Asteroid tracking array: new fifth-force and ultralight dark sector tests

Yu-Dai Tsai

Research Associate @ Fermilab / U Chicago

w/ Youjia Wu, Sunny Vagnozzi, Luca Visinelli

arXiv:2107.04038, submitted to *PRL*

OUTLINE

- **Precessions** and **general relativity**
- **Introductions to asteroids**
- **Ultralight new physics & fifth forces**
- **Outlook & future projects**

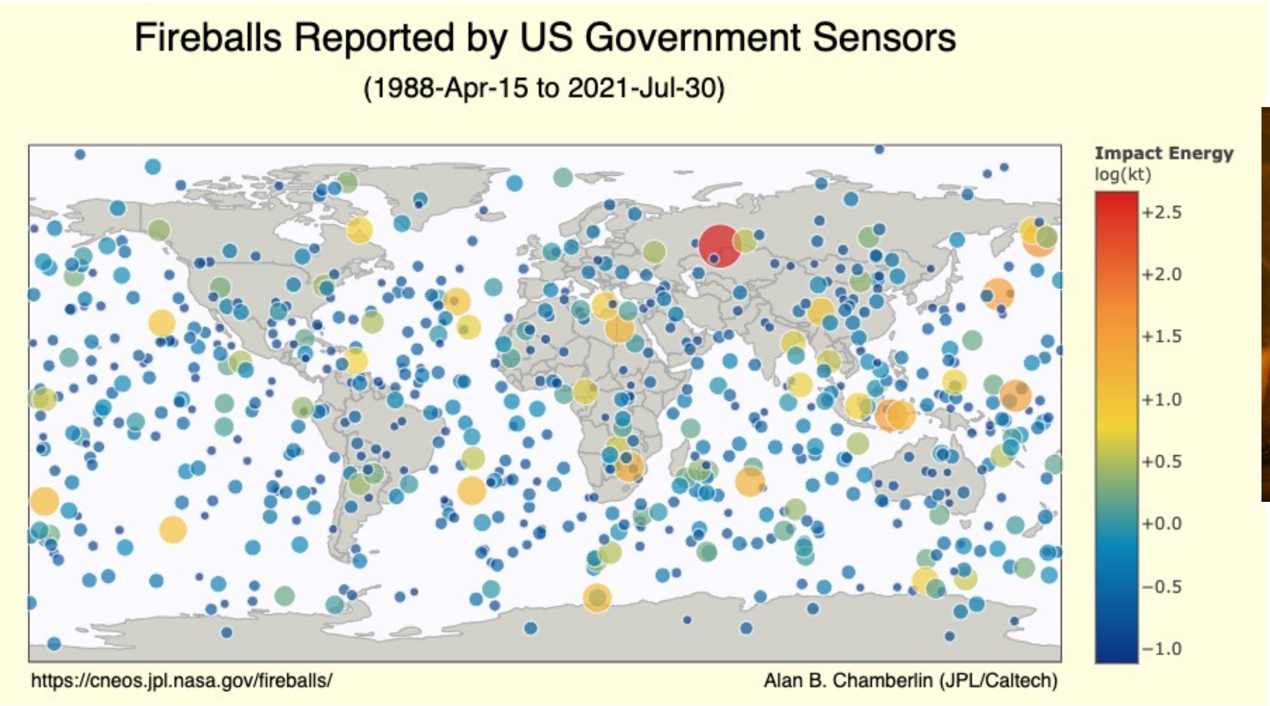
Theme of this talk:

Using **asteroid astrometry** to study **new physics**

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

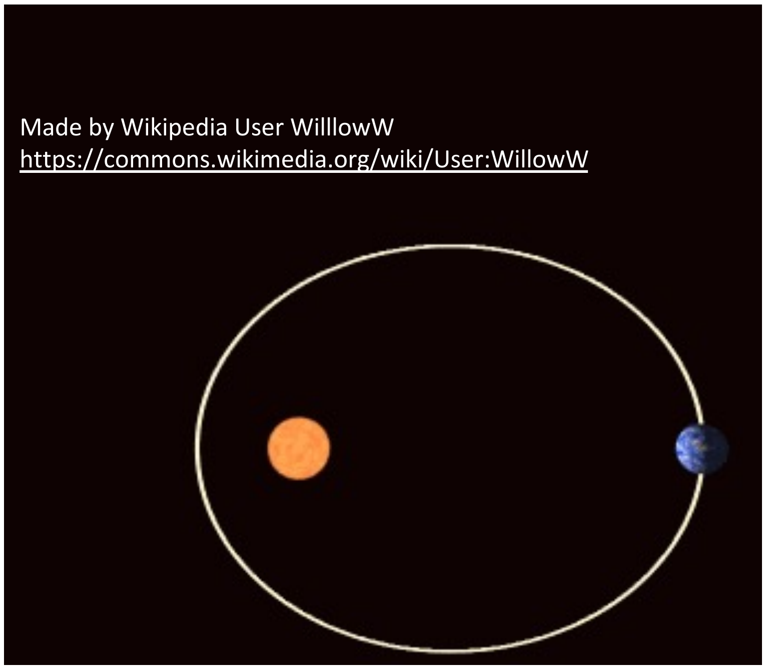


~ 65 million years ago

Tracking asteroids is extremely important

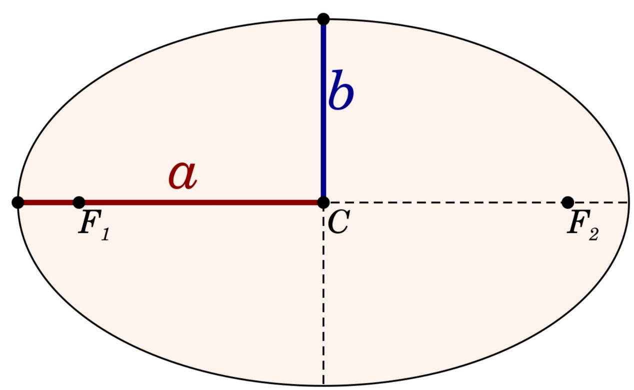
Theoretical Breakthrough: Einstein's Success

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



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

Precession by General Relativity (GR)

Precession of Mercury's perihelion

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

(GR)

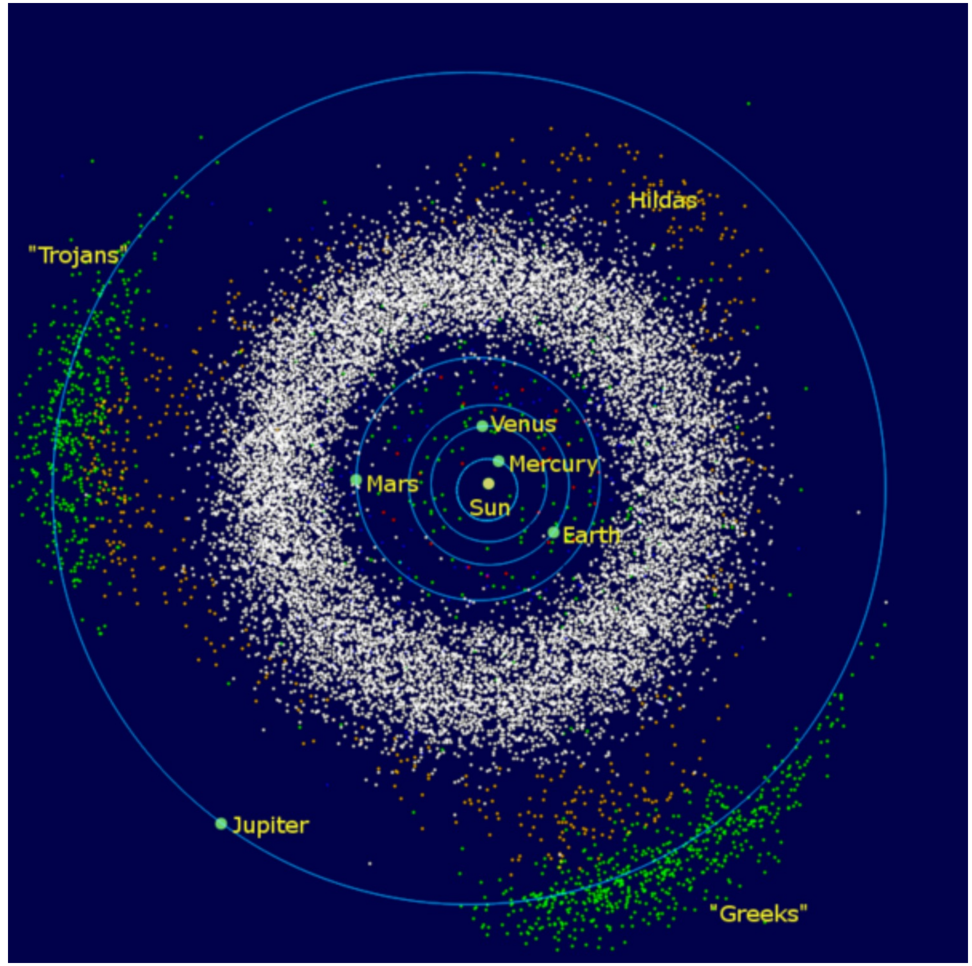
- a is the semi-major axis
- e is the essentricity
- Β, γ are the two parameterized post Newtonian parameters,
  both **equal to 1 in GR**
  tightly constrained by Solar System probes
- β represents the amount of nonlinearity in the superposition law for gravity
- γ represents the amount of curvature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

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

Asteroids:

New targets for fundamental new physics

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.

- **Radar astronomy** help reduce the uncertainty of near-Earth distance to **30 m – 1 km!**

- Utilizing Mission Operations and Navigation Toolkit Environment (MONTE) simulation from JPL

Nine NEOs with excellent radar observations

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

Analysis

- **Verma, Margot, Greenberg, arXiv:1707.08675, 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

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. **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)

2. **Baryon-coupled ultralight scalars**

$$\mathcal{L}_\phi = (g_p \bar{p} p + g_n \bar{n} n)\phi.$$

   g_p= g_n= g_ϕ.

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.

Low-Mass/Ultra Long-Range Force 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**
- **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**

Our Estimation of New Physics Parameter

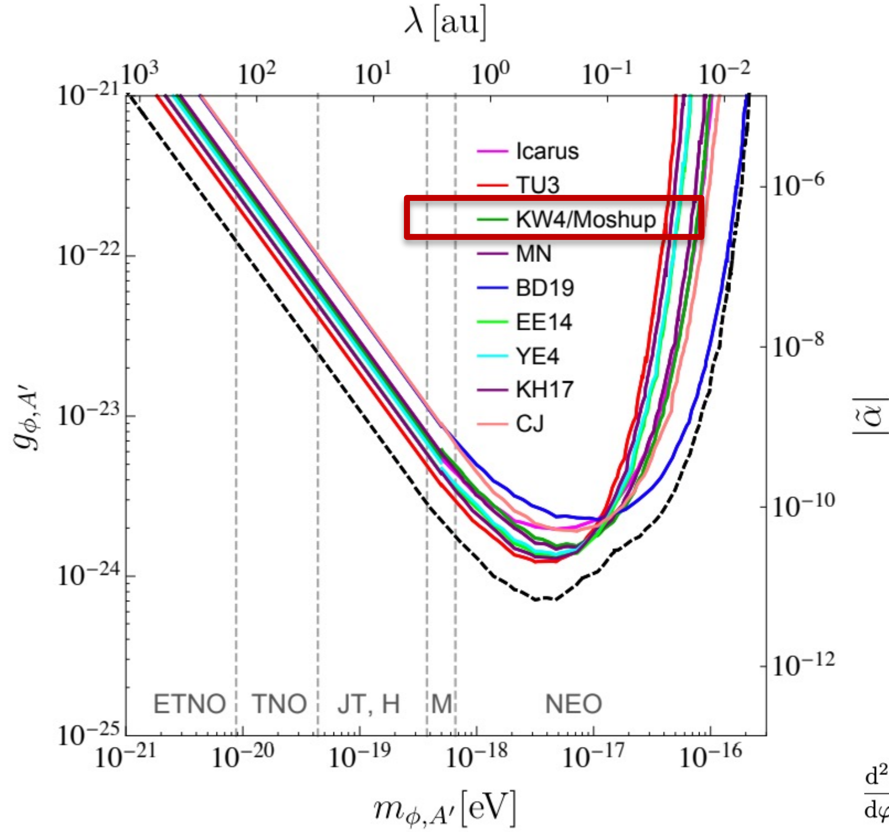
$$\frac{\mathrm{d}^2 u}{\mathrm{d}\varphi^2} + u - \frac{GM_\odot}{L^2} = \frac{3GM_\odot}{c^2} u^2 + \widetilde{\alpha} \frac{GM_\odot}{L^2} \left(1 + \frac{1}{\lambda u}\right) e^{-\frac{1}{\lambda u}} \,,$$

Solving full differential equation

$$\Delta\varphi^2_{\phi, A'} < \left| \frac{\partial \Delta\varphi_0}{\partial \beta} \right|^2 \sigma_\beta^2 + \text{ (Solar Oblateness Contributions)}.$$

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

Results for the new physics



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

Optimal 2022 results

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

Best reach:

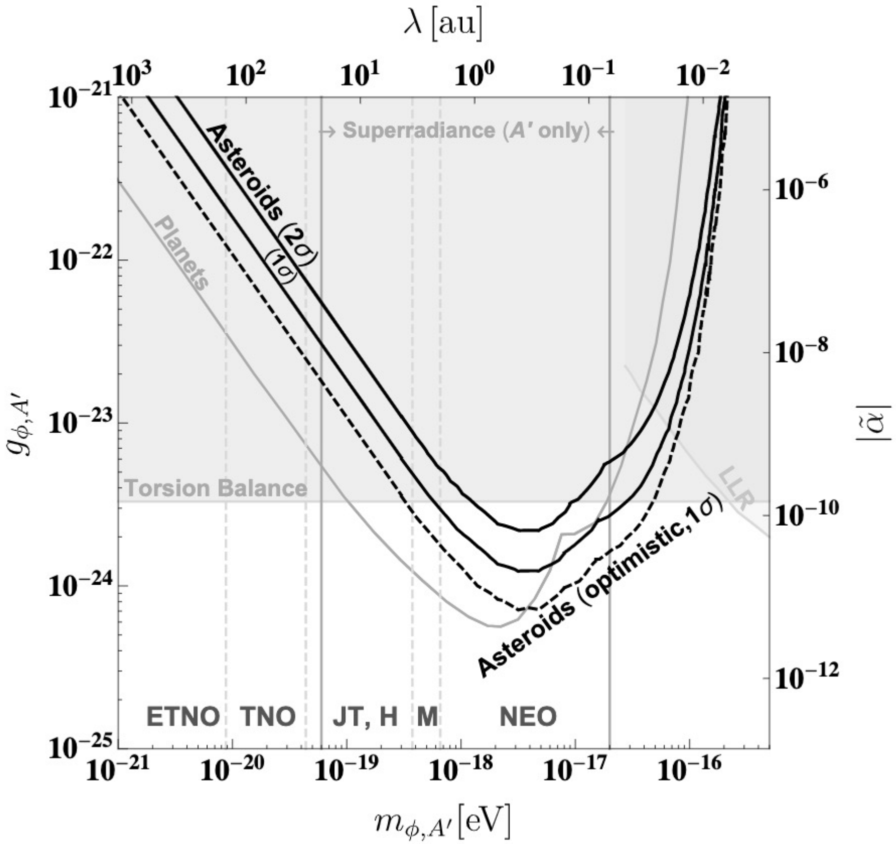
TU3, MN, BD19

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

$$\Delta\varphi^2_{\phi,A'} < \left|\frac{\partial \Delta\varphi_0}{\partial \beta}\right|^2 \sigma_\beta^2 + \text{(Solar Oblateness Contributions)}.$$

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

Comparing to the bounds

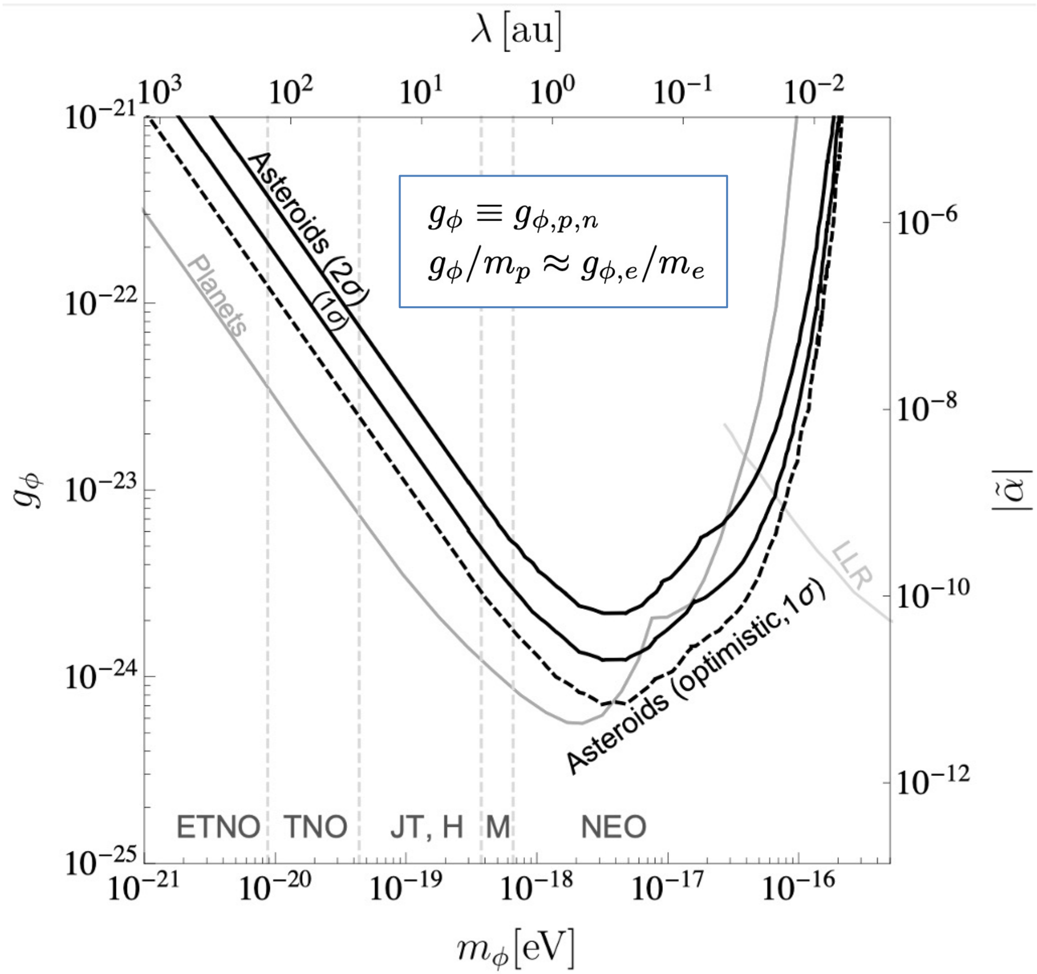


- **Best reach: TU3, MN, BD19**
- **Torsion Balance Exp:** Schlamminger, Choi, Wagner, Gundlach, Adelberger, PRL 08
- **Superradiance:** Baryakhtar, Galanis, Lasenby, and Simon, PRD 21
- **LLR: Lunar Laser Ranging** Williams, Turyshev, Boggs, PRL 04
- **Planets:** Poddar, Mohanty, Jana, EPJC 21

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

We are conducting a detailed study with people from JPL & ESA for this study

Comparing to the bounds



- **Torsion Balance Exp is like Pisa experiment: measuring the difference of acceleration**
  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, submitting to *PRL*

We are conducting a detailed study with people from JPL & ESA for this study

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 $a(1 - \mathsf{e}) < 1.3\,\text{au}$.

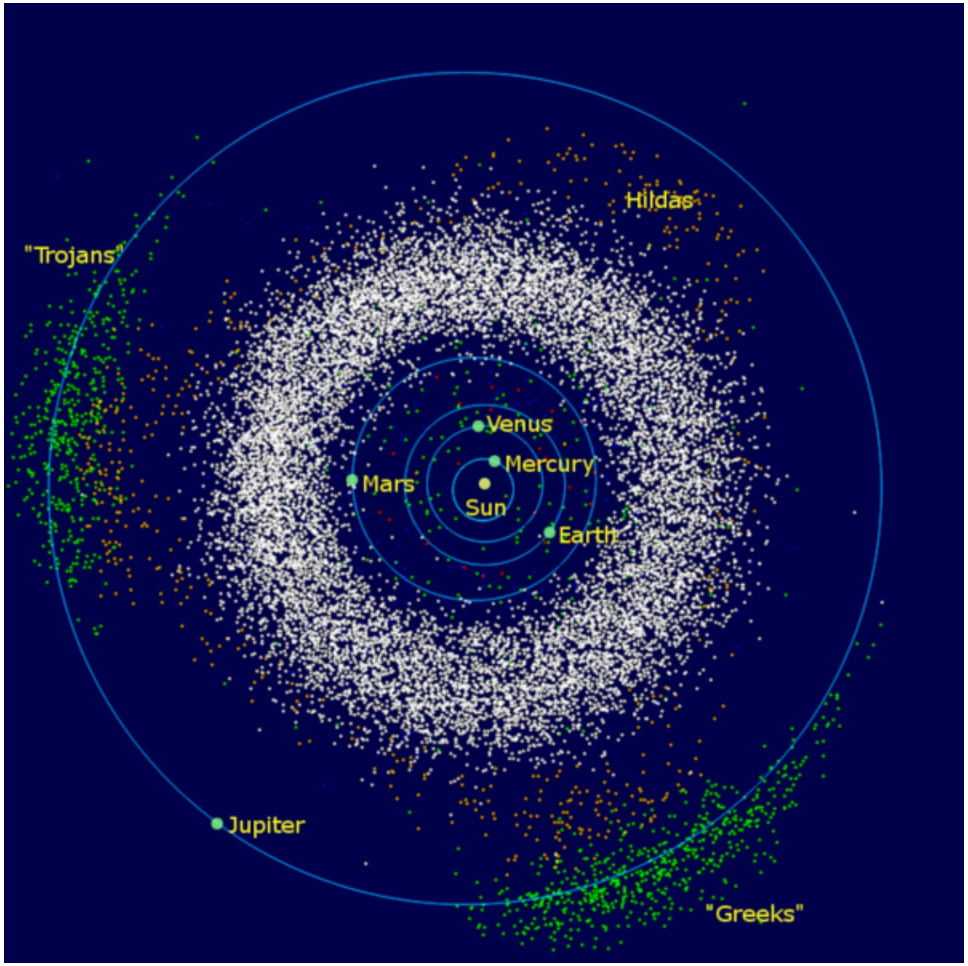
$$|\Delta\varphi_{\phi,A'}| \simeq \frac{2\pi}{1 + \frac{g^2}{4\pi G m_p^2}} \frac{g^2}{4\pi G m_p^2} \left(\frac{amc}{\hbar}\right)^2 (1 - \mathsf{e})\,.$$

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

Asteroids

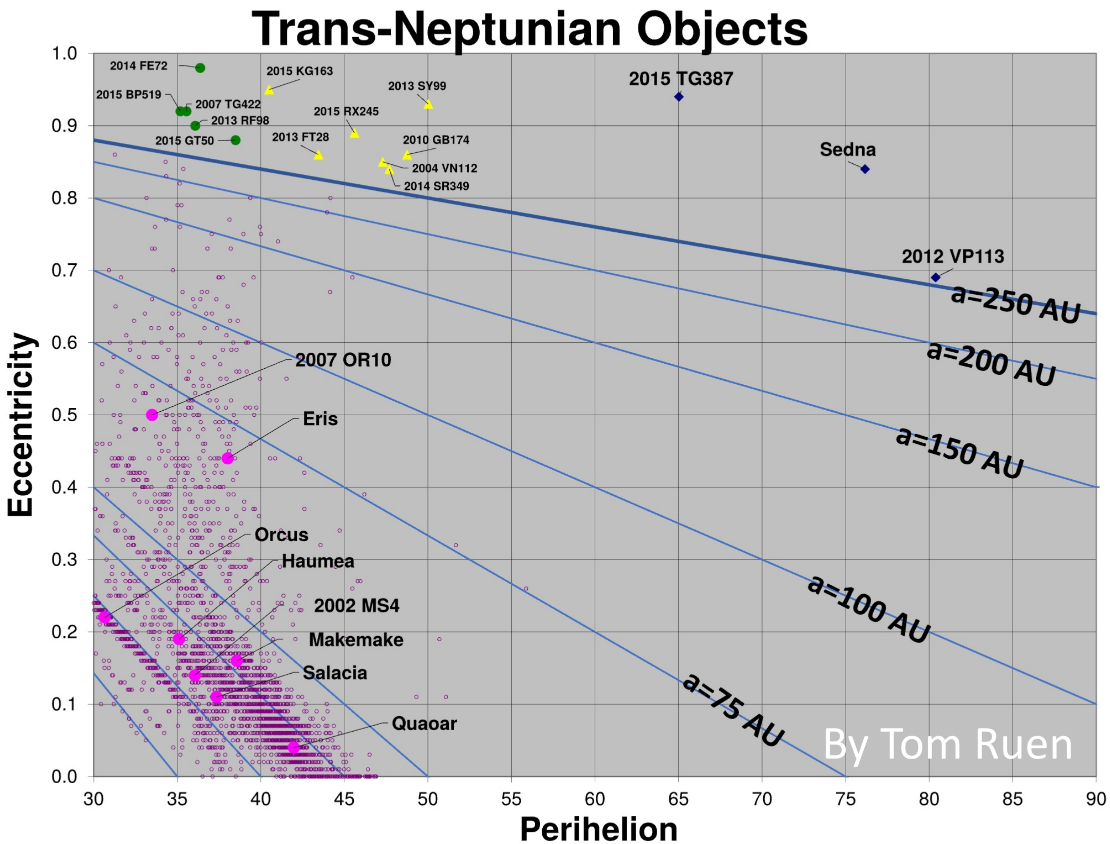
- Different new physics can be studied in different groups of asteroids

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



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

TNO / ETNO

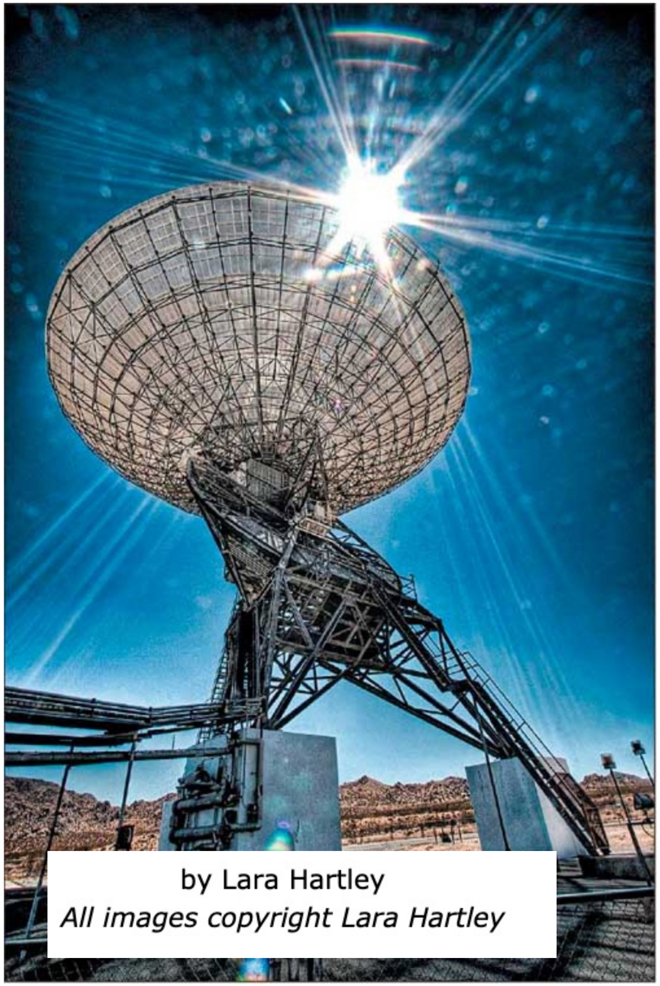


https://en.wikipedia.org/wiki/Extreme_trans-Neptunian_object#/media/File:Extreme_trans-Neptunian_objects_eccentricity_vs_perihelion.svg,
https://arxiv.org/pdf/1810.00013.pdf

- Much **less solar thermal effects** or **gravitational objects** to affect their trajectories

Observations

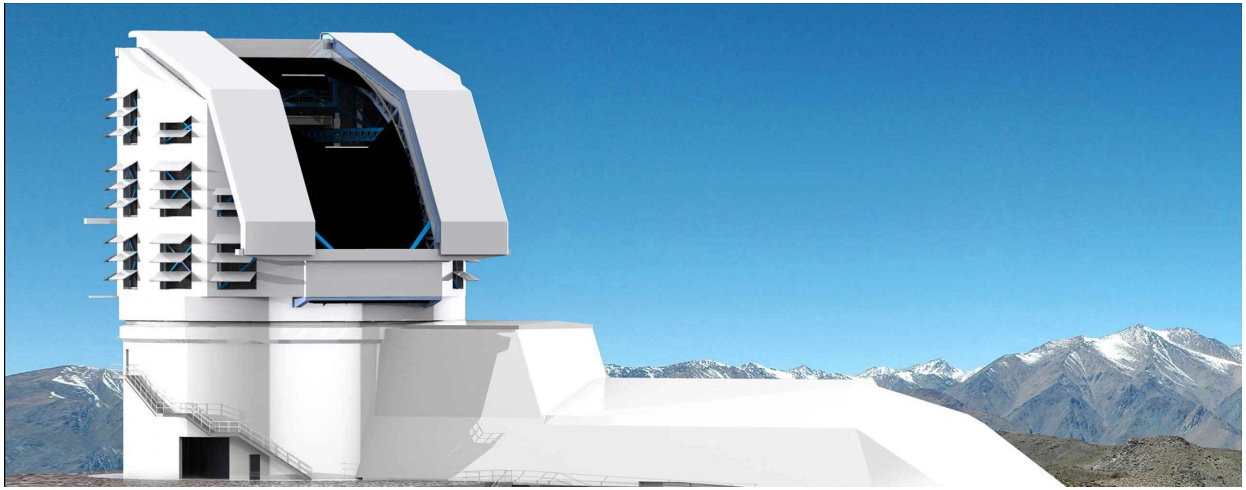
- Radar – **Goldstone Observatory**: Provide very precise location and velocity information of the asteroids
- Radar astronomy is a technique of observing nearby astronomical objects by reflecting microwaves off target objects and analyzing the reflections.
- Radar astronomy differs from radio astronomy in that the latter is a passive observation and the former an active one.



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

Optical Observations, GAIA, Space Mission

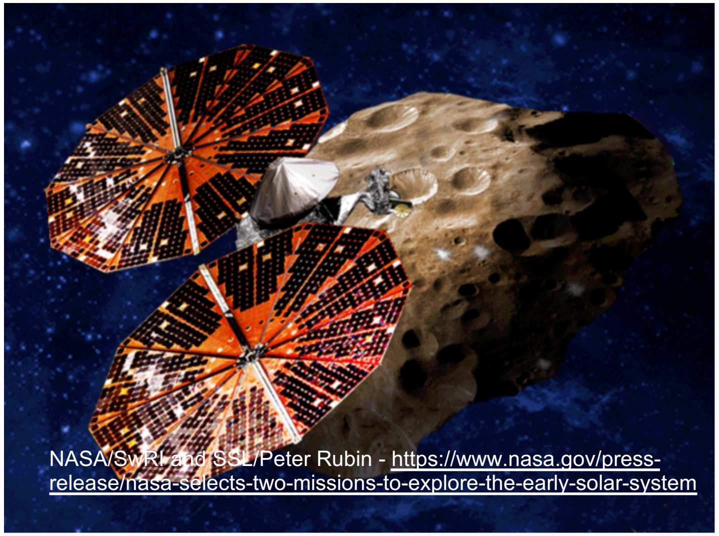


A photograph and rendering mix of the exterior of the Vera C. Rubin Observatory building on Cerro Pachón in Chile. Image credit: Rubin Obs./NSF/AURA
https://www.aura-astronomy.org/centers/nsfs-oir-lab/rubinobservatory/

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

GAIA provides **stellar reference for asteroid localization**

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



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

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

Big Picture & Outlook

- Planetary astrometry is a strong new tool to study new physics: **many more models and related new techniques**

- **Asteroid tracking array as a probe for gravitational waves!**

For background, see Fedderke, Graham, Rajendran, PRD21

- Planetary studies has **defense purposes;** also **made significant discovery ('Oumuamua)**

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

- **Space Quantum Technologies:** new projects with Prof. Safranova

Thank you!