

Asteroid astrometry as a fifth-force and ultralight dark sector probe

Yu-Dai Tsai,^{1,2,*} Youjia Wu,^{3,†} Sunny Vagnozzi,^{4,‡} and Luca Visinelli^{5,6,§}

¹*Fermi National Accelerator Laboratory (Fermilab), Batavia, IL 60510, USA*

²*Kavli Institute for Cosmological Physics (KICP), University of Chicago, Chicago, IL 60637, USA*

³*Leinweber Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109, USA*

⁴*Kavli Institute for Cosmology (KICC), University of Cambridge, Cambridge CB3 0HA, United Kingdom*

⁵*INFN, Laboratori Nazionali di Frascati, C.P. 13, I-100044 Frascati, Italy*

⁶*Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, 200240 Shanghai, China*

(Dated: August 20, 2021)

We study for the first time the possibility of probing long-range fifth forces utilizing asteroid astrometric data, via the fifth force-induced orbital precession. We examine nine Near-Earth Object (NEO) asteroids whose orbital trajectories are accurately determined via optical and radar astrometry. Focusing on a Yukawa-type potential mediated by a new gauge field (dark photon) or a baryon-coupled scalar, we estimate the sensitivity reach for the fifth-force coupling strength and mediator mass in the mass range $m \simeq 10^{-21} - 10^{-15}$ eV. Our estimated sensitivity is comparable to leading limits from torsion balance experiments, potentially exceeding these in a specific mass range. The fifth forced-induced precession increases with the orbital semi-major axis in the small m limit, motivating the study of objects further away from the Sun. We discuss future exciting prospects for extending our study to more than a million asteroids (including NEOs, main-belt asteroids, Hildas, and Jupiter Trojans), as well as trans-Neptunian objects and exoplanets.

Introduction — The study of precessions has revealed some of the deepest secrets of Nature. Most notably, the correct prediction for Mercury’s precession rate from General Relativity (GR) is one of the theory’s major successes [1–3]. The findings of the *Muon $g - 2$* experiment measuring the muon anomalous precession frequency might hint at the existence of physics beyond the Standard Model (SM) [4, 5]. New exciting connections between microscopic physics and macroscopic planetary science can be established by studying the precessions of celestial objects, due to long-range forces mediated by (new) ultralight particles.

There are strong motivations to investigate the existence of new light, weakly-coupled degrees of freedom beyond the SM, which are generic features of string theory [6–9], and are candidates for the dark matter (DM) and dark energy (DE) [10–14]. For example, ultralight (fuzzy) DM may play a significant role in shaping galactic structure [15–17], and DE could be in the form of a quintessential axion [18–20]. Efforts towards detecting the signatures of new light particles and their associated fifth forces range from laboratory and space tests [21–40] to cosmological [41–50] and astrophysical studies [51–61].

New studies of asteroids to probe fundamental physics are perfectly aligned with the NASA [62] and European Space Agency (ESA) [63] asteroid missions: in fact, for reasons including planetary defense purposes [64], the motion of asteroids is continuously and carefully monitored. These studies benefit from current and future radar and optical data, including from facilities and missions such as Arecibo (decommissioned), Goldstone, Catalina, the Vera Rubin Observatory (VRO), and Gaia [65–68]. However, such studies are not without challenges, as asteroid trajectories are subject to several per-

turbations, ranging from gravitational effects from other celestial objects, to non-gravitational effects due to the thermal and reflective properties of the asteroid’s surface. Recent advances in extracting physical parameters and detecting relevant physical processes (including the GR parameters, solar quadrupole moment, and Yarkovsky effect) from asteroid data, taking into account all these perturbations [69, 70], inspire us for the first time to examine the possibility of using the astrometric data to study new physics.

In this *Letter*, we provide the first proof-of-principle study using asteroid precessions and astrometric data to probe new ultralight particles. Previously, planets, exoplanets, and Kuiper Belt Objects (KBOs) were used to test GR and/or search for dark sector particles [71–90], yet the potential of probing new physics using asteroids remains mostly unharvested. Thanks to advances in radar and optical astrometry, the motion of asteroids, especially those classified as Near-Earth Objects (NEOs), is tracked much more precisely than KBOs and exoplanets. The use of asteroids over planets [91] also carries several advantages, ranging from their sheer number, to their spread in orbital radius allowing to probe a wide range of parameter space. Focusing on light mediators in the mass range $m \simeq 10^{-21} - 10^{-15}$ eV, we estimate the sensitivity reach of asteroid precessions to the mediator mass and coupling, which we find to be competitive with some of the most stringent torsion balance fifth-force constraints [21, 26, 28], and outline further steps to improve the analysis. Unlike GR, in the small m limit the precession contribution from a Yukawa-type potential grows with the asteroid’s semi-major axis, motivating studies of objects further away from the Sun. While we focus on gauged SM symmetries and baryon-coupled ultralight

scalars as concrete examples, our study is broadly applicable to various well-motivated new physics models.

We expect our study to open up new research directions aimed towards probing fundamental new physics from asteroid astrometry. We delineate the possibility of conducting similar studies using extended asteroid catalogs, Trans-Neptunian Objects (TNO), and exoplanets. The growing wealth of available optical and radar data would lead to significant improvements in our results.

Light particles and orbital precessions — We consider a celestial body of mass M_* orbiting the Sun, whose mass is M_\odot . At time t the radial, azimuthal, and polar components of the object's orbit are (r, φ, θ) . The object's motion is governed by the metric $g_{\mu\nu}$ and the following action:

$$S = -\frac{1}{c} \int d\tau \left[M_* c^2 \sqrt{-g_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau}} + \frac{dx^\nu}{d\tau} A_\nu \right], \quad (1)$$

where for a static observer at infinity the current components are $A_i = 0$ and $A_0 = V(r)$, with $V(r)$ being the potential associated to the fifth force mediated by a new light particle, and τ being proper time. We take $V(r)$ to be of the Yukawa form:

$$V(r) = \tilde{\alpha} \frac{GM_\odot M_*}{r} \exp\left(-\frac{r}{\lambda}\right), \quad (2)$$

where r is the distance between the centre of masses of the object and the Sun, $\tilde{\alpha} > 0$ ($\tilde{\alpha} < 0$) is the coupling strength for repulsive (attractive) interactions, and λ is the Yukawa force range. This potential leads to deviations from the body's Newtonian orbit, introducing (alongside GR effects) an orbital precession.

For our analytical estimation we consider planar motion and fix $\theta = \pi/2$. Adopting the inverse radius variable $u \equiv 1/r = u(\varphi)$ and extremizing the action in Eq. (1), we obtain the orbit's fundamental equation (in SI units) [91]:

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

where L is the orbital angular momentum per unit mass. The first term on the right-hand side of Eq. (3) is at the origin of corrections due to GR effects, while the second term leads to fifth force-induced corrections. Solving Eq. (3) numerically determines the fifth force-induced precession which, upon comparison to observations, can be used to constrain the fifth-force coupling strength given a mediator mass.

Examples to which our study can be applied include gauged $U(1)_B$ [92, 93], $U(1)_{B-L}$ [94–96], $L_\mu - L_{e,\tau}$ [97–99], and baryon-coupled scalar [100–103] models. The Yukawa potential associated to the light mediator is:

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

where g and m are the coupling strength and mediator mass respectively. For illustrative purposes, we shall focus on the mediator being either a gauged $U(1)_B$ dark photon or an ultralight scalar coupled to baryon number. The coupling is given by $g = g_{\phi, A'}$ for either a scalar (ϕ) or vector (A') mediator, whose mass is $m = m_{\phi, A'}$. In this phenomenological study, we assume no self-interaction for the scalar. Moreover, $Q_* \equiv M_*/m_p$ and $Q_\odot \equiv M_\odot/m_p$ are the celestial object and Sun total baryon numbers respectively, with m_p the proton mass. The gauged $U(1)_B$ has a chiral anomaly, and anomaly cancellation can be achieved for example by introducing additional particles with their corresponding constraints [104, 105] and invoking extra model building [106–108]. We focus on the asteroid phenomenology of these models and we emphasize again that our method is not limited to the $U(1)_B$ dark photon and baryon-coupled scalar mediators case studies.

Method — We specialize to asteroids being the celestial objects of interest. Our goal is to estimate the sensitivity reach for the coupling strength and mediator mass of a Yukawa-type fifth force, using the induced orbital precession. To this end, we focus on nine asteroids with precise radar and optical trajectory determinations, studied in detail in Ref. [69]. These asteroids are NEOs with $a \in [0.64, 1.08]$ au and $e \in [0.48 - 0.90]$.

We are condensing the impact of the fifth force into the induced orbital precession. A fully-fledged analysis entails *a*) computing the fifth-force impact on the asteroid trajectory via an appropriate integrator, accounting for perturbations from all nearby objects, and *b*) using raw astrometric measurements of the asteroid's trajectory to constrain the fifth force. As this is the first time a study of this type is being performed, our aim is simply to estimate the fifth-force sensitivity reach, to lay the foundations for future analyses.

Various effects contribute to asteroid orbital precession, two contributors being GR effects and solar oblateness [69]. These two effects contribute to the perihelion precession as measured from a fixed reference direction per orbital period, for an orbit of semi-major axis a , eccentricity e , and inclination with respect to the solar equator i_{eq} , as [109]:

$$\Delta\varphi_0 = \frac{6\pi GM_\odot}{a(1-e^2)c^2} \left[\frac{2-\beta+2\gamma}{3} \right] + 3\pi R_\odot^2 \frac{2-3\sin^2 i_{\text{eq}}}{2a^2(1-e^2)^2} J_2, \quad (5)$$

where R_\odot is the solar radius, J_2 is the solar quadrupole moment [110], and γ, β are the two parameterized post-Newtonian parameters, both equal to 1 in GR [111], with deviations from unity tightly constrained by Solar System probes [112–114]. We verified that the precession cross-contribution from both J_2 and $\tilde{\alpha}$ is sub-dominant.

To estimate the fifth-force sensitivity reach, we impose that the new physics contribution to the orbital precession in Eq. (6) does not exceed the uncertainty budget

associated to the two major precession contributors β and J_2 (as $|1 - \gamma|$ is more tightly constrained than $|1 - \beta|$). We lean upon the results of Ref. [69], who estimated the sensitivity to β and J_2 obtainable from a fully-fledged analysis of the 9 asteroids: the analysis was based on the Mission Operations and Navigation Toolkit Environment (MONTE) software [115], which numerically integrates the orbit equations of motion, using a dynamical model including gravitational perturbations from nearby celestial objects and accounting for Yarkovsky drift [116].

We obtain the precession $\Delta\varphi$ by numerically solving Eq. (3) with initial conditions $u(0) = [a(1 - e)]^{-1}$ and $u'(0) = 0$, corresponding to an elliptic orbit with eccentricity e and at its perihelion for $\varphi = 0$. The induced precession is estimated by expressing $u = [a(1 - e^2)]^{-1}[1 + e \cos \varphi(1 - \delta)]$, solving for δ , and deriving the precession as $\Delta\varphi = 2\pi\delta/(1 - \delta)$. The new physics contribution is then $\Delta\varphi_{\phi, A'}(g_{\phi, A'}, m_{\phi, A'}) = \Delta\varphi - \Delta\varphi_{\text{GR}}$.

The very light mediator limit $m \ll \hbar/ac$ admits an analytical expression for the fifth force-induced precession, obtained by expanding around the exponential term:

$$|\Delta\varphi_{\phi, A'}| \simeq \frac{2\pi}{1 + \frac{g^2}{4\pi G m_p^2}} \frac{g^2}{4\pi G m_p^2} \left(\frac{amc}{\hbar}\right)^2 (1 - e). \quad (6)$$

We stress that we *do not* use this approximation to estimate our sensitivity reach, but numerically solve Eq. (3), later verifying that Eq. (6) holds when $mc \ll \hbar/a$. Note that the precession goes to zero in the limit $m \rightarrow 0$ where the Newtonian $1/r$ potential is recovered. In this limit $|\Delta\varphi_{\phi, A'}| \propto a^2$, which carries a different functional dependence on a compared to the GR and the solar oblateness contributions. Therefore, studying objects within a wide range of a and e can help differentiate the contributions from these terms.

Note that $\left|\frac{\partial\Delta\varphi_0}{\partial\beta}\right| \sigma_\beta \sim \left|\frac{\partial\Delta\varphi_0}{\partial J_2}\right| \sigma_{J_2}$, meaning both parameters are determined to comparable levels as far as precessions are concerned, and we want to estimate the range of uncertainty for the new physics coupling g at a given m . We therefore require that the new physics precession contribution does not exceed the uncertainty budget associated to β and J_2 :

$$\Delta\varphi_{\phi, A'}^2 < \left|\frac{\partial\Delta\varphi_0}{\partial\beta}\right|^2 \sigma_\beta^2 + \left|\frac{\partial\Delta\varphi_0}{\partial J_2}\right|^2 \sigma_{J_2}^2 + 2\rho \left|\frac{\partial\Delta\varphi_0}{\partial\beta}\right| \left|\frac{\partial\Delta\varphi_0}{\partial J_2}\right| \sigma_{J_2} \sigma_\beta. \quad (7)$$

The above inequality is a function of the fifth-force parameters $g_{\phi, A'}$ and $m_{\phi, A'}$, and values thereof for which the inequality is saturated determine our estimated sensitivity reach. We repeat these steps for each of the 9 asteroids, obtaining 9 separate (but comparable) limits in the $m - g$ plane. We implicitly assume that the central values of the measured orbital precessions are consistent with the expectations given GR and all nearby perturbers modelled in Ref. [69], and therefore that there is no detection of fifth force, whose contribution accordingly must not exceed the precession uncertainty budget. In other

words, our analysis is akin to a forecast around a fiducial model with no fifth force.

A covariance analysis of the nine asteroids based on a 2022 sensitivity projection infers $\sigma_\beta = 5.6 \times 10^{-4}$ and $\sigma_{J_2} = 2.7 \times 10^{-8}$, and a correlation coefficient $\rho = -0.72$, with a Monte Carlo forecast recovering comparable figures [69]. We base our sensitivity reach estimate on the 2022 values to reflect the current sensitivity. We also present an estimate based on the ‘‘optimistic’’ 2022 values $\sigma_\beta = 2 \times 10^{-4}$ and $\sigma_{J_2} = 10^{-8}$ reported in Ref. [69].

Results and Discussion — In Fig. 1 we show the estimated sensitivity to the $U(1)_B$ dark photon and baryon-coupled ultralight scalar couplings, as a function of their masses. In these examples, all the baryons in the Sun and the asteroids are charged and the specific compositions thereof do not affect our results. Three specific asteroids, i.e. TU3, MN, and BD19, deliver the strongest projected limits (see Fig. 2 in the Appendix for the sensitivity reaches for each of the asteroids), given by the solid curve in the figure (whereas the dashed curve shows a stronger sensitivity reach based on the optimistic projection described earlier). We have chosen to report the *tightest* sensitivity reach since all 9 curves are comparable. Unsurprisingly, the peak sensitivity is achieved for mediator masses approximately corresponding to the (inverse) orbital radius of each asteroid. On the same figure, we also mark the regions corresponding to typical orbital radii of other (non-NEO) asteroids and TNOs. Finally, we note that the inferred sensitivity to the fifth-force coupling strength and mediator mass within the $U(1)_B$ model can easily be converted to other long-range forces, including those associated to gauged $U(1)_{B-L}$ and $L_e - L_{\mu, \tau}$ symmetries, following Refs. [117, 118].

For a fixed coupling strength and mediator mass, the repulsive (attractive) force from a vector dark photon (scalar) mediator would yield a precession of essentially equal magnitude, as we have checked numerically, resulting in Eq. (7) delivering identical sensitivity reaches. A fully-fledged analysis of the raw asteroid astrometric data should account for the different sign in the precession contribution, and might therefore return different constraints for the two cases.

Also shown in Fig. 1 are existing leading bounds from torsion balance [21, 26, 28], black hole superradiance [119], and precessions of planets [91]. Lunar Laser Ranging (LLR) [23, 120] provides the leading bound for masses $\gtrsim 10^{-16}$ eV and is included for completeness. Only the vector superradiance bound is present since the scalar superradiance one requires further studies on supermassive black holes, owing to large uncertainties due to their environments. We emphasize that, unlike existing laboratory constraints and other derived bounds, asteroids offer an actual probe of fifth forces with range beyond the au scale. For torsion-balance tests, for example, more complex long-range force models may be invoked to bypass these constraints [14].

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 $a(1 - e) < 1.3$ au.

Prospects for advancing our understanding of these nine asteroids, including their hazardous or complex nature, are bright. For example, the binary-asteroid system (66391) 1999 KW4/Moshup is a potential threat to Earth due to its orbital trajectory, and is the subject of intense studies [121].

Conclusions and Future Prospects — Our work is among the first attempts at connecting fundamental new physics and planetary dynamical data. Focusing on nine near-Earth asteroids, our analysis provides a general recipe and sensitivity reach estimate for long-range fifth forces induced by ultralight mediators. Follow-up works in which exciting opportunities would entail are detailed below.

New target objects — There are opportunities to extend our study to $\mathcal{O}(10^6)$ minor planets, classified in Table I. Including asteroids and comets, there are ~ 25000 NEOs (comets are less ideal for our study since they are subject to strong non-gravitational perturbations), a significant number of which have orbits that can be tracked to a similar level of precision as the nine asteroids considered. Among these nine asteroids, the one whose trajectory is determined to lowest accuracy is 2004 KH17, whose semi-major axis is nonetheless measured to $\simeq 1$ km precision. Currently ~ 1800 NEOs have orbits known to comparable or higher accuracy: 247 of these has been analyzed to study Yarkovsky drift [70]. Neglecting systematics, ~ 1800 NEOs can potentially improve our sensitivity reach by more than 1 order of magnitude.

Beyond NEOs, other asteroids including main-belt asteroids (M), Hildas (H), and Jupiter Trojans (JT) can be used for similar studies. These asteroids are still of great interest: with larger semi-major axes, their sensitivity reaches would peak at lower mediator masses, allowing us to probe lighter dark-sector particles. Achieving precision comparable to NEOs might be challenging, but spacecraft ranging could provide data with precision rivalling/surpassing radar observations: for example, the LUCY space mission [122] will provide precision data for

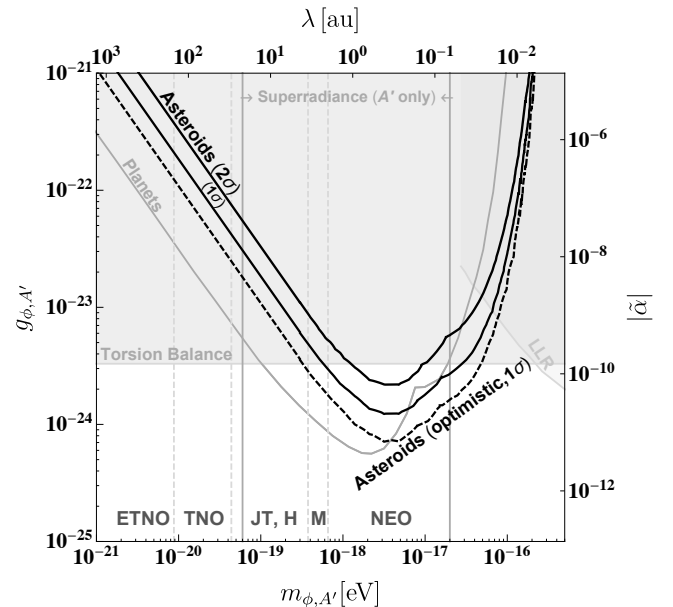


FIG. 1. Estimated sensitivity reach for the mass and coupling strength of $U(1)_B$ dark photons and baryon-coupled scalars, obtained by studying the precessions of nine NEO asteroids with $a \in [0.64, 1.08]$ au and $e \in [0.48 - 0.90]$. The solid black curve shows the tightest 1σ and 2σ sensitivity reaches from asteroids TU3, MN, and BD19, while the dashed black curve is the 1σ sensitivity reach based on the optimistic 2022 projection of Ref. [69]. Existing comparable constraints include those from planets [91], torsion balance [28], and vector superradiance [56], the latter is only applicable to the dark photon A' . LLR [23] provides the leading bound for masses $\gtrsim 10^{-16}$ eV and is included for completeness.

Trojan asteroids.

TNOs and ETNOs, residing in the outer Solar System, are of extreme interest owing to their trajectories being subject to significantly less gravitational perturbations and solar thermal effects. Their large semi-major axes mean they can be used to probe ultra-light mediators at even lower masses. All these objects are labelled in Fig. 1 according to their typical semi-major axes.

New observations — Radar studies including Goldstone and the recently decommissioned Arecibo [65] have been collecting high-precision NEOs astrometrical data. VRO will discover a factor of 5 more Solar System minor objects (see Table 1 of [67]), while other optical sky surveys such as Catalina [66], Pan-STARRS [123], ATLAS [124], DECam [125], and ZTF [126] will also be of great use to such studies. High precision astrometry is also achievable with space-based telescopes such as Hubble [127], James Webb [128], Euclid [129], and Roman [130]. The LUCY space mission [122] will visit Trojan asteroids and the JANUS spacecraft will investigate two binary asteroids [131, 132], providing valuable information to extend our study thereto. New astrometrical techniques such as occultation can substantially im-

prove orbital trajectory determinations [133]. Asteroids also affect gravitational-wave detections through gravity gradient noise [134].

Data storage and dedicated software development — Our work motivates the study and inclusion of precession measurements for objects stored in the JPL small objects [135] and Minor Planet Center [136] databases. On the analysis side, a fully-fledged study entails re-analyzing the (raw) astrometric asteroid trajectory data. Dedicated computing platforms such as MONTE [115], self-consistently modelling all relevant effects (including gravitational perturbations from nearby objects), can be used to this end, after appropriate modification to include the fifth-force effect. We expect this to be an important task for future studies [137].

Theory — Our study can be viewed as an investigation of a specific example of deviations from GR and/or the SM. Of course, the method can be extended to test other theories of gravity (e.g. [138–142]), or other types of dark-sector models [100, 143–150], by computing their effects on the dynamics of celestial objects [137]. Also, one can consider the asteroid tracking arrays (ATAs), similar to the pulsar timing arrays (PTAs), to study gravitational waves and other fundamental physics.

Final outlook — We expect to open up a new field aimed towards probing fundamental physics from astrometric data for minor planets in the inner and outer Solar System. More generally, alongside seminal works [71–90], we have only just begun exploring the full potential of connections between microscopic new physics and macroscopic planetary observations, from near (NEOs) to far (exoplanets) celestial objects.

ACKNOWLEDGMENTS

We thank Alex Drlica-Wagner, Davide Farnocchia, Adam Greenberg, Nick Gnedin, Marco Micheli, Matthew Payne, Darryl Seligman, Leo Stein, and Quanzhi Ye for useful discussions regarding asteroid studies, and astronomy and planetary observations in general. We also thank Masha Baryakhtar, Nikita Blinov, Cedric Delaunay, Robert Lasenby, Tanmay Kumar Poddar, Tracy Slatyer, Yotam Soreq, Liantao Wang, Yue Zhang, and Yue Zhao for discussions regarding ultralight dark sector studies. We are grateful to Yuval Grossman, Marco Micheli, and Darryl Seligman for their invaluable comments on our draft.

This document was prepared by Y-D.T. using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by the Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Y-D.T. also thanks KICP, University of Chicago, for hospitality. Y.W. acknowledges support from an MICDE Catalyst grant at University of Michigan, DoE grant DE- SC007859, and

the LCTP at the University of Michigan. S.V. is supported by the Isaac Newton Trust and the Kavli Foundation through a Newton-Kavli Fellowship, and by a grant from the Foundation Blanceflor Boncompagni Ludovisi, née Bildt. S.V. acknowledges a College Research Associateship at Homerton College, University of Cambridge. L.V. acknowledges support from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 754496 (H2020-MSCA-COFUND-2016 FELLINI).

APPENDIX

Our method estimates a sensitivity reach for each of the nine individual asteroids, as shown in Fig. 2 in the mass-coupling plane. It is clear that the spread in sensitivity reach is small and the results are comparable across all asteroids.

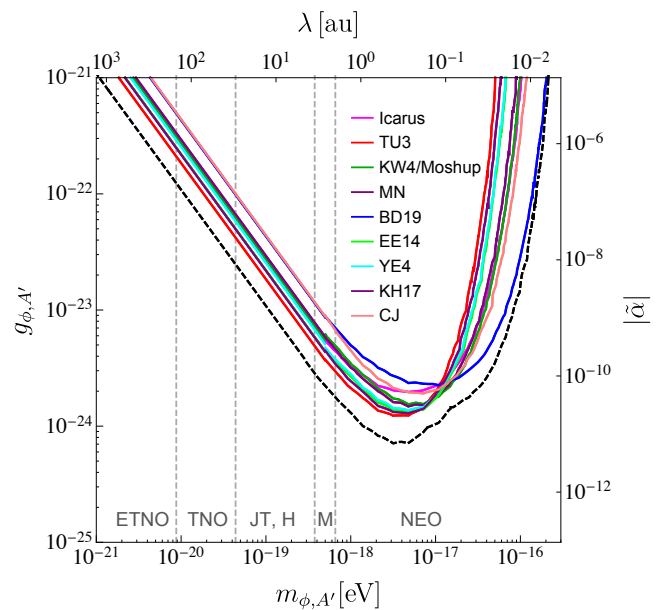


FIG. 2. Estimated sensitivity reach from each of the 9 asteroids (solid colored curves), and leading sensitivity reach based on the optimistic projection in Ref. [69] (dashed black curve). Asteroids are new probes of long-range forces in the \sim au range. The sensitivity can be improved by investigating an additional \sim 25000 NEOs. Long-range forces at larger distances can be studied using main-belt asteroids (M), Jupiter Trojans (JT), Hildas (H), TNOs, and ETNOs, as discussed in the main text.

* yt444@cornell.edu
† youjiawu@umich.edu
‡ sunny.vagnozzi@ast.cam.ac.uk
§ luca.visinelli@sjtu.edu.cn

[1] U.J. Le Verrier, *Theorie du mouvement de Mercure*, *Annales de l’Observatoire de Paris* **5** (1859) 1.

- [2] A. Einstein, *The Foundation of the General Theory of Relativity*, *Annalen Phys.* **49** (1916) 769.
- [3] C. Corda, *The secret of planets' perihelion between Newton and Einstein*, *Phys. Dark Univ.* **32** (2021) 100834.
- [4] MUON G-2 collaboration, *Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL*, *Phys. Rev. D* **73** (2006) 072003 [[hep-ex/0602035](#)].
- [5] MUON G-2 collaboration, *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, *Phys. Rev. Lett.* **126** (2021) 141801 [[2104.03281](#)].
- [6] P. Svrcek and E. Witten, *Axions In String Theory*, *JHEP* **06** (2006) 051 [[hep-th/0605206](#)].
- [7] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper and J. March-Russell, *String Axiverse*, *Phys. Rev. D* **81** (2010) 123530 [[0905.4720](#)].
- [8] M. Cicoli, M. Goodsell and A. Ringwald, *The type IIB string axiverse and its low-energy phenomenology*, *JHEP* **10** (2012) 146 [[1206.0819](#)].
- [9] L. Visinelli and S. Vagnozzi, *Cosmological window onto the string axiverse and the supersymmetry breaking scale*, *Phys. Rev. D* **99** (2019) 063517 [[1809.06382](#)].
- [10] R.D. Peccei, J. Sola and C. Wetterich, *Adjusting the Cosmological Constant Dynamically: Cosmons and a New Force Weaker Than Gravity*, *Phys. Lett. B* **195** (1987) 183.
- [11] C. Wetterich, *Cosmology and the Fate of Dilatation Symmetry*, *Nucl. Phys. B* **302** (1988) 668 [[1711.03844](#)].
- [12] B. Ratra and P.J.E. Peebles, *Cosmological Consequences of a Rolling Homogeneous Scalar Field*, *Phys. Rev. D* **37** (1988) 3406.
- [13] C. Wetterich, *Probing quintessence with time variation of couplings*, *JCAP* **10** (2003) 002 [[hep-ph/0203266](#)].
- [14] J. Khoury and A. Weltman, *Chameleon cosmology*, *Phys. Rev. D* **69** (2004) 044026 [[astro-ph/0309411](#)].
- [15] W. Hu, R. Barkana and A. Gruzinov, *Cold and fuzzy dark matter*, *Phys. Rev. Lett.* **85** (2000) 1158 [[astro-ph/0003365](#)].
- [16] L. Hui, J.P. Ostriker, S. Tremaine and E. Witten, *Ultralight scalars as cosmological dark matter*, *Phys. Rev. D* **95** (2017) 043541 [[1610.08297](#)].
- [17] P. Mocz et al., *First star-forming structures in fuzzy cosmic filaments*, *Phys. Rev. Lett.* **123** (2019) 141301 [[1910.01653](#)].
- [18] J.E. Kim and H.P. Nilles, *A Quintessential axion*, *Phys. Lett. B* **553** (2003) 1 [[hep-ph/0210402](#)].
- [19] M. Ibe, M. Yamazaki and T.T. Yanagida, *Quintessence Axion Revisited in Light of Swampland Conjectures*, *Class. Quant. Grav.* **36** (2019) 235020 [[1811.04664](#)].
- [20] G. Choi, W. Lin, L. Visinelli and T.T. Yanagida, *Cosmic Birefringence and Electroweak Axion Dark Energy*, **2106.12602**.
- [21] Y. Su, B.R. Heckel, E.G. Adelberger, J.H. Gundlach, M. Harris, G.L. Smith et al., *New tests of the universality of free fall*, *Phys. Rev. D* **50** (1994) 3614.
- [22] C.D. Hoyle, D.J. Kapner, B.R. Heckel, E.G. Adelberger, J.H. Gundlach, U. Schmidt et al., *Sub-millimeter tests of the gravitational inverse-square law*, *Phys. Rev. D* **70** (2004) 042004 [[hep-ph/0405262](#)].
- [23] J.G. Williams, S.G. Turyshev and D.H. Boggs, *Progress in lunar laser ranging tests of relativistic gravity*, *Phys. Rev. Lett.* **93** (2004) 261101 [[gr-qc/0411113](#)].
- [24] D.F. Mota and D.J. Shaw, *Evading Equivalence Principle Violations, Cosmological and other Experimental Constraints in Scalar Field Theories with a Strong Coupling to Matter*, *Phys. Rev. D* **75** (2007) 063501 [[hep-ph/0608078](#)].
- [25] P. Brax, C. van de Bruck, A.-C. Davis, D.F. Mota and D.J. Shaw, *Detecting chameleons through Casimir force measurements*, *Phys. Rev. D* **76** (2007) 124034 [[0709.2075](#)].
- [26] S. Schlamminger, K.Y. Choi, T.A. Wagner, J.H. Gundlach and E.G. Adelberger, *Test of the equivalence principle using a rotating torsion balance*, *Phys. Rev. Lett.* **100** (2008) 041101 [[0712.0607](#)].
- [27] P. Brax and G. Pignol, *Strongly Coupled Chameleons and the Neutronic Quantum Bouncer*, *Phys. Rev. Lett.* **107** (2011) 111301 [[1105.3420](#)].
- [28] T.A. Wagner, S. Schlamminger, J.H. Gundlach and E.G. Adelberger, *Torsion-balance tests of the weak equivalence principle*, *Class. Quant. Grav.* **29** (2012) 184002 [[1207.2442](#)].
- [29] C. Burrage, E.J. Copeland and E.A. Hinds, *Probing Dark Energy with Atom Interferometry*, *JCAP* **03** (2015) 042 [[1408.1409](#)].
- [30] R. Foot and S. Vagnozzi, *Diurnal modulation signal from dissipative hidden sector dark matter*, *Phys. Lett. B* **748** (2015) 61 [[1412.0762](#)].
- [31] MADMAX WORKING GROUP collaboration, *Dielectric Haloscopes: A New Way to Detect Axion Dark Matter*, *Phys. Rev. Lett.* **118** (2017) 091801 [[1611.05865](#)].
- [32] L. Perivolaropoulos, *Submillimeter spatial oscillations of Newton's constant: Theoretical models and laboratory tests*, *Phys. Rev. D* **95** (2017) 084050 [[1611.07293](#)].
- [33] C. Burrage and J. Sakstein, *Tests of Chameleon Gravity*, *Living Rev. Rel.* **21** (2018) 1 [[1709.09071](#)].
- [34] P. Touboul et al., *MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle*, *Phys. Rev. Lett.* **119** (2017) 231101 [[1712.01176](#)].
- [35] L. Perivolaropoulos and L. Kazantzidis, *Hints of modified gravity in cosmos and in the lab?*, *Int. J. Mod. Phys. D* **28** (2019) 1942001 [[1904.09462](#)].
- [36] C. Blanco, M. Escudero, D. Hooper and S.J. Witte, *Z' mediated WIMPs: dead, dying, or soon to be detected?*, *JCAP* **11** (2019) 024 [[1907.05893](#)].
- [37] ADMX collaboration, *Extended Search for the Invisible Axion with the Axion Dark Matter Experiment*, *Phys. Rev. Lett.* **124** (2020) 101303 [[1910.08638](#)].
- [38] L. Di Luzio, M. Giannotti, E. Nardi and L. Visinelli, *The landscape of QCD axion models*, *Phys. Rept.* **870** (2020) 1 [[2003.01100](#)].
- [39] I.M. Bloch, A. Caputo, R. Essig, D. Redigolo, M. Sholapurkar and T. Volansky, *Exploring new physics with O(keV) electron recoils in direct detection experiments*, *JHEP* **01** (2021) 178 [[2006.14521](#)].
- [40] S. Vagnozzi, L. Visinelli, P. Brax, A.-C. Davis and J. Sakstein, *Direct detection of dark energy: the XENON1T excess and future prospects*, **2103.15834**.
- [41] R. Hlozek, D. Grin, D.J.E. Marsh and P.G. Ferreira, *A search for ultralight axions using precision cosmological data*, *Phys. Rev. D* **91** (2015) 103512 [[1410.2896](#)].

- [42] D. Baumann, D. Green, J. Meyers and B. Wallisch, *Phases of New Physics in the CMB*, *JCAP* **01** (2016) 007 [1508.06342].
- [43] F. D’Eramo, R.Z. Ferreira, A. Notari and J.L. Bernal, *Hot Axions and the H_0 tension*, *JCAP* **11** (2018) 014 [1808.07430].
- [44] SIMONS OBSERVATORY collaboration, *The Simons Observatory: Science goals and forecasts*, *JCAP* **02** (2019) 056 [1808.07445].
- [45] S. Vagnozzi, *New physics in light of the H_0 tension: An alternative view*, *Phys. Rev. D* **102** (2020) 023518 [1907.07569].
- [46] S. Vagnozzi, L. Visinelli, O. Mena and D.F. Mota, *Do we have any hope of detecting scattering between dark energy and baryons through cosmology?*, *Mon. Not. Roy. Astron. Soc.* **493** (2020) 1139 [1911.12374].
- [47] D. Green et al., *Messengers from the Early Universe: Cosmic Neutrinos and Other Light Relics*, *Bull. Am. Astron. Soc.* **51** (2019) 159 [1903.04763].
- [48] M. Escudero Abenza, *Precision early universe thermodynamics made simple: N_{eff} and neutrino decoupling in the Standard Model and beyond*, *JCAP* **05** (2020) 048 [2001.04466].
- [49] W. Giarè, E. Di Valentino, A. Melchiorri and O. Mena, *New cosmological bounds on hot relics: Axions & Neutrinos*, *Mon. Not. Roy. Astron. Soc.* **505** (2021) 2703 [2011.14704].
- [50] E. Di Valentino, O. Mena, S. Pan, L. Visinelli, W. Yang, A. Melchiorri et al., *In the Realm of the Hubble tension – a Review of Solutions*, **2103.01183**.
- [51] B. Jain, V. Vikram and J. Sakstein, *Astrophysical Tests of Modified Gravity: Constraints from Distance Indicators in the Nearby Universe*, *Astrophys. J.* **779** (2013) 39 [1204.6044].
- [52] A. Arvanitaki, M. Baryakhtar and X. Huang, *Discovering the QCD Axion with Black Holes and Gravitational Waves*, *Phys. Rev. D* **91** (2015) 084011 [1411.2263].
- [53] M. Giannotti, I. Irastorza, J. Redondo and A. Ringwald, *Cool WISPs for stellar cooling excesses*, *JCAP* **05** (2016) 057 [1512.08108].
- [54] R. Foot and S. Vagnozzi, *Solving the small-scale structure puzzles with dissipative dark matter*, *JCAP* **07** (2016) 013 [1602.02467].
- [55] A. Caputo, J. Zavala and D. Blas, *Binary pulsars as probes of a Galactic dark matter disk*, *Phys. Dark Univ.* **19** (2018) 1 [1709.03991].
- [56] M. Baryakhtar, R. Lasenby and M. Teo, *Black Hole Superradiance Signatures of Ultralight Vectors*, *Phys. Rev. D* **96** (2017) 035019 [1704.05081].
- [57] M.J. Stott and D.J.E. Marsh, *Black hole spin constraints on the mass spectrum and number of axionlike fields*, *Phys. Rev. D* **98** (2018) 083006 [1805.02016].
- [58] R. Roy and U.A. Yajnik, *Evolution of black hole shadow in the presence of ultralight bosons*, *Phys. Lett. B* **803** (2020) 135284 [1906.03190].
- [59] D. Croon, S.D. McDermott and J. Sakstein, *New physics and the black hole mass gap*, *Phys. Rev. D* **102** (2020) 115024 [2007.07889].
- [60] M.J. Stott, *Ultralight Bosonic Field Mass Bounds from Astrophysical Black Hole Spin*, **2009.07206**.
- [61] H. Desmond, J. Sakstein and B. Jain, *Five percent measurement of the gravitational constant in the Large Magellanic Cloud*, *Phys. Rev. D* **103** (2021) 024028 [2012.05028].
- [62] J.L. Gustetic, V. Friedensen, J.L. Kessler, S. Jackson and J. Parr, *Nasa’s asteroid grand challenge: Strategy, results, and lessons learned*, *Space Policy* **44-45** (2018) 1–13.
- [63] “The european space agency: Science and exploration.” https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Asteroids, 2021.
- [64] S.J. Ostro et al., *Radar Imaging of Binary Near-Earth Asteroid (66391) 1999 KW₄*, *Science* **314** (2006) 1276.
- [65] S.P. Naidu, L.A.M. Benner, J.-L. Margot, M.W. Busch and P.A. Taylor, *Capabilities of Earth-based Radar Facilities for Near-Earth Asteroid Observations*, *Astrophys. J.* **152** (2016) 99 [1604.01080].
- [66] S.G. Djorgovski et al., *The Catalina Real-Time Transient Survey (CRTS)*, **1102.5004**.
- [67] Vera C. Rubin Observatory LSST Solar System Science Collaboration, R.L. Jones, M.T. Bannister, B.T. Bolin, C.O. Chandler, S.R. Chesley et al., *The Scientific Impact of the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST) for Solar System Science*, *arXiv e-prints* (2020) arXiv:2009.07653 [2009.07653].
- [68] B. Carry et al., *Potential asteroid discoveries by the esa gaia mission*, *Astron. Astrophys.* **648** (2021) A96.
- [69] A.K. Verma, J.-L. Margot and A.H. Greenberg, *Prospects of Dynamical Determination of General Relativity Parameter β and Solar Quadrupole Moment $J_{2\odot}$ with Asteroid Radar Astronomy*, *Astrophys. J.* **845** (2017) 166 [1707.08675].
- [70] A.H. Greenberg, J.-L. Margot, A.K. Verma, P.A. Taylor and S.E. Hodge, *Yarkovsky drift detections for 247 near-earth asteroids*, *The Astronomical Journal* **159** (2020) 92.
- [71] L. Iorio, *On the effects of the Dvali-Gabadadze-Porrati braneworld gravity on the orbital motion of a test particle*, *Class. Quant. Grav.* **22** (2005) 5271 [gr-qc/0504053].
- [72] S.L. Adler, *Planet-bound dark matter and the internal heat of Uranus, Neptune, and hot-Jupiter exoplanets*, *Phys. Lett. B* **671** (2009) 203 [0808.2823].
- [73] A. Jordan and G.A. Bakos, *Observability of the General Relativistic Precession of Periastra in Exoplanets*, *Astrophys. J.* **685** (2008) 543 [0806.0630].
- [74] L. Iorio, *Classical and relativistic long-term time variations of some observables for transiting exoplanets*, *Mon. Not. Roy. Astron. Soc.* **411** (2011) 167 [1007.2780].
- [75] D. Hooper and J.H. Steffen, *Dark Matter And The Habitability of Planets*, *JCAP* **07** (2012) 046 [1103.5086].
- [76] L. Iorio, *Constraints on a MOND effect for isolated aspherical systems in the deep Newtonian regime from orbital motions*, *Class. Quant. Gravit.* **30** (2013) 165018 [1211.3688].
- [77] J. Overduin, J. Mitcham and Z. Warecki, *Expanded solar-system limits on violations of the equivalence principle*, *Class. Quant. Grav.* **31** (2014) 015001 [1307.1202].
- [78] L. Iorio, *Post-Keplerian corrections to the orbital periods of a two-body system and their measurability*, *Mon. Not. Roy. Astron. Soc.* **460** (2016) 2445

- [1407.5021].
- [79] A. Ain, S. Kastha and S. Mitra, *Stochastic Gravitational Wave Background from Exoplanets*, *Phys. Rev. D* **91** (2015) 124023 [1504.01715].
- [80] K. Masuda and Y. Suto, *Transiting planets as a precision clock to constrain the time variation of the gravitational constant*, *Publ. Astron. Soc. Jap.* **68** (2016) L5 [1602.02513].
- [81] L. Blanchet, G. Hébrard and F. Larrouturou, *Detecting the General Relativistic Orbital Precession of the Exoplanet HD 80606b*, *Astron. Astrophys.* **628** (2019) A80 [1905.06630].
- [82] J. Bramante, A. Buchanan, A. Goodman and E. Lodhi, *Terrestrial and Martian Heat Flow Limits on Dark Matter*, *Phys. Rev. D* **101** (2020) 043001 [1909.11683].
- [83] B. Sun, Z. Cao and L. Shao, *Constraints on fifth forces through perihelion precession of planets*, *Phys. Rev. D* **100** (2019) 084030 [1910.05666].
- [84] R. Garani and P. Tinyakov, *Constraints on Dark Matter from the Moon*, *Phys. Lett. B* **804** (2020) 135403 [1912.00443].
- [85] J. Scholtz and J. Unwin, *What if Planet 9 is a Primordial Black Hole?*, *Phys. Rev. Lett.* **125** (2020) 051103 [1909.11090].
- [86] M.L. Ruggiero and L. Iorio, *Probing a r^{-n} modification of the Newtonian potential with exoplanets*, *JCAP* **06** (2020) 042 [2001.04122].
- [87] M.H. Chan and C.M. Lee, *Constraining the spin-independent elastic scattering cross section of dark matter using the Moon as a detection target and the background neutrino data*, *Phys. Rev. D* **102** (2020) 023024 [2007.01589].
- [88] R.K. Leane and J. Smirnov, *Exoplanets as Sub-GeV Dark Matter Detectors*, *Phys. Rev. Lett.* **126** (2021) 161101 [2010.00015].
- [89] H. Wei and Z.-X. Yu, *Inverse Chameleon Mechanism and Mass Limits for Compact Stars*, **2103.12696**.
- [90] R.K. Leane and T. Linden, *First Analysis of Jupiter in Gamma Rays and a New Search for Dark Matter*, **2104.02068**.
- [91] T. Kumar Poddar, S. Mohanty and S. Jana, *Constraints on long range force from perihelion precession of planets in a gauged $L_e - L_{\mu,\tau}$ scenario*, *Eur. Phys. J. C* **81** (2021) 286 [2002.02935].
- [92] C.D. Carone and H. Murayama, *Possible light $U(1)$ gauge boson coupled to baryon number*, *Phys. Rev. Lett.* **74** (1995) 3122 [hep-ph/9411256].
- [93] P. Fileviez Perez and M.B. Wise, *Baryon and lepton number as local gauge symmetries*, *Phys. Rev. D* **82** (2010) 011901 [1002.1754].
- [94] A. Davidson, *$B - L$ as the fourth color within an $SU(2)_L \times U(1)_R \times U(1)$ model*, *Phys. Rev. D* **20** (1979) 776.
- [95] R.N. Mohapatra and R.E. Marshak, *Local $B-L$ Symmetry of Electroweak Interactions, Majorana Neutrinos and Neutron Oscillations*, *Phys. Rev. Lett.* **44** (1980) 1316.
- [96] A. Davidson and K.C. Wali, *Universal Seesaw Mechanism?*, *Phys. Rev. Lett.* **59** (1987) 393.
- [97] R. Foot, *New Physics From Electric Charge Quantization?*, *Mod. Phys. Lett. A* **6** (1991) 527.
- [98] X.-G. He, G.C. Joshi, H. Lew and R.R. Volkas, *Simplest Z -prime model*, *Phys. Rev. D* **44** (1991) 2118.
- [99] M. Escudero, D. Hooper, G. Krnjaic and M. Pierre, *Cosmology with A Very Light $L_\mu - L_\tau$ Gauge Boson*, *JHEP* **03** (2019) 071 [1901.02010].
- [100] N. Blinov, S.A.R. Ellis and A. Hook, *Consequences of Fine-Tuning for Fifth Force Searches*, *JHEP* **11** (2018) 029 [1807.11508].
- [101] S. Sibiryakov, P. Sørensen and T.-T. Yu, *BBN constraints on universally-coupled ultralight scalar dark matter*, *JHEP* **12** (2020) 075 [2006.04820].
- [102] E. Izaguirre, G. Krnjaic and M. Pospelov, *Probing New Physics with Underground Accelerators and Radioactive Sources*, *Phys. Lett. B* **740** (2015) 61 [1405.4864].
- [103] M. Pospelov and Y.-D. Tsai, *Light scalars and dark photons in Borexino and LSND experiments*, *Phys. Lett. B* **785** (2018) 288 [1706.00424].
- [104] J.A. Dror, R. Lasenby and M. Pospelov, *New constraints on light vectors coupled to anomalous currents*, *Phys. Rev. Lett.* **119** (2017) 141803 [1705.06726].
- [105] J.A. Dror, R. Lasenby and M. Pospelov, *Dark forces coupled to nonconserved currents*, *Phys. Rev. D* **96** (2017) 075036 [1707.01503].
- [106] M.B. Green and J.H. Schwarz, *Anomaly Cancellation in Supersymmetric $D=10$ Gauge Theory and Superstring Theory*, *Phys. Lett. B* **149** (1984) 117.
- [107] D.B. Kaplan, *Flavor at SSC energies: A New mechanism for dynamically generated fermion masses*, *Nucl. Phys. B* **365** (1991) 259.
- [108] A. Pierce, K. Riles and Y. Zhao, *Searching for Dark Photon Dark Matter with Gravitational Wave Detectors*, *Phys. Rev. Lett.* **121** (2018) 061102 [1801.10161].
- [109] L. Iorio, *Advances in the measurement of the Lense-Thirring effect with planetary motions in the field of the Sun*, *Schol. Res. Exch.* **2008** (2008) 105235 [0807.0435].
- [110] C.W. Misner, K.S. Thorne and J.A. Wheeler, *Gravitation*, W. H. Freeman, San Francisco (1973).
- [111] C.M. Will and K. Nordtvedt, Jr., *Conservation Laws and Preferred Frames in Relativistic Gravity. I. Preferred-Frame Theories and an Extended PPN Formalism*, *Astrophys. J.* **177** (1972) 757.
- [112] S.C. Solomon et al., *The MESSENGER mission to Mercury: scientific objectives and implementation*, *Planet. Space Sci.* **49** (2001) 1445.
- [113] B. Bertotti, L. Iess and P. Tortora, *A test of general relativity using radio links with the Cassini spacecraft*, *Nature* **425** (2003) 374.
- [114] D.E. Smith et al., *Gravity Field and Internal Structure of Mercury from MESSENGER*, *Science* **336** (2012) 214.
- [115] S. Evans et al., *MONTE: the next generation of mission design and navigation software*, *CEAS Space Journal* **10** (2018) 79.
- [116] G is measured independently from cold-atom experiments and other techniques to 2×10^{-5} relative standard uncertainty [151, 152].
- [117] E.G. Adelberger, B.R. Heckel, S.A. Hoedl, C.D. Hoyle, D.J. Kapner and A. Upadhye, *Particle Physics Implications of a Recent Test of the Gravitational Inverse Square Law*, *Phys. Rev. Lett.* **98** (2007) 131104 [hep-ph/0611223].
- [118] P. Fayet, *MICROSCOPE limits on the strength of a new force, with comparisons to gravity and*

- electromagnetism, *Phys. Rev. D* **99** (2019) 055043 [1809.04991].
- [119] M. Baryakhtar, M. Galanis, R. Lasenby and O. Simon, *Black hole superradiance of self-interacting scalar fields*, *Phys. Rev. D* **103** (2021) 095019 [2011.11646].
- [120] T.W. Murphy, *Lunar laser ranging: the millimeter challenge*, *Rept. Prog. Phys.* **76** (2013) 076901 [1309.6294].
- [121] “Jpl small-body database browser - 66391 moshup (1999 kw4).” <https://ssd.jpl.nasa.gov/sbdb.cgi?sstr=1999+KW4&orb=1>, 2021.
- [122] C.B. Olkin et al., *Lucy Mission to the Trojan Asteroids: Instrumentation and Encounter Concept of Operations*, *arXiv e-prints* (2021) arXiv:2104.04575 [2104.04575].
- [123] L. Denneau et al., *The Pan-STARRS Moving Object Processing System*, *Publ.Astron.Soc.Pac.* **125** (2013) 357 [1302.7281].
- [124] J.L. Tonry et al., *ATLAS: A High-cadence All-sky Survey System*, *Publ.Astron.Soc.Pac.* **130** (2018) 064505 [1802.00879].
- [125] N. Golovich, N. Lifset, R. Armstrong, E. Green, M.D. Schneider and R. Pearce, *A New Blind Asteroid Detection Scheme*, **2104.03411**.
- [126] M.J. Graham et al., *The zwicky transient facility: Science objectives*, *Publ.Astron.Soc.Pac.* **131** (2019) 078001.
- [127] A.A. Parfeni, L.I. Caramete, A.M. Dobre and N. Tran Bach, *Detection of asteroid trails in Hubble Space Telescope images using Deep Learning*, *arXiv e-prints* (2020) arXiv:2010.15425 [2010.15425].
- [128] A.S. Rivkin, F. Marchis, J.A. Stansberry, D. Takir and C. Thomas, *Asteroids and the james webb space telescope*, *Publ. Astron. Soc. Pac.* **128** (2016) 018003.
- [129] B. Carry, *Solar system science with esa euclid*, *Astron. Astrophys.* **609** (2018) A113.
- [130] R. Akeson, L. Armus, E. Bachelet, V. Bailey, L. Bartusek, A. Bellini et al., *The Wide Field Infrared Survey Telescope: 100 Hubbles for the 2020s*, *arXiv e-prints* (2019) arXiv:1902.05569 [1902.05569].
- [131] C. Lewicki, A. Graps, M. Elvis, P. Metzger and A. Rivkin, *Furthering Asteroid Resource Utilization in the Next Decade through Technology Leadership*, *arXiv e-prints* (2021) arXiv:2103.02435 [2103.02435].
- [132] D. Seligman and K. Batygin, *The onset of chaos in permanently deformed binaries from spin-orbit and spin-spin coupling*, *The Astrophysical Journal* **913** (2021) 31.
- [133] J.N. Winn, *Transits and occultations*, 2014.
- [134] M.A. Fedderke, P.W. Graham and S. Rajendran, *Gravity Gradient Noise from Asteroids*, *Phys. Rev. D* **103** (2021) 103017 [2011.13833].
- [135] “Jpl small-body database search engine.” https://ssd.jpl.nasa.gov/sbdb_query.cgi, 2021.
- [136] “The international astronomical union minor planet center.” <https://www.minorplanetcenter.net/>, 2021.
- [137] Y.-D. Tsai, S. Vagnozzi, Y. Wu and L. Visinelli, *Fundamental Physics and Planetary Science*, in preparation (2021) .
- [138] P.G. Bergmann, *Comments on the scalar tensor theory*, *Int. J. Theor. Phys.* **1** (1968) 25.
- [139] M. Milgrom, *A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis.*, *Astrophys. J.* **270** (1983) 365.
- [140] T.P. Sotiriou and V. Faraoni, *f(R) Theories Of Gravity*, *Rev. Mod. Phys.* **82** (2010) 451 [0805.1726].
- [141] T. Clifton, P.G. Ferreira, A. Padilla and C. Skordis, *Modified Gravity and Cosmology*, *Phys. Rept.* **513** (2012) 1 [1106.2476].
- [142] S. Nojiri, S.D. Odintsov and V.K. Oikonomou, *Modified Gravity Theories on a Nutshell: Inflation, Bounce and Late-time Evolution*, *Phys. Rept.* **692** (2017) 1 [1705.11098].
- [143] D.E. Kaplan, G.Z. Krnjaic, K.R. Rehermann and C.M. Wells, *Atomic Dark Matter*, *JCAP* **05** (2010) 021 [0909.0753].
- [144] Y. Farzan and A.R. Akbarieh, *VDM: A model for Vector Dark Matter*, *JCAP* **10** (2012) 026 [1207.4272].
- [145] F.-Y. Cyr-Racine and K. Sigurdson, *Cosmology of atomic dark matter*, *Phys. Rev. D* **87** (2013) 103515 [1209.5752].
- [146] K. Petraki, L. Pearce and A. Kusenko, *Self-interacting asymmetric dark matter coupled to a light massive dark photon*, *JCAP* **07** (2014) 039 [1403.1077].
- [147] L. Randall and M. Reece, *Dark Matter as a Trigger for Periodic Comet Impacts*, *Phys. Rev. Lett.* **112** (2014) 161301 [1403.0576].
- [148] R. Foot and S. Vagnozzi, *Dissipative hidden sector dark matter*, *Phys. Rev. D* **91** (2015) 023512 [1409.7174].
- [149] Y.-D. Tsai, R. McGehee and H. Murayama, *Resonant Self-Interacting Dark Matter from Dark QCD*, **2008.08608**.
- [150] S. Knapen, T. Lin and K.M. Zurek, *Light Dark Matter: Models and Constraints*, *Phys. Rev. D* **96** (2017) 115021 [1709.07882].
- [151] G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli and G.M. Tino, *Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms*, *Nature* **510** (2014) 518 [1412.7954].
- [152] C. Xue, J.-P. Liu, Q. Li, J.-F. Wu, S.-Q. Yang, Q. Liu et al., *Precision measurement of the Newtonian gravitational constant*, *Natl. Sci. Rev.* **7** (2020) 1803.