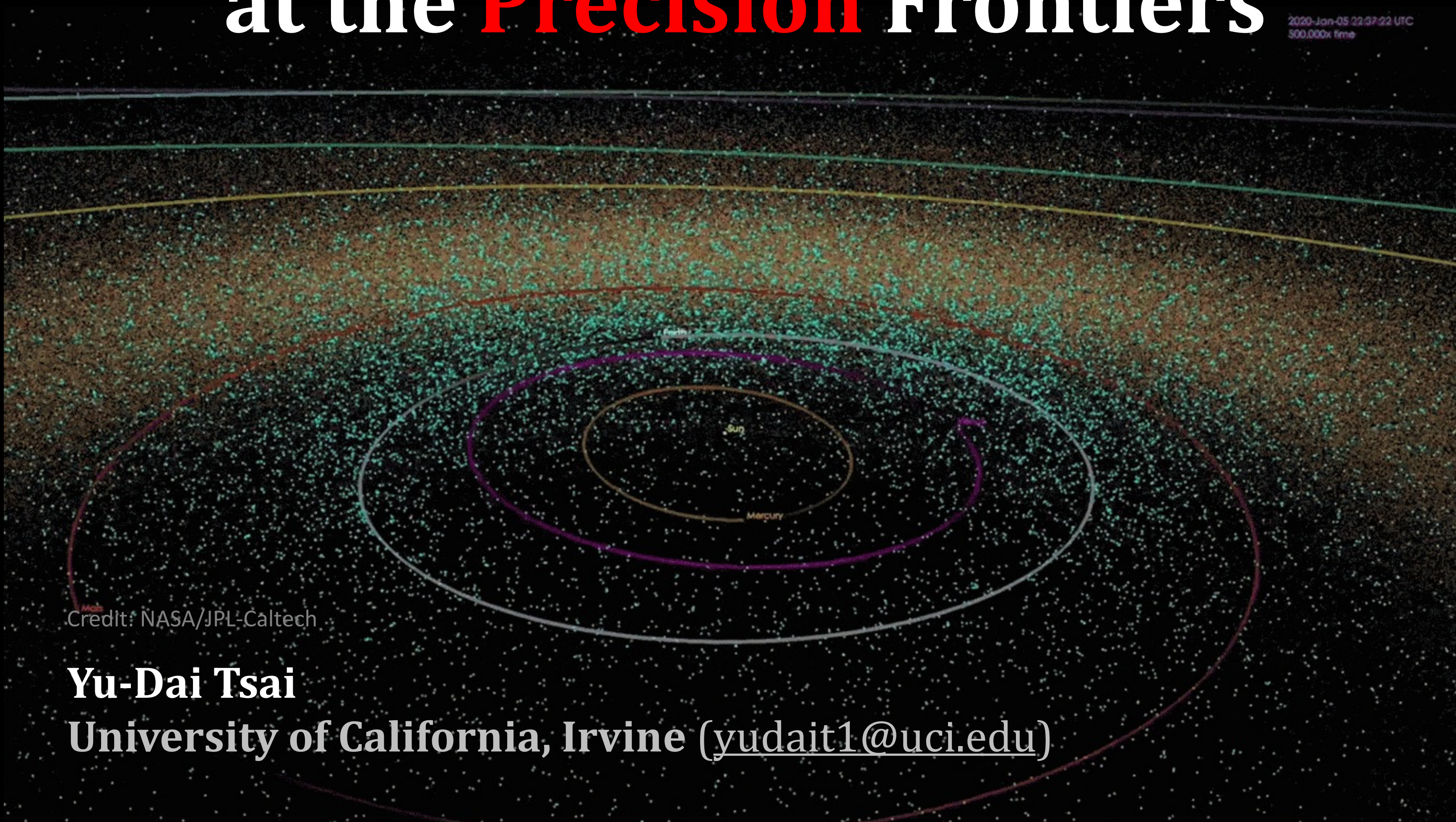
# The Elusive Universe

## at the Precision Frontiers

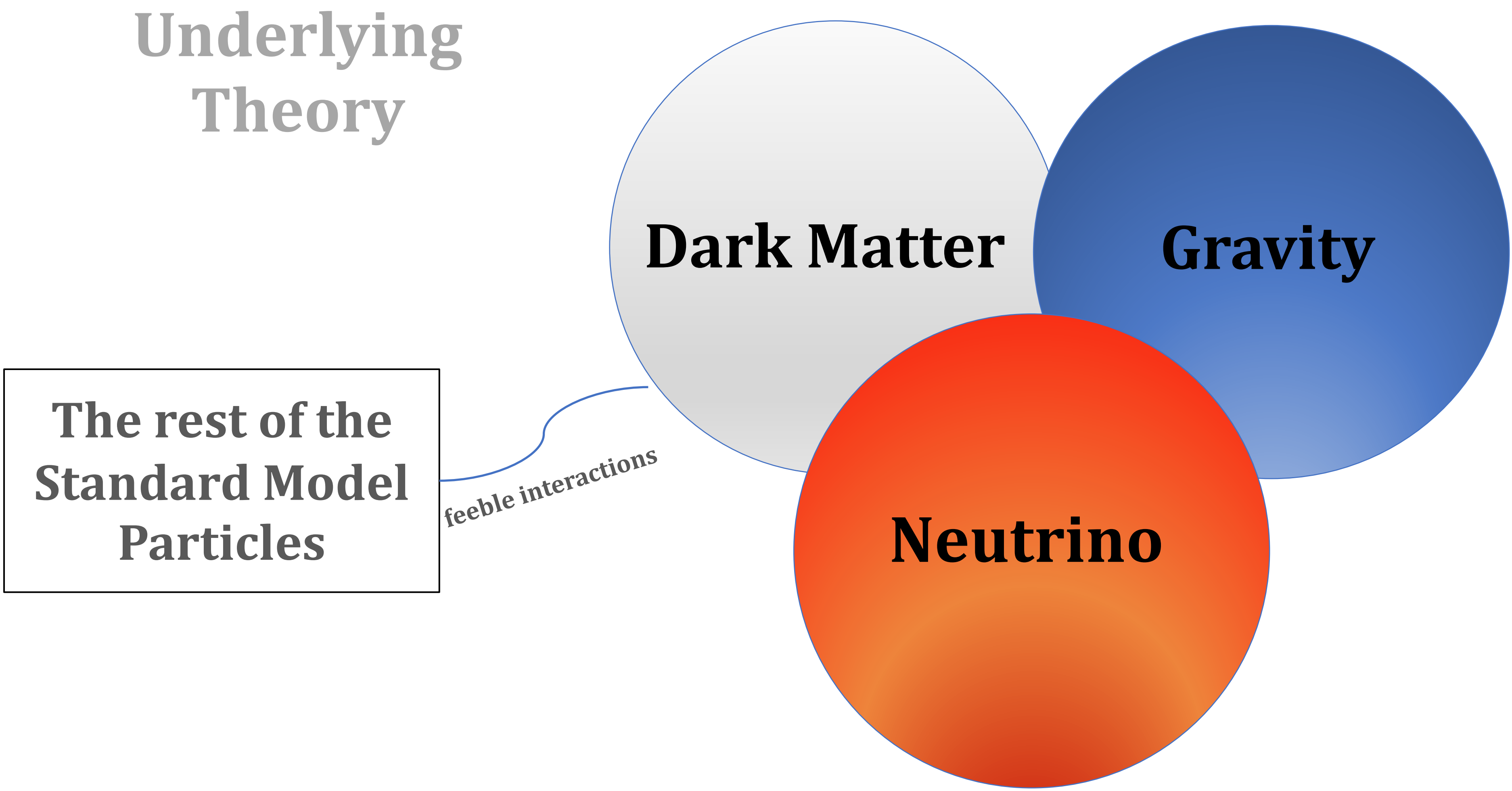



Credit: NASA/JPL-Caltech

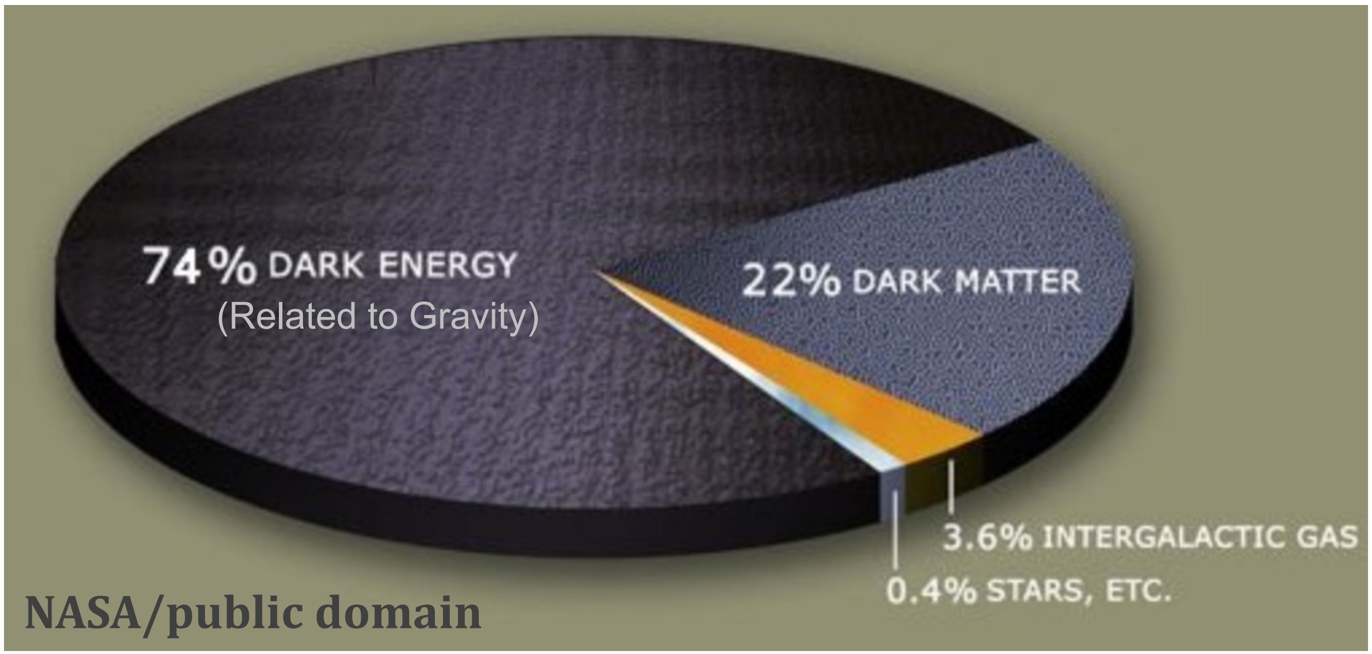
**Yu-Dai Tsai**

**University of California, Irvine** (yudait1@uci.edu)

# The Elusive Universe

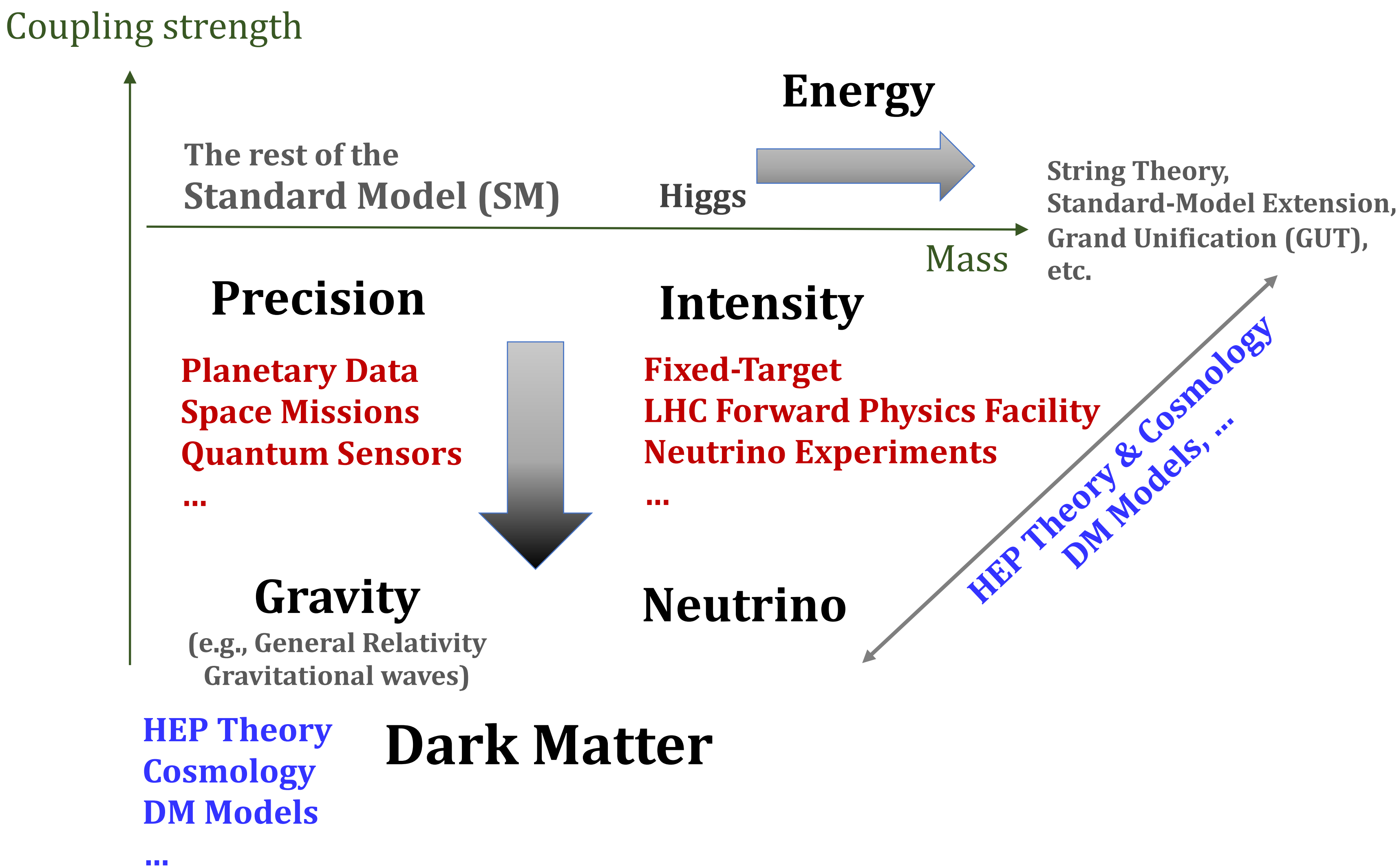


# Explore the Elusive Universe




**Most of the universe is not fully understood**
**We won't stop until we understand all of it**

# Strong Probes of the Elusive Universe



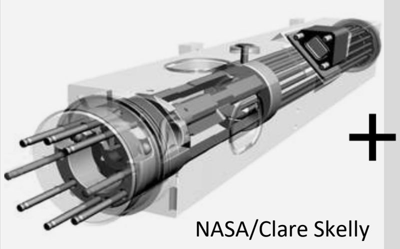
# Novel Directions at the Precision Frontier

New technologies with many **practical** applications. **Keep us safe & punctual!**

1. **The precise tracking of asteroids with space missions,**
   **e.g., OSIRIS-REx tracking the dangerous asteroid Bennu**
   $\sim$ 1 meter precision for objects in 1 AU ($\sim 10^{11}$meter-distant) distance
- **Tsai** *et al*, arXiv:2210.03749 for dark matter (DM) & cosmic neutrinos

2. **The precise time keeping (e.g., NASA Deep Space Atomic Clock)**
- **lose 1 second every 10 million years**
  **Tsai**, Eby, Safronova, Nature Astronomy (2022)
  for **ultralight dark matter (ULDM) searches**

**Searching for ultralight DM bound to Sun**




+


# Theme of this talk:

Bridging **High Energy Theory, Precision Astronomy, & Space Quantum Technology!**

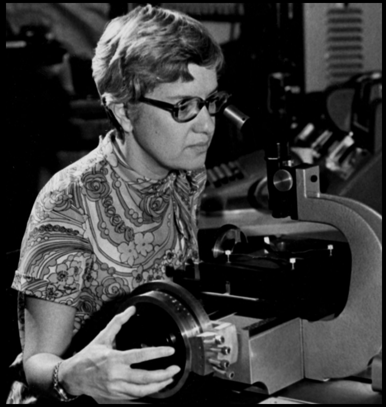
# Outline

1. **Precision Astrometry:**

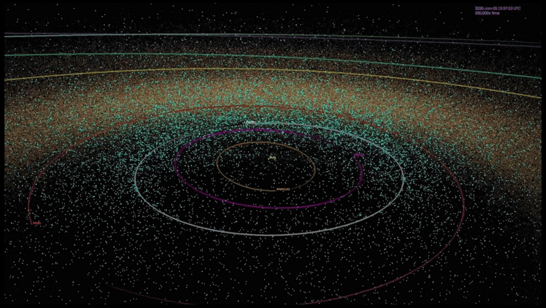
   **Dark Matter & Cosmic Neutrinos**

2. **Quantum Probe for Ultralight Dark Matter**

   **(Backup Slides)**



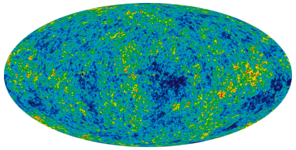
Vera Rubin
Carnegie Institution for Science



Albert Einstein
Mount Wilson Observatory, California

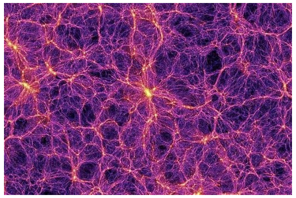
# How do we know dark matter exist?

**Size**



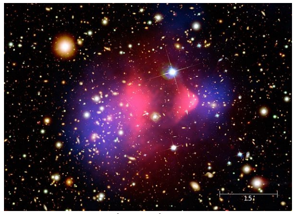
Credit: NASA / WMAP

**Cosmic Microwave Background**



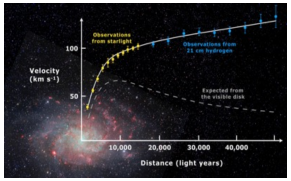
Credit: Springel et al. 2015 (10-100 Gpc)

**Large Scale Structure**



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

**Bullet Cluster Merger**




Credit: De Leo-Winkler(10 kpc)

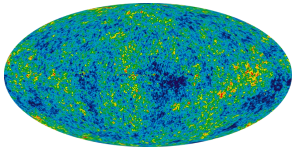
**Galactic Rotation Curves**

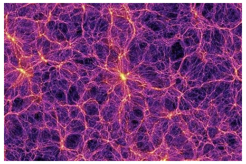
DM Gravitational Interactions

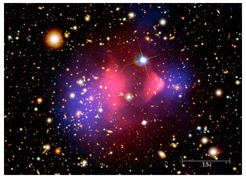
Modified from a slide from Tien-Tien Yu (U of Oregon)

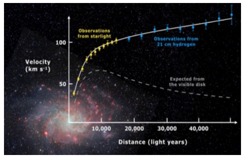
# DM Gravity in Smaller Scale?

**Size**





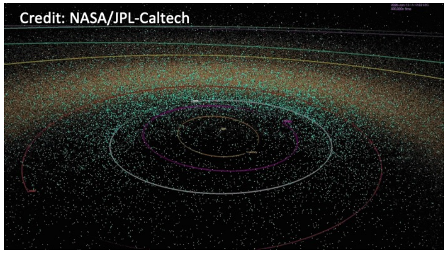




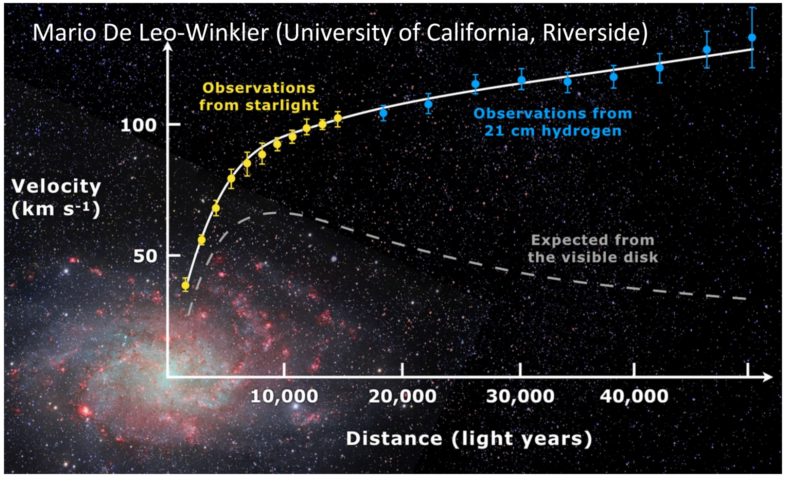

**DM Gravitational Interactions**

Precision Astrometry

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



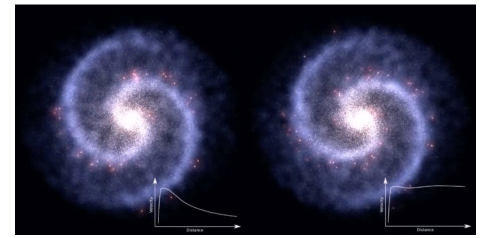
# A question we asked



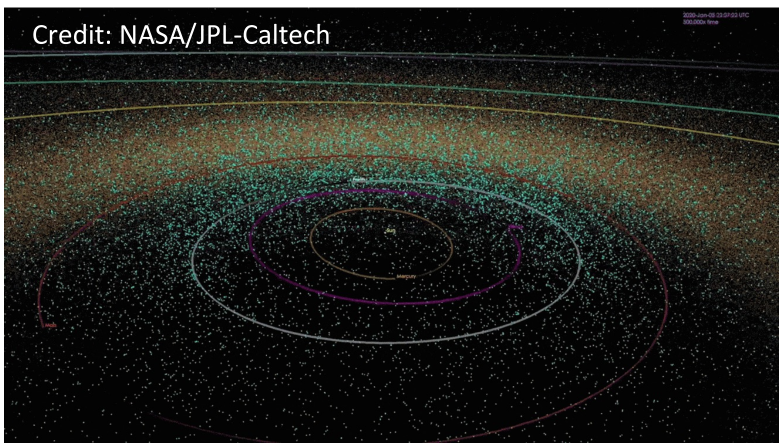

**Stars**

$\rho_{\rm DM}$ for galaxies

Vera Rubin



From: https://en.wikipedia.org/wiki/File:Galaxy_rotation_under_the_influence_of_dark_matter.ogv under the Creative Commons Attribution-Share Alike 3.0 Unported license.

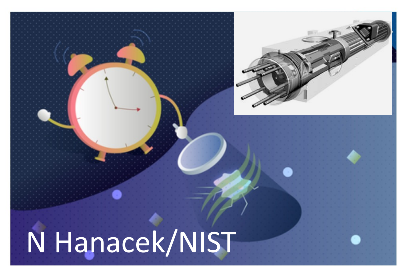



**Solar System Objects**

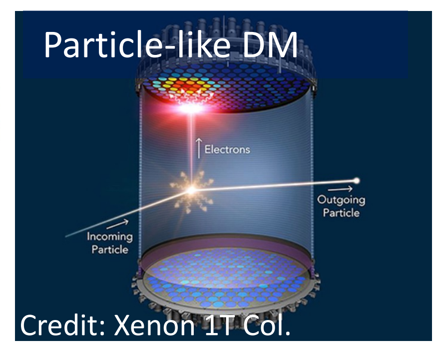
$\rho_{\rm DM}(r)$ for solar system

## Crucial for Direct Detection of DM

Wave-like DM

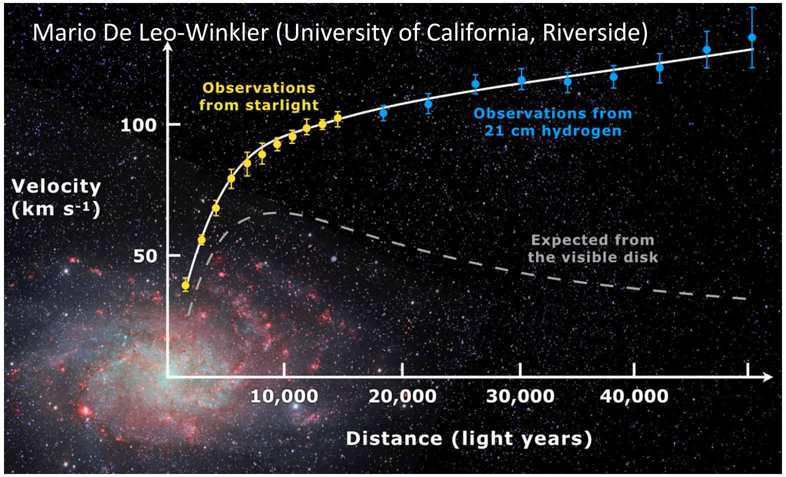



Credit: N. Hanacek/NIST

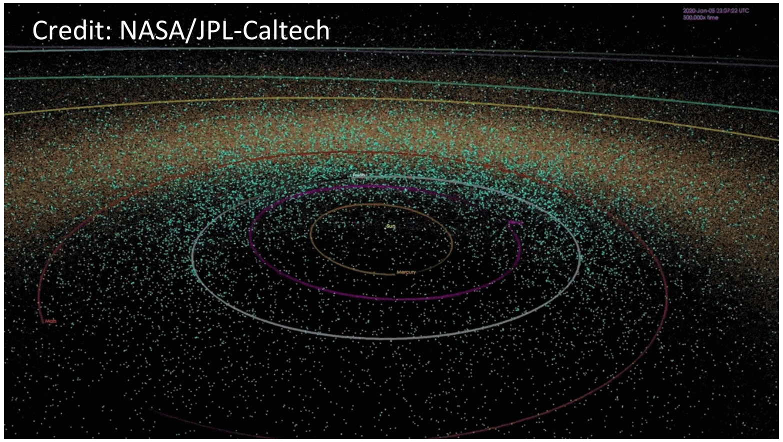



Yu-Dai Tsai (UC Irvine)

# A question we asked




**Stars**




**Solar System Objects**

→ $\rho_{\rm DM}$ for galaxies

→ $\rho_{\rm DM}(r)$ for solar system

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

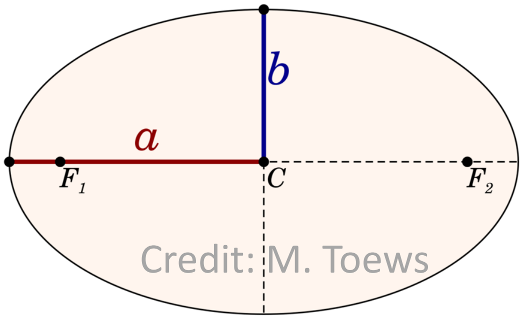
$\bar{\rho}_{DM} = 0.3\ {\rm GeV/cm^3}$, $\bar{\rho}_{\rm DM} \sim 10^{-18}\,\frac{m_\odot}{({\rm AU})^3}$

Velocity measurements ineffective

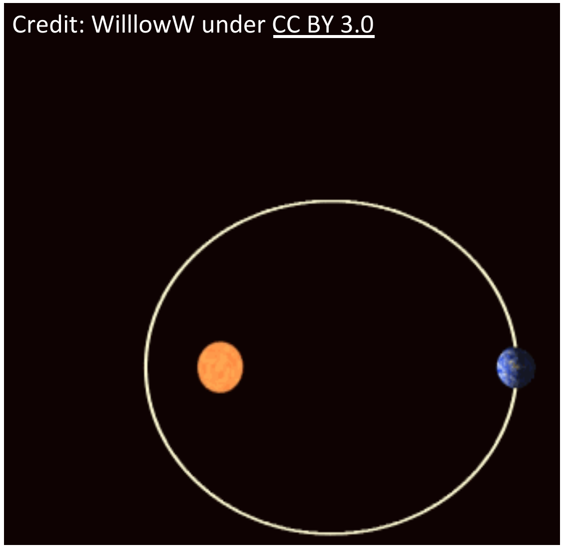
We need to go beyond it!

# Beyond Velocity: Perihelion Precession

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

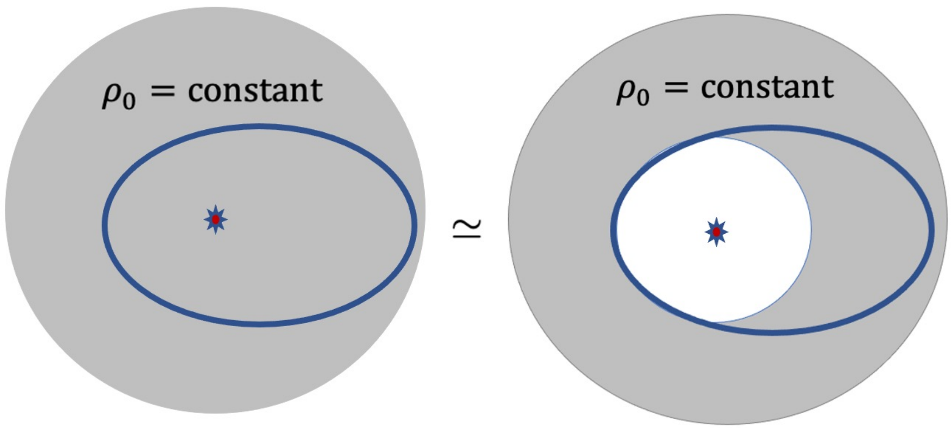


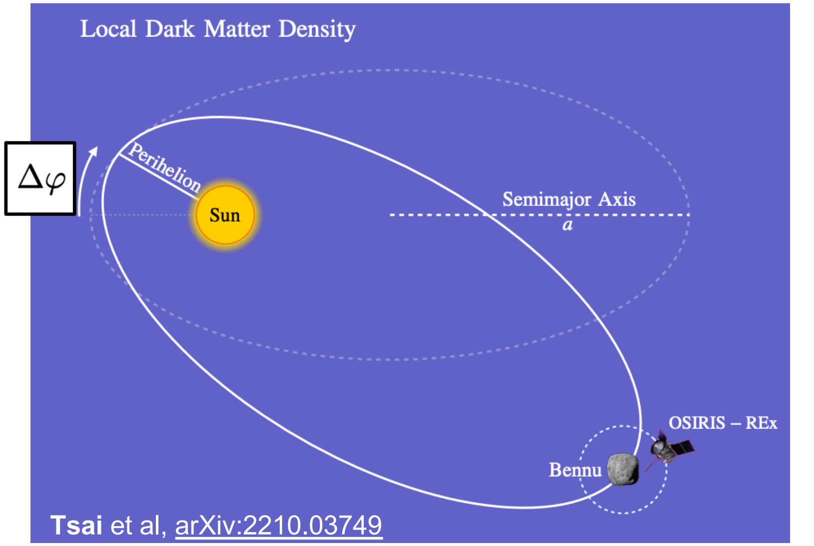

- $a$ is the semi-major axis
- e is the eccentricity, quantify how non-spherical the orbit is.




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

# Our Project:
# Local DM or Cosmic Neutrinos Induce Precessions



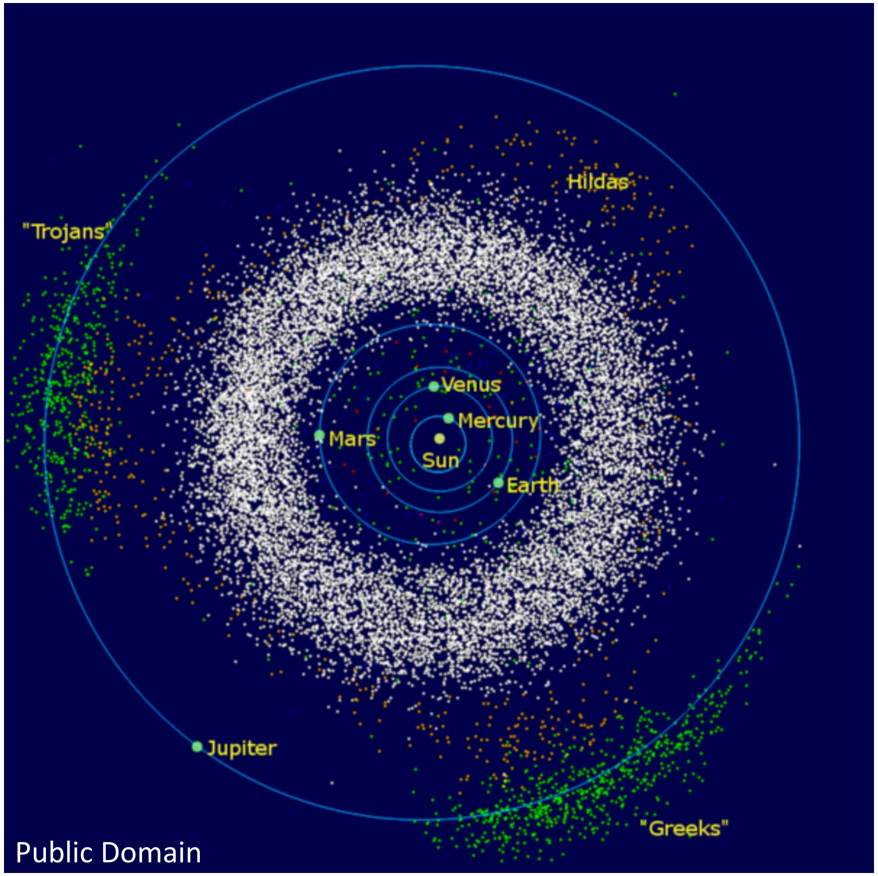

Dark Matter Gravity: $$\mathbf{F}(\mathbf{r}) = \frac{2\pi}{3} G m \rho_0 \left( \frac{2r_0^3}{r^2} - 2r \right) \hat{\mathbf{r}}$$

$$\simeq -\frac{4\pi}{3} G m \rho_0 r \hat{\mathbf{r}} + \frac{4\pi}{3} G m \rho_0 \frac{r_0^3}{r^2} \hat{\mathbf{r}}.$$

$m$ is the mass of the object

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

# Asteroids & Other Solar System Objects





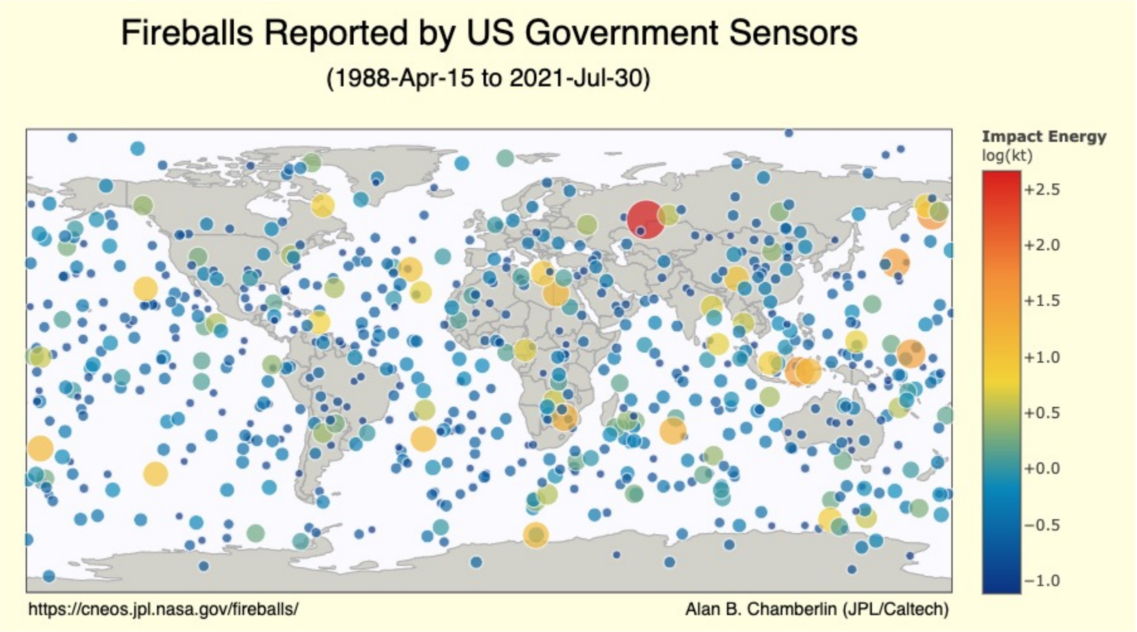
Radar (Goldstone)


Optical (Pan-STARRS, LSST)

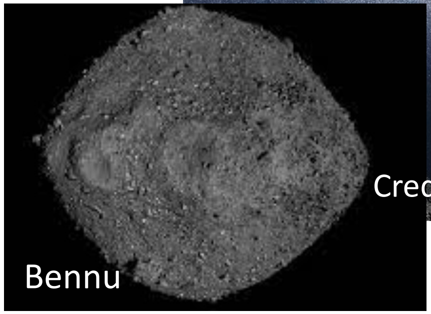

Space Missions

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

# Asteroids & Planetary Defense

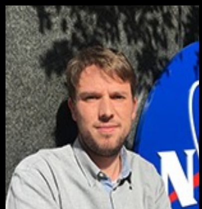






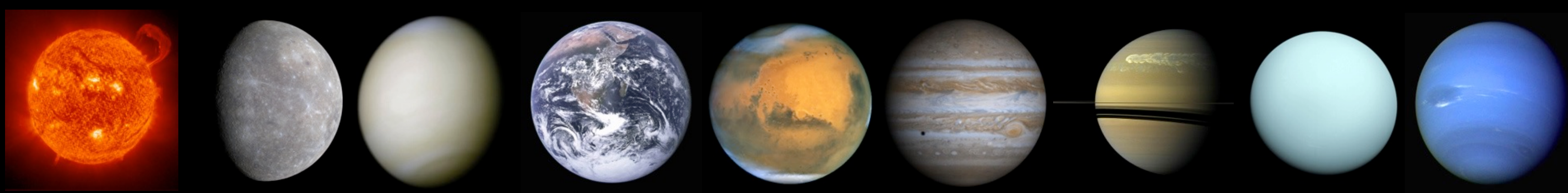

- Tracking asteroids is important to our safety
- We have space missions, like OSIRIS-REx, to track dangerous asteroids like Bennu, return sample.
- **NASA Plan**: OSIRIS-REx will track Apophis and become OSIRIS-APEX

# Robust Analysis: High-Fidelity Force Model

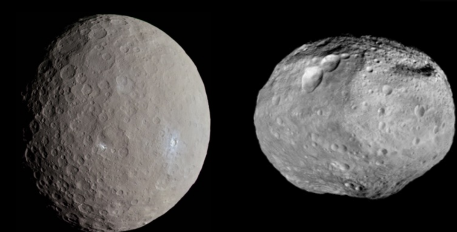


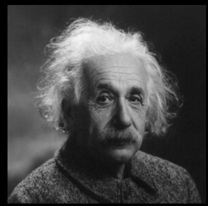
**NASA JPL** & **OSIRIS-REx** Expert
Davide Farnocchia

JPL Planetary Ephemerides DE441



343 Small-body Perturbers





Relativistic Effects

Oblateness

The Yarkovsky effect based on in-situ characterization, solar radiation pressure, Poynting-Robertson drag, etc.

# Adding Dark Matter to the Force Model

Force terms considered by Davide Farnocchia

$$\ddot{\mathbf{r}}_i = \sum_{j\neq i} \frac{\mu_j\left(\mathbf{r}_j - \mathbf{r}_i\right)}{{r_{ij}}^3}\left\{1 - \frac{2(\beta+\gamma)}{c^2}\sum_{l\neq i}\frac{\mu_l}{r_{il}} - \frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}}\right.$$

$$+\gamma\left(\frac{\dot{s}_i}{c}\right)^2 + (1+\gamma)\left(\frac{\dot{s}_j}{c}\right)^2 - \frac{2(1+\gamma)}{c^2}\dot{\mathbf{r}}_i\cdot\dot{\mathbf{r}}_j$$

$$\left. - \frac{3}{2c^2}\left[\frac{\left(\mathbf{r}_i - \mathbf{r}_j\right)\cdot\dot{\mathbf{r}}_j}{r_{ij}}\right]^2 + \frac{1}{2c^2}\left(\mathbf{r}_j - \mathbf{r}_i\right)\cdot\ddot{\mathbf{r}}_j\right\}$$

$$+\frac{1}{c^2}\sum_{j\neq i}\frac{\mu_j}{{r_{ij}}^3}\left\{\left[\mathbf{r}_i - \mathbf{r}_j\right]\cdot\left[(2+2\gamma)\dot{\mathbf{r}}_i - (1+2\gamma)\dot{\mathbf{r}}_j\right]\right\}\left(\dot{\mathbf{r}}_i - \dot{\mathbf{r}}_j\right)$$

$$+\frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{\mu_j\ddot{\mathbf{r}}_j}{r_{ij}}$$

+

The **dark matter** contribution

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

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

**List of uncertainties considered:**

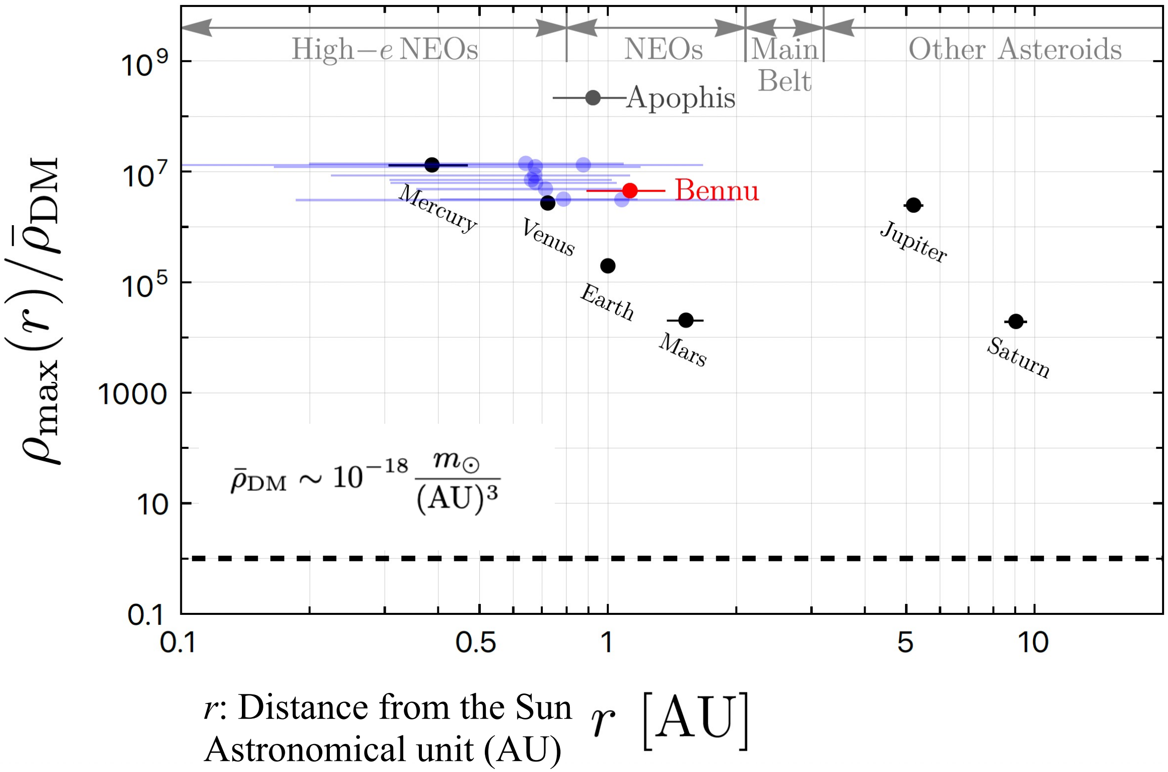
1) Errors in planetary trajectories and masses; 2) Errors in perturber masses & trajectories; 3) Higher order relativistic terms; 4) Higher order gravity terms; 5) Simplified assumptions in nongravitational force model (non-spherical effects, Yarkovsky, solar torque, physical parameter evolution, etc.);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

Planetary constraints, see Pitjev, Pitjeva, Astronomy Letters (2013)

# New Model-Independent Constraints on DM Profile

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

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

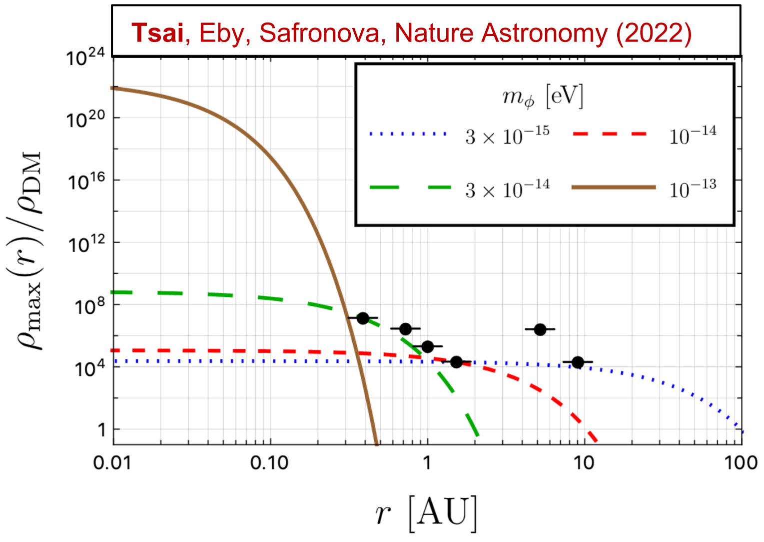


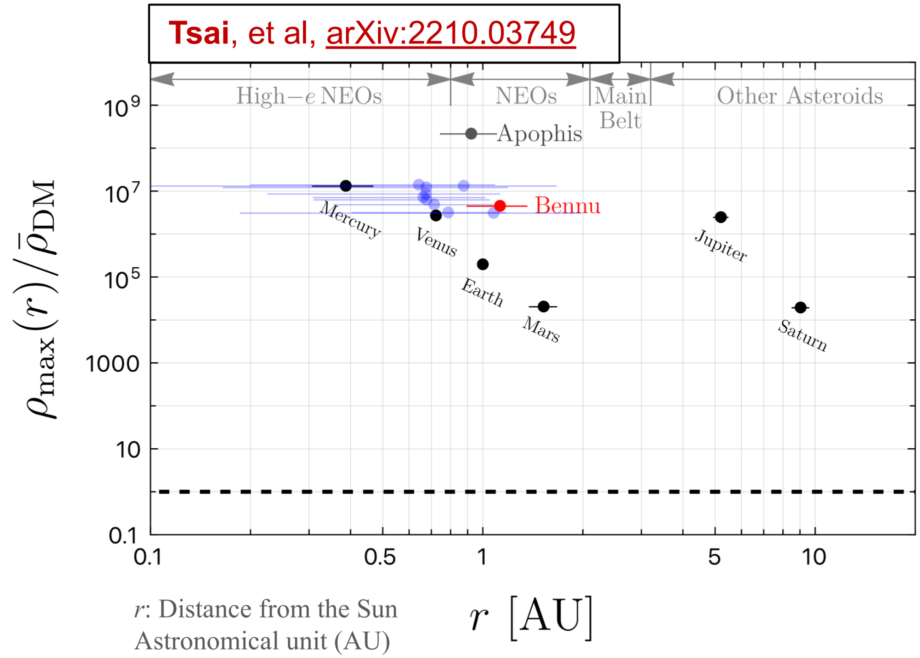

$r$: Distance from the Sun
Astronomical unit (AU)

- The **horizontal lines** are NOT error bars, but the **coverage of the constraints**.

# The Implications of Our Constraints

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

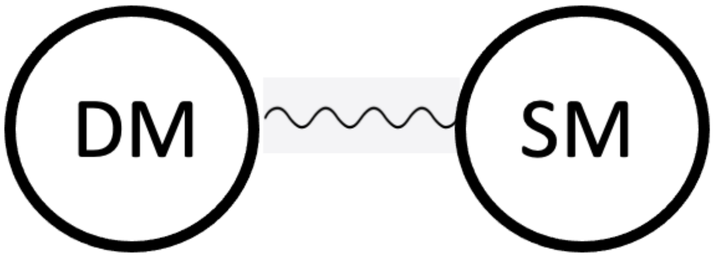


# Implications of the Constraints: DM-SM Interaction

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

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

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

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

Dedicated search for CvB see, e.g., the PTOLEMY proposal, PTOLEMY collaboration, arXiv:1808.01892 (2022)

Other CvB phenomenology, see, e.g., Brdar et al, *PLB* (2022)

# Summary of High-Energy Theory Targets

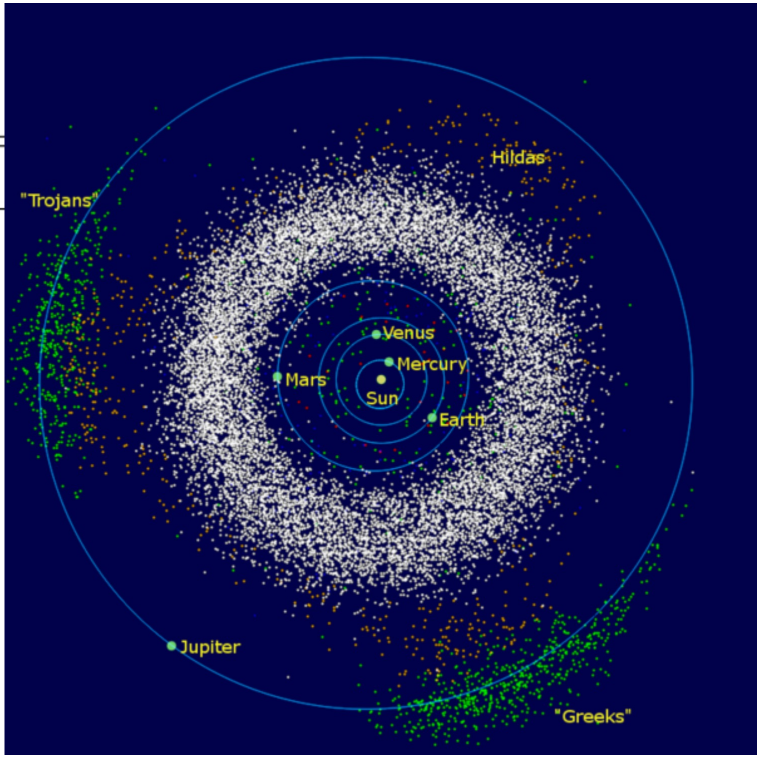
- GR Test: $$\Delta\varphi = \frac{6\pi G M_\odot}{a(1-e^2)c^2}\left[\frac{4-\beta}{3}\right] \propto a^{-1}$$
- Fifth Forces: $$|\Delta\varphi_{\phi,A'}| \simeq a(1-e)\left[\left(\frac{mc}{\hbar}\right)^2 \frac{g^2}{4\pi G m_p^2}\frac{2\pi}{1+\frac{g^2}{4\pi G m_p^2}}\right] \propto a$$
  (light mediator limit $m \ll \hbar/ac$), see **Tsai** et al arXiv:2107.04038
- Dark Matter: $$\Delta\varphi \simeq -4\pi^2\rho_0 a^3(1-e^2)^{1/2}/M_\odot \propto a^3$$
- HEP theory inputs are crucial
- Calling for modern data-analysis approaches

# Millions of Objects of Interest

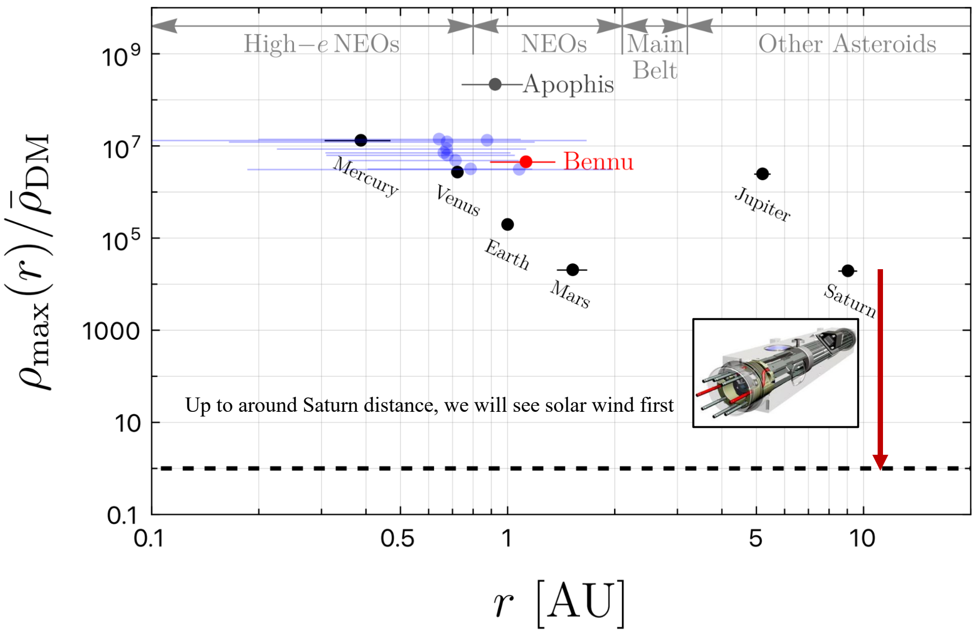
**Tsai**, Wu, Vagnozzi, Visinelli, 2107.04038

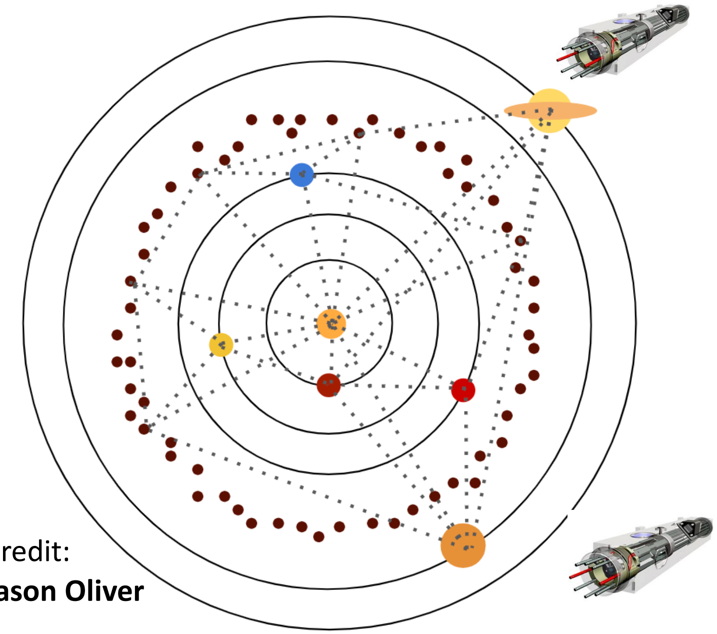
| Minor Planets | $a$ [au] | $\sim$ Numbers |
|---|---|---|
| Near-Earth Object (NEO) | $< 1.3^*$ | $> 25000$ |
| Main-Belt Asteroid (M) | $\sim 2-3$ | $\sim$ 1 million |
| Hilda (H) | 3.7 - 4.2 | $> 4000$ |
| Jupiter Trojan (JT) | 5.2 | $> 9800$ |
| Trans-Neptunian Object (TNO) | $> 30$ | 2700 |
| Extreme TNO (ETNO) | $> 150$ | 12 |

*NEOs are defined as having perihelia $a(1-\mathsf{e}) < 1.3\,\text{au}$.



# Roadmap to Observe Local Dark Matter through Gravity



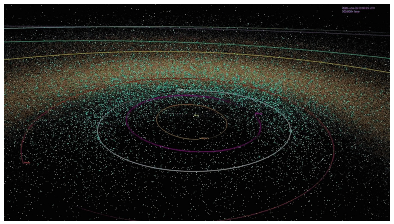

**Tsai**, Aishik, Arakawa *et al.*

The "**Asteroid Network**" project for fundamental physics,

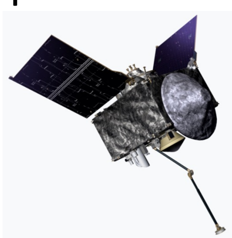
1. Increase **precision** (e.g., with quantum clocks onboard of space missions)
2. Consider **more asteroids & minor planets** (near Sun & far from Sun)

# Summary & Results & Plans

Precision Astrometry

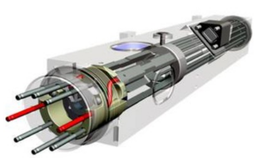


Space Missions



OSIRIS-REx → **OSIRIS-APEX**

Quantum Sensors



NASA DSAC I → **DSAC II**

National Institute of Standards and Technology

**Precision Frontier**:
**HEP Theories** &
New Precision Probes

**Plan**:
Study more **HEP Theory & cosmology** topics
Collaborate with particle theorists & cosmologists, space scientists, astronomers, machine-Learners, and quantum experts

Improved understanding of

1. Dark Matter Local Distribution
   **Tsai** *et al.*, arXiv:2210.03749
2. Cosmic Neutrino Local Distribution
   **Tsai** *et al.*, arXiv:2210.03749
3. Ultralight Dark Matter
   **Tsai**+, Nature Astronomy (2022)
4. Fifth Force
   **Tsai** *et al.*, arXiv:2107.04038
5. Gravity Theories; **Many Other Topics**

# Future Observations

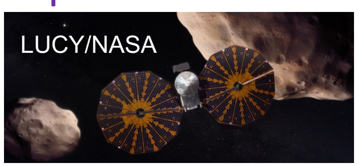
Rubin Observatory/LSST

Credit: LSST/NSF/AURA

LSST: Large Synoptic Survey Telescope

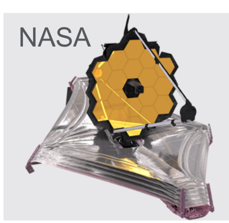
**5 times more asteroids**

Space Missions




Explore **Jupiter's Trojan asteroids**

James Webb Space Telescope (JWST)




**Cosmic Frontier**:
**HEP Theories** & New Data

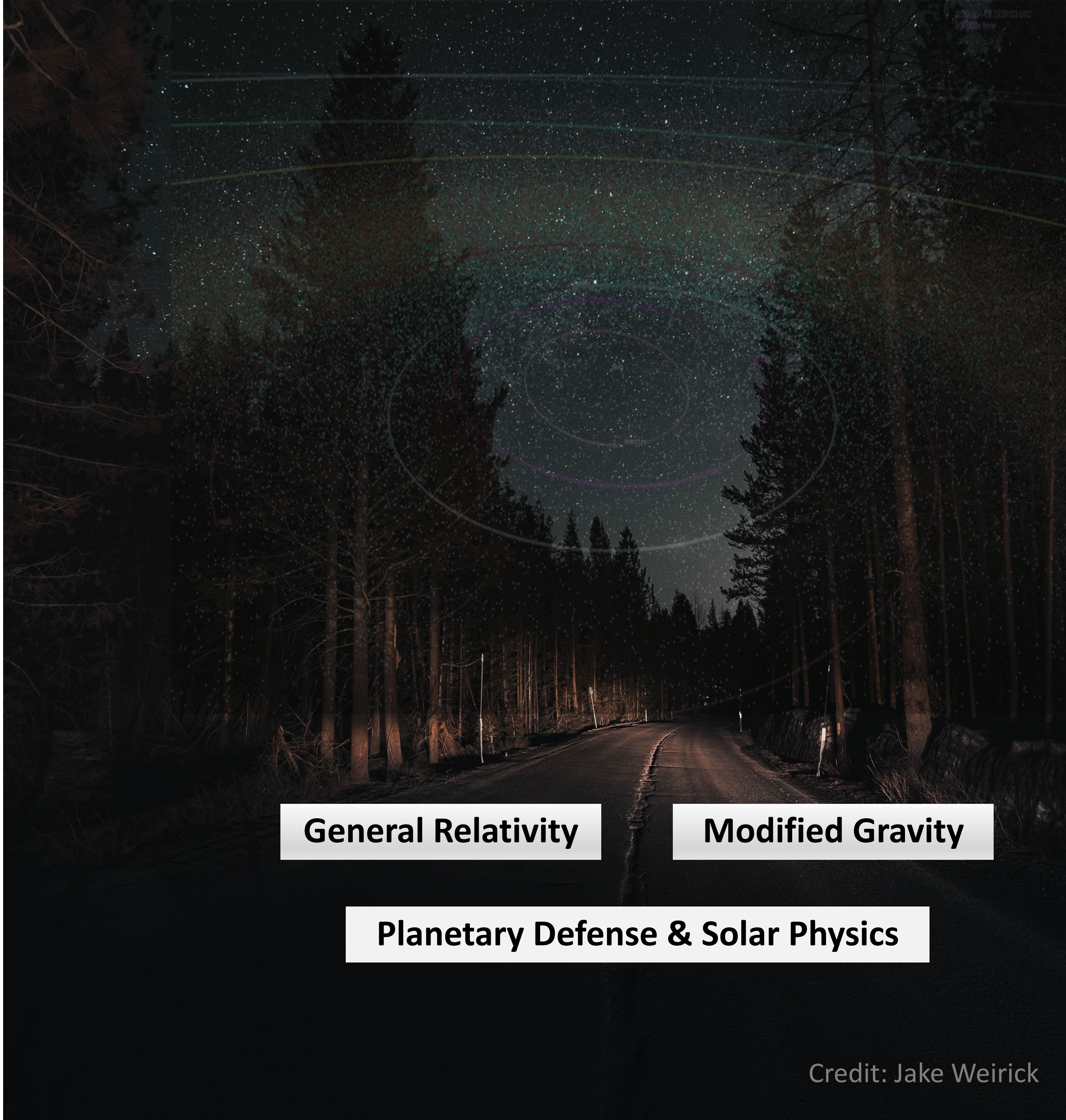
**Plan**:

- Study more **HEP Theory & cosmology** topics
- Conduct robust analysis; with data-intense techniques

Improved understanding of

1. Dark Matter Local Distribution
   **Tsai** *et al.*, arXiv:2210.03749
2. Cosmic Neutrino Local Distribution
   **Tsai** *et al.*, arXiv:2210.03749
3. Ultralight Dark Matter
   **Tsai**+, Nature Astronomy (2022)
4. Fifth Force
   **Tsai** *et al.*, arXiv:2107.04038
5. Gravity Theories; **Many Other Topics**

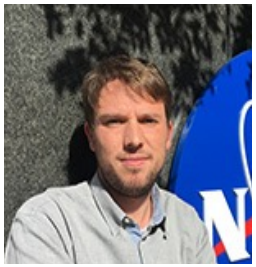
# My Understanding Before Our Projects



# New Precision Lab for HEP Theories Cosmology and Astrophysics

# The Team: SpaceQ & Asteroid Network

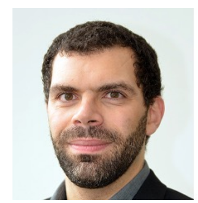
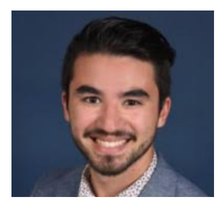
**Defenders of the Earth**
Davide Farnocchia (NASA JPL)
Marco Micheli (ESA)




**AMO & Quantum Expert**
Marianna Safronova
(UDel & NIST)

***postdocs**
****student**

**Cosmologists**
Sunny Vagnozzi (Cambridge/Trento)
Luca Visinelli (TDLI)
Jason Arakawa* (UDel)
Josh Eby* (IPMU)

**Astronomers**
Johanna Paine** (UCI)
Paul Robertson (UCI)

+


**AI & Machine Learners (ATLAS@LHC)**
Aishik Ghosh*, Daniel Whiteson (UCI)

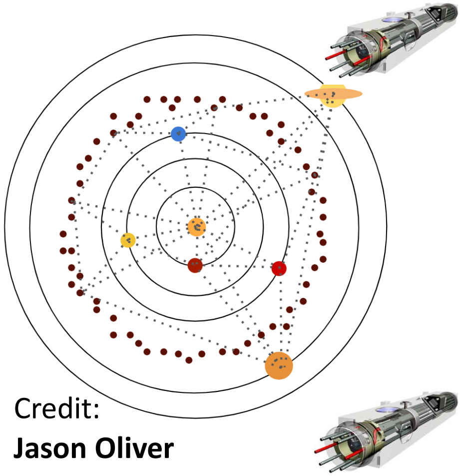

**"Neuro Network for Asteroid Network"**

**Big thanks to the team!**

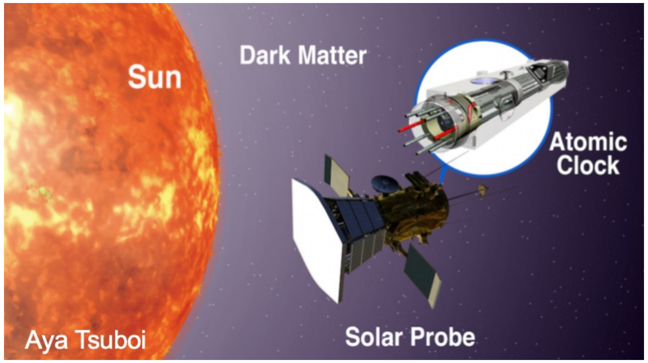
- **SpaceQ** was featured by **DOE Office of Science Newsletter**, NIST Cal Presidential Office, U Chicago News, VICE Magazine, etc.
- Also, you can find my **outreach interview** about **fifth-forces** [here]

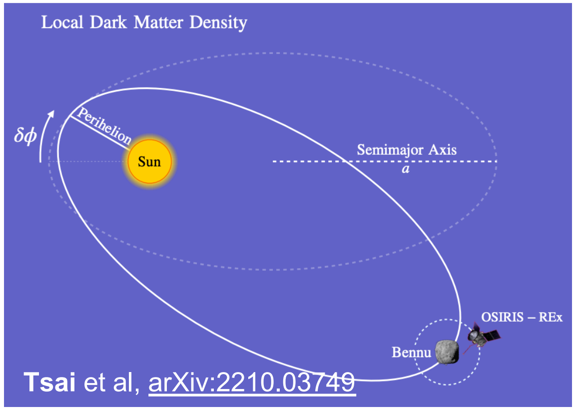
Frederick Reines
Nobel Prize Laureate. Professor at UC Irvine
Utilized a **nuclear reactor to study free neutrinos**

# The Elusive Universe is at the horizon
# I presented a practical roadmap to explore it
# wide & deep
# Thank you for listening!



Credit:
**Jason Oliver**



The relevant literatures are growing fast, please let us know if we forgot to include your important works.

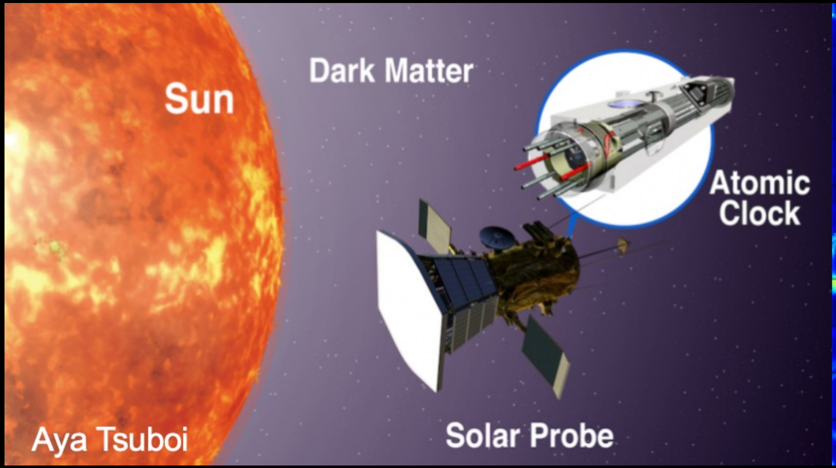
Contact: yudait1@uci.edu

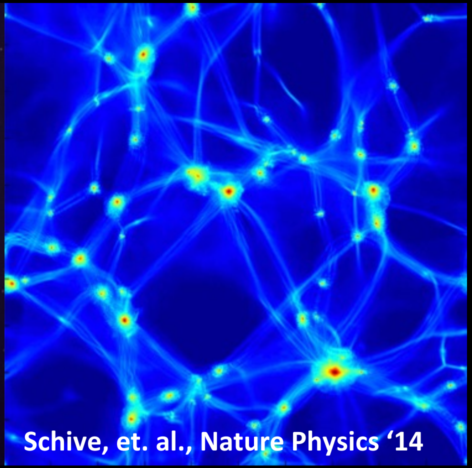
# Outline

1. Precision Astrometry:

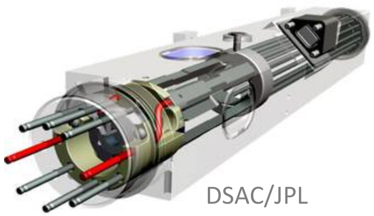
   Dark Matter, Cosmic Neutrinos, Fifth Forces & GR

2. **Quantum Probe for Ultralight Dark Matter**



# 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**
- The clock has operated for more than **12 months in space; long-term fractional frequency stability of $3 \times 10^{-15}$**, Burt et al., Nature (2021)
- Exceeds previous space clock performance by up to an order of magnitude
- Clock-Comparison for CPT & Lorentz Violation, Kostelecký, Vargas, PRD '18

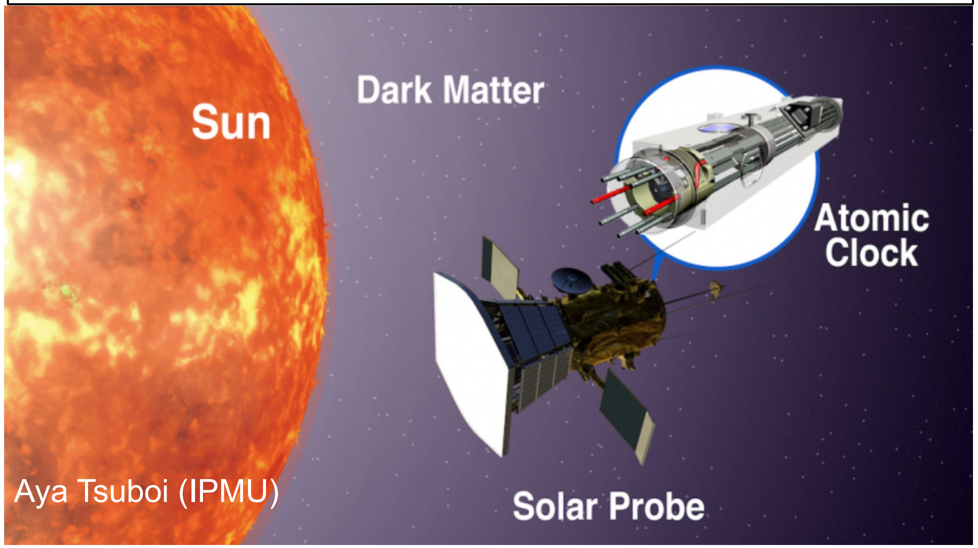
Size of PSP ~ 1.0 × 3.0 × 2.3 m
(685 kg → 555 kg)

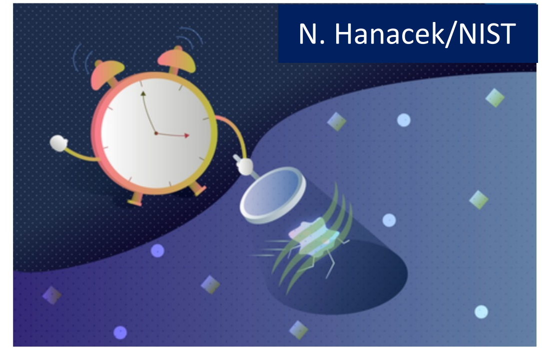
- **Parker Solar Probe (PSP)**
- see, e.g., "Probing the energetic particle environment near the Sun," McComas et al, Nature (2019)

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

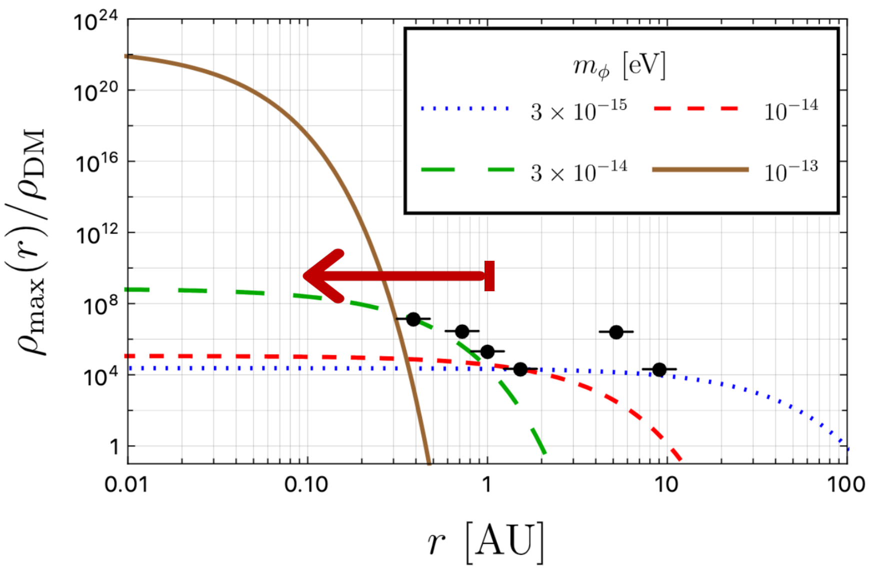
# SpaceQ Mission Concept

**Tsai**, Eby, Safronova, Nature Astronomy (2022)




Credit: N. Hanacek/NIST




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

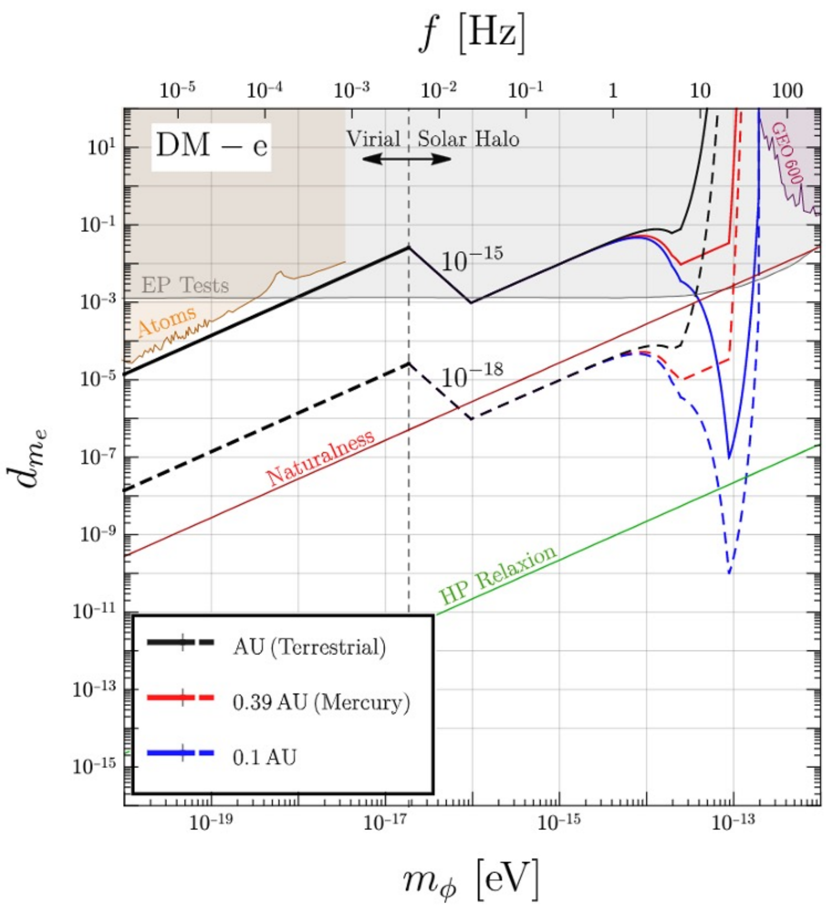
(Non-relativistic solution)

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

- **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**

Marianna Safronova
(UDel & NIST)

$\mathcal{L} \supset g_e \phi \bar{e} e$ (+ 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)

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

fine-structure constant ($\alpha$); electron to proton mass ratio ($\mu$); quark and QCD parameters ($m_q/\Lambda_{QCD}$)

$\delta U$: change in gravitational potential .

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