VERA RUBIN OBSERVATORY AND LSST

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The Vera C. Rubin Observatory [1] is a large, 8-meter class, wide field of view optical telescope instrumented with a gigantic, 3 billion pixel, astronomical camera. It is designed to carry out a photometric survey of the southern sky and will map more than half of the sky every 4 nights.

The main survey is expected to start early 2026, and last 10 years, following a period of commissioning observations in 2025. The unrivalled combination of the depth of the LSST (Legacy Survey of Space and Time) and the sky area covered will result in an exceptional data set that will be a major asset for cosmology, and many other fields in astrophysics. The LSST concept was originally developed at the end of 1990's, as the Dark Matter Telescope [2], with emphasis on weak lensing as a probe to reveal dark matter distribution and shed light on dark energy and dark matter. The project gathered momentum in the first decade of the 21st century; the design was refined by a team of scientists and engineers from major US universities, the DOE lab SLAC, as well as the French CNRS/IN2P3 laboratories. The LSST was ranked as the top priority large ground-based project in 2010, by the US National Academies in the astronomy decadal survey [3], and the joint funding by the NSF and DOE approved in 2014. The project benefited from donations from private sources, notably the Charles Simonyi Fund, which made possible some R&D work, as well as procurement of some long lead items such as the primary mirror. IN2P3 in France is the only research organisation which outside the USA and Chile has contributed to the Rubin construction through R&D and construction of the camera.

Telescope and camera

The Rubin observatory is located at the top of Cerro Pachón, at an altitude of 2650 m, in northern Chile, about 50 km south-east of La Serena. The telescope (Simonyi Survey Telescope or SST) design was guided by the • • •

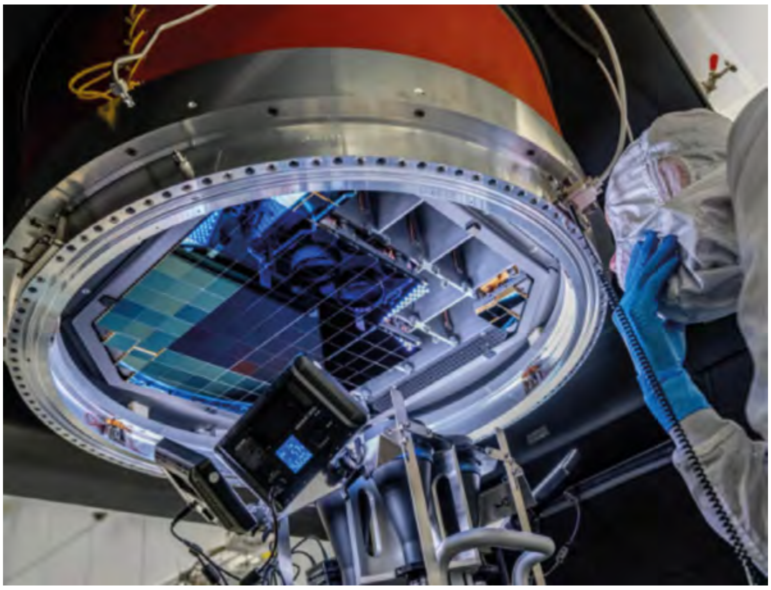
● ● ● requirement of a large collecting area (A), to the benefit of the survey depth, and a very large instantaneous field of view (FOV or Ω), to ensure fast survey speed. The efficiency of carrying out a sky survey can be characterised by the Etendue = AΩ, which reaches 319 m^2 deg^2 for LSST, more than an order of magnitude larger than previous instruments. In addition, a high image quality is required over the full FOV, driven mostly by the weak lensing study requirements.

The telescope optical configuration is a three-mirror modified Paul-Baker design and features an 8.4 m diameter combined primary-tertiary mirror [4]. This leads to a compact altitude-azimuth mechanical mount for this 10.3meters focal length (f/1.234) telescope, capable of fast repointing, requiring only a few seconds to move to a nearby target field.

The FOV has a diameter ∅=3.5 degrees, seven times larger than the moon diameter, covering 9.6 deg^2 on sky in a single snapshot. This translates into a 64 cm diameter area on the focal plane, or 370 times the image area of high-end full frame photographic cameras. The Rubin focal plane is covered by 189 CCD's, each with 16 million (4k×4k) pixels at 10µ pitch, providing images at 0.2" angular resolution. An optimised highly parallel readout electronics, with custom designed circuits (ASIC), enables rather fast readout, requiring less than 10s to digitise the 3200 megapixels.

The camera, which houses also the filter exchange systems, weighs about 3 tons, and has cost about 150 million € to build, around a quarter to a third of the total project construction cost, organised with four sub-systems, the Telescope & Site, the Camera, the Data Management and the Education & Public Outreach.

▾ FIG. 1: A closeup view of the LSST camera focal plane, with 14 out of 21 camera rafts installed. Each raft groups 9 (3×3) CCD's with the associated readout electronics. Credit: Jacqueline Ramseyer Orrell/ SLAC National Accelerator Laboratory.



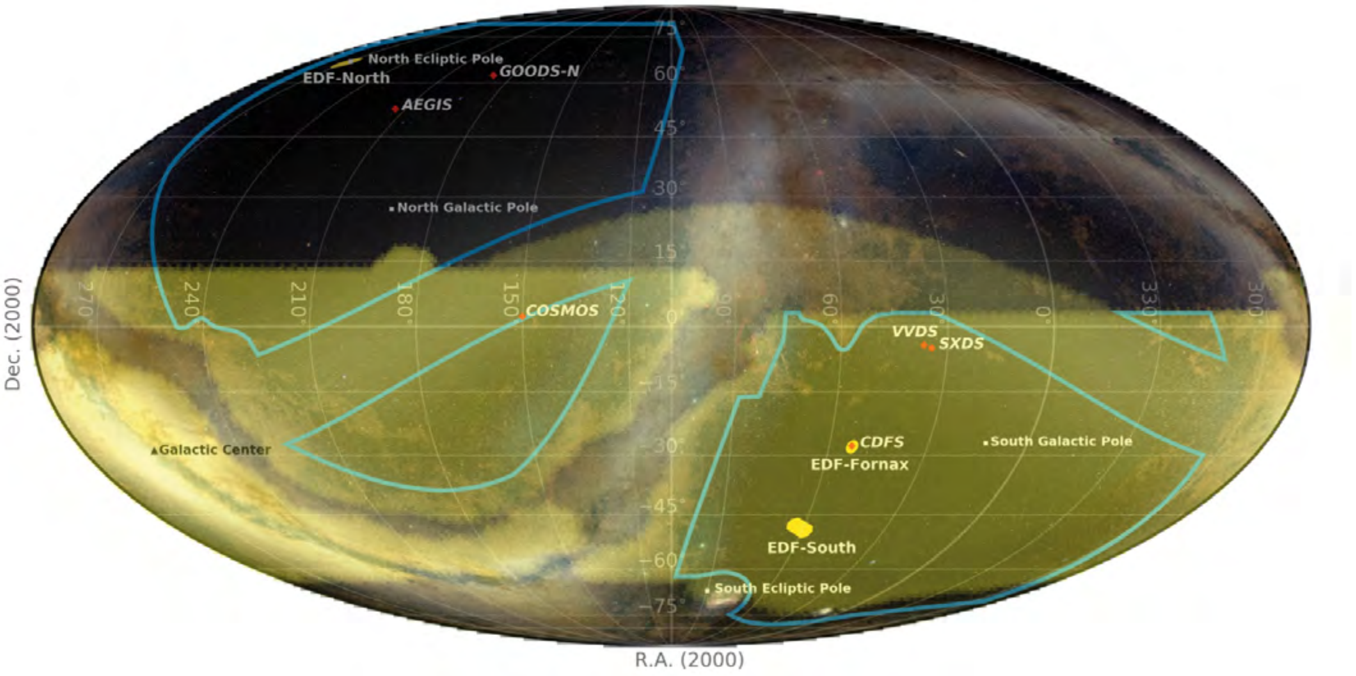
LSST survey and science

LSST will image more than half of the sky, all of the southern sky and a fraction of the northern sky, through 6 photometric bands (u,g,r,i,z,y), from the near UV at 320 nm in the u-band, to near infra-red, in the z and y band, up to 1050 nm. These bands, similar to the SDSS ones, are defined by six giant optical filters, 75cm in diameter and weighing each more than 40 kg. The sky will be mapped through short 30s exposures, thanks to the fast camera readout and telescope repointing.

Each field will be revisited every 3-5 nights, leading to a total of about 1000 visits over the full 10 years of the survey. The survey strategy adopted for LSST, where long integration time of several hours is obtained through co-addition of short individual exposures, contribute to the overall survey uniformity, avoiding saturation by bright sources. In the r-band, where the deepest images are expected, single exposure depth equals 24 magnitudes (AB mag), and is expected to reach or exceed rmag=27 at the end of the survey on the co-added images. LSST data products are expected to reach unprecedented photometric and astrometric precision for a ground-based instrument, better than 10 mmag photometric accuracy, *i.e.* relative flux uncertainty calibration of a better than 1%, and astrometric accuracy of 10 mas.

The LSST includes several scientific programmes [5], the WFD (Wide Field Survey) is the largest programme, covering slightly more than 18000 deg2 to a median of 825 visits. Several smaller programs, representing 10%-20% of the total observation time, complement the WFD, such as the DDF (Deep Drilling Fields), NES (North Ecliptic Side), GP (Galactic Plane) or SCP (South Celestial Pole). A target of opportunities time allocation is also being discussed, to search for optical counterparts of gravitational wave events for example.

Indeed, a number of probes such as weak lensing, strong lensing, galaxy clustering & BAO or supernovae can be used to explore the cosmological model and nature of dark energy and dark matter using the survey data. Although the cosmology has been the primary science driver for the instrument design and survey strategy, LSST will also enable several other major science programmes [5]. The inventory of the solar system will help to understand its birth and evolution, while mapping the Milky Way, to reveal the structure and stellar content of its halo, will provide clues to the Galaxy formation. Complementary to other optical/NIR telescopes such as the HST and JWST, LSST will also enable the study of galaxy evolution, combined with mm observations (ALMA) and at high energy (X-ray). Finally, Rubin will be a marvelous instrument to explore the transient optical sky. Indeed, it will be possible to search for variabilities over a large fraction of sky, down to very faint limiting magnitude, at time scales ranging from hours to years, and even below a minute over smaller sky area.



▲ **FIG. 2:** The Rubin/LSST survey footprint shown as the yellow colour area, over a map of the sky showing the Milky Way, as well as the ESA Euclid survey area. The total number of visits for different sky regions, snapshots over the full 10 years survey and in the 6 photometric bands is shown as shades of yellow, from light to deep colours,, ranging 100 to 1000 visits. Image of the MW with Euclid coverage adapted from arXiv:2405.13491.

The time domain astronomy may well be the discovery field for Rubin/LSST, with the detection and analysis of rare and exotic objects, such as neutron stars and black hole binaries, or Gamma-ray Bursts optical counterparts.

Cosmology with LSST

The standard cosmological model (ΛCDM), a specific flavor of Big Bang models, is based on general relativity. ΛCDM describes accurately a wealth of astronomical observations, with only a handful of parameters. One needs however to postulate the existence of two yet unknown, mysterious components which dominate the universe overall energy density. The dark matter, on the one hand, is a form of matter with little to no interaction with ordinary matter, except via gravity. It was introduced in the 1930's by Fritz Zwicky and is thought to make up 85% of the total matter content of the universe. It is therefore shaping the structure of the universe on the largest scales, under the opposite forces of gravity and cosmic expansion. This structure is often described as the cosmic web and includes dense regions, where galaxies and clusters of galaxies form, connected by thin filaments and separated with immense cosmic voids. On the other hand, the dark energy, a strange form of energy that permeates all space, acts as repulsive gravity on large scales. It fuels the expansion of the universe and would be responsible for the observed late time acceleration of its rate. This was originally suggested through observations of very distant supernovae, over twenty years ago, by two independent teams [7], and has since been confirmed multiples times. Dark matter and dark energy enter the model in mathematically simple terms, but their nature still eludes us, and remains among the biggest mysteries in Physics.

Thanks to its design and observation strategy, the LSST will tackle these questions through a combination of cosmological probes, observing a huge number of distant astronomical objects, both variable or transient, and static on human time scales. Indeed, the short exposure strategy will enable the detection of transient objects, such as supernovae, through image differencing, while the faintest galaxies will be detected on deep images obtained through co-addition of up to few hundred snapshots.

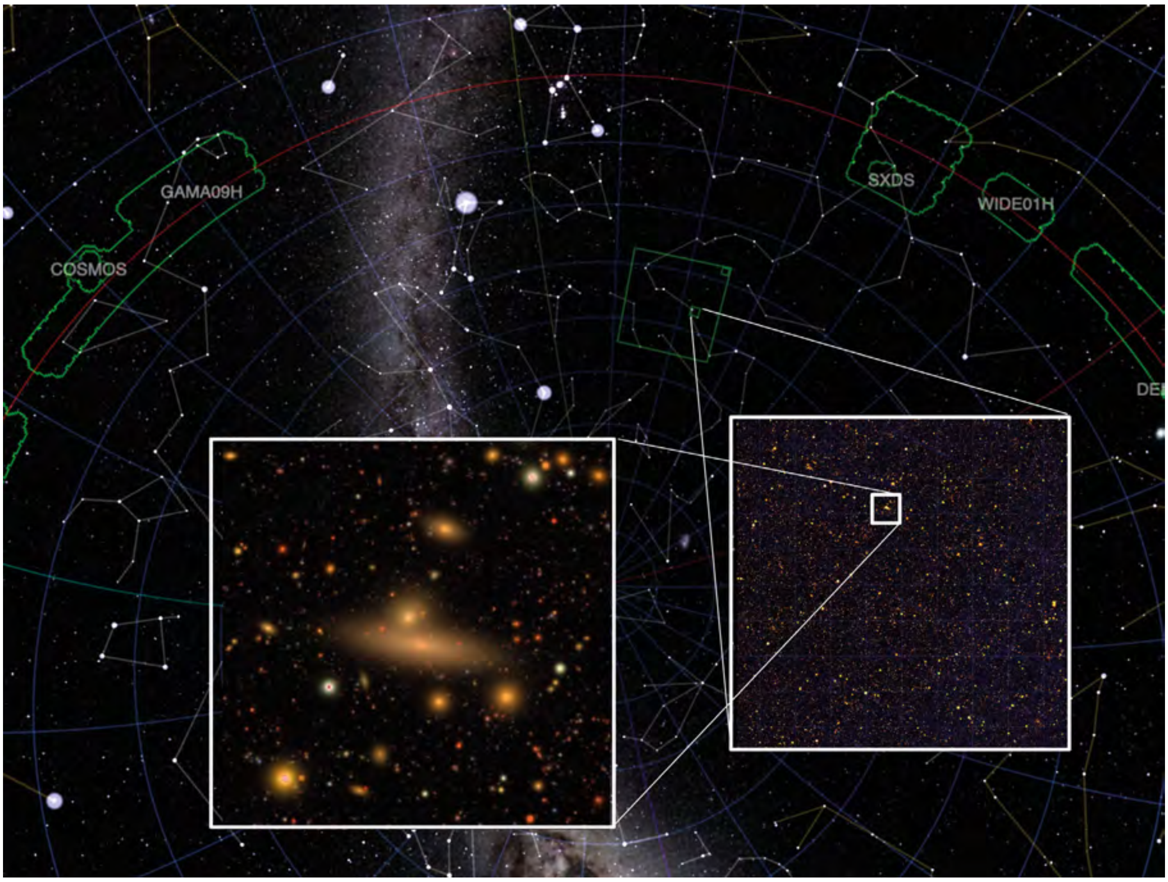
A major challenge comes from the fact that three-dimensional positions are needed for most cosmological probes, in order to track the evolution of the expansion rate and to map the large-scale structure. These positions are obtained from the source angular coordinates on sky and its redshift. The latter correspond to the increase in the wavelengths of photons emitted by distant objects due to cosmic expansion, which can be related to their line-of-sight distances. LSST provides multi-band photometry which is used as a low-resolution spectrum to infer the redshift of individual objects. However, it is extremely difficult to obtain accurate absolute calibration of photometric redshifts. It is thus inevitable to complete this fragmented information by redshifts measured through spectroscopy for a small subset of the detected objects, to enable the reconstruction of full sample redshift distributions. And even doing so, the fraction of outlier objects, with large or catastrophic redshift errors and the absolute calibration of these distributions remain two of the most important systematic effects for all considered cosmic probes [8].

With this data in hand, the LSST Dark Energy Science Collaboration [9] will be able to push further the tests of the coherence of the cosmological model and constrain the properties of dark matter and dark energy. ● ● ●

• • • A set of cosmic probes will be used, some mainly sensitive to the space-time geometry of the universe, and others to the formation of large-scale structure (LSS) through gravitational collapse.

Supernovae are rare cosmic explosions, during which a single star becomes as bright as a whole galaxy for a few weeks — making them observable at cosmic distances. The light curves of type Ia supernovae (SNIa), *i.e.* their apparent luminosity variation over the scale of a few weeks, has been demonstrated in the 1990s to allow precise estimation of their intrinsic or absolute luminosities. The comparison of their apparent and absolute luminosity is used to infer their distances for different redshifts, and, in turn, to derive a direct measurement of the expansion rate of the universe. The LSST will add hundreds of thousands of type Ia supernovae to the distance-vs-redshift curve, called the Hubble diagram, up to and above redshift z=1, which will lead to strong constraints on the equation of state of dark energy.

The LSST will also detect about twenty billion of galaxies, up to redshift 2-3 — their light emitted up to 12 billion years ago. These distant galaxies follow the overall distribution of matter, and the evolution of their clustering over time traces the formation of the large-scale structure. The statistical properties of cosmic galaxy clustering are thus another powerful probe of dark matter and dark energy. However, the LSST was initially designed to measure the gravitational lensing of distant galaxies by the large-scale structure itself. Light rays emitted by distant galaxies are deflected by the gravitational field created by the intervening matter on the line of sight, acting like an optical lens. This weak lensing effect, called the cosmic shear, causes small, but coherent distortions in the apparent shapes of galaxies located behind a massive cosmic structure; round objects appear slightly elliptical, with tangential elongation. Correlations in the shapes of galaxies can then be used to mathematically reconstruct the three-dimensional distribution of matter in the universe [10]. The light bending being due to the gravitation potential, the weak lensing sees the total matter inhomogeneities, including dark matter, and not only the stellar light. In addition, it is impacted by different systematics compared to galaxy clustering, which suffers from theoretical uncertainties connected to the complex process of galaxy formation. Therefore, it is highly complementary to galaxy clustering, with which it can be cross-correlated to remove certain degeneracies about galaxy-to-matter biases. Measuring the weak lensing signal requires however a very tight control of the instrument PSF (Point Spread Function), as well as an estimate of the intrinsic alignment of galaxies due to the tidal gravitational field. The lensing by a very massive structure leads to the formation of characteristic elongated shapes, or giant arcs in the images. The signal in this strong lensing regime can be used to infer the total mass of individual lenses.



▸ **FIG. 3:** Multi-color rendering of simulated LSST images, overlayed on the ESO Milky Way Panoramic Image along with Subaru HSC Survey PDR2 regions. Credit: J. Cohen-Tanugi & LSST DESC.

At last, LSST data will reveal thousands of galaxy clusters, dwelling within massive haloes of dark matter. These are the largest structures bounded by gravity in the universe, containing hundreds of galaxies, with total masses up to 10^{15} times the mass of the Sun. The cluster mass is dominated by the dark matter, which makes up around 85% of the total mass, followed by the hot gas, filling the space between galaxies and representing about 10% of the total mass. The galaxies, dominated by dark matter themselves, represent the remaining 5%.

As the most massive structures in the universe, their abundance depends on the balance between gravity and expansion, hence on cosmological parameters. The number density of clusters as a function of their mass and its evolution with redshift is yet another cosmic probe used with LSST data to constrain the cosmological model. However, cluster masses are not directly observables; one has to rely on proxies, *i.e.* observables quantities such as the number of member galaxies to obtain their masses. Using weak and strong lensing signals on background galaxies, masses can be estimated for a fraction of LSST clusters. Combining the information from these multiple probes, LSST scientists will be able to gain insight on the nature of dark matter, dark energy, and gravity on cosmic scales.

Data processing and alert system

LSST will capture a snapshot of nearly 10 deg^2 of the sky every 30s, each weighing 6.4GB, generating a stream of about 20TB of raw data per night. That corresponds to 5.5 million images over ten years, for a whopping 100PB of processed data, including 15PB of object catalogues.

The raw data will be processed by several pipelines with widely different time scales. A fast analysis pipeline, runs at the summit and process images within 60s after their acquisition. This first pipeline will generate 10 millions of alerts corresponding to transient objects every night. This alert stream will feed a set of brokers designed by the community to sift noteworthy detections through the data and organise follow-ups. They will also enrich the data, by cross-matching LSST alerts with other sources, and use AI powered algorithms to classify them.

The data will then be transferred to the US, Chilean, UK and French Rubin data access centres. There, images will be processed and calibrated, and catalogues of detections from difference images will be generated daily, covering transient, variable and Solar system objects.

The full set of images will be reprocessed yearly (40% in France, 35% in the US, 25% in the UK) to generate public data releases, accessible through the Rubin Science Platform, including calibrated visit and co-added images, and searchable catalogues of Solar, Galactic and extragalactic objects. In turn, the eight Science Collaborations will analyse this unprecedented data chasing discoveries in a wide range of astronomical fields.

Beyond the sheer volume of data generated by the Vera Rubin Observatory, the processing of images for celestial object catalog production and calibration of LSST observations represent a major challenge for the community. As a ground-based instrument, it is impacted by the atmosphere which absorbs certain wavelengths in variable amounts — an effect that will be monitored by a dedicated Auxiliary Telescope, equipped with a slit-less spectrograph, to enhance the photometric calibration. The atmosphere also blurs the images — no adaptive optics system can correct such a wide FOV. The blurring increases the confusion on deep co-added images of dense regions of the universe, and objects may appear overlapping, an effect called blending. Algorithmic developments are underway to correct for this effect using multi-band images, and machine-learning tools, including generative models, are being explored. Another avenue, that is already considered by the community to yield optimal science return, will be to jointly analyse the images of the Rubin/LSST with those of the ESA Euclid satellite and the Nancy Grace Roman Space Telescope missions, leveraging the advantages of the higher resolution and near-infrared observations from space, with the depth of LSST images. ■

About the Authors

Réza Ansari is a founding member of the French consortium of CNRS/IN2P3 laboratories contributing to LSST. He is also a pioneer in 21 cm Intensity Mapping.

Cyrille Doux is a CNRS researcher working on weak lensing cosmology and a member of the LSST Dark Energy Science Collaboration.

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