Euclid space mission is set for launch: Here's how it will test alternative theories of gravity

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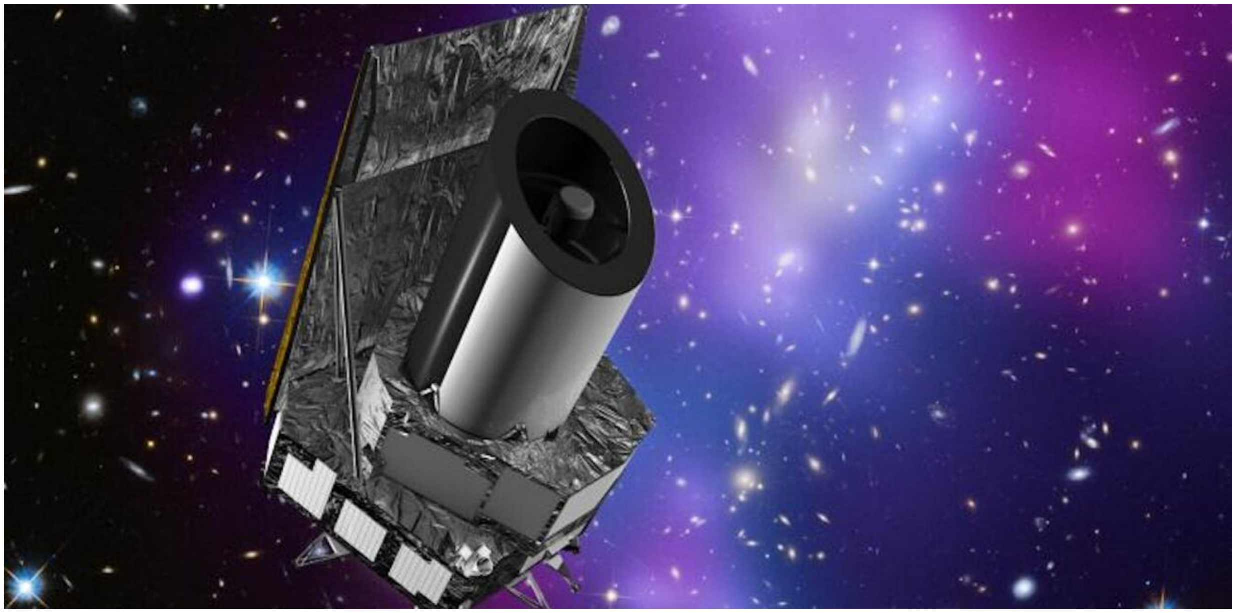


Credit: NASA

The European Space Agency's (Esa) Euclid mission will launch into space on a Falcon9 rocket from SpaceX on July 1, or soon after. Many of us who have worked on it will be in Florida to watch the nail-biting event.

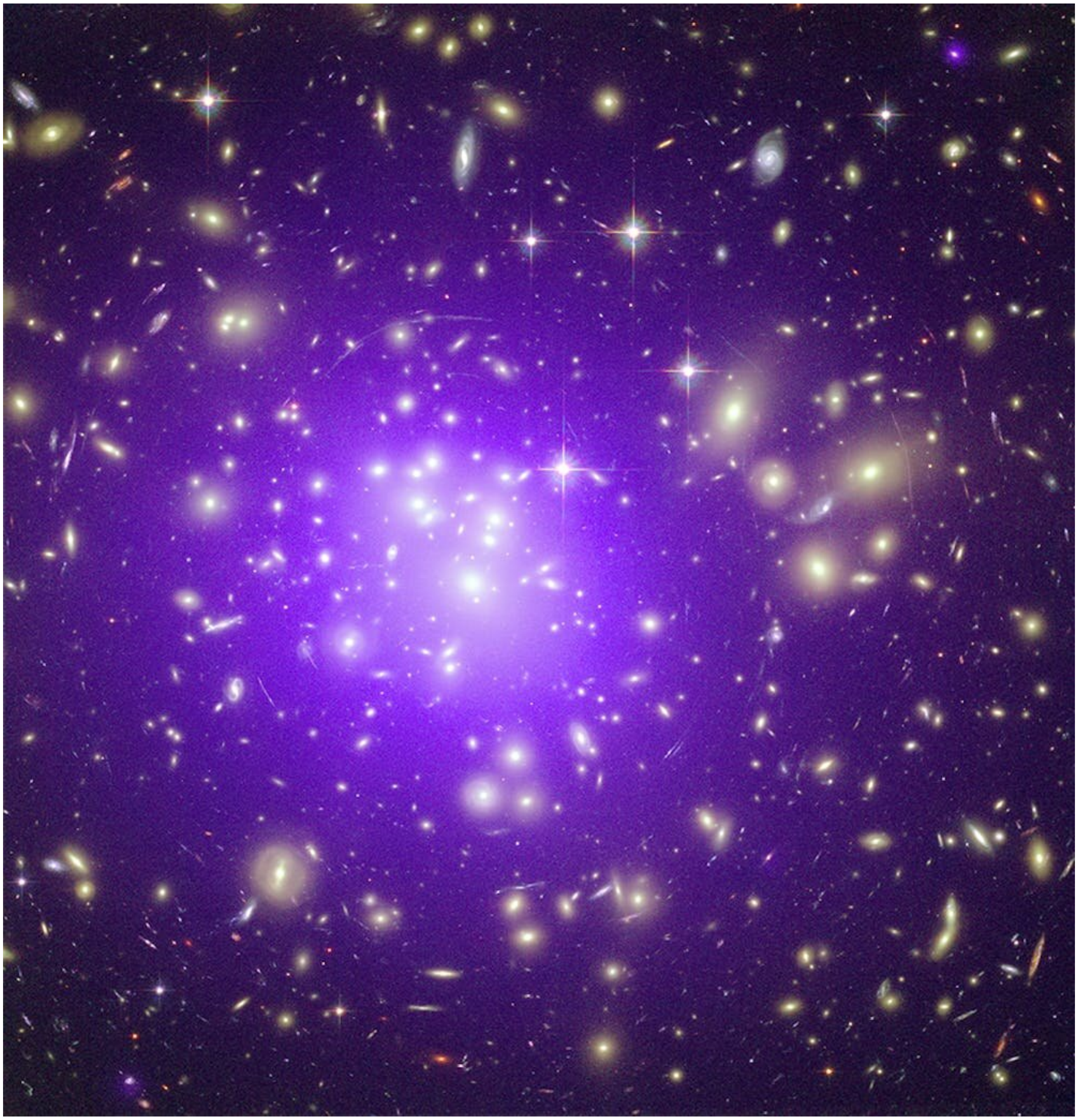
The mission is specifically designed to study the dark universe, probing both "dark matter" and "dark energy"—unknown substances thought to make up 95% of the energy density of the universe.

But it will also be able to test some strange, alternative models of gravity —potentially challenging Albert Einstein's great theory of general relativity.

Scientists have known about the existence of dark matter for nearly a century now. It was proposed after astronomers noted that galaxies in clusters had mysteriously high speeds. Such speeds should cause the clusters to evaporate unless there was some extra mass holding them together. As this matter wasn't shining in the same way as the visible galaxies, it was dubbed dark matter.

Gravitational lensing is a new tool to see this dark material. This effect relies on our understanding of general relativity. As light travels to us from distant galaxies, its path is bent by large clumps of matter (dark or bright) in the foreground—changing their appearance (and location).

This change is easily seen near the cores of massive clusters (see image below)—with galaxies stretched into arcs, appearing to be long, thin and curved. We can use this warping to determine the amount of matter in the foreground cluster. And that confirms again that much of the mass in these clusters is indeed dark.



Gravitational lensing in the galaxy cluster Abell 1689. Credit: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/STScI

But what could it be made of? Many physicists believe it is an unknown elementary particle. A popular candidate, which is yet to be detected, is axions, which were originally introduced to explain why certain fundamental symmetries of nature appear to be broken.

However, there are other possibilities. Rather than postulating the need for dark matter, one can probe gravity. The strength of gravity may become weaker than predicted on the scale of galaxies and beyond. On these scales, there are some alternative models of gravity that can explain galaxy rotation curves without assuming there's any dark matter. The challenge for any of these alternatives is to do so consistently on all scales.

While there are several Earth-based searches for dark matter particles, they have so far not found significant evidence. Therefore, astronomical observations of galaxy clusters remain our best option for testing the various theories that can explain dark matter. This is where Euclid will excel due to its outstanding resolution, providing a sharpness similar to the Hubble space telescope (see image) across a third of the sky. By comparison, Hubble has observed only 5% of the whole sky.

The number of images we will obtain of clusters will increase a hundred-fold with Euclid, allowing us to study in detail the distribution of dark matter within such clusters to high precision. How the dark matter is distributed may be key to its origin and mass, ruling out a range of possible candidate particles and gravity theories along the way.

Dark energy and gravity

Dark matter is potentially easy to understand compared to dark energy, which was proposed to explain the discovery that the expansion of the universe is accelerating—at odds with the prediction from Einstein's theory of gravity. This strange substance is vexing to physicists and cosmologists, with the simplest idea being that dark energy is just the energy of empty space ("vacuum energy").

Essentially, as we gain more space in an expanding universe, we gain more vacuum energy, which then drives the observed acceleration.

This simple explanation is reasonable except for the uncomfortable truth that the observed density of dark energy is many orders of magnitude lower than predicted by quantum theory, which rules the universe on the smallest of scales. In short, this simple explanation asks more questions than it answers.

As with dark matter, an alternative explanation for dark energy is that it isn't really a substance or form of energy at all, but again a sign that gravity is behaving differently on the largest scales.

This has led to a flurry of new ideas that extend our theory of gravity beyond general relativity. For example, could gravity exist in more than the four dimensions (three spatial dimensions plus time) that the rest of the universe experiences? Are there new fundamental fields that we don't know about yet, which interact with gravity?

Or perhaps Einstein's theory is valid for the weak gravitational fields we experience on Earth, but becomes radically different in extremely strong gravitational fields, like those near the event horizons of black holes.

The challenge for all these alternative gravity models is to work together, for both dark matter and dark energy. Ideally, they should work on all scales and masses, as a single theory. Physicists believe strongly in Occam's razor—that the best theories have the least number of assumptions.

Euclid will help us test these exotic gravity models by mapping the positions of millions of galaxies over vast regions of the universe. This allows us to trace the "cosmic web," a sponge-like structure of filaments and voids in space. These seem to be laid down first in dark matter and then sprinkled with galaxies.

This cosmic web is formed by billions of years of gravitational collapse, meaning its structure and statistics are sensitive to the laws of gravity at work on cosmological scales. By measuring its properties, we can determine whether a new theory of gravity would fit the data better than Einstein's theory.

As we return to Earth, there is much excitement in the astrophysics community about what Euclid will do. This is the first time we've had a satellite dedicated to mapping dark matter and dark energy.

The Euclid data will last a lifetime and generations of cosmologists will spend their careers studying it. As we watch Euclid launch into the Florida sky, we will be one step closer to answering some of the most fundamental questions in science.

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