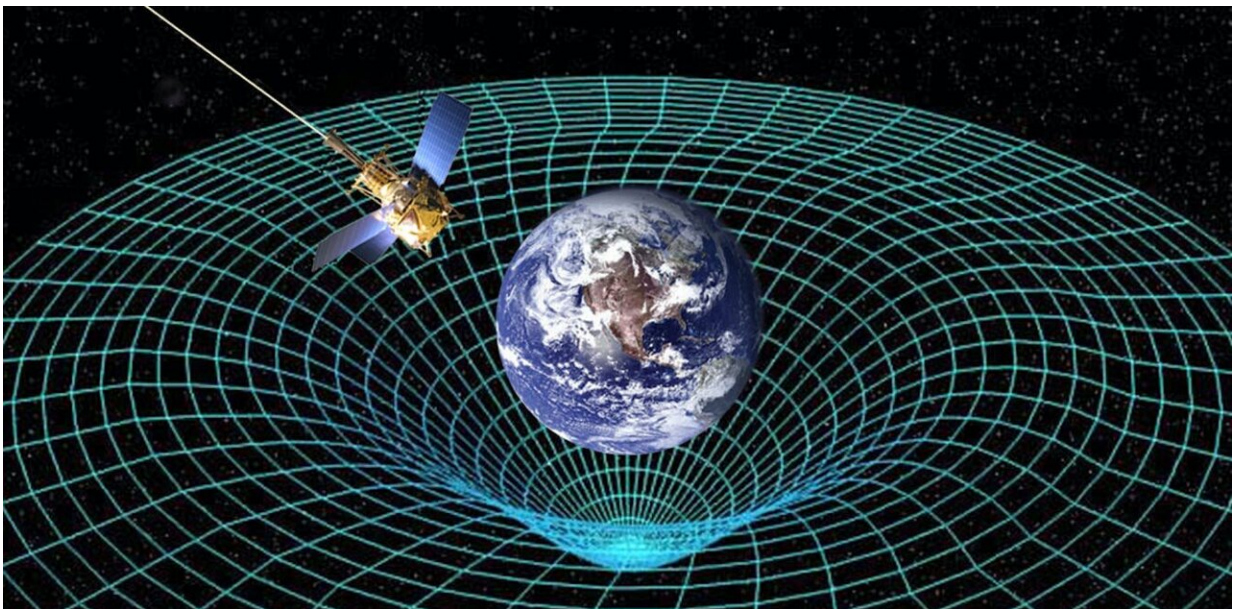


# Gravitational distortion of time helps tell modified gravity apart from a dark force

October 5 2023, by Levon Pogosian and Camille Bonvin

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Artist concept of Gravity Probe B orbiting the Earth to measure space-time, a four-dimensional description of the universe including height, width, length, and time. Credit: NASA

With his theory of General Relativity in 1915, Albert Einstein revolutionized how we think about our universe. Rather than the cosmos simply providing the room for the planets and stars to orbit each other, space and time themselves were now dynamical entities in one ever-evolving play with matter and light.

Einstein's equations described how [stars, galaxies and all other matter curve or warp space and time](#). The galaxies and the light rays then travel in this distorted space-time according to [the equation provided by the 18th-century Swiss mathematician Leonhard Euler](#).

With the help of modern telescopes, we can watch this dance and compare it to the choreography scripted by the two giants of science, Einstein and Euler. But can we differentiate a universe where Einstein's equations were violated from a universe where Euler's equation were modified? In other words, if what we observed with telescopes disagreed with what Einstein and Euler prescribed, would we be able to tell which one of the two was wrong?

## **A universe filled with unknowns**

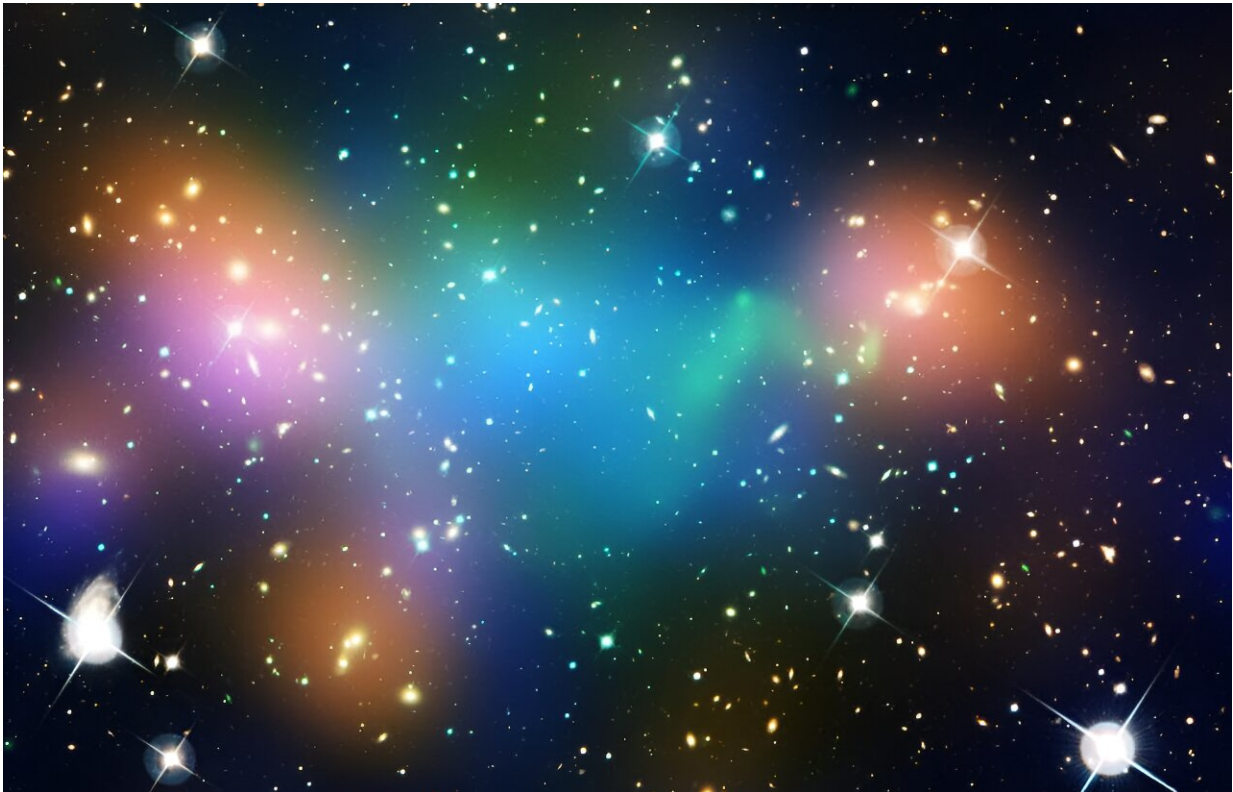
You may wonder why one would want to doubt Einstein or Euler in the first place. After all, existing observations have beautifully confirmed the validity of their theories. The reason to put those to the test comes from the fact that our universe is filled with unknowns.

In the 1930s, the Swiss-American astrophysicist Fritz Zwicky observed that there was five times more matter in the universe than we can detect with our telescopes. He called this new matter "dark matter."

Nearly 100 years later, [we still don't know what dark matter is](#): we have never detected a particle of dark matter and we don't know how it moves. It is therefore legitimate to question if it behaves as ordinary matter and obeys Euler's law. Could it be affected by other forces and interactions, which would change the Euler equation?

Then, in 1998, two groups of astrophysicists observed that [the expansion of our universe is accelerating](#), contrary to the deceleration expected because of the [gravitational attraction](#) between galaxies.

As of today, we don't know what causes this strange behavior: is it due to the presence of yet another "dark" substance that has repulsive gravity? Or is it due to gravity itself, meaning Einstein's predictions of how it behaves over very large distances would be wrong? Testing Einstein's and Euler's equations is therefore the logical consequence of the mysteries we face.



A composite image showing the distribution of dark matter, galaxies and hot gas in the core of the merging galaxy cluster Abell 520, formed from a violent collision of massive galaxy clusters. Credit: NASA, ESA, CFHT, CXO, M.J. Jee (University of California, Davis), and A. Mahdavi (San Francisco State University)

## Vast distances of the universe

Checking if Einstein's gravity works over the vast distances of the universe has become an active field of research. Theoreticians propose new ideas for how gravity could work differently, while astronomers use increasingly advanced facilities to provide the data needed to test them.

Researchers have identified a particular "smoking gun" signature of modified gravity known as the "[gravitational slip](#)." General Relativity predicts that the pathways of light and matter should bend in the same way when traveling through the same distorted [space-time](#).

This is much like the fact that different objects fall at the same rate in Earth's gravity (if the air resistance could be neglected)—[something Galileo famously demonstrated from the tower of Pisa](#). By comparing the way galaxies fall into gravitational wells to how the light from these galaxies is deflected by [gravitational lensing](#), one can deduce if they feel the same gravity.

If one finds them to be different, we would say there was a [gravitational slip](#). Measuring the slip is one of the main targets of Euclid, [a wide-angle space telescope launched by the European Space Agency on a Space-X rocket](#).

But what if Euclid found that there was a slip? Could we be certain that it occurs due to a modification of gravity, or could it also be due to a modification of Euler's equation? The latter would be different if, for example, the dark matter in the galaxies were subject to a new force.

## Gravitational slips

The two of us approached this question from different perspectives: one involved developing tests of [modified gravity](#), while the other



investigated the subtle corrections General Relativity adds to [what we measure with galaxy surveys](#).

To our surprise, while both of us came into this thinking that the answer would be obvious, our initial answers were opposite to each other. After intensive discussion, we eventually came to an agreement, [resulting in a paper published in \*Nature Astronomy\*](#).

Our conclusion was that, despite the common expectation, measuring the gravitational slip would not allow one to distinguish a modification of Einstein's laws from a modification of Euler's equation.

However, the distinction may be possible if one could measure the effect called "gravitational redshift," which should be possible with telescopes such as the [Dark Energy Spectroscopic Instrument](#) and the upcoming [Square Kilometer Array](#).

One of our key realizations was that to determine if the measured gravitational slip signals a breakdown of General Relativity, one would need to measure the velocity of normal matter when it is not confined to a galaxy. In practice, however, we can only observe the light from stars that reside in galaxies, and hence move together with the dark matter.

Telescopes can only measure the collective motion of a galaxy that contains both normal matter and dark matter. So, if a galaxy were to fall into a gravitational potential in a way that was not consistent with our expectations, we would be unable to tell if it's because the dark matter is doing something, or because gravity was modified.

## **Light and gravity**

There *is* a way to probe the gravitational potential directly through the way it distorts time via gravitational redshift.

The time kept by a clock [that's on top of a tall mountain is different from that of a clock at the sea level](#). These differences are extremely tiny but are, in fact, very important in the design of satellite navigation systems.

When the light from a galaxy escapes the [gravitational potential](#) it is falling into, its color shifts closer to red. This gravitational redshift is solely due to time distortion. Gravitational lensing, which differs from redshift, is due to both space and time distortions, as opposed to just time.

We need to have both lensing and redshift in order to isolate the gravitational slip. It is this ability to separate the distortion of space and time from the distortion of time alone that is key to measuring true gravitational slip.

A measurement of the gravitational redshift is impossible if one cannot easily keep track if a pair of galaxies swapped their positions. While it's not that hard to tell any two galaxies measured by a telescope apart, when running a [statistical analysis](#) on a catalog of millions of galaxies, you can quickly lose the ability to assign any identity to the galaxies; at some point they are all treated as points on the sky.

Techniques have, however, been developed to split [galaxies](#) into different populations and [keep track of swaps between them](#). In time, new technologies will be able to detect the tiny effects of [gravitational redshift](#), and consequently distinguish a modification of Euler's equation for [dark matter](#) from a modification of gravity.

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