Solar System Astronomy with SDSS, and LSST

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And the rest of the MOC team: Mario Jurić & Robert Lupton,

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Roman Rafikov, Steve Kent, Mike Solontoi & Becker et al.

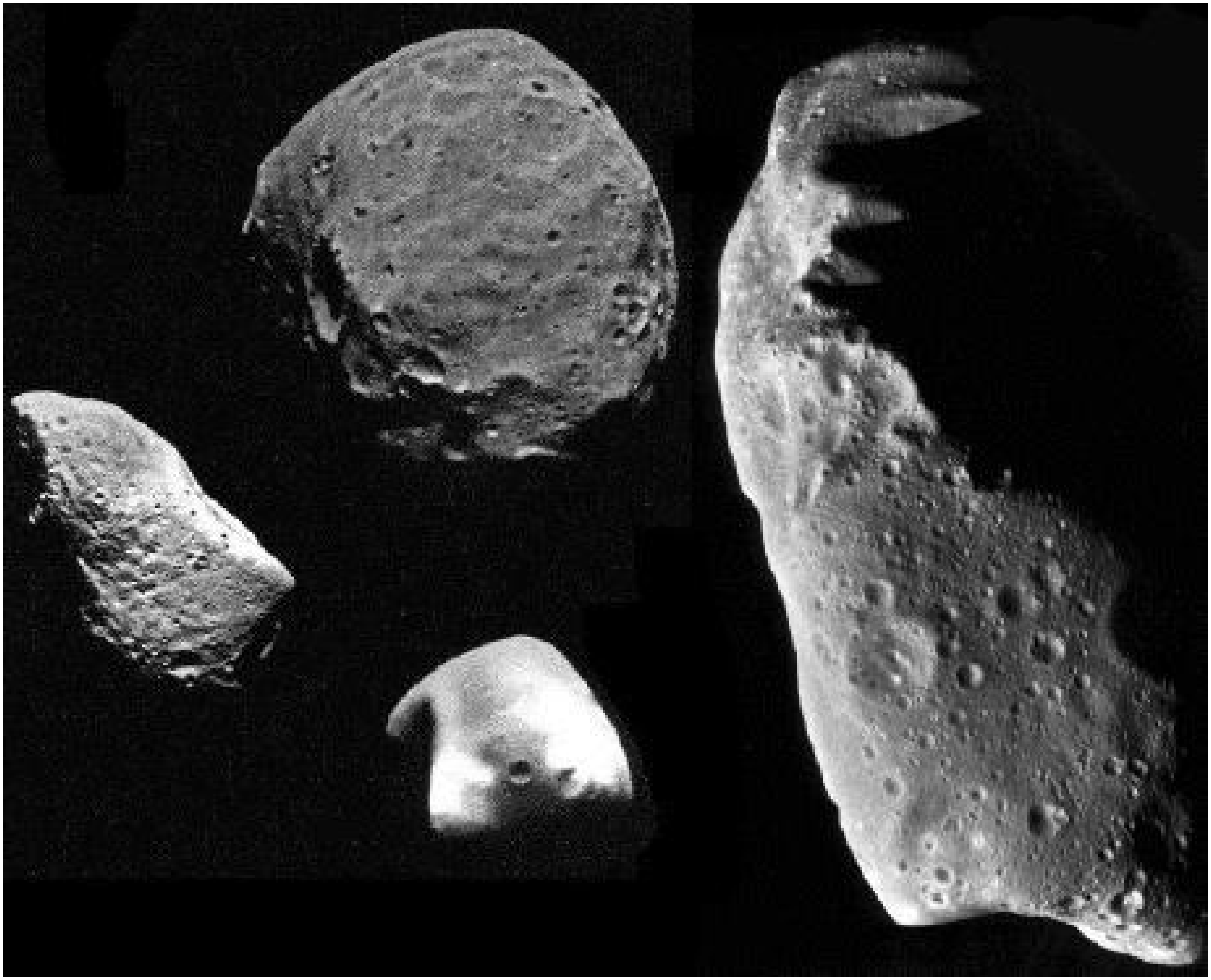
The SDSS: from Asteroids to Cosmology, Aug 18, 2008, Chicago

Solar System Science with SDSS

- Introduction
- Main-Belt Asteroids
- Jovian Trojans
- Outer Solar System
- Near-Earth Objects
- Comets

and LSST

- Solar System Science
- System Overview and Comparison to SDSS
- Other Science Drivers



Asteroids as seen from spacecrafts

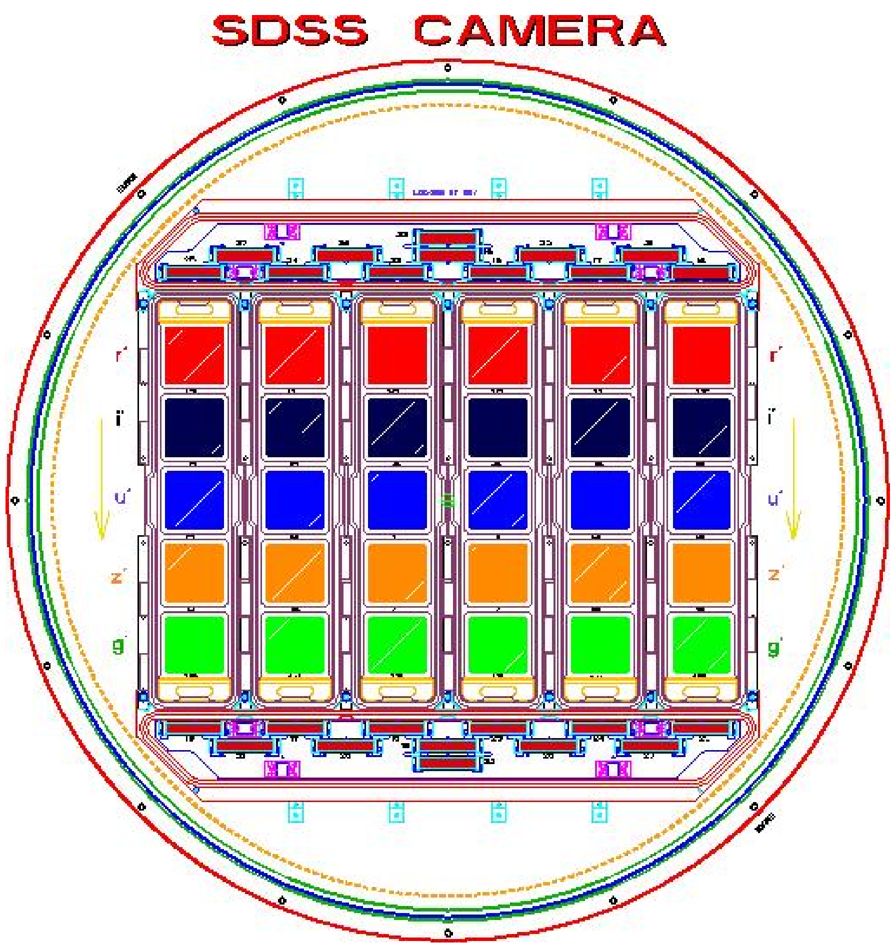
What is the significance of ground based asteroid studies in an era when spacecrafts can obtain such breathtaking photographs?

The answer is simple; the SDSS asteroid observations provide

- A sample 100,000 times larger than the one shown in previous figure: statistical analysis
- Five-color images, rather than black-and-white images
- Sensitivity to detect asteroids smaller than the smallest craters visible on the four objects in previous figure

SDSS Asteroid Observations

Moving objects in Solar System can be efficiently detected out to $\sim$ 20 AU even in a single scan: 5 minutes between the exposures in the r and g bands is sufficient to detect motion.



Asteroids move during 5 minutes and thus appear to have peculiar colors.

The images map the i-r-g filters to RGB. The data is taken in the order riuzg, i.e. GR··B

SDSS Asteroid Observations

- Moving objects must be efficiently found to prevent the contamination of quasar candidates (and other objects with non-stellar colors): implemented in *photo* pipeline (but crucially dependent on *astrom* outputs)

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- The sample completeness is 95%, with a contamination of 5%, to several magnitudes fainter completeness limit than available before

- The velocity errors 2-10%, sufficient for a recovery within a few weeks (and for estimating heliocentric distance within 5-10%)

- Accurate ($\sim$0.02 mag) 5-band photometry

- **SDSS Moving Object Catalog 4 is public at www.sdss.org**

Cataloged $\sim$500,000 moving objects, $\sim$200,000 are identified with previously known objects, $\sim$100,000 are unique

Asteroid Naming

- SDSS detections are not sufficient to determine orbits.

- But if SDSS detection is the first one, and other later data enable orbit determination, SDSS still gets naming rights.

- Currently, there are over 100 objects to be named, and there will be more.

Asteroid Naming

- Naming algorithm:

  - Can submit a few objects per month

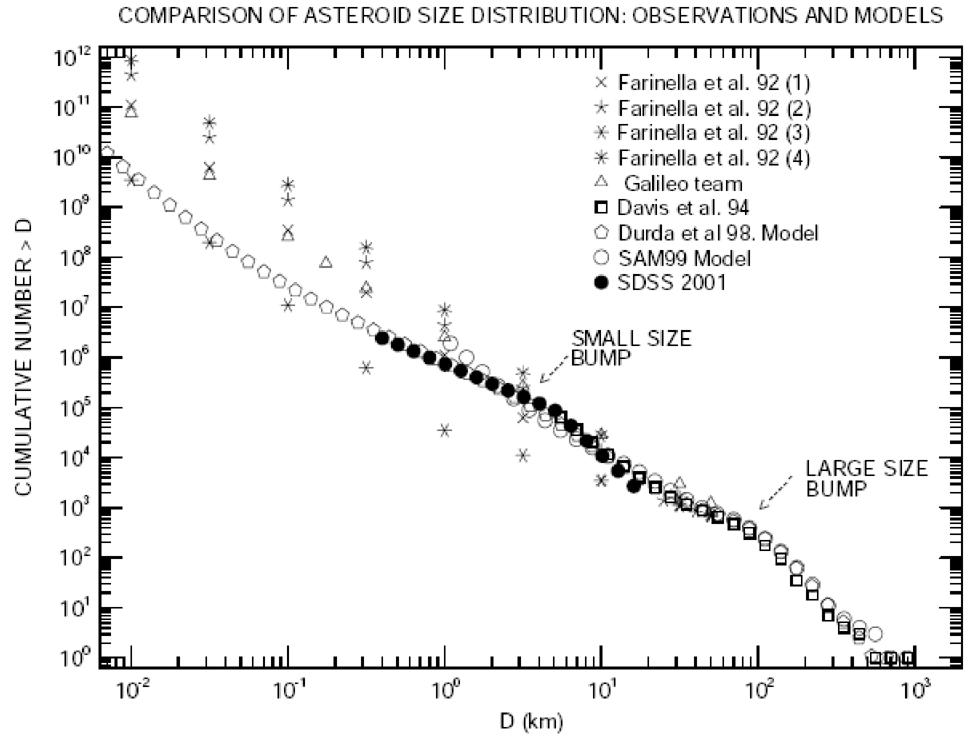
  - Customary to name the first ones after observatory. The first four will be named APO, SDSS, and (Jim) Gray and (John) Bahcall

  - The second batch: SDSS MOC developers (Ivezić, Jurić, Lupton)

  - The third batch: SDSS observers (about a dozen)

  - And then: Builders in alphabetical order, starting with EDR paper, then DR1, and so on...

Main SDSS Asteroid Results



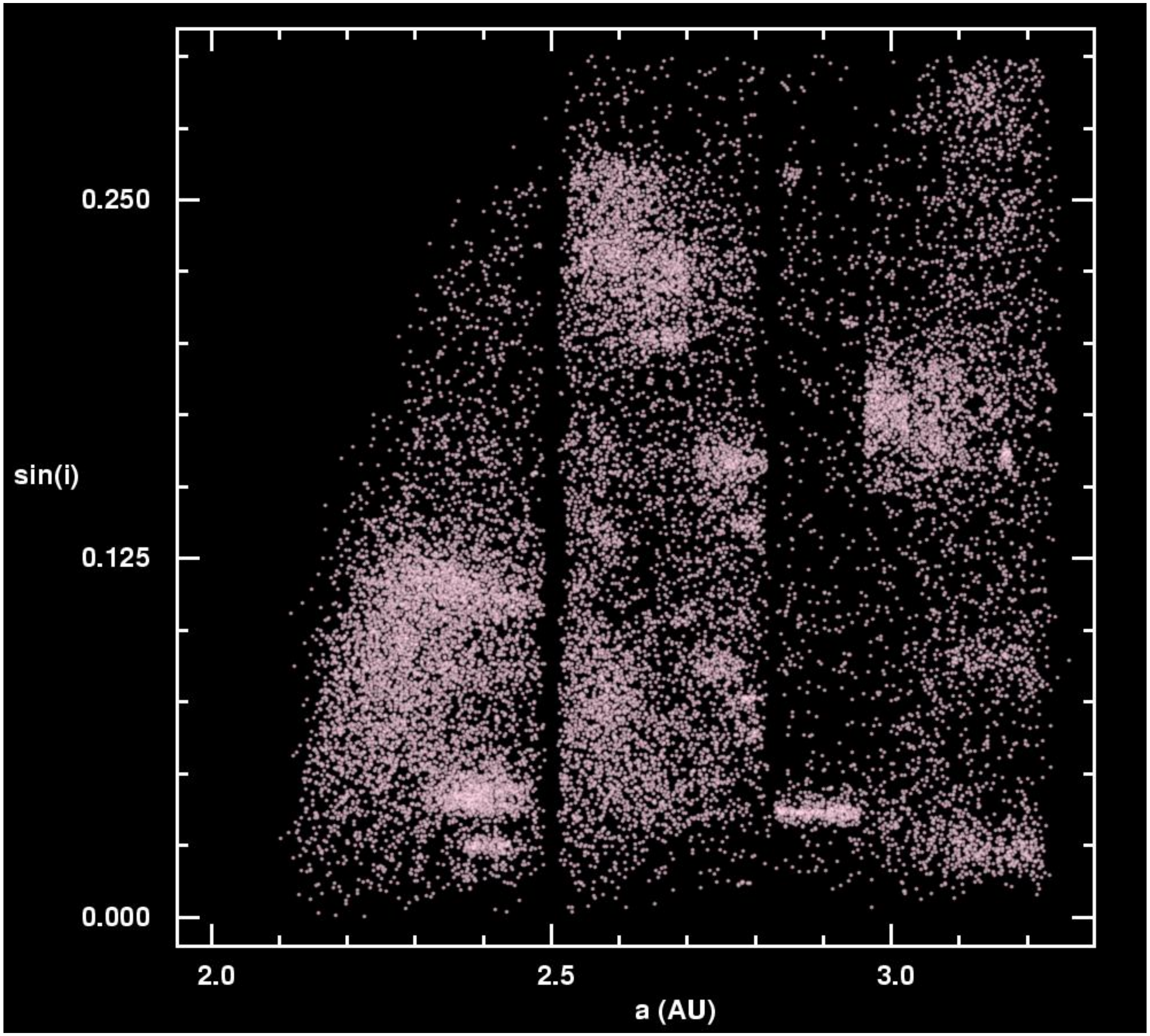
(Davis 2002)

- **The size distribution for main-belt asteroids:**
  - measured to a significantly smaller size limit ($<$ 1 km) than possible before: discovery of a change of slope at $D \sim 5$ km
  - a smaller number of asteroids compared to previous work by a factor of ~2 (N(D>1km) ~0.75 million)

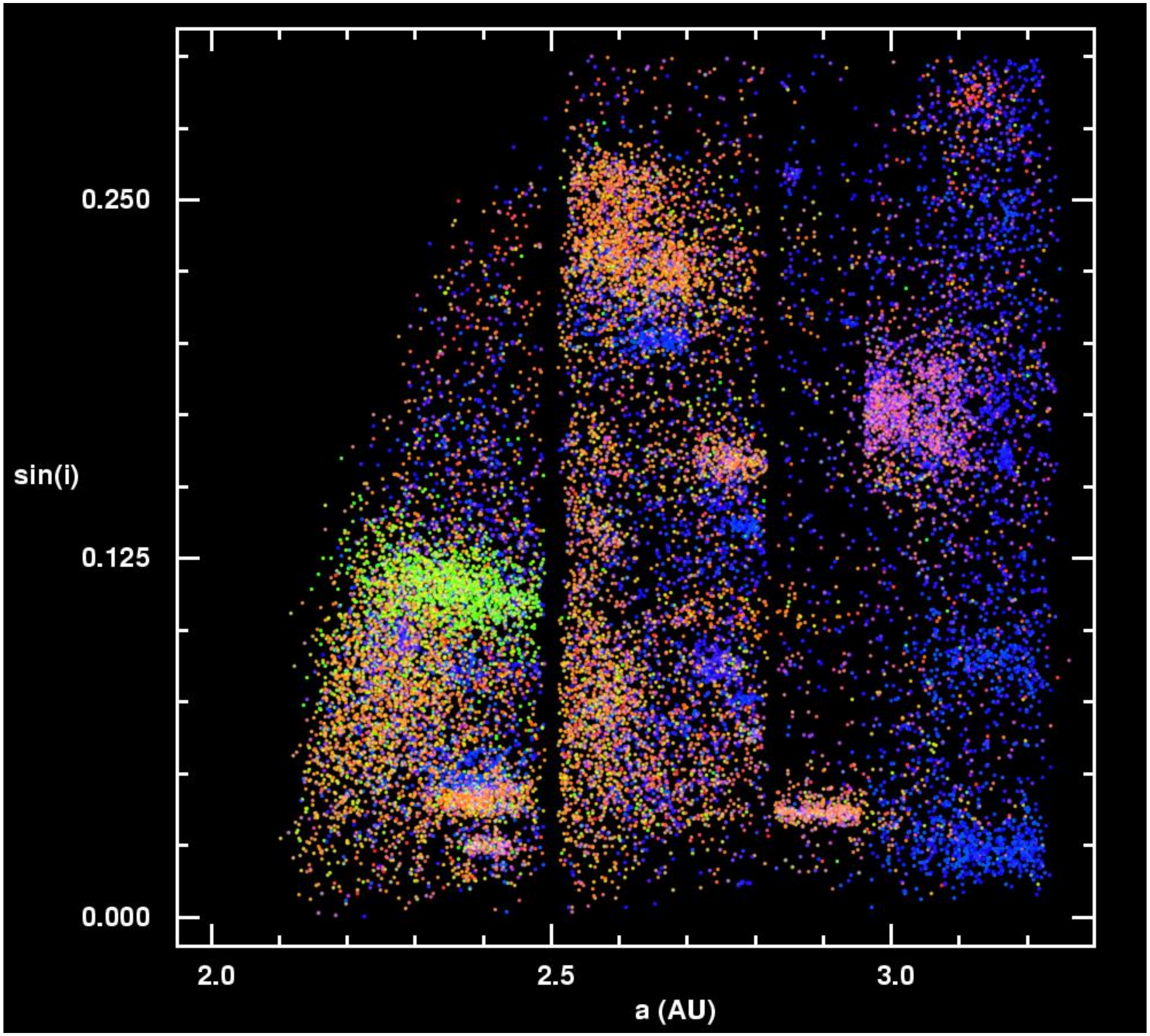
Main SDSS Asteroid Results

- **The size distribution for main-belt asteroids** (encodes collisional history and size-strength relationship)

- **Strong correlation between colors and position/dynamics:** Confirmation of color gradient: rocky S-type in the inner belt vs. carbonaceous C type asteroids in the outer belt; dynamical families have distinctive colors;

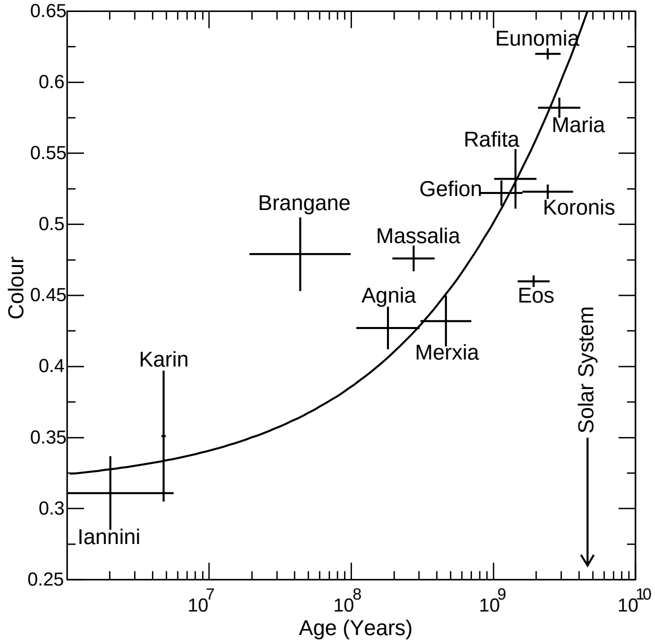


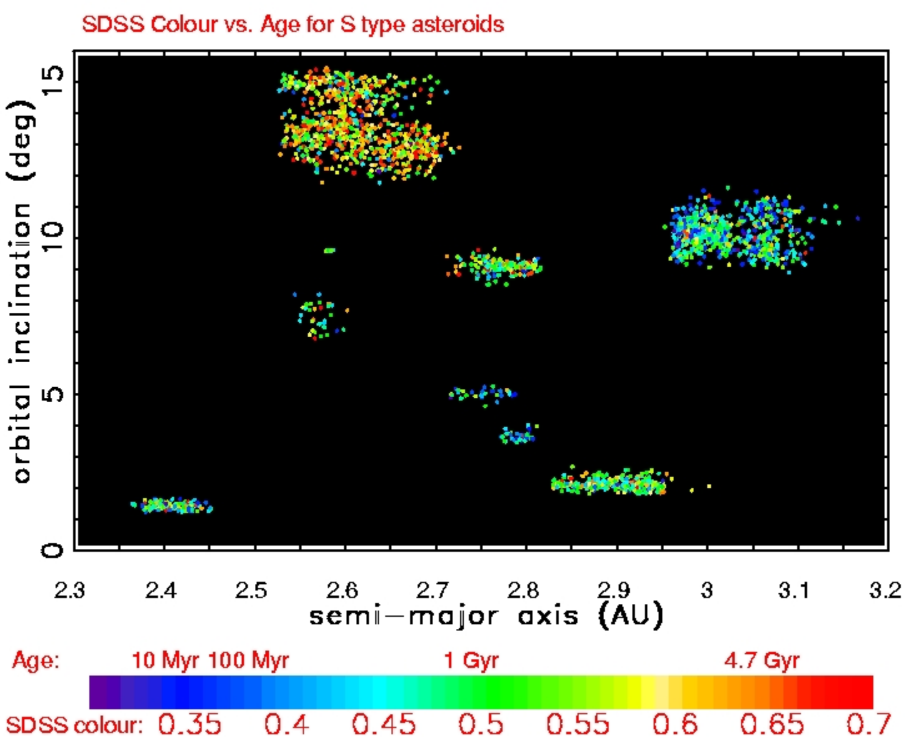
The semi-major axis v. (proper) inclination for asteroids with known orbits that were observed by SDSS



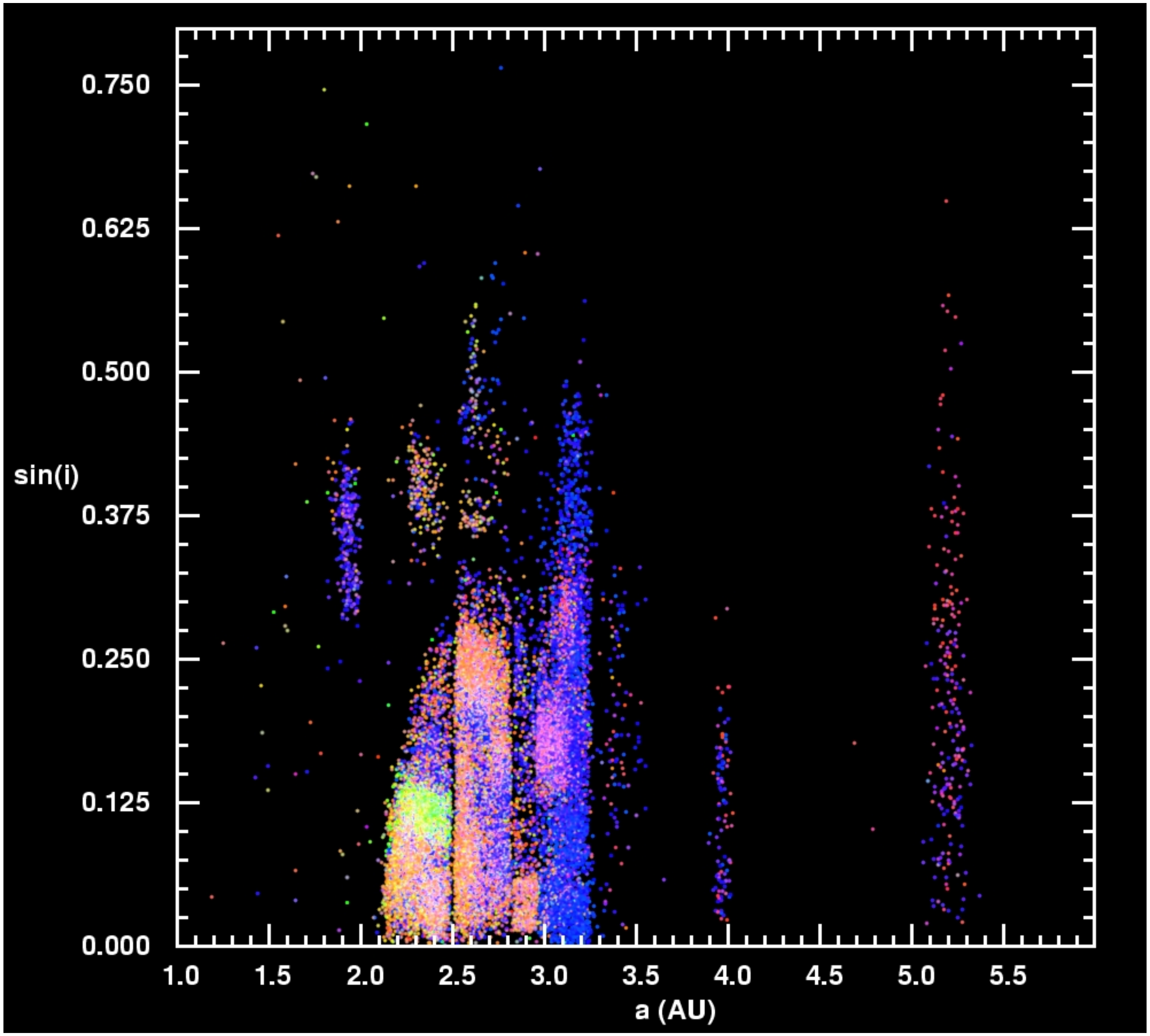
The semi-major axis v. (proper) inclination for known asteroids color-coded using **measured** SDSS colors

What is the meaning of different color shades?





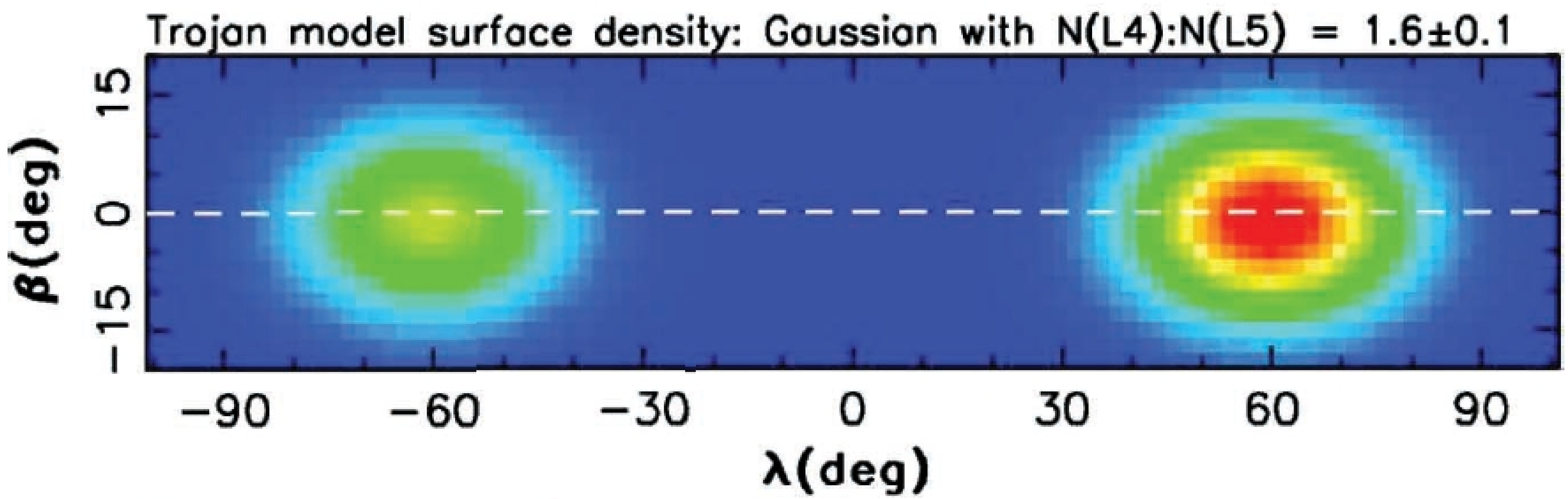
- Chemistry, of course, for the gross differences (red vs. blue), but what about different shades of red or blue?
- Family ages can be estimated using dynamics
- Within a given chemical class, colors depend on age: SDSS colors can be used to date asteroids
- Space weathering: the first in situ measurement of its rate
- Solves the puzzle of mismatched colors between meteorites and asteroids



The osculating inclination vs. semi-major axis diagram.

The Properties of Jovian Trojan Asteroids

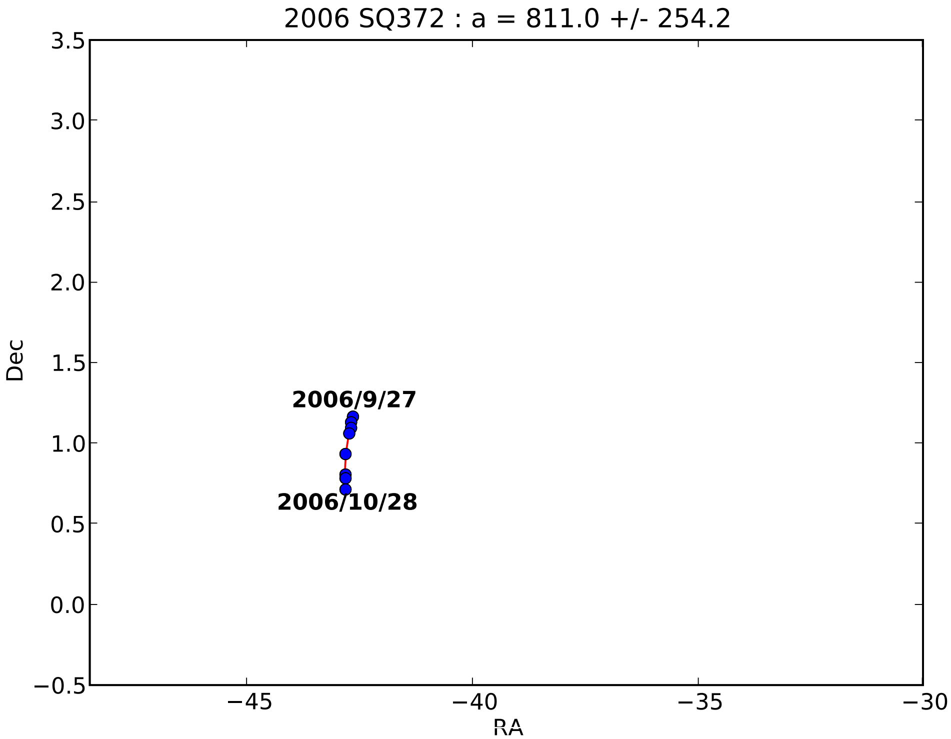
- There are (1.6±0.1) more objects in the leading swarm: long suspected, but proven by SDSS (due to a large sample and well understood selection effects)

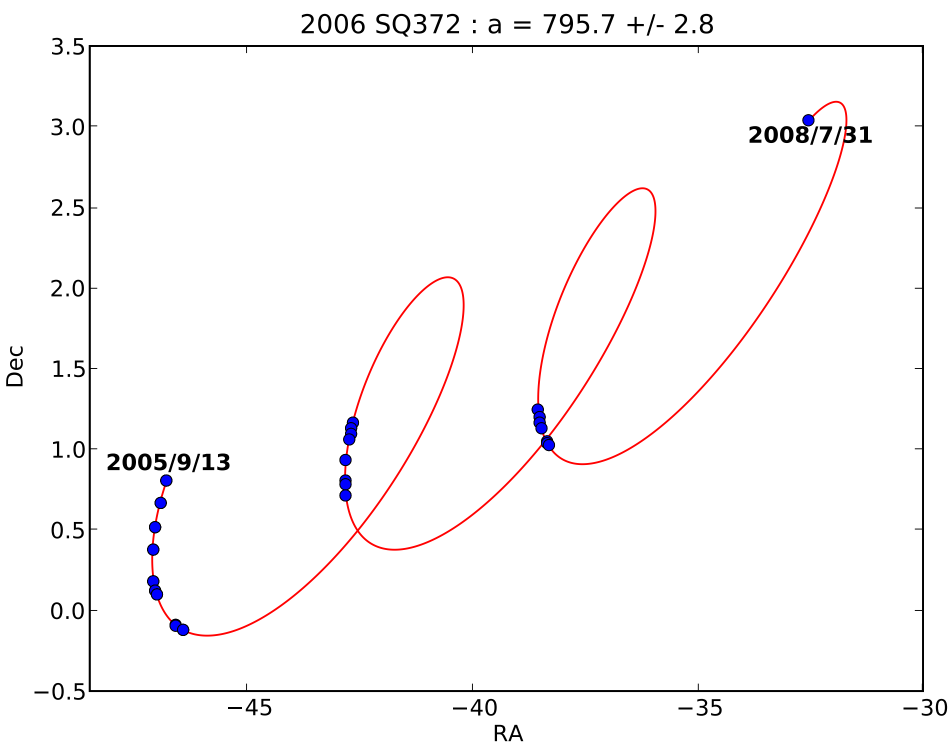


The Properties of Jovian Trojan Asteroids

- There are (1.6 ± 0.1) more objects in the leading swarm
- Trojans' color depends on orbital inclination (families?)
- The leading and trailing swarm have different color distributions
- A break in the size distribution, similar to the main belt, but with a larger characteristic size ($\sim$40 km)
- Down to the same size limit, there are as many Trojan asteroids as main-belt asteroids!

Outer Solar System (Becker et al.)





- Single epoch data not good enough, need multi-epoch data: stripe 82 and SDSS-II SN survey
- Used proto-LSST software to link observations
- Discovered 2 (out of 6 known) Neptunian Trojans
- Discovered ∼50 Kuiper belt objects
- 2006 SQ 372: the most interesting object with a semi-major axis of ∼800 AU!
- Simulations strongly suggest that this object was recently scattered into inner Solar System from Oort cloud! **press release**
- Exciting, but we need deeper data to get large samples!

The Legacy of SDSS:

- Over 100 times larger sample with accurate color measurements: taxonomy almost as good as that from spectroscopy

- Faint flux limit: surprises in size distribution

- Well understood selection effects: surprises from Jovian Trojans

- Stripe 82: a demonstration of next-generation linking codes and a hint of future discoveries beyond Kuiper Belt

Future discoveries from: SkyMapper, Pan-STARRS, DES, LSST

Killer Asteroids!

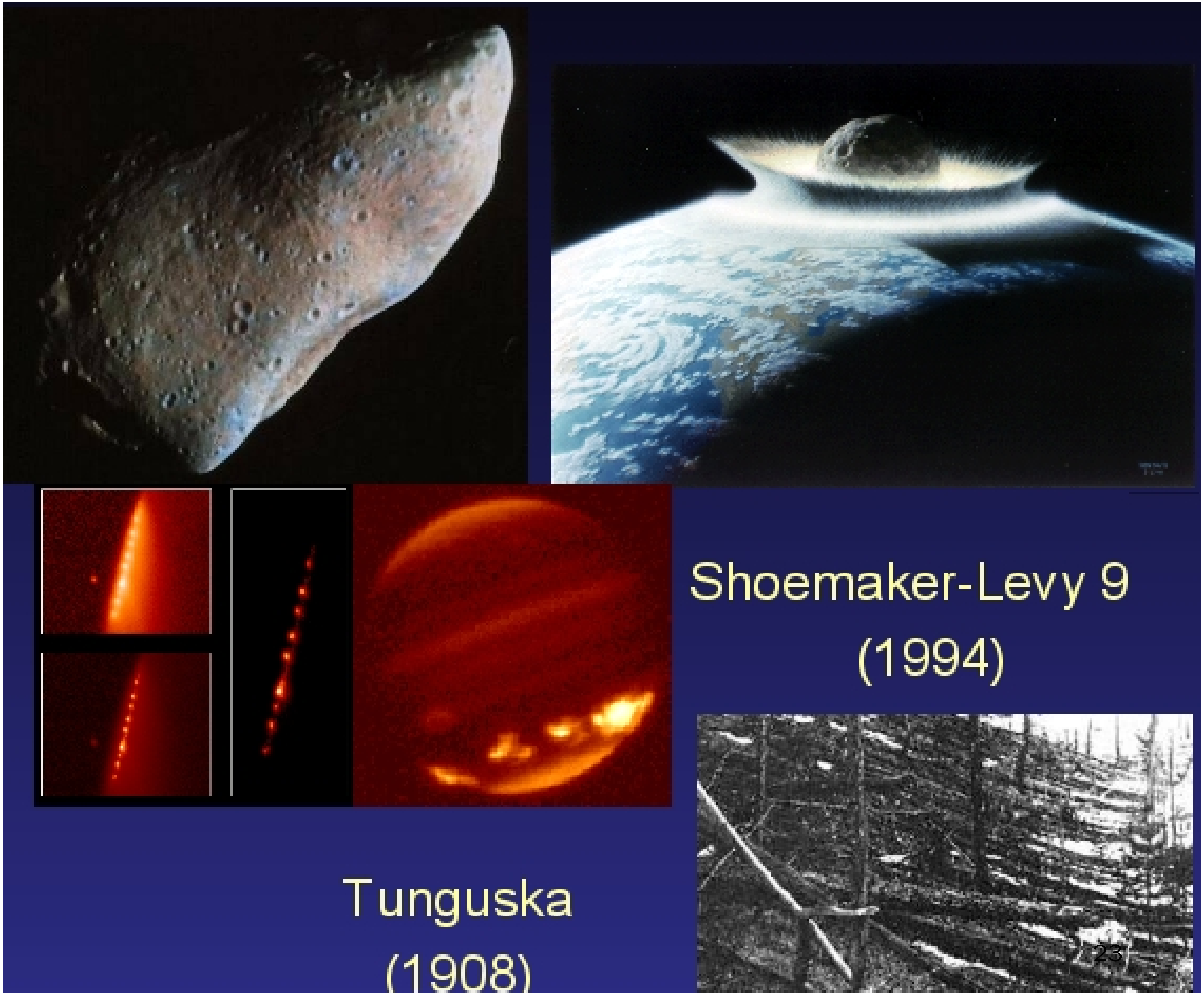
The objectives of the George E. Brown, Jr. NEO Survey Act (Public Law No. 109-155) are to detect, track, catalog, and characterize the physical characteristics of NEOs equal to or larger than 140 meters in diameter with a perihelion distance of less than 1.3 AU (Astronomical Units) from the Sun, achieving 90 percent completion of the survey within 15 years after enactment of the NASA Authorization Act of 2005.

The Act was signed into law by President Bush on December 30, 2005:

NASA should find 90% of 140m or larger NEOs by 2020.

N.B. d(risk)/d(size) decreases below 140m (smaller objects don't make big tsunamis)

Killer Asteroids: they do exist!



Direct implications of the Congressional NEO mandate:

- Telescope Aperture: 140m object size implies r ~25 imaging, to reach r ~25 in 15 sec **need a 10m-class telescope**

- Field of view: in order to cover the sky frequently enough, **need a ~5-10 deg^2 large field of view**, therefore $A\Omega$ product (etendue) needs to be at least several hundred m^{2}deg^2 (also, a large FOV implies a gigapixel-class camera)

- Data Rate: frequent coverage of the whole sky at subarcsec resolution implies **enormous data rates** (e.g. for LSST ~30 TB/night, 60 PB over 10 years)

- Conclusions: A system with an etendue of several hundred m^{2}deg^2 (for SDSS: 6 m^{2}deg^2), with a gigapixel-class camera and a sophisticated and robust data management system, is required to fulfill the Congressional mandate

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

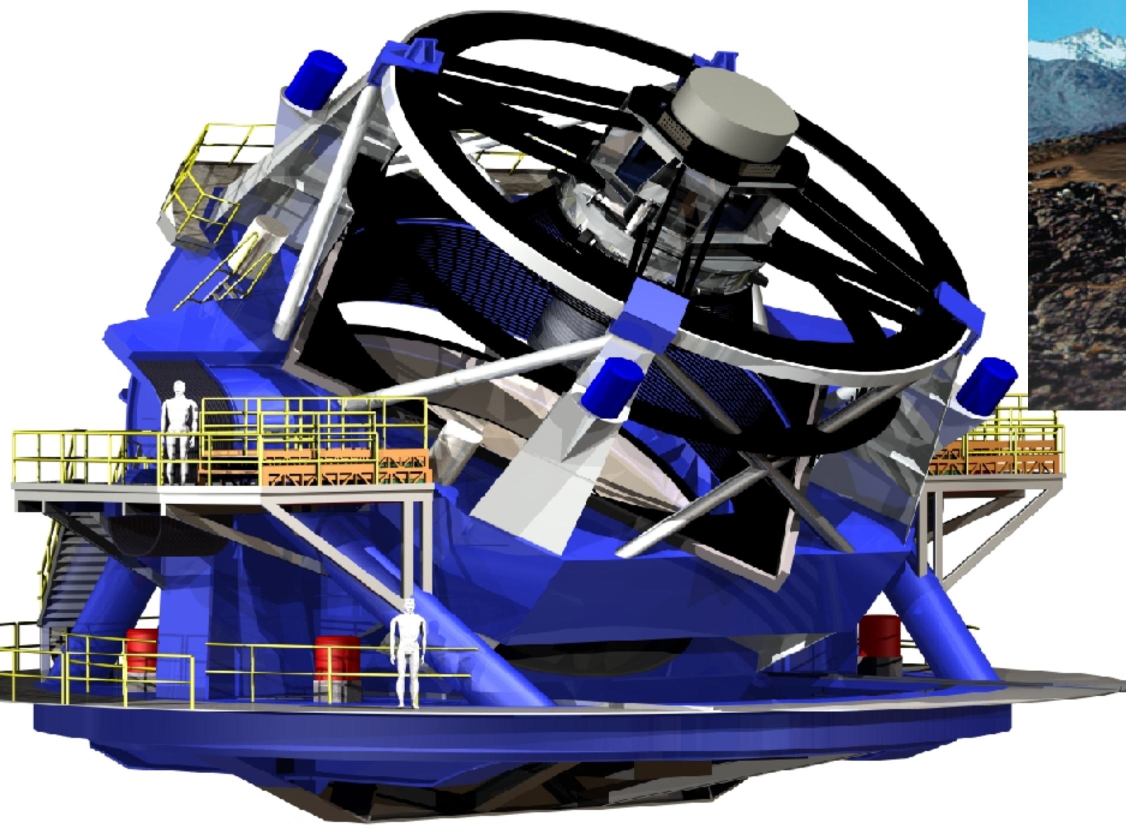
Different science drivers lead to similar system requirements (NEO mandate, main-sequence stars to 100 kpc, weak lensing, SNe,...)

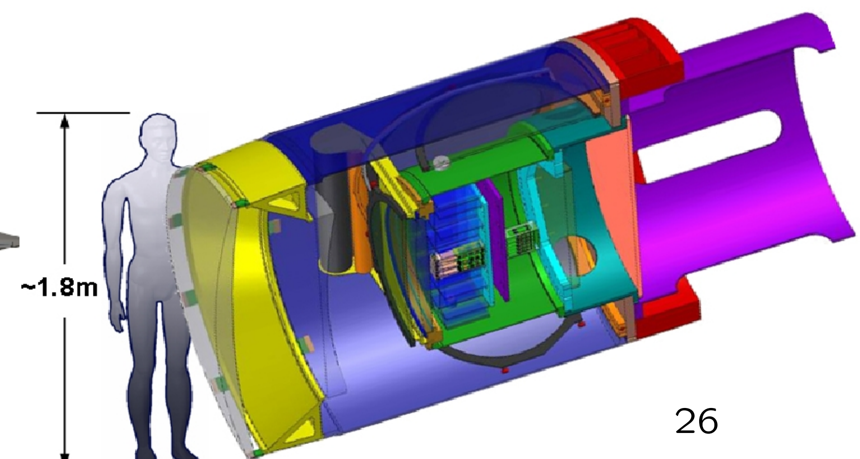
The same dataset serves the majority of science programs and leads to high system efficiency: **SDSS legacy!**

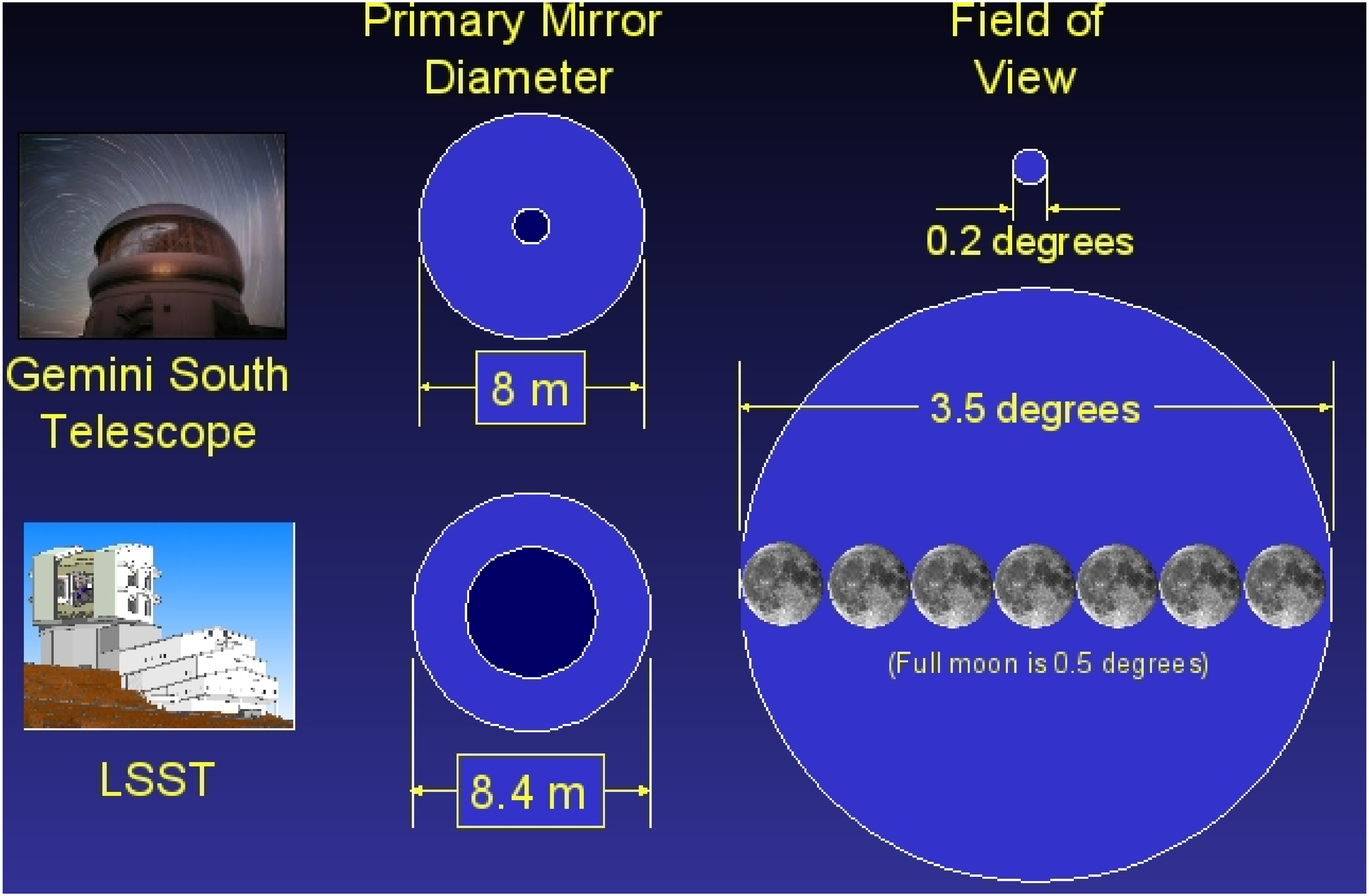
Main LSST Characteristics:

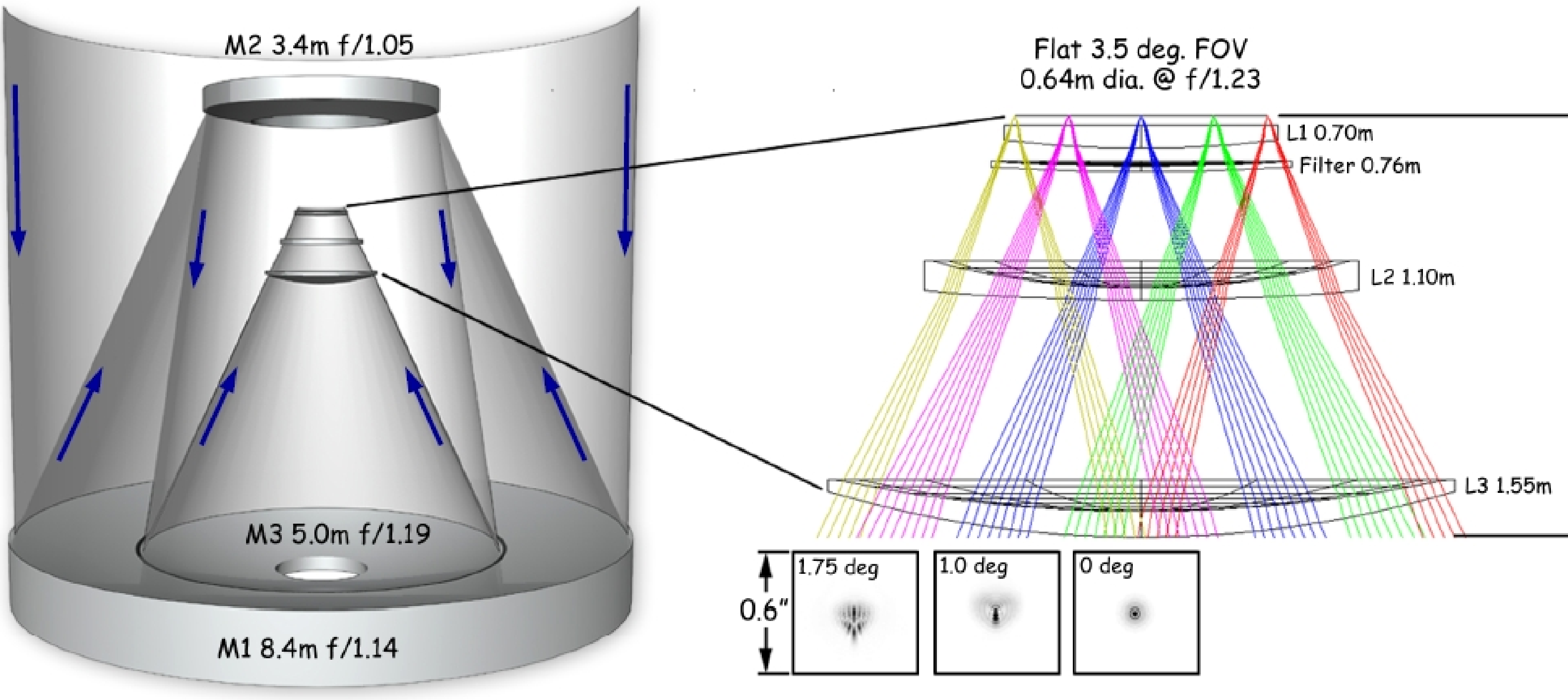
- 8.4m aperture (6.5m effective)
- 3200 Megapix camera
- Sited at Cerro Pachon, Chile
- First light in 2015
- Construction cost: 400 M$ (public-private partnership)

Large Synoptic Survey Telescope

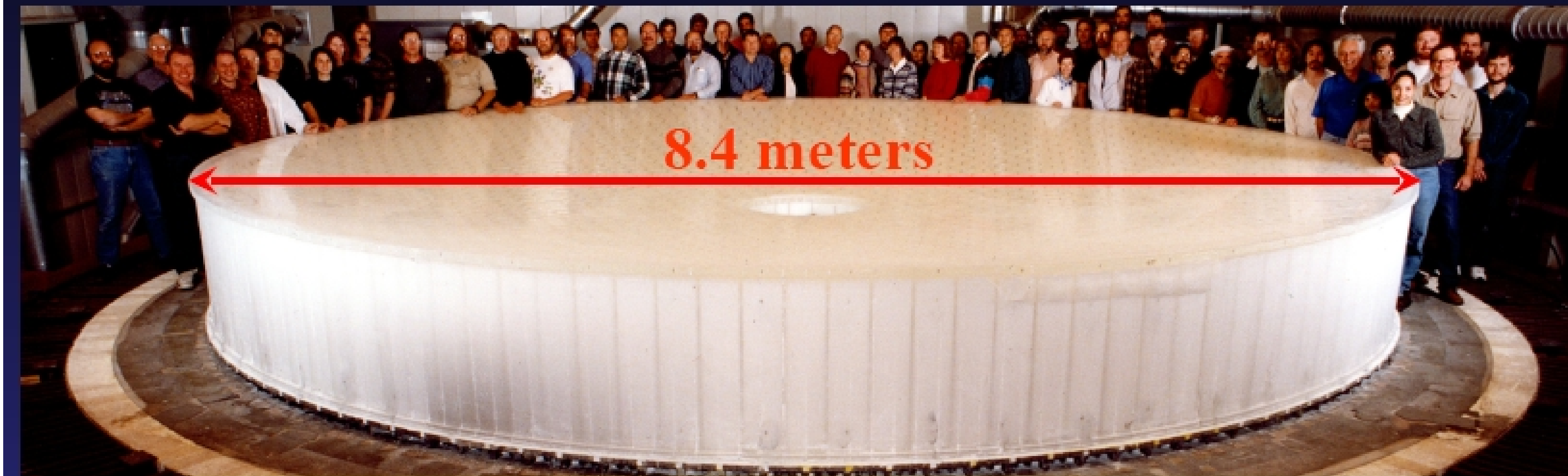


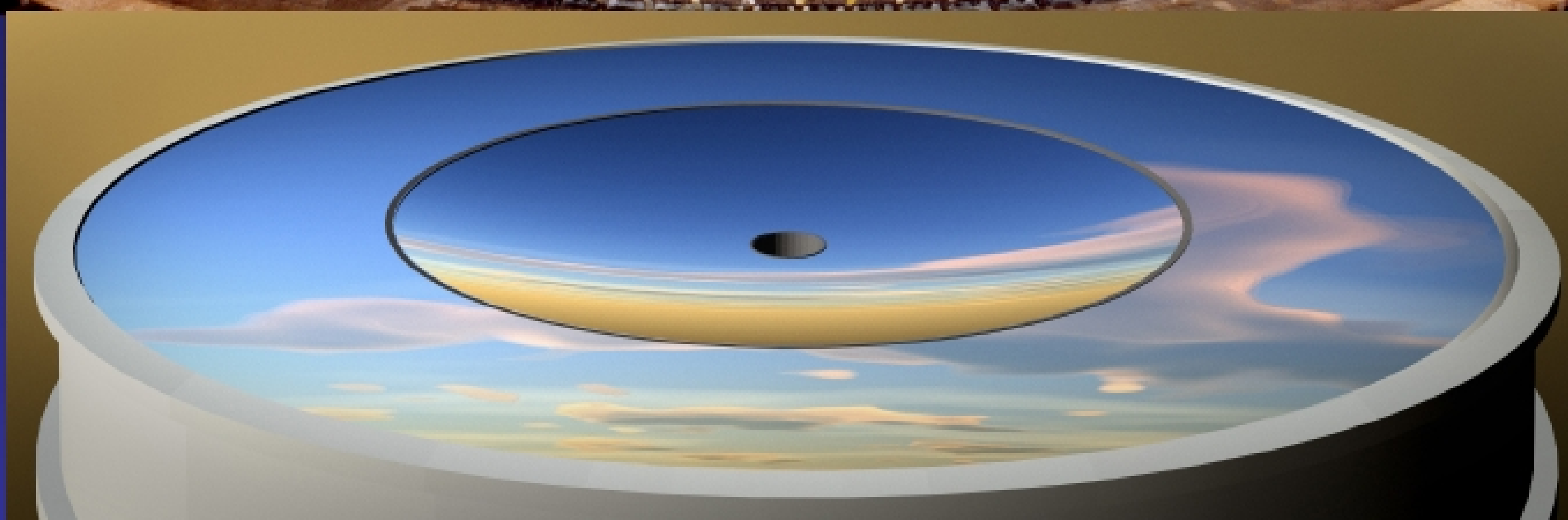



Primary Mirror Diameter
Field of View
Gemini South Telescope
8 m
0.2 degrees
3.5 degrees
LSST
8.4 m
(Full moon is 0.5 degrees)


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

- Very unique monolithic primary mirror has both M1 and M3 surfaces
- Cast borosilicate construction





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

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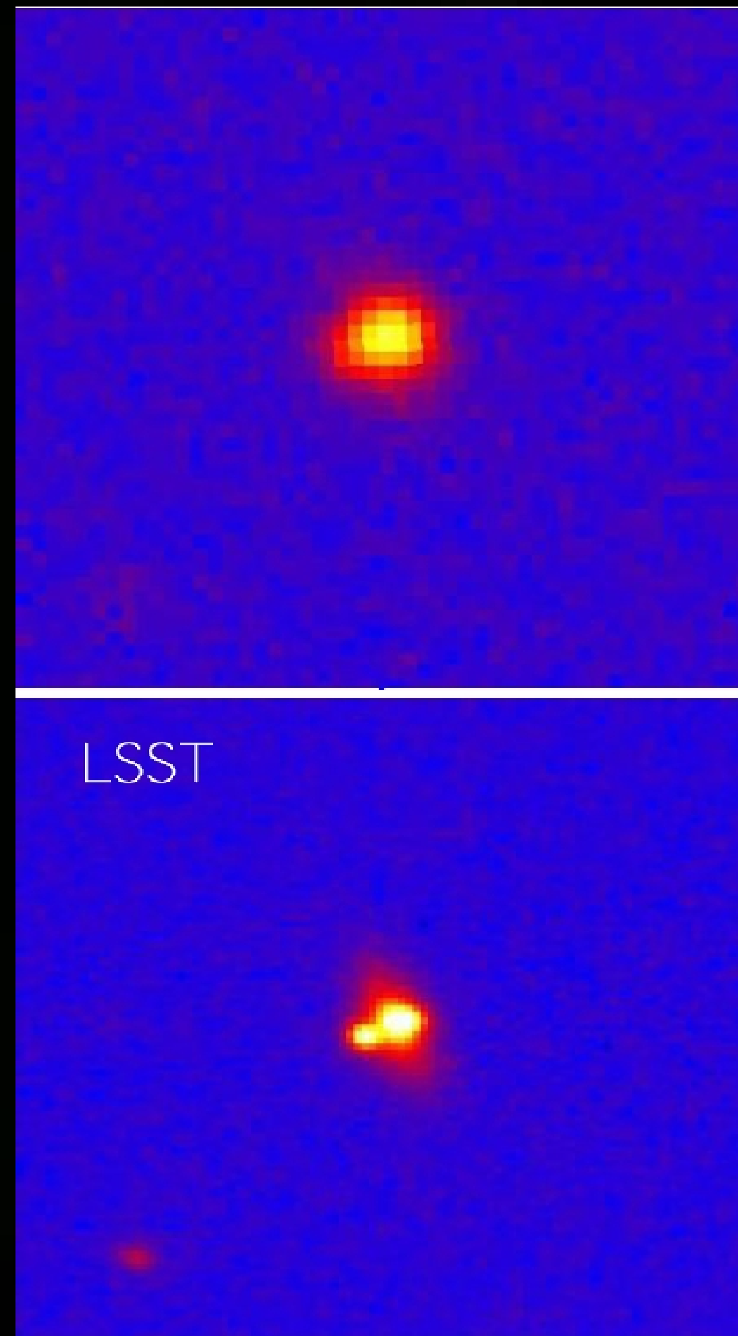
LSST: a digital movie of the sky

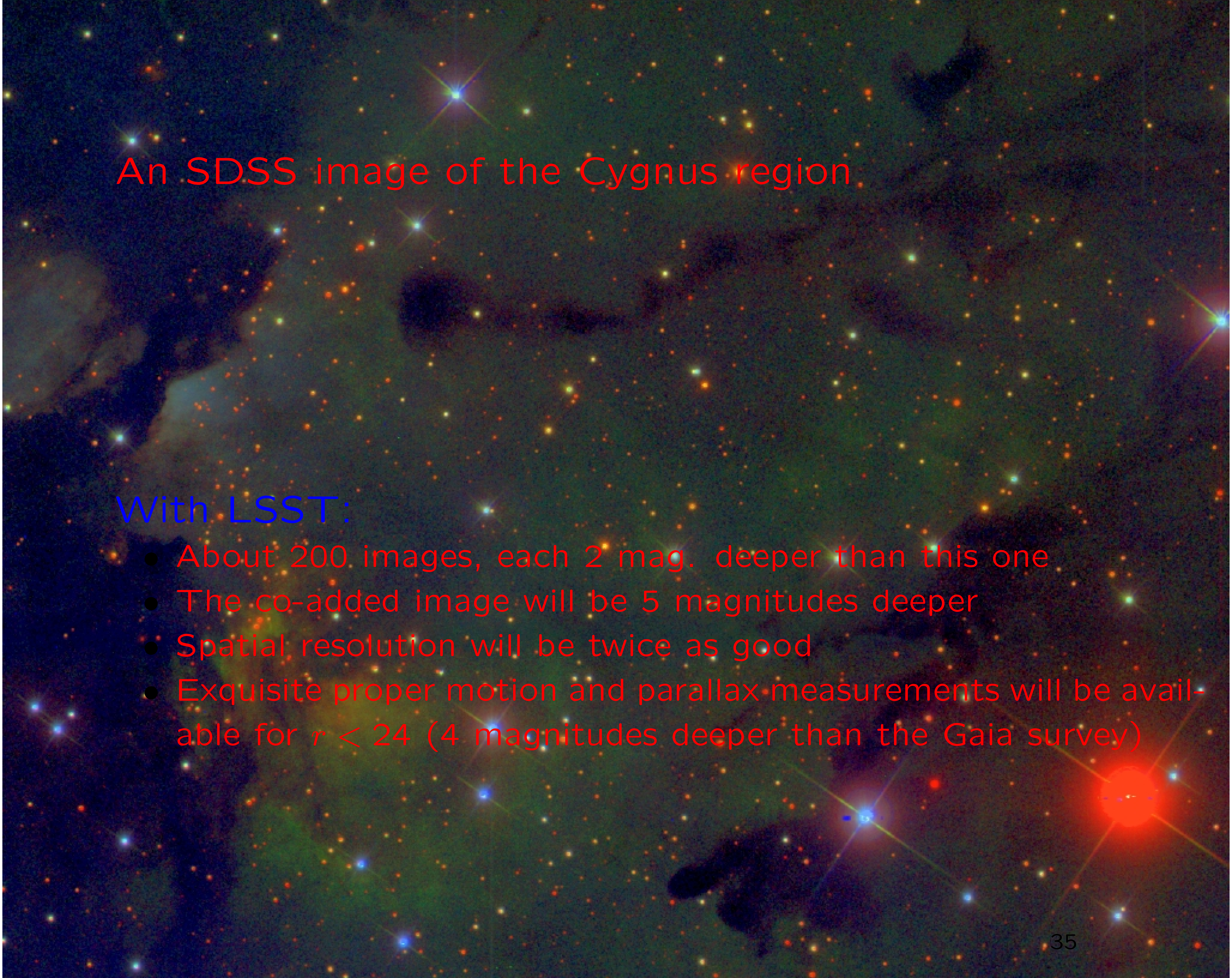
LSST data will immediately become public

(transients within 30 sec)

NB: open call to join LSST Science Collaborations (deadline: Aug 29, 2008!)


LSST

An SDSS image of the Cygnus region

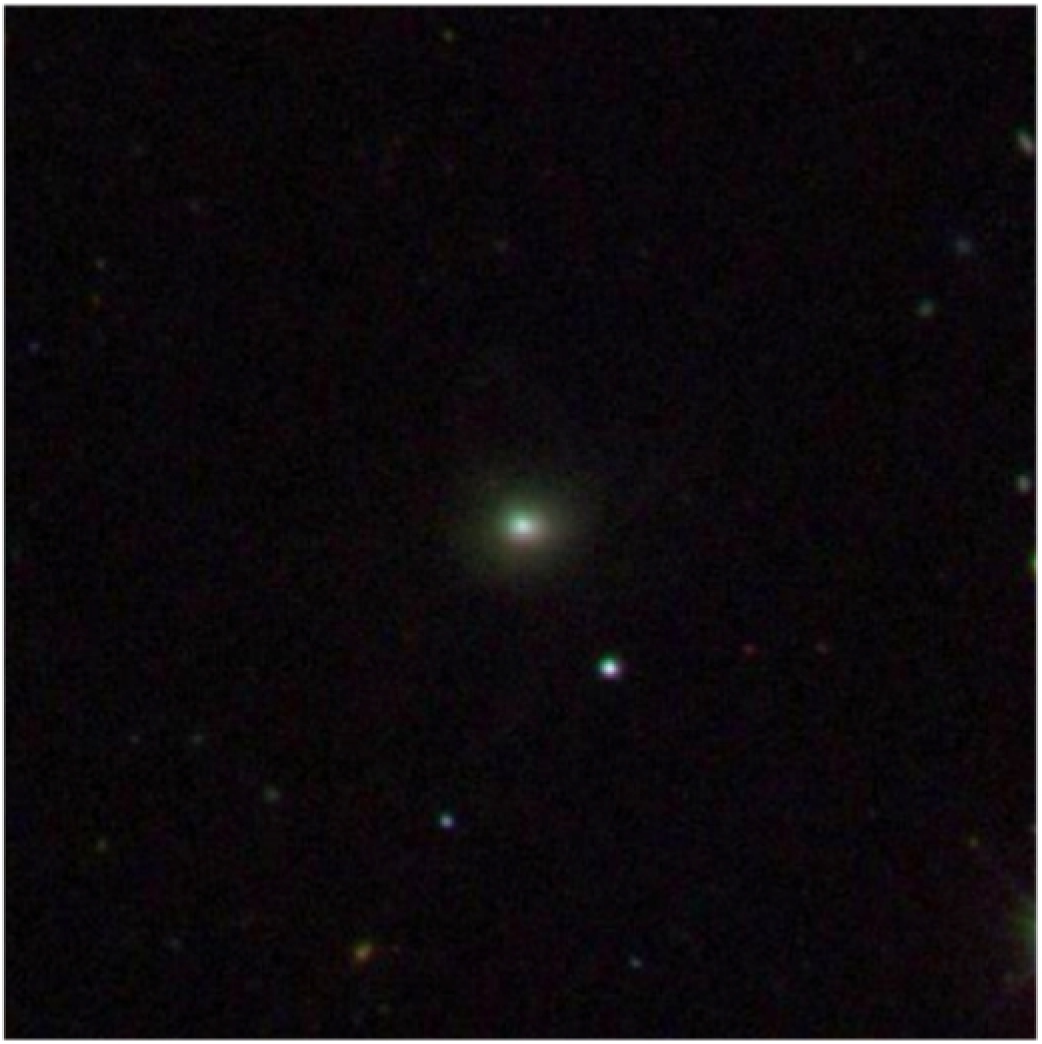


An SDSS image of the Cygnus region

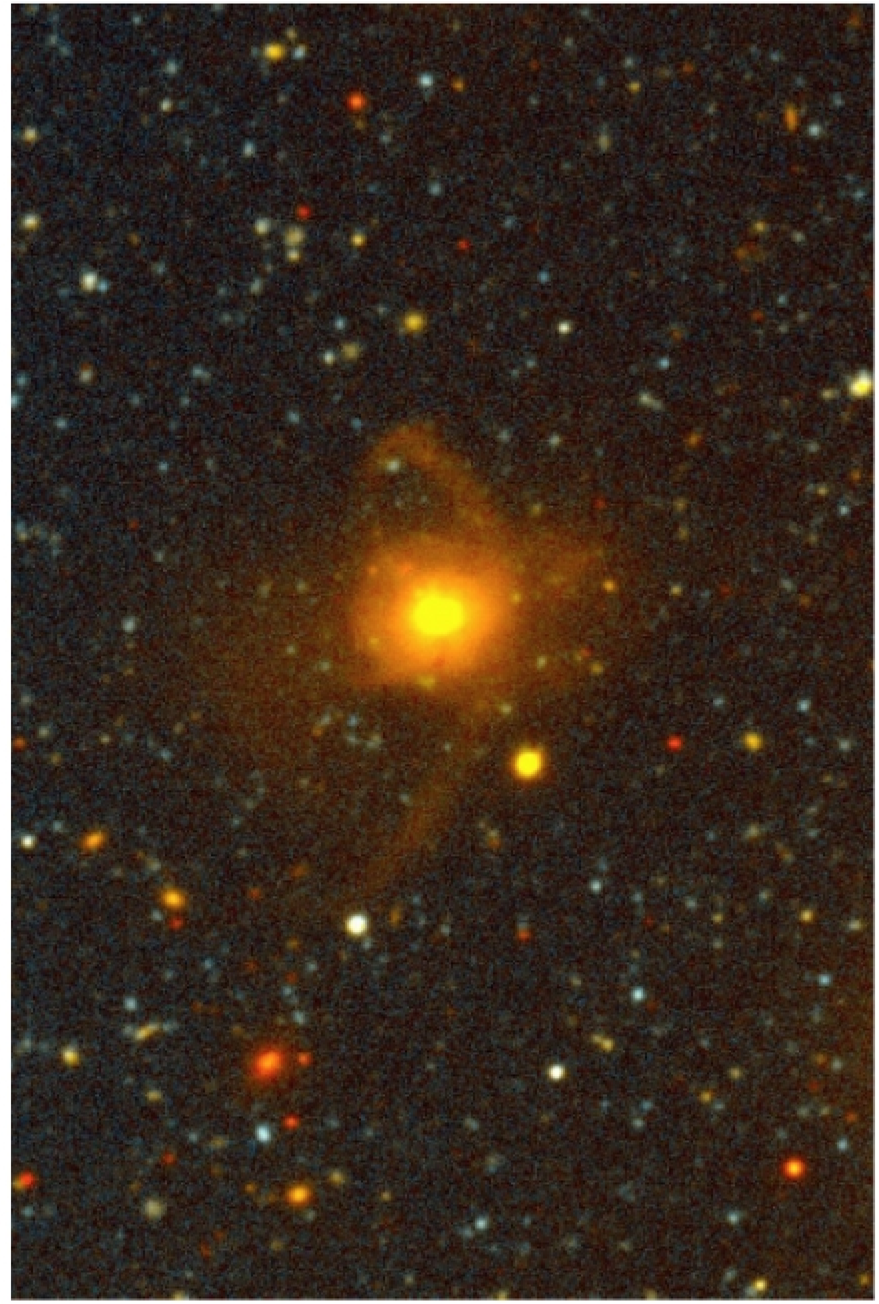
With LSST:

- 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)

SDSS

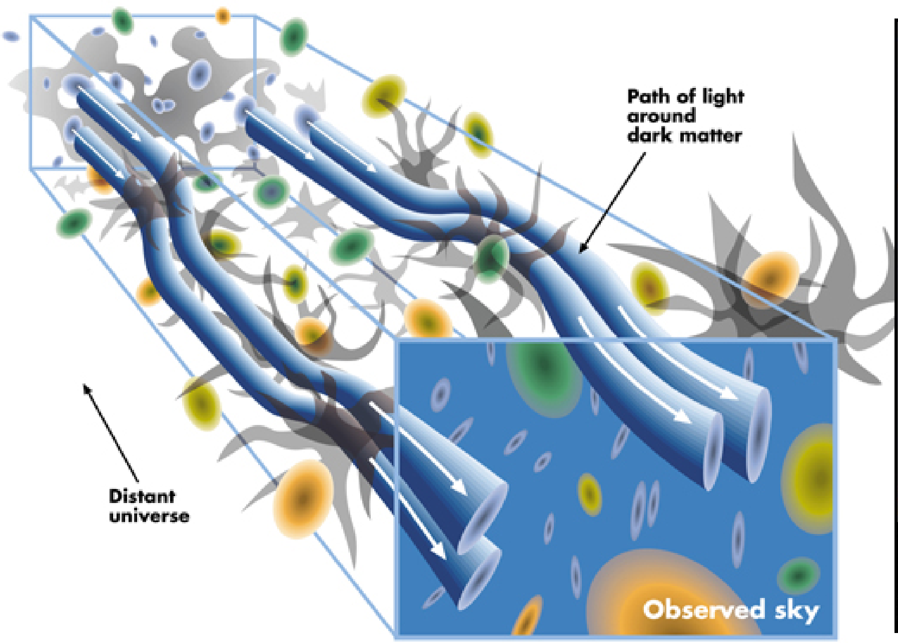


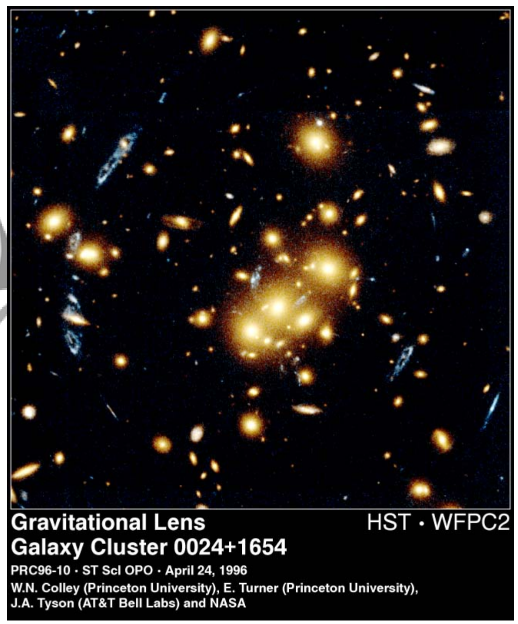
MUSYC

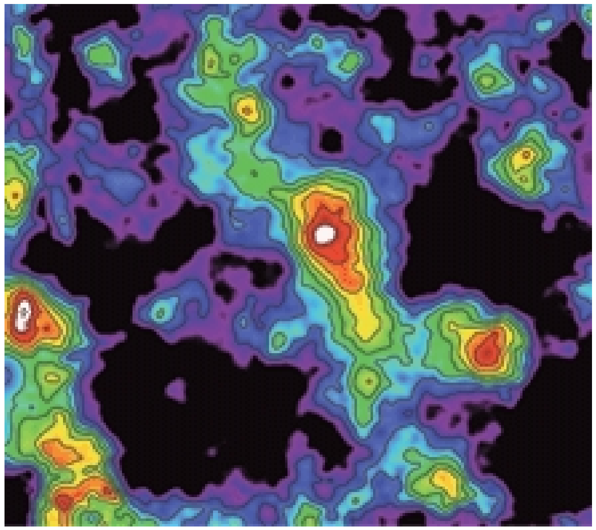


LSST Science Drivers

- 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. **Supernovae:** standard candle
  4. **Baryon Acoustic Oscillations:** standard ruler

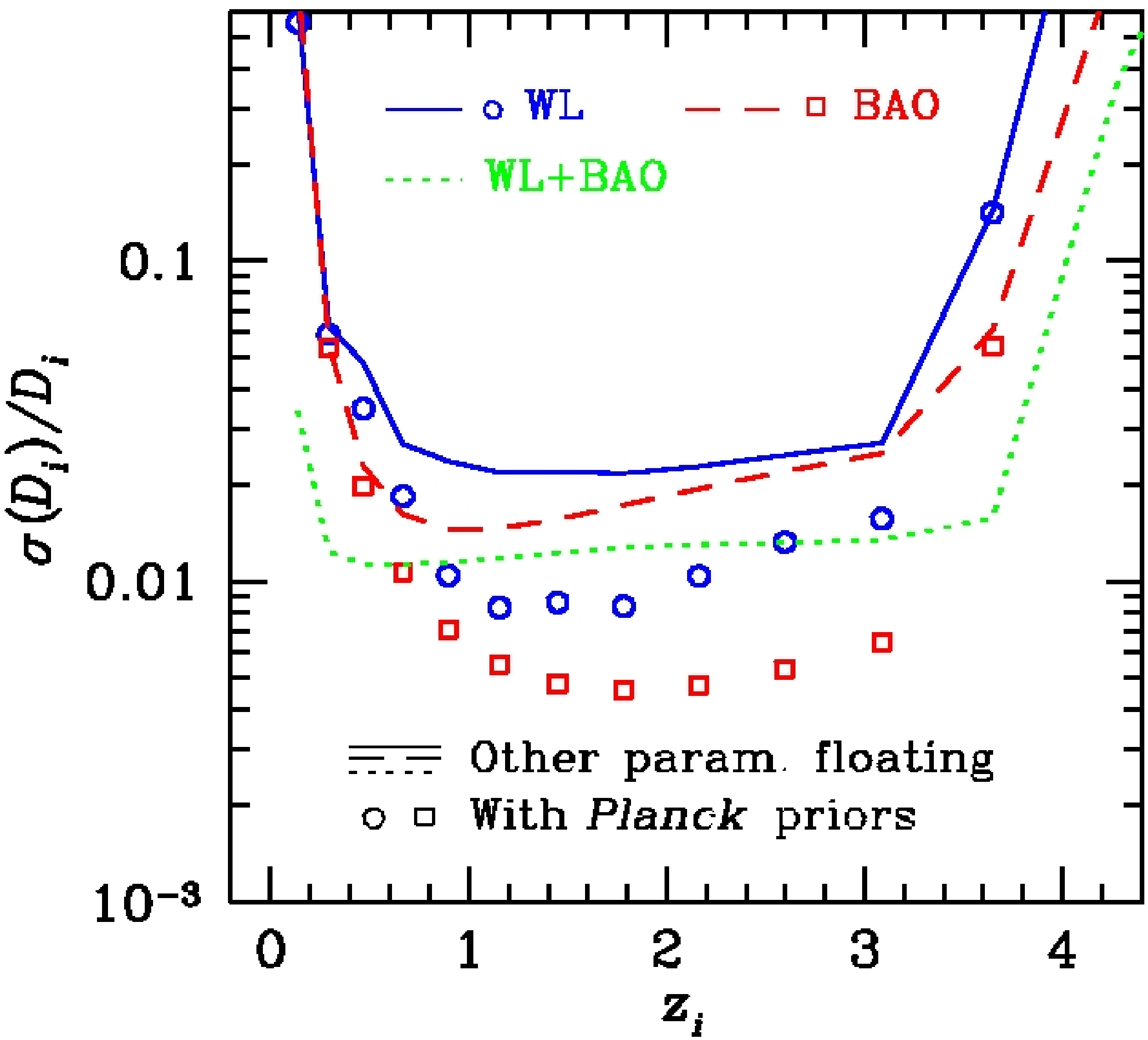






About a hundred-to-thousand-fold increase in precision over precursor experiments: the key is multiple probes!

LSST Science Drivers



(Zhan, Knox & Tyson 2008, in prep) **SDSS-III: 1% at z=0.3,0.6,2.3**

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
- 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)

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

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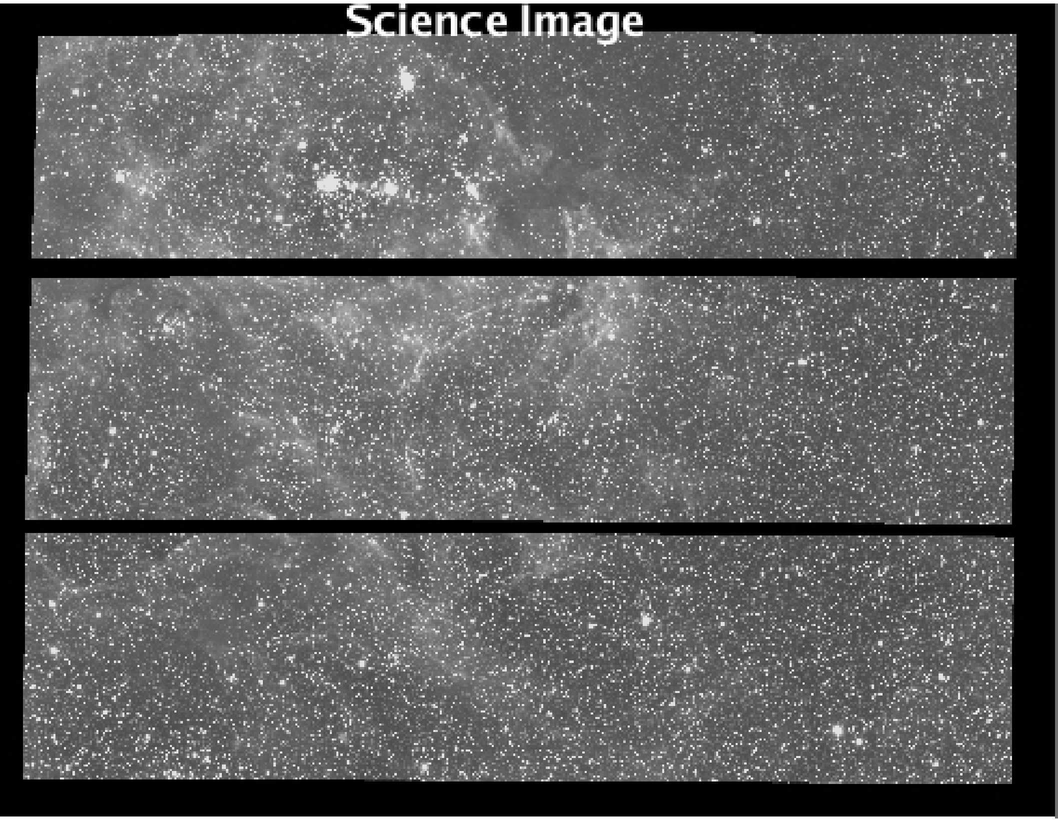
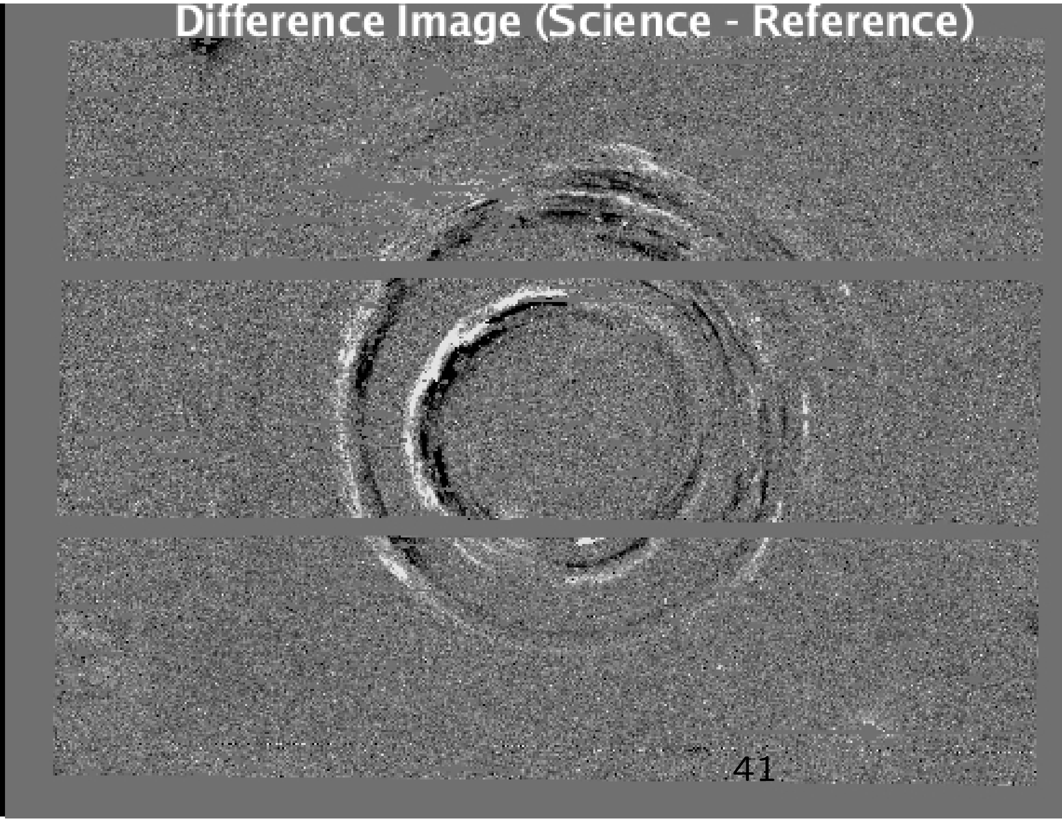
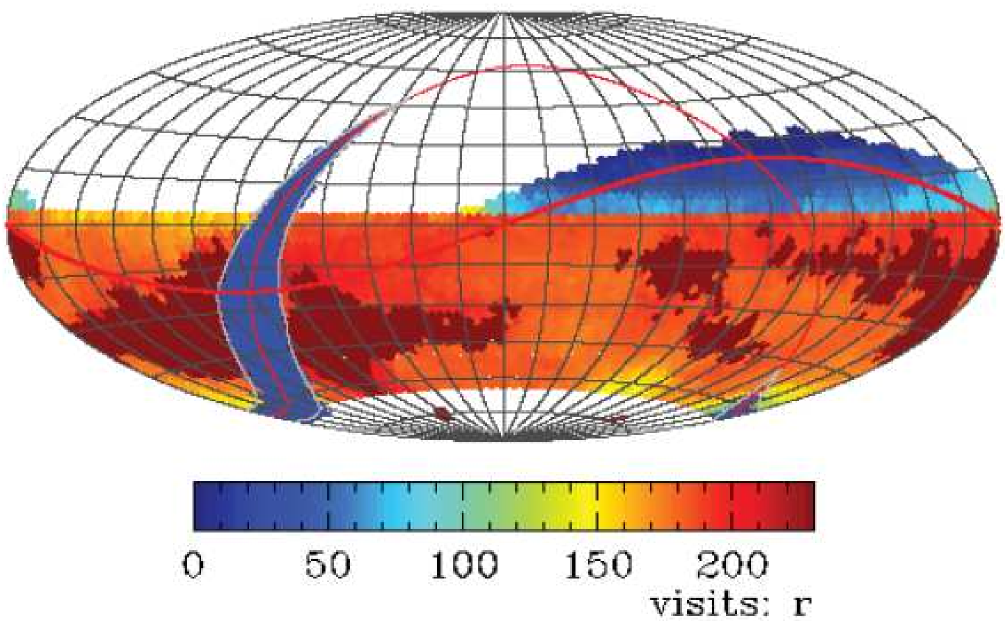
Not only point sources: echo of a supernova explosion (by Andy Becker)

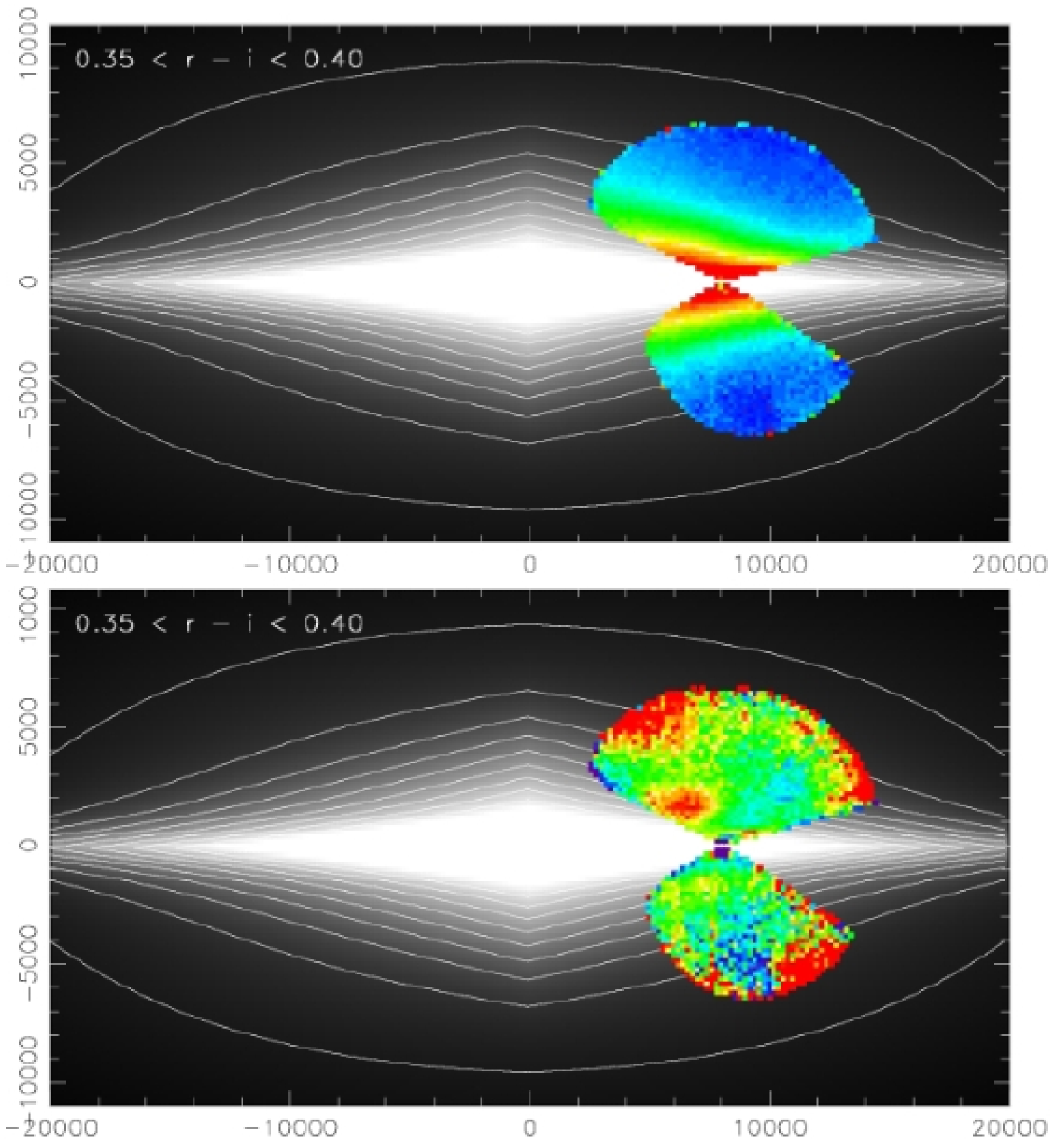




Deciphering the Past

- 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
  - geometric parallaxes for all stars within 500 pc
  - kinematics from proper motions (extending Gaia 4 mag)
  - photometric metallicity (the u band rules!)





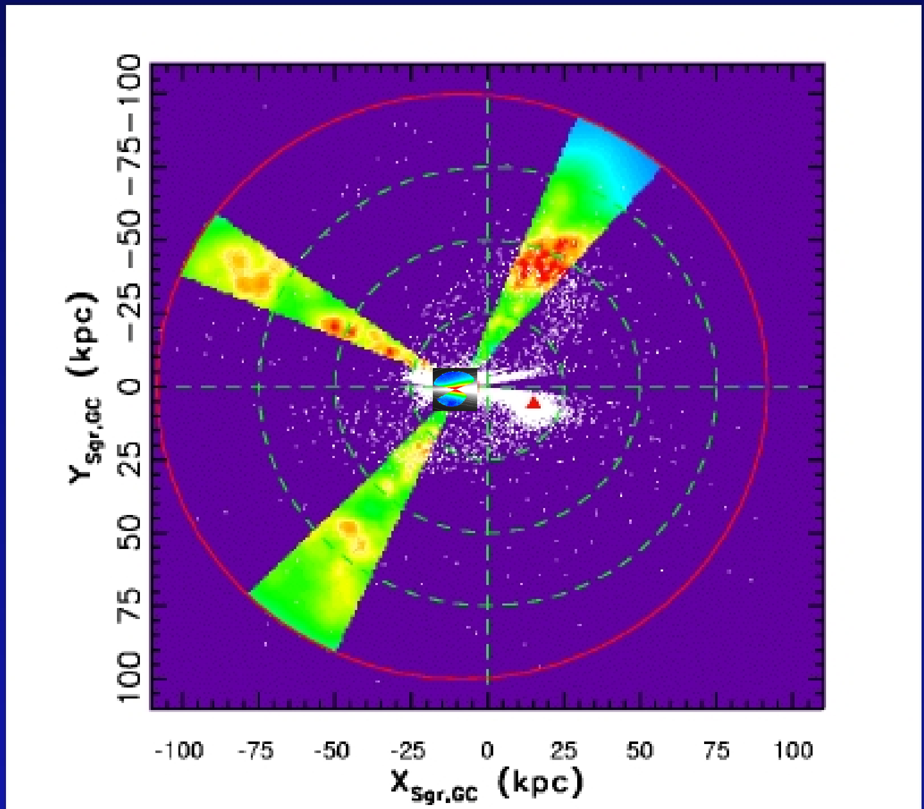
The limitations of SDSS data and LSST

- **Sky Coverage:** "only" ~1/4 of the sky 1/2 of the sky
- **Depth:** main-sequence stars to ~10 kpc; RR Lyrae stars to 100 kpc 100 and 400 kpc
- **Photometric Accuracy:** ~0.02 mag for the u band, limits the accuracy of photometric metallicity estimates to ~0.2 dex 0.01 mag and 0.1 dex
- **Astrometric Accuracy:** the use of POSS astrometry (accurate to ~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

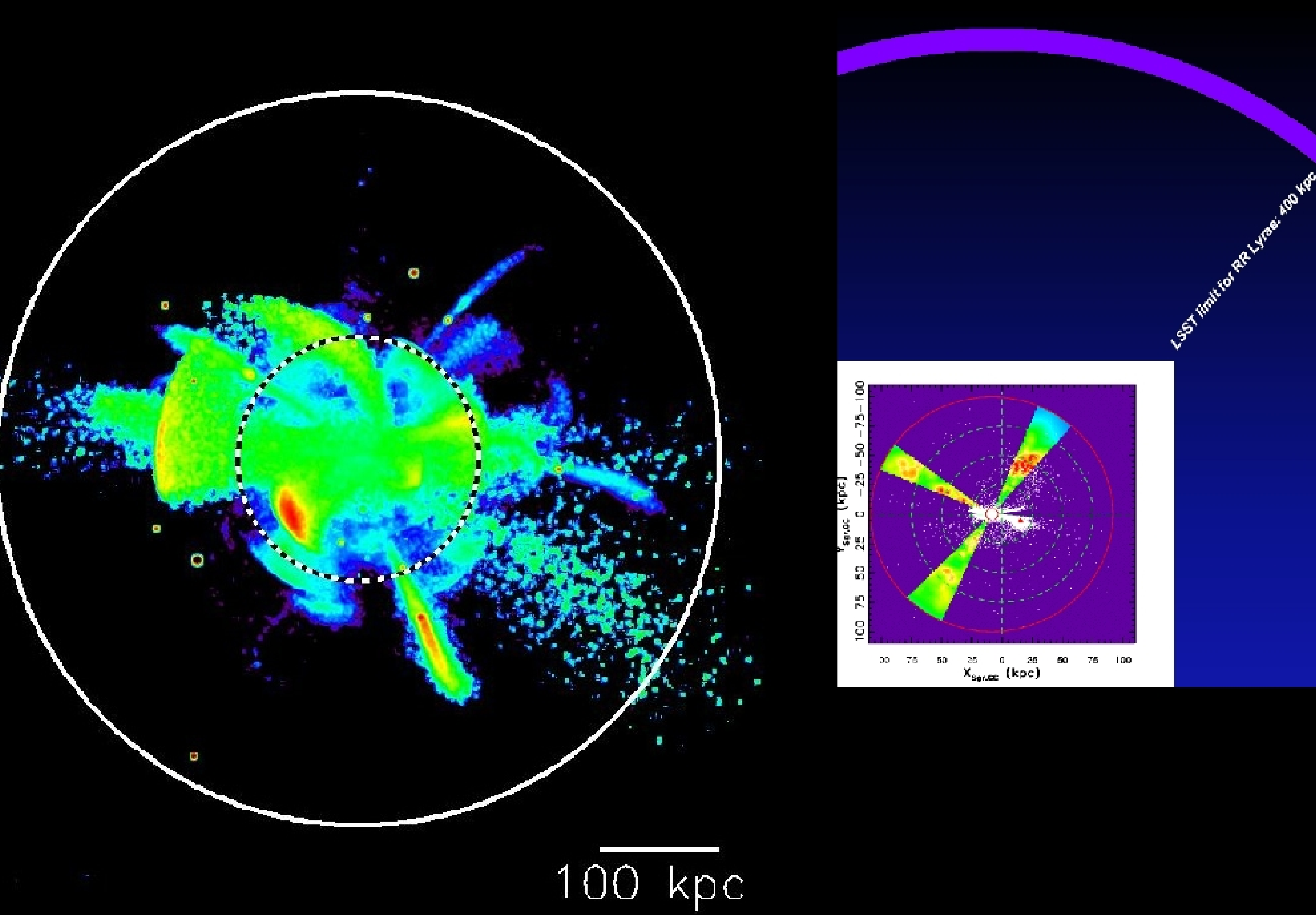
The large blue circle: the ~400 kpc limit of future LSST studies based on RR Lyrae

LSST limit for RR Lyrae: 400 kpc

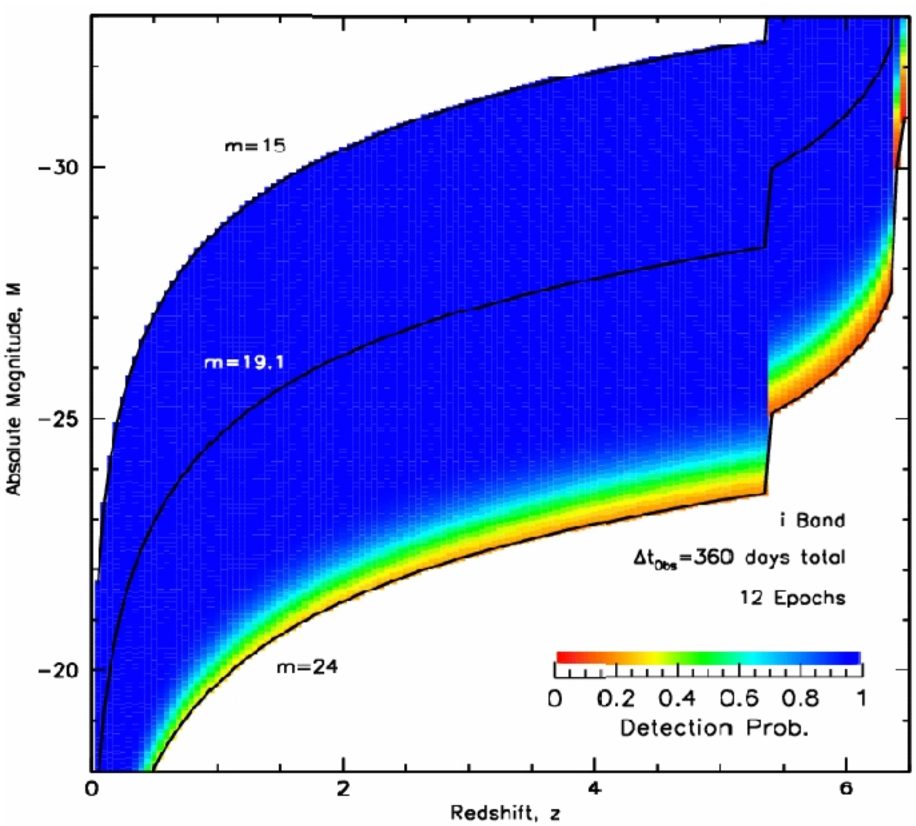
The large red circle: the ~100 kpc limit of future LSST studies based on main-sequence stars (and the current limit for RR Lyrae studies)



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

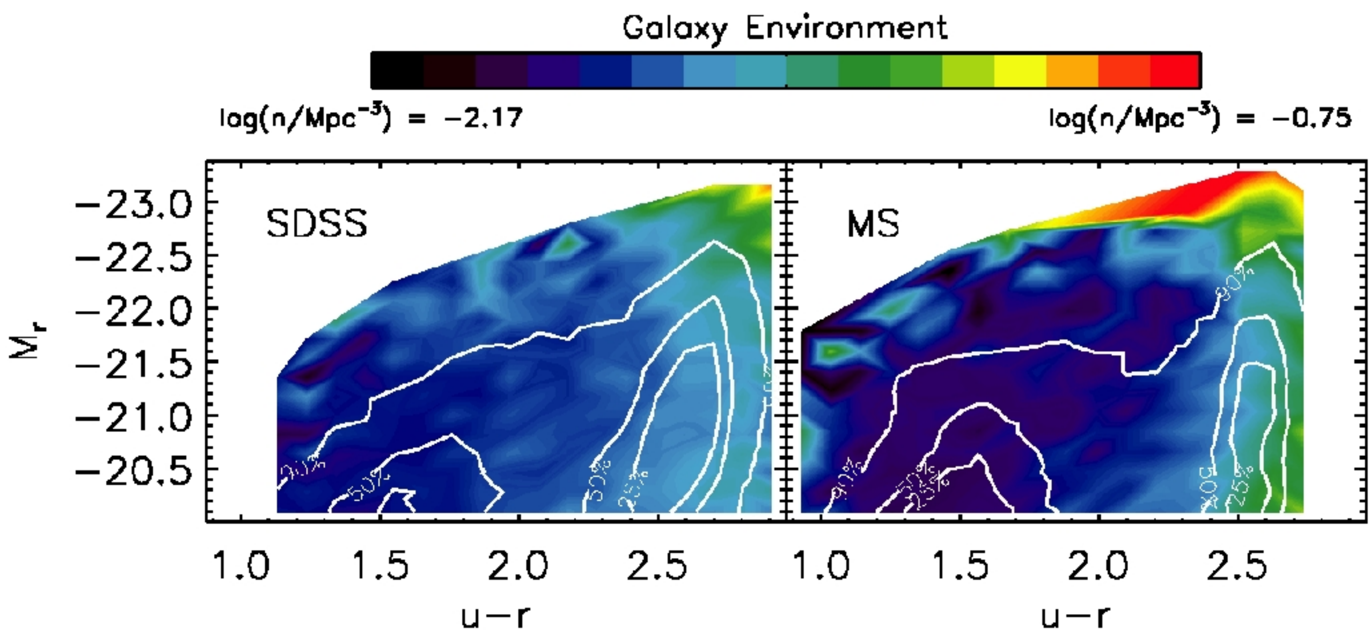


Left: Models (Bullock & Johnston) **Right:** SDSS and 2MASS observations, and predictions for LSST



"Other" 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 $i < 25$)



If you liked SDSS, you'll love LSST:

- **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. (it's so cool to be an astronomer!)

For more details: astro-ph/0805.2366