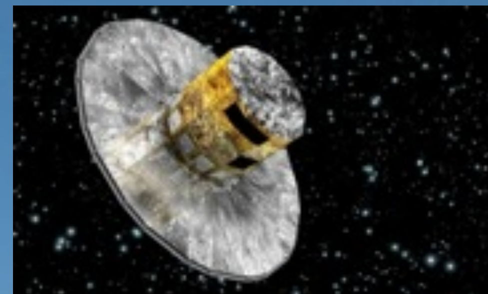
What shall we learn about the Milky Way using Gaia and LSST?

Astr 511: Galactic Astronomy

Winter Quarter 2015

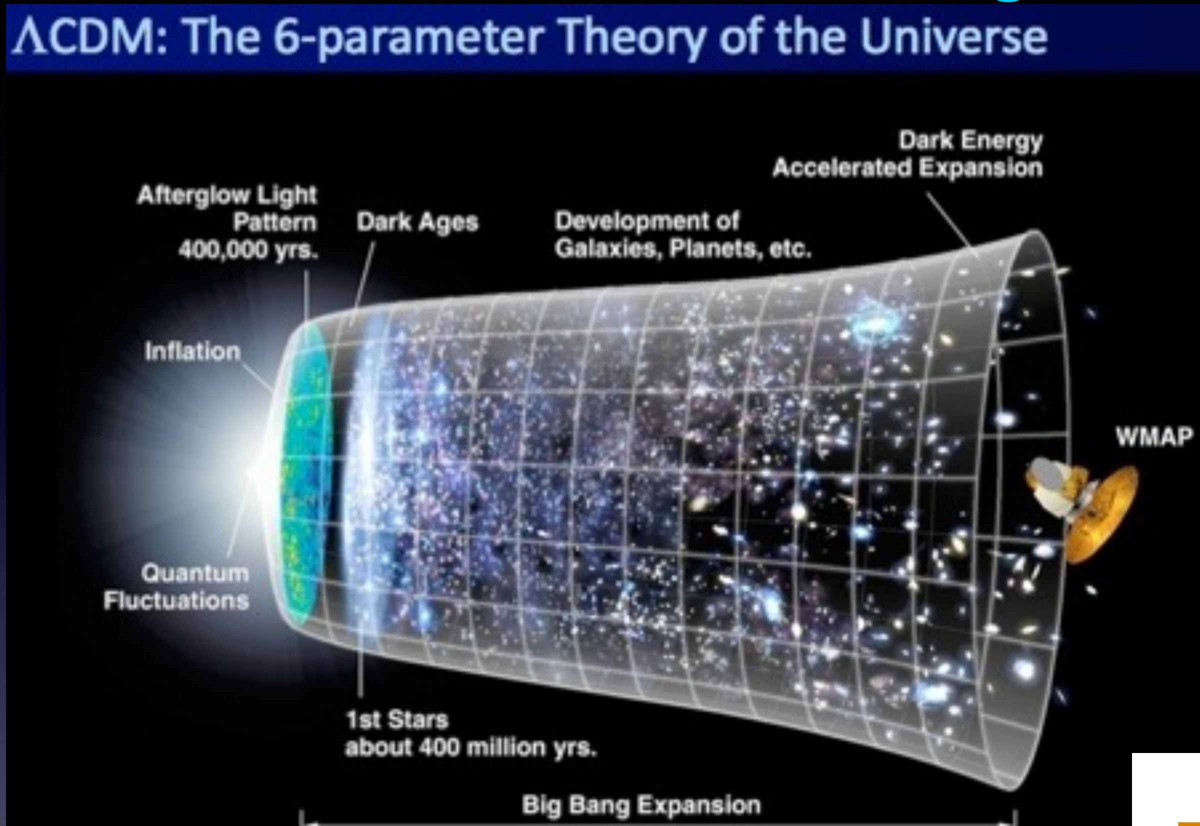
University of Washington, Željko Ivezić

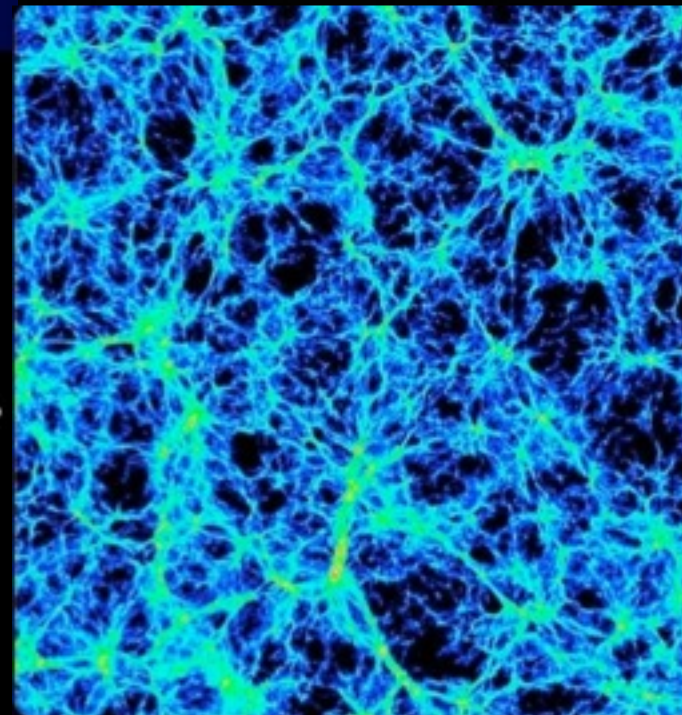


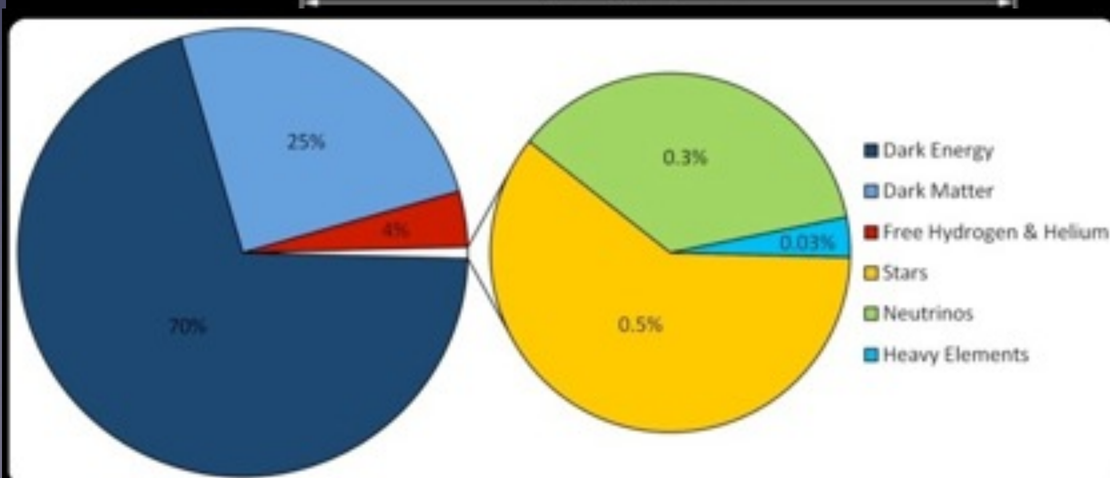
The era of surveys...

- Standard: “What data do I have to collect to (dis)prove a hypothesis”?
- Data-driven: “What theories can I test given the data I already have?”

New Cosmological Puzzles







The modern cosmological models can explain all observations, but need to **postulate** dark matter and dark energy (though gravity model could be wrong, too)

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 20 billion stars and 20 billion galaxies with exquisite photometry, astrometry and image quality!

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*

Outline

- Brief introduction to LSST
  – science drivers
  – system design
- The promise of LSST: 2020 vision
  - multi-color time-resolved faint sky map
  - 20 billion galaxies (median redshift ~1)
  - 20 billion stars (all the way to the edge of the Milky Way)
  - millions and millions of supernovae, quasars, asteroids…
- Gaia vs. LSST comparison
  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

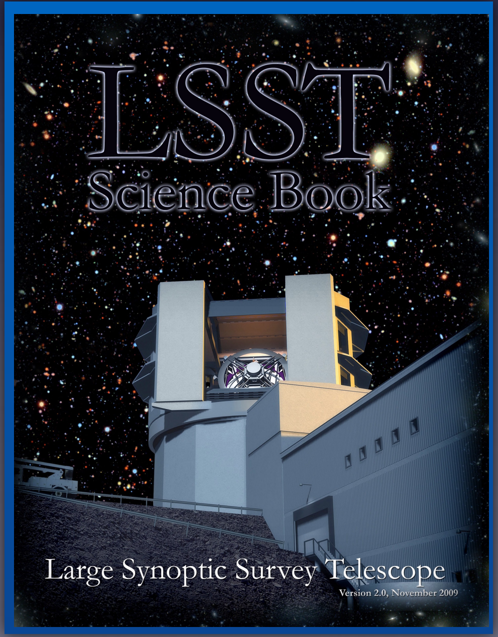
LSST Science Themes

- 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

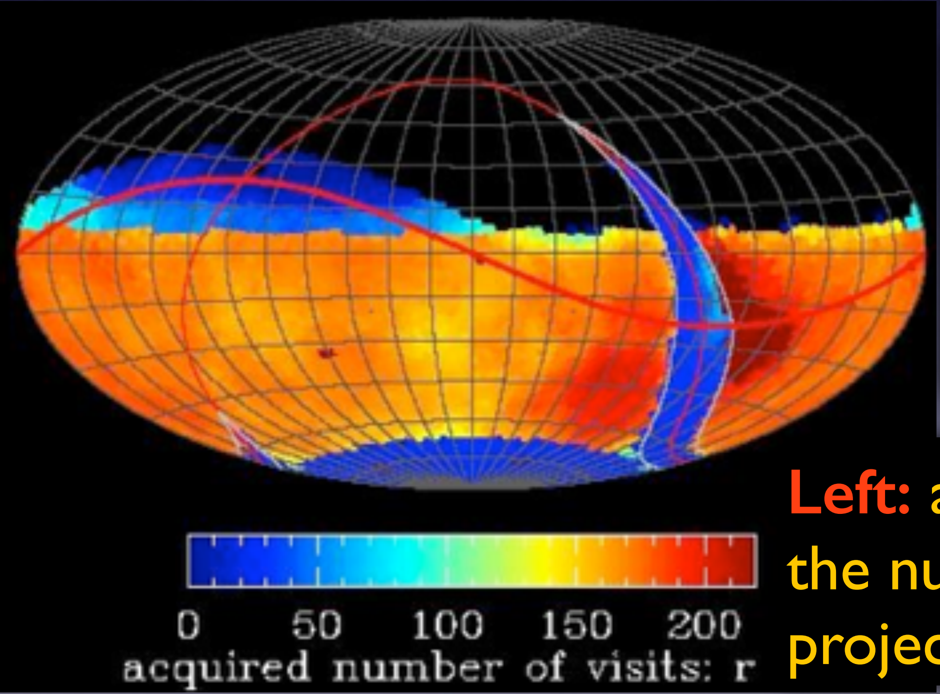
Summarizes LSST hardware, software, and observing plans, science enabled by LSST, and educational and outreach opportunities

245 authors, 15 chapters, 600 pages



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 40 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)

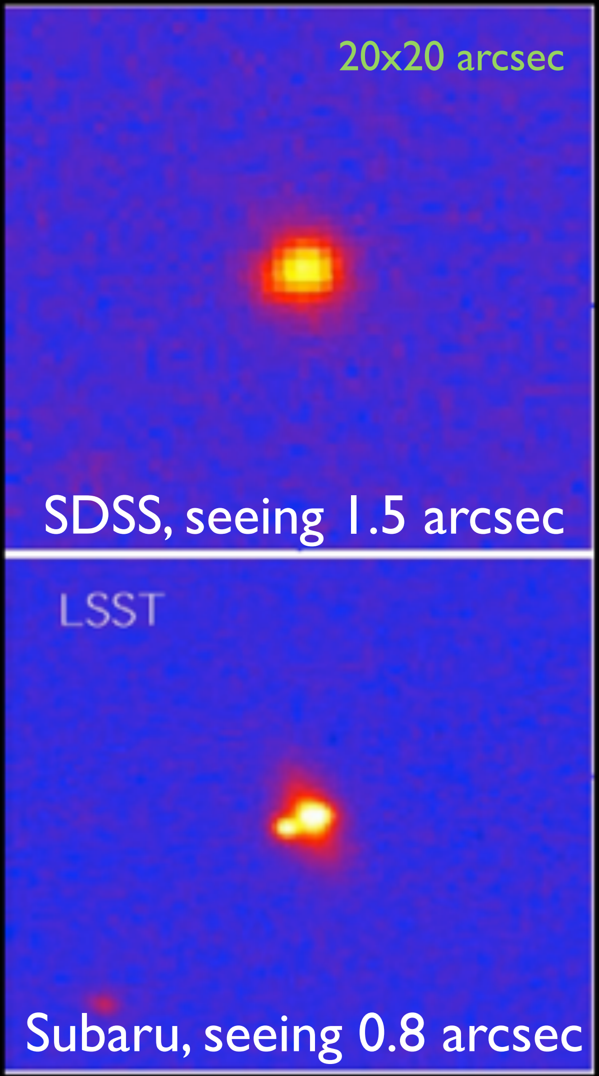
SDSS vs. LSST comparison: LSST=d(SDSS)/dt, LSST=SuperSDSS

3x3 arcmin, gri

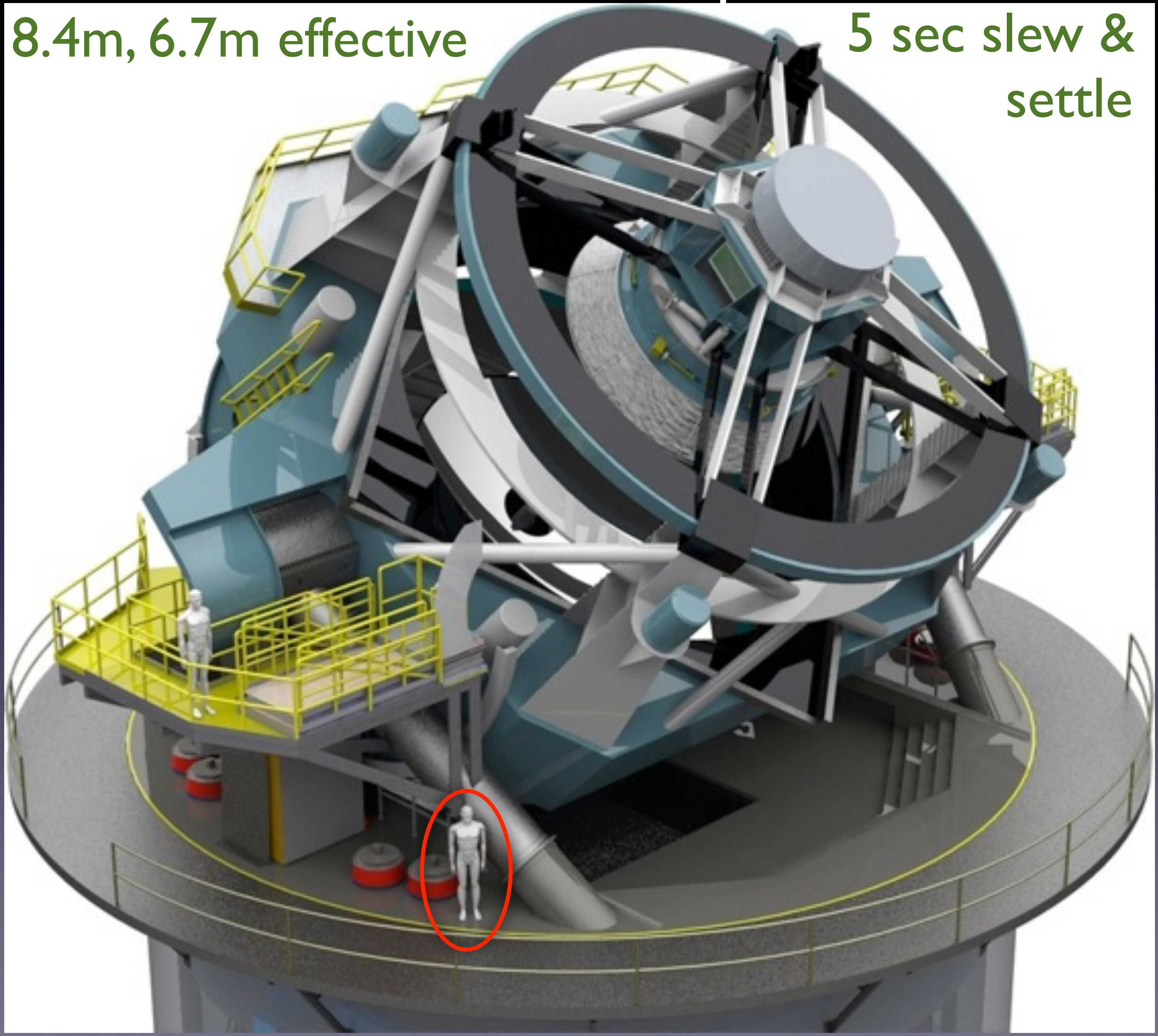
3 arcmin is 1/10 of the full Moon's diameter

(almost) like LSST depth (but tiny area)

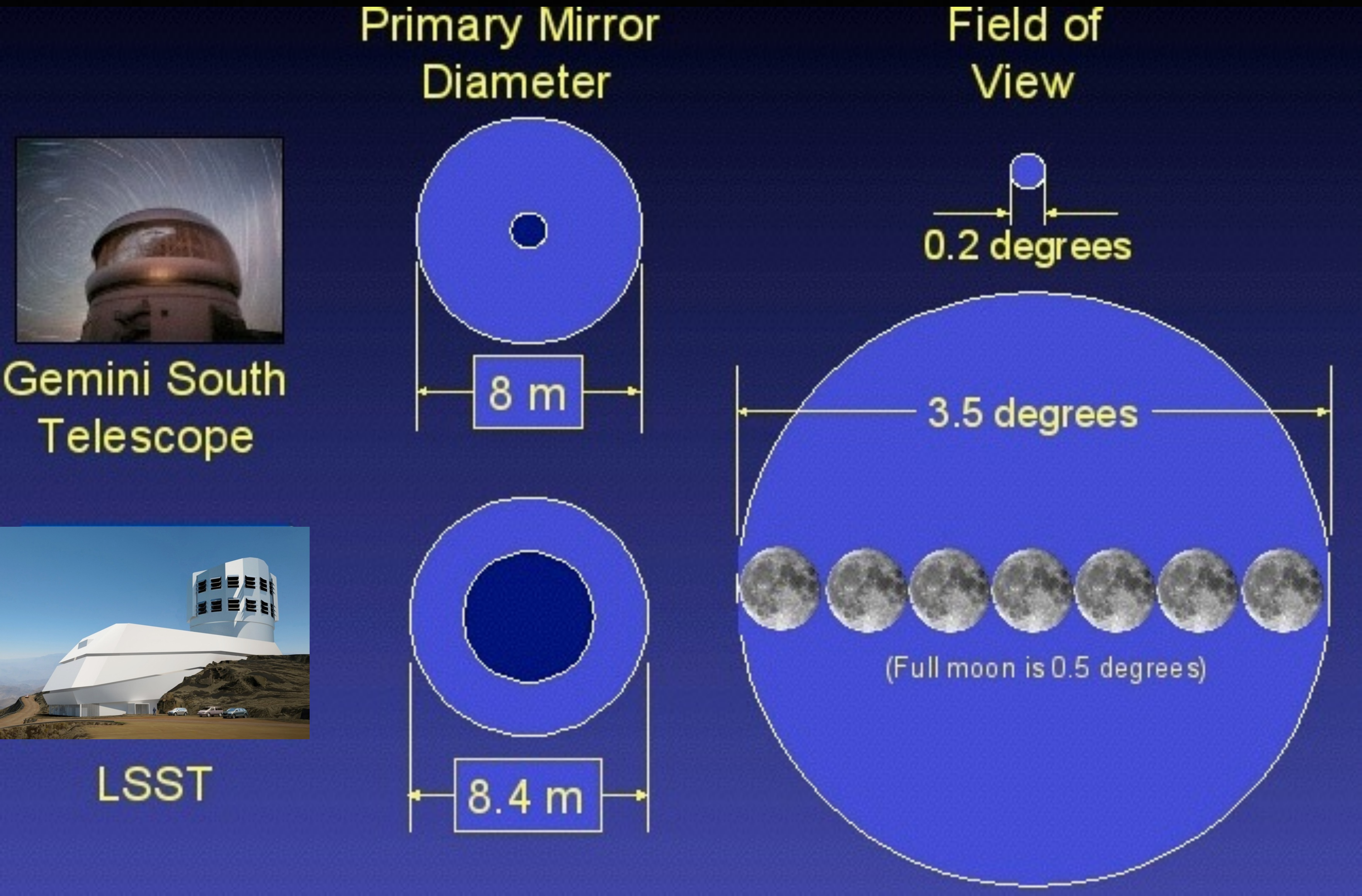
20x20 arcsec; lensed SDSS quasar (SDSS J1332+0347, Morokuma et al. 2007)



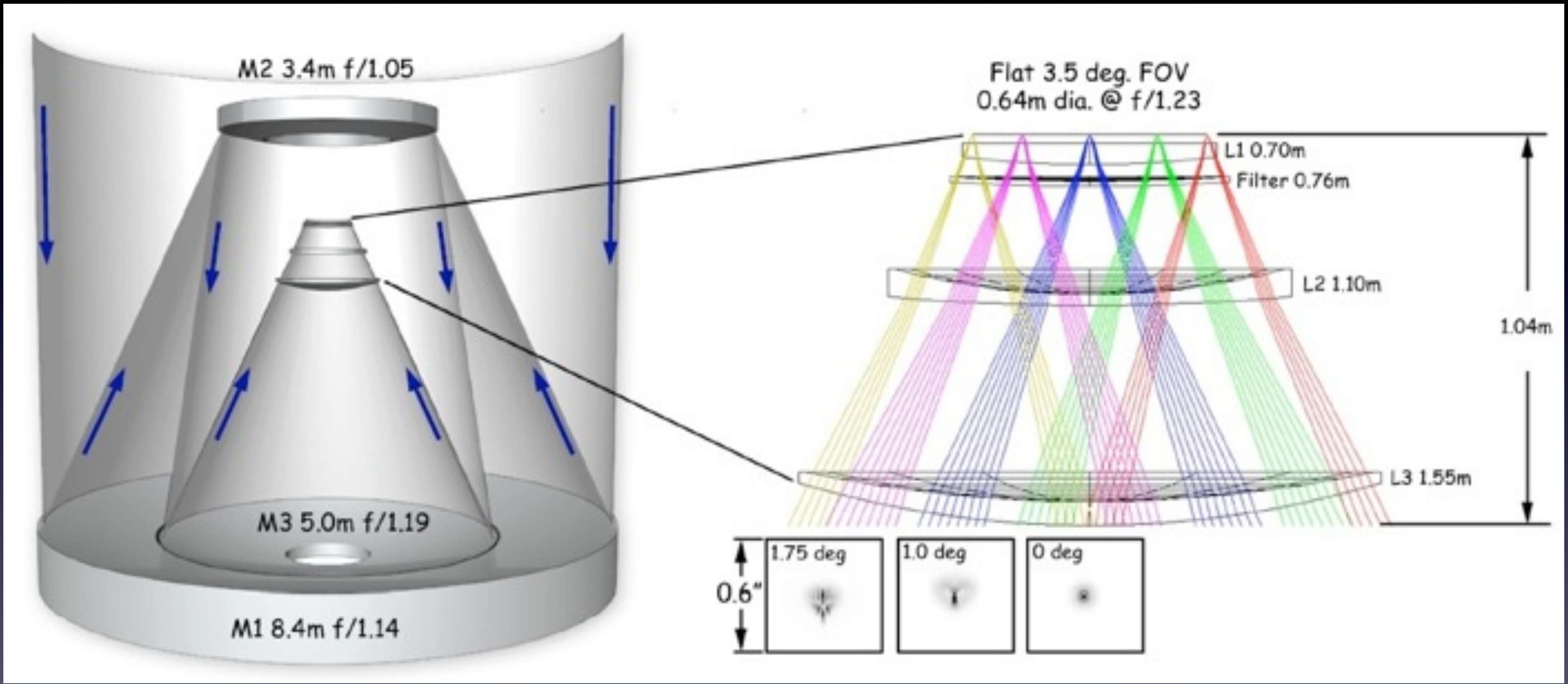
LSST Telescope



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

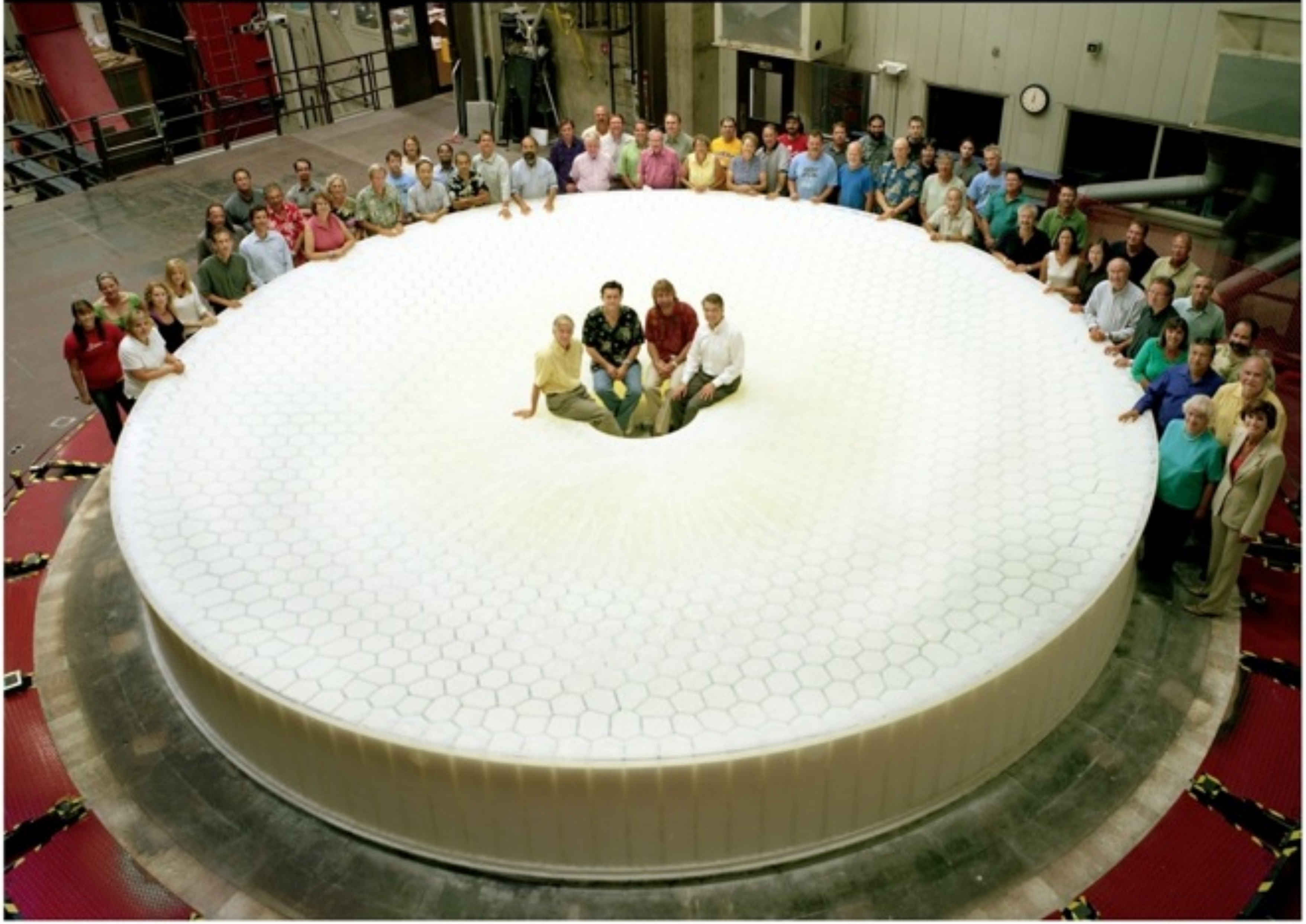


Optical Design for LSST



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

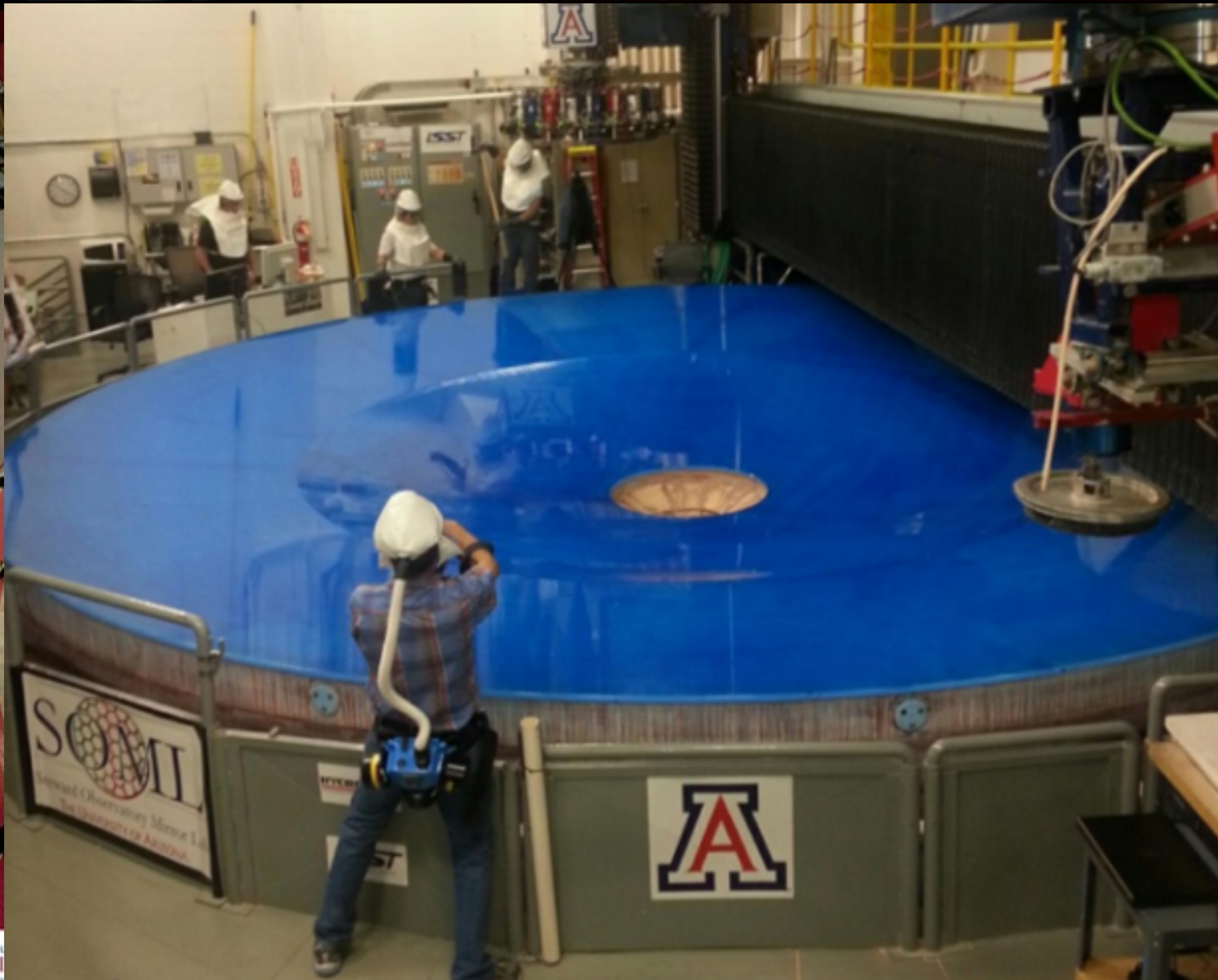
Large Synoptic Survey Telescope



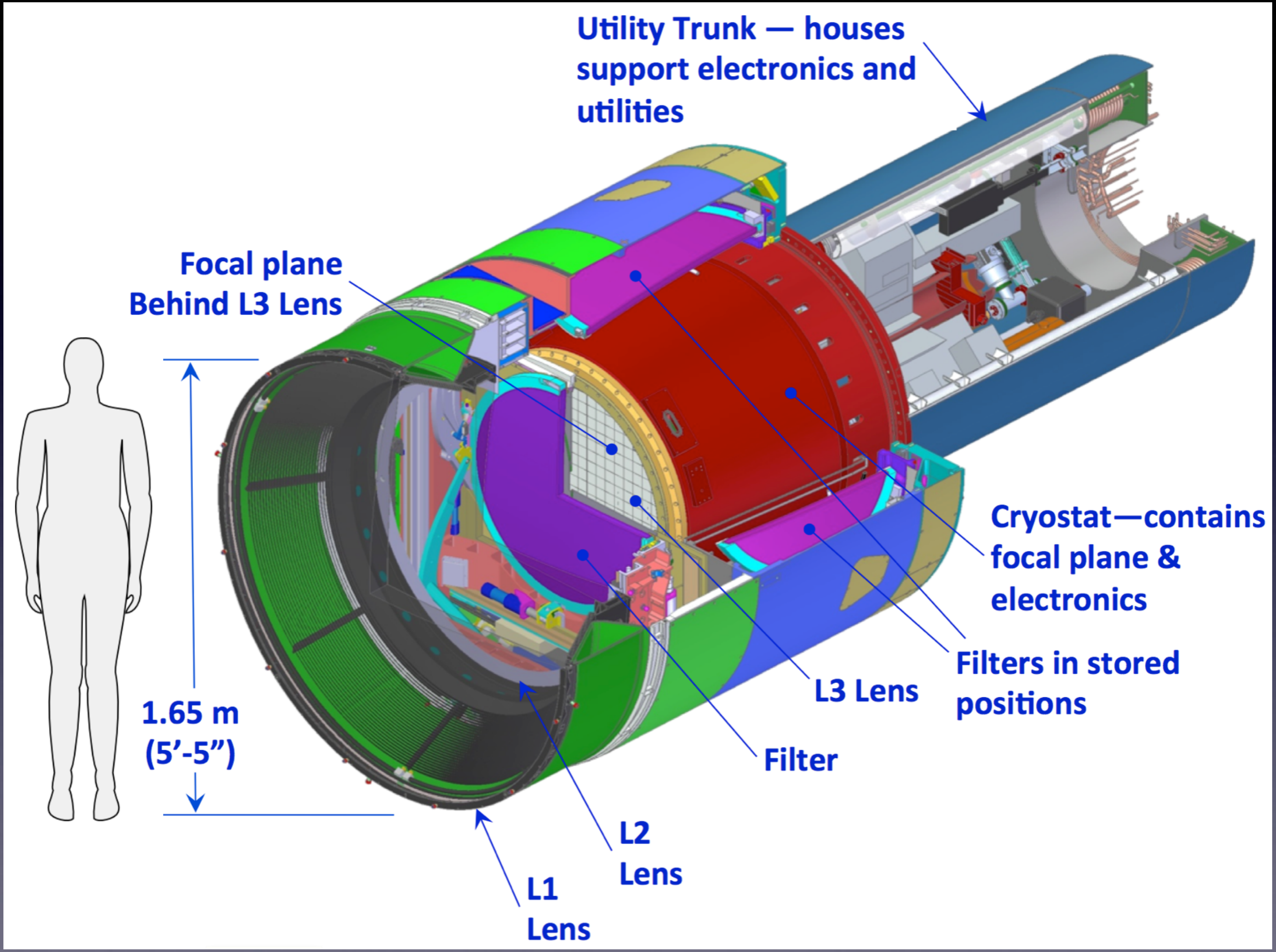
LSST Primary/Tertiary Mirror Blank
August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona

Large Synoptic Survey Telescope

Large Synoptic Survey Telescope

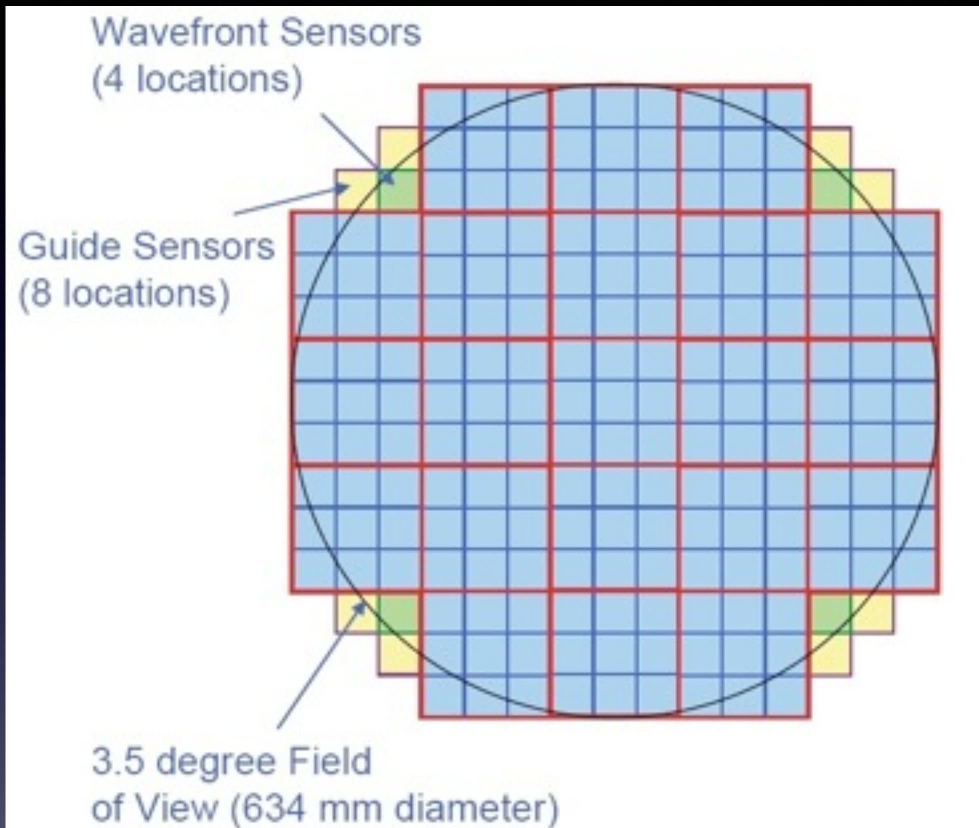


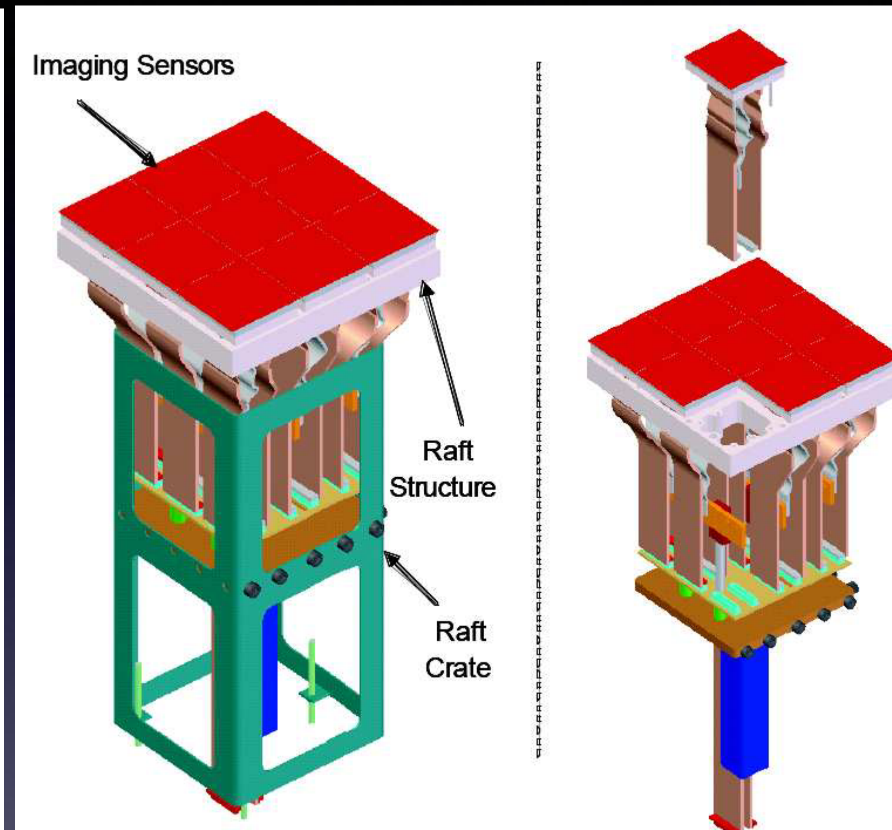
LSST camera



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

At the highest level, LSST objectives are:

1) Obtain about 5.5 million images, with 189 CCDs (4k x 4k) in the focal plane; this is about **a billion 16 Megapixel images of the sky**

2) Calibrate these images (and provide other metadata)

3) Produce catalogs ("model parameters") of detected objects (37 billion)

4) **Serve** images, catalogs and all other metadata, that is, **LSST data products to LSST users**

The ultimate deliverable of LSST is not just the telescope, nor the camera, but **the fully reduced science-ready data** as well.

Software: the subsystem with the highest risk

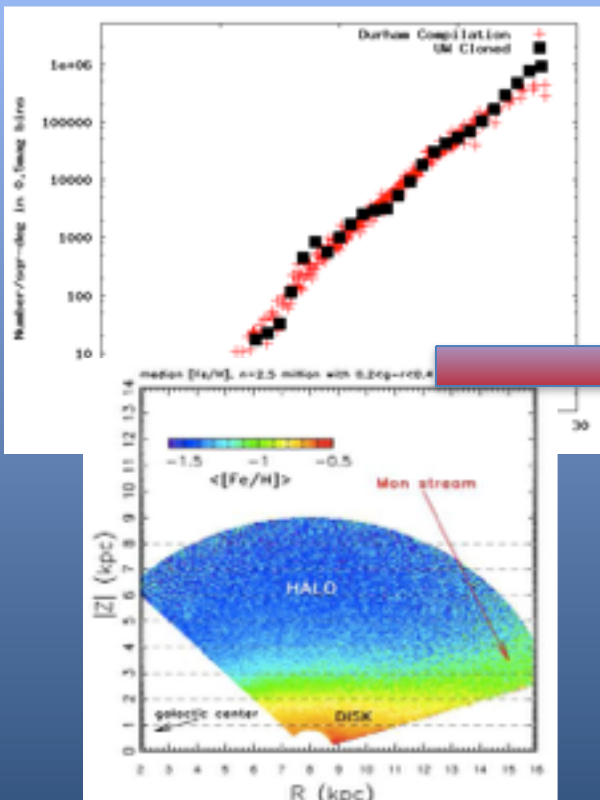
- 20 TB of data to process every day (~one SDSS/day)
- 1000 measurements for 40 billion objects during 10 years
- Existing tools and methods (e.g. SDSS) do not scale up to LSST data volume and rate (100 PB!)
- About 5-10 million lines of new code (C++/python)

LSST simulations: a virtual system

End-to-end modeling creates a virtual prototype of the LSST system:

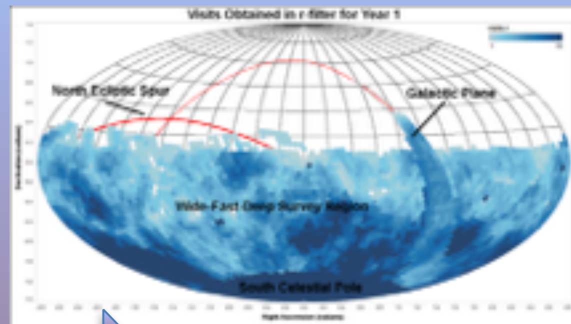
learning and preparing prior to first light!

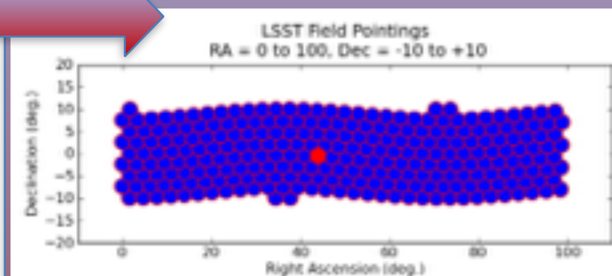
A simulated sky



Galaxies (de Lucia et al 2006)
Stars (Juric et al 2008)
Asteroids (Grav et al 2007)

Observing sequence simulation

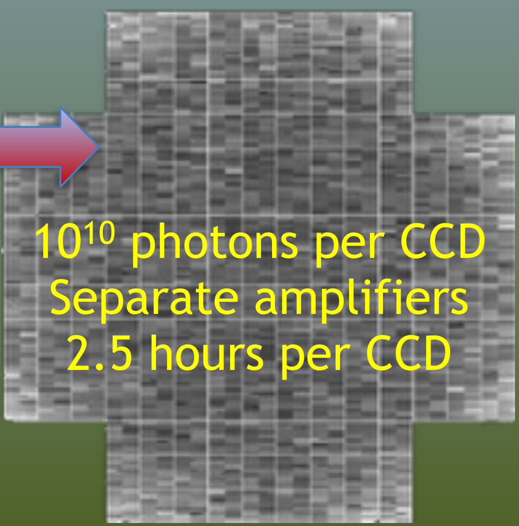




Pointing, Filter, Airmass, Time and Atmosphere from Op Sim

Custom instance of field of view

Producing a simulated image



10^{10} photons per CCD
Separate amplifiers
2.5 hours per CCD

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)

Modern Cosmological Probes

- Cosmic Microwave Background (the state of the Universe at the recombination epoch, at redshift ~1000)
- Weak Lensing: growth of structure
- Galaxy Clustering: growth of structure
- Baryon Acoustic Oscillations: standard ruler
- Supernovae: standard candle

Except for CMB, measuring H(z) and growth of structure G(z)
$H(z) \sim d[\ln(a)]/dt$, $G(z) = a^{-1}\delta\rho_m/\rho_m$, with $a(z) = (1+z)^{-1}$

LSST is designed to reach Stage IV level from DETF report
which kinda means **"It will be awesome and better than anything today!"**

Galaxies:

- **Photometric redshifts:** random errors smaller than 0.02, bias below 0.003, fewer than 10% >3σ outliers

- These photo-z requirements are one of the primary drivers for the photometric depth and accuracy of the main LSST survey (and the definition of filter complement)

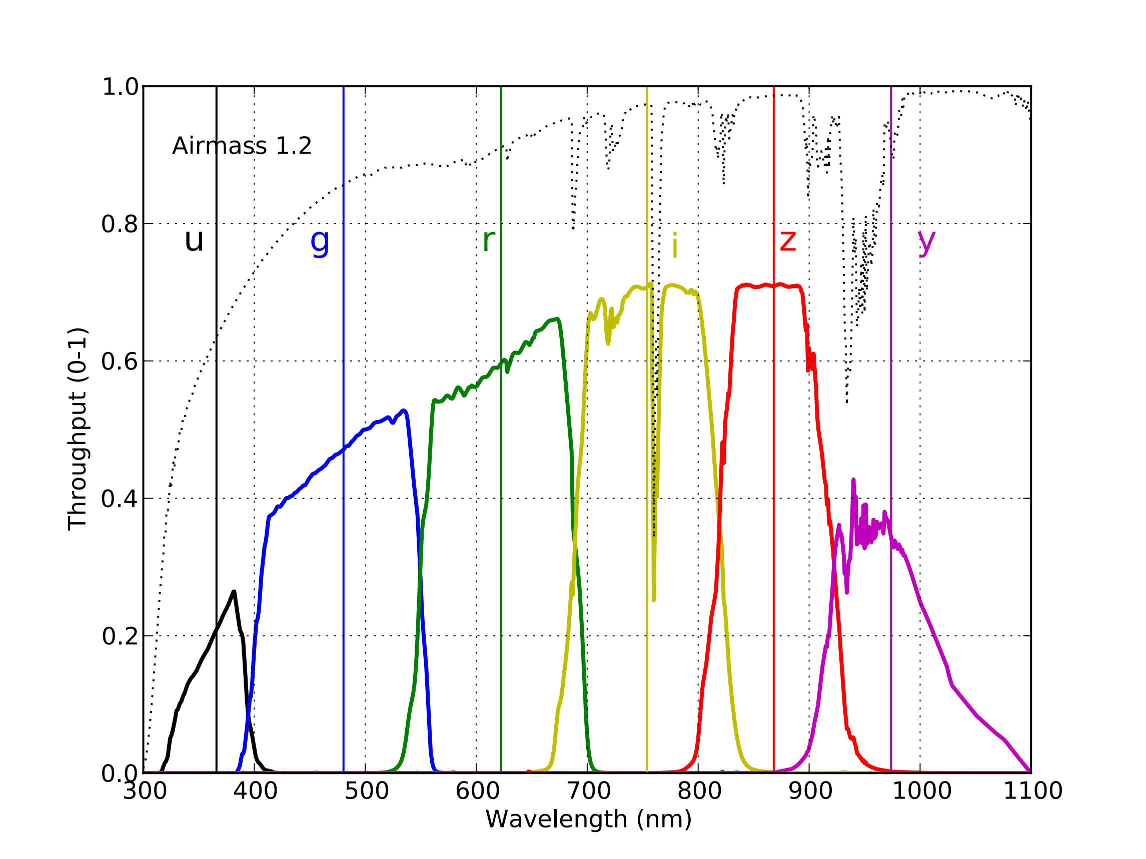


Photo-z requirements correspond to r~27.5

with the following per band time allocations:

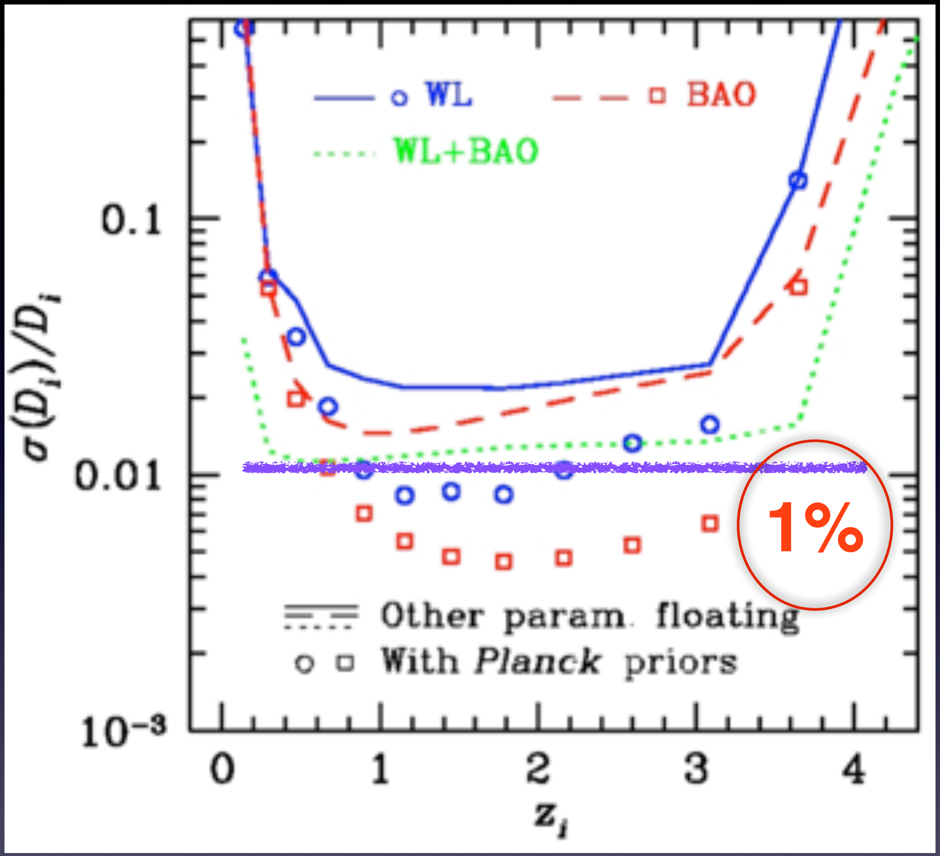
u: 8%; g: 10%

r: 22%; i: 22%

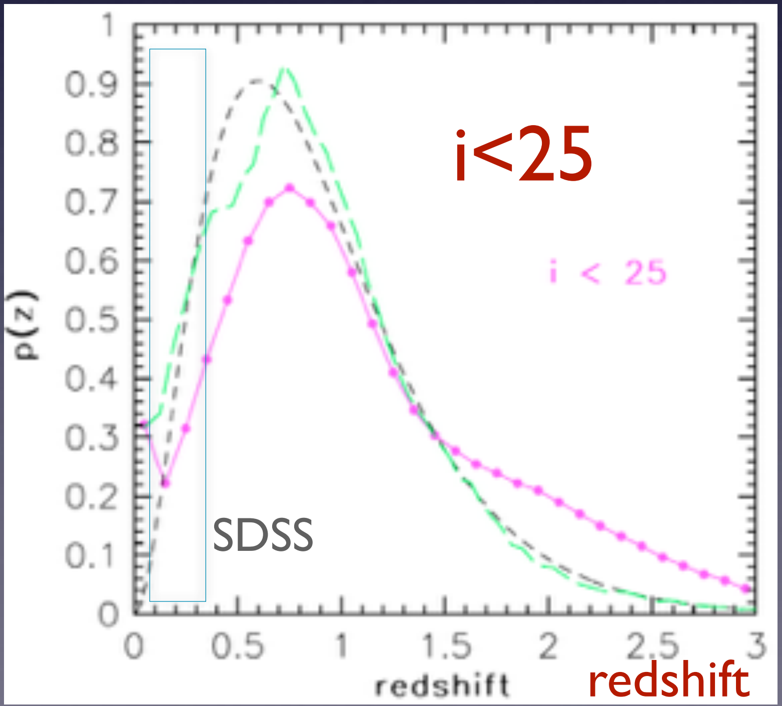
z: 19%; y: 19%

Consistent with other science themes (stars)

Extragalactic astronomy/cosmology: 20 billion galaxies

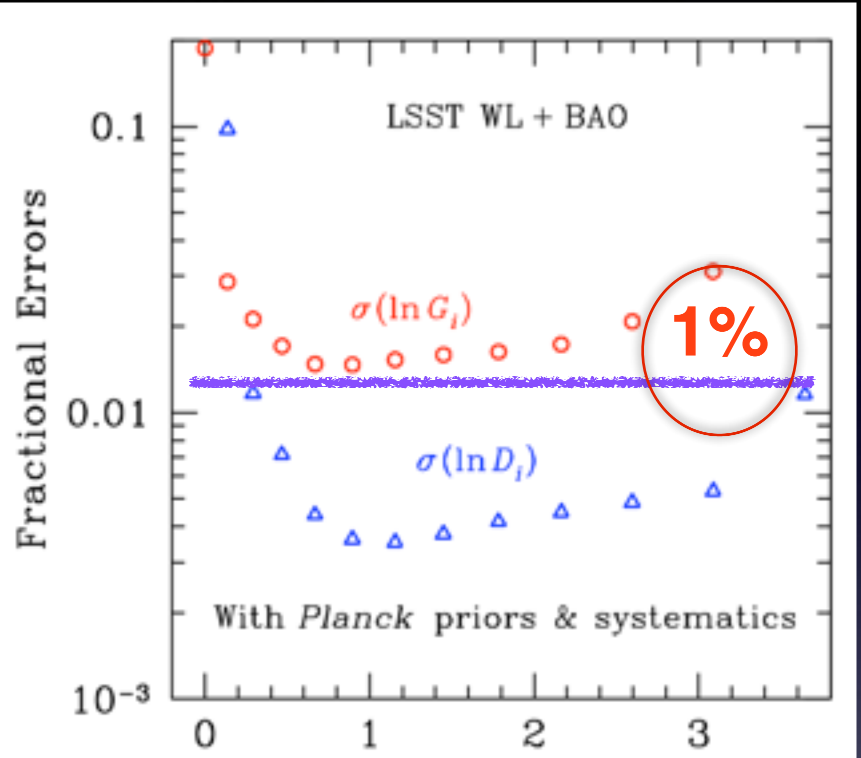


- Derived from 4 billion galaxies with accurate photo-z and shape measurements
- Measuring distances and growth of structure with a percent accuracy for $0.5 < z < 3$



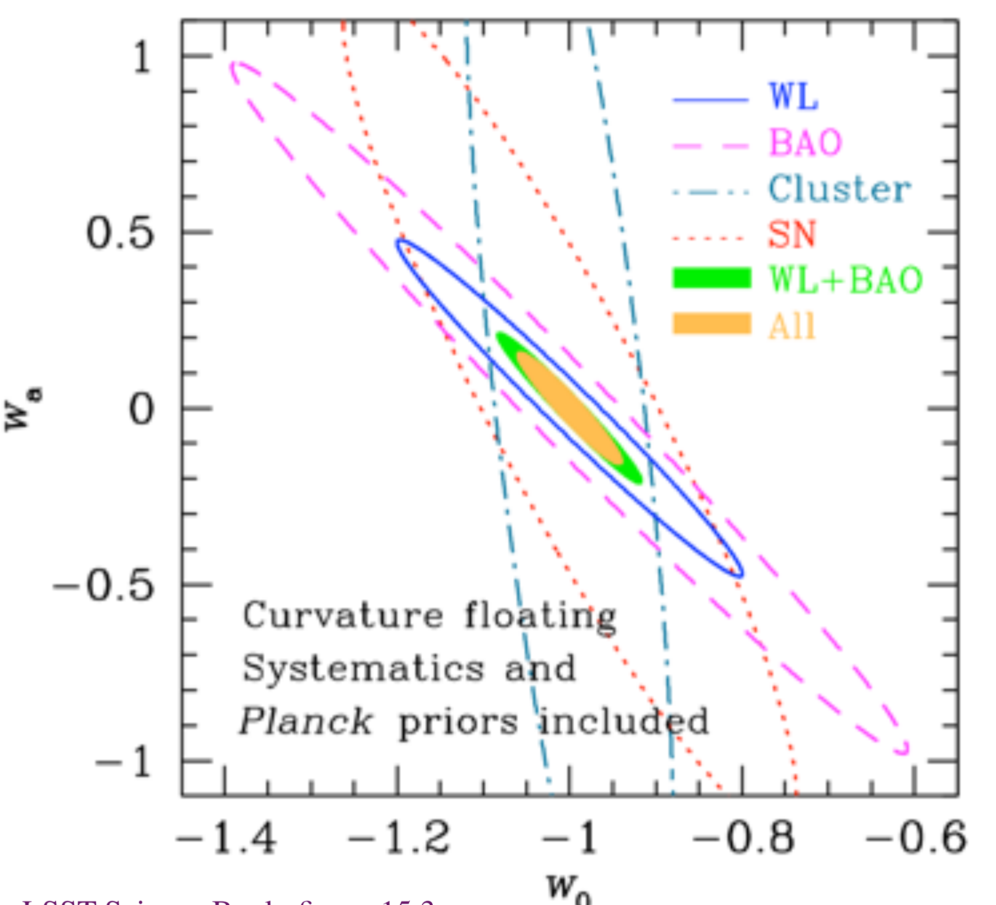
By simultaneously measuring growth of structure and curvature, LSST data will tell us whether the recent acceleration is due to **dark energy or modified gravity.**

Cosmology with LSST: high precision measurements



LSST Science Book, figure 15.2

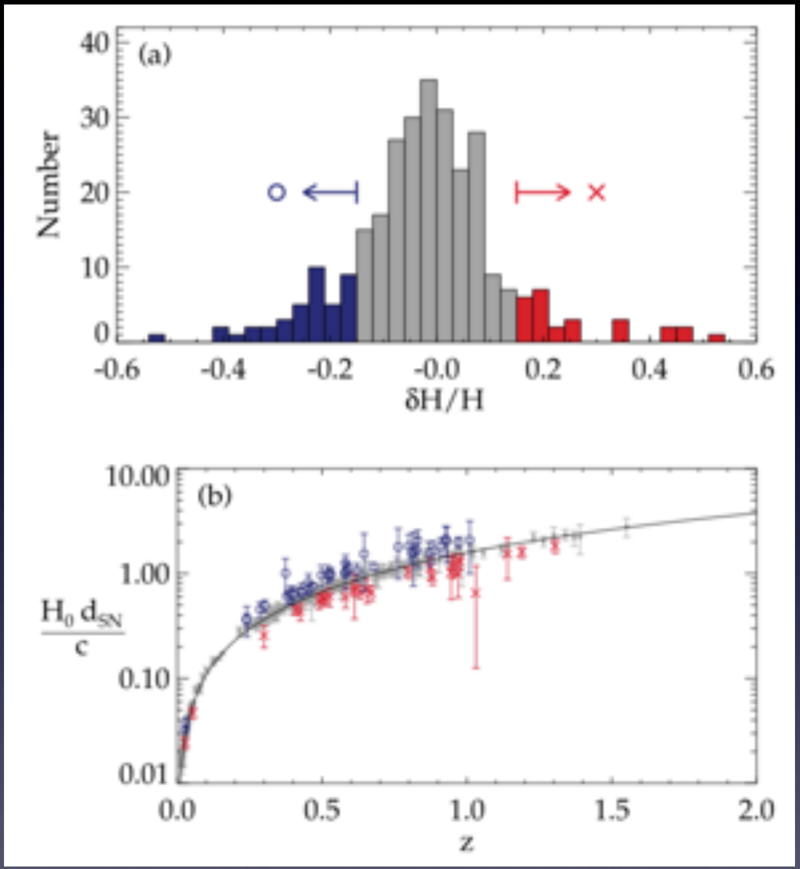
- Measuring distances, H(z), and growth of structure, G(z), with a percent accuracy for 0.5 < z < 3
- Multiple probes is the key!



LSST Science Book, figure 15.3

By simultaneously measuring growth of structure and curvature, LSST data will tell us whether the recent acceleration is due to **dark energy or modified gravity.**

Cosmology with LSST SNe: is the cosmic acceleration the same in all directions?



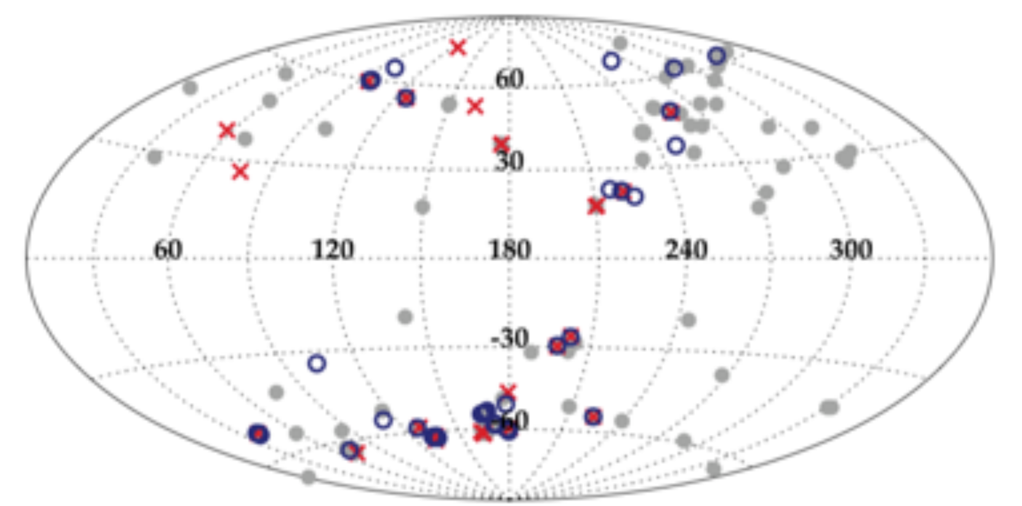


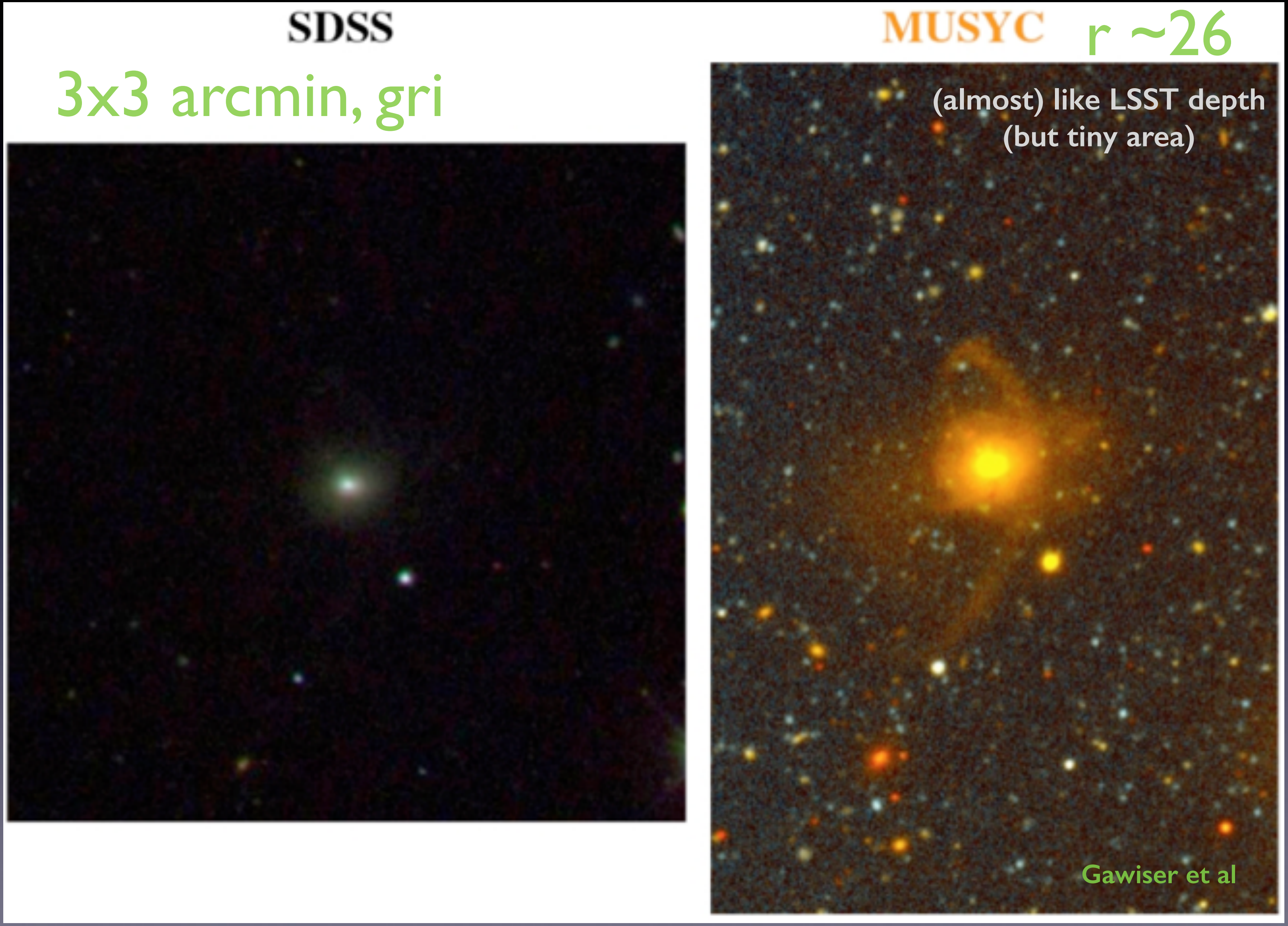
Figure 1. A projection of the spatial distribution of the Union SNe Ia sample in Galactic coordinates. Note the relative uniformity of the points, except around the Galactic plane. The symbols correspond to those in Fig. 2, and are explained in Section 3.1.

Cooke & Lynden-Bell (2009, MNRAS 401, 1409)

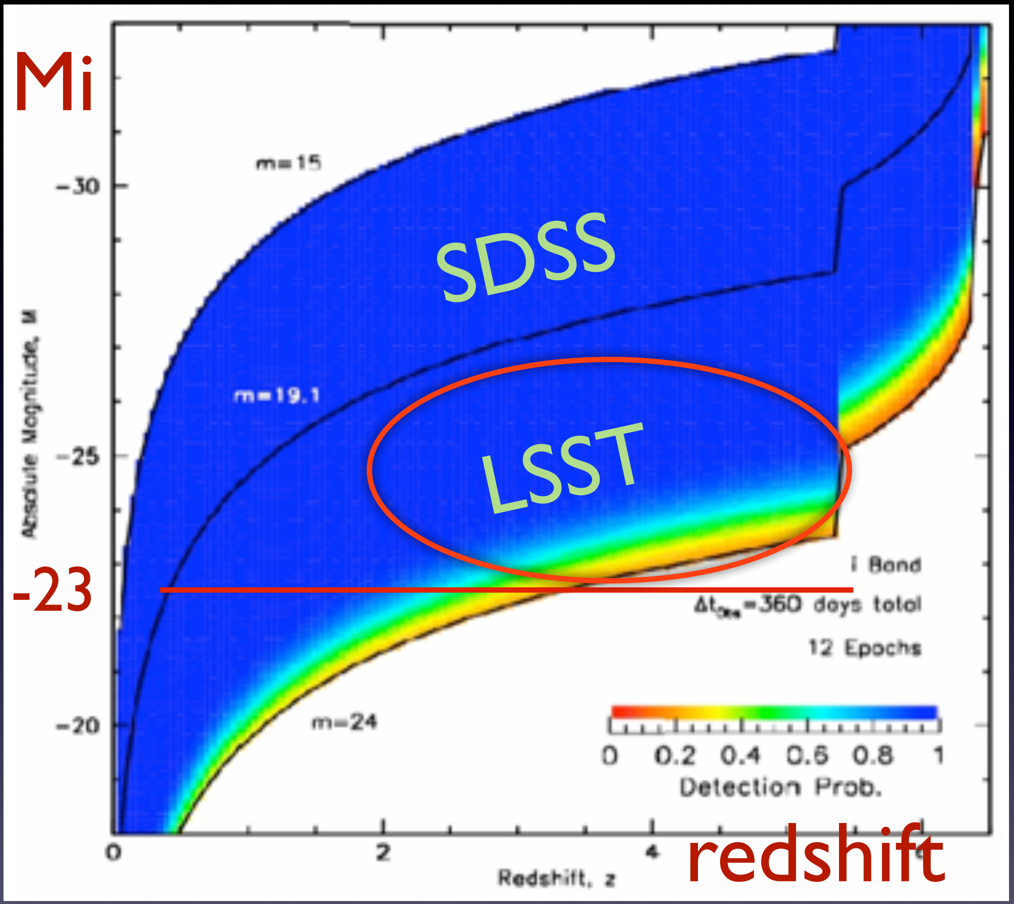
Is there spatial structure in the SNe distance modulus residuals for the concordance model?

- Even a single supernova represents a cosmological measurement!
- LSST will obtain light curves for several million Type Ia supernovae!

Extragalactic astronomy: faint surface brightness limit



Extragalactic astronomy: quasars



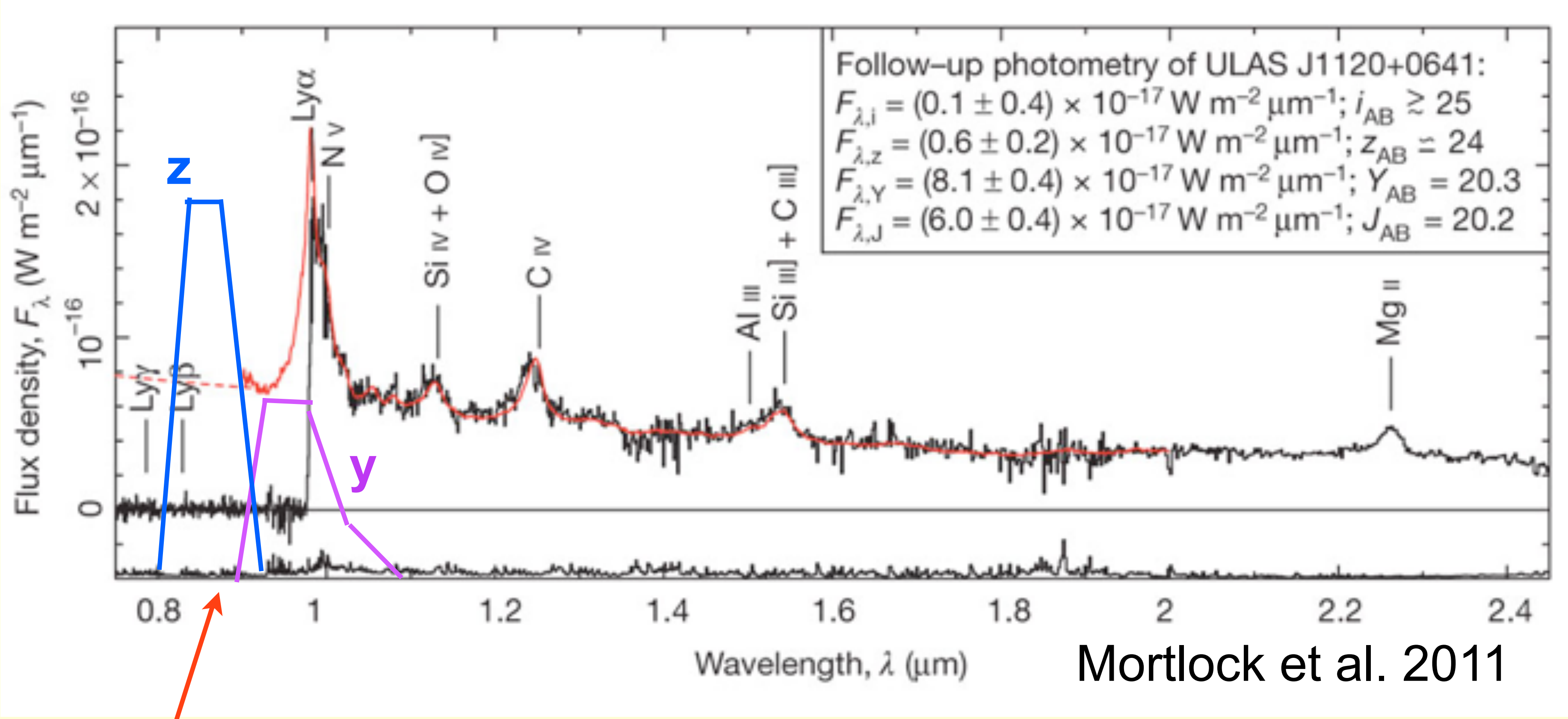
Top: absolute magnitude vs. redshift diagram for quasars

- About 10 million quasars will be discovered using variability, colors, and the lack of proper motions
  Really?? SDSS: yes!
- The sample will include Mi=-23 objects even at redshifts beyond 3
- Quasar variability studies will be based on millions of light curves with 1000 observations over 10 yrs

Today: ~31 quasars with 6<z<7.5 **Reionization studies**

LSST will detect ~10,000 quasars with 6<z<7.5!

The Highest Redshift Quasar at z=7.085 from UKIDSS



Such a quasar would be detected by LSST as a z-band dropout
(multi-epoch data will greatly help with false positives)

LSST will discover about 1,000 quasars with z>7
Today: one quasar with z>7

Time Domain: objects changing in time

positions: asteroids and stellar proper motions

brightness: cosmic explosions and variable stars

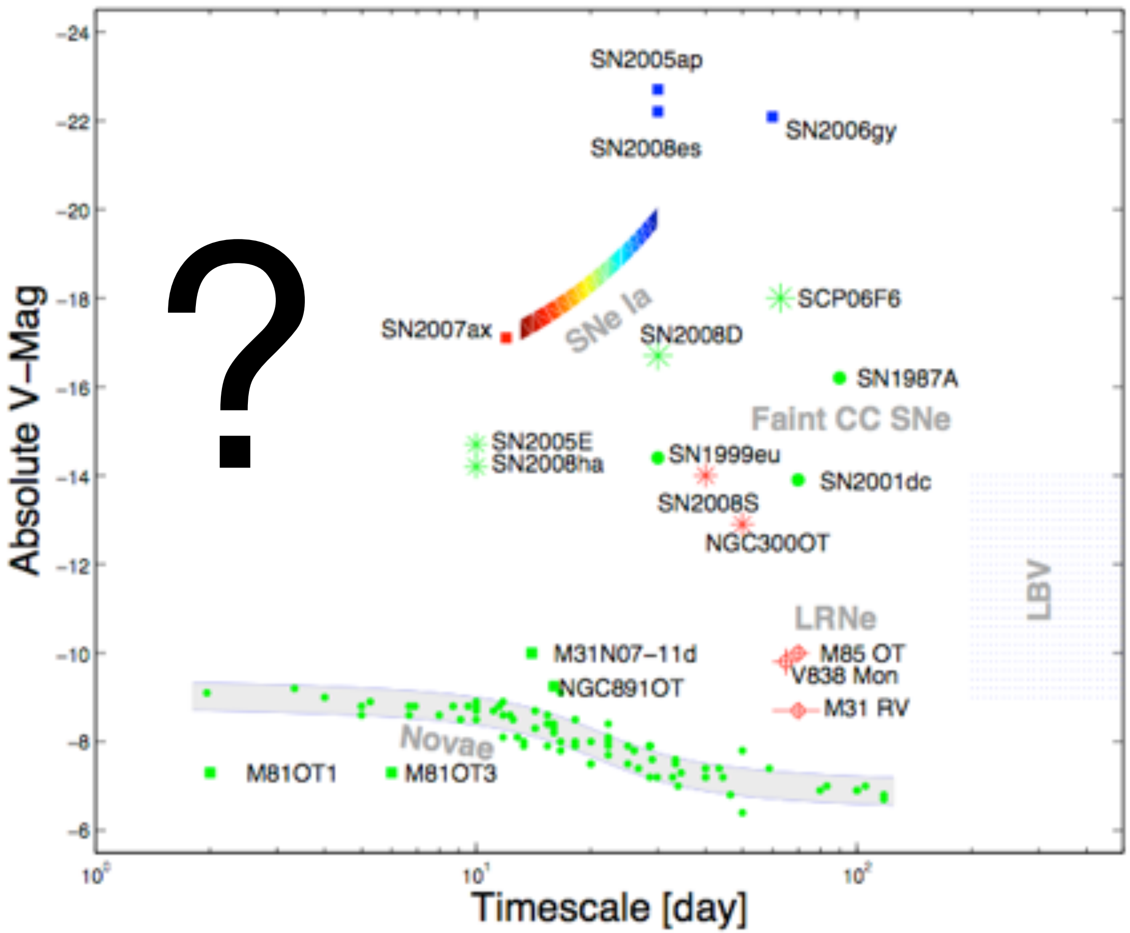


FIG. 29.— The phase space of cosmic explosive and eruptive transients as represented by their absolute V band peak brightness and the event timescale (adapted from Kulkarni et al. 2007).

LSST will extend time-volume space a thousand times over current surveys (new classes of object?)

known unknowns
unknown unknowns

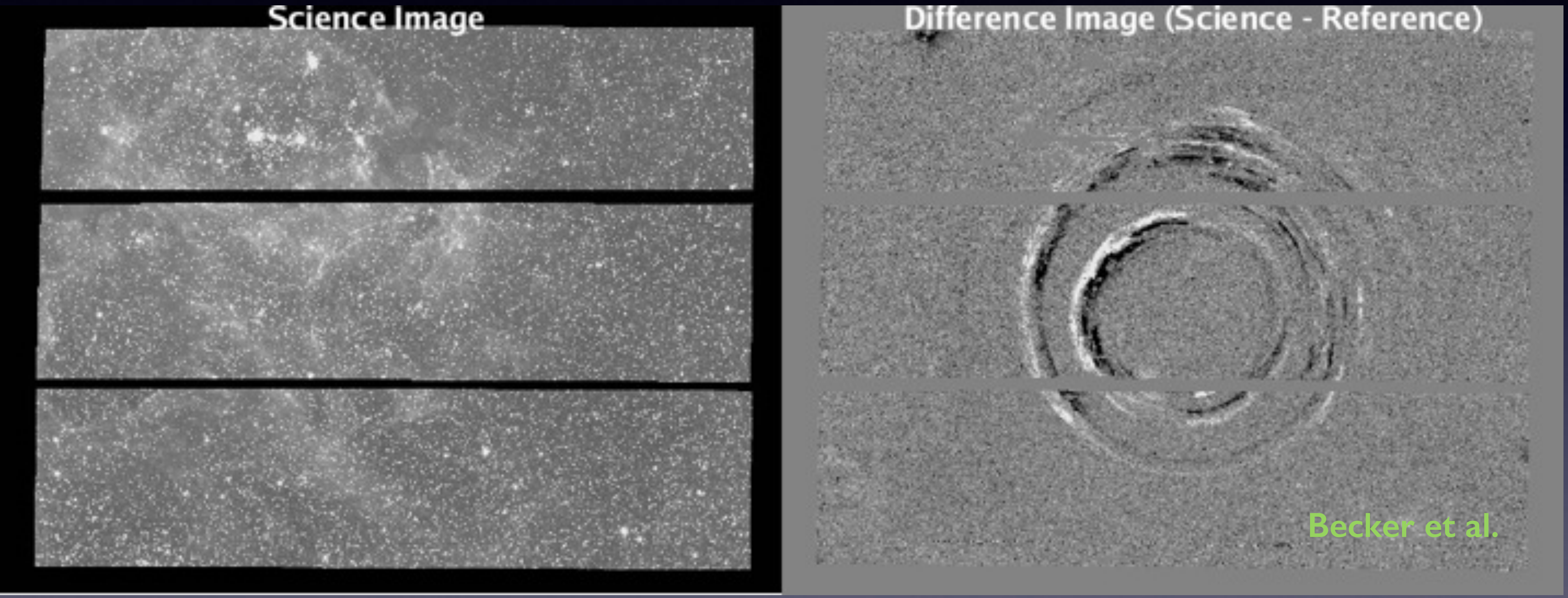
agnoiology, n.
[‘ The study of the nature of ignorance or of what is impossible to know’]

Time Domain: objects changing in time

positions: asteroids and stellar proper motions

brightness: cosmic explosions and variable stars

Not only point sources - echo of a supernova explosion:



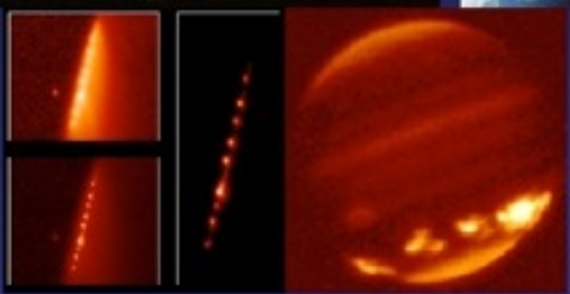
As many variable stars from LSST, as all stars from SDSS

Web stream with data for transients within 60 seconds.

Real time alerts!

Killer asteroids: the impact probability is not 0!

photomontage!



Shoemaker-Levy 9
(1994)

Tunguska
(1908)

LSST is the only survey capable of delivering completeness specified in the 2005 USA Congressional NEO mandate to NASA (to find 90% NEOs larger than 140m)

The Barringer Crater, Arizona: a 40m object 50,000 yr. ago

Killer asteroids: the impact probability is not 0!

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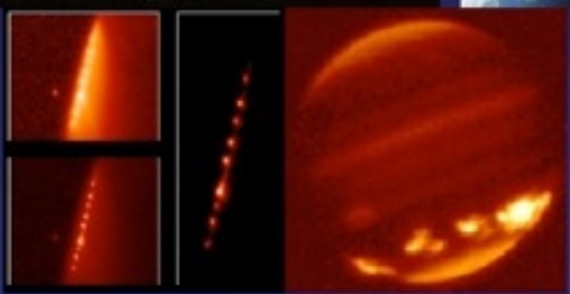


Shoemaker-Levy 9 (1994)

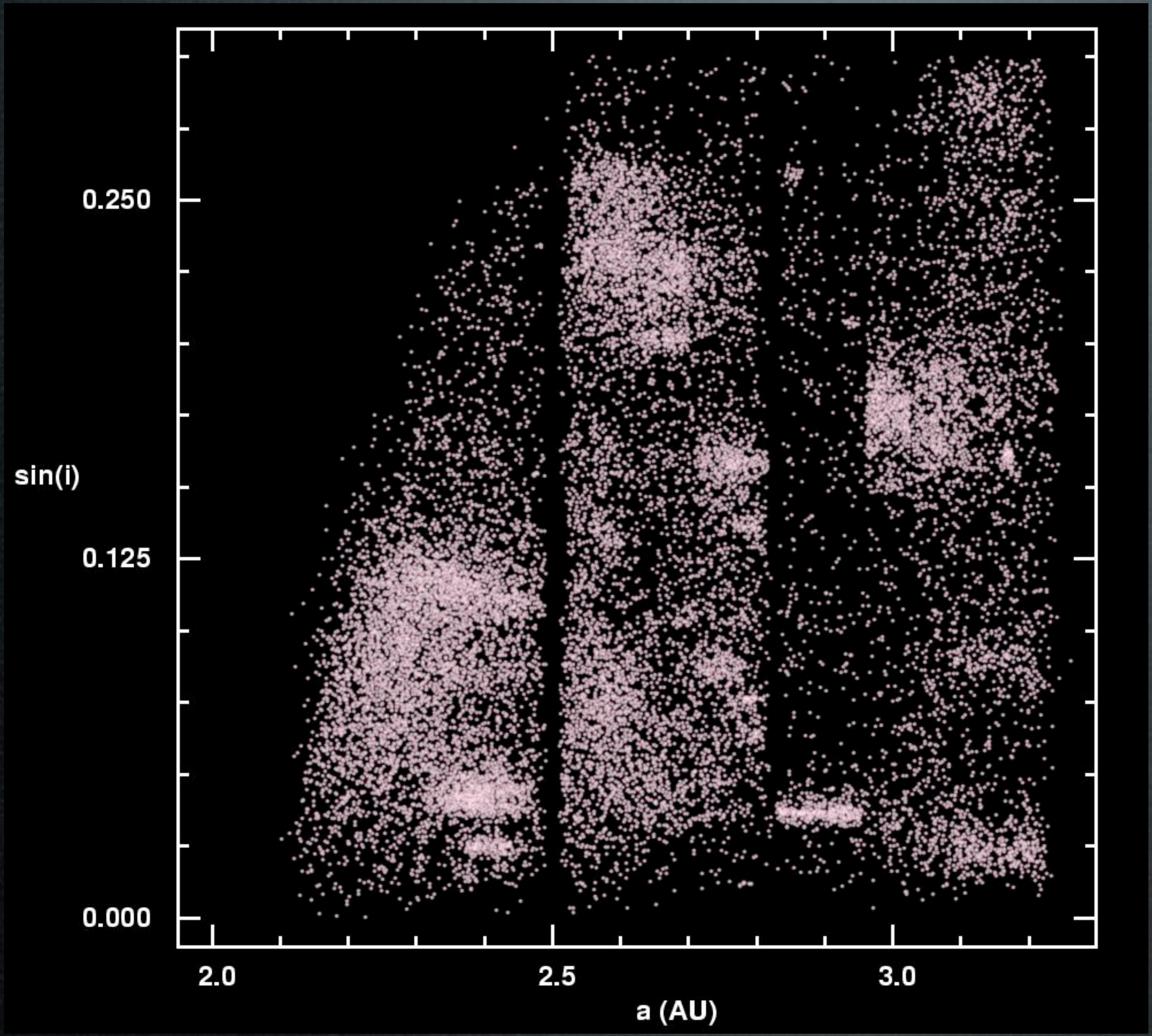
Tunguska (1908)

The Barringer Crater, Arizona: a 40m object 50,000 yr. ago

Inventorying the Solar System

- **Large statistical samples of asteroids and comets**
- Serendipitous discoveries of rare events or objects
  - Asteroid collisions (P/2010 A2)
  - Retrograde TNO (2008 KV42)
- Discover new, incoming comets even before they become active
- Model shapes of asteroids from measurements of their brightness
- Discover links between different populations
  - How are NEOs and Main Belt asteroids related?
  - Are irregular satellites actually captured TNOs?
- Expand our knowledge of all small bodies to provide a better understanding of the formation and evolution of our Solar System

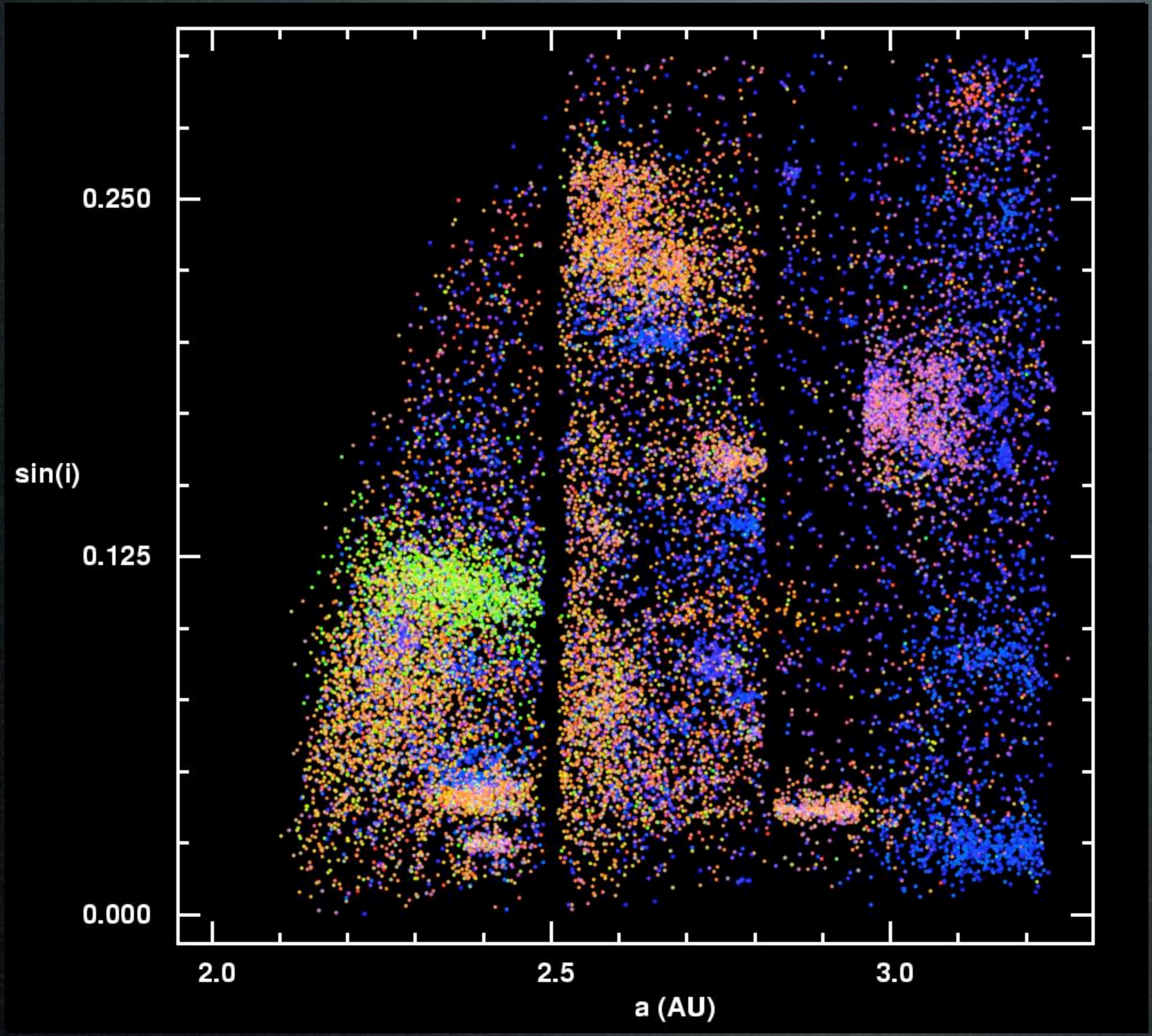
Main-belt Inventory



30,000 Asteroids with SDSS colors and proper orbital elements

(Ivezic, Juric, Lupton 2002)

Main-belt Inventory



30,000
Asteroids with
SDSS colors and
proper
orbital elements

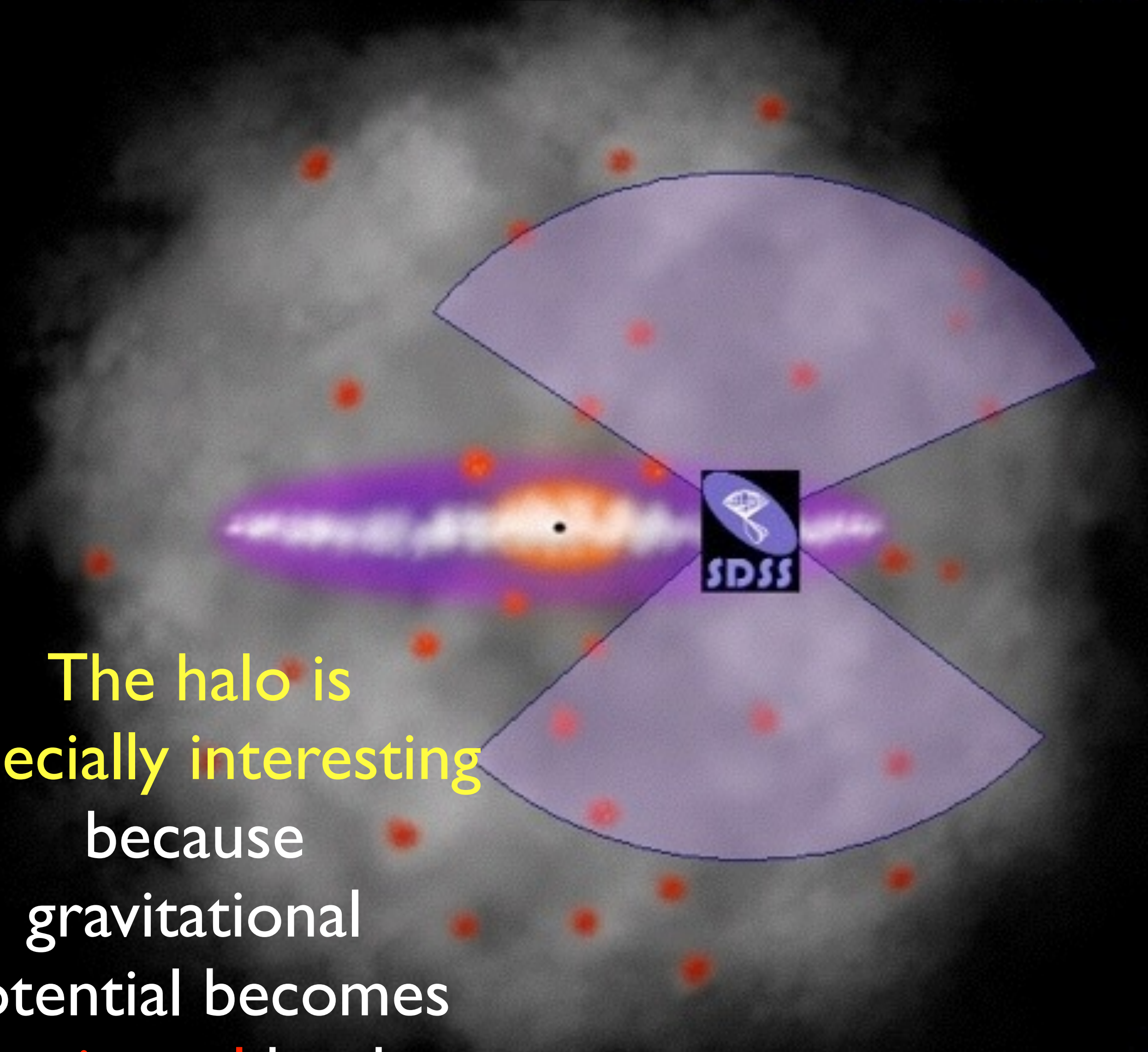
(Ivezic, Juric, Lupton 2002)

Color-coded with
SDSS colors

Colors help with the definition of asteroid families.

LSST will also provide color light curves!

Classical Decomposition of the Milky Way Components

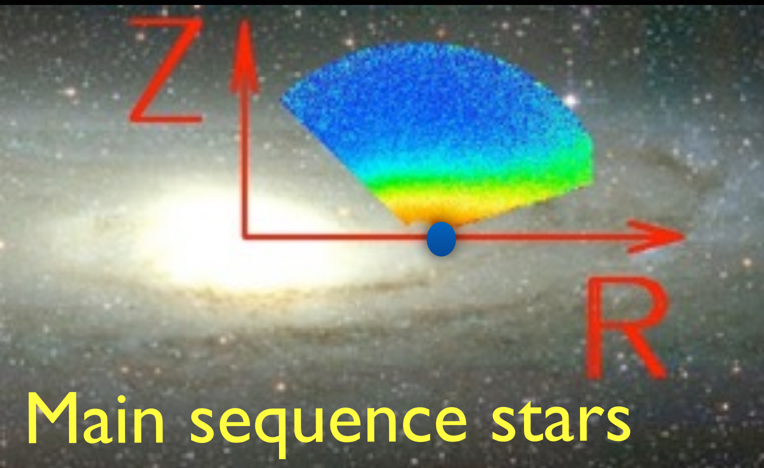


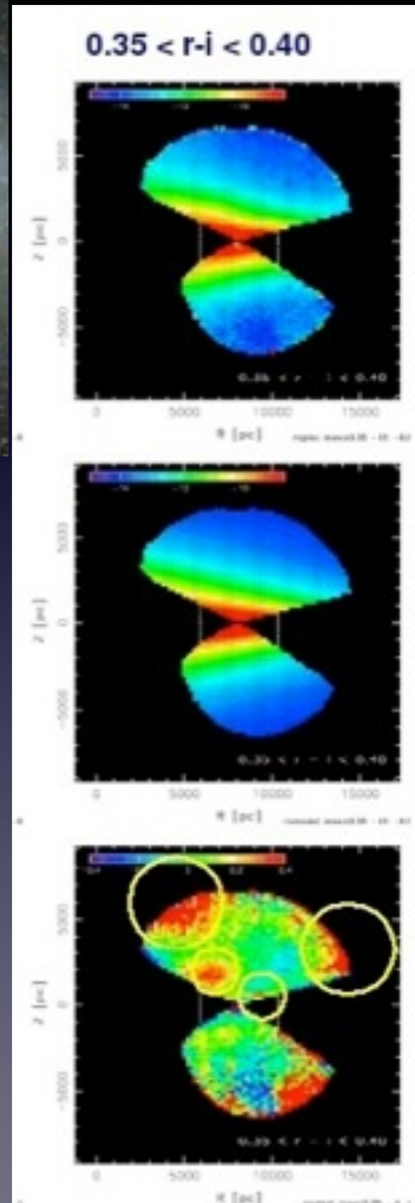
- Thin/thick disk
- Galactic bulge
- Stellar halo

The halo is especially interesting because gravitational potential becomes dominated by the dark matter halo

- Components trace the DM dominated potential
- They are a product of Milky Way formation and evolution

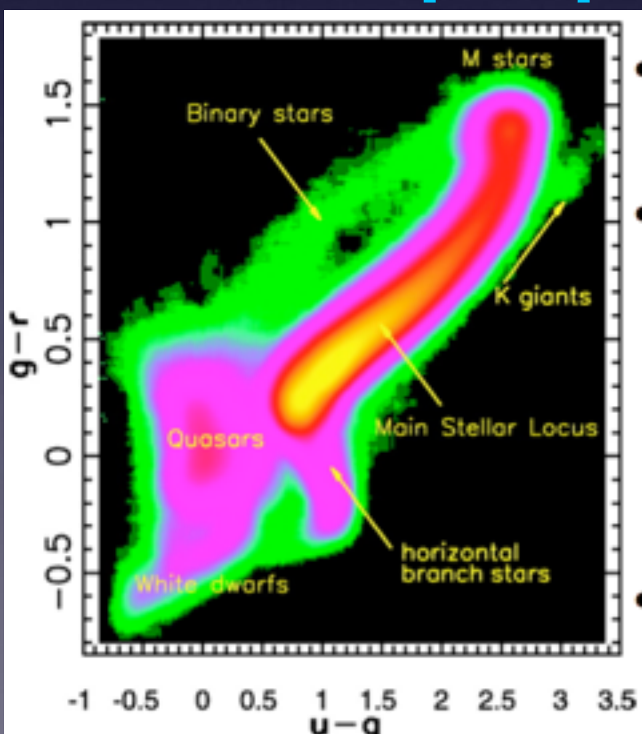
The Milky Way structure: 20 billion stars, time domain massive statistical studies!

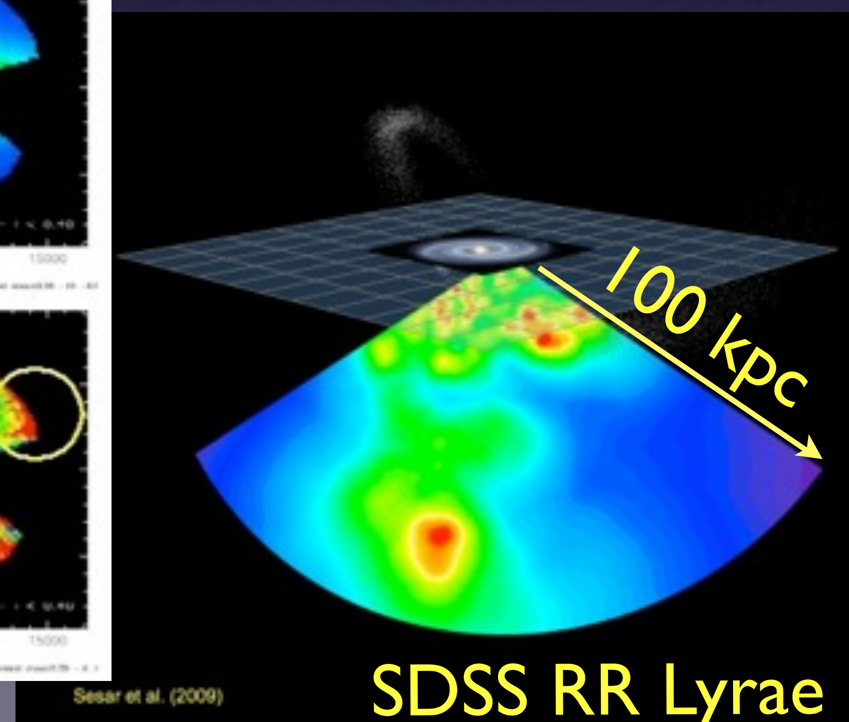


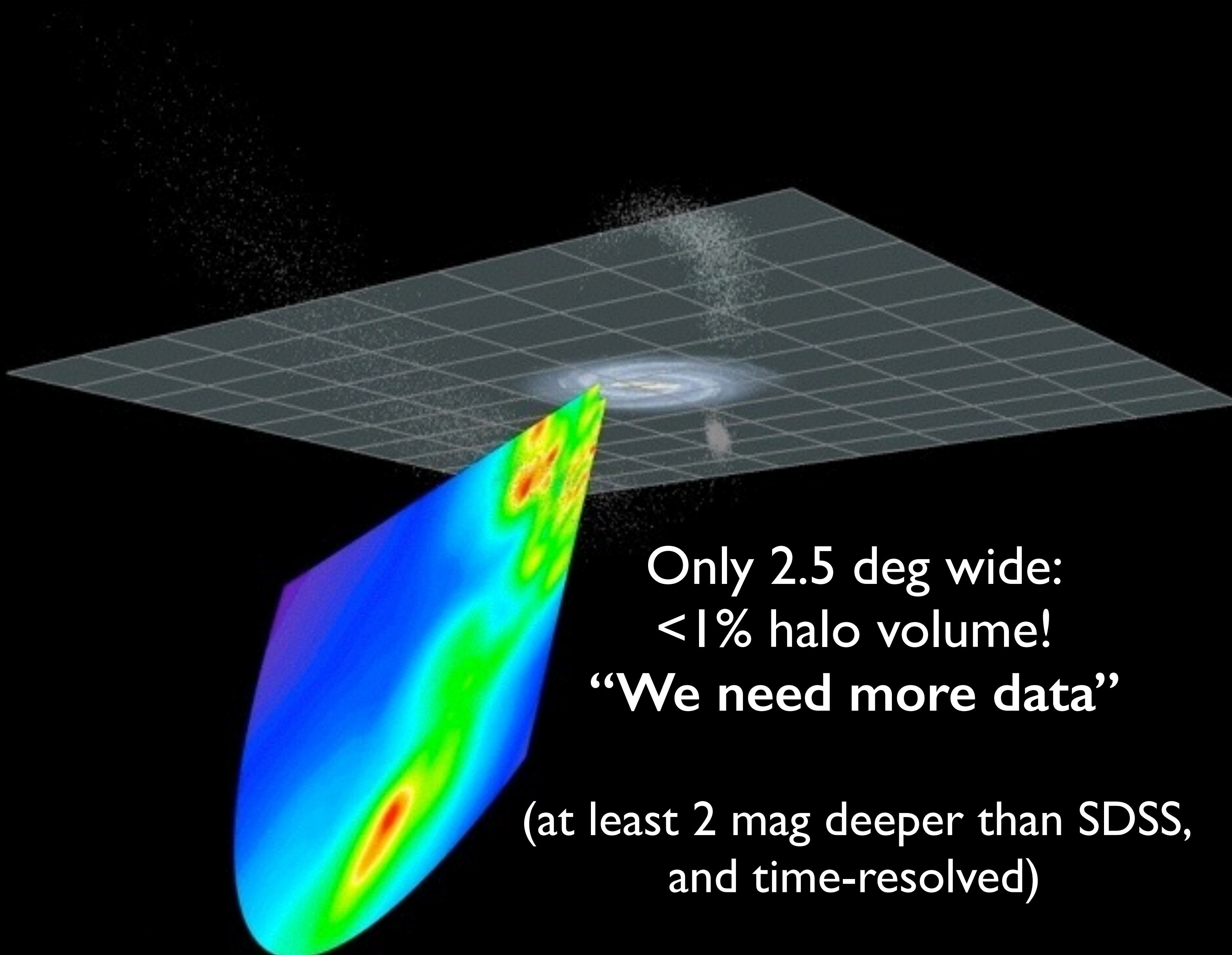


Compared to SDSS: LSST can "see" about 40 times more stars, 10 times further away and over twice as large sky area

Distance and [Fe/H]:



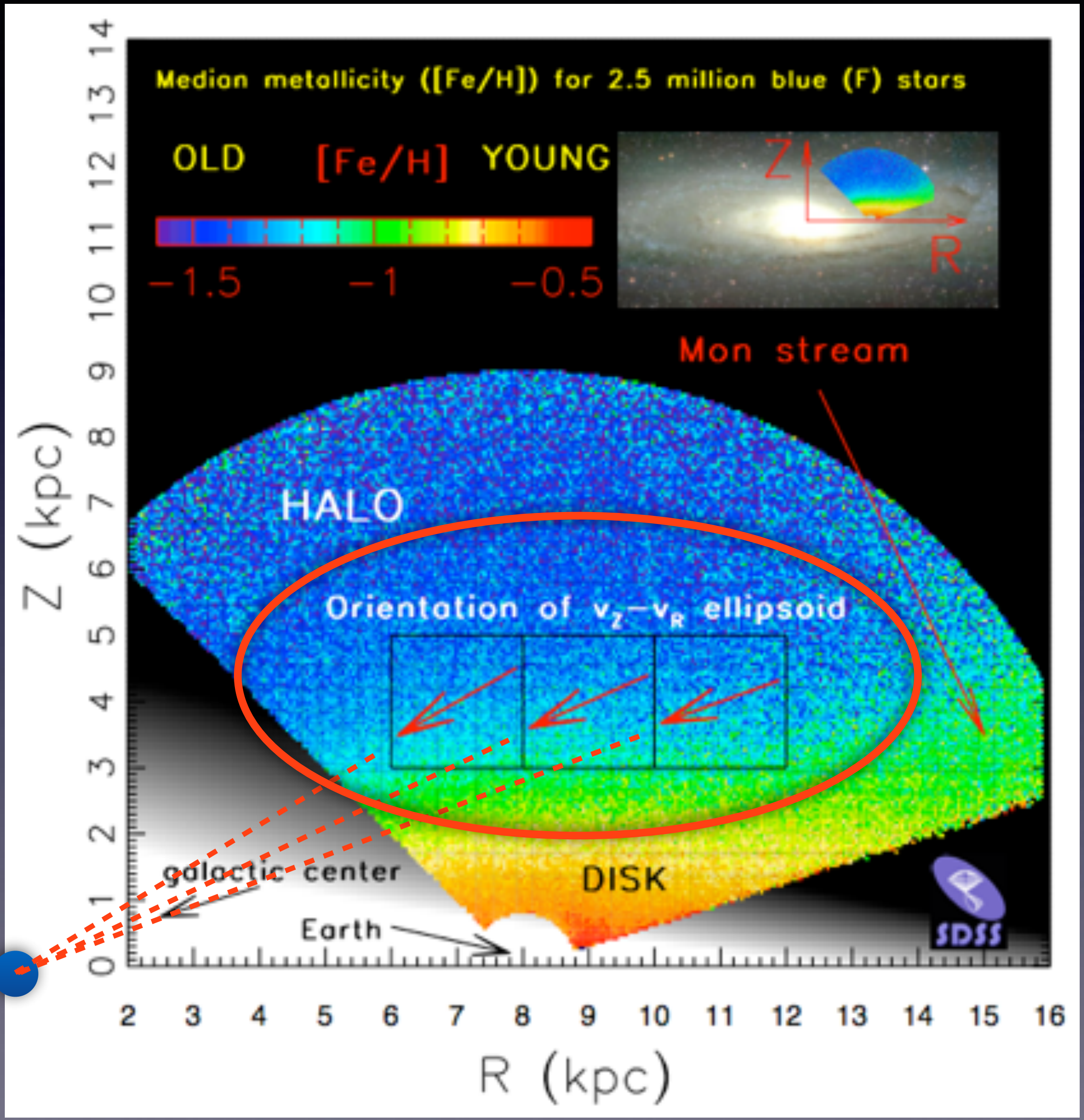




Only 2.5 deg wide:
<1% halo volume!
"We need more data"

(at least 2 mag deeper than SDSS,
and time-resolved)

Velocity distribution for (nearby) halo stars



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

velocity ellipsoid is nearly invariant in spherical coordinate system

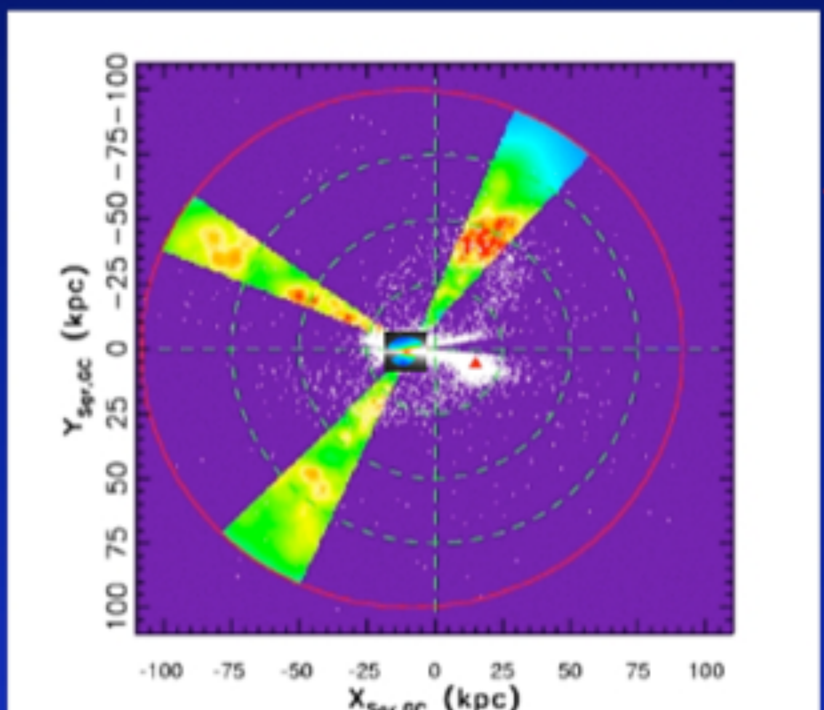
Bond et al. (2010, ApJ, 716, 1)

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

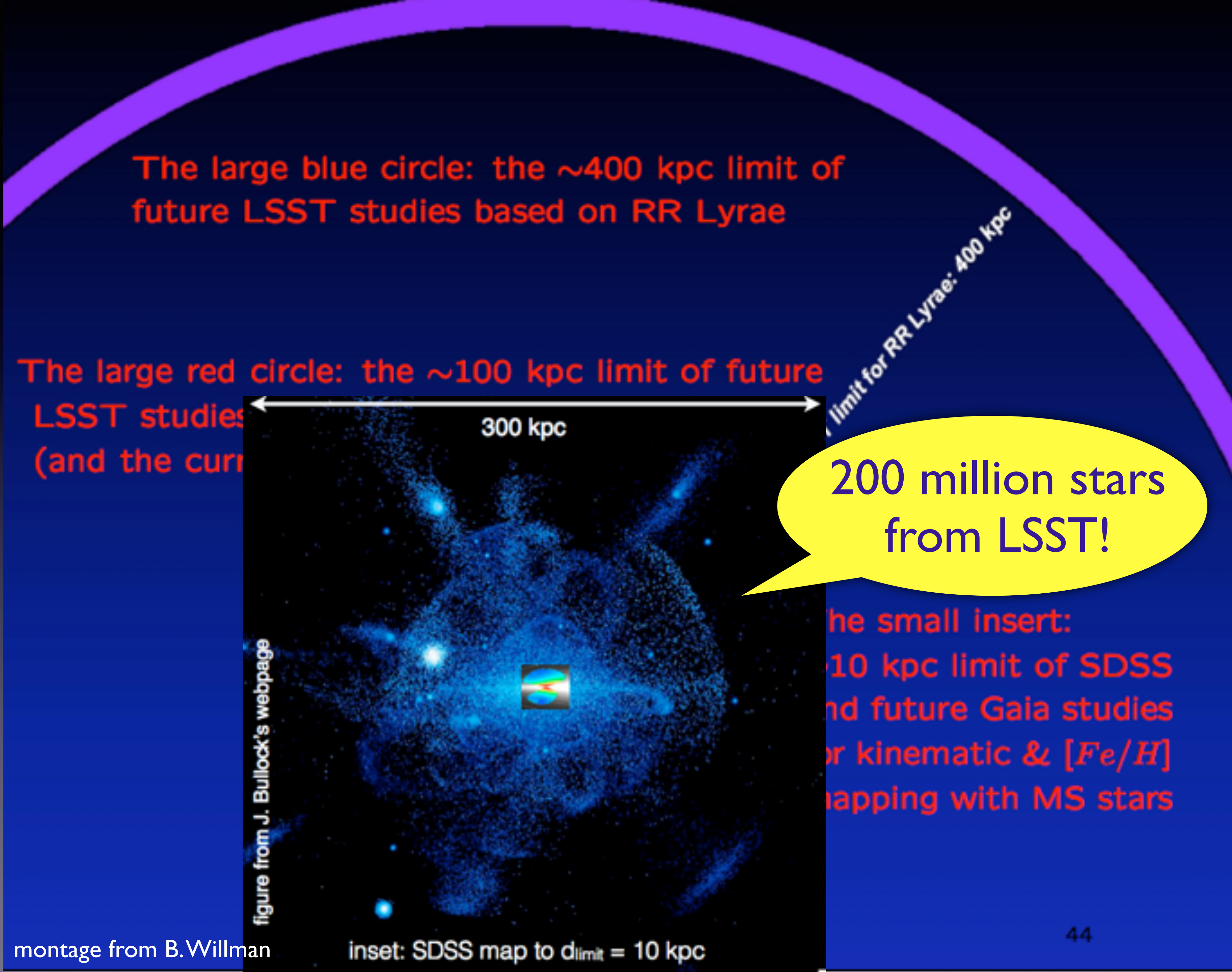
LSST limit for RR Lyrae: 400 kpc

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)

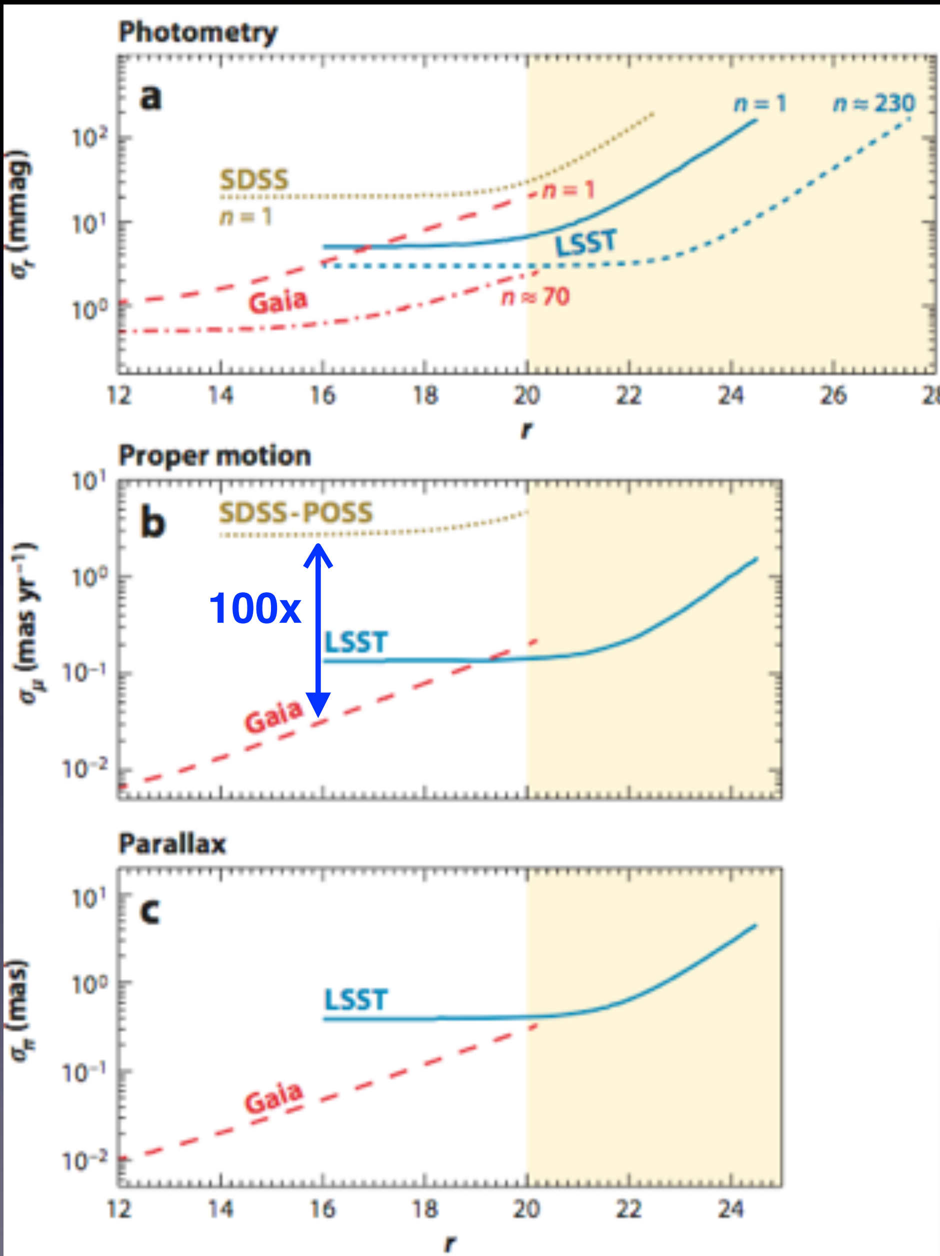
6D information from LSST: 3D spatial, 2 velocities, [Fe/H]



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 cur
300 kpc
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
figure from J. Bullock's webpage
inset: SDSS map to d_{limit} = 10 kpc
montage from B. Willman
44

Gaia vs. LSST comparison

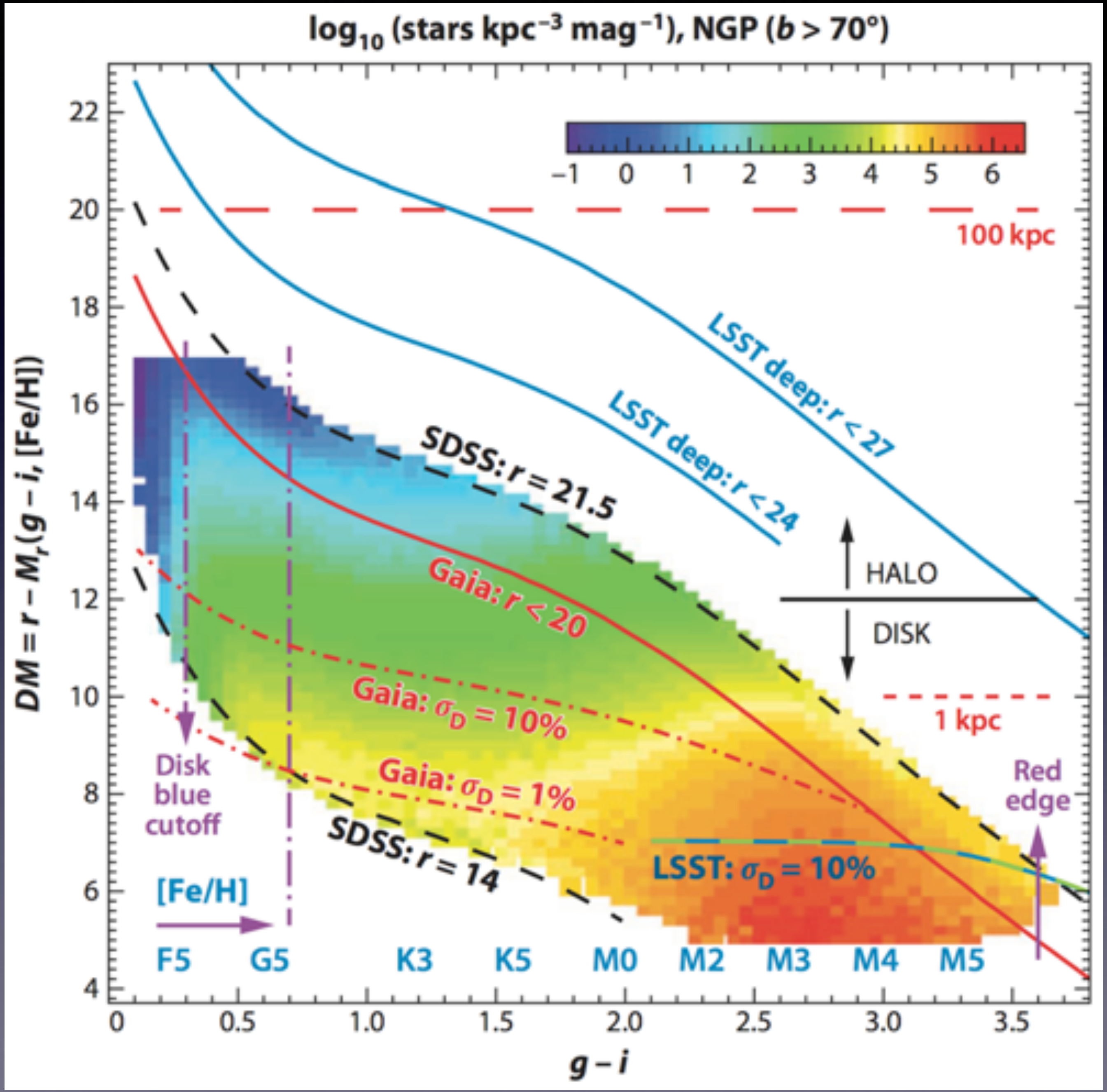


Ivezić, Beers, Jurić 2012, ARA&A, 50, 251

- **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).

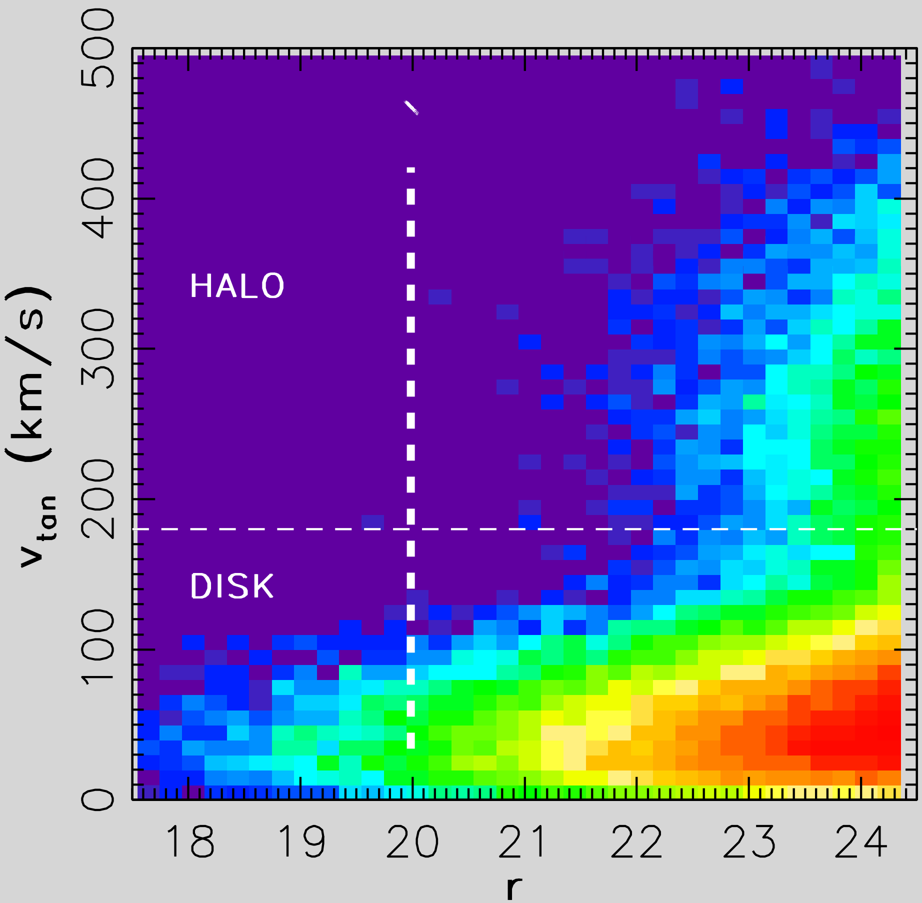
Comparison of SDSS, Gaia and LSST for main sequence stars:



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

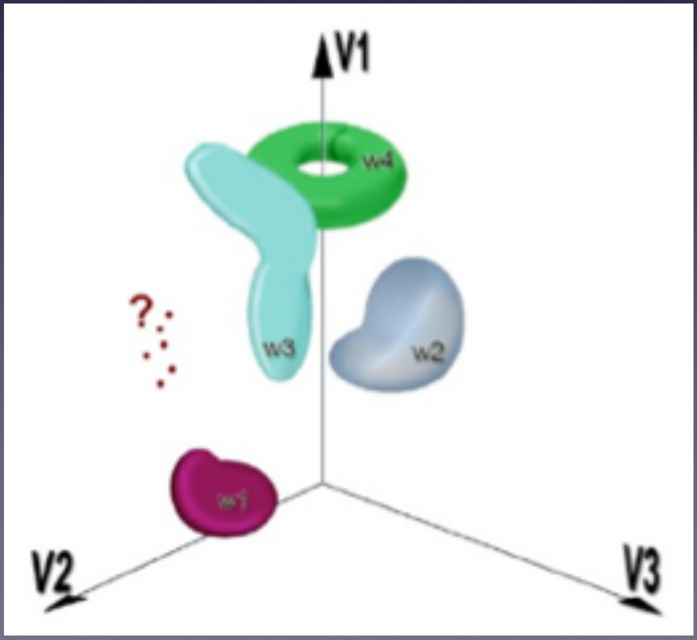
Compared to UKIDSS, 5 times larger sample of T dwarfs, with parallaxes and 10-20 times more accurate proper motions

(~100 Y dwarfs [model based])

Statistical analysis of a massive LSST dataset

- A large (100 PB) database and sophisticated analysis tools: for each of 40 billion objects there will be about 1000 measurements (each with a few dozen measured parameters)

Data mining and knowledge discovery



- 10,000-D space with 40 billion points
- Characterization of known objects
- Classification of new populations
- Discoveries of unusual objects

Clustering, classification, outliers

astroML

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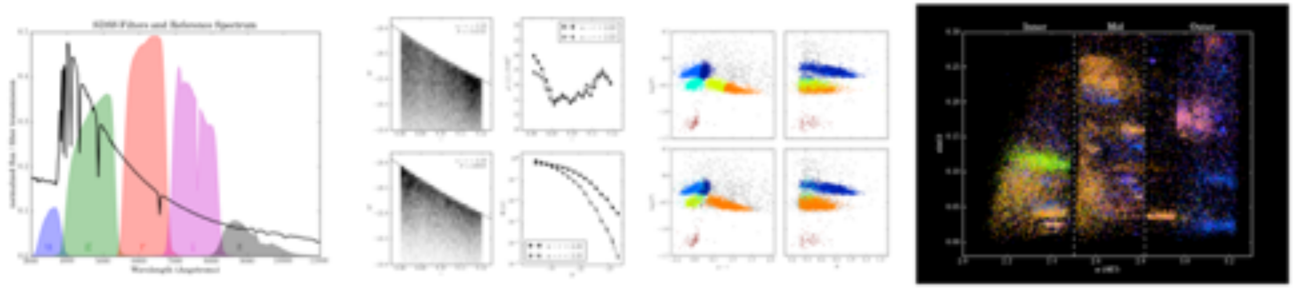
AstroML: Machine Learning and Data Mining for Astronomy

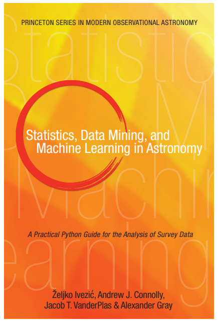


AstroML is a Python module for machine learning and data mining built on numpy, scipy, scikit-learn, and matplotlib, and distributed under the 3-clause BSD license. It contains a growing library of statistical and machine learning routines for analyzing astronomical data in python, loaders for several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

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!" And Gaia...