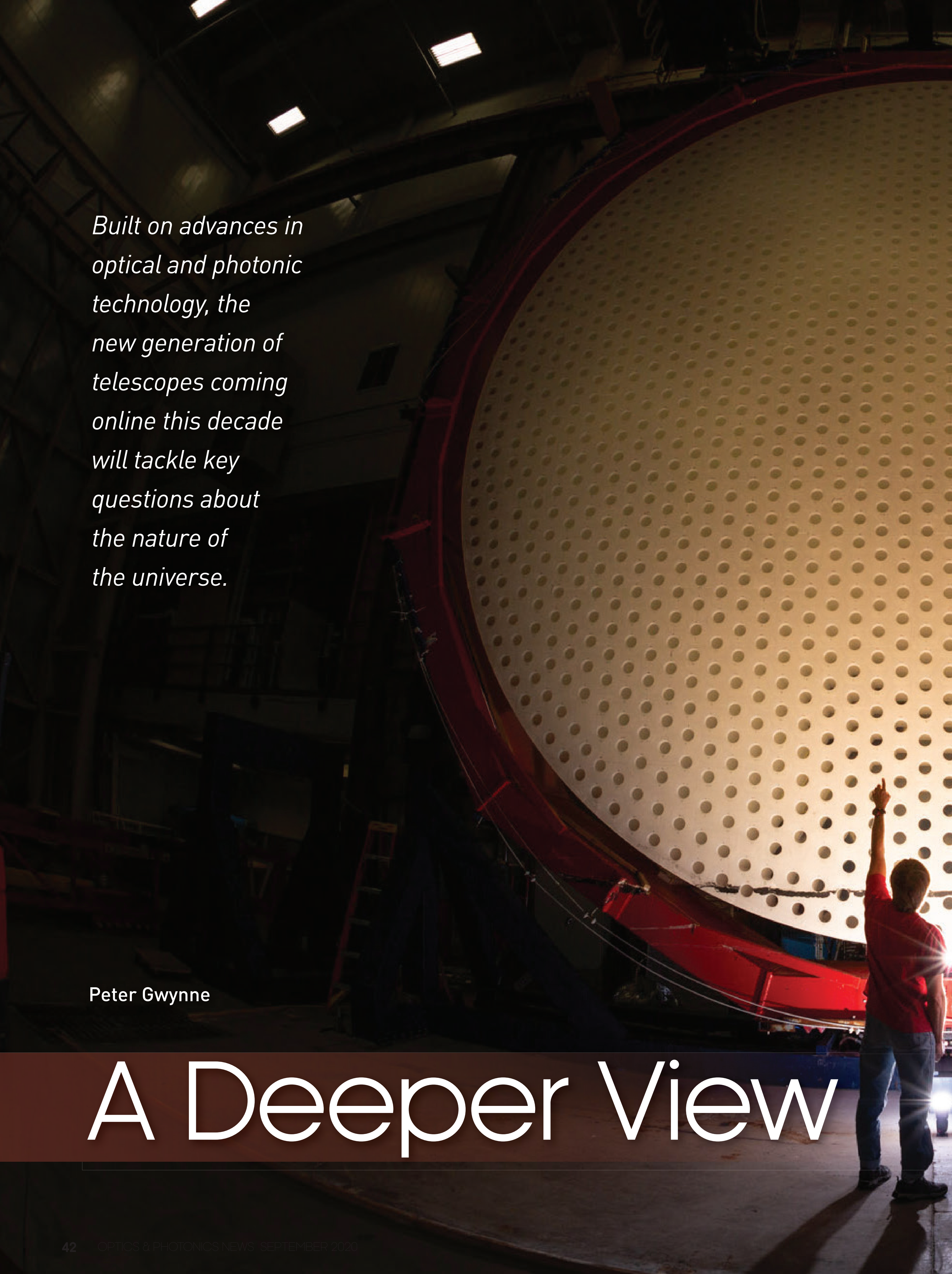
A Deeper View

Built on advances in optical and photonic technology, the new generation of telescopes coming online this decade will tackle key questions about the nature of the universe.

Peter Gwynne



of the Cosmos

One of the seven primary mirrors of the Giant Magellan Telescope, under construction.

Giant Magellan Telescope – GMTO Corp.

During the 2020s, a series of optical telescopes—some already online, some under construction, and some on the drawing boards—promises to dramatically expand humanity's view of the universe. Based on Earth or in space, and gathering light at a range of wavelengths, the new observatories will harvest data bearing on key astronomical and astrophysical questions: the 3D structure of the universe; the composition of exoplanet atmospheres; the characteristics of the first galaxies, dark energy and dark matter.

These instruments rest on decades of improvement in optical and photonic technology that could enable cosmic perspectives of unprecedented sharpness, scope and depth. Many of the projects themselves are gargantuan, and thus face the same issues—technical quirks, funding availability and siting complications—that bedevil any such giant undertaking. They also confront one issue previous projects haven't had to deal with: the global impact of the COVID-19 pandemic.

Nevertheless, astronomers remain optimistic that, by the end of the 2020s, they will have access to a new array of observatories that will vastly broaden their view and understanding of the cosmos. Here's an update on a few of the major projects under way.

Ground-based giants

The most visible of the new observatories are three behemoth ground-based optical reflecting telescopes now under construction—the mirrors (and hence apertures) of which are far larger those in any existing instrument. Their combination of size, location and advanced optical technology will give them observing capability that that will significantly exceed that of any telescope in action today.

The largest of the anticipated new arrivals is the European Southern Observatory's Extremely Large Telescope (ELT), with a mirror diameter of 39 m. That will make it easily the world's largest optical observatory when it receives first light. Located in Cerro Amazones, Chile, a region with more than 300 nights per year of excellent viewing, the ELT will have 256 times the light-gathering area of the Hubble space telescope, which will enable the observatory to produce images 16 times sharper than Hubble's.

The ELT's mirror will dwarf that of the current record holder, the Great Canary Telescope (GCT) in the Canary Islands, which measures just 10.4 m across. The ELT also wins on mirror complexity: while the GCT mirror consists of 36 segments, the ELT's primary mirror will contain 798—each hexagonal in shape, 1.4 m across and polished to an accuracy of 15 nm.

To maintain the vast mirror's surface shape, 4,608 edge sensors will continually measure the relative positions of contiguous segments. Overall, designers say, the mirror will be smooth to an accuracy of 50 nm (see infographic, "Extremely Large Telescopes," OPN, May 2019). Light reflected from the primary mirror will be routed via four other mirrors—including a deformable quaternary mirror to handle adaptive optics—to the telescope's suite of instruments.

Two other giant facilities—both smaller than the ELT, and both involving international consortia led by U.S. universities or scientific organizations—are also at various stages of development. The Thirty Meter Telescope (TMT), if completed as specified, will be able to observe

Deep questions

Whether on the ground or in space, the next generation of optical telescopes will grapple with a wide range of astrophysical and astronomical puzzles.

The earliest universe. Many of the new observatories hope to peer back in time, observing the first stars, galaxies and large-scale structures in the early universe, and exploring the "dark age" when the universe's first sources of light and heavy elements arose.

Black holes. Several new observatories aim at studies of massive and supermassive black holes throughout cosmic time.

Star and galaxy formation. The telescopes will also look at the evolution of more recently formed (and forming) stars and galaxies—using infrared wavelengths in particular to penetrate the opaque clouds and dust of nebulae, or "stellar nurseries."

The dark side. Giant new Earth-based telescopes and Earth and space-based wide-field surveys will scour the sky for evidence of dark energy and clues to the nature of dark matter.

Extrasolar planets and systems. Many observatories plan deep dives into exoplanets and far-flung planetary systems, including searches for water and organic matter in protoplanetary disks, examination of exoplanet formation, and analyses—using tools such as coronagraphs and infrared spectrography—of faint exoplanet atmospheres and, perhaps, hints of life.

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across a range of wavelengths, from the ultraviolet to the mid-infrared. Unlike the other two facilities, it will be located in the northern hemisphere; the currently favored site lies high on the Hawaiian mountain Mauna Kea, though that siting remains uncertain (see below).

Like the ELT, the TMT will use a segmented primary mirror—30 m across, as the telescope's name implies—comprising 492 hexagonal elements of zero-expansion glass. Each segment is backed by a "whiffletree" lever support system that spreads the gravitational load on the segment, to prevent unsought distortion. The telescope's 3.1-m secondary mirror equals the size of several primary mirrors in current observatories. An elliptical 3.5×2.5-m tertiary mirror will allow for switching of light from the primary and secondary mirrors among the telescope's science instruments, and for tracking in two axes to keep the beam aligned with the telescope as it changes zenith angle.

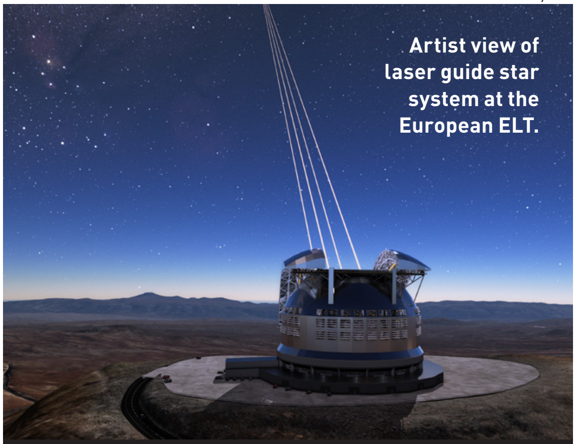
The TMT instrument will rest in a spherically shaped building containing a minimally sized aperture to be opened only for observations. The dome's calotte (cap) shape, according to the designers, was chosen "to minimize its mass and size, with enhanced control and performance during scientific observations." It should also, the designers add, enable the pointing direction to be changed rapidly, and provide protection from "wind-induced vibrations and dome-seeing degradation." The system's design successfully passed a production readiness review in March.

With a 24.5-m optical surface, the Giant Magellan Telescope (GMT), to be located on Chile's Las Campanas peak, is the smallest of the three new optical behemoths, and its design differs significantly from the other two. It will possess seven primary mirrors, each 8.4 m in diameter, to create a collecting area of 368 m^2. Incoming light will reflect off those mirrors, reflect again off seven secondary mirrors, and then travel through an aperture in the central primary mirror to advanced CCD imaging cameras.

Rocky road

Of these three giant telescopes, the ELT is farthest along in construction. At present, first light for the facility is

ESO/L. Calçada



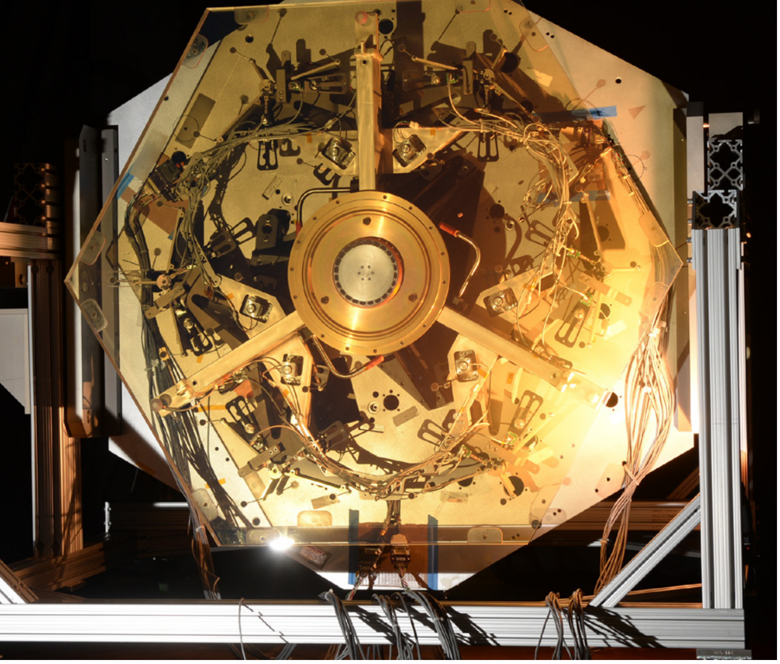
Artist view of laser guide star system at the European ELT.

Adaptive optics

Adaptive optics (AO)—using deformable mirrors and other elements to shape the incoming wavefront, and compensate for atmospheric distortions—has revolutionized Earth-based astronomy over the past several decades. While many current telescopes have had AO systems "bolted on" after the fact, the creators of the next-gen extremely large telescopes have baked AO into the facilities' designs.

The AO system of the ELT, for example—built on technology pioneered in ESO's Very Large Telescope (VLT)—will include six lasers that will be used to excite mid-atmospheric sodium atoms to create a small constellation of glowing artificial "guide stars." Those artificial points of light, at a known position in the atmosphere, will allow the wavefront error attributable to atmospheric turbulence to be calculated in real time; once that's done, some 5,600 actuators in the telescope's 2.4-m deformable quaternary mirror, M4, will reshape the mirror—thousands of times per second—to compensate. The expected result: images 16 times sharper than those from the Hubble Space Telescope.

The TMT and GMT will likewise deploy AO systems out of the box. The GMT's system will reshape the wavefront through deformations of its secondary mirror, whose seven mirror segments each can be reshaped by 672 actuators. The TMT will include adaptive optics as a separate module. Like the ELT, both will take advantage of both natural and artificial guide stars.



One of the 492 hexagonal segments of the TMT primary mirror, showing whiffletree lever system.
TMT International Observatory/Harris/F. Kamphues

scheduled for late 2025—though the ESO administrators, hedging that optimism a bit, admit that there's a "natural risk" of unforeseen difficulties "when building such a one-of-a-kind huge and complex machine."

The two U.S.-led projects—both of which currently are targeting first light in 2029—have encountered a rockier road. For example, as has been widely reported, Indigenous Hawaiian groups and allies have blocked access to Mauna Kea by TMT construction crews, arguing that the mountain, regarded as sacred by Native Hawaiians, already contains too many telescopes. The TMT's international consortium does have a backup site in mind—on La Palma, one of Spain's Canary Islands. But the consortium still hopes that the Hawaiian site can be made to work: while in the northern hemisphere, the La Palma site, at an elevation of only 2250 m versus 4050 m at Mauna Kea, is considered inferior for doing astronomy, particularly for some observations in the infrared.

Funding has also emerged as a big question mark for the TMT and GMT. While the European ELT continues to publicly cite a total cost of just over €1.17 billion (roughly US$1.3 billion at current exchange rates), the cost estimates of the TMT and GMT facilities have recently ballooned to US$2 billion or more for each facility. The numbers reportedly leave both telescopes hundreds of millions of dollars short, and filling that funding gap has become a major preoccupation. Indeed, in an effort to improve their fortunes, in mid-2018, the two U.S. telescope consortia—which long had competed for the same pool of funds—agreed to join forces in the financing effort.

Quite apart from advancing funding prospects, collaboration between the TMT and GMT will also make sense astronomically, according to the consortia behind the instruments. For one thing, the two observatories together can view both the northern and southern skies.

ESO

Staff at an ELT open house stand before a full-size mockup of the telescope's primary mirror.

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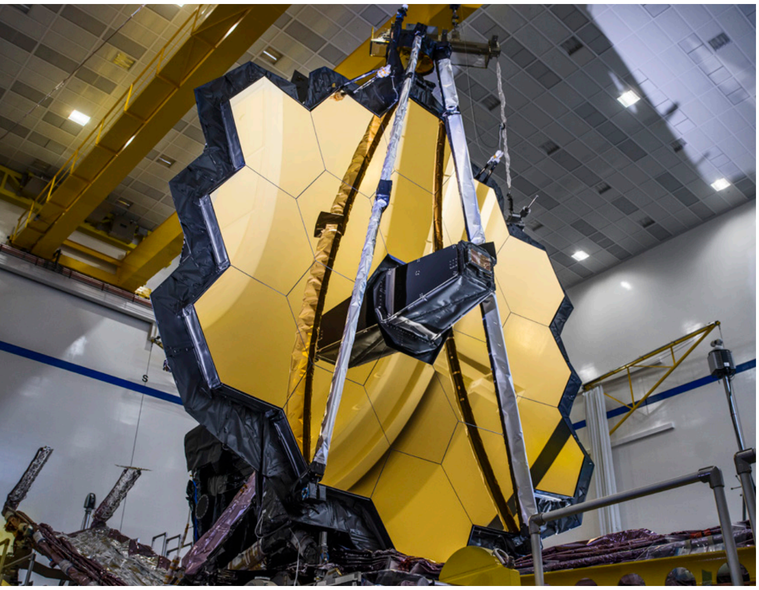
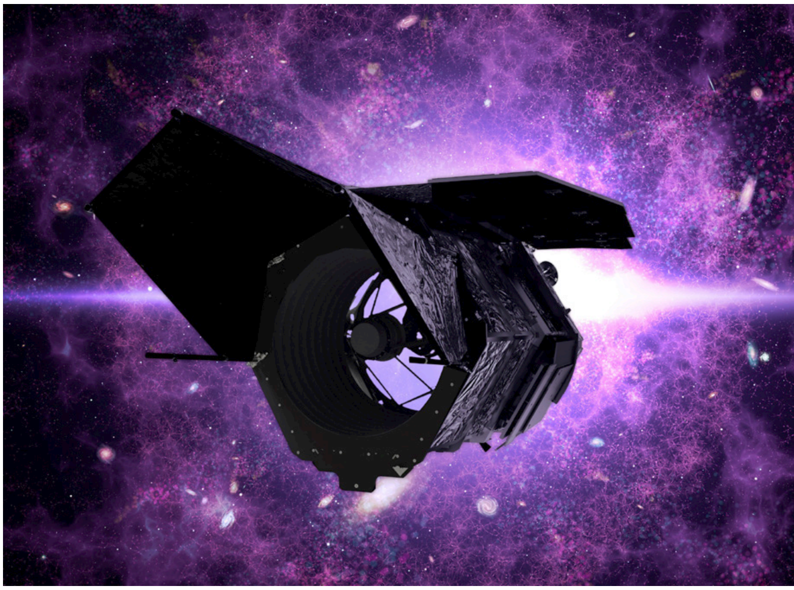




Left: Primary mirror of the James Webb Space Telescope, expected to launch sometime in 2021. Right: The Nancy Grace Roman Space Telescope is a wide-field infrared instrument projected to launch in 2025. NASA

While their combined apertures would only match that of the single ELT, they will be able to focus on a broader swath of the sky, with a 50% overlap that, the projects' organizers say, will permit complementary suites of instruments to undertake joint and even simultaneous studies of certain targets.

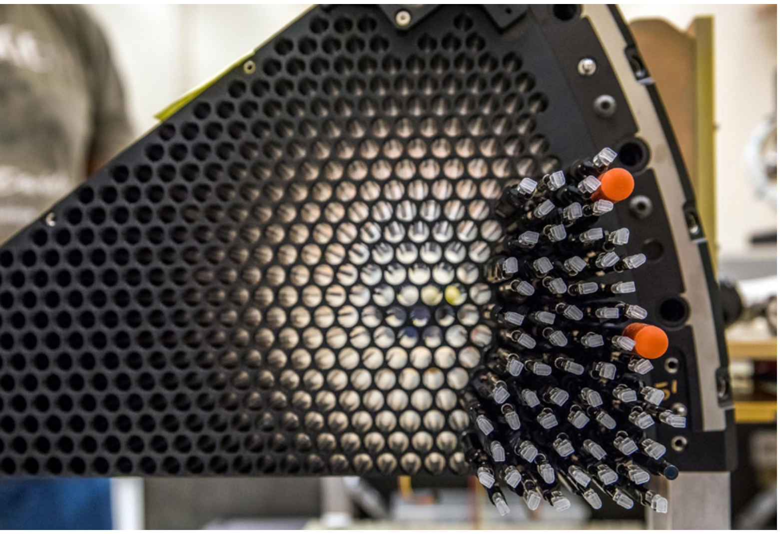
"Two platforms can offer a greater variety of instrumentation than would be available on a single telescope, and more observing hours to support long-term variability and large-scale programs that would otherwise take many years to complete," the TMT team points out. For example, the all-sky coverage that the combination facilitates, the team maintains, will enable astronomers to spot relatively rare phenomena, such as the number of rocky exoplanets in the habitable zone.

New generation in space

In addition to working together on Earth, the TMT and GMT may also have the opportunity to collaborate with the first of the new generation of observatories in space. That observatory is the James Webb Space Telescope, tentatively scheduled for launch next year and described by NASA as "the most powerful and complex space telescope ever built and launched." In part because of that complexity, the telescope's preparation for space hasn't been easy: Conceived in the 1990s for completion in 2007 at a cost of US$500 million, the project has encountered repeated engineering challenges, launch-date delays and price increases. As of the beginning of this year, NASA was eyeing a revised launch date of 30 March 2021 and a projected total cost of US$9.7 billion.

Webb's most recent nemesis, though, has been not technical, but biological—COVID-19. The intervention of the coronavirus forced a three-month suspension of much of the testing effort during the first half of the year, and the testing team was unable to resume clean-room activities until May. In July, NASA announced a revised launch target of 31 October 2021 for spacecraft, with around half of the seven-month delay attributable to COVID-19 complications and half to additional schedule padding to address some technical issues.

When it does launch, Webb will be NASA's next major observatory after the Hubble Space Telescope, launched 30 years ago—and will exceed Hubble in



Each of the ten petal-shaped segments of the Dark Energy Spectroscopic Instrumentfocal plane includes 500 robotically controlled, light-gathering fiber optic cables—enabling the instrument to focus on as many as 5,000 different galaxies every 20 minutes. Marilyn Chung/LBNL

size, instrumentation and scientific capability. Webb's 6.5-m-diameter primary mirror will give it more than six times as much collecting area as Hubble's 2.4-m mirror. While Hubble operates mainly in optical and ultraviolet wavelengths, the Webb will observe the cosmos primarily in infrared.

That infrared coverage, outside Earth's atmosphere, will enable Webb to take on a number of science goals, including the formation of the first (and highly redshifted) stars and galaxies in the universe. Other themes for the observatory will include comparison of the earliest galaxies with those readily visible today, to help understand galactic evolution; and observing the births of stars and planetary systems in clouds and dust that are opaque to observation in visible wavelengths. Astronomers also expect the observatory to reveal details about the atmospheres of planets orbiting distant suns—and, more speculatively, to find evidence for the building blocks of life elsewhere in the universe.

While the story of the in-orbit effort to correct for aberrations in Hubble's mirror is legendary (see "Saving Hubble," OPN, March 2013), that option won't be available for Webb. That's because the spacecraft will be far more distant from Earth than Hubble, orbiting the second Lagrange point (L2), some 1.5 million km away from Earth in interplanetary space—a gravitationally stable "sweet spot" that's the present or planned home for a number of other missions as well. That location will make Webb impossible to service in space; its designers and engineers will need to get it right the first time.

A wider view

Though the Webb telescope hasn't yet found its way into space, NASA is already at work on a complementary infrared instrument, the Nancy Grace Roman Space Telescope. Originally called the Wide Field Infrared Survey Telescope, it was renamed in May 2020 to recognize the woman who became the agency's first chief astronomer. (Roman, who died in 2018, advocated development of the Hubble Space Telescope so effectively that she became known as "the mother of Hubble.")

Scheduled for launch in 2025, the Roman telescope has the goal of providing a clearer and more expansive view of the universe than astronomers have ever seen. Based on a decommissioned satellite telescope that the National Reconnaissance Office gave NASA in 2012, the observatory will consist of a 2.4-m primary mirror and two scientific instruments. One, a wide-field instrument, will have the ability to take images as sharp as those obtained by Hubble, with a field of view a hundred times larger. By making precise measurements of the distribution of galaxies over time, the instrument will provide clues to the evolution of dark energy. The second device is a coronagraph instrument that will carry out high-contrast imaging and spectroscopy of exoplanets orbiting stars at distances beyond the present capability (see "Next-Generation Coronagraphs," OPN, February 2020).

Funding for the Roman telescope has been something of a political football. The Trump administration has consistently tried to cancel it in its proposed annual budgets in favor of larger projects (including Webb), while the U.S. Congress has just as consistently supported the mission, with a current budget of $3.2 billion. The recent name change indicates that NASA, at least, believes in the telescope's future.

Surveying the entire sky

Back on the ground, other instruments will also monitor the entire sky for clues to the nature of dark energy and dark matter. The Dark Energy Spectroscopic Instrument (DESI), which saw its first light last year, is designed to provide the data necessary to produce 3D maps of the universe in greater detail than any now available. It will do so by identifying and measuring the red-shifted fingerprints that clusters of galaxies have deposited through cosmic history. Astrophysicists hope that the resulting map will yield insights into acceleration of

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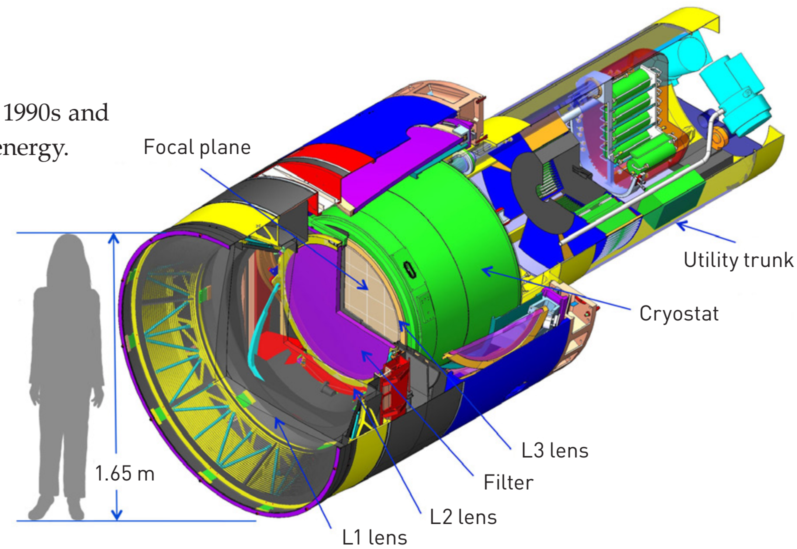
the universe's expansion, identified in the 1990s and thought to stem from the mysterious dark energy.

Mounted atop the Mayall Telescope on Kitt Peak, Arizona, and operated by the Lawrence Berkeley National Laboratory, USA, DESI consists of a robotic array of computer-controlled fiber optic cables that feed data to a bank of spectrographs. The instrument's focal plane is organized in ten wedge-shaped petals, each containing 500 cables; a camera that lets the system point and focus; and a spectrograph that splits the light from each chosen galaxy into three color bands from 360 to 980 nanometers. In action, the cables will undergo what DESI organizers call a "choreographed dance" to focus on individual galaxies at a rate of 5,000 every 20 minutes. The system will take just five years to observe 35 million galaxies and quasars—many too faint to be visible in conventional telescopes.

Starting in 2022, another survey instrument, at the Vera C. Rubin Observatory in Chile, is expected to begin taking more than 800 panoramic images of the complete visible sky each night. Previously known as the Large Synoptic Survey Telescope, and renamed early this year for the discoverer of dark matter, the Rubin Observatory will scan the entire visible sky twice weekly, with sufficient resolution to detect objects 10 million times fainter than the human eye can perceive. The system will enable not only insights into dark energy and dark matter, but also studies of the Milky Way galaxy and even opportunities to detect and track objects, such as asteroids, that might threaten Earth.

The Rubin Observatory's telescope will feature a unique three-mirror, three-lens optical assembly and what is billed as the world's largest CCD camera. About the size of a small car, the camera is a large-aperture, wide-field optical imager that can view light in a wavelength range of 300–1000 nm and provide a 3.5-degree field of view. The amount of data that it will gather—around 20 terabytes per night—will require sophisticated data management infrastructure, middleware and applications.



The design for the Vera C. Rubin Observatory (formerly the Large Synoptic Survey Telescope) includes what is said to be the world's largest digital camera.
Rubin Observatory/DOE

A wealth of new perspectives

Here we've touched on only a few of the bigger projects on the horizon—and have necessarily left out many more. These include Euclid, the planned dark-matter and dark-energy surveyor of the European Space Agency, slated for 2022 launch; solar explorers such as the European Solar Orbiter and NASA's Parker Solar Probe, as well as the Earth-based Daniel K. Inouye Solar Telescope, which will allow new insights on space weather; and a wealth of other projects.

And, of course, there's still Hubble—which launched its own golden astronomical era three decades ago and is still going strong. In a July press event, Webb Space Telescope program officer Eric Smith said that the Hubble mission is now "predicted to last into the 2030s," and noted that the community is "looking forward to having both [Hubble and Webb] working at the same time" to compare observations of the same targets in different wavelength ranges. Thus Hubble's continued contributions will complement the vast array of fresh perspectives from the new generation of telescopes. OPN

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