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Scanning the dark Universe with the

VERA RUBIN OBSERVATORY

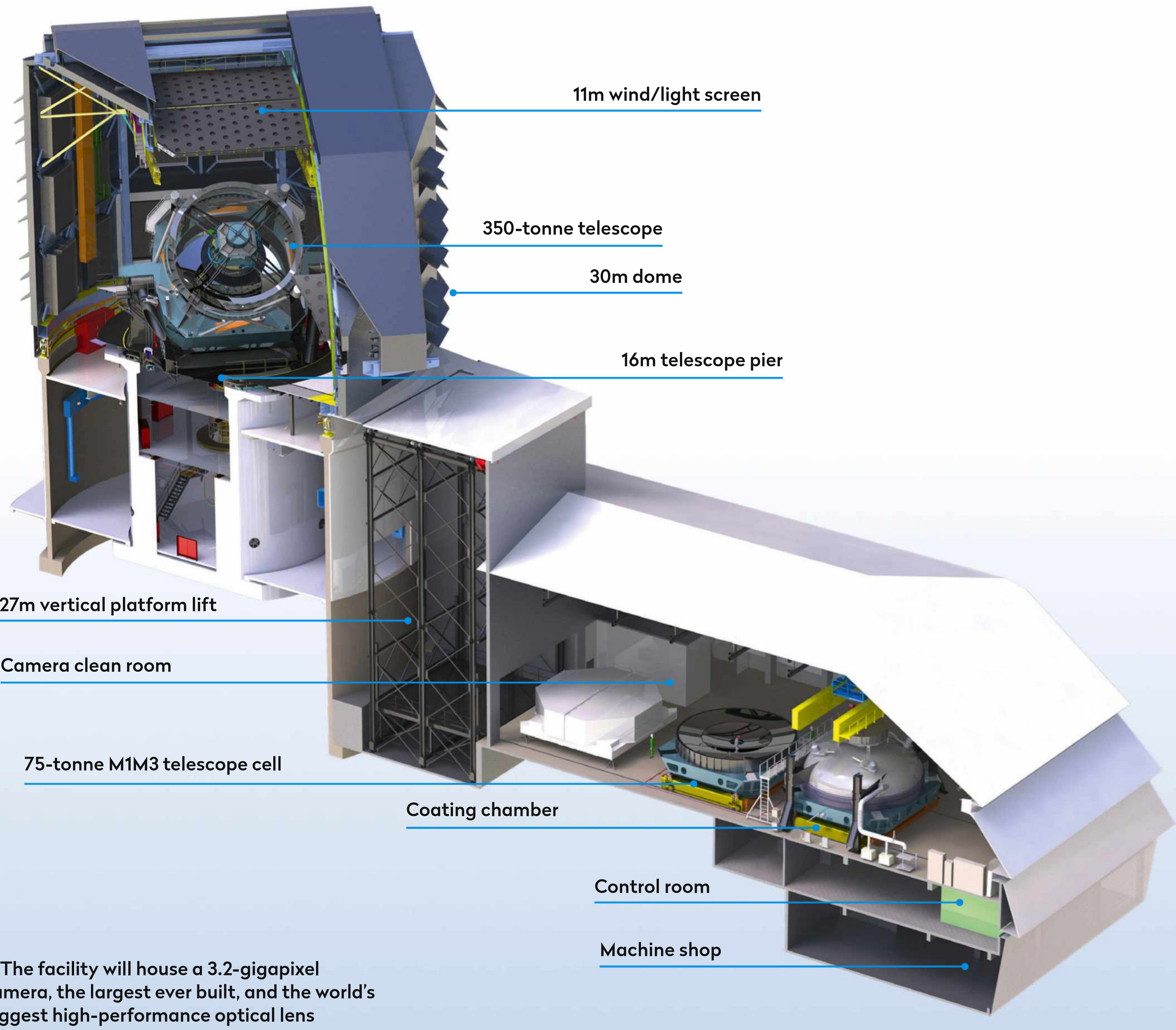
Govert Schilling visits the revolutionary new observatory in Chile that's set to lift the lid on the mysterious, invisible dark matter that dominates the Universe

RUBIN OBSERVATORY/NOIRLAB/AURA/NSF/B. QUINT

Some 15 minutes west of the town of Vicuña, in the Valle del Elqui in northern Chile, a steep and winding gravel road leads south from Highway 41 to the summit of Cerro Pachón, almost 2,700 metres above sea level. Since the early 2000s, the mountaintop has been home to the 8.1-metre Gemini South Telescope and the 4.1-metre Southern Astrophysical Research Telescope. But today, the scene is dominated by a huge, futuristic cylindrical building, housing a revolutionary telescope that will uncover the Universe's darkest secrets. Welcome to the Vera C Rubin Observatory.

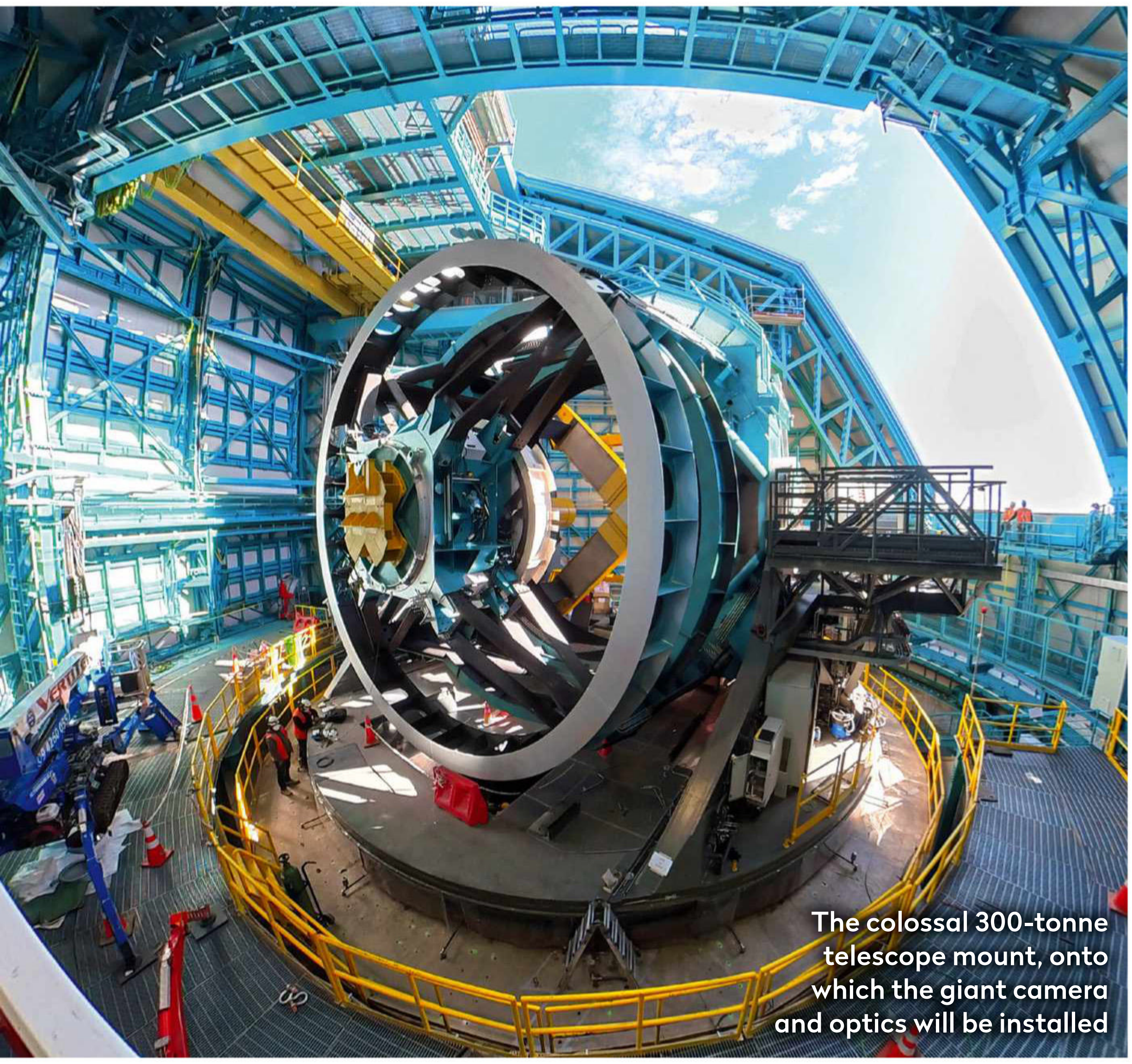
The observatory's main telescope is unlike any other ever built. Its 8.4-metre diameter mirror – a novel combination of a ring-like primary mirror surrounding a much more strongly curved tertiary mirror cut from the same glass blank – has a giant 3.5° field of view, as wide as seven full Moons strung together. Two to three times a week, a monstrous 3.2-gigapixel digital camera – the largest ever built – will snap a razor-sharp and extremely deep image every 30 seconds, covering all of the night sky visible from Chile. In 10 years' time, each and every visible star and galaxy in the southern sky will have been visited by Rubin at least 800 times: the most comprehensive survey of the cosmos ever made. ▸

High and mighty: Rubin Observatory will produce the deepest ever image of the entire southern sky



▲ The facility will house a 3.2-gigapixel camera, the largest ever built, and the world's biggest high-performance optical lens

RUBIN OBSERVATORY/J. ANDREW, RUBIN OBSERVATORY/NOIRLAB/NSF/AURA, ESA/C. CARREAU, GSFC/SVS, ANTONIOSOLANO/ISTOCK/GETTY IMAGES, JACQUELINE RAMSEYER ORRELL/SLAC NATIONAL ACCELERATOR LABORATORY



The colossal 300-tonne telescope mount, onto which the giant camera and optics will be installed

▸ "Rubin is absolutely unique," says Robert Blum, director for operations of the observatory. "Nothing like this survey has been done before."

Cosmologist Catherine Heymans of the Royal Observatory Edinburgh, and the Astronomer Royal for Scotland, is equally thrilled. "This visionary project has been part of my academic life since I started my PhD in 2000," she says. "I was so delighted when the UK joined Rubin in 2015 and I officially became a part of this groundbreaking new initiative. Everyone is excited about what we might find."

Completion of the new observatory, which is a partnership of the US National Science Foundation (NSF) and the US Department of Energy (DOE), was delayed by a couple of years because of the COVID-19 pandemic, but according to Blum, first light is now expected in early 2024, with full science operations scheduled to start later that year. "All of the main telescope subsystems and mirrors are in Chile and nearly ready for integration," he says. Initial alignment of the system, including installation of a smaller commissioning camera, should have been done by the time you read this article. "We hope to ship the main camera to Chile around February 2023," says Blum.

This giant camera, built by DOE's SLAC National Accelerator Laboratory in California and weighing

Rubin's goals include unravelling how dark energy influences galaxy clusters like the Virgo Cluster

more than three tonnes, is an engineering marvel in itself. Its 25-inch diameter focal plane is covered by 189 CCD detectors of 16 million pixels each. Cooled down to –100°C for better sensitivity, the array registers stars as faint as 25th magnitude in exposures of a mere 30 seconds through one of six broadband filters. After each exposure, the extremely compact and stiff telescope will slew to its next position in just five seconds, night after cloudless night. Known as the Legacy Survey of Space and Time (LSST), the project will take a whopping 200,000 images per year and has an expected data rate of 10–20 terabytes every night.

Bigger, wider, deeper

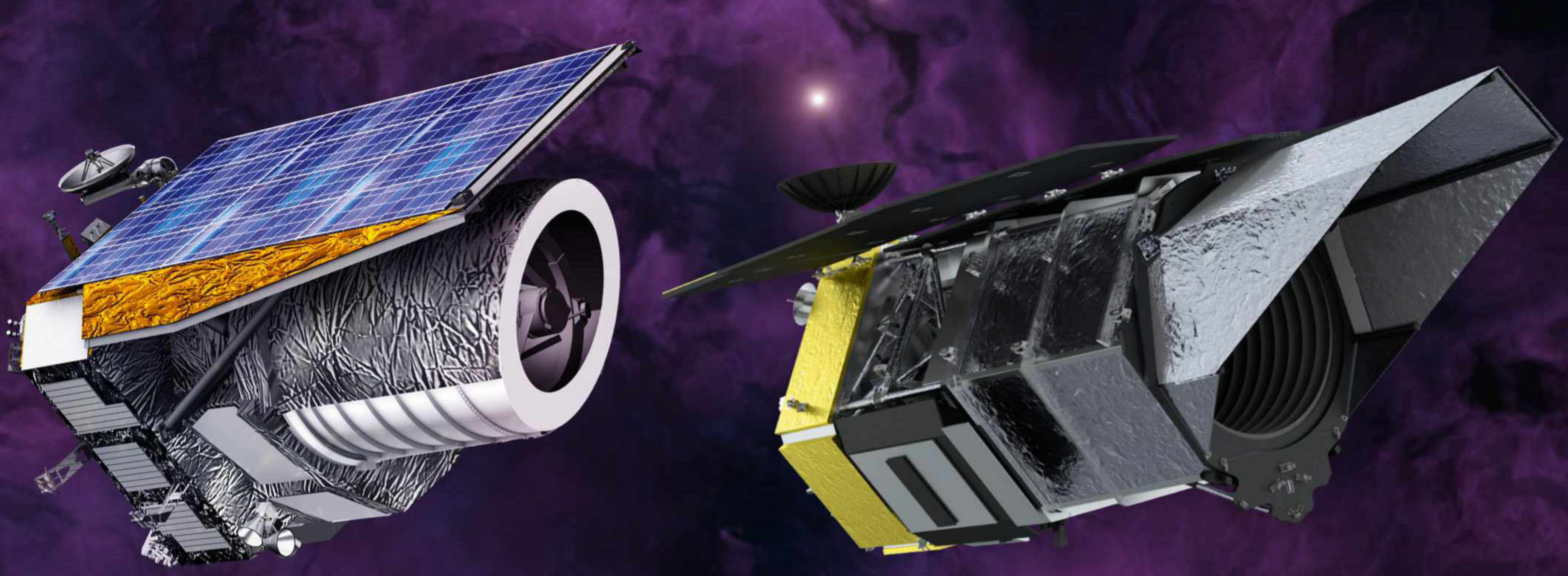
LSST is not the first deep cosmological survey. “There have been some wonderful projects before,” says camera project scientist Steven Ritz from University of California at Santa Cruz, “but the combination of the Vera C Rubin Observatory's large field of view and depth really makes for something new altogether.”

Heymans notes that Rubin will cover almost 700 times the area of the Hyper Suprime-Cam (HSC) deep survey on the Japanese 8.2-metre Subaru Telescope in Hawaii (which has a more or less comparable sensitivity), while it produces significantly deeper images than the Dark Energy Survey (DES) on the nearby 4-metre Victor M Blanco Telescope at Cerro Tololo Inter-American Observatory, which covered 3.6 times less sky than Rubin will.

Like DES and the smaller HSC survey, the Legacy Survey of Space and Time is a dark energy experiment. Dark energy is a theoretical energy that is pushing the Universe apart, which has been hypothesised to explain why cosmic expansion is accelerating. One of the goals of the Rubin Observatory is to find out how this mysterious property has evolved over cosmic time and how it has influenced the growth of large-scale structures like clusters and superclusters. This can be achieved by precisely mapping the three-dimensional distribution of billions of galaxies.

▲ The camera team celebrate attaching the cryostat, with its 28-inch lens and 201 sensors, onto the camera body

Moreover, it will be able to study minute distortions in the images of galaxies – caused by a phenomenon known as weak gravitational lensing – which can directly measure how mass is distributed in space, ▸



▲ Like Rubin, Euclid (left) and Nancy Roman (right) will scour the skies for dark energy and dark matter

The view from space

Two upcoming space telescopes will work together with Rubin to understand the unseen Universe

In 2023, even before the Vera C Rubin Observatory begins its unprecedentedly thorough survey of the distant Universe, the European Space Agency will launch its 1.2-metre diameter Euclid space telescope, which is pursuing very similar goals: studying dark energy and dark matter by precisely mapping and imaging billions of galaxies. Four years later, NASA will follow suit with its 2.4-metre Nancy Grace Roman Space Telescope. So how do the three projects compare?

According to Catherine Heymans from the Royal Observatory Edinburgh, Rubin will dwarf Euclid and Roman in terms of sensitivity, because of its much larger primary mirror. But, she adds, the Rubin Observatory sits underneath the Earth's atmosphere and won't be able to obtain images as crisp as those captured by the two space telescopes.

"The secret that is rarely openly discussed, however," she says, "is that these telescopes need each other in order to truly succeed in their scientific goals. Euclid requires Rubin's multicolour imaging, and Rubin can benefit from high-resolution data [from space] to untangle the many blended galaxy images it will see."

How exactly the data from these instruments will be combined is still a topic of hot discussion, says Heymans, but by working together they will be able to address a wide array of different science goals.

ILLUSTRATION

▸ including the invisible dark matter that is believed to make up some 85 per cent of all the gravitating stuff in the Universe.

Astronomers are confident that dark energy and dark matter play a pivotal role in the evolution of the Universe, but they have few clues as to the true nature of these two mysterious ingredients. "With the avalanche of data that Rubin brings, we will be confronting a wide range of both conventional and exotic theories on the dark side of our Universe," says Heymans.

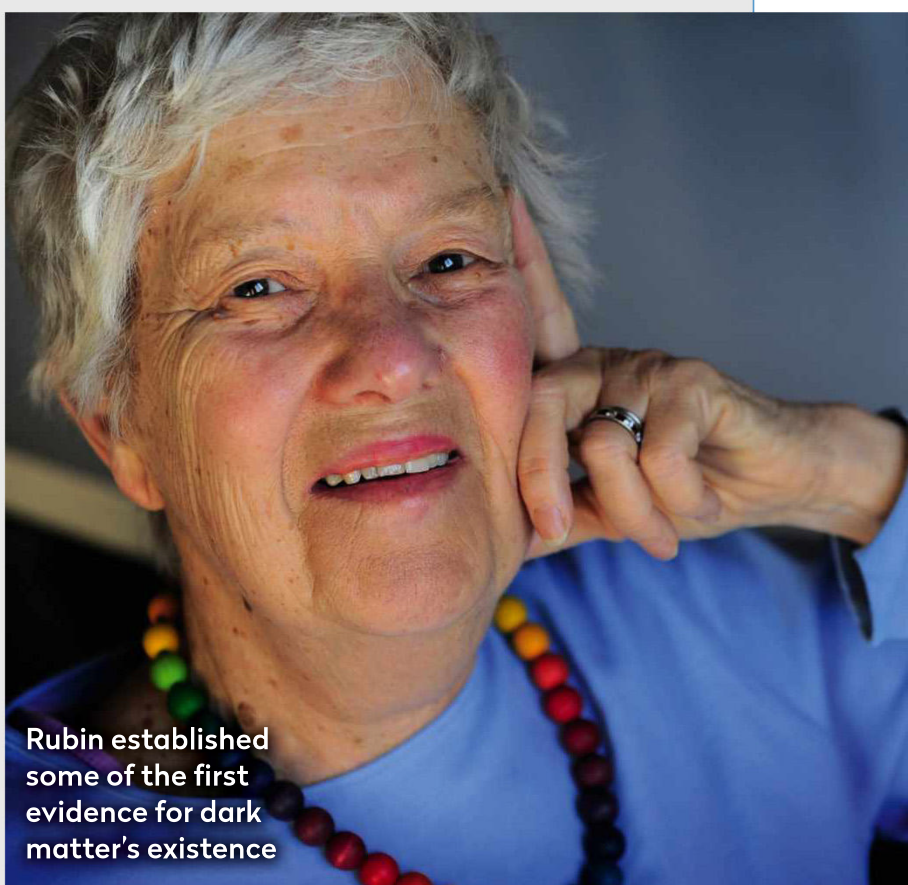
Apart from stationary stars and galaxies, Rubin will also discover millions of moving objects, like remote comets, asteroids, Kuiper Belt objects (which lie beyond Neptune's orbit), near-Earth objects that might pose an impact threat to our home planet,

The name game

The observatory is named after pioneering astronomer Vera C Rubin

The revolutionary telescope under construction at Cerro Pachón was originally called the Large Synoptic Survey Telescope, but in early 2020 it was announced the new observatory would be named after American astronomer Vera C Rubin (1928–2016). Starting in the late 1960s, Rubin, together with her Carnegie Institution of Washington colleague Kent Ford, measured the rotational properties of the Andromeda Galaxy and a number of other nearby spiral galaxies, and found convincing evidence for the existence of invisible, dark matter in the outskirts of these stellar systems.

The concept of dark matter is much older and radio astronomers had made similar observations before, but US Congress decided on the name change to honour Rubin's pioneering work in the field of dark matter research, as well as in overcoming gender-based discrimination, paving the way for other women in astronomy. The 8.4-metre telescope of the observatory is now officially known as the Simonyi Survey Telescope, after a major private donor. Meanwhile, the original acronym LSST was saved: it now denotes the observatory's Legacy Survey of Space and Time.



Rubin established some of the first evidence for dark matter's existence

FABIAN NEYER/CCDGUIDECOM, GETTY, NAZARII NESHCHERENSKYI/ISTOCK/GETTY IMAGES

Interview: J Anthony Tyson

Tyson first proposed the observatory that would become Rubin in 1996, directed the project for 15 years and is now its chief scientist

What are the differences between your original Dark Matter Telescope proposal and the final observatory?
Not that much. The large aperture and the corresponding need for a gigapixel camera are set by the needed throughput to carry out one comprehensive deep-sky survey. So that hasn't changed. The main difference is the huge effort we have put into data management and software development.

How has the 1998 discovery of dark energy impacted the science case for the project?
The discovery of dark energy, using a previous camera we built called the Big Throughput Camera, added an important new science motivation for what was originally called the Large Synoptic Survey Telescope [now renamed the Legacy Survey of Space and Time]. But an even more important development has been the growth of time-domain astronomy. A good example is gravitational wave bursts, which Rubin will follow up.

Which results are you looking forward to most?
My main interest is in cosmology; the 'new' physics of dark matter and dark energy. There are multiple probes of that with the upcoming survey. But I'm most excited about the discovery of the unexpected.

Planet Nine – an unseen ninth world possibly hiding in our Solar System – could finally be within grasp

ILLUSTRATION

and maybe even the hypothetical Planet Nine in the distant reaches of the Solar System. "The wealth of new Solar System objects we will uncover is super-exciting," says Blum.

There are many other discovery opportunities, especially in time-domain astronomy: the ability to study how the whole sky changes over a wide range of timescales, which Heymans refers to as 'whoosh-flash-bang astronomy'.

"There's a lot going on that we don't yet understand," says Ritz.

Data avalanche on its way

Rubin's repeated visits to the same areas of sky will yield hundreds of 'alerts' per second where something has changed: countless variable stars, stellar flares, novae and supernovae, but also the optical counterparts of explosive events like gamma-ray bursts, fast radio bursts, tidal disruption events and gravitational wave sources.

"I am most excited to see how our community works with the alert stream," says Blum. "I am also anxious to see how successful we will be in setting up a network of telescopes for follow-up observations."

Operated by NSF's National Optical-Infrared Astronomy Research Laboratory (NOIRLab) and SLAC, the Vera C Rubin Observatory will take 10 years to complete the LSST project. Right now, no one knows what it will bring.

"I have learned not to speculate," says Ritz. "Science often has surprises, which is great. We really want to see what doesn't fit our expectations, because that's often the first step in a great discovery."

As for the cosmological conundrums that scientists are faced with, Heymans sees two possible scenarios. The first is what many astronomers already think is the case: that dark energy doesn't change over time. "I fear that would lead us no further in our journey to truly understand the origin of the dark Universe," says Blum.

"The second scenario is that we find evidence of dark energy evolving and changing with time or space. That would allow for the existence of a new force field, which could possibly be coupled to the gravitational field.

Who knows what we'll find – but with Rubin the discovery potential is endless."

Govert Schilling's book *The Elephant in the Universe* is published by Harvard University Press