Revealing the Threshold of Galaxy Formation with a Census of Milky Way Satellites Over 3/4 of the Sky

Keith Bechtol

on behalf of the DES Collaboration

ICRC

31 July 2019

THE DARK ENERGY SURVEY

THE UNIVERSITY of WISCONSIN MADISON

Galaxy-Halo Connection for the Darkest Galaxies

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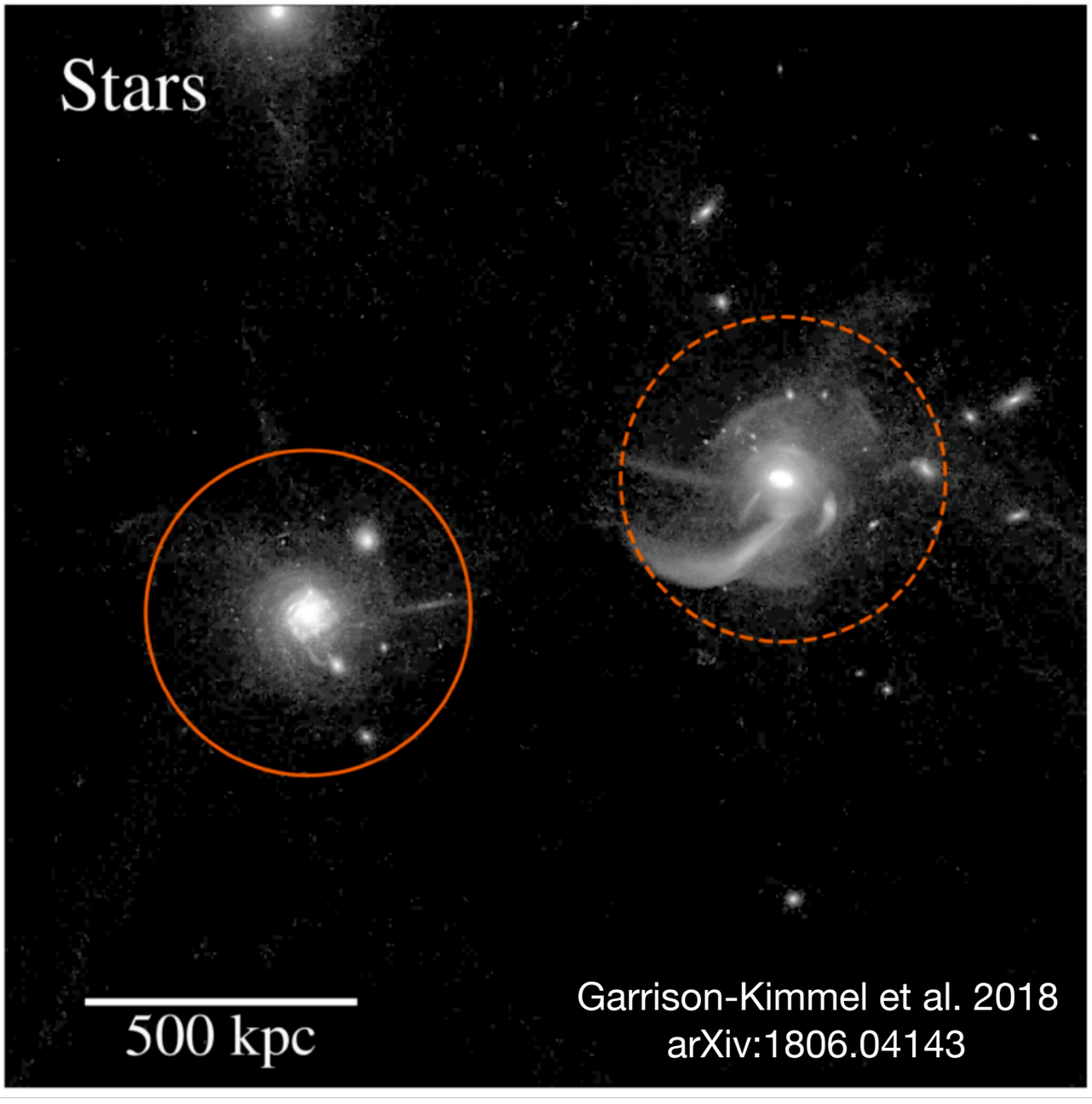
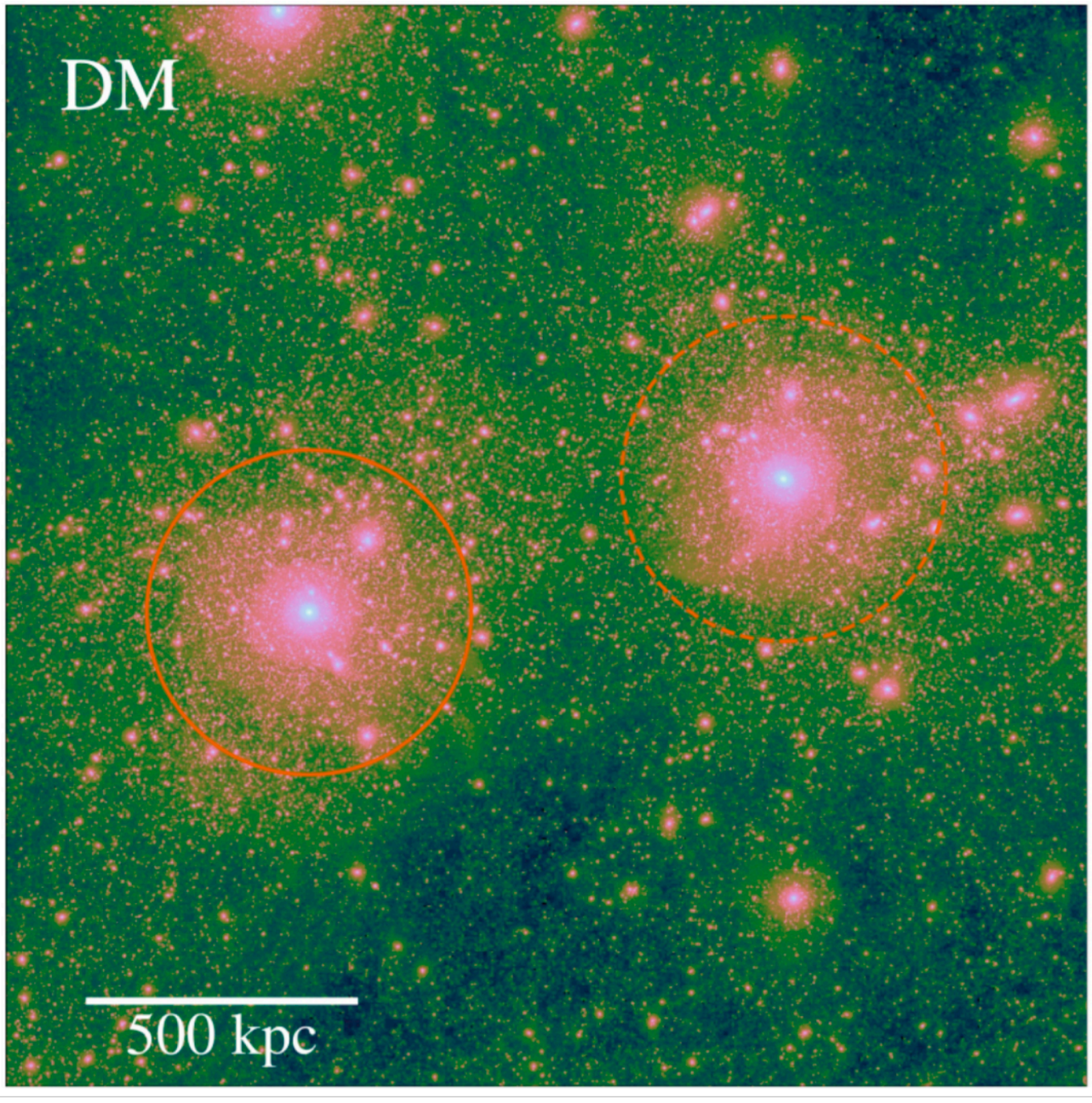
Observed Demographics of Milky Way Satellite Galaxies

Galaxy Formation Physics
Epoch of Reionization
Fundamental Nature of Dark Matter





Distribution of Dark Matter at “Sub-galactic” Scales

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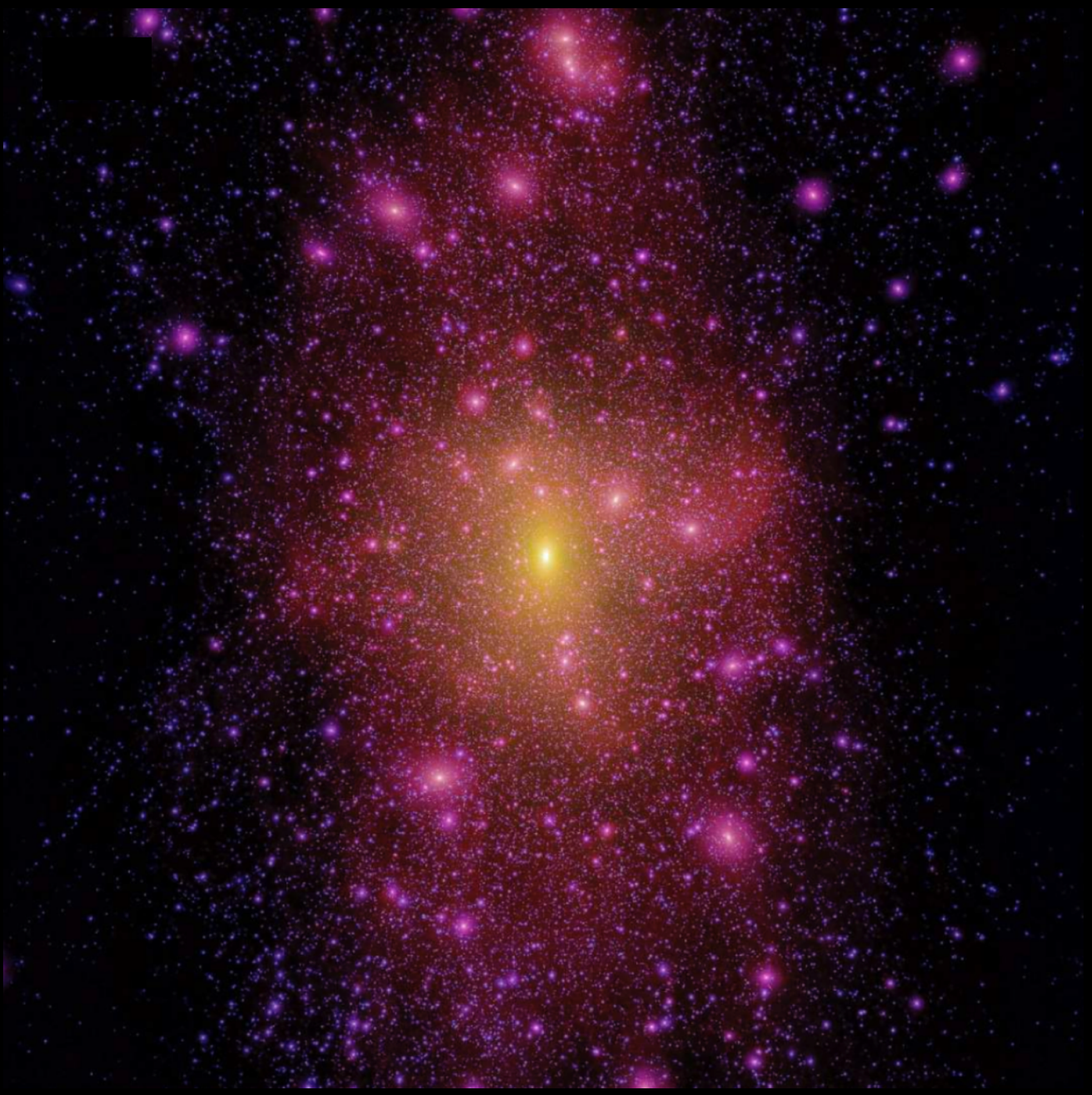
Lovell et al. 2012



Cold Dark Matter

Distribution of Dark Matter at “Sub-galactic” Scales

THE DARK ENERGY SURVEY

Lovell et al. 2012

Cold Dark Matter

Warm Dark Matter

Distribution of Dark Matter at "Sub-galactic" Scales

THE DARK ENERGY SURVEY

Lovell et al. 2012

Astrophysical probes of small-scale structure are sensitive to a wide range of dark matter models including

- warm dark matter
- self-interacting dark matter
- ultra-light boson dark matter (axions)
- baryon scattering dark matter
- decaying dark matter

Cold Dark Matter **Warm Dark Matter**

Dark Energy Survey (DES) Years 1-3 + Pan-STARRS (PS1)

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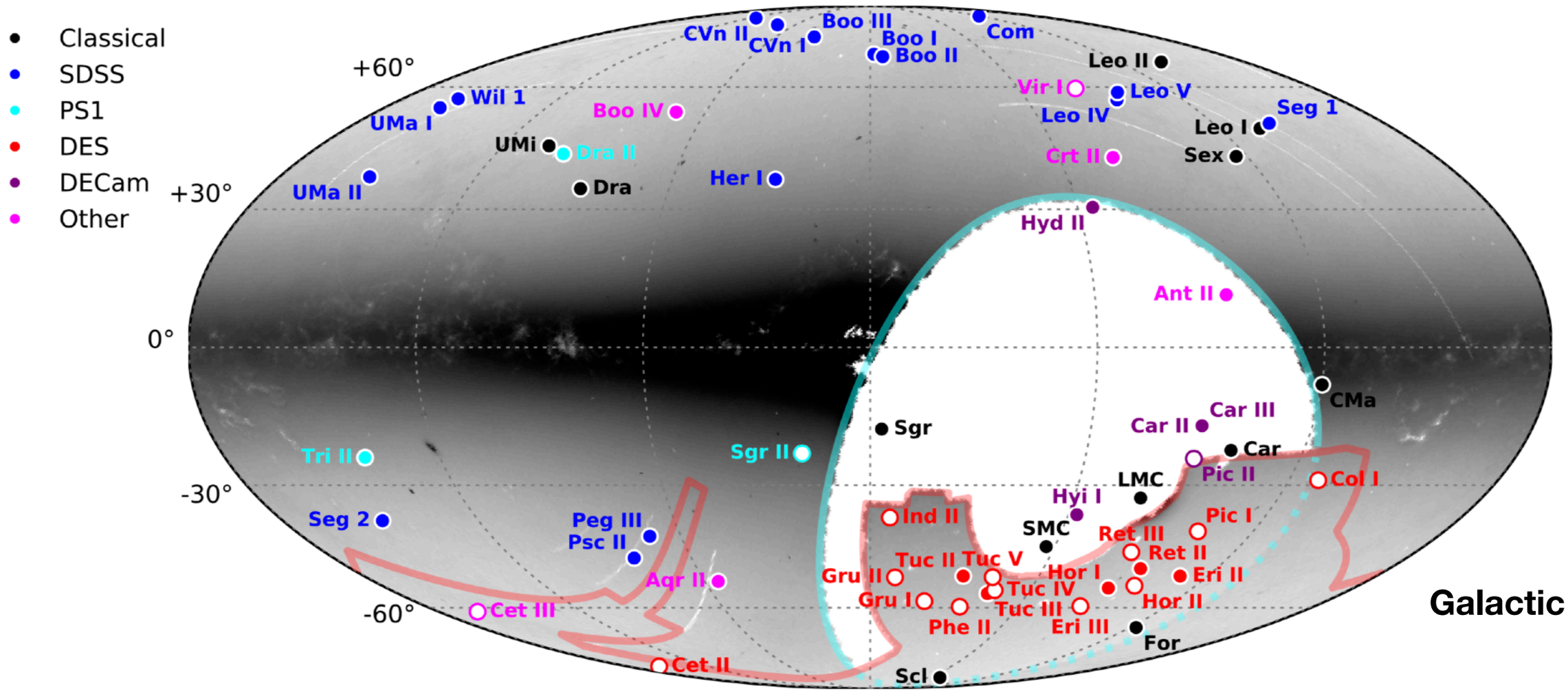
Deep optical imaging over nearly the entire high-Galactic-latitude sky



Sample of known Milky Way satellites has grown from ~25 to ~60 since 2015

Analysis Overview

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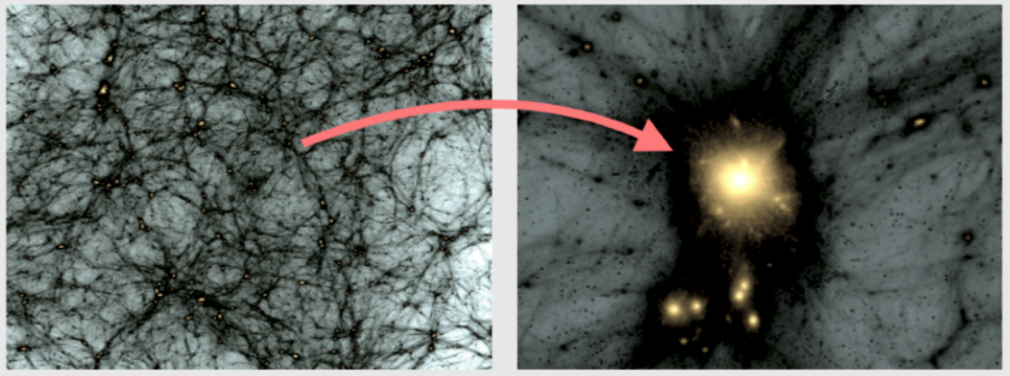
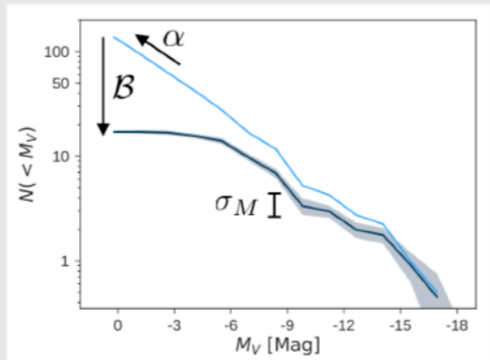
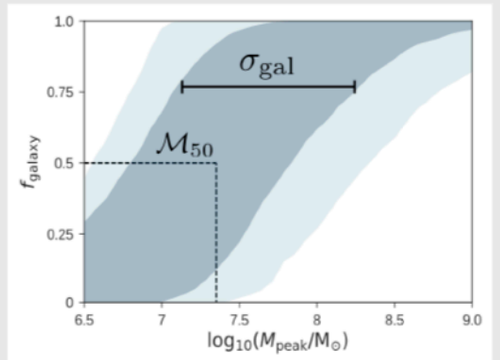
Markov Chain Monte Carlo

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

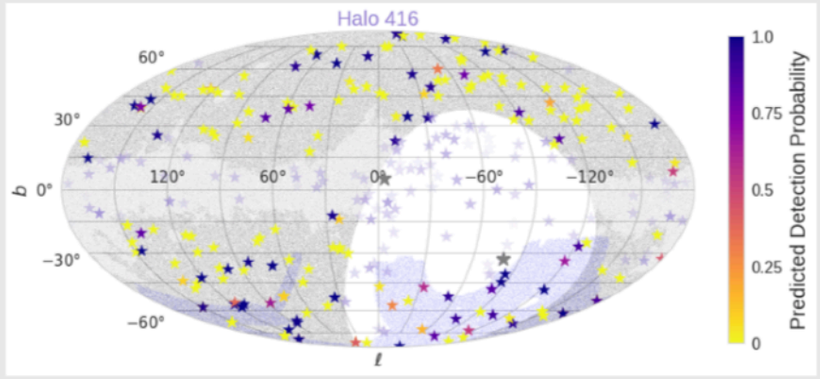


2. **Paint satellite galaxies onto subhalos using galaxy—halo model.**

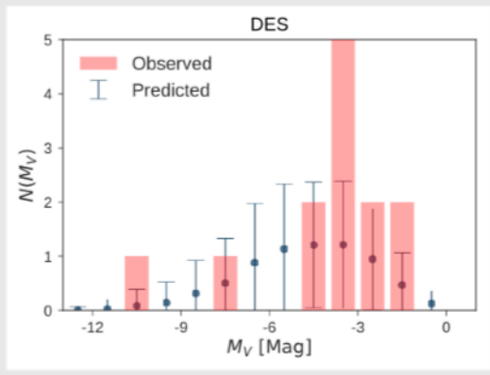


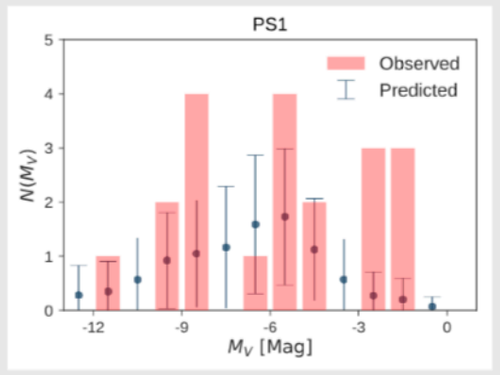


3. **Apply observational selection effects based on imaging data.**

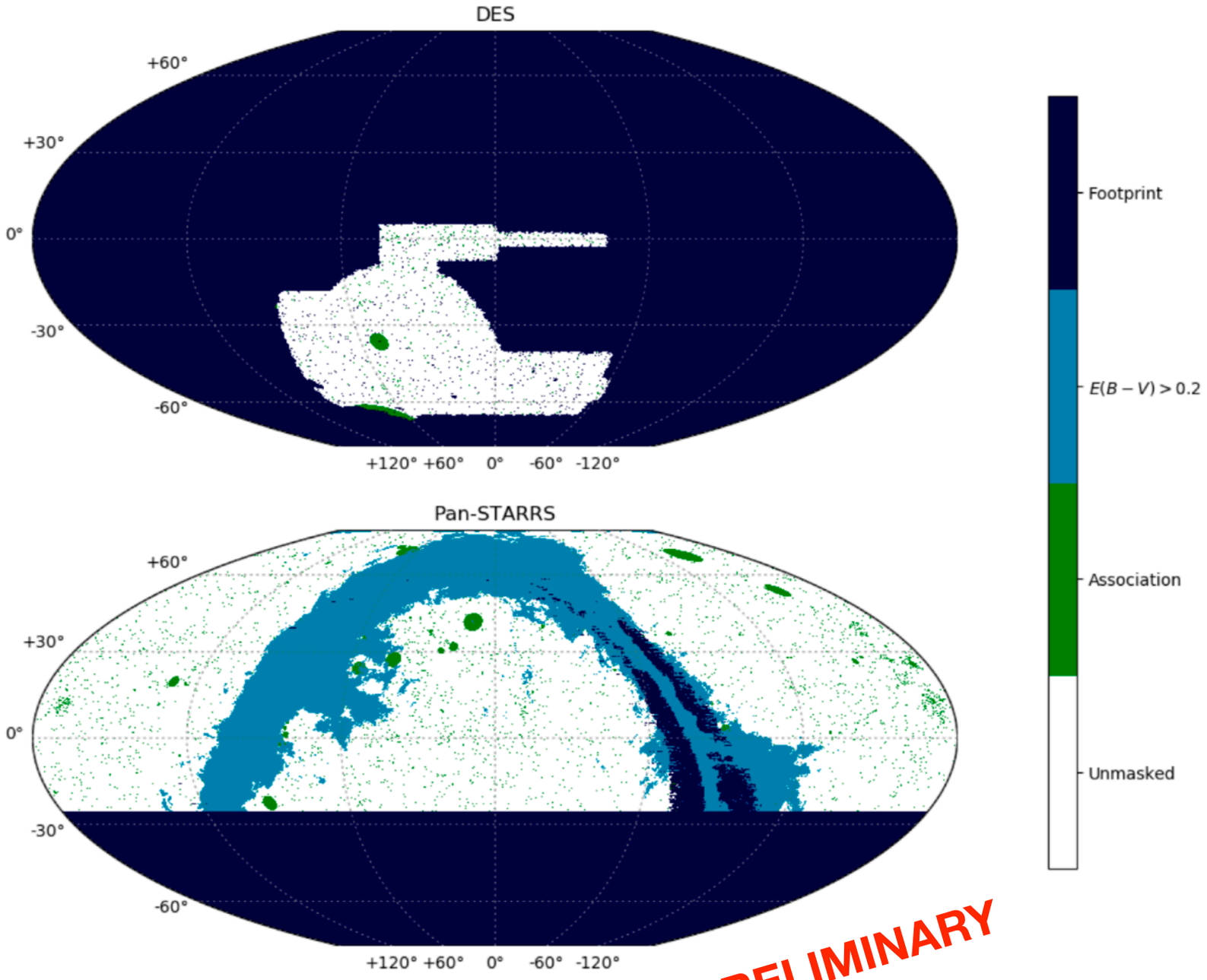


4. **Calculate likelihood of observed satellites given galaxy—halo connection parameters.**





DES + PS1 Sky Coverage and Survey Masks



PRELIMINARY

We find that the great majority of statistically significant “hot spots” are concentrated in problematic regions of the survey (e.g., high dust extinction, bright stars and galaxies).

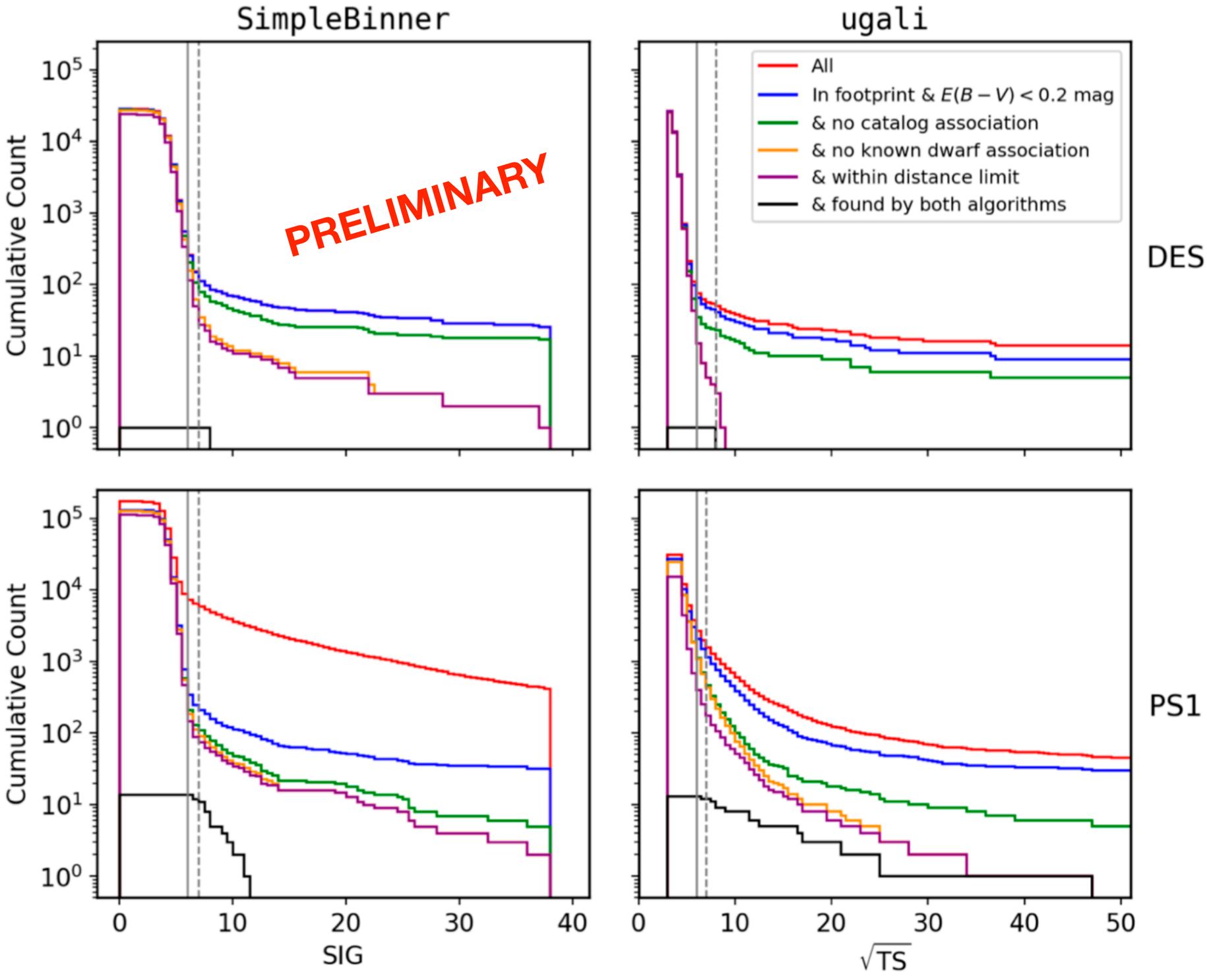
Apply a **geometric mask** based on reddening maps and external catalogs.

Search Results on Survey Data

With automated detection criteria, we **recover majority of published Milky Way satellites**

~10 unassociated “hot spots” remain — all are recognized as artifacts or other astrophysical objects

No new unpublished candidates above significance threshold



Search Results on Simulations: Detectability Parameter Space

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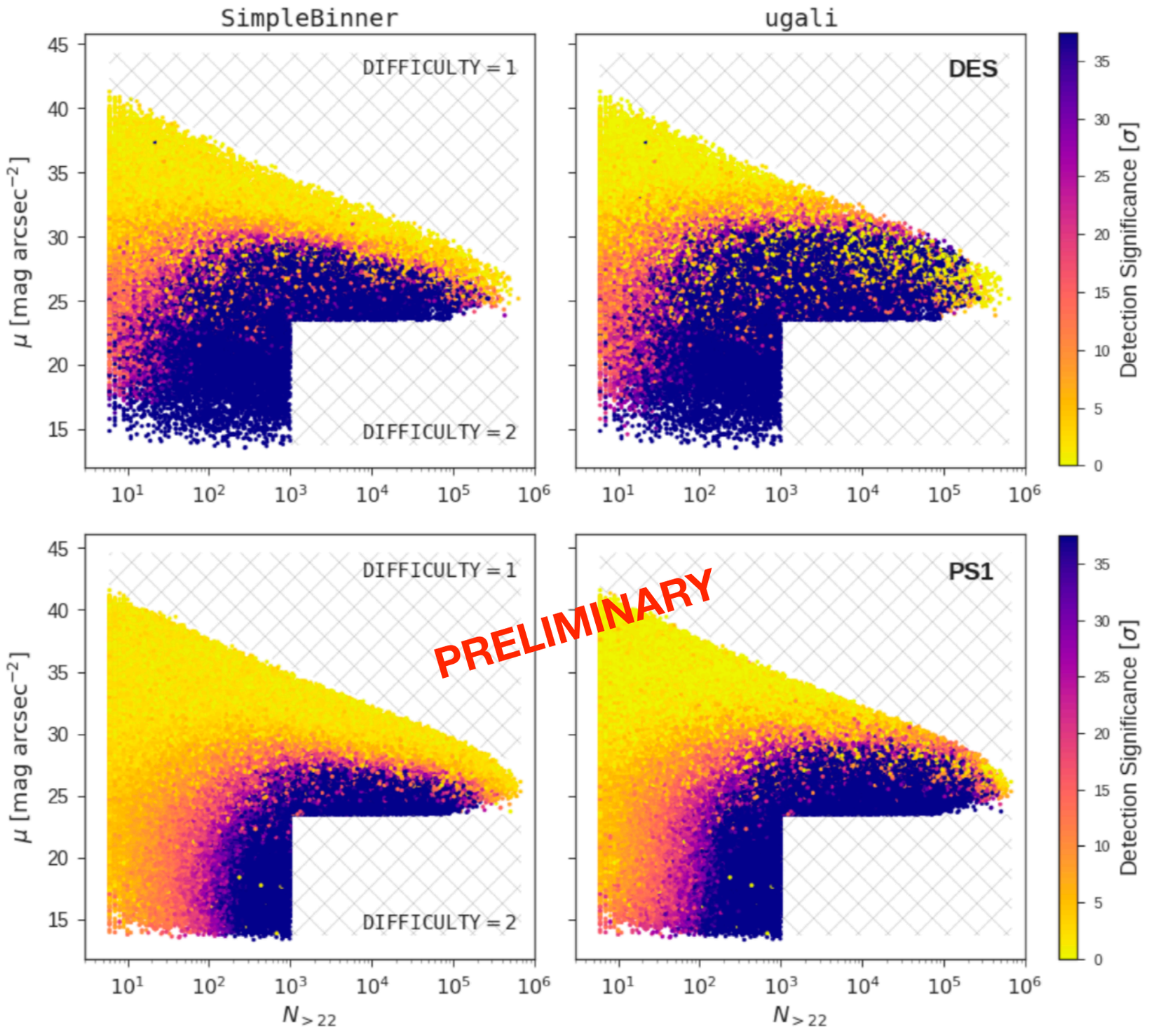
Clean separation of detectable and non-detectable satellites in parameter space of **# of bright stars (flux)** and **surface brightness**

These are most important features identified in training



High detection probability
Low detection probability

Survey Selection Function: Predicting Satellite Detectability

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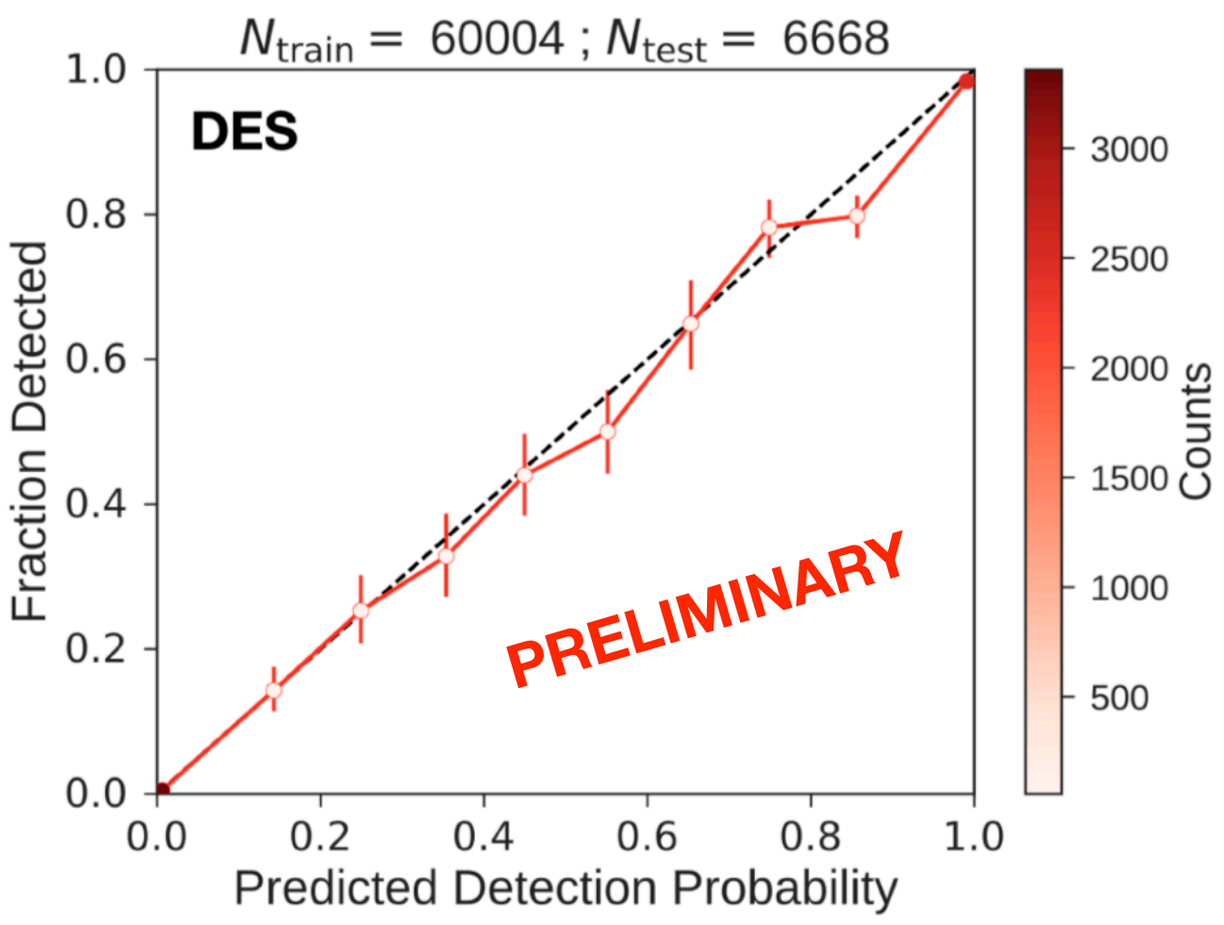
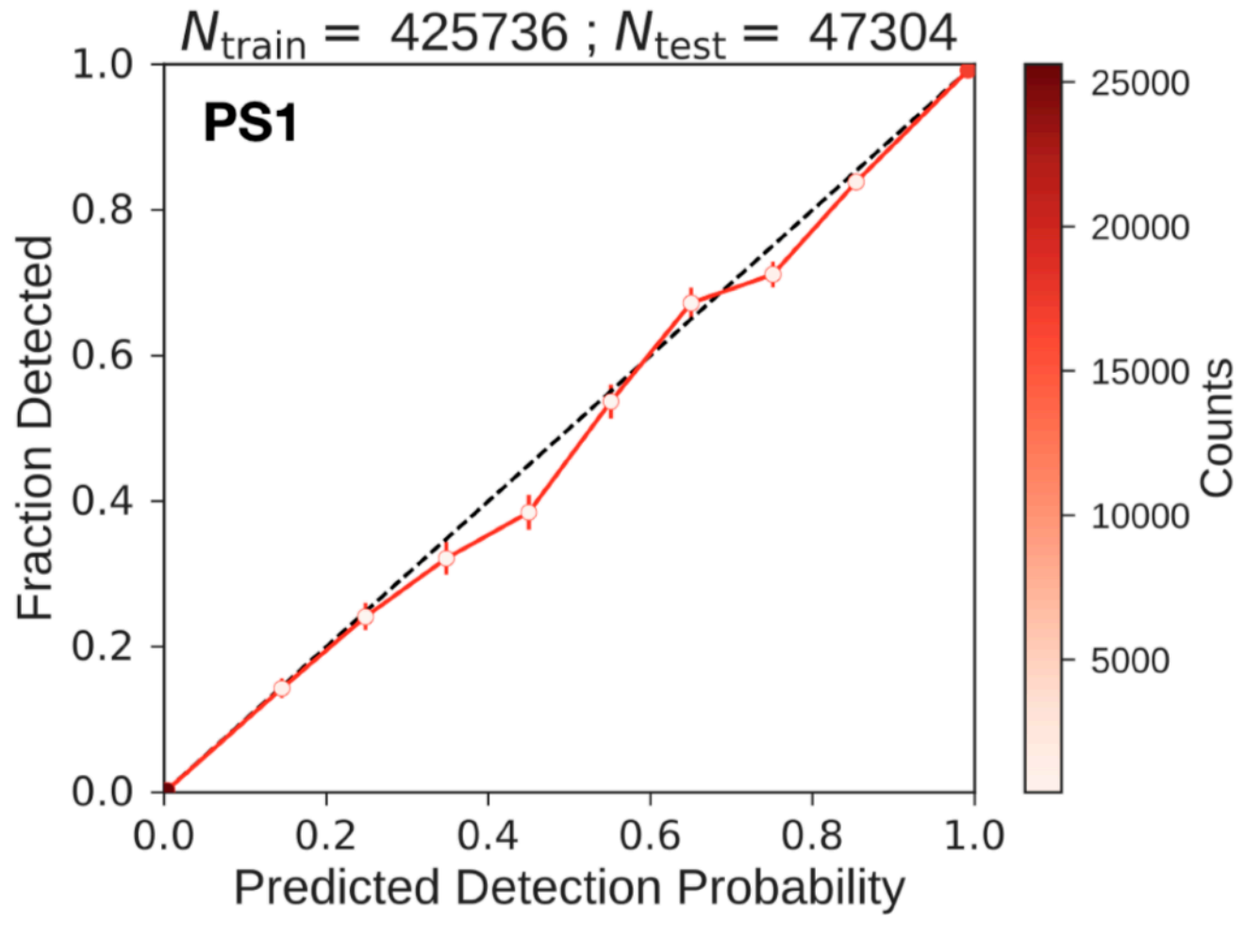
Use machine learning approach to accurately predict the detectability of a satellite given intrinsic structural properties and position (including survey conditions)





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

Preliminary Findings from DES + PS1

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- Evidence for anisotropy in the Milky Way satellite population due to satellites that arrived with the Large Magellanic Cloud
- Sensitive to lowest mass halos that host galaxies (~10^8 $M_\odot$)
- Sensitive to the occupancy fraction of dark matter halos in mass range 10^7 $M_\odot$ < M_{Vir} < 10^9 $M_\odot$

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In the following slides, showing results on **Classical + SDSS satellites** to illustrate the methodology

Preliminary DES + PS1 results improve upon these previous constraints

Milky Way Satellite Galaxy Luminosity Function

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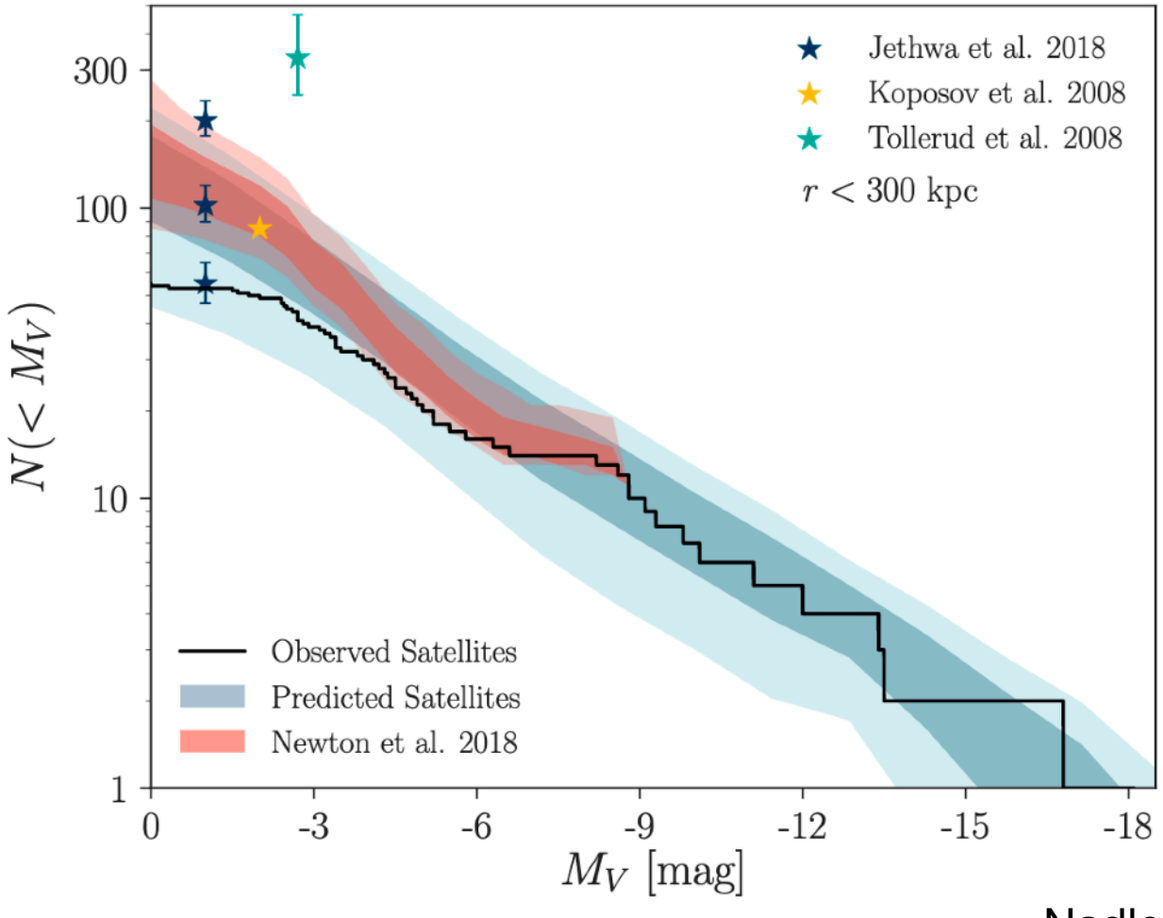
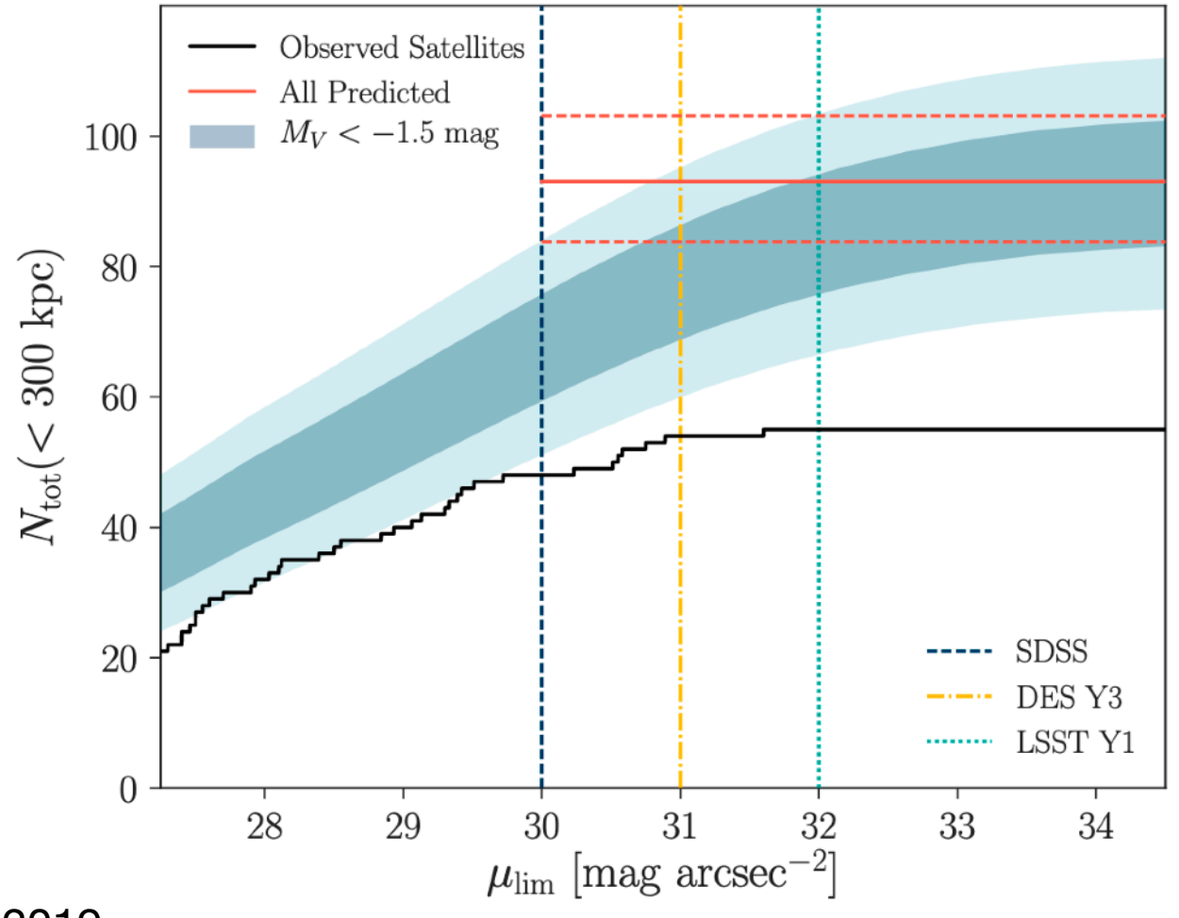
Even with the doubling of known Milky Way satellites since 2015, the majority of Milky Way satellites remain hidden because they either contain **too few bright stars** or are **too low surface brightness**

Classical + SDSS

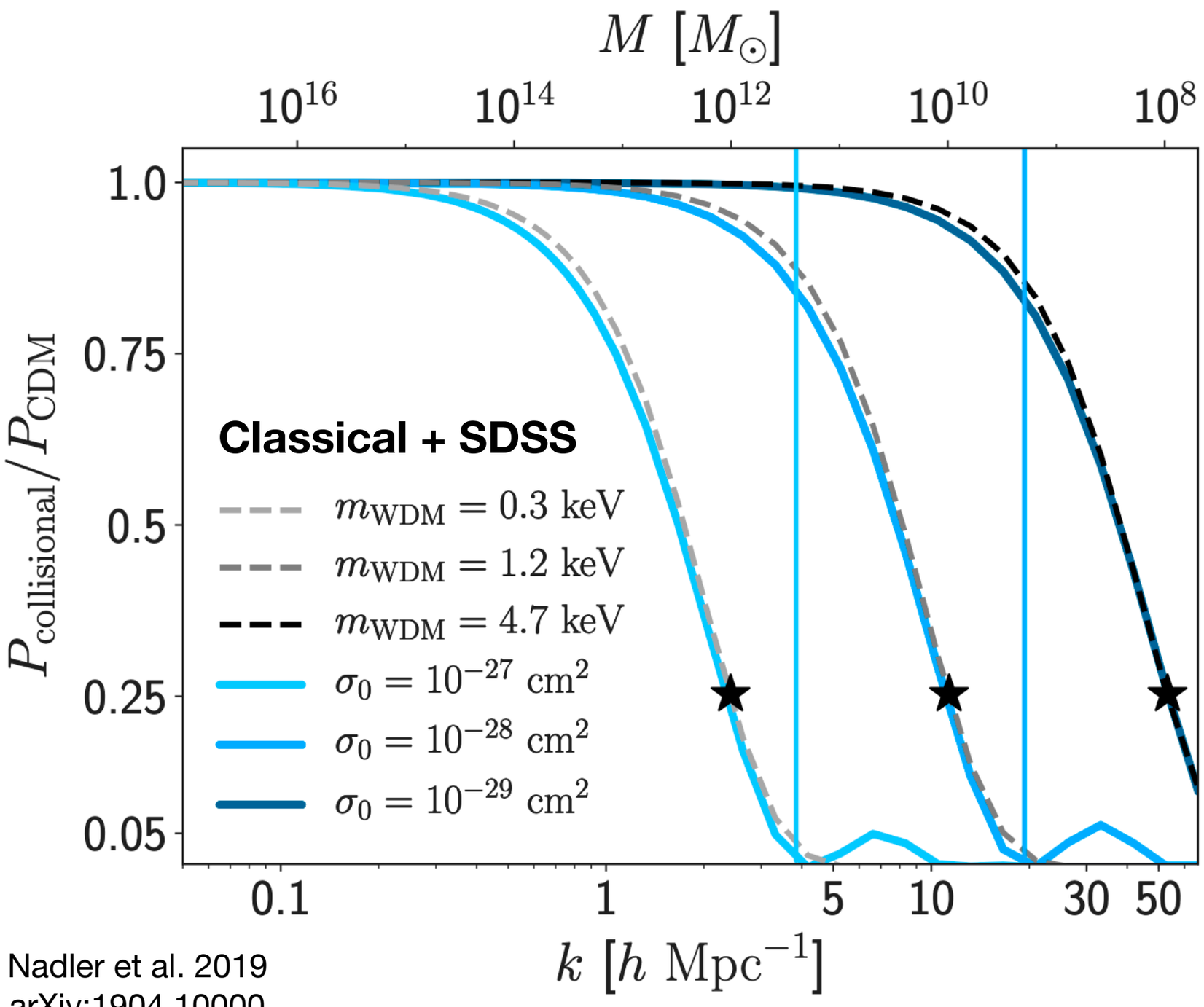




Nadler et al. 2019
arXiv:1809.05542

Example Constraints on Dark Matter Microphysics

The transfer function shape is roughly universal for a large class of dark matter models



Nadler et al. 2019
arXiv:1904.10000

Example shown here:

- Warm dark matter
- Baryon-scattering dark matter
- (Fuzzy/ultra-light dark matter)

DES + PS1 analysis expected to yield $m_{WDM} > 4$ keV (compare to zoom-in simulations)

Example Constraints on Dark Matter Microphysics

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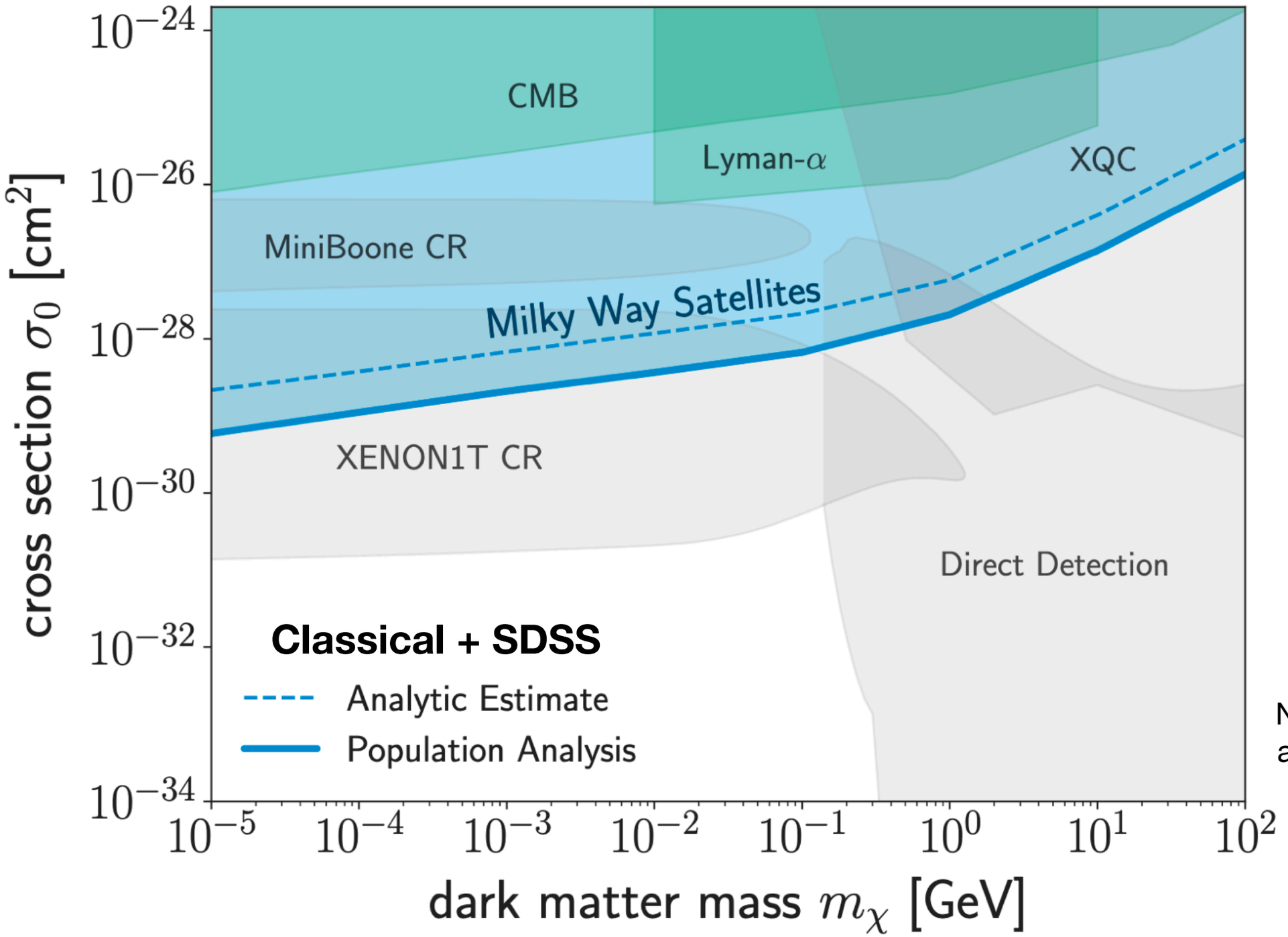
Lowest mass dark matter halo sensitive to dark matter-baryon scattering in early Universe



Nadler et al. 2019
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Summary

Satellite galaxies of the Milky Way are attractive targets for indirect dark matter searches, and can also test a **much wider range of dark matter models beyond the WIMP paradigm**.

Gains in the depth, coverage, and quality of **optical surveys**, higher fidelity modeling of **baryonic processes**, and **integrated interpretation** frameworks are now allowing us to recognize the minimum halo mass for galaxy formation.

Next step is to interpret new DES + PS1 search results in context of a variety of non-minimal dark matter models, including uncertainties in galaxy formation physics.

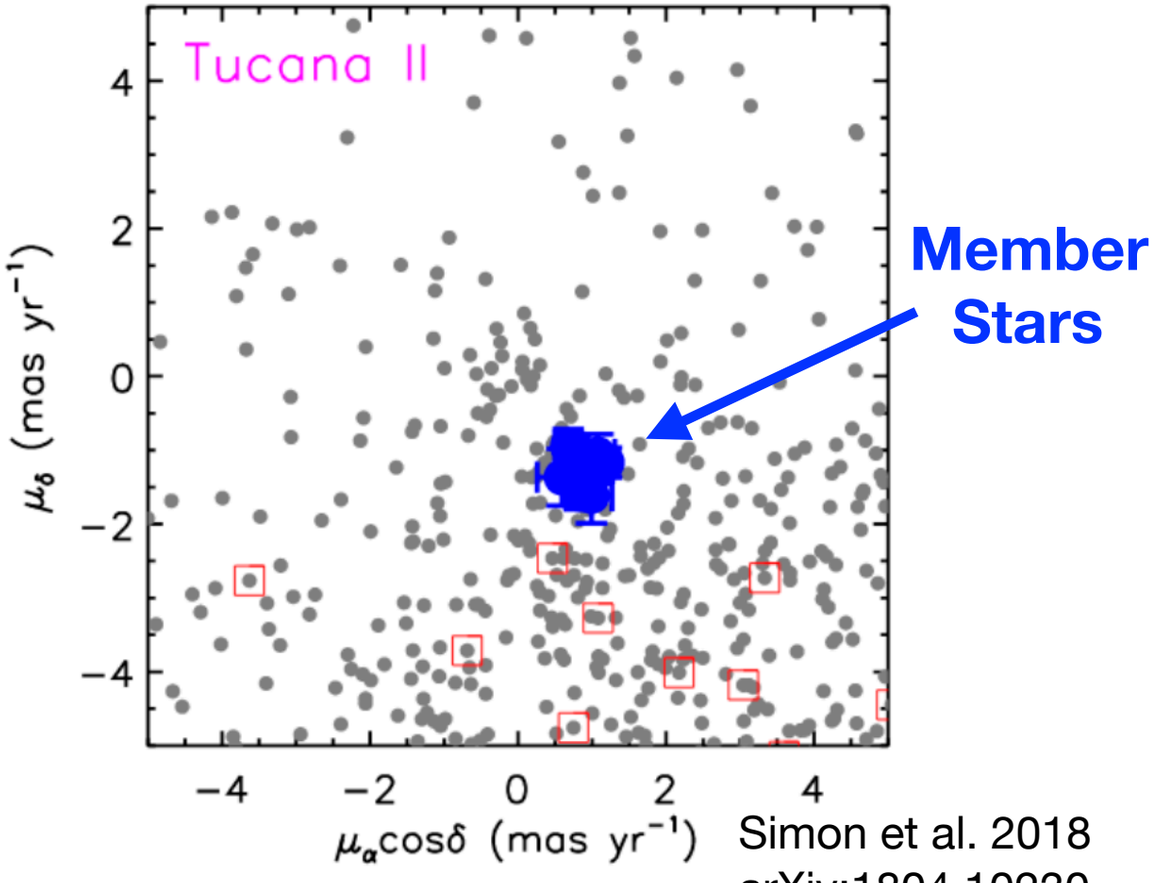
Bonus Slides

DES Y6 and Beyond…

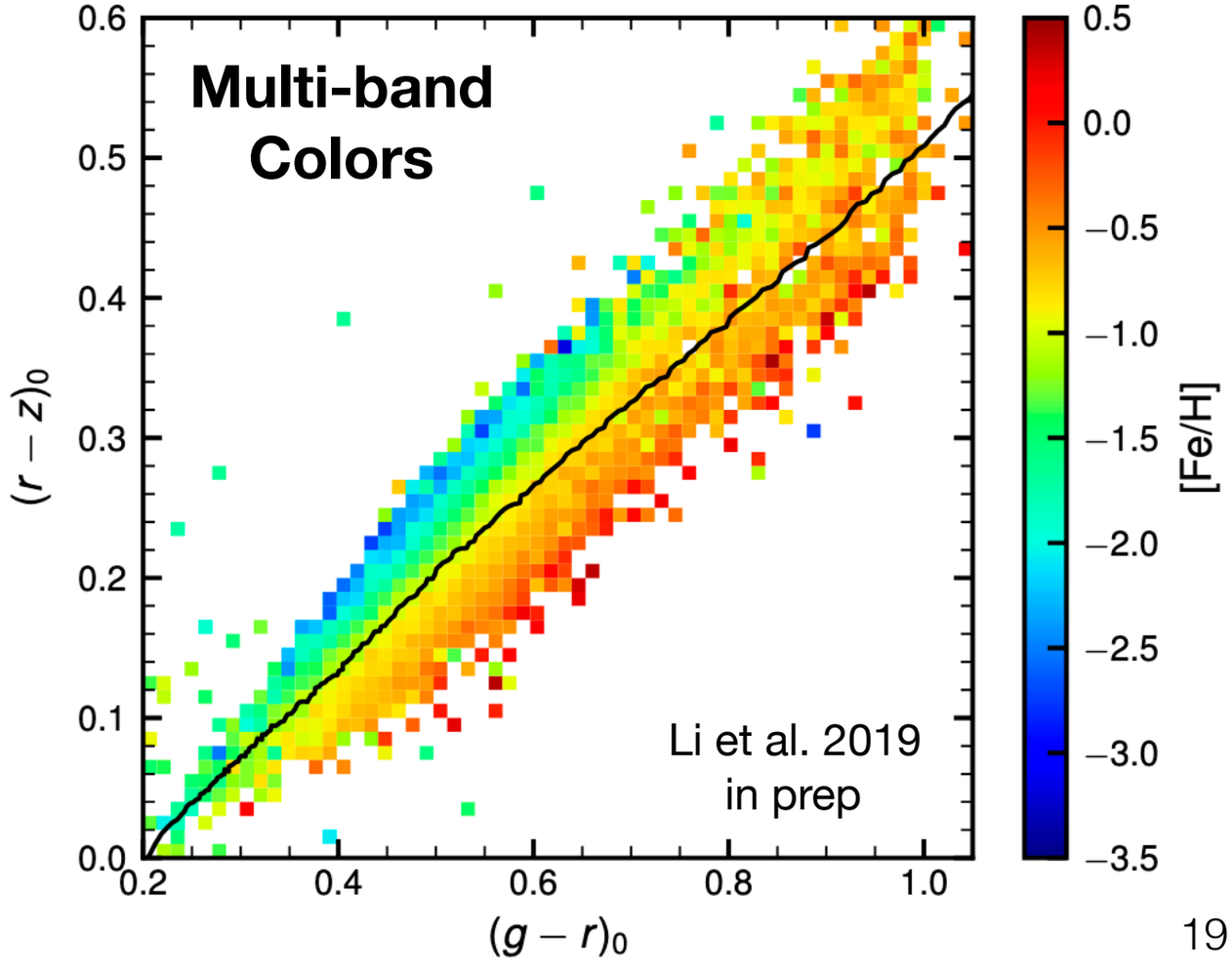
Milky Way Satellite search sensitivity anticipated to further increase with gains in exposure from DES Y3 to Y6, a reduced SNR threshold for object detection, and incorporating multi-band color information together with proper motions (Gaia DR2+)

MagLiteS + DELVE (125 nights) together with DECADE processing

Proper Motions



Simon et al. 2018
arXiv:1804.10230



Milky Way Satellite Discovery Timeline