What did we learn about the Milky Way during the last decade, and what shall we learn using Gaia and LSST?

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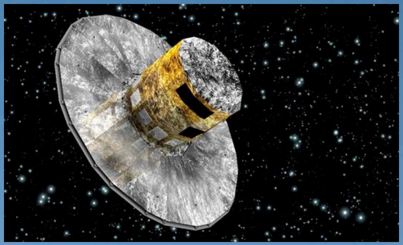
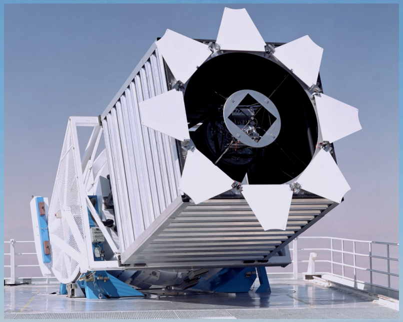
NOAC, Bejing
May 29, 2013





Outline

- Why to study the Milky Way?
  – "near-field cosmology" (galaxy formation and evolution)
  – hey, it's **our** Galaxy!
  – it's fun to describe galaxies with more than a few numbers

- The progress over the past decade: 3 vignettes
  Global stellar maps: Leaving the Solar neighborhood!!
  Disk: Can we map dust?
  Halo: Can we map dark matter?

- The promise of Gaia and LSST: 2020 vision
  Gaia: extraordinary astrometry will deliver precise trigonometric distances and proper motions to V<20
  LSST: multi-color time-resolved faint (V<24.5) sky map: can probe all the way to the edge of the Milky Way galaxy with (numerous) main sequence stars

Why to study the Milky Way?

- **To help answer general questions about galaxies:**
- How did galaxies form?
- How did galaxies evolve?
- What do they tell us about the Universe?
- **Disadvantage:** a single spiral galaxy
- **A major advantage:** no other galaxy can be studied in such an exquisite detail as our Galaxy

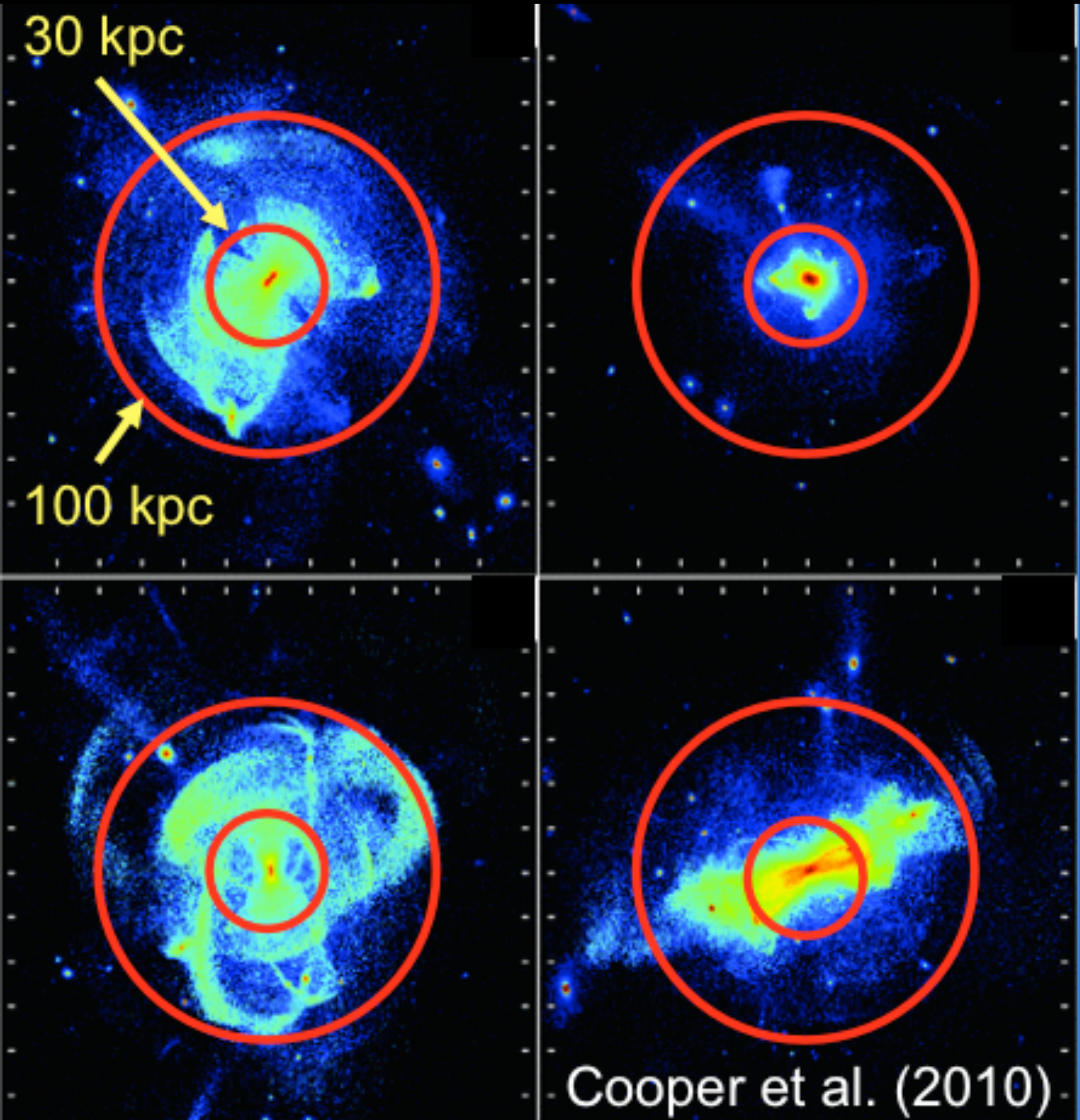
For individual stars in our Galaxy we can today measure:

a) 3D positions (and luminosity)
b) 3D motions (accelerations only close to the black hole)
c) chemical composition ([Fe/H], [α/Fe], individual abund.)
d) age and mass (sometimes)

Rapid progress!!!

Ivezić, Beers, Jurić 2012, ARA&A, 50, 251

Rapid progress in observations and simulations



- **10 years ago:**

Only a ~dozen stars detected beyond 30 kpc

3D velocities limited to <100 pc (Hipparcos)

<10,000 stellar spectra

- **Today:**

Several thousand stars beyond 30 kpc

3D velocities to ~10 kpc for >100,000 stars

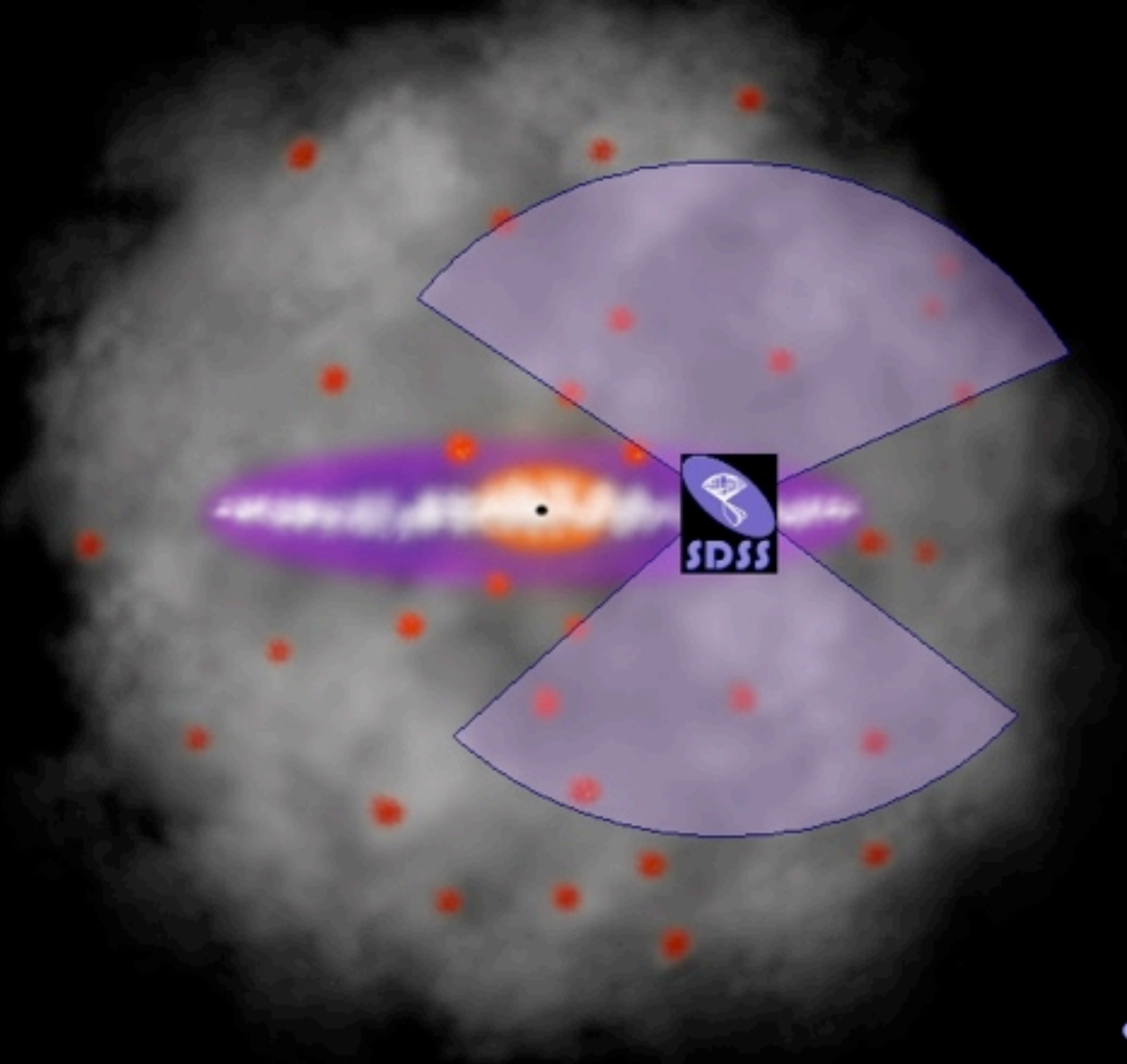
~1 million stellar spectra

And look at these sims!

Big questions about the Milky Way

- **Observers' view:**
- Decompose Galaxy into main components
- Describe the spatial distribution of stars
- Describe stellar kinematics as a function of position
- Describe chemical composition as a function of position and kinematics (and ultimately age)
- **Theoreticans'/modelers' view:**
- Can we understand/model the behavior of stars in the position-kinematics-chemistry space?
- Can we use kinematics and other data to infer dynamics?
- Are the results from the Milky Way studies consistent with extragalactic constraints?

Classical Decomposition of the Milky Way Components

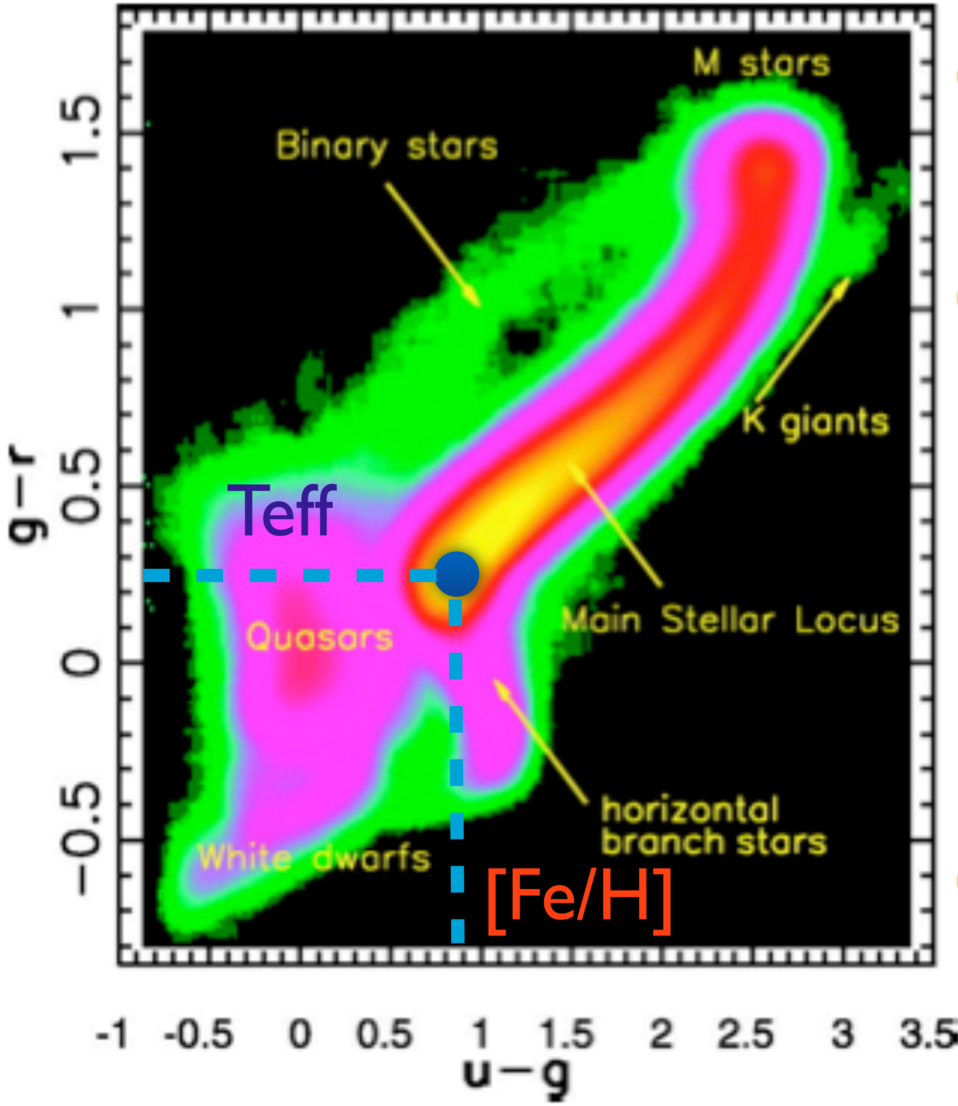


- Thin/thick disk
- Galactic bulge
- Stellar halo

- Components trace the DM dominated potential

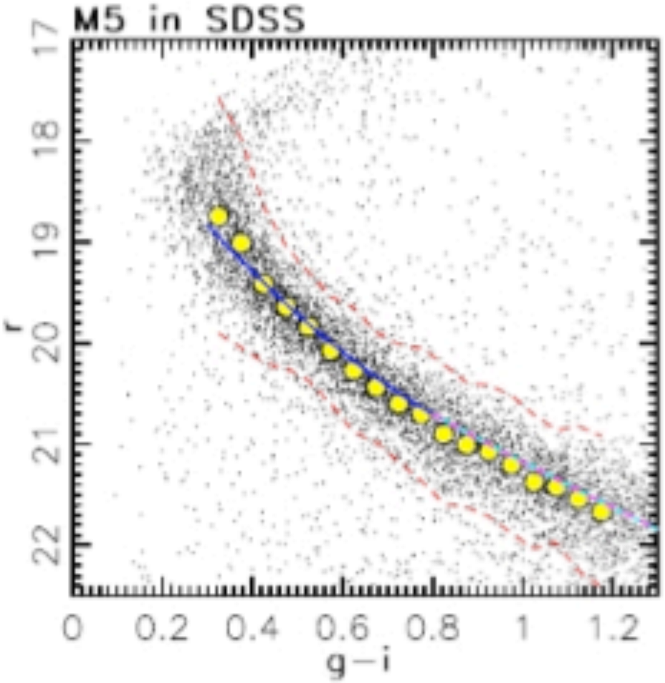
- They are a product of Milky Way formation and evolution

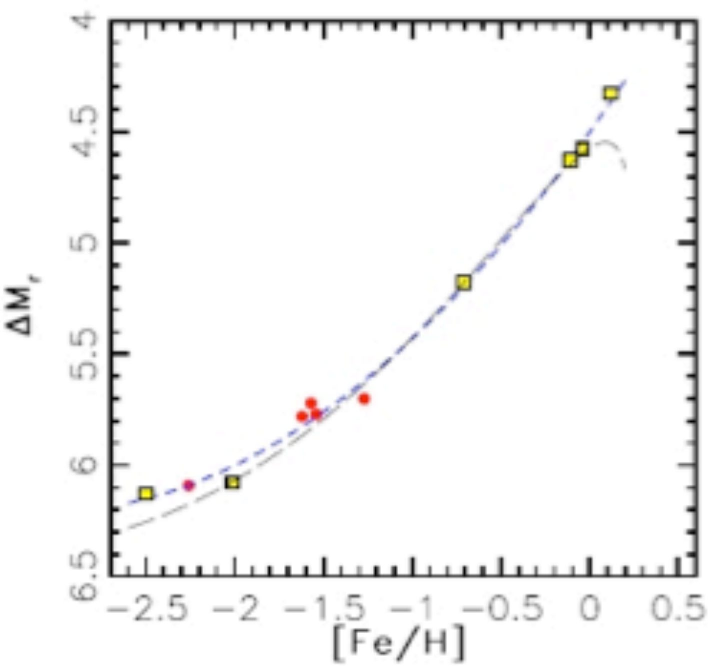
A Primer on Dissecting the Milky Way with SDSS



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!)**



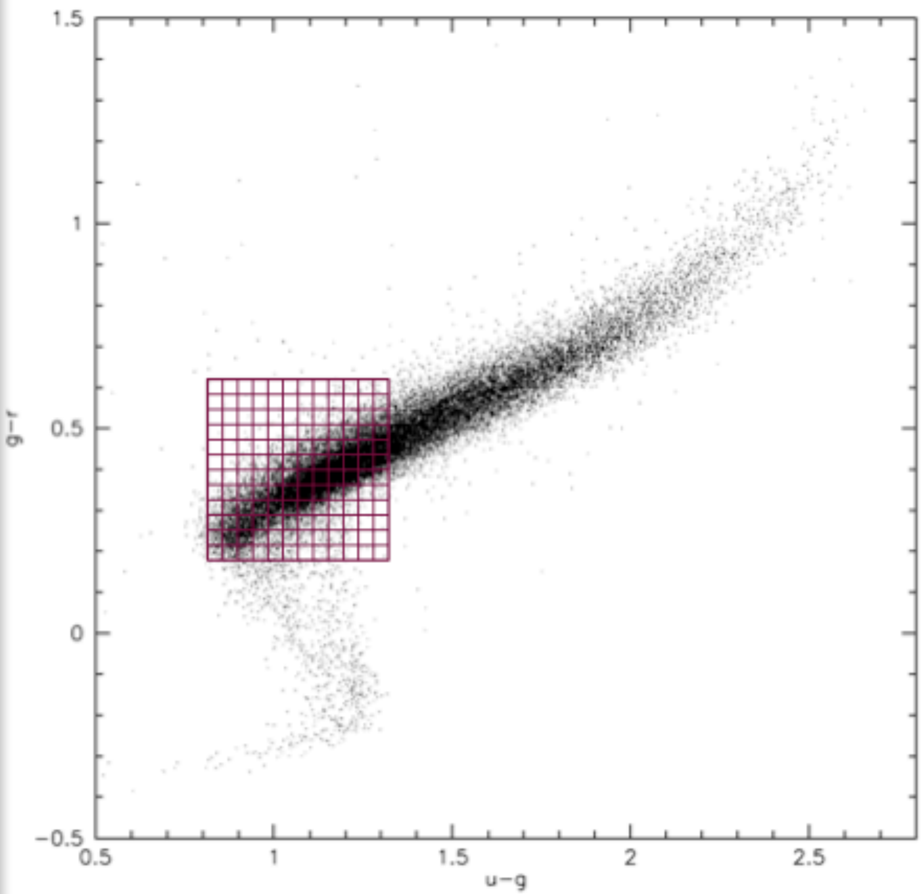


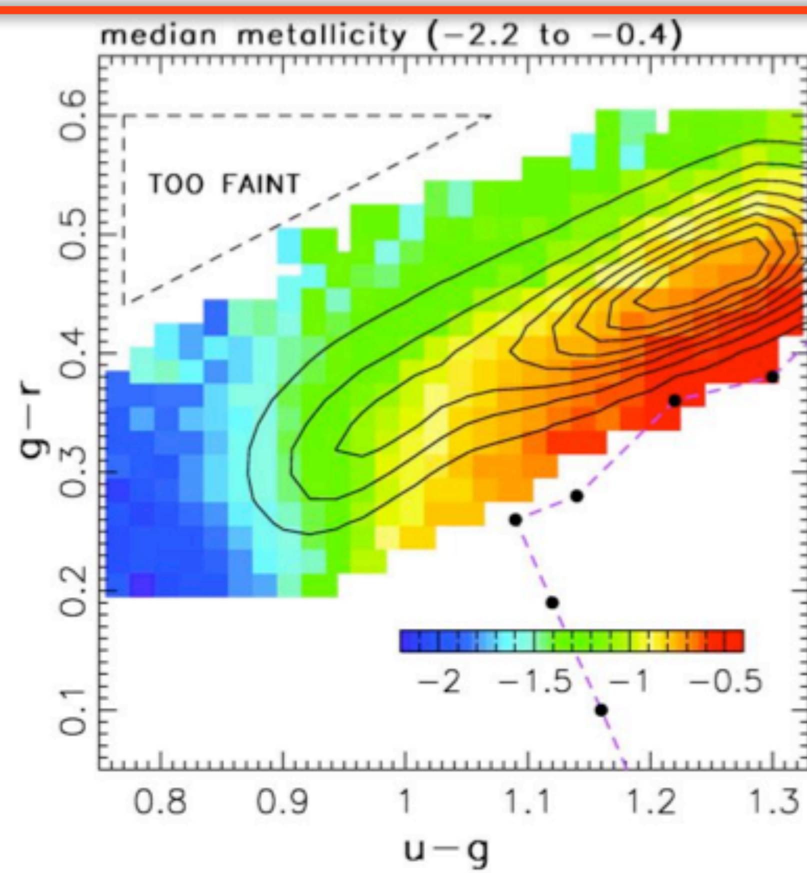
Photometric Distance and Photometric [Fe/H]

- 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

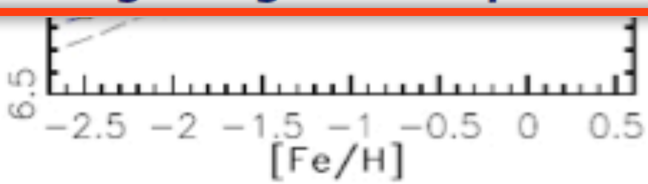
This method was known half a century ago, but never before applied to tens of millions of stars because large-scale surveys did not have the required photometric accuracy

Photometric Distance and Photometric [Fe/H]

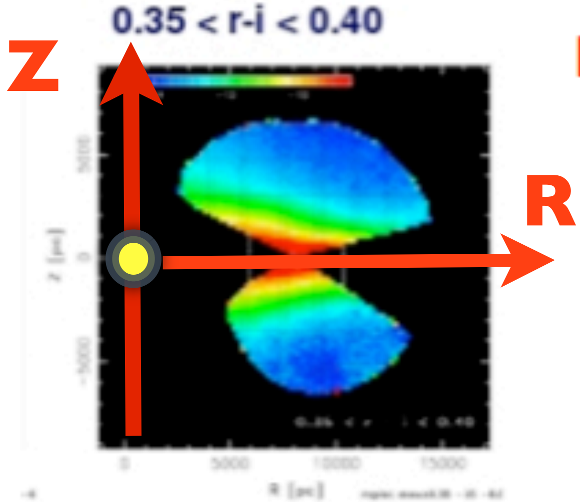




- u-g and g-r colors provide an estimator of metallicity, [Fe/H]

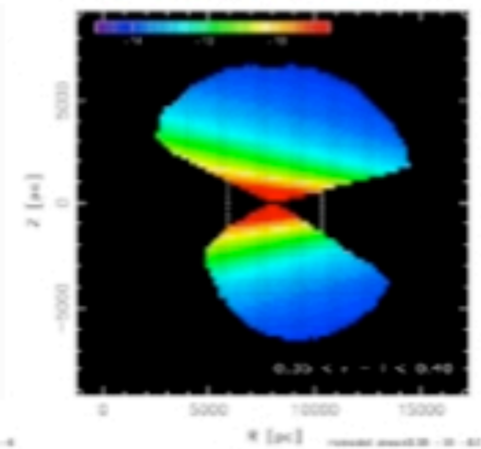


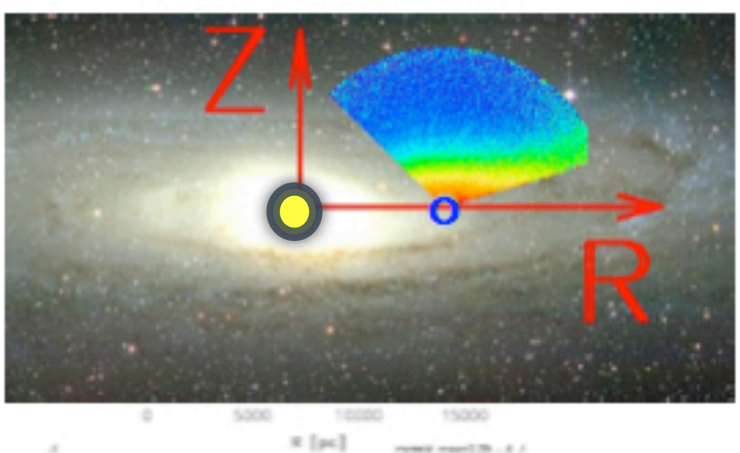
because large-scale surveys did not have the required photometric accuracy

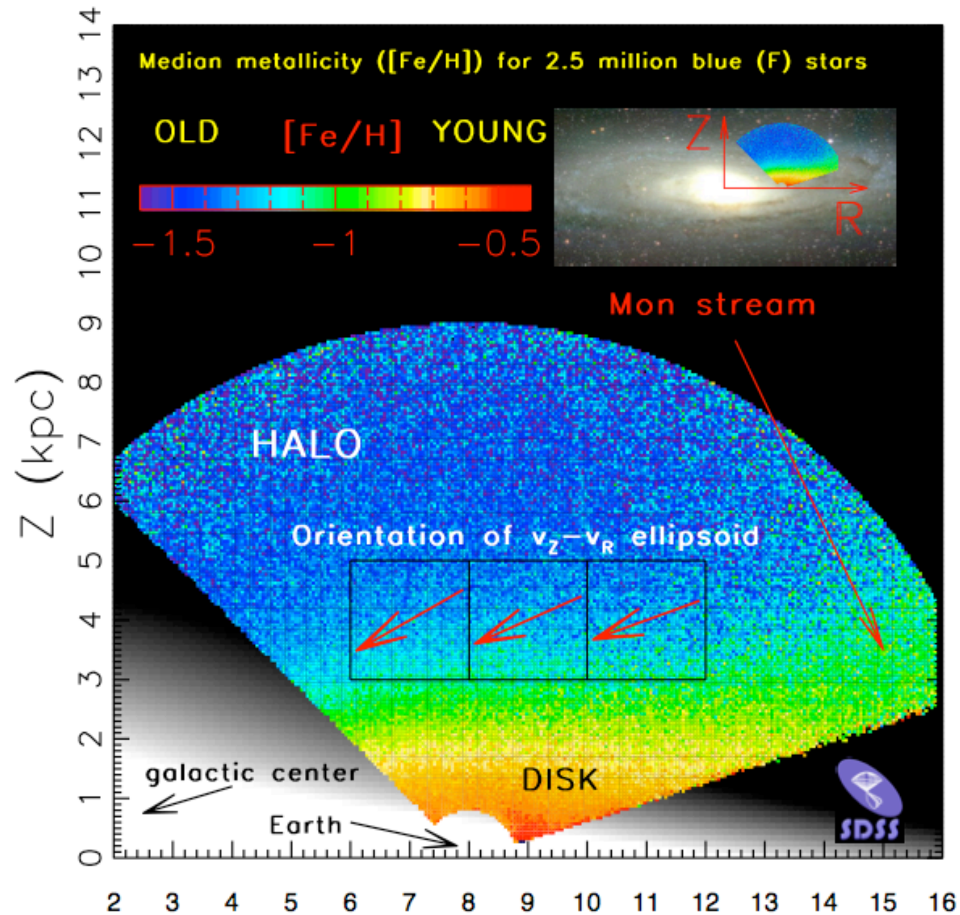


Dissecting the Milky Way with SDSS

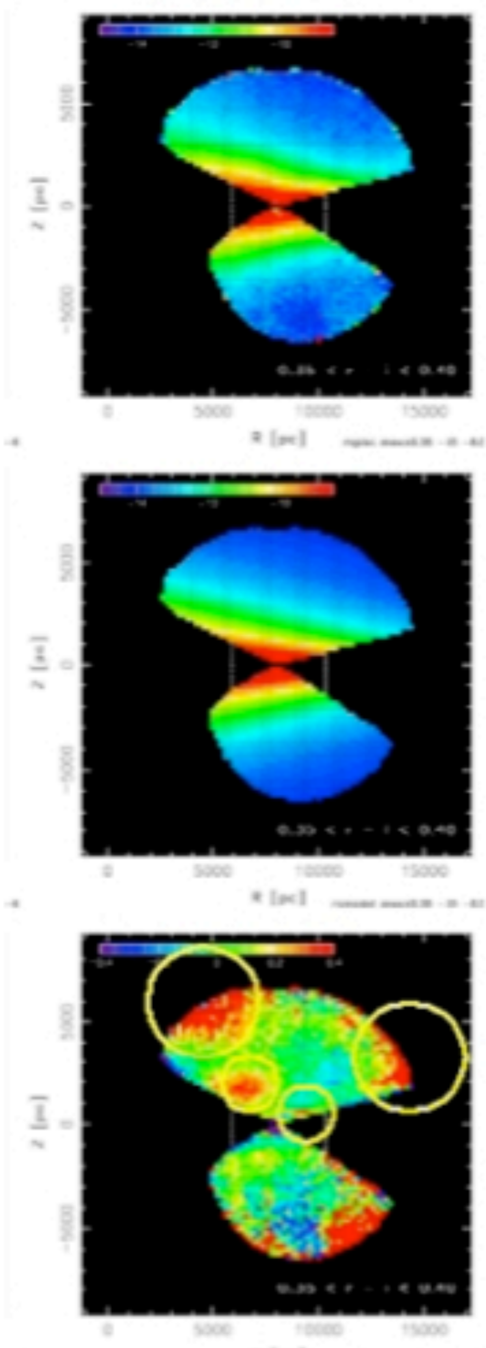
- Panoramic view of the Milky Way, akin to observations of external galaxies; good support for standard Galactic models (with amazing signal-to-noise!)
- Metallicity mapping supports components inferred from number counts mapping:







0.35 < r-i < 0.40

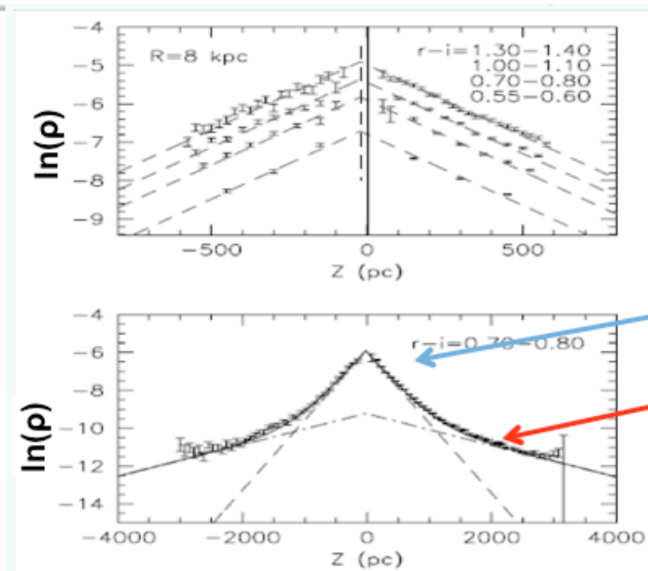


Dissecting the Milky Way with SDSS

- 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

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

- 

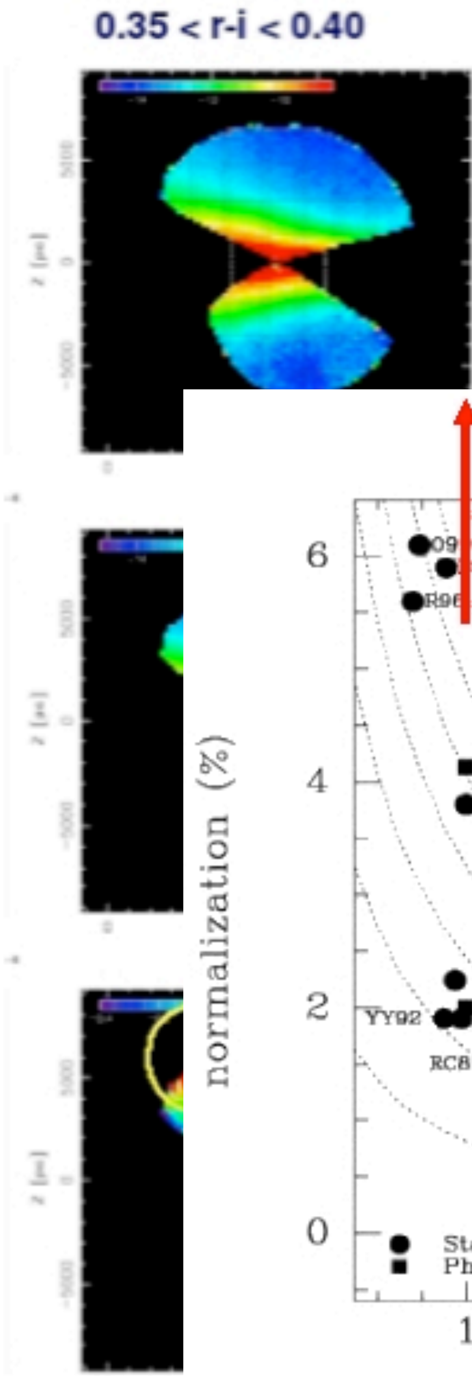
Thin disk

Two component fit!

Thin disk

Thick disk

Juric et al. 08



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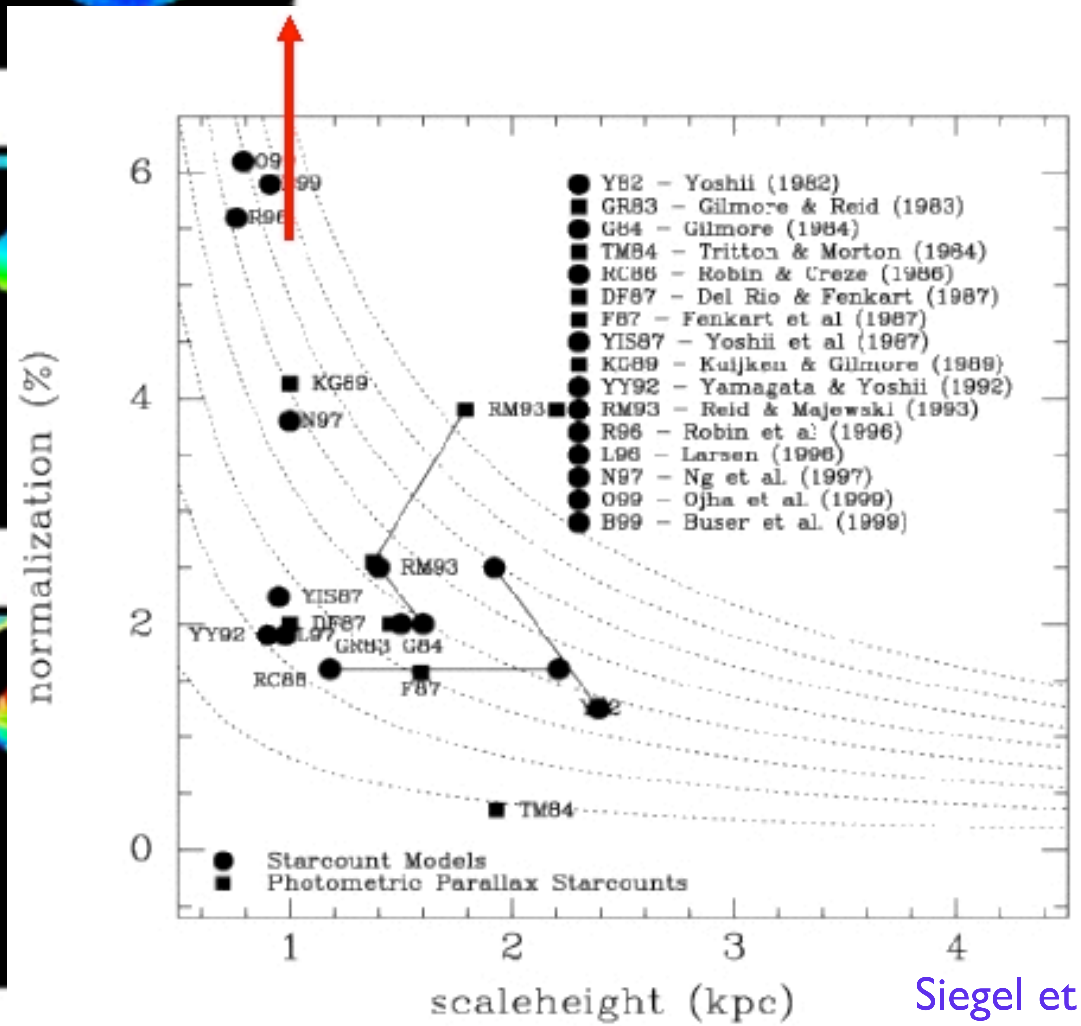


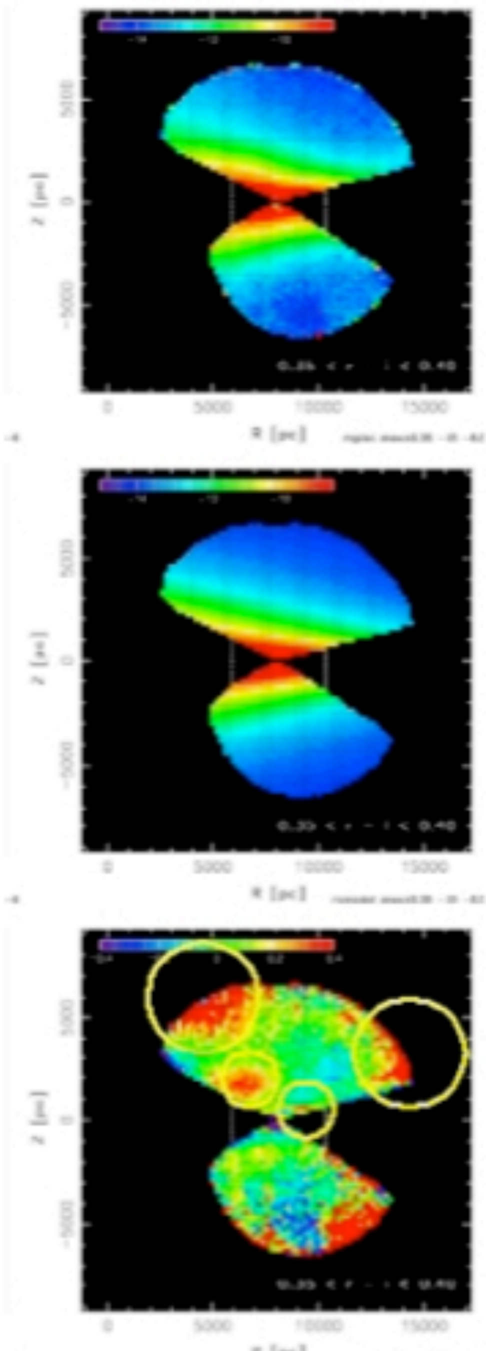
Comparison with prior measurements:

SDSS is off scale!

H(pc)	f(%)
S02: 750	8.5
J08: 900	12

Siegel et al. (2002, ApJ, 578, 151)

$0.35 < r-i < 0.40$



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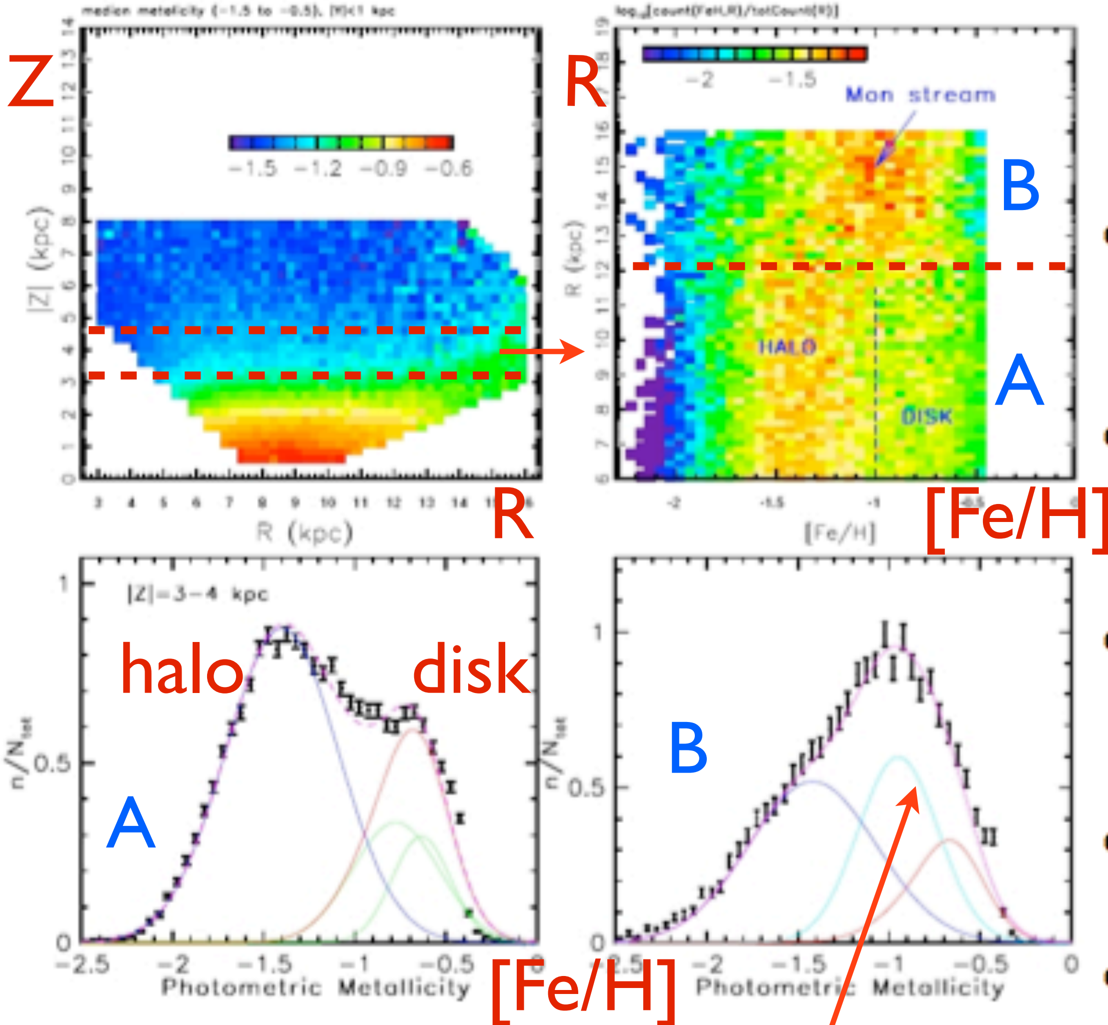
- The merger history of the Milky Way can be deciphered by mapping the substructure (spatially, and in velocity space, as a function of chemical composition [metallicity])



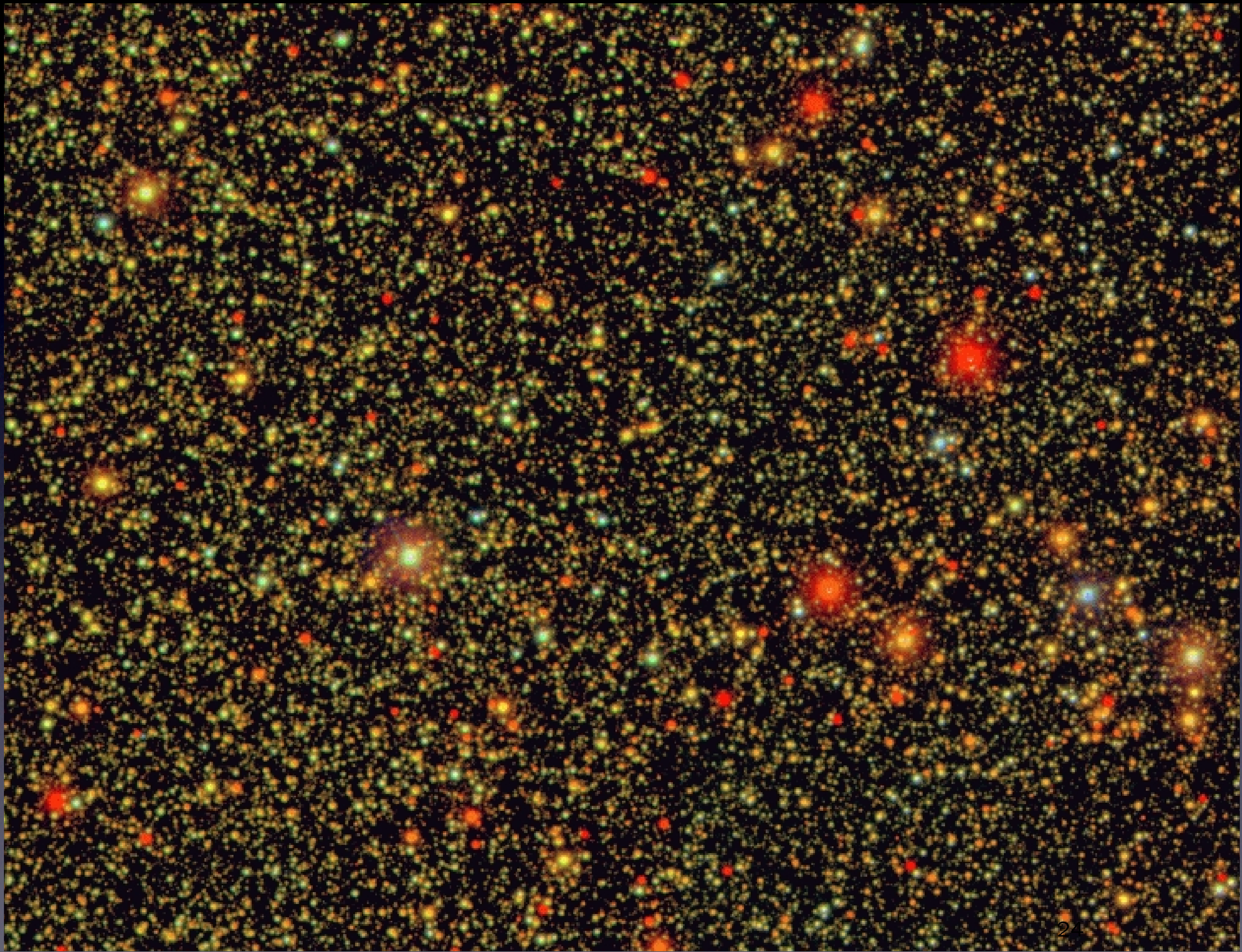
Substructure can be identified using stellar spatial distribution, and the metallicity and kinematic maps!

Deviations from the Smooth Model

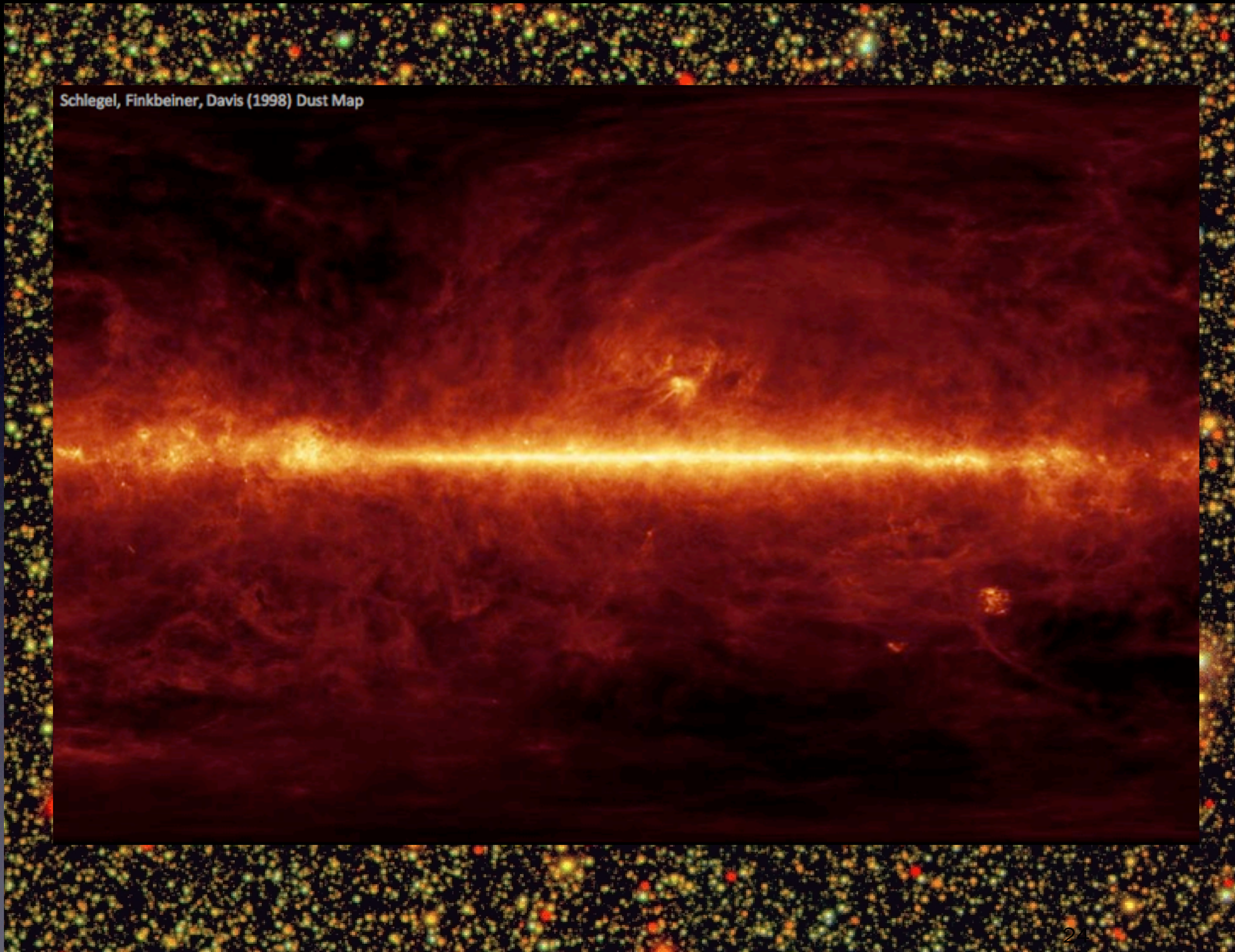
- Monoceros stream was discovered using stellar counts (**Newberg et al. 2002**)
- It is also identified as a substructure in metallicity space... LEFT
- And kinematics, too: it rotates faster than LSR by ∼50 km/s
- More details: Ivezić et al. 2008 (ApJ 684, 287)
- Search for substructure using radial velocity: more effective at large distances (Schlaufman et al. 2009, Klement et al. 2009)

Li+2012 (ApJ 757, 151) Monoceros (or Lynx? at l=180,b=30)

SDSS view along the Milky Way Disk



But there is dust there! (not to scale)



ISM dust in the MW thin disk:

SFD maps **cannot** be used to correct low-latitude optical photometry for extinction: a major obstacle for mapping stellar distribution

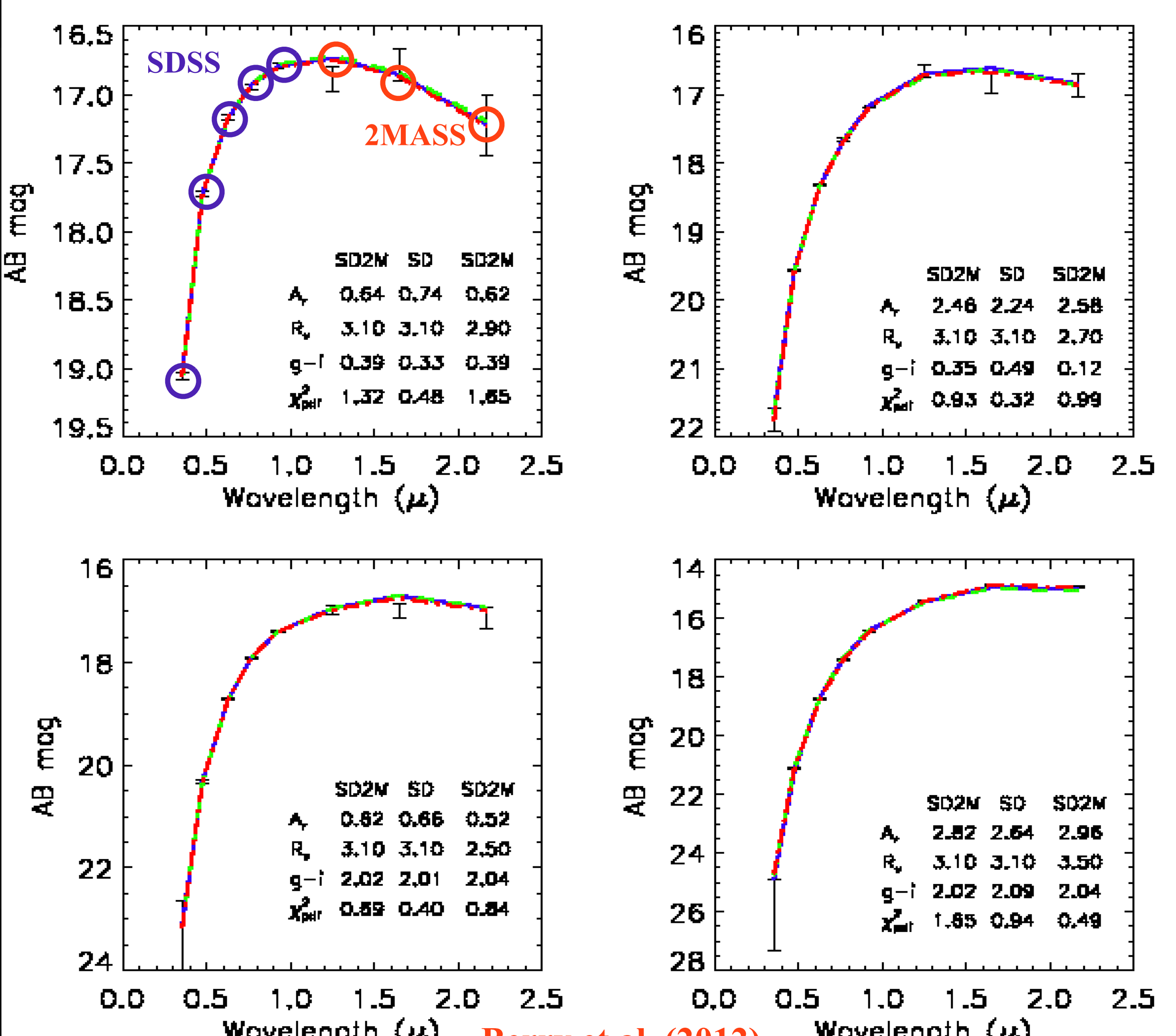
- At high Galactic latitude ($|b|>30°$), stars are mostly behind dust
- At low Galactic latitude ($|b|<30°$), stars are **embedded** in dust

Major Challenge

There is a degeneracy between dust reddening and intrinsic stellar colors!

With high-precision photometry from SDSS and 2MASS, this degeneracy can be lifted (for most stars)

Stellar SEDs are parametrized at high latitudes as a (nearly) one-parameter family; dust extinction is parametrized as a two-parameter family **Berry et al. (2012, ApJ, 757, 166)**

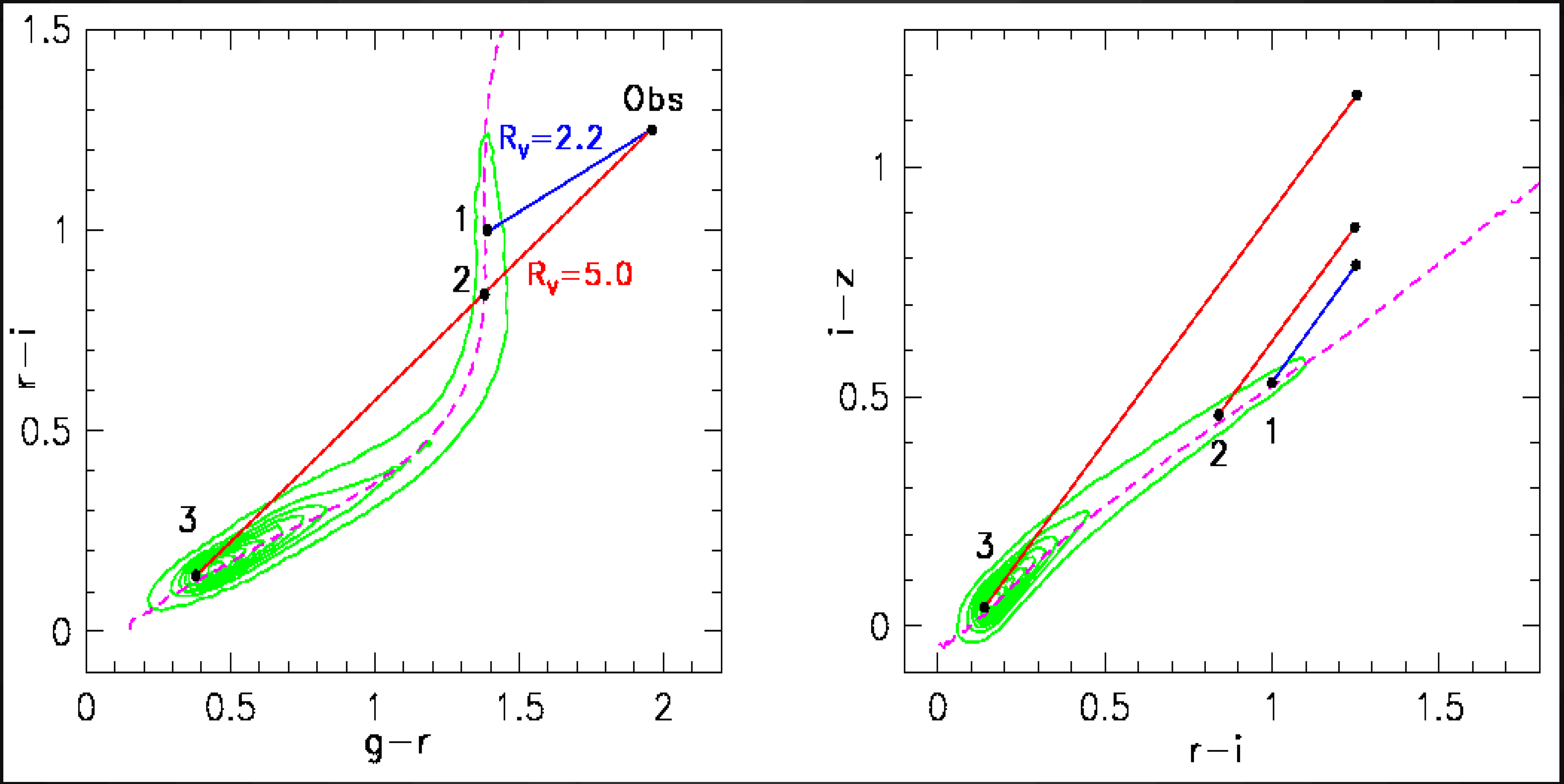


Berry et al. (2012)

Determine intrinsic stellar SED and the dust extinction along the line of sight by fitting seven SDSS-2MASS colors with 2-3 free parameters

Since distance to main sequence stars can be estimated, this yields 3D dust map

Why does this work? Near-IR colors break degeneracy between the stellar color and dust reddening:



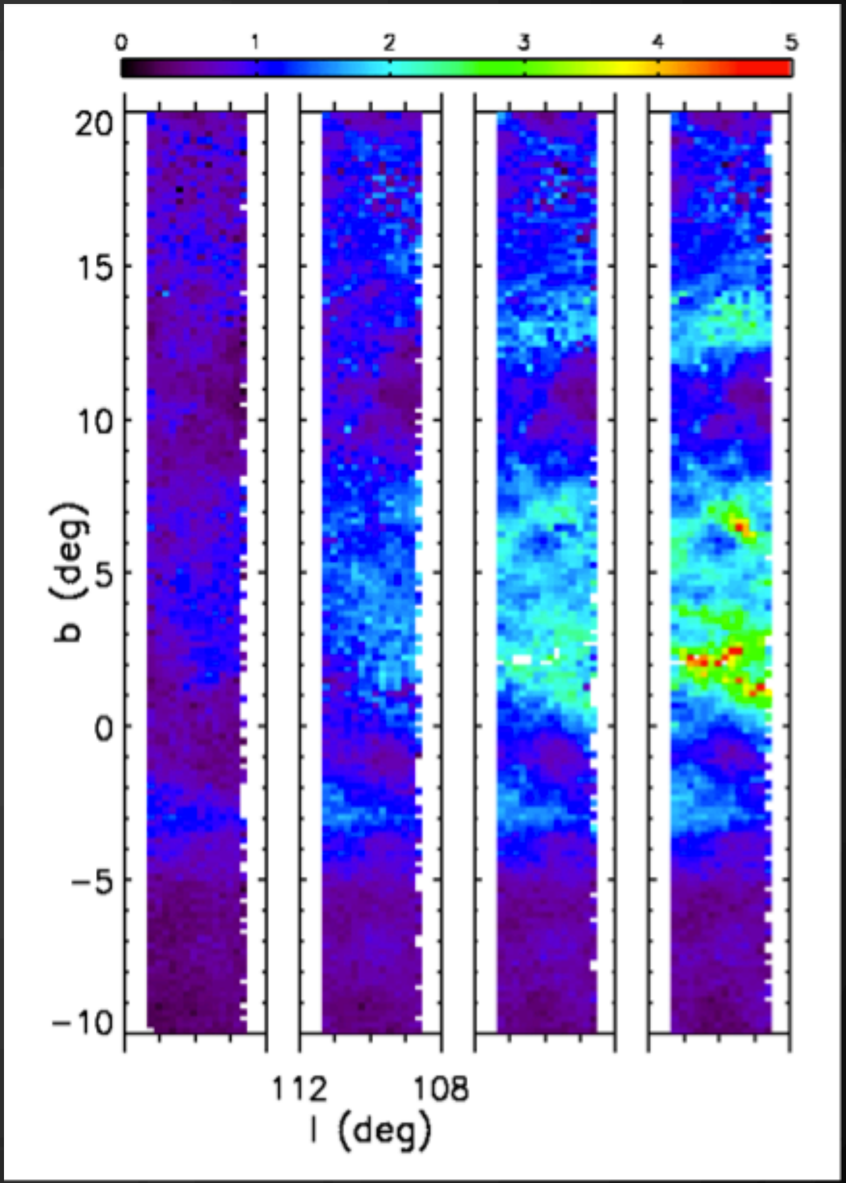
But wide wavelength baseline (UV to near-IR) and precise photometry (errors ~0.02 mag or smaller) is required (i.e. SDSS & 2MASS)

Distance Bracketing

Distance bins are (from left to right, in kpc): 0.1-0.5, 0.5-0.7, 0.7-0.9, 0.9-1.1

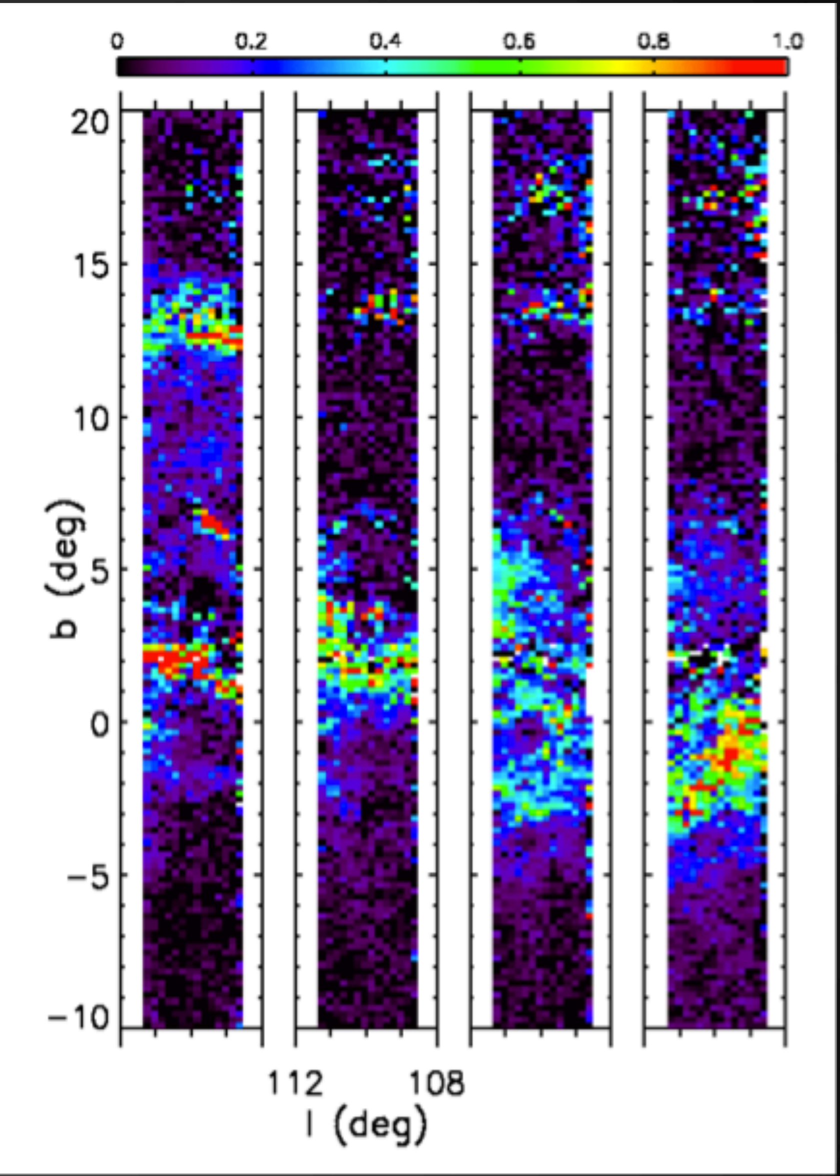
Note the abrupt jump in A_r at b~2º for stars with D>0.9 kpc

- Lower limit for the distance to this dust cloud
- Implies molecular clouds have D>1kpc



Spatial Distribution of Dust

- Difference in median A_r along the line of sight for distances:
  - 1kpc, 1.5kpc, 2kpc, 2.5kpc
- The dust structures at b~2º and b~13º are confined to 1-1.5kpc
- The substructure at -3º<b<0º is at D~2.5kpc

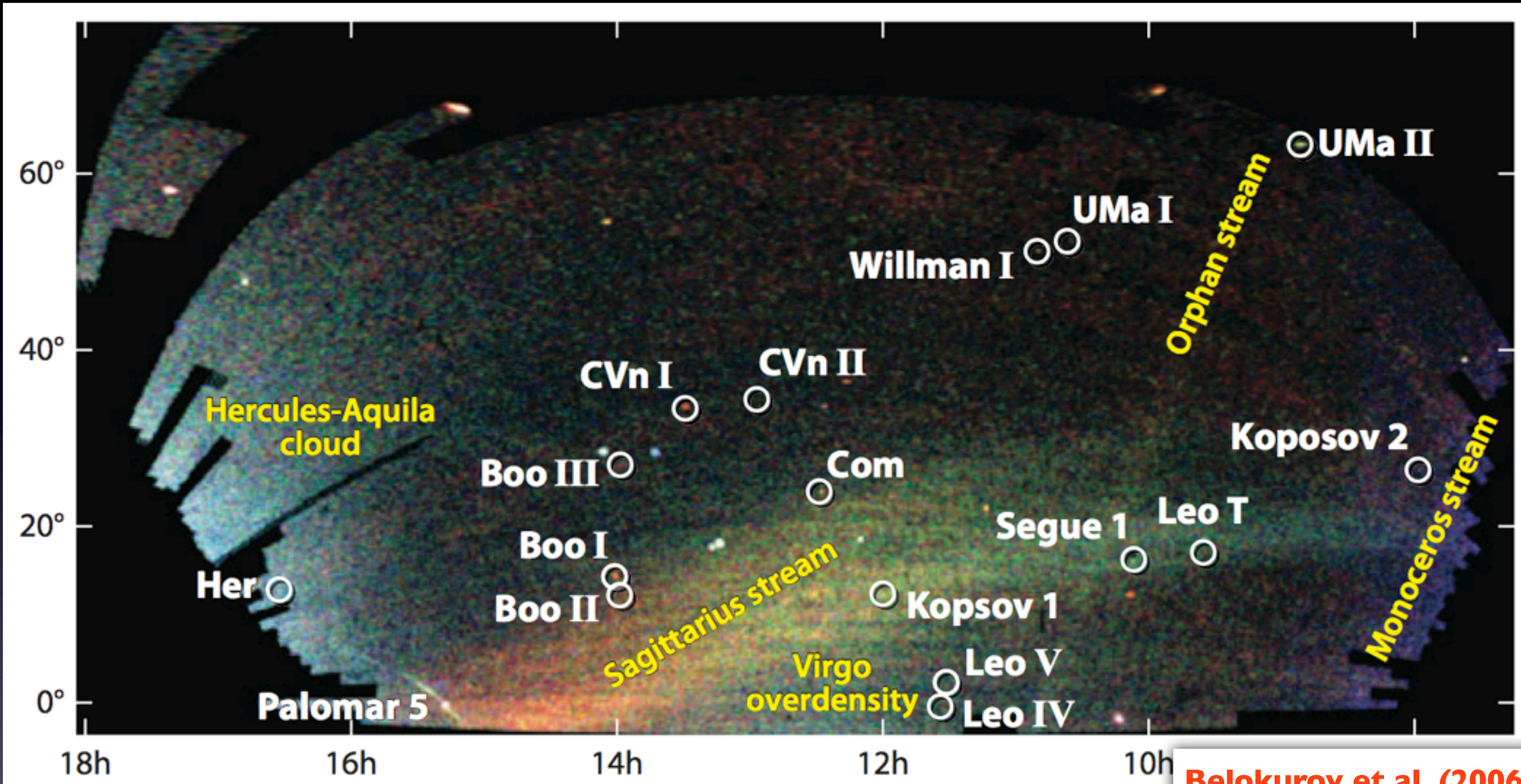


3D dust tomography!

All data (fits) are public:

http://www.astro.washington.edu/users/ivezic/r_datadepot.html

The Milky Way halo: not smooth, not simple

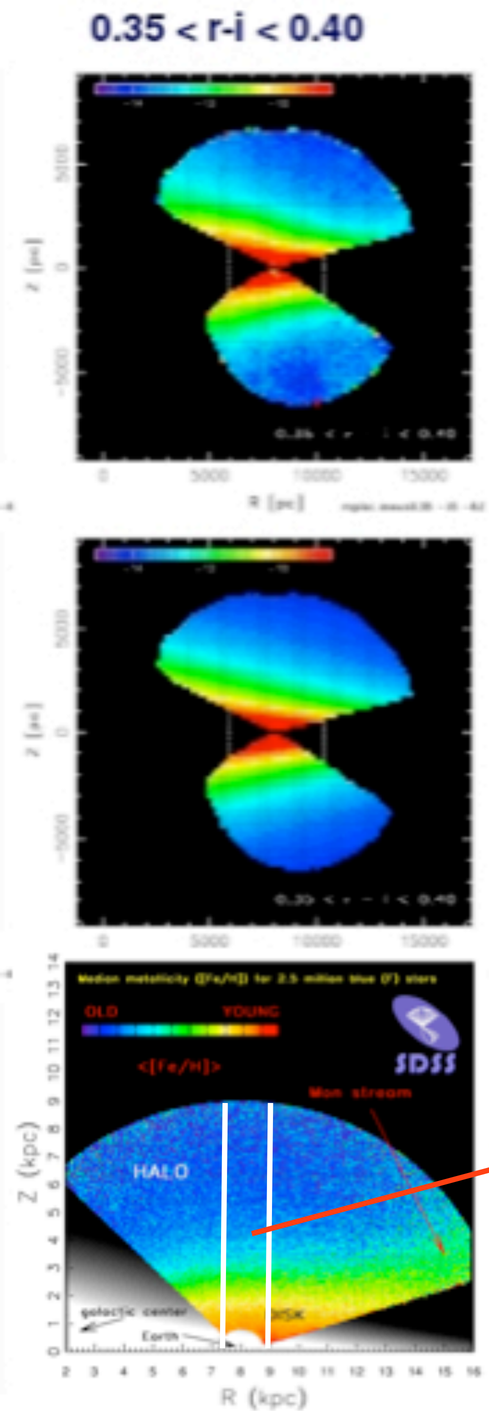


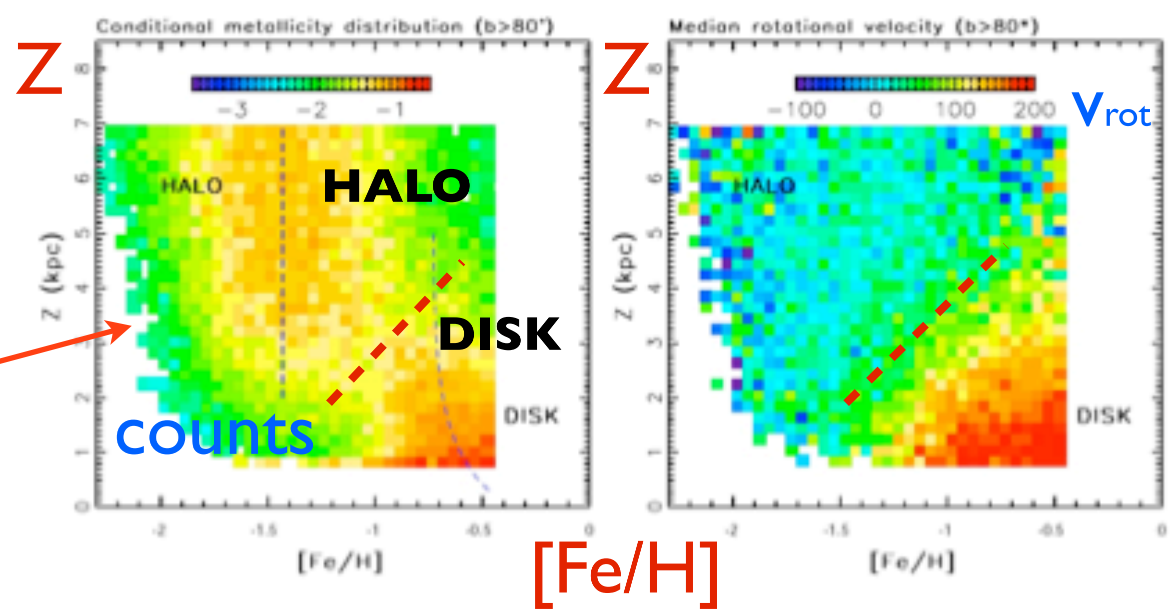
Belokurov et al. (2006)

The halo structure is interesting because:
1) dynamical times are long (merger history), and
2) gravitational potential becomes dominated by the dark matter halo

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



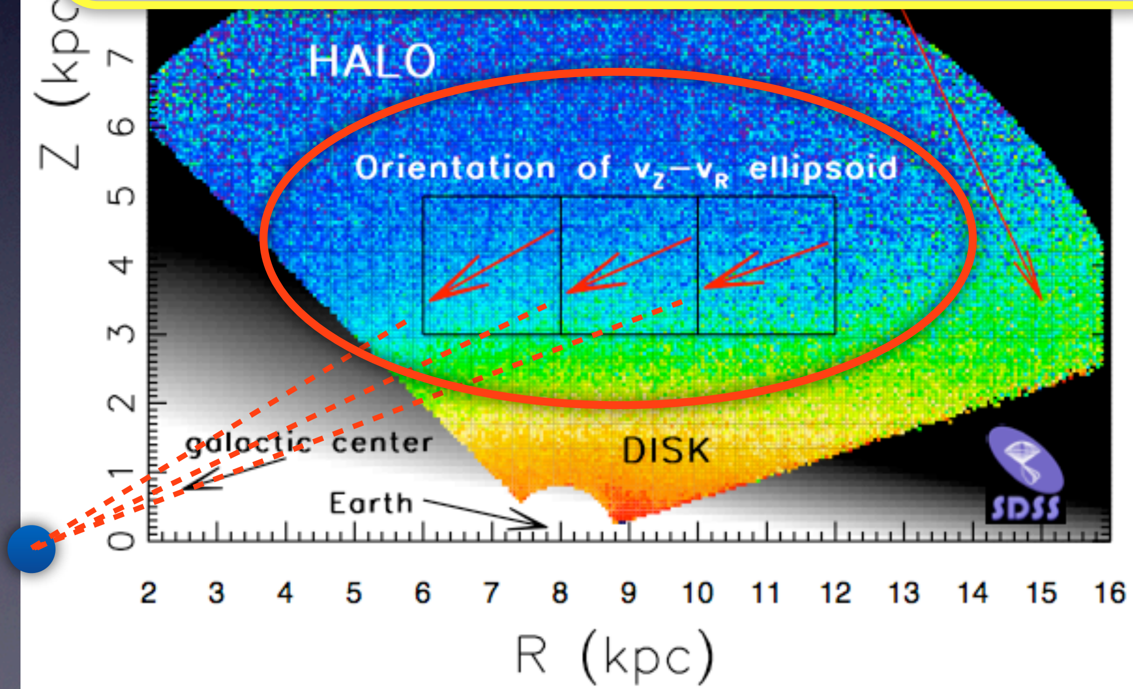


Velocity distribution for (nearby) halo stars

Kinematic data constrain dark matter via Jeans equations

$$a_R = \sigma^2_{RR} \times \frac{\partial(\ln\nu)}{\partial R} + \frac{\partial\sigma^2_{RR}}{\partial R} + \sigma^2_{RZ} \times \frac{\partial(\ln\nu)}{\partial Z} + \frac{\partial\sigma^2_{RZ}}{\partial Z} + \frac{\sigma^2_{RR}}{R} - \frac{\sigma^2_{\phi\phi}}{R} - \frac{\overline{v_\phi}^2}{R},$$

$$a_Z = \sigma^2_{RZ} \times \frac{\partial(\ln\nu)}{\partial R} + \frac{\partial\sigma^2_{RZ}}{\partial R} + \sigma^2_{ZZ} \times \frac{\partial(\ln\nu)}{\partial Z} + \frac{\partial\sigma^2_{ZZ}}{\partial Z} + \frac{\sigma^2_{RZ}}{R}.$$



Kinematics of halo stars based on SDSS-POSS proper motions:

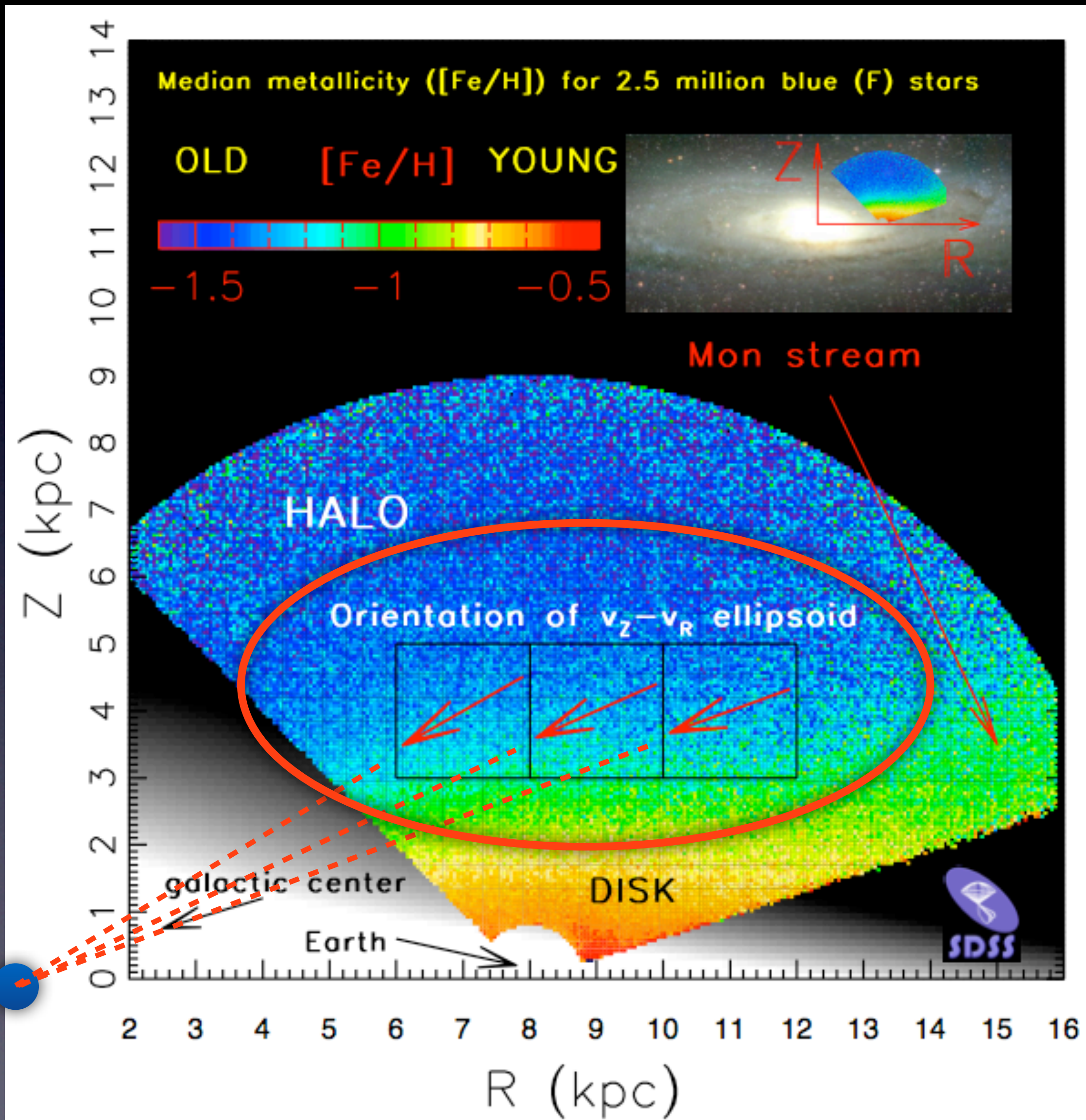
velocity ellipsoid is nearly invariant in spherical coordinate system

Given stellar distribution from Juric+2008 and stellar kinematics from Bond+2010, we can apply **Jeans equations** and infer the gravitational potential, and ultimately the distribution of dark matter!

Can we really?

Velocity distribution for (nearby) halo stars

Kinematic data constrain dark matter via Jeans equations



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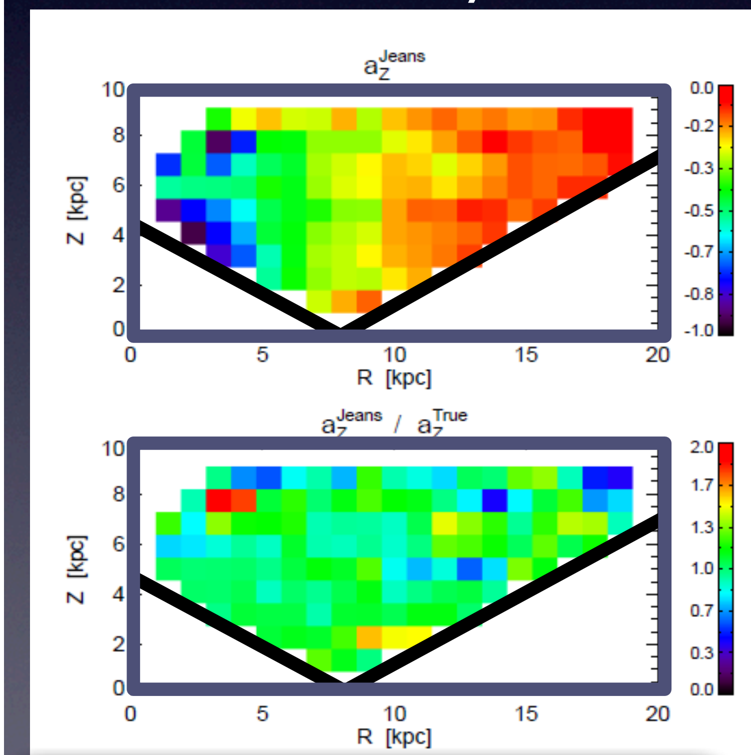

N-body model (Governato et al.)

Velocity distribution for (nearby) halo stars

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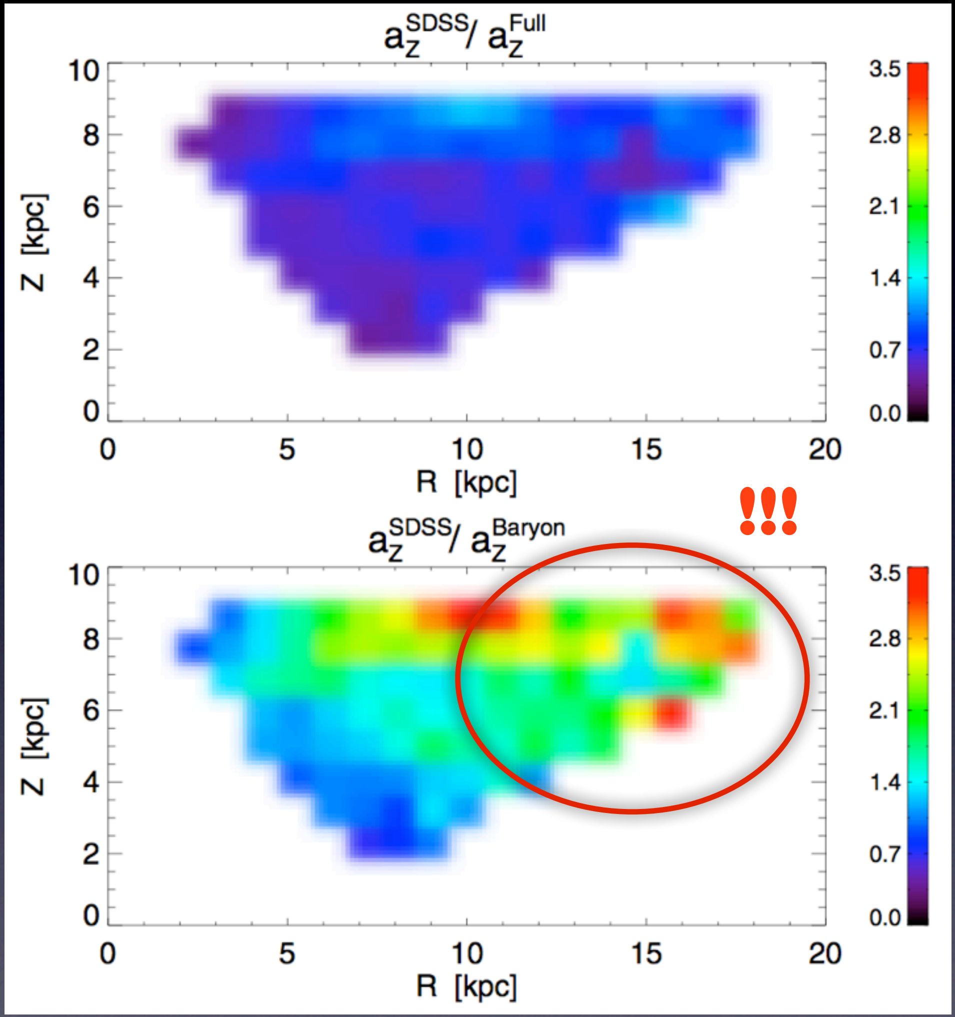

SDSS aZ normalized by model aZ
Top: model with DM; bottom: no DM

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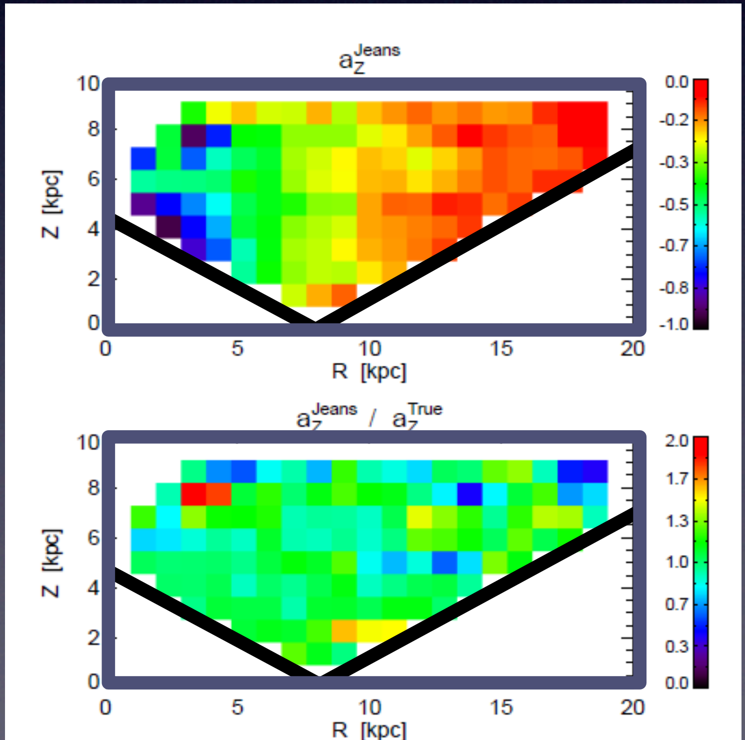

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acc. ratio Obs/ Mod

THE ASTROPHYSICAL JOURNAL LETTERS, 758:L23 (6pp), 2012 October 10

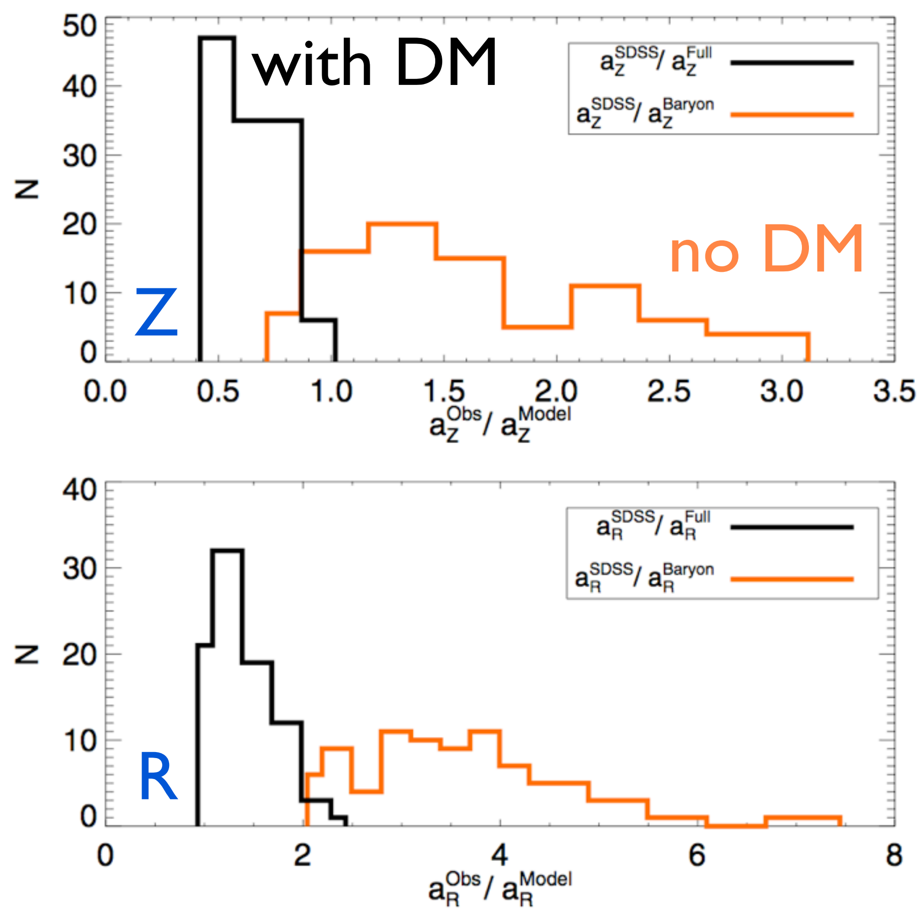
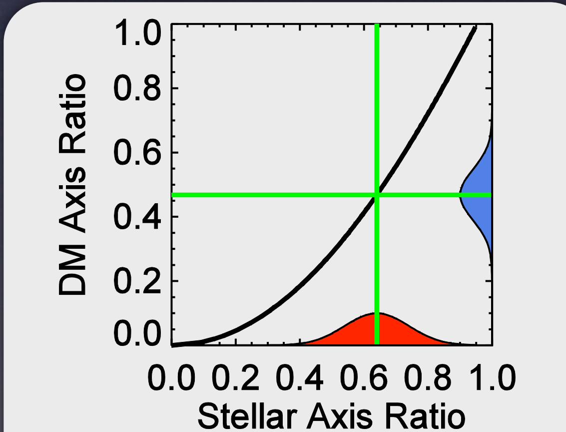


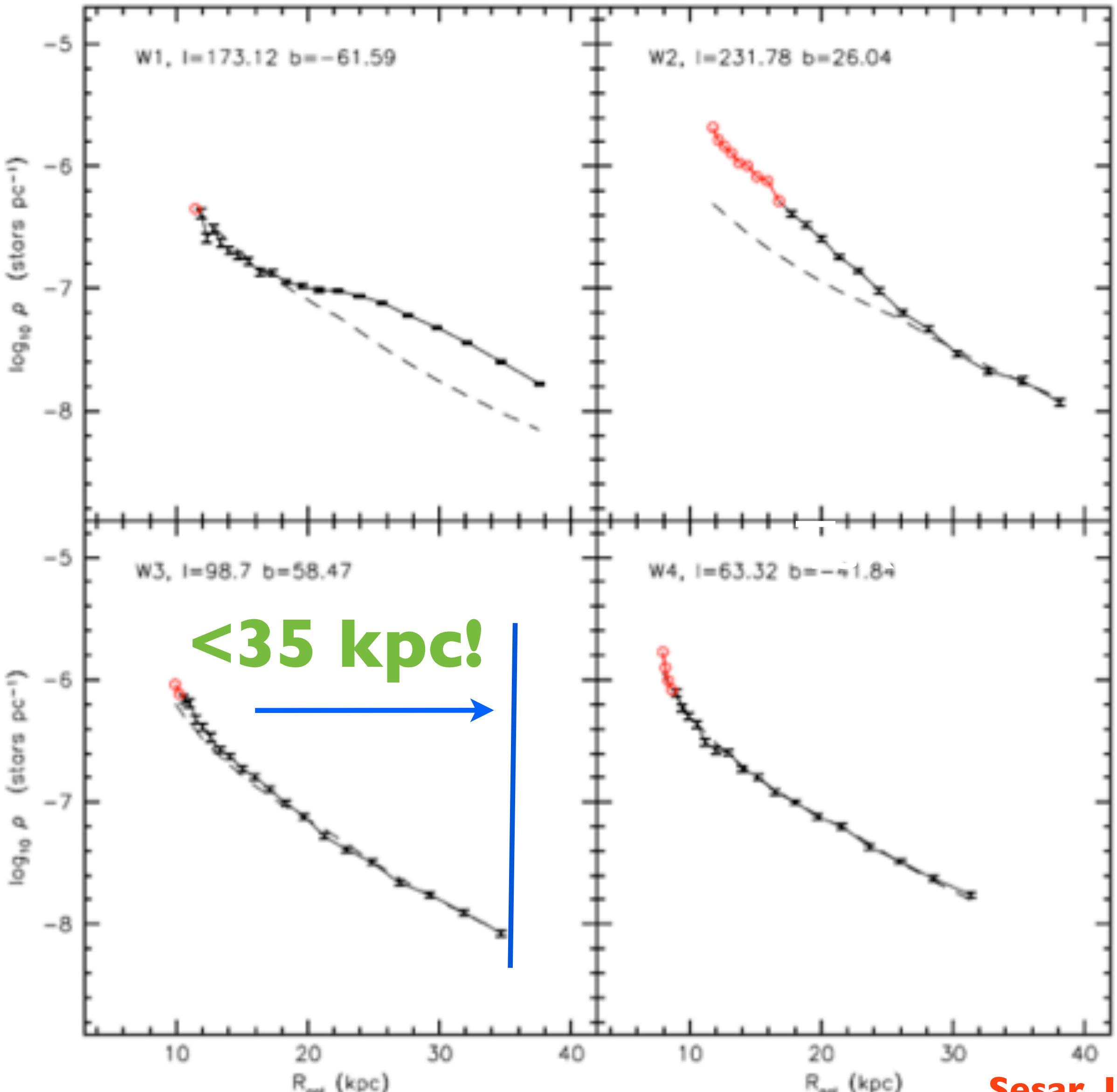
Figure 5. Pixel-by-pixel comparison of the acceleration values implied by the SDSS data and the two model predictions that include (black lines) and do not include (red lines) contributions from dark matter. The top panel corresponds to the a_Z acceleration maps shown in Figure 4 and the bottom panel to the a_R acceleration maps. The model-based acceleration maps that include a dark matter contribution provide a significantly better description of the acceleration maps derived from the SDSS data.

Kinematics of halo stars based on SDSS-POSS proper motions:
velocity ellipsoid is nearly invariant in spherical coordinate system, which implies that **the DM halo is oblate! q=0.5±0.1** (Loebman et al. 2012; ApJ, 758, L23)



van der Marel (1991) method

Halo density profiles out to 35kpc



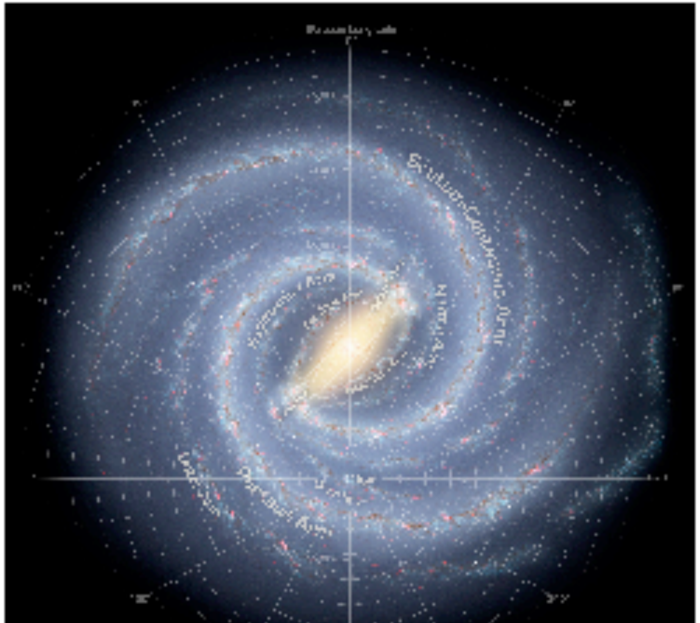
- q=0.7, n=-2.6 inner profile
- q=0.7, n=-3.8 outer profile
- transition at R_{break} ~ 28kpc

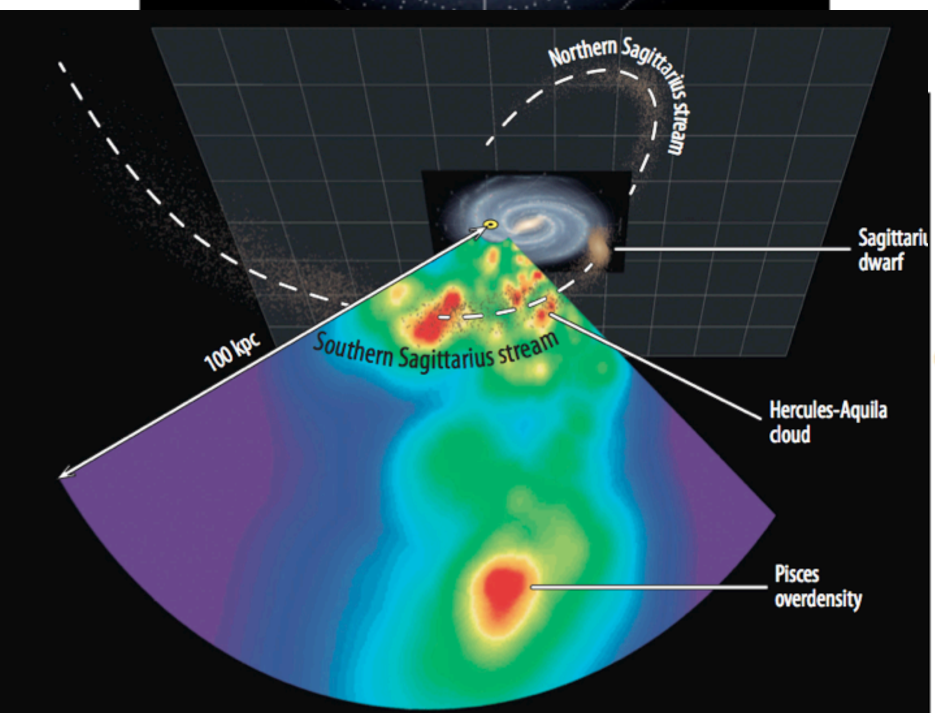
- no evidence for triaxiallity
- no evidence for change of oblateness

Use RR Lyrae to get to 100 kpc

Sesar, Jurić, Ivezić (2011, ApJ, 731, 4)

Outer halo studies: RR Lyrae from SDSS Stripe 82

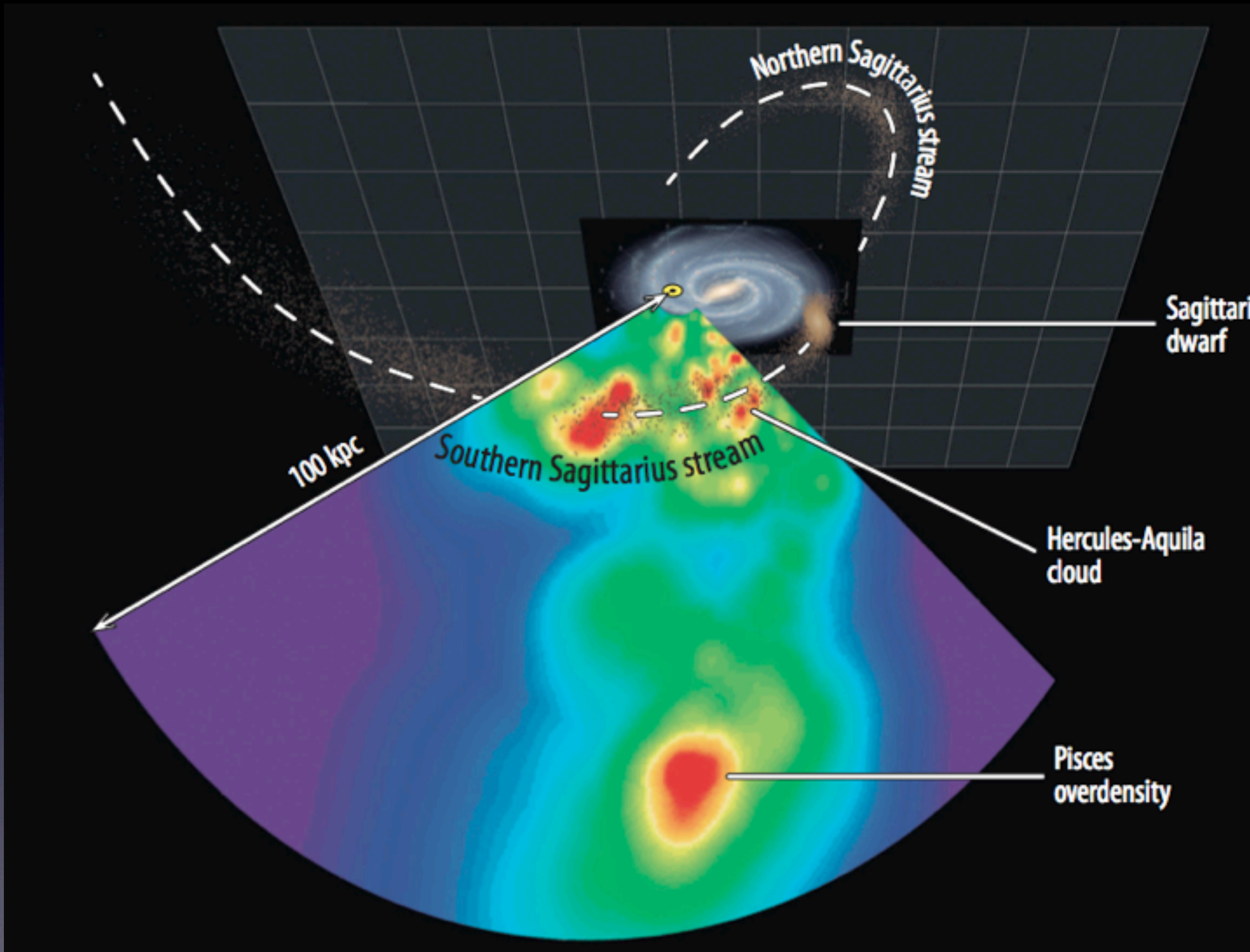




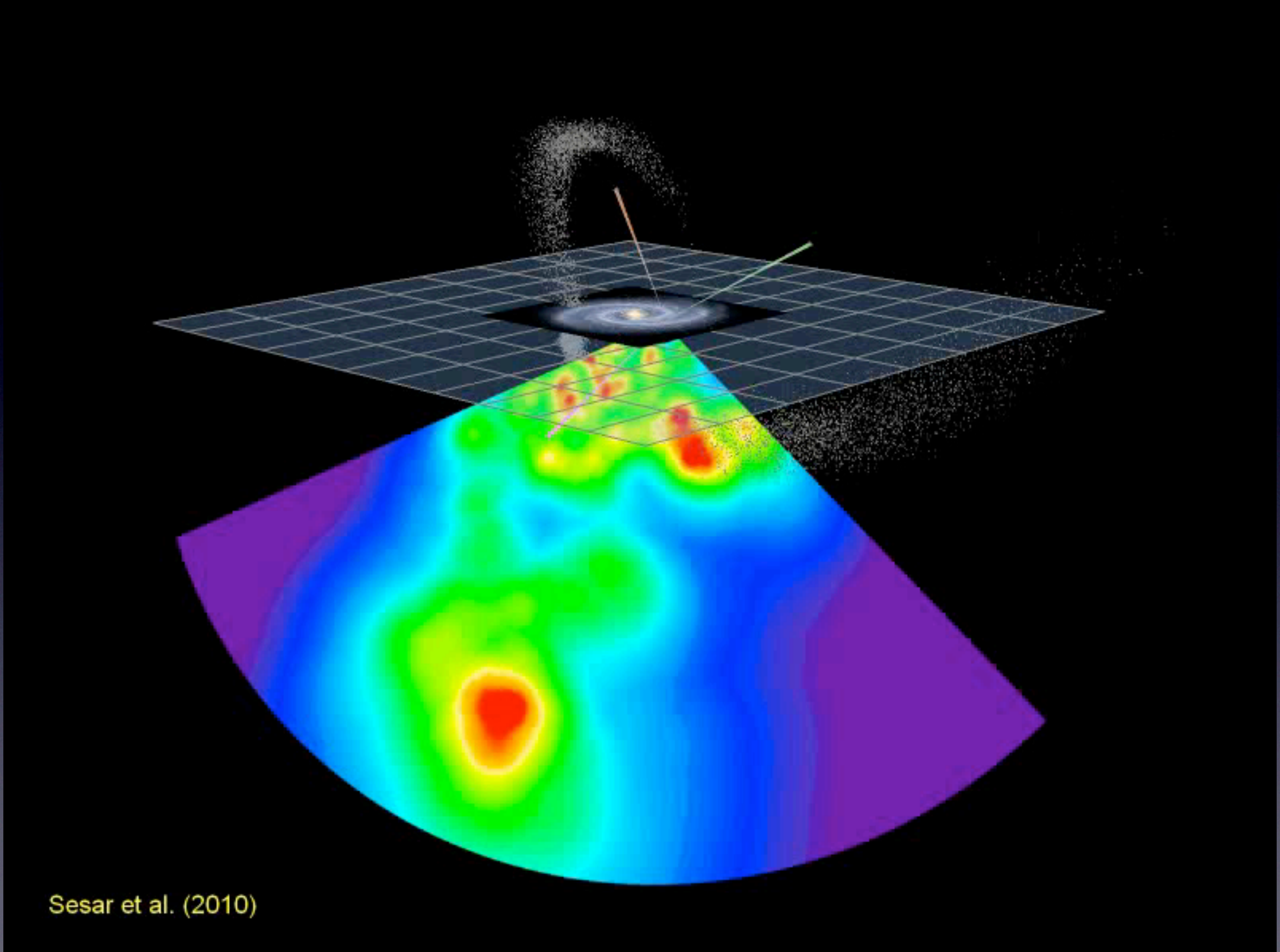
Sesar et al. (2010, ApJ, 708, 717)

- **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 Milky Way is complex and big!



And interesting and informative!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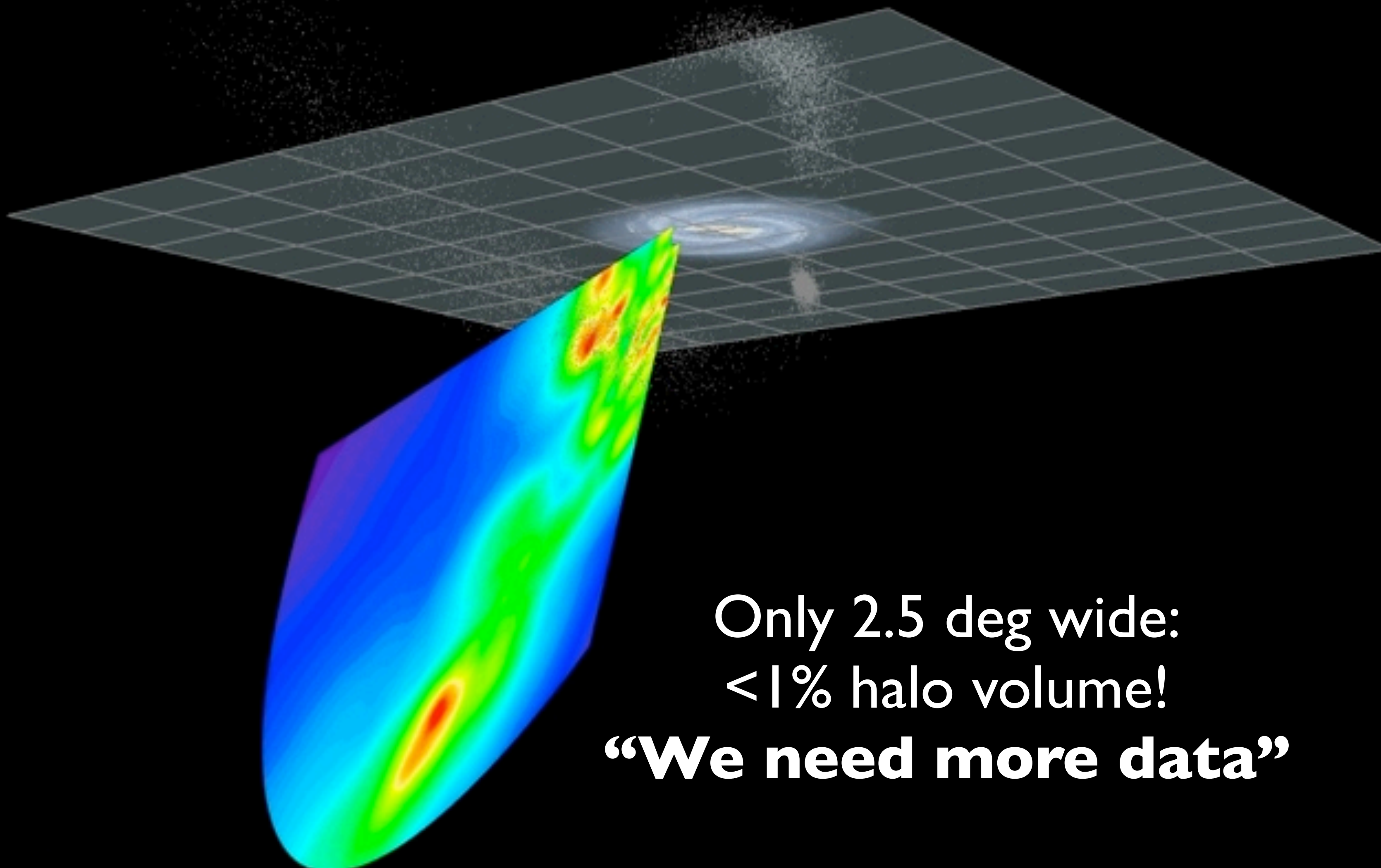


Only 2.5 deg wide:
<1% halo volume!
“We need more data”

U.S. Decadal Survey 2010

Priorities:

- Spaced-based:

1) *Wide-Field Infrared Survey Telescope WFIRST*
2) *The Explorer Program* *"rapid response"*
3) *Laser Interferometer Space Antenna LISA*
4) *International X-ray Observatory IXO*

- Ground-based:

1) ***Large Synoptic Survey Telescope LSST***
2) *Mid-scale Innovations Program* *"rapid response"*
3) *Giant Segmented Mirror Telescope (30m) GSMT*
4) *Atmospheric Čerenkov Telescope Array (ϒ) ACTA*
5) *Cerro Chajnantor Atacama Telescope (submm) CCAT*

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

LSST in one sentence:

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

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

A catalog of 10 billion stars and 10 billion galaxies with exquisite photometry, astrometry and image quality!

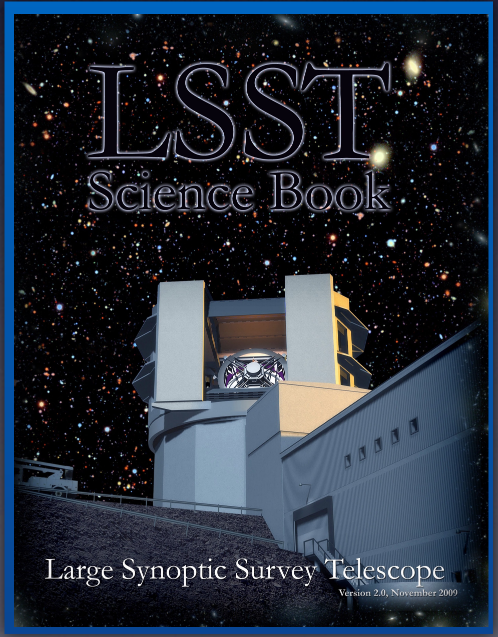
LSST Science Themes

- Dark matter, dark energy, cosmology
  (spatial distribution of galaxies, gravitational lensing, supernovae, quasars)
- Time domain
  (cosmic explosions, variable stars)
- The Solar System structure (asteroids)
- The Milky Way structure (stars)

LSST Science Book: arXiv:0912.0201

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

245 authors, 15 chapters, 600 pages



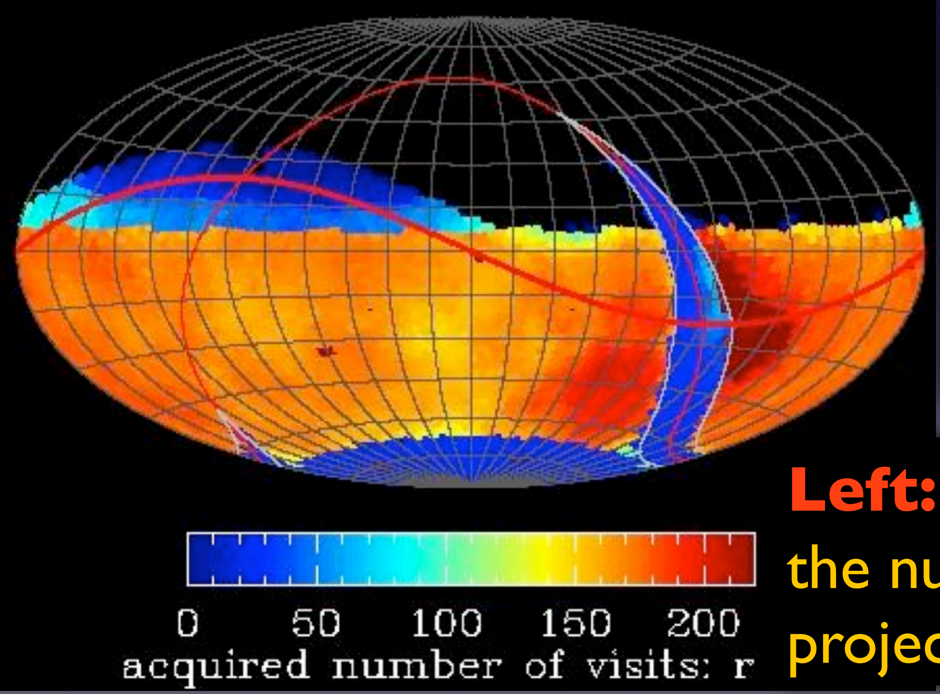
LSST Science Themes

- Dark matter, dark energy, cosmology (spatial distribution of galaxies, gravitational lensing, supernovae, quasars)
- Time domain (cosmic explosions, variable stars)
- The Solar System structure (asteroids)
- The Milky Way structure (stars)

These drivers not only require similar hardware and software systems, but also motivate a universal cadence: **about 90% of time will be spent on a uniform survey**

Basic idea behind LSST: **a uniform sky survey**

- 90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night
- after 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky
- ~100 PB of data: about a billion 16 Mpix images, enabling **measurements for 20 billion objects!**



LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 825 visits over a 10-year period: deep wide fast.

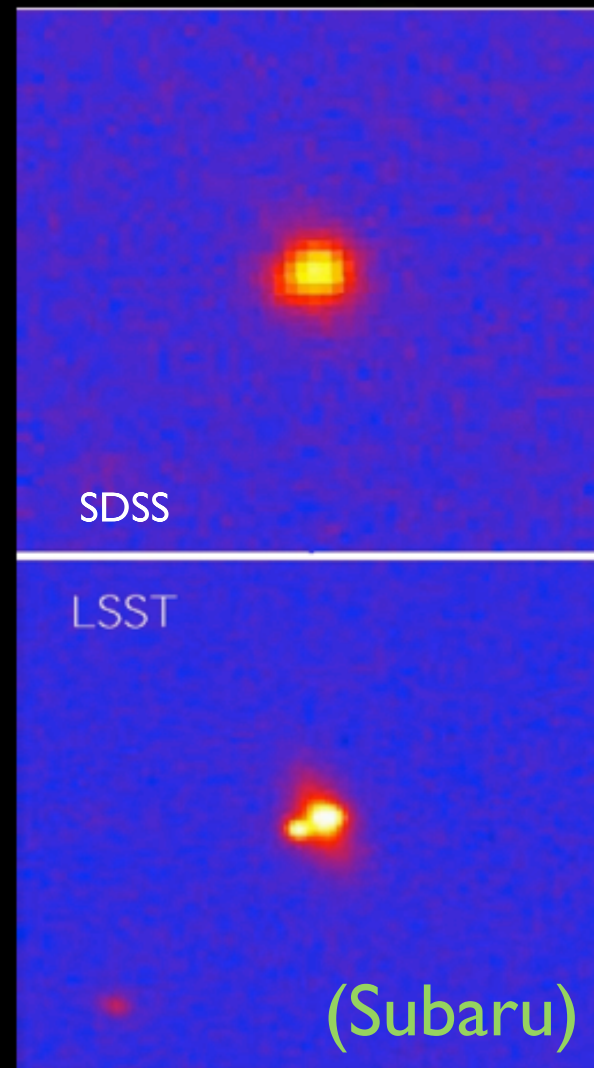
Left: a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)

Cadence details still open to optimization (e.g. see Gould, arXiv:1304.3455)

SDSS-LSST comparison: LSST=d(SDSS)/dt, LSST=SuperSDSS

7x7 arcmin, gri

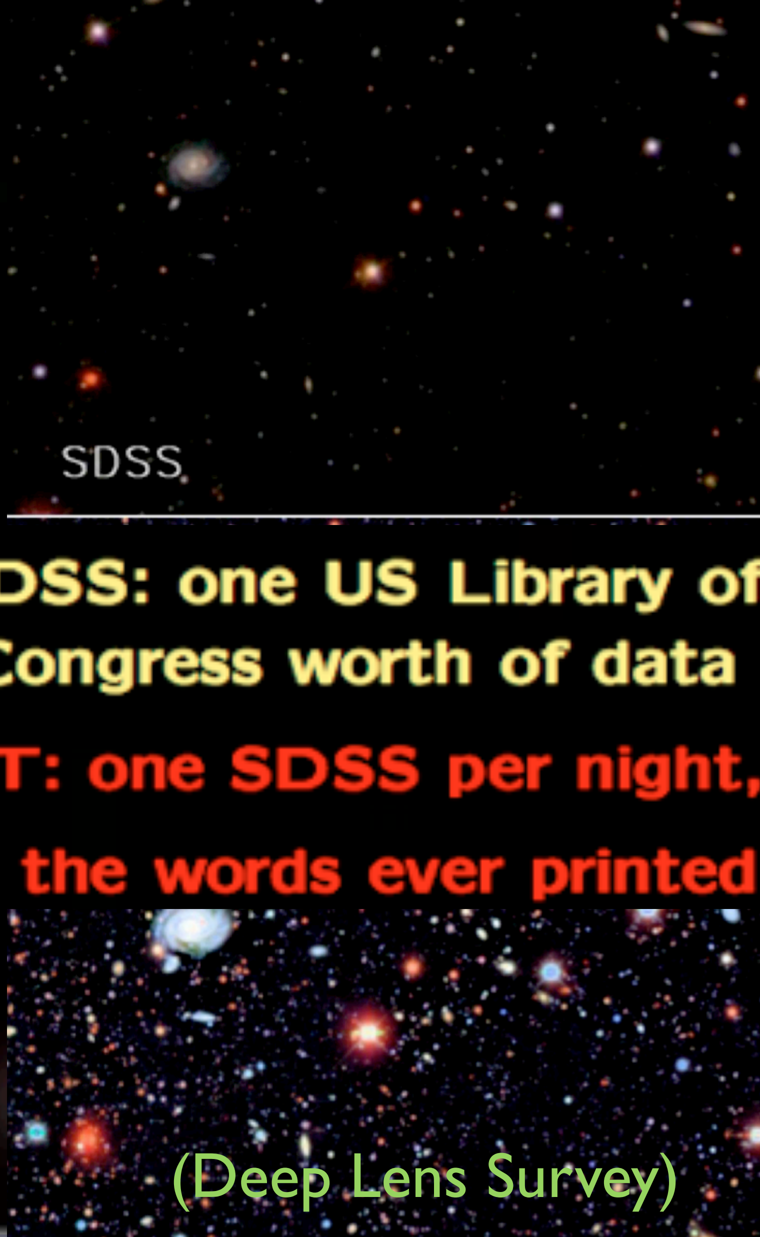
(Deep Lens Survey)



(Subaru)

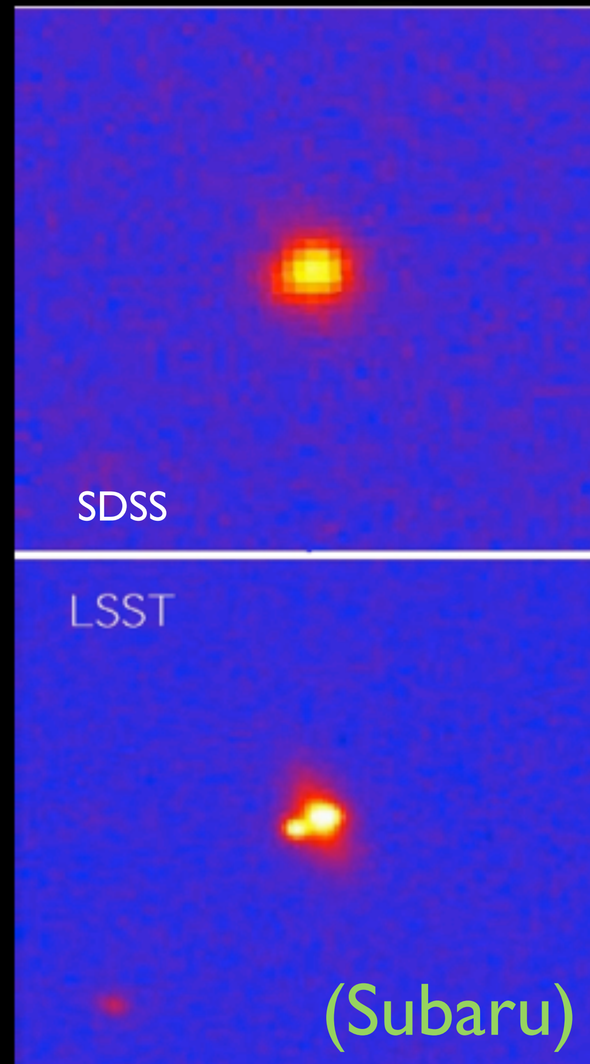
SDSS-LSST comparison: LSST=d(SDSS)/dt, LSST=SuperSDSS

7x7 arcmin, gri



SDSS: one US Library of Congress worth of data

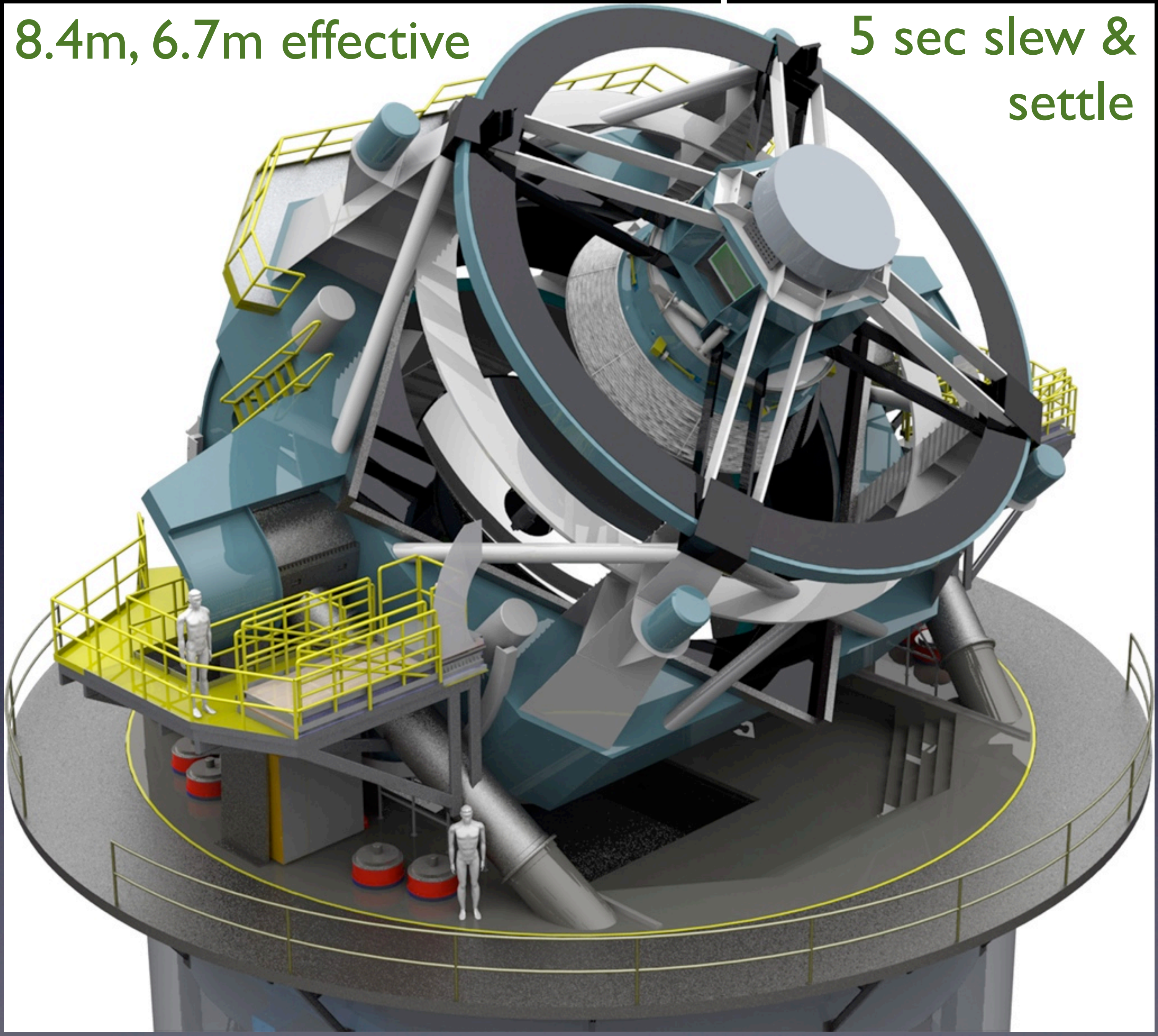
LSST: one SDSS per night, or all the words ever printed!



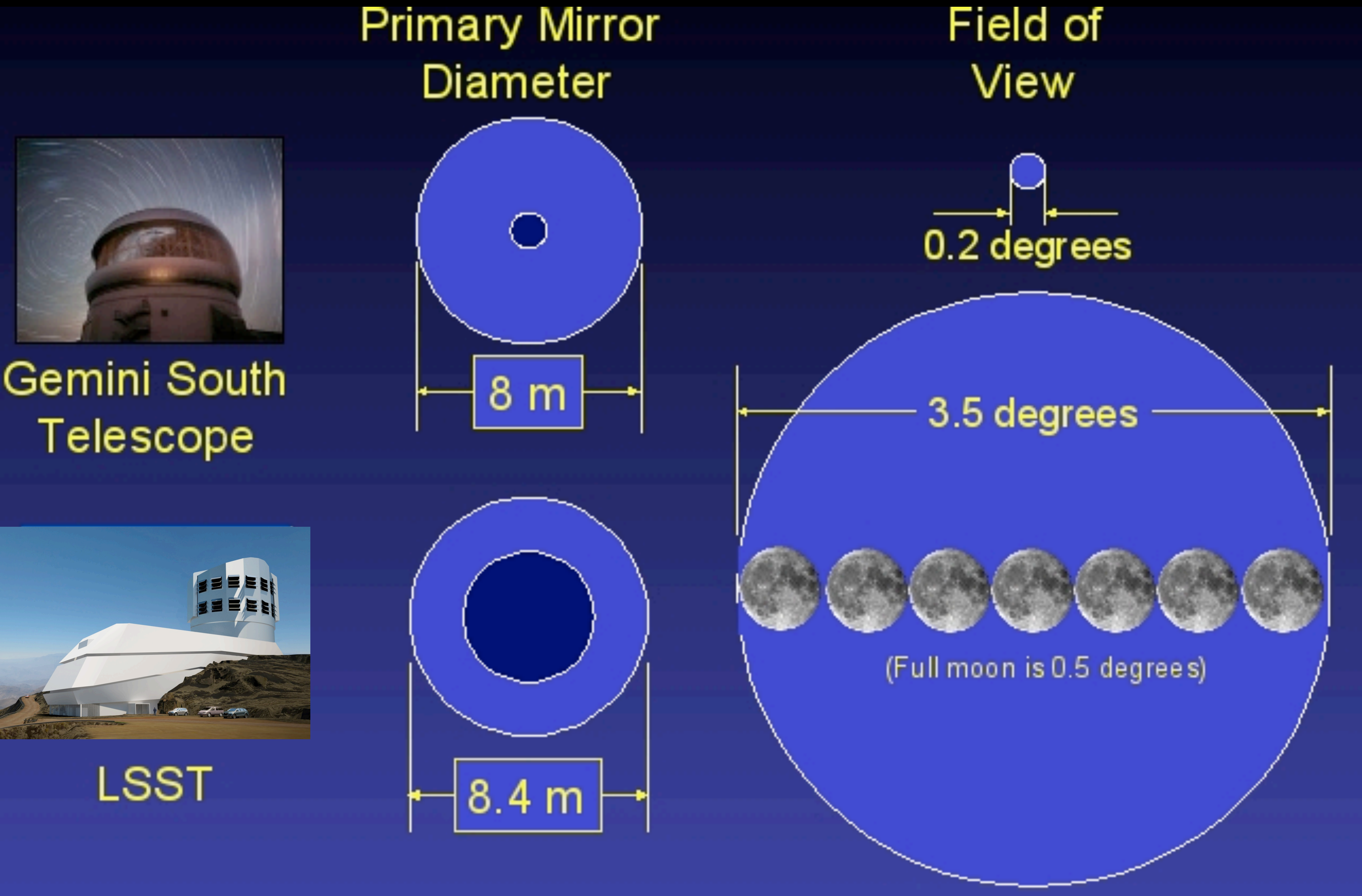
LSST system

Telescope
Camera
Software

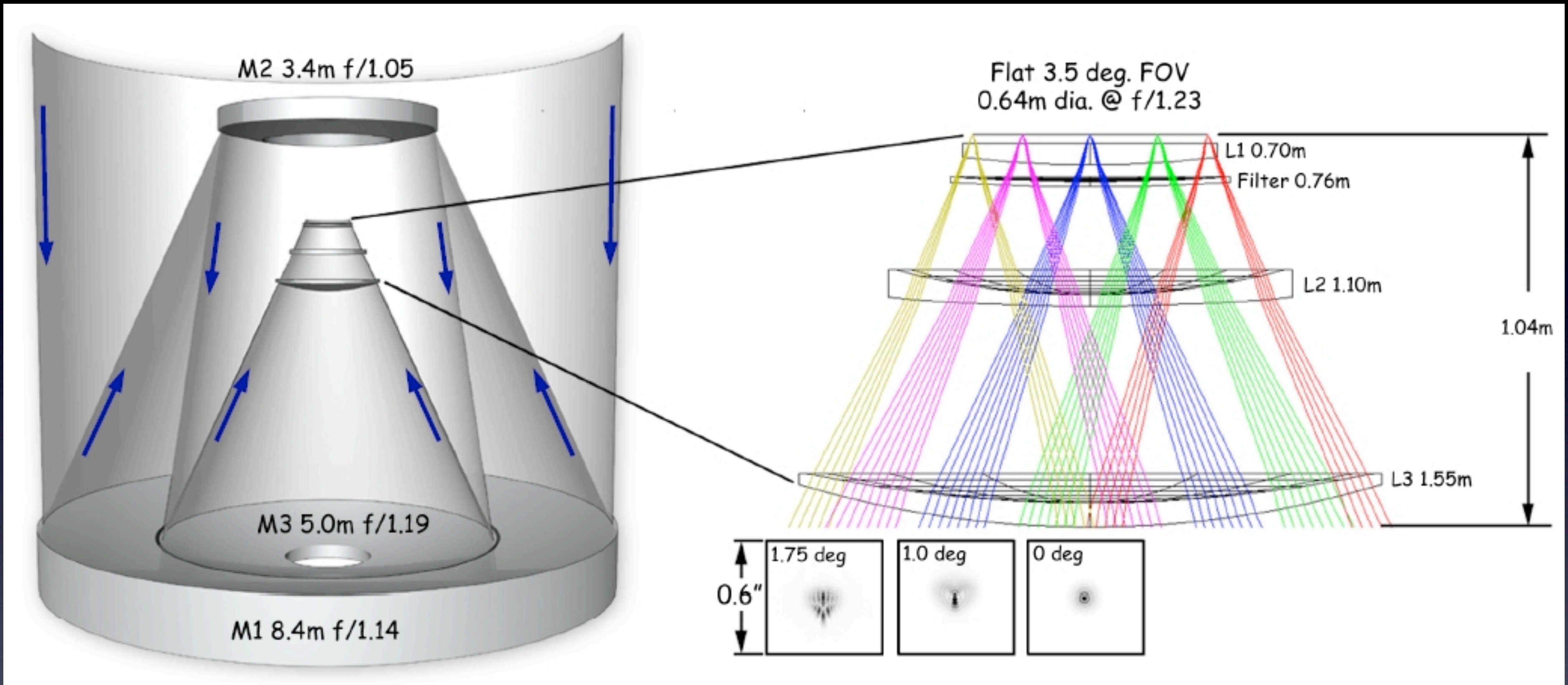
LSST Telescope



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

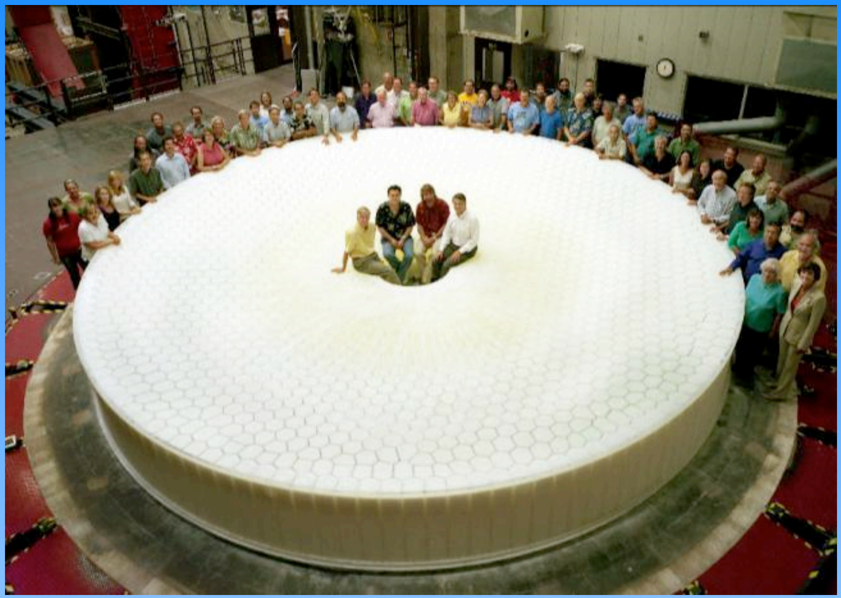


Optical Design for LSST



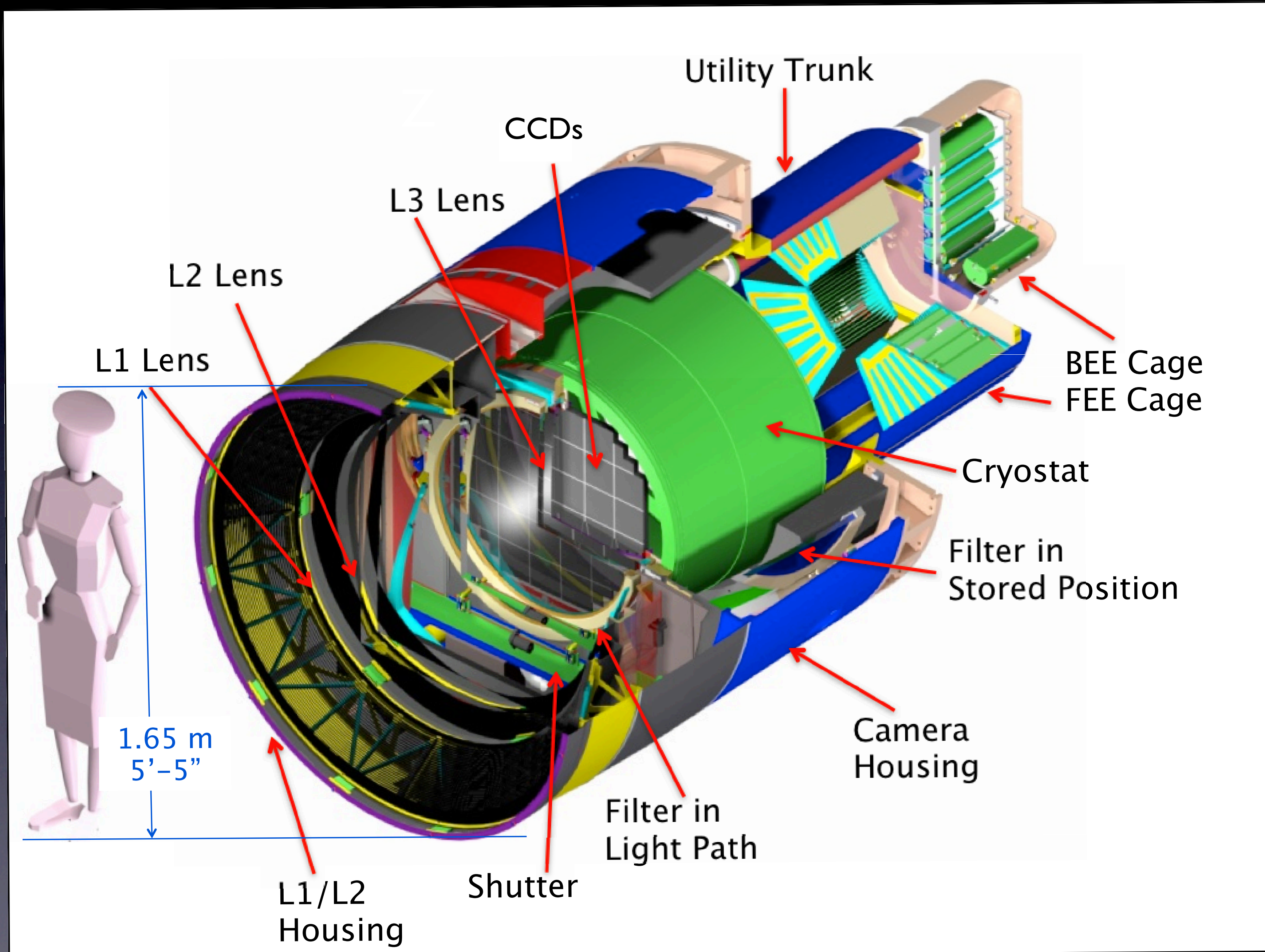
Three-mirror design (Paul-Baker system)
enables large field of view with excellent image quality:
delivered image quality is dominated by atmospheric seeing

Mirror fabrication is advanced - Private funding enabled early start of both reflective optics

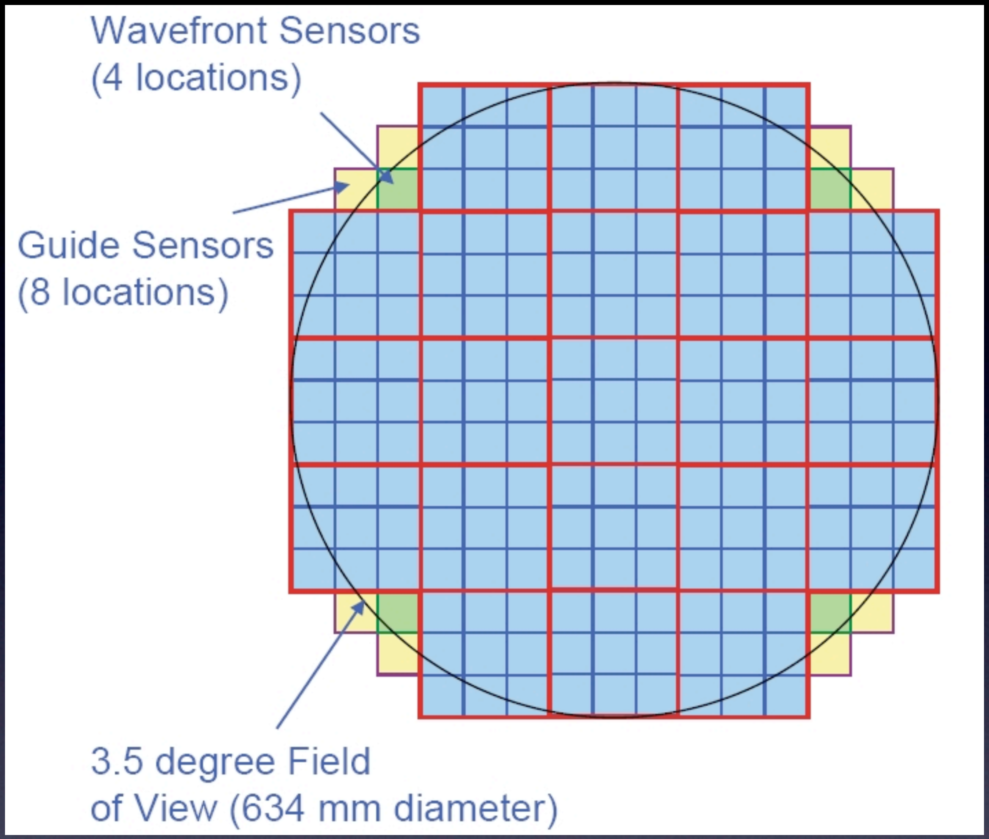


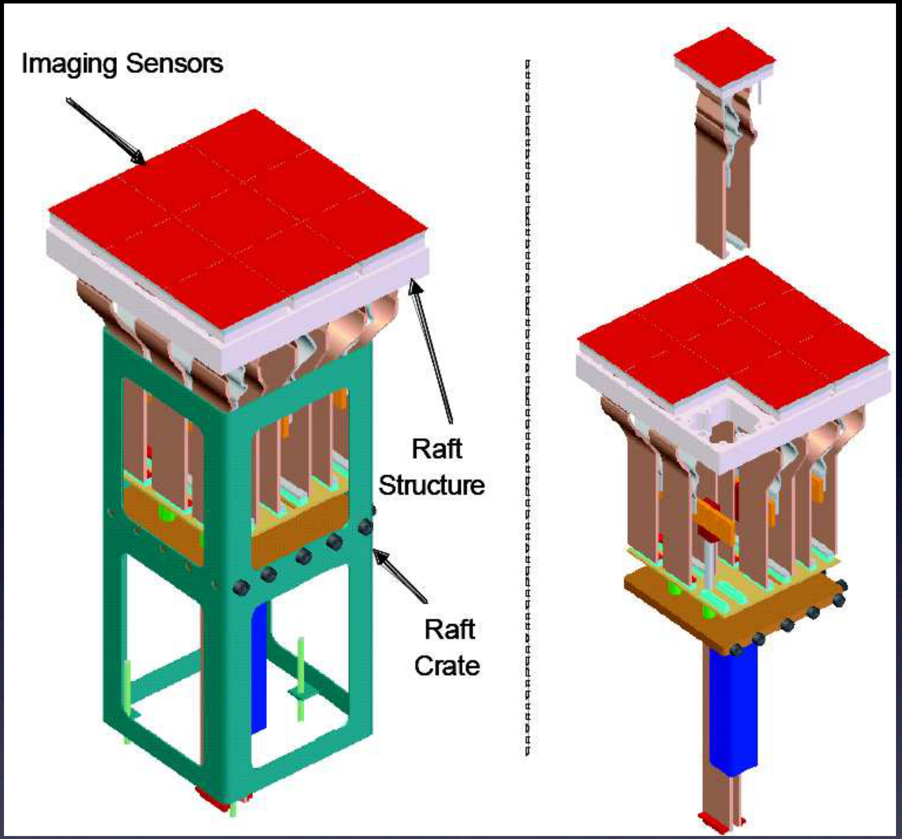
- Primary-Tertiary was cast in 2008
- Fabrication completed in 2013
- Secondary substrate fabricated by Corning in 2009.

The largest astronomical camera: 2800 kg, 3.2 Gpix



LSST camera



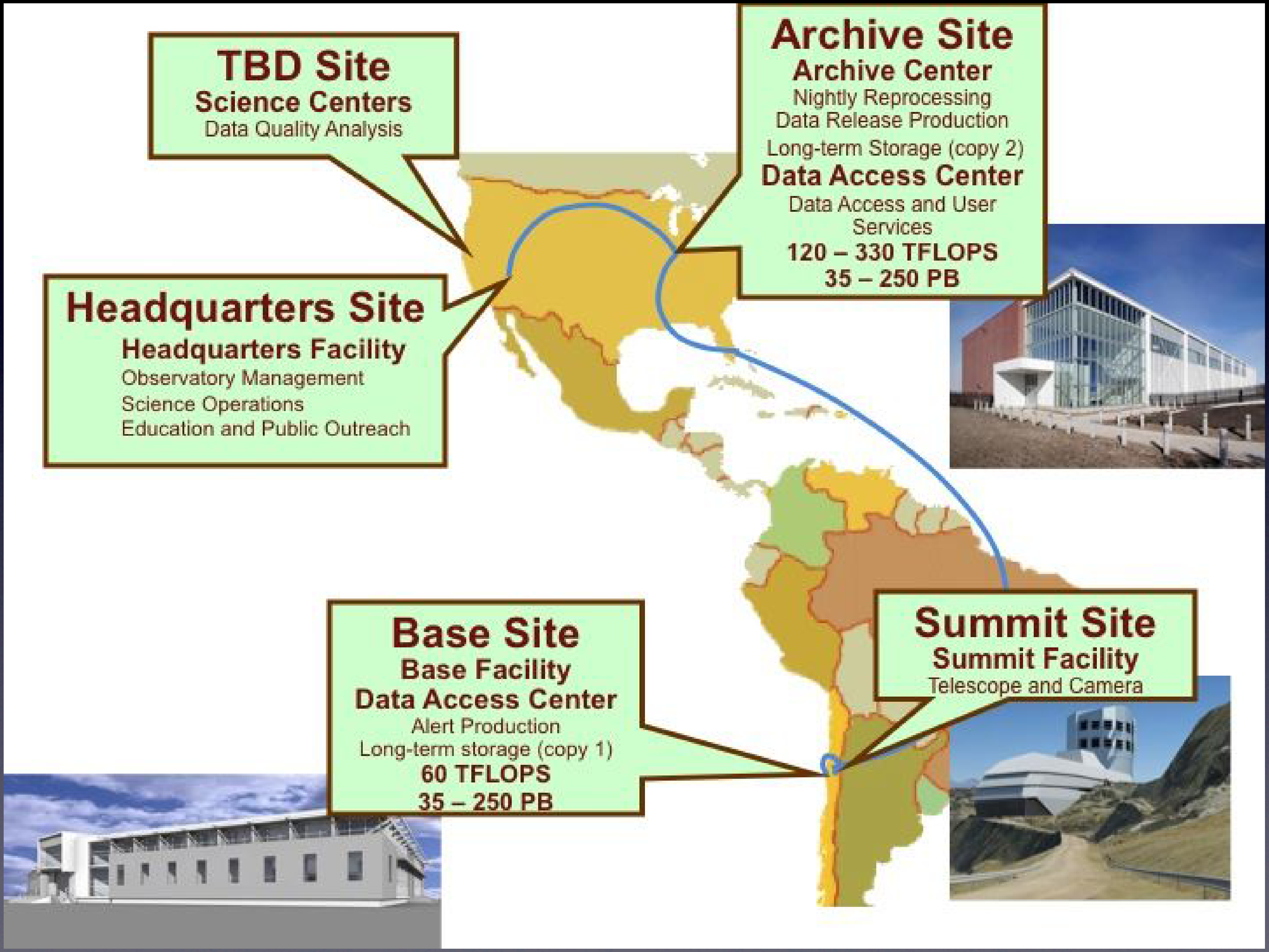


Modular design: 3200 Megapix = 189 x16 Megapix CCD

9 CCDs share electronics: raft (=camera)

Problematic rafts can be replaced relatively easily

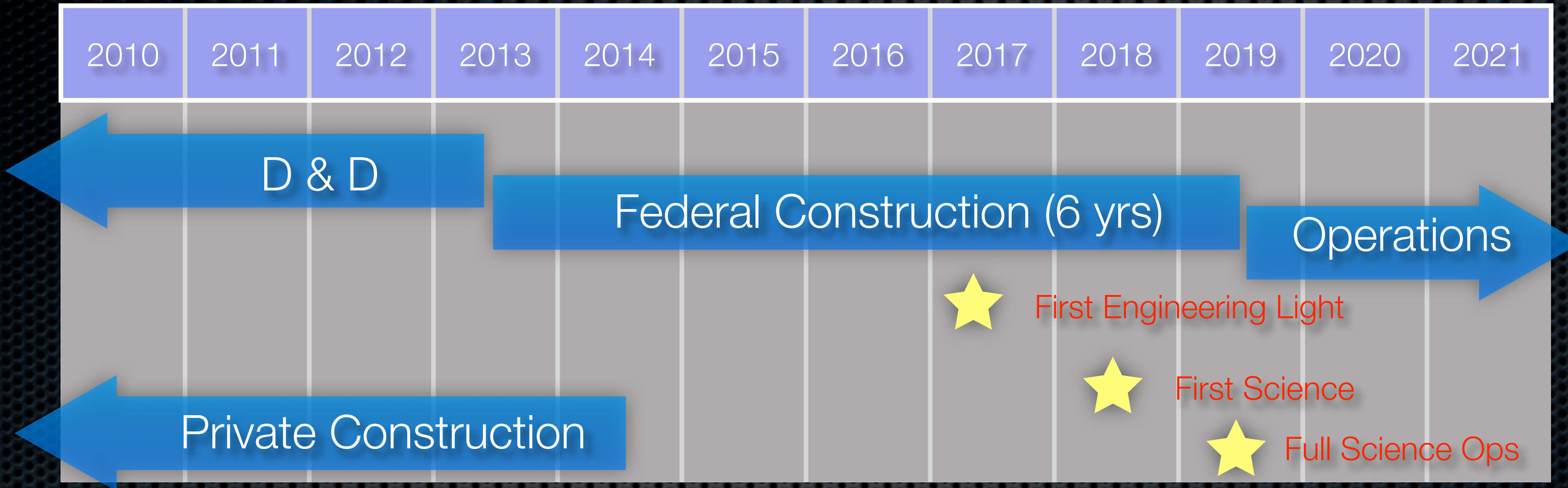
LSST Software



Software: the subsystem with the highest risk

- 20 TB of data to process every day (~one SDSS/day)
- 1000 measurements for 20 billion objects during 10 years
- Existing tools and methods (e.g. SDSS) do not scale up to LSST data volume and rate (100 PB!)

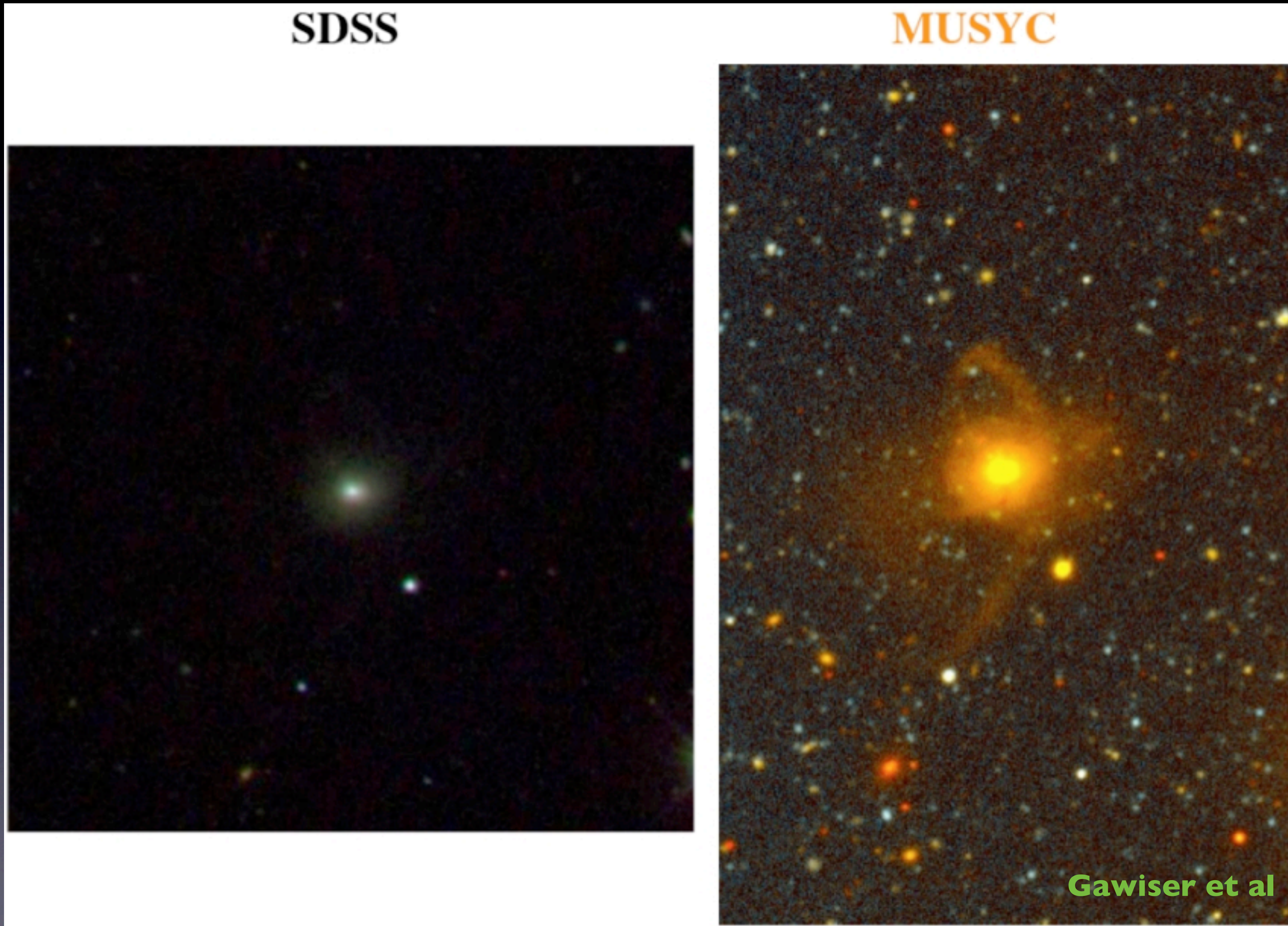
LSST Timeline



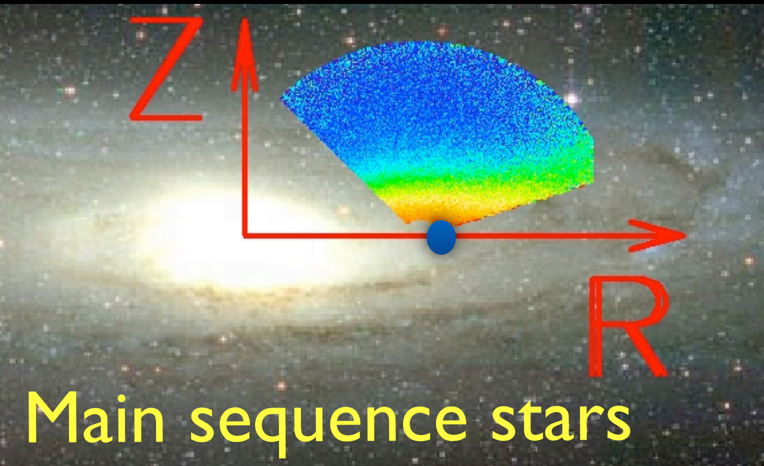
- **Estimate: survey operations begin in 2019 (if MREFC in FY2014)**
  - Primary/Tertiary Mirror being polished, have secondary mirror blank
  - Sensor development program delivered first prototype sensors
  - Processing pipelines under construction, hand-in-hand with simulations of Operations, Images, Catalogs
- **Cost:** ~$850M in $2011

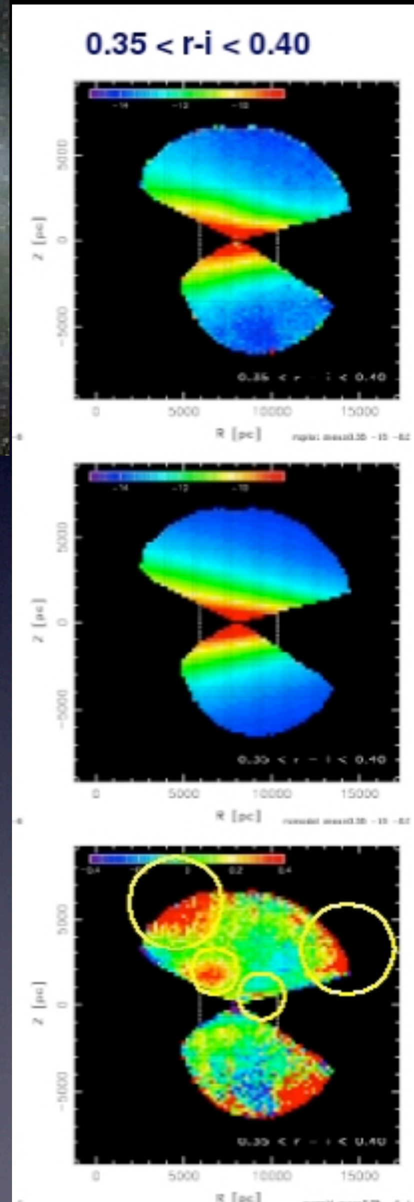
  contributions from NSF, DOE and private gifts

Extragalactic astronomy: 10 billion galaxies



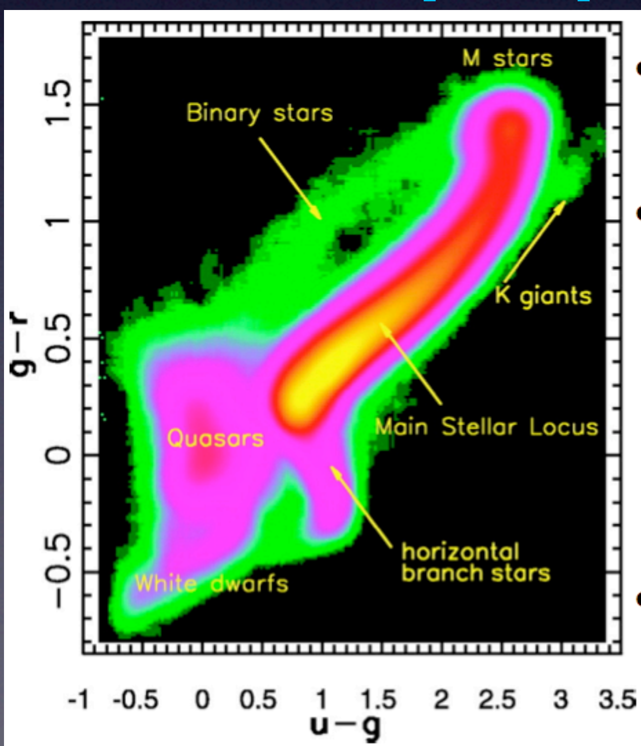
The Milky Way structure: **10 billion stars, time domain massive statistical studies!**

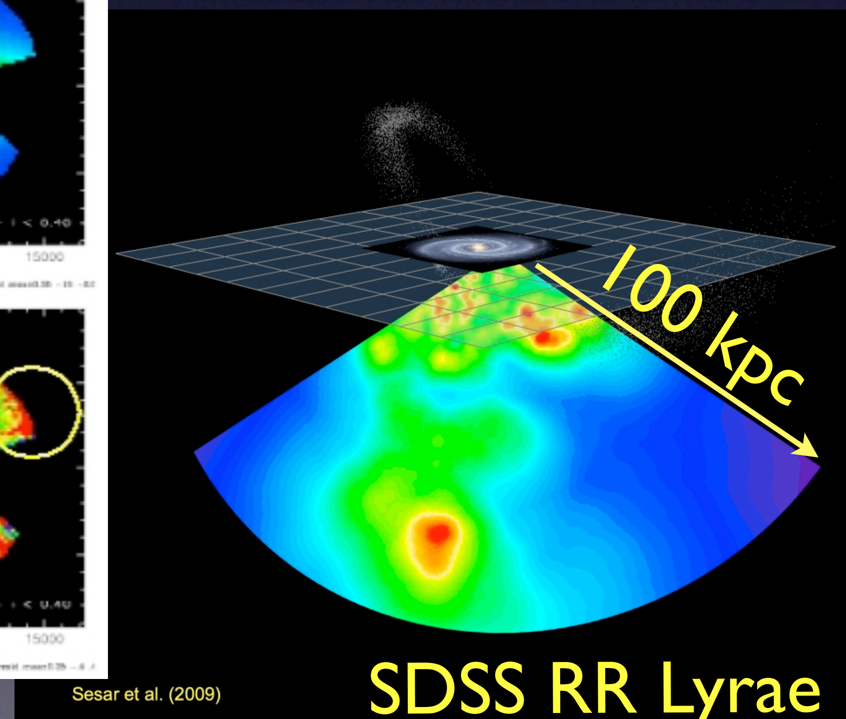




Compared to SDSS: LSST can "see" about 40 times more stars, 10 times further away and over twice as large sky area

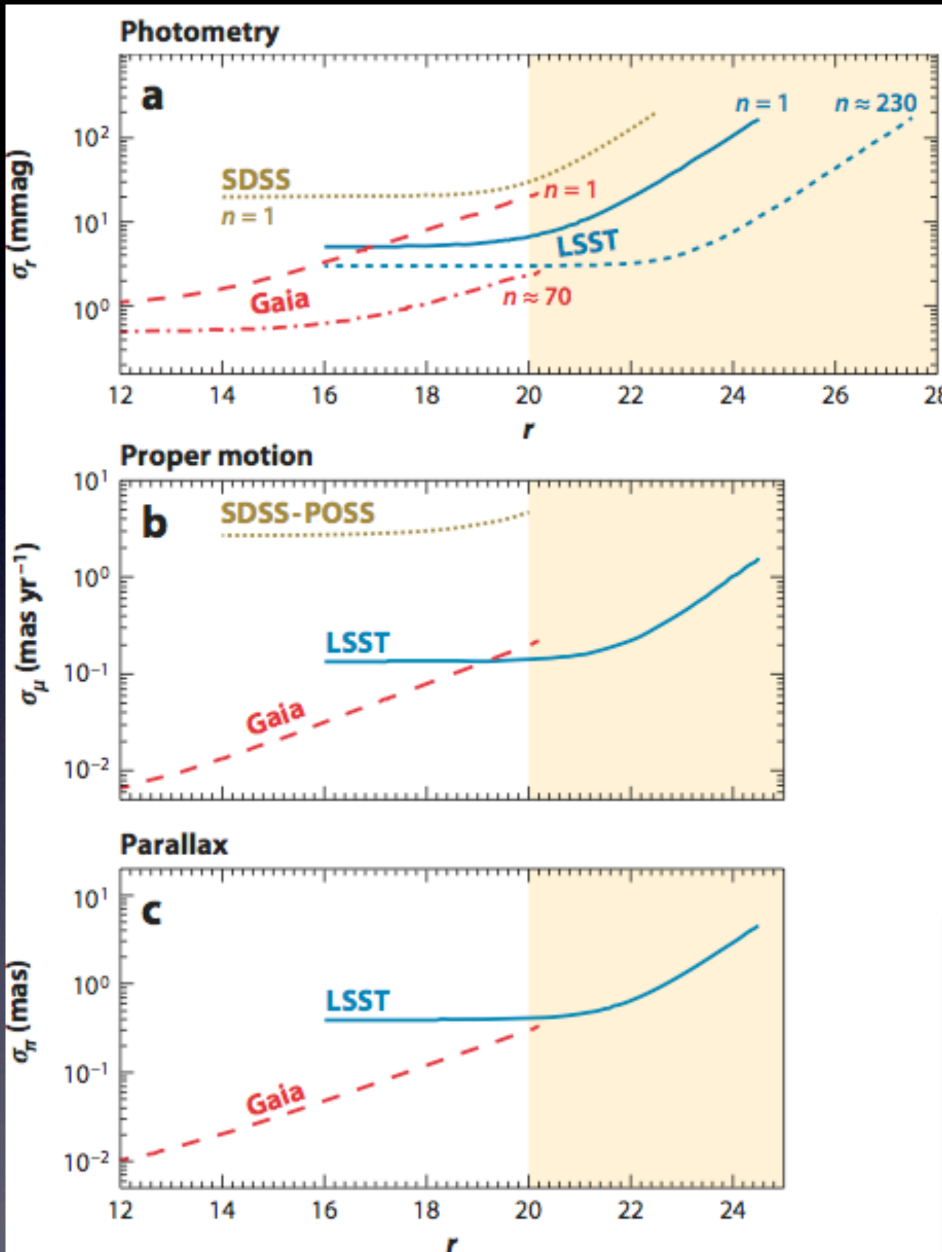
Distance and [Fe/H]:





SDSS RR Lyrae

Gaia vs. LSST comparison

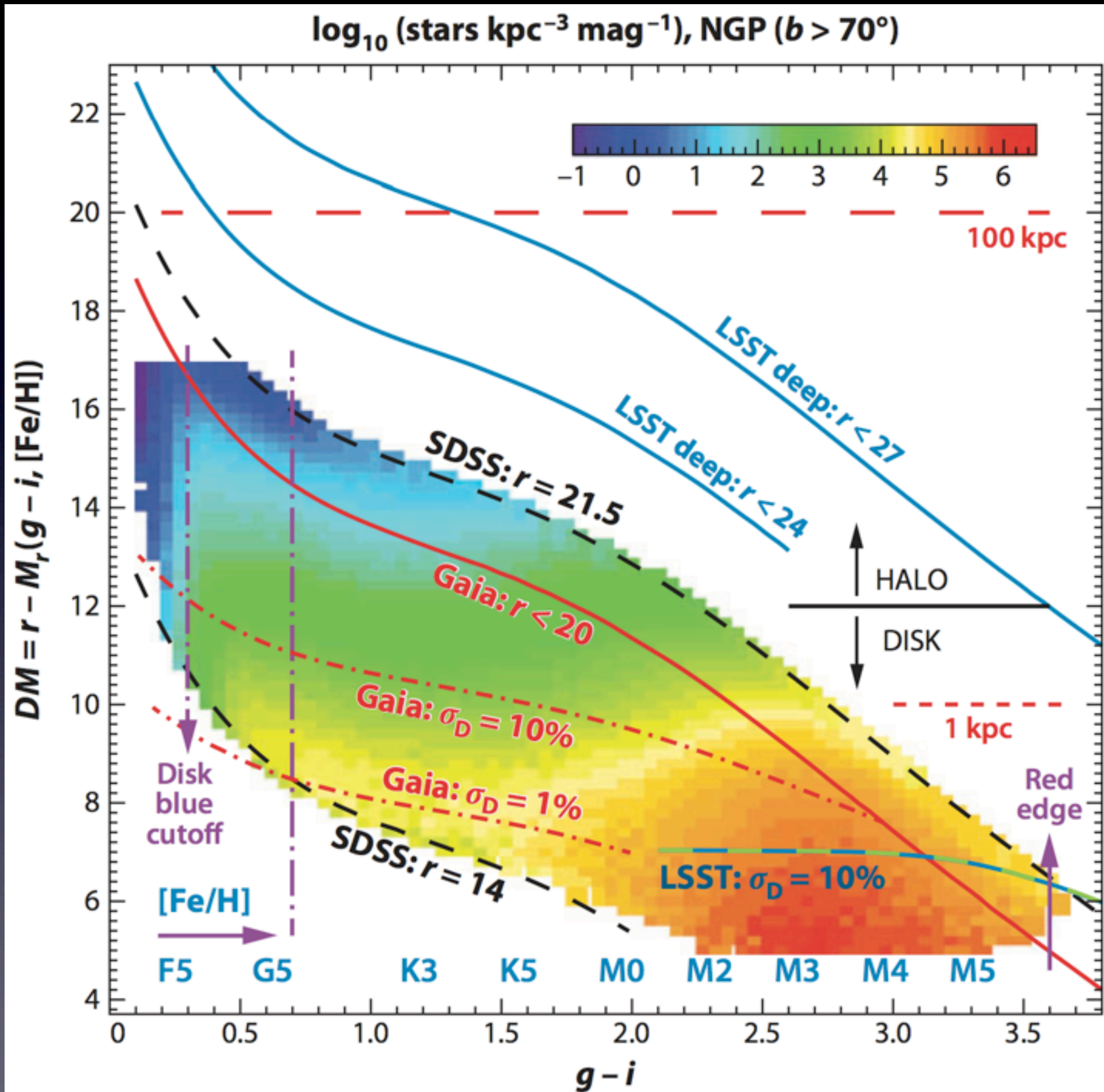


Ivezić, Beers, Jurić 2012, ARA&A, 50, 251

- **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=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).

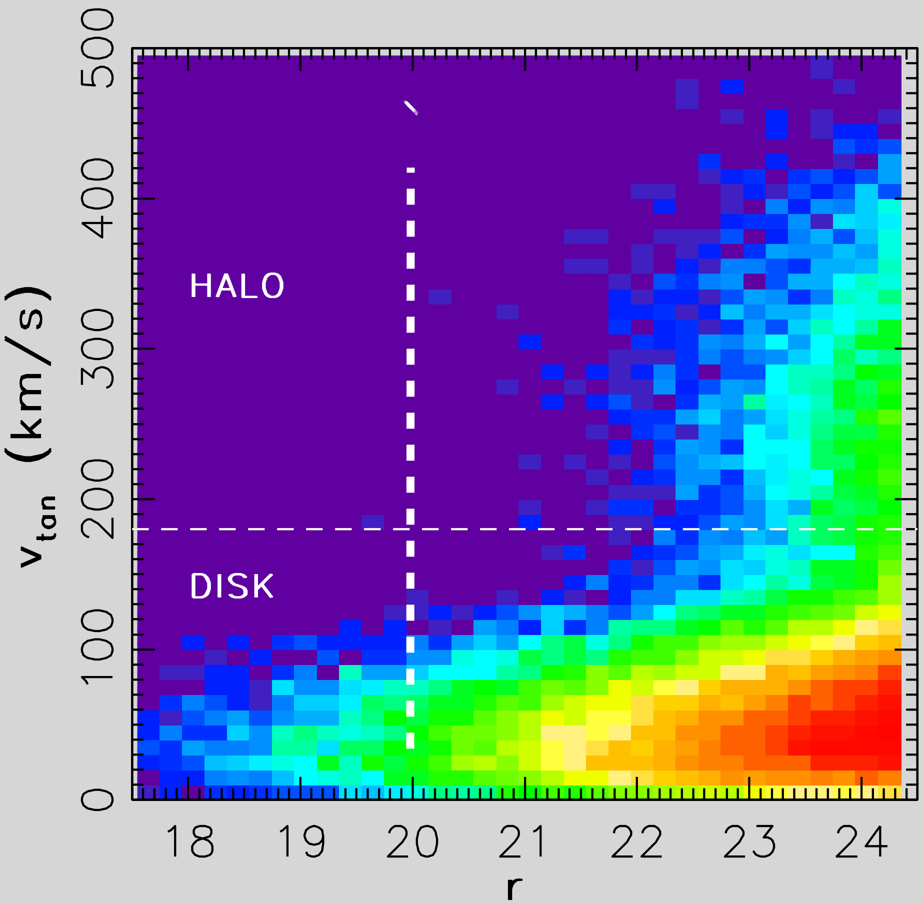
Comparison of SDSS, Gaia and LSST for main sequence stars:



Dwarfs in LSST

White dwarfs: LF is age probe

~400,000 halo white dwarfs from LSST (10 million total):



L / T dwarfs: L dwarfs are dime a dozen: 200,000 in LSST with proper motion and trigonometric parallax measurements

Simulations predict 2400 T dwarfs with >5σ proper motion and parallax measurements

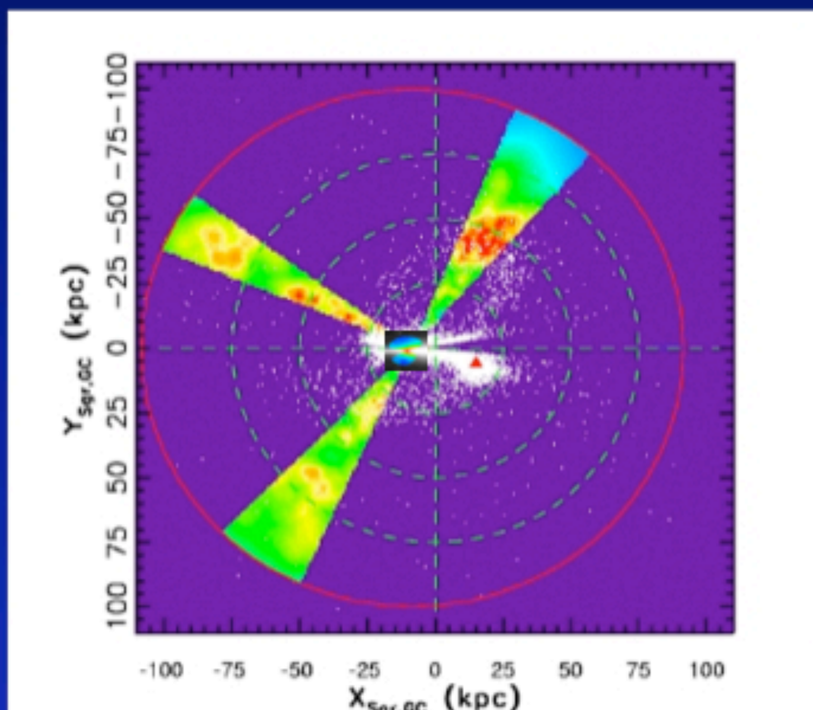
Compared to UKIDSS, 5 times larger sample of T dwarfs, with parallaxes and 10-20 times more accurate proper motions

(~100 Y dwarfs [model based])

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)



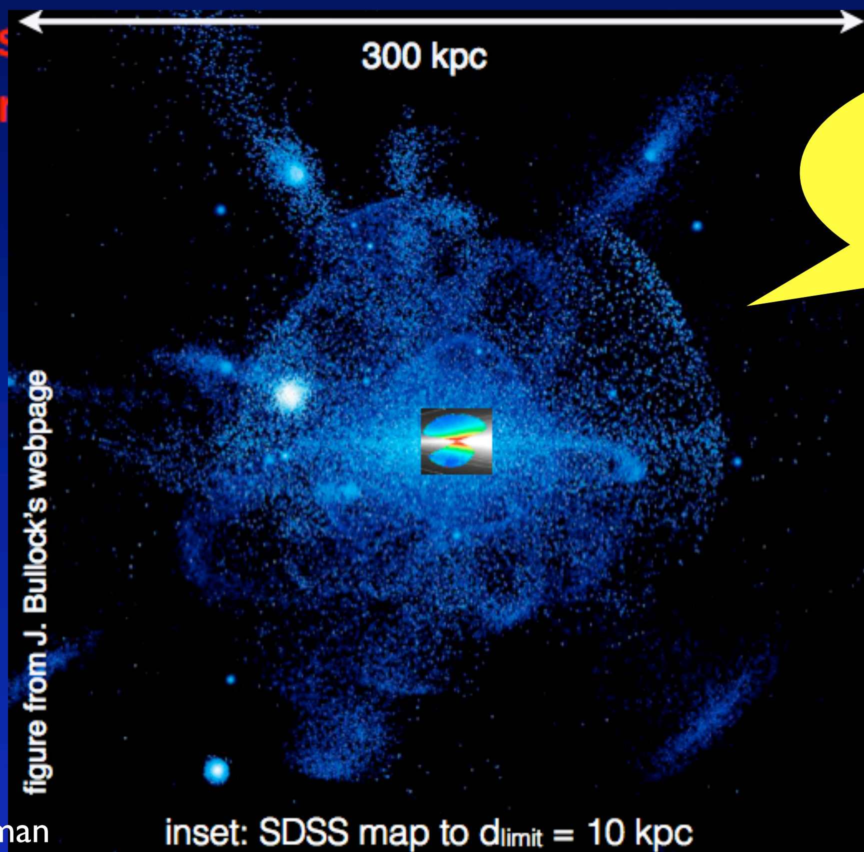
6D information from LSST: 3D spatial, 2 velocities, [Fe/H]

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

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

limit for RR Lyrae: 400 kpc

The large red circle: the ~100 kpc limit of future
LSST studie
(and the curr



200 million stars from LSST!

he small insert:
10 kpc limit of SDSS
nd future Gaia studies
r kinematic & $[Fe/H]$
apping with MS stars

montage from B. Willman

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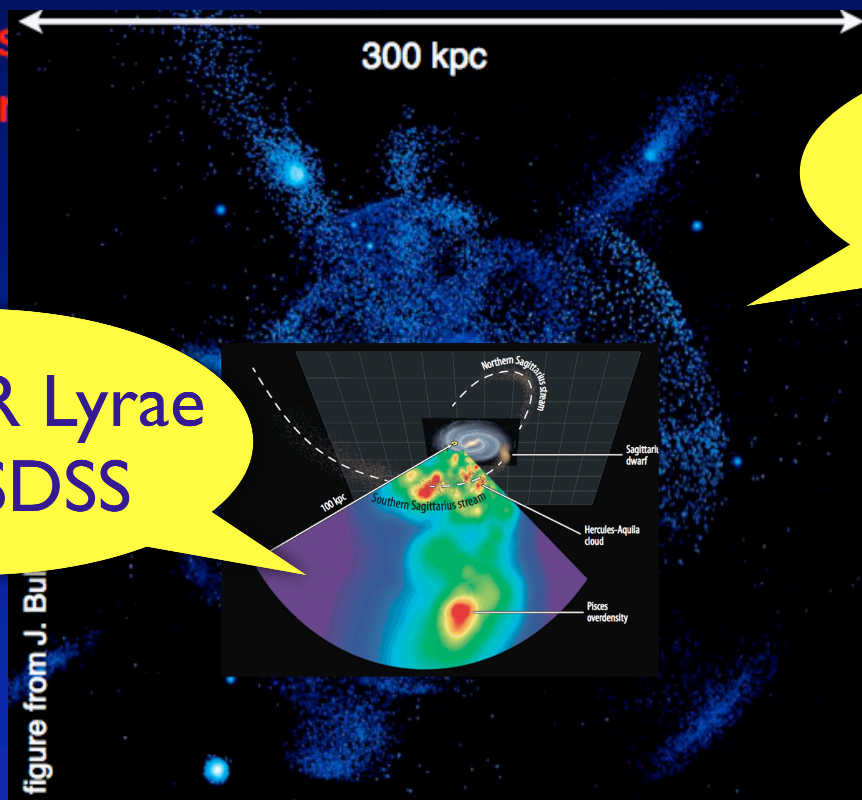

inset: SDSS map to d_{limit} = 10 kpc

200 million stars from LSST!

~500 RR Lyrae from SDSS

he small insert:
10 kpc limit of SDSS
nd future Gaia studies
r kinematic & $[Fe/H]$
apping with MS stars

montage from B. Willman

Data analysis challenges in the era of LSST

1) Large data Volume

2) Large number of objects

3) Highly multi-dimensional space

4) Unknown statistical distributions

5) Time-series data

6) Truncated, censored and missing data

7) Unreliable quantities (e.g. unknown systematics and random errors)

Statistics, Data Mining and Machine Learning in Astronomy

Željko Ivezić, Andrew Connolly, Jacob Vanderplas, Alex Gray

Princeton University Press, 2013

- Complete *Practical* guide to statistical analysis, data exploration, and machine learning
- Example-driven approach, using real data (SDSS, LIGO, LINEAR, WMAP, and others)
- All book figures and examples generated in python (matplotlib), with code available online – for free!
- Makes use of *numpy, scipy, matplotlib, scikit-learn, pymc, healpy,* and others
- Supporting python package: *astroML*

New book!

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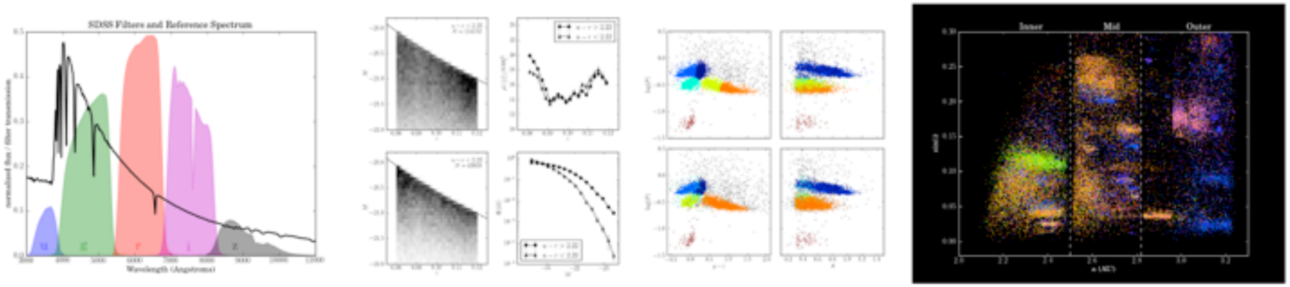
AstroML: Machine Learning and Data Mining for Astronomy



AstroML is a Python module for machine learning and data mining built on numpy, scipy, scikit-learn, and matplotlib, and distributed under the 3-clause BSD license. It contains a growing library of statistical and machine learning routines for analyzing astronomical data in python, loaders for several open astronomical datasets, and a large suite of examples of analyzing and visualizing astronomical datasets.

Downloads

- Released Versions: Python Package Index
- Bleeding-edge Source: github

The goal of astroML is to provide a community repository for fast Python implementations of common tools and routines used for statistical data analysis in astronomy and astrophysics, to provide a uniform and easy-to-use interface to freely available astronomical datasets. We hope this package will be useful to researchers and students of astronomy. The astroML project was started in 2012 to accompany the book **Statistics, Data Mining, and Machine Learning in Astronomy** by Zeljko Ivezic, Andrew Connolly, Jacob VanderPlas, and Alex Gray, to be published in late 2013. The table of contents is available here: `here(pdf)`.

User Guide

1. Introduction

- 1.1. Philosophy

News

October 2012: astroML 0.1 has been released! Get the source on Github

Our Introduction to astroML paper received the CIDU 2012 best paper award.

Links

astroML Mailing List

GitHub Issue Tracker

Videos

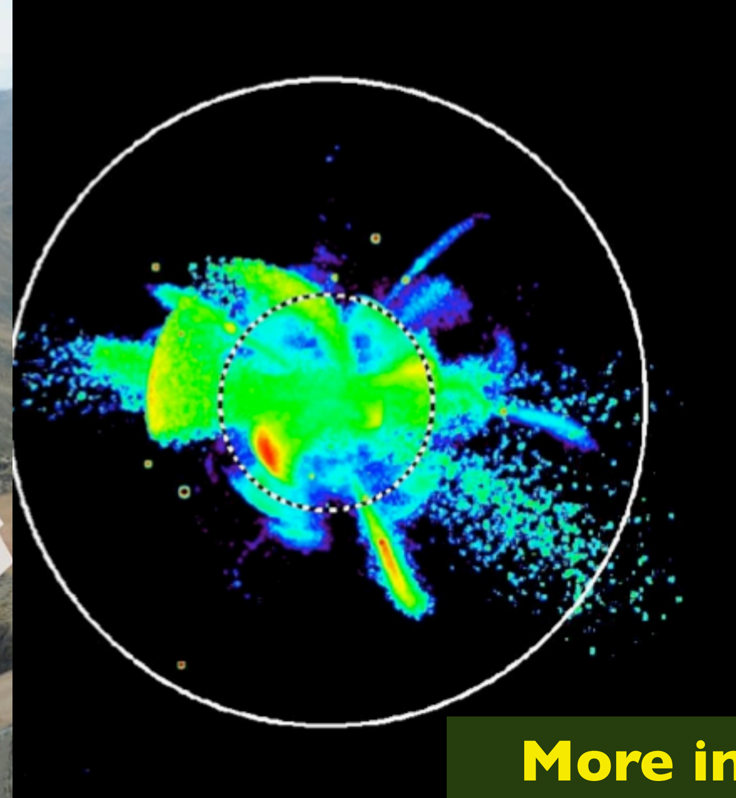
Scipy 2012 (15 minute talk)

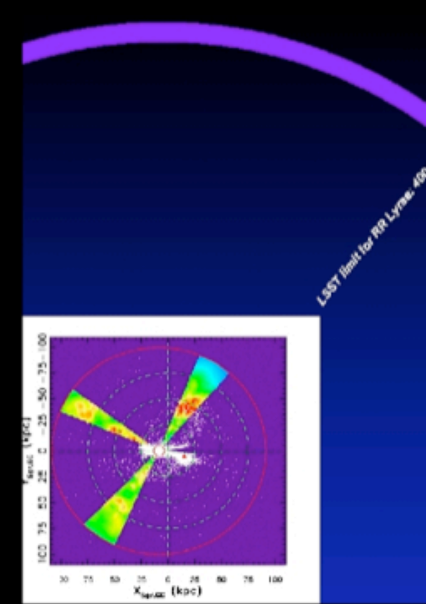
Citing

If you use the software, please consider citing astroML.

Open source!

www.astroML.org





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

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)

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

“If You Liked SDSS, You will Love LSST!”