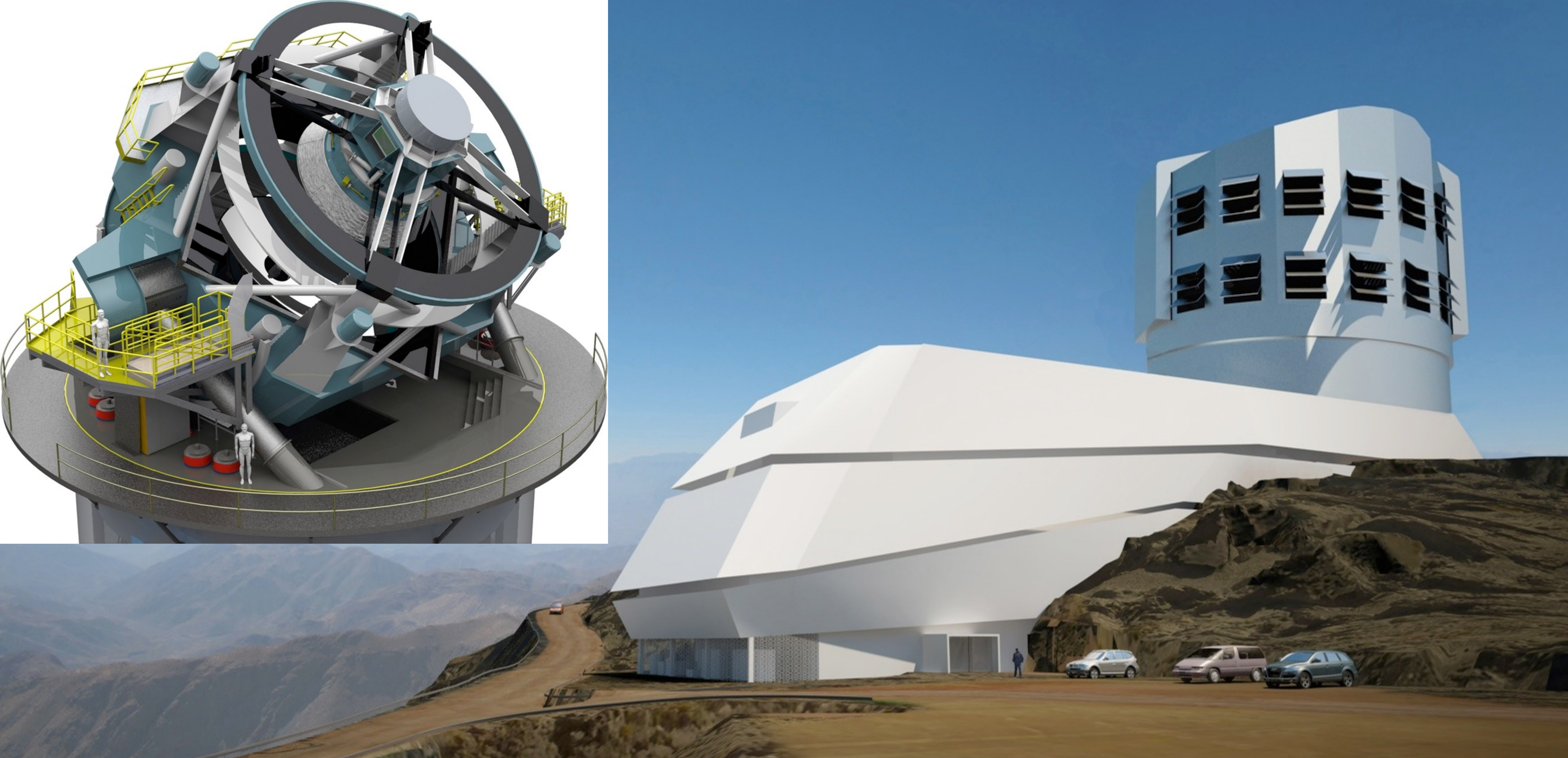


Astronomical surveys and **LSST**

Astr 323, Lecture 9

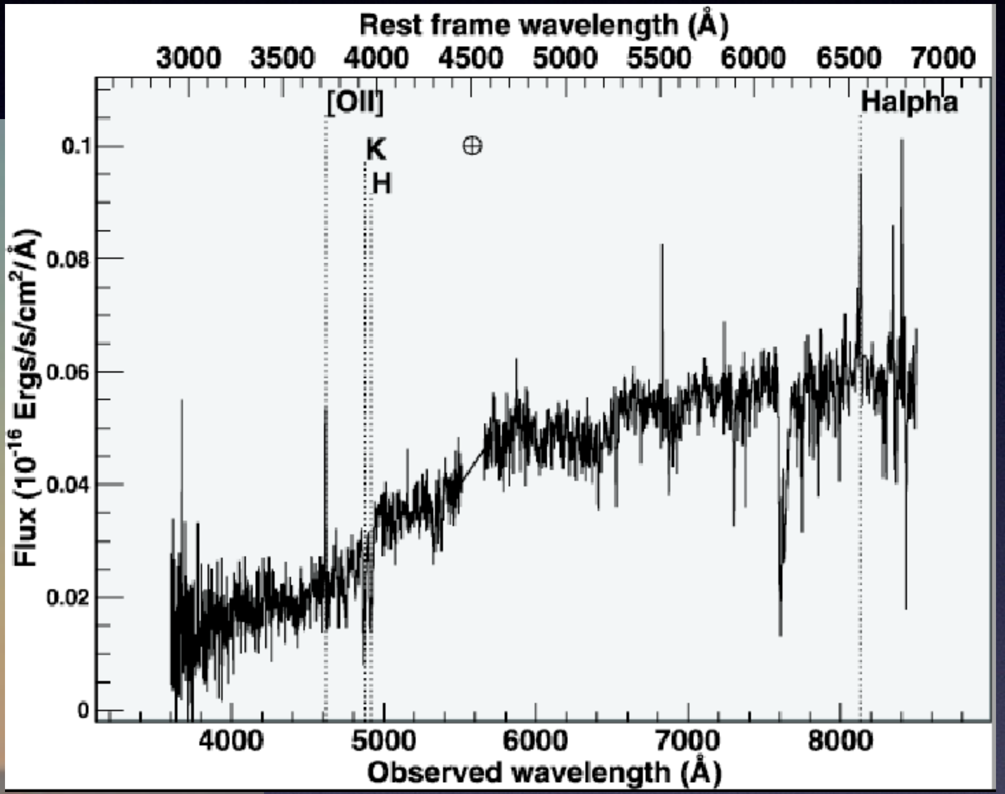
Spring 2014, University of Washington

Outline

- Astronomical surveys
- LSST system summary
  - o Science Themes
  - o System Characteristics
- LSST science examples
  - o Extragalactic astronomy and cosmology
  - o The Milky Way and the Local Group
  - o Time Domain
- The road ahead

Context: modern observational methods in astronomy and astrophysics:

- Large telescopes (~10m): faint objects, especially spectroscopy



The Keck telescopes on Mauna Kea (Hawaii)

Context: modern observational methods in astronomy and astrophysics:

- Telescopes above the atmosphere: high angular resolution (e.g., the Hubble Space Telescope) and other wavelength regions (X-ray, radio, infrared)

The HST in orbit and an example of a galaxy image

Context: modern observational methods in astronomy and astrophysics:

- Large telescopes (~10m): faint objects, especially spectroscopy
- Telescopes above the atmosphere: high angular resolution (e.g., the Hubble Space Telescope) and other wavelength regions (X-ray, radio, infrared)
- Large sky surveys: digital sensor technology, information technology, automated data processing and data distribution

Key point: modern sky surveys make all their data (images and catalogs) publicly available

Why are sky maps useful?

- **Sky map:**
  - a list of all detected objects (stars, galaxies, ...)
  - measured parameters (size, color, brightness,...)

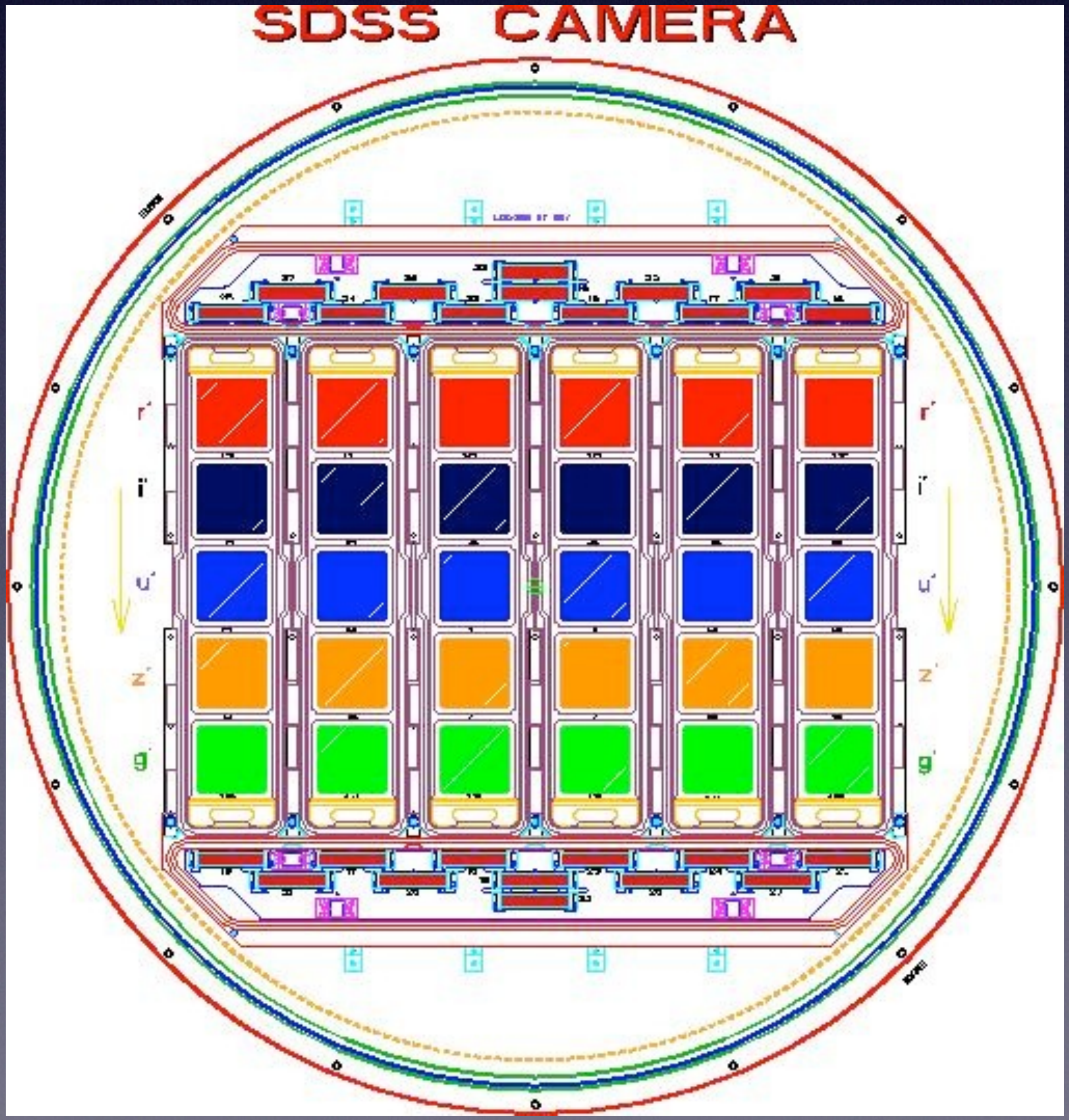
- **The utility of sky maps:**

  Discoveries of new objects: "Is this a new asteroid, or is it already cataloged?"
  Object classification: "What types of galaxies exist?"
  Statistical population studies: "Do quasars change their properties with time?"
  Search for unusual objects: "Is this star very weird?"
  Cosmological measurements: "How fast does the Universe expand?"

"Science-ready database": measurements can be (simply) analyzed without the need for (complex) image processing

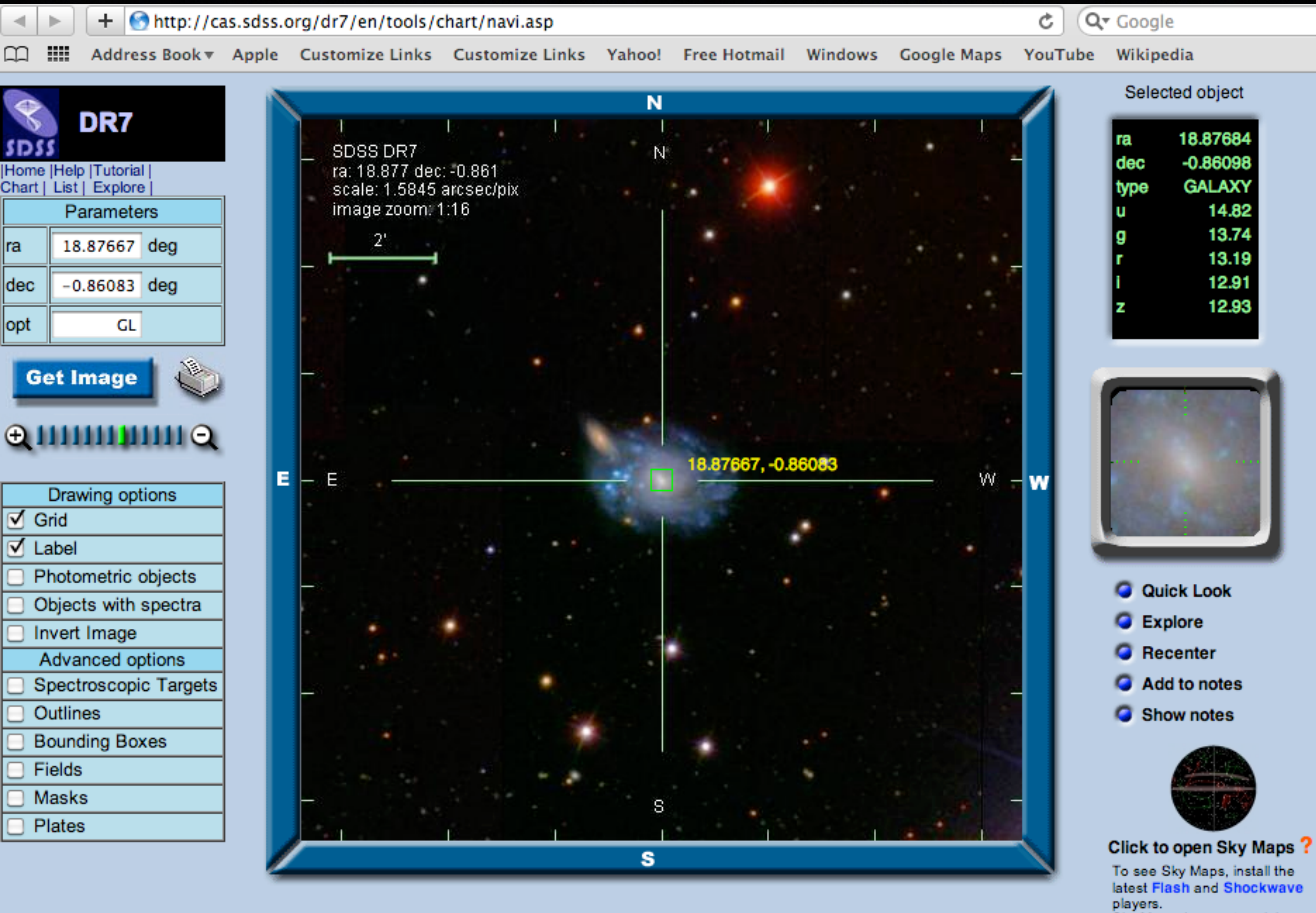
The last decade: Sloan Digital Sky Survey

- Digital sky survey with a 120 Megapix CCD camera
- Precise measurements for 400,000,000 objects
- Revolution in astronomy: public databases



Astronomy "from your armchair", from everywhere

"Navigation" around the sky...



Additional, more detailed, information...

http://cas.sdss.org/dr7/en/tools/explore/obj.asp?ra=18.87667&dec=-0.86083

Address Book ▾ Apple Customize Links Customize Links Yahoo! Free Hotmail Windows Google

DR7 SDSS

Explore Home

Search by
ObjId
Ra,dec
5-part SDSS
Plate-MJD-Fiber
SpecObjId

Summary

PhotoObj
PhotoTag
More Observations
Field
Frame
PhotoZ
Neighbors
Finding chart
Navigate
FITS

SpecObj
All Spectra
SpecLine
SpecLineIndex
XCredShift
ELredShift
Spectrum
Plate
FITS

NED search
SIMBAD search
AKARI FIS
AKARI IRC
ADS search

Notes
Save in Notes
Show Notes

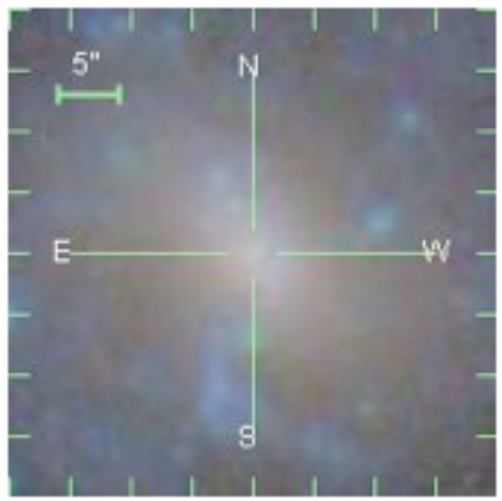
Print

SDSS J011530.44-005139.5

GALAXY ra=18.87683906, dec=-0.86097998, ObjId = 587731511532060697

Column names link to glossary entries. Move mouse over a column name to get its units.

mode	PRIMARY
status	TARGET PRIMARY OK_STRIPE OK_SCANLINE PSEGMENT RESOLVED OK_RUN GOOD SET
flags	DEBLEND_DEGENERATE BAD_MOVING_FIT BINNED1 INTERP COSMIC_RAY NOPETRO CHILD
PrimTarget	TARGET_GALAXY TARGET_GALAXY_RED TARGET_QSO_CAP
SecTarget	



u	g	r	i	z
14.82	13.74	13.19	12.91	12.93

err_u	err_g	err_r	err_i	err_z
0.01	0.00	0.00	0.00	0.00

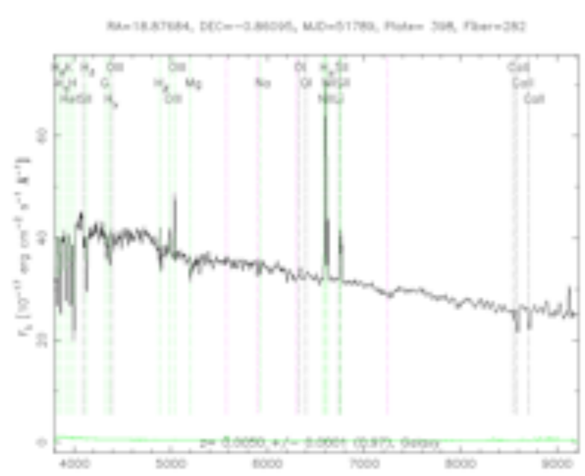
run	rerun	camcol	field	obj	rowc	colc
2738	40	1	44	25	972.5	1786.6

fiberMag_r	petroMag_r	devMag_r	expMag_r	psfMag_r	modelMag_r
17.56	12.97	13.14	13.19	18.16	13.19

extinction_r	petroRad_r	parentId	nChild
0.11	106.724	587731511532060693	0

SpecObjID = 112249473974927360

plate	mjd	fiberId	z	zErr	zConf	specClass	ra	dec	fiberMag_r	objId
398	51789	282	0.005	0.00006	0.969081	GALAXY	18.87684	-0.86095	17.53	587731511532060697



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zWarning	OK
PrimTarget	TARGET_GALAXY TARGET_GALAXY_RED
SecTarget	
eClass	0.095797
emZ	0.006
emConf	0.874995
xcZ	0.005
xcConf	0.969081

Cross-identifications

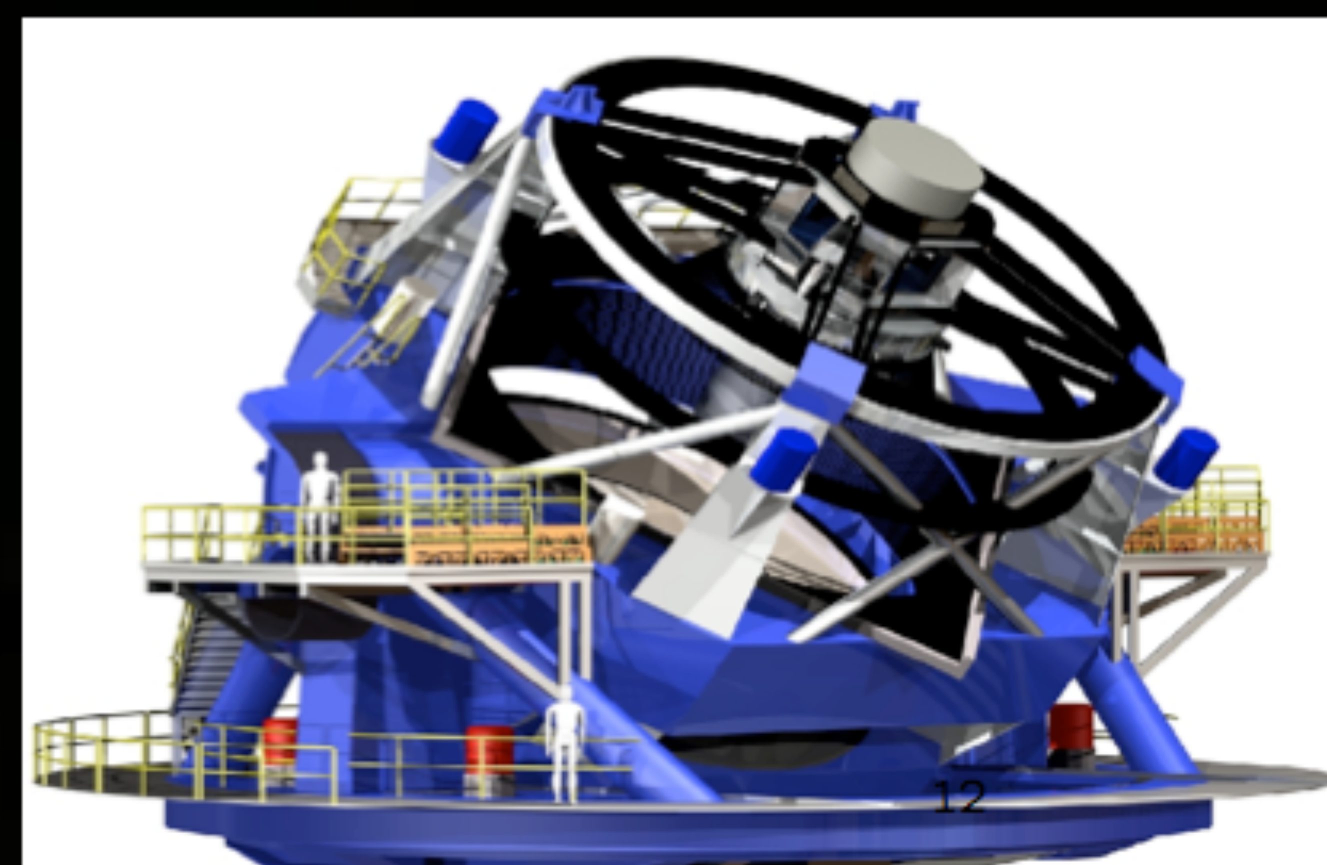
“Ask Not What Data You Need To Do Your Science, Ask What Science You Can Do With Your Data.”

The era of surveys...

- Standard: “What data do I have to collect to (dis)prove a hypothesis”?
- Data-driven: “What theories can I test given the data I already have?”

SDSS: one US Library of Congress worth of data

LSST: one SDSS per night, or all the words ever printed!



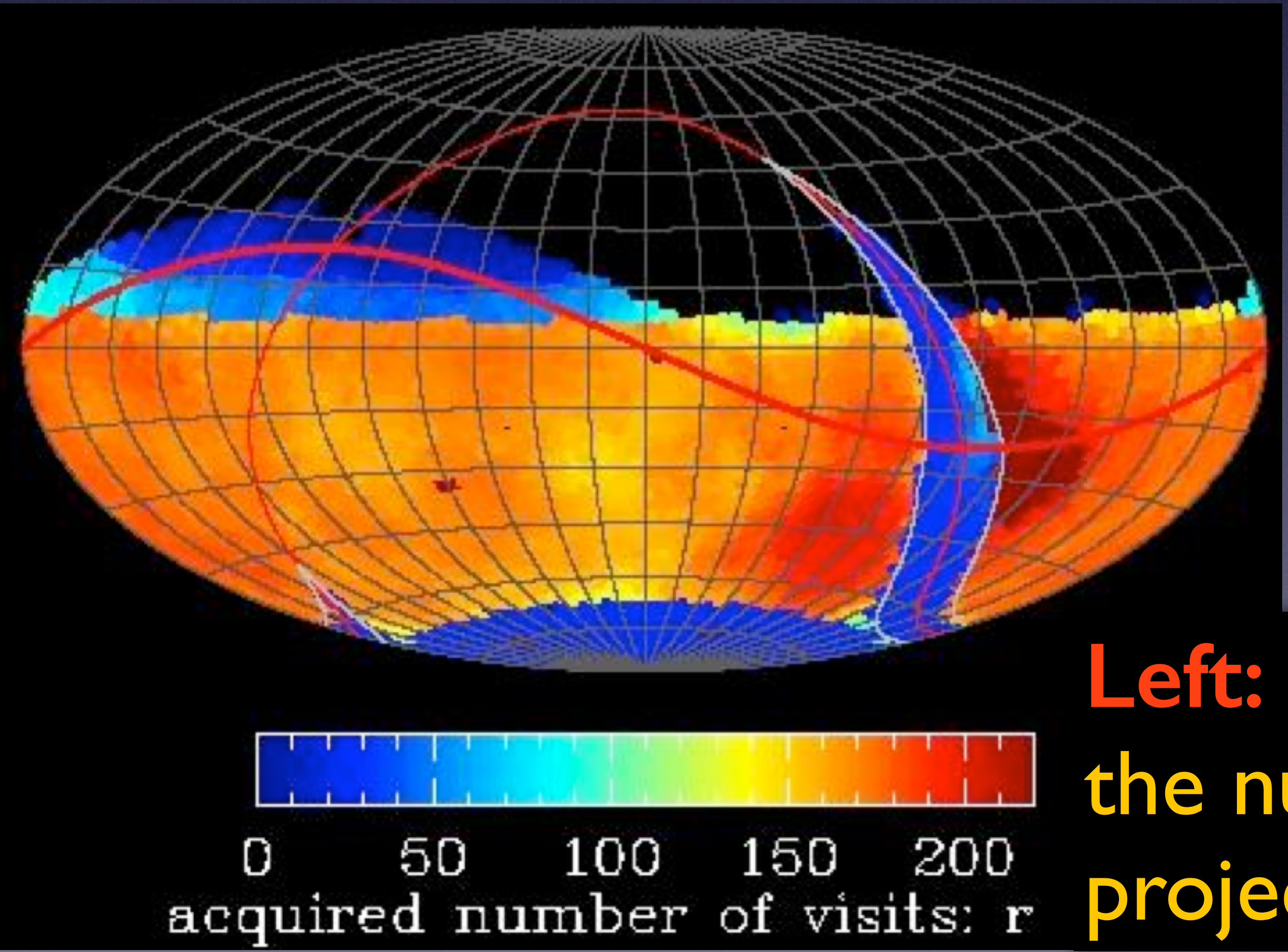
LSST Science Themes

- Dark matter, dark energy, cosmology
  (spatial distribution of galaxies, gravitational lensing, supernovae, quasars)
- Time domain
  (cosmic explosions, variable stars)
- The Solar System structure (asteroids)
- The Milky Way structure (stars)

These drivers not only require similar hardware and software systems, but also motivate a uniform cadence:
about 90% of time will be spent on a uniform survey

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 PB 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) based on 1000 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 vs. LSST comparison: LSST=d(SDSS)/dt, LSST=SuperSDSS

3x3 arcmin, gri

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

(almost) like LSST depth (but tiny area)

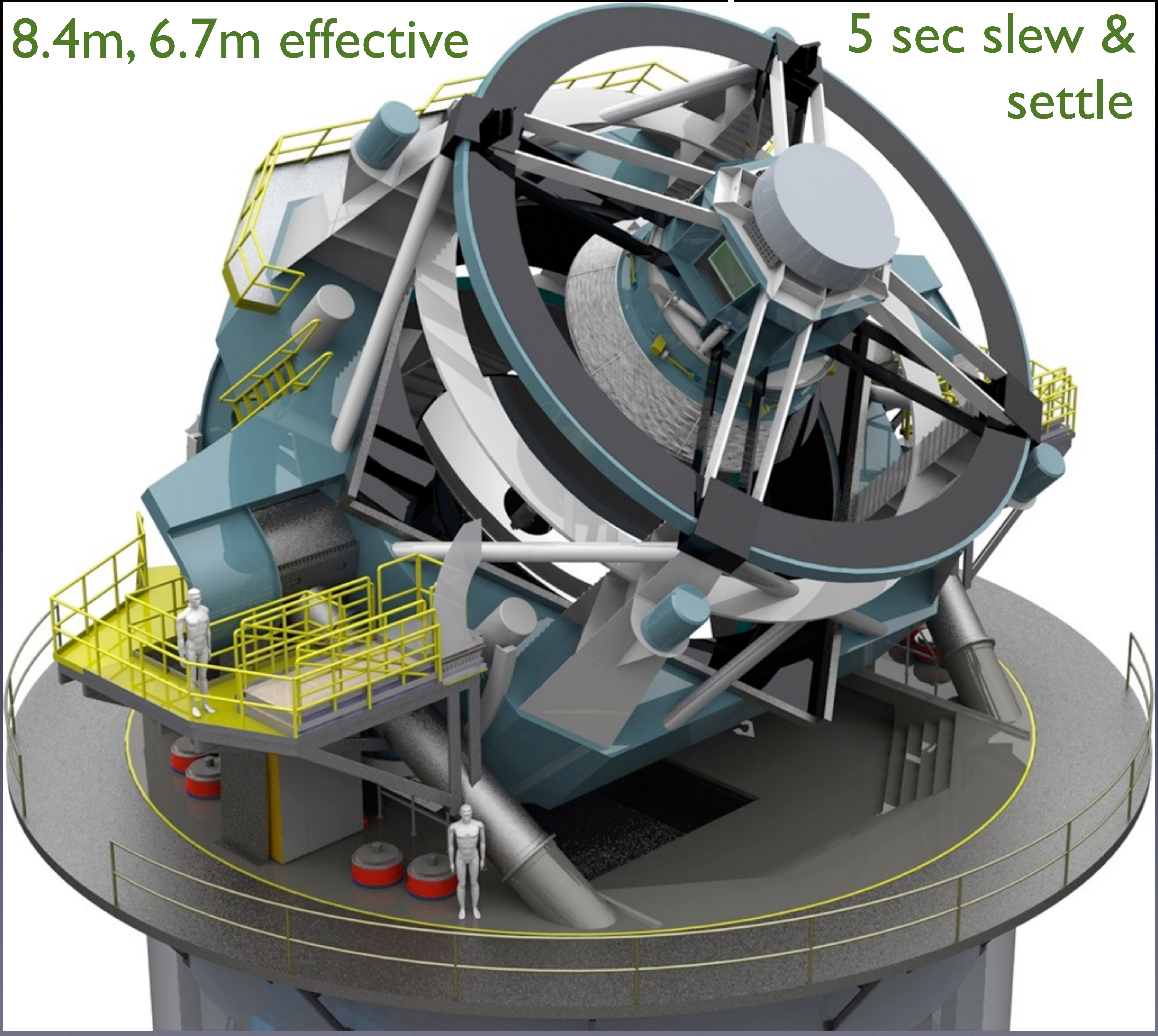
20x20 arcsec; lensed SDSS quasar (SDSS J1332+0347, Morokuma et al. 2007)

Required system characteristics

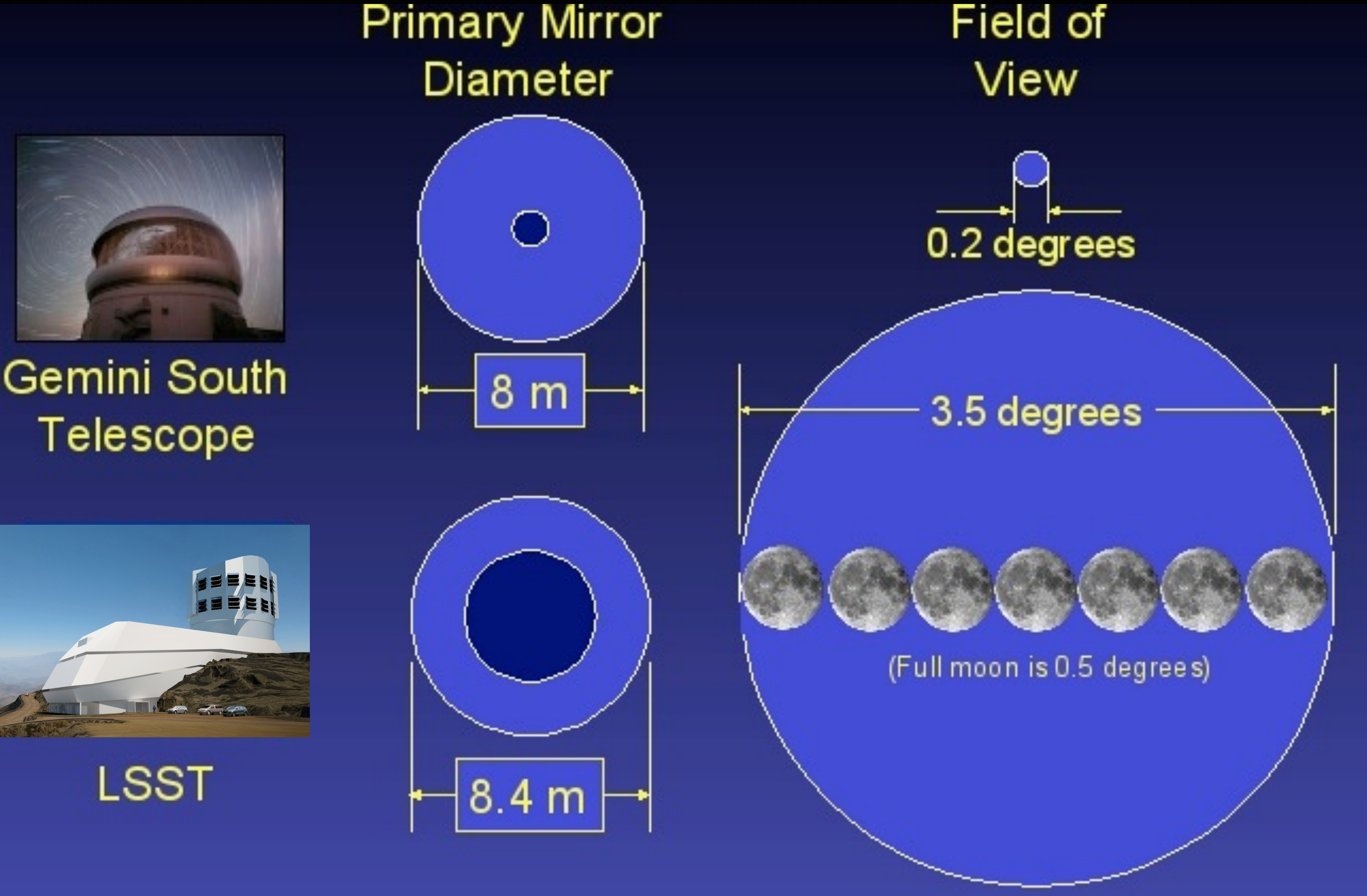
- Large primary mirror (at least 6m) to go faint and to enable short exposures (30 s)
- Agile telescope (5 sec for slew and settle)
- Large field of view to enable fast surveying
- Impeccable image quality (weak lensing)
- Camera with 3200 Mpix
- Sophisticated software (20,000 GB/night, 20 billion objects, 20 trillion measurements)


LSST system
Telescope
Camera
Software

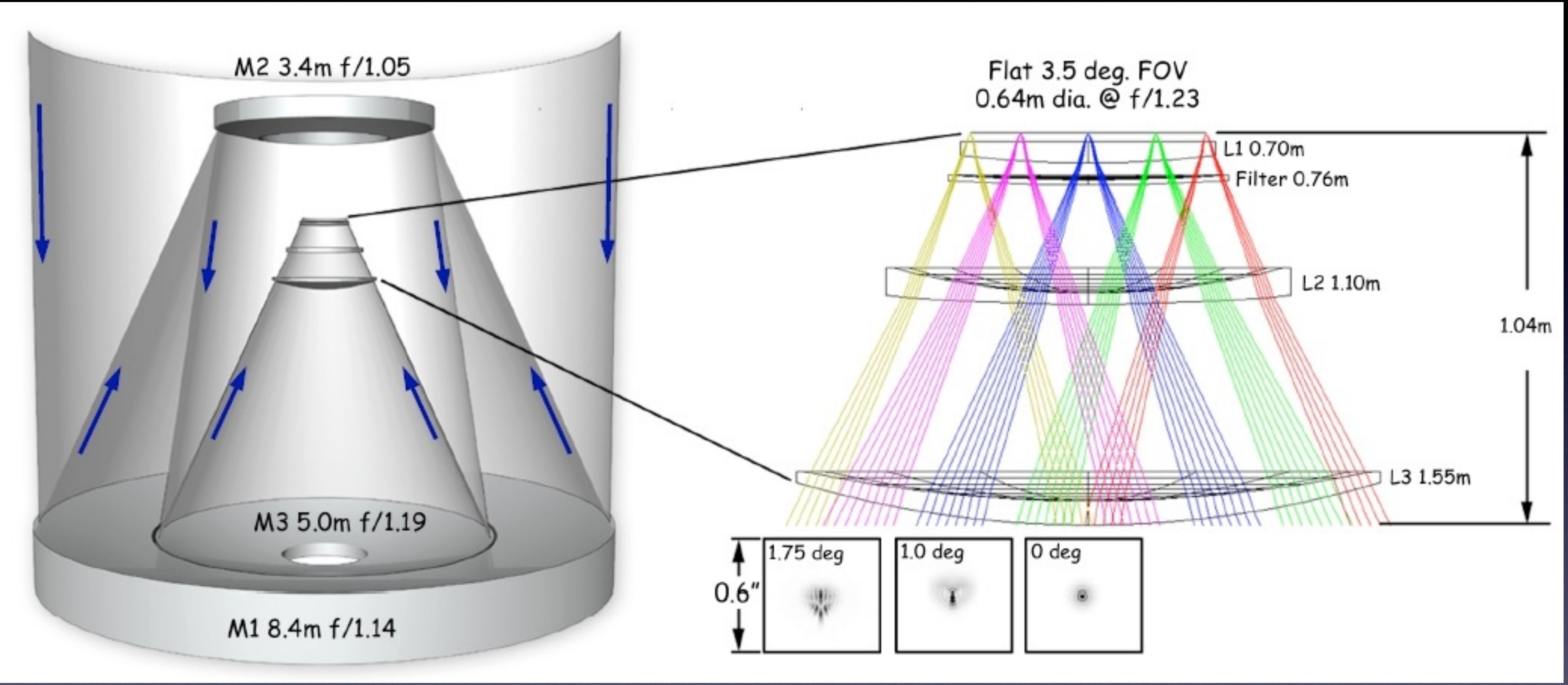
LSST Telescope



The field-of-view comparison: Gemini vs. LSST

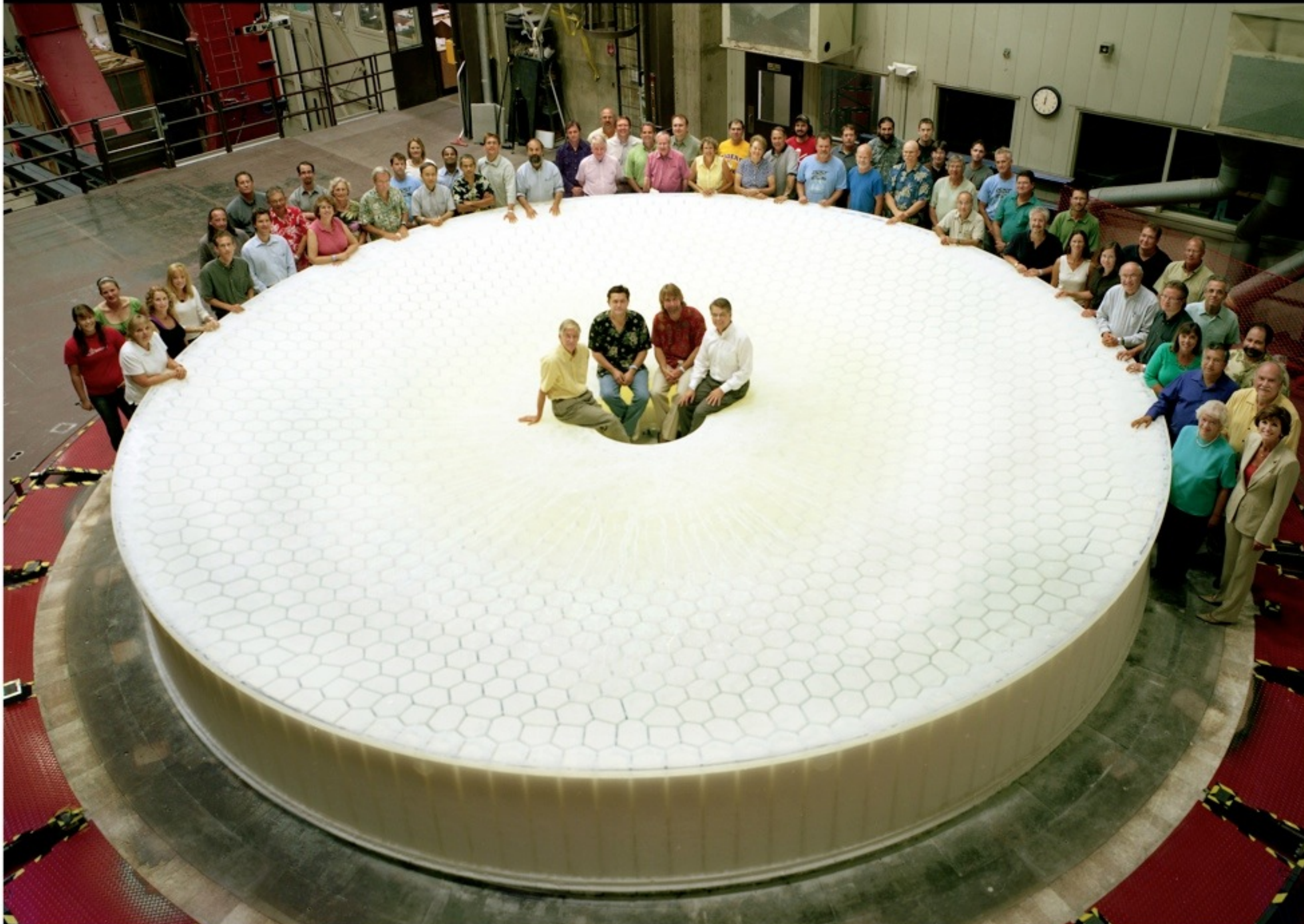


Optical Design for LSST



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

Large Synoptic Survey Telescope



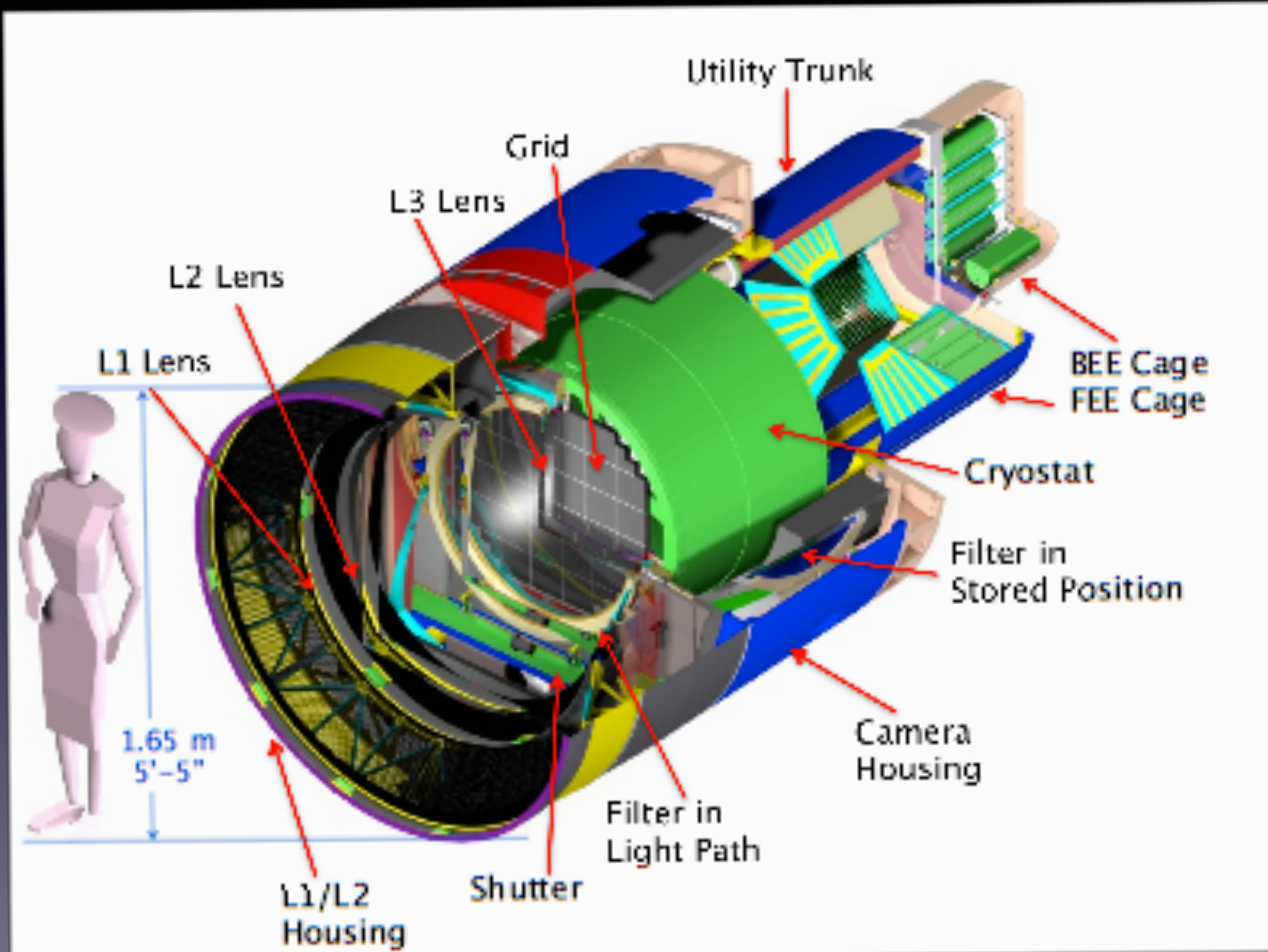
LSST Primary/Tertiary Mirror Blank
August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona

THE UNIVERSITY OF ARIZONA. TUCSON ARIZONA

SOML

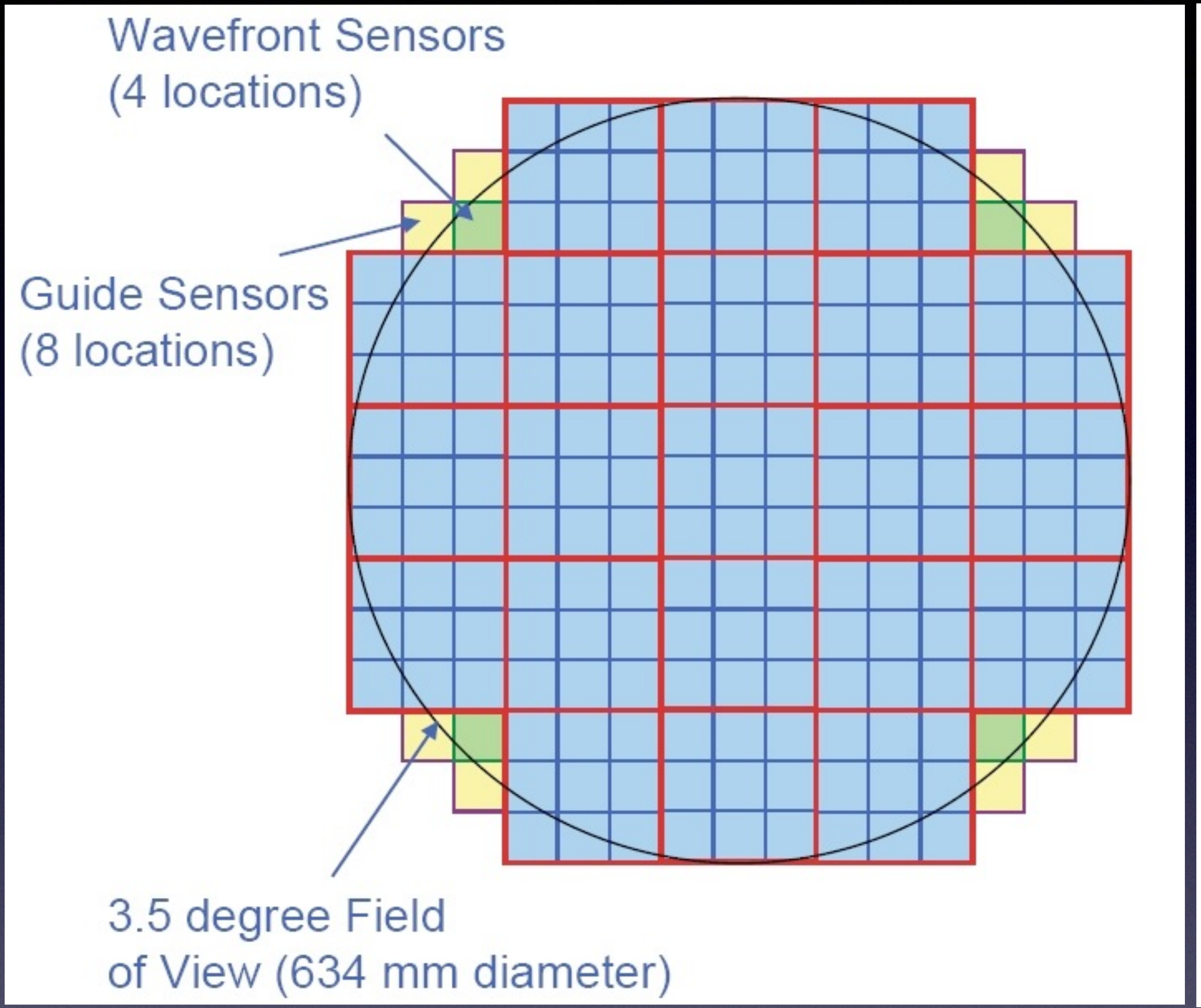
Large Synoptic Survey Telescope

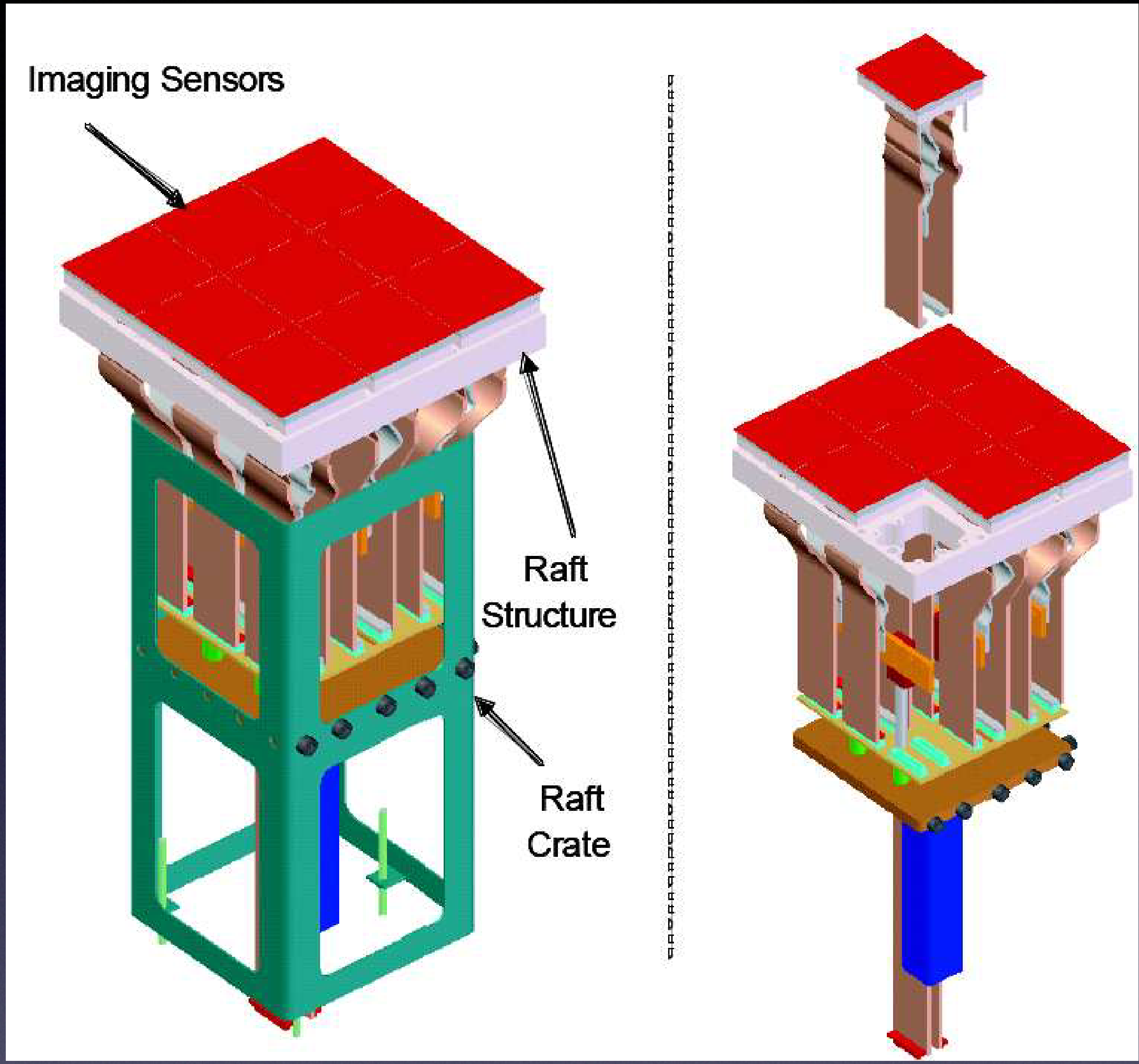
LSST camera



The largest astronomical camera: 2800 kg, 3.2 Gpix

LSST camera



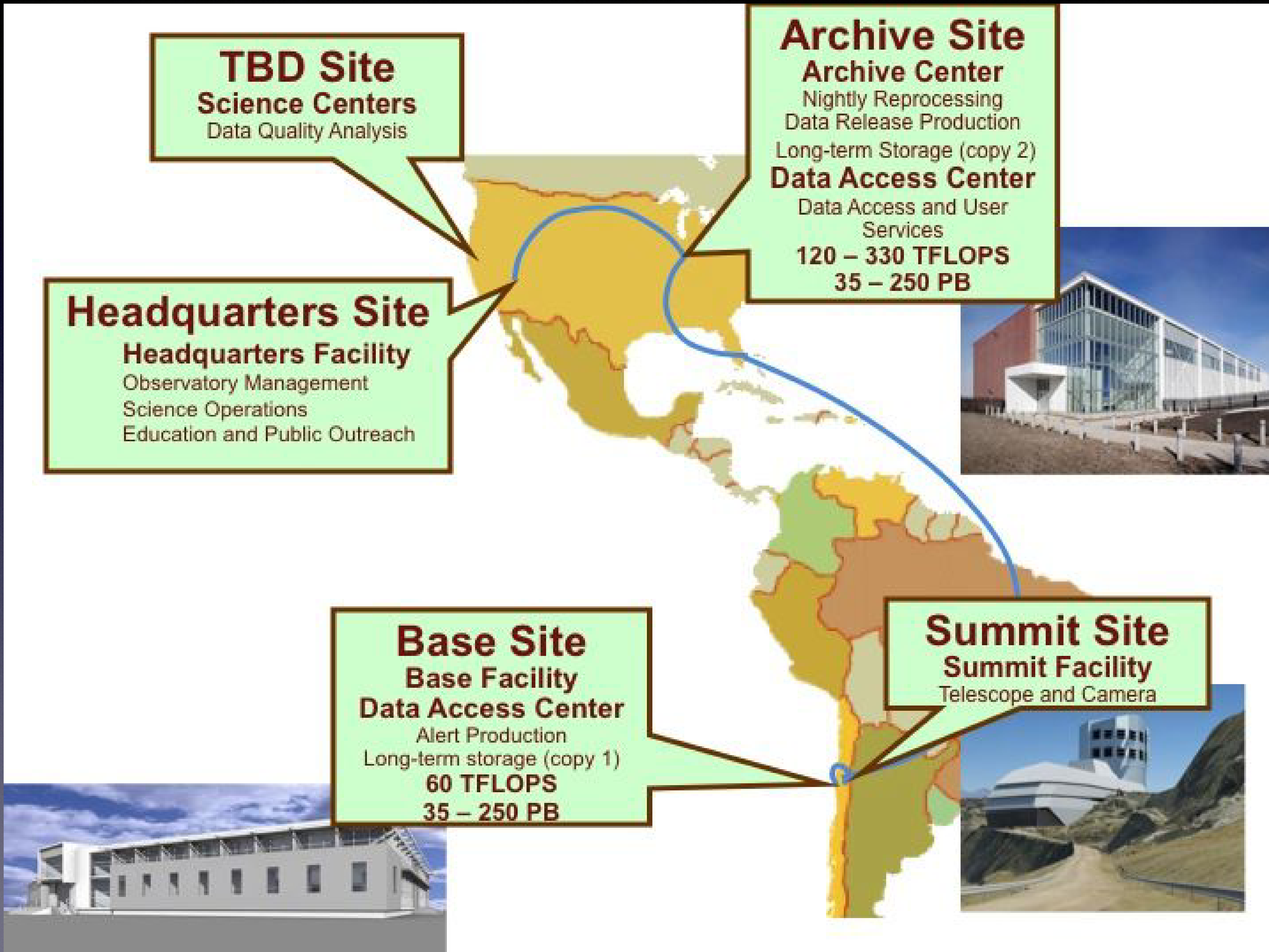


Modular design: 3200 Megapix = 189 x16 Megapix CCD

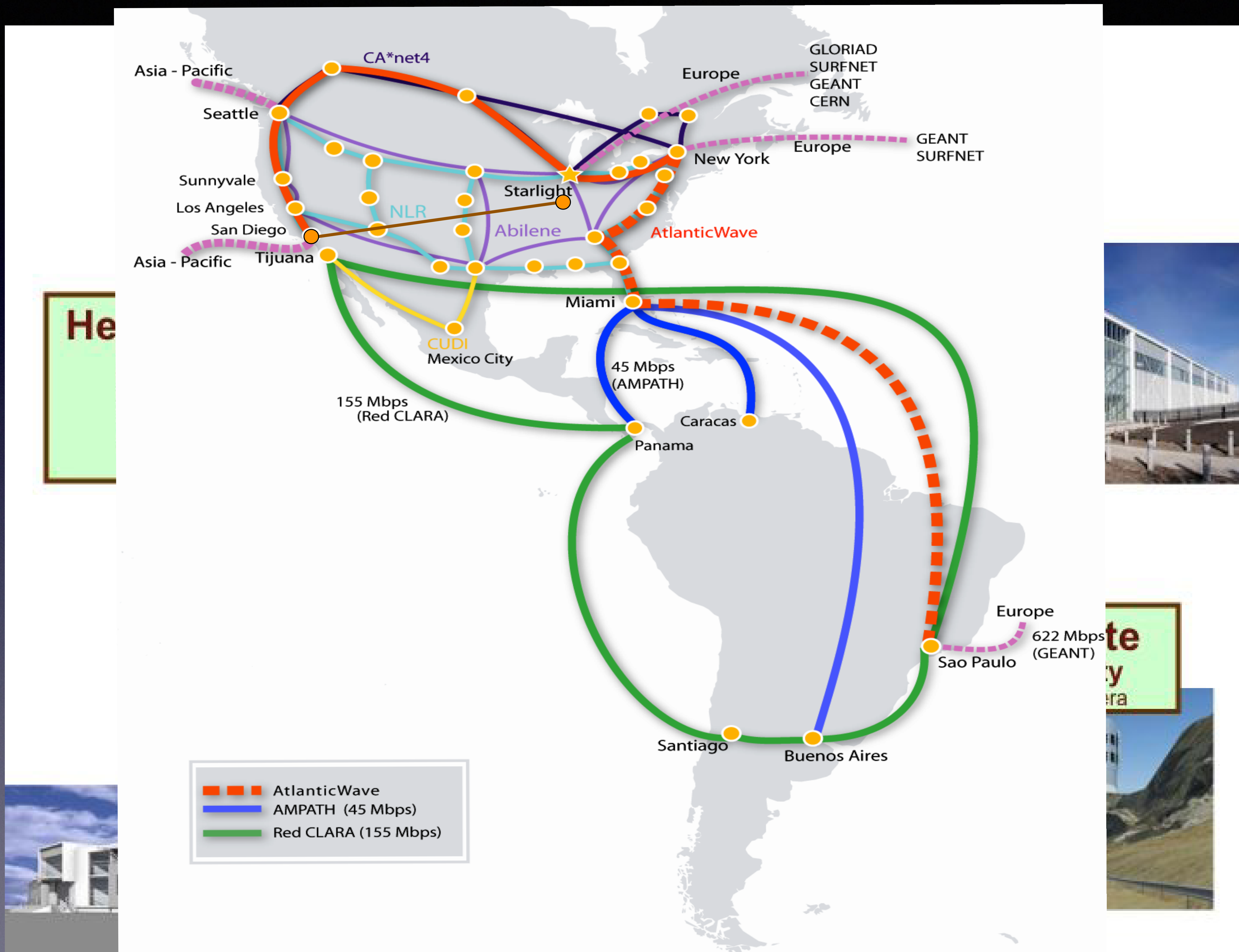
9 CCDs share electronics: raft (=camera)

Problematic rafts can be replaced relatively easily

LSST Software



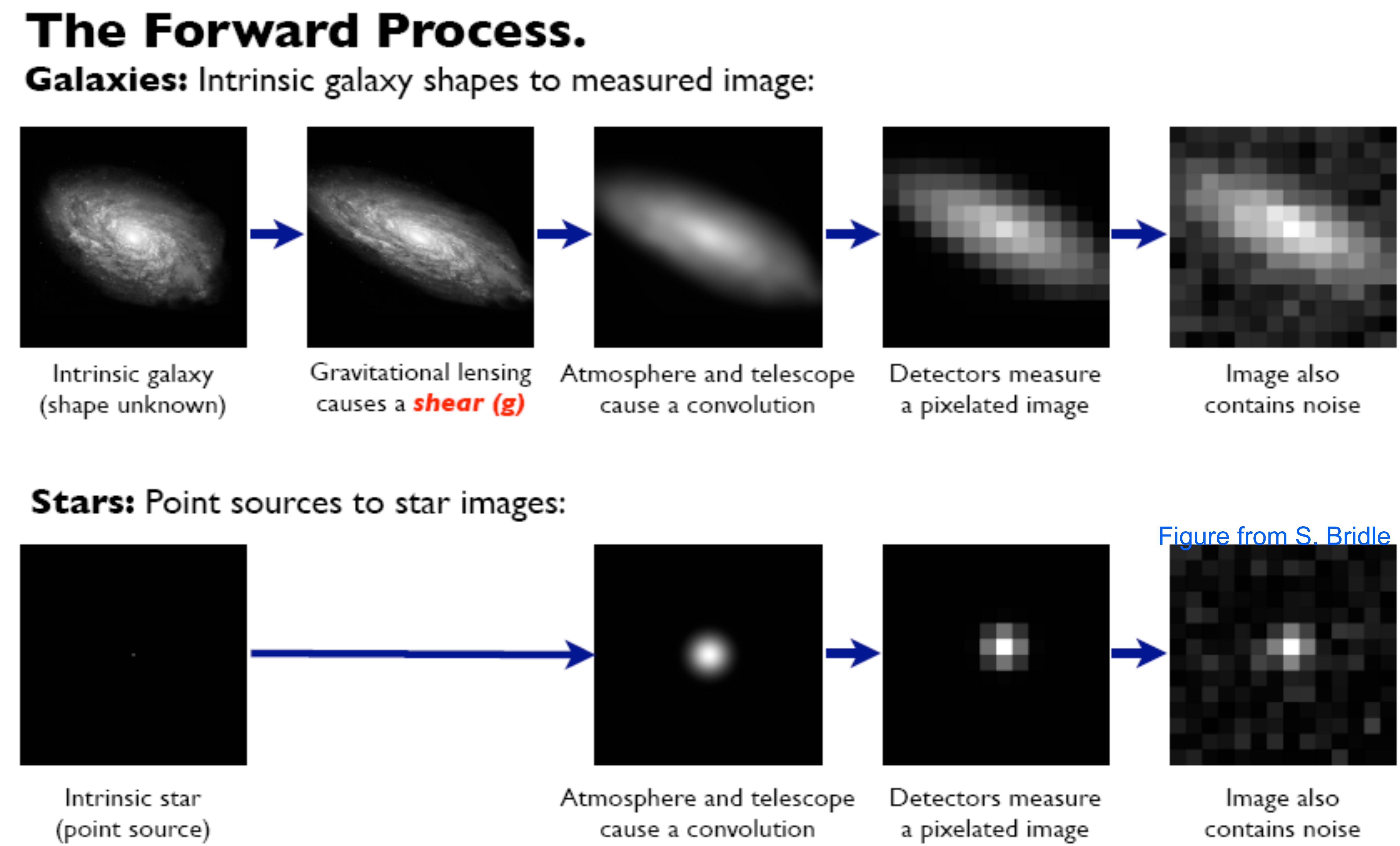
LSST Software



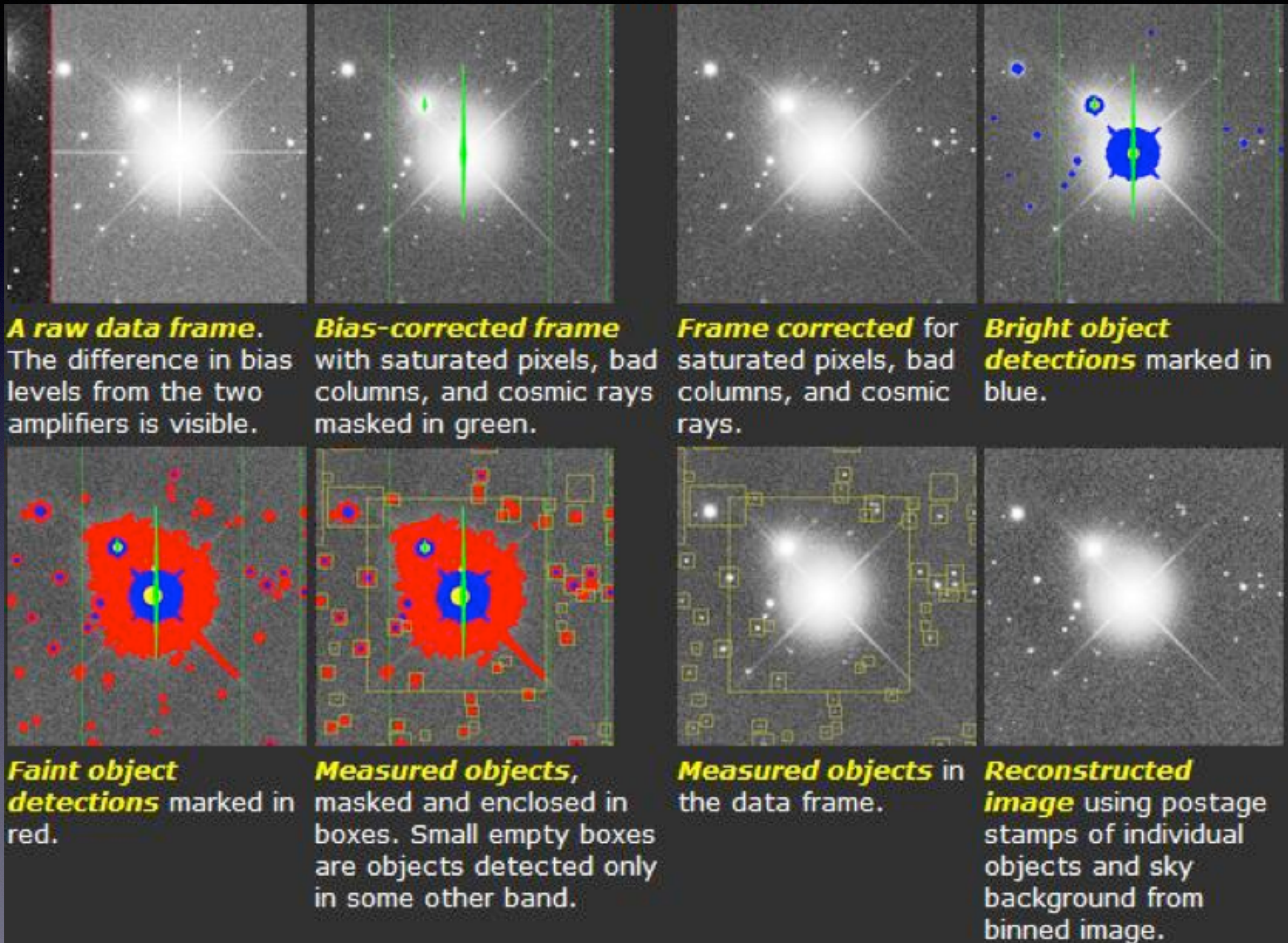
Software: the subsystem with the highest risk

- 20 TB of data to process every day (~one SDSS/ day)
- 1000 measurements for 40 billion objects during 10 years
- Existing tools and methods (e.g. SDSS) do not scale up to LSST data volume and rate (100 PB!)
- About 5-10 million lines of new code (C++/python)

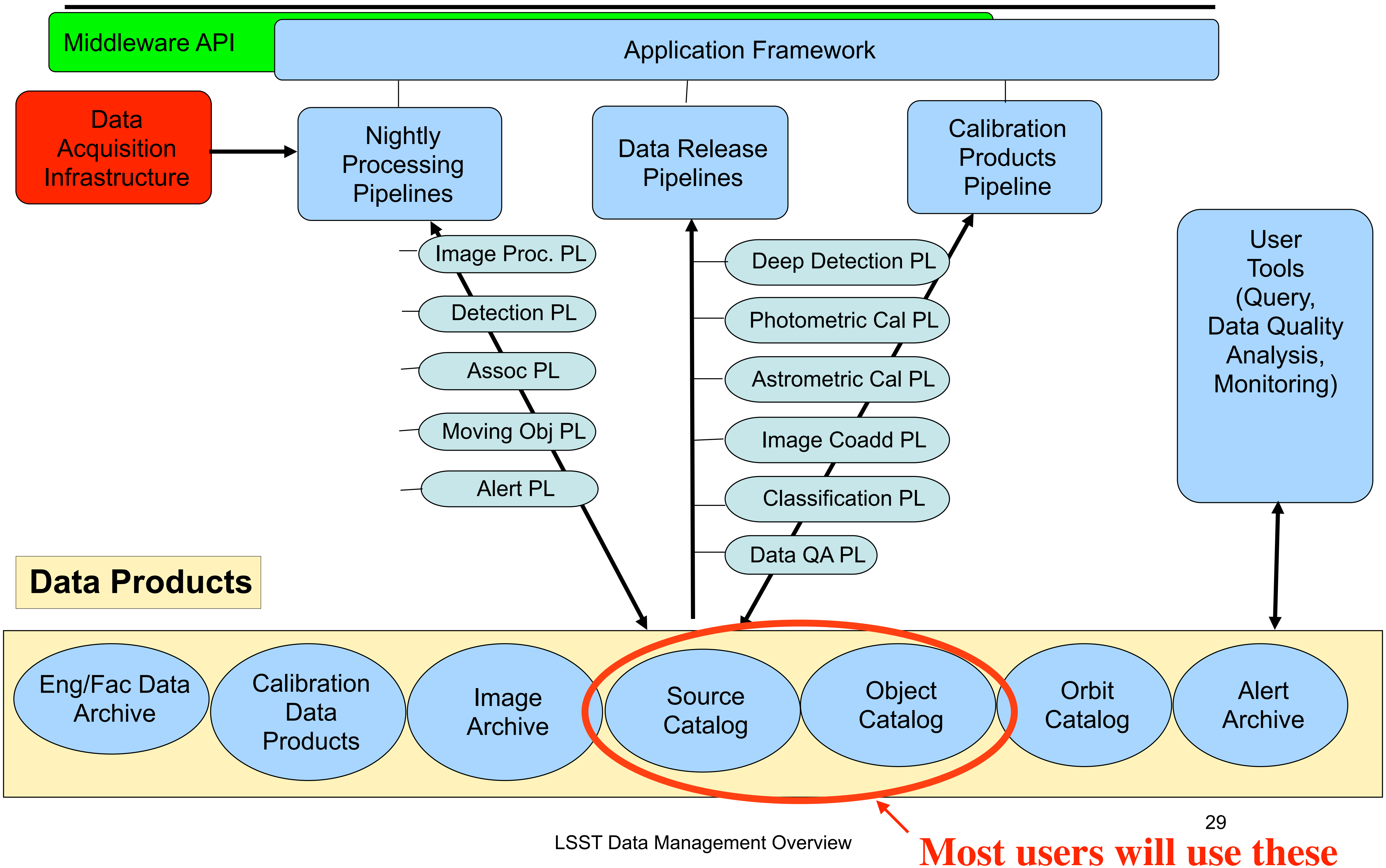
• Measuring galaxy shear: a subtle effect



LSST imaging processing: an example



LSST image processing pipelines



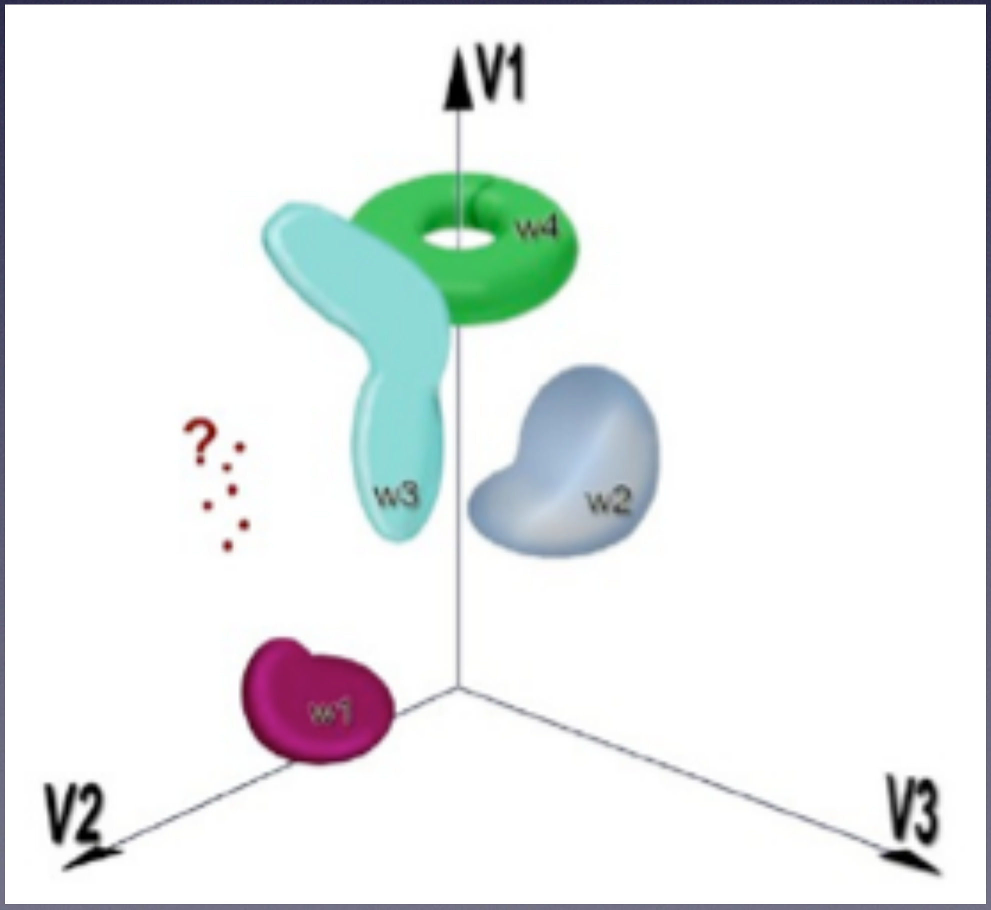
A comparison of LSST data processing with other software projects:

- **Complexities we have to deal with in DM**
  - Very high data volumes (transfer, ingest, and especially query)
  - Advances in scale of algorithms for photometry, astrometry, PSF estimation, moving object detection, shape measurement of faint galaxies
  - Provenance recording and reprocessing
  - Evolution of algorithms and technology
- **Complexities we DON'T have to deal with in DM**
  - Tens of thousands of simultaneous users (e.g. online stores)
  - Fusion of remote sensing data from many sources (e.g. earthquake prediction systems)
  - Millisecond or faster time constraints (e.g. flight control systems)
  - Very deeply nested multi-level transactions (e.g. banking OLTP systems)
  - Severe operating environment-driven hardware limitations (e.g. space-borne instruments)
  - Processing that is highly coupled across entire data set with large amount of inter-process communication (e.g. geophysics 3D Kirchhoff migration)

Statistical analysis of a massive LSST dataset

- A large (100 PB) database and sophisticated analysis tools: for each of 20 billion objects there will be about 1000 measurements (each with a few dozen measured parameters)

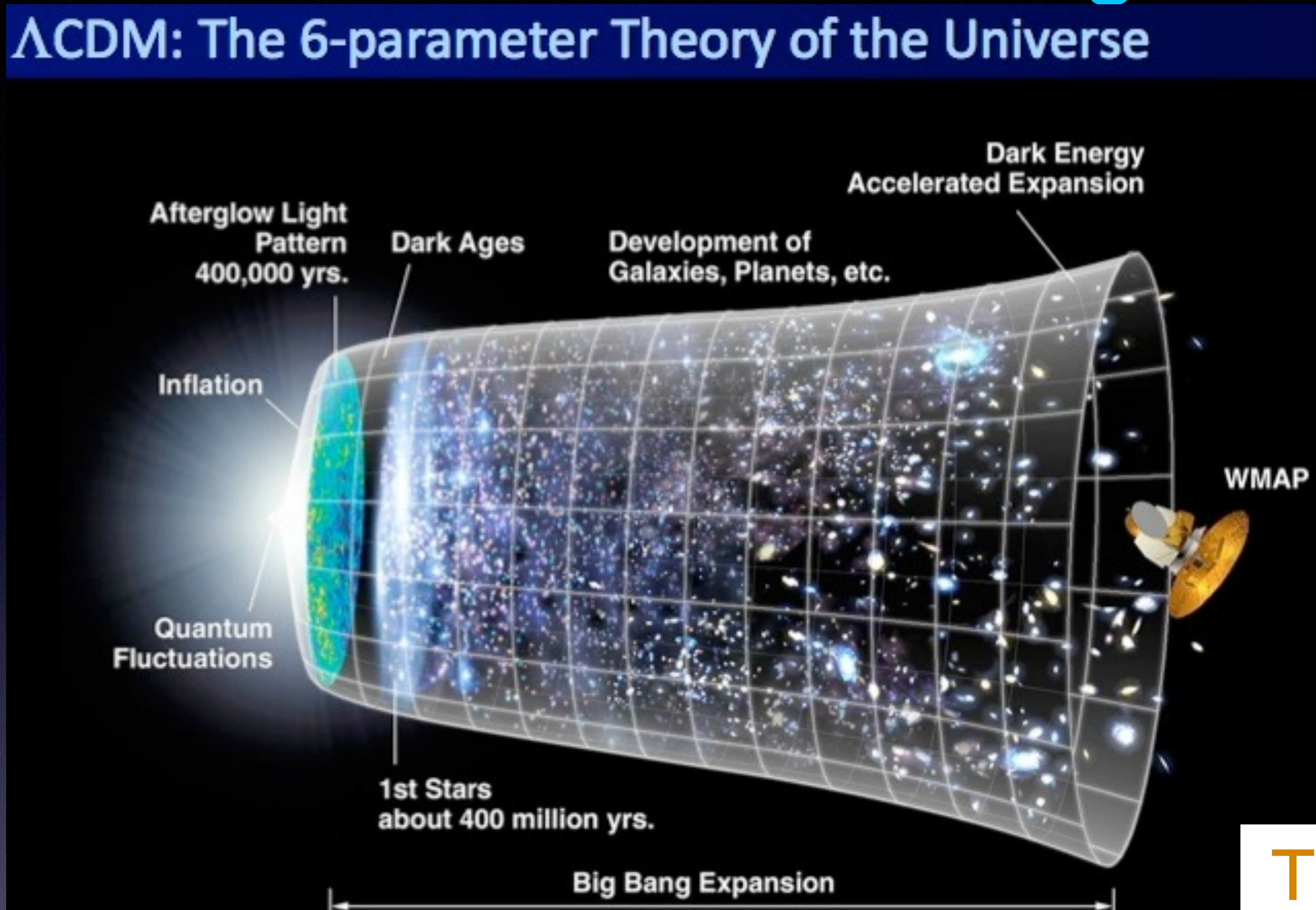
Data mining and knowledge discovery

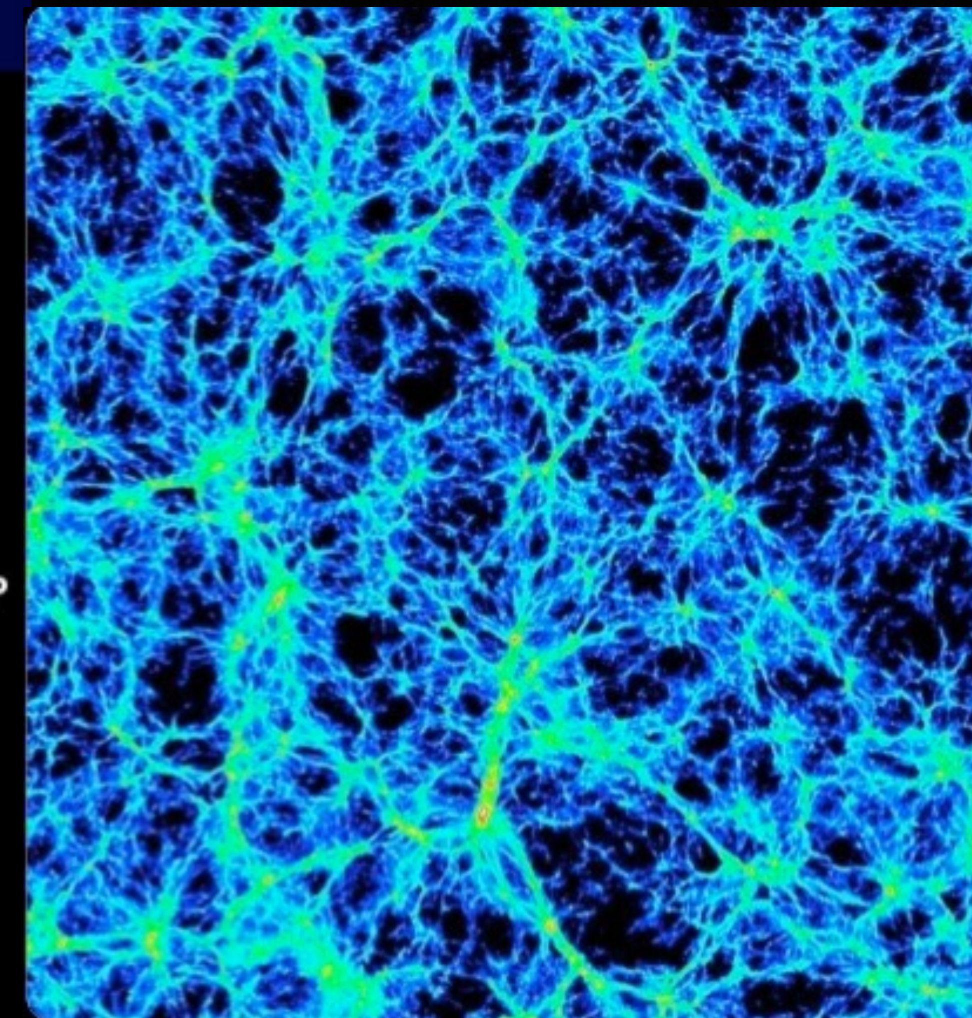


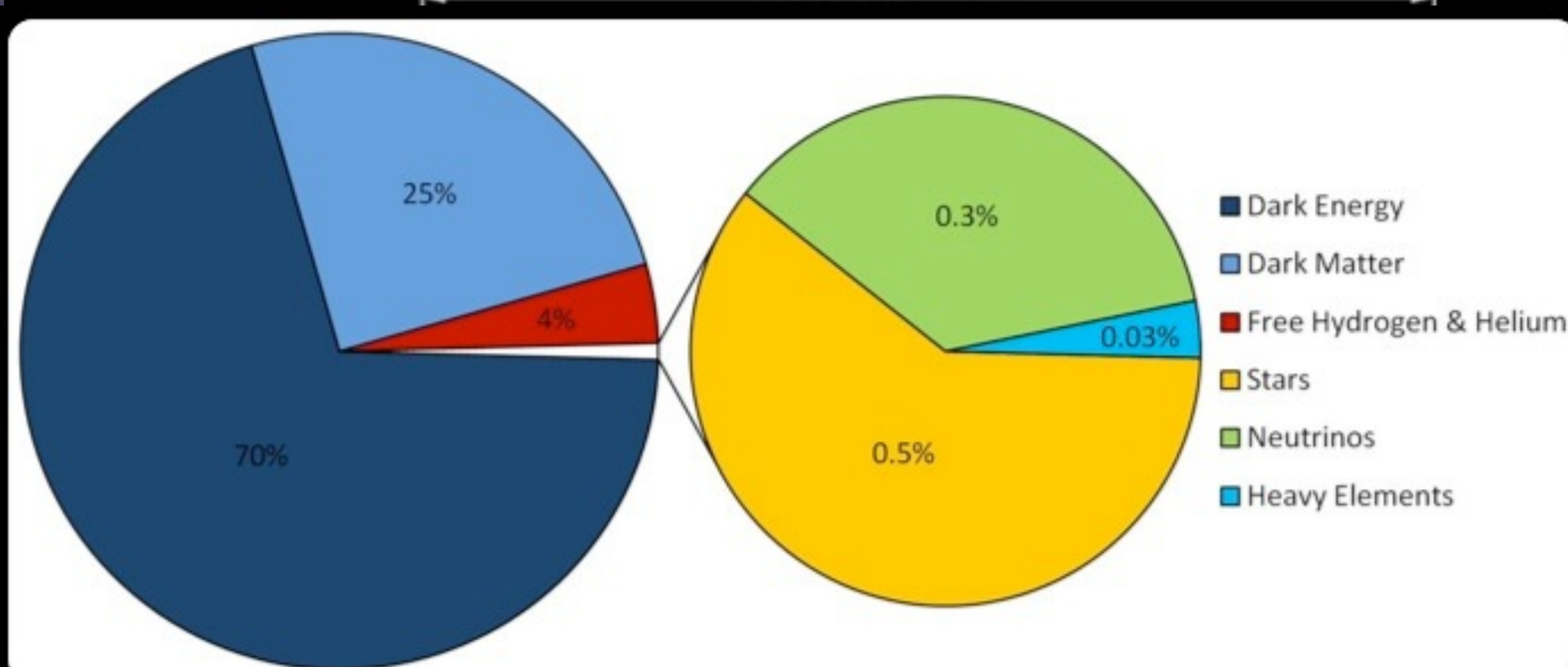
- 10,000-D space with 20 billion points
- Characterization of known objects
- Classification of new populations
- Discoveries of unusual objects

Clustering, classification, outliers

New Cosmological Puzzles







The modern cosmological models can explain all observations, but need to **postulate** dark matter and dark energy (though gravity model could be wrong, too)

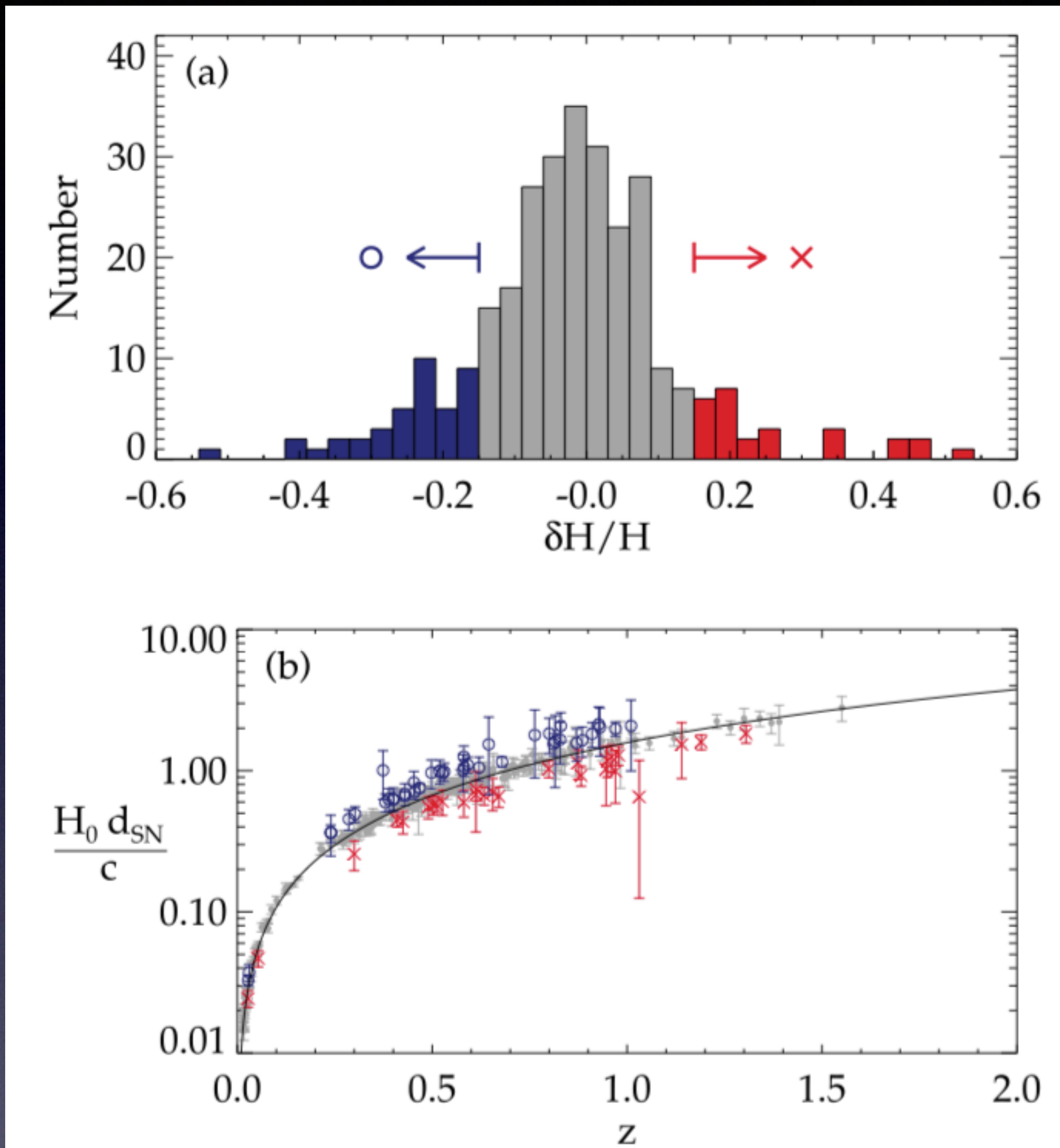
Modern Cosmological Probes

- 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

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 $a(z) = (1+z)^{-1}$

LSST is designed to reach Stage IV level from DETF report
which kinda means **"It will be awesome and better than anything today!"**

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



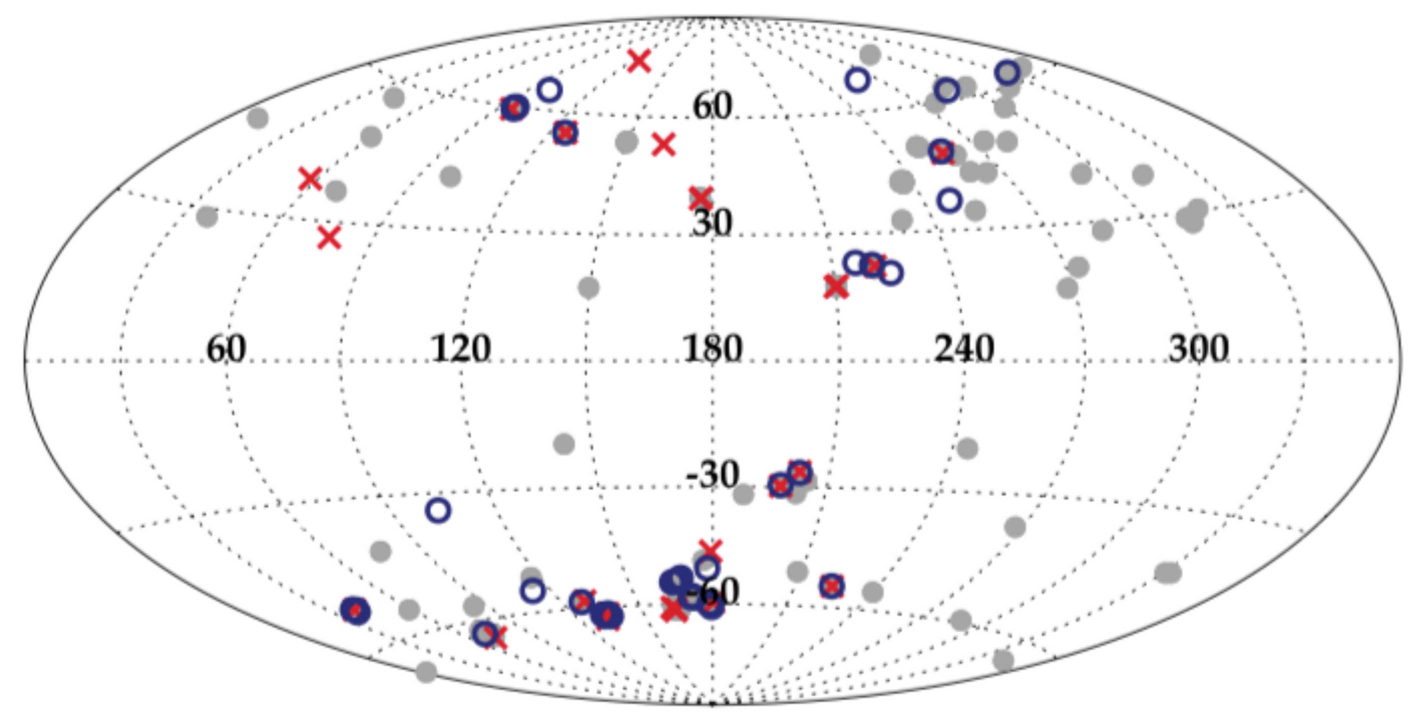


Figure 1. A projection of the spatial distribution of the Union SNe Ia sample in Galactic coordinates. Note the relative uniformity of the points, except around the Galactic plane. The symbols correspond to those in Fig. 2, and are explained in Section 3.1.

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!

Galaxies:

- **Photometric redshifts:** random errors smaller than 0.02, bias below 0.003, fewer than 10% >3σ outliers

- These photo-z requirements are one of the primary drivers for the photometric depth and accuracy of the main LSST survey (and the definition of filter complement)

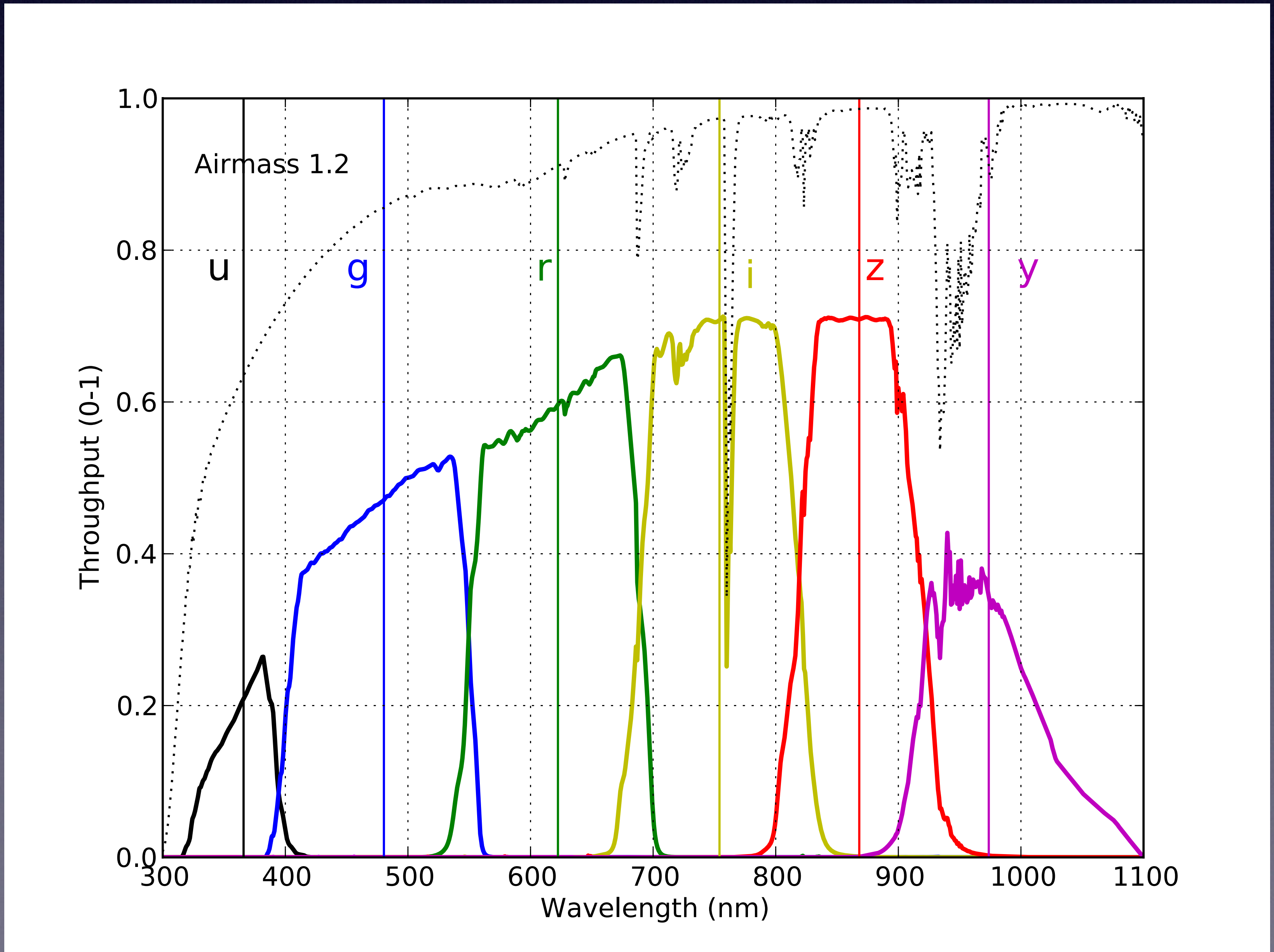


Photo-z requirements correspond to r~27.5

with the following per band time allocations:

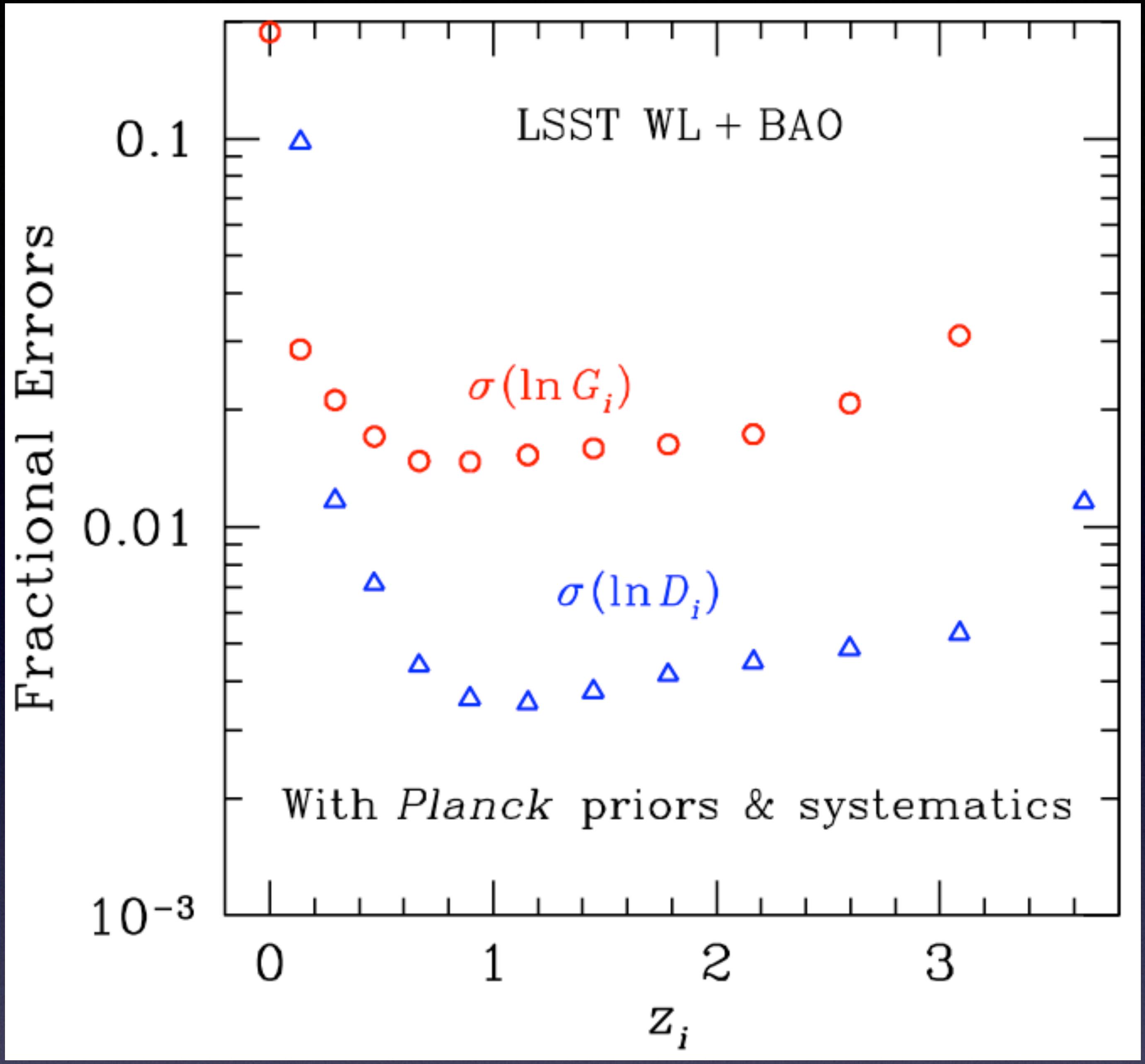
u: 8%; g: 10%

r: 22%; i: 22%

z: 19%; y: 19%

Consistent with other science themes (stars)

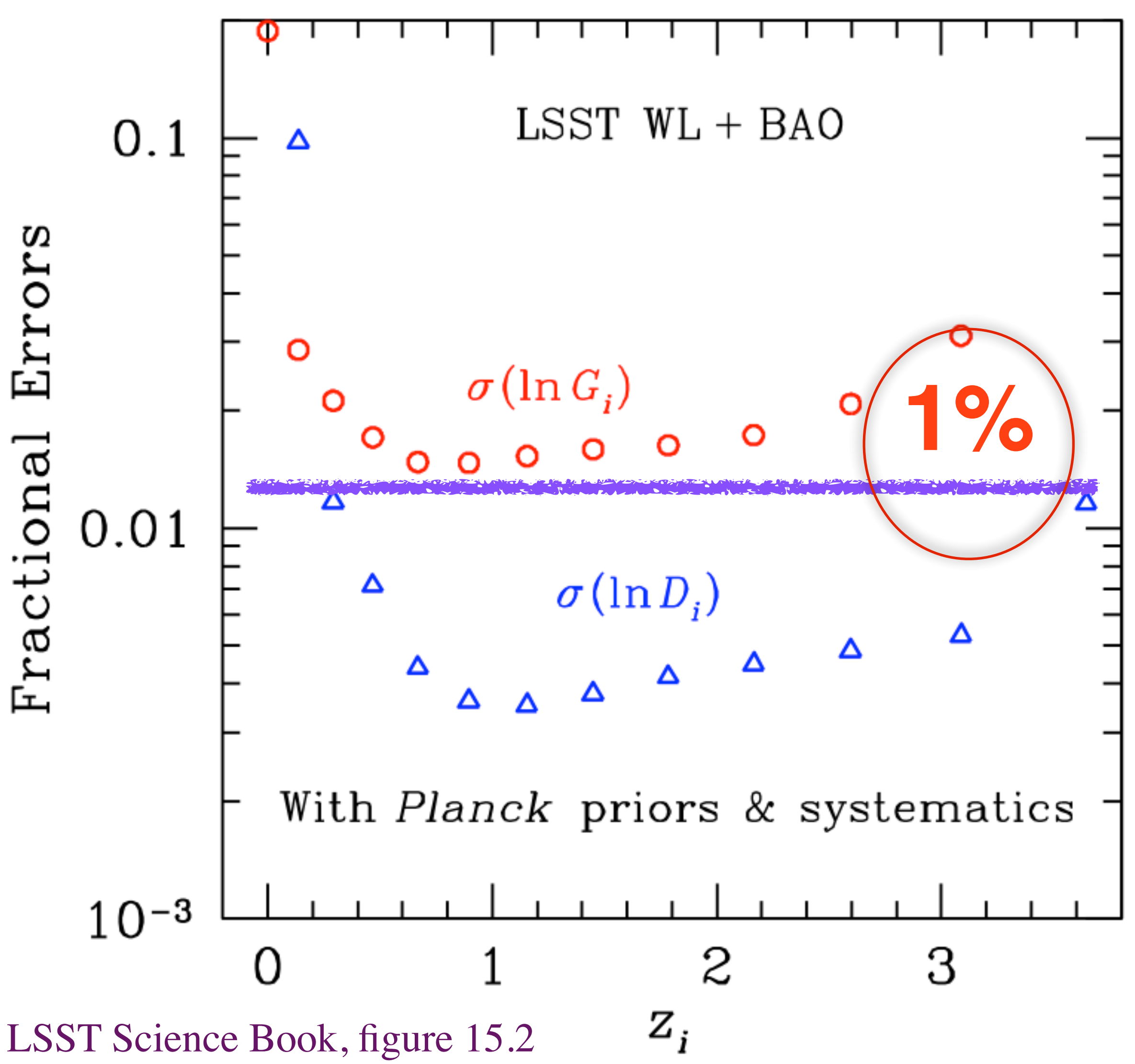
Cosmology with LSST



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.

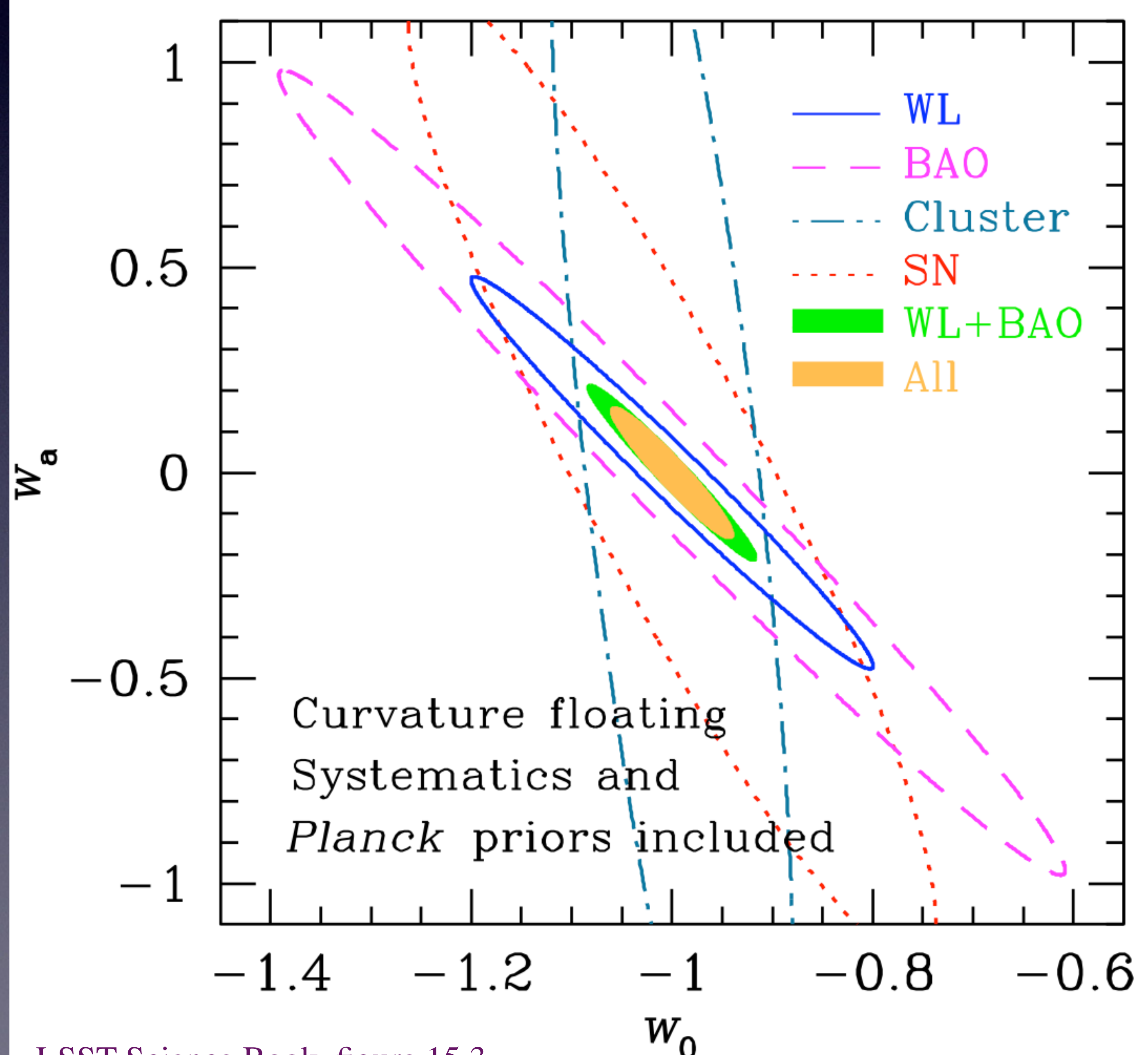
- Derived from 4 billion galaxies (i<25.3, SNR>20)with accurate photo-z and shape measurements
- Measuring distances and growth of structure with a percent accuracy for $0.5 < z < 3$
- SNe will provide a high angular resolution probe of homogeneity and

Cosmology with LSST: high precision measurements



LSST Science Book, figure 15.2

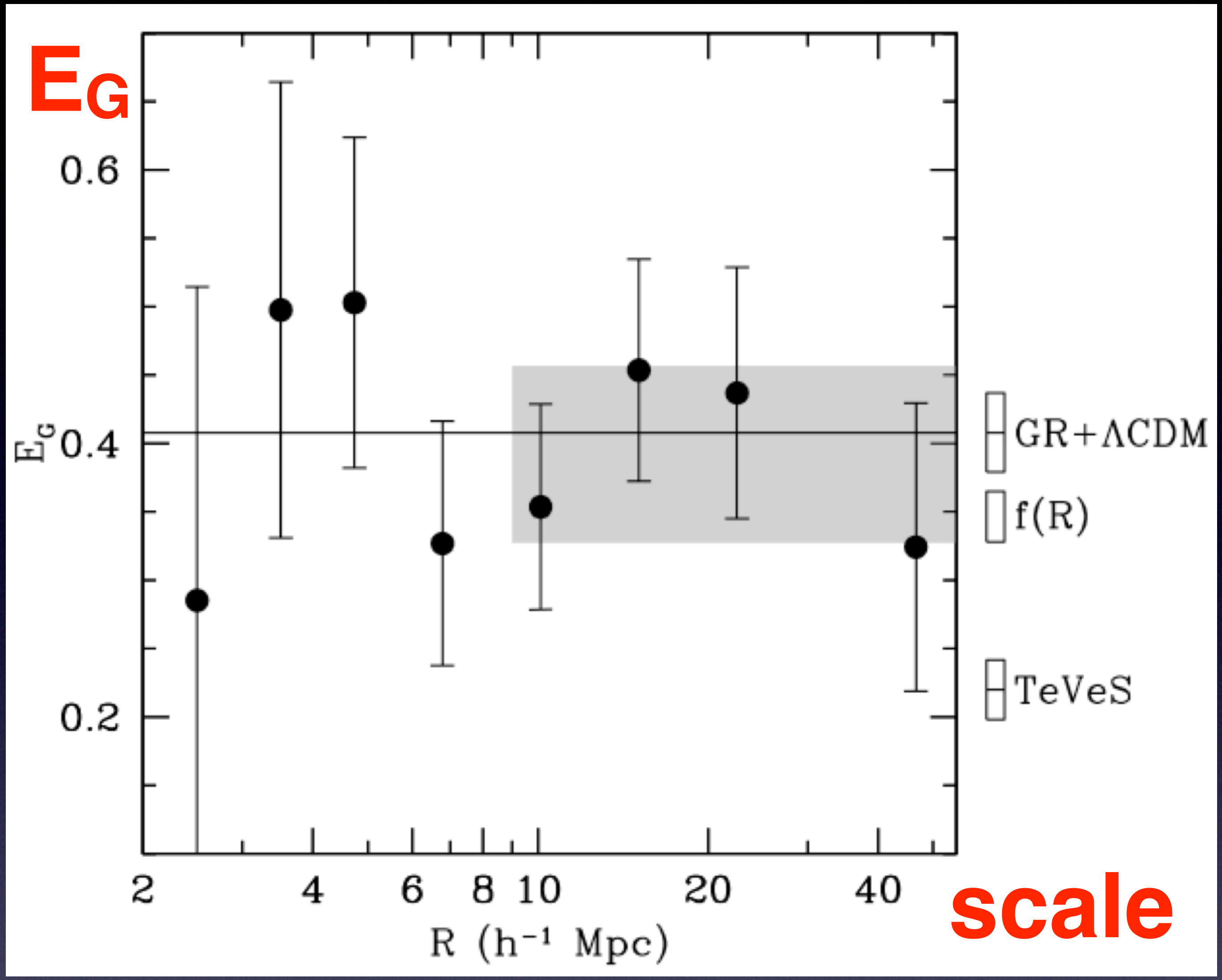
- Measuring distances, H(z), and growth of structure, G(z), with a percent accuracy for 0.5 < z < 3
- Multiple probes is the key!



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: dark energy vs. modified gravity

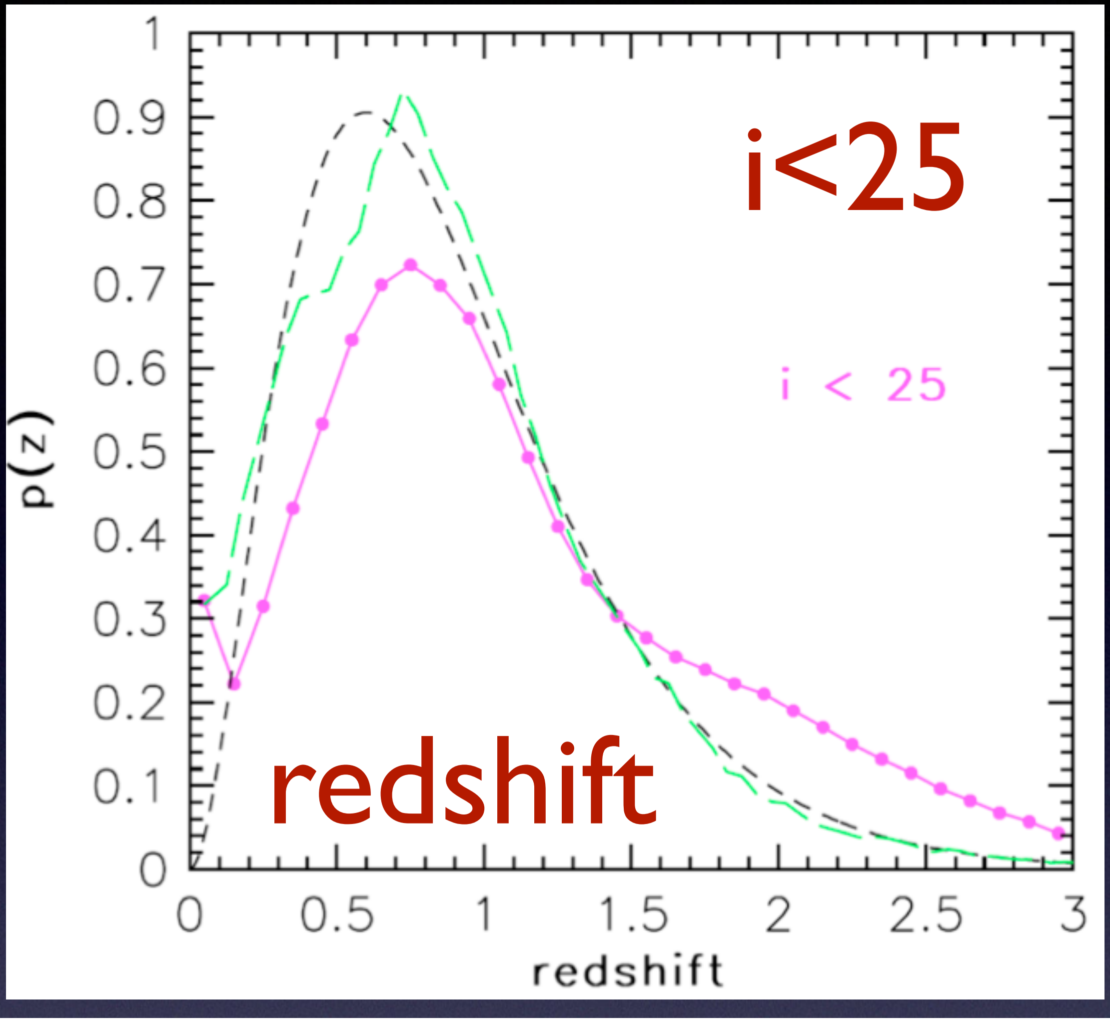


Reyes et al. (2010, Nature 464, 256)

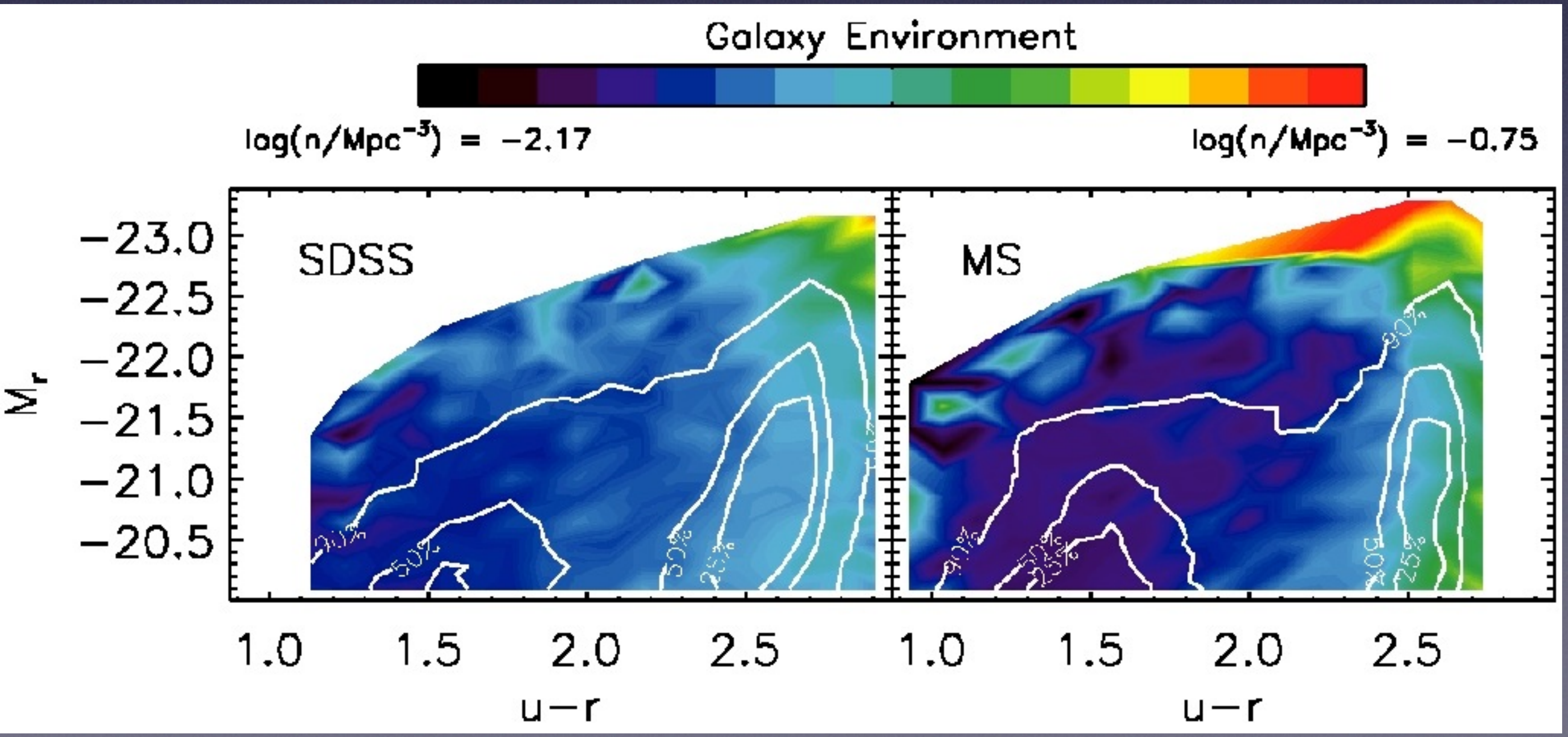
LSST will measure E_G about 10 times more precisely and will be able to rule out a large class of modified gravity theories (or GR!)

- 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)

Extragalactic astronomy: galaxies



- About 10 billion galaxies, with 4 billion in a "gold" sample defined by i<25.3
- The "gold" sample extends to redshifts of >2.5: evolution

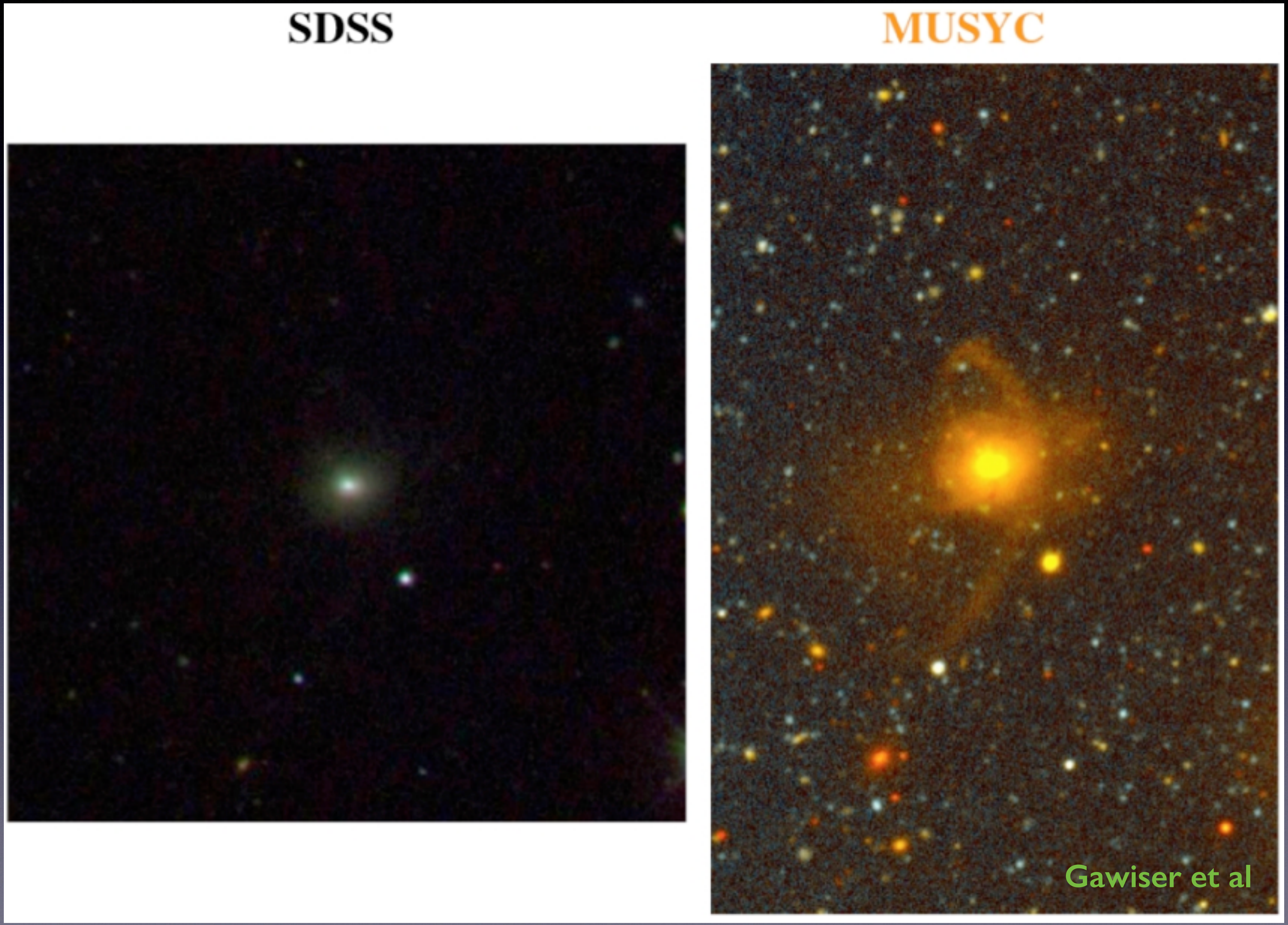


SDSS: snapshot at z~0

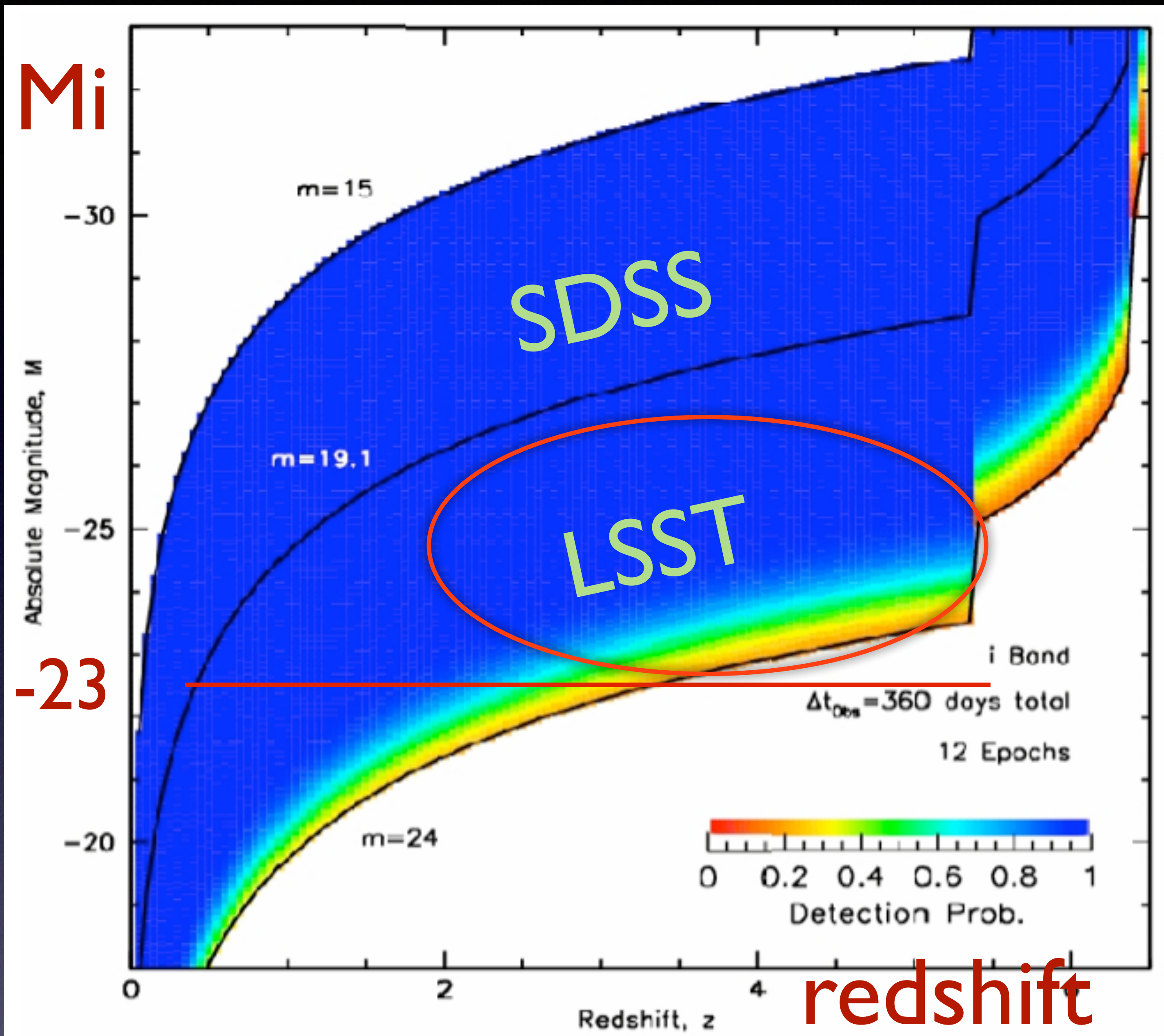
LSST:

a galaxy evolution movie to z~2.5

Extragalactic astronomy: galaxies



Extragalactic astronomy: quasars



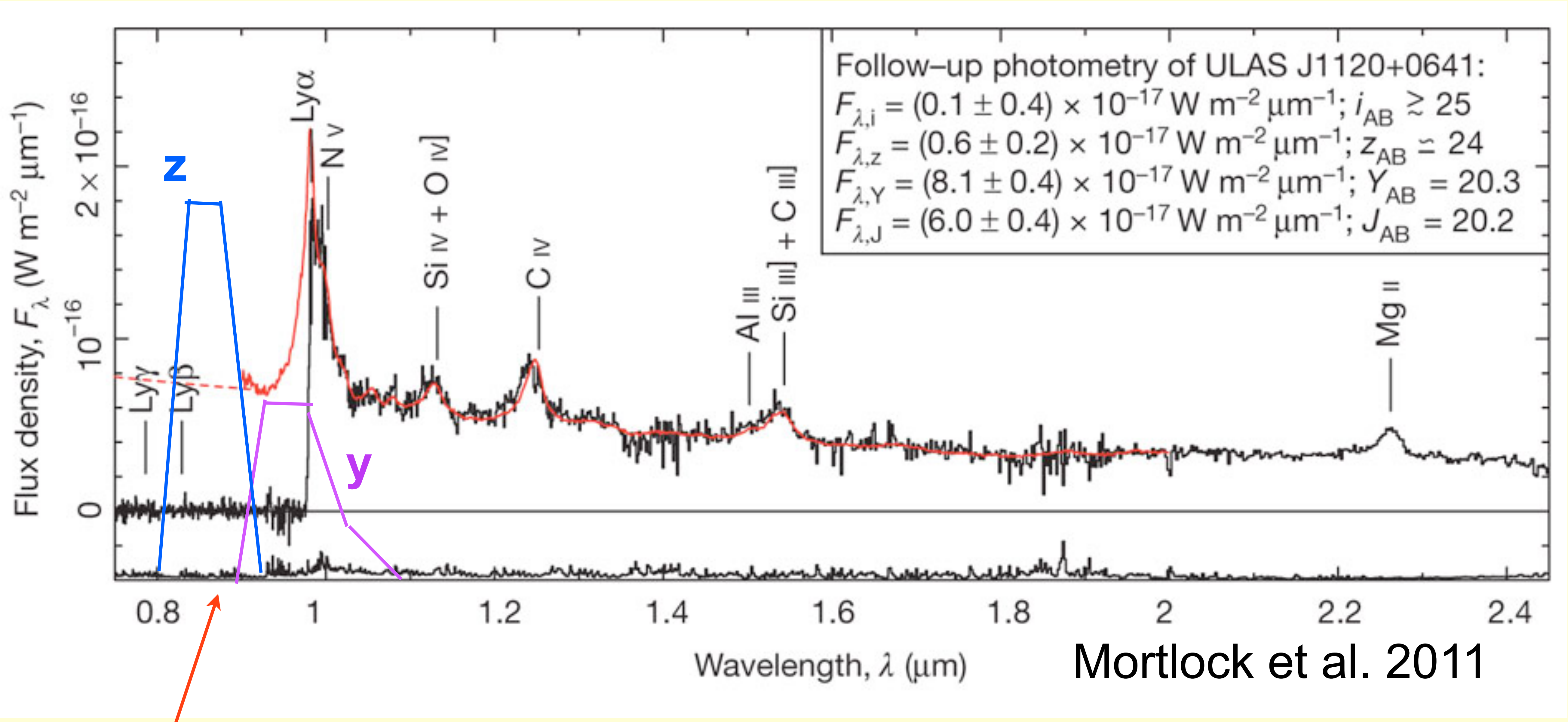
Top: absolute magnitude vs. redshift diagram for quasars

- About 10 million quasars will be discovered using variability, colors, and the lack of proper motions
  Really?? SDSS: yes!
- The sample will include Mi=-23 objects even at redshifts beyond 3
- Quasar variability studies will be based on millions of light curves with 1000 observations over 10 yrs

Today: ~31 quasars with 6<z<7.5 **Reionization studies!**

LSST will detect ~10,000 quasars with 6<z<7.5!

The Highest Redshift Quasar at z=7.085 from UKIDSS



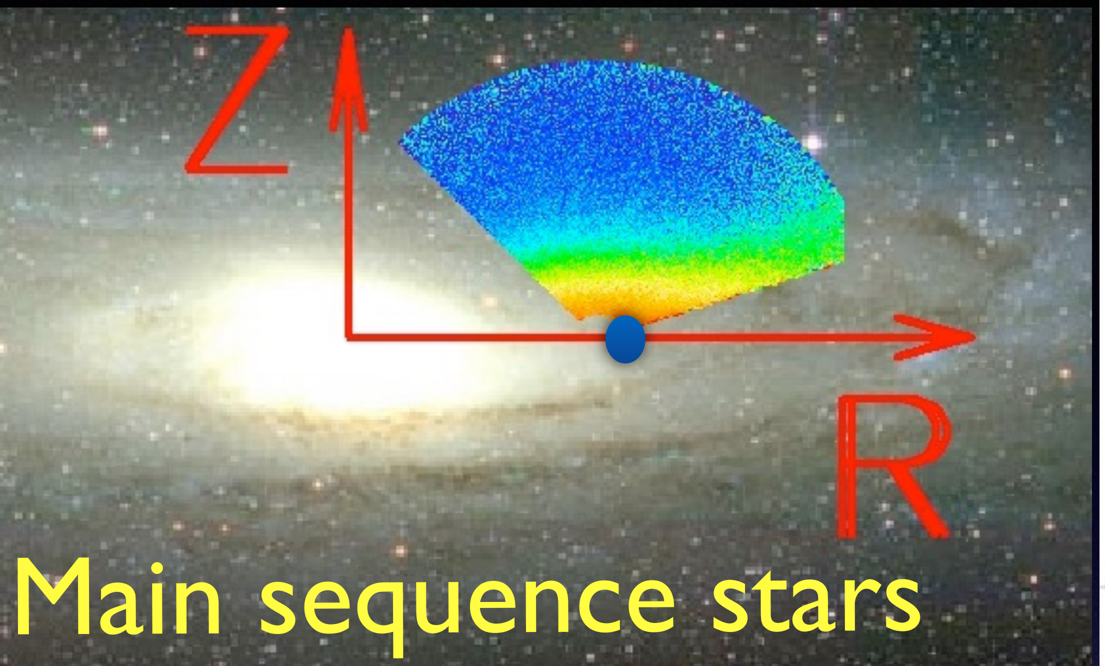
Such a quasar would be detected by LSST as a z-band dropout

(multi-epoch data will greatly help with false positives)

LSST will discover about 1,000 quasars with z>7

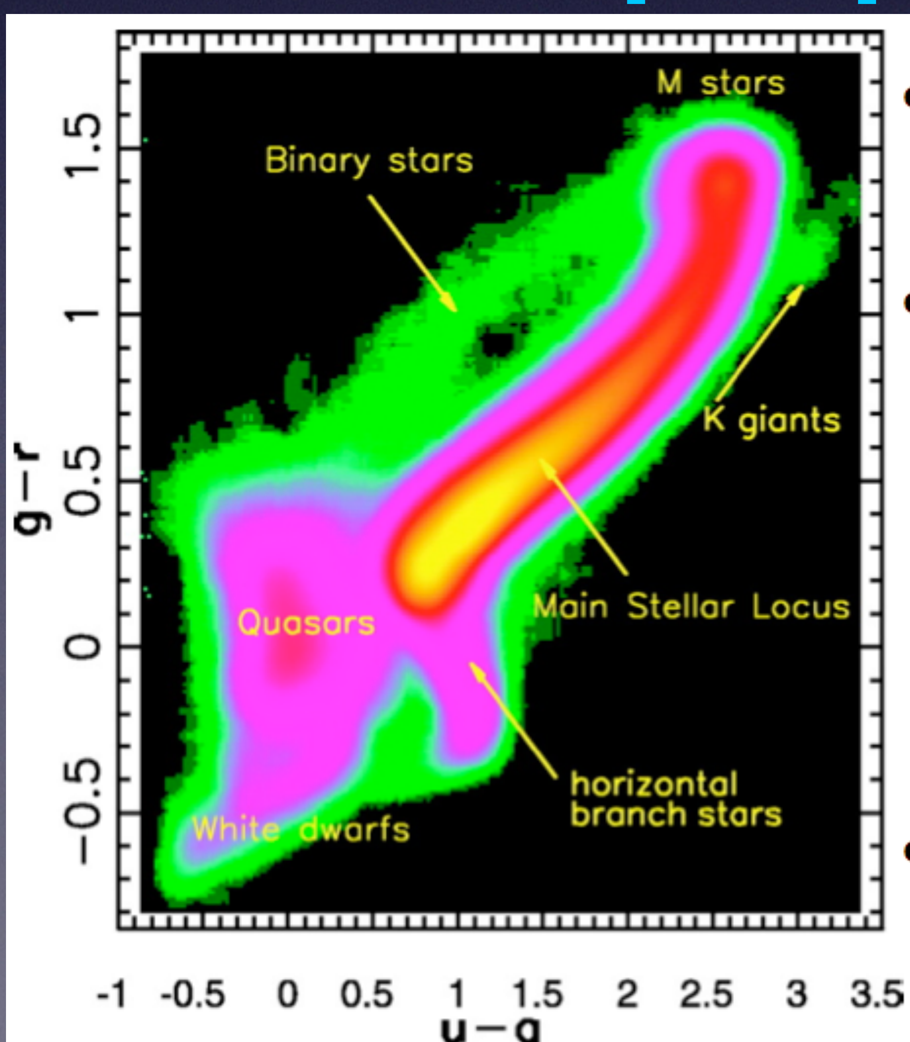
Today: one quasar with z>7

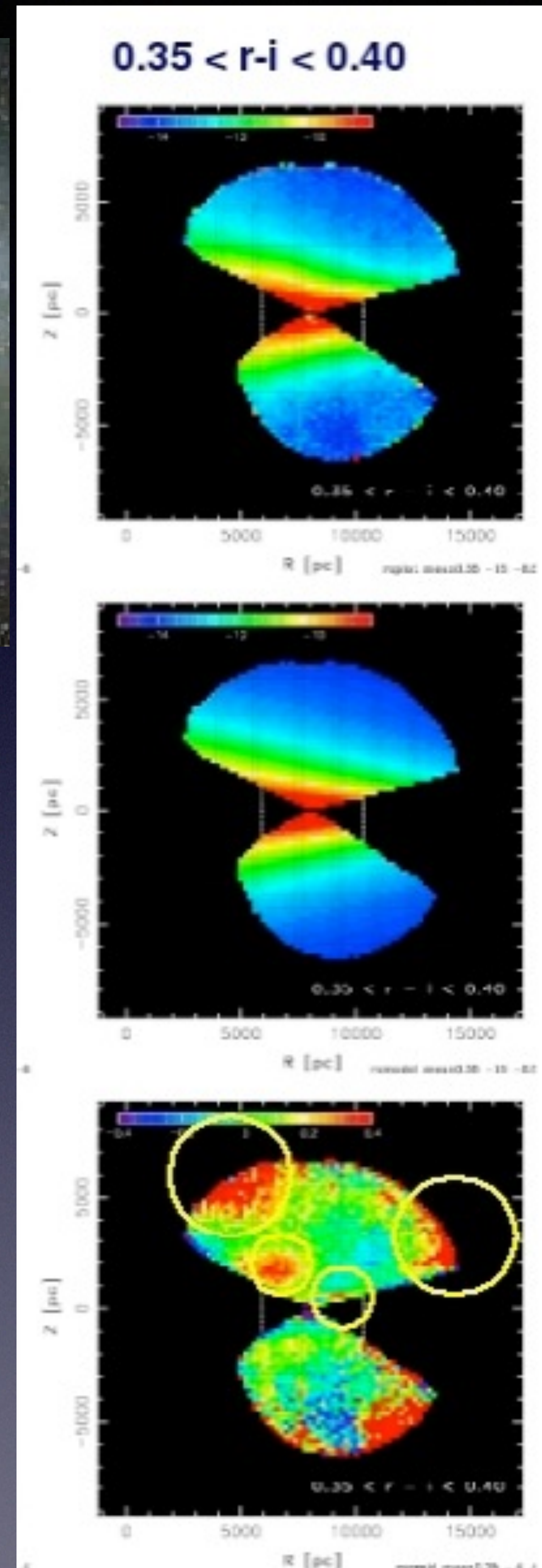
The Milky Way structure: 10 billion stars, time domain

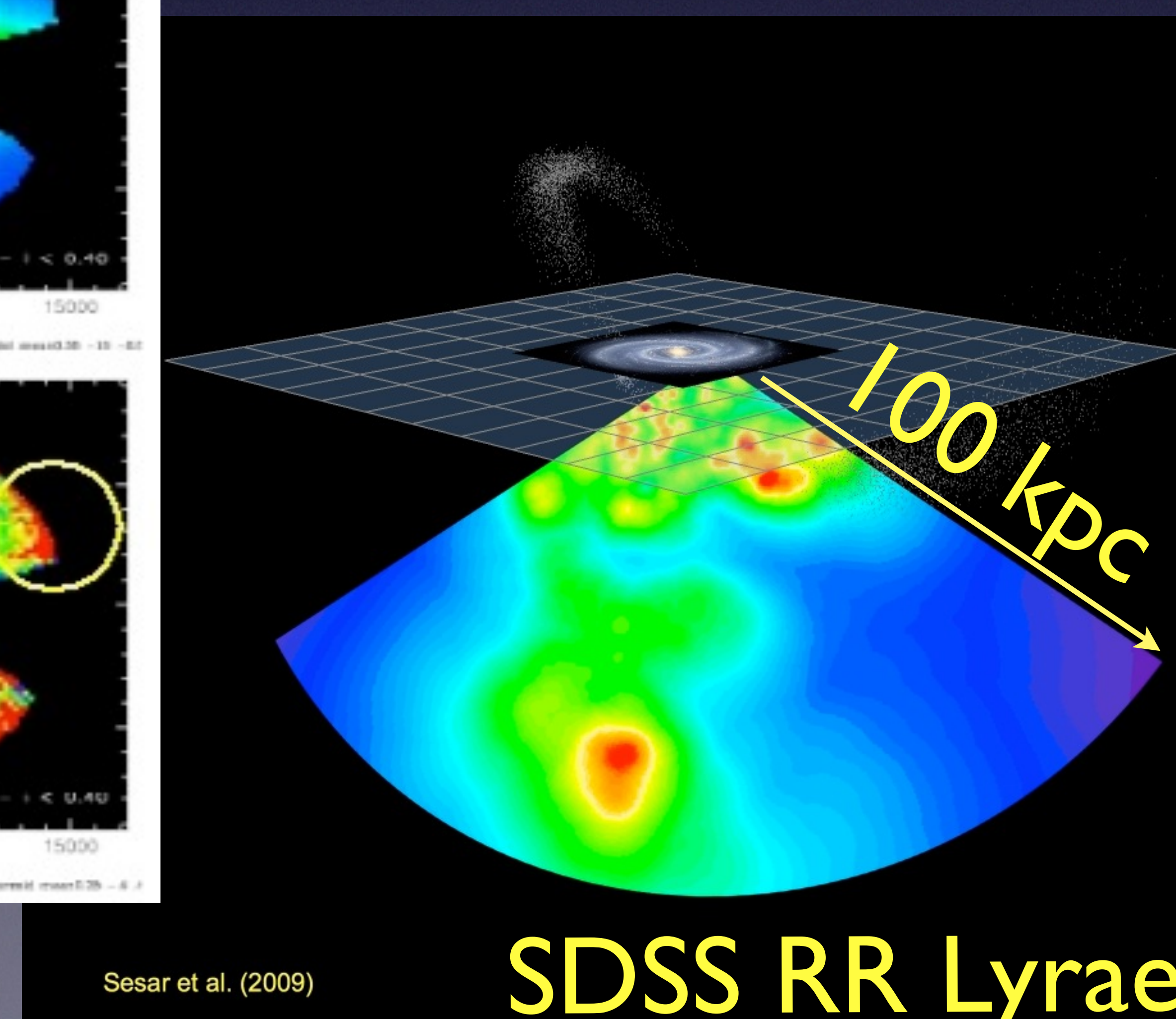


Compared to SDSS: LSST can "see" 10 times further away and over twice as large an area

Distance and [Fe/H]:



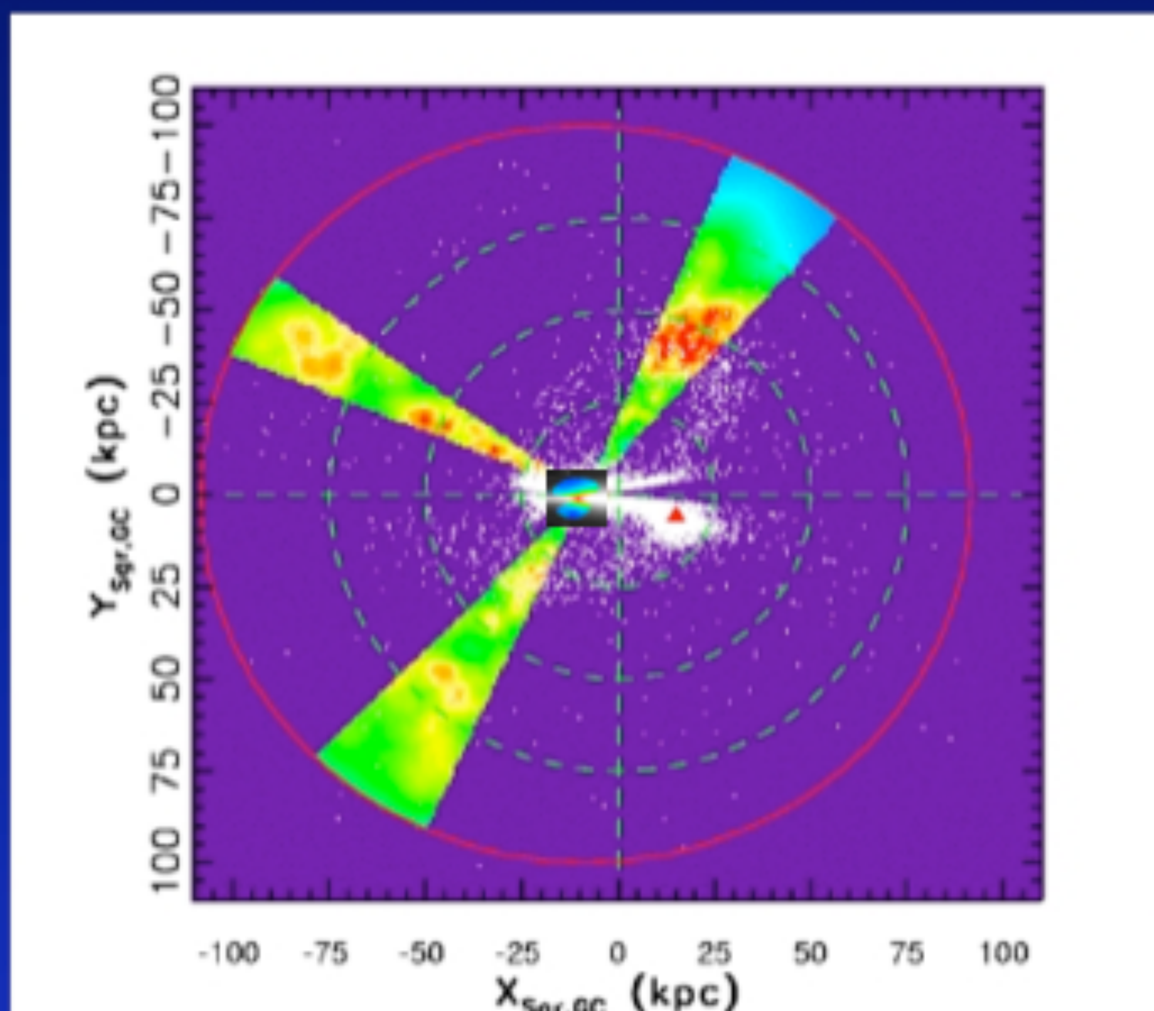




The large blue circle: the ~400 kpc limit of future LSST studies based on RR Lyrae

LSST limit for RR Lyrae: 400 kpc

The large red circle: the ~100 kpc limit of future LSST studies based on main-sequence stars (and the current limit for RR Lyrae studies)



The small insert: ~10 kpc limit of SDSS and future Gaia studies for kinematic & $[Fe/H]$ mapping with MS stars

Time Domain: objects changing in time

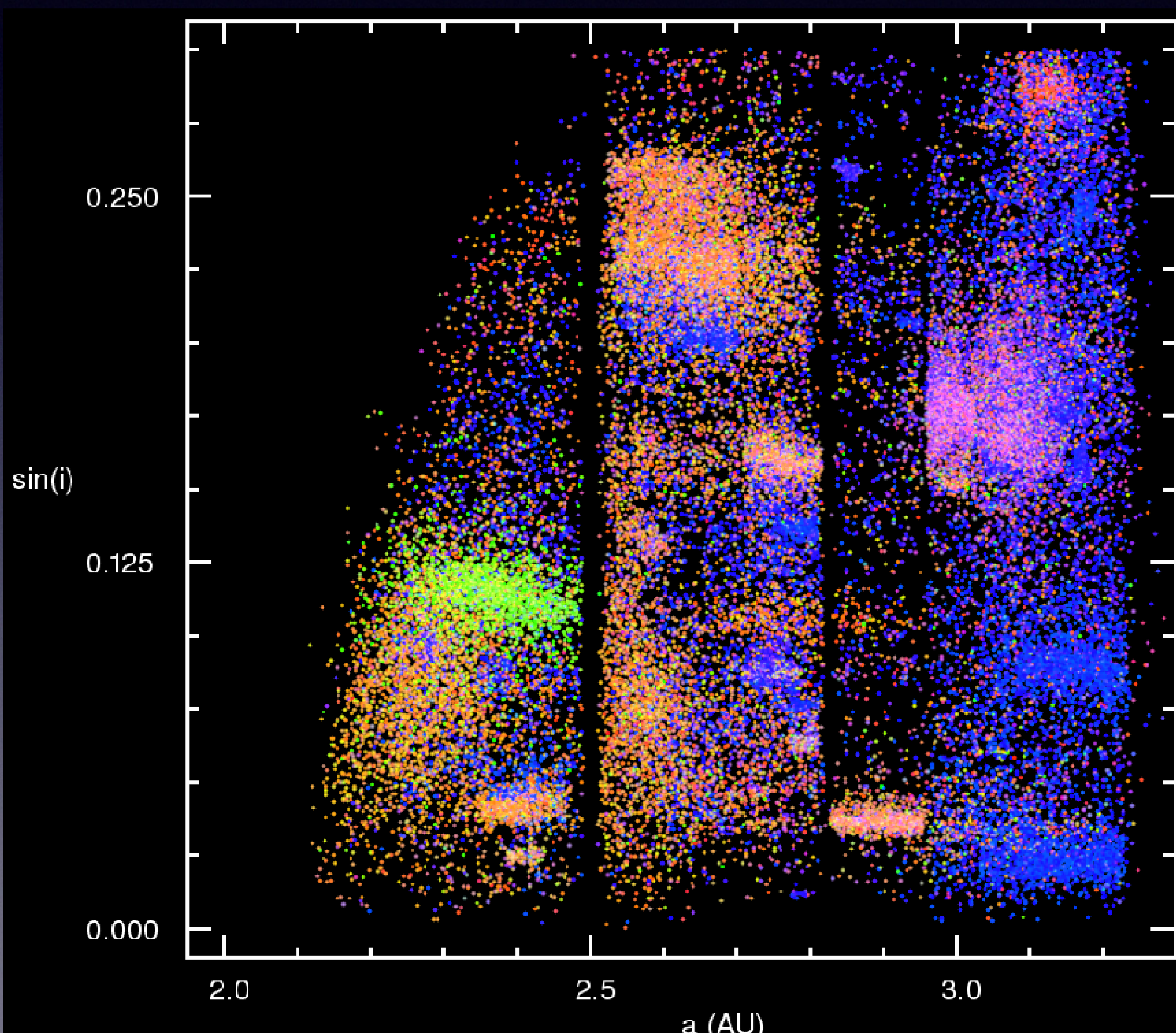
positions: asteroids and stellar proper motions

brightness: cosmic explosions and variable stars

Time Domain: objects changing in time

positions: asteroids and stellar proper motions

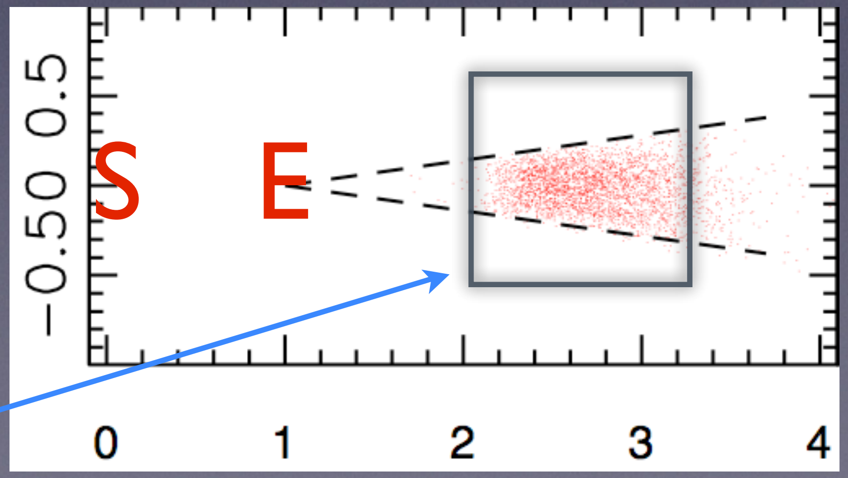
brightness: cosmic explosions and variable stars



For example:

SDSS demonstrated that asteroid families have distinct colors: chemical composition

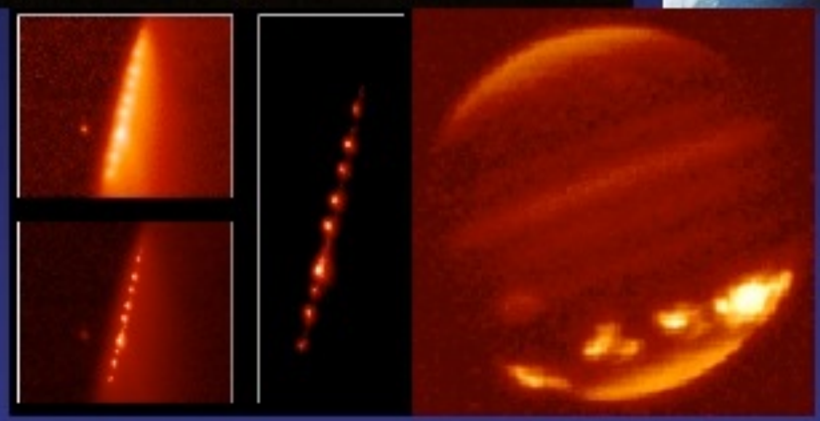
LSST will turn this diagram into a movie (millions of asteroids)



Killer asteroids: the impact probability is not 0

photomontage!

LSST is the only survey capable of delivering completeness specified in the 2005 Congressional NEO mandate to NASA (to find 90% NEOs larger than 140m)



Shoemaker-Levy 9 (1994)

Tunguska (1908)

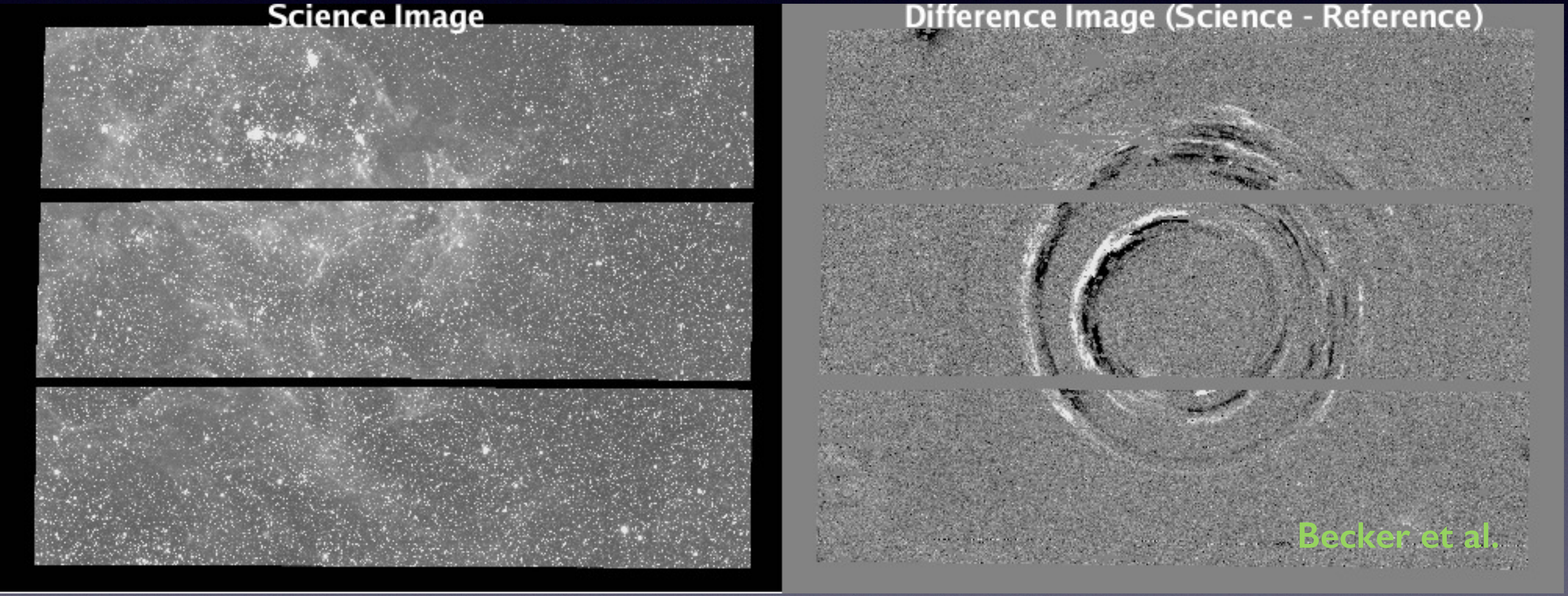
The Barringer Crater, Arizona: a 40m object 50,000 yr. ago

Time Domain: objects changing in time

positions: asteroids and stellar proper motions

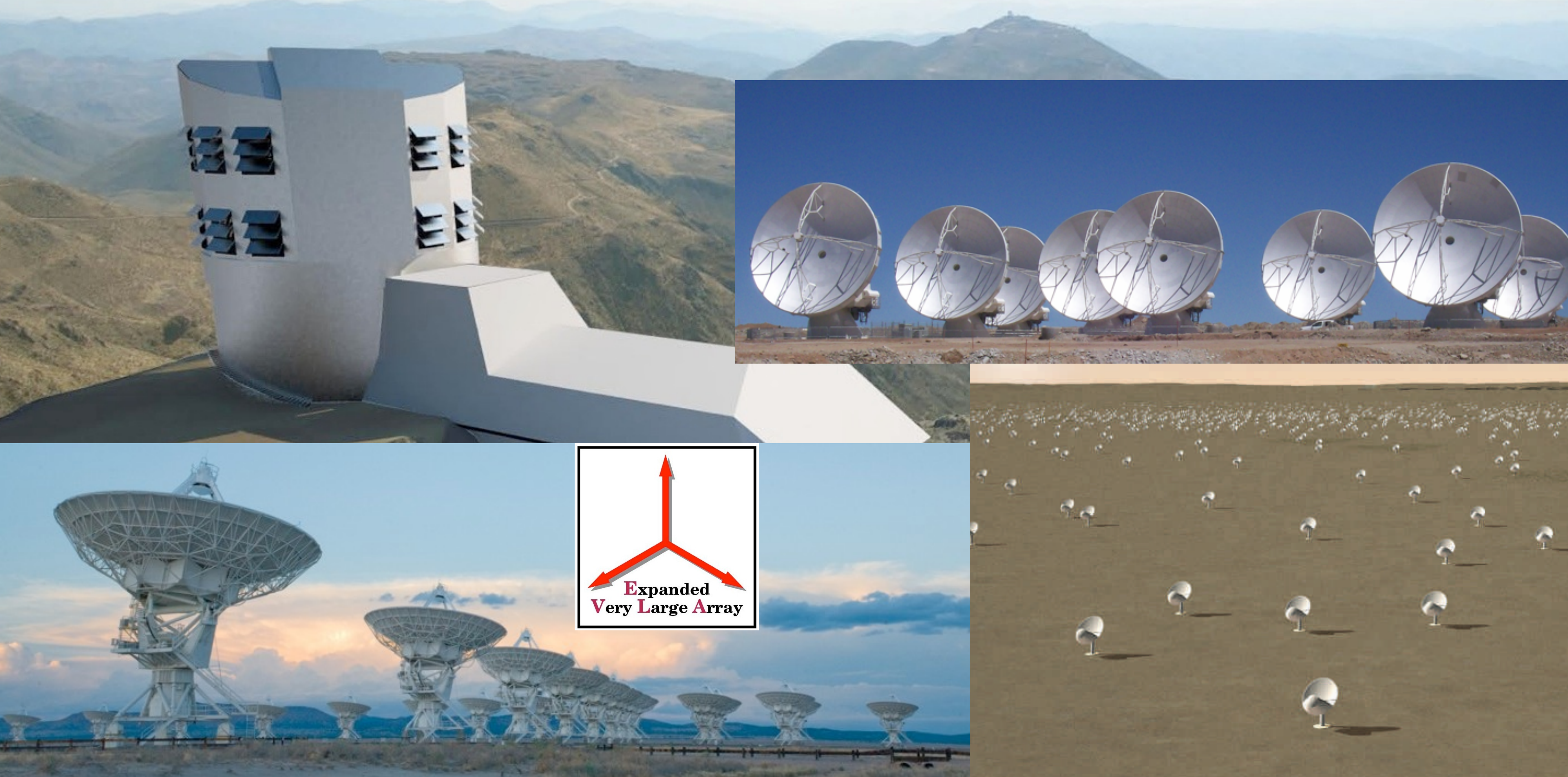
brightness: cosmic explosions and variable stars

Not only point sources - echo of a supernova explosion:



As many variable stars from LSST, as **all** stars from SDSS

Web stream with data for transients within 60 seconds



The impact of LSST on other wavelengths, and vice versa:

1) Science Results (e.g. galaxy/AGN evolution)

2) Tools and Methods (e.g. massive databases [radio])

3) Supplemental data (coeval, identification, physical processes)

Also non-EM: e.g. Advanced LIGO

Outline

- **LSST system summary**
  - Science Themes
  - System Characteristics
- **LSST science examples**
  - Extragalactic astronomy and cosmology
  - The Milky Way and the Local Group
  - Time Domain
- **The road ahead**

Decadal Survey 2010

Priorities:

- Spaced-based:

1) *Wide-Field Infrared Survey Telescope WFIRST*
2) *The Explorer Program "rapid response"*
3) *Laser Interferometer Space Antenna LISA*
4) *International X-ray Observatory IXO*

- Ground-based:

1) ***Large Synoptic Survey Telescope LSST***
2) *Mid-scale Innovations Program "rapid response"*
3) *Giant Segmented Mirror Telescope (30m) GSMT*
4) *Atmospheric Čerenkov Telescope Array (ϒ) ACTA*
5) *Cerro Chajnantor Atacama Telescope (submm) CCAT*

Decadal Survey 2010

- **Why LSST?**

The top rank accorded to LSST is a result of:

(1) "its **compelling science case** and capacity to address so many of the science goals of this survey", [and]

(2) "**its readiness** for submission to the MREFC process as informed by its technical maturity, the survey's assessment of risk, and appraised construction and operations costs."

Also: "education and public outreach"

Bill Gates: "LSST will be the ultimate network peripheral device to the Universe"

Google Sky, World Wide Telescope, ...

Decadal Survey 2010

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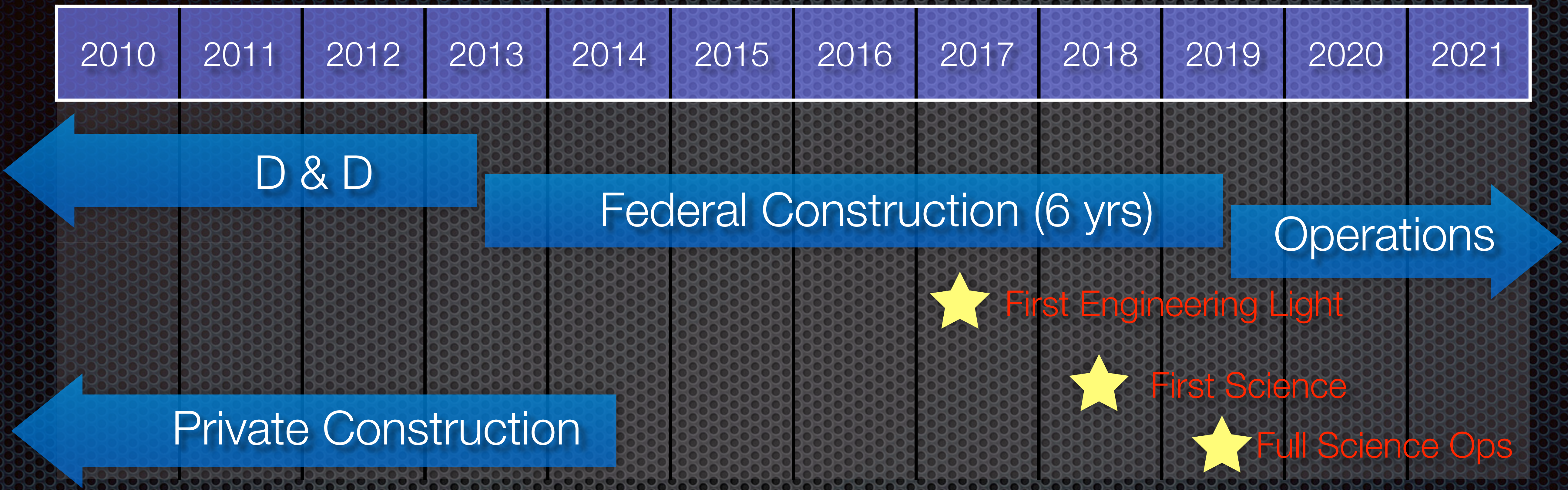
LSST Science Book

Summarizes the basic parameters of the LSST hardware, software, and observing plans, discusses educational and outreach opportunities, and describes a broad range of science that LSST will revolutionize

245 authors, 15 chapters, 600 pages

LSST Timeline

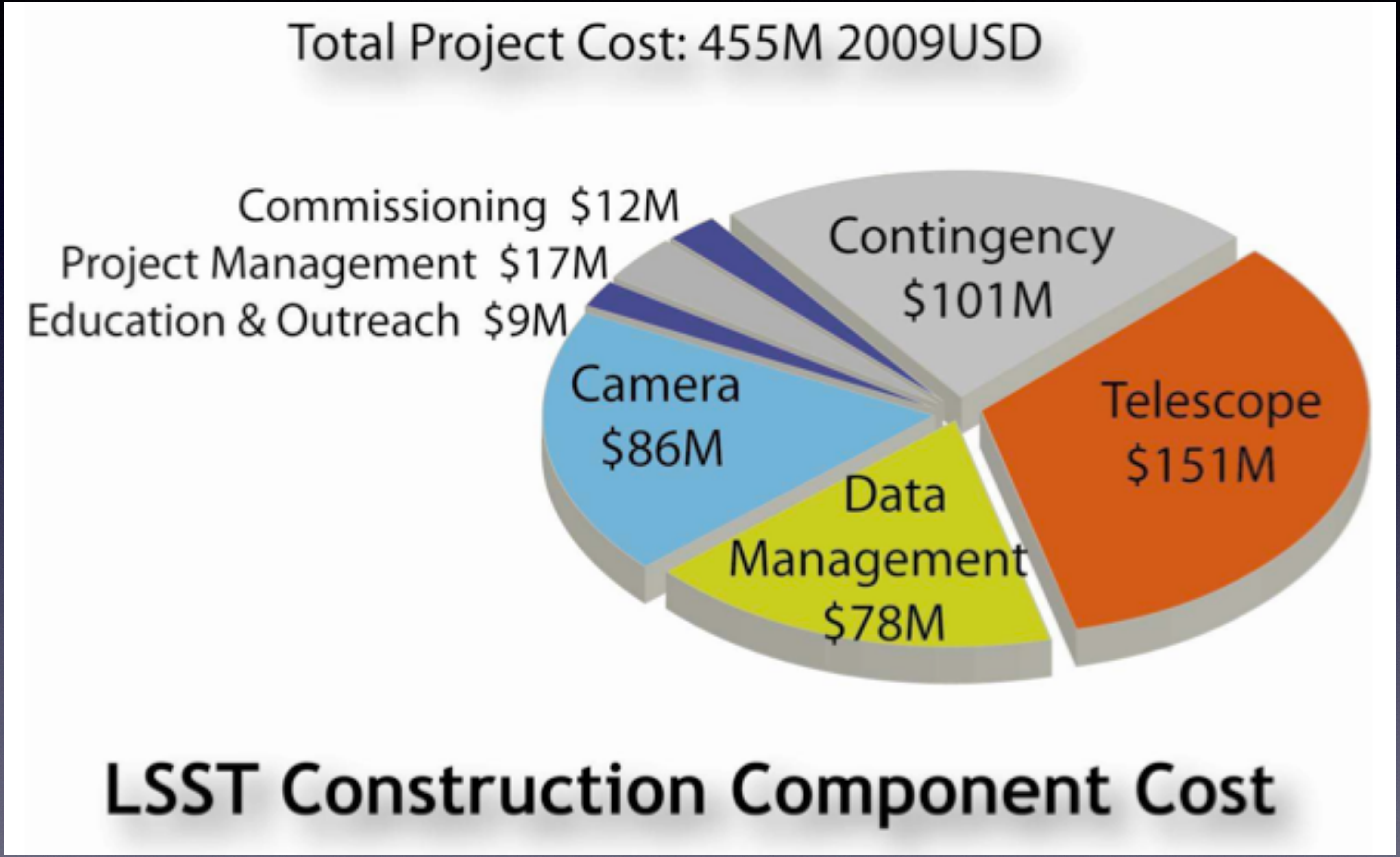


- **Estimate: survey operations begin in 2019 (if MREFC in FY2014)**
  - Primary/Tertiary Mirror being polished, have secondary mirror blank
  - Sensor development program delivered first prototype sensors
  - Processing pipelines under construction, hand-in-hand with simulations of Operations, Images, Catalogs
- **Cost:** ~$850M in $2011

  contributions from NSF, DOE and private gifts

How to spend a billion dollars?

Half for construction, half for 10 years of operations



First light: around 2019 (if federal constr. in FY2014)

El Penon: Mar 8, 2011

At 8:56:00 the first blast was detonated on the El Penon summit in preparation for the LSST...


April 12, 2011

Useful LSST Links:

Main public website:
http://www.lsst.org/

Science Requirements Document:
http://www.lsst.org/files/docs/SRD.pdf

Overview paper:
http://www.lsst.org/files/docs/overviewV2.0.pdf

LSST Science Book:
http://www.lsst.org/lsst/scibook