LSST survey: millions and millions of quasars

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“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?”

OUTLINE

Terminology hereafter: a **quasar** is a point source in ground-based seeing, while an **AGN** is a resolved galaxy

- **Finding quasars/AGNs with SDSS**
  color selection of quasars
  (but skipping AGN selection using galaxy spectra)

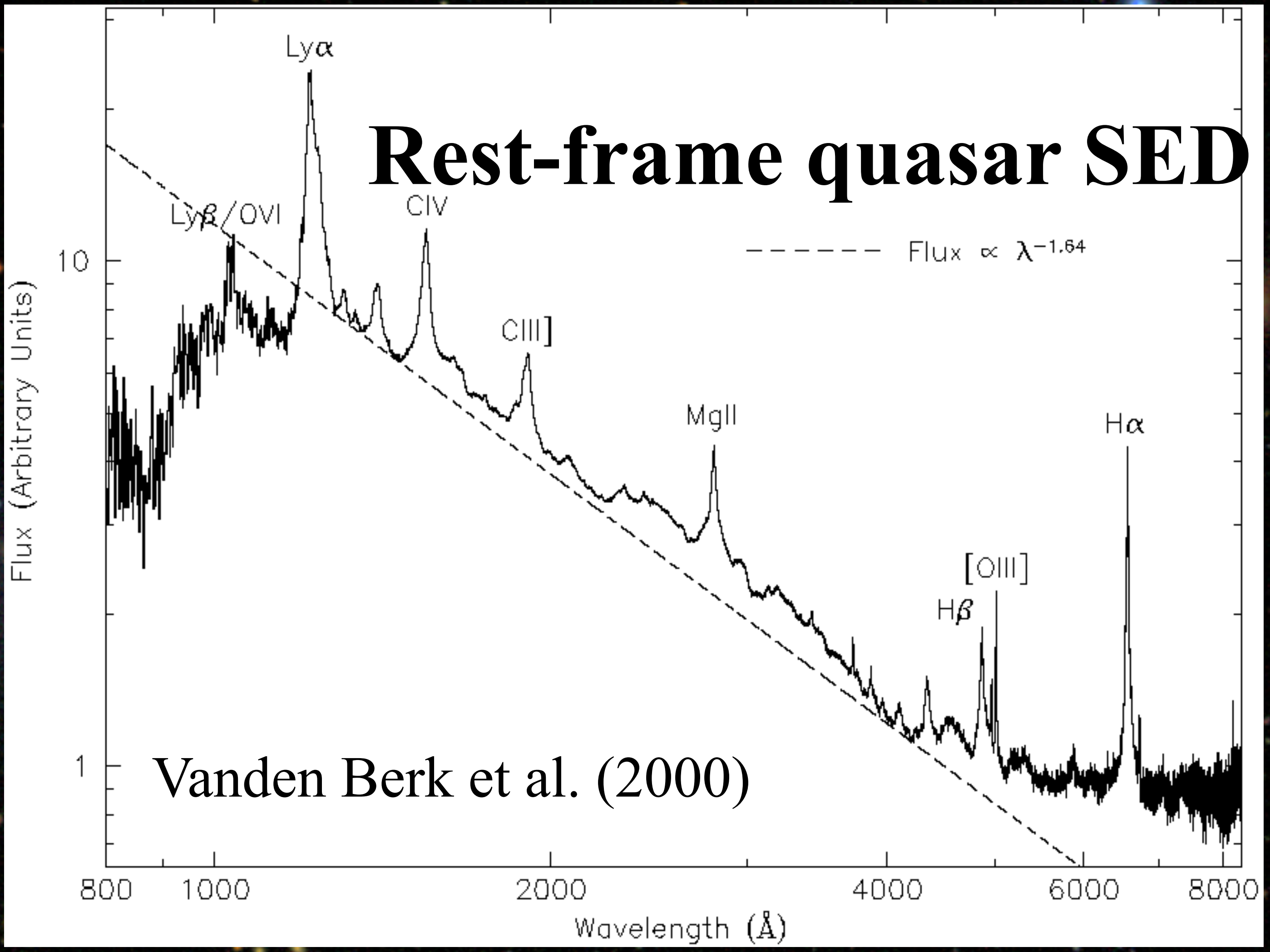
- **Brief introduction to LSST**
  science drivers, system overview, expected survey data products

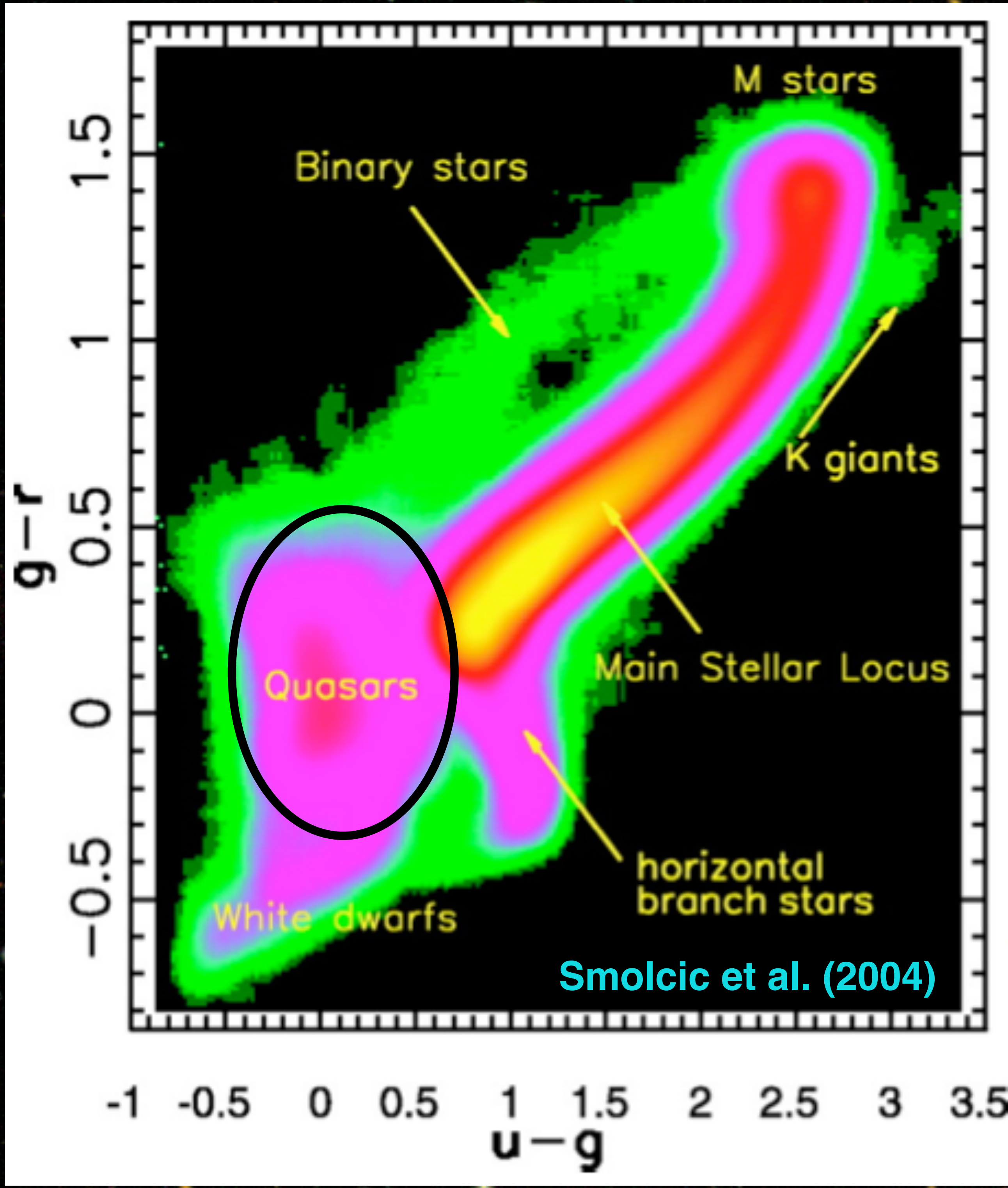
- **Finding quasars/AGNs with LSST**
  photometry (colors, variability) **and** astrometry (no proper motion, DCR)

Finding the Quasars

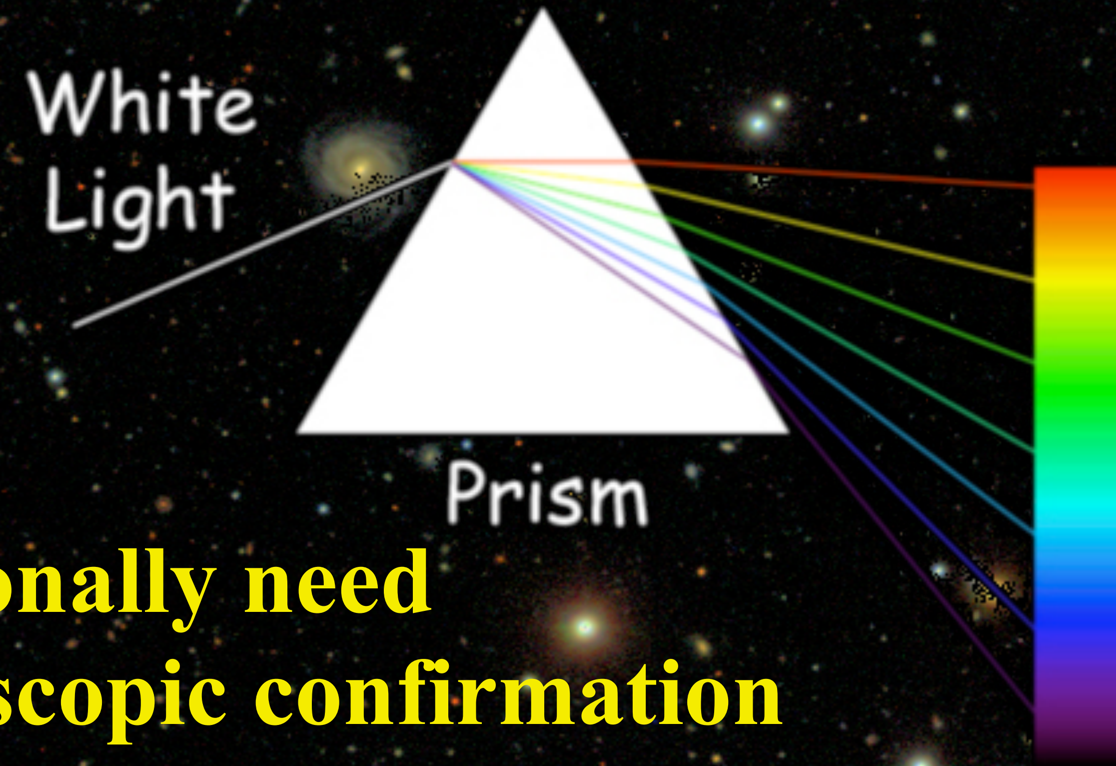
Quasars with z<2.2 have UV excess (e.g. U-B, u-g) compared to stars with similar blue colors (e.g. B-V, g-r):

Observed SEDs greatly differ because a given observed wavelength range samples varying rest-frame wavelength range

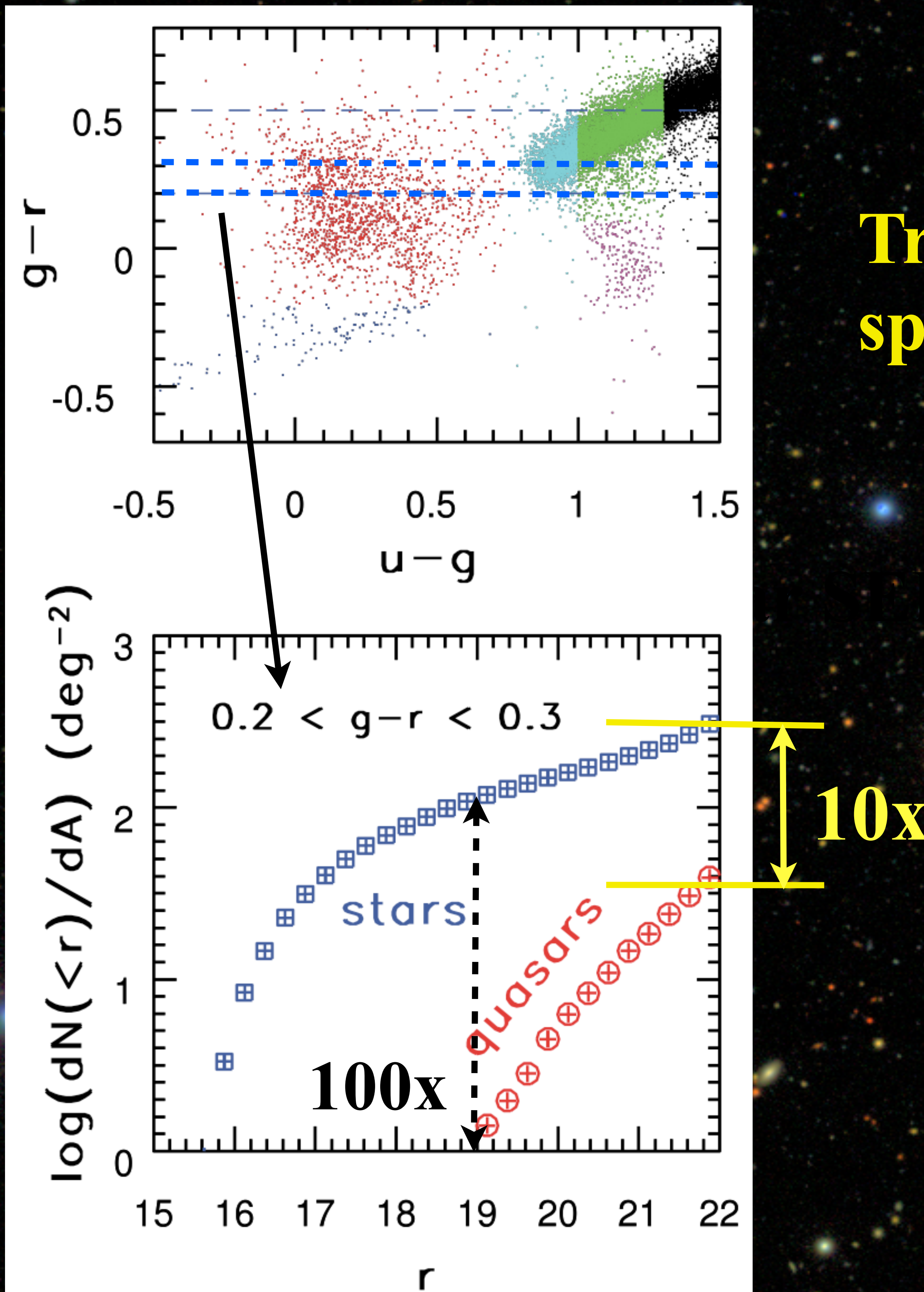


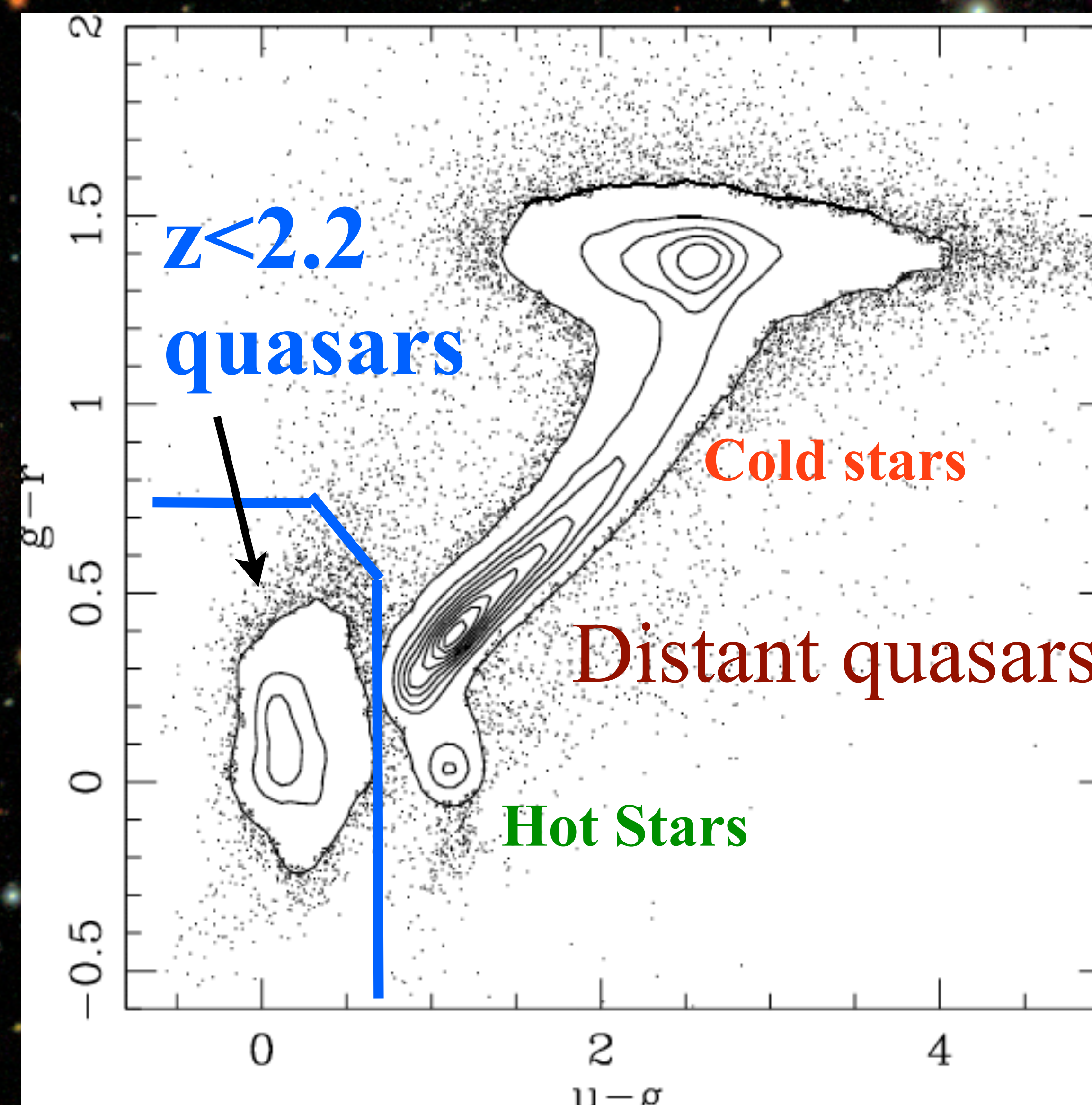


Finding the Quasars



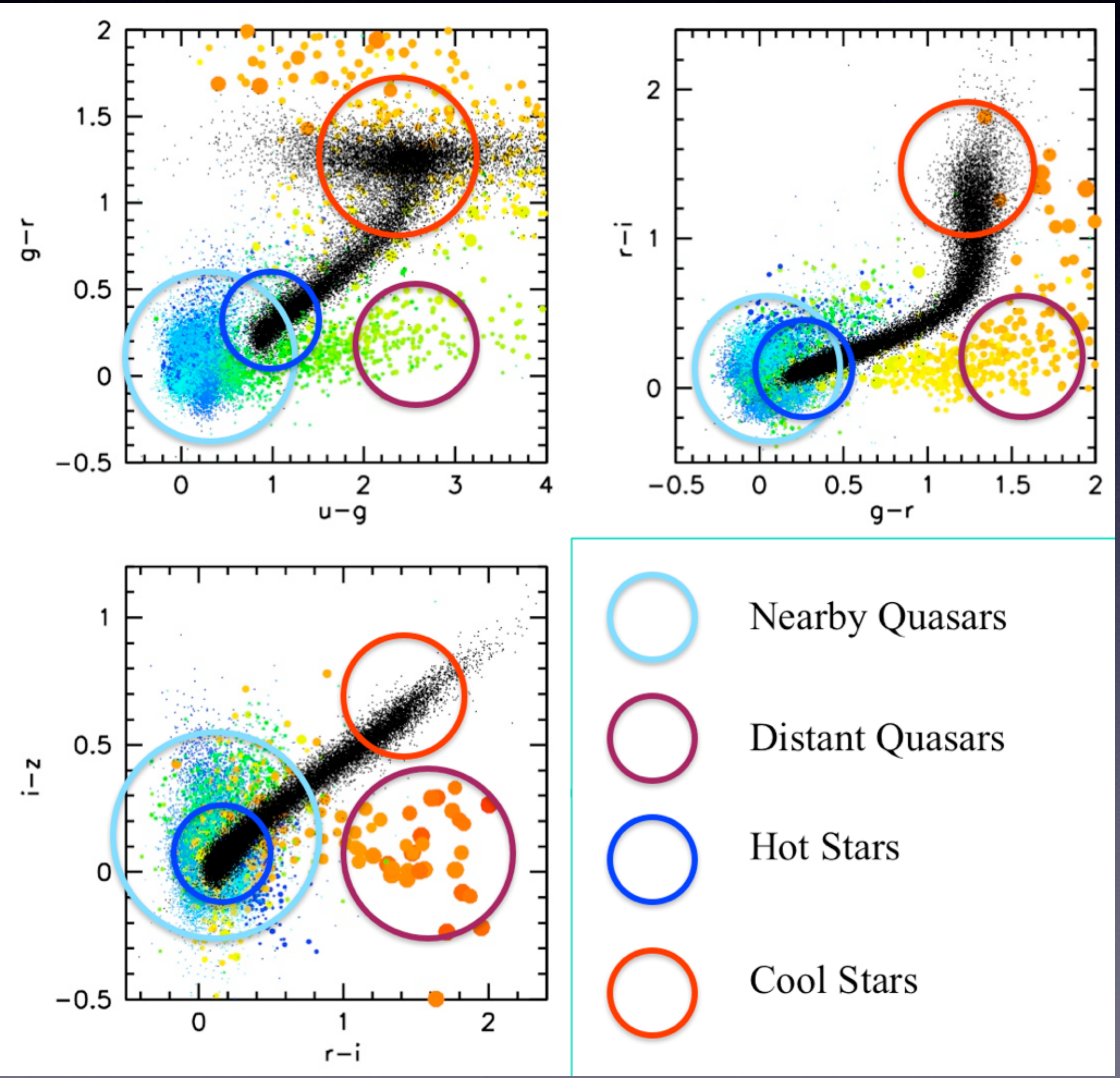
Traditionally need spectroscopic confirmation





Sloan Digital Sky Survey Quasar Catalogs:

- about 1/4 of the sky, spectroscopically confirmed
- SDSS I & II: 105,783 (Schneider et al. 2010)
- SDSS III: + 78,086 (Paris et al. 2012)



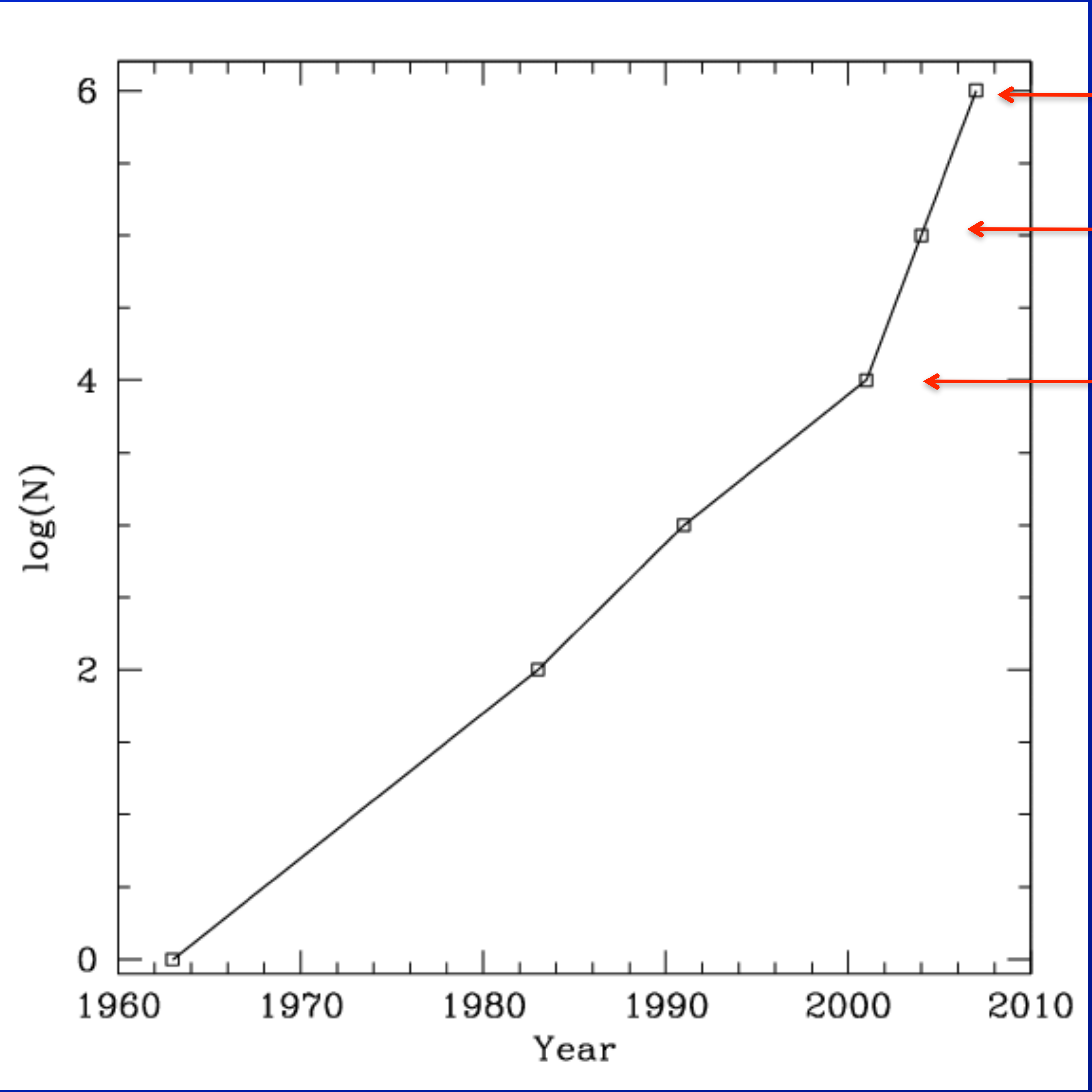
- mostly color-selected, but also radio (FIRST), see Richards et al. (2002)
- over half with i<19
- 56 with z>5

~200,000 quasars!

Completeness: >90%

Efficiency of color selection: >65%

Breaking the 1,000,000 Mark



Richards et al. 2009

Richards et al. 2004

Croom et al. 2000
Schneider, Richards et al. 2002

Can we get to 10 million?

Can we get to 10 million?

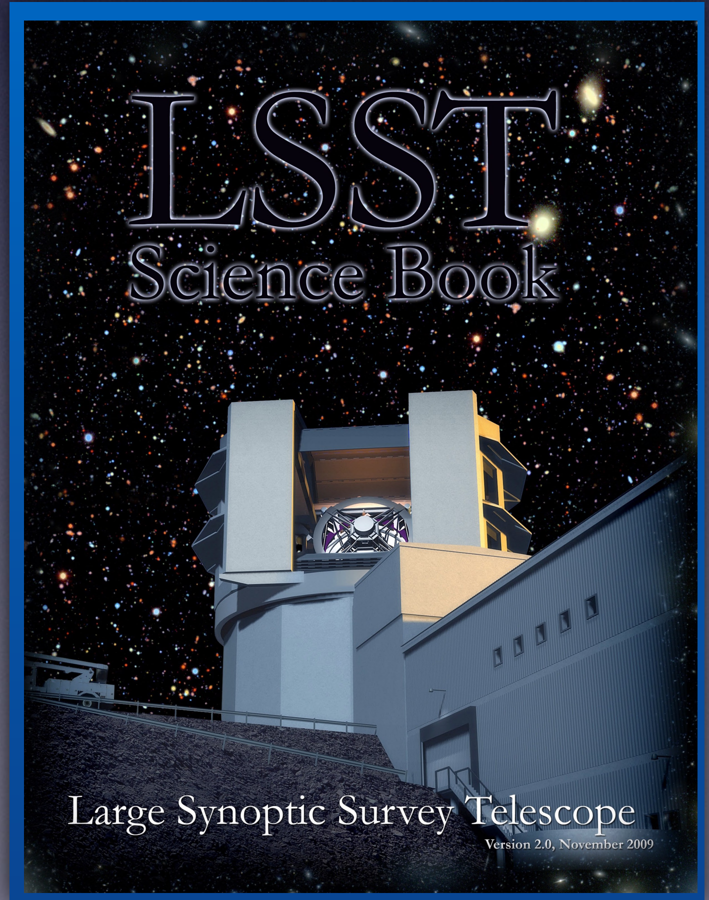
LSST Science Themes

- 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)

LSST Science Book: arXiv:0912.0201

Summarizes LSST hardware, software, and observing plans, science enabled by LSST, and educational and outreach opportunities

245 authors, 15 chapters, 600 pages



U.S. Decadal Survey 2010

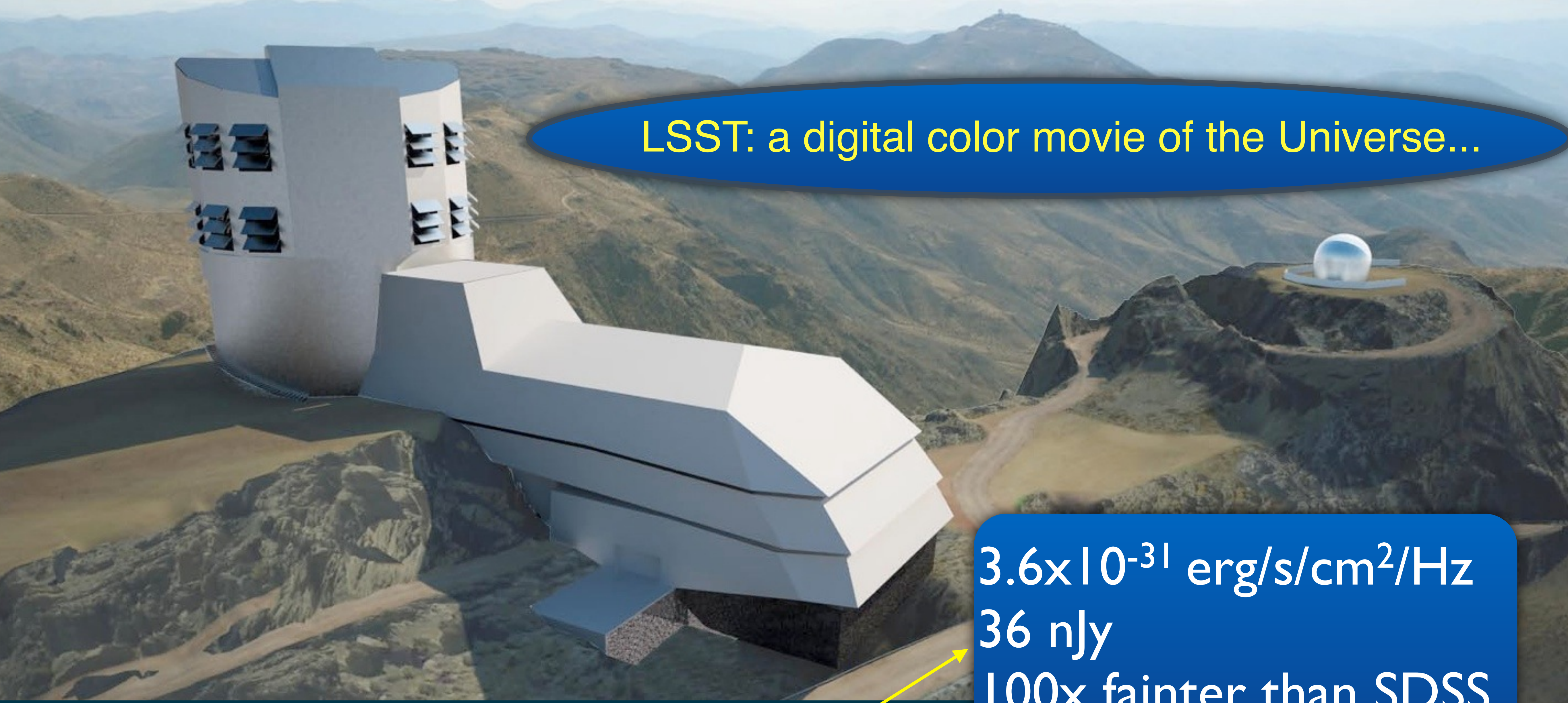
Priorities:

- 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*



LSST: a digital color movie of the Universe...

3.6×10^{-31} erg/s/cm^2/Hz
36 nJy
100x fainter than SDSS

LSST in one sentence:

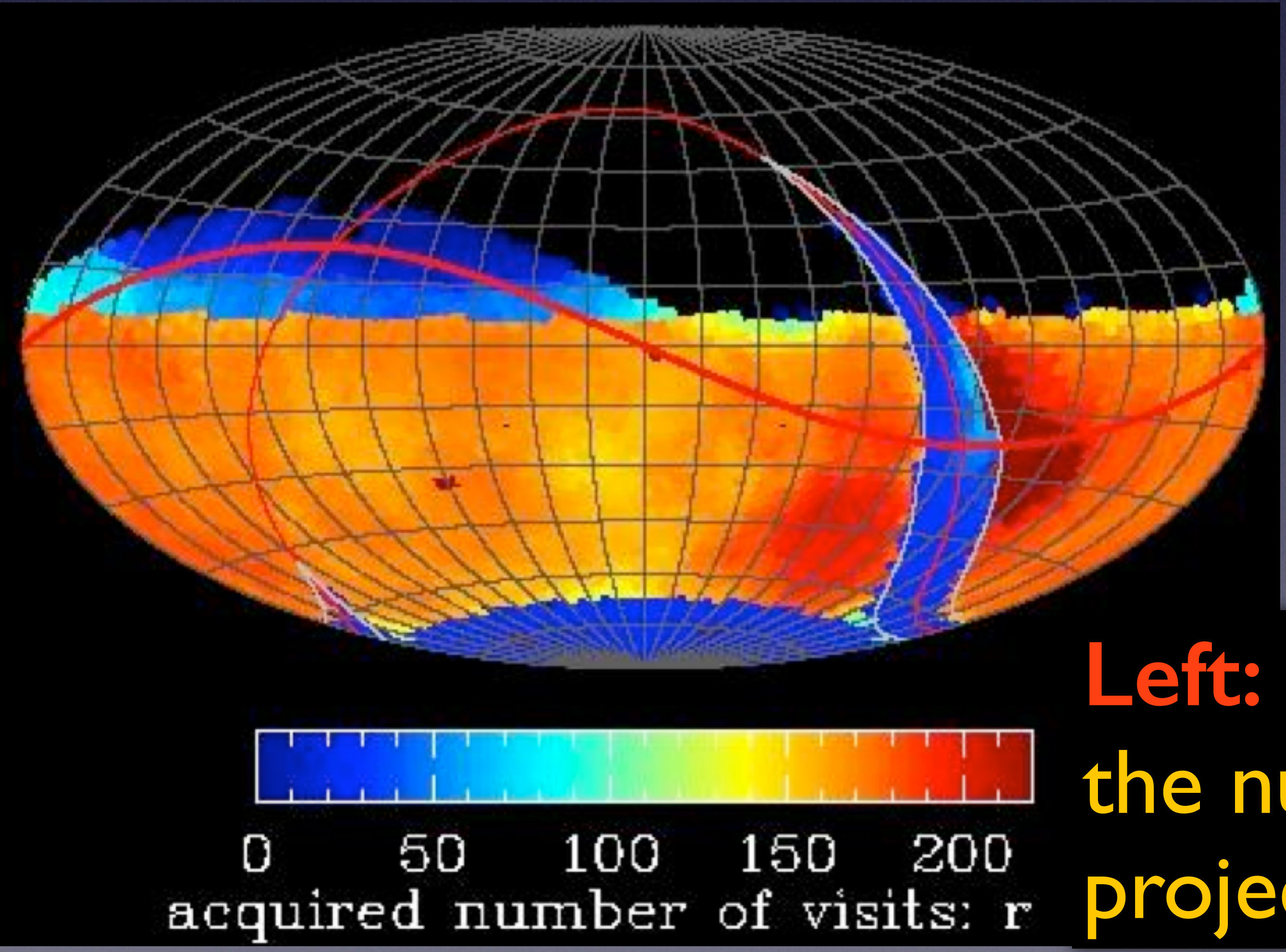
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 based on ~1000 visits over a 10-year period:

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

A catalog of 20 billion stars and 20 billion galaxies with exquisite photometry, astrometry and image quality!

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 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)

LSST First Stone Ceremony
April 14, 2015

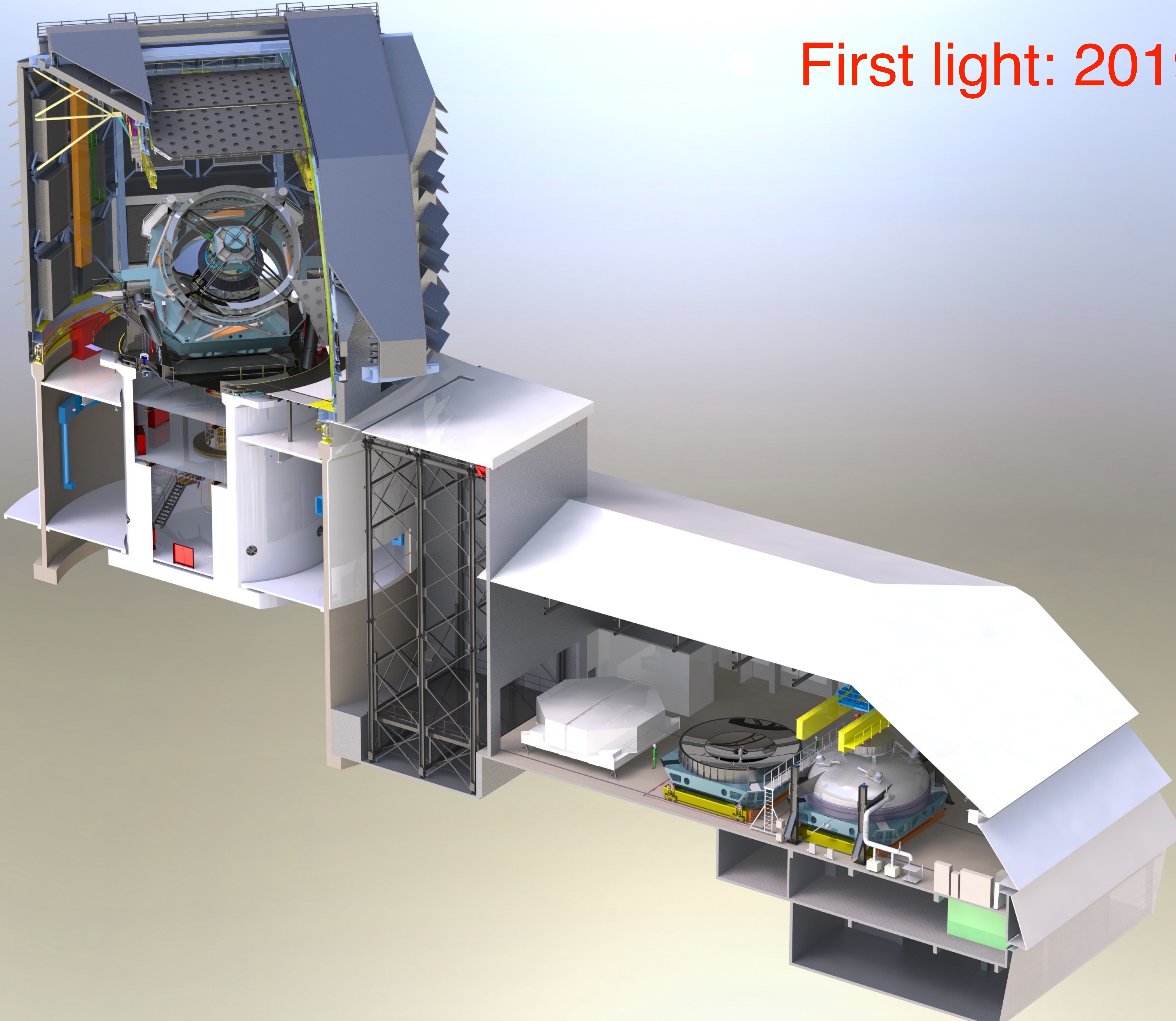
LSST First Stone Ceremony
April 14, 2015

and while dignitaries are celebrating…

some are happily doing real work!

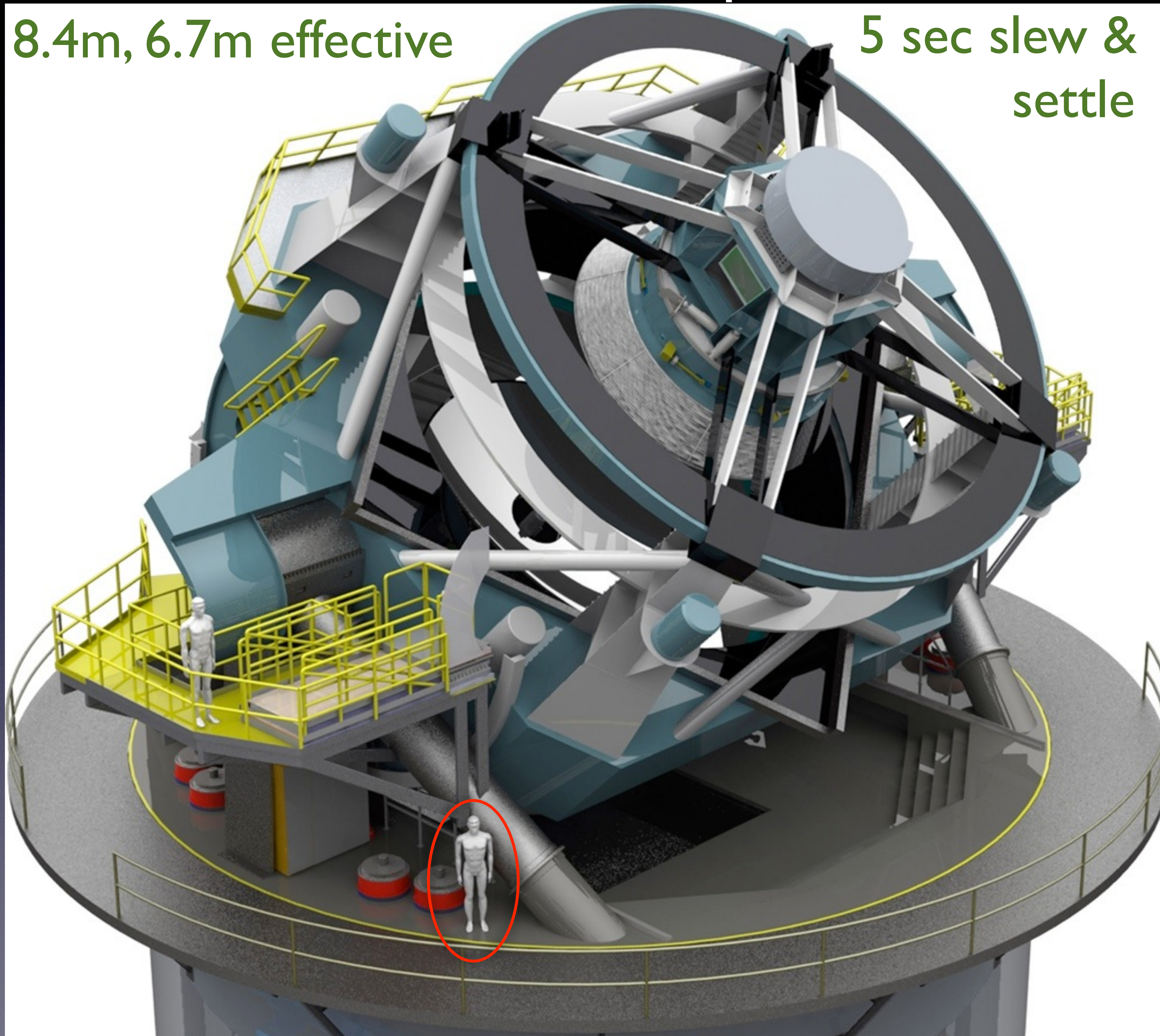
LSST Construction – Above Ground on Pachón!


February 15, 2016
material staging
Provisional plywood walkways
Excavation for telescope pier foundation - rebar placed for pour Feb 22 to 24
Excavation for platform lift
Excavation for lower enclosure foundation
Service building concrete structure in progress
Elec. & tank area
Formwork for beams to support level 3 floor & mirror cart rails

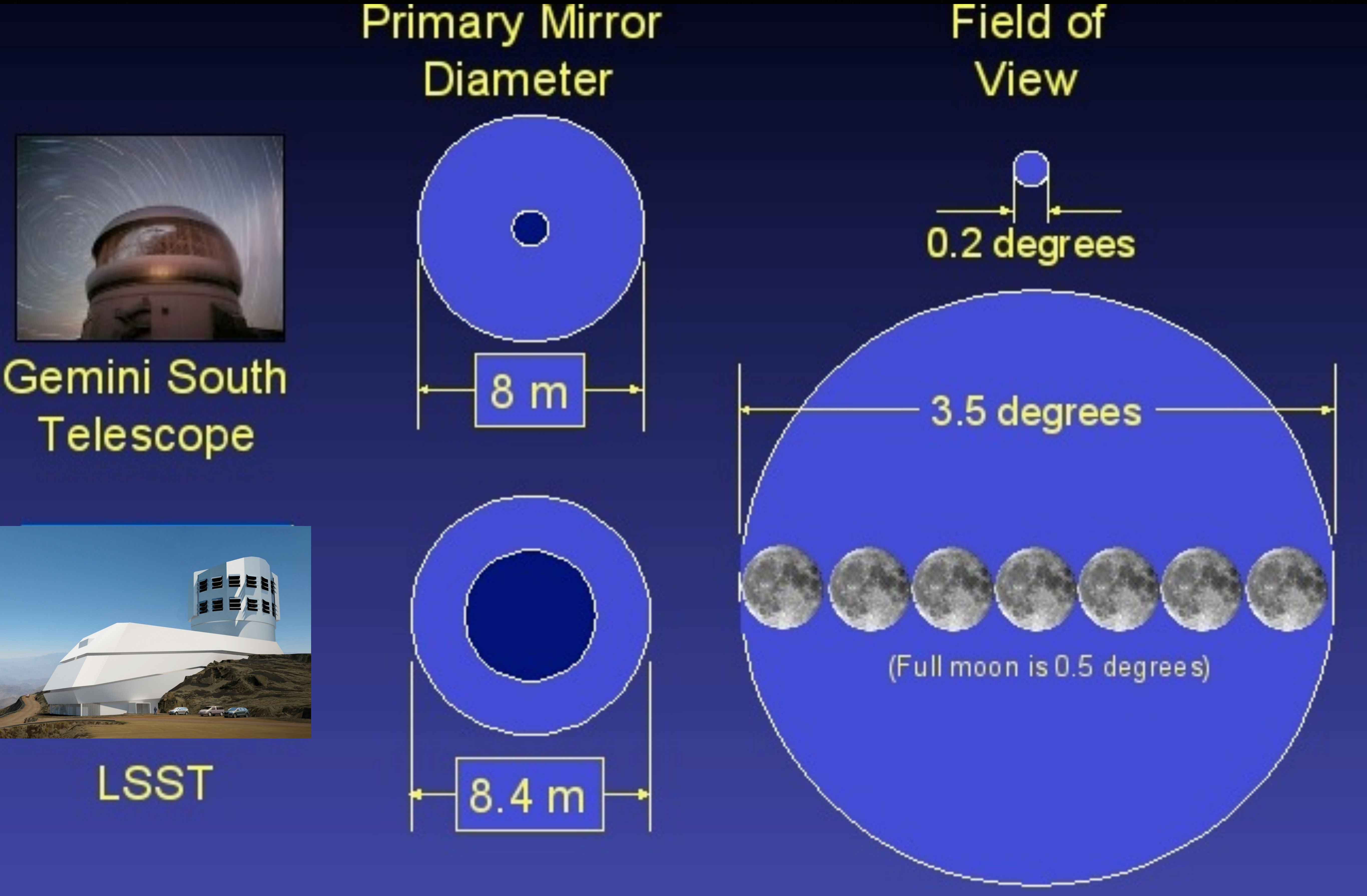


First light: 2019

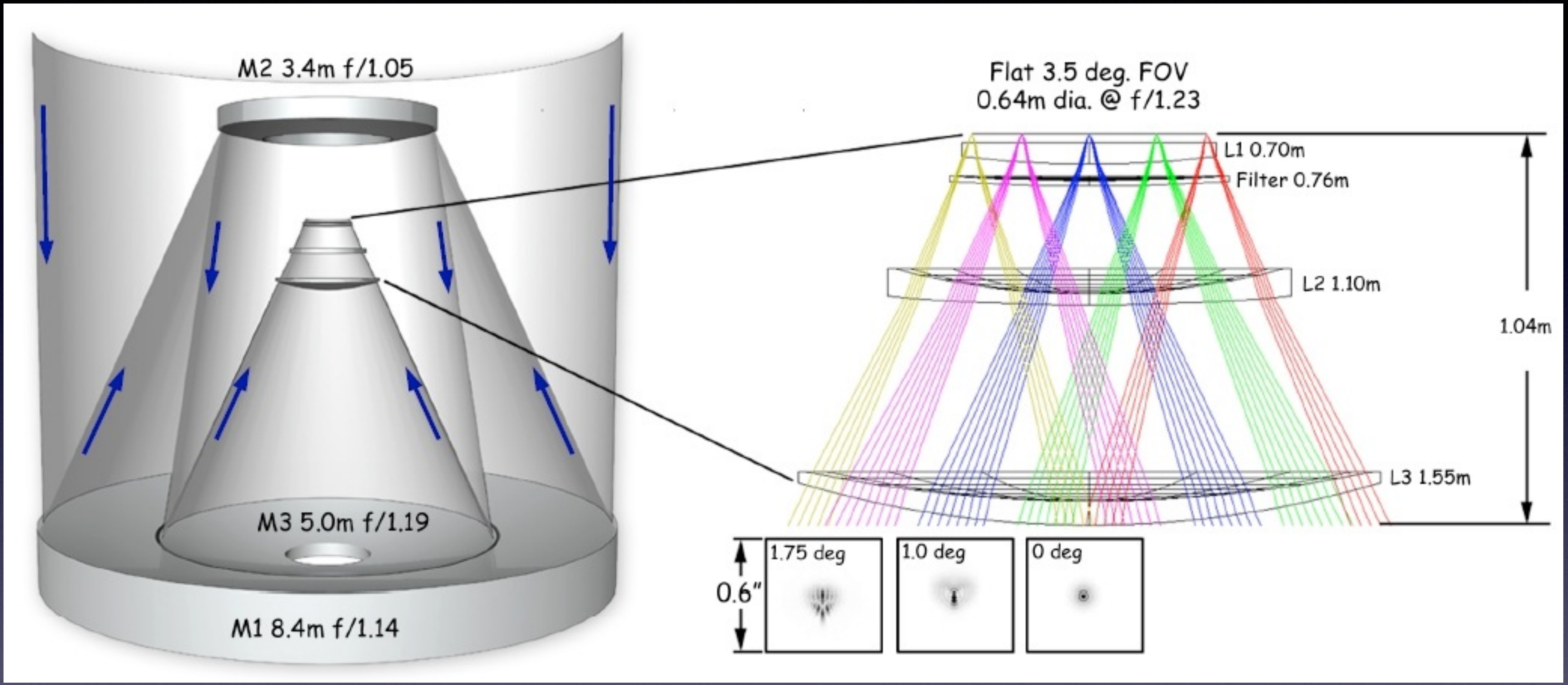
LSST Telescope



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

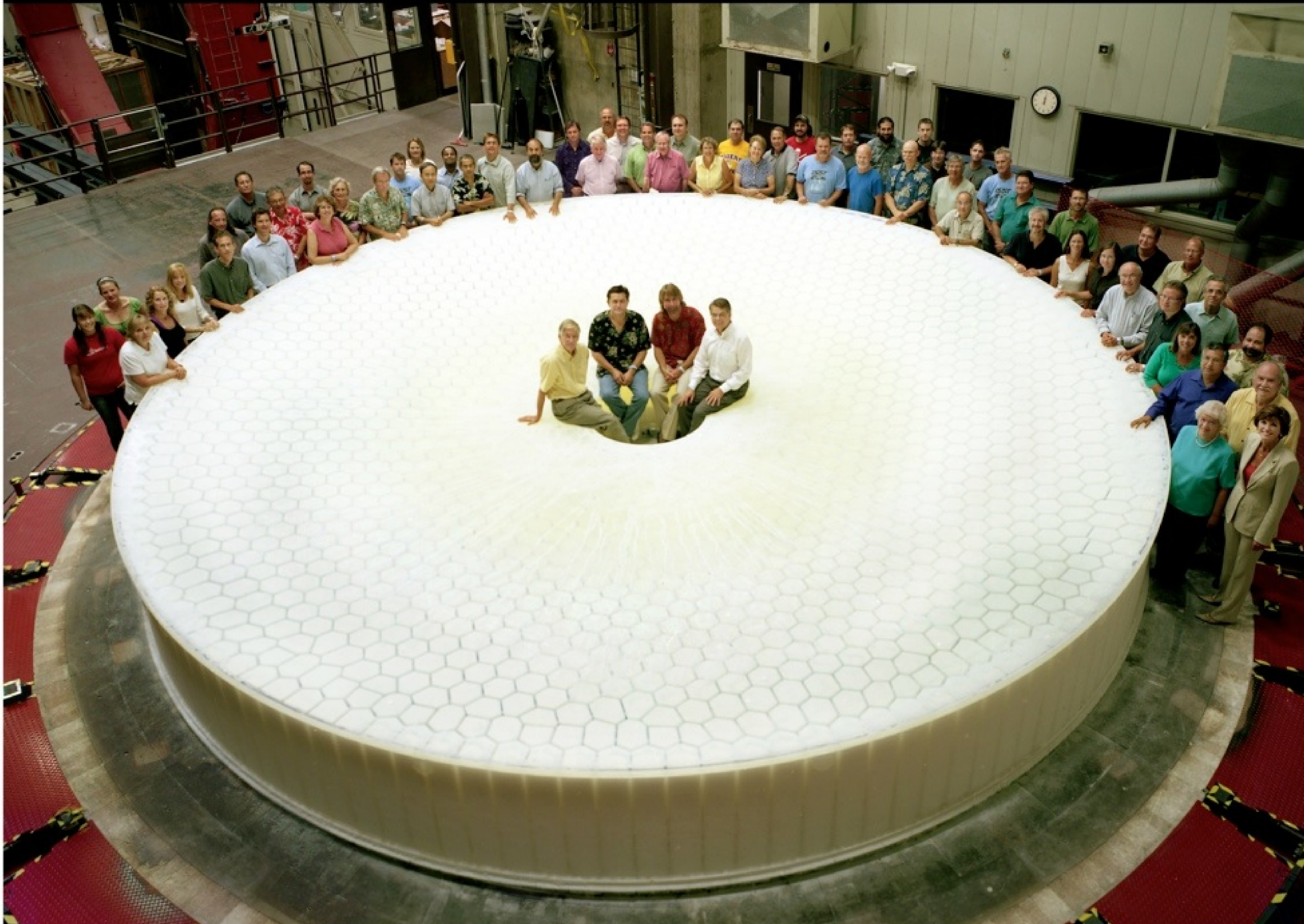


Optical Design for LSST



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



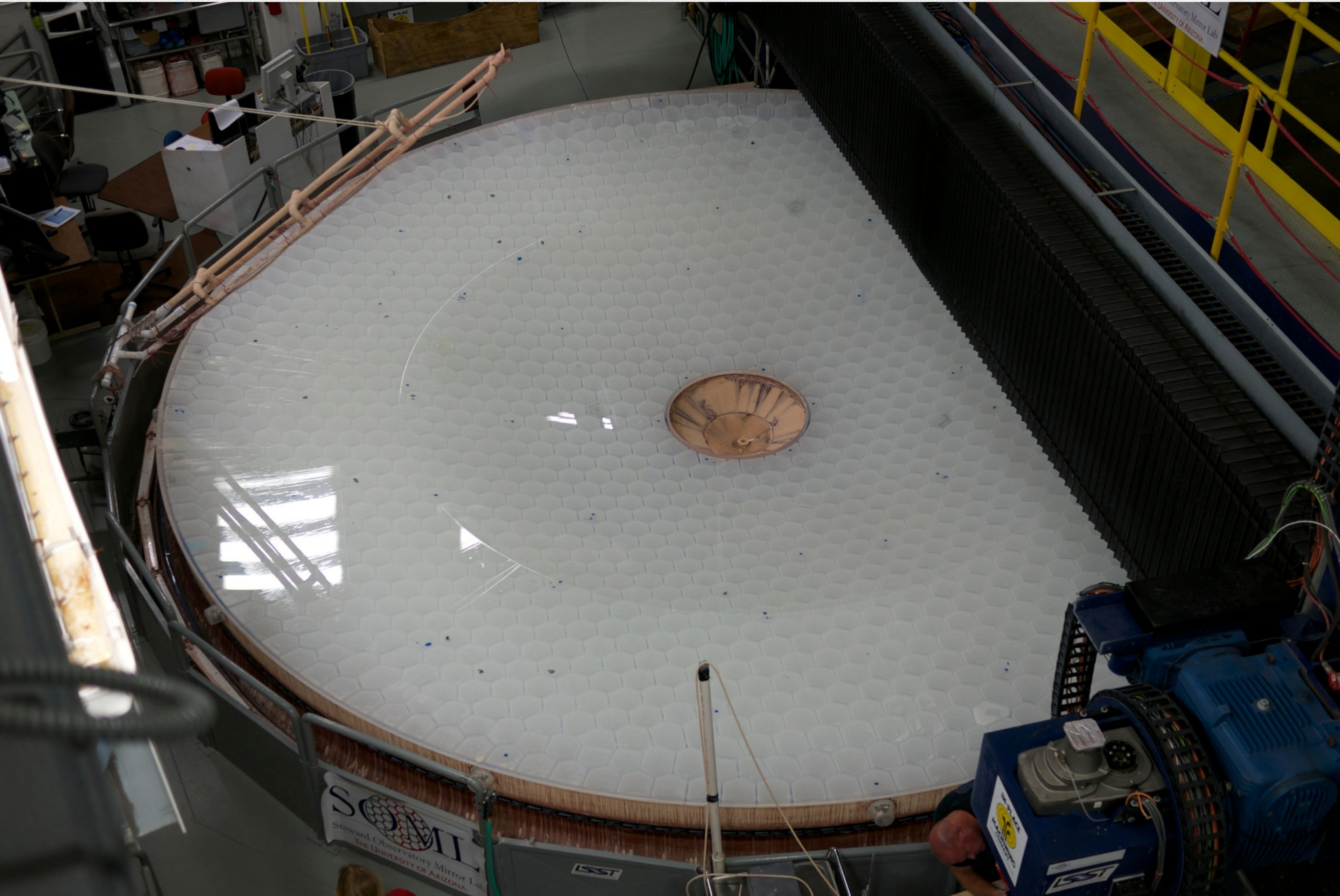
THE UNIVERSITY OF ARIZONA
TUCSON ARIZONA

SOML

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

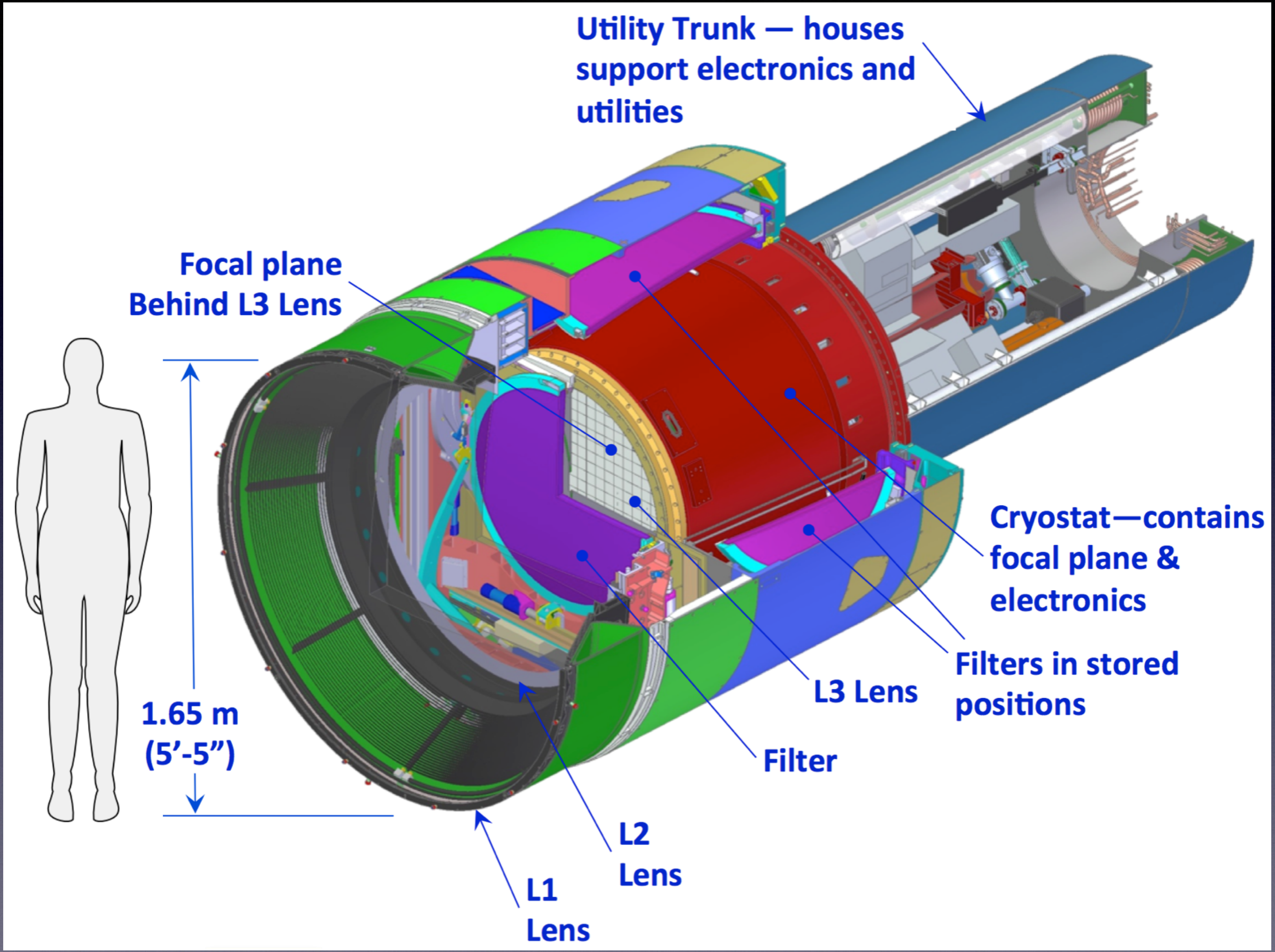
LSST
Large Synoptic Survey Telescope

Done!



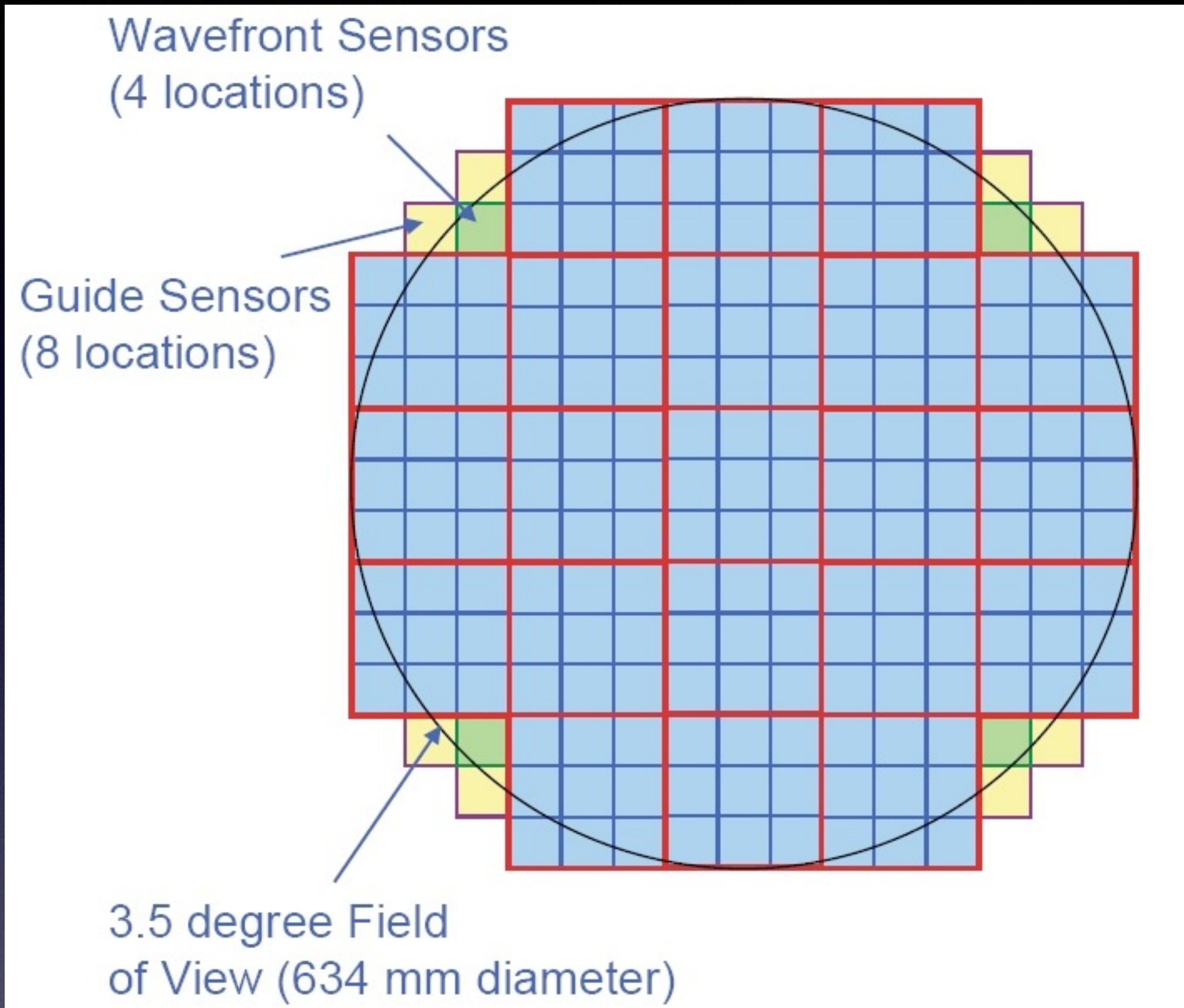
SOML
Steward Observatory Mirror Lab
THE UNIVERSITY OF ARIZONA
LSST

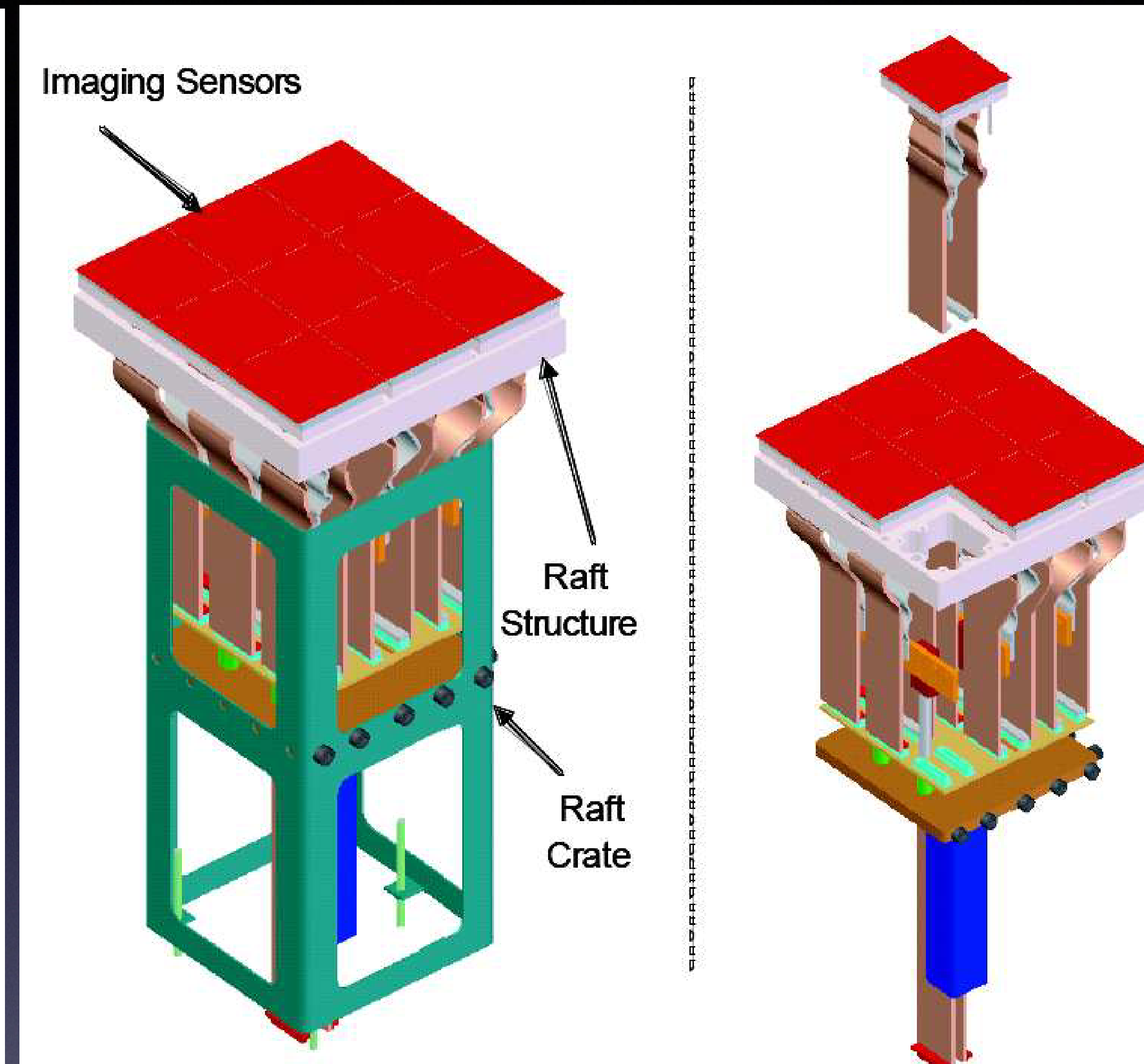
LSST camera



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

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)

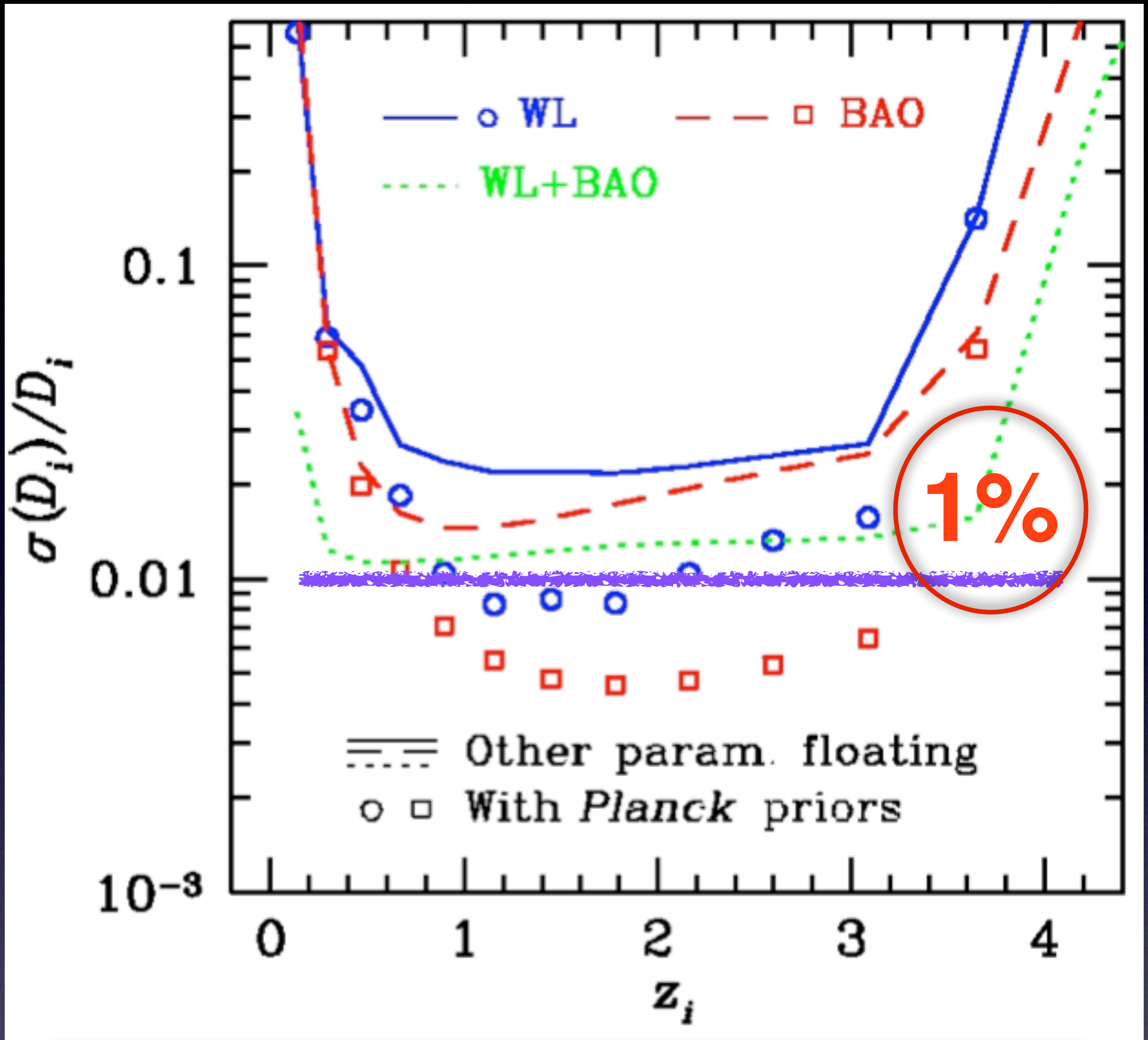
4) **Serve** images, catalogs and all other metadata, that is, **LSST data products to LSST users**

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

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++ and python)

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 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

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)

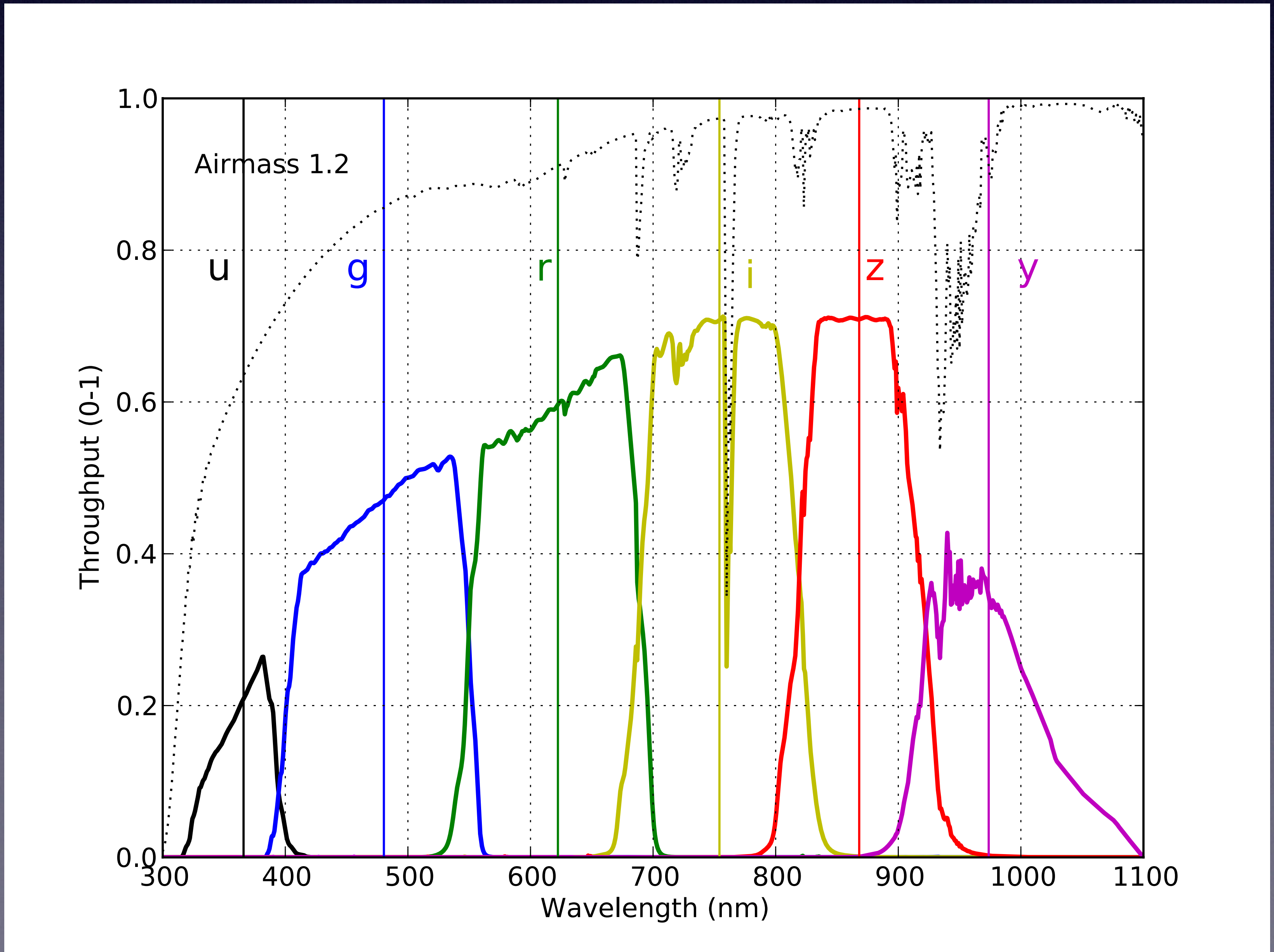


Photo-z requirements correspond to r~27.5 with the following per band time allocations:

u: 8%; g: 10%

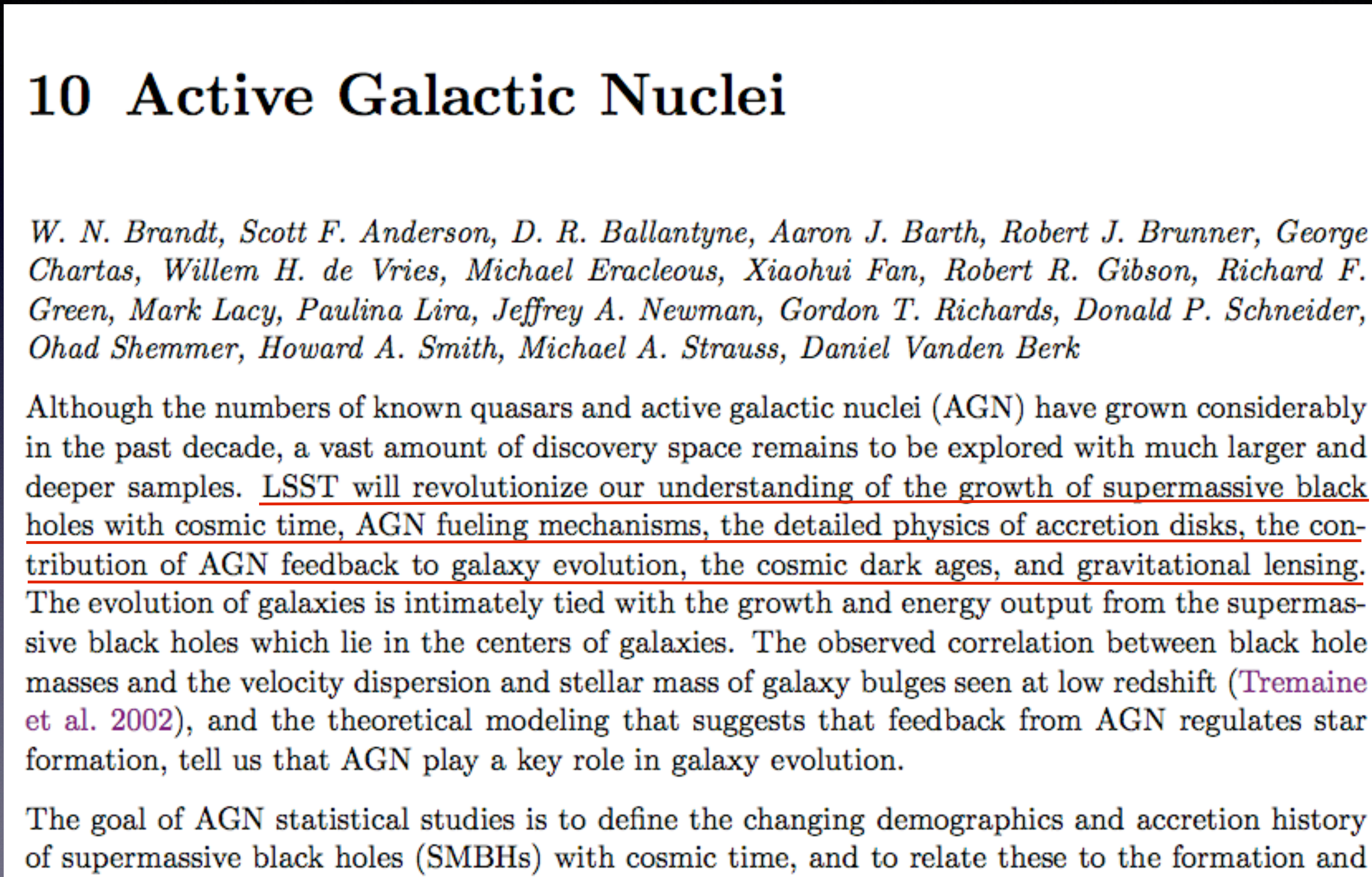
r: 22%; i: 22%

z: 19%; y: 19%

Consistent with other science themes (stars)

Extragalactic astronomy: AGNs

From LSST Science Book (arXiv:0912.0201):

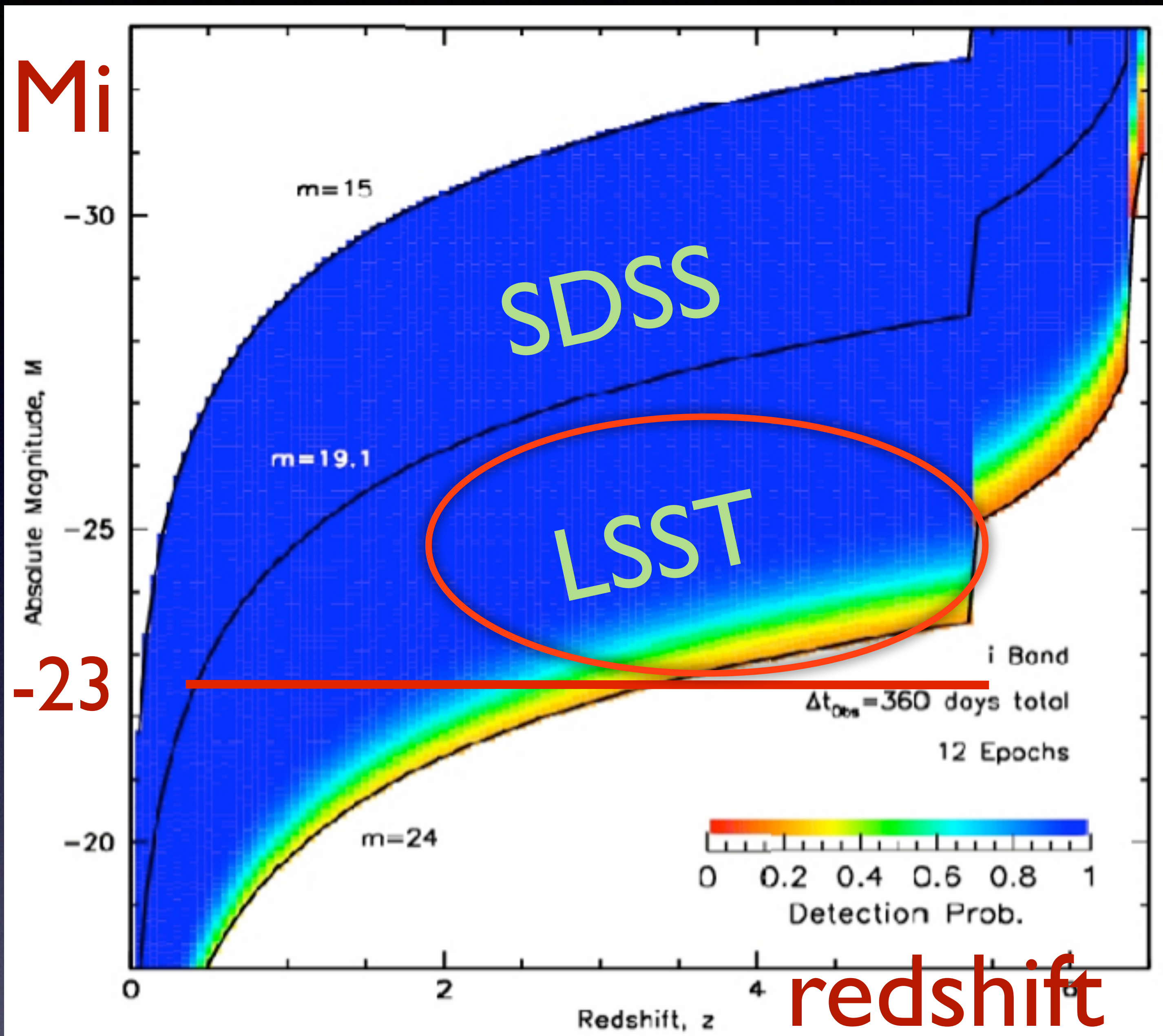

10 Active Galactic Nuclei

W. N. Brandt, Scott F. Anderson, D. R. Ballantyne, Aaron J. Barth, Robert J. Brunner, George Chartas, Willem H. de Vries, Michael Eracleous, Xiaohui Fan, Robert R. Gibson, Richard F. Green, Mark Lacy, Paulina Lira, Jeffrey A. Newman, Gordon T. Richards, Donald P. Schneider, Ohad Shemmer, Howard A. Smith, Michael A. Strauss, Daniel Vanden Berk

Although the numbers of known quasars and active galactic nuclei (AGN) have grown considerably in the past decade, a vast amount of discovery space remains to be explored with much larger and deeper samples. LSST will revolutionize our understanding of the growth of supermassive black holes with cosmic time, AGN fueling mechanisms, the detailed physics of accretion disks, the contribution of AGN feedback to galaxy evolution, the cosmic dark ages, and gravitational lensing. The evolution of galaxies is intimately tied with the growth and energy output from the supermassive black holes which lie in the centers of galaxies. The observed correlation between black hole masses and the velocity dispersion and stellar mass of galaxy bulges seen at low redshift (Tremaine et al. 2002), and the theoretical modeling that suggests that feedback from AGN regulates star formation, tell us that AGN play a key role in galaxy evolution.

The goal of AGN statistical studies is to define the changing demographics and accretion history of supermassive black holes (SMBHs) with cosmic time, and to relate these to the formation and

Extragalactic astronomy: quasars



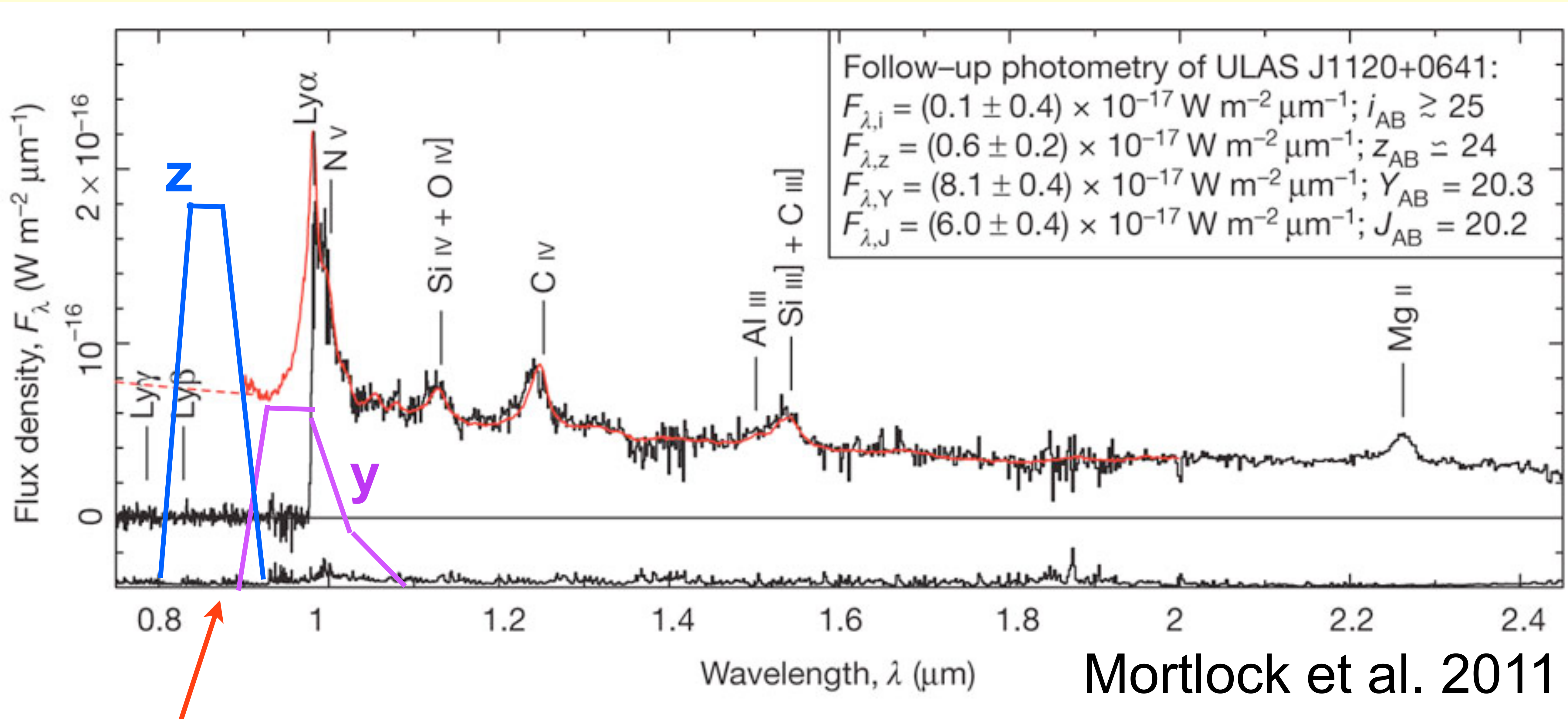
Top: absolute magnitude vs. redshift diagram for quasars

- 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

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

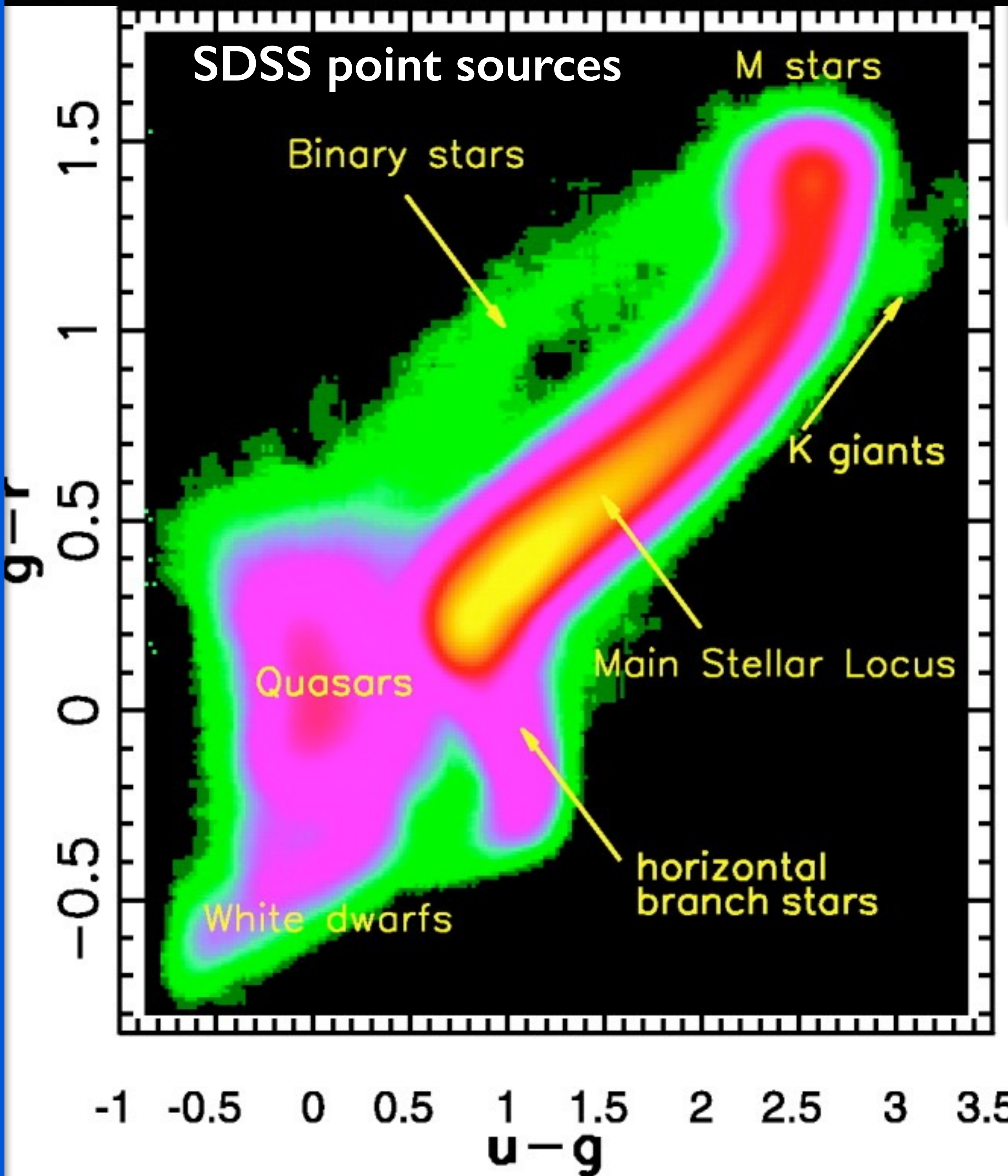
The Highest Redshift Quasar at z=7.085 from UKIDSS

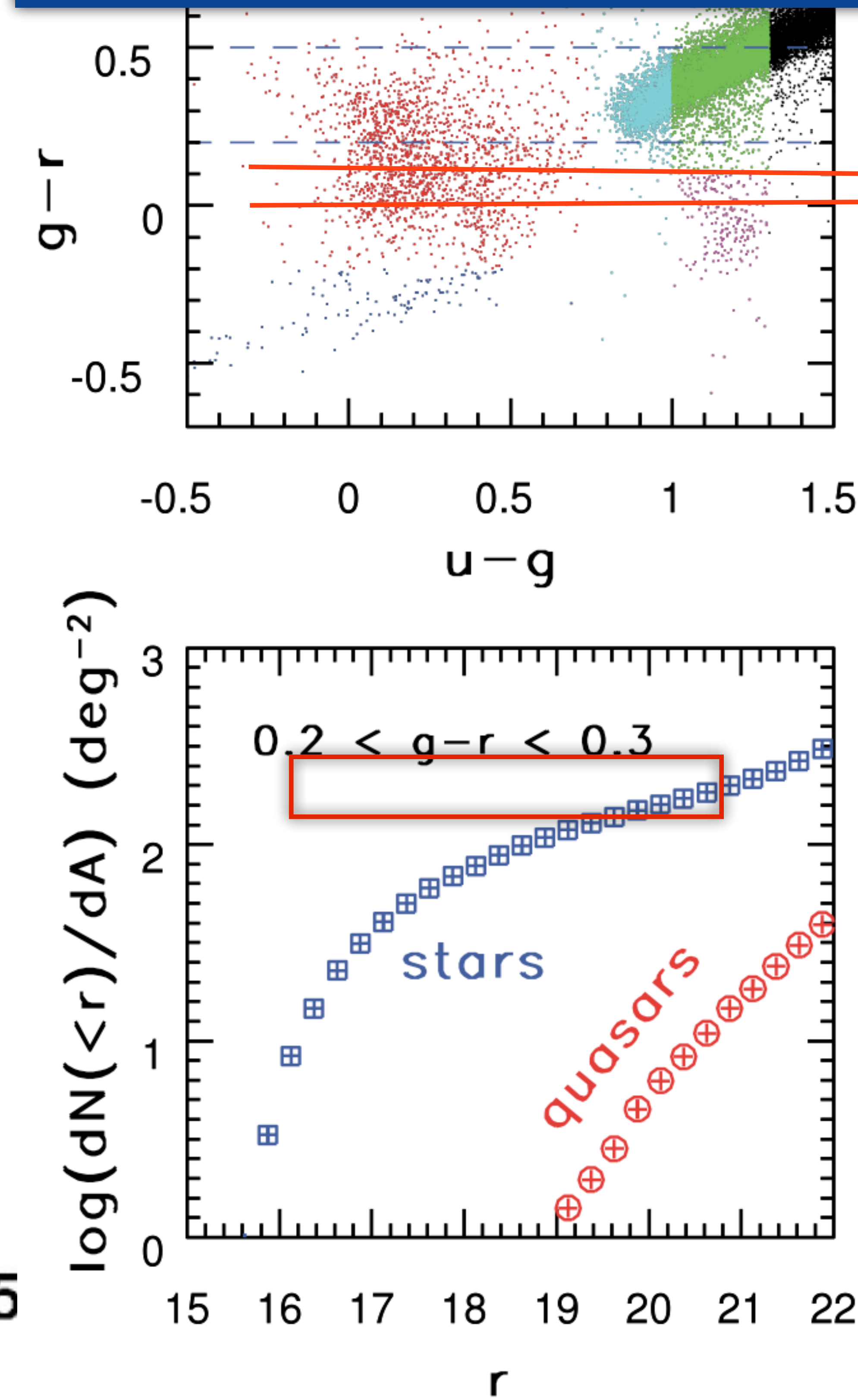


Such a quasar would be detected by LSST as a z-band dropout
(multi-epoch data will greatly help with false positives)

LSST will discover about 1,000 quasars with z>7
Today: one quasar with z>7

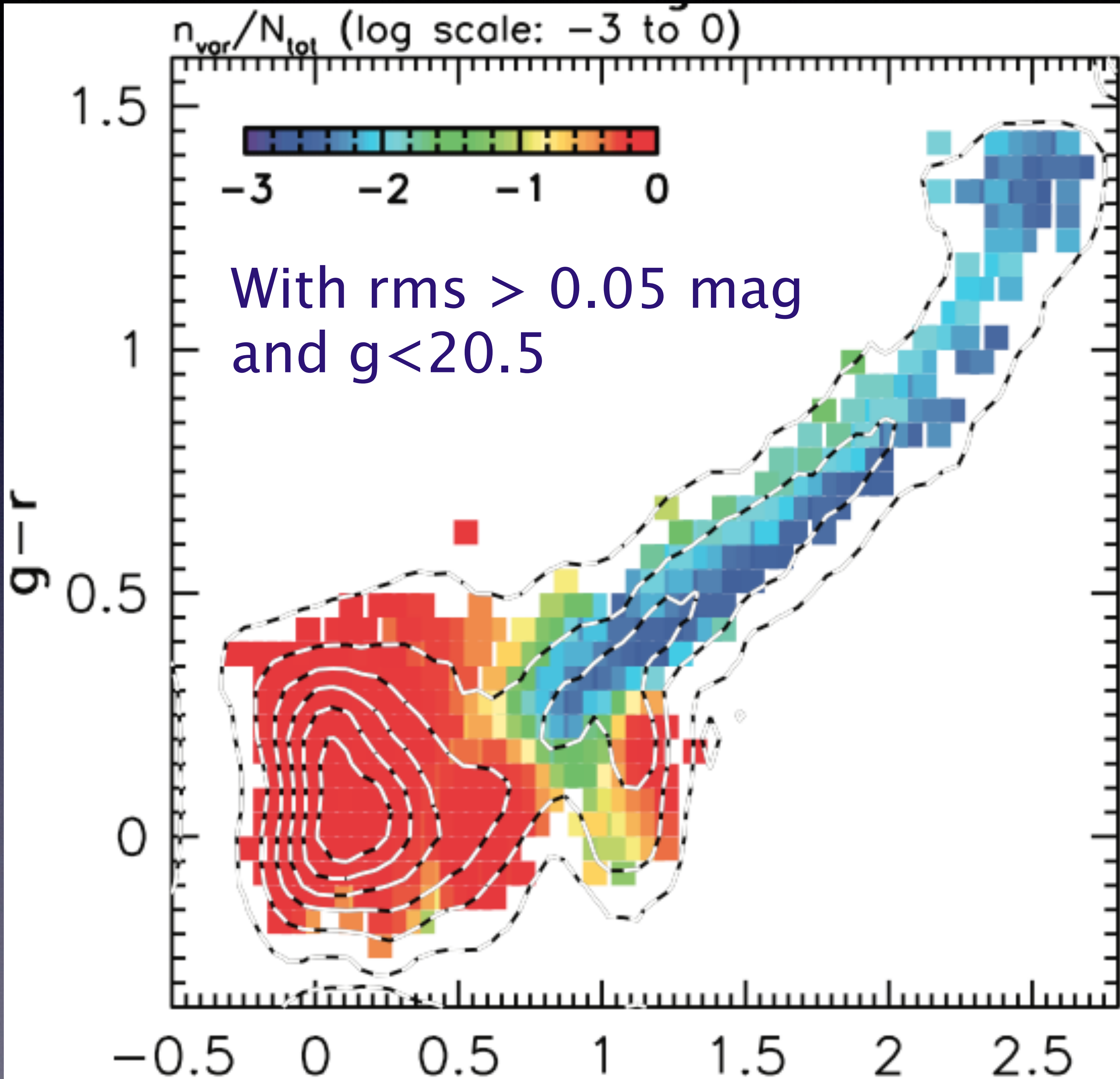
Static sky!
More information in time domain...





Practically all quasars are variable!

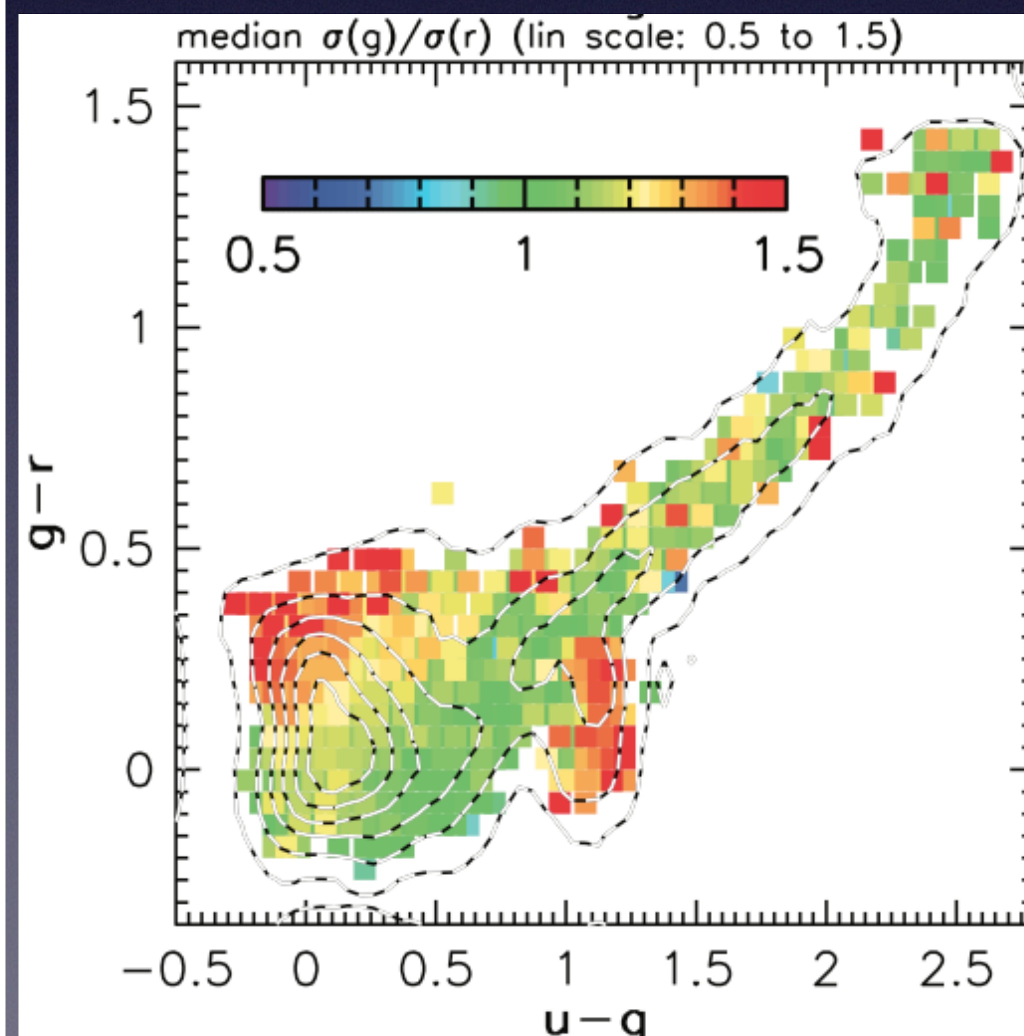
The fraction of variable objects in SDSS Stripe 82:



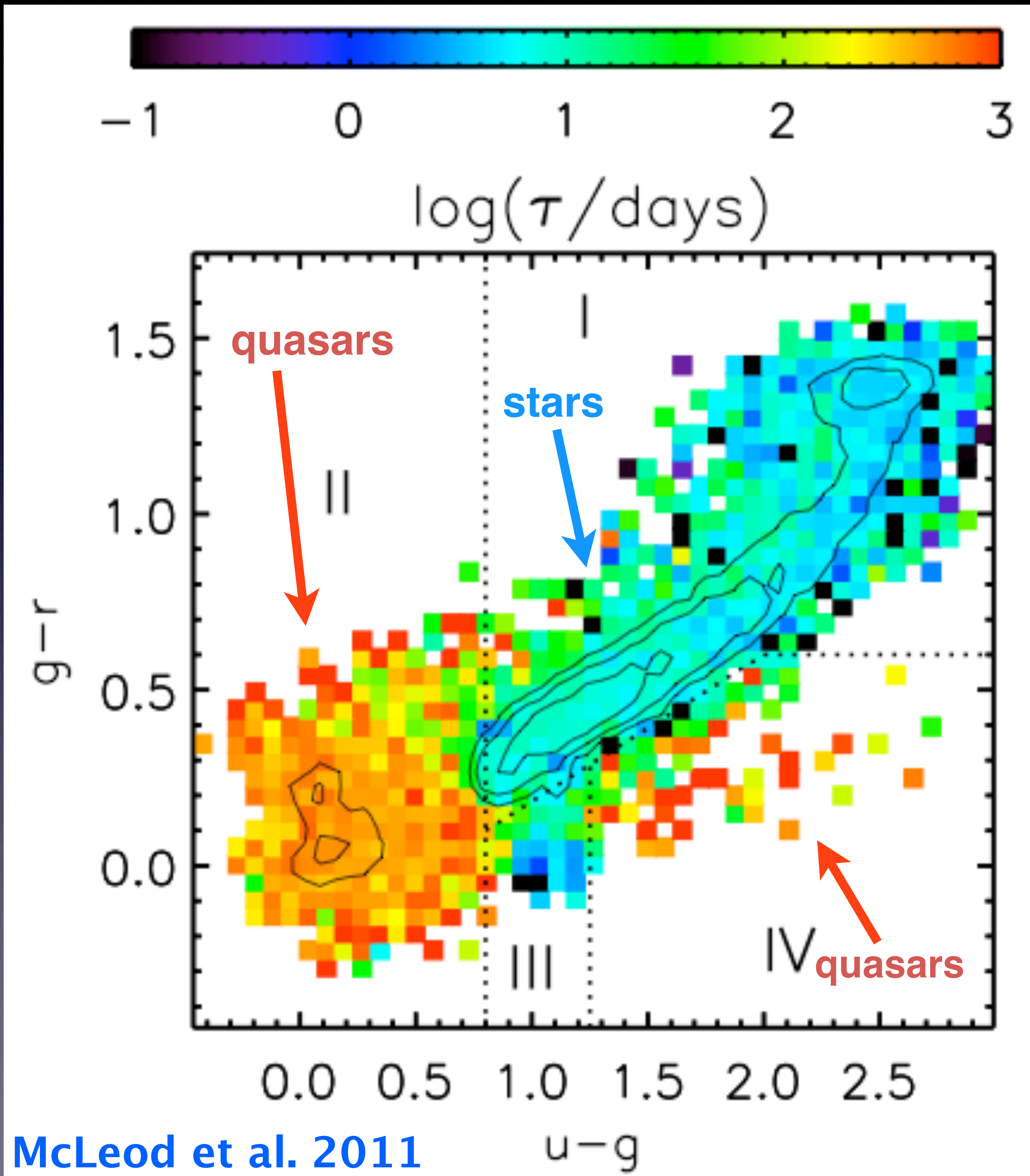
Sesar et al. 2007

The sample is dominated by quasars and RR Lyrae.

Quasars and RR Lyrae have different variability properties: rms(g)/rms(r)



The variability time scales



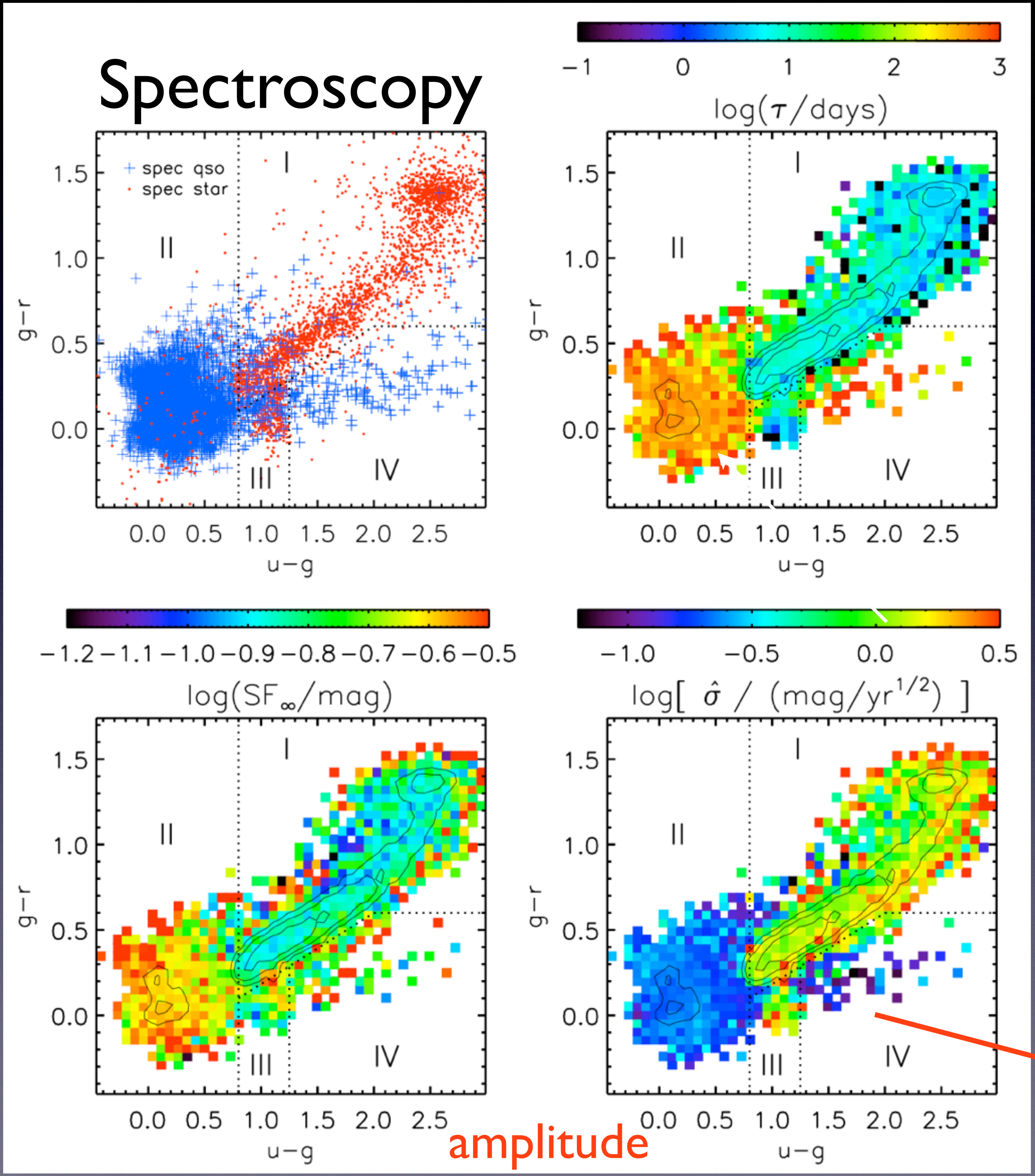
Time scale τ is defined via **damped random walk** (because not all variable sources are periodic)

Quasars are easily distinguished from stars by their long time scales.

Variability is even better than color selection!

Case study: light curve data and proper motion data for over 1 million sources from SDSS Stripe 82 (all are publicly available)

Damped random walk fits to SDSS Stripe 82



3-parameter fits: DRW time scale, amplitude, and mean magnitude

Using variability, one gets the same morphology in the g-r vs. u-g diagram as when using spectroscopy!

True even for short observation spans

Wonderful, but can we do variability selection with extended sources? YES!

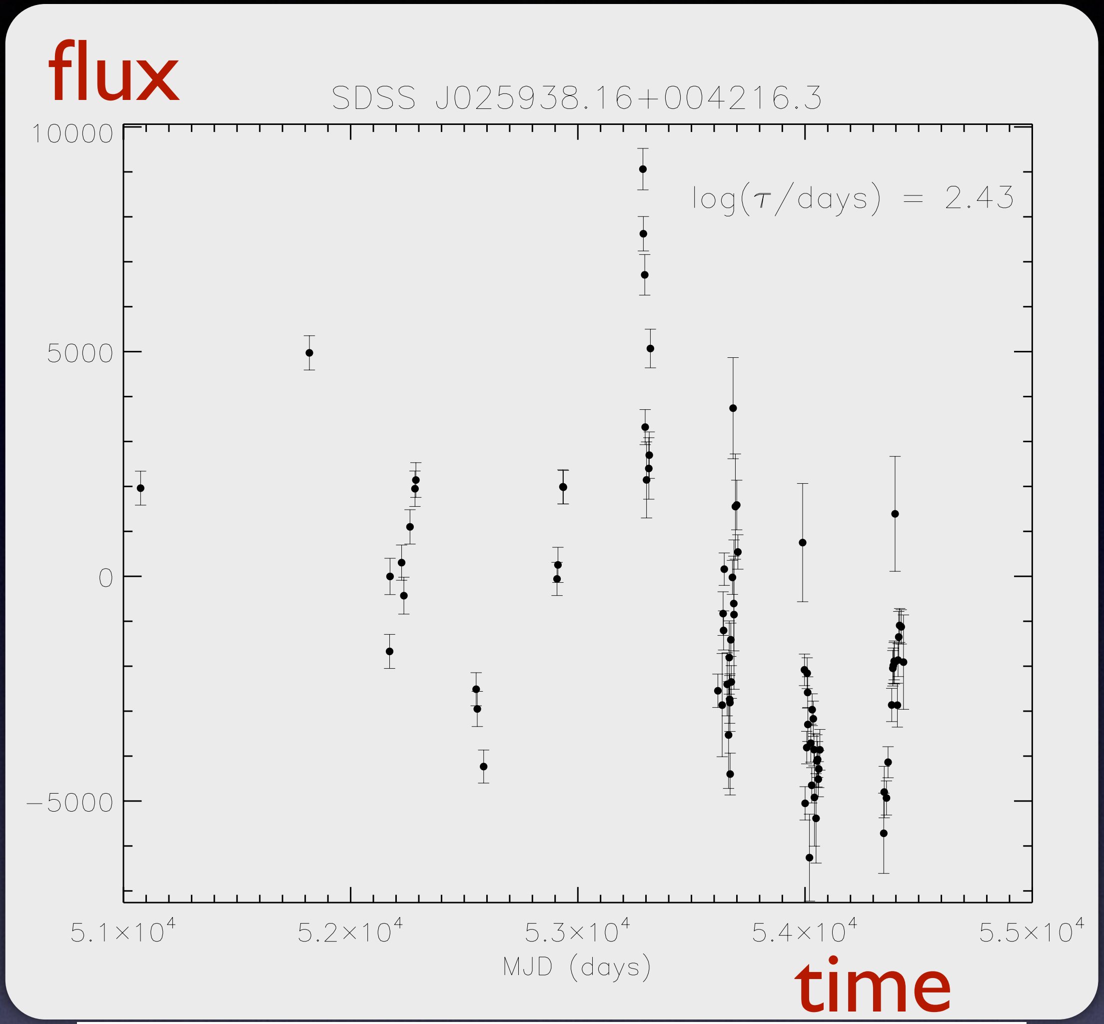
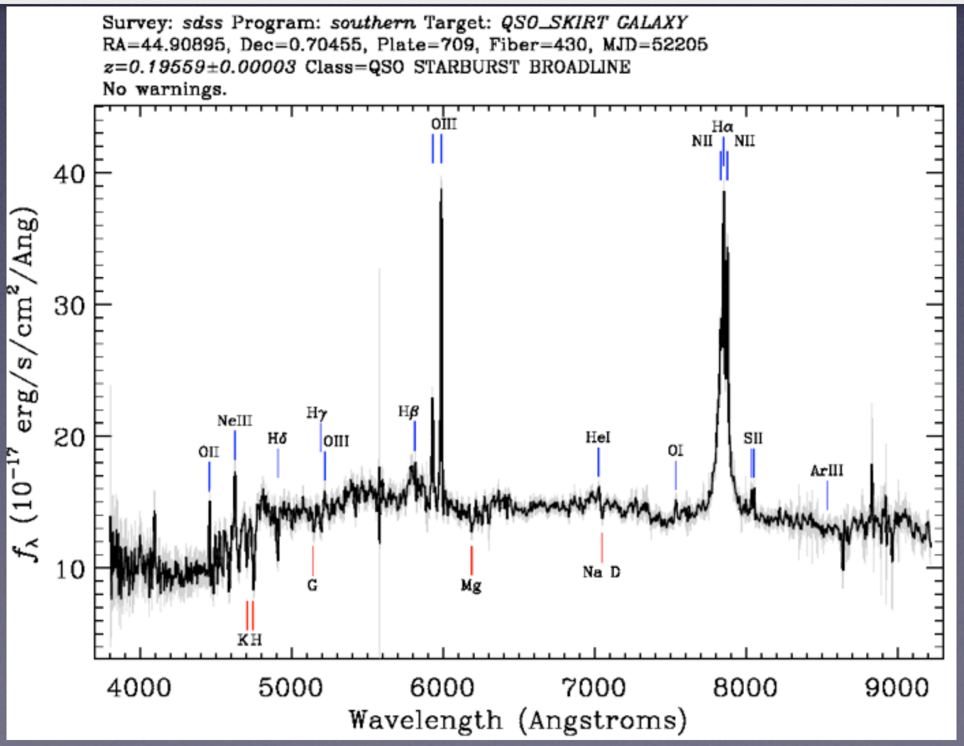
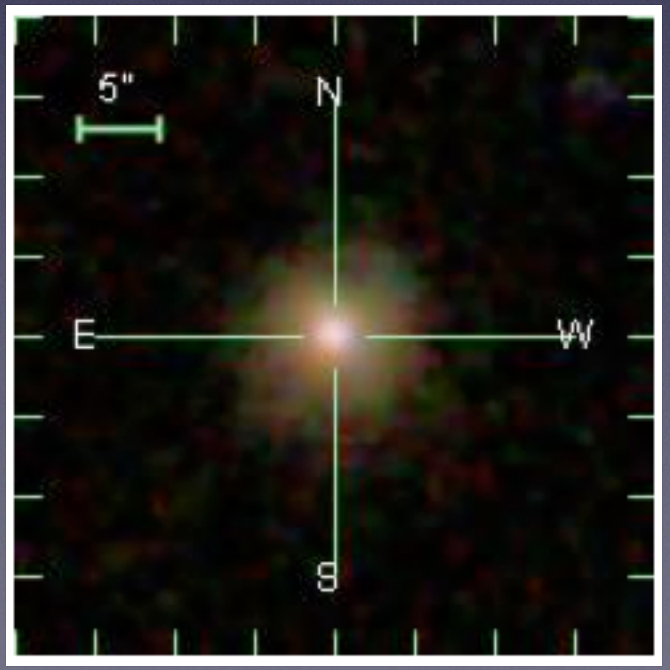


Image differencing can be used to extract light curves for extended sources with nearly the same SNR as for unresolved sources

Case study: image differencing using SDSS Stripe 82 (Choi+2014, ApJ 782, 37): light curves that have time scales as long as AGNs are independently confirmed as AGNs using X-ray data and optical emission lines (BPT diagram)!

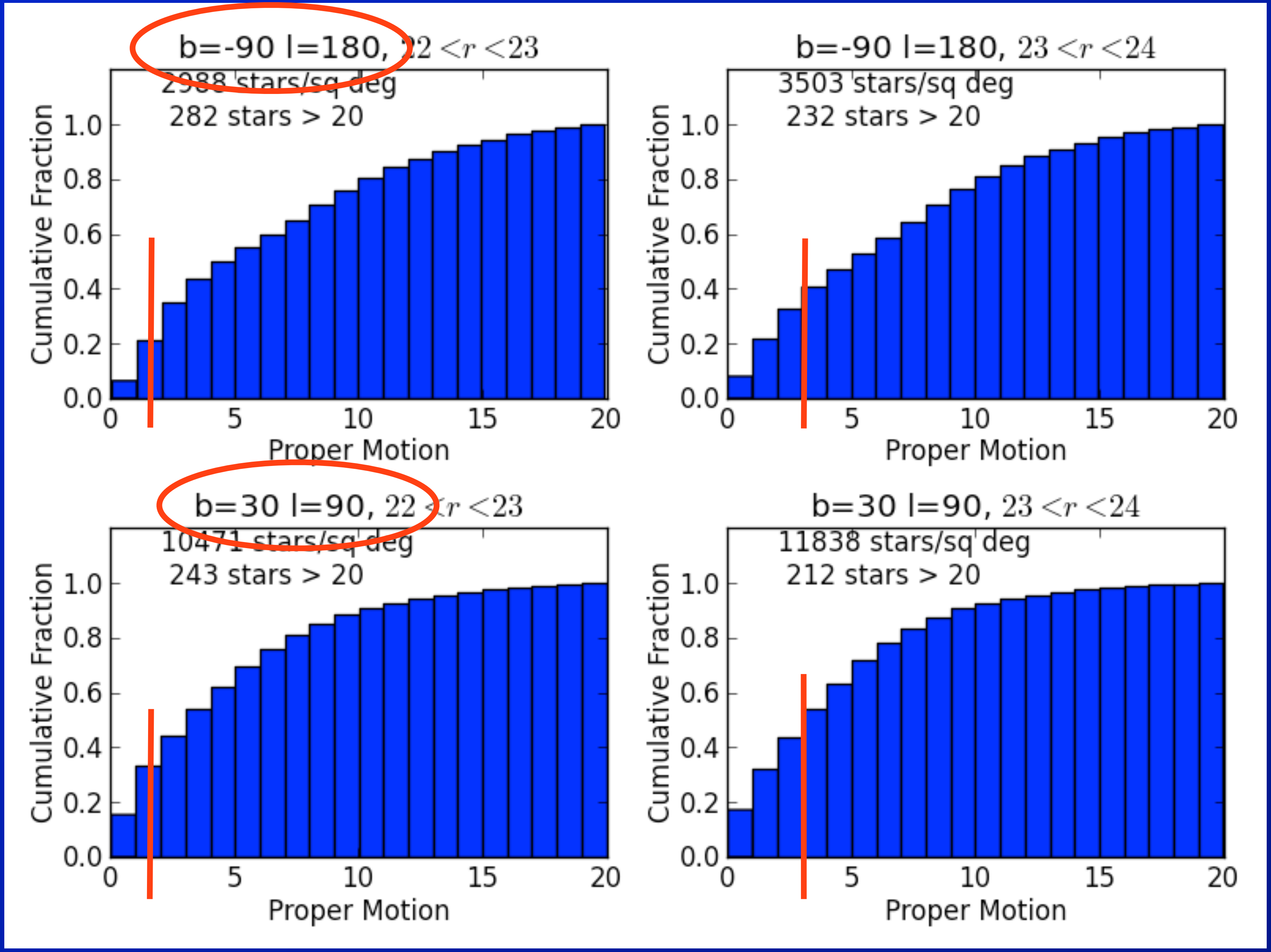




How will LSST proper motion measurements help with the selection of faint quasars?

LSST proper motion errors: 0.5 mas/yr for r=23 and 1.0 mas/yr for r=24.

22 < r < 23 **23 < r < 24**



By adopting a 3sigma rejection cut:

About 2/3 of faint stars rejected due to proper motions <u>without</u> any selection by color or photometric variability, even at the faint end!

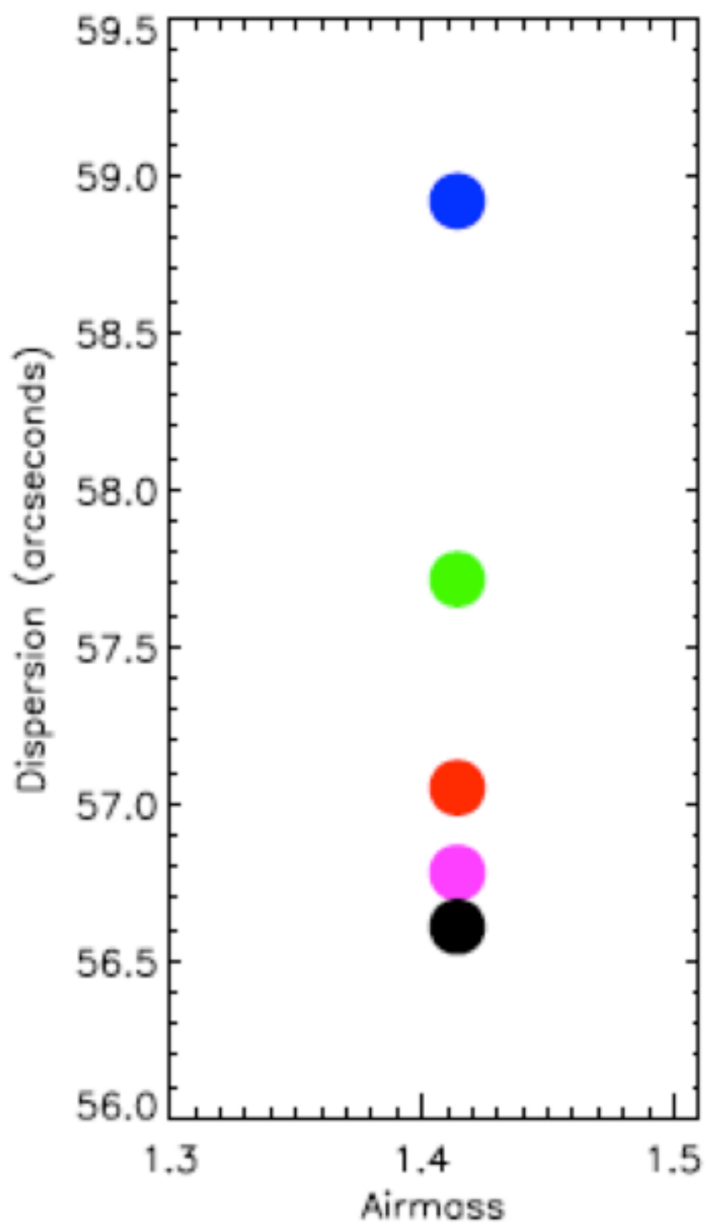
Astrometric Classification **Kaczmarczik et al. (2009)**

1) Atmospheric refraction depends on object's SED (within a passband)
2) Astrometric solution is derived using stars (with different SEDs than quasars')
3) Quasar's calibrated position will change with airmass of observation:

$$R \simeq R_0 \tan(Z),$$

$$R_0 = \frac{n^2 - 1}{2n^2}$$

$$[n(\lambda) - 1]10^6 = 64.328 + \frac{29498.1}{146 - (1/\lambda)^2} + \frac{255.4}{41 - (1/\lambda)^2}$$



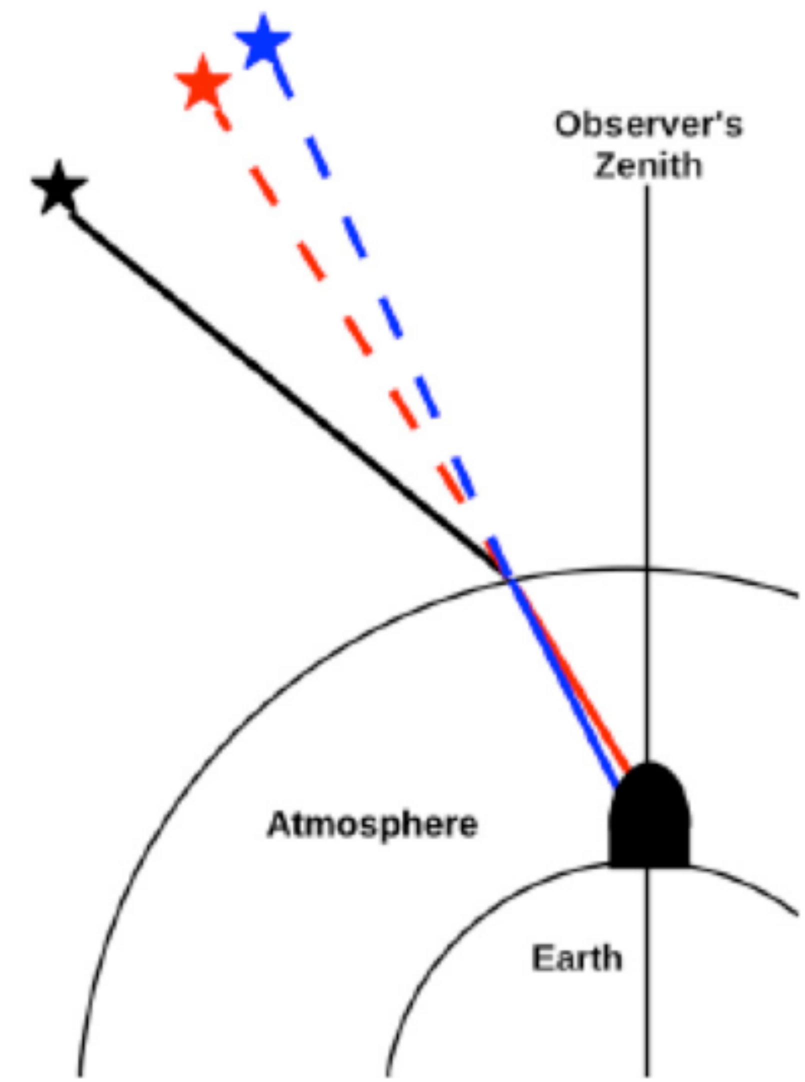
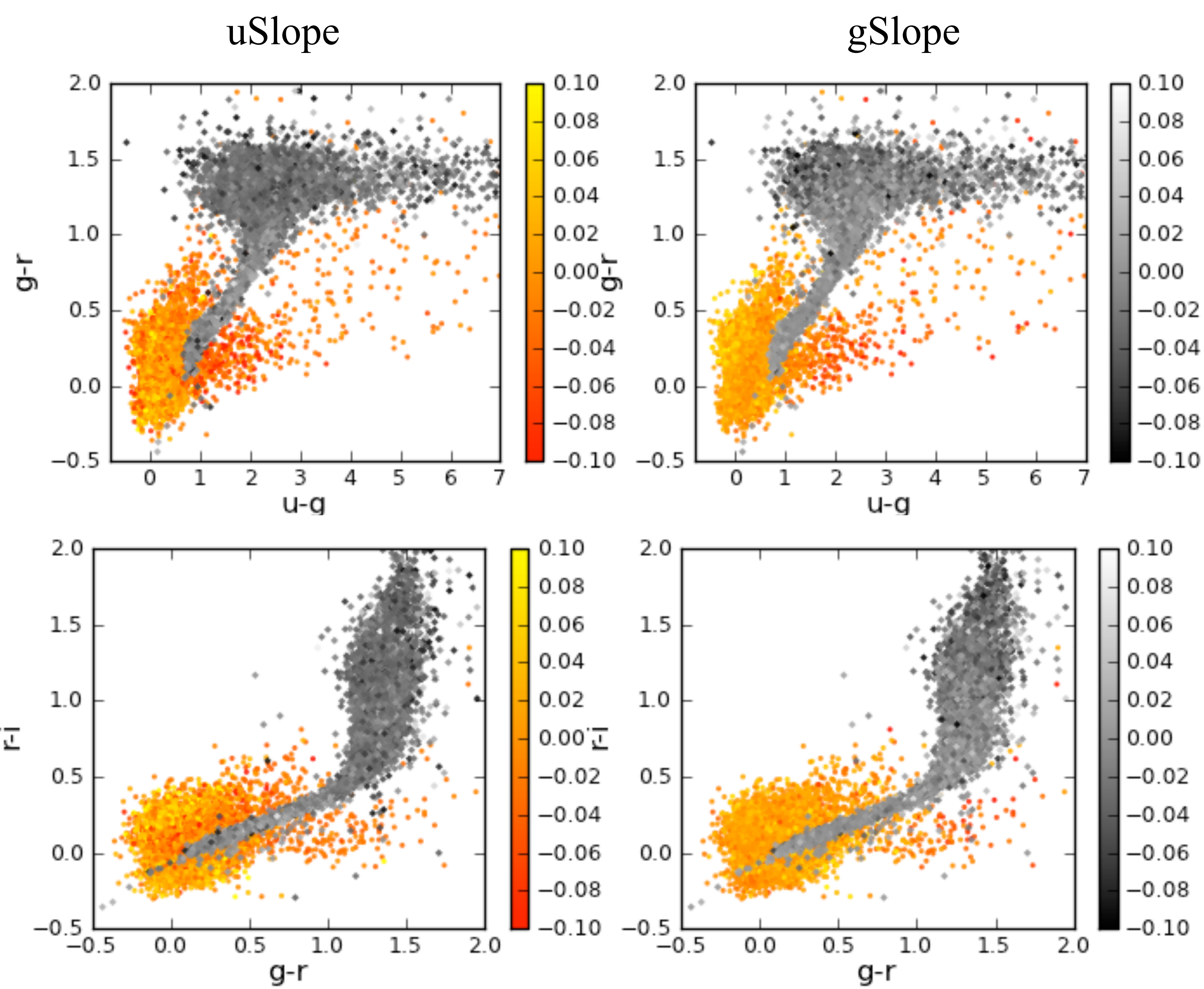


Figure 1. Left: DCR for a flat-spectrum object observed in the SDSS photometric system at a zenith angle of 45° (AM = 1.414). The color coding is u = blue, g = green, r = red, i = magenta, and z = black. Objects appear higher in the sky when observed in blue bandpasses than in red bandpasses. Right: DCR schematic example. The solid black line indicates the incoming multi-chromatic light rays. The solid red and blue lines indicate the DCR of the incoming beam, with blue light rays being bent more than red. The dashed blue and red lines indicate the apparent location on the sky of the object as seen by the blue and red filters.

1) Atmospheric refraction depends on object's SED (within a passband)
2) Astrometric solution is derived using stars (with different SEDs than quasars')
3) Quasar's calibrated position will change with airmass of observation:

The slope of the change of the object's position with the airmass of observation clearly differentiates quasars and stars:



Additional quasar selection method:
DCR
the variation of position with airmass (relative to the reference frame set by stars)

Kaczmarczik et al.:
it is sufficient to sample airmass <1.4 (which is consistent with the baseline LSST survey cadence)

SUMMARY

- **Finding quasars/AGNs with SDSS**
  color selection of quasars produced samples with ~200,000 spectroscopically confirmed objects, and ~1 million quasar candidates!
- **Finding quasars/AGNs with LSST**
  a combination of photometry (colors and variability) **and** astrometry (no proper motion and DCR) will yield a highly clean and complete sample of 10 million objects, including ~10,000 quasars at redshifts exceeding ~6!

SDSS: a digital color **map** of the night sky

LSST: a digital color **movie** of the sky

"If You Liked SDSS, You will Love LSST!"