LSST Chemo-Dynamical Survey of the Milky Way and Synergy with Gaia

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Outline

1. **LSST Overview**
   - Science Drivers
   - System Design

2. **What LSST will do that other Galactic surveys will not?**
   - Comparison to Gaia
   - Detailed halo maps out to 100 kpc
   - LTY Dwarfs
   - White Dwarfs
   - 3D Dust Maps (both A_V and R_V)

The Era of Massive Optical Surveys

- Many surveys: Super-Macho, SDSS, QUEST, CFHT, DES, Pan-STARRS, LSST, and many others, in no particular order: fast progress!
- Currently, the best large-area optical survey is SDSS: **the first digital color map of the sky**
- Among proposed optical surveys for the next decade or so, the two "best" ones are Pan-STARRS (PS4) and LSST (but excellent photometric data will also come from the SkyMapper and the Dark Energy Survey)
- PS4: about 10 times more surveying power than SDSS
- LSST: about 10 times more surveying power than PS4
- PS4: first light in 2013 (?), LSST in 2017 (?)

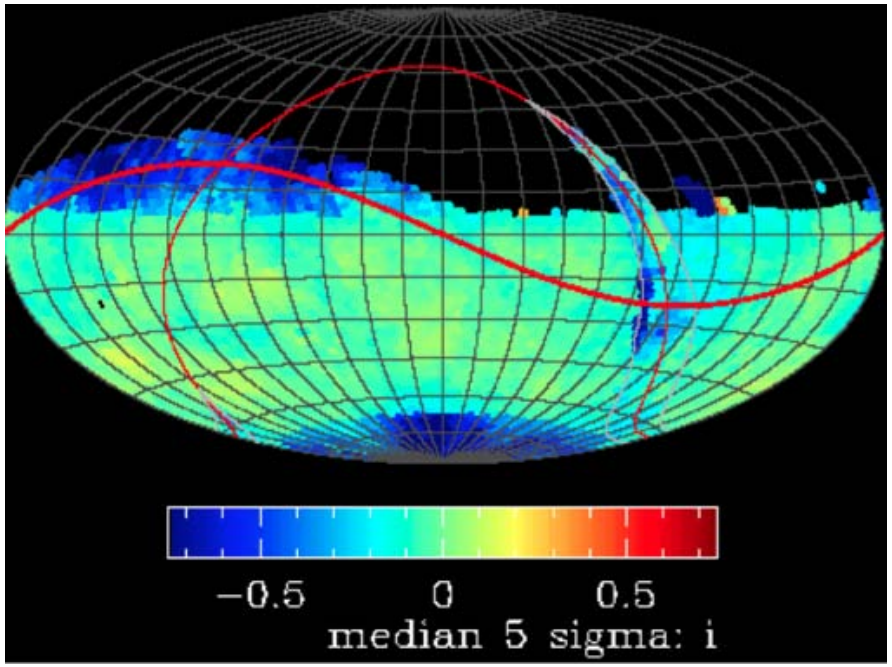
What will LSST do?

the first digital color movie of the sky

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



The Main LSST Science Themes

- **Dark Energy and Dark Matter** (four billion galaxies with excellent photometry and shape measurements, a 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)

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

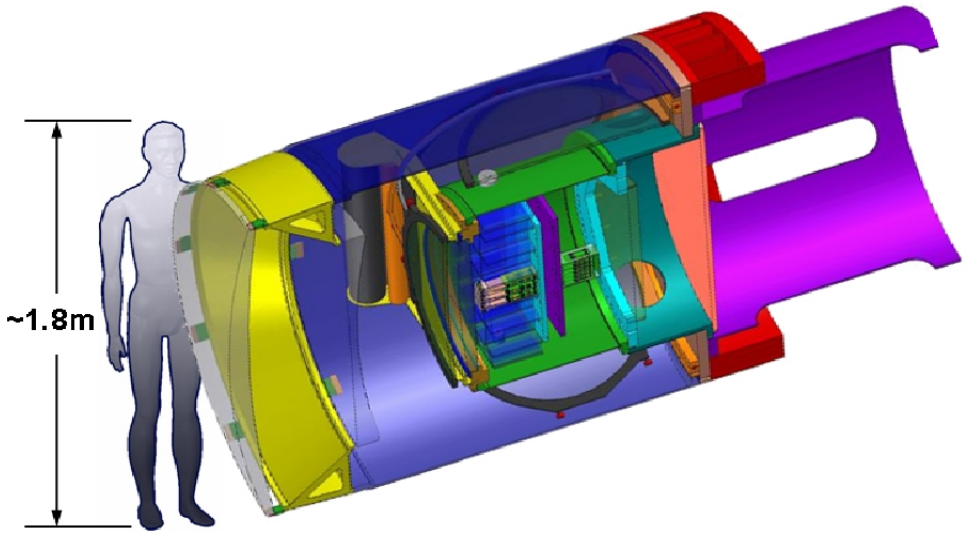
Different science drivers lead to similar system requirements (NEOs, main-sequence stars to 100 kpc, weak lensing, SNe,...):

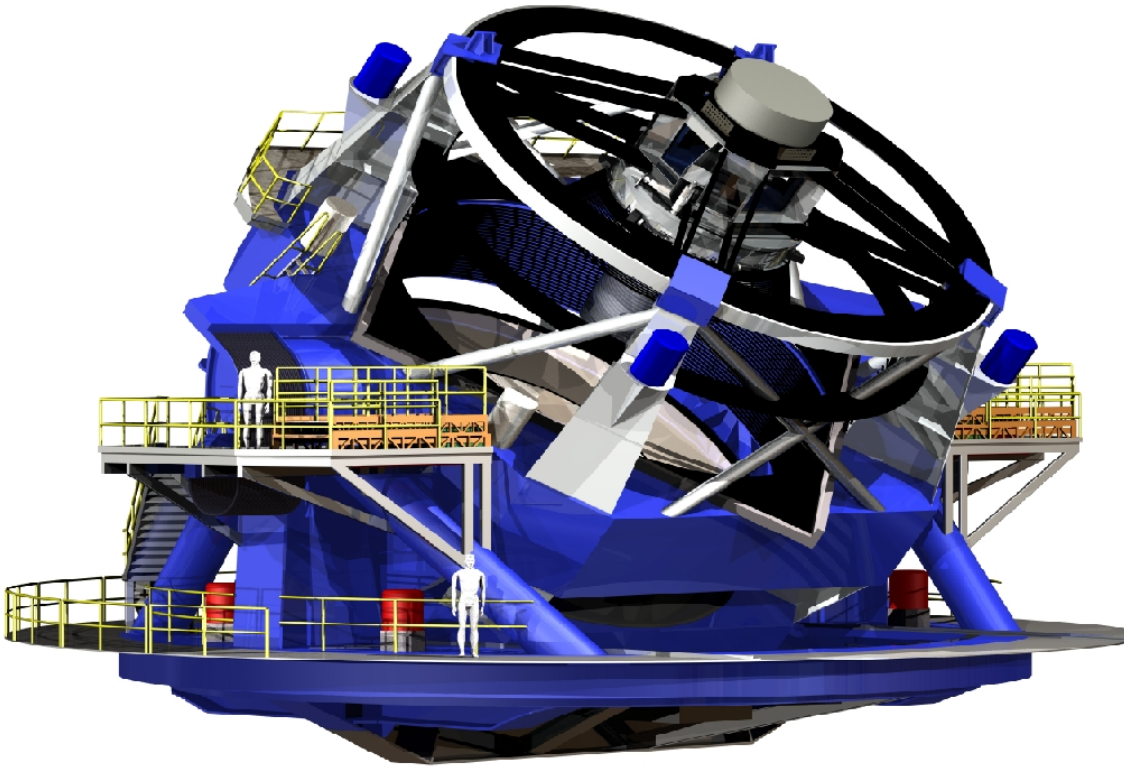
Main LSST Characteristics:

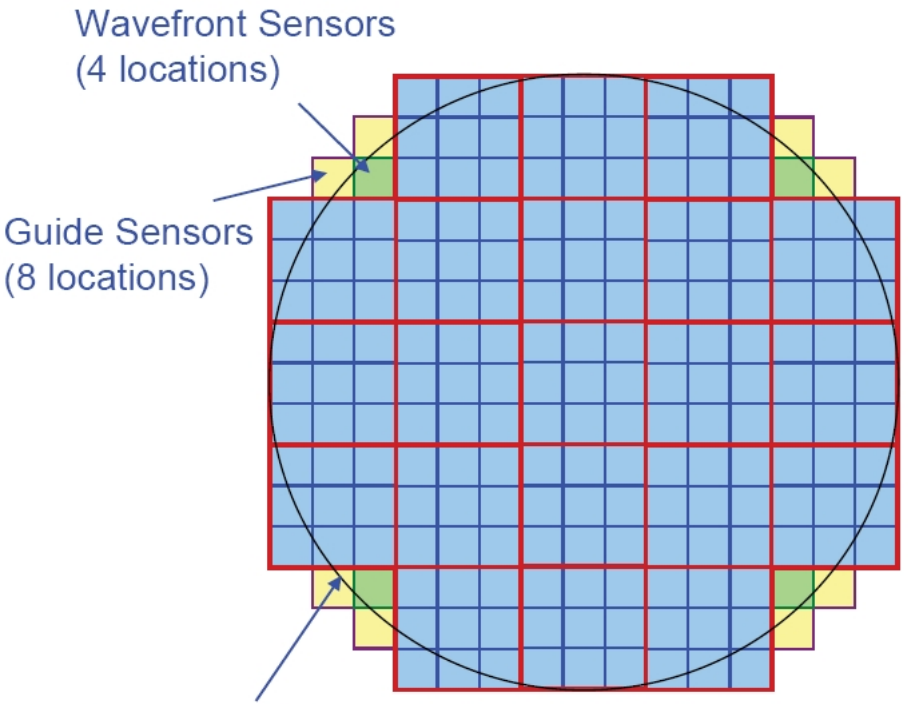
- 8.4m aperture (6.5m effective), $\sim$10 deg^2 FOV
- 3.2 Gigapix camera (20 TB, or one SDSS, per night)
- Sited at Cerro Pachon, Chile
- First light in 2017
- Construction cost: 455 M$ (public-private partnership)

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)




~1.8m



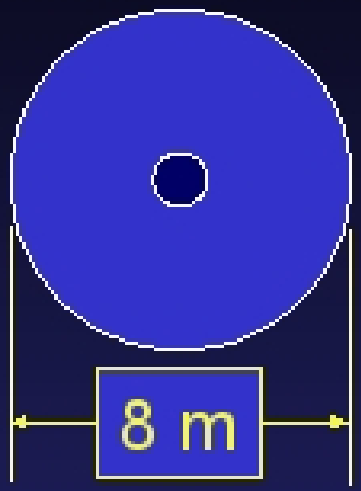

Wavefront Sensors
(4 locations)
Guide Sensors
(8 locations)
3.5 degree Field
of View (634 mm diameter)

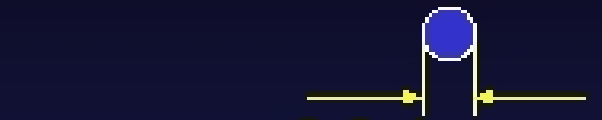
Primary Mirror Diameter

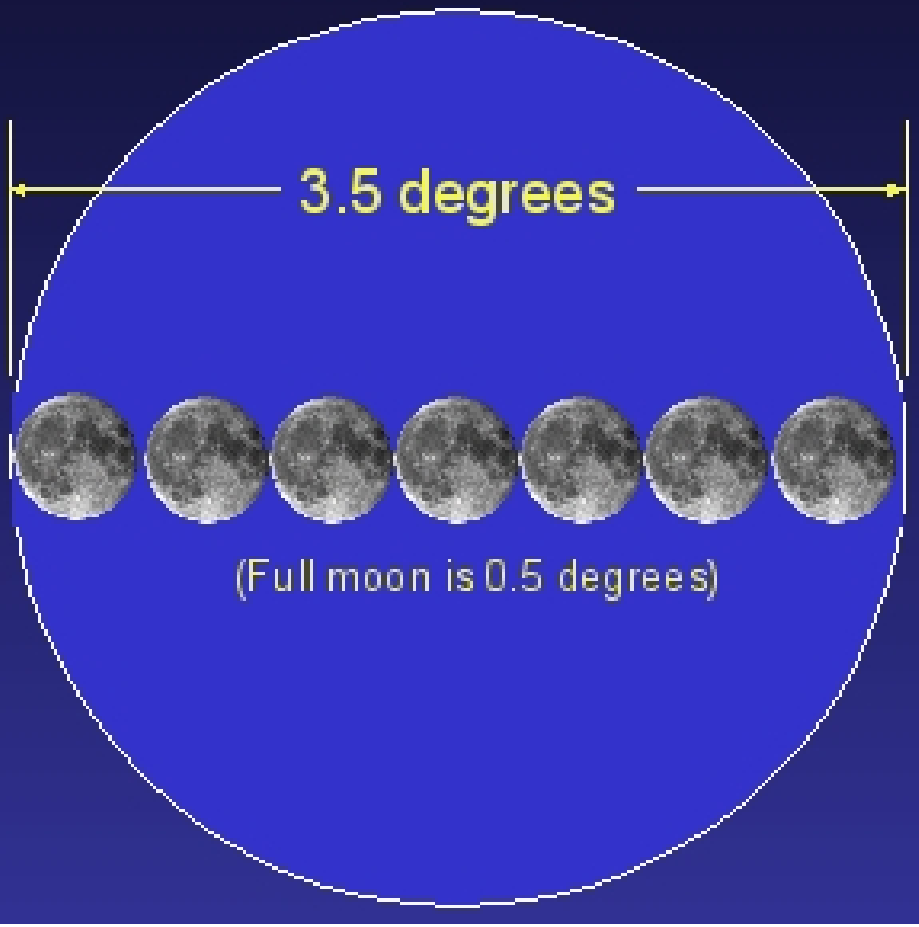
Field of View

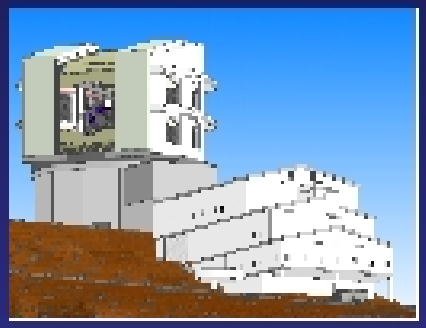


Gemini South Telescope

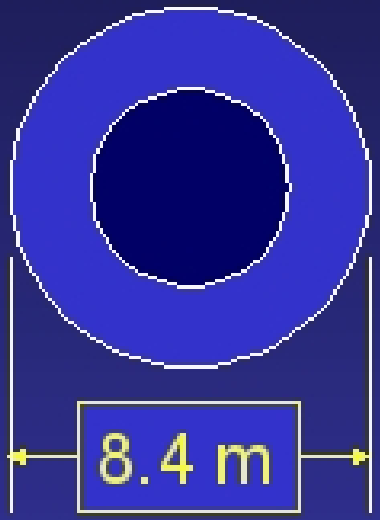


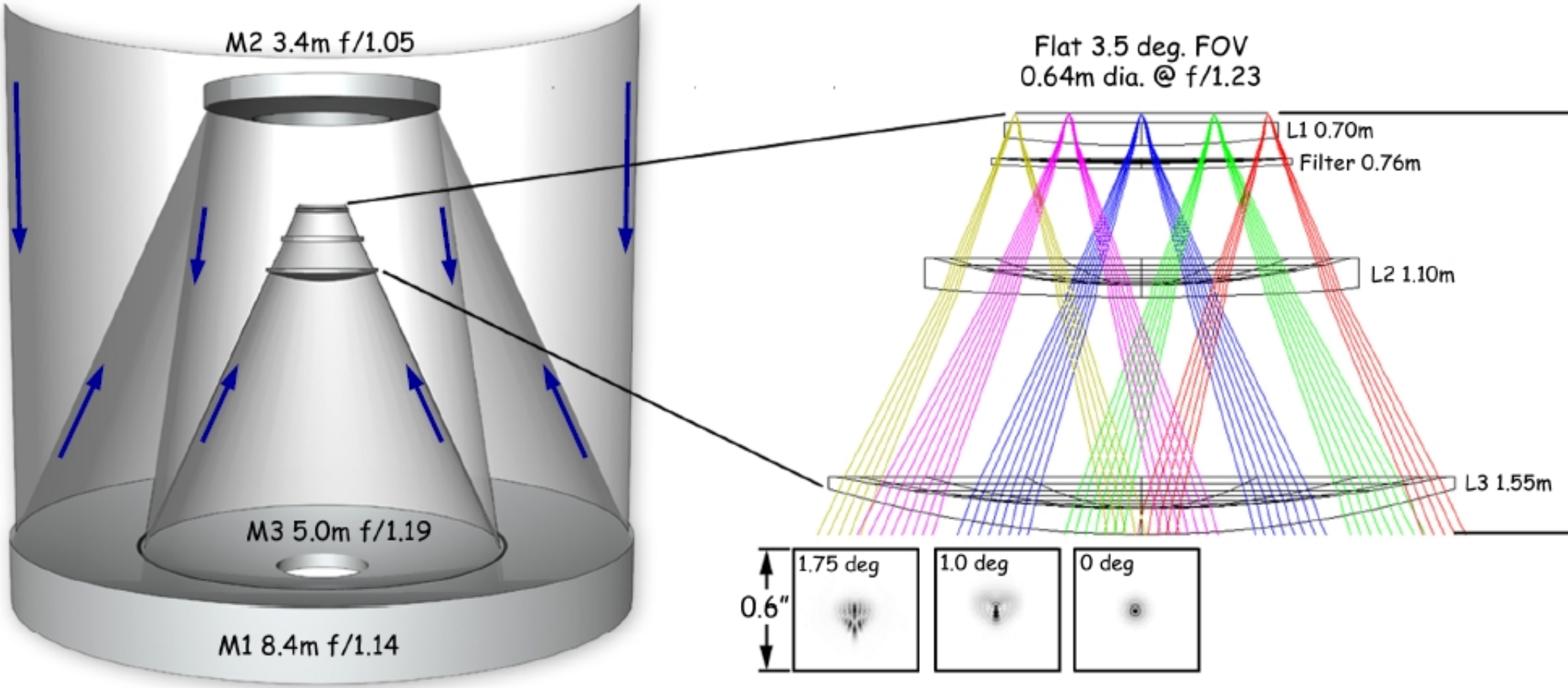






LSST




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



The University of Arizona. Tucson, Arizona SOML

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

LSST Large Synoptic Survey Telescope

LSST vs. SDSS comparison

Currently, the best large-area faint optical survey is

SDSS: the first digital map of the sky

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

- LSST = d(SDSS)/dt: an 8.4m telescope with 2x15 sec visits to r$\sim$24.5 over a 9.6 deg^2 FOV: the whole (observable) sky in two bands every three nights, 1000 visits over 10 years

- LSST = Super-SDSS: an optical/near-IR survey of the observable sky in multiple bands (ugrizy) to r$>$27.5 (coadded); a catalog of $\sim$10 billion stars and $\sim$10 billion galaxies

LSST: a digital movie of the sky

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LSST: a digital movie of the sky

LSST data will immediately become public
(transients within 60 sec, with a goal of 30 sec)



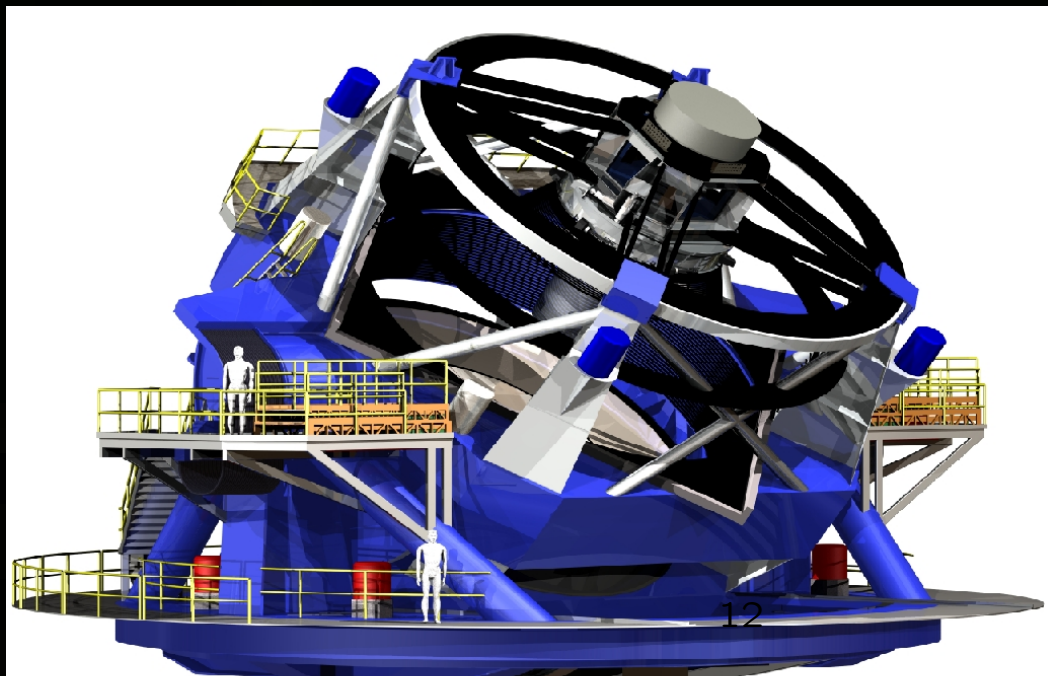






SDSS: one US Library of Congress worth of data

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



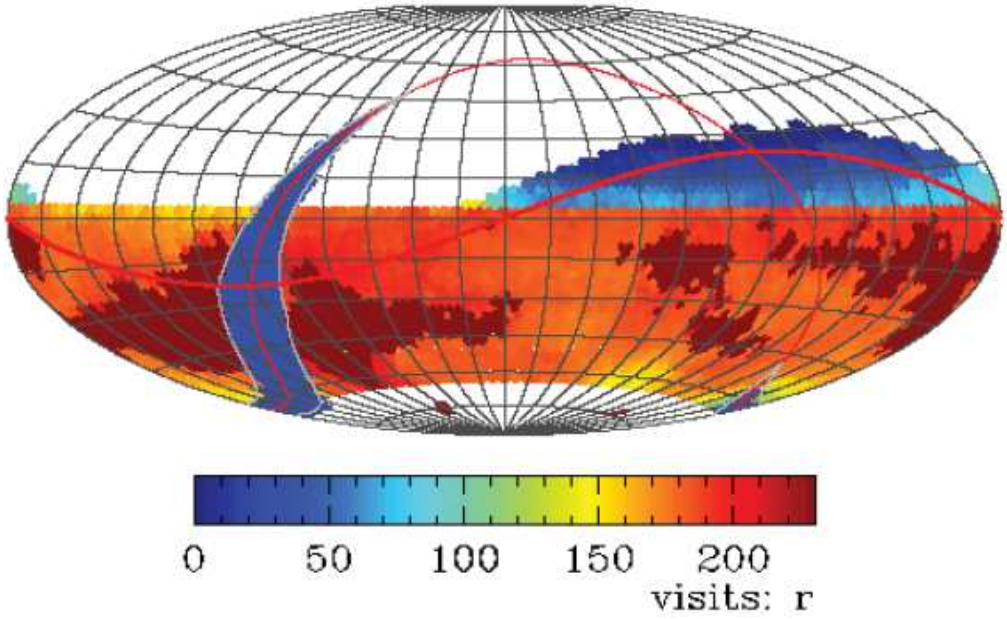
The Data Challenge

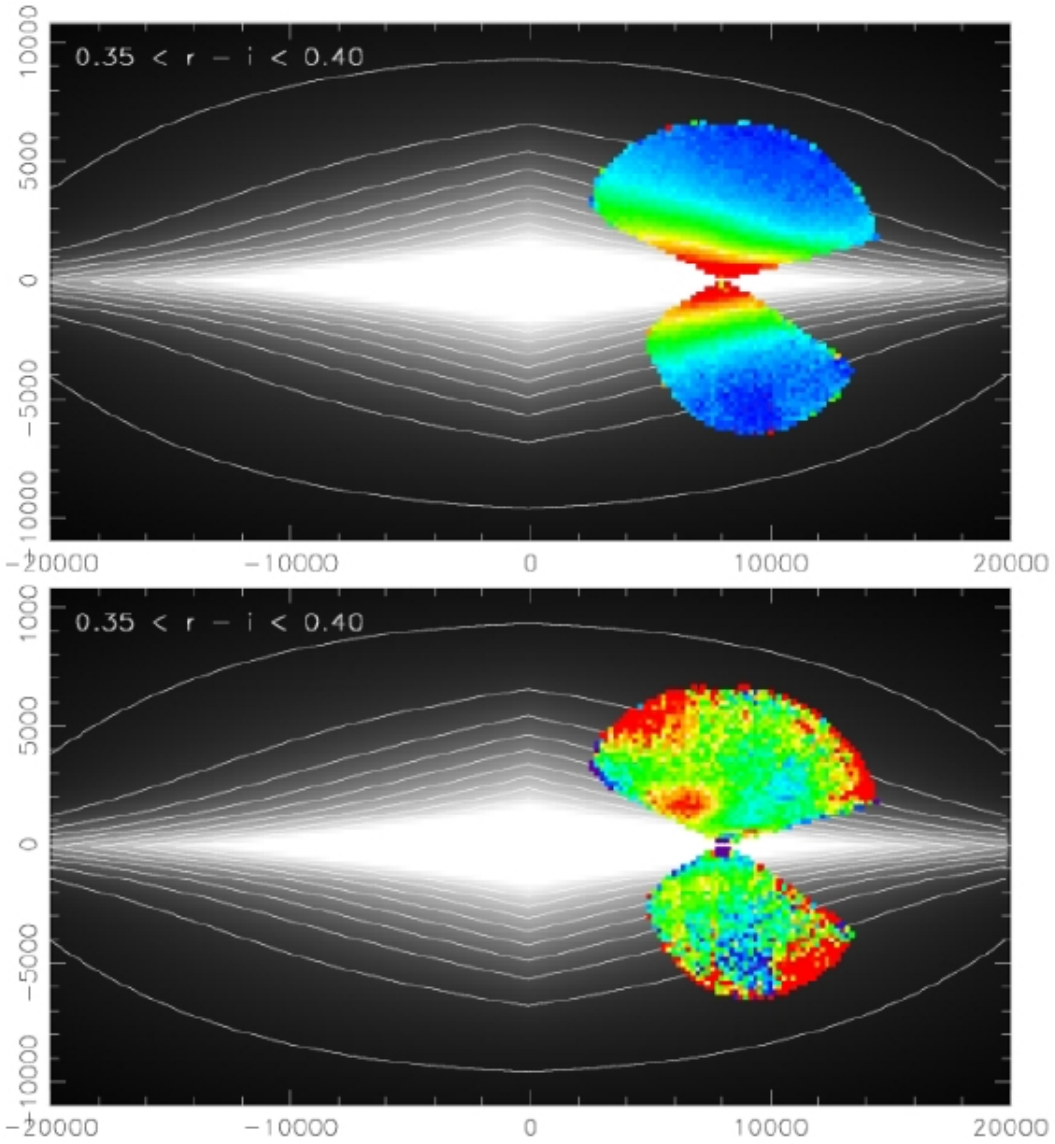
- ~3 Terabytes per hour that must be mined in real time.
- 20 billion objects will be monitored for important variations in real time.
- A new approach must be developed for knowledge extraction in real time.



The Milky Way Surveys with LSST

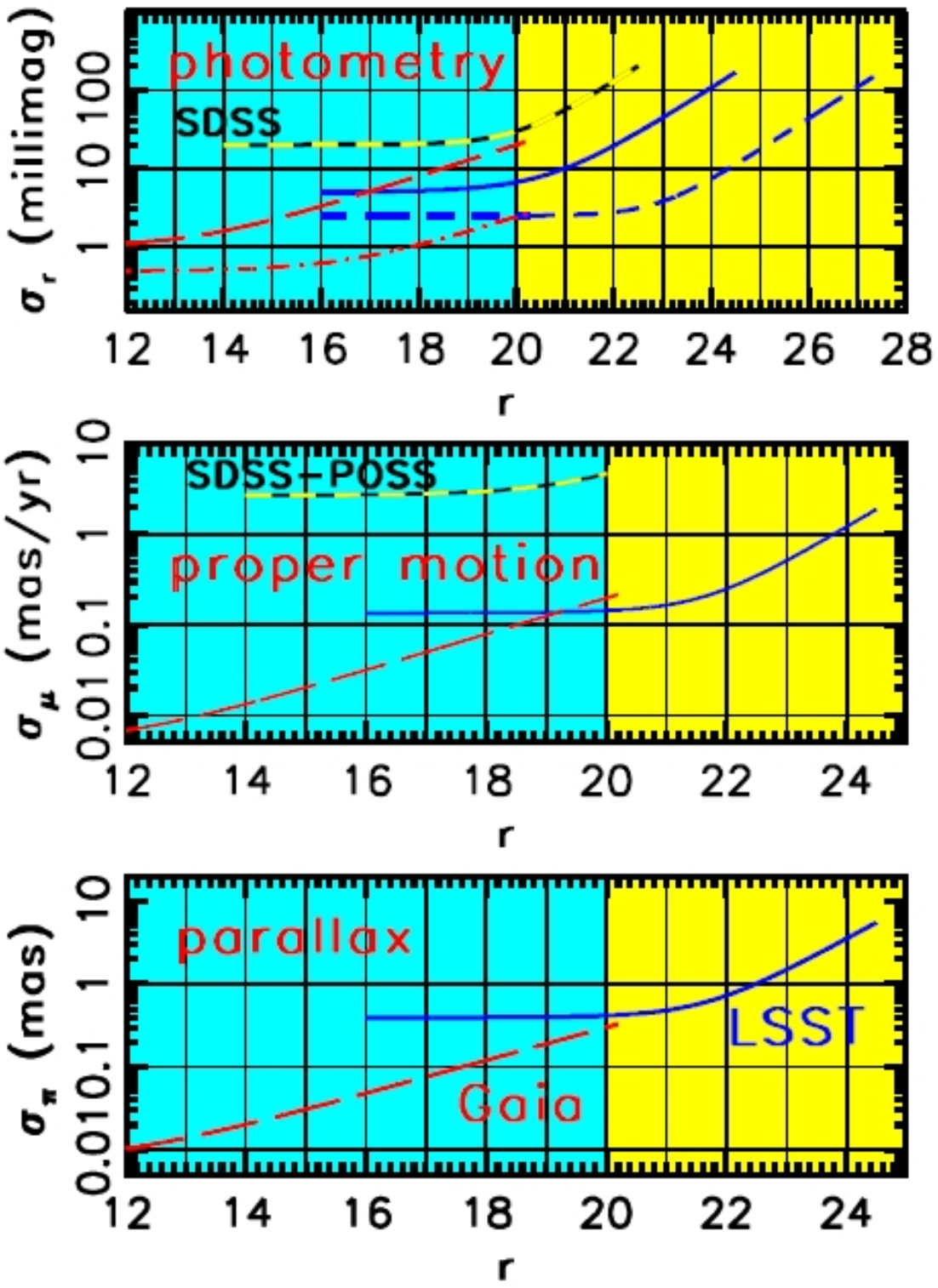
- **Why is LSST good for Milky Way studies:**
  - about 10 billion stars ($16 < r < 27$)
  - hundreds of millions of halo main-sequence stars to 100 kpc
  - trigonometric parallaxes for all stars within 500 pc
  - kinematics from proper motions (extending Gaia by 4 mag)
  - photometric metallicity (the u band)
  - RR Lyrae stars to 400 kpc
  - Large sky coverage (20,000 deg^2):





The limitations of SDSS data and LSST

- **Sky Coverage:** "only" ∼1/4 of the sky 1/2 of the sky
- **Depth:** main-sequence stars to ∼10 kpc; RR Lyrae stars to 100 kpc 100 and 400 kpc
- **Photometric Accuracy:** ∼0.02 mag for the u band, limits the accuracy of photometric metallicity estimates to ∼0.2 dex 0.01 mag and 0.1 dex
- **Astrometric Accuracy:** the use of POSS astrometry (accurate to ∼150 mas after recalibration) limits proper motion accuracy to 3 mas/yr 0.2 mas/yr at r=21 and 1.0 mas/yr at r=24

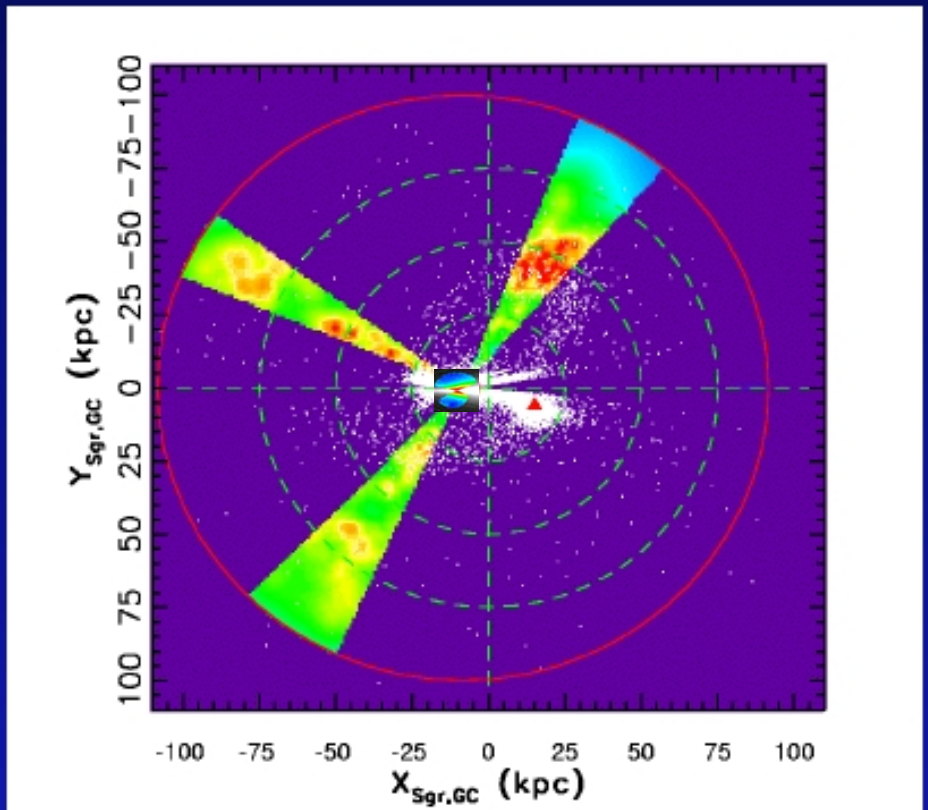


Gaia, UKIDSS, WISE vs. LSST

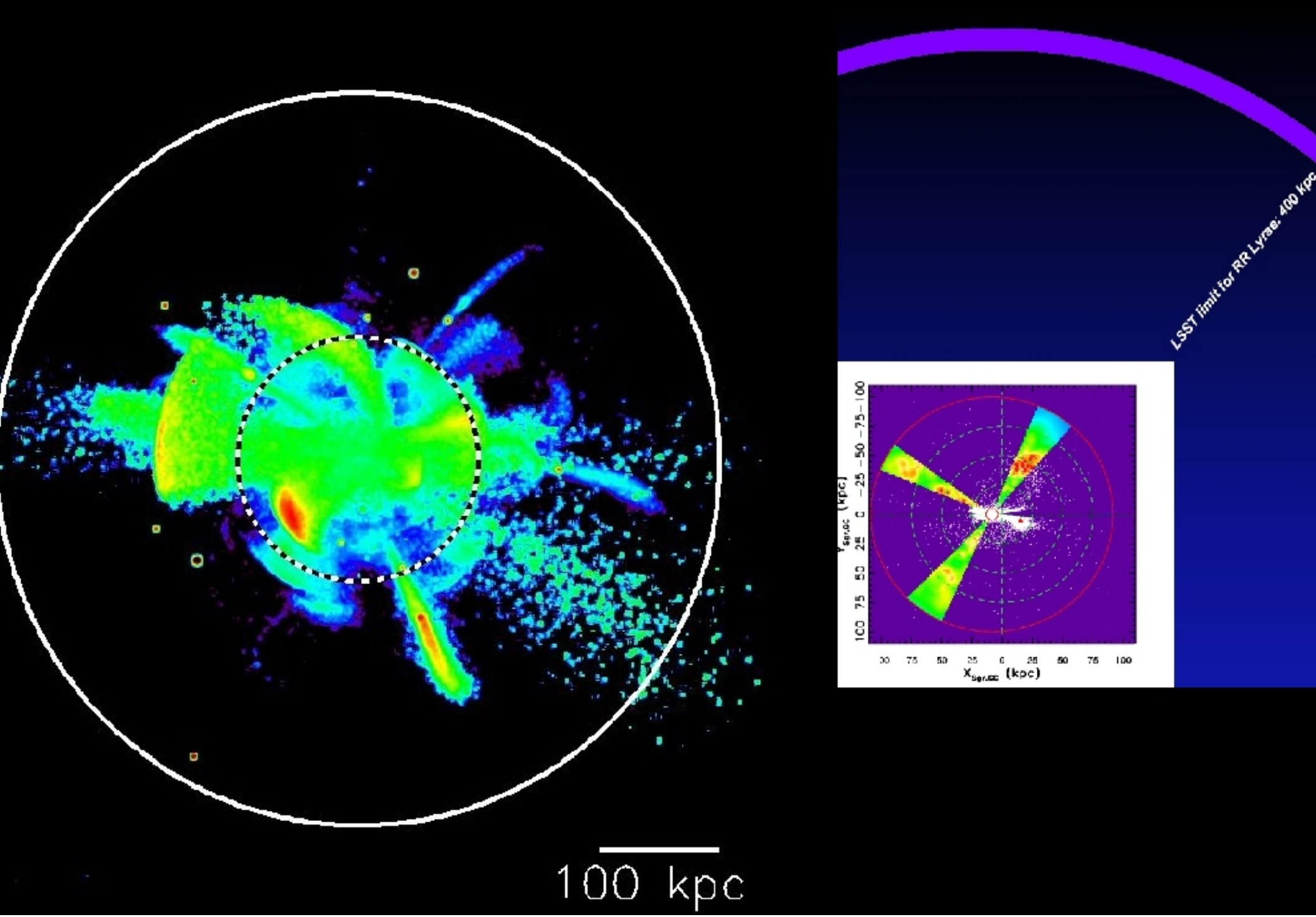
- **Gaia:** excellent astrometry (and photometry), but only to $r < 20$
- **LSST:** photometry to $r < 27.5$ and time resolved measurements to $r < 24.5$
- **Complementarity:** at $r \sim 20$, the photometric, proper motion and trigonometric parallax errors are similar; for example, with main-sequence stars, Gaia will map to ∼10 kpc, LSST to ∼100 kpc
- More details in Eyer, Ivezić, et al. (2011)
- **UKIDSS, WISE: excellent for red sources, but many epochs with LSST**

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

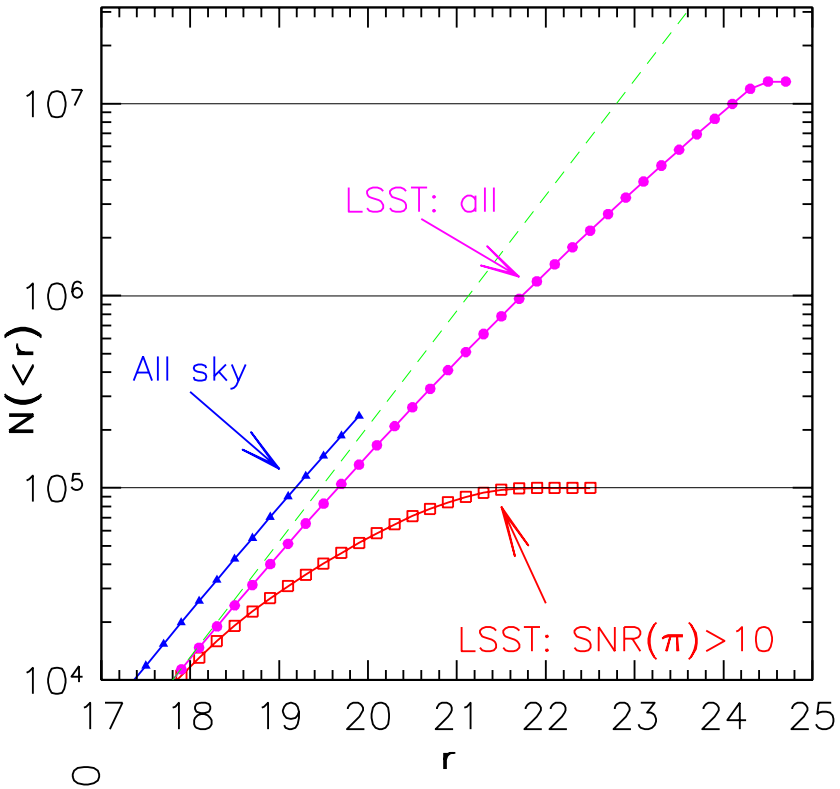
The large red circle: the ∼100 kpc limit of future LSST studies based on main-sequence stars (and the current limit for RR Lyrae studies)

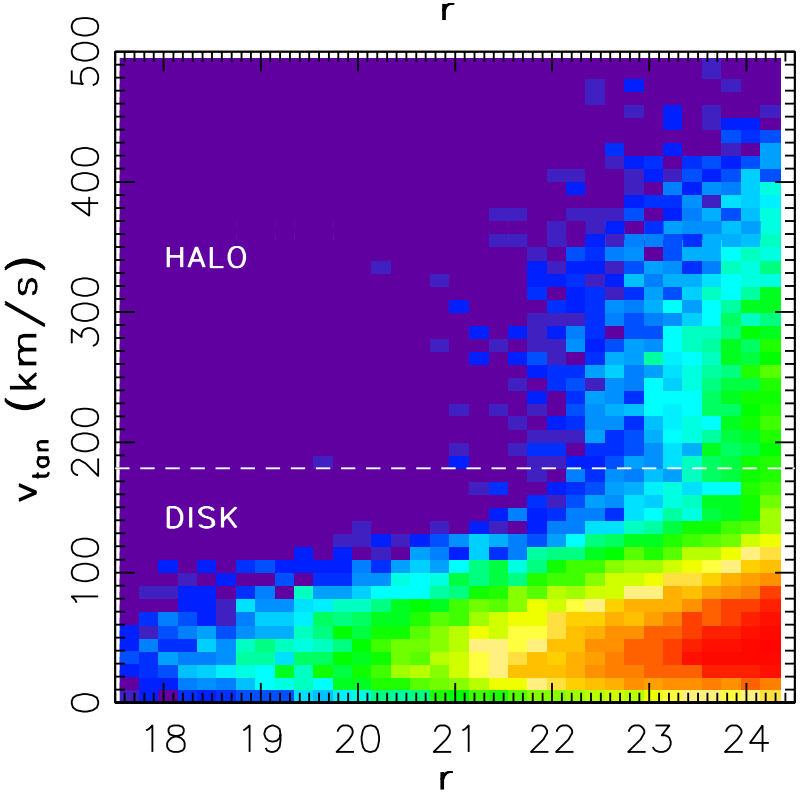


The small insert: ∼10 kpc limit of SDSS and future Gaia studies for kinematic & $[Fe/H]$ mapping with MS stars



Left: Models (Bullock & Johnston) **Right:** SDSS and 2MASS observations, and predictions for LSST



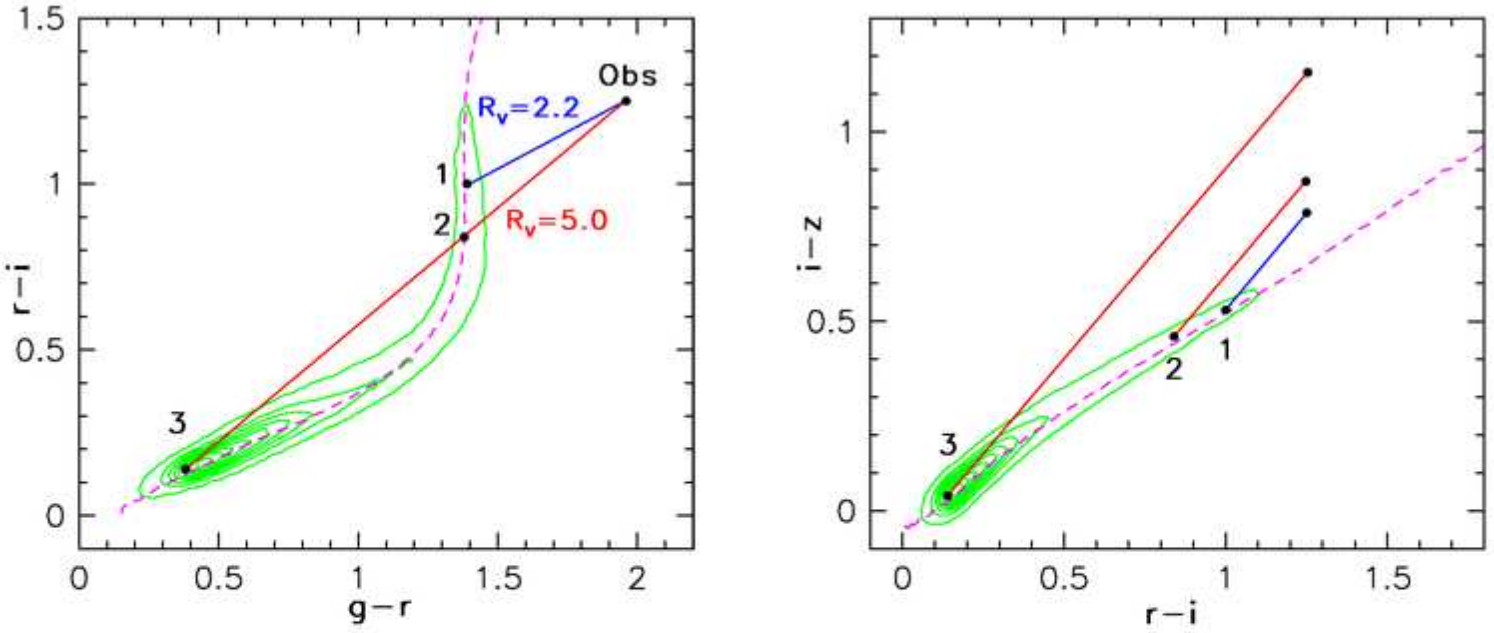


White Dwarfs with LSST

- **Top Left:** Counts of white dwarfs: about 300,000 detected by Gaia, over 10,000,000 for LSST with $r < 24.5$ (50 million for < 27.5)
- **Time resolved measurements** yield proper motion and trigonometric parallax; **coadded photometry** yields accurate colors (e.g. can photometrically separate H and He sequences, and estimate log(g) to 0.05 dex for some temperature intervals)
- **Bottom Left:** Disk and halo white dwarfs can be kinematically separated; there will be 400,000 halo white dwarfs in the LSST $r < 24.5$ sample (currently, fewer than 100 are known)
- **The white dwarfs luminosity function is sensitive to the population age; it will be measured separately for thin and thick disks, and halo**

LTY Dwarfs with LSST

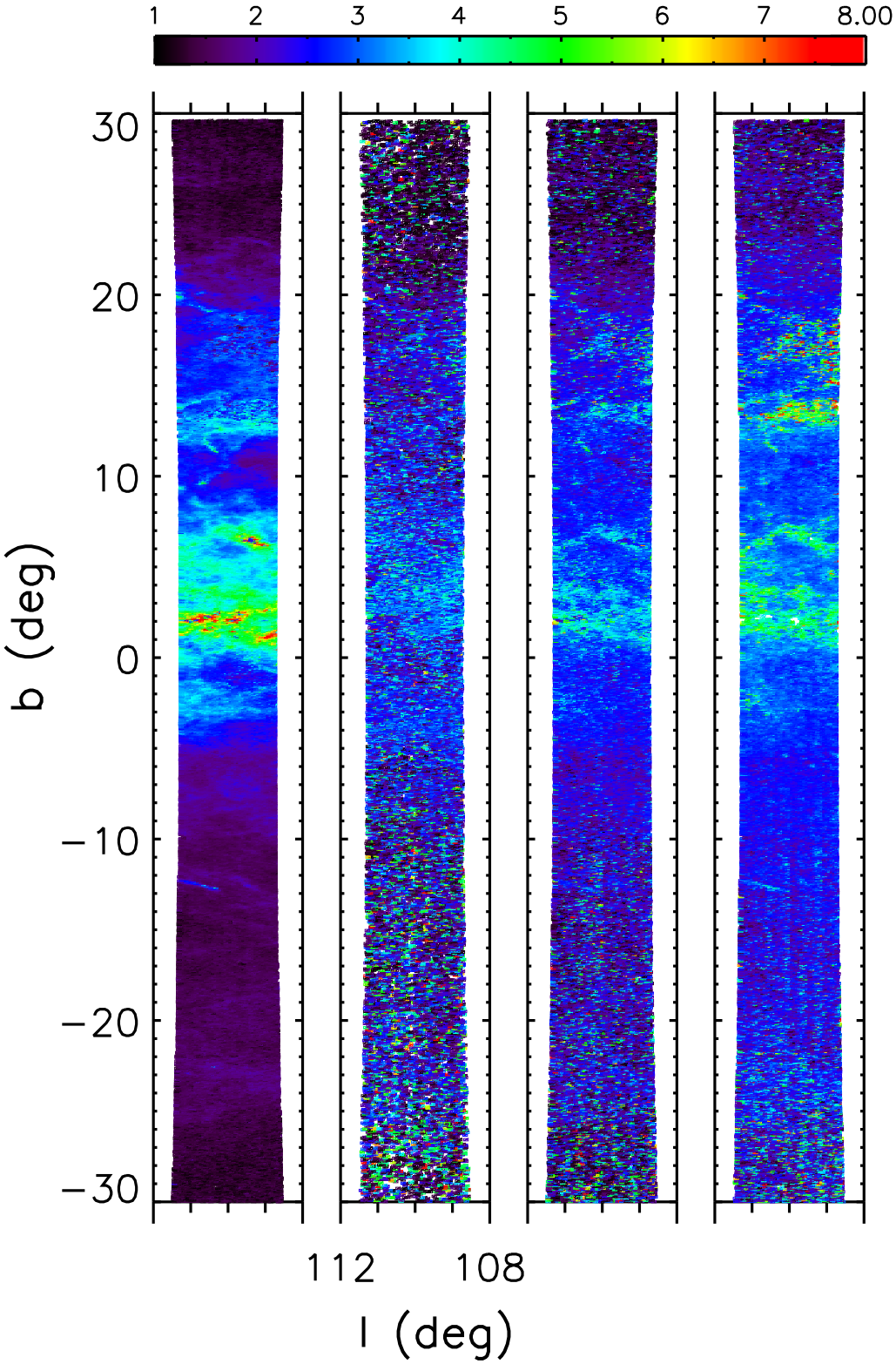
- **T dwarfs: a quantitative example** (L dwarfs are dime a dozen: 200,000 in LSST with proper motion and trigonometric parallax measurements; no Y dwarfs are confirmed yet, though based on models expect ∼100 from LSST)
- **Simulations predict 2400 T dwarfs with** $y < 21.4$ (now ∼100)
- For $y < 21.4$ proper motion ($\sigma = 2$ mas/yr) and trigonometric parallax measurements (σ=6 mas) based on 200 y band detections: 5-10σ measurements even for the faintest objects
- The $z - y$ color will be accurate to better than 0.1 mag even for the faintest objects: it will be possible to construct robust M_z **vs.** $z - y$ **color-magnitude diagrams** (exquisite LFs!)
- The $y < 21.4$ LSST T dwarf sample has roughly the same JHK magnitude limits as the UKIDSS Large Area Survey (4,000 deg^2)
- **Compared to UKIDSS, LSST will obtain about 5 times larger sample of T dwarfs, with proper motions about 10-20 times more accurate, and also with trigonometric parallax measurements** (due to larger sky area, note that our simulations imply that UKIDSS will detect about 500 T dwarfs)



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 $> 10\sigma$ detections (23 million also detected by 2MASS)



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 $R_V \sim 4 - 6$

Summary

- **LSST:** extending SDSS to twice as large sky area (1/2 sky), 2 mag deeper per visit, with several hundred visits, coadded 5 mag deeper than SDSS
- **Halo studies:** spatial distribution, metallicity distribution and kinematics to ∼100 kpc with ∼200 million blue (F/G) main sequence stars; RR Lyrae to 400 kpc
- **Disk studies:** huge samples of intrinsically faint objects: white dwarfs, LTY dwarfs; dust distribution and properties

LSST will smoothly extend Gaia's error vs. magnitude curves 4 magnitudes fainter. **LSST and Gaia will be complementary:** the Gaia survey will provide calibration checks at the bright end for proper motions and trigonometric parallax measurements by LSST, and LSST will extend the Gaia survey four magnitudes deeper.

For more details about LSST: www.lsst.org and Ivezić et al. 2008 (arXiv:0805.2366).