Studying Fundamental Physics with Planetary Data & Space Quantum Technology

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w/ Youjia Wu, Sunny Vagnozzi, Luca Visinelli,

arXiv:2107.04038, under review by *PRL*

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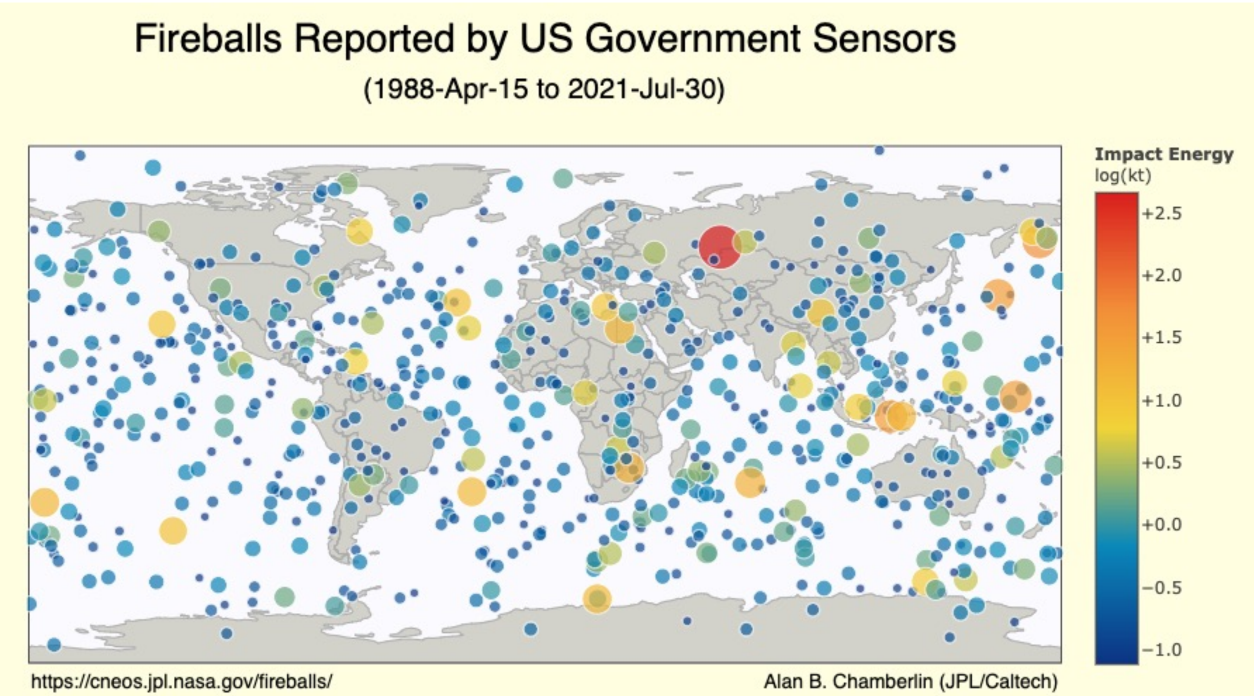
Theme of this talk:

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

Warning: this talk may have real-life consequences!

https://www.youtube.com/watch?v=dpmXyJrs7iU
(Tuvix72, Youtube video on asteroid hitting Earth)

Asteroids hitting the earth



~ 65 million years ago

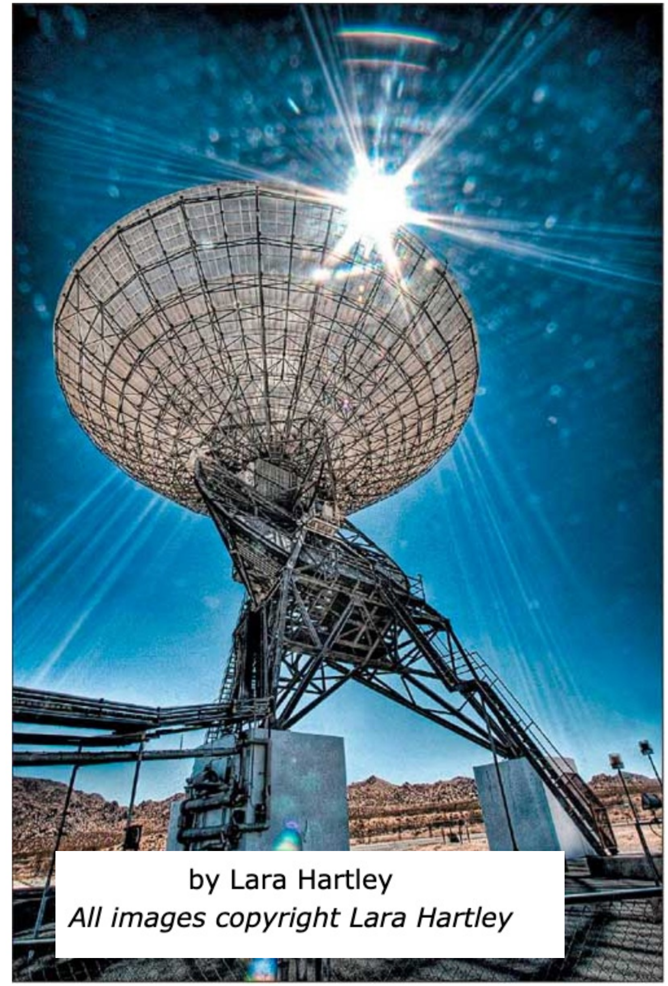
Tracking asteroids is extremely important

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

Also, **near-Earth asteroid search** accidentally found **'Oumuamua**

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 - **Distance**
- **Doppler measurement: - LOS velocity**

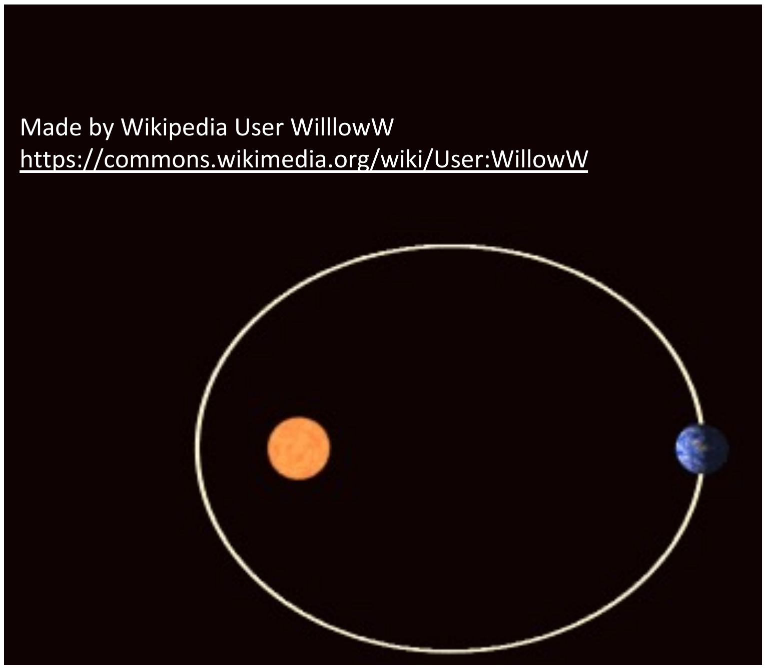


Students can control the huge Echo radio telescope to collect data from objects in the universe at which the antenna is pointed.

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

Perihelion Precession: Einstein’s Success

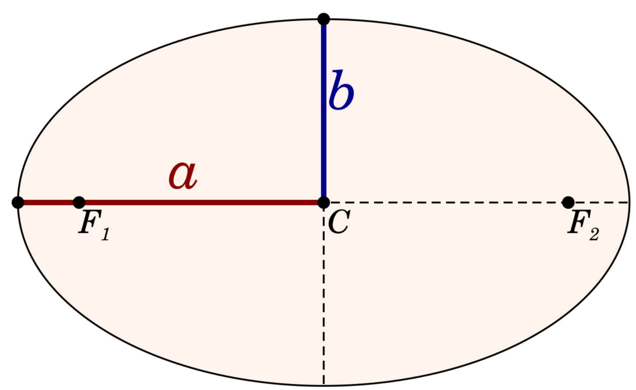
Precession of Mercury's perihelion (closest point to the Sun)



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

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

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



M. W. Toews (CC0)

Precession by General Relativity (GR)

Perihelion precession from GR

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

(GR)

- a is the semi-major axis
- e is the eccentricity
- **B, γ** are the two parameterized post Newtonian parameters,
  both **equal to 1 in GR**
  tightly constrained by Solar System probes
- β represents the amount of nonlinearity in the superposition law for gravity
- γ represents the amount of curvature produced by a unit mass

Nine Near-Earth Objects/Asteroids

Table 1. Selected asteroids and orbital elements: Semimajor Axis (a), Eccentricity (e), and Inclination with Respect to the Ecliptic (i_{ec}) and Sun's equator (i_{eq}).

Target	a (au)	e	i_{ec} (deg)	i_{eq} (deg)	$\delta\dot{\omega}$ ($''$ cy^{-1})
1566 Icarus	1.078	0.827	22.9	15.8	10.1
1998 TU3	0.787	0.484	5.41	3.41	9.11
1999 KW4	0.642	0.688	38.9	46.0	22.1
1999 MN	0.674	0.665	2.02	5.25	18.5
2000 BD19	0.876	0.895	25.7	28.0	26.9
2000 EE14	0.662	0.533	26.5	26.1	15.0
2001 YE4	0.677	0.541	4.82	11.0	14.4
2004 KH17	0.712	0.499	22.1	14.9	12.0
2006 CJ	0.676	0.755	10.3	16.1	23.7

The ecliptic is the plane of Earth's orbit around the Sun.

Nine NEOs with excellent radar observations

Verma, Margot, Greenberg, arXiv:1707.08675, APJ 17

- **Radar astronomy** help reduce the uncertainty of near-Earth distance to **30 m – 1 km!**
  + fast improving optical obs.
- **Fractional uncertainty:** $\mathbf{10^{-8} - 10^{-9}}$
- **1999 KW4 / 66391 Moshup**
  Nearest point ~ 5 x $\mathbf{10^9}$ meters
  uncertainly 40 – 300 meters
- Utilizing **Mission Operations and Navigation Toolkit Environment (MONTE)** simulation from JPL

Analysis

- **Verma, Margot, Greenberg, APJ '17**

- **Dynamical Modeling + MONTE to simulate the trajectories**; Dynamical model includes gravitational forces from the Sun, 8 planets, and 21 minor planets with well-determined masses (Konopliv et al. 2011), general relativistic effects, and perturbations due to the oblateness of the Sun

- Construct a covariant matrix analysis, with the observed data from optical and radar observations

- Determine the allowed range from the nominal (Standard Model) values of the **β** parameter considering the diagonal elements of the covariant

$$\sigma_\beta = 5.6 \times 10^{-4}, \qquad \sigma_\beta \sim 2 \times 10^{-4},$$

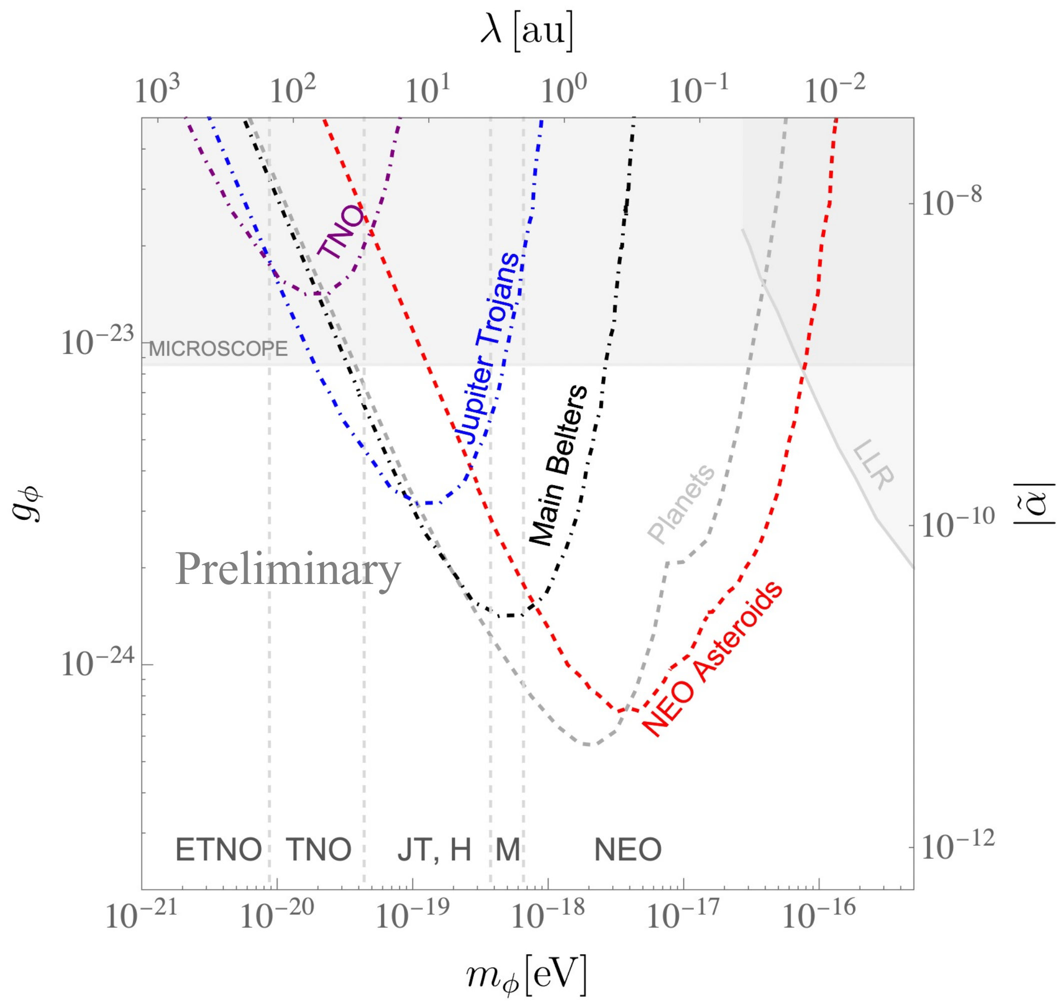
(Optimal 2022 results)

Ultralight Dark Sector

Why is asteroids interesting?

- **Large statistics**
- **Large spread in orbit radius**

Upshot: Exploring New Physics

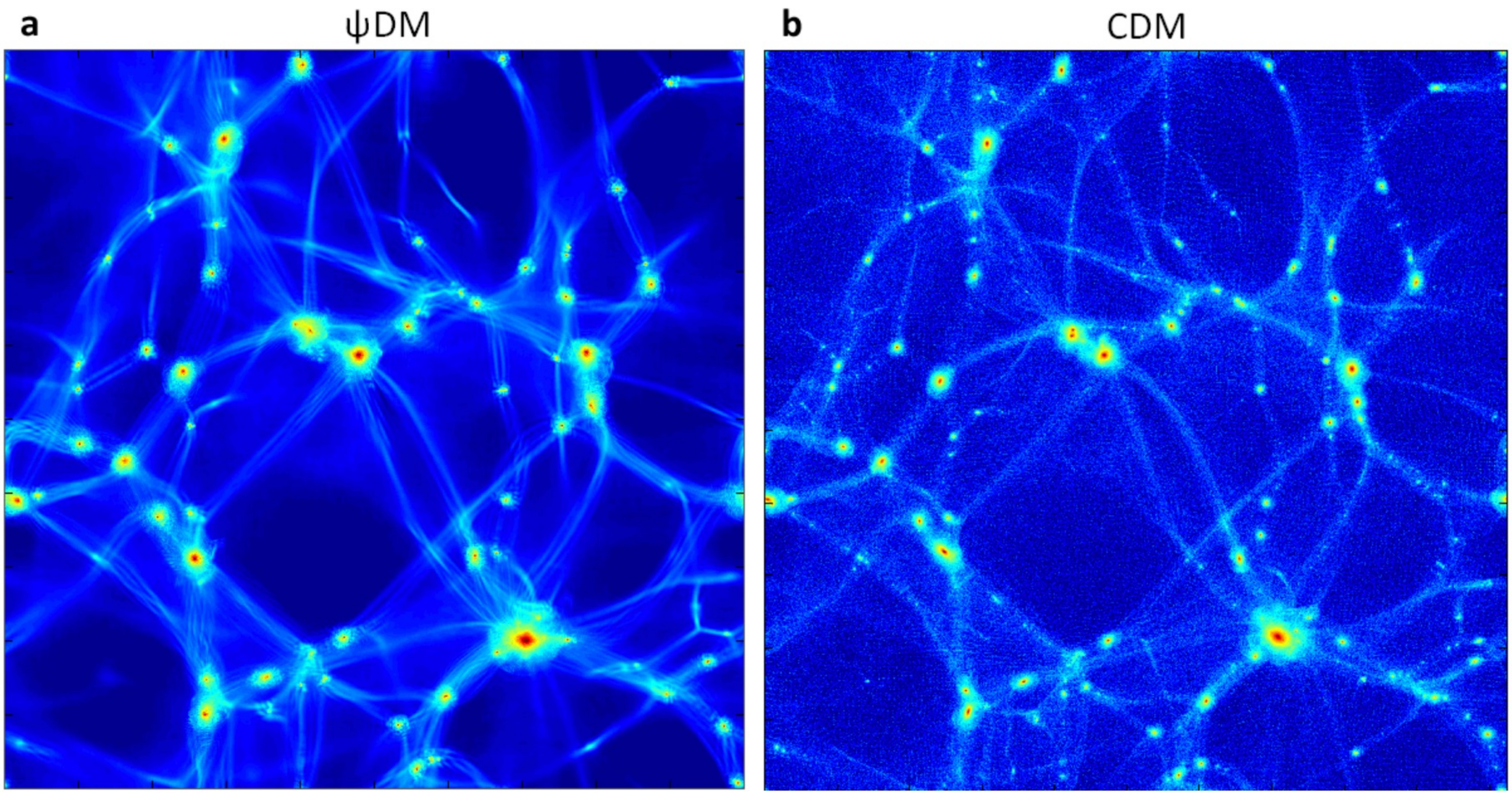


- **LLR: Lunar Laser Ranging Williams, Turyshev, Boggs, PRL 04**
- **Apache Point Observatory Lunar Laser-ranging Operatio (APOLLO), Murphy *et al* (led by UCSD!)**
- **Planets:** Poddar, Mohanty, Jana, EPJC 21
- **Asteroidal / Planetary / Lunar Probes are the strongest for equivalence principle conserving fifth forces.**

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038, submitting to *PRL*

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

Motive 1: Ultralight 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.

Motive 2:
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

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**

$$\mathcal{L}_\phi = \left(g_p \bar{p}p + g_n \bar{n}n + g_e \bar{e}e\right)$$

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

Precession (Analytical) at Low-Mass Limit

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

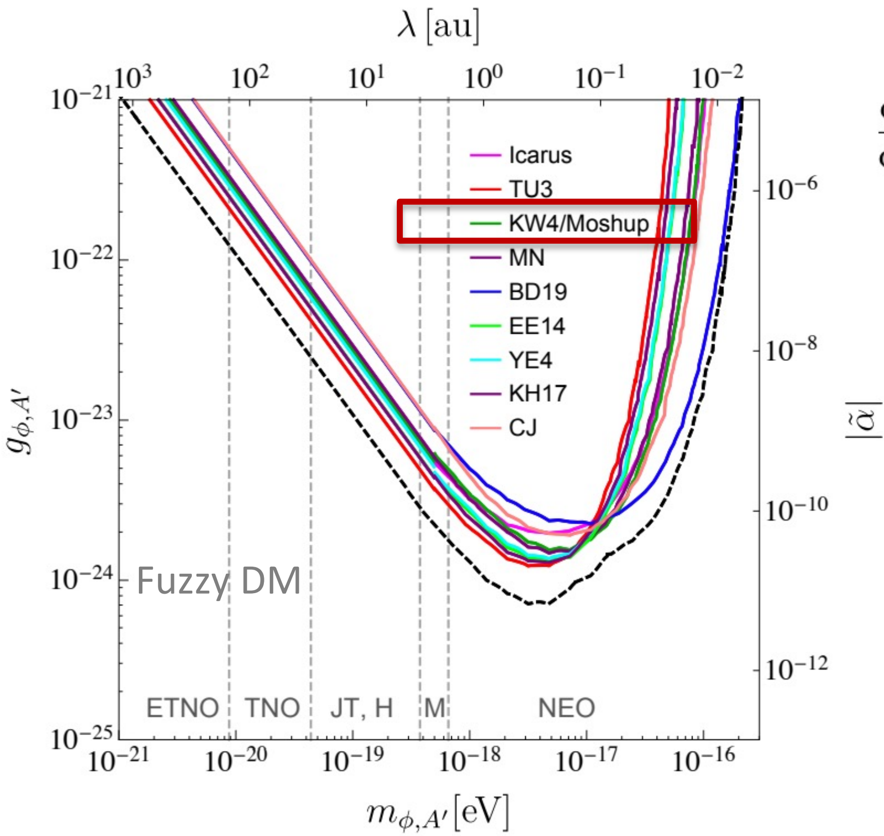
(fifth force)

- 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**

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

(GR)

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

$\sigma_\beta = 5.6\times10^{-4}$, Verma, Margot, Greenberg, APJ ‘17

Optimal 2022 results,

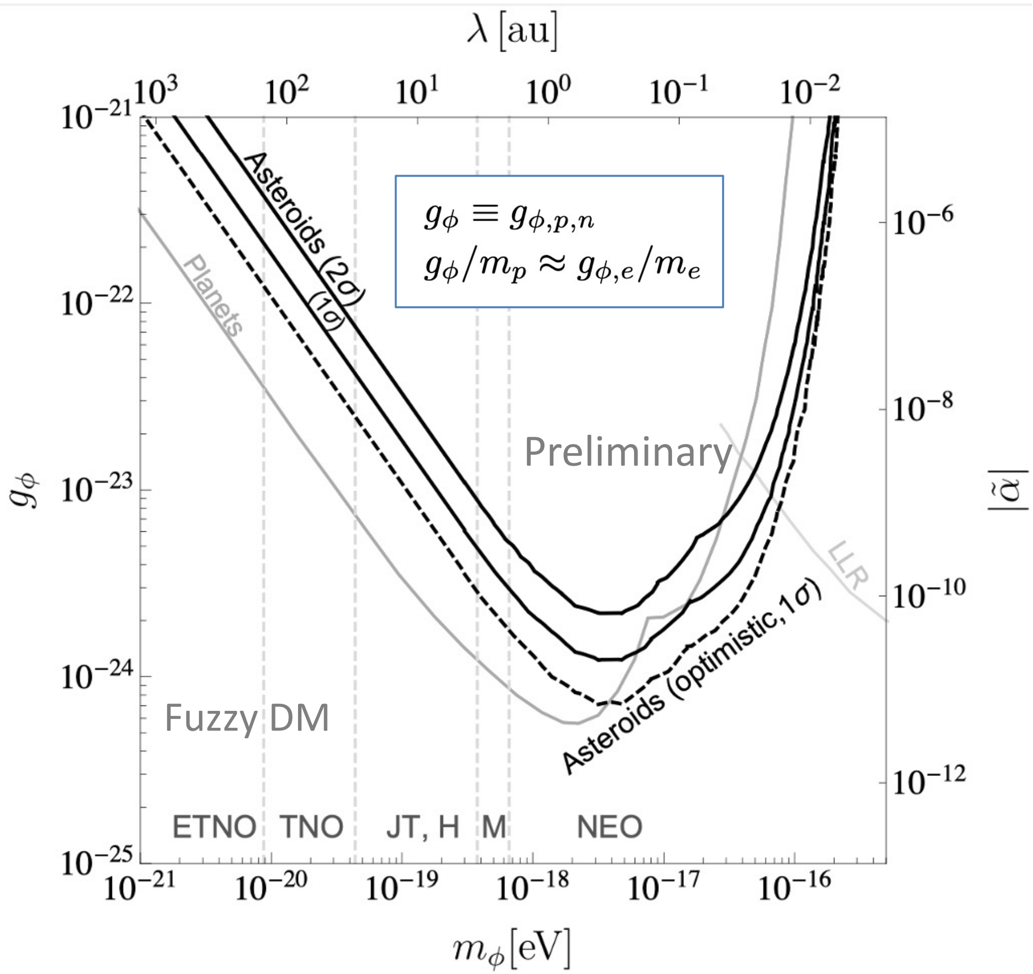
$\sigma_\beta \sim 2\times10^{-4}$,

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, submitting to *PRL*

Asteroid Constrain EP Conserving 5$^{\text{th}}$ forces



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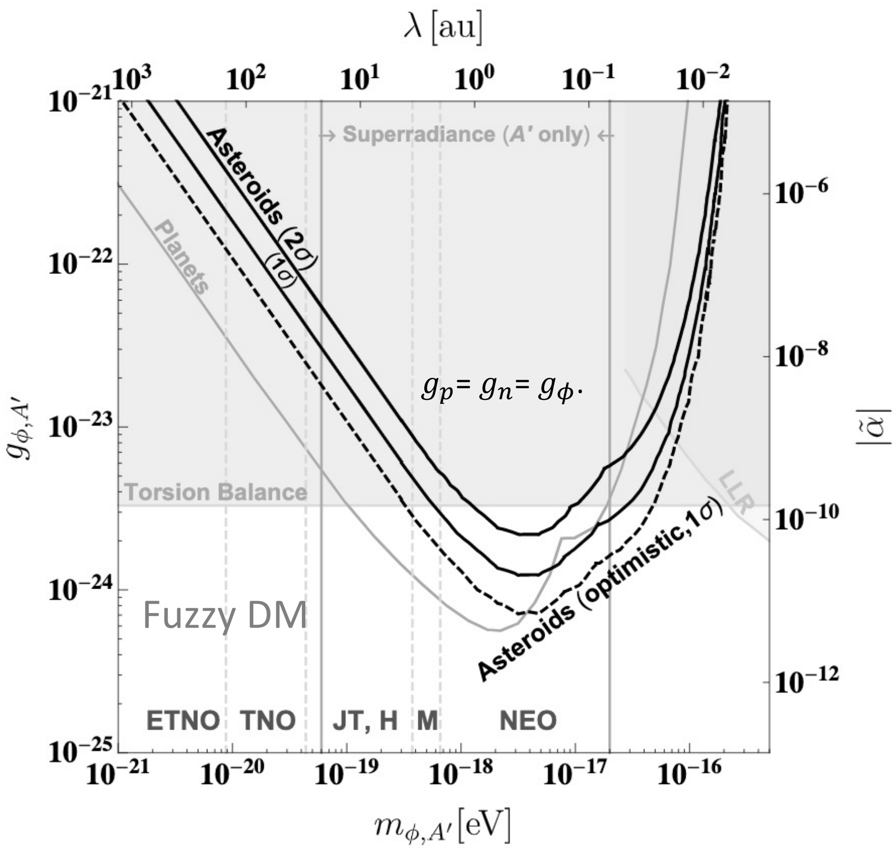
Equivalence Principle-Breaking Fifth Forces



- **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

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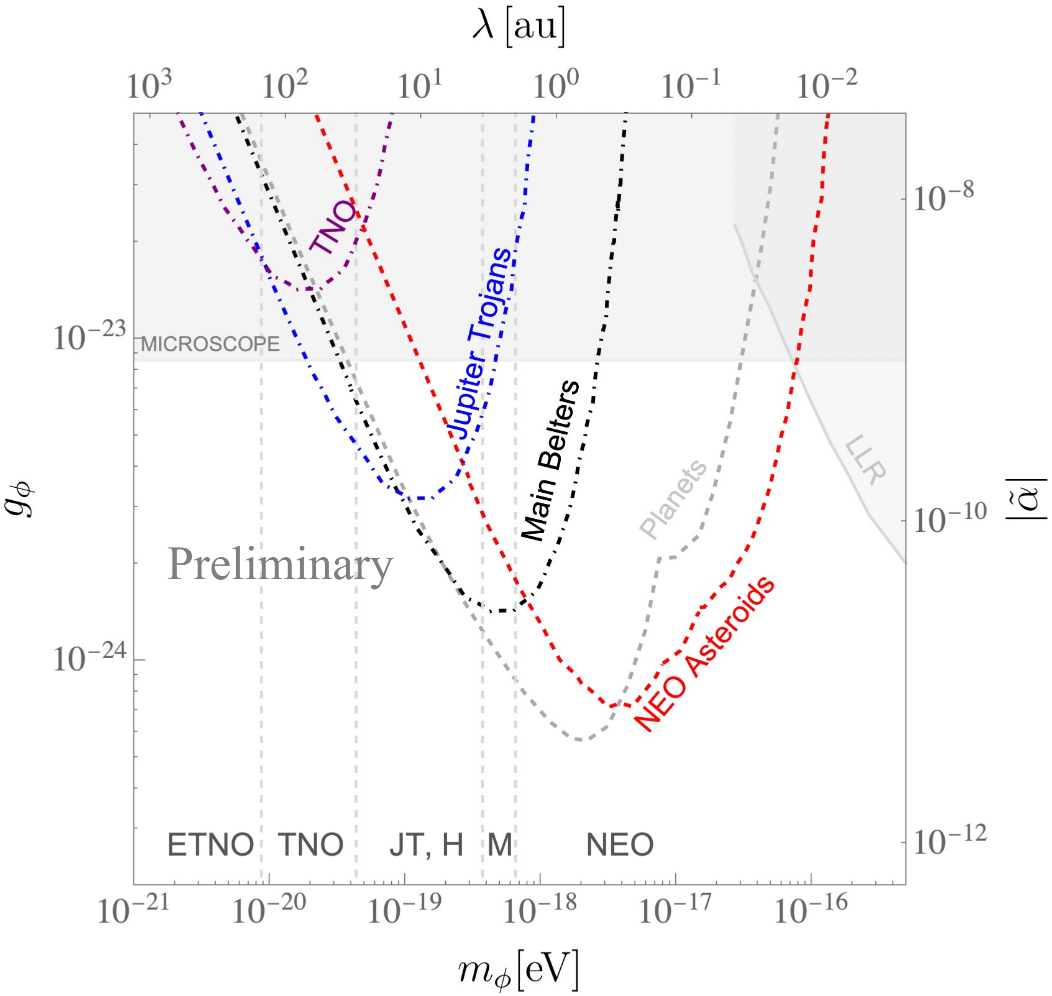
Rough Projections of Near-Future Analysis



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

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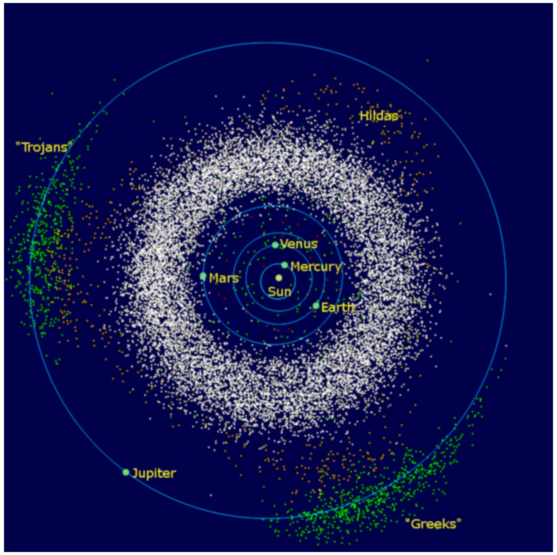
Future objects of interest

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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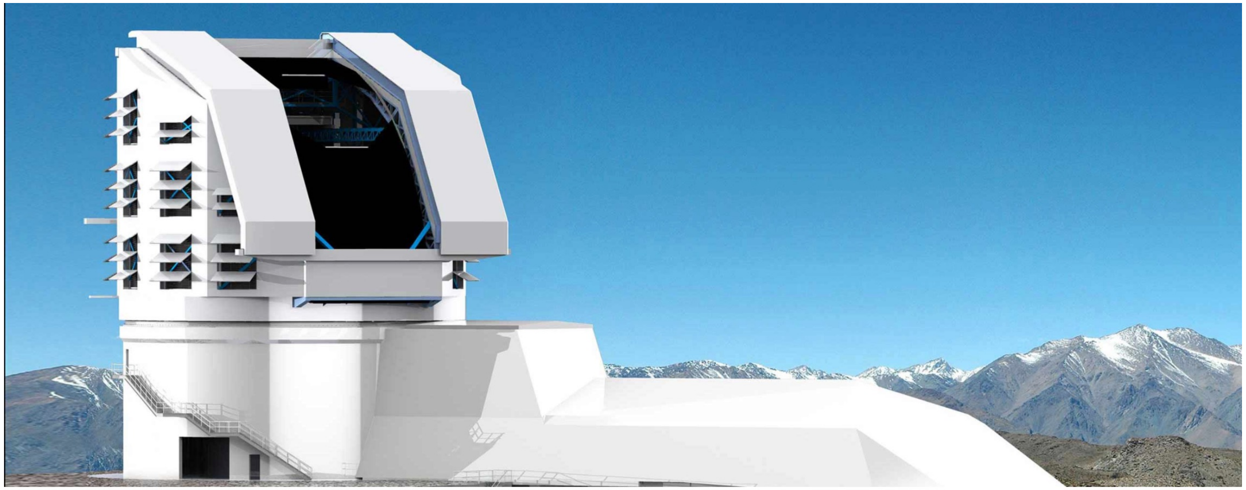
- ***Can also probe dark matter, primordial black hole, etc***

Optical Observations, GAIA, Space Mission

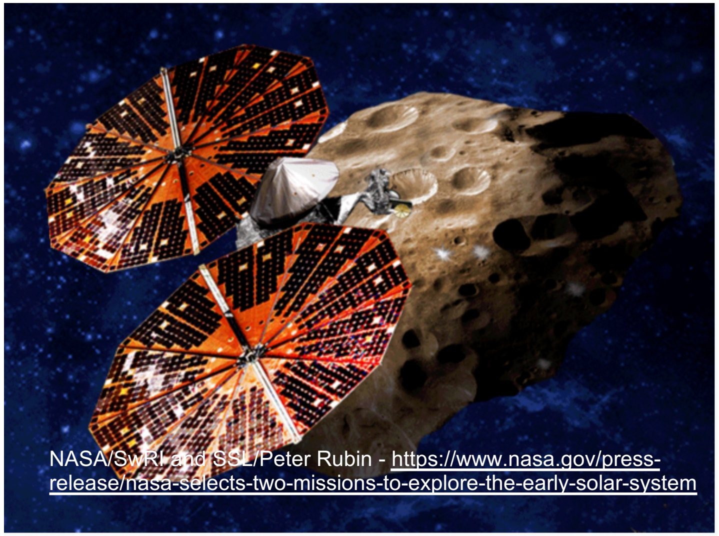


A photograph and rendering mix of the exterior of the Vera C. Rubin Observatory building on Cerro Pachón in Chile. Image credit: Rubin Obs./NSF/AURA

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

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

LUCY is a planned NASA space probe that will complete a 12-year journey to seven different **asteroids.**



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

New projects

Yu-Dai Tsai, Fermilab → UC Irvine, '21,
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Some References

- 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

Three Exciting Research Directions

- **Asteroidal/Planetary Tracking Array**
  develop a tracking array to study **bosonic ultralight dark matter** (possible) and **gravitational wave** (difficult), see references in previous slides

- **Lunar Laser + Radar Ranging**
  LLR + **transponder**; **multi-messenger localization**
  discussing with NSF funded **Q-SEnSE collaboration**

- **Space – Q: Space Quantum Technologies**
  Probing **fundamental physics** with **space quantum technologies**
  with Josh Eby (IPMU) & Marianna Safronova (Delaware)
  coming out this week!

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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Thank you!

Especially thank Youjia, Sunny, & Luca

Happy to discuss more!

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