Construction Status of the Rubin Observatory and Cosmology with LSST

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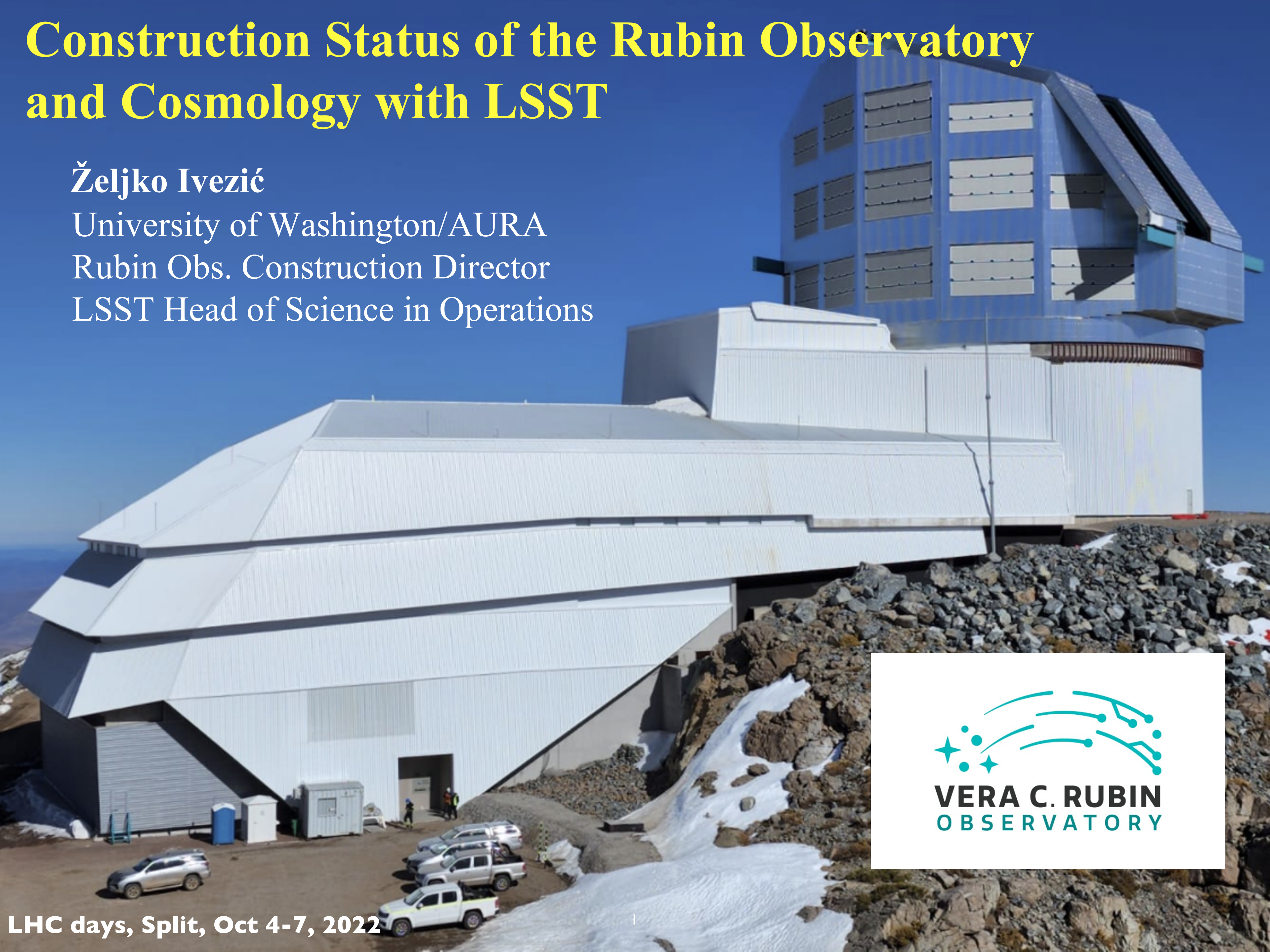


LHC days, Split, Oct 4-7, 2022

Construction Status of the Rubin Observatory and Cosmology with LSST

Outline

- Brief introduction to science drivers for the Rubin Observatory and LSST
- Rubin Observatory construction status

Legacy Survey of Space and Time (LSST) will be

the first 10-year project at the Vera C. Rubin Observatory

What did we learn so far from cosmological measurements?

- the expansion of the Universe is accelerating but we don’t know whether there is really a new major (70%) constituent of mass-energy in the Universe, or perhaps Einstein was wrong?
- with existing data cannot tell which hypothesis is more likely explanation: to change this, we need to obtain precise data for about 10 billion galaxies
- to get such an unprecedented dataset, we need a very unique observatory: Rubin Observatory and LSST; we need **both** a large telescope mirror to be sensitive enough to faint galaxies, and a large field-of-view for fast sky scanning speed

Cosmology with LSST: dark energy vs. modified gravity

- Even for a model with modified gravity, it is possible to assume that GR is correct and always find "dark energy" with suitable w(z) to explain data for H(z). 😱

- However, the growth of structure will be different and thus when both H(z) and G(z) are measured, the degeneracy can be broken and DE vs. modified gravity models distinguished (Jain & Zhu 2008, PhysRevD 78, 063503)

$$ds^2 = -(1+2\psi)\ dt^2 + (1-2\phi)\ a^2(t)\ d\vec{x}^2$$

- ϕ is the curvature perturbation and ψ is the potential perturbation

- In General Relativity $\phi = \psi$ in the absence of anisotropic stresses. A metric theory of gravity relates the two potentials above to the perturbed energy-momentum tensor.
  ϕ and ψ can be constrained with astronomical observations 😄

Modern Cosmological Probes

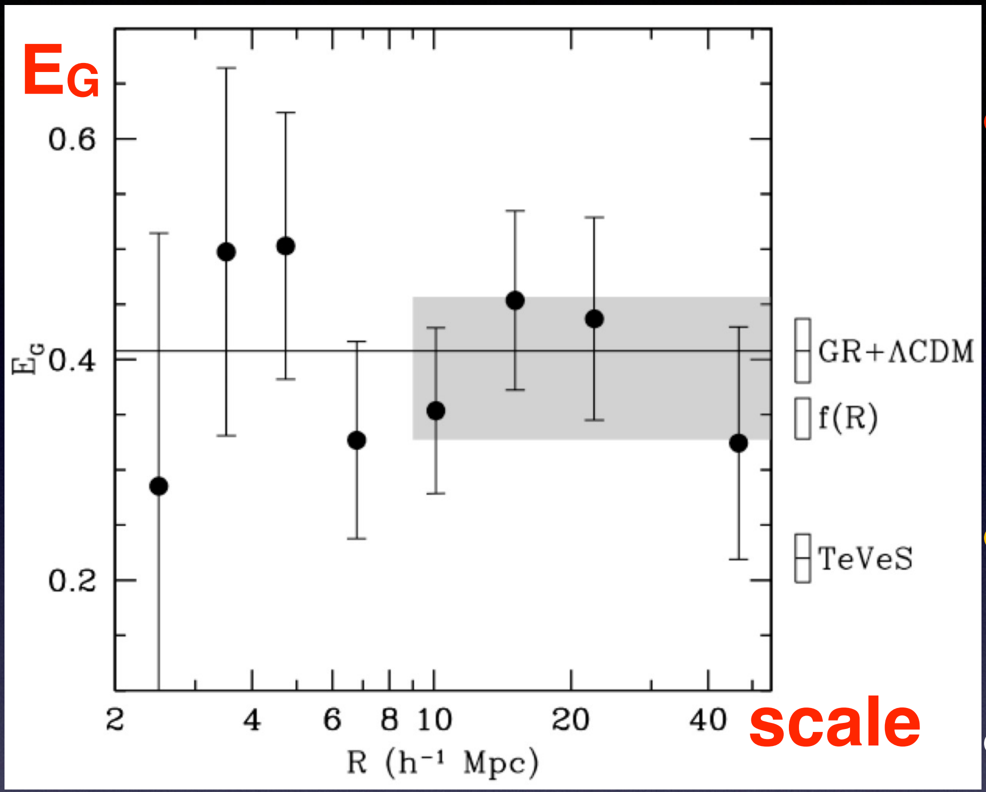
- Cosmic Microwave Background (the state of the Universe at the recombination epoch, at redshift ~1000)
- Weak Lensing: growth of structure
- Galaxy Clustering: growth of structure
- Baryon Acoustic Oscillations: standard ruler
- Supernovae: standard candle

Possible with LSST

Except for CMB, measuring H(z) and growth of structure G(z)

$H(z) \sim d[\ln(a)]/dt$, $G(z) = a^{-1}\delta\rho_m/\rho_m$, with $a(z) = (1+z)^{-1}$

Cosmology with LSST: dark energy vs. modified gravity

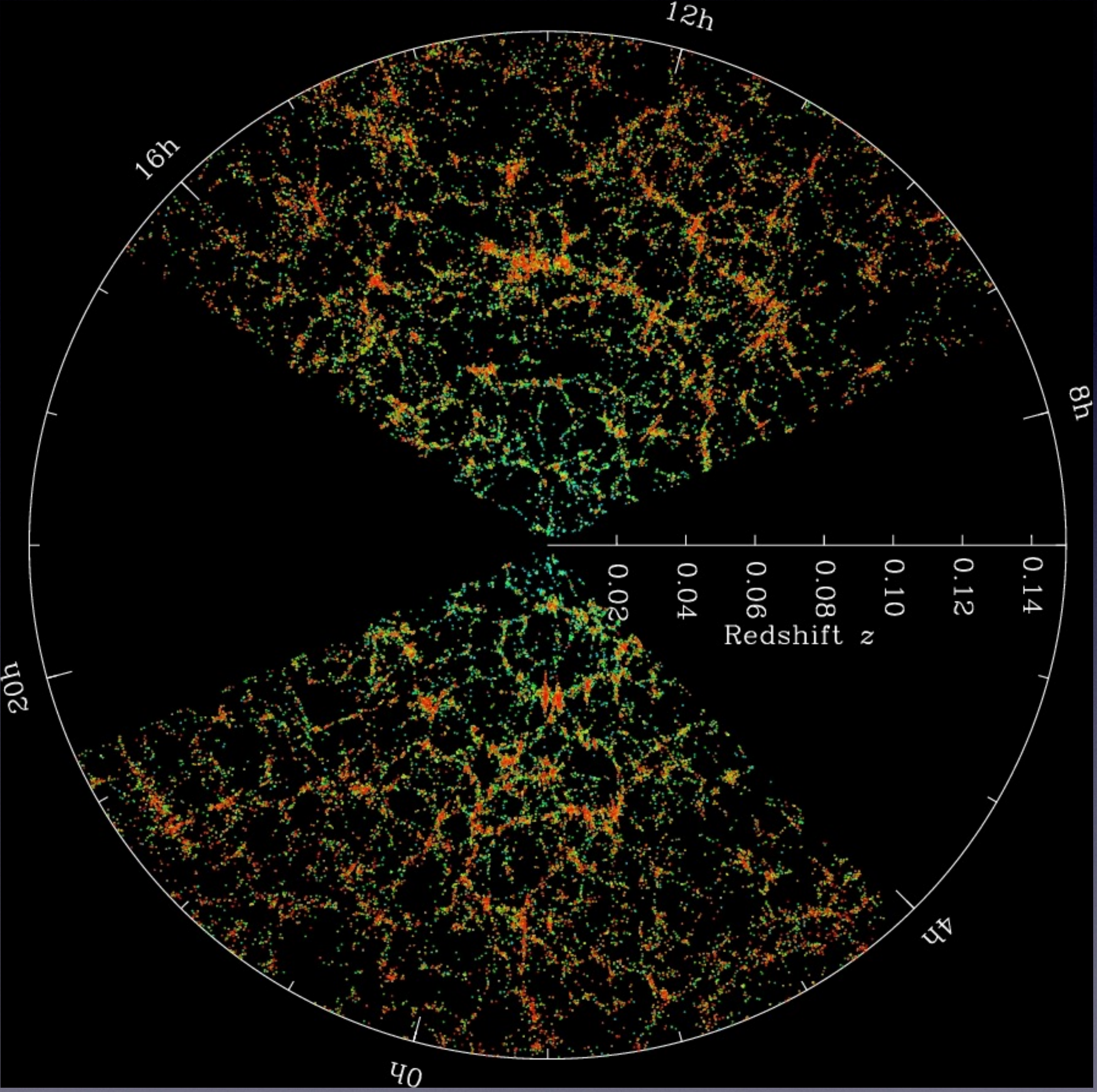


Reyes et al. (2010, Nature 464, 256)

LSST will measure E_G about 10 times more precisely and will be able to rule out a large class of modified gravity theories (or GR!)

- E_G combines 3 measures of large-scale structure: galaxy-galaxy lensing (ϕ+ψ), galaxy clustering (ϕ) and galaxy velocities (from galaxy redshifts; measures G(z))
- SDSS data enabled a test of GR at 15% level: it passed!
- SDSS data already excludes a model within the tensor-vector-scalar gravity theory, which modifies both Newtonian and Einstein gravity.
- Five times better precision needed to rule out f(R)

Spatial distribution of galaxies



Left: each dot is one galaxy from SDSS

Note that the galaxy distribution is highly **inhomogeneous:** statistical details of that distribution contain rich cosmological information

Spatial distribution of galaxies

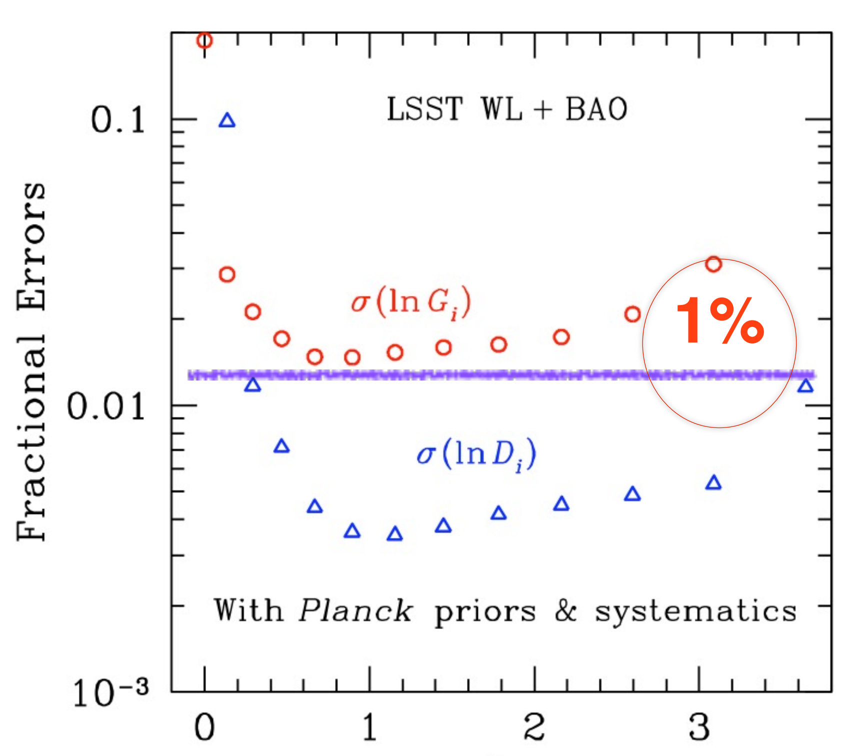
LSST goal:
map galaxies to a ten times larger distance limit than possible today!

20 billion galaxies!

Precise cosmological parameter constraints.

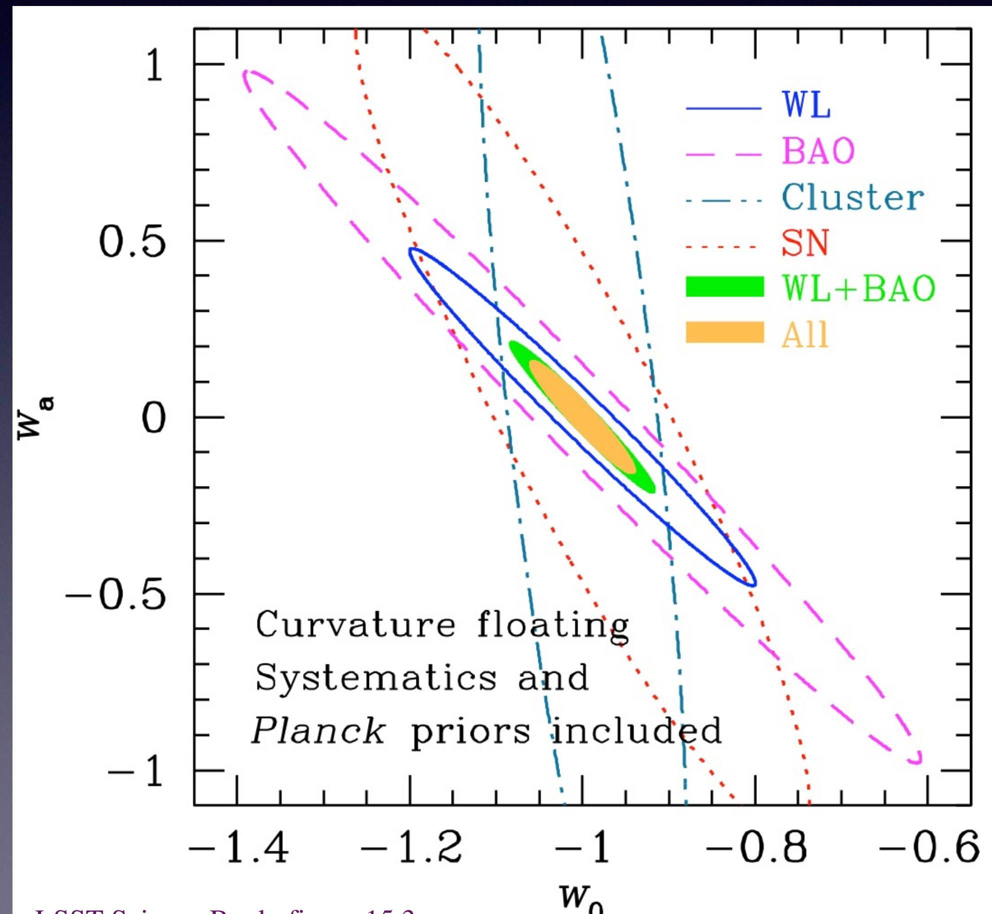
Sum of neutrino masses with accuracy of ~0.04 eV from the power spectrum of dark matter fluctuations.

Cosmology with LSST: high precision measurements



LSST Science Book, figure 15.2

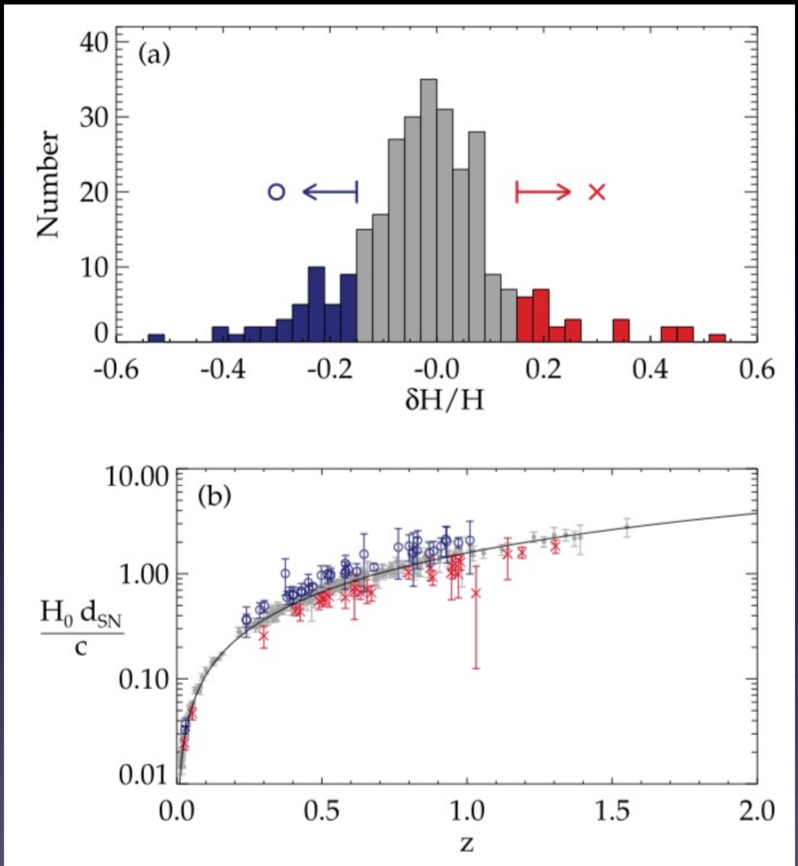
- Measuring distances, H(z), and growth of structure, G(z), with a percent accuracy for 0.5 < z < 3
- Multiple probes is the key!



LSST Science Book, figure 15.3

By simultaneously measuring growth of structure and curvature, LSST data will tell us whether the recent acceleration is due to **dark energy or modified gravity.**

Cosmology with LSST SNe: is the cosmic acceleration the same in all directions?



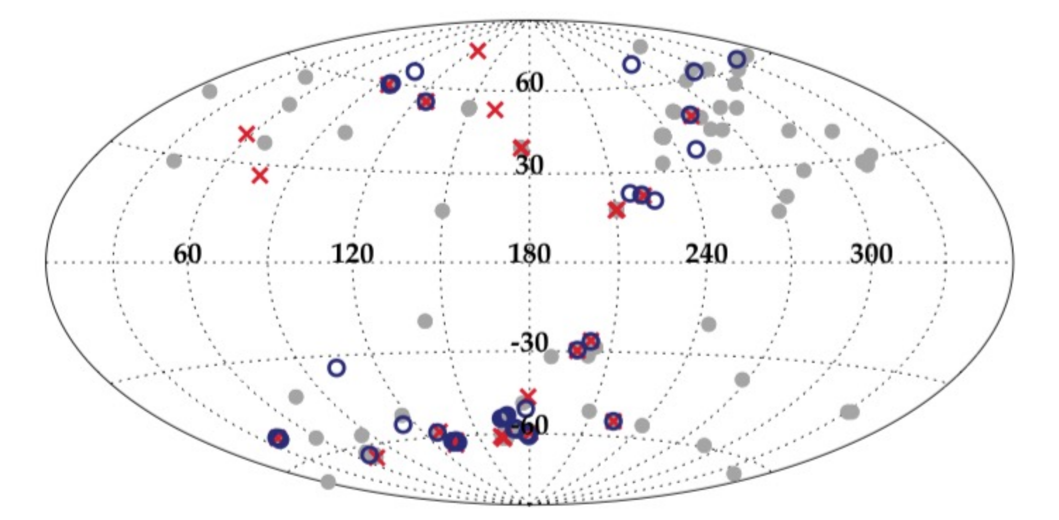


Figure 1. A projection of the spatial distribution of the Union SNe Ia sample in Galactic coordinates. Note the relative uniformity of the points, except around the Galactic plane. The symbols correspond to those in Fig. 2, and are explained in Section 3.1.

Cooke & Lynden-Bell (2009, MNRAS 401, 1409)

Is there spatial structure in the SNe distance modulus residuals for the concordance model?

- Even a single supernova represents a cosmological measurement!
- LSST will obtain light curves for several million Type Ia supernovae!

Science motivation for undertaking the Legacy Survey of Space and Time:

More details about science drivers and system design: Ivezic et al. (2019) ls.st/lop

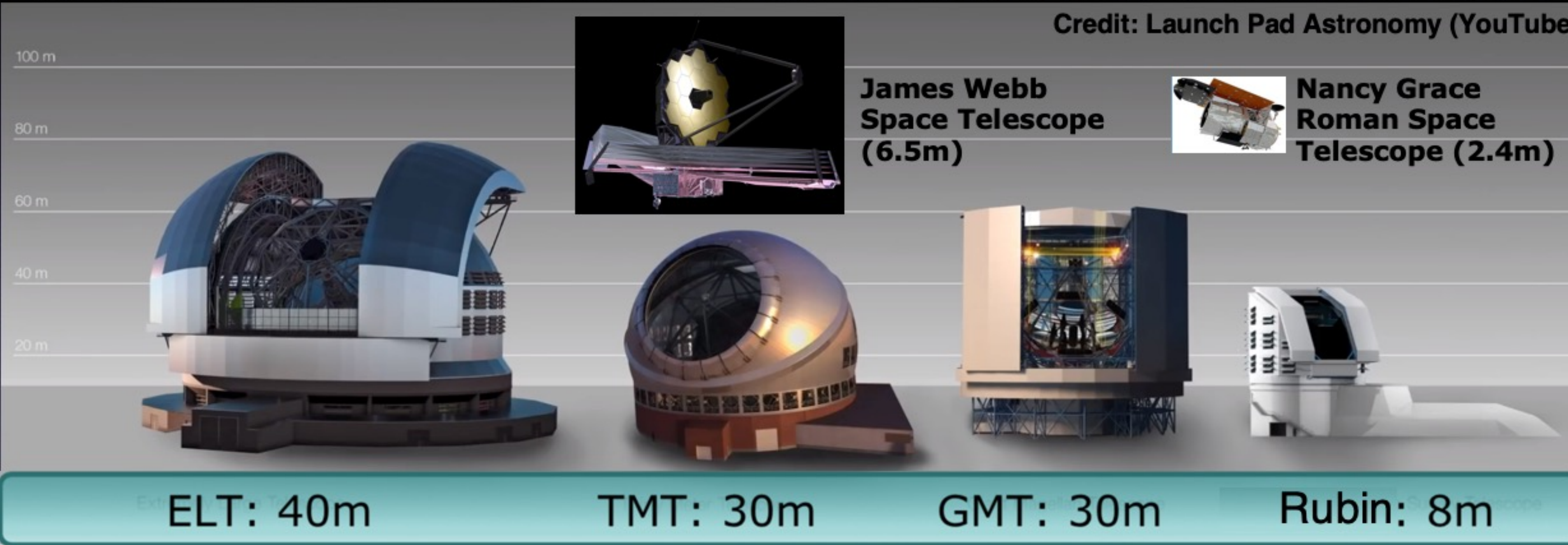
Expansion and history of the Universe and the growth of structure
(dark matter, dark energy, cosmology, spatial distribution of galaxies, gravitational lensing, supernovae): "Was Einstein right?"

Time domain: what changes on the sky?
(cosmic explosions, variable stars, unknown unknowns)

The Solar System structure
(near-Earth hazardous asteroids, main-belt asteroids, trans-Neptunian objects, comets)

The Milky Way structure
(stars as tracers of the structure and evolution of our Galaxy, interstellar matter, the physics of stars)

A key point: most of science programs will utilize the same dataset.

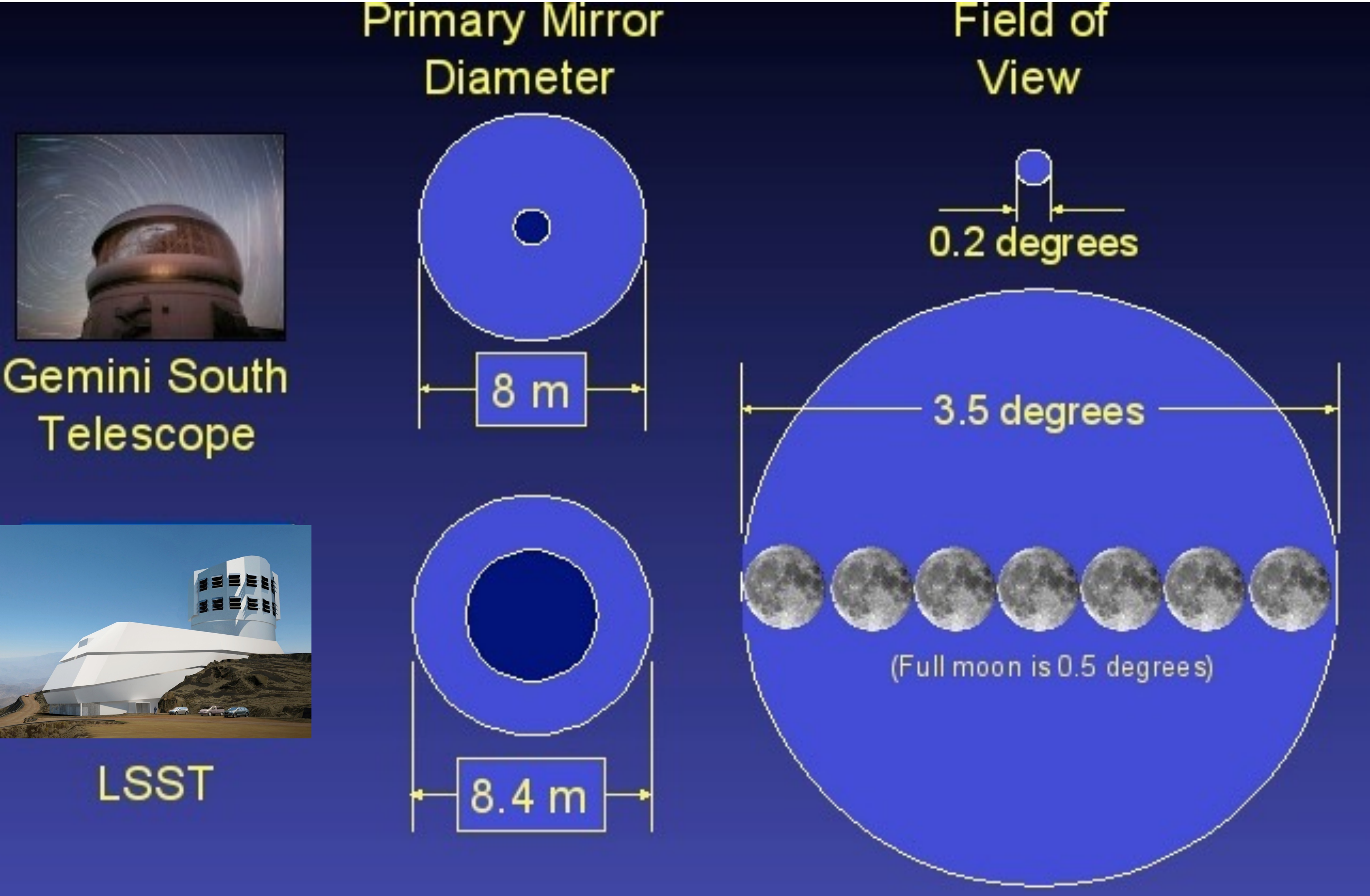


Rubin Obs. will not have the largest mirror but will have by far the largest product of the mirror area and the field-of-view size (etendue or throughput)

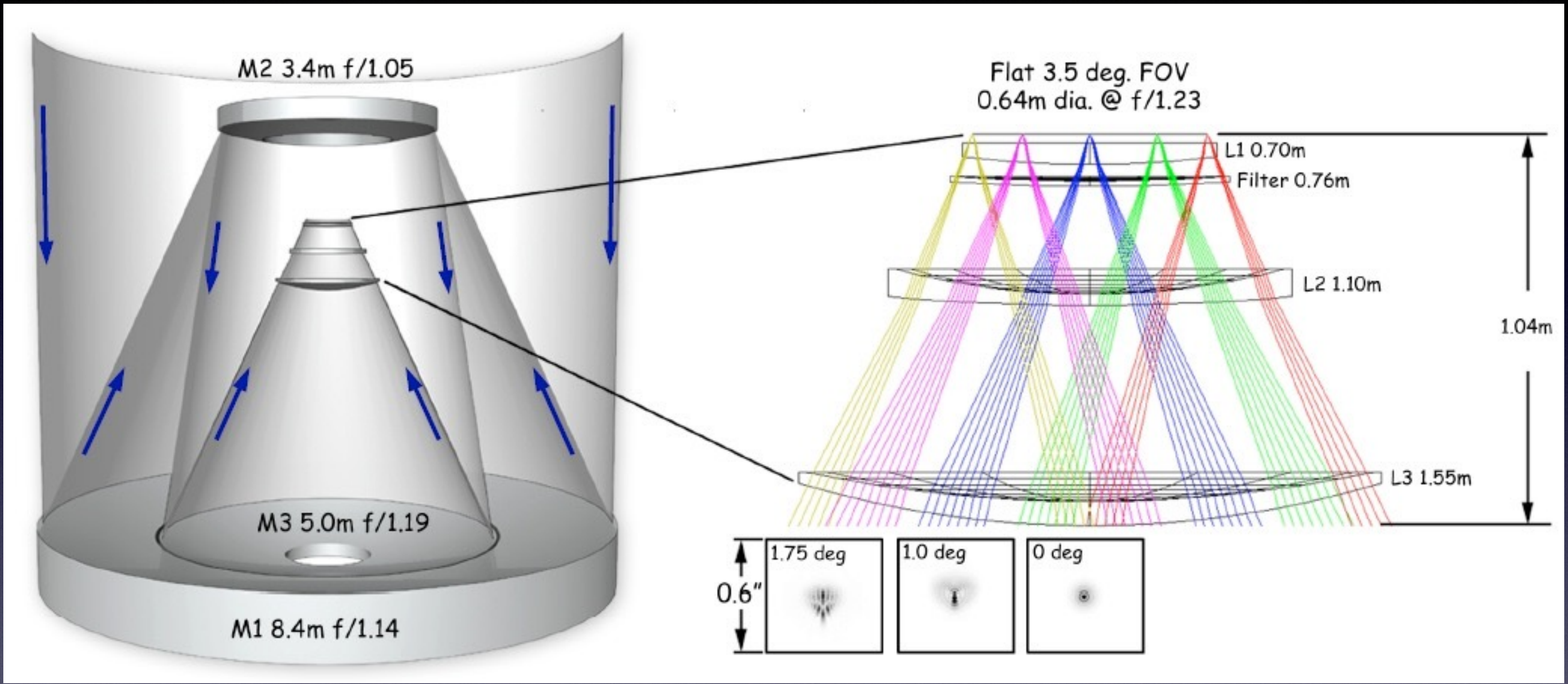
LSST will be delivered by the Vera C. Rubin Observatory, as its first, 10-year, project

To deliver LSST, Rubin Observatory will observe about half of the sky close close to 1000 times over 10 years.

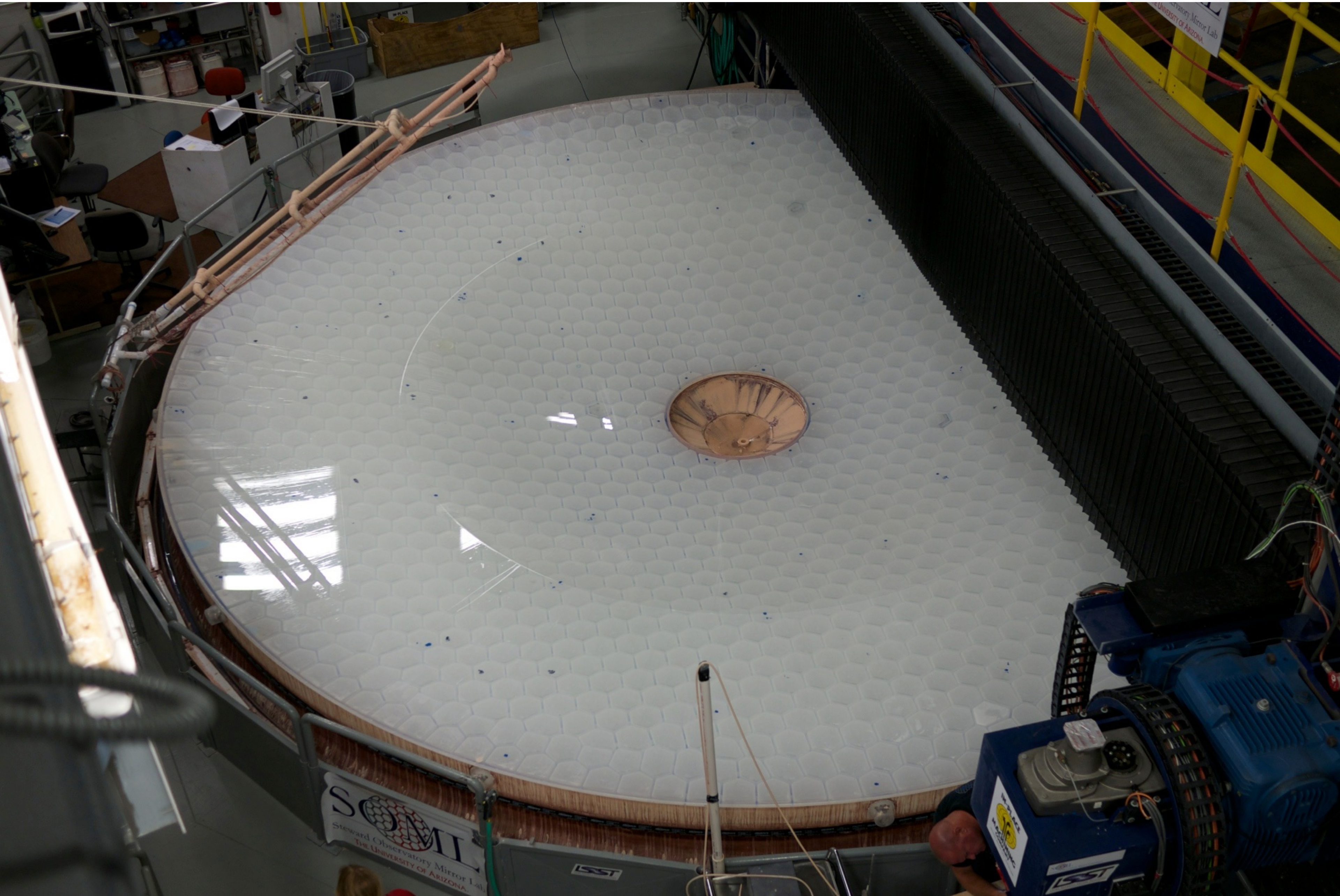
Field-of-view comparison: Gemini vs. LSST



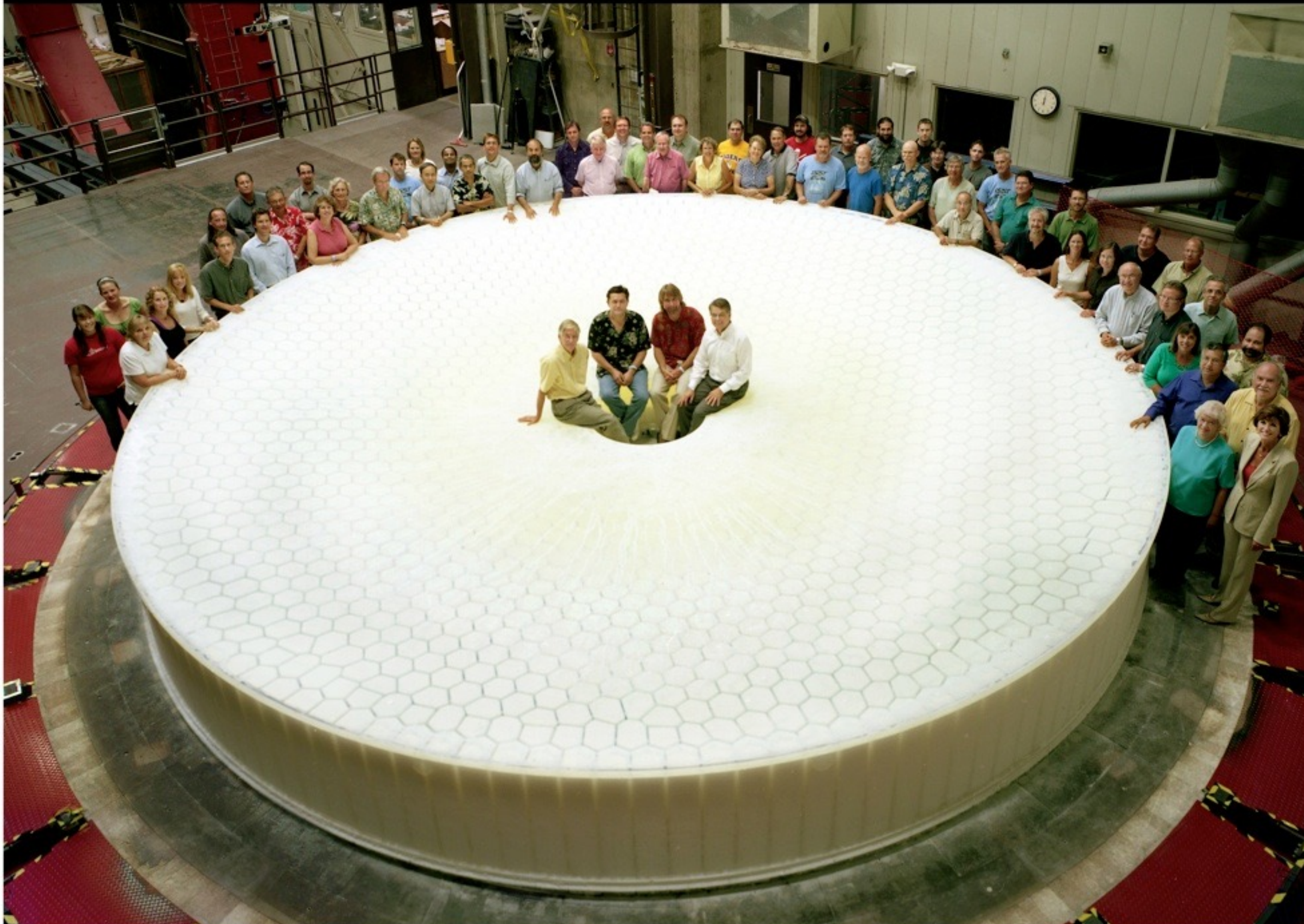
Optical Design for LSST



Three-mirror design (Paul-Baker system)
enables large field of view with excellent image quality:
delivered image quality is dominated by atmospheric seeing


SOML
Steward Observatory Mirror Lab
THE UNIVERSITY OF ARIZONA
LSST

Large Synoptic Survey Telescope

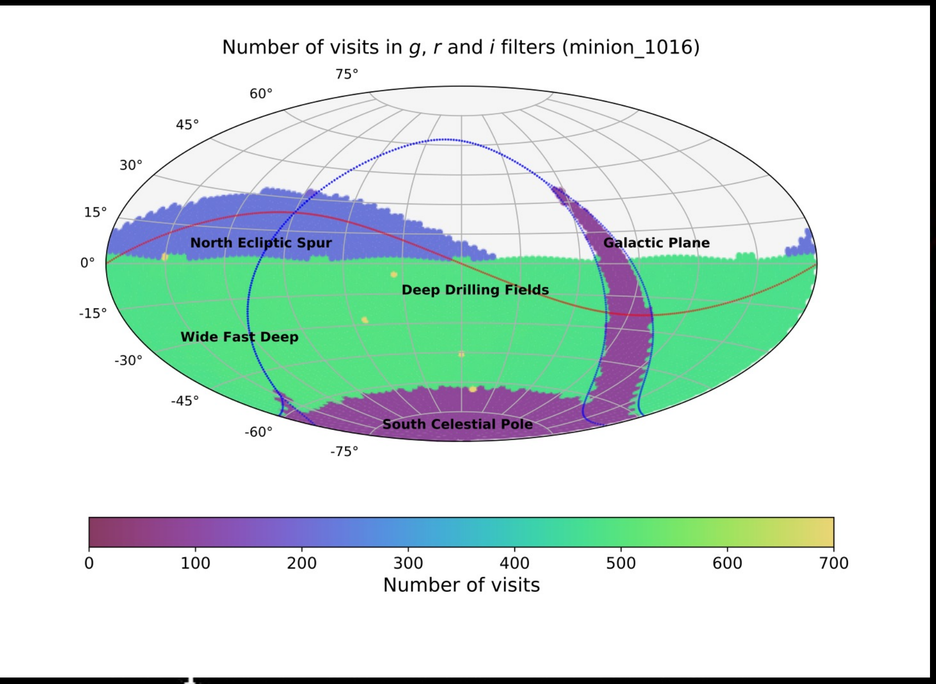


LSST Primary/Tertiary Mirror Blank
August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona

The University of Arizona. Tucson Arizona · SOML · LSST Large Synoptic Survey Telescope

Basic idea behind LSST: **a uniform sky survey**

- 90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night
- after 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky
- ~100 PetaBytes of data: about a billion 16 Mpix images, enabling **measurements for 40 billion objects**



LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy, 3.6×10^{-31} erg/s/cm^2/Hz) based on 825 visits over a 10-year period: deep wide fast.

Left: a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)

SDSS
gri
3.5'x3.5'
r~22.5

3 arcmin
is 1/10
of the full
Moon's
diameter

HSC
gri
3.5’x3.5’
r~27

3 arcmin is 1/10 of the full Moon’s diameter

like LSST depth (but tiny area)

LSST will deliver 5 million such images

Large Synoptic Survey Telescope

LSST Operations:
Sites & Data Flows

and a British site, too!

French Site
Satellite Processing Center
Data Release Production
Long-term Storage (copy 3)

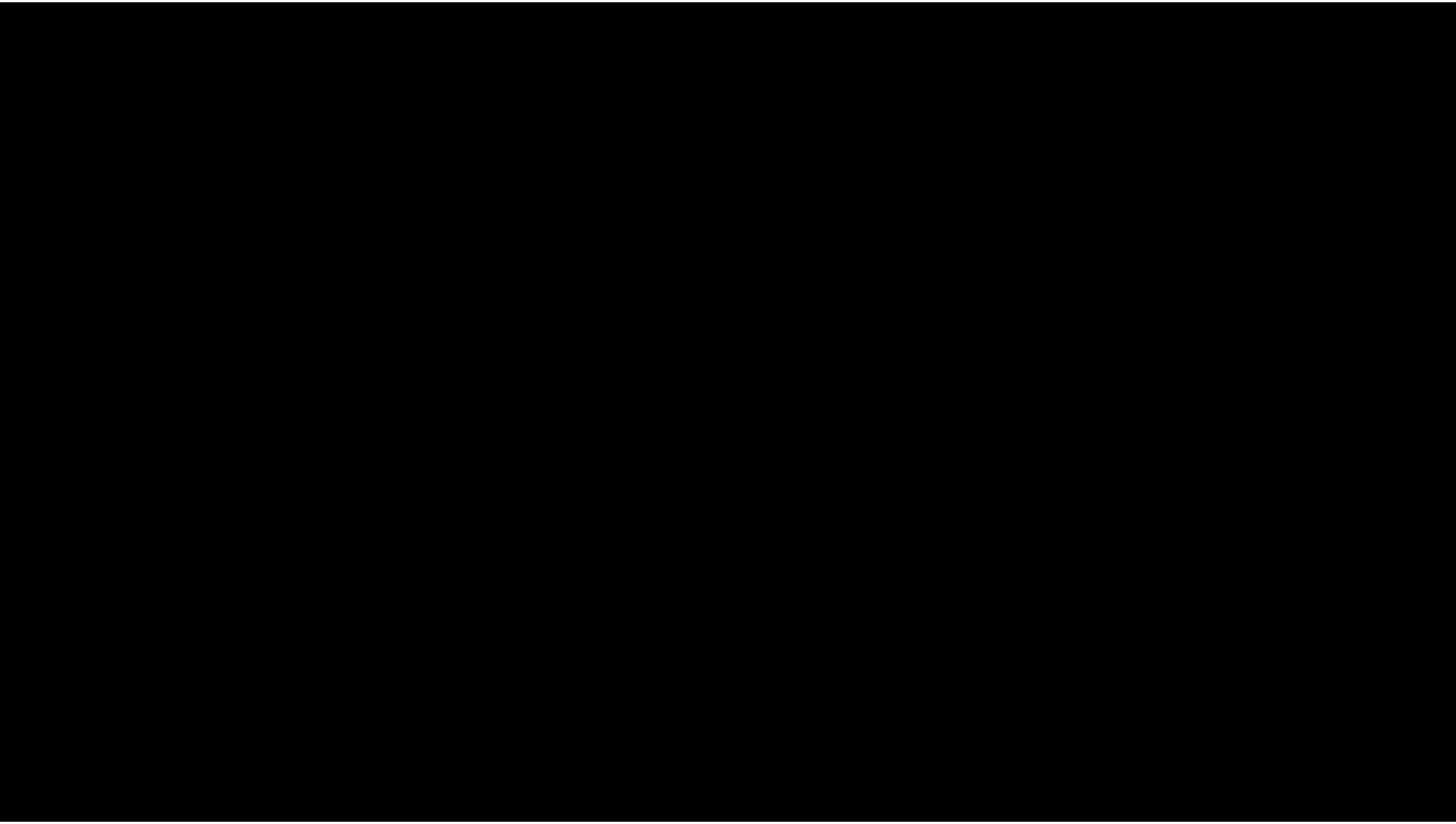
HQ Site
Science Operations
Observatory Management
Education & Public Outreach

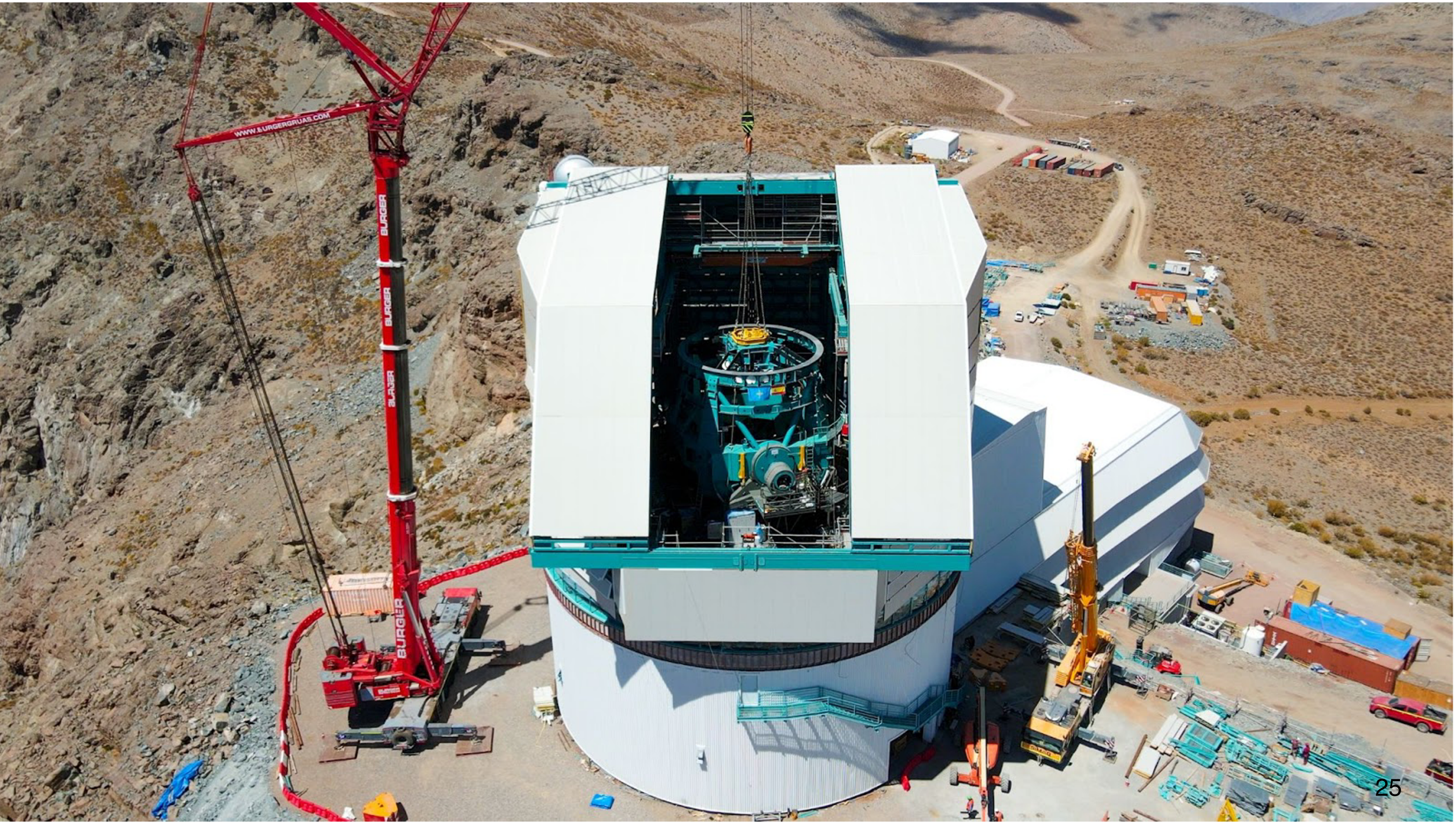
Archive Site
Archive Center
Alert Production
Data Release Production
Calibration Products Production
EPO Infrastructure
Long-term Storage (copy 2)
Data Access Center
Data Access and User Services

Base Site
Base Center
Long-term storage (copy 1)
Data Access Center
Data Access & User Services

Summit Site
Telescope & Camera
Data Acquisition
Crosstalk Correction

The rise of Rubin Observatory

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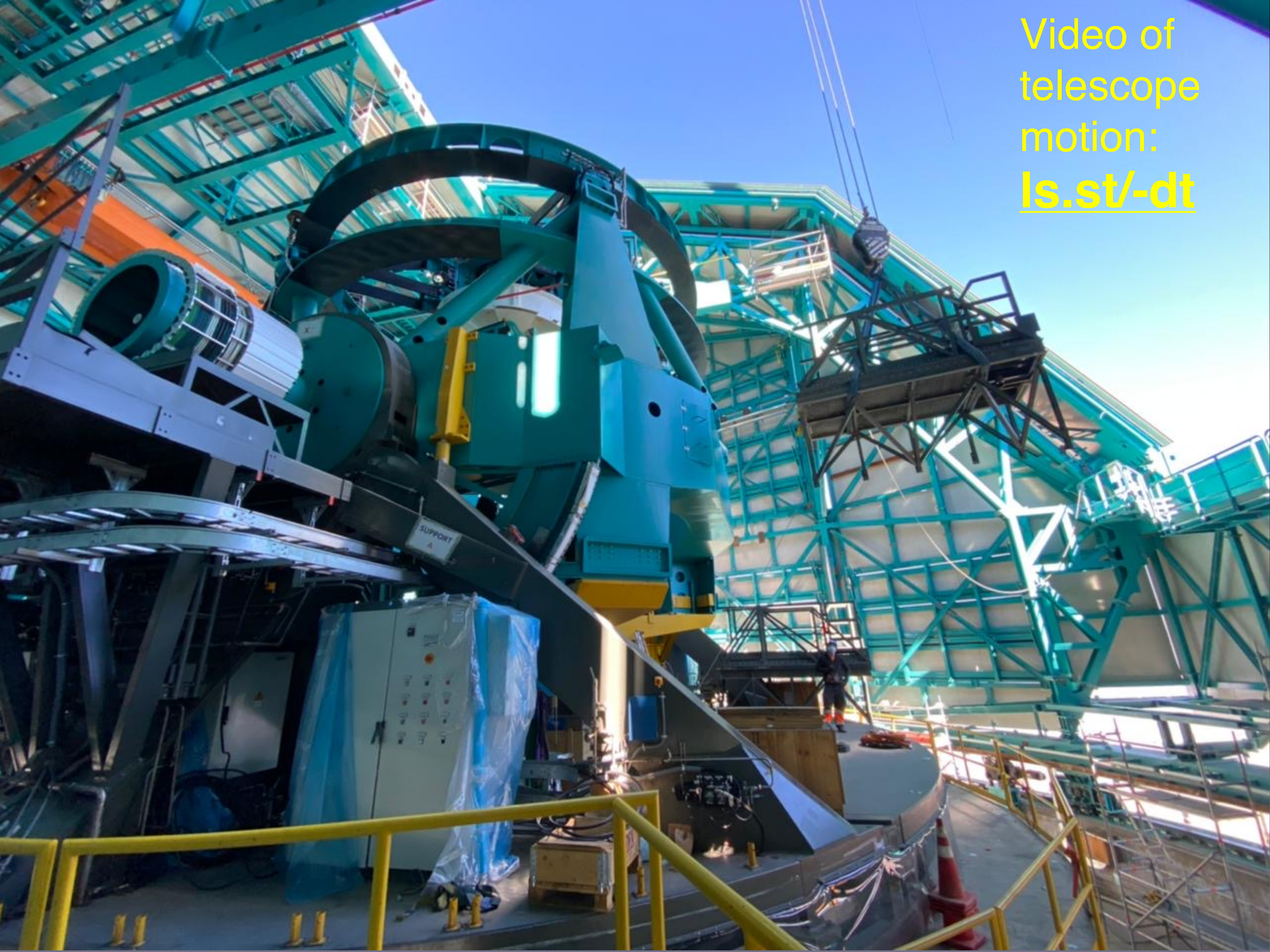
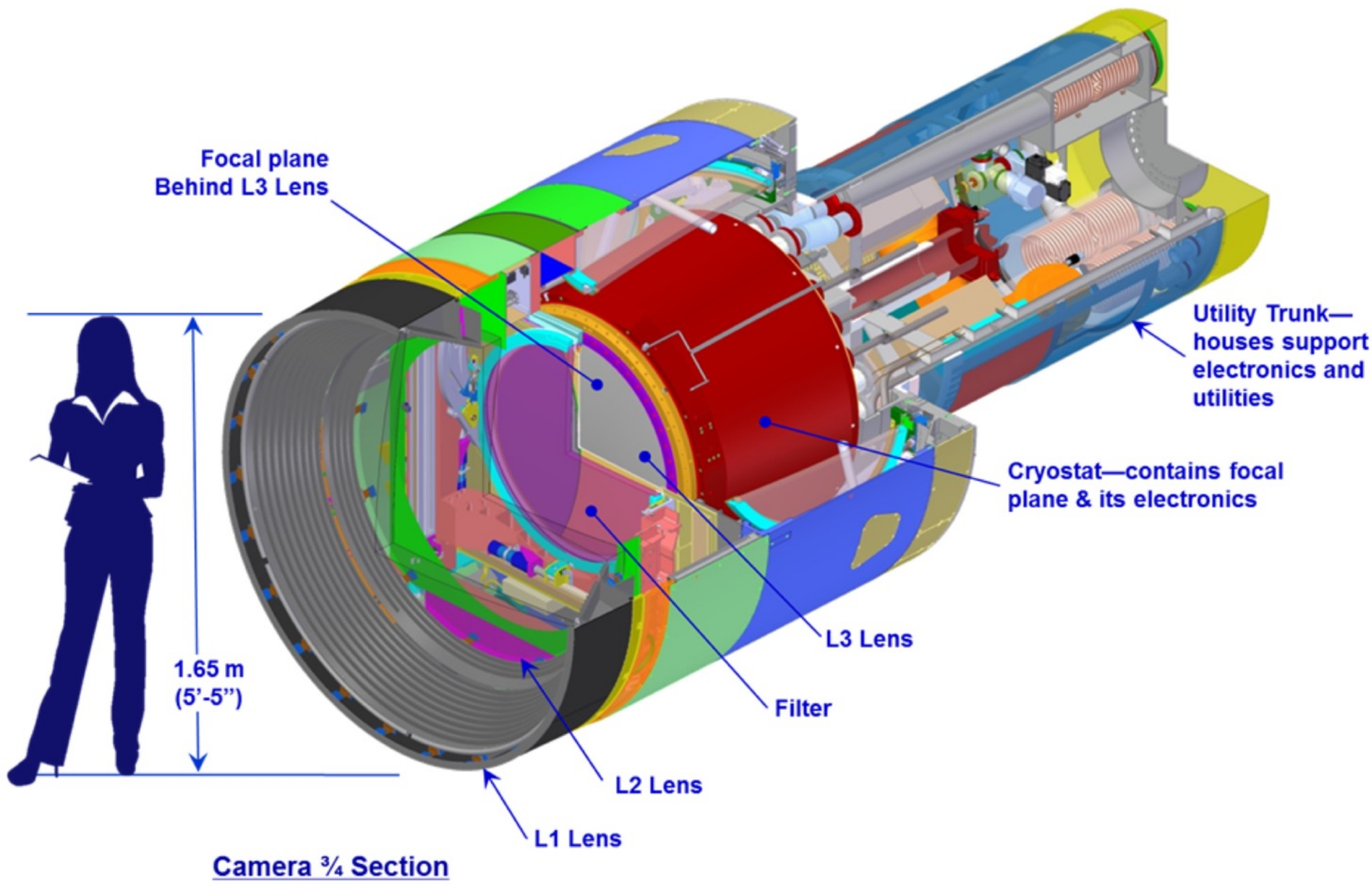
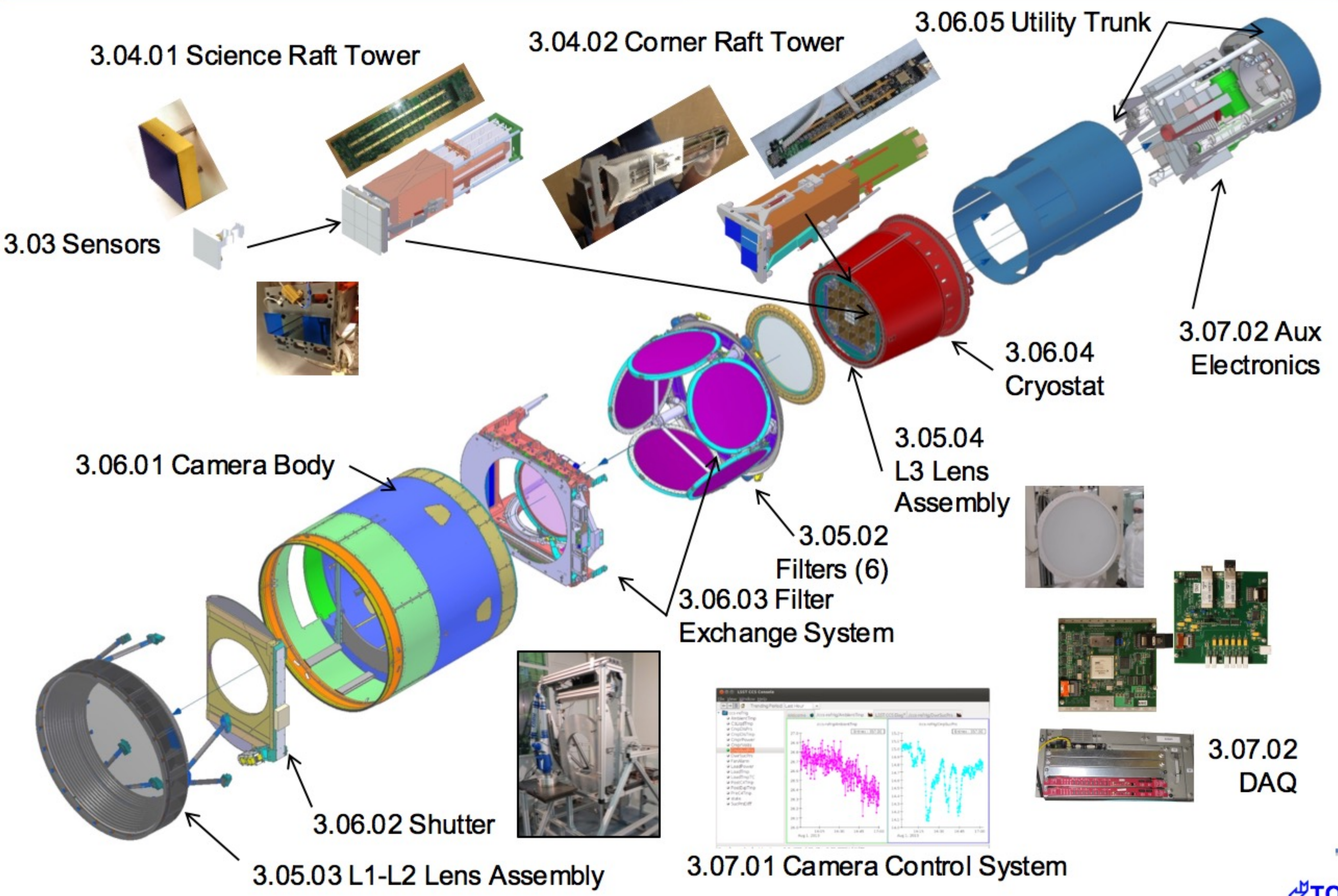

Video of
telescope
motion:
ls.st/-dt



Focal plane
Behind L3 Lens
Utility Trunk—
houses support
electronics and
utilities
Cryostat—contains focal
plane & its electronics
L3 Lens
Filter
1.65 m
(5'-5")
L2 Lens
L1 Lens
Camera ¾ Section

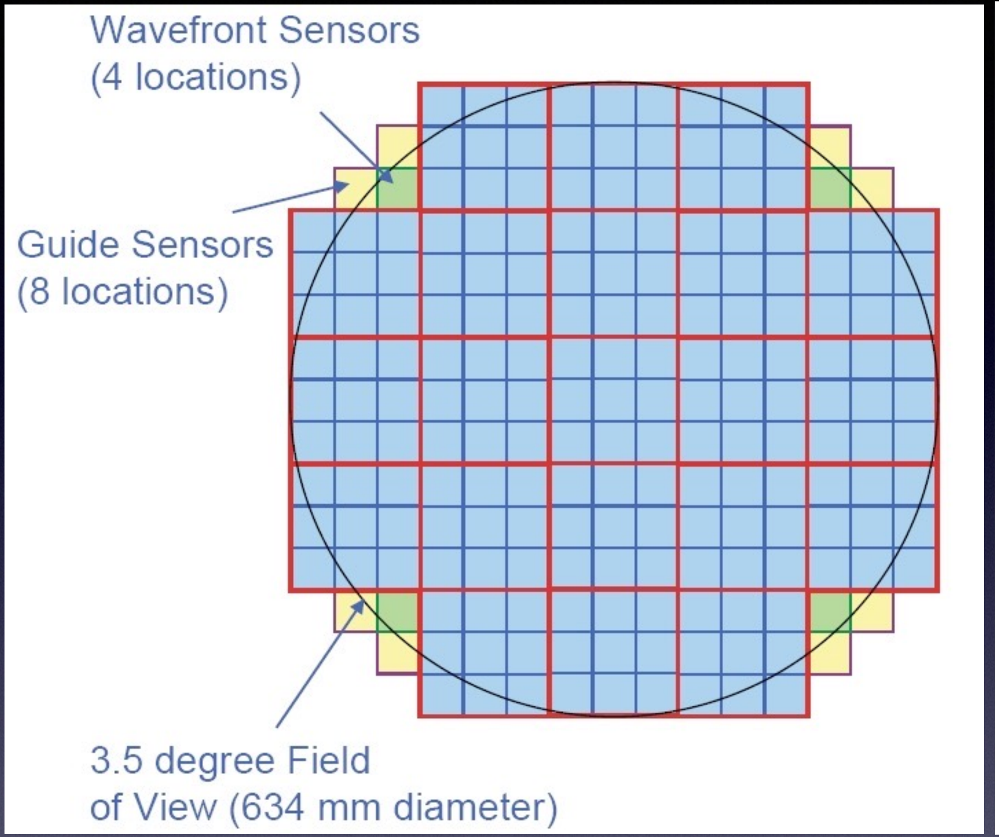
Major Camera Elements

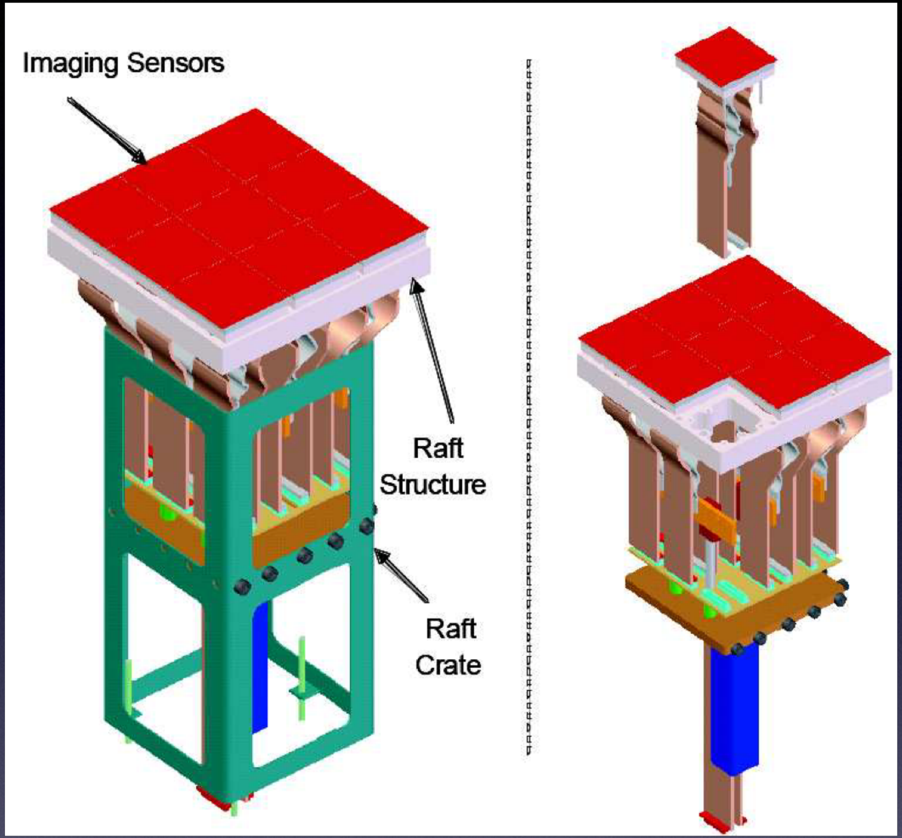


L-1, the largest lens ever produced, is the front lens of the LSST camera

D = 1.57m

LSST camera

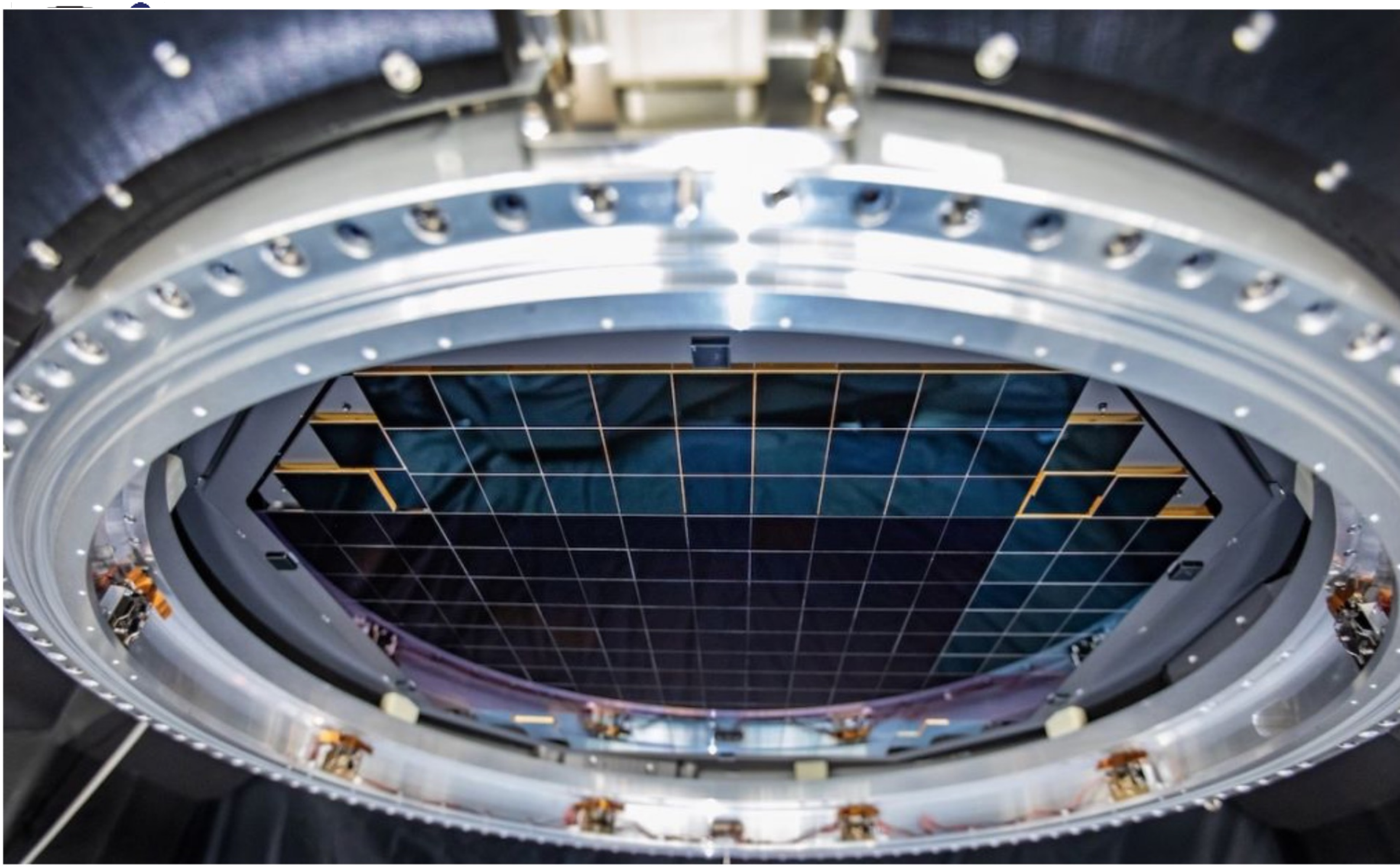




Modular design: 3200 Megapix = 189 x16 Megapix CCD
9 CCDs share electronics: raft (=camera)
Problematic rafts can be replaced relatively easily


OPTO ENGINEERING

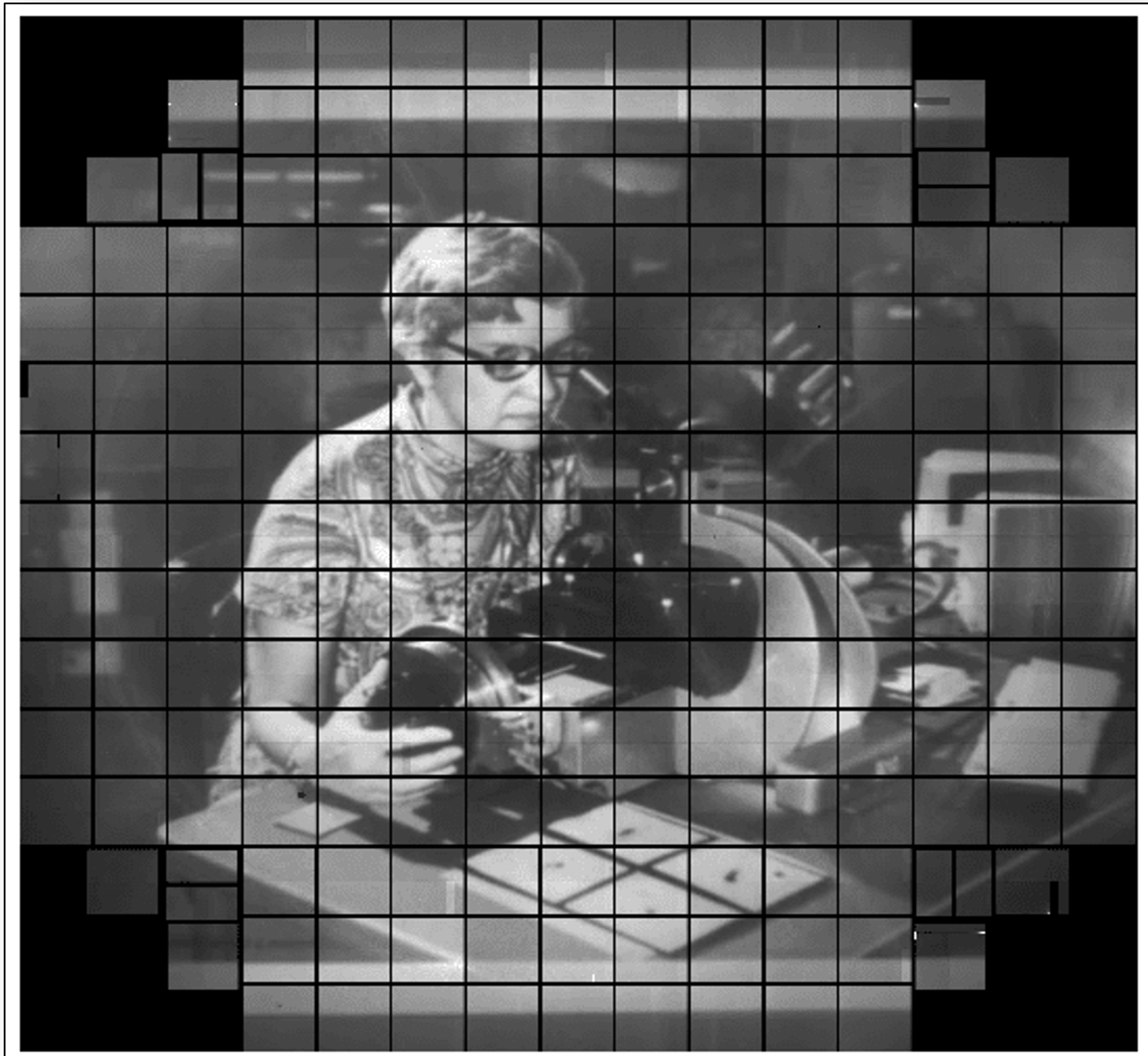
The largest astronomical camera in the world: 3,200 Megapix



The complete focal plane of the future LSST Camera is more than 2 feet wide and contains 189 individual sensors that will produce 3,200-megapixel images.

It works!

(well, 3 amplifiers, out of 3024, don't...)



At the highest level, LSST objectives are:

1) Obtain about 5.5 million images, with 189 CCDs (4k x 4k) in the focal plane; this is about **a billion 16 Megapixel images of the sky**

2) Calibrate these images (and provide other metadata)

3) Produce catalogs ("model parameters") of detected objects (37 billion)

4) **Serve** images, catalogs and all other metadata, that is, **LSST data products to LSST users**

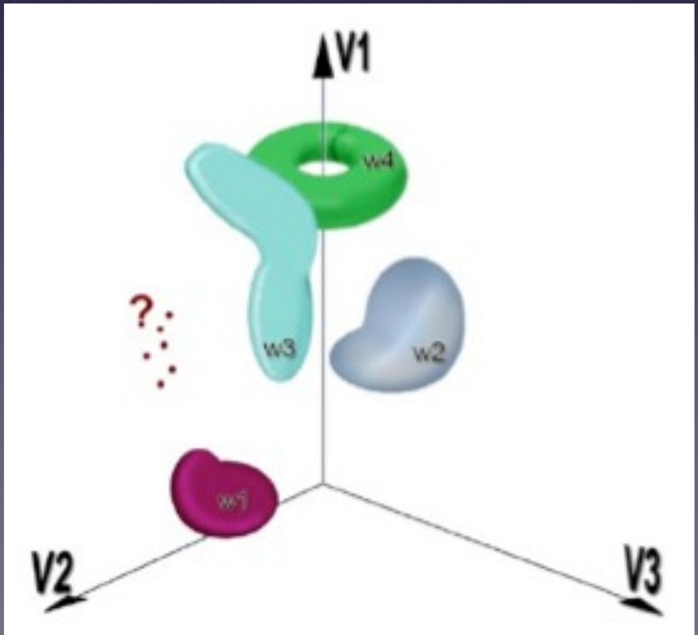
The ultimate deliverable of LSST is not just the telescope, nor the camera, but **the fully reduced science-ready data** as well. **Software!**

About a million lines of in-house C++ and python.

Statistical analysis of a massive LSST dataset

- A large (100 PB) database and sophisticated analysis tools: for each of 40 billion objects there will be about 1000 measurements (each with a few dozen measured parameters)

Data mining and knowledge discovery



- 10,000-D space with 40 billion points
- Characterization of known objects
- Classification of new populations
- Discoveries of unusual objects

Clustering, classification, outliers

Schedule to Rubin Obs. Completion

- Despite the progress during the COVID Pandemic the critical path suffered dramatically
- Schedule continues to adjust to conditions
    - **ComCam: Engineering First Light: July 2023**
    - **LSSTCam: System First Light: March 2024**
    - **Start of Operations and LSST: Fall 2024**

Still months of uncertainty in first light dates, but we will get there!

Legacy Survey of Space and Time: a 10-year survey starting in 2024

More details: ls.st/lop

multi-color time-resolved faint sky map

- 20 billion galaxies
- 20 billion stars
- 10 billion alerts
- “millions and millions” of SNe, quasars, asteroids…