SpaceQ – Direct Detection of Ultralight Dark Matter with Space Quantum Sensor

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- **https://arxiv.org/abs/2112.07674, Nature Astronomy (2022)**
- **https://arxiv.org/abs/2107.04038, under review by NA**
- **https://arxiv.org/abs/2210.03749 , under review by NA**
- **INSPIRE: https://inspirehep.net/authors/1274923**

Image: Parker Solar Probe
Credit: NASA/Johns Hopkins APL/Steve Gribben

Collaborations on Various Projects

UNIVERSITY OF DELAWARE

ASU

NASA

KAVLI IPMU

- **Quantum technologies in Space: Q-SEnSE + SpaceQ informal meeting**

Big Questions

- Can planetary data set meaningful constraints on
  Dark matter?
  General Relativity?
  5th forces?

- Can we use current or future **Space Quantum Technologies** to study fundamental physics?

Answers

- Can planetary data set meaningful dark matter constraints?
  General Relativity?
  5th forces?
  Yes! Many opportunities

- Can we use current or future space Quantum Technology to study fundamental physics? **Yes! I will show you an example today.**

Outline

- New Technologies & Ultralight Dark Matter
- Space Quantum Clocks & Sensitivity
- Model-Independent Constraints on Dark Matter & Cosmic Neutrinos: Rubin + Einstein!

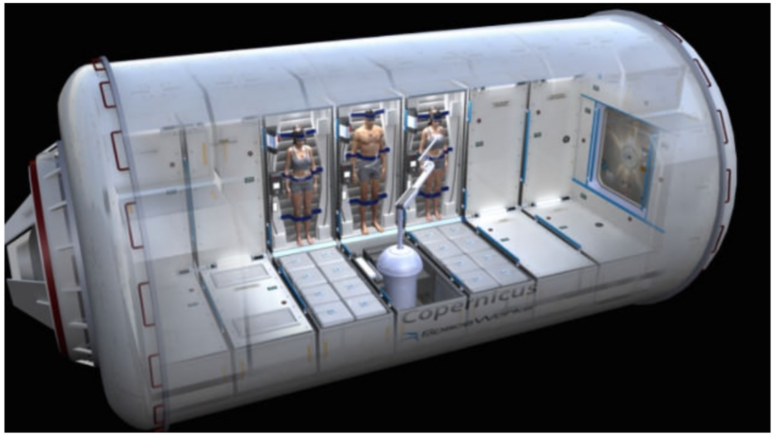
Bridging Planetary Science, Space/Quantum Technologies, and Fundamental Physics

Many real-life applications & consequences!

Sun Devils / Anteaters - Starship

Why Space Quantum Clocks?
Auto-Navigating Spacecraft & Space Travel


NASA Kennedy Space Center's Visitor Complex (Public Domain)

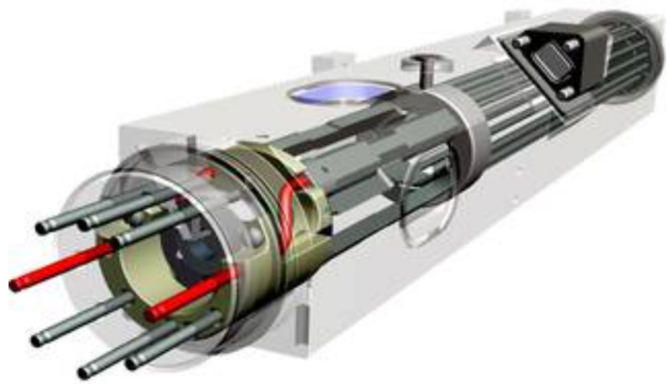

Artist's concept for Mars-ready habitat. Image Credit: SpaceWorks Torpor/NASA collaboration

Exploring the deep space: **auto-driving Spacecraft; needs precision timing!!!**

NASA Deep Space Atomic Clocks (current technology!) & Deep space and global navigation satellite system (GNSS)

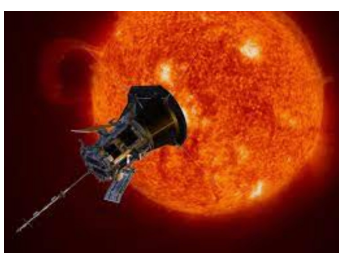
Can we use the technology to study fundamental physics?

NASA DSAC & Parker Solar Probe



- **Deep Space Atomic Clock loses one second every 10 million years**, as proven in controlled tests on Earth.
- The clock has operated for more than **12 months in space; demonstrated long-term fractional frequency stability of 3×10^{-15}**
  Burt, Prestage, Tjoelker, Enzer, Kuang, Murphy et al., Nature 595 (2021) 43.

- Exceeds previous space clock performance by up to an order of magnitude



(1.0 m × 3.0 m × 2.3 m)

Parker Solar Probe
Kasper, Klein, Lichko, Huang, Chen, Badman et al.,
Parker solar probe enters the magnetically dominated solar corona, Phys. Rev. Lett. (2021)

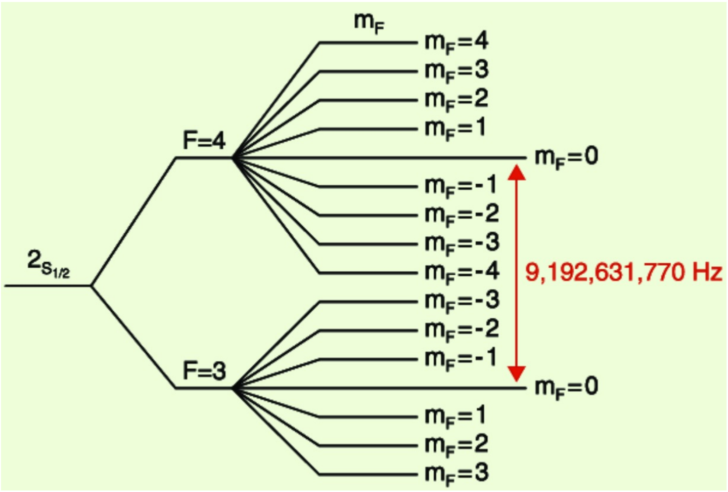
- **Why don't we put a quantum clock on a solar probe? What can we do with that?**

Atomic Clock & Caesium Standard

- Atomic clocks: used to measure the distance between objects by timing how long it takes a signal to travel from A to B.

- For space exploration, clocks must be extremely precise:

- **An error of even one second can mean the difference between landing on Mars or missing it by hundreds of thousands of miles.**



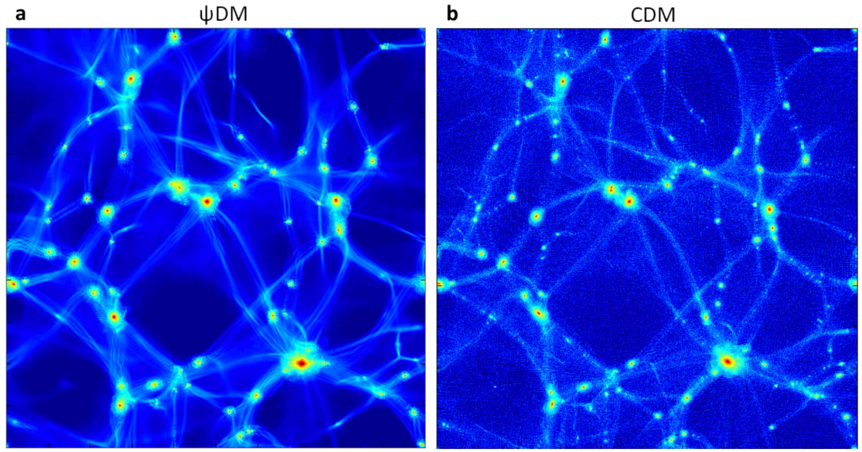
Definition of a second!

http://hyperphysics.phy-astr.gsu.edu/hbase/acloc.html
Reference: U.S. Naval Observatory, Cesium Clocks

Wave-Like (Fuzzy) Particles as Dark Matter

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

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



Schive, Chiueh, Broadhurst, Nature Physics '14
arXiv:1406.6586,

- For ultralight m << 30 eV, the occupancy NdB is so large that the particles are best described by classical waves
- like electromagnetism, a state with a large number of photons is described by the classical EM fields.
- It would consist of extremely light scalar particles with masses go **as low as 10^{-22} eV (rough lower bound)**:
  de Broglie wavelength λ ~ 1kpc: affect **structure formation.**

Oscillation of Wave-like Scalars

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

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

Dark Matter Coupling

Electrons photons gluons

$$\mathcal{L} \supset \kappa\phi \left(d_{m_e} m_e \bar{e} e + \frac{d_\alpha}{4} F_{\mu\nu} F^{\mu\nu} + \frac{d_g \beta_3}{2 g_s} G^A_{\mu\nu} G^{A\mu\nu} \right), \quad (1)$$

Dark Matter

where e is the electron field, $F^{\mu\nu}$ ($G^{A\mu\nu}$) is the electromagnetic (QCD) field strength, g_s and β_3 are the strong interaction coupling constant and beta function (respectively), and $\kappa = \sqrt{4\pi}/M_P$ with $M_P = 1.2 \times 10^{19}$ GeV.

Atomic Physics Probe

$$\mathcal{L} \supset \kappa\phi \left(d_{m_e} m_e \bar{e}e + \frac{d_\alpha}{4} F_{\mu\nu}F^{\mu\nu} + \frac{d_g\,\beta_3}{2g_s} G^A_{\mu\nu}G^{A\mu\nu} \right), \quad (1)$$

$$\mu(\phi) \simeq \mu_0 \left(1 + d_{m_e}\kappa\phi\right), \quad \alpha(\phi) \simeq \alpha_0 \left(1 - d_\alpha \kappa\phi\right)$$
$$\alpha_s(\phi) \simeq \alpha_{s,0} \left(1 - \frac{2d_g\beta_3}{g_s}\kappa\phi\right), \quad (2)$$

where $\mu = m_e/m_p$ is the electron-proton mass ratio, and the subscript $_0$ denotes the central (time-independent) value of μ, α, and α_s.

Atomic Probe Basics

$$\mathcal{L} \supset \kappa\phi \left(d_{m_e} m_e \bar{e}e + \frac{d_\alpha}{4} F_{\mu\nu}F^{\mu\nu} + \frac{d_g\,\beta_3}{2g_s} G^A_{\mu\nu}G^{A\mu\nu} \right), \tag{1}$$

Turning off d_{m_e} and d_g for demonstrations,

$f_A \propto \alpha^{\xi_A+2}$, f is the frequency of a (clock) transition.

$$\alpha = \alpha_0(1 + d_\alpha \kappa\phi(t)).$$

$$\frac{\delta(f_A/f_B)}{f_A/f_B} \simeq (\xi_A - \xi_B) d_\alpha \kappa\phi(t).$$

- **Experimental observable!** See arXiv:1405.2925, Arvanitaki, Huang, Tilburg, PRD 15
- For example, if **A is a hyperfine microwave transition and B is an electronic optical transition, ζA = 1 and ζB = 0.**
- Clock ($\sim$ **10^{-15} for DSAC**) stability translate to how well we can measure $\frac{\delta(f_A/f_B)}{f_A/f_B}$

Solar Bound-State Halo

An example of DM overdensity

Yu-Dai Tsai, UC Irvine, '22
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Scalar DM Halo

Stable solution can be supported by external potential

$$V_{\text{ext}} = \begin{cases} -\dfrac{G\, m_\phi\, M_{\text{ext}}}{r} & \text{for } R_\star > R_{\text{ext}}\,, \\ -\dfrac{3\, G\, m_\phi\, M_{\text{ext}}}{2\, R_{\text{ext}}} \left[1 - \dfrac{1}{3}\left(\dfrac{r}{R_{\text{ext}}}\right)^2\right] & \text{for } R_\star \le R_{\text{ext}}\,, \end{cases}$$

$$\rho(r) \simeq \rho_\star \exp\left(-2r/R_\star\right), \quad \text{for } R_\star > R_{\text{ext}}$$

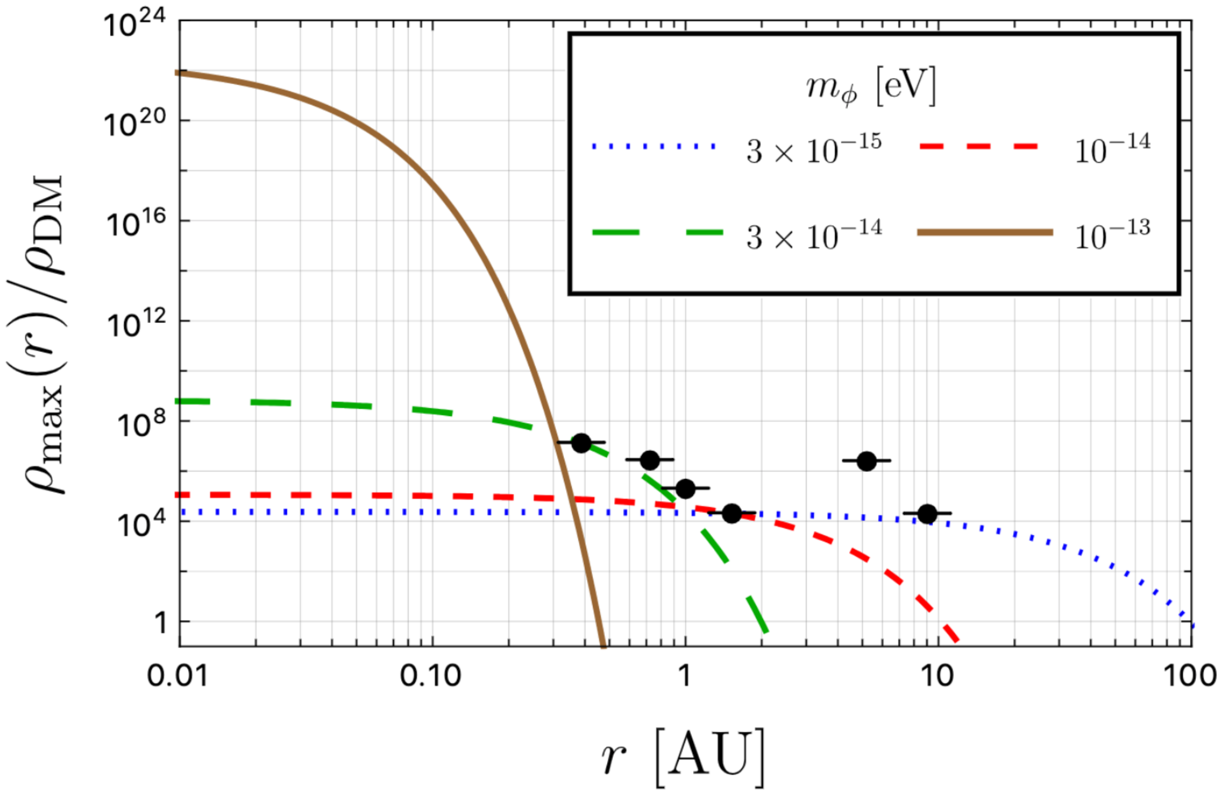
$$R_\star \simeq \frac{M_P^2}{M_{\text{ext}}\, m_\phi^2},$$

where $M_{\text{ext}} = M_\odot$ is the mass of the external host body; note that $R_\star$ is independent of the total mass in the halo

$$v_\star = (m_\phi\, R_\star)^{-1},$$

Banerjee, Budker, Eby, Flambaum, Kim, Matsedonskyi, and Perez, 1912.04295

Dark matter in solar system? **Planetary constraint!**



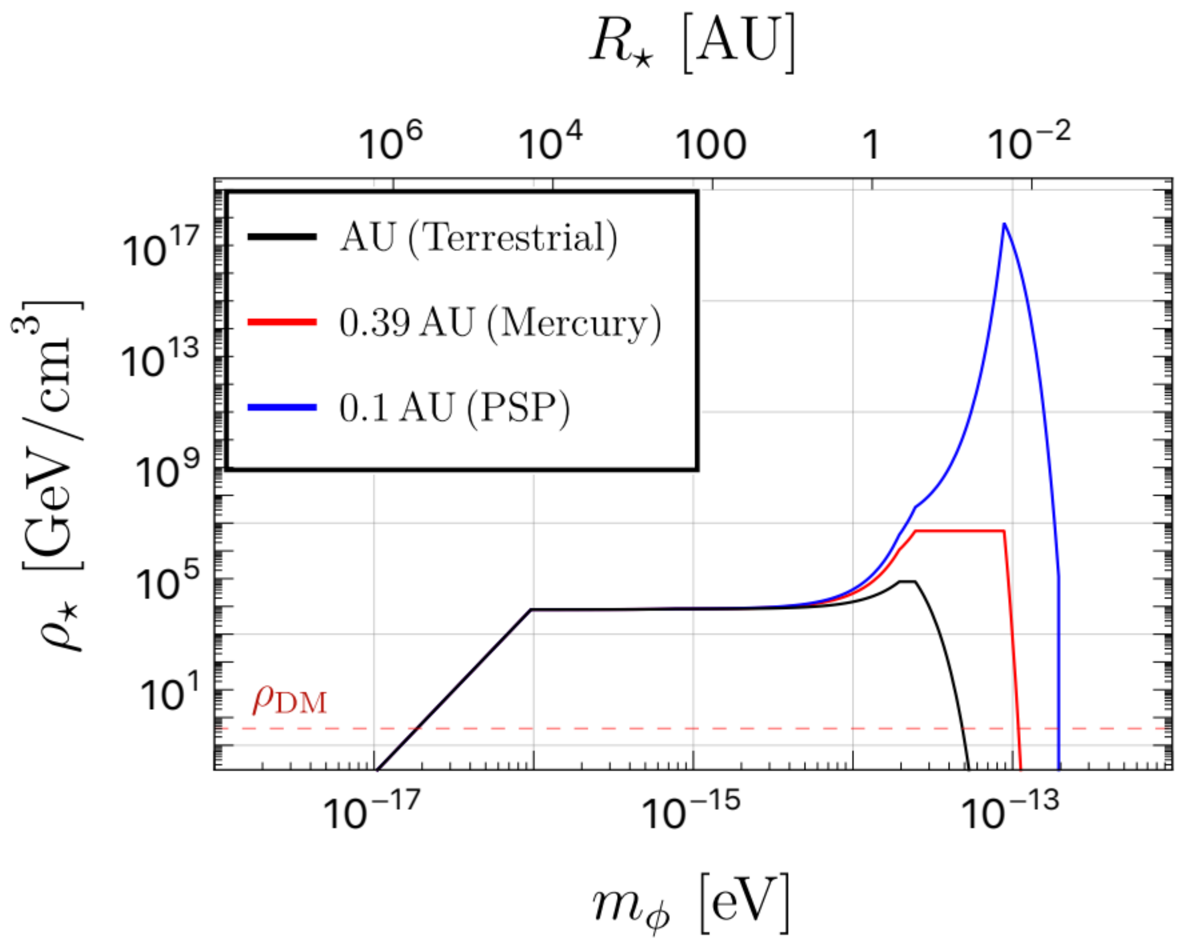
- **Black data points are model-independent constraints!**
- **Dark matter induce precessions to the planets**

Mercury, Venus, Earth, Mars, Jupiter, Saturn

Pitjev, Pitjeva, 1306.5534, Astronomy Letters ’13

Tsai, Eby, Safronova, 2112.07674

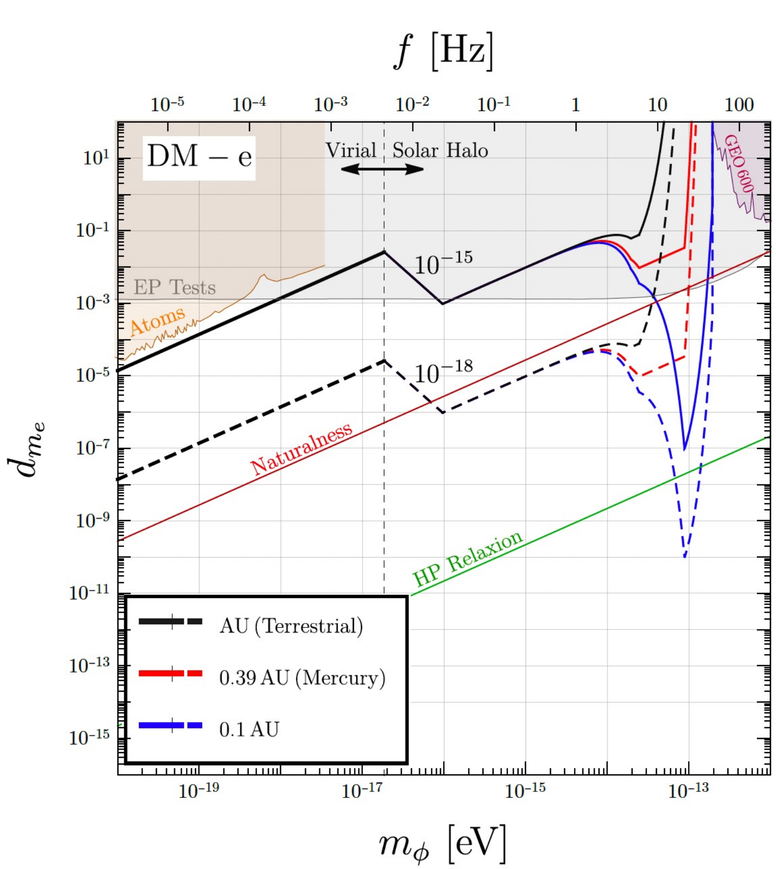
Enhancement of the DM Density

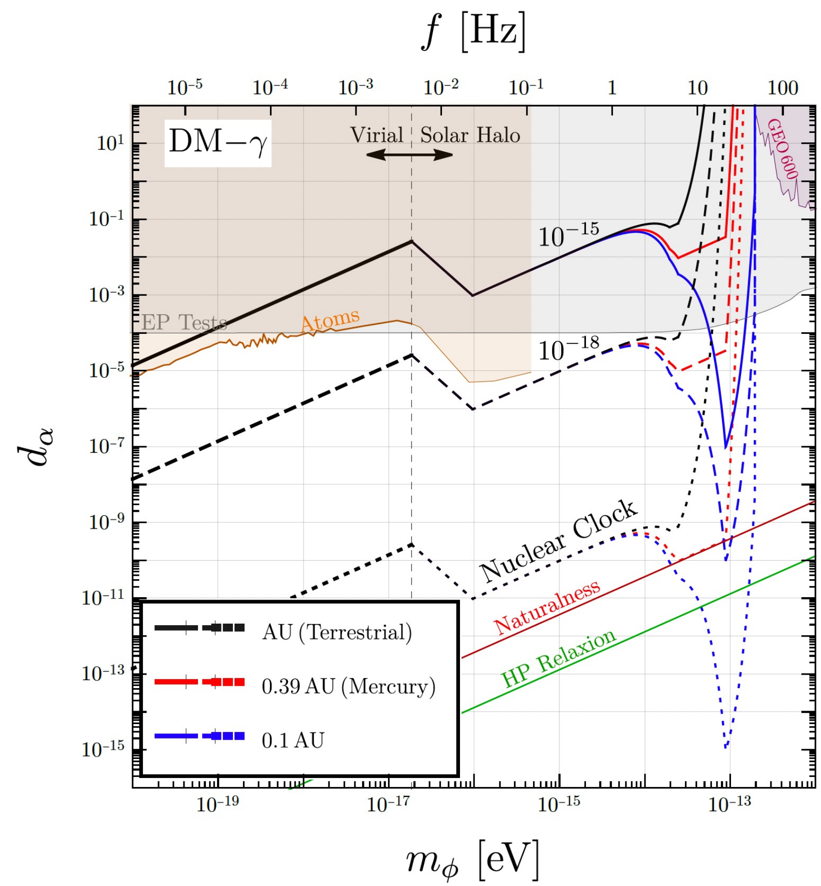


PSP: Parker Solar Probe

Tsai, Eby, Safronova, arXiv:2112.07674

Results





- Motivate **Specific Frequency Region!**
- Motivate **Nuclear Clocks!**
- **Tsai**, Eby, Safronova, arXv:2112.07674, Nature Astronomy (2022)

$$\mathcal{L} \supset \kappa\phi \left(d_{m_e} m_e \bar{e} e + \frac{d_\alpha}{4} F_{\mu\nu} F^{\mu\nu} + \frac{d_g\, \beta_3}{2 g_s} G^A_{\mu\nu} G^{A\mu\nu} \right), \quad (1)$$

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

Naturalness condition

Spatial Variation of Fundamental Constants

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

δU: change in gravitational potential .

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

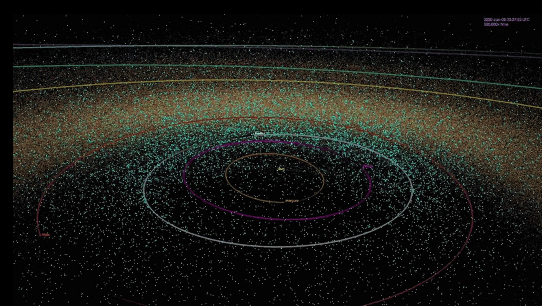
$\delta U/c^2 \sim 9 \times 10^{-8}$, from Earth to Solar probe at 0.1 AU.

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

New Directions at Precision Frontier

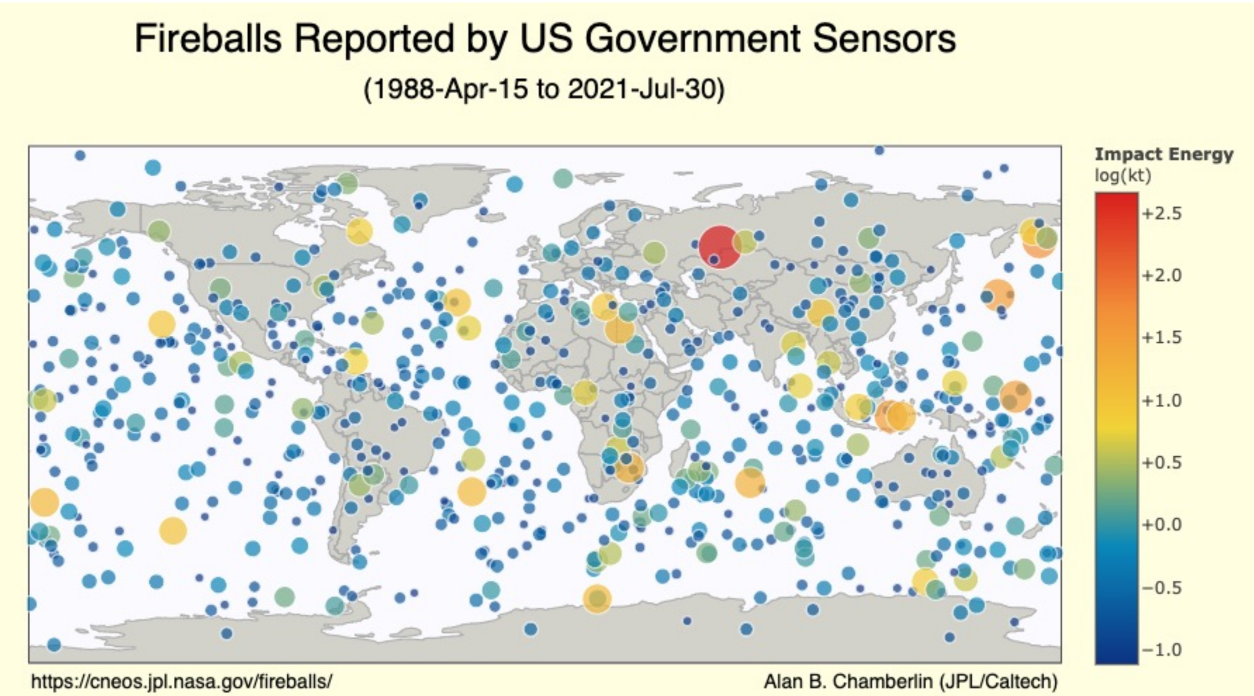
- Planetary Defense & Dark Matter:
  Model-Independent Probes of **Any** Dark Matter Candidates
  (especially purely gravitational dark matter)

Vera Rubin
Carnegie Institution for Science



Albert Einstein
Mount Wilson Observatory, California

Asteroids hitting the Earth



~~Don't~~ Please Look Up

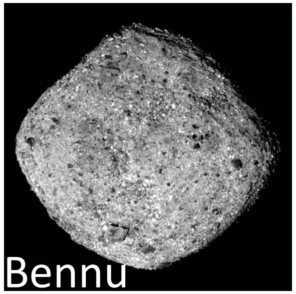
~ 65 million years ago

Tracking asteroids is extremely important

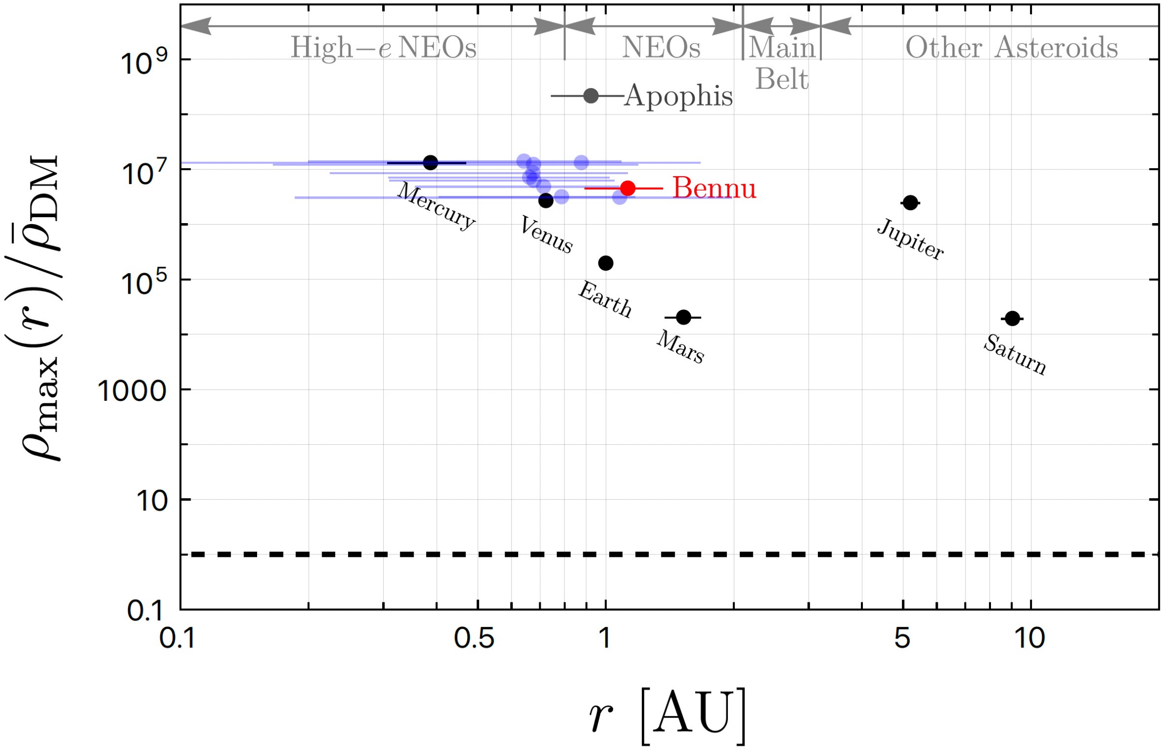
e.g., unexpected 2013 Chelyabinsk meteor injured >1500 people

Also, near-Earth asteroid search accidentally found 'Oumuamua

New Project: New Model Independent Constraints!

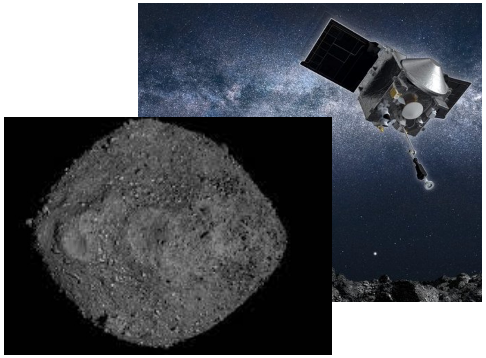


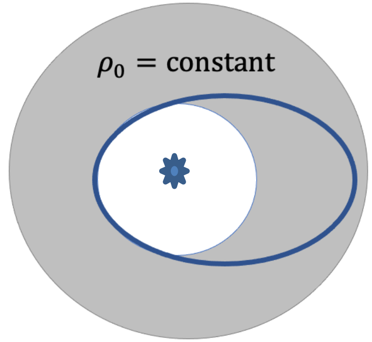
A dangerous asteroid;
NASA/Goddard/University of Arizona



Tsai, Farnocchia, Eby, Arakawa, Safronova, arXiv:2210.03749
Obtained results from NASA JPL Sentry-II code & OSIRIS-Rex+ data
Can be applied to ideas like Solar-Basin & Axion Mini-cluster (more refs in paper)

Astrometric Probe of the DM Gravity (and Cosmic Neutrinos!)

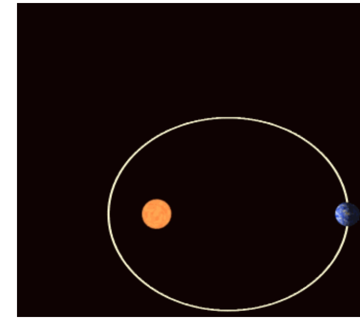




DM Gravitational Force

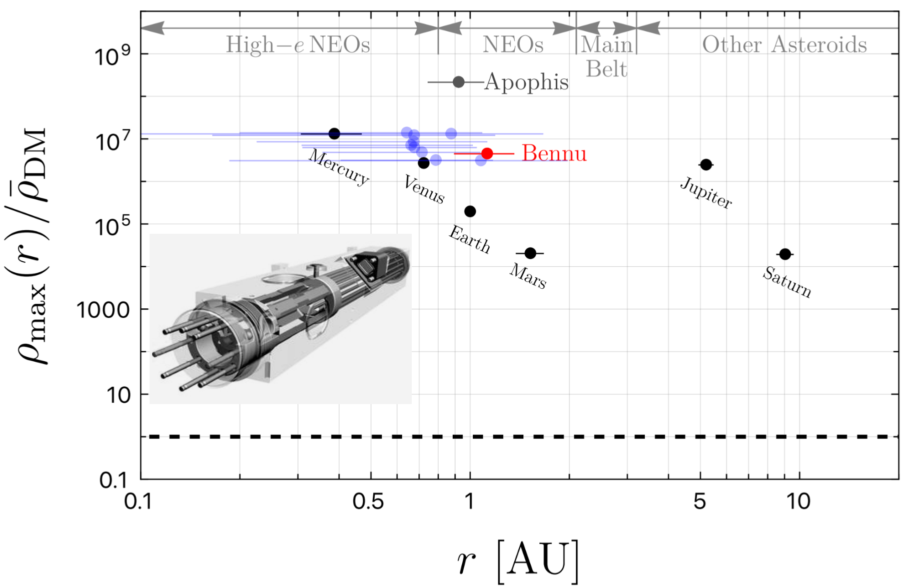
$$F(r) = \frac{2\pi}{3} G m \rho_0 \left(\frac{2 r_0^3}{r^2} - 2r \right) \hat{\mathbf{r}}$$

$$\simeq -\frac{4\pi}{3} G m \rho_0 r \hat{\mathbf{r}} \quad + \ldots$$



Highly exaggerated eccentricity

Collaborate with NASA expert, Davide Farnocchia, to derive the bounds



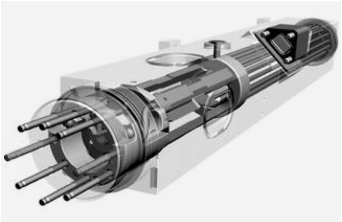
- **New bounds on local DM profile from gravity** (applicable to all models, but most meaningful for **solar bound halo**, **axion mini-cluster, solar basin**, etc.)

To reach usual **galactic DM density** $\overline{\rho}_{DM}$ = 0.3 GeV/cm^3

1. **Quantum sensor** (e.g., NASA DSAC) can improve the result
2. Can consider **DM-SM long-range interaction**, only 4-order stronger than gravity

Probing Fundamental Physics with Solar-System Study & Quantum Sensors

- **Space quantum sensor to study solar bound dark matter,**
  Tsai, Eby, Marianna, arXiv:2112.07674
  to appear on Nature Astronomy



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- **Pure Gravitational Constraints on Dark Matter & Cosmic Neutrino Profiles**
  Tsai et al., arXiv:2210.03749

- **My outreach interview on this topic gathered > 77 K views worldwide! Click link below:**
  https://www.youtube.com/watch?v=xDX9XwLHBuM

Millions of objects to study

LSST can increase the observed objects by a factor of 5-10.

- **GR/Modified Gravity (inc. Dark Energy models)**
- **Gravitational Waves**
- **Fifth Forces,**
  Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038
- **Primordial Black Holes**
- **Topological Defects**

Let’s protect the Earth & find dark matter;
happy to discuss more

Thank you!

Thank Josh, Marianna, Luca, Sunny, Youjia for comments

Outreach / interview:
https://www.youtube.com/watch?v=xDX9XwLHBuM

Yu-Dai Tsai, UC Irvine, yt444@cornell.edu / yudait1@uci.edu

I also work on …

- Fixed-target searches for dark matter & long-lived particles (FerMINI & LongQuest) with Pospelov et al.
- LHC Forward Experiments: Forward Physics Facility, FORMOSA (a millicharge experiment I proposed), with Feng et al.
- Dark matter model building (dark sector QCD, Strongly Self-Interacting Dark Matter, SIMP/ELDER), with Murayama, Slatyer, Perelstein et al.
- Dark matter searches using neutron star / compact merger / multi-messenger astronomy, with Profumo, Sathyaprakash et al.
- Neutrino physics (cosmic neutrino background) & neutrino BSM, with Shoemaker et al.
- My works on Inspire HEP & my outreach interview (> 76K views!)

More References

- Seto, Cooray, arXiv:0405216, PRD 04
- LLR Experiments: Williams, Turyshev, Boggs, PRL 04
  Murphy , Rept. Prog. Phys 13
- Atomic / nuclear clocks for fundamental physics:
  Peik, Schumm, Safronova, Pálffy, Weitenberg, Thirolf, 2012.09304
- GW background, Fedderke, Graham, Rajendran, PRD21
- Quantum Technologies in Space, Kaltenbaek, Exp Astron 21