Searching for Satellite Galaxies of the Milky Way in the Dark Energy Survey

Keith Bechtol
Kavli Institute for Cosmological Physics at the University of Chicago
Fermilab Particle Astrophysics Center Seminar
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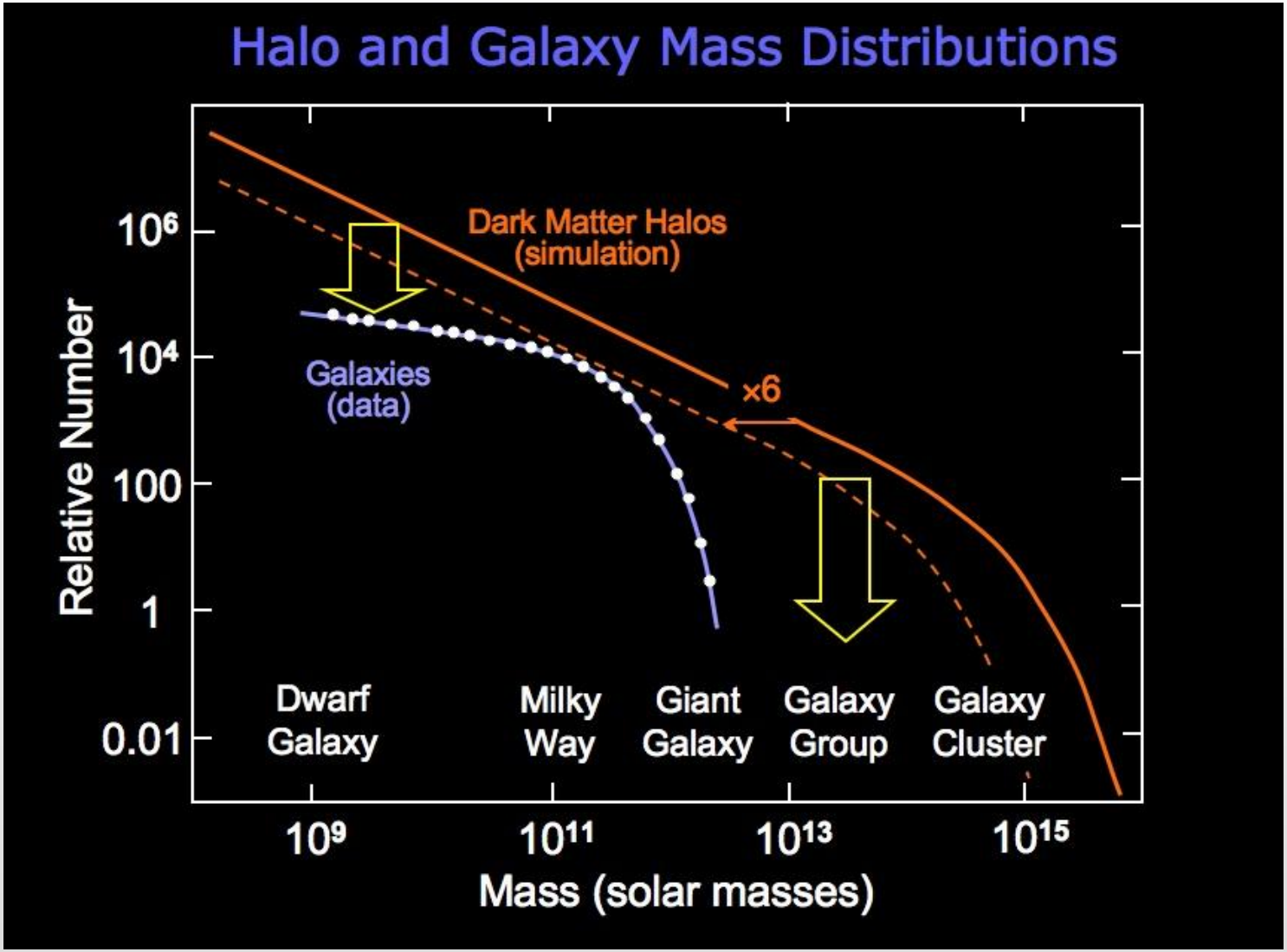
The Dark Energy Survey is Happening NOW!

- Stage III Dark Energy Experiment
- 5 year, 5000 deg^2 optical imaging survey
  - 5 filters: *grizY* (400 – 1000 nm)
  - New 570 Mpixel camera on Blanco 4m at CTIO
- Context with similar surveys:
  - Successor to SDSS
  - Contemporary with, e.g., Pan-STARRs, HSC
  - Precursor to LSST
- Status
  - Science Verification in 2012-2013 season
  - Main survey began 31 August 2013

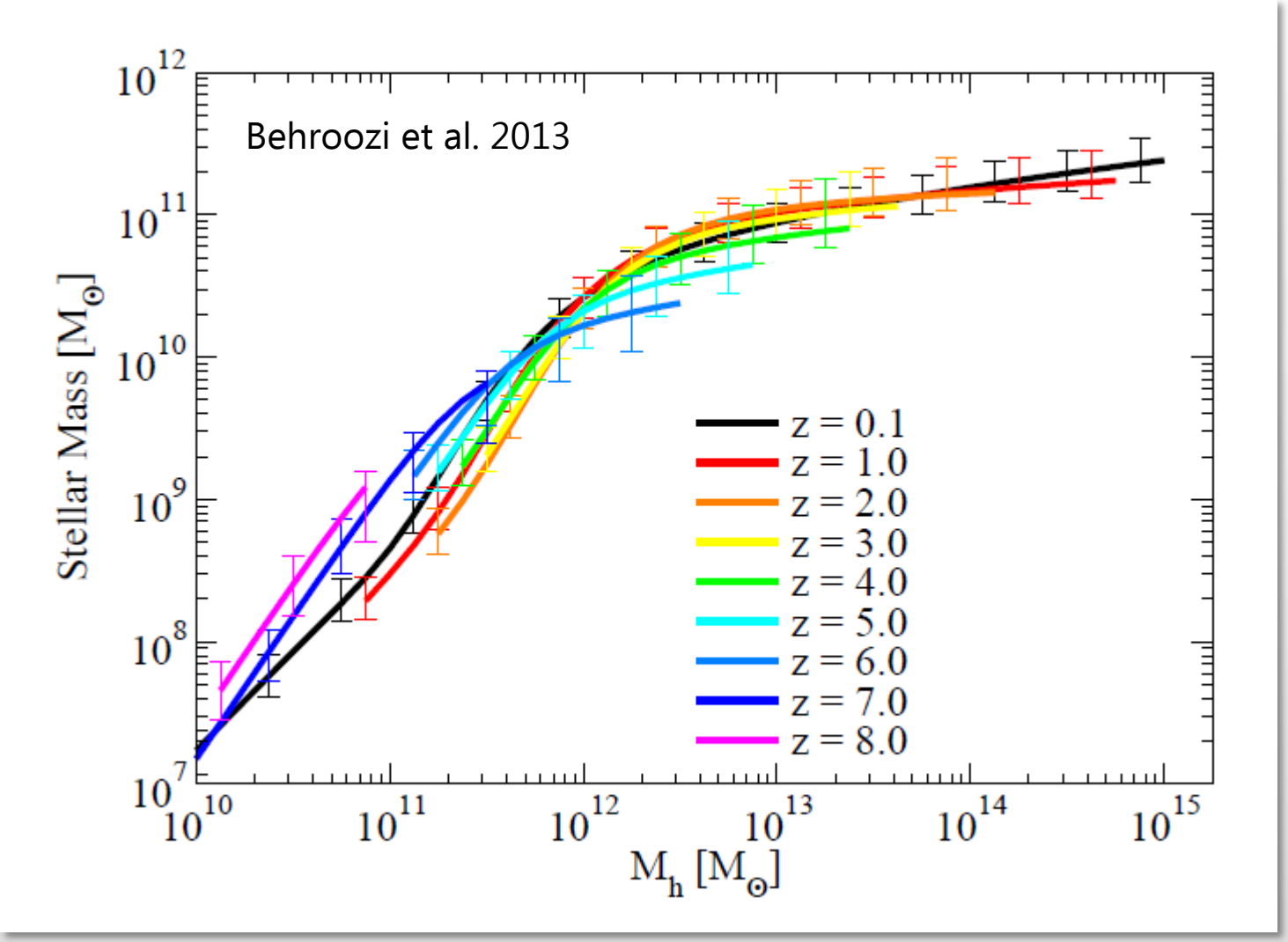
Part 1

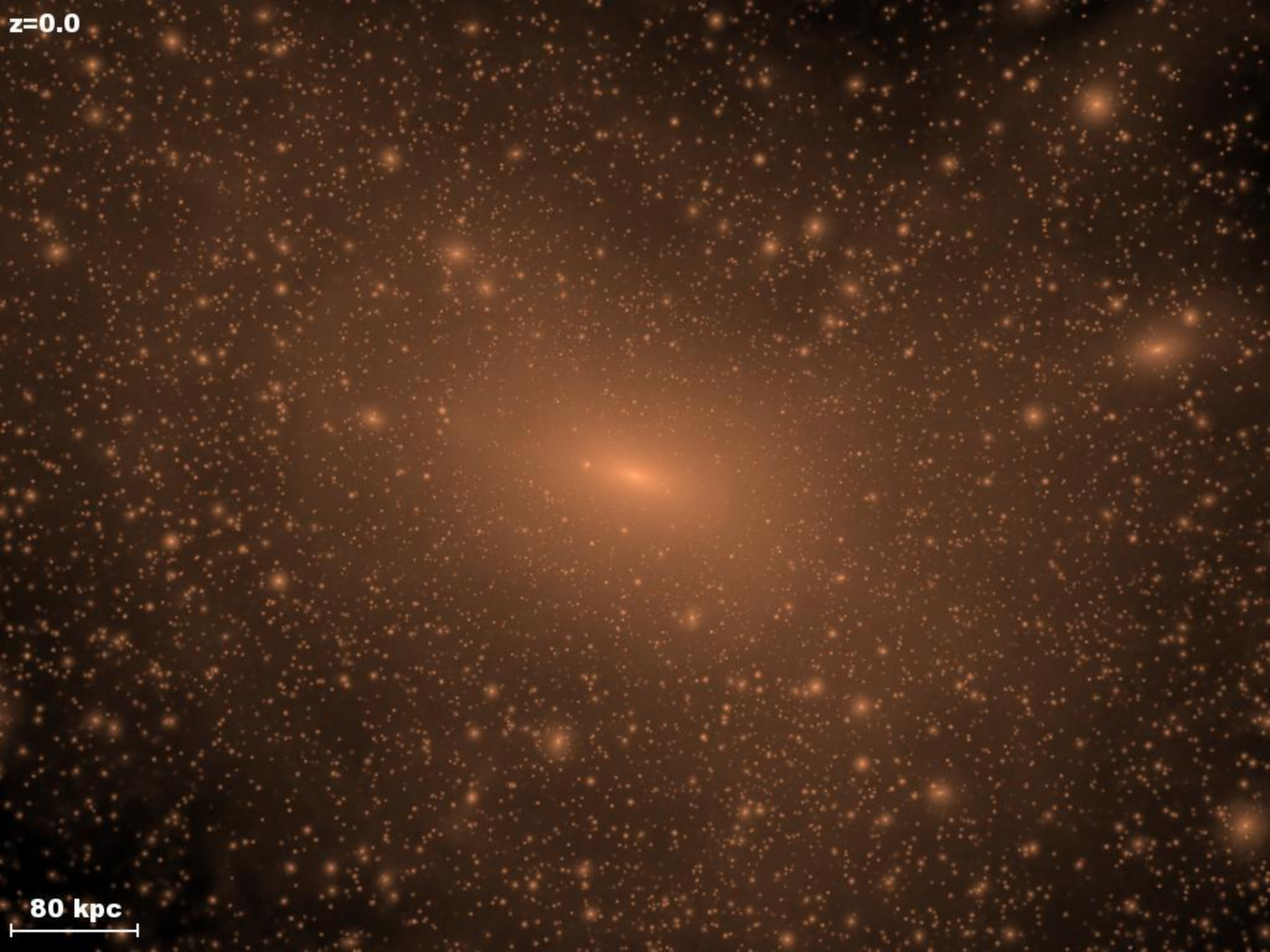
The Darkest Galaxies

Abundance Matching



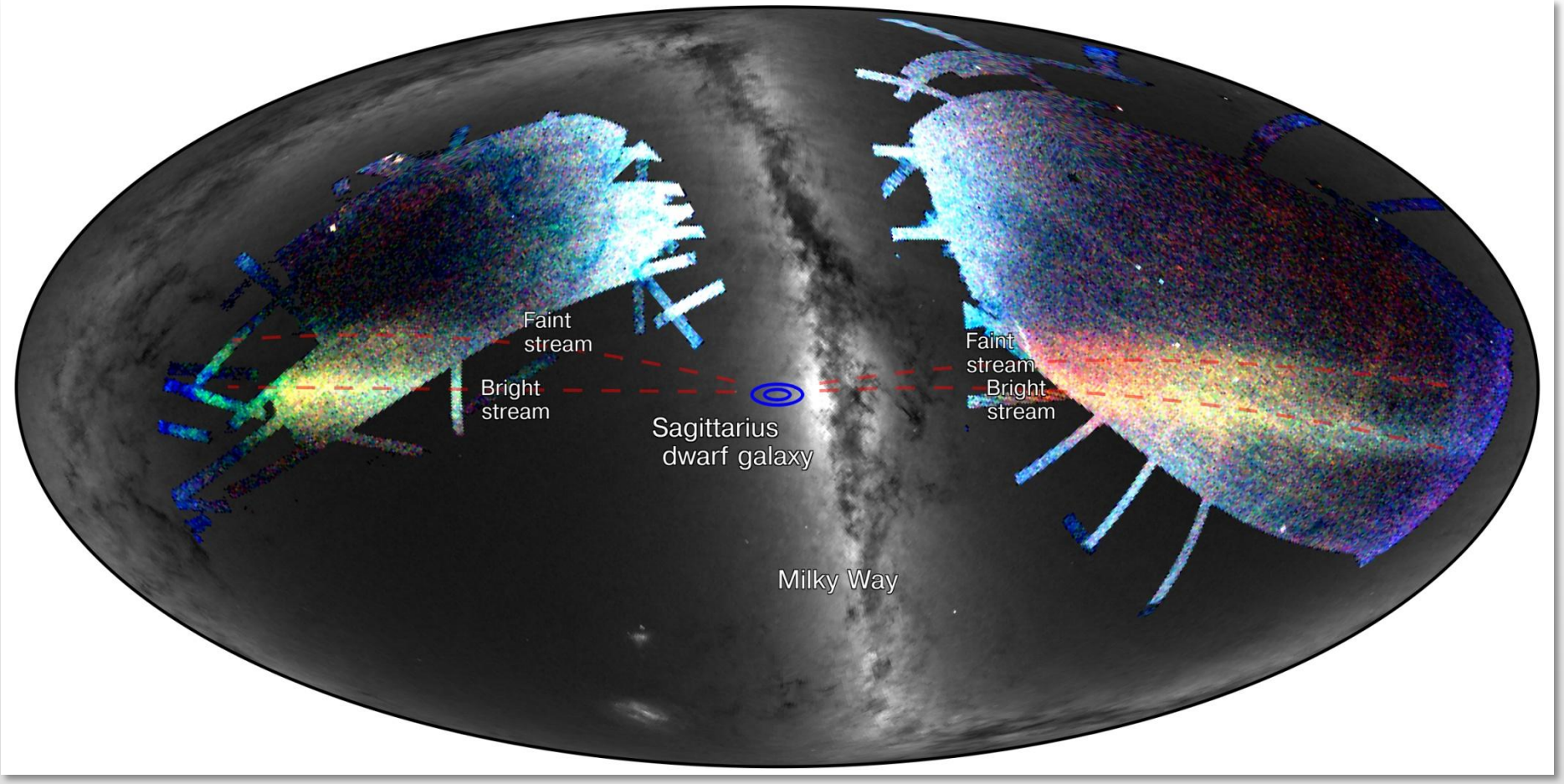
Stellar Mass – Halo Mass




z=0.0
80 kpc

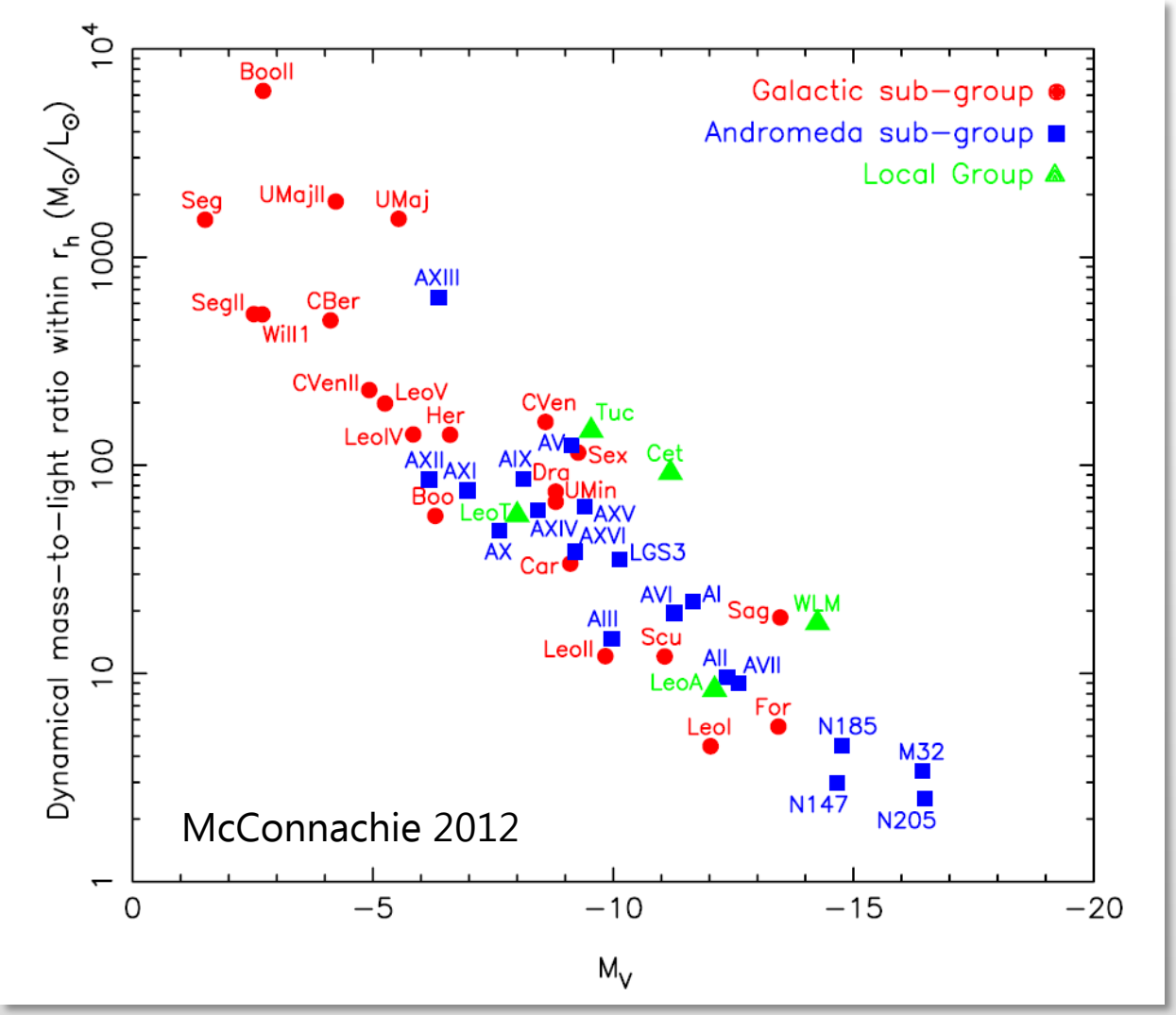
Enter SDSS

S. Koposov and the SDSS-III Collaboration

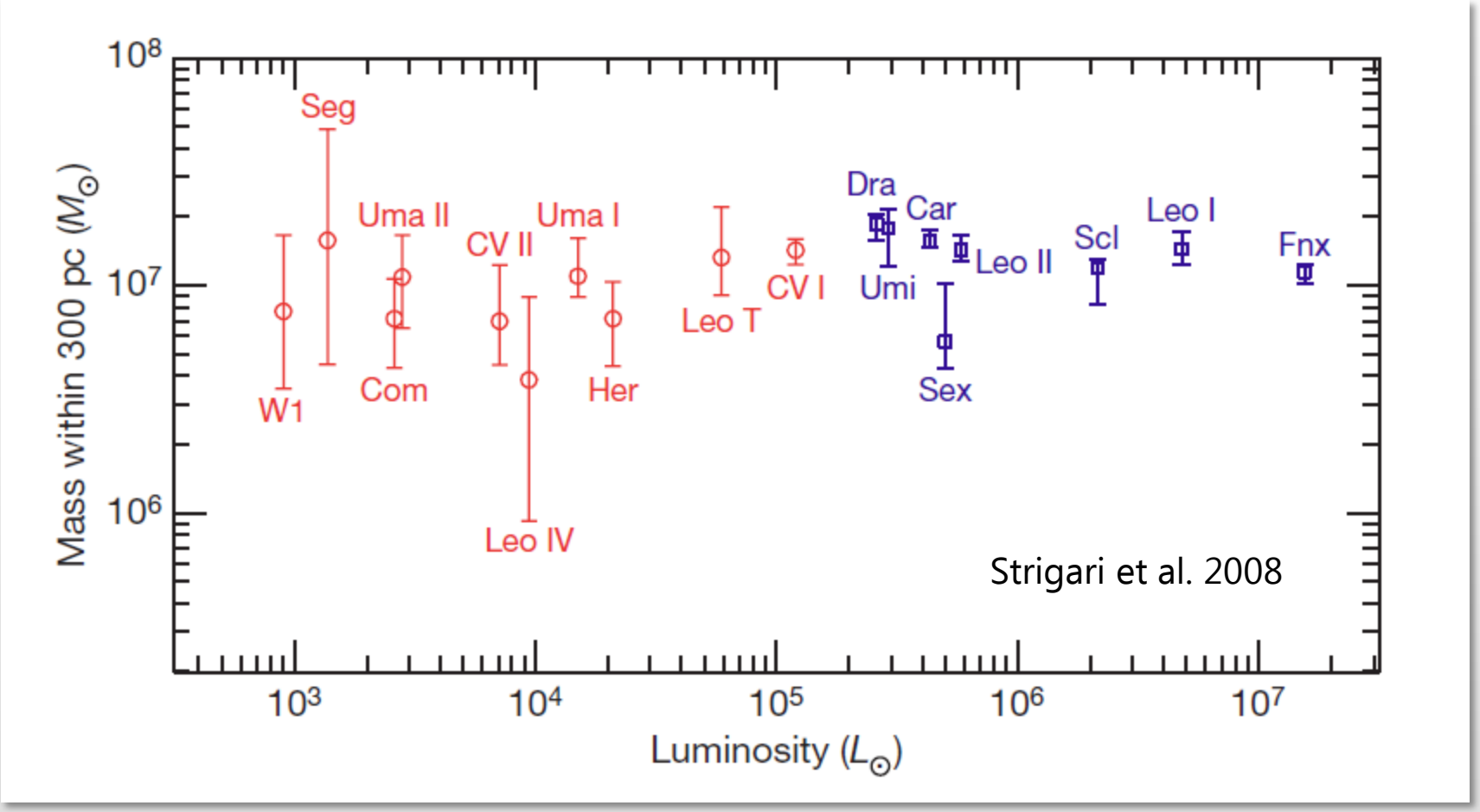


Color corresponds to distance with blue being near and red being far

The Darkest Galaxies



A Common Mass Scale for Milky Way Satellites?



Defining "Galaxy"

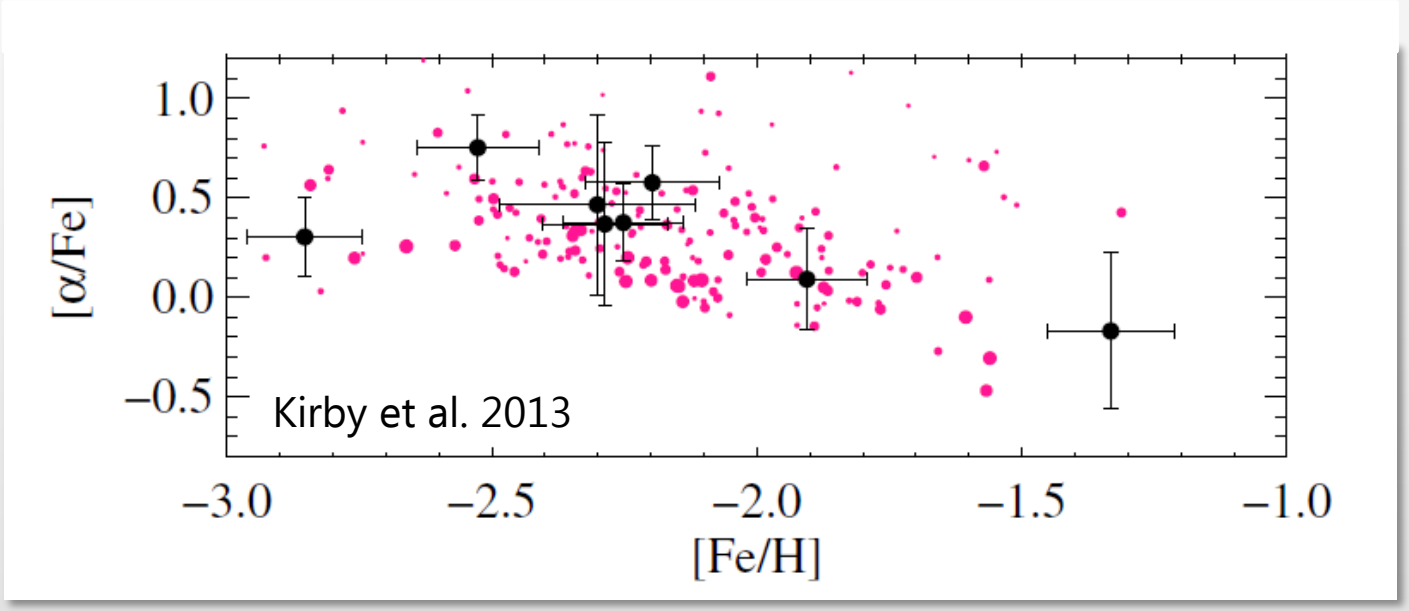
"a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity."

Willman & Strader 2012

Curious Case of Segue II

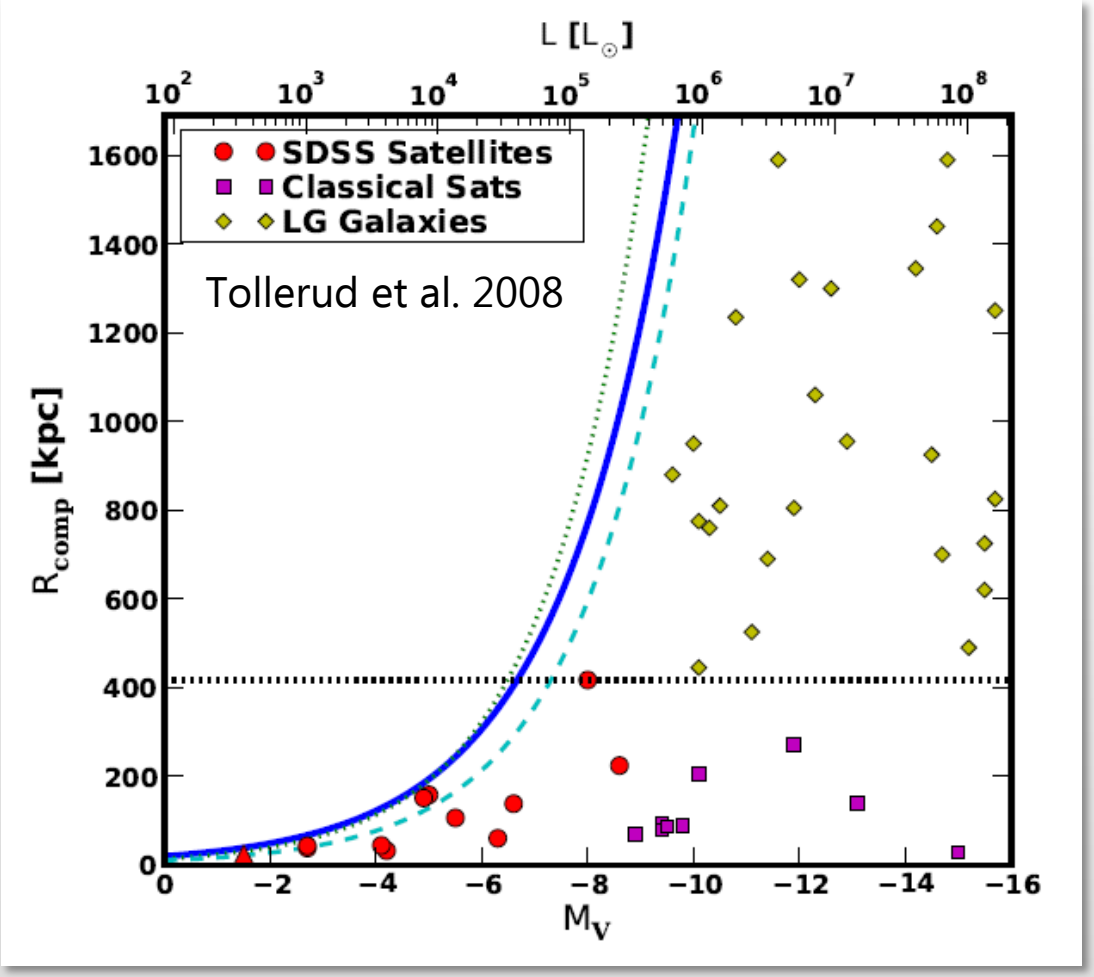
Updated spectroscopic measurements (Kirby et al. 2013) used to infer that Segue II is least massive galaxy known, with σ_v < 2.6 km s^{-1} (95%)

But argue chemical measurements show Segue II retained multiple generations of type Ia SNe ejecta, i.e., star formation lasted ~100 Myr.



(1) Segue II was more massive (x 10^2 - 10^3), but now tidally stripped
(2) Segue II formed at present stellar mass and metallicity

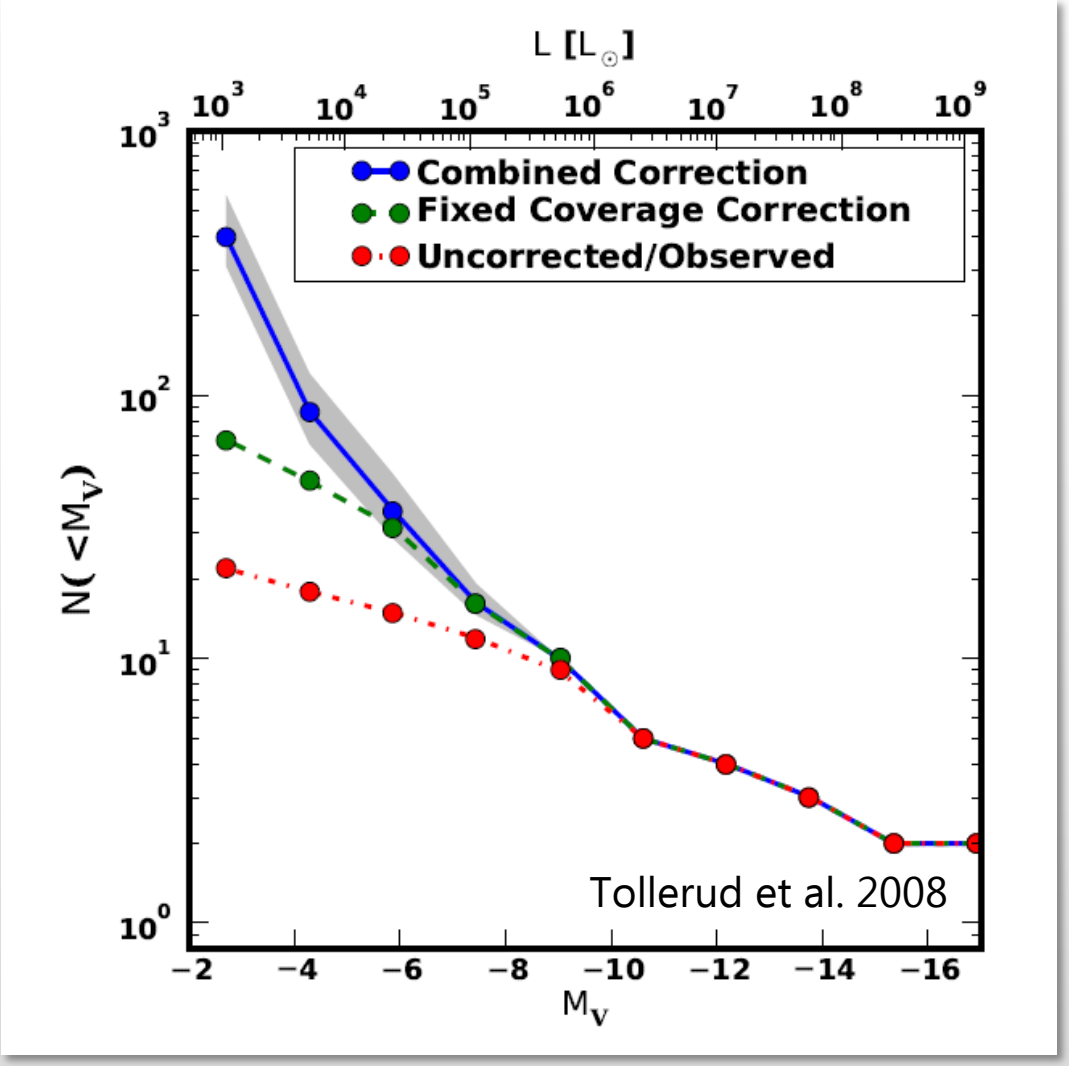
Luminosity Function of Milky Way Satellites



At high luminosities, the volume out to the Milky Way virial radius ~300 kpc has already been covered

At low luminosities, only a small fraction of this volume has been effectively surveyed

Luminosity Function of Milky Way Satellites



At high luminosities, the volume out to the Milky Way virial radius ~300 kpc has already been covered

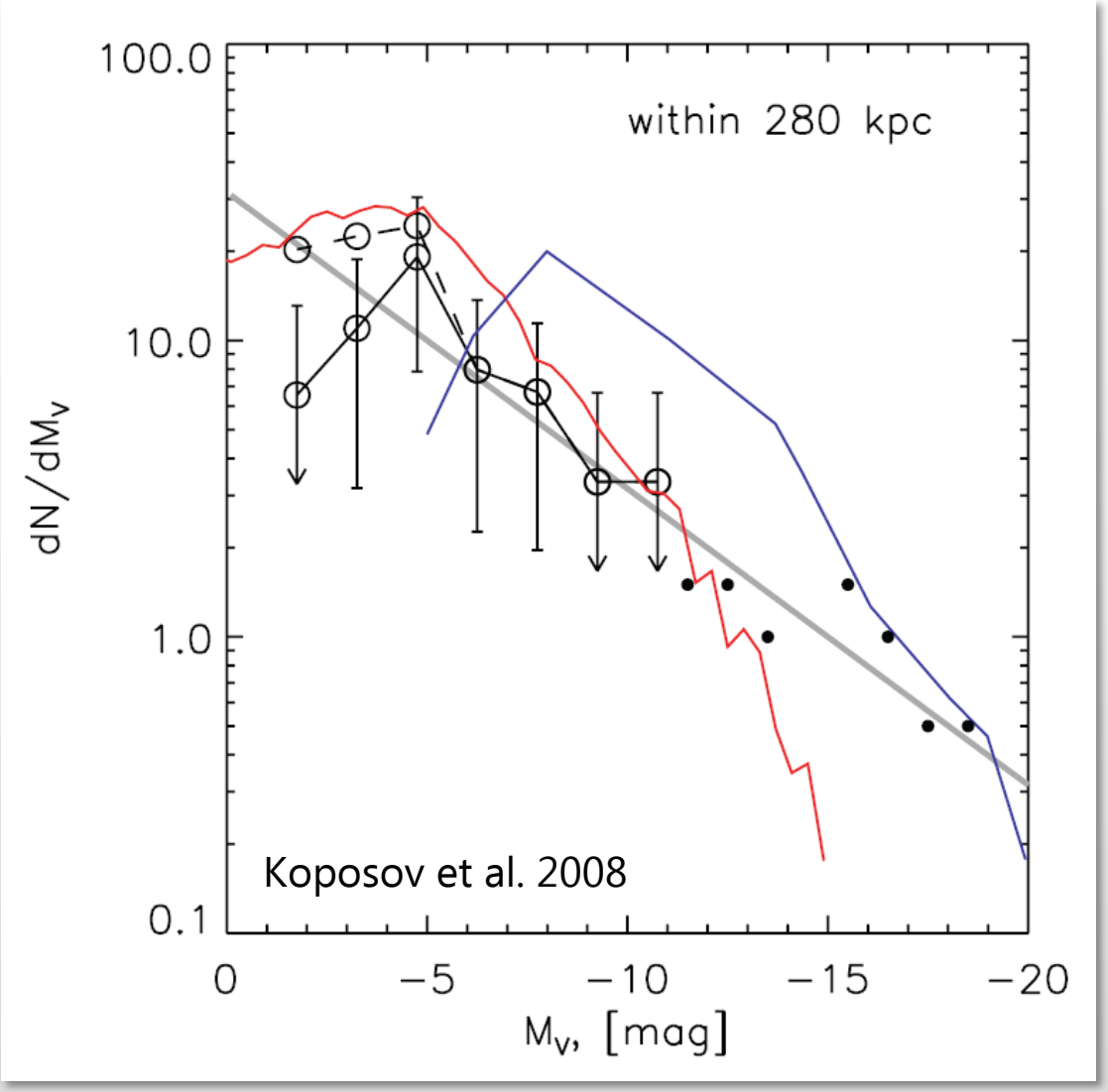
At low luminosities, only a small fraction of this volume has been effectively surveyed

Inferred luminosity function depends on assumed radial distribution of satellites (also suffers from low-count statistics)

Potentially several hundred satellites yet to be discovered?

Luminosity Function of Milky Way Satellites

But different adopted detection thresholds and assumed radial distributions can lead to more modest predictions



Part 2

Indirect Dark Matter Detection Outlook

Collaborators

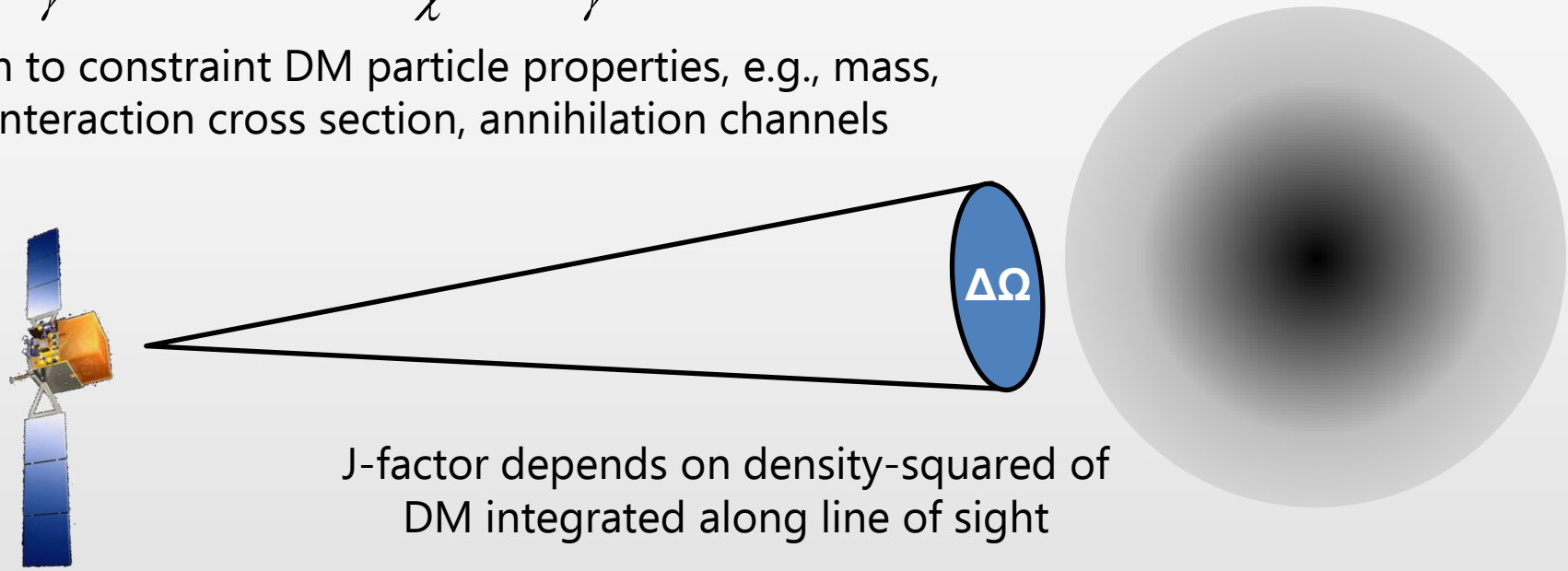
- Chen He (UChicago)
- Andrew Hearin (Fermilab)
- Dan Hooper (Fermilab/UChicago)

arXiv:1309.4780

Dark Matter Annihilation Gamma-ray Signal

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma} \times J(\Delta\Omega)$$

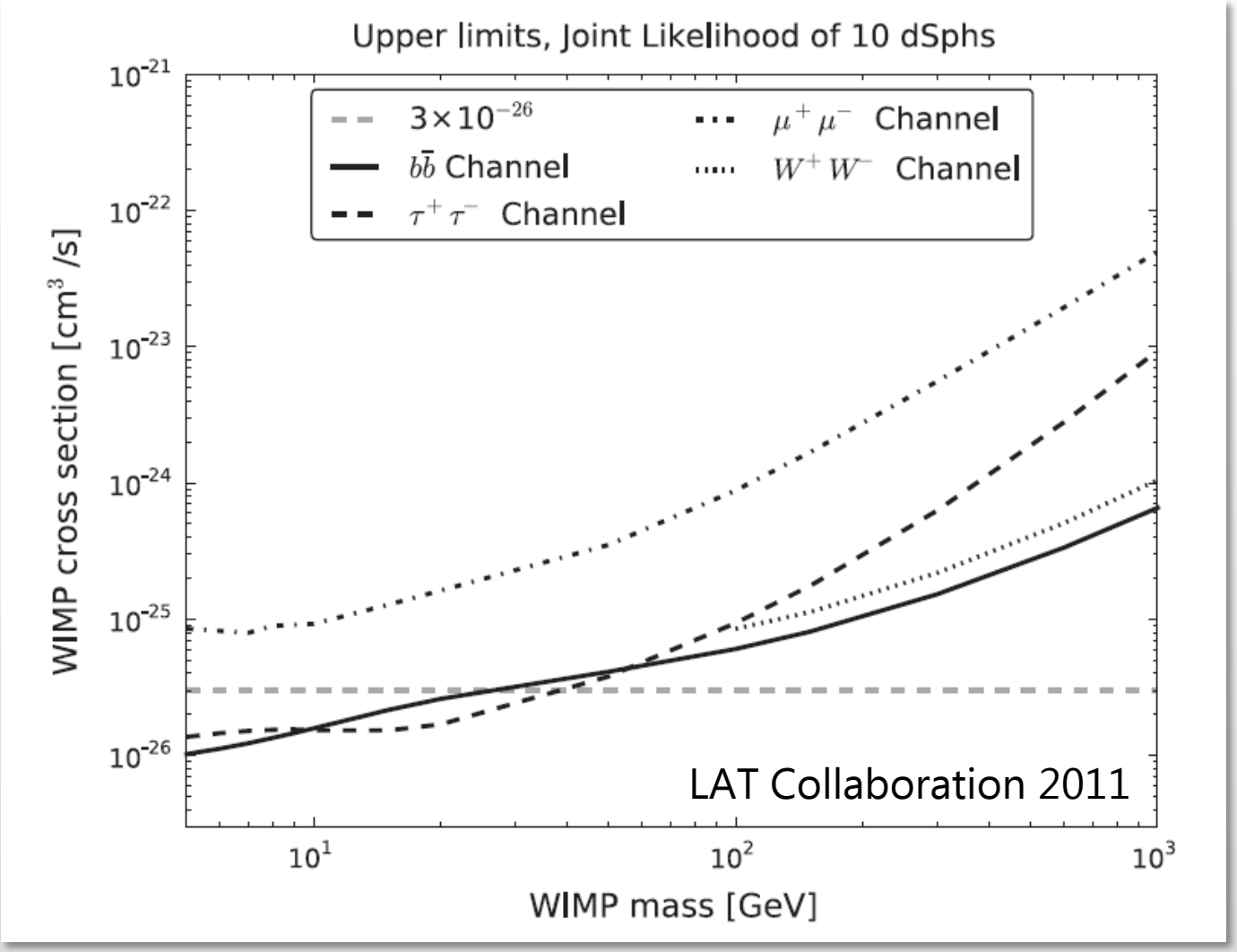
Aim to constraint DM particle properties, e.g., mass, interaction cross section, annihilation channels



J-factor depends on density-squared of DM integrated along line of sight

$$J(\Delta\Omega) = \int_{\Delta\Omega}\int \rho^2(l,\Omega)\,dl\,d\Omega$$

24-month *Fermi*-LAT Annihilation Constraints



Indirect searches now begin reaching DM cross sections to explain the thermal relic abundance

Joint likelihood analysis of 10 dwarfs

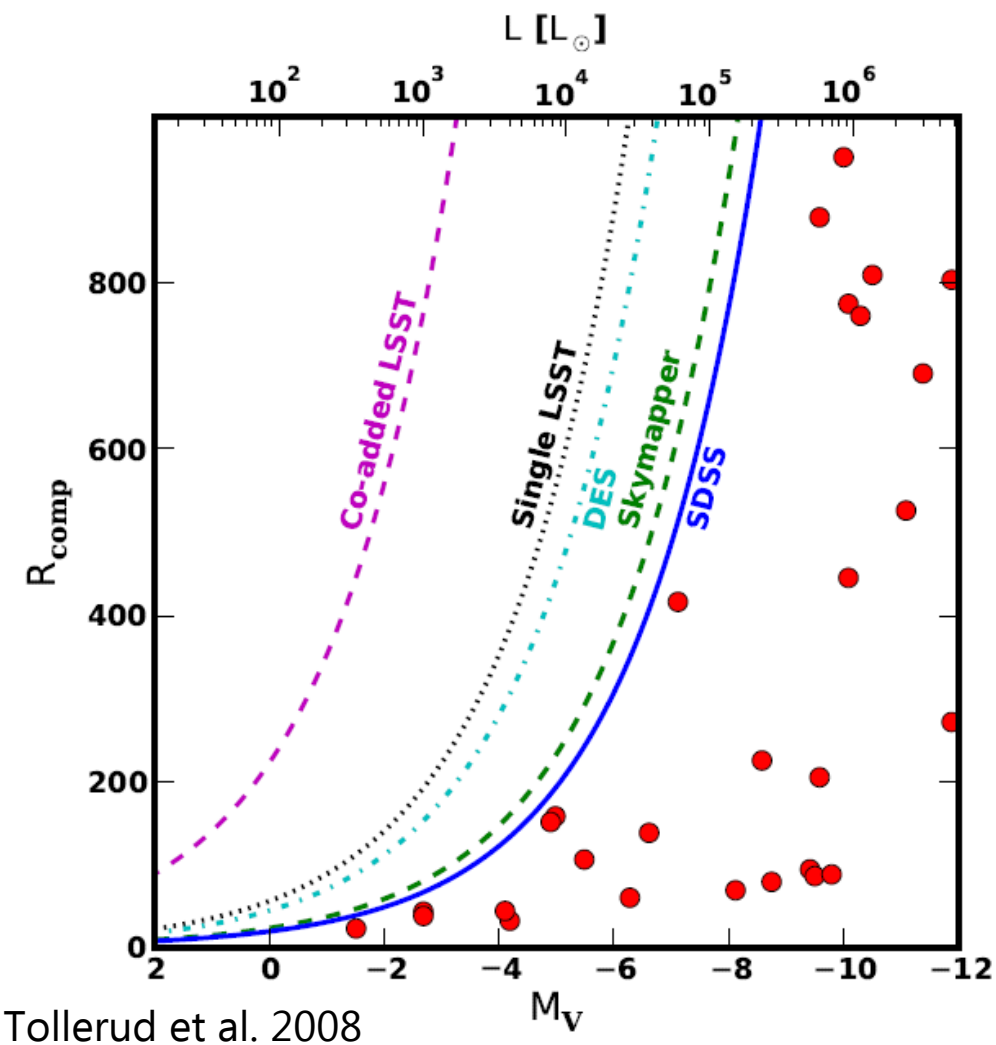
*Updated constraints from the LAT Collaboration to be published shortly…

Ask Alex Drlica-Wagner for details

Current and Upcoming Optical Surveys

As next-generation optical surveys discover more satellites in different parts of the sky and at lower luminosities / further distances, **how will the DM limits improve?**

Our study focuses on the **demographics** of satellites that could be found in the next decade, i.e., the distribution of J-factors



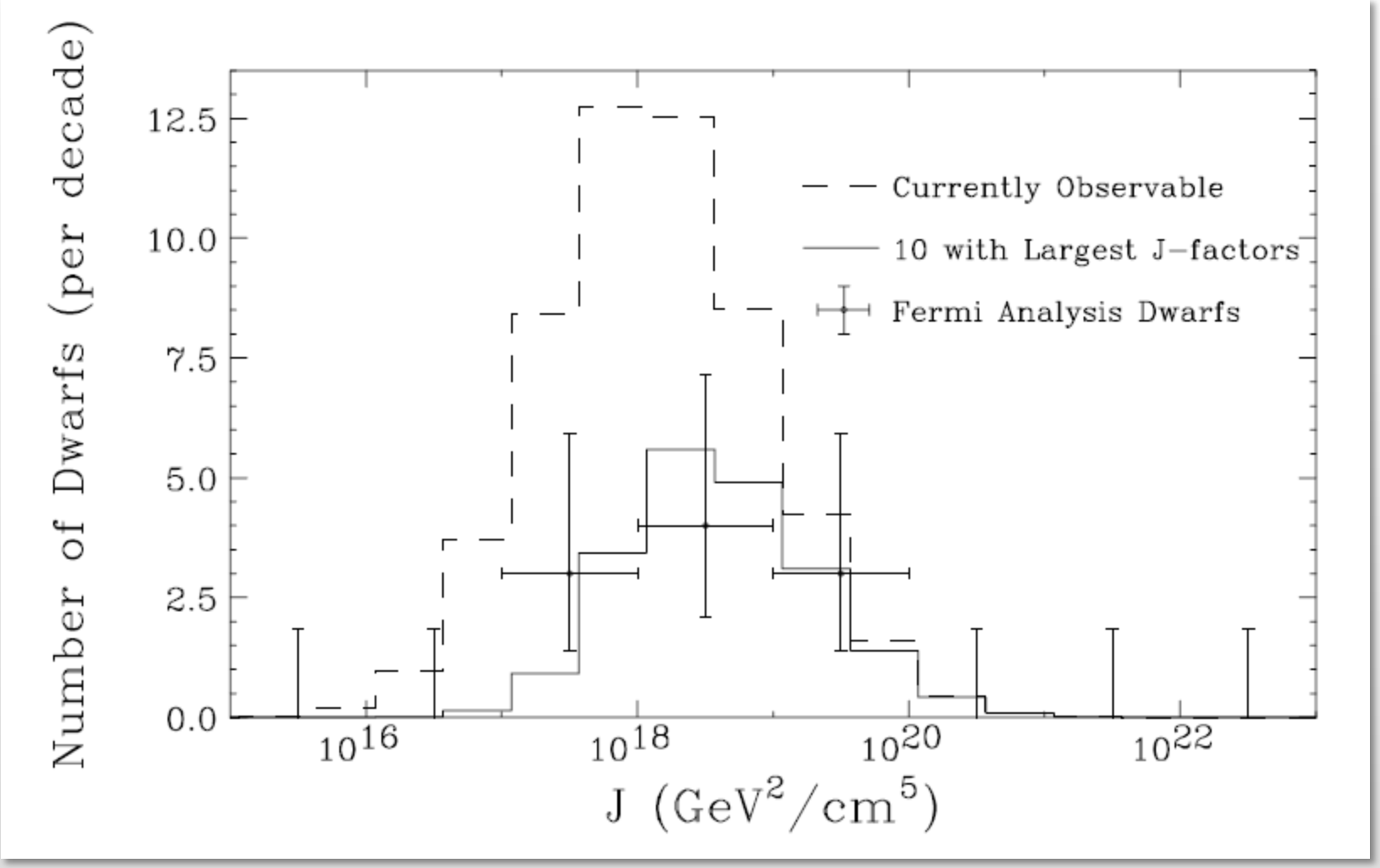
Tollerud et al. 2008

Which Satellites Will be Found?

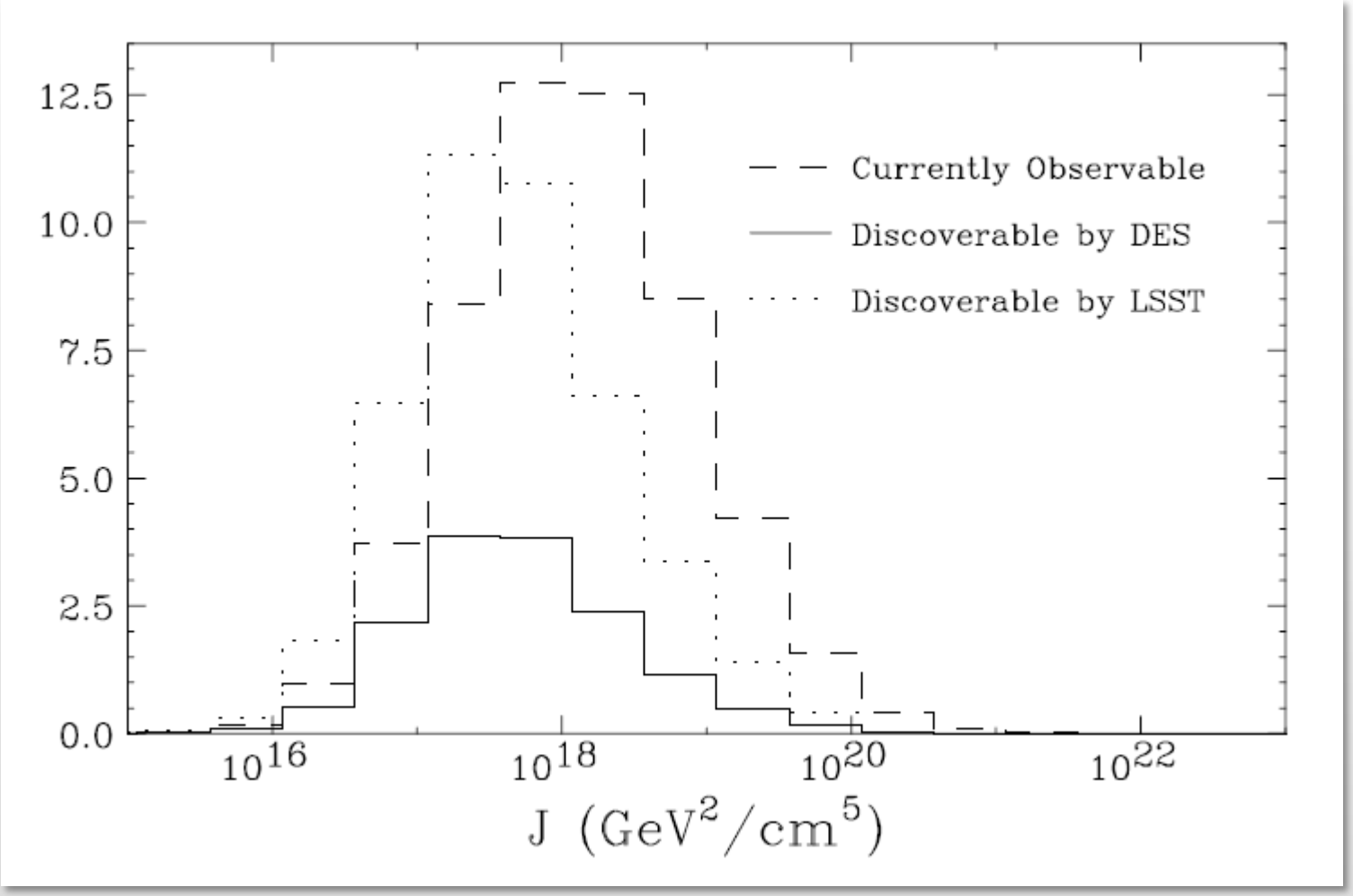
- Ingredients:
  - Aquarius semi-analytic model for DM halos and their optical luminosities (Font et al. 2003)
  - Radial distribution from *Via Lactea* simulation

- Adopted detection thresholds in absolute magnitude relative to SDSS (Walsh et al. 2009):
  - DES: 1.9 mag fainter
  - LSST: 5.3 mag fainter

J-factor Distributions
Model and Data Comparison

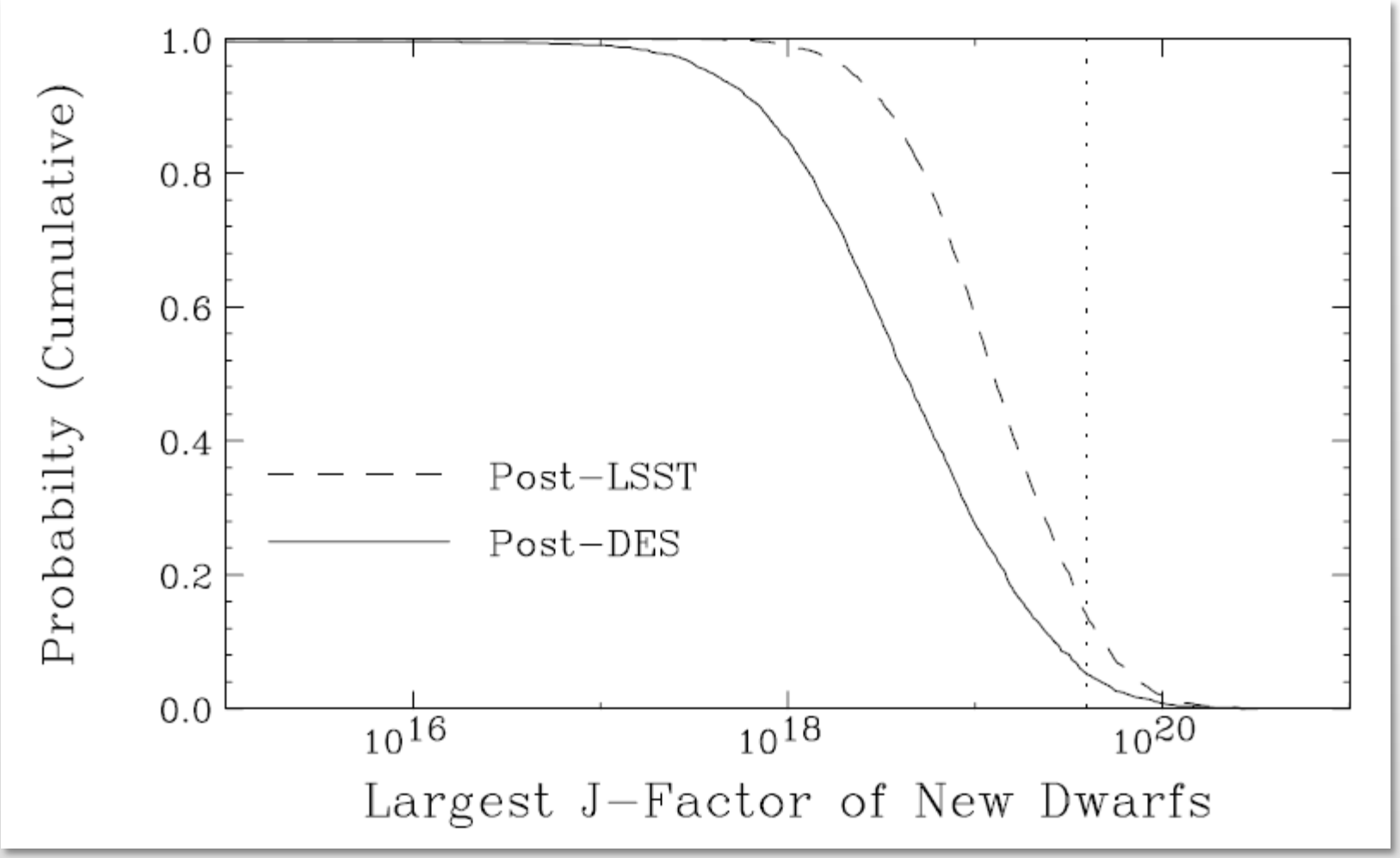


J-factor Distributions
Model Predictions

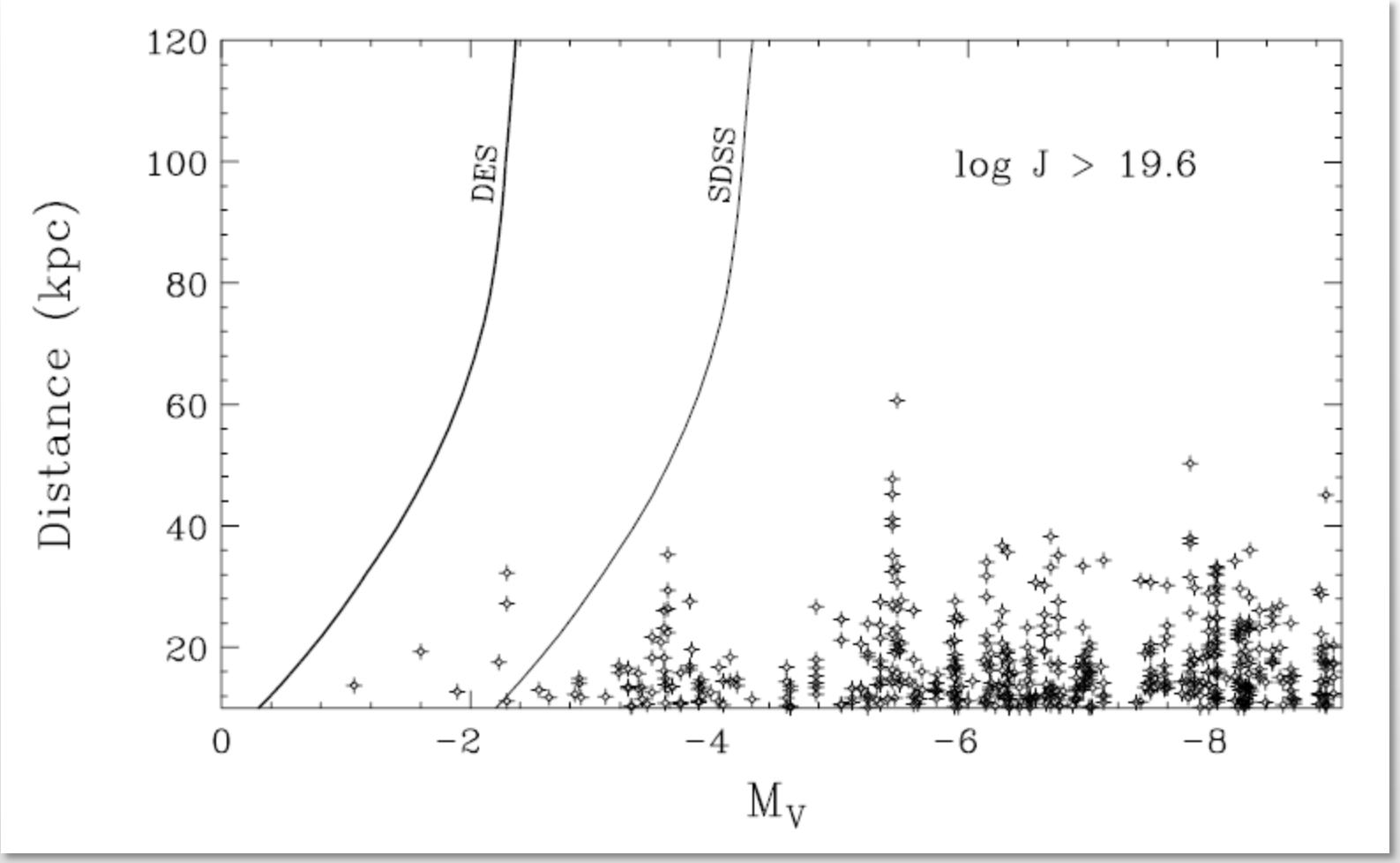


Highest Newly Discovered J-factor Model Predictions

Joint limits largely driven by the highest J-factor satellite galaxy in sample

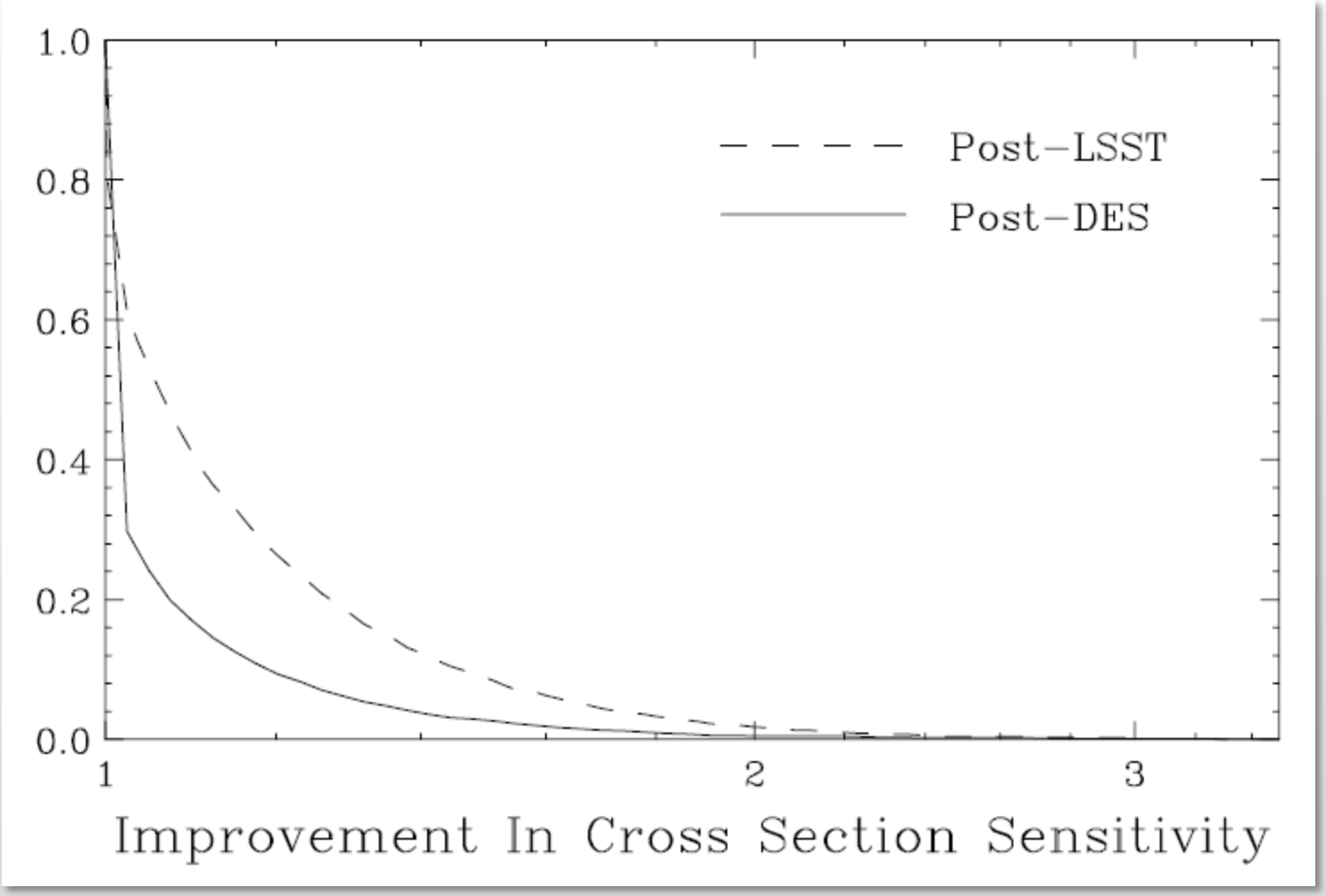


High J-factor Satellites Model Predictions



Sensitivity Improvement From New Satellite Discoveries

Using simple photon stacking (total counts & total background from "best" targets)



DARK ENERGY SURVEY

Caveats

- Baseline modeling choices imply sensitivity gains >2 are unlikely even after LSST
  - Excludes gains in LAT exposure, improved analysis methods, J-factor determinations, etc.)

- But at faint end, neither the radial distribution nor the luminosity function of satellites are observationally well constrained at present

Part 3

UGALI:
Ultra-faint Galaxy Likelihood

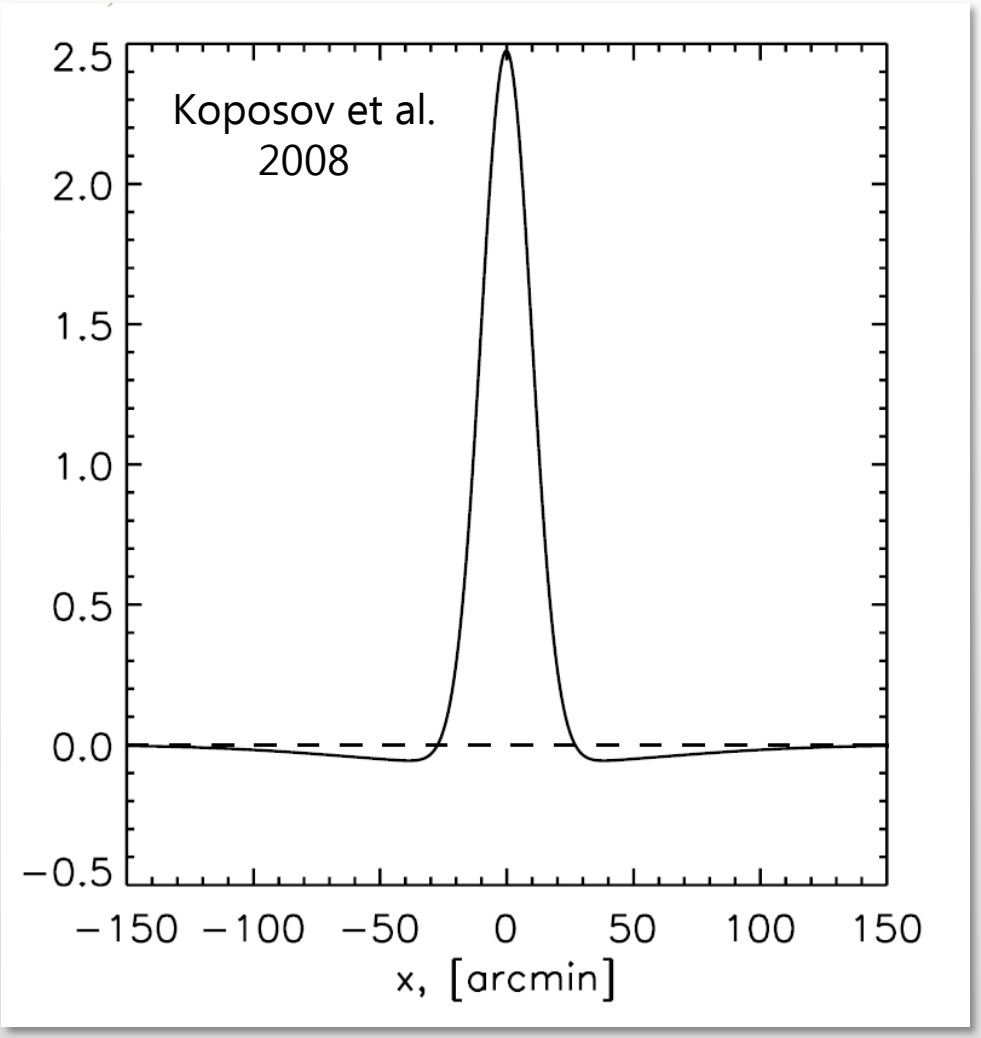
The Challenge

- Satellite stellar populations could be characterized by *at least* 7 parameters
  - Longitude, Latitude, distance, size, age, metallicity, normalization, …
- Characteristic size of a few arcmin relative to surveys of several thousand deg^2
- Tens of visible stars relative to field population of $>10^4$ deg^{-2} at DES depth (Rossetto et al. 2011)

Search Strategies in the SDSS Era

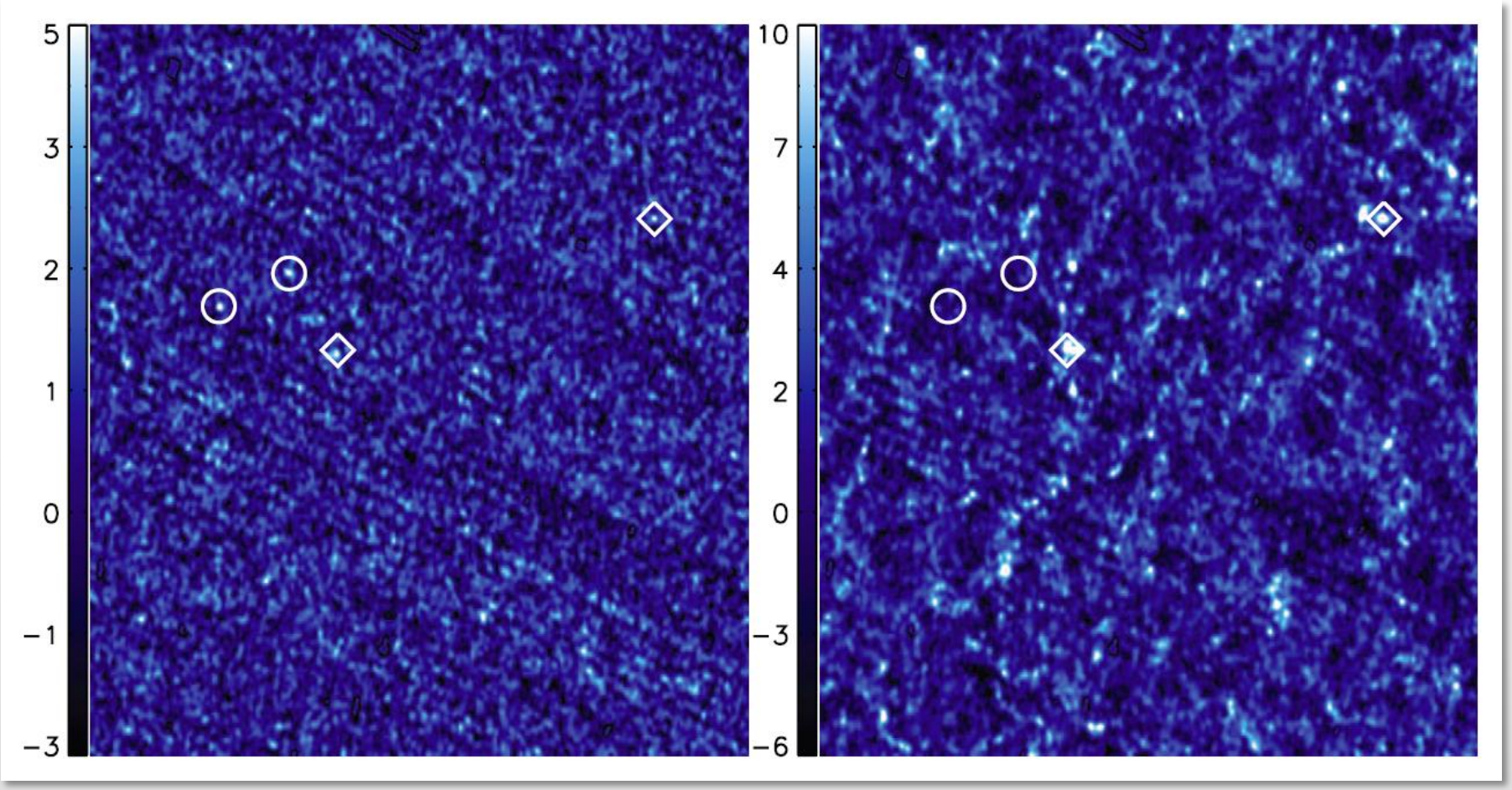
Convolve stellar catalog with a spatial kernel (which also captures fluctuations in local field) and search for over-densities

Fast, robust, and straightforward to quantify search efficiency via simulation



Search Strategies in the SDSS Era

Star Catalog **Galaxy Catalog**

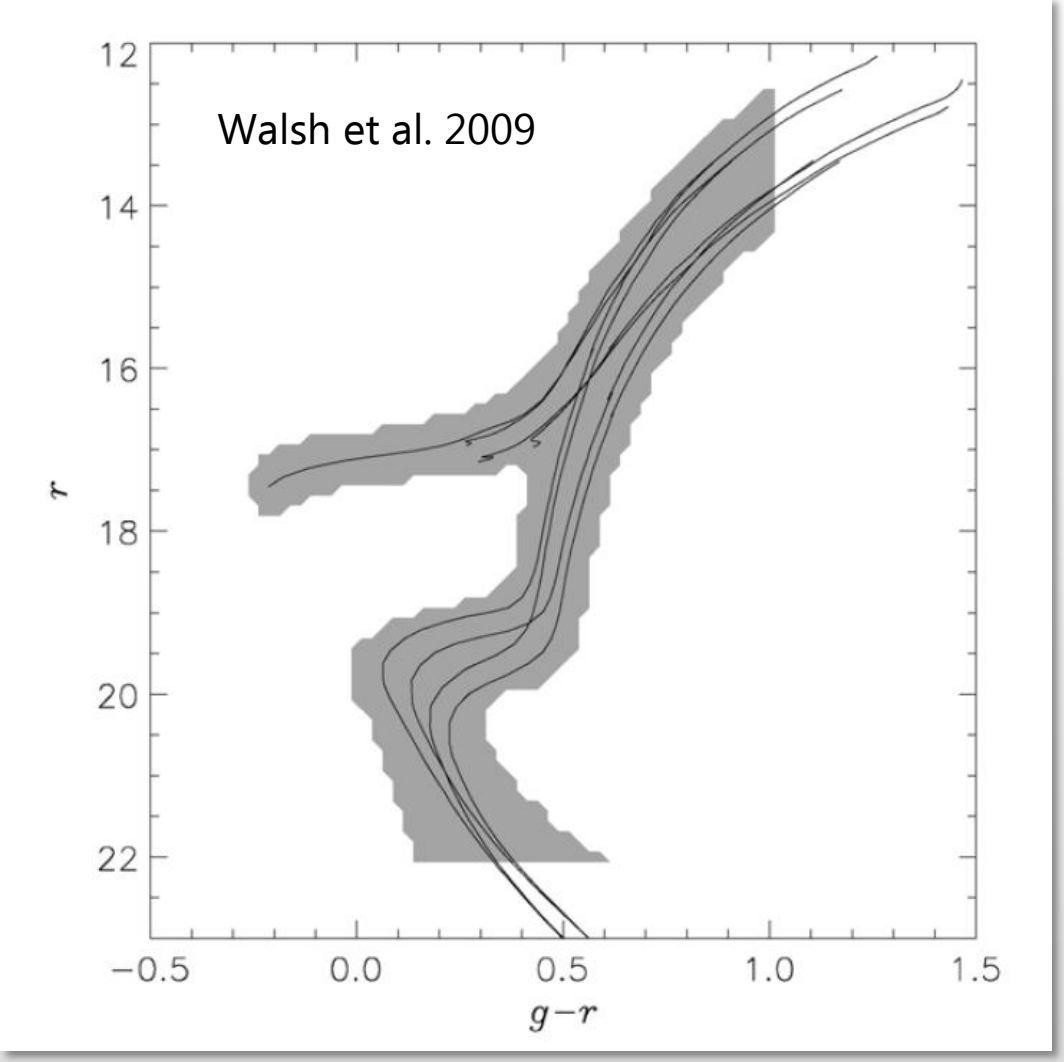


22 deg x 22 deg field containing
Ursa Major I, Willman I, Abell 773, and Abell 1000

Koposov et al. 2008

Search Strategies in the SDSS Era

Increase signal-to-noise by applying a hard cut in color-magnitude space (distance dependent)



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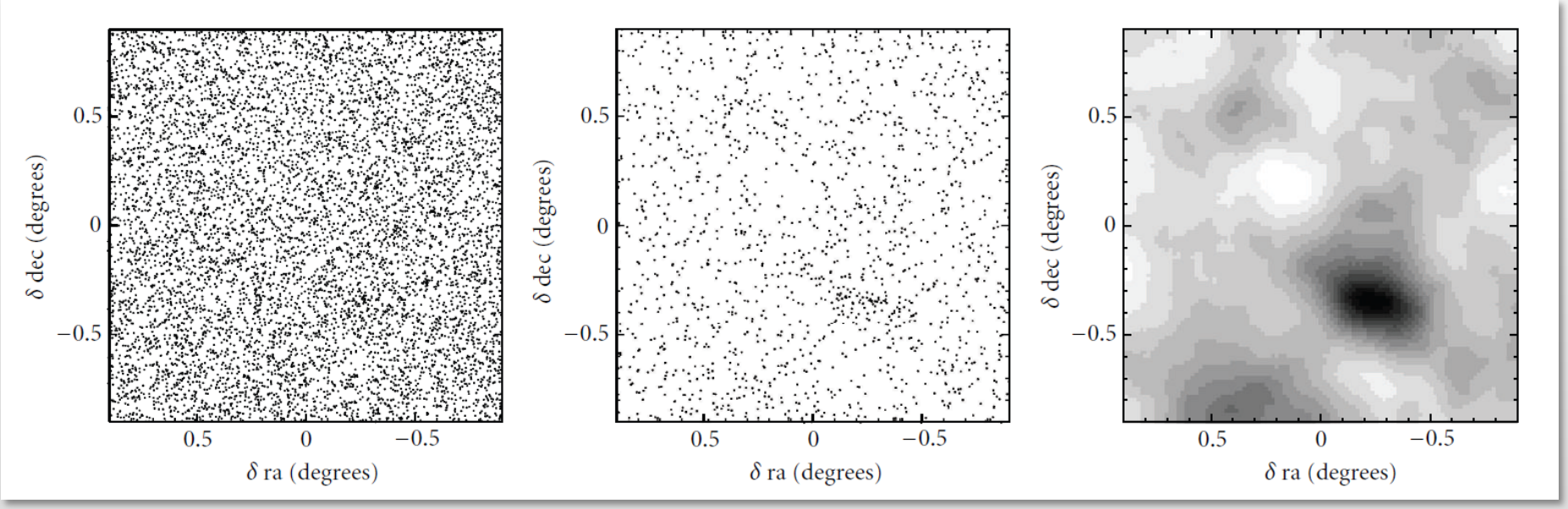
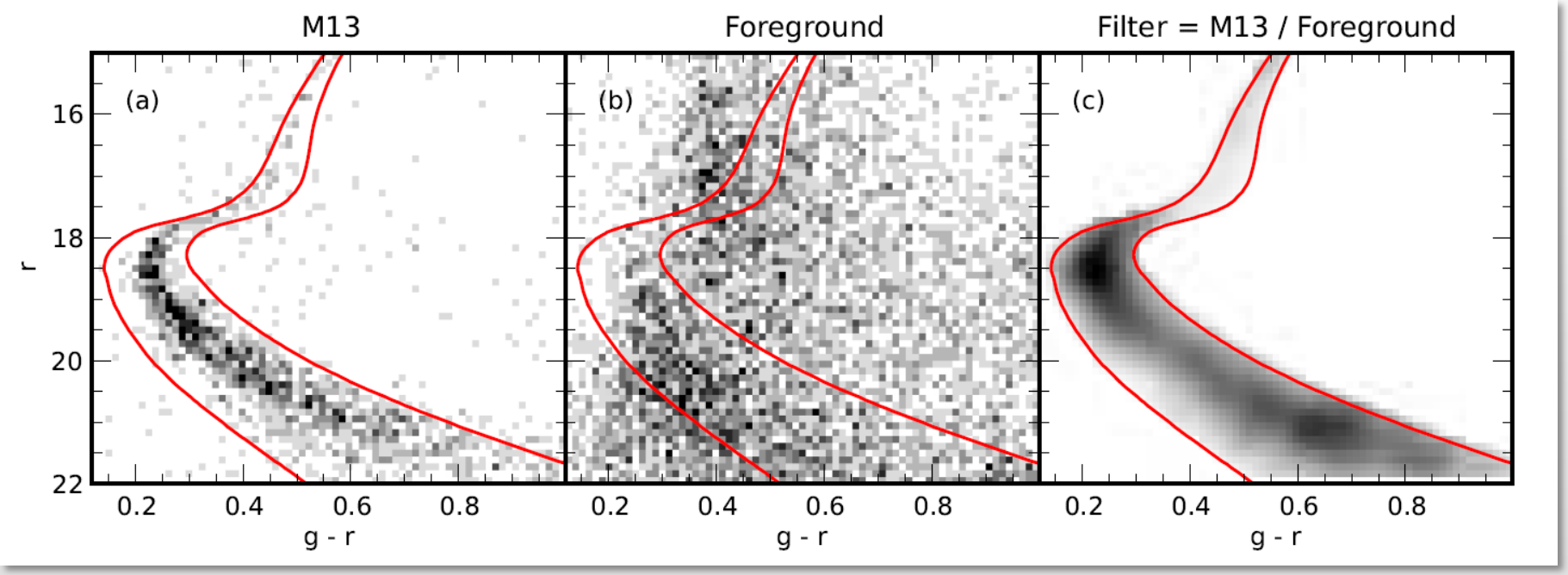


Search Strategies in the SDSS Era

Weight stars according to location in color-magnitude space using an empirical template based on a globular cluster

Bonaca et al. 2012



Maximum Likelihood Approach

Express likelihood as product of Poisson probabilities for detecting objects given their **positions, colors, magnitudes, and magnitude uncertainties** (6-dimensional space)

$$L = \prod_{i \in \mathrm{Bins}} P(k \mid \lambda u_i + b_i)$$

Model contains expected background counts $\boldsymbol{b}$, and signal counts $\boldsymbol{\lambda u}$, where $\boldsymbol{u}$ is the signal PDF and $\boldsymbol{\lambda}$ is the total number of stars (richness)

In limit of small bins (each bin contains 0 or 1 object), we can iterate over objects instead of bins

See also Dolphin 2002 for derivation of star formation histories, as well as de Jong et al. 2008 for application to known SDSS

Maximum Likelihood Approach

Rearrange to see a more physical interpretation, the **membership probability** for each individual object

$$\log L = -\sum_{i \in \text{Stars}} \log(1 - p_i) - f\lambda$$

p is the membership probability of each star and ***f*** is the fraction of stars which are observable in a given survey

$$p_i = \frac{\lambda u_i}{\lambda u_i + b_i} \qquad \lambda = \frac{1}{f} \sum_{i \in \text{Stars}} p_i$$

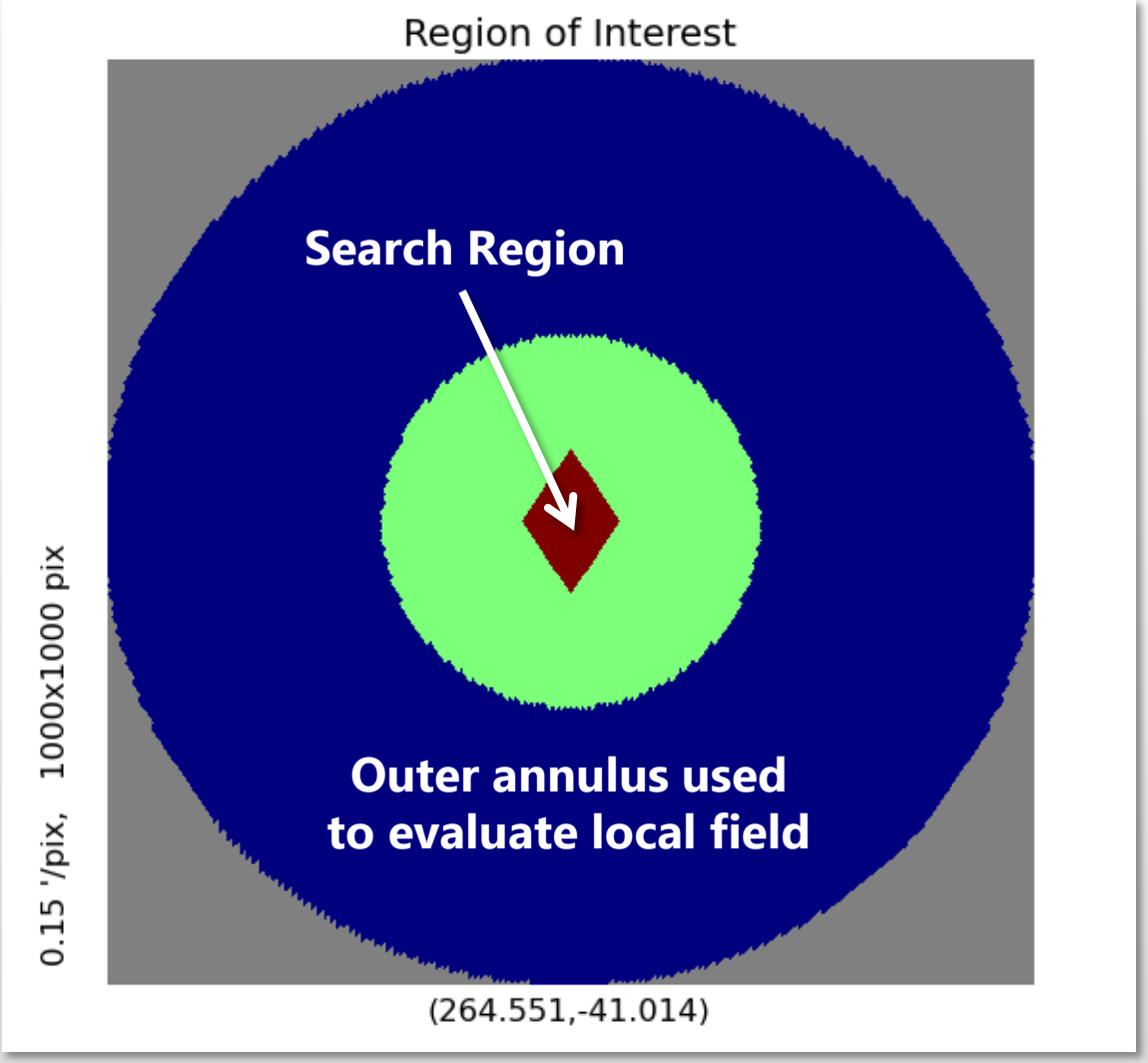
Borrowing ides from "richness" estimator used in redMaPPer galaxy cluster finder algorithm of Rykoff & Rozo

Implementation Details: Regions of Interest

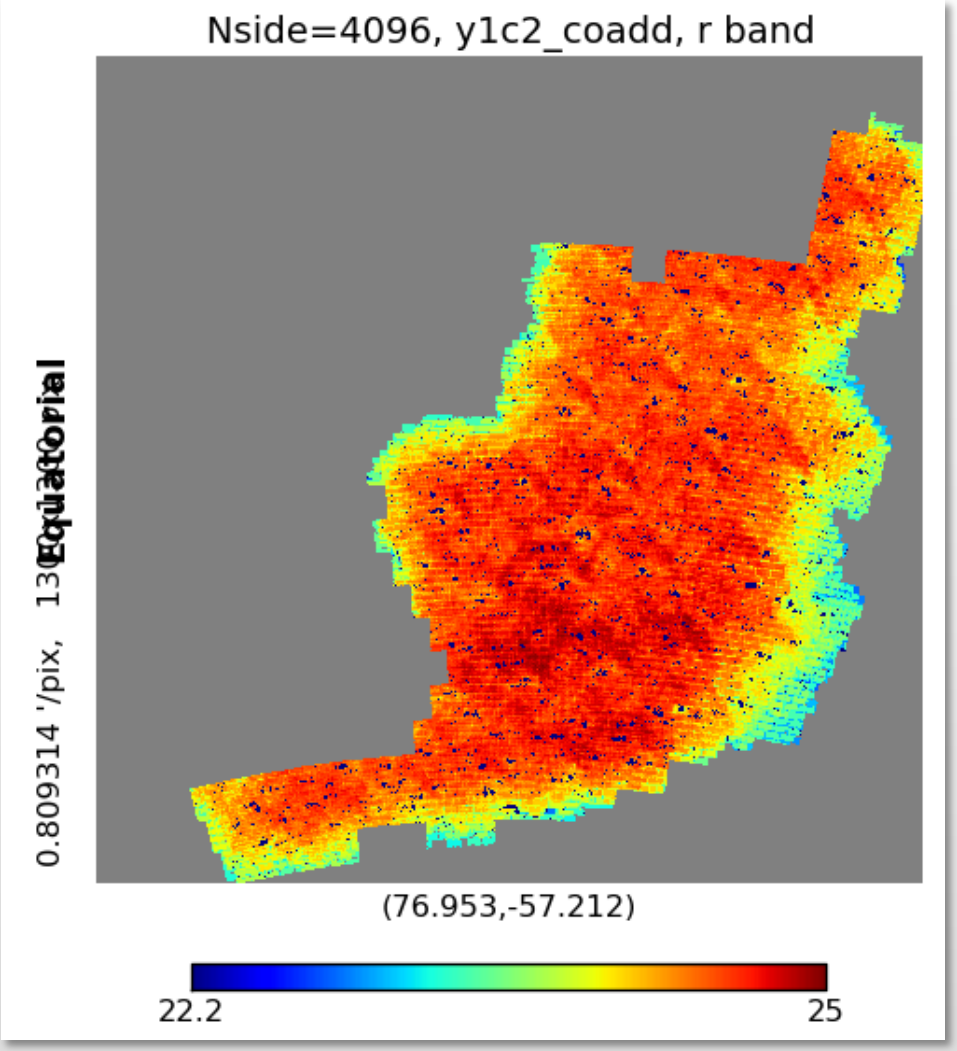
Parallelize search by segmenting survey on a HEALPix grid with a distinct "Region of Interest" for analyzing each patch of sky

Use finer grid to evaluate survey depth and bin objects

2.5 deg in this example



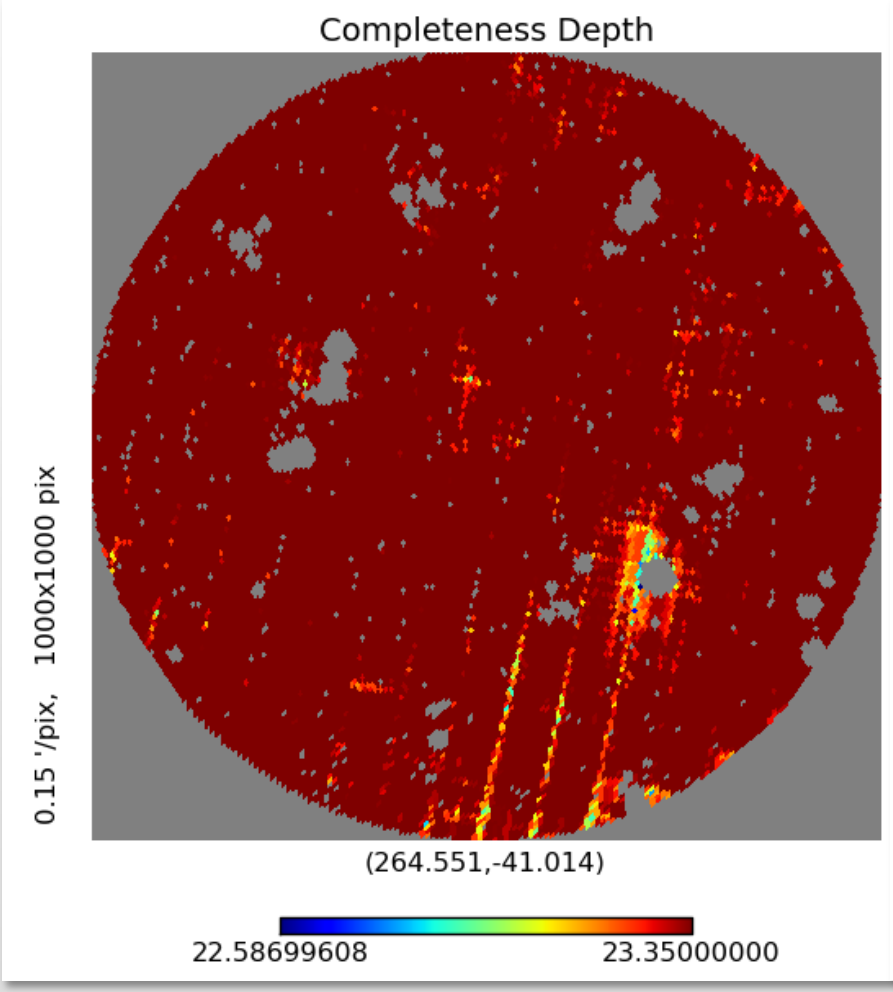
Accounting for Unseen Stars: Survey Masks



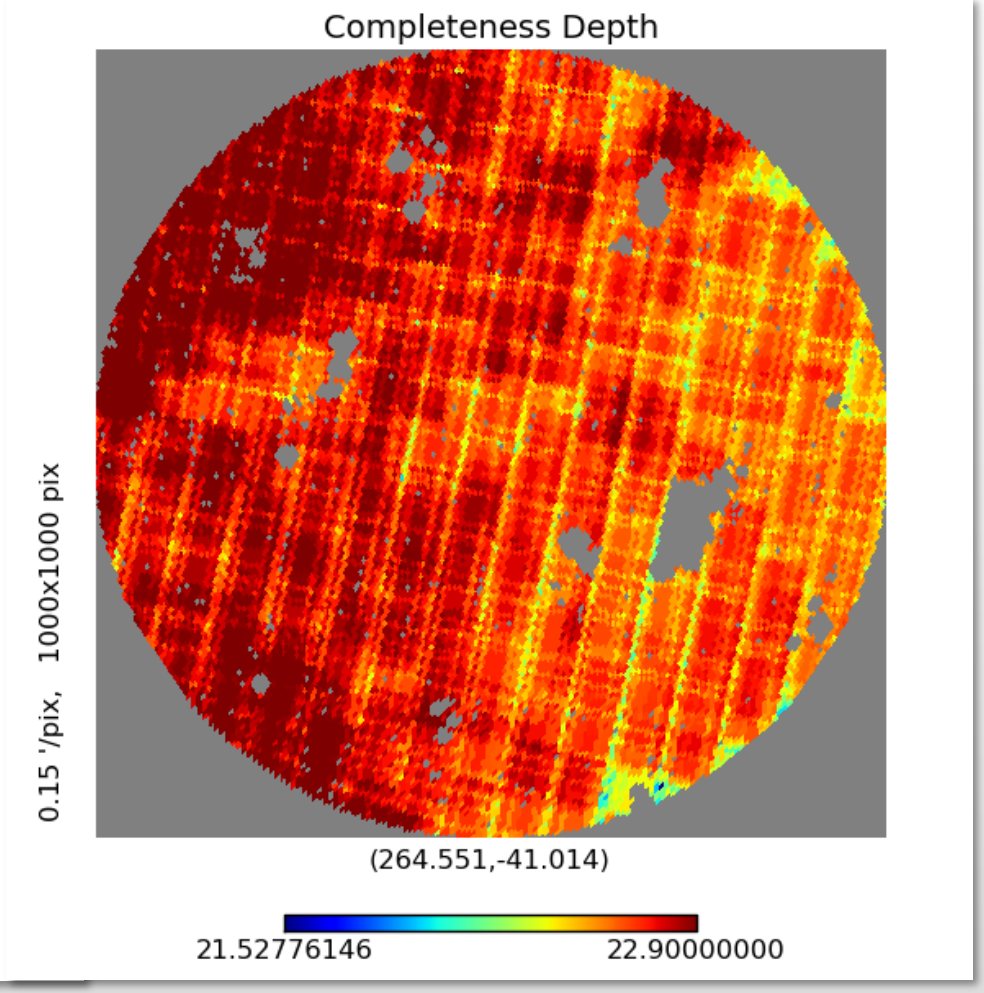
Example **completeness depth map** (10 σ detection in 1.5" aperture) for the "SPT East" Science Verification field (~110 deg^2)

Accounting for Unseen Stars: Survey Masks

***r*-band (clipped)**



***i*-band (clipped)**

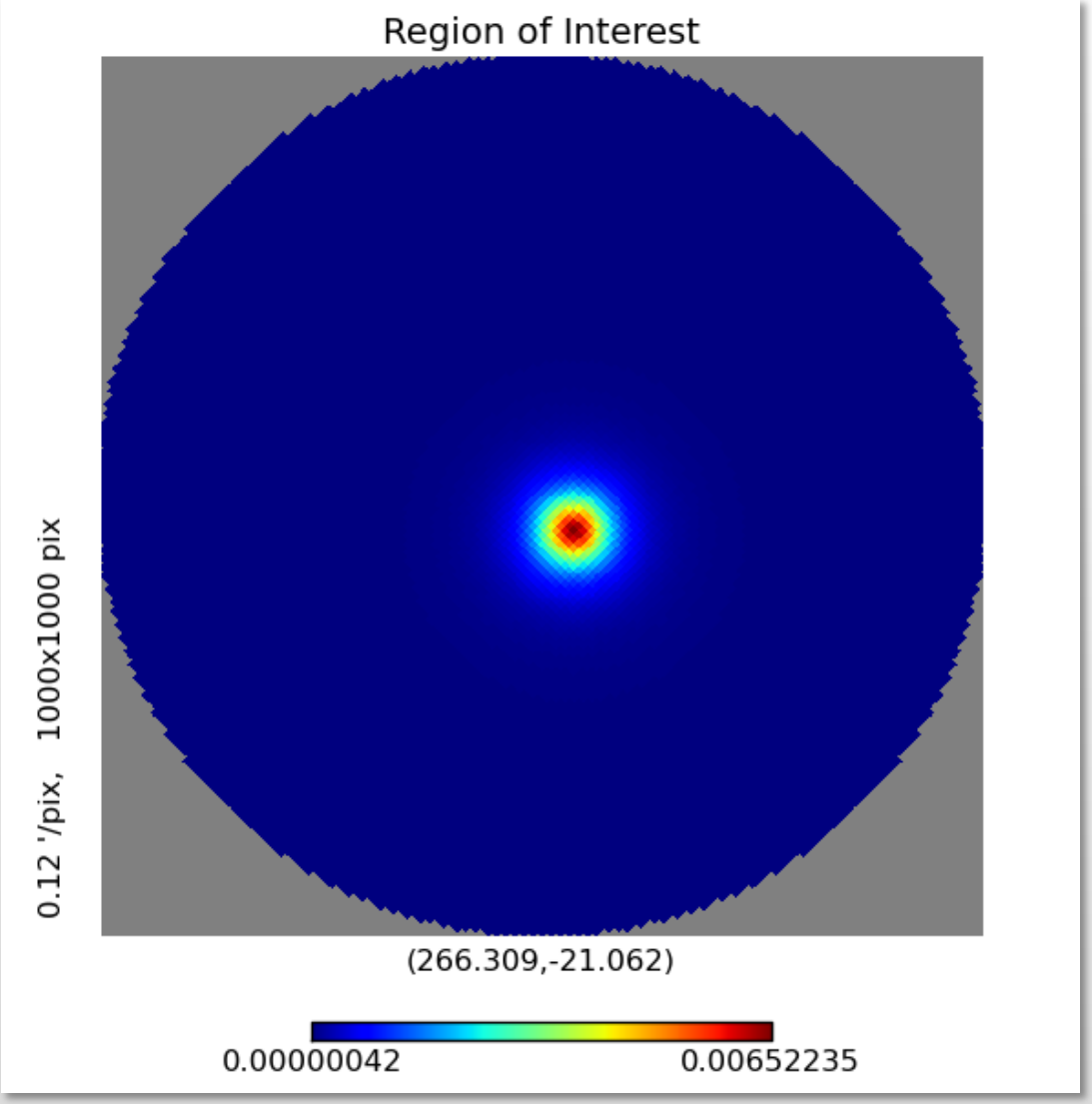


Satellite Spatial Model

Signal PDF is a consists of (separable) spatial and spectral templates

For satellite search, one-parameter **Plummer profile** (half-light radius)

See Munoz et al. (2013) for recent studies measuring the spatial properties of ultra-faint satellites

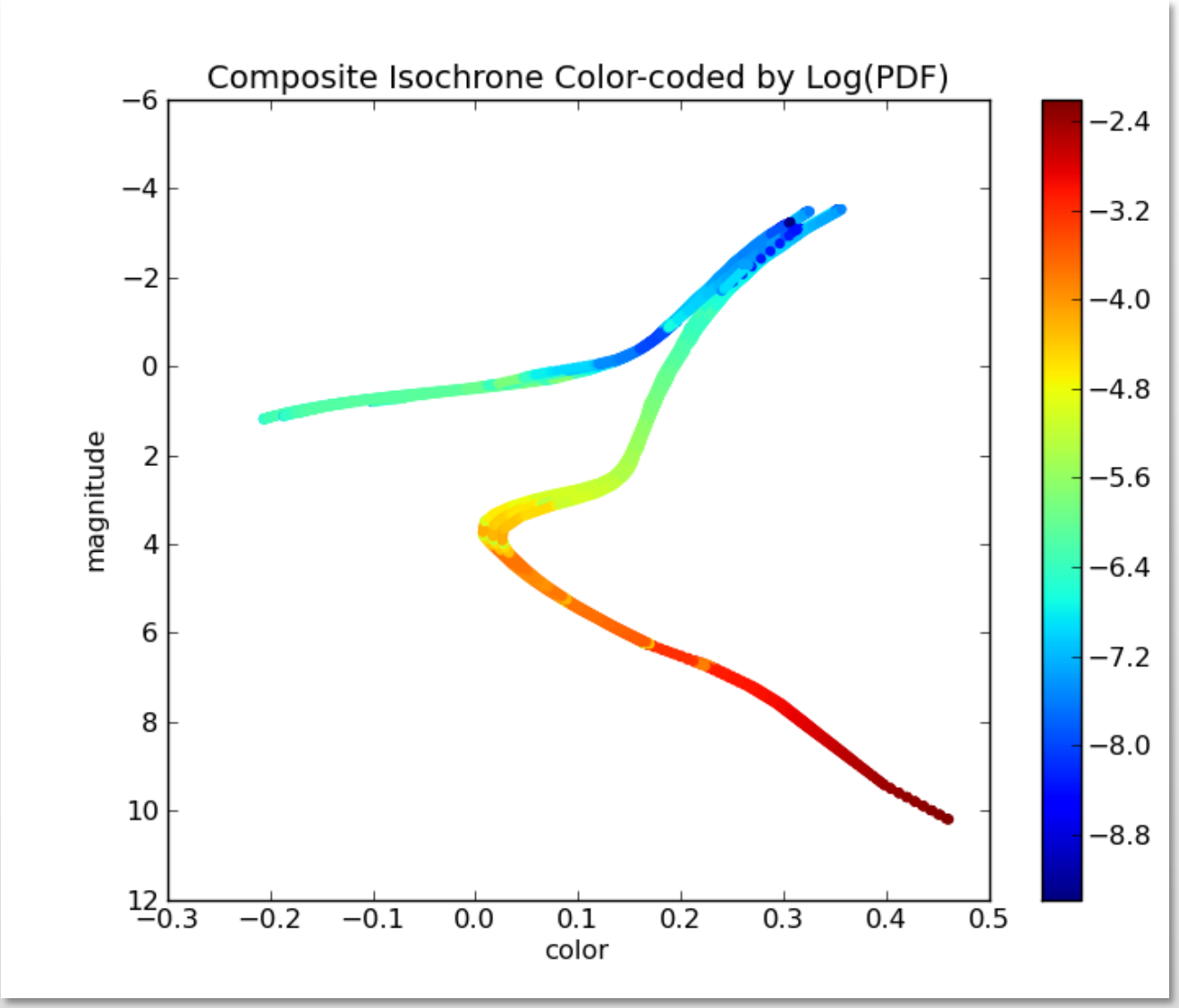


Satellite Spectral Model

Model color-magnitude distribution of satellite stars using **composite isochrone**

Populate isochrones with an **initial mass function**

Currently using Chabrier initial mass function, but another choice may be more applicable for ultra-faint galaxies (Geha et al. 2013)

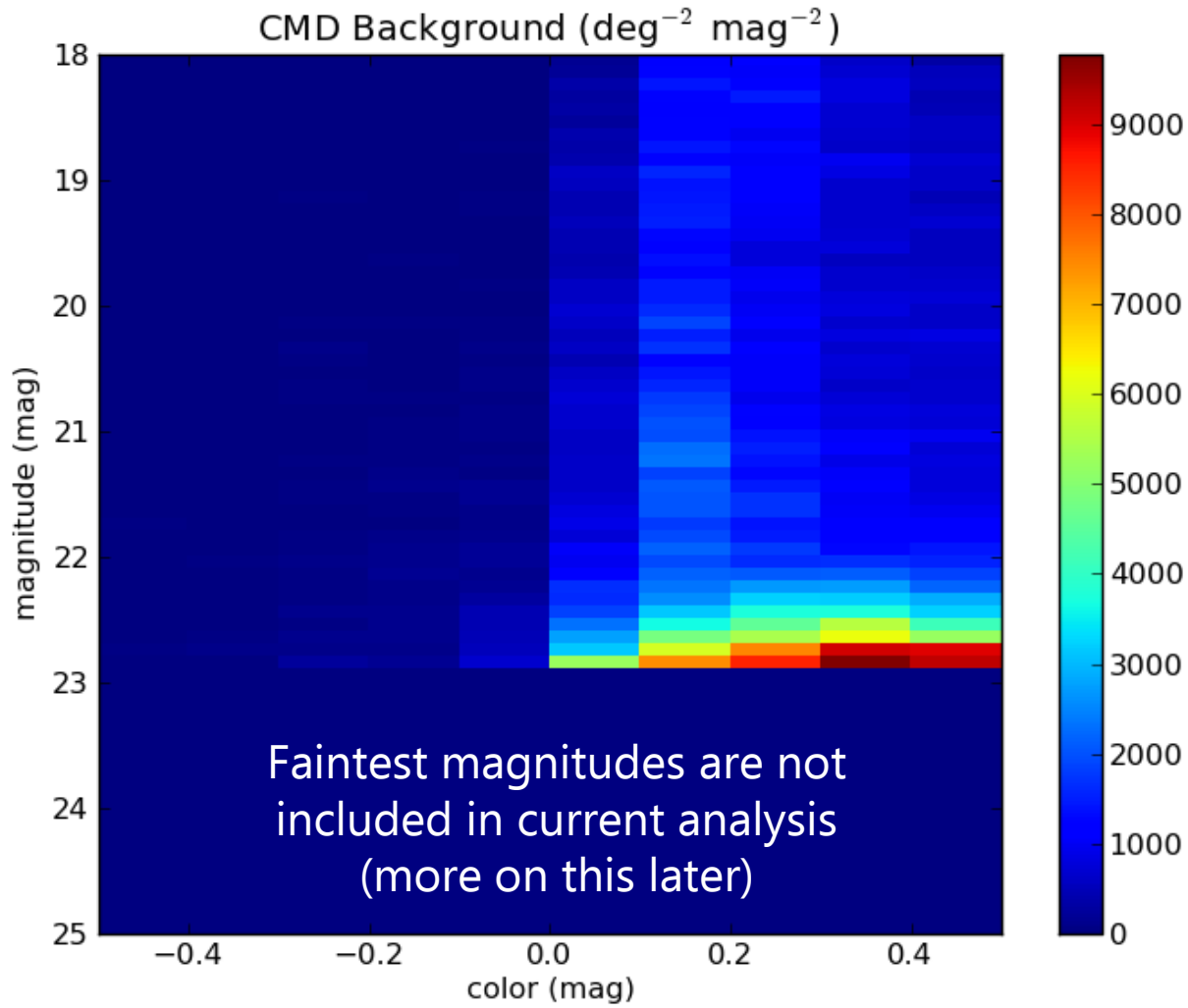


Field Model

Empirical "field" model generated from all catalog objects in ROI outer annulus

Field model varies with Galactic coordinates, star-galaxy separation, etc.

Cloud-in-cells binning algorithm



Color = $r - i$
Magnitude = i

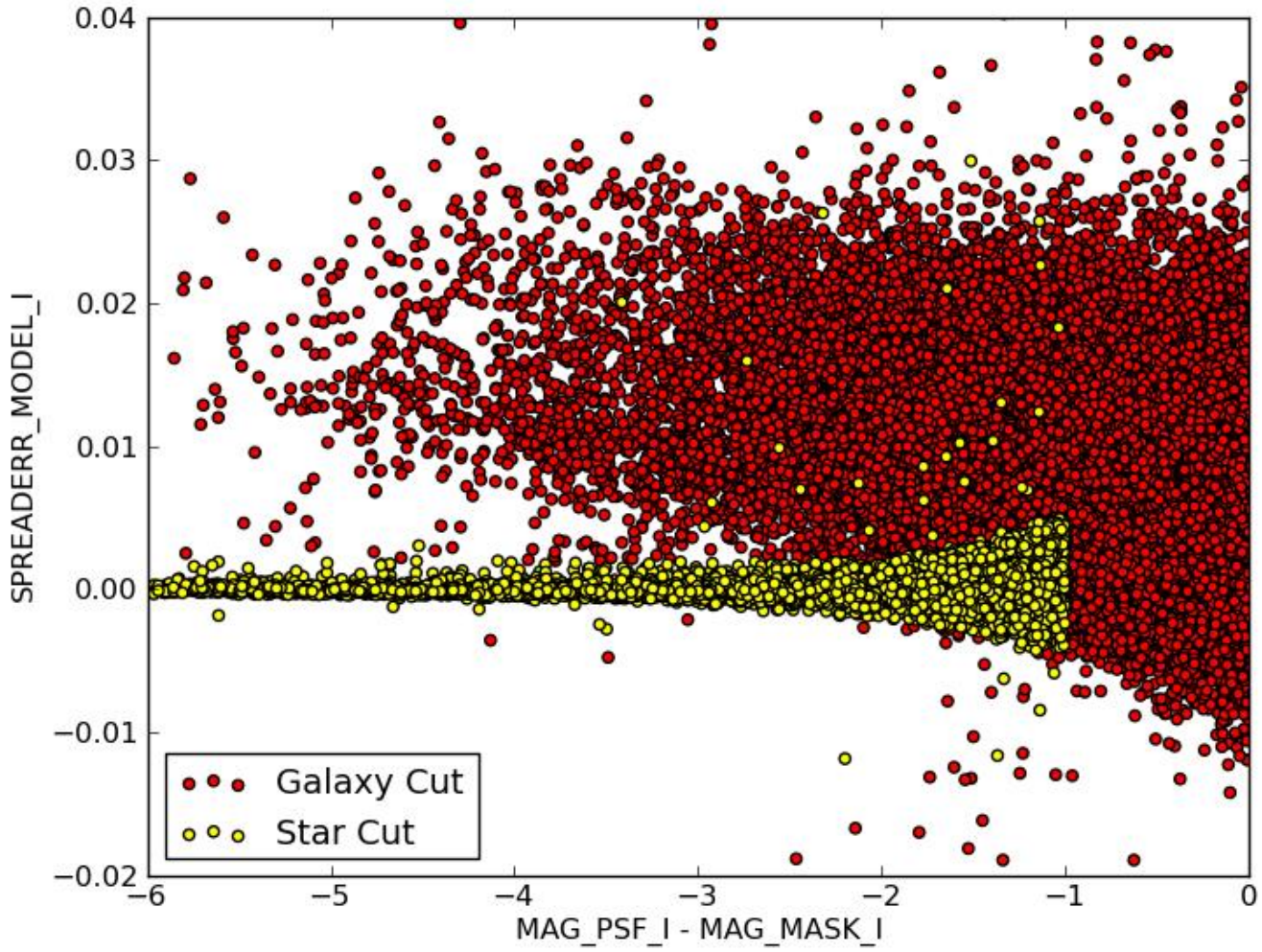
Part 4

Application to the Dark Energy Survey

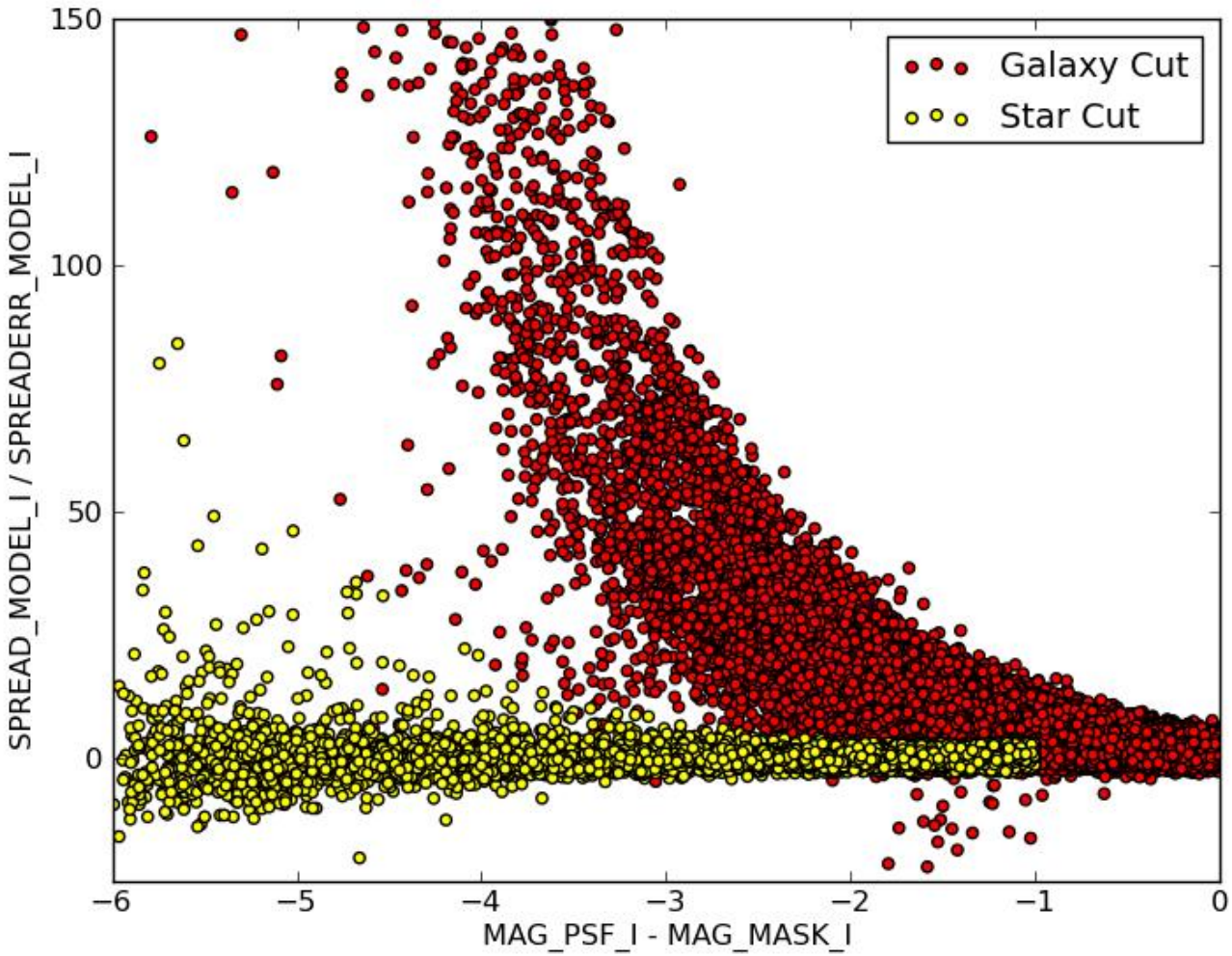
Collaborators

Dark Energy Survey Collaboration

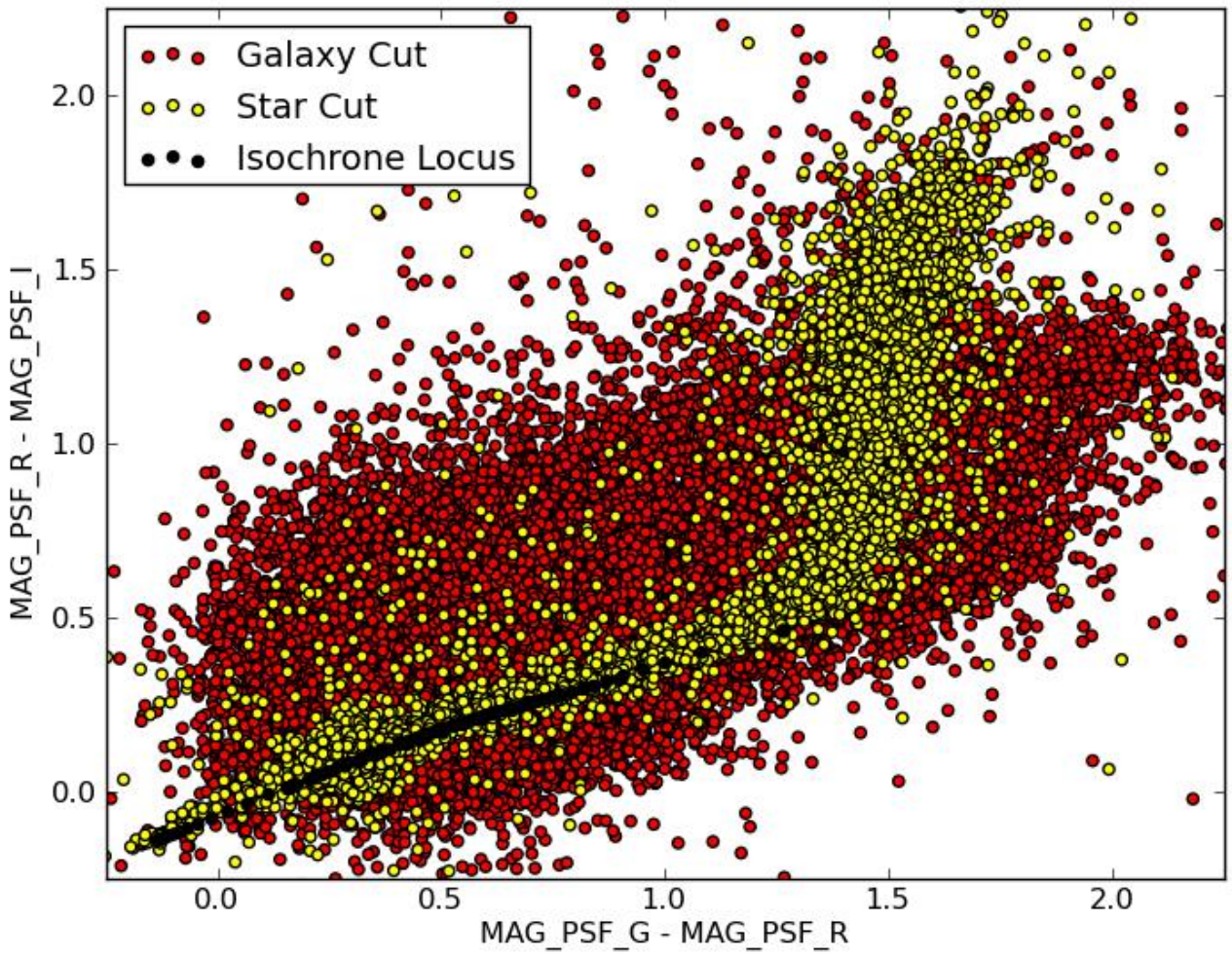
Star / Galaxy Separation



Star / Galaxy Separation



Star / Galaxy Separation
Stellar Locus

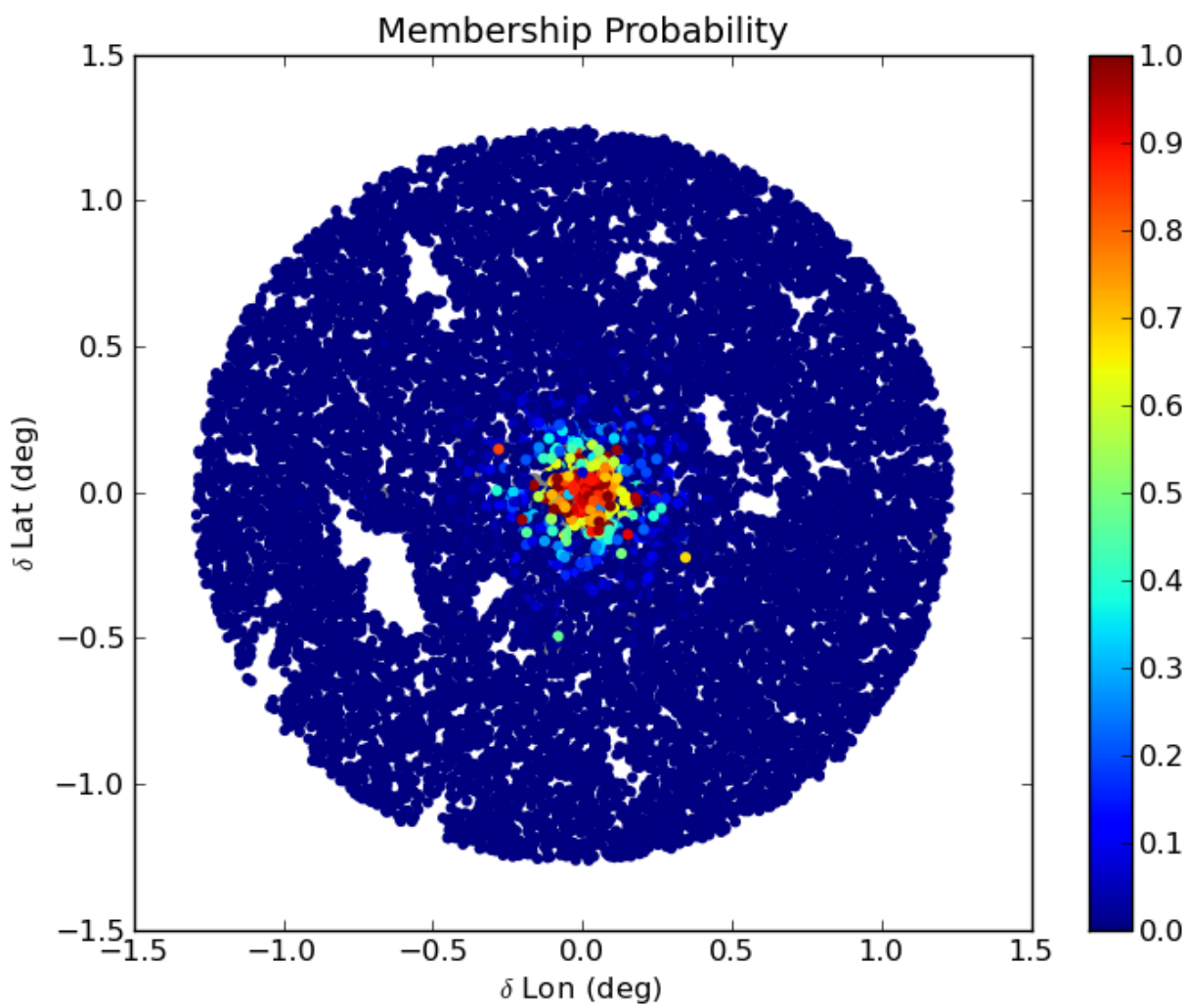


Monte Carlo Simulations

- Insert simulated satellite galaxies into real DES Science Verification data
  - Know exactly which stars belong to satellites
- First, examine individual satellites to test method (e.g., membership probabilities)
- Second, generate a population of satellites to evaluate overall accuracy of algorithm and sensitivity for DES

Membership Probabilities

$M_\star$ = 3.e4 M_{Sol}
d = 100 kpc
r_h = 0.1 deg



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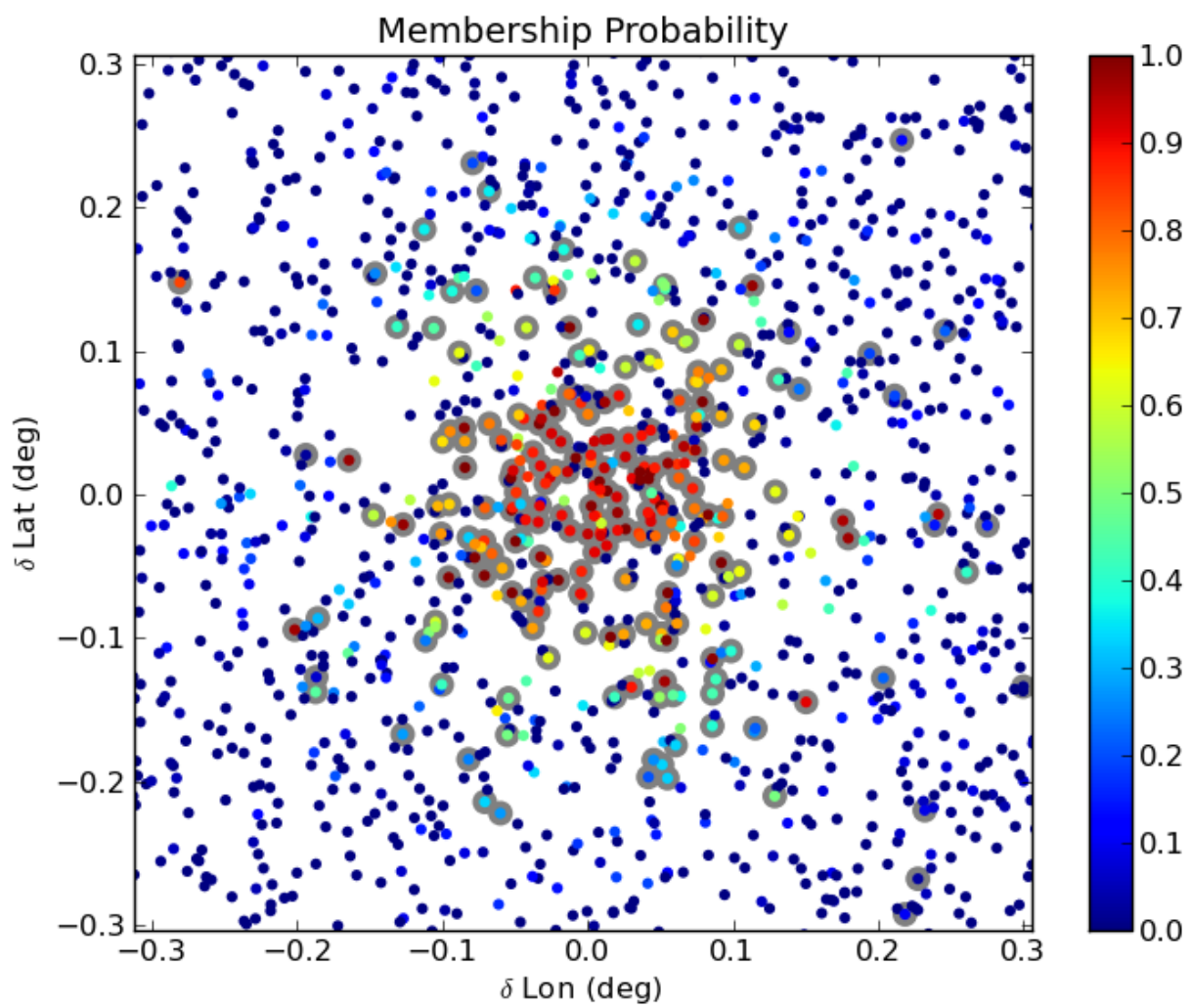

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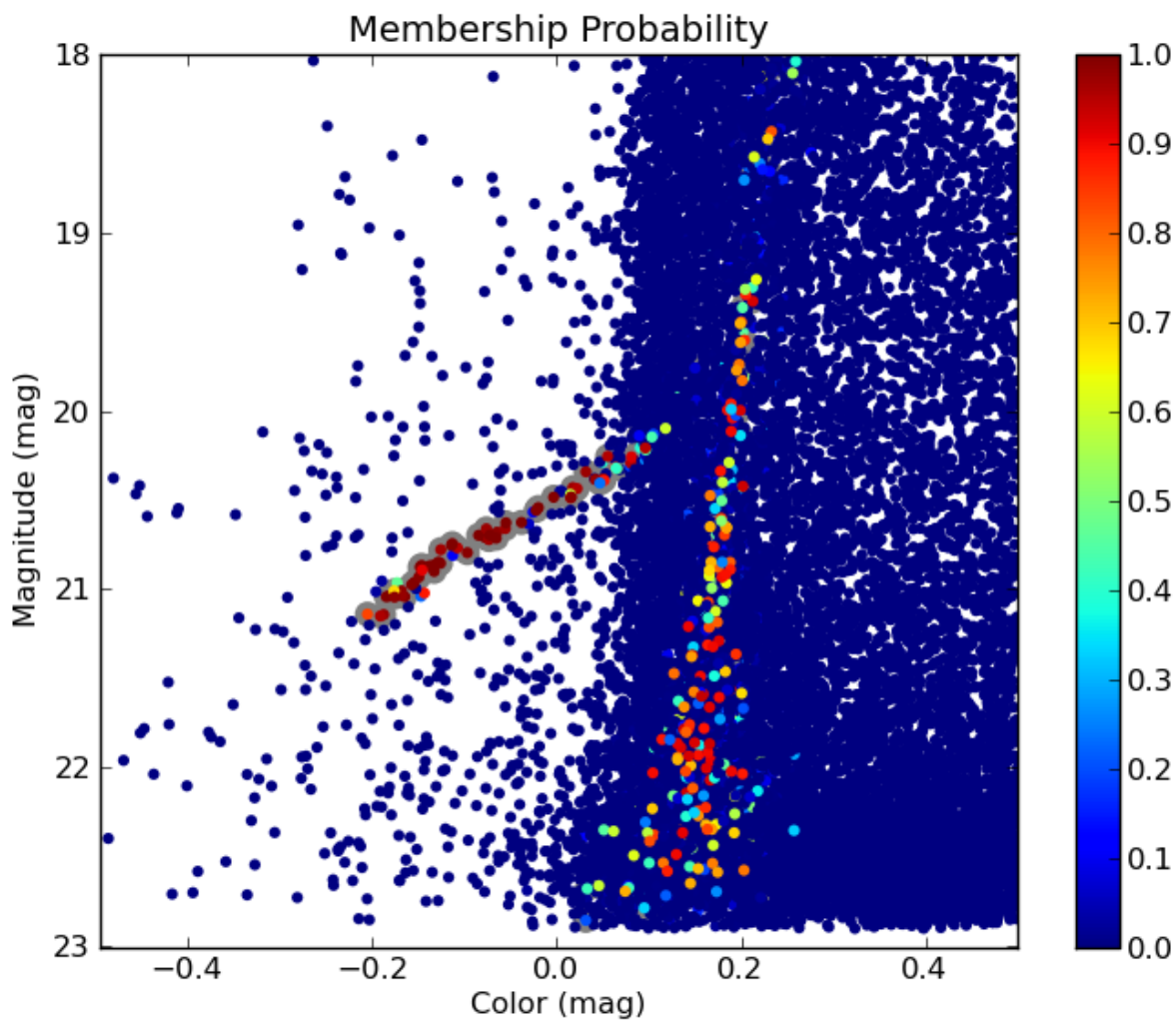

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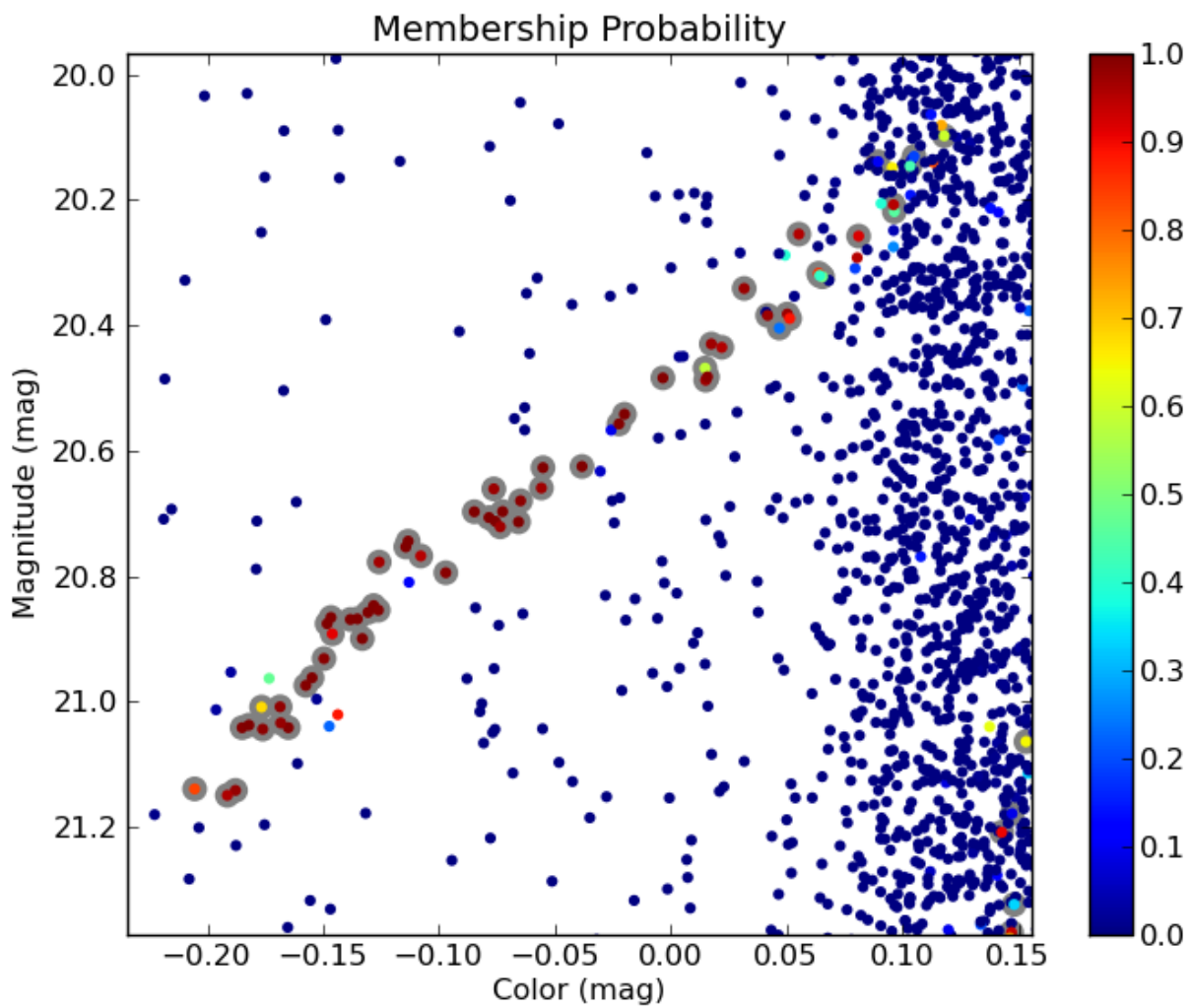

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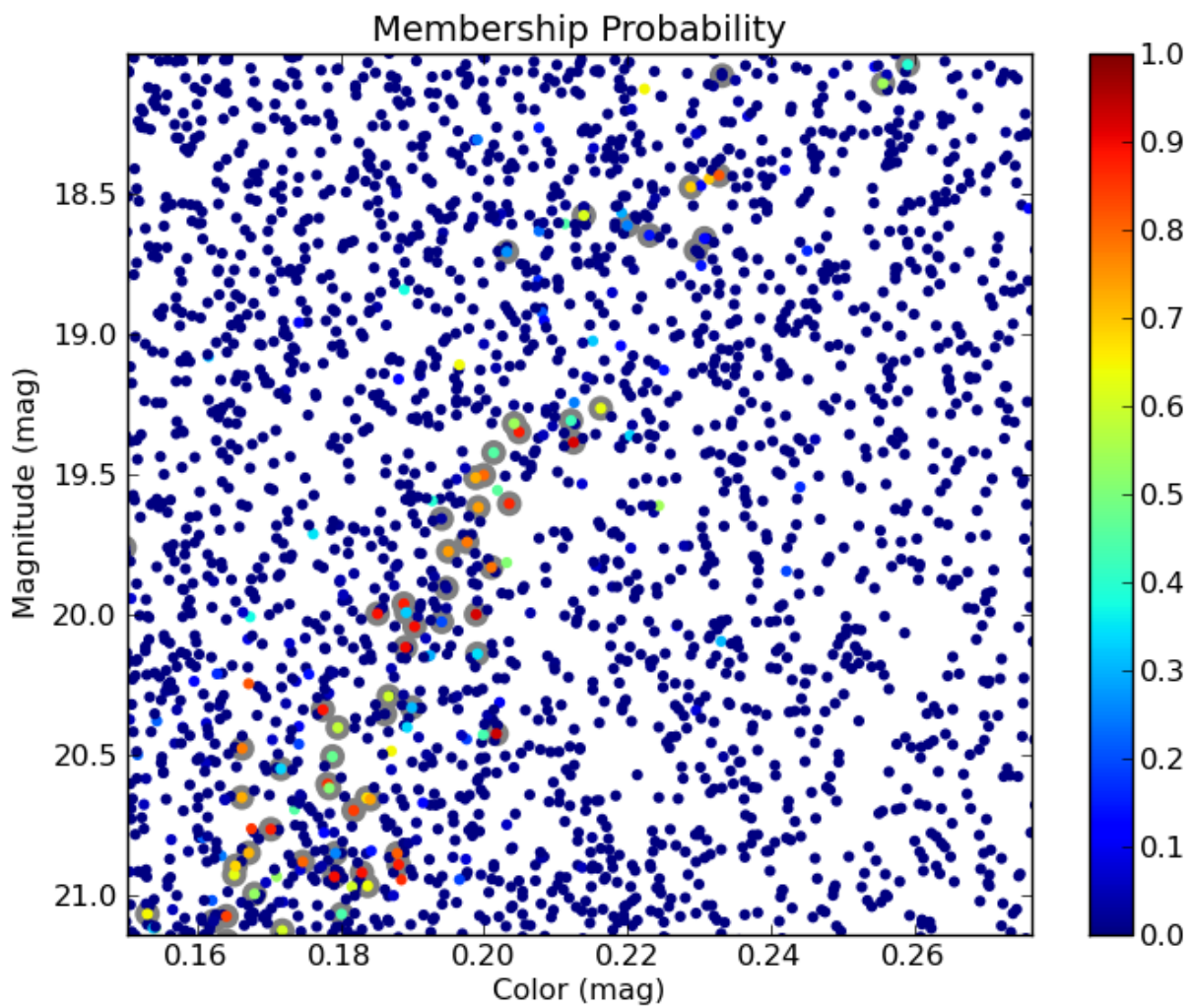

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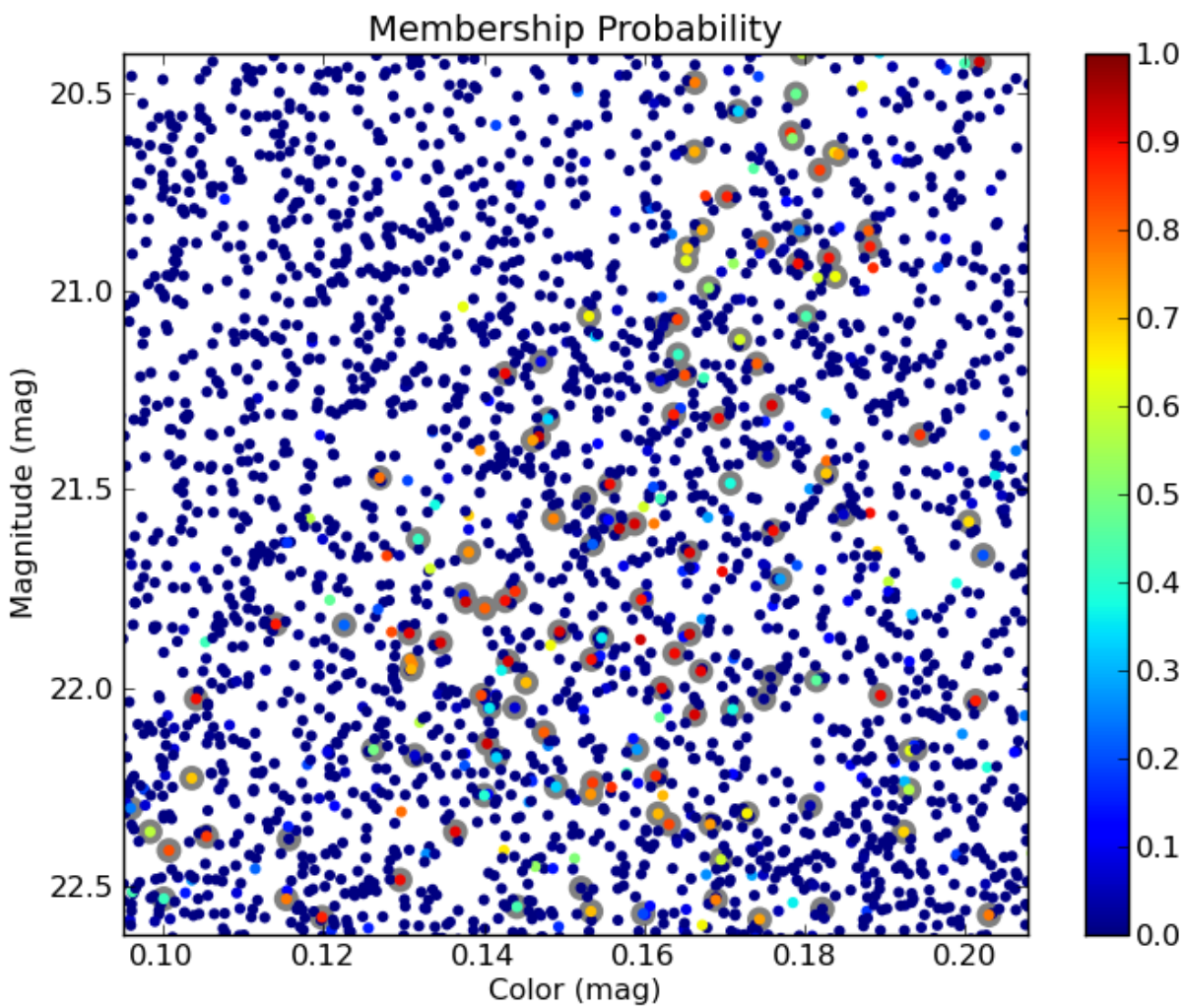

Membership Probabilities

$M_\star$ = 3.e4 M_{Sol}
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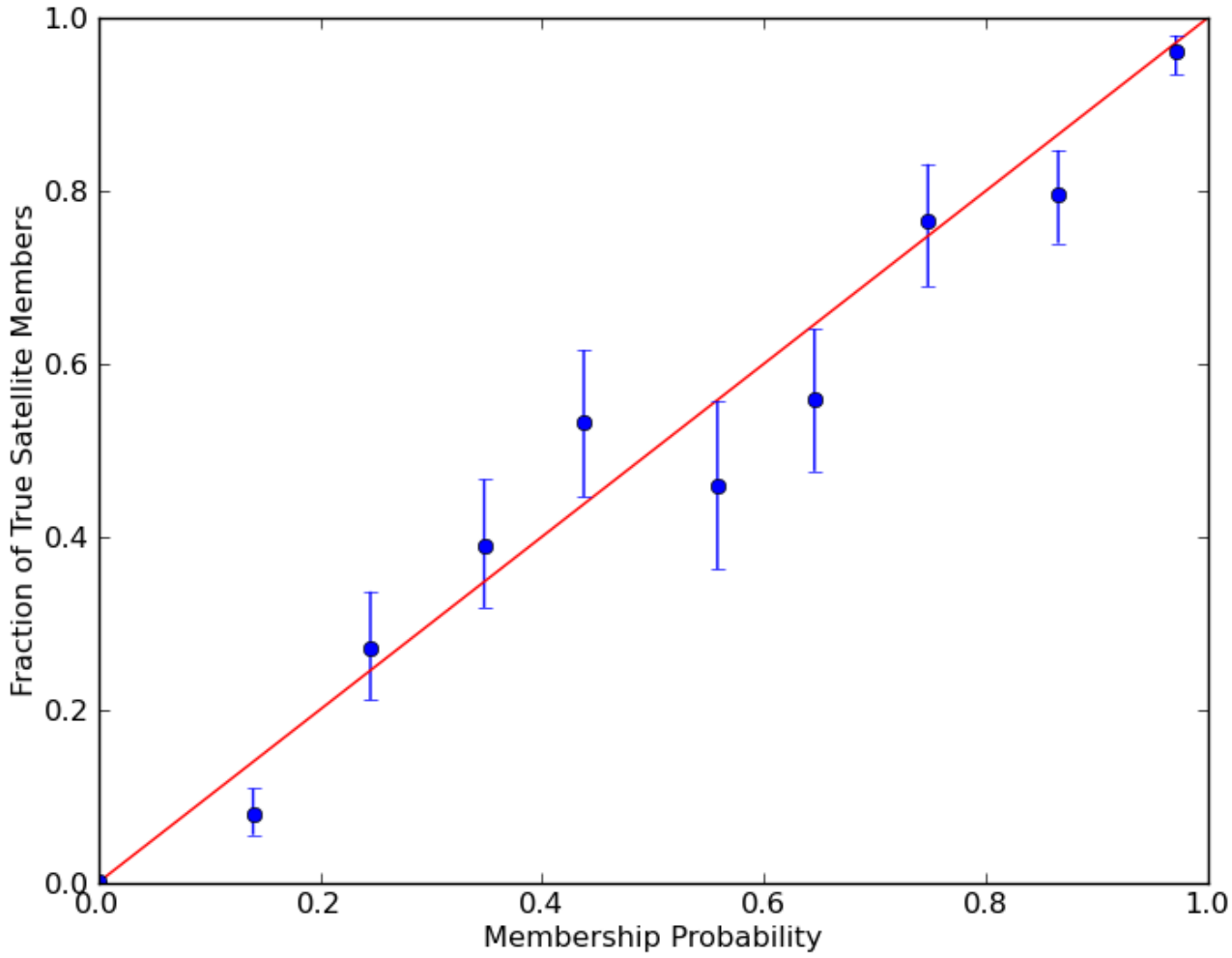
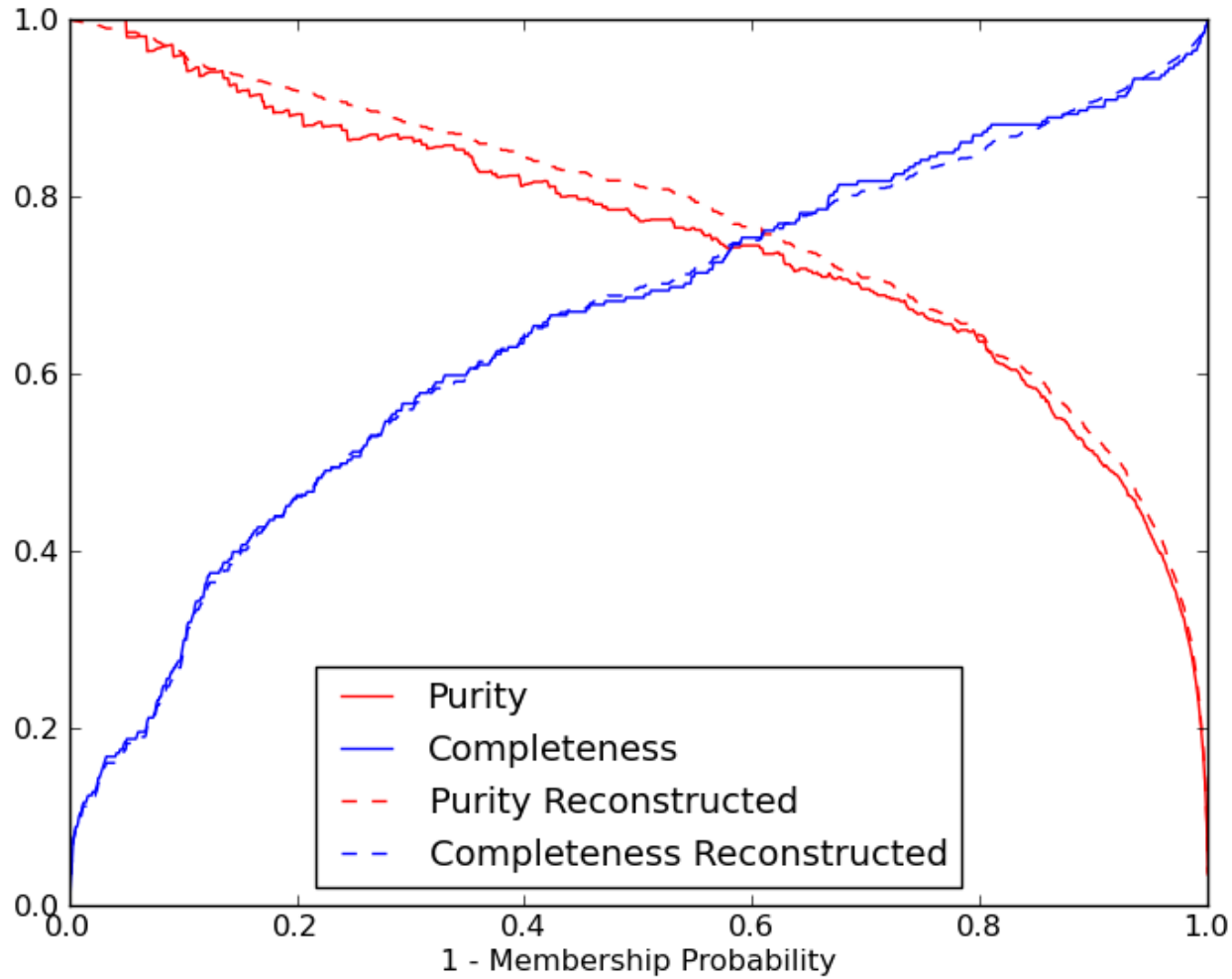
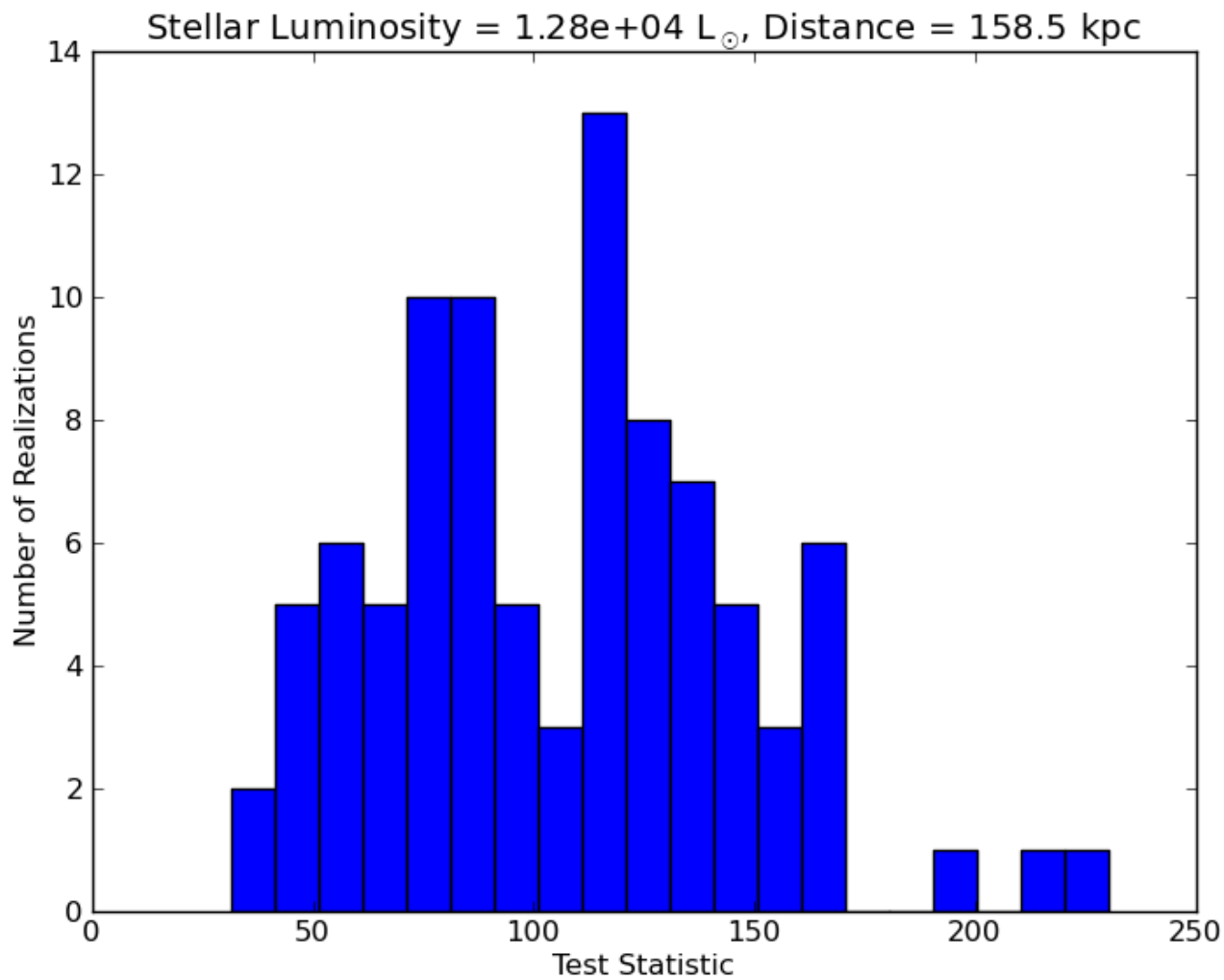


Purity and Completeness

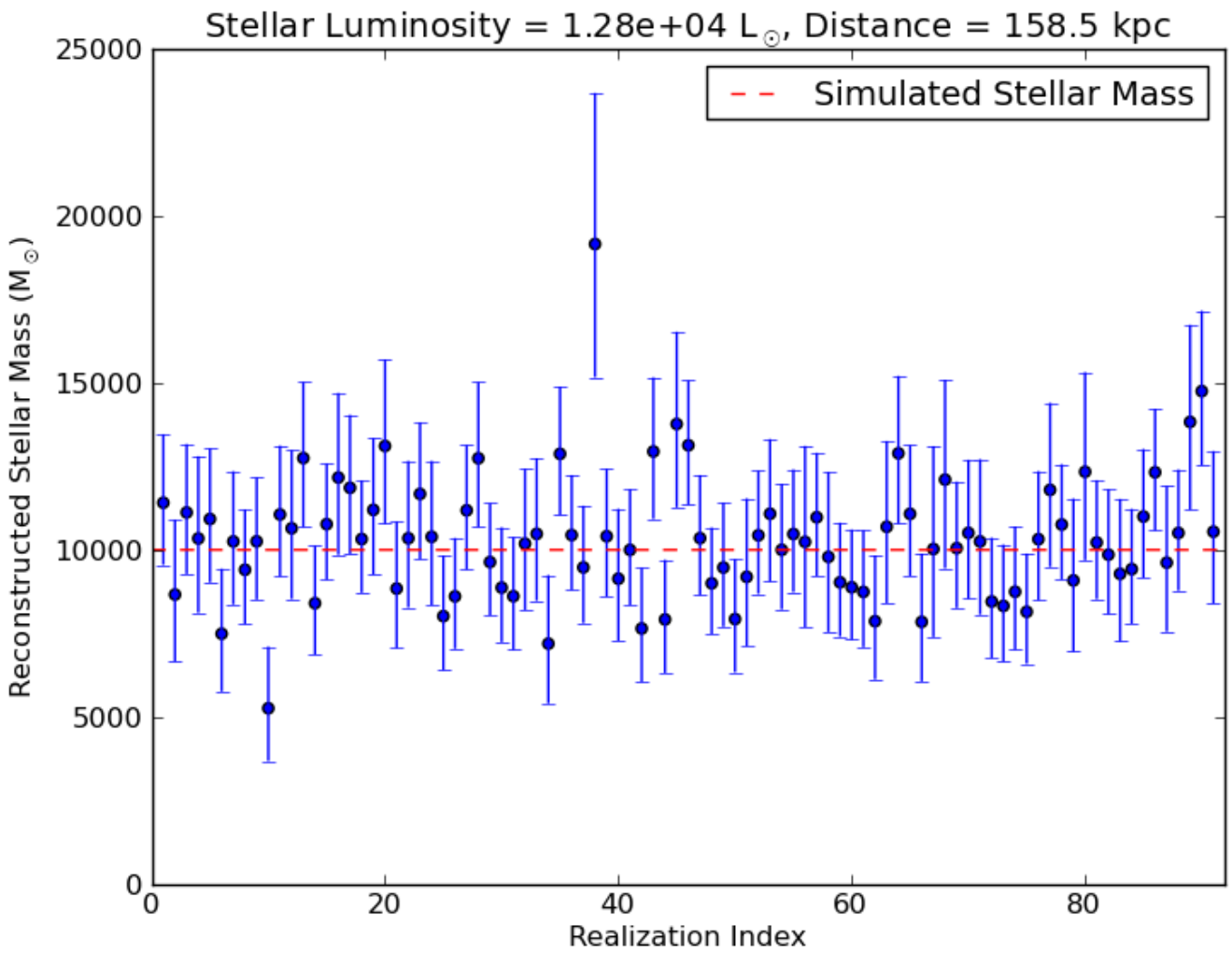
$M_\star$ = 3.e4 M_{Sol}
d = 100 kpc
r_h = 0.1 deg



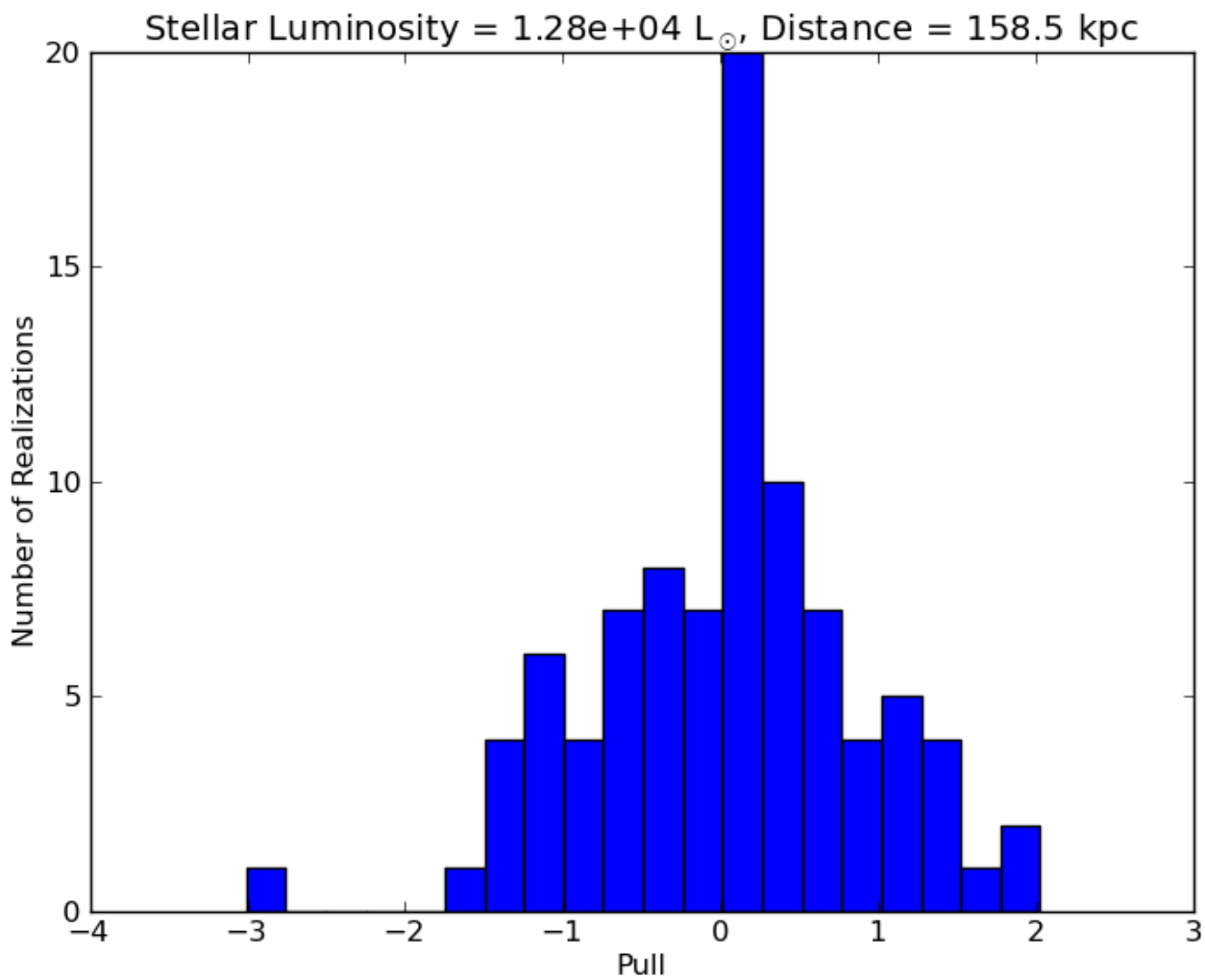
Detection Significance



Reconstruction Accuracy



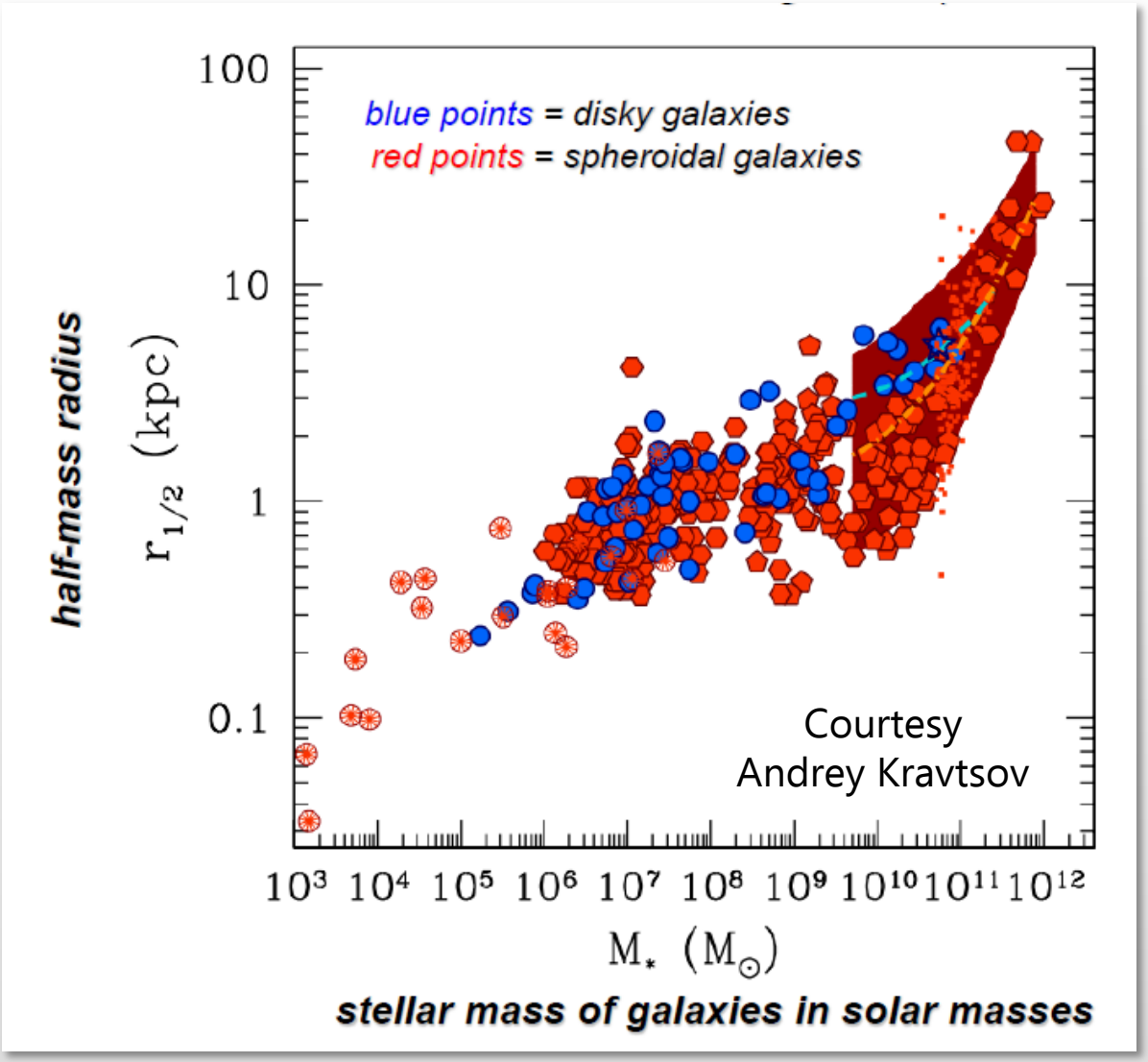
Reconstruction Accuracy



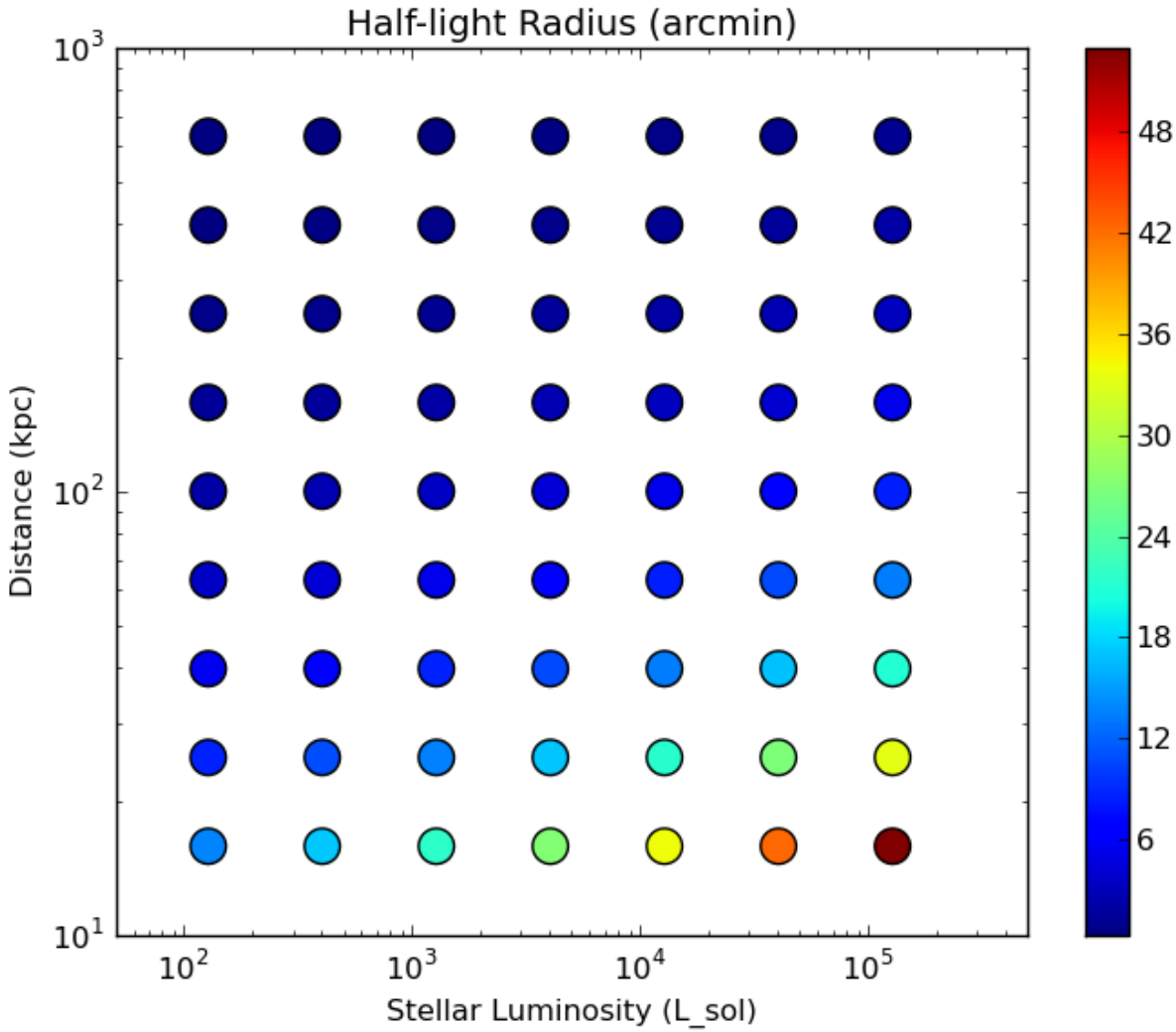
Stellar Mass – Size

Current observations give rough idea for the characteristic sizes of satellite galaxies

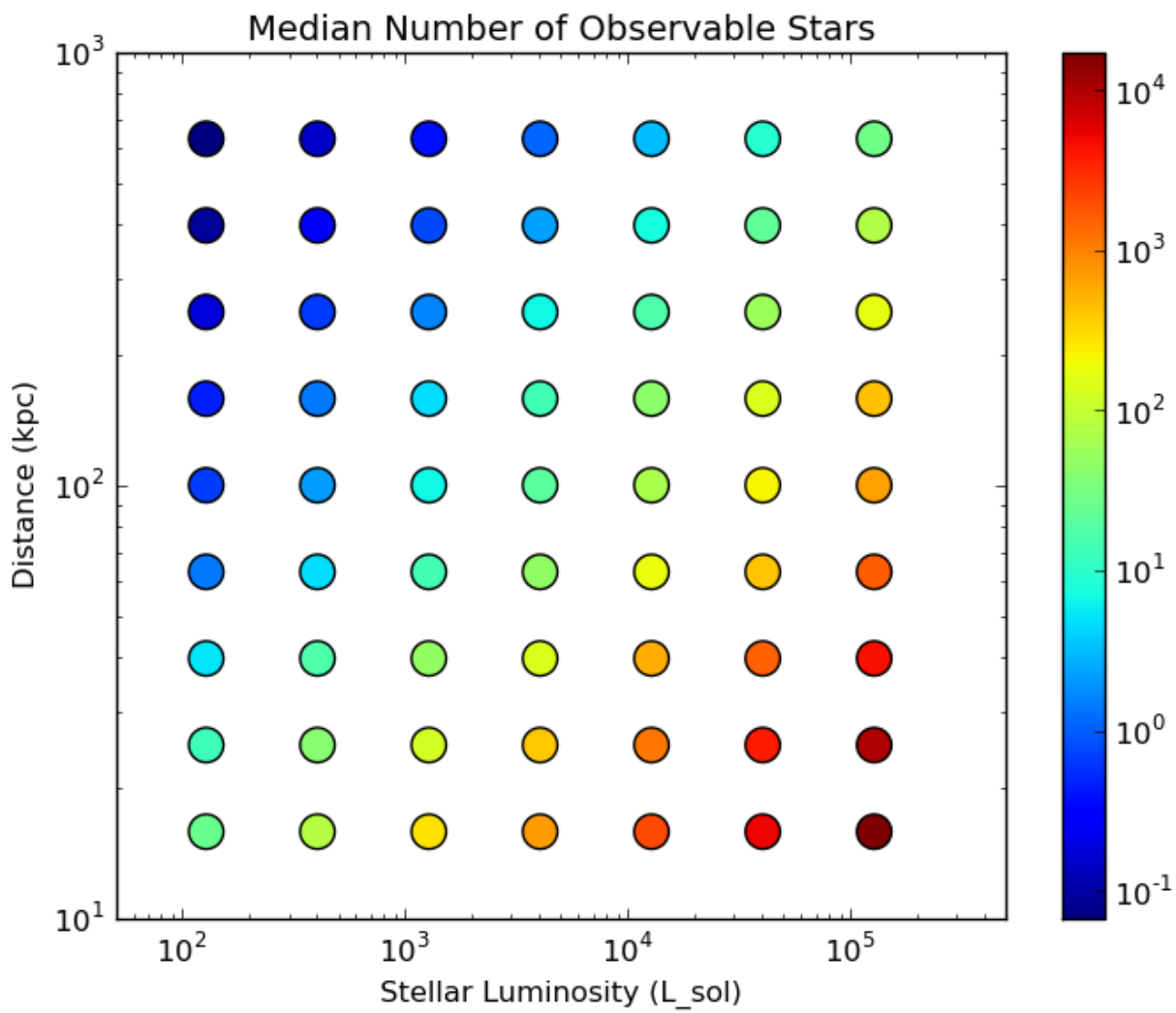
Use stellar mass – size relation as starting point for simulation testbed



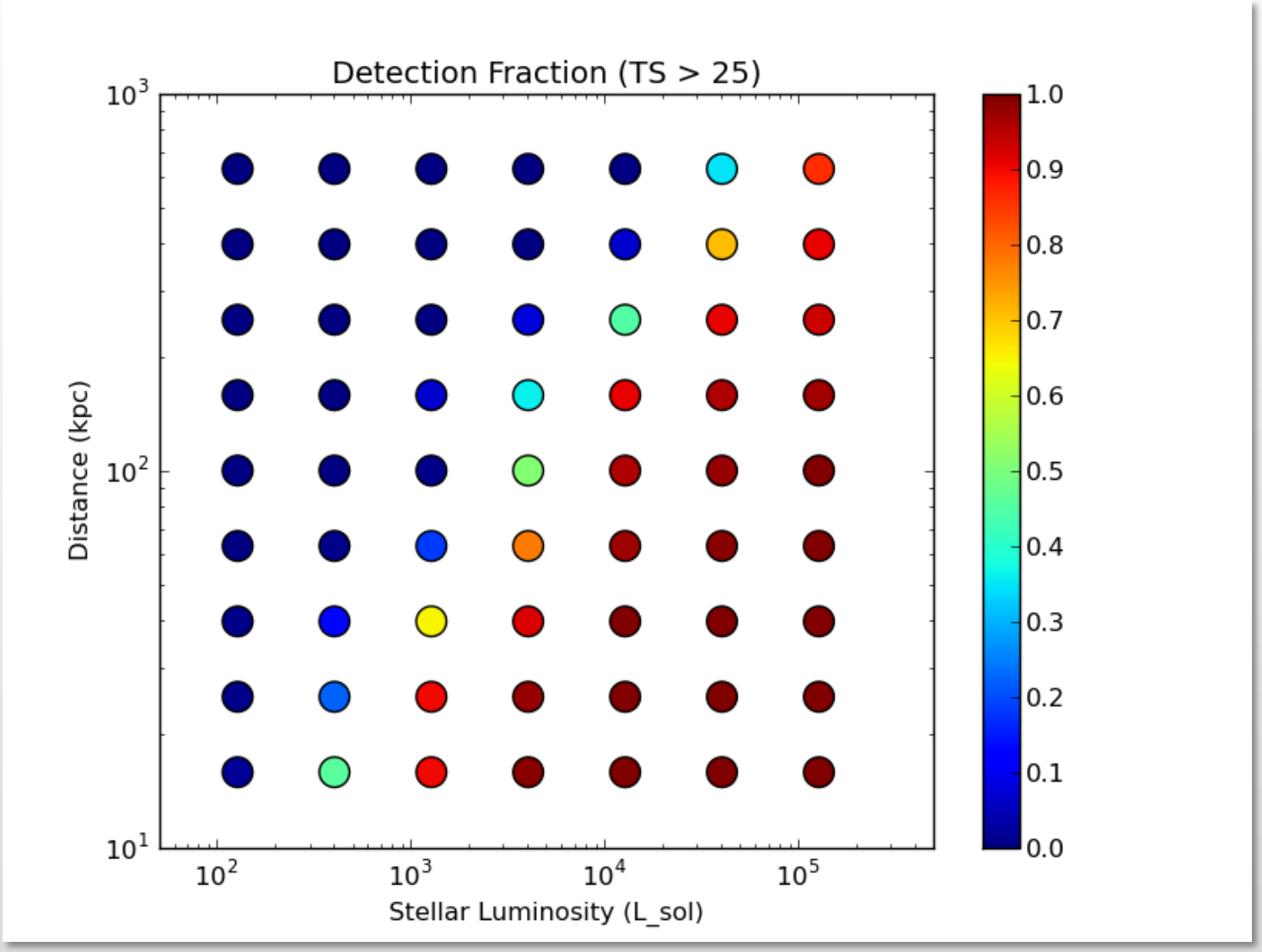
Stellar Mass – Size



Number of DES-Observable Stars



DES Detection Sensitivity (Simulations in SPT-E Field)



Future Challenges: Star / Galaxy Separation

- Transition in field population with ever deeper surveys
  - Bright magnitudes: foreground stars
  - Faint magnitudes: unresolved galaxies

- Algorithm improvements would allow for some star incompleteness in order to substantially boost star purity at faint end

- Star selection at faint magnitudes
  - Algorithms using color information (Fadely et al. 2012)
  - Using multiple SExtractor outputs (Soumagnac et al. 2013)

Closing Remarks

- UGALI algorithm designed as matched-filter, maximum-likelihood algorithm efficient enough to search for and characterize Milky Way satellites in wide-field surveys
  - Code up and running on UChicago "midway" compute cluster
- Hoping for new discoveries in the ~2500 deg^2 to be covered in first year of DES
- Work in progress – feedback / suggestions welcome!

DARK ENERGY
SURVEY

Back-up Slides