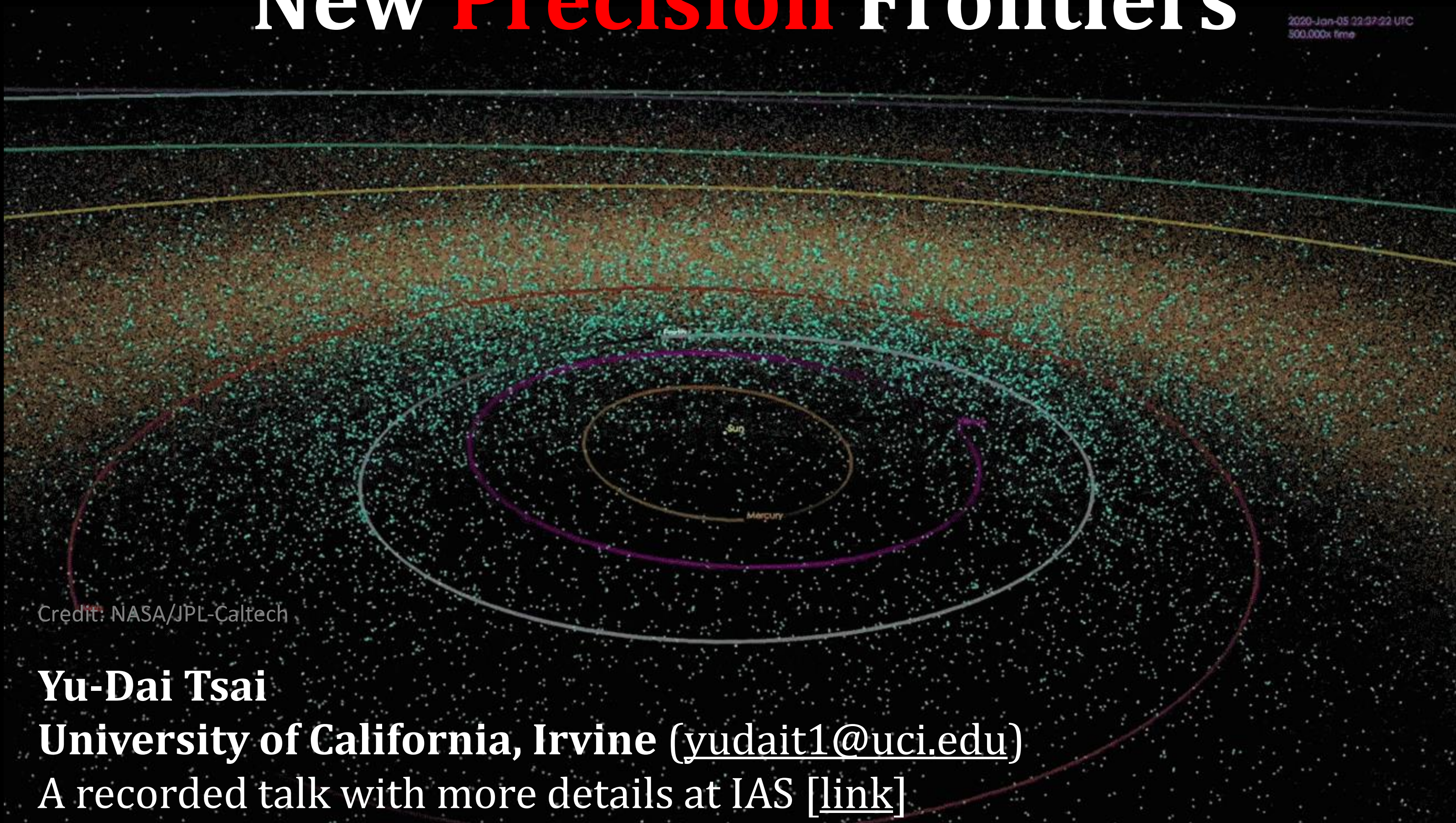
The Elusive Universe:

New Precision Frontiers



Credit: NASA/JPL-Caltech

Yu-Dai Tsai
University of California, Irvine (yudait1@uci.edu)

A recorded talk with more details at IAS [link]

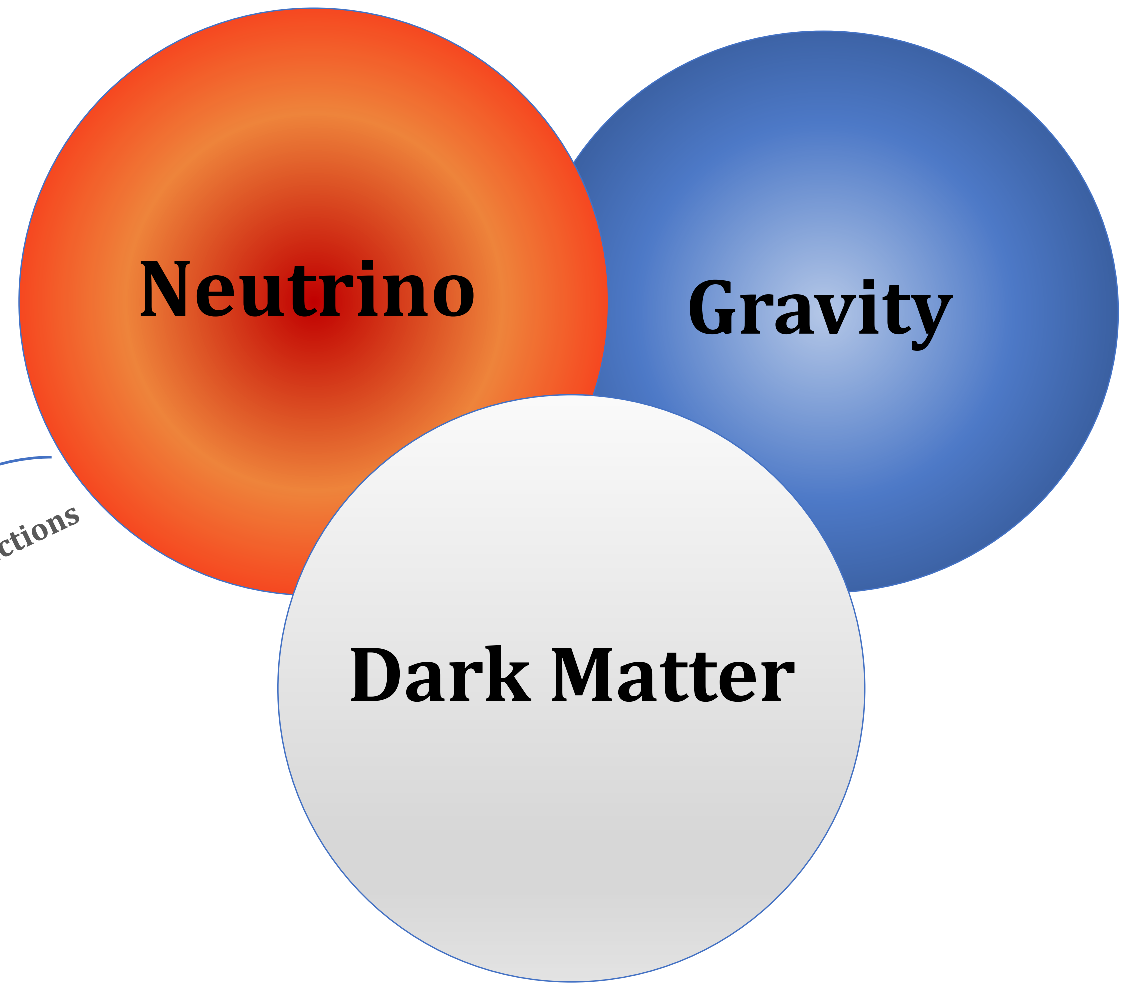
2112.07674 (Nature Astronomy 22), 2107.04038 (JCAP 23), 2210.03749

The Elusive Universe

Underlying Theory

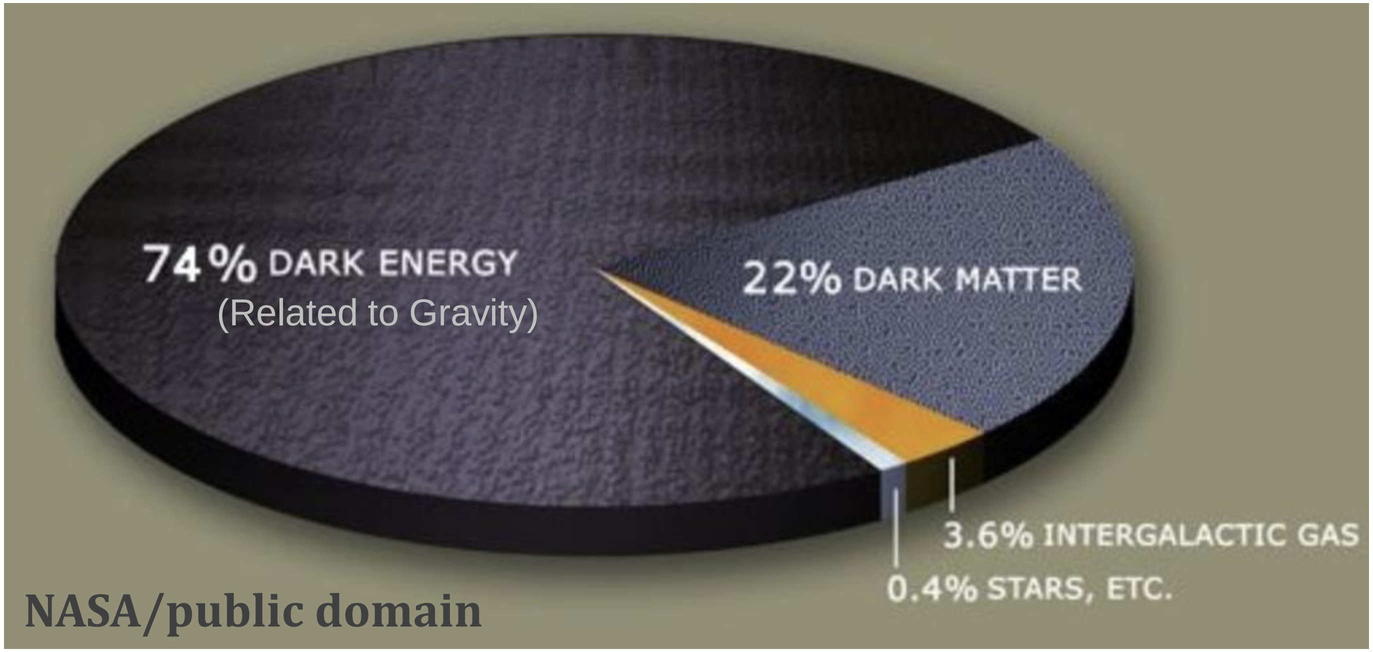
The rest of the Standard Model Particles

feeble interactions



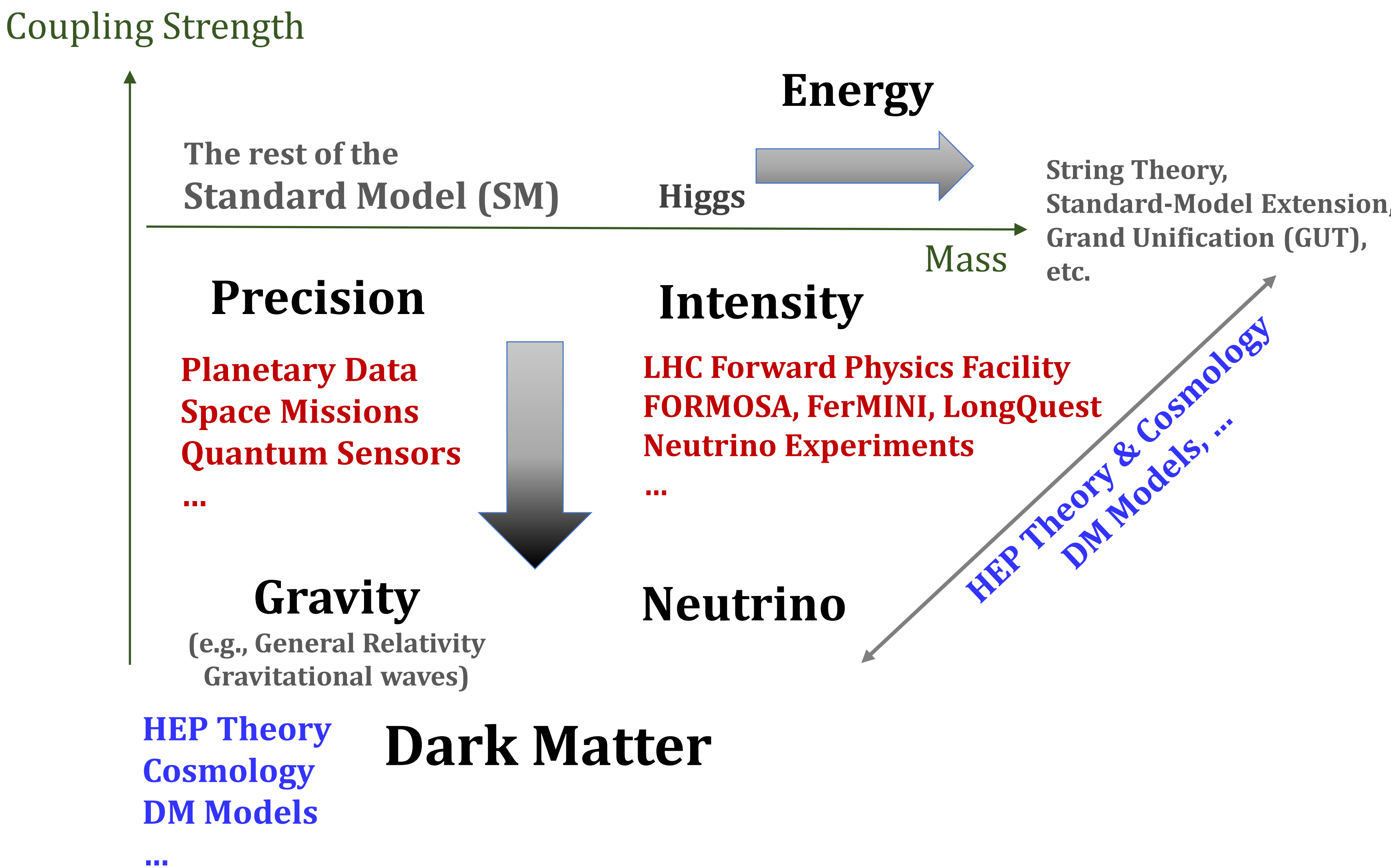
What I have been thinking about for the past decade

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!**

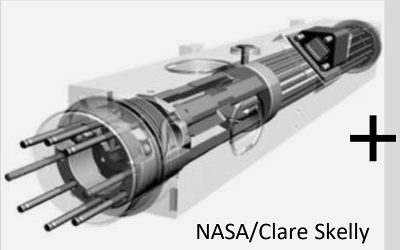
1. **The precise tracking of asteroids with space missions, e.g., OSIRIS-REx tracking the dangerous asteroid Bennu**
   $\sim$ 1 meter precision for objects in 1 AU ($\sim 10^{11}$meter-distant) distance

- **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



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Theme of this talk:

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

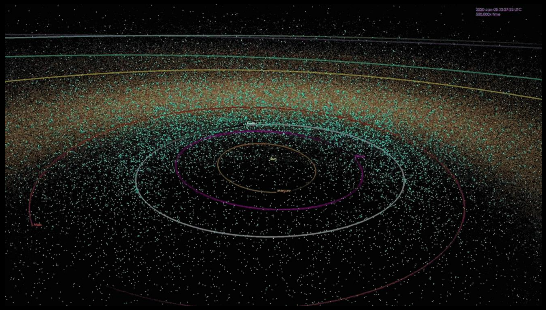
Outline

1. **Precision Astrometry:**

   Dark Matter & Cosmic Neutrinos

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

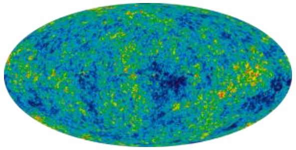
Vera Rubin
Carnegie Institution for Science



Albert Einstein
Mount Wilson Observatory, California

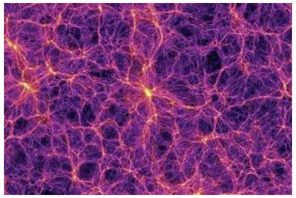
How do we know dark matter exist?

Size



Credit: NASA / WMAP

Cosmic Microwave Background

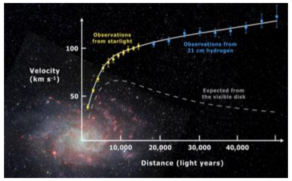


Credit: Springel et al. 2015 (10-100 Gpc)

Large Scale Structure

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

Bullet Cluster Merger



Credit: De Leo-Winkler(10 kpc)

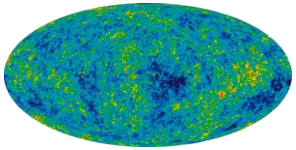
Galactic Rotation Curves

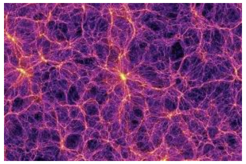
DM Gravitational Interactions

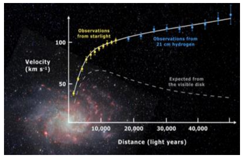
Modified from a slide from Tien-Tien Yu (U. of Oregon)

DM Gravity in Smaller Scale?

Size



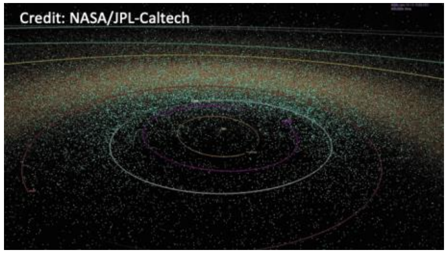




DM Gravitational Interactions

Precision Astrometry

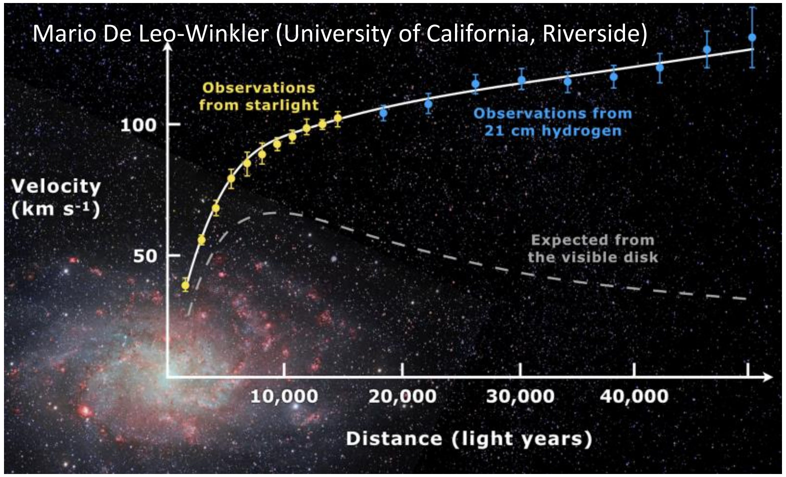
Tsai *et al.*, arXiv:2210.03749
(under review by Nature Astronomy)



Mechanical Sensors

See, e.g., Carney, Lang *et al.*
Quantum Sci. Technol. 2021,
Rafael's talk on Saturday

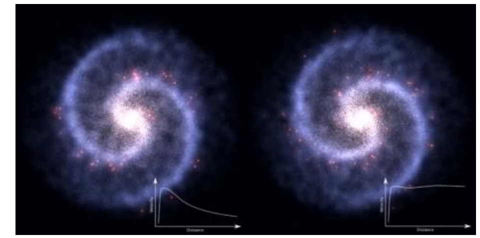
A question we asked



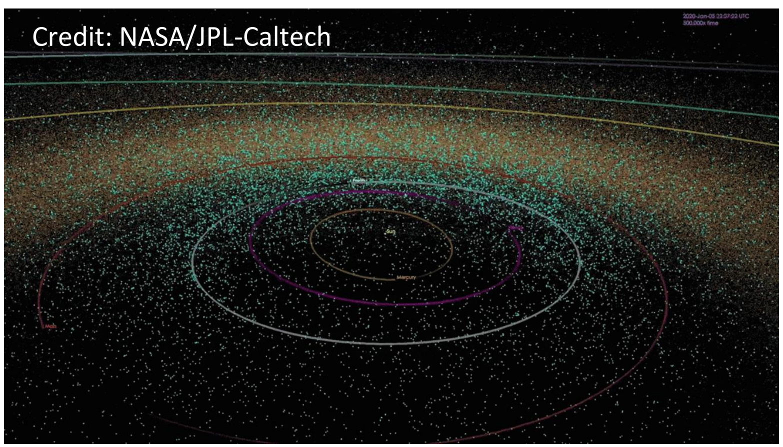
Stars

ρ_{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.

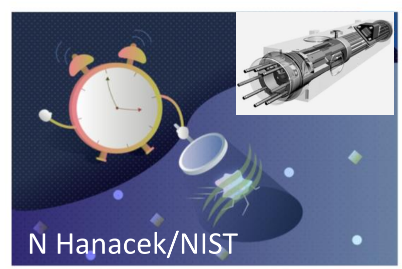


Solar System Objects

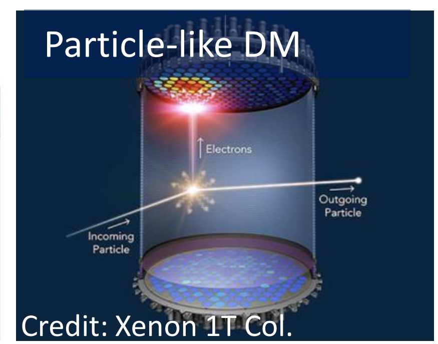
$\rho_{\mathrm{DM}}(r)$ for solar system

Crucial for Direct Detection of DM

Wave-like DM

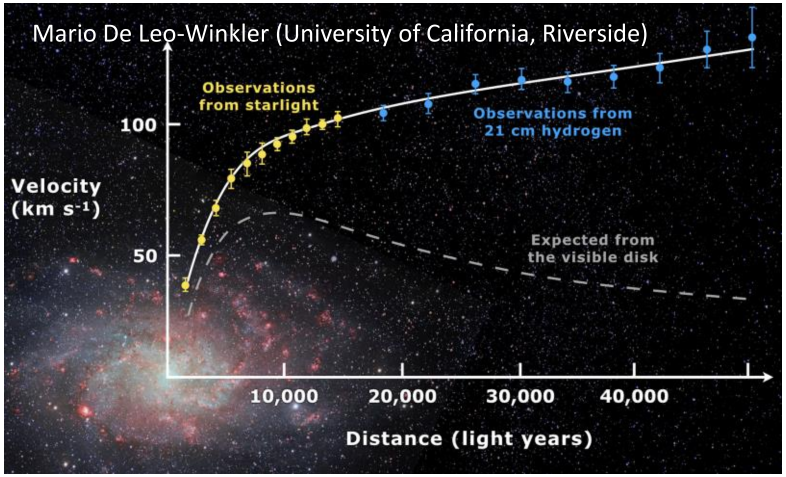


Credit: N. Hanacek/NIST



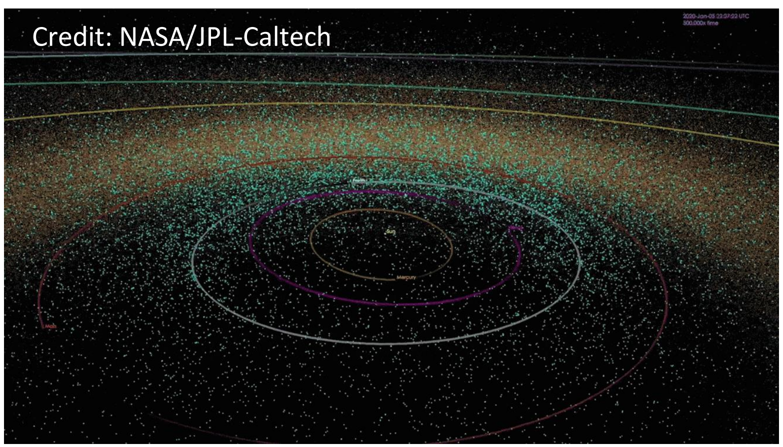
Yu-Dai Tsai (UC Irvine)

A question we asked



Stars

$\rho_{\rm DM}$ for galaxies



Solar System Objects

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

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

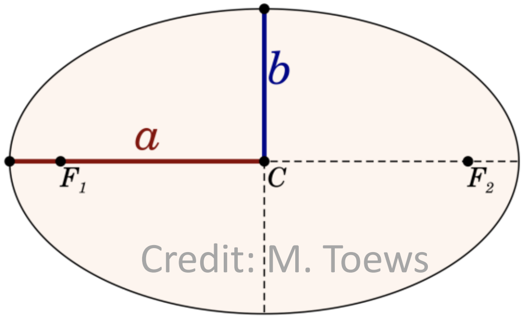
$\bar{\rho}_{DM} = 0.3$ GeV/cm^3, $\bar{\rho}_{\rm DM} \sim 10^{-18} \frac{m_\odot}{({\rm AU})^3}$

Velocity measurements ineffective

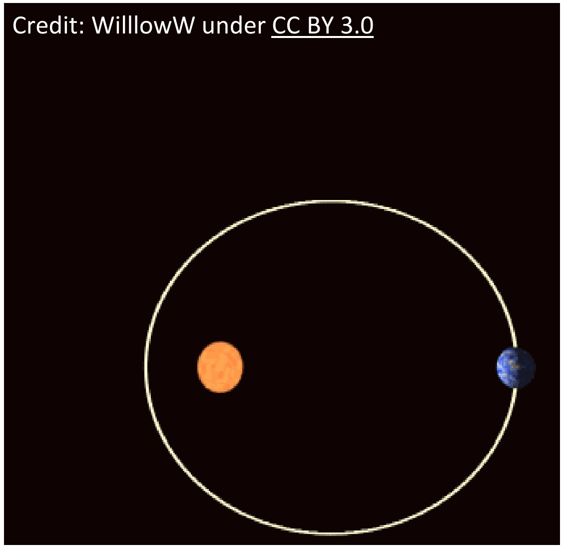
We need to go beyond it!

Beyond Velocity: Perihelion Precession

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

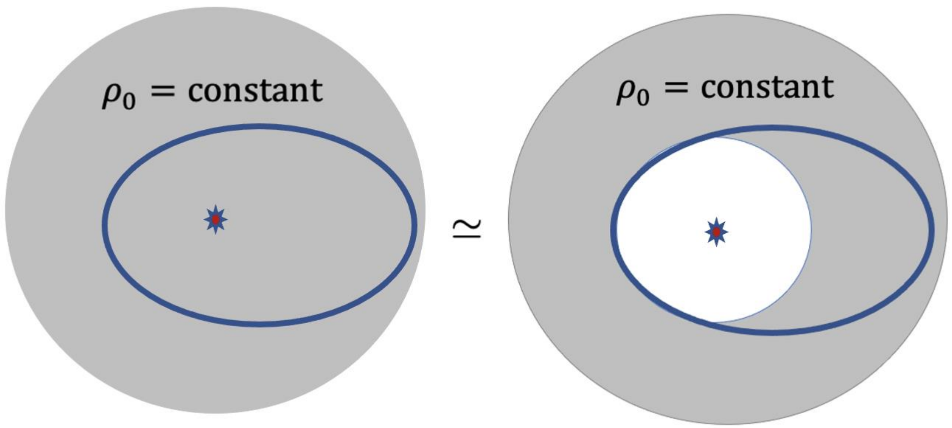


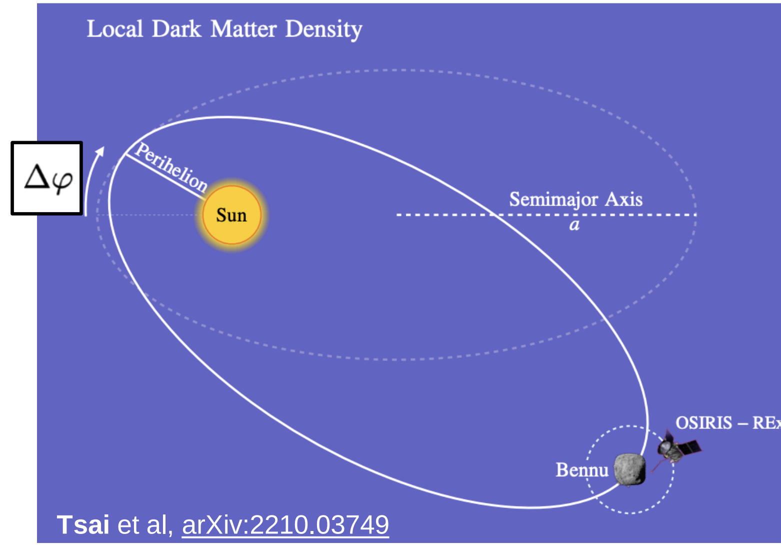
- a is the semi-major axis
- e is the eccentricity, quantify how non-spherical the orbit is.



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

Our Project:
Local DM or Cosmic Neutrinos Induce Precessions





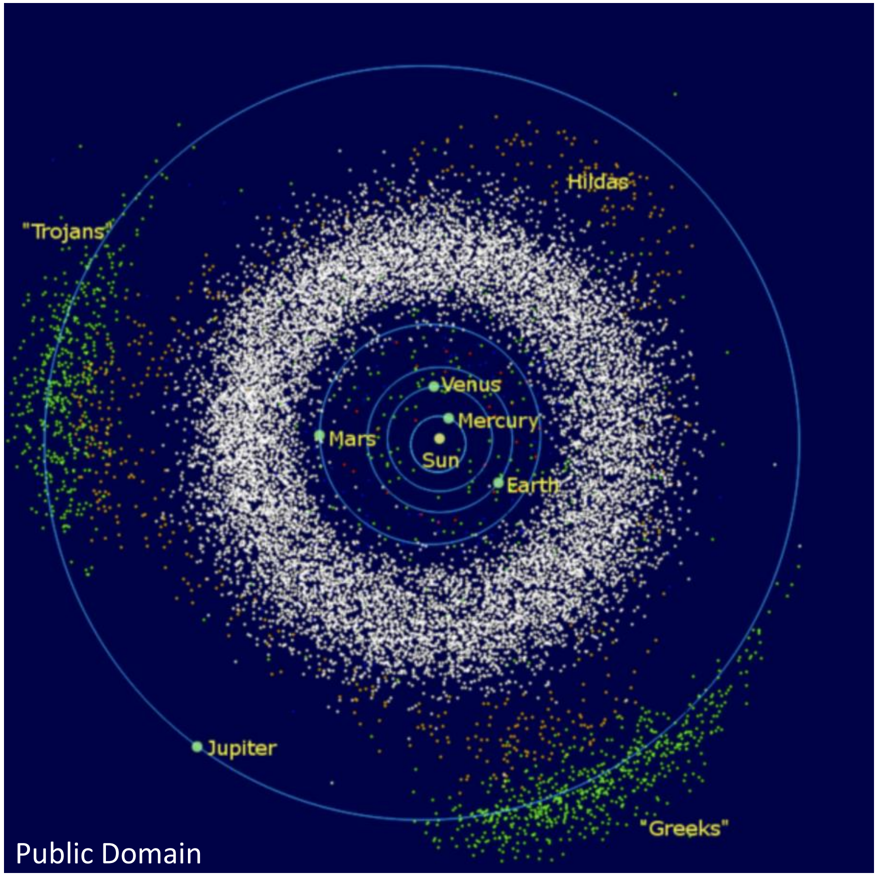
Dark Matter Gravity: $$\mathbf{F}(\mathbf{r}) = \frac{2\pi}{3} G m \rho_0 \left(\frac{2r_0^3}{r^2} - 2r \right) \hat{\mathbf{r}}$$

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

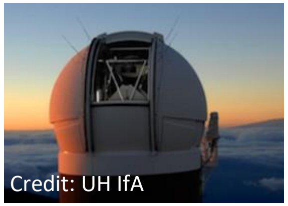
m is the mass of the object

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)

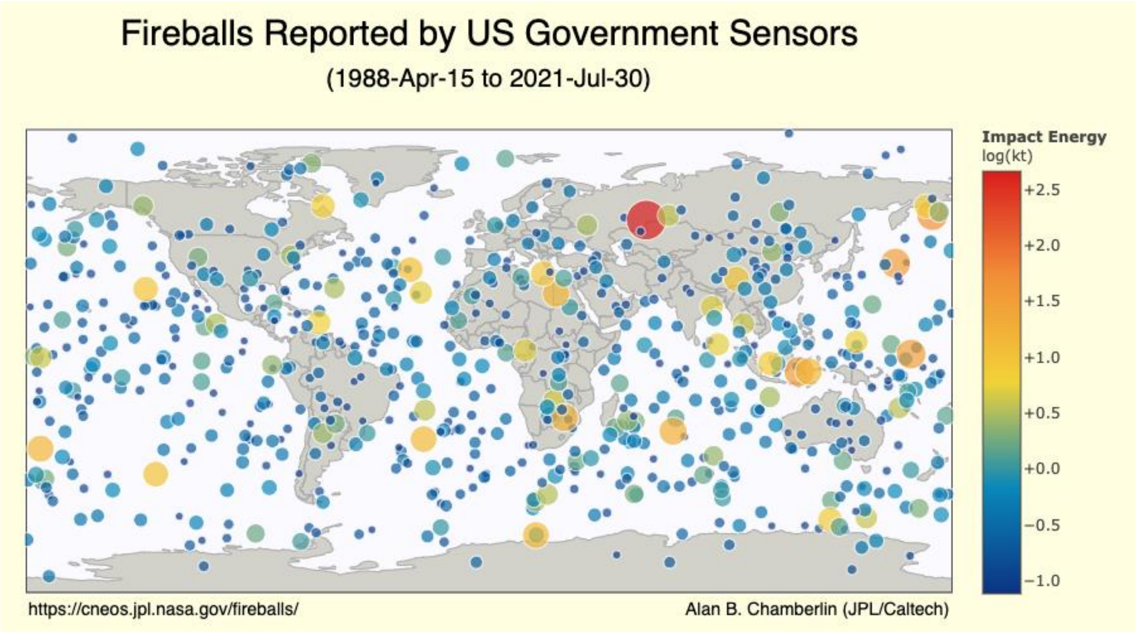


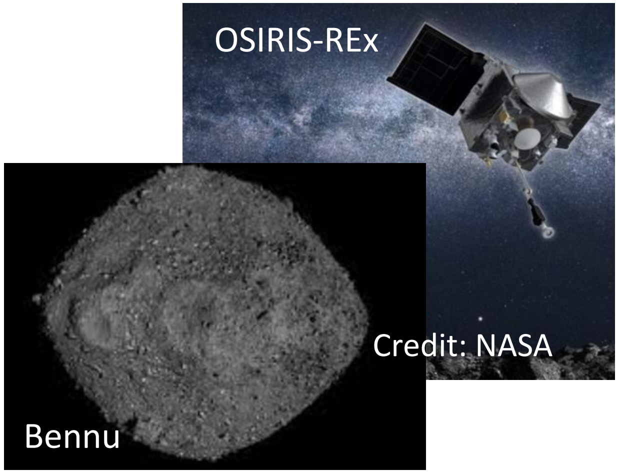
Optical (Pan-STARRS, LSST)

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.

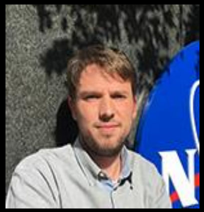
Asteroids & Planetary Defense





- 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

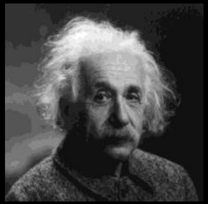
Robust Analysis: High-Fidelity Force Model



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

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

$$+ \frac{1}{c^2}\sum_{j\neq i}\frac{\mu_j}{{r_{ij}}^3}\left\{\left[\mathbf{r}_i - \mathbf{r}_j\right]\cdot\left[(2+2\gamma)\dot{\mathbf{r}}_i - (1+2\gamma)\dot{\mathbf{r}}_j\right]\right\}\left(\dot{\mathbf{r}}_i - \dot{\mathbf{r}}_j\right) + \frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{\mu_j\ddot{\mathbf{r}}_j}{r_{ij}}$$

+

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:

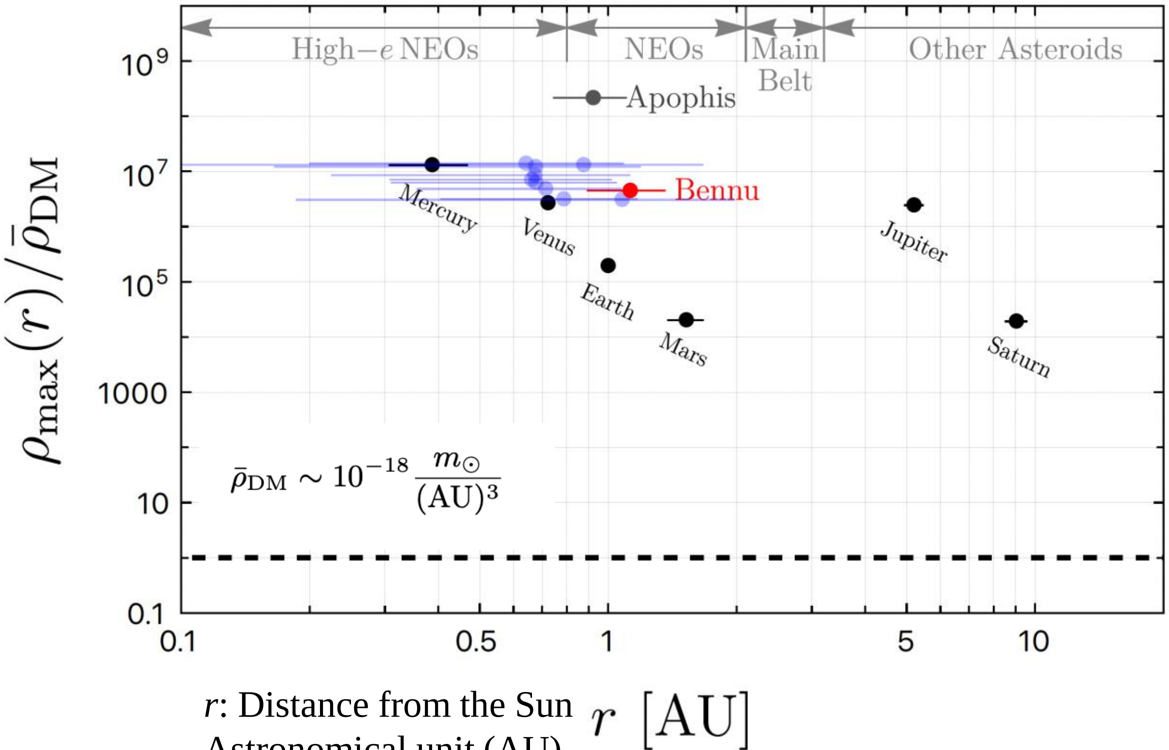
1) Errors in planetary trajectories and masses; 2) Errors in perturber masses & trajectories; 3) Higher order relativistic terms; 4) Higher order gravity terms; 5) Simplified assumptions in nongravitational force model (non-spherical effects, Yarkovsky, solar torque, physical parameter evolution, etc.); 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

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

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

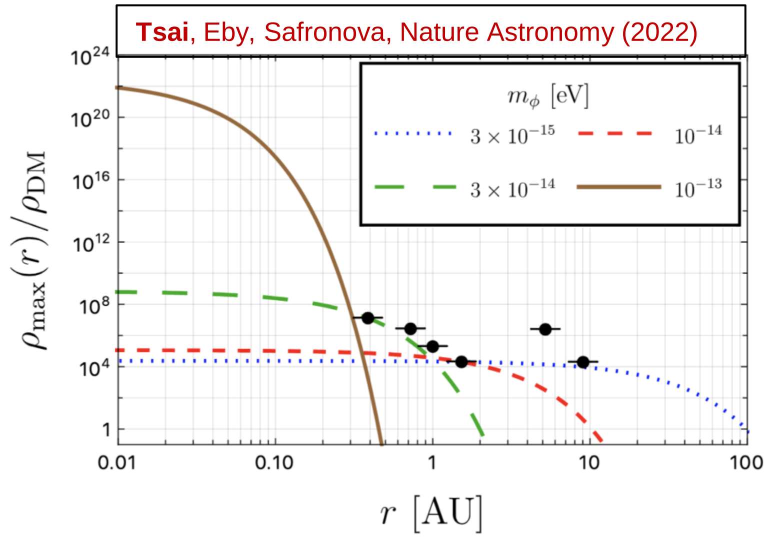


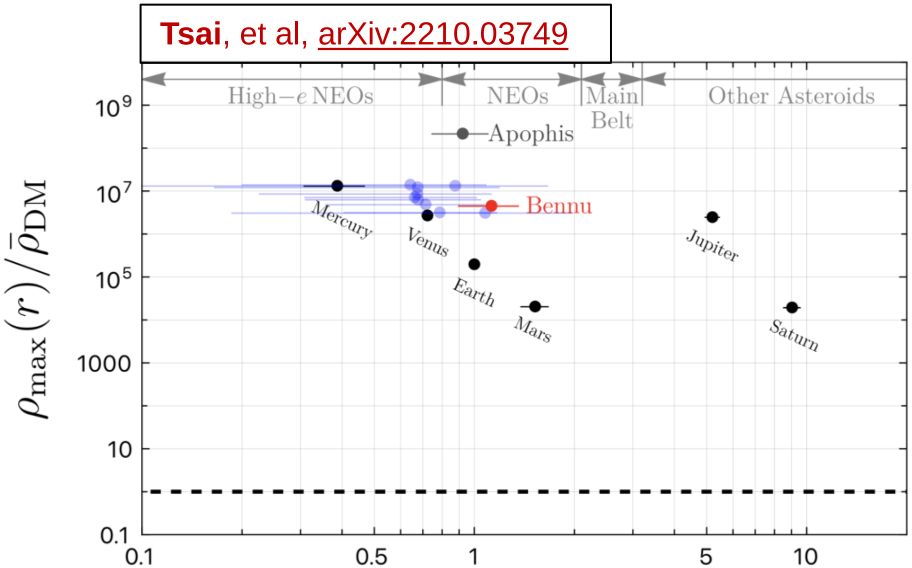
r: Distance from the Sun
Astronomical unit (AU)

- 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.



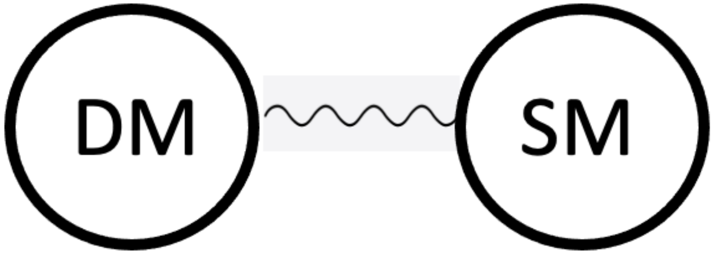


r: Distance from the Sun
Astronomical unit (AU)

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.

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

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

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

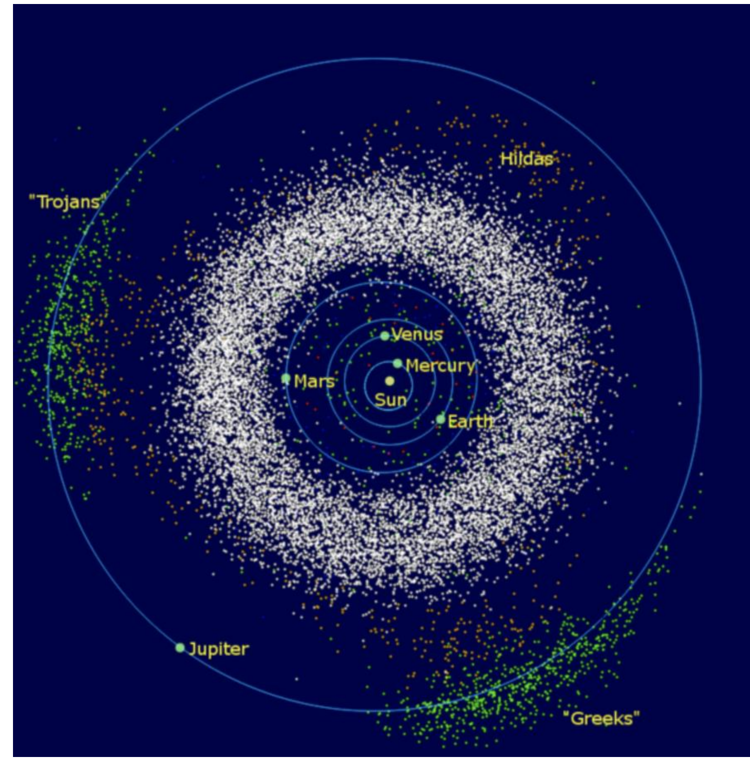
- GR Test: $$\Delta\varphi = \frac{6\pi G M_\odot}{a(1-e^2)c^2}\left[\frac{4-\beta}{3}\right] \propto a^{-1}$$
- Fifth Forces: $$|\Delta\varphi_{\phi,A'}| \simeq a(1-e)\left[\left(\frac{mc}{\hbar}\right)^2 \frac{g^2}{4\pi G m_p^2}\frac{2\pi}{1+\frac{g^2}{4\pi G m_p^2}}\right] \propto a$$
  (light mediator 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, Probing long-range fifth forces & ultralights, *JCAP* (2023), 2107.04038

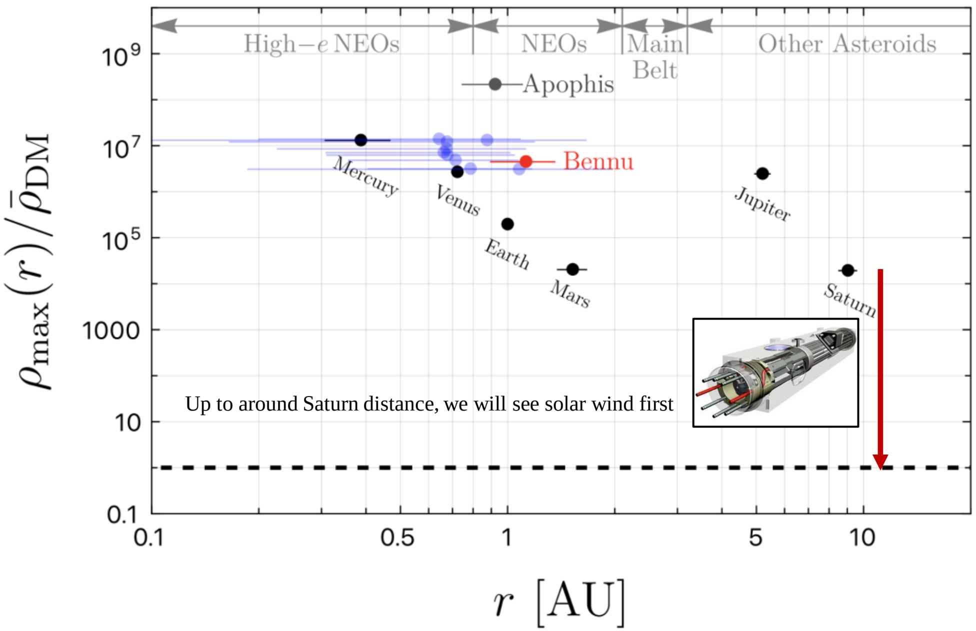
Minor Planets	a [au]	$\sim$ Numbers
Near-Earth Object (NEO)	$< 1.3^*$	> 25000
Main-Belt Asteroid (M)	$\sim 2 - 3$	~ 1 million
Hilda (H)	3.7 - 4.2	> 4000
Jupiter Trojan (JT)	5.2	> 9800
Trans-Neptunian Object (TNO)	> 30	2700
Extreme TNO (ETNO)	> 150	12

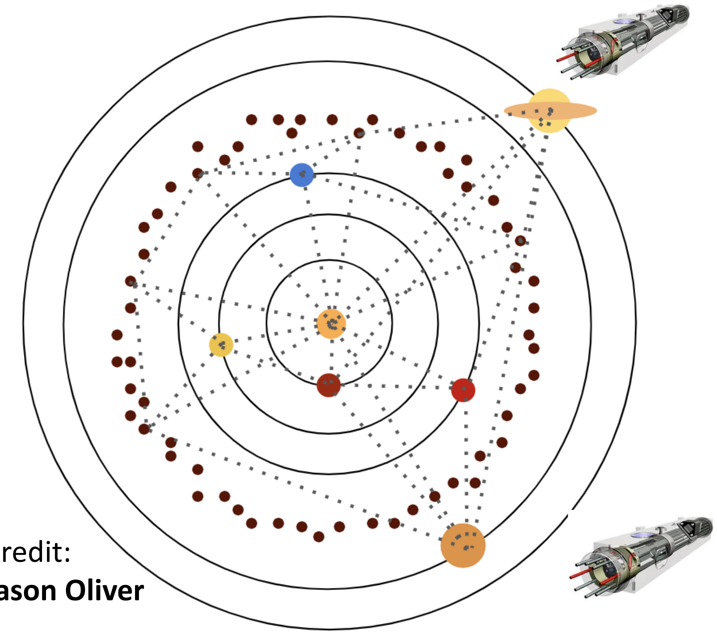
*NEOs are defined as having perihelia $a(1 - \mathrm{e}) < 1.3\,\mathrm{au}$.



Fedderke, Graham, and Rajendran, PRD (2022)
Study Gravitational Wave with Asteroids

Roadmap to Observe Local Dark Matter through Gravity





Credit:
Jason Oliver

Tsai, Aishik, Arakawa *et al.*

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

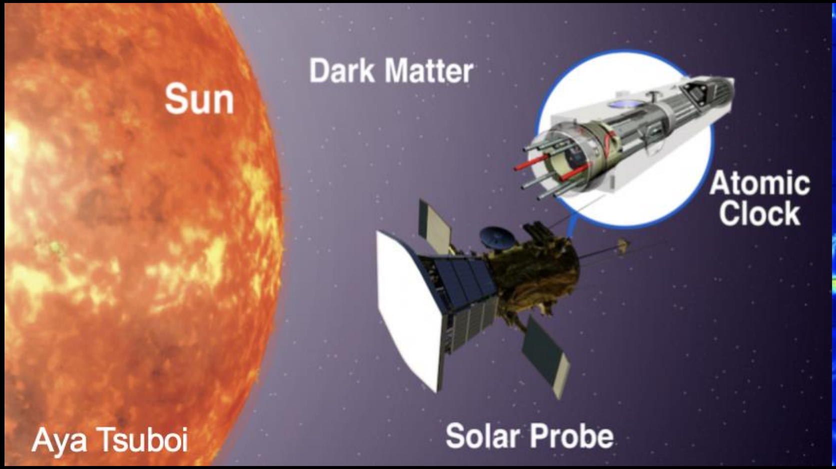
1. Increase **precision** (e.g., with quantum clocks onboard of space missions)
2. Consider **more asteroids & minor planets** (near Sun & far from Sun)

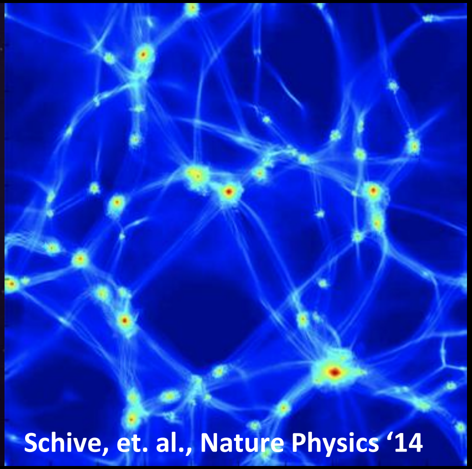
Outline

1. Precision Astrometry:

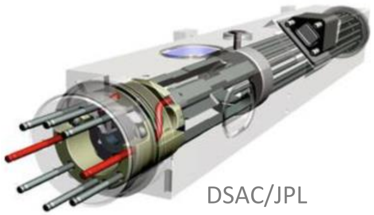
   Dark Matter, Cosmic Neutrinos, Fifth Forces & GR

2. Space 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 3×10^{-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

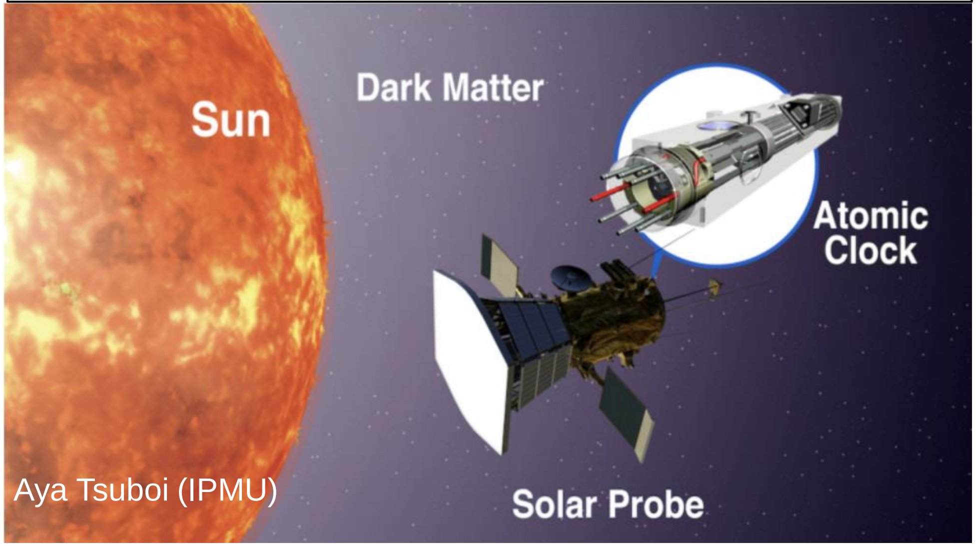
Size of PSP ~ 1.0 × 3.0 × 2.3 m
(685 kg → 555 kg)

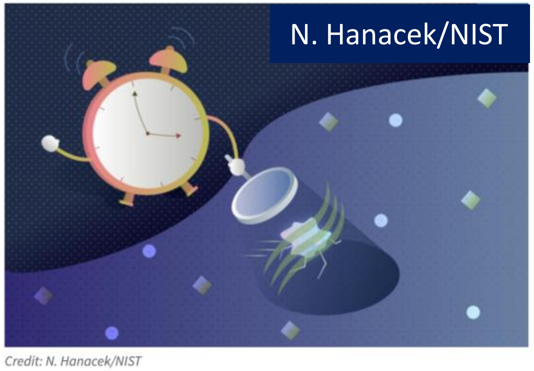
- **Parker Solar Probe (PSP)**
- see, e.g., "Probing the energetic particle environment near the Sun," McComas et al, Nature (2019)

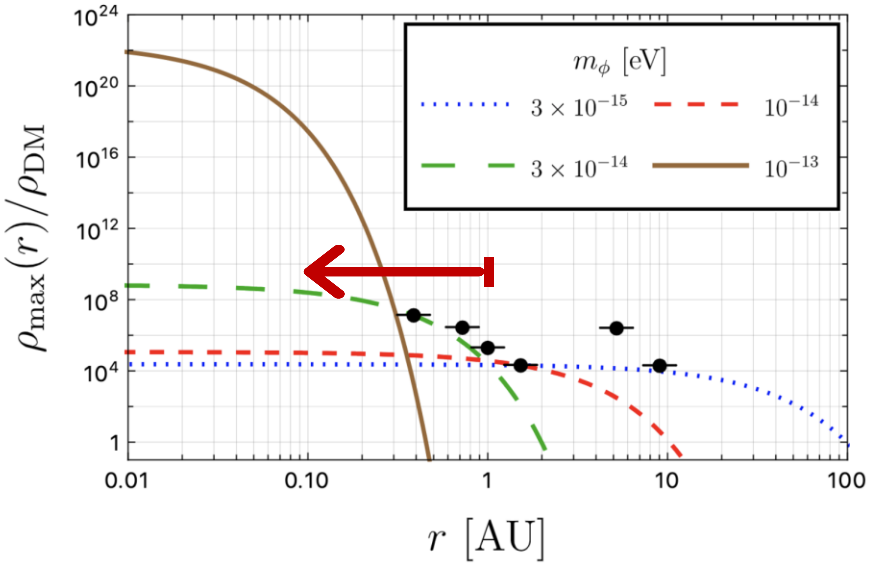
My Question: Why don't we put a quantum clocks on a solar probe?
What fundamental physics can we study?

SpaceQ Mission Concept

Tsai, Eby, Safronova, Nature Astronomy (2022)







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

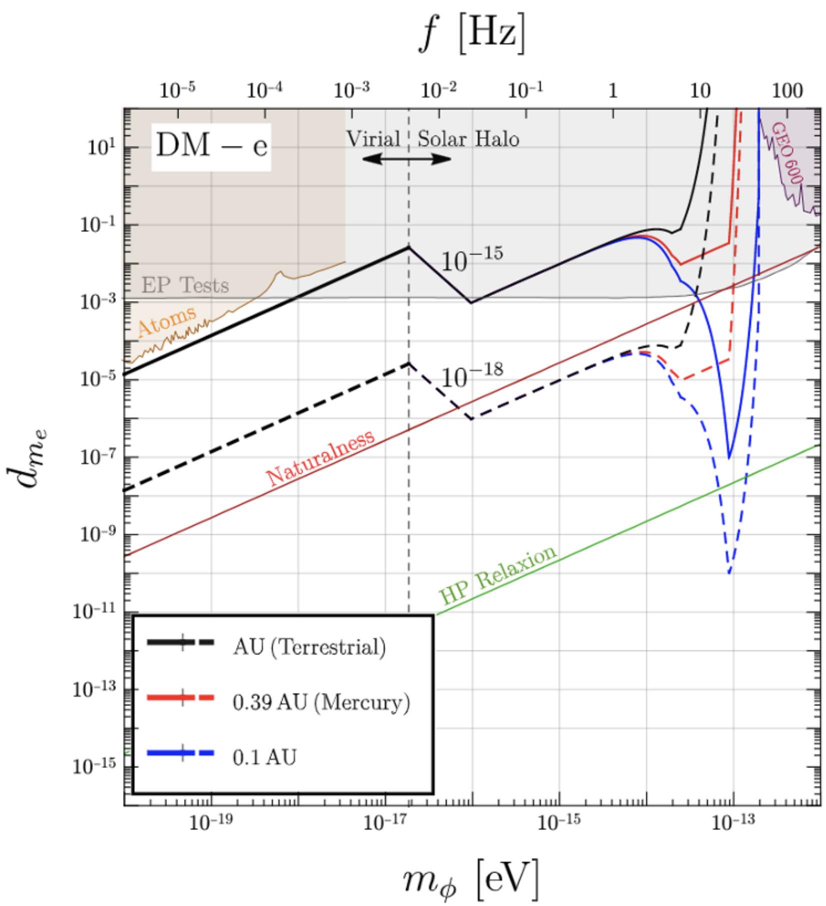
(Non-relativistic solution)

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

- **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**

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

AMO convention

Motivate Nuclear 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 .

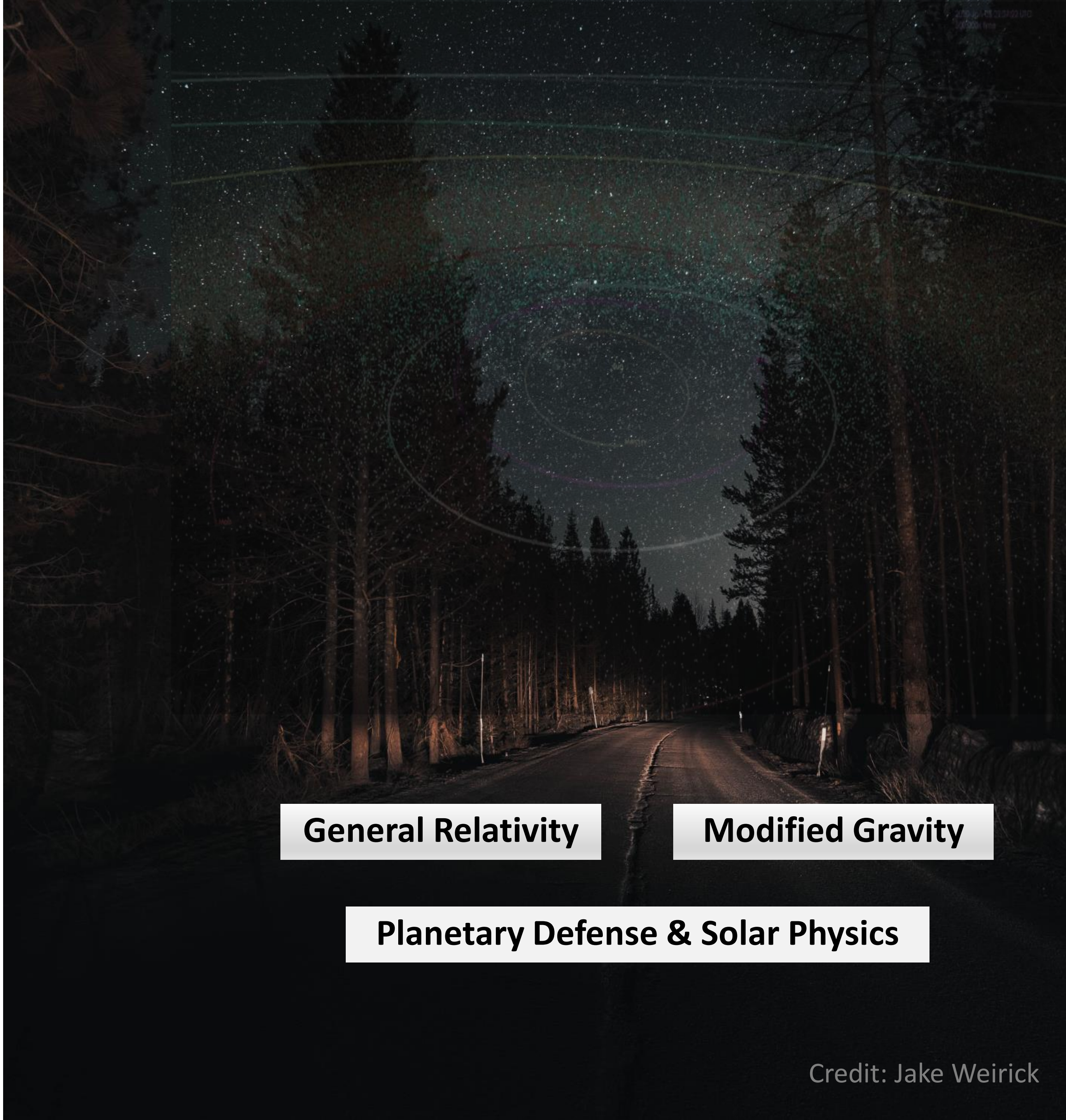
$\delta U/c^2 \simeq 3.3 \times 10^{-10}$, Earth variation

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

My Understanding Before Our Projects



New Precision Lab for HEP Theories Cosmology and Astrophysics

Rubin Observatory/LSST

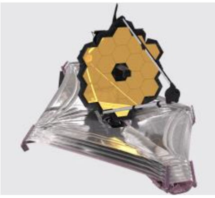
LSST: Large Synoptic Survey Telescope

5 times more asteroids

Space Missions

Explore **Jupiter's Trojan asteroids**

JWST

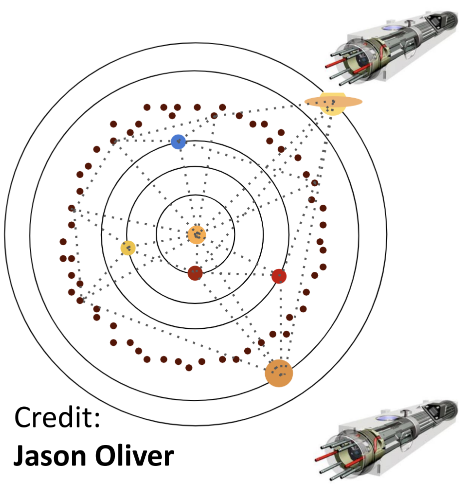


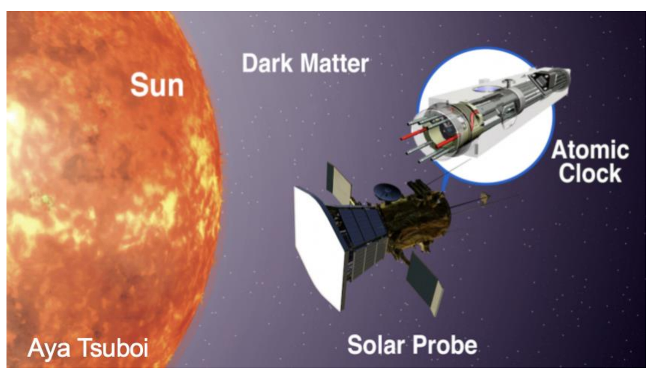
OSIRIS-REx
→ **OSIRIS-APEX**

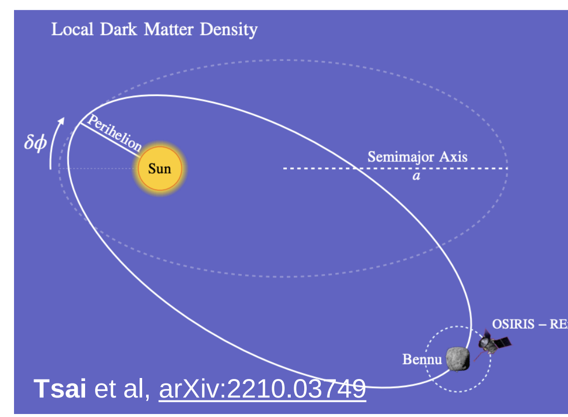
NASA DSAC I
→ **DSAC II**

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!

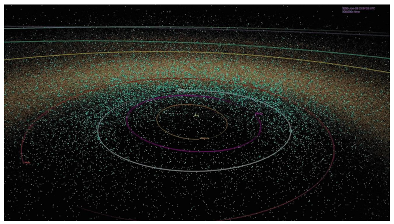






Summary & Results & Plans

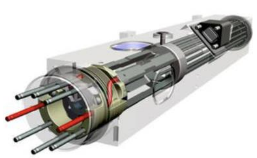
Precision Astrometry



Space Missions

OSIRIS-REx → **OSIRIS-APEX**

Quantum Sensors



NASA DSAC I → **DSAC II**

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

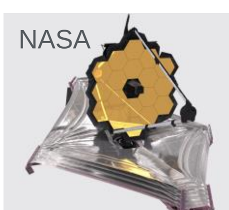
LSST: Large Synoptic Survey Telescope

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
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