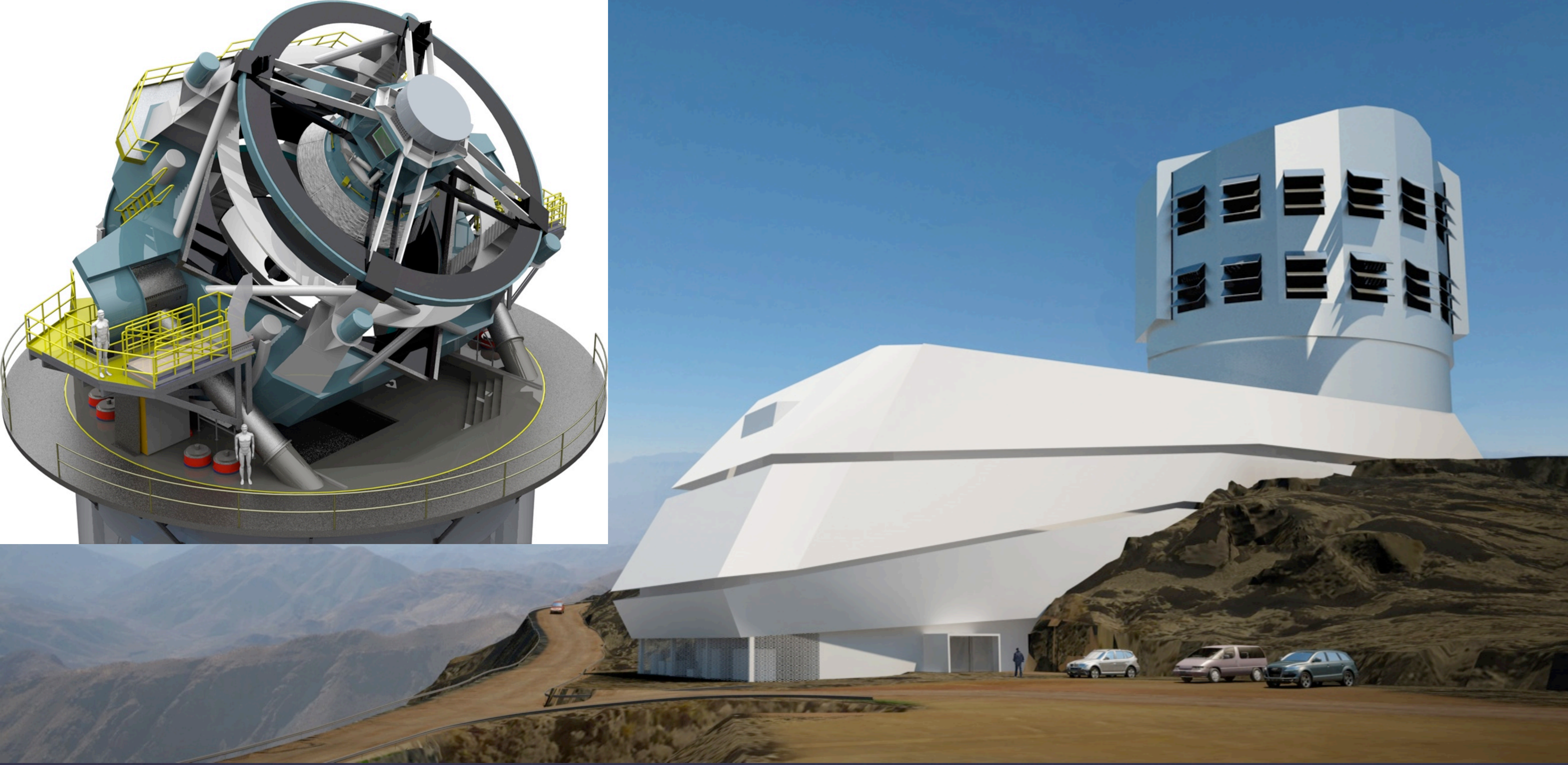

LSST: a digital color movie of the Universe

Željko Ivezić, LSST Project Scientist
Department of Astronomy, University of Washington

MIT colloquium, April 19, 2011

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

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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."

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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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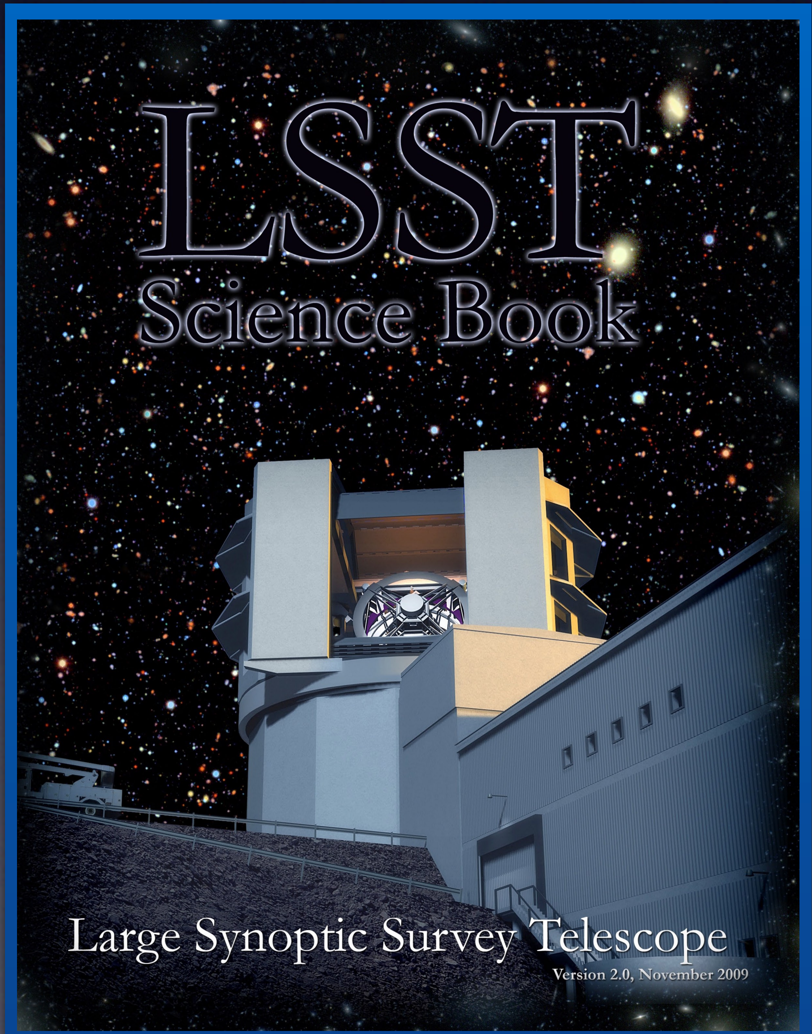
Also: "education and public outreach"

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



Outline

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

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)

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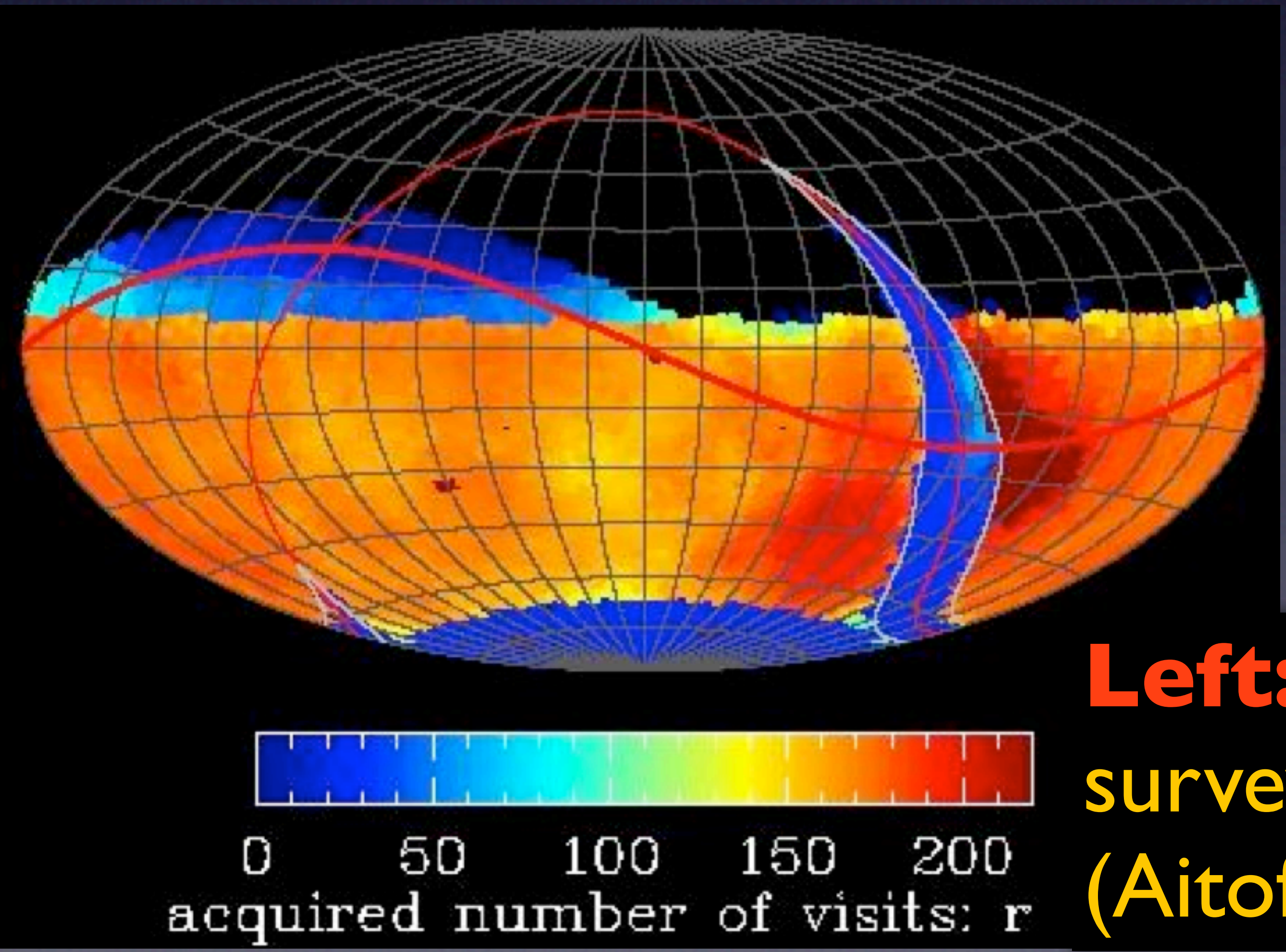
- The Solar System structure (asteroids)
- The Milky Way structure (stars)

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 20 billion objects**

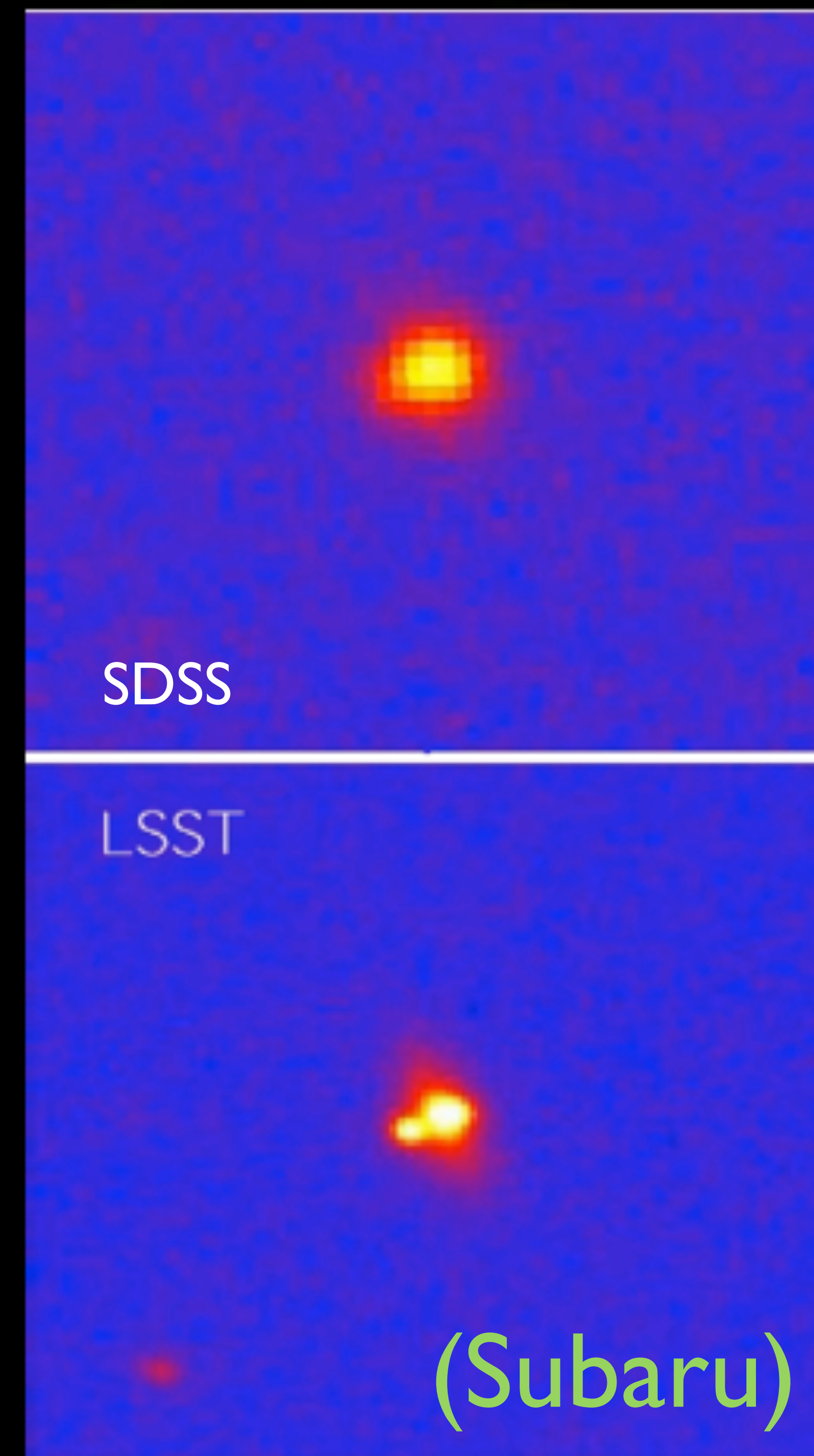


LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 1000 visits over a 10-year period: deep wide fast.

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

SDSS-LSST comparison: LSST=d(SDSS)/dt, LSST=SuperSDSS

3x3 arcmin, gri

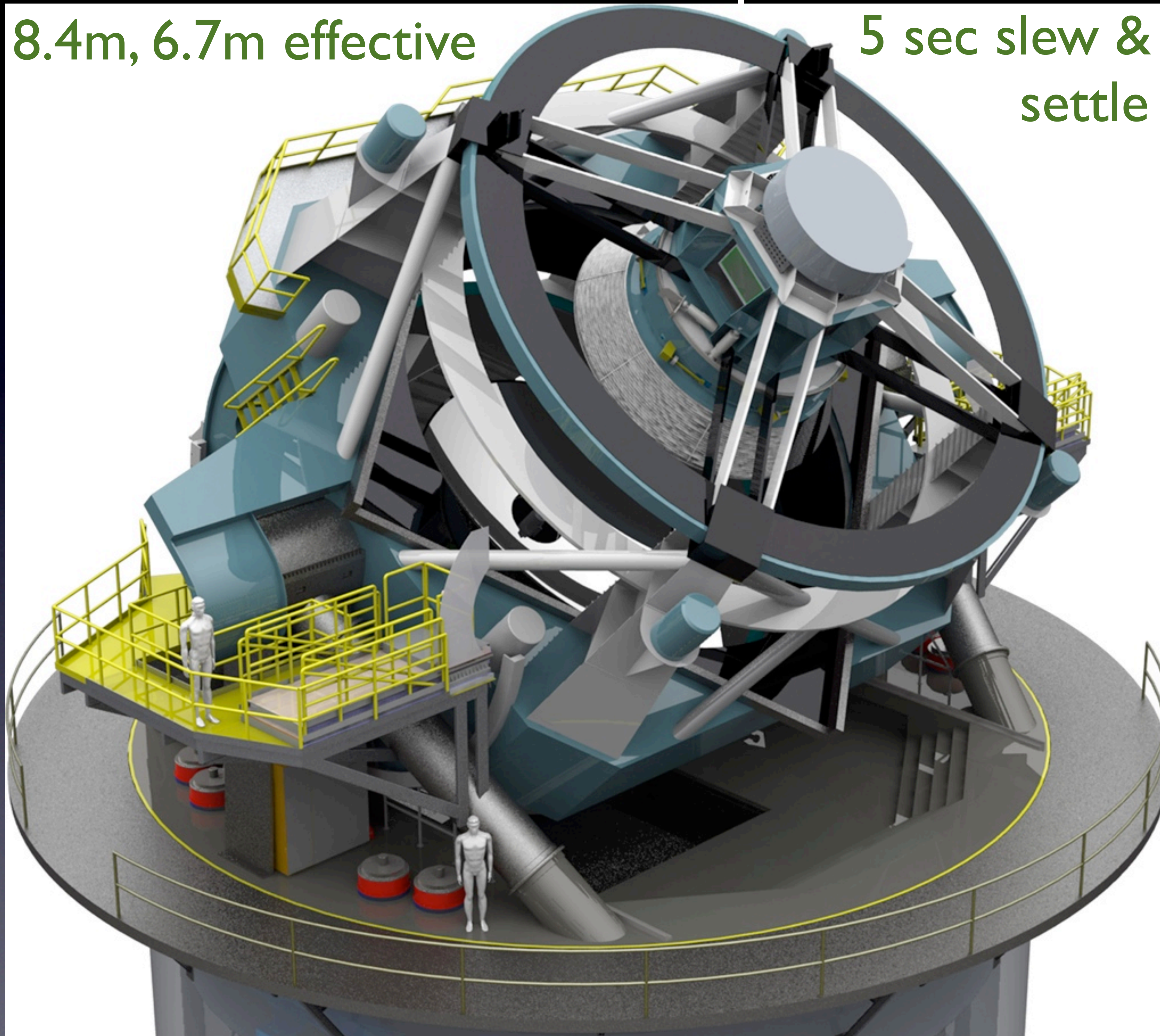


Required system characteristics

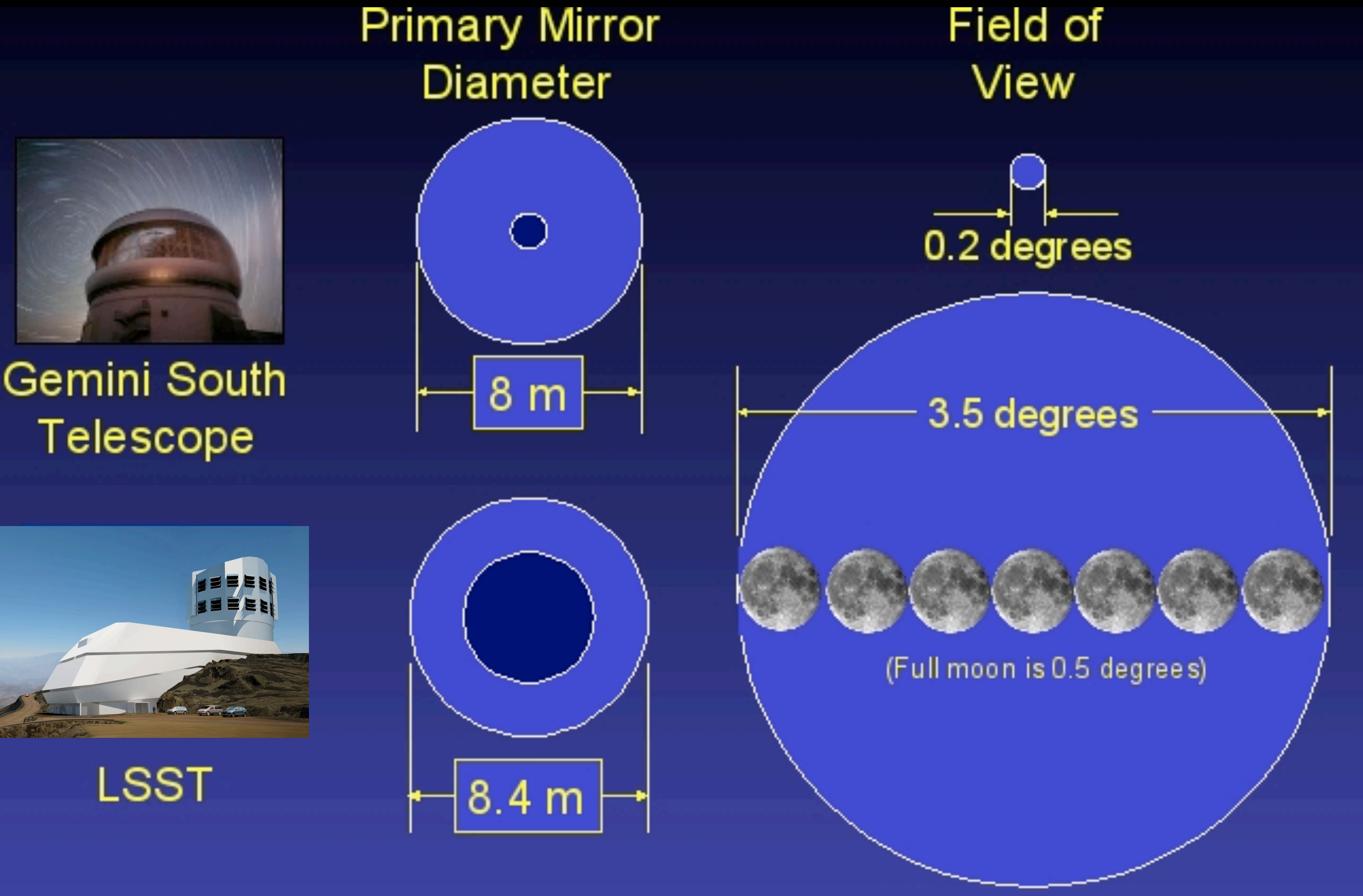
- Large primary mirror (at least 6m) to go faint and to enable short exposures (30 s)
- Agile telescope (5 sec for slew and settle)
- Large field of view to enable fast surveying
- Impeccable image quality (weak lensing)
- Camera with 3200 Mpix
- Sophisticated software (20,000 GB/night, 20 billion objects,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


LSST system
Telescope
Camera
Software

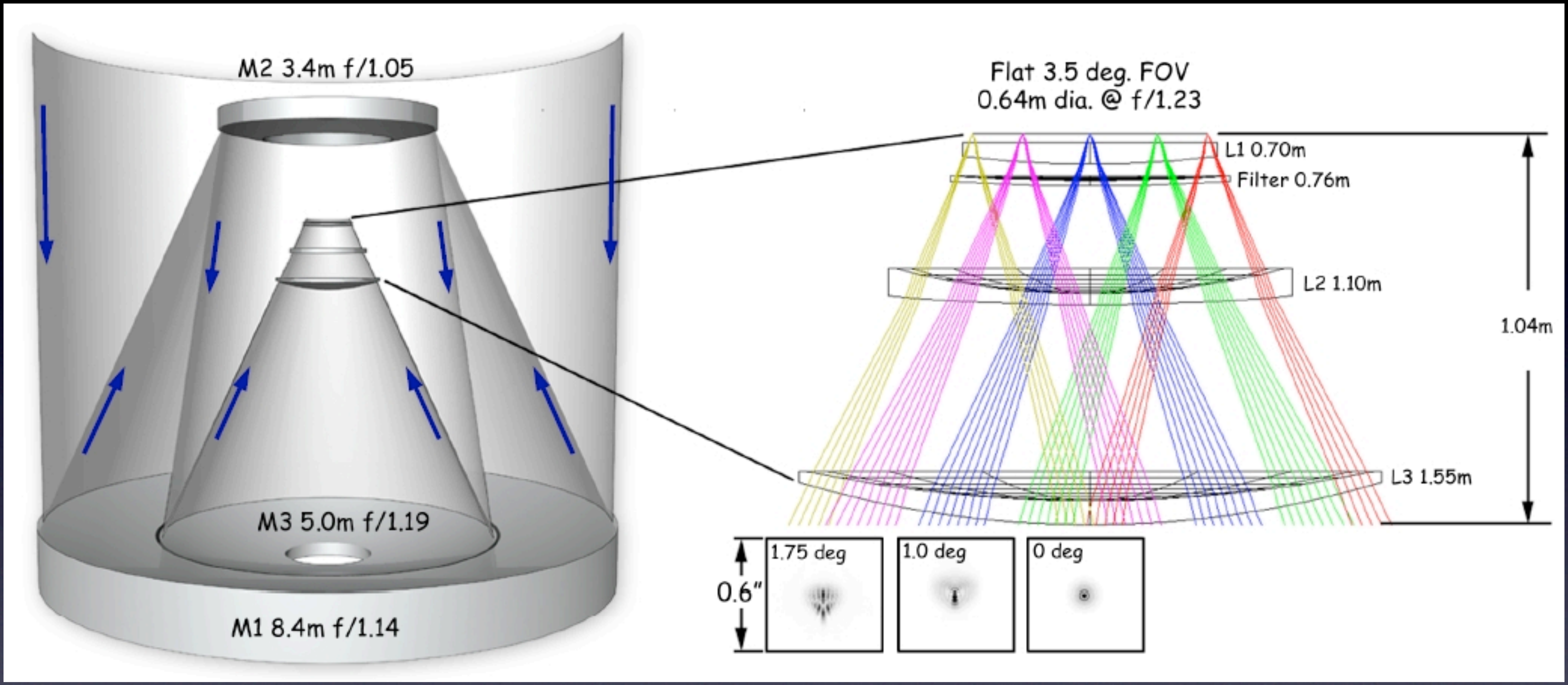
LSST Telescope



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

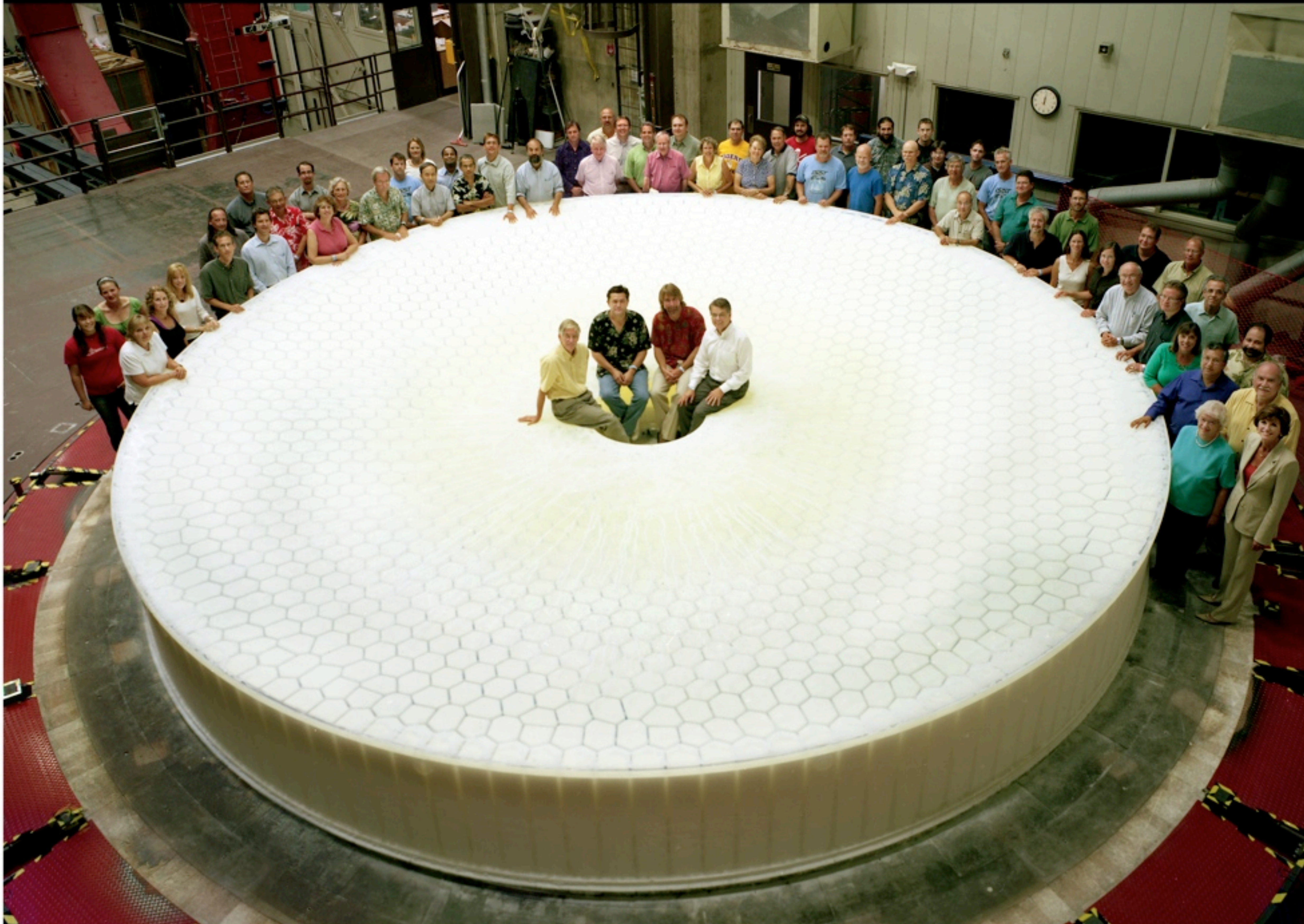


Optical Design for LSST



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

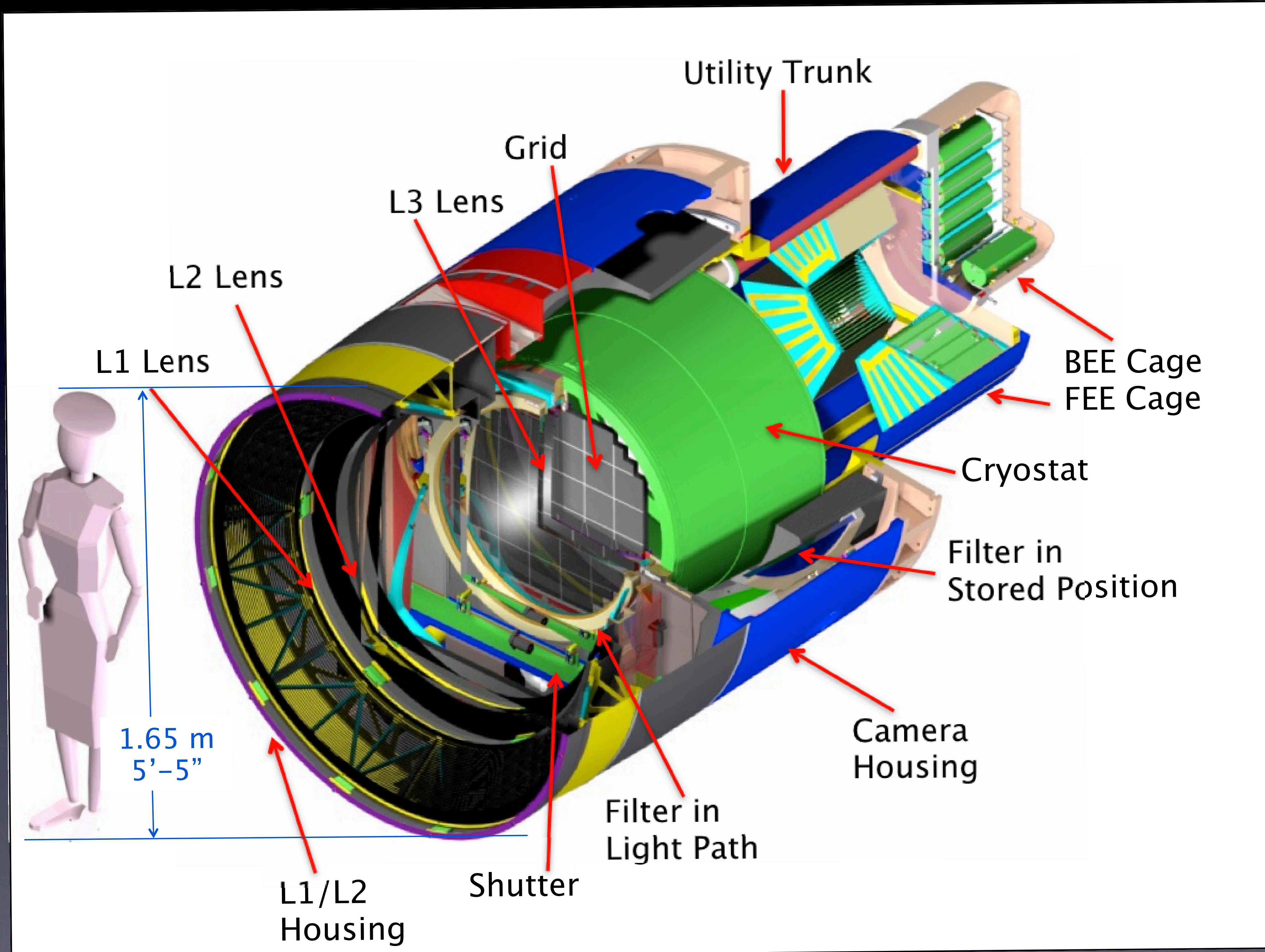
August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona

The University of Arizona. Tucson Arizona

SOML

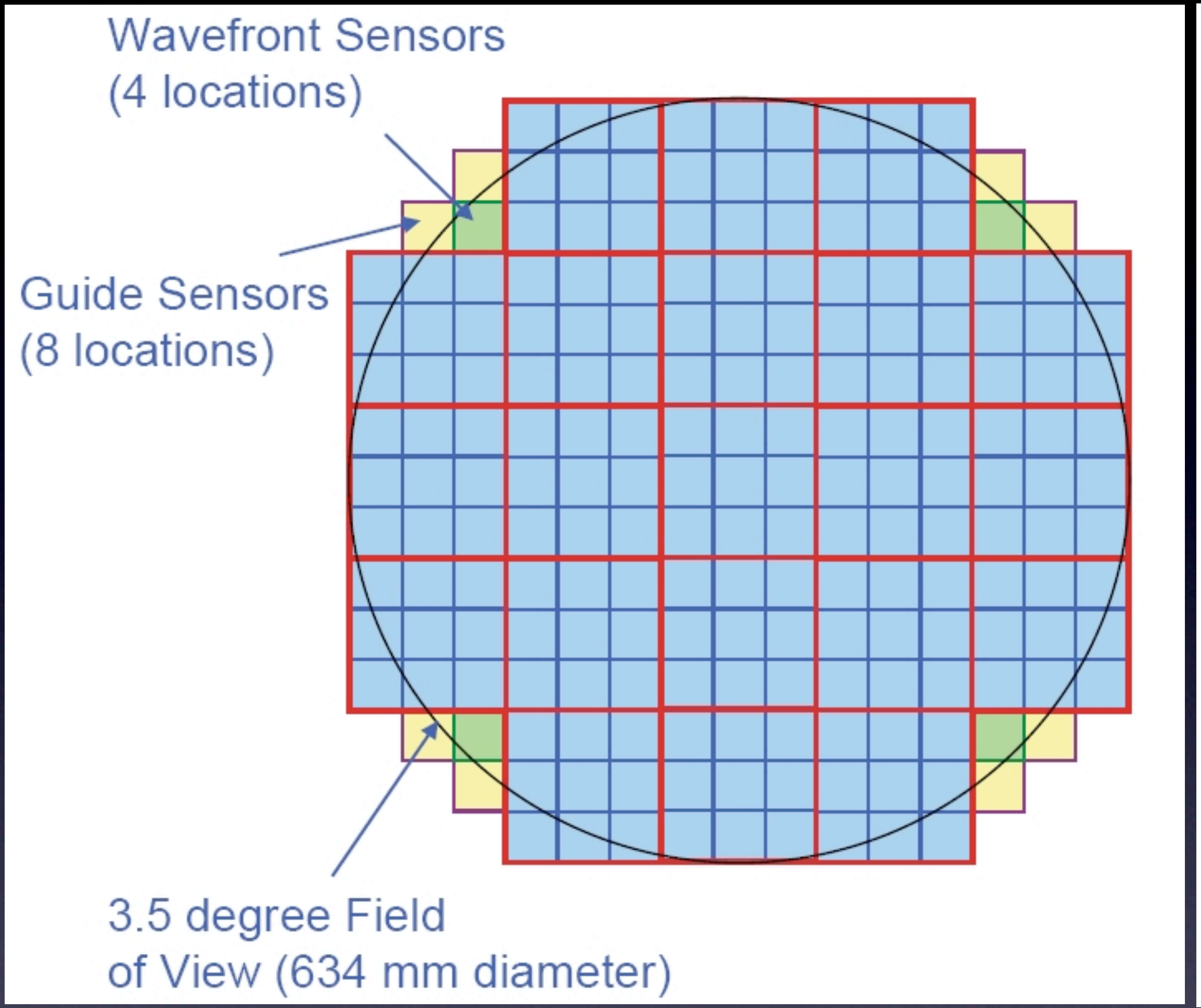
Large Synoptic Survey Telescope

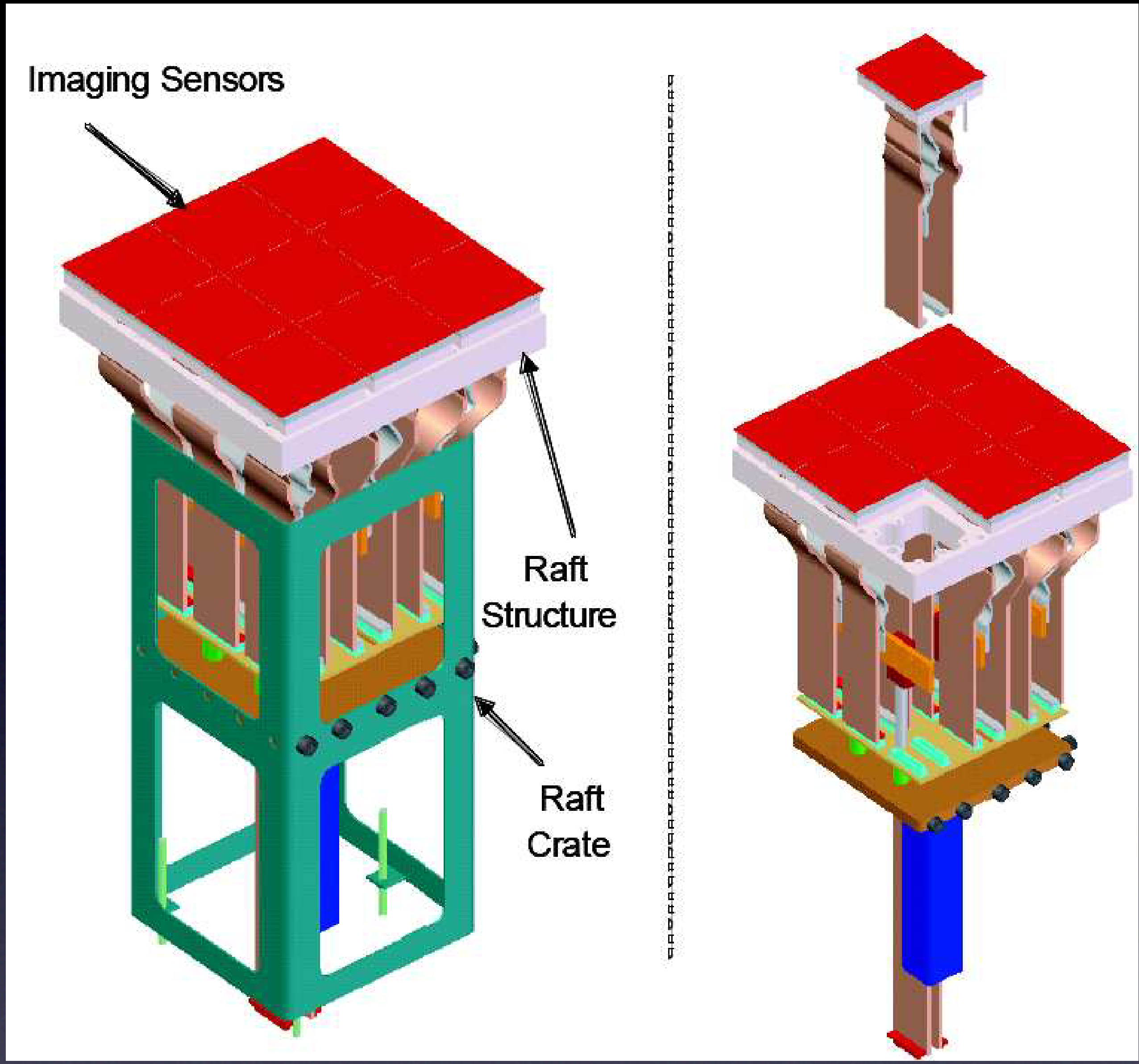
LSST camera



The largest astronomical camera: 2800 kg, 3.2 Gpix

LSST camera



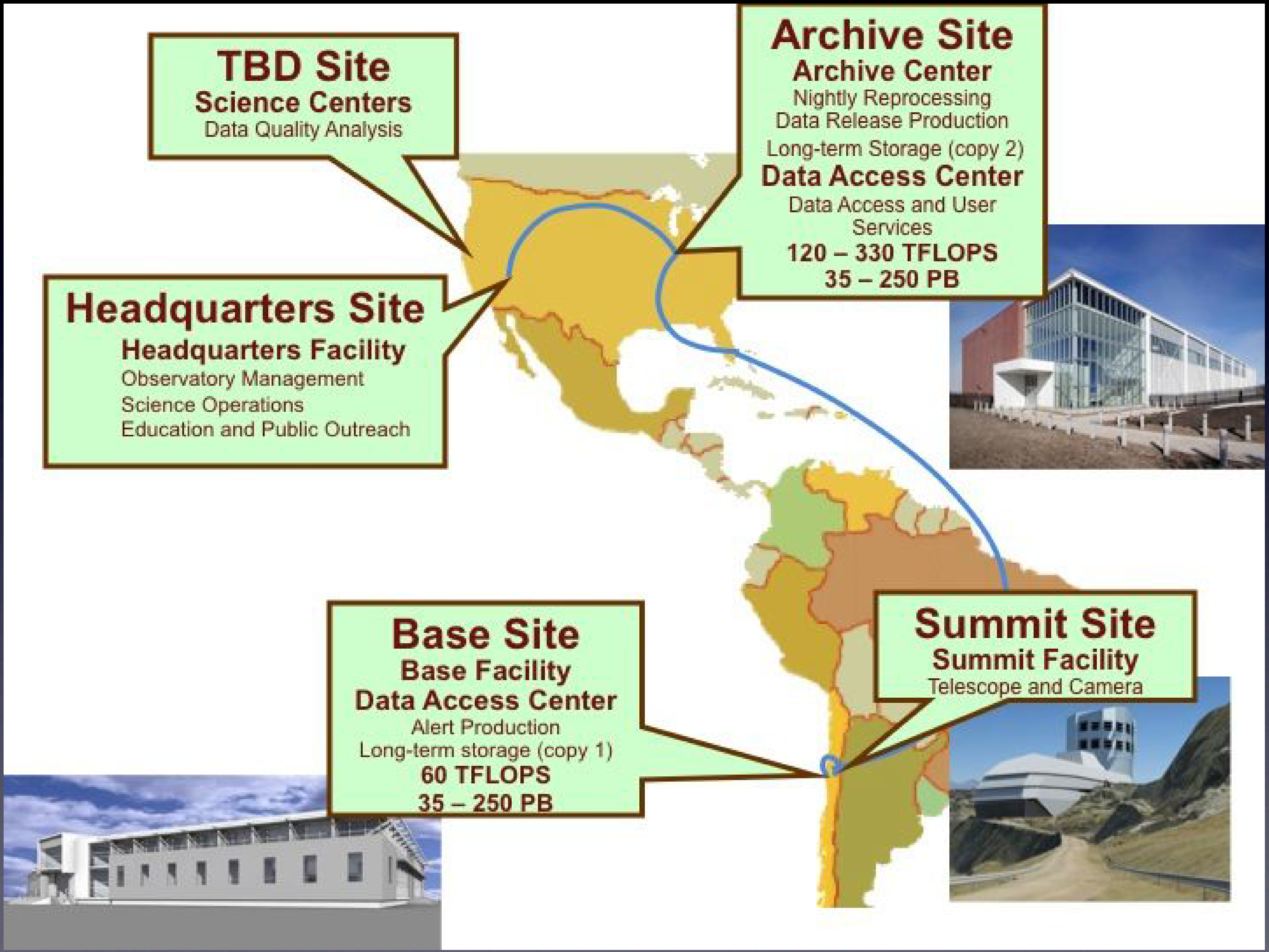


Modular design: 3200 Megapix = 189 x16 Megapix CCD

9 CCDs share electronics: raft (=camera)

Problematic rafts can be replaced relatively easily

LSST Software



Software: the subsystem with the highest risk

- 20 TB of data to process every day
- 1000 measurements for 20 billion objects during10 years
- Existing tools and methods (e.g. SDSS) do not scale up to LSST data volume and rate

Software: the subsystem with the highest risk

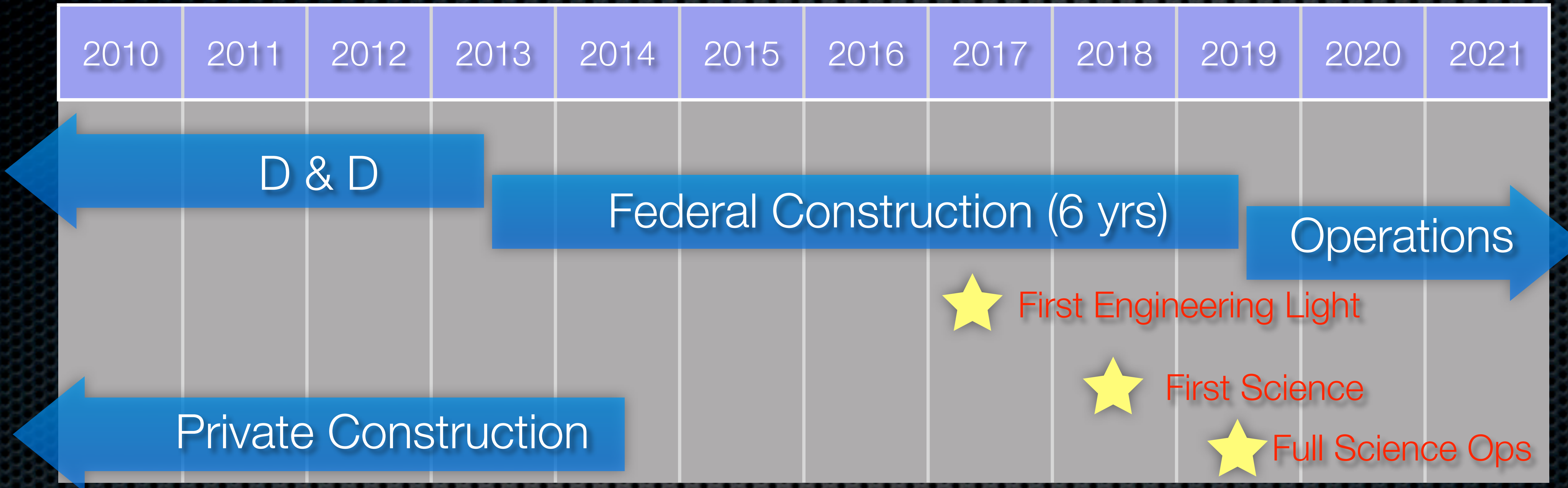
- 20 TB of data to process every day
- 1000 measurements for 20 billion objects during10 years
- Need for new tools and methods: **software, software, software!**

Changing paradigms...

Software: the subsystem with the highest risk

- 20 TB of data to process every day
- 1000 measurements for 20 billion objects during10 years
- Need for new tools and methods: **software, software, software!**
- About 5-10 million lines of new code
- C++/python
- A collaboration of astronomers, physicists and professional programmers

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: about the same as CATE estimate**
  (~$850M in $2011, contributions from NSF, DOE and private gifts)

El Penon: Mar 8, 2011

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

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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)

Modern Cosmological Probes

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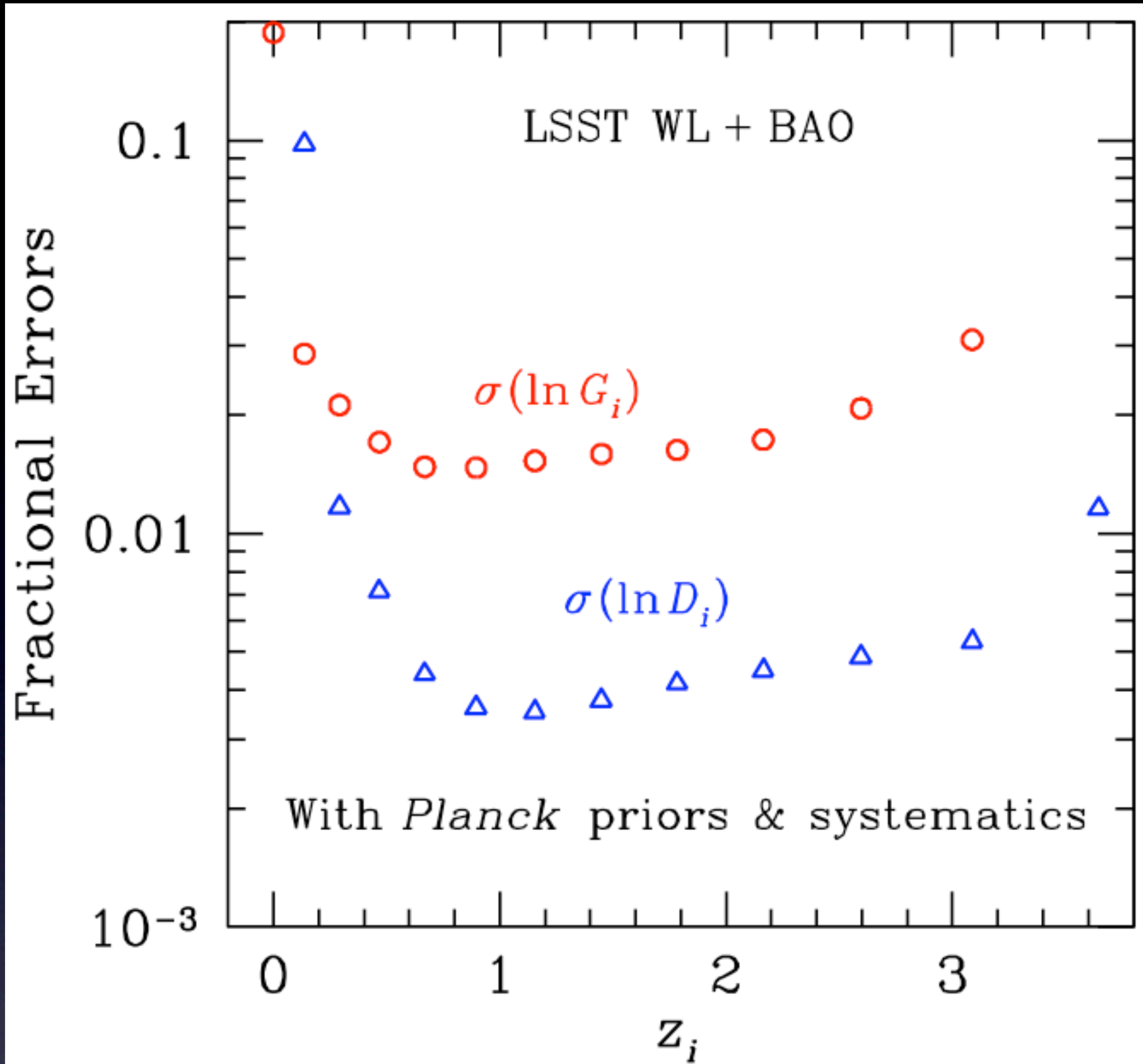
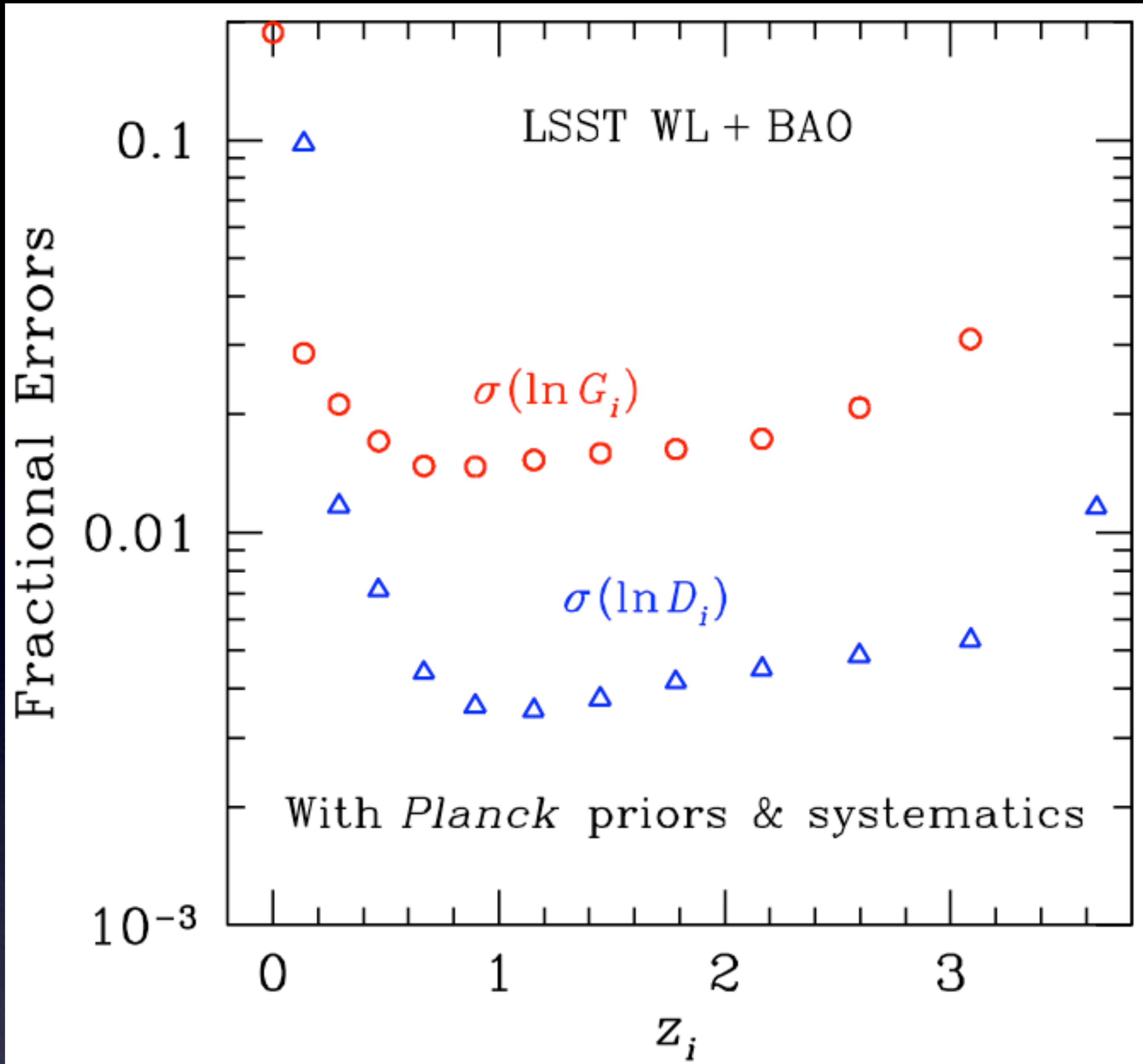
The Next Generation of Measurements: the Planck satellite for CMB, large optical/IR sky surveys for other methods: Dark Energy Survey, Pan-STARRS, LSST, WFIRST



Cosmology with LSST

- 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 isotropy of the Universe



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

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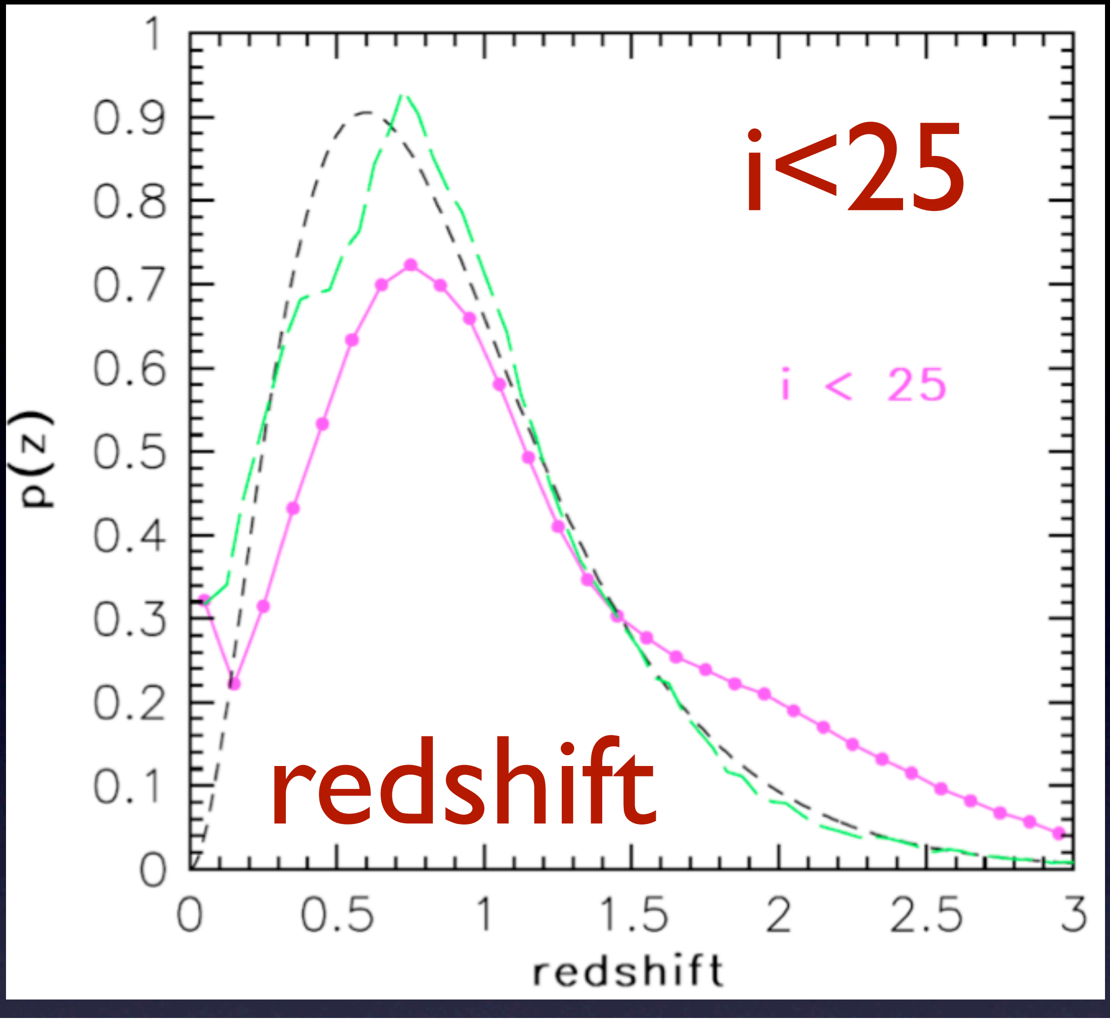
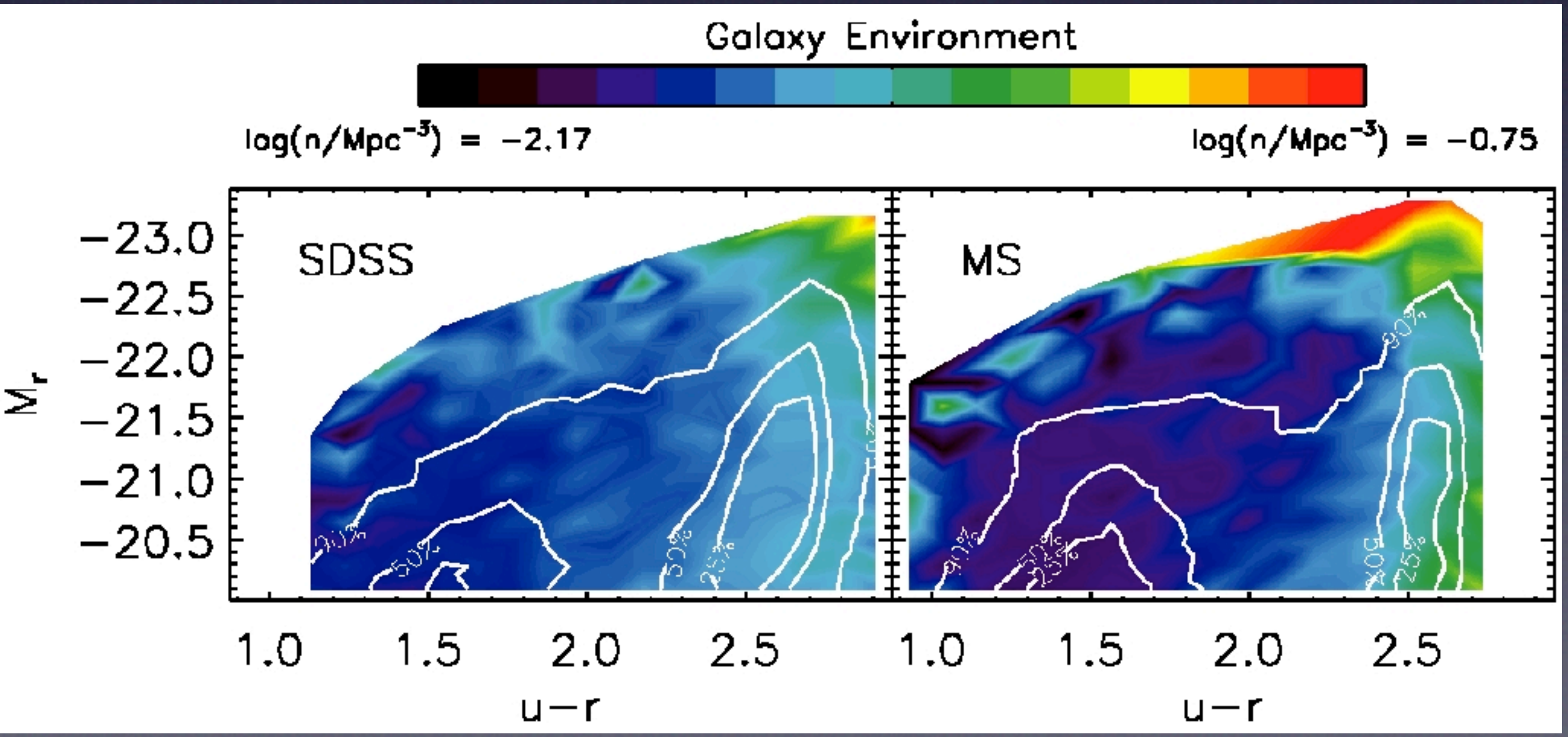
Extragalactic astronomy: galaxies



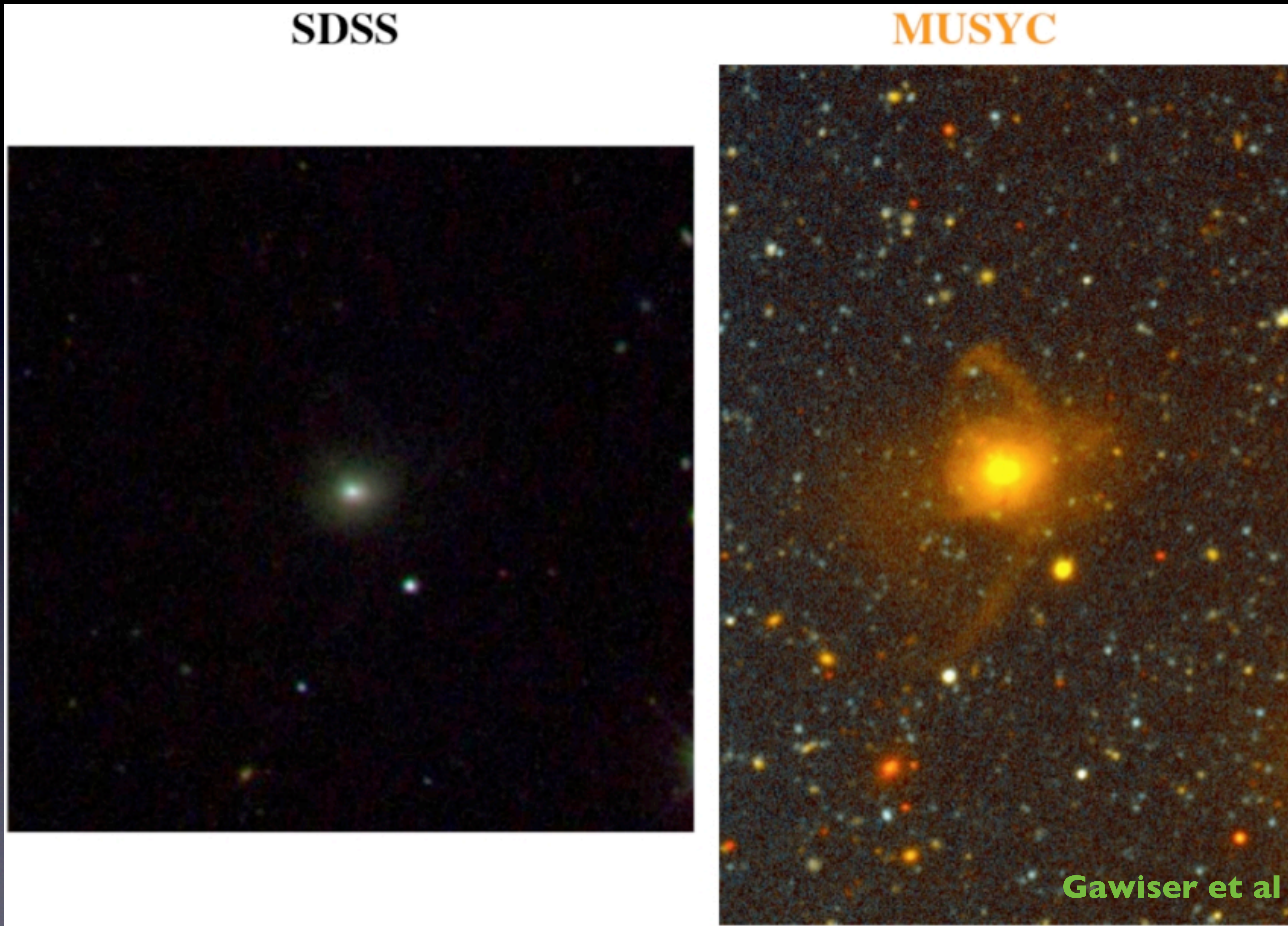
- About 10 billion galaxies, with 4 billion in a "gold" sample defined by i<25.3
- The "gold" sample extends to redshifts of >2.5: **evolution**



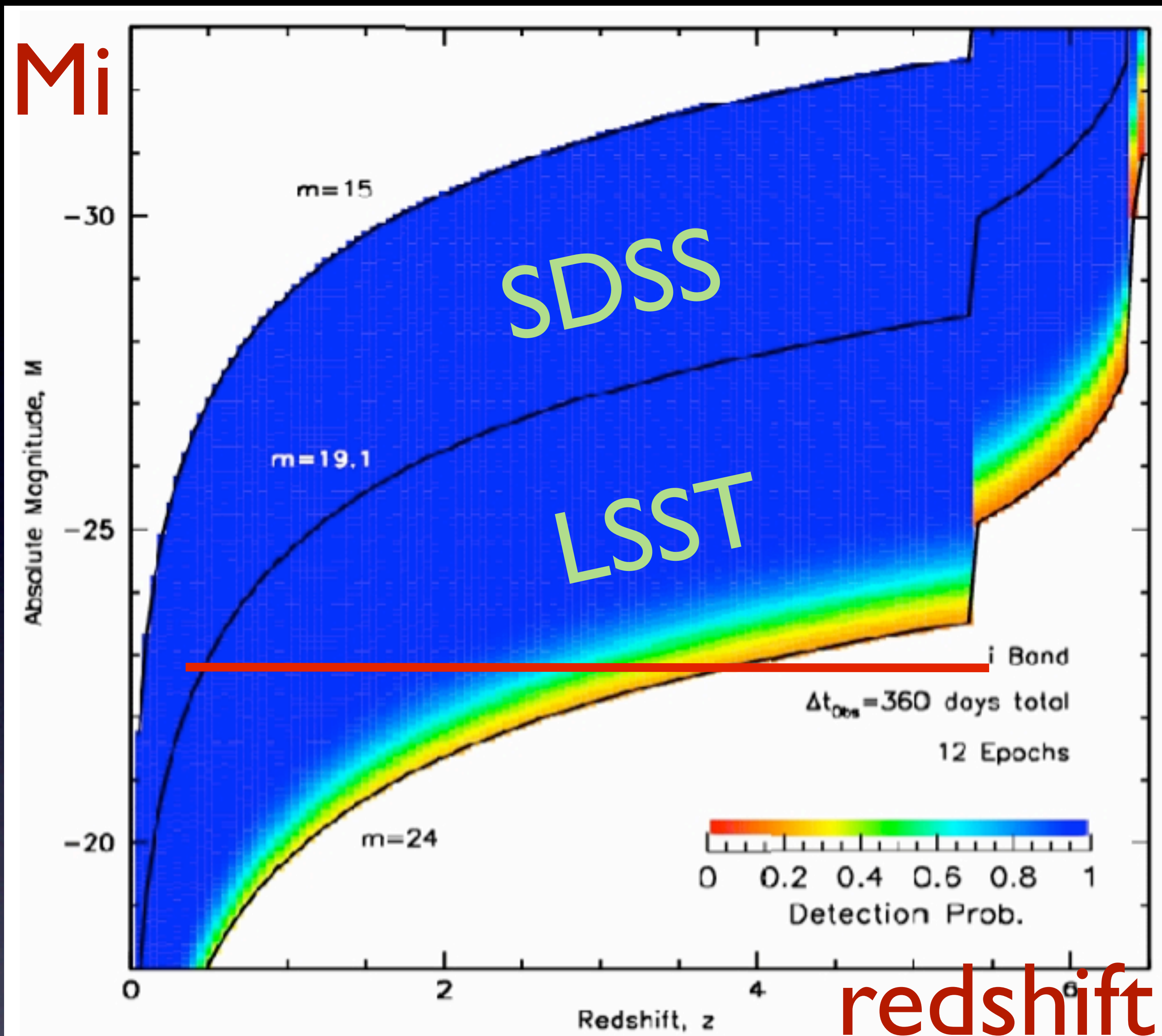
SDSS: snapshot at z~0

LSST: a galaxy evolution movie to z~2.5

Extragalactic astronomy: galaxies



Extragalactic astronomy: quasars

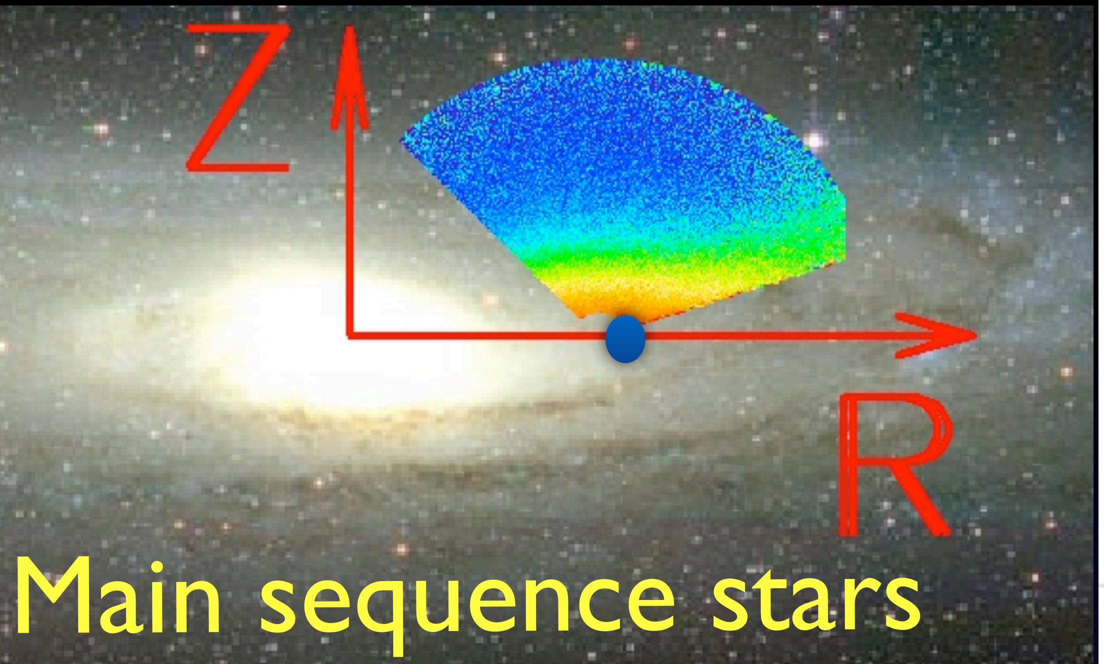


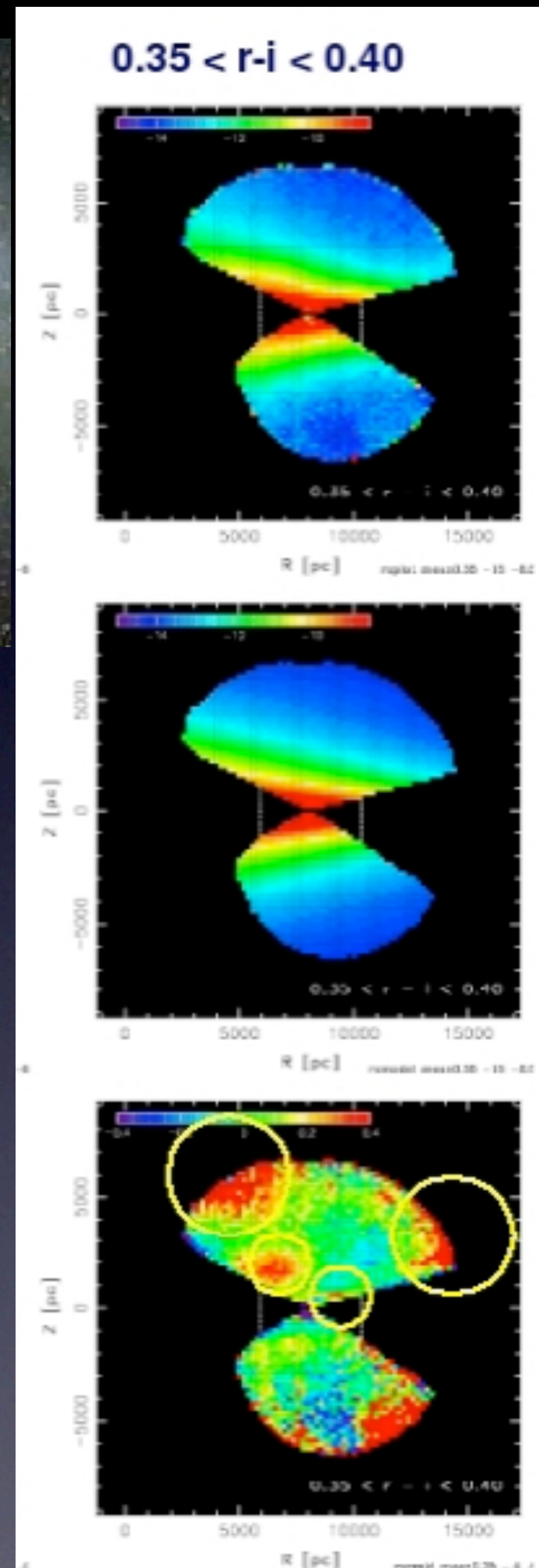
Top: absolute magnitude vs. redshift diagram for quasars

- About 10 million quasars will be discovered using variability, colors, and the lack of proper motions
- 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

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

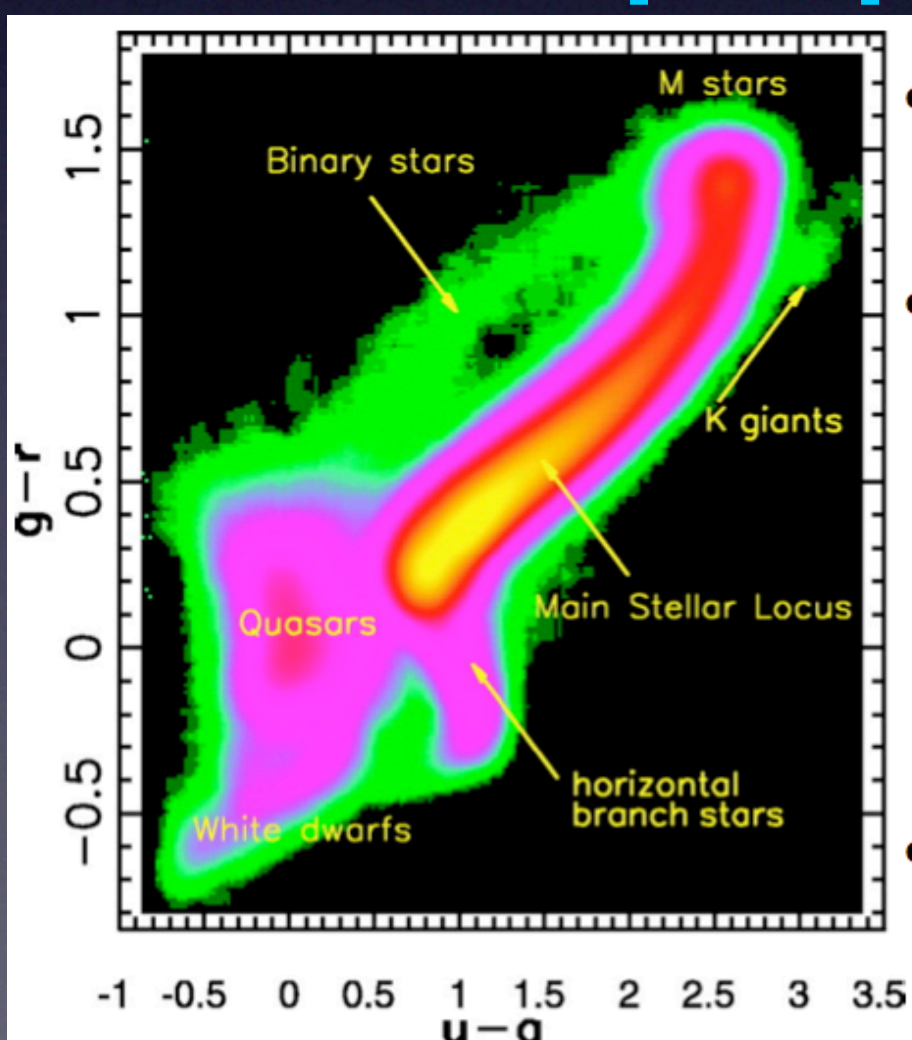
The Milky Way structure: 10 billion stars, time domain

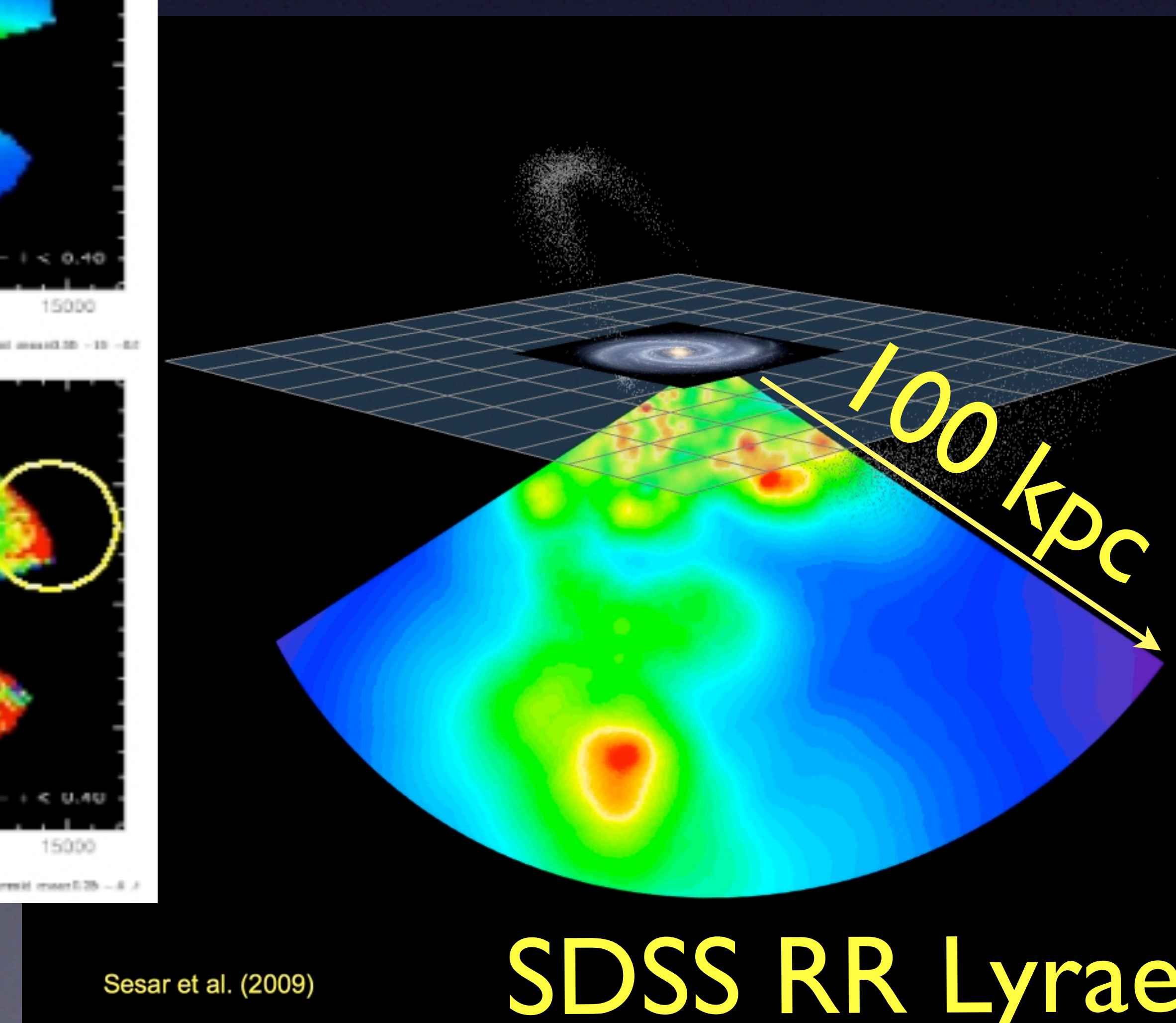




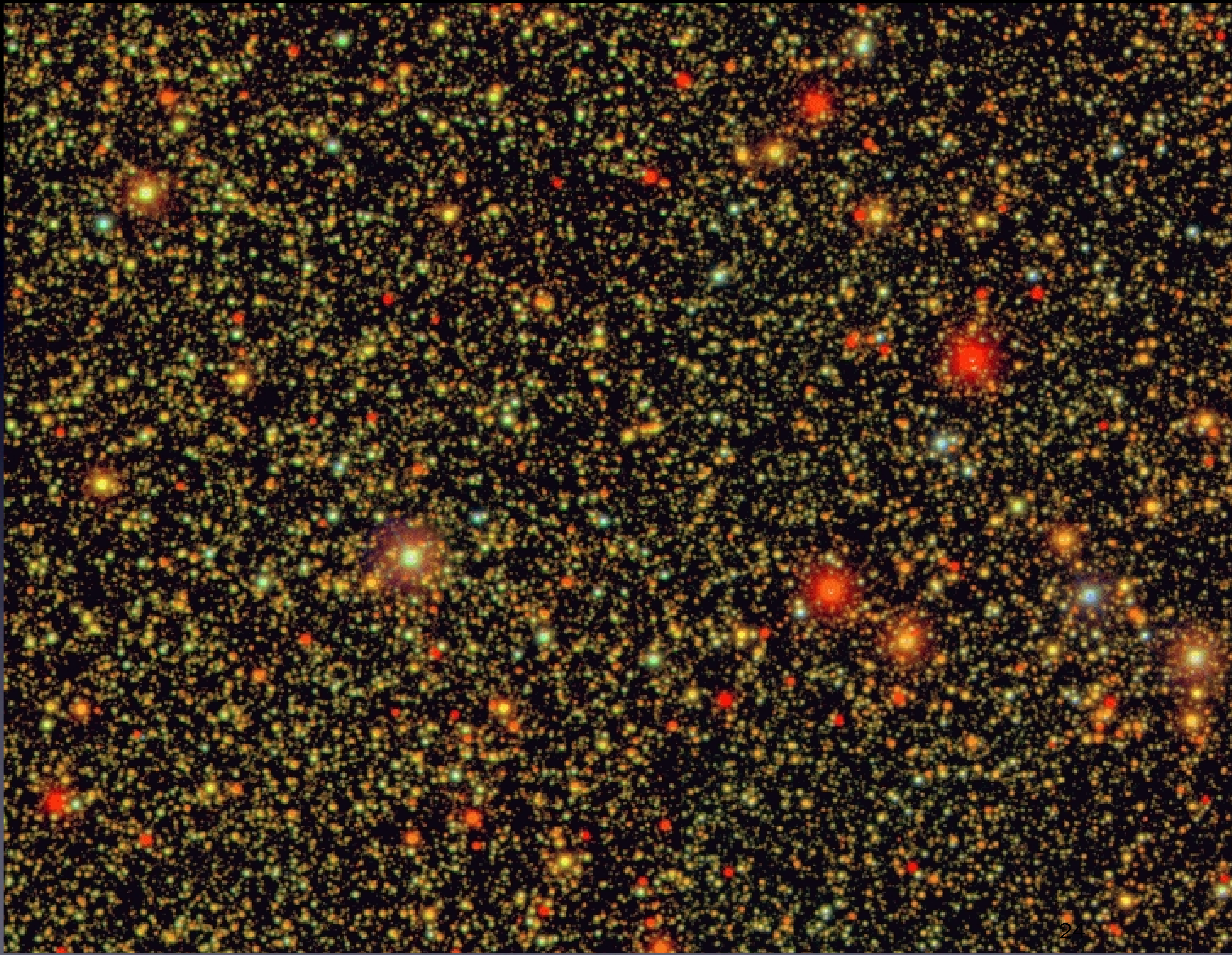
Compared to SDSS: LSST can “see” 10 times further away and over twice as large an area

Distance and [Fe/H]:

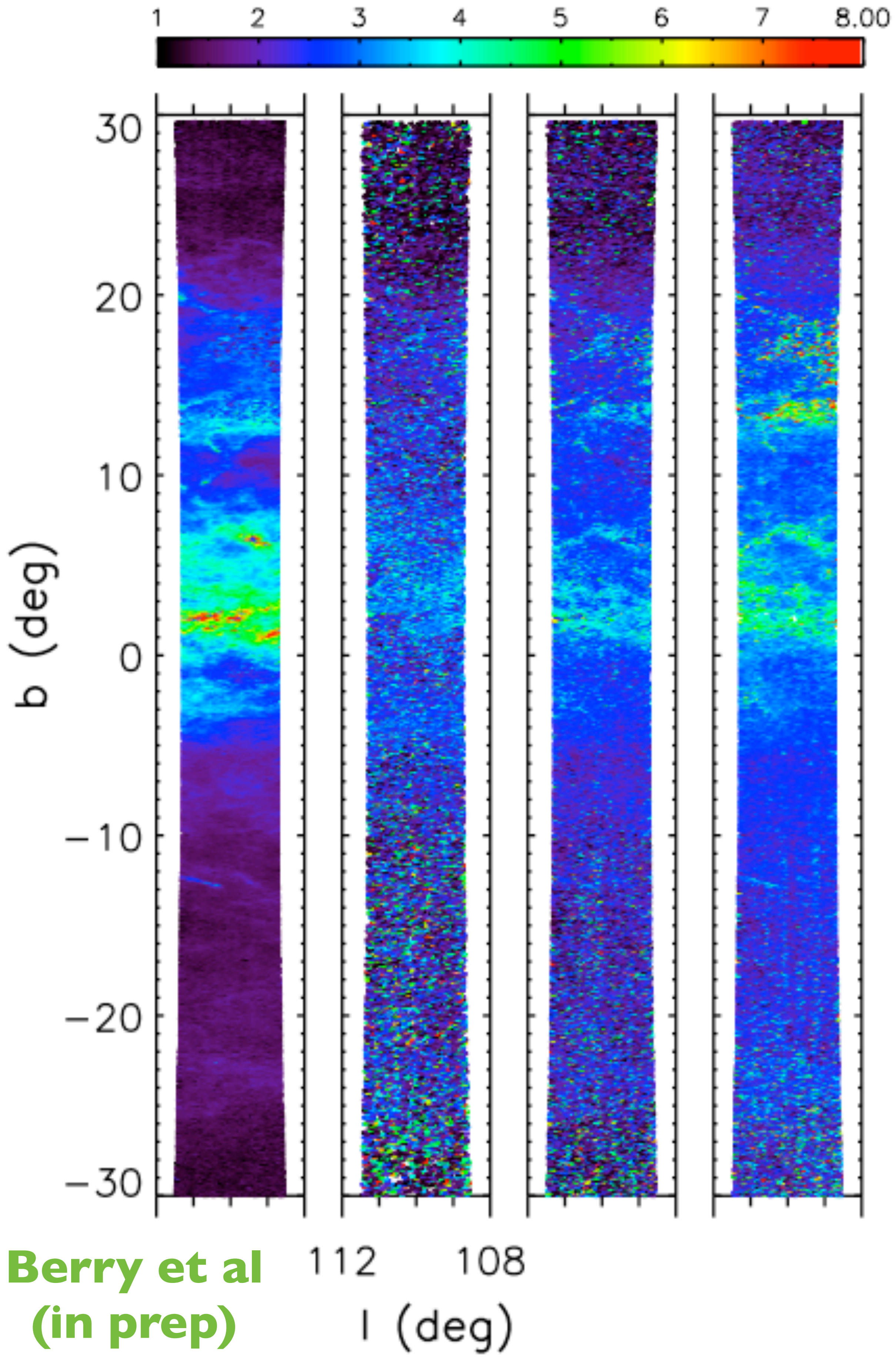




SDSS view through the Milky Way plane



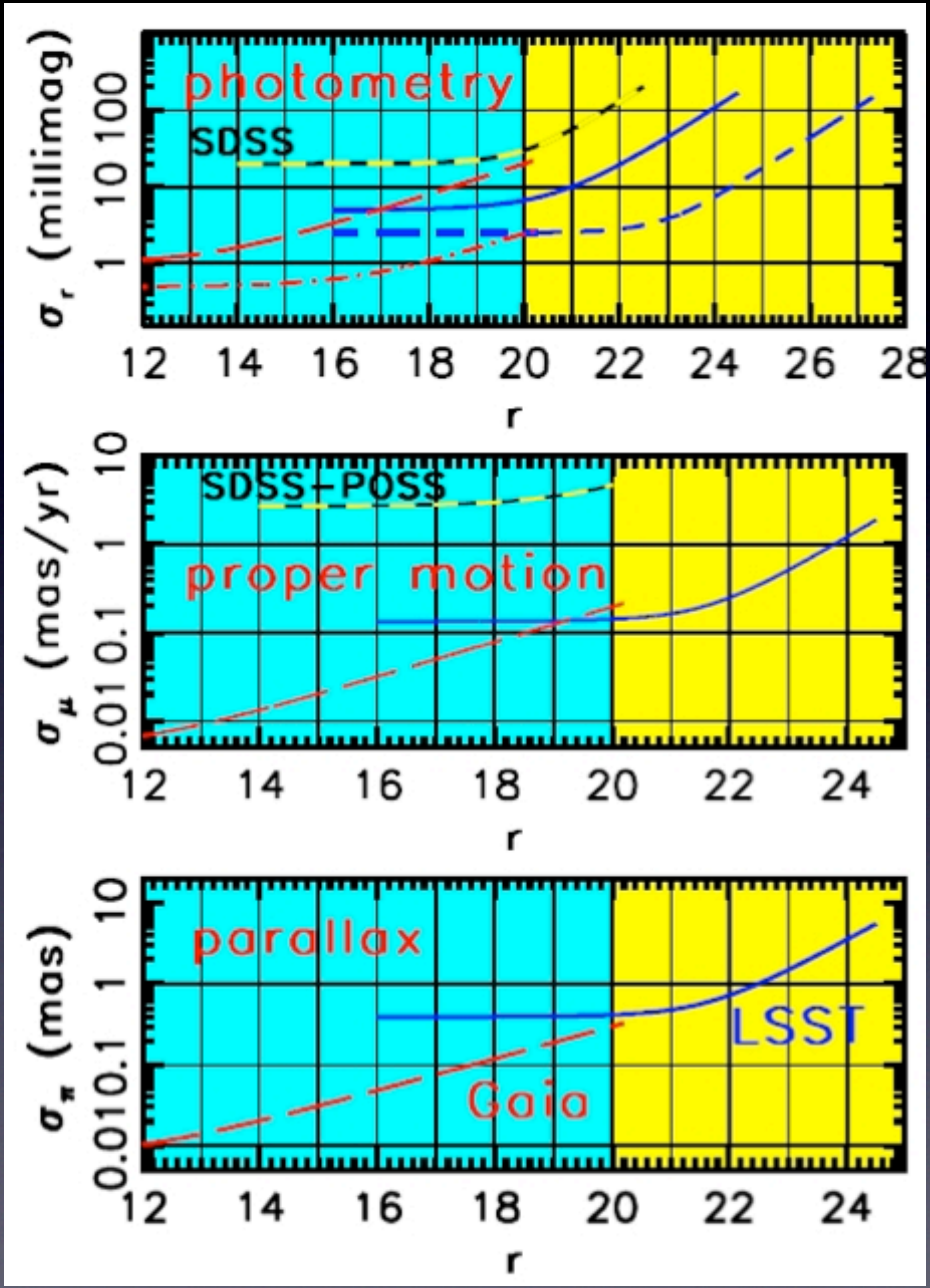
3D Dust properties with ugrizy: from SED fitting



Berry et al (in prep)

- The data not only constrain the Rv distribution, but do so in a 3D space!
- First column: Ar map determined from SED fits to SDSS ugriz data
- Columns 2-4: Rv maps for stars selected from distance slices (0.1-0.5 kpc; 0.5-1 kpc; 1-2 kpc)
- **With LSST:** much better sky coverage, deeper and more accurate photometry

Gaia vs. LSST comparison



Eyer et al (in prep)

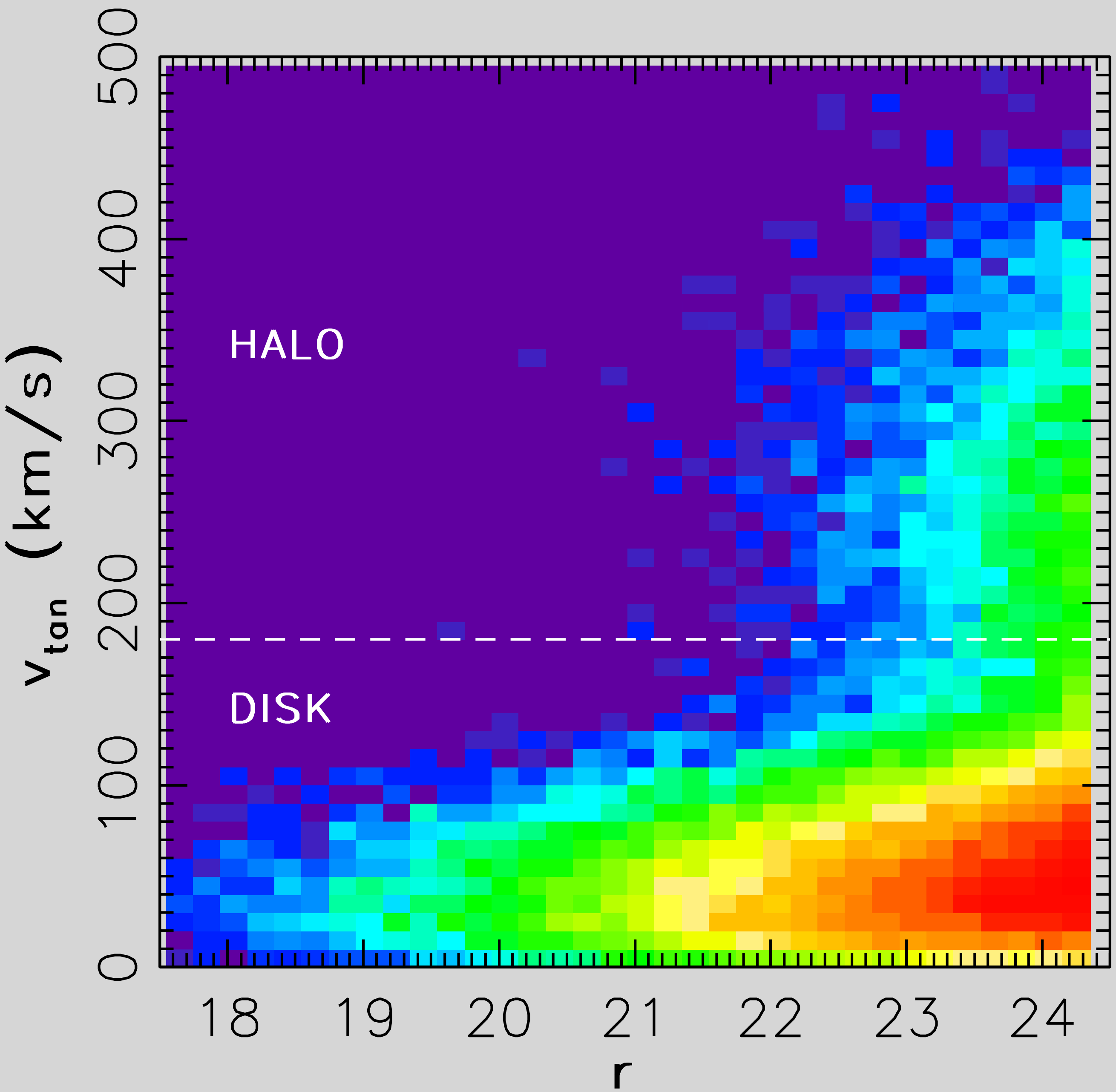
- **Gaia:** excellent astrometry (and photometry), but only to r < 20
- **LSST:** photometry to r < 27.5 and time resolved measurements to r < 24.5
- Complementarity of the two surveys: photometric, proper motion and trigonometric parallax errors are similar around r=20

The Milky Way disk “belongs” to Gaia, and the halo to LSST (plus very faint and/or very red sources, such as white dwarfs and LT(Y) dwarfs).

Dwarfs in LSST

White dwarfs: LF is age probe

~400,000 halo white dwarfs from LSST (10 million total):



L / T dwarfs: L dwarfs are dime a dozen: 200,000 in LSST with proper motion and trigonometric parallax measurements

Simulations predict 2400 T dwarfs with >5σ proper motion and parallax measurements

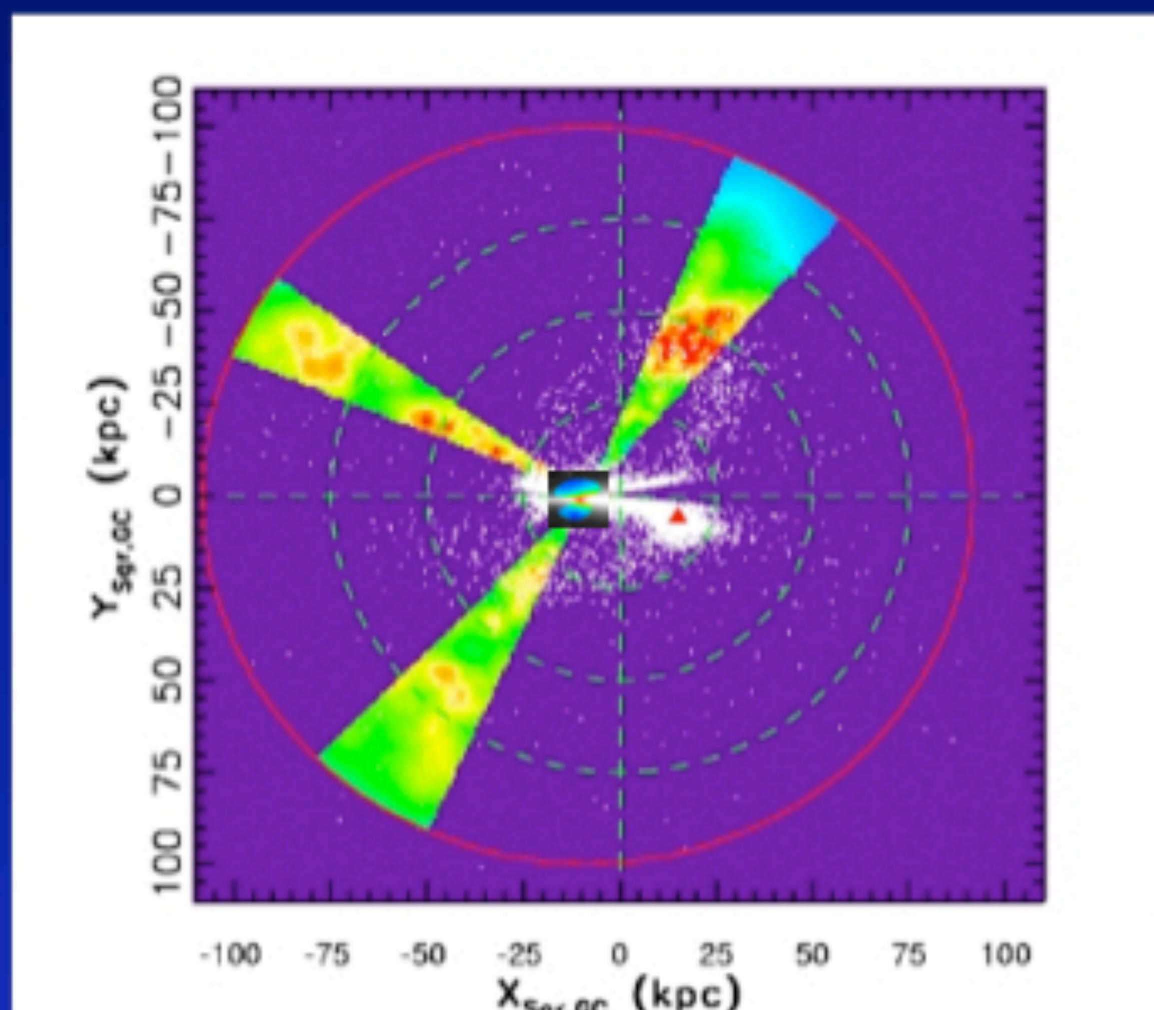
Compared to UKIDSS, 5 times larger sample of T dwarfs, with parallaxes and 10-20 times more accurate proper motions

(if Y dwarfs exist, expect about 100 from LSST [model based])

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

The Planetary Science Decadal Survey

"Vision and Voyages for Planetary Science in the Decade 2013-2022"

was released on March 7, 2011:

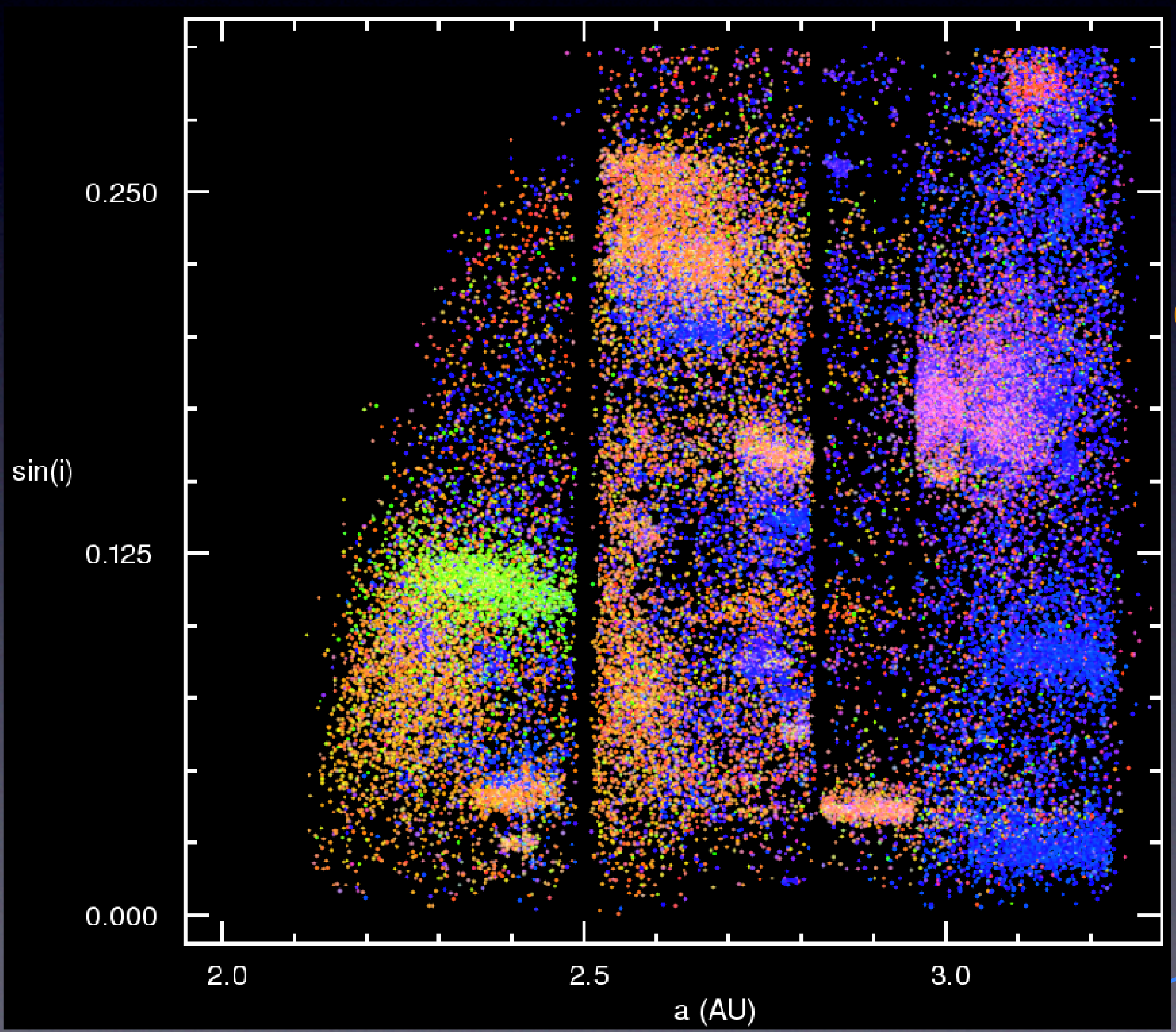
http://solarsystem.nasa.gov/docs/Vision_and_Voyages-FINAL.pdf

"One of the future NSF-funded facilities most important to planetary science is the Large Synoptic Survey Telescope (LSST). The committee encourages the timely completion of LSST, and stresses the importance of its contributions to planetary science once telescope operations begin."

Time Domain: objects changing in time

positions: asteroids and stellar proper motions

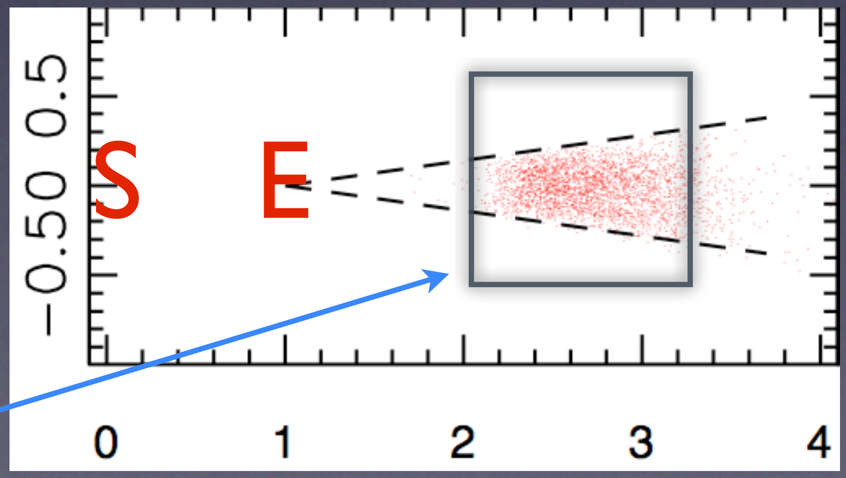
brightness: cosmic explosions and variable stars



For example:

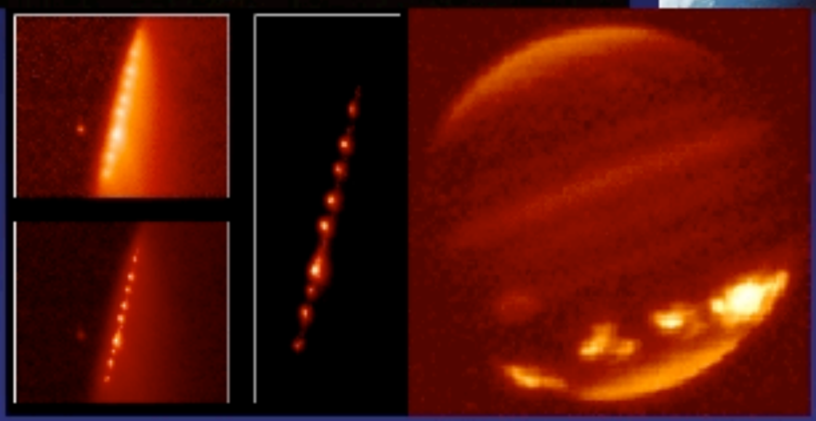
SDSS demonstrated that asteroid families have distinct colors: chemical composition

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



Killer asteroids: the impact probability is not 0

photomontage!



Shoemaker-Levy 9 (1994)

Tunguska (1908)

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)

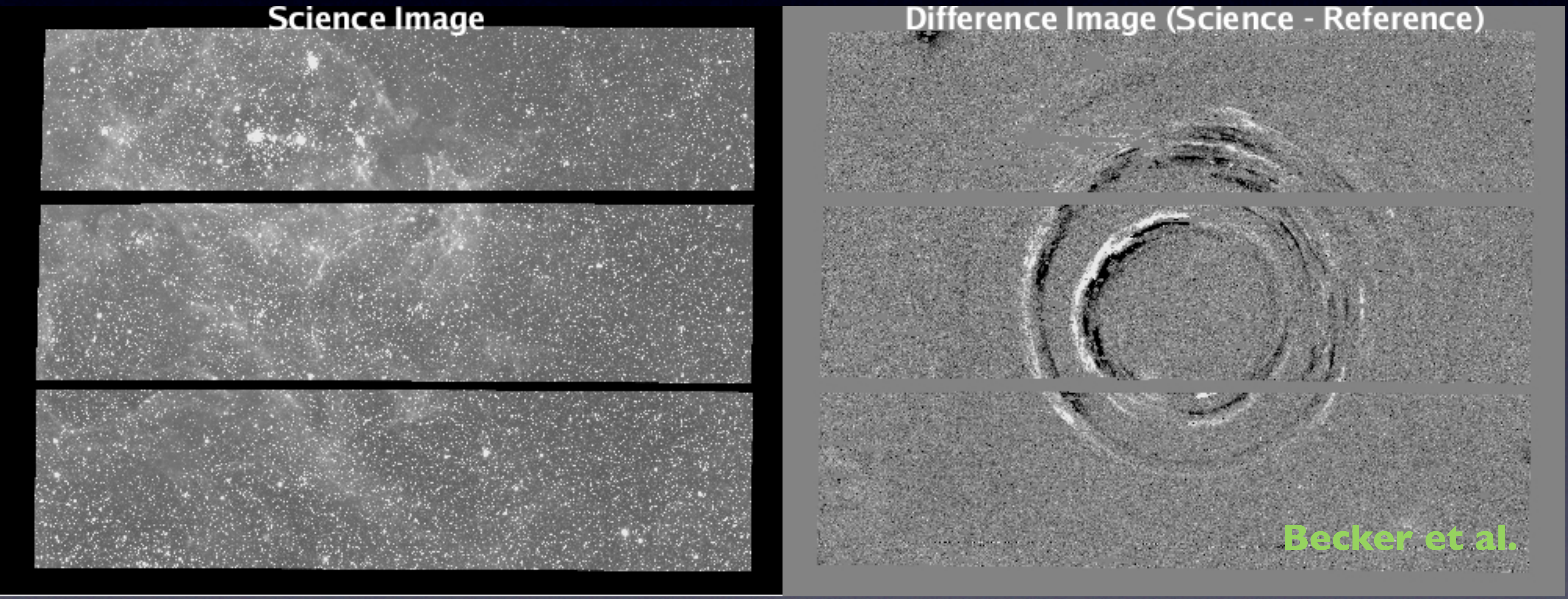
The Barringer Crater, Arizona: a 40m object 50,000 yr. ago

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

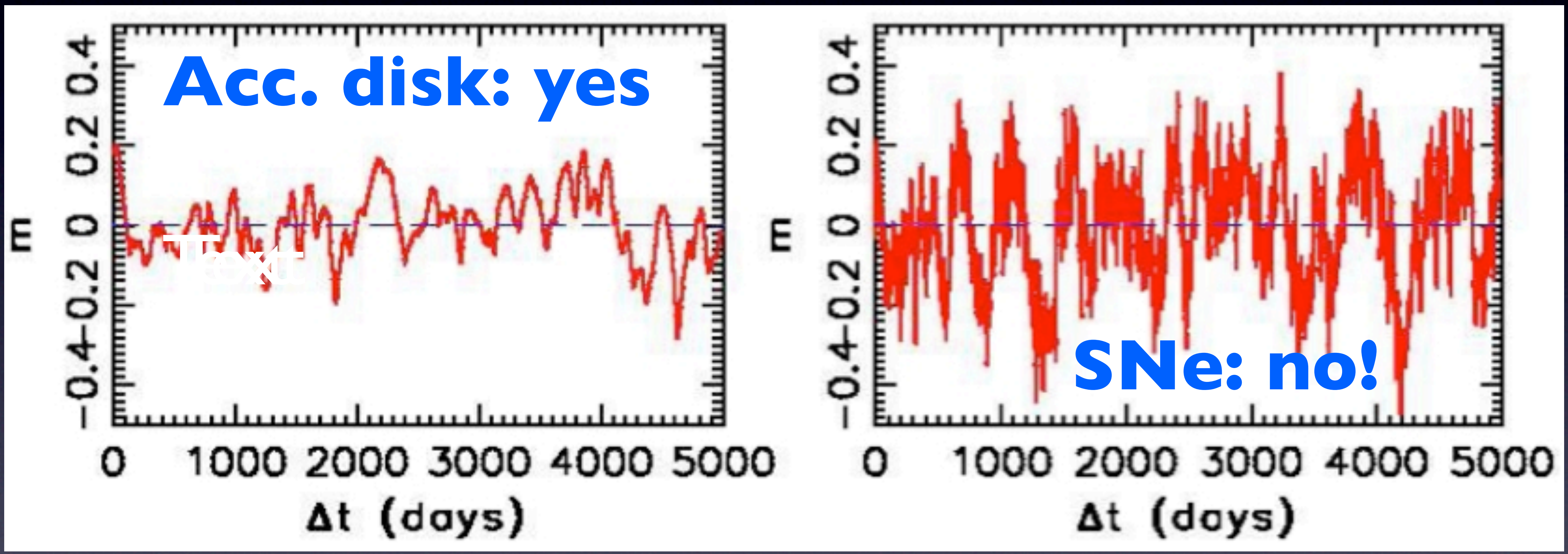
Web stream with data for transients within 60 seconds

Quasar Variability

Competing theories for the origin of variability:

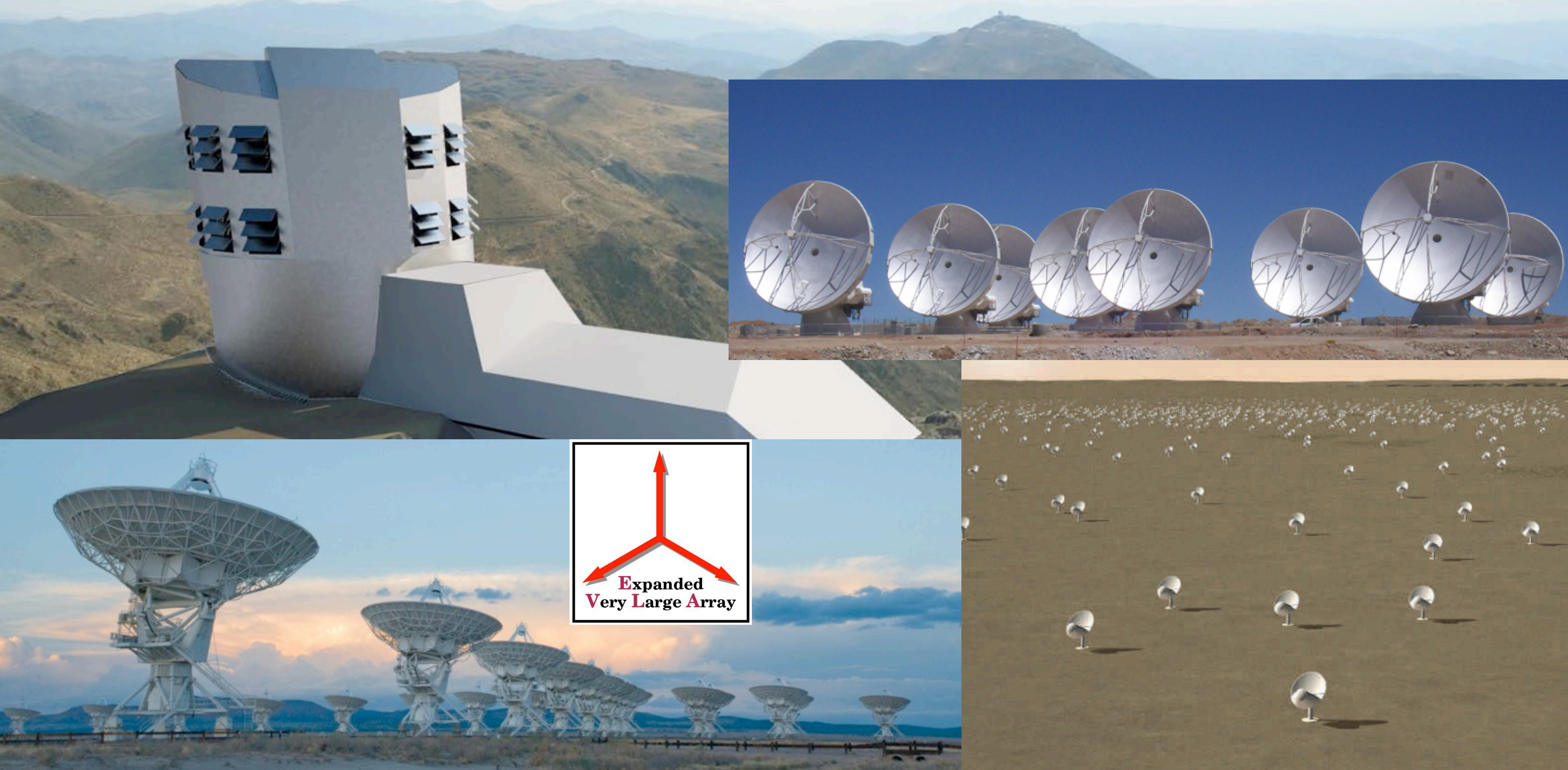
• Microlensing • Bursts of Supernovae • Accretion disk instabilities

SDSS observations indicate rich information content and can already reject some models (MacLeod et al. 2010):



Variability is a tool, just like imaging, spectroscopy and multi-wavelength X-ray to radio observations, for studying quasars

LSST data will be excellent for continuing such studies: millions of objects, thousands of precise measurements.



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

LSST will be **your** survey

LSST in one sentence:

An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 based on 1000 visits over a 10-year period:

More information at www.lsst.org and arXiv:0805.2366

a catalog of 10 billion stars and 10 billion galaxies with exquisite photometry, astrometry and image quality.

Q&A slides

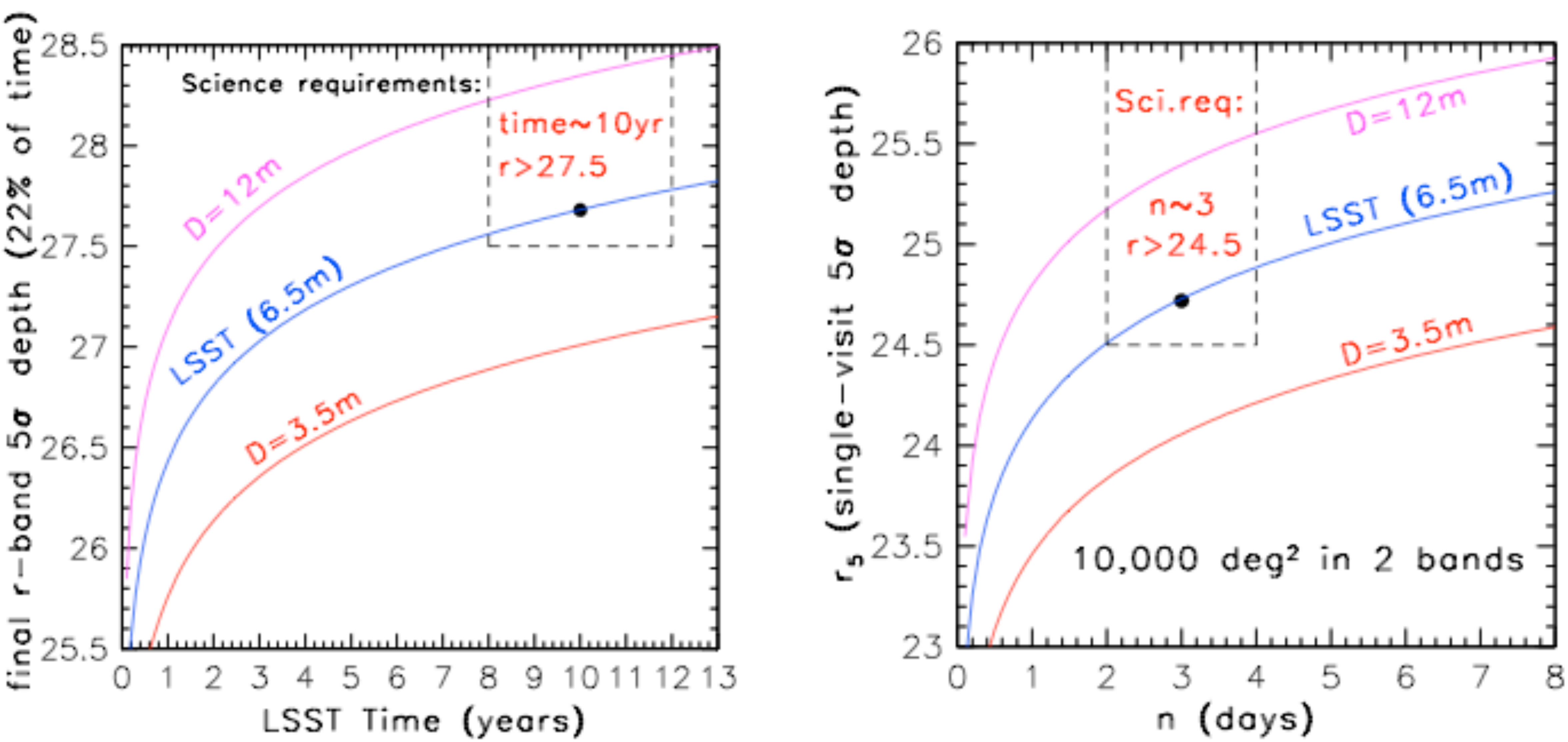
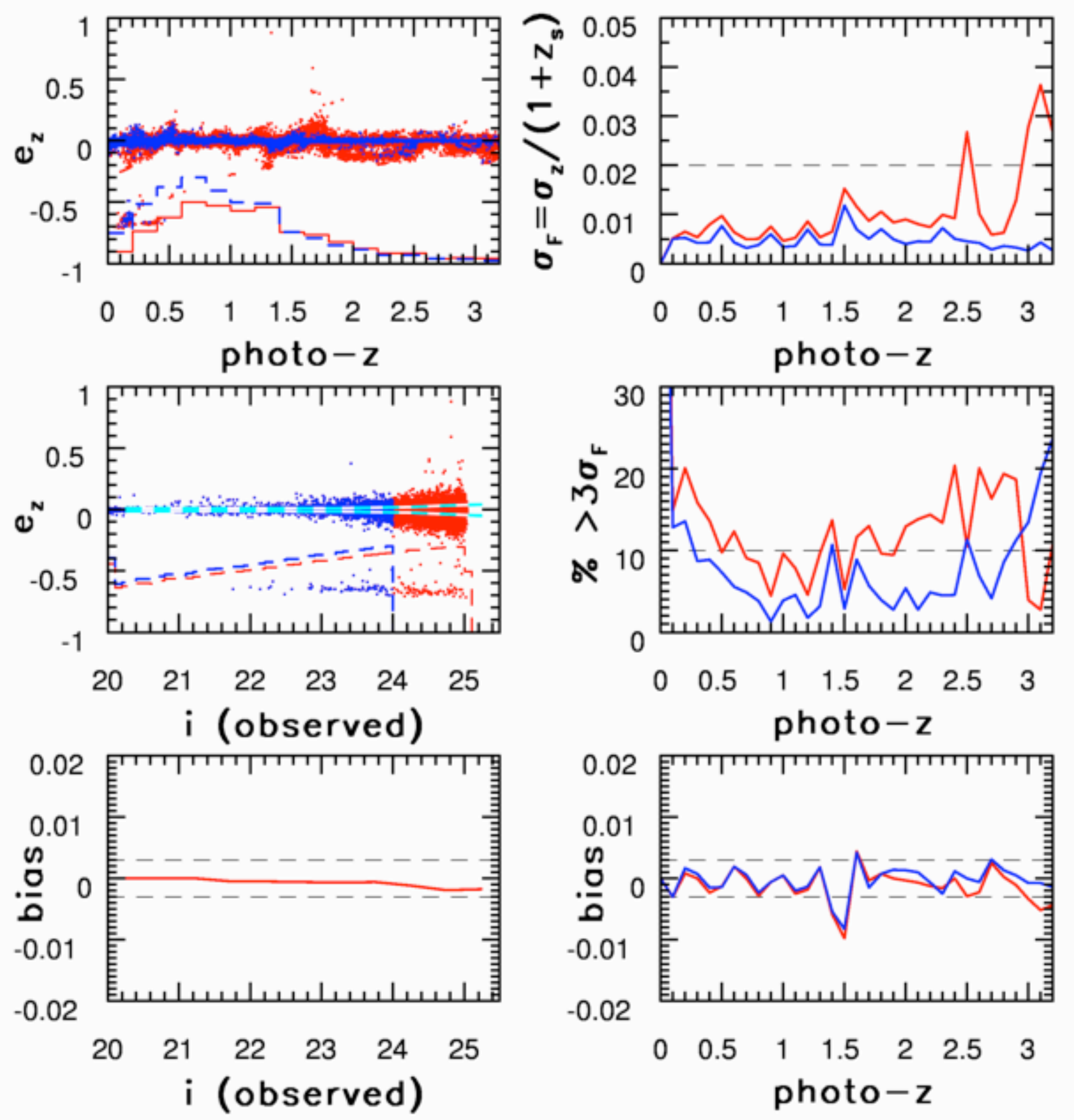
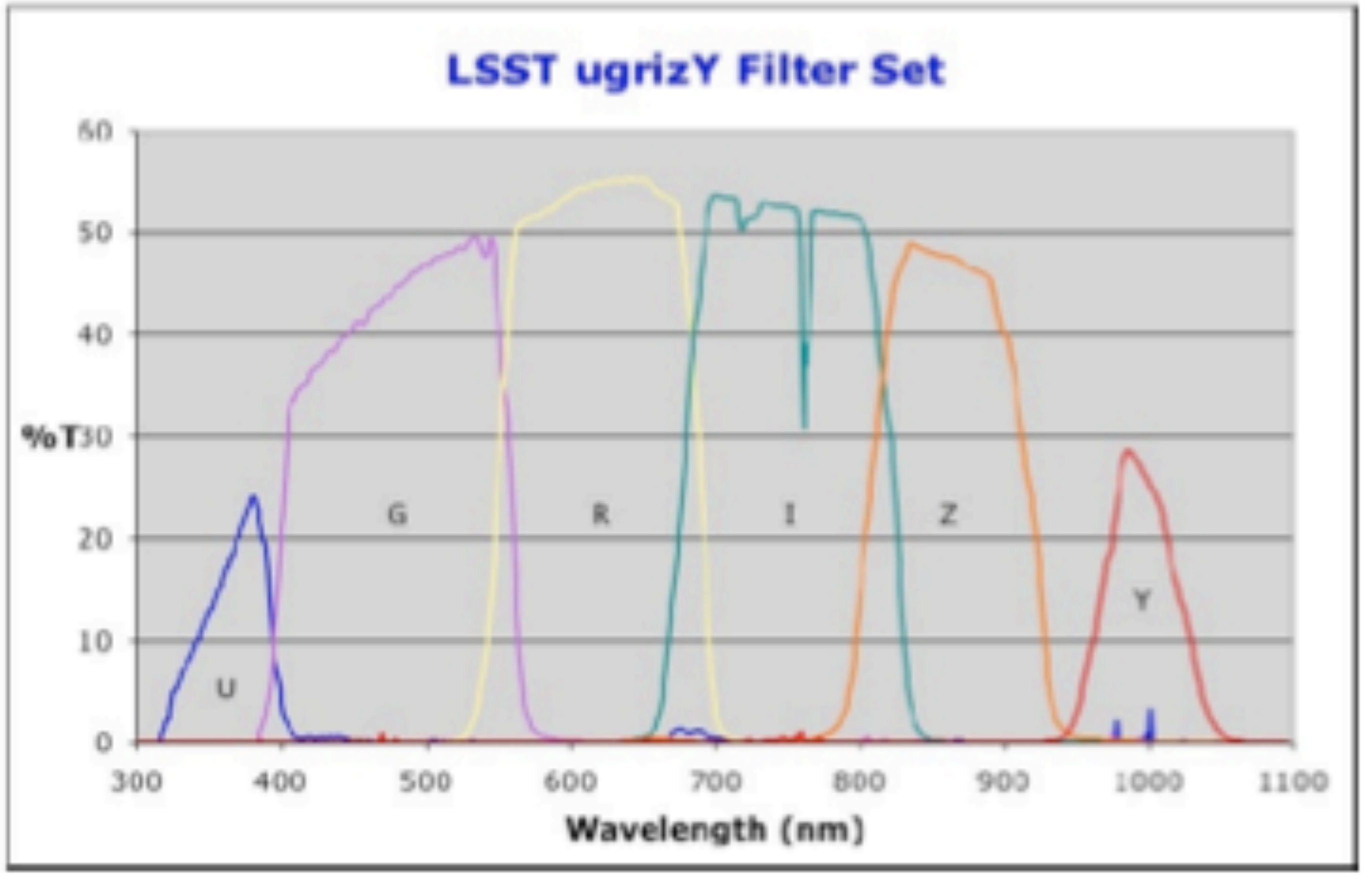
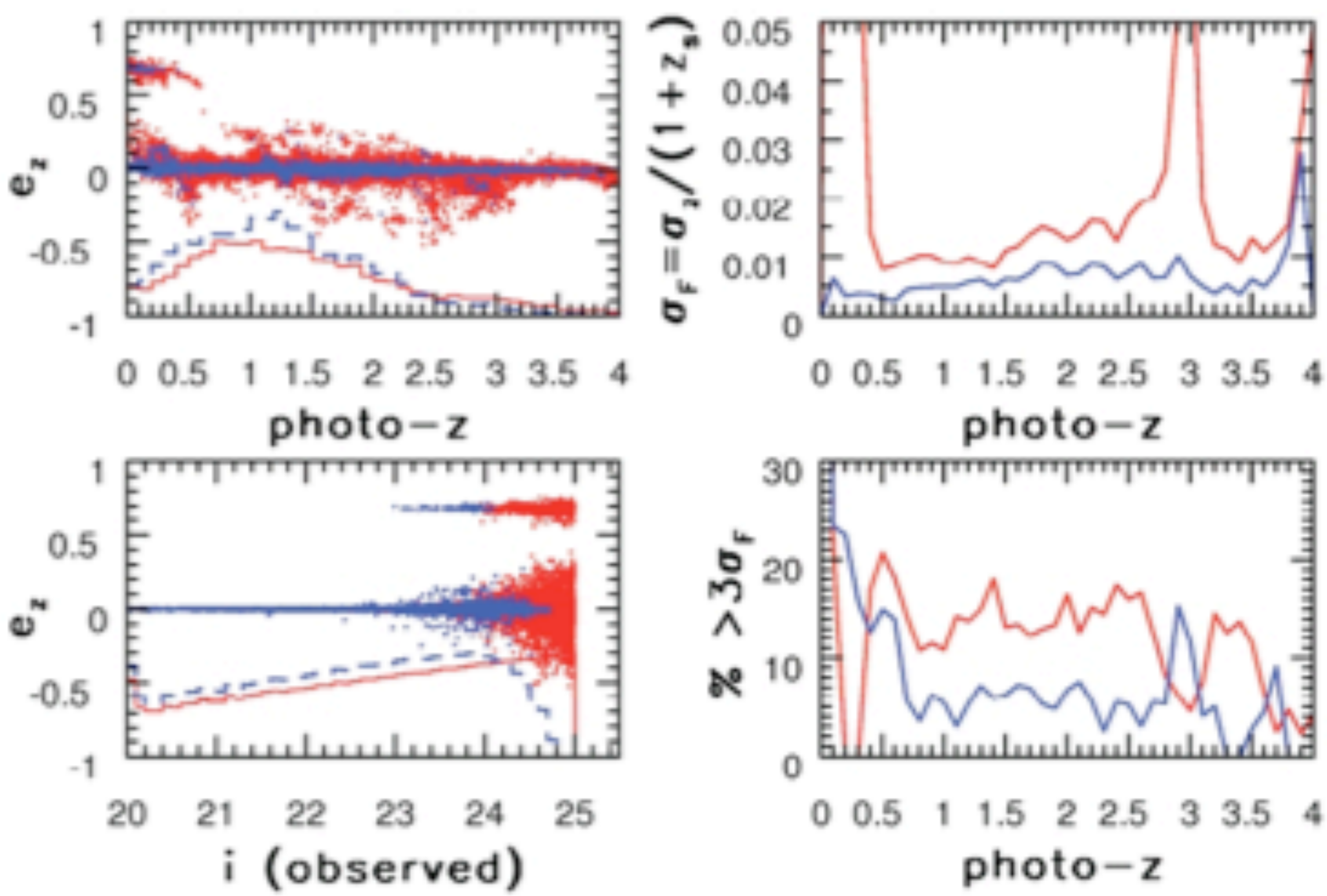


Figure 1.1: (a) The coadded depth in the r band (AB magnitudes) vs. the effective aperture and the survey lifetime. It is assumed that 22% of the total observing time (corrected for weather and other losses) is allocated for the r band, and that the ratio of the surveyed sky area to the field-of-view area is 2,000. (b) The single-visit depth in the r band (5σ detection for point sources, AB magnitudes) vs. revisit time, n (days), as a function of the effective aperture size. With a coverage of 10,000 deg^2 in two bands, the revisit time directly constrains the visit exposure time, $t_{vis} = 10n$ seconds; these numbers can be directly scaled to the 20,000 deg^2 and six filters of LSST. In addition to direct constraints on optimal exposure time, t_{vis} is also driven by requirements on the revisit time, n, the total number of visits per sky position over the survey lifetime, N_{visit}, and the survey efficiency, ϵ (see Equation 1.3). Note that these constraints result in a fairly narrow range of allowed t_{vis} for the main deep-wide-fast survey. From Ivezić et al. (2008).



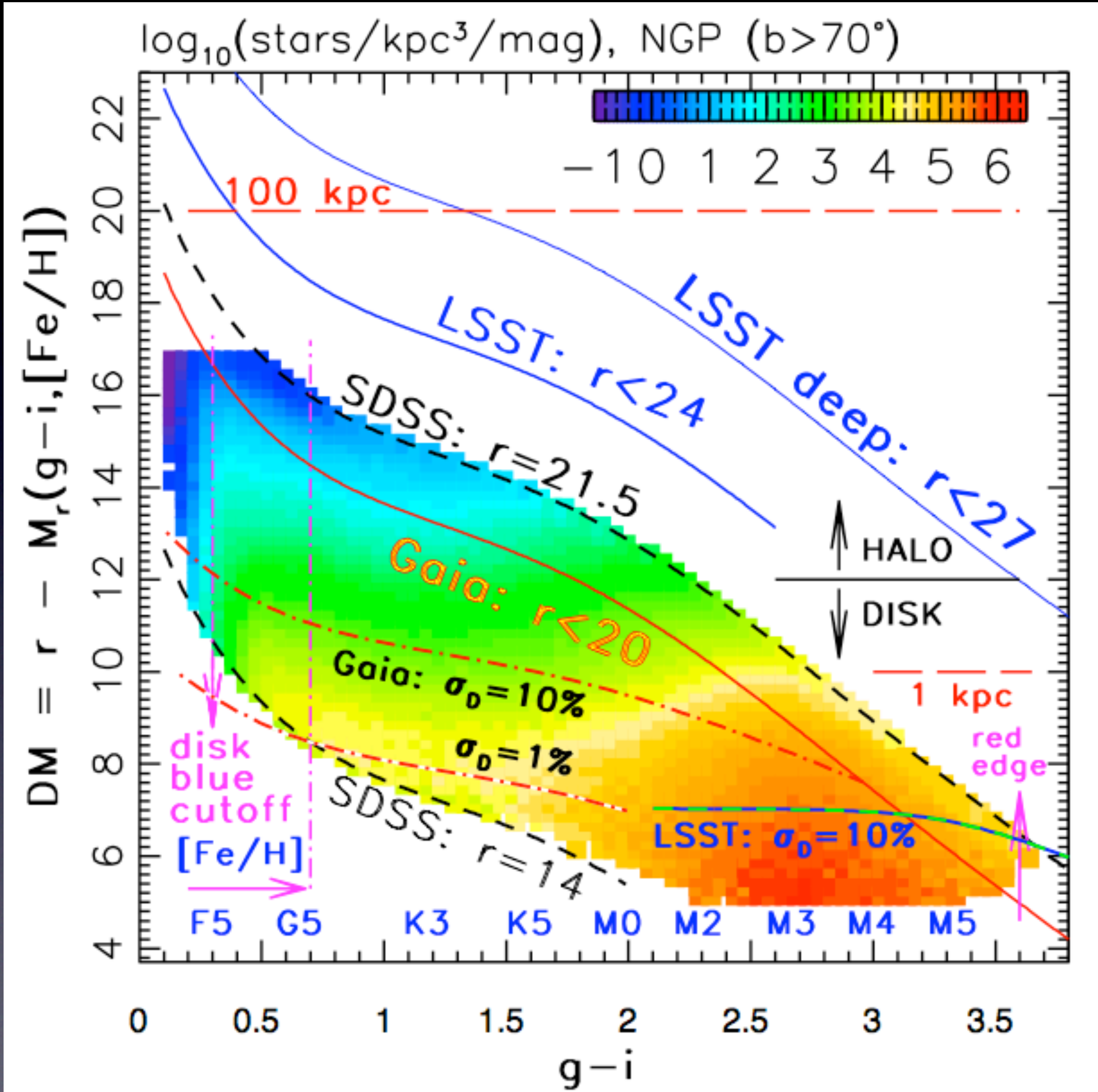
e_z
photo−z
$\sigma_F = \sigma_z/(1+z_s)$
photo−z
e_z
i (observed)
$\% > 3\sigma_F$
photo−z
bias
i (observed)
bias
photo−z



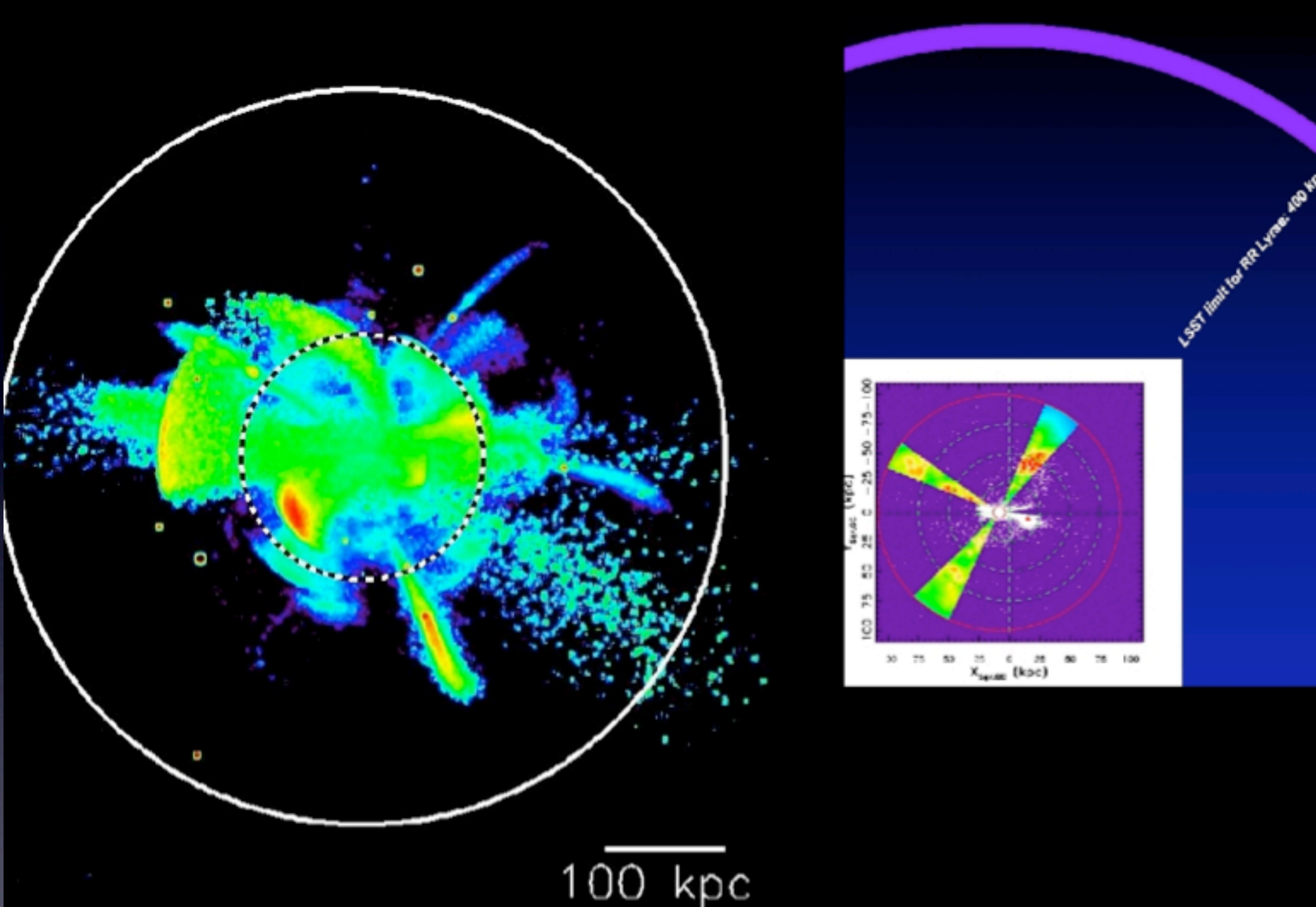


Control of systematics

- Image quality: large aperture to get a sufficiently large PSF correlation angle that enables the use of stars to correct shear systematics; large number of exposures (several hundred) to enable multiple chops
- Photometric redshifts: exquisite photometric accuracy (0.01 mag) and 6 photometric bands
- Cross-checks using different cosmological probes!
- Expect 3-4 times more accurate photo-z than assumed in the DETF Report



log10(stars/kpc³/mag), NGP (b>70°)
−1 0 1 2 3 4 5 6
100 kpc
LSST: r<24
LSST deep: r<27
SDSS: r=21.5
Gaia: r<20
HALO
DISK
1 kpc
Gaia: σD=10%
σD=1%
disk blue cutoff
[Fe/H]
SDSS: r=14
LSST: σD=10%
red edge
F5 G5 K3 K5 M0 M2 M3 M4 M5
DM = r − Mr(g−i,[Fe/H])
g−i



SDSS: main sequence to 10 kpc, RR Lyr to 100 kpc

LSST: 100 kpc i 400 kpc (half way to Andromeda)

LTY Dwarfs with LSST

- **T dwarfs: a quantitative example** (L dwarfs are dime a dozen: 200,000 in LSST with proper motion and trigonometric parallax measurements; no Y dwarfs are confirmed yet, though based on models expect ∼100 from LSST)
- **Simulations predict 2400 T dwarfs with $y < 21.4$** (now ∼100)
- For $y < 21.4$ proper motion ($\sigma = 2$ mas/yr) and trigonometric parallax measurements (σ=6 mas) based on 200 y band detections: 5-10σ measurements even for the faintest objects
- The $z - y$ color will be accurate to better than 0.1 mag even for the faintest objects: it will be possible to construct robust **M_z vs. $z - y$ color-magnitude diagrams** (exquisite LFs!)
- The $y < 21.4$ LSST T dwarf sample has roughly the same JHK magnitude limits as the UKIDSS Large Area Survey (4,000 deg^2)
- **Compared to UKIDSS, LSST will obtain about 5 times larger sample of T dwarfs, with proper motions about 10-20 times more accurate, and also with trigonometric parallax measurements** (due to larger sky area, note that our simulations imply that UKIDSS will detect about 500 T dwarfs)