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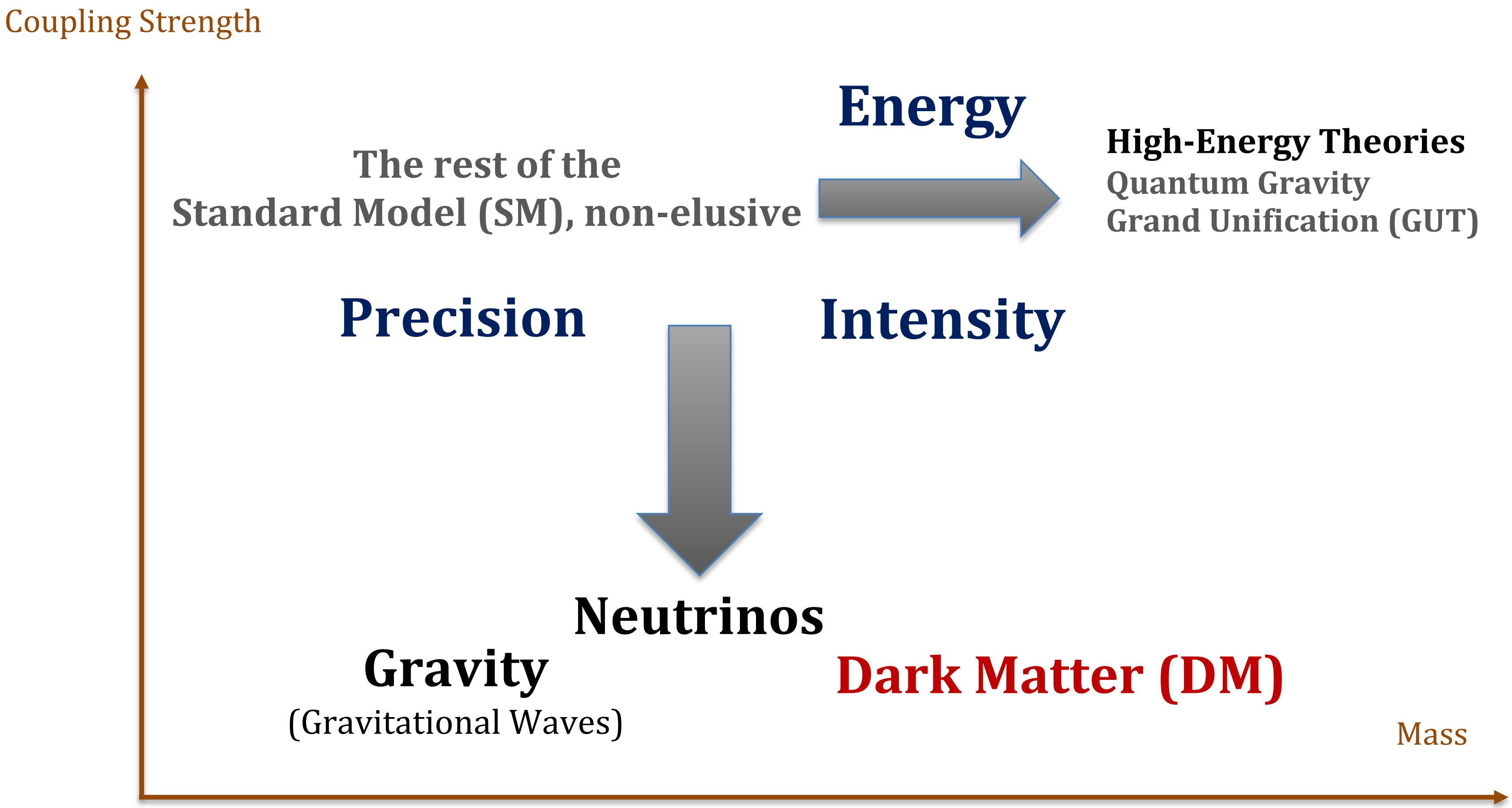
Discovering the Elusive Universe

Yu-Dai Tsai
The University of Manchester

MANCHESTER
1824
The University of Manchester

Explorations of Particle Physics



Coupling Strength

Energy

The rest of the
Standard Model (SM), non-elusive

High-Energy Theories
Quantum Gravity
Grand Unification (GUT)

Precision

Intensity

Neutrinos

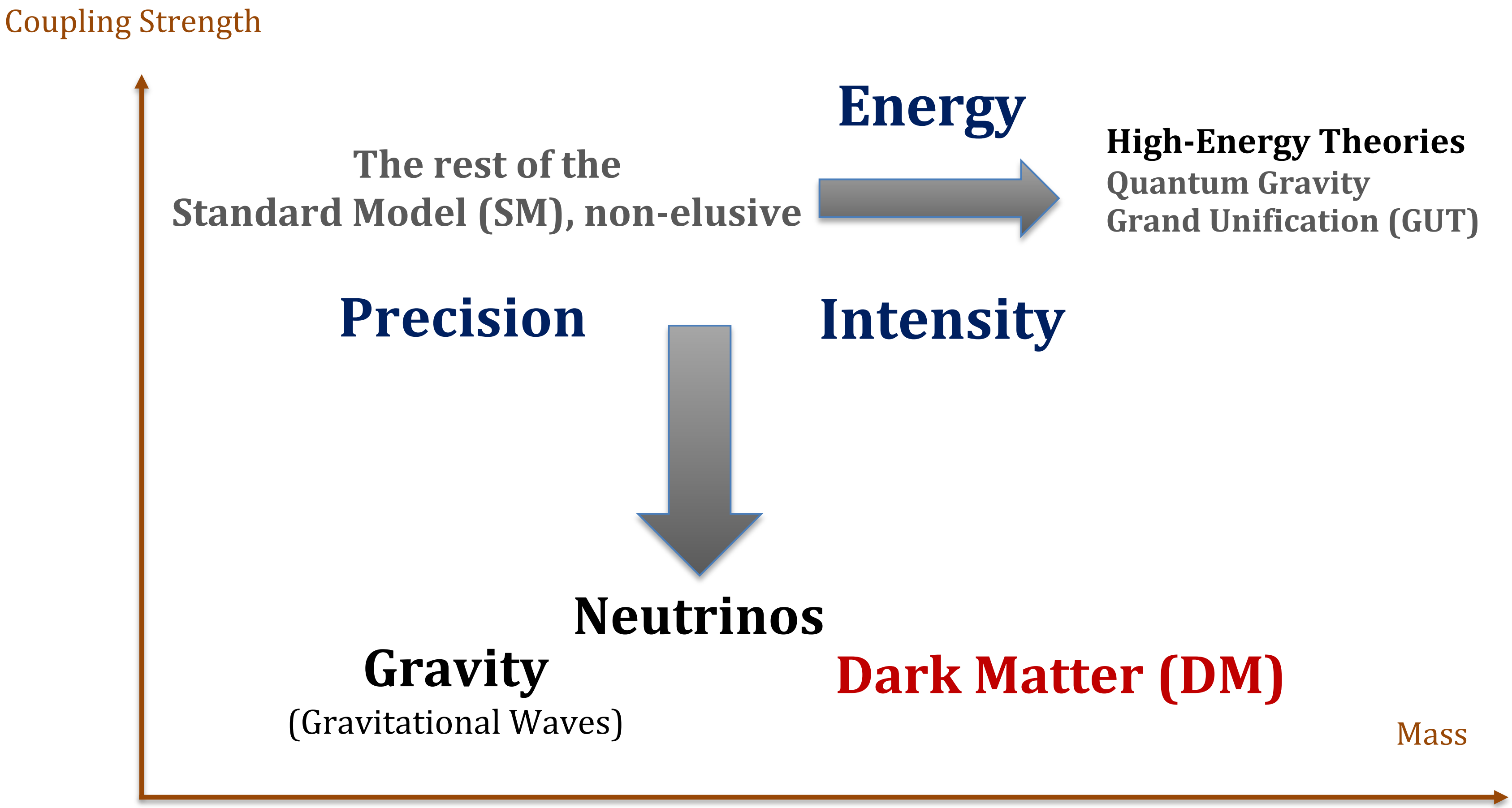
Gravity
(Gravitational Waves)

Dark Matter (DM)

Mass

Exploring Standard Model & Beyond (Higgs, QCD, neutrinos, CPV, etc.)
see, e.g., Cox, Pilkington, Forshaw, *PLB* (2011), Englert et al., *PLB* (2011)
Parkes, *J. Phys. G* (2017), Pilaftsis, *PRL* (2005)

Explorations of Particle Physics



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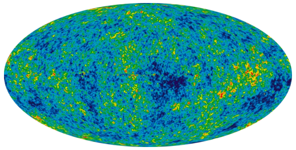
Mass

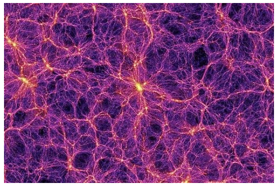
A comprehensive effort is crucial in studying the Elusive Universe

How much do we know about dark matter?

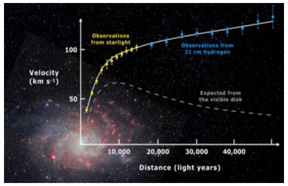
Size



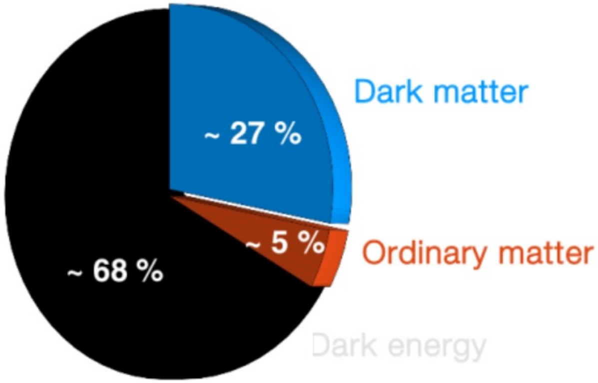
Cosmic Microwave Background (CMB)
Snapshot of the early universe



Large Scale Structure
Clusters of galaxies



Galaxy Rotation Curves



Credit: Public Doman

Dark Matter & Gravitational Interaction: Discovered

?

But never in solar-system scale
Never detected in experiments
The nature of dark matter still unknown

Research Goals

1. **Theory & Cosmology of Dark Matter (DM)**
   Kuflik, Perelstein, Lorier, **Tsai,** *Phys. Rev. Lett*. (2016)
   Tsai, McGehee, Murayama, *Phys. Rev. Lett*. (2022)

2. **Discovering Dark Matter Pure Gravitationally in the Solar System** (focus of this talk)
   Tsai et al, *Nature Astronomy* (2022)
   Tsai et al, *Comm. Phys.--Nature* (2024)

3. **Particle DM & Neutrino Properties**
   Tsai, de Niverville, Liu, *Phys. Rev. Lett*. (2021)
   Abraham, Foroughi-Abari, Kling, **Tsai**, *Phys. Rev. D (2025)*

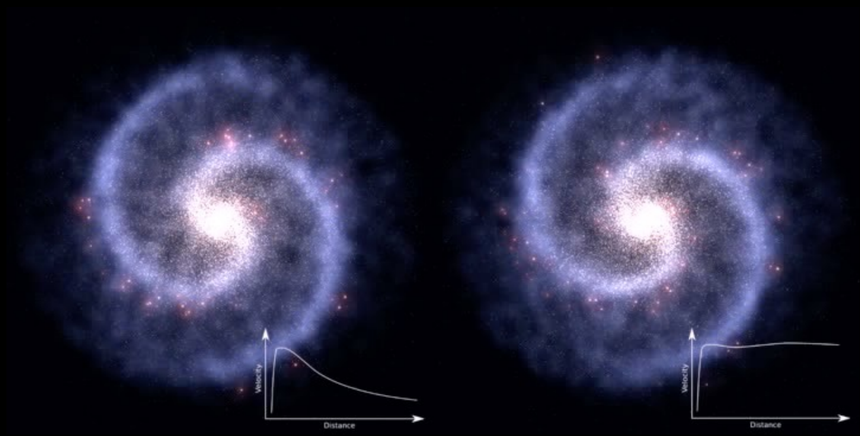
Probing Dark Matter with Precision Space Missions

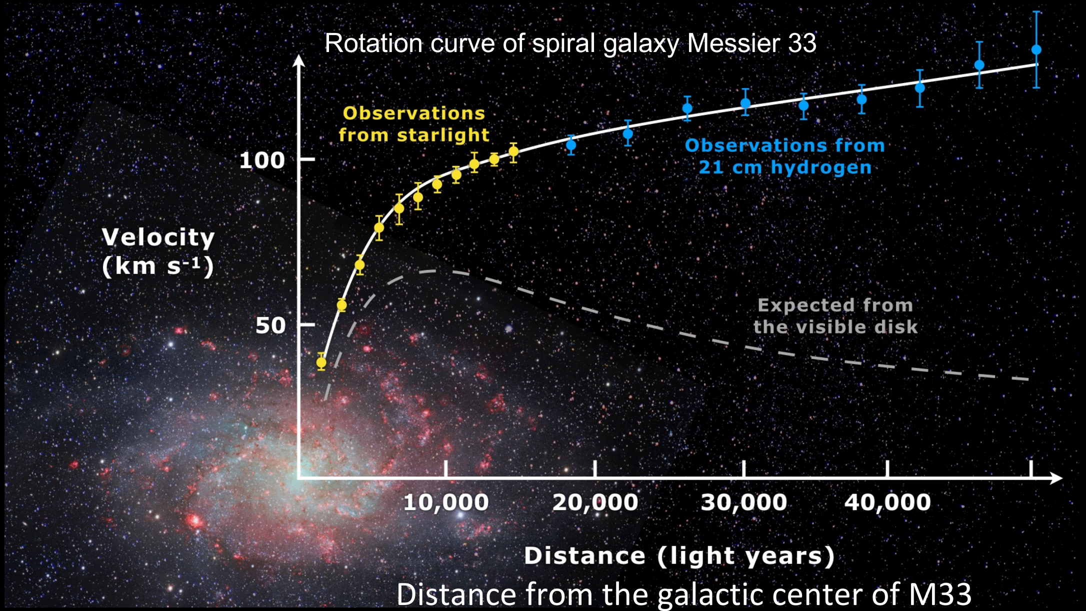
How was dark matter discovered

Vera Rubin

Carnegie Institution for Science

Rubin, Ford, APJ 70

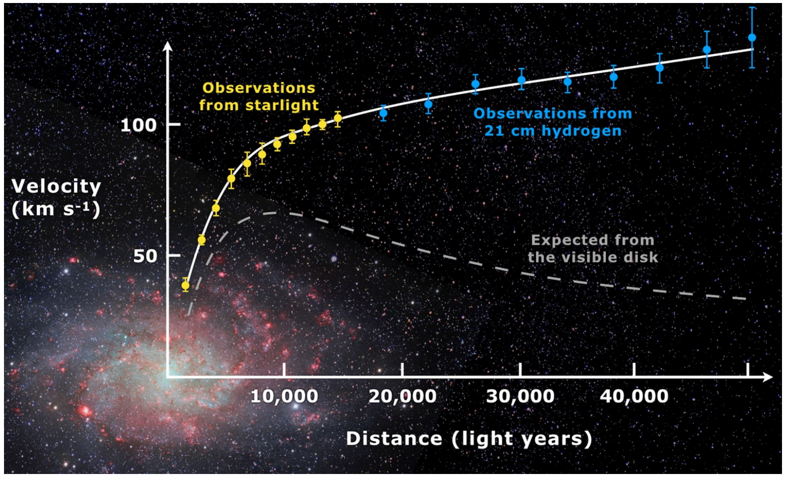



Rotation curve of spiral galaxy Messier 33

Distance from the galactic center of M33

Credit: Mario De Leo-Winkler (University of California, Riverside) & Wikipedia

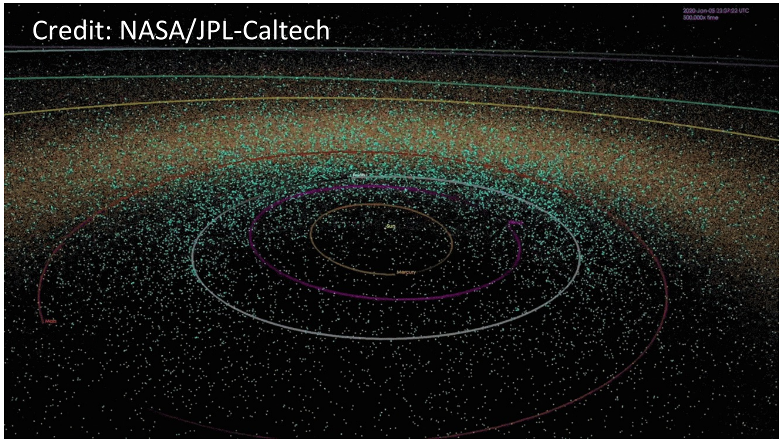
How do we measure DM density?



Galaxy & Stars

$\rho_{\rm DM}$ for galaxies

DM density comparable or more than visible density



Credit: NASA/JPL-Caltech

Solar System Objects

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

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

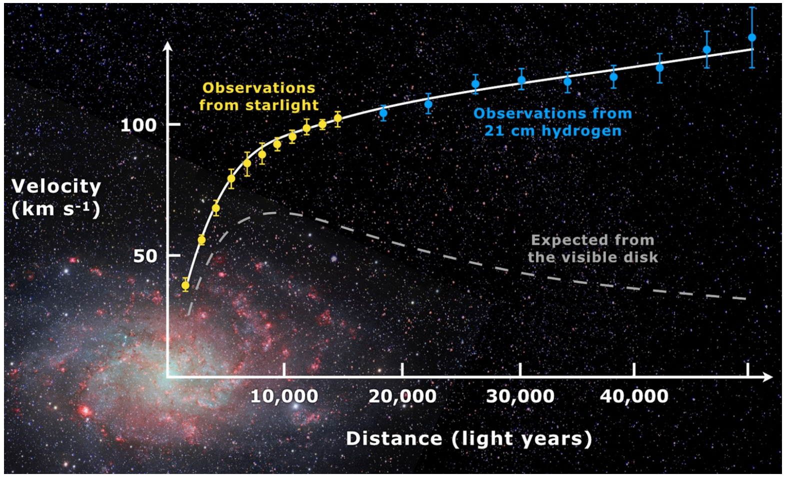
$\bar{\rho}_{DM}$ = 0.3-0.4 GeV/cm^3 , $\bar{\rho}_{\rm DM} \sim 10^{-18}\,\frac{m_\odot}{({\rm AU})^3}$

Velocity measurements ineffective

We need to go beyond it!

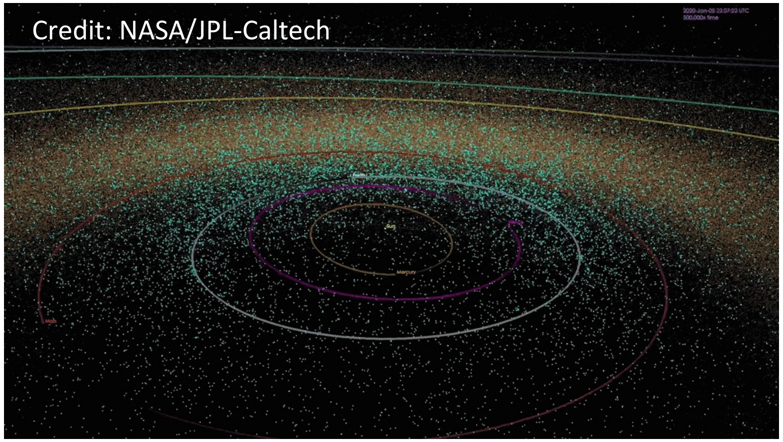
$\bar{\rho}_{DM}$ = 5.3 × 10^{-25} g/cm^3(SI units) = 0.3 GeV/cm^3 (Nature units, $\hbar$ = c = 1)

How do we measure DM density?



Galaxy & Stars

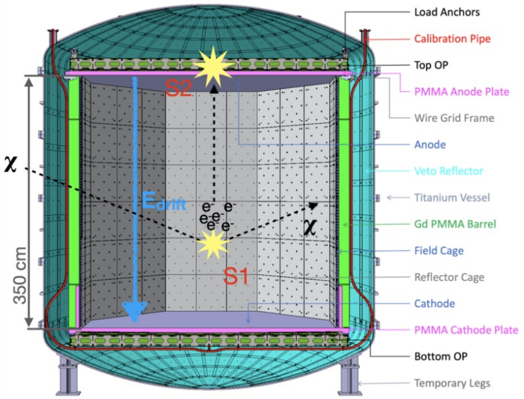
➡ ρ_{DM} for galaxies


Credit: NASA/JPL-Caltech

Solar System Objects

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

Particle-like DM



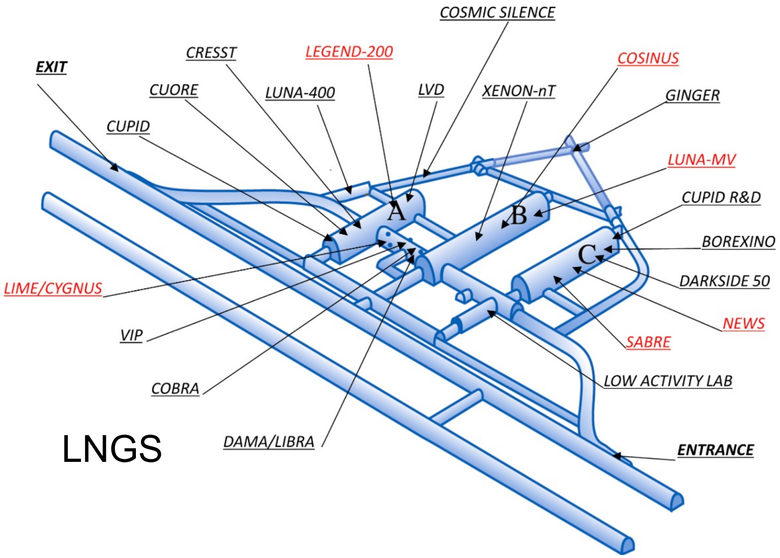
DarkSide Experiment

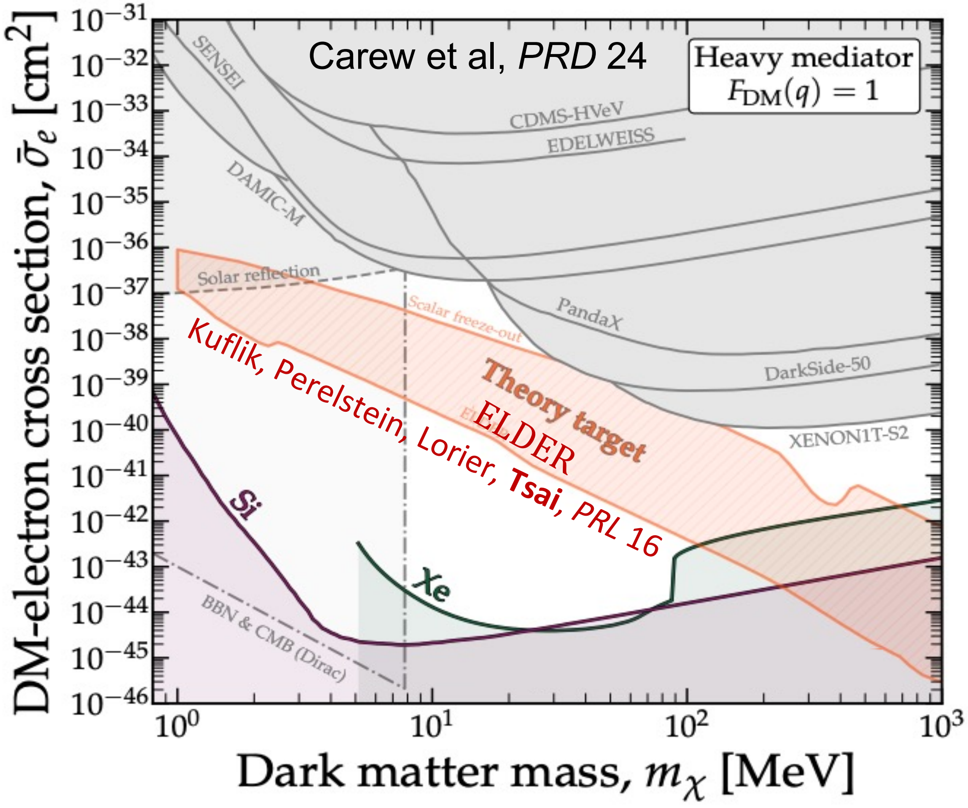
Credit: DarkSide, NASA, UC Riverside

Kuflik, Perelstein, Lorier, **Tsai**, *PRL* 16 & *JHEP* 17

DM Theory & Target for Direct-Detection Experiments

- **Target** for **direct detection: SENSEI, DarkSide-50, DAMIC-M, CDMS-HVeV, EDELWEISS**
  Elastically Decoupling Relics (ELDER)





- **Follow-up papers:**
  Tsai, McGehee, Murayama, *PRL* 22,
  Fitzpatrick, Liu, Slatyer, **Tsai,** *PRD* 22
  Lee, **Tsai**, 2504.00076

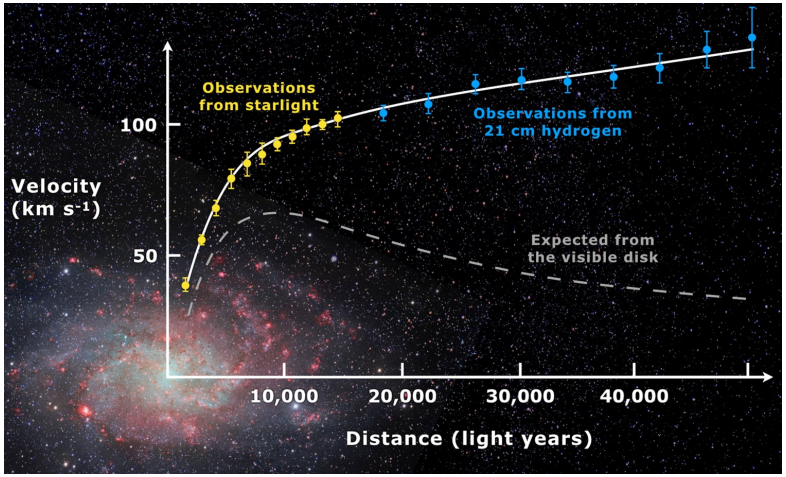
$$\frac{d\rho_\chi}{dt} + 3H(\rho_\chi + P_\chi) = \langle \sigma_{\rm el} v \cdot \delta E \rangle n_\chi n_\gamma^{\rm eq}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{3\to 2} v^2 \rangle (n_\chi^3 - n_\chi^2 n_\chi^{\rm eq})$$

Credit: Laboratori Nazionali del Gran Sasso (LNGS)

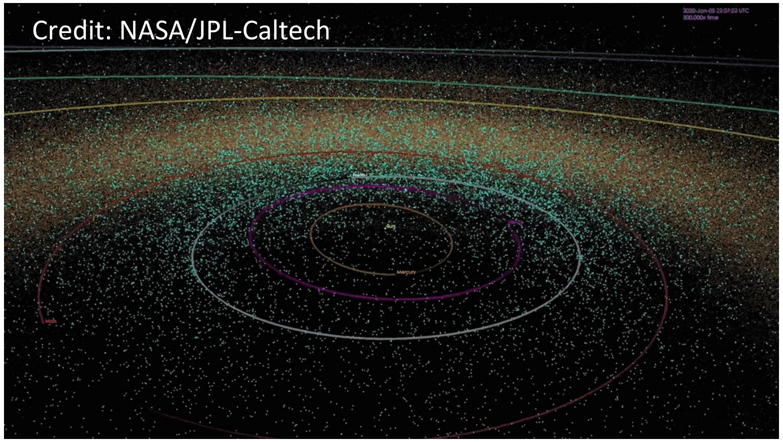
Coupled Boltzmann Equations

How do we measure DM density?



Galaxy & Stars

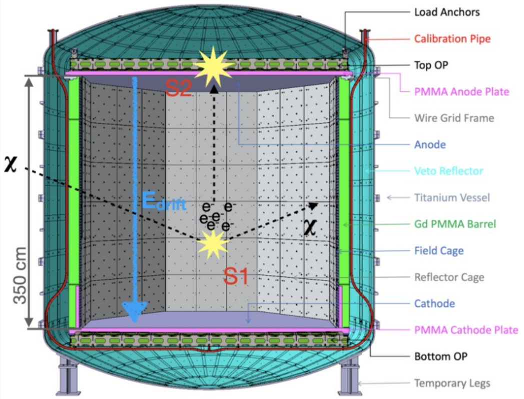
ρ_{DM} for galaxies


Credit: NASA/JPL-Caltech

Solar System Objects

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

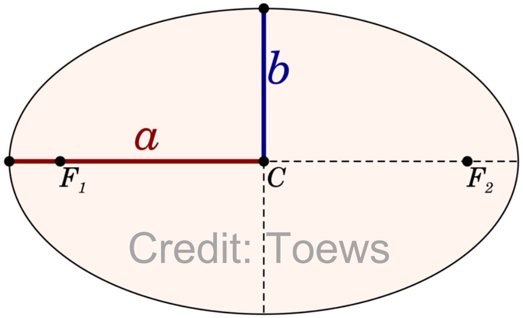
Particle-like DM



Crucial for Direct Detection of DM on Earth

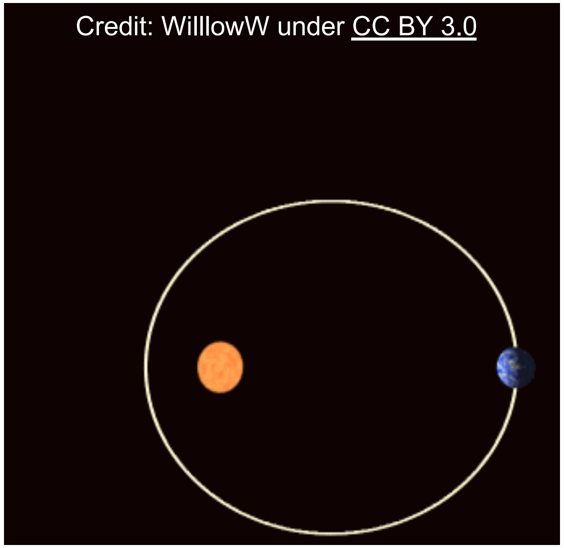
Credit: Darkside, NASA, UC Riverside

Beyond Velocity: Perihelion Precession



- a is the semi-major axis
- e is the eccentricity, $e \equiv \sqrt{1 - b^2/a^2}$

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


Credit: WilllowW under CC BY 3.0

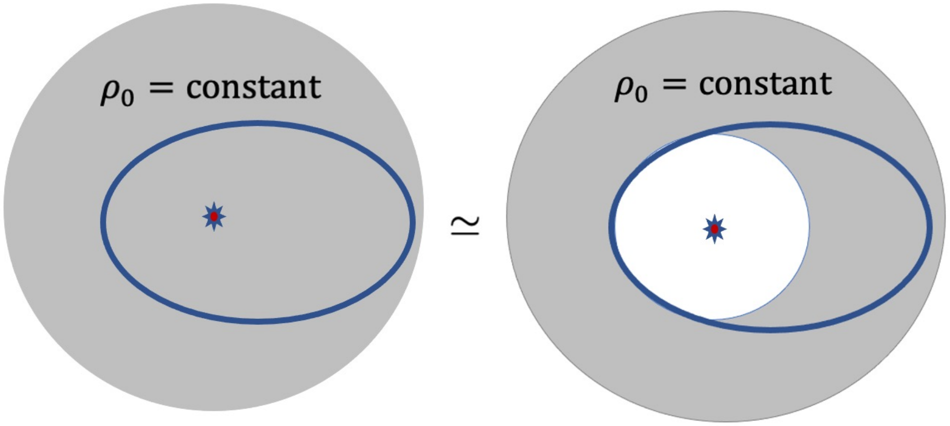
- **Anomalous precession of Mercury's perihelion:**

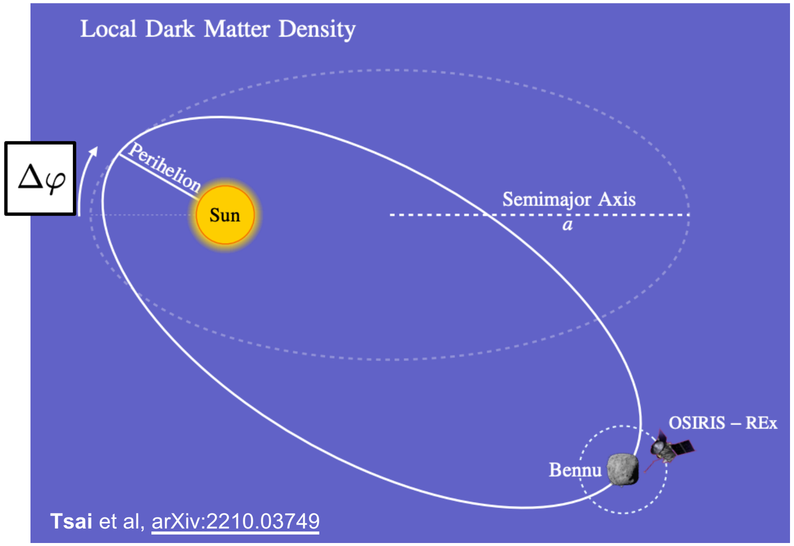
  one of the first ways to confirm **General Relativity**

- **Perihelion precession: a great target,**

  can be directly connected to DM density

Local DM Density Induce Precession



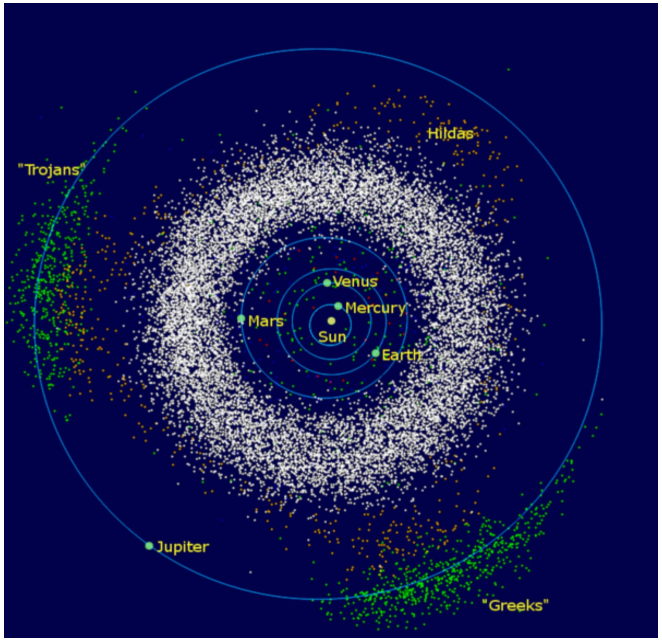


Tsai et al, arXiv:2210.03749

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

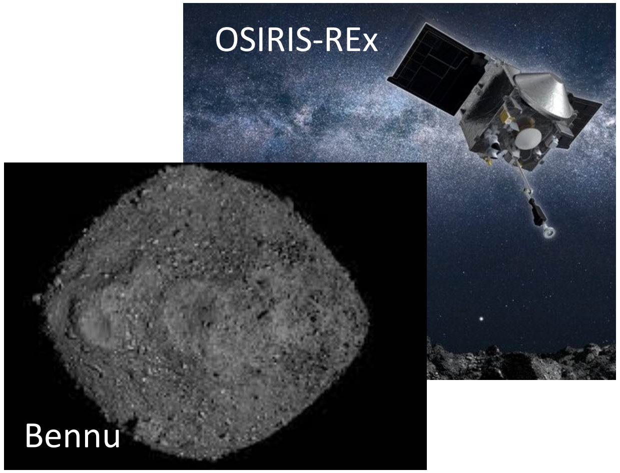
Induced Precession: $$\Delta\varphi \simeq -4\pi^2 \rho_0 a^3 (1 - e^2)^{1/2} / M_\odot$$

Study Asteroids & Other Solar System Objects



Radar (Goldstone)

Optical (Pan-STARRS)



Credit: NASA

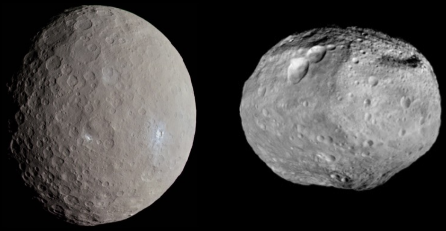
- Use **millions of solar-system objects** to study many **fundamental physics topics.**
- Need **theory** & **data** expertise to realize the full potential of the dataset.

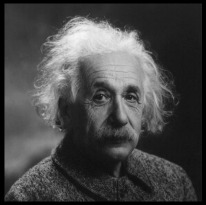
Credits: Public Domain & Named Telescopes

Robust Analysis: High-Fidelity Force Model

JPL Planetary Ephemerides DE424

343 Small-body Perturbers





Relativistic Effects

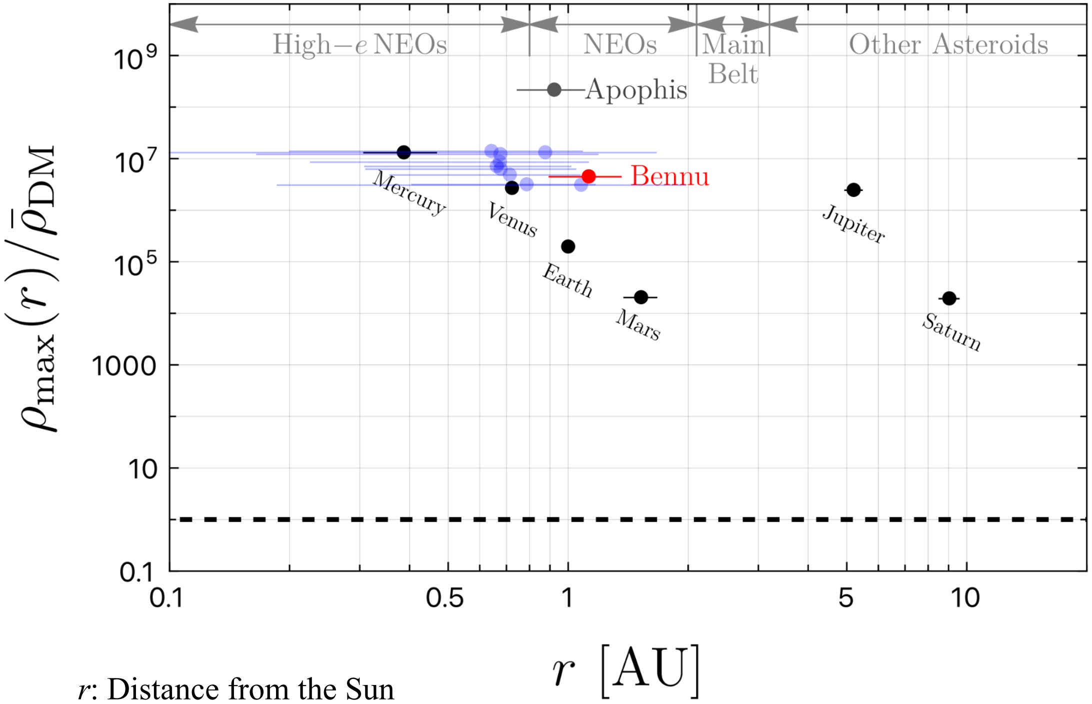
Oblateness

1) Yarkovsky effect
2) Solar radiation pressure
3) Poynting-Robertson drag,
Farnocchia et al., Icarus 369 (2021) 114594.

Planetary Constraints on DM Over-density

These constraints only assume dark matter gravitational interaction!

Tsai et al, *JCAP* (2024), arXiv:2210.03749

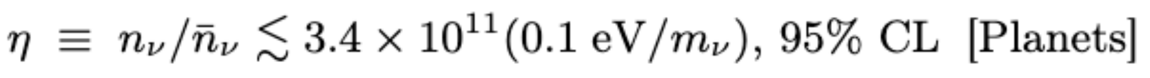


r: Distance from the Sun
Astronomical unit (AU)

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

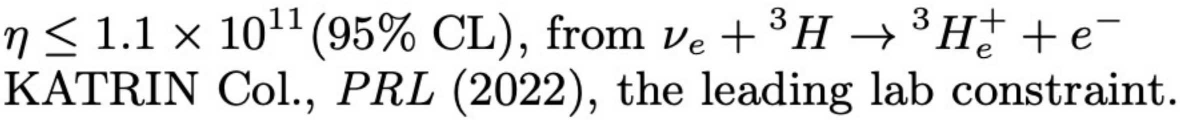
Constraints on CvB Over-density

One of the leading constraints on **cosmic neutrino background (CvB)** over-density profile.



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

Tsai et al, *JCAP* (2024), arXiv:2210.03749



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

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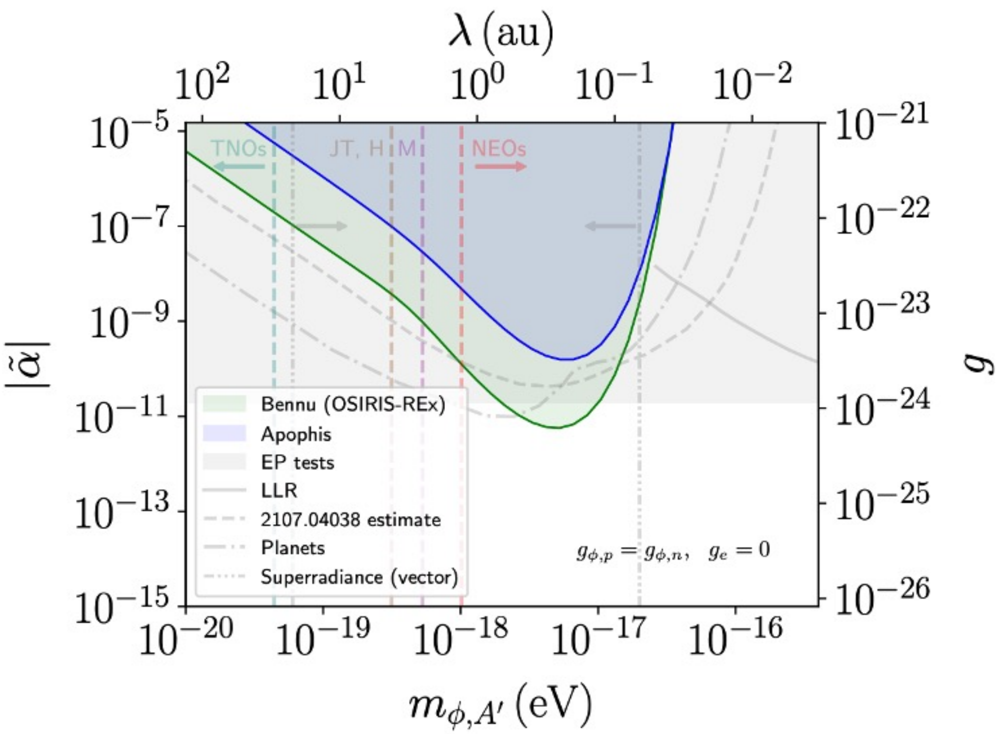
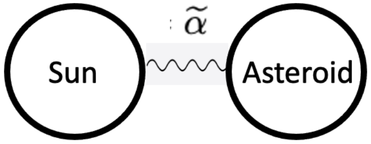
Constraints on Fifth Forces

Tsai *et al.*, *Comms. Phys.-Nature* (2024), 2309.13106



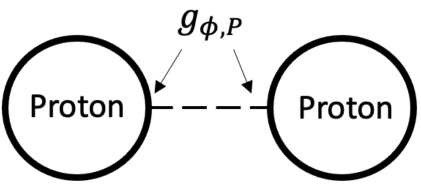
$$V(r) = \tilde{\alpha}\frac{GM_{\odot}M_{*}}{r}\exp\left(-\frac{r}{\lambda}\right),$$

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.
See recent papers for theoretical developments, e.g., Millington & Udemba, *JCAP* (2026)

Summary of Particle Theory Targets

- General Relativity 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: $|\Delta\varphi_{\phi,A'}| \simeq a(1-e)\left[\left(\frac{mc}{\hbar}\right)^2 \frac{g^2}{4\pi G m_p^2}\frac{2\pi}{1+\frac{g^2}{4\pi G m_p^2}}\right] \propto a$

  $(\text{light mediator limit } m \ll \hbar/ac)$
- 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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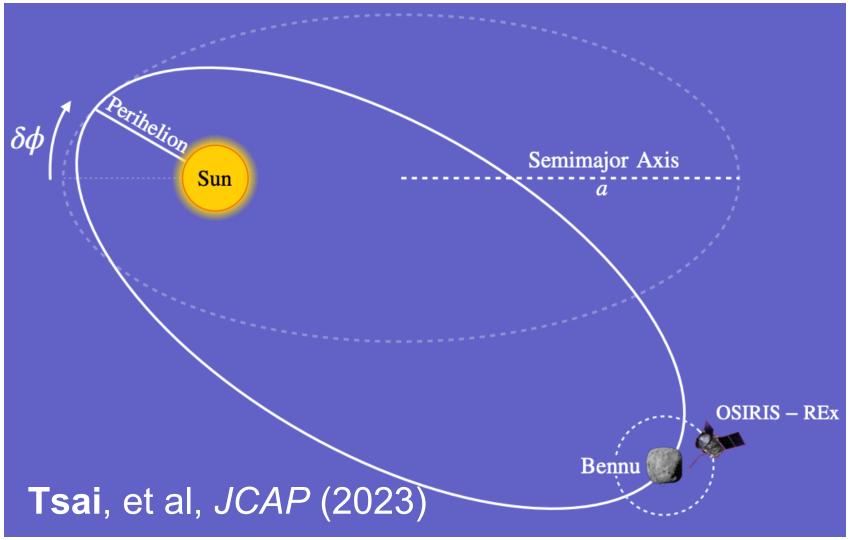
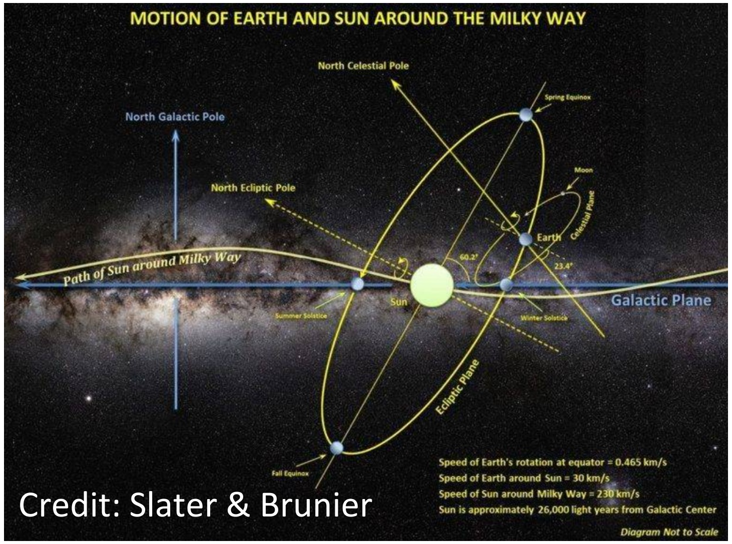
Tsai et al, *Nature Astronomy (2022), JCAP (2022), JCAP (2023)*

Plan Forward: Detect DM Pure Gravitationally



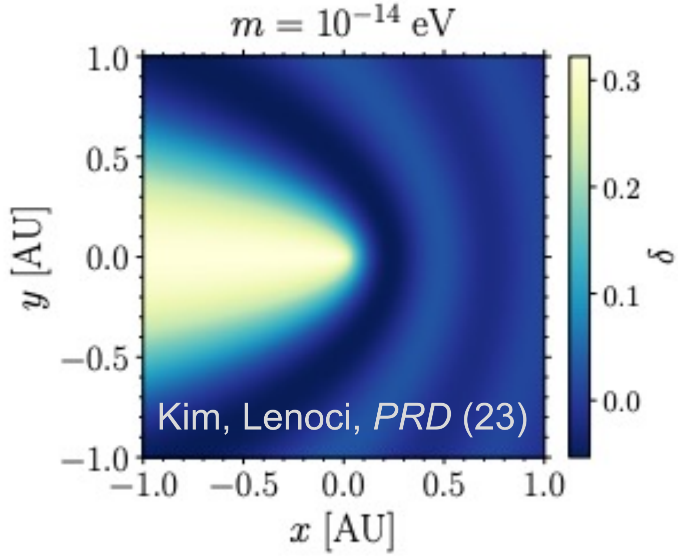
Tsai, et al, *JCAP* (2023)



Credit: Slater & Brunier

Plan

- **Analyze rich asteroidal data**
- **Simulate the over-density predictions**
- **Develop a new, dedicated precision space mission**



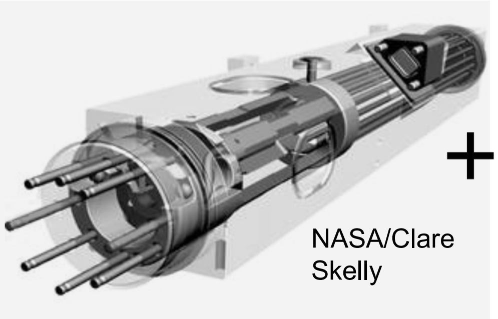
Kim, Lenoci, *PRD* (23)

The "Precision" Frontier

1. **The precise tracking of asteroids with space missions,**
   e.g., OSIRIS-REx is 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**
   Tsai *et al.*, JCAP (2023), 2107.04038 for **hidden fifth forces**

2. **The precise time keeping (e.g., NASA Deep Space Atomic Clock)**

- **lose 1 second every 10 million years**
  Terrestrial clocks can do even better
- **Tsai** *et al., Nature Astronomy* (2022)
  for ultralight dark matter (ULDM) searches



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

Also advance fundamental particle physics.

Quantum Sensors for Wave-Like Dark Matter

Wave-Like Particles as Dark Matter

$$\lambda_{\mathrm{dB}} \equiv \frac{2\pi}{mv}$$

$$N_{\mathrm{dB}} \sim \left(\frac{34\,\mathrm{eV}}{m}\right)^4 \left(\frac{250\,\mathrm{km/s}}{v}\right)^3 \text{ in } \lambda_{\mathrm{dB}}^3$$

- For m << 34 eV, the occupancy number of DM, N_{dB} is so large that the particles are best described by **classical waves**

- Analogous to electromagnetism (EM), large number of photons is described by the classical EM waves

Yu-Dai Tsai (Manchester), yu-dai.tsai@manchester.ac.uk

Oscillation of Wave-like Scalars

$$\boxed{V(\phi) = \frac{1}{2} m_\phi^2 \phi^2} + \frac{1}{3} a_\phi \phi^3 + \frac{1}{4} \lambda_\phi \phi^4.$$

Dark matter potential

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

(Non-relativistic solutions)

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

Oscillation frequency ~ dark matter mass

Yu-Dai Tsai (Manchester), yu-dai.tsai@manchester.ac.uk

Atomic Clocks

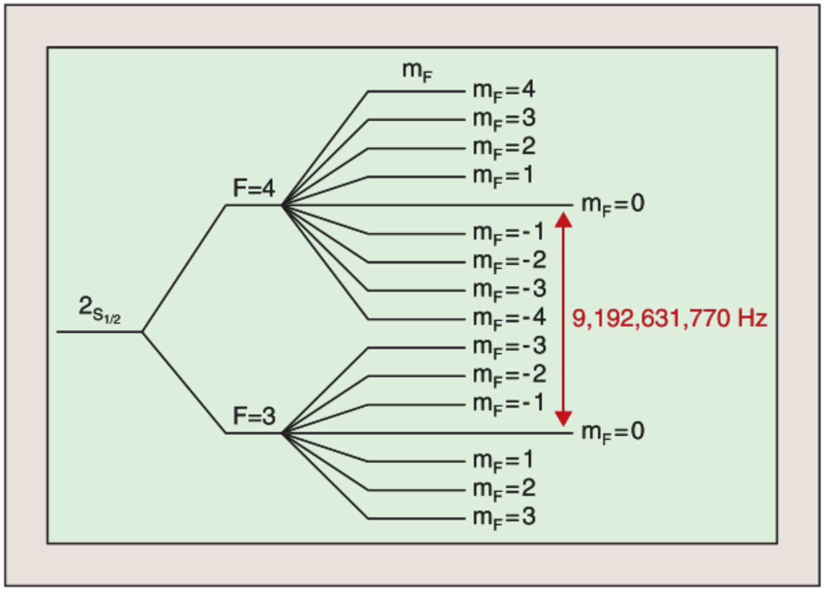
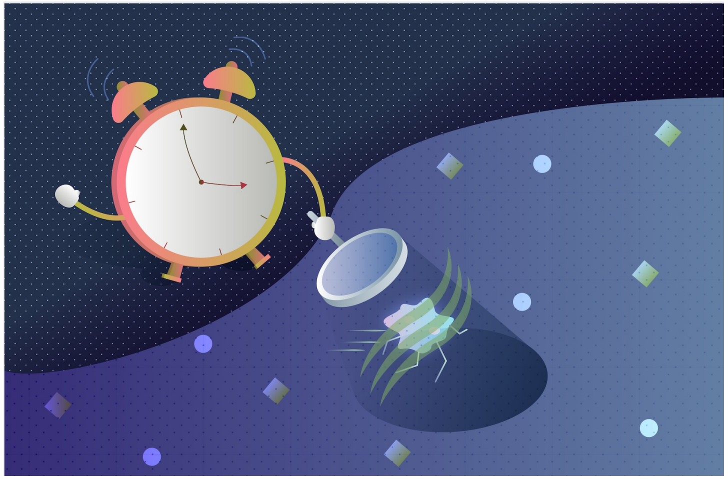


Fig. 1. The cesium clock transition.

M. Lombardi, NIST



Credit: N. Hanacek/NIST

- Cesium atoms absorb microwaves with a frequency of 9,192,631,770 cycles per sec.
- The electronics in the clock can count the cycle; measure a tiny fraction of a second — 1/9,192,631,770 of a second.
- The atomic clocks can measure **frequency of a transition** very precisely.

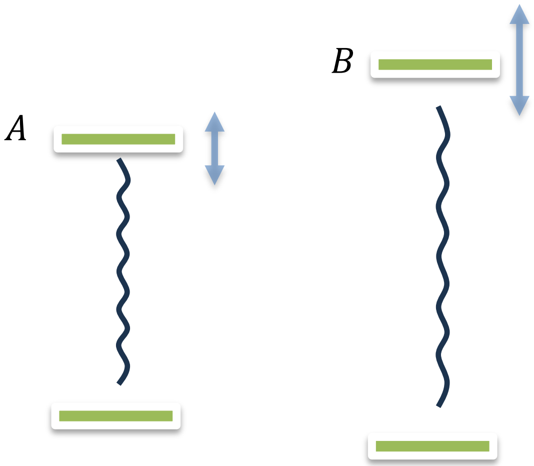
DM Couplings & Atomic-Physics Probes

Here, we consider dark matter only coupling to electron, for simplicity

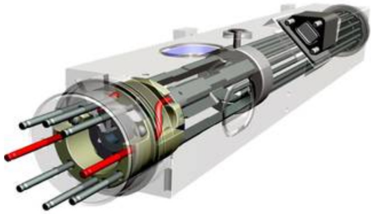
$\mathcal{L} \supset g_e \phi \bar{e} e$ (also couple to photons & gluons, through, e.g., Higgs mixing)

$\mu(\phi) \simeq \mu_0 \left(1 + \frac{g_e}{m_e}\phi(t)\right)$, $\mu = m_e/m_P$: electron-proton mass ratio, 0 is the central value

Consider transition A & B with frequencies being measured by clocks



NASA DSAC & Parker Solar Probe



29 × 26 × 23 cm (17.5 kg)

DSAC/JPL

- **NASA Deep Space Atomic Clock (DSAC)**
  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.

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

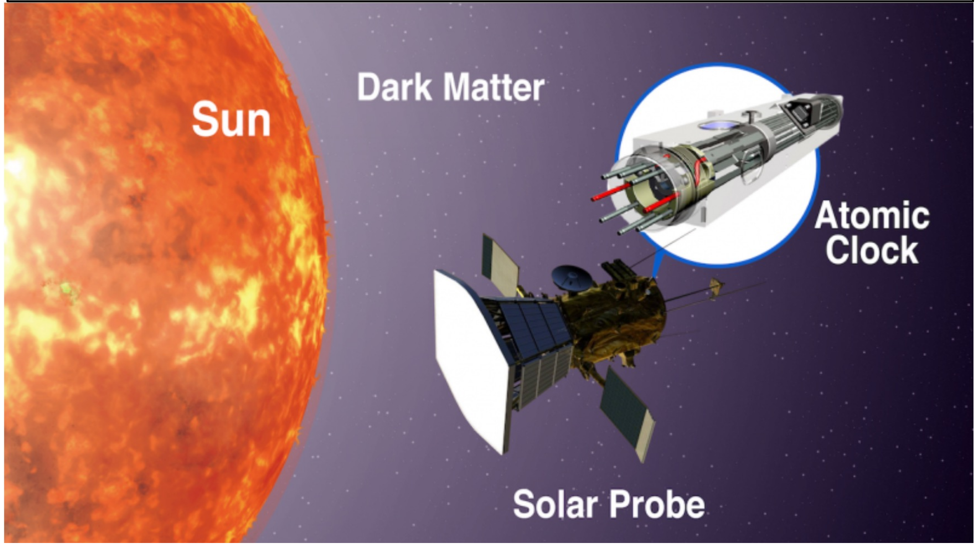
- **Parker Solar Probe (PSP)** ~ $1.5 billion
  see, "Probing the energetic particle environment near the Sun," McComas, William Matthaeus et al, Nature (2019)

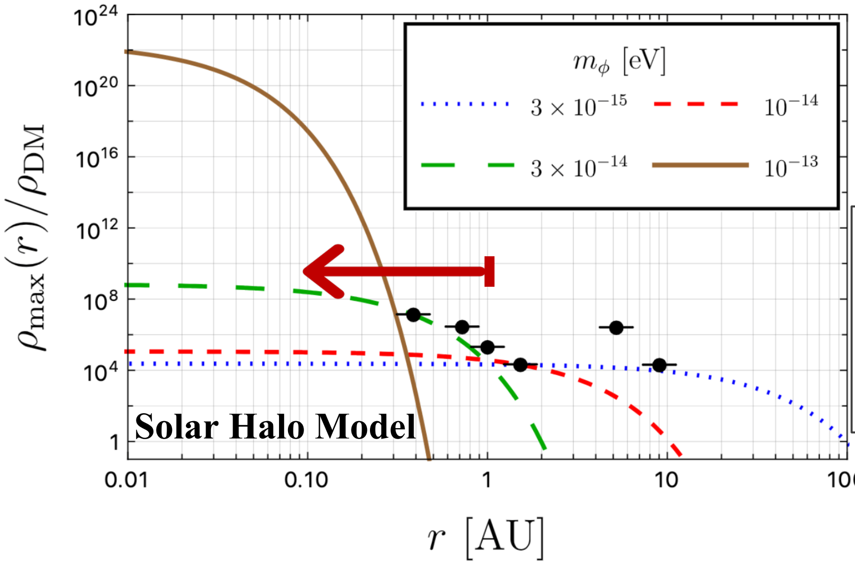
Why don't we put a quantum clocks on a solar probe?

What fundamental physics can we study?

SpaceQ Mission

Tsai, Eby, Safronova, Nature Astronomy (2022)





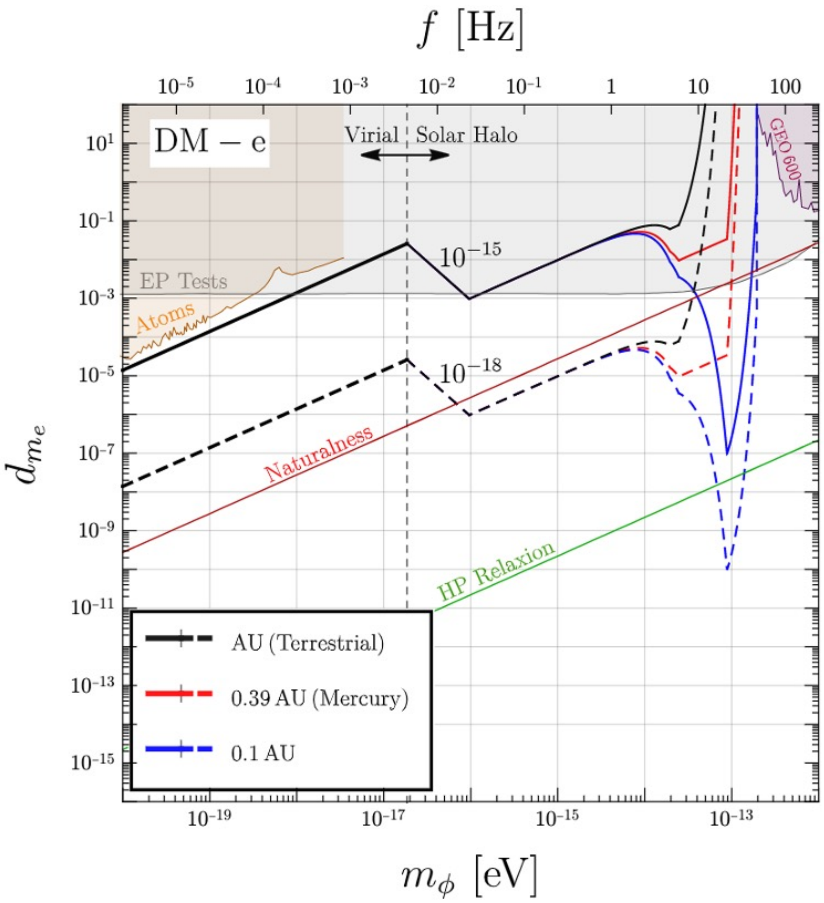
$$\phi(t,\vec{x}) = \phi_0 \cos(m_\phi t - \vec{k}_\phi \cdot \vec{x} + \dots).$$

$\omega \simeq m_\phi.$ (Non-relativistic solution)

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

Projected Sensitivity for Wave-like DM

Tsai *et al.*, Nature Astronomy (2022)



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

AMO convention

Motivate Novel (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.

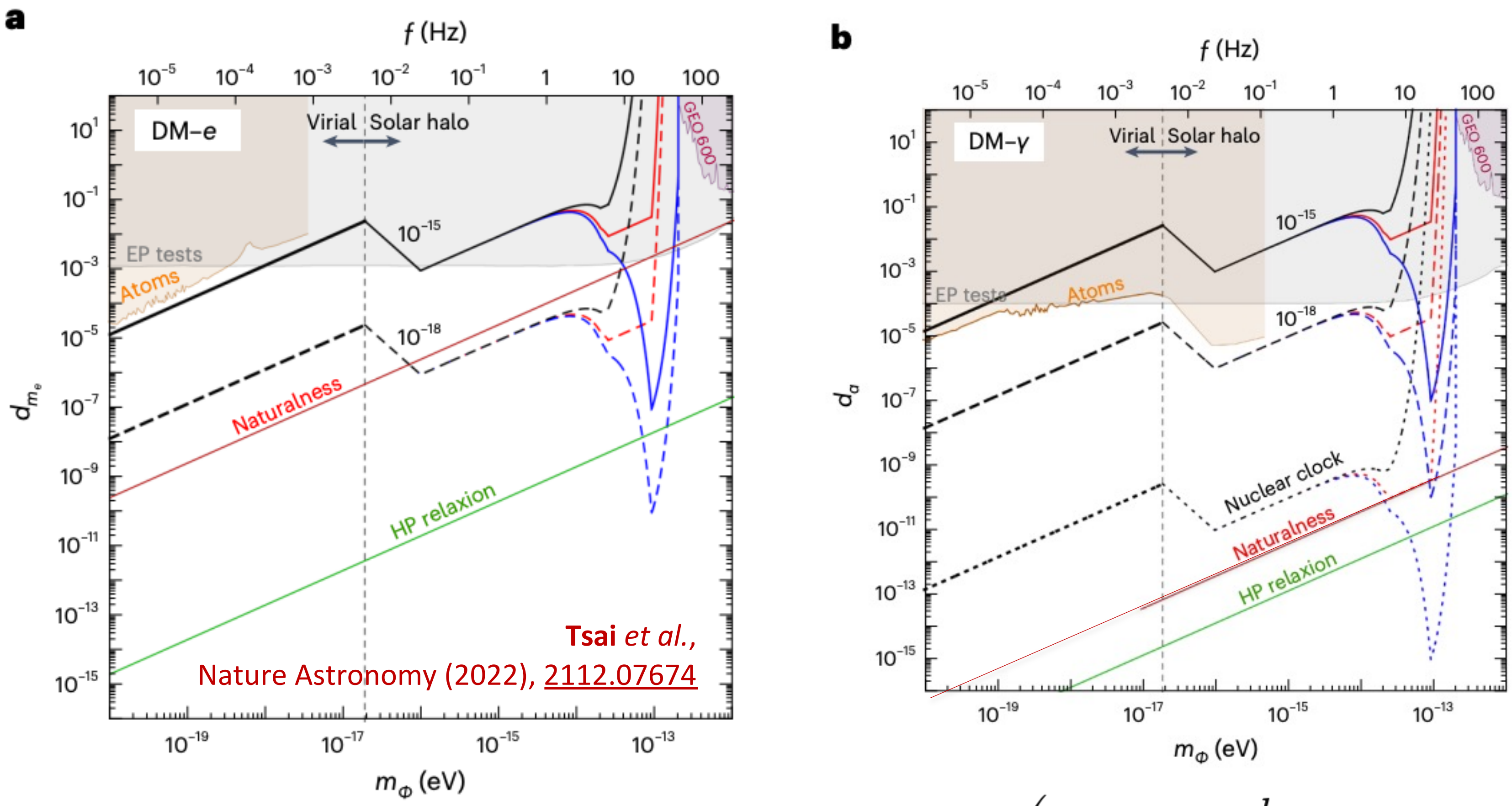
$m_e = 0.511$ MeV is just a normalization.

Naturalness condition:

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

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

Projected Sensitivity for Wave-like DM



Tsai *et al.*,
Nature Astronomy (2022), 2112.07674

Relaxion Parameters:
Graham, Kaplan, Rajendran, *PRL* 15
Flacke, Frugiuele, Fuchs, Gupta & Perez, *JHEP* 17

“Qupiter”: Tsai, Hajkarim, 2504.02039

$$\mathcal{L} \supset \kappa\phi \left(d_{m_e}\, m_e \bar{e} e + \frac{d_\alpha}{4} F_{\mu\nu}F^{\mu\nu} + \ldots \right)$$

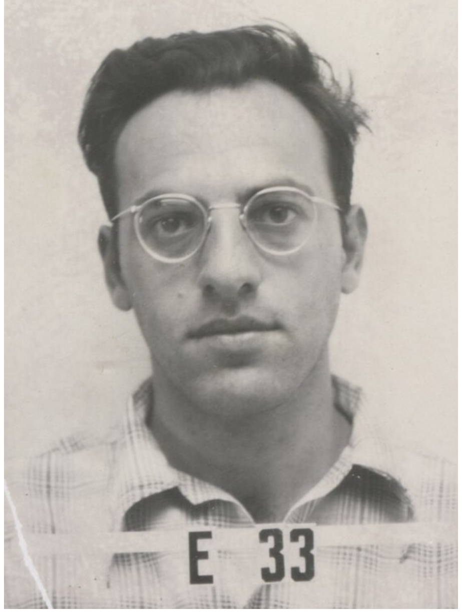
$$\boxed{\frac{g_e^2 \Lambda^2}{(4\pi)^2} \lesssim m_\phi^2, \quad \Lambda = 4\pi v_{EW} \simeq 3\ \mathrm{TeV}.}$$

Naturalness condition

Other Quantum Sensors for Fundamental Physics

- Vijayan et al., “Cavity-mediated long-range interactions in levitated optomechanics,” *Nature Physics* (2023).
- Battye, Garbrecht, McDonald, Pace, Srinivasan, “Dark matter axion detection in the radio/mm-waveband,” *PRD* (2020).
- Aggarwal et al., “Challenges and Opportunities of Gravitational Wave Searches above 10 kHz,” Living Rev Relativ (2025)

Particle DM & Neutrino Properties

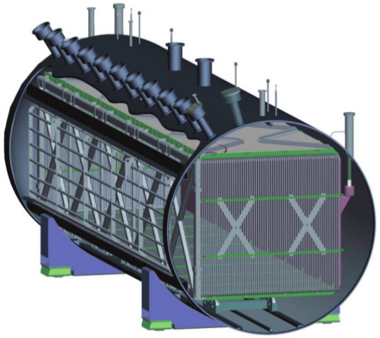


LANL **Division T-1**

“So why did we want to detect the free neutrino? Because everybody said, we couldn't do it."

Particle DM & Neutrino Properties

“So why did we want to detect the free neutrino?
Because everybody said, we couldn't do it.”
-- Frederick Reines



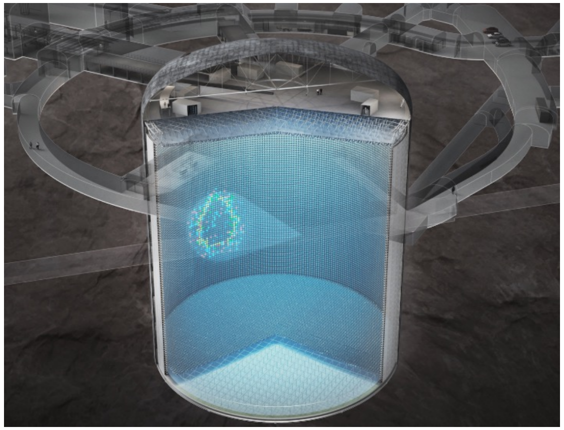
MicroBooNE

Ref: see, e.g., Waiton, Bateman, Evans, Finnerud, Gramellini, Guenette, Guzowski, Kedziora, Soldner-Rembold, arXiv:2509.18859 (Physics Education)

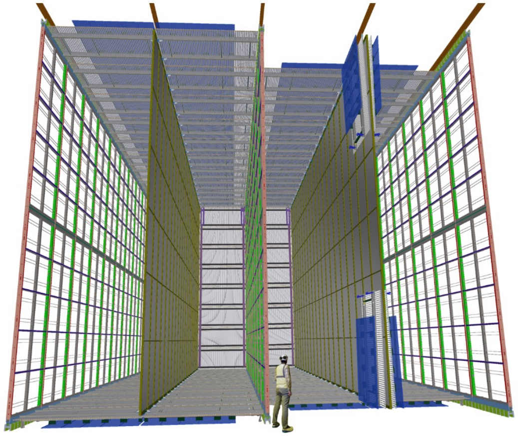
Plestid, Takhistov, **Tsai**+, *PRD* 20, Cui, Kuo, Pradler, **Tsai**, *PRD* 22

DM & Neutrinos in Large Observatories & Detectors

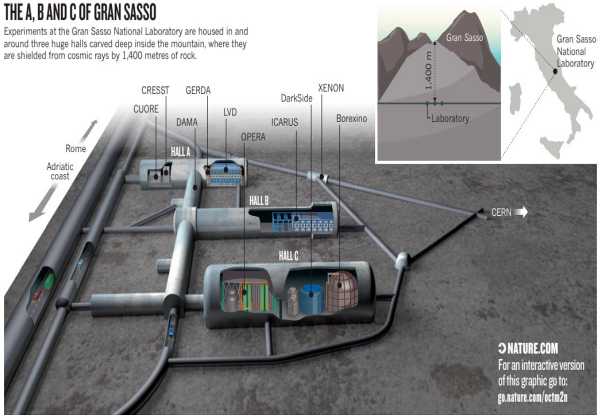
Cosmic-ray productions (or supernova productions)



Hyper-K (Japan)



DUNE (USA)



THE A, B AND C OF GRAN SASSO

Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.

NATURE.COM
For an interactive version of this graphic go to: go.nature.com/octm2n

LNGS (Italy)

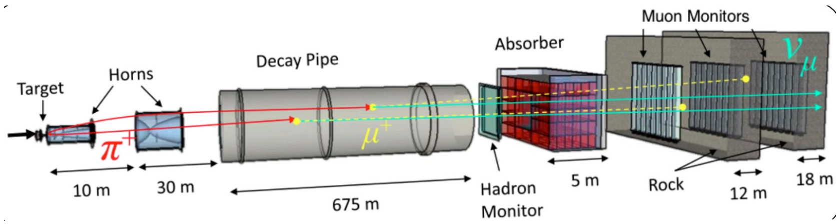
Ref: see, e.g., DarkSide Collaboration (including Price & Sandford), *PRL* (2023).

Credits: all pictures are from the named collaborations & laboratories

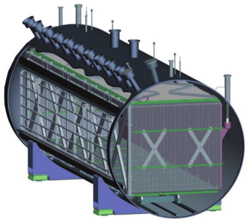
Tsai, et al., *PRL* 21; Argüelles, Hostert, **Tsai**, *PRL* 19

Particle DM & Neutrinos at the Intensity Frontier

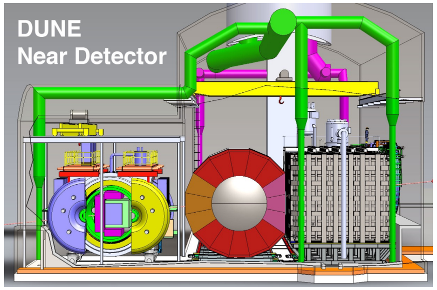
Fixed-Target Facilities: NuMI Beam



Scattering & Decay Studies

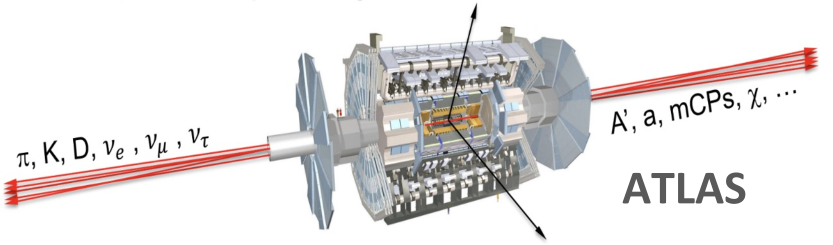


MicroBooNE



DUNE

Forward Collider Productions: LHC



ATLAS

Compact Detectors (I proposed)

FORMOSA at LHC

1) Study various DM scenarios with existing & future data
2) Make the **first detection of neutrino-photon interactions**
Ref: muon neutrino cross-section, FASER, *PRL* (2025).

Credits: all pictures are from the named collaborations

International Collaborations

- **Compact experiments proposed utilizing facilities with different energies and intensities of beams**

Energy

1. **FORMOSA @ LHC, CERN**
   - Abari, Kling, **Tsai**, *PRD 21*
   - Featured on US P5 Summary Report
   - Prototype built. Analyzing data

2. **LongQuest @ Fermilab (120 GeV)**
   - **Tsai**, et al., *Phys. Rev. Lett.* (2021)

3. **LANSCE-mQ @ LANL (800 MeV)**
   - **Tsai** et al., arXiv:2407.07142
   - **Co-I: R&D $165k funding (2025)**
   - A “pathfinder” is taking data

Intensity

Samantha Kelly (PhD Student)

From Theory to Discovery

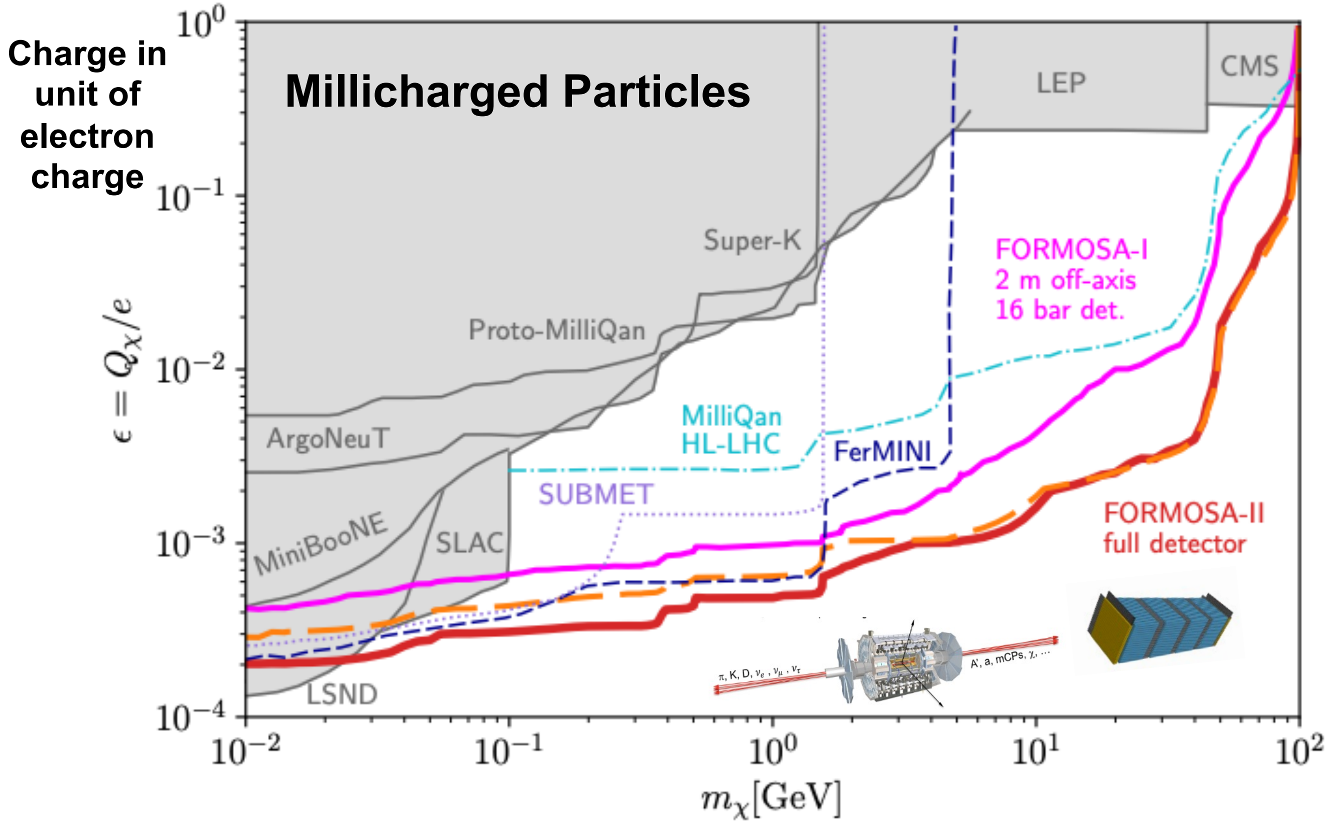
Particle Theory
Models
Simulations

+

Proposals
Experiments
Analyses

➡

Discovery



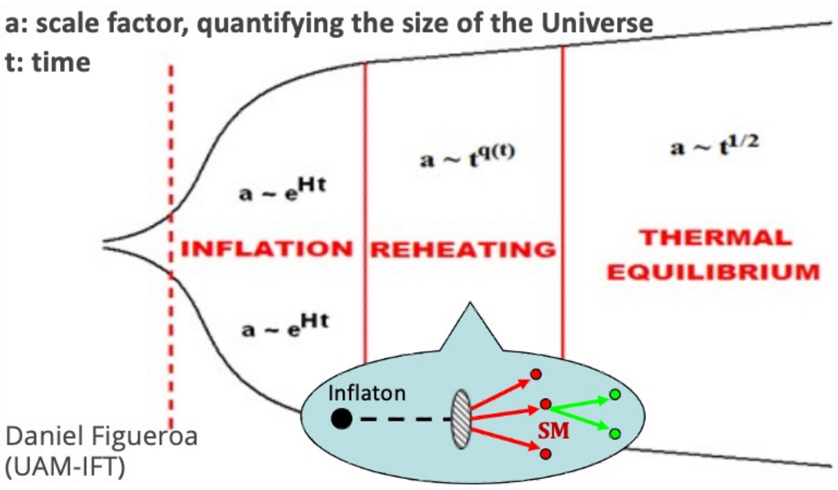
Charge in unit of electron charge

Number Theory in Quantum Physics:
Lee, Takahashi, **Tsai,**
arXiv:2603.12320

"Theory Review of Millicharged & Fractionally Charged Particles"
Planned review for Progress in Particle and Nuclear Physics (PPNP)

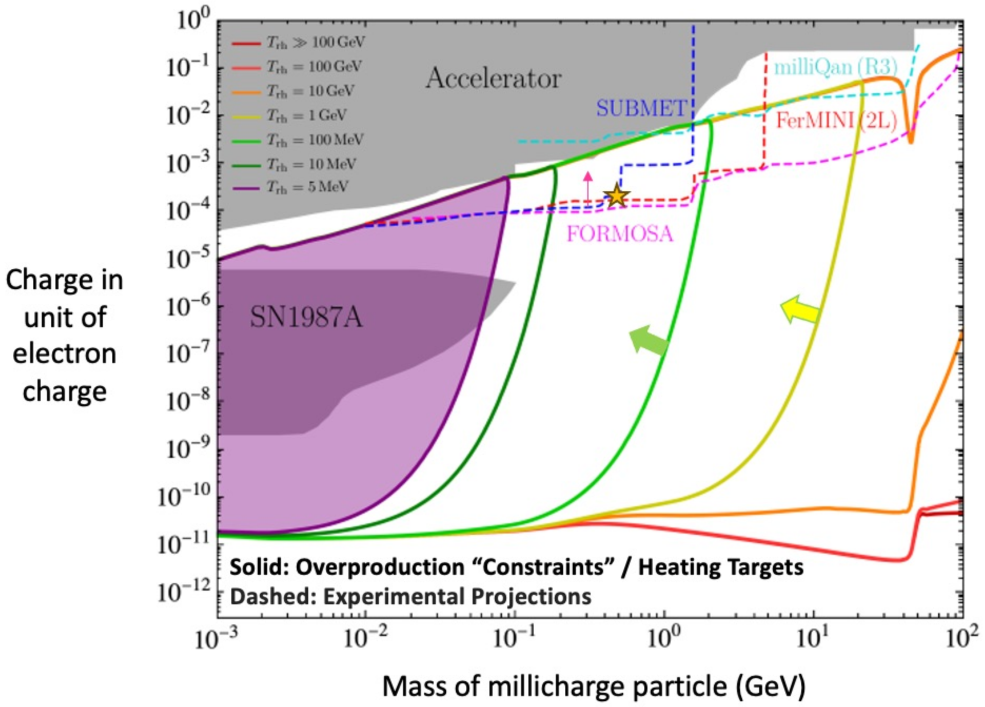
Gan, **Tsai**, *JHEP* 25, arXiv:2308.07951

Connecting Searches to Reheating Cosmology

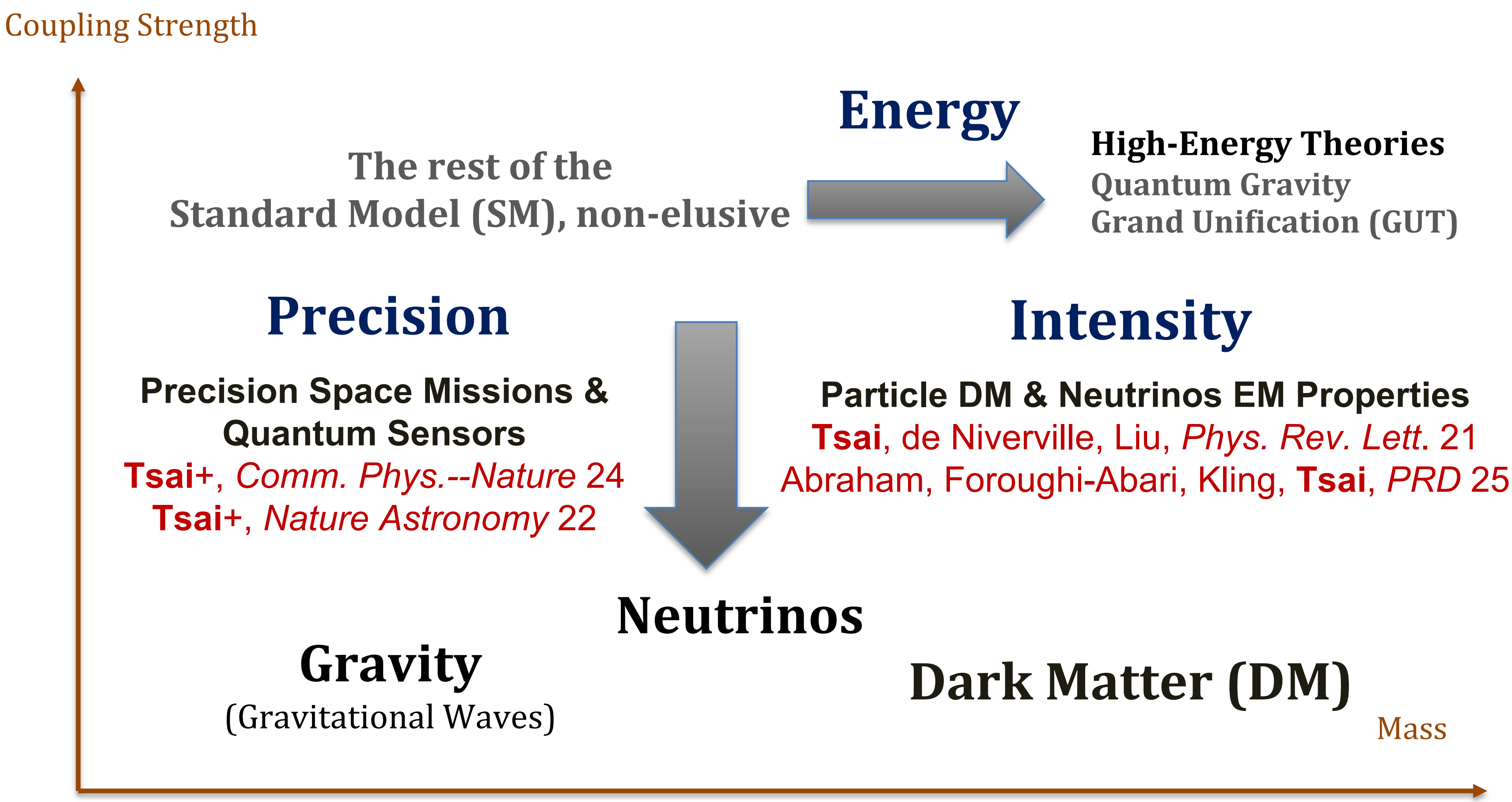


$$T_{\rm GUT}(\sim 10^{16}\,{\rm GeV}) \gtrsim T_{\rm rh} \gtrsim T_{\rm BBN}(\sim {\rm MeV})$$

Cosmic Millicharge Background



New Probes of the Elusive Universe



Coupling Strength

Energy

The rest of the
Standard Model (SM), non-elusive

High-Energy Theories
Quantum Gravity
Grand Unification (GUT)

Precision

Precision Space Missions &
Quantum Sensors
Tsai+, *Comm. Phys.--Nature* 24
Tsai+, *Nature Astronomy* 22

Intensity

Particle DM & Neutrinos EM Properties
Tsai, de Niverville, Liu, *Phys. Rev. Lett*. 21
Abraham, Foroughi-Abari, Kling, **Tsai**, *PRD* 25

Neutrinos

Gravity
(Gravitational Waves)

Dark Matter (DM)

Mass

Very exciting parallel program analyzing cosmological data

A comprehensive effort is crucial in exploring the Elusive Universe