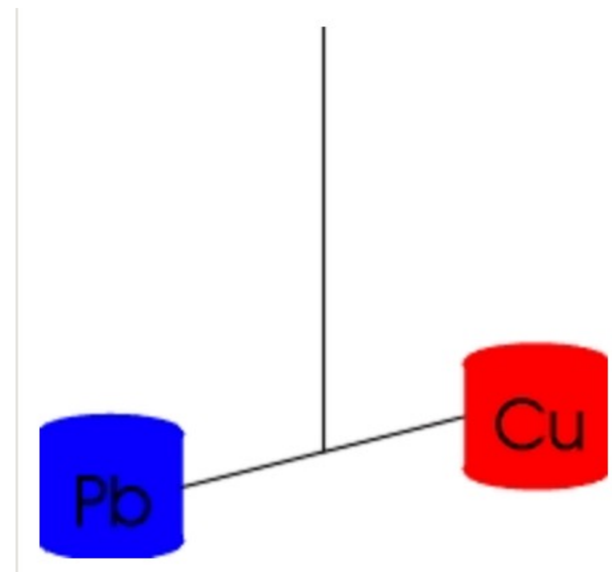
- **Tsai**, Wu, Vagnozzi, Visinelli, arXiv:2107.04038
- ***Can also probe dark matter, primordial black hole, etc***

Torsion Balance: Modern-Day Tower of Pisa experiment

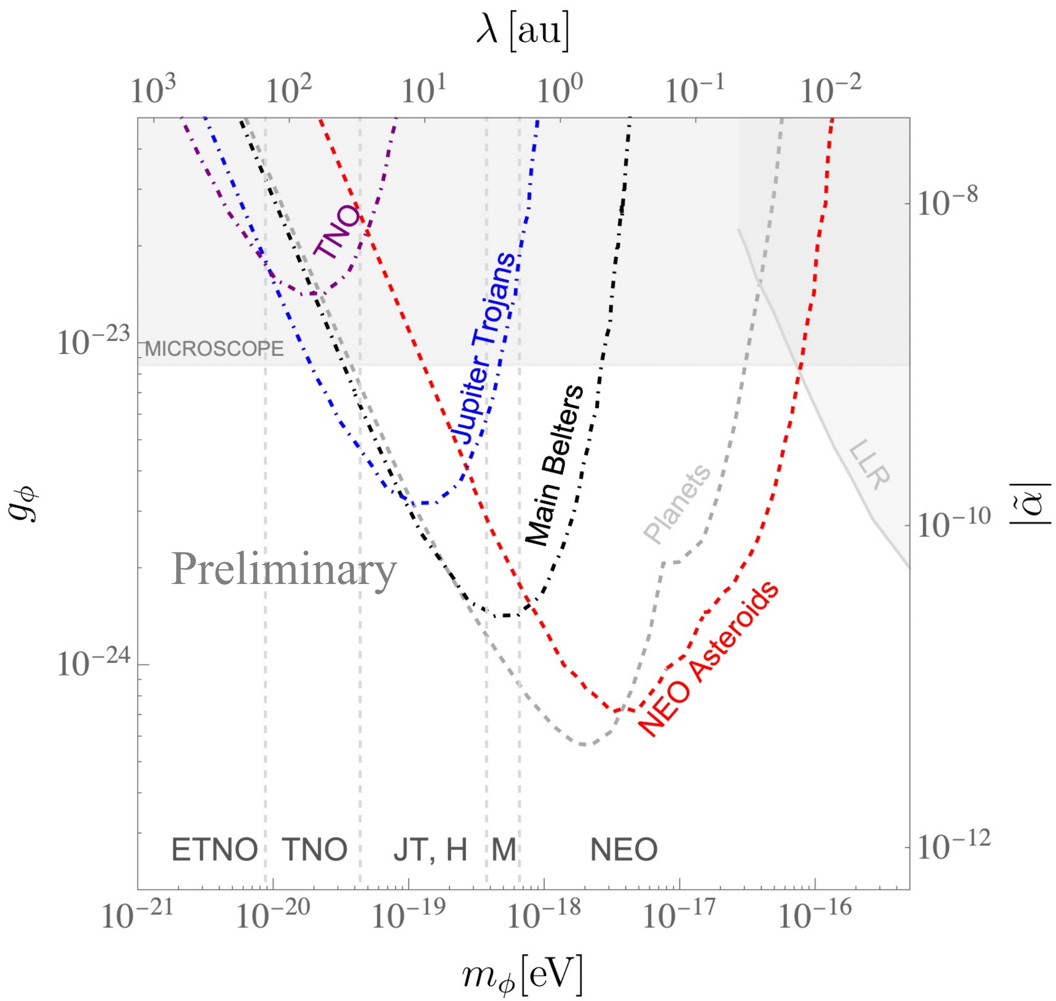


Wikipedia



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

Compilations of Various Probes



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Adding Fifth Forces or Dark Matter to the Force Model

$$\begin{aligned}
\ddot{\mathbf{r}}_i = \sum_{j\neq i} \frac{\mu_j(\mathbf{r}_j - \mathbf{r}_i)}{r_{ij}^3}\Bigg\{ & 1 - \frac{2(\beta+\gamma)}{c^2}\sum_{l\neq i}\frac{\mu_l}{r_{il}} - \frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} \\
& + \gamma\left(\frac{\dot{s}_i}{c}\right)^2 + (1+\gamma)\left(\frac{\dot{s}_j}{c}\right)^2 - \frac{2(1+\gamma)}{c^2}\dot{\mathbf{r}}_i\cdot\dot{\mathbf{r}}_j \\
& - \frac{3}{2c^2}\left[\frac{(\mathbf{r}_i-\mathbf{r}_j)\cdot\dot{\mathbf{r}}_j}{r_{ij}}\right]^2 + \frac{1}{2c^2}(\mathbf{r}_j-\mathbf{r}_i)\cdot\ddot{\mathbf{r}}_j\Bigg\} \\
& + \frac{1}{c^2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}^3}\left\{[\mathbf{r}_i-\mathbf{r}_j]\cdot[(2+2\gamma)\dot{\mathbf{r}}_i-(1+2\gamma)\dot{\mathbf{r}}_j]\right\}(\dot{\mathbf{r}}_i-\dot{\mathbf{r}}_j) \\
& + \frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{\mu_j\ddot{\mathbf{r}}_j}{r_{ij}}
\end{aligned}$$

From Dr. Davide Farnocchia's (NASA, JPL) slide

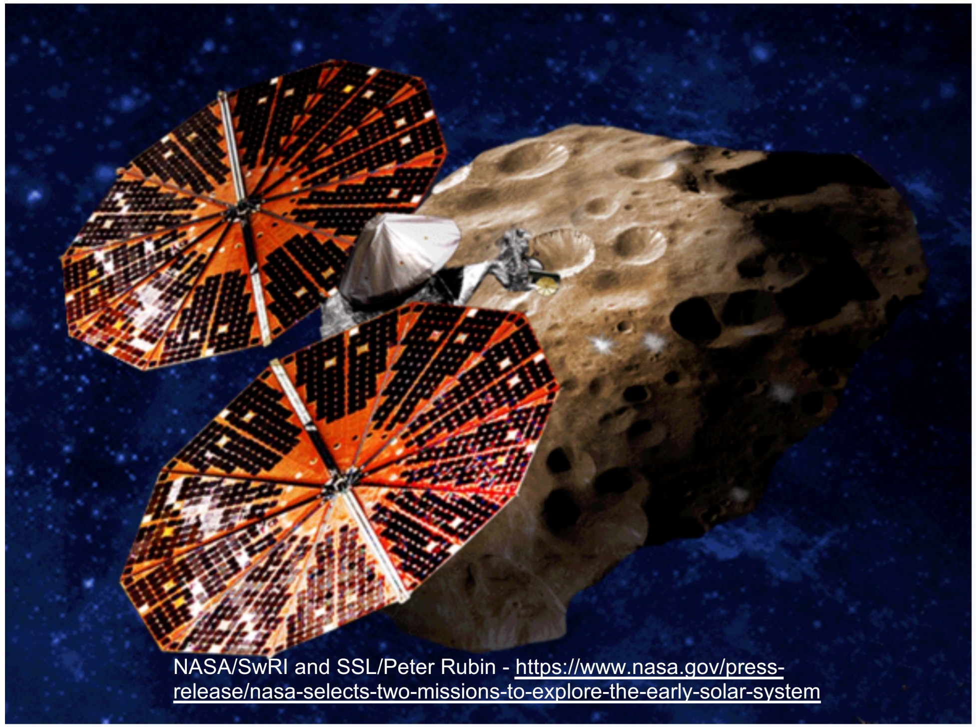
Fifth forces

$$F = \frac{A0\, e^{-\frac{r}{r0}}}{r^2} + \frac{A0\, e^{-\frac{r}{r0}}}{r\, r0}$$

General dark matter

Some Upcoming Observations

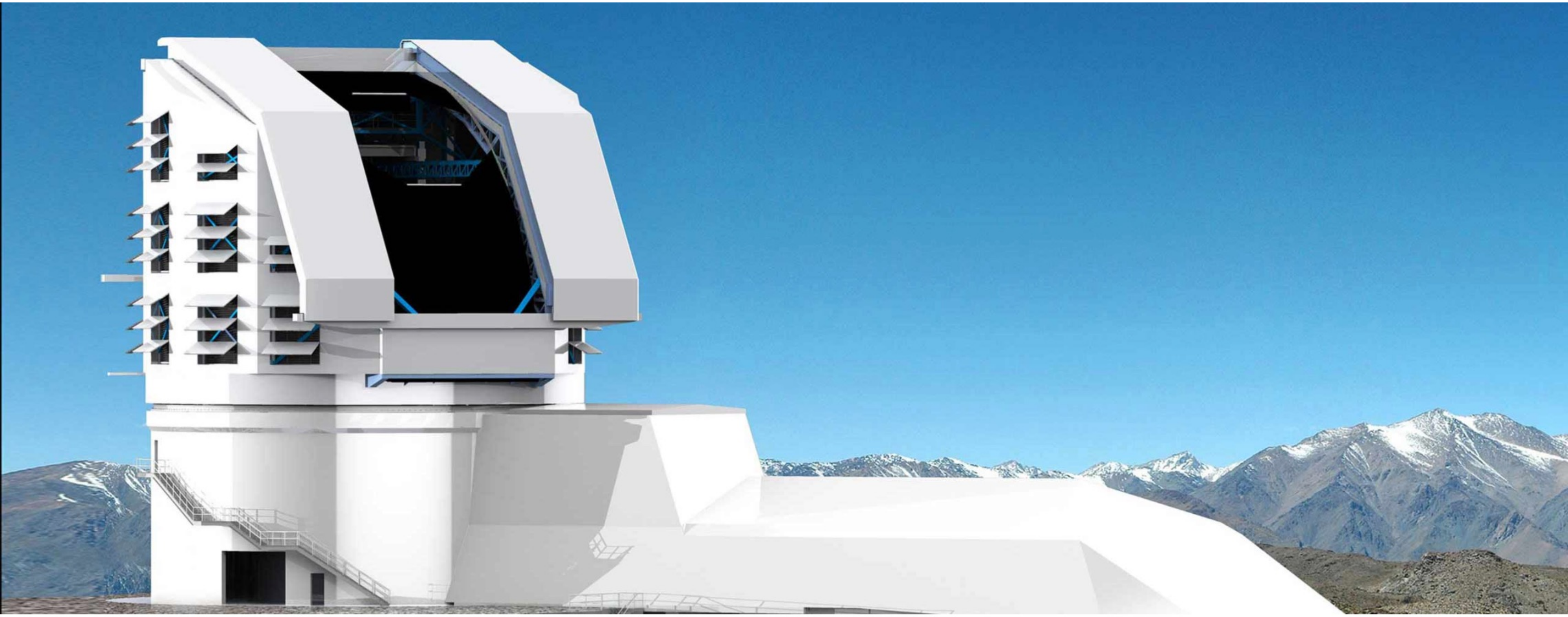
Space Mission: Visiting Asteroids!



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

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

Observations - Optical

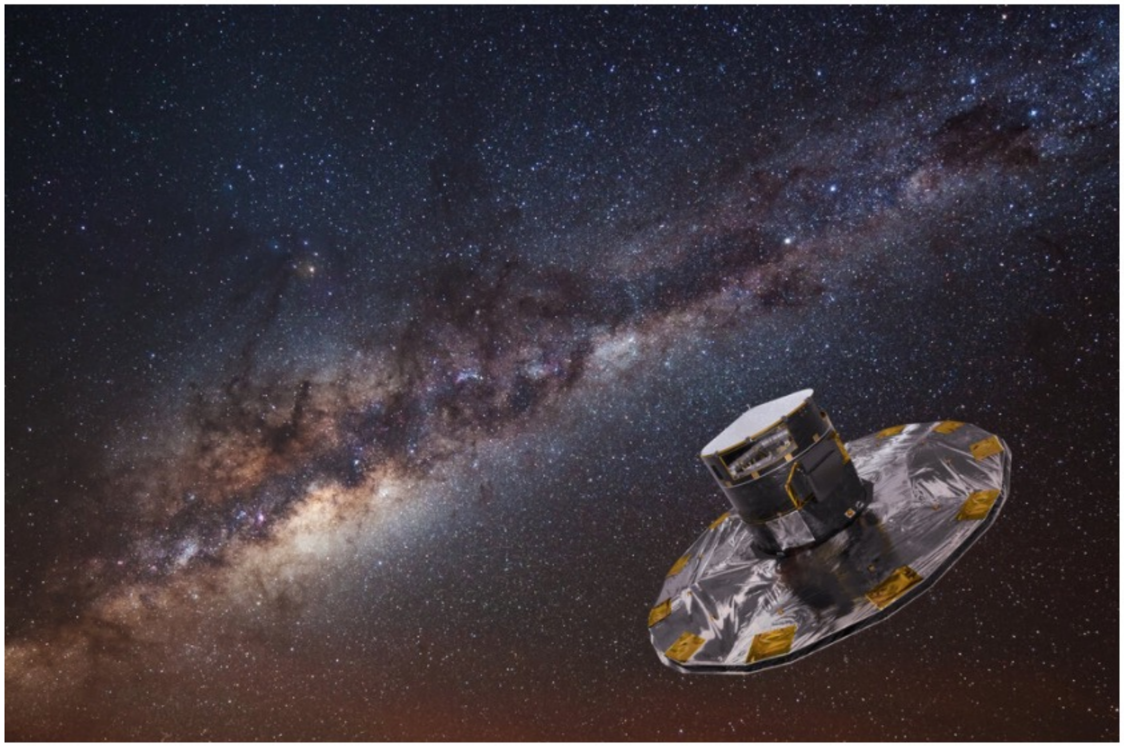


A photograph and rendering mix of the exterior of the Vera C. Rubin Observatory building on Cerro Pachón in Chile. Image credit: Rubin Obs./NSF/AURA

https://www.aura-astronomy.org/centers/nsfs-oir-lab/rubinobservatory/

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

GAIA



— Gaia mapping the stars of the Milky Way

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

Finding Dark Matter While Protecting the Earth

Yu-Dai Tsai

University of California, Irvine

with **Josh Eby**, **Marianna Safronova**

with Youjia Wu, Sunny Vagnozzi, Luca Visinelli

Contact: yudait1@uci.edu & yt444@cornell.edu

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

To appear on Nature Astronomy!

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

Under review by Nature Astronomy

INSPIRE: https://inspirehep.net/authors/1274923

NASA's OSIRIS-REx mission readies itself to touch the surface of asteroid Bennu.
Credits: NASA/Goddard/University of Arizona