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

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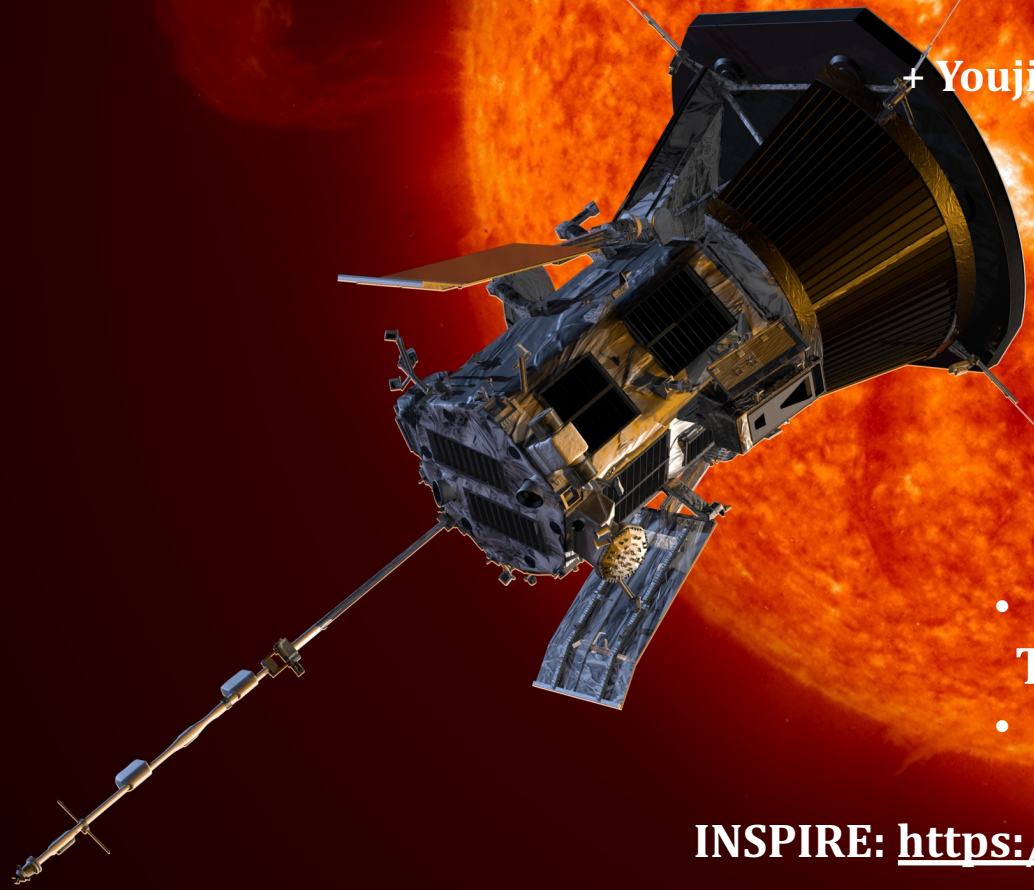


- **https://arxiv.org/abs/2112.07674**
  To appear on Nature Astronomy!
- **https://arxiv.org/abs/2107.04038**
  Under review by Nature Astronomy

INSPIRE: https://inspirehep.net/authors/1274923

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

Collaborations on Various Projects

- **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?

- Clustering mechanisms of purely gravitational dark matter or cosmic neutrinos?

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
- Constraints on Fifth Forces

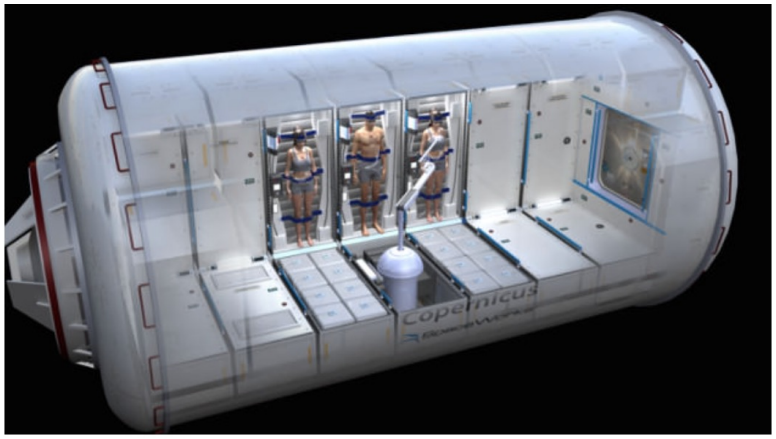
Bridging Planetary Science, Space/Quantum Technologies, and Fundamental Physics

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)

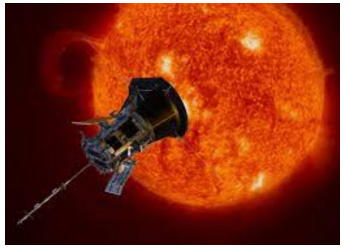
Can we use the technology to study fundamental physics?

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)

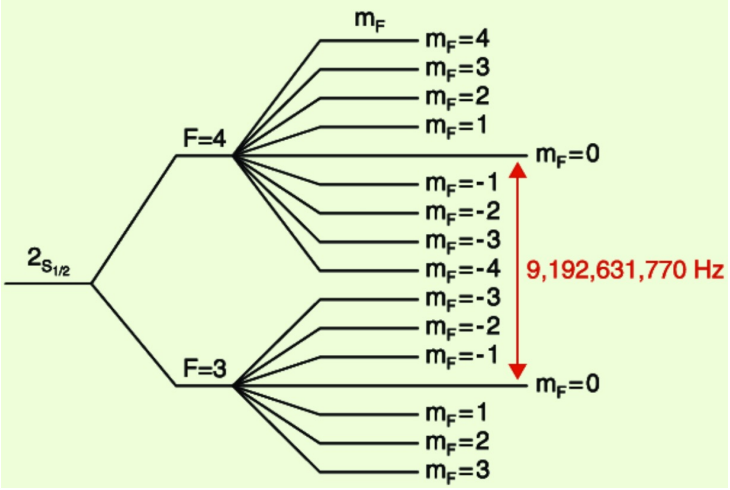
Parker Solar Probe

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.**



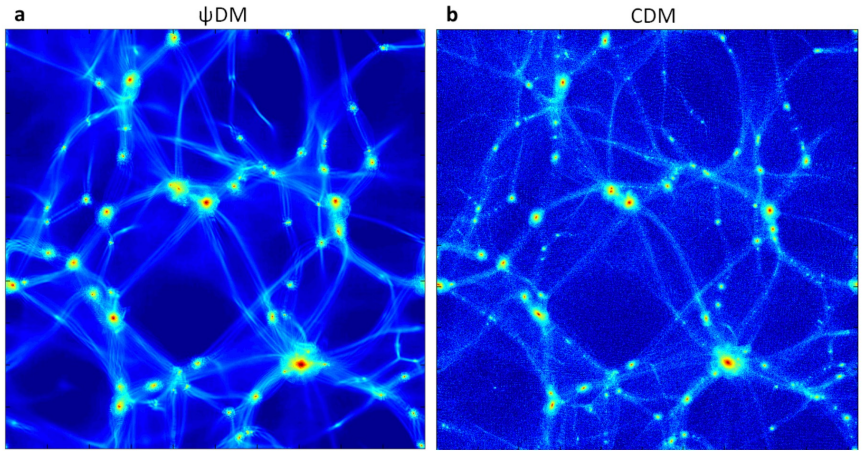
Definition of a second!

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

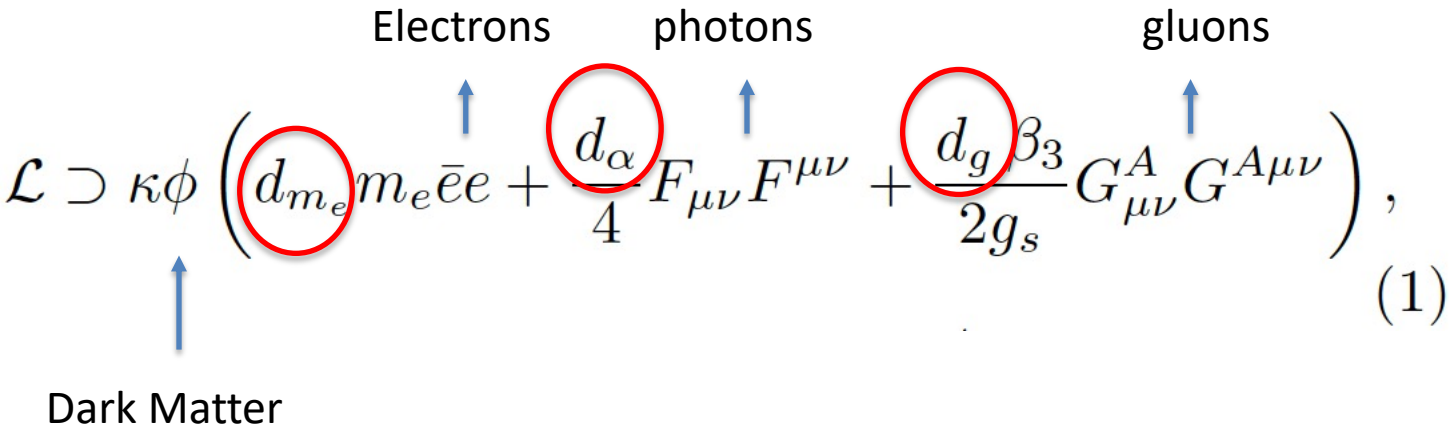
$$\phi(t, \vec{x}) = \phi_0 \cos(m_\phi t - \vec{k}_\phi \cdot \vec{x} + \dots).$$

(Non-relativistic solutions)

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

Oscillation frequency ~ dark matter mass

Dark Matter Coupling



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

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

$$\mu(\phi) \simeq \mu_0 \left(1 + d_{m_e} \kappa\phi\right), \quad \alpha(\phi) \simeq \alpha_0 \left(1 - d_\alpha \kappa\phi\right)$$

$$\alpha_s(\phi) \simeq \alpha_{s,0} \left(1 - \frac{2 d_g \beta_3}{g_s} \kappa\phi\right), \tag{2}$$

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

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

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 (~ **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

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Scalar DM Halo

Stable solution can be supported by external potential

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

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

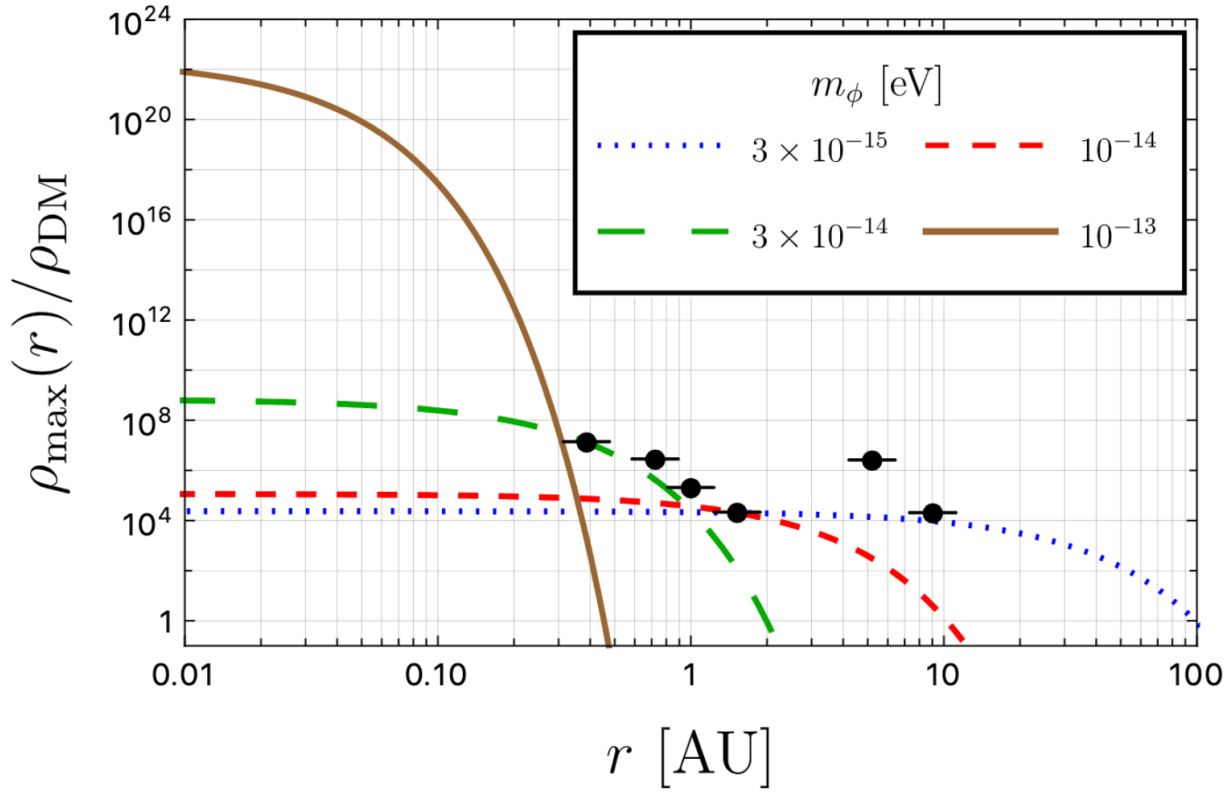
$$R_\star \simeq \frac{M_P^2}{M_{\rm ext}\, m_\phi^2},$$

where $M_{\rm ext} = M_\odot$ 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!**



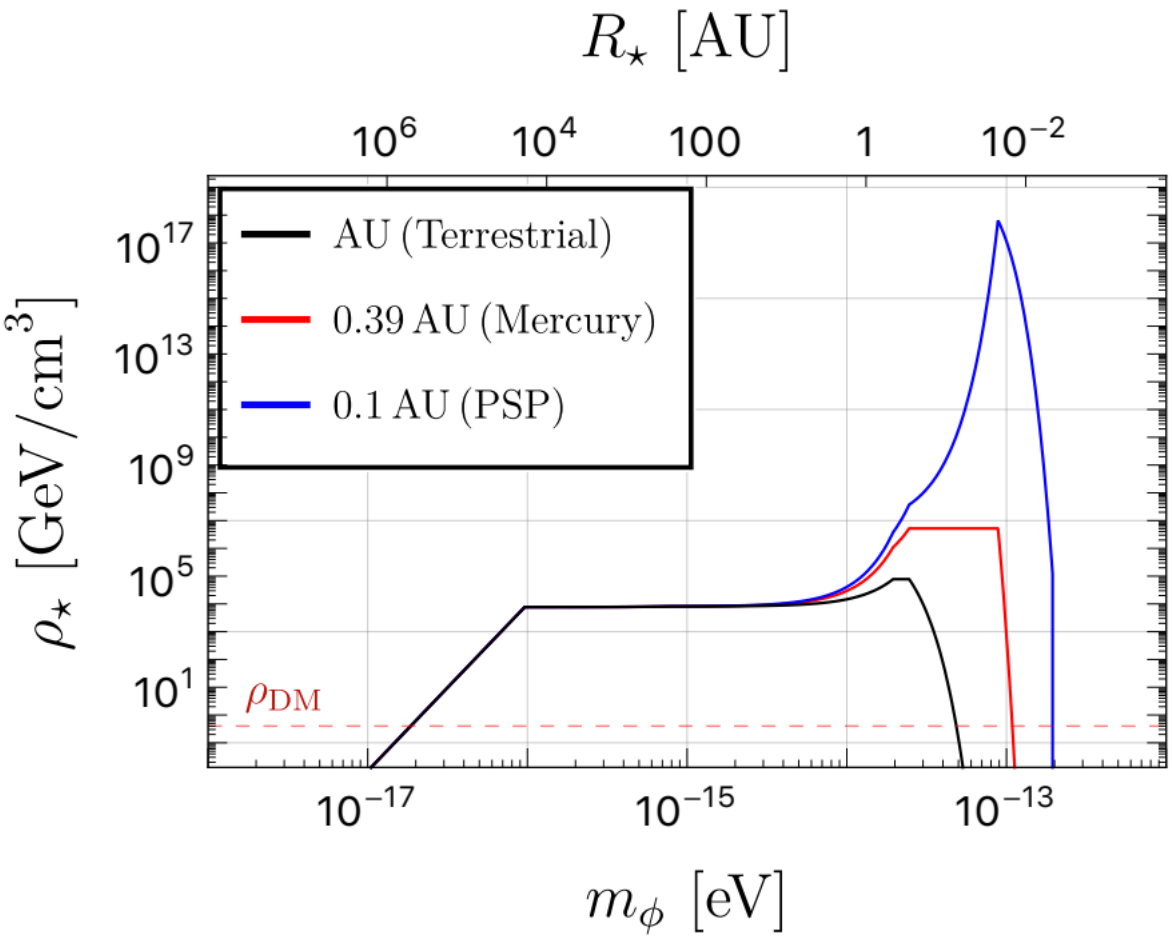
- **Black data points are model-independent constraints!**
- **Dark matter induce precessions to the planets**

Mercury, Venus, Earth, Mars, Jupiter, Saturn

Pitjev, Pitjeva, 1306.5534, Astronomy Letters '13

Tsai, Eby, Safronova, 2112.07674

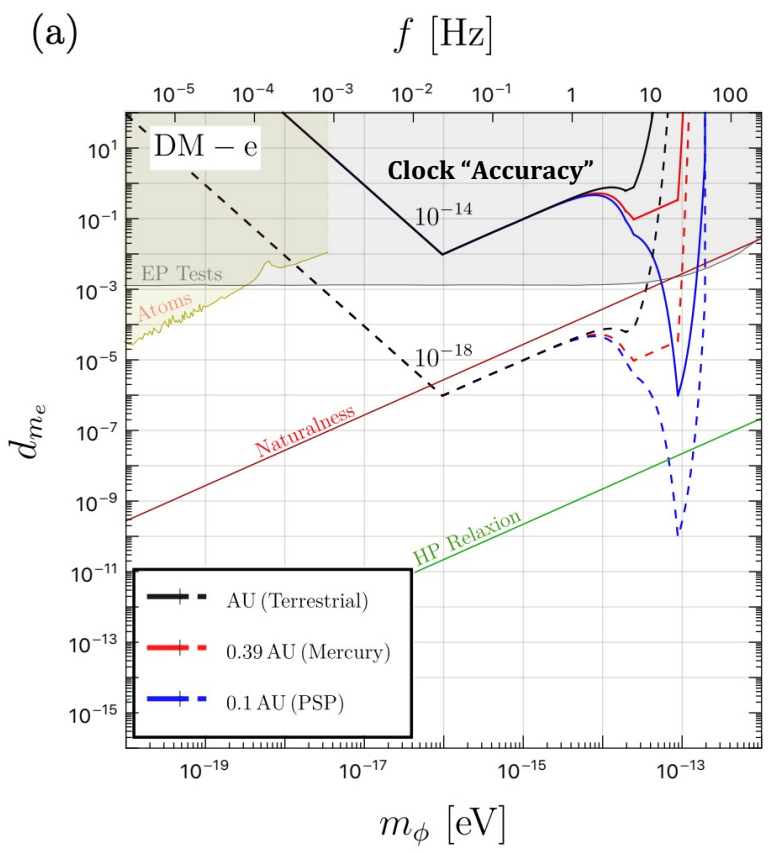
Enhancement of the DM Density

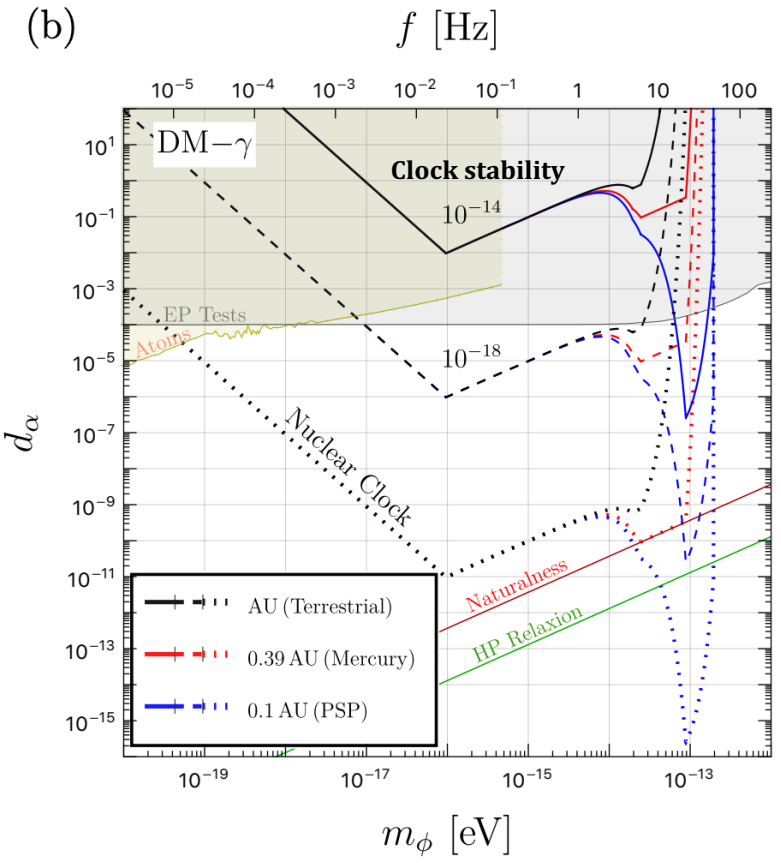


PSP: Parker Solar Probe

Tsai, Eby, Safronova, arXiv:2112.07674

Results





- Motivate **Specific Frequency Region!**
- Motivate **Nuclear Clocks!**
- **Tsai**, Eby, Safronova, arXv:2112.07674

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

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

Naturalness condition

Spatial Variation of Fundamental Constants

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

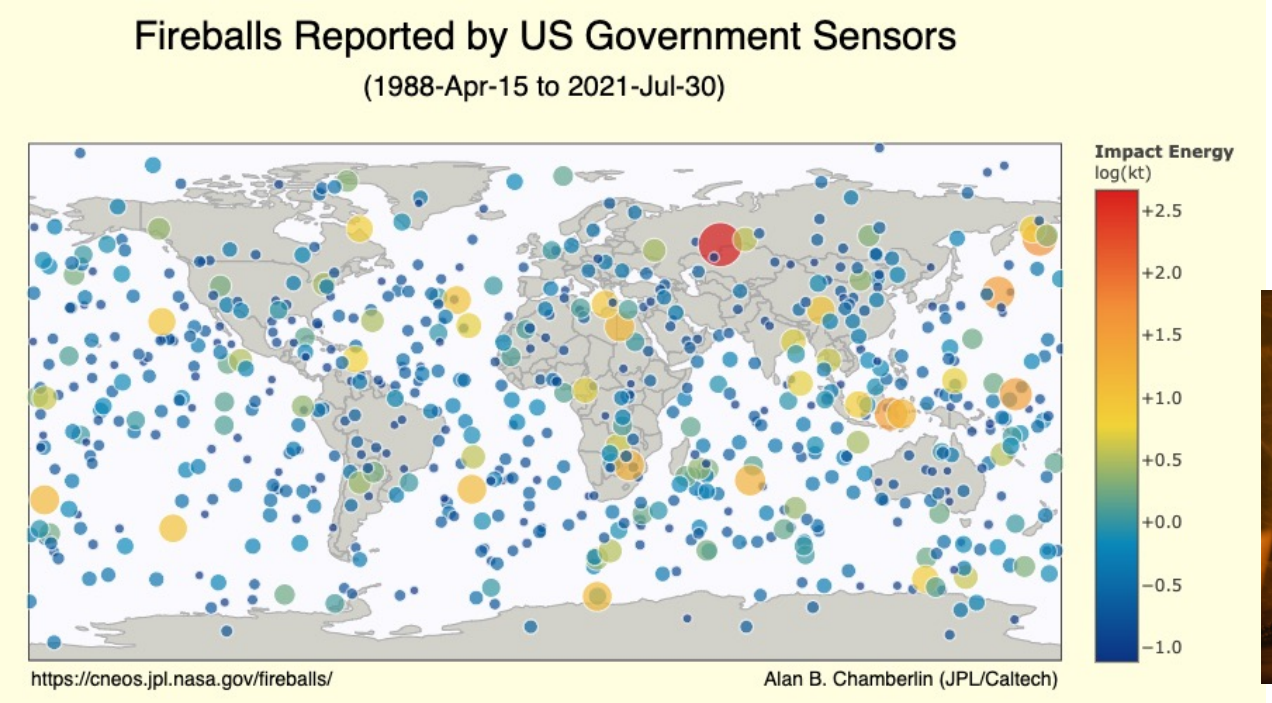
δU: change in gravitational potential .

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

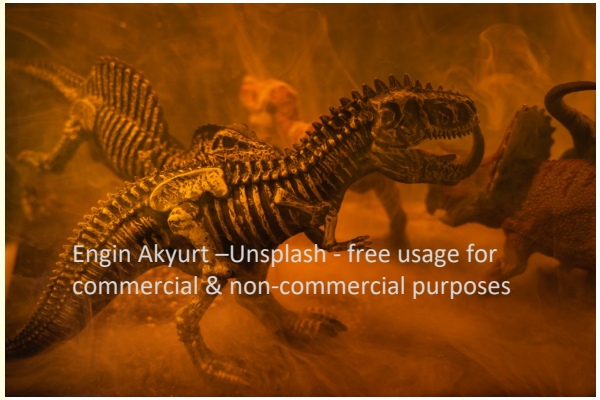
$\delta U/c^2 \sim 9 \times 10^{-8}$, from Earth to Solar probe at 0.1 AU.

- Achieve constraints on k_X that are a factor of $\sim$ 300 stronger!

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

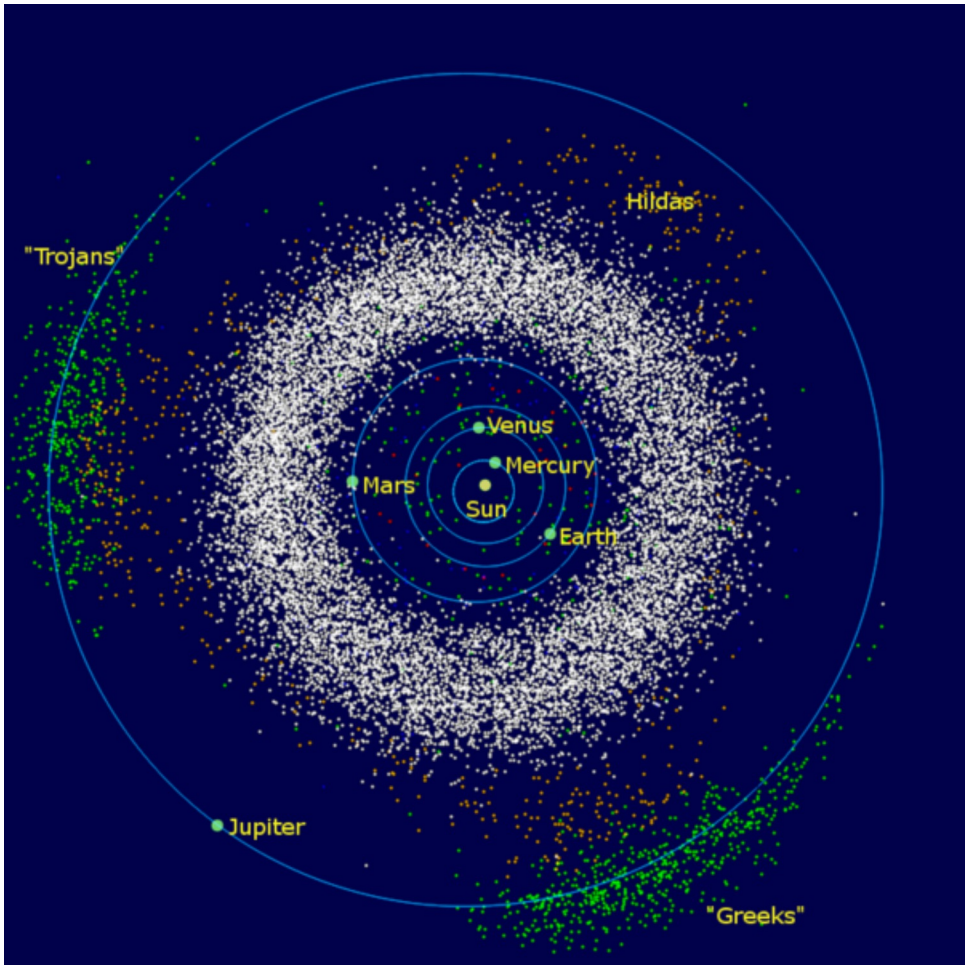
Asteroids

By Sidney Paget

"PROFESSOR MORIARTY STOOD BEFORE ME."

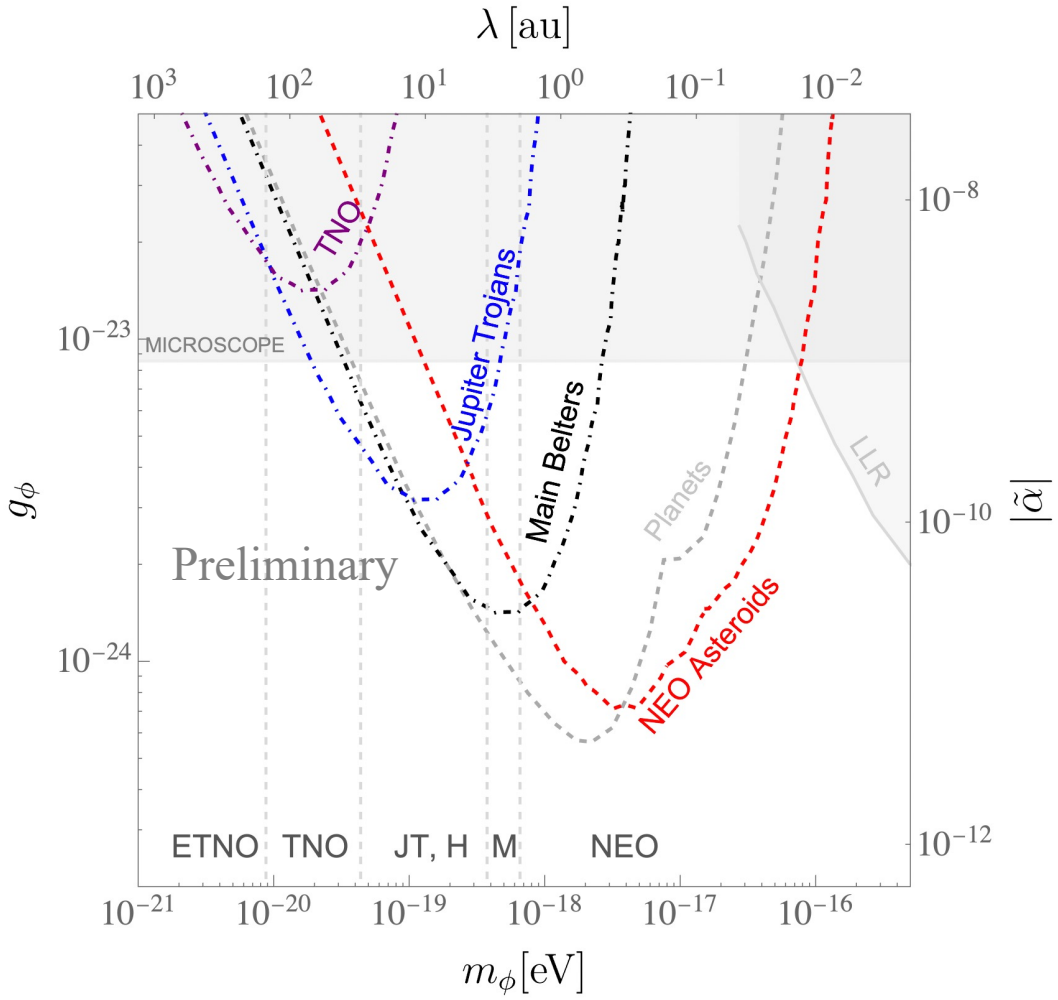
"Is he not the celebrated author of *The Dynamics of an Asteroid*, a book which ascends to such rarefied heights of pure mathematics that it is said that there was no man in the scientific press capable of criticizing it?
— *Sherlock Holmes, The Valley of Fear*

"The mor hazardous the asteroids, the better for fundamental Physics"
-- Professor Moriarty (maybe)



https://commons.wikimedia.org/wiki/File:InnerSolarSystem-en.png, public domain, granted usage for any purposes

Probing Fifth Force & Ultralight Mediators



- **LLR: Lunar Laser Ranging**
  Williams, Turyshev, Boggs, PRL 04
- **Planets:**
  Poddar, Mohanty, Jana, EPJC 21
- **Asteroidal / Planetary / Lunar Probes are the strongest for equivalence principle conserving fifth forces.**
- **More reference & details in the backup slides**

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038, under review by Nature Astronomy
Conducting a **detailed study** collaborating with researchers from **NASA & ESA**

Big Picture & Outlook

- Bridging **planetary science, space (quantum) technology, and fundamental physics**

- **Our result is exciting now and has significant potential given the future measurements:**
  radar, **optical**, and **space missions** will bring tremendous progress!

- **Atomic clocks on the moon, spacecraft, satellite,**
  Asteroid Tracking Array, and Advanced Lunar Ranging:
  Many exciting projects forward!
  Collaborating with NIST, NASA, ESA, etc people on proposals

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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