Impact of the Large Magellanic Cloud on the Full-sky Milky Way Satellite Population

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for the DES Collaboration

Cosmic Controversies, KICP
5 October 2019

THE DARK ENERGY SURVEY

THE UNIVERSITY of WISCONSIN MADISON


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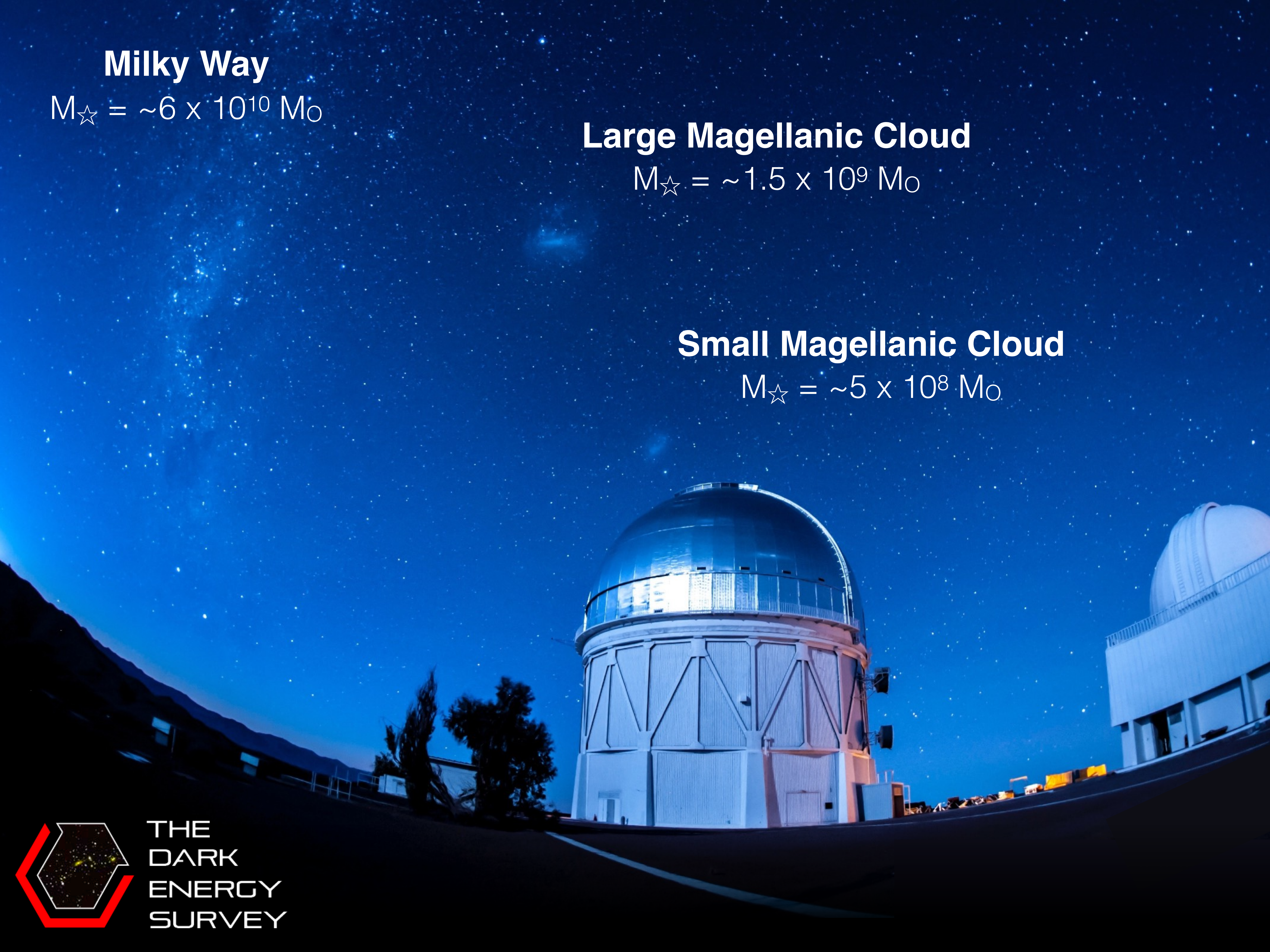
DARK
ENERGY
SURVEY



Milky Way
$M_{☆} = \sim 6 \times 10^{10} M_{\odot}$
Large Magellanic Cloud
$M_{☆} = \sim 1.5 \times 10^{9} M_{\odot}$
Small Magellanic Cloud
$M_{☆} = \sim 5 \times 10^{8} M_{\odot}$
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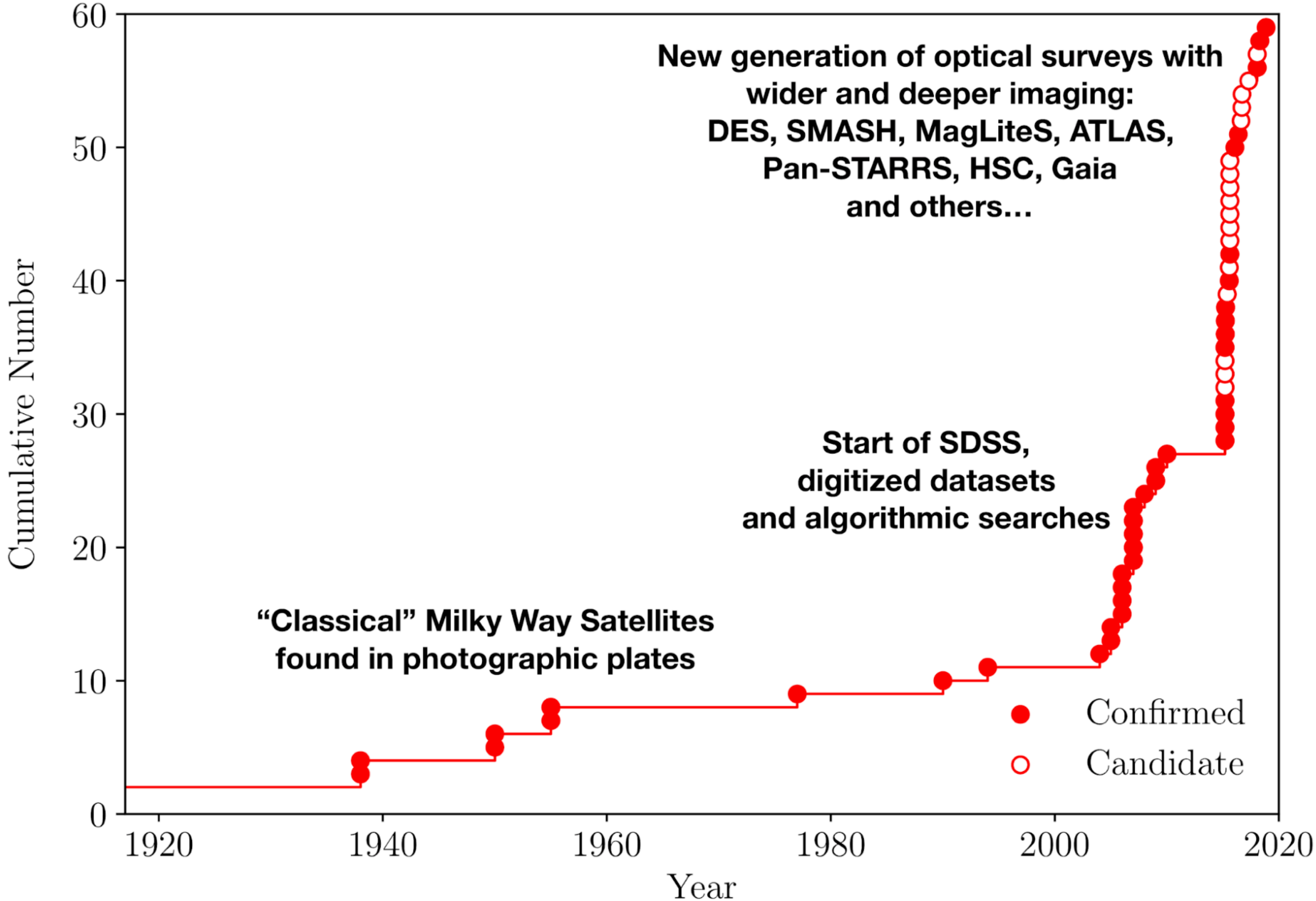
Growing Sample of Milky Way Satellites…



… but we know the current sample is still highly incomplete

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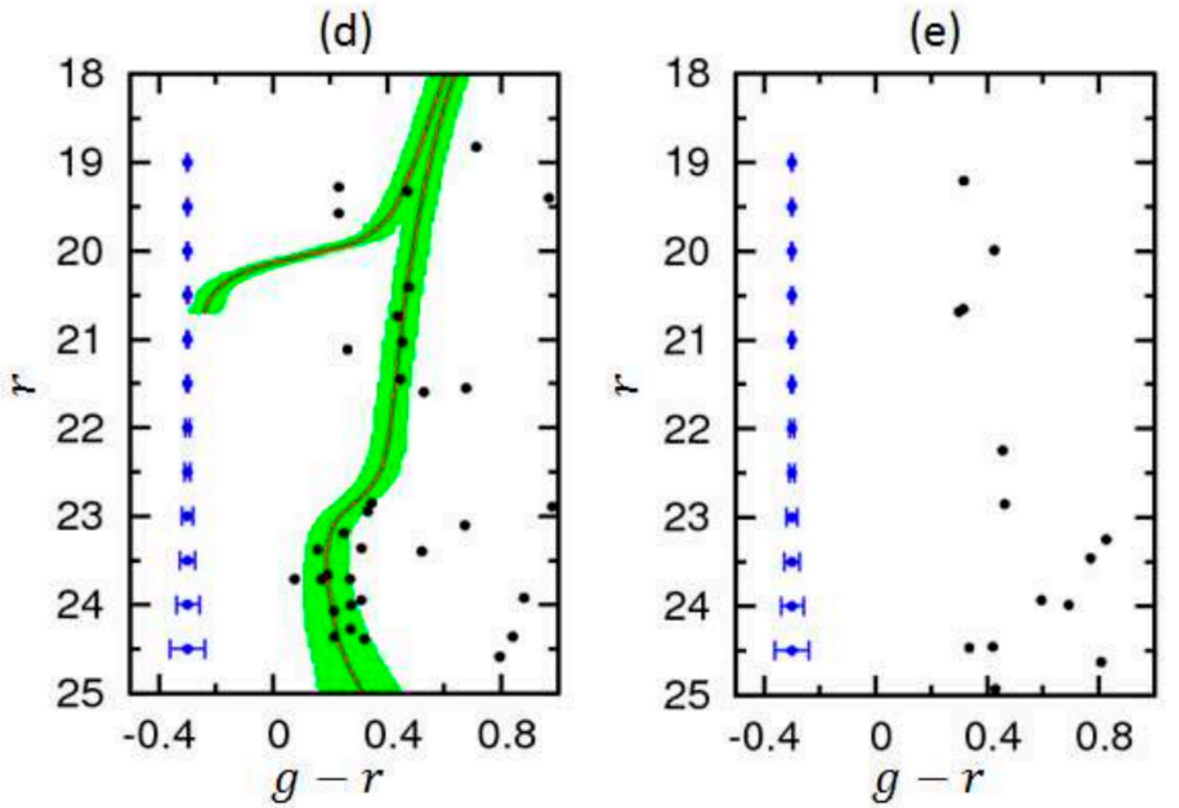
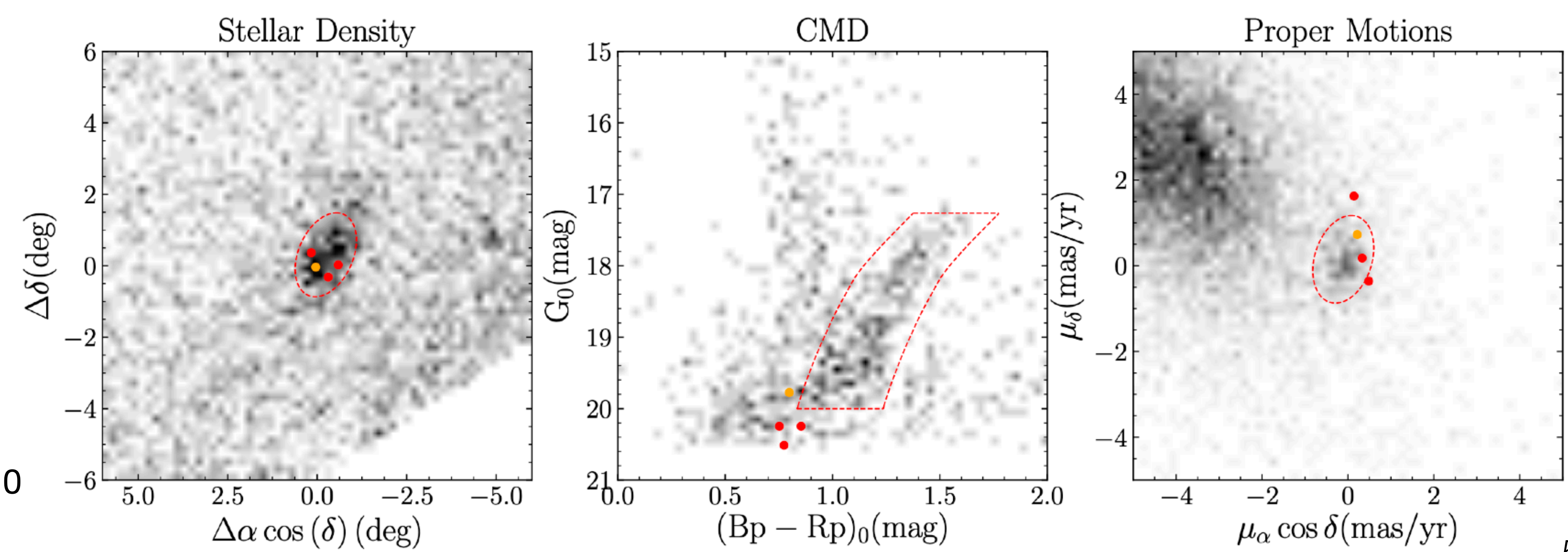


Three extremely low luminosity, distant, and low surface brightness satellites found in first ~700 deg² of HSC-SSP

Homma et al. 2016, 2019
arXiv:1609.04346
arXiv:1906.07332

Virgo I

Antlia 2 discovered w/ Gaia proper motions and RR Lyrae at μ ~ 32 mag arcsec^{-2}



Torrealba et al. 2010
arXiv:1811.04082

New Search of 3/4 of the Sky using DES Y3 + Pan-STARRS PS1

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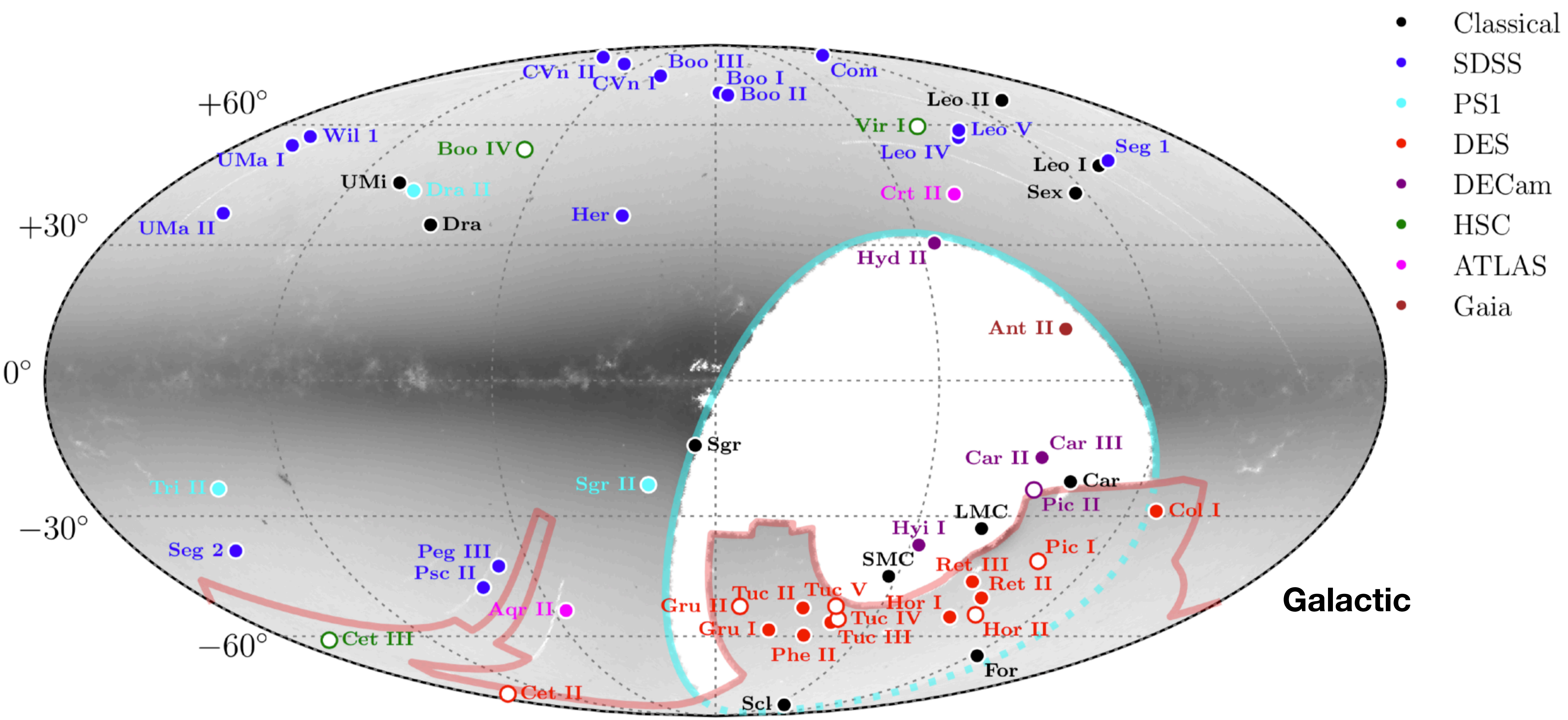
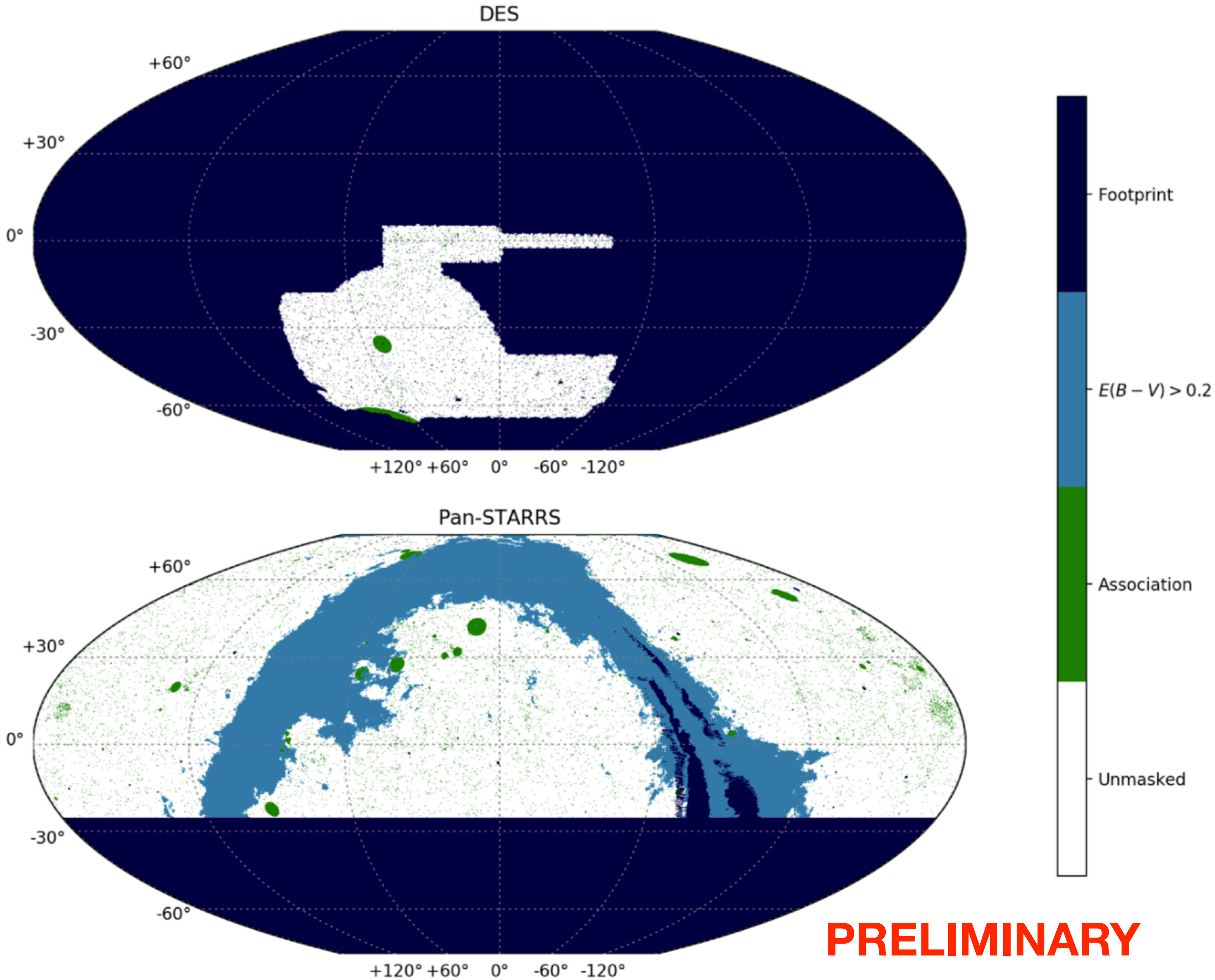
Deep optical imaging over nearly the entire high-Galactic-latitude sky



Total coverage ~32,500 deg^2

including over 75% of non-dusty sky (~24,300 deg^2 after masking)

New Search of 3/4 of the Sky using DES Y3 + Pan-STARRS PS1



PRELIMINARY

Automated search using **two independent algorithms**

Apply a **geometric mask** based on reddening maps and external catalogs to remove spurious "hotspots"

Recover majority of known satellites with automated pipeline; **no new satellite galaxy candidates detected**

17/20 known satellites in DES footprint
20/31 known satellites in PS1 footprint
9 known satellites outside these footprints

Search Sensitivity from Simulations

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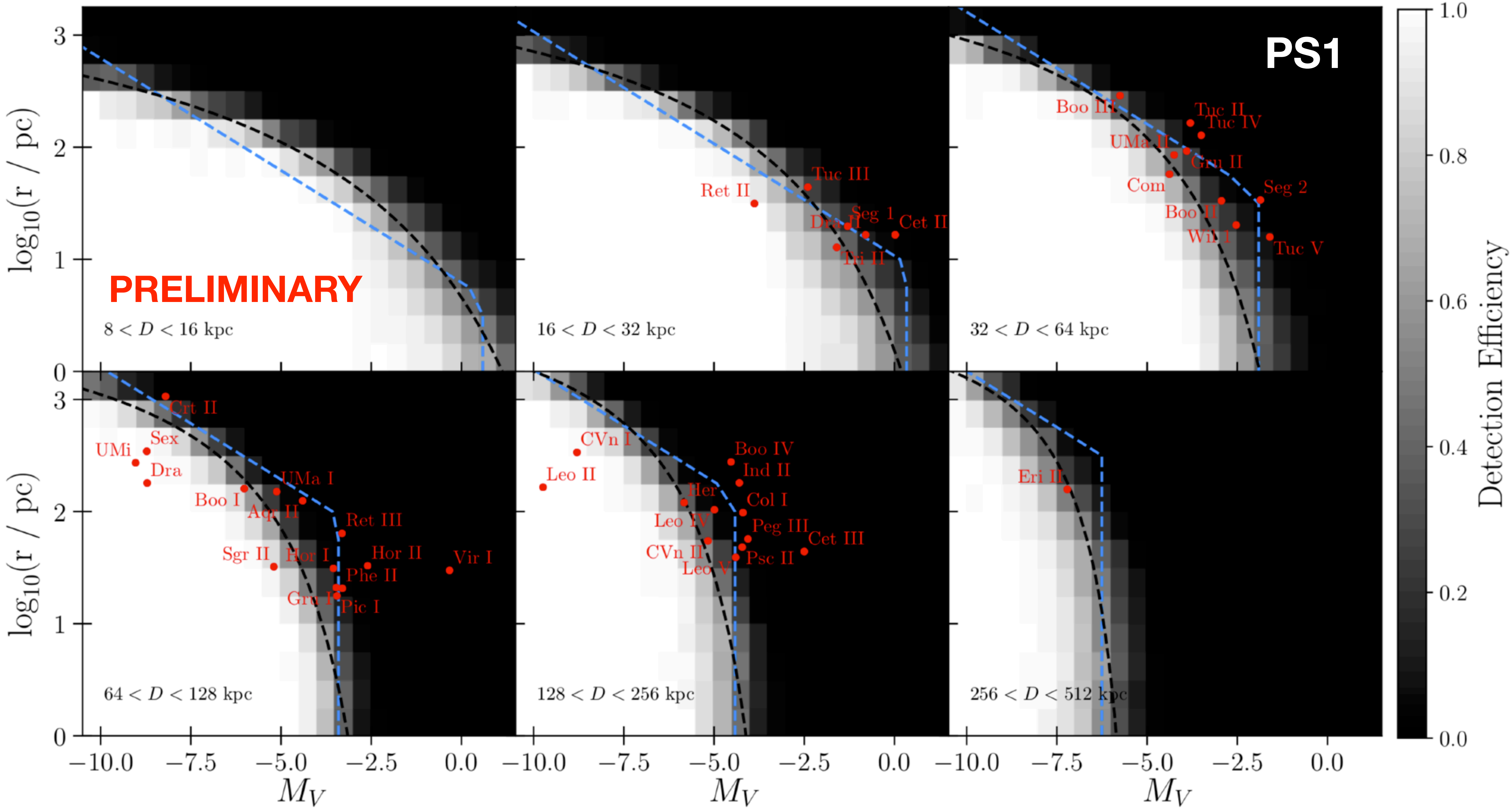
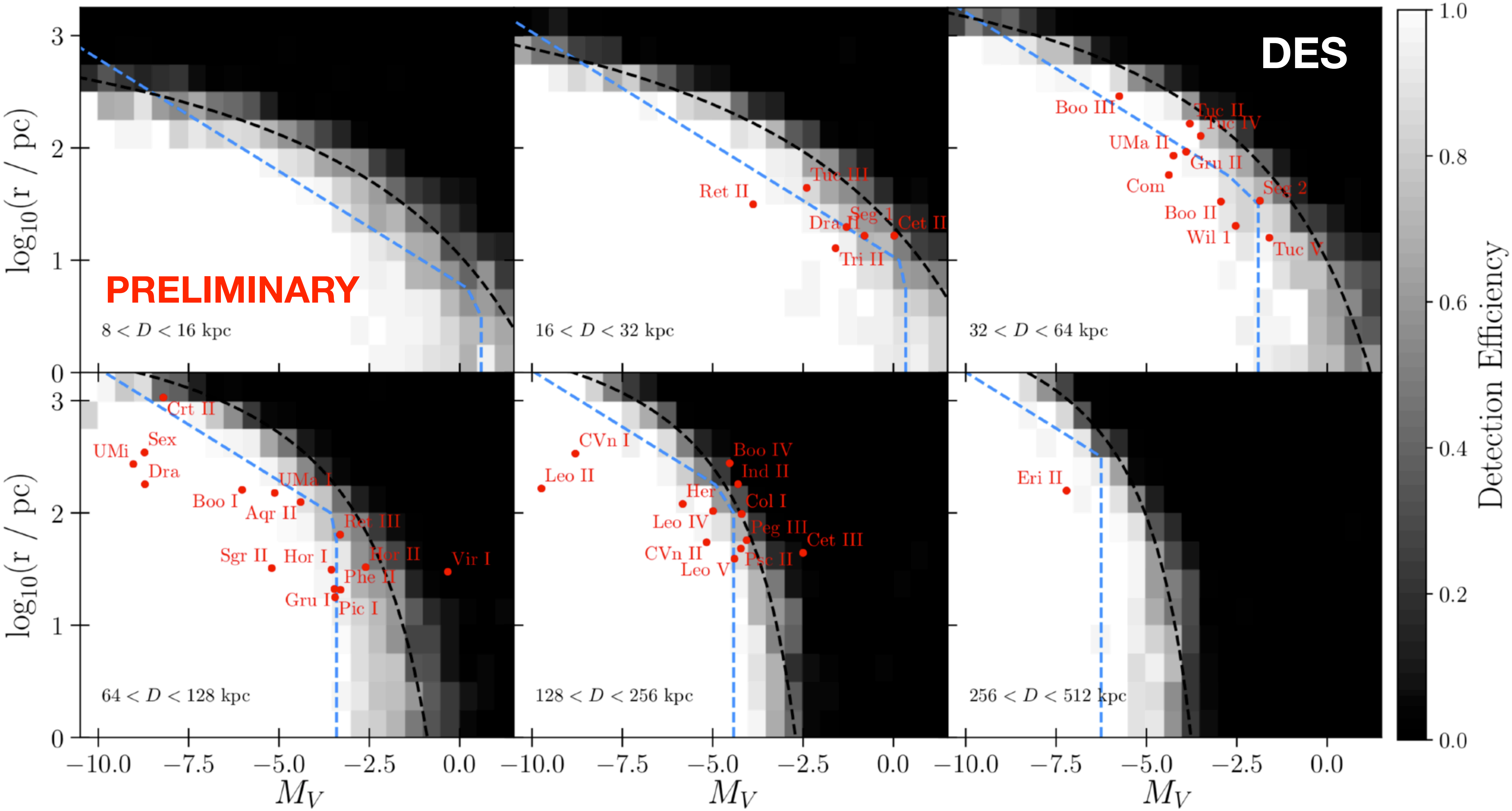
Inject and analyze >1M simulated satellites using same search pipeline



Encode sensitivity w/ machine-learning trained classifier (to be publicly released)

Search Sensitivity from Simulations

Inject and analyze >1M simulated satellites using same search pipeline



Encode sensitivity w/ machine-learning trained classifier (to be publicly released)

Analysis and Interpretation Overview

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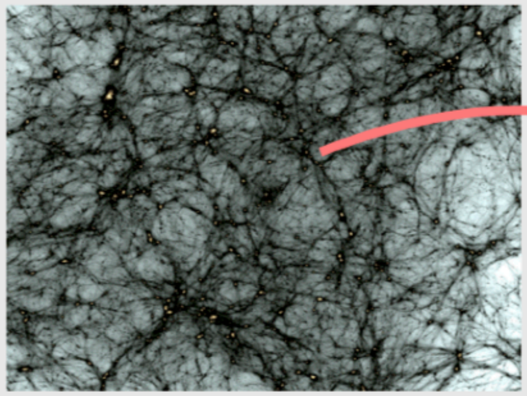
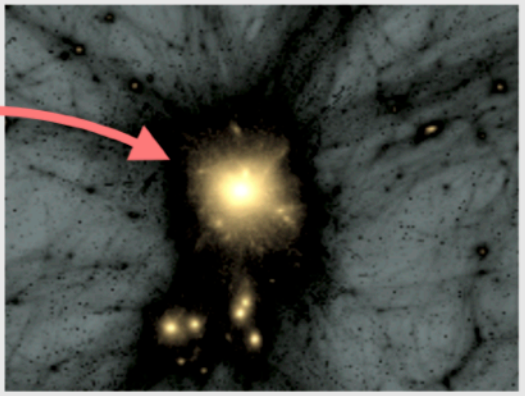
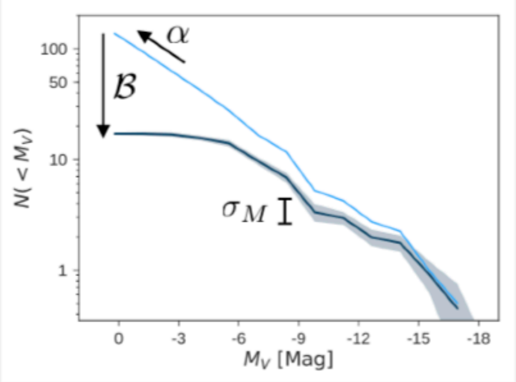
Markov Chain Monte Carlo

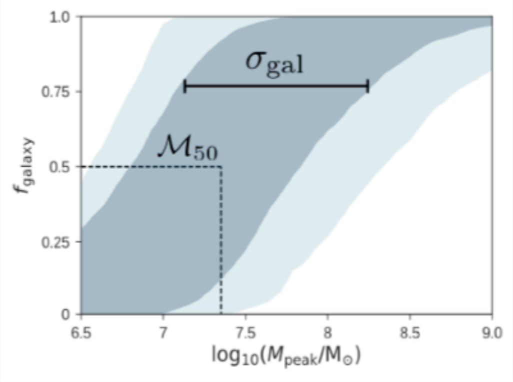
1. Resimulate Milky Way-like halos from large cosmological volume.



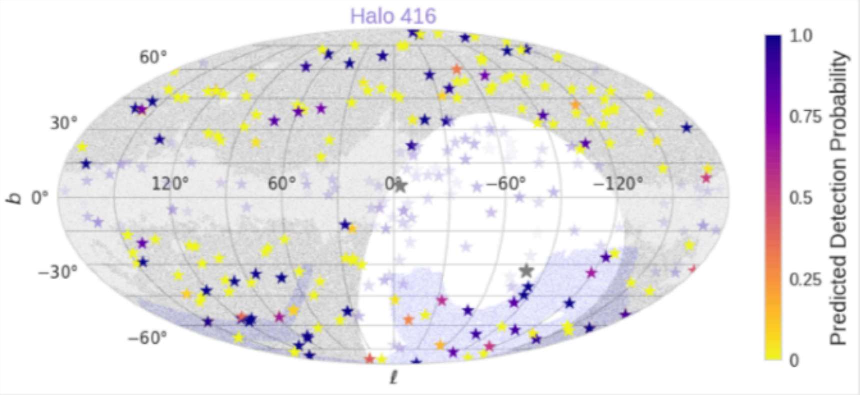


2. Paint satellite galaxies onto subhalos using galaxy—halo model.

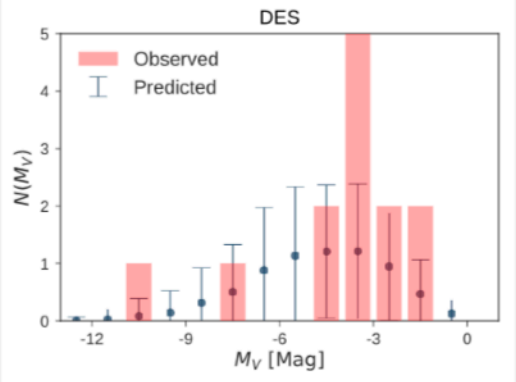


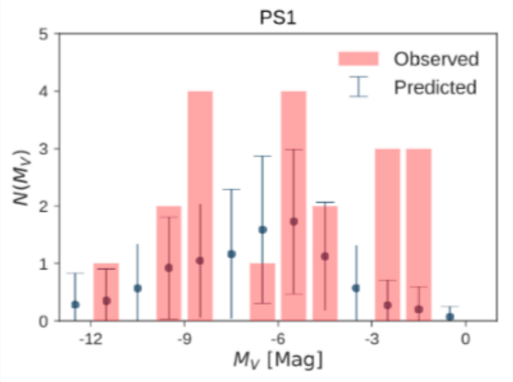


3. Apply observational selection effects based on imaging data.

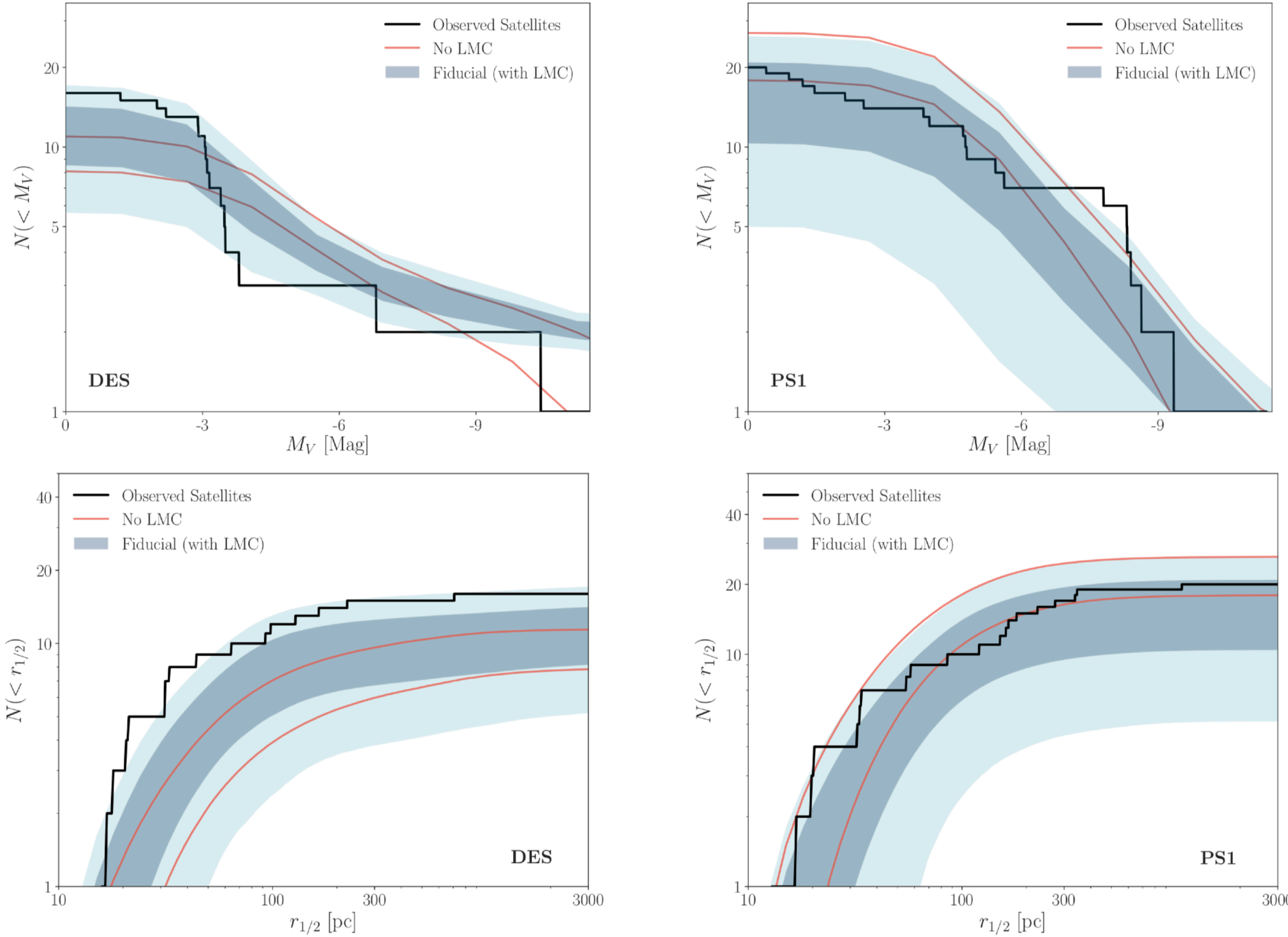


4. Calculate likelihood of observed satellites given galaxy—halo connection parameters.



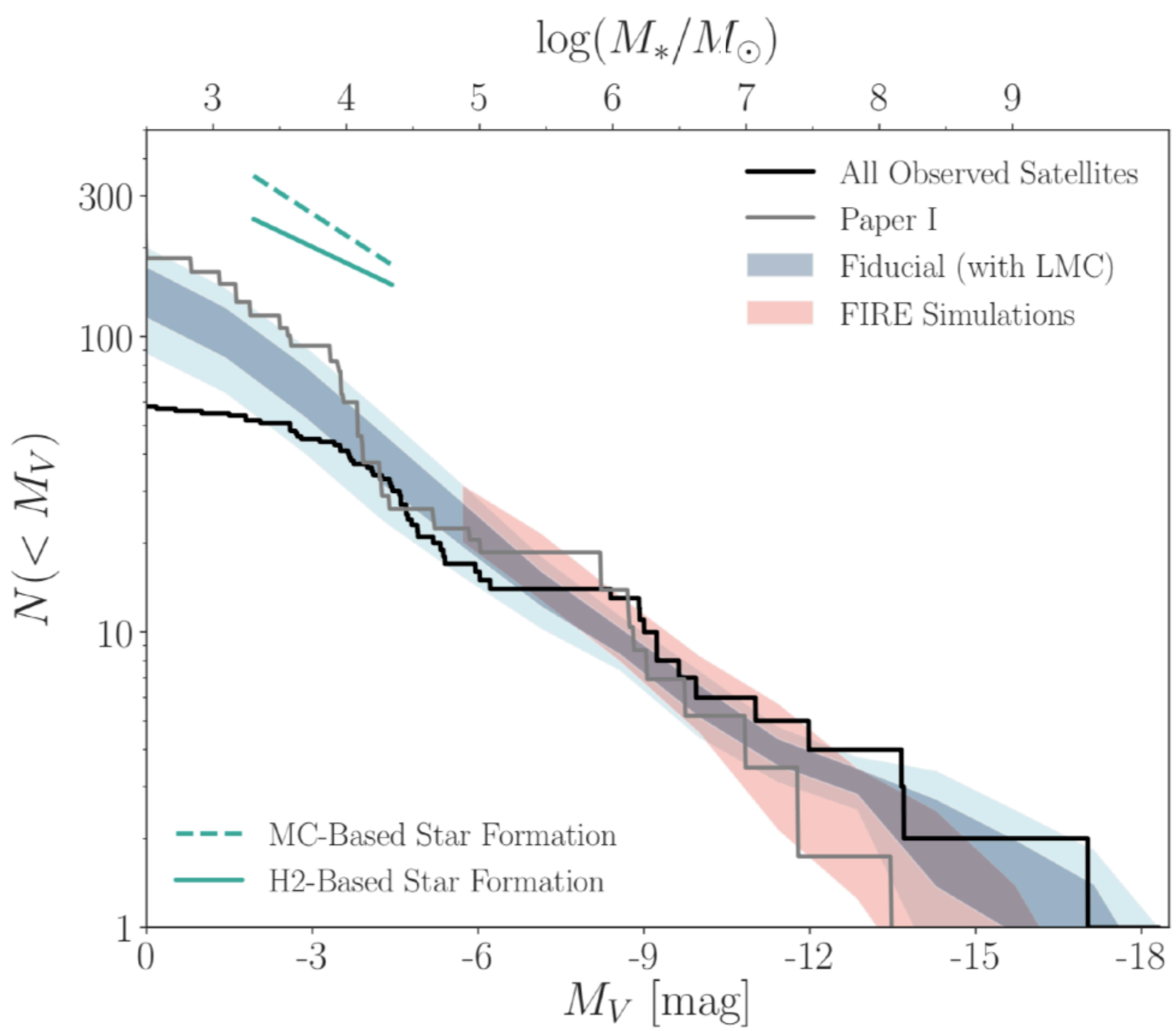


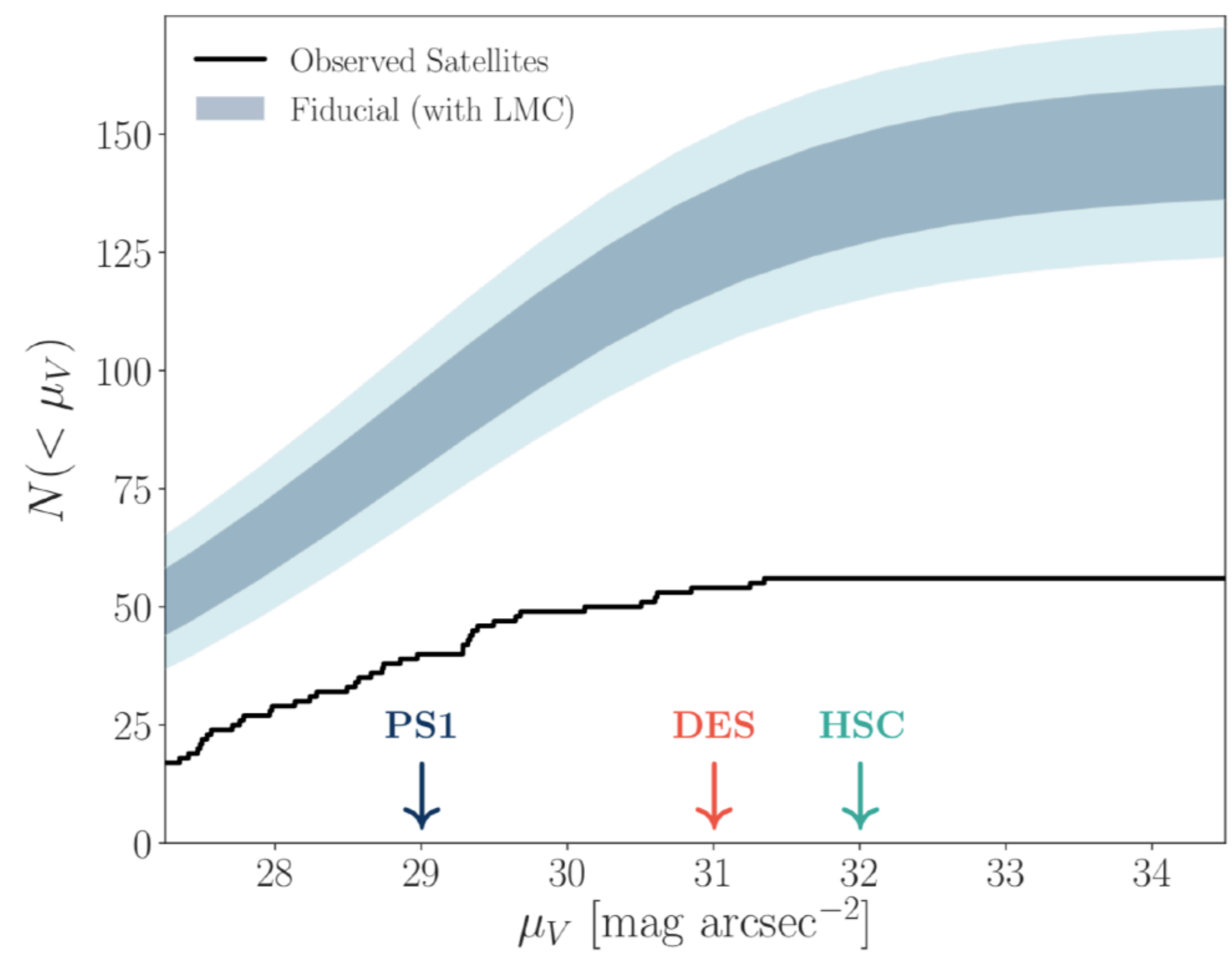
Luminosity and Size Distributions



The as yet Unseen Milky Way Satellite Population

Even with the doubling of known Milky Way satellites since 2015, the majority of Milky Way satellites remain hidden because they either contain **too few bright stars** or are **too low surface brightness**





144 ± 28 total within MW viral radius; ~100 undiscovered;
40 ± 8 satellites passed with LMC viral radius prior to infall on MW

Galaxy Occupation Model and Extreme Faint-end Luminosity Function

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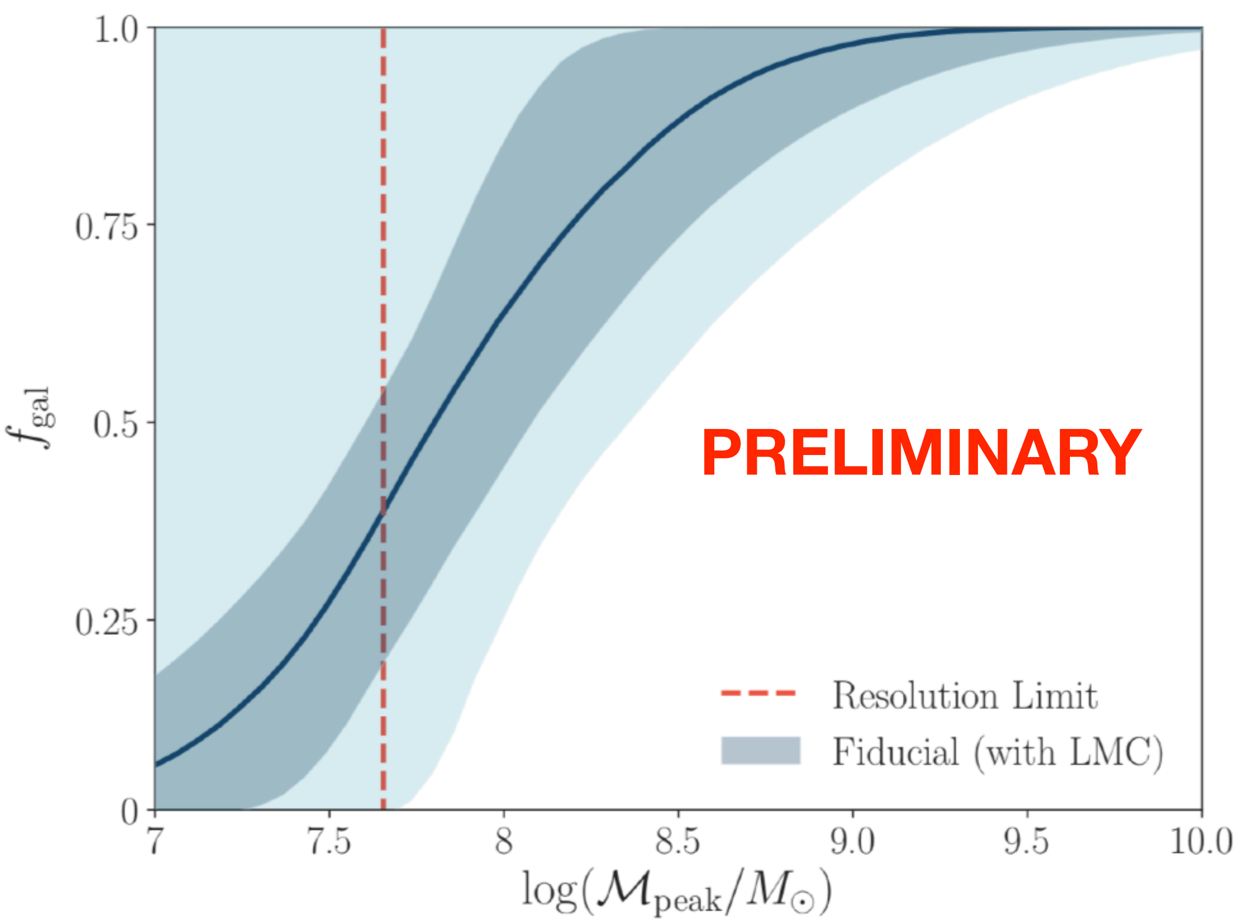
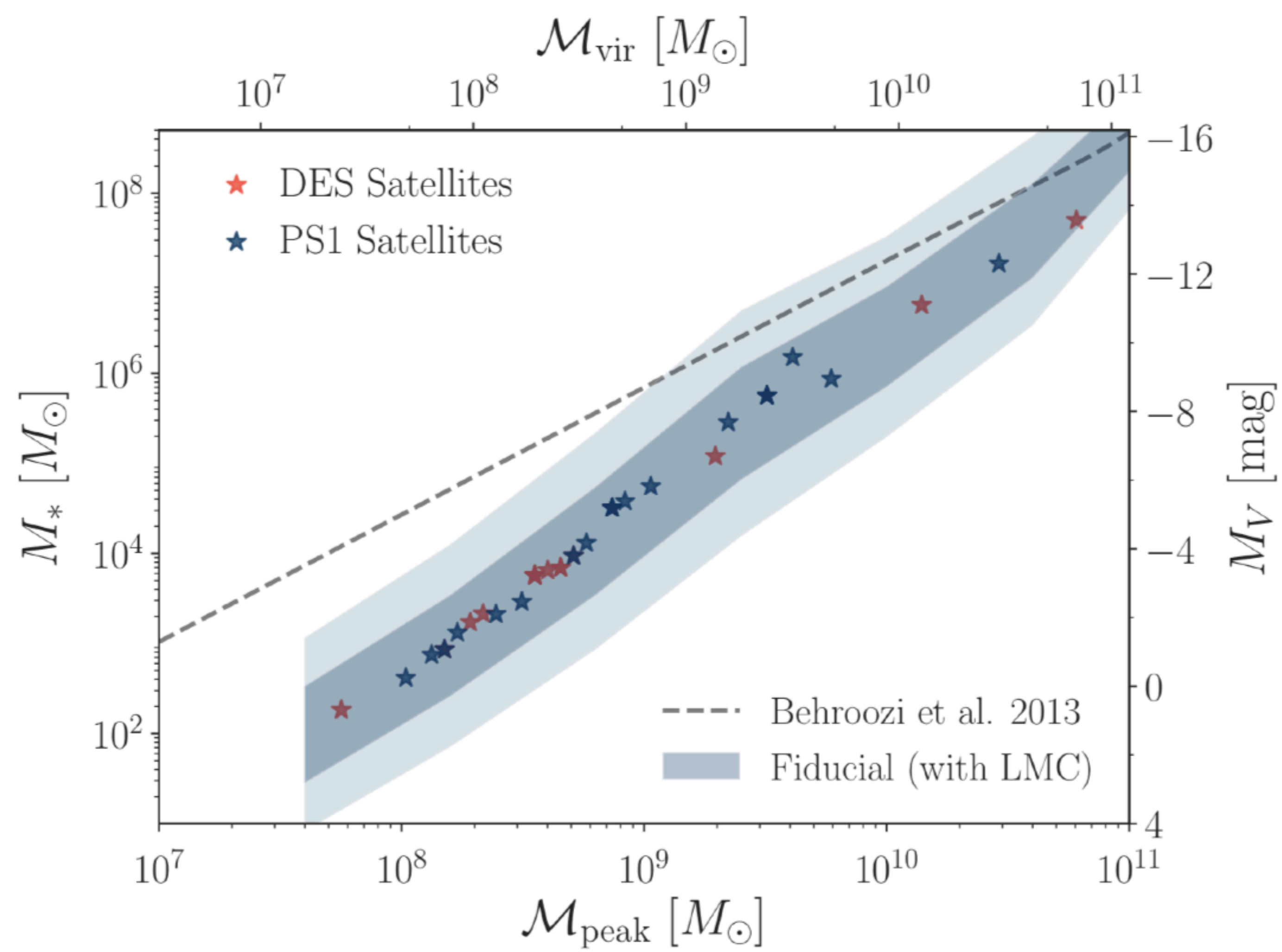
Galaxy Occupation



Faint-end Luminosity Function



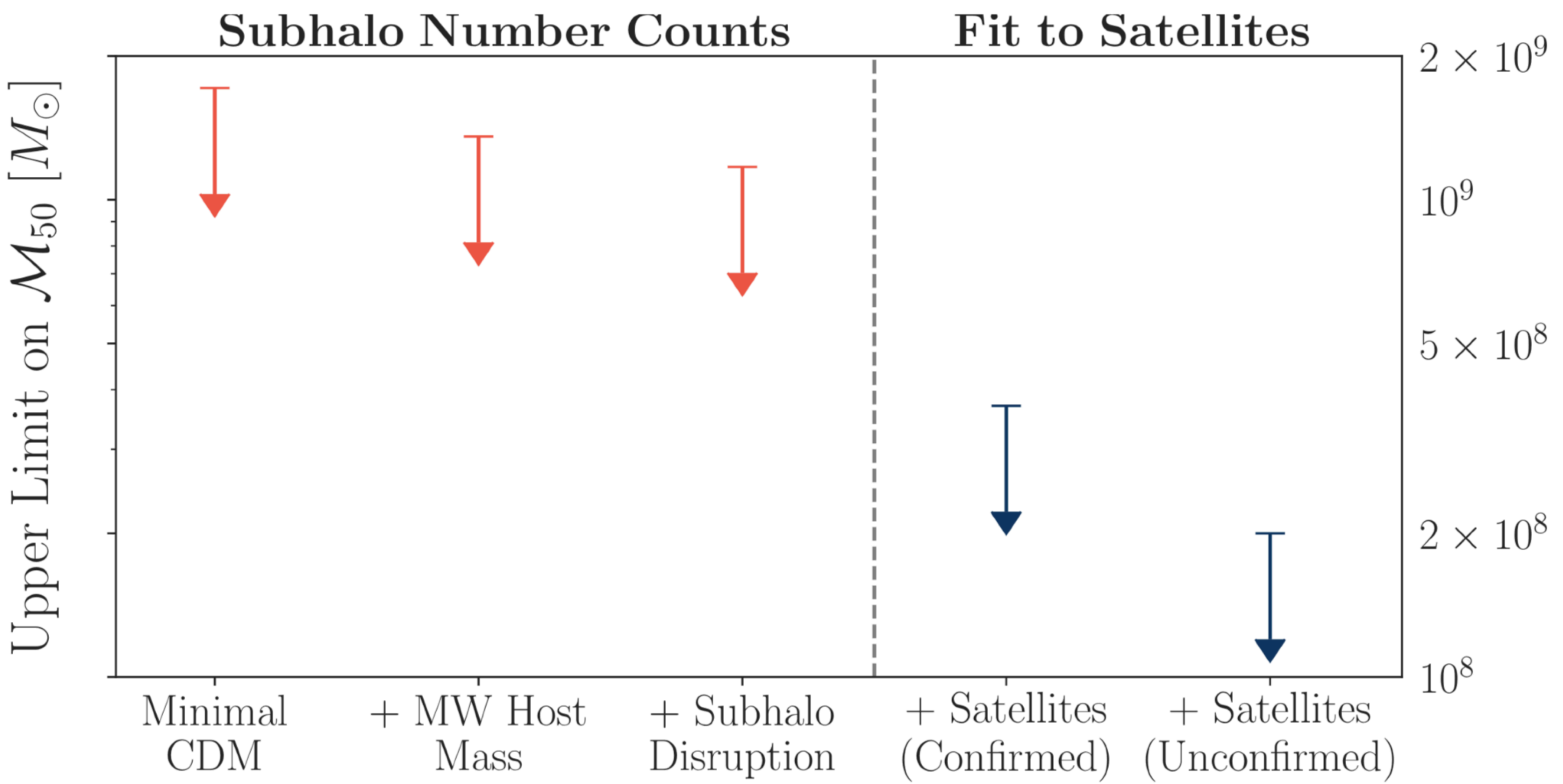
M_{min} < 2 x 10^8 $M_\odot$ (95% CL)

v_{peak} < 20 km s^{-1} (95% CL)

Detected MW satellites likely occupy halos of mass M_{peak} 10^8 $M_\odot$ (95% CL)

Theoretical Uncertainties

Scenario with no-scatter abundance matching and no baryonic tidal disruption gives conservative upper bound on minimum halo mass (but poor quality fit to data)



Gains in sensitivity to minimum halo mass largely from modeling of the observational selection function and galaxy-halo connection

Decisive Statistical Evidence that…

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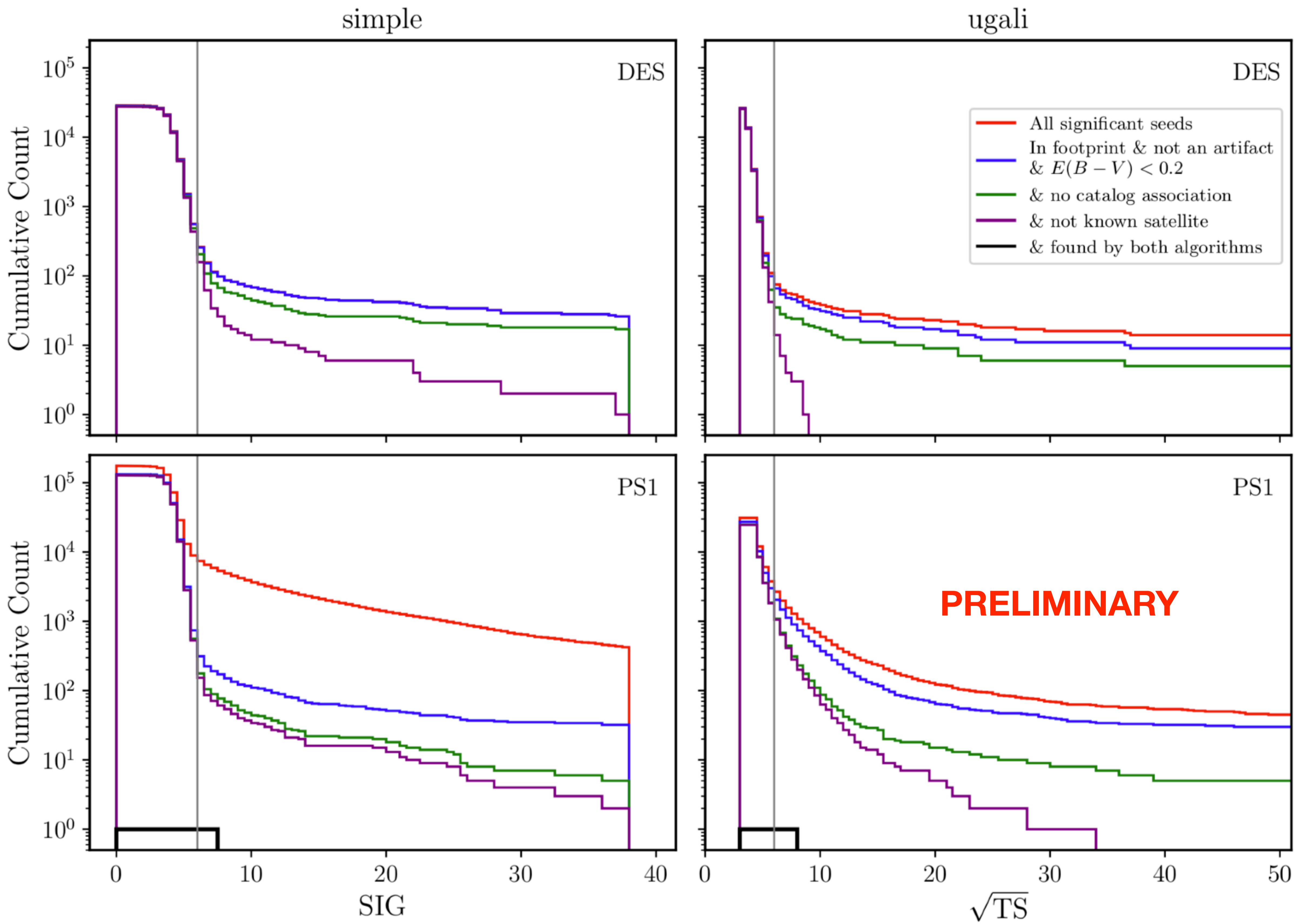
- The LMC impacts the observed MW satellite population, contributing 5.4 ± 1.3 (1.6 ± 0.5) LMC-associated satellites to the observed DES (PS1) samples
  - *Hierarchical structure formation on the scale of dwarf galaxies*
- The LMC fell into the MW within the last 2 Gyr
  - *Consistent with Gaia proper motions for MW satellites*
- Some of the faintest known satellites occupy halos with peak viral masses below 2 x 10^8 $M_\odot$ (95% CL)
  - *Approaching the atomic cooling limit v_{peak} ~ 20 km s^{-1}*
  - *Constraints on dark matter microphysics from minimum halo mass comparable to those from Lyman-α forest and strong lensing*
- The faintest detectable satellites occupy halos with peak viral masses above 10^6 $M_\odot$
  - *Gravity-only techniques will be needed to push to lower masses*

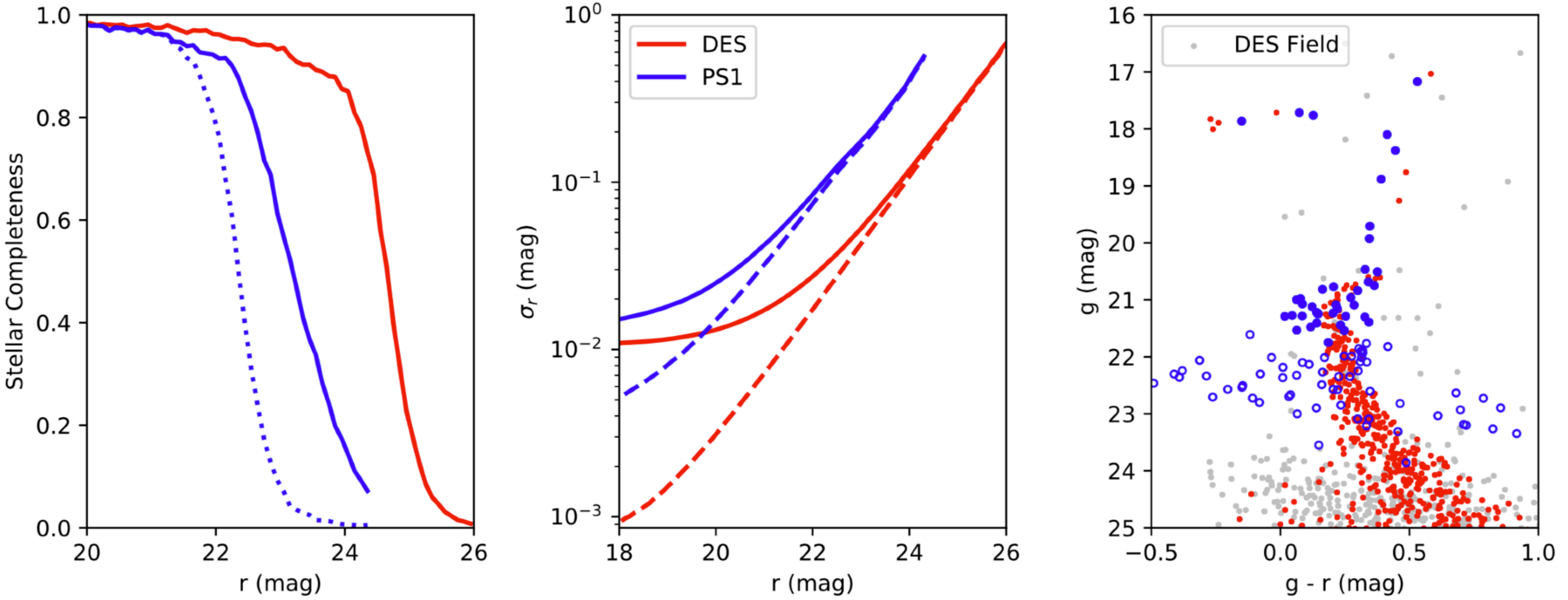
See talk by Ethan Nadler Monday morning for further dark matter interpretation

Extras

Significance Distributions and Candidate Selection Criteria



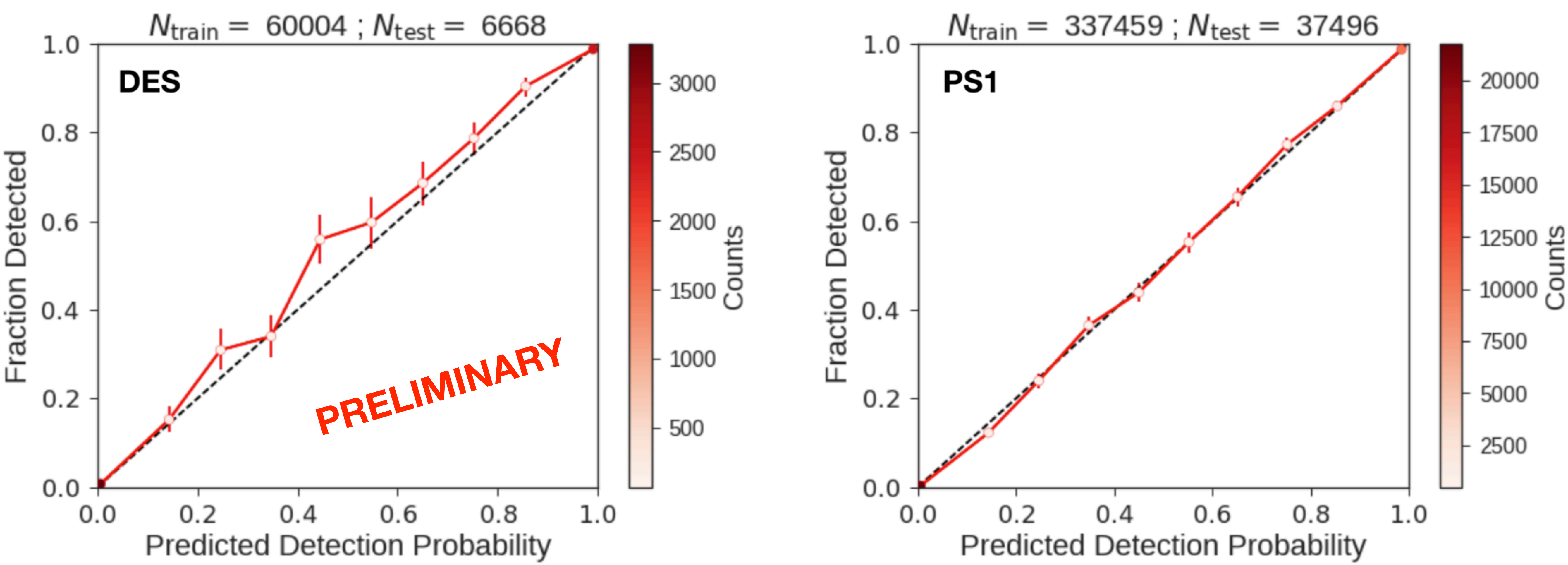
Example Simulated Satellite



PRELIMINARY

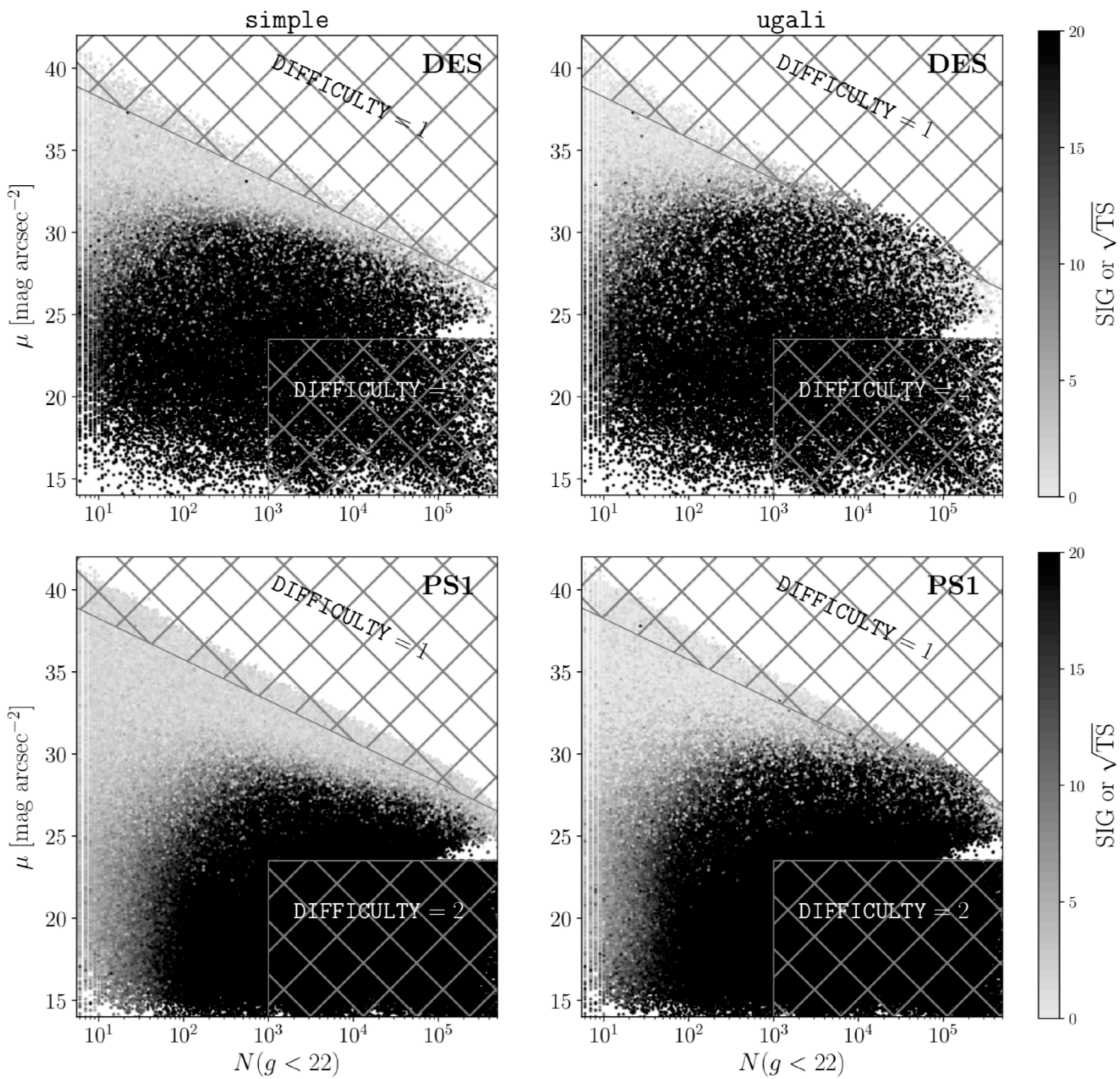
Survey Selection Function: Predicting Satellite Detectability

Use machine learning approach to accurately predict the detectability of a satellite given intrinsic structural properties and position (including survey conditions)



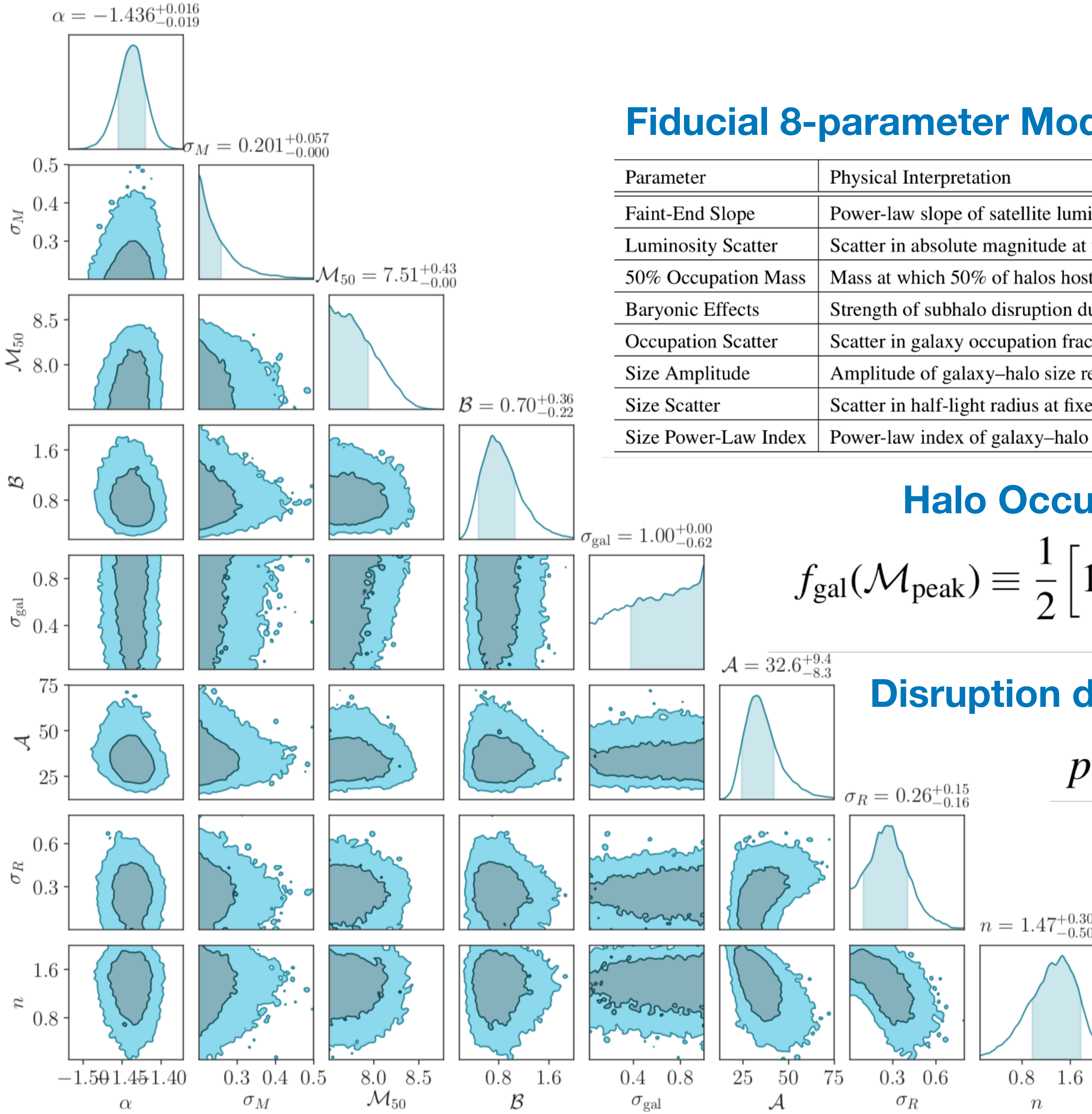
Plan to publicly release the full DES + PS1 survey selection function to facilitate theory comparisons

Recovery of Simulated Satellites



Inject and analyze >1 M simulated satellites using identical pipeline as real data

# of bright stars (flux) and **surface brightness** are two most important features to predict detectability



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Fiducial 8-parameter Model

Parameter	Physical Interpretation	95% Confidence Interval
Faint-End Slope	Power-law slope of satellite luminosity function.	$-1.47 < \alpha < -1.4$
Luminosity Scatter	Scatter in absolute magnitude at fixed $V_{\rm peak}$.	0.2 dex$^* < \sigma_{\rm M} < 0.32$ dex
50% Occupation Mass	Mass at which 50% of halos host galaxies.	$7.5^* < \log(\mathcal{M}_{50}/M_\odot) < 8.27$
Baryonic Effects	Strength of subhalo disruption due to baryons.	$0.26 < \mathcal{B} < 1.54$
Occupation Scatter	Scatter in galaxy occupation fraction.	0 dex$^* < \sigma_{\rm gal} < 1$ dex*
Size Amplitude	Amplitude of galaxy–halo size relation.	16 pc $< \mathcal{A} < 55$ pc
Size Scatter	Scatter in half-light radius at fixed halo size.	0 dex$^* < \sigma_{\rm R} < 0.6$ dex
Size Power-Law Index	Power-law index of galaxy–halo size relation.	$0.4 < n < 2^*$

Halo Occupation Model

$$f_{\rm gal}(\mathcal{M}_{\rm peak}) \equiv \frac{1}{2}\left[1+\mathrm{erf}\left(\frac{\mathcal{M}_{\rm peak}-\mathcal{M}_{50}}{\sqrt{2}\sigma_{\rm gal}}\right)\right]$$

Disruption due to Baryonic Effects

$$p_{\rm disrupt} \equiv (p_{\rm disrupt,0})^{1/\mathcal{B}}$$

Size Model

$$r_{1/2} \equiv \mathcal{A}\left(\frac{R_{\rm vir}}{R_0}\right)^n$$

PRELIMINARY

By Measuring **Where** Dark Matter Is, We Find Out **What** It Is

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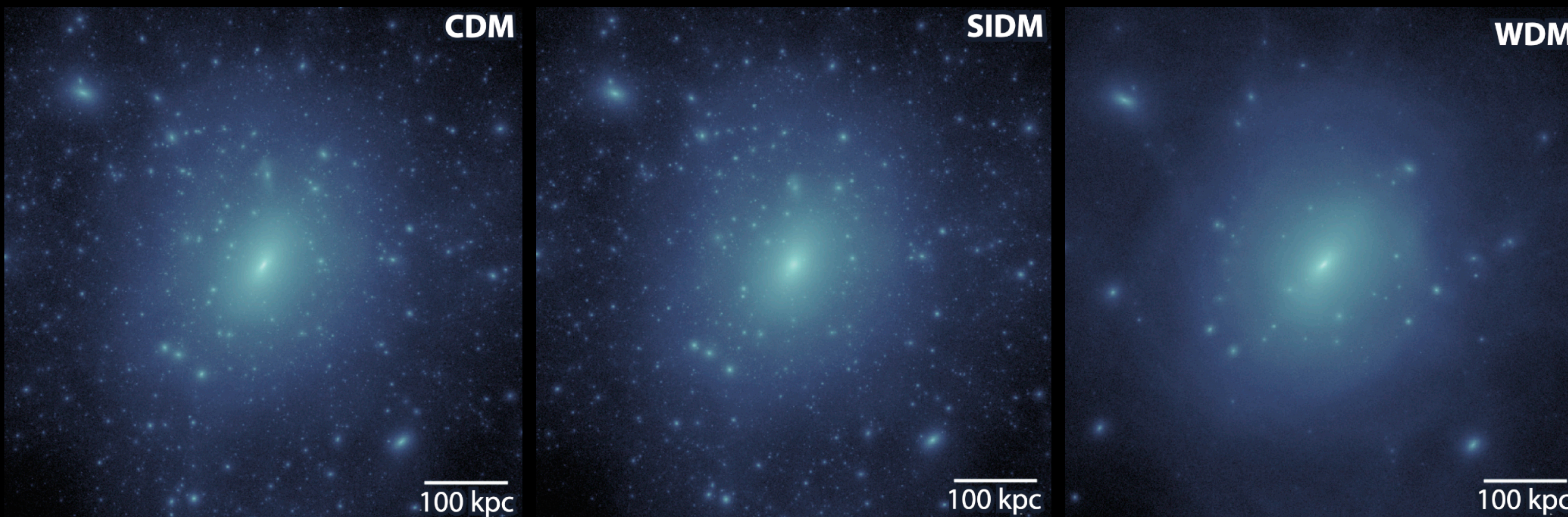
Cold Dark Matter | **Self-Interacting Dark Matter** | **Warm Dark Matter**



Cored Density Profiles (Self-Interacting Dark Matter)

Fewer Substructures (Warm Dark Matter)

Reviewed by Bullock & Boylan-Kolchin 2017

Don’t Forget the Baryons…

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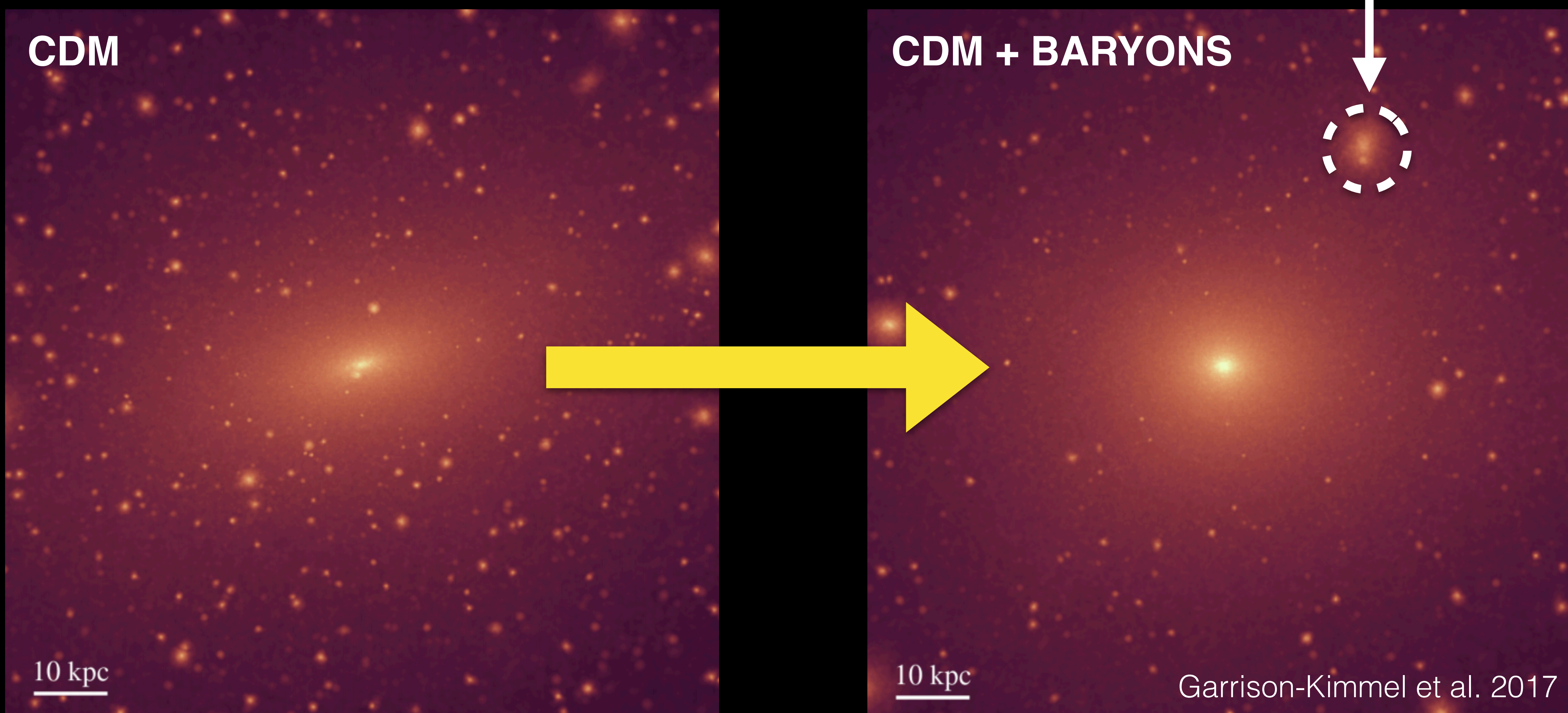
Rich galaxy formation physics to explore at small scales, e.g., reionization, feedback, tidal disruption.



Galaxy-Halo Connection Reference Model

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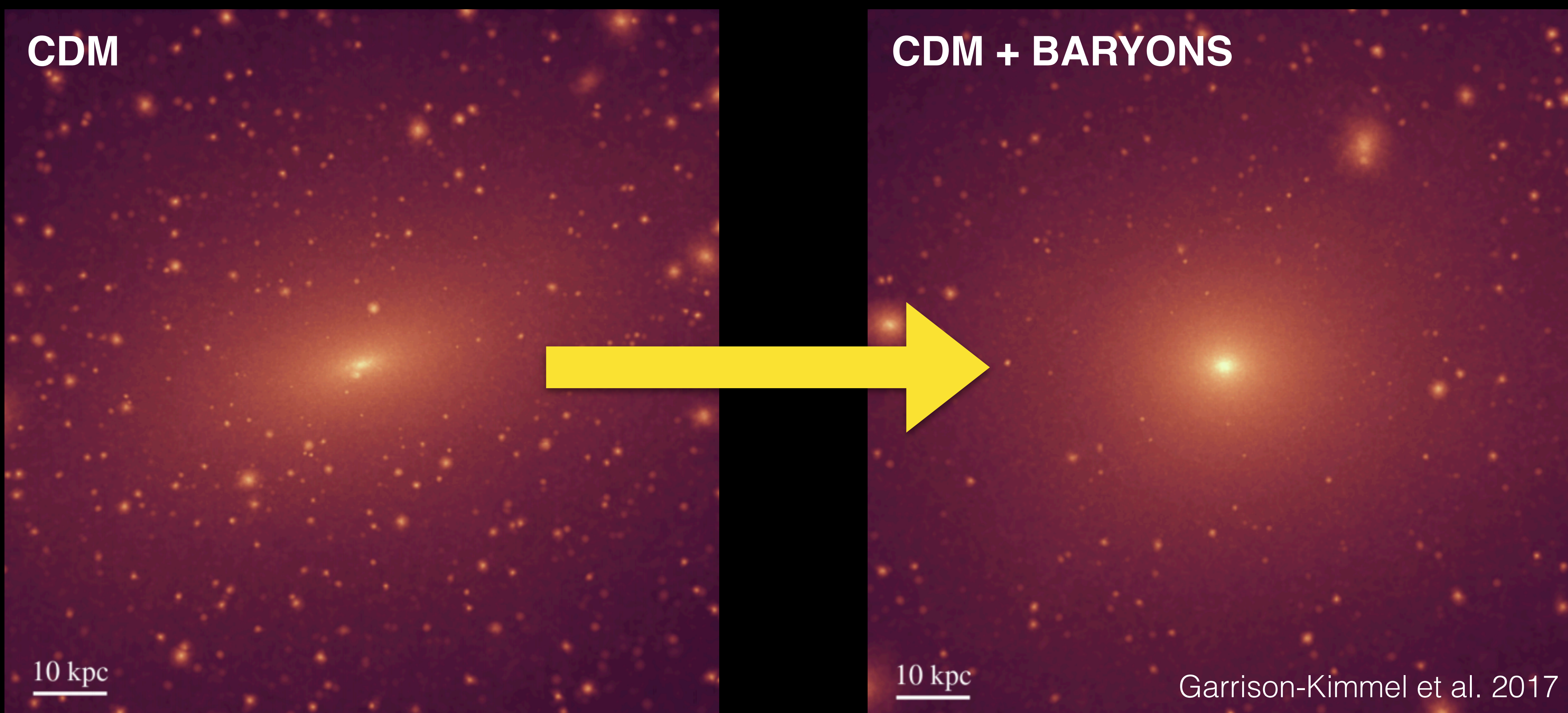
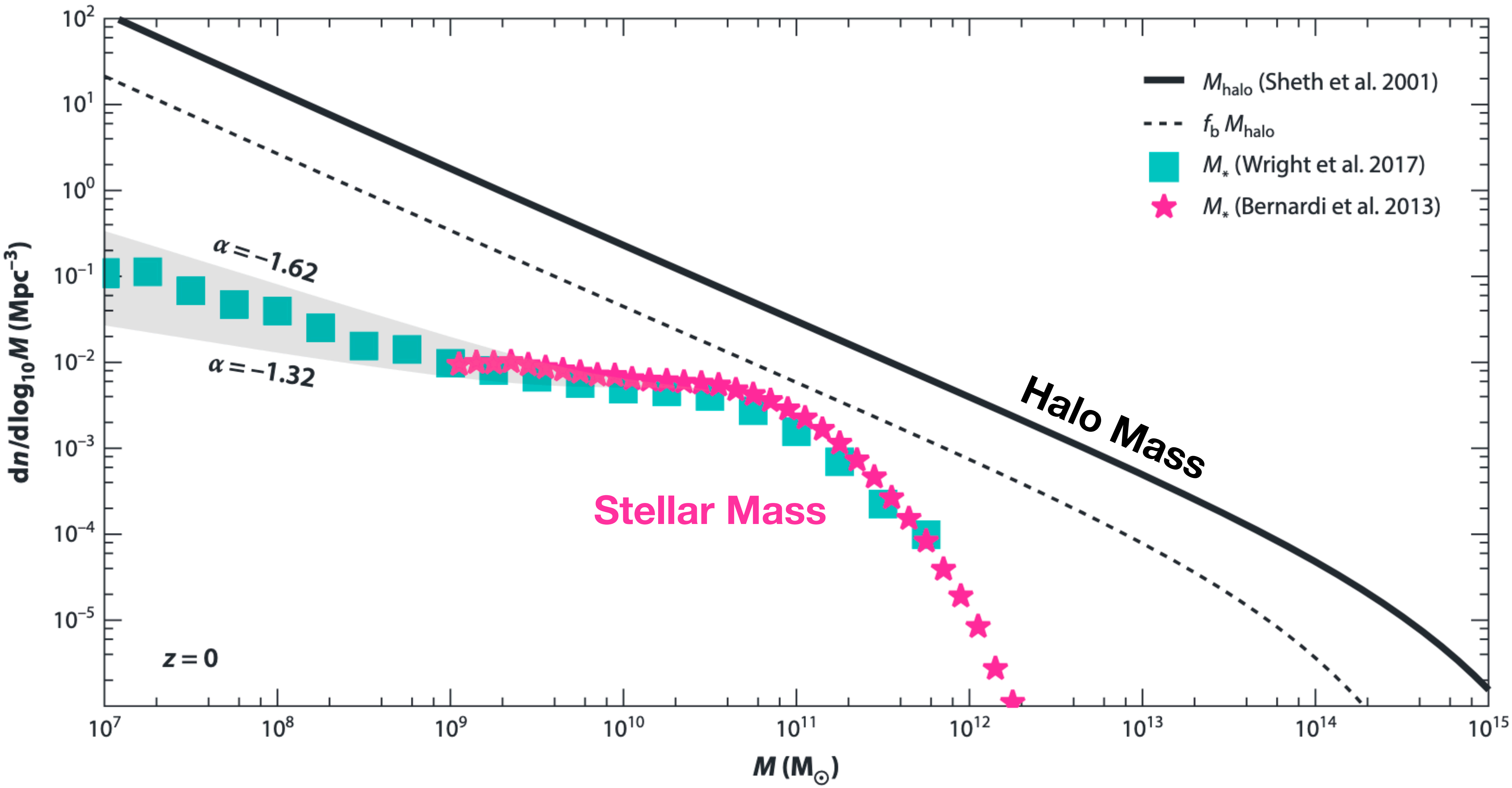
Use suite of zoom-in N-body simulations for sufficient statistics. Train on hydrodynamical simulations (FIRE) to account for baryonic effects, including halo disruption in the presence of Milky Way disk. See Nadler et al. 2019 (arXiv:1809.05542) for details.



Galaxy-Halo Connection

Abundance Matching (simplified):

The most massive galaxies (stars) live in the most massive dark matter halos



Bullock & Boylan-Kolchin 2017

Galaxy-Halo Connection

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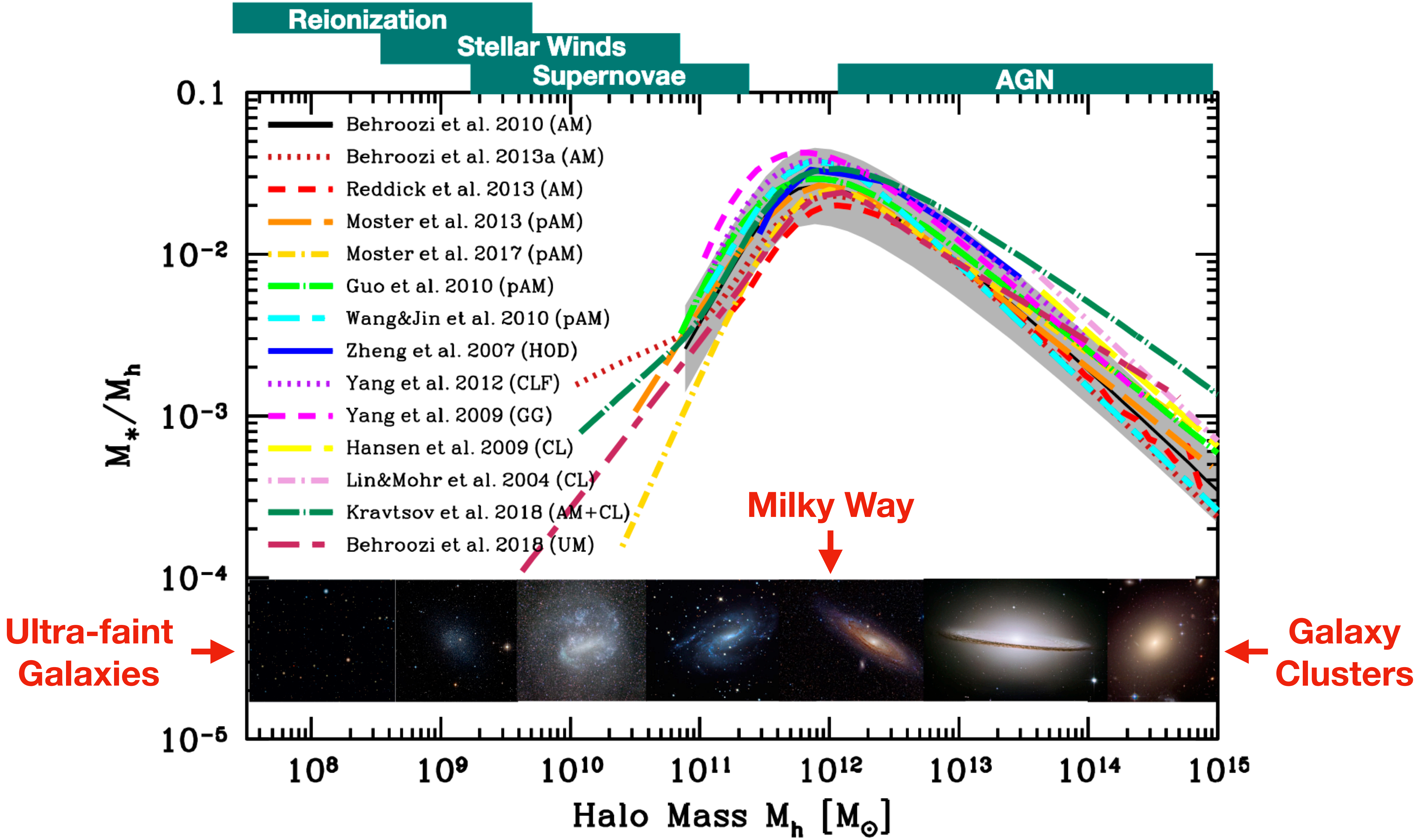
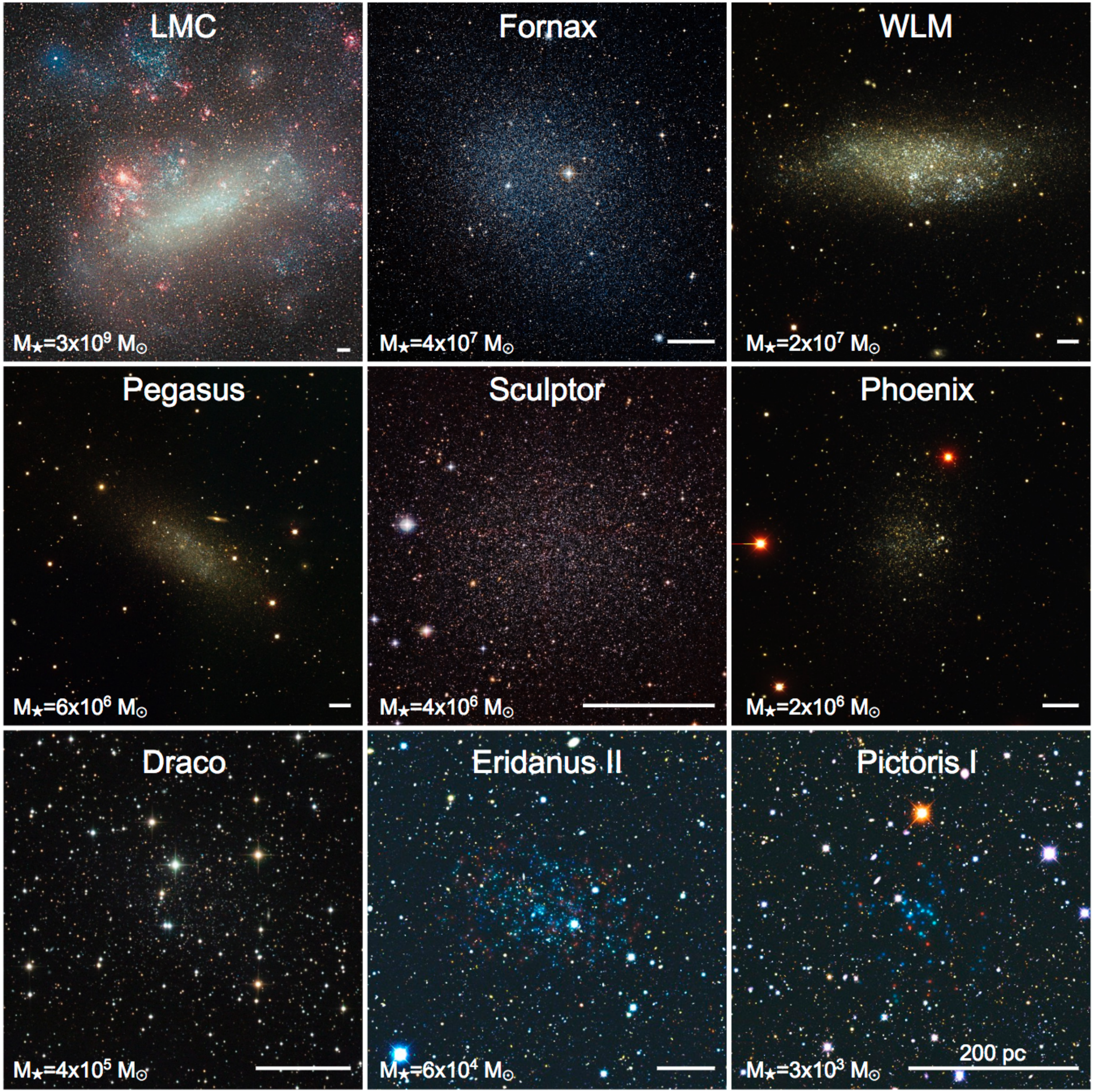


Wechsler & Tinker 2018
arXiv:1804.03097



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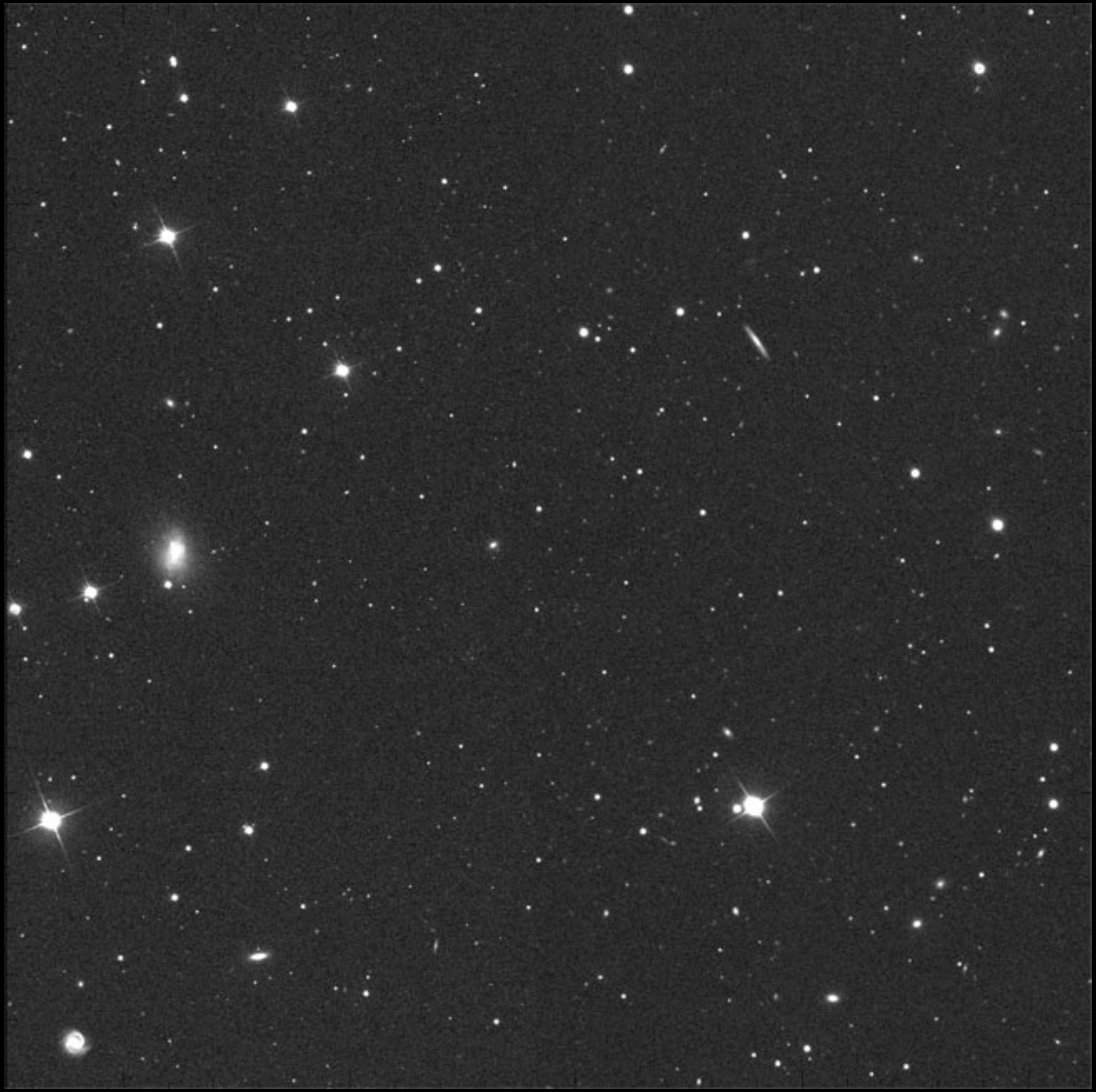
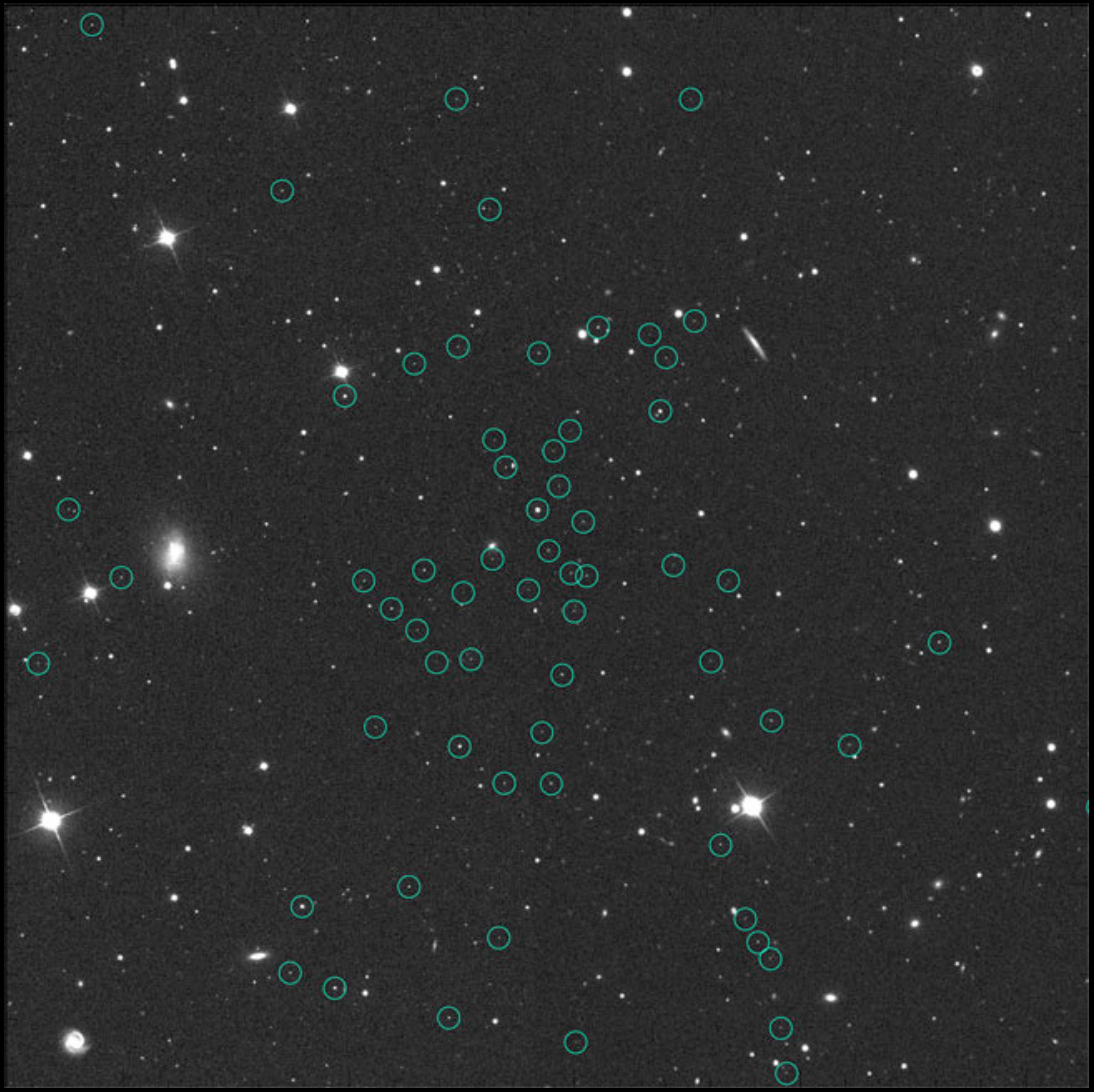
Bullock & Boylan-Kolchin
2017
arXiv:1707.04256



Segue 1

$M_{☆} = \sim 300\ M_{\odot}$

Credit: Marla Geha

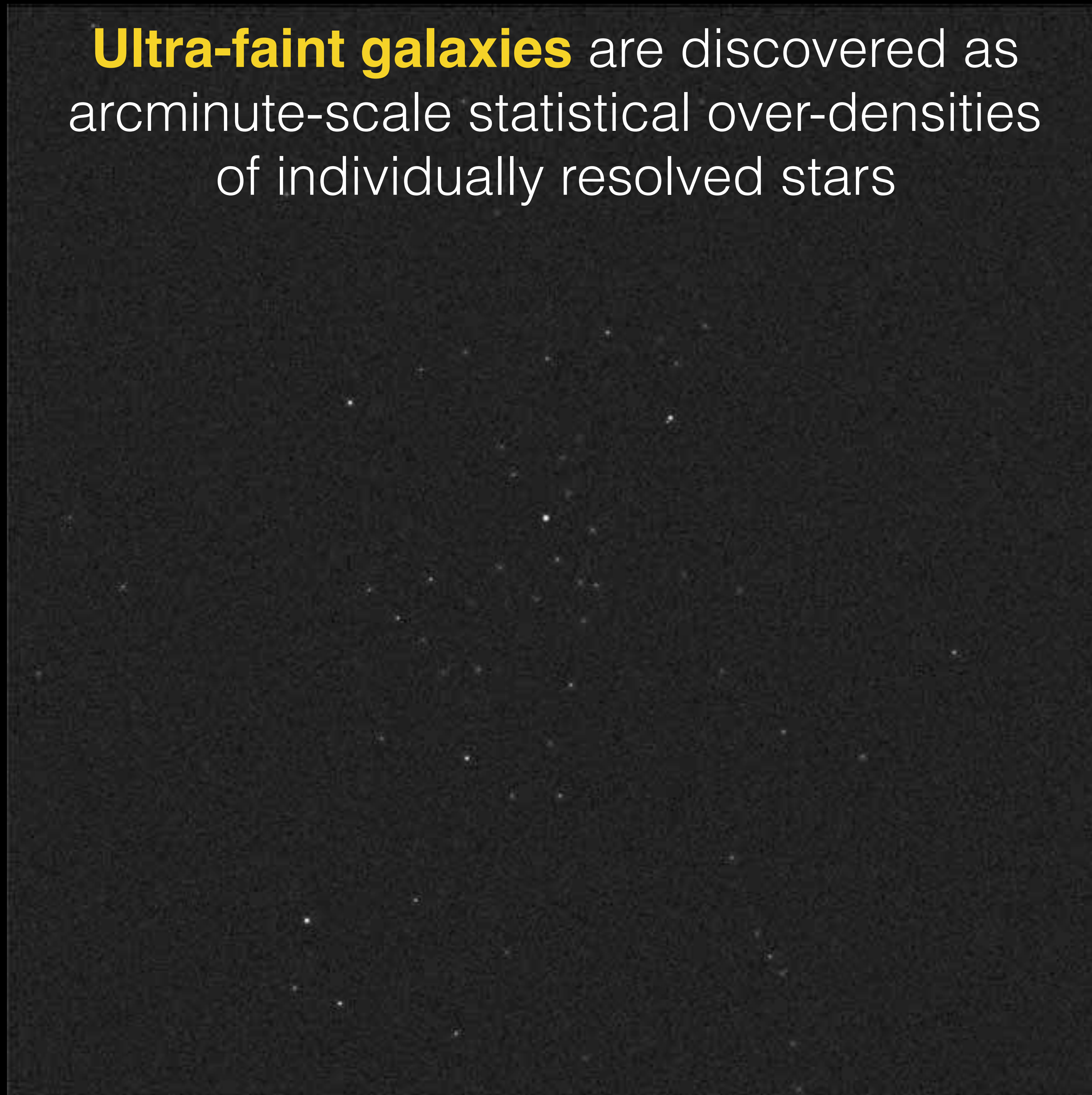


Segue 1

$M_☆$ = ~300 $M_⊙$

Credit: Marla Geha

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



Segue 1

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

Credit: Marla Geha