HOT MESS:
When Stars Collide
PAGE 12

PLANETS:
Jupiter Returns at Dawn
PAGE 46

STELLAR DUOS:
The Best Star Pairs
PAGE 20

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JUNE 2024

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Page 62

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Rubin's Revol

The Rubin Observatory is set to bring astronomers a data deluge on everything from asteroids to dark energy.

The future of astronomy is under construction on a mountaintop in Chile. Soon after this issue goes to press, the largest digital camera in history will arrive on Cerro Pachón, a mountaintop 2,700 meters (8,900 feet) high in a rugged and remote area just south of Chile's Elqui Valley. Engineers will integrate the camera with the 8.4-meter Simonyi Survey Telescope, the main instrument of the Vera C. Rubin Observatory. First light for the new facility is expected in early 2025, and by the end of that year, the 10-year Legacy Survey of Space and Time (LSST) will commence, providing astronomers with an unprecedented view of the cosmos.

Every three nights or so, the huge observatory will image the whole visible sky down to 24th magnitude. Its survey will discover countless transient phenomena like remote supernovae, stellar flares, and *tidal disruption events*, in which whole stars are shredded and feasted upon by gluttonous supermassive black holes. It will bring to light millions of previously unknown small bodies in the solar system — asteroids, comets, and Kuiper Belt objects. And it is expected to shed light on the mysterious dark energy that is currently speeding up the expansion of the universe, as well as on the equally puzzling dark matter that holds galaxies together. "Nothing like this has ever been done before," says the observatory's operations director, Robert Blum (National Optical-Infrared Astronomy Research Laboratory, or NOIRLab).

Back in the 1960s and 1970s, American astronomer Vera Rubin, the observatory's namesake, showed that spiral galaxies, like our own Milky Way and nearby Andromeda, are dominated by invisible stuff. In fact, back in 1996 when Chief Scientist J. Anthony Tyson (University of California, Davis) first proposed what would eventually become the

▶ **NEARLY READY** The Rubin Observatory looks out from its perch on Cerro Pachón at sunset. The round dome to Rubin's left holds the Auxiliary Telescope, which will use stars' spectra to measure how well different wavelengths pass through the atmosphere where Rubin is looking.

Rubin Observatory, he called it the Dark Matter Telescope. "After the discovery of the accelerating expansion of the universe in 1998, we immediately knew that the telescope would also be a key tool in probing the physics of dark energy," Tyson says. "We were going to open up a whole new window on the universe."

Both of the independent teams that discovered dark energy made use of observations with the Big Throughput Camera on the 4-meter Blanco Telescope at the Cerro Tololo Inter-American Observatory in Chile — an earlier project led by Tyson. "We realized that we could do better," he says, "with a larger telescope, a wider field of view, and bigger CCD mosaics." The astronomical community agreed, endorsing the project in both the 2001 and 2010 decadal survey reports, which present astronomers' funding recommendations to the government.

And now, almost three decades after Tyson first envisioned it, the Rubin Observatory is finally nearing completion.

A Telescope Like No Other

To carry out an all-encompassing multi-year survey of the night sky, you need to put your telescope on a site with consistently good observing conditions throughout the year, explains the observatory's project manager, Victor Krabbendam (Association of Universities for Research in Astronomy, or AURA). "For us, average good seeing is more important than incidental excellent seeing," he says. "Also, you don't want to be on a site where you lose the same period of each year due to periodic poor weather conditions."

Galactic Archaeologist

Among its many goals, the LSST survey will catalog more than 10 billion stars in our own Milky Way, all the way out into our galaxy's halo and even into neighboring galaxies. (The European Gaia mission, in comparison, has pinpointed nearly 2 billion stars. Rubin is more sensitive, but Gaia's positions are more accurate.) Measuring stars' distances, motions, colors, ages, and chemical compositions will yield valuable information on *galactic archaeology* — the way in which our home galaxy has grown by devouring smaller dwarf galaxies in the past — as well as on stellar populations, and even on exoplanet statistics.

NOIRLAB / NSF / AURA / P. HORÁLEK

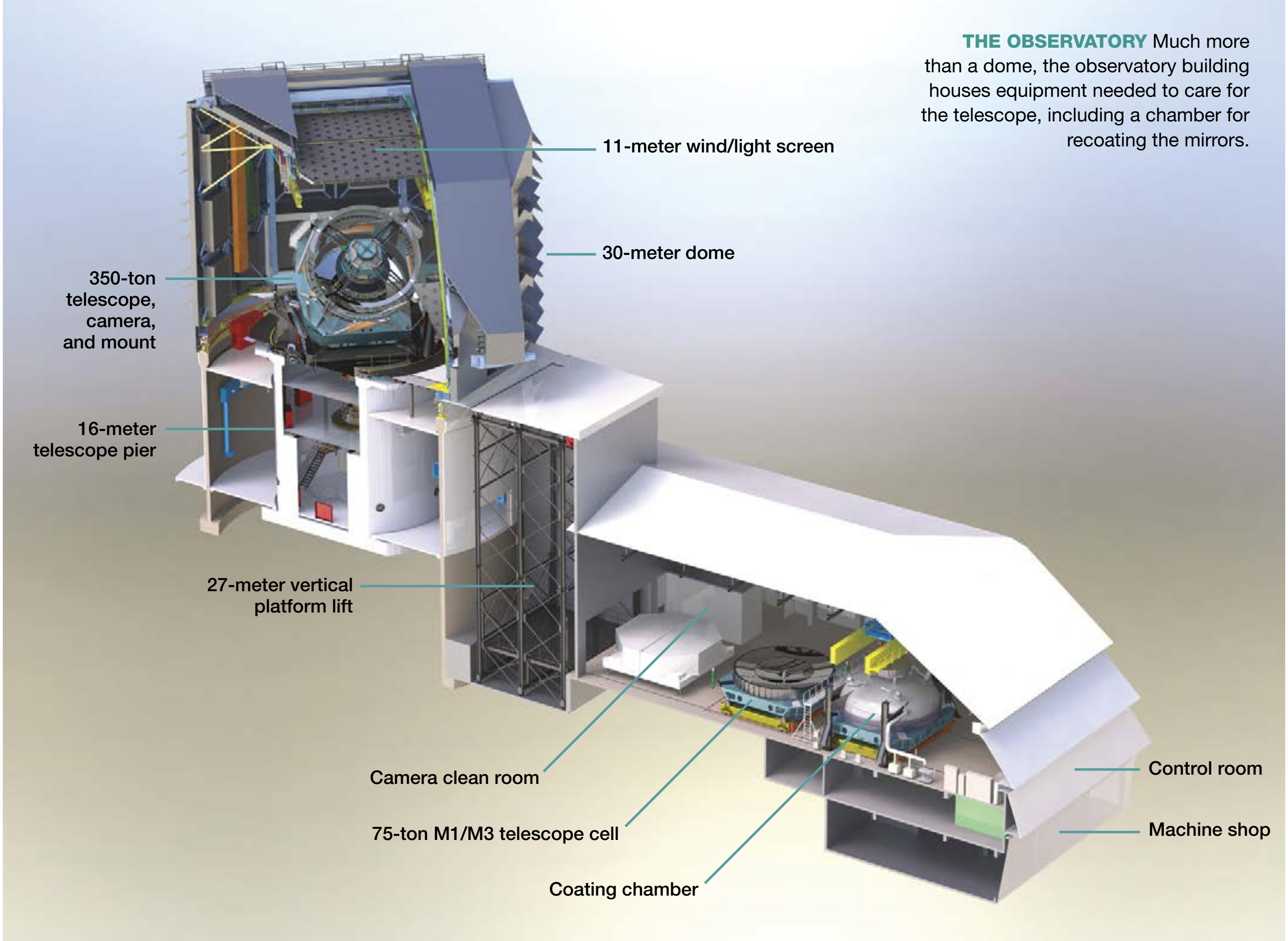
After considering locations in Mexico, the Canary Islands, and Chile, astronomers selected Cerro Pachón in 2006 as the best location for Rubin. This was partly because of the existing infrastructure — the mountaintop (not too far from Cerro Tololo) is already home to the 8.1-meter Gemini South telescope and the 4.1-meter Southern Astrophysical Research Telescope (SOAR).

The project received the official green light in August 2014, and the ceremonial "unveiling of the first stone" was done on April 14, 2015, by Chilean president Michelle Bachelet. The lion's share of the $670 million construction cost has been ponied up by the National Science Foundation (NSF) and the Department of Energy (DOE), with smaller contributions from private donors like Microsoft's Bill Gates and Charles Simonyi, after whom the telescope is officially named. NSF's NOIRLab will operate and manage the facility.

Back in 2014, planners hoped the observatory would be ready in 2022. "The COVID pandemic has been the major source of construction delays," says Krabbendam, "but right now, everything is coming together quite nicely."

The telescope's three-mirror design is like no other. Its 8.4-meter primary mirror (M1) is among the largest monolithic telescope mirrors ever built, and it's actually two mirrors in one: The central part, 5 meters in diameter, has a much stronger curvature and acts as the instrument's tertiary mirror (M3). Grinding and polishing both mirrors from one huge slab of glass ensured a very stiff optical system. Although it's impressively large, the telescope is also extremely compact: The 3.4-meter convex secondary (M2) sits less than 6.5 meters above M1, resulting in a very wide field of view 3.5 degrees across — as wide as seven full Moons. Each image obtained by Rubin will cover almost 10 square degrees, which is about as large as the head of the constellation Hydra, the Water Snake.

To capture such an enormous area of sky in full detail, the Rubin Observatory LSST Camera, designed and built by the DOE's SLAC National Accelerator Laboratory in California, features a 25-inch-diameter focal plane, covered by 189 CCDs of 16 million pixels each. As large as a car and weighing almost 3 tons, it is the largest astronomical camera ever built, sporting a whopping 3.2 billion 0.01-millimeter-wide pixels in total, with a resolution of 0.2 arcsecond per pixel. According to Beth Willman, the CEO of the LSST Discovery Alliance, in order to display one Rubin image at full resolution



THE OBSERVATORY Much more than a dome, the observatory building houses equipment needed to care for the telescope, including a chamber for recoating the mirrors.

RUBIN OBSERVATORY / J. ANDREW

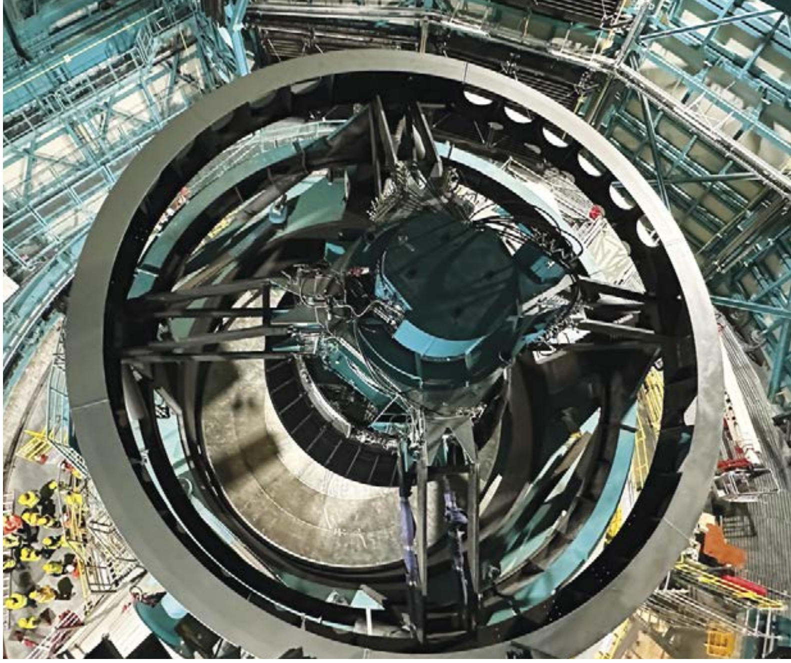
you would need 10 of the largest LCD screens on Earth.

The detector array will be cooled to −100°C (−150°F) during operations, to enhance its sensitivity. Images are captured through six broadband filters, registering stars as faint as 24th magnitude in just 15 seconds of exposure time.

"To test the entire optical system with real sky data, we will use a smaller commissioning camera that has already been installed in August 2022," says Krabbendam. "This makes it easier to solve potential problems that you don't want to run into with the full survey camera. First you crawl, then you walk, then you run." Rubin's *technical first light*, using this so-called ComCam, is foreseen in the summer of 2024; the survey camera should be installed in the fall. Incidentally, ComCam is quite impressive by itself: Even though it has a "mere" 144 million pixels, it is about the same size as its more powerful successor.

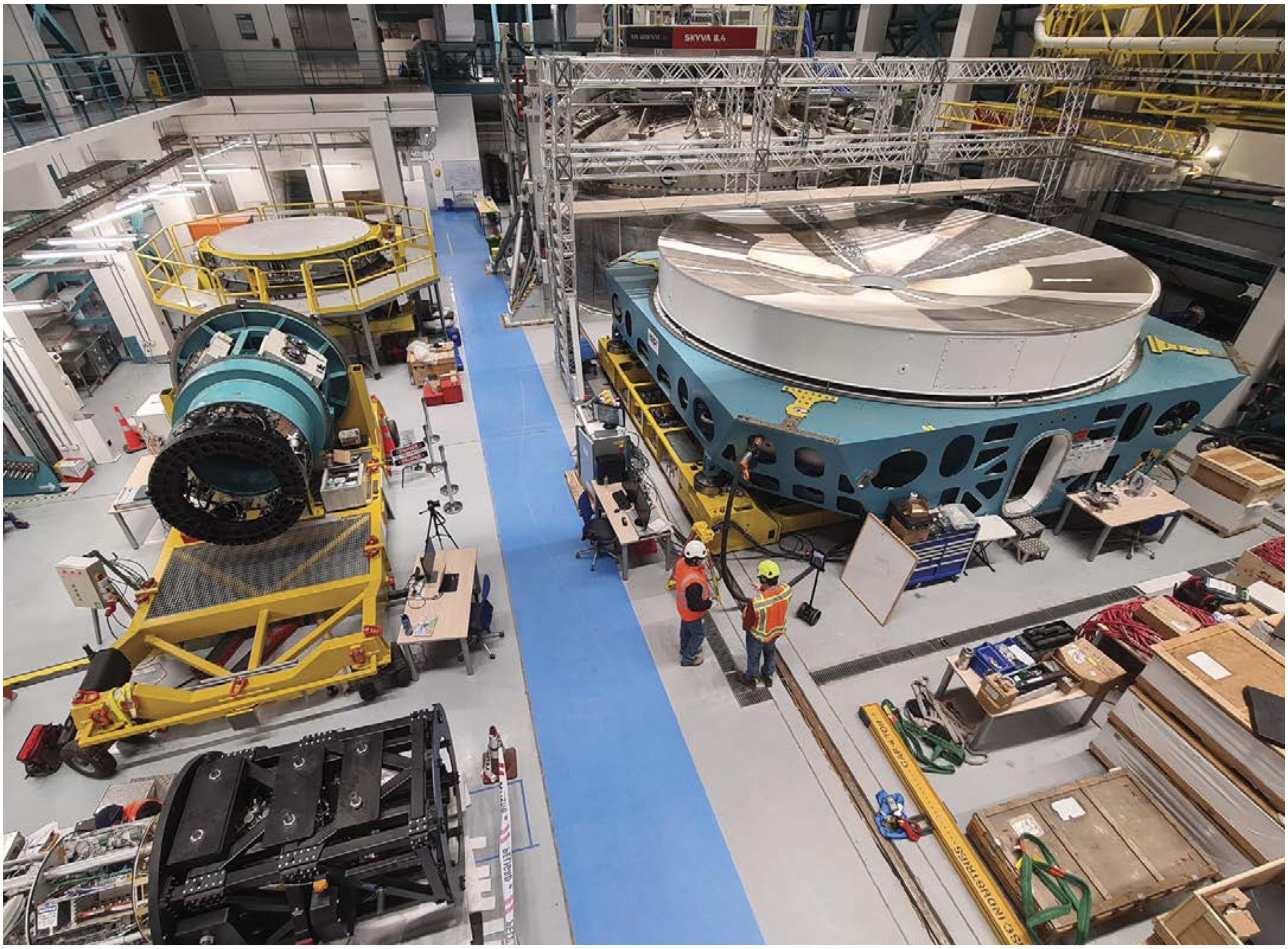
Transformational Science

Most large astronomical telescopes carry out a wide variety of research programs, carefully selected from hundreds of observing proposals from astronomers all over the world. Not so with Rubin. During its first 10 years, its sole goal is



▲ **BIG EYE** Seen from above in November 2023, the Rubin Observatory telescope mount waits for its primary mirror.

▼ **BUILD-OUT** Equipment fills the integration and maintenance hall during construction in 2021. At left is the commissioning camera, and at right is the surrogate mirror used during testing.



BIG EYE: RUBIN OBSERVATORY / NSF / AURA / A. ALEXOV; MAINTENANCE HALL: RUBIN OBSERVATORY / NSF / AURA to carry out the Legacy Survey of Space and Time, which will yield a humongous treasure-trove of data for other astronomers to explore and study (*S&T:* Sept. 2016, p. 14).

To that end, researchers have established eight Science Collaborations, bringing together more than 2,000 astronomers from over 30 countries who are planning the survey and preparing the data flow. "Everyone is excited about what we might find," says cosmologist Catherine Heymans (University of Edinburgh). No one doubts that keeping a vigilant and sensitive eye on the whole sky for a decade is bound to uncover myriads of new objects and exciting phenomena.

In our own solar system alone, Rubin is expected to find some 5 million new objects, most of them in the asteroid belt between the orbits of Mars and Jupiter but others elsewhere, such as in the Kuiper Belt beyond the orbit of Neptune. It should also find thousands of new comets. Collecting 10 years' worth of data on these small bodies will "transform everything," says Megan Schwamb (Queen's University Belfast, UK), who is the co-chair of Rubin's Solar System Science Collaboration. "Usually we find them, and that's it," she says. "But now we will also monitor their brightness variations, rotational properties, color change, and potential activity."

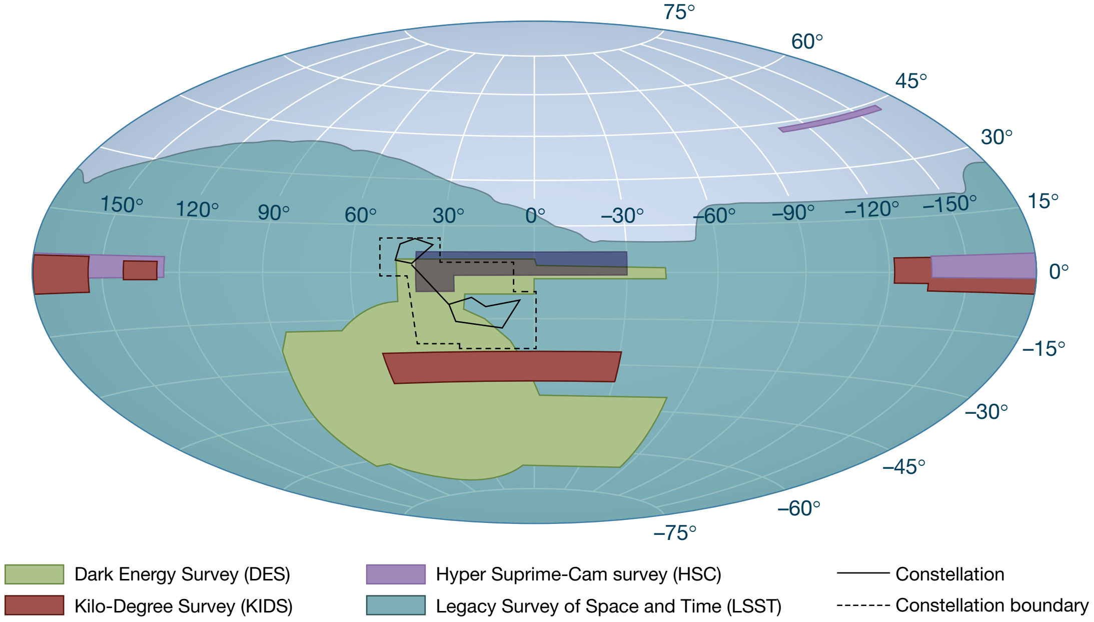
Thanks to its huge sensitivity, the survey will also find many more near-Earth objects and *potentially hazardous asteroids* (PHAs), helping to deliver on the Congressional mandate of finding 90% of the Earth-threatening bodies larger than 140 meters in diameter, says Schwamb. Rubin may even uncover Planet Nine, a proposed large planet beyond the Kuiper Belt that might be the cause of an observed "alignment" of the orbits of a number of small objects in the solar system's outermost regions — if the planet exists, that is. "I'm sure many groups will dive into the data to look for it," says Schwamb. "It's very exciting." Finally, she expects Rubin to find additional temporary visitors from beyond the solar system, comparable to the mysterious object 1I/'Oumuamua that flew by in 2017 and Comet 2I/Borisov in 2019.

Beyond the solar system, the LSST survey's repeated images of the same area of sky will reveal a multitude of variable sources, explosive events, and other astronomical transients, bolstering *time-domain astronomy*, a.k.a. "whoosh-flash-bang astronomy." "With current facilities, we already discover some 20,000 transients per year," says Craig Pellegrino (University of Virginia), "compared to a few hundred back in 2013. Rubin will exponentially accelerate this growth." These phenomena include quasar activity in distant galaxies, feasting black holes, the aftermath of merging neutron stars (so-called *kilonovae*), optical counterparts to gamma-ray bursts, and, of course, supernovae. According to Willman, Rubin should discover a new remote supernova every two minutes or so, corresponding to some 3 million finds in 10 years.

Tyson has high expectations for Rubin's transient program. "I'm convinced that a hundred years from now, this observatory will be remembered for discovering mind-blowing, unexpected things," he says. "Like some new class of object that explodes in a completely novel way. That's almost guaranteed."

Constraining Cosmological Models

As for cosmology, the expected wealth of supernova discoveries in distant galaxies will help cosmologists like Tyson to better understand the expansion history of the universe. After studying the relationship between the distances of Type Ia supernovae and the *redshifts* of their spectra (which reveal how quickly the universe's expansion is carrying the supernova's host galaxy away from us), scientists announced in 1998 that cosmic expansion is currently accelerating (*S&T:* Feb. 2024, p. 26). Adding so many new data should reveal further details about the puzzling dark energy in empty space that is



▶ **SKY COVERAGE** LSST will dwarf other major cosmological surveys. The Hyper Suprime-Cam (HSC) survey covers 1,400 square degrees, the Kilo-Degree Survey (KIDS) covers 1,500 square degrees, and the Dark Energy Survey (DES) covers 5,000 square degrees. LSST, in comparison, will cover some 18,000 square degrees, surpassing even the Sloan Digital Sky Survey's latest data release (14,555 square degrees). The Cetus stick figure and constellation boundary lines are included for comparison: Cetus covers just over 1,230 square degrees.

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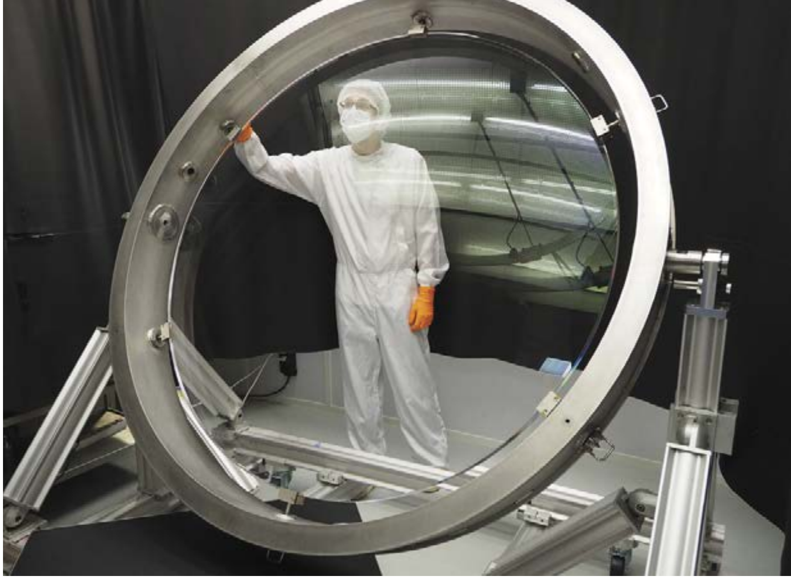


▲ **READY FOR A CLOSE-UP** A team member inspects the largest of the three lenses in Rubin's LSST camera.

thought to be responsible for this expansion boost.

"Cosmology is one of the main pillars for the LSST survey," says cosmologist and Rubin Operations Scientist Andrés Plazas Malagón (SLAC). "By comparing our huge data sets with computer simulations of cosmic evolution, we can constrain our cosmological models" of the content and evolution of the universe.

According to Plazas Malagón, four other analysis techniques, in addition to the supernova technique, will be applied to the survey data in order to get a better grip on the fundamental properties of our universe. These four methods will all be based on Rubin's observations of galaxies, some 20 billion of which are expected to show up in the survey data.

First, as a result of *weak lensing* (see sidebar, page 40), the apparent shapes of galaxies are slightly distorted by gravitating matter along our line of sight to each galaxy. Most of this matter is dark, so statistically studying this effect will shed light on the 3D distribution of dark matter.

Second, astronomers will follow the growth of the large-scale structure of the universe through cosmic time. This growth is essentially the result of the tug of war between dark matter and dark energy. Researchers can study it by measuring the number and masses of galaxy clusters at different distances, corresponding to different look-back times.

Finally, the expansion history of the universe leaves two telltale fingerprints. One is a change in the size of *baryon acoustic oscillations* (BAOs), the imprint of sound waves in the newly born universe. BAOs have been frozen into the distribution of matter at a specific scale, and they are still recognizable in the 3D distribution of galaxies, their size growing over time as everything expands (*S&T:* Feb. 2024, p. 20). The other fingerprint is time delays between brightness fluctuations in multiple images of the same remote quasar. These images result when the gravity of a foreground, massive galaxy or galaxy cluster strongly lenses the distant quasar's light. The light of each image travels along a different path, each with its own length and duration and, therefore, amount of expansion.

Eventually, says Plazas Malagón, astronomers will refine the measurements so much that they'll be able to distinguish between various theoretical frameworks for how the universe behaves. "For instance, we hope to discover whether or not dark energy is changing with time," he says — something that might alleviate a number of nagging cosmological issues. These include discrepancies between measurements and predictions for both the expansion rate of today's universe and the "clumpiness" of cosmic structure.

Data Deluge

Right now, the various science collaborations are preparing for a true avalanche of data, says Schwamb. "With so many

▲ **TIGHT SQUEEZE** After arriving at the port of Coquimbo in Chile in 2018, the telescope's coating chamber was divided into two parts like an Oreo and transported to the summit of Cerro Pachón. Along the way, hanging signs, utility cables, and lights had to be removed to make room. Here, the chamber makes its way through the narrowest tunnel along the route. (Planners decided the telescope's size with this tunnel in mind.)

LENS: SAFRAN; TELESCOPE TRANSPORT: MANUEL PAREDES / NSF / AURA / GEMINI (2)

science drivers, it's hard to optimize the survey strategy — how often do we want to return to a particular part of the sky, what filters do we want to use, et cetera. Everybody wants something else. But we're getting ready for it."

To collect all these data, the telescope will be working like mad. The camera will capture a 6-gigabyte image in just 15 seconds. Reading out the CCDs takes some 2 seconds. Next, the 62-ton telescope, which rests on a hollow, 16-meter-wide concrete pier, will slew to a new sky position in a mere 5 seconds, to start another 15-second exposure just half a minute after the first. This will go on night after night, for 10 years in a row. "It's an awesome sight to see this huge, massive instrument move so fast and quiet," Krabbendam says.

During the survey, a 1.2-meter Auxiliary Telescope, erected close to the 8.4-meter giant, will continuously monitor *atmospheric transmission*. Always pointing at the same part of the sky as the main instrument, the small telescope will measure the precise way in which certain wavelengths of light are affected or absorbed by Earth's atmosphere, dependent on weather conditions, altitude on the sky, and so on. Astronomers will use this information to calibrate and correct Rubin's observations before they end up in the survey catalog.

Rubin will collect some 20 terabytes of raw data per night, for a total of 60 petabytes (i.e., 60 million gigabytes) at the end of the survey — three times the total digital content of the Library of Congress. By then, the project will have amassed millions of individual images. These will become available to the wider astronomical community after two years.

The only interruptions to the constant grind of the observing cycle will be when the massive primary/tertiary mirror has to be recoated with a thin layer of aluminum, about once every two years. On those occasions, a giant 80-ton-capacity elevator will transport the mirror to the coating plant, which lies four levels below the telescope floor in the service and operations building. (This building also houses offices, workshops, computer rooms, and a control room.) The silver coating of the smaller secondary mirror needs to be renewed once every five years.

Founding father Tyson, for one, is looking forward to Rubin's first-light ceremony in early 2025. To him, this is not so much the completion of a project but the start of a new era in astronomy. "Of course it's very gratifying to see how everything has come together after more than 25 years of hard work, thanks to a very strong and dedicated team," he says. "But to any scientist, and in particular to the young astronomers who weren't even born when I first came up with the idea, the start of something new is always much more exciting."

■ Contributing Editor **GOVERT SCHILLING** last visited Cerro Pachón in 2017, when the Vera C. Rubin Observatory was still very much a construction site. He looks forward to visiting the completed observatory in early 2025.

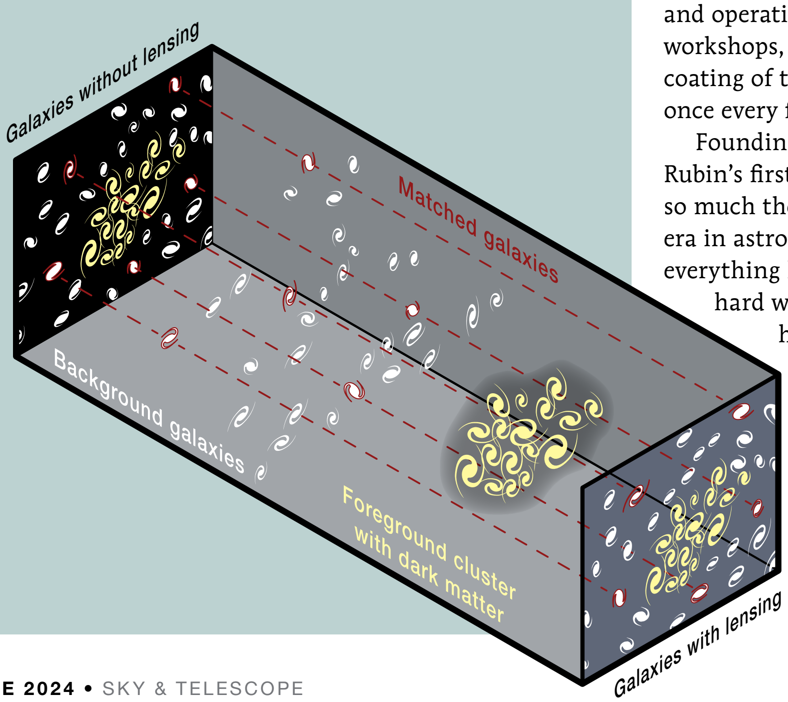
Weak Lensing

Light is bent by gravity. We see this phenomenon often enough in the Hubble and Webb photos of gravitationally lensed galaxies, their images magnified, multiplied, and/or stretched into light arcs by the gravity of a foreground cluster.

But apart from this *strong lensing* effect, there's also *weak lensing*: the slight distortion in the shape of each and every distant galaxy's image that's produced by the accumulating gravitational effect of all matter between the galaxy and Earth (*S&T:* Sept. 2016, p. 34). If remote galaxies were perfectly spherical, this effect would be easy to observe. Instead, since galaxies usually look elongated to start with from our point of view, astronomers need to study the appearances of thousands or millions of them in a particular area on the sky, to look for preferential distortions in a particular direction. From such a statistical analysis, they can map the distribution of intervening matter, both luminous and dark — a technique pioneered by the Vera C. Rubin Observatory's founding father, J. Anthony Tyson, in 1990.

Combining this approach with distance measurements, Rubin's detailed observations of billions of galaxies will be used to map the distribution of gravitating matter through space and time.

▼ **SUBTLE EFFECT** As the light from background galaxies skirts the outer edges of a large, foreground galaxy cluster, the distant galaxies' apparent shapes are slightly stretched. This *weak lensing* effect is too subtle to be visible in a single galaxy's image; rather, astronomers must combine a large sample of galaxies to see it. (The diagram below magnifies the effect in order to make it visible.)



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