Testing quantum effects of gravity and dark energy at laboratory scales

Kenath Arun[1], Avijeet Prasad[2], C Sivaram[3]

[1]Department of Physics & Electronics, CHRIST (Deemed to be University), Bangalore, India

[2]Institute of Theoretical Astrophysics, University of Oslo, Oslo, Norway

[3]Indian Institute of Astrophysics, Bangalore, India

Gravity and quantum mechanics

- One of the biggest challenges in modern physics is how to unify gravity with quantum theory.
- The current understanding of gravity is based on the general theory of relativity (in the framework of classical physics).
- However, this description is incomplete as quantum mechanics is considered to be more fundamental.
- Although there are several different approaches to the problem of quantizing gravity, fully consistent theory is yet to emerge.
- So far, the proposed tests of quantum effects of gravity have focussed on specific models, phenomenology, and cosmological observations.

Schulz, 1409.7977v1[gr-qc], 2014; Penrose, Gen. Rel. Grav. 28 (1996) 581; Kiefer, Annalen Phys. 15 (2005) 129; Hossenfelder, 1010.3420v1[gr-qc], 2010; Ashoorioon, Dev, Mazumdar, Mod. Phys. Lett. A 29 (2014) 1450163; Pikovski et al., Nature Phys. 8 (2012) 393; Albrecht, Retzker, Phys. Rev. A 90 (2014) 033834;

Gravity and quantum mechanics

- All fundamental forces – except gravity – have messenger particles.
- Similar messenger particle must exist for gravity (?) - hypothetical graviton.
- Graviton : gravity :: photon : electromagnetism
- GR requires them to follow the quantum mechanical description of interacting theoretical spin-2 massless particles.
- Many of the accepted unified theory assume the existence of graviton.
- An important theoretical step in quantum mechanical description of gravity,
- but generally believed to be undetectable because they interact too weakly.

Gupta, Rev. Mod. Phys. 29 (1957) 334; Deser, Gen. Rel. Grav. 1 (1970) 9; Rothman, Boughn, Found. Phys. 36 (2006) 1801

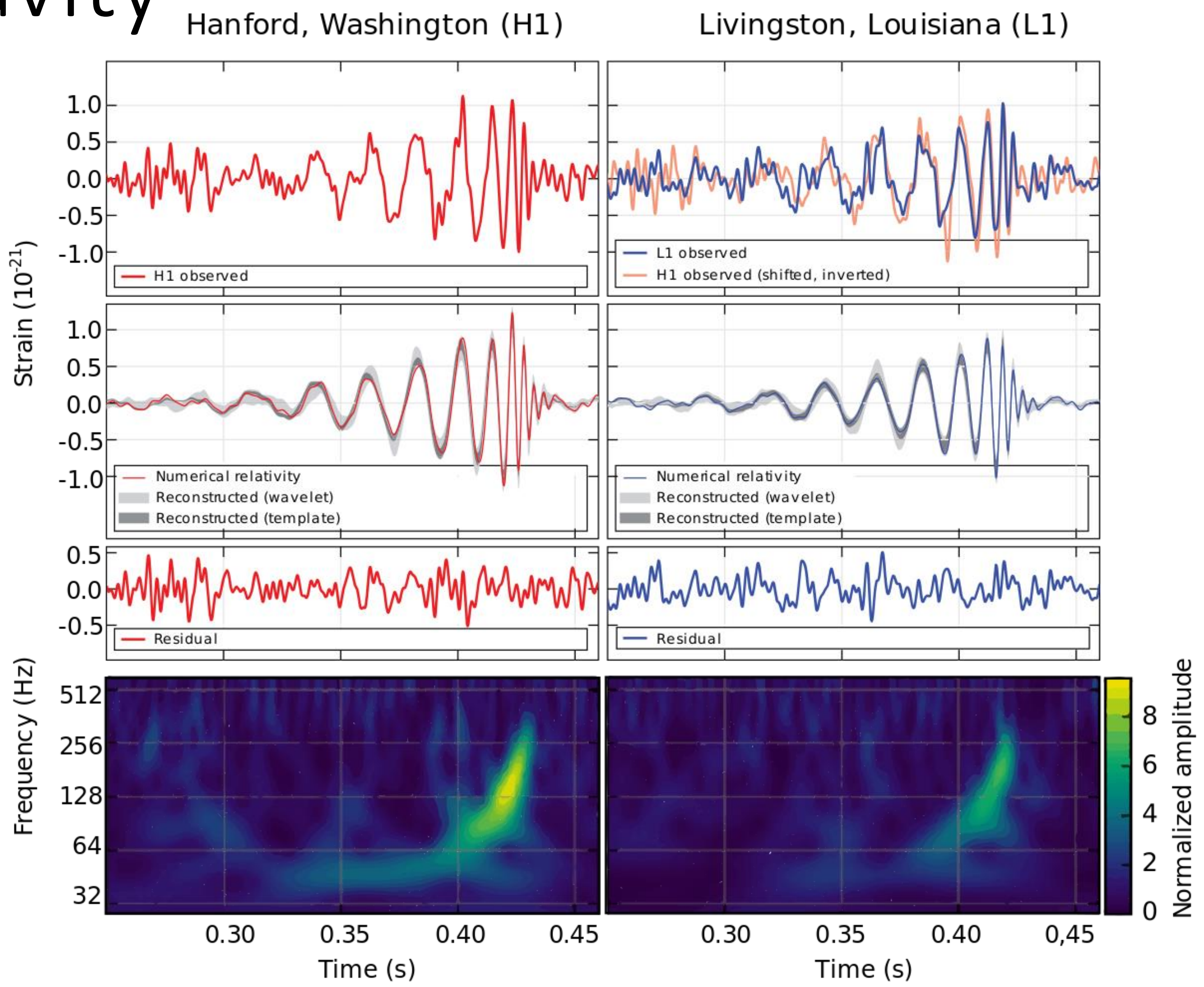
Planck scale

- Conventionally it is thought that the effects of quantum gravity occur only at high energies (Planck scale $\sim 10^{19} GeV$).
- Planck energies (or scales) are likely to remain inaccessible in the foreseeable future.
- The most intense laser intensity: $\sim 10^{26} W/m^2$
- Corresponding electric field of $\sim 10^{14} V/m$
- With this E, arm length of accelerator should be a few light-years to achieve Planck energies
- Even in cosmic rays we do not see such high energy particles (maximum energy being $\sim 10^{21} eV$).
- So we are left looking for testability at lower energies (laboratory scales).

Linsley, Phys. Rev. Lett. 10 (1963) 146

Classical theory of gravity

- Direct detection of gravitational waves from the merger of two black holes and neutron stars.



Abbott et al., Phys. Rev. Lett. 116 (2016) 061102; Abbott et al., Astrophys. J. 848 (2017) L12

Classical theory of gravity

- Laboratory experiments – tests of the equivalence principle, precision measurements of gravitational constant, validity of Newton’s law at micro-scales.
- New results – the gravitational coupling between two gold spheres of 1 millimetre radius – extends the gravity measurements to small, single source masses and to low gravitational field strengths
- This provides a viable path to explore a regime of gravitational physics that involves precision tests of gravity of microscopic masses at around the Planck mass $(\sim 10^{-5} g)$.
- This could help us in understanding how gravity fits with quantum mechanics on smaller scales.

Westphal et al., Nature 591 (2021) 225

Novel quantum effects of gravity

- Even in the absence of a complete theory, there are interesting implications of quantum gravity that are testable.
- There could be certain novel quantum effects of gravity that can become significant even at lower energies and could be tested at laboratory scales.
- Also leads to a few indirect effects of dark energy that can show up at laboratory scales.
- Consequently set observational constraints on radio recombination lines of the Rydberg atoms.
- High-precision measurements of Casimir effects for smaller plate separation could also show some manifestations of the presence of dark energy.

Quantum effects and modification of Newtonian gravity

- In a possible unified description (of gravity and quantum theory) the role of the uncertainty principle should be fundamental.
- Since quantum theory is more general (with classical theory being a special case).
- At smaller scales, the momentum increases and a wave packet of wavelength λ will have an effective mass given by $h\ /\ \lambda c$.
- A particle of mass m cannot be localized to a distance less than $h\ /\ mc$ (the spread of the wave packet).
- With particles' separation at r, the uncertainty principle implies their mutual gravitational force,

$$F = G\frac{\left(\frac{\hbar}{rc}\right)\left(\frac{\hbar}{rc}\right)}{r^2} = \frac{\hbar^2 G}{c^2}\frac{1}{r^4} = \frac{\hbar c}{r^4}\left(\frac{\hbar G}{c^3}\right)$$

de Sabbata, Sivaram, Borzeszkowski, Treder, Annalen Phys. 503 (1991) 497; Sivaram, Current Sci. 79 (2000) 413

Quantum effects and modification of Newtonian gravity

$$F = \frac{\hbar c L_{pl}^2}{r^4};\ L_{pl} = \sqrt{\frac{\hbar G}{c^3}}$$

- We have a $\frac{1}{r^4}$ dependence rather than the usual Newtonian $\frac{1}{r^2}$.
- At short distances, the gravitational force would be very different from the classical case - testing with smaller masses on smaller scales could shed some light on such quantum modifications of gravity.
- At the beta decay length ($r_\beta = 10^{-17} cm$), $F_\beta \approx 8 \times 10^{-15} dyne$.
- At proton Compton wavelength ($\sim 2 \times 10^{-14} cm$), force $\approx 5 \times 10^{-28} dyne$.
- Current experimental detection limit, $F_{limit} \approx 10^{-19} dyne$, $r_{limit} \approx 2 \times 10^{-16} cm$.

Biercuk, Nature Nanotech. 5 (2010) 646

Consequences for black holes

- This modification may also have consequences for avoiding the singularity in BHs.
- The particles can't be localized to smaller distances (due to the uncertainty principle).
- The force will be maximum at the Planck length, i.e. at $r = L_{pl}$

$$F_{max} = \frac{c^4}{G}$$

- This maximal force would imply a finite radius (for collapsing mass inside the horizon):

$$r_{min} = \left(\frac{GM}{a_{max}}\right)^{1/2}$$

a_{max} – the maximum acceleration (field strength) corresponding to F_{max}.

de Sabbata, C. Sivaram, Found. Phys. Lett. 6 (1993) 561; Sivaram, Arun, Astrophys. Space Sci. 337 (2012) 169; Sivaram, Astrophys. Space Sci. 167 (1990) 335

Rydberg atoms

- An excited atom with a very high principal quantum number, *n.*
- Common in interstellar space – density (best vacuum attainable)
- Reissner-Nordström solution for (particle of mass m and charge e) by including Λ (considered to be dark energy) in the energy-momentum tensor, we still have an exact solution (Kottler metric).
- This solution has $g_{00} = 1 - \frac{2Gm}{rc^2} + \frac{Ge^2}{c^4r^2} - \frac{\Lambda r^2}{3}$
- For electron mass, $m = m_e$, the second term is negligible.
- Third and fourth terms – the electrostatic and dark energy terms – become comparable $\left(\frac{Ge^2}{c^4r^2} = \frac{\Lambda r^2}{3}\right)$ for:

$$r^4 = \frac{3Ge^2}{\Lambda c^4} \Rightarrow r = \left(\frac{3Ge^2}{\Lambda c^4}\right)^{1/4} \approx 10^{-3} cm$$

Rydberg atoms

- Physically this would imply that for an electron, the two terms become comparable for a region of this extent.
- Rydberg atoms (those atoms with high principal quantum number, n) can have sizes of this order, with the atomic radius:

$$r = \frac{n^2\hbar^2}{m_e e^2} \approx n^2 r_B$$

- With $r \approx 10^{-3} cm$, it implies that $n < 10^3$.
- Rydberg atomic states well observed in astrophysics as radio recombination lines (transition energy involved are in the radio wavelengths).
- Highest n observed is around 700
- DE density and electrostatic energy density become comparable for atoms of this size, could be a possible reason why we do not observe higher n hydrogen recombination lines.

Sivaram, 1607.08114v1[gr-qc], 2016; Dunning et al., J. Phys. B: At. Mol. Opt. Phys. 42 (2009) 022001

Higher Z atoms

- The balance between electrostatic and dark energy would occur at: $r = \left(\frac{3GZe^2}{\Lambda c^4}\right)^{1/4}$
- For $Z = 12$, this would give about twice the radius, $r \approx 1.8 \times 10^{-3} cm$ as before.
- The size of the higher Z Rydberg atoms: $r = \frac{n^2\hbar^2}{m_e Z e^2}$
- The limiting n would have a dependence on the atomic number: $n \propto Z^{5/8}$
- For $Z = 12$, this limit on n would be $< (12)^{5/8} \times 10^3 \approx 4.7 \times 10^3$
- This is consistent with the highest observed carbon recombination lines.
- This balance of forces could be tested with experiments with single ions or electrons in devices like Penning traps etc.
- There could thus be manifestations of dark energy at laboratory scales.

Stepkin et al., Mon. Not. R. Astron. Soc. 374 (2007) 852

Casimir effect

- When tested over sub-micron scales could reveal anomalies or deviations from expected results due to quantum vacuum background.
- In Casimir effect, the force between two plates becomes significant, with the force per unit area

$$\frac{F_{Cas}}{A} = \frac{\pi^2 \hbar c}{240 r^4}$$

- This is a purely quantum effect independent of any coupling.
- With the background DE density, the force becomes important at a separation of $\sim 10^{-4} - 10^{-5} cm$.
- These effects can come under the purview of future high precision measurements of Casimir effect.
- Hence, when tested for smaller plate separation, could show some manifestation of the presence of the dark energy background.

Takeaways

- Novel quantum effects of gravity can be tested ***without having to achieve Planck energies***.
- Also the possibility of looking for ***effects of dark energy*** at ***atomic scales***.
- The possible tests for the ***quantum effects of gravity*** at laboratory scales include the ***manifestations of dark energy***.
- Consequences for atomic physics, with set constraints on the radio recombination lines of Rydberg atoms – ***which are consistent with observations***.
- Predict the limit of highest n for higher Z atoms will be higher, ***scaling as*** $\boldsymbol{Z^{5/8}}$.
- Future high-precision measurements of the Casimir effect with smaller plate separation, could also show some manifestations of dark energy, ***which are again testable***.

Sivaram, Arun, Prasad, doi:10.20944/preprints202105.0420.v1, 2021