Mapping The Galaxy With Large Photometric Surveys

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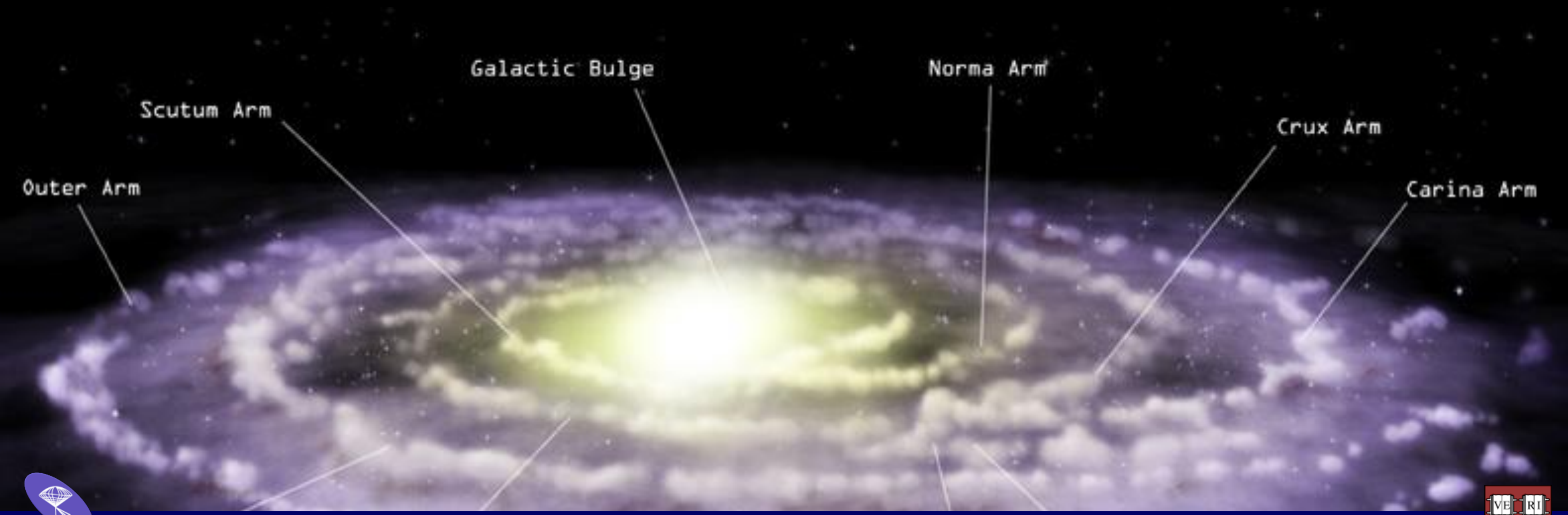


Overview

1. *Mapping the Milky Way with SDSS*
   (7D maps with photometry and astrometry)

2. *Modeling*
   (the *galfast* code and model)

3. *LSST: to Virial Radius and Beyond*
   (and synergies with GAIA)

SDSS in 30 seconds

Sloan Digital Sky Survey

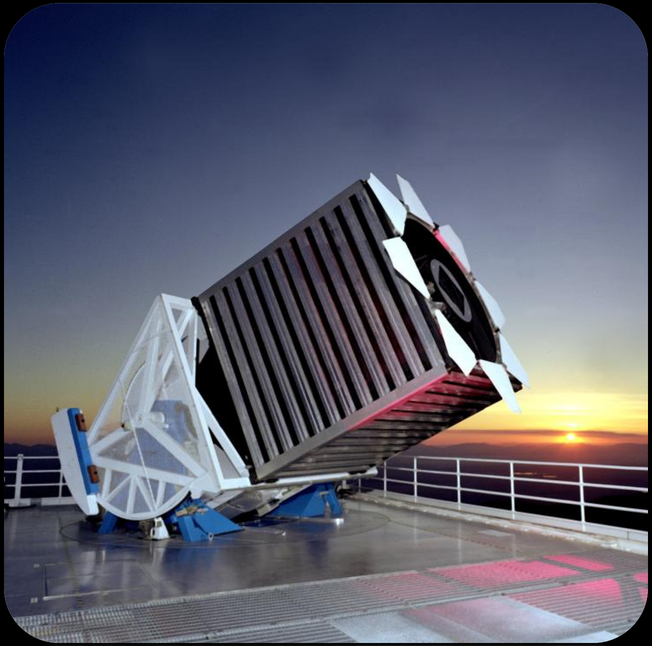
2.5m telescope

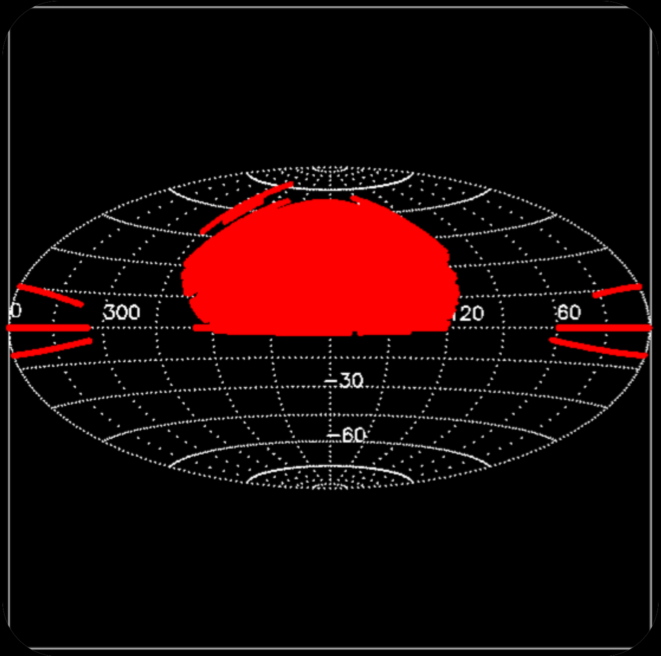
8000 deg^2

0.1” astrometry

r<22.5 flux limit

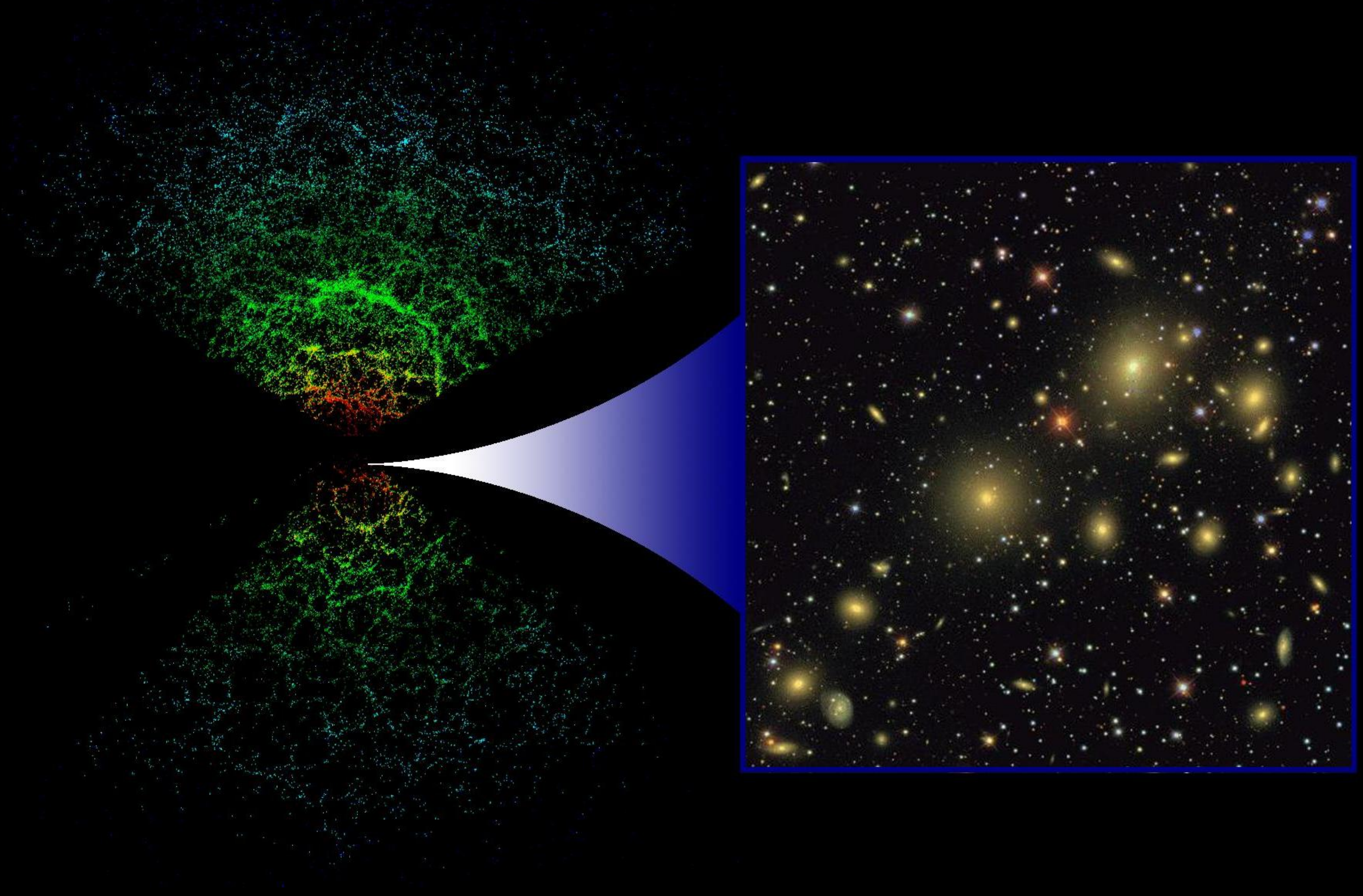
5 band, 2%, photometry for >50M stars
>280k R=2000 stellar spectra





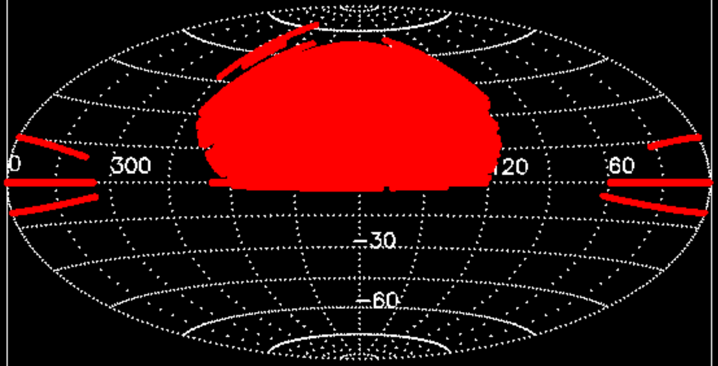
SDSS I: The P(k) Machine

Image credit: Max Tegmark (MIT)



Sloan Digital Sky Survey (2000-2005; 2005-2008; 2008-)

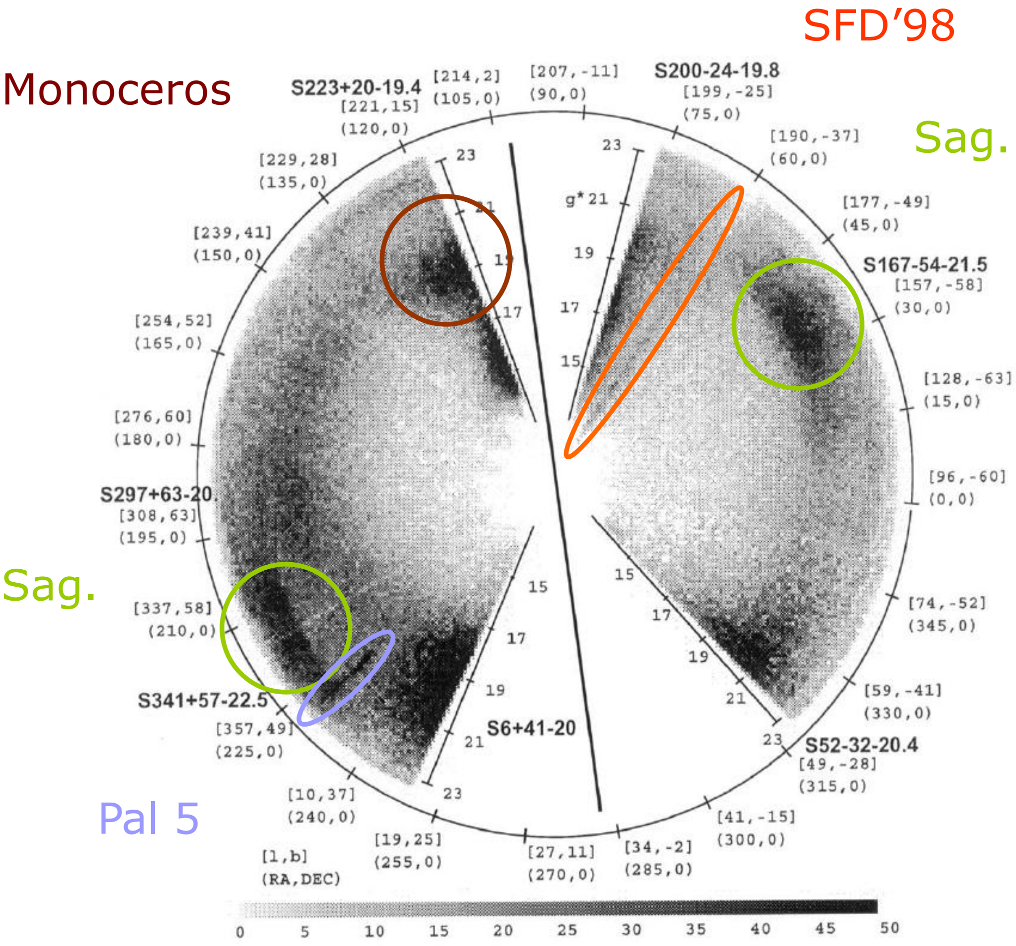
- An excellent tool for Galactic structure
  - Accurate m'band photometry: distance and metallicity estimates
  - Accurate astrometry: proper motions
  - Large area and faint flux limit: representative volume



SDSS DR6 Imaging Sky Coverage
(Adelman-McCarthy et al. 2008, ApJS, 175, 297)

- Tracers
  - RR Ly / BHB
  - Giants
  - Main sequence turn-off (MSTO)
  - Main sequence

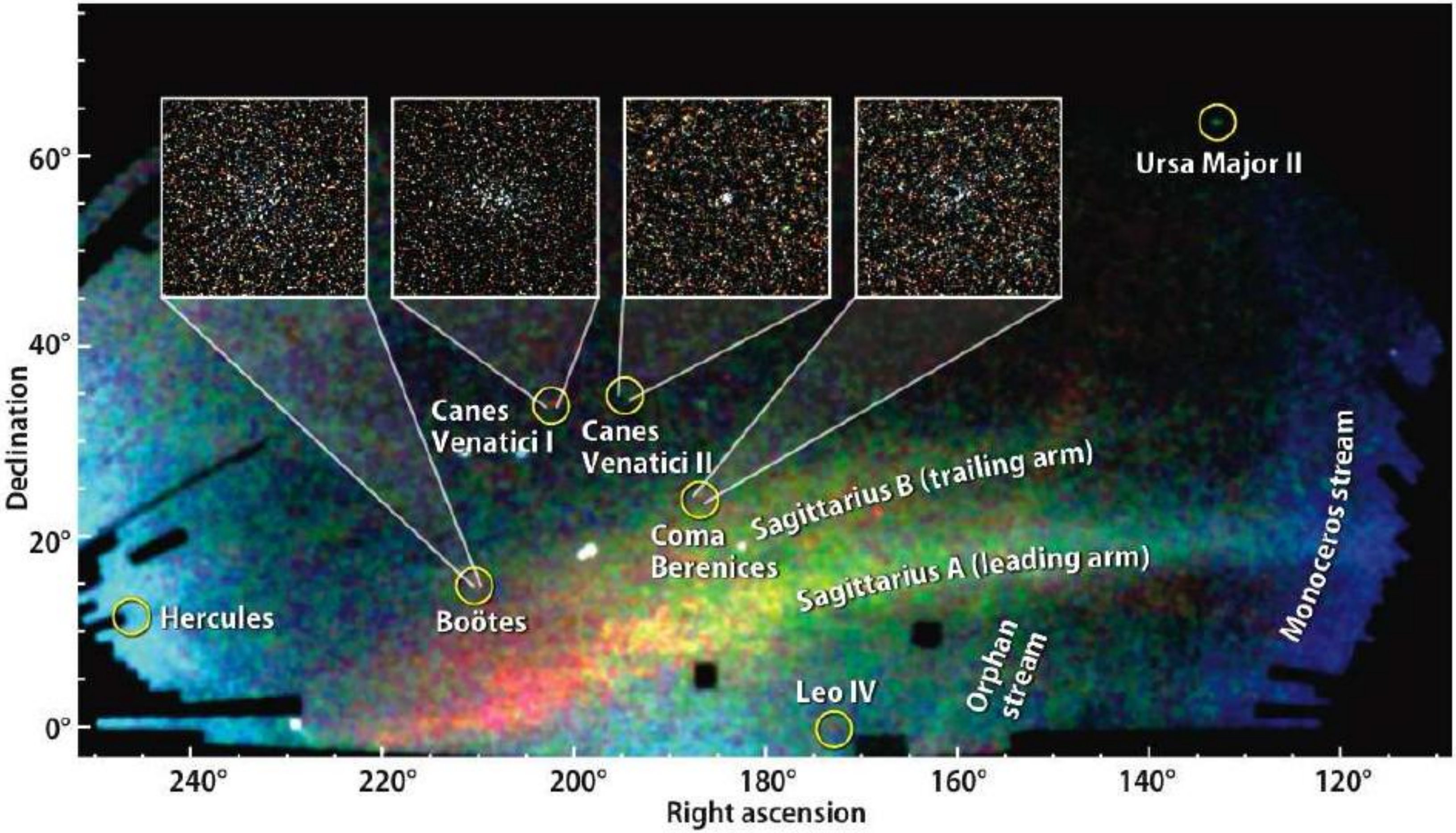
2D: Newberg et al. (2002)



- **"The Ghost of Sagittarius and Lumps in the Halo of the Milky Way" Newberg et al. (2002)**
- **SDSS Equatorial Stripe, Early Data Release**
- **MSTO F-star color cut**

3D: The Field of Streams

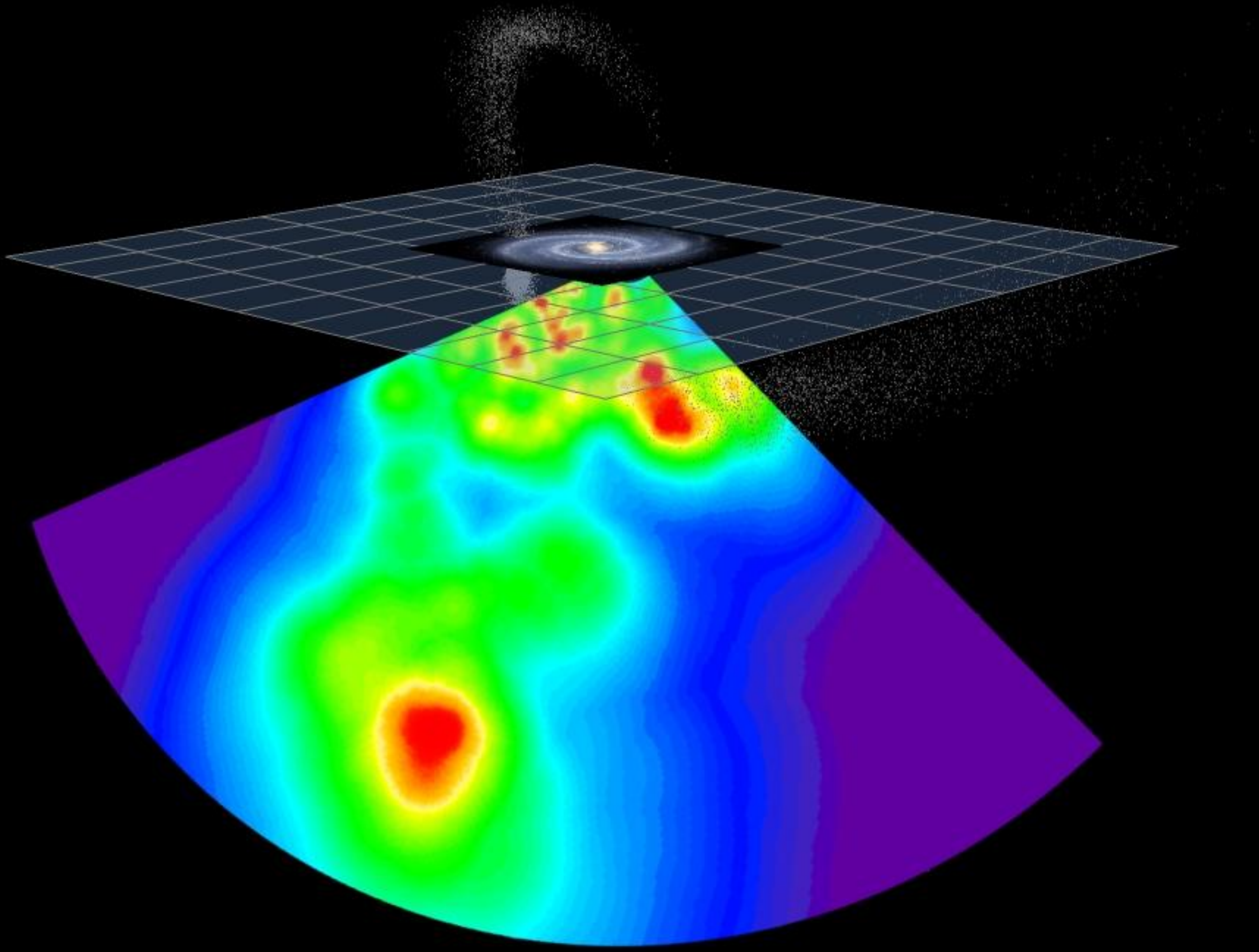
Belokurov et al (2007)



- **Turnoff stars**
- **RGB: apparent magnitude (blue – close, red – distant)**
- **Brightness: the number of stars**

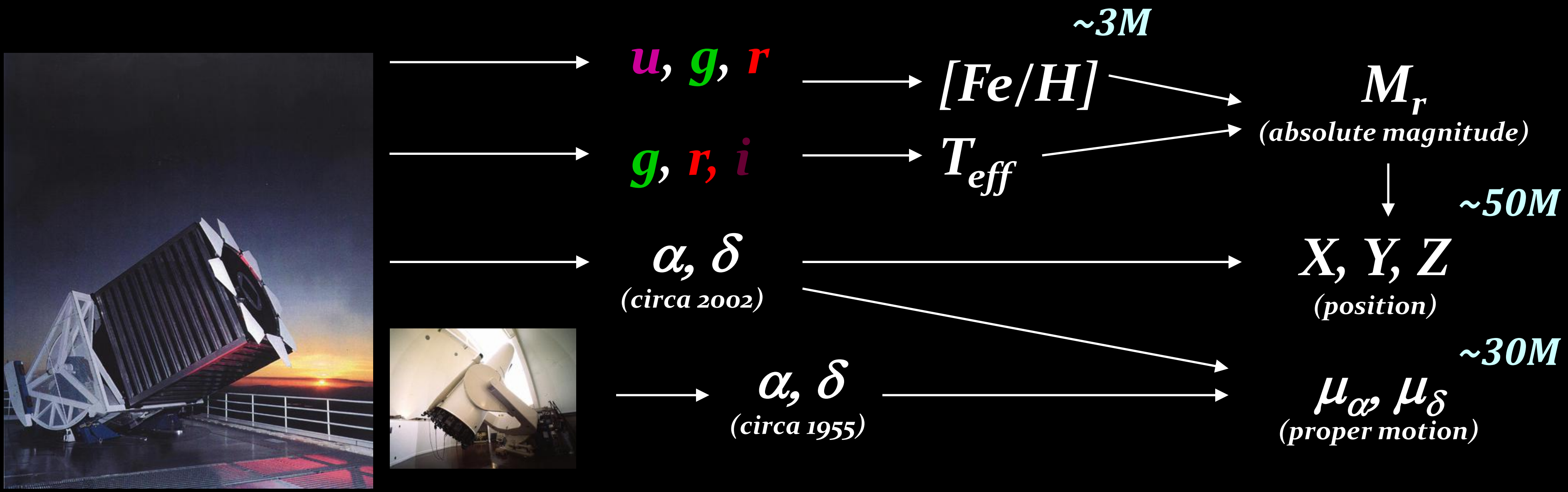
RR Lyrae in SDSS Equatorial Stripe

Sesar et al (2009)



Mapping with Main Sequence Stars (95% of *!)

Estimating Luminosity, Fe/H, Distance, and Proper Motion



~3M

u, g, r → [Fe/H] → M_r

g, r, i → T_{eff} → M_r

(absolute magnitude)

~50M

α, δ (circa 2002) → X, Y, Z (position)

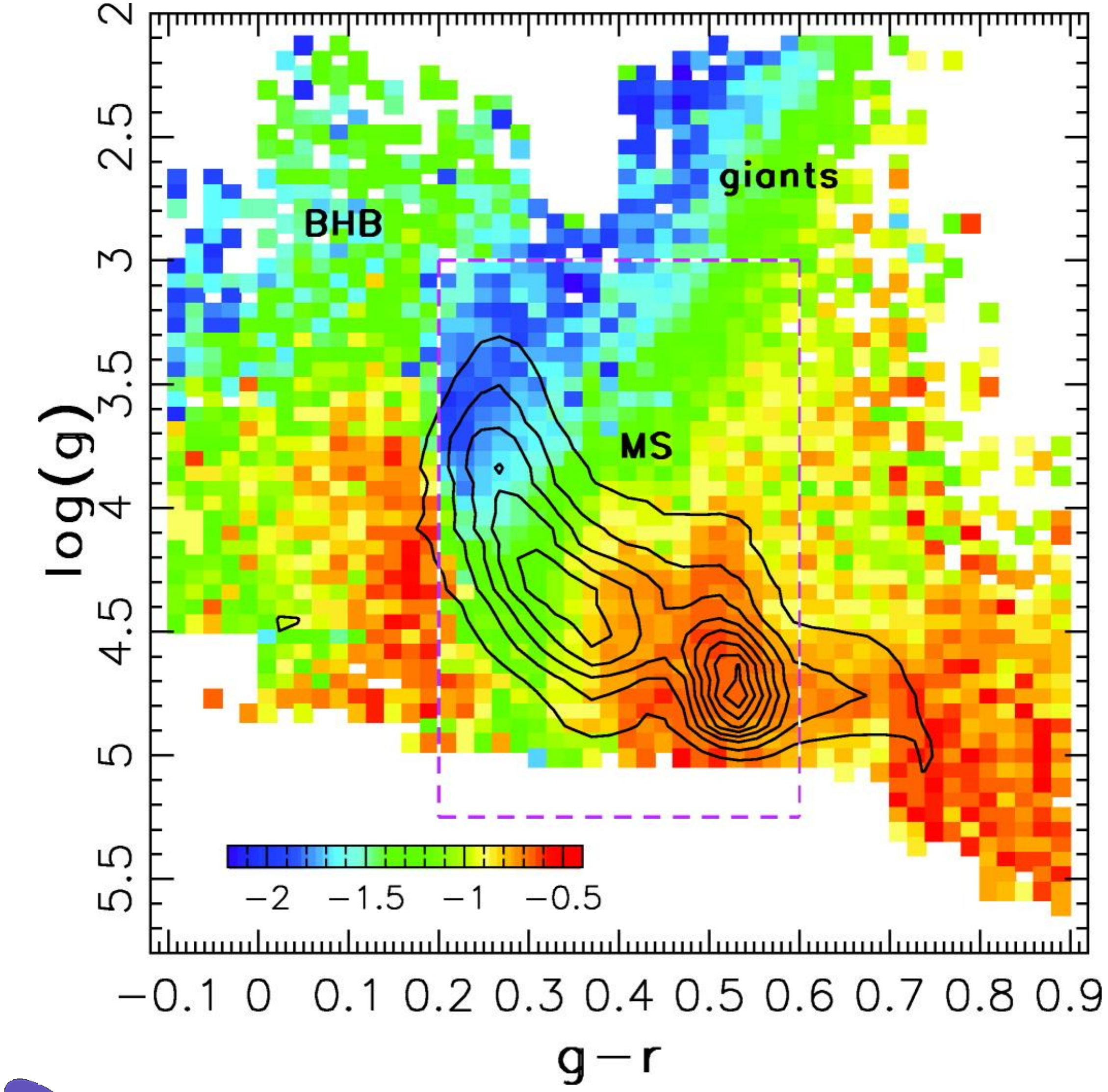
~30M

α, δ (circa 1955) → μ_α, μ_δ (proper motion)

POSS (USNO-B catalog)

Same methods and codes directly applicable to future wide-field surveys (PanSTARRS, SkyMapper+RAVE, DES, LSST)

Stellar parameters: SEGUE Spectra



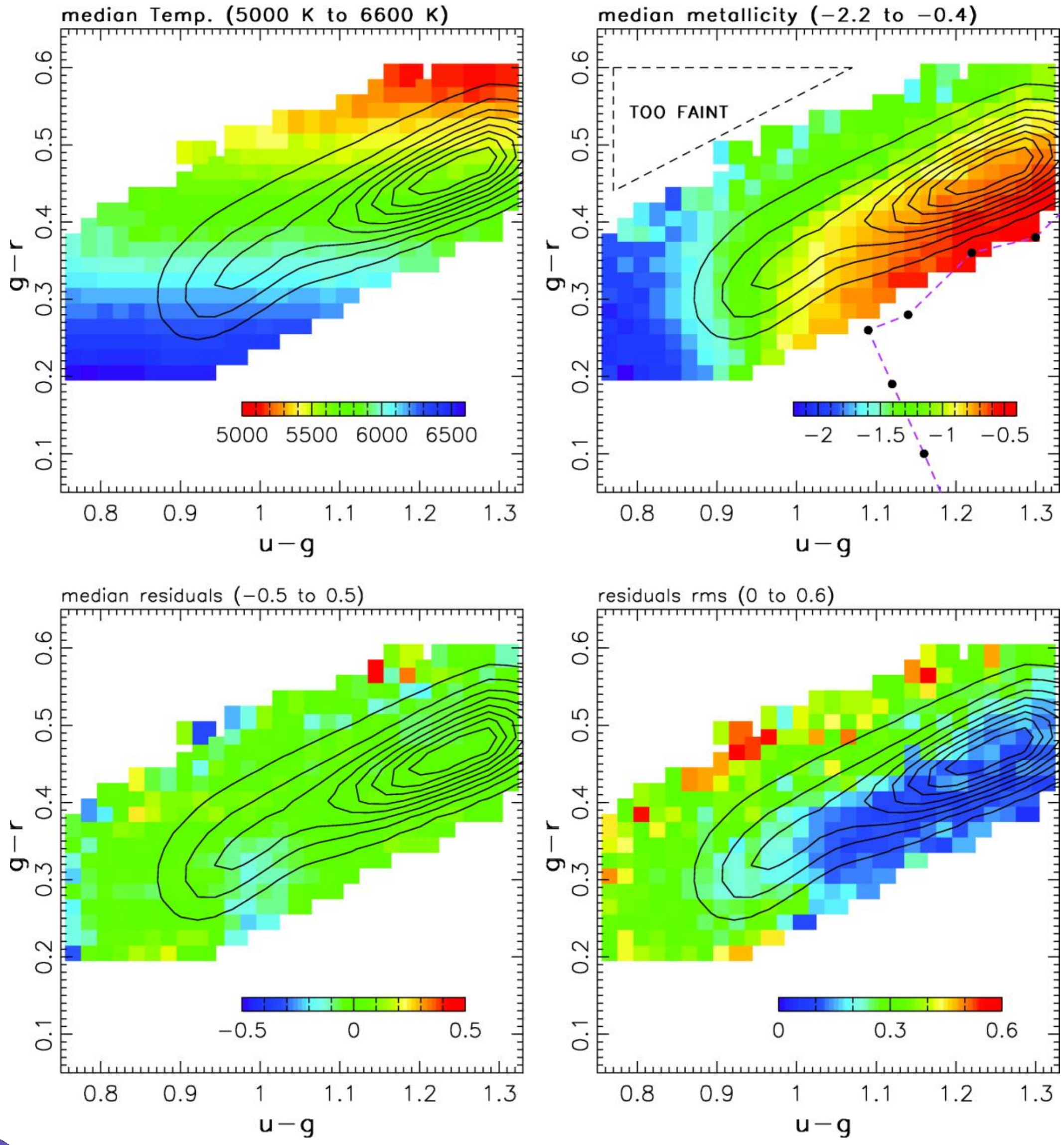
- SEGUE Stellar Parameters Pipeline (Beers et al, Allende Prieto et al. 2006, Lee et al. 2007.)

- ~280,000 stars
- colors: median [Fe/H] contours: counts

- σ(Teff) ~ 100K
- σ(log g) ~ 0.25 dex
- σ([Fe/H]) ~ 0.2 dex

Photometric Metallicity: Calibration

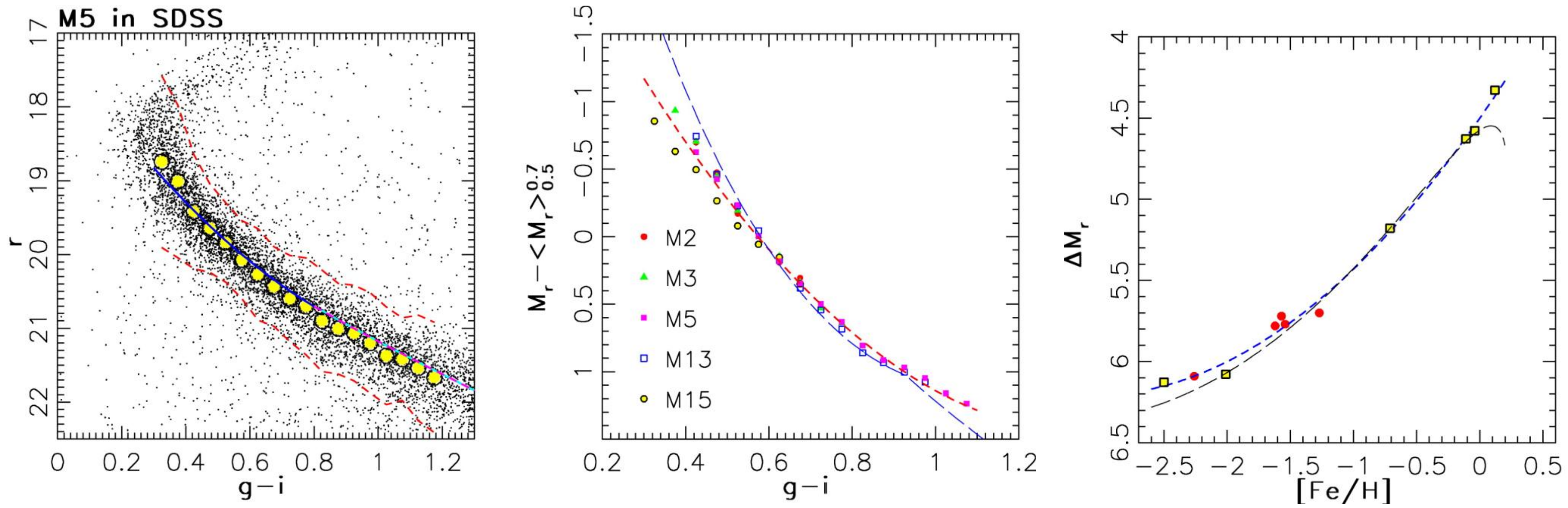
Ivezic et al. (2008), Bond et al. (2010)



- (u-g, g-r) colors strongly correlate with spectroscopic metallicity and temperature
- Linear effective temperature fit
- Metallicity:
  - ~f(u-g) only for for g-r < 0.4
  - Depends on g-r for g-r > 0.4
- Precision and accuracy:
  - Teff ~ 100K
  - [Fe/H] ~ 0.09dex (rms, calibration), avg. ~0.25 dex per star (bounded by photometry)
- **Caveat: Works only for g-r < 0.6 (~F through mid-G dwarfs)**

Calibrating the photometric parallax relation

Ivezic et al (2008)



Left: Example of SDSS globular cluster main sequence observation (M5)

Middle: Main sequences of five globular clusters, offset to match for g-i~0.6

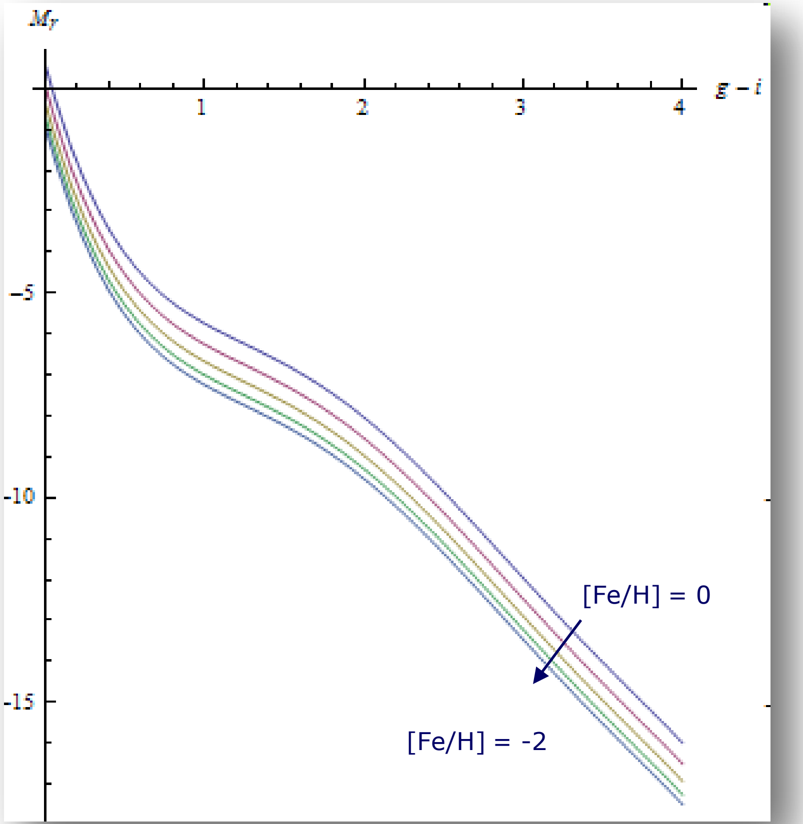
Right: The offset needed to produce the right panel (after accounting for different distances), vs. cluster metallicity

Photometric Parallax

Ivezic et al (2008)

$$M_r(gi,0) = -0.56 + 14.32\,gi - 12.97\,gi^2 + 6.127\,gi^3 - 1.267\,gi^4 + 0.0967\,gi^5 \qquad 0.3 < g-i < 4$$

$$\Delta M_r([Fe/H]) = -1.11[Fe/H] - 0.18[Fe/H]^2 \qquad -2 < [Fe/H] < 0$$



1. Metallicity-dependent photometric parallax relation for MS stars
2. Tied to globular clusters on the blue end (g-i<1)
3. Tied to Hipparcos at 1<g-i<2
4. Tied to ground-based trigonometric parallaxes for g-i>2
5. **Distance estimates to about 15% (likely around 10% on the blue end)**
6. **Applicable to any (u)gri survey (PanSTARRS, SkyMapper, DES, LSST, …)**

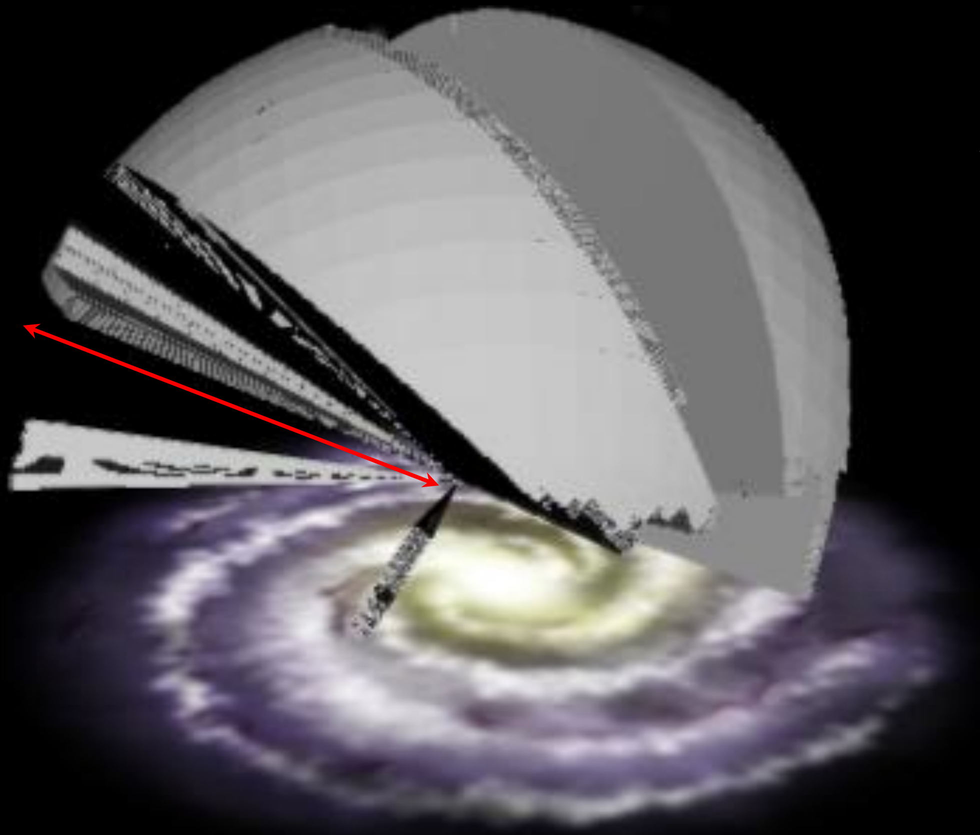
Volume limited 3D distributions of ρ, [Fe/H], μ_l, μ_b in 19 r-i color bins (spectral types ~F8-M5)

maps & models:
MJ et al. (2008)
Ivezic et al. (2008)
Bond et al. (2010)

galfast code:
MJ et al. (2010)

E.g: r-i=0.1-0.15 (late F)

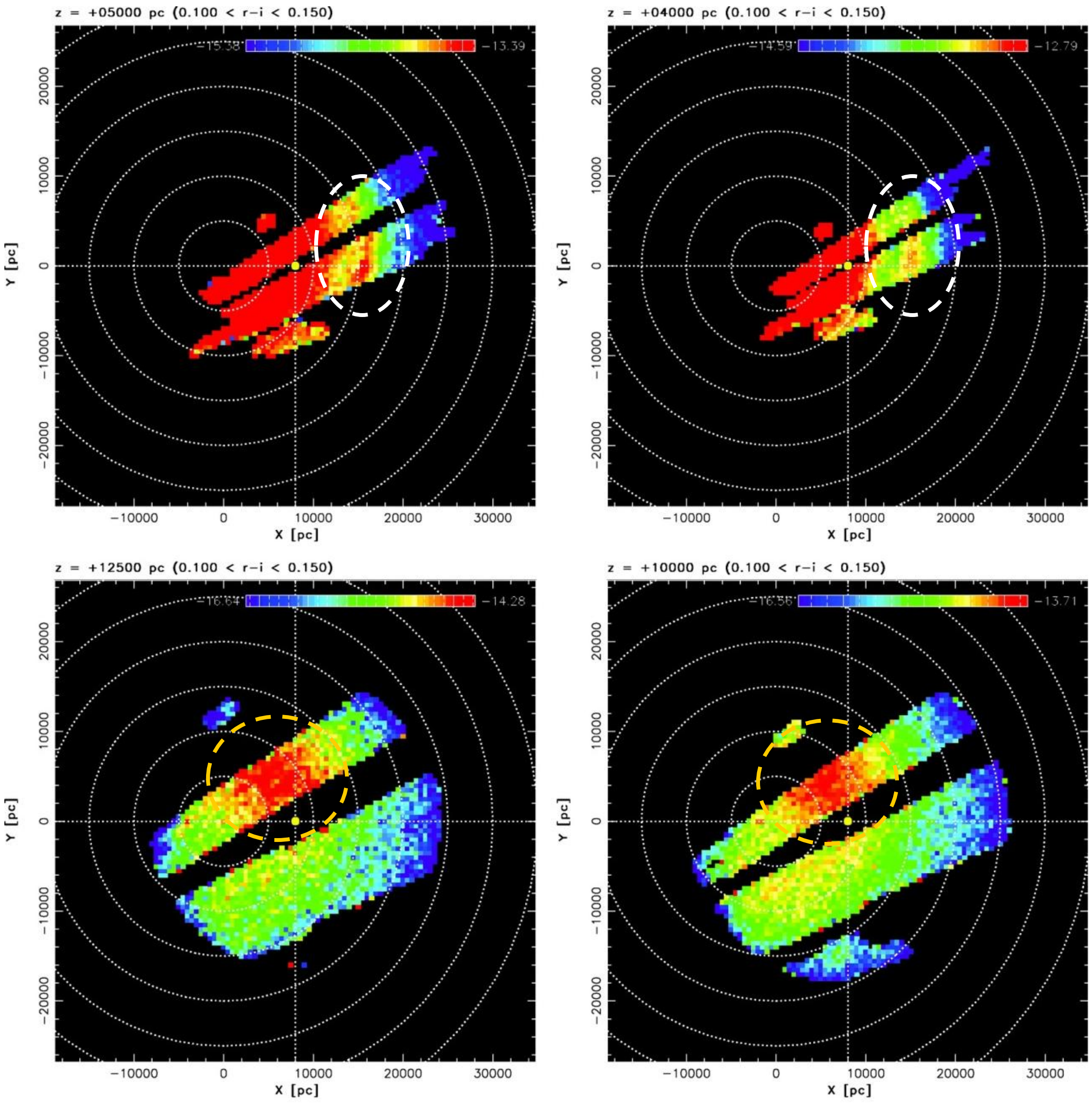
20 kpc (density)
8 kpc (Fe/H, μ)



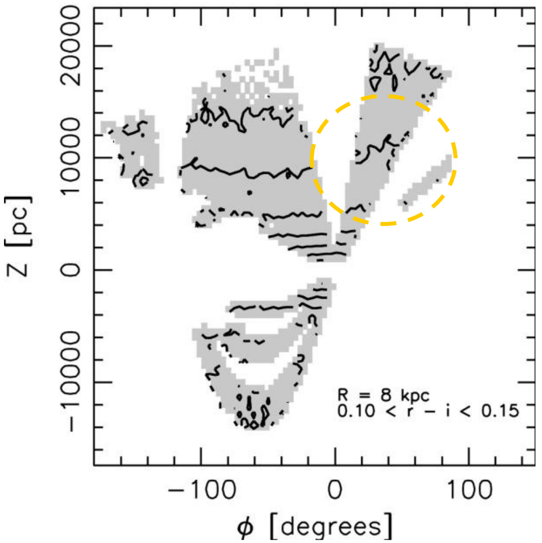
~8000 deg^2

Density Maps: D > 3kpc (F, G, early K)

MJ et al (2008)

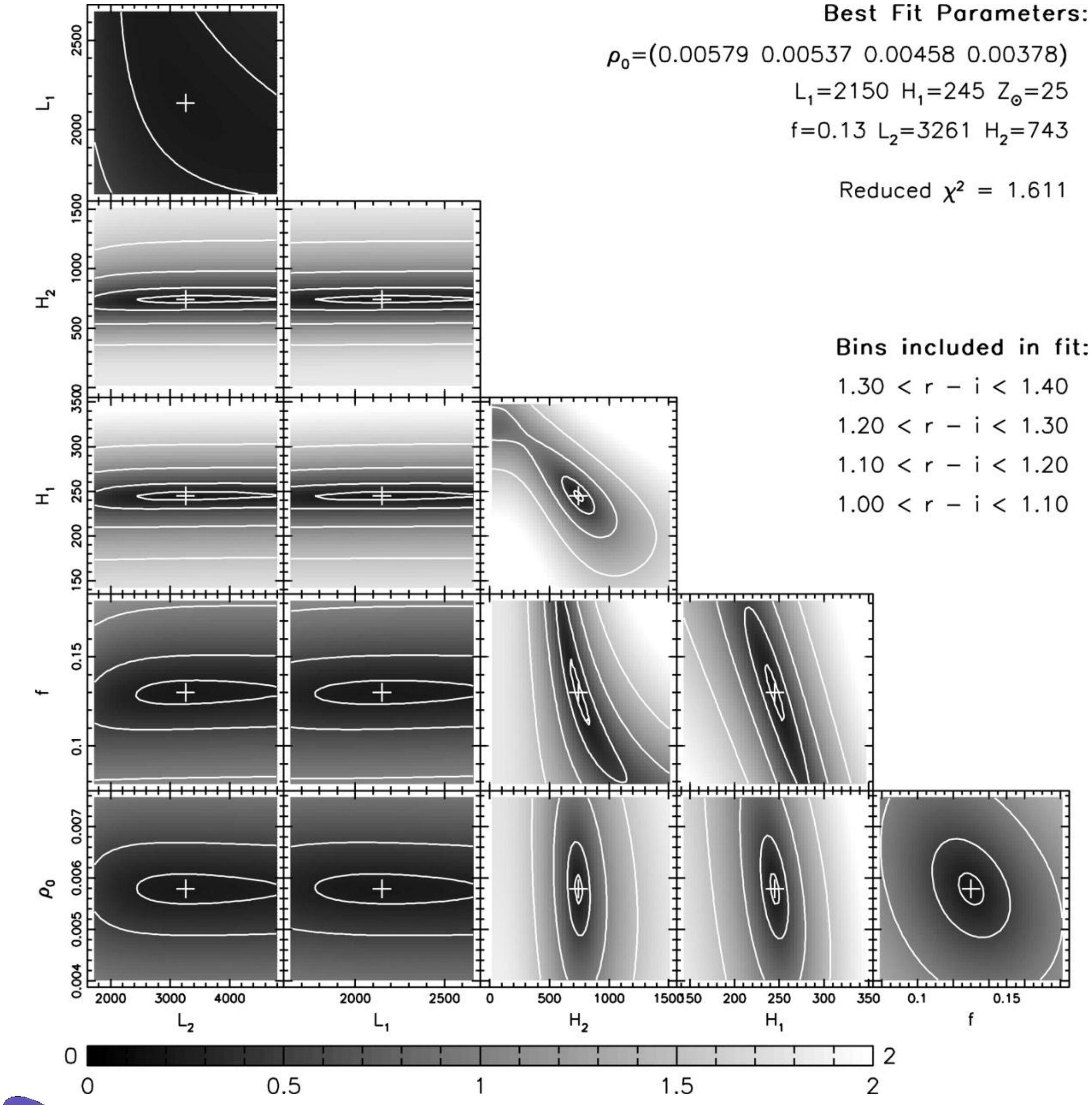


- Right: X-Y maps of number density distribution at Z=5, 4, 12, 10 kpc for .1 < r-i < .15 stars (~F/G SpT)
- Signatures of overdensities



Galactic Model Fit

MJ et al (2008)



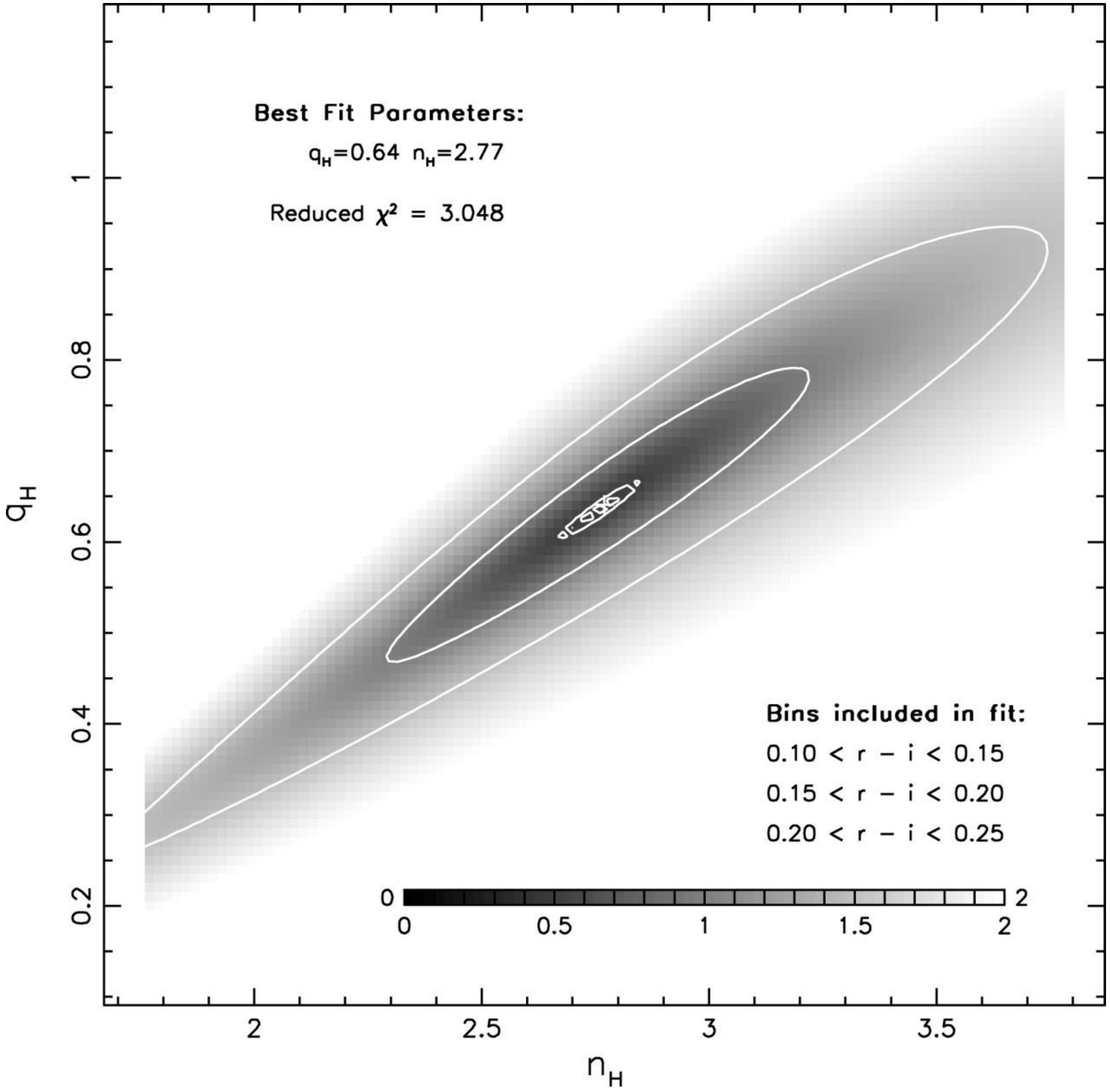
- M-dwarfs (D < 2 kpc) excellently fit by two exponentials

- Best fit:
  - Z_0 = 25 pc
  - H_1=245 pc, H_2=740 pc
  - L_1=2.15 kpc, L_2=3.3 kpc
  - *f=13%*
  - Reduced χ^2=1.6

- Uncertainties and covariances easily seen in χ^2 plots (left)

- Same values obtained when allowing the scales to vary in adjacent color bins

Halo Fits

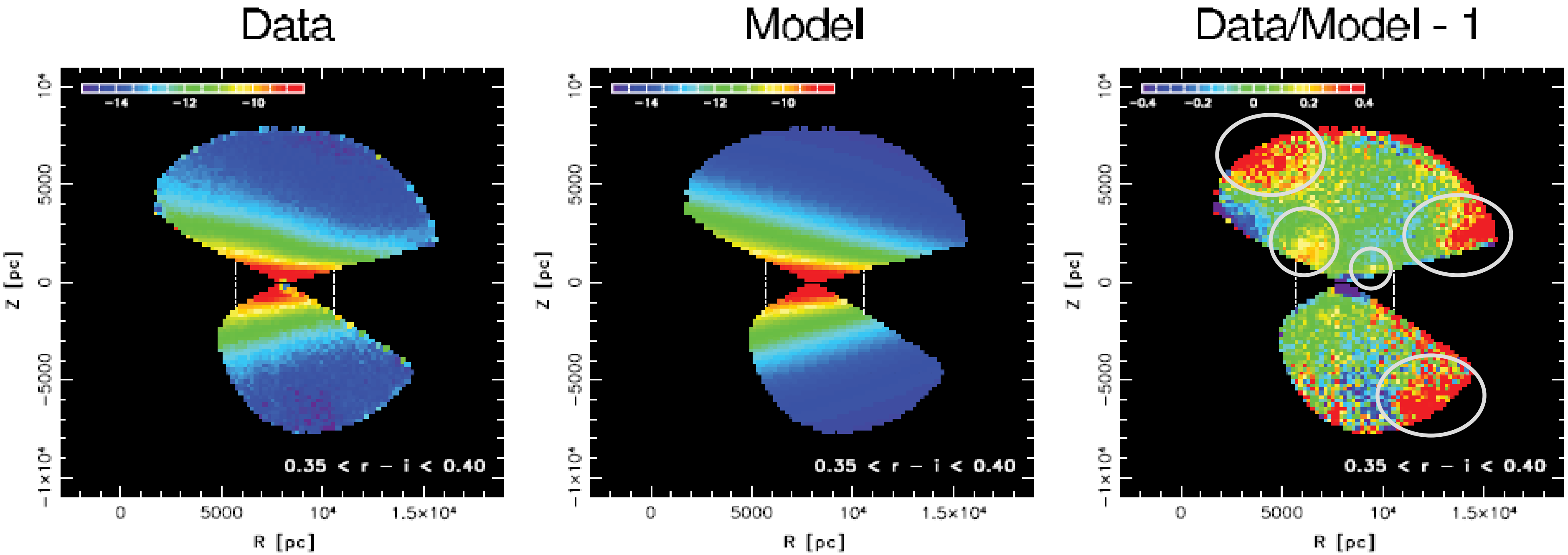


- 10kpc < D < 20kpc
- Power law
  - $n_H = 2.8$
- Clearly aspherical, oblate
  - $q_H = 0.6$
- Normalization: $f_H = 0.5\%$,

- Poorer fit (reduced $\chi^2 \sim 3$)
  - Indicative of large scale departures from simple power law (dual halo)
  - Or clumpiness of the halo (Bell et al. 2008)

Residual Features

MJ et al (2008)



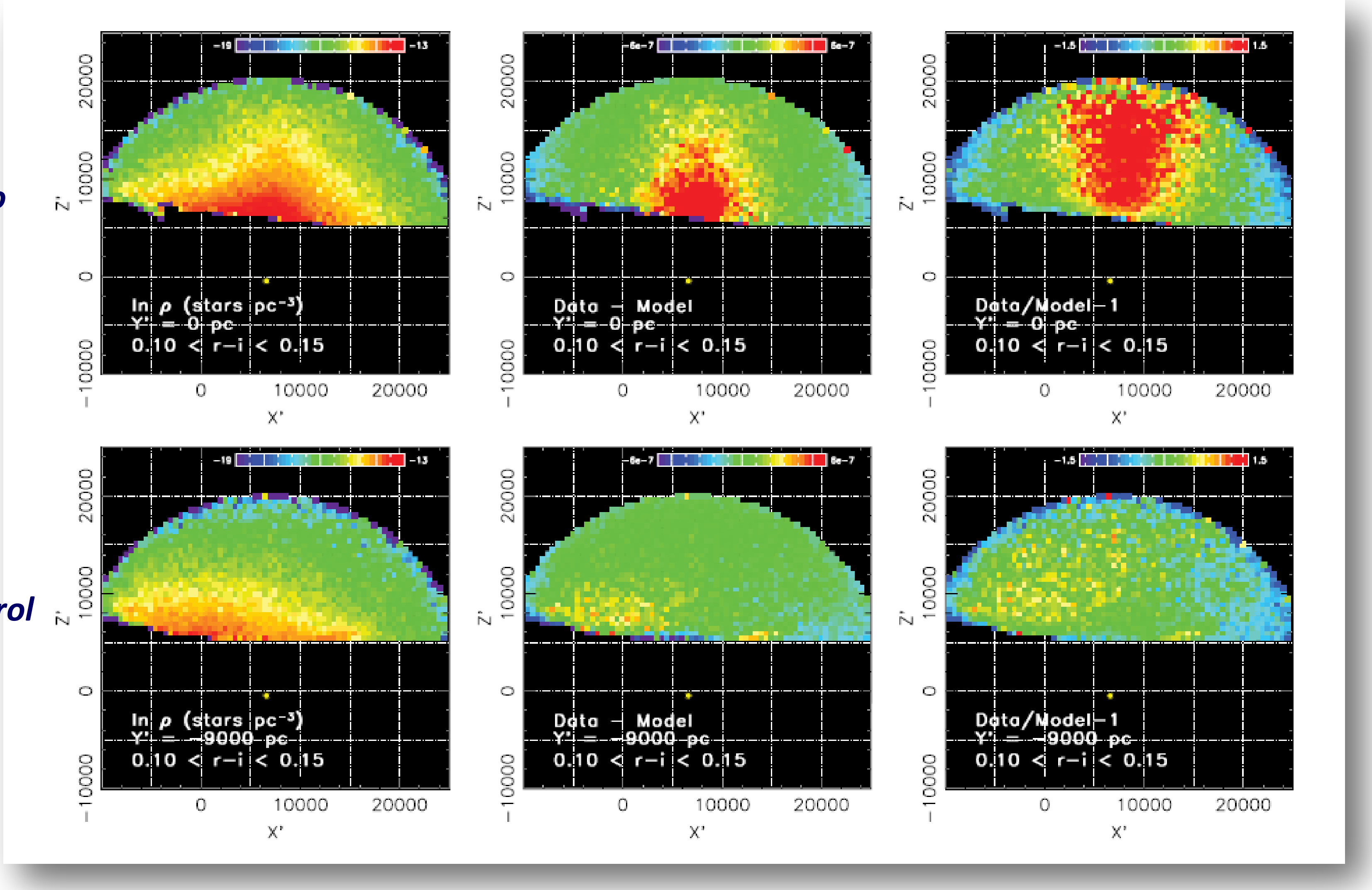
Virgo Overdensity Cross-section

MJ et al (2008)

Data | **Data-Model** | **Data/Model - 1**

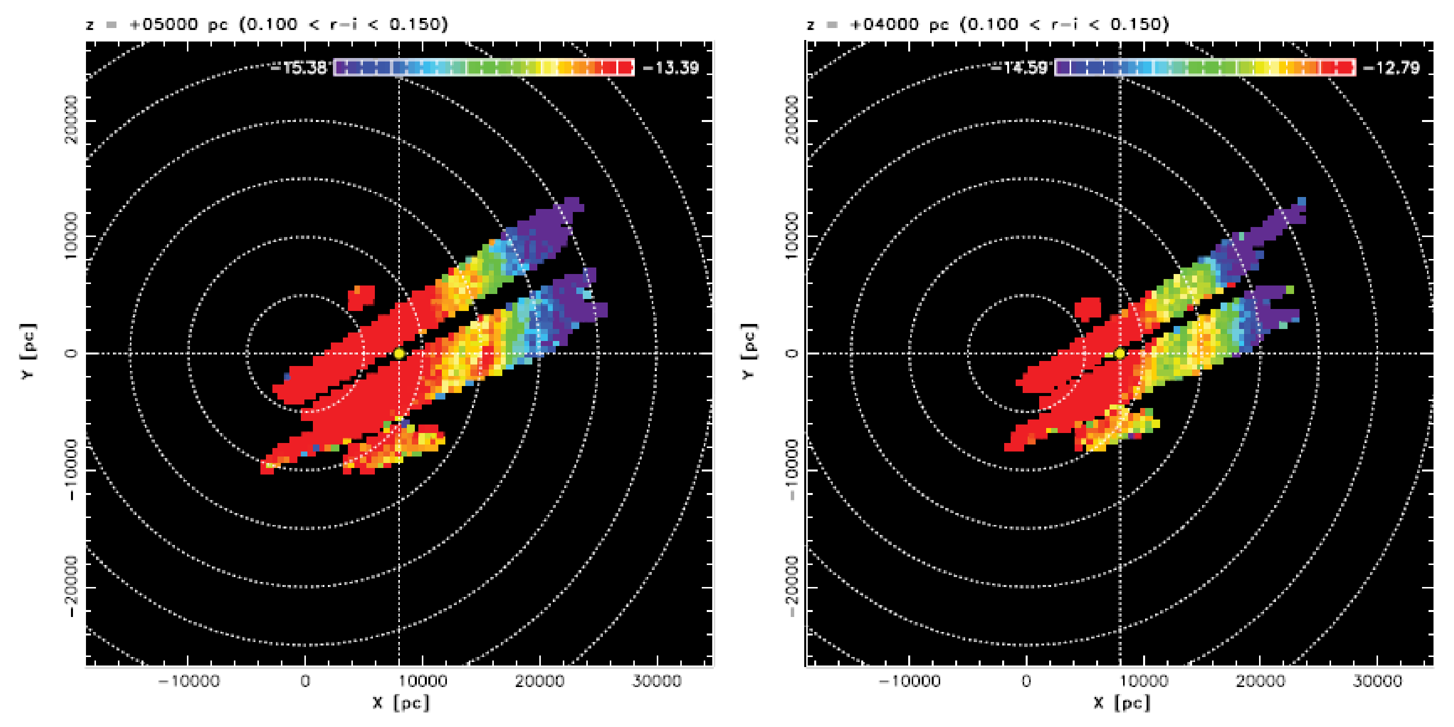
Virgo

Control



Monoceros Stream

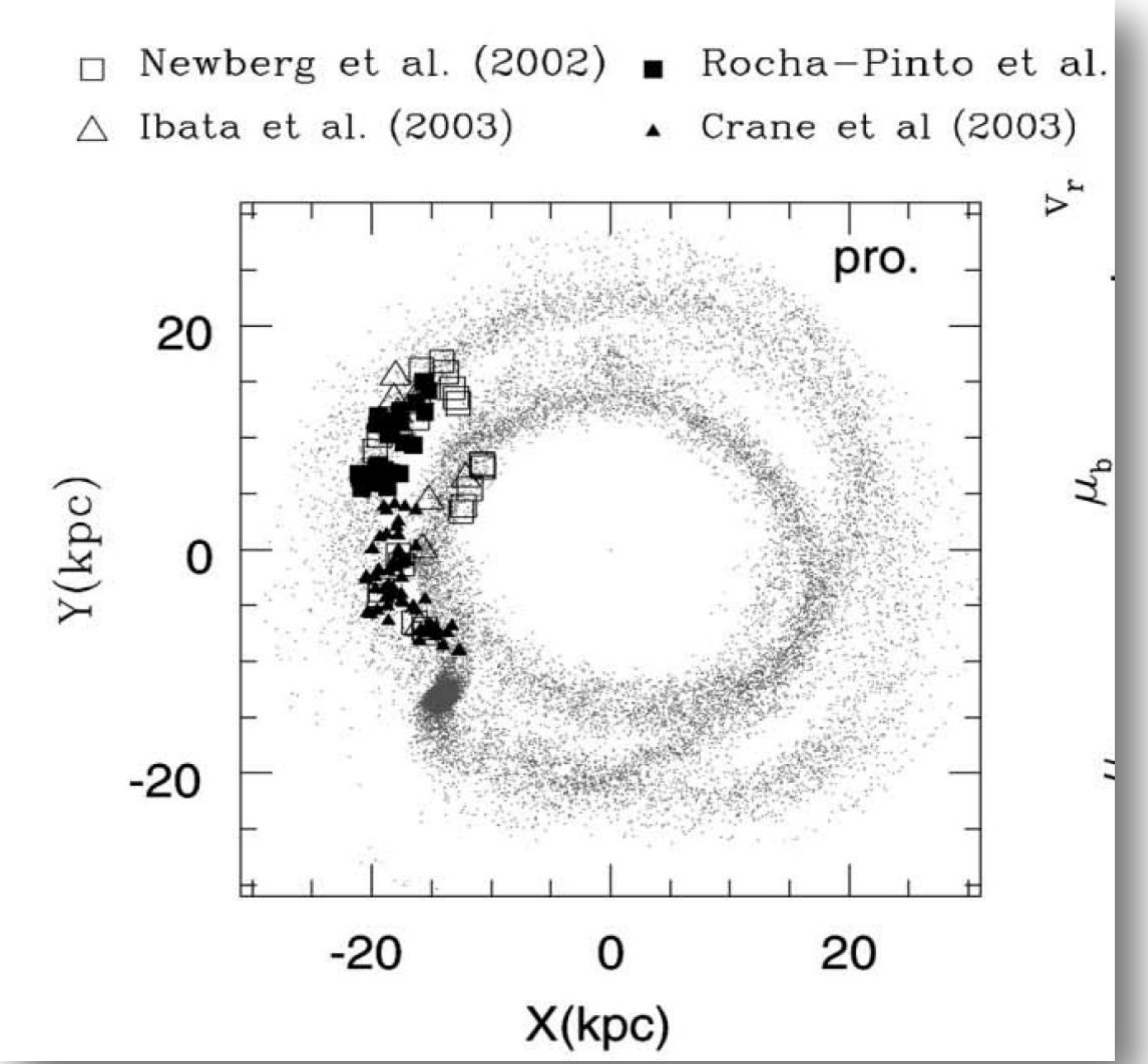
MJ et al (2008)



- Monoceros Stream (Newberg et al. 2002; Yanny et al. 2003)
- Ring-like feature (inconsistent with a disk flare)
- Extent: R~17kpc, width ΔR~3kpc, $110 < l < 250$ (at least)

Accreted Event

Penarrubia et al. (2005)

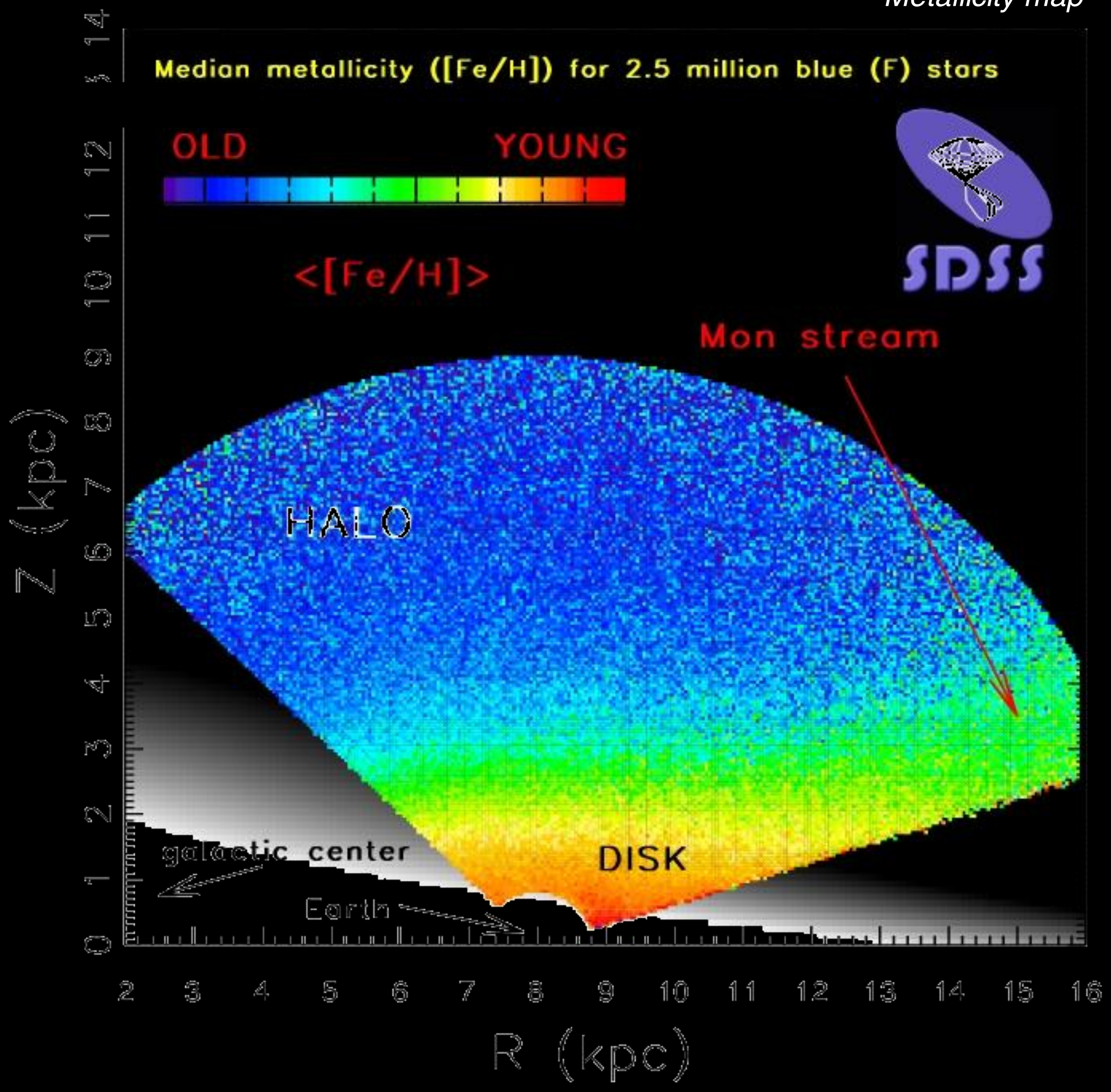


- Monoceros as a result of an accretion event (Penarrubia et al. 2005)
- Progenitor: *3-9 10^8 M_O*
- Nearly circular (e=0.05), almost in-plane orbit (i=25deg)

Milky Way Metallicity Maps

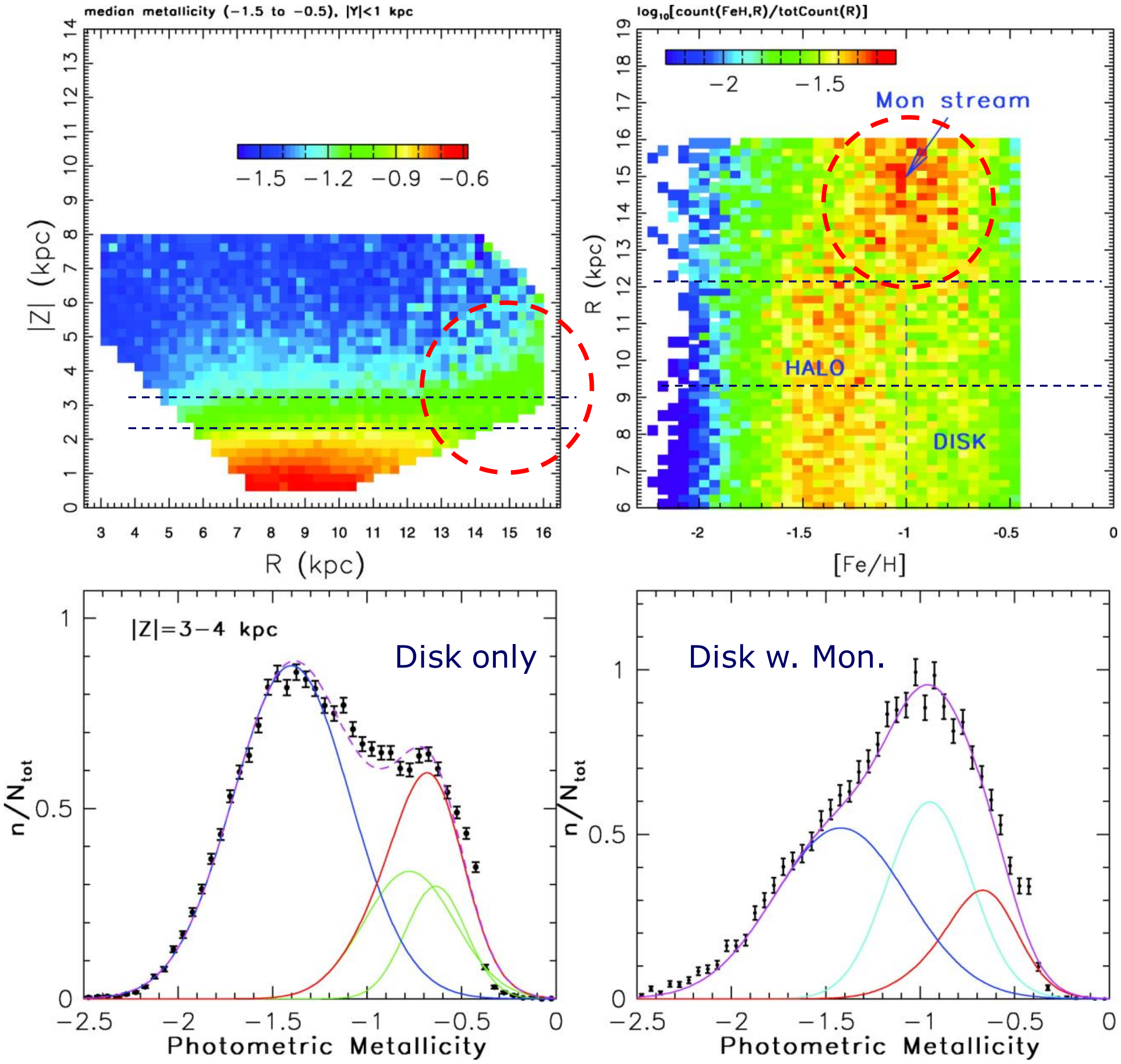
Ivezic et al. (2008)

Metallicity map



Monoceros Stream MDF

Ivezic et al. (2008)



- Monoceros stream (Newberg et al. 2002) clearly distinct in metallicity space
- Metal poor compared to the disk, but metal rich compared to the halo ([Fe/H] = -0.95 dex)
  - [α/Fe] ~ 0.2, [Fe/H]~-1 (SEGUE, Schlaufman et al.)
  - Further spectroscopic followup (Frebel & MJ, in prep)
- Strong evidence for external origin (merger remnant, as opposed to disk flaring or excitation)

Structural Parameters: Double-Exponential + Clumps

MJ et al. (2008); SDSS III update Ana Bonaca & MJ (in prep)

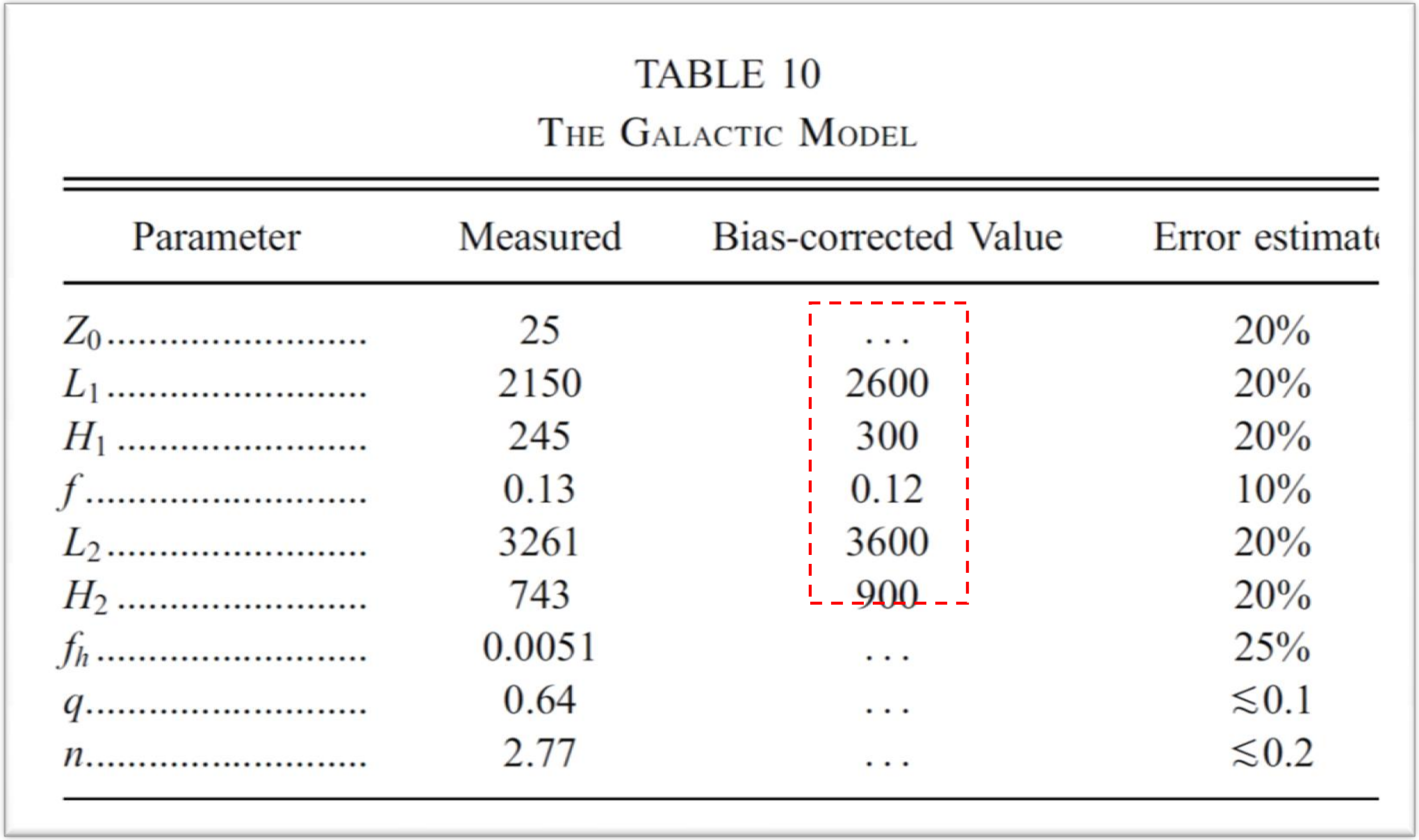


TABLE 10

THE GALACTIC MODEL

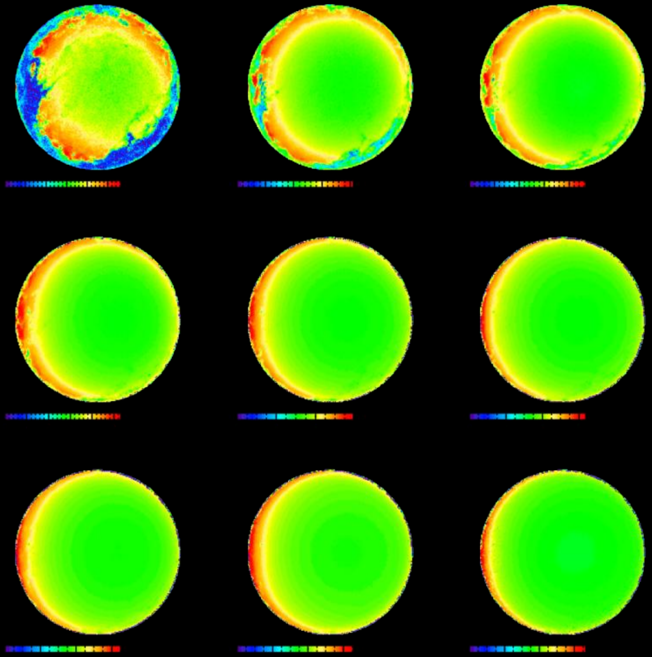
Parameter	Measured	Bias-corrected Value	Error estimat
Z_0	25	...	20%
L_1	2150	2600	20%
H_1	245	300	20%
f	0.13	0.12	10%
L_2	3261	3600	20%
H_2	743	900	20%
f_h	0.0051	...	25%
q	0.64	...	$\lesssim 0.1$
n	2.77	...	$\lesssim 0.2$

Based on ~6500 sq. deg of r<21.5 observations

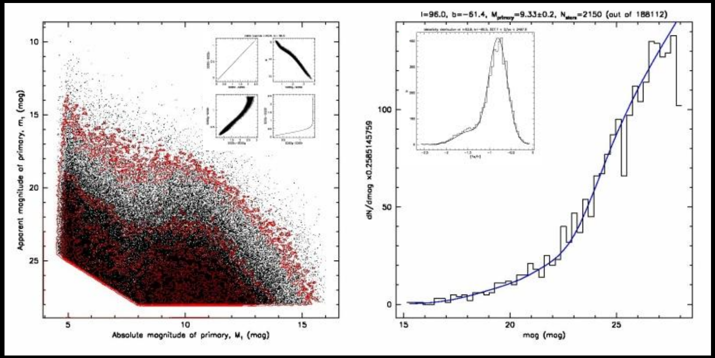
galfast – the fast catalog generator code

Juric et al. (in prep)

- A realistic model of the observed 7D sky (and, by extension, the Galaxy)
- Does <u>not</u> attempt a full population synthesis modeling (Besancon/TRILEGAL);



- Inputs: (arbitrary) distributions (density, kinematics, dust, …), and arbitrary relations (e.g. isochrones), empirically calibrated wherever possible.
- Observational system definition (obsv. errors)

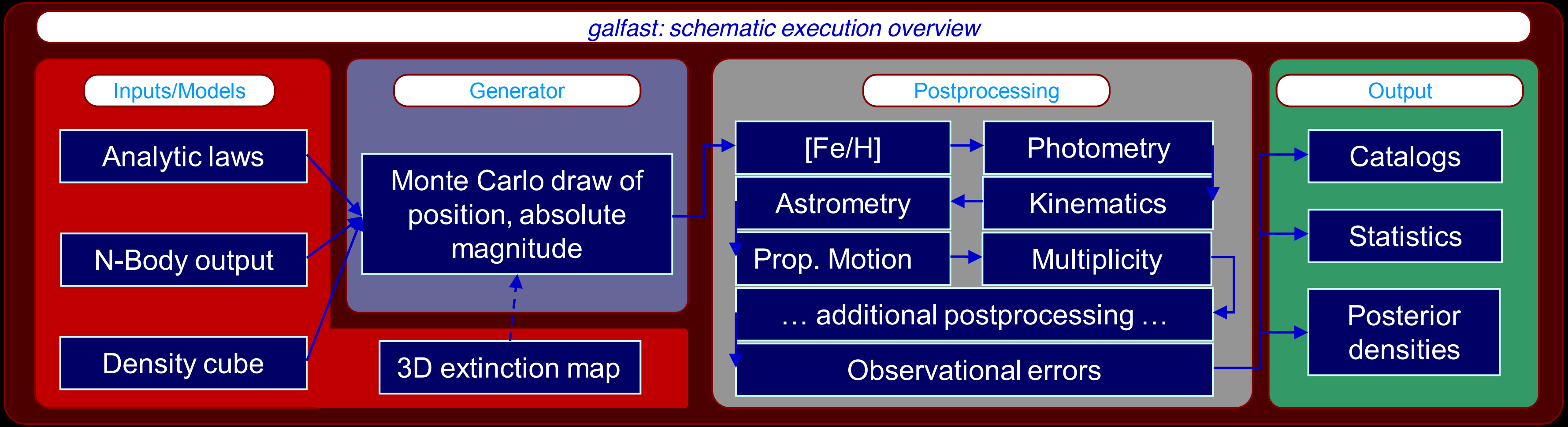


- Creation of realistic catalogs (used for LSST, we could do GAIA as well)
- Crucial for understanding the actual data and system
- Testing of “what-if” scenarios

Juric et al. (2010)

A really fast direct 4D PDF sampler: $\rho(X, Y, Z, M)$ or $\rho(l, b, DM, M)$

Stellar properties given as P(prop|XYZM) and assigned in postprocessing



galfast: schematic execution overview

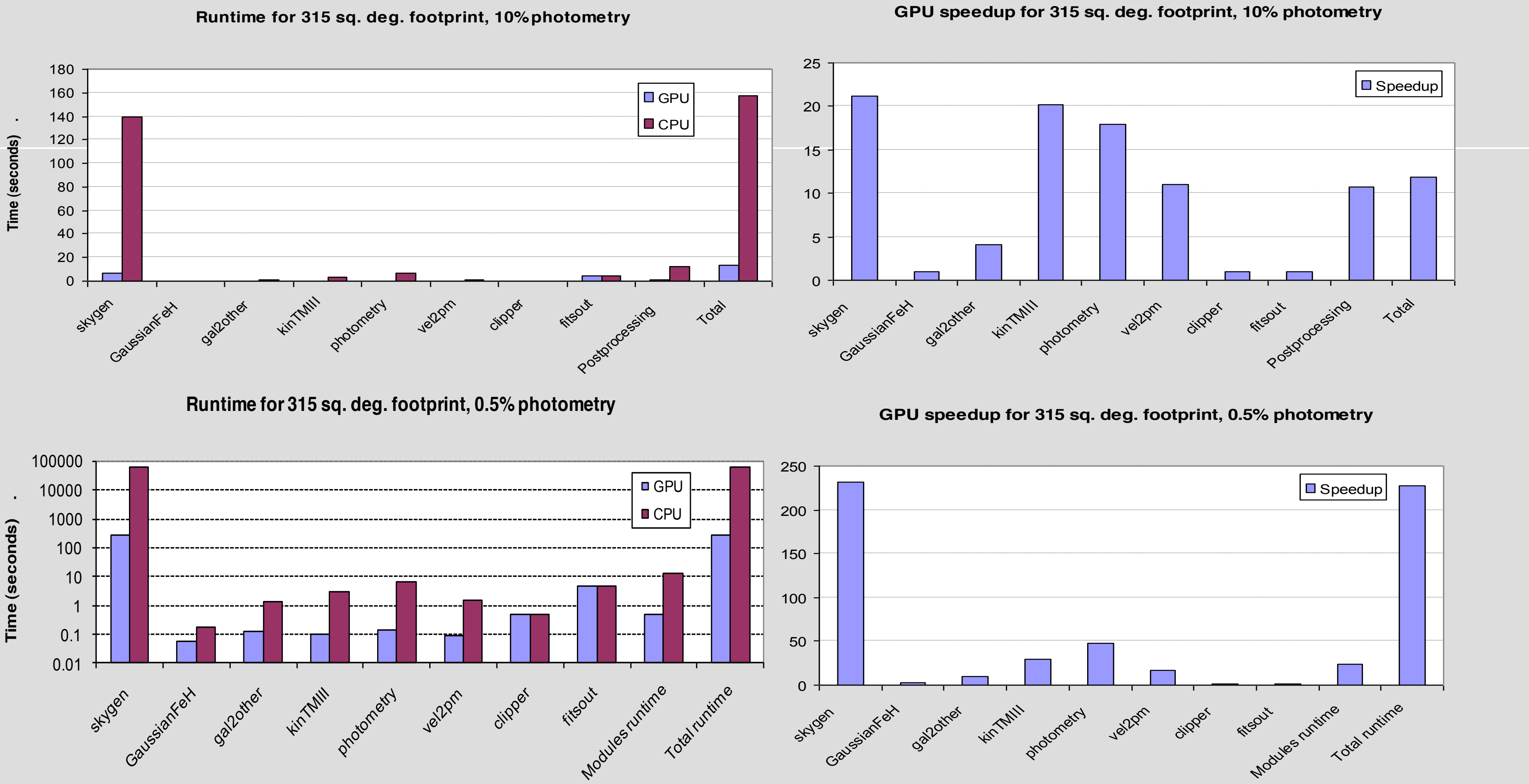
Inputs/Models
- Analytic laws
- N-Body output
- Density cube

Generator
- Monte Carlo draw of position, absolute magnitude
- 3D extinction map

Postprocessing
- [Fe/H]
- Photometry
- Astrometry
- Kinematics
- Prop. Motion
- Multiplicity
- … additional postprocessing …
- Observational errors

Output
- Catalogs
- Statistics
- Posterior densities

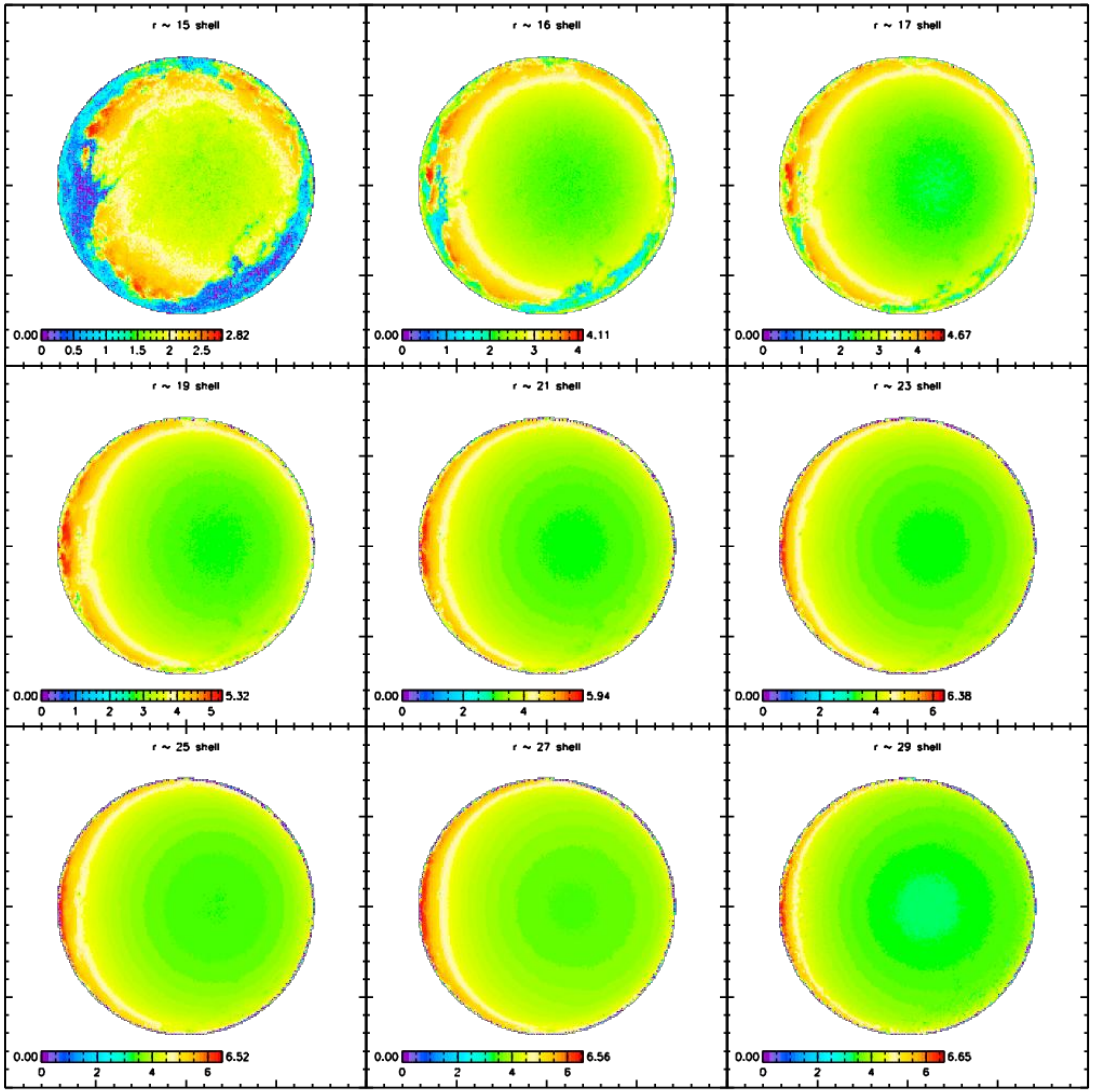
1. Flexibility (arbitrary inputs and outputs)
2. <u>Speed</u>



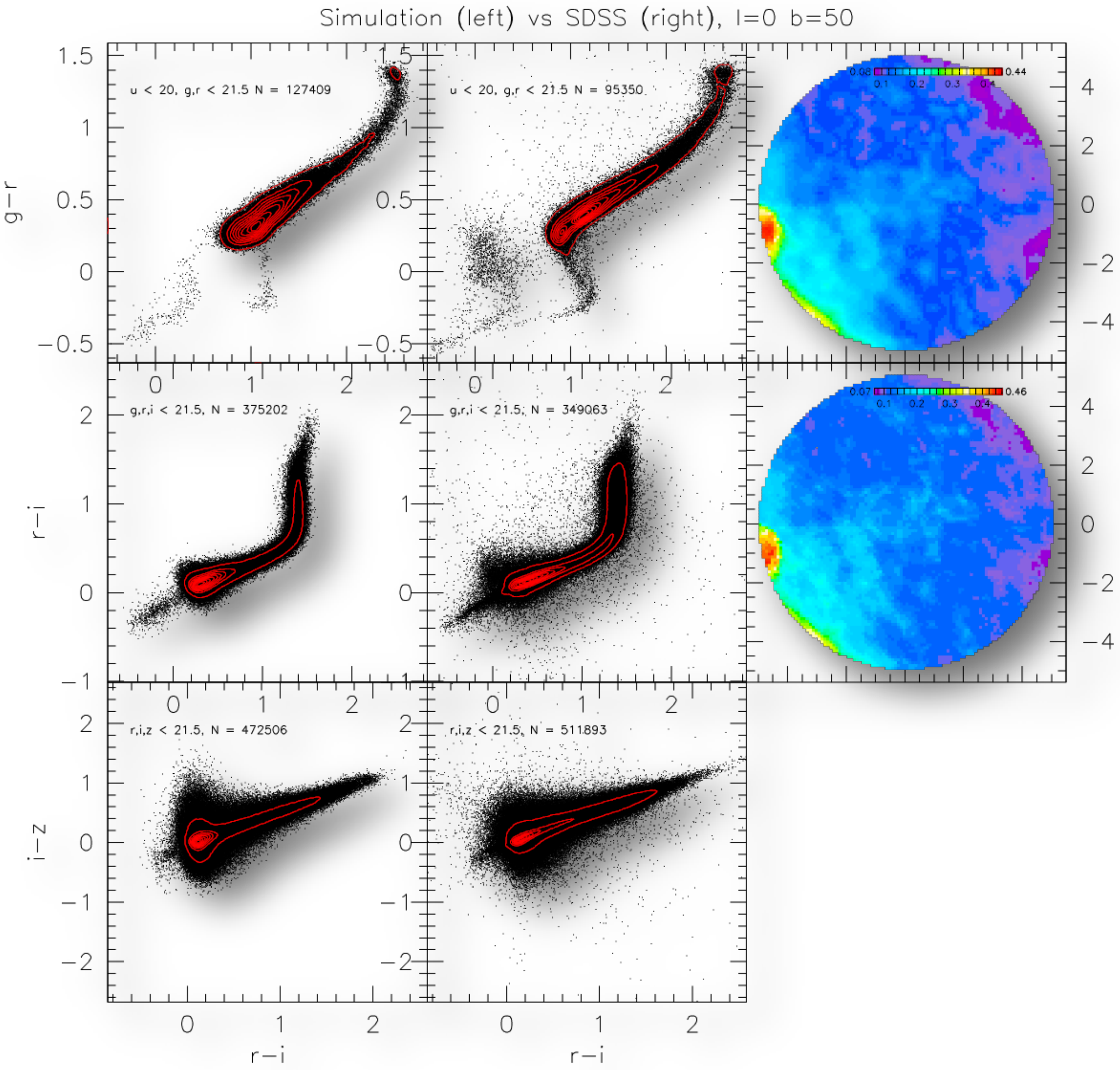
Above: The graphs to the right show the execution time of various *galfast* stages running on a single Tesla S1070 GPU (blue) vs a single core of an Intel Xeon E5405 2.0GHz CPU (purple). The graphs to the left show the ratio of the two (the GPU speedup). In all cases the code was generating a flux-limited catalog in a 20deg diameter pencil beam towards the North Galactic pole; for the top row the photometric accuracy was set to 0.1mag, while it was 0.005 for the bottom (as needed for generation of realistic LSST source catalogs).

The GPU accelerated *galfast* outperforms the CPU version by a factor of ~20x for the low accuracy case, and a factor of >200x in the (relevant!) high accuracy scenario. The difference can be attributed to initial kernel startup costs associated with the GPU and CUDA runtime, that dominate runtimes of short kernels. The overall speedup is due to a) parallel computation on 240 cores b) hardware implementation of texture lookups, and c) fast arithmetic and transcendental function implementation on the GPU.

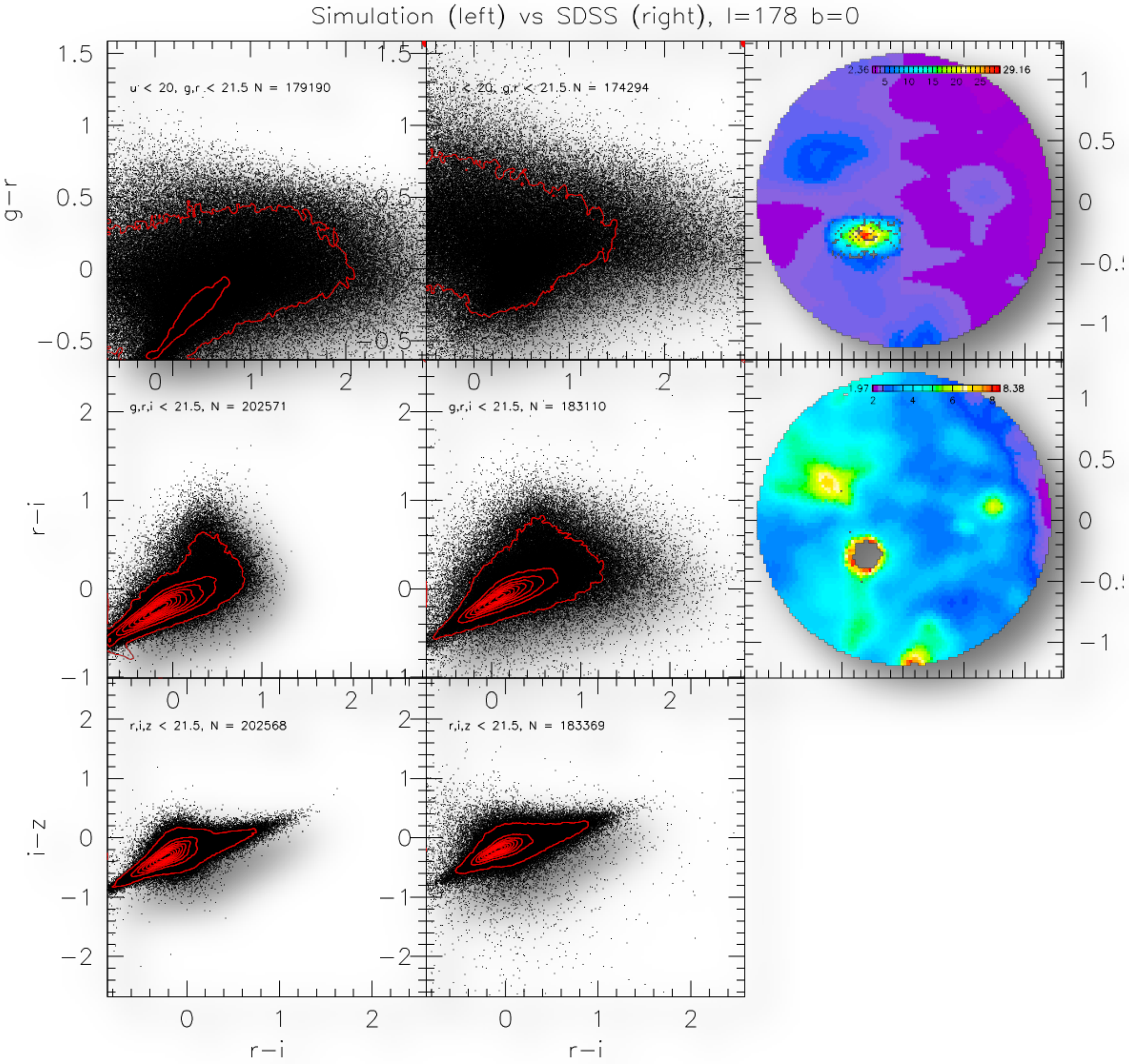
LSST Star Count Maps to r=29mag



Color-Color Diagrams w. Multiple Stellar Populations


Simulation (left) vs SDSS (right), l=0 b=50

CCDs in High Extinction Areas

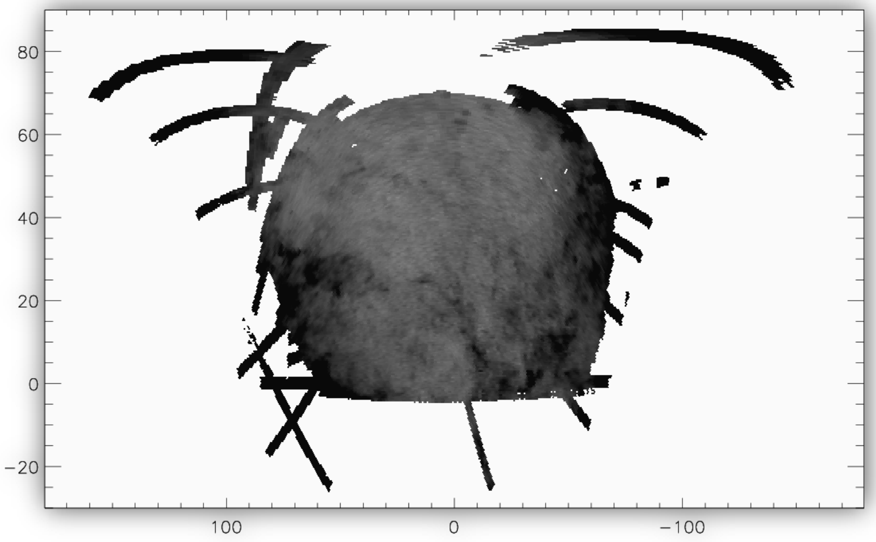

Simulation (left) vs SDSS (right), l=178 b=0

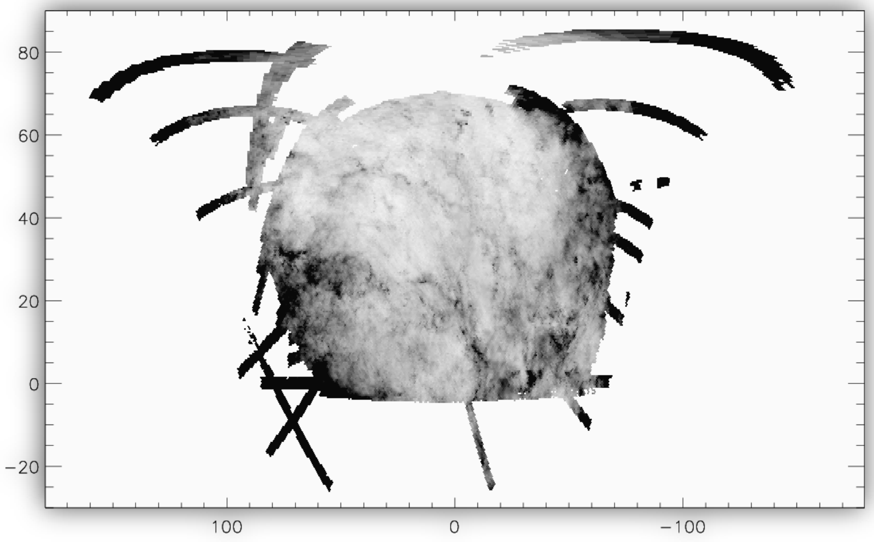
Reddening Maps

Schlafly, Finkbeiner et al. (submitted)

Measuring reddening using the "Blue Tip of the stellar locus" method

galfast provides mocks for tests of the method and verification of the results





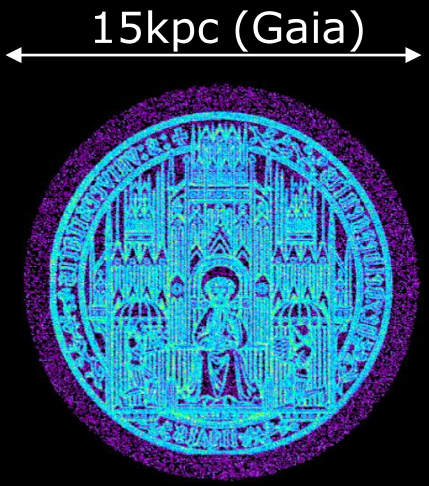
Getting and using *galfast*

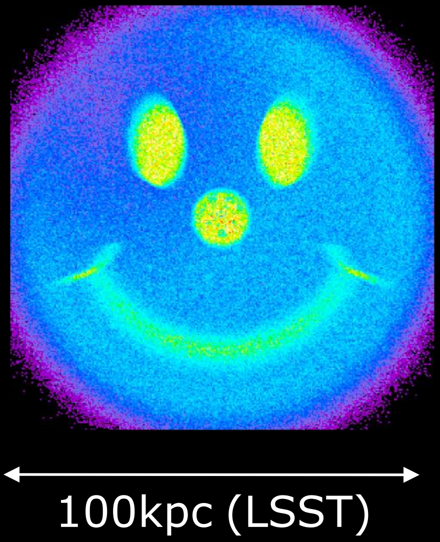
Juric et al. (in prep)

- Availability
  - Web service: http://hybrid.mwscience.net/galfast
  - “Secret code”: Mars
  - Caveat: old version, unsupported

- Source
  - C++/CUDA code
  - Available on request (still beta) (mjuric@cfa.harvard.edu)
  - Requires an NVIDIA GPU + appropriate toolkits
  - As easy as ./configure
  - Docs: http://mwscience.net/trac

- Uses
  - Interpreting SDSS photometry
  - Pan-STARRS PS1
  - LSST





LSST in 30 seconds

http://lsst.org

Large Synoptic Sky Survey

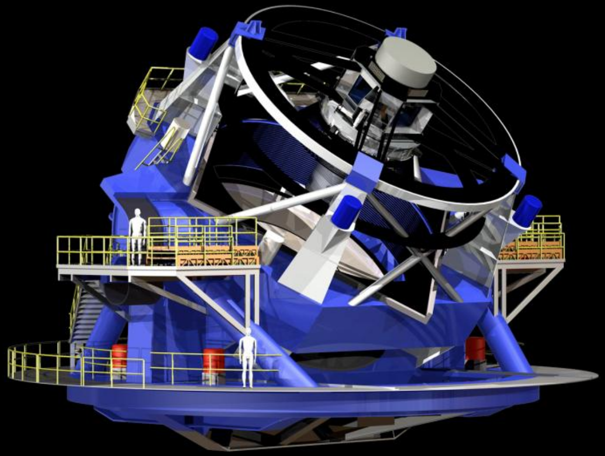
8.4m telescope

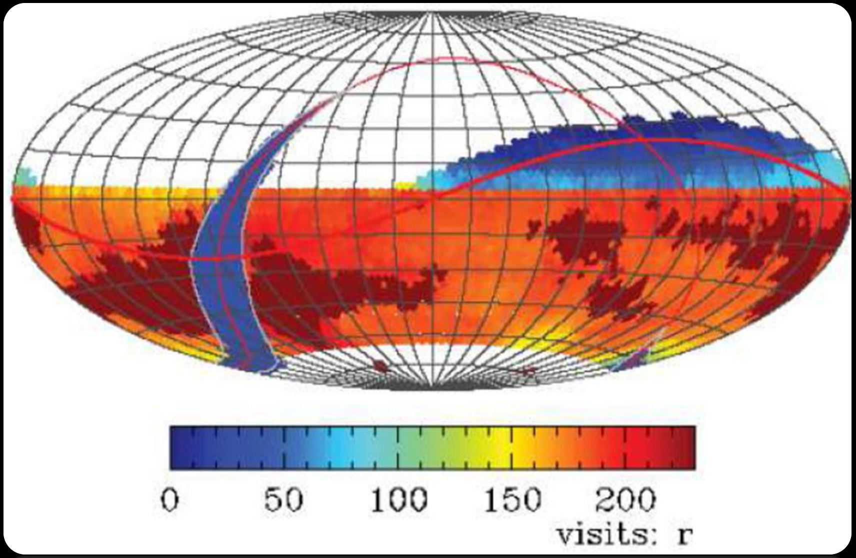
20000 deg^2

10mas a'metry

g<25 (<27.5@10yr)

6 band, 1%, photometry for ~13B stars





3.2Gpix camera

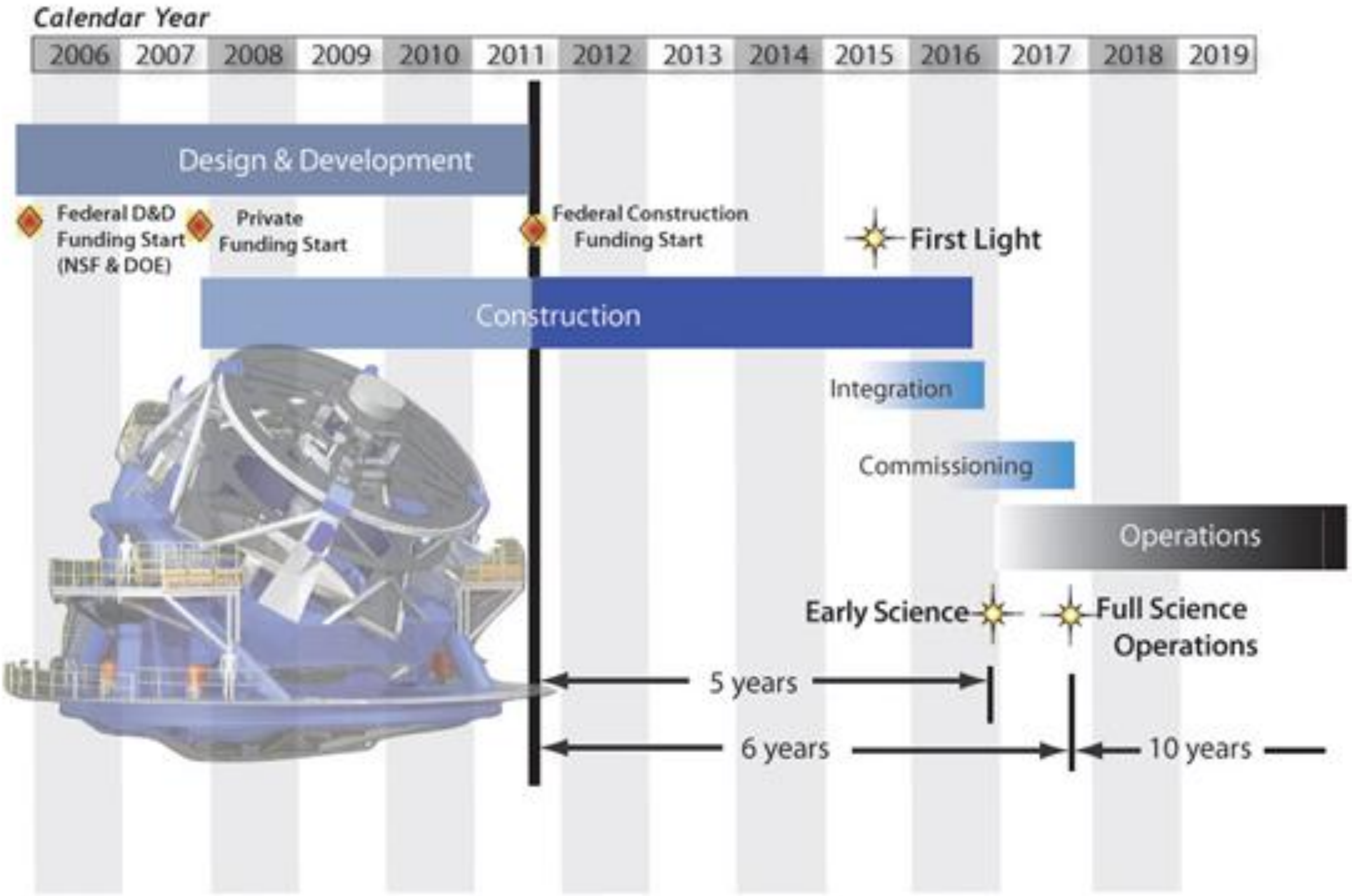
30sec exp/2sec rd

15TB/night

0.6 PB catalogs/yr

Covering the visible sky once every 3 days for 10 years

LSST Project Schedule



Calendar Year

2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

Design & Development

Federal D&D Funding Start (NSF & DOE)

Private Funding Start

Federal Construction Funding Start

First Light

Construction

Integration

Commissioning

Operations

Early Science

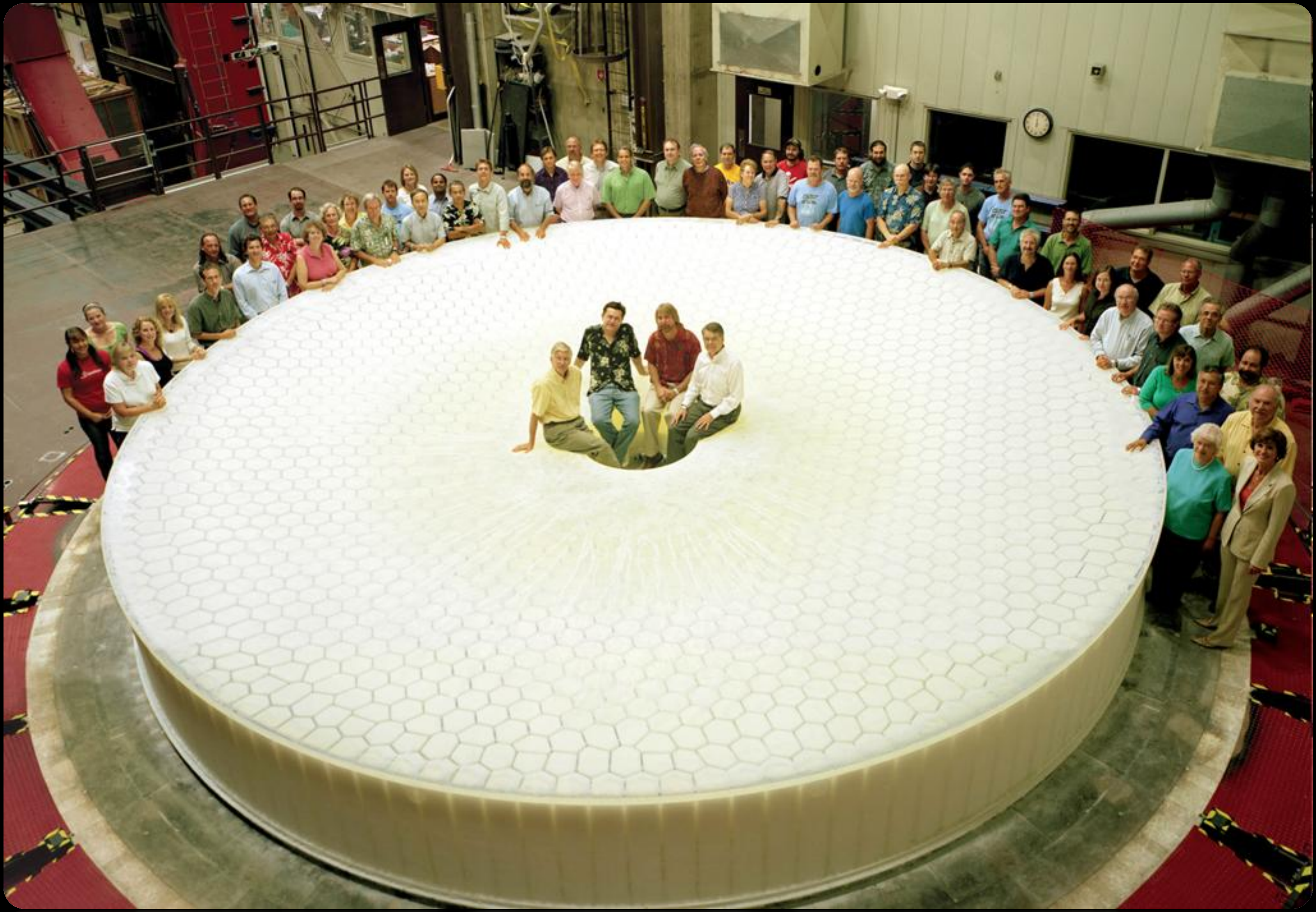
Full Science Operations

5 years

6 years

10 years

LSST Primary Mirror Blank



LSST First Image! *

LSST Science Book v2.0, arXiv:0912.0201

1 chip (4kx4k)

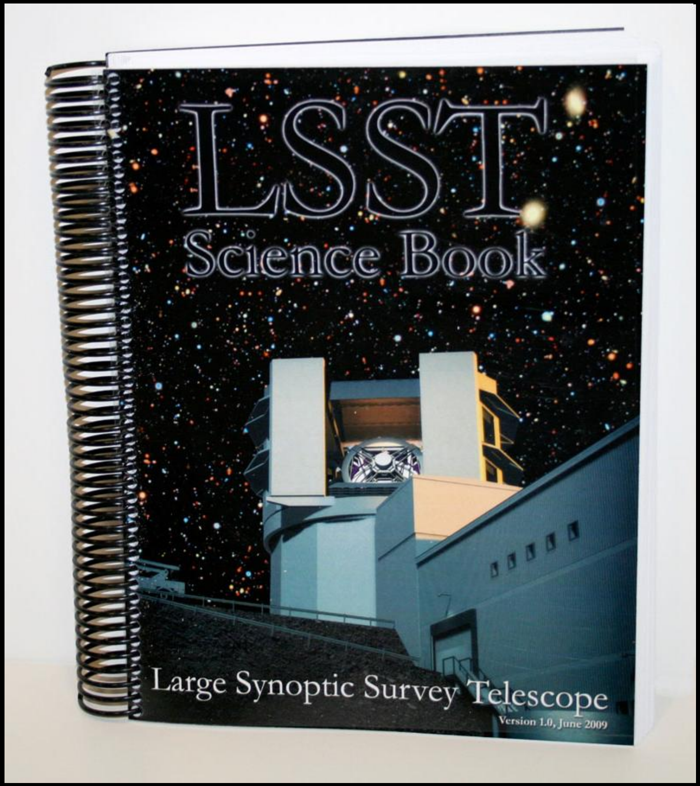
0.5% of the focal plane (189 chips)

(*) simulated

LSST Science

LSST Science Book v2.0, arXiv:0912.0201

1. A Comprehensive Survey of the Solar System
2. Structure and Stellar Content of the Milky Way
3. Transient and Time Variable Phenomena
4. Galaxy Formation and Evolution
5. The Nature of Dark Energy and Matter



LSST
Science Book
Large Synoptic Survey Telescope
Version 1.0, June 2009

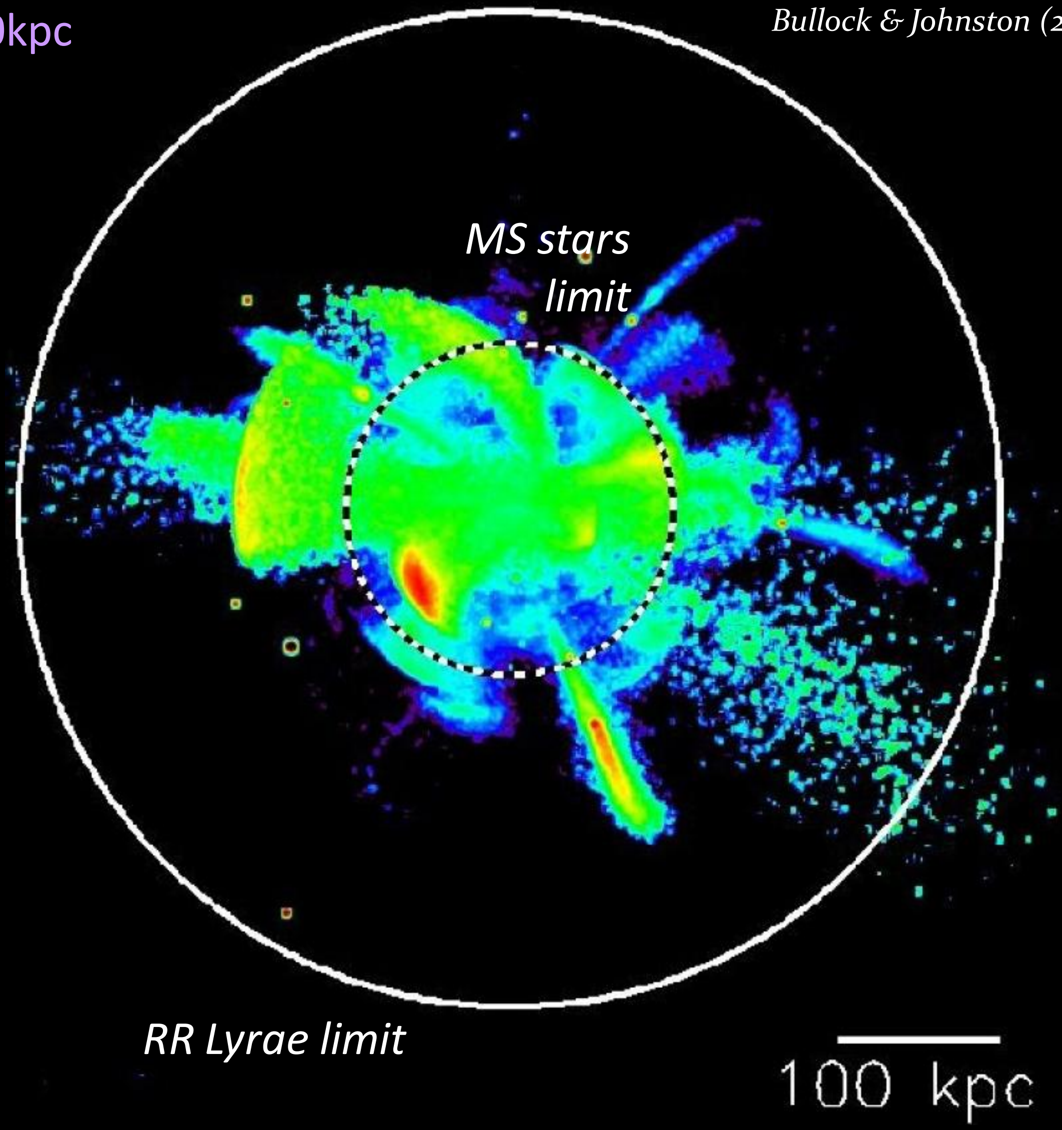
http://arxiv.org/abs/0912.0201

(246 authors, 596 pages)

The Local Group Tomography With LSST

LSST Science Book v2.0, arXiv:0912.0201

- - Maps of (sub)structure to 100kpc (MS stars), 400kpc (RRLyrae)
- - Streams and Structure in the Stellar Halo
- - Census of ultra-faint dwarfs
- - A complete stellar census within 300pc
- - Hypervelocity stars (esp. low mass)
- - 3-dimensional dust maps
- - Secular Evolution of Bulge and Disk
- - Galactic and Intergalactic Globular clusters
- …..

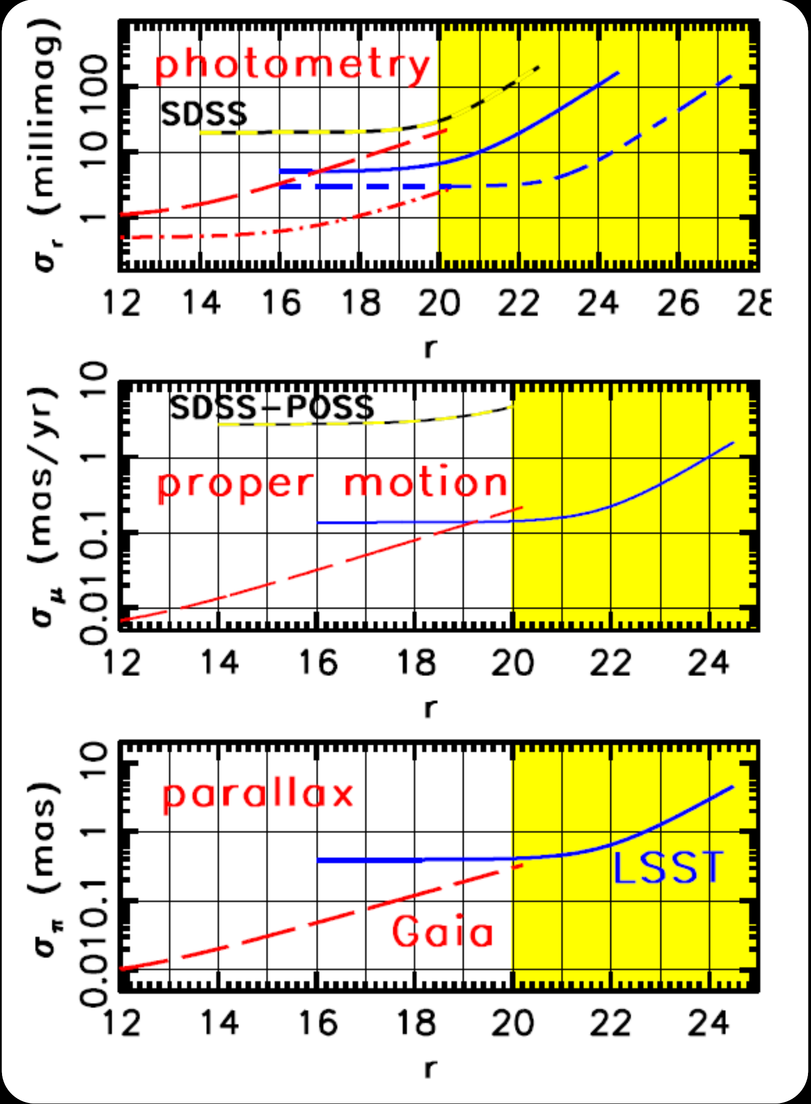


Bullock & Johnston (2005)

LSST and GAIA

LSST Science Book v2.0, arXiv:0912.0201 (Eyer, Ivezic & Monet)

- GAIA will be unsurpassed in astrometry and photometry of bright sources
- LSST will excel in deep+wide photometry (g~27.5, stacked) and multiple epochs
  - ~200 epochs/filter/object
- Highly complementary
  - GAIA: an excellent standard candle calibrator that LSST can see to 10x greater distances
    - Provide accurate distance moduli to main sequence stars of varying spectral types and abundances (colors)
    - The same for other, brighter, tracers (including variables)
  - Interest in GAIA catalogs sooner, rather than later, even if imprecise (!)



Release Early, Release Often, Release Everything

- Why:
  1. Catch and fix important errors early on (“Linus’ Law”)
  2. Enable synergies and ancillary science with other projects
  3. Quickly react to discoveries

- What and How:
  1. Data in standardized formats (or methods of access)
  2. Documentation
  3. Code

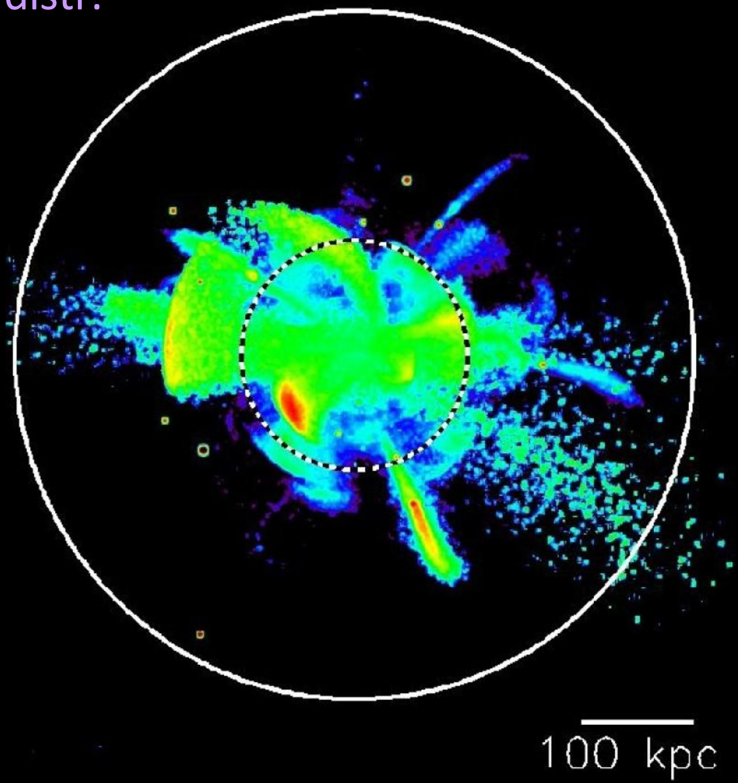
- SDSS:
  - ~yearly data releases, nearly immediate data availability within the collaboration
- LSST:
  - Immediate public data availability
  - Yearly Data Releases (DRs); more stringent Q/A
  - All source code publicly available, with support provided for setting up and building the code

Mapping with SDSS and Beyond: A Summary

- SDSS: Direct mapping of stellar number density distr. with two orders of magnitude more tracers, in volumes approaching representative

- Discoveries and characterization of >dozen streams, at distances ranging from 2-30 kpc, with multiple methods
  - Measuring halo shape and profile
  - Constraining the level of halo clumpiness
  - Measuring halo mass

- LSST – The next two orders of magnitude
  - “The local volume exploration machine”
  - Deep complement to Gaia



- SDSS Legacy
  - SDSS discoveries and/or characterization of numerous streams and dwarf galaxies ushered an era of true observational near-field cosmology and the capability to observationally test ΛCDM predictions in small scale regime.
  - Showed the way forward for future surveys – PanSTARRS PS1, SkyMapper, LSST, etc.