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Topical: Towards gravity's frontiers

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1 The dark sector

General Relativity (GR) describes gravitation as the simple manifestation of spacetime's geometry, while recovering Newton's description of gravitation as a classical inverse-square law (ISL) force in weak gravitational fields and for velocities small compared to the speed of light. It has so far successfully passed all experimental tests [Will, 2014, Ishak, 2019].

The Standard Model (SM) was built from the realization that the microscopic world is intrinsically quantum. It is both highly predictive and efficient not only at describing the behavior of microscopic particles, but also at mastering key technologies. Increasingly large particle accelerators and detectors have allowed for the discovery of all particles predicted by the model, up to the Brout-Englert-Higgs boson [Aad et al., 2012, Chatrchyan et al., 2012].

Although both GR and SM leave few doubts about their validity in their respective regimes, difficulties have been lurking for decades. Firstly, the question of whether GR and the SM should and could be unified remains open. Major theoretical endeavors delivered models such as string theory, but still fail to provide a coherent, unified vision of our world. Secondly, unexpected components make up most of the Universe's mass-energy budget: dark matter and dark energy are the largest conundrums of modern fundamental physics.

Dark matter has been the intangible elephant in the room for nearly 90 years, since Zwicky [1933] pinpointed the problem of missing matter in the Coma galaxy cluster. Direct detection experimentations, based on putative electromagnetic or nuclear interaction between baryonic matter and well-motivated particle physics candidates for dark matter, remain blind to it despite its undeniable gravitational effects.

The observation of the accelerated expansion of the Universe [Riess et al., 1998, Perlmutter et al., 1999] and its confirmation by independent probes [Planck Collaboration et al., 2016, Abbott et al., 2018] marked the advent of dark energy, a dynamical, repulsive fluid. In the dark energy view, GR keeps its central role as the theory of gravitation, assumed valid on all scales while the content of the Universe is modified. The accelerated expansion can also be explained the other way around: no new component is added to the Universe, but GR is subsumed by a more general theory of gravitation that passes Solar System and laboratory tests while having a different behavior on cosmological scales.

Experimentally testing gravity and digging the dark sector is a fundamental, pressing question that can be assessed with upcoming space probes.

2 Shedding light on the local Galactic dark sector

2.1 Modified gravity and the Equivalence Principle

GR describes the gravitational force as mediated by a single rank-2 tensor field. There are good reasons to couple matter fields to gravity in this way, but there is no good reason to think that the field equation of gravity should not contain other fields. It is then possible to speculate on the existence of other such fields. The simplest way to go beyond GR and modify gravity is then to add an extra scalar field: such scalar-tensor theories are well established and studied theories of Modified Gravity [Damour and Esposito-Farese, 1992]. From a phenomenological point of view, scalar-tensor theories link the cosmic acceleration to a deviation from GR on large scales. They can therefore be seen as candidates to explain the accelerated rate of expansion without the need to consider dark energy as a physical component. Furthermore, they arise naturally as the dimensionally reduced effective theories of higher dimensional theories, such as string theory; hence, testing them can allow us to shed light on the low-energy limit of quantum gravity theories.

Scalar fields that mediate a long range force able to affect the Universe's dynamics should also significantly modify gravity in the Solar System, in such a way that GR should not have passed any experimental test. Screening mechanisms have been proposed to alleviate this difficulty [Joyce et al., 2015]. In these scenarios, (modified) gravity is environment-dependent, in such a way that gravity is modified at large scales (low density) but is consistent with the current constraints on GR at small scale (high density). Furthermore, extensions of the standard model group to an extra U(1) can lead to a new gauge boson mediating a fifth force effectively coupled to baryon and/or lepton numbers [Fayet, 1990], with a very weak intensity possibly related to the very large energy scale of inflation [Fayet, 2018]. These modified gravity models all predict the existence of a new, fifth force, that should be detectable through a violation of the ISL or of the equivalence principle.

2.2 Dark energy and gravitation's low-acceleration frontier

Baker et al. [2015] classify probes and experimental/observational tests of gravitation in the potential–curvature plane (Fig. 1). There, the potential ϵ and curvature ξ are loosely defined as the Newtonian gravitational potential and the Kretschmann scalar created by a spherical body. This plane is divided in four main regions:

- highest curvatures and potentials correspond to compact objects and can be tested with gravitational waves observatories
- smaller curvatures correspond to Solar System objects (small potential) and to Galactic center's S-stars (higher potential); the former can be tested with planets ephemeris and man-made spacecrafts, while the latter can be tested with Galactic center observations
- very small curvatures correspond to cosmological probes (galaxies, large scale structures) and can be tested e.g. with CMB observations or galaxy surveys
- a desert of probes and of tests lies between the Solar System scale tests and cosmological tests. All kind of speculation can be allowed in this regime, and we can easily imagine that gravitation enjoys a gradual change of regime between compact objects and Solar System scales ("high" curvature, where GR holds) and cosmological scales ("very low" curvature, where GR seems to break), without even needing any screening mechanism.

Past and current Solar System tests are shown by the "Earth S/C" symbols and the filled circles lying on the black slanted line (that stands for the Sun as the source of gravitation). It is clear that in order to barely approach the potential–curvature desert, we must precisely monitor how trans-Neptunian objects (either planetoids or spacecrafts) behave under the influence of the Sun's gravity. Having a test-mass at least 150 AU from the Sun would allow us to actually enter that uncharted desert.

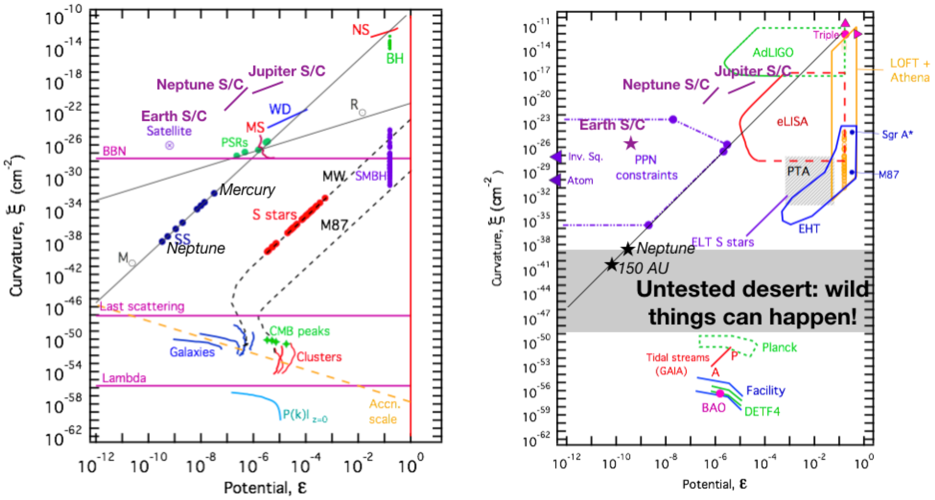

Figure 1: Gravitational potential–curvature plane. *Left*: Astrophysical, cosmological and experimental probes. *Right*: Observationally and experimentally tested regions are shown in color; the shaded region is the so called "desert", where no experimental is currently available, but where a new intermediate regime of gravitation could be found, bridging between GR at higher curvature and "dark energy gravitation" at smaller curvature. Figure adapted from Baker et al. [2015].

2.3 Dark matter density measurement

Although dark matter mostly interacts gravitationally with baryonic matter, direct detection may be possible via tiny non-gravitational signatures. Direct detection techniques aim to look for different species of dark matter: axions are looked for via their resonant conversion in an external magnetic field using microwave cavity experiments [Kuster et al., 2008], while WIMPs (Weakly Interactive Massive Particles) are expected to occasionally interact with heavy nuclei, creating a detectable nuclear recoil [Schumann, 2019]; light dark matter can be searched via scatters off electrons [Essig et al., 2012] or violations of the equivalence principle [Hees et al., 2018], while ultra-light dark matter can cause tiny but apparent oscillations in the fundamental constants that can cause minute variations in the frequency of atomic transitions [e.g. Hees et al., 2016] and a fifth force [e.g. Bergé et al., 2018].

For illustrative purpose, we now focus on the spin-independent direct detection of WIMPs, through the elastic scattering off nuclei. The differential rate for WIMP scattering is degenerate between the local WIMP density ρ_0 (an average of the Galactic dark matter halo density in a small region about the Solar System extrapolated to the laboratory) and the WIMP-nucleus differential cross-section. Therefore, were ρ_0 revised, current upper limits on the WIMP cross-section would be affected [Green, 2017]. Traditionally, ρ_0 is estimated e.g. (i) from the measurement of the rotation curve of the Galaxy, in relation of a model of the dark matter halo or (ii) from the observation of vertical motion of stars close to the Sun. We can in principle use these techniques by tracking a spacecraft in the Solar System, the spacecraft replacing the stellar tracers.

Since the measured ρ_0 must be extrapolated to the position of the Earth, the local homogeneity of the dark matter halo is an important point. In particular, any clump or stream of dark matter, as well as dark matter trapped by the Sun's potential [Peter, 2009] may bias the extrapolation. However, although dark matter simulations' resolution is no better than a dozen parsecs, we have good reasons to consider the local dark matter halo as homogeneous [Read, 2014]. Nevertheless, although measurements of ρ_0 relying on dark-matter-only simulation are very robust, adding baryons (which cannot be ignored) to the simulations significantly complicates things.

Better understanding the respective contributions and distributions of dark matter and baryons through experimental in-situ measurements is thus not only important for direct detection experiments (as it allows us to better estimate ρ_0) but also to improve our knowledge of our local environment. Although dark-matter-only simulations expect a smooth dark matter distribution, we could be surprised to discover small clumps, streams and passing clouds of dark matter.

3 Future space experiments

3.1 Weak Equivalence Principle (WEP)

The WEP can be simply tested through the universality of free fall, as done recently by the MICROSCOPE mission [Touboul et al., 2017]. Improving MICROSCOPE's accuracy by two orders of magnitude seems reachable with current technology (e.g. by improving its electrostatic accelerometer charge management, e.g. by adapting that of LISA Pathfinder [Armano et al., 2016]). Three test masses of different composition will enrich MICROSCOPE's test (which was limited to one pair of test masses) and allow for looking for a dependence of the WEP on the baryon composition.

Atomic accelerometers may also allow for more tests, not only of the WEP, but also of modified gravity in the satellite [Chiow and Yu, 2020, Loriani et al., 2020, Pernot-Borràs et al., 2021], while improving the precision of the electrostatic accelerometer, the bias of which can then be directly measured.

3.2 Low-acceleration gravitation

Gravitational potential and Einstein Equivalence Principle (EEP) The universal redshift of clocks when subjected to a gravitational potential is one of the key predictions of all metric theories of gravitation (including GR). It represents an aspect of the EEP often referred to as Local Position Invariance [Will, 2014], and it makes clocks direct probes of the gravitational potential. GR can thus be tested by measuring the frequency difference of two distant ideal clocks, e.g. one aboard an outbound Solar System probe and the other on Earth to maximize the potential difference between them.

Assuming that the Earth station motion and its local gravitational potential can be known and corrected to uncertainty levels below 10^{-17} in relative frequency (10 cm on geocentric distance), which are within present capabilities, then for an onboard clock similar to ACES' PHARAO, with a 10^{-17} bias [Reynaud et al., 2009], at a distance of 150 AU this corresponds to a test with a relative uncertainty of 10^{-9}, an improvement by almost four orders of magnitude on the uncertainty obtained by the currently most sensitive experiments [Delva et al., 2018, Herrmann et al., 2018].

Inverse Square Law violation A definitive deviation from the ISL can be detected as a deviation from the trajectory predicted by GR when taking into account the gravity of the Solar System's bodies. What is needed is an accurate orbit restitution, making sure that the spacecraft follows a geodesics. The former can be done through orbit tracking with Radio-Science, while the latter can be ensured with a drag-free spacecraft, whose trajectory is forced to be a geodesics by actively canceling non-gravitational forces; alternatively, we can measure the non-gravitational forces with a DC accelerometer, and correct for them when estimating the orbit, therefore not needing a drag-free spacecraft. Although a model of non-gravitational forces is commonly used to correct for them, we argue that no model can replace an empirical measurement, and hence that an accelerometer (or drag-free spacecraft) is needed to definitely confirm any measured deviation from the ISL.

The required accuracy of non-gravitational forces is driven by the accuracy on the orbit estimation and depends on the time of integration for the orbit restitution. As shown by Hees et al. [2012], a one-meter deviation from a Keplerian orbit can be detected in a few days, requiring a precision on non-gravitational forces of the order of 10^{-12} m/s^2. Getting down to such a precision would significantly improve the current constraints given by the Pioneer probes, which assumed a bias in acceleration of 10^{-10} m/s^2. A combination of electrostatic (such as those of the MICROSCOPE or GRACE missions) and cold atom accelerometers should allow for unprecedented constraints of the ISL on Solar System scales.

3.3 Dark matter: search and local density measurement

A payload made of clock and an accelerometer will detect inhomogeneities in the dark matter distribution. An accelerometer will be perfectly suited to measure the baryon distribution through the friction applied to the spacecraft, combining its measurements with ranging data should enable us to detect massive enough inhomogeneities in the gravitational field, possibly originating from dark matter clumps or streams.

Ultra-light dark matter can cause minute variations in the frequency of atomic transitions; an atomic clock going through such a cloud would be temporarily desynchronized compared to Earth-bound clocks [Derevianko and Pospelov, 2014, Wcisło et al., 2016, Roberts et al., 2017]. Moreover, if the clump is sufficiently massive, its crossing can be determined by the precise monitoring of the spacecraft's trajectory.

4 Conclusion

We discussed three related science objectives aimed at testing gravity and characterizing the dark sector in space. While the WEP and the EEP can be tested in the Earth neighborhood, testing gravity in its potential–curvature desert requires flying out of the Solar System. Measuring the dark matter local density can be accommodated with both experiments. A payload consisting of atomic clocks and accelerometers (electrostatic and atomic) can allow for those experiments. Mission concepts are detailed in Battelier et al. [2021] and Bergé et al. [2021].

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