Study Dark Matter & Cosmic Neutrinos while Defending the Earth

Yu-Dai Tsai
University of California, Irvine
With **Josh Eby**, **Jason Arakawa**, **Marianna Safronova**
Youjia Wu, Sunny Vagnozzi, Luca Visinelli
Contact: yudait1@uci.edu & yt444@cornell.edu
Cornell -> Fermilab -> UC Irvine

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

- **https://arxiv.org/abs/2112.07674**
- **https://arxiv.org/abs/2107.04038**

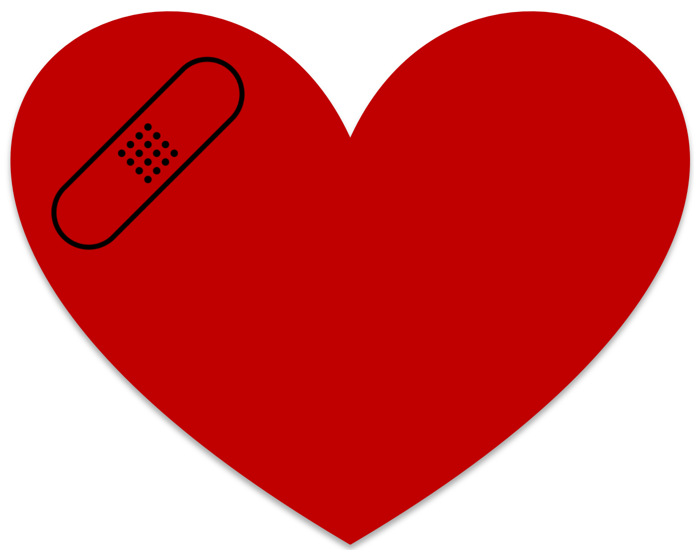
Under review by Nature Astronomy

My outreach interview: https://www.youtube.com/watch?v=xDX9XwLHBuM (> 76K views!)

I will first have the mental-health discussion, as it is very important!

Hidden Sector of Diversity

1. **Normalize** the discussion of **mental health**
2. **Understand & support invisible disabilities**
3. **Value neurodiversity**



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Academia’s Mental Health Crisis

- We are doing way worse than national average
- We cannot wait for a national outcry to improve this issue
  “**41% of graduate students scored as having moderate to severe anxiety on the GAD07 scale as compared to 6% of the general population**”, see https://www.nature.com/articles/nbt.4089, Evans et al.
- Many other studies support this.
- It is not hard to improve it: implement useful changes

My Definitions for Discussions

- **Invisible disabilities**: diagonalizable disabilities including ADHD, PTSD, autism, learning disabilities, chronic pain (often pre-existing; not visible)

- **Mental health issues**: general behavioral or mental pattern that causes distress or impairment of personal functioning

- **Neurodiversity**: variations in the human brain and cognition, for instance in sociability, learning, attention, mood, and other mental functions

My journey

- I have **55 publications including research & white papers; roughly 1,400 citations**. But being different, I often feel like an outsider
- **Taiwan had serious child abuse issues in school**, conducted by teachers & normalized in society
- I overcame untreated invisible disabilities; but **without treating them & proper support, my life expectancy, personal functioning, and relationships were greatly impaired**
- **It's not enough to treat them. We also need understandings.**
- **I realized that I can be a unique voice in our community**

Open-up is difficult, but very helpful!

- **I benefit from a senior/respected collaborator open-up about the personal struggles in social media**
- **It finally urged me to face my own invisible disabilities & I received medical treatments**
- **Life is so much better. I now have longer life expectancy & satisfaction (backed by studies!)**

Aspen Mental Health Lunch

The lunch is confidential, but one can cover topics include

1. Utilize resource inc. HR, lab/school sources, etc.
2. Develop mentoring & group meeting plans
3. Increase representation of neurodiverse people; Reduce negative connotation/descriptions
4. Conflict resolution for neuro-diverse people
5. Co-learning with LGBTQIA community
6. Intersectionality: gender, racial, cultural discussions

I am happy to be your guest host such a lunch in your department :)

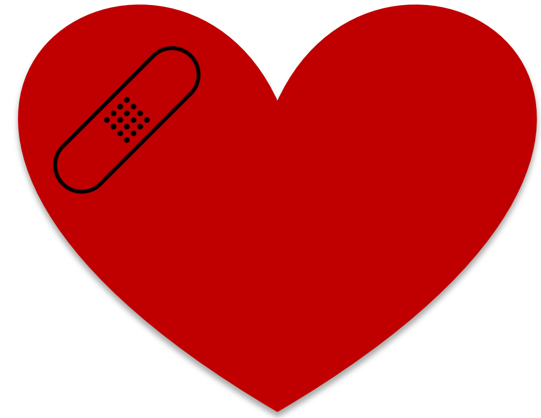
Important Efforts

1. A. Welsh, "Mental health for academics;" Slack channel

2. Assamagan, **Bitter**, Chen, Choi, Esquivel, Jepsen, Lewis, Muronga, Walkowicz, **Zhang**, **Snowmass Whitepaper:** "Building a Culture of Equitable Access and Success for Marginalized Members in Today's Particle Physics Community," https://arxiv.org/abs/2206.01849
   Specifically discussed invisible disability!

3. S. Charley, "How to be human in physics,"
   looking for your stories to share.

Let us all



1. **Normalize** the discussion of **mental health**
2. **Support & understand invisible disabilities**
3. **Value neurodiversity**

I encourage your own neuro-diverse ways to improve our community!

- **My vision is one day we can all open up about our struggles without the fear of discrimination**
- **Follow mental-health science**
- **Increase representation of people with invisible disabilities**
- **Reduce nepotism & <u>support independence</u>: an academia for everyone**

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

We can also discus & collaborate 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.
- Collaborating with **many awesome early-career collaborators.**

Invisible disabilities cultivate diverse abilities

Planetary Defense & Space Quantum Technologies for Fundamental Physics

Yu-Dai Tsai

University of California, Irvine

With **Josh Eby**, **Jason Arakawa,** **Marianna Safronova**

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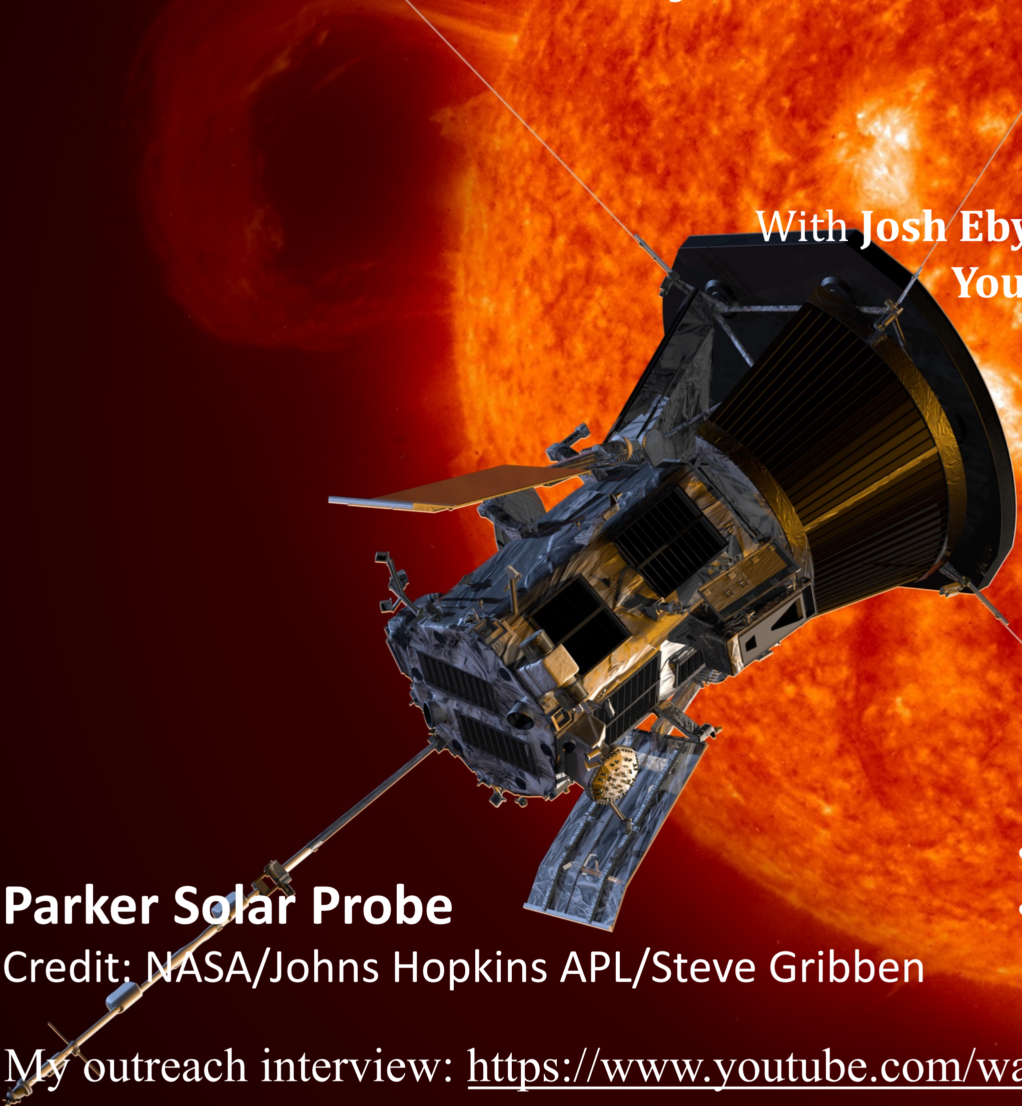

Parker Solar Probe

Credit: NASA/Johns Hopkins APL/Steve Gribben

- **https://arxiv.org/abs/2112.07674**
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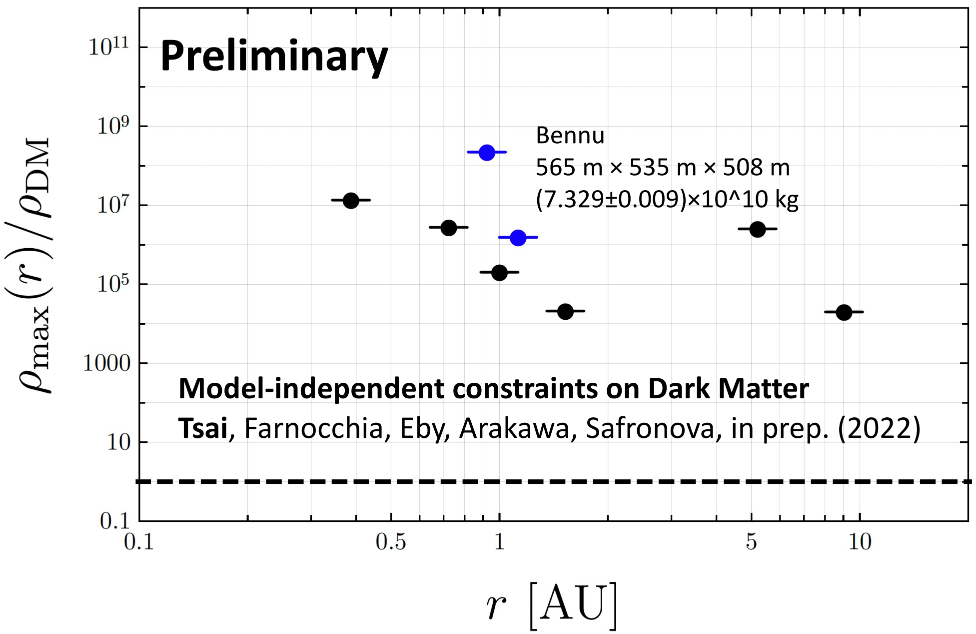
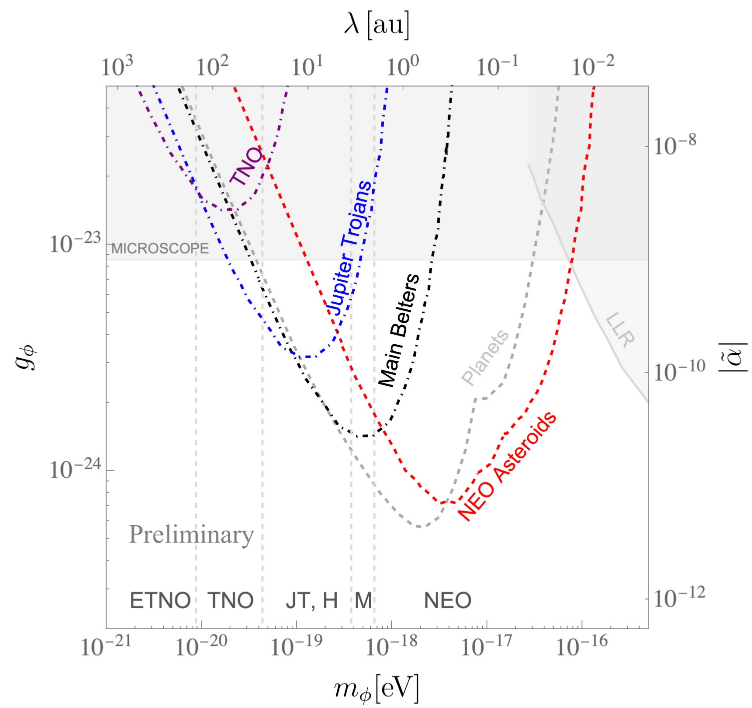
Submitted to Nature Astronomy

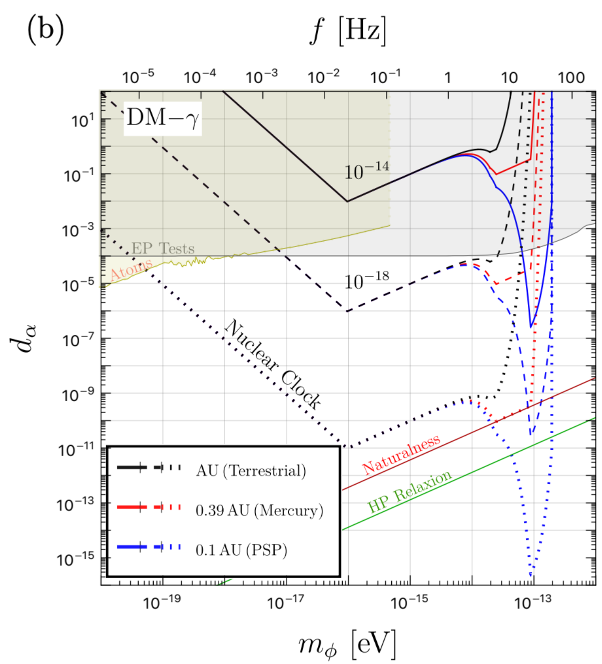
My outreach interview: https://www.youtube.com/watch?v=xDX9XwLHBuM (> 75K views!)





5th-force Analysis

https://arxiv.org/abs/2107.04038



Ultralight DM & Quantum Sensor

https://arxiv.org/abs/2112.07674

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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?

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

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.

- **Robust analyses underway in collaboration with a NASA JPL planetary defense expert & an AMO expert**

Outline

- Planetary Defense & Fifth Forces Studies
- Model-Independent Probes of **ANY** Dark Matter Candidates
  (especially purely gravitational dark matter!)
- Space Quantum Clocks & Ultralight Dark Matter
- New Projects & Visions for the Future

Theme of this talk:

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

Many real-life applications & consequences!

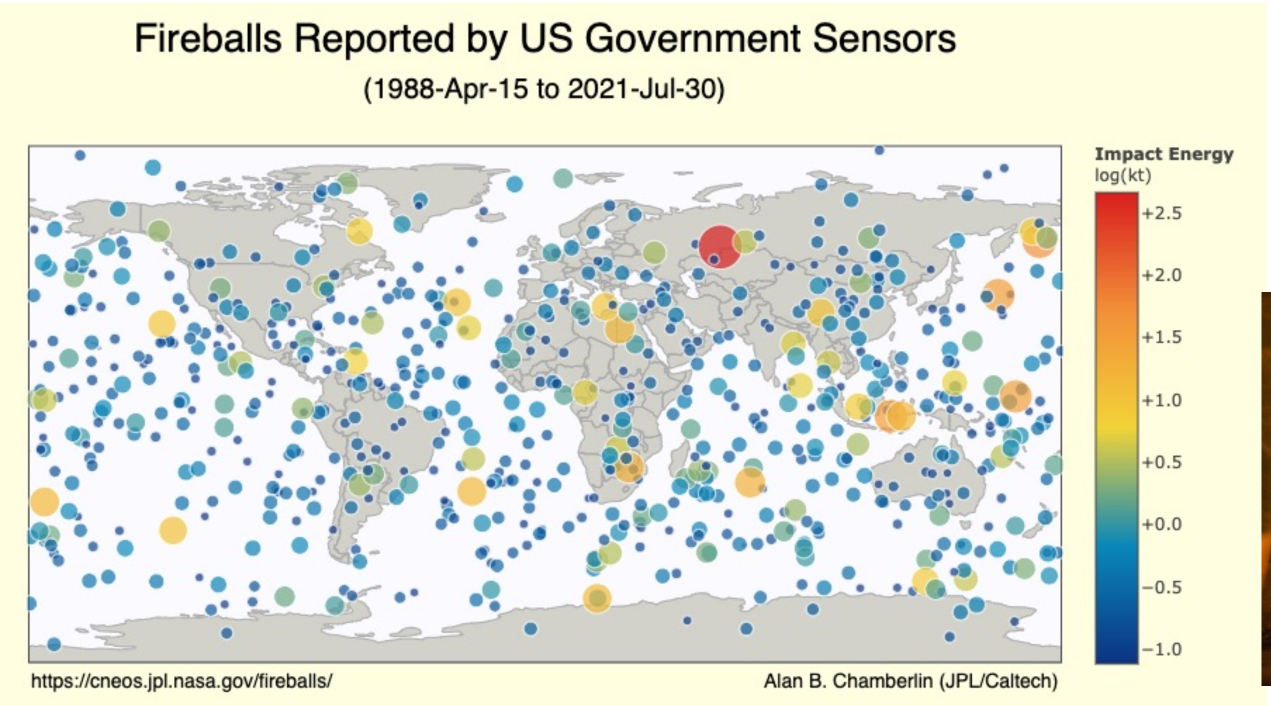
Self-driving Spacecraft!

Please Look Up

Planetary Constraints:
Dark Matter & Fifth Forces

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

Asteroids hitting the earth



~~Don't~~ Please Look Up

~ 65 million years ago

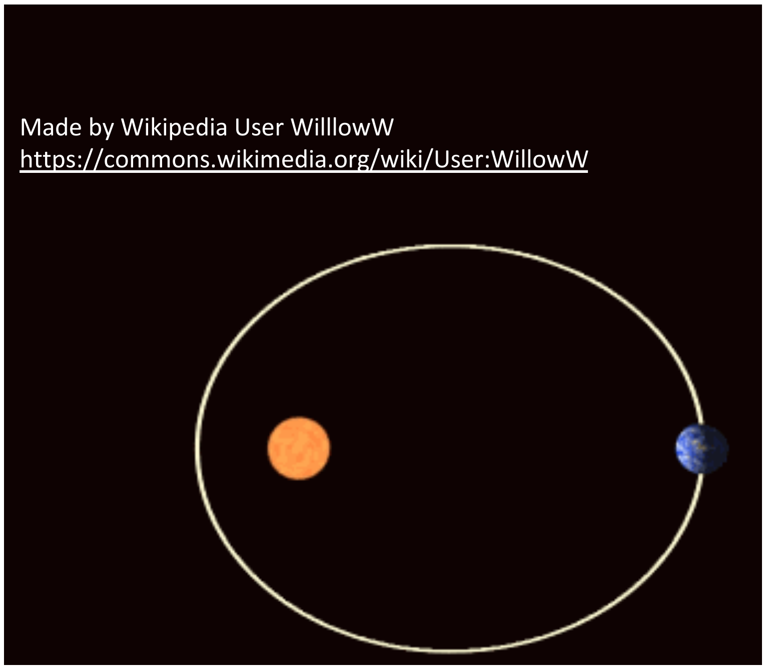
Tracking asteroids is extremely important

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

Also, near-Earth asteroid search accidentally found ‘Oumuamua

Perihelion Precession: Einstein's Success

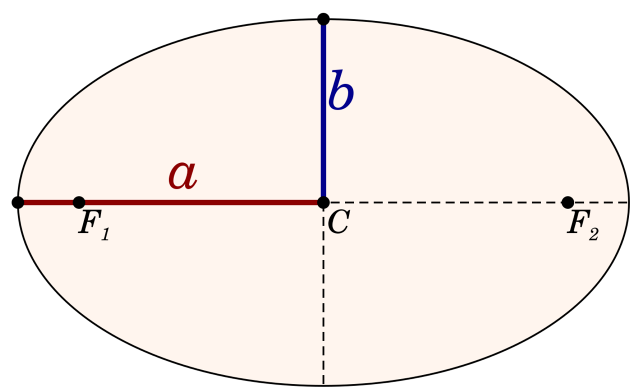
Precession of Mercury's perihelion (closest point to the Sun)



https://en.wikipedia.org/wiki/Apsidal_precession#/media/File:Precessing_Kepler_orbit_280frames_e0.6_smaller.gif under CC BY 3.0

$$\frac{\mathrm{d}^2u}{\mathrm{d}\varphi^2} + u - \frac{GM_\odot}{L^2} = \boxed{\frac{3GM_\odot}{c^2}u^2.}$$ **(GR)**

- Consider planar motion and fix θ = π/2.
- Define inverse radius variable u ≡ 1/r = u(φ)
- $a = \frac{L^2}{M_\odot(1-e^2)}$, a is the semi-major axis



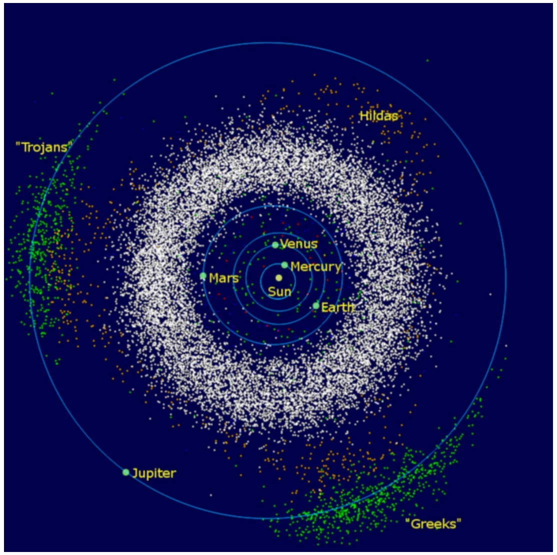
M. W. Toews (CC0)

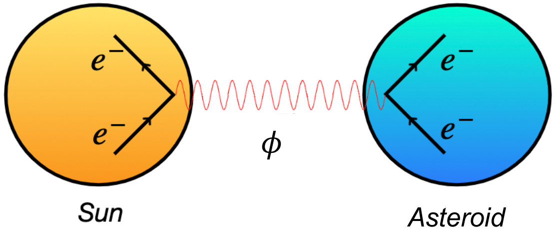
Objects of interest

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

TABLE I. Targets for our future studies, for which exciting opportunities are provided by sheer numbers and observational programs, classified roughly based on their typical semi-major axes.
*NEOs are defined as having perihelia $a(1-\mathrm{e}) < 1.3\,\mathrm{au}$.

$$|\Delta\varphi_{\phi,A'}| \simeq \frac{2\pi}{1+\frac{g^2}{4\pi G m_p^2}} \frac{g^2}{4\pi G m_p^2} \left(\frac{amc}{\hbar}\right)^2 (1-\mathrm{e})\,.$$





Modified From Tanmay Poddar

- **Tsai**, Wu, Vagnozzi, Visinelli, arXiv:2107.04038
- ***Can also probe dark matter, primordial black hole, etc***

Ultralight Mediators & Fifth Forces

Gauged $\boldsymbol{U(1)_{EM}}$ (Standard Model) ⇨ photons

1. Gauged $\boldsymbol{U(1)_{X's}}$ (hypothetical) ⇨ "Dark" photons

- **X can be bayon number, lepton number, etc**:
  Standard Model Global Symmetries

- Motivated by baryogenesis (matter-anti matter asymmetry) & dark matter:

  The ultralight mediators **CAN** but does not have to be dark matter

2. Ultralight scalars coupled to Standard Model particles

$$\mathcal{L}_\phi \subset (g_{\phi,p}\bar{p}p + g_{\phi,n}\bar{n}n + g_{\phi,e}\bar{e}e)\phi$$

5^{th} force and Yukawa Potential

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

$$V(r) = \mp\frac{g^2}{4\pi}\frac{Q_\odot Q_*}{r}\exp\left(-\frac{mc^2}{\hbar c}r\right),$$

$$\frac{\mathrm{d}^2u}{\mathrm{d}\varphi^2} + u - \frac{GM_\odot}{L^2} = \frac{3GM_\odot}{c^2}u^2 + \boxed{\widetilde{\alpha}\frac{GM_\odot}{L^2}\left(1+\frac{1}{\lambda u}\right)e^{-\frac{1}{\lambda u}},}$$

(fifth force)

- Gauge boson, dark photon of $U(1)_B$ or scalar coupled to baryon number
- g is new physics coupling constant, and m is the mediator mass
- See, e.g., Poddar et al, https://arxiv.org/abs/2002.02935

Precession (Analytical) at Low-Mass Limit

$$|\Delta\varphi_{\phi,A'}| \simeq \frac{2\pi}{1+\frac{g^2}{4\pi G m_p^2}} \frac{g^2}{4\pi G m_p^2} \left(\frac{amc}{\hbar}\right)^2 (1-\mathrm{e}) \,.$$

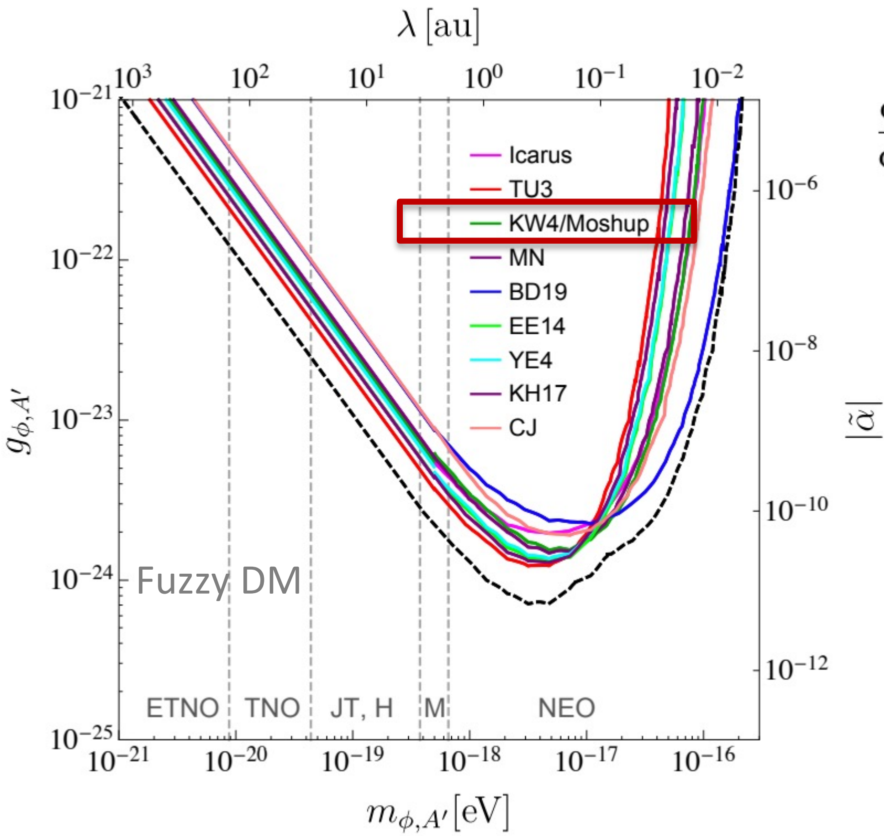
(fifth force)

$$\Delta\varphi_0 = \frac{6\pi G M_\odot}{a(1-\mathrm{e}^2)c^2}\left[\frac{2-\beta+2\gamma}{3}\right]$$

(GR)

- **m_p is proton mass**
- **for low mass, m << 1/ a (Natural Unit)**
- **The term gets larger with a**
- That's why we should explore **objects further away from the Sun:** not just Mercury or other planets
- **Not depending on target celestial bodies' mass**

Results for the new physics



$$\frac{d^2u}{d\varphi^2} + u - \frac{GM_\odot}{L^2} = \frac{3GM_\odot}{c^2}u^2 + \tilde{\alpha}\frac{GM_\odot}{L^2}\left(1+\frac{1}{\lambda u}\right)e^{-\frac{1}{\lambda u}}, \tag{3}$$

Recast

$\sigma_\beta = 5.6 \times 10^{-4}$, Verma, Margot, Greenberg, APJ '17

Optimal 2022 results,

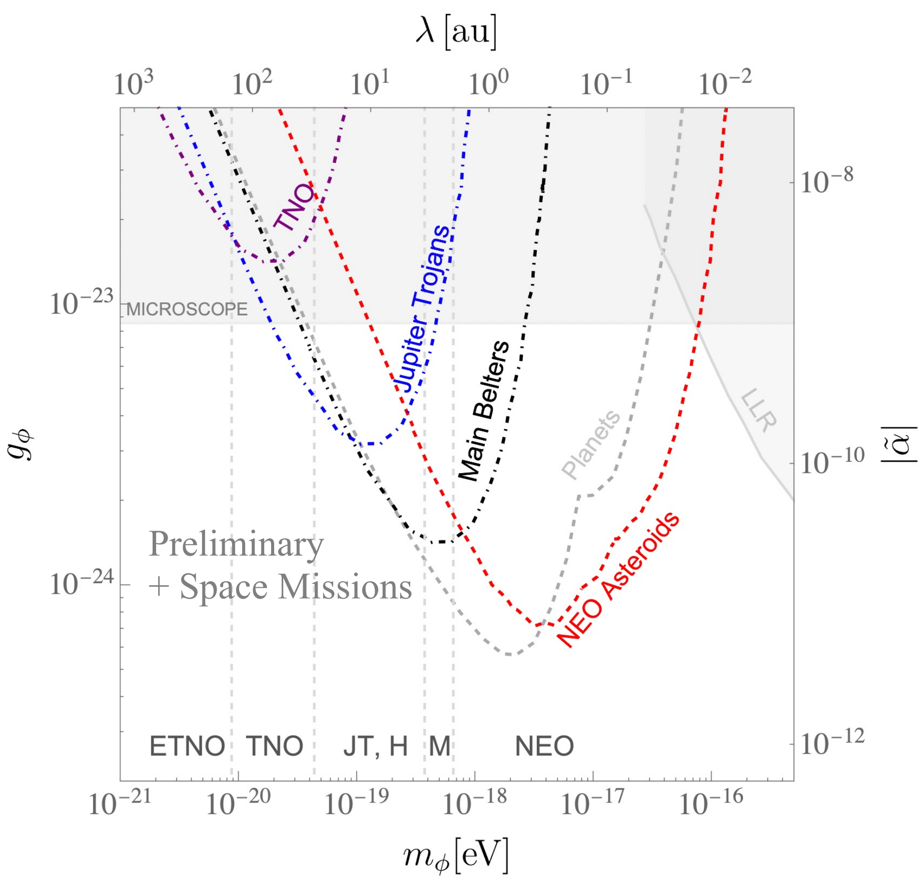
$\sigma_\beta \sim 2 \times 10^{-4}$,

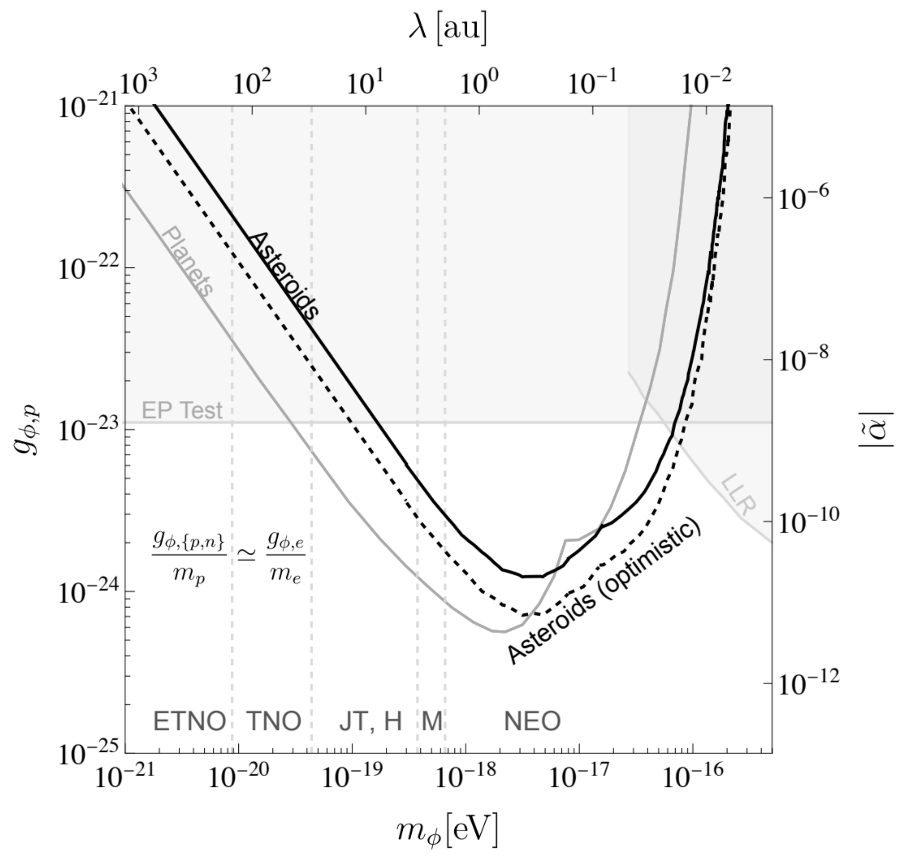
Best reach:
TU3, MN, BD19

$$\Delta\varphi^2_{\phi,A'} < \left|\frac{\partial\Delta\varphi_0}{\partial\beta}\right|^2\sigma_\beta^2 + \left|\frac{\partial\Delta\varphi_0}{\partial J_2}\right|^2\sigma_{J_2}^2 + 2\rho\left|\frac{\partial\Delta\varphi_0}{\partial\beta}\,\frac{\partial\Delta\varphi_0}{\partial J_2}\right|\sigma_{J_2}\sigma_\beta\,.$$

Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

Compilations of Various Probes



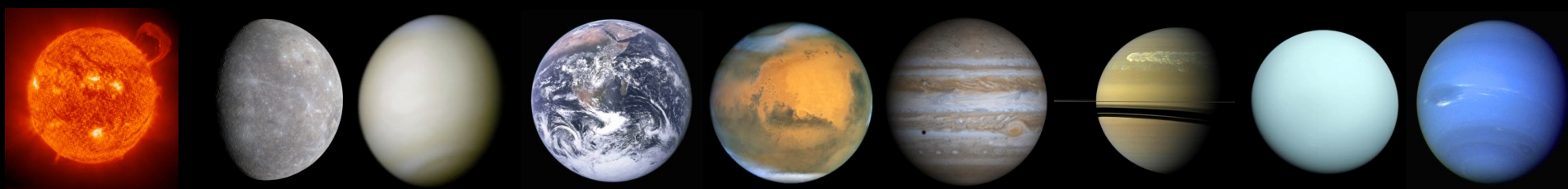


Tsai, Wu, Vagnozzi, Visinelli, arXiv:2107.04038

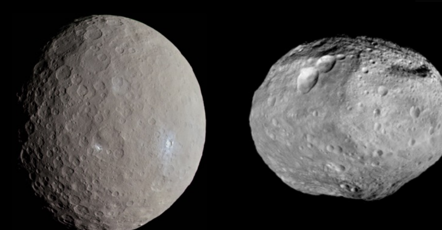
We are conducting a **detailed study** using **MONTE** with people from **JPL & ESA**

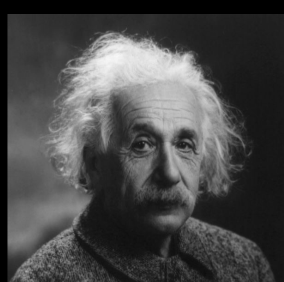
Robust Analysis: High-fidelity force model

JPL Planetary Ephemerides DE441



Small-body perturbers





PPN formulation for relativity

Oblateness, …

Dr. Davide Farnocchia’s (NASA, JPL) slide

Adding Fifth Forces or Dark Matter to the Force Model

$$
\begin{aligned}
\ddot{\mathbf{r}}_i = \sum_{j \neq i} \frac{\mu_j \left(\mathbf{r}_j - \mathbf{r}_i\right)}{r_{ij}^{3}} \Bigg\{ & 1 - \frac{2(\beta+\gamma)}{c^2} \sum_{l \neq i} \frac{\mu_l}{r_{il}} - \frac{2\beta - 1}{c^2} \sum_{k \neq j} \frac{\mu_k}{r_{jk}} \\
& + \gamma \left(\frac{\dot{s}_i}{c}\right)^2 + (1+\gamma)\left(\frac{\dot{s}_j}{c}\right)^2 - \frac{2(1+\gamma)}{c^2} \dot{\mathbf{r}}_i \cdot \dot{\mathbf{r}}_j \\
& - \frac{3}{2c^2} \left[\frac{\left(\mathbf{r}_i - \mathbf{r}_j\right) \cdot \dot{\mathbf{r}}_j}{r_{ij}} \right]^2 + \frac{1}{2c^2} \left(\mathbf{r}_j - \mathbf{r}_i\right) \cdot \ddot{\mathbf{r}}_j \Bigg\} \\
& + \frac{1}{c^2} \sum_{j \neq i} \frac{\mu_j}{r_{ij}^{3}} \left\{ \left[\mathbf{r}_i - \mathbf{r}_j\right] \cdot \left[(2+2\gamma)\, \dot{\mathbf{r}}_i - (1+2\gamma)\, \dot{\mathbf{r}}_j \right] \right\} \left(\dot{\mathbf{r}}_i - \dot{\mathbf{r}}_j\right) \\
& + \frac{3+4\gamma}{2c^2} \sum_{j \neq i} \frac{\mu_j \ddot{\mathbf{r}}_j}{r_{ij}}
\end{aligned}
$$

From Dr. Davide Farnocchia's (NASA, JPL) slide

Fifth forces

$$F = \frac{A0\, e^{-\frac{r}{r0}}}{r^2} + \frac{A0\, e^{-\frac{r}{r0}}}{r\, r0}$$

General dark matter

?

Uncertainties?

- Errors in planetary trajectories and masses
- Missing perturbers, errors in perturber masses & trajectories
- Higher order relativistic terms
- Higher order gravity terms
- Poynting-Robertson drag
- Simplifying assumptions in nongravitational force model (non-spherical effects, Yarkovsky, solar torque, physical parameter evolution, etc)
- Solar mass loss and solar wind
- Meteoroid impacts
- Spacecraft interaction
- Whatever else could be missing...

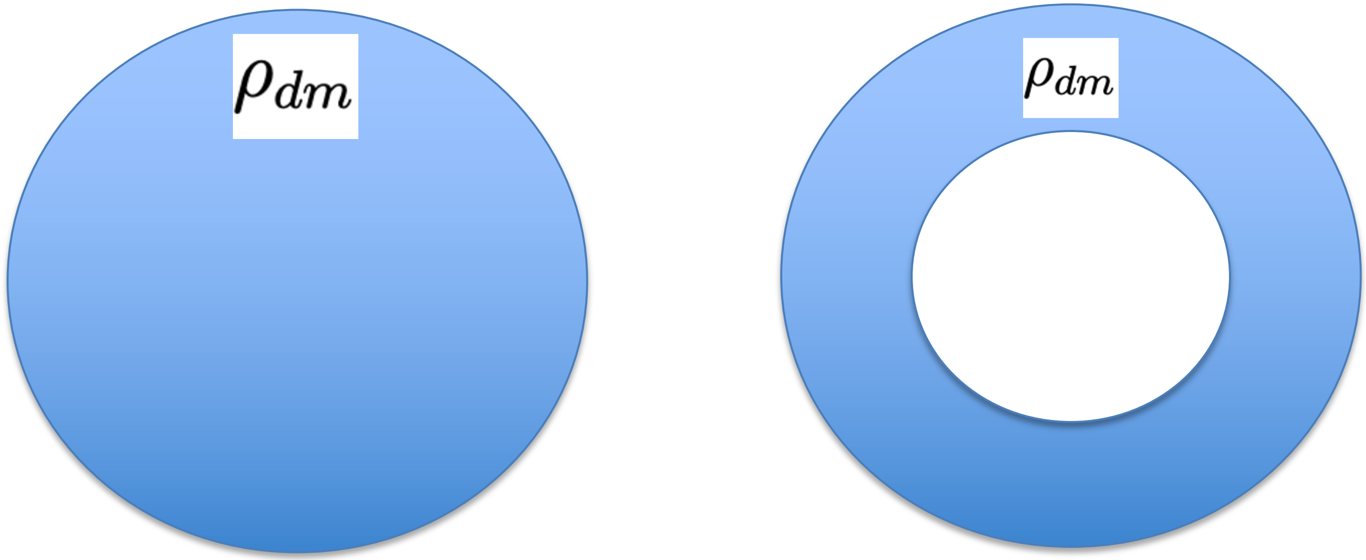
Dr. Davide Farnocchia's (NASA, JPL) slide

Model-Independent Constraints on Dark Matter

Preliminary Results

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

Dark Matter Profile & Planetary Precession



$$\Delta\theta_0 = -4\pi^2 \rho_{dm} a^3 (1-e^2)^{1/2} / M_\odot,$$

Adding Dark Matter to the Force Model

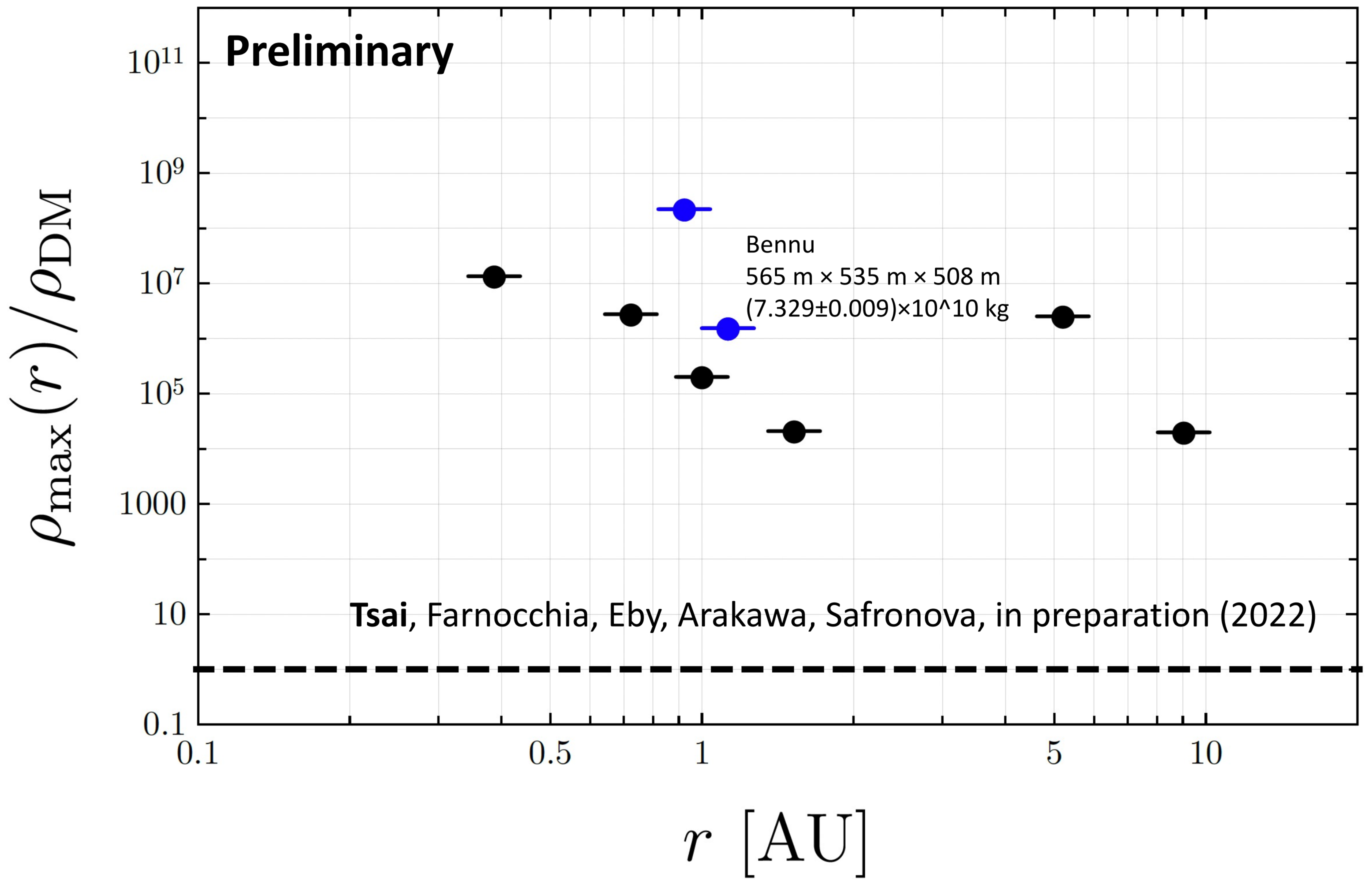
$$
\begin{aligned}
\ddot{\mathbf{r}}_i = \sum_{j\neq i} \frac{\mu_j\left(\mathbf{r}_j - \mathbf{r}_i\right)}{r_{ij}{}^3} \Bigg\{ & 1 - \frac{2(\beta+\gamma)}{c^2}\sum_{l\neq i}\frac{\mu_l}{r_{il}} - \frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} \\
& + \gamma\left(\frac{\dot{s}_i}{c}\right)^2 + (1+\gamma)\left(\frac{\dot{s}_j}{c}\right)^2 - \frac{2(1+\gamma)}{c^2}\dot{\mathbf{r}}_i\cdot\dot{\mathbf{r}}_j \\
& - \frac{3}{2c^2}\left[\frac{\left(\mathbf{r}_i - \mathbf{r}_j\right)\cdot\dot{\mathbf{r}}_j}{r_{ij}}\right]^2 + \frac{1}{2c^2}\left(\mathbf{r}_j - \mathbf{r}_i\right)\cdot\ddot{\mathbf{r}}_j \Bigg\} \\
& + \frac{1}{c^2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}{}^3}\left\{\left[\mathbf{r}_i - \mathbf{r}_j\right]\cdot\left[(2+2\gamma)\,\dot{\mathbf{r}}_i - (1+2\gamma)\,\dot{\mathbf{r}}_j\right]\right\}\left(\dot{\mathbf{r}}_i - \dot{\mathbf{r}}_j\right) \\
& + \frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{\mu_j\ddot{\mathbf{r}}_j}{r_{ij}}
\end{aligned}
$$

From Dr. Davide Farnocchia's (NASA, JPL) slide

Dark matter

$$
\begin{aligned}
F(r) &= \frac{2\pi}{3}Gm\rho_0\left(\frac{2r_0^3}{r^2} - 2r\right)\hat{\mathbf{r}} \\
&\simeq -\frac{4\pi}{3}Gm\rho_0 r\hat{\mathbf{r}}
\end{aligned}
$$

New Project: New Model Independent Constraints!



Preliminary! Will be out next week!

Improve the constraint with asteroid data! Model independent!

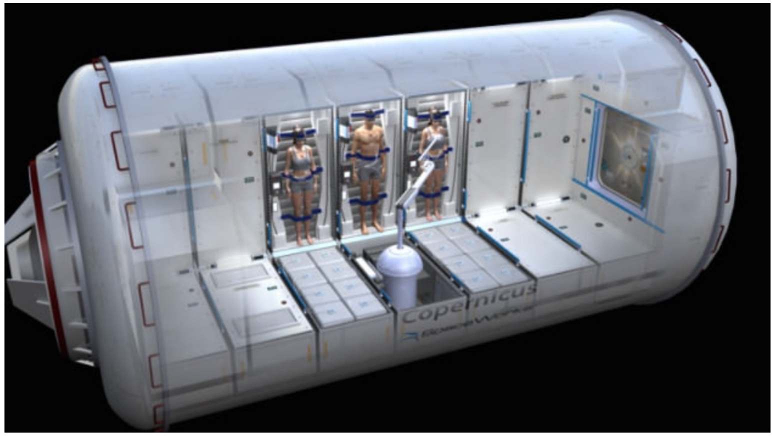
Tsai, Farnocchia, Eby, Arakawa, Safronova, in preparation

Obtained preliminary results from NASA JPL code.

More on Space Missions & Quantum Sensors

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!!!**

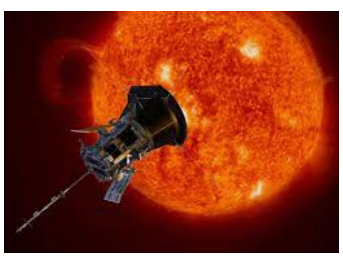
NASA Deep Space Atomic Clocks (current technology!) & Deep space and global navigation satellite system (GNSS)

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)

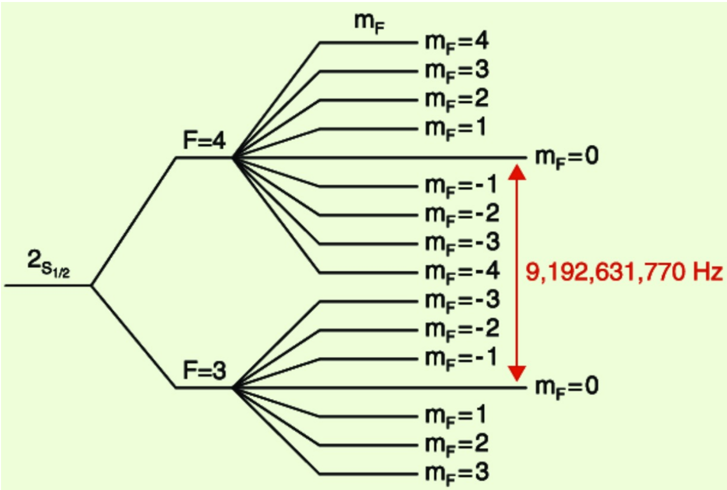
- **Why don’t we put a quantum clock on a solar probe? What can we do with that?**

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.**



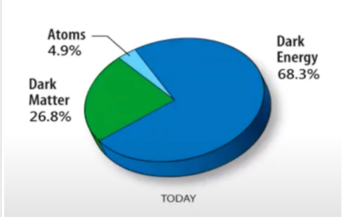
Definition of a second!

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

Wave-Like Particles as Dark Matter

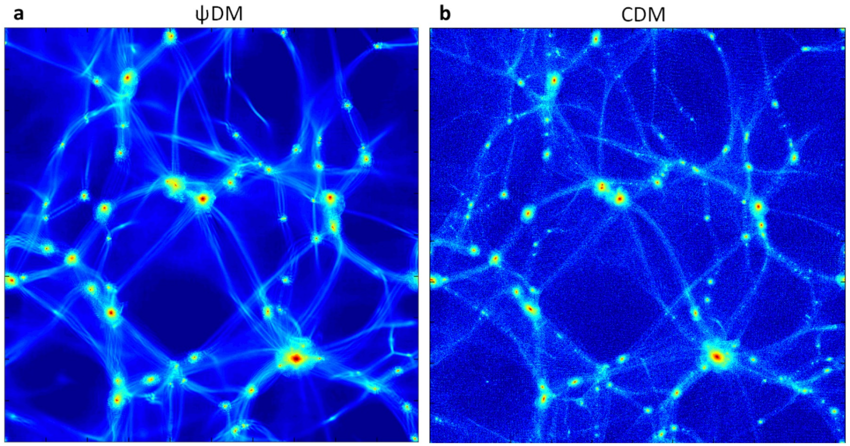
$$\lambda_{\mathrm{dB}} \equiv \frac{2\pi}{mv}$$

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



UC Riverside Physics Department https://physics.ucr.edu/image/dark-matter-dark-energy-pie-chart

- For 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.



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

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

Dark Matter Coupling

Electrons photons gluons

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

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

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

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

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

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

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

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

Scalar DM Halo

Stable solution can be supported by external potential

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

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

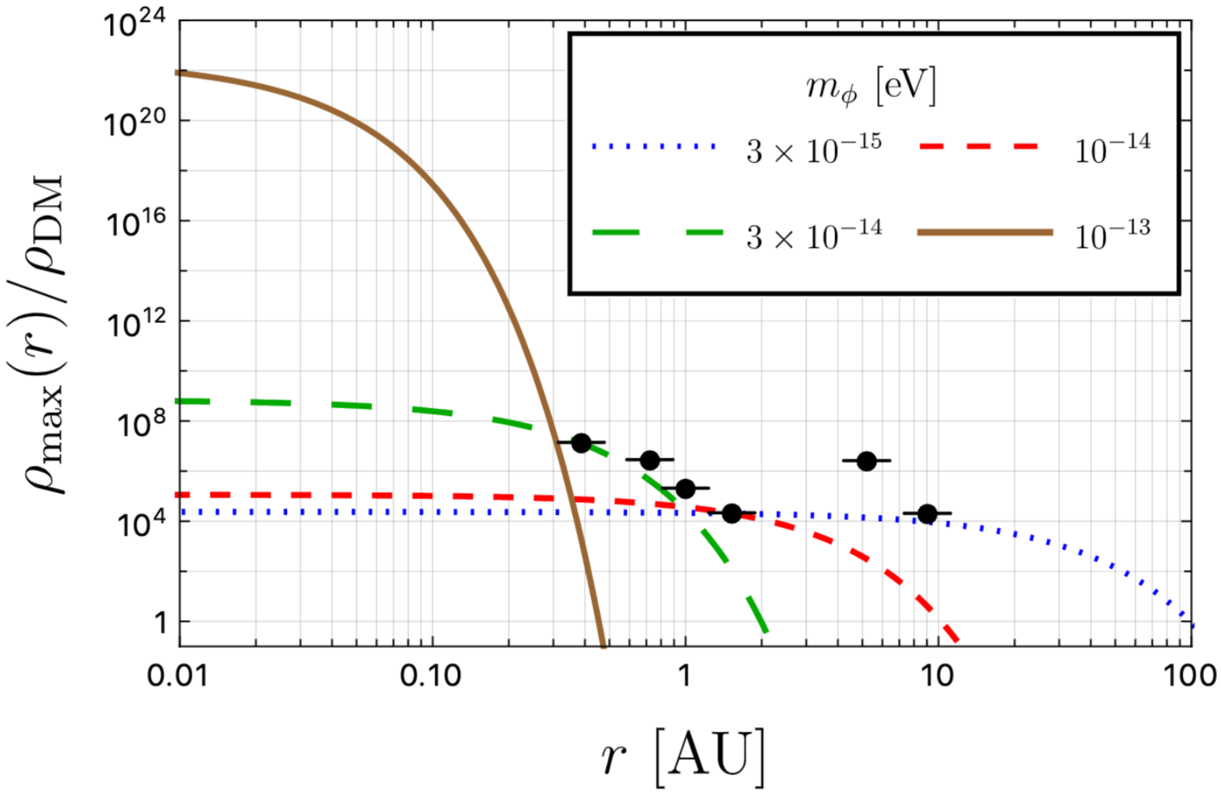
$$R_\star \simeq \frac{M_P^2}{M_{\rm ext}\, m_\phi^2},$$

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!**



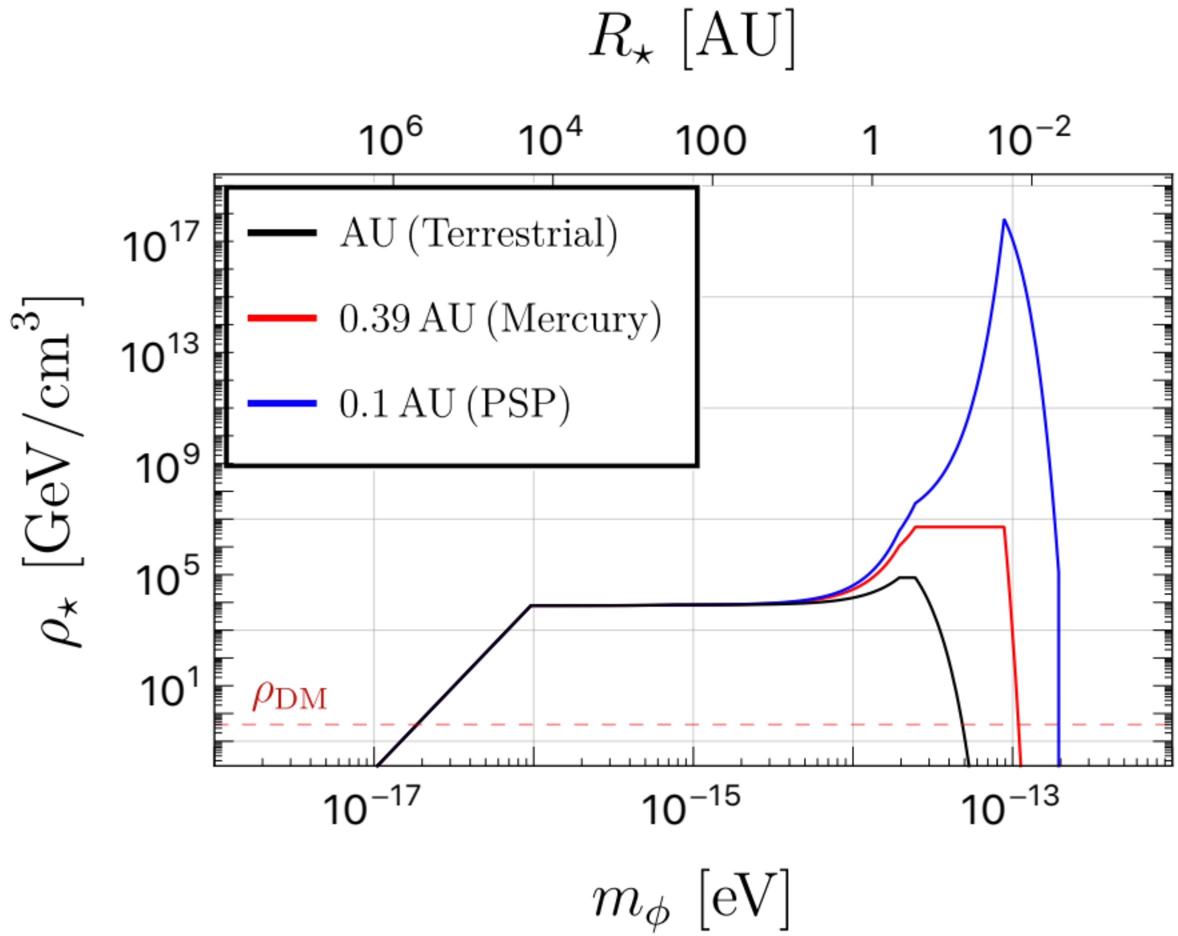
- **Black data points are model-independent constraints!**
- **Dark matter induce precessions to the planets**

Mercury, Venus, Earth, Mars, Jupiter, Saturn

Pitjev, Pitjeva, 1306.5534, Astronomy Letters ’13

Tsai, Eby, Safronova, 2112.07674

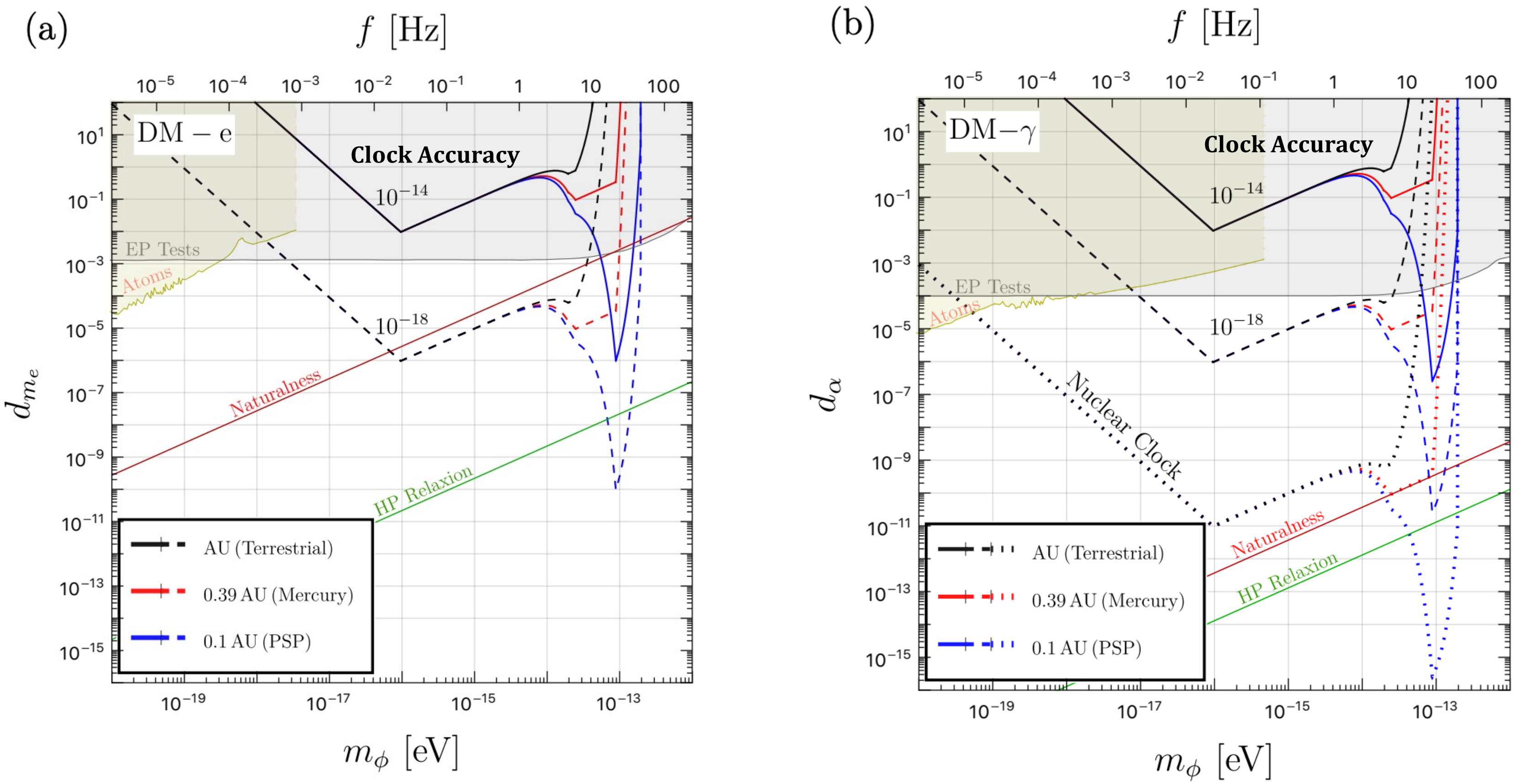
Enhancement of the DM Density



PSP: Parker Solar Probe

Tsai, Eby, Safronova, arXiv:2112.07674

Results



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

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

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

Naturalness condition

Relaxion Prediction

- For the Higgs portal-like theories, scalar couplings to matter are generated by mixing with the Higgs, and so can be parameterized by a relaxion **ϕ-higgs mixing angle sinθ;**

- One has g_e= y_e sinθ and $g_\gamma \sim$ (α/4πv) sinθ, where y_e is the Higgs Yukawa coupling to the electron, v is the Electroweak vacuum expectation value.

- The green line is assuming maximum relaxion-higgs mixing, which is of order $\boldsymbol{g_e}$ **~** $\boldsymbol{y_e}$ **(**$\boldsymbol{m_\phi / m_H}$**)**

- see, e.g. , Banerjee, Budker, Eby, Kim, Perez , 1902.08212 for more discussions.

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.

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

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

Space Mission & Telescopes

An artist's impression of the Lucy spacecraft performing a flyby of a Jupiter trojan.

NASA/SwRI and SSL/Peter Rubin - https://www.nasa.gov/press-release/nasa-selects-two-missions-to-explore-the-early-solar-system

Lucy is a planned NASA space probe that will complete a 12-year journey to seven different **asteroids. Human landing?**

A photograph and rendering mix of the exterior of the Vera C. Rubin Observatory building on Cerro Pachón in Chile. Image credit: Rubin Obs./NSF/AURA

- Optical – **Vera Rubin Observatory**: increase the **number of solar-system objects by 5 times**.

— Gaia mapping the stars of the Milky Way

Optical – **GAIA** provides stellar reference for asteroid localization

Exciting Research Directions for Discussions

1. **Asteroidal/Planetary Tracking Array**
   develop a tracking array to study **bosonic ultralight dark matter** (possible) and **gravitational wave** (difficult);

2. **Probing dark energy and cosmology-motivated modified-gravity theories**

3 **Consider non-gravitational dark matter-SM interactions**

- **Quantum technologies in Space: Q-SEnSE + SpaceQ meeting**
- **See many relevant references in the backup slides**

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We can also discus & collaborate 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.
- Collaborating with **many awesome early-career collaborators.**

Invisible disabilities cultivate diverse abilities

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

Yu-Dai Tsai, UC Irvine, '21
yt444@cornell.edu

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

Thank you!

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

My outreach interview:
https://www.youtube.com/watch?v=xDX9XwLHBuM (> 76K views!)

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

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
  GW measurement with atomic clocks, Fedderke, Graham, Rajendran, 2112.11431
- Quantum Technologies in Space, Kaltenbaek, Exp Astron 21

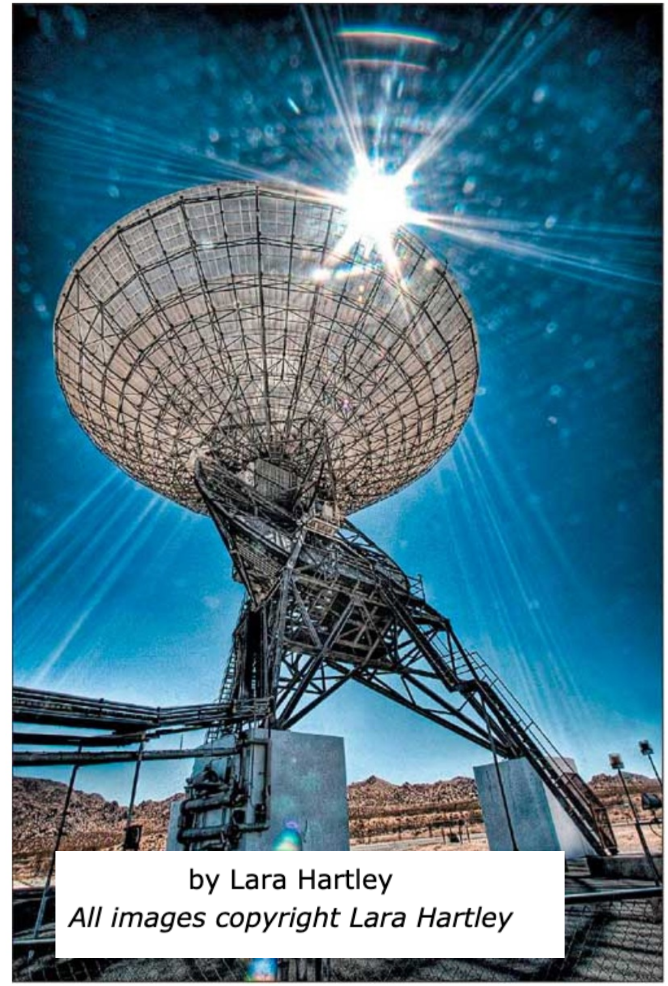
Radar Observations

- Radar – **Goldstone Observatory**: Provide very precise location and velocity information of the asteroids

- **Radar astronomy:** observing nearby astronomical objects by reflecting microwaves off target objects and analyzing the reflections.

- **Round-trip light time (RTLT):** The elapsed time taken by a signal travelling from the Earth to a spacecraft or other celestial body

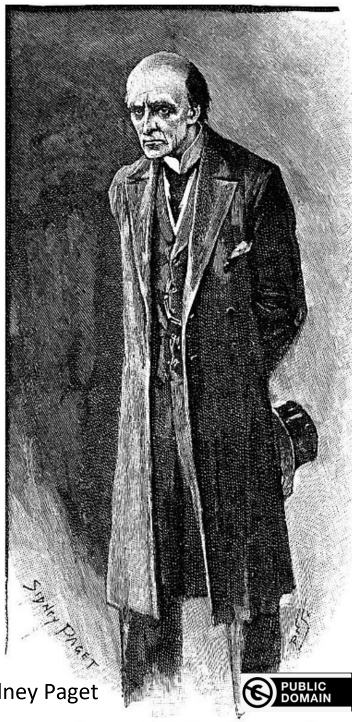
- **Doppler shift:**



Students can control the huge Echo radio telescope to collect data from objects in the universe at which the antenna is pointed.

https://www.desertusa.com/desert-california/goldstone-deep-space.html

Asteroids



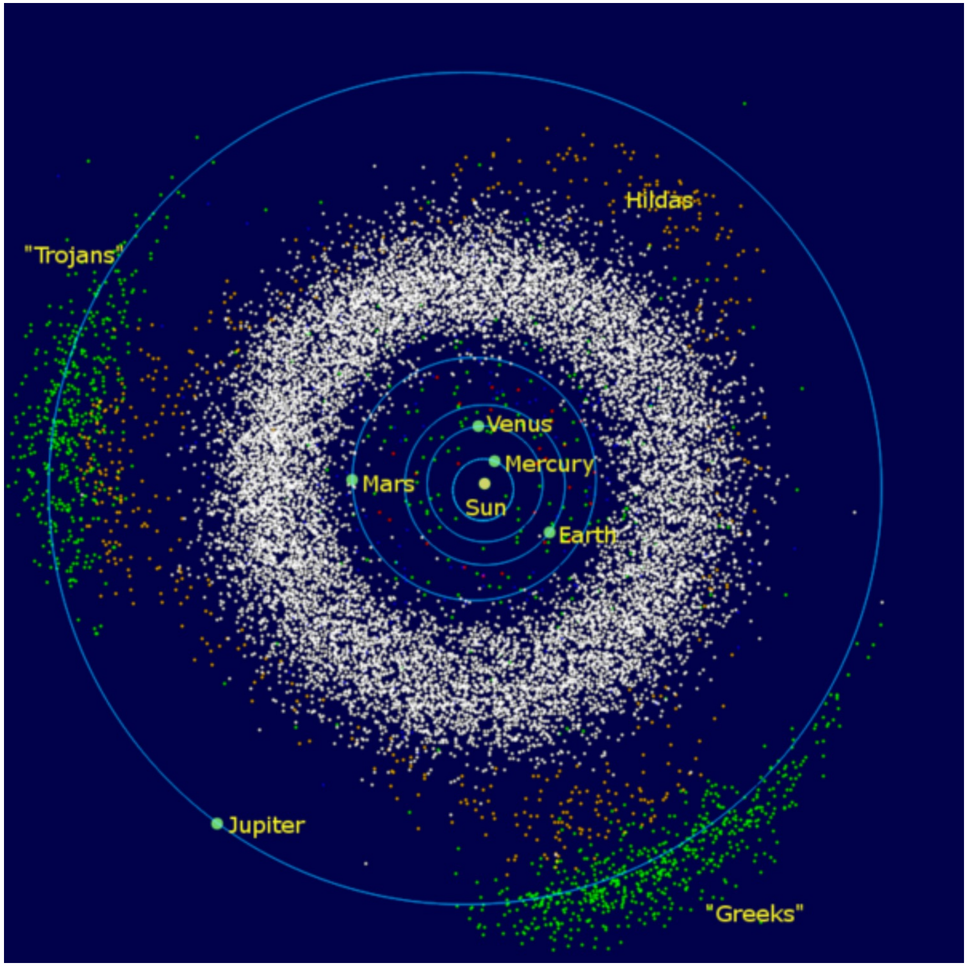
By Sidney Paget

" 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?

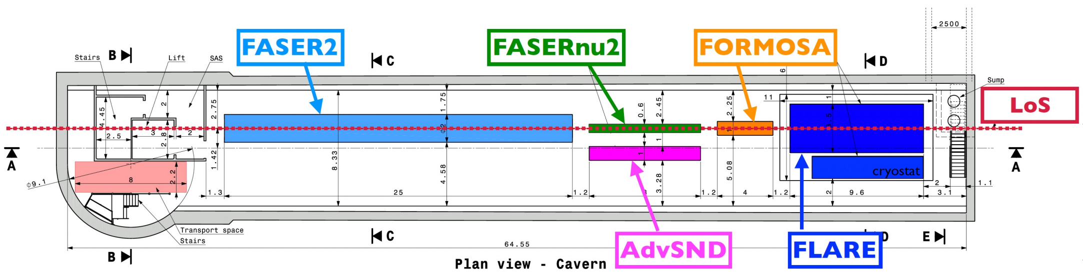
— Sherlock Holmes, The Valley of Fear

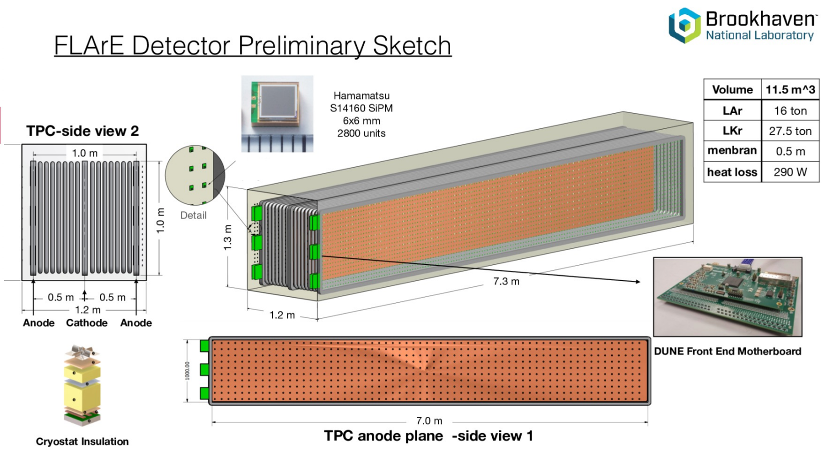
"The mor hazardous the asteroids, the better for fundamental Physics"
-- Professor Moriarty (maybe)



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

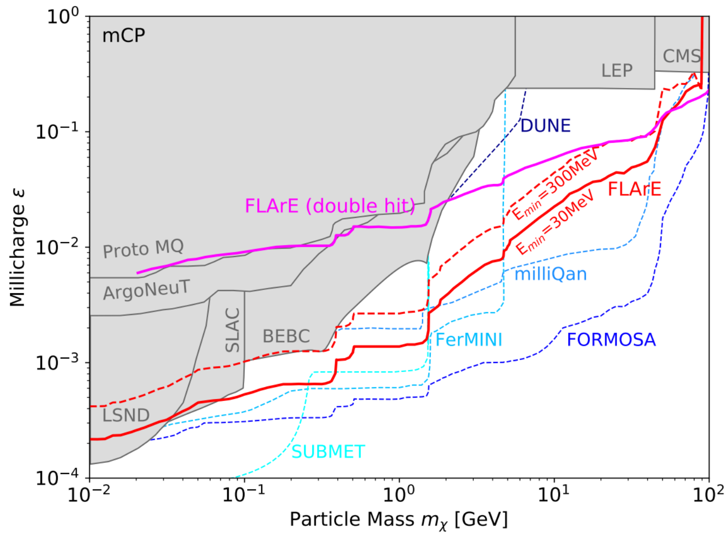
FLArE up millicharges & EM-form factor dark sector

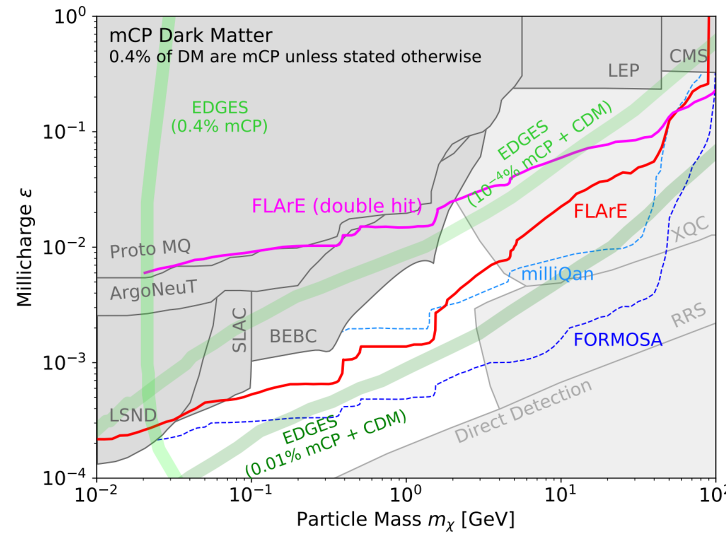




Batell, Feng, Trojanowski, PRD 21

Liquid Argon Detector lead by Diwan@BNL





Kling, Kuo, Trojanowski, Tsai, arXiv:2205.09137