Search for 'dark energy' could illuminate origin, evolution, fate of universe

May 3 2021, by Seth Palmer

The Hobby-Eberly Telescope. Credit: Marty Harris, McDonald Observatory, UT Austin

The universe we see is only the very tip of the vast cosmic iceberg.

The hundreds of billions of galaxies it contains, each of them home to billions of stars, planets and moons as well as massive star-and-planet-forming clouds of gas and dust, and all of the visible light and other energy we can detect in the form of electromagnetic radiation, such as radio waves, gamma rays and X-rays—in short, everything we've ever seen with our telescopes—only amounts to about 5% of all the mass and energy in the universe.

Along with this so-called normal matter there is also dark matter, which can't be seen, but can be observed by its gravitational effect on normal, visible matter, and makes up another 27% of the universe. Add them together, and they only total 32% of the mass of the universe—so where's the other 68%?

Dark energy.

So what exactly is dark energy? Put simply, it's a mysterious force that's pushing the universe outward and causing it to expand faster as it ages, engaged in a cosmic tug-of-war with dark matter, which is trying to pull the universe together. Beyond that, we don't yet understand what dark energy is, but Penn State astronomers are at the core of a group that's aiming to find out through a unique and ambitious project 16 years in the making: HETDEX, the Hobby-Eberly Telescope Dark Energy Experiment.

"HETDEX has the potential to change the game," said Associate Professor of Astronomy and Astrophysics Donghui Jeong.

Dark energy and the expanding universe

Today there is consensus among astronomers that the universe we inhabit is expanding, and that its expansion is accelerating, but the idea of an expanding universe is less than a century old, and the notion of dark energy (or anything else) accelerating that expansion has only been around for a little more than 20 years.

In 1917 when Albert Einstein applied his general theory of relativity to describe the universe as a whole, laying the foundations for the big bang theory, he and other leading scientists at that time conceived of the cosmos as static and nonexpanding. But in order to keep that universe from collapsing under the attractive force of gravity, he needed to introduce a repulsive force to counteract it: the cosmological constant.

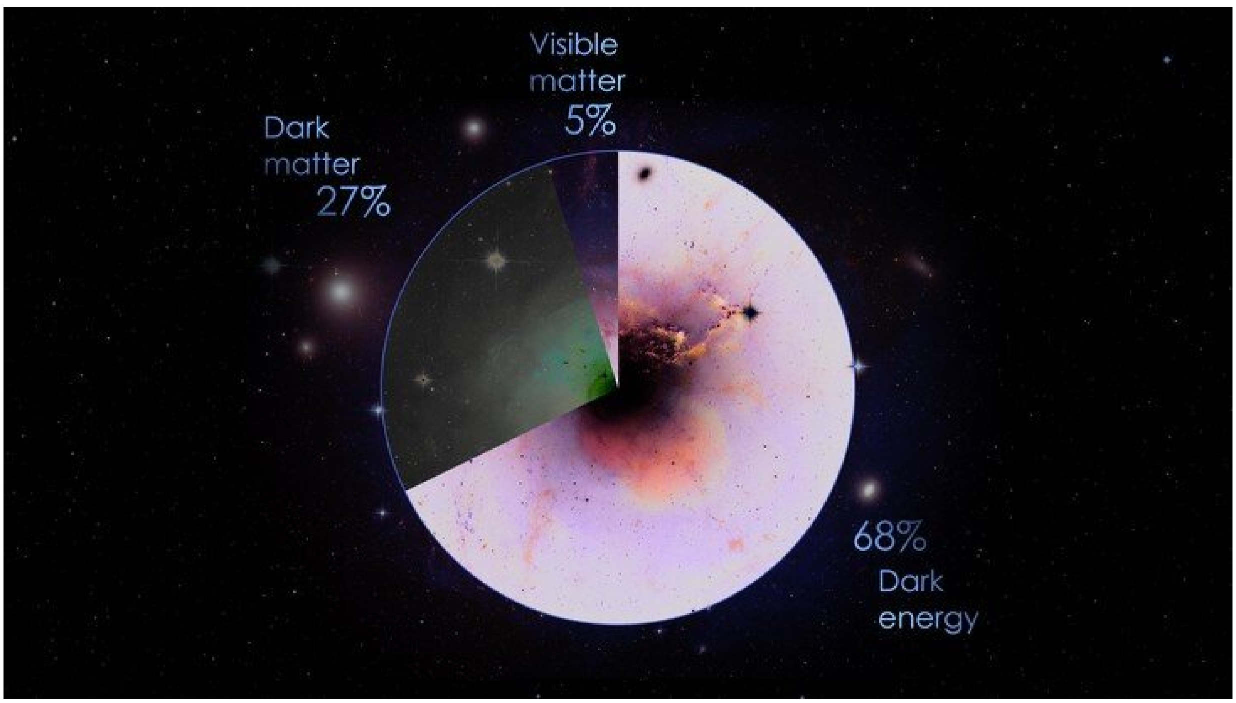
It wasn't until 1929 when Edwin Hubble discovered that the universe is in fact expanding, and that galaxies farther from Earth are moving away faster than those that are closer, that the model of a static universe was finally abandoned. Even Einstein was quick to modify his theories, by the early 1930s publishing two new and distinct models of the expanding universe, both of them without the cosmological constant.

But although astronomers had finally come to understand that the universe was expanding, and had more or less abandoned the concept of the cosmological constant, they also presumed that the universe was dominated by matter and that gravity would eventually cause its expansion to slow; the universe would either continue to expand forever, but ever-increasingly slowly, or it would at some point cease its expansion and then collapse, ending in a "big crunch."

"That's the way we thought the universe worked, up until 1998," said Professor of Astronomy and Astrophysics Robin Ciardullo, a founding member of HETDEX.

That year, two independent teams—one led by Saul Perlmutter at Lawrence Berkeley National Laboratory, and the other led by Brian Schmidt of the Australian National University and Adam Riess of the Space Telescope Science Institute—would nearly simultaneously publish astounding results showing that the expansion of the universe was in fact accelerating, driven by some mysterious antigravity force. Later that year, cosmologist Michael Turner of the University of Chicago and Fermilab coined the term "dark energy" to describe this mysterious force.

The discovery would be named Science magazine's "Breakthrough of the Year" for 1998, and in 2011 Perlmutter, Schmidt and Reiss would be awarded the Nobel Prize in physics.



This pie chart shows rounded values for the three known components of the universe: normal matter, dark matter, and dark energy. Credit: NASA's Goddard Space Flight Center

Competing theories

More than 20 years after the discovery of dark energy, astronomers still don't know what, exactly, it is.

"Whenever astronomers say 'dark," that means we don't have any clue about it," Jeong said with a wry grin. "Dark energy is just another way of saying that we don't know what's causing this accelerating expansion."

There are, however, a number of theories that attempt to explain dark energy, and a few major contenders.

Perhaps the most favored explanation is the previously abandoned cosmological constant, which modern-day physicists describe as vacuum energy. "The vacuum in physics is not a state of nothing," Jeong explained. "It is a place where particles and antiparticles are continuously created and destroyed." The energy produced in this perpetual cycle could exert an outward-pushing force on space itself, causing its expansion, initiated in the big bang, to accelerate.

Unfortunately, the theoretical calculations of vacuum energy don't match the observations—by a factor of as much as 10^{120}, or a one followed by 120 zeroes. "That's very, very unusual," Jeong said, "but that's where we'll be if dark energy turns out to be constant." Clearly this discrepancy is a major issue, and it could necessitate a reworking of current theory, but the cosmological constant in the form of vacuum energy is nonetheless the leading candidate so far.

As a result of its design, HETDEX is collecting a massive amount of data, extending well beyond its intended targets and providing additional insights into things like dark matter and black holes, the formation and evolution of stars and galaxies, and the physics of high-energy cosmic particles such as neutrinos.

Another possible explanation is a new, yet-undiscovered particle or field that would permeate all of space; but so far, there's no evidence to support this.

A third possibility is that Einstein's theory of gravity is incorrect. "If you start from the wrong equation," Jeong said, "then you get the wrong answer." There are alternatives to general relativity, but each has its own issues and none has yet displaced it as the reigning theory. For now, it's still the best description of gravity we've got.

Ultimately, what's needed is more and better observational data—precisely what HETDEX was designed to collect like no other survey has done before.

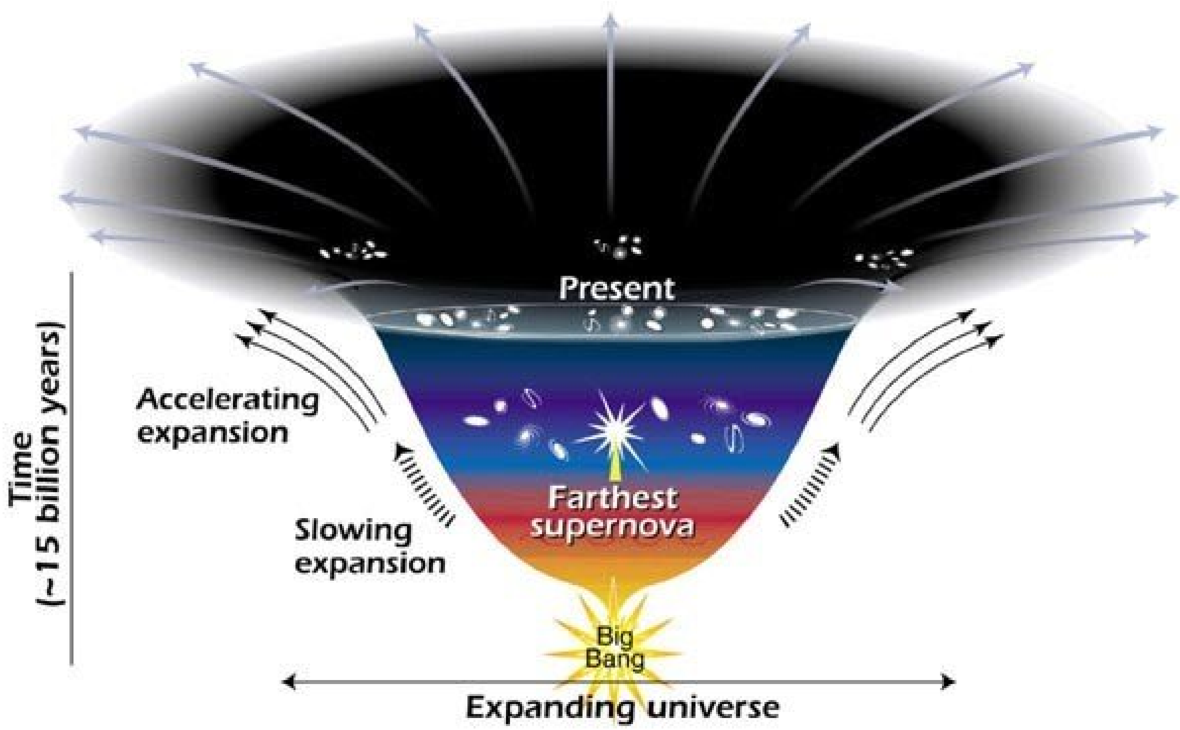
A map of stars and sound

"HETDEX is very ambitious," Ciardullo said. "It's going to observe a million galaxies to map out the structure of the universe going over two-thirds of the way back to the beginning of time. We're the only ones going out that far to see the dark energy component of the universe and how it's evolving."

Ciardullo, an observational astronomer who studies everything from nearby stars to faraway galaxies and dark matter, is HETDEX's observations manager. He's quick to note, though, that he's got help in that role (from Jeong and others) and that he and everyone else on the project wears more than one hat. "This is a very big project," he said. "It's over $40 million. But if you count heads, it's not very many people. And so we all do more than one thing."

Jeong, a theoretical astrophysicist and cosmologist who also studies gravitational waves, was instrumental in laying the groundwork for the study and is heavily involved in the project's data analysis—and he's also helping Ciardullo determine where to point the 10-meter Hobby-Eberly

Telescope, the world's third largest. "It's kind of interesting," he noted with a chuckle, "a theorist telling observers where to look."



This diagram shows the changes in the rate of expansion since the universe's birth. The shallower the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious force — dark energy — that is pulling galaxies apart. I. Credit: NASA/STScI/Ann Feild

While other studies measure the universe's expansion using distant supernovae or a phenomenon known as gravitational lensing, where light is bent by the gravity of massive objects such as galaxies and black holes, HETDEX is focused on sound waves from the big bang, called baryonic acoustic oscillations. Although we can't actually hear sounds in the vacuum of space, astronomers can see the effect of these primordial sound waves in the distribution of matter throughout the universe.

During the first 400,000-or-so years following the big bang, the universe existed as dense, hot plasma—a particle soup of matter and energy. Tiny disturbances called quantum fluctuations in that plasma set off sound waves, like ripples from a pebble tossed into a pond, which helped matter begin to clump together and form the universe's initial structure. The result of this clumping is evident in the cosmic microwave background (also called the "afterglow" of the big bang), which is the first light, and the farthest back, that we can see in the universe. And it's also imprinted in the distribution of galaxies throughout the universe's history—like the ripples on our pond, frozen into space.

"The physics of sound waves is pretty well known," Ciardullo said. "You see how far these things have gone, you know how fast the sound waves have traveled, so you know the distance. You have a standard ruler on the universe, throughout cosmic history."

As the universe has expanded so has the ruler, and those variances in the ruler will show how the universe's rate of expansion, driven by dark energy, has changed over time.

"Basically," Jeong said, "we make a three-dimensional map of galaxies and then measure it."

New discovery space

To make their million-galaxy map, the HETDEX team needed a powerful new instrument.

A set of more than 150 spectrographs called VIRUS (Visible Integral-Field Replicable Unit Spectrographs), mounted on the Hobby-Eberly Telescope, gathers the light from those galaxies into an array of some 35,000 optical fibers and then splits it into its component wavelengths in an ordered continuum known as a spectrum.

Galaxies' spectra reveal, among other things, the speed at which they are moving away from us—a measurement known as "redshift." Due to the Doppler effect, the wavelength of an object moving away from its observer is stretched (think of a siren that gets lower in pitch as it speeds away), and an object moving toward its observer has its wavelength compressed, like that same siren increasing in pitch as it gets nearer. In the case of receding galaxies, their light is stretched and thus shifted toward the red end of the spectrum.

Measuring this redshift allows the HETDEX team to calculate the distance to those galaxies and produce a precise three-dimensional map of their positions.

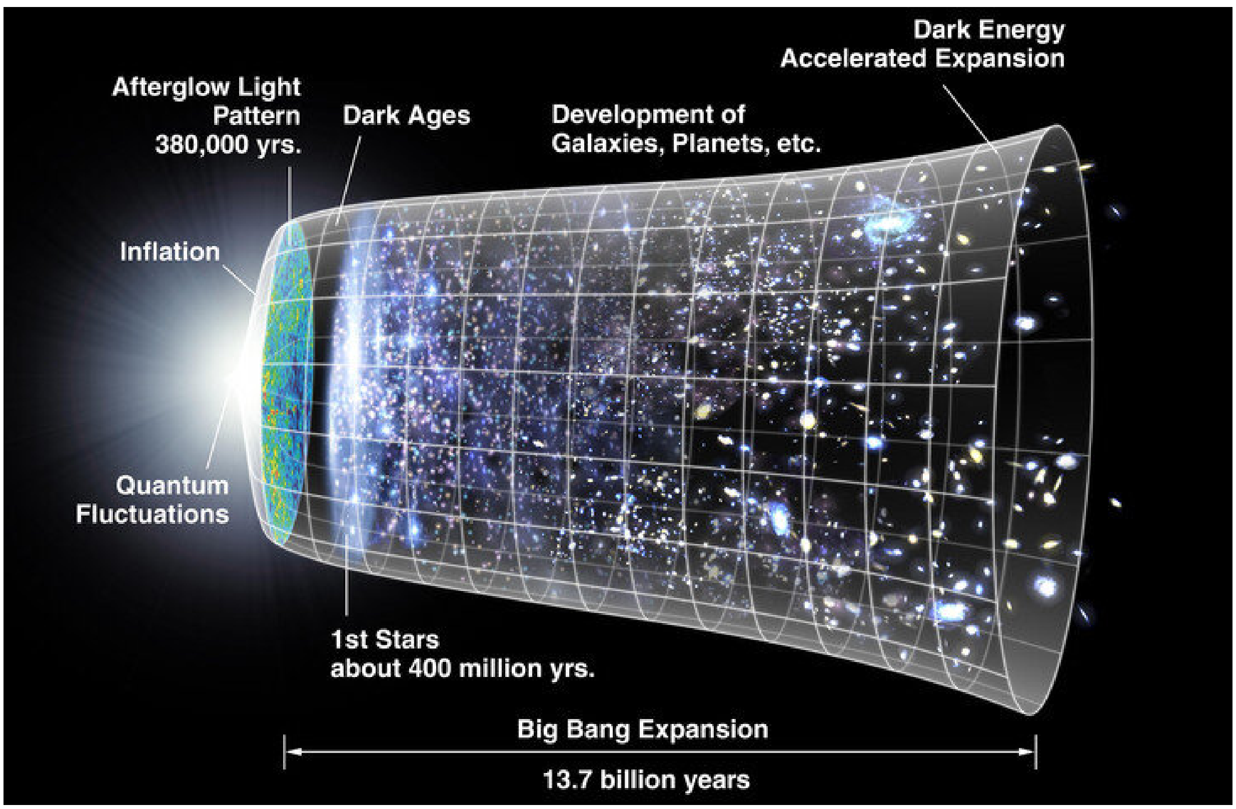
Among the galaxies HETDEX is observing are what are known as Lyman-alpha galaxies—young star-forming galaxies that emit strong spectral lines at specific ultraviolet wavelengths.

"We're using Lyman-alpha-emitting galaxies as a 'tracer particle,'" explained Research Professor of Astronomy and Astrophysics Caryl Gronwall, who is also a founding member of HETDEX. "They're easy to find because they have a very strong emission line, which is easy to find spectroscopically with the VIRUS instrument. So we have this method that efficiently picks out galaxies at a fairly high redshift, and then we can measure where they are, measure their properties."

Gronwall, who along with Ciardullo has been studying Lyman-alpha galaxies for nearly 20 years, leads HETDEX's efforts in this area, while

Associate Professor of Astronomy and Astrophysics Derek Fox lends his expertise to calibrating the VIRUS instrument, using incidental observations of stars with well-known properties to fine-tune its spectra.

"Every shot we take with HETDEX, we observe some stars on the fibers," Fox explained. "That's an opportunity, because the stars are telling you how sensitive your experiment is. If you know the brightness of the stars and you see the data that you collect on them, it offers an opportunity to keep your calibration on point."



In this representation of the evolution of the universe, the far left depicts the earliest moment we can now probe, when a period of “inflation” produced a burst of exponential growth. The afterglow light (known as the cosmic microwave background) was emitted about 375,000 years after inflation and has traversed the universe largely unimpeded since then. The conditions of earlier times are imprinted on this light, which also forms a backlight for later developments of the universe. Credit: NASA/WMAP Science Team

One of HETDEX's biggest strengths is that it was designed as a blind survey—observing broad swaths of sky instead of specific, predetermined objects. "Nobody has tried doing a survey like this before," Ciardullo said. "It's always "Find your objects, then do the spectroscopy." We're the first ones to try to do a whole lot of spectroscopy and then figure out what we saw."

As a result of this design, HETDEX is collecting a massive amount of data, extending well beyond its intended targets and providing additional insights into things like dark matter and black holes, the formation and evolution of stars and galaxies, and the physics of high-energy cosmic particles such as neutrinos.

"That's very different and very interesting," Jeong said. "We have huge discovery space."

Ciardullo added, "One thing you can infer—if you first have to see an object before pointing your spectroscope there, well that's fine, but it requires that the object be able to be seen. HETDEX can observe spectra of things that you can't see."

This means that in addition to the known data it's collecting, HETDEX is opening a window to unexpected findings, discoveries yet unforeseen. "We will be a pathfinder for more experiments," Ciardullo said, and that sentiment is echoed by others on the team, including Fox.

"We're definitely going to be blazing trails out there," he said. "There's big, big potential for really exciting discoveries."

Back to roots, and beyond

The futuristic science of HETDEX is, in a strange twist, very much in line with the ideas that drove the development of the Hobby-Eberly Telescope (HET) nearly 40 years ago.

"HET was initially conceived as the Penn State Spectroscopic Survey Telescope," explained Professor Emeritus of Astronomy and Astrophysics Larry Ramsey, who invented the telescope in 1983 with then Penn State colleague Dan Weedman, and later served as chairman of the HET's board of directors. "The original mission was to conduct spectroscopic surveys, and in the almost 20 years between when we first dedicated the telescope and when we started HETDEX, the telescope was not really doing surveys. So in a very real sense HETDEX is taking the HET back to its roots, and it has grown into a really interesting project."

"The scale of this survey is very futuristic, even now," Jeong said. Recalling a recent cosmology conference, he related a discussion about the future of galactic surveys. "I sat there and listened, and it was basically what we're doing," he said. "HETDEX is a future survey that exists now."

In addition to what HETDEX discovers about dark energy, the data it's collecting will also provide fodder for future studies far beyond the scope of its own mission. And chances are, HETDEX will continue doing "spacebreaking" science on the distant, high-redshift universe for quite a few years to come.

"Even currently planned future surveys don't go beyond HETDEX," Jeong said. "I think we will still be at the forefront, even 10 years from now."

More information: This story first appeared in the Winter 2021 issue of the Science Journal, the Eberly College of Science magazine.

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