Searching for the Darkest Galaxies

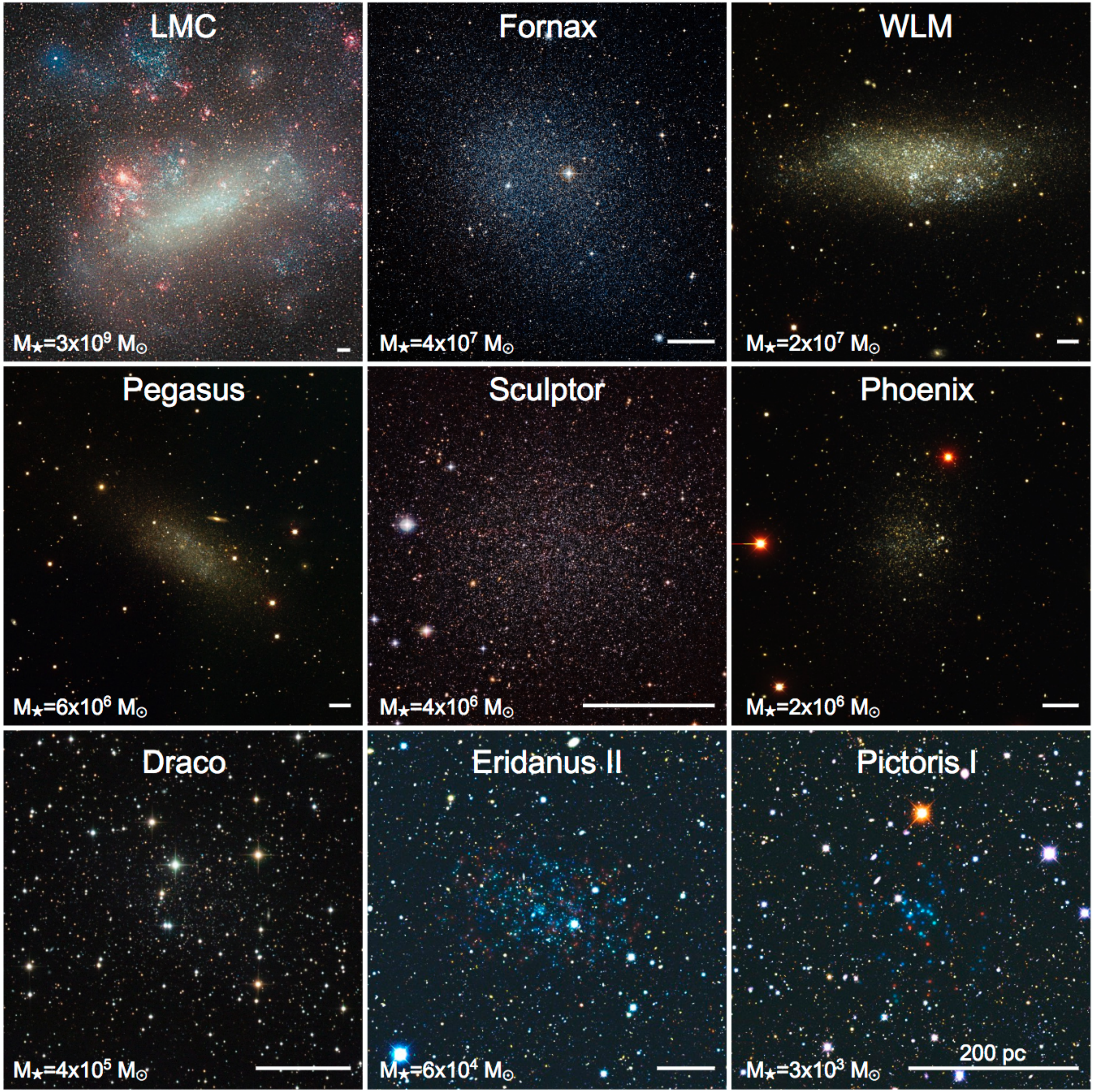
Keith Bechtol

LSST

(w/ many results from DES)

KITP Seminar
18 May 2018


Milky Way
$M_{\star} = \sim 6 \times 10^{10}\ M_{\odot}$
Large Magellanic Cloud
$M_{\star} = \sim 1.5 \times 10^{9}\ M_{\odot}$
Small Magellanic Cloud
$M_{\star} = \sim 5 \times 10^{8}\ M_{\odot}$



Bullock & Boylan-Kolchin
2017
arXiv:1707.04256

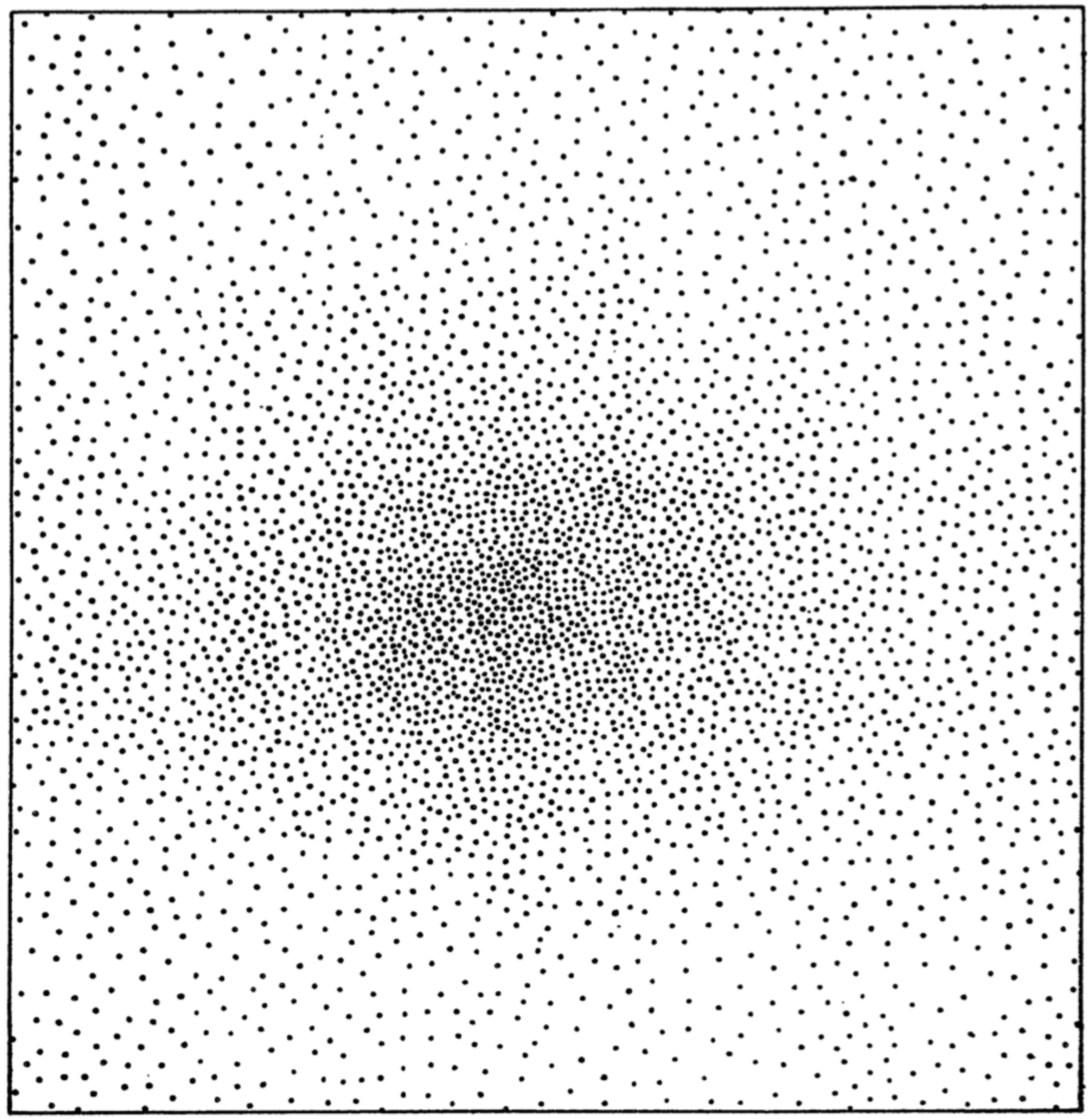
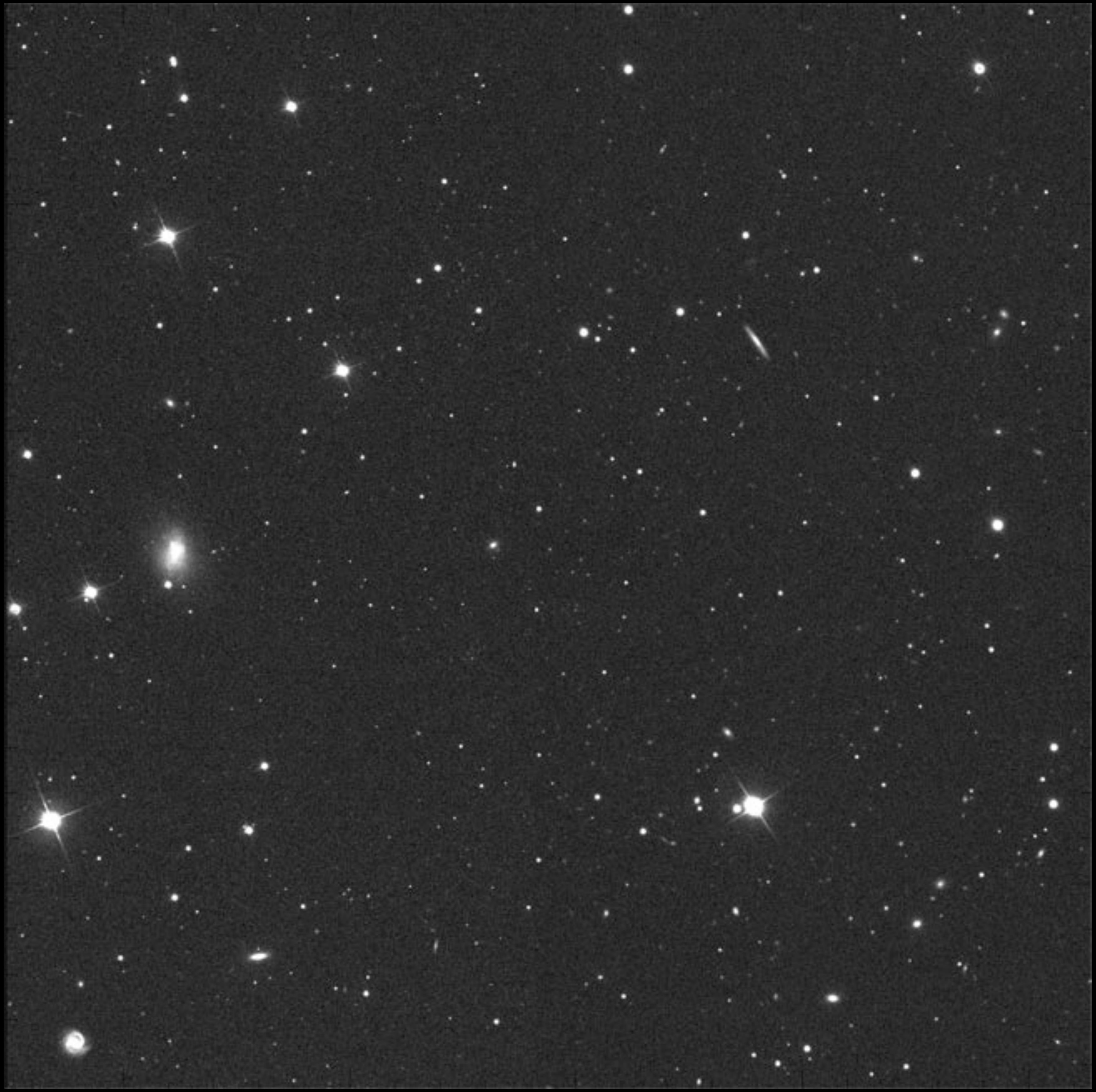


FIGURE 2.— DISTRIBUTION OF STARS IN CENTRAL SQUARE DEGREE

Sculptor

In many respects it appeared to be unlike any known stellar organization. The finding more recently of a similar system in Fornax … suggests that a description of these objects may be of general interest.

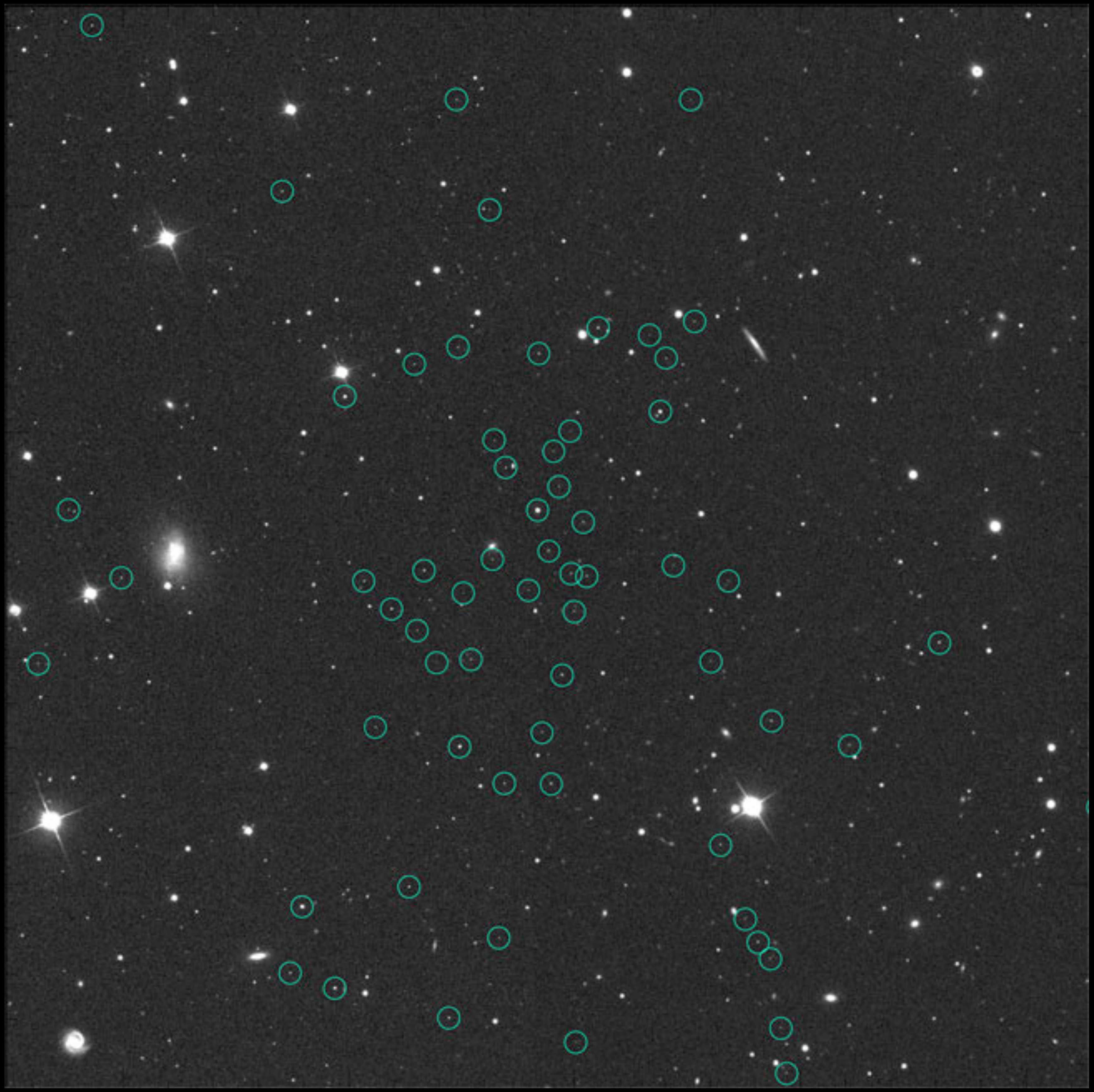
- Harlow Shapley, 1938



Segue 1

$M_{\star} = \sim 300\ M_{\odot}$

Credit: Marla Geha



Segue 1

$M_{\star}$ = ~300 $M_{\odot}$

Credit: Marla Geha

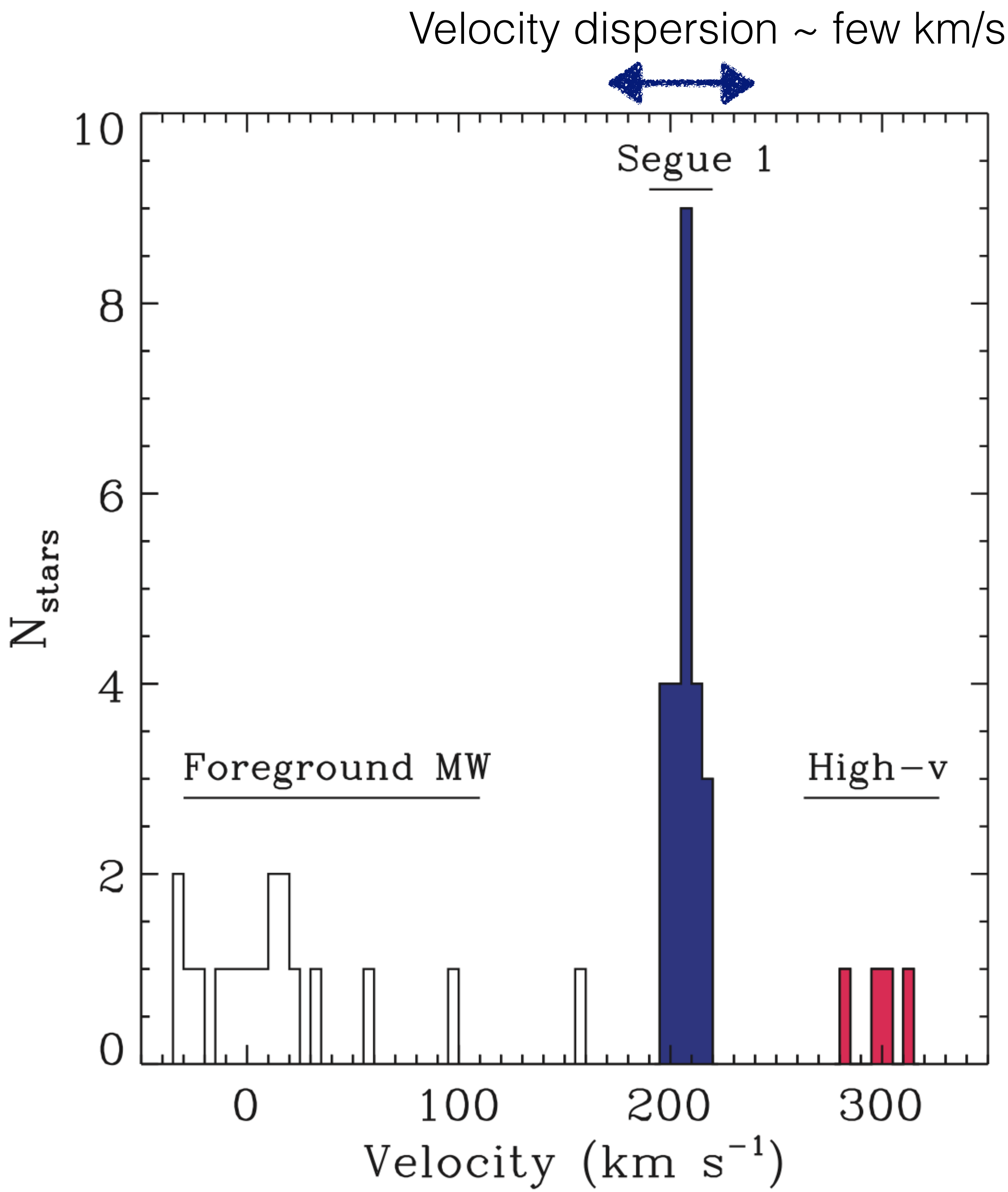
Ultra-faint galaxies are discovered as arcminute-scale statistical over-densities of individually resolved stars

Segue 1

$M_{\star} = \sim 300\ M_{\odot}$

Credit: Marla Geha

Spectroscopic Follow-up: Stellar Kinematics



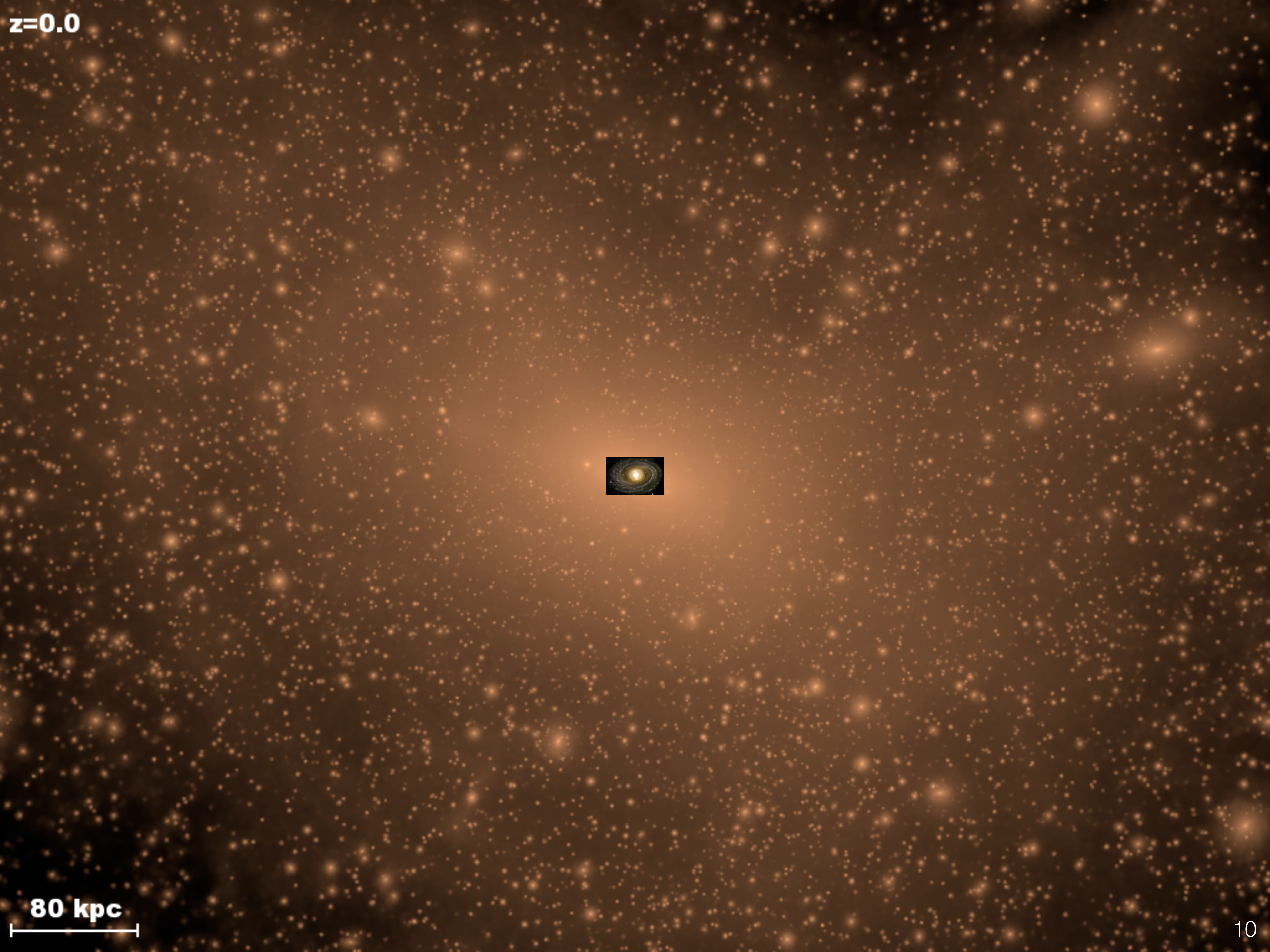
Measure Doppler shifts of individual stars

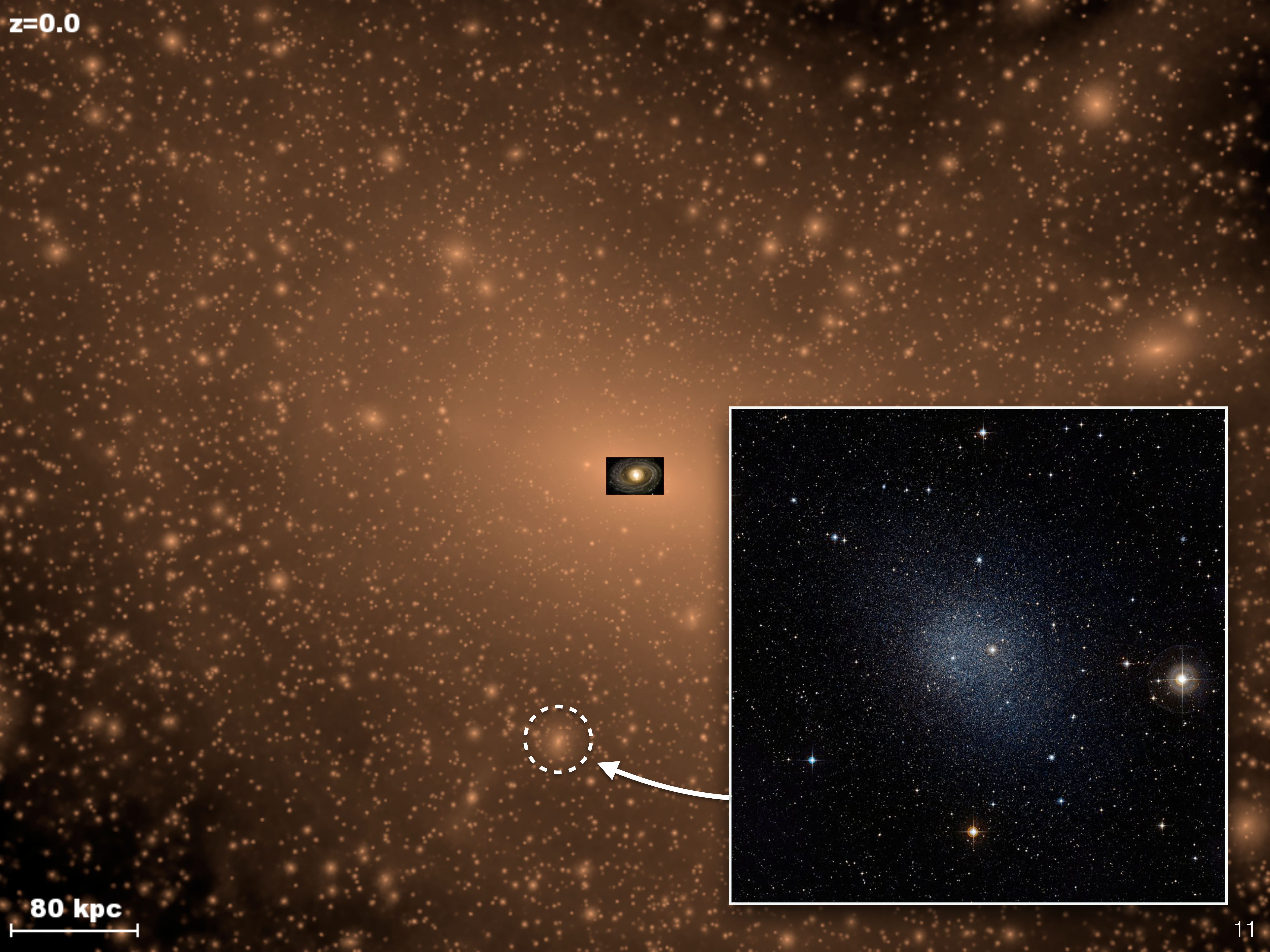
Satellite member stars are distinguished by their **distinct locus in velocity-space**

The **velocity dispersion** is too large to be explained by the stellar mass alone

Segue 1 has mass-to-light ratio of >1000 within the half-light radius!

Geha et al. 2009, ApJ, 692, 1464


z=0.0
80 kpc


z=0.0
80 kpc

“Galaxy” Defined

A galaxy is 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, AJ, 144, 76

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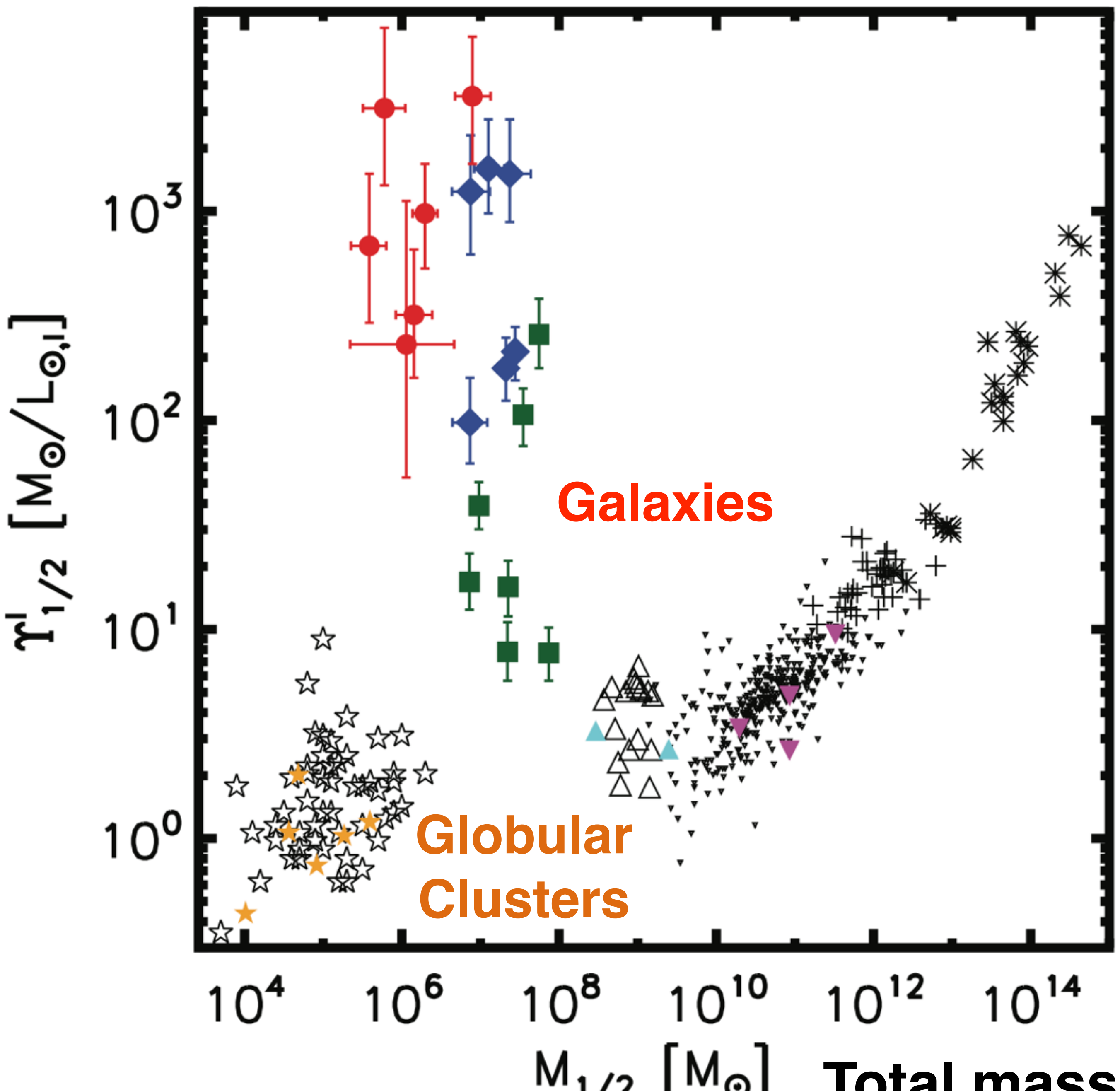
Mass-to-light ratio within half-light radius



Wolf et al. 2010, MNRAS, 406, 1220

Total mass within half-light radius

"Galaxy" Defined

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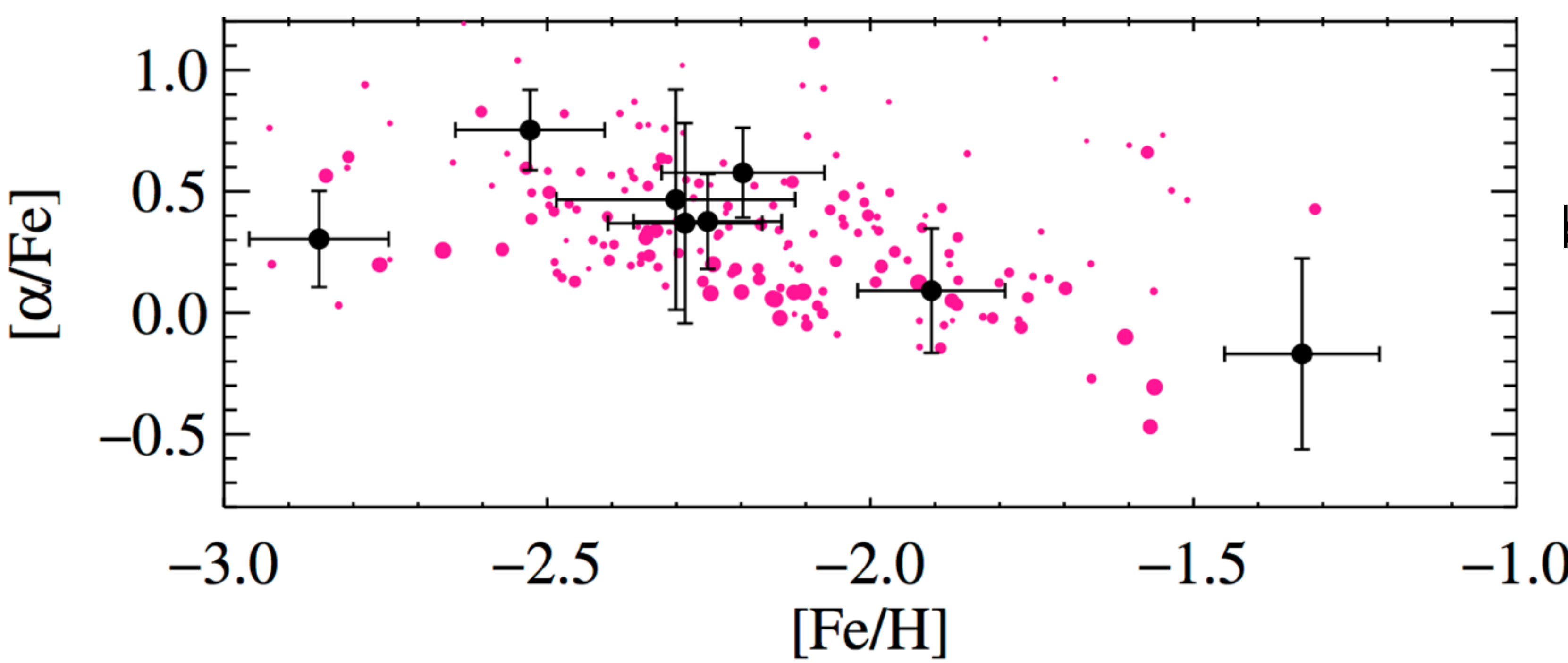
Willman & Strader 2012, AJ, 144, 76



Kirby et al. 2013, ApJ, 770, 16

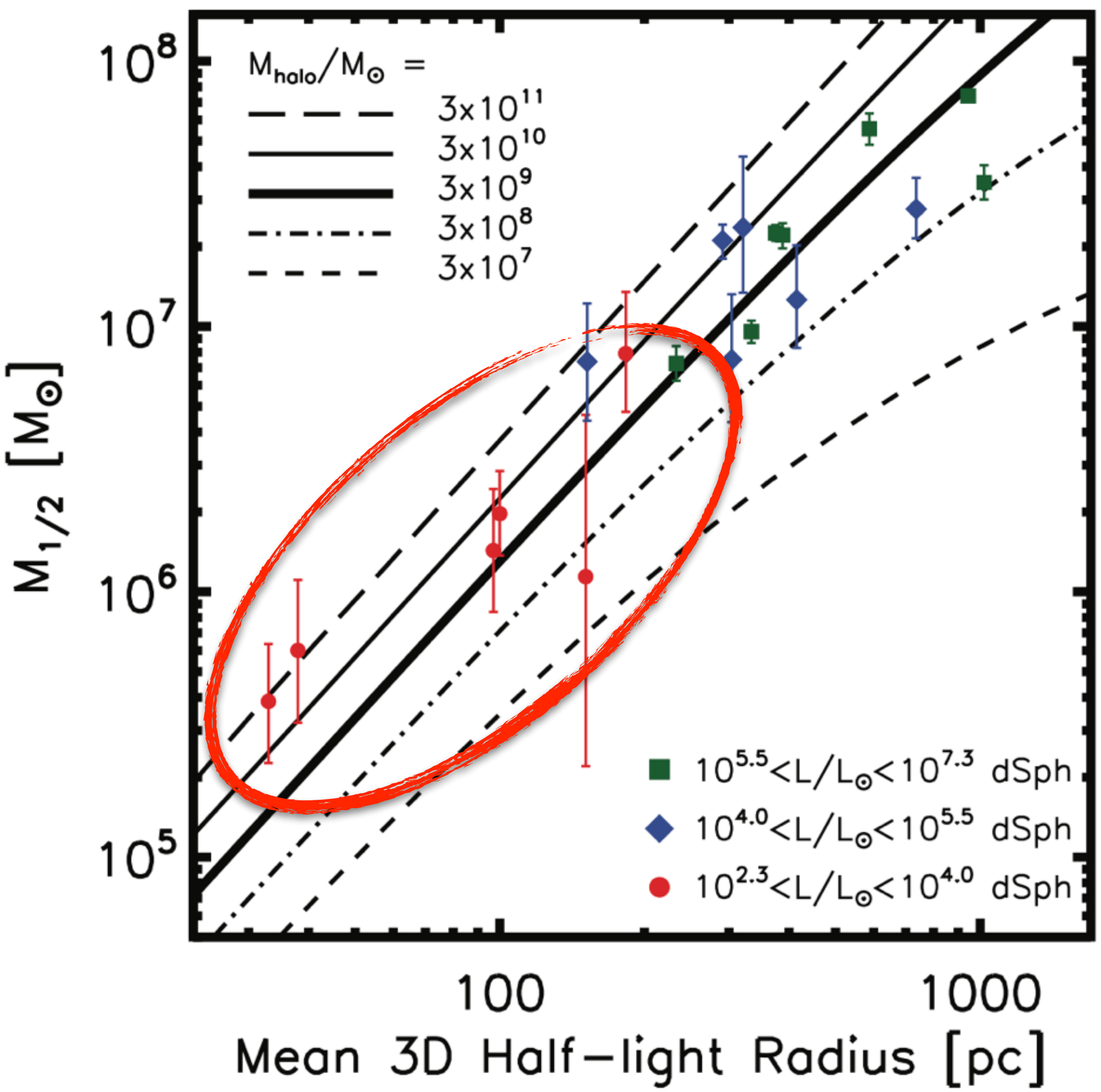
Segue 2 has an upper limit on velocity dispersion (< 2.2 km s^{-1}), but exhibits **metallicity dispersion** characteristic of a galaxy; suggests that supernova ejecta was contained

In dark matter context, **galaxies are born in dark matter halos**

Total Masses of Ultra-faint Galaxies (?)

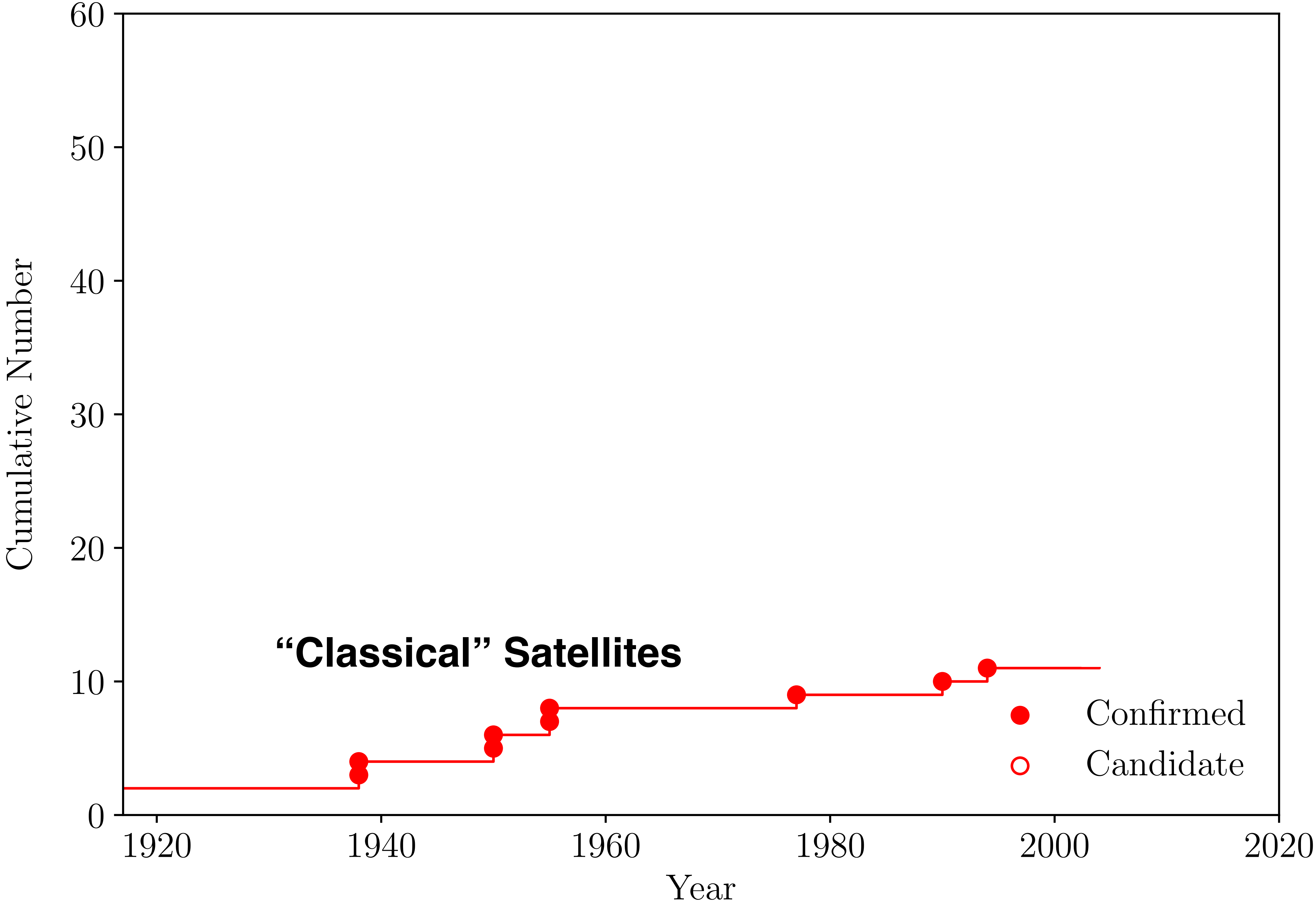
For galaxies with a small number of velocity measurements (tens), the most robustly constrained quantity is the total mass within the stellar 3D half-light radius
— ***a small fraction of the total halo mass***

Mass-to-light ratio of ultra-faint galaxies within full halo extent could be much larger than mass-to-light ratio within the half-light radius (the typically quoted quantity)



Wolf et al. 2010, MNRAS, 406, 1220

Milky Way Satellite Discovery Timeline



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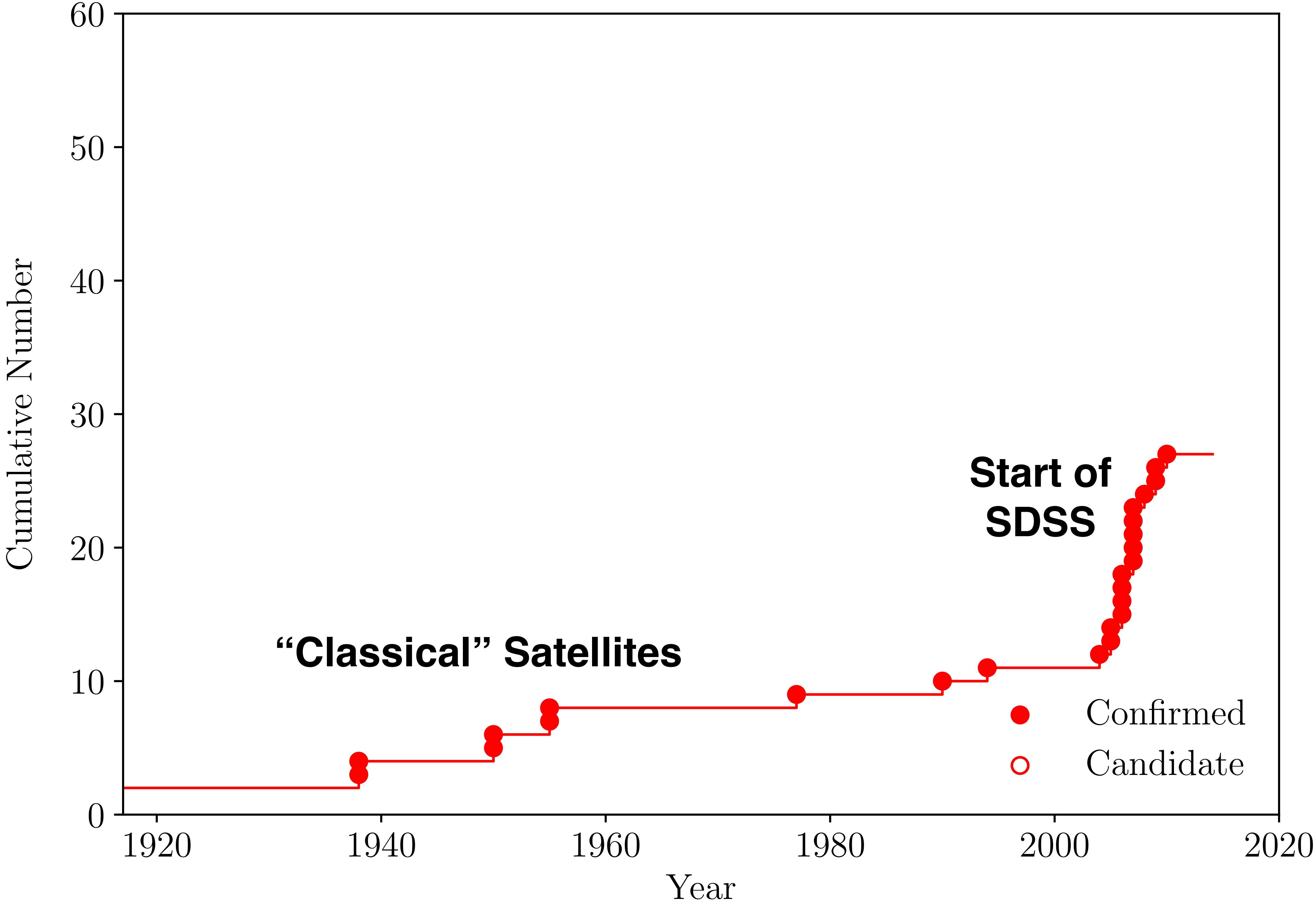

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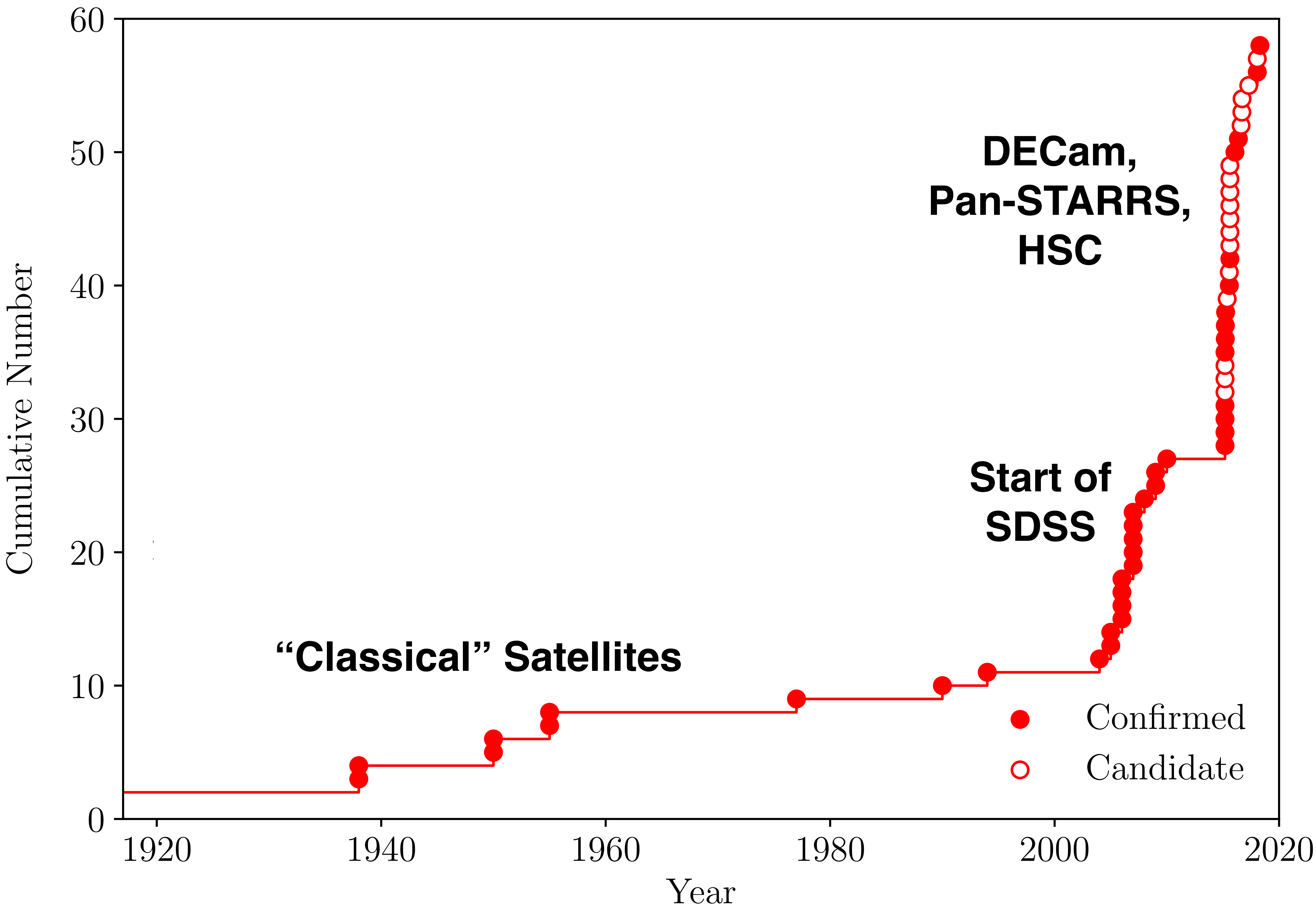
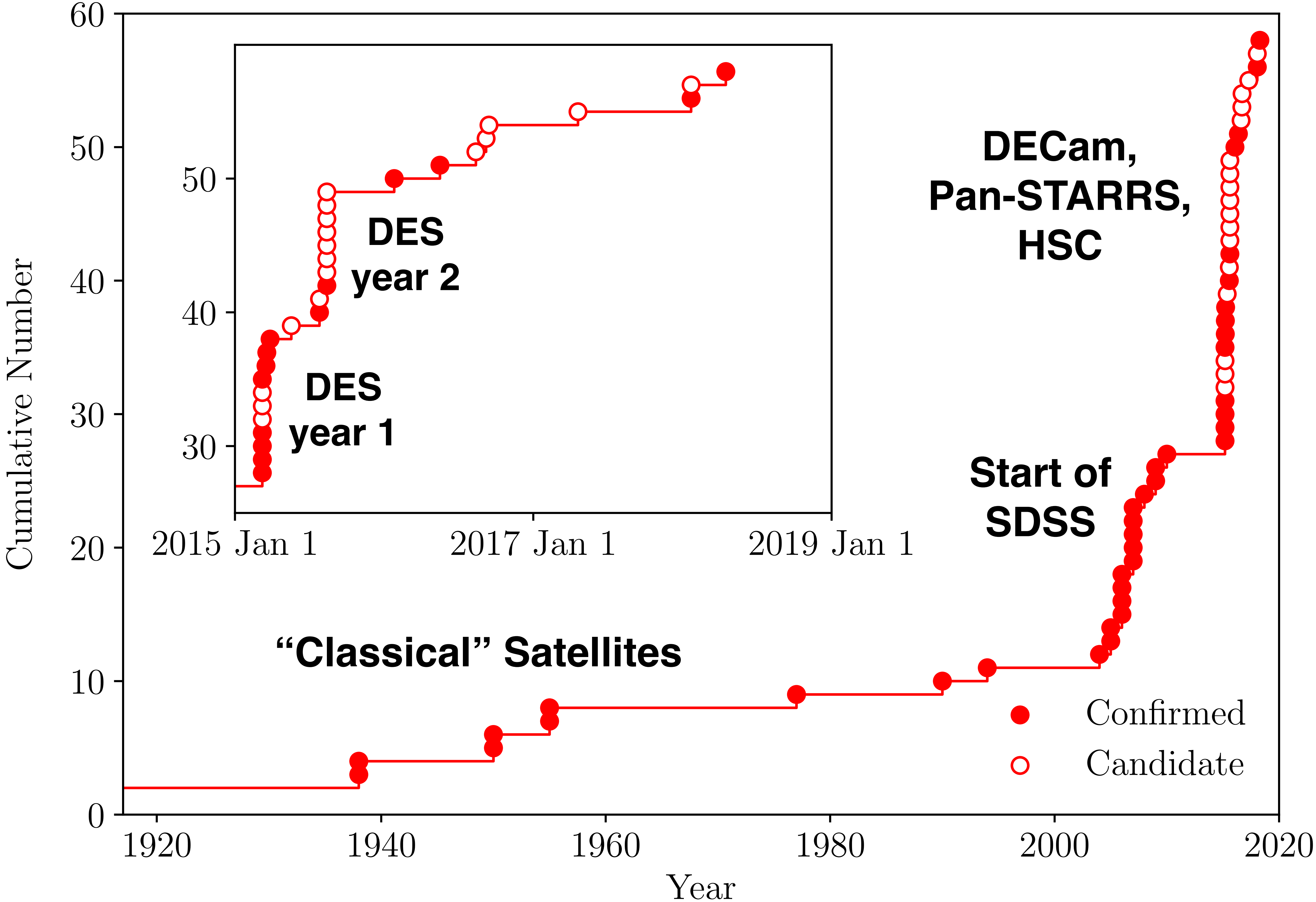


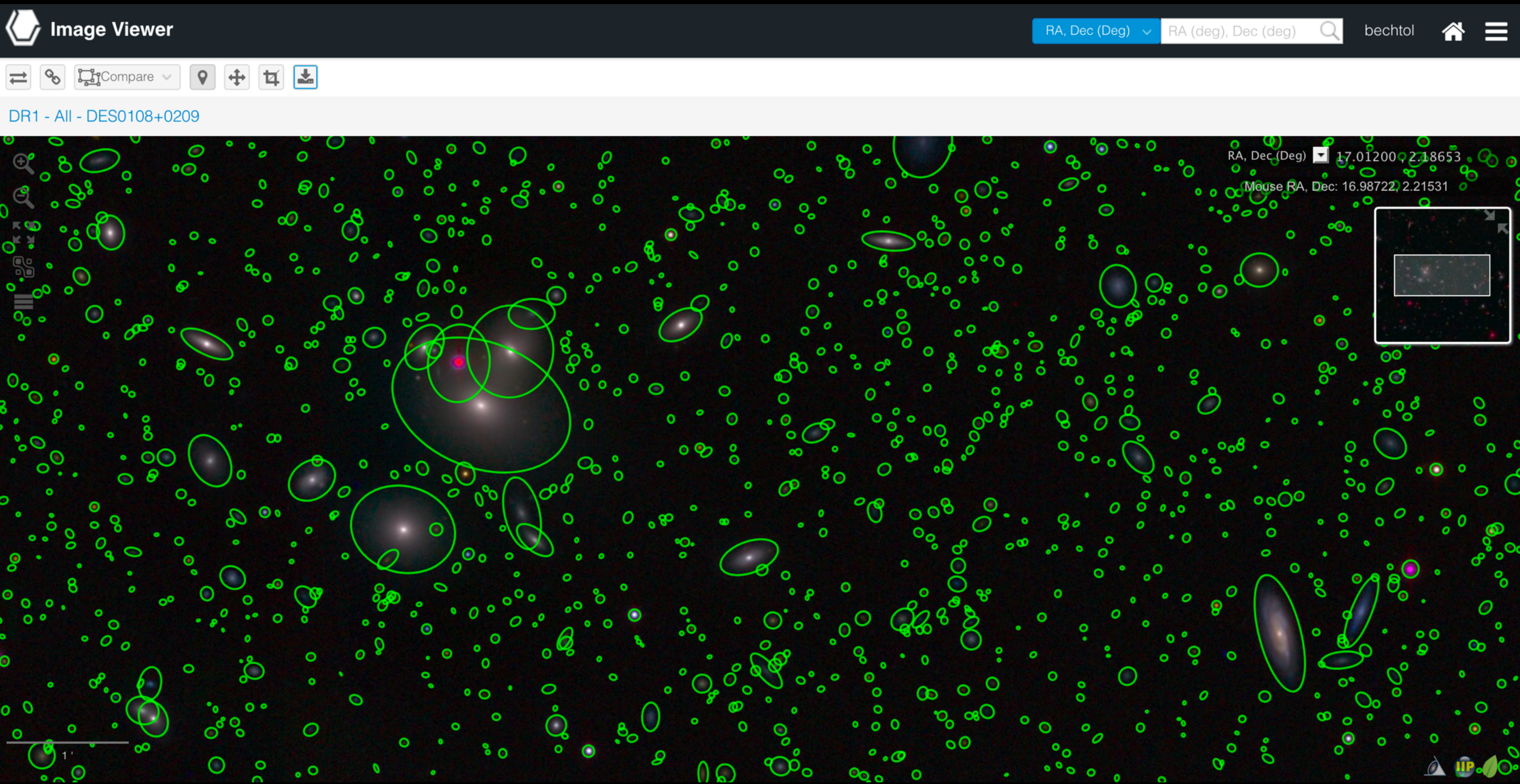
Milky Way Satellite Discovery Timeline



Sample DES Imaging

THE DARK ENERGY SURVEY

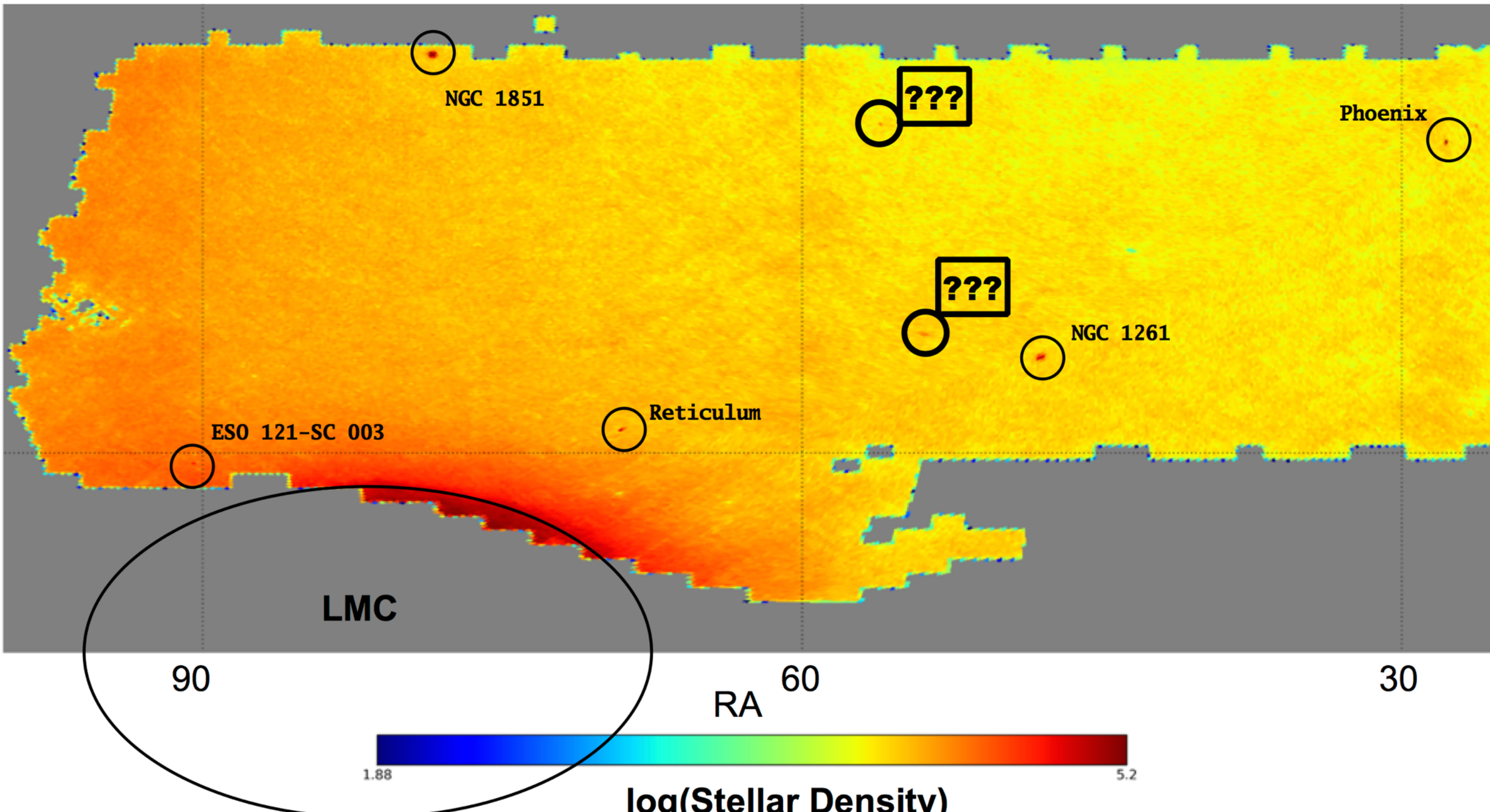
400M objects detected in coadd images from DES Y1-Y3



0.15 deg

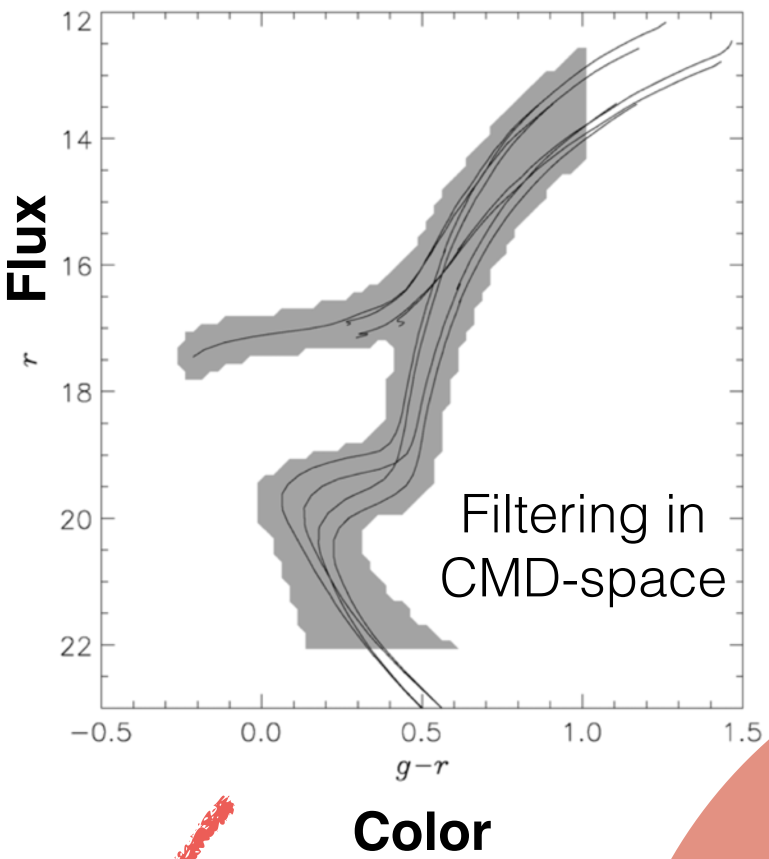
62 science DECam CCDs are each 0.30 deg x 0.15 deg

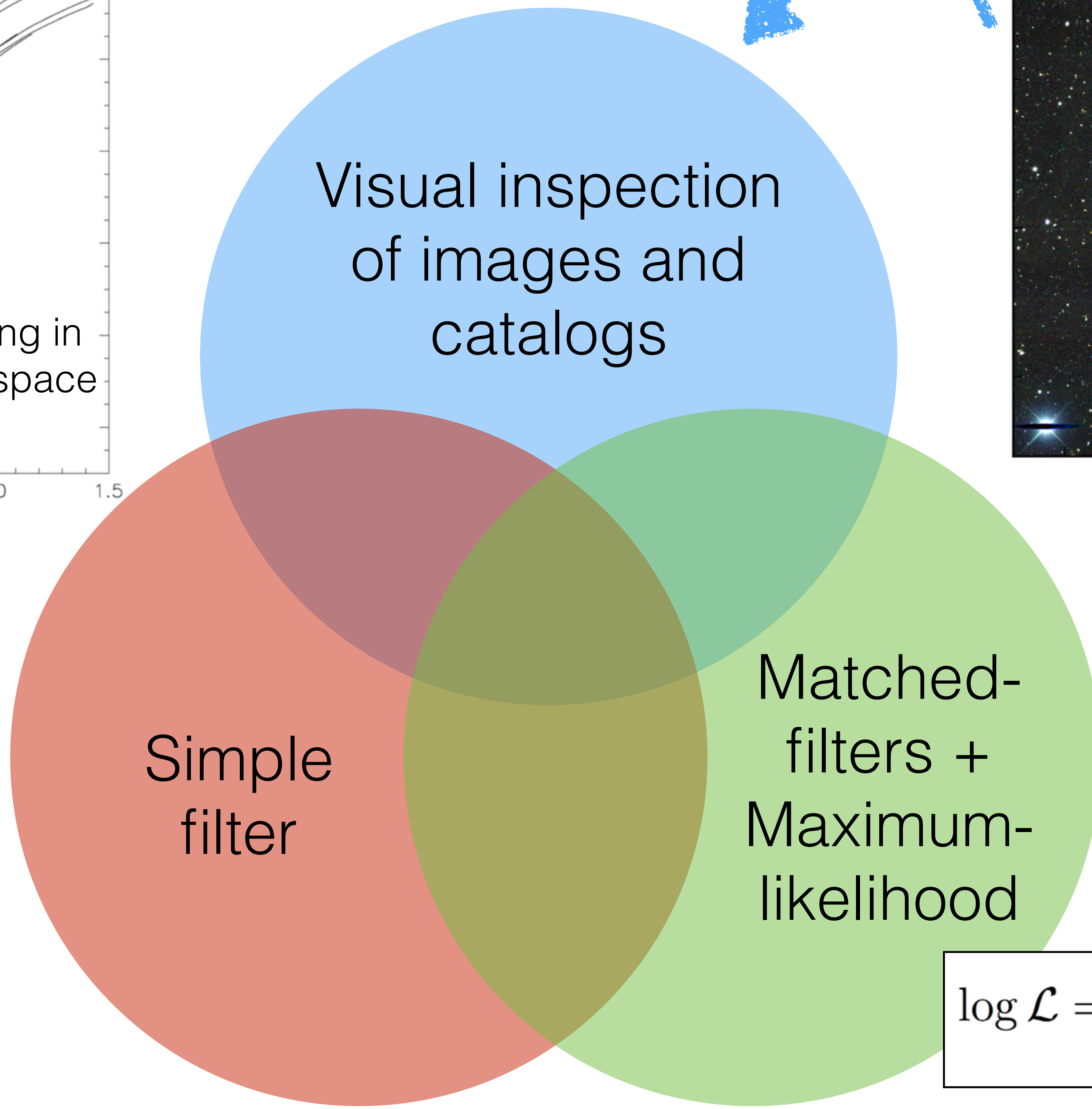
Stellar Density Field from First-year Dark Energy Survey Data



Union of Search Strategies

Walsh et al. 2009, AJ, 137, 450





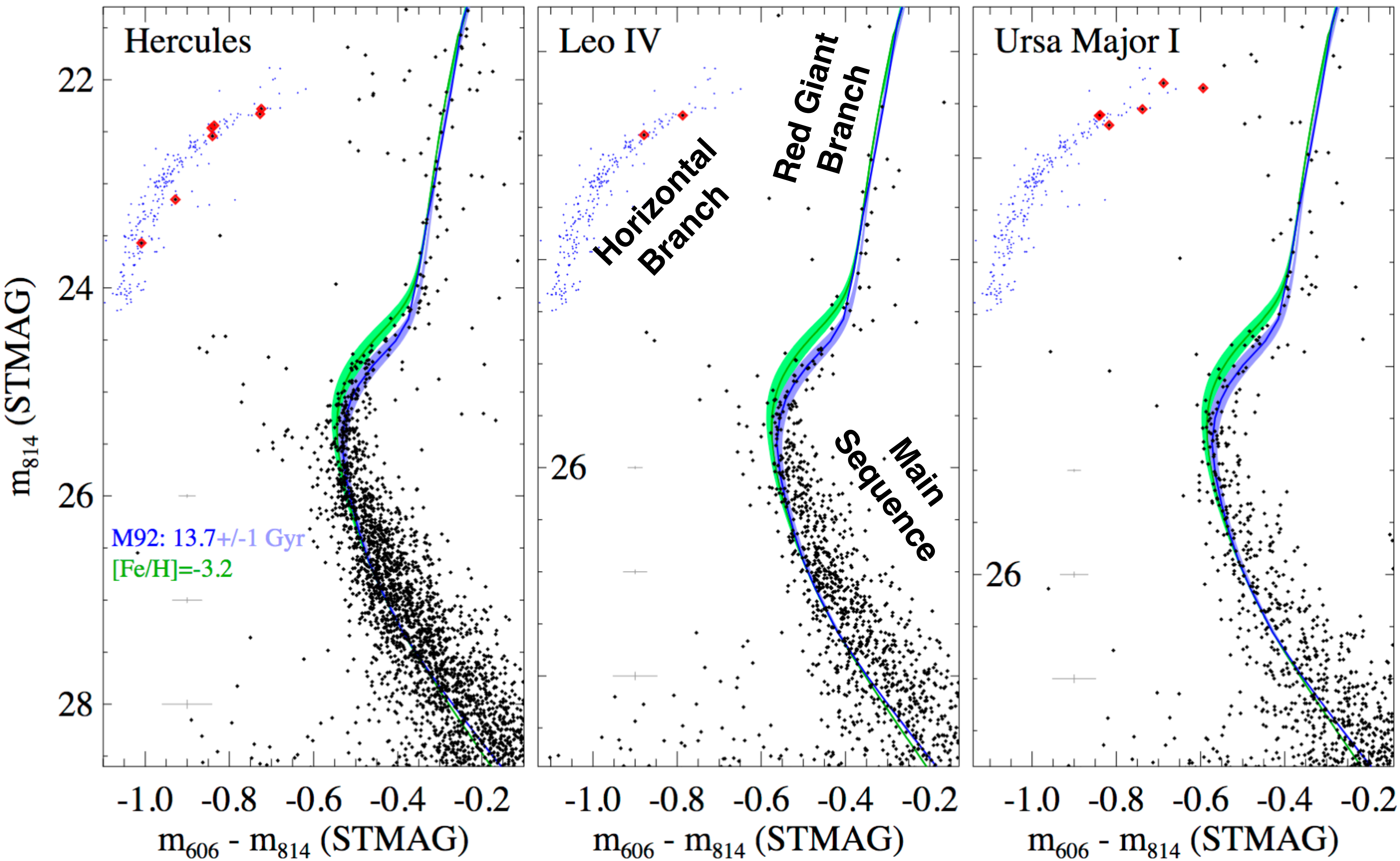
$$\log \mathcal{L} = -f\lambda + \sum_i (1 - p_i)$$

Bechtol et al. 2015, ApJ, 807, 50   Luque et al. 2015, arXiv:1508.02381

“Primeval” Stellar Populations of Ultra-faint Galaxies

THE DARK ENERGY SURVEY

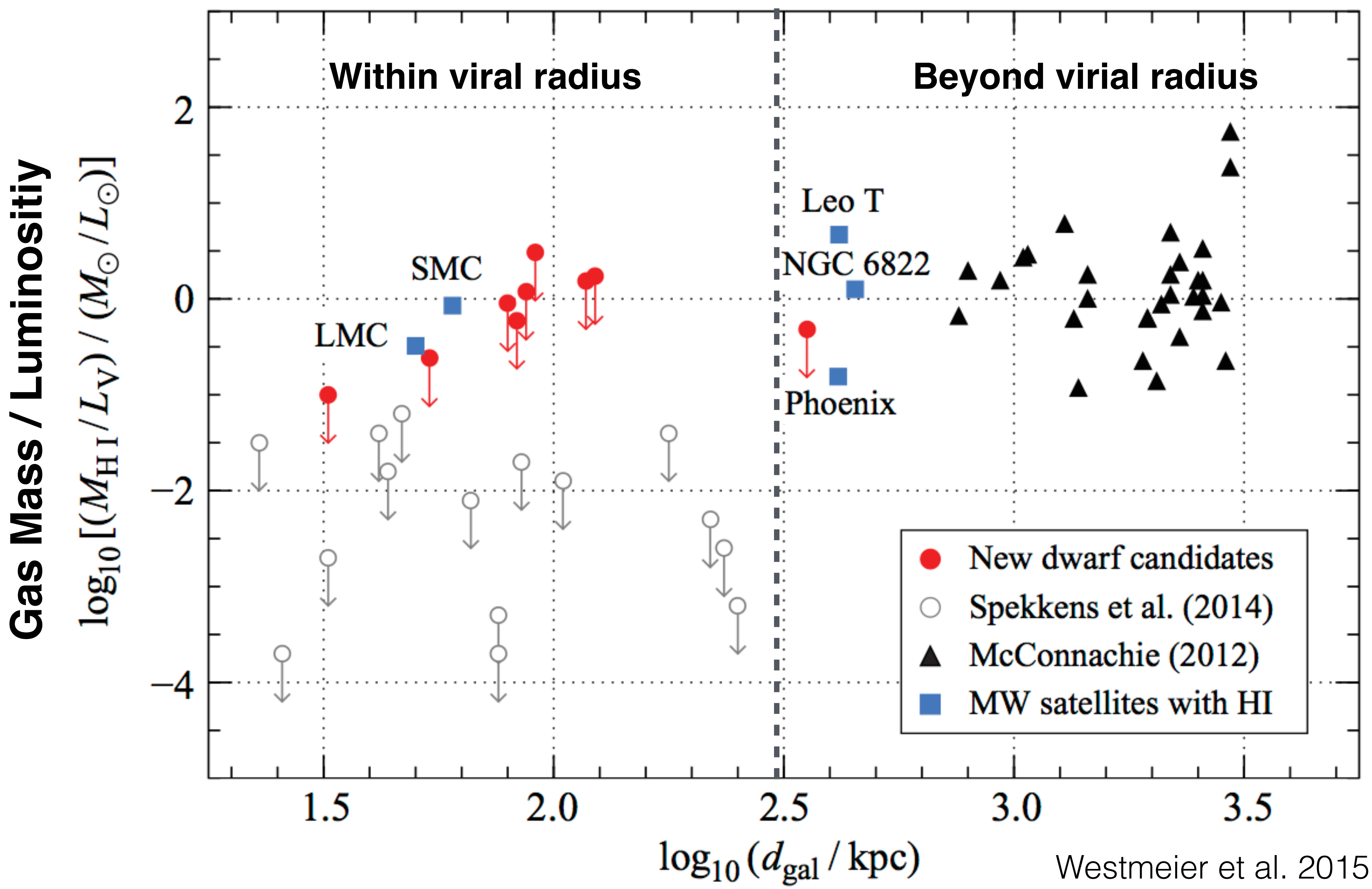
Deep *Hubble* imaging confirms extremely old (~13 Gyr) and metal poor stellar populations (< 10^{-2} Solar)



Brown et al. 2012 arXiv:1206.0941

Low Neutral Gas Content

Nine dSphs found in first-year DES data found to have low neutral gas content, similar to previously known dSphs around the Milky Way



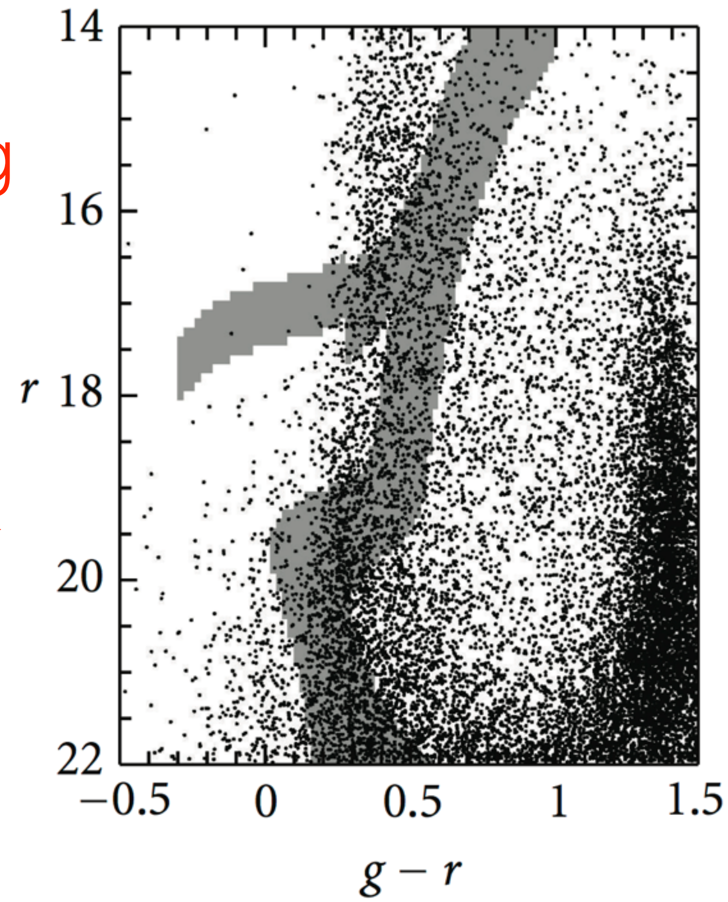
Westmeier et al. 2015, MNRAS, 453, 338

Galaxies beyond Milky Way virial radius tend to be more gas rich than those within

A Representative Search Algorithm

THE DARK ENERGY SURVEY

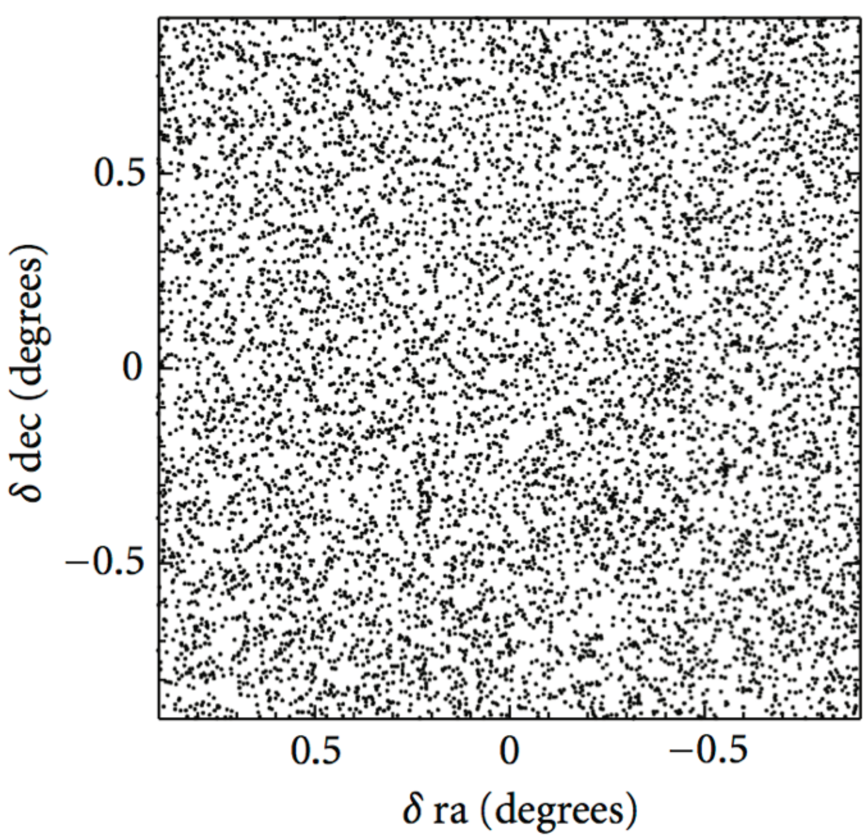
(1) Filter in CMD-space using isochrone for old and metal-poor stellar population

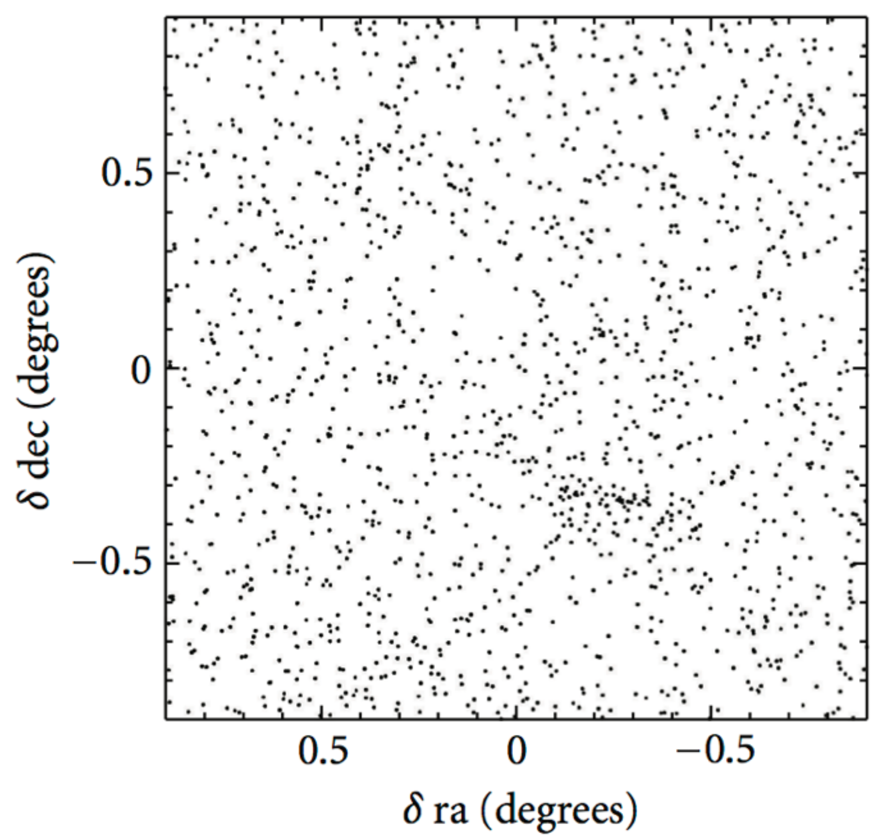


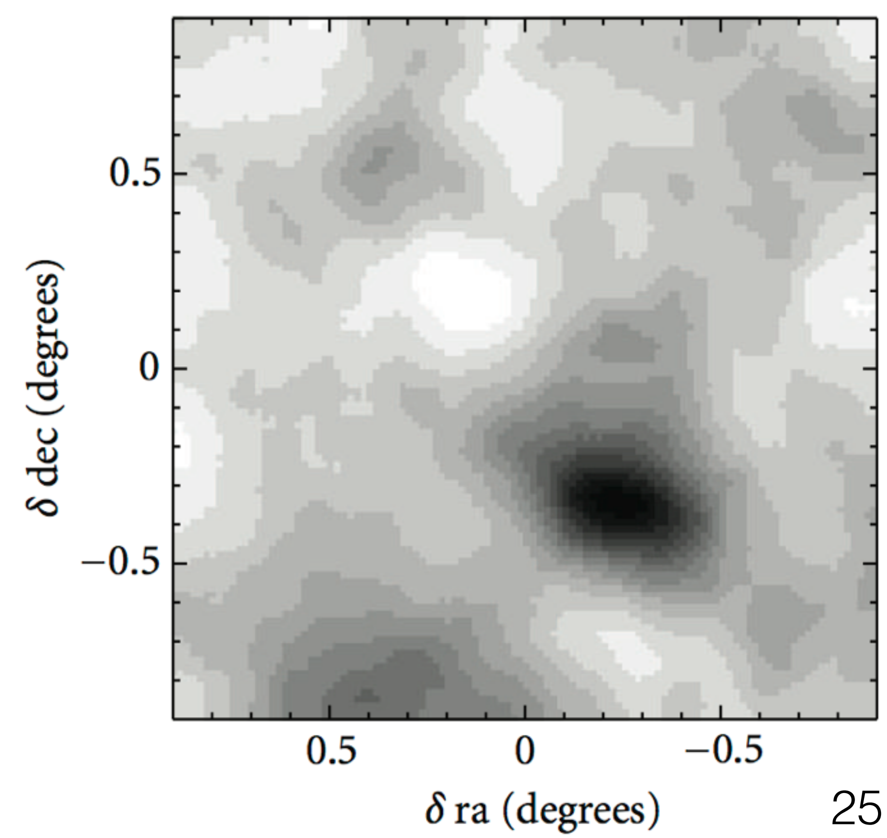
Advantages
Simple, fast,
relatively model-independent

(2) Smooth with spatial kernel

Willman 2010







Likelihood Formalism

Unbinned Poisson Likelihood

Total number of member stars

$$\log \mathcal{L} = -f\lambda + \sum_i (1 - p_i)$$

Fraction of all member stars that are observable in survey (typically few %)

Membership Probabilities

Satellite PDF

$$p_i \equiv \frac{\lambda u_i}{\lambda u_i + b_i}$$

Field density

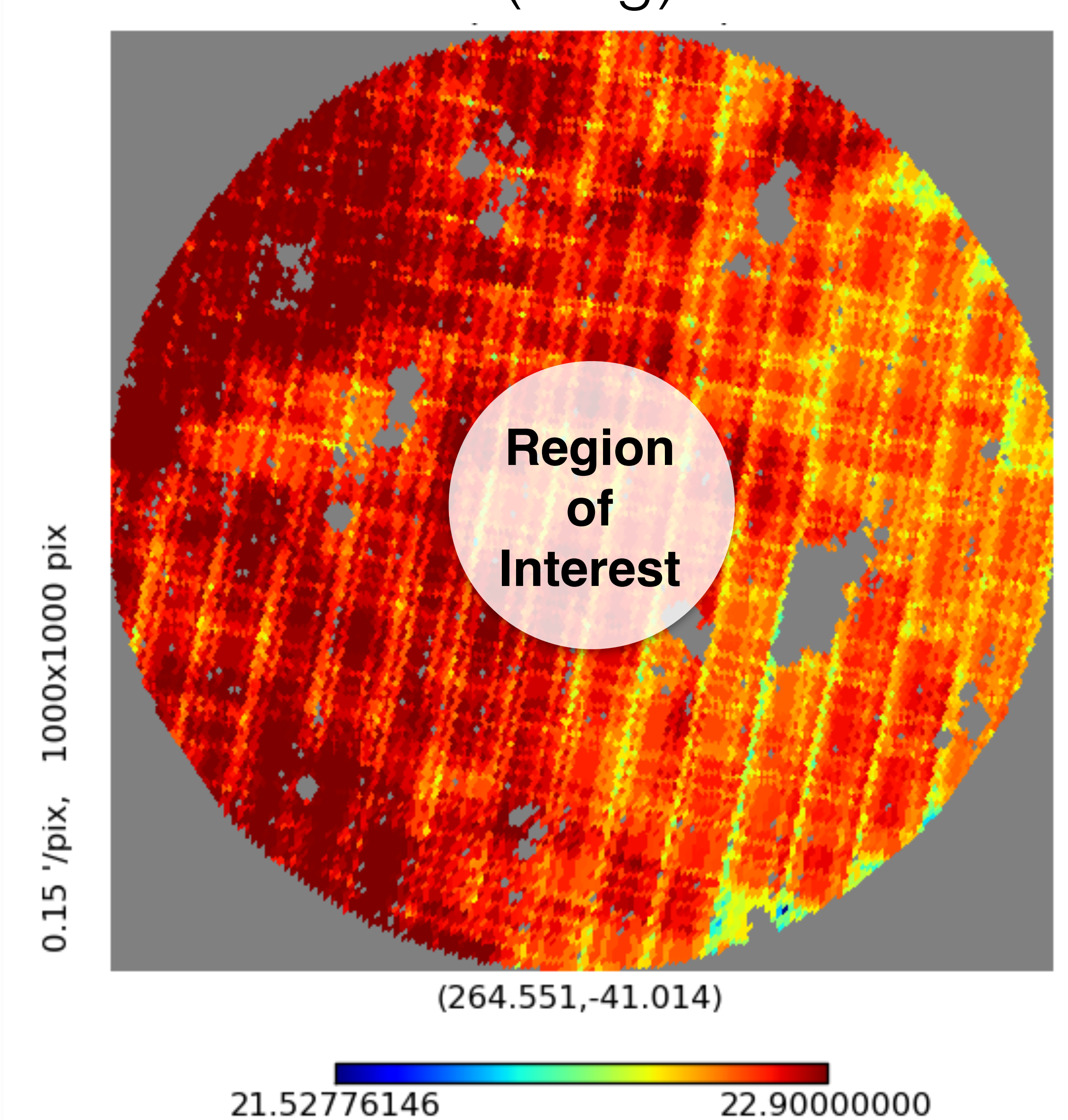
Pipeline Steps

1. Scan for seeds
2. Characterize seeds

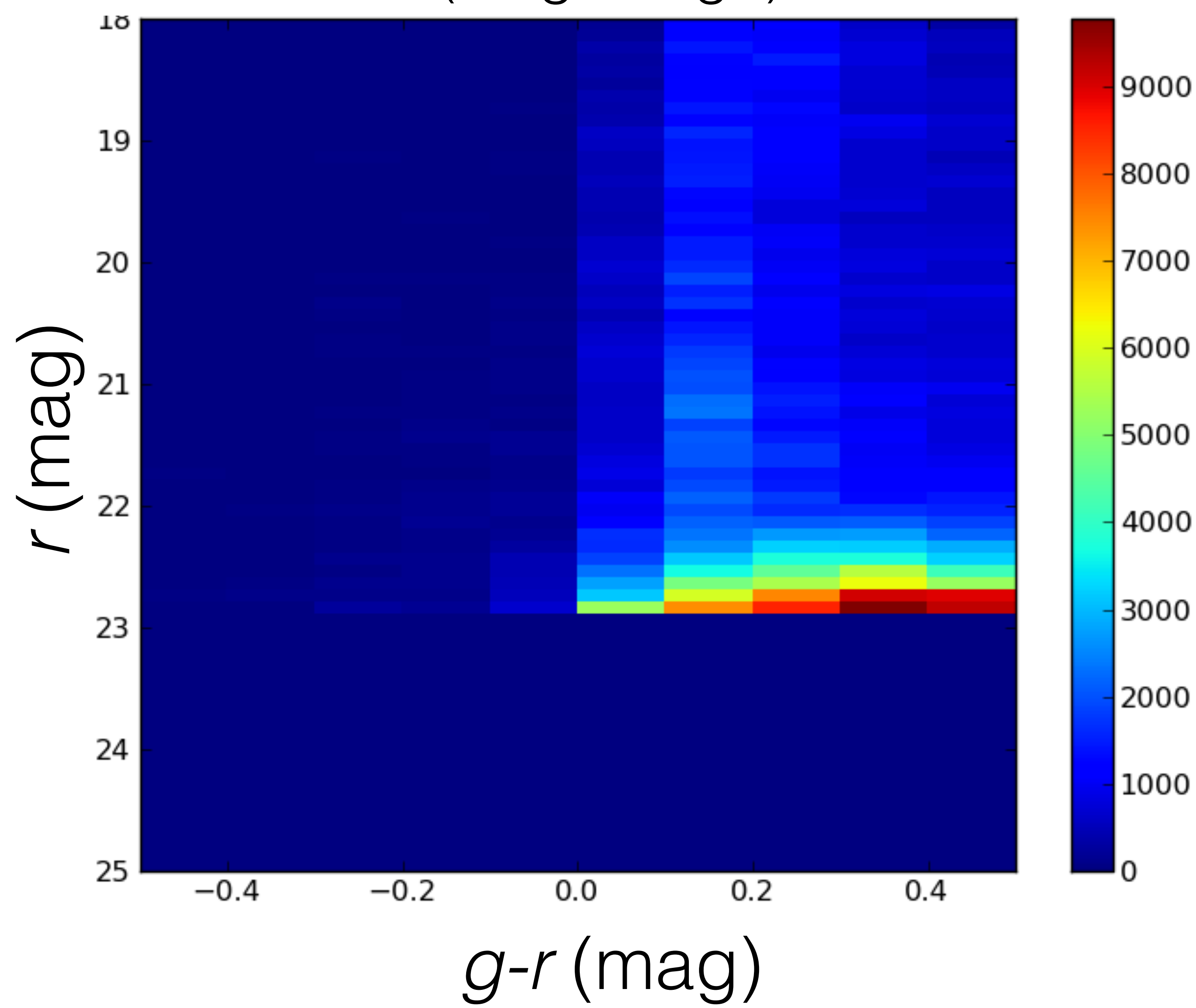
Likelihood Formalism: Field Model

Taking survey depth into account

Survey Geometry and depth
(mag)

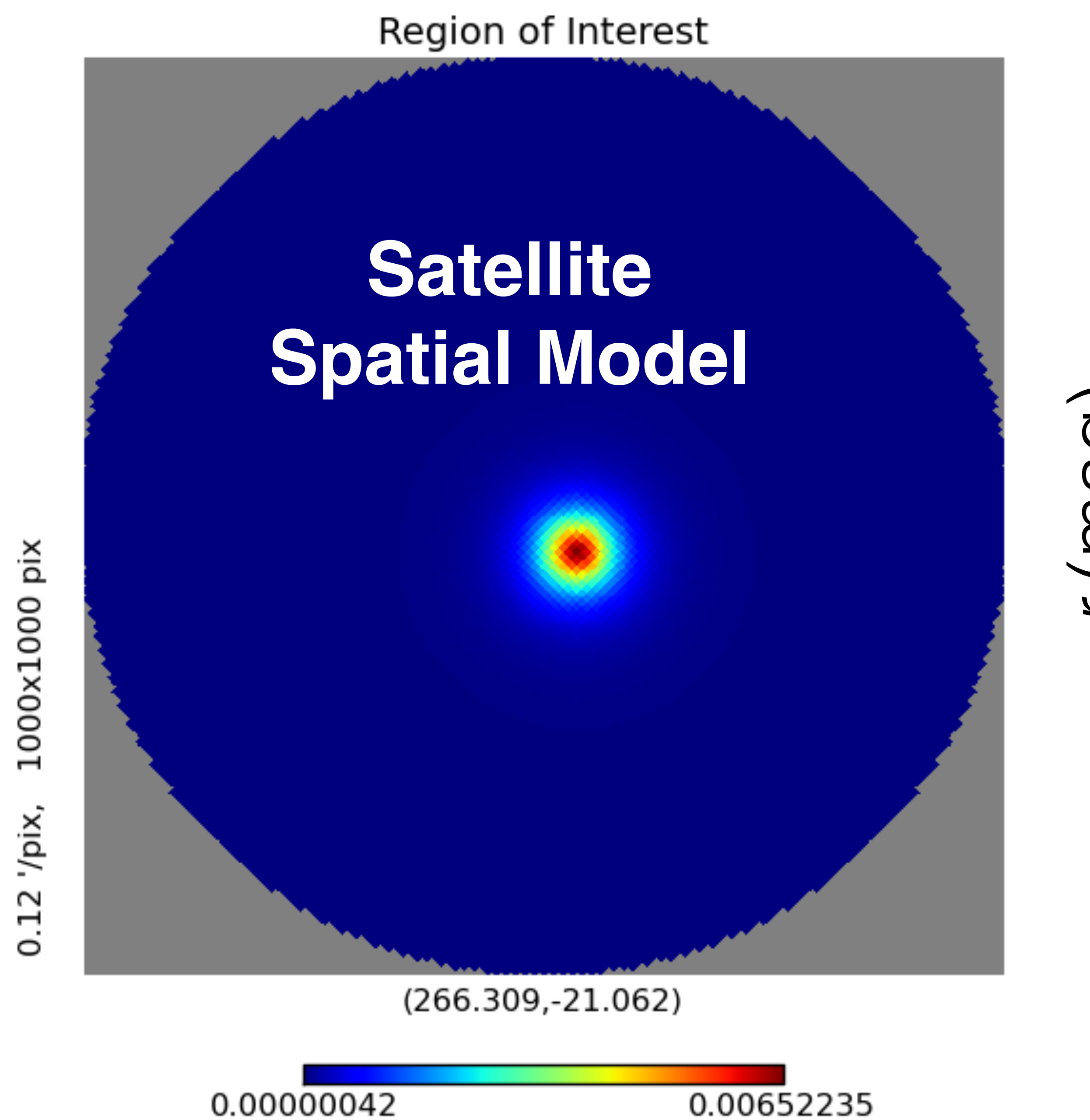


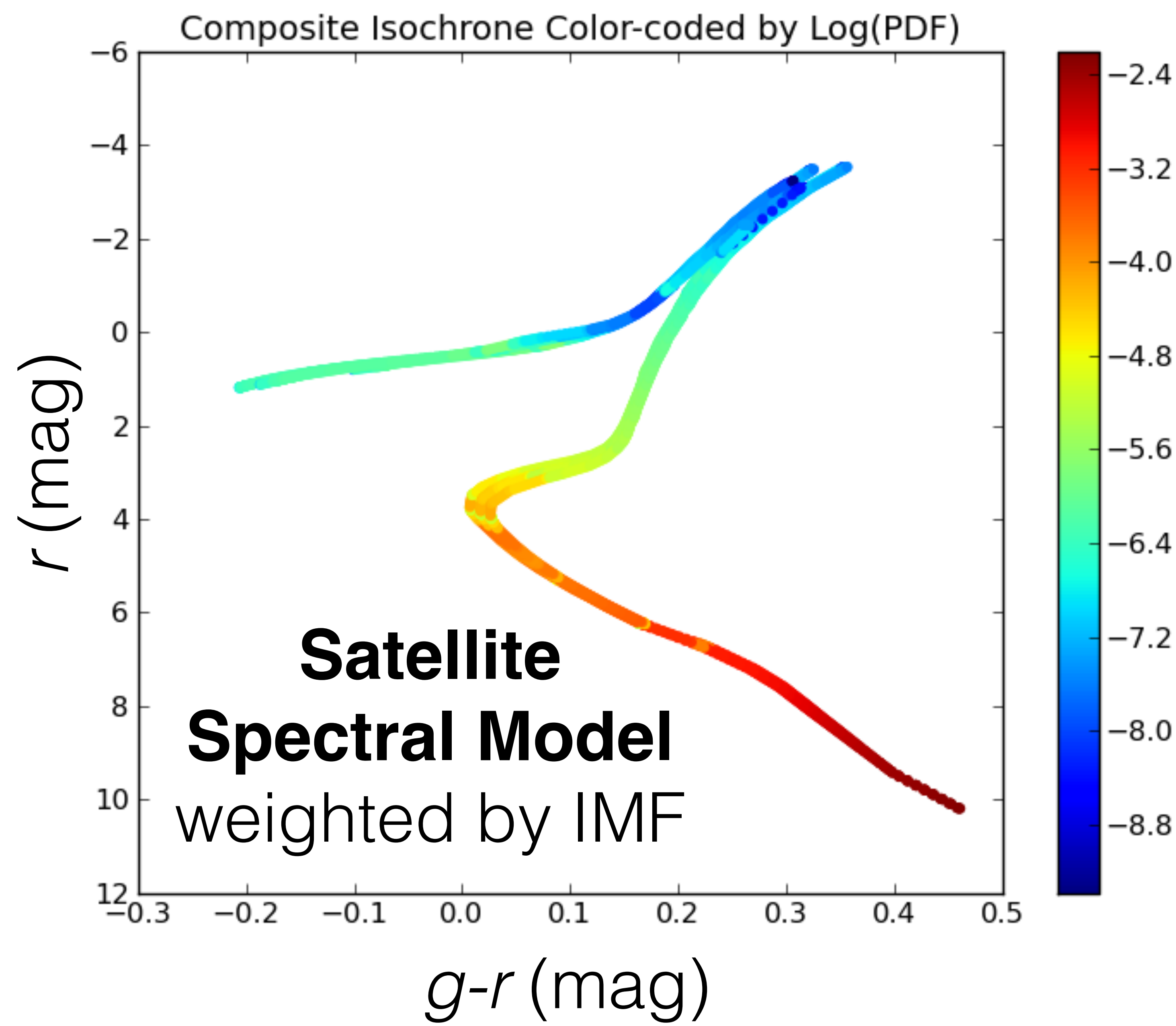
Color-magnitude diagram of "field stars"
(mag^{-2} deg^{-2})



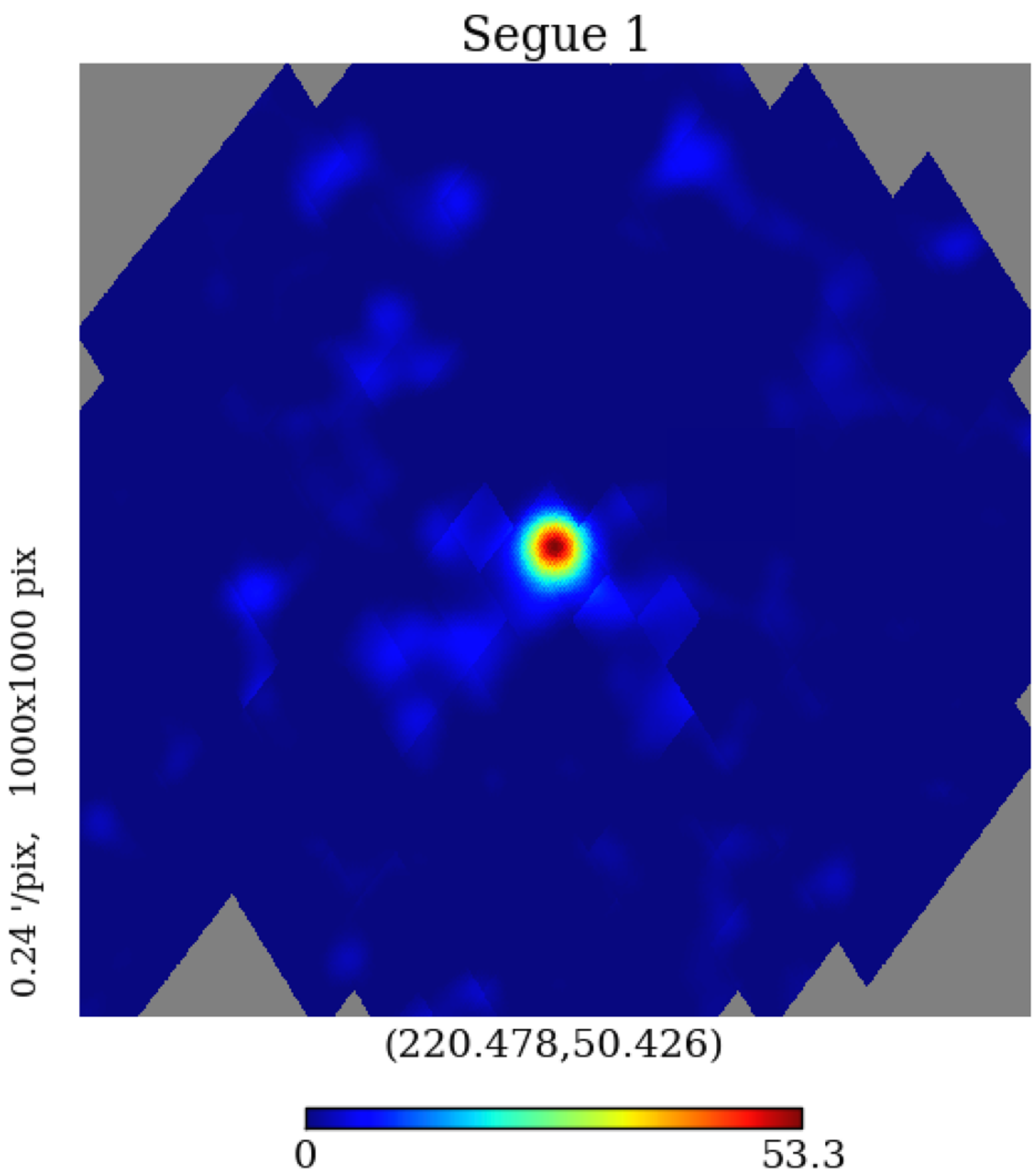
Likelihood Formalism: Satellite Model

Searching for a **population** of stars consistent with known ultra-faint dwarfs (i.e., metal-poor, 10+ Gyr old)



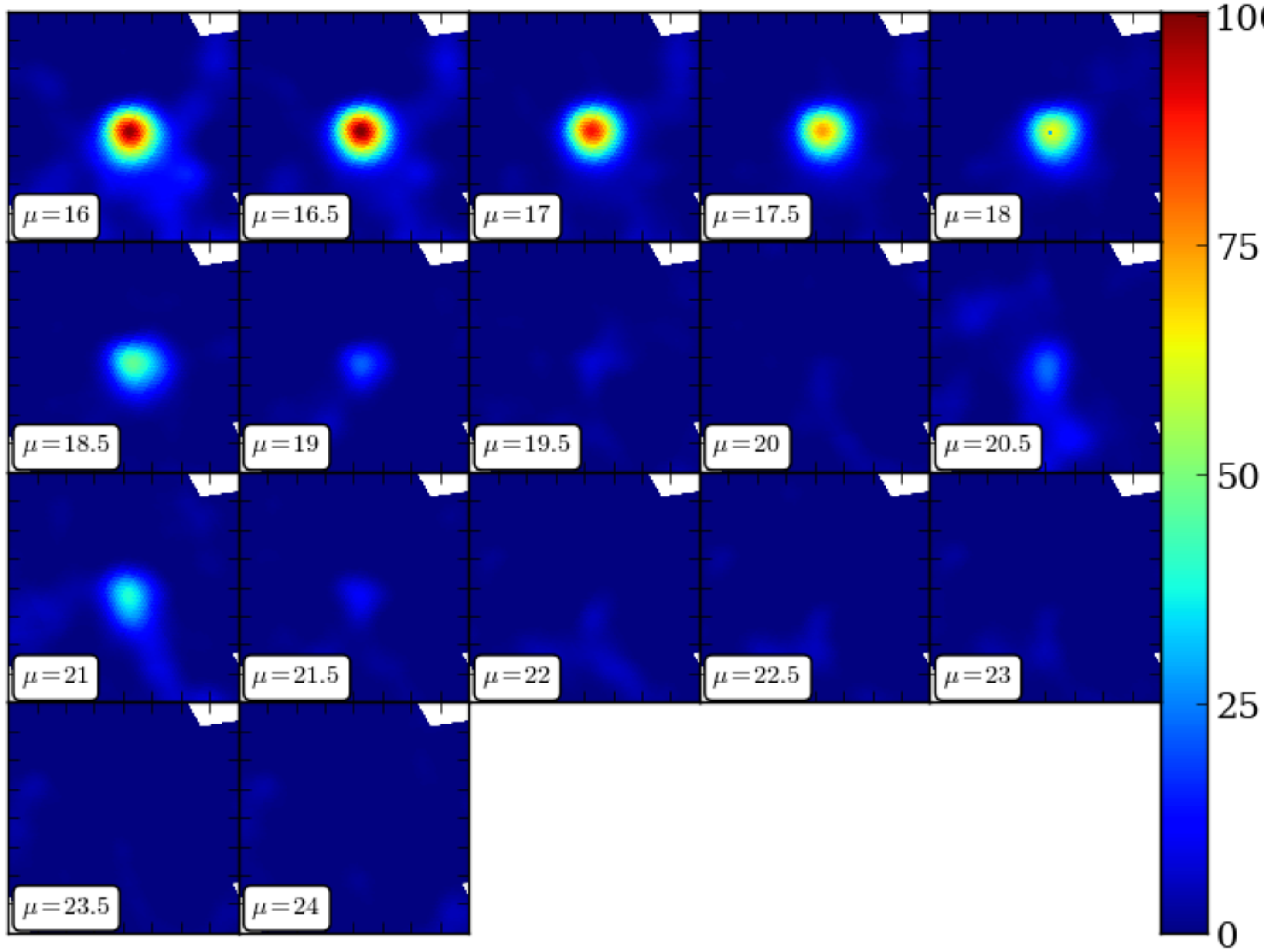


Significance Maps



At single distance…

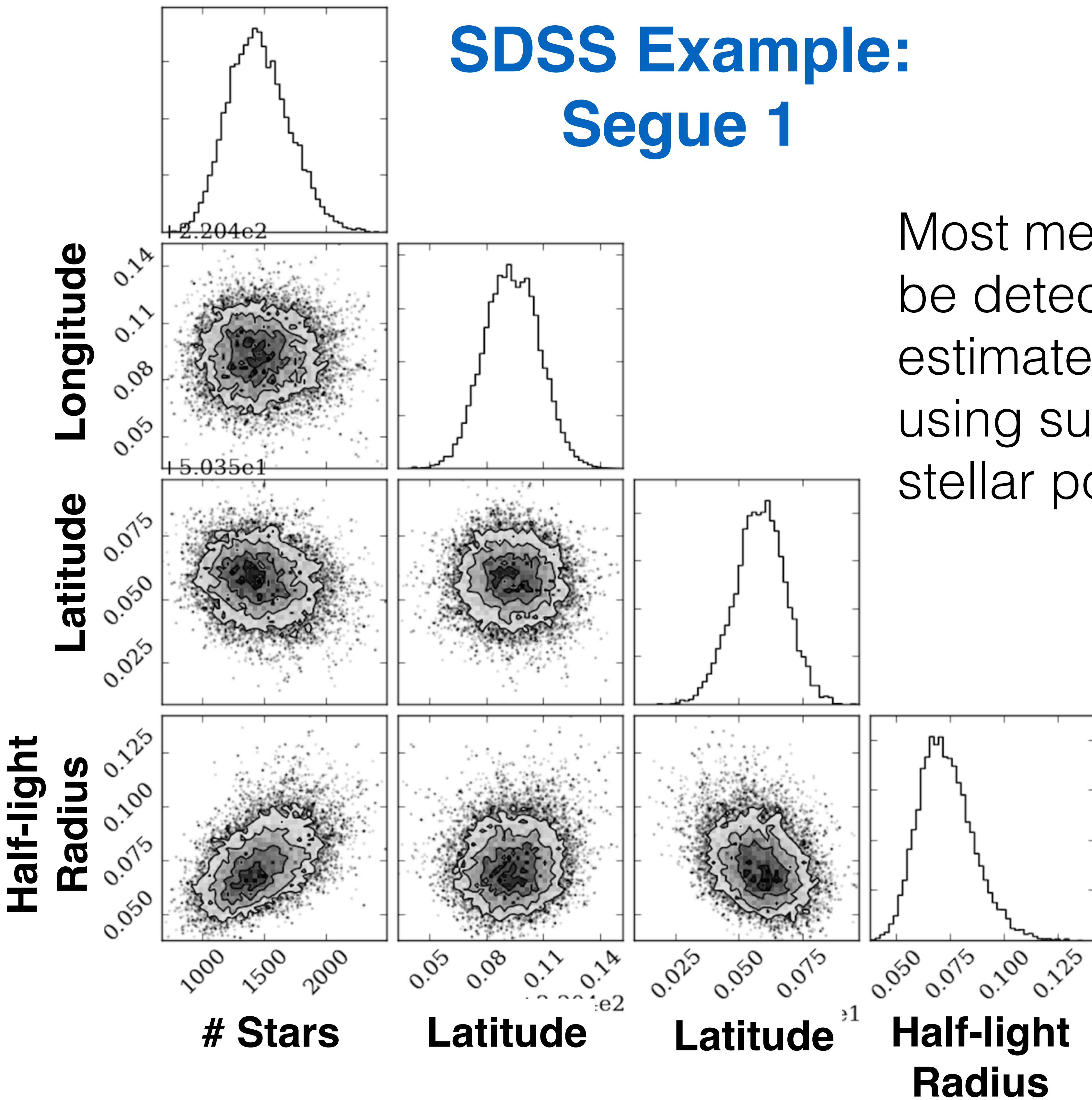
…scanning in distance



Color scale indicates significance (likelihood ratio)

MCMC Parameter Estimation

SDSS Example: Segue 1

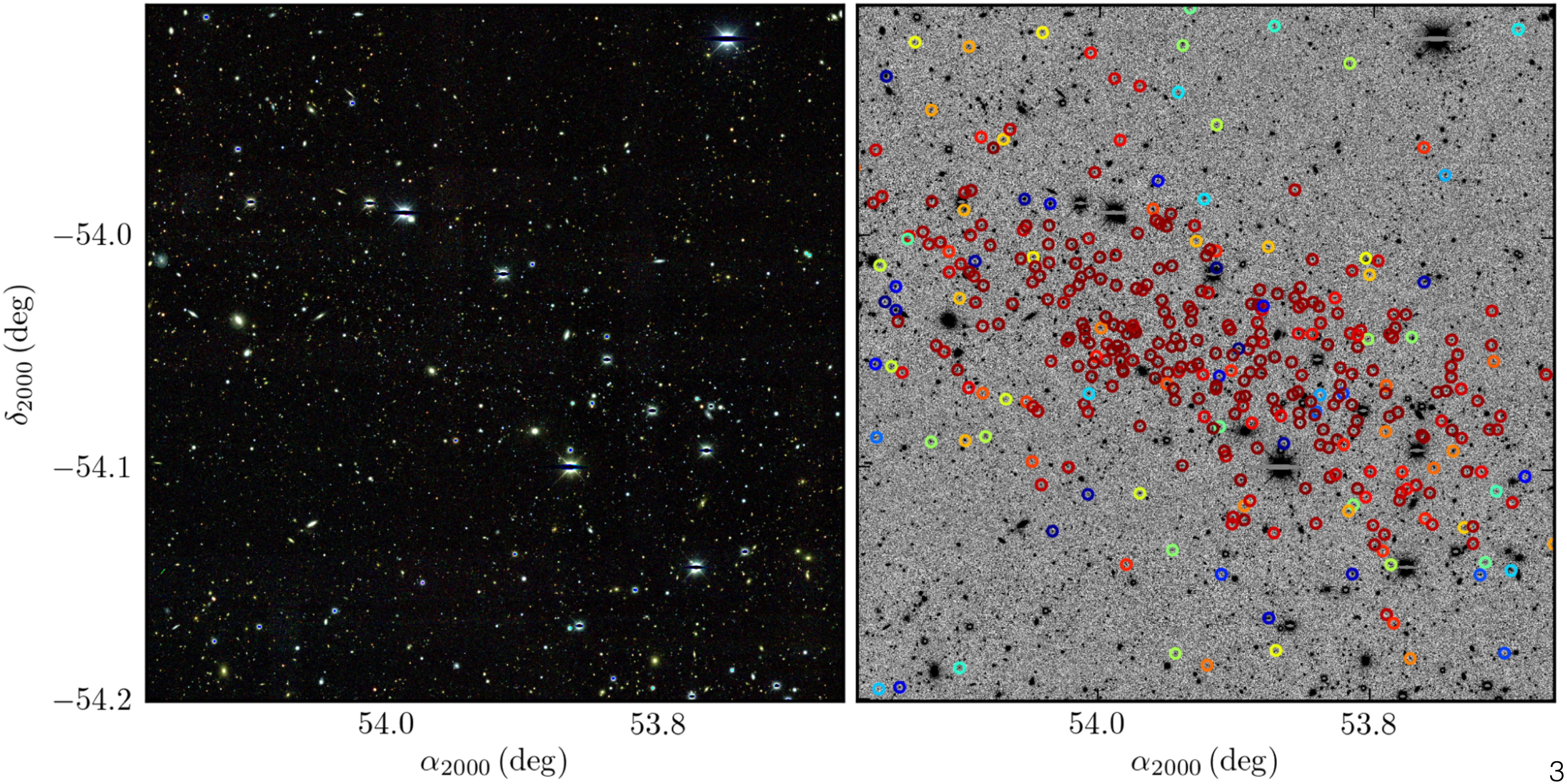


Most member stars are too faint to be detected, but still possible to estimate total stellar mass because using survey depth information and stellar population model

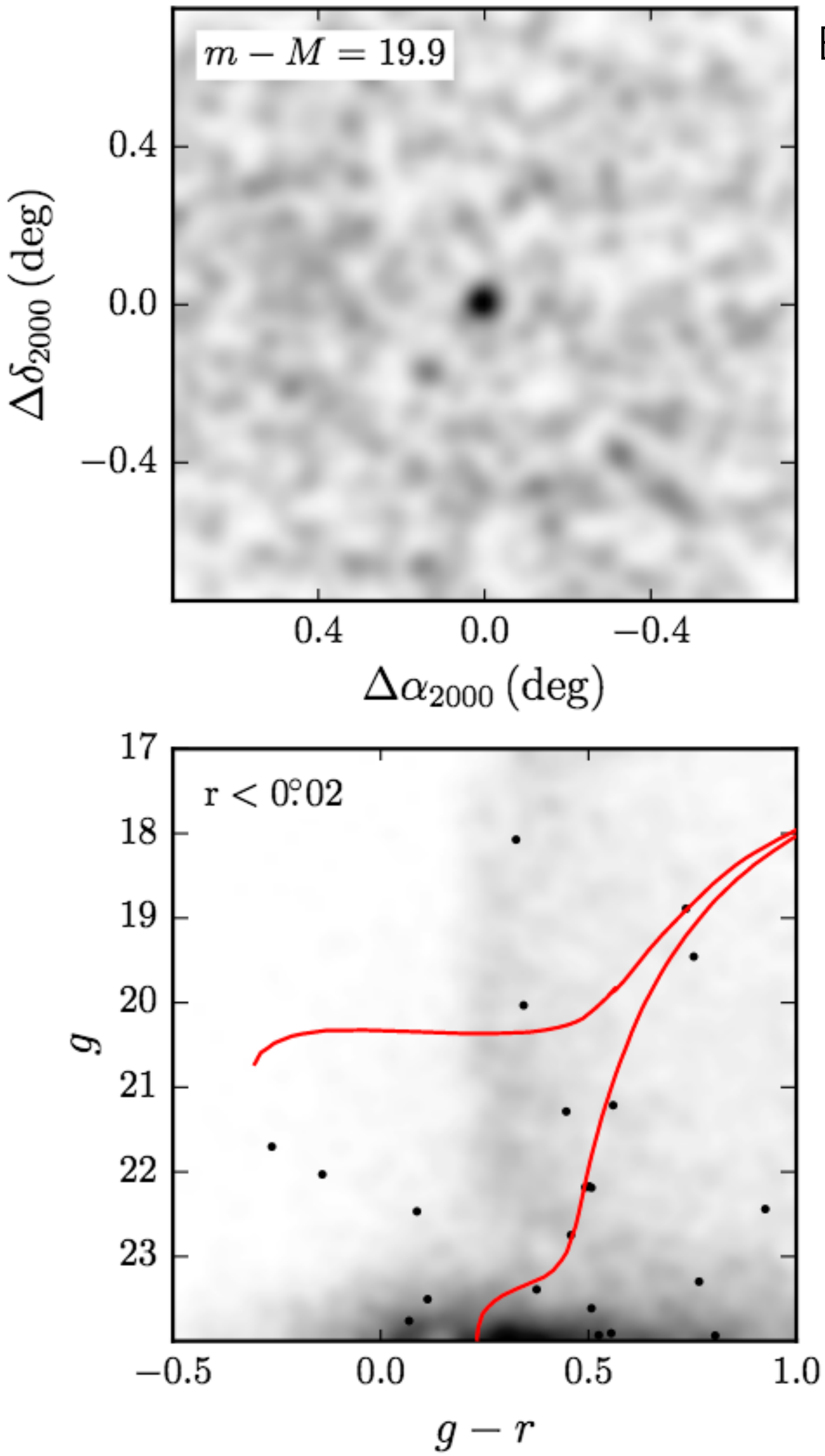
Membership Probabilities in Action

Example: Reticulum II

High membership probability
Lower membership probability



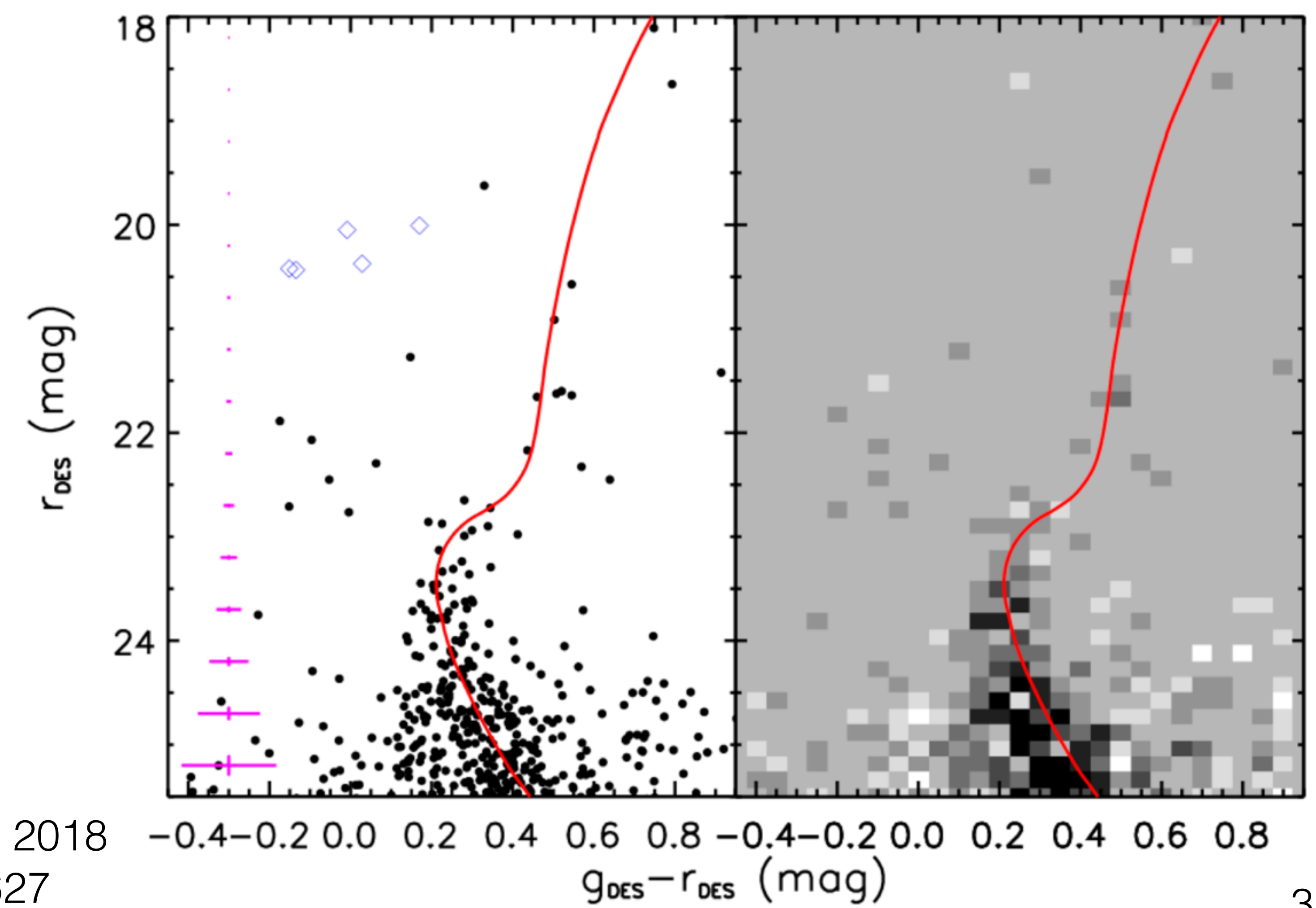
Usually Discovered as "Candidate" Ultra-faint Galaxies



Bechtol et al. 2015
arXiv:1503.02584

Is it a genuine physical system?

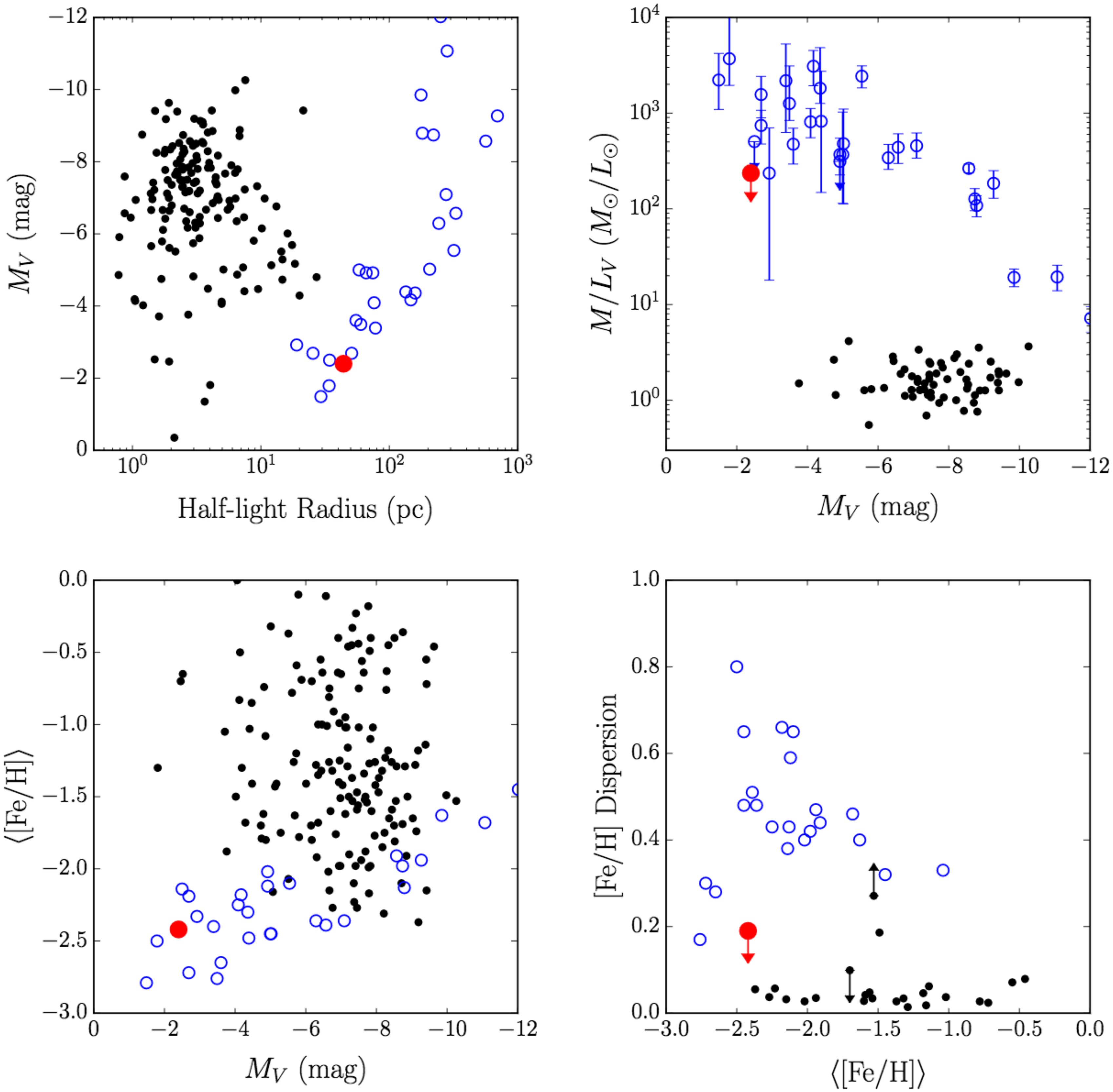
e.g., "Phoenix II" / DES J2339.9-5424



Mutlu-Pakdil et al. 2018
arXiv:1804.08627

Usually Discovered as “Candidate” Ultra-faint Galaxies

THE DARK ENERGY SURVEY

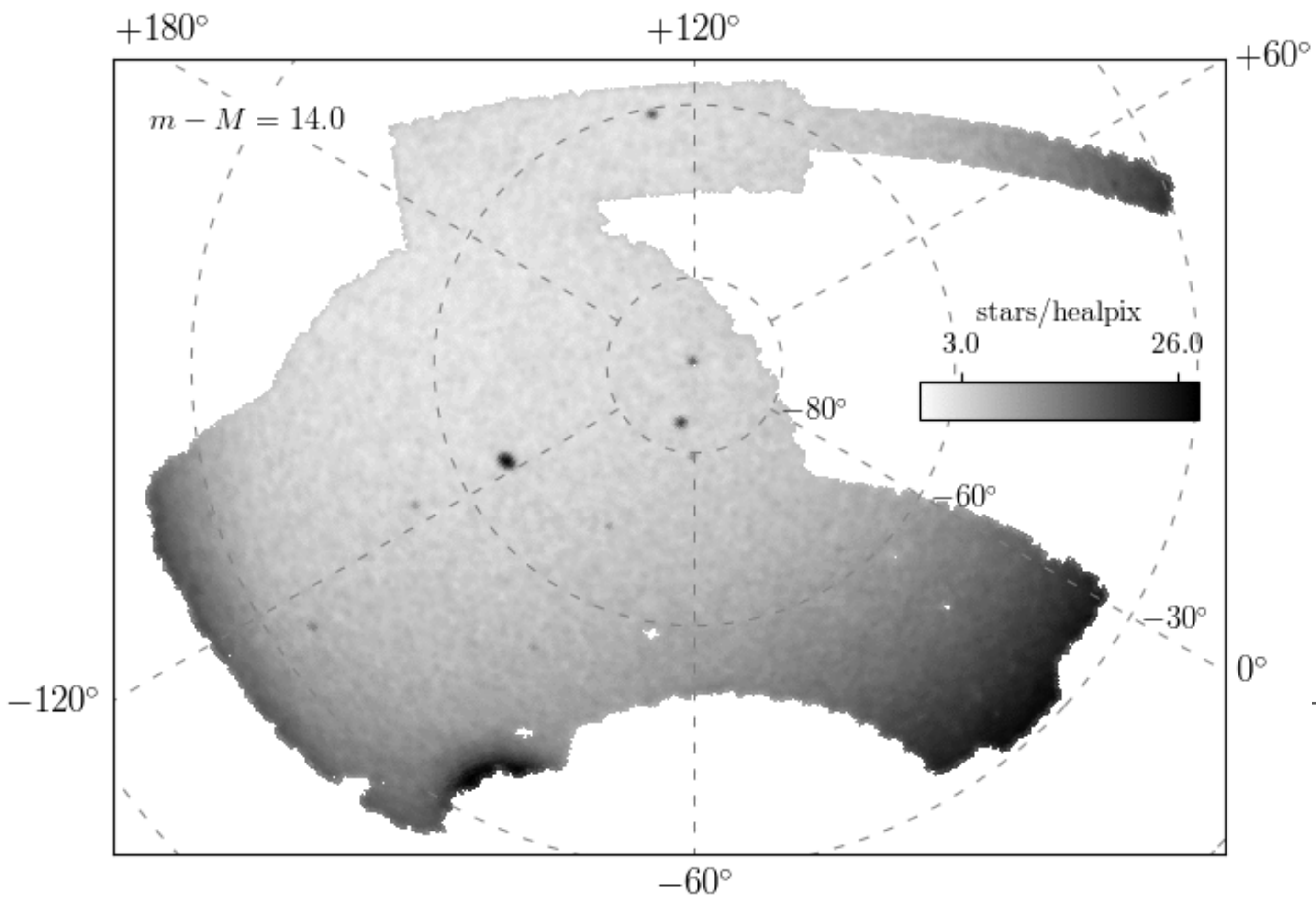


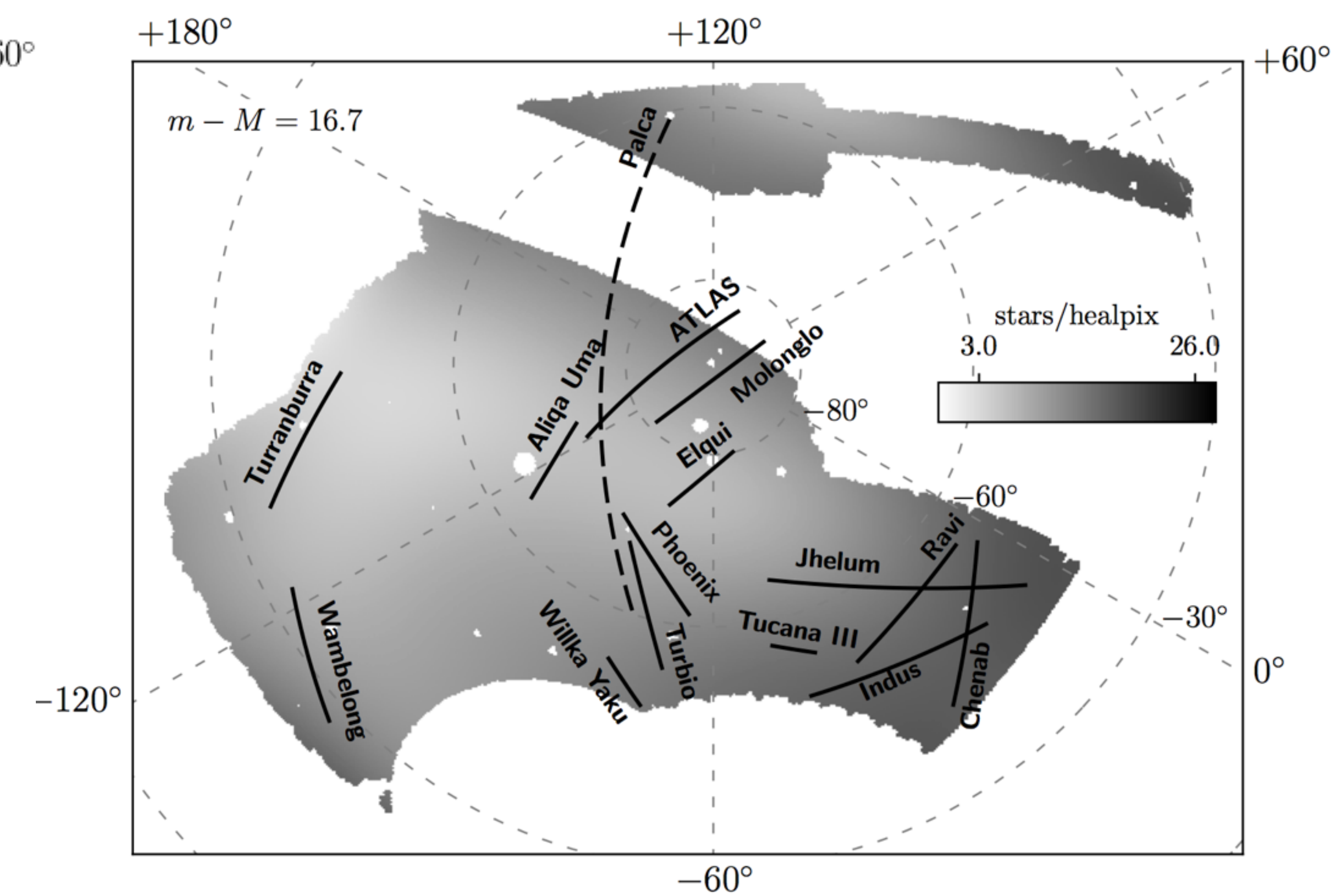
Is it a dark-matter-dominated dwarf galaxy?

e.g., “Tucana III”

Simon et al. 2017 arXiv:1610.05301

Aside: Similar Techniques Used to Discovery New Stellar Streams





Selecting stars in intervals
of increasing heliocentric distance

Shipp et al. 2018
arXiv:1801.03097

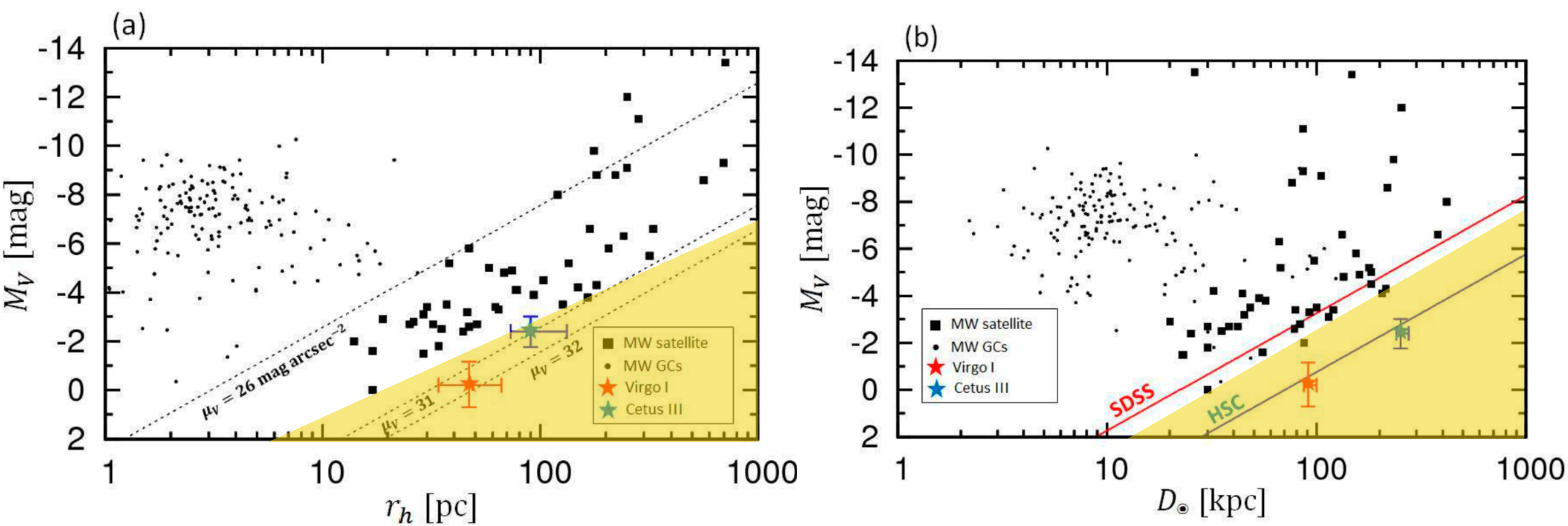
11 new stellar streams, 4 previously known streams

Generally more distant (out to 50 kpc) and lower surface brightness ($\sim$33 mag arcsec^{-2}) than previously known streams

Dynamical tracers of Milky Way gravitational potential and dark matter substructures

Our Incomplete View of the Least Luminous Stellar Systems

Two new ultra-faint galaxy candidates found in first 300 deg² of Hyper-Suprime Cam SSP data (<1% of 4π celestial sphere) that are likely undetectable in any previous survey



Homma et al. 2017
arXiv:1704.05977

LSST might discover tens to hundreds of similar ultra-faint galaxy candidates

e.g., Hargis et al. 2014

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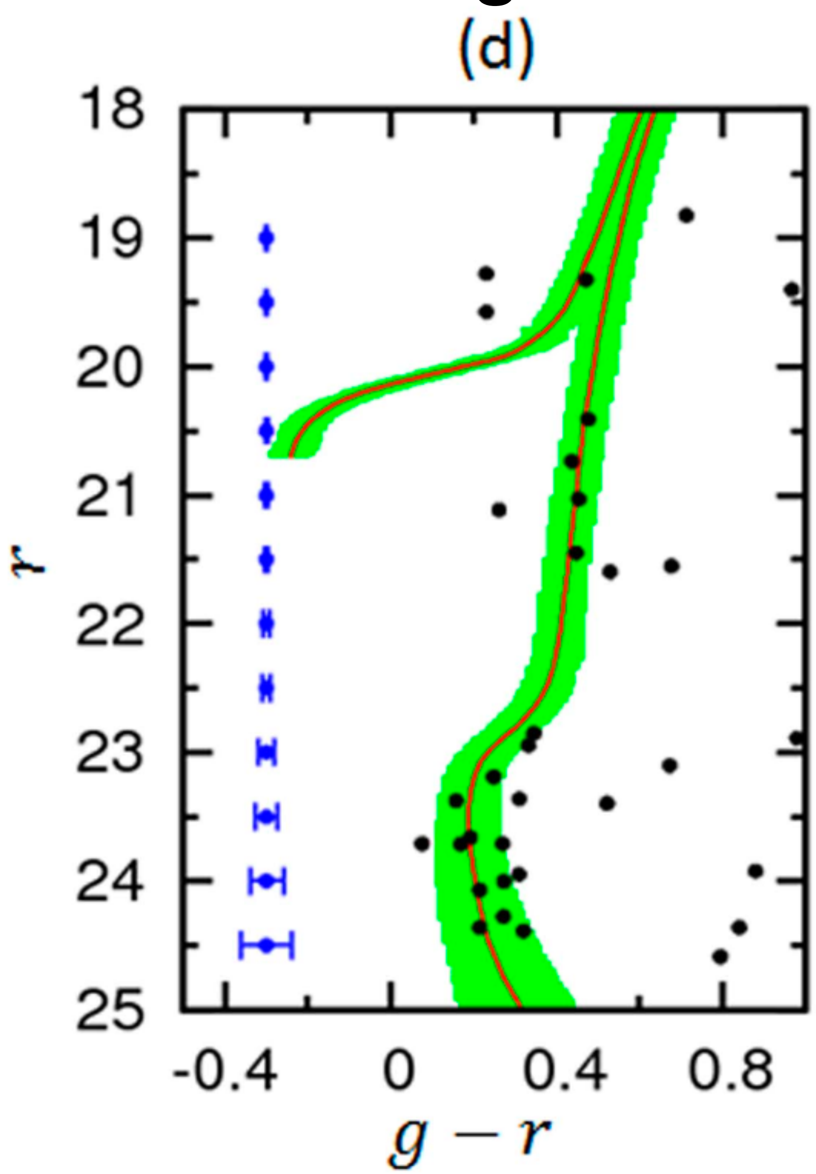
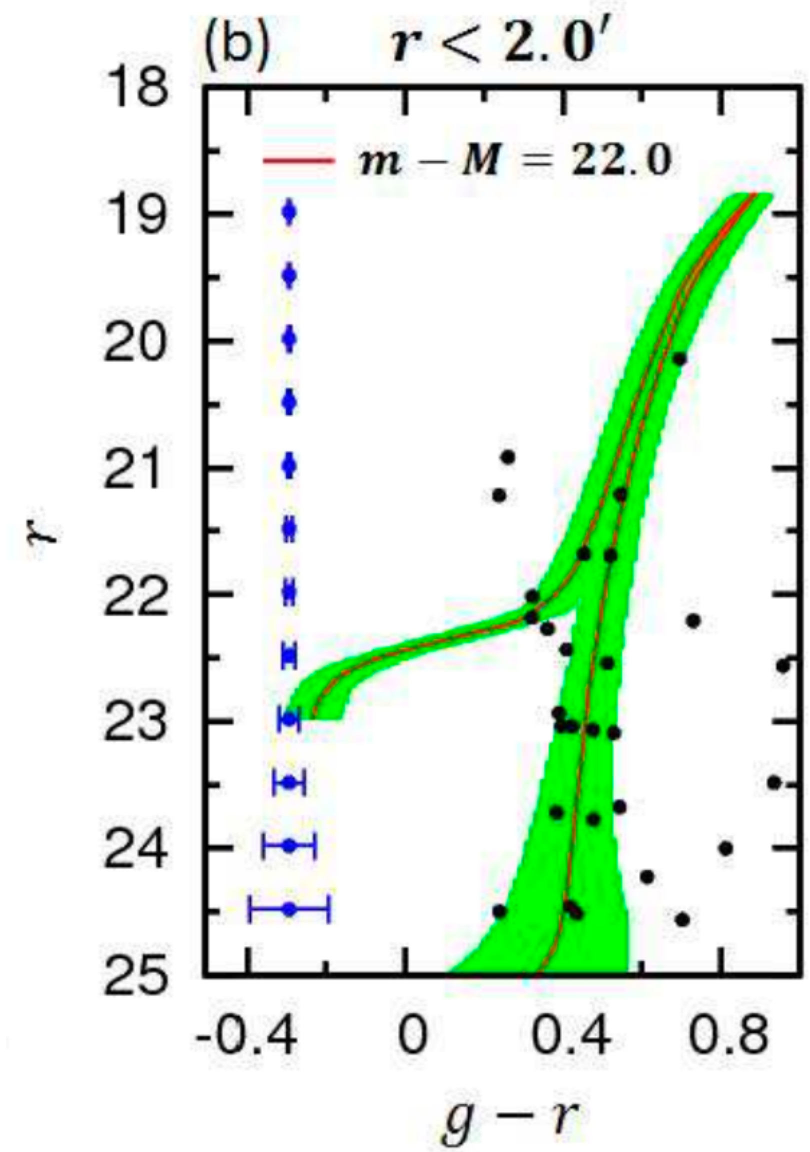
Homma et al. 2016
arXiv:1609.04346

Virgo I



Cetus III



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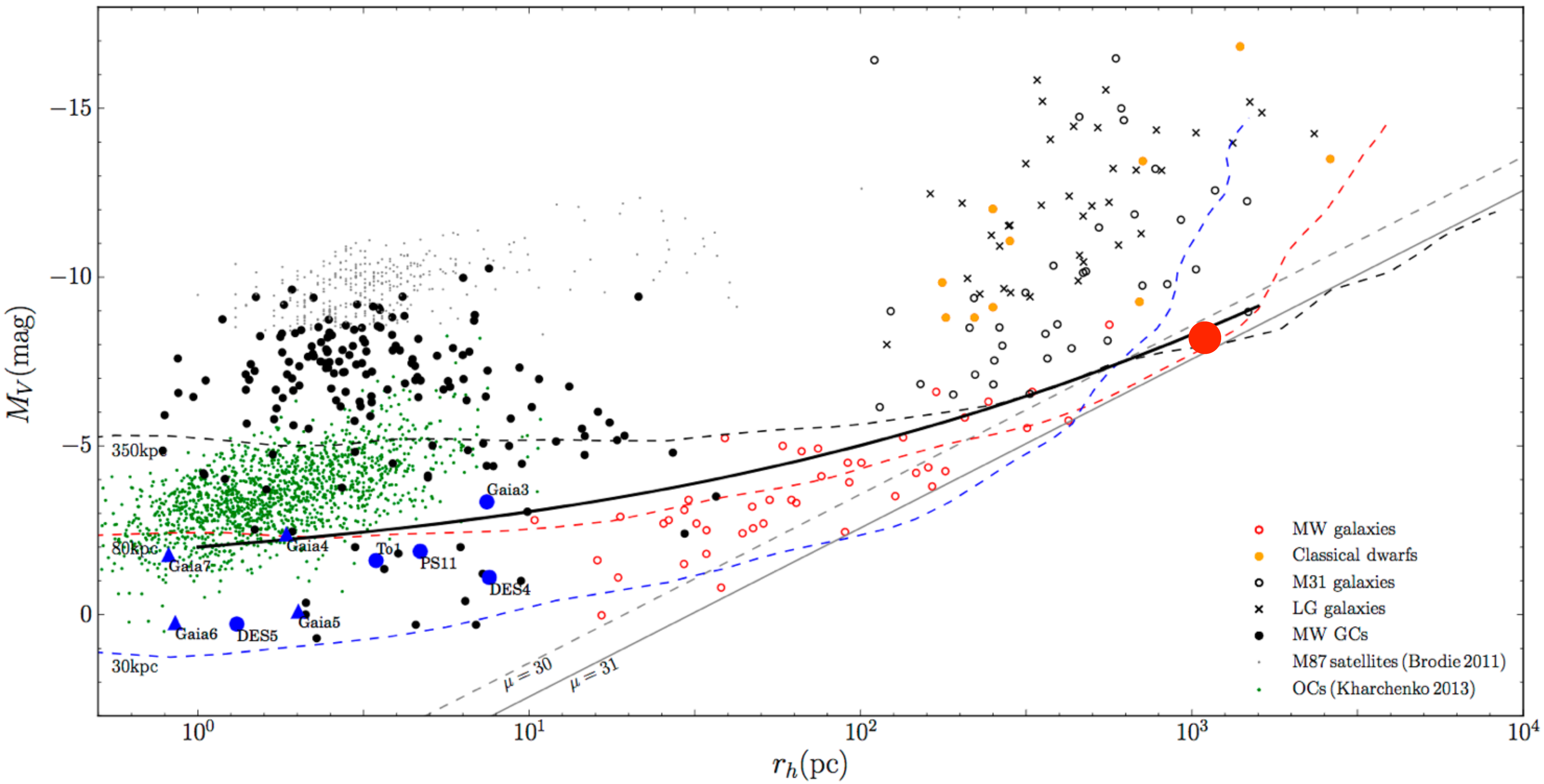


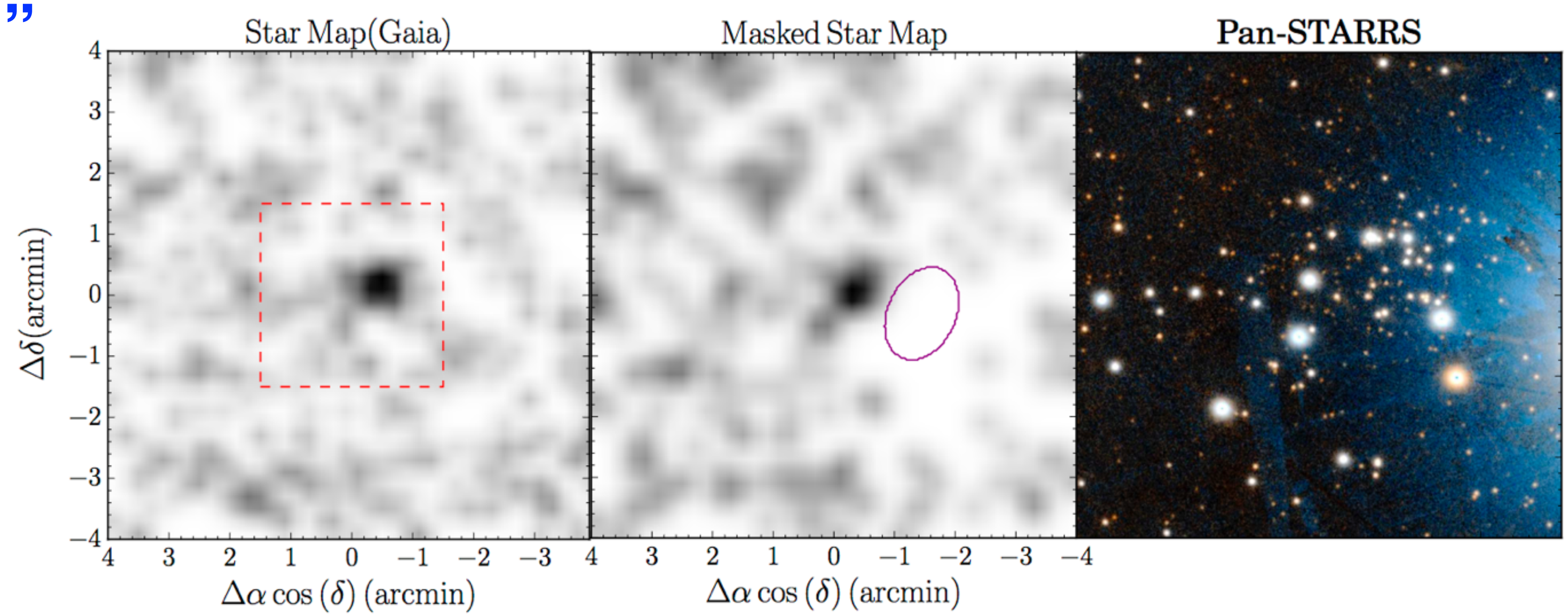
"Feeble giant"

Half-light radius ~ 31 arcmin

Torrealba et al. 2016
arXiv:1601.07178

"Nine tiny star clusters"

Half-light radius < 1 arcmin
Torrealba et al. 2018
arXiv:1805.06473



DES Y3 Survey Selection Function Analysis Pipeline

THE DARK ENERGY SURVEY

1. Inject ensemble of simulated satellites into actual DES data at the catalog level with realistic photometric errors, etc.

2. Run multiple search algorithms on actual data and injected satellites

3. Apply same criteria to candidates from real data and simulation

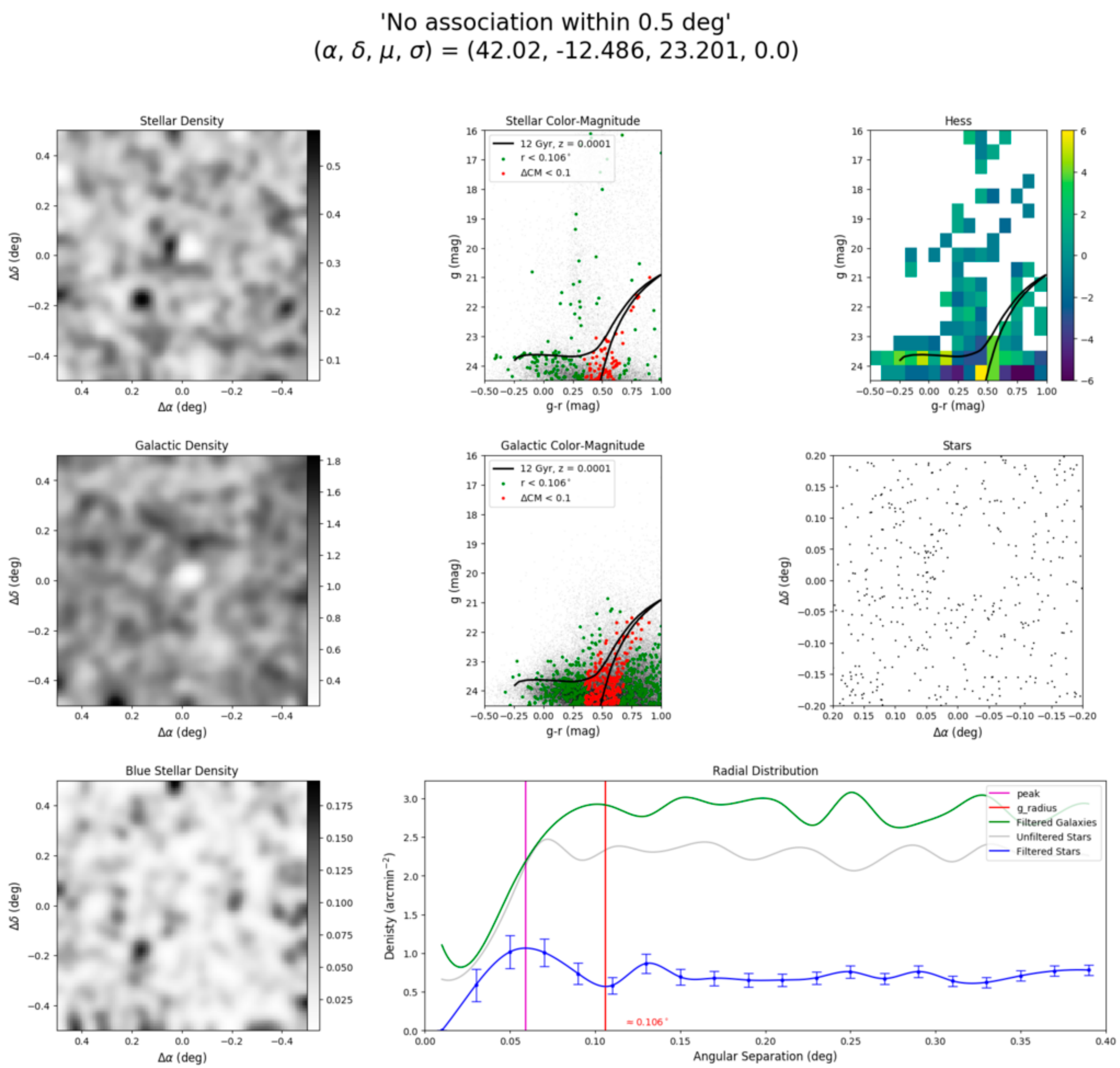
4. Train survey selection function to predict detectability for arbitrary set of intrinsic satellite structural parameters and location with respect to survey footprint

5. Forward-fold cosmological models for the Milky Way satellite population through the survey selection function
   — *see Ethan Nadler's talk on Monday!*

w/ Alex Drlica-Wagner, Sid Mau, Ethan Nadler, Risa Wechsler, ++

Why we don't detect some luminous and high surface brightness satellites

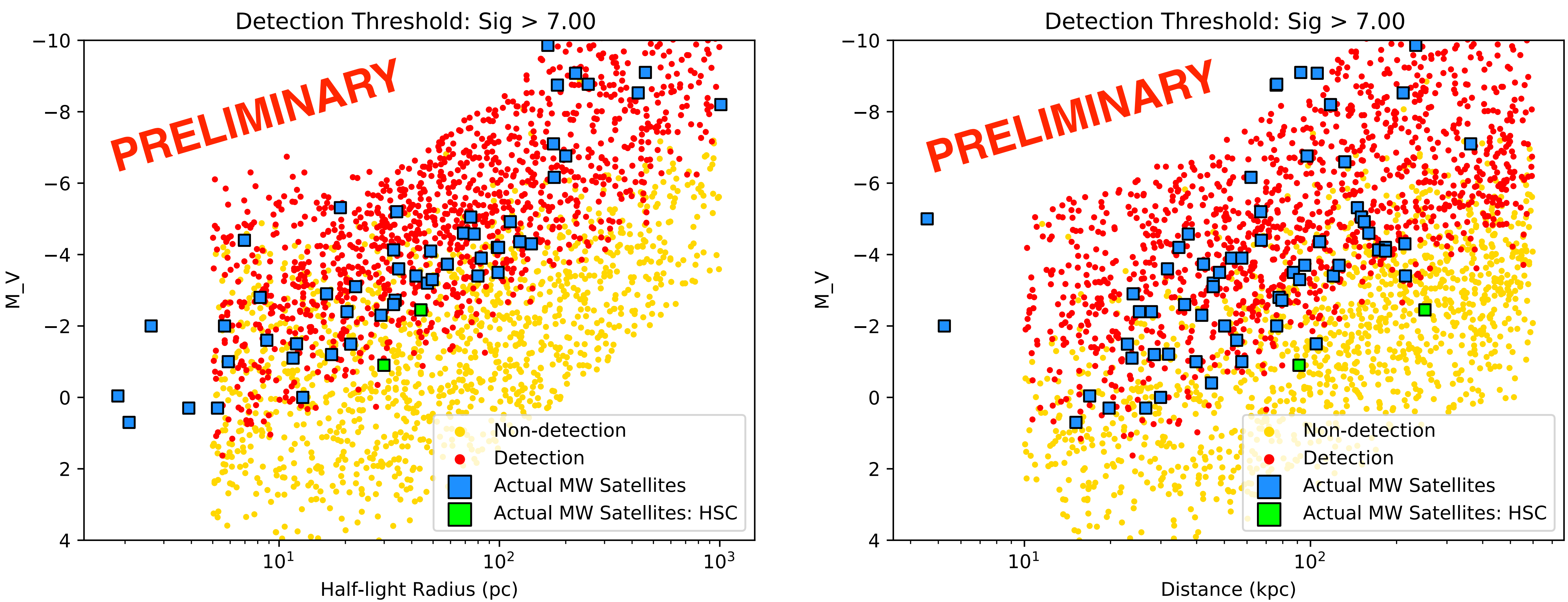
Surface brightness < 27 mag arcsec^{-2} and > 50 stars at g < 24



Star hole!

Simulated Satellite Detectability

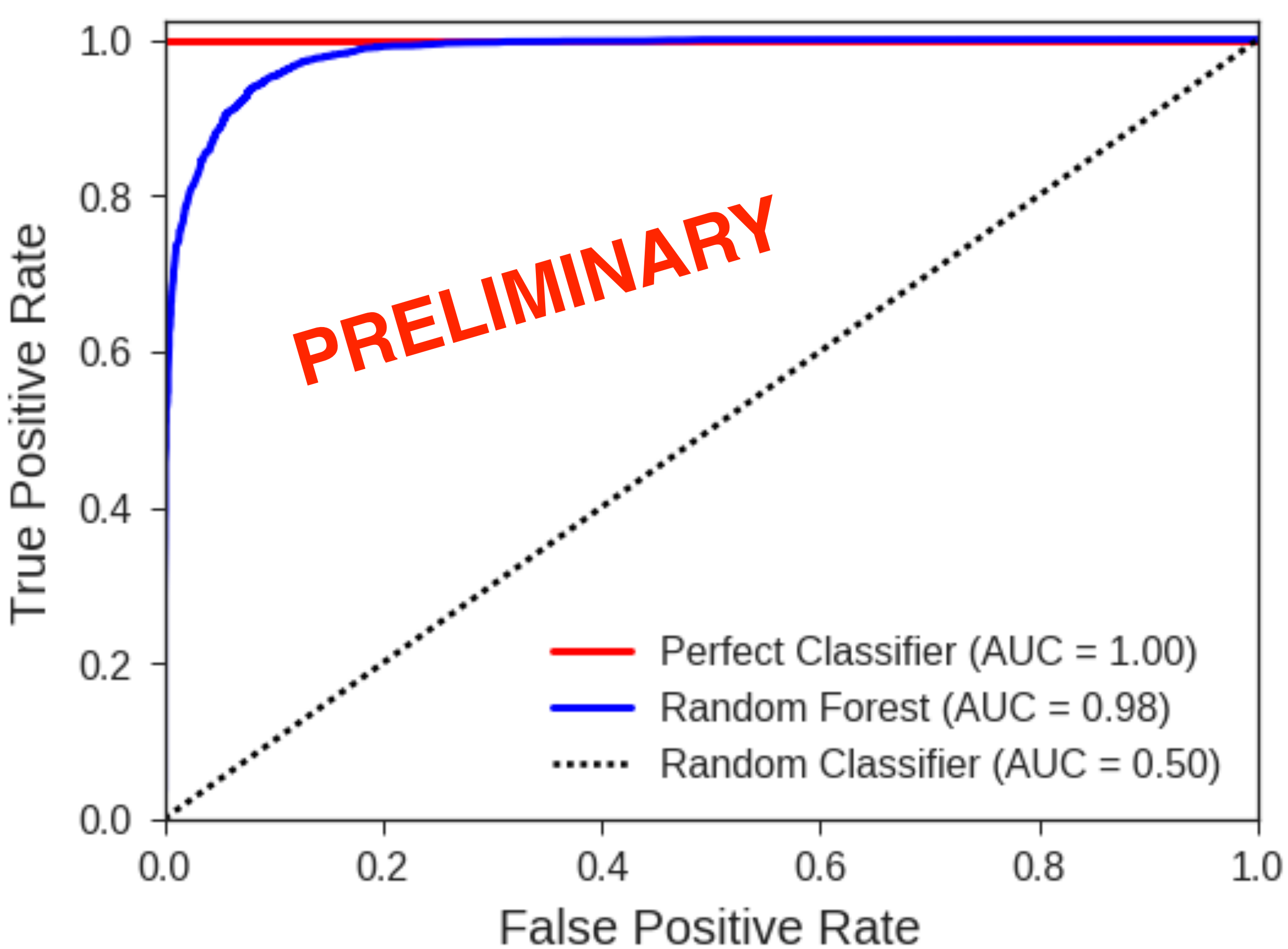
The detectability is somewhat challenging to visualize in a given two-dimensional projection into parameter space. However, one can see that the inferred sensitivity seems to match well with the actual detected MW satellite population, with the exception of the two HSC satellites (HSC is deeper than DES)

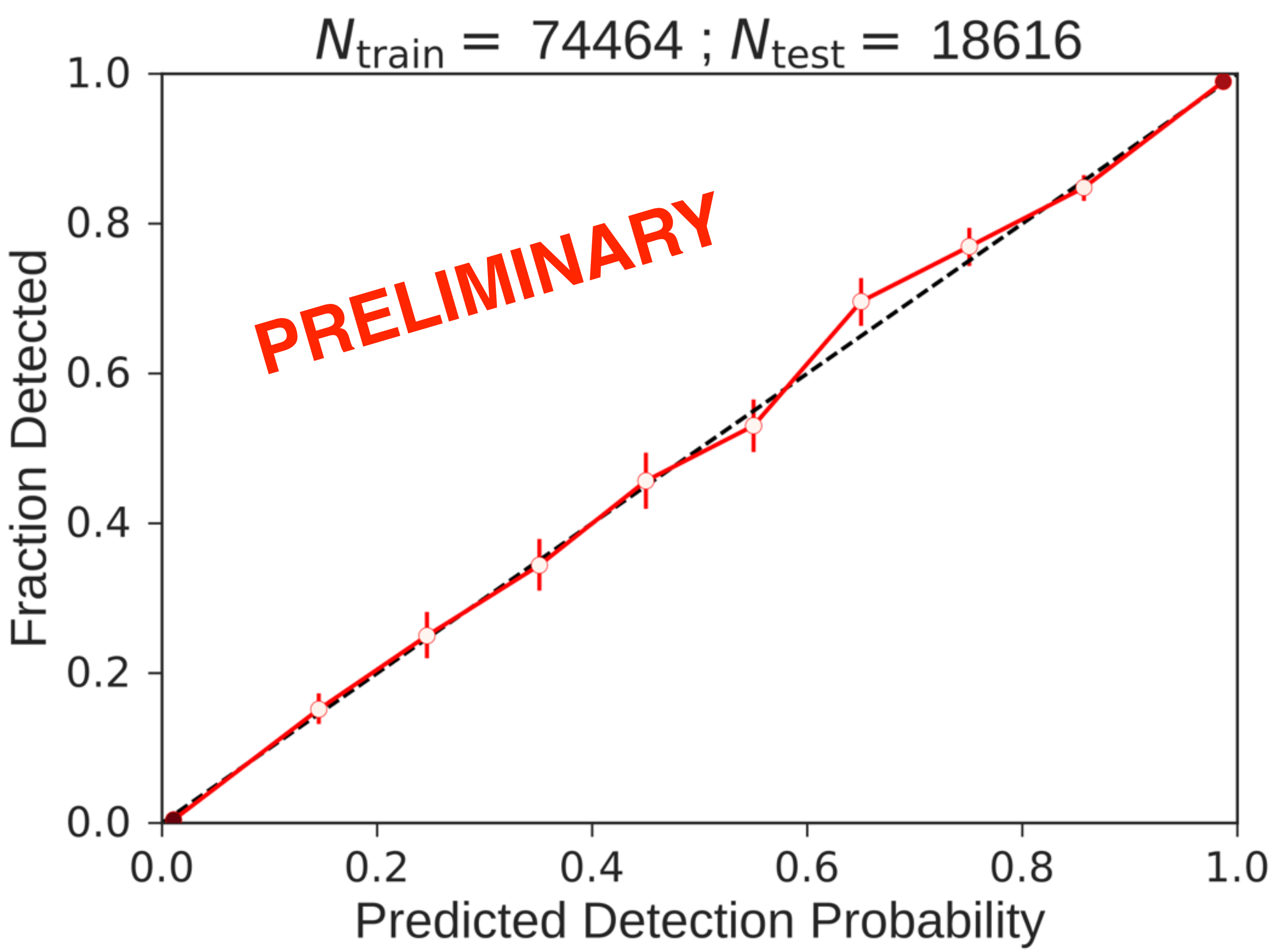


Training the Survey Selection Function

THE DARK ENERGY SURVEY

Use random forest to classify whether objects would be detected
Currently training on {magnitude, physical size, distance}

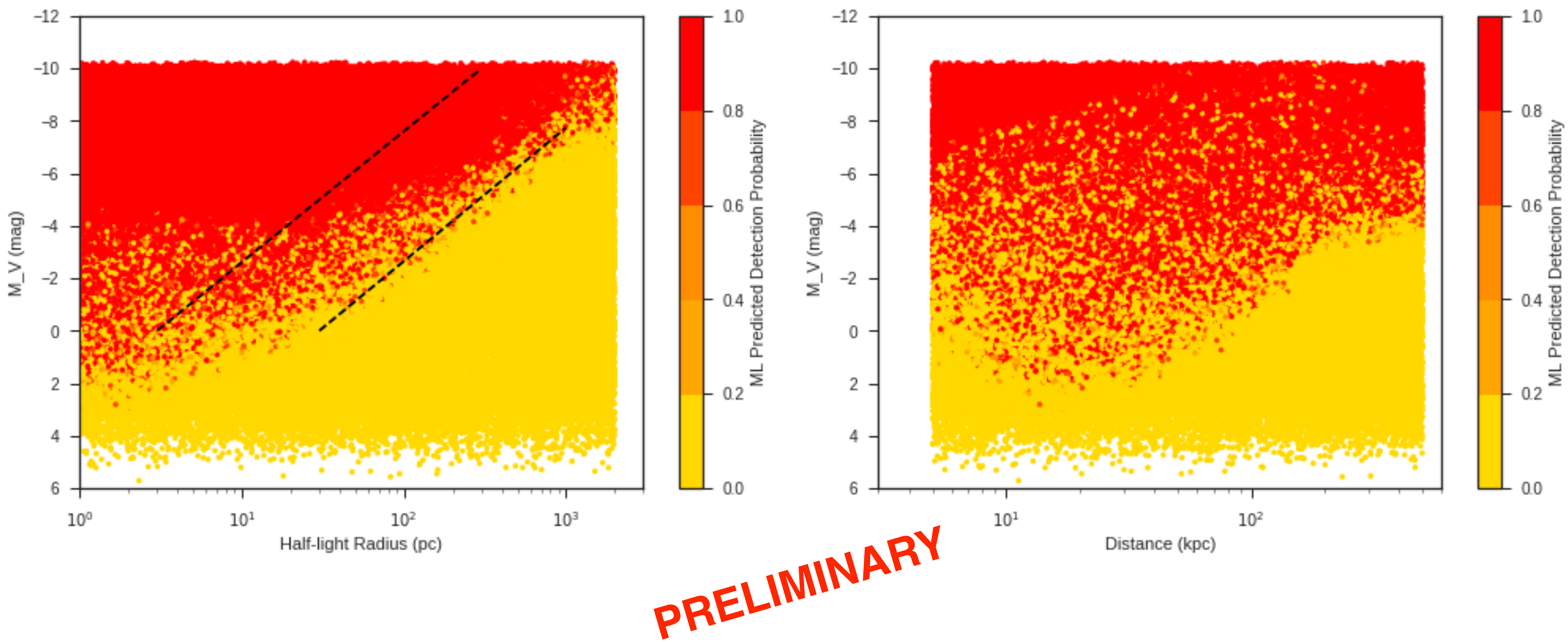




DES Y3 Satellite Galaxy Search Sensitivity

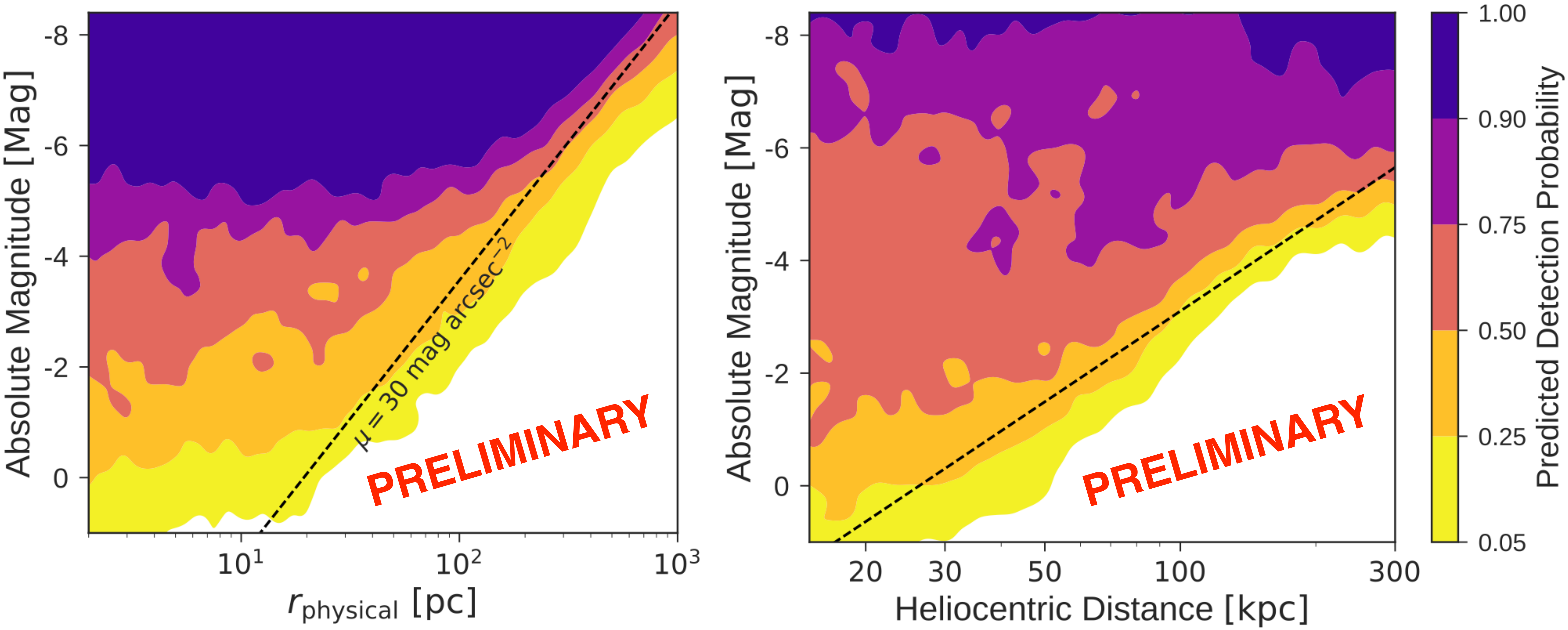
THE DARK ENERGY SURVEY

Detection probabilities for **individual satellites** (i.e., each point is a single simulated satellite)
Note that a given panel shows a 2D projection of a higher dimensional parameter space



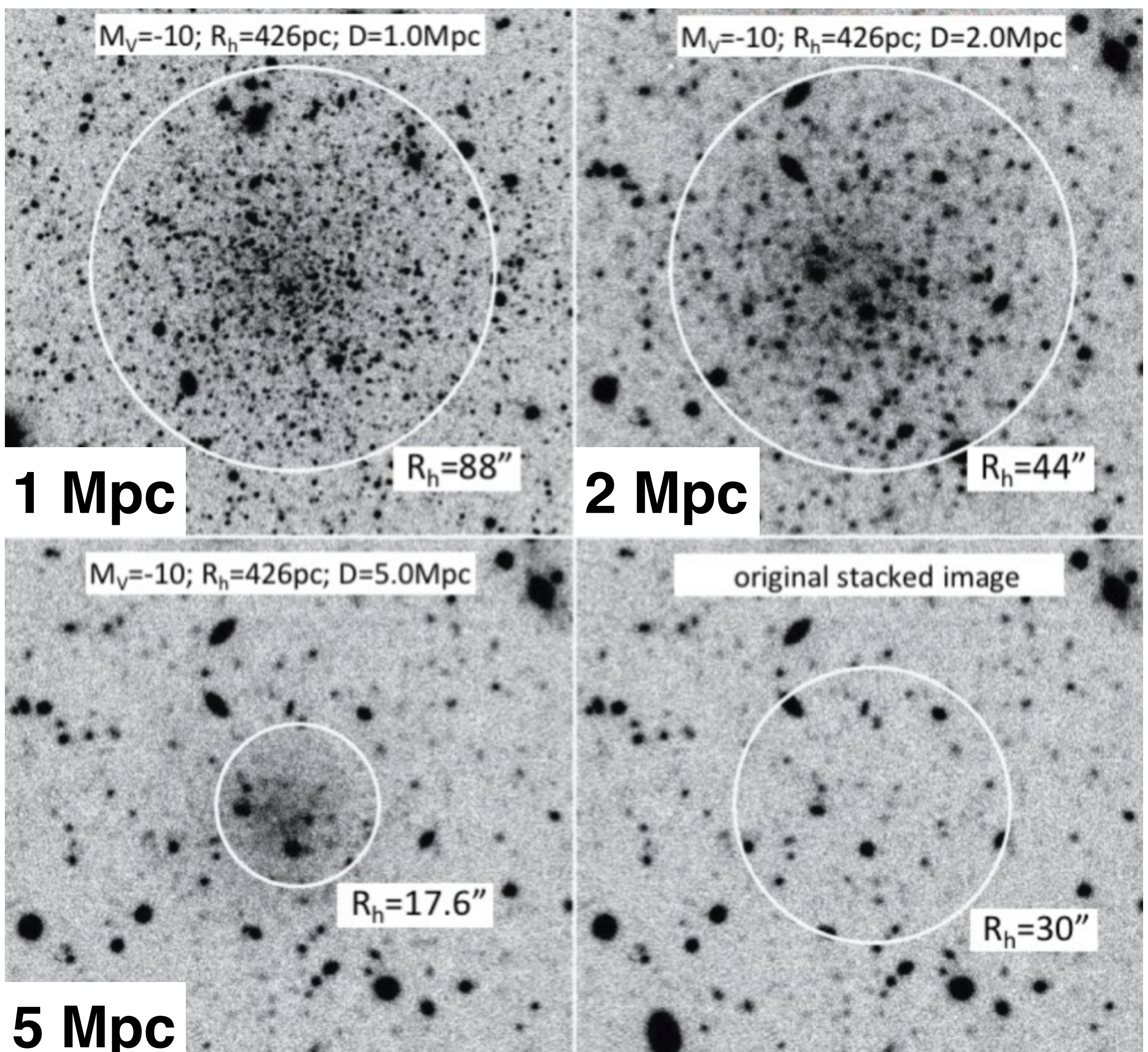
DES Y3 Satellite Galaxy Search Sensitivity

Average detection probabilities (binned in regions of parameter space)
Note that a given panel shows a 2D projection of a higher dimensional parameter space



Previewing Challenges of the LSST Era

Detection by resolved and diffuse light

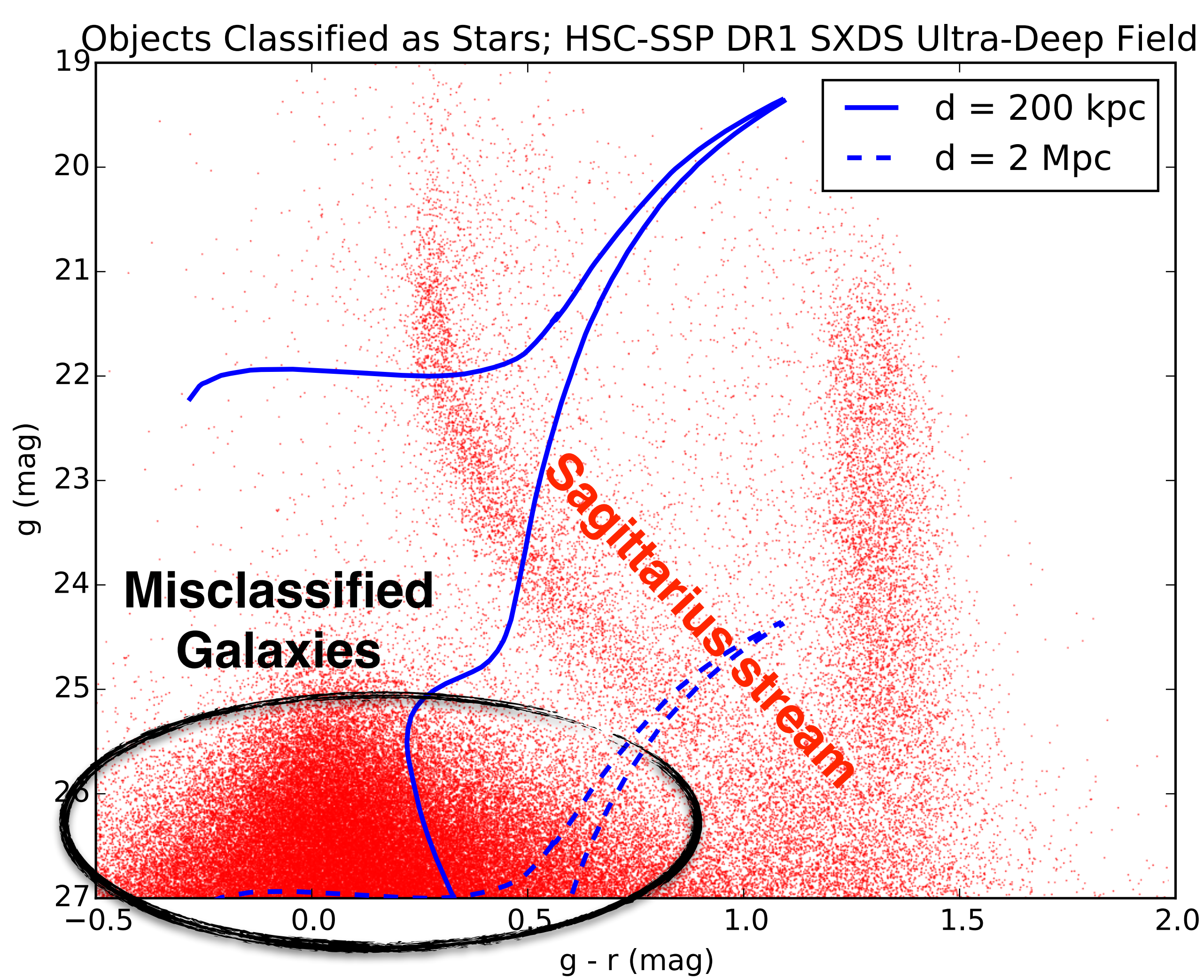


Star/galaxy separation challenge

HSC-SSP DR1 SXDS Ultra-Deep Field

Comparable to LSST Wide-Fast-Deep 10 yr depth (27th mag)

0.6" seeing



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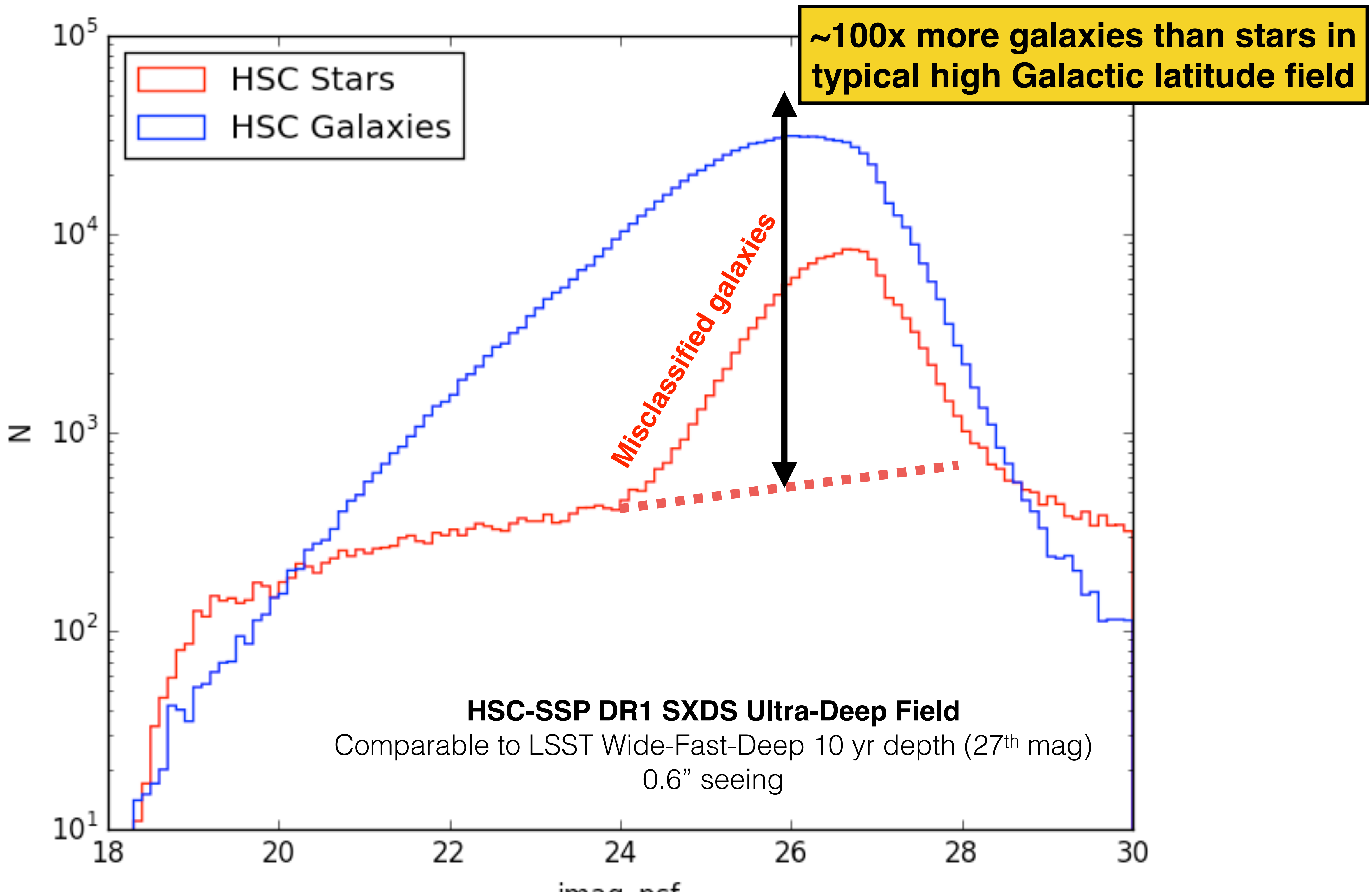


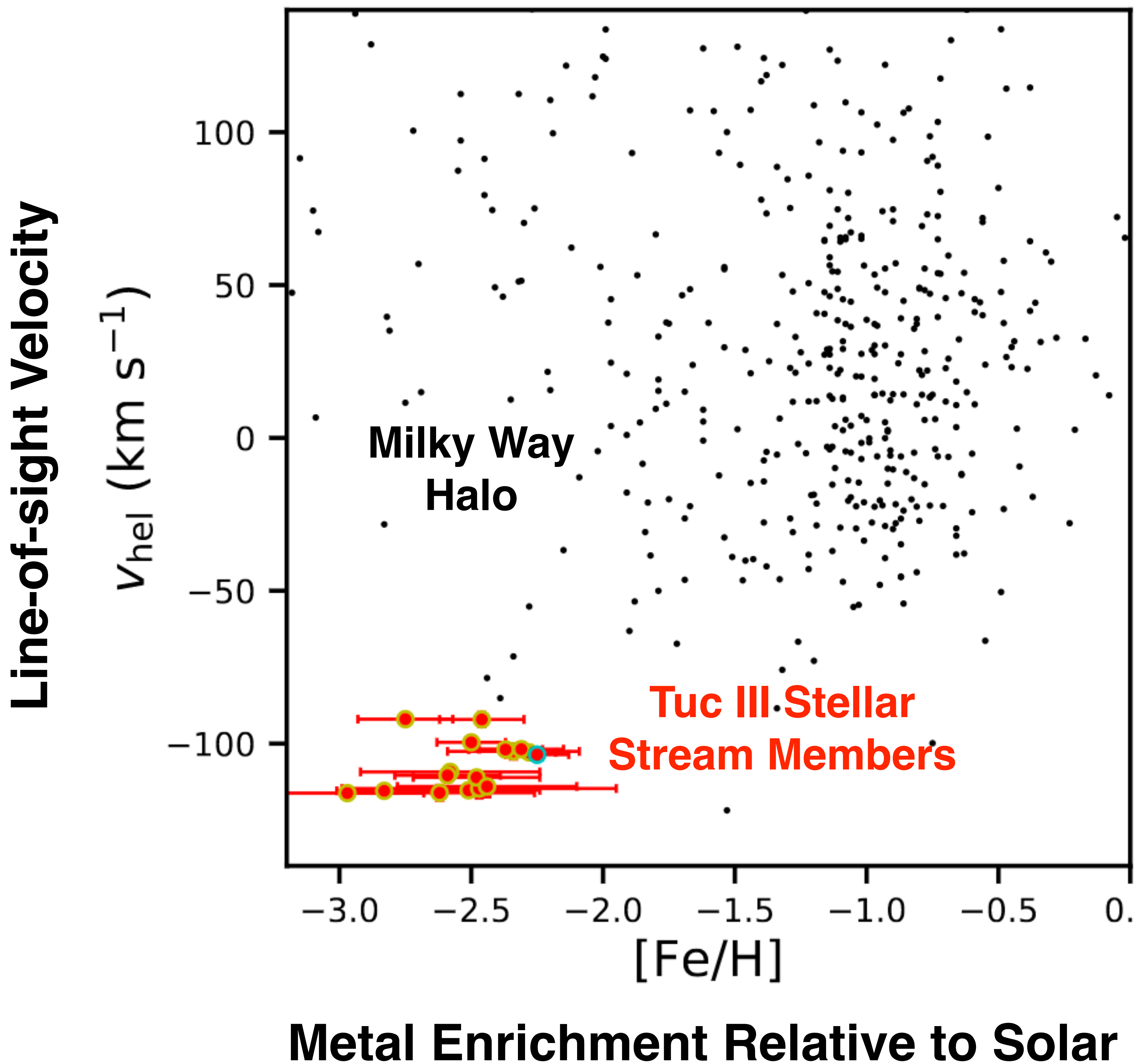
Maximizing Discovery Potential

- All (?) of the ultra-faint galaxy discoveries to this point have been made with ground-based wide-area optical imaging data using search algorithms based on an isochrone selection in color-magnitude space and spatial kernels

- Additional information that might be used:
  - [Line-of-sight velocities]
  - [Wide-area space-based imaging]
  - Variability (e.g., RR Lyrae stars)
  - Diffuse light (not resolved into individual stars)
  - Multi-band photometry to remove unresolved (point-like) galaxies and select metal-poor stars
  - Proper motions

Tucana III Stellar Stream: Recognizing the Member Stars

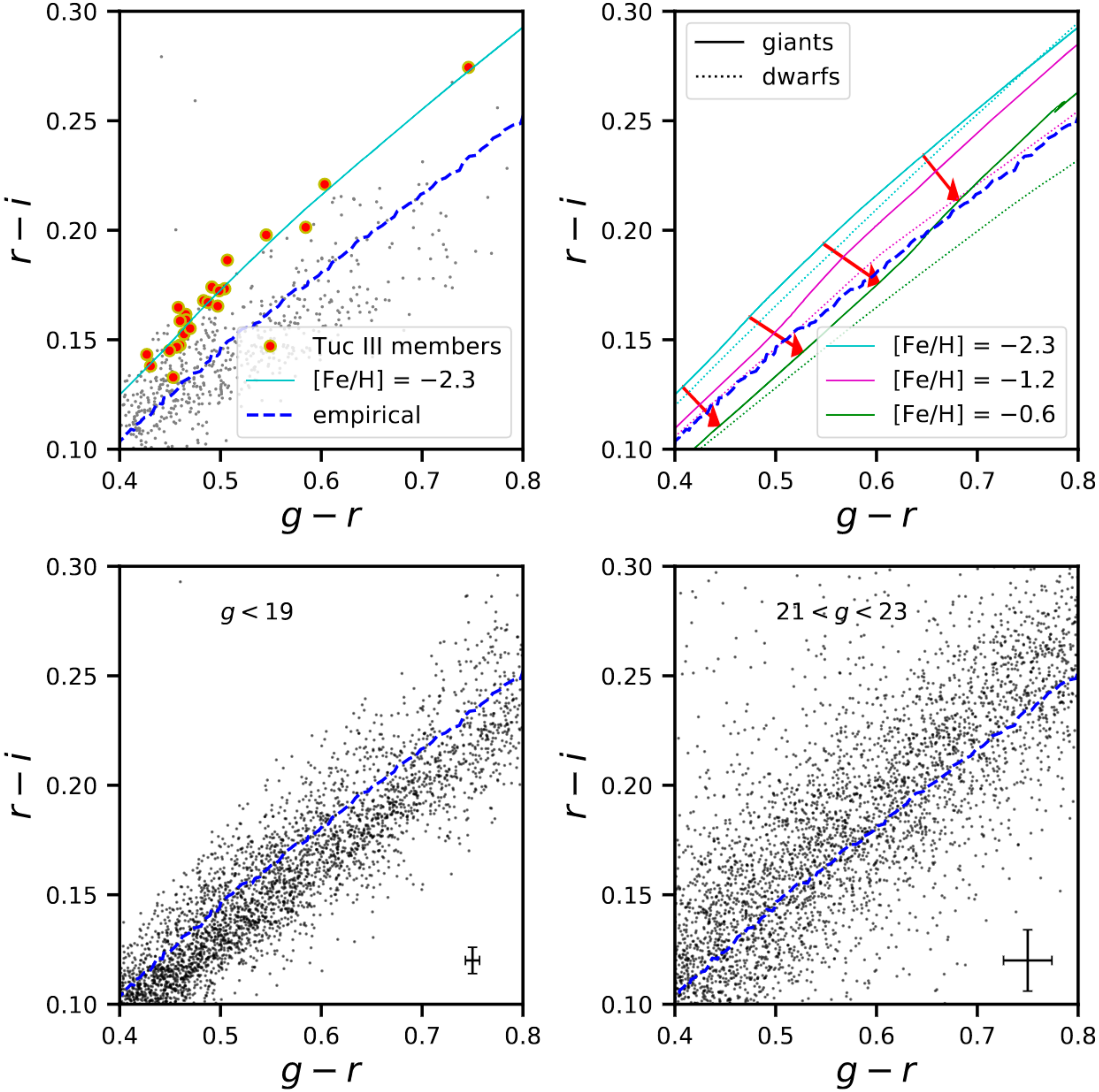
Li et al. 2018 submitted



Li et al. 2018
arXiv:1804.07761

Tucana III Stellar Stream: Recognizing the Member Stars

Tuc III stream member stars have distinct locus in color-space (~2 % effect)



Stellar colors allow metallicity estimate

Metal Rich Milky Way Disk Stars

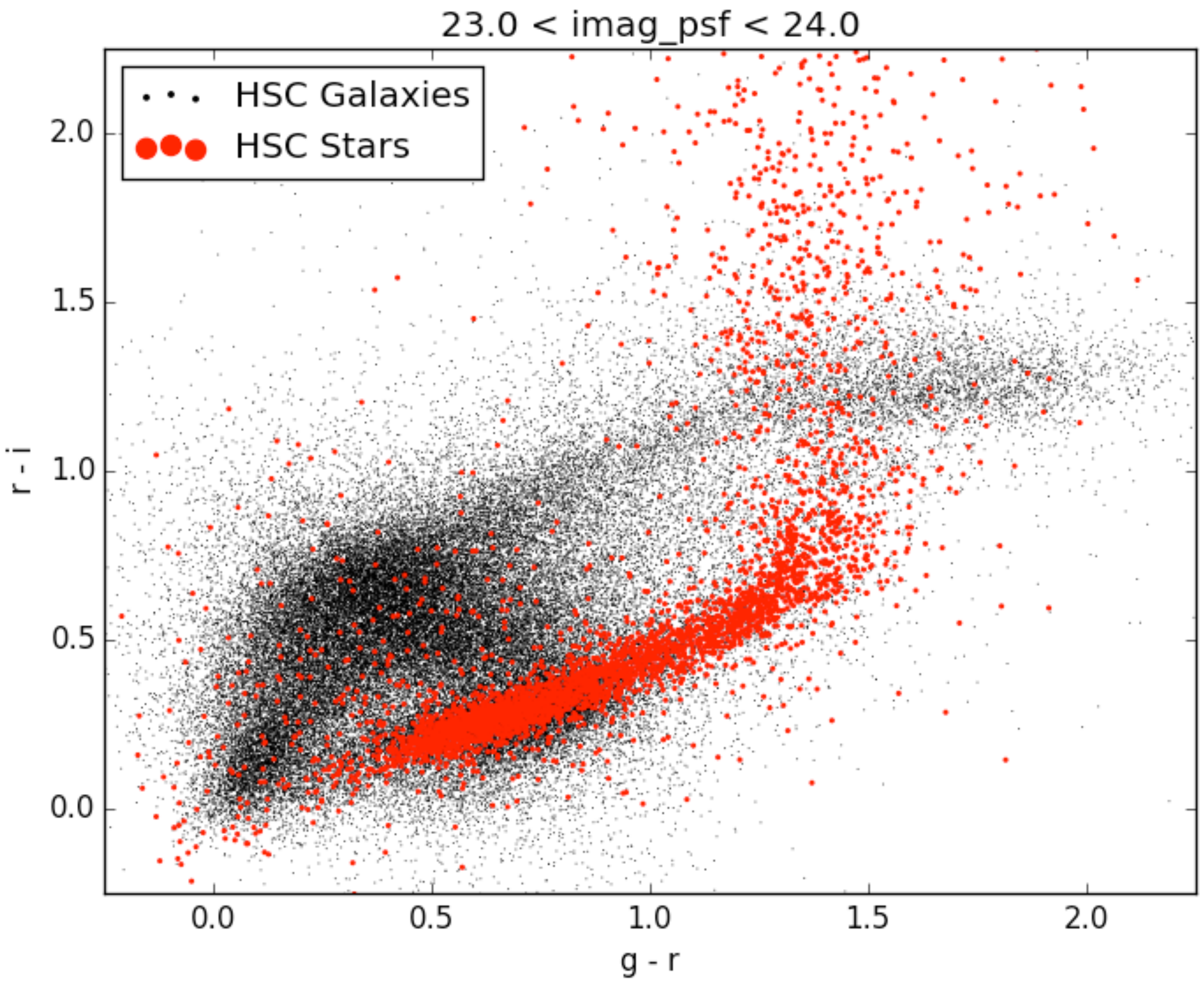
Metal Poor Milky Way Halo Stars

Li et al. 2018
arXiv:1804.07761

Color Selections for Stars

Optical bands

Galaxies vs **Stars**



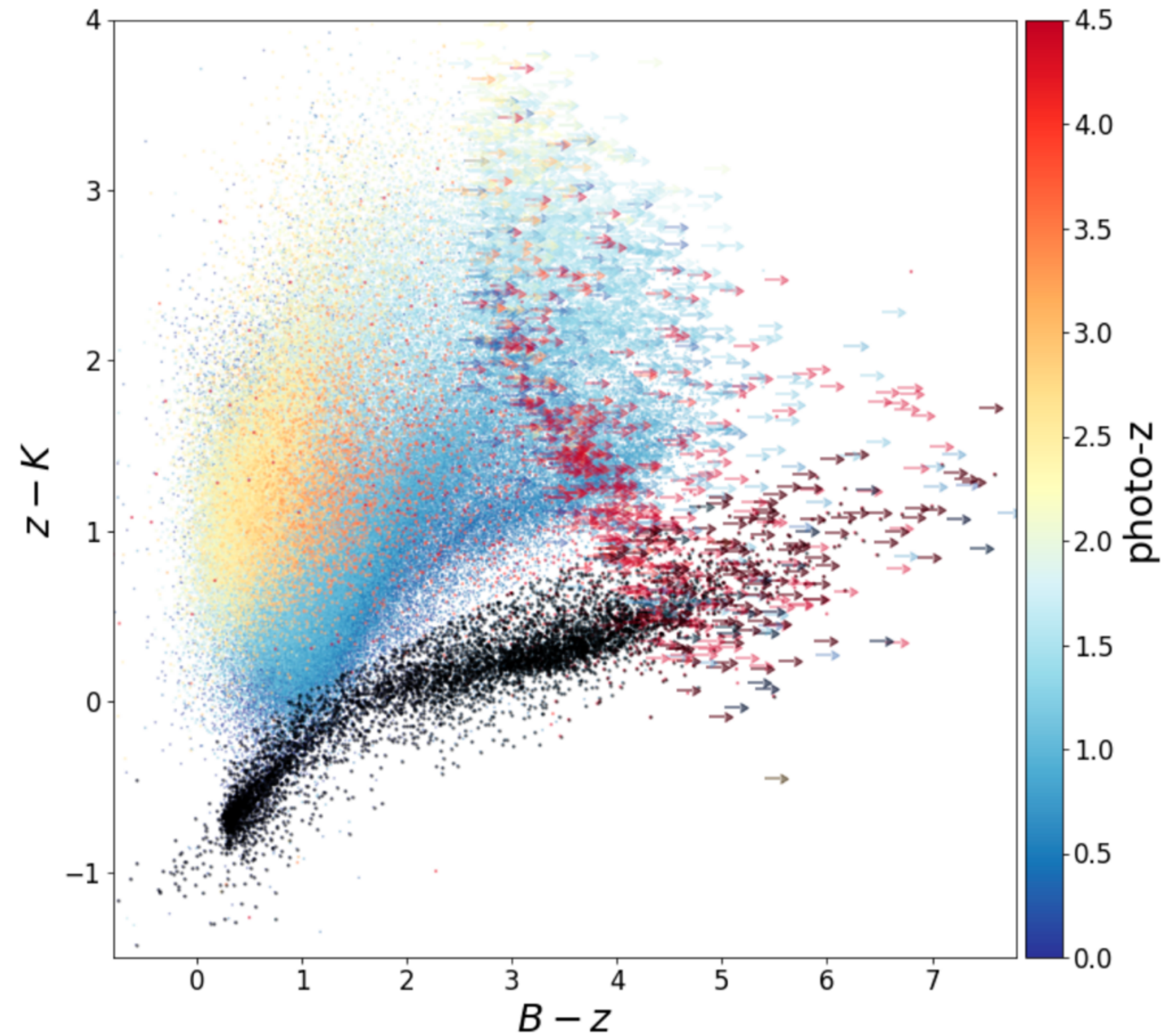
HSC-SSP DR1 SXDS Ultra-Deep Field

Comparable to LSST Wide-Fast-Deep 10 yr depth (27th mag)

0.6" seeing

Optical + NIR bands

Galaxies vs **Stars**

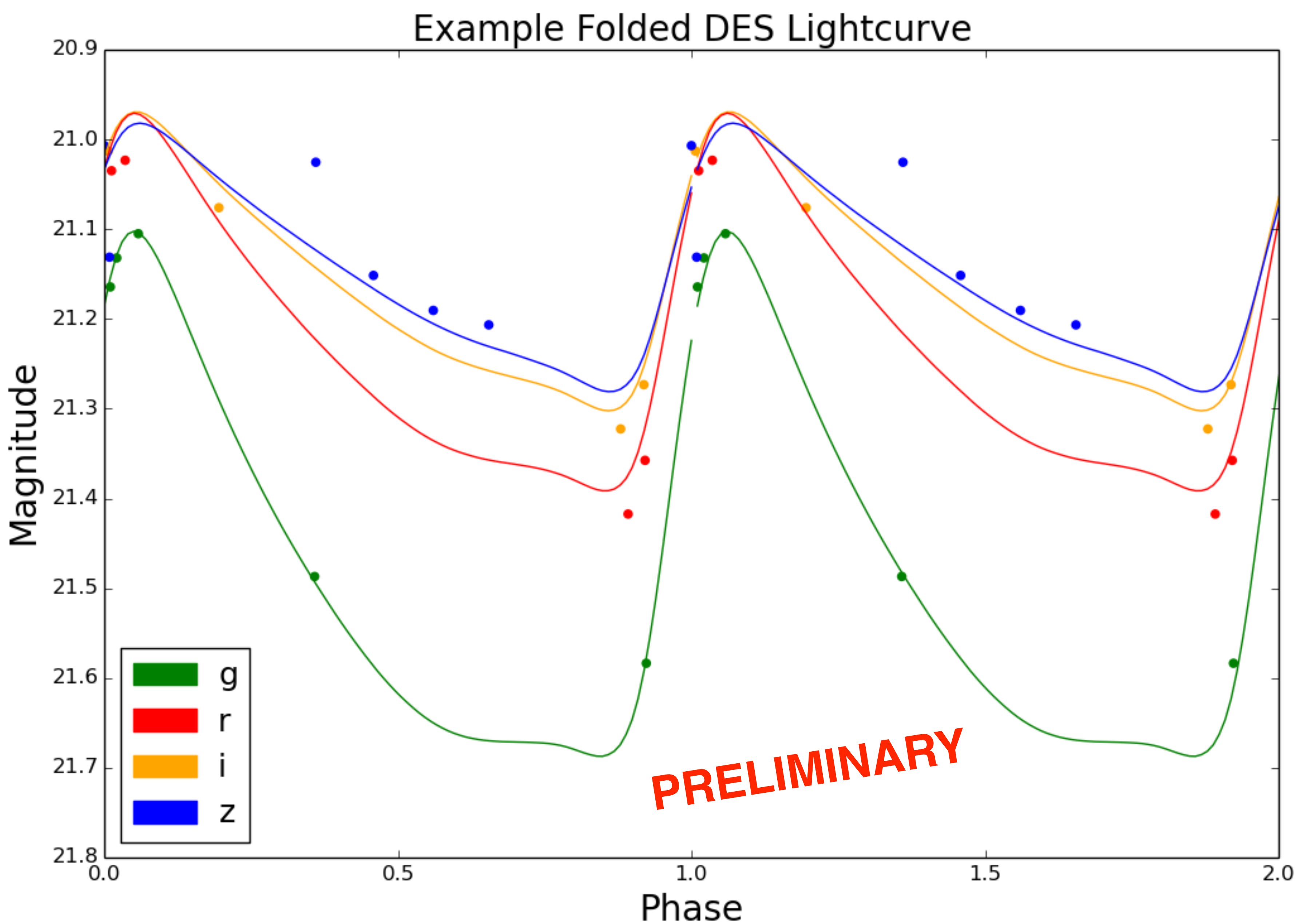


Mehta et al. 2017
arXiv:1711.05280

Using RR Lyrae to Identify Substructures in the Milky Way Halo

At least one RR Lyrae (variable star standard candle) has been identified in *every* dSph with published time-series observations

Baker & Willman 2015



Sparse sampling: total of ~50 DES observations distributed across 5 bands over 5 years (typical pulsation periods range from 0.25 to 0.8 days)

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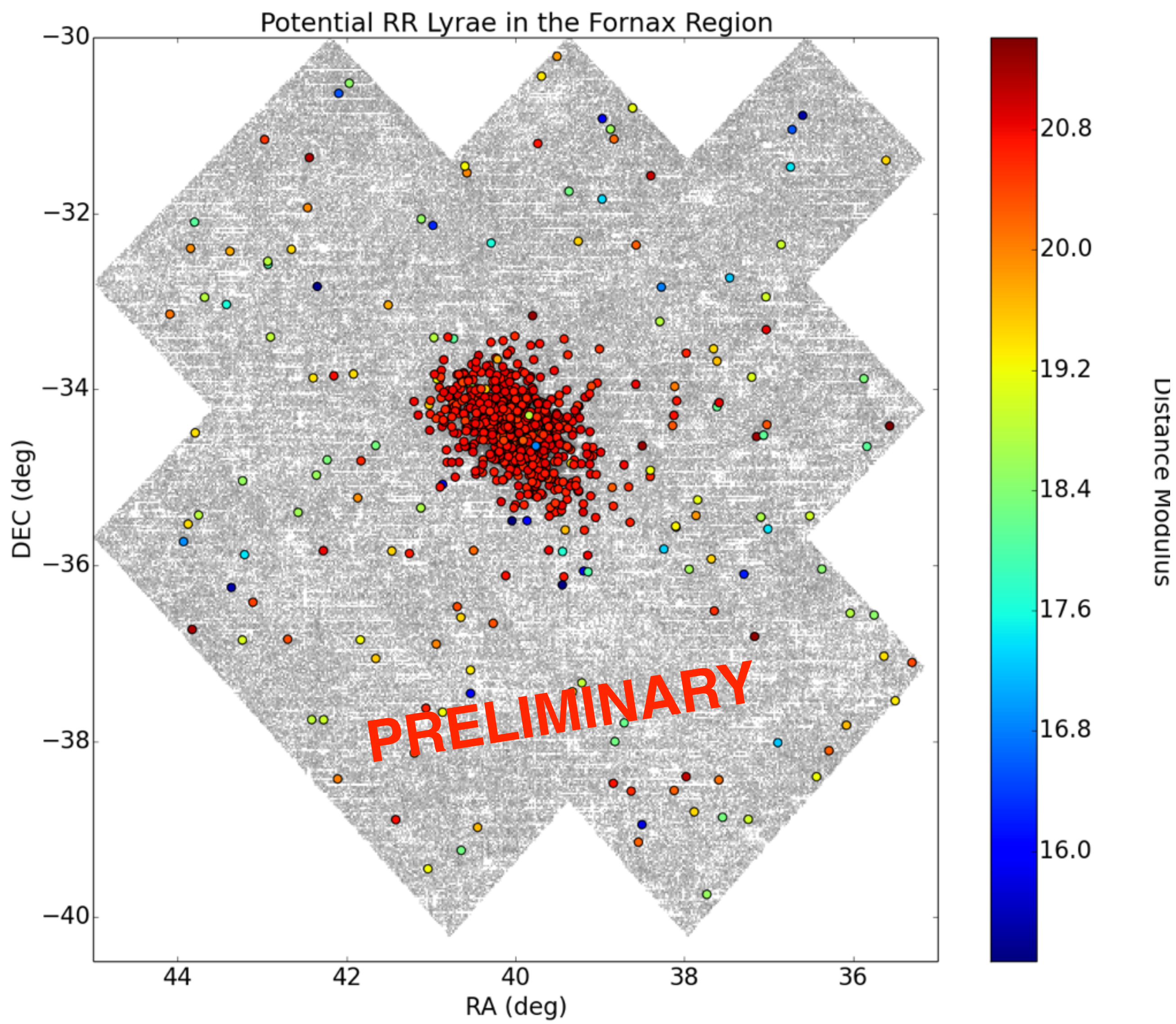
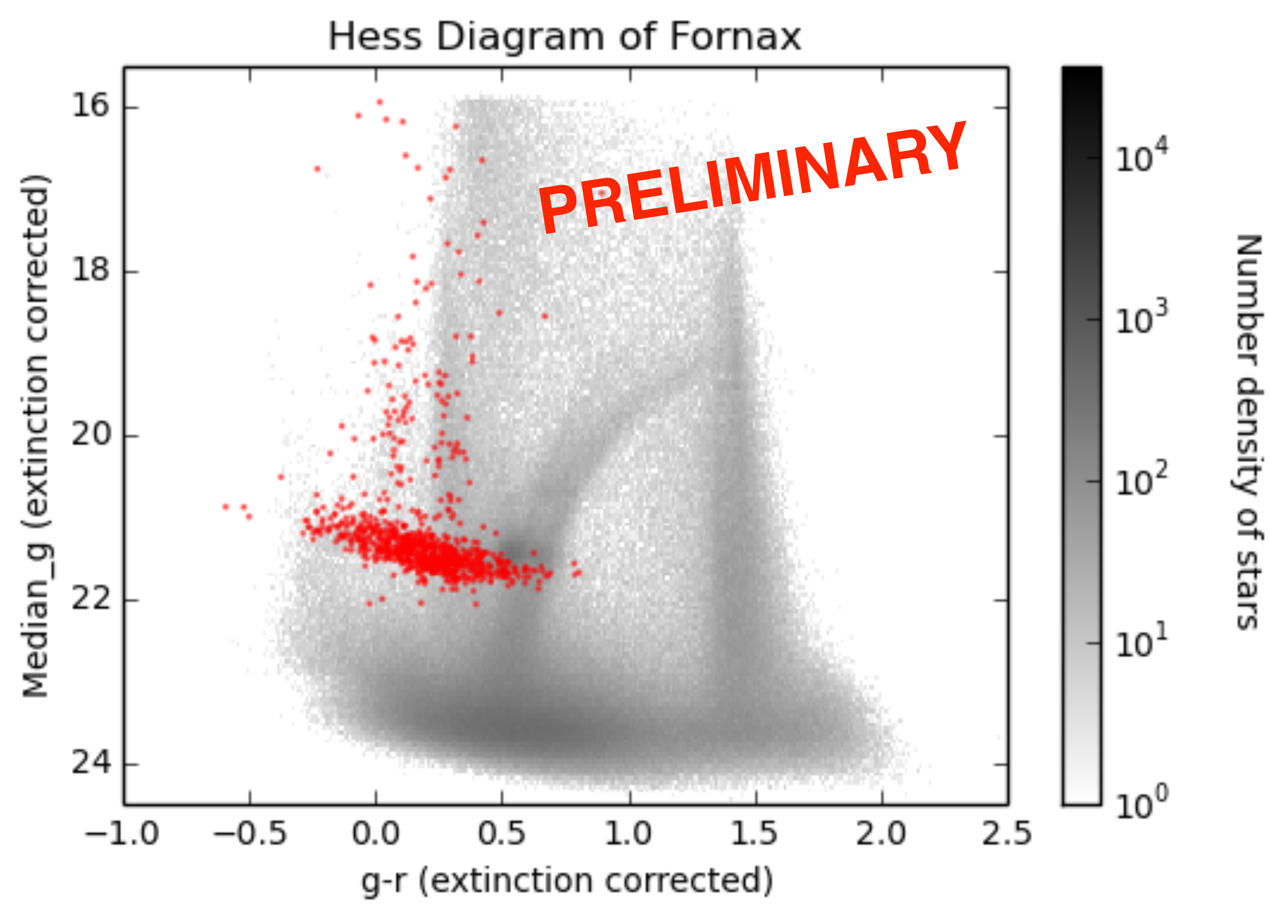
Baker & Willman 2015

DES Candidate RR Lyrae in Fornax region



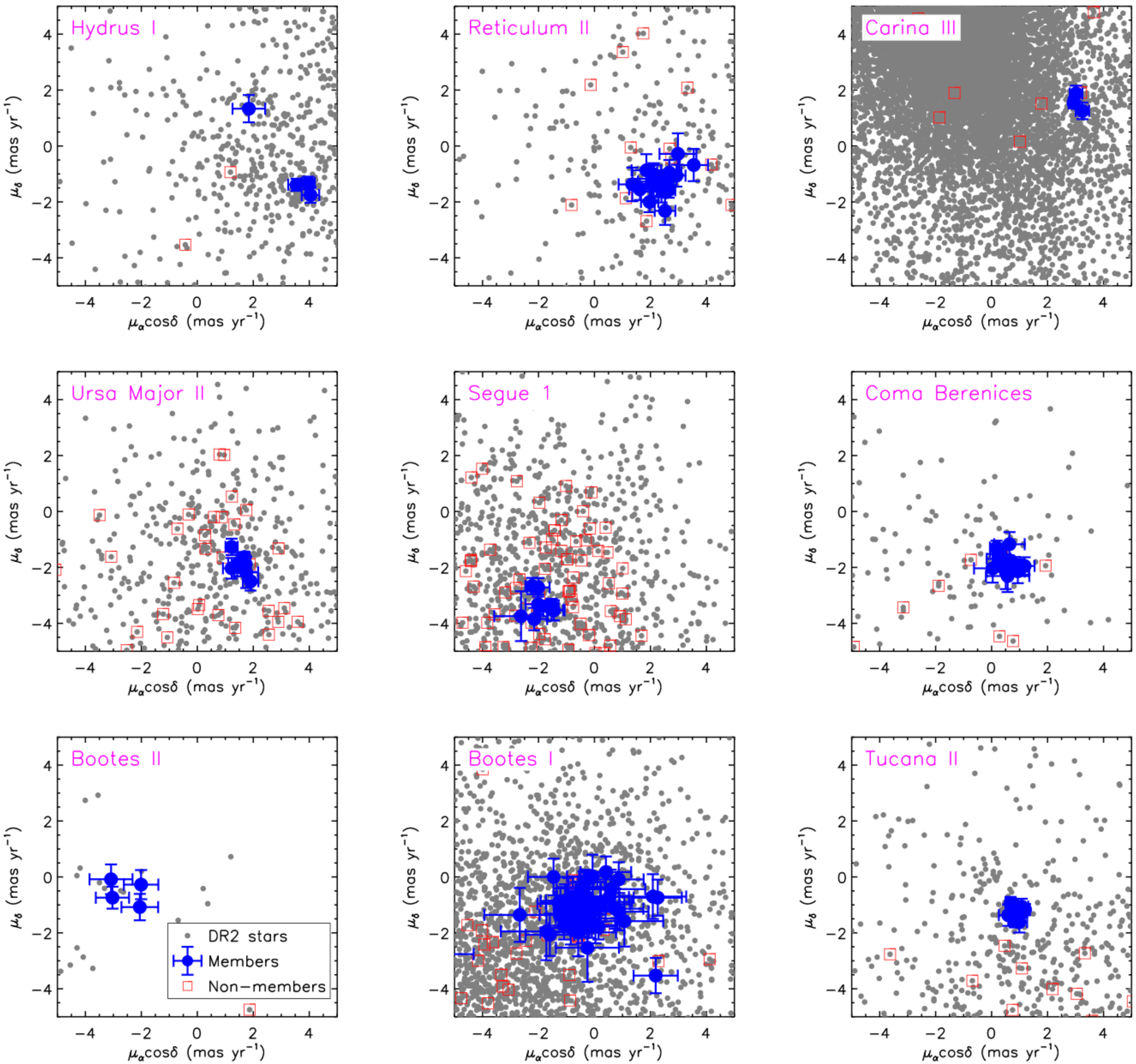
Color-coded by distance

Location in Color-Flux Space



Candidates are concentrated in specific region of color-flux space consistent with being RR Lyrae at the distance of Fornax

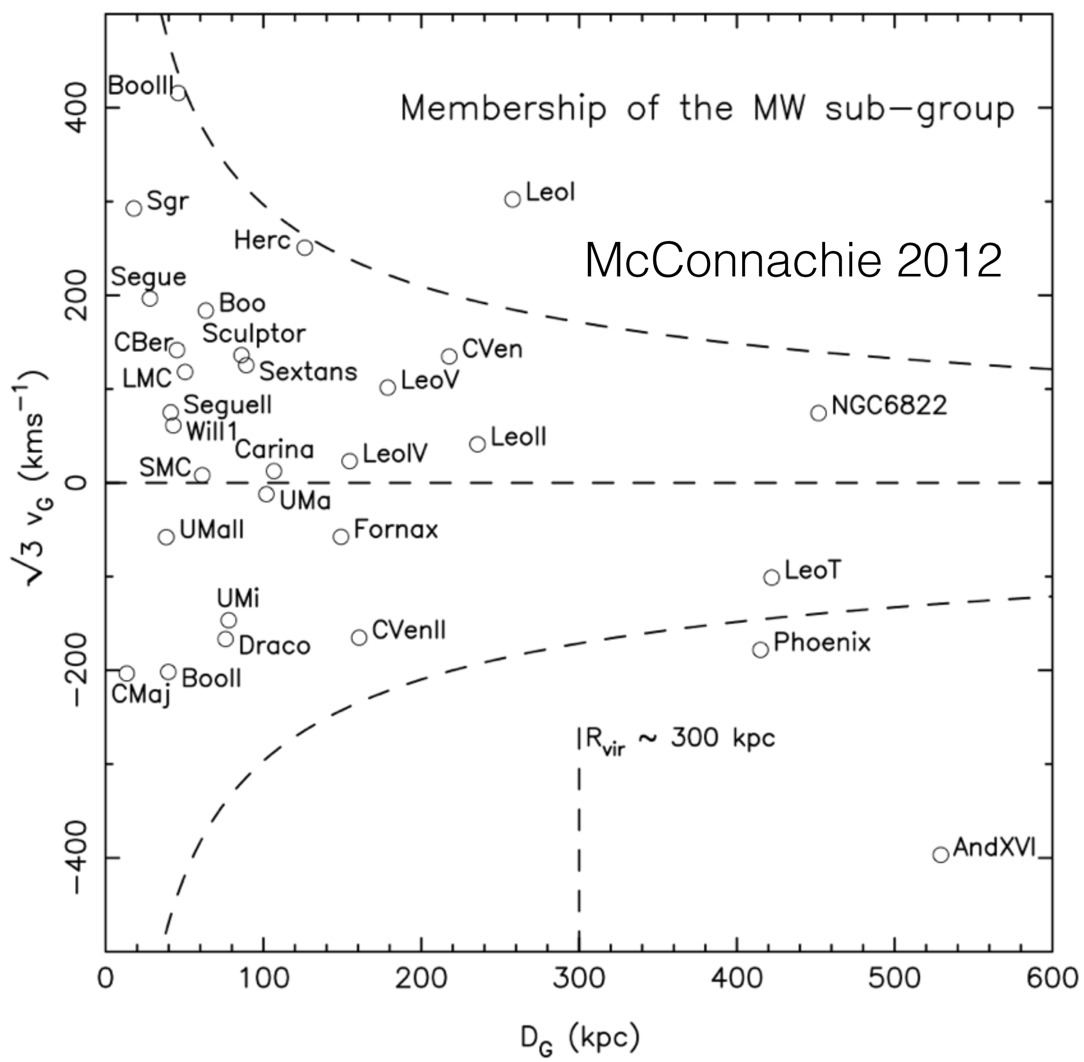
Using Proper Motions



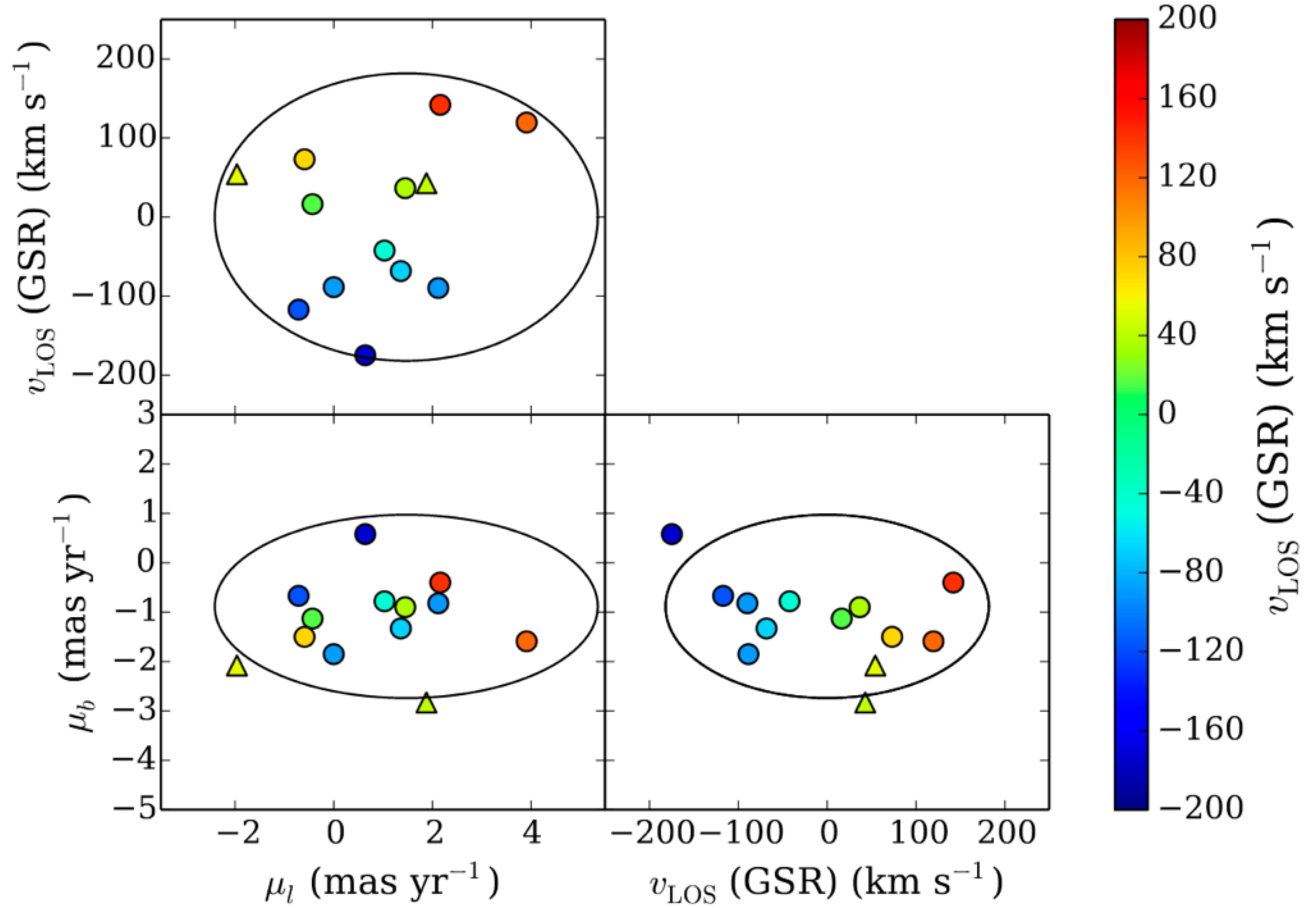
Spectroscopic members (line-of-sight velocity)

Simon 2018
arXiv:1804.10230

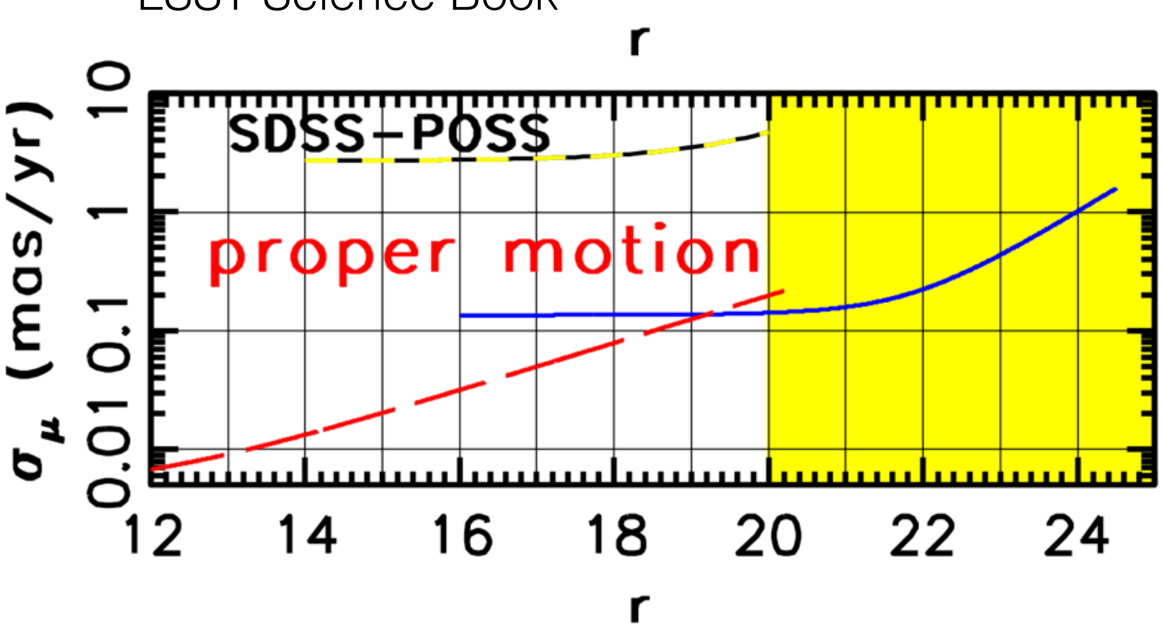
Proper Motions



Cunningham et al. 2016
arXiv:1602.03180

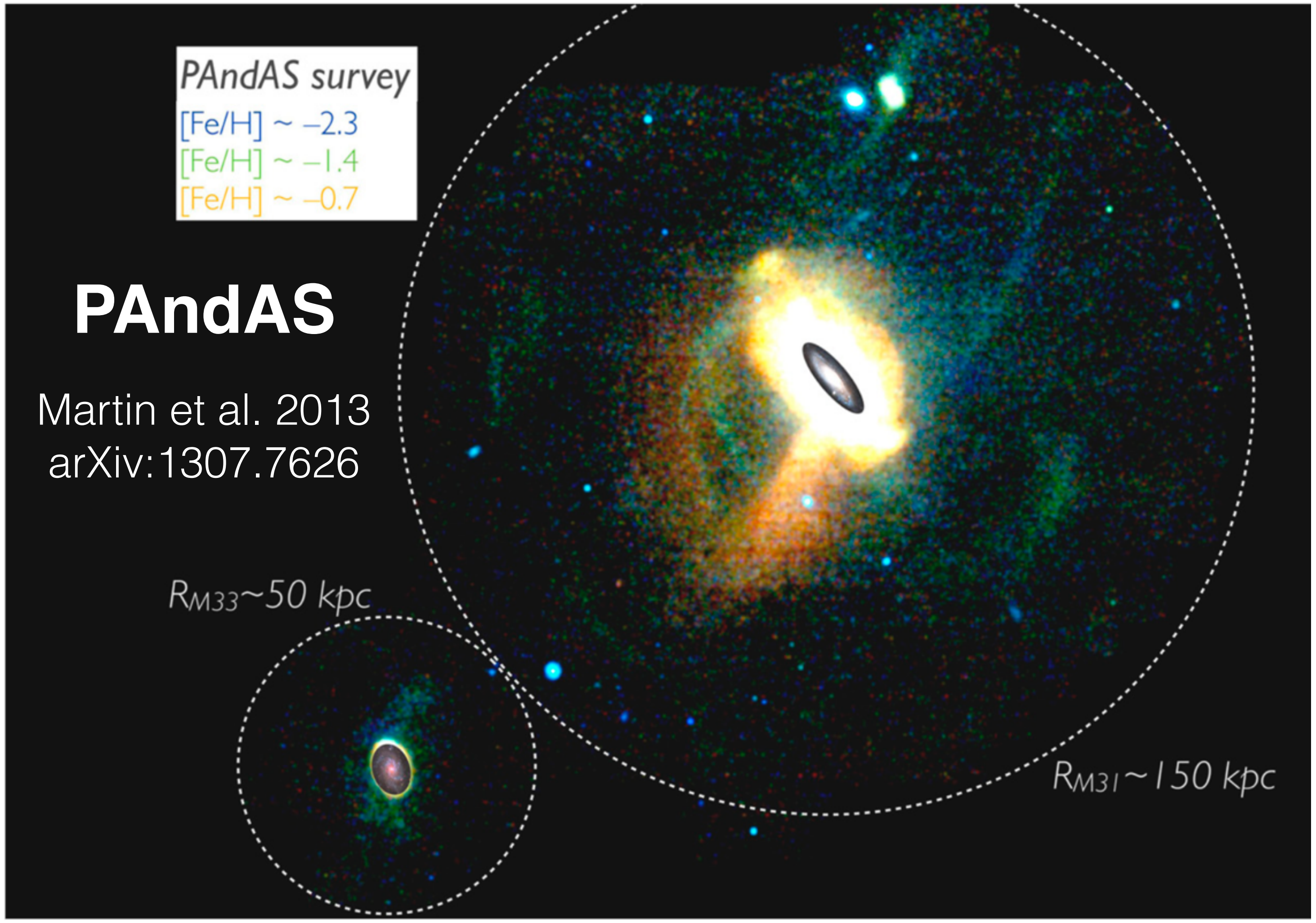


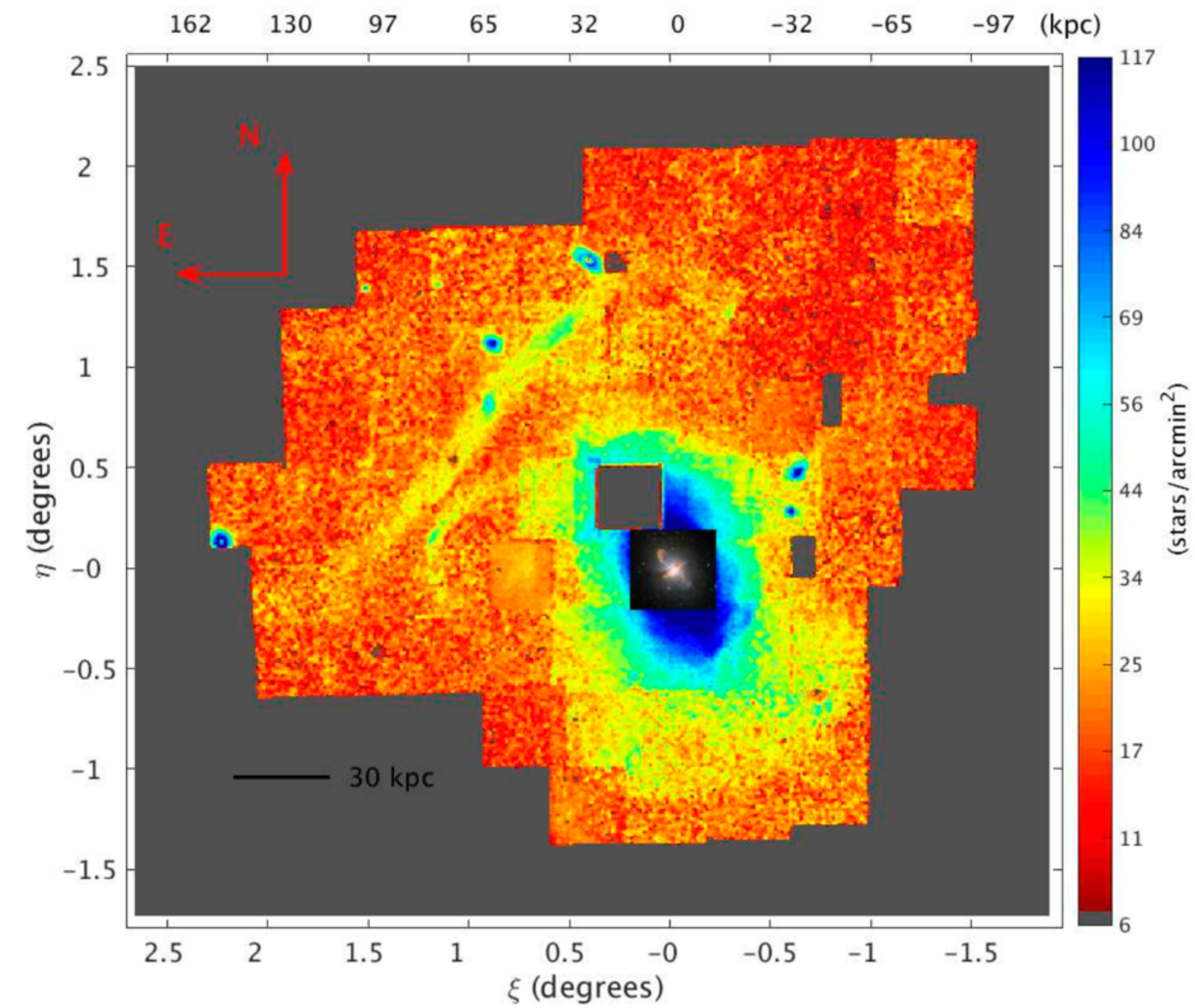
LSST Science Book



First sample of halo stars with measured 3D kinematics outside the solar neighborhood
13 main sequence stars at ~25 kpc

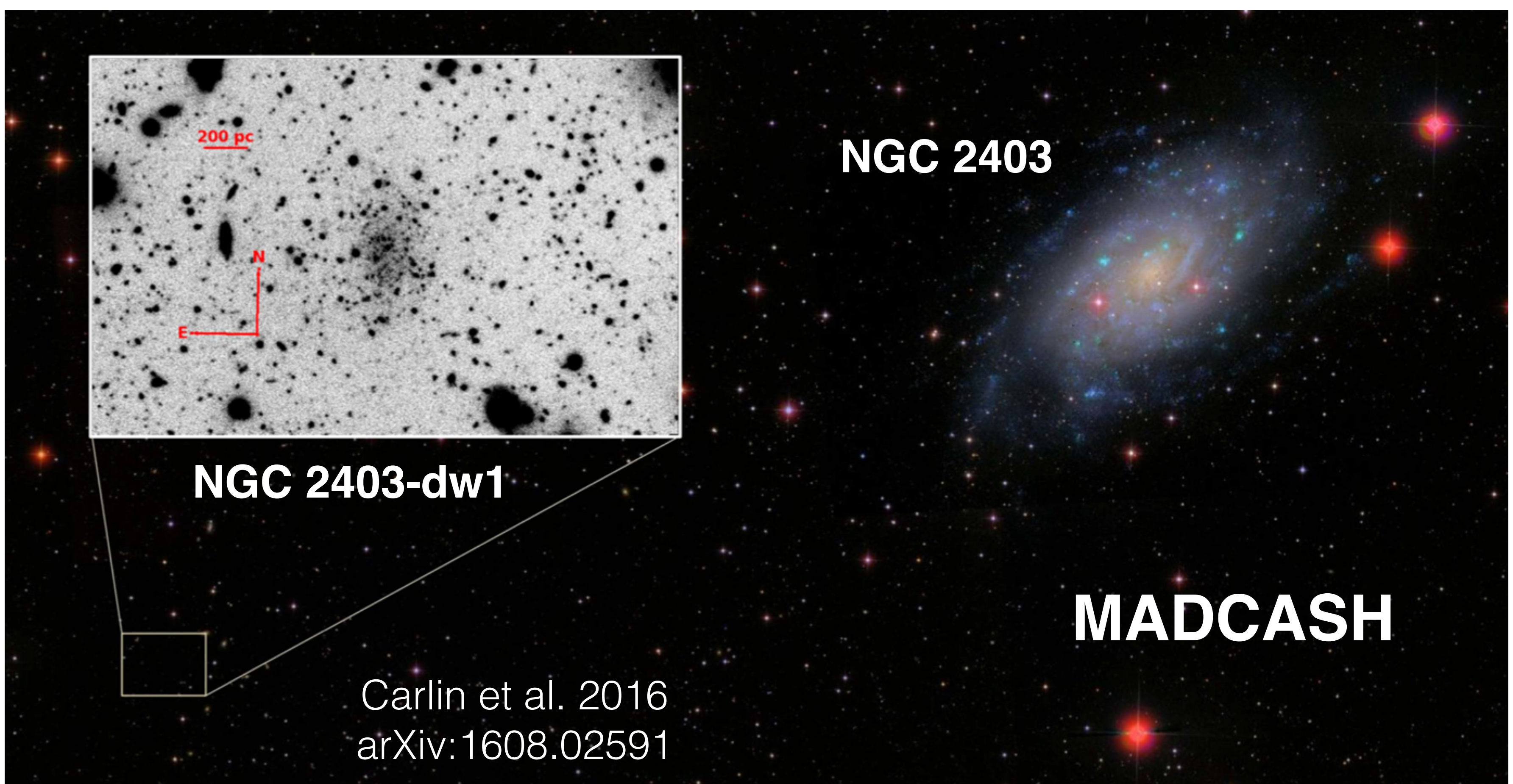
$$\mu\ [\text{mas yr}^{-1}] = 0.21\ v_t\ [\text{km s}^{-1}]\ /\ d\ [\text{kpc}]$$





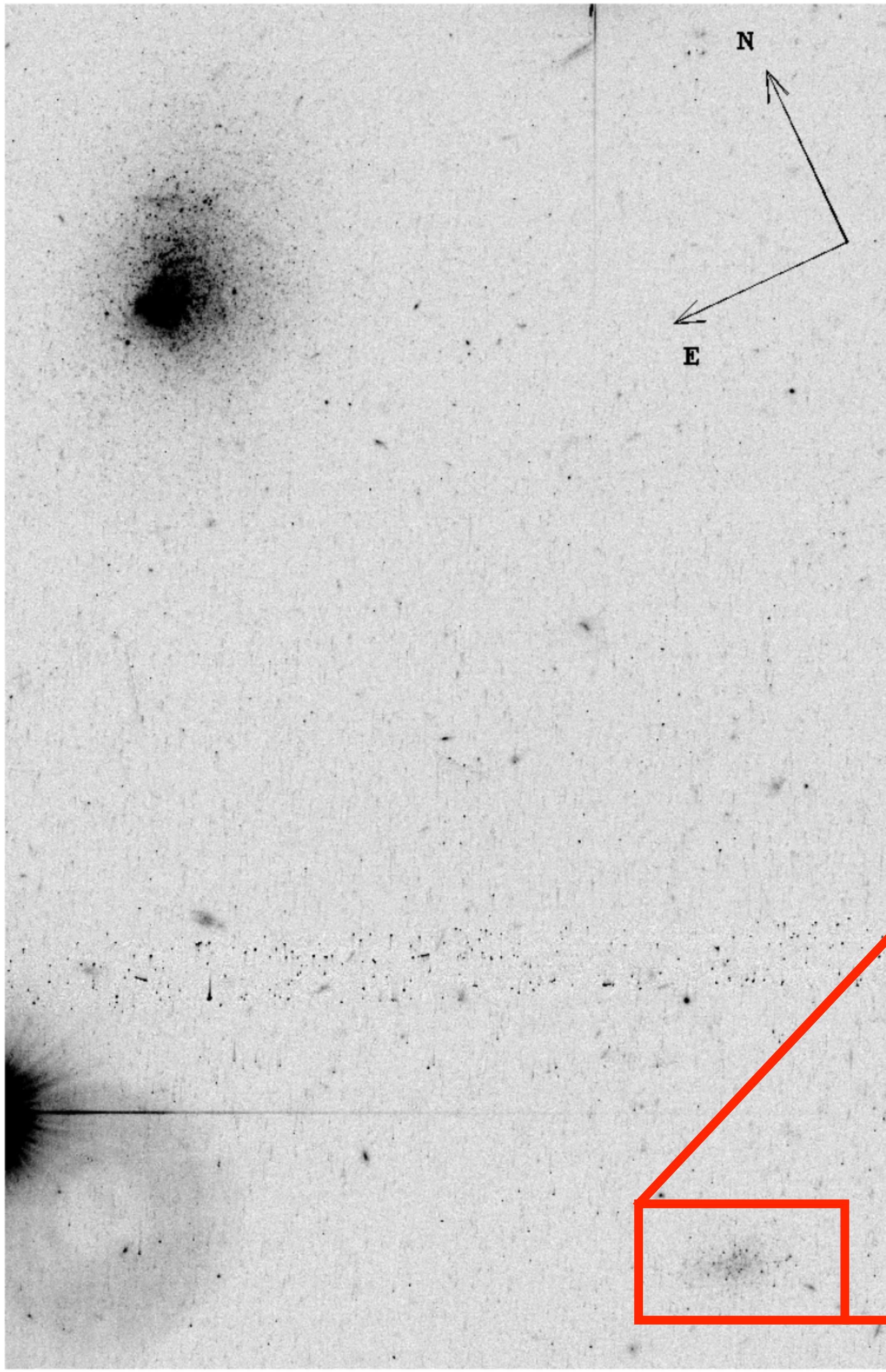
Centaurus A

Crnojevic et al. 2016
arXiv:1512.05366

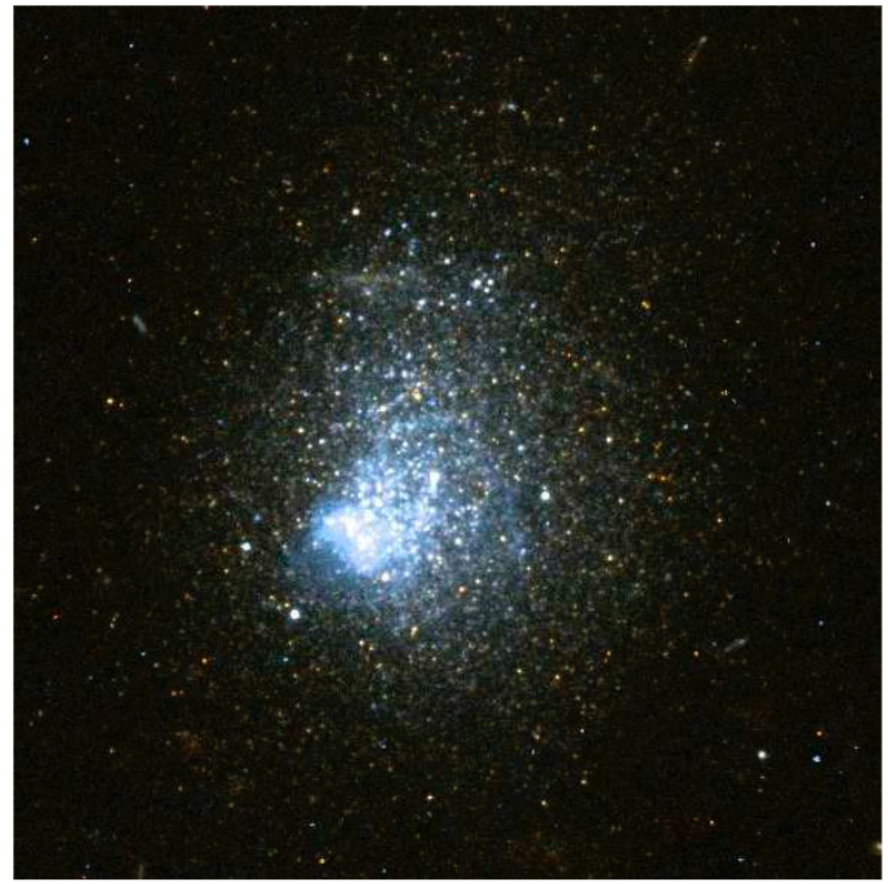


Targeted searches now identifying dwarf satellites comparable to most luminous ultra-faints / least luminous “classical” Milky Way satellites (Draco analogs) around a variety of hosts out to several Mpc

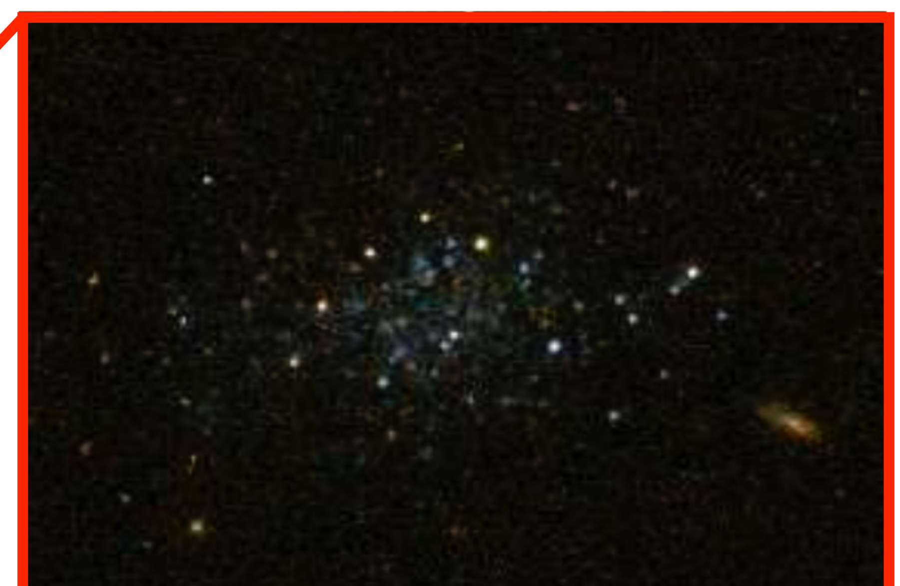
Serendipitous Discovery with HST



Predict ~2K similar galaxies within 10 Mpc



Makarova et al. 2017
arXiv:1711.00696



Draco dwarf analog

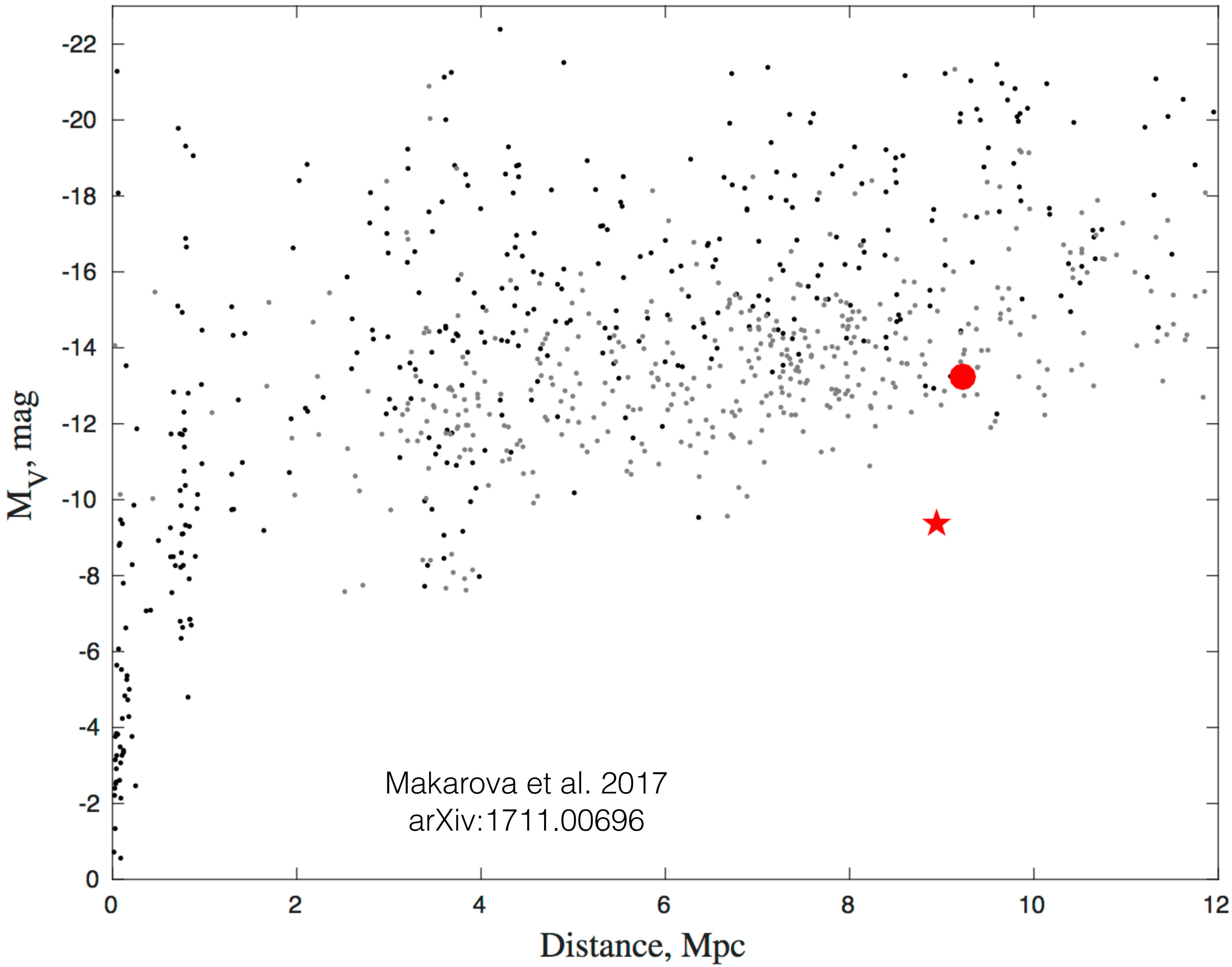
$m_V = 20.4$
$M_V = -9.4$
$D = 9$ Mpc

Appears in SDSS!

http://skyserver.sdss.org/dr12/en/tools/explore/summary.aspx?ra=179.470833&dec=56.613611

Serendipitous Discovery with HST

Predict ~2K similar galaxies within 10 Mpc



LMC, $M_{\star}$ ~ 1.5 x 10^9 $M_{\odot}$

SMC, $M_{\star}$ ~ 5 x 10^8 $M_{\odot}$

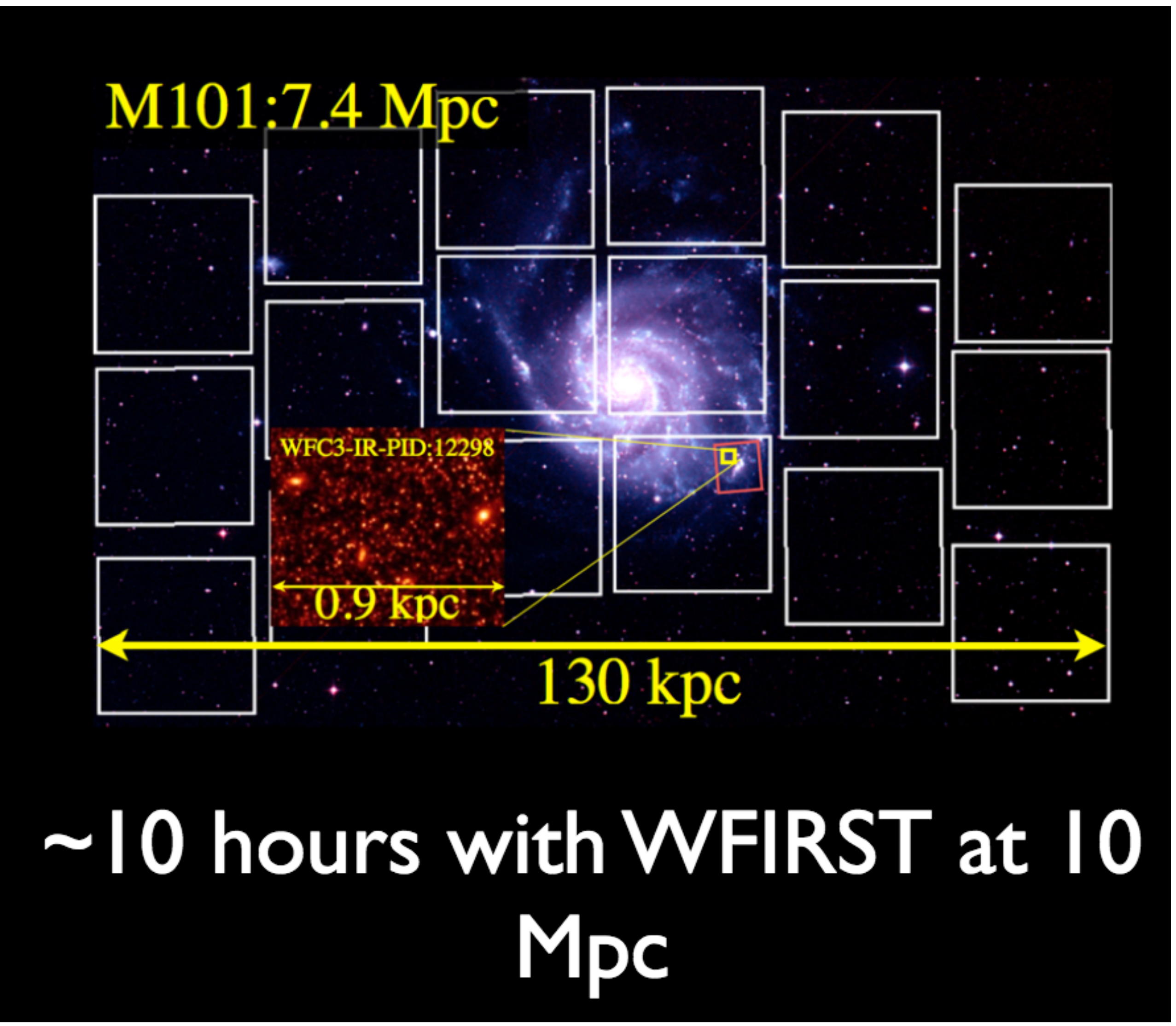
Fornax, $M_{\star}$ ~ 2 x 10^7 $M_{\odot}$

Draco, $M_{\star}$ ~ 3 x 10^5 $M_{\odot}$

Segue 1, $M_{\star}$ ~ 3 x 10^2 $M_{\odot}$

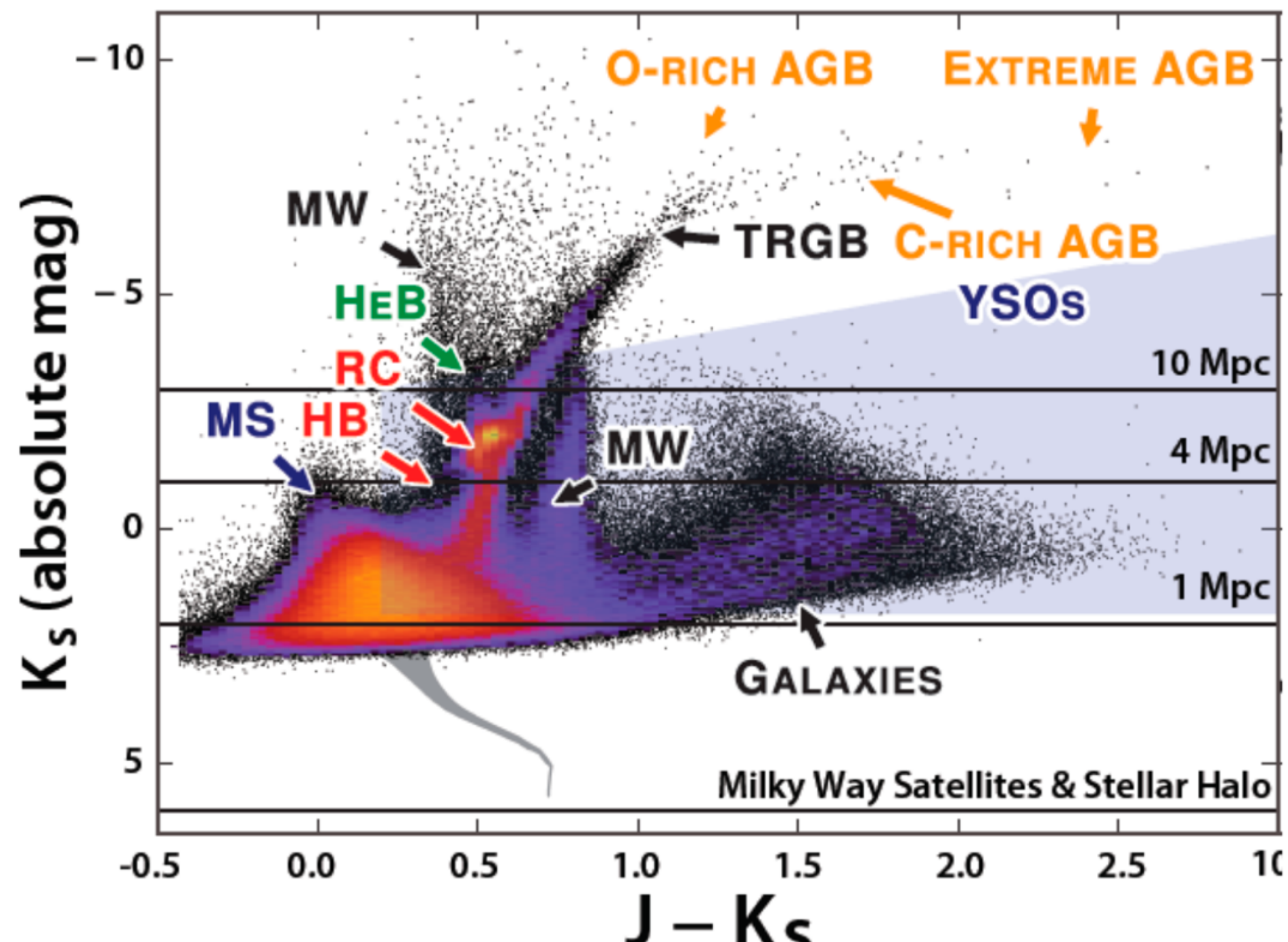
Wide-field Resolved Stellar Populations throughout Local Volume with WFIRST

Ben Williams, WINGS

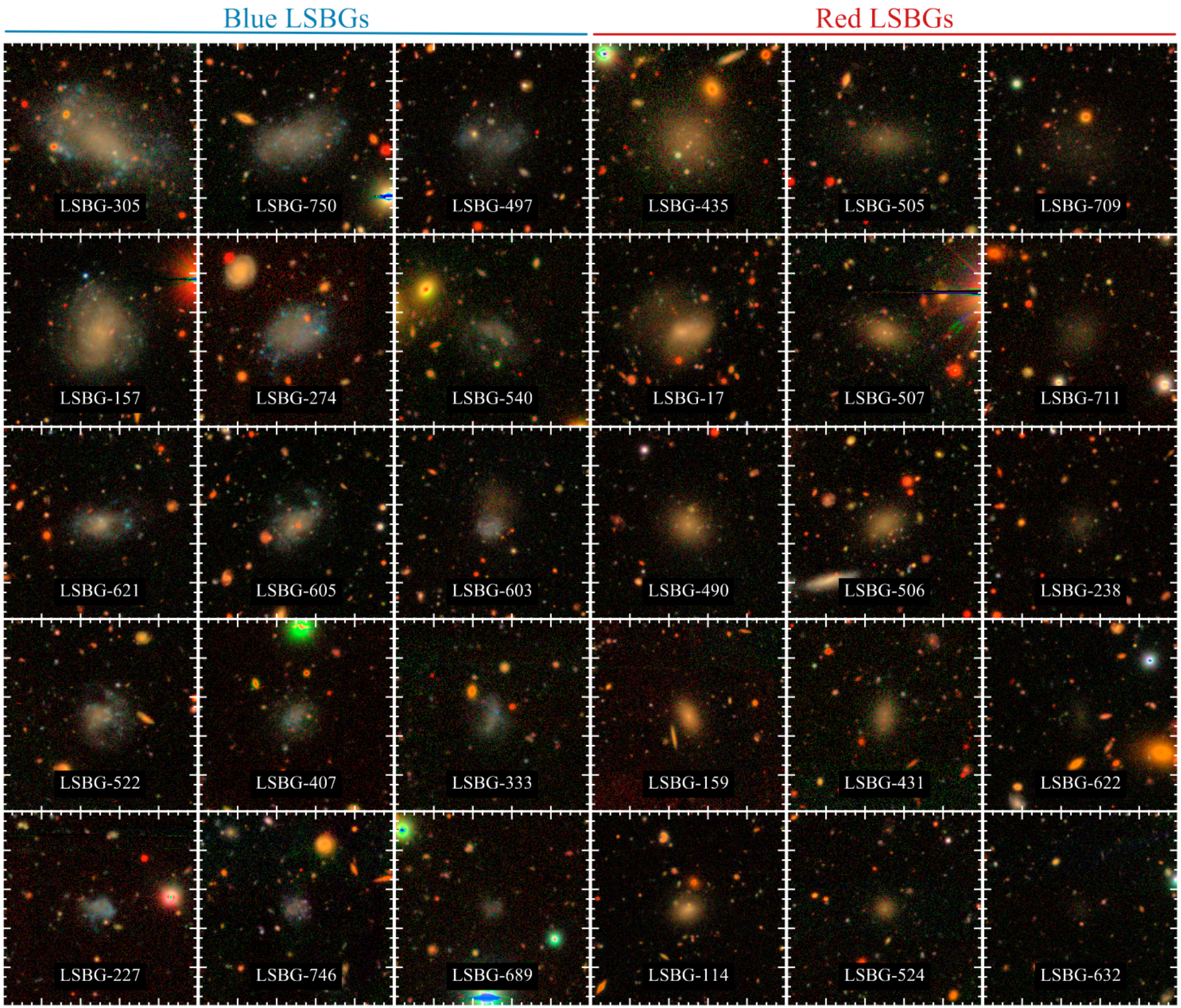


+ precise proper motions for fainter stars

Sanderson et al. 2017
arXiv:1712.05420



Low Surface Brightness Galaxies in HSC



Sample of ~800 galaxies with mean $\mu_{\rm eff}$(g) > 24.3 mag arcsec^{-2} in first 200 deg^2 of HSC-SSP imaging

Estimate distances in broad range of at least 30-100 Mpc and stellar masses $M_☆$ ~10^7-10^8 $M_{\odot}$

(SMC: $M_☆$ ~ 5 x 10^8 $M_{\odot}$)

Greco et al. 2017
arXiv:1709.04474

Satellite Galaxy Populations around Milky Way Analogs (e.g., SAGA survey)

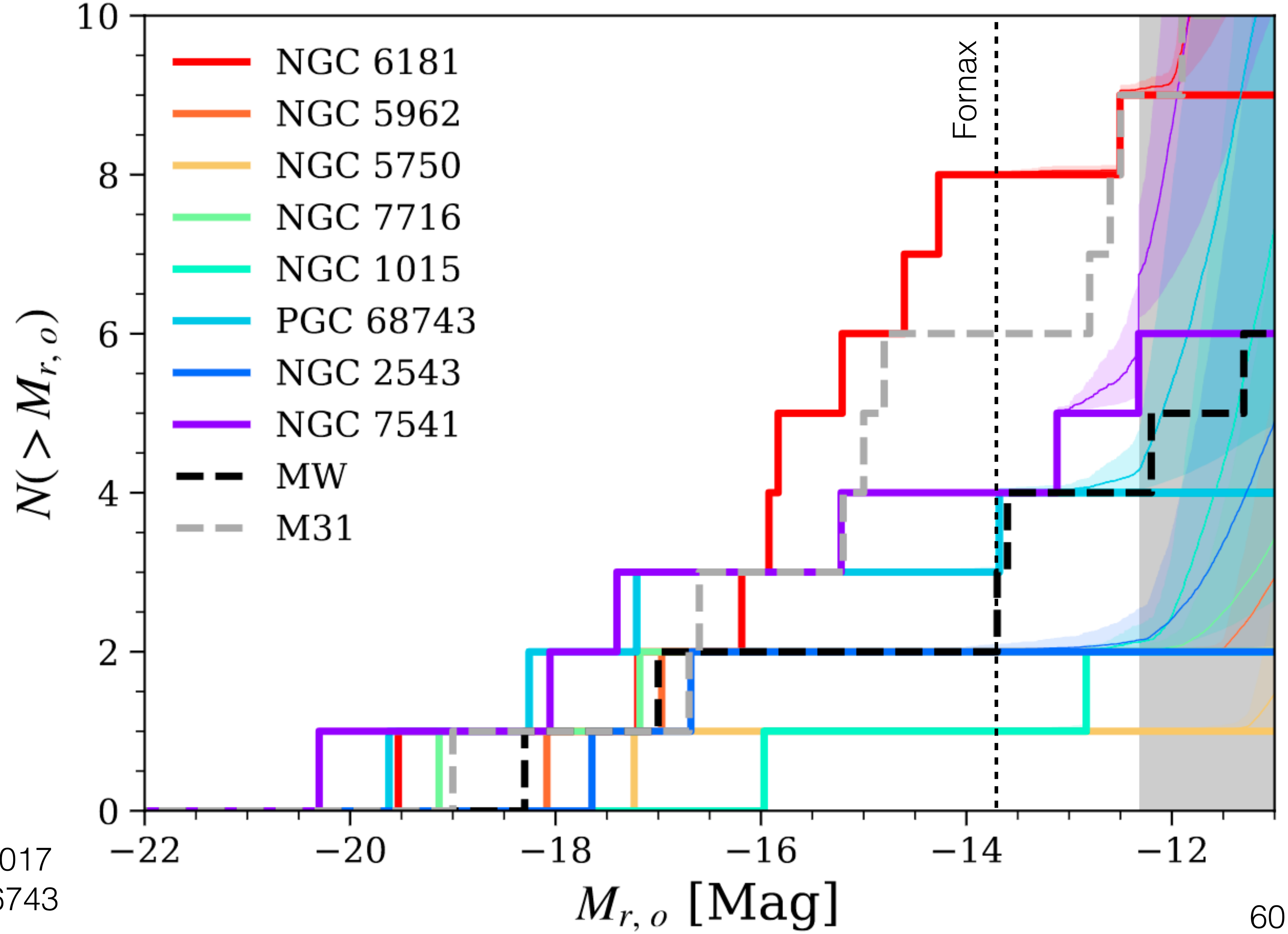
Milky Way analogs at distances 20 to 40 Mpc

Spectroscopic targeting of satellite candidates nearly complete to r ~ 20.75 mag

Stellar masses down to $M_\star \sim 3 \times 10^6$

>17K spectra obtained so far

Satellite galaxy cumulative luminosity functions for first 8 out of a goal total of 100 Milky Way analogs



Geha et al. 2017
arXiv:1705.06743

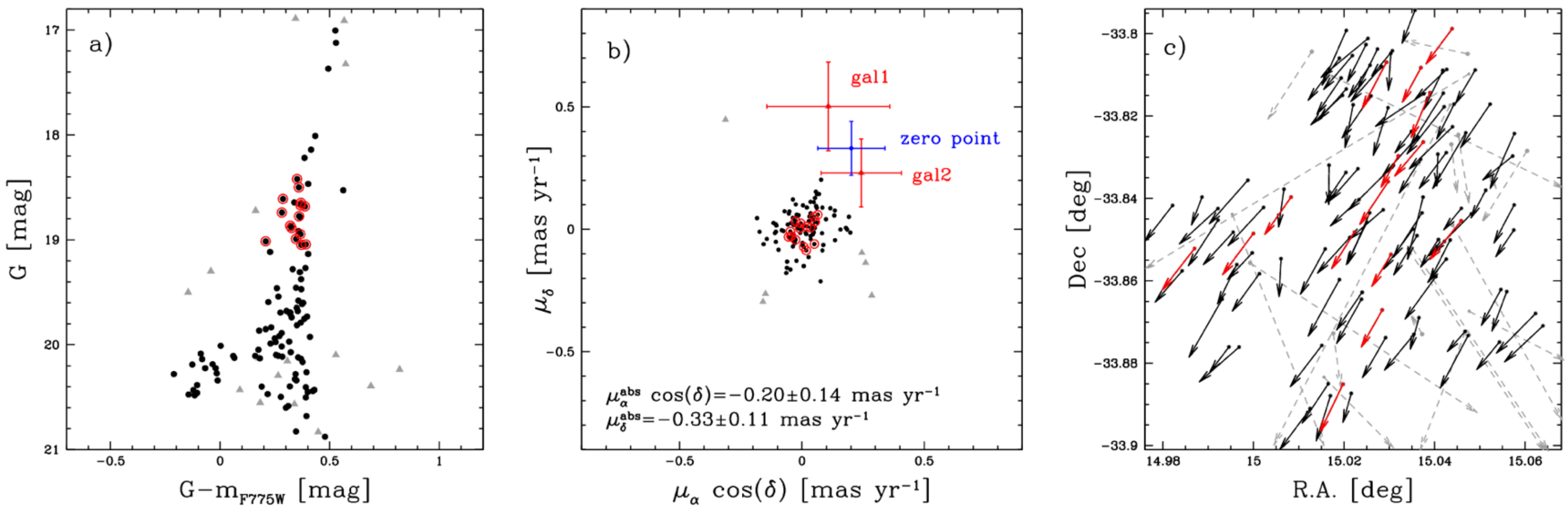
Concluding Thoughts

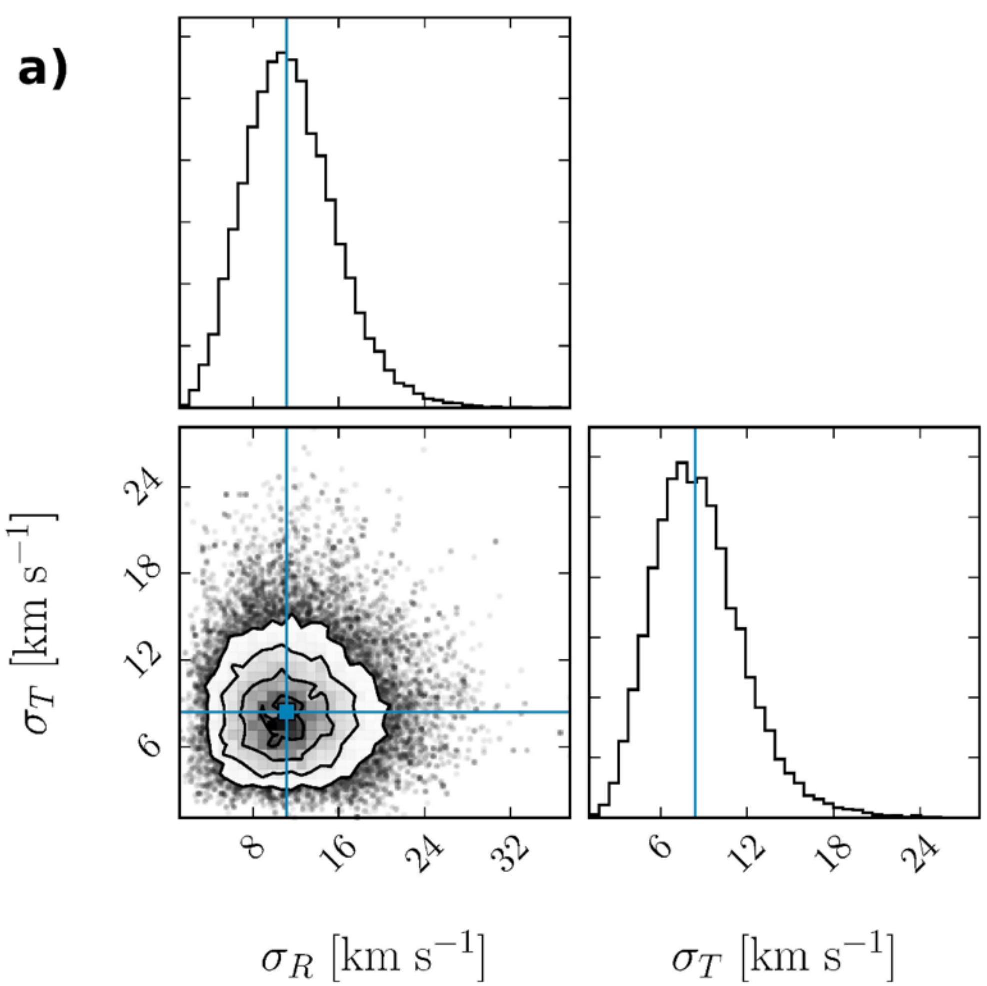
I'm optimistic that the observational landscape for ultra-faint galaxies will be *qualitatively* advanced during the next decade through access to new facilities and clever analysis methods
— ***one piece of the dark matter puzzle***

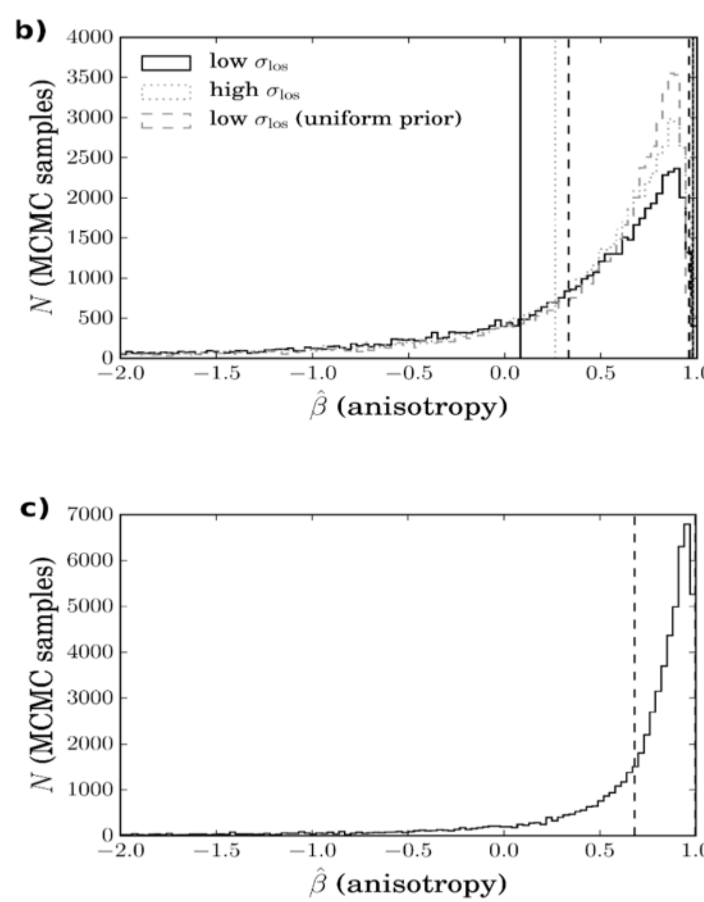
Some observational benchmarks of the next decade:

- Detect field population of ultra-faint galaxies out to a few Mpc
- Statistical populations of Draco-analogs throughout Local Volume
- Evidence of hierarchical structure formation at dwarf galaxy scales
- Threshold of galaxy formation — *how few stars are needed to make a detection if precision photometry, positions, variability, metallicity, and proper motion are all used?*
- 5-dimensional phase space information for stars in ultra-faint galaxies

Internal Proper Motions in Sculptor Dwarf







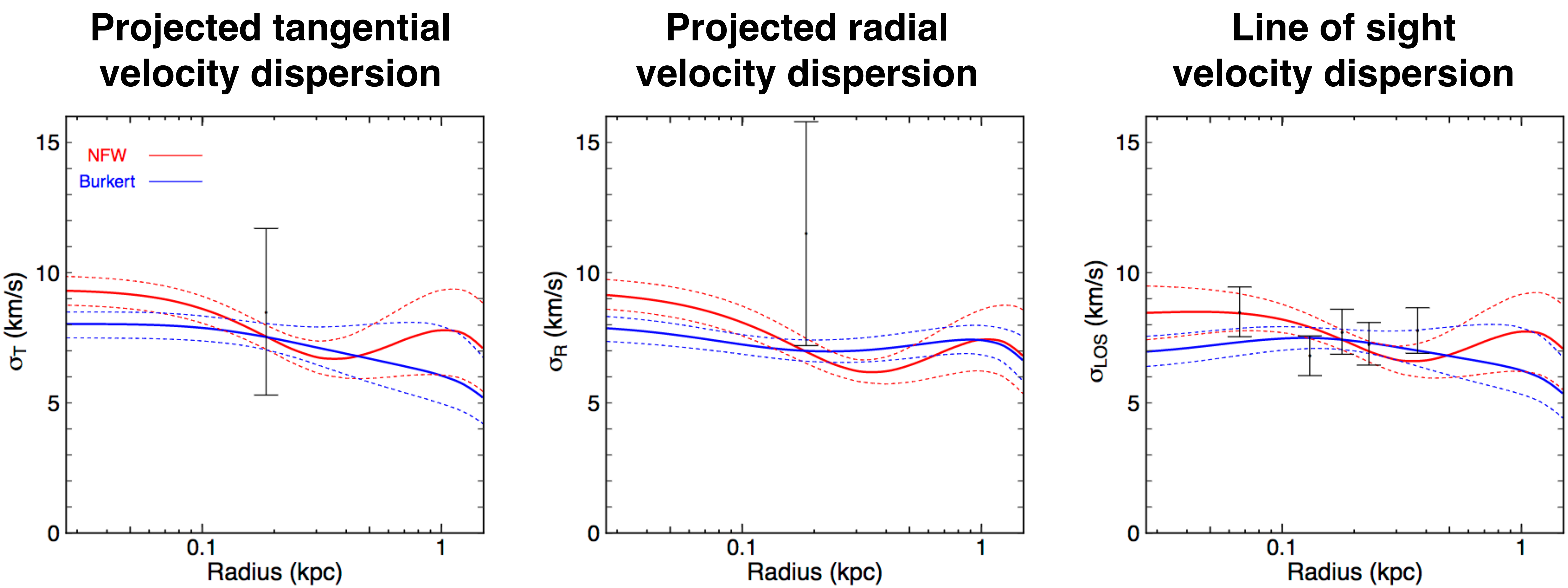
Massari et al. 2017
arXiv:1711.08945

HST + Gaia for 15 stars
12 year baseline

Proper motions constrain the orbital anisotropy

Internal Proper Motions in Sculptor Dwarf

Robustly determining core or cusp profile “would require PMs or LOS velocities for a few thousand stars with individual uncertainties well below 5 km/s”



Strigari et al. 2018
arXiv:1801.07343