Astr 511: Galactic Astronomy

Winter Quarter 2013, University of Washington, Željko Ivezić

Lecture 11:

The Road Ahead: Gaia and LSST

Sky surveying is experiencing a bonanza as detectors, telescopes and computers become ever more powerful: data-intensive astronomy

Sky surveying is experiencing a bonanza as detectors, telescopes and computers become ever more powerful: data-intensive astronomy

1. Modern Sky Surveys: Lessons from SDSS
2. LSST: The System Parameters
3. LSST: Science Drivers
4. Space astrometric survey Gaia
5. Mapping of the Milky Way with Gaia and LSST

Lessons from SDSS

Extraordinary range of science themes and huge scientific legacy

- Uniform surveys yield diverse and cutting-edge science: in less than a decade >2,000 SDSS papers with >100,000 citations

- In 2003, 2004, and 2006 the most productive astronomical observatory (in 2005 second after WMAP), as measured by the citation rate

- A new paradigm for astronomy: a large collaboration (>100 people) reminiscent of high-energy physics (the MACHO survey is another good example)

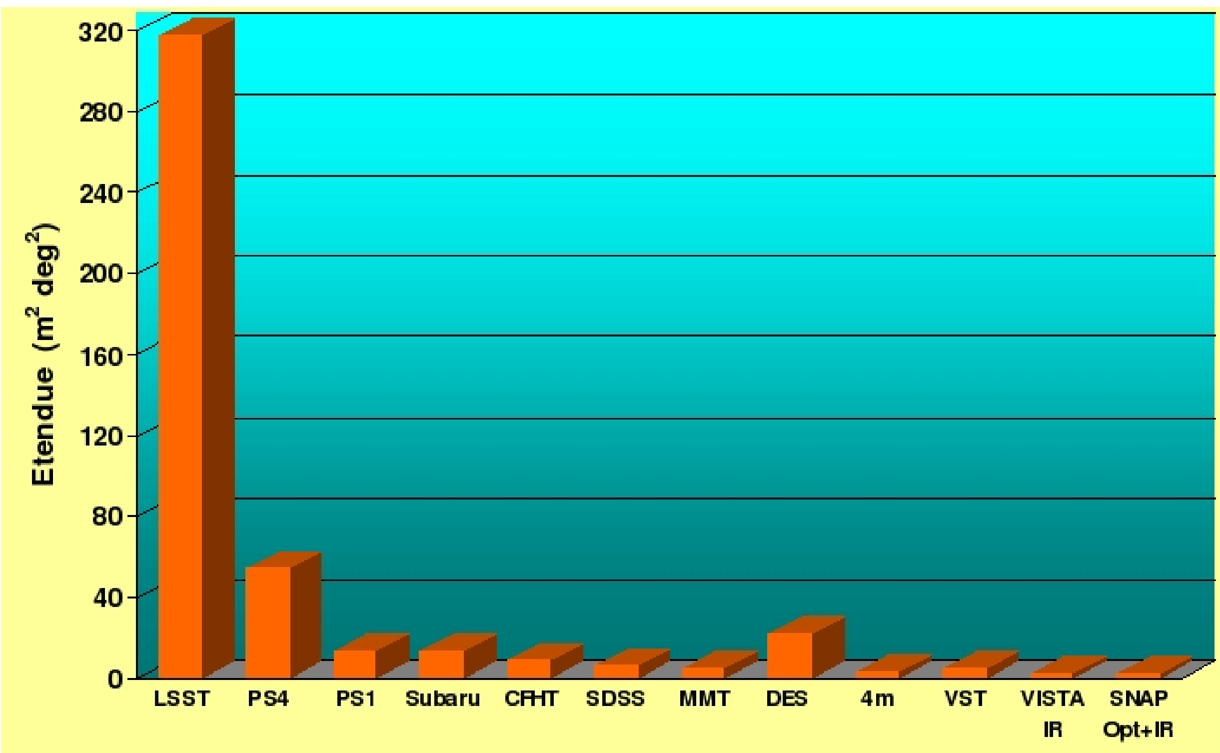
- Legacy: many upcoming and proposed optical surveys (SkyMapper, Dark Energy Survey, Pan-STARRS, LSST); invariably large collaborations of astronomers and physicists

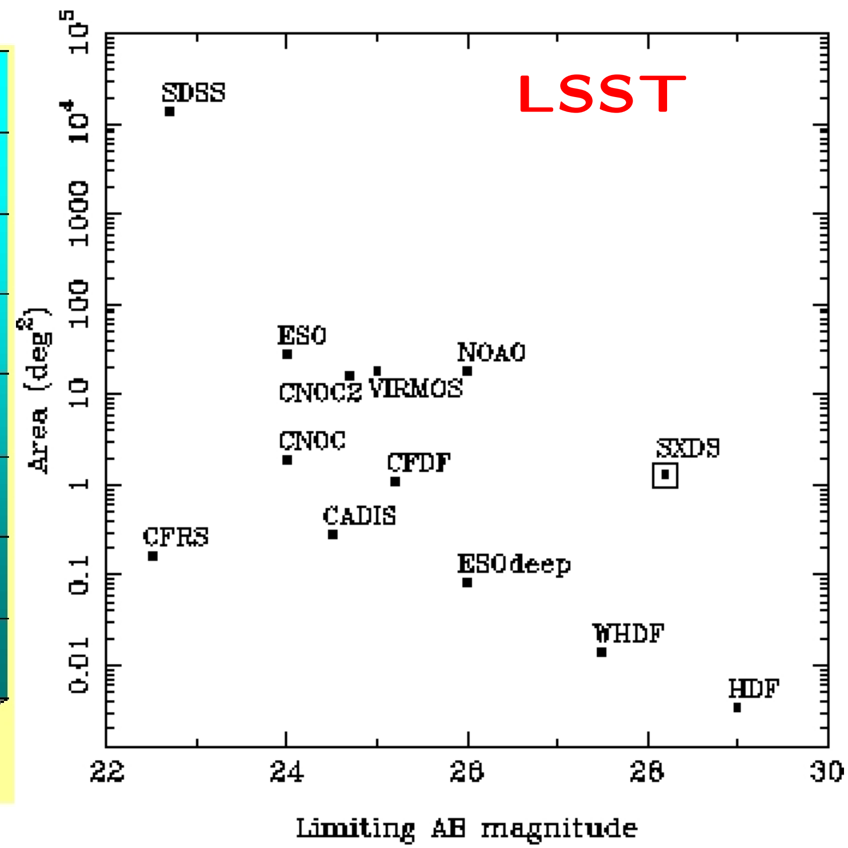
Notably, physicists are also attracted to large sky surveys for several reasons:

- hardware challenges (e.g. sensors, camera electronics)
- software challenges (large data rates, e.g. 20 TB/night for LSST)
- science questions, including but not limited to, dark matter and dark energy (e.g. statistical physics, computational physics, relativity)

The Era of Massive Optical Surveys

- Super-Macho, SDSS, QUEST, CFHT, DES, Pan-STARRS, LSST, and many others, in no particular order: fast progress!
- All these surveys want to explore some part of the depth-color-cadence-area parameter space (with varying measurement accuracy and image quality) Aiming for both depth and area:





The Era of Massive Optical Surveys

- Currently, the best large-area optical survey is SDSS: **the first digital map of the sky**
- Among proposed surveys for the next decade or so, the two "best" ones are Pan-STARRS (PS4) and LSST
- PS4: about 10 times more surveying power than SDSS
- **LSST:** about 6 times more surveying power than PS4
- First light: PS4 in 2015? (N sky), LSST in 2018? (S sky)

What will LSST do?

the first digital movie of the sky

LSST Science Drivers

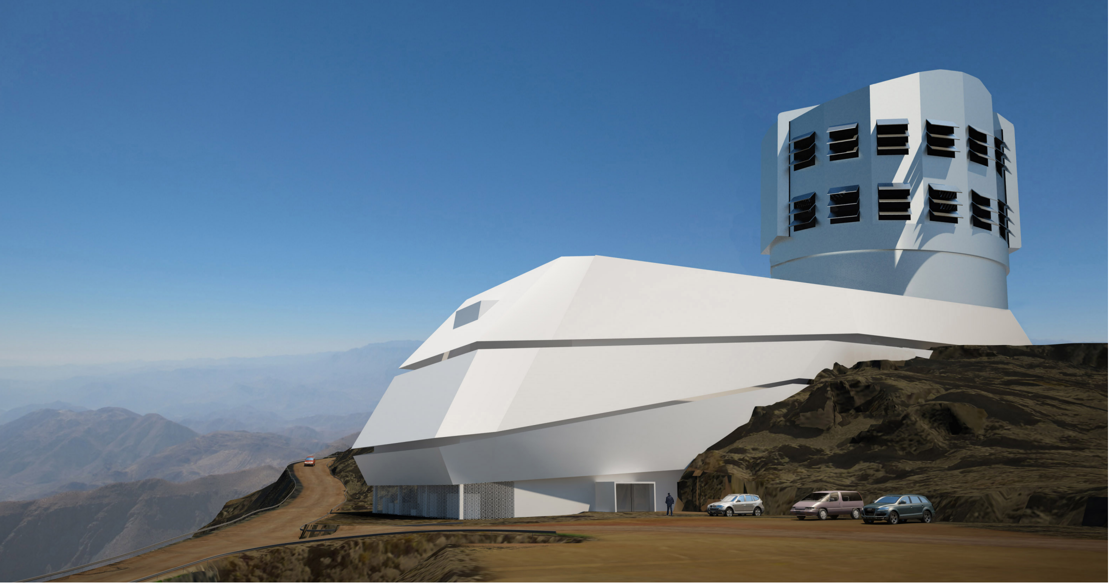
1. The Fate of the Universe: Dark Energy and Matter
2. Taking an Inventory of the Solar System
3. Exploring the Unknown: Time Domain
4. Deciphering the Past: mapping the Milky Way

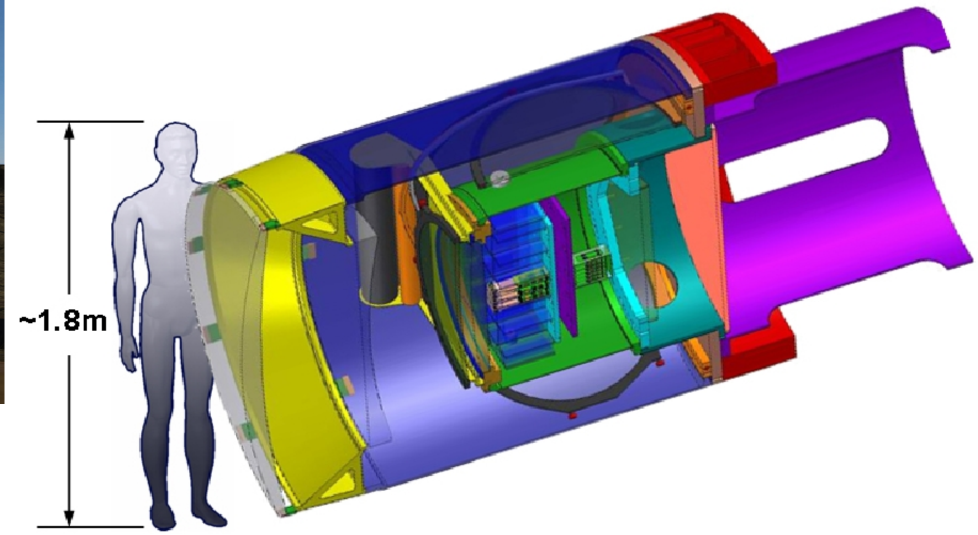
Different science drivers lead to similar system requirements (NEOs, main-sequence stars to 100 kpc, weak lensing, SNe,...):

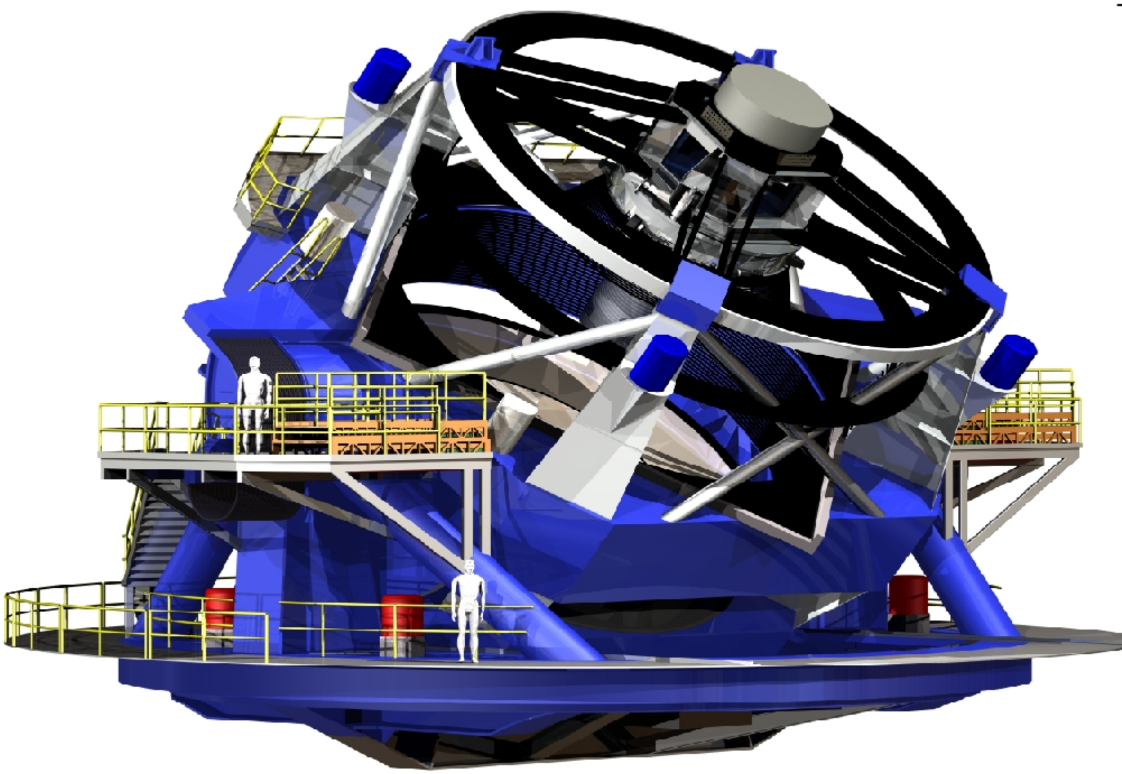
Main LSST Characteristics:

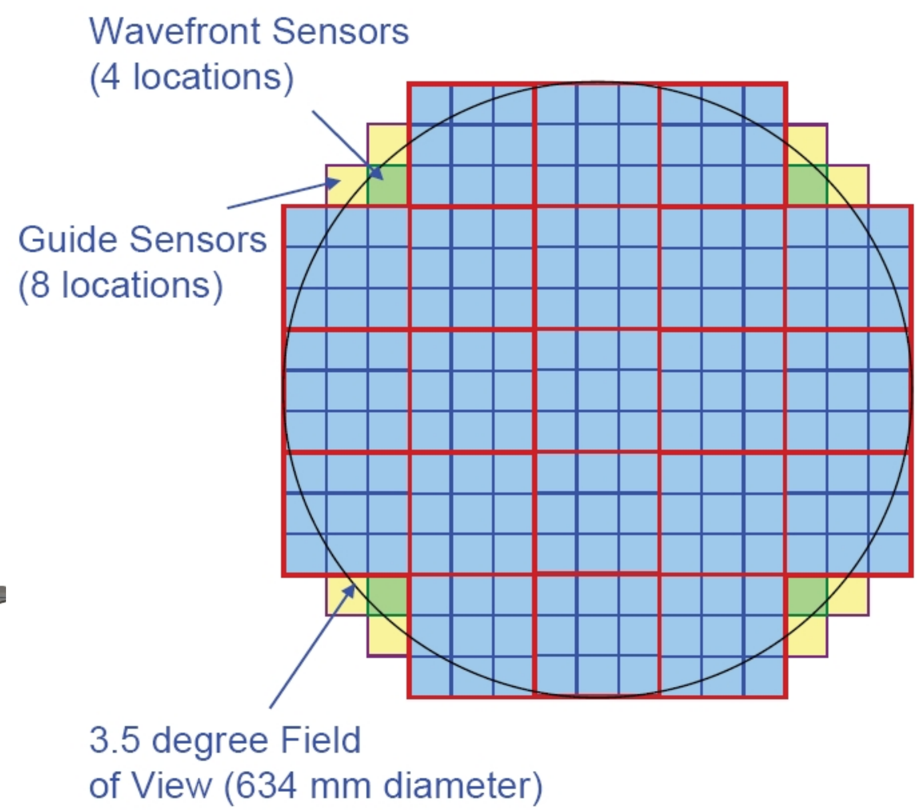
- 8.4m aperture (6.5m effective), $\sim$10 deg^2 FOV
- 3.2 Gigapix camera (20 TB, or one SDSS, per night)
- Sited at Cerro Pachon, Chile
- First light in 2018
- Cost: $\sim$0.5 B$ for construction (public-private partnership); almost as much for operations (10 years)

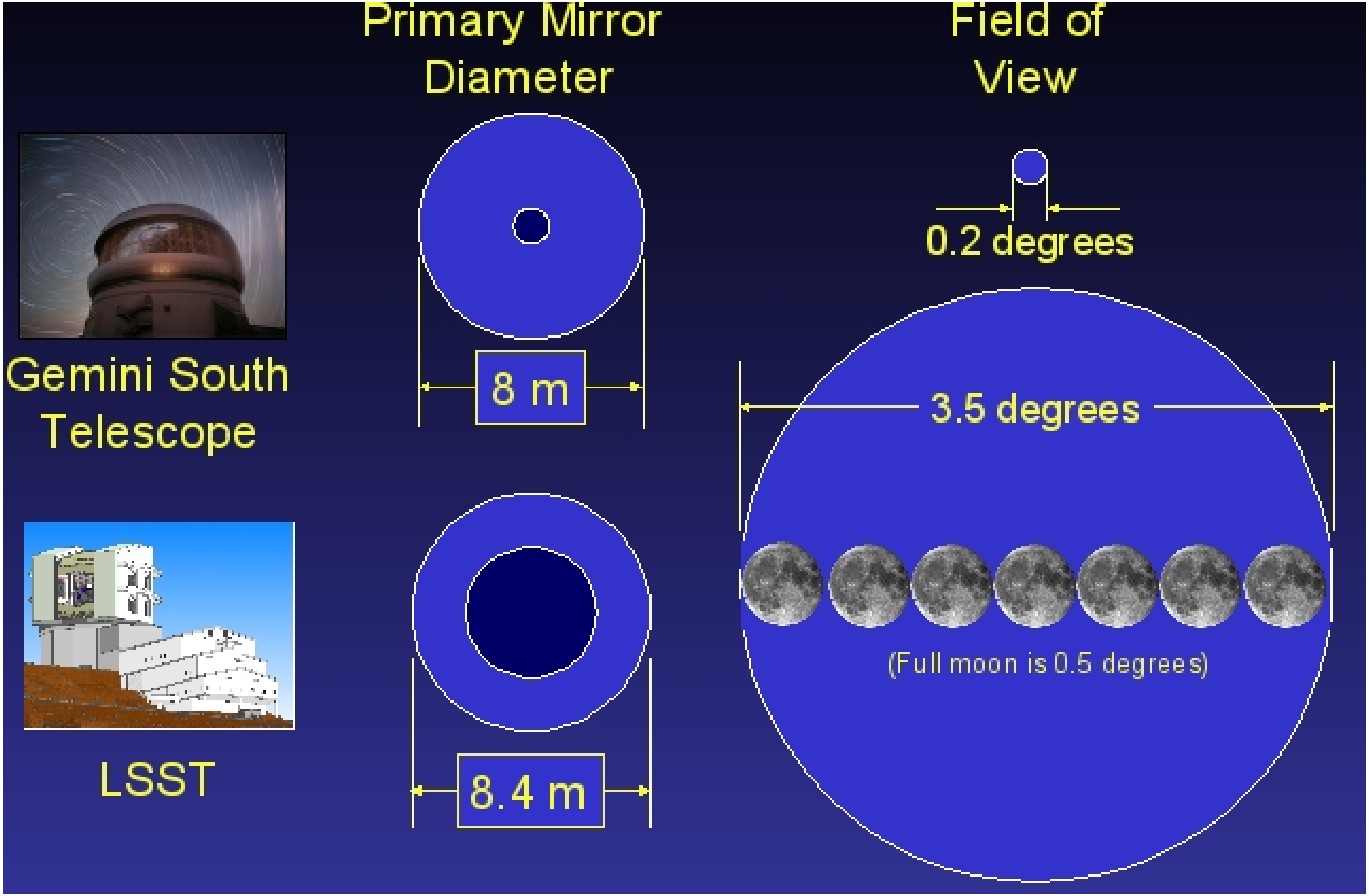
And also to the same observing strategy (cadence): a homogeneuos dataset will utilize 90% of observing time and serve the majority of science programs (with a high system efficiency)



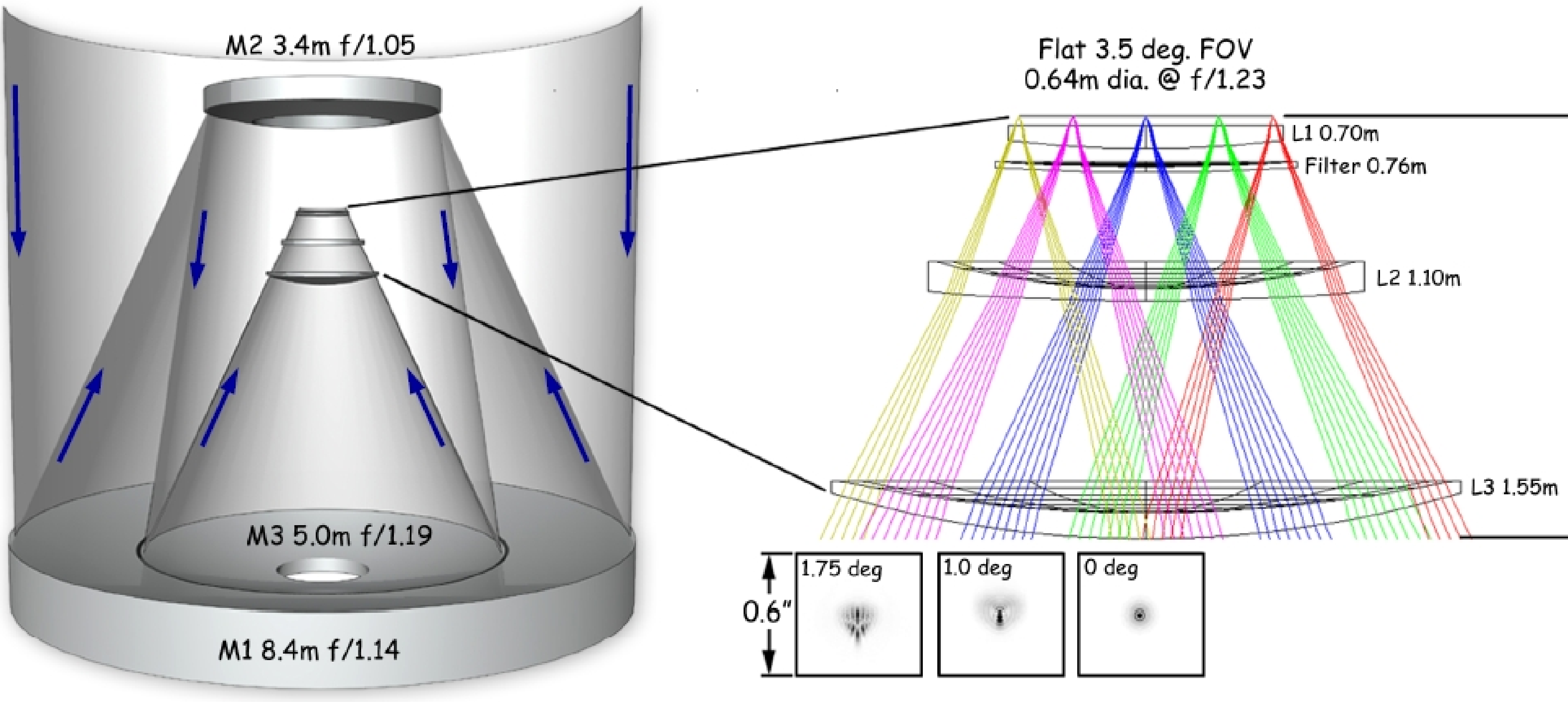

~1.8m



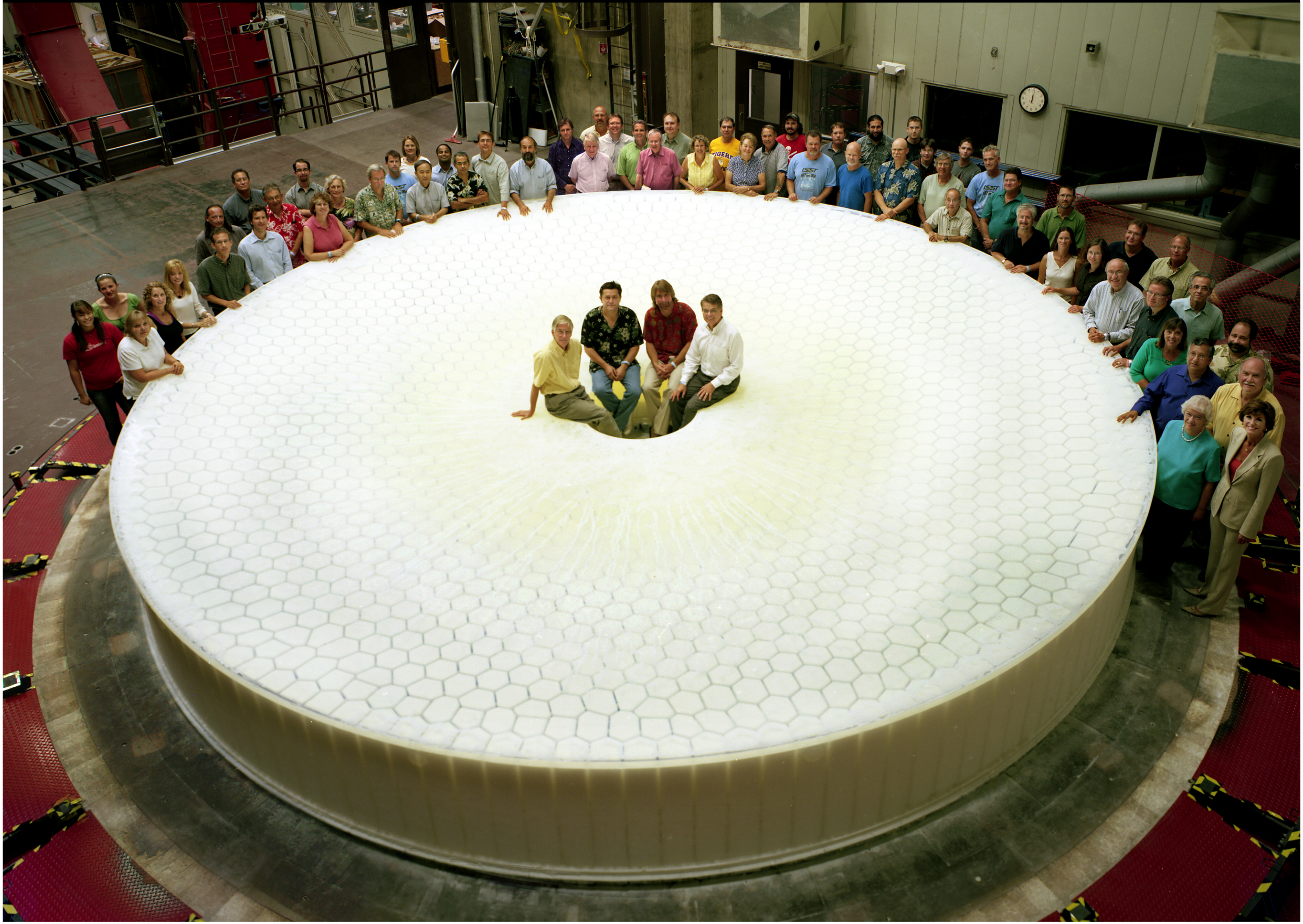

Wavefront Sensors
(4 locations)
Guide Sensors
(8 locations)
3.5 degree Field
of View (634 mm diameter)



Primary Mirror Diameter
Field of View
Gemini South Telescope
8 m
0.2 degrees
3.5 degrees
(Full moon is 0.5 degrees)
LSST
8.4 m


M2 3.4m f/1.05
M3 5.0m f/1.19
M1 8.4m f/1.14
Flat 3.5 deg. FOV
0.64m dia. @ f/1.23
L1 0.70m
Filter 0.76m
L2 1.10m
L3 1.55m
0.6"
1.75 deg
1.0 deg
0 deg

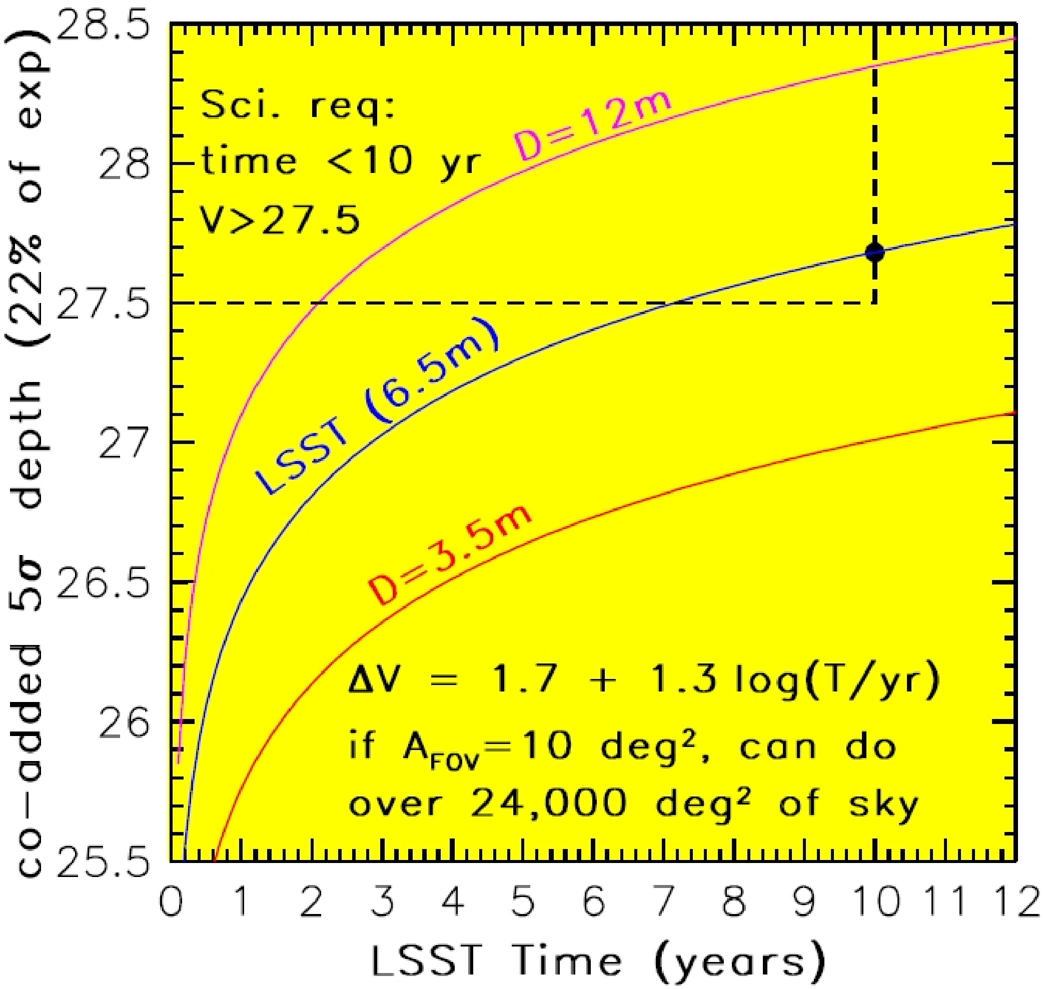
Large Synoptic Survey Telescope



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

The University of Arizona
Tucson Arizona

SOML



Co-added depth vs. time

Given $T = 10$ yrs, $A_{FOV} = 10$ deg^2, simulations show that the exposure time budget is about 8 hours per field.

To reach $V > 27.5$ (from galaxy counts), $D_{\rm eff} > 6.5$m

Depth Requirements

- Minimum integrated étendue:

$$ET \propto D^2 A_{FOV} T \qquad (1)$$

- The field-of-view size, A_{FOV}, is limited to about 10 deg^2 if the image quality and sampling is to be maintained;
- The survey lifetime, T, should be about 10 years; shorter time limits science such as proper motion measurements, NEO search, and long-term variability; longer times may result in "stale" science
- A requirement on integrated étendue becomes a requirement on the primary mirror effective diameter

LSST vs. SDSS comparison

Currently, the best large-area faint optical survey is

SDSS: the first digital map of the sky

r$\sim$22.5, 1-2 visits, 300 million objects

- LSST = d(SDSS)/dt: an 8.4m telescope with 2x15 sec visits to r$\sim$24.5 over a 9.6 deg^2 FOV: the whole (observable) sky in two bands every three nights, 1000 visits over 10 years

- LSST = Super-SDSS: an optical/near-IR survey of the observable sky in multiple bands (ugrizy) to r$>$27.5 (coadded); a catalog of $\sim$10 billion stars and $\sim$10 billion galaxies

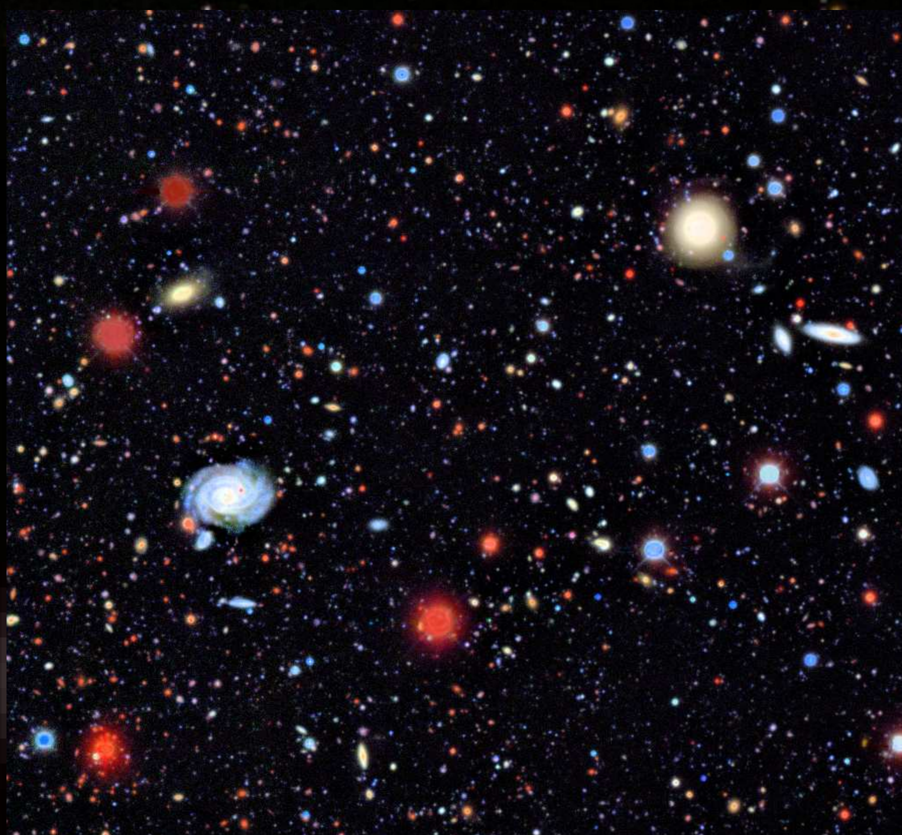
LSST: a digital movie of the sky

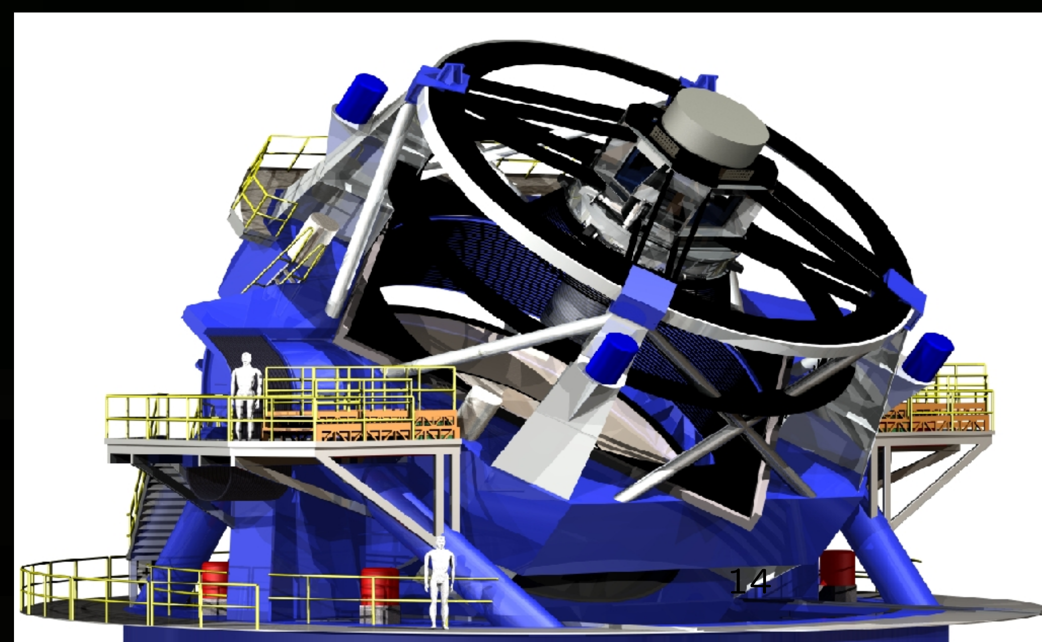
LSST data will immediately become public

(transients within 60 sec)

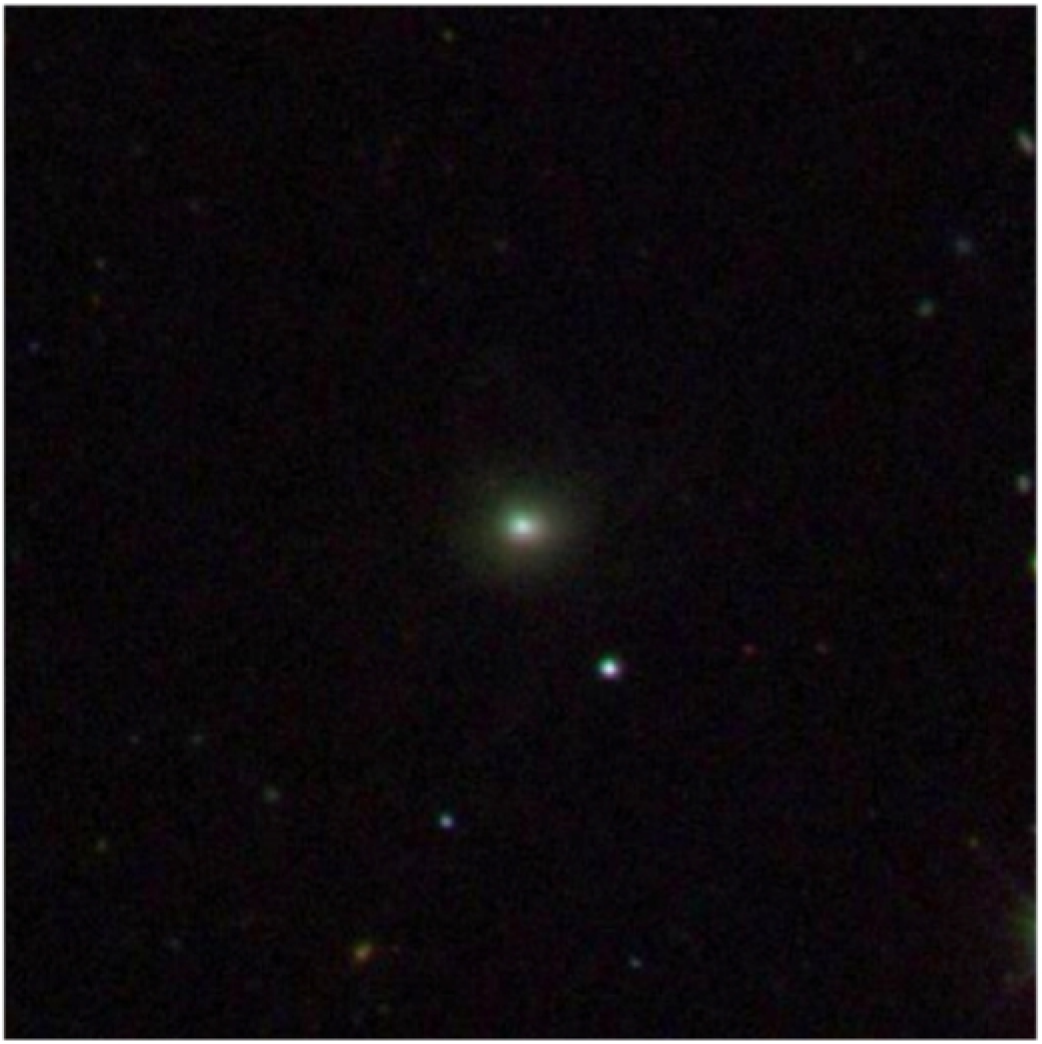
SDSS: one US Library of Congress worth of data

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

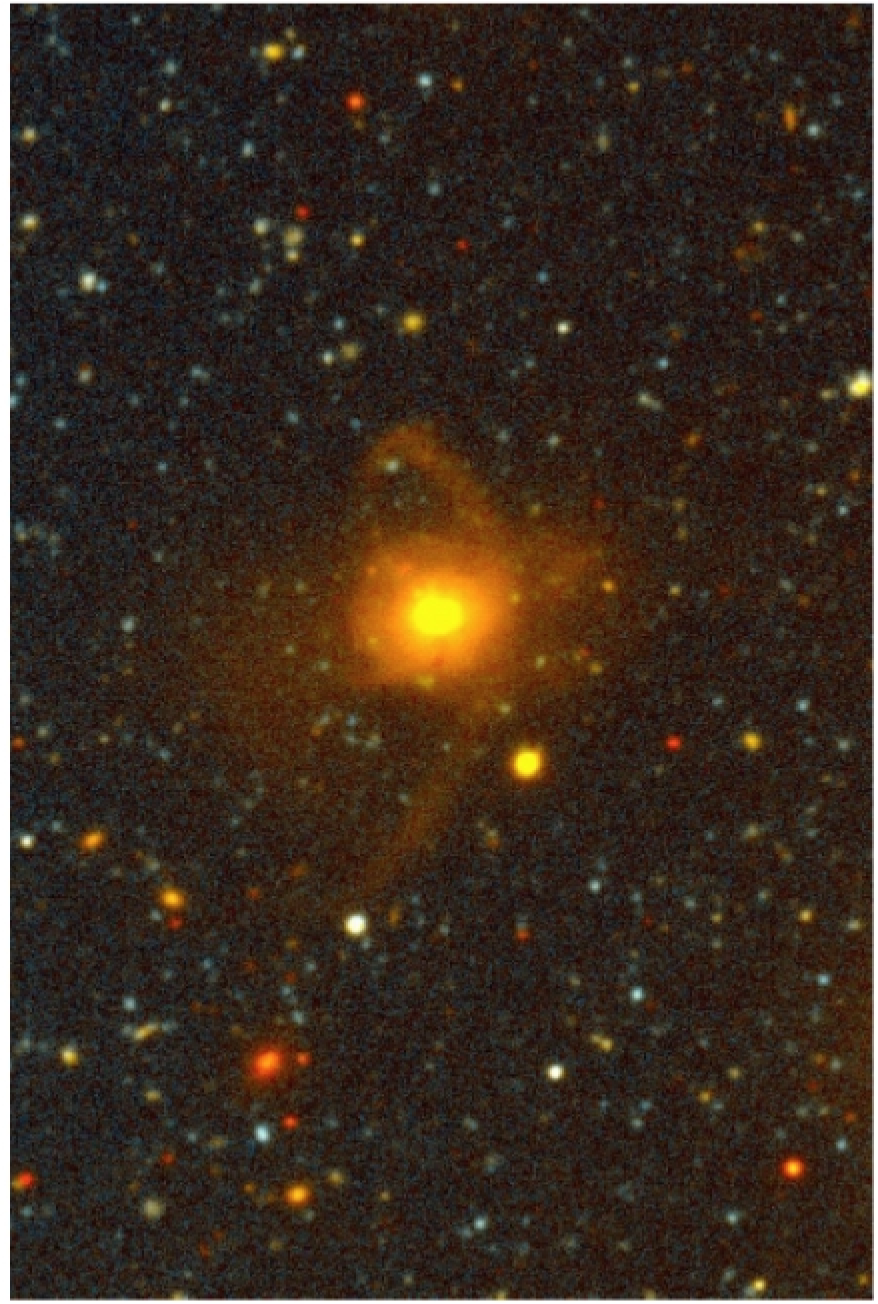




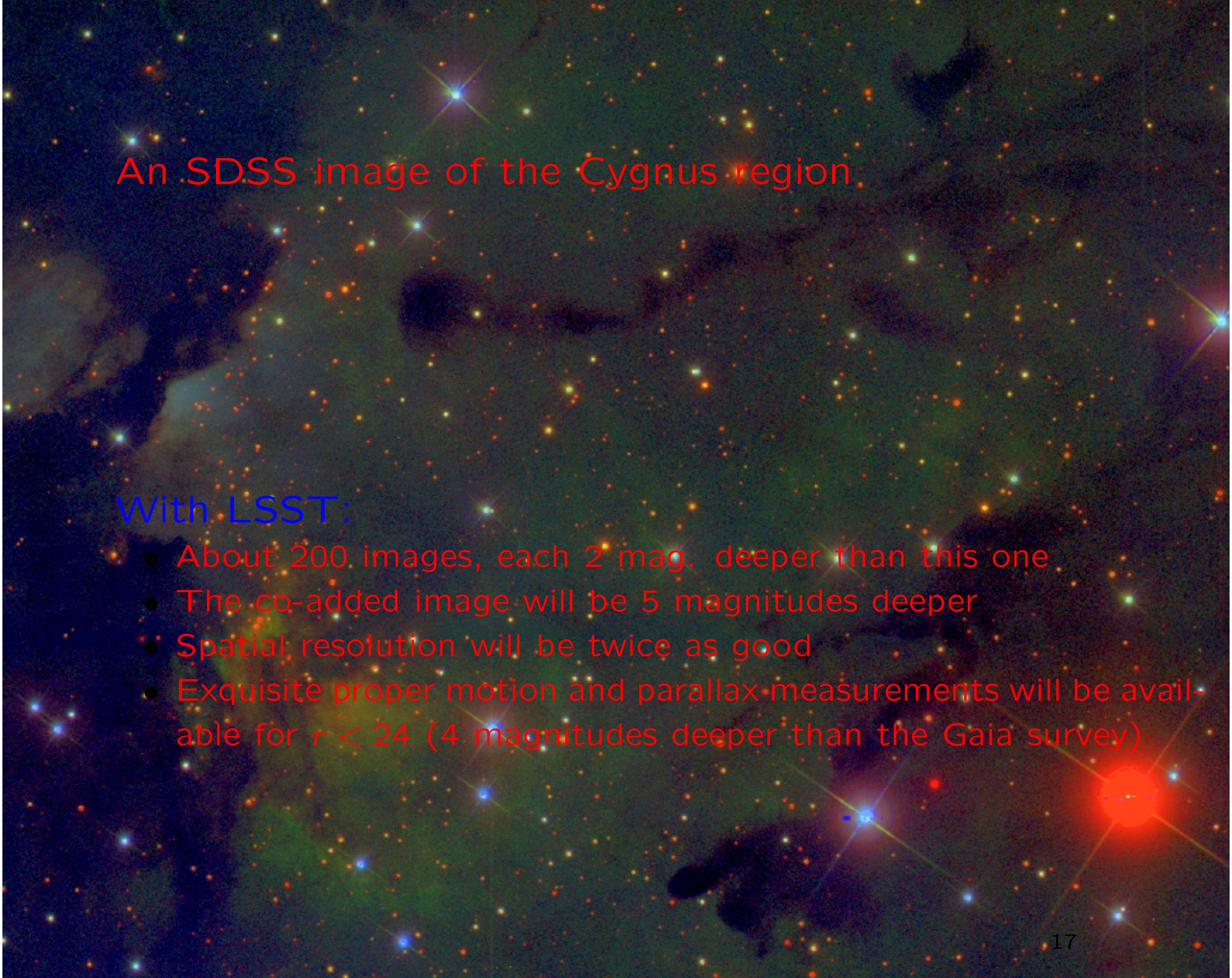
SDSS



MUSYC




An SDSS image of the Cygnus region



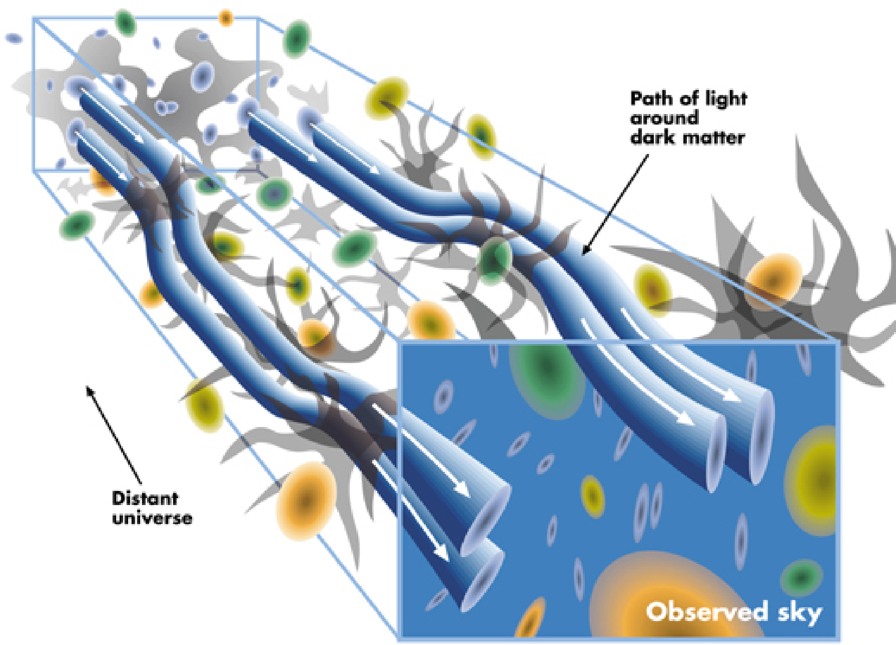
An SDSS image of the Cygnus region

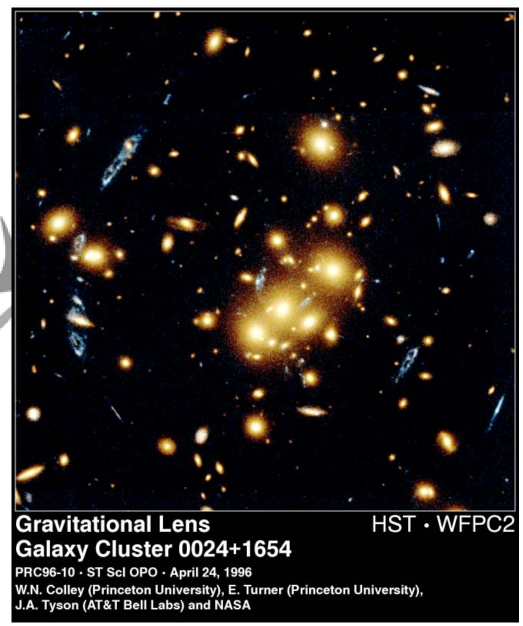
With LSST:

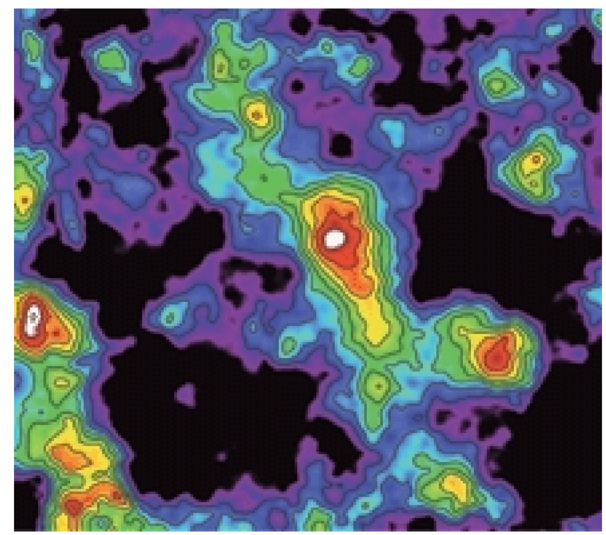
- About 200 images, each 2 mag. deeper than this one
- The co-added image will be 5 magnitudes deeper
- Spatial resolution will be twice as good
- Exquisite proper motion and parallax measurements will be available for $r < 24$ (4 magnitudes deeper than the Gaia survey)

LSST Science Drivers

- The Fate of the Universe (Dark Energy and Matter):
  use a variety of probes and techniques in synergy to fundamentally test our cosmological assumptions and gravity theories:
  1. **Weak Lensing:** growth of structure
  2. **Galaxy Clusters:** growth of structure
  3. **Baryon Acoustic Oscillations:** standard ruler
  4. **Supernovae:** standard candle







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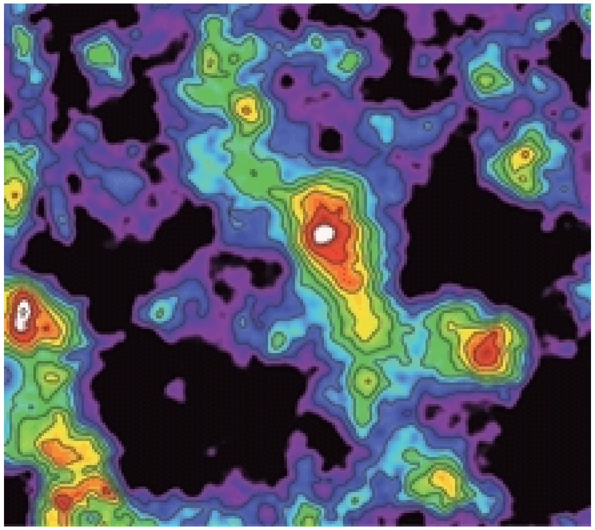
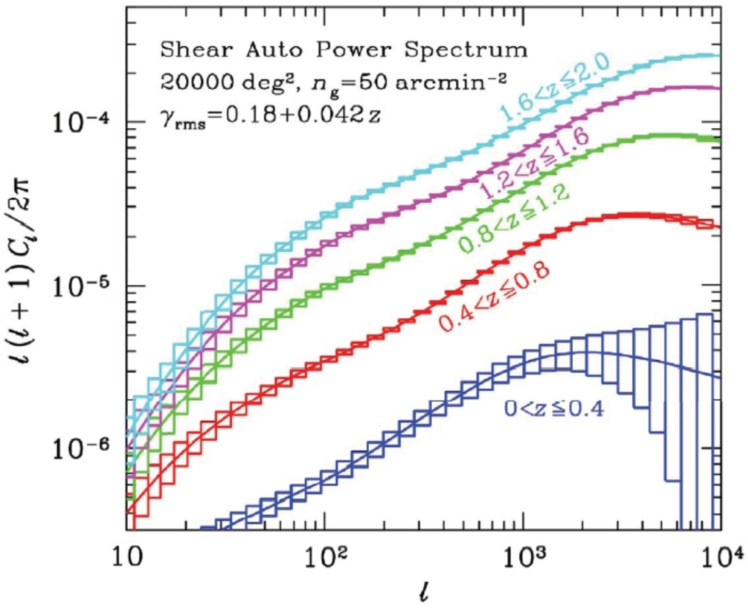
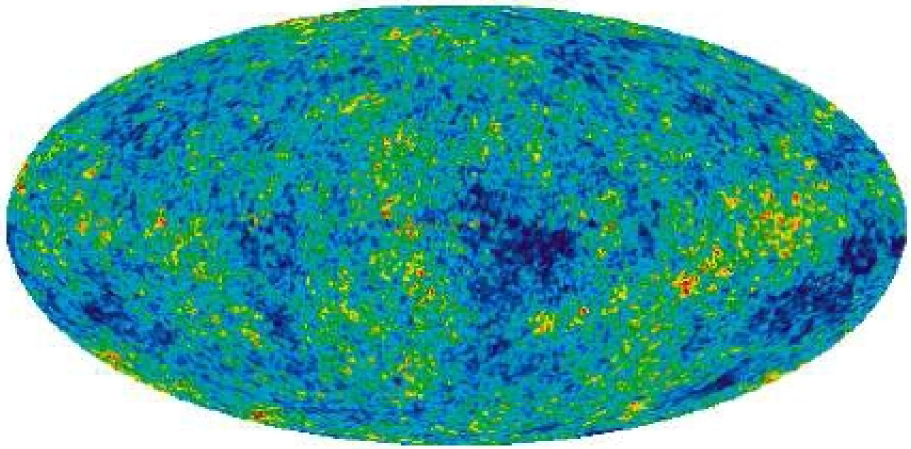


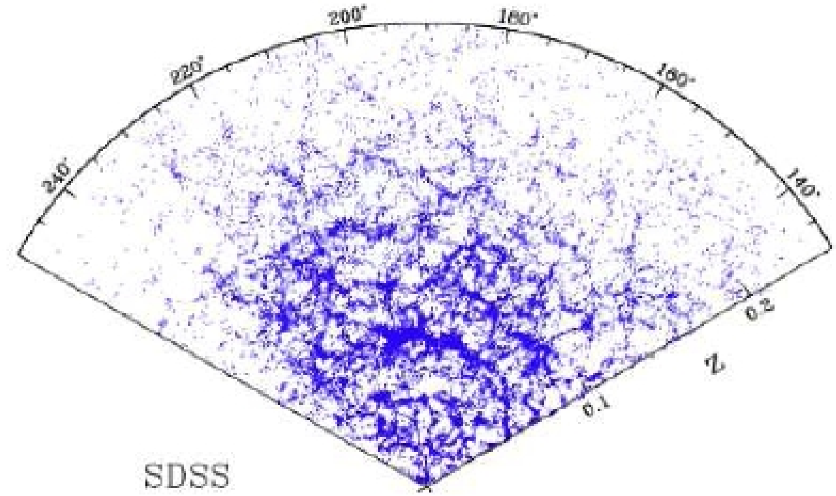


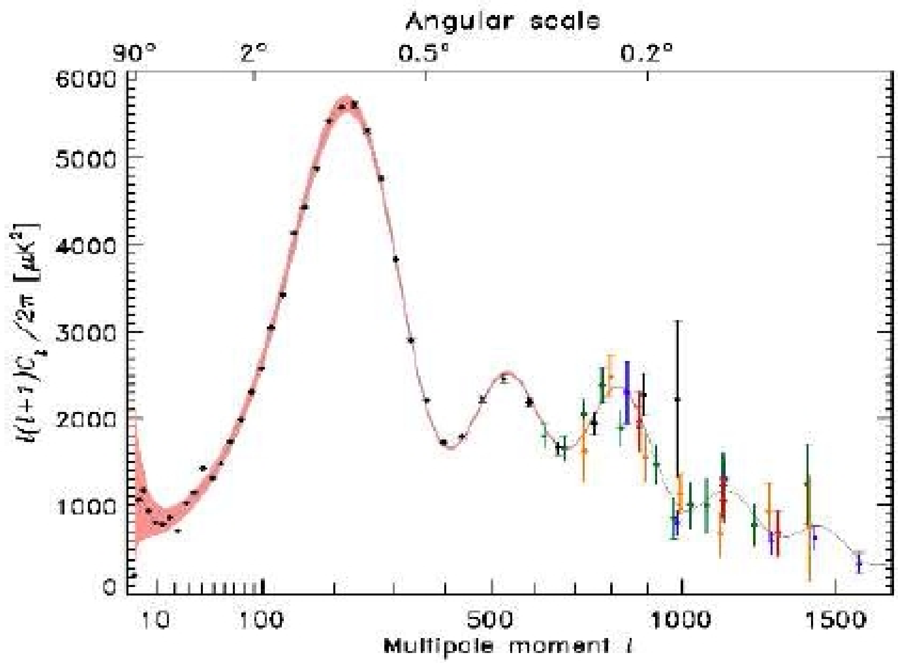
Weak lensing shear power spectrum provides strong constraints on cosmological parameters, dark matter distribution, and even the sum of neutrino masses (to better than 0.04 eV).

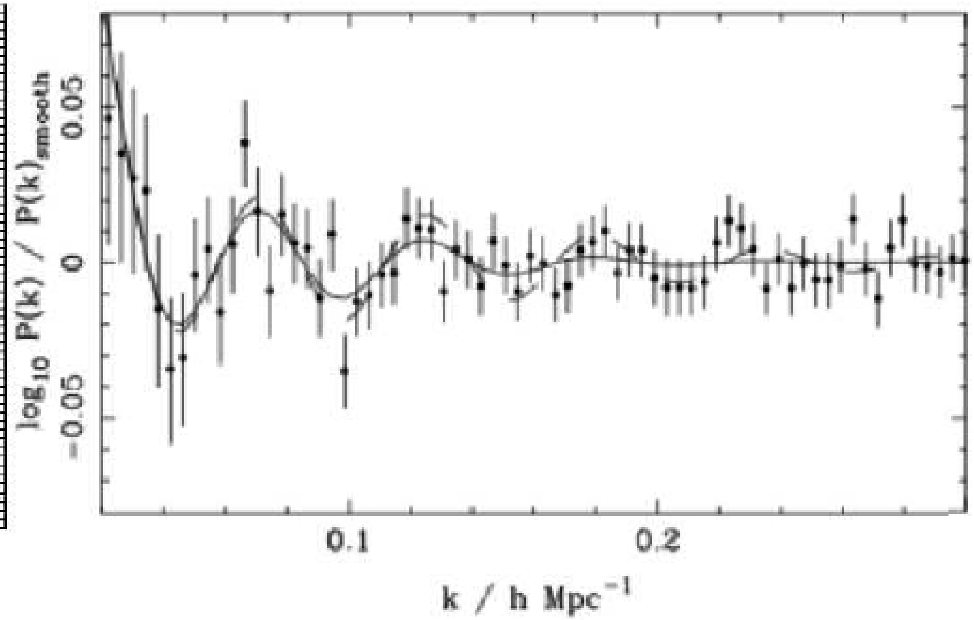
CMB



Galaxies

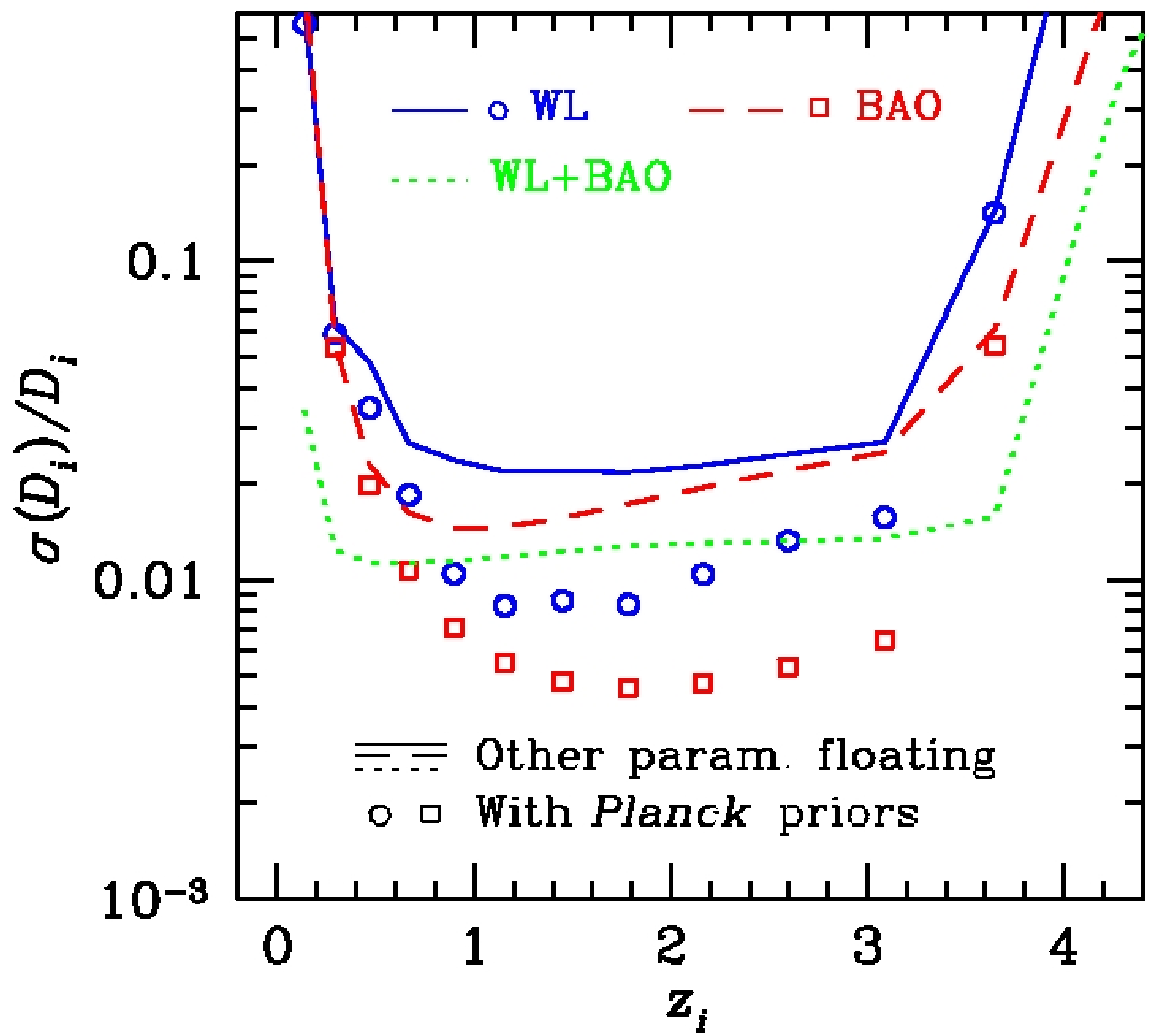




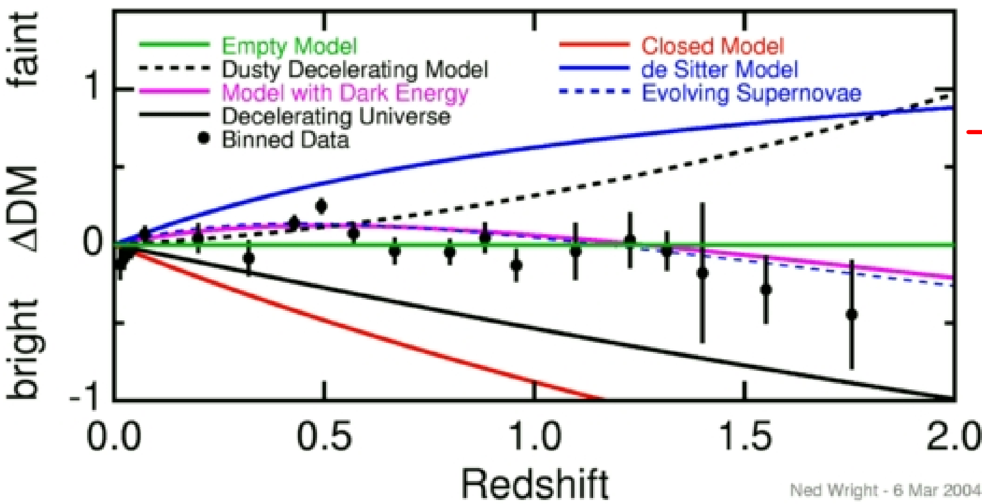


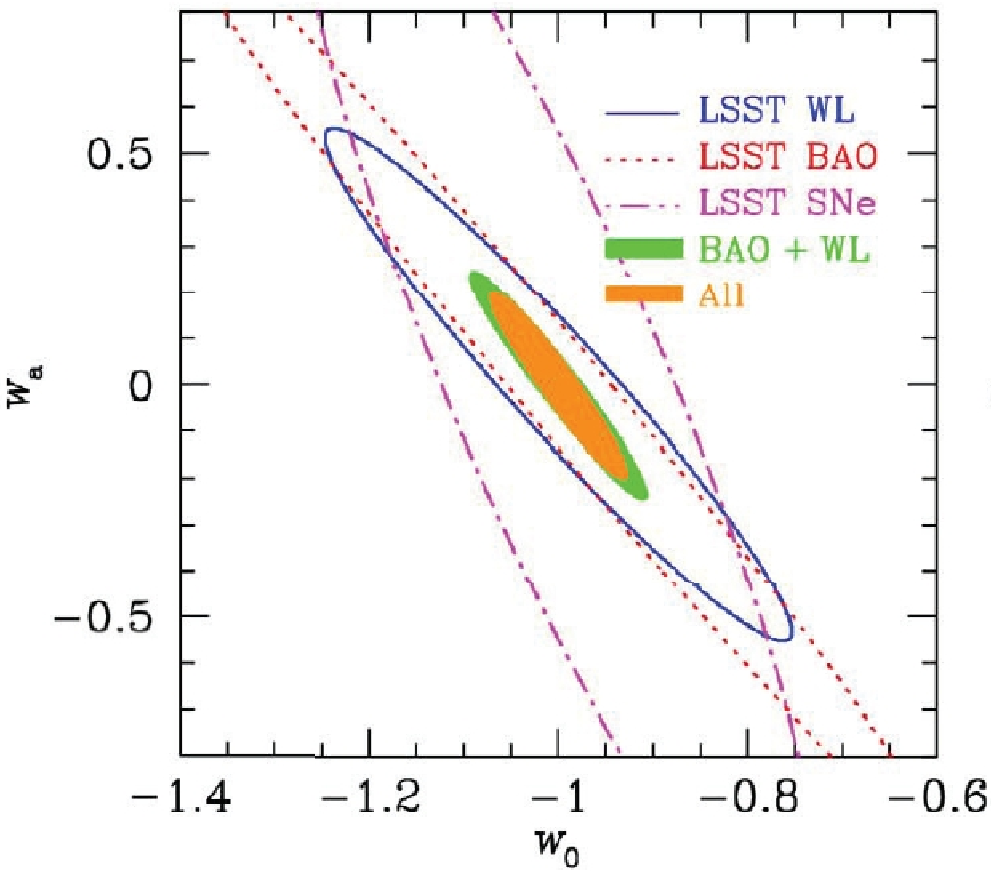
Baryon acoustic oscillations:
standard ruler – a new cosmological tool

LSST Science Drivers



Measuring distances with a percent accuracy for $0.5 < z < 3$





Type Ia Supernovae Cosmology with LSST

- **Type Ia Supernovae:** provide strong support for the existance of dark energy and recent acceleration of the Hubble expansion
- **Systematics:** can be calibrated using WL and BAO
- **LSST SNe:** about 10 million, **the only probe to provide high angular resolution constraints on the homogeneity and isotropy of the Universe**

LSST Science Drivers

- The Fate of the Universe (Dark Energy and Matter): use a variety of probes and techniques in synergy to fundamentally test our cosmological assumptions and gravity theories:
  1. **Weak Lensing:** growth of structure
  2. **Galaxy Clusters:** growth of structure
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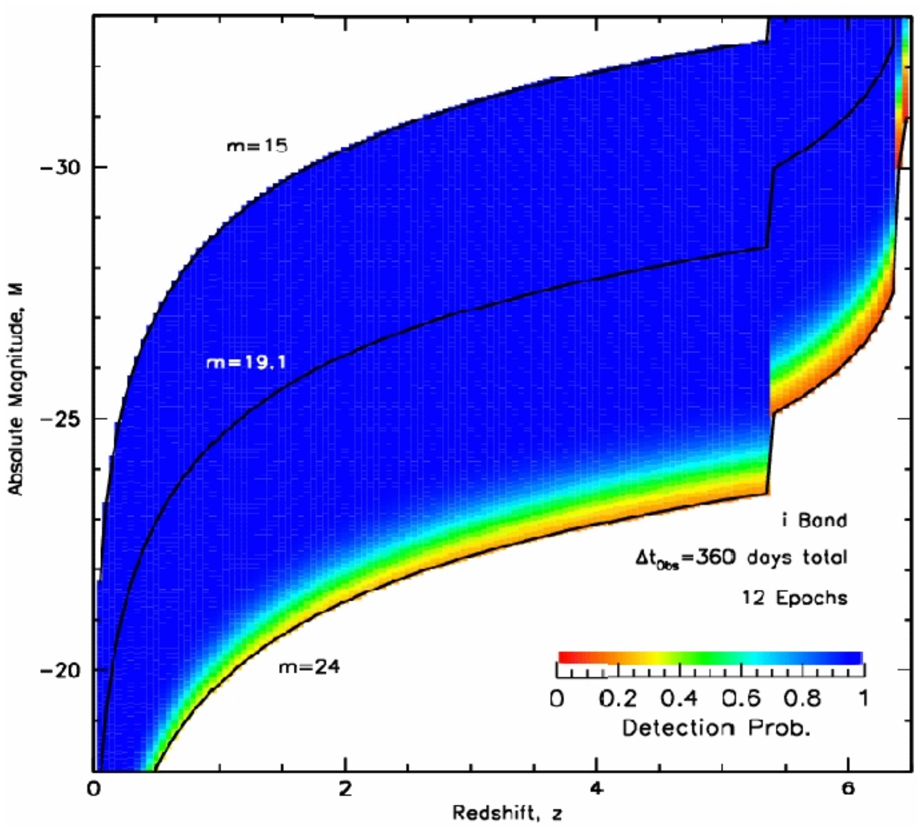
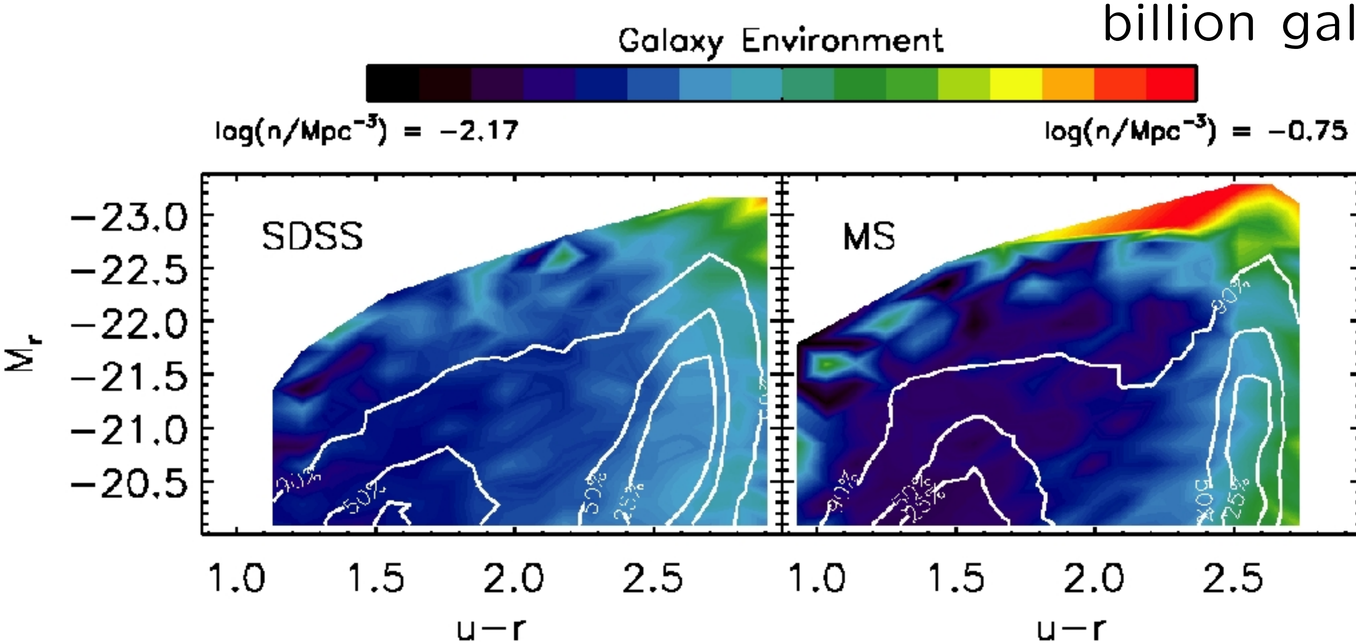
About a hundred-to-thousand-fold increase in precision over precursor experiments: Stage IV Experiment (Dark Energy Task Force nomenclature)

Multiple accurate cosmological probes with the same facility (and data): 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.**



"Other" extragalactic science

- **Quasars:** discovered using colors and variability; about 10,000,000 in a "high-quality" sample; will reach $M_B = -23$ even at redshifts beyond 3
- **Galaxies:** color-morphology-luminosity-environment studies in thin redshift slices to $z \sim 3$ (high-SNR sample of 4 billion galaxies with $i < 25$)

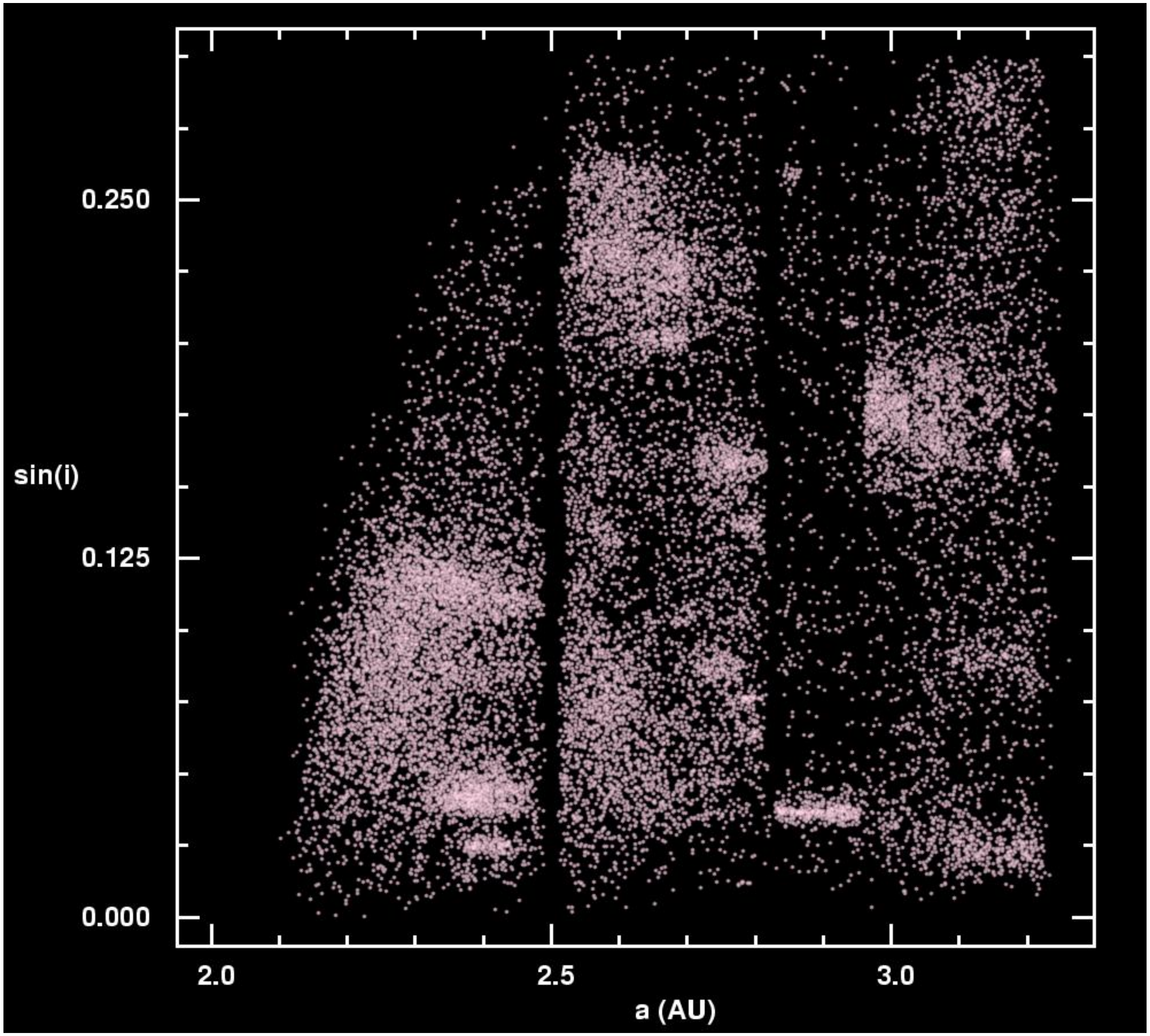


The Solar System Inventory

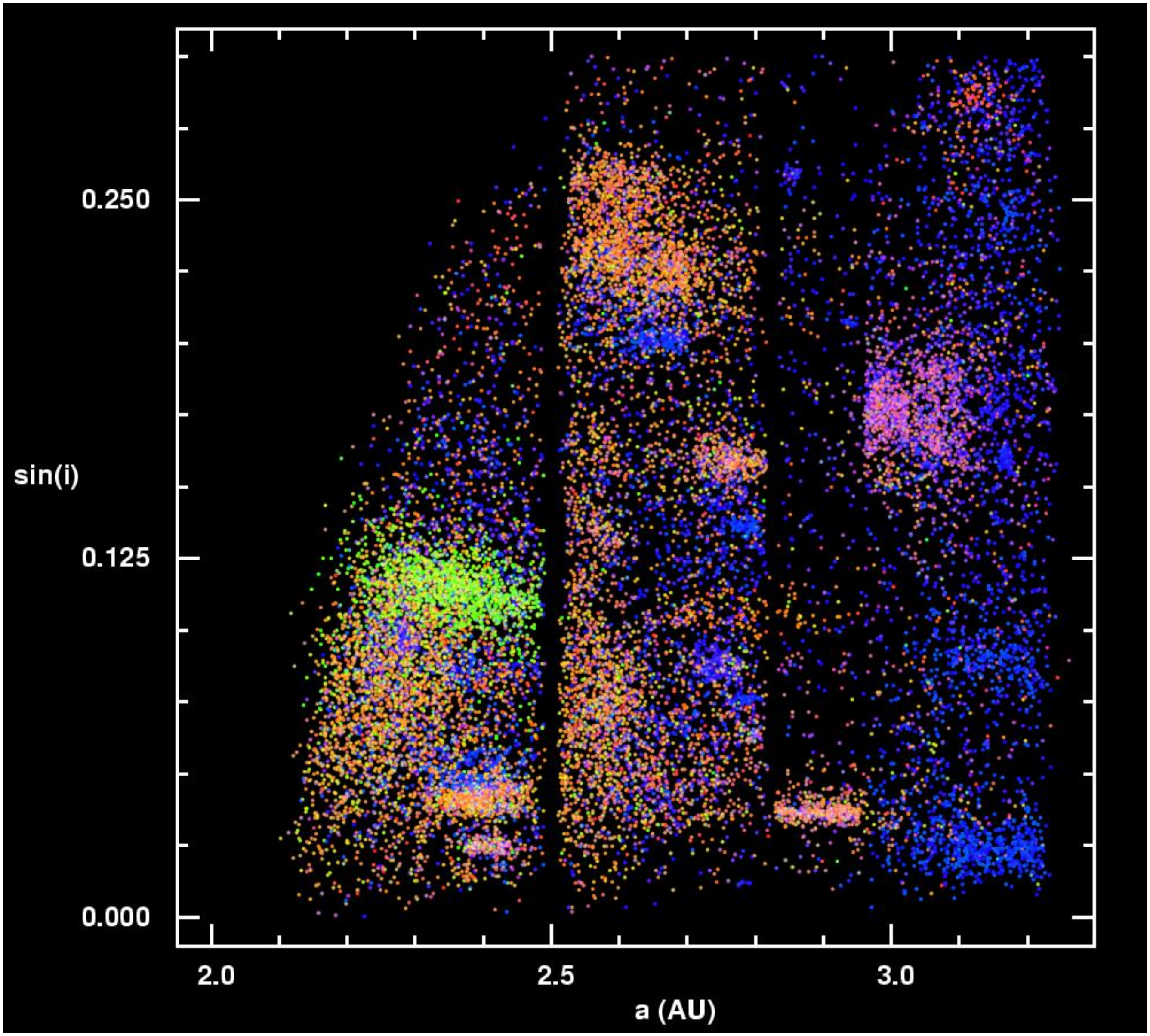
Studies of the distribution of orbital elements as a function of color and size; studies of object shapes and structure using colors and light curves.

- Near-Earth Objects: about 100,000 **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)
- Main-Belt Asteroids: about 10,000,000
- Centaurs, Jovian and non-Jovian Trojans, trans-Neptunian objects: about 200,000
- Jupiter-family and Oort-cloud comets: about 3,000–10,000, with hundreds of observations per object
- Extremely distant solar system: the search for objects with perihelia at several hundred AU (e.g. Sedna will be observable to 200-300 AU).

Solar System as a detailed test of planet formation theories (just like the Galaxy is a detailed test of galaxy formation theories)

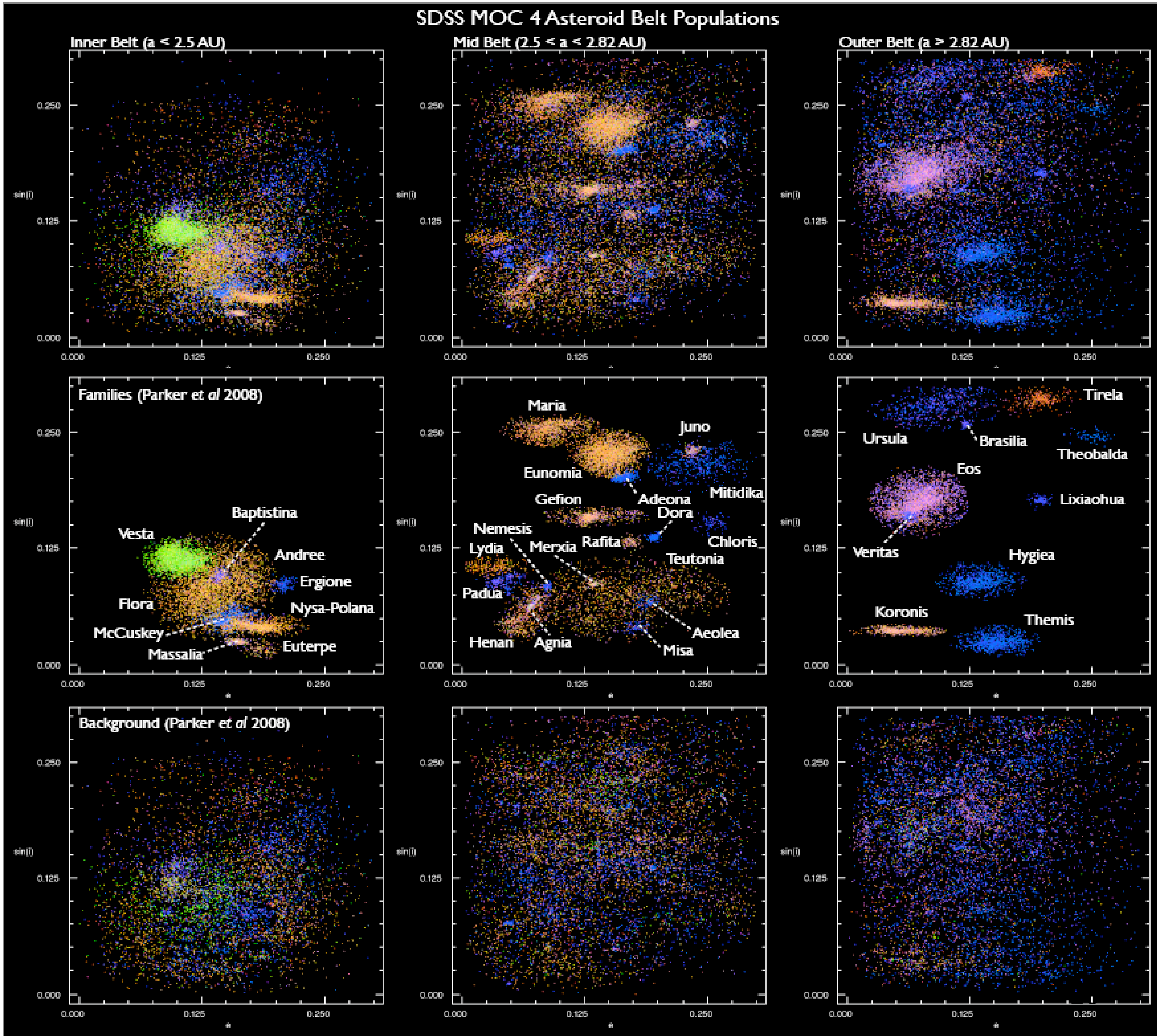


The semi-major axis vs. inclination (proper elements)

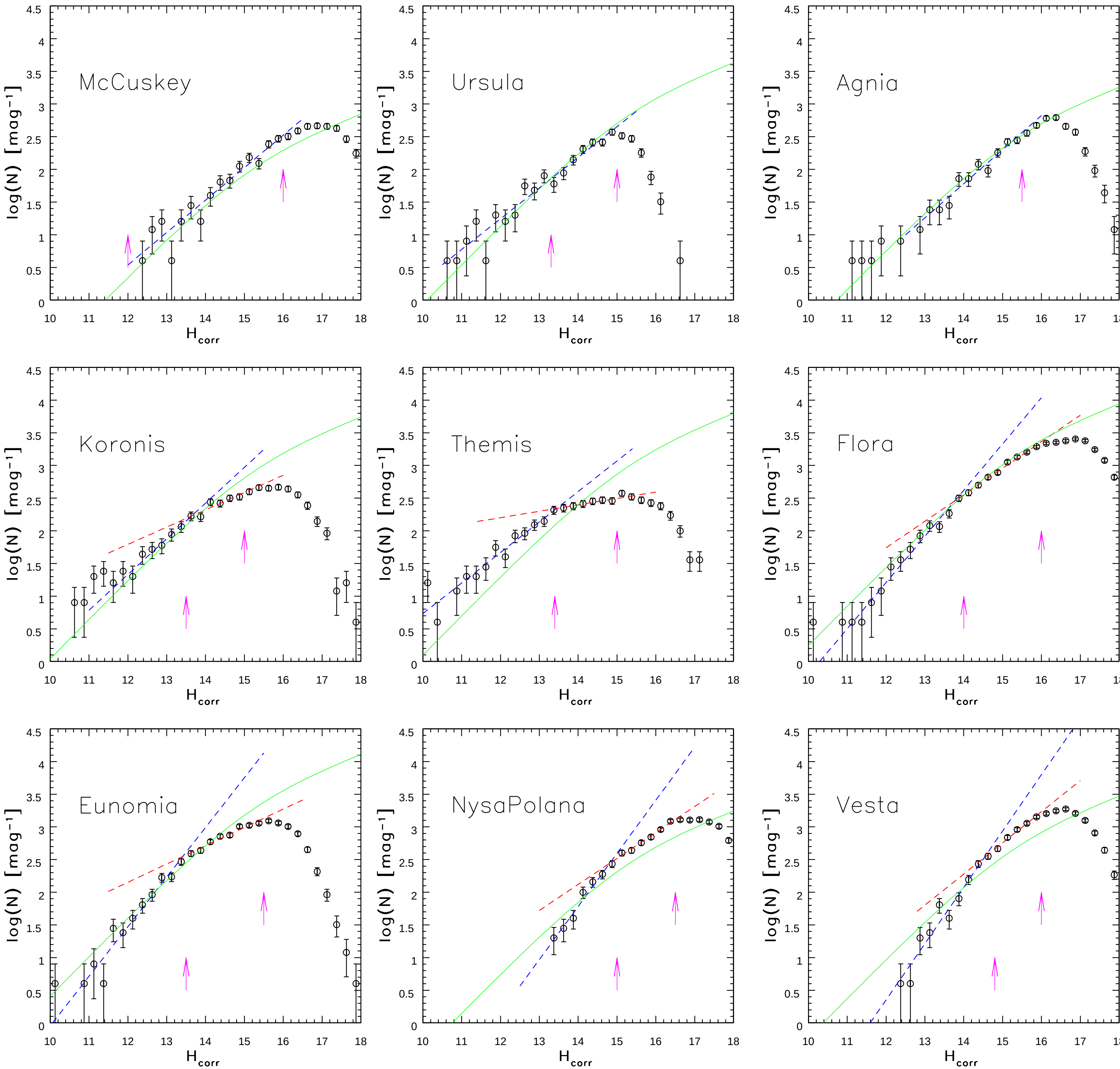


The semi-major axis vs. inclination: color-coded using optical colors measured by SDSS

Detailed population studies: Parker et al. (2008, Icarus 198, 138)



Size distributions of main-belt families: LSST will go 5 mag deeper!



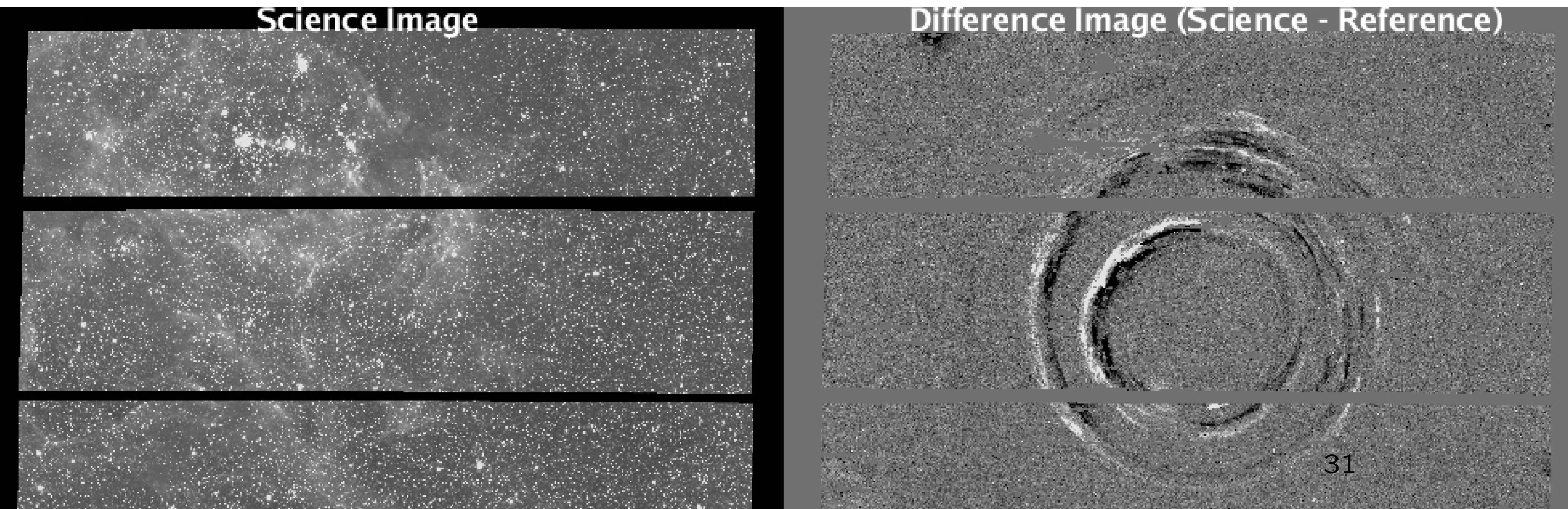
Time Domain: Exploring the Unknown

- Characterize known classes of transient and variable objects, and discover new ones: a variety of time scales ranging from $\sim$10 sec, to the whole sky every 3 nights, and up to 10 yrs; large sky area, faint flux limit (as many **variable** stars in LSST as **all** stars in SDSS: $\sim$100 million)
- Transients will be reported within 60 sec of closing shutter

Time Domain: Exploring the Unknown

- Characterize known classes of transient and variable objects, and discover new ones: a variety of time scales ranging from ~10 sec, to the whole sky every 3 nights, and up to 10 yrs; large sky area, faint flux limit (as many **variable** stars in LSST as **all** stars in SDSS: ~100 million)
- Transients will be reported within 30 sec of closing shutter

Not only point sources: echo of a supernova explosion (from A. Becker)



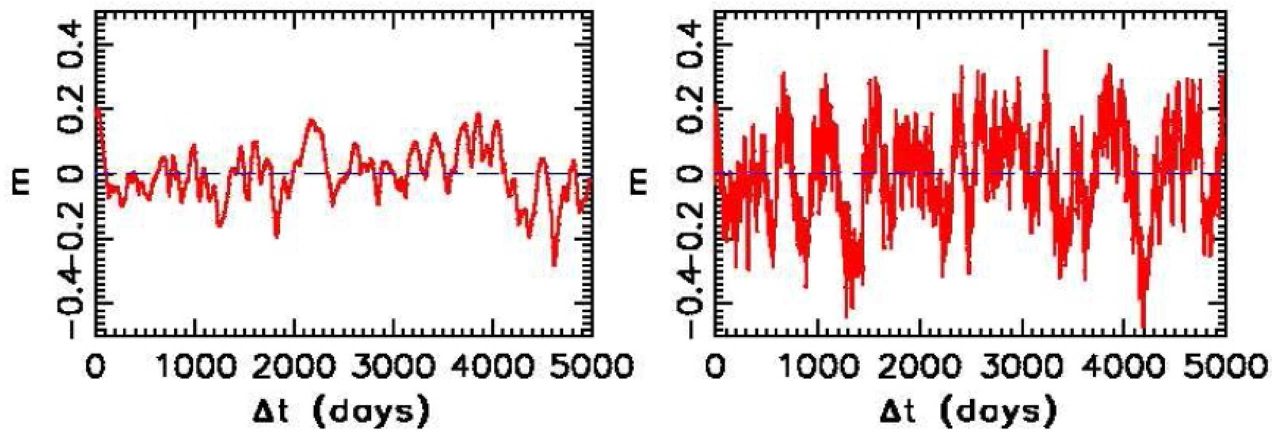
Quasar/AGN Variability

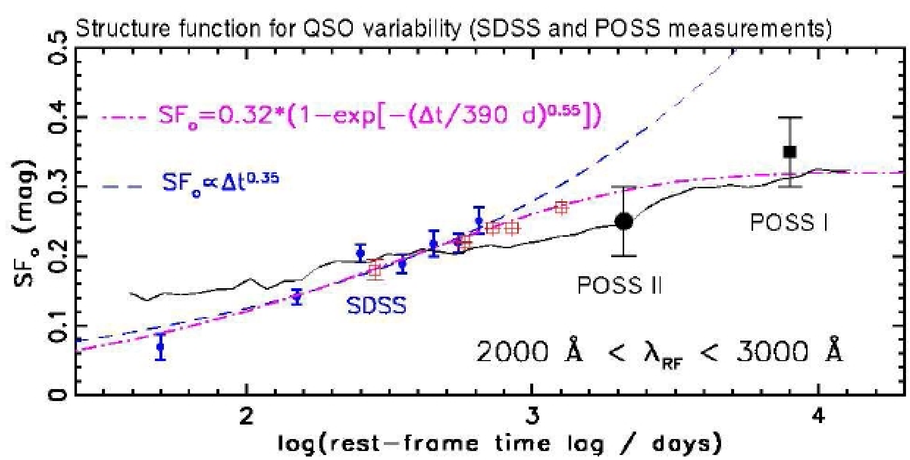
Competing theories for the origin of variability:

- Microlensing
- Bursts of Supernovae
- Accretion disk instabilities

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

SDSS observations indicate rich information content:

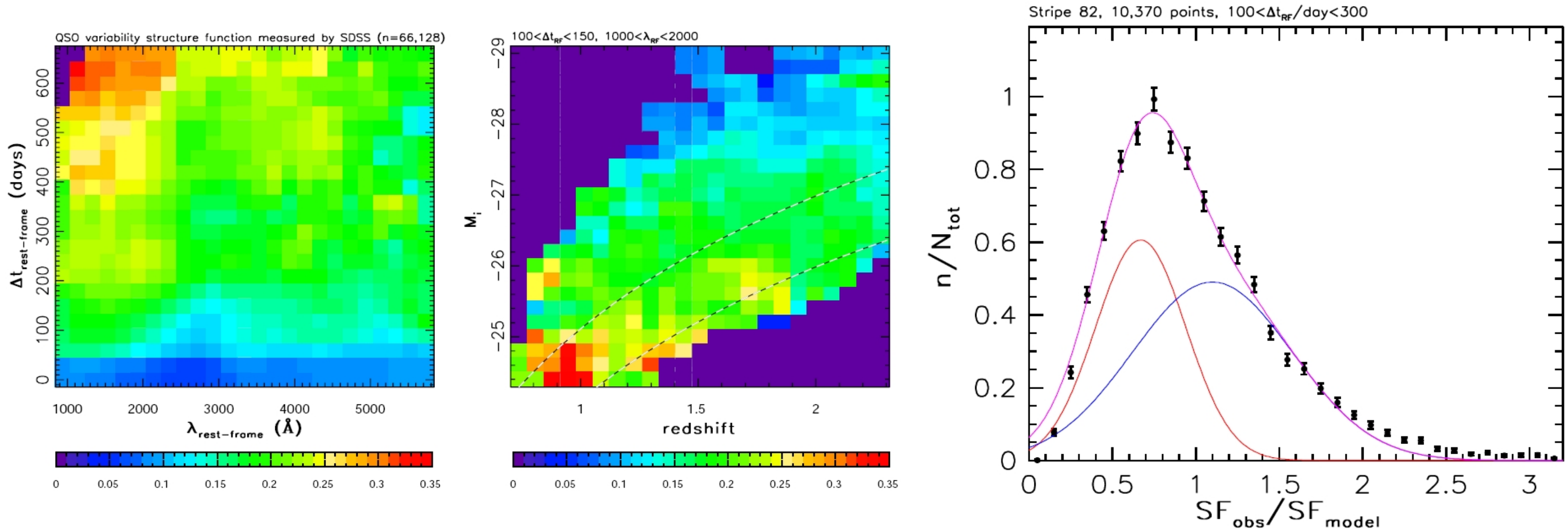




Quasar/AGN Variability

SDSS observations show that quasar variability depends on time scale, wavelength and luminosity, but **not on redshift**.

Rich observational dataset: what is it telling us?



Left: the quasar ensemble rms variability as a function of rest-frame wavelength and time scale.

Middle: the quasar ensemble rms variability as a function of redshift and luminosity.

Right: the ratio of observed and expected variability for individual light curves: much wider than expected!

Quasar/AGN Variability

Datasets with only two observations per object do not capture all the information about variability: **damped random walk** is a convenient (if only statistical) tool to interpret data (Kelly et al. 2009; etc).

SDSS observations show that quasar variability depends on time scale, wavelength and luminosity, but **not on redshift**. The variability amplitude is strongly correlated with the Eddington factor, but there is additional impact of either luminosity or black hole mass.

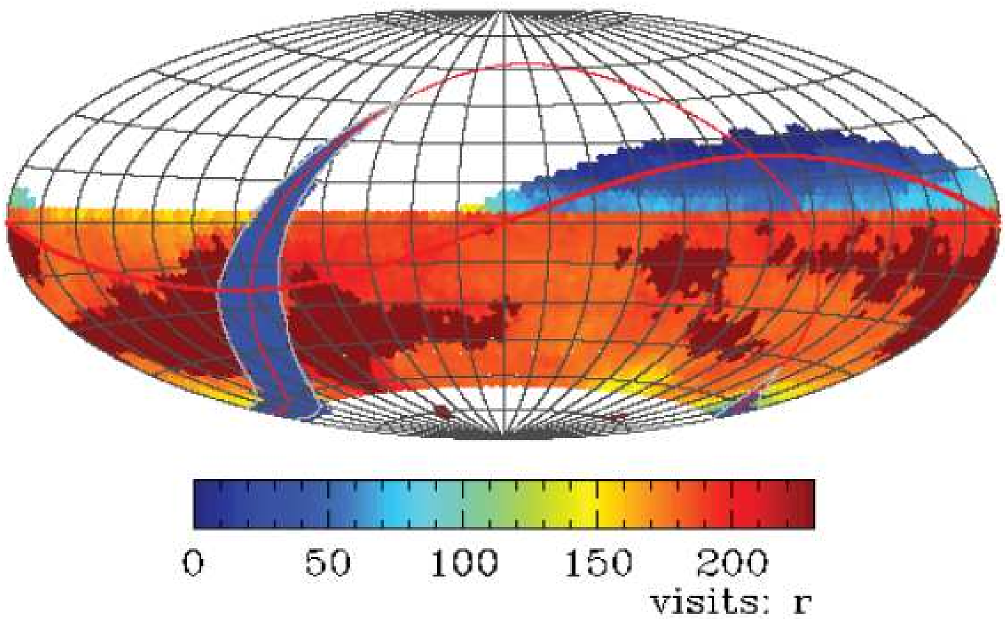
Even when all these variables are controled, the characteristic time scale still shows a fairly wide distribution (MacLeod et al. 2010; ApJ 721, 1014).

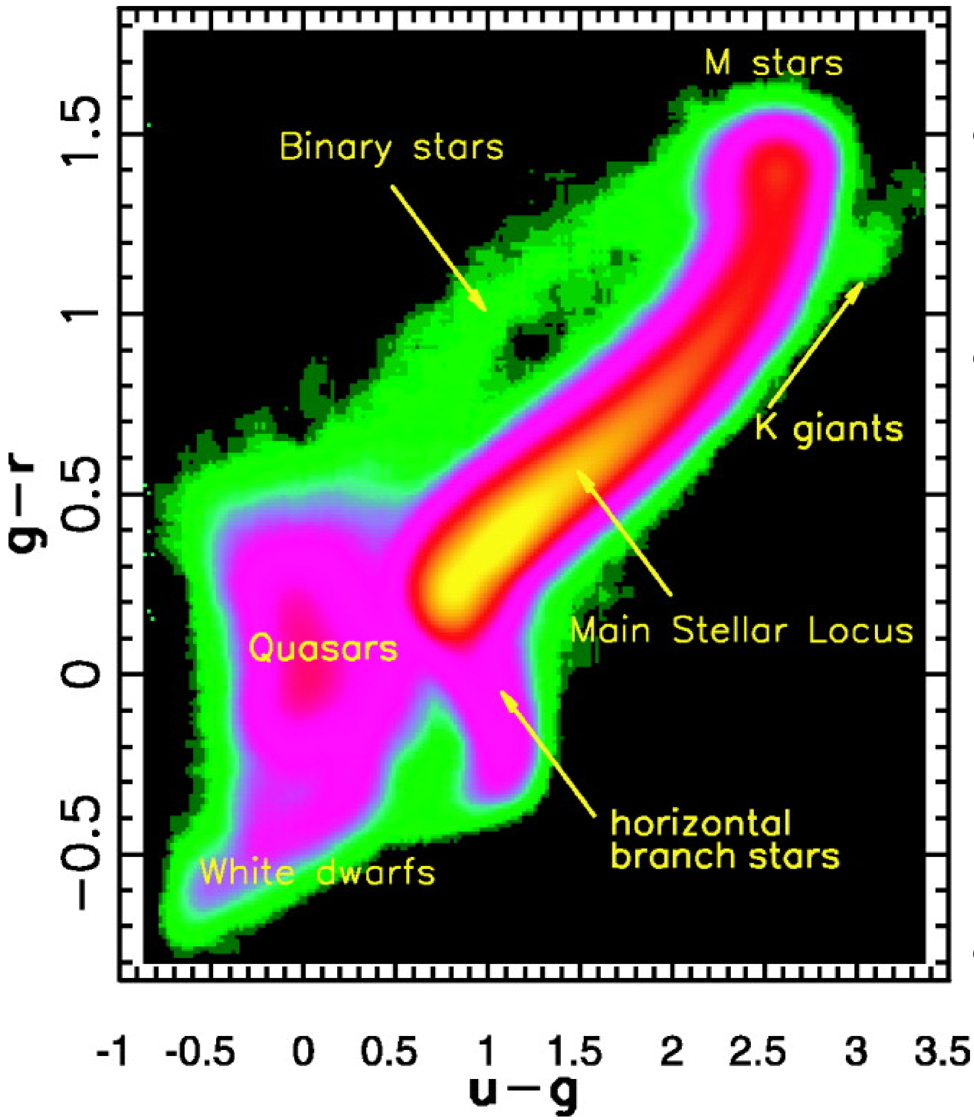
LSST data will be excellent for continuing such studies (of accretion processes around black holes):

- About 100-1000 times larger sample
- Better sampling (uniform coverage, about 5 times more data points per object)

Deciphering the Past: mapping the Milky Way

- Map the Milky Way all the way to its edge with high-fidelity to study its formation and evolution:
  - **about 10 billion stars**
  - hundreds of millions of halo main-sequence stars to 100 kpc
  - RR Lyrae stars to 400 kpc
  - trigonometric parallaxes for all stars within 500 pc
  - kinematics from proper motions (extending Gaia 4 mag)
  - photometric distances and metallicity

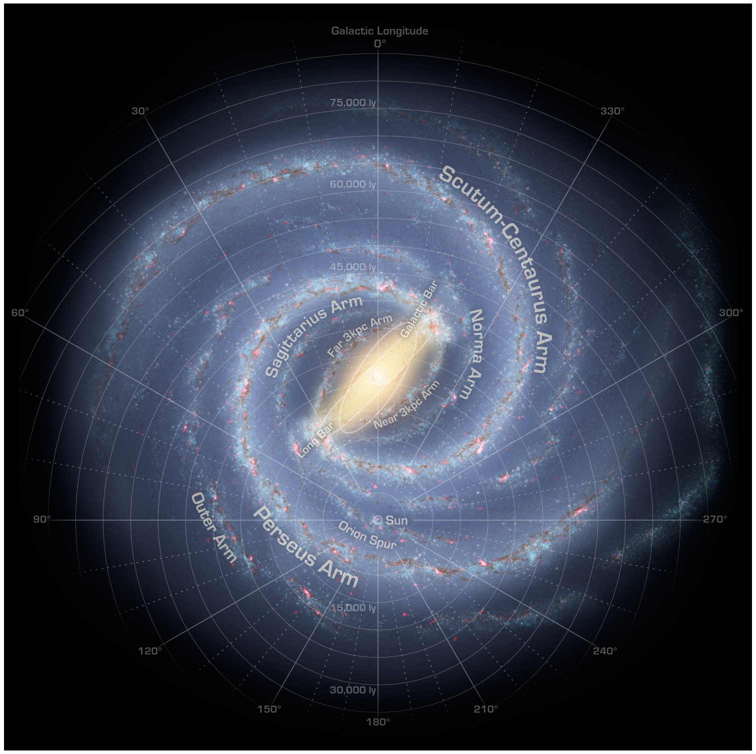


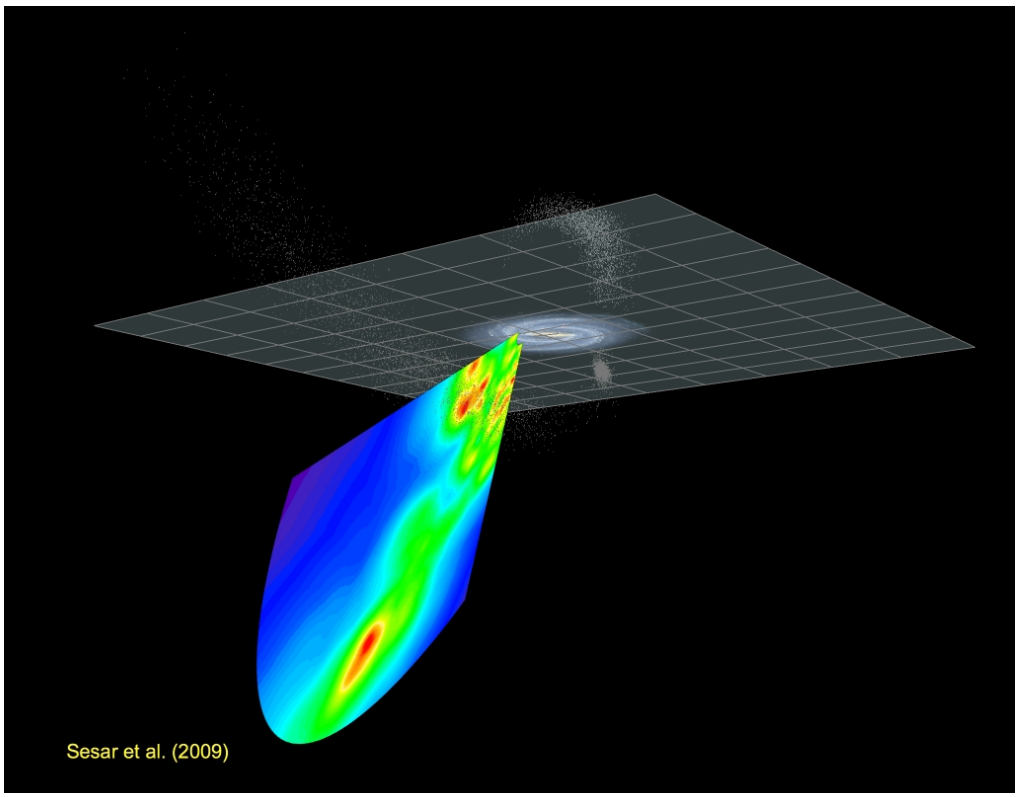


Wide wavelength coverage, and accurate and robust photometry

Dissecting the Milky Way with SDSS

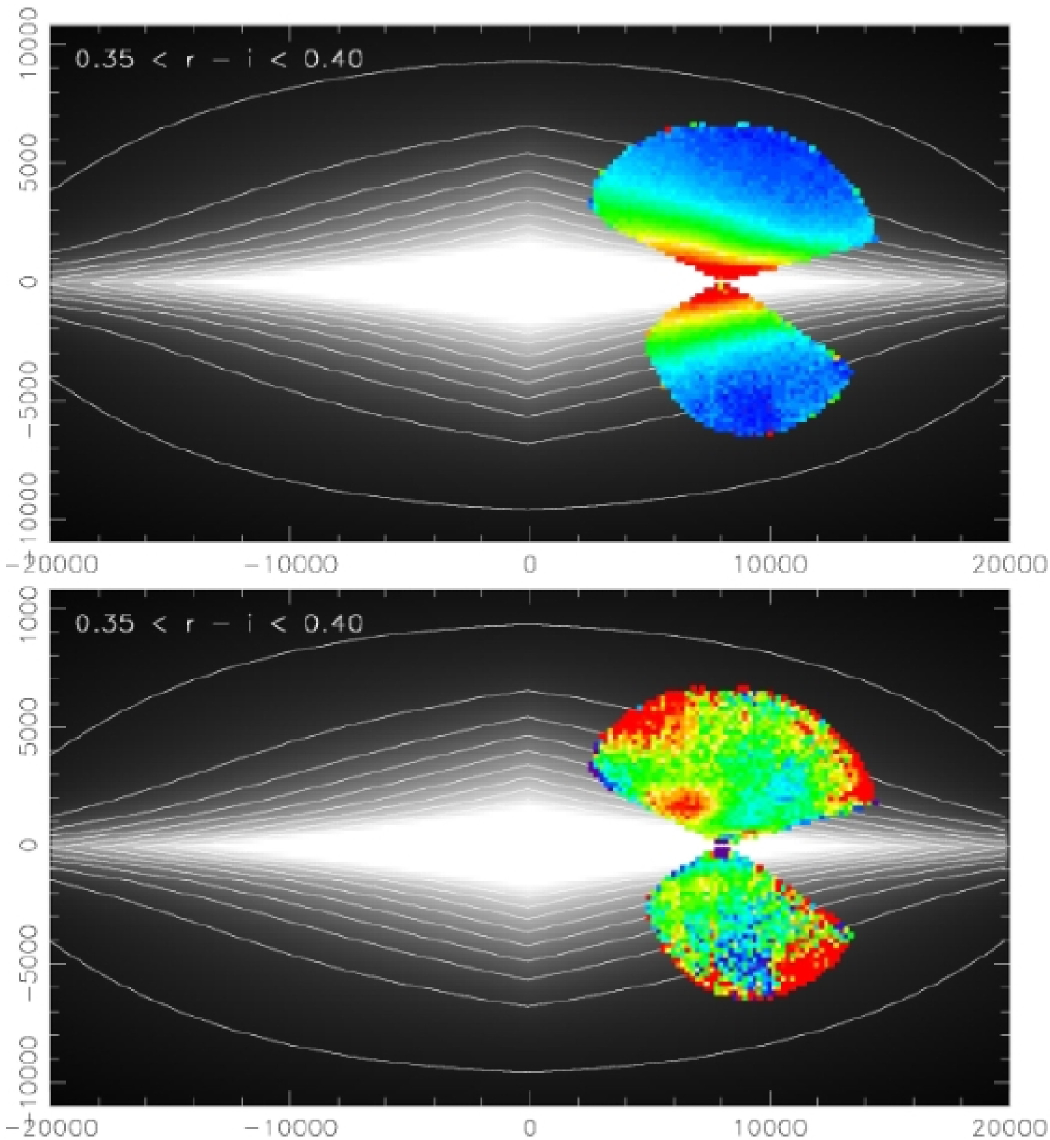
- Stars on the main stellar locus are dominated (∼98%) by main sequence stars (for $r > 14$)
- The position of main-sequence stars on the locus is controlled by their effective temperature/luminosity/[Fe/H], and thus can be used to estimate distance: photometric parallax method for ∼100 million stars **(with LSST several billion!)**
- Accurate $u - g$ color enables photometric metallicity estimates for 6 million SDSS F/G stars to 10 kpc; **(with LSST 200 million to 100 kpc!)**





Outer halo studies: RR Lyrae from SDSS Stripe 82

- **Top left:** the disk structure (artist's conception based on the Spitzer and other surveys of the Galactic plane)
- **Bottom left:** the halo density (multiplied by R^3; yellow and red are overdensities relative to mean $\rho(R) \propto R^{-3}$ density) as traced by RR Lyrae from SDSS Stripe 82 (Sesar et al. 2009), compared in scale to the top panel
- Conclusions: the spatial distribution of halo stars is highly inhomogeneous (clumpy); when averaged, the stellar volume density decreases as $\rho(R) \propto R^{-3}$. **Limited by data!**



The limitations of SDSS data and LSST

- **Sky Coverage:** "only" $\sim$1/4 of the sky 1/2 of the sky
- **Depth:** main-sequence stars to $\sim$10 kpc; RR Lyrae stars to 100 kpc 100 and 400 kpc
- **Photometric Accuracy:** $\sim$0.02 mag for the u band, limits the accuracy of photometric metallicity estimates to $\sim$0.2 dex 0.01 mag and 0.1 dex
- **Astrometric Accuracy:** the use of POSS astrometry (accurate to $\sim$150 mas after recalibration) limits proper motion accuracy to 3 mas/yr 0.2 mas/yr at r=21 and 1.0 mas/yr at r=24

Gaia: optical astrometric and photometric space survey mission

- A major European project with many collaborating institutions: "Super-Hipparcos" with 10,000 times larger sample!

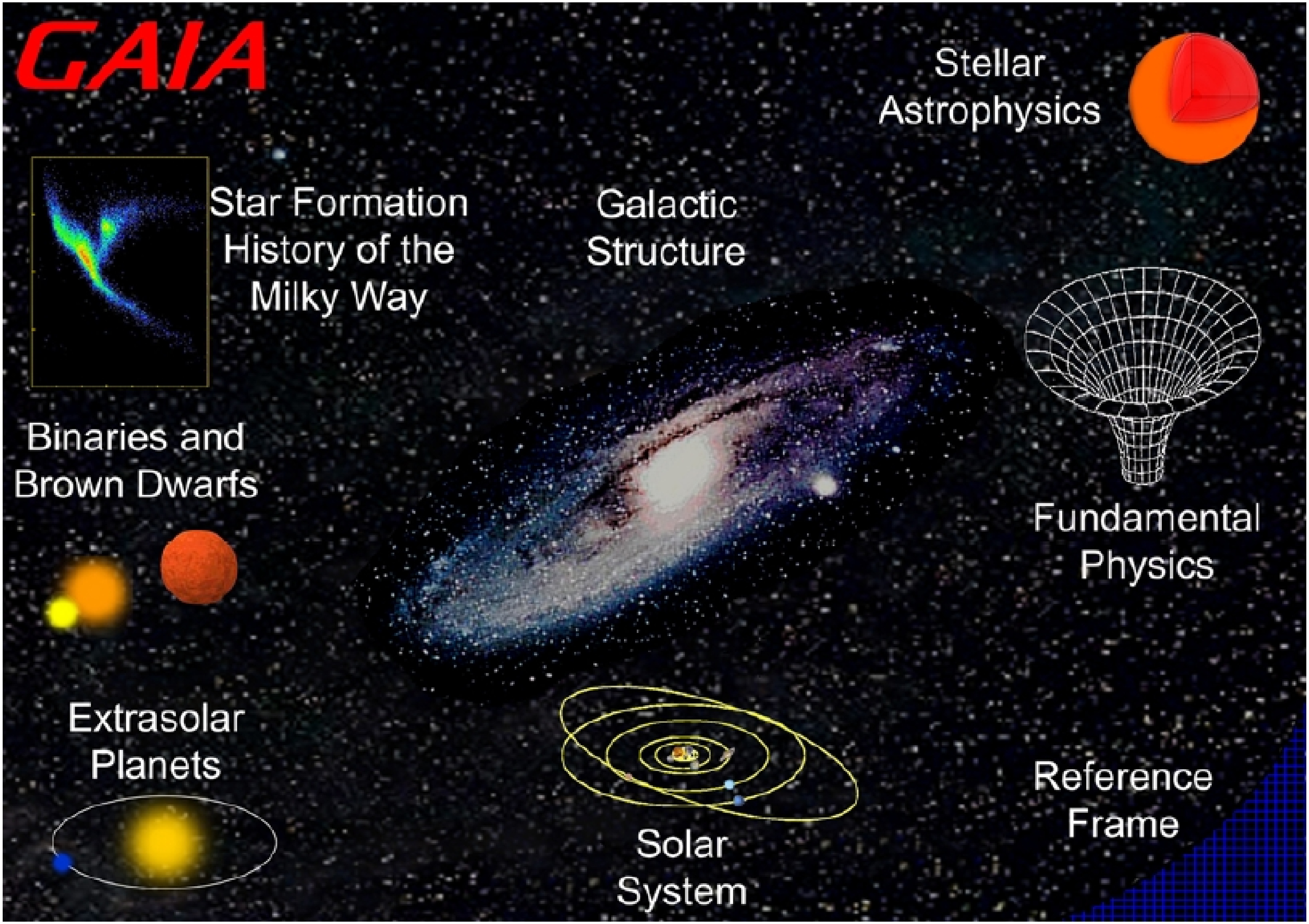
- Accurate positions (a few μarcsec) and spectrophotometry: distances and proper motions for about a billion stars, and radial velocities for about 100 million stars!

- Complete to $V \sim 20$, radial velocity to $V \sim 17$': 1% distances for a few million stars!

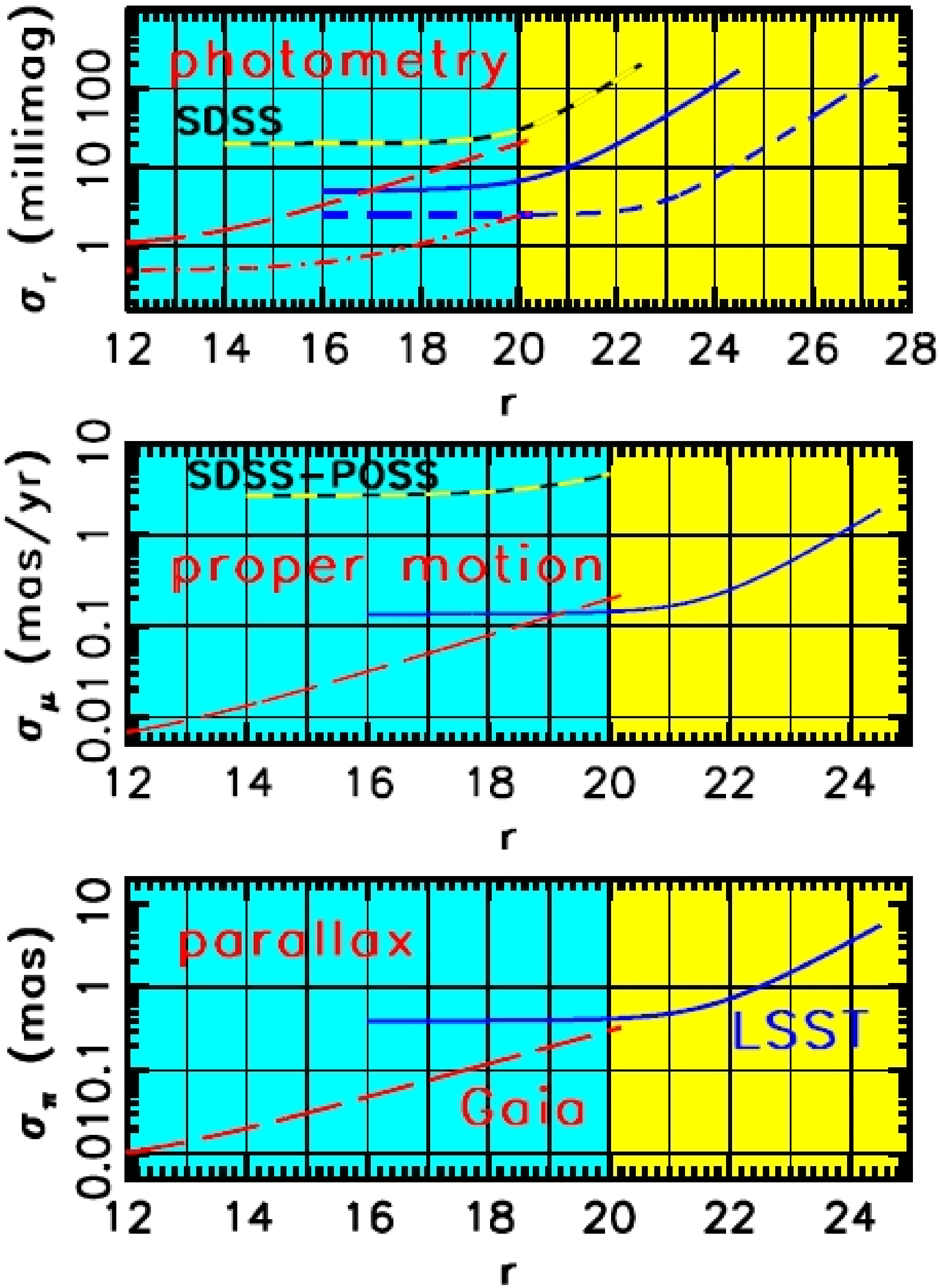
- Science Drivers:

  1. star formation and stellar evolution

  2. formation and evolution of the Milky Way


GAIA
Stellar Astrophysics
Star Formation History of the Milky Way
Galactic Structure
Binaries and Brown Dwarfs
Fundamental Physics
Extrasolar Planets
Solar System
Reference Frame

Gaia vs. LSST comparison: errors

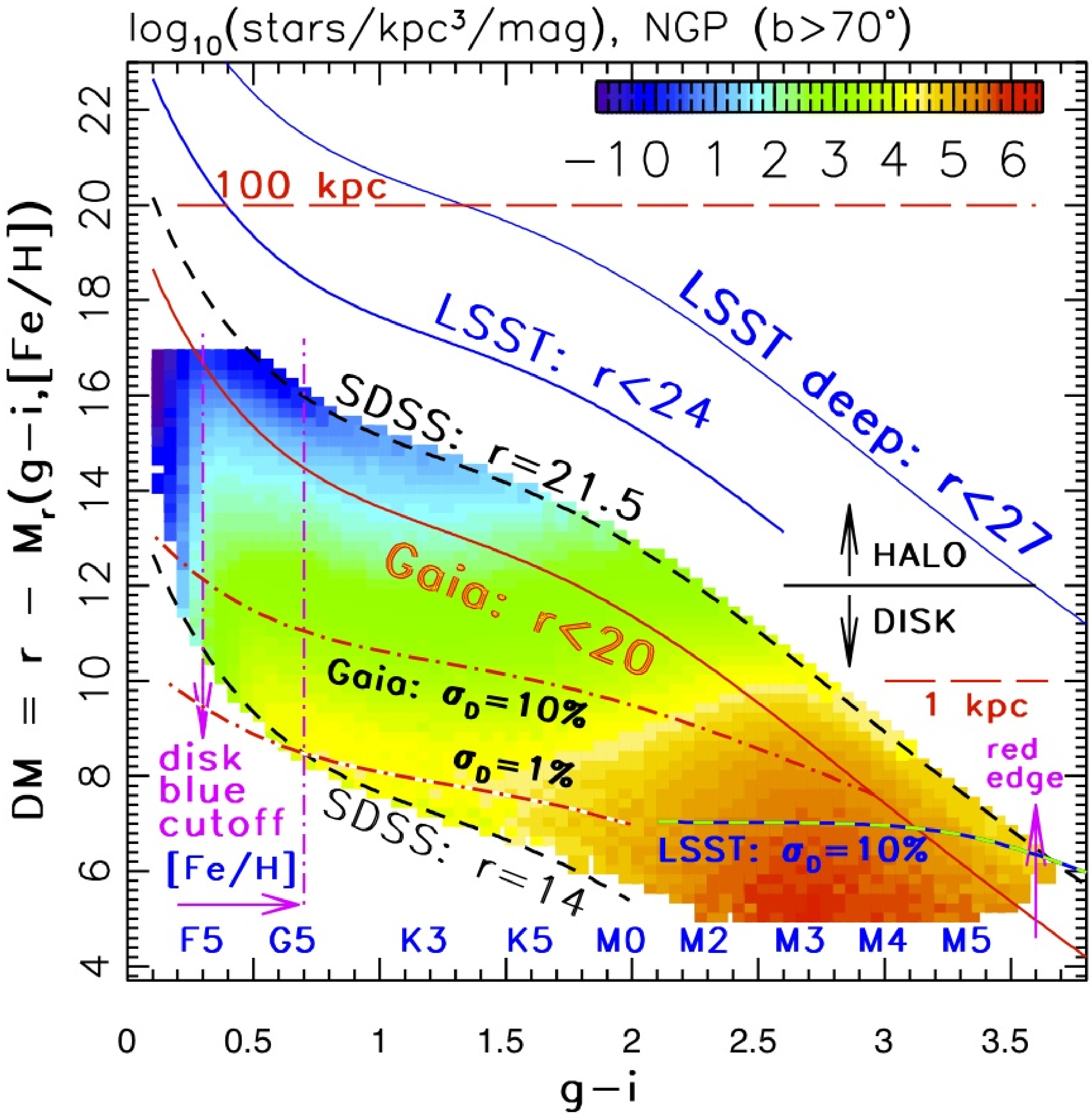


- **Gaia:** excellent astrometry (and photometry), but only to $r < 20$
- **LSST:** photometry to $r < 27.5$ and time resolved measurements to $r < 24.5$
- **Complementarity** of the two surveys: photometric, proper motion and trigonometric parallax errors are similar around $r \sim 20$

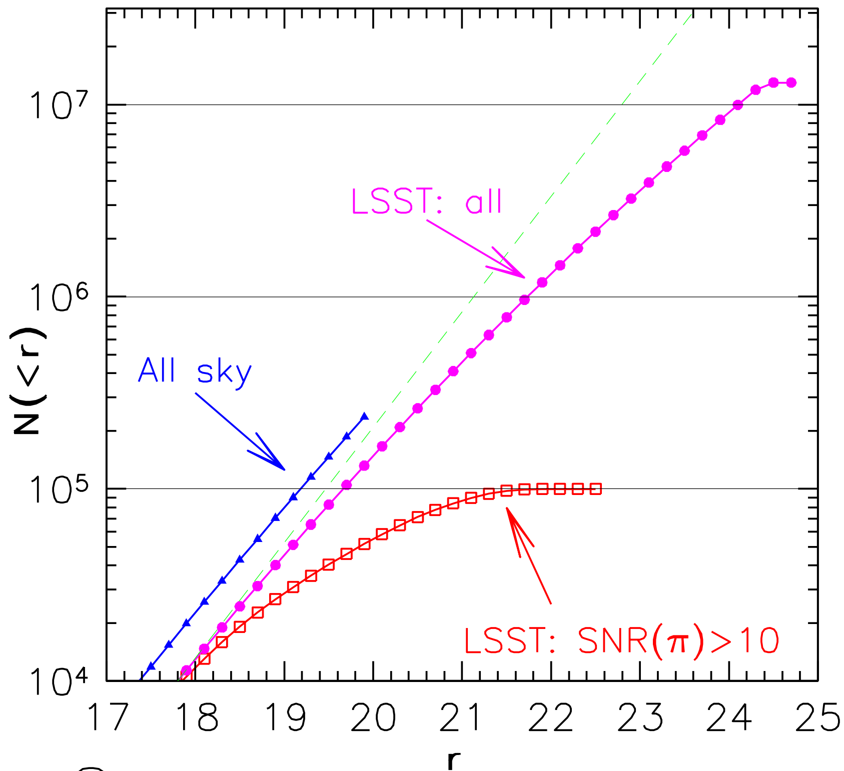
The Milky Way disk "belongs" to Gaia, and the halo to LSST (plus very faint and/or very red sources, such as white dwarfs and LT(Y) dwarfs).

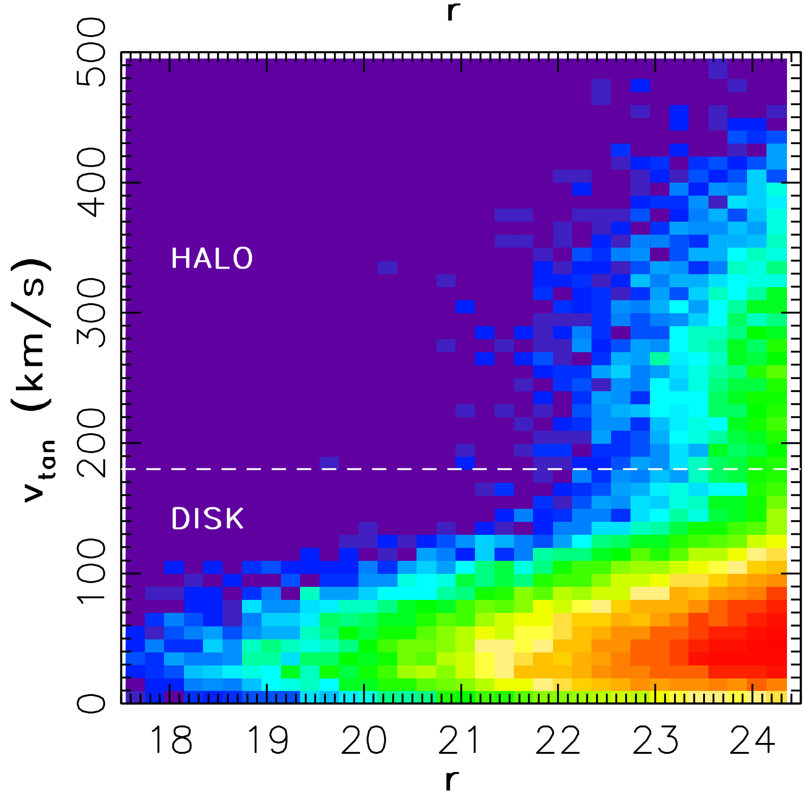
Gaia vs. LSST comparison: distance limits

- **Main sequence stars:** color map is the number density measured by SDSS; lines show DM limits for LSST and Gaia.



White Dwarfs with Gaia and LSST



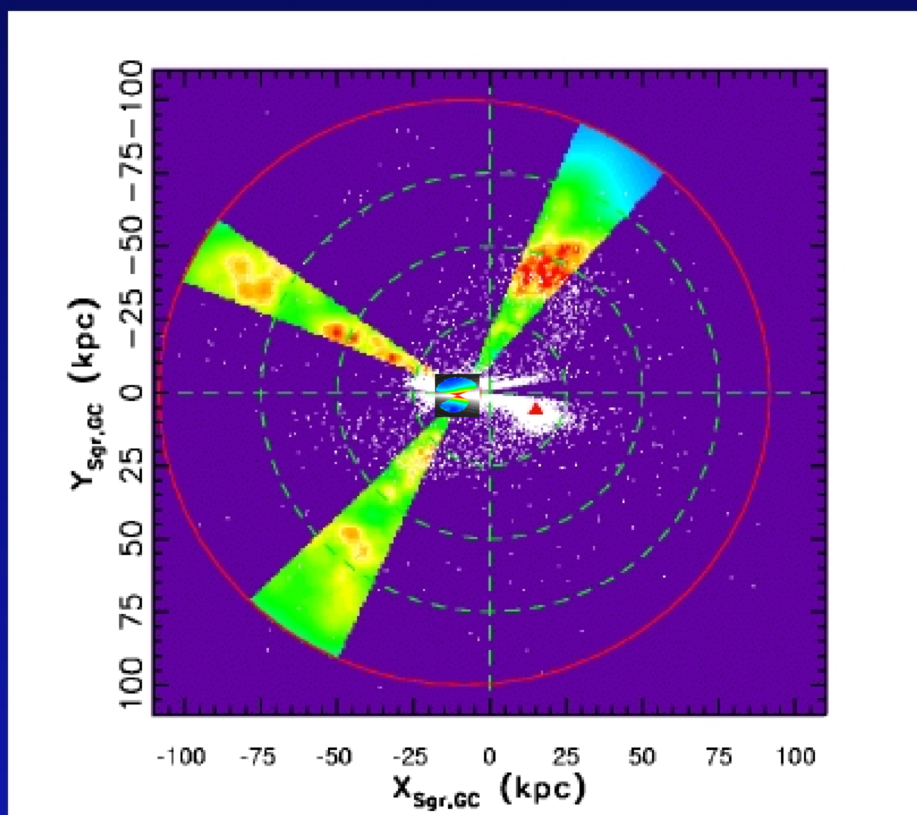


- **Top Left:** Counts of white dwarfs: about 300,000 detected by Gaia, over 10,000,000 for LSST with $r < 24.5$ (50 million for < 27.5)
- **Time resolved measurements** yield proper motion and trigonometric parallax; **coadded photometry** yields accurate colors (e.g. can photometrically separate H and He sequences, and estimate log(g) to 0.05 dex for some temperature intervals)
- **Bottom Left:** Disk and halo white dwarfs can be kinematically separated; there will be 400,000 halo white dwarfs in the LSST $r < 24.5$ sample (currently, fewer than 100 are known)
- **The white dwarfs luminosity function is sensitive to the population age; it will be measured separately for thin and thick disks, and halo**

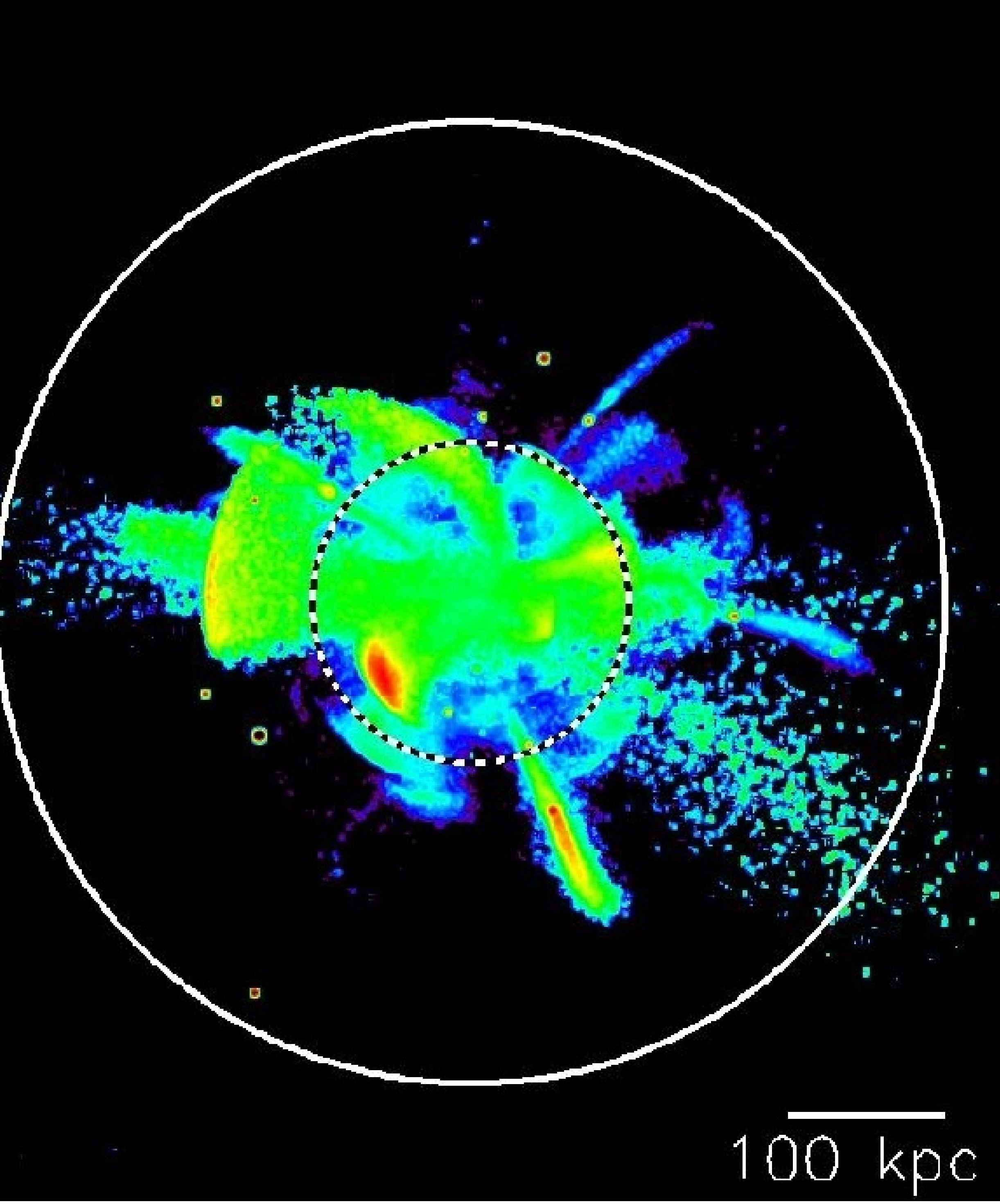
The large blue circle: the ~400 kpc limit of future LSST studies based on RR Lyrae

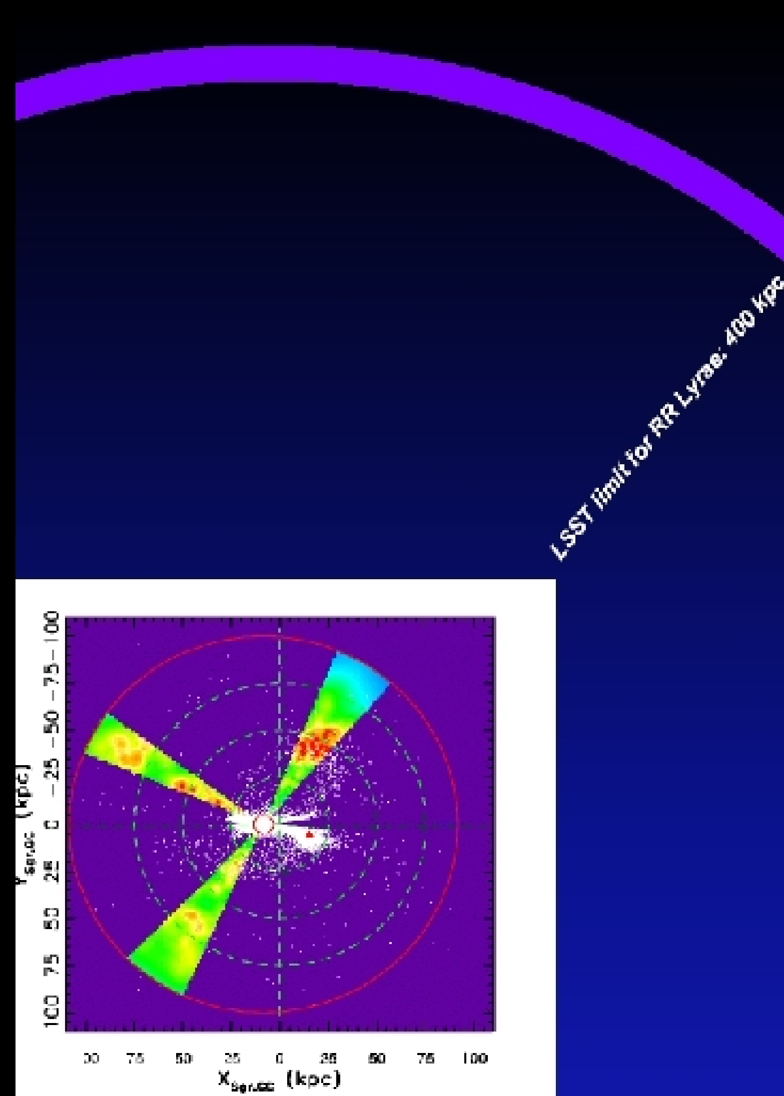
LSST limit for RR Lyrae: 400 kpc

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





Left: Models (Bullock & Johnston) **Right:** SDSS and 2MASS observations, and predictions for LSST

LSST briefly

- **The Best Sky Image Ever:** 60 petabytes of astronomical image data (resolution equal to 3 million HDTV sets)
- **The Greatest Movie of All Time:** digital images of the entire observable sky every three nights, night after night, for 10 years (11 months to "view" it)
- **The Largest Astronomical Catalog:** 20 billion sources (for the first time in history more than living people)

But the total impact of LSST may turn out to be much larger than that directly felt by the professional astronomy and physics communities: **with an open 60 PB large database that is available in real-time to the public at large, LSST will bring the Universe home to everyone.**

For more details:
LSST Science Book (www.lsst.org)
LSST overview paper (arXiv:0805.2366)