Testing Einstein's equivalence principle near a supermassive black hole

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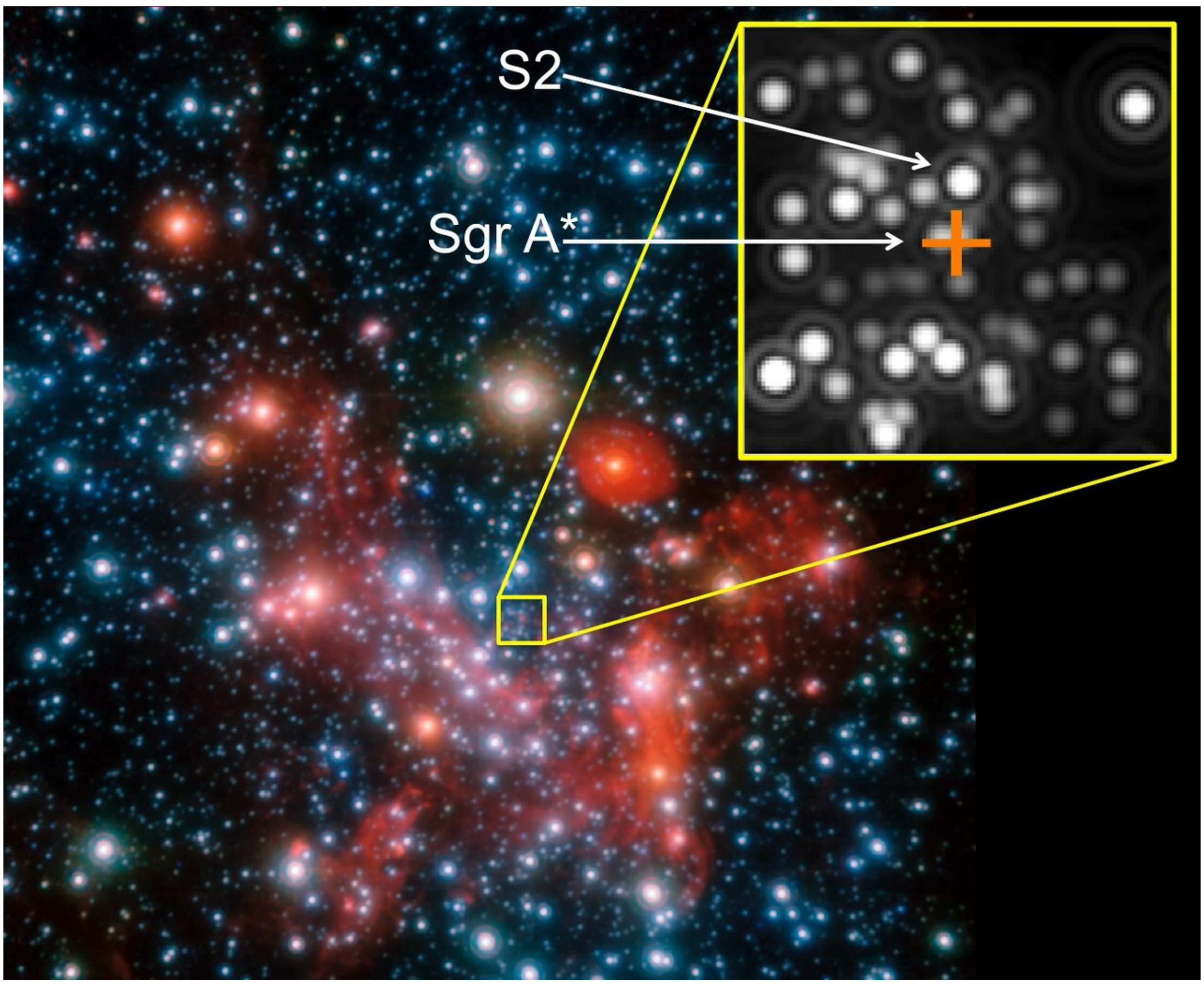

Image of the Galactic Centre. Credit: European Southern Observatory (ESO).

The GRAVITY Collaboration, a team of researchers at several renowned institutes including the Max Planck Institute, LESIA Paris Observatory and the European Southern Observatory, has recently tested part of the Einstein Equivalence Principle, namely the local positon invariance (LPI), near the galactic center supermassive black hole. Their study, published on Physics Review Letters (PRL), investigated the dependency of different atomic transitions on the gravitational potential in order to give an upper limit on LPI violations.

"General relativity and in general all metric theories of gravity are based on the equivalence of inertial mass and gravitational mass, formalized in the Einstein equivalence principle," Maryam Habibi, one of the researchers who carried out the study, told Phys.org. "General relativity is the best theory of gravity that we have, however, there are still many unanswered puzzles that are closely tied to our incomplete understanding of gravity."

The equivalence principle, a crucial part of Einstein's general relativity theory, states that the gravitational force experienced in any small region of space-time is the same as the pseudo-force experienced by an observer in an accelerated frame of reference. Testing this principle is of key importance, as it could lead to interesting observations and broaden our current understanding of gravity.

"Einstein's equivalence principle consists of three main principles," Habibi explained. "One of them, called the local position invariance (LPI), states that non-gravitational measurements should be independent of the location in space time (characterized by gravitational potential) where they are carried out. The main part of our study focuses on testing the LPI principle."

Past observations suggest that most, if not all, massive galaxies contain a supermassive black hole, which is typically located at the center of a galaxy. The mass of the Milky Way's galactic center supermassive black hole is 4 million times greater than that of the sun. It thus generates the strongest gravitational field in the galaxy, which makes it the ideal place to hunt for unexplored phenomena and test general relativity principles.

Star S2, one of the brightest stars in the Milky Way's innermost region, has its closest encounter with the galactic center supermassive black hole at a distance of 16.3 light hours. In other words, the star takes 16 years to make a complete orbit around the black hole, which in astronomical time scales is extremely short. S2 moves in and out of the black hole's gravitational field, hence the GRAVITY collaboration team decided to use it to test part of Einstein's equivalence principle.

"As it was predicted, and we showed in a previous study published in June 2018, during the closest approach of the star S2 to the black hole we observe the 'gravitational redshift' in the light of the star," Habibi explained. "Gravitational redshift occurs because intense gravity on the star's surface slows the vibration of light waves, stretching them and making the star appear redder than normal from Earth."

To test Einstein's LPI principle, the researchers used two different types of atoms in S2's stellar atmosphere: hydrogen and helium atoms. The LPI principle states that the gravitational redshift seen in a star that is flying in and out of a strong gravitational field only depends on the gravitational potential and does not rely on other parameters, such as the internal structure of the atom.

Image shows one of the Unit Telescopes of ESO's Very Large Telescope (VLT) array, pointing a laser beam towards the Milky Way to create an artificial star. Credit: European Southern Observatory (ESO).

"We measured the frequency change of light from these atoms moving through a varying potential," Habibi said. "The vibration of light waves was measured by fitting the line-of-sight velocity of the S2's spectrum using the Hydrogen and Helium spectral lines separately. By measuring the difference in frequency change for both atoms we were able to give an upper limit on the LPI violation during the pericenter passage. If there was an obvious violation of LPI, we should have measured very different vibration of light waves, from the helium and hydrogen lines."

The equivalence principle and general relativity at large are merely theories, thus they need to be tested in order to ascertain their validity. So far, most researchers have carried out tests on Earth and in the solar system.

However, these theories should also be tested in extreme scenarios, as this can determine whether they still hold and lead to more conclusive evidence. Such tests could rule out some of the principles that shape our current understanding of gravity or identify violations from the theory of general relativity.

"Testing the equivalence principle in all different regimes is important as several alternative theories of gravitation predict a violation from it under extreme conditions," Felix Widmann, another researcher involved in the study, told Phys.org. "For me the most meaningful finding of our study is that we were able to test the equivalence principle in this most extreme case: close to a supermassive black hole that is over 20 thousand light years away. The limits we put on a violation are not very restrictive yet, but they are in a gravitational regime that was completely untested before."

Habibi, Widmann and their colleagues were among the first to test part of the equivalence principle near the Milky Way's central supermassive black hole. Their work provides valuable insight about the validity of general relativity, particularly the LPI principle.

"The past year was exceptionally successful for the GRAVITY collaboration," Widmann said. "For the first time, we observed relativistic effects in the orbit of a star around a supermassive black hole and used this star to test the Equivalence Principle. We also observed material orbiting very close to the black hole, another observation which would have been impossible without GRAVITY. However, this is more of a start than an end for us."

With the optimal season for galactic center observation just around the corner, the researchers at GRAVITY collaboration will continue to point their telescopes to S2 and the galactic center supermassive black hole. According to Widmann, the team might soon be able to detect subtler relativistic effects in the orbit of S2, which will allow them to test the theory of general relativity once again. In their future observations, the researchers also hope that they will see more flare activity around the black hole, as this would enable further studies aimed at broadening their understanding of the Milky Way's galactic center black hole and black holes in general.

"With future telescopes like the Extremely Large Telescope, which has a mirror of 39m in diameter, we will be able to perform similar experiments and look for 1 million times smaller effects of possible violations of LPI, compared to what it is possible today," Widmann added. "This will allow us to test the other part of Einstein's equivalence principle, called weak equivalence principle, which states that an object in gravitational free fall is physically equivalent to an object that is accelerating with the same amount of force in the absence of gravity. The galactic center is a unique observatory and with GRAVITY and future telescopes we want to learn as much about it as possible."

More information: A. Amorim et al. Test of the Einstein Equivalence Principle near the Galactic Center Supermassive Black Hole, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.122.101102

Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole, *Astronomy & Astrophysics* (2018). DOI: 10.1051/0004-6361/201833718