Mapping the Milky Way with SDSS and LSST

Željko Ivezić

Department of Astronomy
University of Washington

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Outline

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1. **The Era of Large Optical Surveys:** from SDSS to LSST

2. **The Milky Way Structure:** as seen by SDSS

   - Maps of the stellar distribution, metalicity and kinematics using main sequence stars within 10 kpc

   - Difficulties with thin/thick disk decomposition

   - Halo structure with RR Lyrae to 100 kpc

   - 3D maps of dust distribution and R_V

3. **Extrapolation to LSST:** a step forward by a factor of 100

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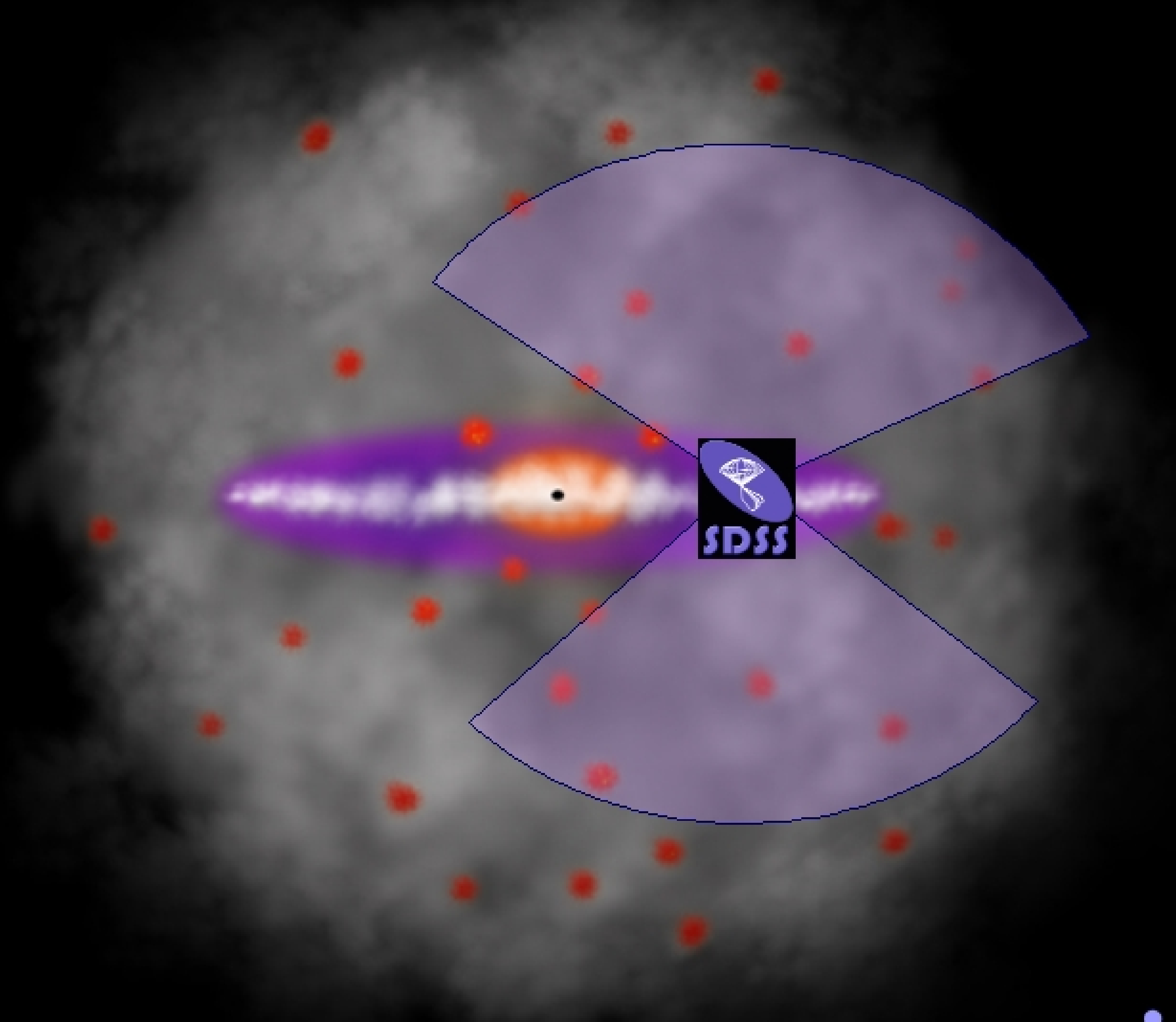
What will LSST do?
the first digital color movie of the sky

SDSS results can be used to "predict" the impact of LSST
A case study: the Milky Way structure "Near-field Cosmology"

Classical Decomposition of the Milky Way Components



- Thin/thick disk
- Galactic bulge
- Stellar halo

- Components trace the DM dominated potential

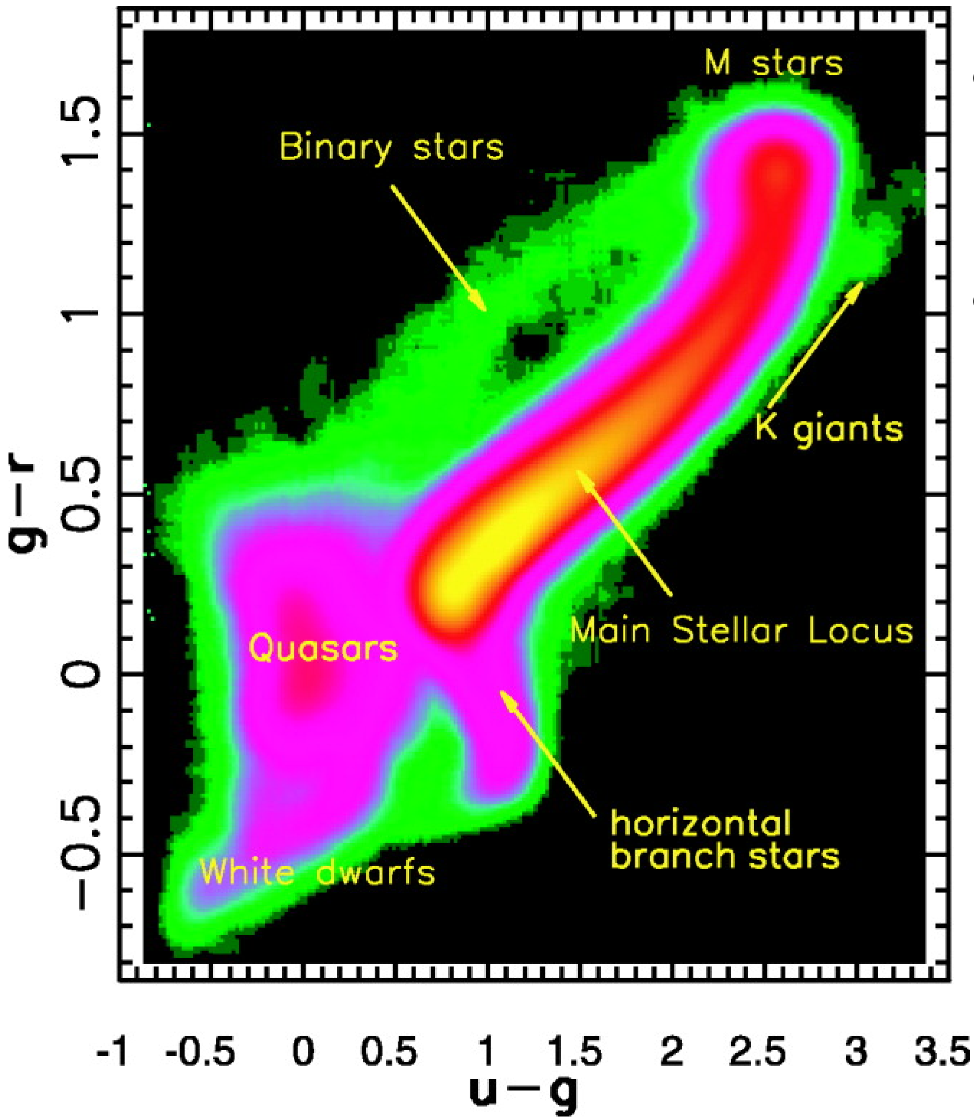
- They are a product of Milky Way formation and evolution

A Brief Overview of SDSS

- Imaging and Spectroscopic Survey
  - $\sim$10,000 deg^2 (1/4 of the full sky)
  - 5 bands (ugriz: UV-IR), 0.02 mag photometric accuracy
  - $<$ 0.1 arcsec astrometric accuracy
  - Over 100,000,000, mostly main sequence, stars
  - Spectra for $>$200,000 stars (radial v to $\sim$10 km/s)

- Advantages for studying the Milky Way structure
  - Accurate photometry: distance and [Fe/H] estimates
  - Numerous stars: small random errors for number density
  - Large area and faint limit: good volume coverage

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!)**

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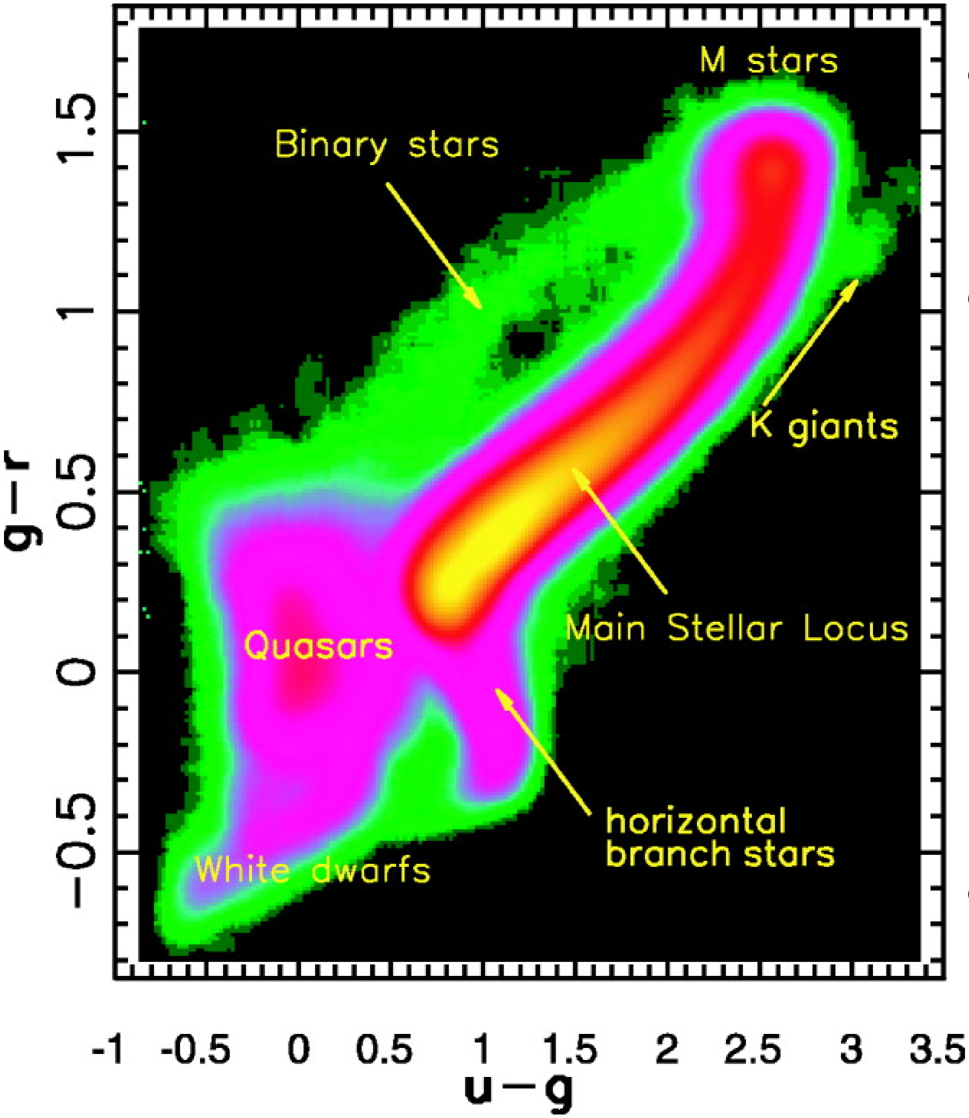

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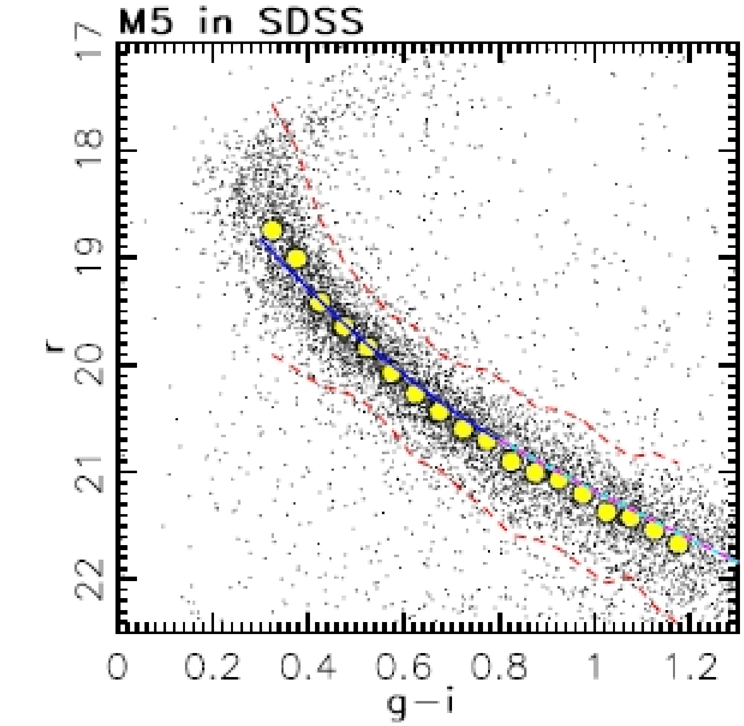
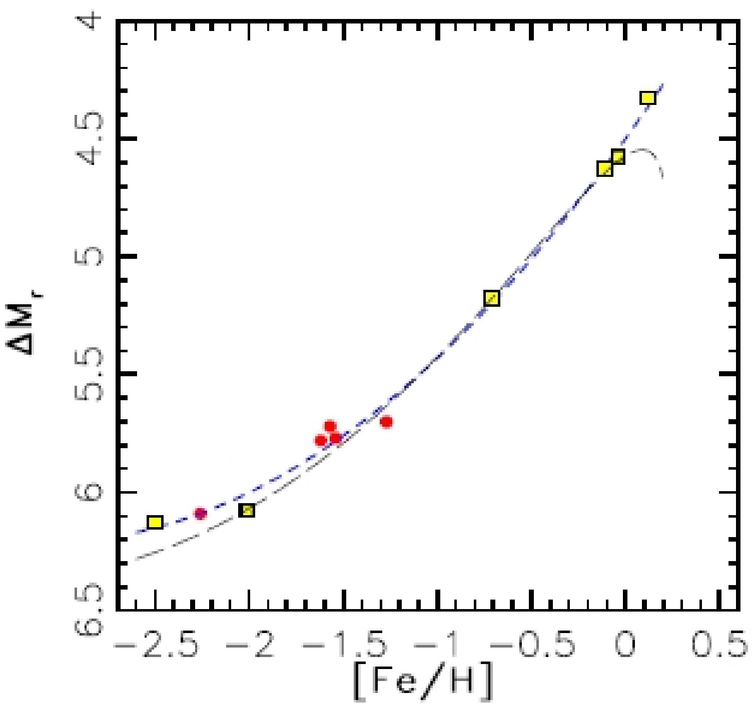
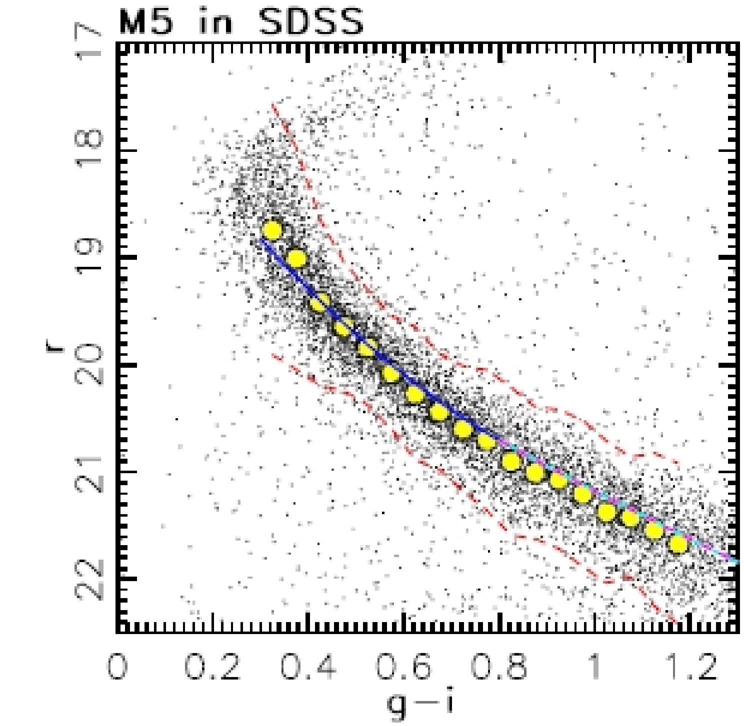
- Accurate $u - g$ color enables photometric metallicity estimates for 6 million SDSS F/G stars to 10 kpc; **(with LSST 200 million to 100 kpc!)**

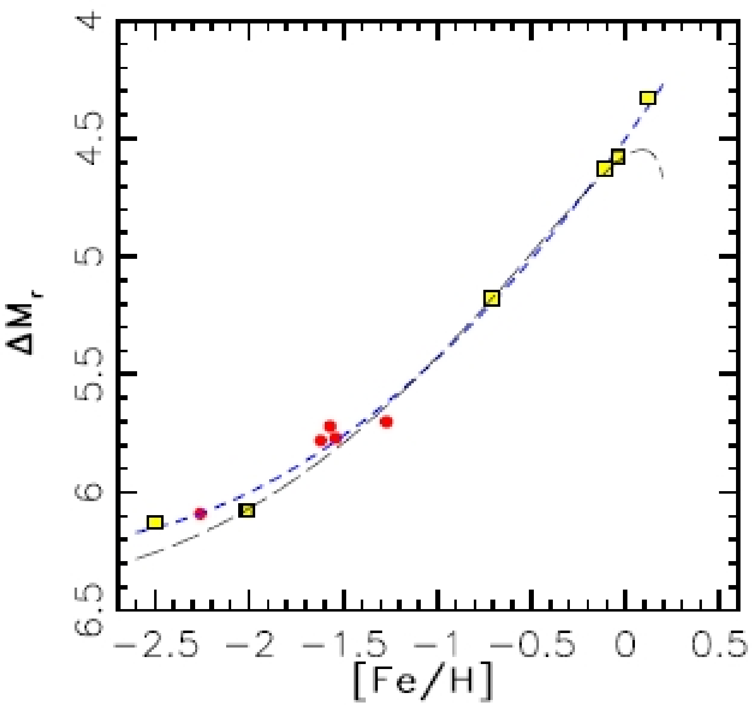




Photometric Distance and Photometric [Fe/H]

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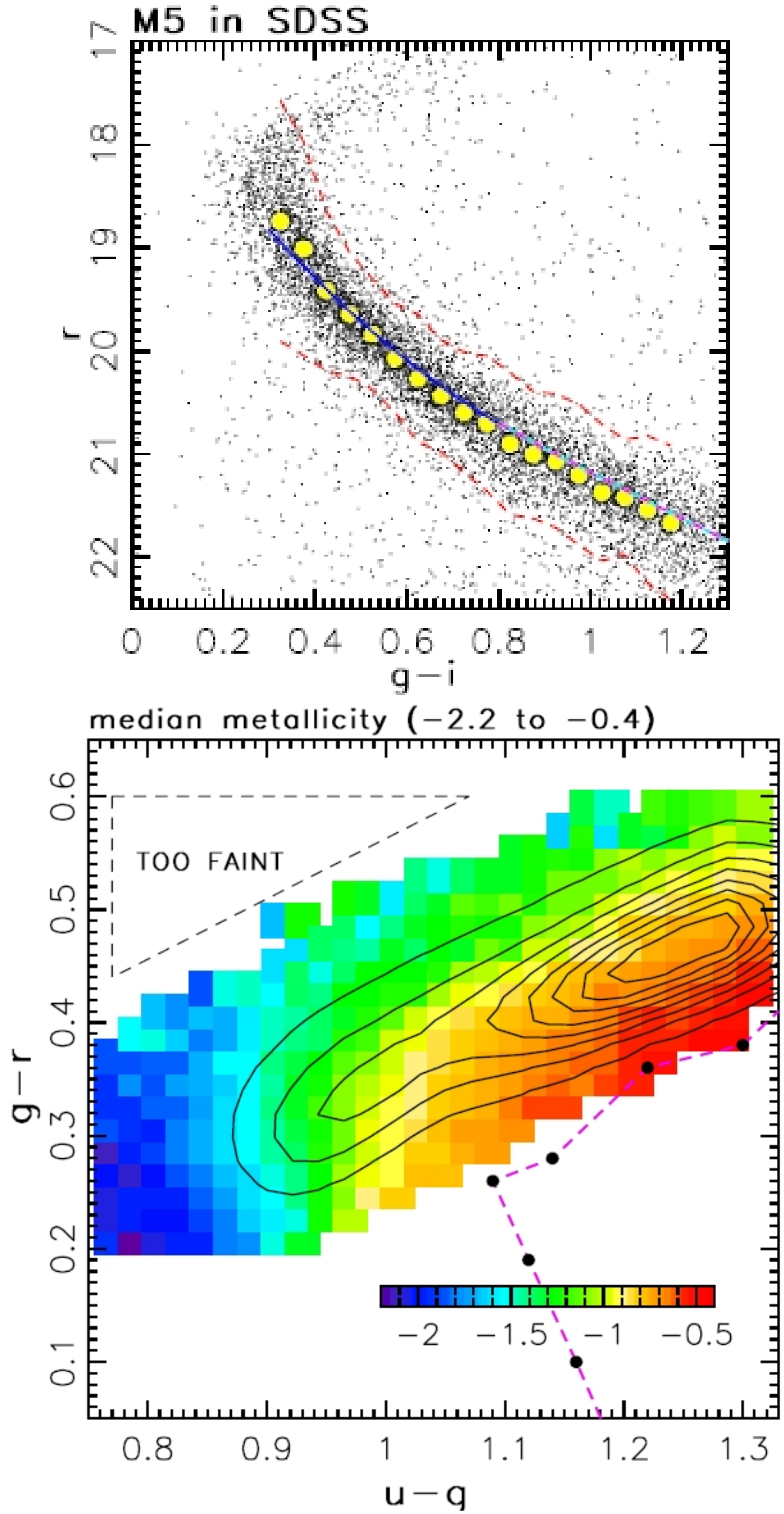
This method was known half a century ago, but never before applied to tens of millions of stars because large-scale surveys did not have the required photometric accuracy



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- **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!

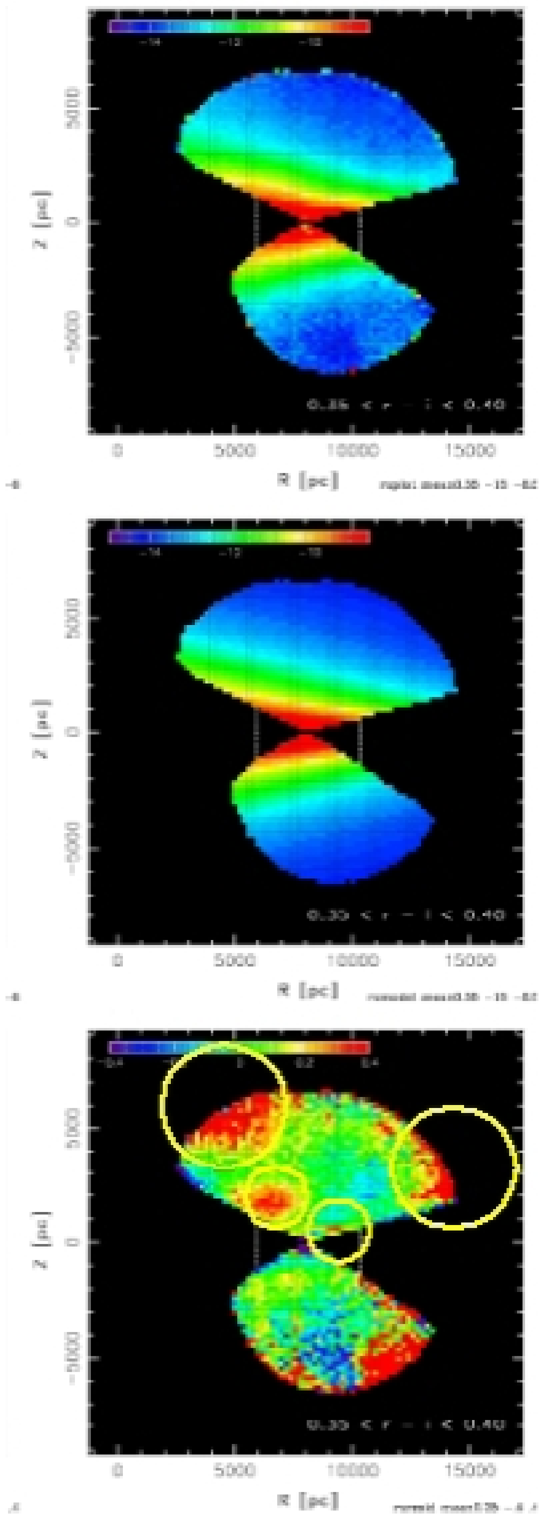
Dissecting Milky Way with SDSS: a New Tool

Good ugriz photometry gives decent distance estimates for PRACTICALLY EVERY SINGLE STAR (and for F/G stars metallicity too) within areal and flux limits, and greatly simplifies the data analysis:

- Traditional approach: assume initial mass function, fold with models for stellar evolution; assume mass-luminosity relation; assume some parametrization for the number density distribution; vary (numerous) free parameters until the observed and model counts agree. Uniqueness? Validity of all assumptions?

- SDSS photometric parallax approach: adopt color-luminosity relation, estimate distance to each star, bin the stars in XYZ space and directly compute the stellar number density (for each narrow color bin). There is no need to a priori assume, the number of, and analytic form for Galactic components

0.35 < r-i < 0.40

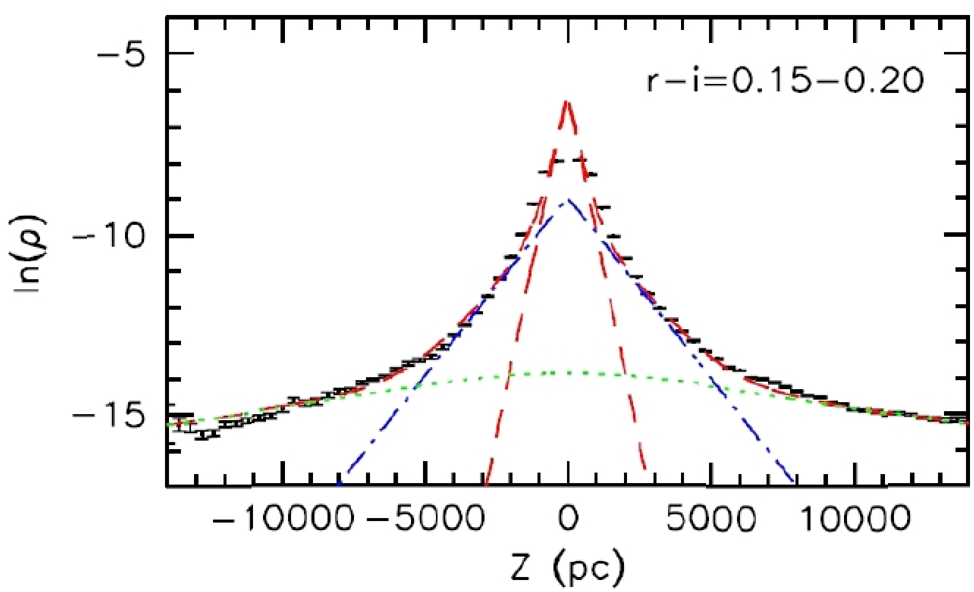


Dissecting the Milky Way with SDSS

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

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

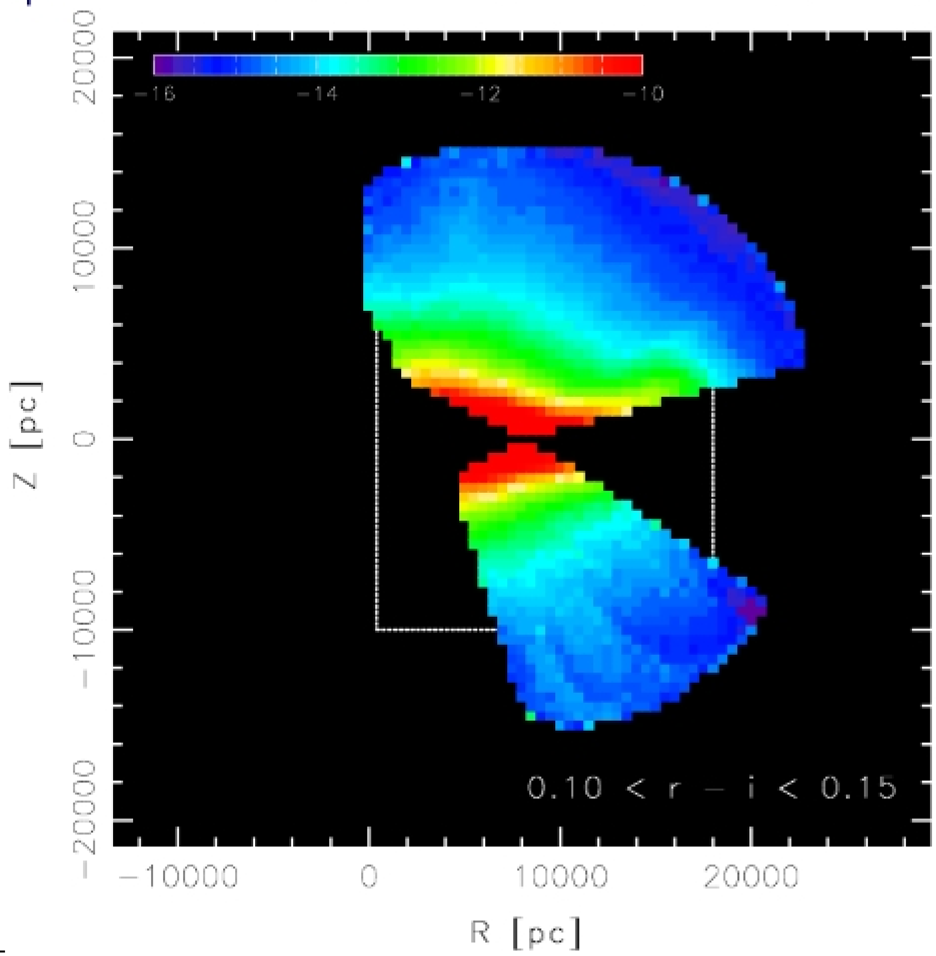
$$\rho(R,Z) = \rho_{thin} e^{-\frac{R-R_e}{l_{thin}} - \frac{|Z+Z_0|}{h_{thin}}} + \rho_{thick} e^{-\frac{R-R_e}{l_{thick}} - \frac{|Z+Z_0|}{h_{thick}}} + \rho_{halo} \left(\frac{R_{GC}}{\sqrt{R^2 + (z+z_0)^2 / q^2}} \right)^n$$

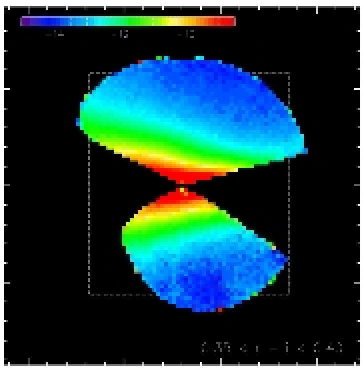


The r-i color bins sample a variety of scales

19 r–i color bins – 19 density maps

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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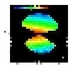
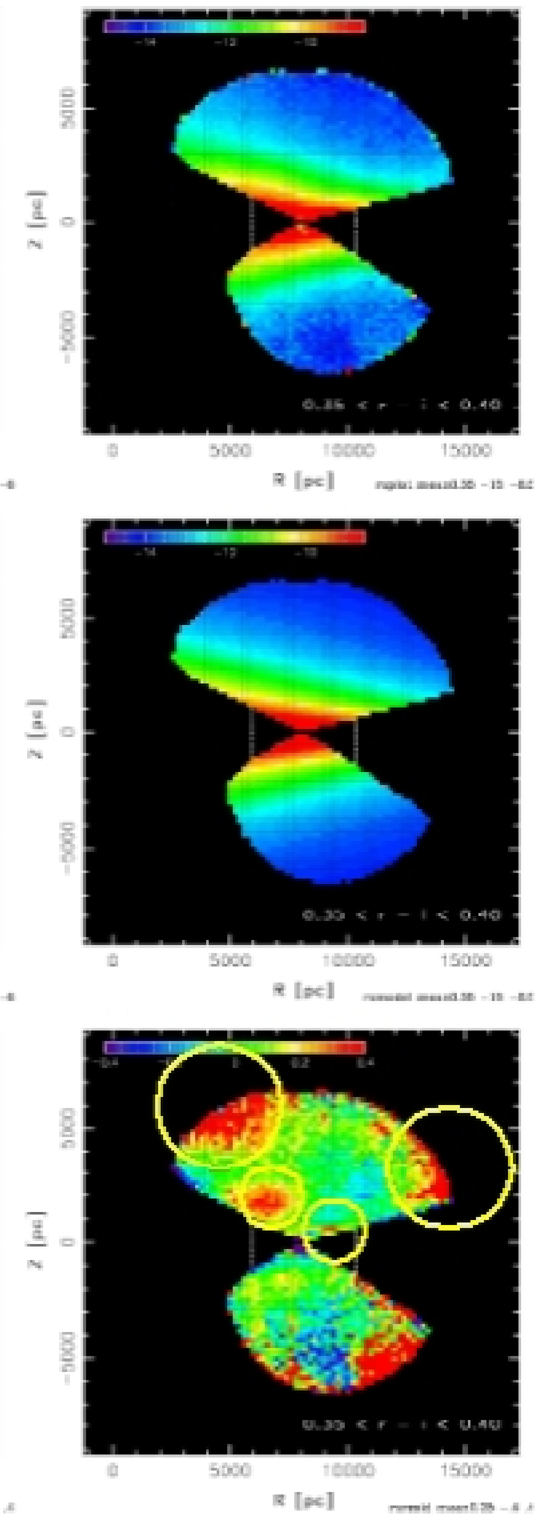


1.3 < r-i < 1.4

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

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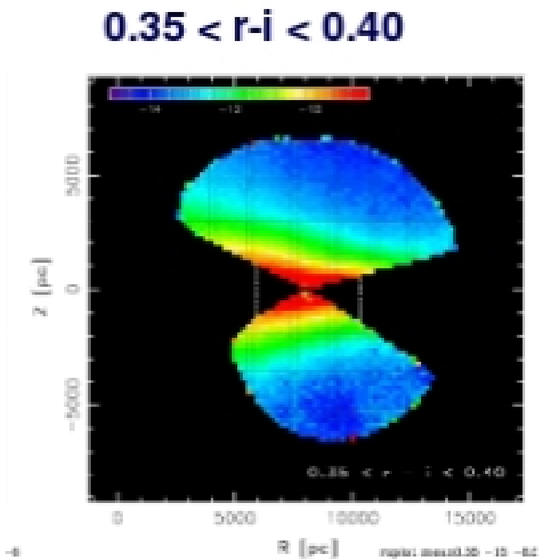
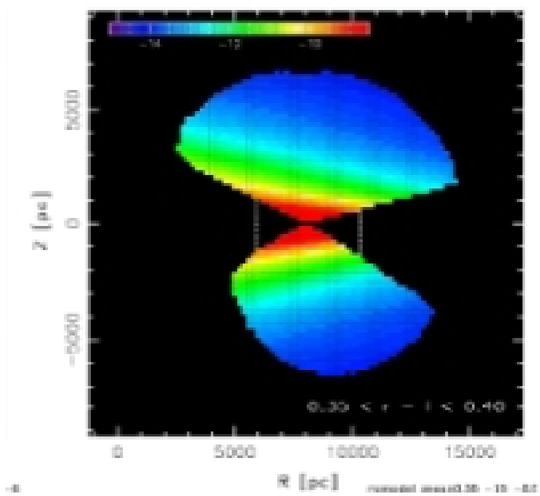
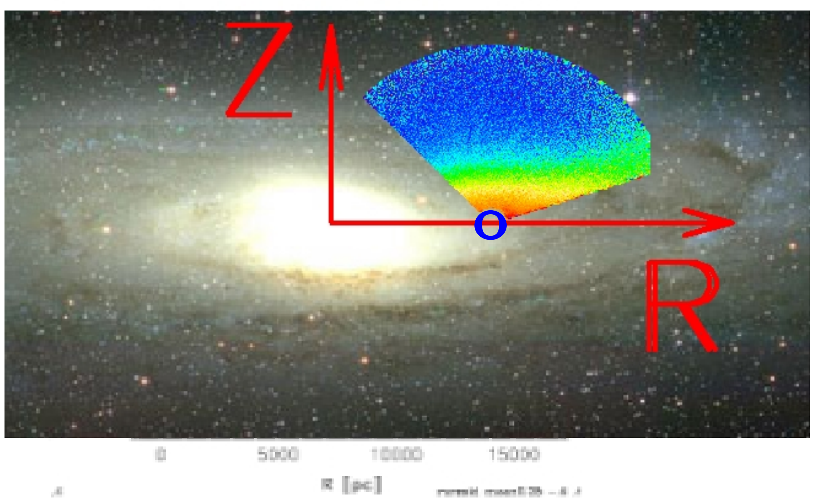
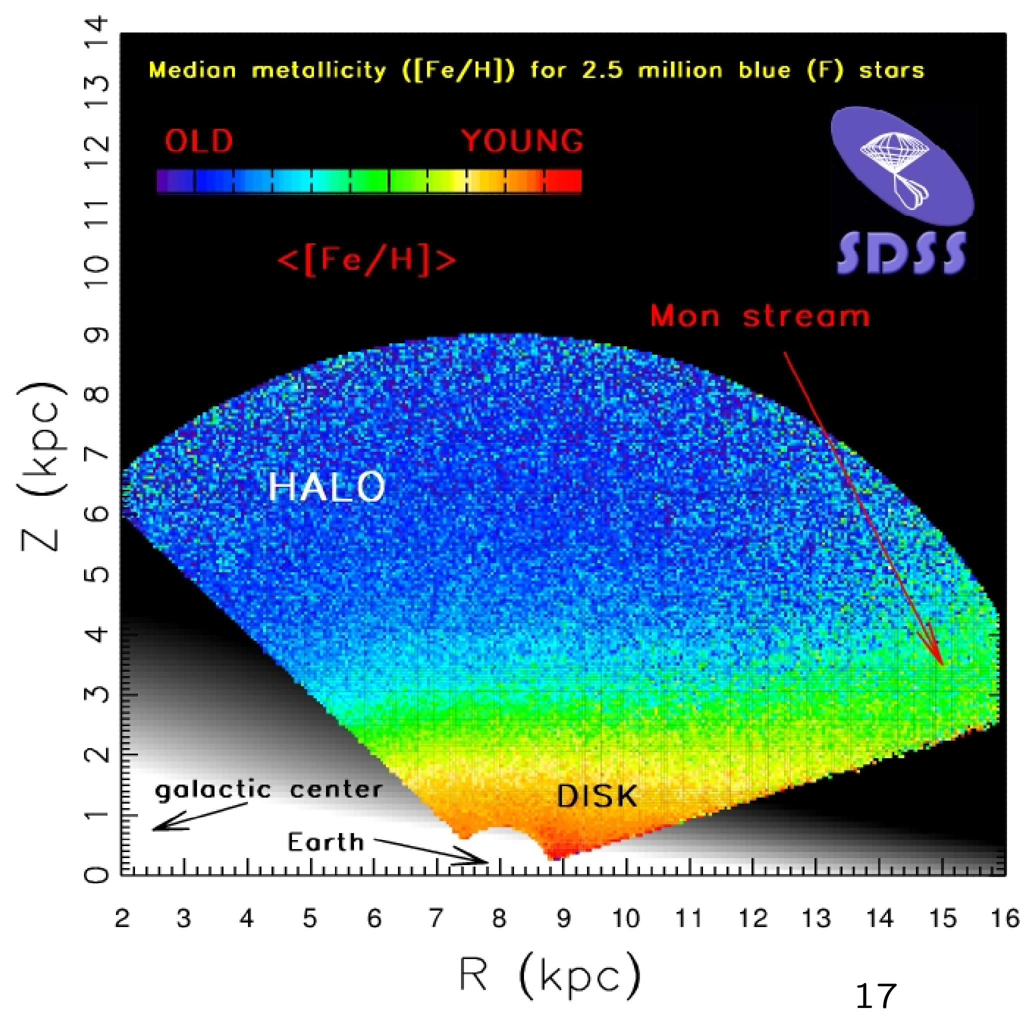
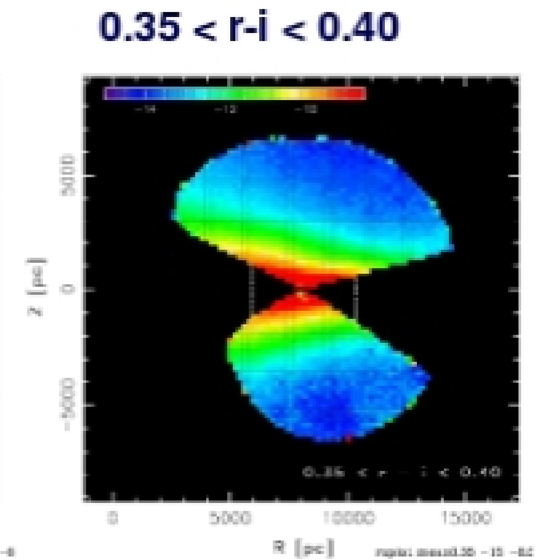
- Metallicity mapping supports components inferred from number counts mapping:

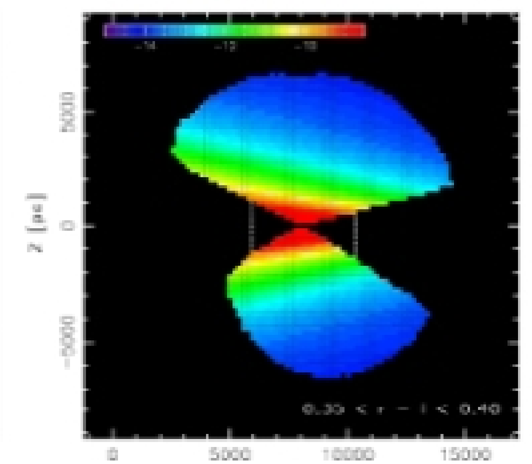


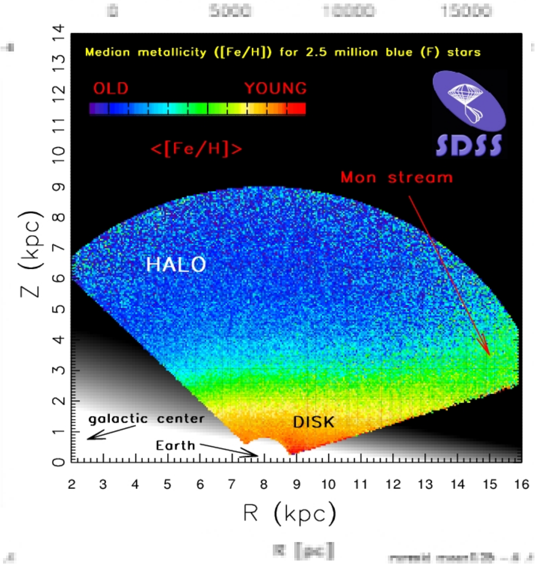












Dissecting the Milky Way with SDSS

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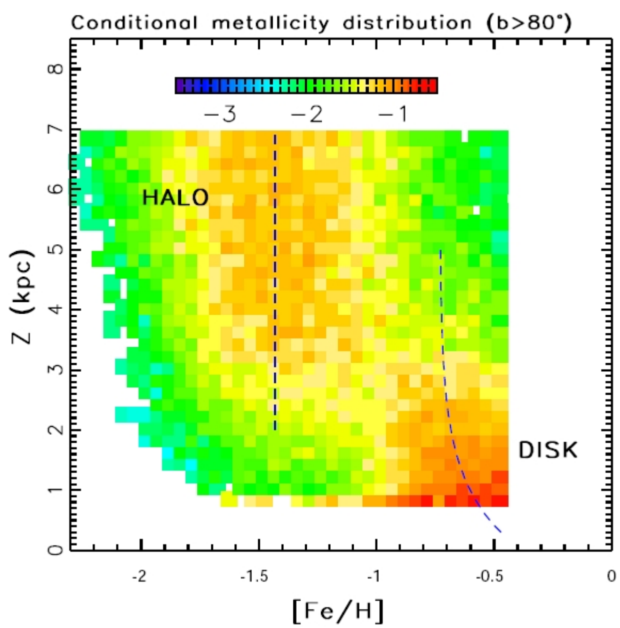
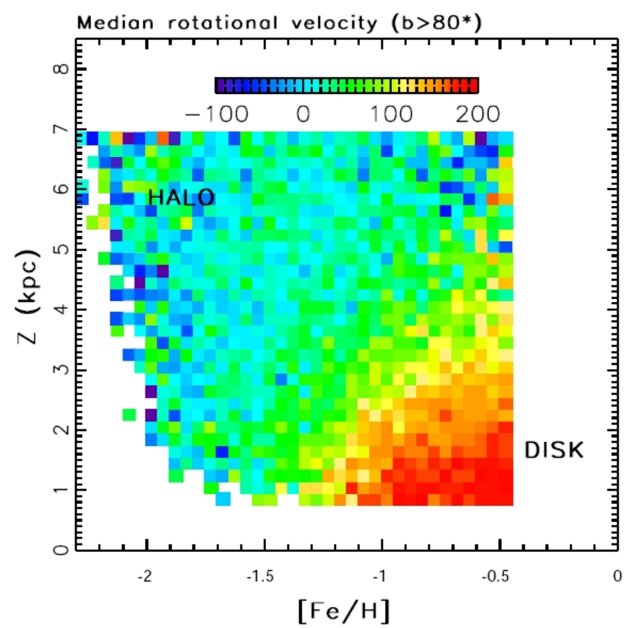
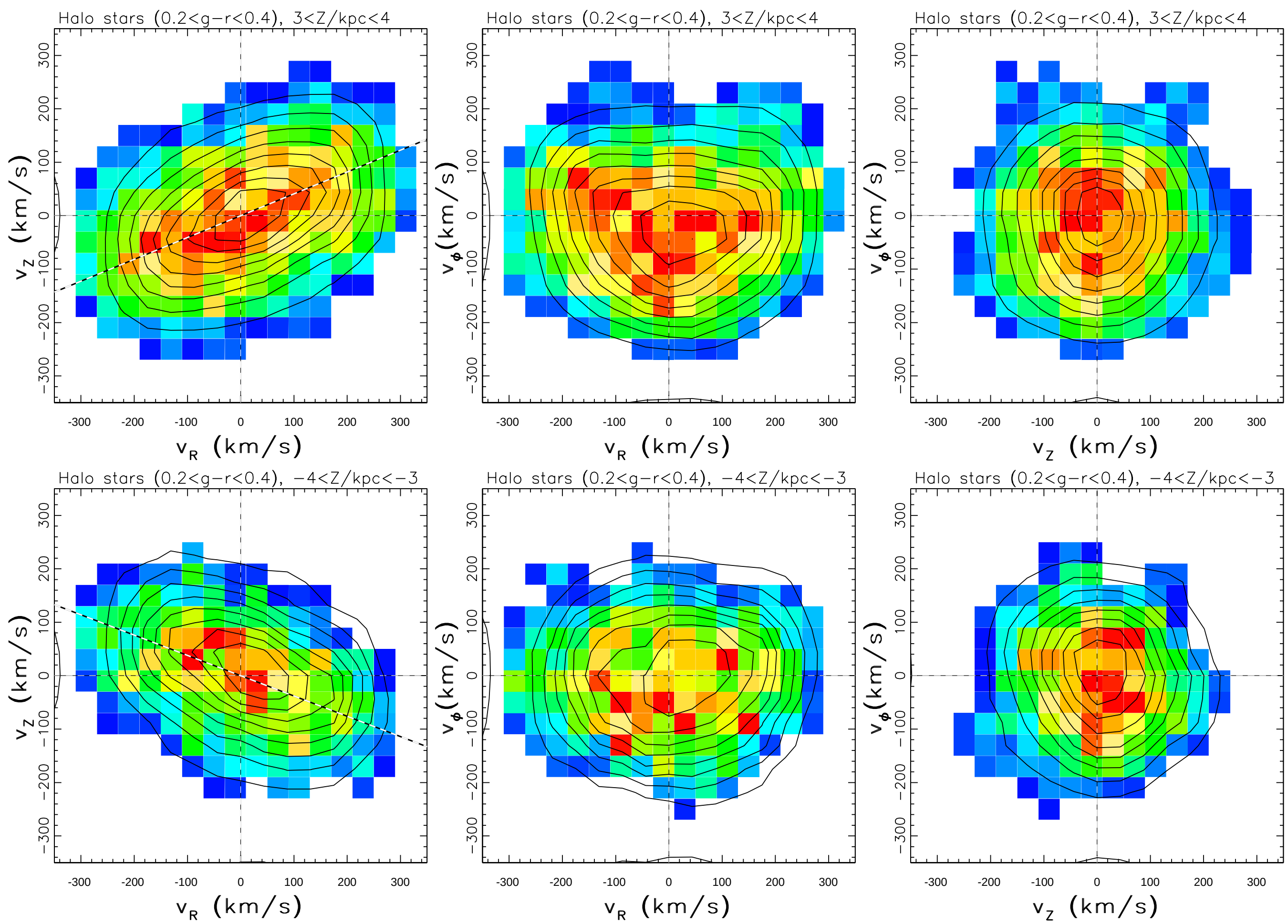
- Metallicity mapping supports components inferred from number counts mapping
- Kinematics correlated with metallicity: high-metallicity (disk) stars rotate, low-metallicity (halo) stars on random highly eccentric orbits





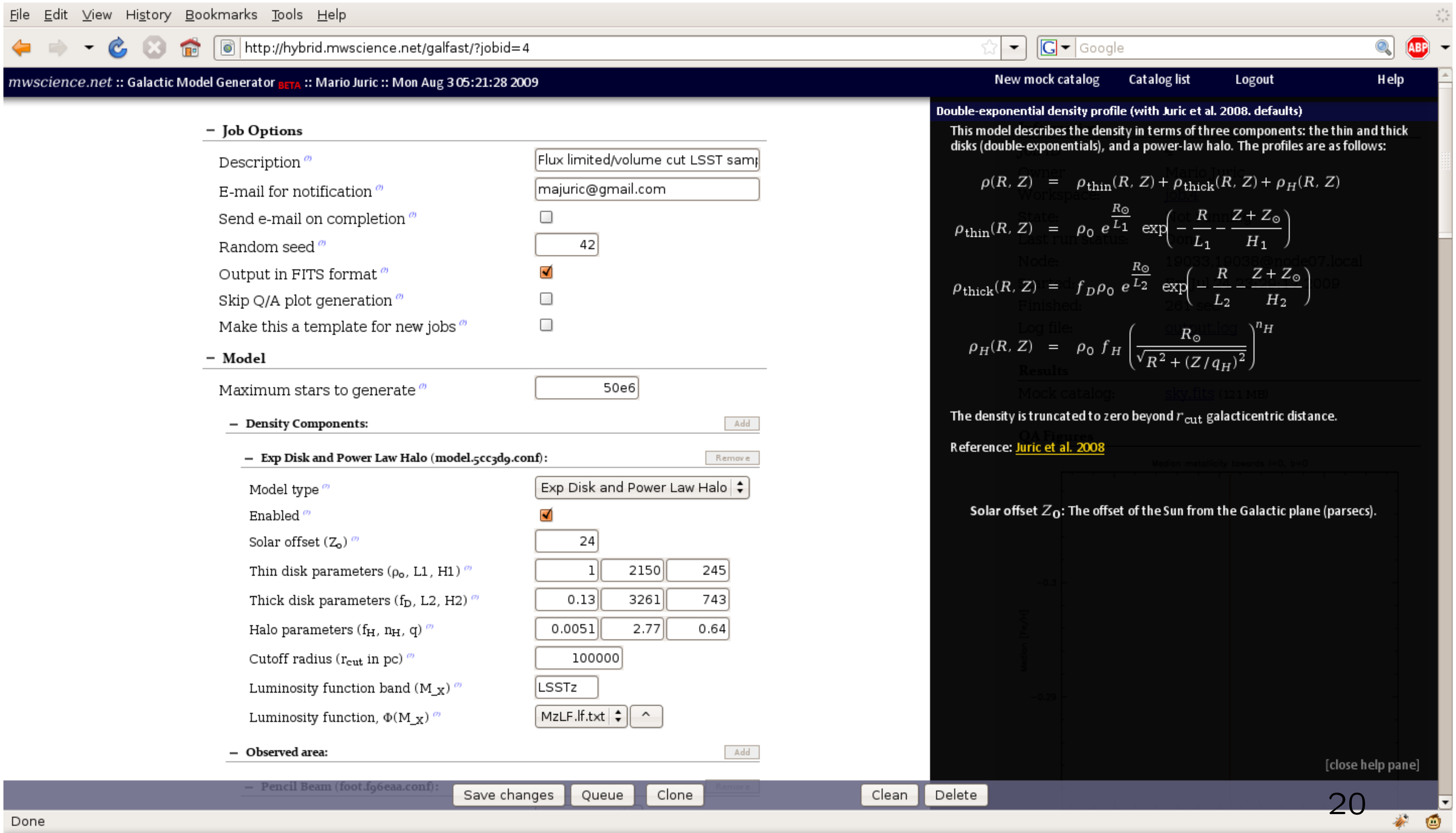
Halo Velocity Ellipsoid Tilt

- Three two-dimensional projections of the velocity distribution for two subsamples of candidate halo stars ($[Fe/H] < -1.1$) with $6 < R/\text{kpc} < 11$, and $3 < Z/\text{kpc} < 4$ (top) and $-4 < Z/\text{kpc} < -3$ (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, and LSST – or any HST field!

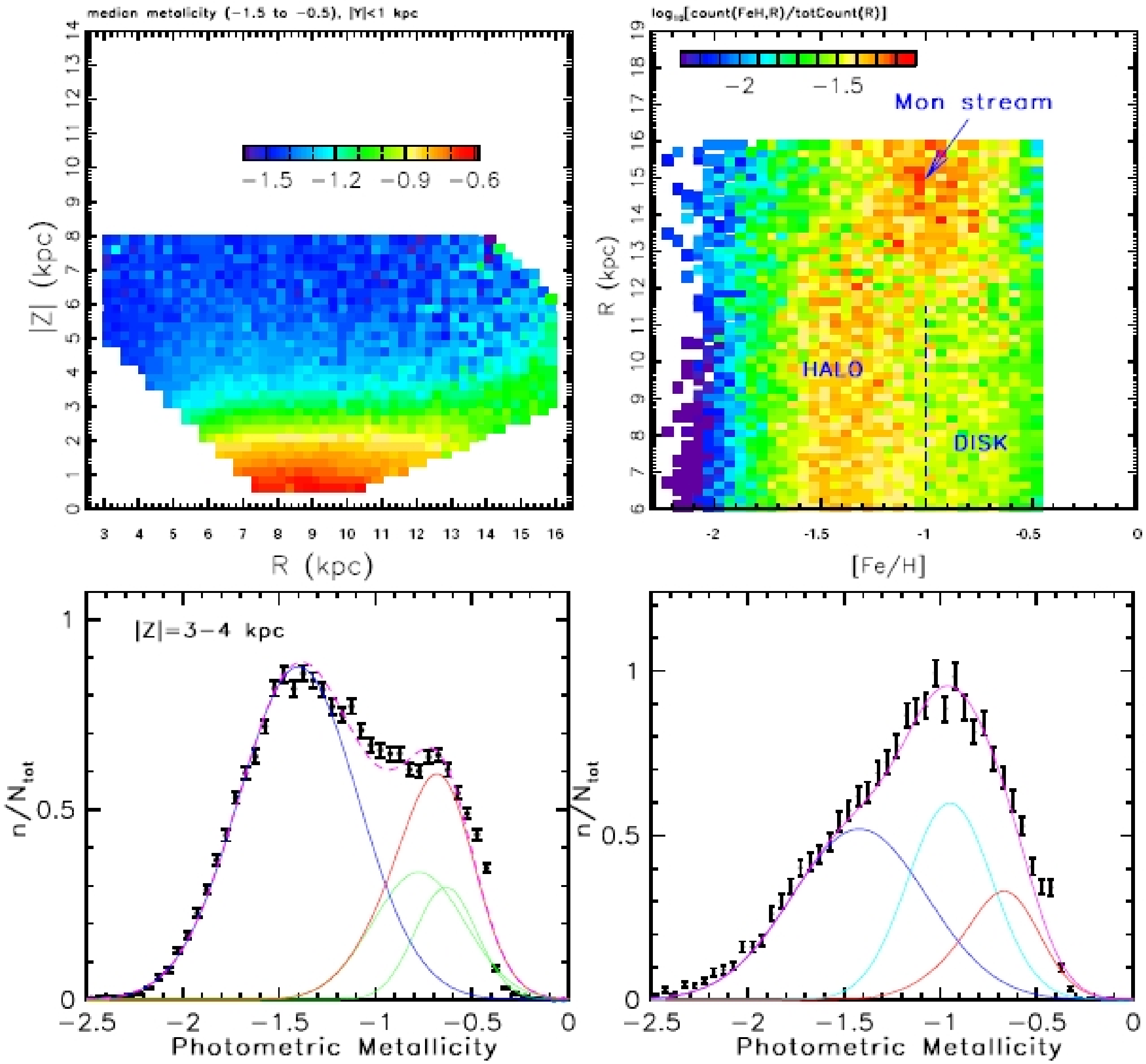


$$\rho(R,Z) = \rho_{\rm thin}(R,Z) + \rho_{\rm thick}(R,Z) + \rho_H(R,Z)$$

$$\rho_{\rm thin}(R,Z) = \rho_0\, e^{\frac{R_\odot}{L_1}} \exp\left(-\frac{R}{L_1} - \frac{Z+Z_\odot}{H_1}\right)$$

$$\rho_{\rm thick}(R,Z) = f_D \rho_0\, e^{\frac{R_\odot}{L_2}} \exp\left(-\frac{R}{L_2} - \frac{Z+Z_\odot}{H_2}\right)$$

$$\rho_H(R,Z) = \rho_0\, f_H \left(\frac{R_\odot}{\sqrt{R^2+(Z/q_H)^2}}\right)^{n_H}$$

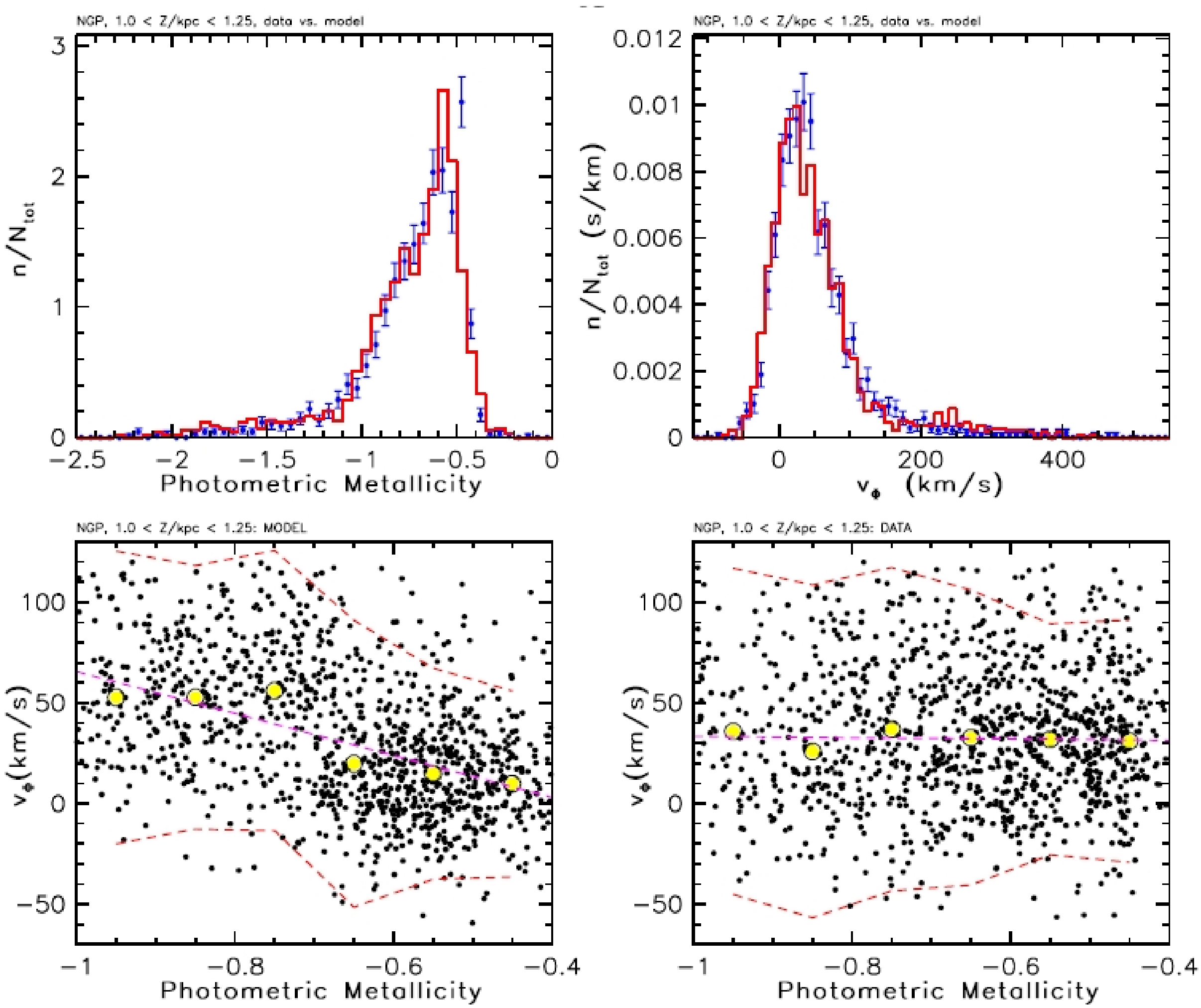


Substructure can be identified using stellar spatial distribution, and the metallicity and kinematic maps!

Deviations from the Smooth Model

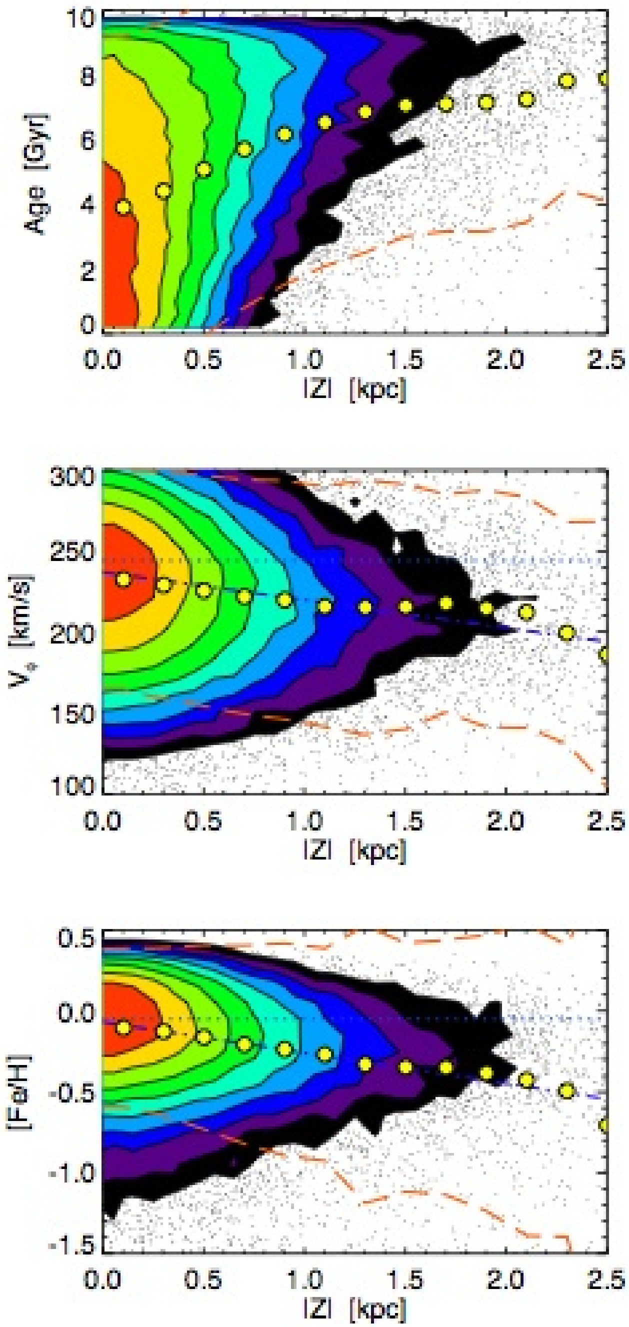
- Monoceros stream was discovered using stellar counts
- It is also identified as a substructure in metallicity space... LEFT
- And kinematics, too: it rotates faster than LSR by ∼50 km/s
- More details: Ivezić et al. 2008 (ApJ 684, 287)
- Search for substructure using radial velocity: more effective at large distances (Schlaufman et al. 2009, Klement et al. 2009)

Difficulties with Thin/Thick Disk Decomposition



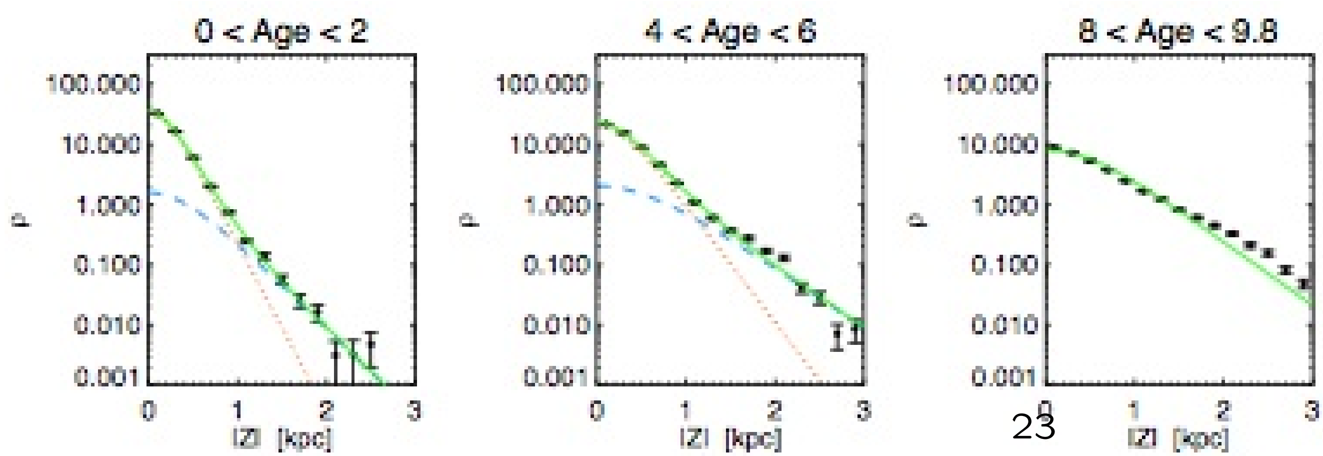
- Both rotational velocity distribution and metallicity distribution for disk stars vary with Z (in the range 0.5 to 5 kpc). Traditionally, these variations are interpreted as due to varying count normalization ratio of thin and thick disk components
- Traditional thin/thick disk decomposition (two components offset by 0.2 dex and 50 km/s) predicts a correlation between metallicity and rotational velocity: **not observed!**

- The **measured** metallicity and rotational velocity are **not** correlated (bottom right): Kendall's $\tau = 0.03 \pm 0.03$!
- The **modeled** metallicity and rotational velocity **are** correlated (bottom left): $\tau = -0.30 \pm 0.03$

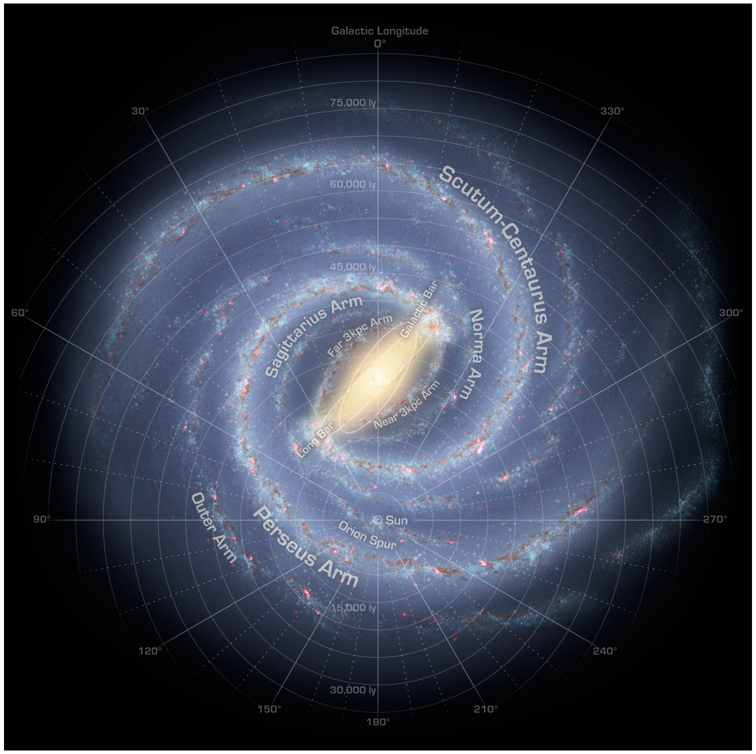


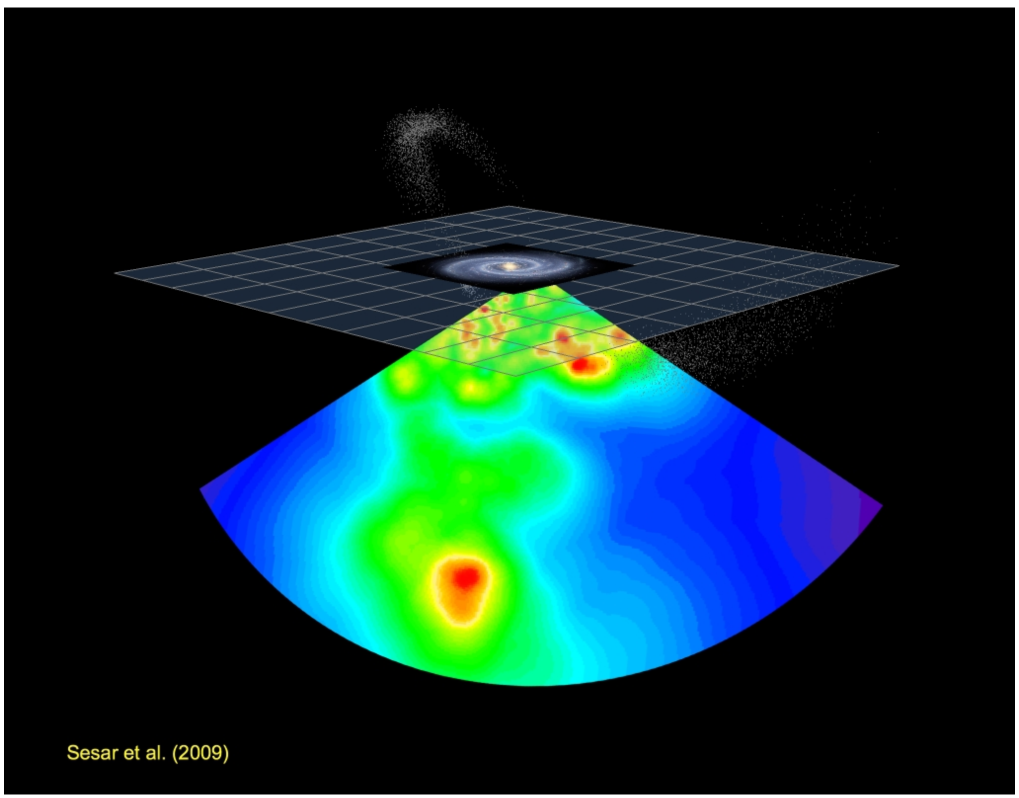
Thin/Thick Disk is an Age Effect!

- Data: Change of slope of stellar counts at ~ 1 kpc, and both rotational velocity distribution and metallicity distribution for disk stars vary with Z
- N-body models with radial migration:
  1) behave like the data, and
  2) provide age information and details about radial migration
- **Models:** Older stars 1) reach larger $|Z|$, 2) have lower [Fe/H], 3) display rotational velocity lag, 4) no [Fe/H]-v_ϕ correlation **Observers call this behavior "thick disk"**



Loebman et al., in prep.
(Roškar et al. models)





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!**

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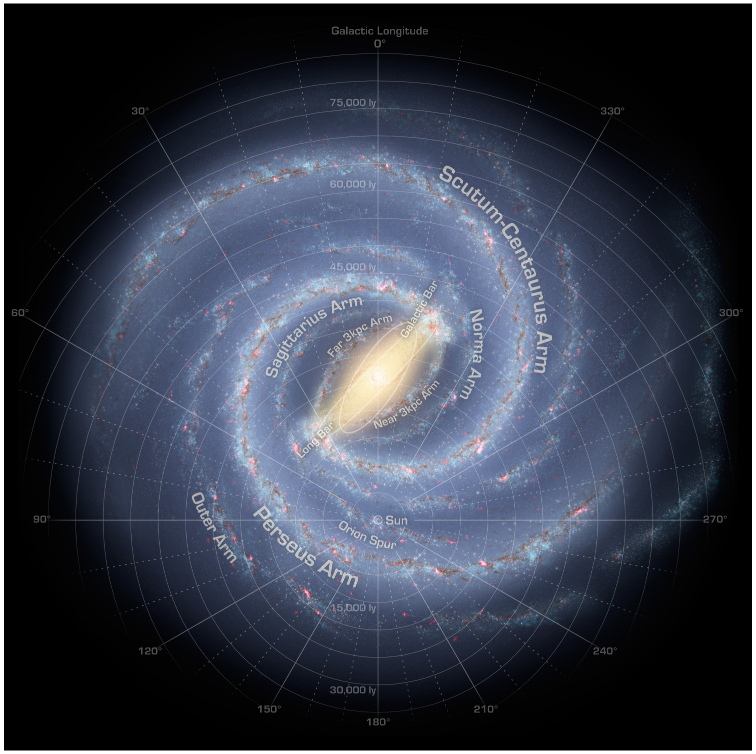

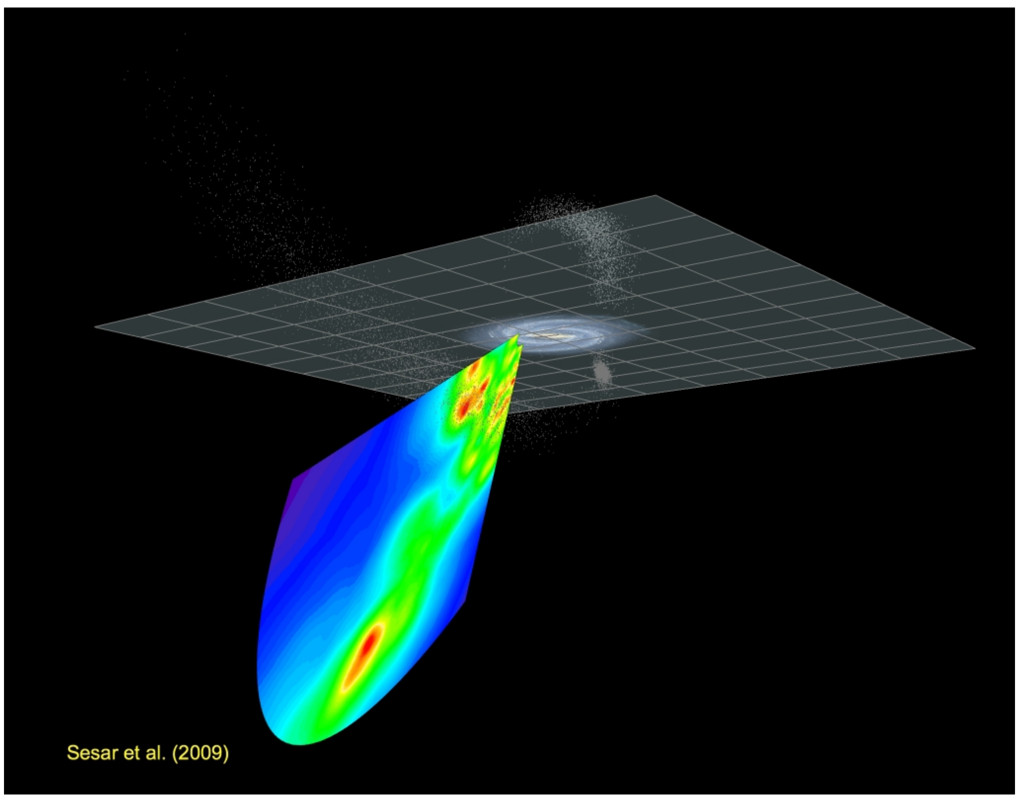

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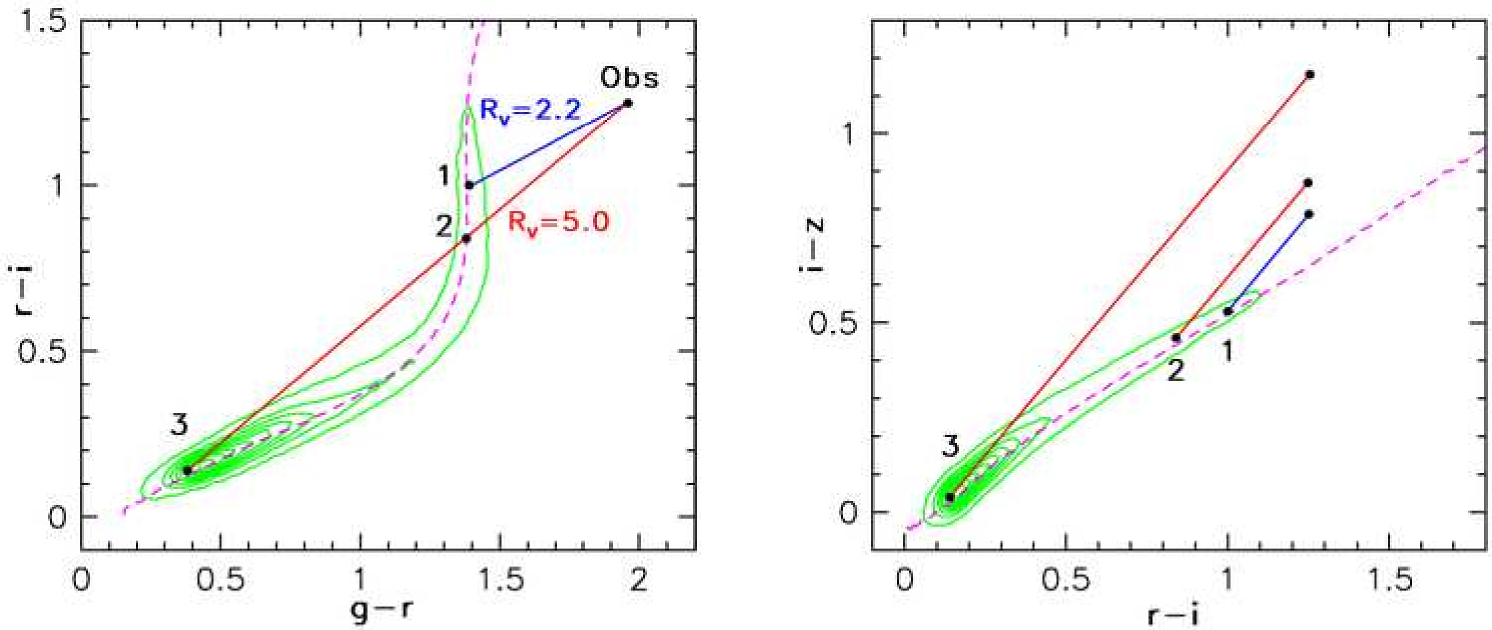
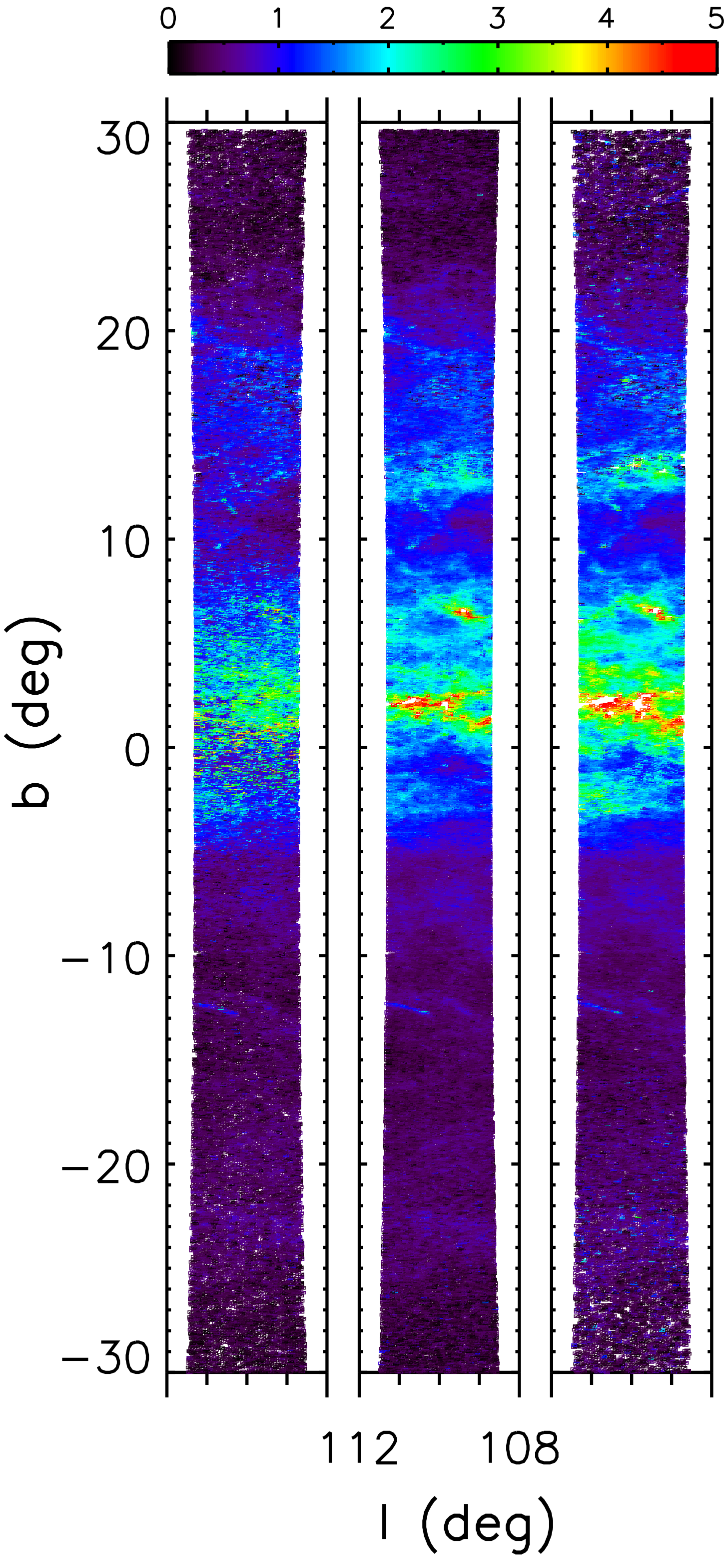


Dust Properties with optical/near-IR photometry

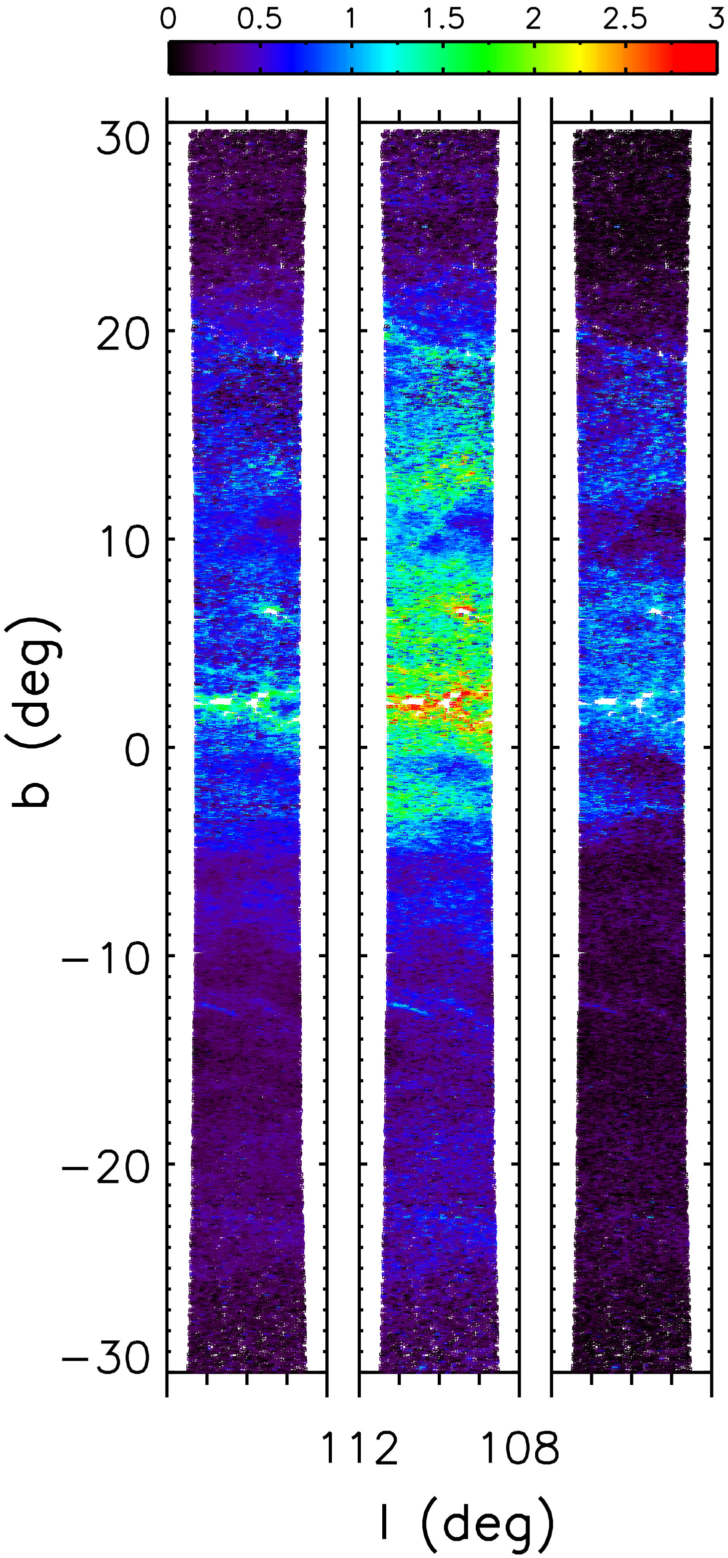
The majority of stars are on main sequence

1. Use the stellar locus in SDSS and SDSS-2MASS color space quantified by Covey al al. (2007) at high $|b|$: stellar model m
2. Assume the dust extinction curve can be described as a function of a single parameter, R_V.
3. For a given set of measured colors, four in SDSS-only case, and seven in SDSS-2MASS case, we **fit SEDs with three free parameters: stellar model, m, dust amount, A_r, and R_V.**
4. Applied to 70 million stars with SDSS $>$ 10σ detections (23 million also detected by 2MASS)



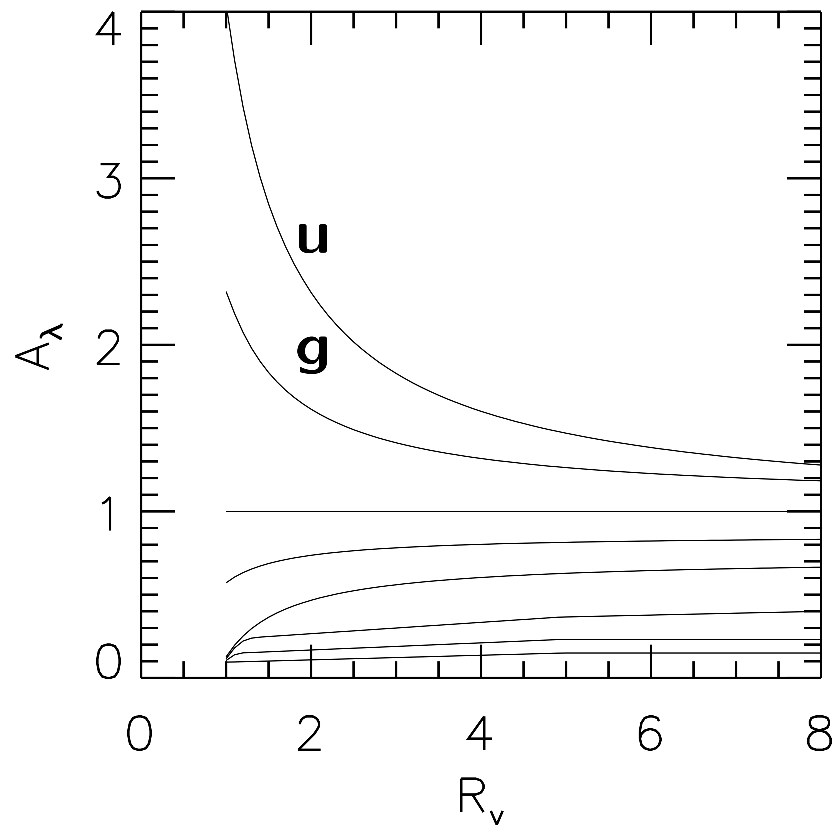
Dust Properties with SDSS: A_r

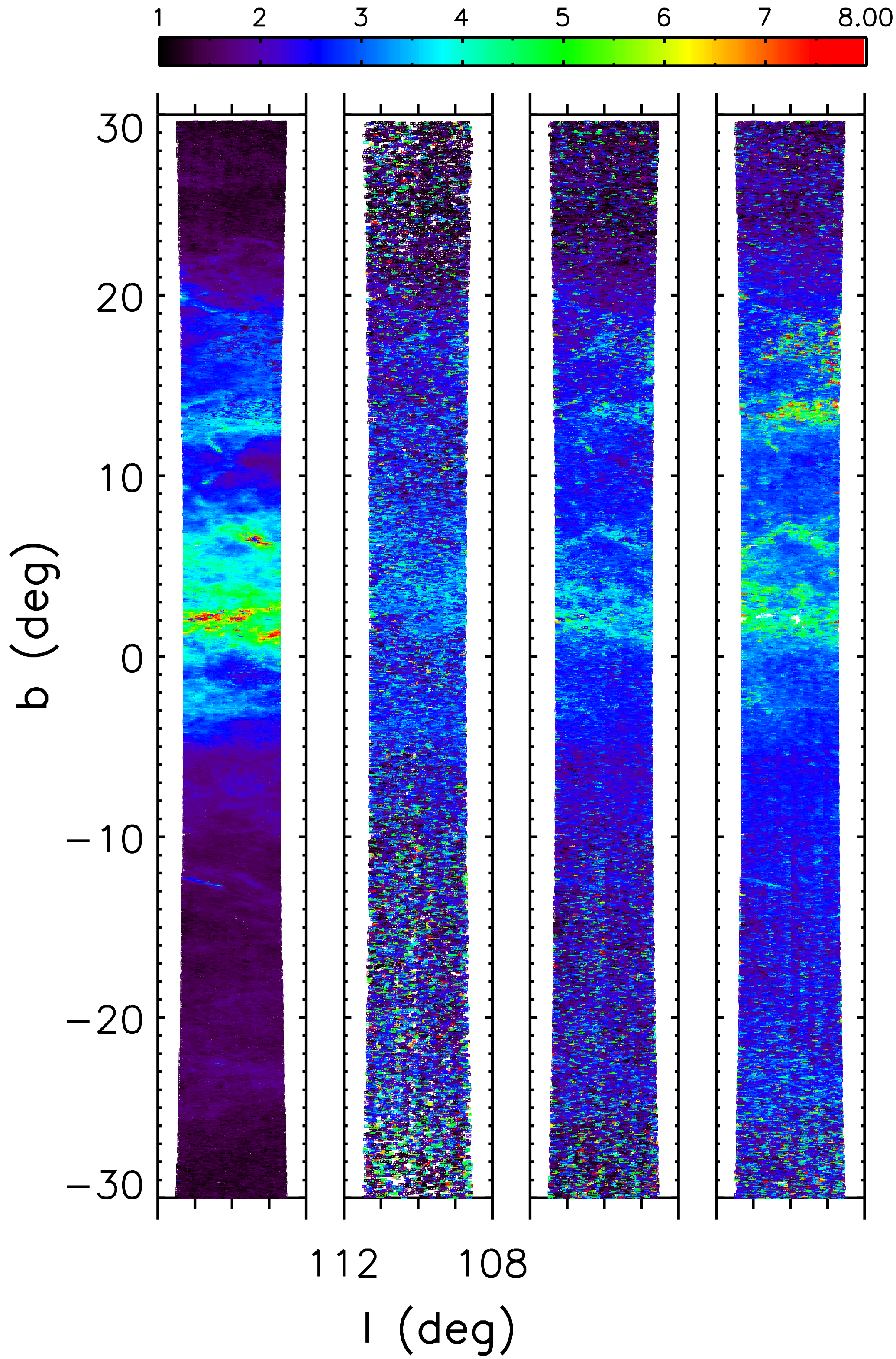
- A_r **maps in three distance slices** for $R_V = 3.1$, color-coded according to the legend on top ($0 < A_r < 5$); 0.3-0.6 kpc (left),1-1.5 kpc (middle) and 2-2.5 kpc (right).
- One of 10 SDSS-II SEGUE strips through the Galactic plane
- Spatial resolution $\sim$ arcmin
- Distance limit for blue main sequence stars: typically several kpc; intrinsic spectral types accurate to a few subtypes
- **The best-fit results enable large array of science, from studying dust to disk structure**
- The results will become public in a month or so (after the submission of supporting paper by Berry et al.)



Dust Properties with SDSS: R_V

- Results depend on assumed R_V:
- **Left panel:** A_r map for $R_V = 2.0$
- **Middle panel:** A_r map for $R_V = 4.0$
- **Right panel:** the difference of the first two maps
- For constraining R_V, the u and g bands are crucial!





Dust Properties with SDSS: R_V

- **Left panel:** A_r map for floating R_V (same color coding as in the previous page)
- **Other panels:** R_V map color-coded according to the legend on top ($1 < R_V < 8$); 0.1-0.5 kpc (left), 0.5-1 kpc (middle) and 1-2 kpc (right).
- The data not only constrain the R_V distribution, but do so in a 3D space!
- **Conclusions:** $R_V = 3.1$ is an excellent fit almost everywhere; however, we confirm the claims that regions with a lot of dust *sometimes* have $R_V \sim 4-6$

Dust Properties with SDSS

Advantages:

1. High angular resolution due to large number of stars (several times better than the SFD map)
2. R_V map
3. Stellar intrinsic color: excellent photometric distance estimate for producing high-resolution 3D A_r, R_V and stellar distribution maps

Disadvantages:

1. Dynamics range of SDSS photometry limits these studies to regions with $A_r < 5$
2. SDSS has only ten 2.5 deg wide stripes that cross the Galactic Plane ($<$ 10% of the area)
3. SDSS limiting depth allows mapping out to only several kpc

With LSST all three disadvantages will be significantly alleviated: better Plane coverage and deeper data.

Summary of SDSS Results on the Milky Way Disk and Halo Structure

- SDSS has obtained complete samples of millions of stars with photometric distance and metallicity estimates, and proper motions from comparison with the Palomar Survey (POSS)

- Clumps/overdensities/streams are an integral part of Milky Way structure, both for halo and disk components; a similar complexity is seen in the kinematics and metallicity distributions (Jurić et al. 2008, ApJ 673, 864; Ivezić et al. 2008, ApJ 684, 287; Bond et al. 2009, arXiv:0909.0013)

- SDSS data can be improved by improving sky coverage, faint limit, and astrometric and photometric accuracy

SDSS is revolutionizing studies of the Galactic structure.

LSST will do even better!

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:

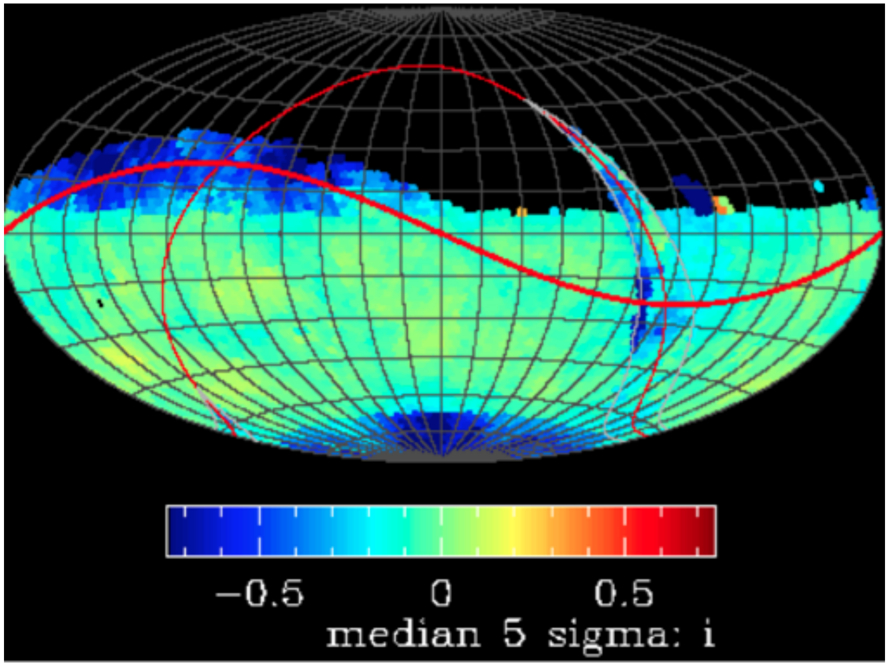
- 8.4m aperture (6.7m effective), $\sim$10 deg^2 FOV
- 3200 Megapix camera (20 TB, or one SDSS, per night)
- Sited at Cerro Pachon, Chile
- First light in 2015
- Construction cost: 455 M$ (public-private partnership)

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:

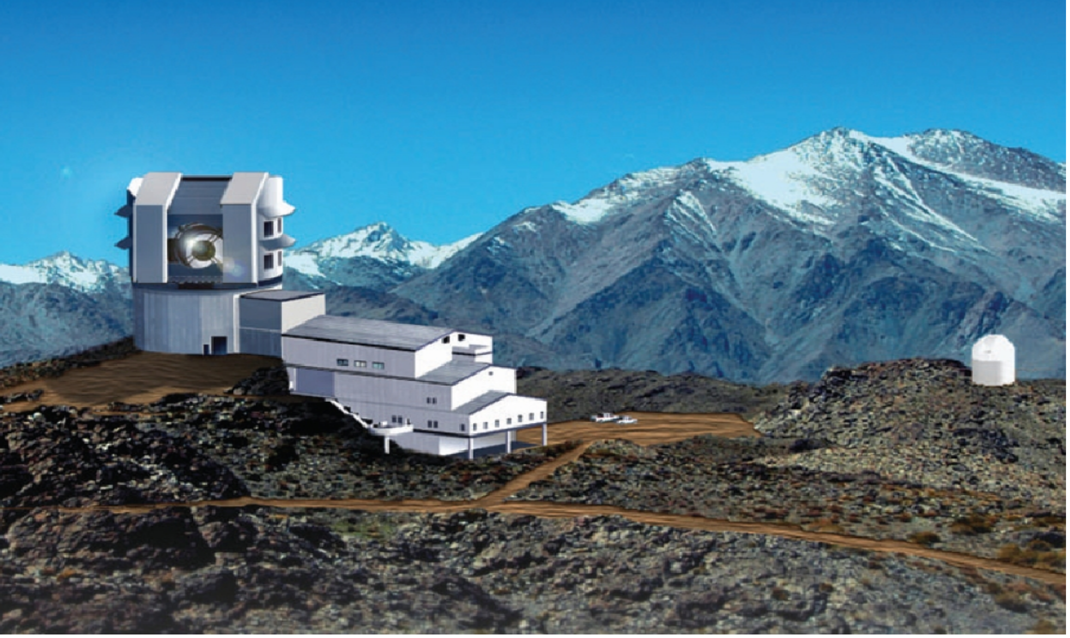
an optical/near-IR survey of half the sky in multiple bands (ugrizy) to r =27.5 based on about 1000 visits over a ten-year period:

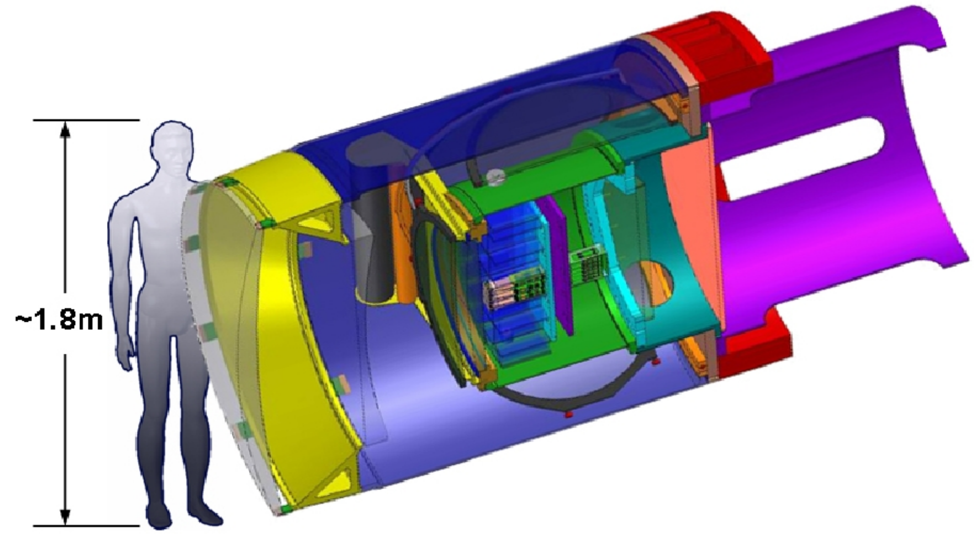
a catalog of ∼10 billion stars and ∼10 billion galaxies with exquisite photometry, astrometry and image quality

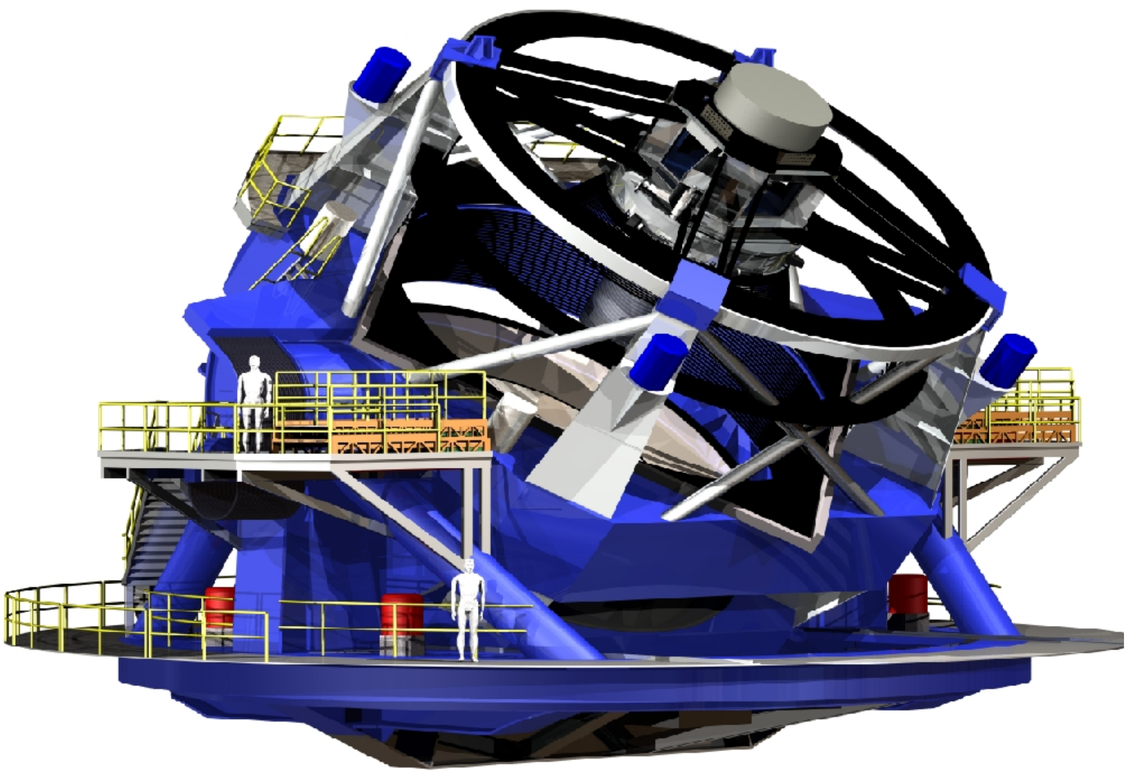


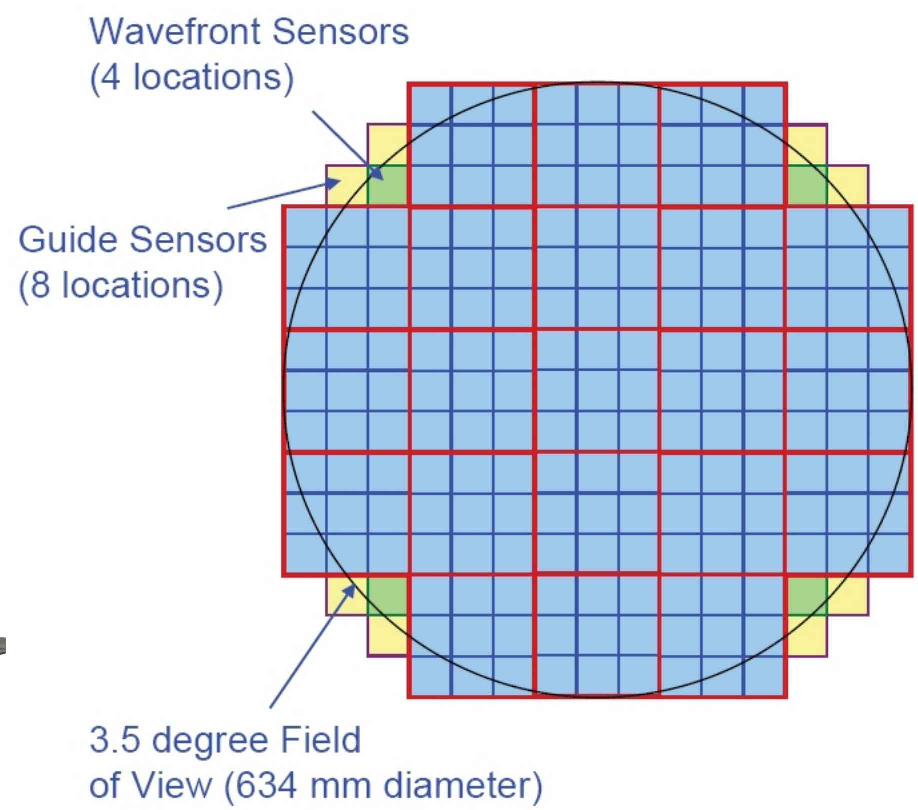
Selected Science Goals

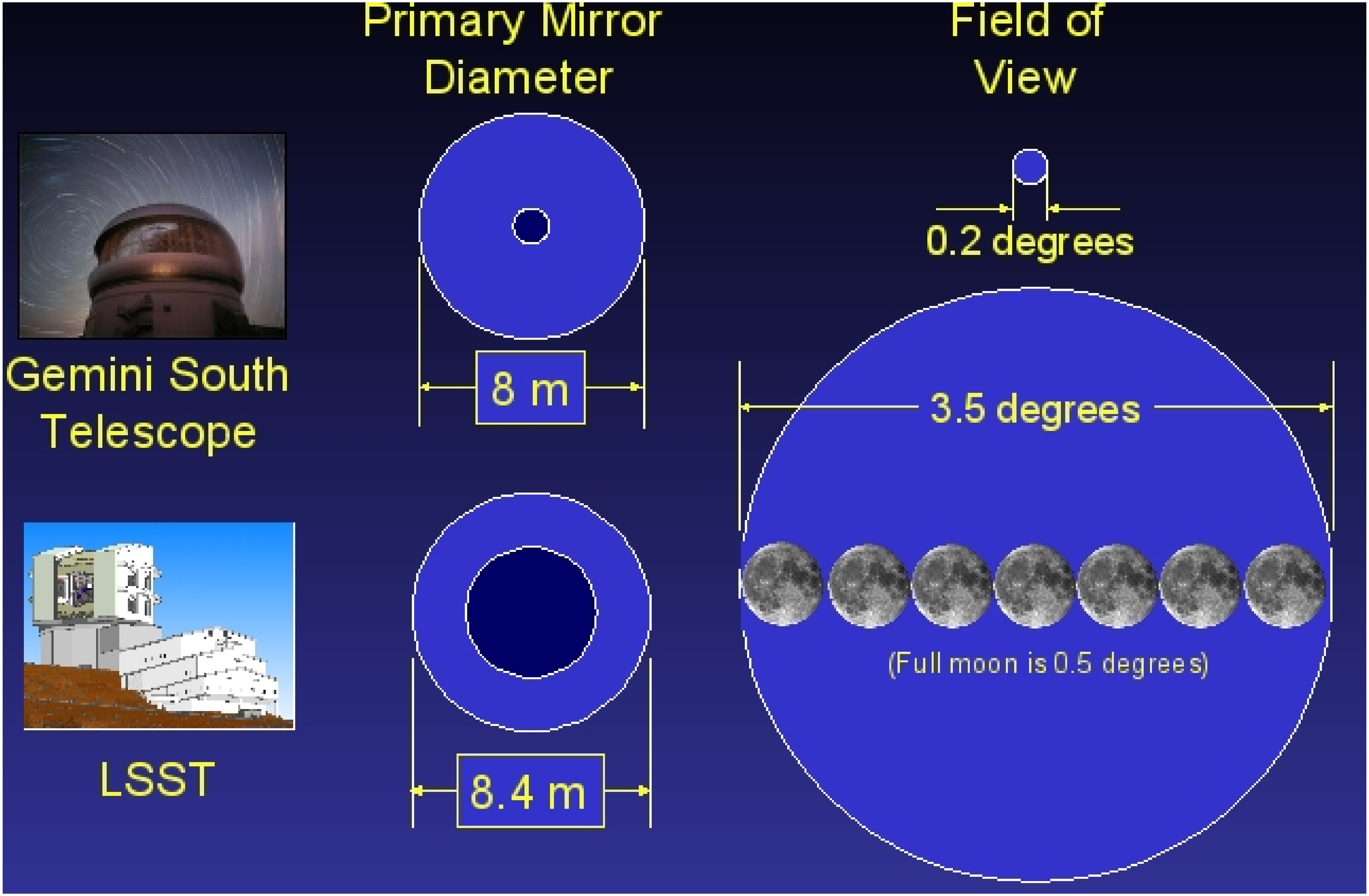
- Dark Energy and Dark Matter (four billion galaxies with excellent photometry and shape measurements, several million SNe, clusters of galaxies, millions of quasars)
- The Solar System Map (140m killer asteroids, several 10^6 main-belt, ∼100,000 trans-Neptunian, Sedna-like to beyond 200 AU)
- The Transient 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)

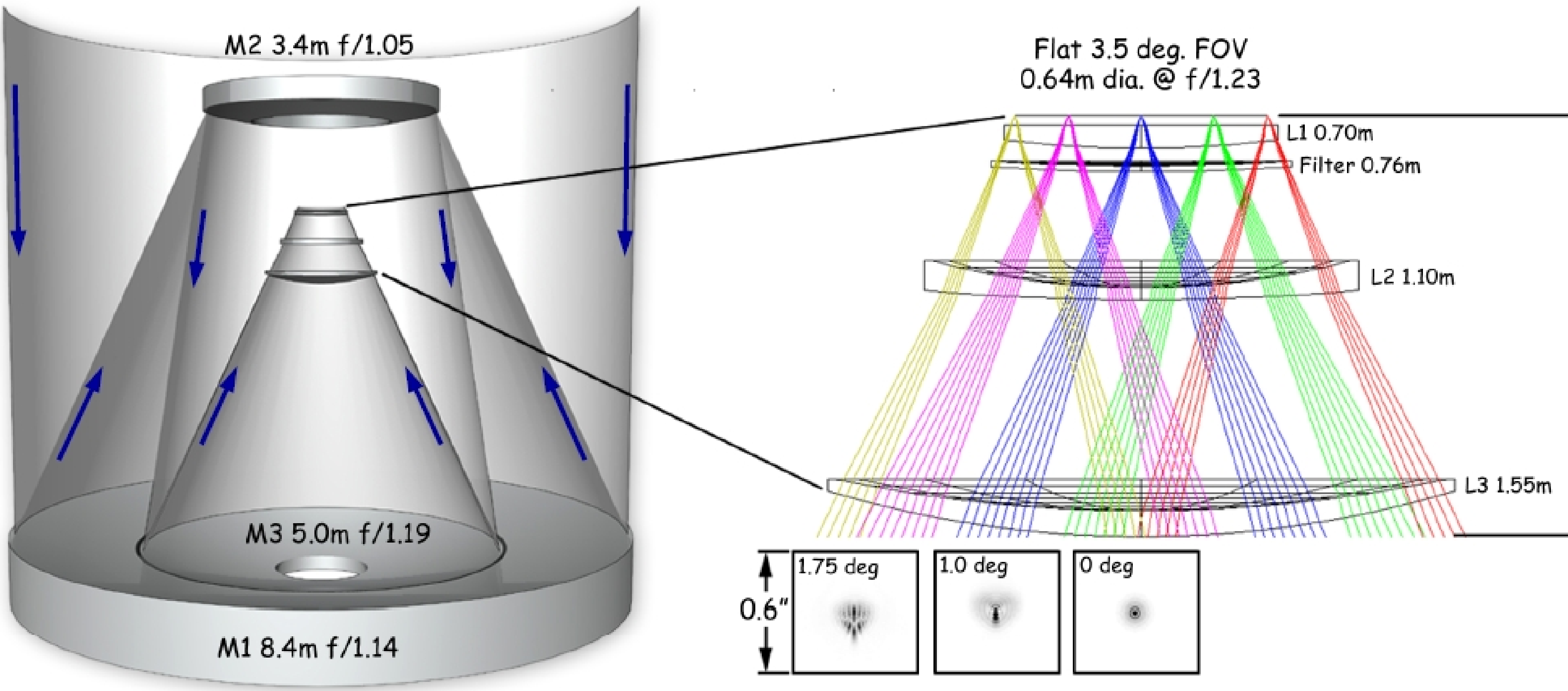



~1.8m

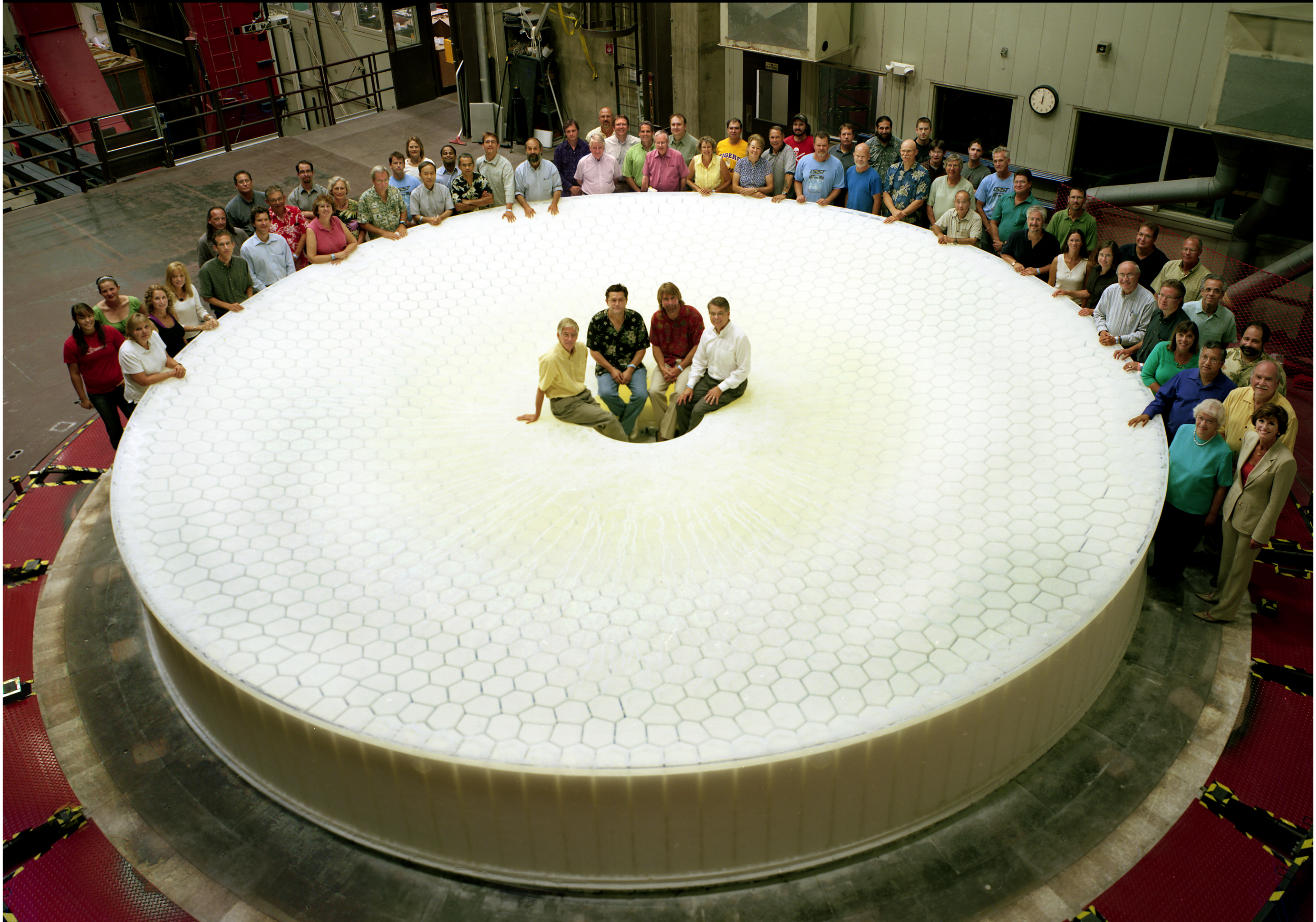



Wavefront Sensors
(4 locations)
Guide Sensors
(8 locations)
3.5 degree Field
of View (634 mm diameter)


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

Large Synoptic Survey Telescope



LSST Primary/Tertiary Mirror Blank

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

LSST vs. SDSS comparison

Currently, the best large-area faint optical survey is

SDSS: the first digital map of the sky

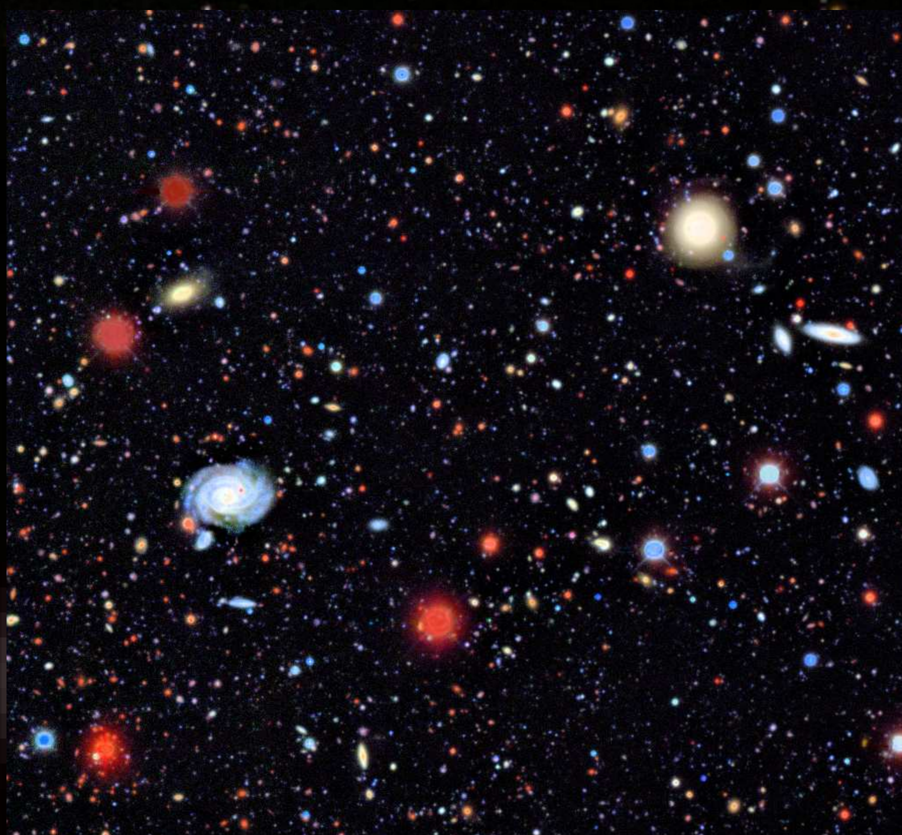
r$\sim$22.5, 1-2 visits, 300 million objects

- 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

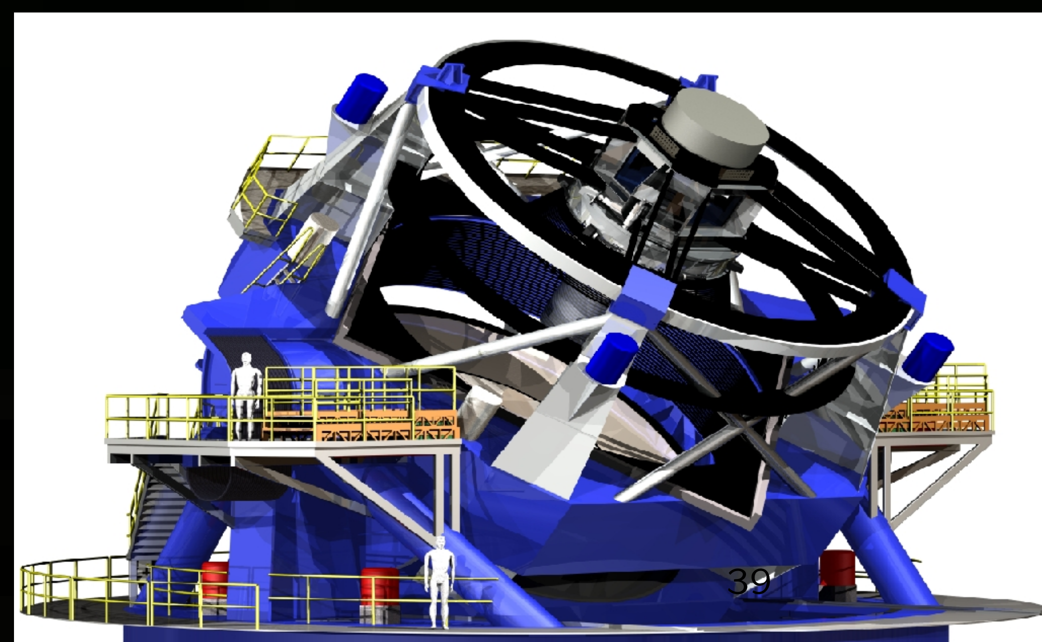
LSST: a digital movie of the sky

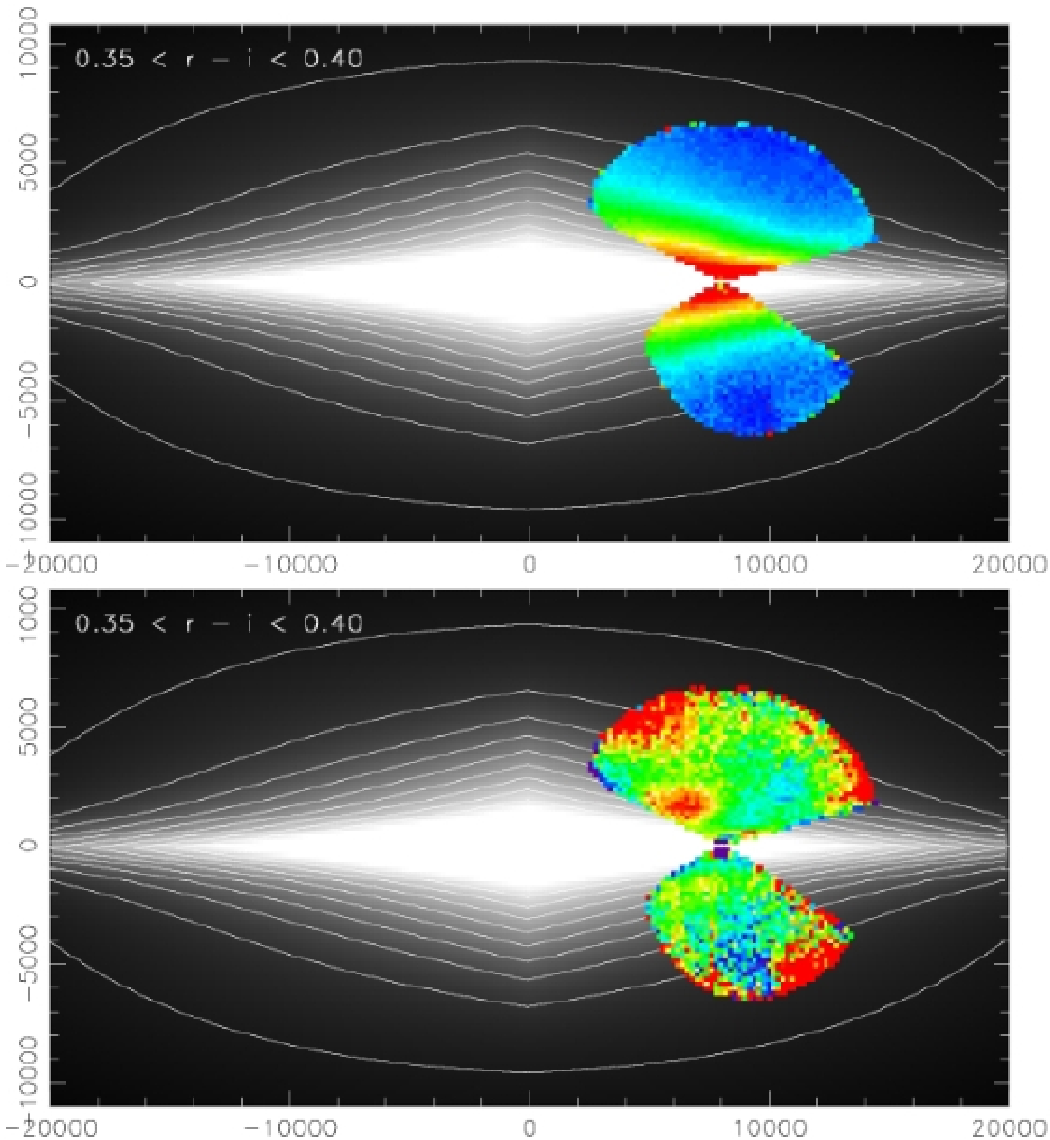
LSST data will immediately become public
(transients within 30 sec)



SDSS: one US Library of Congress worth of data

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





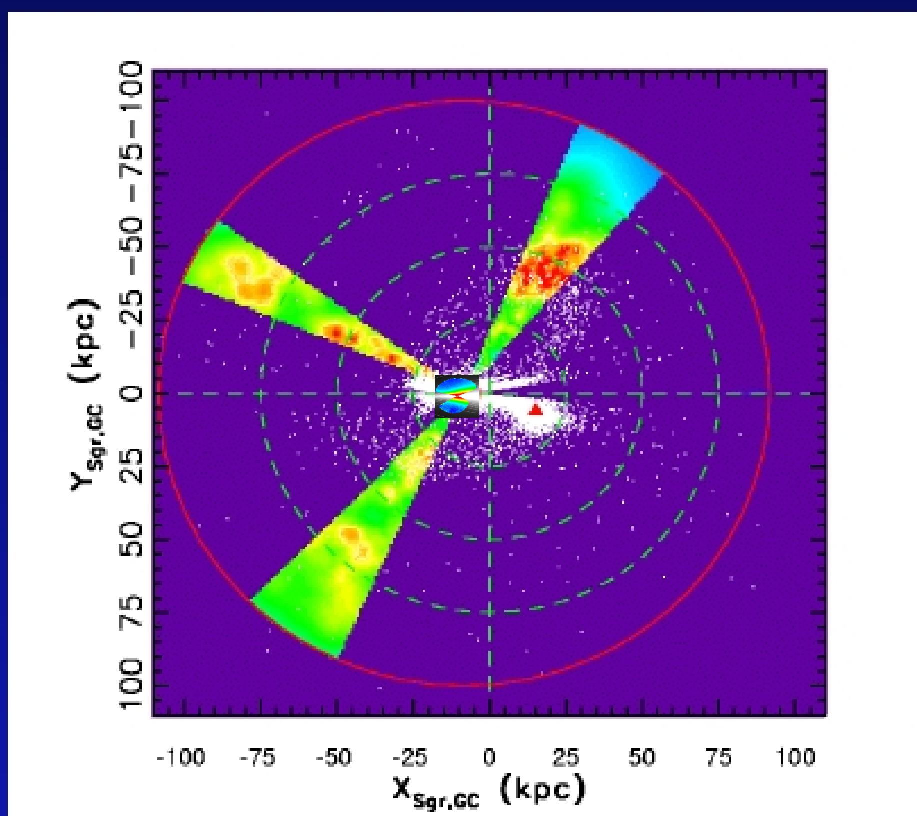
The limitations of SDSS data

- **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

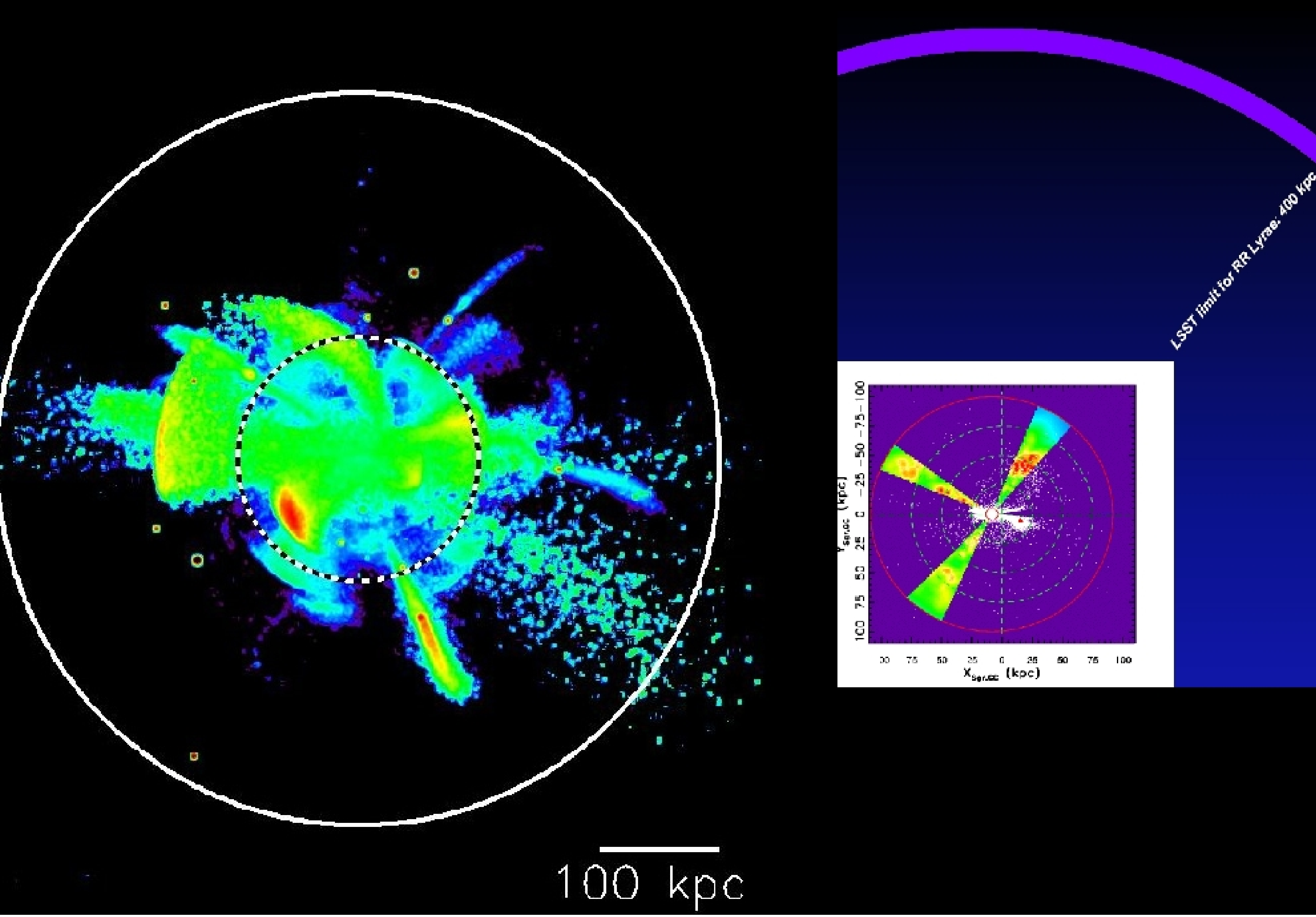
The large blue circle: the ∼400 kpc limit of future LSST studies based on RR Lyrae

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 (astro-ph/0805.2366)