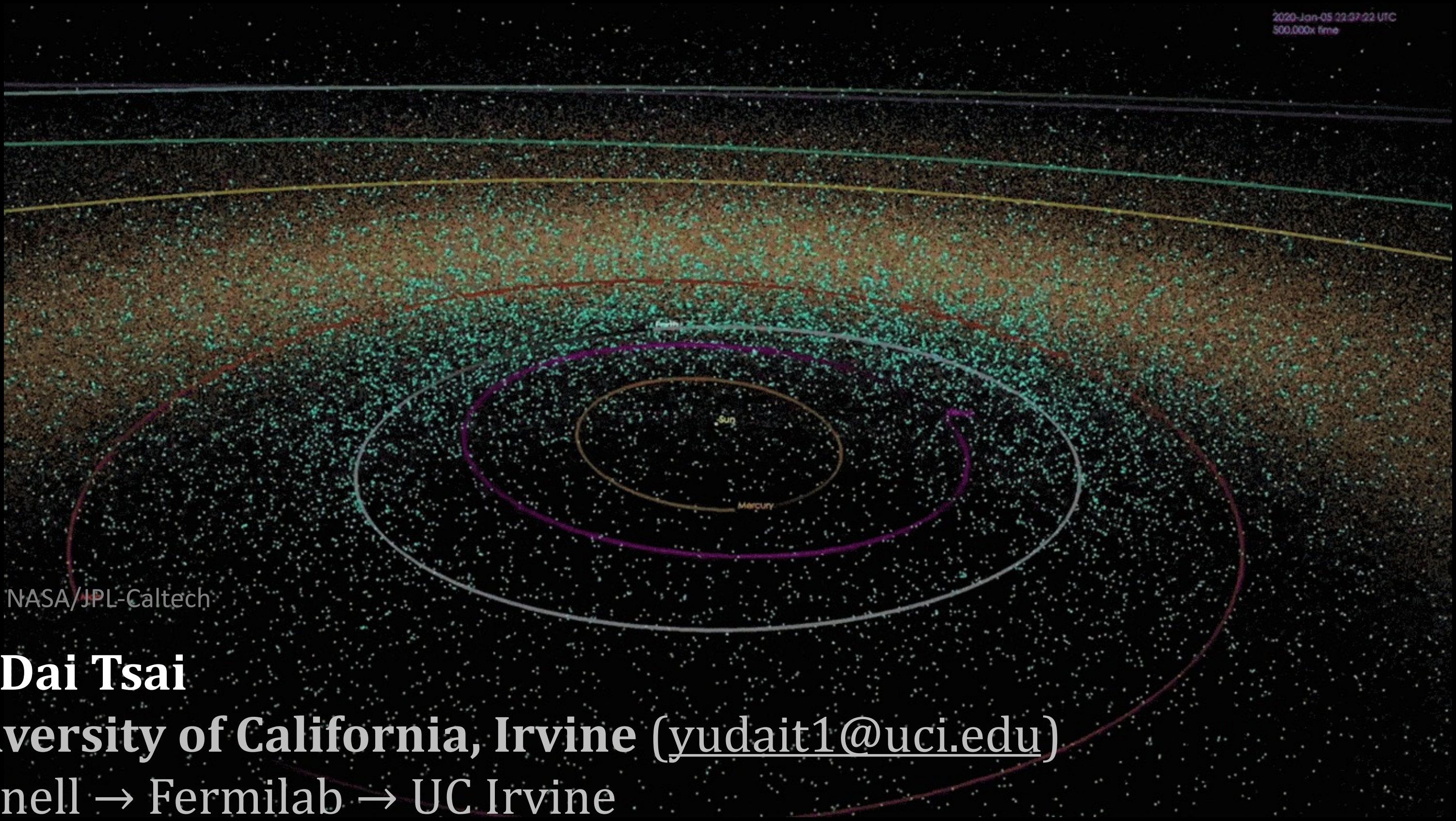
The Elusive Universe: Dark Matter, Cosmic Neutrino, and 5th Forces



Credit: NASA/JPL-Caltech

Yu-Dai Tsai
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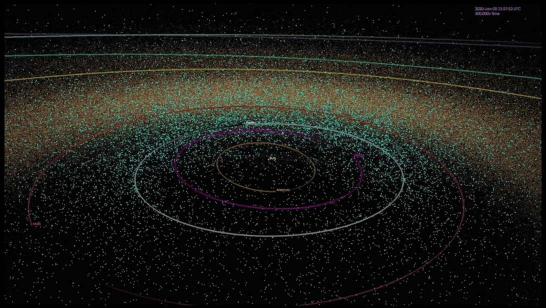
Cornell → Fermilab → UC Irvine

Outline

1. **Dark Matter & (Ultra) Precision Astrometry**
2. **Fifth Forces & General Relativity**
3. **Space Quantum Probe for Ultralight Dark Matter**
4. **Summary & Outlook**

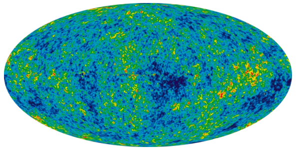
Vera Rubin
Carnegie Institution for Science



Albert Einstein
Mount Wilson Observatory, California

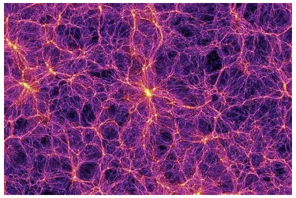
How do we know dark matter exist?

Size



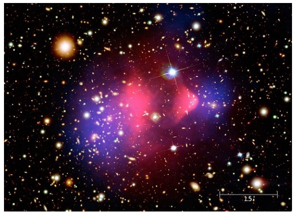
Credit: NASA / WMAP

Cosmic Microwave Background (CMB)



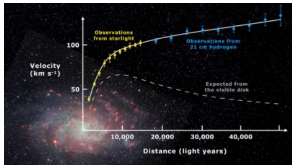
credit: Springel et al. 2015 (10-100 Gpc)

Large Scale Structure



credit: NASA/CXC/M. Weiss (Gpc)

Bullet Cluster Merger



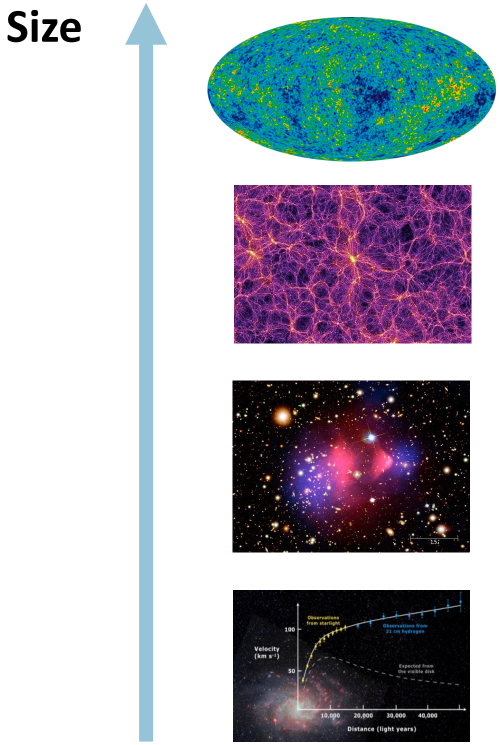
Credit: De Leo-Winkler(10 kpc)

Galactic Rotation Curves

DM
Gravitational
Interactions

Modified from a slide from Tien-Tien Yu (Oregon)

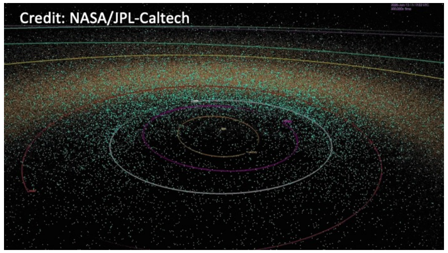
DM Gravity in Smaller Scale?



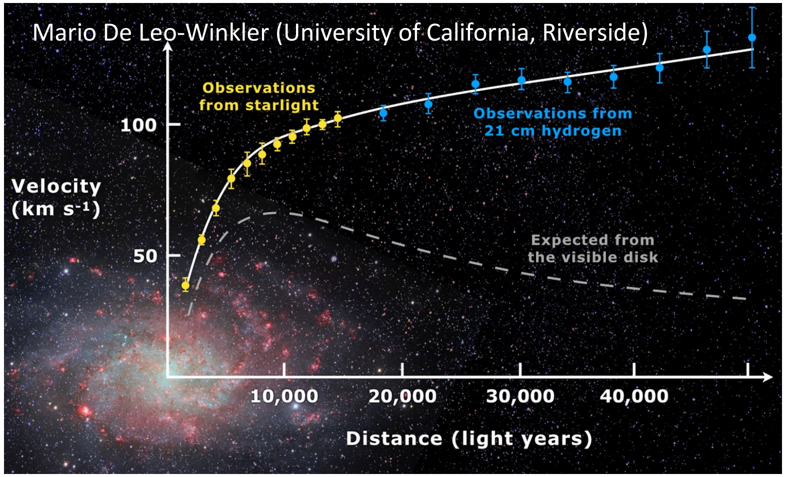
DM Gravitational Interactions

Precision Astrometry

Tsai *et al.*, arXiv:2210.03749
(under review by Nature Astronomy)

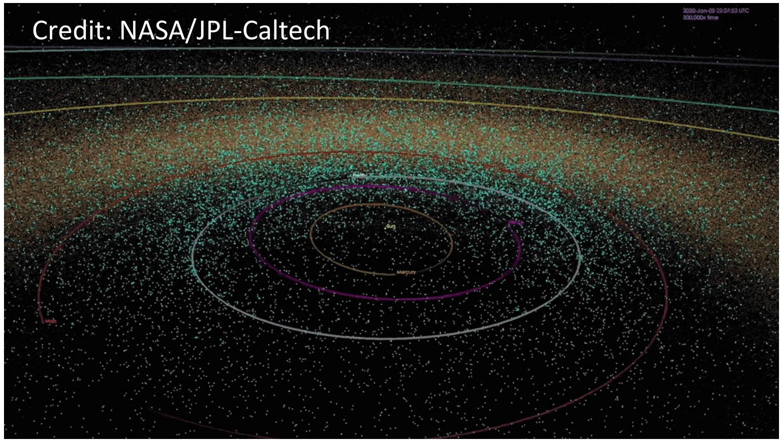

Credit: NASA/JPL-Caltech

A question we asked



Stars

ρ_{DM} for galaxies



Solar System Objects

$\rho_{\mathrm{DM}}(r)$ for solar system

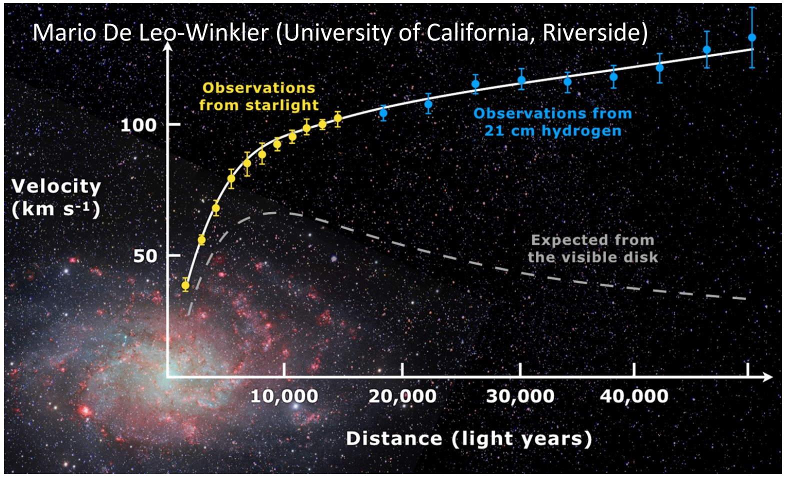
$$\rho_{\mathrm{DM}} \ll \frac{m_{\odot}}{(\mathrm{AU})^3}$$

$\bar{\rho}_{DM} = 0.3\ \mathrm{GeV/cm}^3,$ $\bar{\rho}_{\mathrm{DM}} \sim 10^{-18}\,\frac{m_{\odot}}{(\mathrm{AU})^3}$

Velocity measurements ineffective

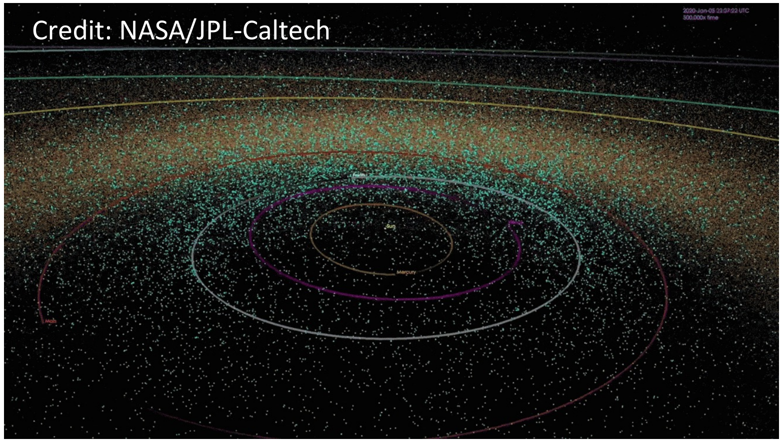
We need to go beyond it!

A question we asked


Mario De Leo-Winkler (University of California, Riverside)

Stars

$\rho_{\rm DM}$ for galaxies

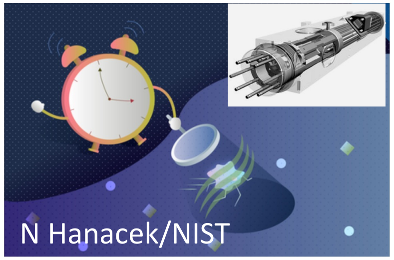

Credit: NASA/JPL-Caltech

Solar System Objects

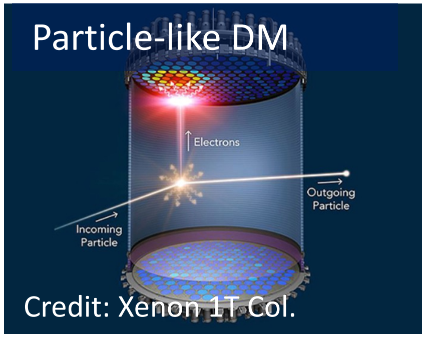
$\rho_{\rm DM}(r)$ for solar system

Crucial for Direct Detection of DM

Wave-like DM


N Hanacek/NIST

Credit: N. Hanacek/NIST

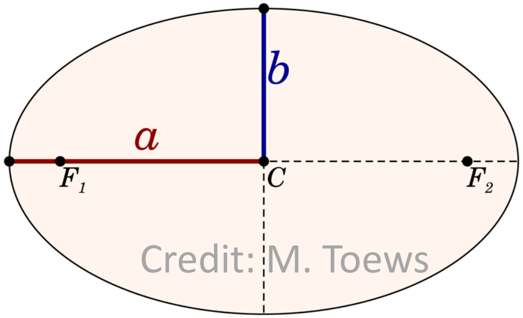

Particle-like DM

Credit: Xenon 1T Col.

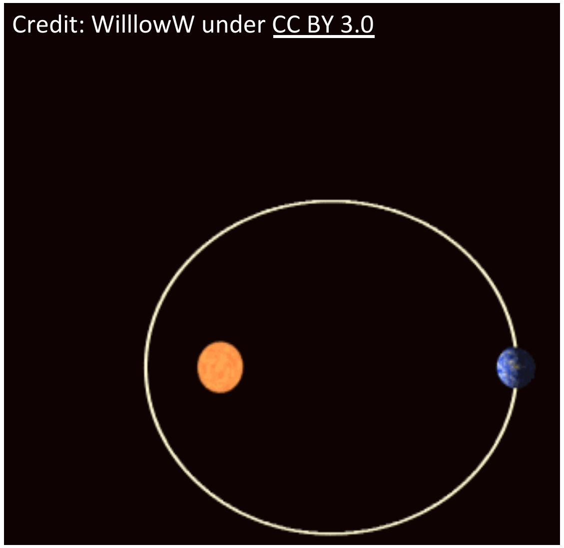
Beyond Velocity: Perihelion Precession

$$\text{Newton}: \quad \mathbf{F}(\mathbf{r}) = -G\frac{m_\odot m_*}{r^2}\hat{\mathbf{r}}, \quad \text{no precession.}$$

- a is the semi-major axis
- e is the eccentricity, quantify how non-spherical the orbit is.



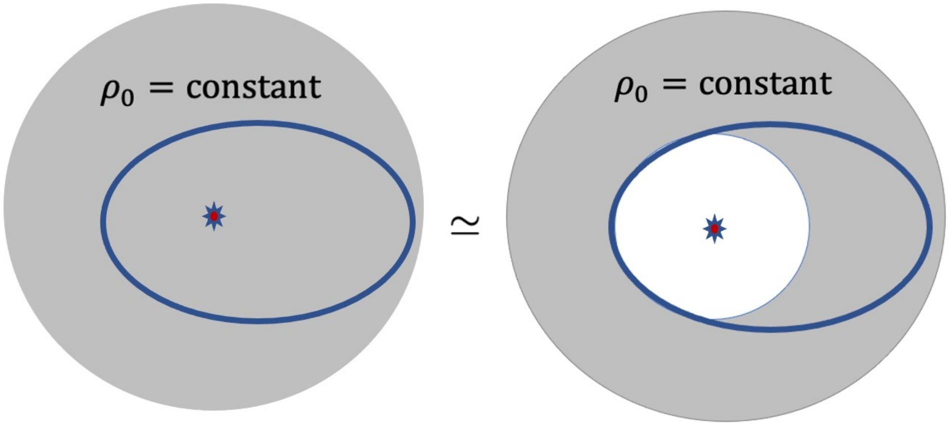
Credit: M. Toews

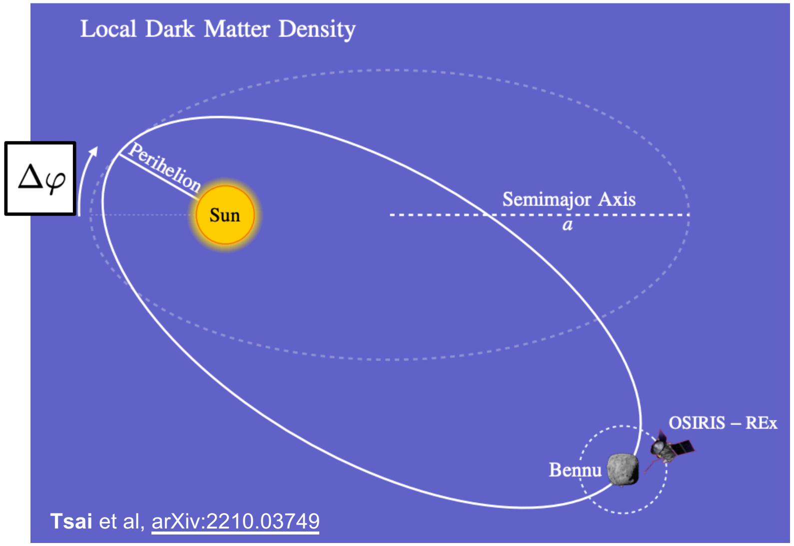


Credit: WilllowW under CC BY 3.0

- **“Anomalous” precession of Mercury's perihelion**
- One of the first ways to confirm **General Relativity**

Our Project: (Local) Dark Matter Induce Precession



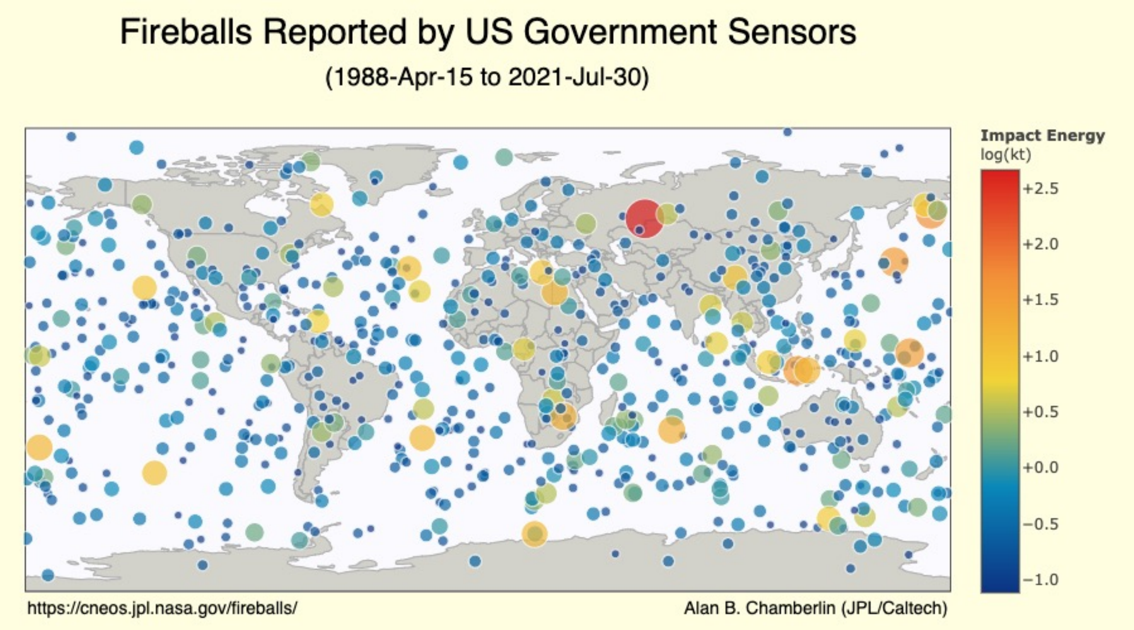


Tsai et al, arXiv:2210.03749

Dark Matter Gravity:
$$\mathbf{F}(\mathbf{r}) = \frac{2\pi}{3} G m \rho_0 \left(\frac{2 r_0^3}{r^2} - 2r \right) \hat{\mathbf{r}}$$
$$\simeq -\frac{4\pi}{3} G m \rho_0 r \hat{\mathbf{r}} + \cancel{\frac{4\pi}{3} G m \rho_0} \frac{r_0^3}{r^2} \hat{\mathbf{r}}.$$

Induced Precession:
$$\Delta\varphi \simeq -4\pi^2 \rho_0 a^3 (1 - e^2)^{1/2} / M_\odot$$

Asteroids & Planetary Defense

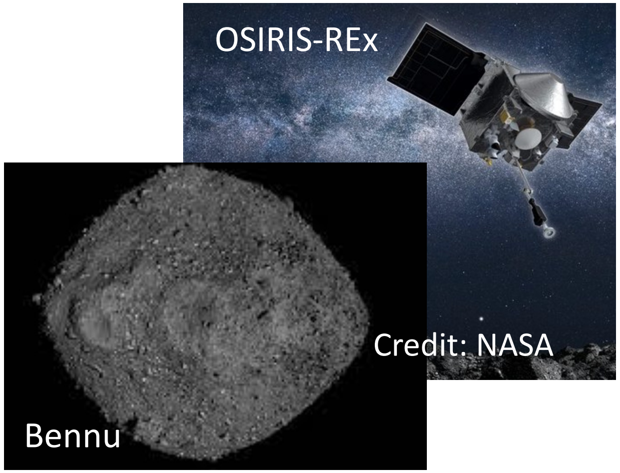


Fireballs Reported by US Government Sensors

(1988-Apr-15 to 2021-Jul-30)

https://cneos.jpl.nasa.gov/fireballs/

Alan B. Chamberlin (JPL/Caltech)



Credit: NASA

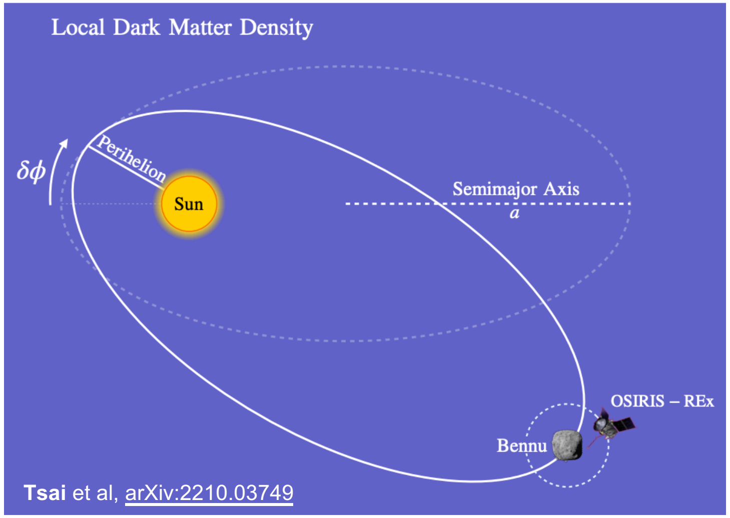
- Tracking asteroids is important to our safety
- We have space missions, like OSIRIS-REx, to track dangerous asteroids like Bennu, return sample.
- **NASA Plan**: OSIRIS-REx will track Apophis and become OSIRIS-APEX

Bennu Data from OSIRIS-REx

- Using OSIRIS-REx X-band radiometric & optical navigation tracking data from December 2018 to October 2020, detailed in, e.g., Farnocchia et al., Icarus 369 (2021) 114594.

- Geocentric pseudo-range points for the Bennu barycenter were derived; Each pseudo-range point represents the roundtrip light time from the geocenter to the Bennu barycenter corrected by solar relativistic effects.

- The uncertainty is 15 ns, corresponding to about **2 m**.

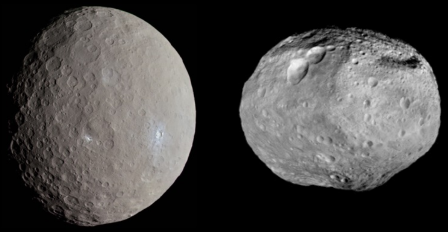


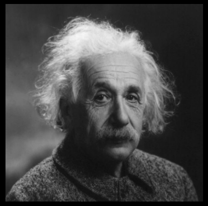
Tsai et al, arXiv:2210.03749

Robust Analysis: High-Fidelity Force Model

JPL Planetary Ephemerides DE424

343 Small-body Perturbers





Relativistic Effects

Oblateness

1) Yarkovsky effect
2) Solar radiation pressure
3) Poynting-Robertson drag,

Farnocchia et al., Icarus 369 (2021) 114594.

Adding Dark Matter to the Force Model

Force terms considered by
Davide Farnocchia

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

✚

The **dark matter** contribution

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

Estimating the ρ_0 parameter

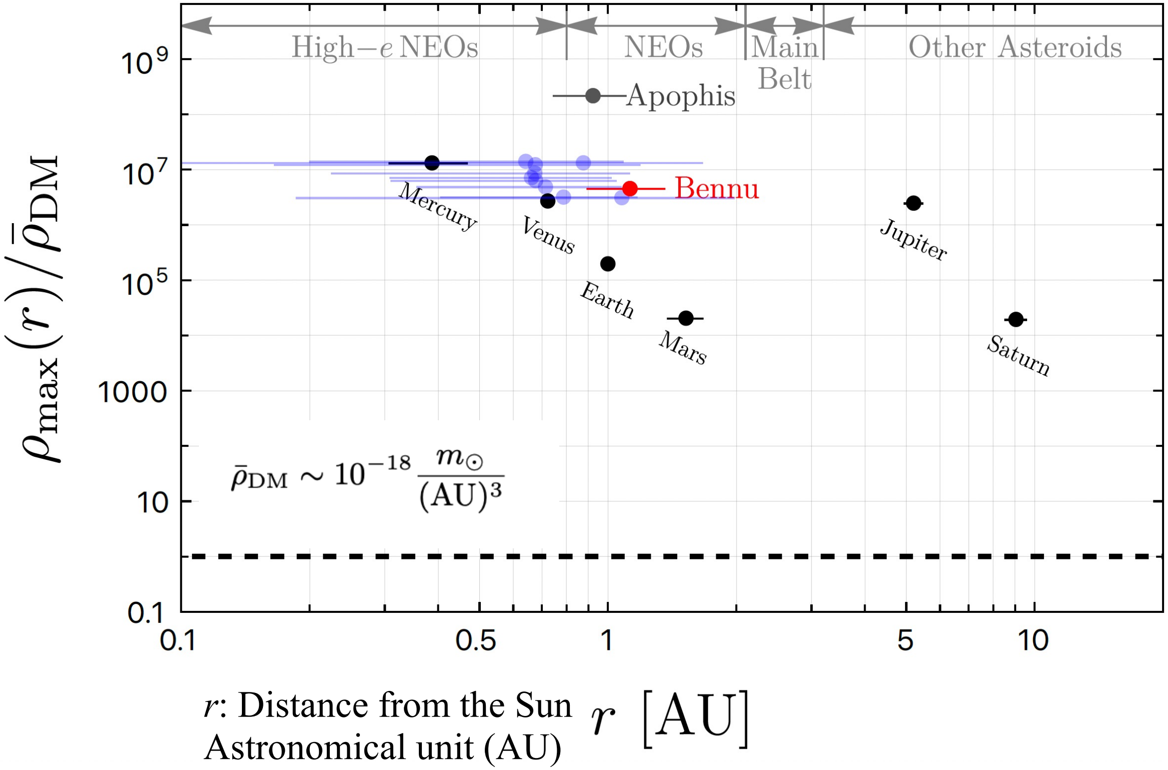
List of additional perturbations considered:

1) Errors in planetary trajectories and masses; 2) Errors in perturber masses & trajectories; 3) Higher order relativistic terms; 4) Higher order gravity terms; 5) Simplified assumptions in nongravitational force model (non-spherical effects, Yarkovsky, solar torque, physical parameter evolution, etc.); 7) Solar mass loss and solar wind;
8) Meteoroid impacts, Spacecraft interaction

New Model-Independent Constraints

- ρ_{max}**(r)** is the derived **upper bound on DM**
- $\bar{\rho}_{DM}$ = 0.3 GeV/cm^3
- NEO: Near-Earth Objects

Tsai, Eby, Arakawa, Farnocchia, Safronova, arXiv:2210.03749



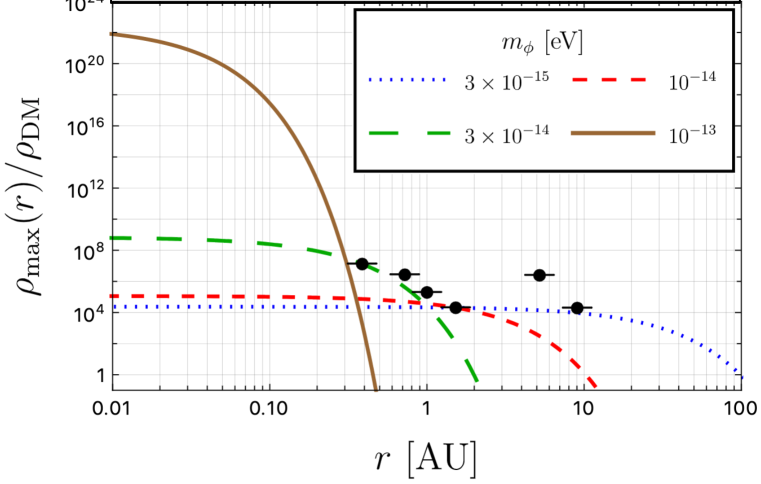
r: Distance from the Sun
Astronomical unit (AU)

- The **horizontal lines** are NOT error bars, but the **coverage of the constraints**.
- The effects of minor perturbers and and other perturbations in backup slides

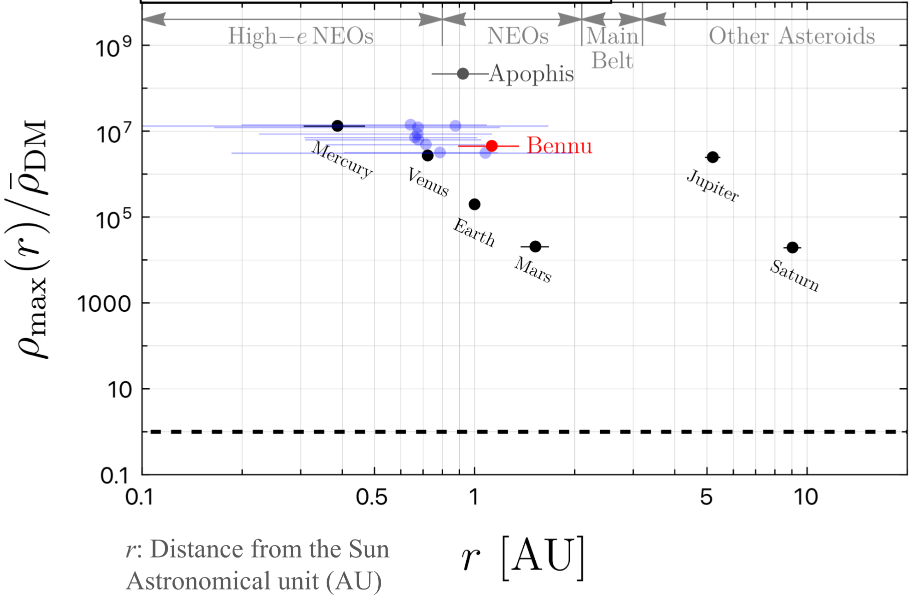
- Bennu result: $\rho_{\rm DM} \leq 1.1 \times 10^{-15}\ {\rm kg/m^3}$

Implication of Our Constraints: DM Over-density (I)

1. **Strong constraints on DM models predict local over-density in solar system**, including **solar halo**, **axion mini-cluster, solar basin**, etc.



Tsai, Eby, Safronova, Nature Astronomy (2022)

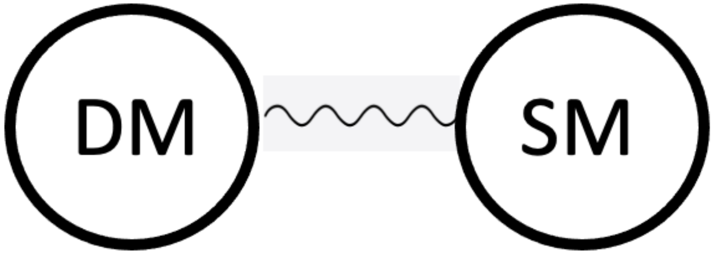


Tsai, et al, arXiv:2210.03749

r: Distance from the Sun
Astronomical unit (AU)

Implications of the Constraints (II)

2. Strong constraints on **DM-SM long-range interaction**, only ~ **4-6 order stronger than gravity: very strong bound**



$$\mathbf{F}_{\rm DM-SM}(\mathbf{r}) \simeq -\tilde{\alpha}_D \frac{4\pi}{3} G m \rho_0' r \hat{\mathbf{r}}.$$

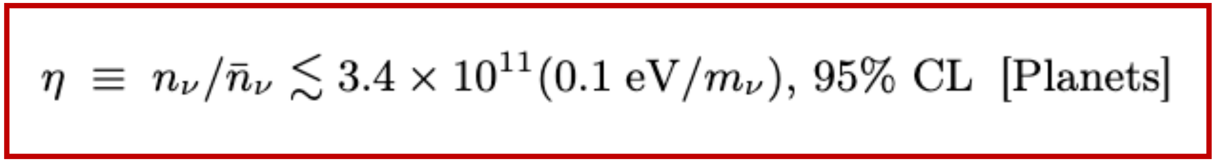
$$\rho_{\rm DM} \lesssim \bar{\rho}_{\rm DM} \left(6 \times 10^6/\tilde{\alpha}_D\right), \text{ Bennu.}$$

$$\rho_{\rm DM} \lesssim \bar{\rho}_{\rm DM} \left(3 \times 10^4/\tilde{\alpha}_D\right), \text{ Saturn.}$$

Constraints on particle physics and cosmology motivated models, Tsai, et al, in progress

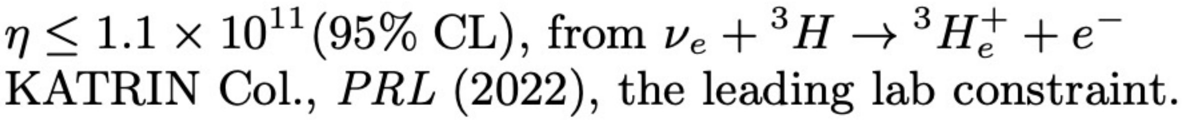
Implications of the Constraints: CvB (III)

3. Close-to-leading constraints on **cosmic neutrino background (CvB)** over-density profile.



$$\eta \equiv n_\nu/\bar{n}_\nu \lesssim 3.4 \times 10^{11}(0.1\ \text{eV}/m_\nu),\ 95\%\ \text{CL}\quad [\text{Planets}]$$

Tsai, et al, arXiv:2210.03749



$\eta \leq 1.1 \times 10^{11}$(95% CL), from $\nu_e + {}^3H \rightarrow {}^3H_e^+ + e^-$
KATRIN Col., *PRL* (2022), the leading lab constraint.

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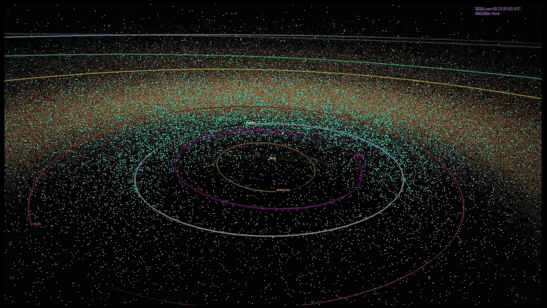
Vera Rubin
Carnegie Institution for Science

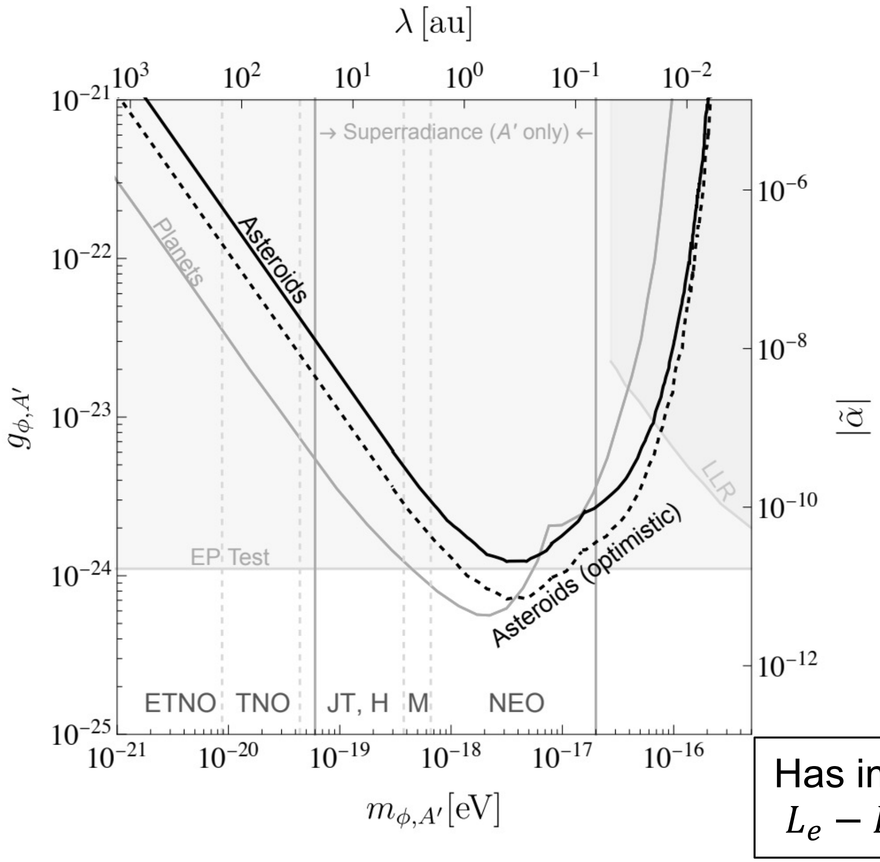


Credit: NASA/JPL-Caltech

Albert Einstein
Mount Wilson Observatory, California

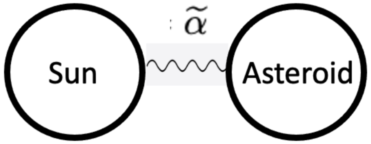
Our Results: Fifth Forces

Tsai, Wu, Vagnozzi, Visinelli, *JCAP* (2023) 2107.04038



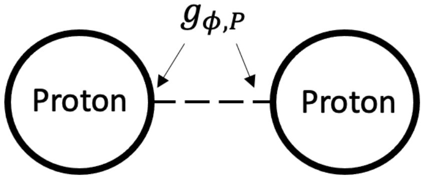
$$V(r) = \tilde{\alpha}\frac{GM_{\odot}M_{*}}{r}\exp\left(-\frac{r}{\lambda}\right),$$

Model Independent Parametrization:



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

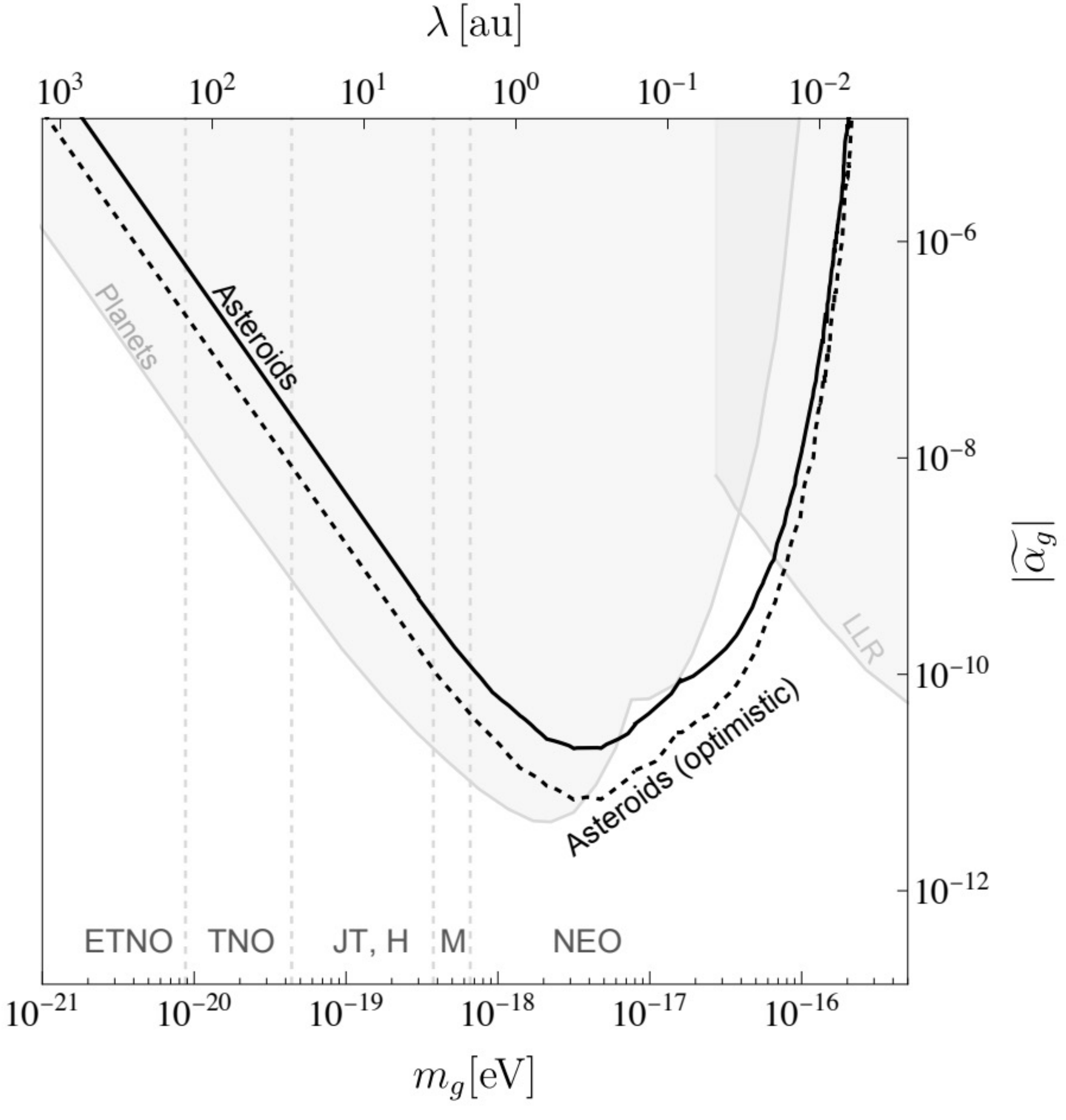
Model Specifics:



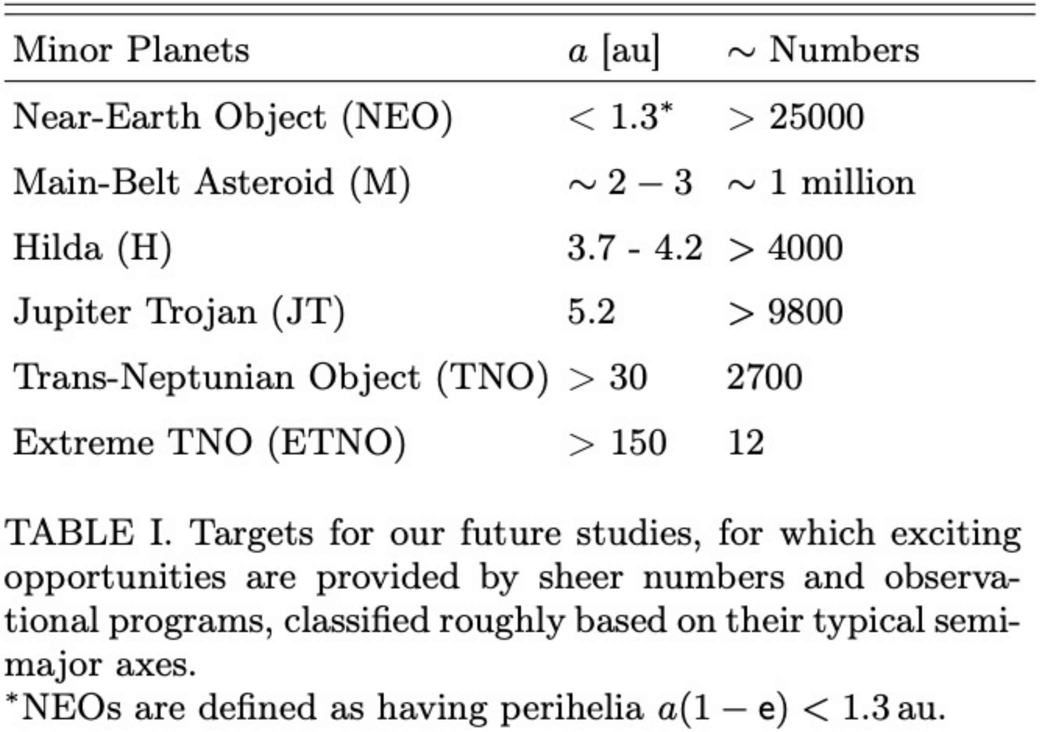
Has implications on **ultralight/fuzzy dark matter,** $L_e - L_{\mu,\tau}$ gauge theories, dark energy models, etc.

For LLR, see, e.g., Williams, Turyshev, Boggs, PRL (2004)

“Yukawa” Gravity Parametrization



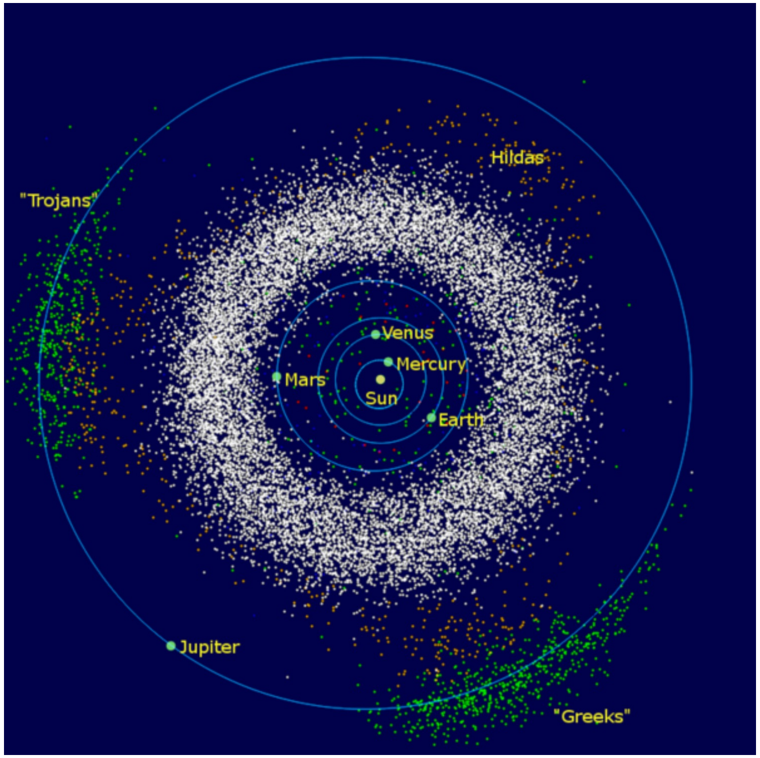
Objects of Interest



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



Summary of High-Energy Theory Targets

- GR Test: $$\Delta\varphi = \frac{6\pi G M_\odot}{a(1-e^2)c^2}\left[\frac{4-\beta}{3}\right] \propto a^{-1}$$
- Fifth Forces: $$|\Delta\varphi_{\phi,A'}| \simeq a(1-e)\left[\left(\frac{mc}{\hbar}\right)^2 \frac{g^2}{4\pi G m_p^2}\frac{2\pi}{1+\frac{g^2}{4\pi G m_p^2}}\right] \propto a$$
  (light mediator limit $m \ll \hbar/ac$)
- Dark Matter: $$\Delta\varphi \simeq -4\pi^2\rho_0 a^3(1-e^2)^{1/2}/M_\odot \propto a^3$$
- Particle theory inputs are crucial
- Calling for modern data-analysis approaches

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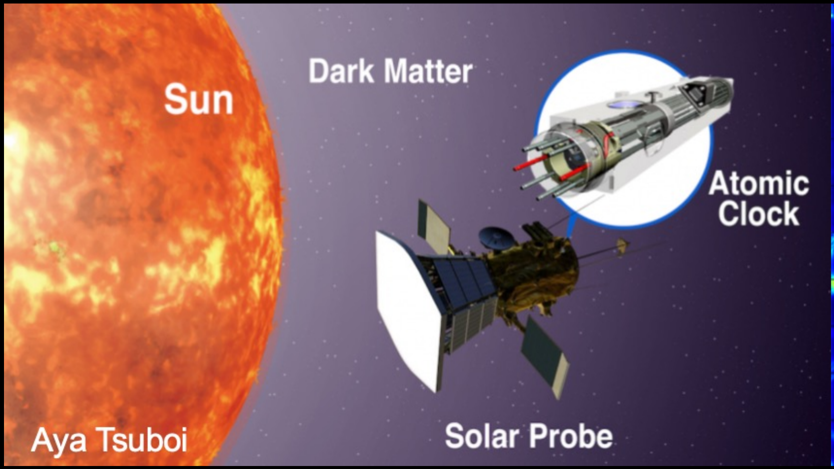
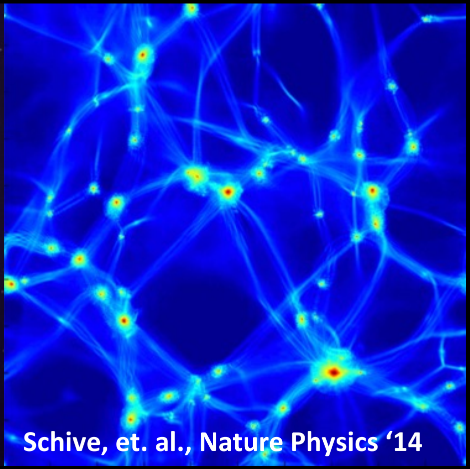
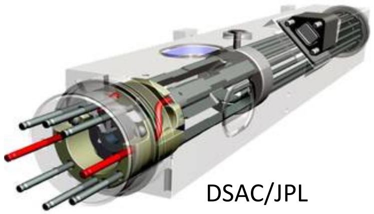


Aya Tsuboi



Schive, et. al., Nature Physics ‘14

NASA DSAC & Parker Solar Probe



29 × 26 × 23 cm (17.5 kg)

- **NASA Deep Space Atomic Clock (DSAC)**
  loses one second every 10 million years, proven in controlled Earth tests.
- The clock has operated for more than **12 months in space; demonstrated long-term fractional frequency stability of 3×10^{-15}**
  Burt et al., Nature 595 (2021) 43.
- Exceeds previous space clock performance by up to an order of magnitude

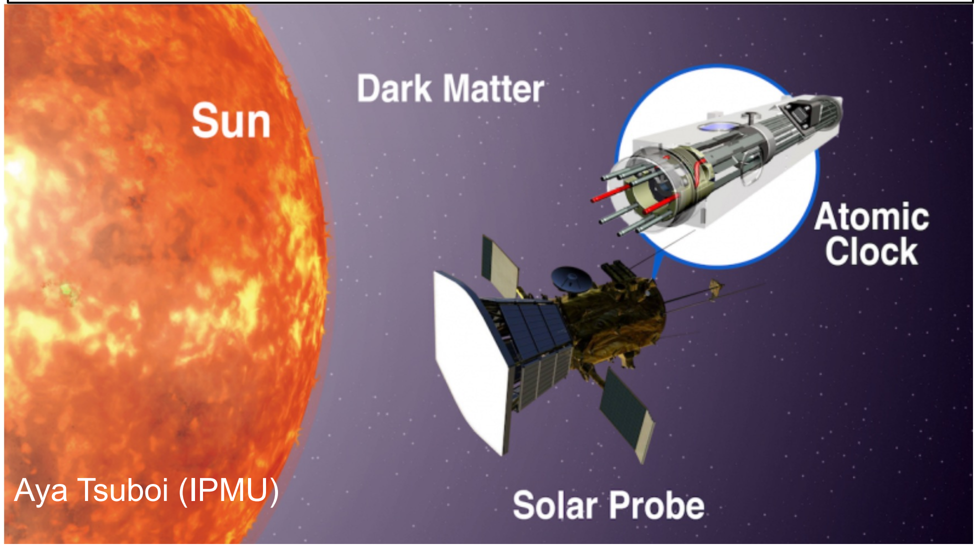
Size of PSP ~ 1.0 × 3.0 × 2.3 m
(685 kg → 555 kg)

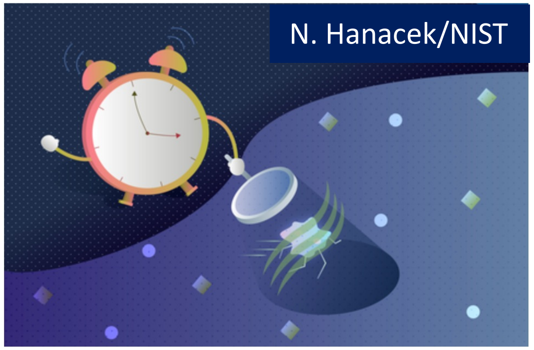
- **Parker Solar Probe (PSP)**
  see, "Probing the energetic particle environment near the Sun," McComas, William Matthaeus et al, Nature (2019).
- **Excited to learn from the experts!**

My Question: Why don't we put a quantum clocks on a solar probe?
What fundamental physics can we study?

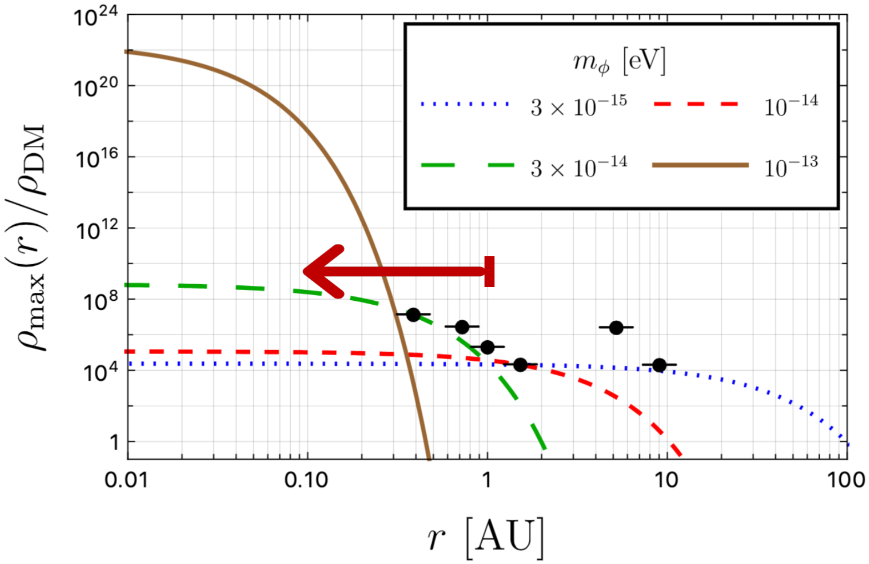
SpaceQ Mission Concept

Tsai, Eby, Safronova, Nature Astronomy (2022)





Credit: N. Hanacek/NIST



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

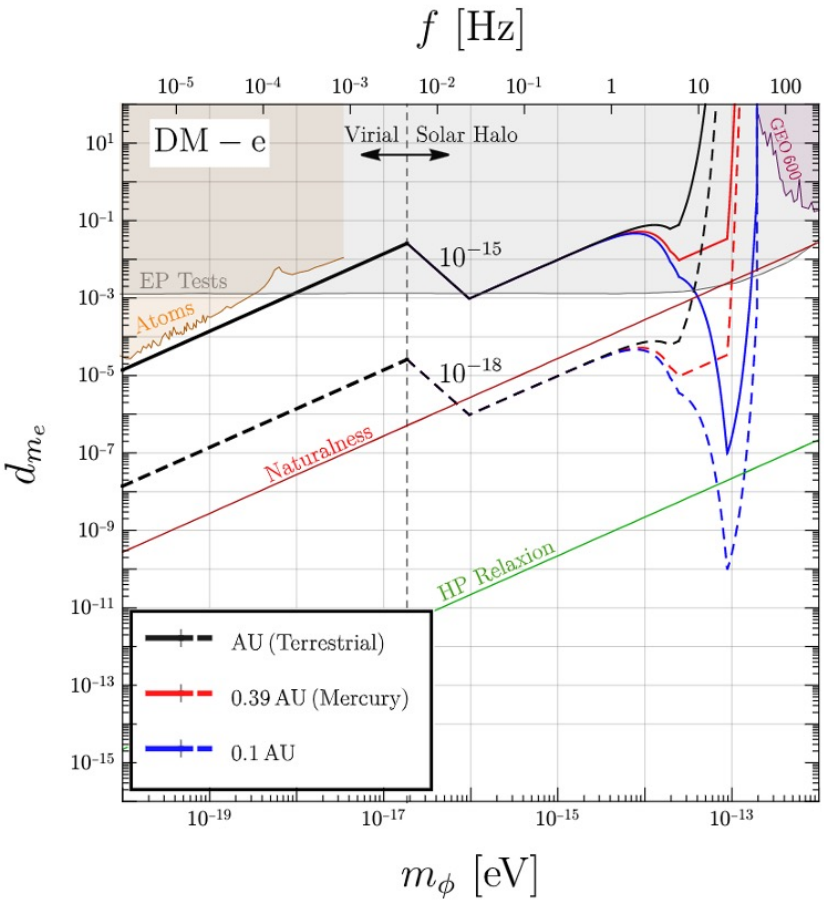
(Non-relativistic solution)

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

- **Oscillation frequency ~ dark matter mass**
- Propose **a two-clock comparison experiment** onboard **a future Solar Probe**

Projected Sensitivity for ULDM

Tsai, Eby, Safronova, Nature Astronomy (2022)



0.1 AU: motivated by the **Parker Solar Probe**

$\mathcal{L} \supset g_e \phi \bar{e} e$ (+ photon & gluon couplings)

AMO convention

Motivate Novel Clocks!

$$\mathcal{L} = \kappa \phi (d_{m_e} m_e \bar{e} e)$$

$\kappa = \sqrt{4\pi}/M_P$ with $M_P = 1.2 \times 10^{19}$ GeV.

$m_e = 0.511$ MeV is just a normalization.

Naturalness condition:

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

Spatial Variation of Fundamental Constants

Tsai, Eby, Safronova, Nature Astronomy (2022)

fine-structure constant

quark and QCD parameters

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

electron to proton mass ratio

δU: change in gravitational potential .

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

Safronova et al, Rev. Mod. Phys. (2018)

Lange et al, PRL (2021)

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

- Achieve constraints on k_X that are a factor of ~ 300 stronger!

Frederick Reines

Nobel Prize Laureate; Professor at UC Irvine

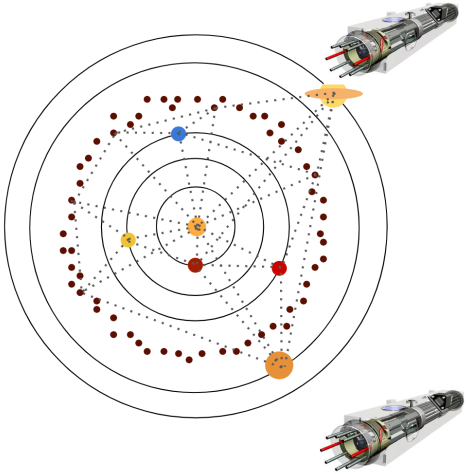
Utilized a **nuclear reactor to study free neutrinos**

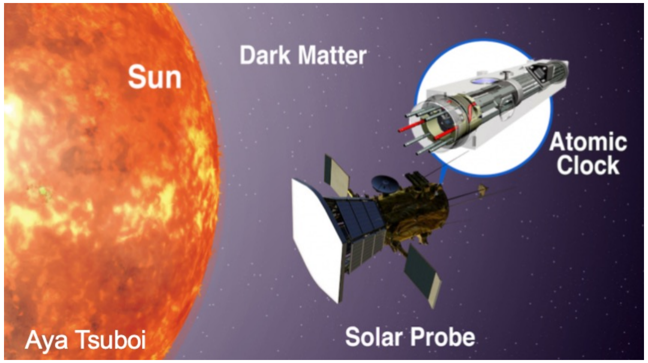
The Elusive Universe is at the horizon

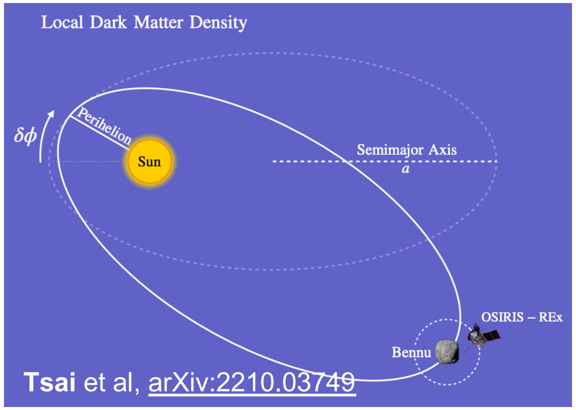
We have a practical roadmap forward

to explore it wide & deep

Thank you for listening!

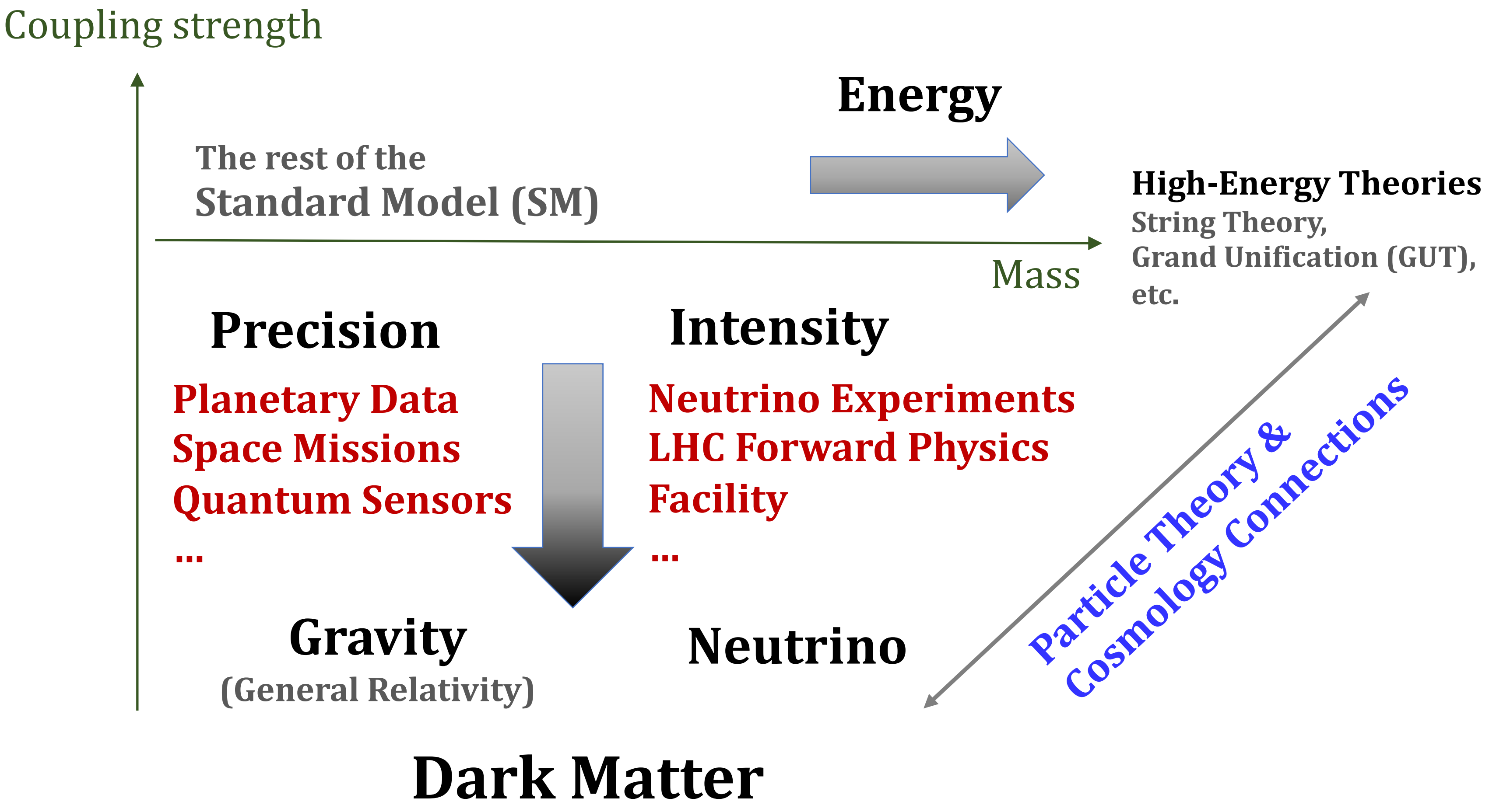






Tsai et al, arXiv:2210.03749

A Strong Probe of the Elusive Universe



Coupling strength

Energy

The rest of the
Standard Model (SM)

High-Energy Theories
String Theory,
Grand Unification (GUT),
etc.

Mass

Precision

Planetary Data
Space Missions
Quantum Sensors
…

Intensity

Neutrino Experiments
LHC Forward Physics
Facility
…

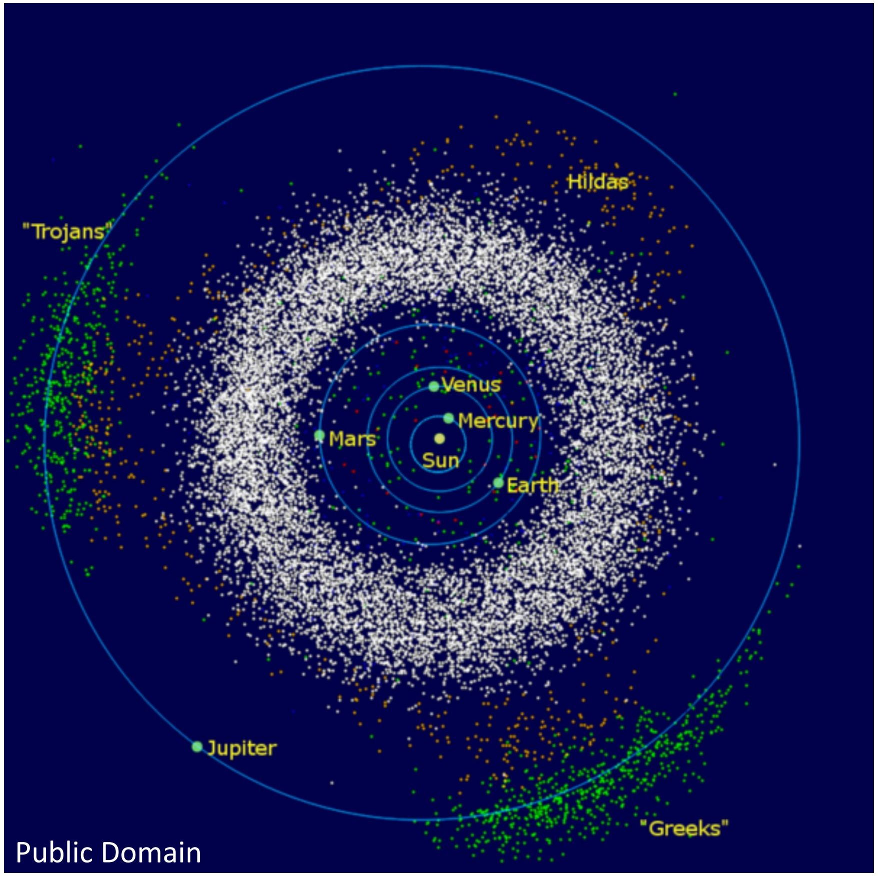
Particle Theory &
Cosmology Connections

Gravity
(General Relativity)

Neutrino

Dark Matter

Asteroids & Other Solar System Objects



Public Domain

Credit: NASA

Radar (Goldstone)

Credit: UH IfA

Optical (Pan-STARRS)

Credit: NASA

Space Missions

Use **millions of solar-system objects** to study many **fundamental physics topics.**
Need **theory** & **data** expertise to realize the full potential of the dataset.