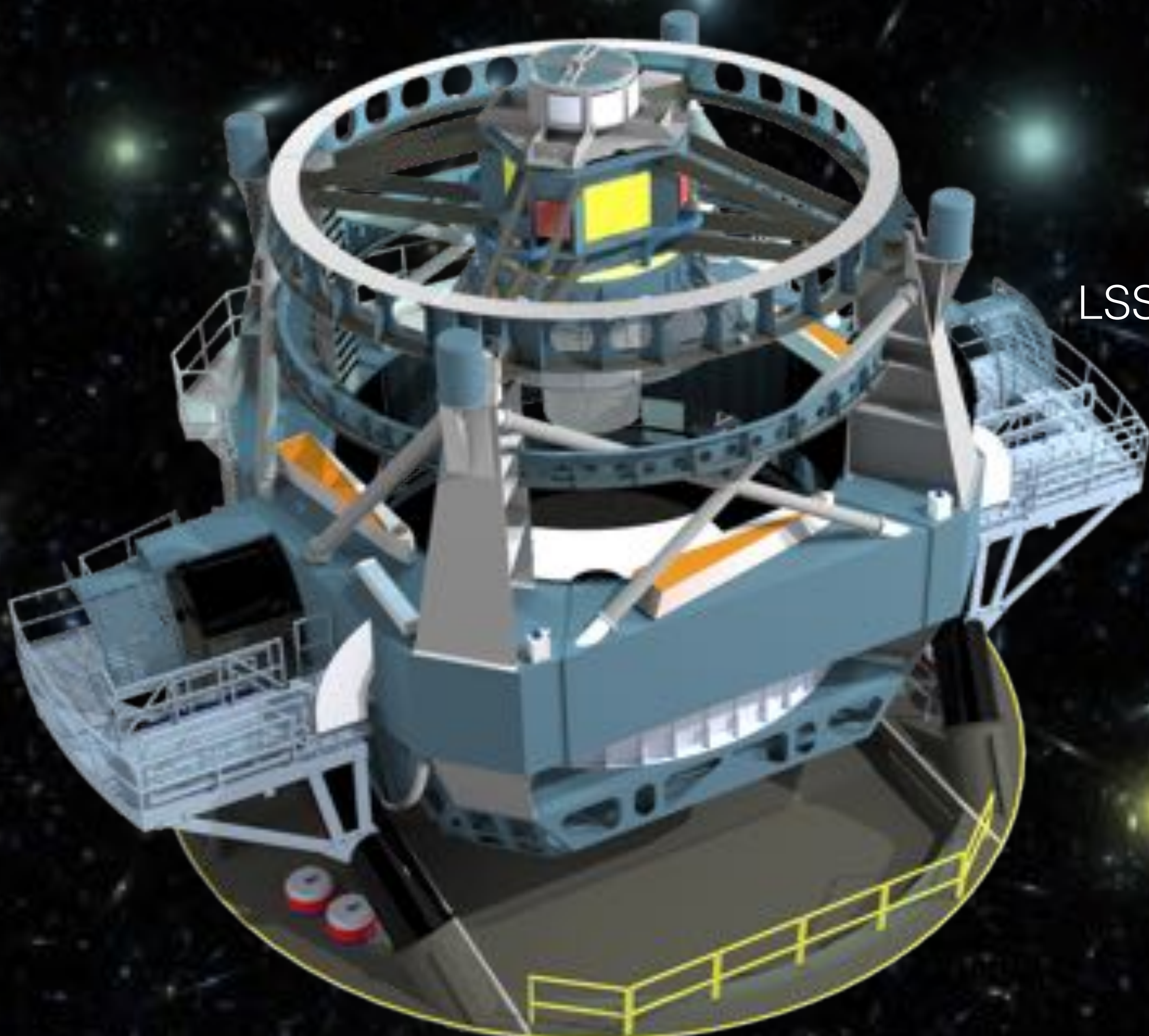
The Large Synoptic Survey Telescope:
A 10-year Color Movie of 40 Billion Stars and Galaxies

Ian Shipsey
LSST Project & Chair, DESC Advisory Board
University of Oxford

for

Beth Willman
LSST Deputy Director/University of Arizona



Outline

The Big Picture

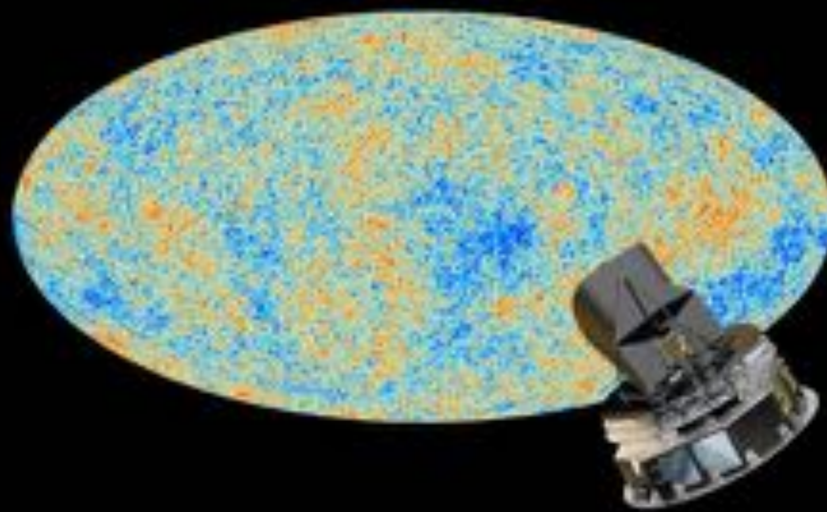
Science Drivers

The Large Synoptic Survey Telescope

Current Status of Construction

Outlook

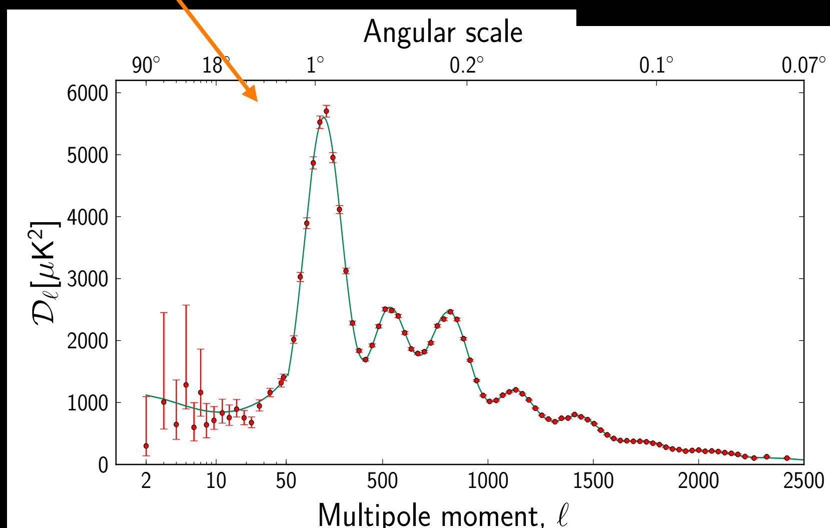
Mystery: The Dark Universe

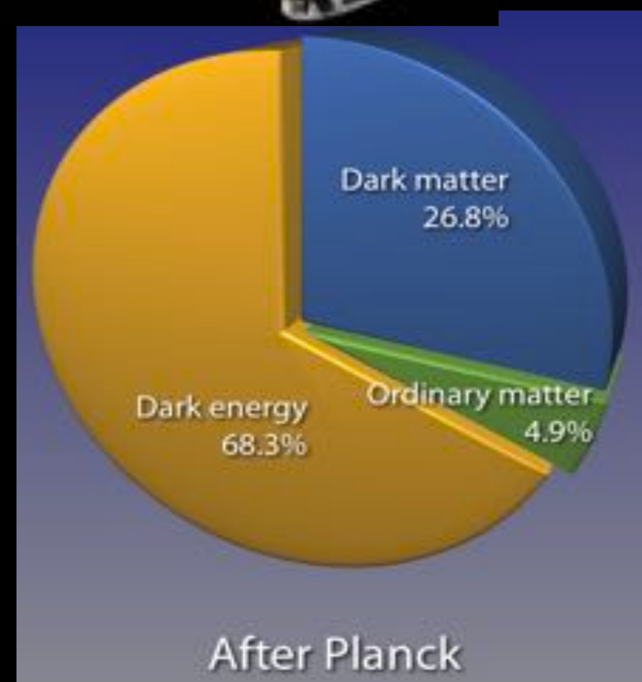


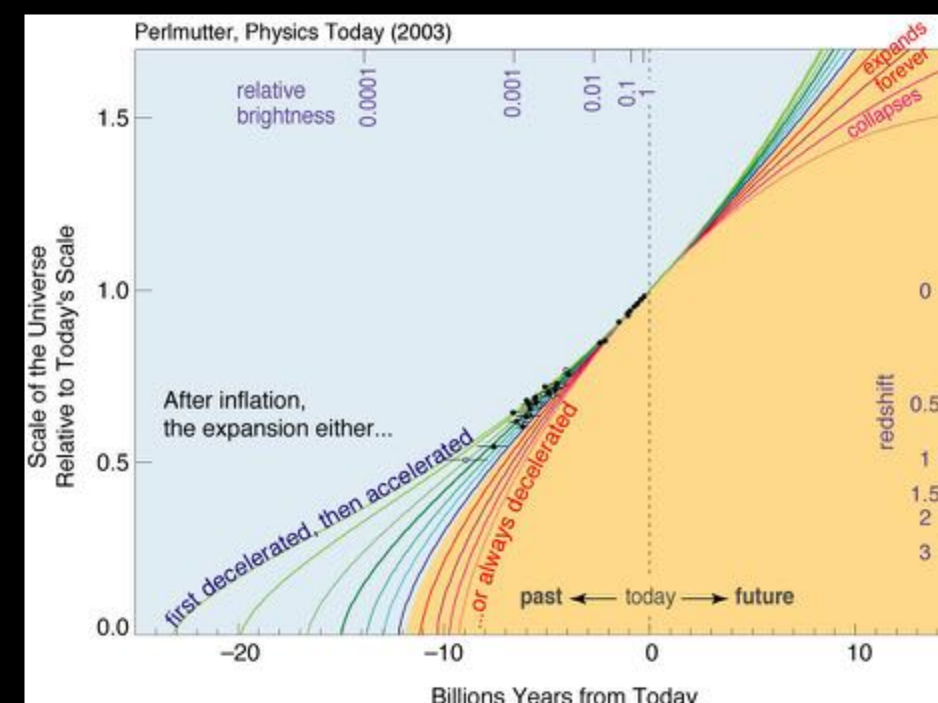
Flat universe

Ω_{total}= 1.02+/-0.02

WMAP+Planck



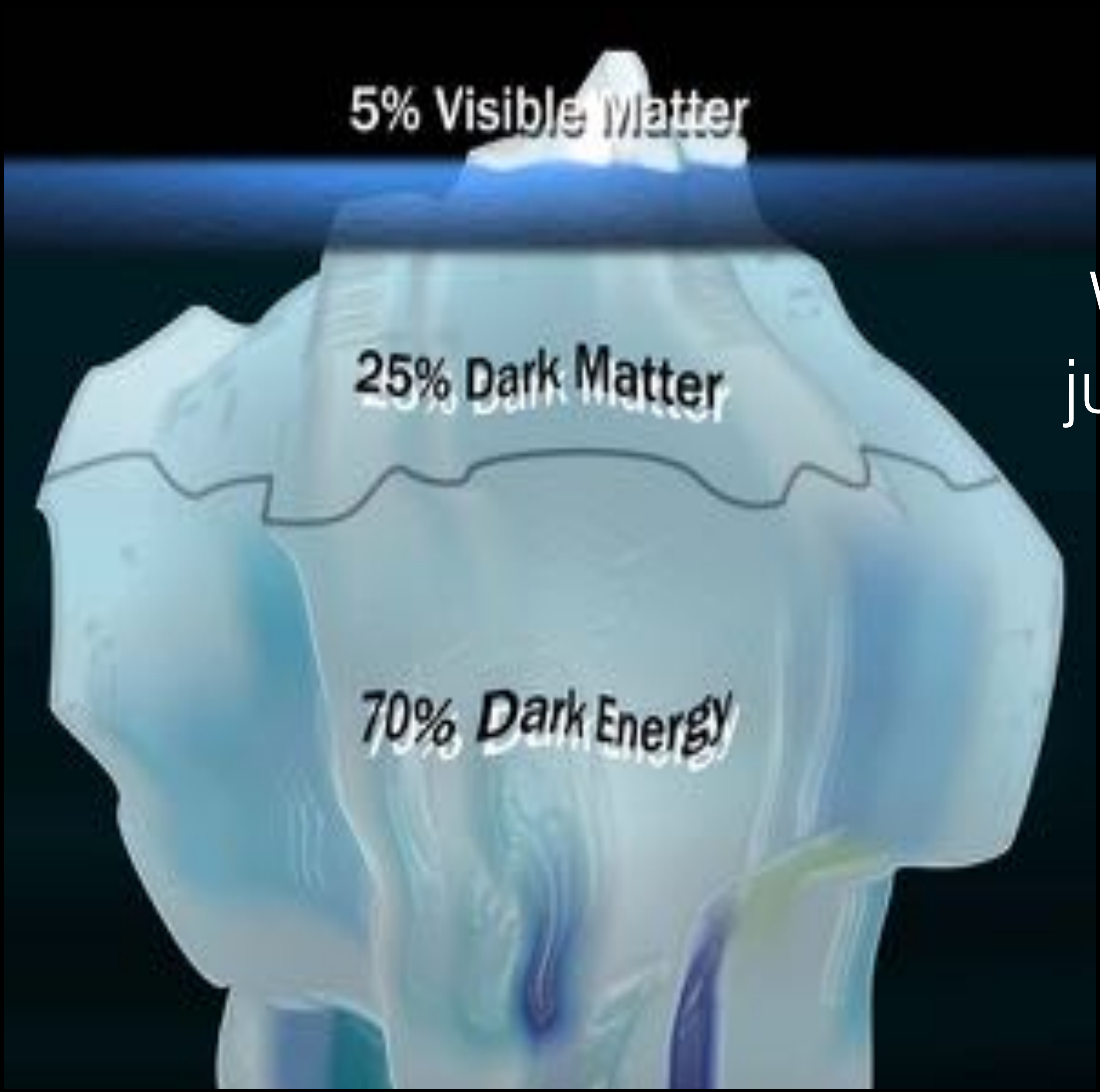




Dark Energy "most of the energy"
Dark Matter "most of the matter"
Together they govern the evolution & fate of the universe.

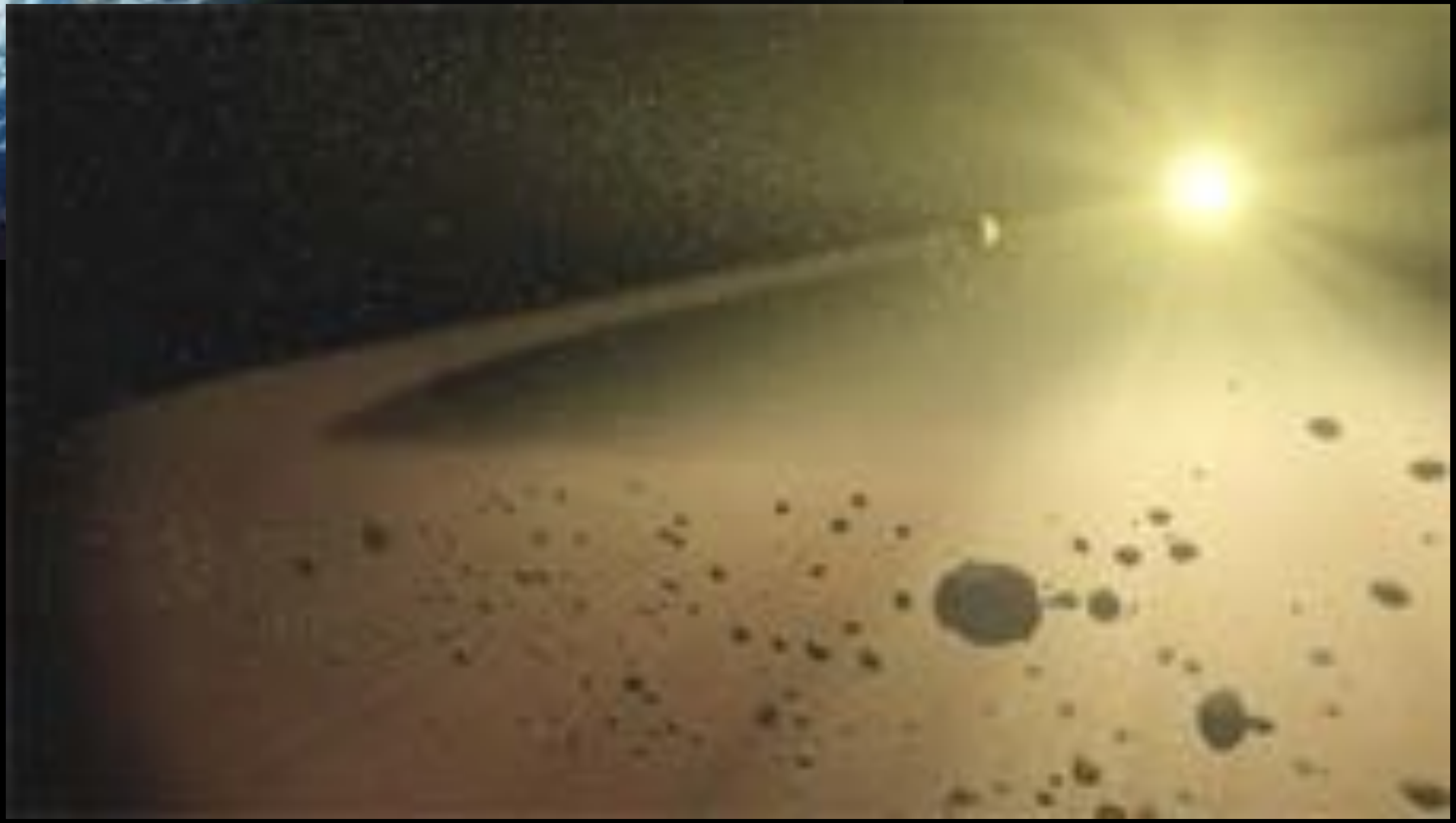
Their nature ranks as one of the greatest questions in the physical sciences

Mystery



What we know: just the tip of the iceberg.

Solar System



Milky Way

The transient universe

“What we know is a droplet, what we don’t know is an Ocean”

Sir Isaac Newton (1643-1727)

Credit: Jim Virdee

There has never been a better time to be an astrophysicist, cosmologist or particle physicist!

Progress in Optical Astronomy

- Bigger Telescopes: *Keck to E-ELT*
- Angular resolution: *Hubble to JWST*
- All Sky Survey: *Sloan Digital Sky Survey to LSST*

A New Kind of Telescope Optimized for Surveys

~2000

Modified 3-mirror Paul-Baker Design
Seeing limited over 3.5 deg field of view
"Dark Matter Telescope"

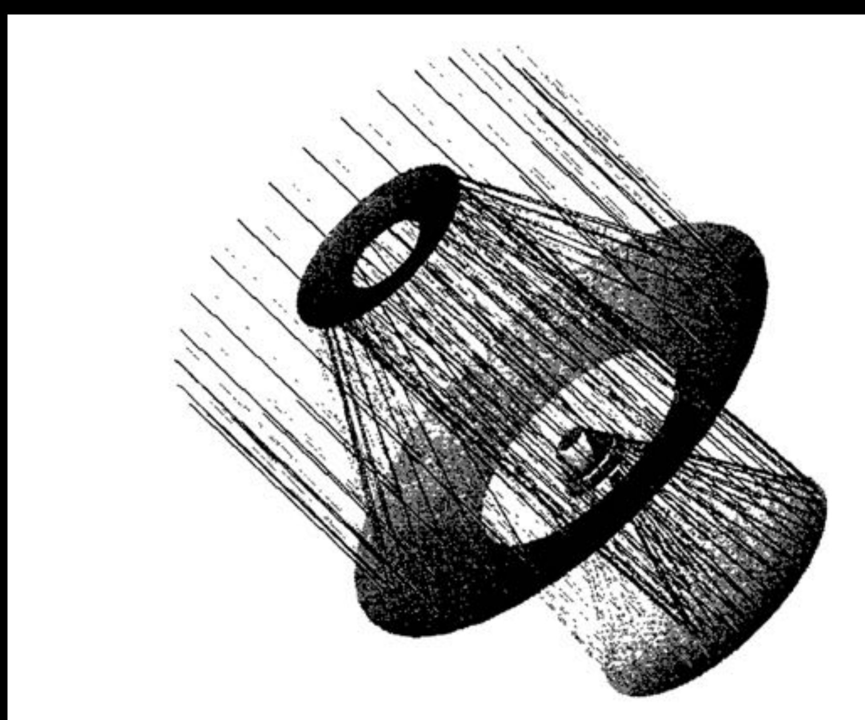
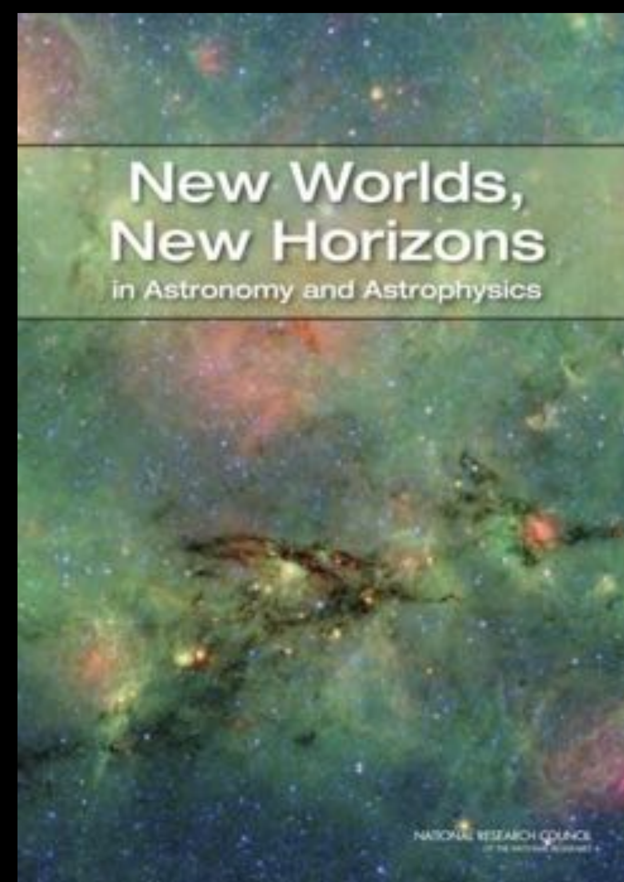


Figure 1. Optical layout with rays at ± 1.5° field angle.

Angel et al. 2000
Seppala et al. 2002

2010

LSST selected as the highest priority US ground-based instrument in the US Decadal Survey



2014

Formal construction start!
Joint DOE + NSF project


wide fast deep

LSST in a nutshell

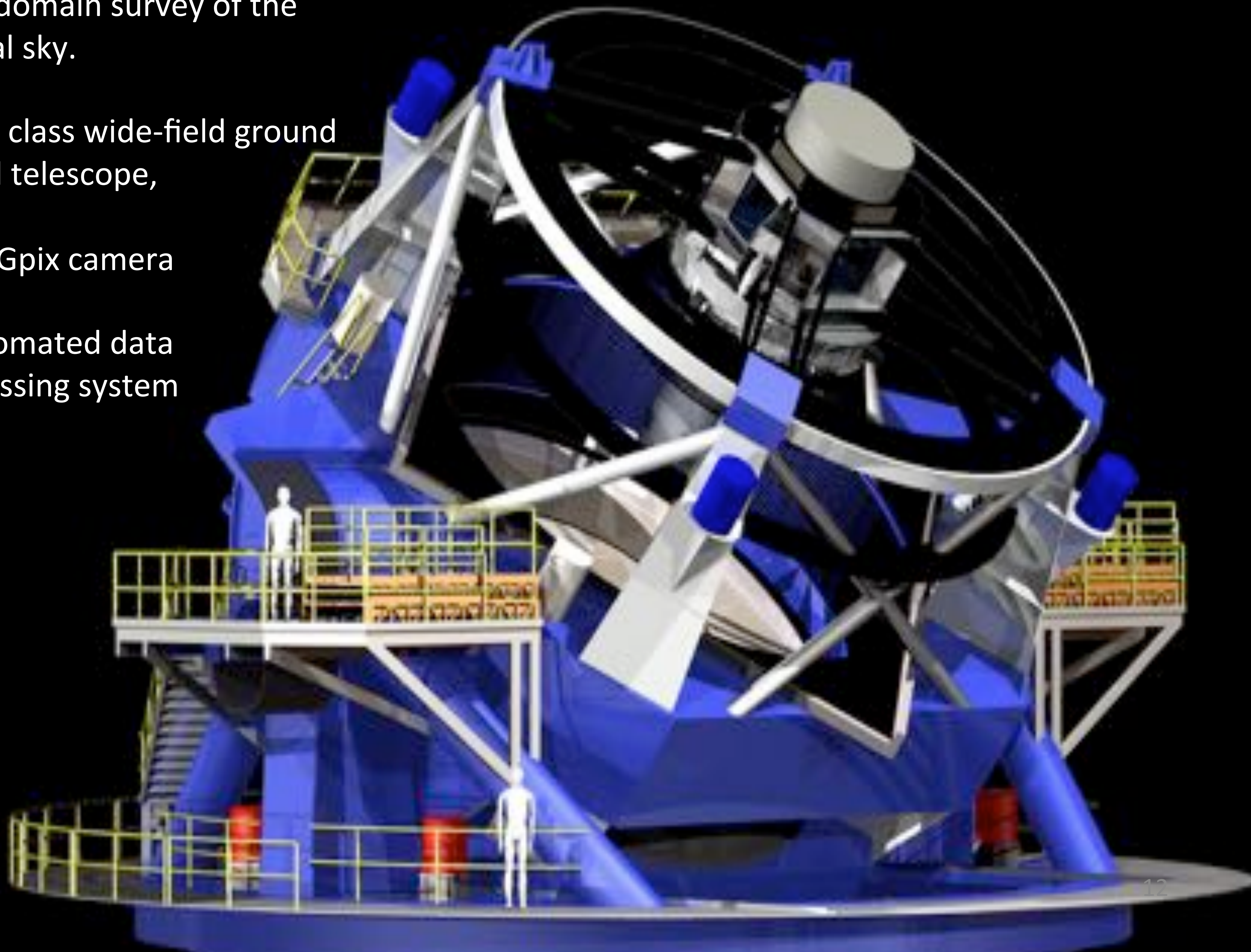
Synoptic =
Big Picture

LSST : an integrated survey system designed to conduct a decade-long*, deep, wide, fast* time-domain survey of the optical sky.

* 8-m class wide-field ground based telescope,

* 3.2 Gpix camera

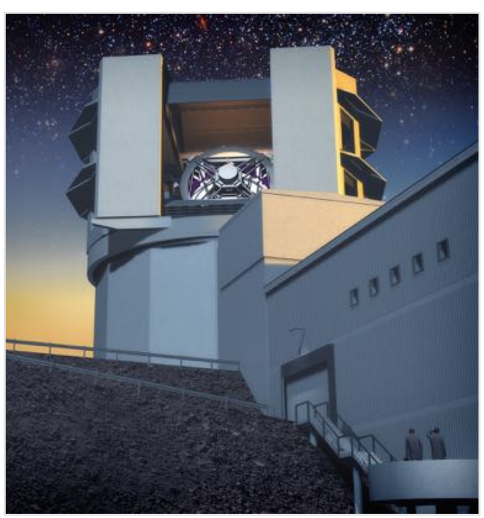
* automated data processing system



Wide

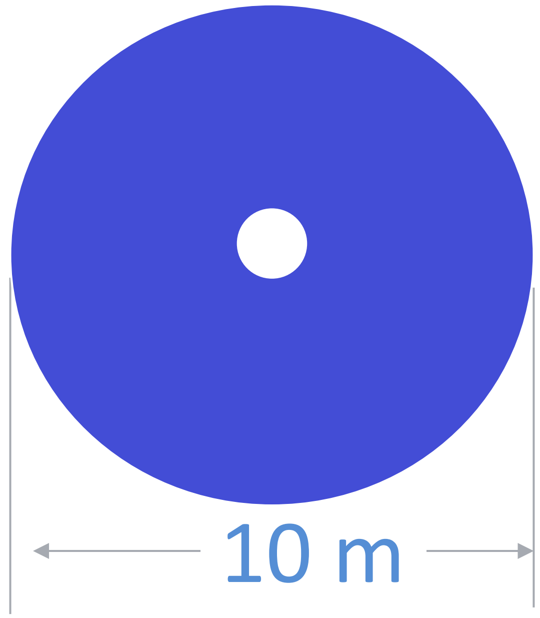
LSST's wide field of view

KECK TELESCOPE



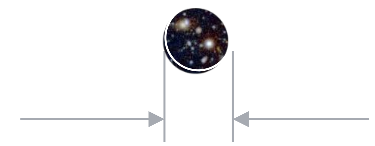
LSST

Primary Mirror Diameter



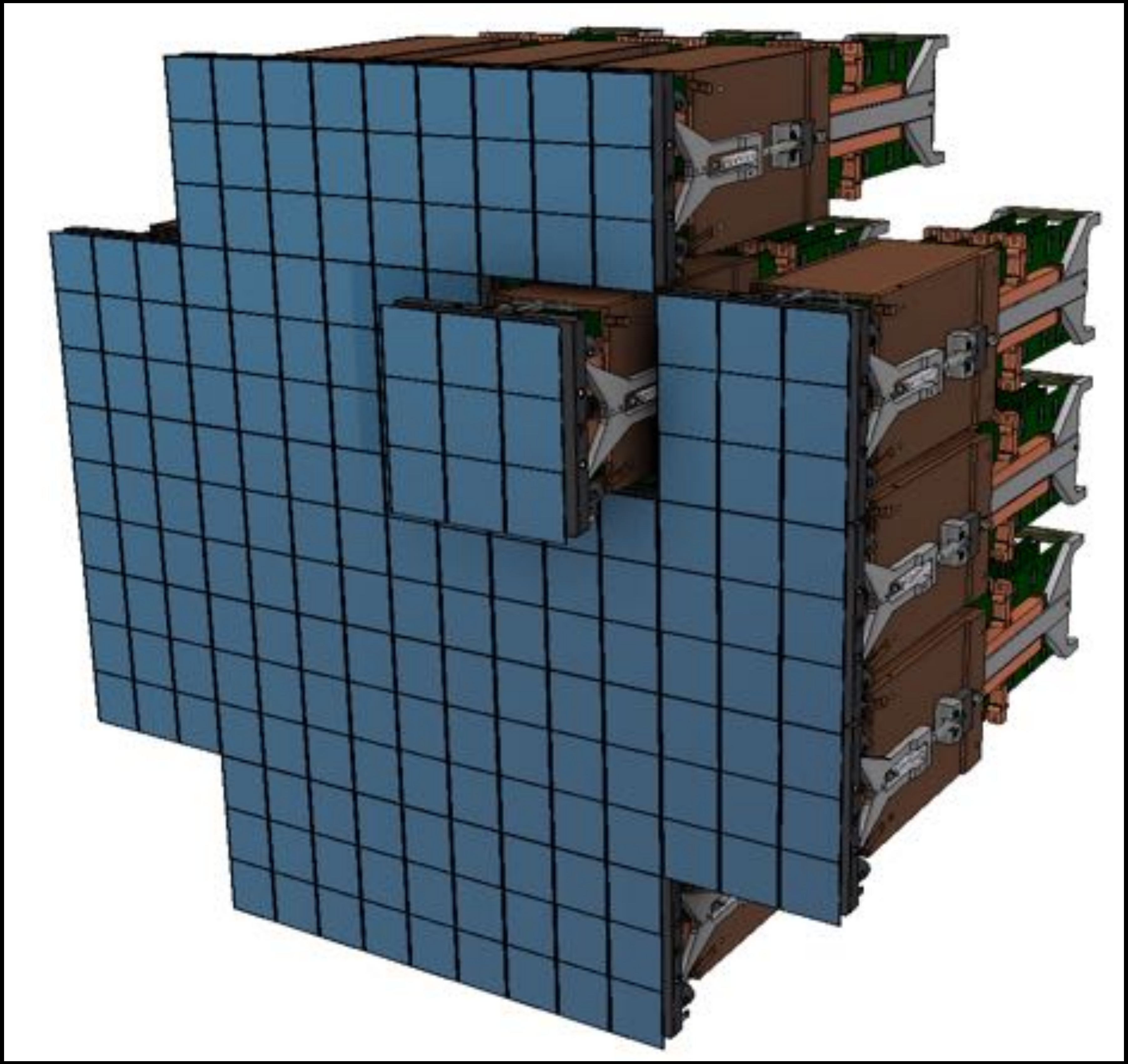
Field of View

(full moon is 0.5 degrees)



Fast

189 4K x 4K CCDs Largest & fast astronomy CCD camera



3 Gpix
multiport CCDs

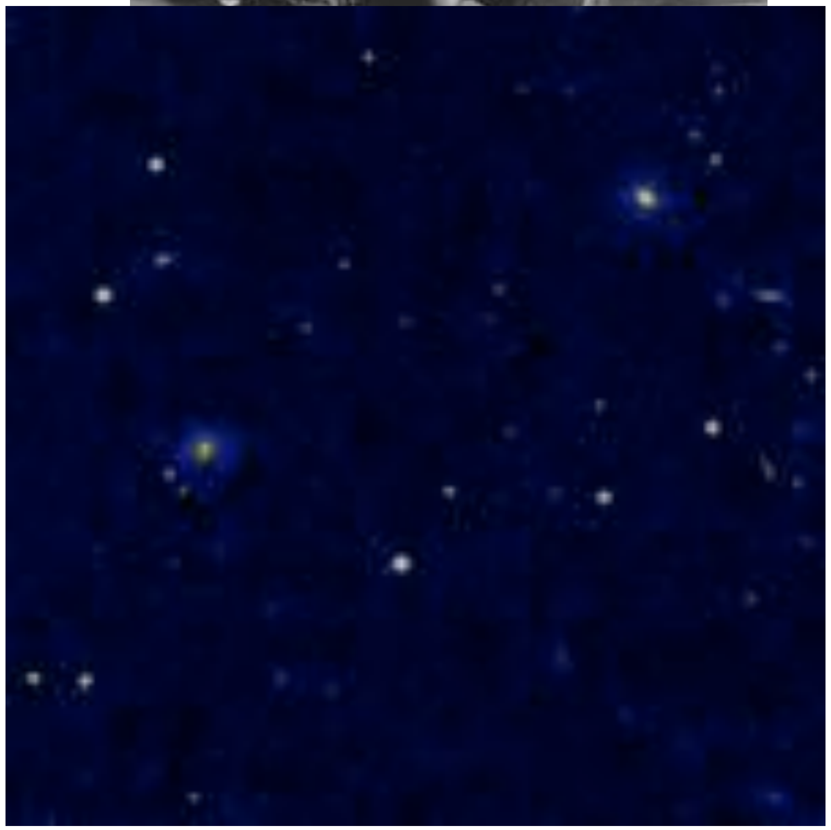
Record image in
15 seconds

Readout image
In 2 seconds

LSST is the next great advance to our vision of the cosmos

DEEP

ca. 1950 POSS
(Photographic)



LSST probes 100x fainter & enables the exploration of the time domain.


Every circle
contains
10 million
galaxies

LSST will make the first movie of the universe

- ~800 images of every field will open up the time domain for large-scale study for the first time: a movie of the universe

A survey of 37 billion objects

(20B galaxies & 17B stars)

in space and time

32 trillion measurements


Day 000


Day 000

LSST 4 Primary Science Drivers

Dark Energy-Dark Matter

Multiple investigations into the nature of the dominant components of the universe

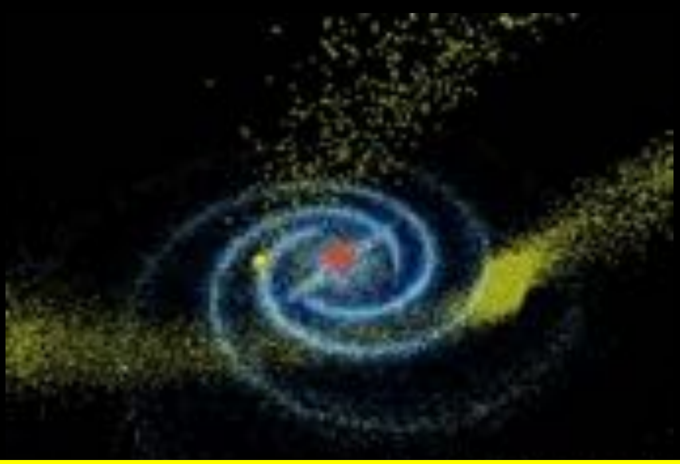
Inventory of the Solar System

Find 90% of hazardous NEOs down to 140 m over 10 yrs & test theories of solar system formation

"Movie" of the Universe: time domain

Discovering the transient & unknown on time scales days to years

Mapping the Milky Way



Map the rich and complex structure of the galaxy in unprecedented detail and extent

All missions conducted in parallel
& discussed in later talks in this session

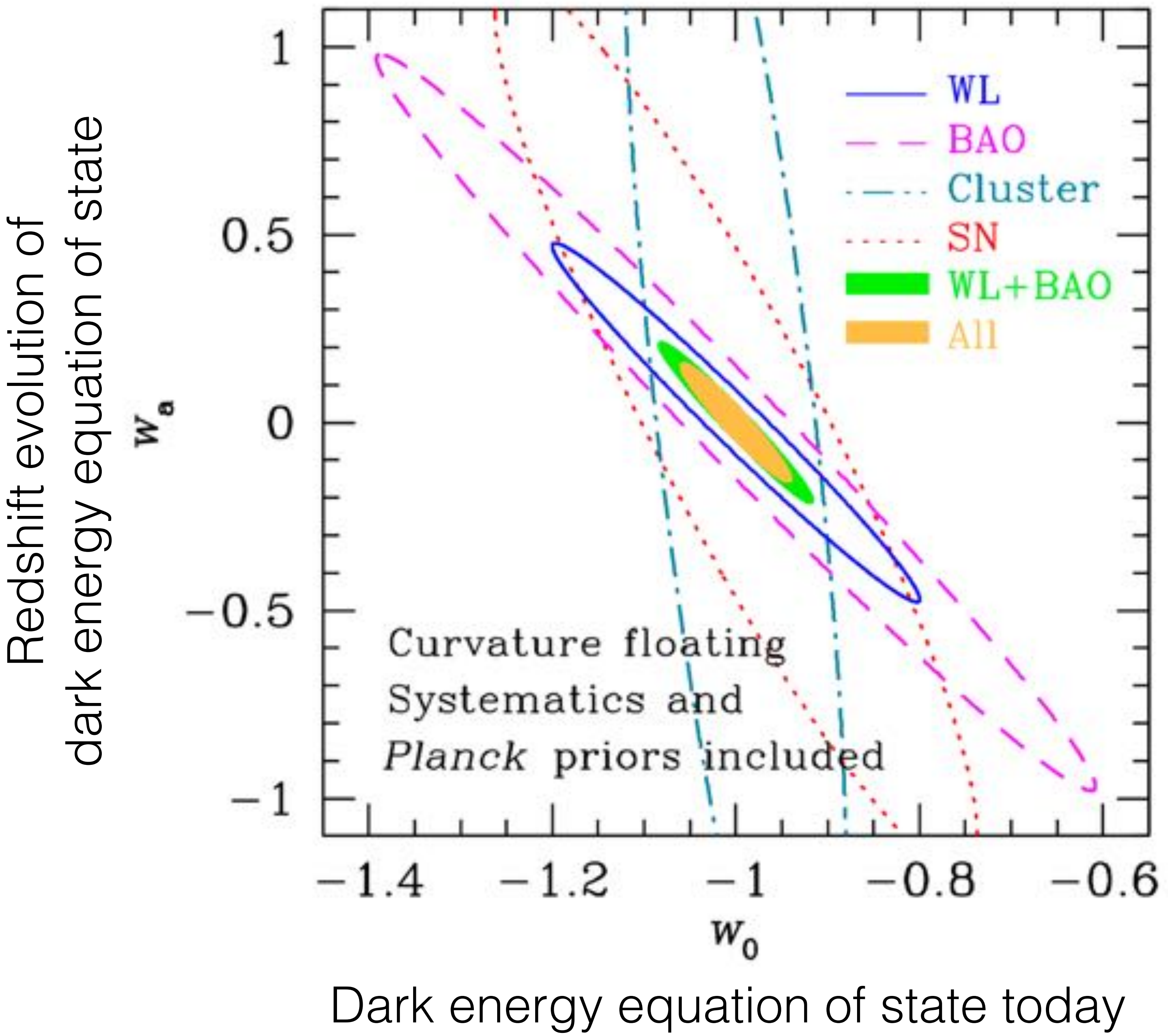
LSST Primary Science Drivers

Cosmology:
- Dark energy
- Dark matter
- Neutrinos

Milky Way:
- Stellar populations
- Streams
- Dwarf Galaxies

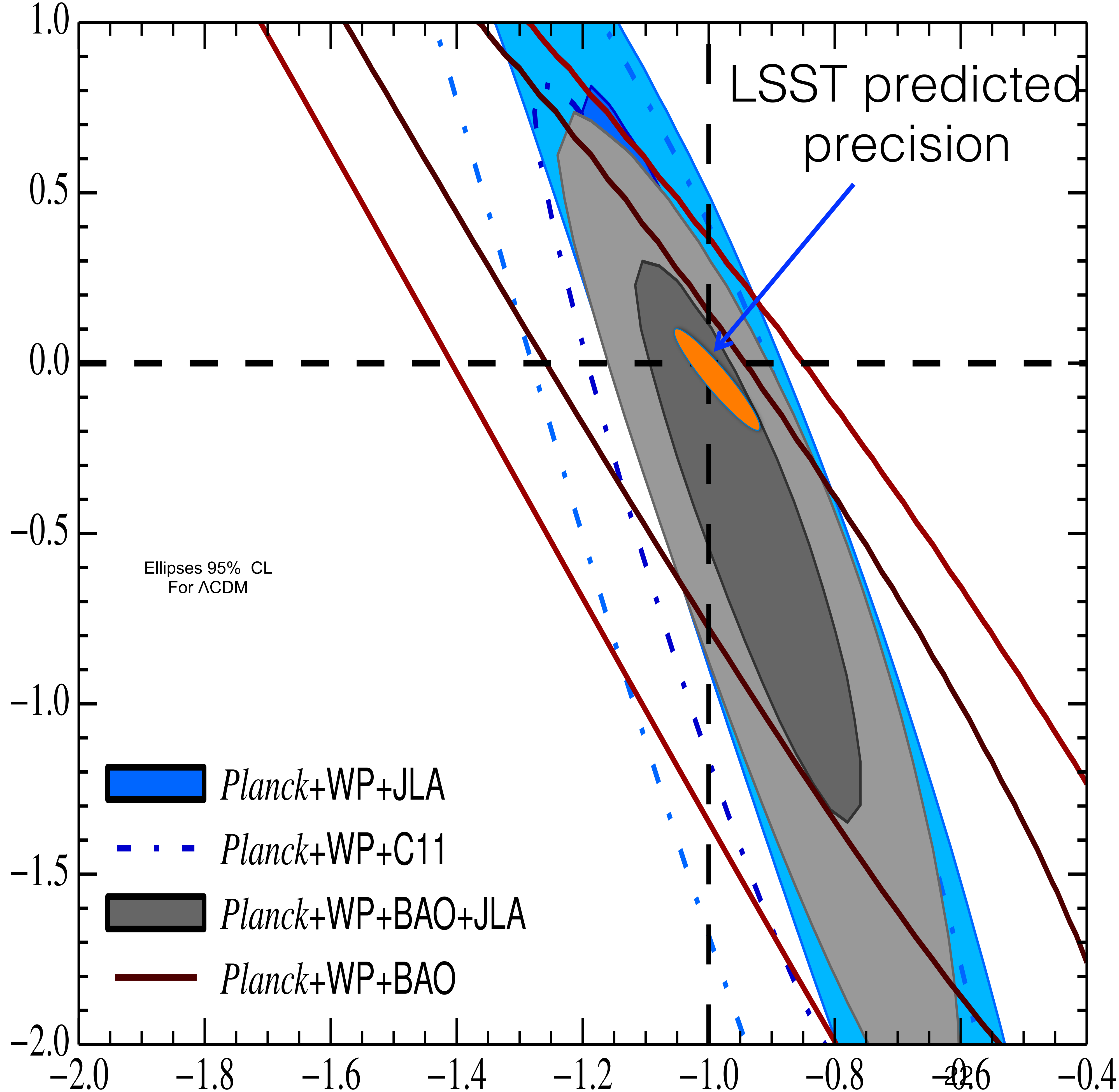
Solar System:
- Near-Earth Objects
- Trans-Neptunian Objects
- Comets

Dynamic Universe:
- Explosive transients
- Multi-messenger counterparts
- Variable stars, quasars
- Lensing events



Multiple complementary probes of expansion history and growth of cosmic structures to explore paramater space beyond ΛCDM

Present state of knowledge



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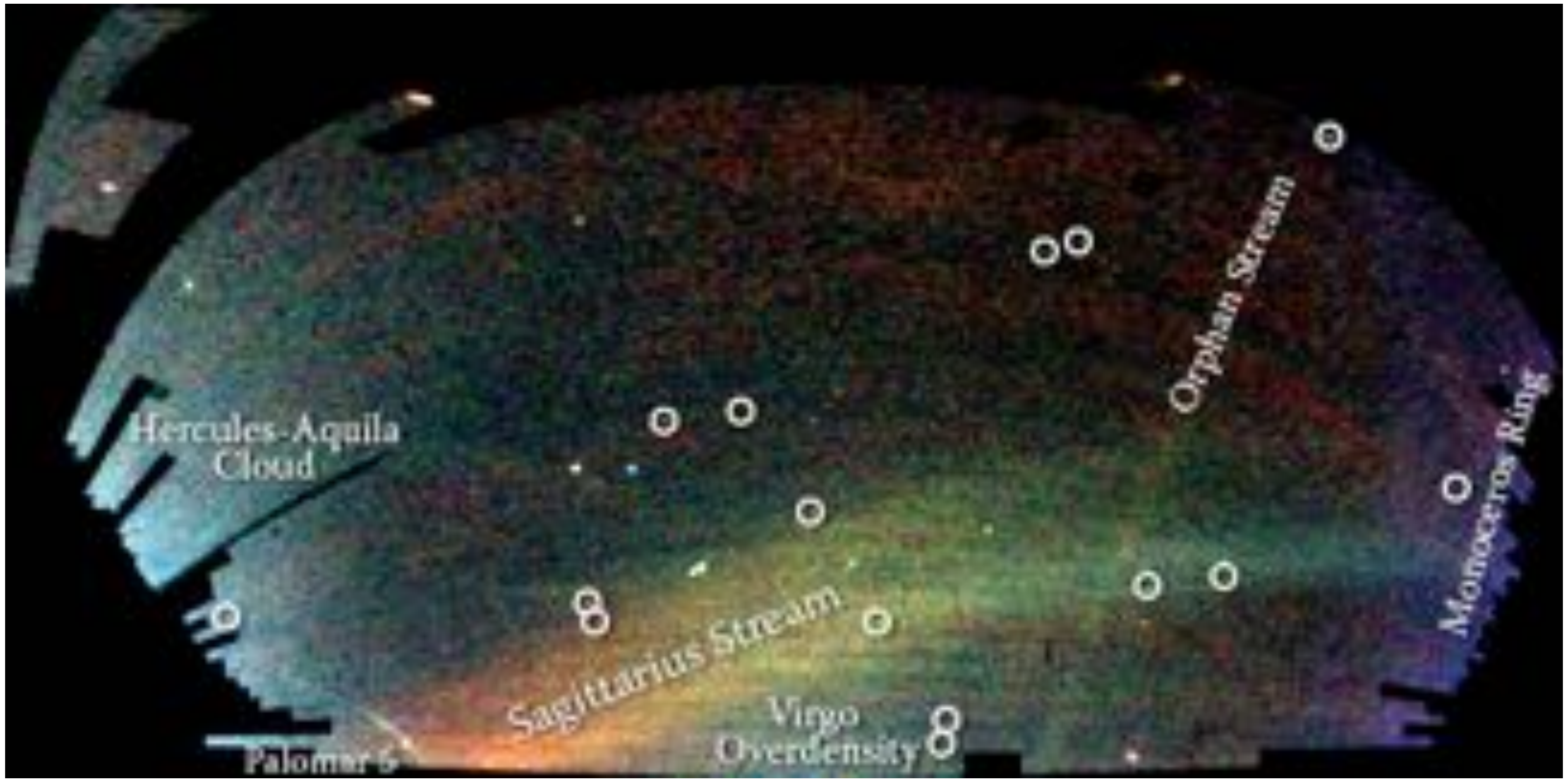
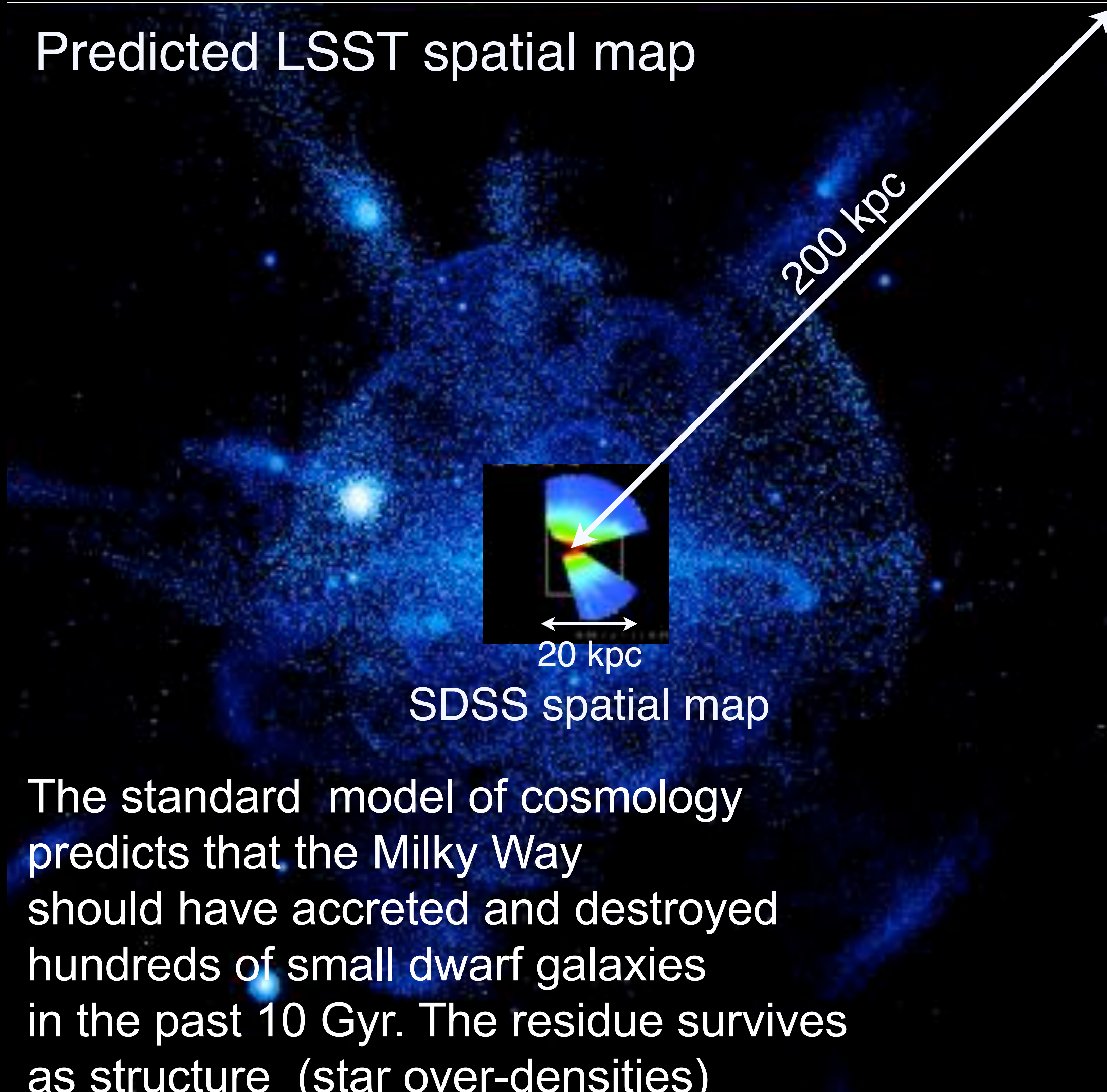


SDSS "Field of Streams"
Image Credit: Vasily Belokurov,

LSST compared to SDSS:
About 200 images, each 2 mag deeper
The co-added images will be 5 mag. deeper
Precise proper motion & parallax measurements will be available for r<24 (4 magnitudes deeper than the Gaia survey)

Example: structure of outer milky way

Large Synoptic Survey Telescope



The standard model of cosmology predicts that the Milky Way should have accreted and destroyed hundreds of small dwarf galaxies in the past 10 Gyr. The residue survives as structure (star over-densities) in the outer halo.

Image: Star density stellar halo simulations

RR Lyrae stars are luminous enough and copious enough to map the outer galaxy

Overdensities found in SDSS star count studies to 100 kpc

LSST RR Lyrae to 400 kpc, extending SDSS mapping volume by a factor of 50.

An important test of the small-scale accretion history of the Galaxy and a test of standard Model of cosmology Constraints on the particle nature of dark matter

Bullock and Johnston (2005)

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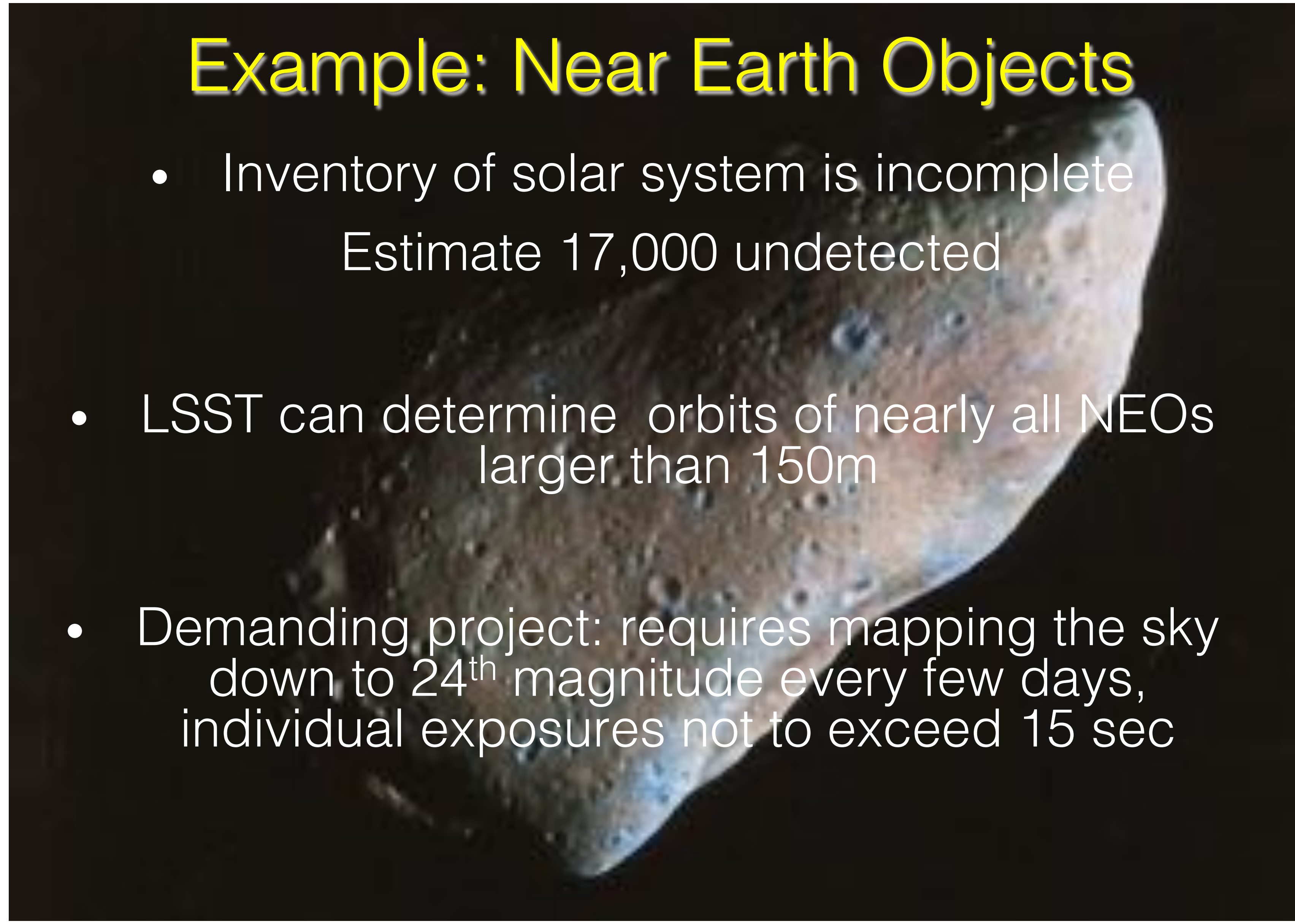


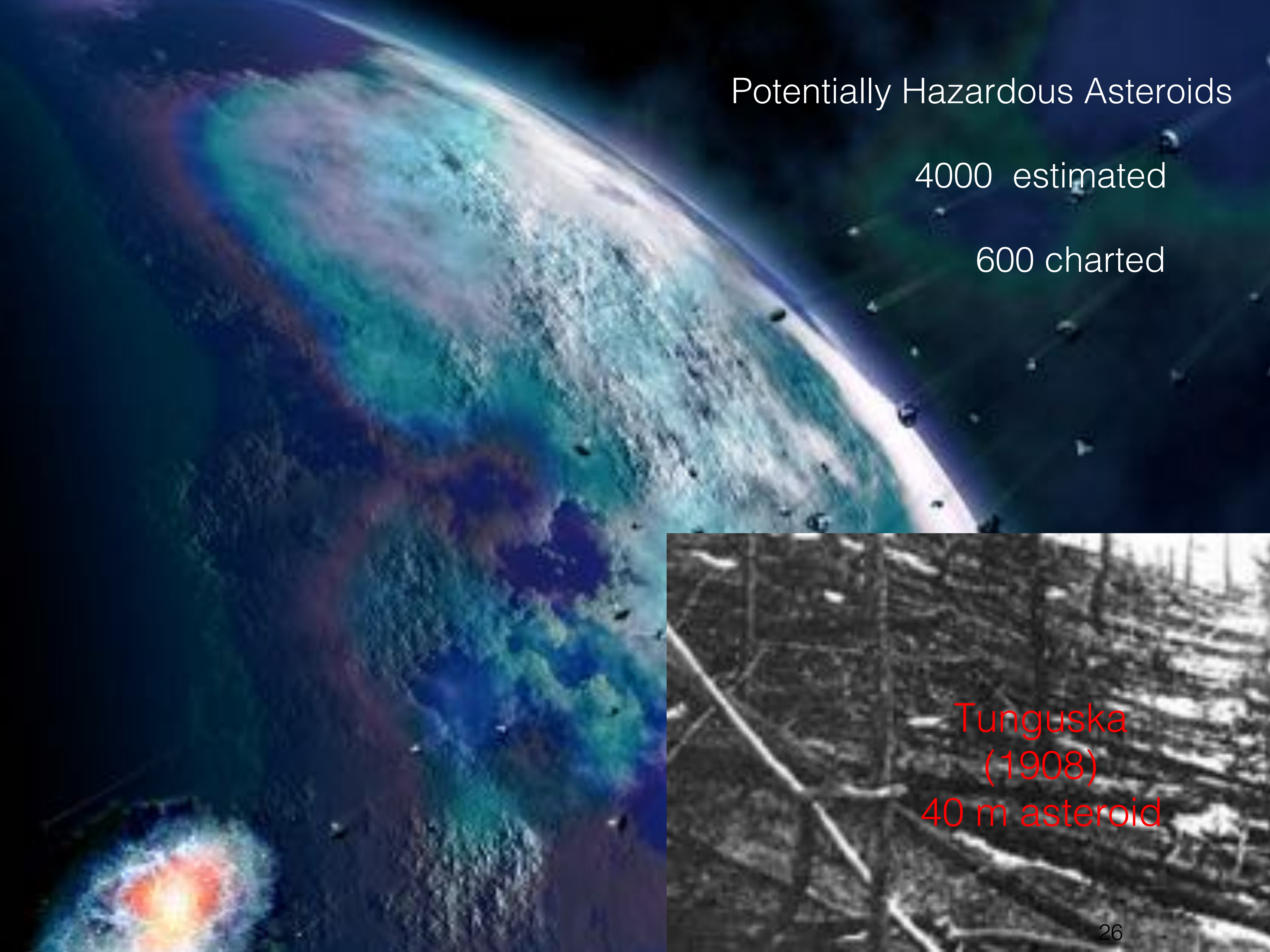
Example: Near Earth Objects

- Inventory of solar system is incomplete

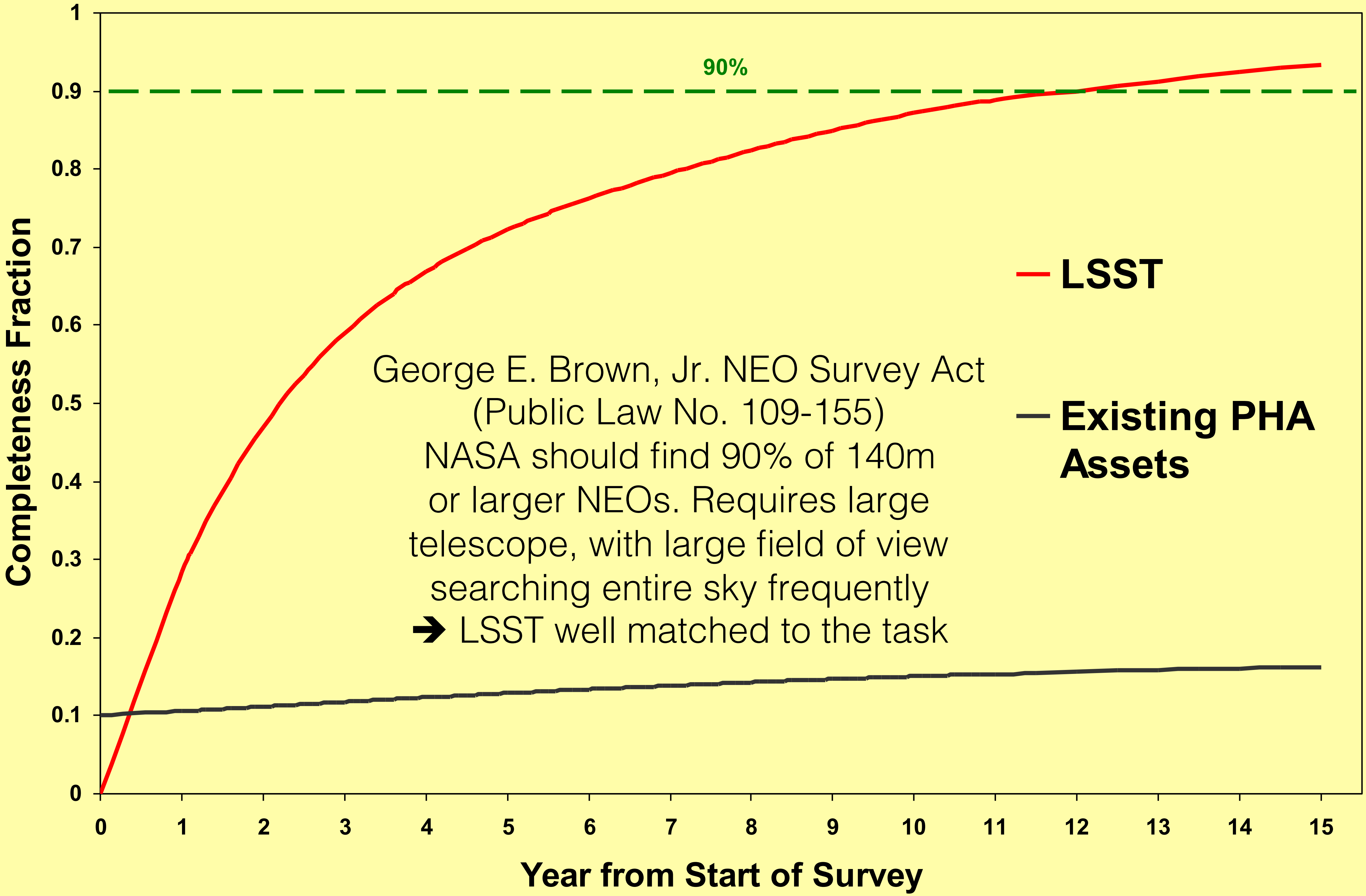
  Estimate 17,000 undetected

- LSST can determine orbits of nearly all NEOs larger than 150m

- Demanding project: requires mapping the sky down to 24th magnitude every few days, individual exposures not to exceed 15 sec


Potentially Hazardous Asteroids
4000 estimated
600 charted
Tunguska
(1908)
40 m asteroid

Percentage of Potentally Hazardous Asteroids Found



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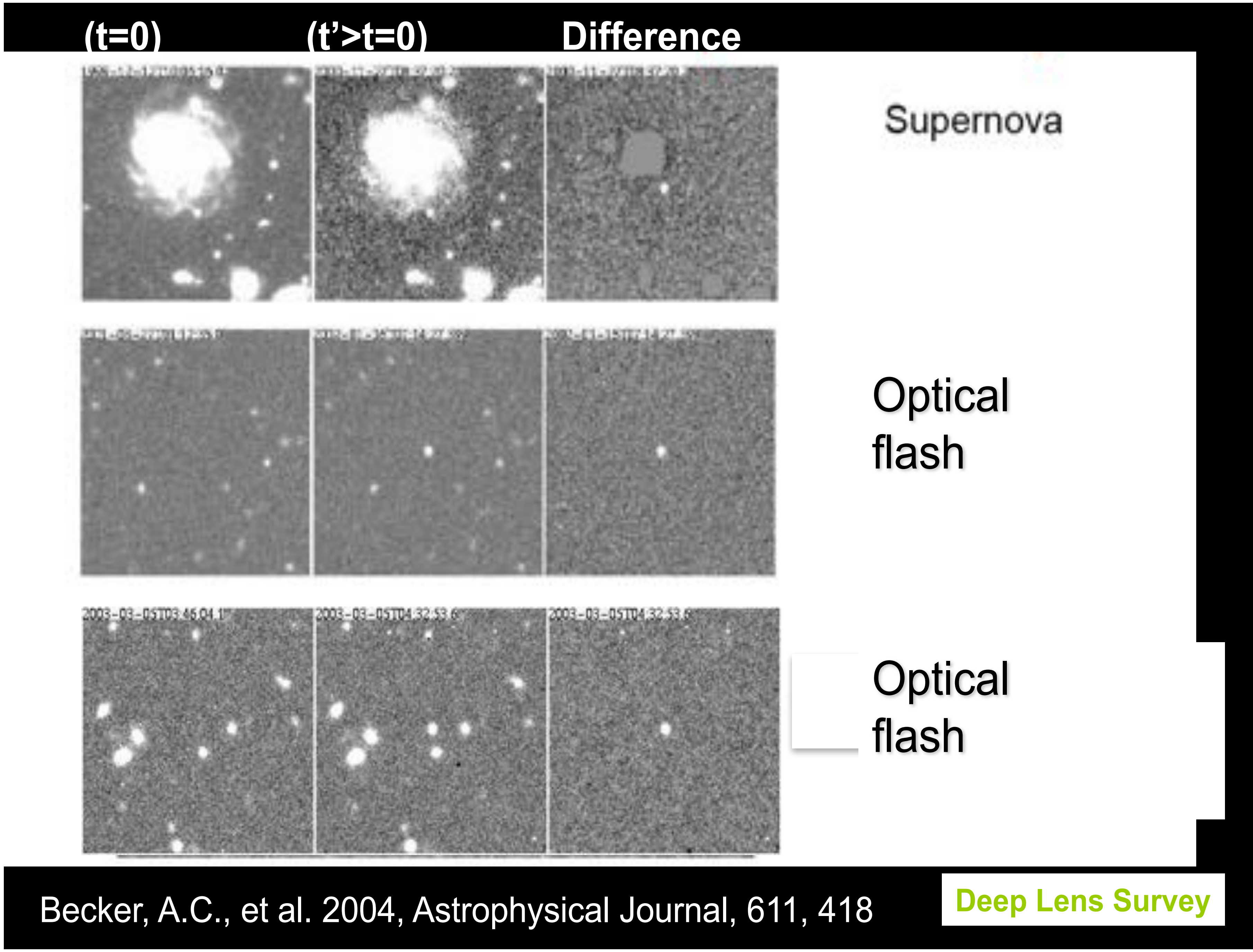

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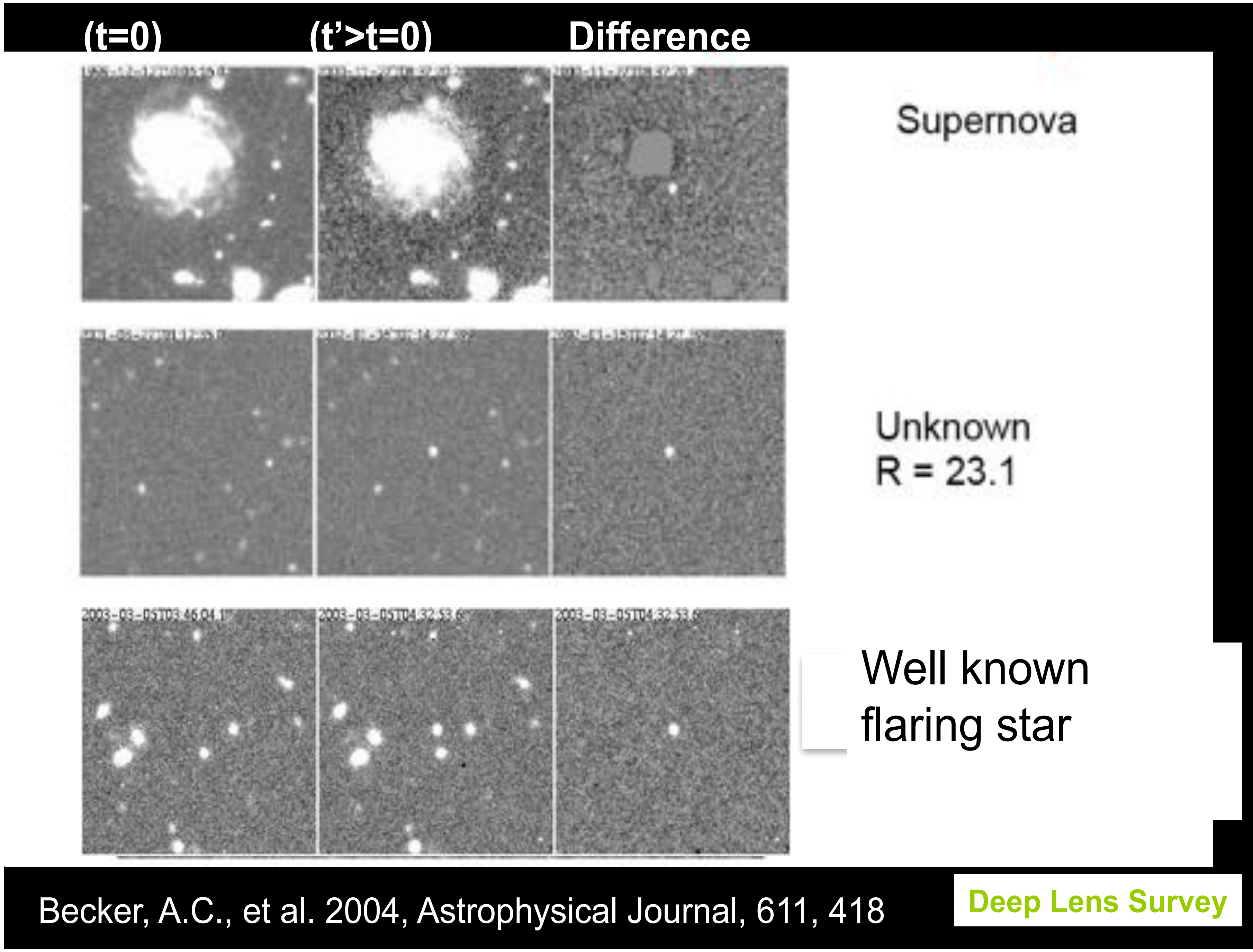

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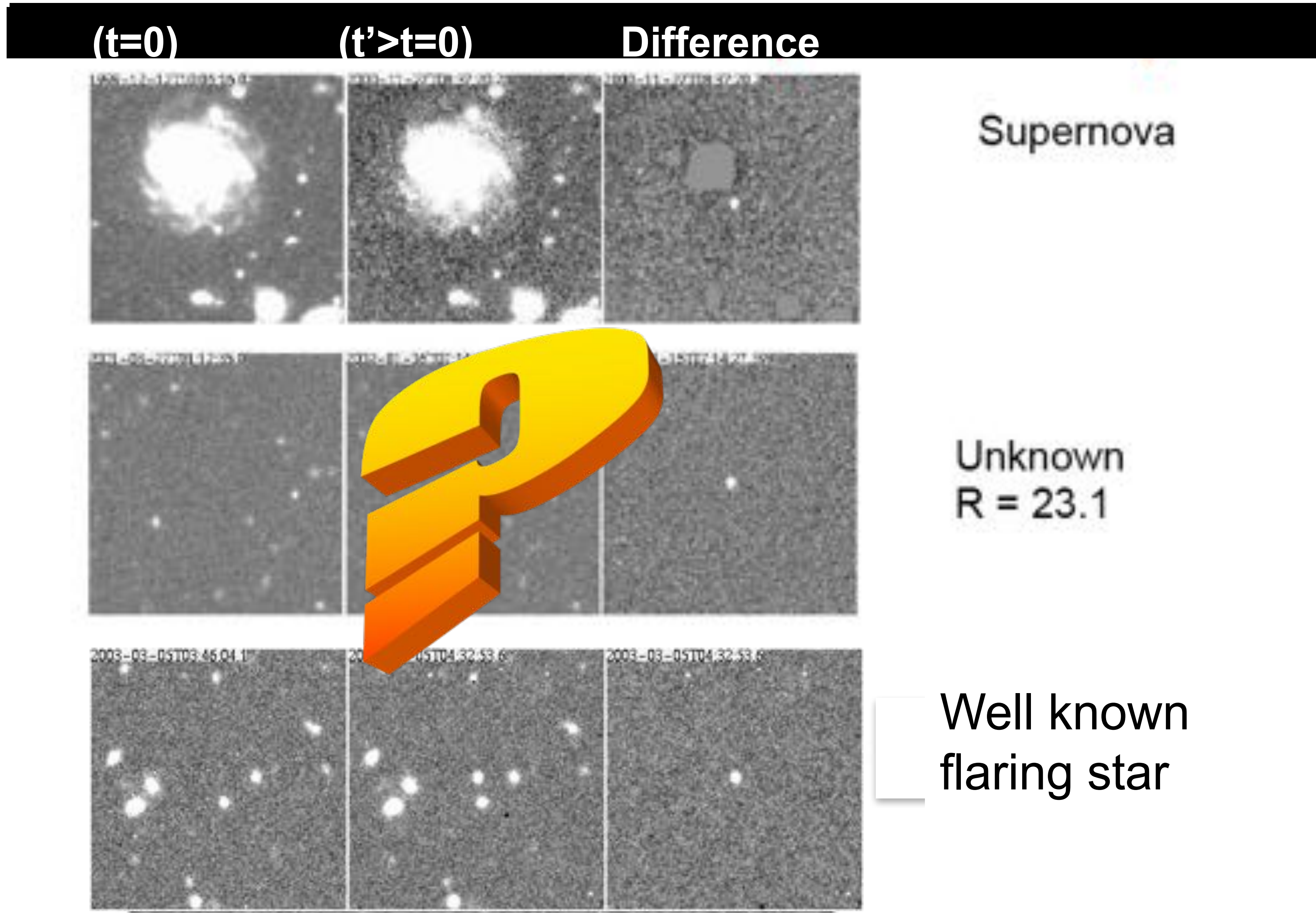
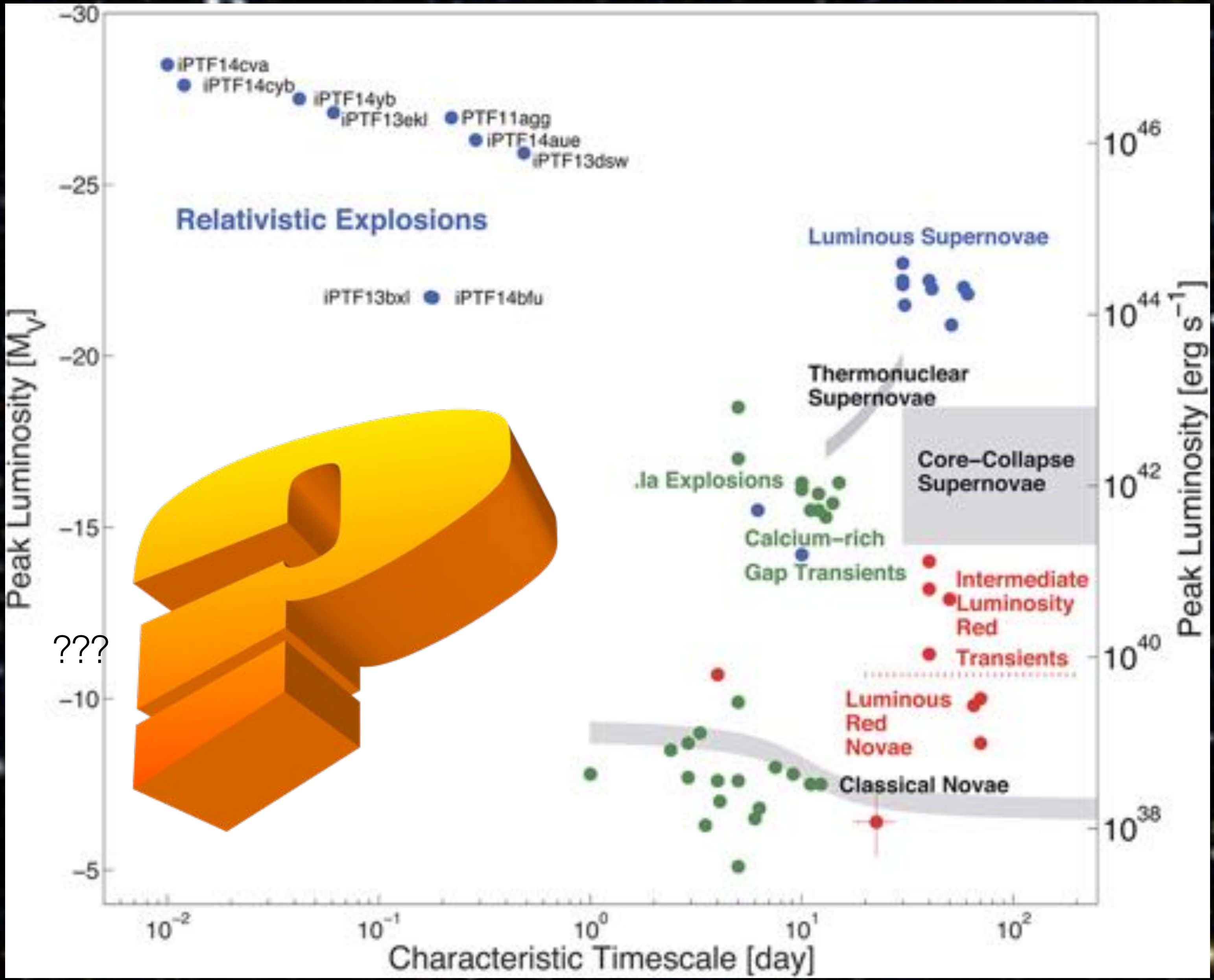


Becker, A.C., et al. 2004, Astrophysical Journal, 611, 418

Deep Lens Survey

Science Driver 4: Transients and Variable Objects

Dynamic Universe
Explosive transients
Multi-messenger counterparts
Variable stars,
Quasars
Lensing events



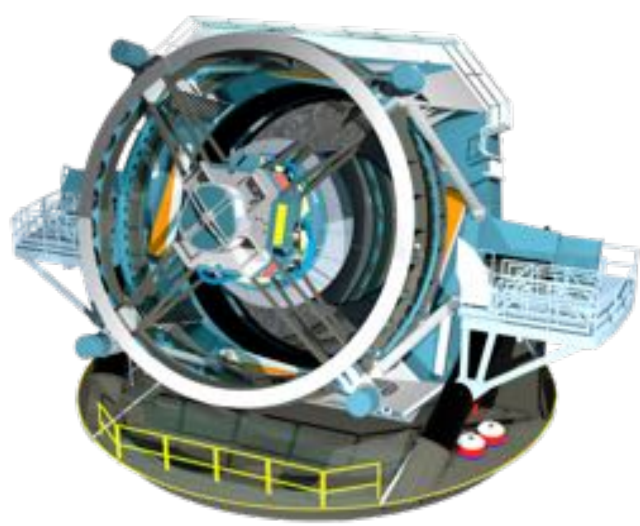
"The parameter space for fast transients with timescales <1 day is largely unexplored

LSST: ~10 million cosmic explosions over most of the observable Universe, extending the volume of the parameter space for discovery by x1,000 reaching unprecedented sensitivity. A movie of the universe

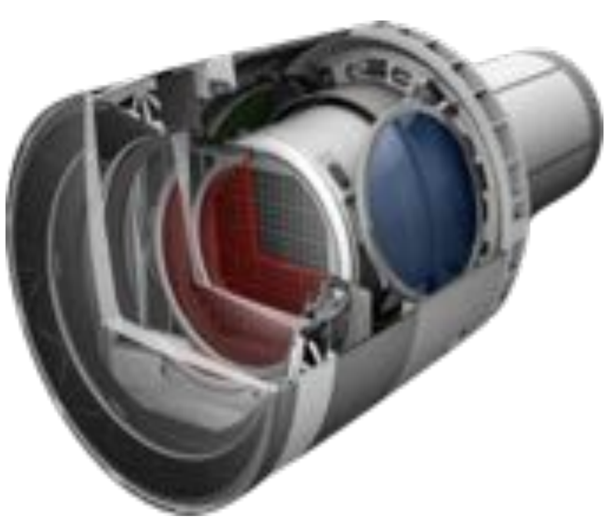
Overview of the LSST System

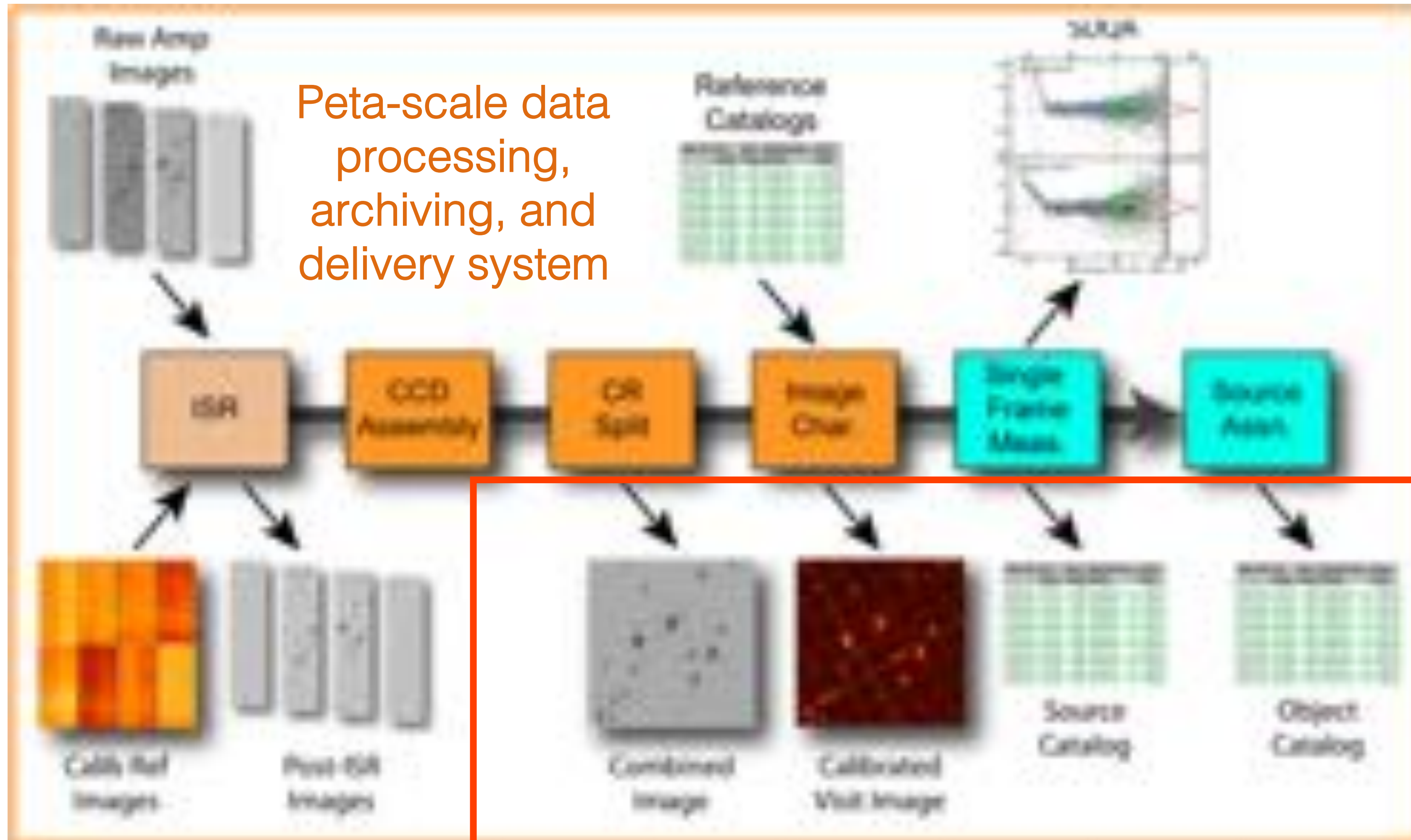
A comprehensive facility that will include: (i) an optical telescope, wide-field camera, 6 broad band optical filters, (ii) a data management system to process, archive, and serve images and data products, (iii) user interfaces.

8.4 m telescope + observatory



3.2 Gpix camera



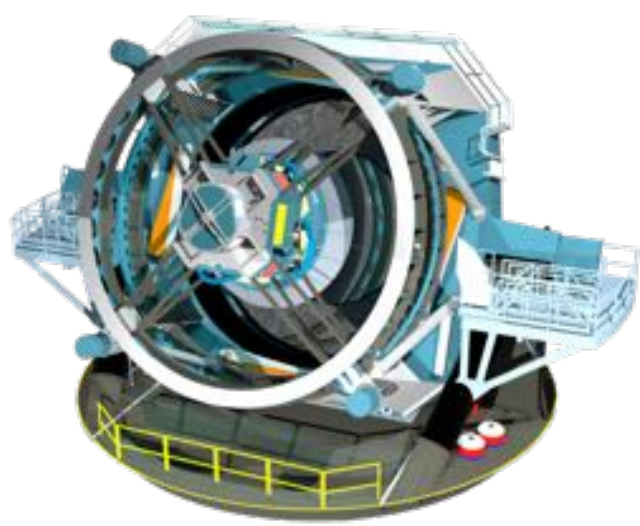


LSST Science Platform will provide community access services

Overview of the LSST System

We will deploy this system in October 2022, for a 10-year, time-domain survey of >18,000 deg^2 of the Southern Sky.

8.4 m telescope + observatory



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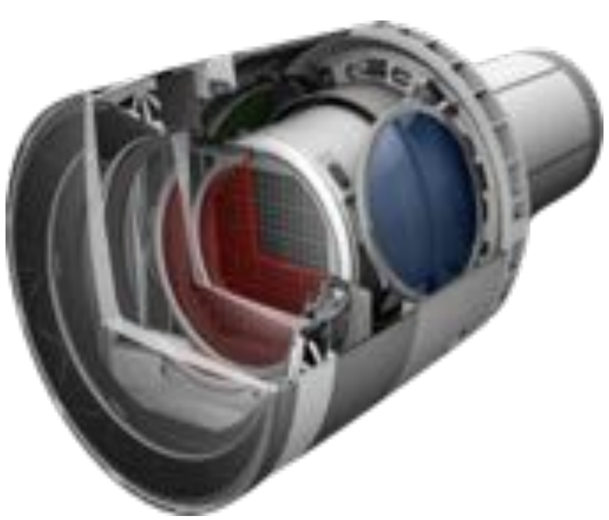
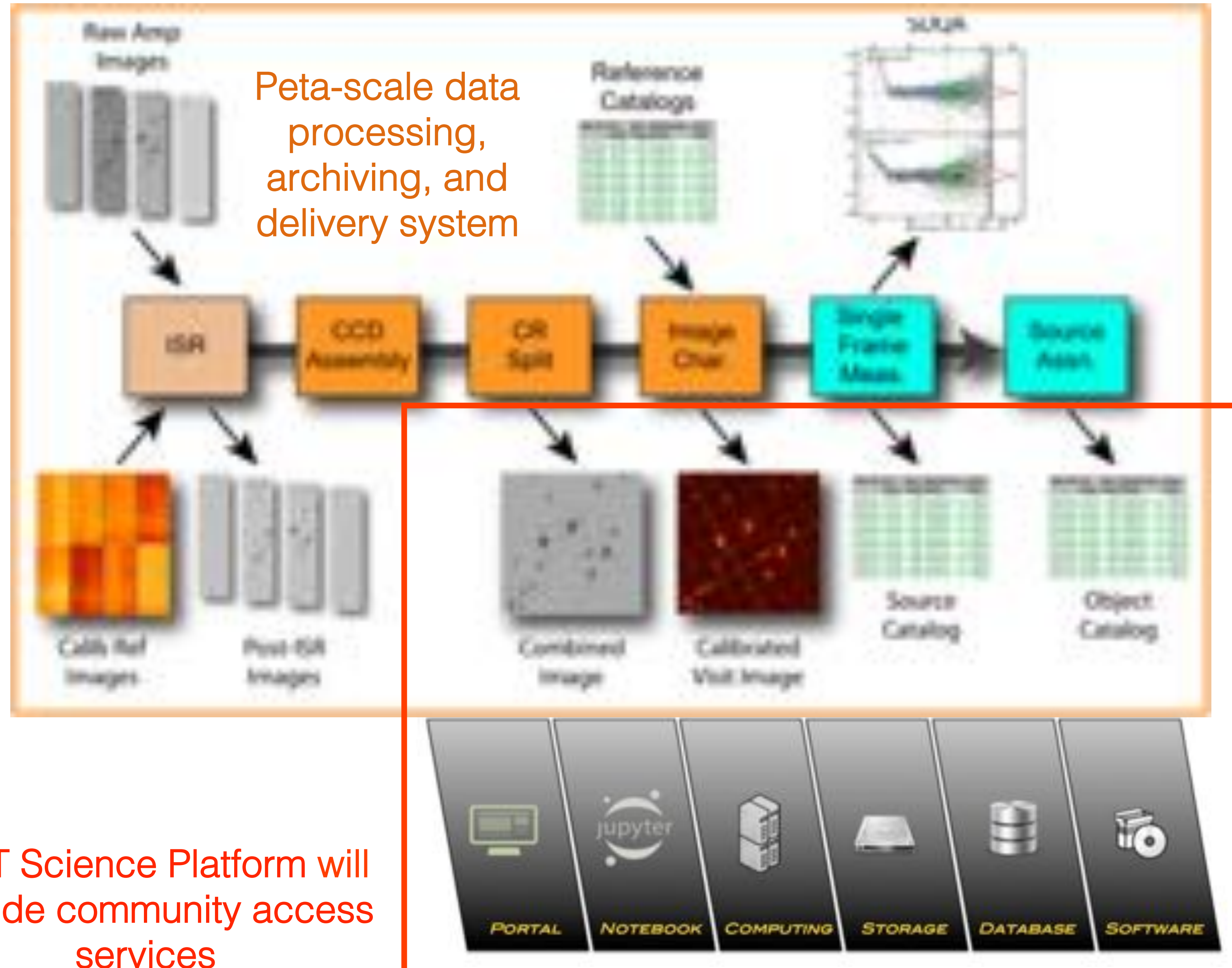




LSST Science Platform will provide community access services

What is the LSST Project?

The LSST Project is the interagency (U.S. NSF MREFC & U.S. DOE MIE) LSST project that is building LSST, that will commission LSST, and that is developing the Operations Plan.

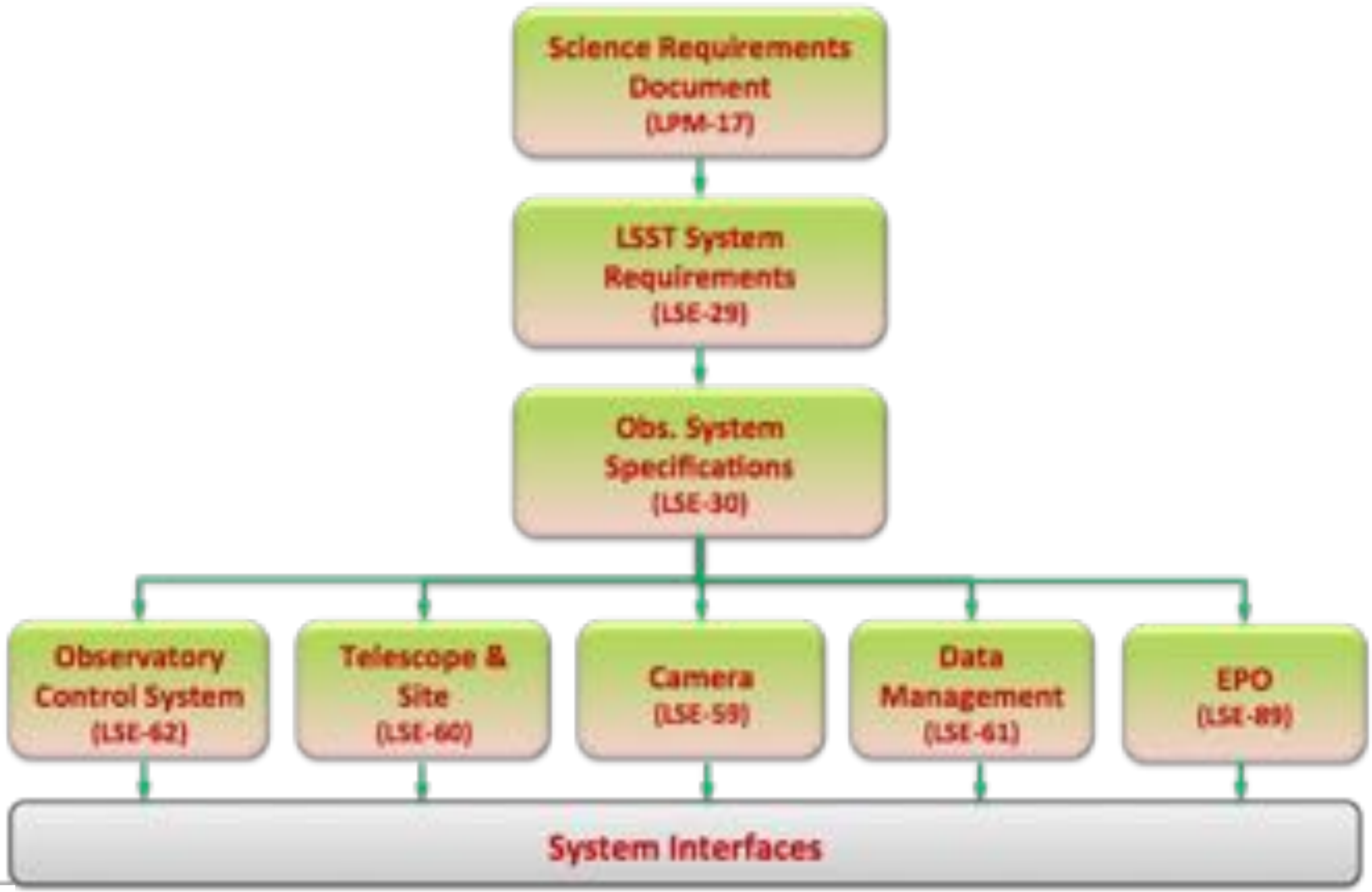
Flowdown from Science Goals to System Requirements

High-level science goals

Defining the system to build

System architecture

Individual subsystems



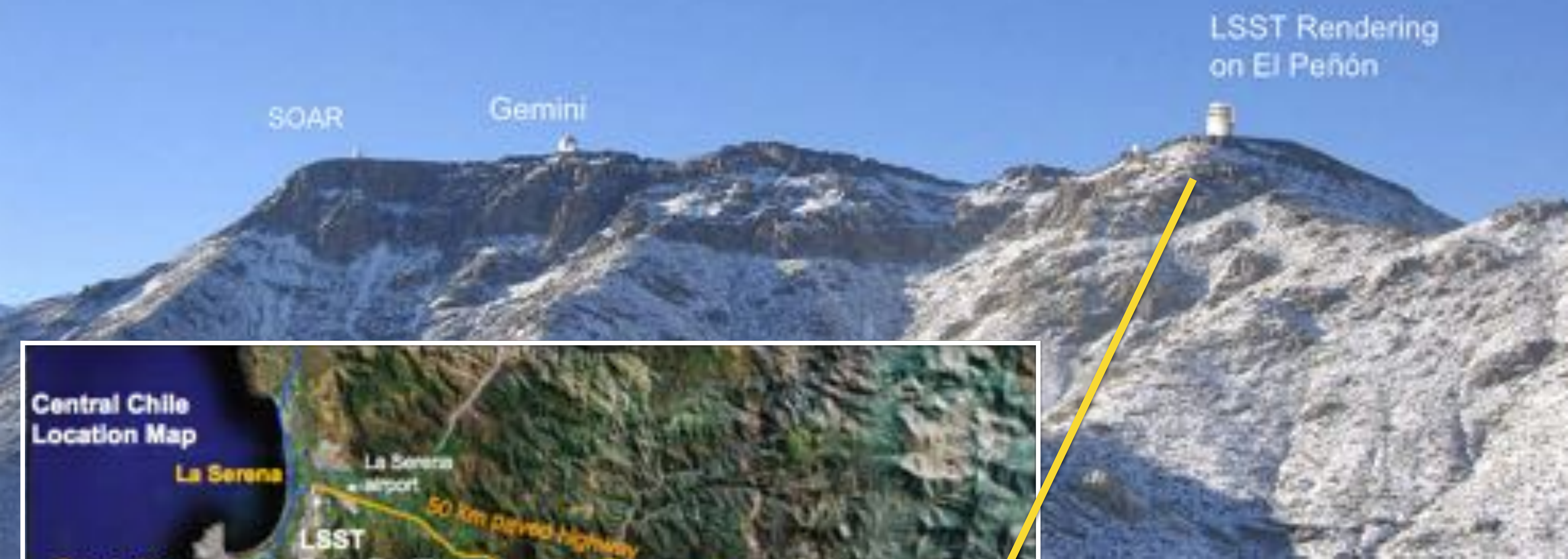
A Selection of High-level Science Requirements

Survey Property	Performance (design value)
Image Depth (single visit)	24.7 mag in *r*-band at SNR = 5
Median Delivered Seeing	0.7″ FWHM
Photometry (single visit)	0.5% repeatability, 1% relative, 1% absolute, 0.5% color
Astrometry (single visit)	10 mas relative, 50 mas absolute
Proper Motion	0.2 mas yr^{-1} at r = 20.5 mag, 1.0 mas yr^{-1} at r = 24.0 mag
Transient Detection	95% purity at 90% detection efficiency for SNR > 6

Note that many of the requirements are specified in terms of a *distribution* (e.g., median and outlier fraction)

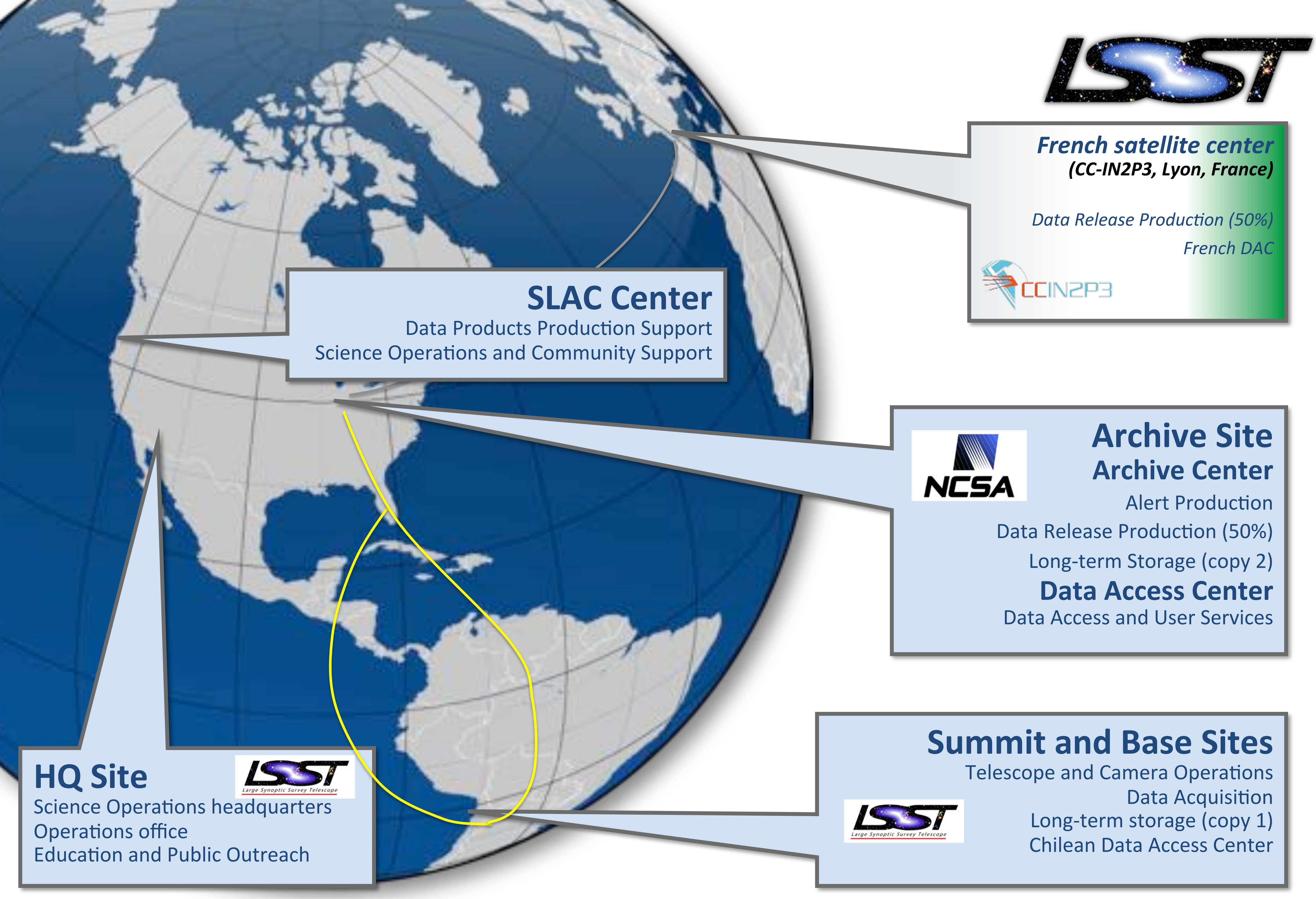
"mas" = milliarcsecond

Cerro Pachón – Future site of the LSST



LSST coordinates
(30° 14′ S, 70° 44′ W)
Elevation 2,700 m

La Serena is 400 km
north of Santiago, Chile


LSST
French satellite center
(CC-IN2P3, Lyon, France)
Data Release Production (50%)
French DAC
CCIN2P3
SLAC Center
Data Products Production Support
Science Operations and Community Support
Archive Site
NCSA
Archive Center
Alert Production
Data Release Production (50%)
Long-term Storage (copy 2)
Data Access Center
Data Access and User Services
Summit and Base Sites
Telescope and Camera Operations
Data Acquisition
Long-term storage (copy 1)
Chilean Data Access Center
LSST
Large Synoptic Survey Telescope
HQ Site
LSST
Large Synoptic Survey Telescope
Science Operations headquarters
Operations office
Education and Public Outreach

LSST Key Numbers

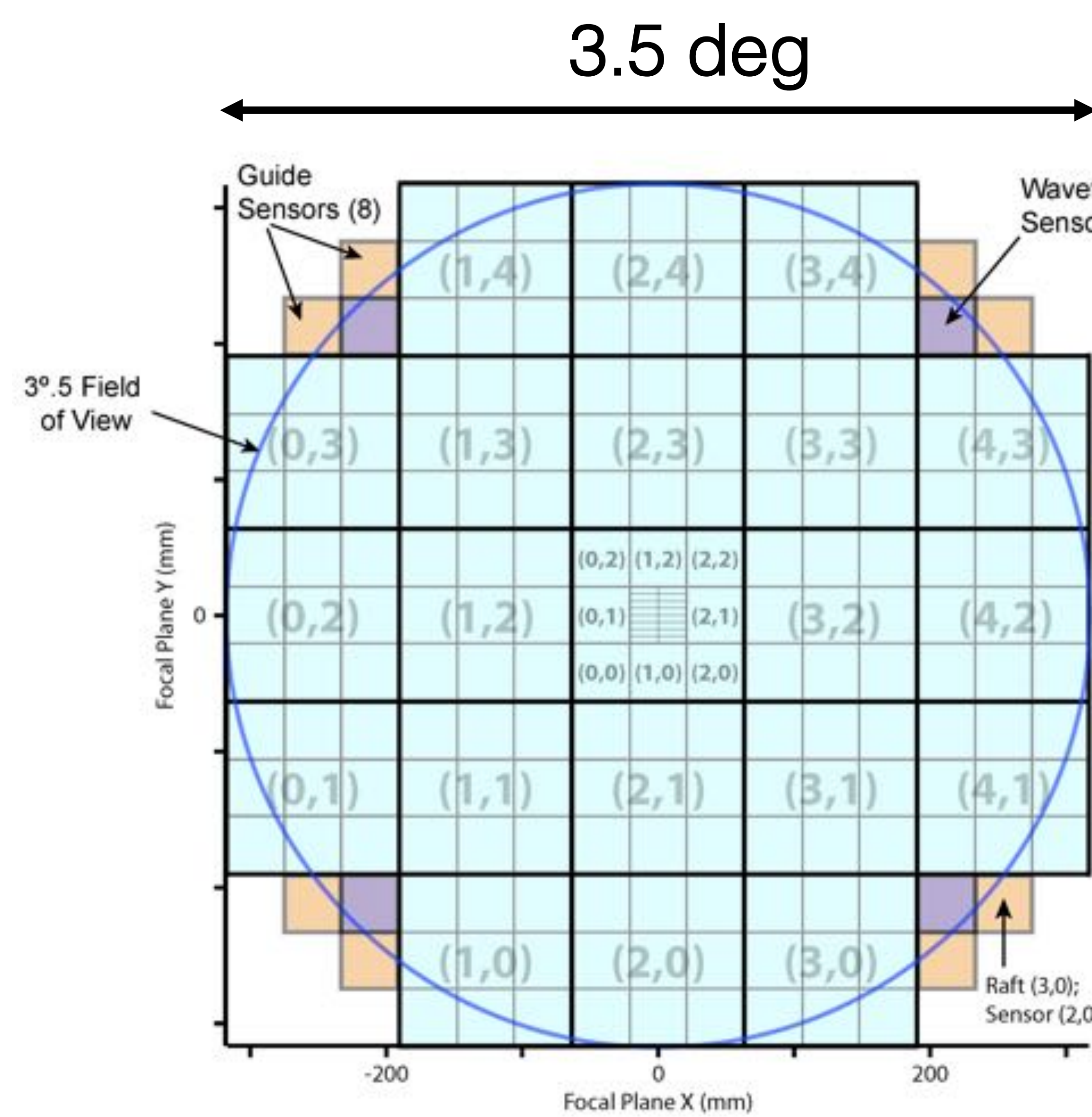
Survey: Telescope field of view = 9.6 deg^2 Main survey area = 18,000 deg^2 Filters = *ugrizy* (6) Visits per night = 1000 Survey Duration = 10 yr Total visits per pointing = 825

Imaging depth: Single visit (*r*, S/N=5) = 24.7 mag Stack depth (*r*, S/N=5) = 27.5 mag

Expected number of objects: Galaxies = 20 billion Stars = 17 billion Sources (single-epoch) = 7 trillion Forced sources = 30 trillion

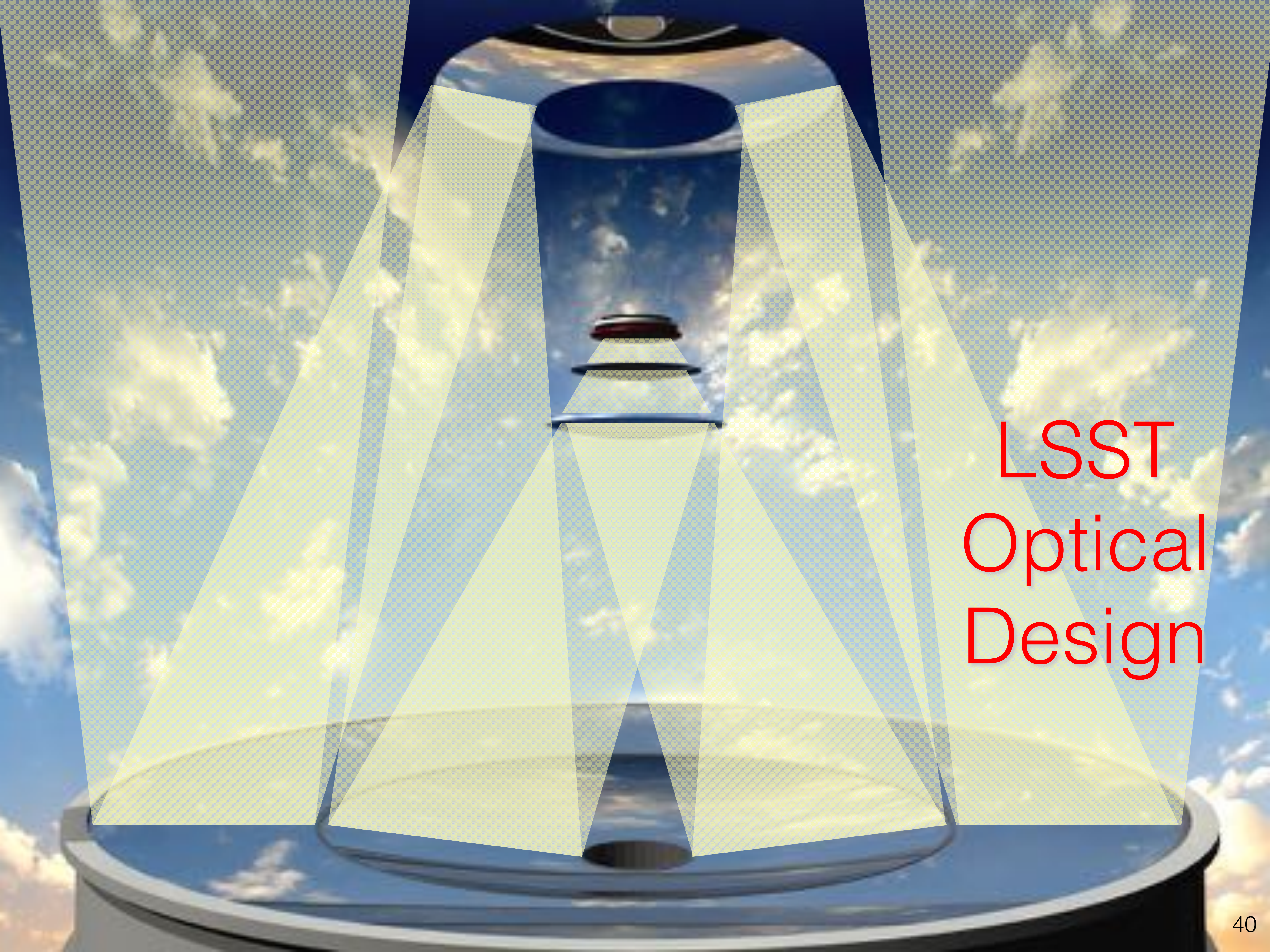
Alert production: Real-time alert latency = 60 sec Throughput = 10 million per night

Data (Data Release 11): Data collected per 24 hr = 15 TB Total image collection = 0.5 EB Database size = 15 PB



Full moon for scale

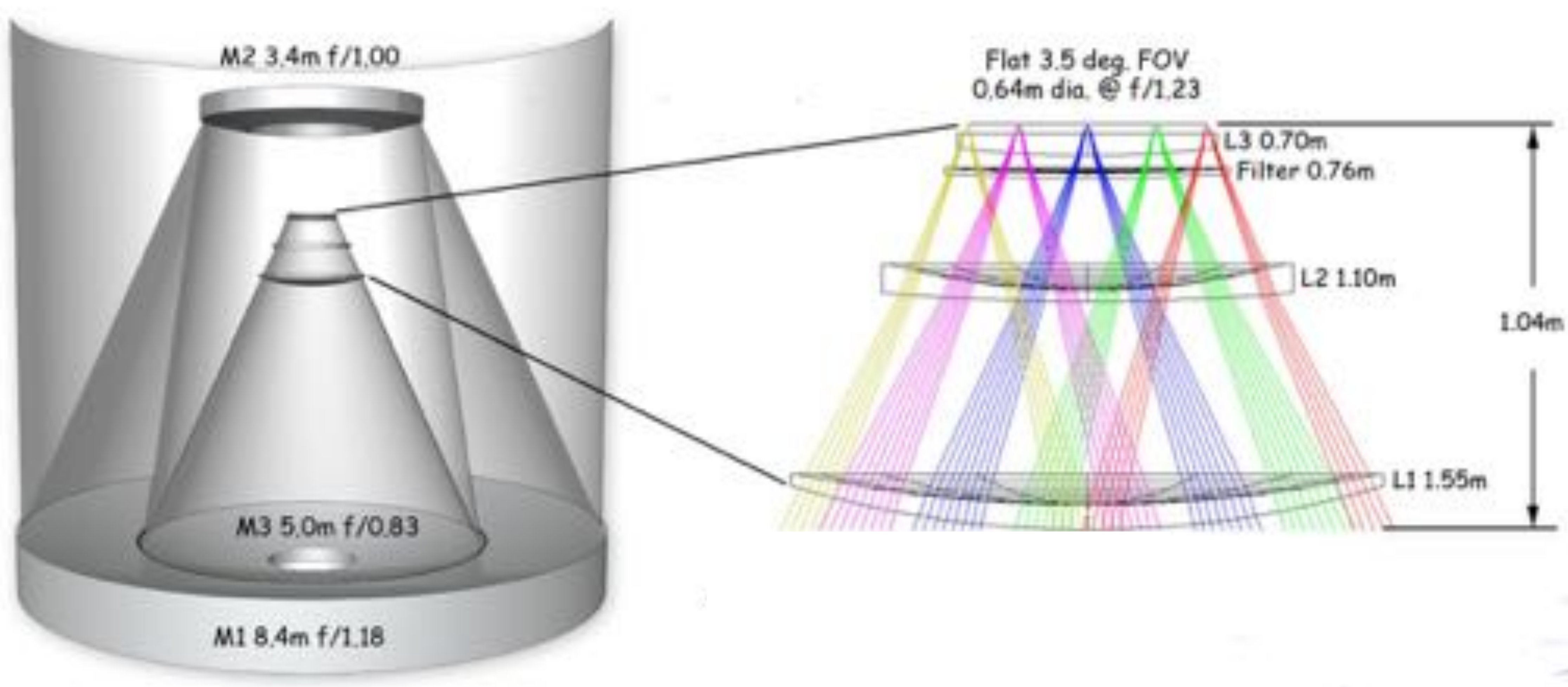
Hubble has field of view of ~0.003 deg^2 (i.e., LSST is >1000 times larger)



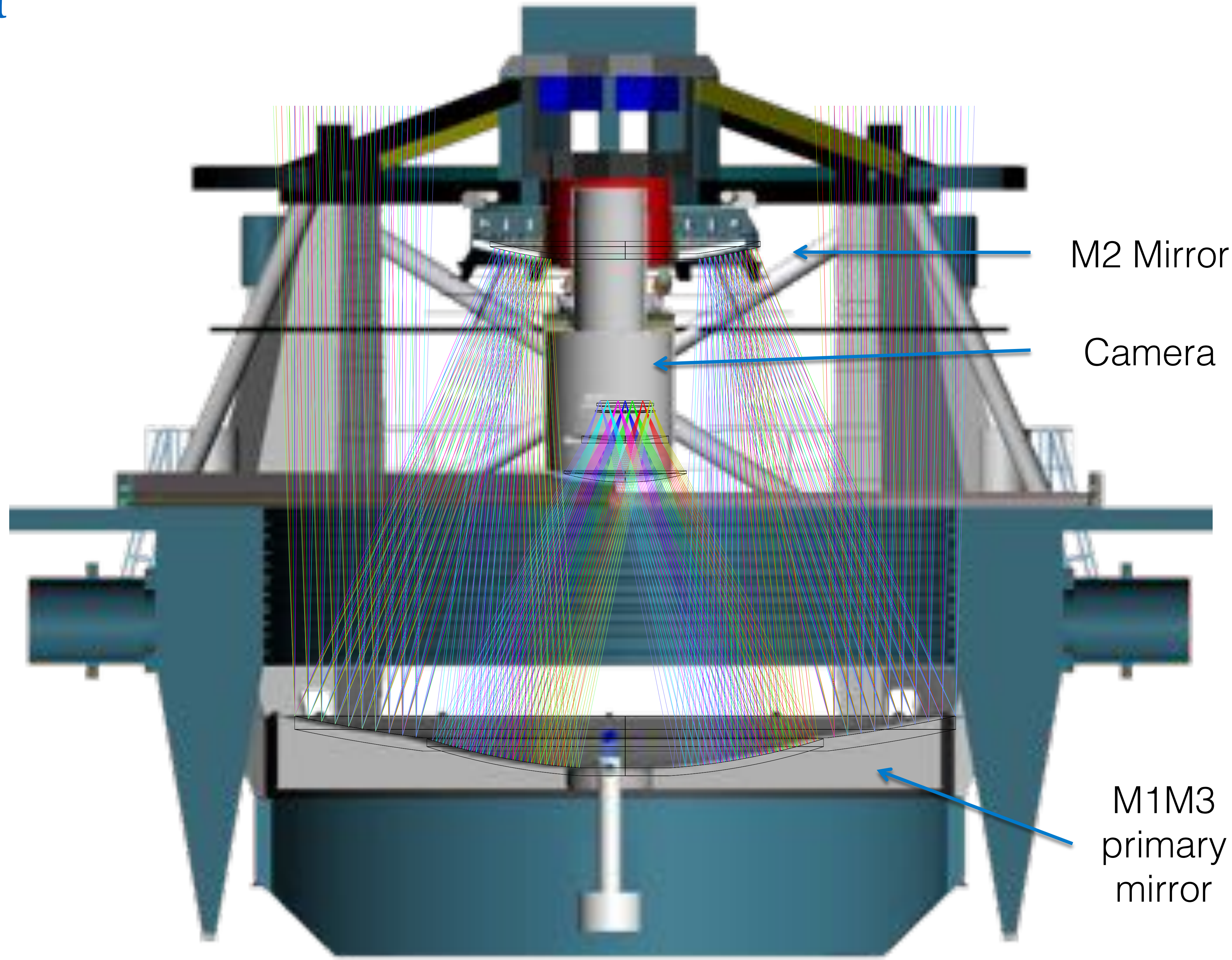
LSST Optical Design

LSST Optical Design

- *f / 1.23* Very short focal length gives wide field of view for given image size
- 3.5 ° FOV over a 64 cm focal plane, Etendue = 319 m^2deg^2
- < 0.20 arcsec FWHM images in six filter bands: 0.3 – 1 μm



Cross section through telescope and camera



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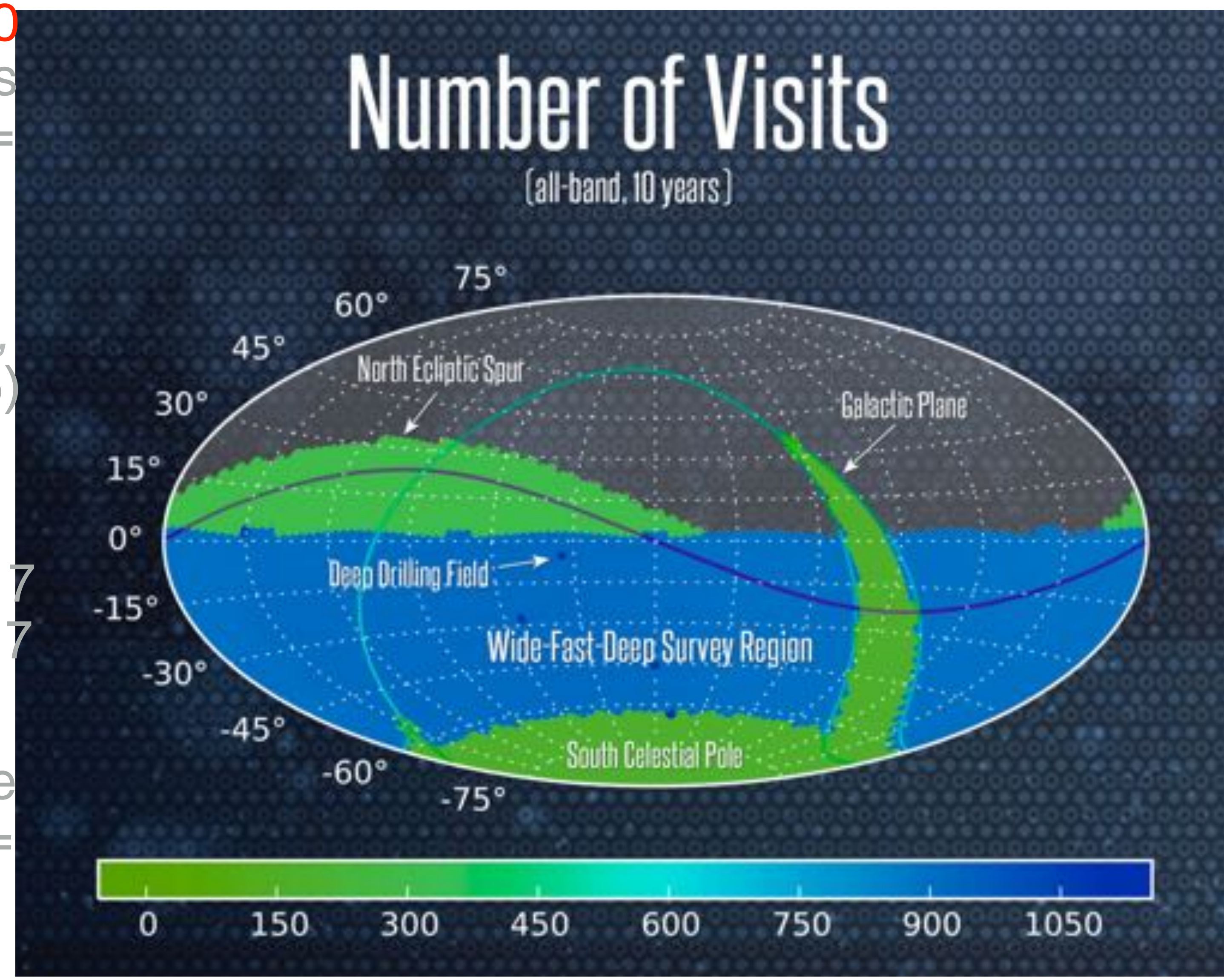

Coverage over the entire southern hemisphere

"Visit" = 16 second exposure
+ 2 second readout
+ 16 second exposure

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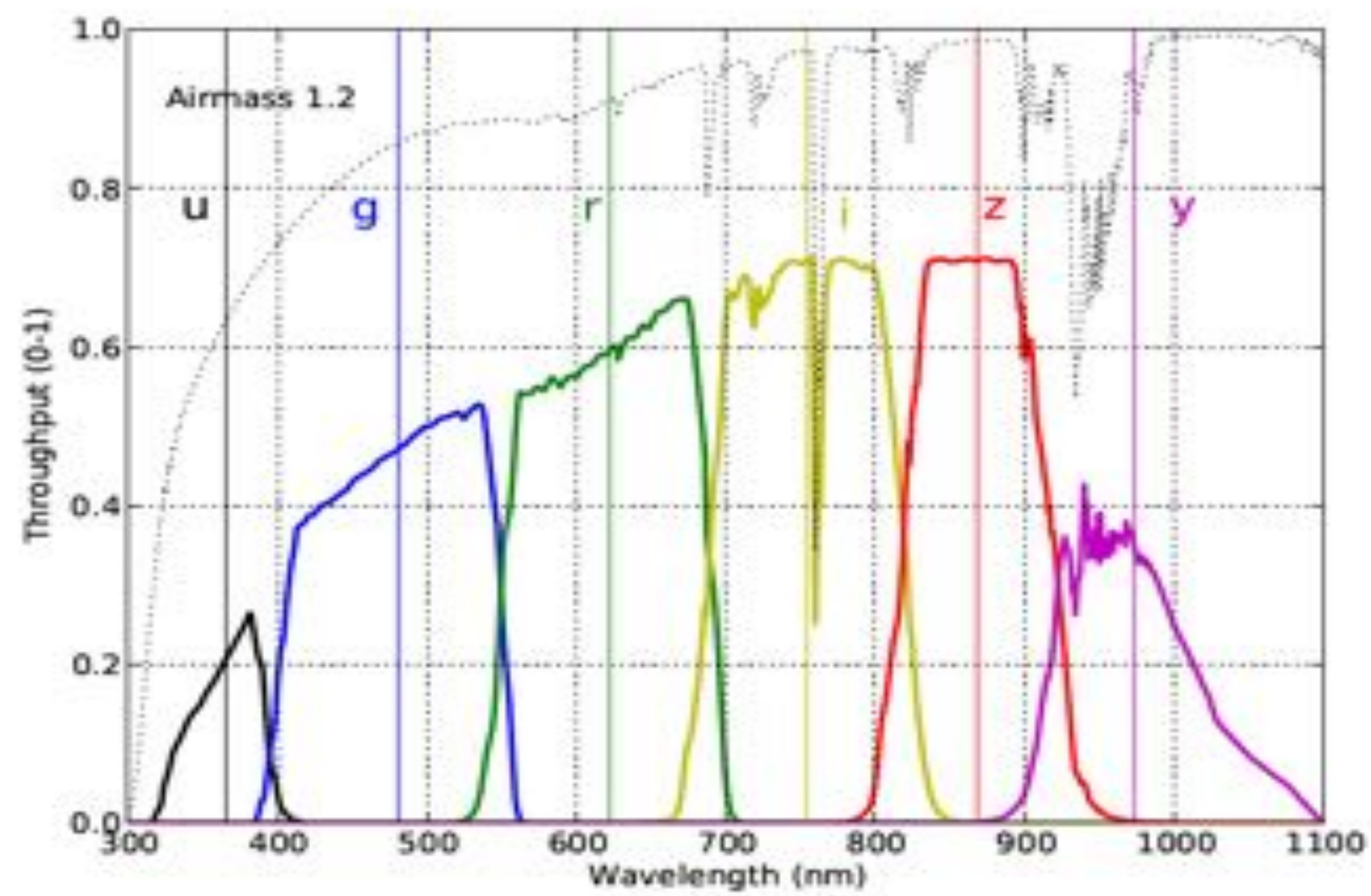

6 broad-band filters spanning 320-1050 nm
near-UV to near-IR

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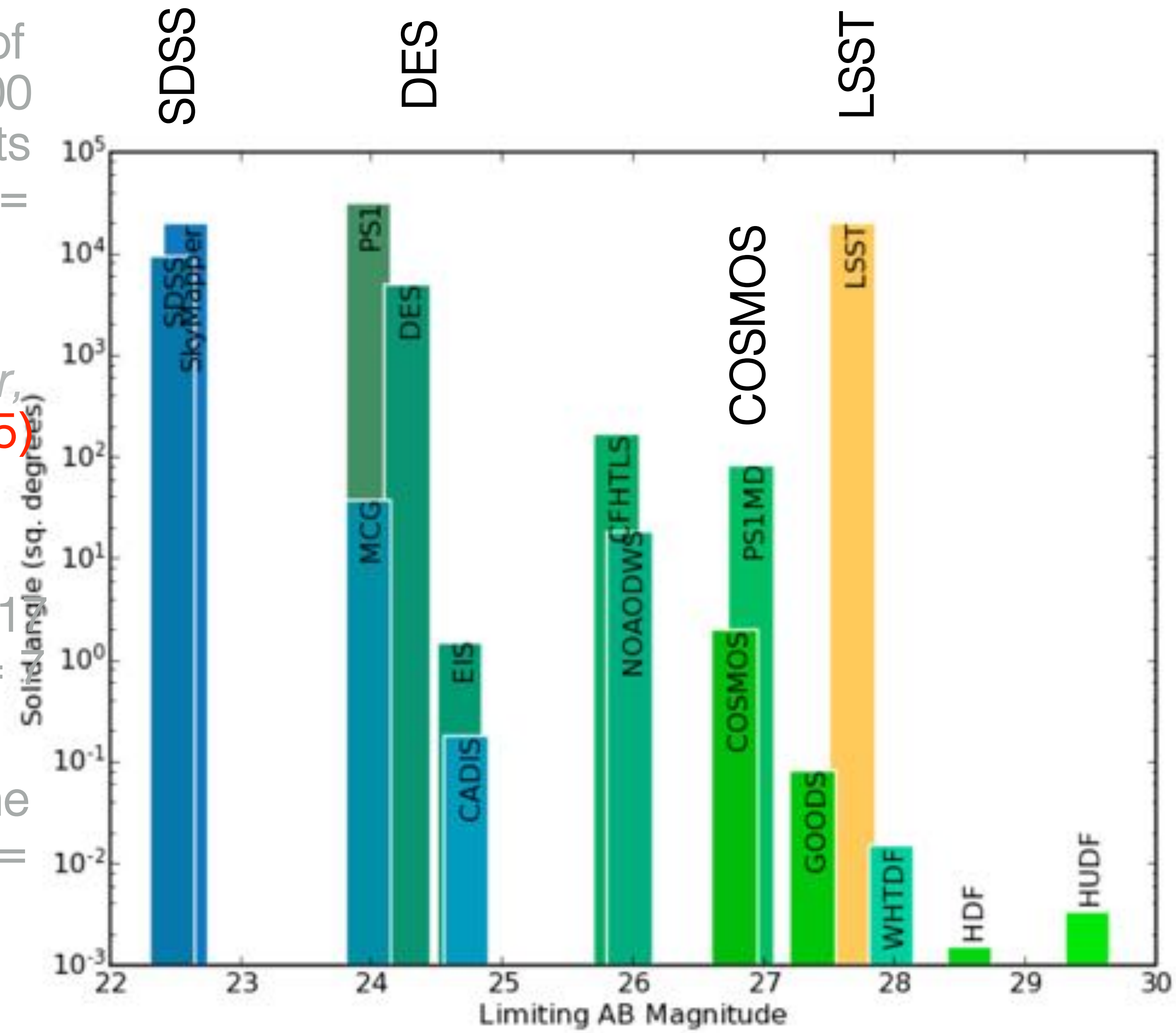


100x deeper than SDSS

>10x deeper than DES

Comparable depth to *Hubble* COSMOS, but over an area 10^4 larger (in 6 filters)

LSST Key Numbers

Survey: Telescope field of
view = 9.6 deg^2 Main survey area = 18,000
deg^2 Filters = *ugrizy* (6) Visits
per night = 1000 Survey Duration =
10 yr Total visits per pointing = 825

Imaging depth: Single visit (*r*,
S/N=5) = 24.7 mag Stack depth (*r*, S/N=5)
= 27.5 mag

Expected number of objects:
Galaxies = 20 billion Stars = 17
billion Sources (single-epoch) = 7
trillion Forced sources = 30 trillion

Alert production: Real-time
alert latency = 60 sec Throughput =
10 million per night

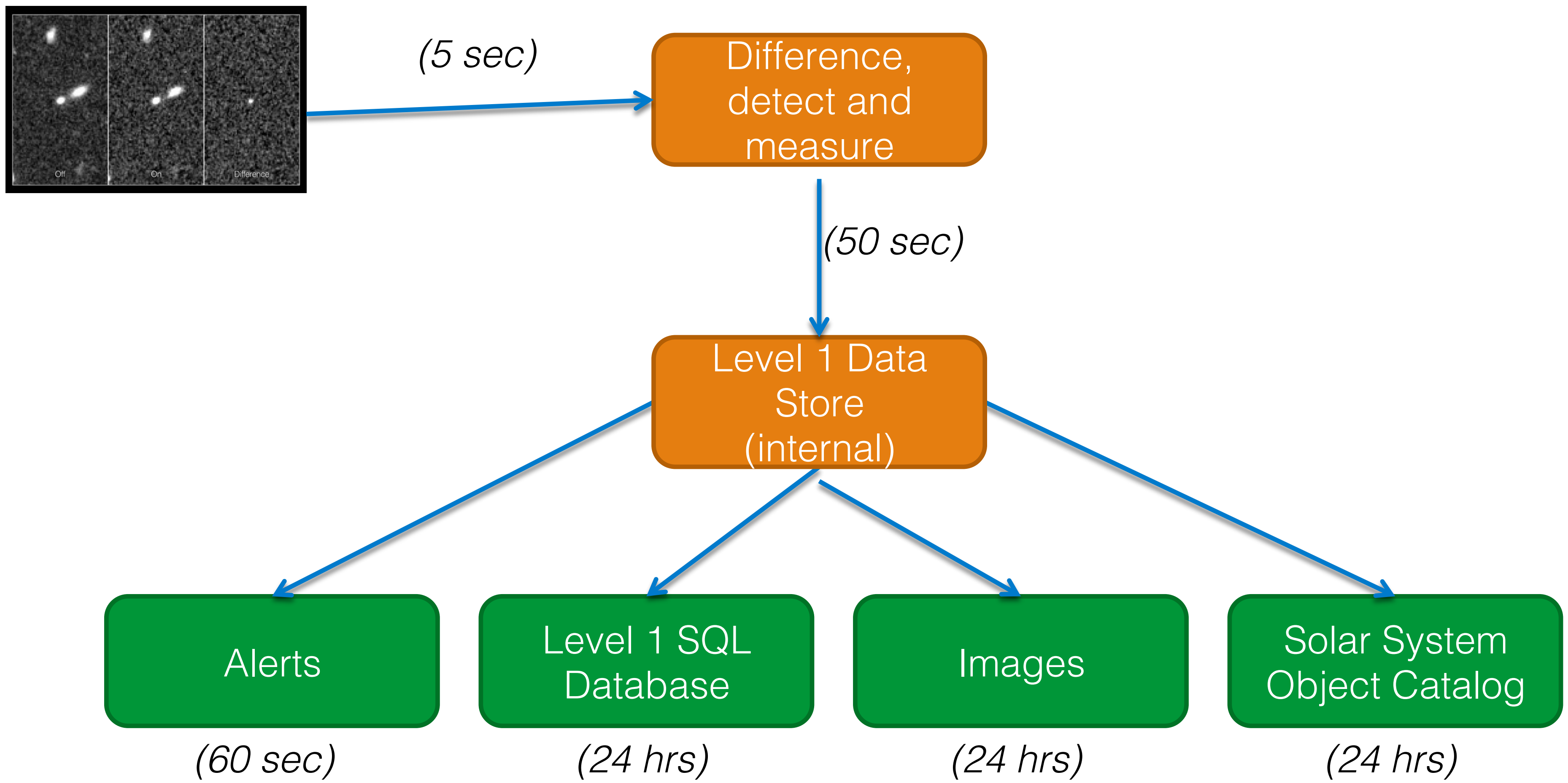
Data (Data Release 11): Data
collected per 24 hr = 15 TB Total image
collection = 0.5 EB Database size = 15 PB

LSST will catalog more stars and galaxies than all previous astronomical surveys combined

…but perhaps even more important is the anticipated *quality* and *richness* of the data, as well as *homogeneous* processing

Nightly Data Products

For every observation (“visit”):



LSST Data Products

- A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
- A catalog of orbits for ~6 million bodies in the Solar System.

Nightly

- A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion observations ("sources"), and ~30 trillion measurements ("forced sources"), produced annually, accessible through online databases.
- Deep co-added images.

Annual

*For more details, see the **"Data Products Definition Document"**, http://ls.st/lse-163*

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Annual

Data products will be available as nightly and annual releases to the LSST community: all US and Chilean scientists, named international contributors.

For more details, see the ***"Data Products Definition Document"***, *http://ls.st/lse-163*

LSST Data Products

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- Deep co-added images.

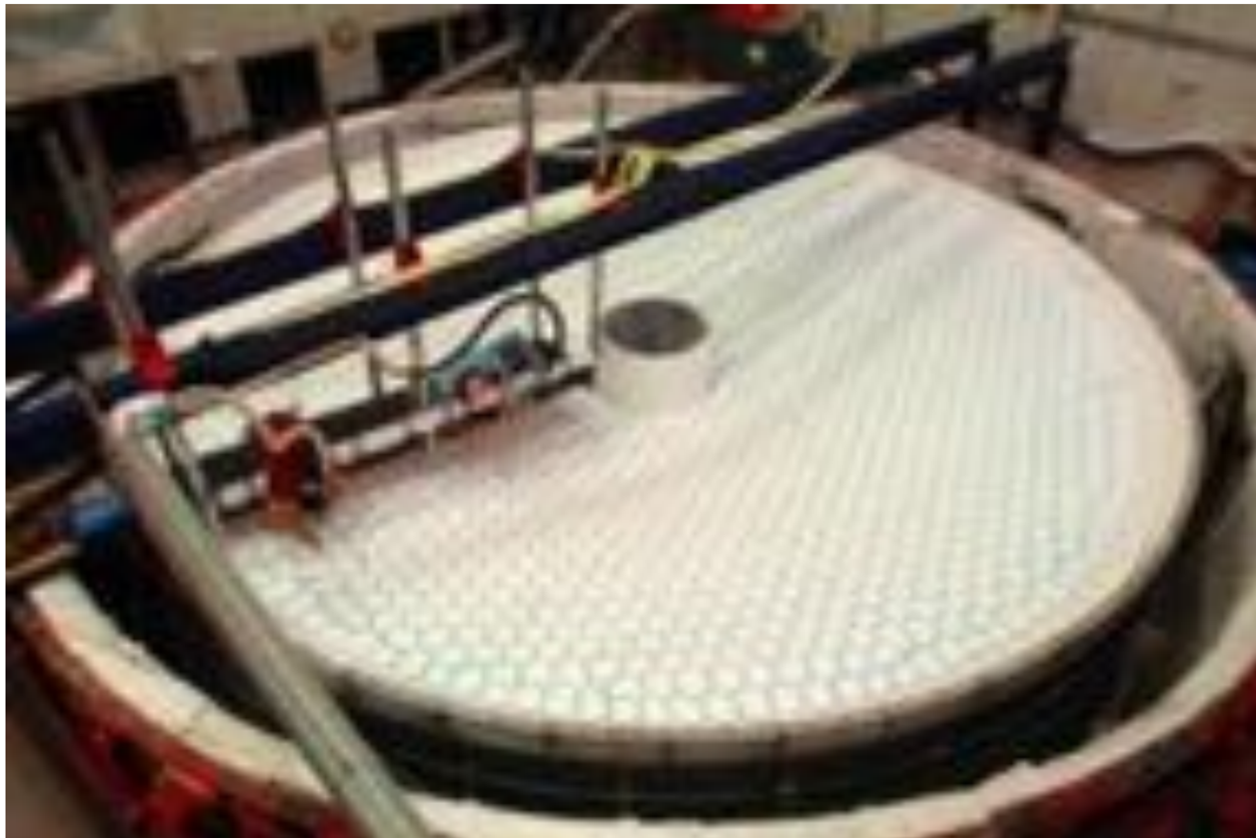
Annual

The production of data products will be transparent: All software is developed open-source and will be available to the community.

For more details, see the ***"Data Products Definition Document"****,* [*http://ls.st/lse-163*](http://ls.st/lse-163)

Project Status

The primary/tertiary mirror is a long lead time item…



Stewart Observatory Mirror Lab Tucson, AZ

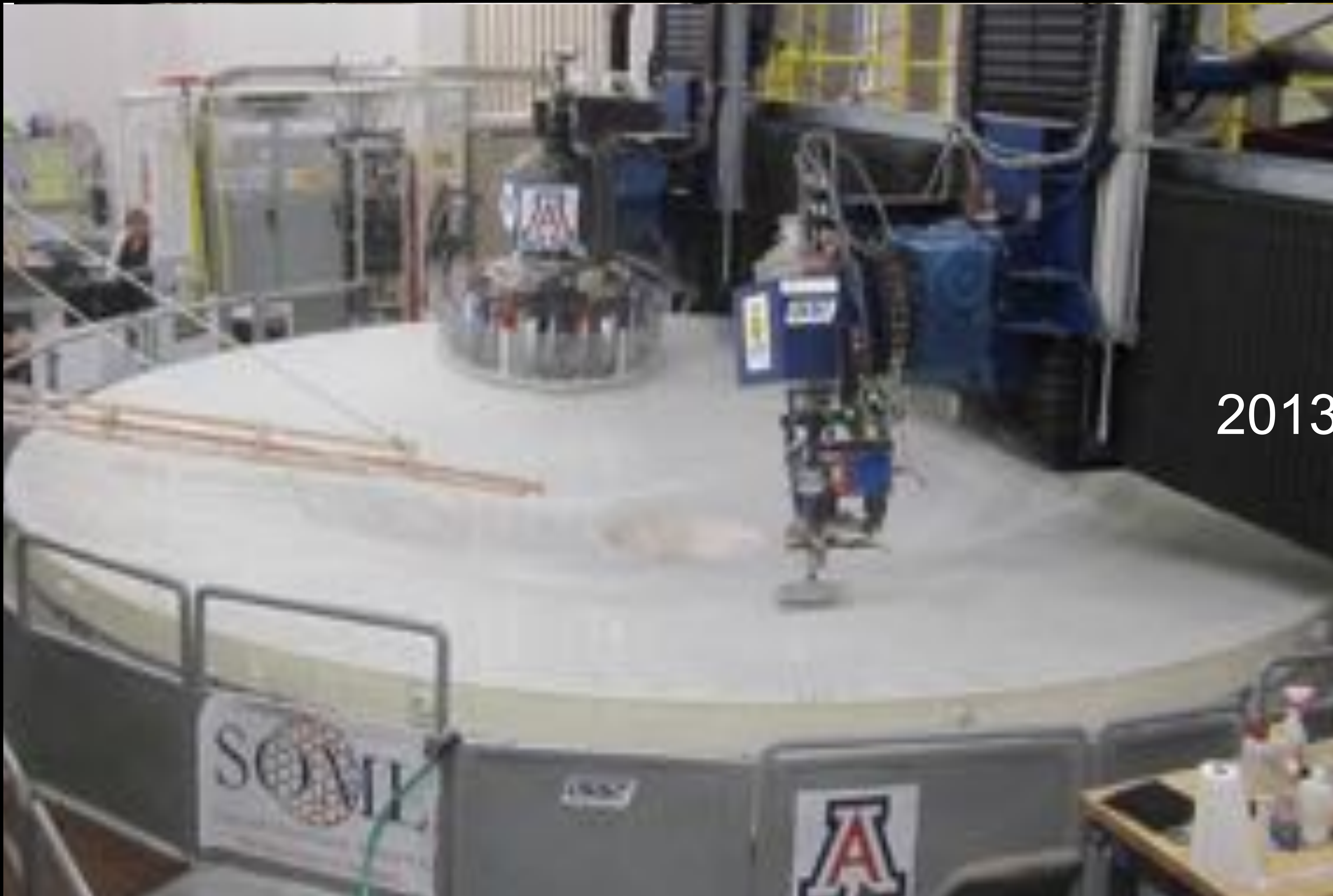
High Fire, March 29 2008

2 September 2008

1165ºC (2125ºF). Then anneal & cool gradually to room temp.

Mirror has been ground, and polished

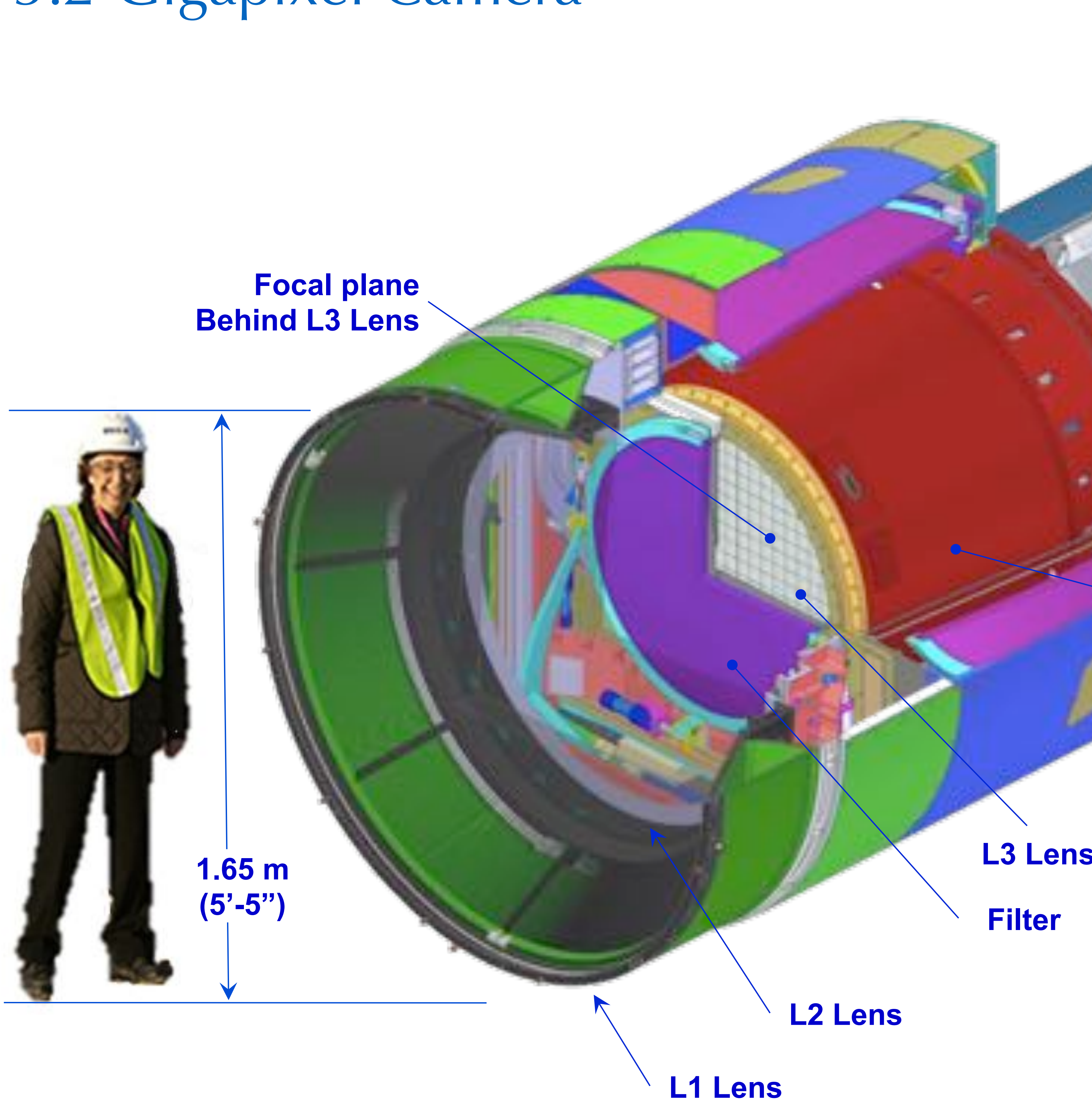
Completion :2015



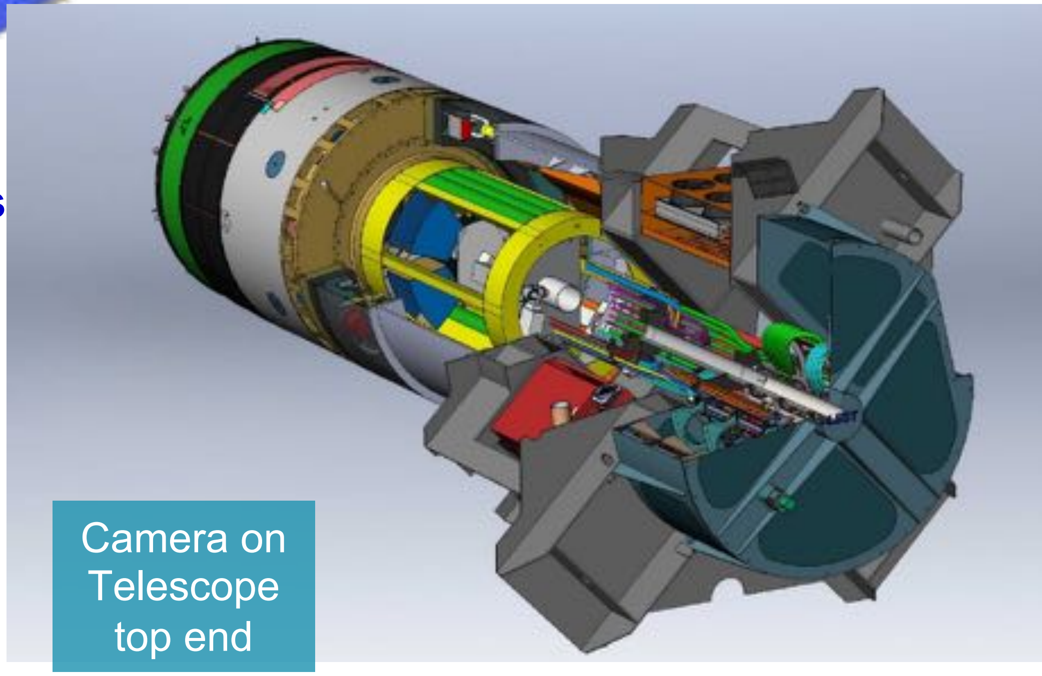
2013


LSST
CAUTION
Mirror
Completion
2015

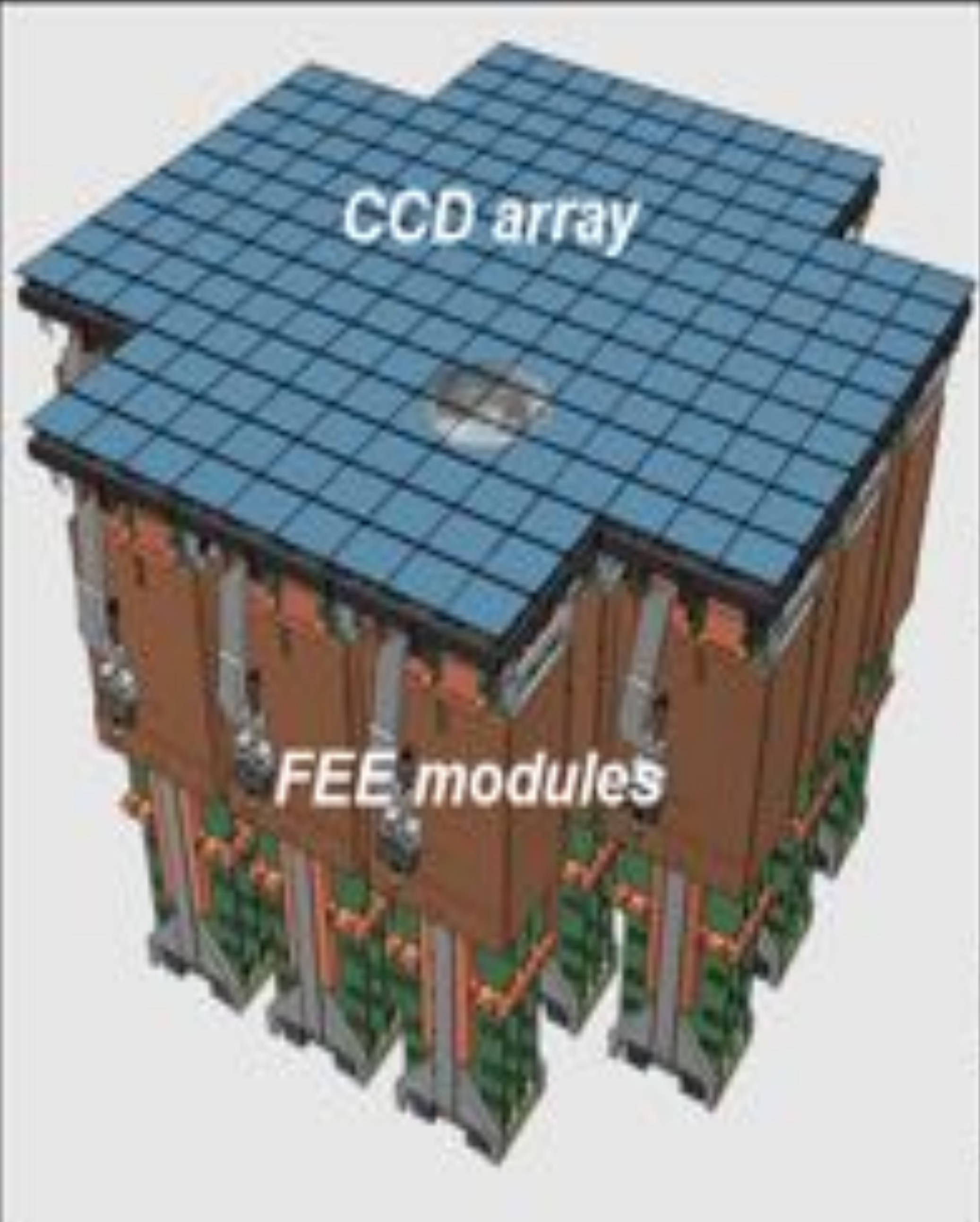
3.2 Gigapixel Camera



Camera ¾ Section



LSST Camera:
21 science rafts, 189 4K x 4K CCDs



CCD Technology	Fully-depleted 100μm thick silicon, ≥ 10kΩ/cm resistivity 10μm pixel pitch 4Kx4K full-frame format 16 outputs/CCD
Science focal plane	189 CCDs, 3.024 Gpixels
Trace pitch:	
Silicon	5mm
Ceramic package	0.4mm (6 layers)
Flex cable	0.64mm (2 layers)
PCB area/channel	8.8cm^2 (full signal chain)
Pixel rate	550Kpix/s
Power budget	350mW/channel total

LSST sensors meet project requirements.

two vendors e2v and ITL

Sensor delivery rate is the critical path pacing item for the LSST camera.

Building Camera Rafts at BNL

Part of the BNL team with Dan Weatherill (LSST:UK post doc)

The first rafts have been delivered to SLAC

Site and observatory: excellent progress

2015

Formal "laying of the 1st stone" for the observatory April 14, 2015

2011

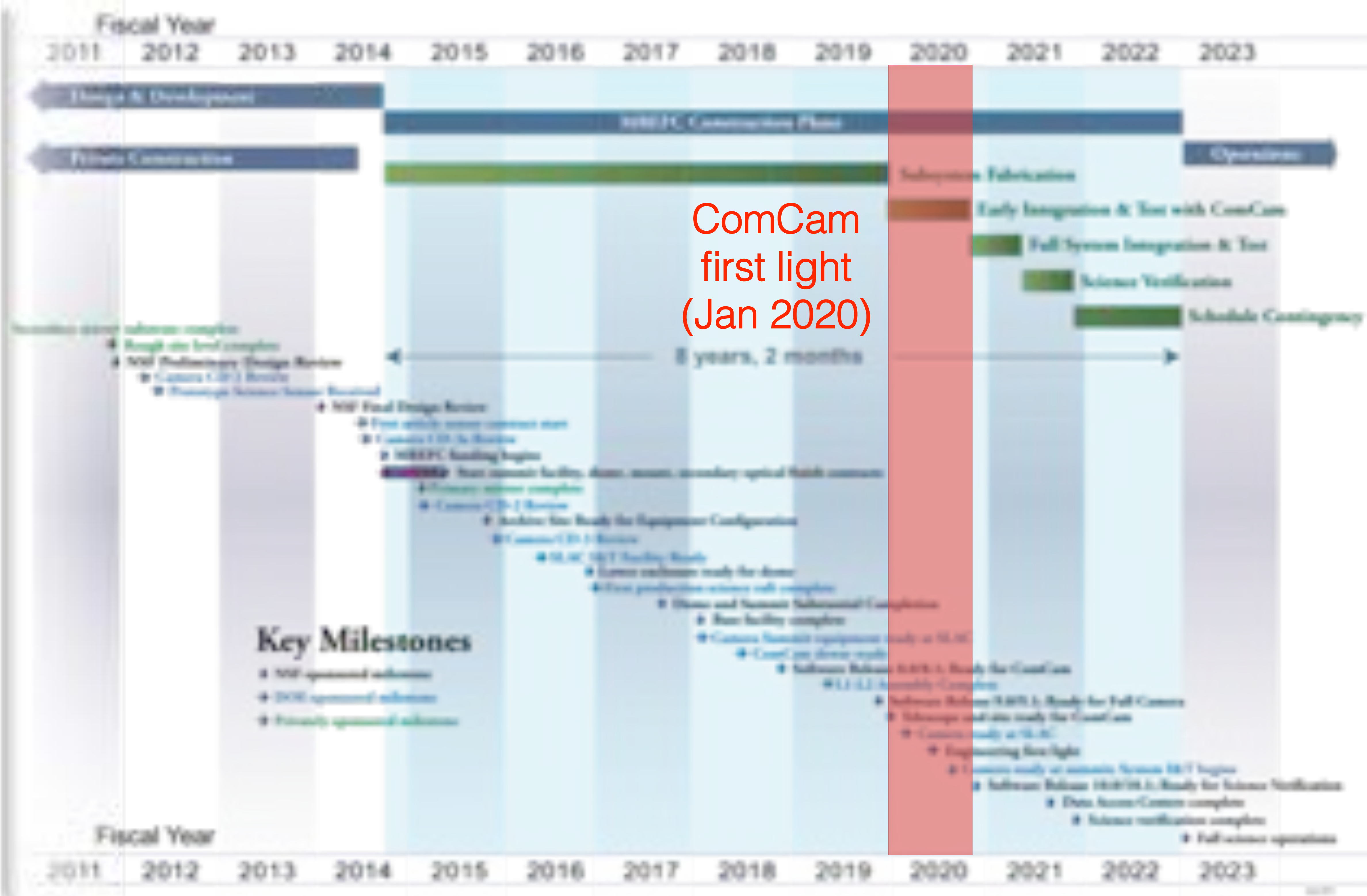
Observatory construction webcam:
https://www.lsst.org/news/see-whats-happening-cerro-pachon

<2 Years Until Summit Facility is Complete

~3 Years Until Commissioning

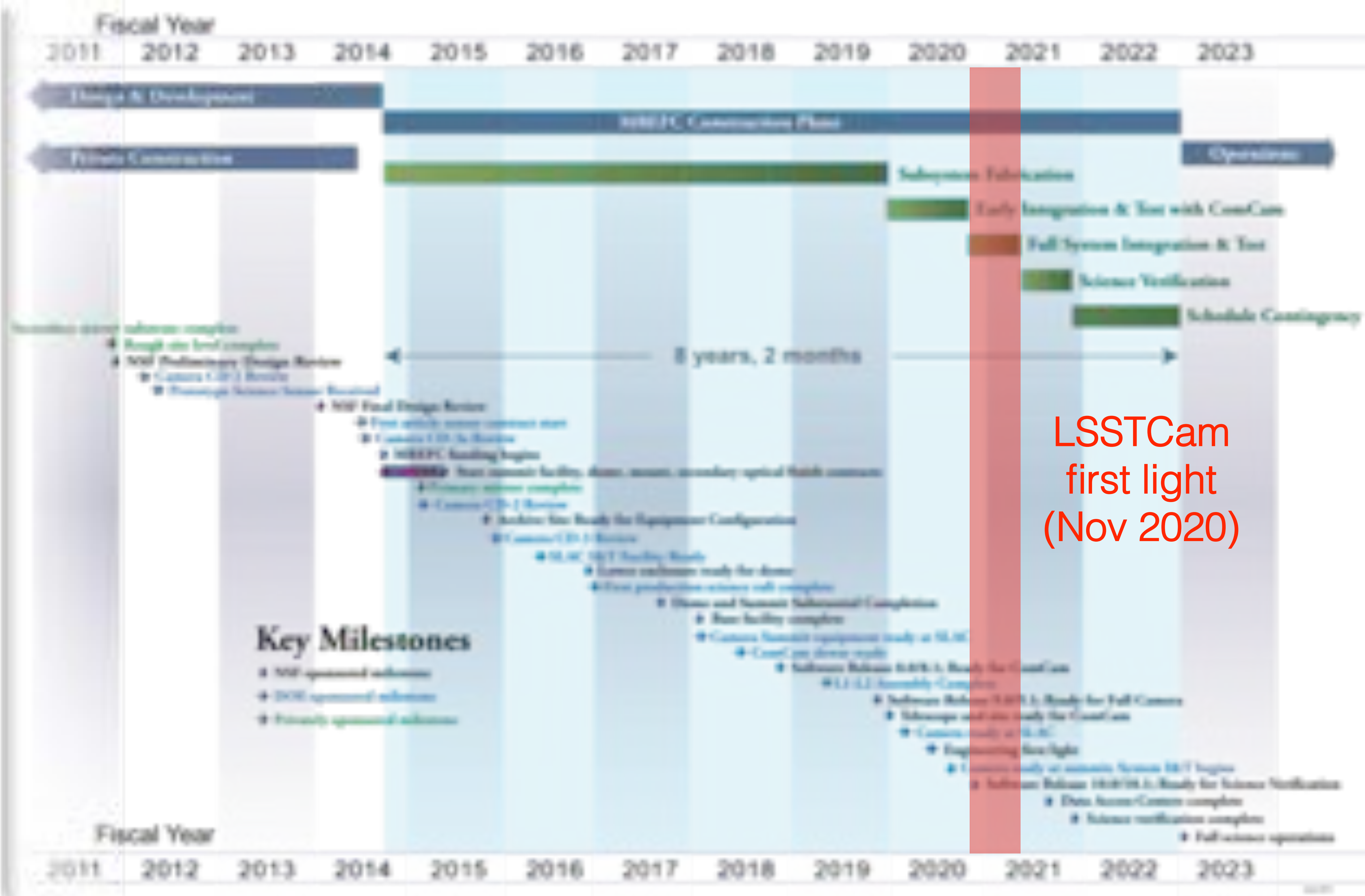
Late 2018 – First calibration data from Auxiliary telescope
Early 2020 – First observations with a commissioning camera
Early 2021 – Scheduler-driven observing with full Camera, SV
October 1 2022 – Full Operations begins

Project Construction Schedule



The project is on track to achieve first light in 2020, and to formally begin the decade of operations on October 1, 2022.

Project Construction Schedule



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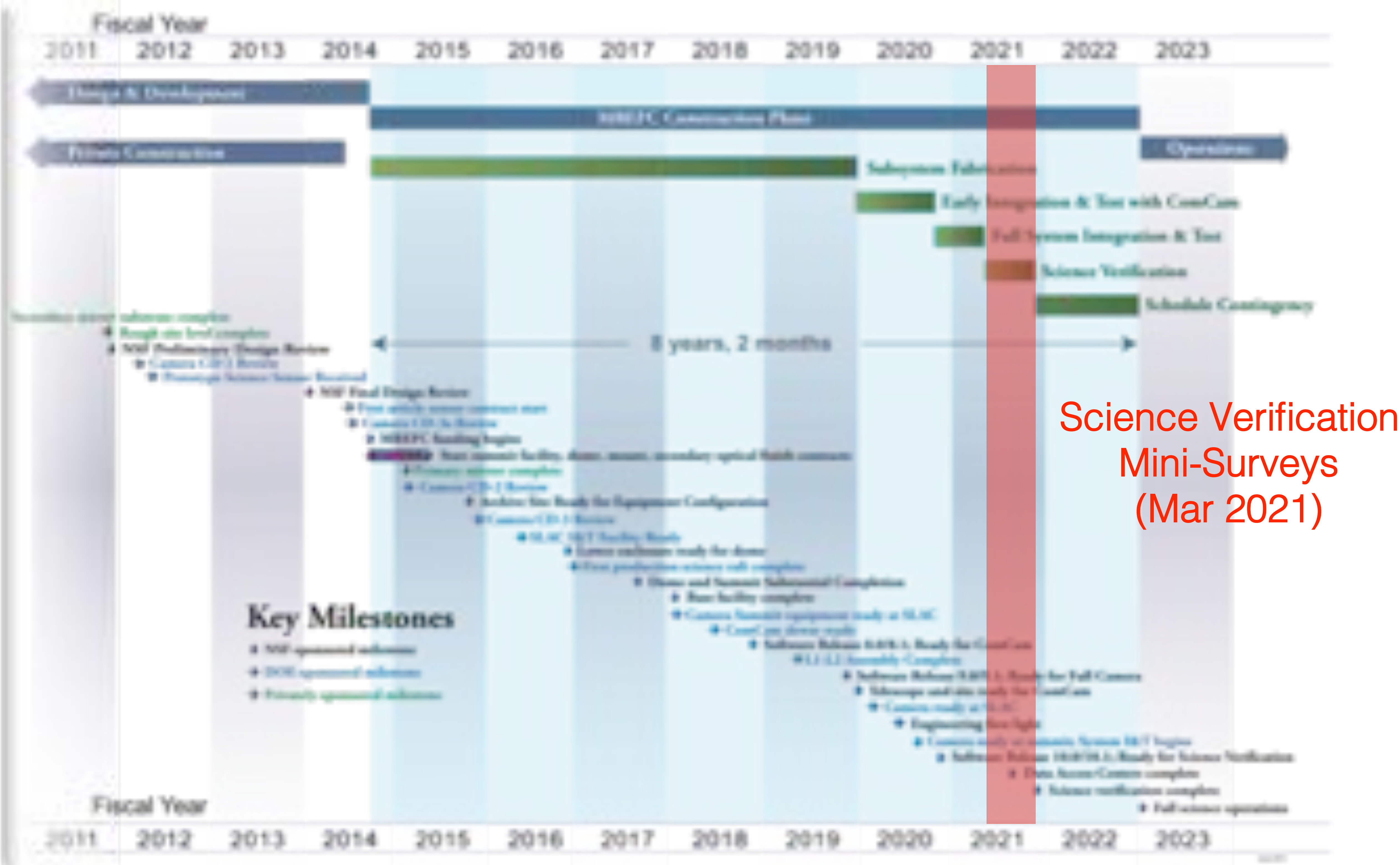
Project Construction Schedule



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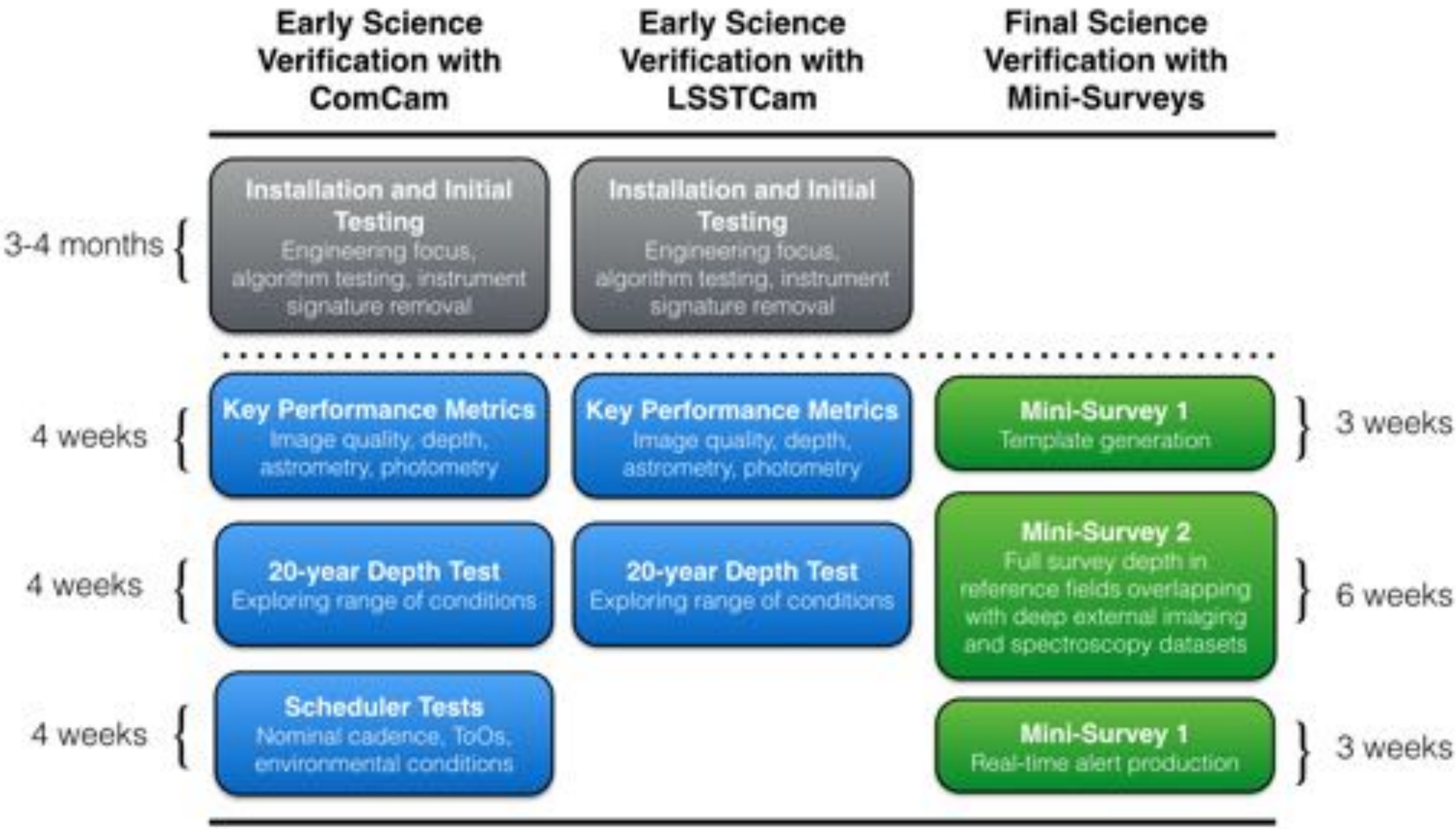
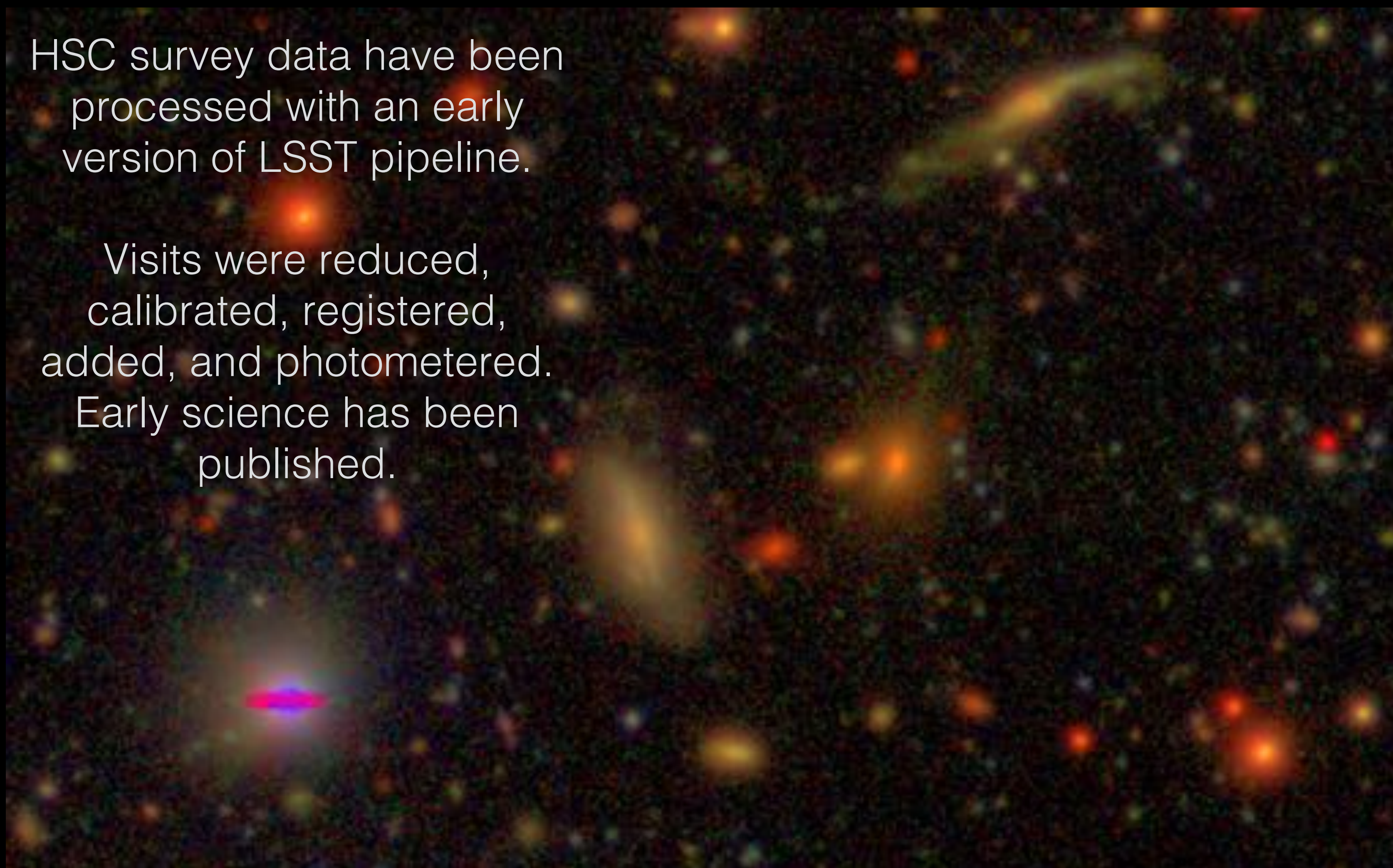
Three Periods of Sustained On-Sky Observations During Commissioning

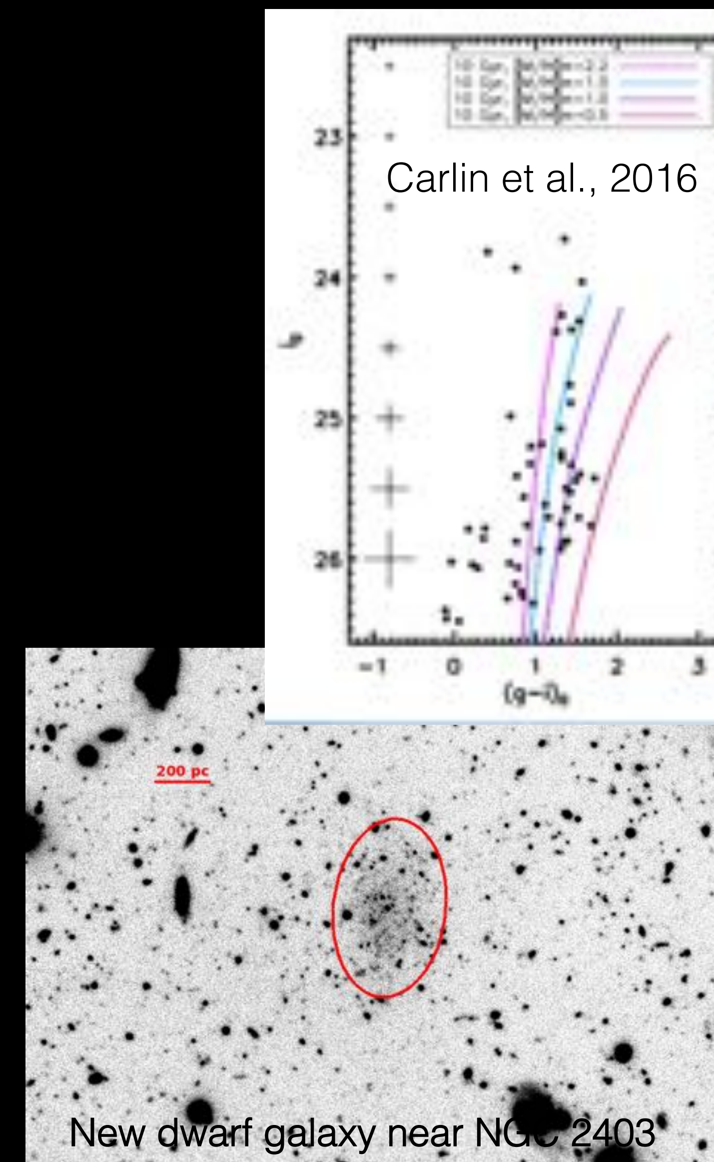


Prototype LSST Pipeline Running on Subaru/HSC Data

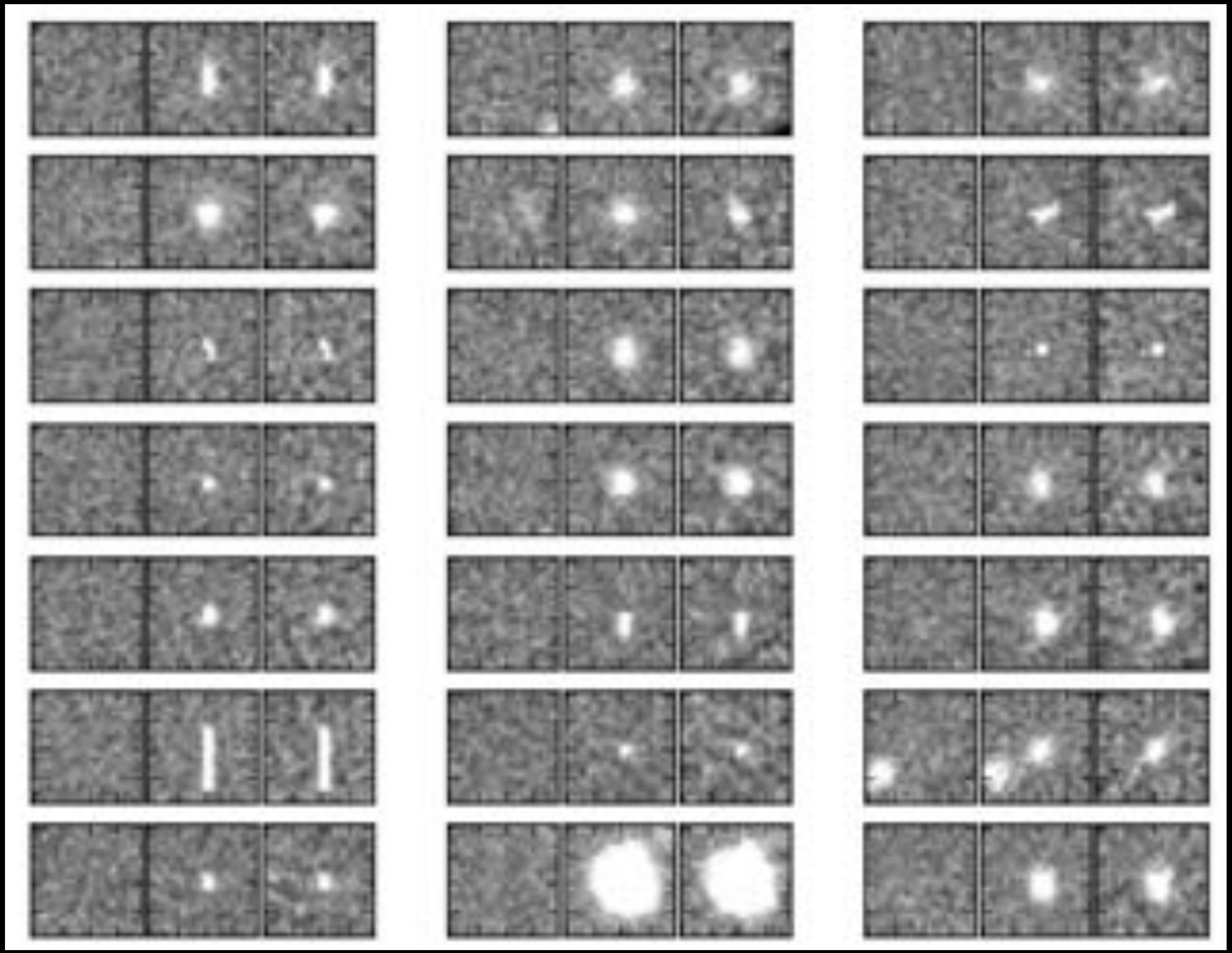


HSC survey data have been processed with an early version of LSST pipeline.

Visits were reduced, calibrated, registered, added, and photometered. Early science has been published.



Prototype LSST Pipeline Running on Time-Domain DECam Data



Exposure 1
Exposure 2
Difference

Credit: Colin Slater and LSST DM @ U. of Washington
Data courtesy of L. Allen, NOAO

LSST Outreach Data will be used in classrooms, science museums, and online

Classroom Emphasis on:

- Data-enabled research experiences
- Citizen Science
- College classes
- Collaboration through Social Networking

ZOONIVERSE
REAL SCIENCE ONLINE

LSST Education & Public Outreach

- LSST is Telescope for Everyone

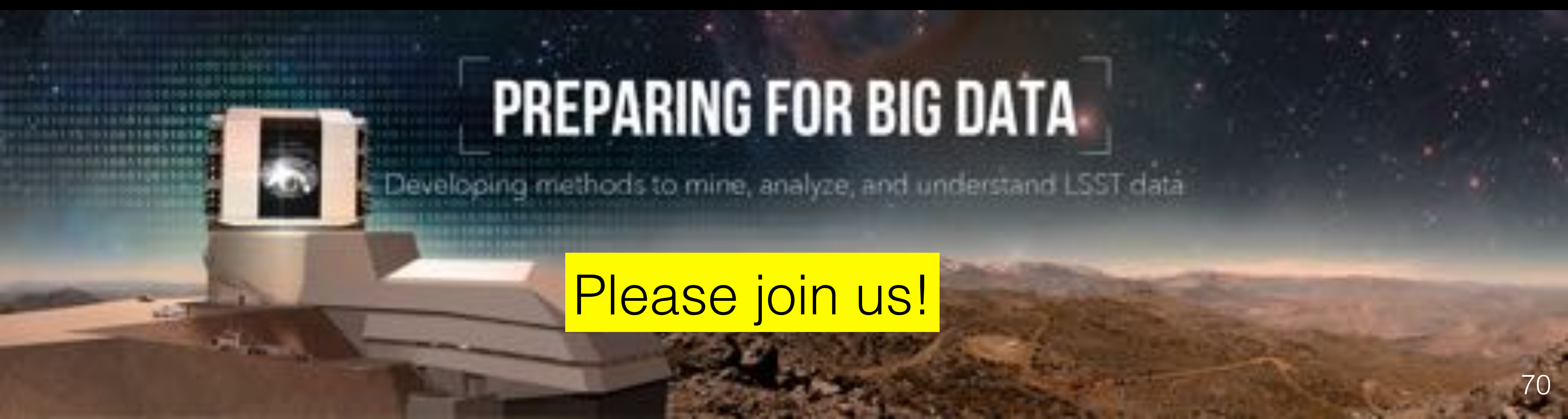
LSST will discover 10 billion new galaxies–
enough for everyone

A school child in South Africa, Chile,
US or UK can discover an island universe

Conclusion

- In the 2020s, LSST will have a central role among a growing number of wide-field, time-domain, and multi-wavelength / multi-messenger astronomical surveys
- Construction is on-schedule, first on-sky data expected in 2020
- Given the anticipated size and complexity of the dataset, now is the time to think about new science questions and methodologies

What would you do with a 10-year colour movie of 40 billion stars and galaxies?



Please join us!

Acknowledgment

Andy Connolly, Daniel Calabrese, Zelijko Ivezic, Suzanne Jacoby, Mario Juric, Iain Goodenow, Steve Kahn, Jeff Kantor, Victor Krabbendam, David Kirby, Rob McKercher, Paul O'Connor Chris Stubbs, Jon Thaler, Tony Tyson, Sidney Woolf, Beth Willman

The LSST Collaboration

At Purdue: Kirk Arndt, Mike Focosi, Bo Xin, Enver Alagoz, John Peterson + many undergraduates

In the UK: Kirk Arndt, Sarah Bridle, Bob Mann, Dan Weatherill

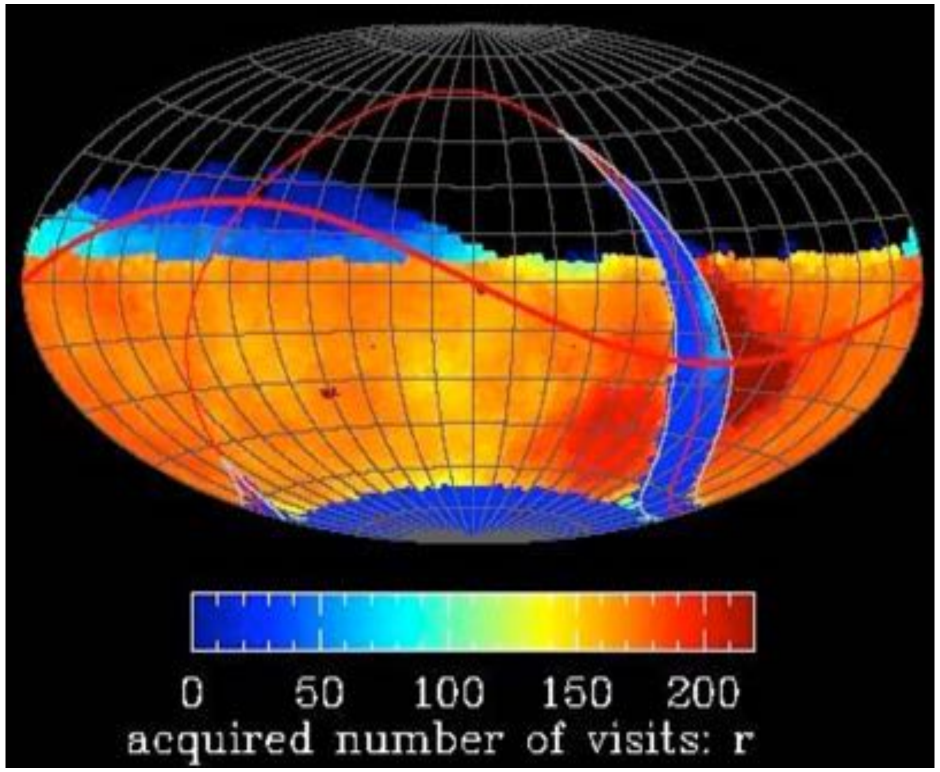
Community Engagement – Observing Strategy

LSST's Observing Strategy has not been finalized

A basic implementation of LSST's 10-year survey can deliver on a wide range of science. The implementation of this strategy can be optimized for science output. We will continue optimizing the Observing Strategy through operations.

Community input on metrics to measure science output of different strategies will be valuable.

We are still developing the process and timeline for decisions about the observing strategy, in collaboration with our Project Science Team and Science Advisory Committee. See community study underway at http://ls.st/o5k



Example LSST Observing Strategy.

Information Resources For the Community

Resource	Description
www.lsst.org	Diverse materials available include: images, key numbers, key project documents, links to simulated data – including simulated observing strategies.
Weekly Digest	A weekly email update with LSST Project and LSST Corporation information sent from the Project out to staff and interested stakeholders in the scientific community. Anyone can sign up at www.lsst.org.
Zenodo.org	An open-access information repository that contains an informal (and incomplete) collection of LSST Data Management technical notes, LSST talks, and other documents.
Community.lsst.org	A Stack Overflow-like forum with public discussions about a wide-range of LSST-related issues. Both Project and community members participate in discussions and ask questions. This tool is available to everyone. Heavy usage from Data Mgmt and EPO.
lsstc.slack.com	Limited to Instant Messaging application for quick conversations. This tool is limited to project and science collaboration members, plus International PIs and a login is required. Both private and public discussion rooms. Numerous Project and Science users.