NSF's National Optical-Infrared Astronomy Research Laboratory

Strategic Vision

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AURA

Executive Summary

A National Laboratory for Astronomy

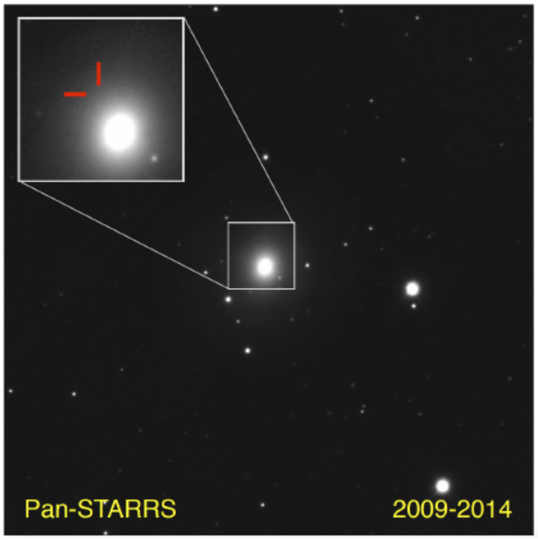
This document describes the strategic vision for NSF's National Optical-Infrared Astronomy Research Laboratory (NOIRLab), a new national center for nighttime astronomy. For the first time, all of the nighttime optical/infrared observatories developed and operated by NSF are unified into a single organization. The integration of the international Gemini Observatory, Rubin Observatory, the Mid-scale observatories in Chile and Arizona and the Community Science and Data Center creates a powerful capability for discovery, technology development, STEM workforce growth and education. NOIRLab empowers astronomers to tackle the most pressing questions in astrophysics today and opens up new discovery space for the future.

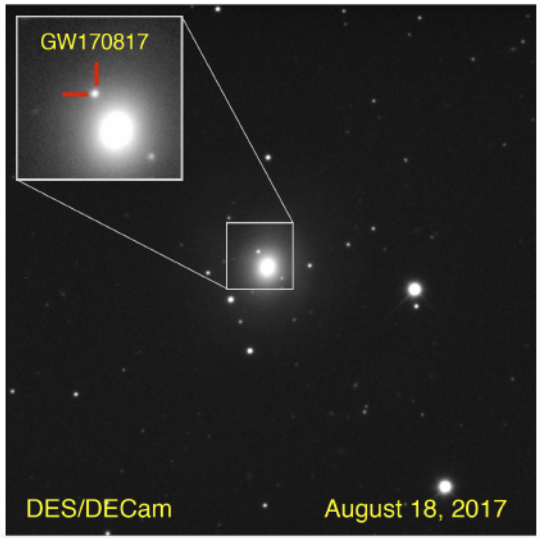
NOIRLab will host a unique science archive of large-area surveys of the deep sky linked to powerful ancillary data sets. Data science schools will train the power users of tomorrow and equip the community with powerful analytic tools. The discovery potential of large uniform datasets is driven not only by their content, but also by the tools and infrastructure available to support them. NOIRLab aims to be the premier big data resource for US optical-infrared astronomy.

Our vision is to create in NOIRLab a national resource that will lead the world in data-intensive astronomy, drive exploration of the new frontier in time-domain astrophysics, lead a national strategy for adaptive optics and astronomical instrumentation, and provide a foundation for scientists to make full use of the coming Extremely Large Telescopes and new tools for discovery in the 2030s and beyond.

An Age of Amazing Discoveries

Astronomy is in a golden age of discovery. In a remarkably short timespan, our knowledge of the Universe and our understanding of our place in the cosmos have changed radically. Our inventory of the contents of the Universe has been turned on its head: 96% of the cosmic mass-energy is in forms undetected in terrestrial laboratories — dark matter and dark energy. The once lonely night sky is now seen to be teeming with other worlds, and many are potentially hospitable to life. Violent events — exploding stars, merging black holes and colliding neutron stars — create ripples in the very fabric of spacetime that expand across the heavens and are ultimately detected on Earth with NSF's LIGO. Merging neutron stars create a brief burst of light visible to NOIRLab's optical-infrared telescopes and leave behind gold dust and other treasures that we find on Earth today. Subatomic particles, accelerated to very nearly the speed of light, fly from the centers of





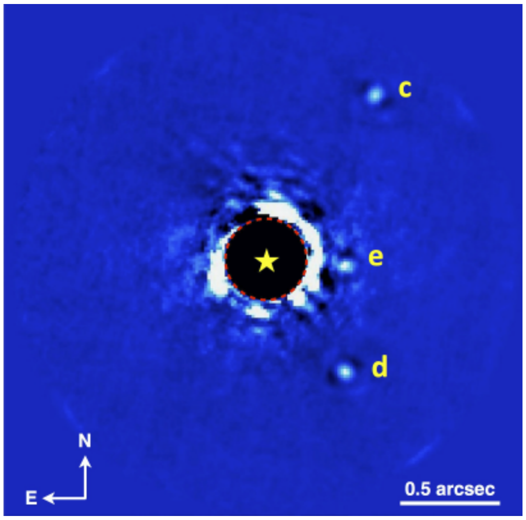
NOIRLab's Víctor M. Blanco 4-meter Telescope in Chile provided discovery images for the optical signature of the LIGO gravitational wave source GW170817. An image from PanSTARRS in 2009 shows that this object was not visible prior to the LIGO detection. This image and spectra taken with NOIRLab and other telescopes combined with the LIGO/VIRGO data identified this as a merger of two neutron stars and established the connection between this event and the creation of heavy atomic nuclei. Credit: P.K. Blanchard, E. Berger, P. Edmonds (2017).

distant galaxies to be captured deep in the Antarctic ice by NSF's IceCube observatory — messengers from black holes a billion times more massive than the Sun and millions of light-years distant. The remnants of stars like the Sun end their days as crystals of pure carbon, diamonds in the sky. The fast, yet finite, speed of light allows us to peer back to the cosmic dawn — a time when the Universe was a small fraction of its current 13.8 billion year age and the first stars and galaxies emerged from the darkness.

These discoveries, and more, have occurred in the past twenty years or so through the innovative use of state-of-the-art observatories working in the visible, infrared and other regions of the spectrum, as well as through new windows on the Universe: gravitational waves and neutrinos. This astronomical research, supported by NSF, NASA and DOE, has led to the award of eight Nobel prizes in physics over the past twenty years, two of which — dark energy and black holes — involved observations with telescopes that are now part of NOIRLab. These acknowledgments are a testament to the power of astrophysics as a gateway to fundamental science.

An Even Brighter Future

The coming decades promise further revolutionary advances in astronomy, astrophysics and fundamental physics. Dark energy was discovered through astronomy, and astronomy will be our only avenue for the empirical investigation of the properties of this dominant form of cosmic mass-energy. Rubin Observatory, an NSF-DOE partnership, and the newest element of the NOIRLab portfolio, will conduct the ten-year Legacy Survey of Space and Time to further our understanding of dark energy. Other collaborations with DOE capitalize on the unique capabilities of NOIRLab telescopes to gauge the evolution of structure in the Universe and the evolving impact of dark energy on the cosmic expansion rate. When these experiments are completed, we will know with some certainty if dark energy is best described by Einstein's cosmological constant or if it is an



Infrared image of three exoplanets orbiting the star HR8799 made using adaptive optics on NOIRLab's Gemini Observatory. Adaptive optics allows us to image faint planets in the glare of their central stars. The image of the central star has been subtracted to make planets easier to see. Planetary systems with multiple planets are common in the Milky Way — most stars have planets and the most common planets are "super-Earths" in orbits similar in size to the orbit of Venus in the Solar System. Credit: international Gemini Observatory/NOIRLab/NSF/AURA/Christian Marois (NRC Canada), Patrick Ingraham (Stanford University) and the GPI Team.

entirely new and perhaps time-varying physical phenomenon. And it is worth noting that the time domain on large scales is a new field for astrophysics, and so there will be a wealth of remarkable science that we have not even thought to define yet.

NOIRLab will be the US portal to the coming Extremely Large Telescopes (ELTs) currently under construction in Hawai'i and Chile. These telescopes will be used to image exoplanets around Sun-like stars and to probe the atmospheres of exoplanets for O_2, CH_4, and other biomarkers. Somewhere in the US there is a high school student who may, a decade or more hence, use the ELTs through NOIRLab to find evidence for life on an exoplanet.

While there are many hospitable places in the galaxy, there are other locations where conditions are quite extreme. The powerful time-domain astronomy capability being assembled at NOIRLab, when coupled to NSF's LIGO and other international gravitational wave observatories, will allow us to probe matter in the most extreme conditions — at the centers of neutron stars — and will give us our best census of the birth rate of intermediate-mass black holes and their massive-star progenitors. A census of kilonovae arising from neutron star mergers will allow us to firmly resolve longstanding questions around the formation of the heavy elements in the lower rungs of the periodic table, elements which seeded planet formation and life itself.

Technology Enables Science and Science Drives Technology

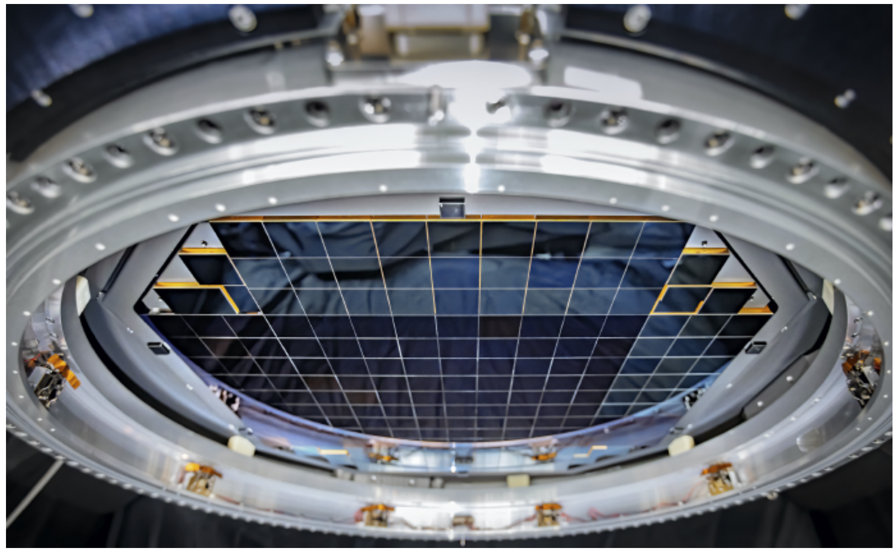
Powerful observatories on remote mountaintops employing sophisticated scientific instruments that are continually updated are the astronomers' laboratories. Investment, innovation, and renewal keep these laboratories at the cutting edge. The bedrock of astronomy, since the time of Galileo and into the foreseeable future, has been ground-based optical-infrared telescopes of ever-increasing light grasp and sophistication.

Ground and space astronomy have a powerful synergy for exploration and discovery. Telescopes in space probe regions of the electromagnetic spectrum that do not penetrate the atmosphere, operate above the blurring effects of the terrestrial atmosphere and can be cooled to reduce thermal backgrounds that impact long wavelengths. Ground-based telescopes can have wide fields of view, can be rapidly pointed to any location on the sky, and can be continually updated.

Adaptive optics allows ground-based telescopes to image selected patches of sky with clarity previously only available from space. Today, Gemini and other large telescopes in Hawai'i and Chile produce images of small targets that can be sharper than those from the Hubble Space Telescope and will complement those from the soon-to-be-launched James Webb Space Telescope. Adaptive optics on ground-based telescopes was central to the 2020 Nobel Prize for the detection of the black hole at the center of the Milky Way. The ELTs under development in Chile and Hawai'i will have the ability to produce images with unmatched angular resolution. Adaptive optics-fed coronagraphs developed for the Gemini Planet Imager serve as technology pathfinders for future space missions, and for ground-based telescopes, aiming to image exoplanets by suppressing the glare from their host stars.

High-precision Doppler spectrographs, benefiting from stable gravity-invariant environments, detect planets through the reflex motions of their host stars — at speeds as slow as one meter per second. The next generation Doppler spectrographs on the WIYN 3.5-meter Telescope — and tomorrow's ELTs — promise precision levels of 10 centimeters per second — enough to detect the gravitational pull of the Earth on the Sun.

In a few years' time, the world's largest visible-light camera will point to the sky in Chile where it will make a nightly motion picture of the sky — in search of dark energy, dark matter, black holes, and the unknown. As Rubin Observatory explores the distant Universe, it will also catalog small bodies throughout the Solar System — and stand watch for potentially hazardous objects. This marvel of technology will be the most impactful element of NSF astronomy in the 2020s and 2030s, and NOIRLab will ensure that the scientific community derives the maximum benefit from its great potential.



Focal plane for the 3-gigapixel camera at the heart of Rubin Observatory. This detector array, designed and built at DOE's SLAC National Accelerator Laboratory, will image the southern sky every three nights. It will open up new discovery space in time-domain astronomy while also underpinning several dark energy and dark matter experiments. Credit: Jacqueline Orrell/SLAC National Accelerator Laboratory/NSF/DOE/Rubin Observatory/AURA.

Big Data for Big Ideas

NOIRLab will host a unique science archive of large-area surveys of the deep sky coupled to ancillary data sets. Data science schools will train the power-users of tomorrow and equip the community with powerful analytic tools. The discovery potential of large uniform datasets is driven not only by their content, but also by the tools and infrastructure available to support the examination and exploration of the data. NOIRLab will be the premier big data resource for US optical-infrared astronomy.

The Astronomical Event Observatory Network connects NOIRLab's observing and data science tools with Rubin Observatory to open up new discovery space in time-domain astronomy. Event alerts from Rubin are identified within 60 seconds of the shutter's closing and are broadcast to scientists around the globe. NOIRLab telescopes will be ready to respond through a network coordinator that matches the science with the telescope, instrument, location and timing. This network creates an unprecedented tool for astronomy that was not possible before the unification of NSF's nighttime observatories under NOIRLab.

The time domain is the least explored frontier in astronomy. NOIRLab is building, and will operate, a powerful network of telescopes for time-critical observations. Powerful software and networking tools will support investigations of all types of time-variable and moving celestial objects. Rubin Observatory will produce ten million "alerts" per night. NOIRLab will provide astronomers with the tools needed to find the most interesting phenomena in this vast data set for detailed investigation. NOIRLab's time-domain astronomy program leverages all of NSF's investments in ground-based optical-infrared astronomical facilities to explore this new frontier.

Astronomy is moving to the massive scale of particle physics in many areas; cosmological studies, the exploration of the structure of the Milky Way, and studies of distant worlds all require highly sophisticated technology and the infrastructure to support them. NOIRLab was created to provide the foundation needed for US astronomy on the global scale. Construction and operation of the ELTs will require world-class scientific, technical, and management structures linked to domestic and international partners to be successful. NOIRLab is the vehicle to make this vision a reality — and to plan and lead future generations of astronomical laboratories on the ground.

At the same time, as astronomy moves to larger-scale projects, care is needed to protect the ecosystem that fosters the small and agile projects that often make breakthrough discoveries and lead to future lines of research. Early-career scientists, academics at small and teaching institutions and individual investigators play a vital role in astronomy, as they do in all sciences. NOIRLab will ensure that they are not left behind as we move to larger-scale science.

Priorities, both scientific and technical, in astronomy and astrophysics are established through a Decadal Survey process led by the National Academies. NOIRLab will work with NSF and their advisory bodies to provide stewardship of the initiatives and priorities coming from the 2020 decadal process. And NOIRLab's scientific staff will play a leading role in fostering dialog and planning in the optical-infrared astronomy community leading up to the Decadal Surveys in 2030, 2040, and beyond.

NOIRLab scientists spend time in classrooms and on other activities that engage young people in hands-on learning about science and astronomy. Credit: international Gemini Observatory/NOIRLab/NSF/AURA/J. Pollard.

Nurturing the STEM Leaders of Tomorrow

None of what we envision can become reality without a diverse and skilled workforce, as well as an engaged and supportive public. NOIRLab has a vital role to play in the development of the STEM workforce, in sharing our passion for discovery, and in keeping the world informed of the exciting work done at our observatories. NOIRLab will train scientific and technical leaders of tomorrow through internships, student programs and post-doctoral research fellowships. We will work to ensure that astronomy, and scientific careers in general, are accessible to a diverse and inclusive community.

The passion for science often blossoms early in life. NOIRLab works in schools in our local communities to bring the excitement of astronomy to the classroom. A vibrant educational program that uses the power of the web, as well as in-person engagement, will leverage our power to grow the STEM workforce that is vital to sustaining US leadership in science and technology.

In the NOIRLab Strategic Vision, we lay out our vision for NOIRLab in 2040 — a national laboratory for astronomy that opens up new frontiers through data science, powerful observatories that operate in harmony with their environments, and a diverse and talented staff that plays a leadership role in the astronomy of tomorrow.