

What to do with 20 billion stars from Rubin Observatory Legacy Survey of Space and Time?

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This talk available as:
<http://ls.st/t62>

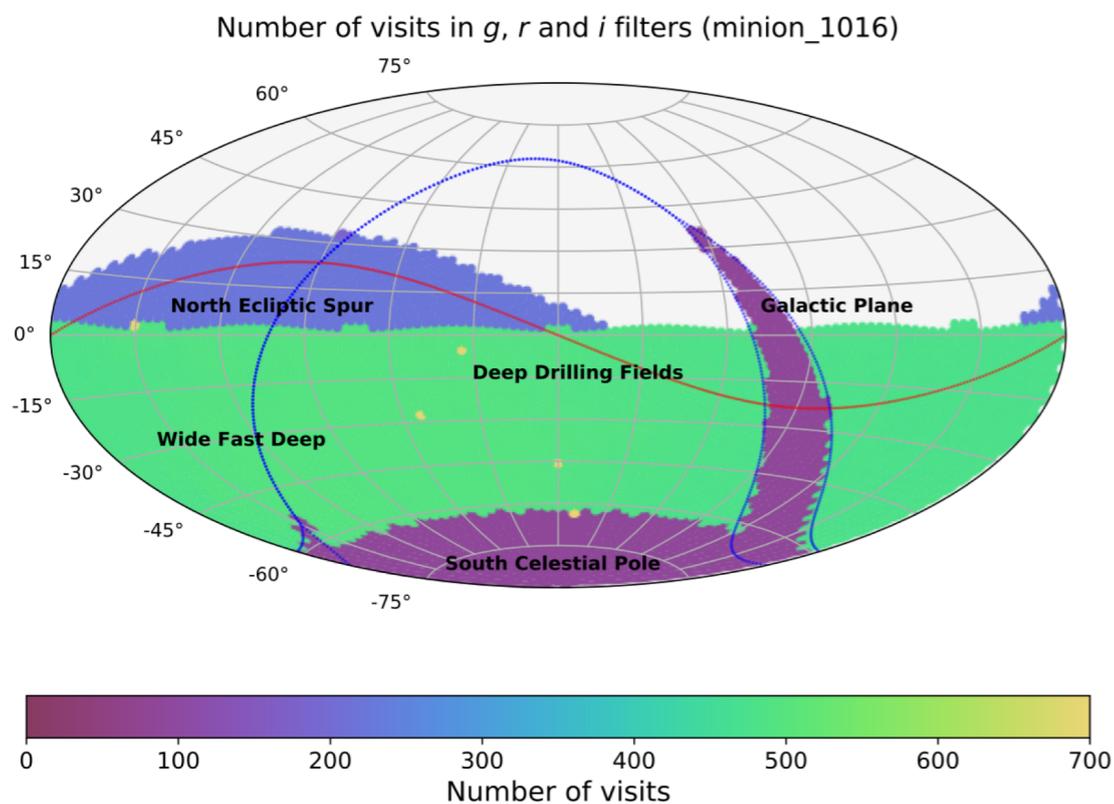
NASA Cosmic Origins seminar
November 2, 2021

Outline

- Introduction: what will LSST measure?
- Variable vs. non-variable stars
- What can you do with non-variable stars?
- LSST vs. Gaia

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 about 20 billion galaxies and 20 billion stars



LSST in one sentence:

An optical/near-IR survey of half the sky in ugrizy bands to $r \sim 27.5$ (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)

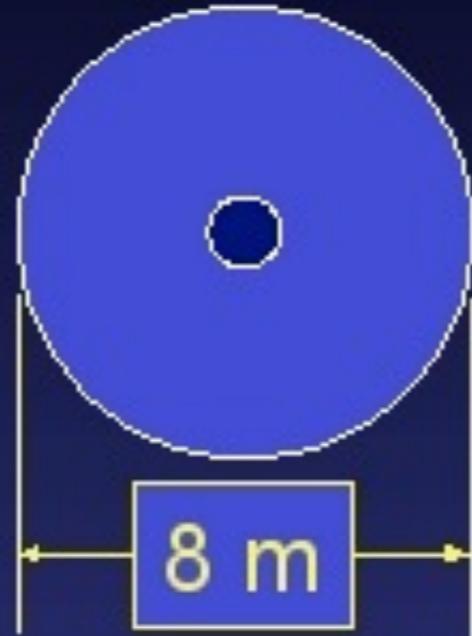
The field-of-view comparison: Gemini vs. LSST

Primary Mirror Diameter

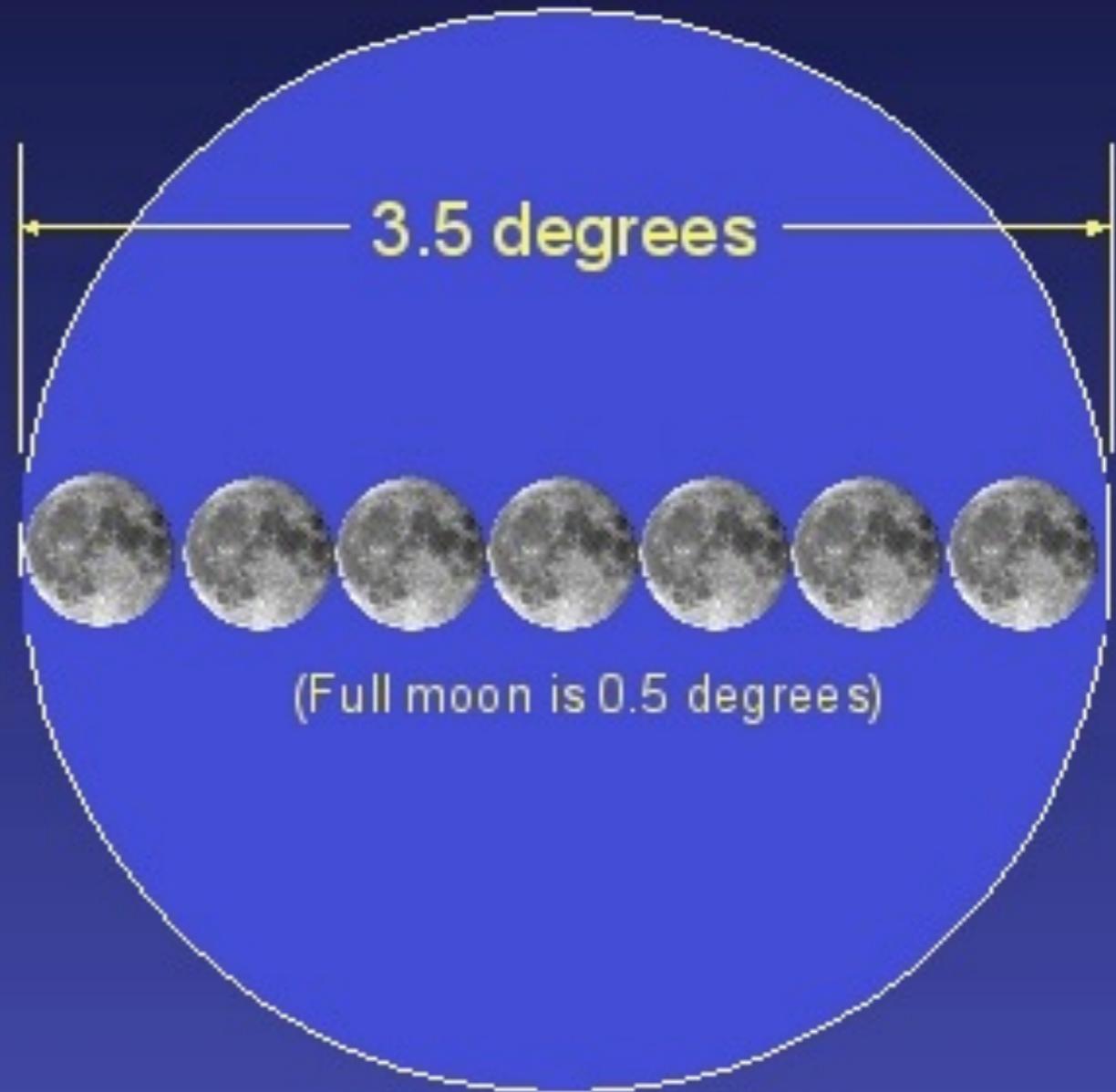
Field of View



Gemini South Telescope



LSST



SDSS

gri

3.5'x3.5'

r~22.5

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



HSC
gri
3.5'x3.5'
r~27

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

like LSST
depth (but
tiny area)

LSST will
deliver 5
million
such
images



Filter complement

- **Photometric redshifts for galaxies:** random errors smaller than 0.02, bias below 0.003, fewer than 10% $>3\sigma$ 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)

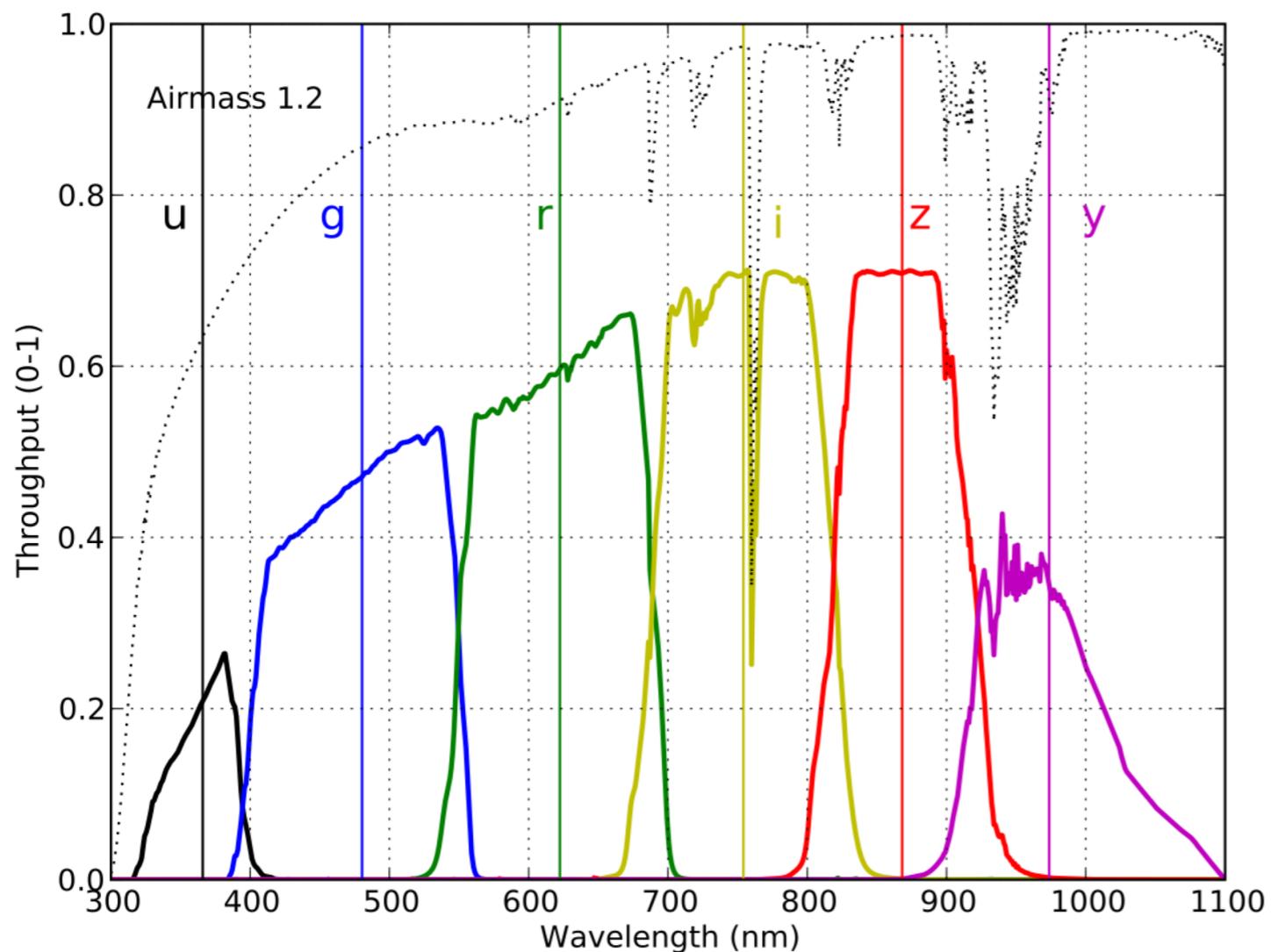


Photo-z requirements correspond to $r \sim 27.5$

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)

Stellar photometry from LSST

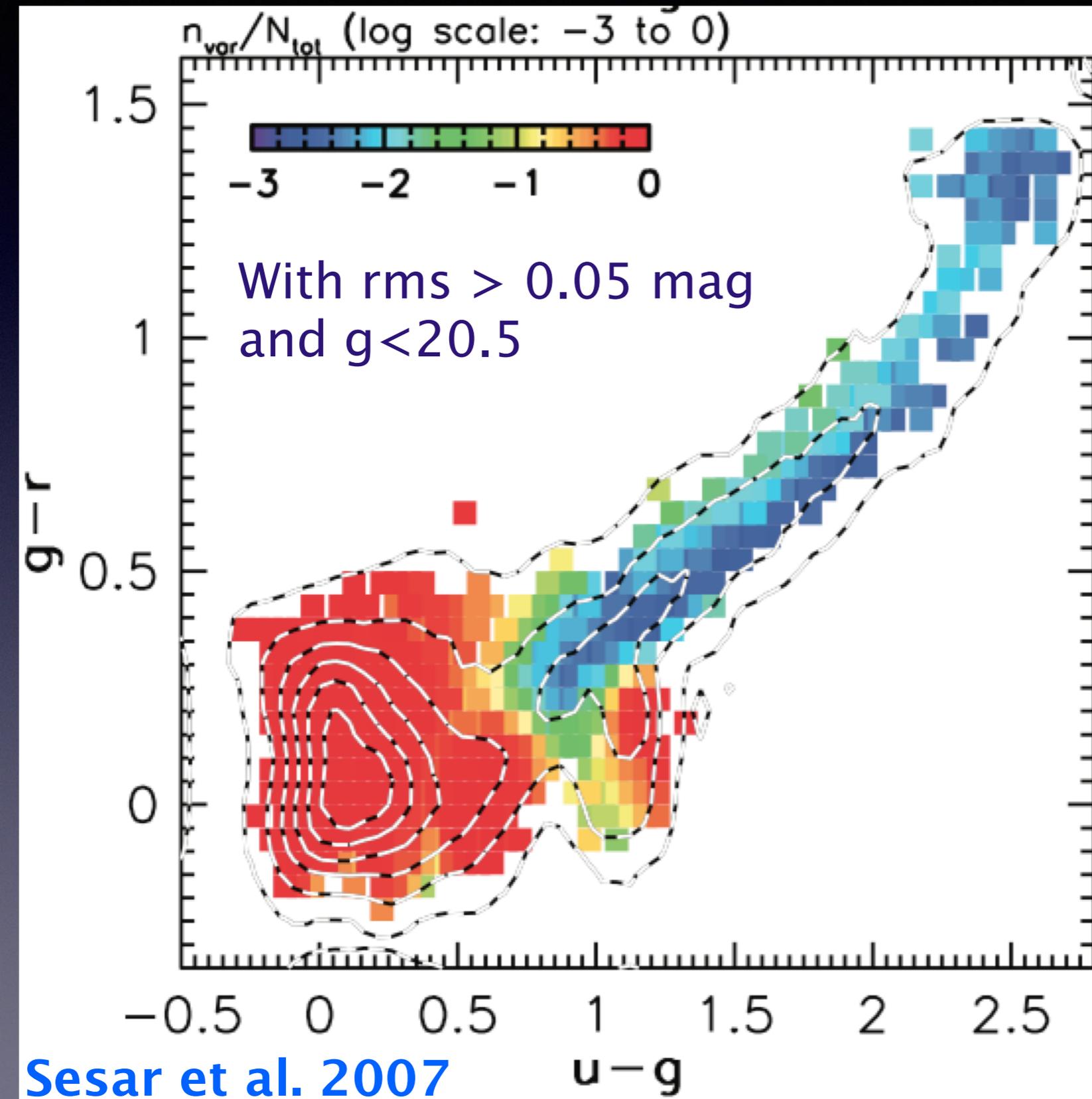
- **Photometric accuracy:** random errors 0.005 mag, calibration to 0.01 *What can you learn from these data?*
- **Time-resolved measurements:** photometric variability, and parallax and proper motions from astrometric measurement
- **SDSS** and other extant surveys: it will be easy to separate variable and non-variable unresolved sources and analyze non-variable stars separately *(even quasars are not a problem)*

Federica Bianco will talk about variable stars

(and I will return to parallax and proper motions)

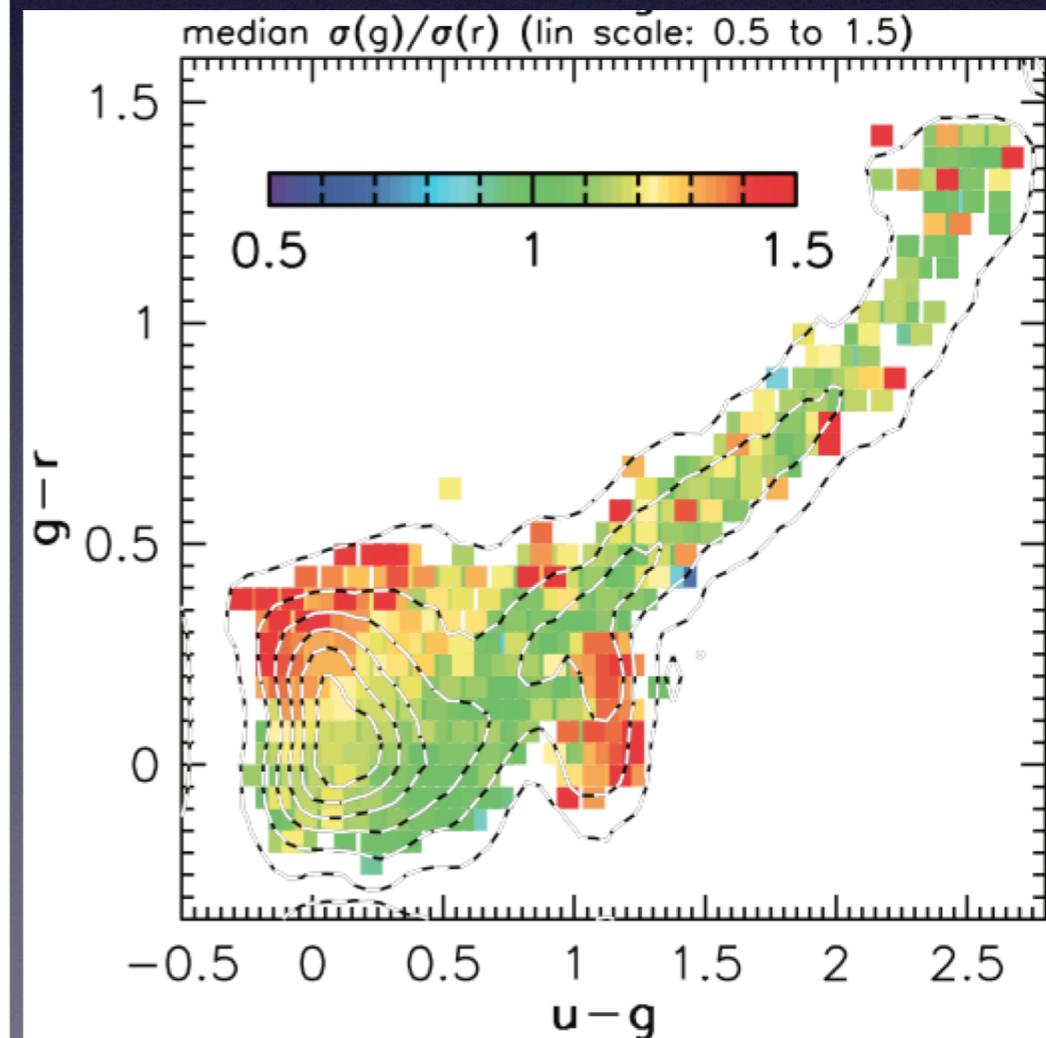
SDSS: practically all quasars are variable!

The fraction of variable objects in SDSS Stripe 82:

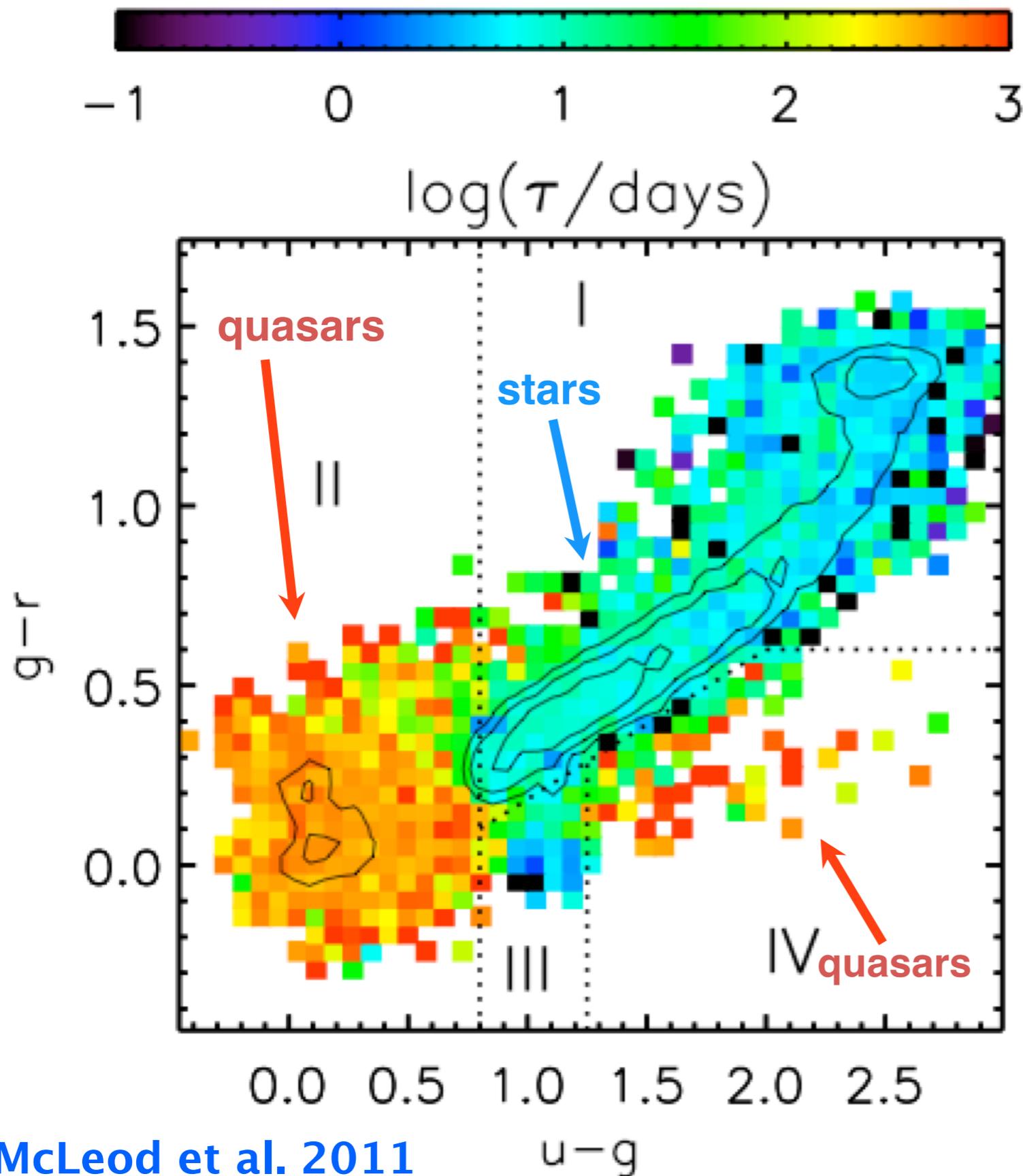


The sample is dominated by quasars and RR Lyrae.

Quasars and RR Lyrae have different variability properties:
 $\text{rms}(g)/\text{rms}(r)$



The variability time scales



McLeod et al. 2011

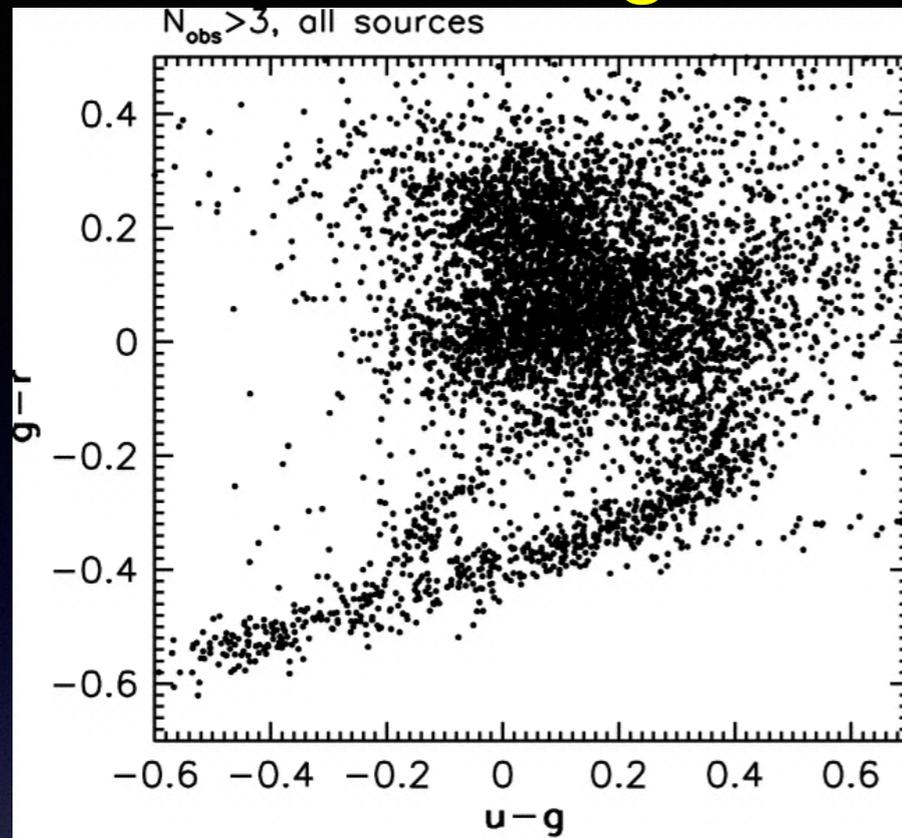
Time scale τ is defined via **damped random walk** (because not all variable sources are periodic)

Quasars are easily distinguished from stars by their long time scales.

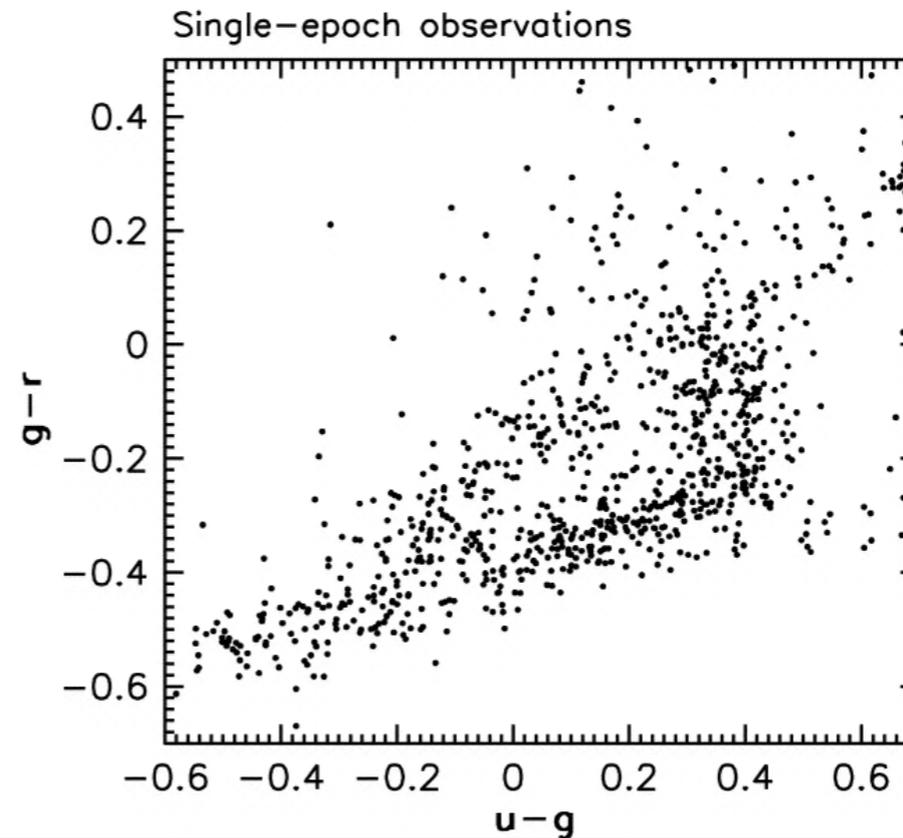
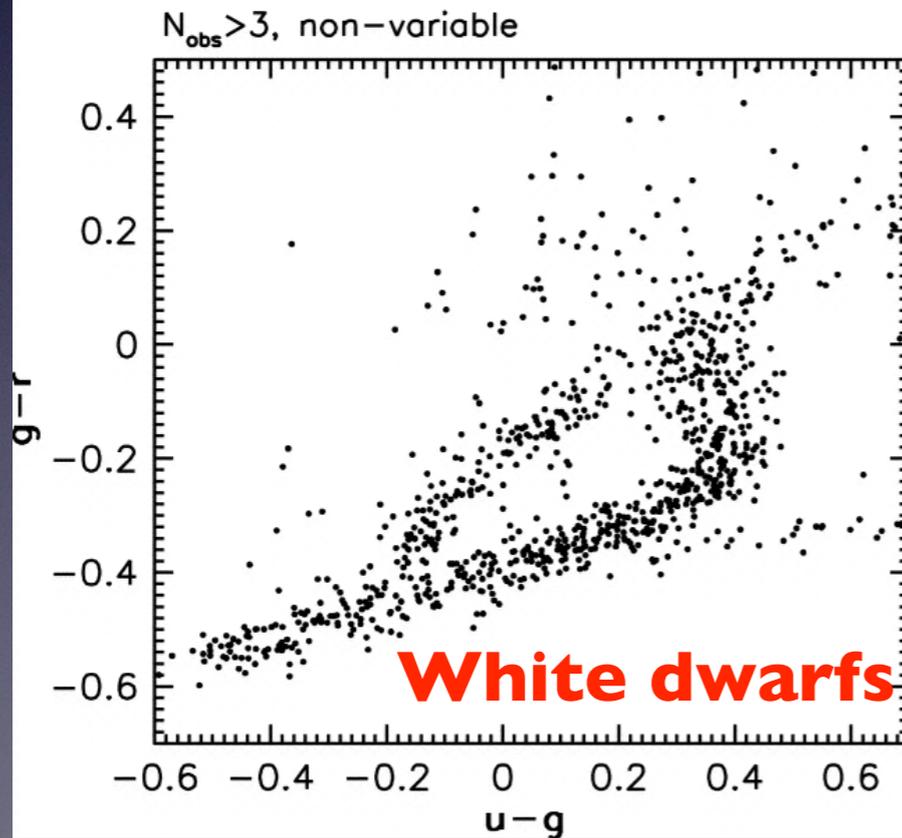
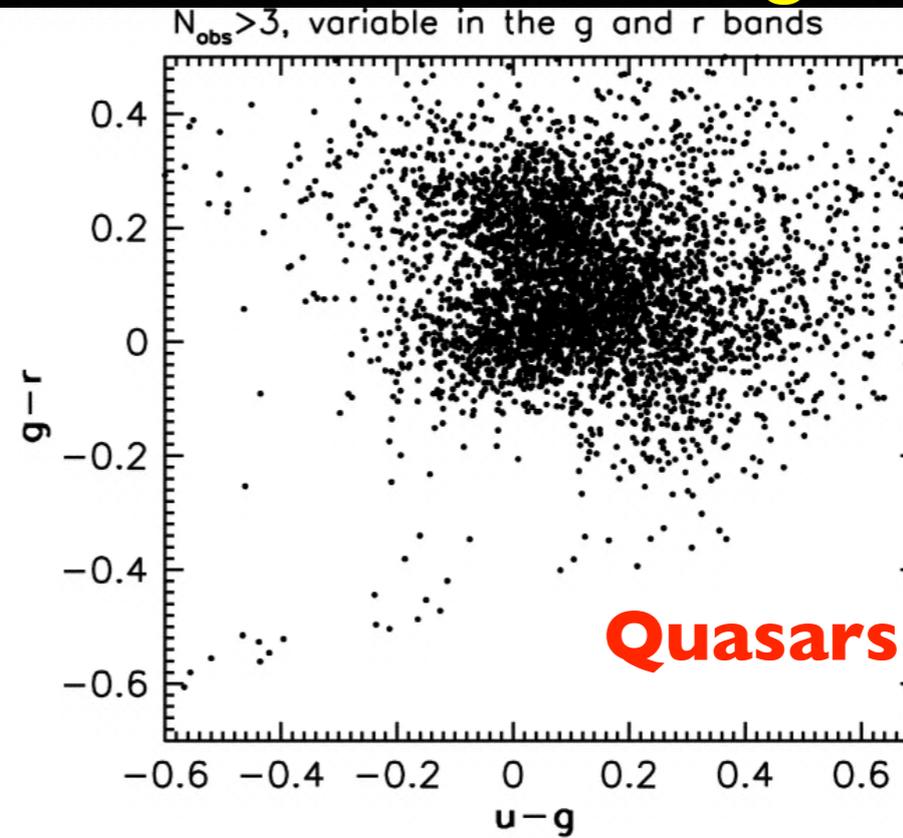
Variability is even better than color selection!

Case study: light curve data and proper motion data for over 1 million sources from SDSS Stripe 82 (all are publicly available)

All, averaged

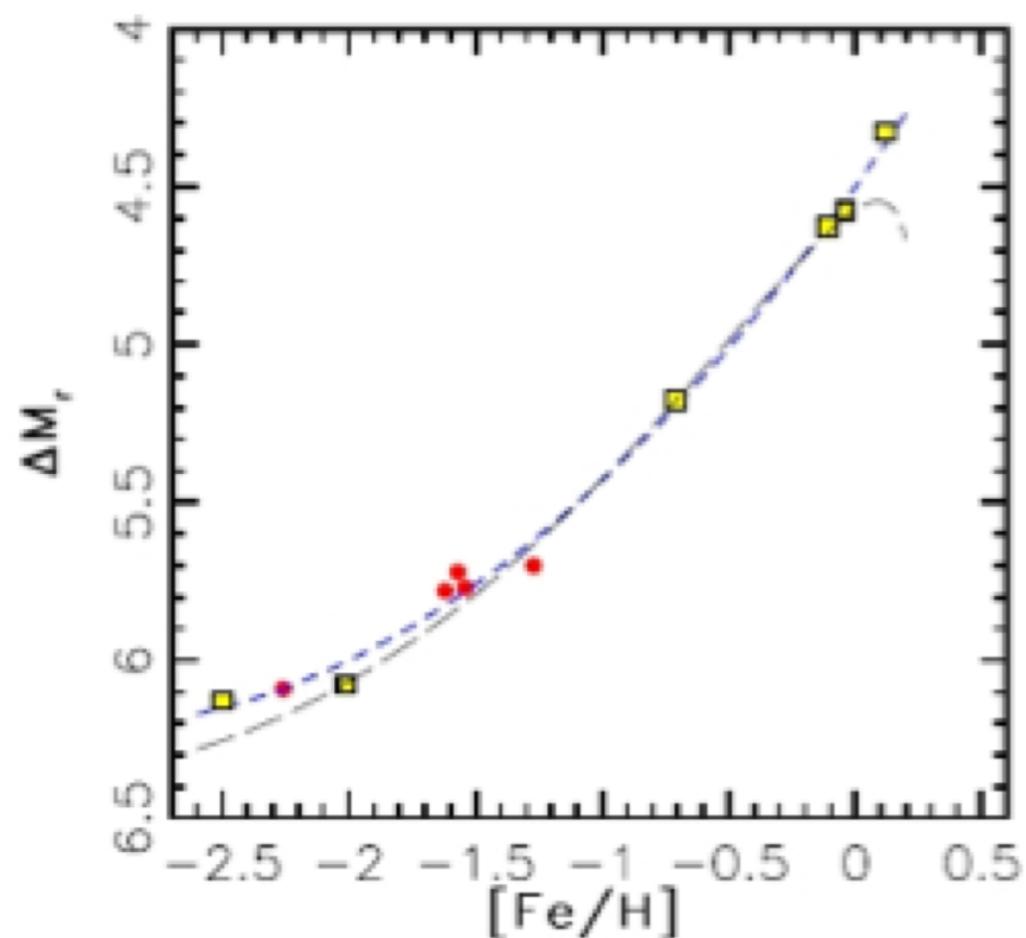
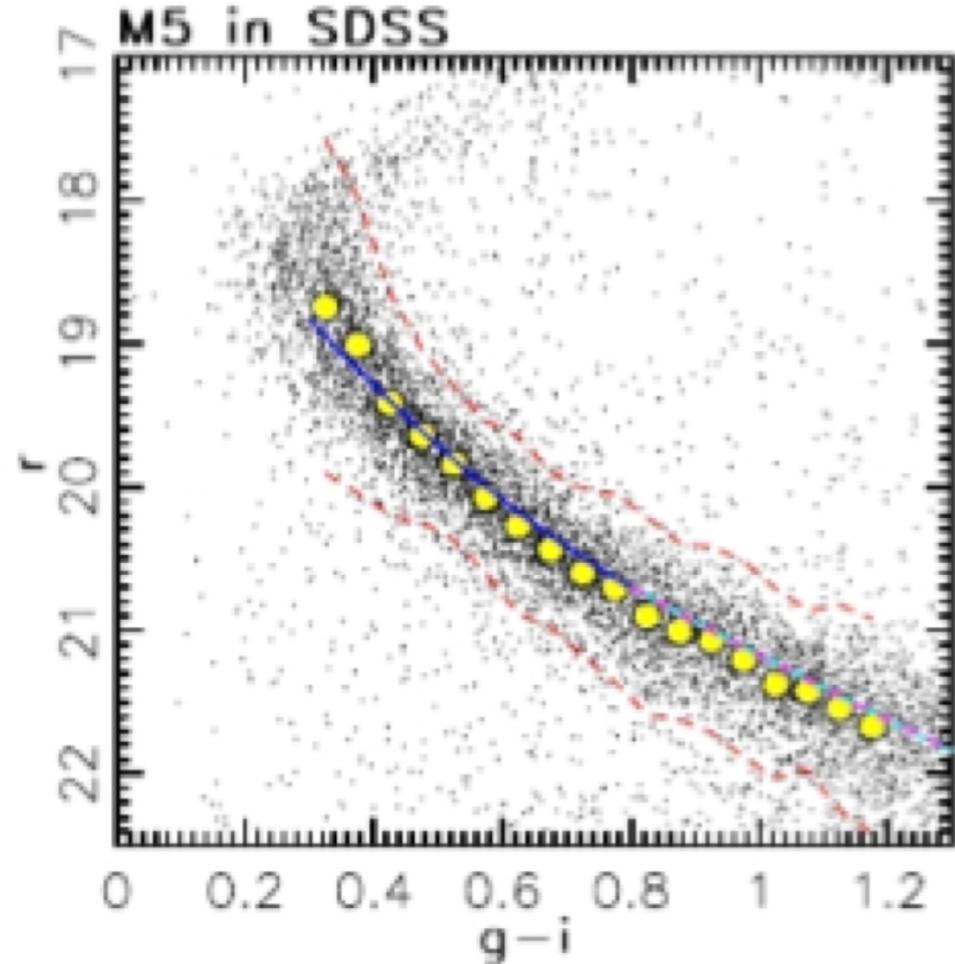


Variable, averaged



Non-variable, averaged

Non-variable, single epoch



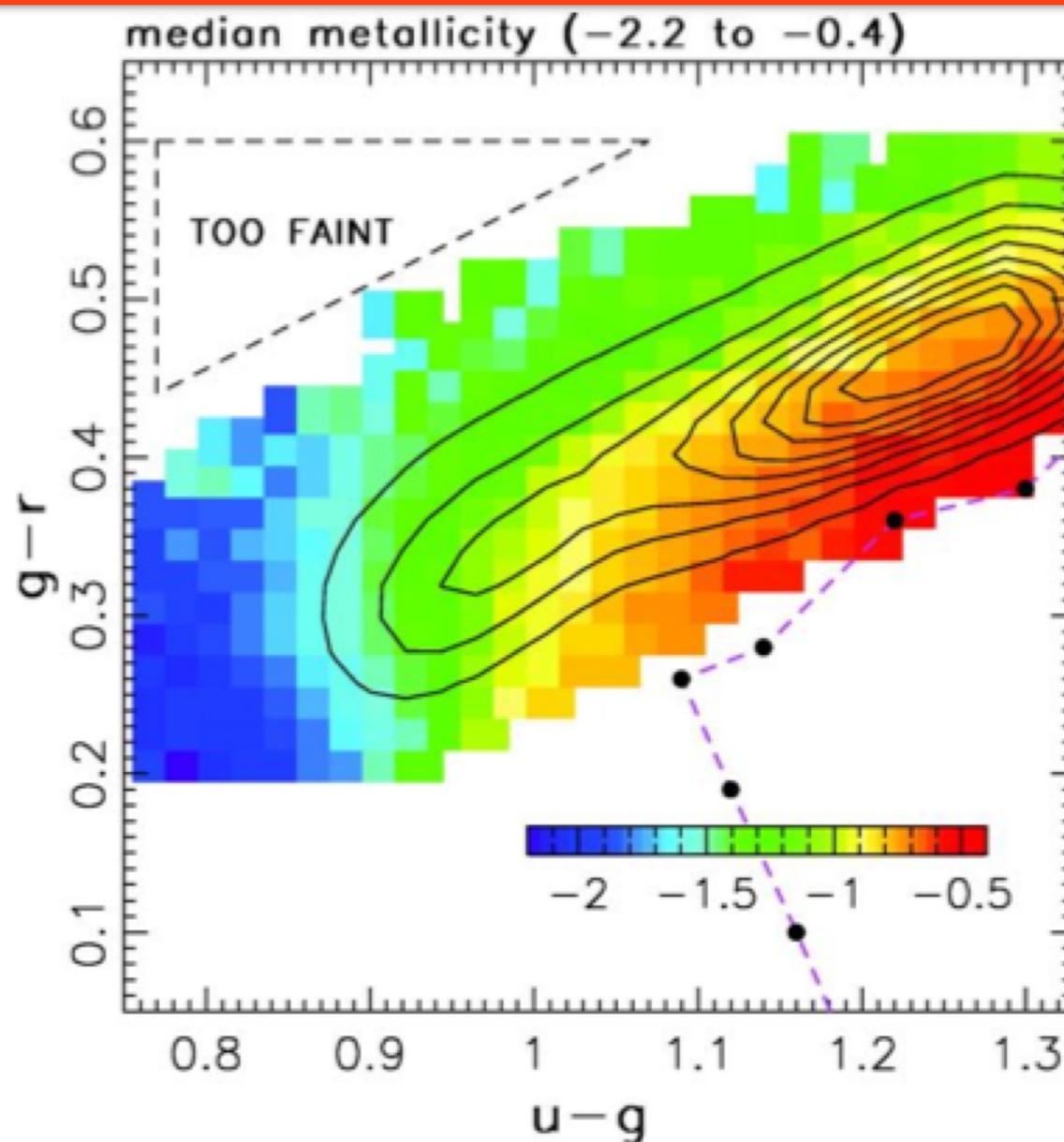
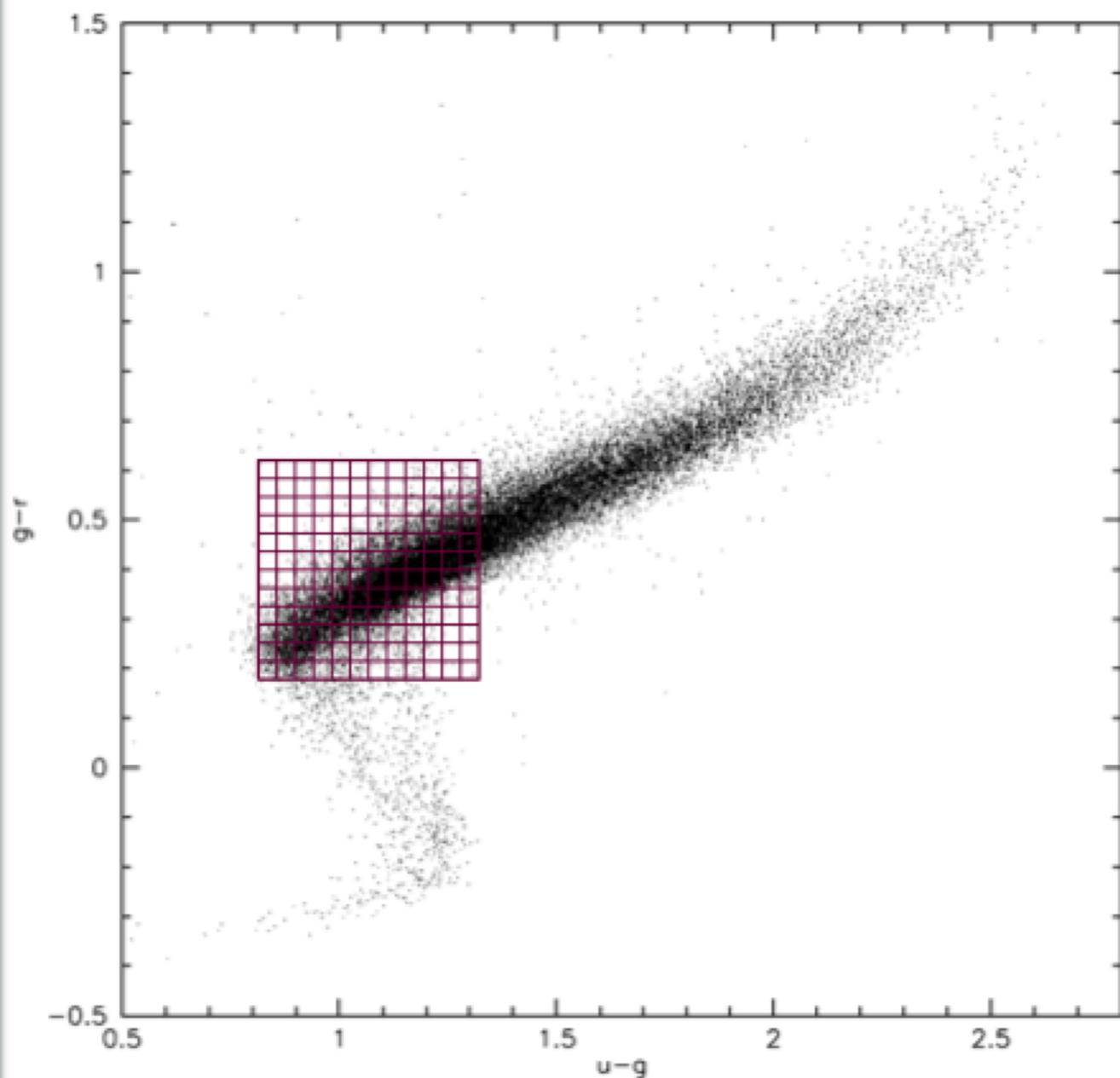
Photometric Distance and Photometric $[Fe/H]$

- 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**

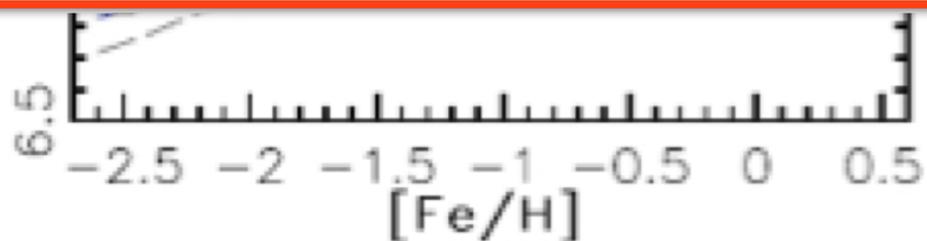
This method was known half a century ago, but never before applied to tens of millions of stars because large-scale surveys did not have the required photometric accuracy



Photometric Distance and Photometric [Fe/H]

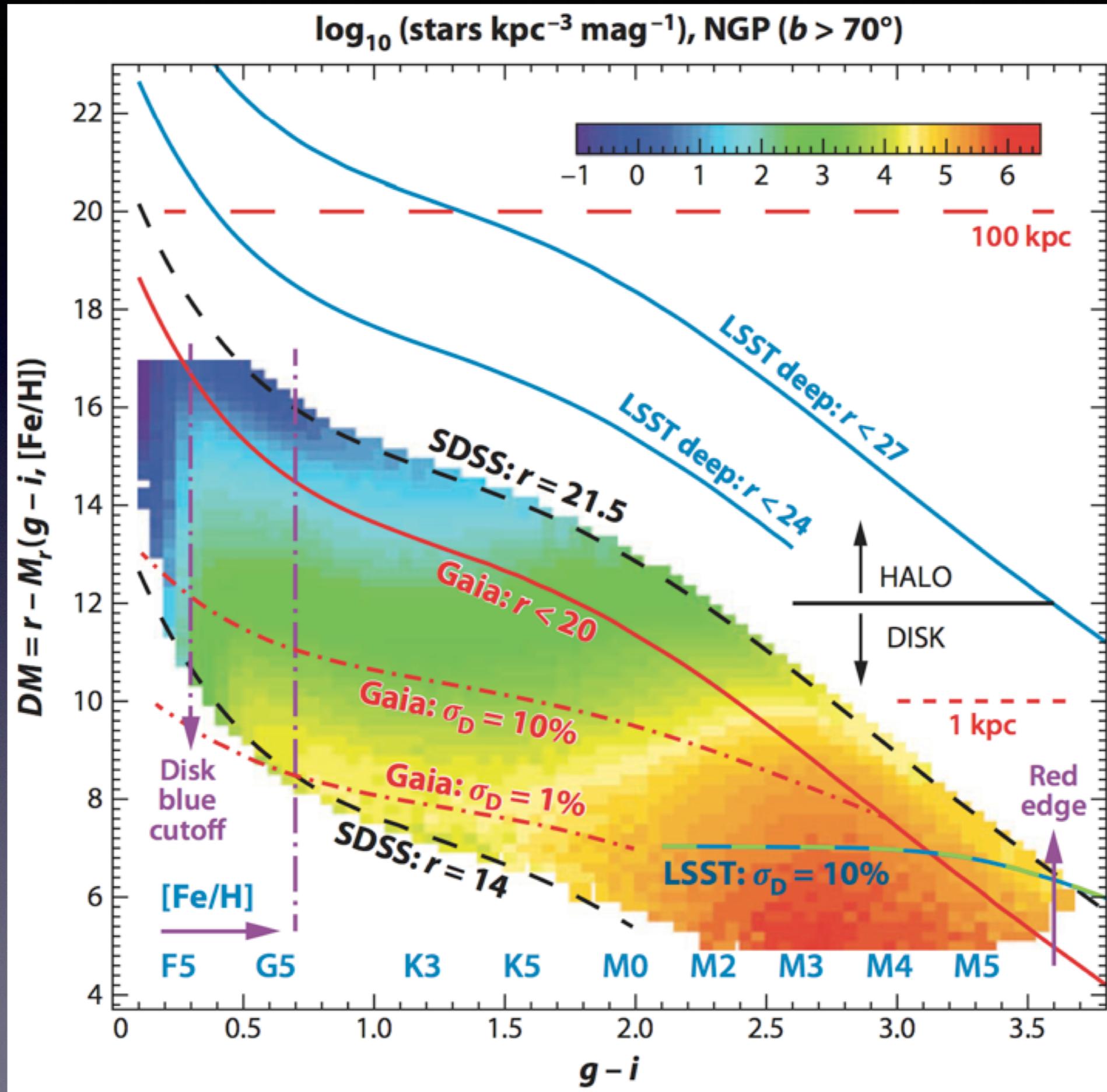


- **$u-g$ and $g-r$ colors provide an estimator of metallicity, $[Fe/H]$**

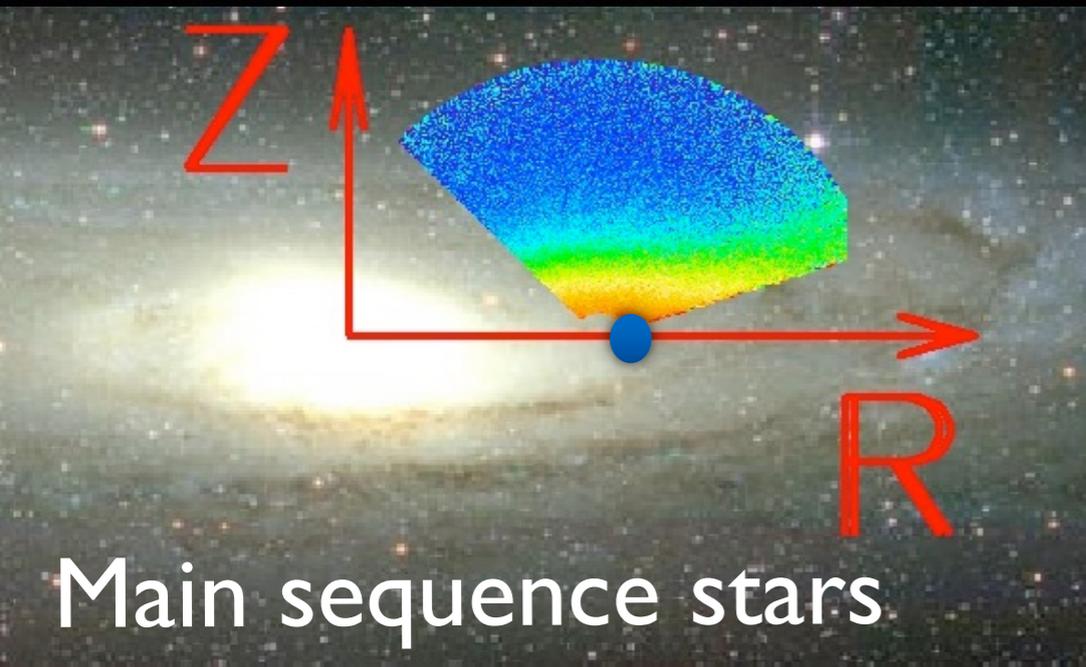


because large-scale surveys did not have the required photometric accuracy

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

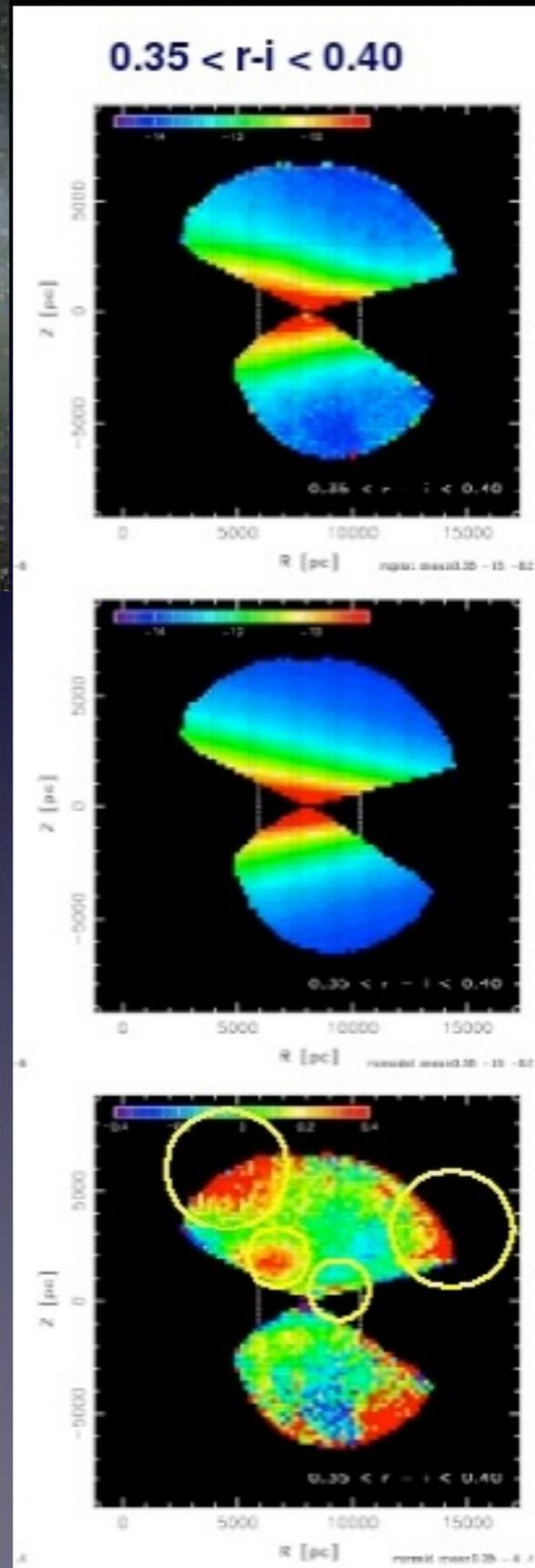
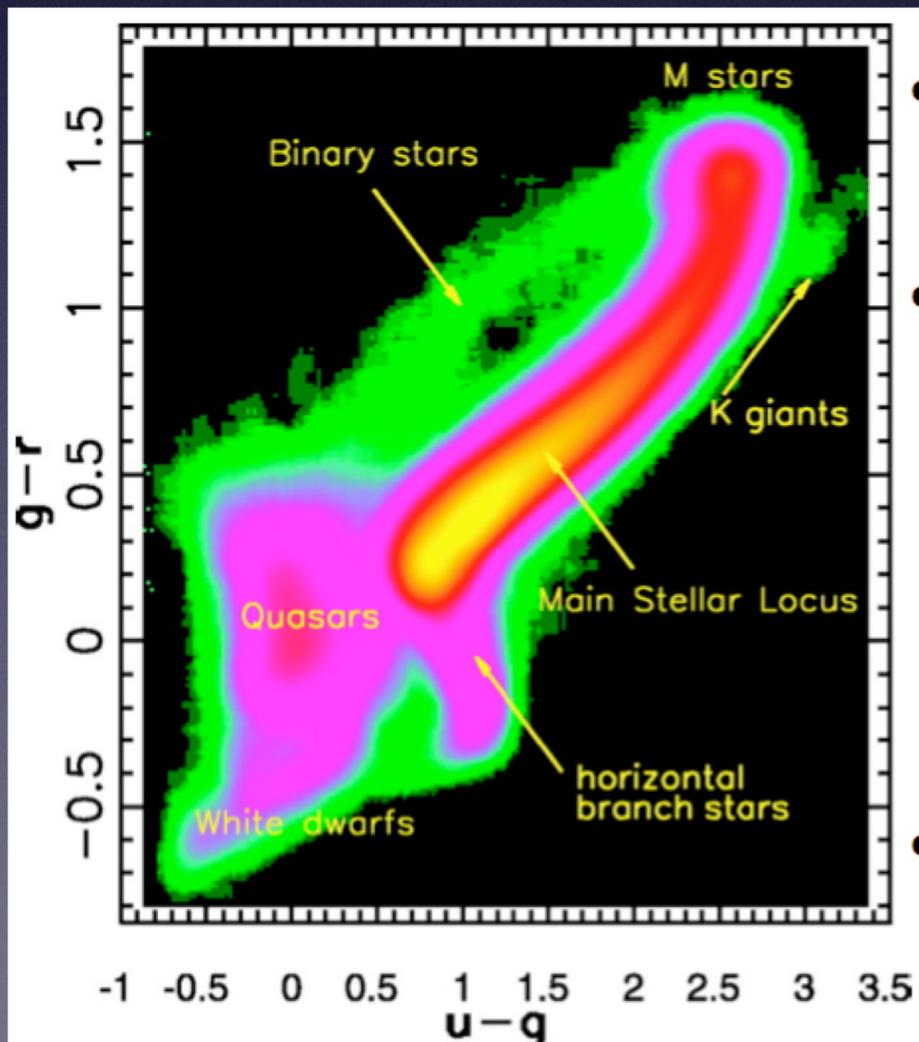


The Milky Way structure: 20 billion stars, time domain massive statistical studies!



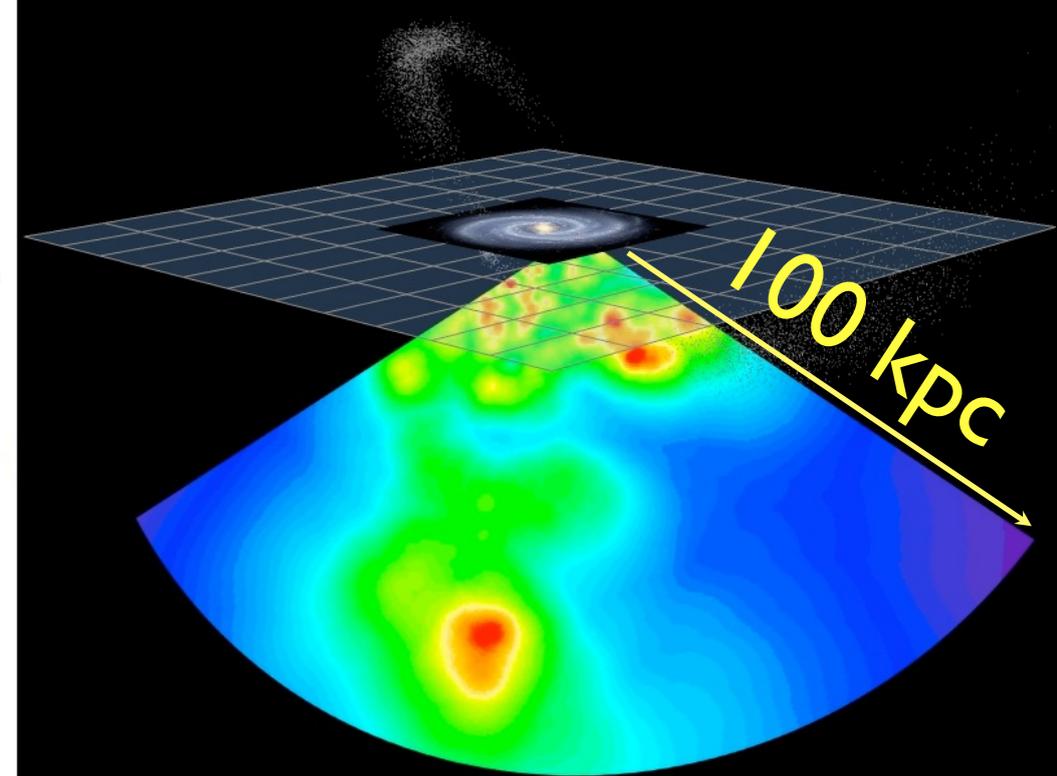
Main sequence stars

Distance and $[Fe/H]$:



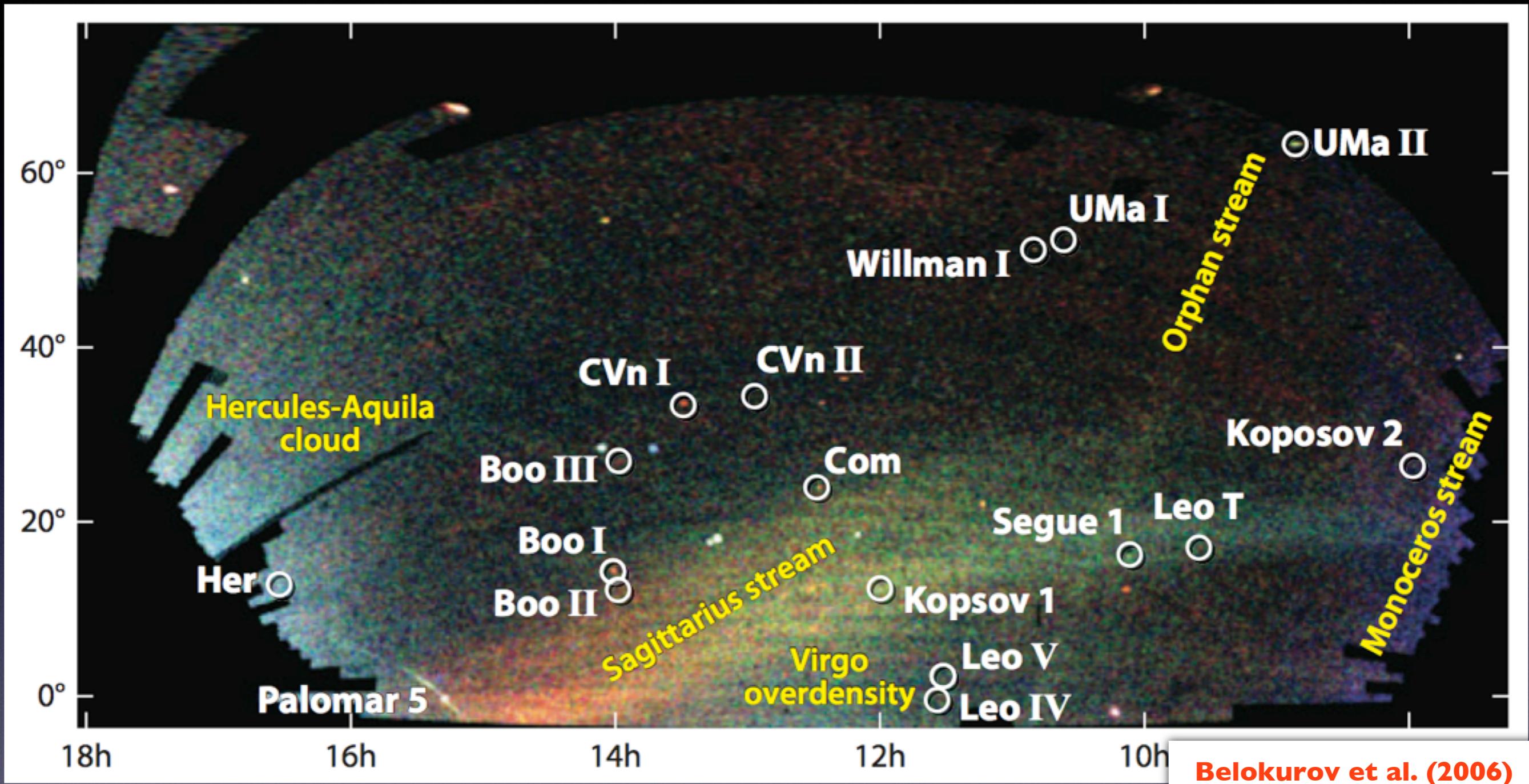
Sesar et al. (2009)

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



SDSS RR Lyrae

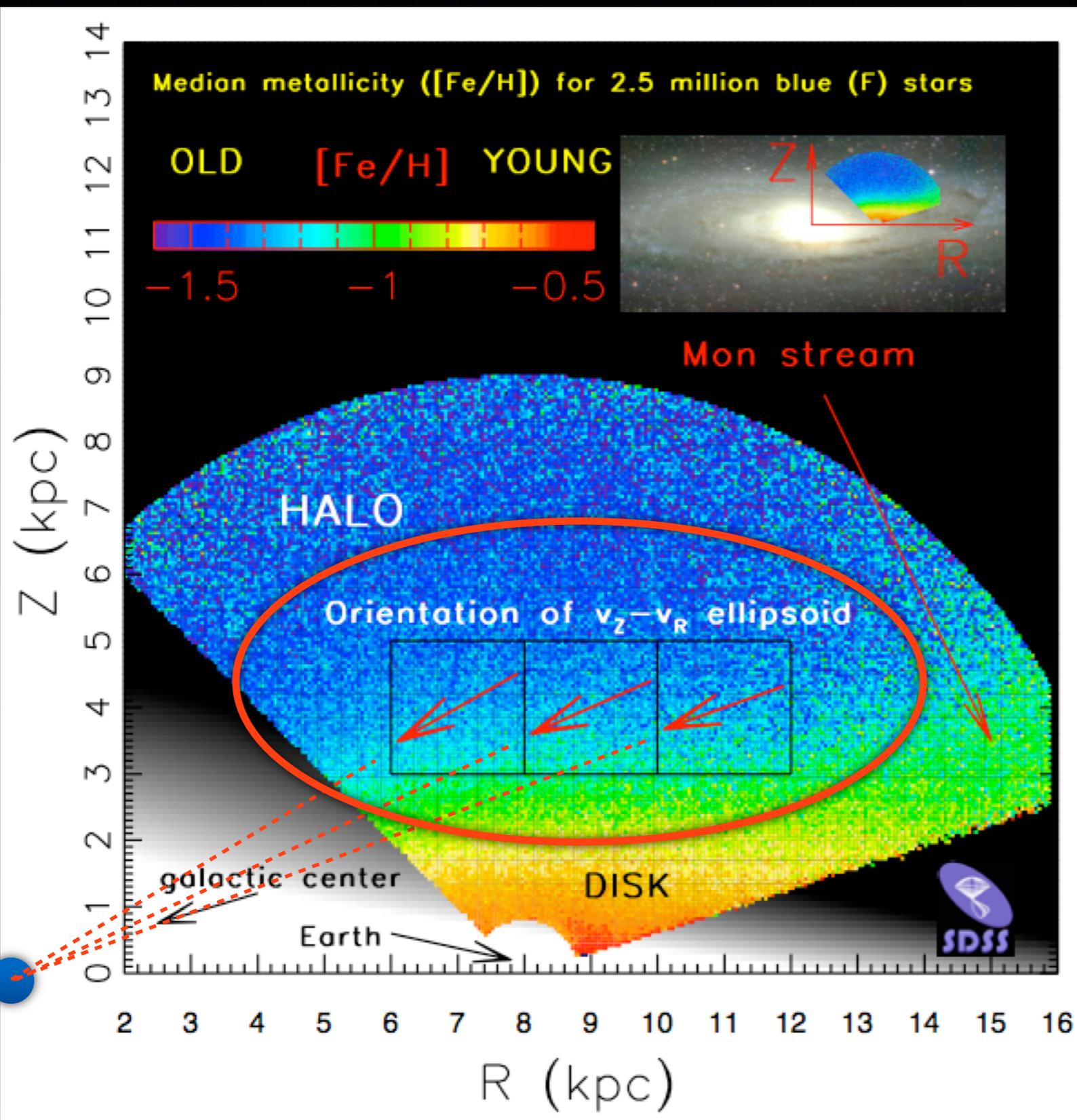
Mapping dark matter in the MW halo



The halo structure is interesting because:

- 1) dynamical times are long (merger history), and
- 2) gravitational potential becomes dominated by the dark matter halo

Velocity distribution for halo stars (SDSS)



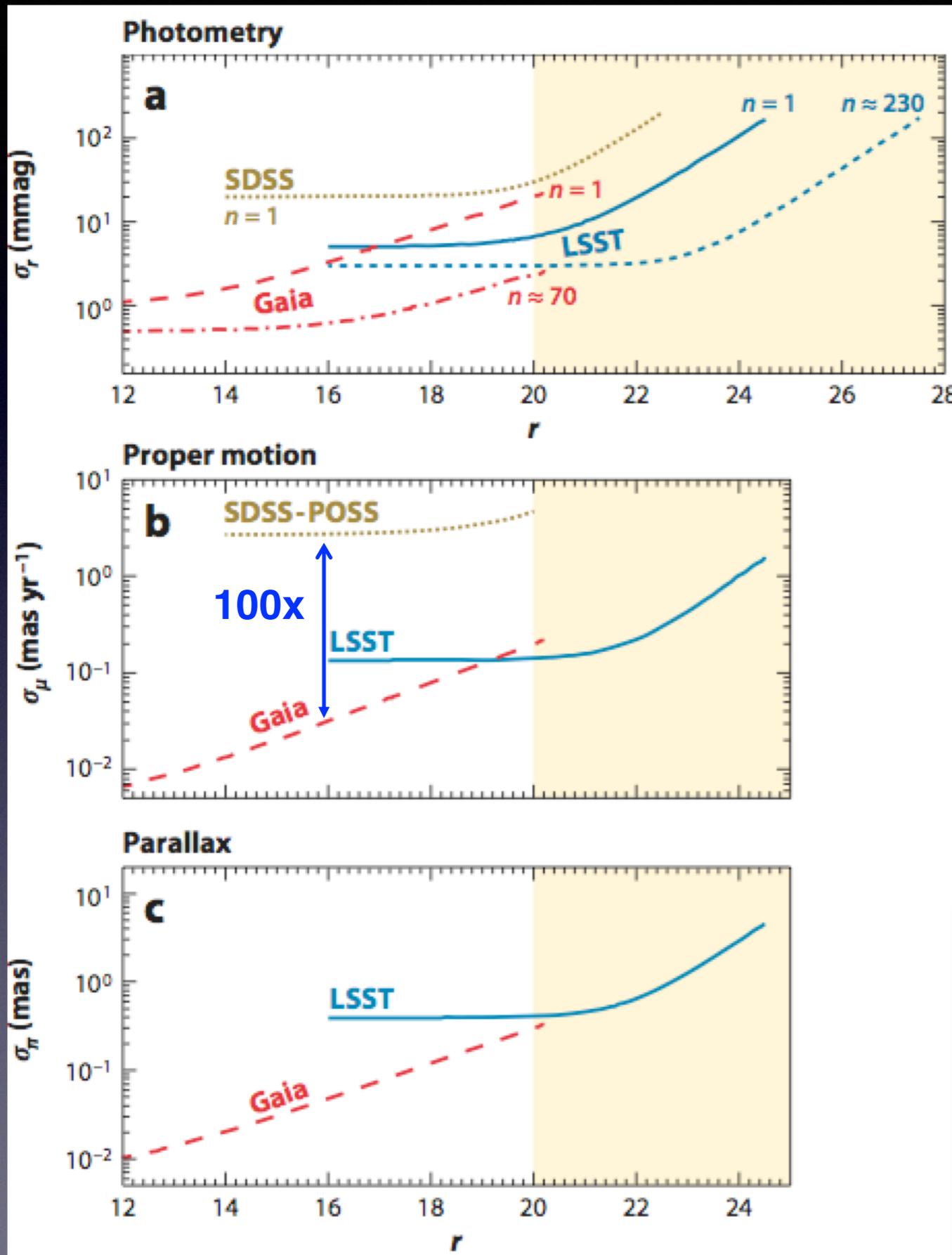
Kinematics of halo stars based on SDSS-POSS proper motions: velocity ellipsoid is nearly invariant in spherical coordinate system

[Bond et al. \(2010, ApJ, 716, 1\)](#)

Given measured stellar spatial distribution and stellar kinematics from proper motions, we can use **Jeans equations** to infer the gravitational potential, and ultimately the distribution of dark matter!

[Loebman et al. \(2014, ApJ, 794, 115\)](#)

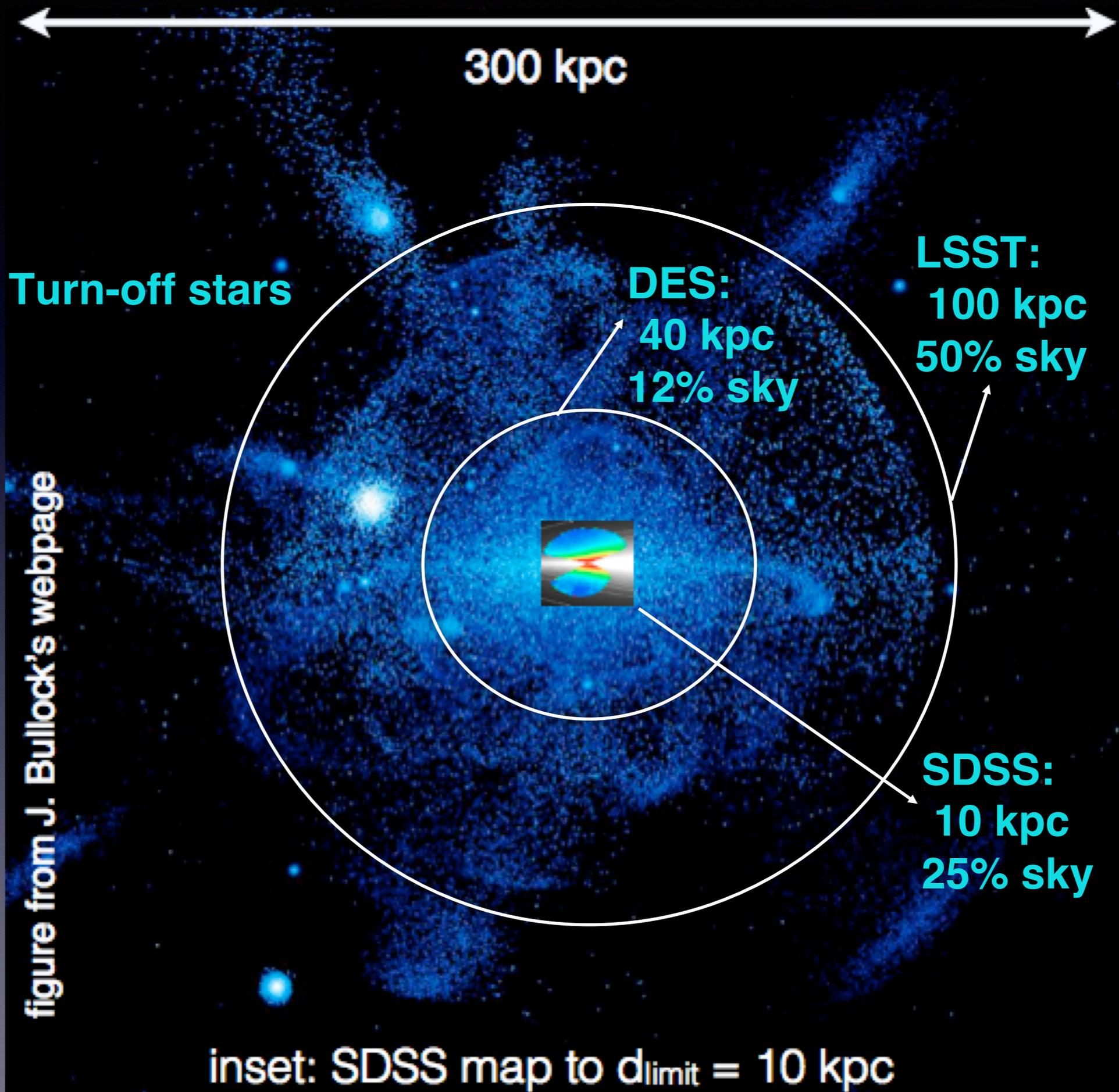
Gaia vs. LSST comparison



- **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 $r=20$

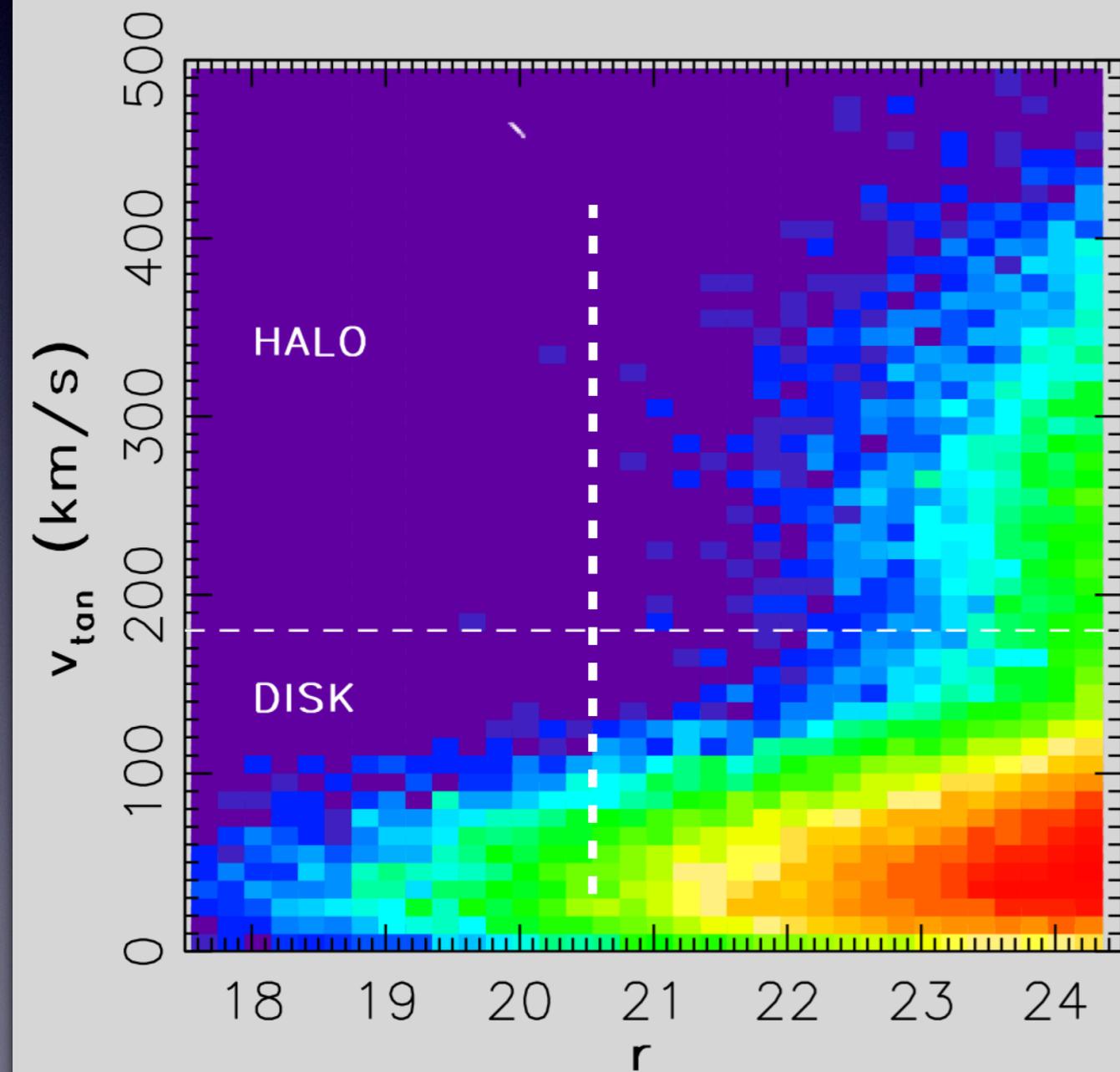
The Milky Way disk “belongs” to Gaia, and the halo to LSST (plus very faint and/or very red sources, such as white dwarfs and LT(Y) dwarfs).

Milky Way science with coadded LSST data



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 $>5\sigma$ 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])

**“Ask Not What Data You Need To Do Your Science,
Ask What Science You Can Do With Your Data.”**



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?”

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