Reaching for the sky with SDSS and LSST

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Sky surveying is experiencing a bonanza as detectors, telescopes and computers become ever more powerful. Using SDSS to illustrate what will be possible with LSST: data-intensive astronomy

1. **Modern Sky Surveys: Lessons from SDSS**

2. **LSST: the System Parameters and Science Drivers**

3. **Three Science Examples from SDSS**

   - **Solar System Inventory:** main-belt asteroids
   - **Time-domain astronomy:** quasar variability
   - **Milky Way Structure:** mapping with main sequence and RR Lyrae stars

The Era of Massive Optical Surveys

- Currently, the best large-area optical survey is SDSS: **the first digital color map of the sky**
- **Lessons from SDSS:** uniform surveys yield diverse and cutting-edge science (>2000 papers from SDSS in <10 years) in a cost-efficient way; public data access leads to democratization and globalization of science

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- LSST: about 100 times more surveying power than SDSS

What will LSST do?
the first digital color movie of the sky

SDSS results can be used to "predict" the impact of LSST: three case studies a bit later...

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 (6.7m effective), $\sim$10 deg^2 FOV
- 3200 Megapix camera (20 TB, or one SDSS, per night)
- Sited at Cerro Pachon, Chile
- First light in 2016 (Decadal Survey Report 2010!)
- Construction cost: 455 M$ (public-private partnership)

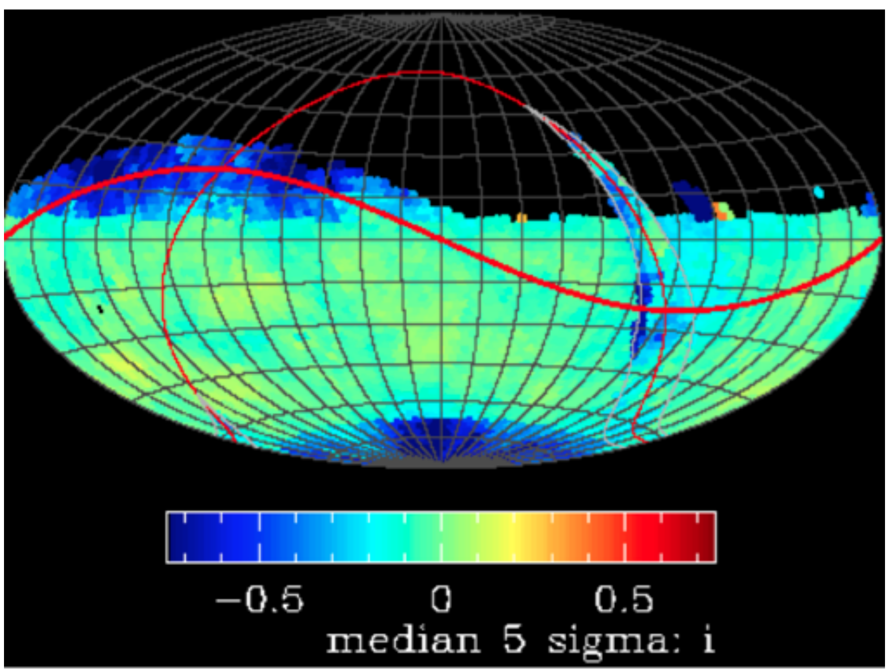
And also to the same observing strategy (cadence):

a homogeneuos dataset will utilize 90% of observing time and serve the majority of science programs (with a high system efficiency)

What is LSST:

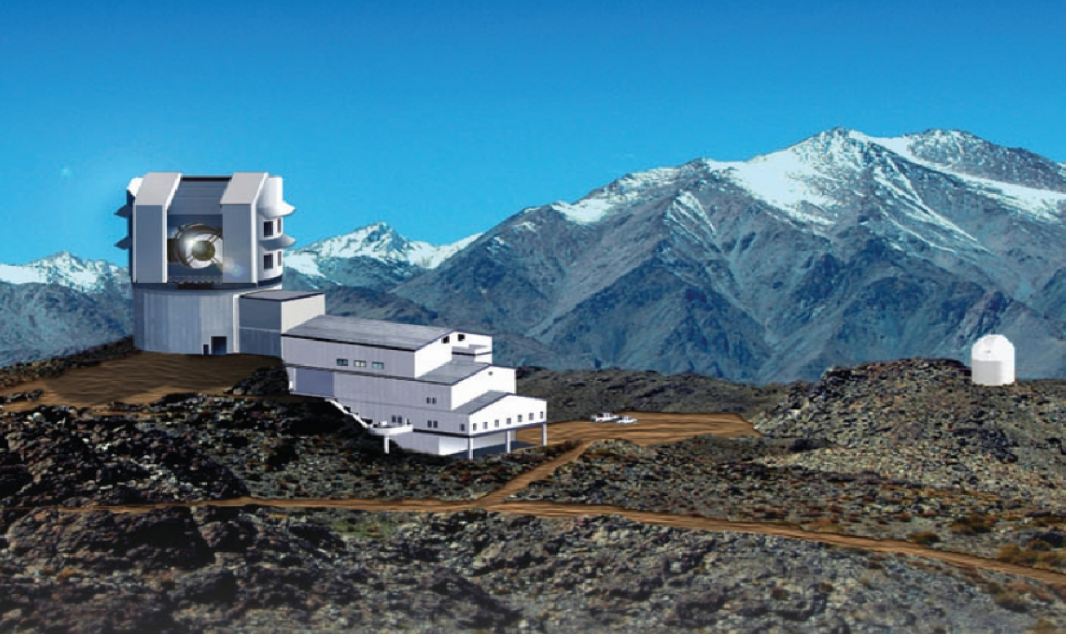
an optical/near-IR survey of half the sky in multiple bands (ugrizy) to r =27.5 based on about 1000 visits over a ten-year period:

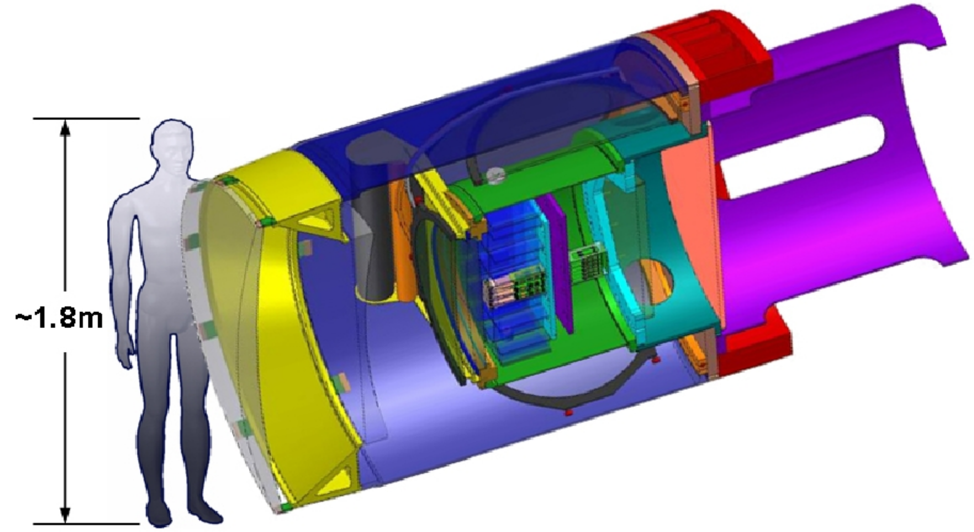
a catalog of ∼10 billion stars and ∼10 billion galaxies with exquisite photometry, astrometry and image quality

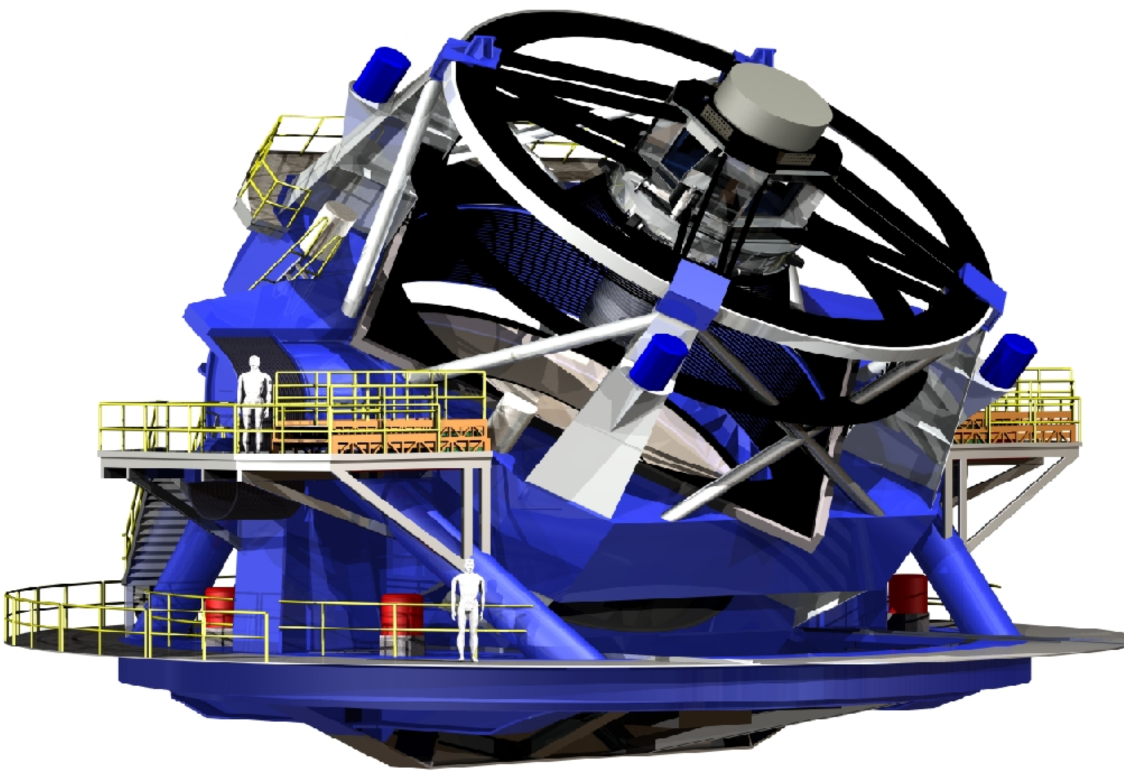


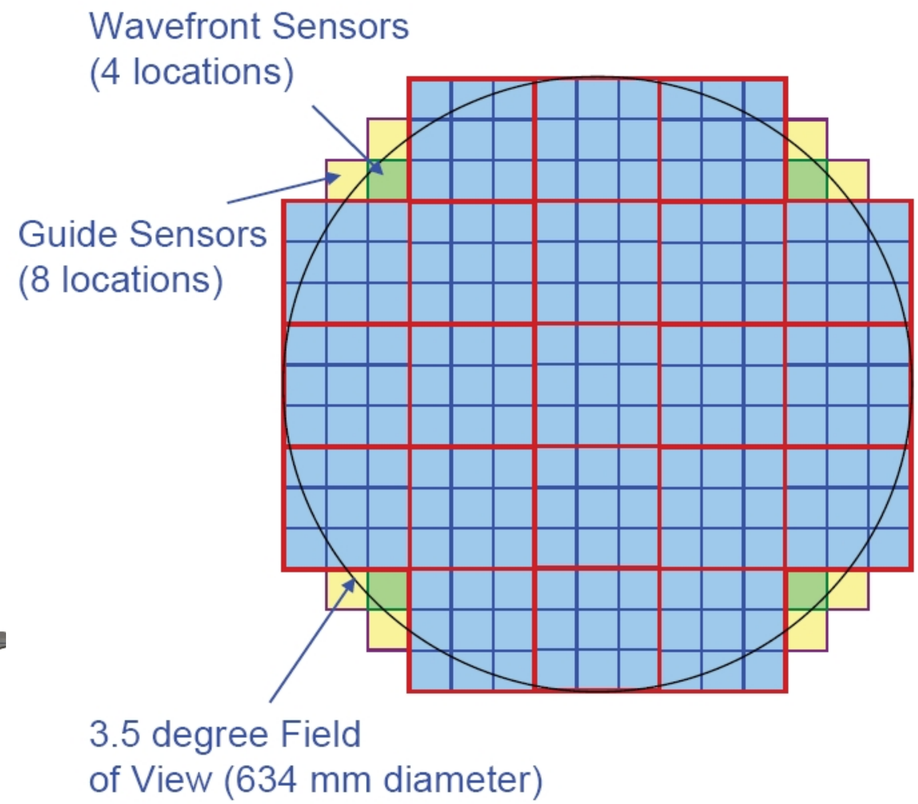
Selected Science Goals

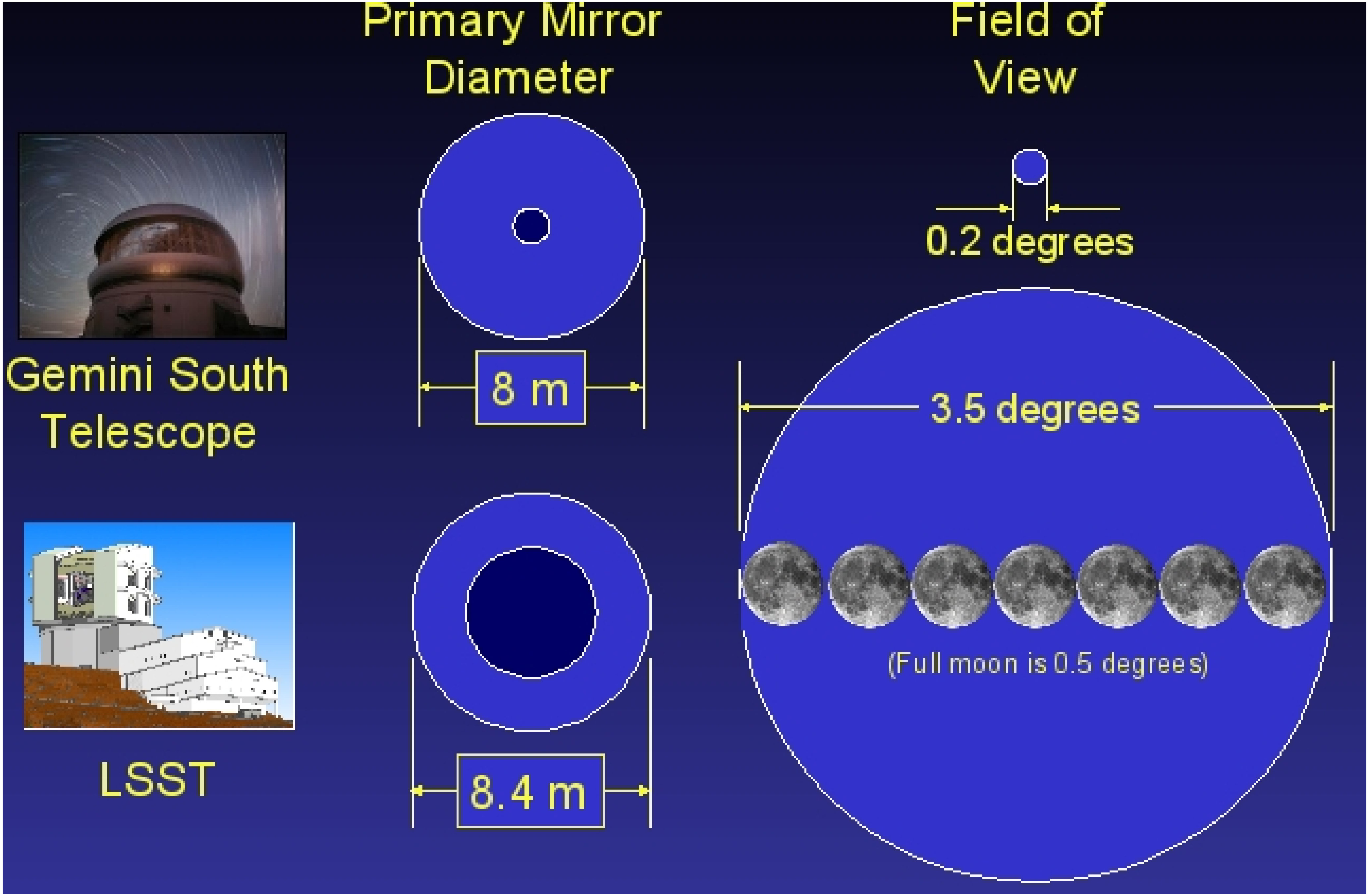
- Dark Energy and Dark Matter (**four billion galaxies** with excellent photometry and shape measurements, several million SNe, clusters of galaxies, millions of quasars)
- The Solar System Map (140m killer asteroids, several 10^6 main-belt, ∼100,000 trans-Neptunian, Sedna-like to beyond 200 AU)
- The Transient Universe (a variety of time scales ranging from ∼10 sec, to the whole sky every 3 nights, 1000 visits)
- The Milky Way Map (main sequence to 100 kpc, RR Lyrae to 400 kpc, geometric parallaxes for all stars within 300 pc)



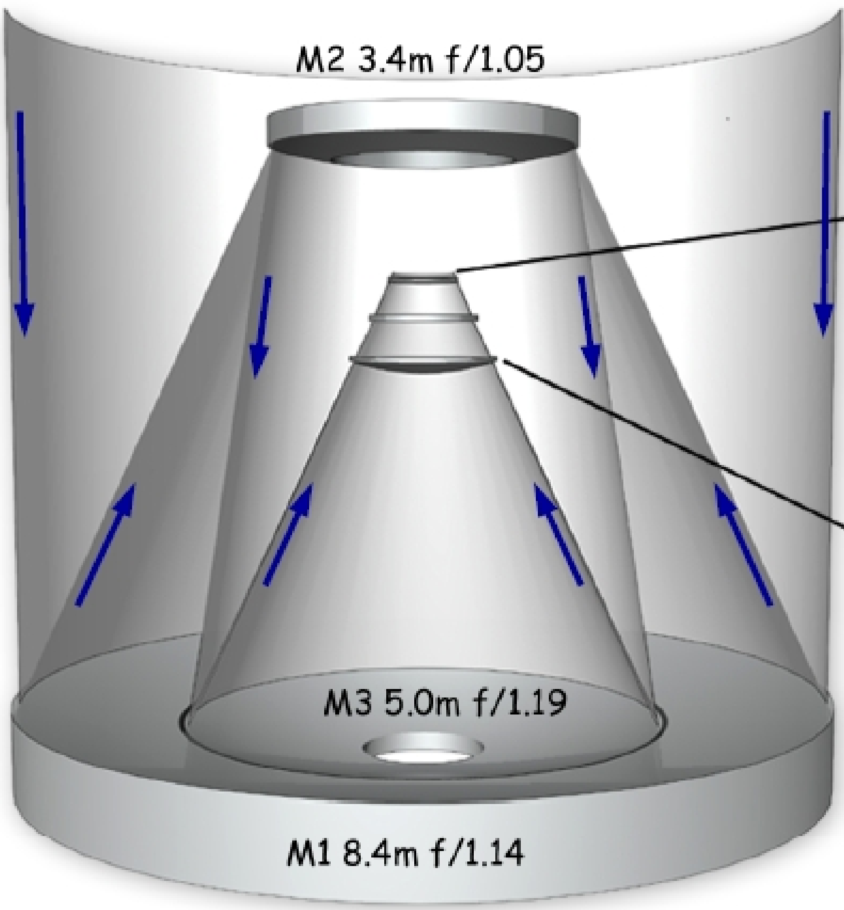

~1.8m

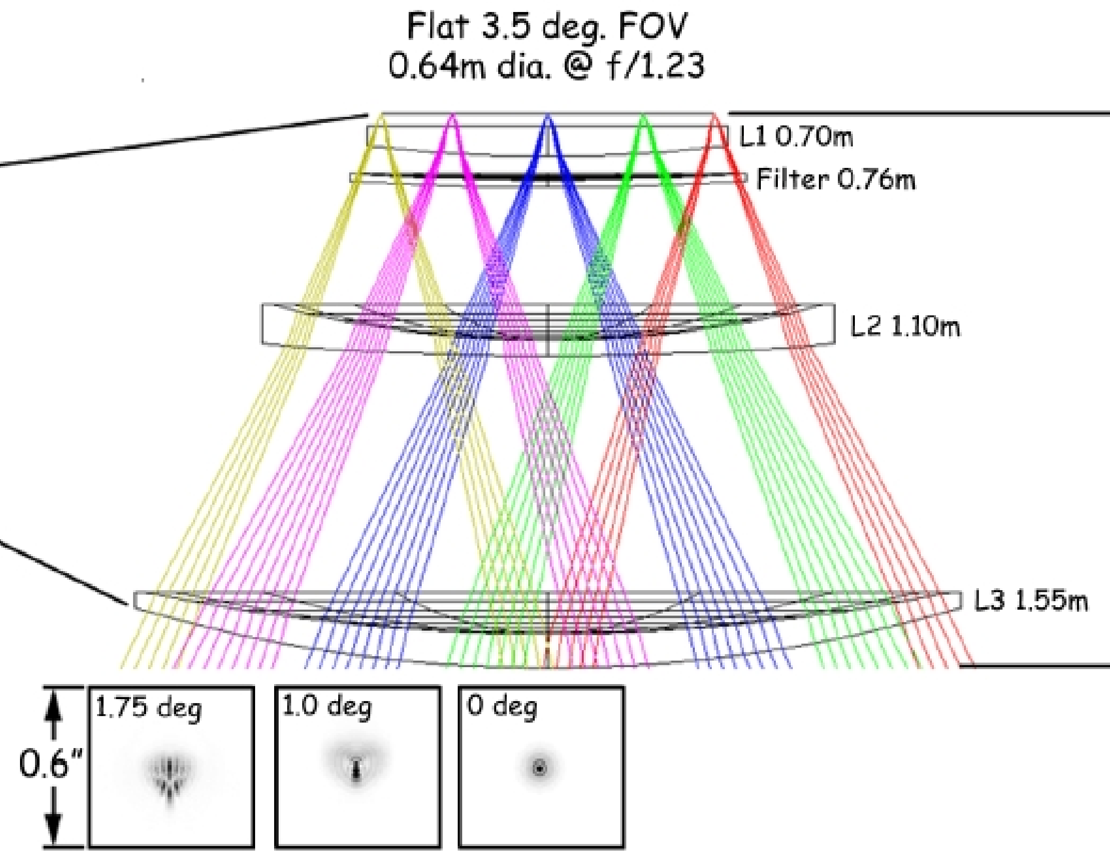



Wavefront Sensors
(4 locations)
Guide Sensors
(8 locations)
3.5 degree Field
of View (634 mm diameter)



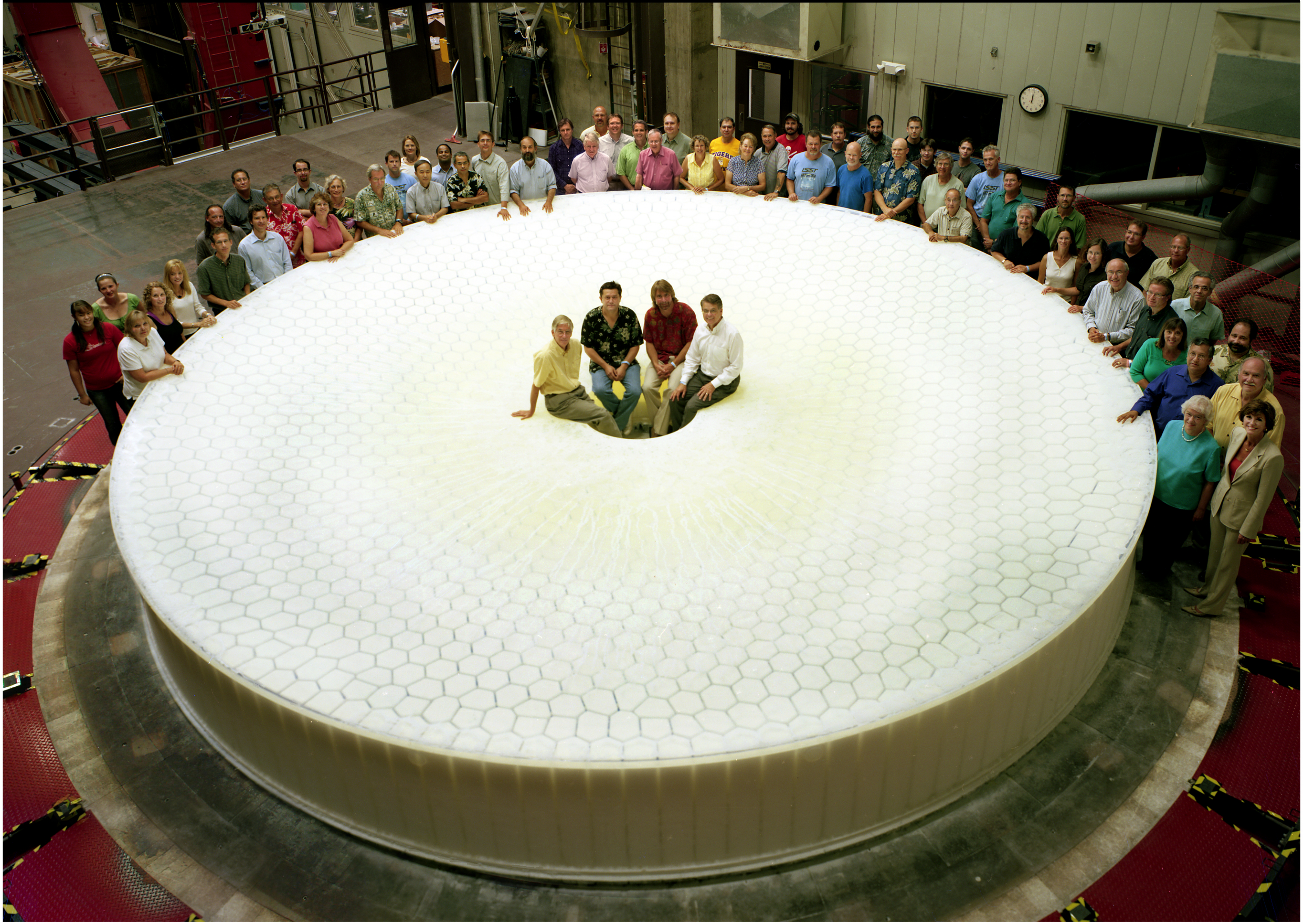
Primary Mirror Diameter
Field of View
Gemini South Telescope
8 m
0.2 degrees
LSST
8.4 m
3.5 degrees
(Full moon is 0.5 degrees)


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

LSST

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

LSST vs. SDSS comparison

Currently, the best large-area faint optical survey is

SDSS: the first digital map of the sky

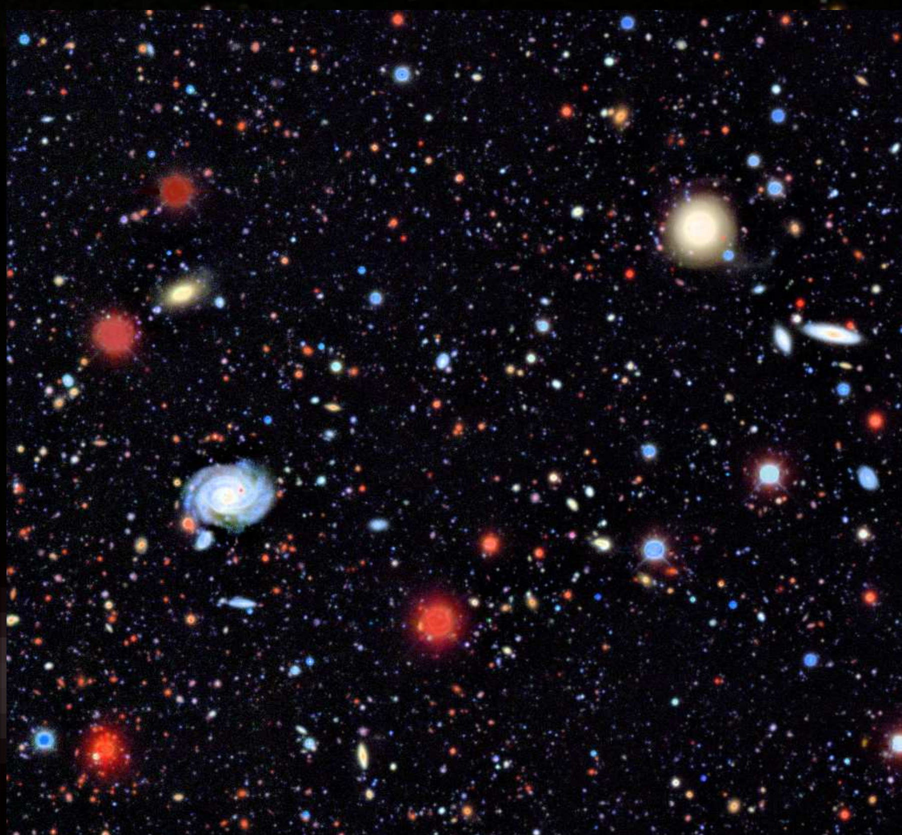
r$\sim$22.5, 1-2 visits, 300 million objects

- 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

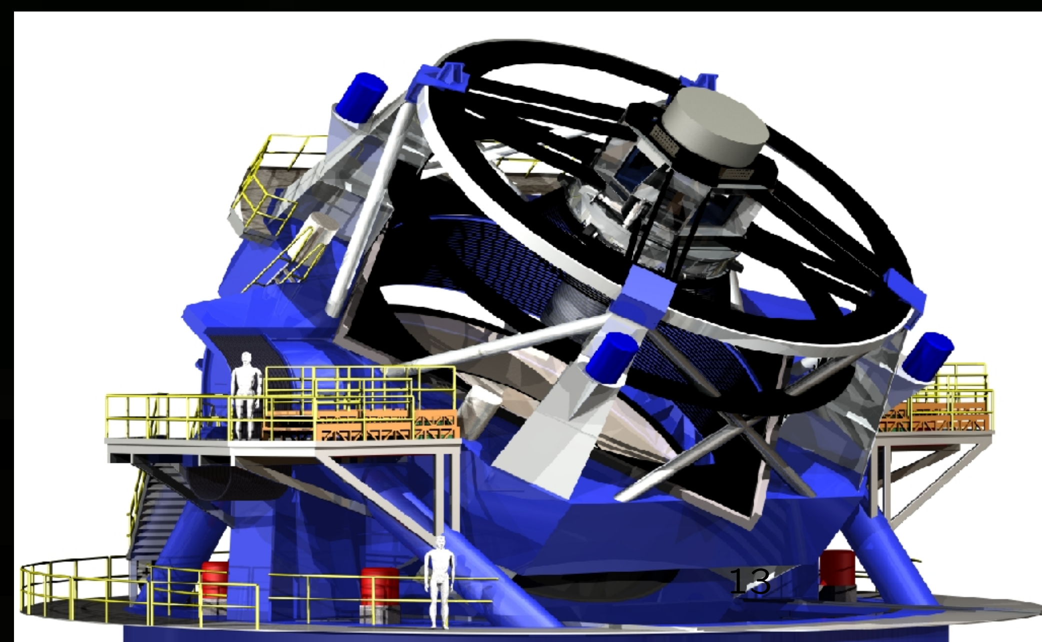
LSST: a digital movie of the sky

LSST data will immediately become public
(transients within 60 sec)

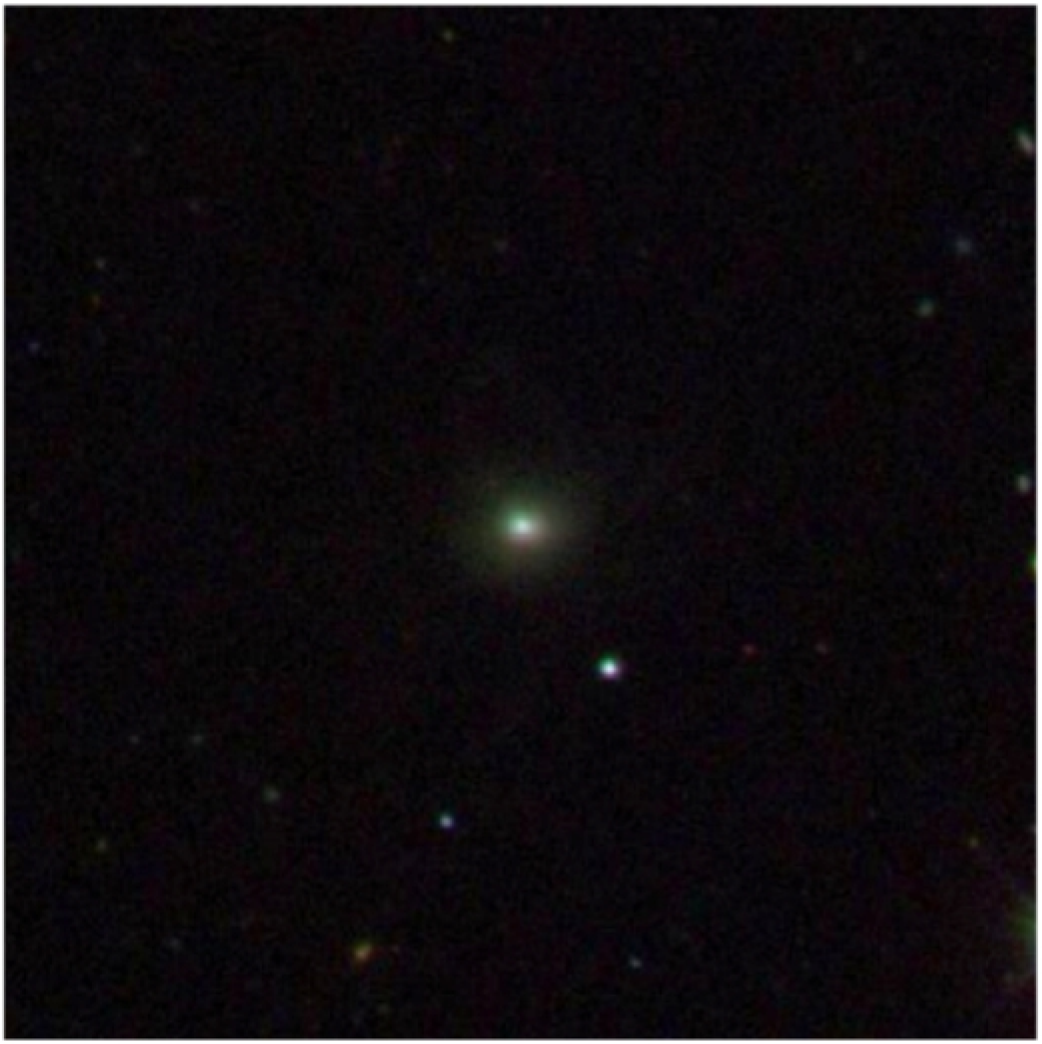


SDSS: one US Library of Congress worth of data

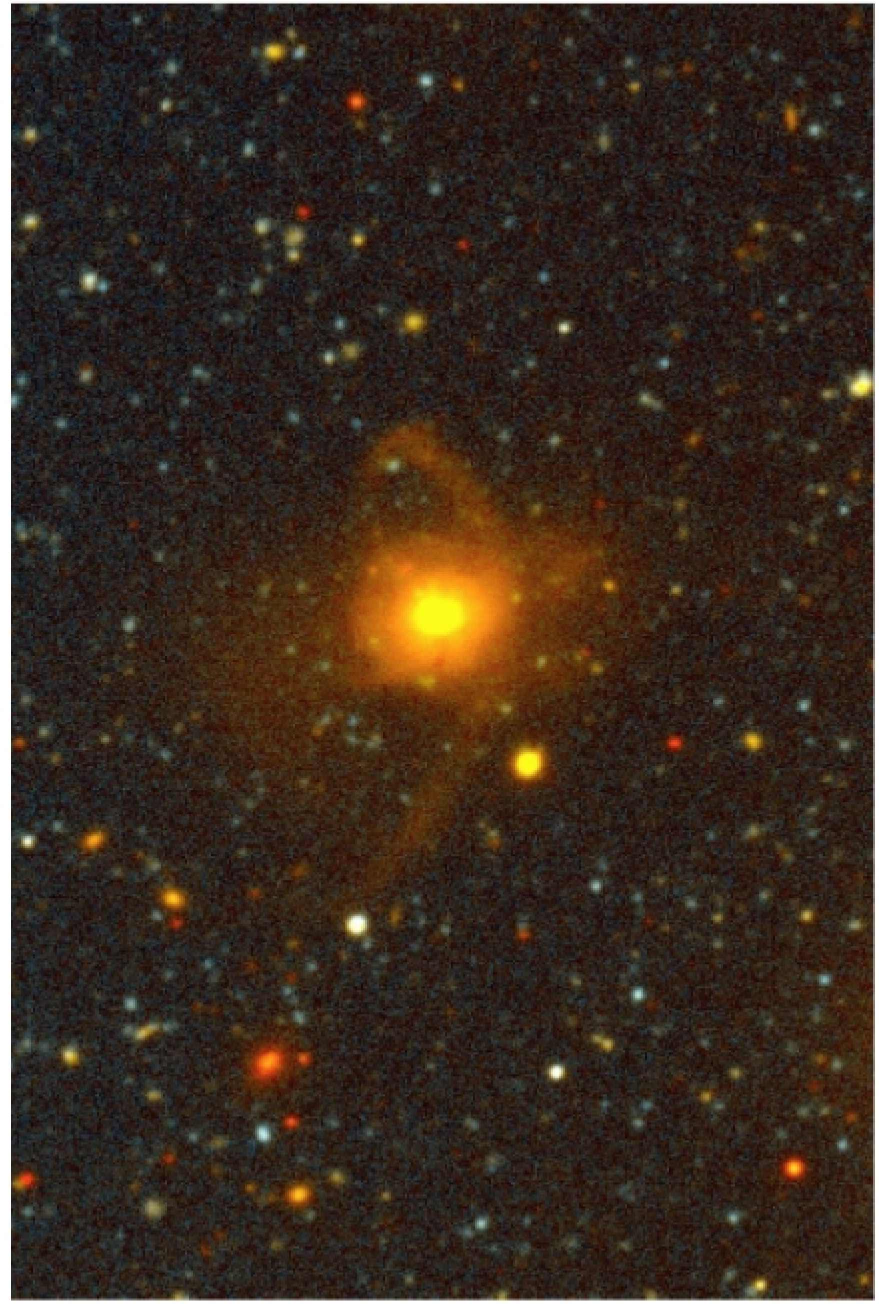
LSST: one SDSS per night, or all the words ever printed!



SDSS

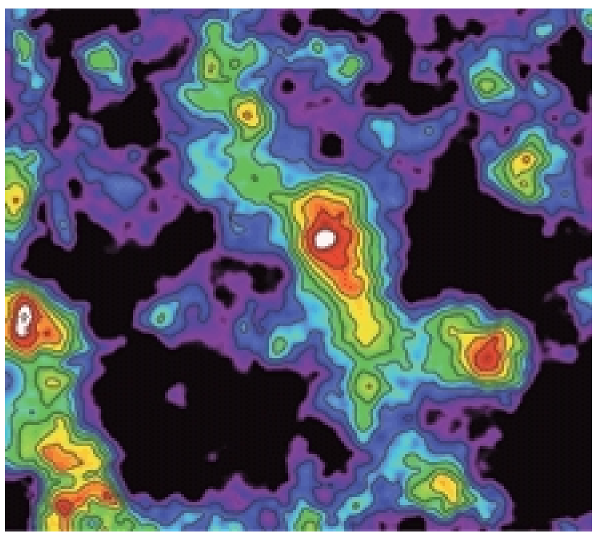


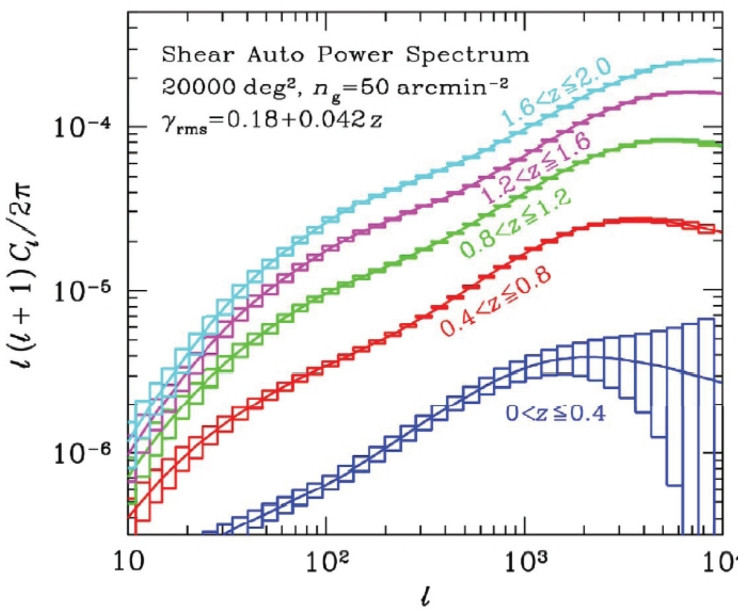
MUSYC



LSST Science Drivers

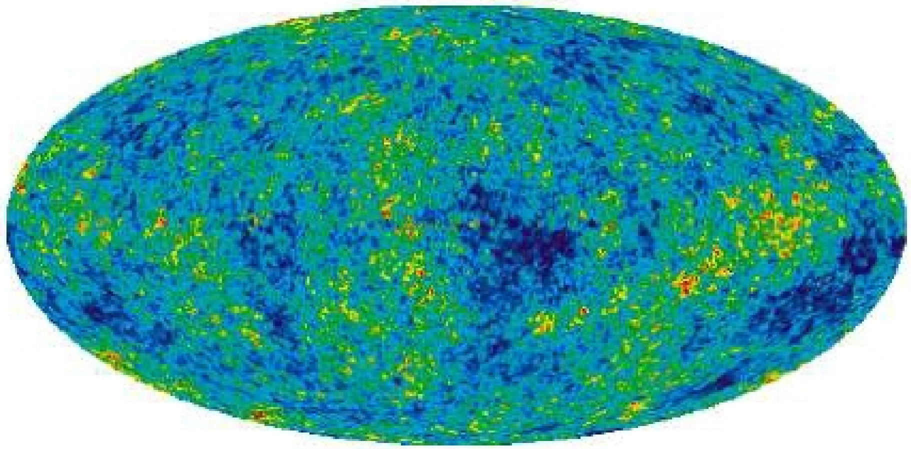
- The Fate of the Universe (Dark Energy and Matter):
  use a variety of probes and techniques in synergy to fundamentally test our cosmological assumptions and gravity theories:
  1. **Weak Lensing:** growth of structure
  2. **Galaxy Clusters:** growth of structure
  3. **Baryon Acoustic Oscillations:**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

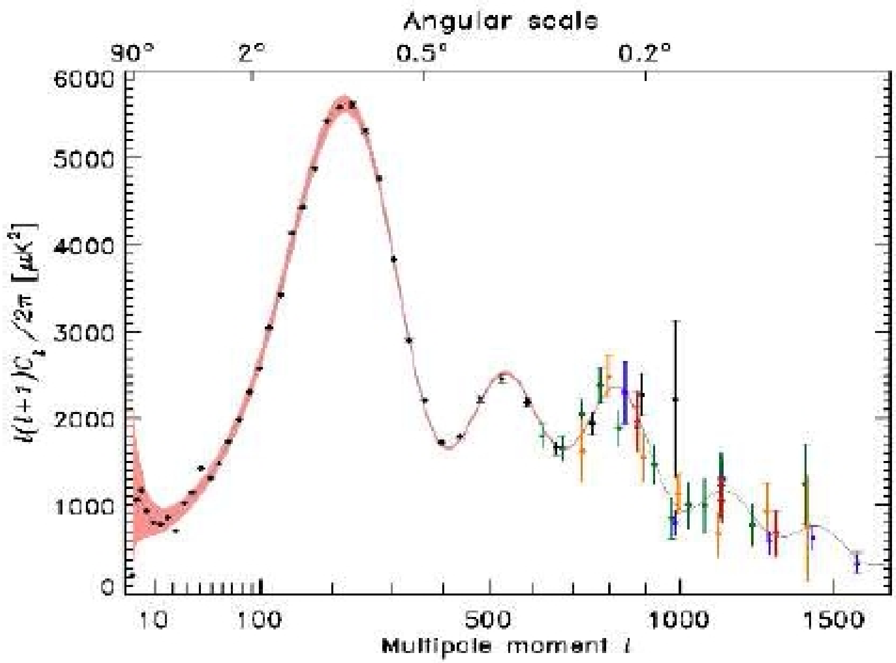




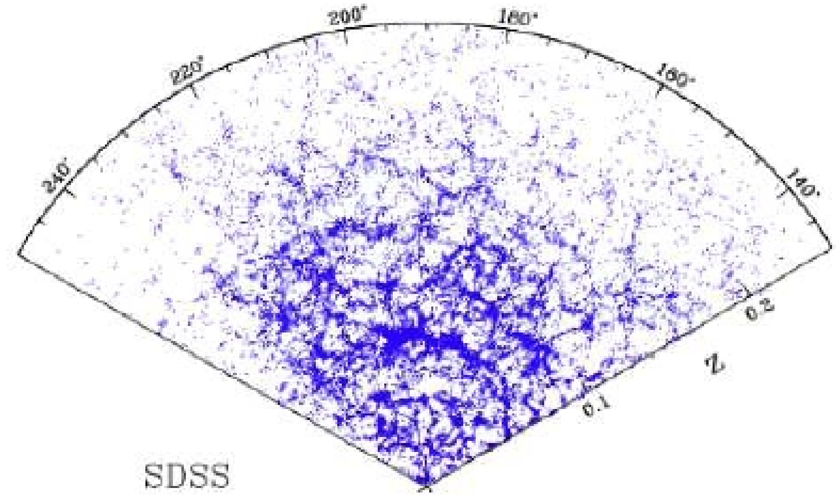
Weak lensing shear power spectrum provides strong constraints on cosmological parameters, dark matter distribution, and even the sum of neutrino masses (to better than 0.04 eV).

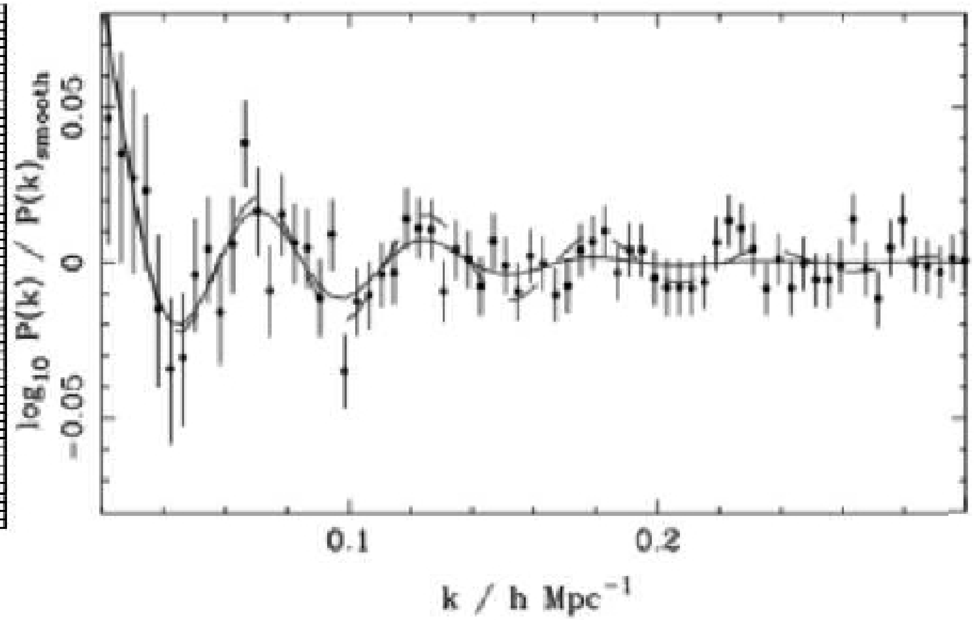
CMB





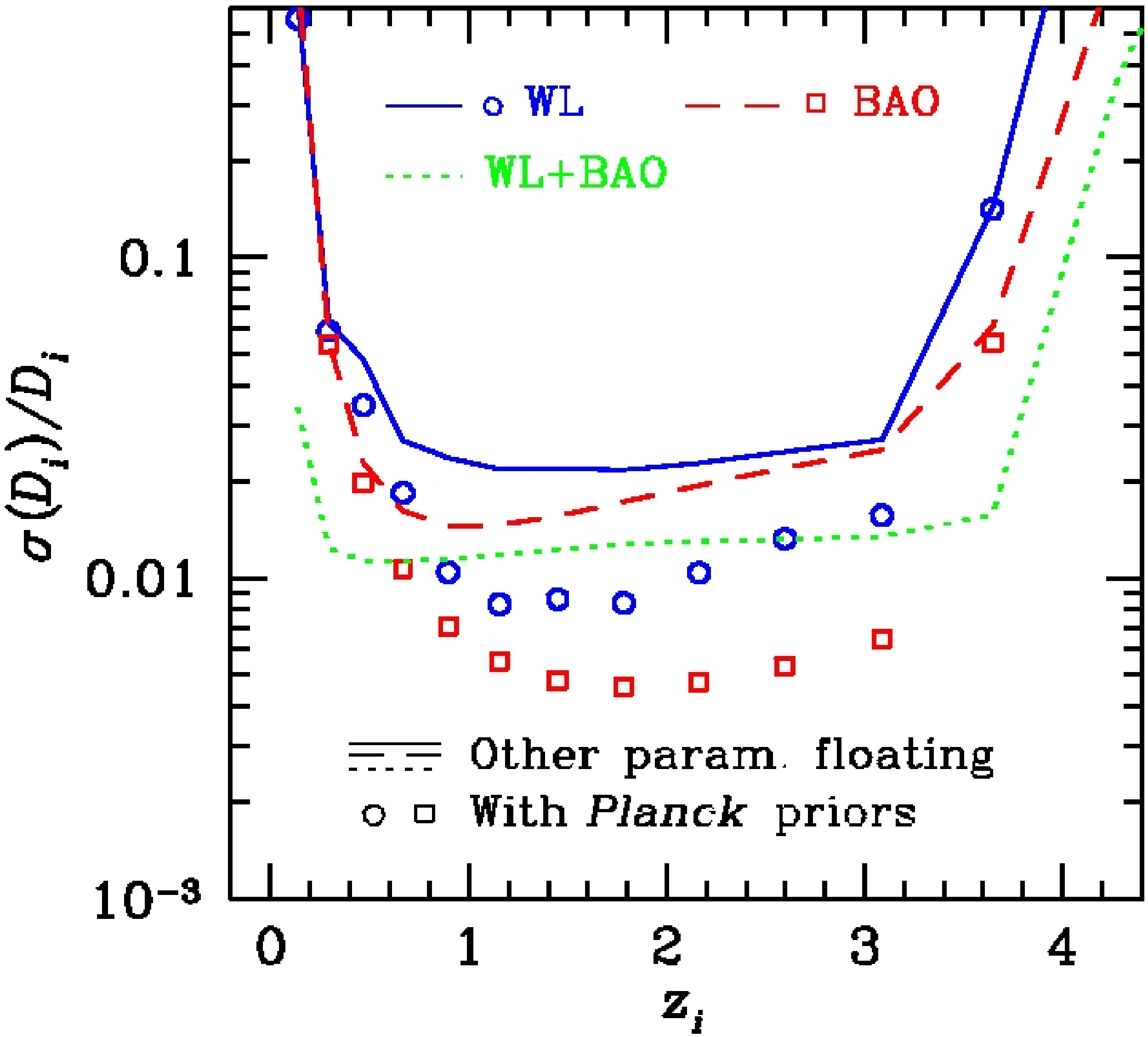
Galaxies



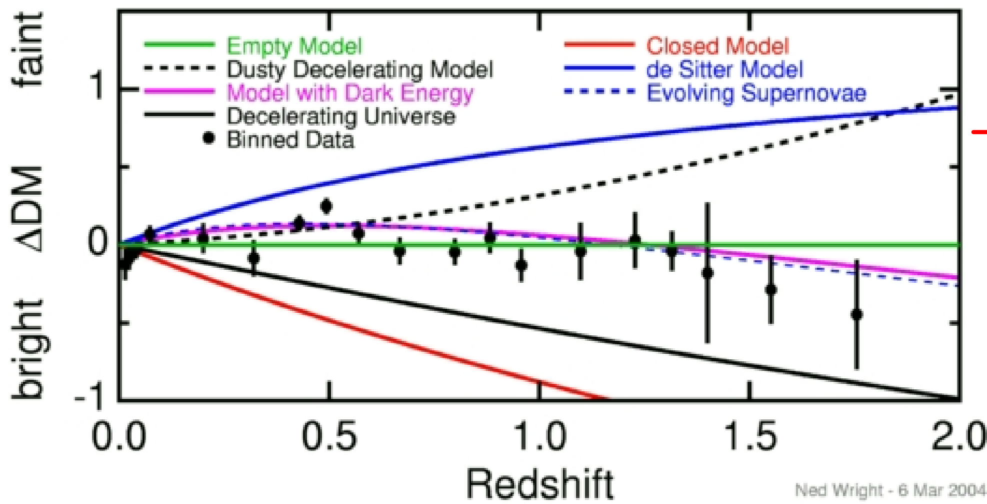


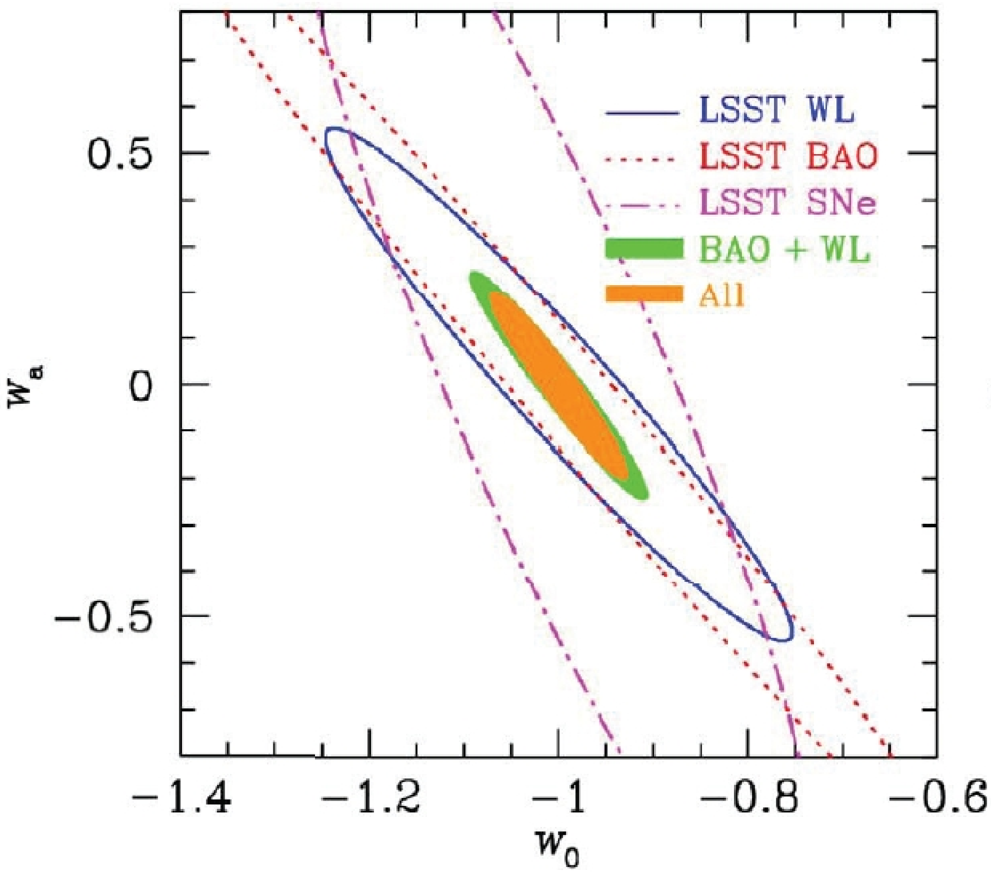
Baryon acoustic oscillations:
standard ruler – a new cosmological tool

Co-moving Distance Measurements with LSST



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:** several million, **the only probe to provide high angular resolution constraints on the homogeneity and isotropy of the Universe**

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About a hundred-to-thousand-fold increase in precision over precursor experiments: Stage IV Experiment (Dark Energy Task Force nomenclature)

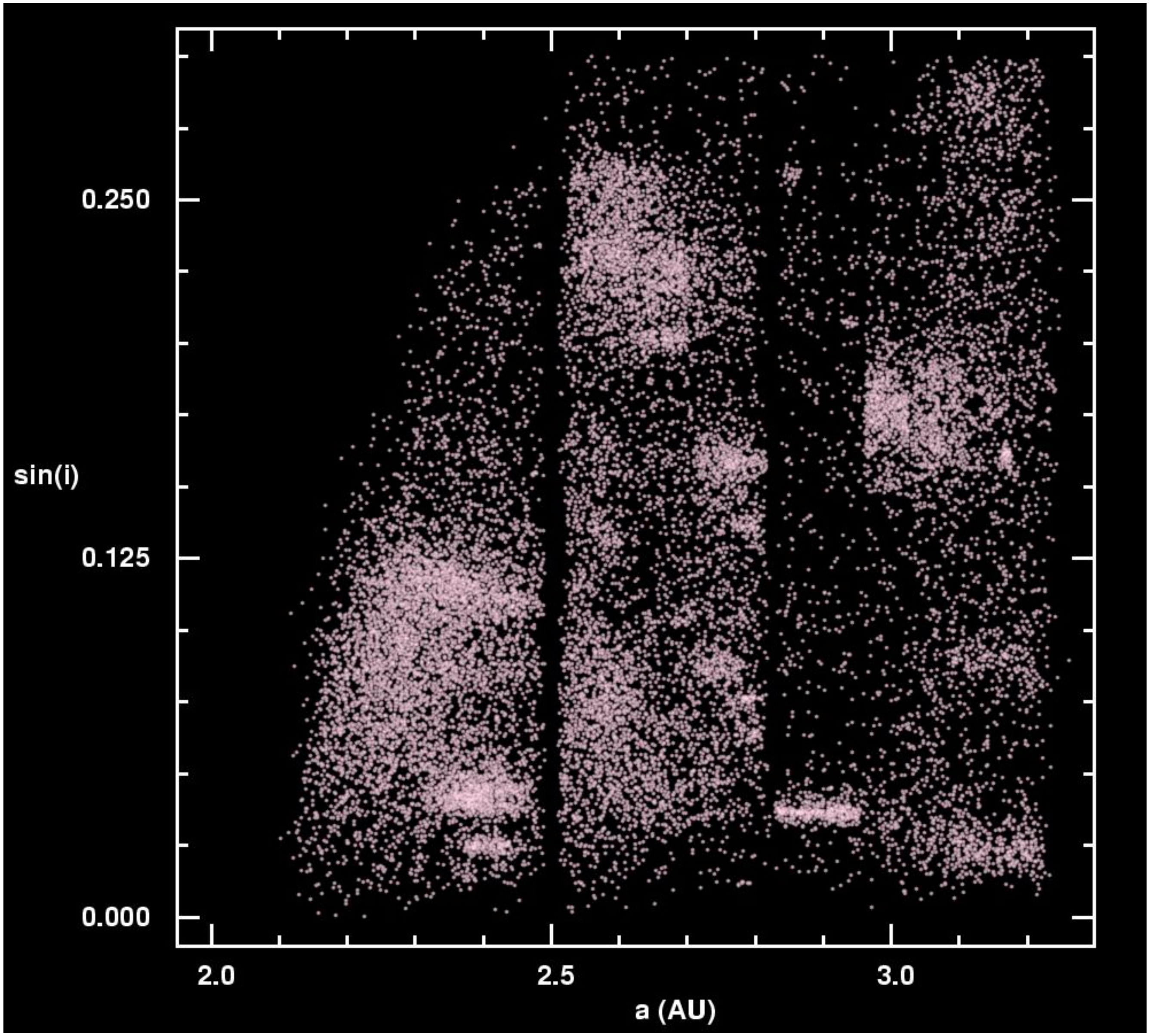
Multiple accurate cosmological probes with the same facility (and data): by simultaneously measuring growth of structure and co-moving distances, **LSST data will tell us whether the recent acceleration is due to dark energy or modified gravity.**

The Solar System Inventory

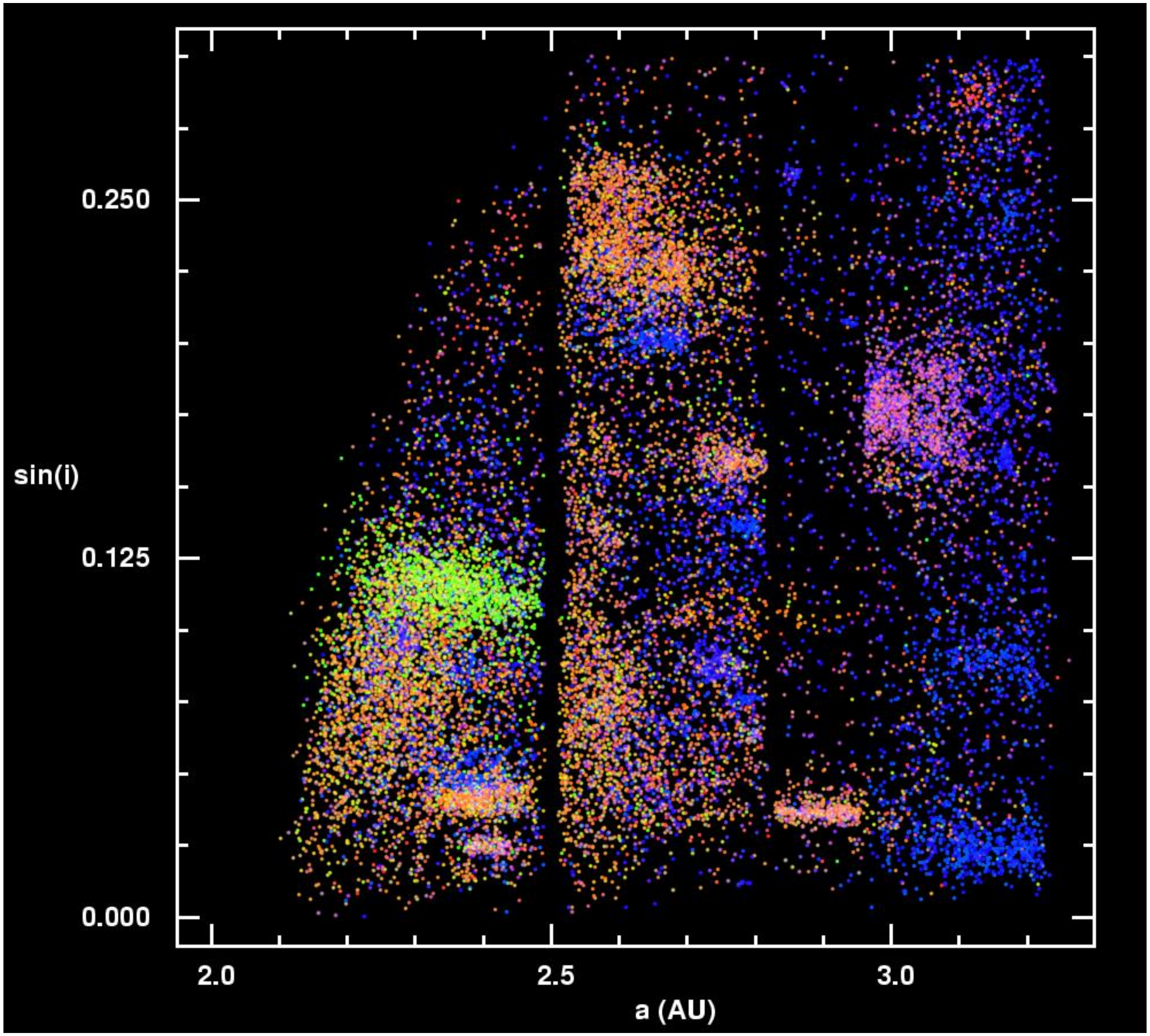
Studies of the distribution of orbital elements as a function of color and size; studies of object shapes and structure using colors and light curves.

- 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
(like the Galaxy is a detailed test of galaxy formation theories)

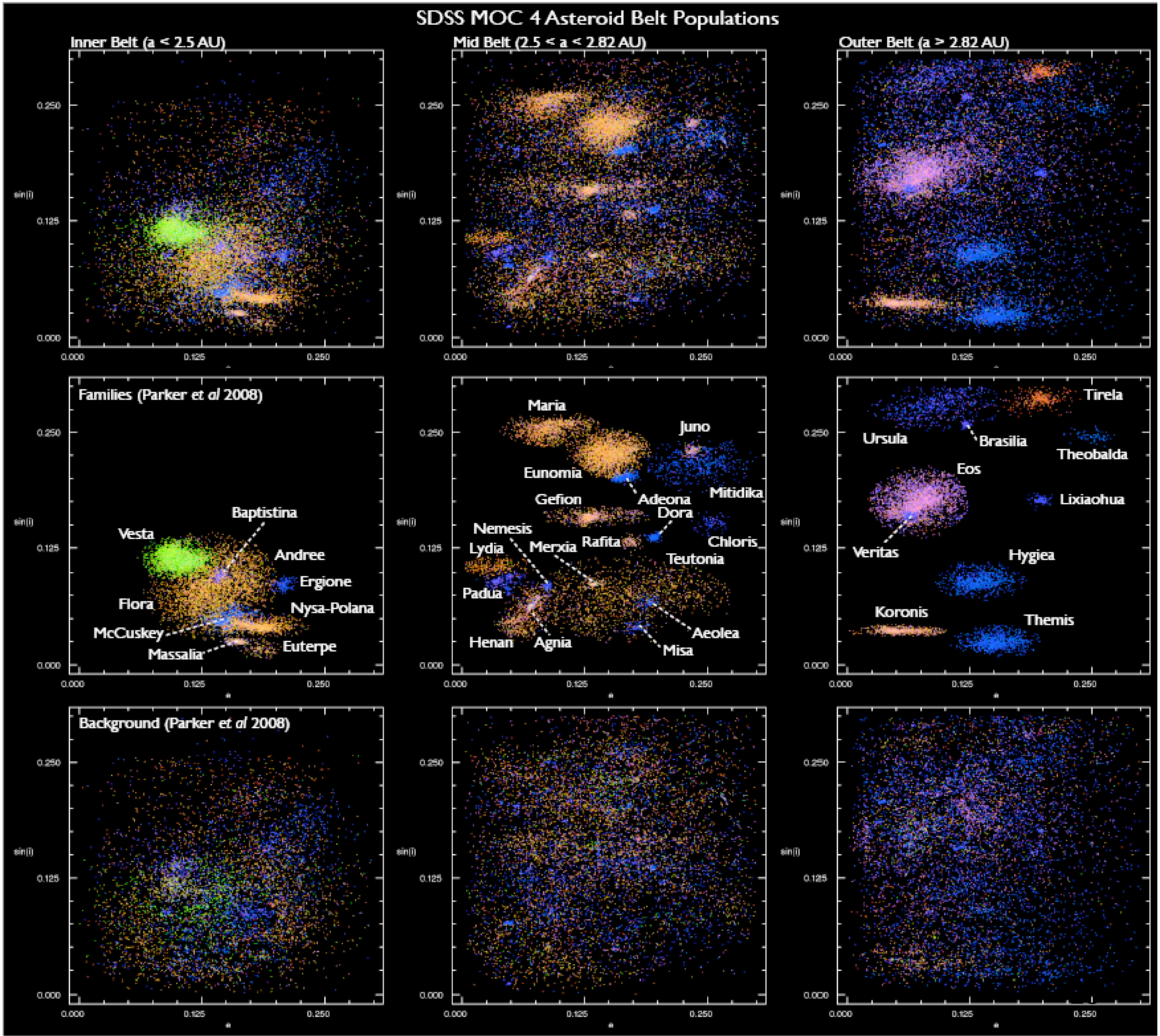


The semi-major axis vs. inclination (proper elements)

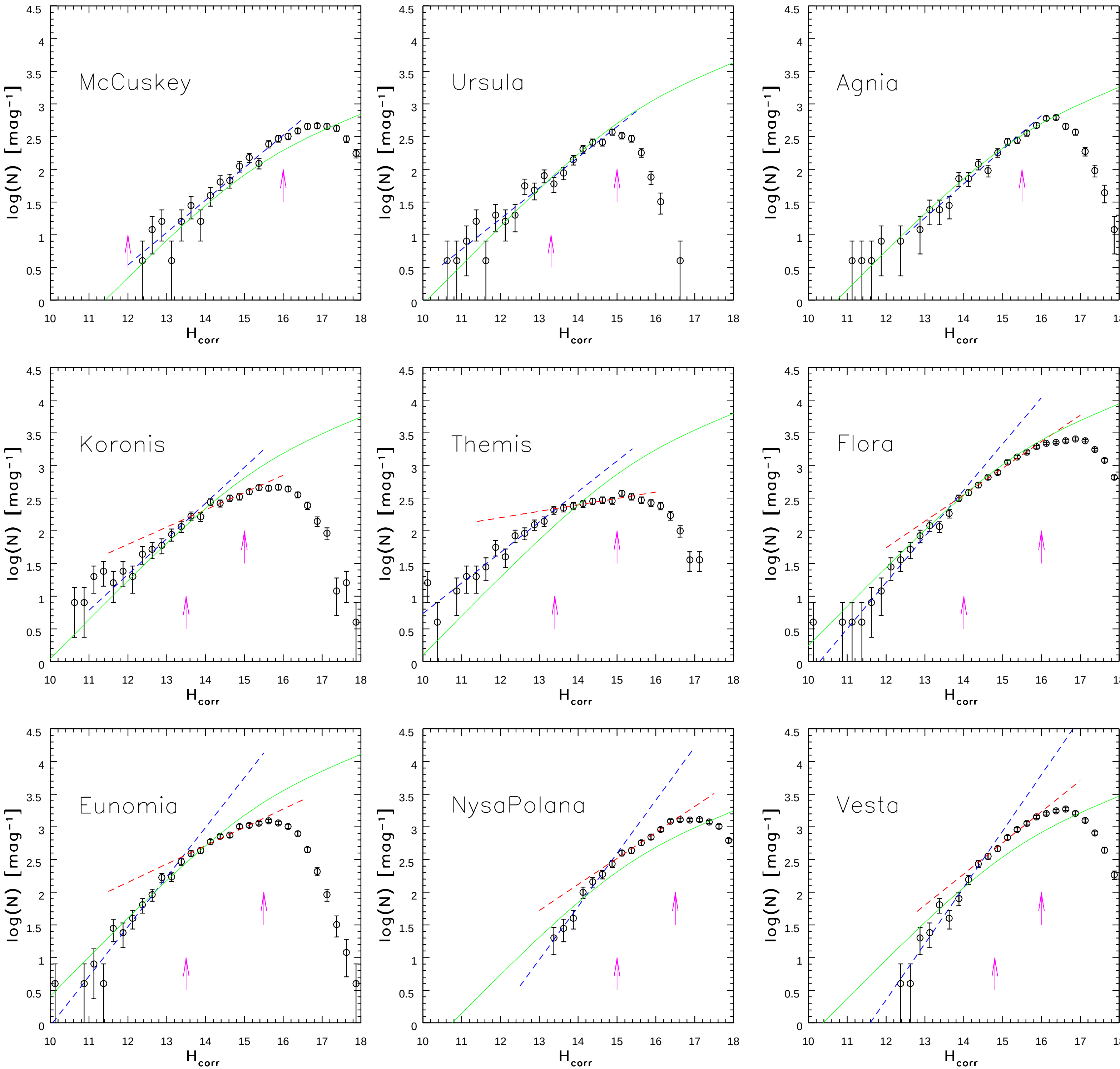


The semi-major axis vs. inclination: color-coded using optical colors measured by SDSS

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

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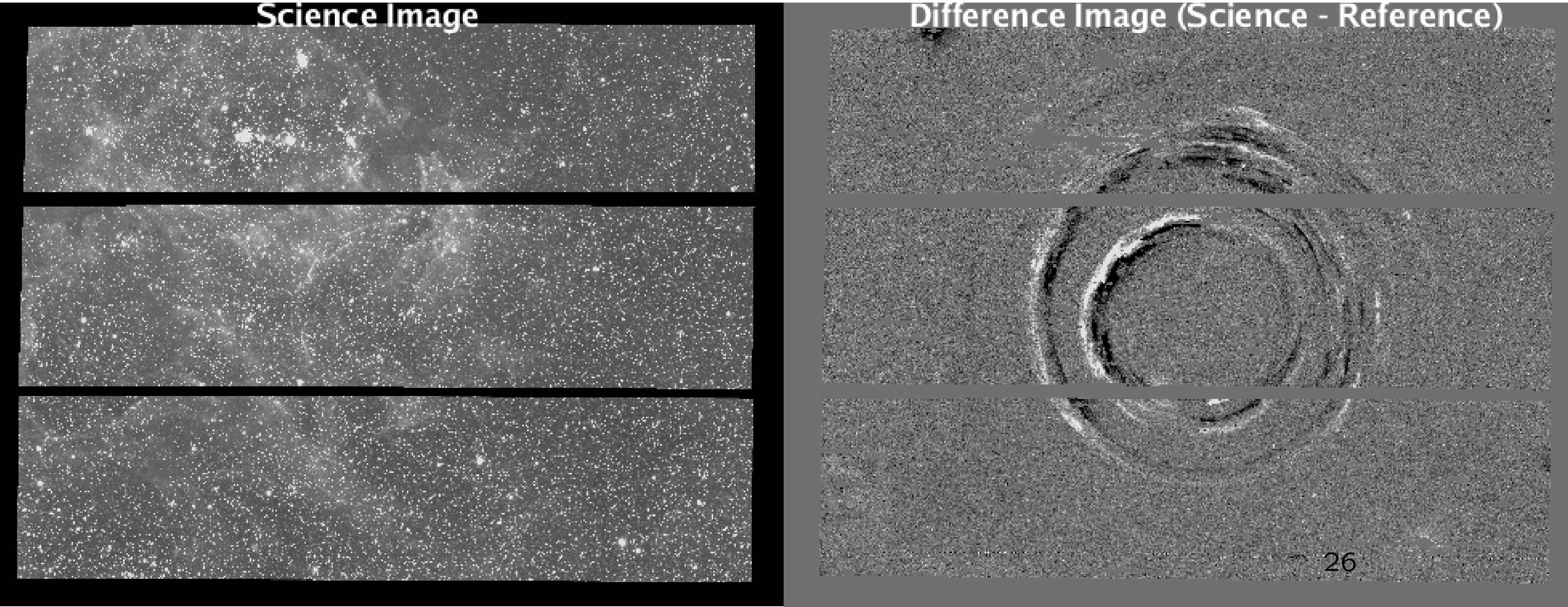
Not only point sources: echo of a supernova explosion



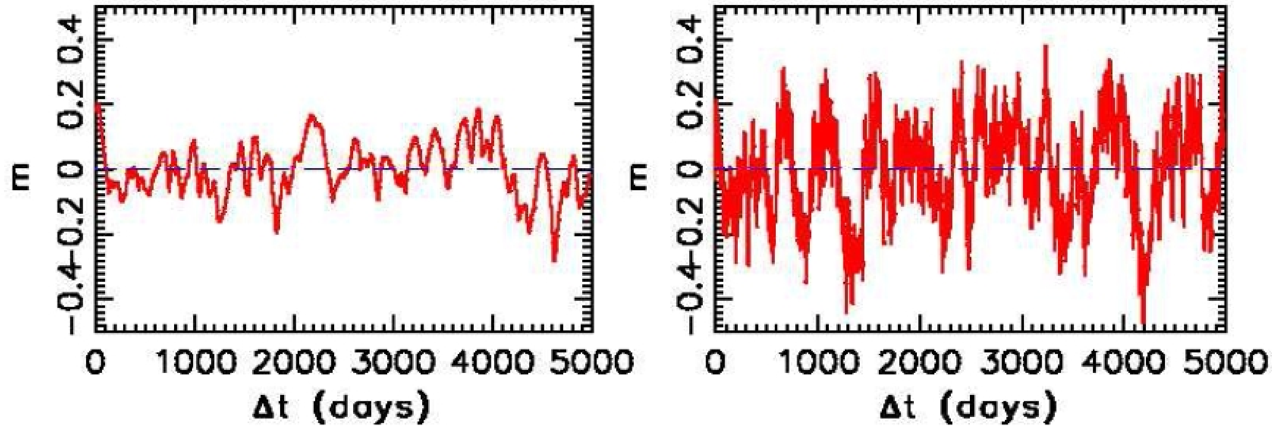
Quasar/AGN Variability

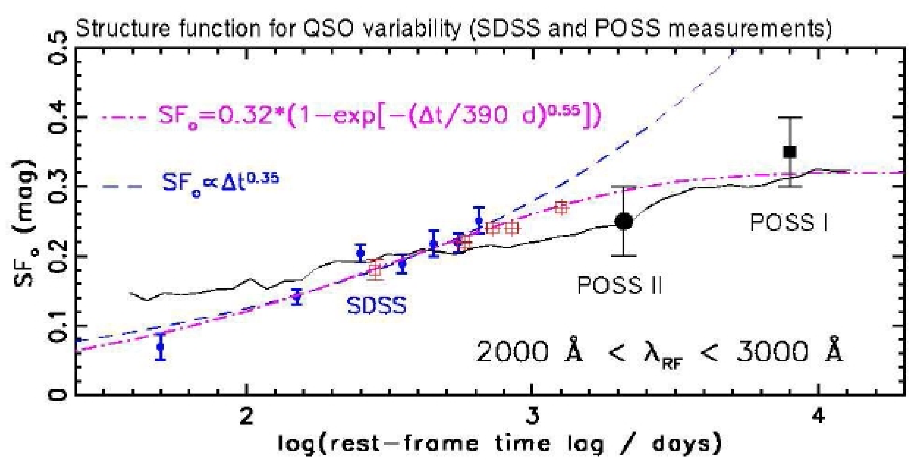
Variability is a tool, just like imaging, spectroscopy and multi-wavelength X-ray to radio observations, for studying quasars/AGNs

Competing theories for the origin of variability:

- Microlensing
- Bursts of Supernovae
- **Accretion disk instabilities**

SDSS observations indicate rich information content:

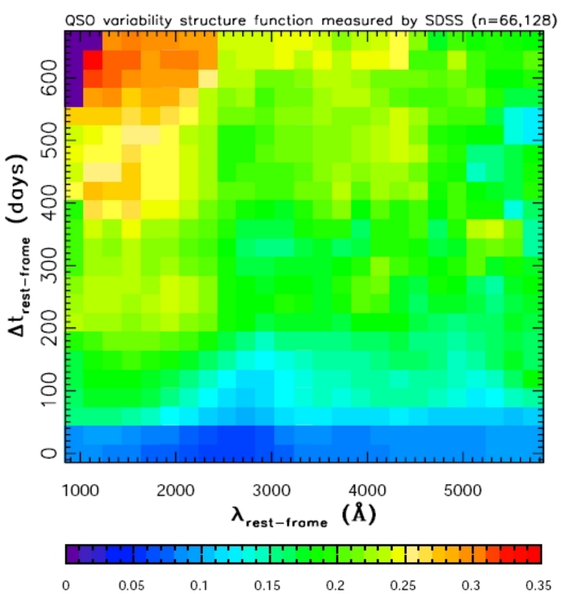


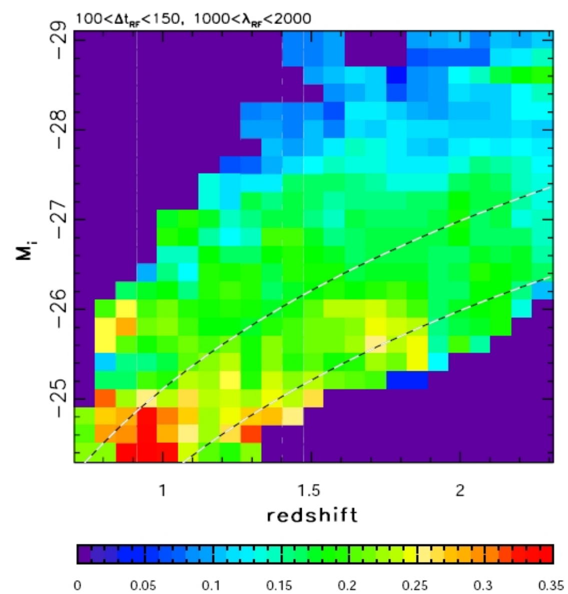


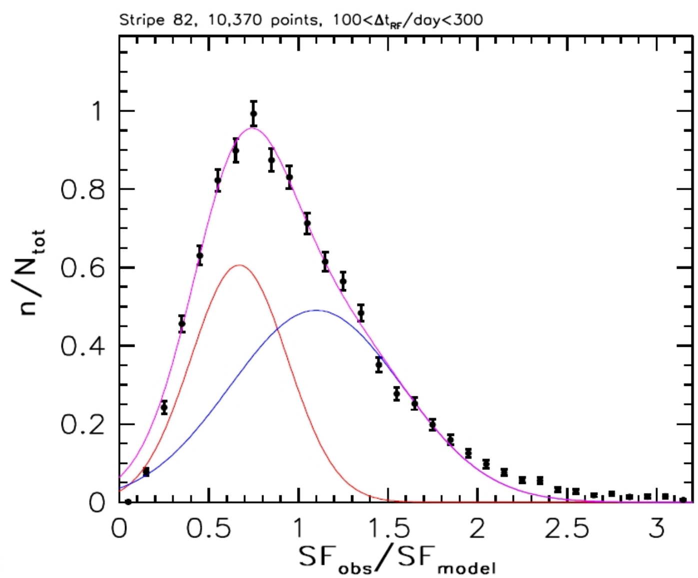
Quasar/AGN Variability

SDSS observations show that quasar variability depends on time scale, wavelength and luminosity, but **not on redshift** (vanden Berk et al. (2004); Ivezić et al. 2004; de Vries et al. (2005)).

Structure function as a function of λ, Δt, L and redshift







Are conclusions based on two-observations samples reliable?

SDSS Stripe 82: subsample of ∼10,000 quasars with light curves: initial indications for two "populations" (MacLeod et al. 2008)

Quasar/AGN Variability

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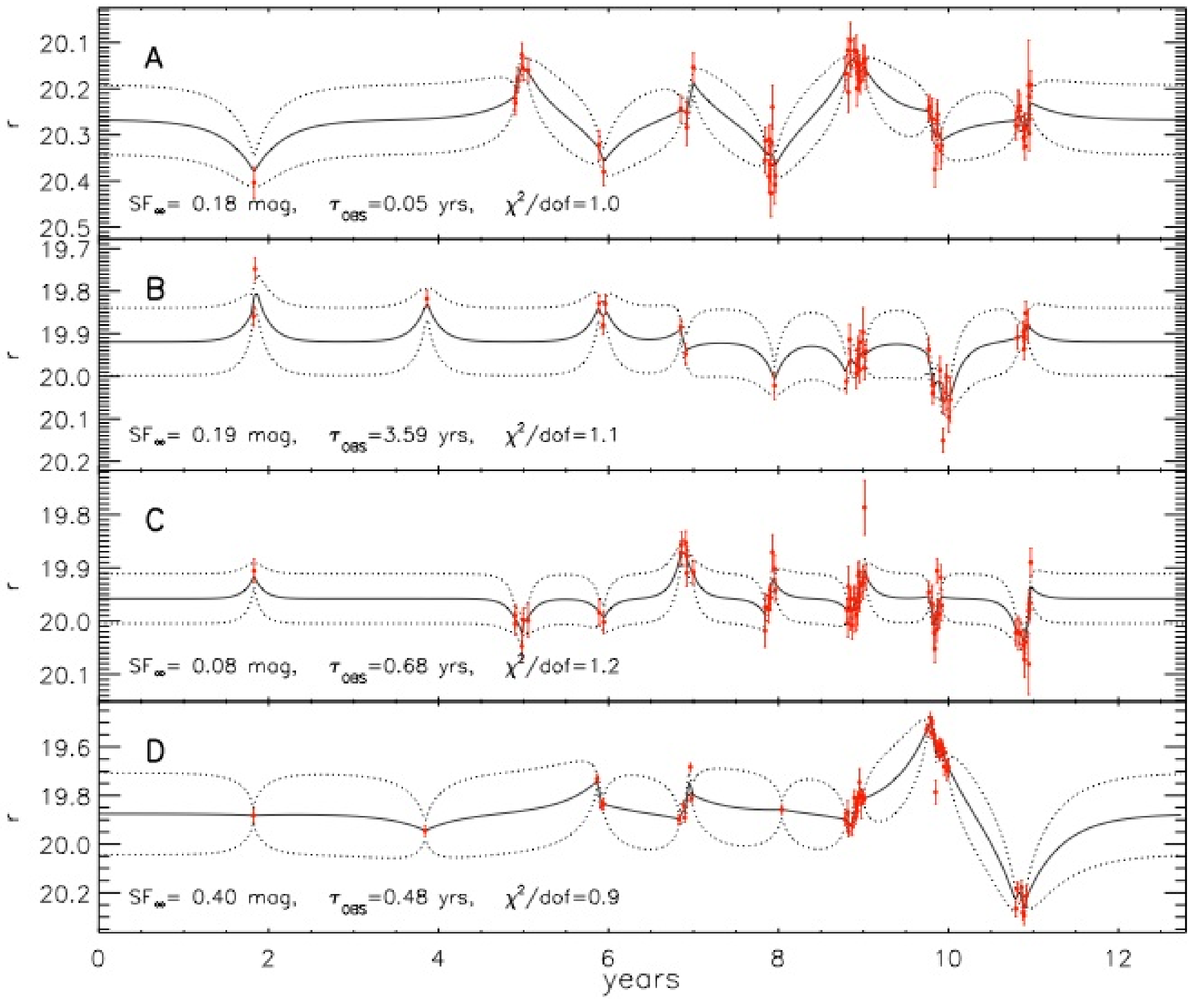
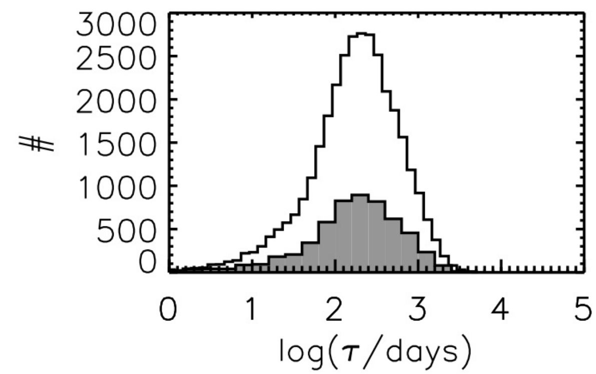
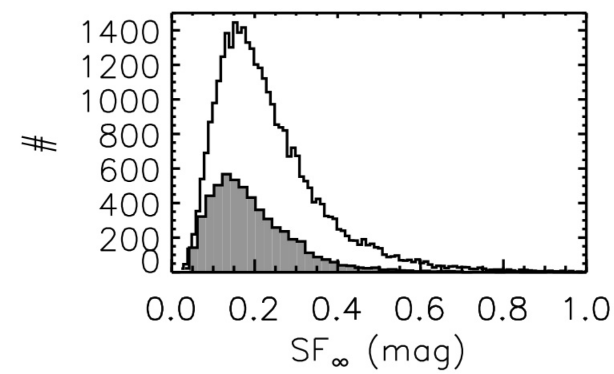
Initial indications for two "populations" (MacLeod et al. 2008)

MacLeod et al. (2010, arXiv:1004.0276): damped random walk model: excellent statistical description

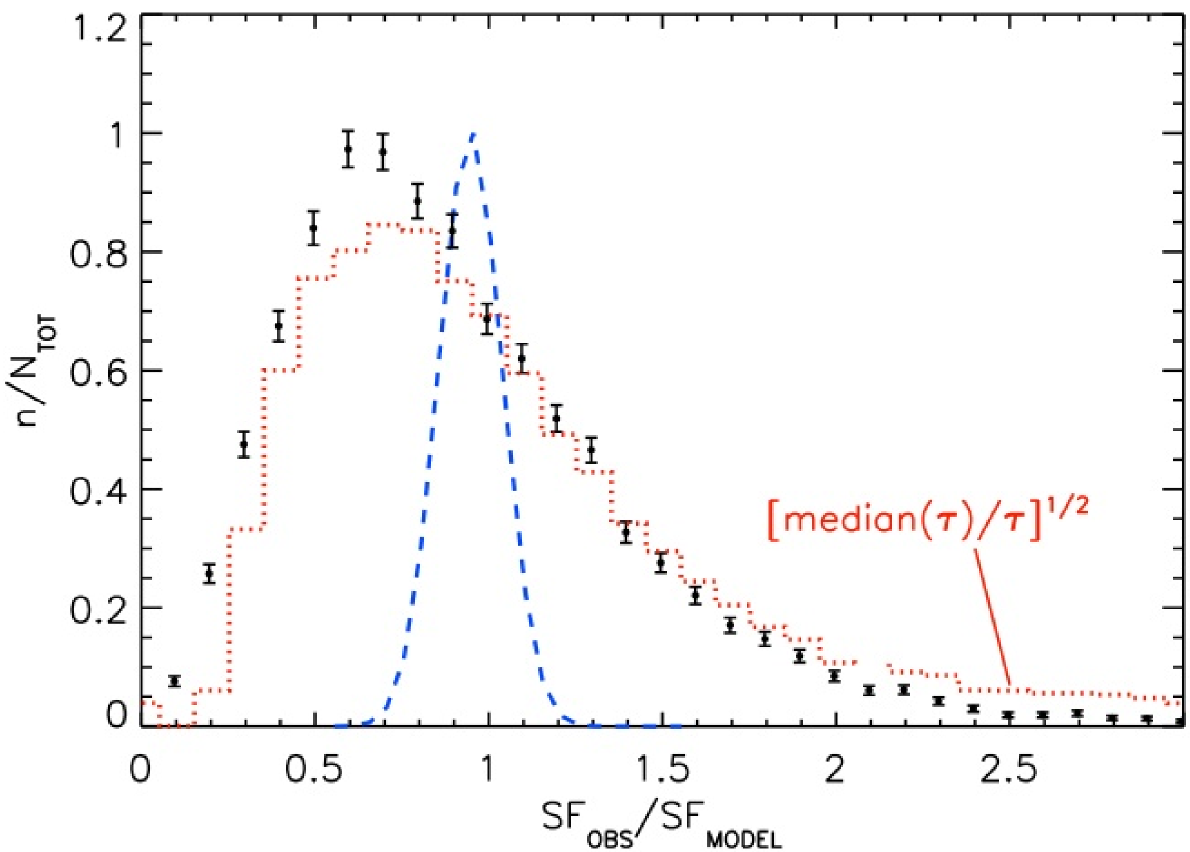


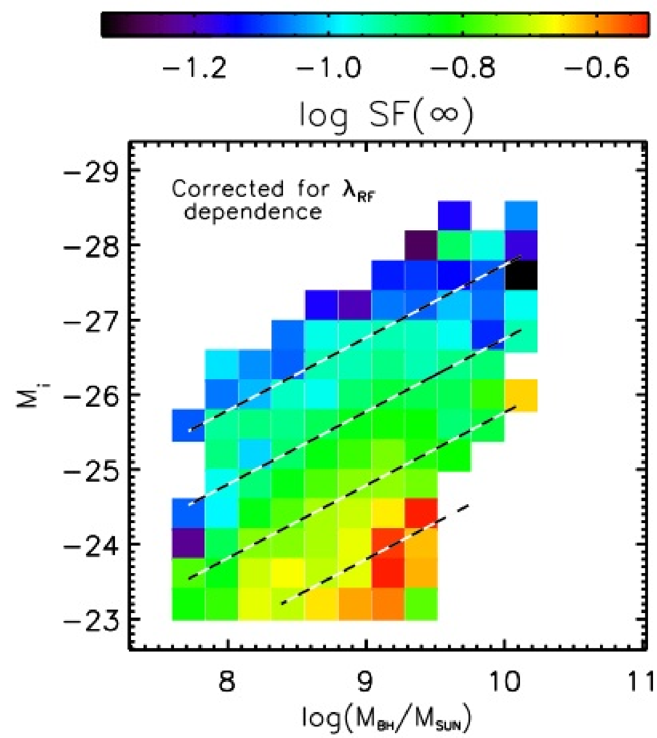




Quasar/AGN Variability

MacLeod et al. (2010): damped random walk model:
at a given wavelength, $SF(t) = SF_\infty\,[1 - \exp(-t/\tau)]^{1/2}$.
For $t < \tau$, $SF(t) \propto (t/\tau)^{1/2}$, with τ as an intrinsic parameter.
SDSS observations show that quasar variability is controlled by time scale, wavelength and luminosity, **and by stochastic τ**.





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).

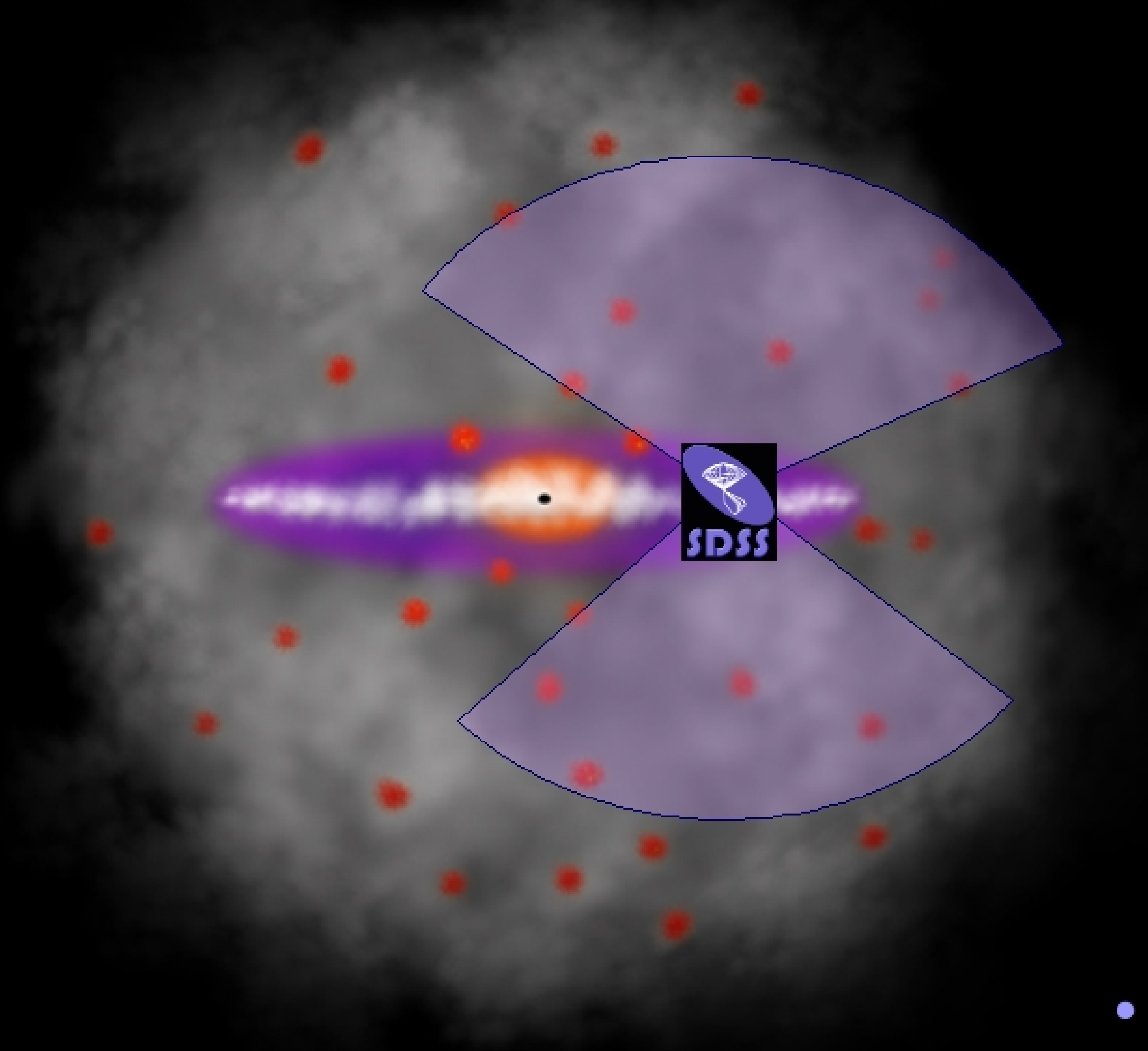
SDSS observations show that quasar variability depends on time scale, wavelength and luminosity, but **not on redshift**. The variability amplitude is strongly correlated with the Eddington factor, but there is additional impact of either luminosity or black hole mass.

Even when all these variables are controled, the characteristic time scale still shows a fairly wide distribution.

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)

Classical Decomposition of the Milky Way Components

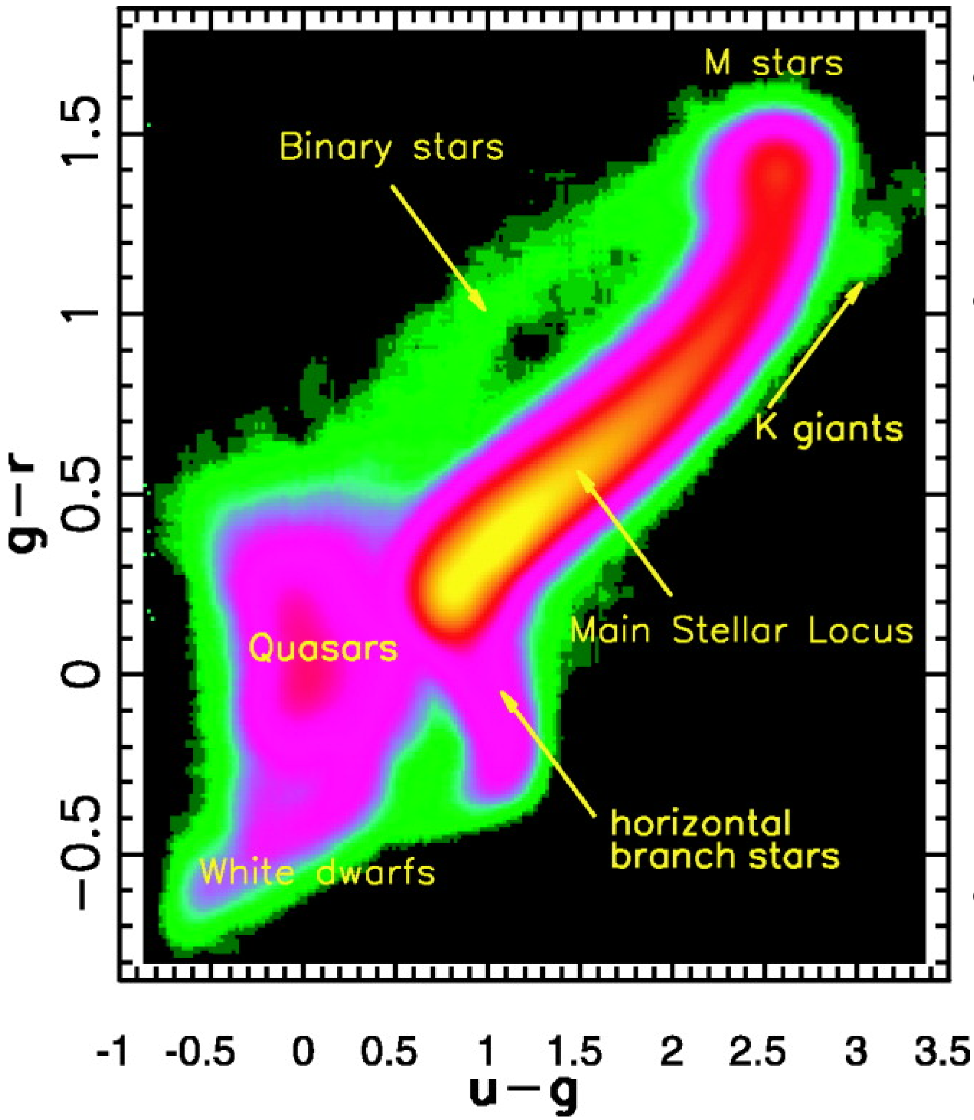


- Thin/thick disk
- Galactic bulge
- Stellar halo

- Components trace the DM dominated potential

- They are a product of Milky Way formation and evolution

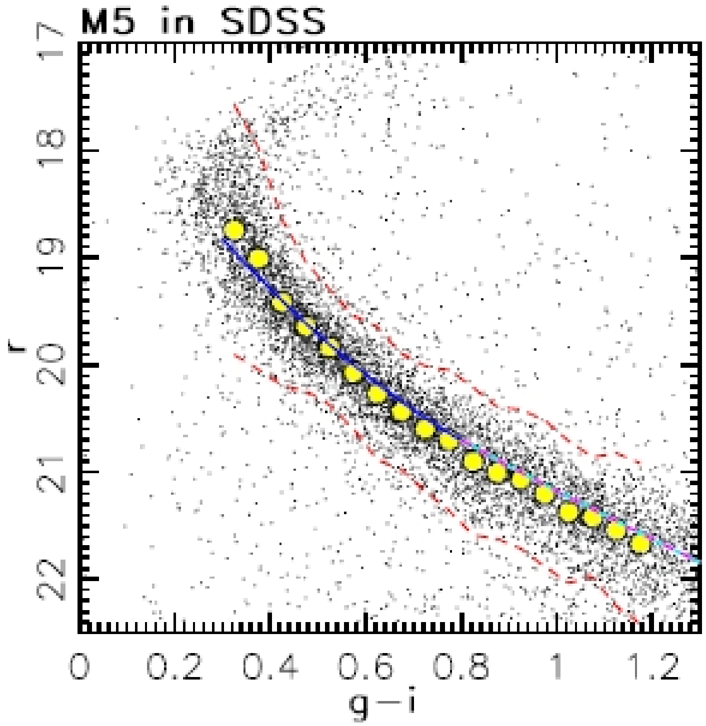
A Primer on Dissecting the Milky Way with SDSS

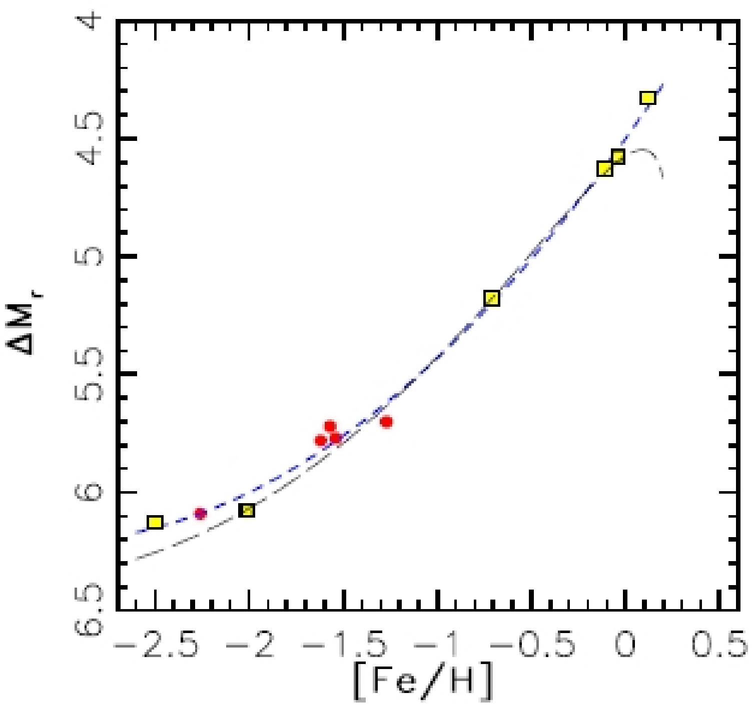


Wide wavelength coverage, and accurate and robust photometry

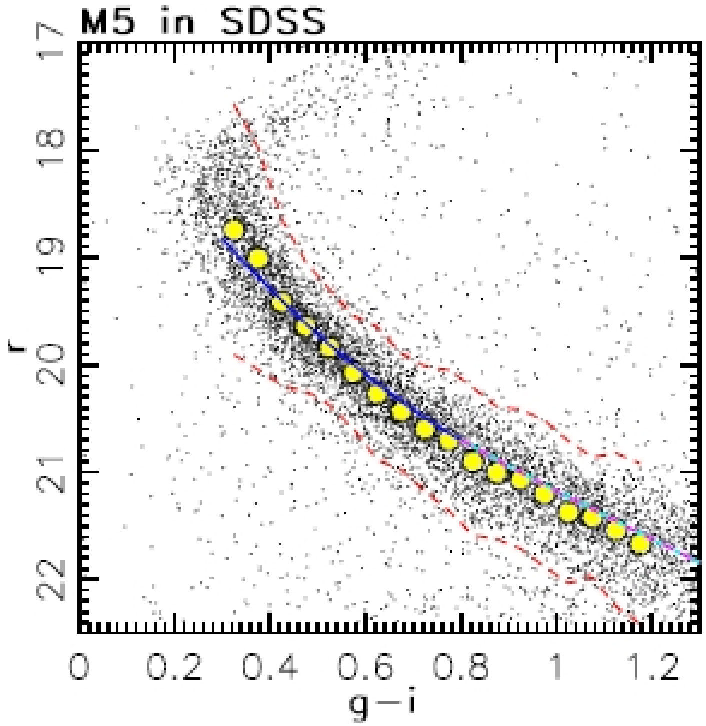
- Stars on the main stellar locus are dominated (~98%) by main sequence stars (for $r > 14$)
- The position of main-sequence stars on the locus is controlled by their effective temperature/luminosity/[Fe/H], and thus can be used to estimate distance: photometric parallax method for ~100 million stars **(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!)**

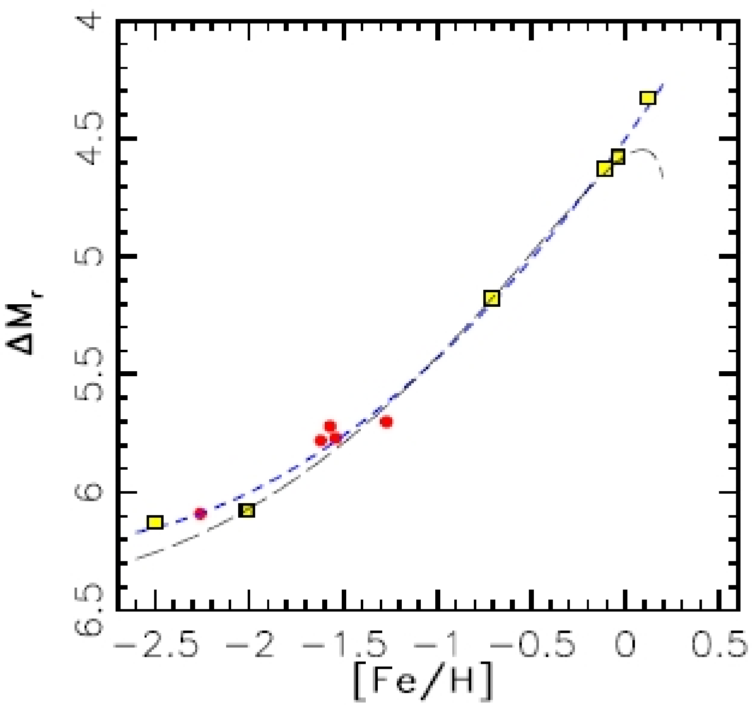
Photometric Distance and Photometric [Fe/H]





- Determined absolute magnitude vs. color vs. metallicity relation using globular clusters observed by SDSS (blue end), and nearby stars with trigonometric parallaxes (red end)
- The $g-i$ color of a main-sequence star constrains its absolute magnitude to within 0.1-0.2 mag (0.3 mag for unresolved binaries), assuming [Fe/H] is known





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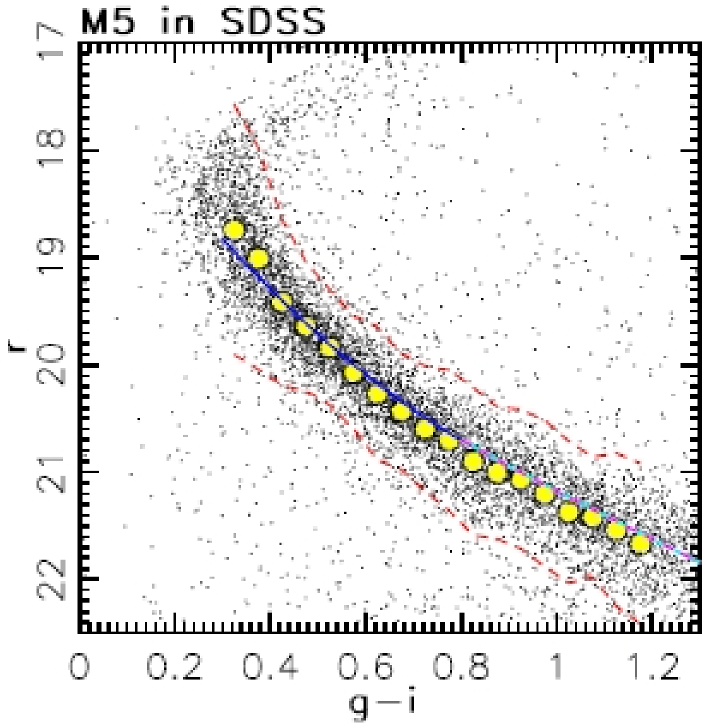
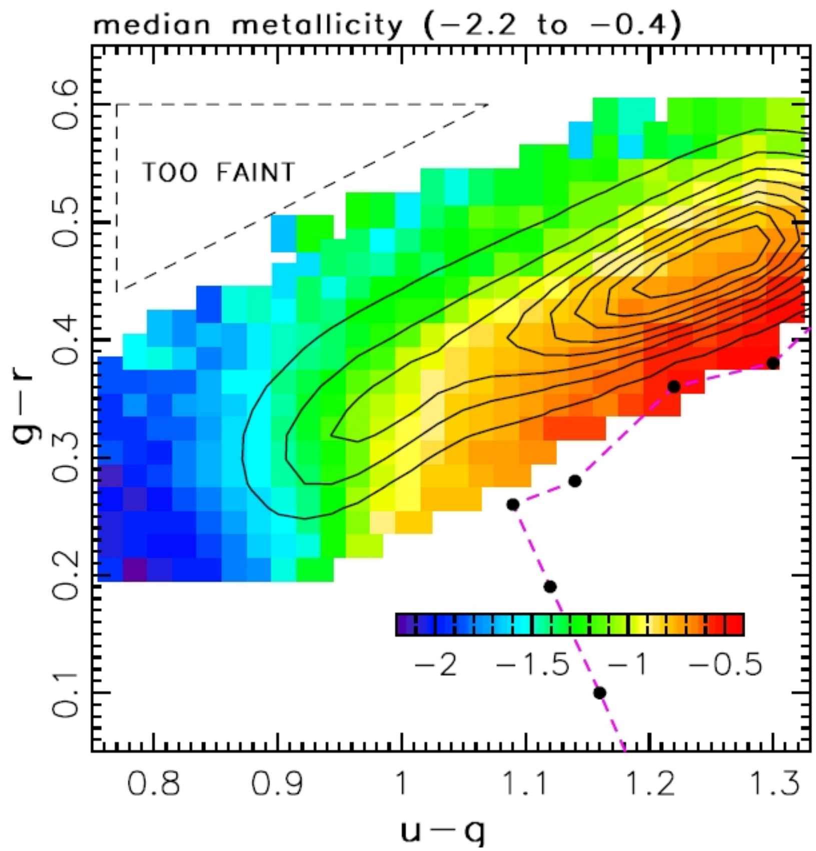
This method was known half a century ago, but never before applied to tens of millions of stars because large-scale surveys did not have the required photometric accuracy

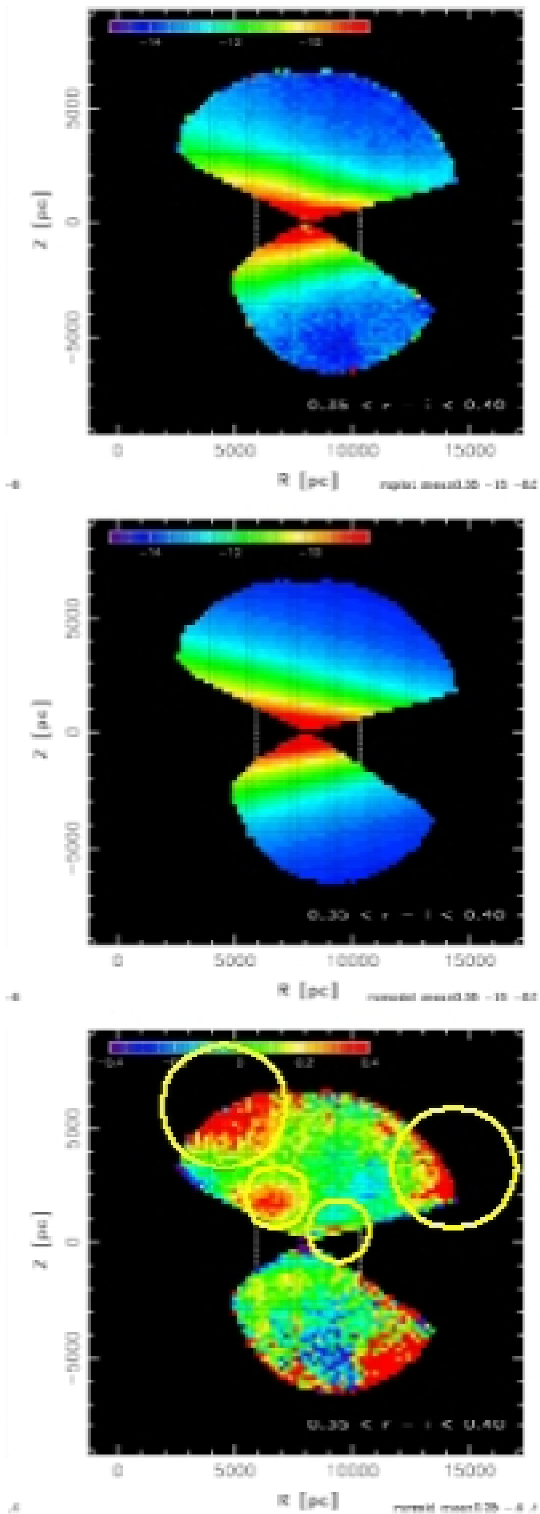




Photometric Distance and Photometric [Fe/H]

- Determined absolute magnitude vs. color vs. metallicity relation using globular clusters observed by SDSS (blue end), and nearby stars with trigonometric parallaxes (red end)
- The $g-i$ color of a main-sequence star constrains its absolute magnitude to within 0.1-0.2 mag (0.3 mag for unresolved binaries), assuming [Fe/H] is known
- **For F and G stars** ($0.2 < g-r < 0.6$), accurate SDSS $u-g$ color measurements enable photometric metallicity estimates as precise (0.1-0.2 dex) as [Fe/H] derived from SDSS spectra!

0.35 < r-i < 0.40

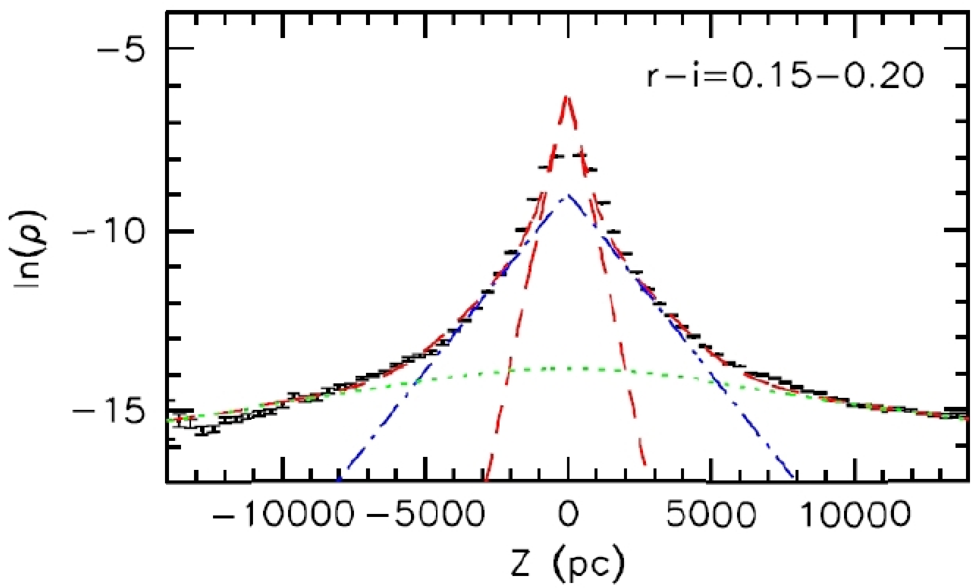


Dissecting the Milky Way with SDSS

- Panoramic view of the Milky Way, akin to observations of external galaxies; good support for standard Galactic models with amazing signal-to-noise! (Jurić et al. 2008)

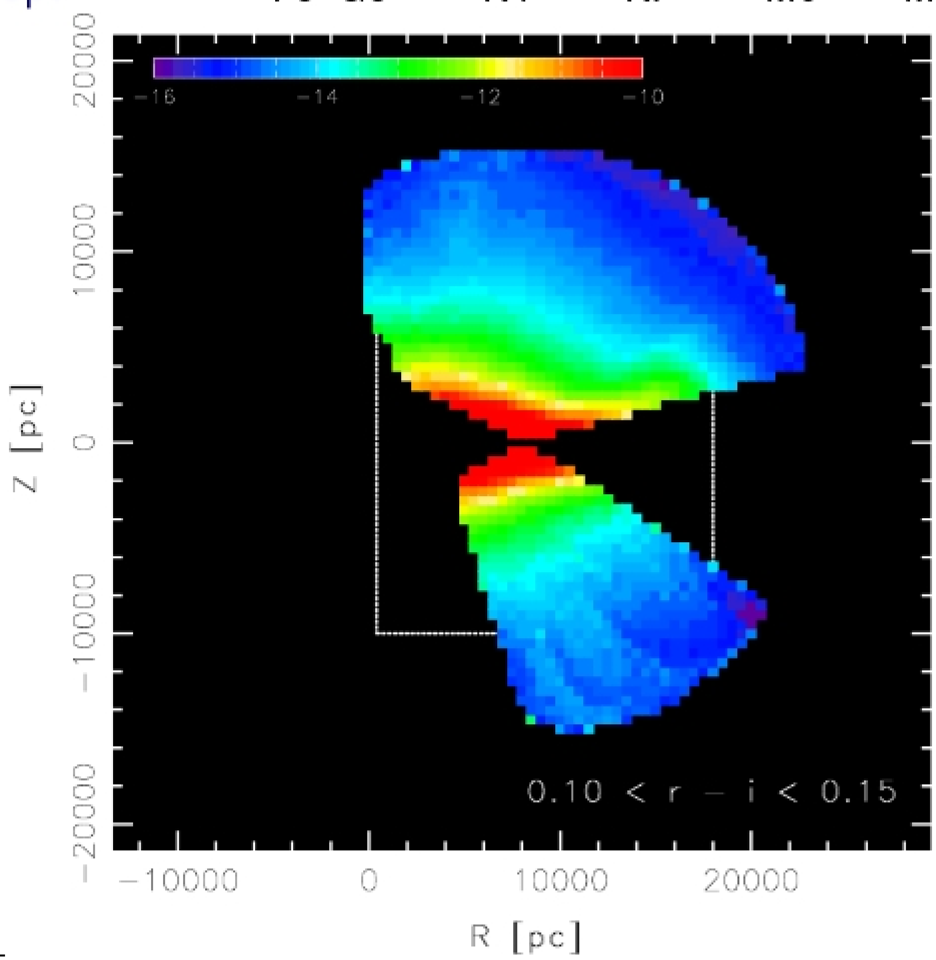
- Removal of obvious clumps
- Fit to least "contaminated" bins
- Exponential disks + halo models

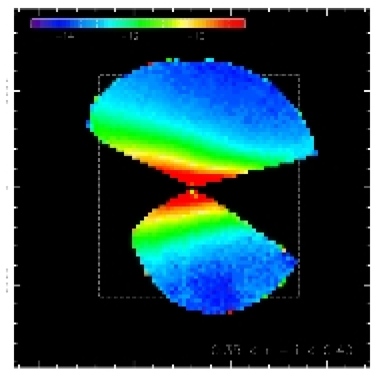
$$\rho(R,Z) = \rho_{thin} e^{-\frac{R-R_e}{l_{thin}} - \frac{|Z+Z_0|}{h_{thin}}} + \rho_{thick} e^{-\frac{R-R_e}{l_{thick}} - \frac{|Z+Z_0|}{h_{thick}}} + \rho_{halo} \left(\frac{R_{GC}}{\sqrt{R^2 + (z+z_0)^2 / q^2}} \right)^n$$



The r-i color bins sample a variety of scales

r - i	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4
D [kpc]	15	13	7	4	3	2	1.5	1
SpT	~F9	G6	K4	K7	M0	M1	M2	M3





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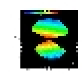
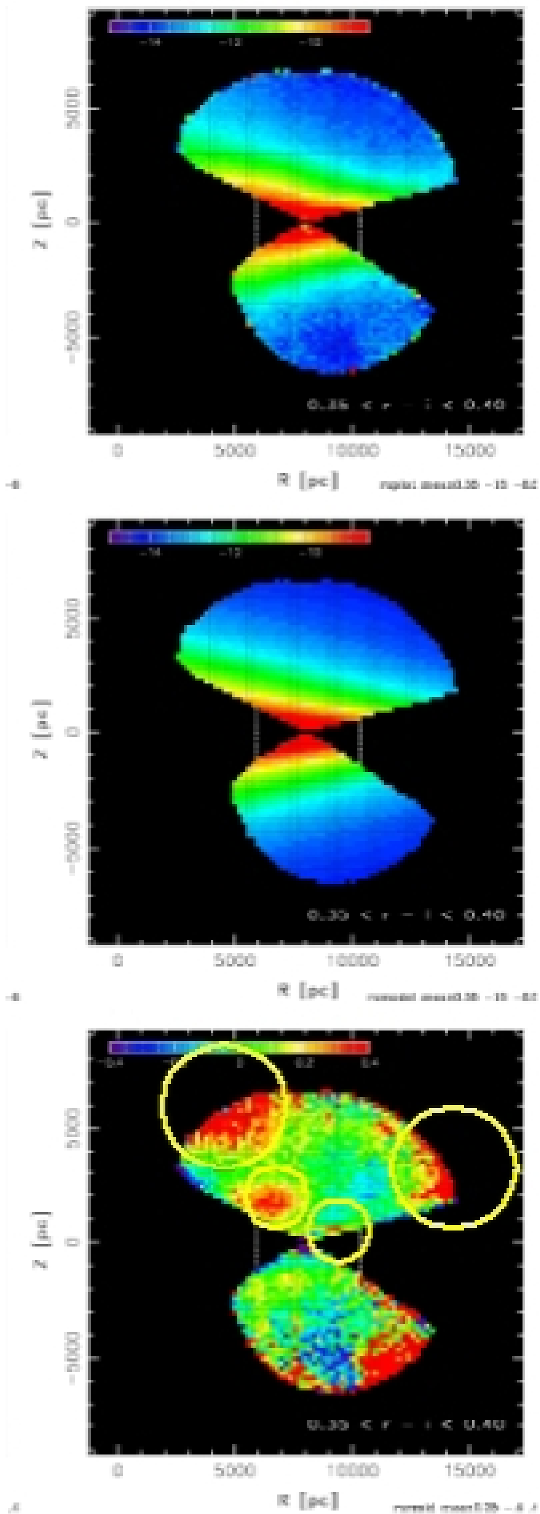


1.3 < r-i < 1.4

0.35 < r-i < 0.40



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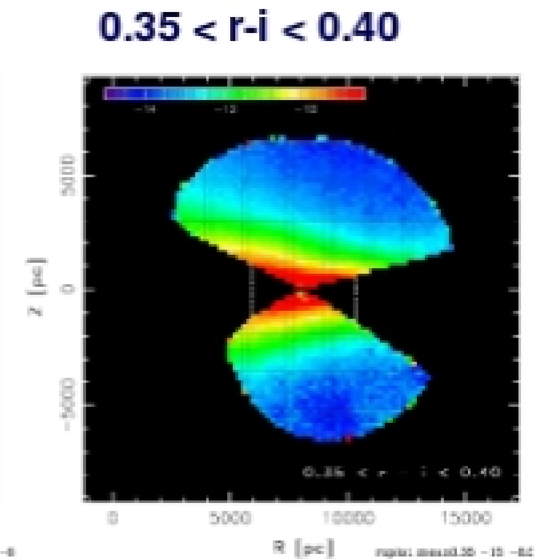
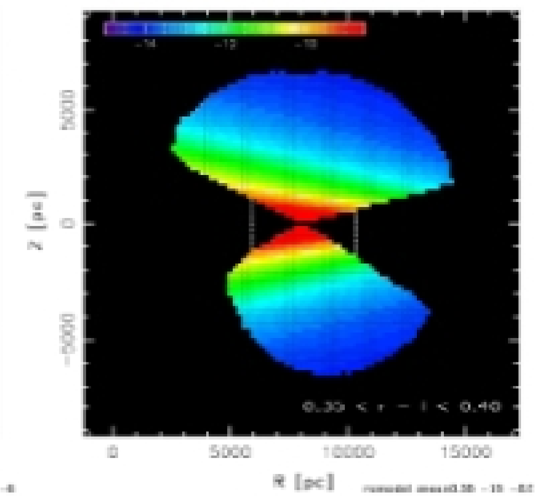
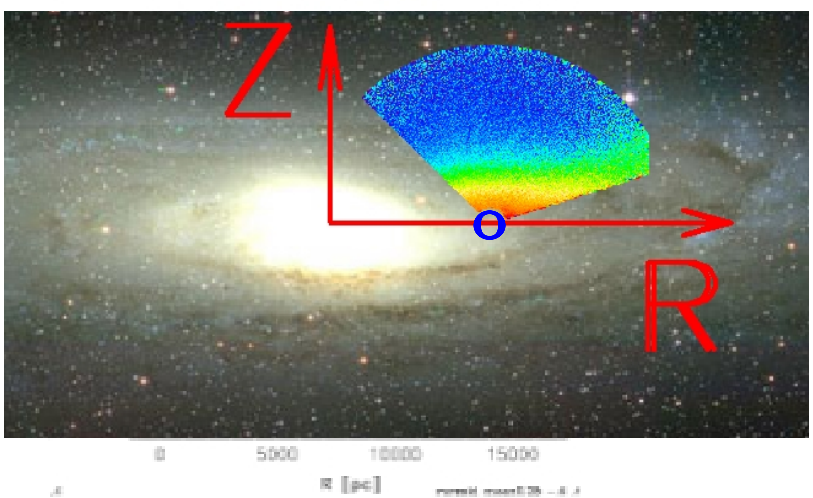
- The merger history of the Milky Way can be deciphered by mapping the substructure (spatially, and in velocity space, as a function of chemical composition [metallicity])

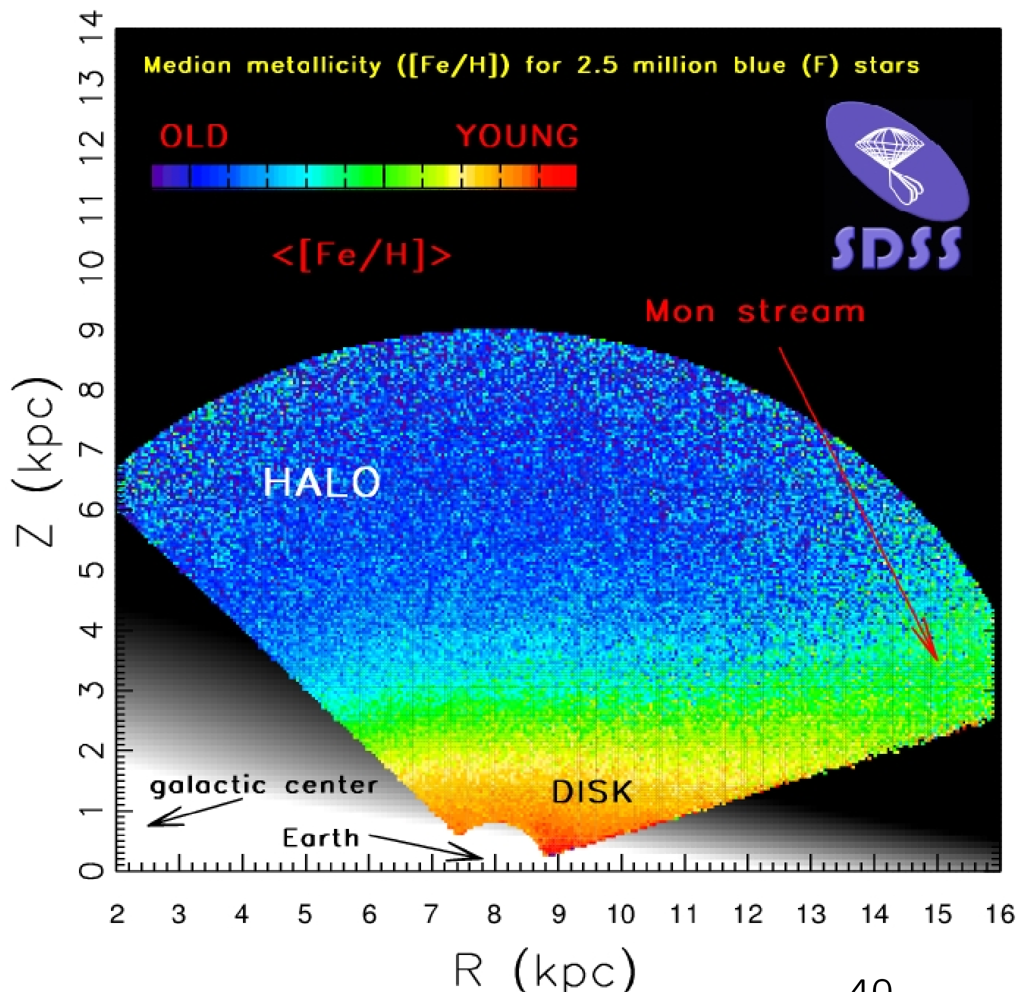
Dissecting the Milky Way with SDSS

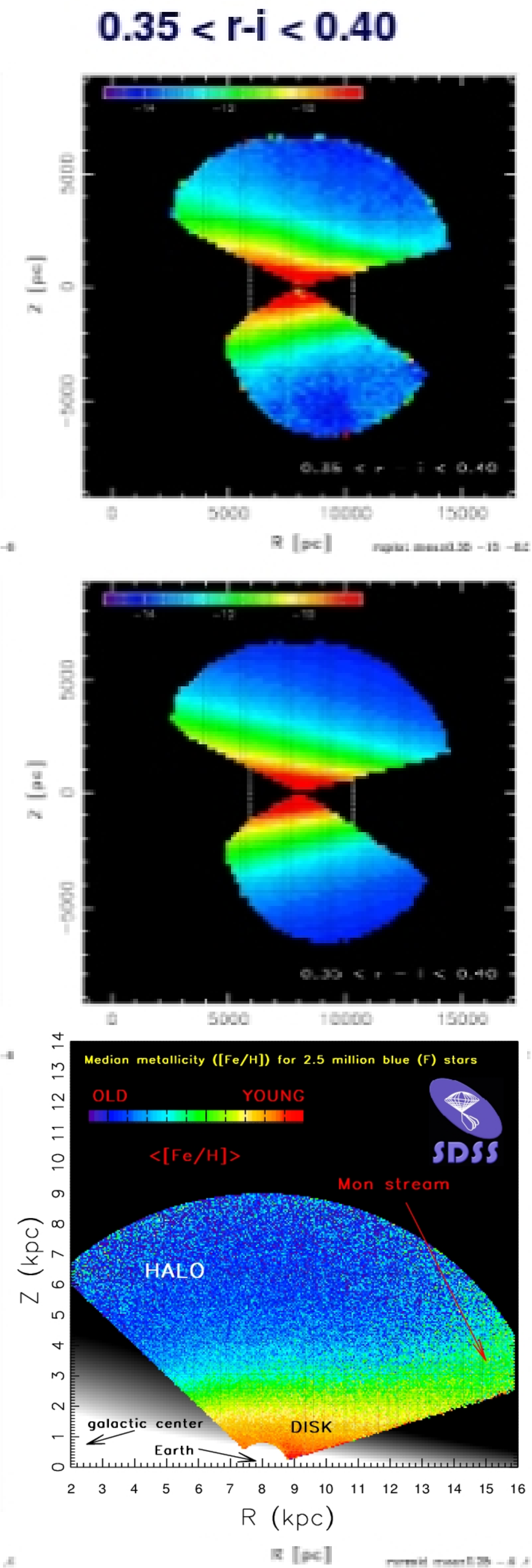
- Panoramic view of the Milky Way, akin to observations of external galaxies; good support for standard Galactic models (with amazing signal-to-noise!)
- Metallicity mapping supports components inferred from number counts mapping:





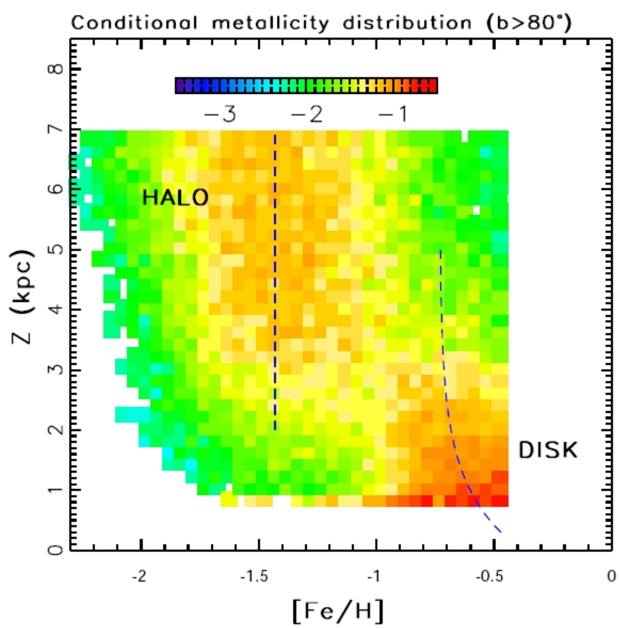


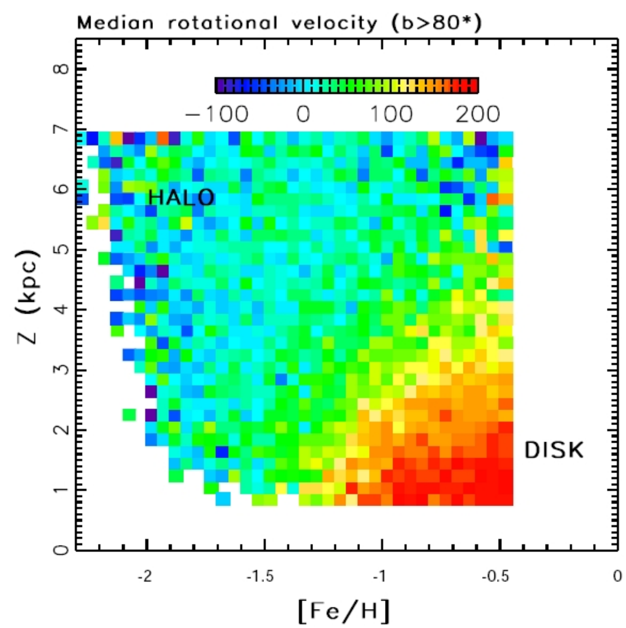




Dissecting the Milky Way with SDSS

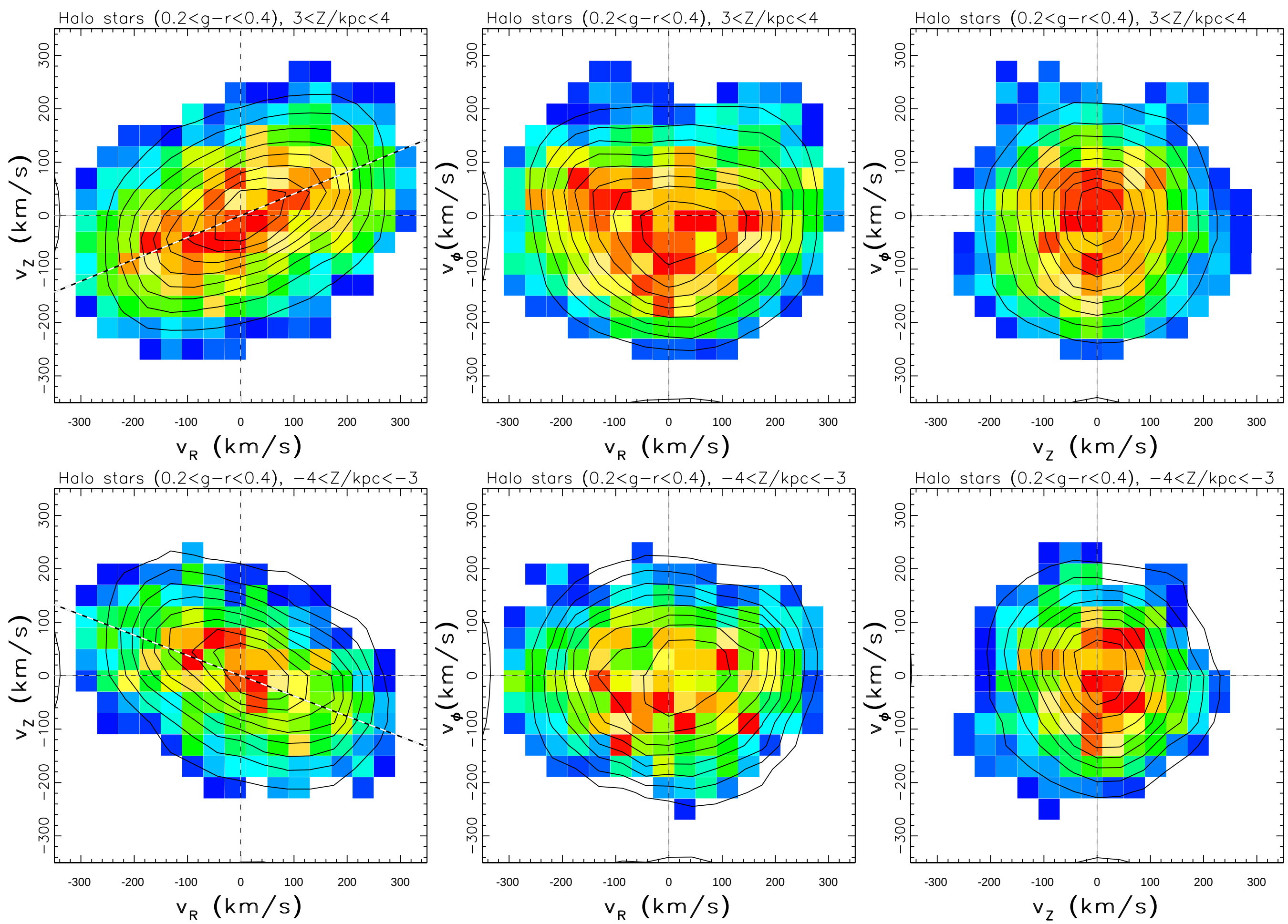
- Panoramic view of the Milky Way, akin to observations of external galaxies; good support for standard Galactic models (with amazing signal-to-noise!)
- Metallicity mapping supports components inferred from number counts mapping
- Kinematics correlated with metallicity: high-metallicity (disk) stars rotate, low-metallicity (halo) stars on random highly eccentric orbits





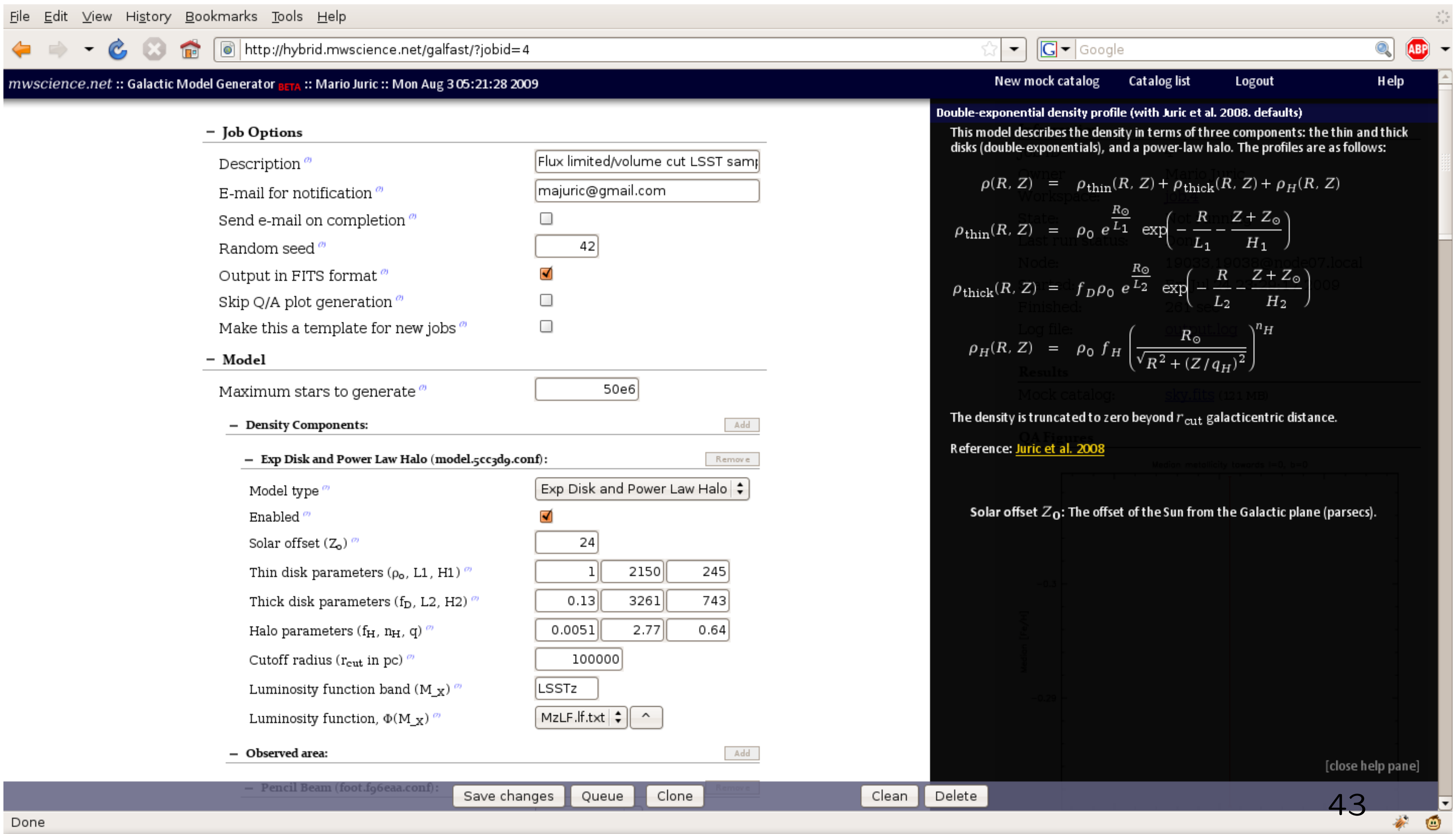
Halo Velocity Ellipsoid Tilt

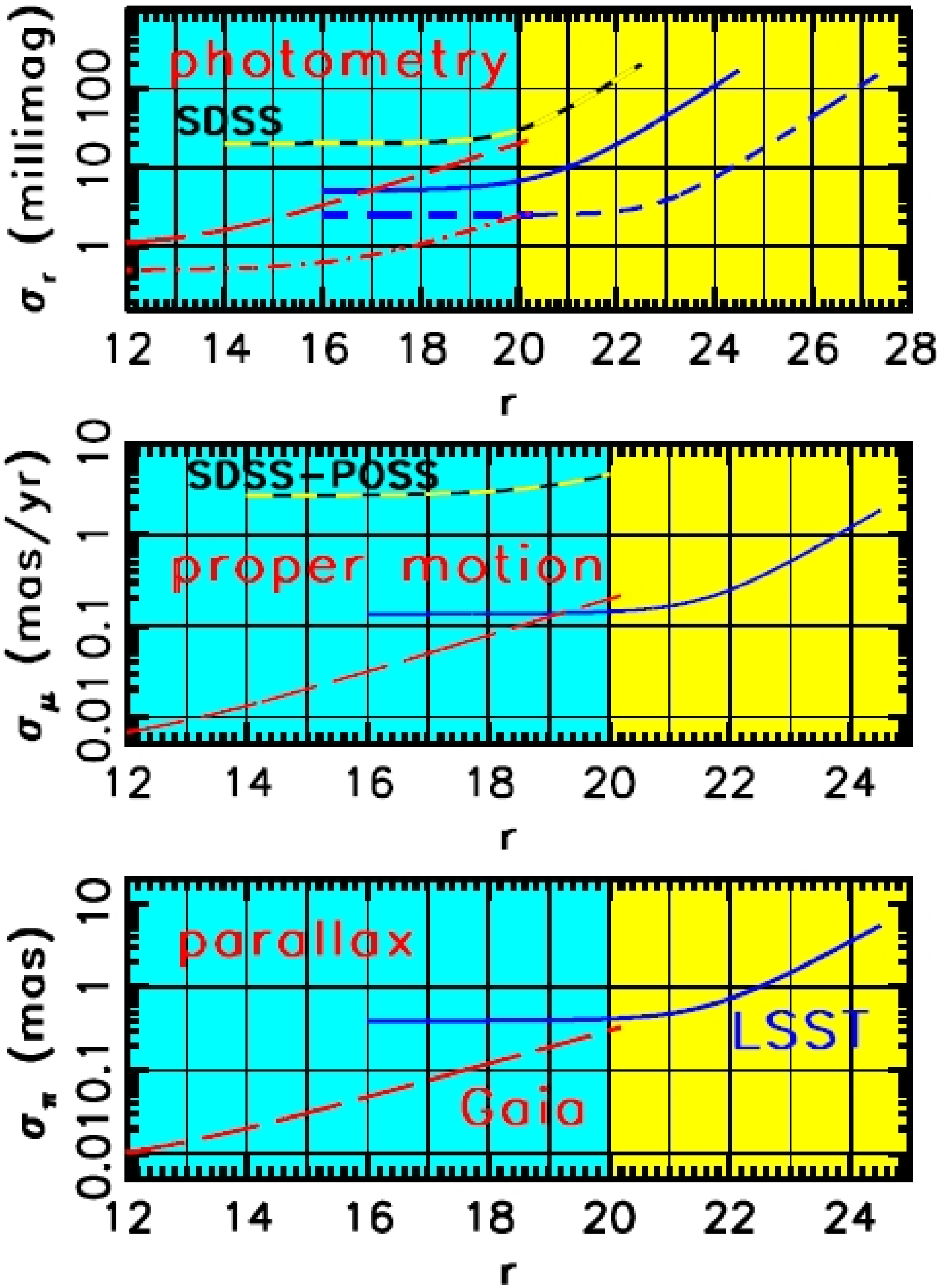
- Three two-dimensional projections of the velocity distribution for two subsamples of candidate halo stars ($[Fe/H] < -1.1$) with $6 < R/\mathrm{kpc} < 11$, and $3 < Z/\mathrm{kpc} < 4$ (top) and $-4 < Z/\mathrm{kpc} < -3$ (bottom)
- The v_Z vs. v_R velocity ellipsoid is aligned with spherical coordinate system (Bond et al. 2010). Confirms results of Smith et al. (2009) over 30 times larger area.



Empirical Model for Mock Catalogs: **Galfast**

- **Web service by Mario Jurić** based on smooth spatial, metallicity and kinematics distributions measured by SDSS
- Available from www.mwscience.net/galfast
- A valuable tool when searching for substructure in data, or comparing to theoretical models
- For example, can easily make mock catalogs for surveys such as SDSS, Pan-STARRS, Gaia, ODI and LSST



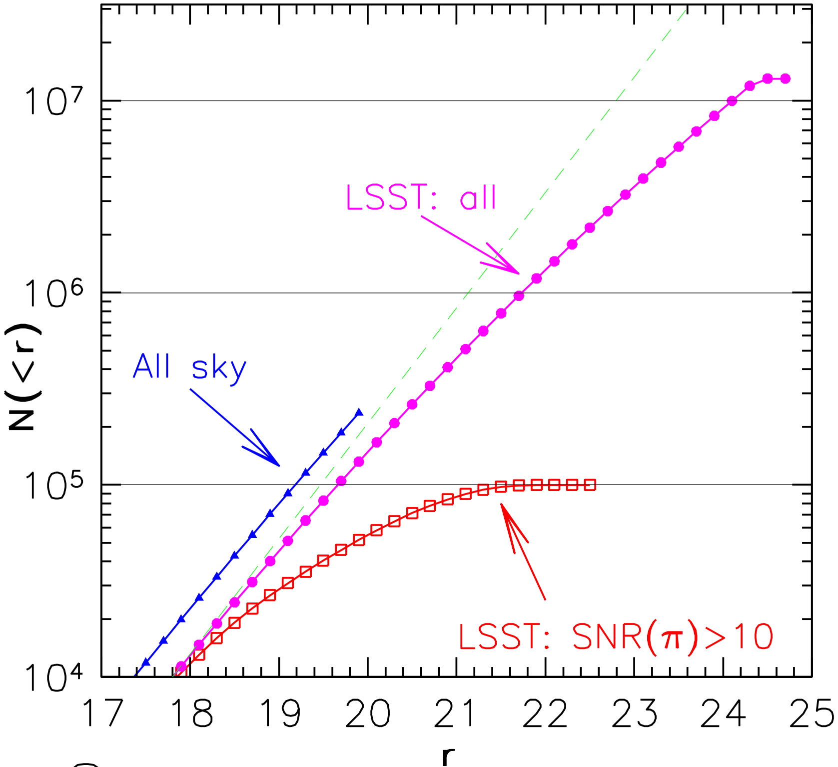


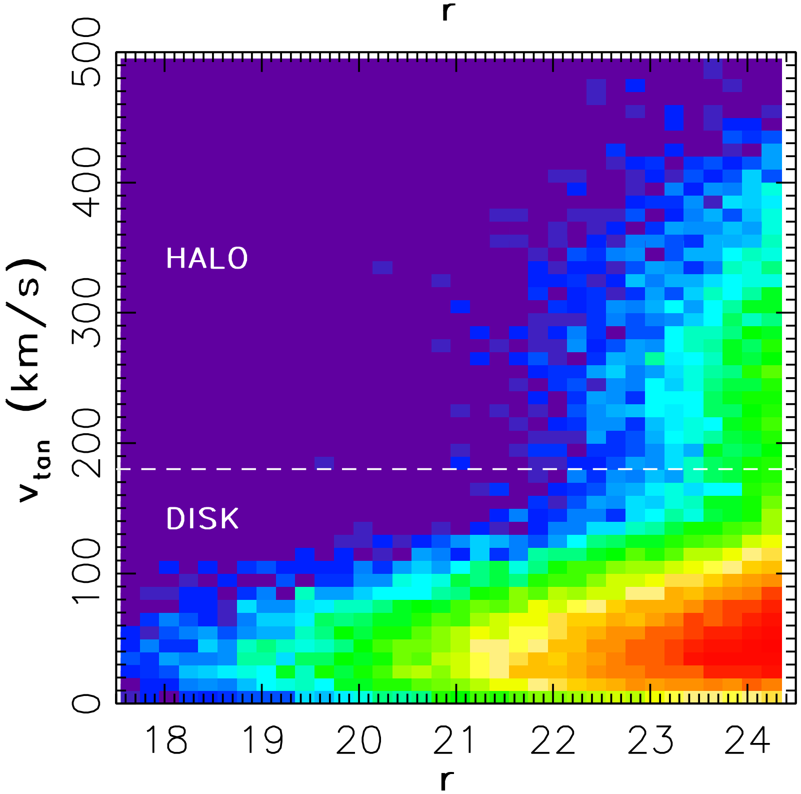
Gaia vs. LSST Comparison

- **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 $r \sim 20$

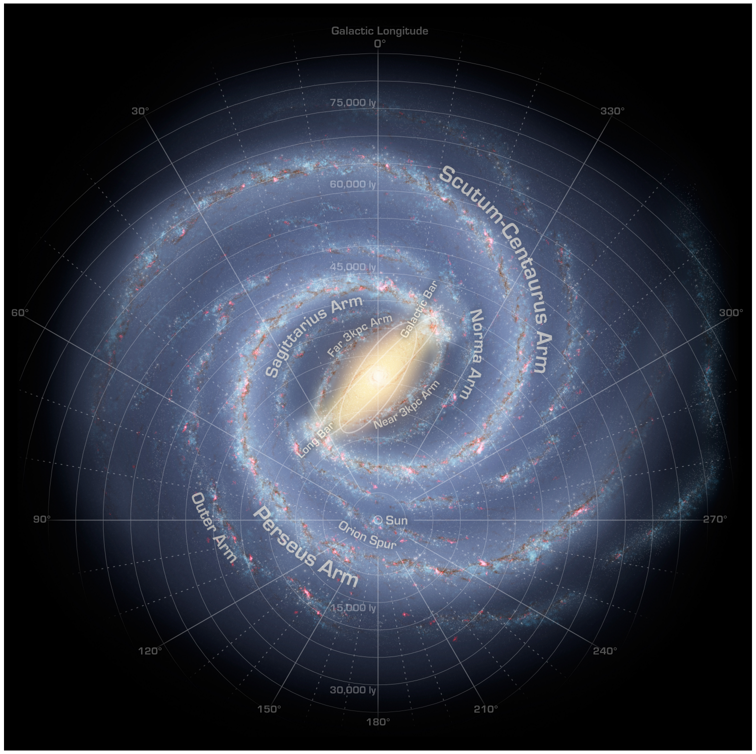
The Milky Way disk "belongs" to Gaia, and the halo to LSST (plus very faint and/or very red sources, such as white dwarfs and LT(Y) dwarfs).

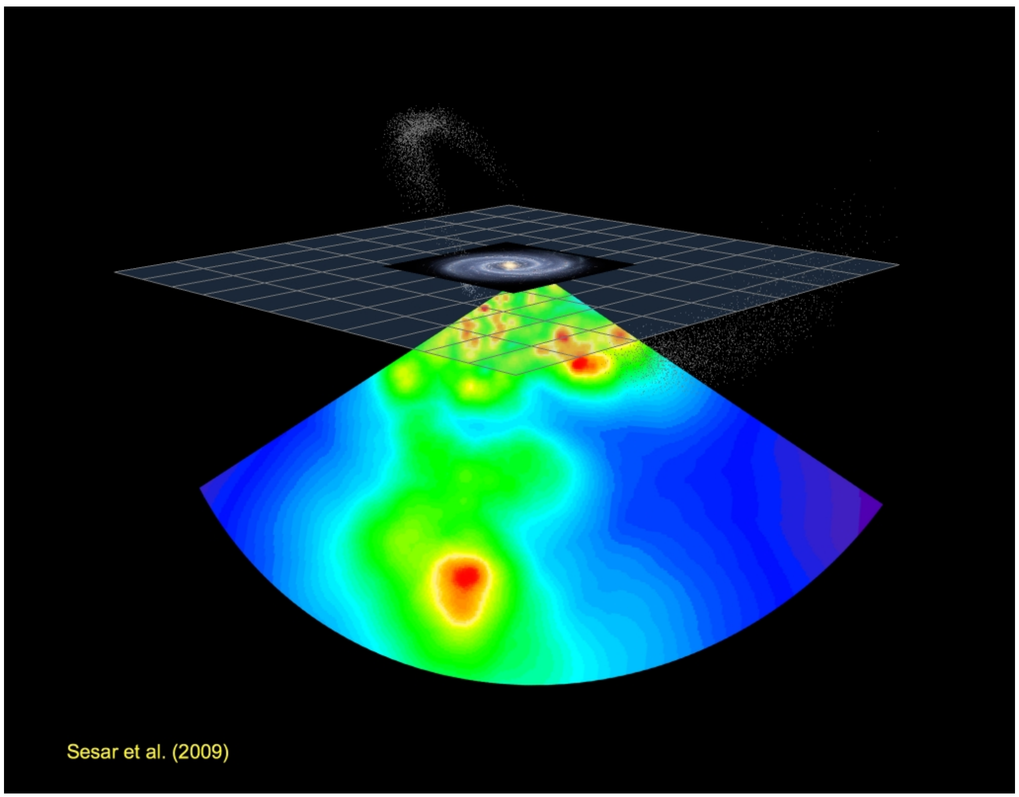
White Dwarfs with LSST





- **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**





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. 2010), 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 $\rho(R) \propto R^{-3}$.

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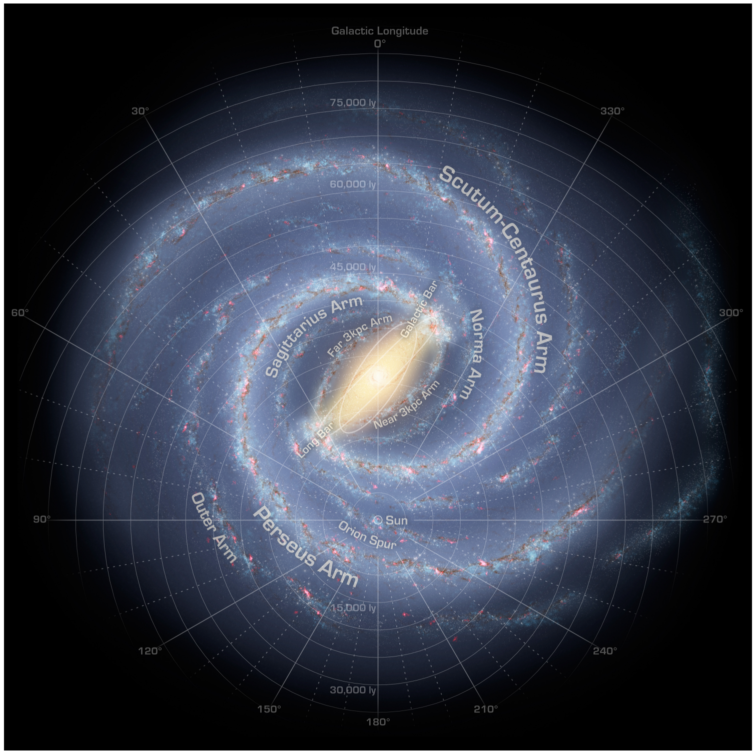

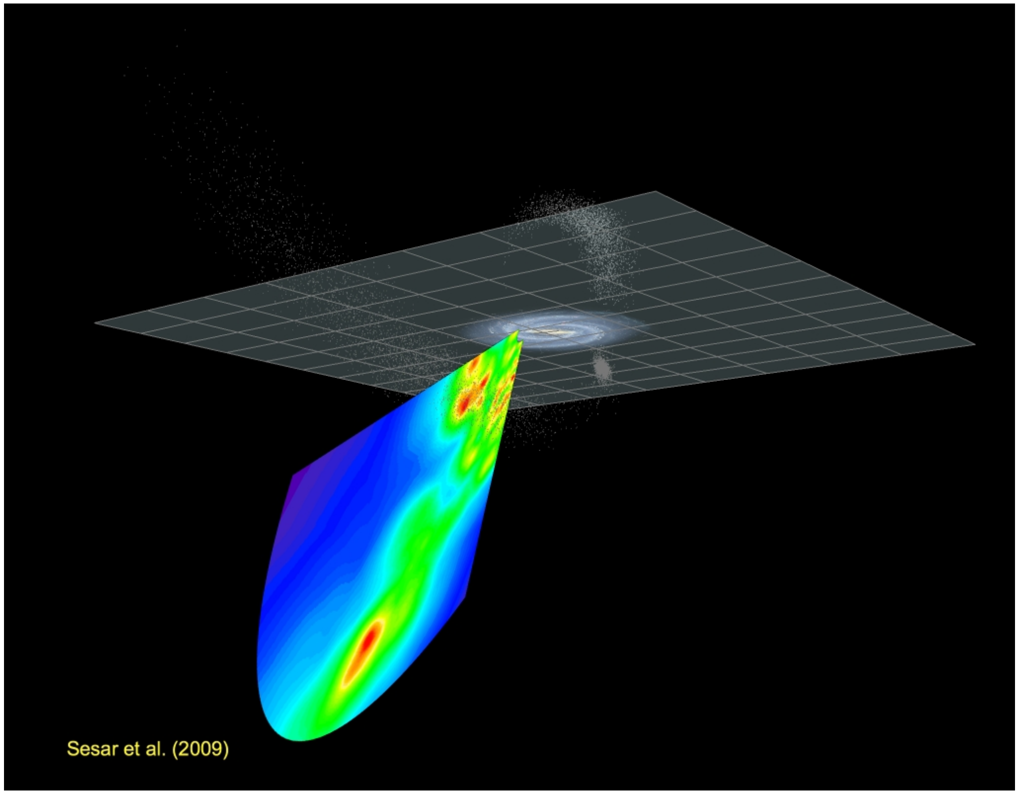

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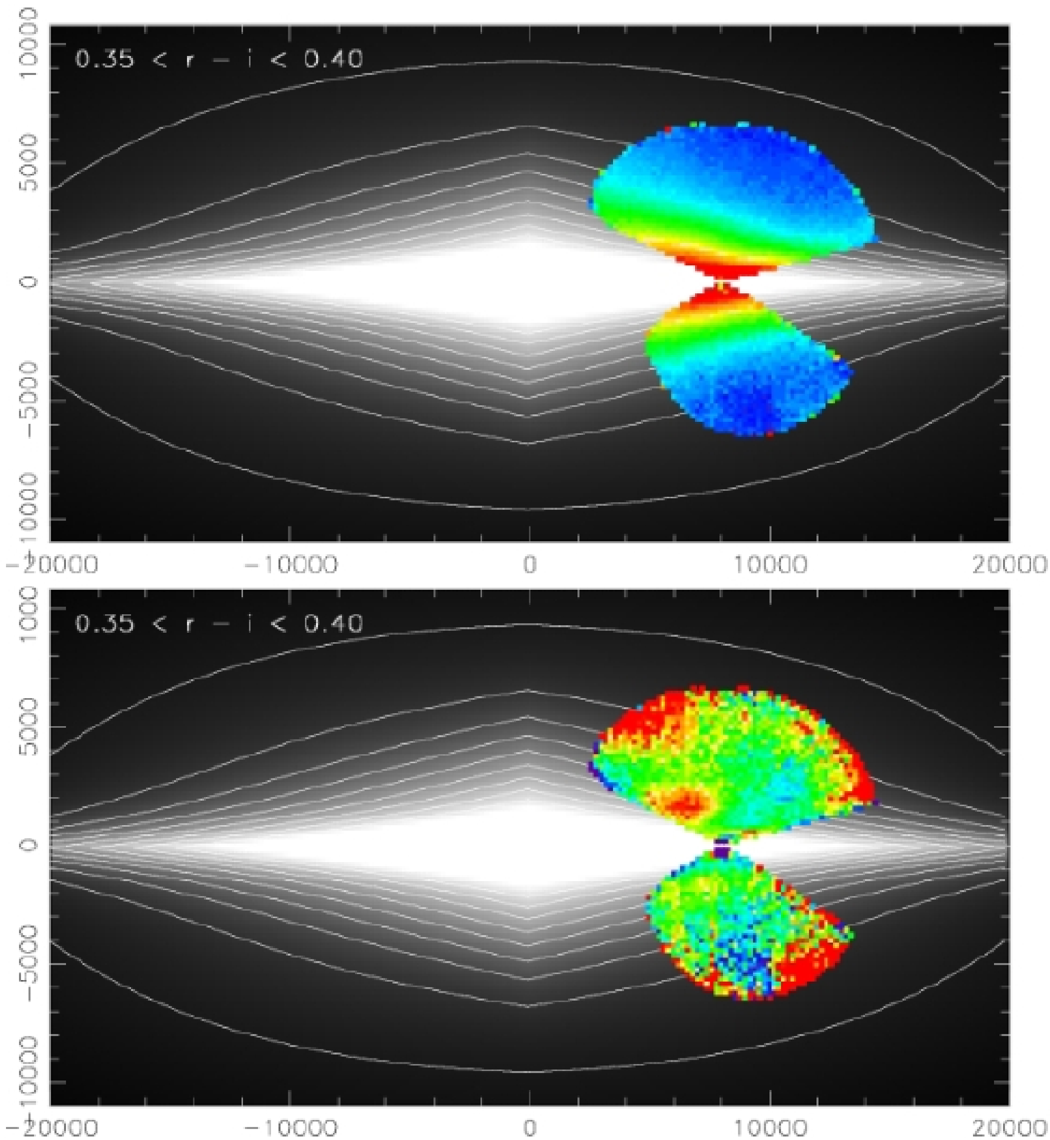
- Conclusions: the spatial distribution of halo stars is highly inhomogeneous (clumpy); when averaged, the stellar volume density decreases as $\rho(R) \propto R^{-3}$. **Limited by data!**



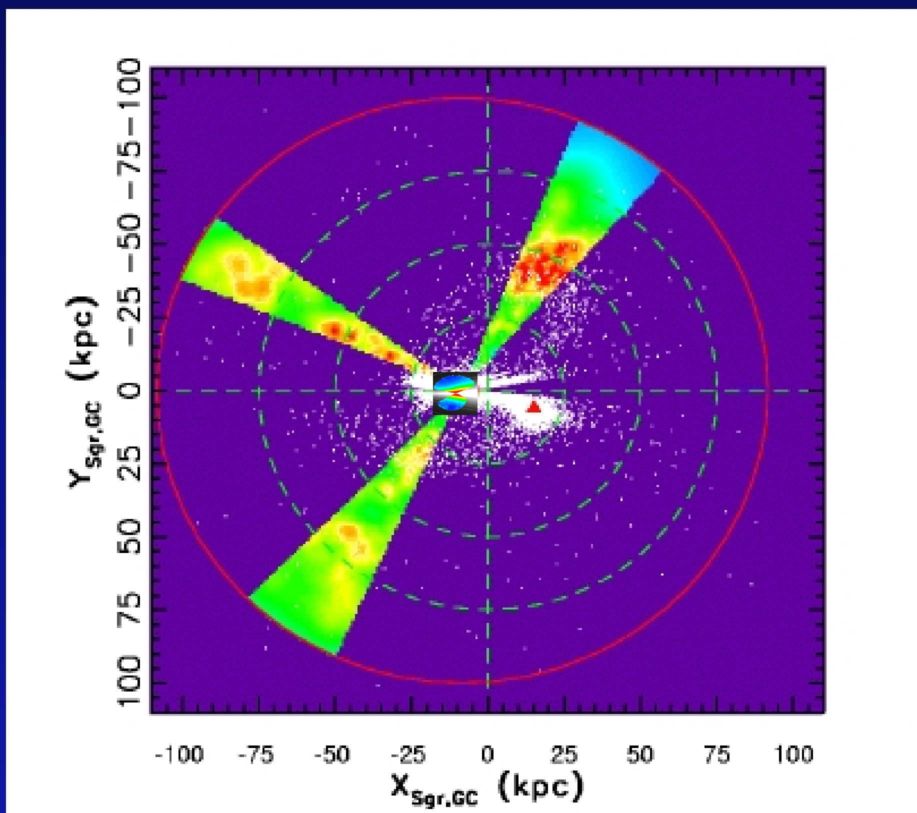
The limitations of SDSS data

- **Sky Coverage:** SDSS ∼1/4 of the sky, LSST over 1/2
- **Depth:** SDSS main-sequence stars to ∼10 kpc; RR Lyrae stars to 100 kpc; LSST to 100 kpc and 400 kpc, respectively
- **Photometric Accuracy:** SDSS: photometric metallicity accurate to ∼0.2 dex; LSST better than 0.1 dex
- **Astrometric Accuracy:** SDSS: proper motion accurate to 3 mas/yr; with LSST 0.2 mas/yr

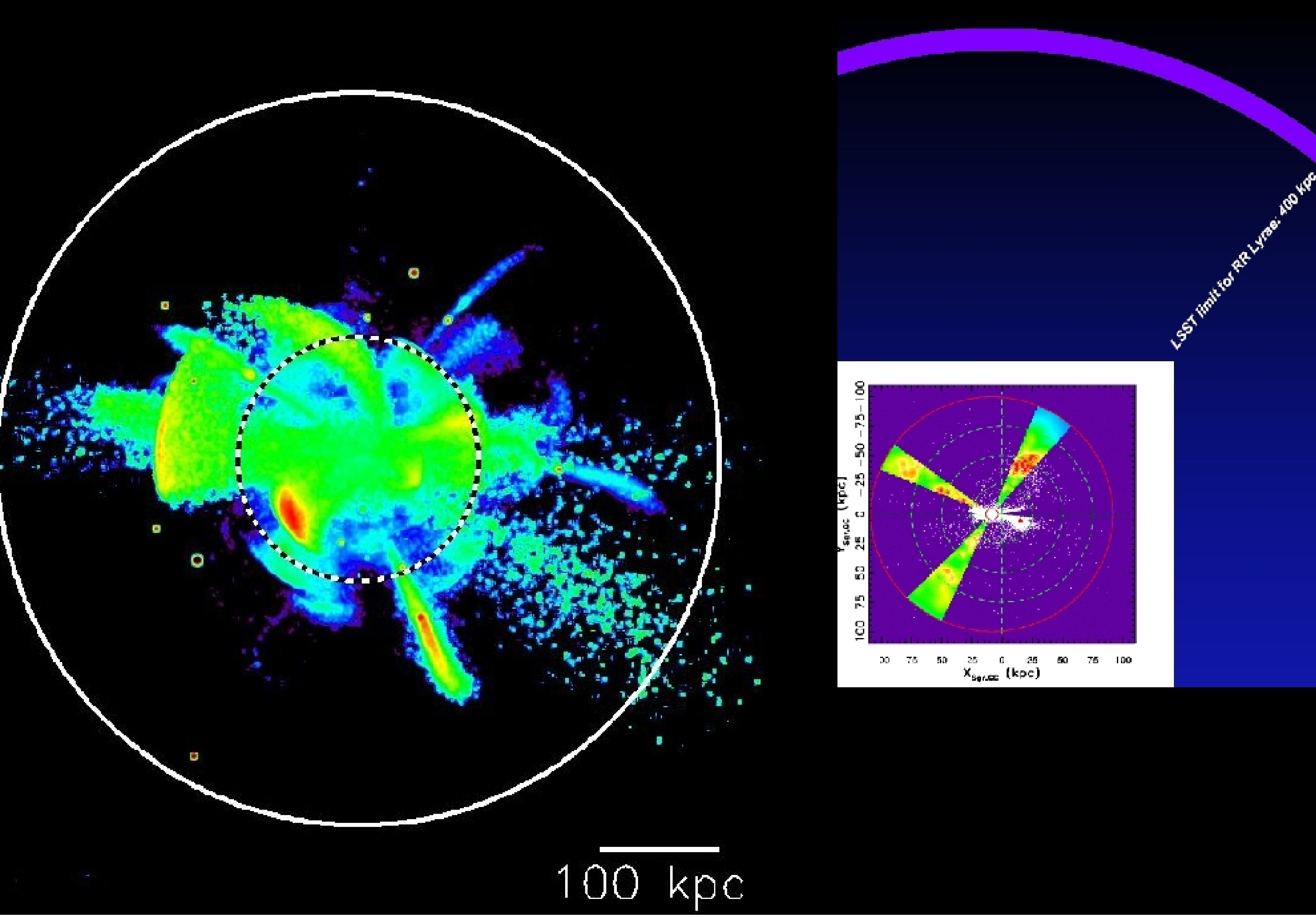
The large blue circle: the ∼400 kpc limit of future LSST studies based on RR Lyrae

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

The Excitement of 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)

LSST data will tell us whether the recent cosmological acceleration is due to dark energy or modified gravity.

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)