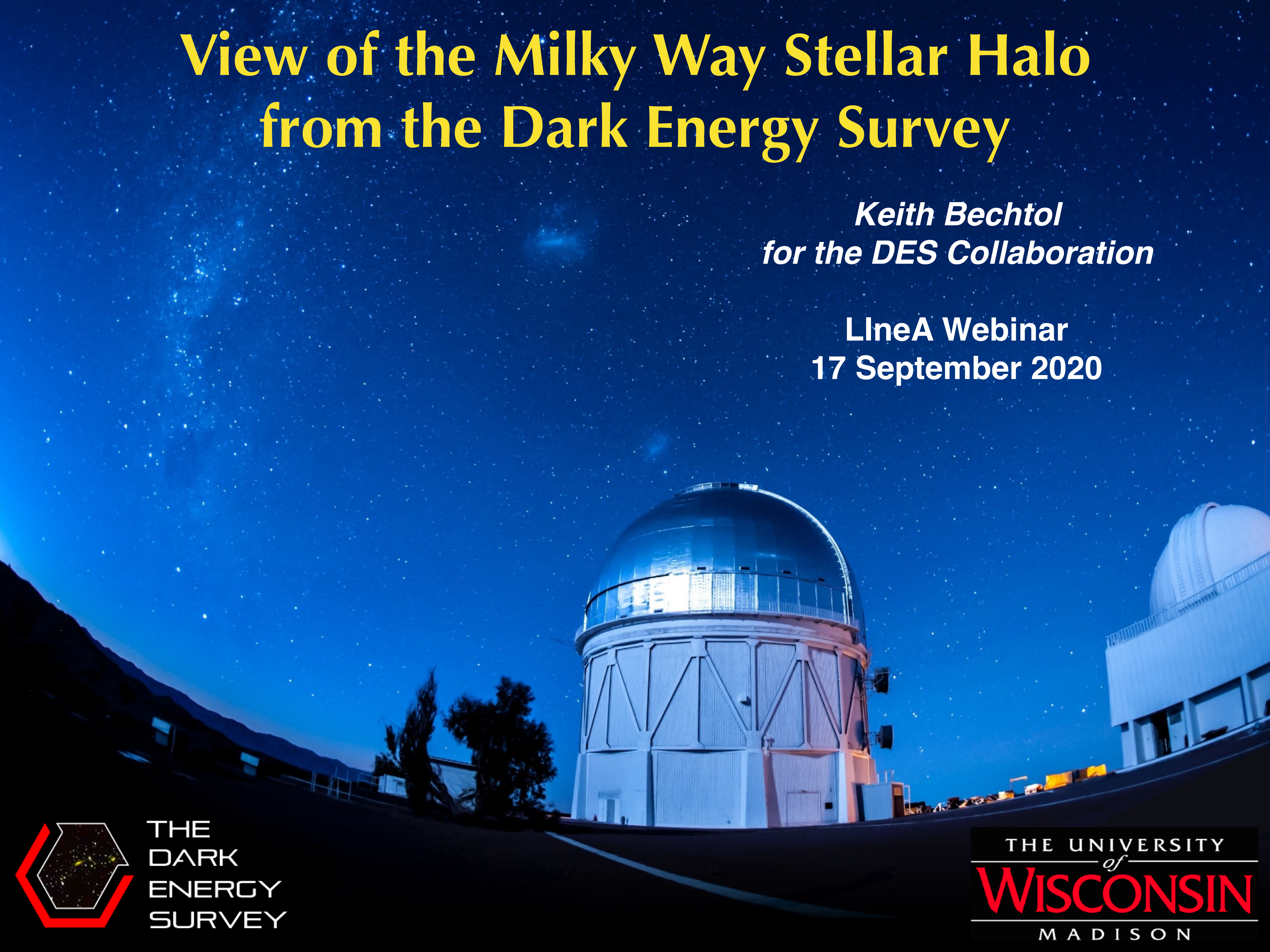


View of the Milky Way Stellar Halo from the Dark Energy Survey

Keith Bechtol
for the DES Collaboration

LIneA Webinar
17 September 2020

THE DARK ENERGY SURVEY

THE UNIVERSITY of WISCONSIN MADISON

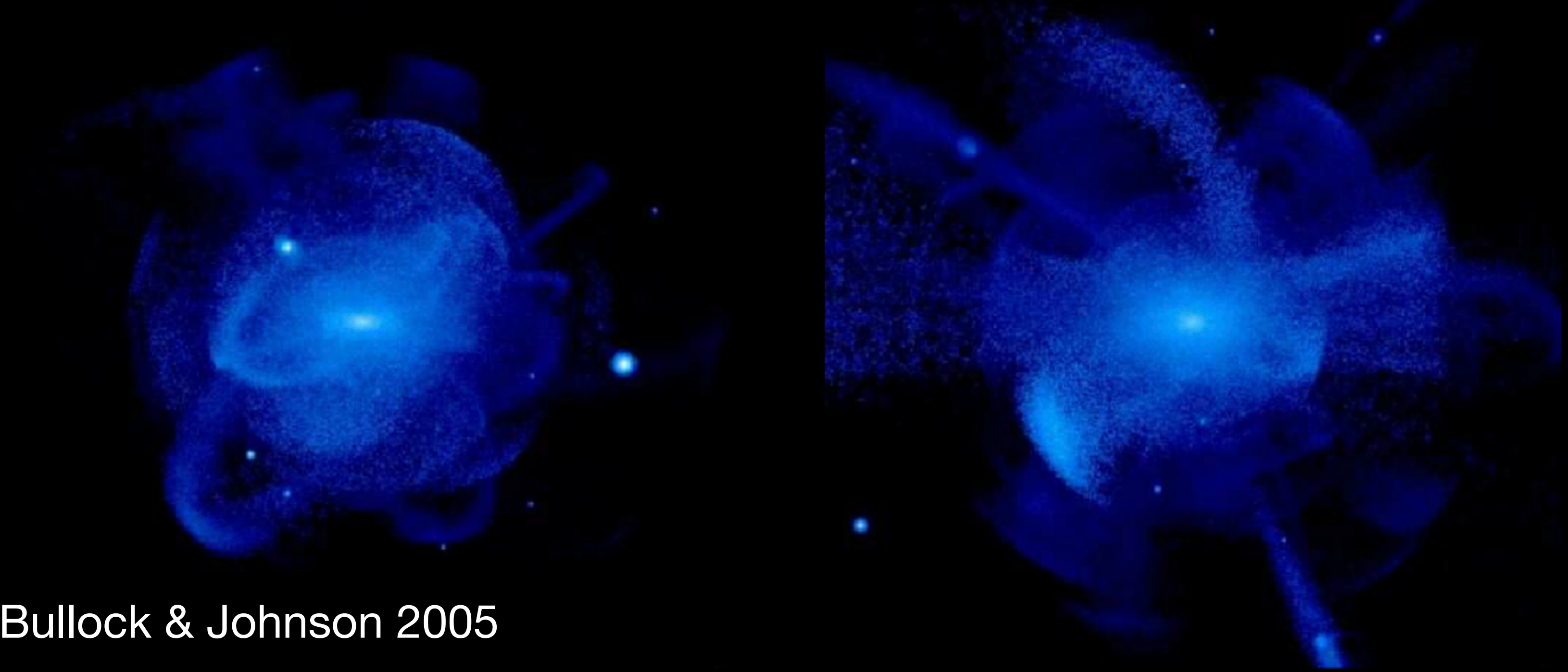
Cosmology in the $z < 10^{-4}$ Universe

Keith Bechtol
for the DES Collaboration

LIneA Webinar
17 September 2019

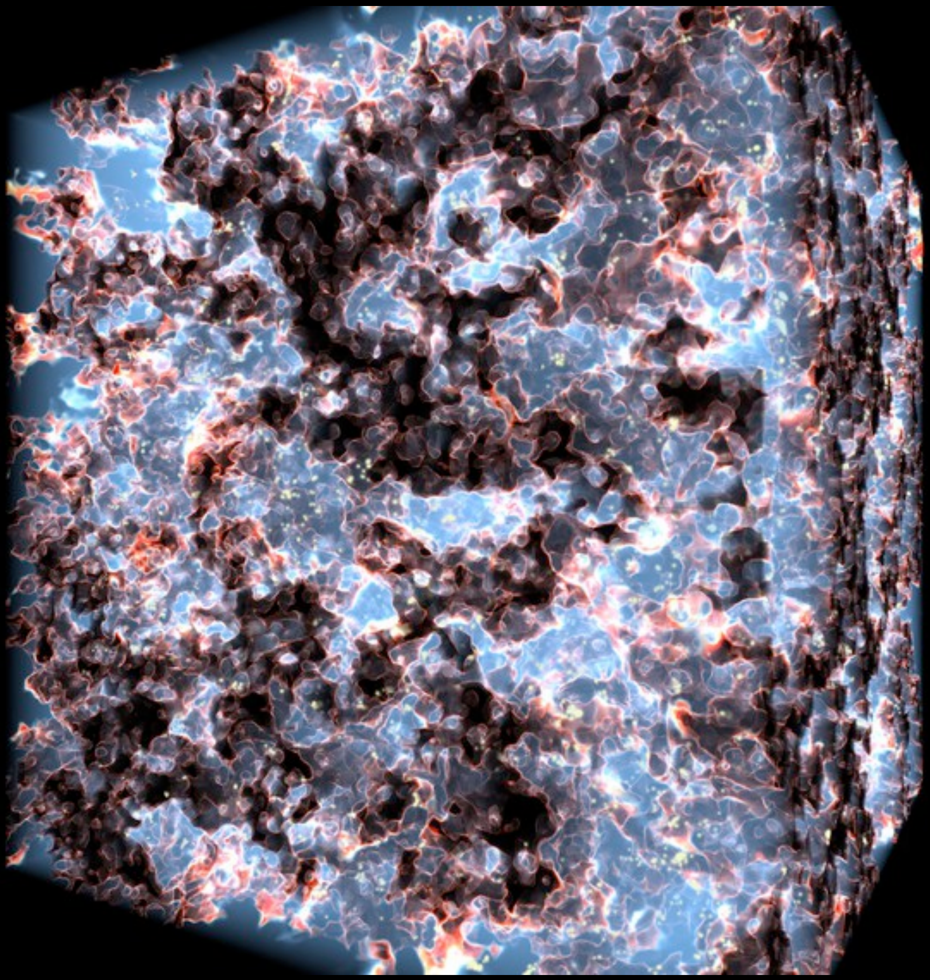
THE DARK ENERGY SURVEY

THE UNIVERSITY of WISCONSIN MADISON

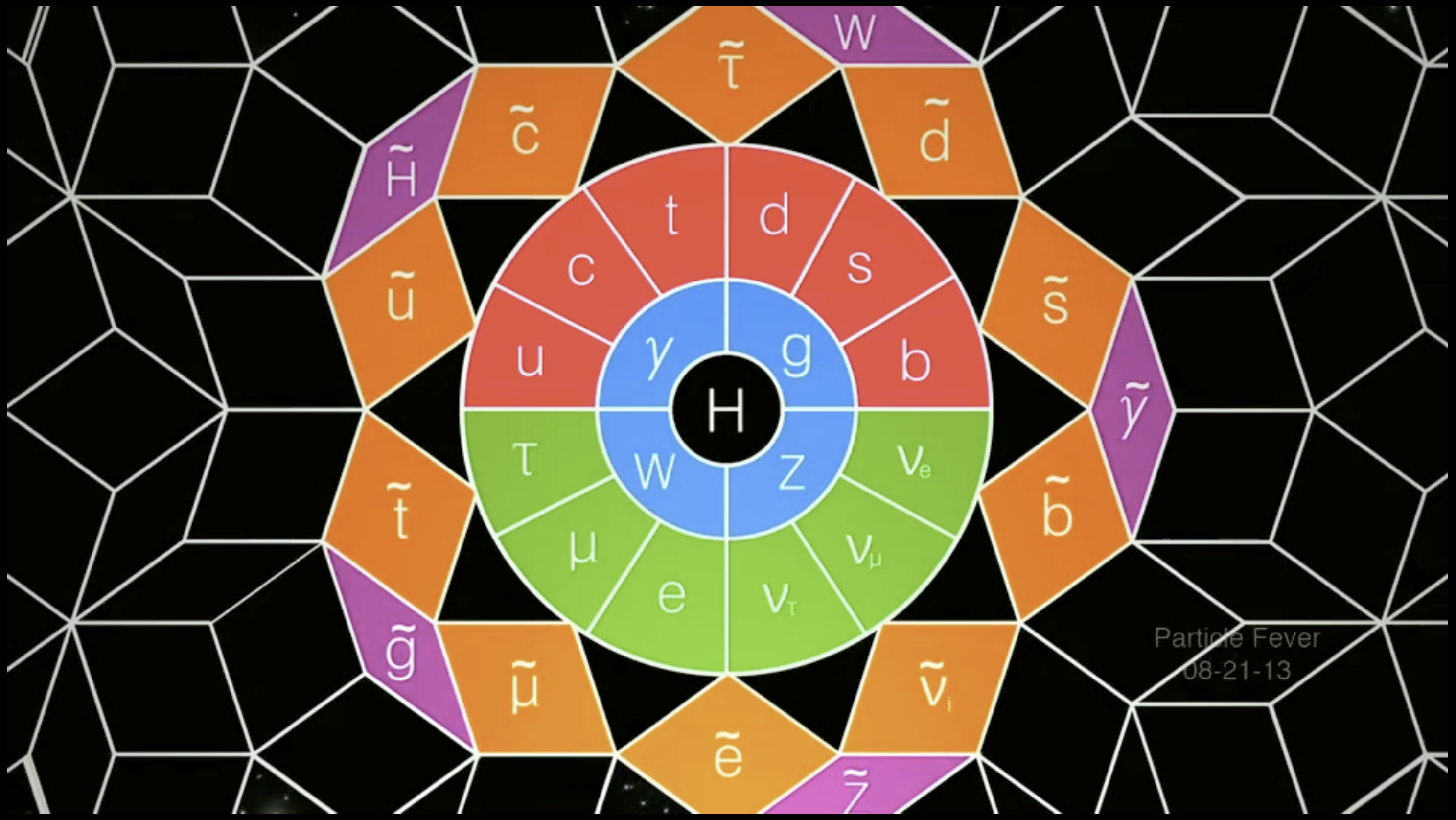


Bullock & Johnson 2005

Formation History of the Milky Way



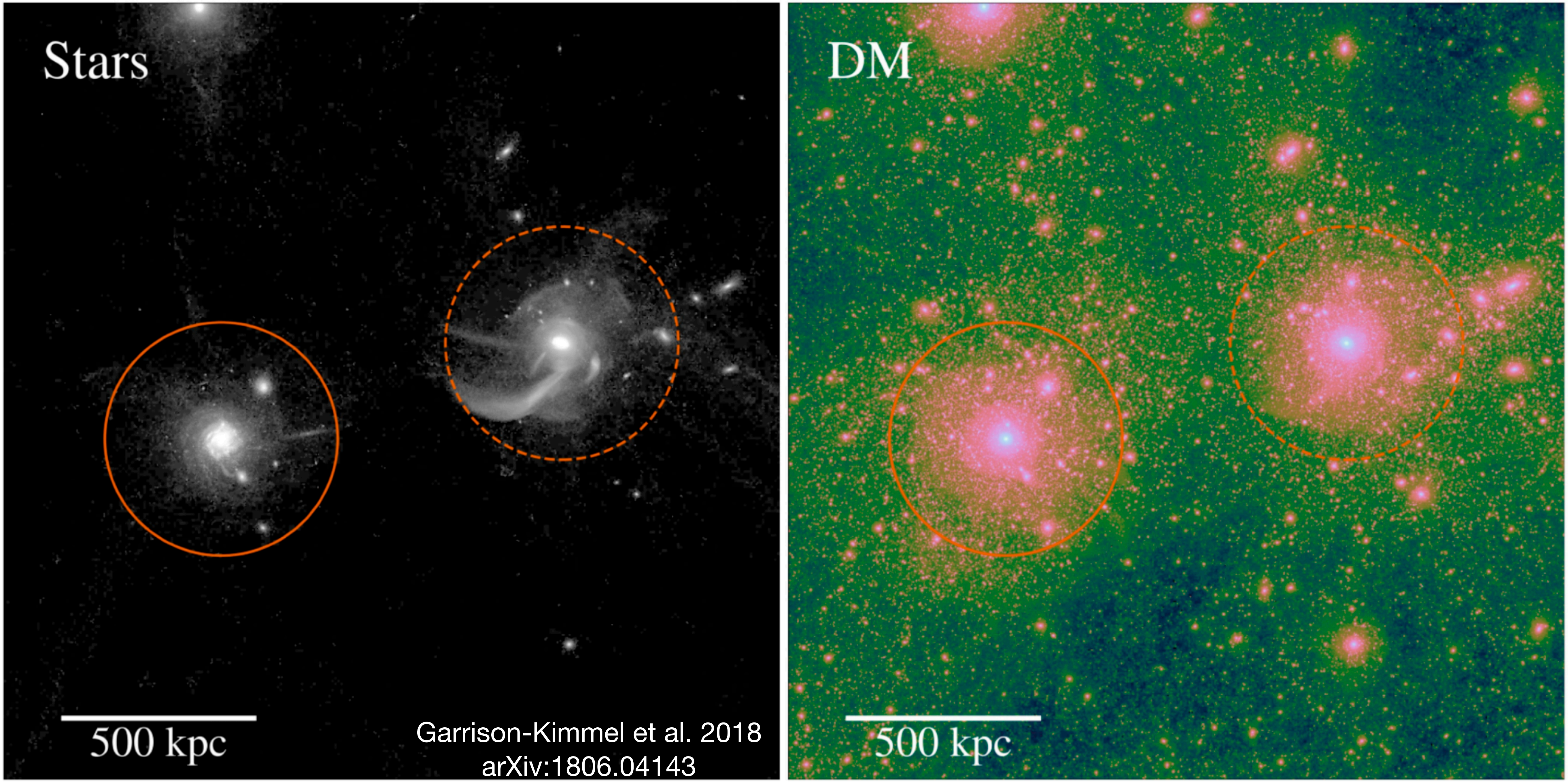
First Stars, First Galaxies, Epoch of Reionization



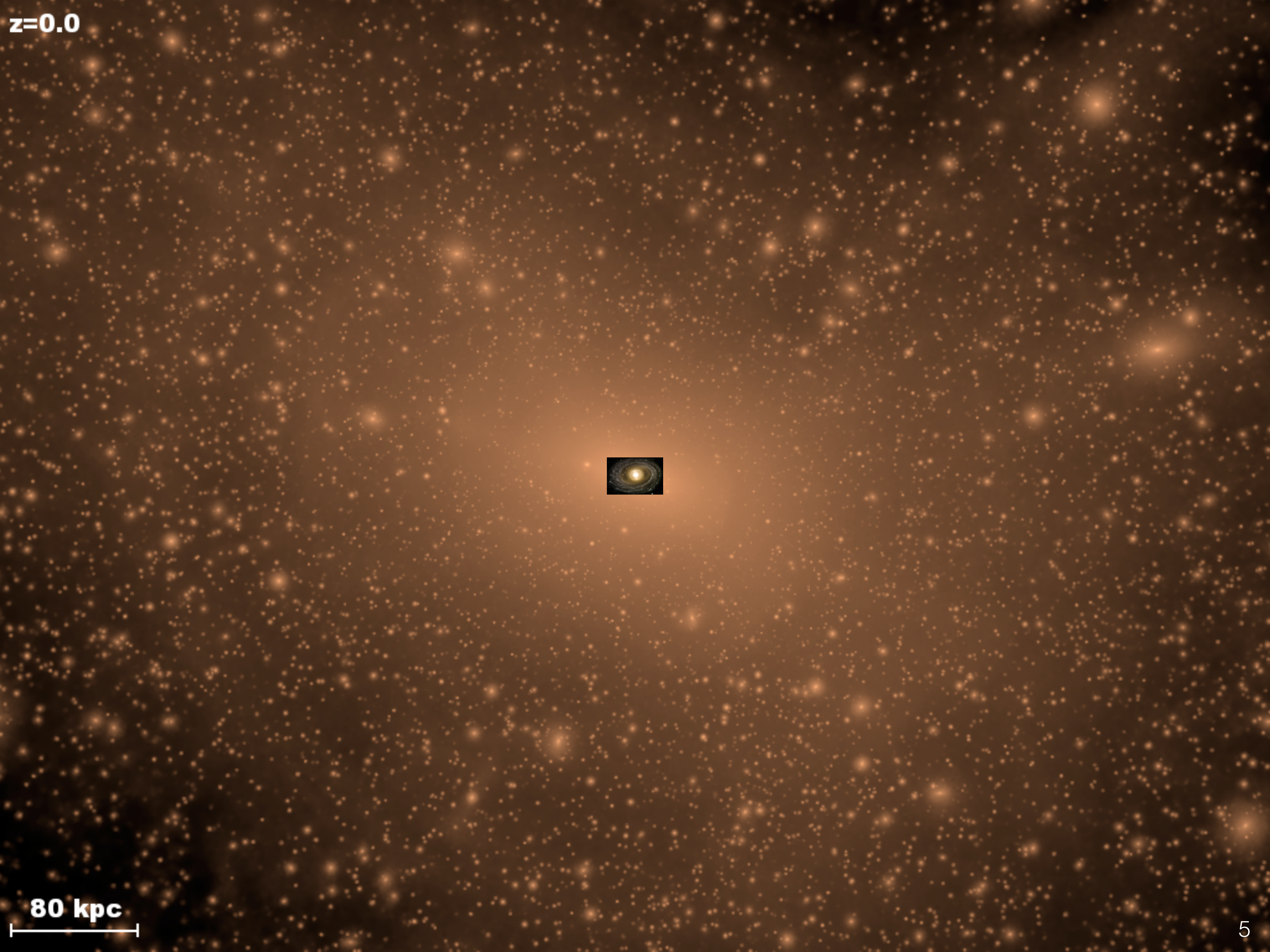
Particle Nature of Dark Matter

Milky Way Stellar Halo

Stellar halo accounts for ~1% of the total stellar mass of the Milky Way



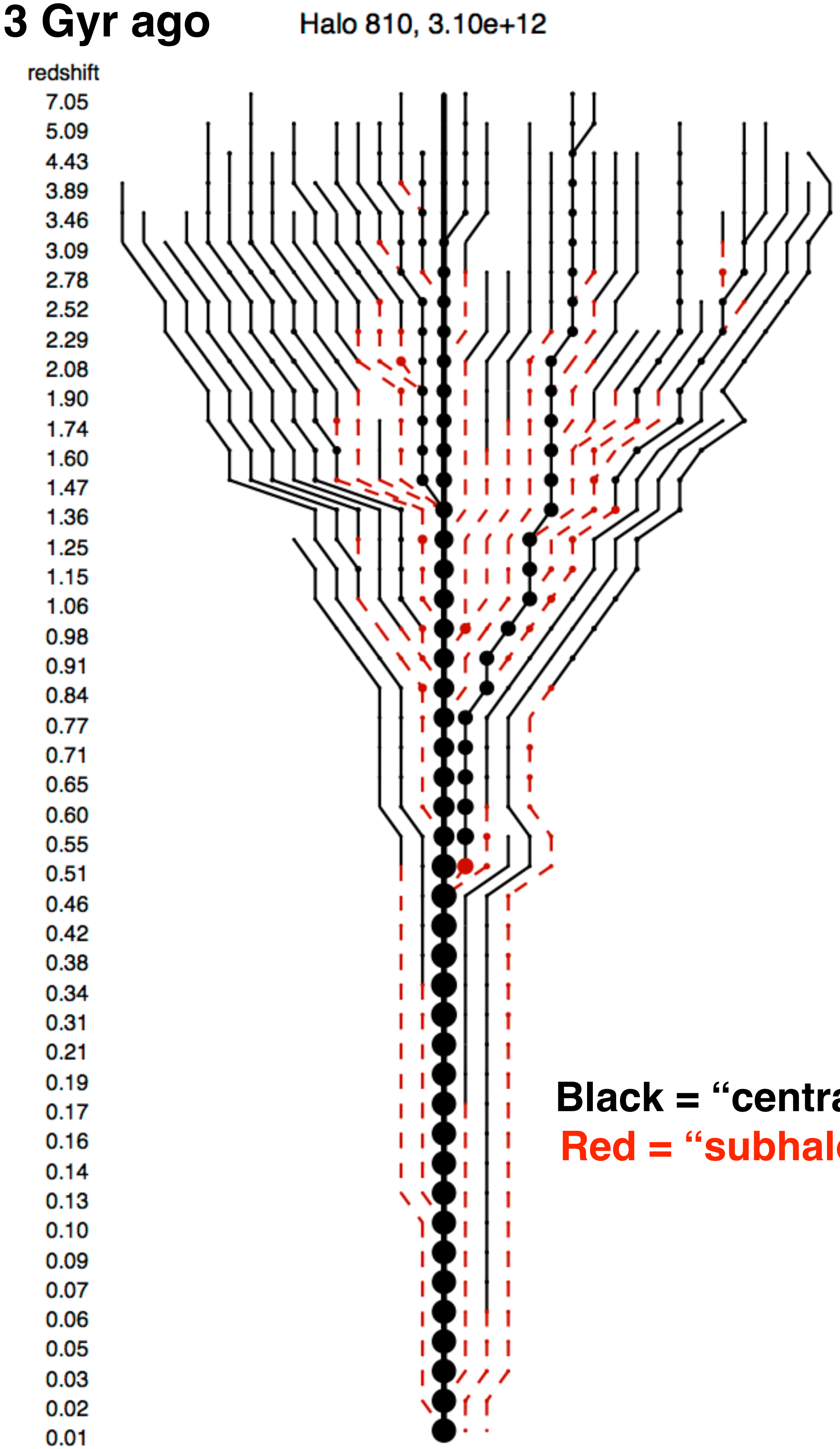
Garrison-Kimmel et al. 2018
arXiv:1806.04143


z=0.0
80 kpc


z=0.0
80 kpc

Hierarchical Assembly

13 Gyr ago

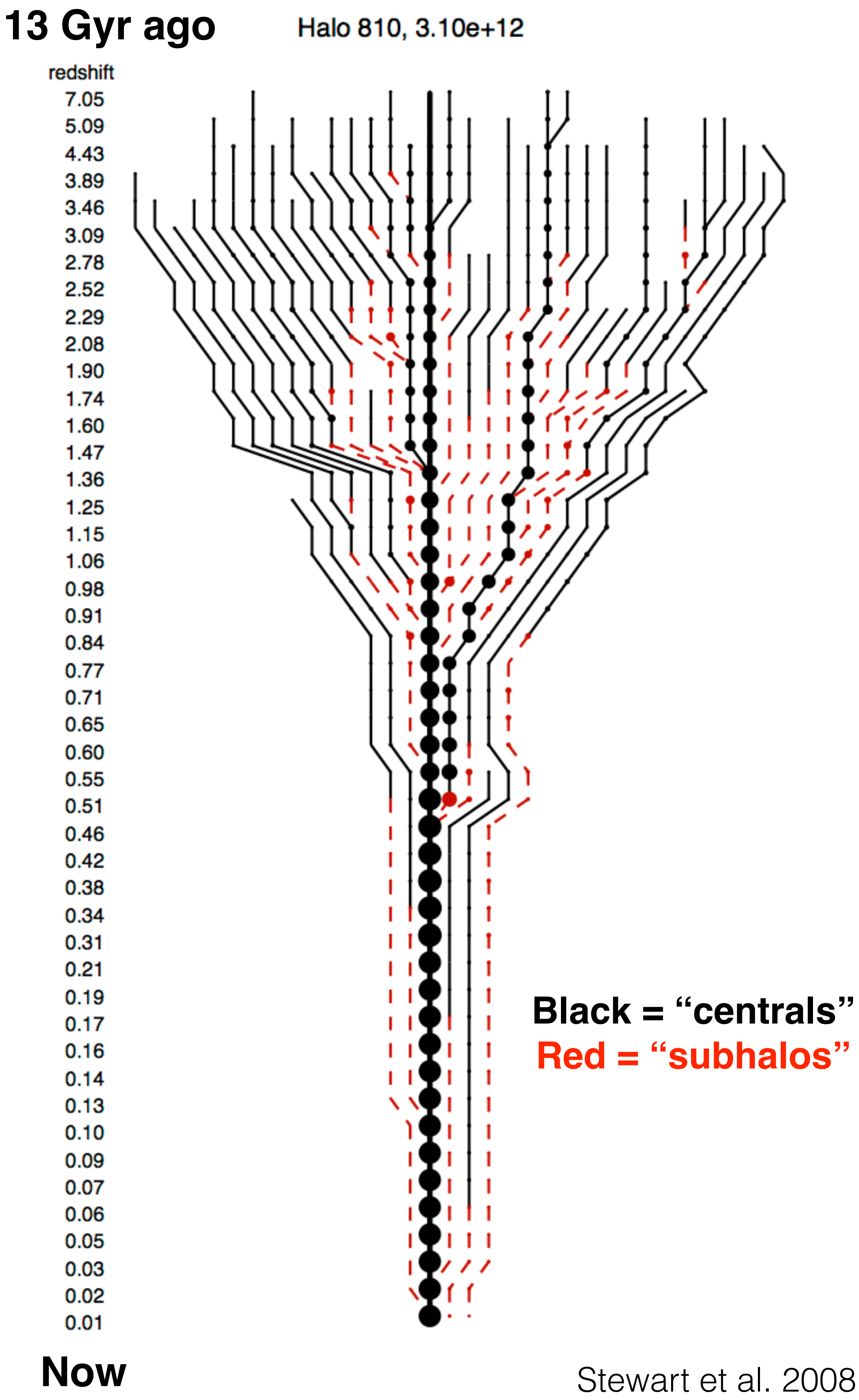


Black = “centrals”
Red = “subhalos”

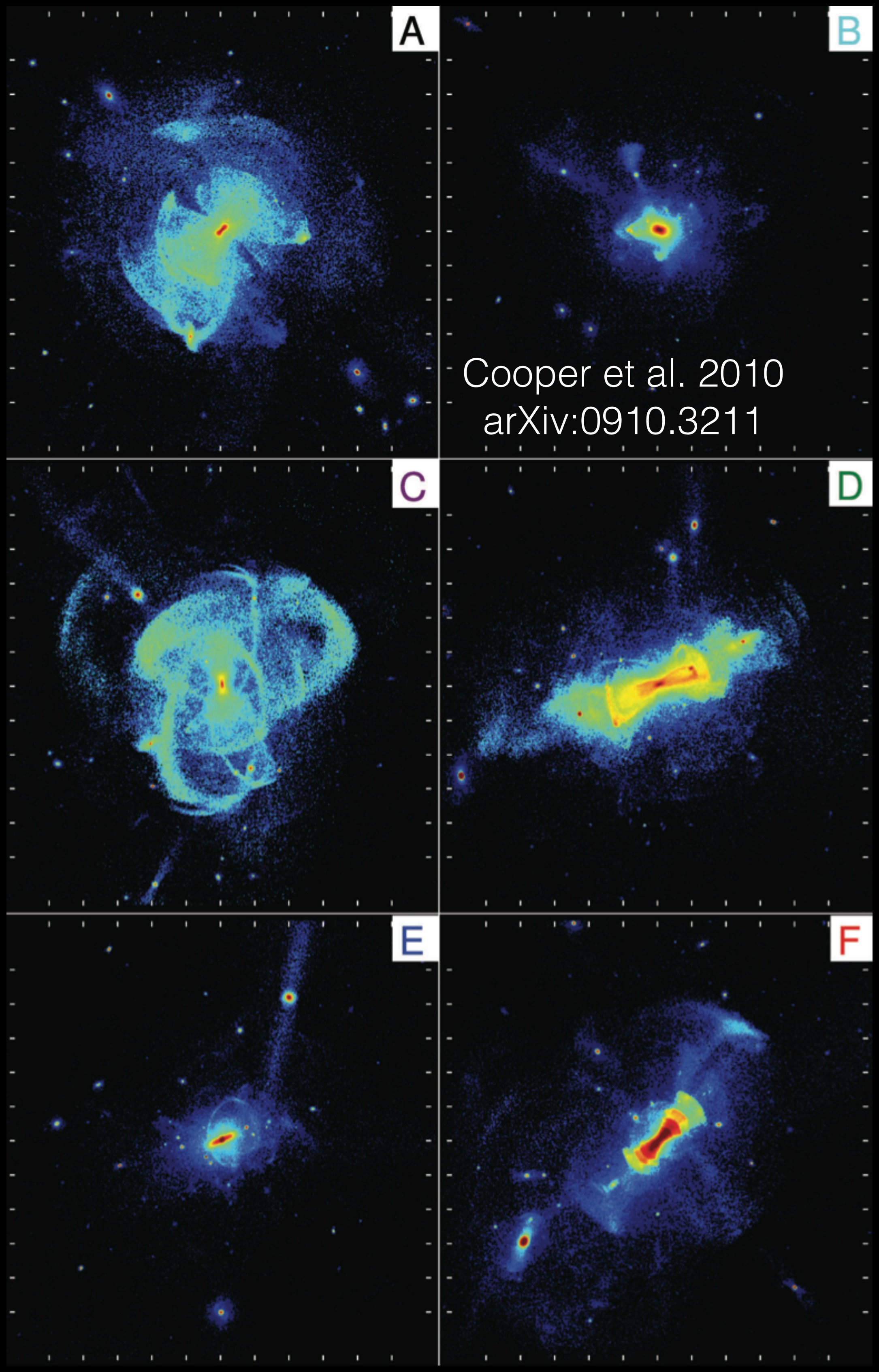
Now

Stewart et al. 2008

Hierarchical Assembly



Stewart et al. 2008

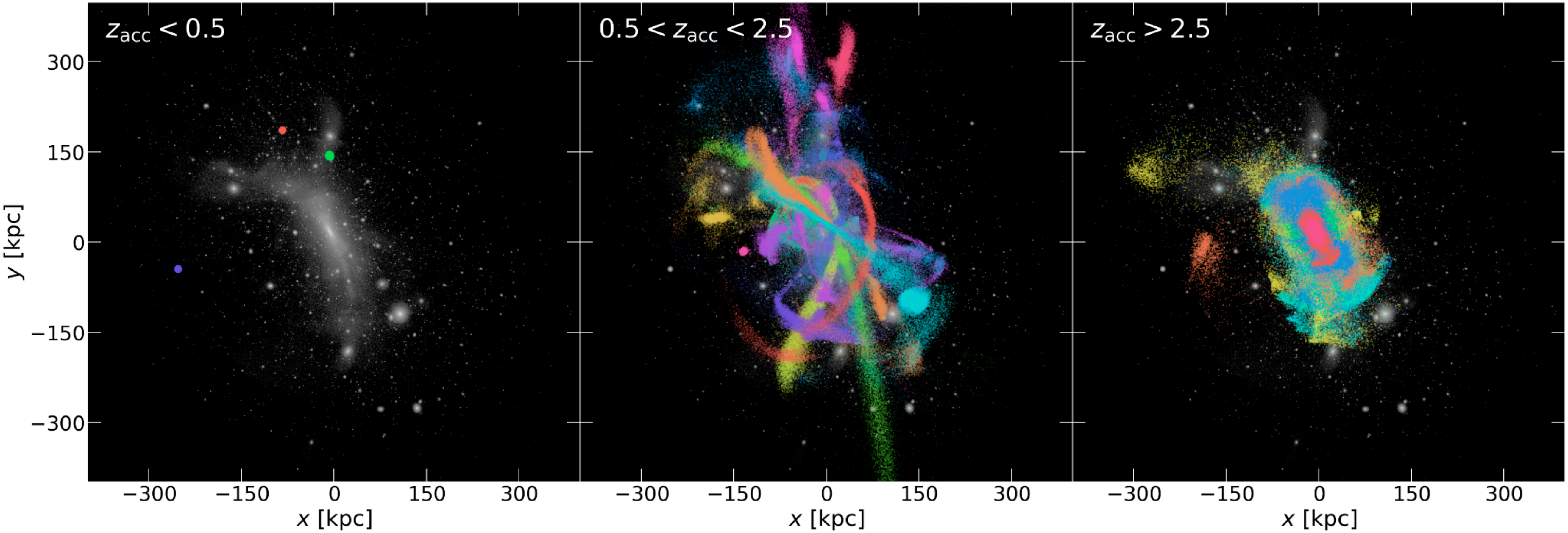


Cooper et al. 2010
arXiv:0910.3211

Six realizations of stars formed in satellites

Accretion History of the Milky Way

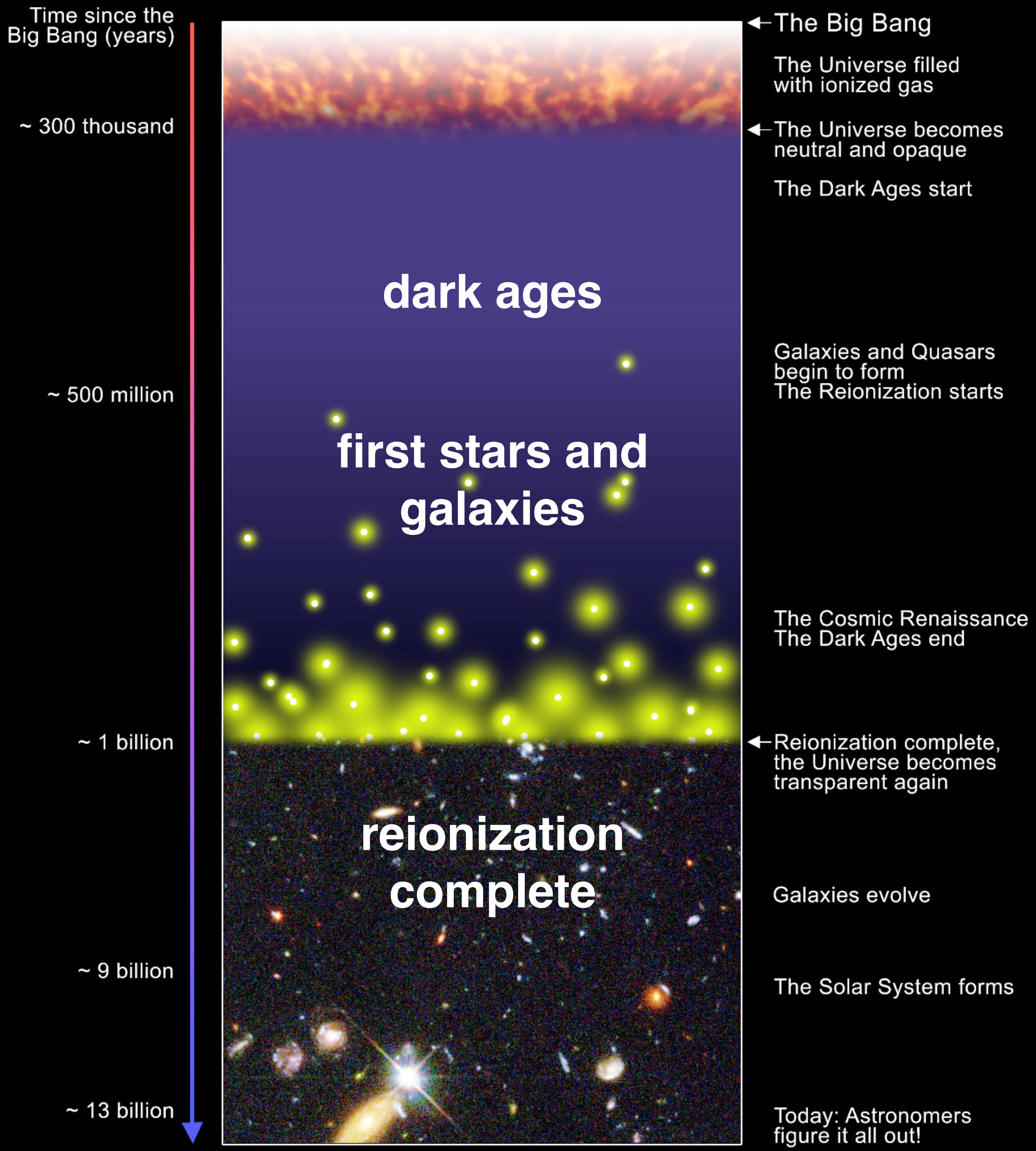
past 5 Gyr **5 Gyr to 11 Gyr ago** **>11 Gyr ago**



Morinaga et al. 2019
arXiv:1901.04748

What is the Reionization Era?

A Schematic Outline of the Cosmic History



S.G. Djorgovski et al. & Digital Media Center, Caltech

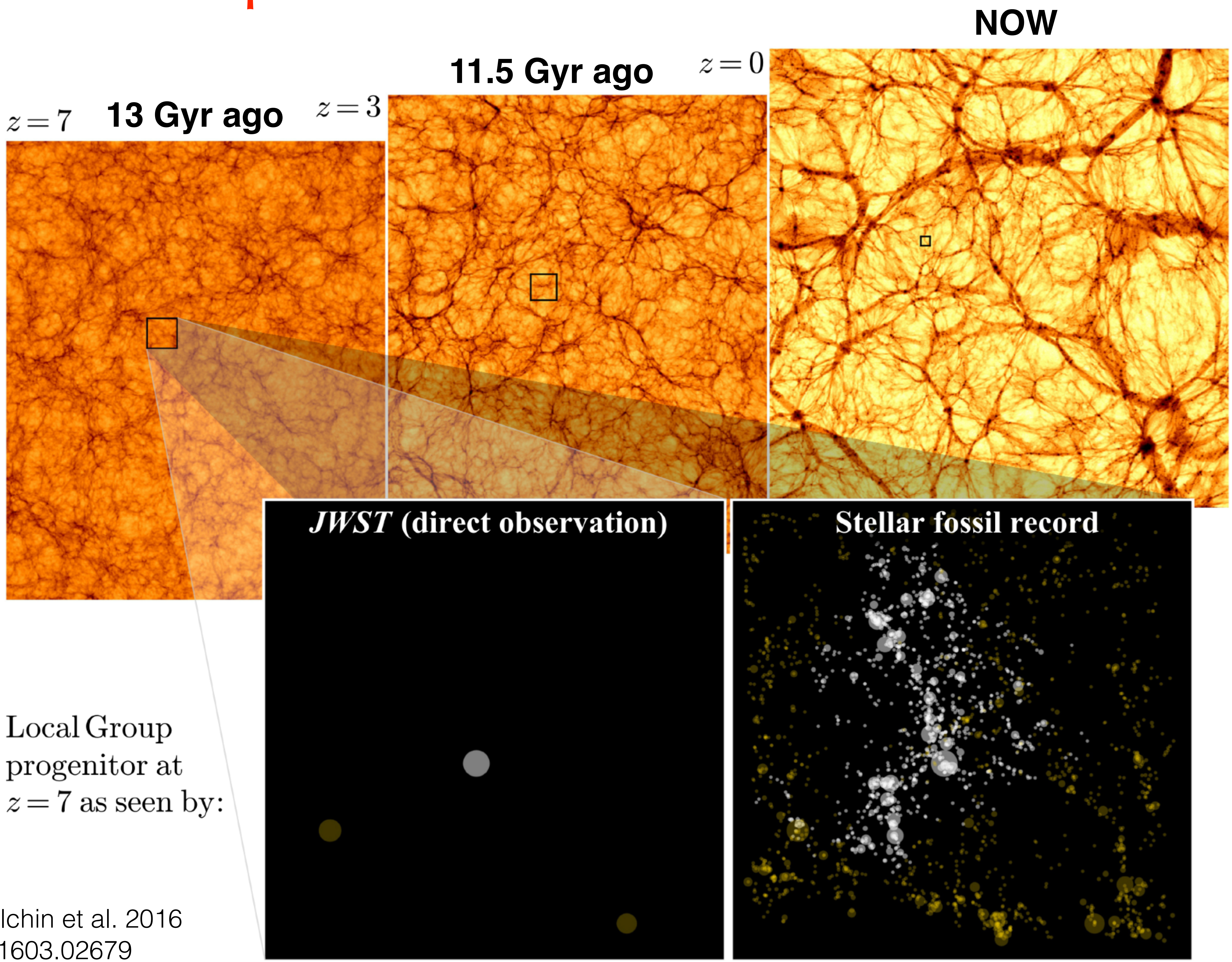
Ultra-faint galaxies
are

(1) sources of ionizing photons

and are

(2) quenched by reionization

Local Group as “Time Machine”

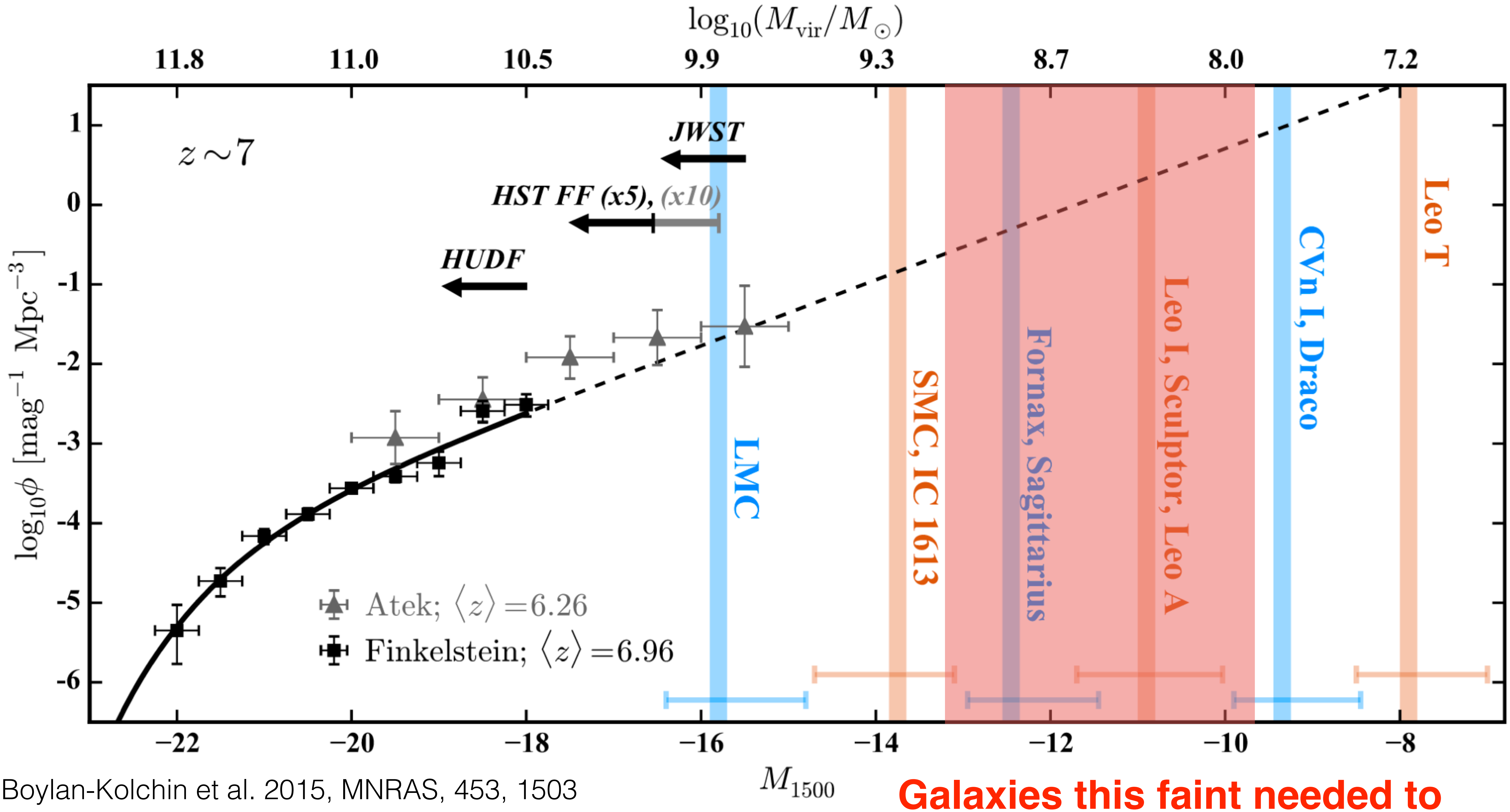


Local Group
progenitor at
$z = 7$ as seen by:

Boylan-Kolchin et al. 2016
arXiv:1603.02679

Local Connection to High-Redshift Universe

Galaxies responsible for reionization are probably too faint to be directly imaged even with *JWST*, but we can study their "fossils" in the Local Volume

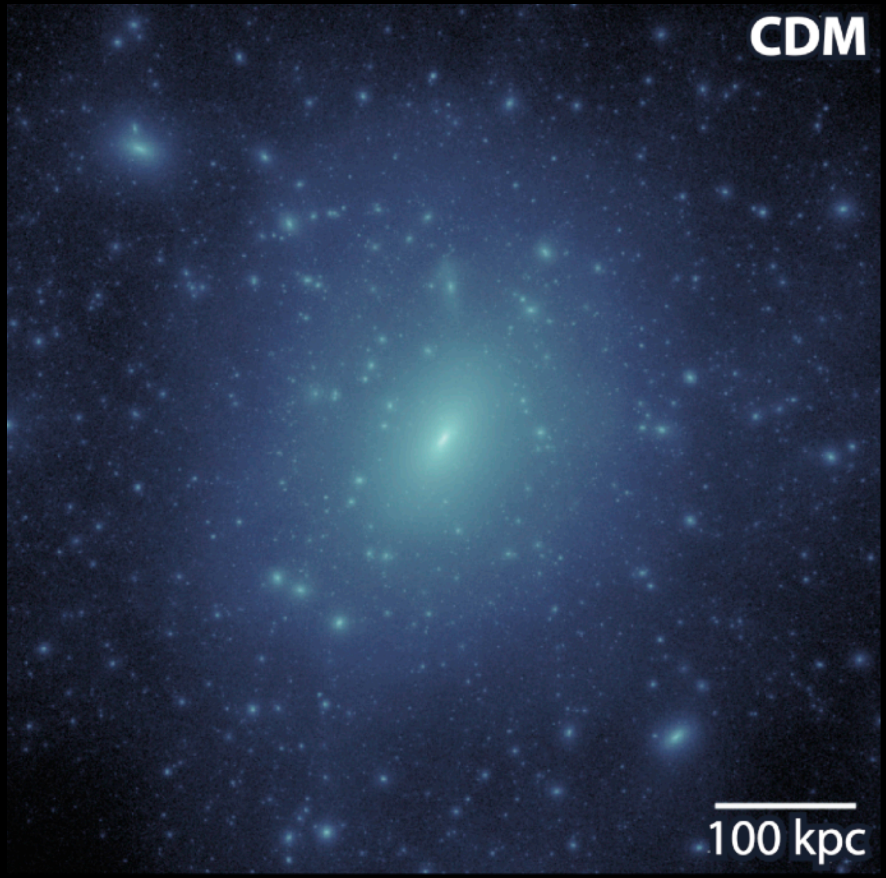


Boylan-Kolchin et al. 2015, MNRAS, 453, 1503

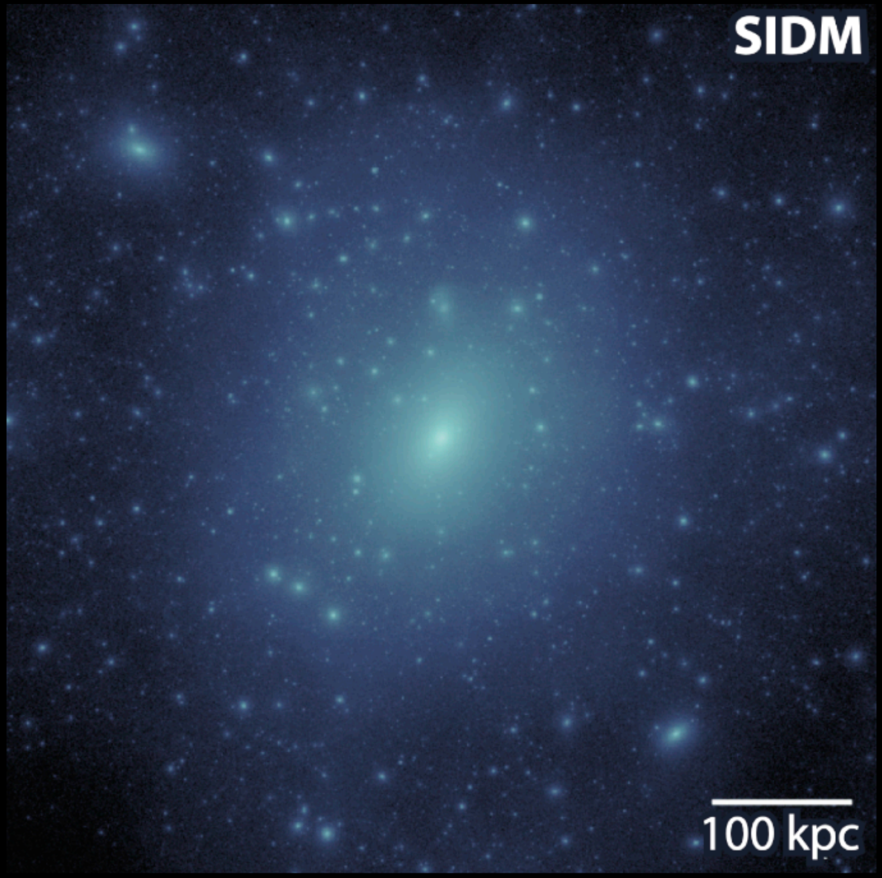
Galaxies this faint needed to provide ionizing radiation

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

Cold Dark Matter

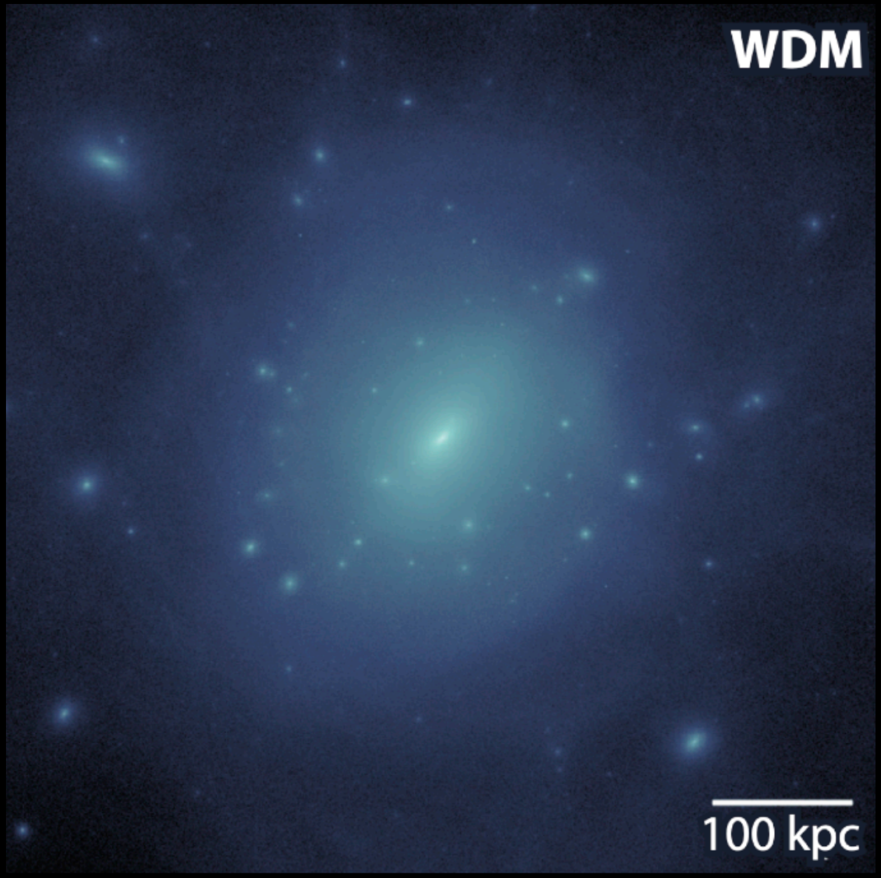


Self-Interacting Dark Matter



Cored Density Profiles

Warm Dark Matter



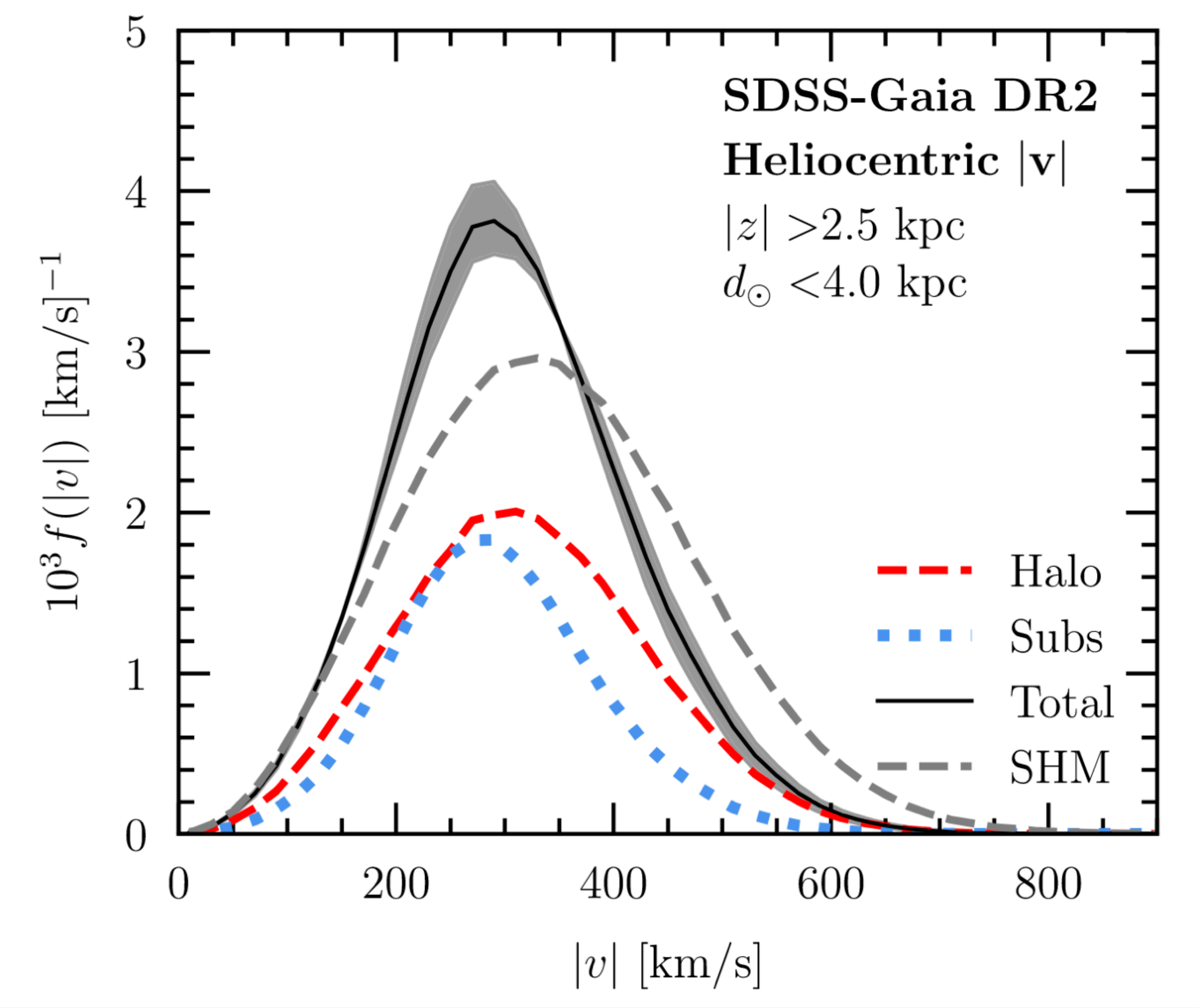
Fewer Substructures

Reviewed by Bullock & Boylan-Kolchin 2017

Tracing the Invisible Dark Matter

THE
DARK
ENERGY
SURVEY

Estimate velocity distribution of Galactic dark matter halo using the kinematics of most metal poor stars



Necib et al. 2019
arXiv:1810.12301

Outline

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- **Overview of the DES stellar object catalog**
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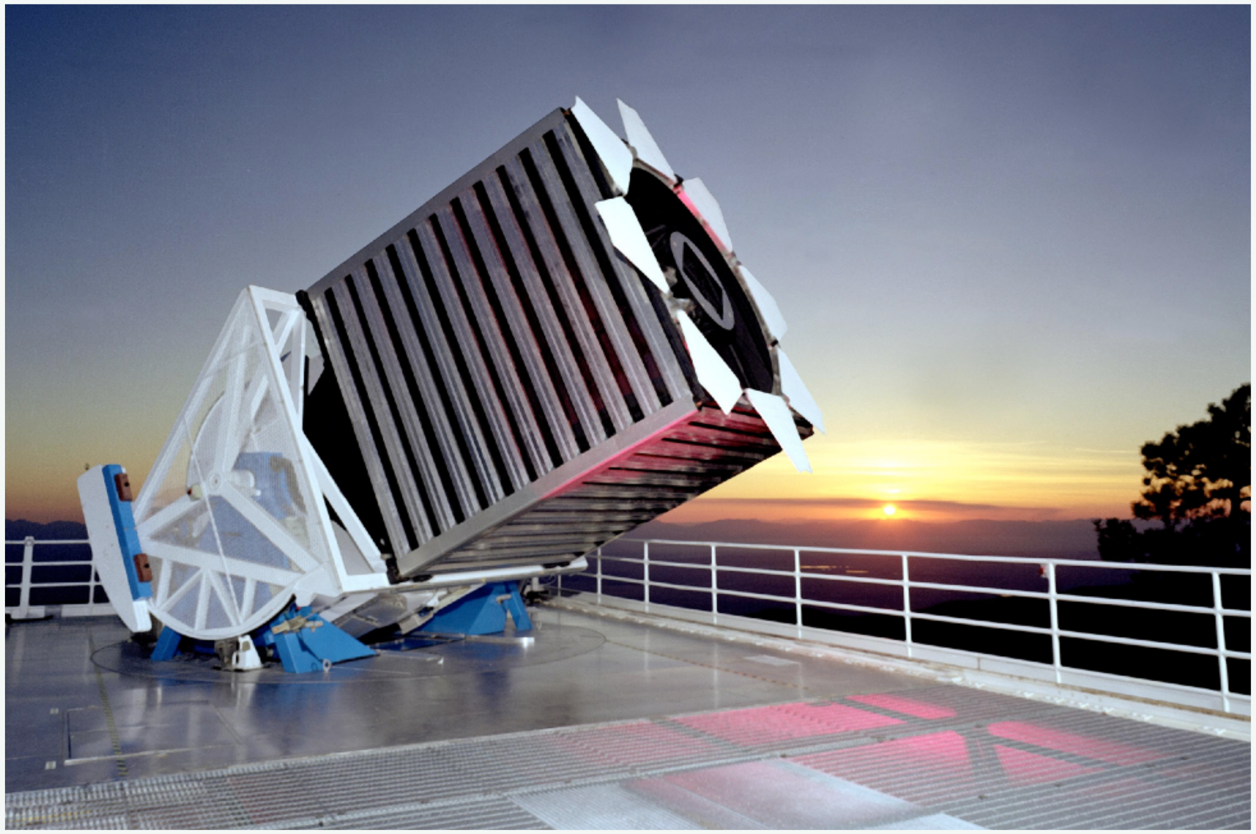
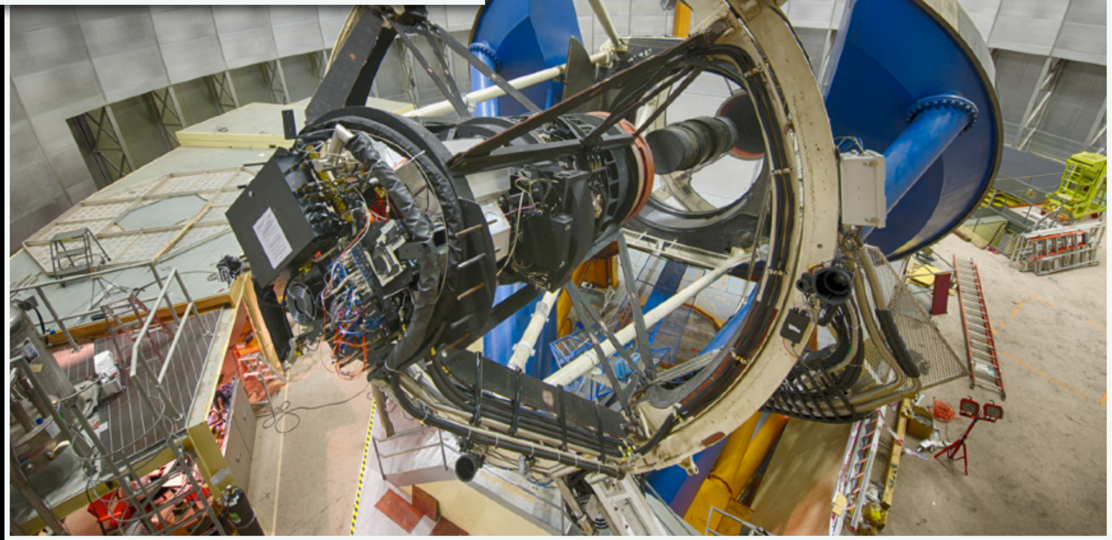
  - Tracer populations: RR Lyrae and brown dwarfs
  - Smooth stellar halo
  - Stellar streams
  - Chemical abundances
  - Luminosity function of Milky Way satellites

Progression of Wide-field Optical Imaging Surveys



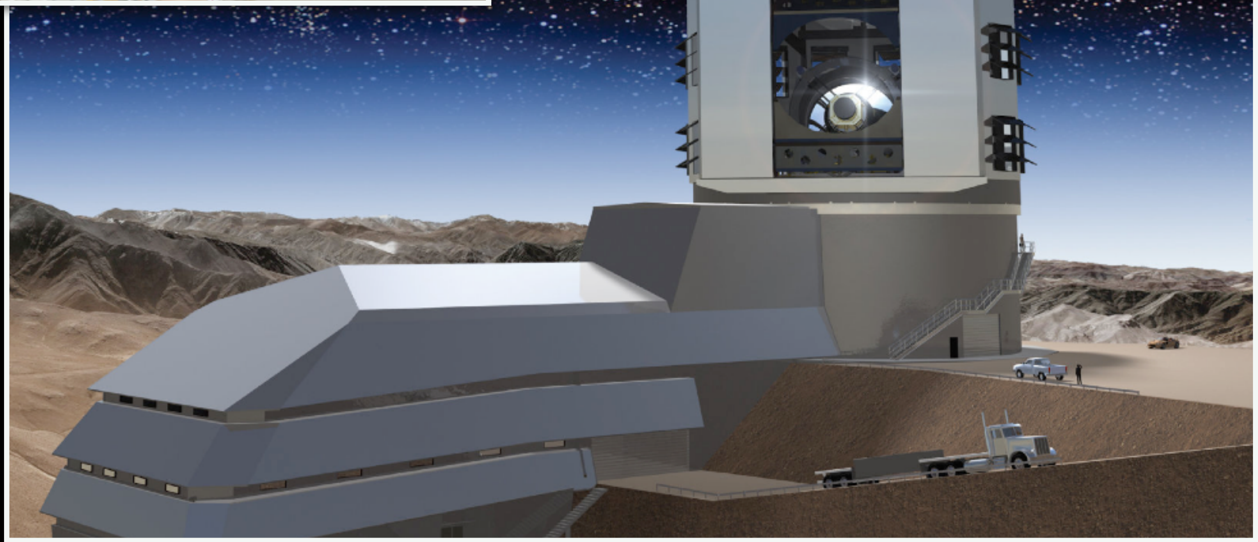
r ~ 22

Stage II
e.g., SDSS



r ~ 24

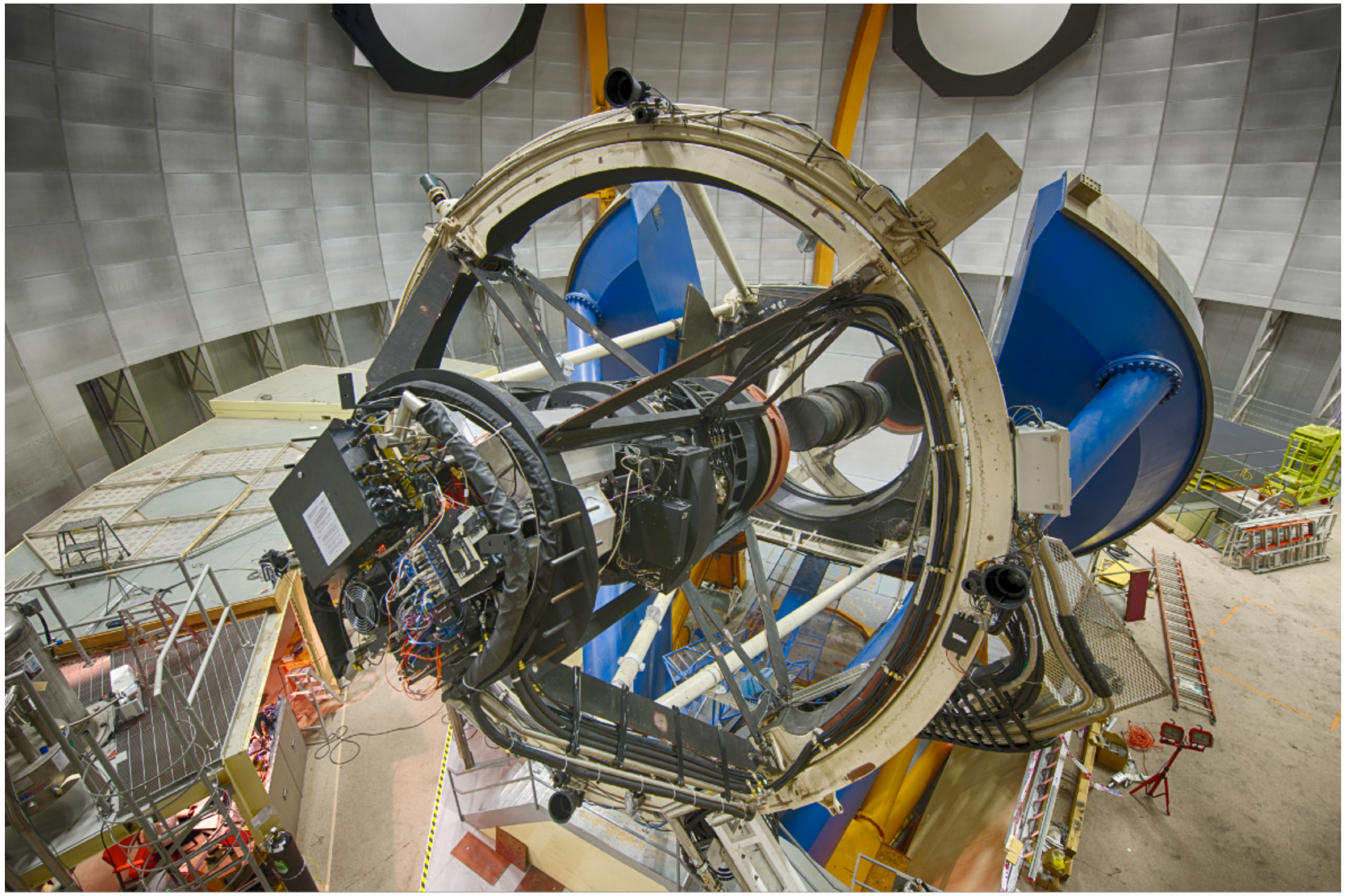
Stage III
e.g., DECam,
Pan-STARRS,
HSC, SkyMapper



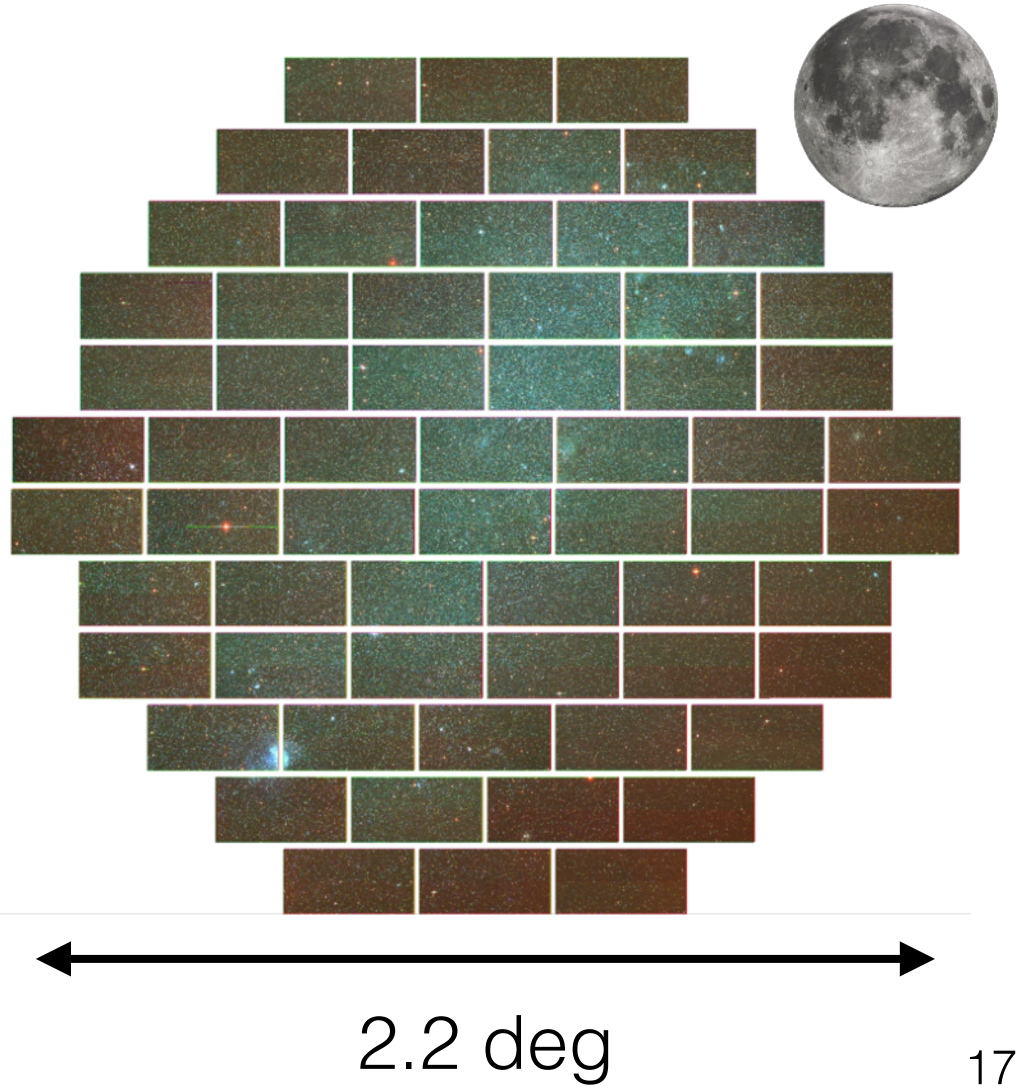
r ~ 26

Stage IV
e.g., LSST

Dark Energy Survey



Dark Energy Camera (DECam)
New 570 Mpix camera
on Blanco 4-m at CTIO



Dark Energy Survey (DES)
5 years, 525 nights, 5000 deg^2
10 visits in each of *grizY*
10σ depth fainter than 24 mag in *gr*

1 of 62 DECam CCDs (18’ x 9’)

90 sec exposure every ~120 sec

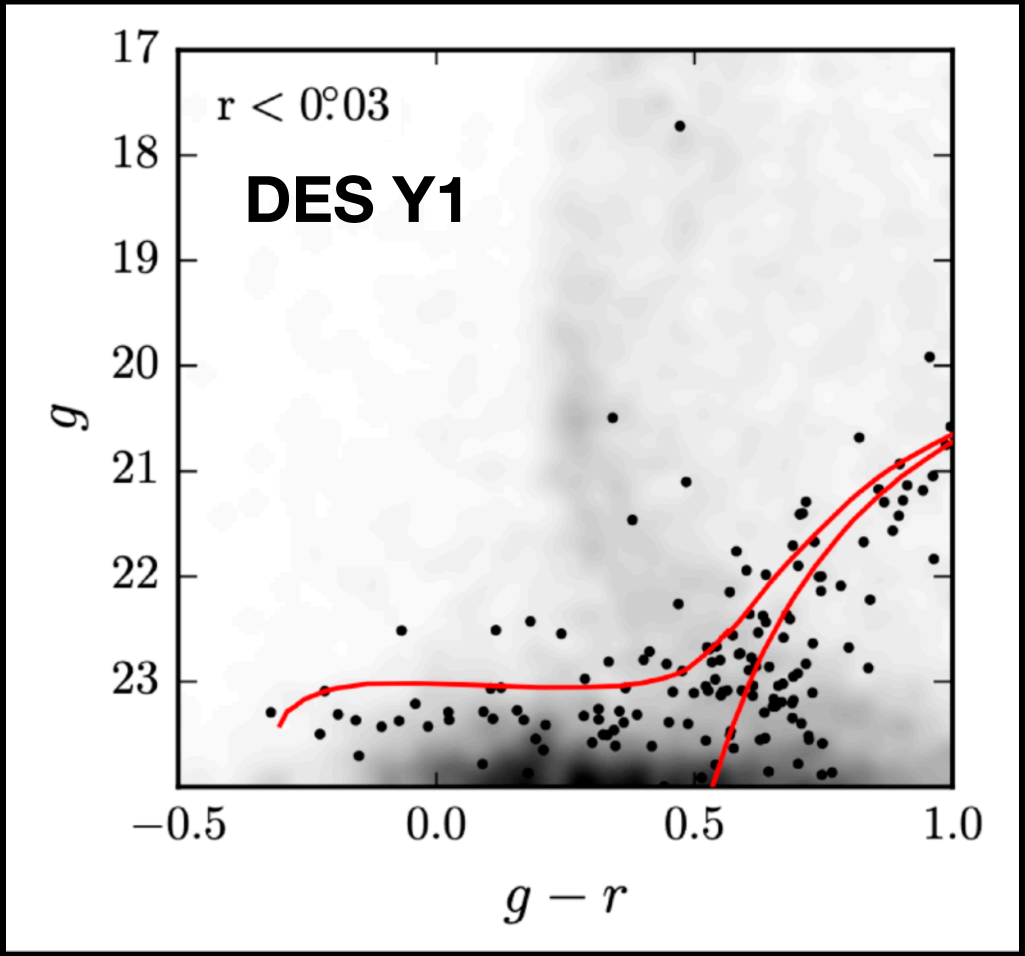
~15,000 exposures per year × 5.5 years

~700M cataloged objects

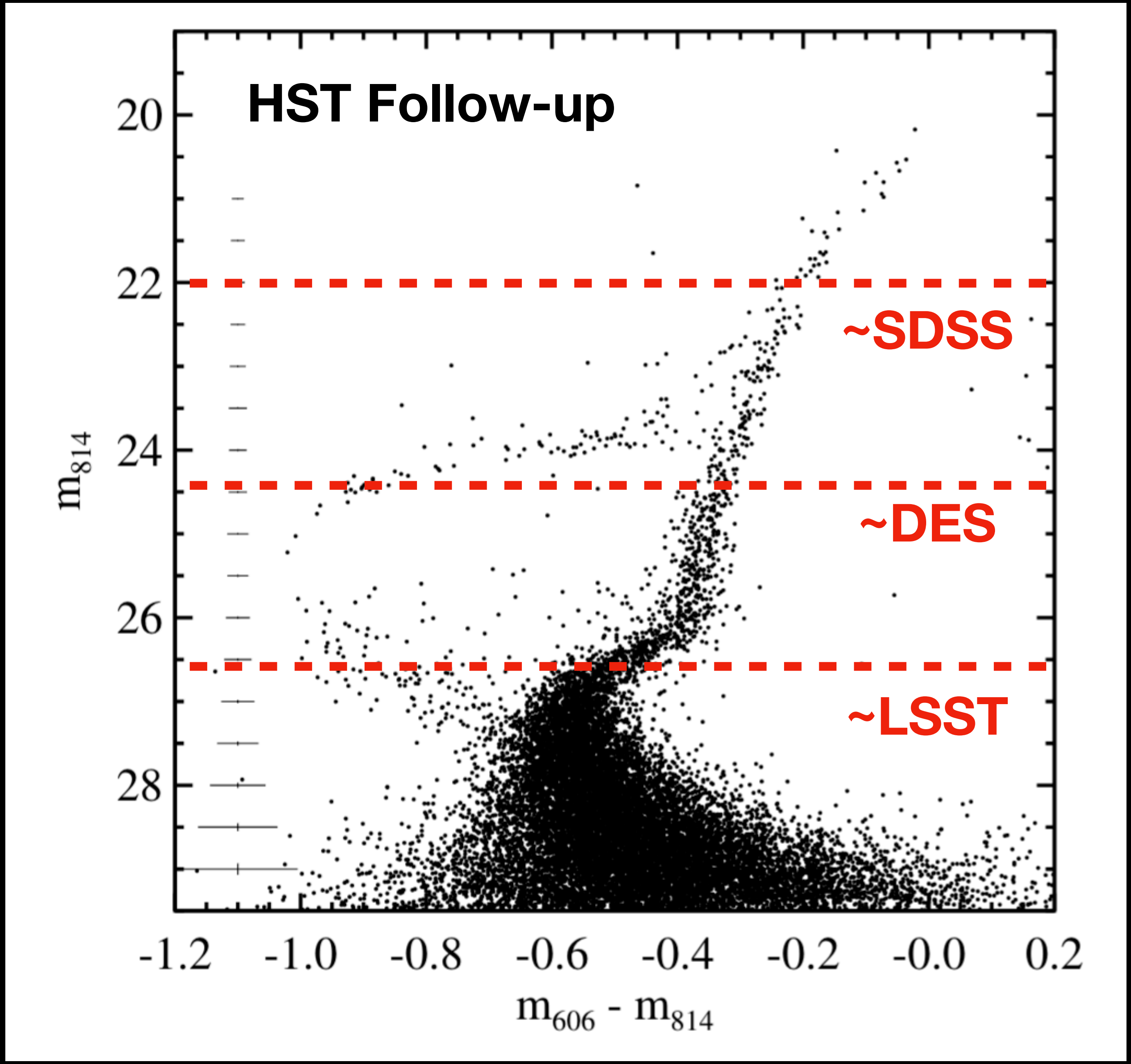
~20% of objects in a typical field are foreground Milky Way stars

Imaging Depth:
Example with Eridanus II dSph

THE DARK ENERGY SURVEY



Simon et al. in prep



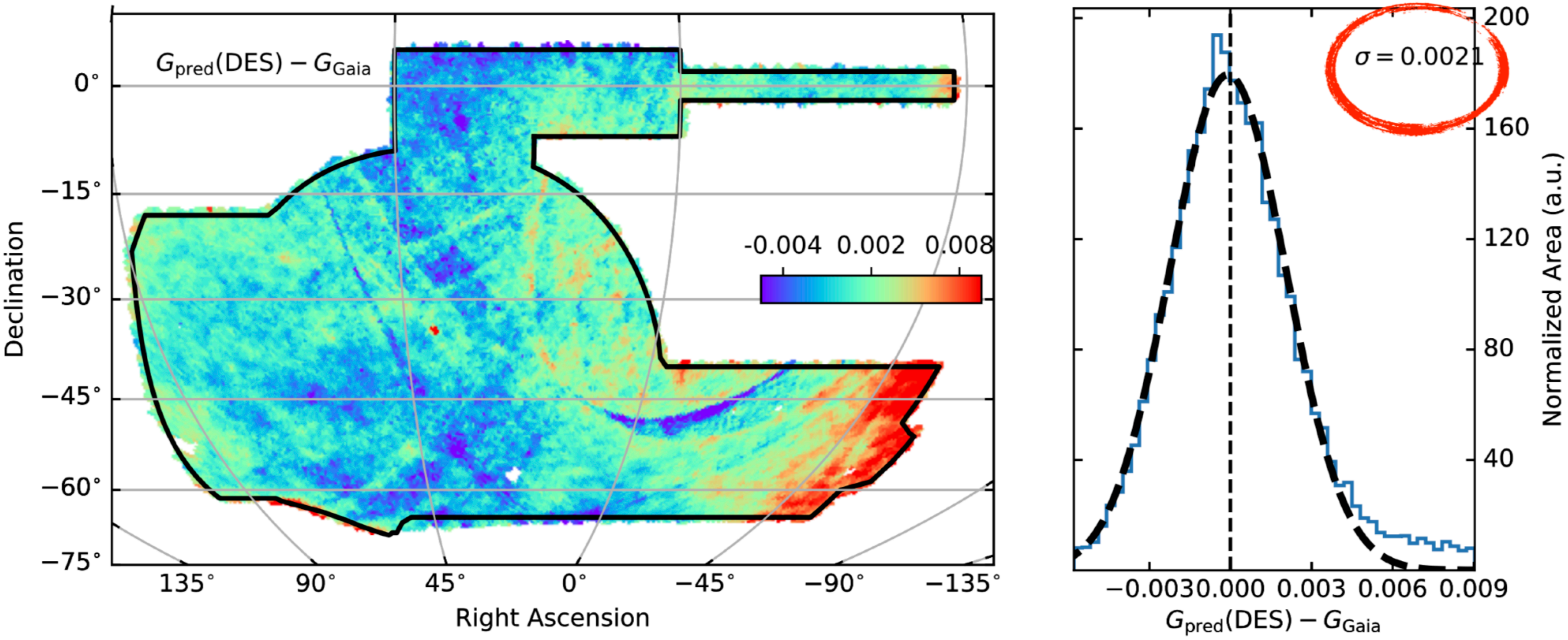
Example for the dwarf galaxy Eridanus II at ~370 kpc, beyond the Milky Way viral radius ~300 kpc

DES stellar sample limited mainly by star-galaxy confusion, rather than detection signal-to-noise

Photometry: Uniformity over the Survey Footprint

THE DARK ENERGY SURVEY

Gaia and DES photometric calibrations are completely independent
Both surveys must be uniform to better than 2 mmag RMS



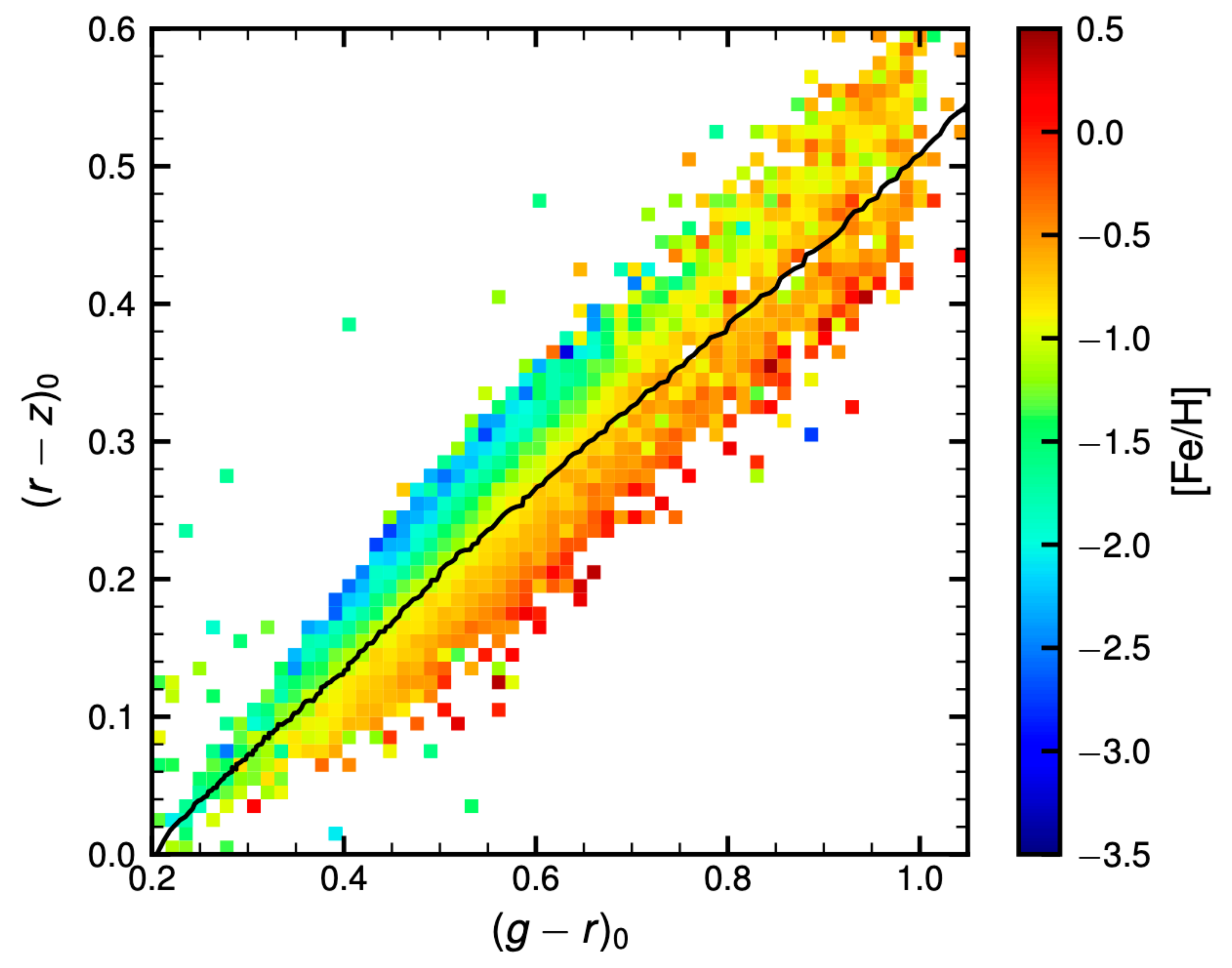
Forward Global Calibration Module (FGCM)

Burke & Rykoff 2017
arXiv:1706.01542

Photometry: Metallicity Estimates

THE DARK ENERGY SURVEY

DES provides *grizY* photometry

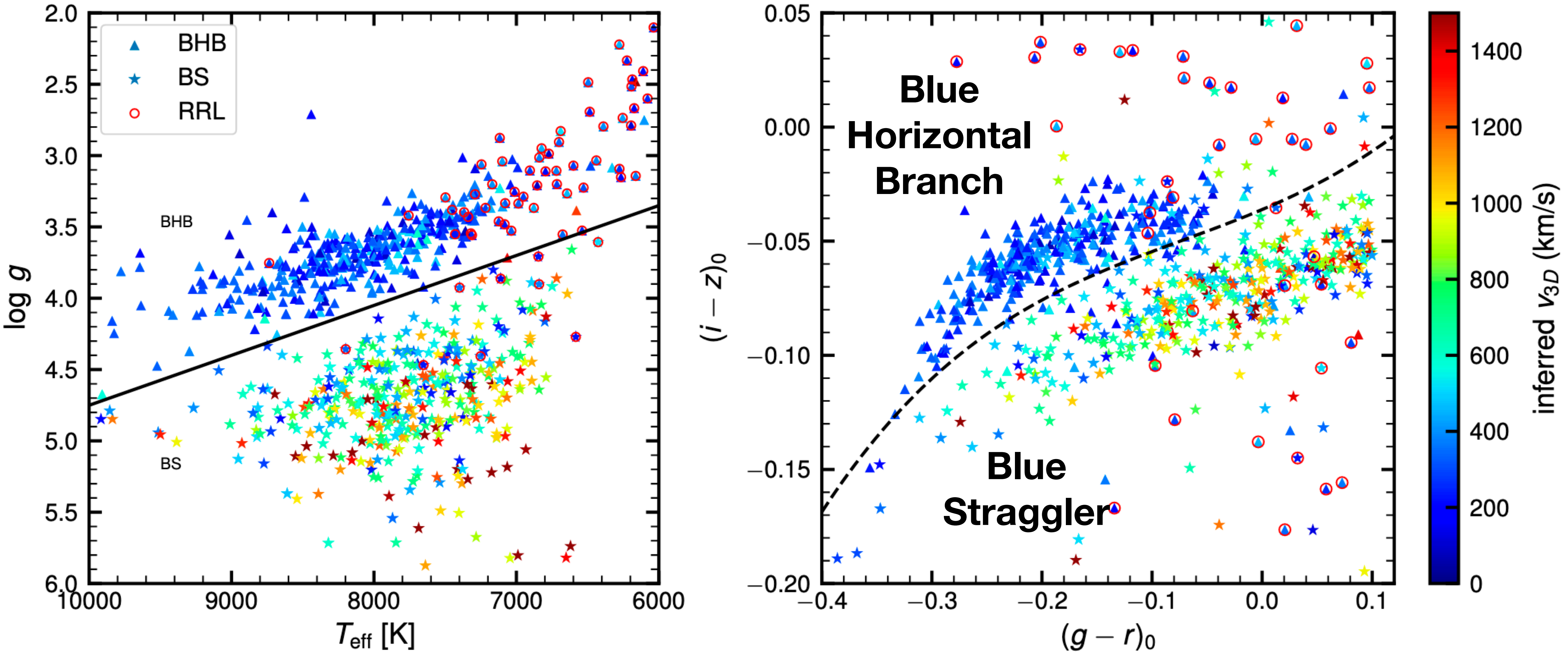


Li et al. 2019
arXiv:1907.09481

Spectroscopic sample from the S5 stellar stream follow-up program

Photometry:
Blue Horizontal Branch Stars

DES provides *grizY* photometry



Li et al. 2019
arXiv:1907.09481

Astrometry: Gaia HR Diagram

$V_T < 40$ km s^{-1}

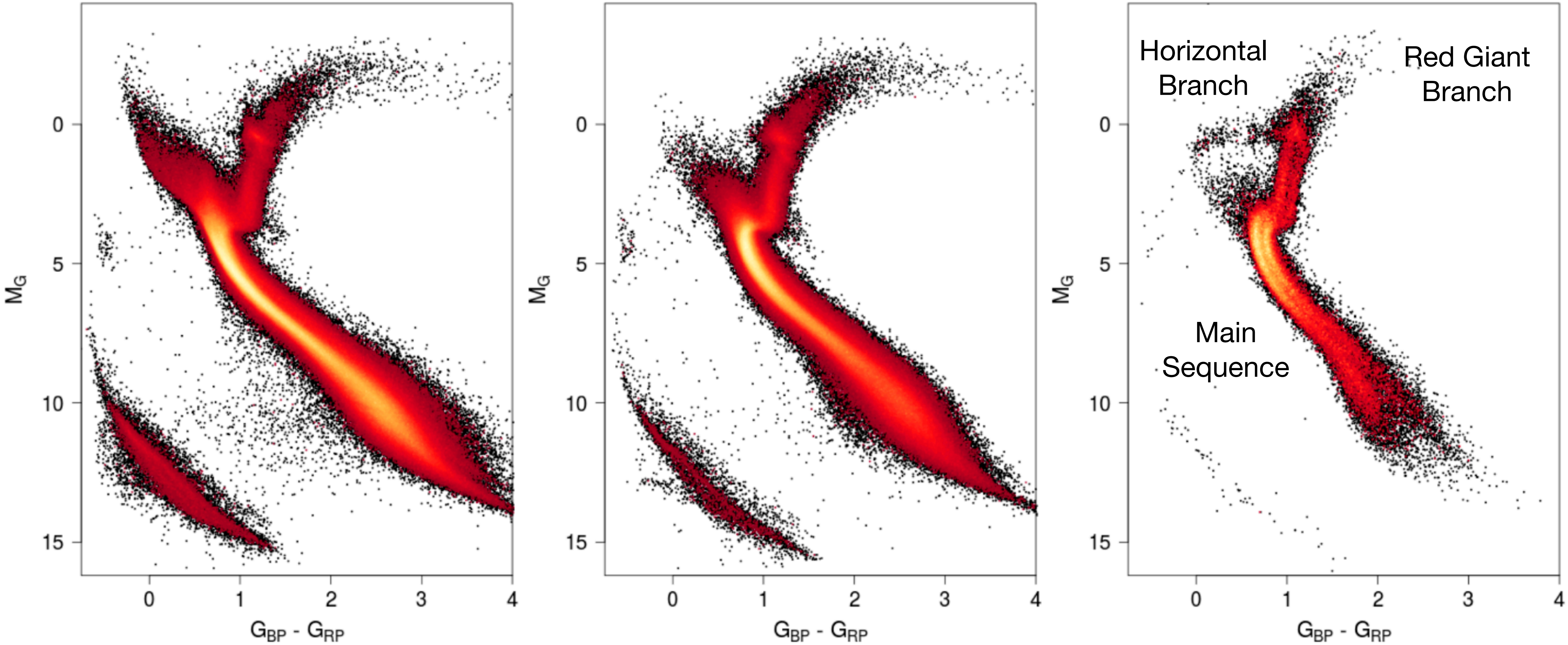
Thin Disk

$60 < V_T < 150$ km s^{-1}

Thick Disk

$V_T > 200$ km s^{-1}

Halo



Added value from matching all the brightest DES stars to Gaia…

Astrometry: Gaia HR Diagram

$V_T < 40$ km s^{-1}

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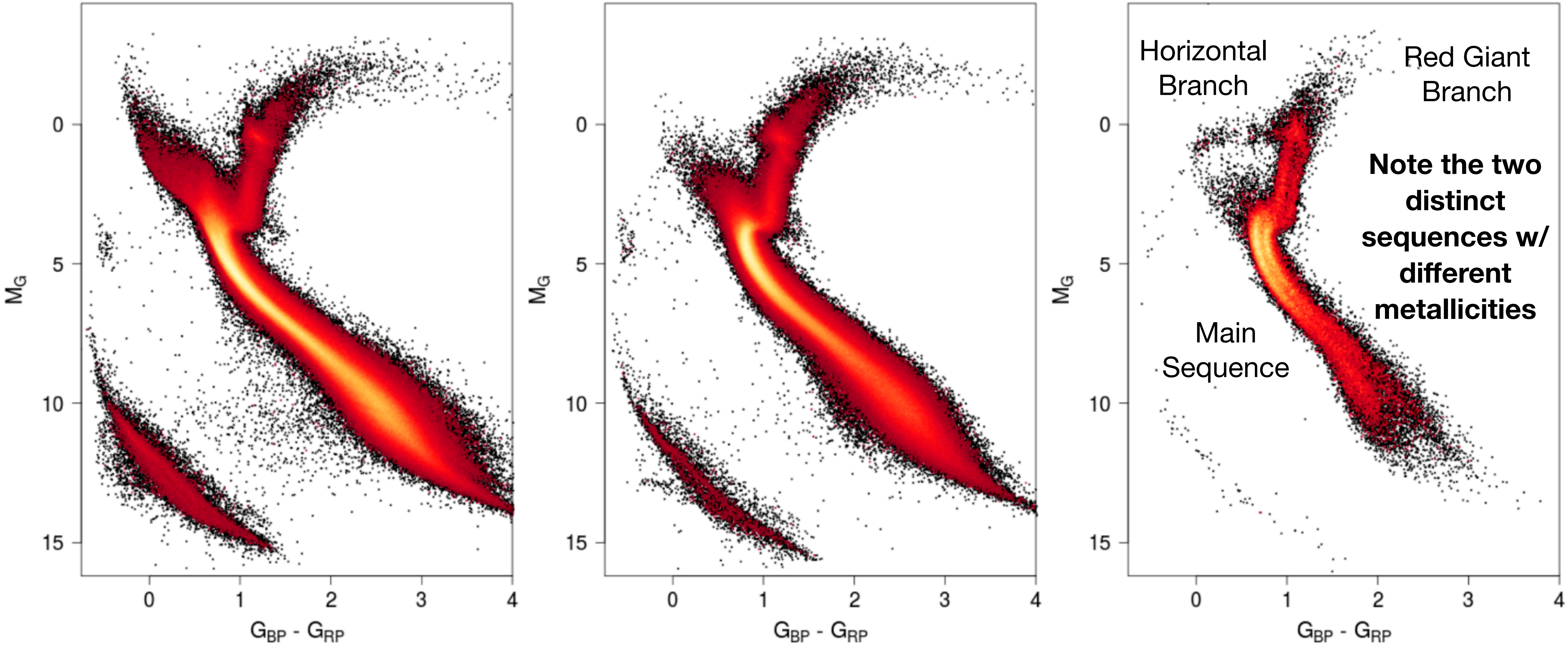
Halo



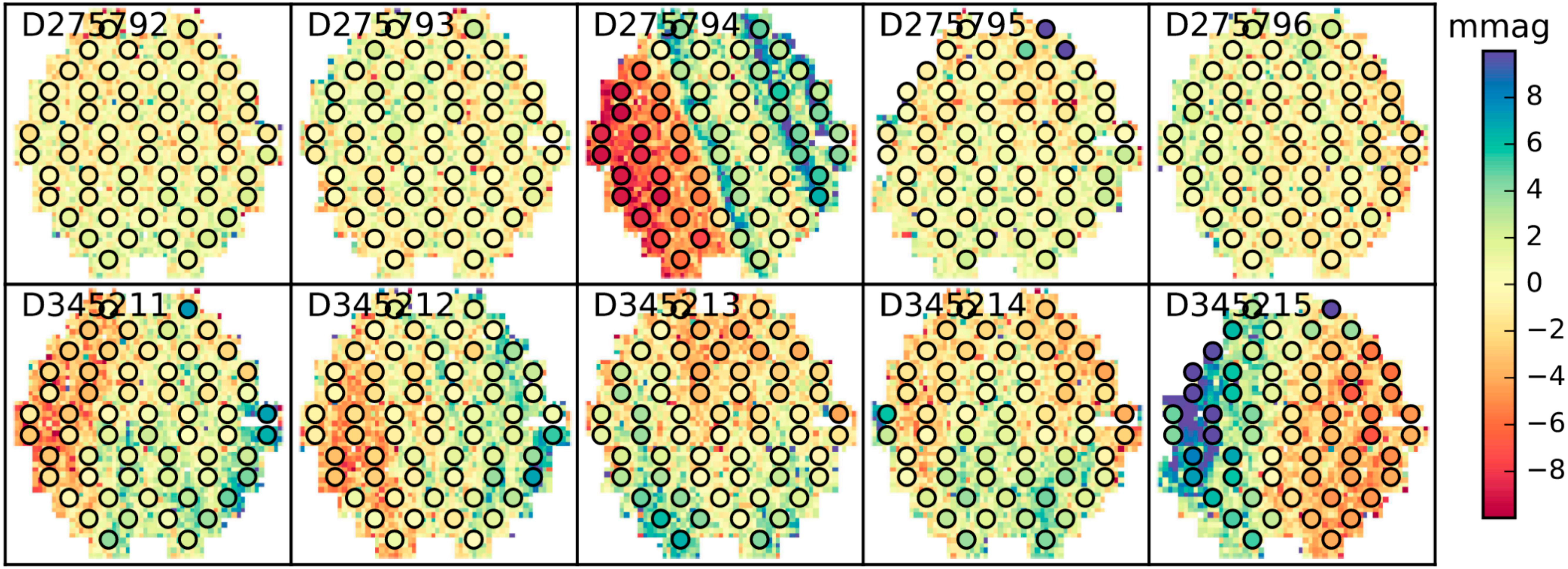
Note the two distinct sequences w/ different metallicities

Added value from matching all the brightest DES stars to Gaia…

Photometry:
Atmospheric Turbulence

THE DARK ENERGY SURVEY

Exposure-to-exposure photometric residuals correlate with local aperture correction

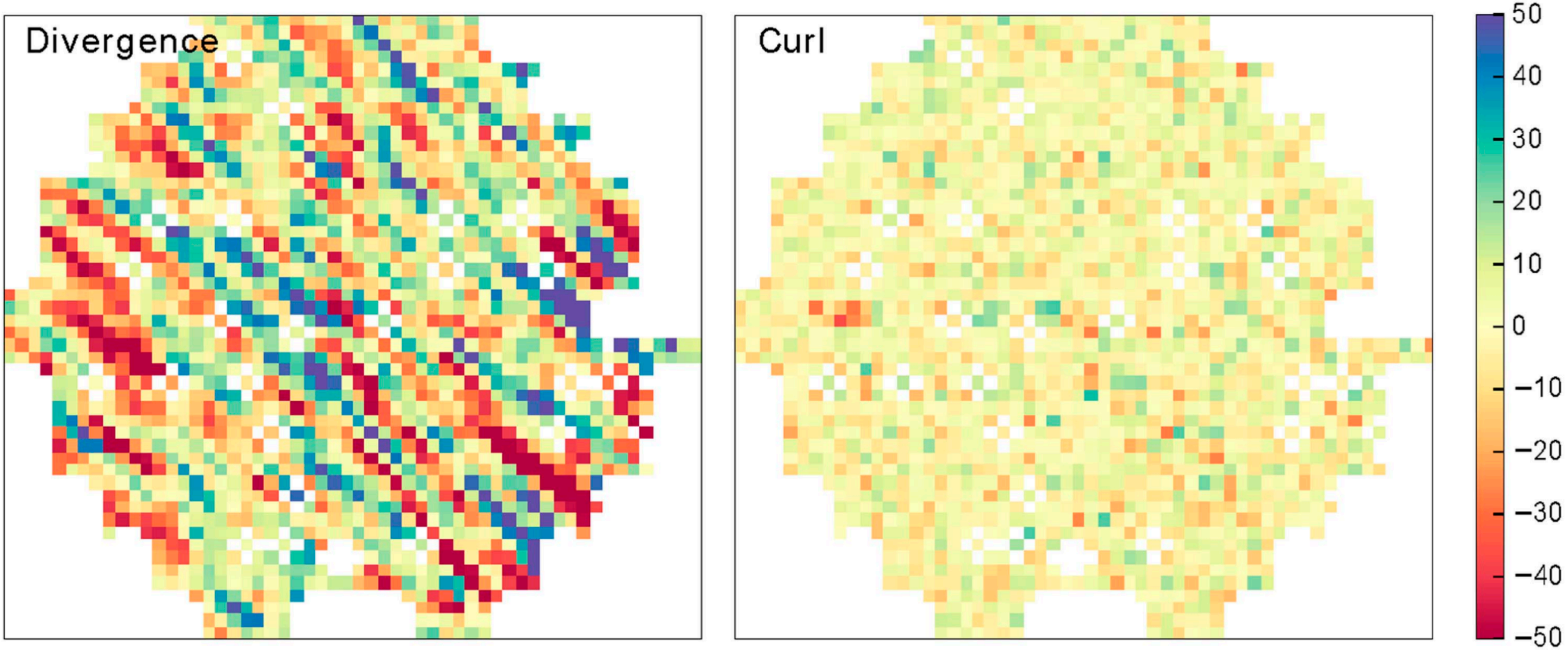


For details, see Gary Bernstein's presentation:
https://project.lsst.org/meetings/law/sites/lsst.org.meetings.law/files/Photometric%20and%20Astrometry%20-%20Gary%20Bernstein.pdf

Astrometry:
Atmospheric Turbulence

THE DARK ENERGY SURVEY

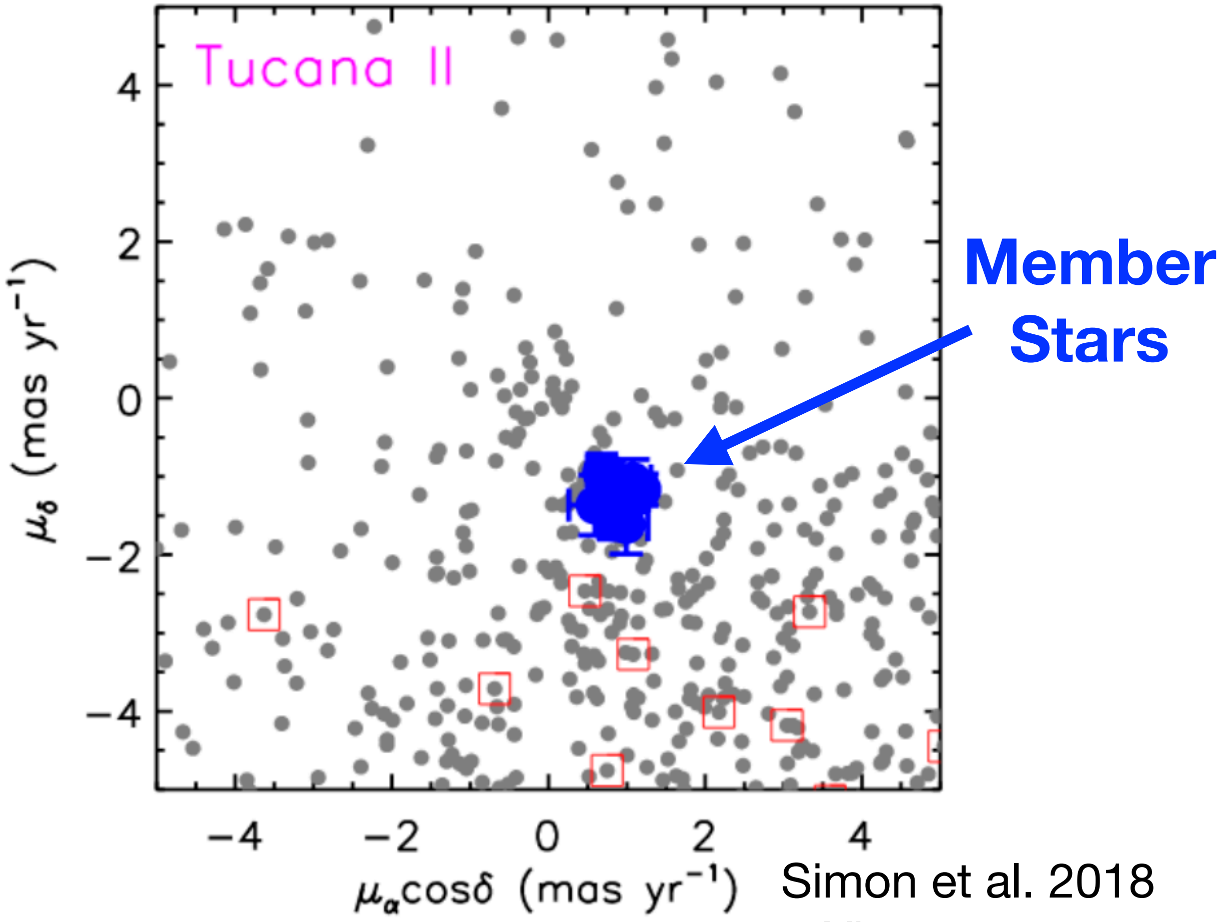
Exposure-to-exposure astrometric residuals correlated on ~10 arcmin scales



For details, see Gary Bernstein's presentation:
https://project.lsst.org/meetings/law/sites/lsst.org.meetings.law/files/Photometric%20and%20Astrometry%20-%20Gary%20Bernstein.pdf

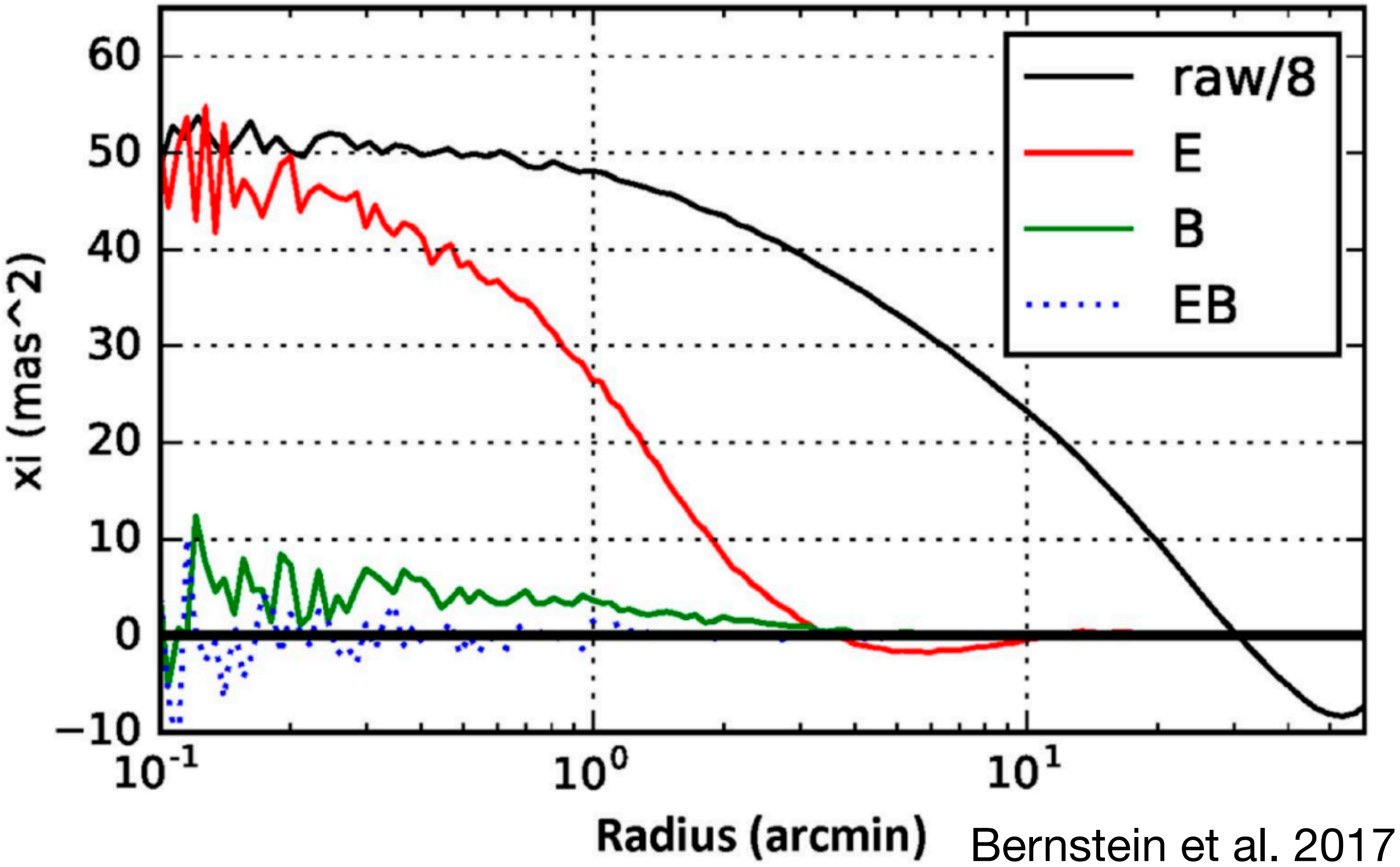
Astrometry: Matching to Gaia and Going Fainter

Proper Motions from Gaia to identify satellite member stars



Simon et al. 2018
arXiv:1804.10230

Use Gaia to measure atmospheric turbulence in individual exposures



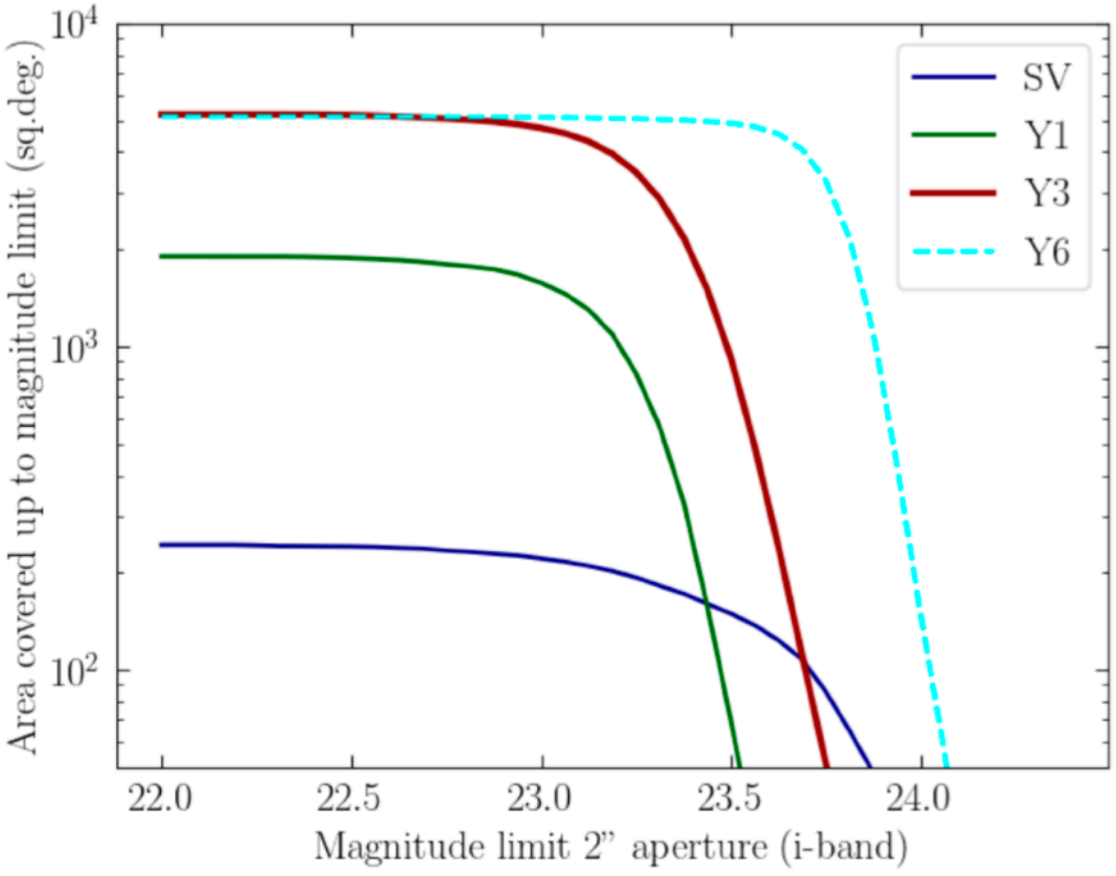
Bernstein et al. 2017
arXiv:1703.01679

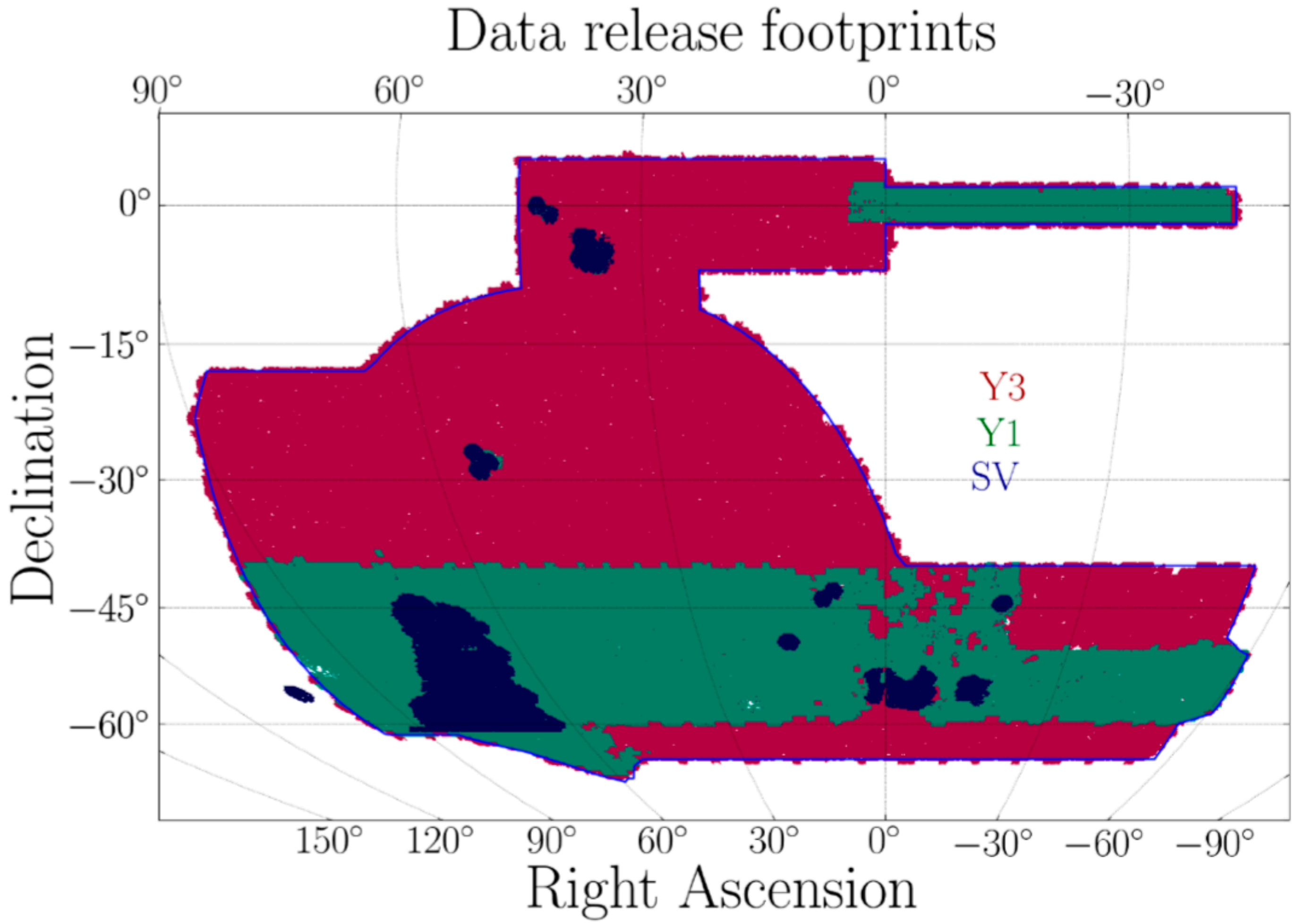
Preliminary results from DES Y6 suggest astrometric errors of 1.5-2 mas yr^{-1} for bright stars (i < 21 mag); extends fainter than Gaia at comparable precision

DES DR2 Coming January 2021

THE DARK ENERGY SURVEY

DES DR2 public release is based on the complete 6 seasons of DES
Same area coverage as Y3 and nearly twice the number of epochs





NCSA

NOIR Lab

ASTRO DATALAB

DES-BRAZIL

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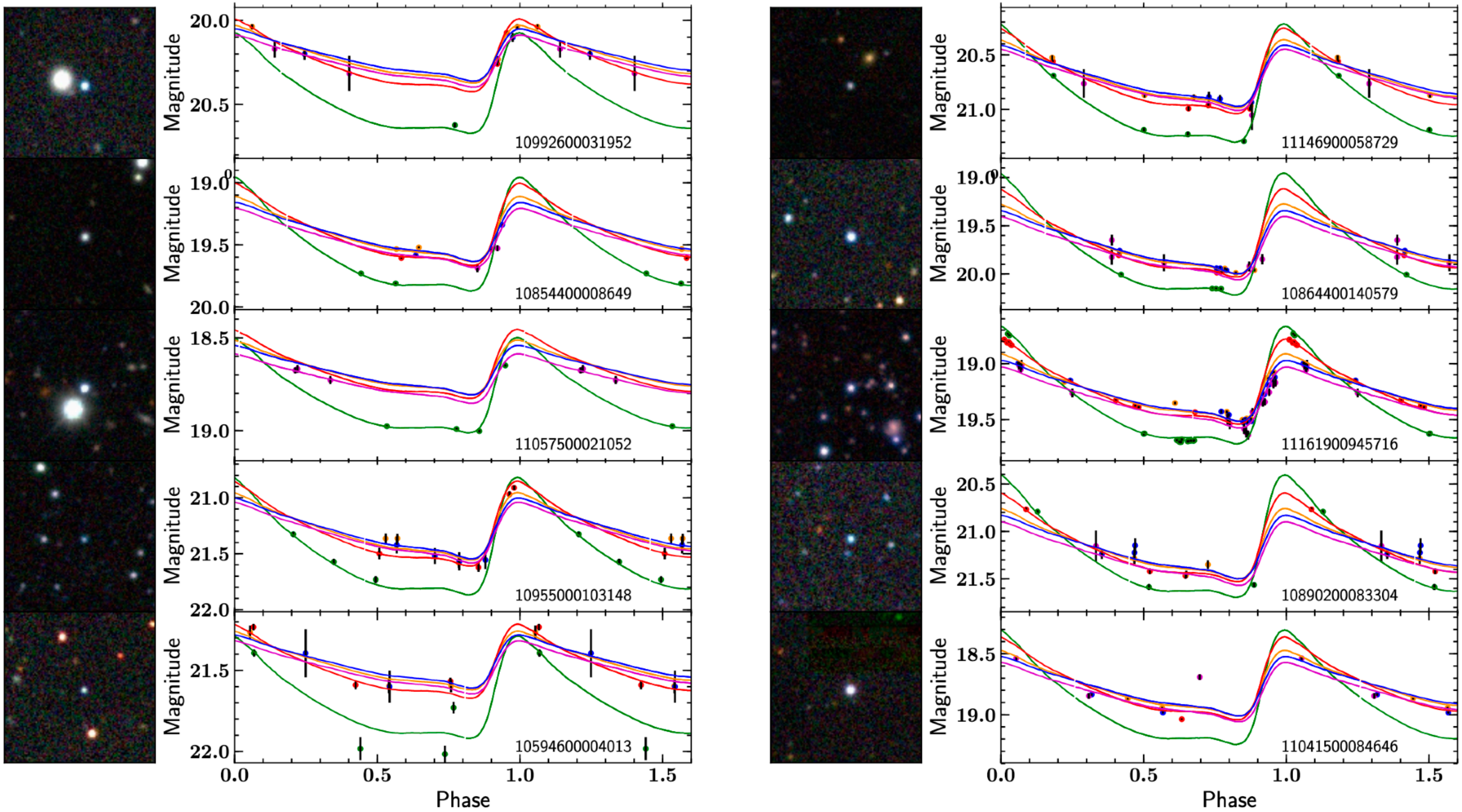
  - Luminosity function of Milky Way satellites

RR Lyrae Stars as Tracers of the Stellar Halo

THE DARK ENERGY SURVEY



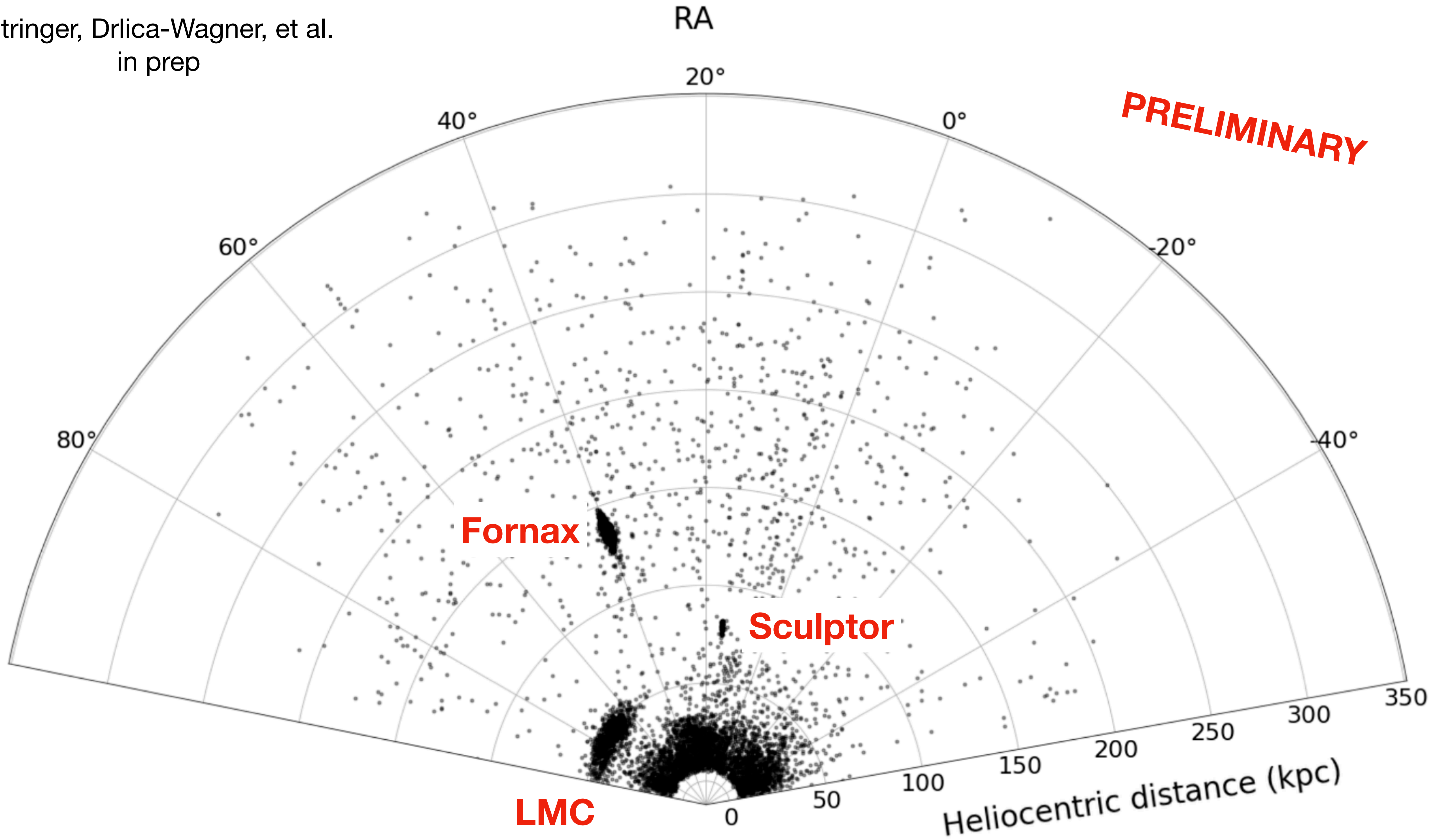
Stringer et al. 2019
arXiv:1905.00428

Reliable distances from period-luminosity relation

RR Lyrae Stars as Tracers of the Stellar Halo

THE DARK ENERGY SURVEY

Stringer, Drlica-Wagner, et al. in prep



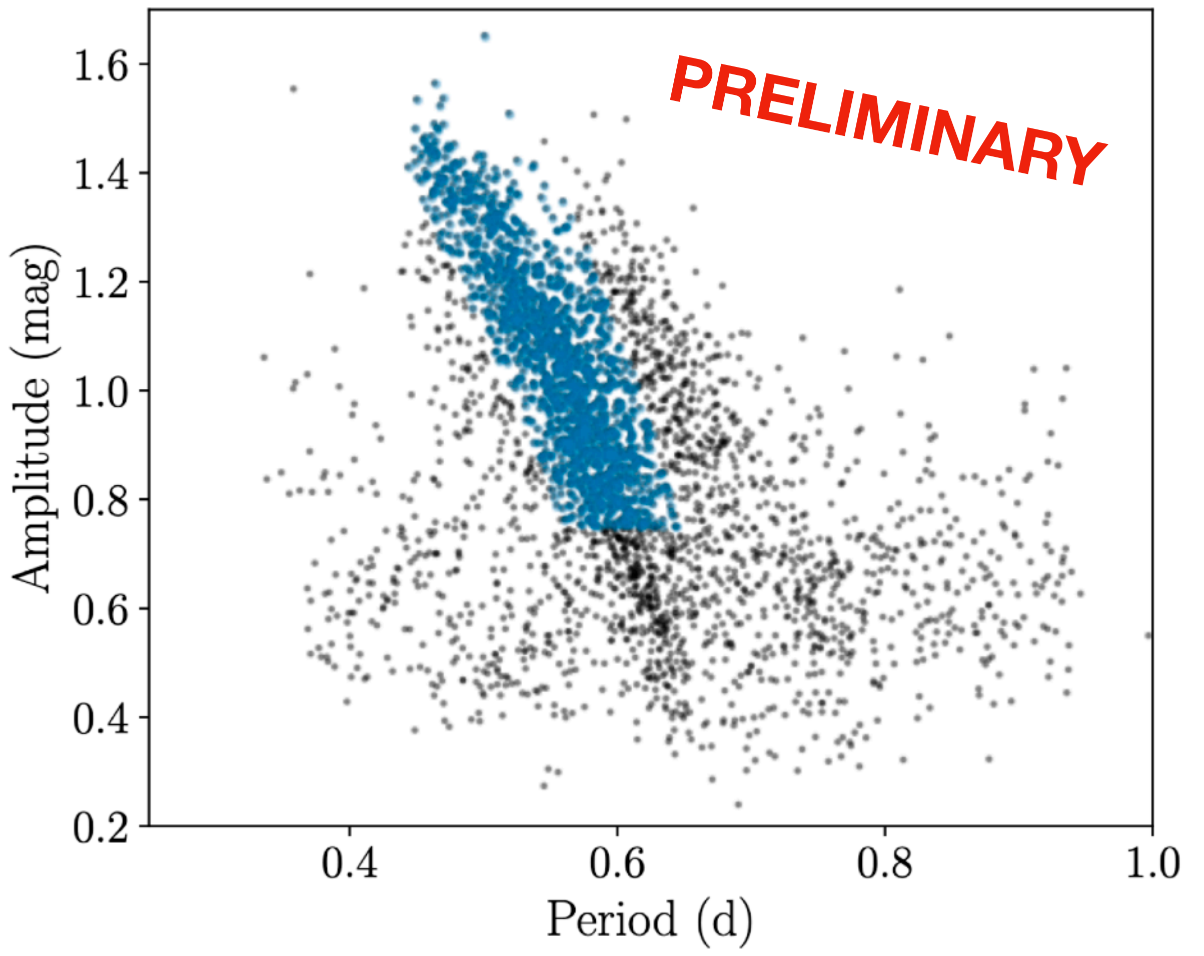
~7000 RR Lyrae candidates in DES Y6 out to ~330 kpc

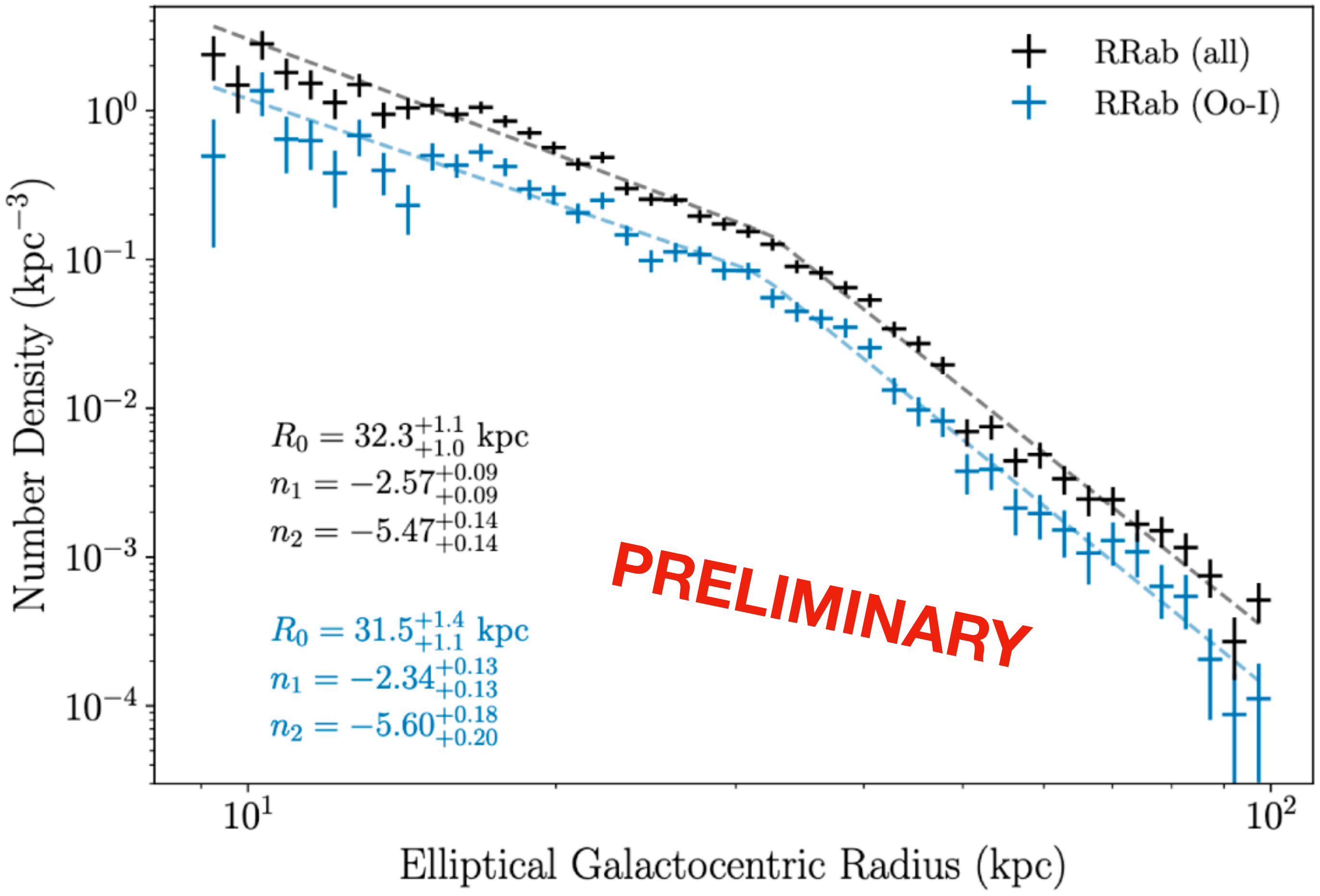
RR Lyrae Stars as Tracers of the Stellar Halo

THE DARK ENERGY SURVEY

Locate RR Lyrae candidates in known dwarf galaxies and globular clusters

Density profile of RR Lyrae exhibits break, consistent with other halo studies



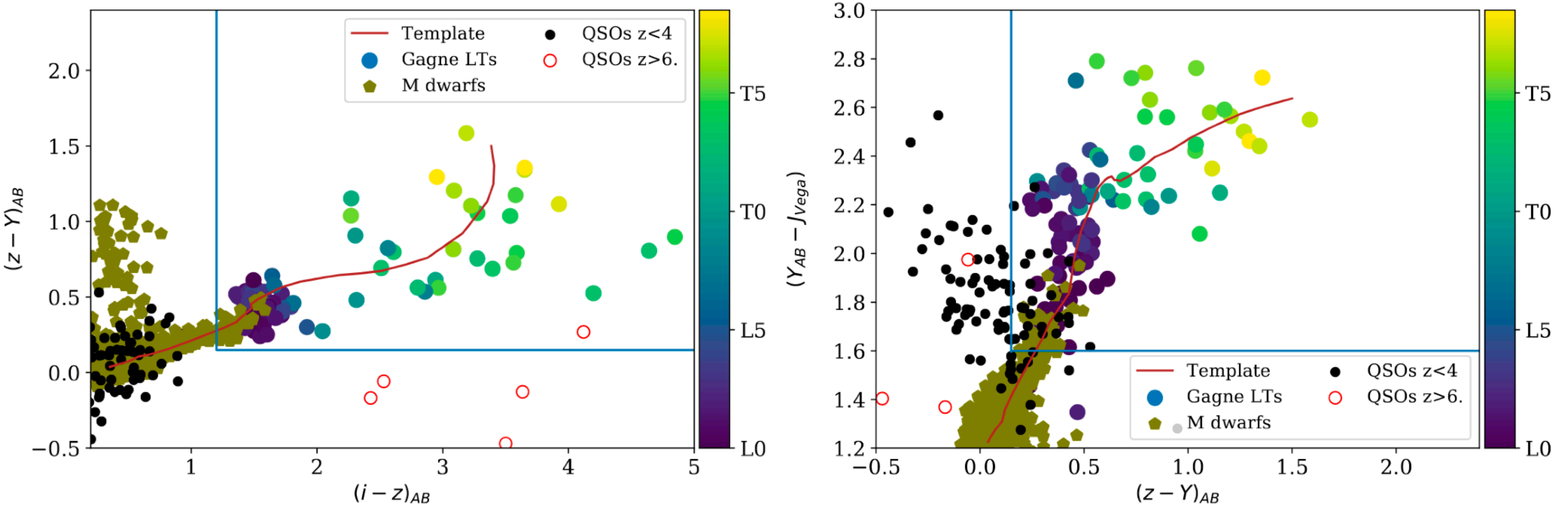


~7000 RR Lyrae candidates in DES Y6 out to ~330 kpc

Ultracool Dwarfs as Tracers of the Thin Disk

Largest single sample of LT brown dwarfs to date (11,700)

made possible from combination of DES (*grizY*) + VHS (*JHK*) photometry

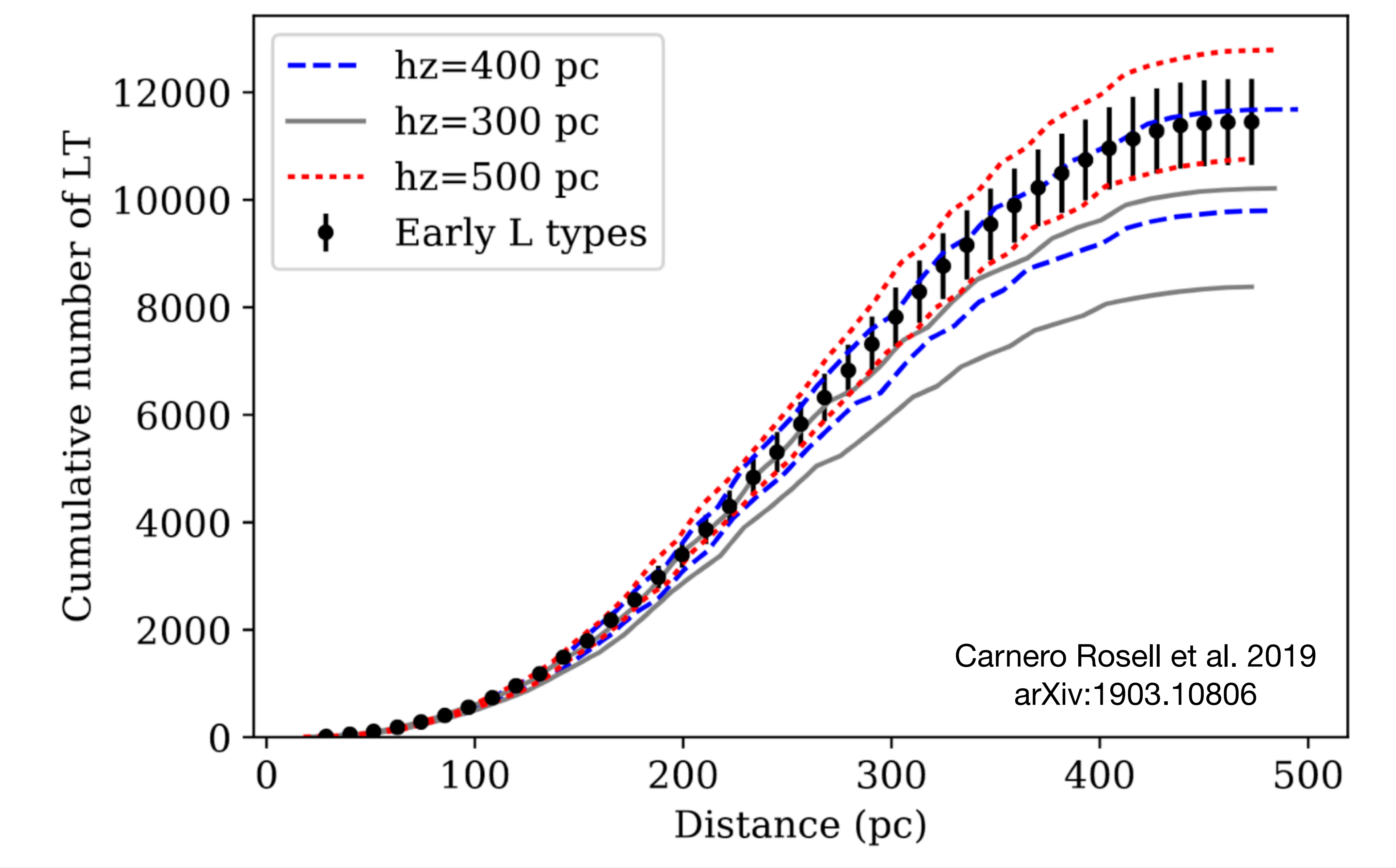


Carnero Rosell et al. 2019
arXiv:1903.10806

Ultracool Dwarfs
as Tracers of the Thin Disk

THE
DARK
ENERGY
SURVEY

DES LT brown draft sample favors thin disc scale height of ~450 pc

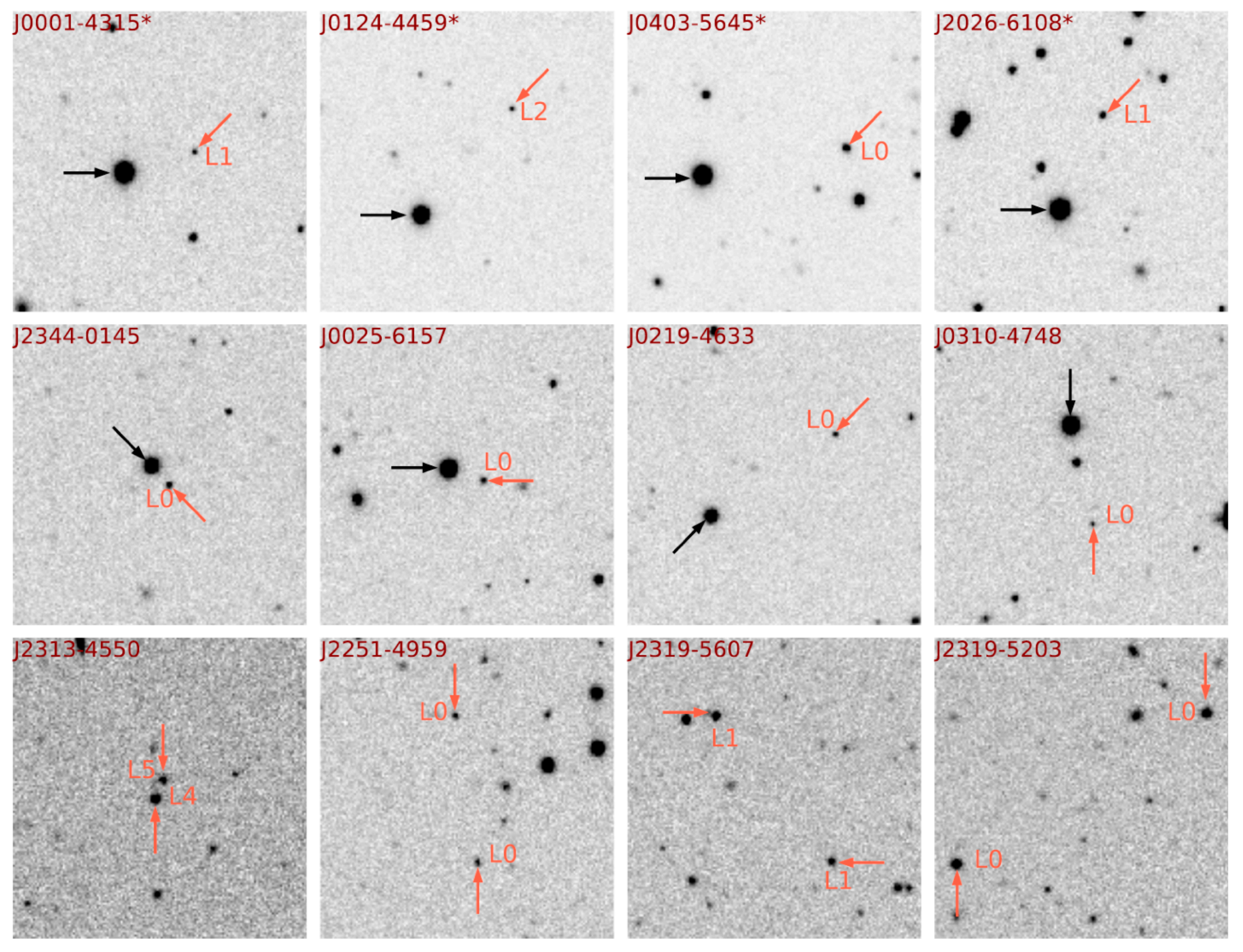


Carnero Rosell et al. 2019
arXiv:1903.10806

Ultracool Dwarfs in Wide Binaries and Multiple Systems

THE DARK ENERGY SURVEY

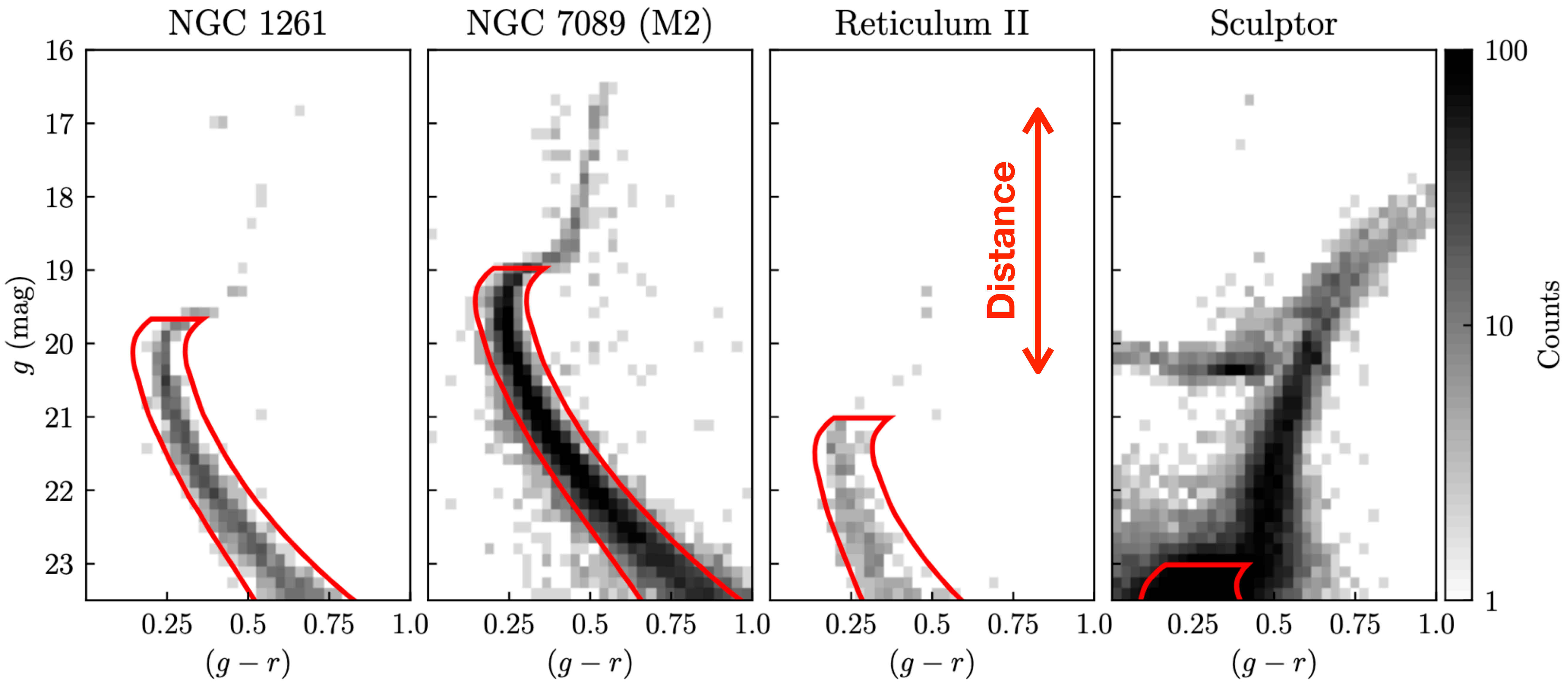
Sample of 255 binary + 5 triple system candidates



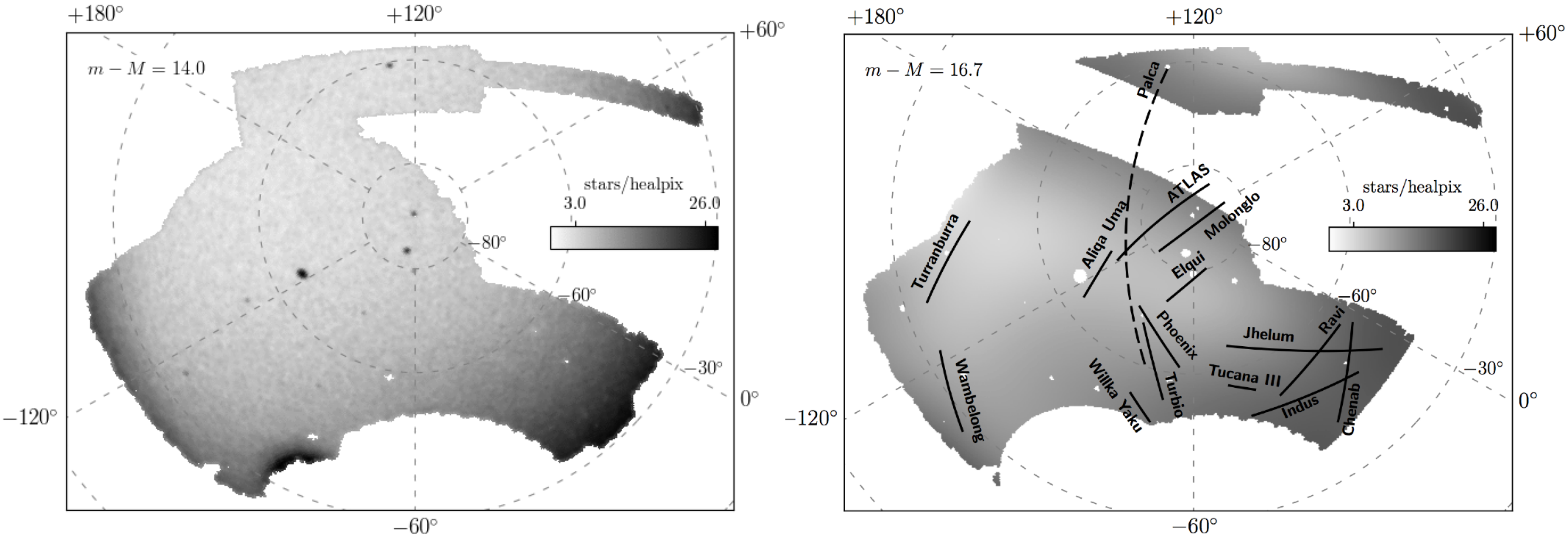
dal Ponte et al. 2020 arXiv:2001.11015

Stellar Streams

Use globular clusters and dwarf galaxies to validate a simple filter in color-magnitude space to select old and metal poor stars at different distances



Newly Discovered Stelllar Streams around the Milky Way



Selecting stars in intervals
of increasing heliocentric distance

Shipp et al. 2018
arXiv:1801.03097

11 new stellar streams, 4 previously known streams

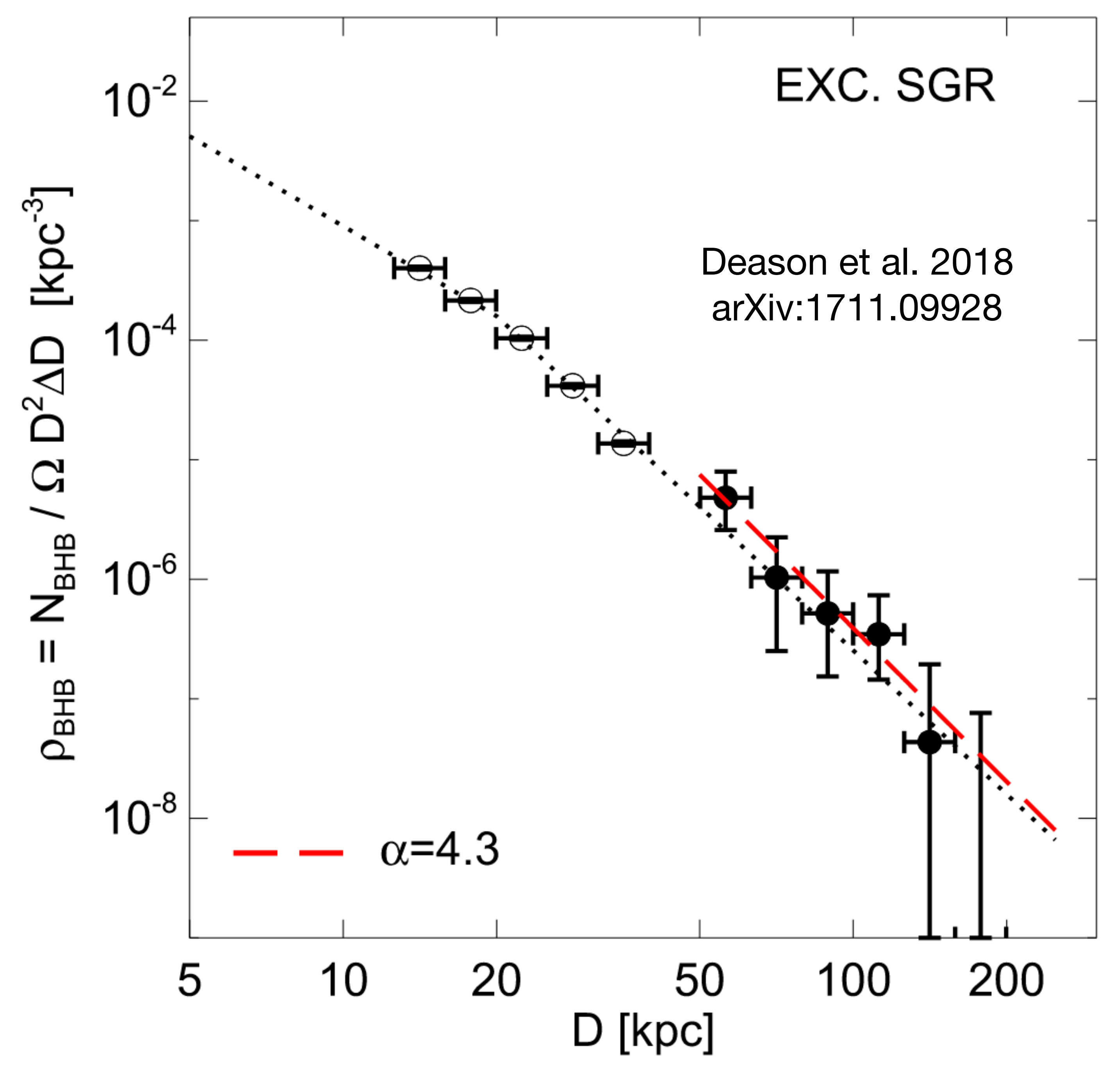
Generally more distant (out to 50 kpc) and lower surface brightness (~33 mag arcsec^{-2}) than previously known streams

Dynamical tracers of Milky Way gravitational potential and dark matter substructures

Milky Way Stellar Halo: Break in Radial Density Profile

THE DARK ENERGY SURVEY

Blue Horizontal Branch stars
100 deg² of HSC-SSP



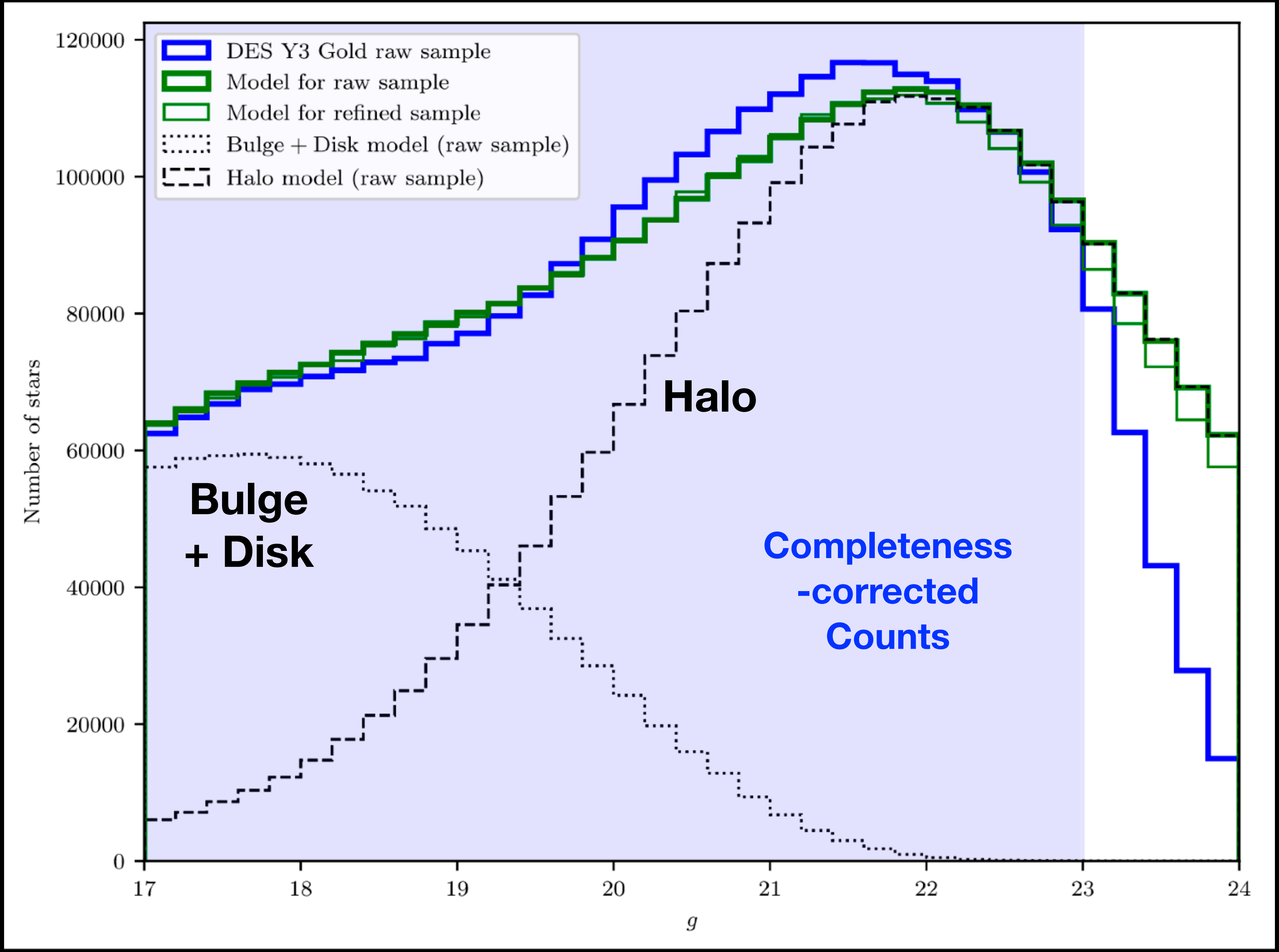
Based on further analysis of SDSS + Gaia, Deason et al. proposed that the break in power-law slope of the radial stellar density profile originates from stars piling up at the orbital apocenter of common dwarf progenitor, likely as massive as Fornax or Sagittarius dwarf galaxies

Deason et al. 2018
arXiv:1805.10288

Milky Way Stellar Halo:
Break in Radial Density Profile

THE DARK ENERGY SURVEY

Modeling full stellar color-magnitude distribution observed with DES over ~2600 deg^2 confirms presence of power-law break at Galactocentric radius ~20 kpc



Pieres et al. 2020
arXiv:1904.04350

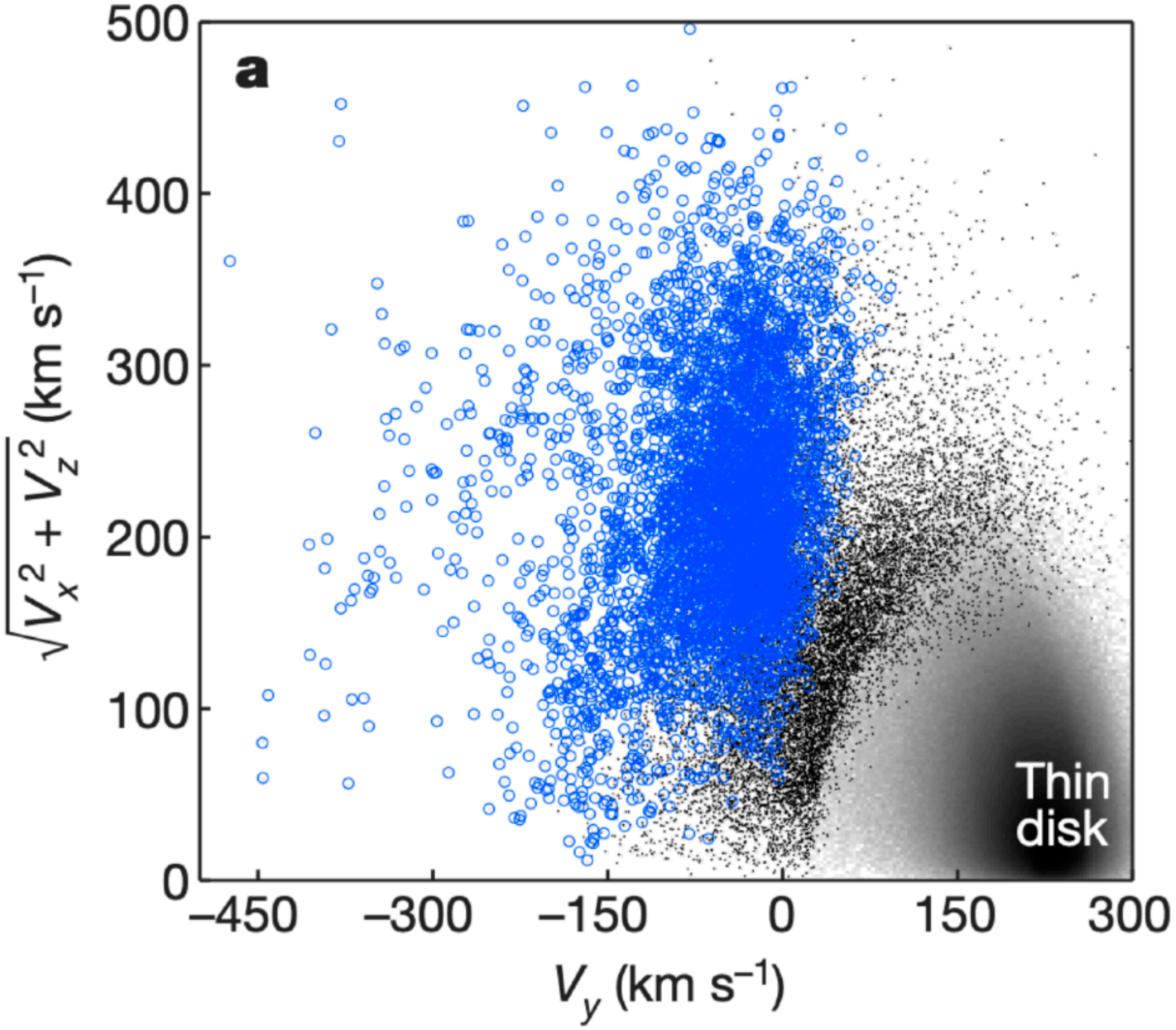
Milky Way Stellar Halo
Gaia-Enceladus

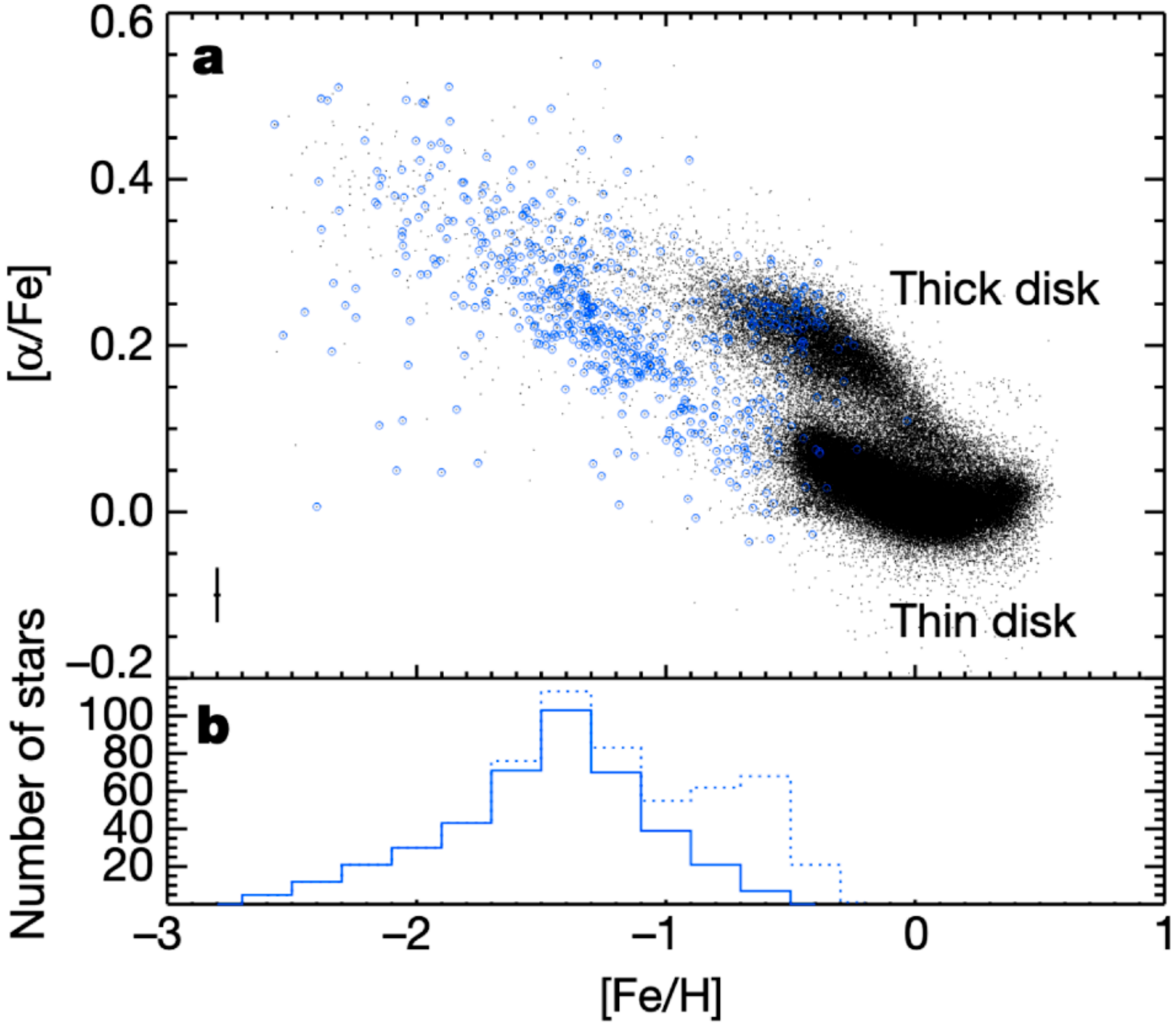
THE
DARK
ENERGY
SURVEY

Infer a merger event ~10 Gyr ago between Milky Way and a galaxy slightly more massive than the Small Magellanic Cloud; formation of thick disk

Structure in Velocity Space
Gaia

Structure in Chemical Space
APOGEE



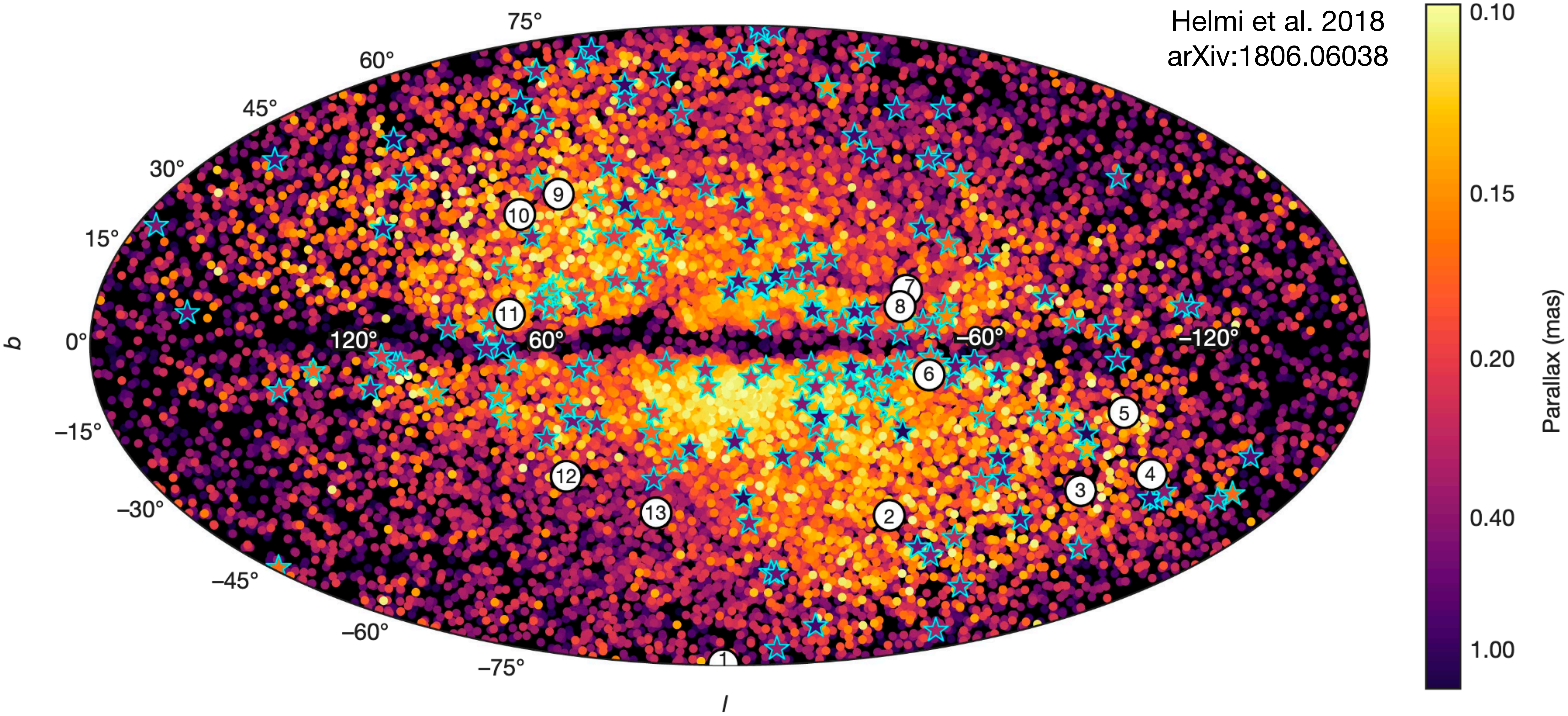


Helmi et al. 2018
arXiv:1806.06038

Milky Way Stellar Halo: Gaia-Enceladus

THE DARK ENERGY SURVEY

Debris from the Gaia-Enceladus accretion event covers the whole sky



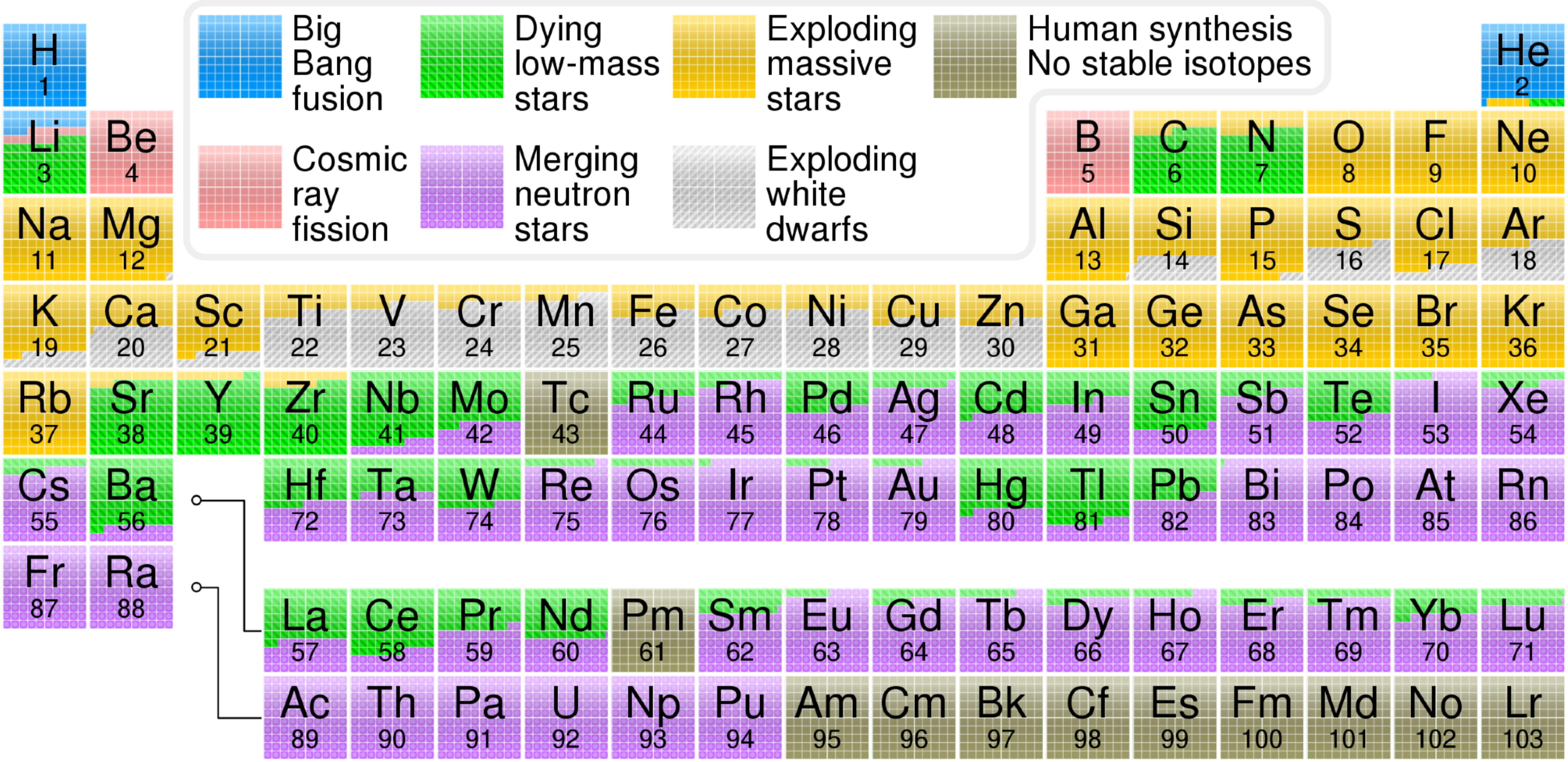
Helmi et al. 2018
arXiv:1806.06038

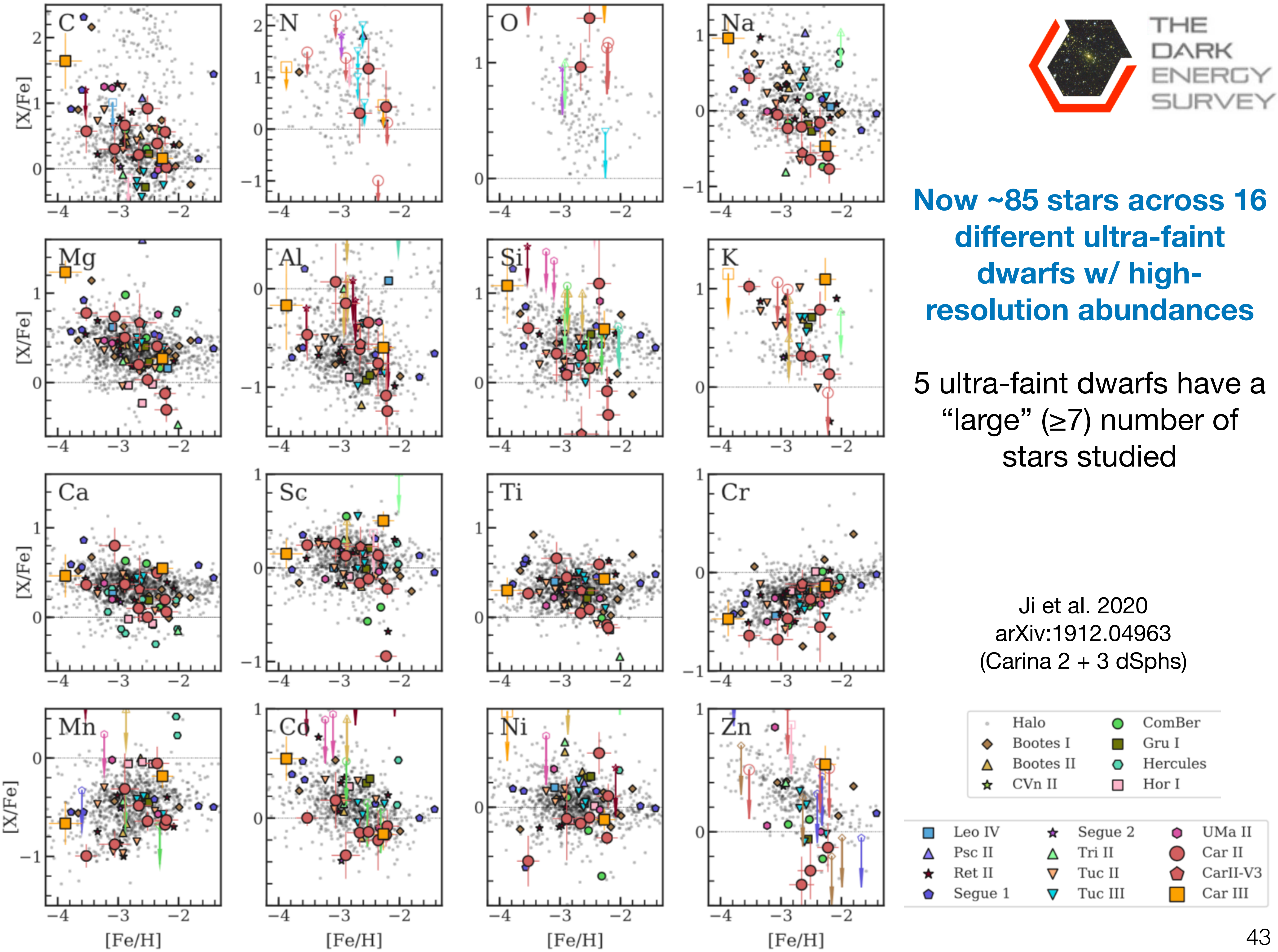
1 NGC 0288
2 NGC 0362
3 NGC 1851
4 NGC 1904
5 NGC 2298
6 NGC 4833
7 ω Cen
8 NGC 5286
9 NGC 6205
10 NGC 6341
11 NGC 6779
12 NGC 7089
13 NGC 7099

Chemical Abundances

Ultra-faint galaxies are the most chemically pristine galaxies known

In principle, it is possible to detect enrichment due to *individual events* (e.g., supernovae neutron star mergers)



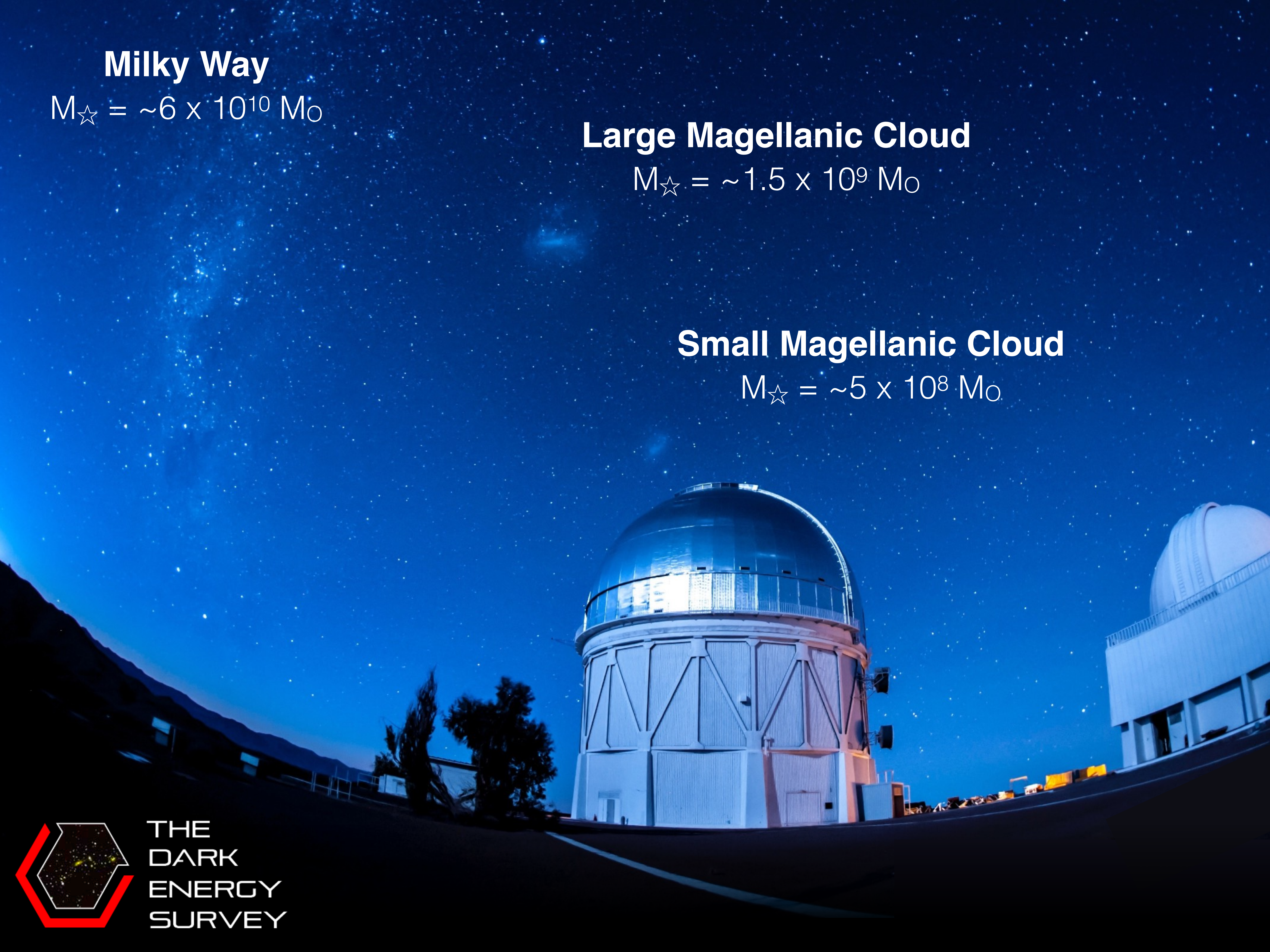


Now ~85 stars across 16 different ultra-faint dwarfs w/ high-resolution abundances

5 ultra-faint dwarfs have a “large” (≥7) number of stars studied

Ji et al. 2020
arXiv:1912.04963
(Carina 2 + 3 dSphs)

THE
DARK
ENERGY
SURVEY



Milky Way

$M_{\star} = {\sim}6 \times 10^{10}\, M_{\odot}$

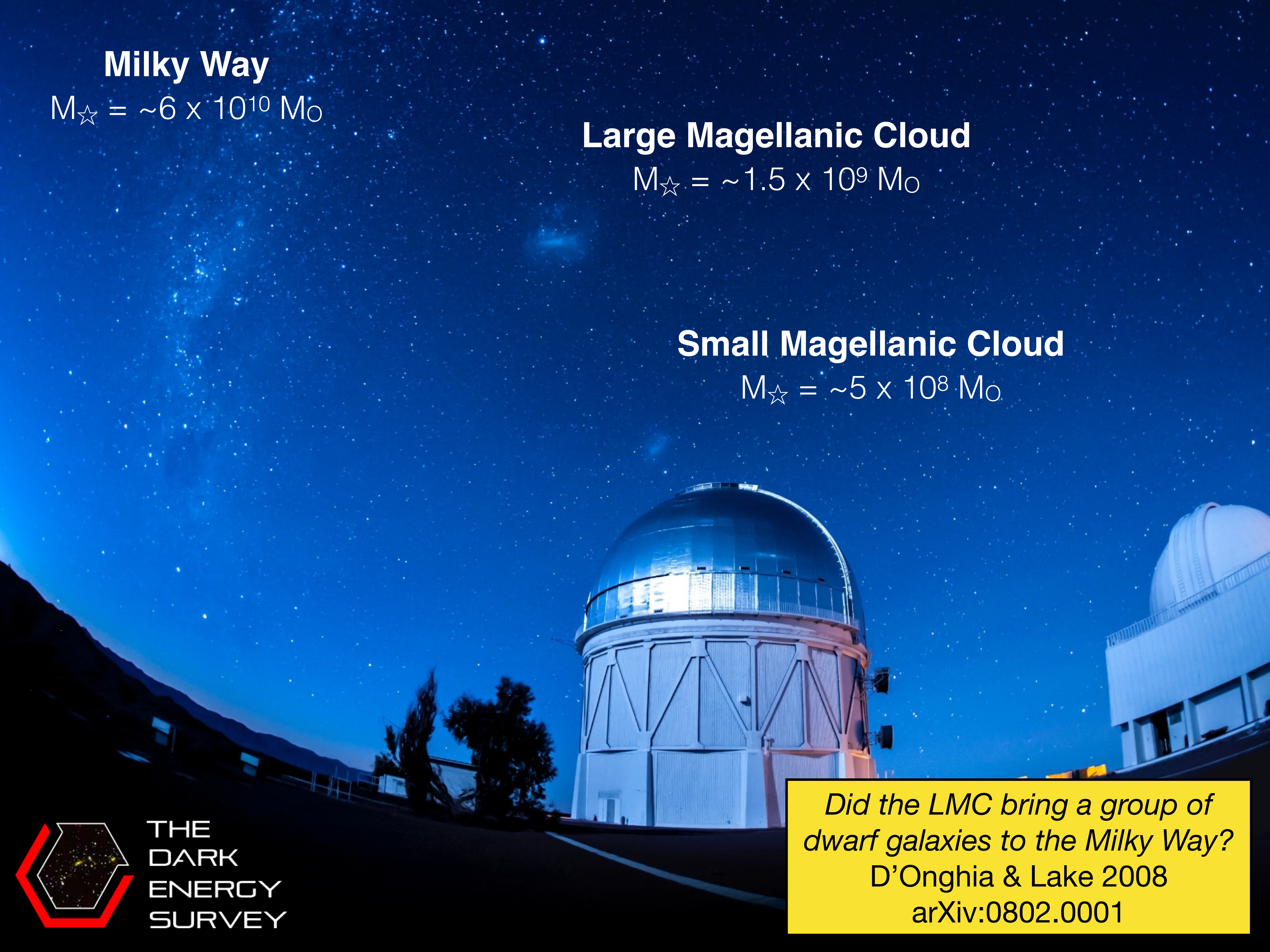
Large Magellanic Cloud

$M_{\star} = {\sim}1.5 \times 10^{9}\, M_{\odot}$

Small Magellanic Cloud

$M_{\star} = {\sim}5 \times 10^{8}\, M_{\odot}$

THE
DARK
ENERGY
SURVEY



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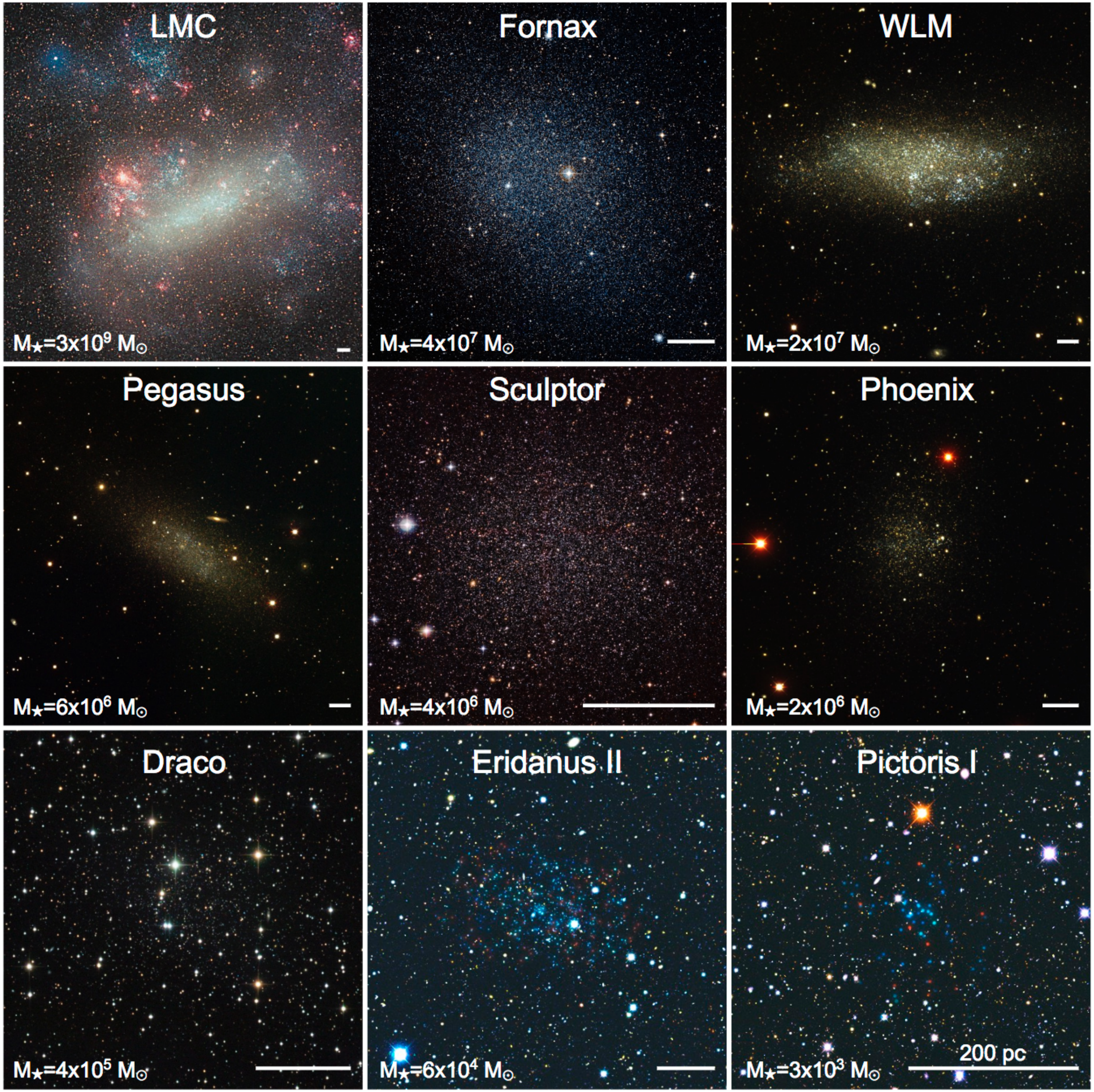
THE
DARK
ENERGY
SURVEY

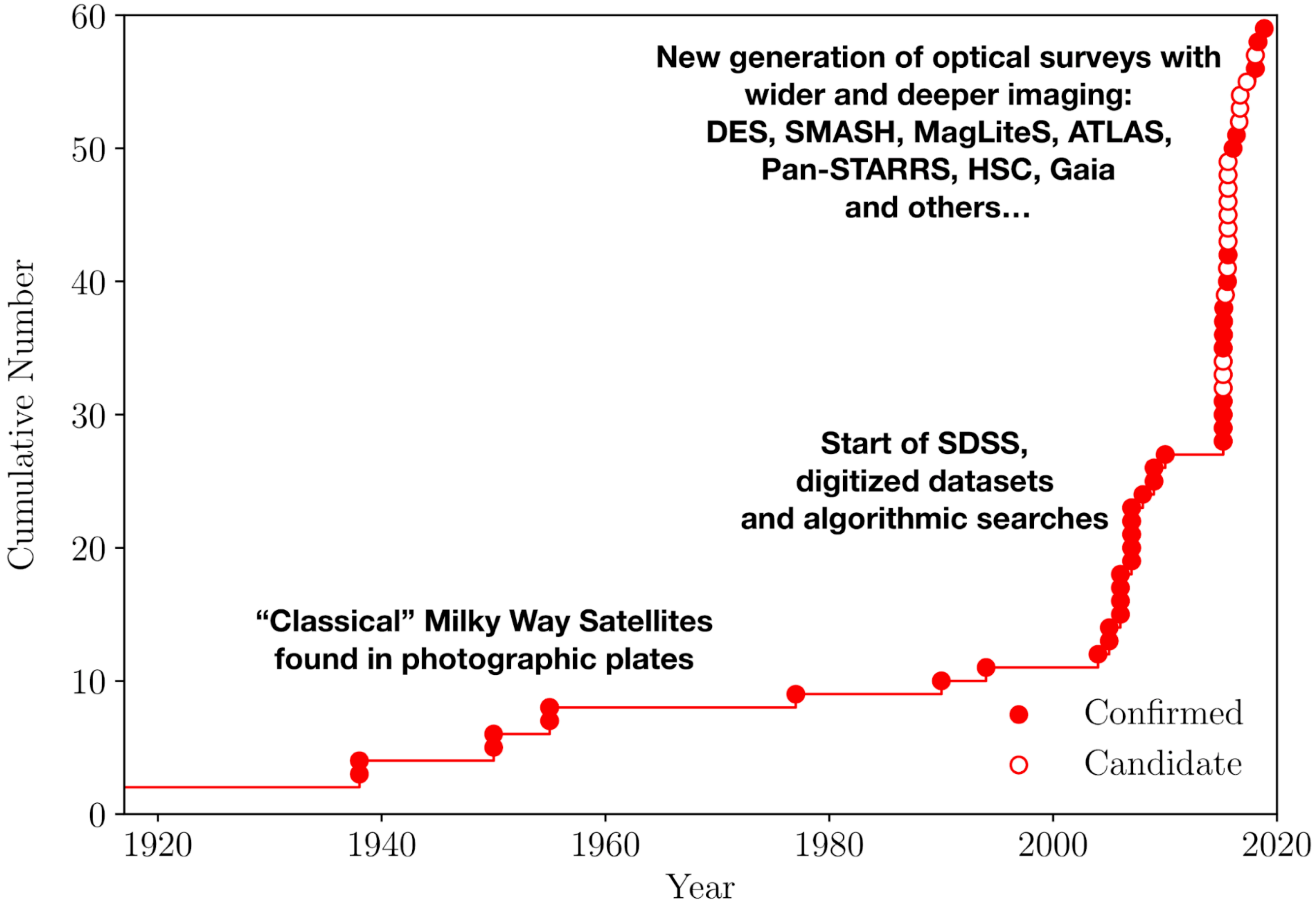
Did the LMC bring a group of dwarf galaxies to the Milky Way?
D'Onghia & Lake 2008
arXiv:0802.0001



THE
DARK
ENERGY
SURVEY

Bullock & Boylan-Kolchin
2017
arXiv:1707.04256

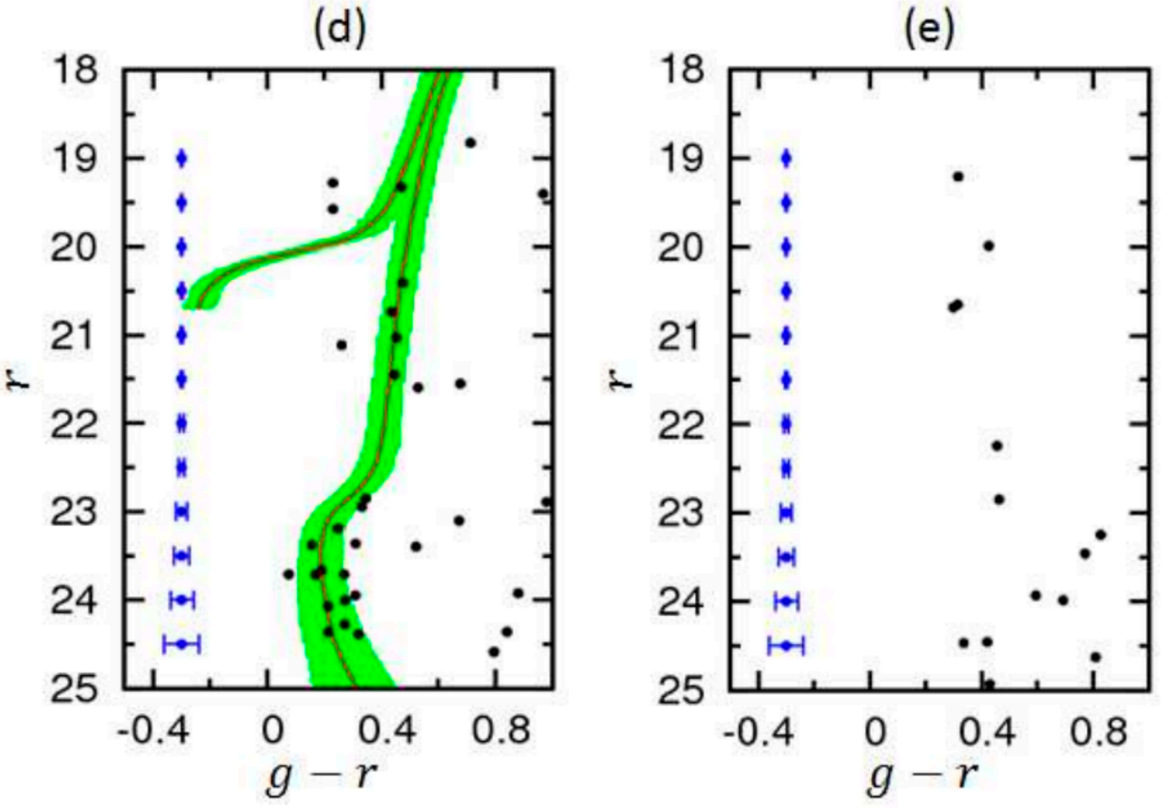
Growing Sample of Milky Way Satellites…



… but we know the current sample is still highly incomplete

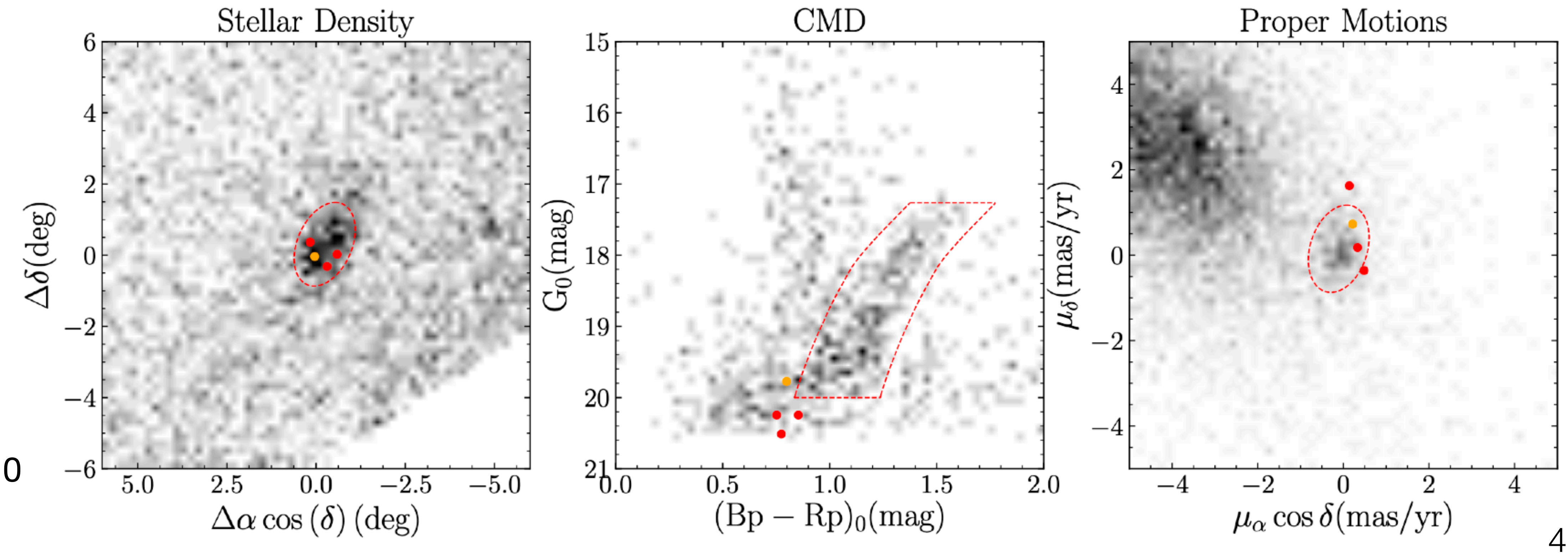
Three extremely low luminosity, distant, and low surface brightness satellites found in first ~700 deg^2 of HSC-SSP

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



Virgo I

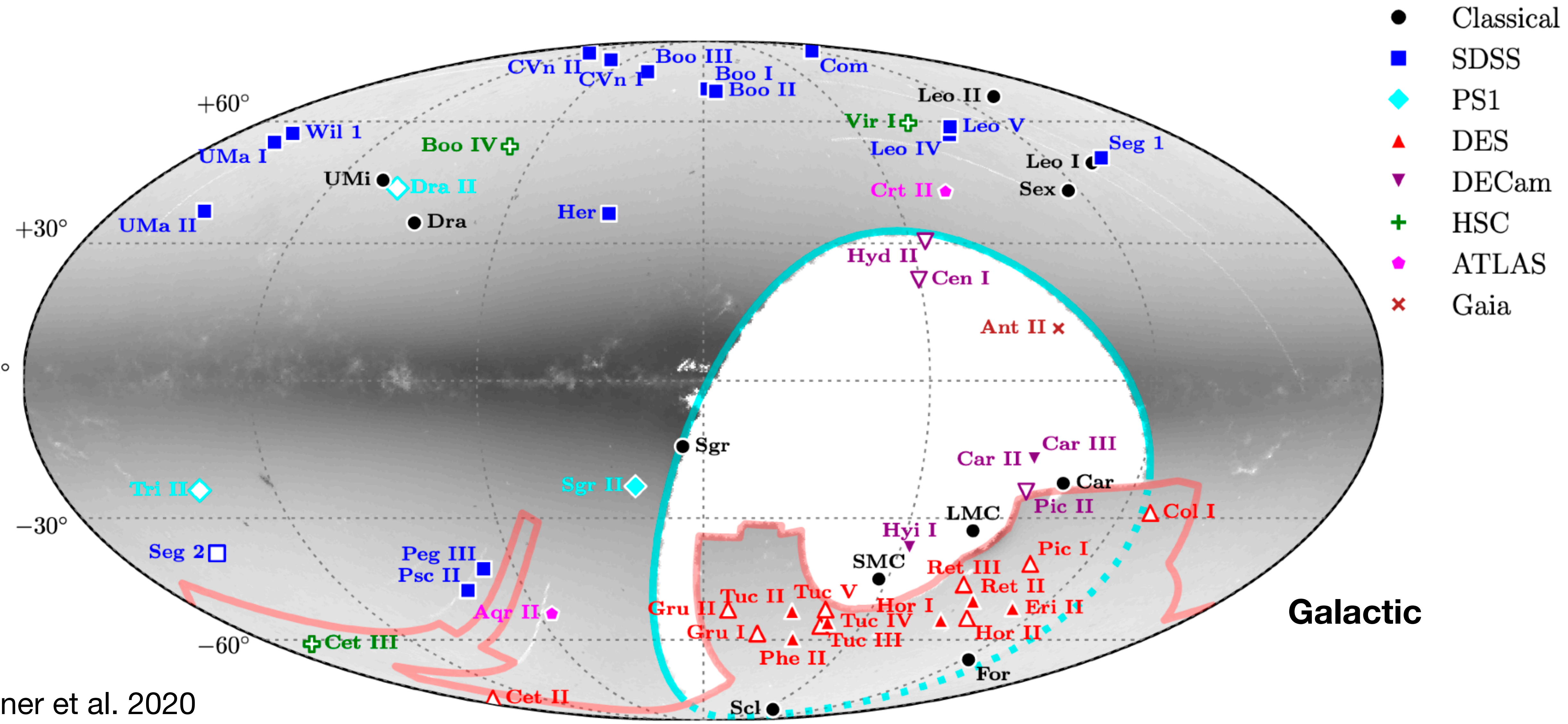
Antlia 2 discovered w/ Gaia proper motions and RR Lyrae at μ ~ 32 mag arcsec^{-2}



Torrealba et al. 2010
arXiv:1811.04082

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

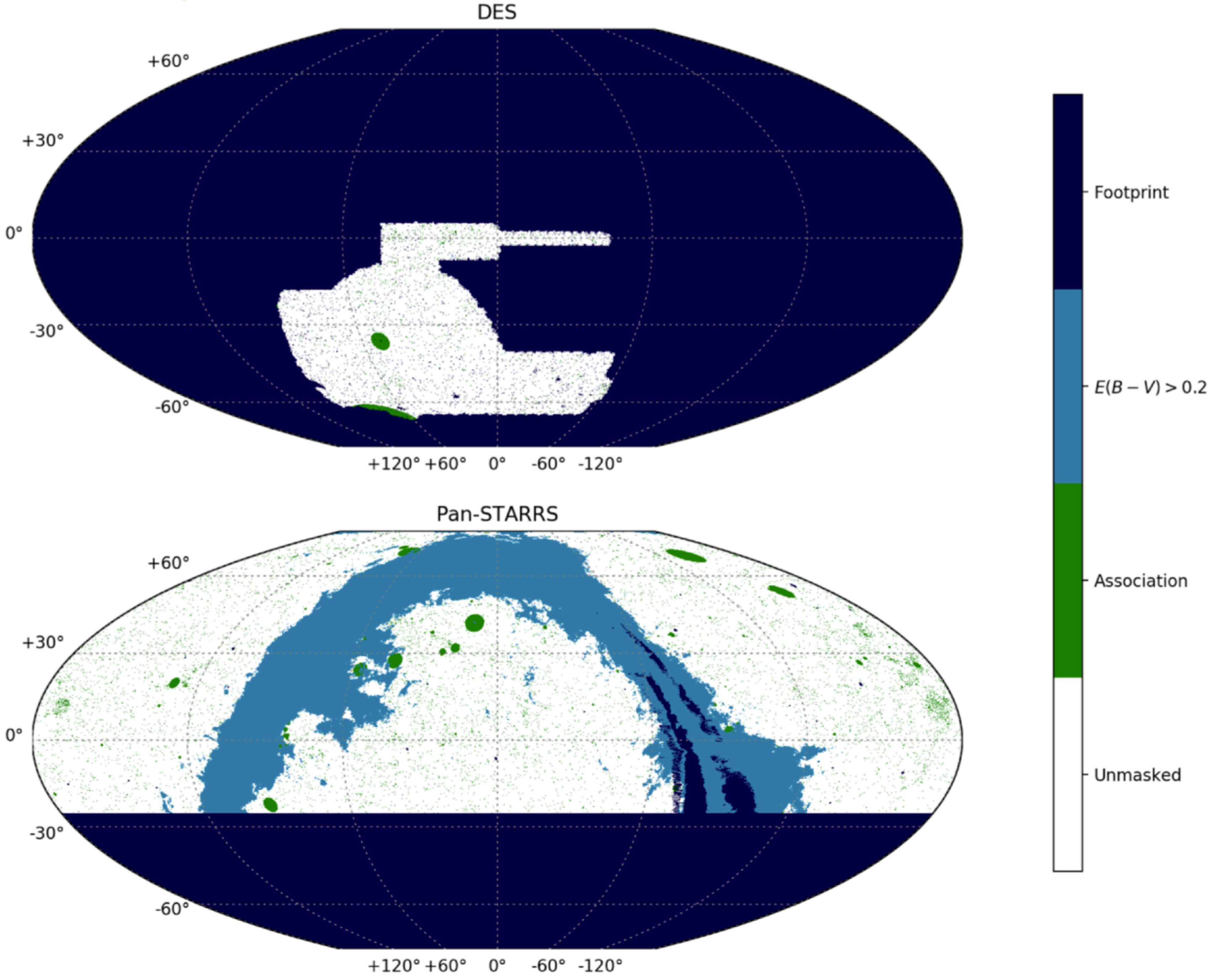
Deep optical imaging over nearly the entire high-Galactic-latitude sky



Drlica-Wagner et al. 2020
arXiv:1912.03302

Total coverage ~32,500 deg²
including over 75% of non-dusty sky (~24,300 deg² after masking)

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



Automated search using **two independent algorithms**

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

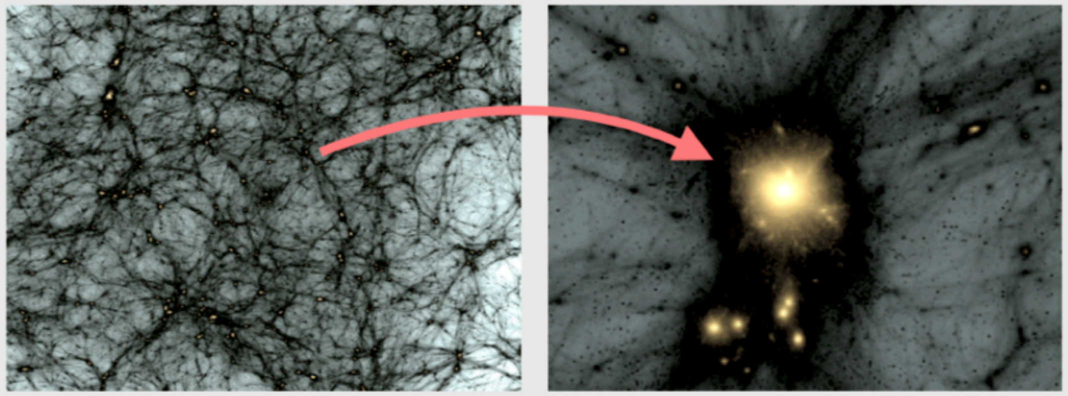
Recover majority of known satellites with automated pipeline; **no new satellite galaxy candidates detected**

18 / 21 known satellites in DES footprint
20 / 32 known satellites in PS1 footprint
9 known satellites outside these footprints

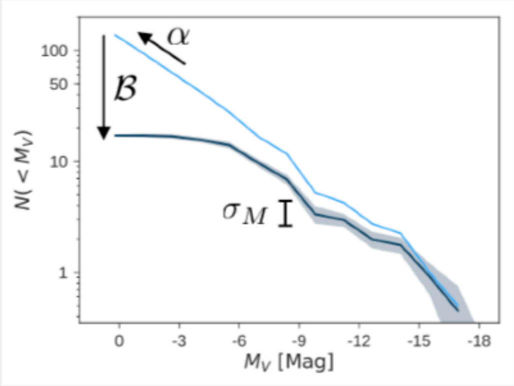
Drlica-Wagner et al. 2020
arXiv:1912.03302

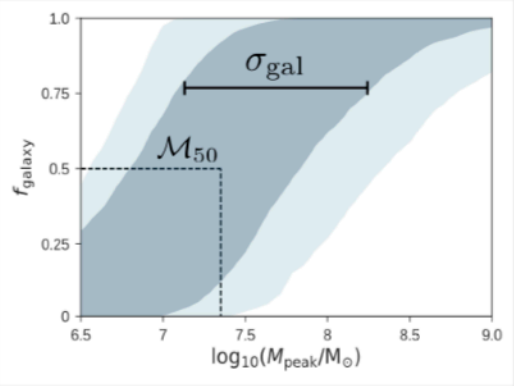
Analysis and Interpretation Overview

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

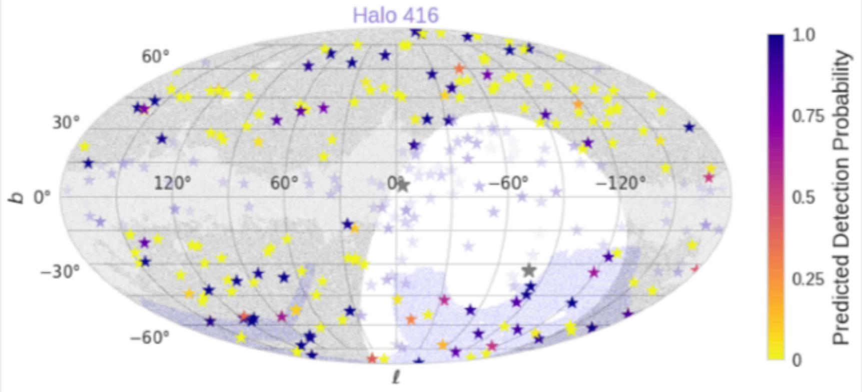


2. Paint satellite galaxies onto subhalos using galaxy—halo model.

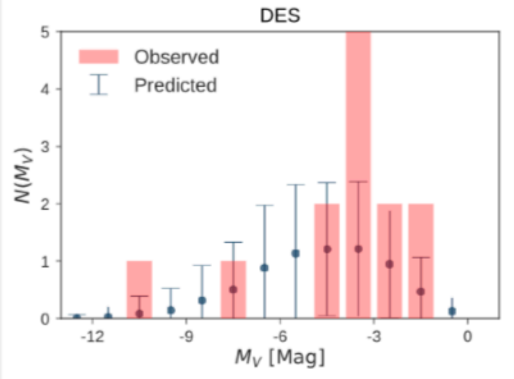


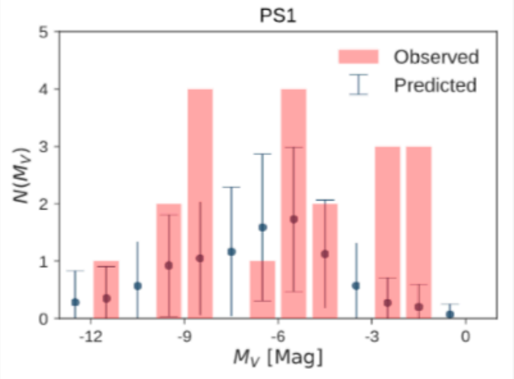


3. Apply observational selection effects based on imaging data.



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

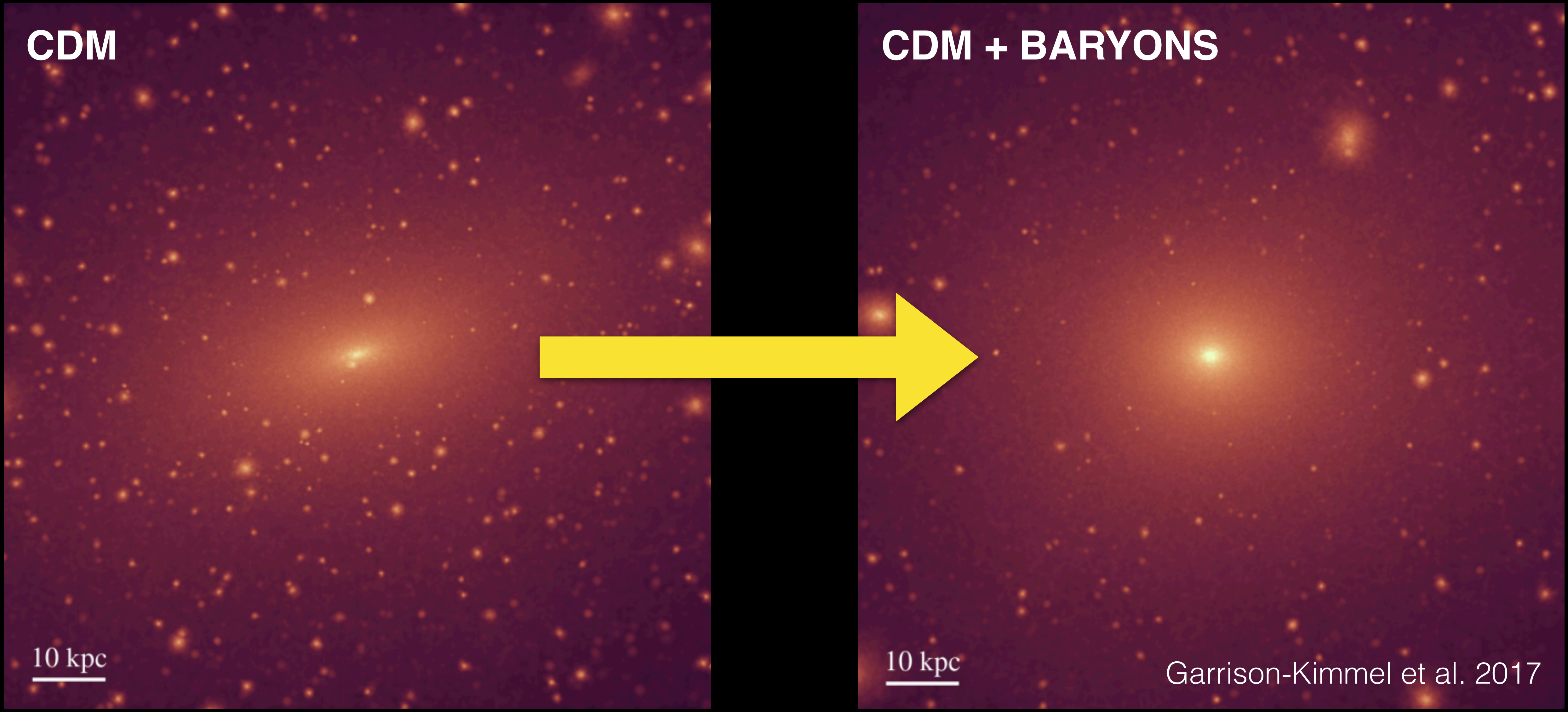




Markov Chain Monte Carlo

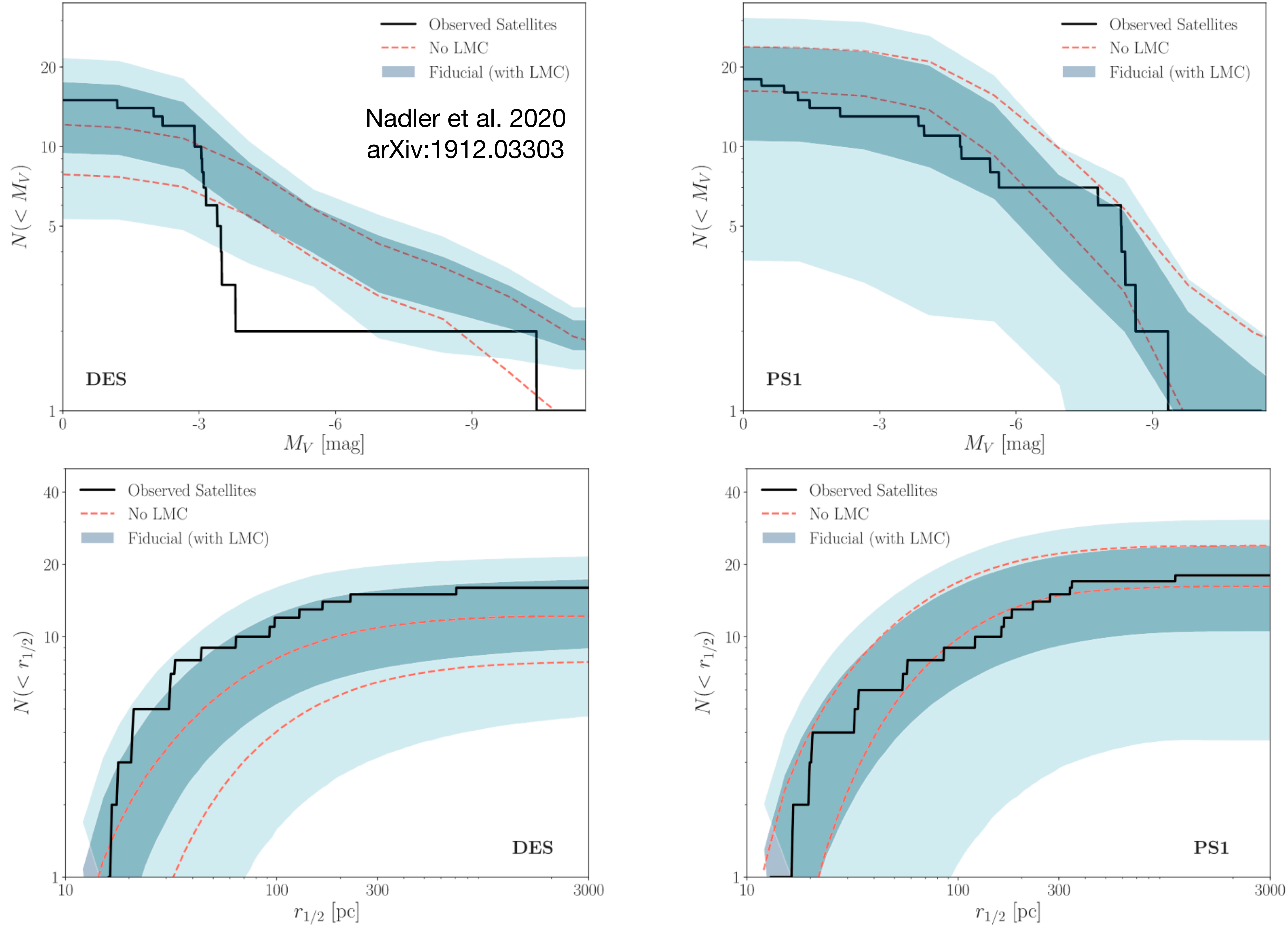
Don’t forget the Baryons

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.



Garrison-Kimmel et al. 2017

Luminosity and Size Distributions



Nadler et al. 2020
arXiv:1912.03303

The as-yet Unseen Milky Way Satellite Population

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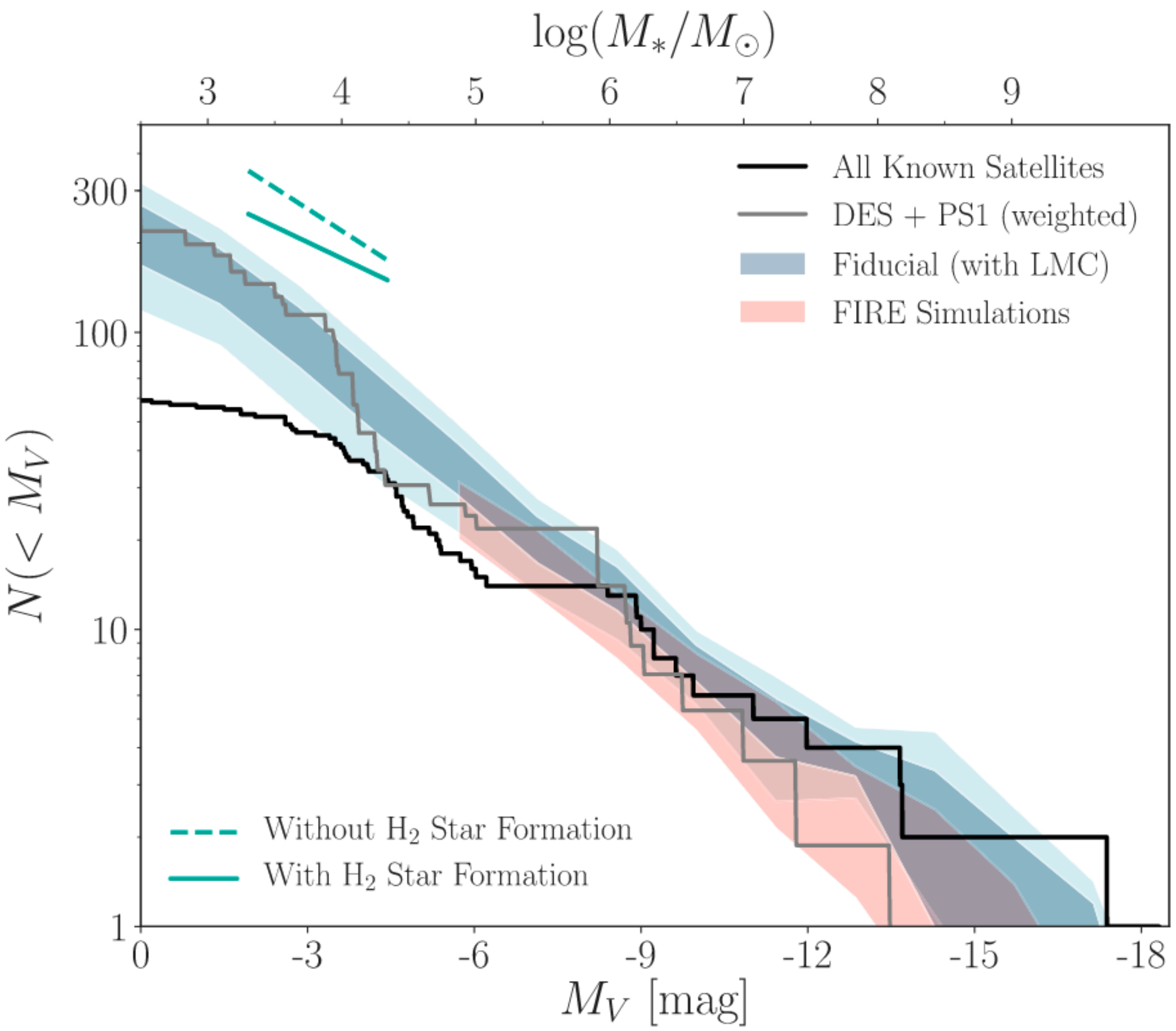
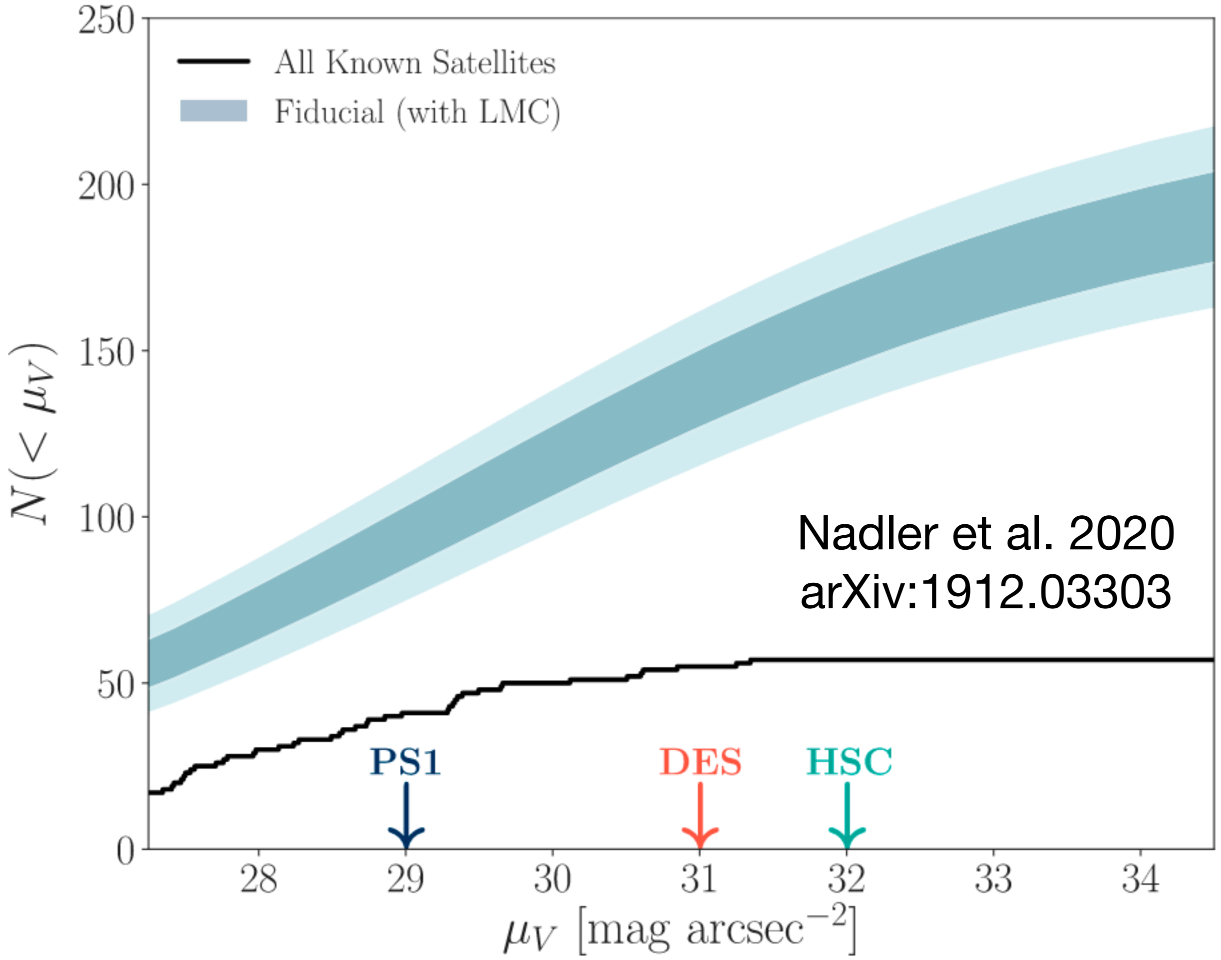
Even with the doubling of known Milky Way satellites since 2015, the majority of Milky Way satellites remain hidden because they either contain **too few bright stars** or are **too low surface brightness**



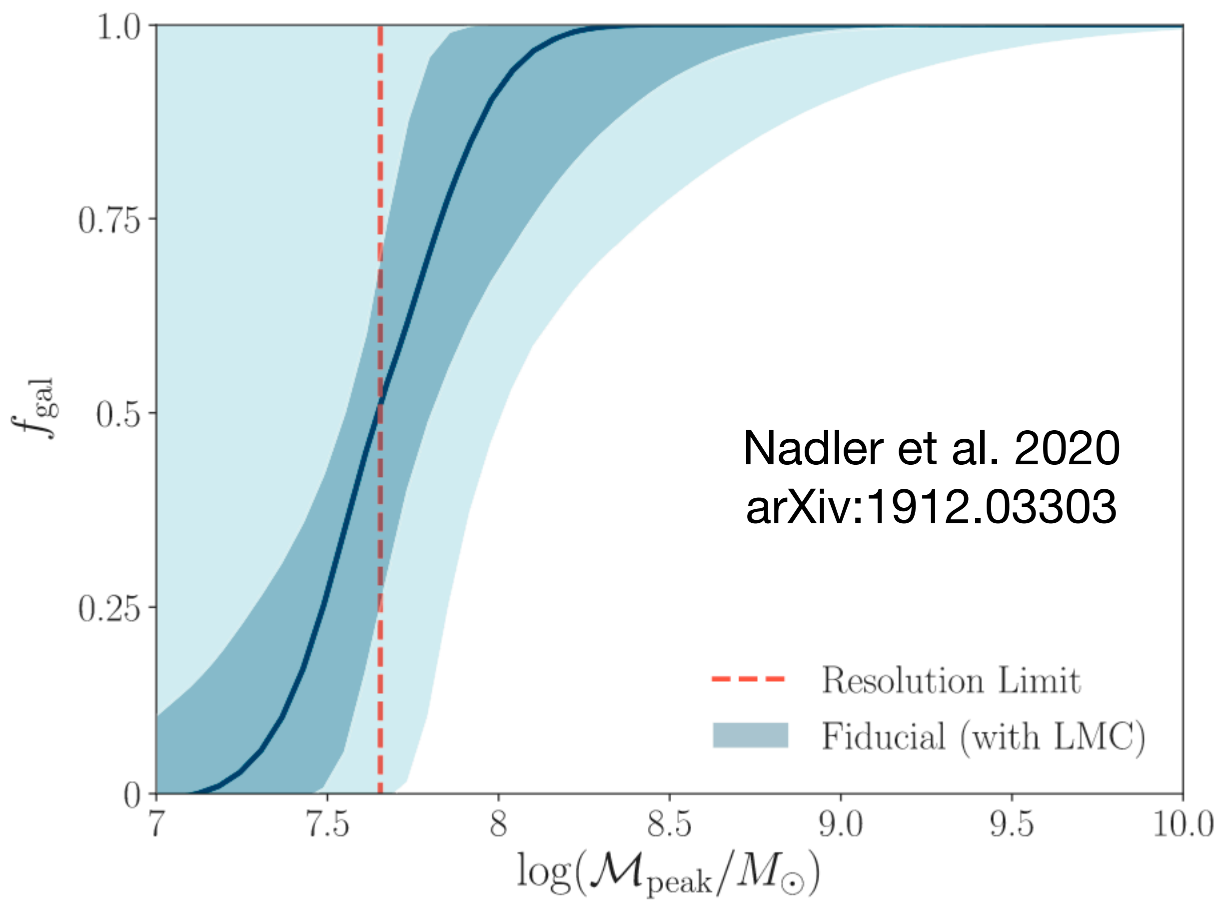


Nadler et al. 2020
arXiv:1912.03303

220 ± 50 total within MW viral radius; ~150 undiscovered;
41 ± 7 satellites within LMC viral radius at time of infall on MW

Galaxy Occupation Model and Extreme Faint-end Luminosity Function

Galaxy Occupation

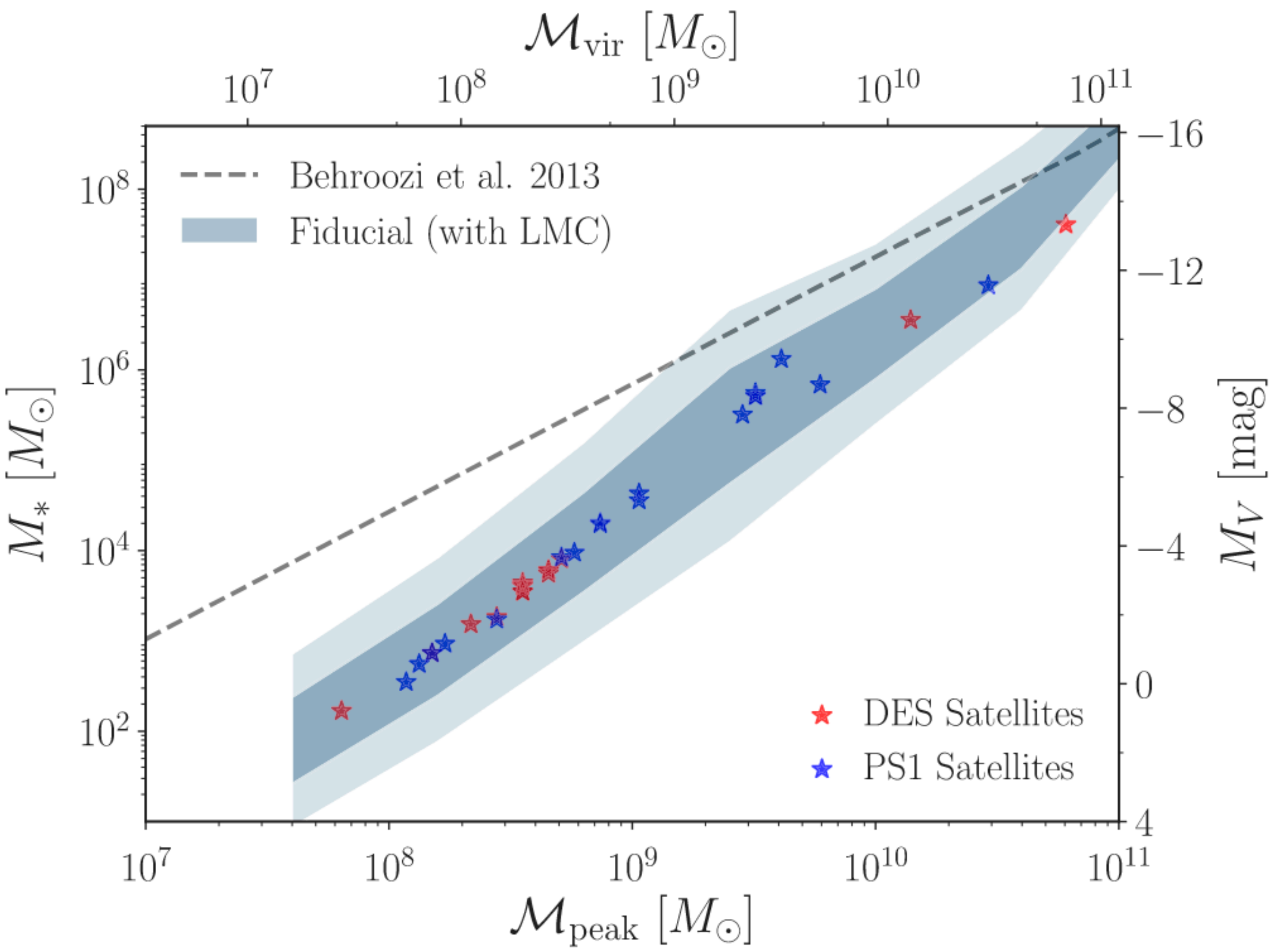


Nadler et al. 2020
arXiv:1912.03303

$M_{min} < 3.2 \times 10^8\ M_\odot$ (95% CL)

$v_{peak} < 21$ km s^{-1} (95% CL)

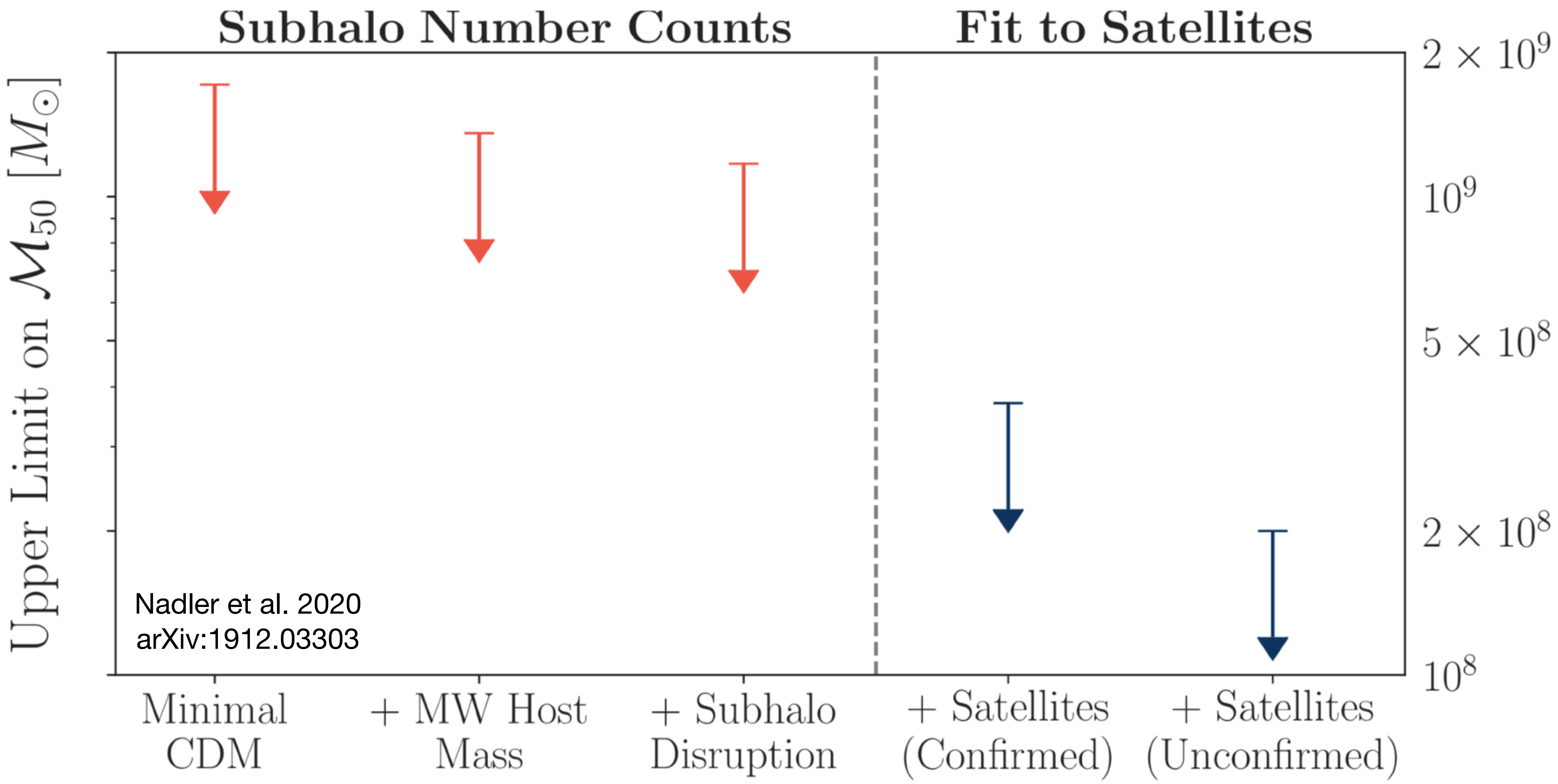
Faint-end Luminosity Function



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

Theoretical Uncertainties

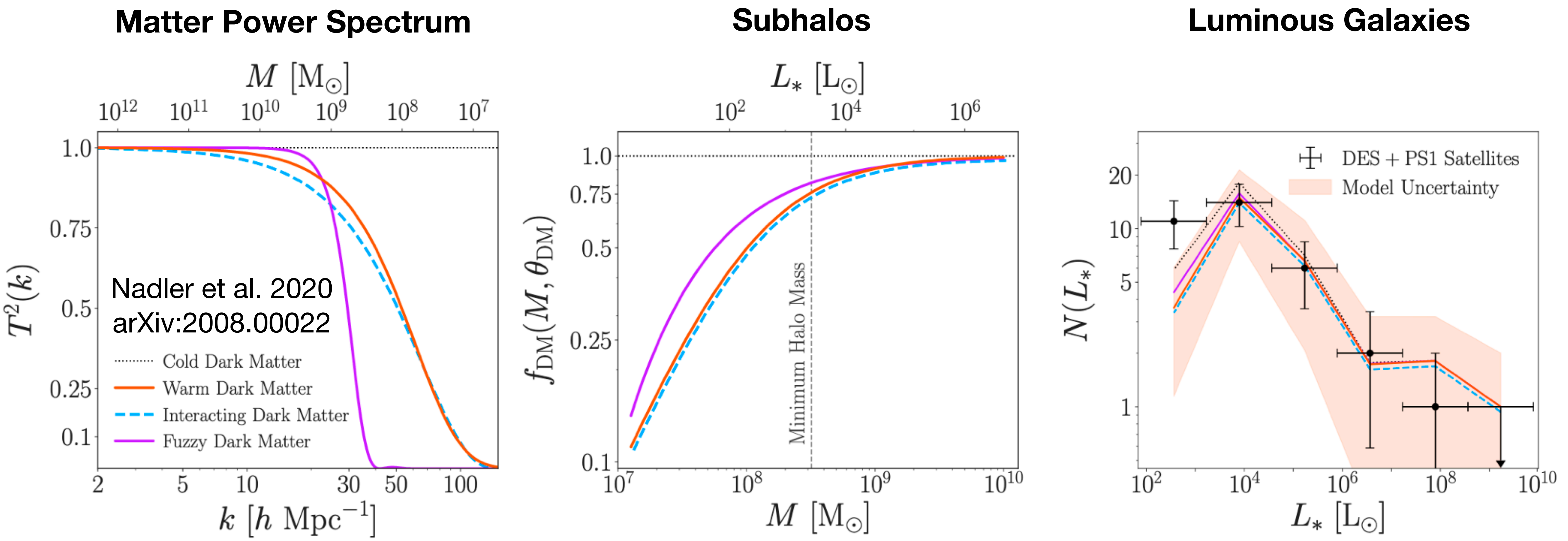
Scenario with no-scatter abundance matching and no baryonic tidal disruption gives conservative upper bound on minimum halo mass (but poor quality fit to data)



Nadler et al. 2020
arXiv:1912.03303

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

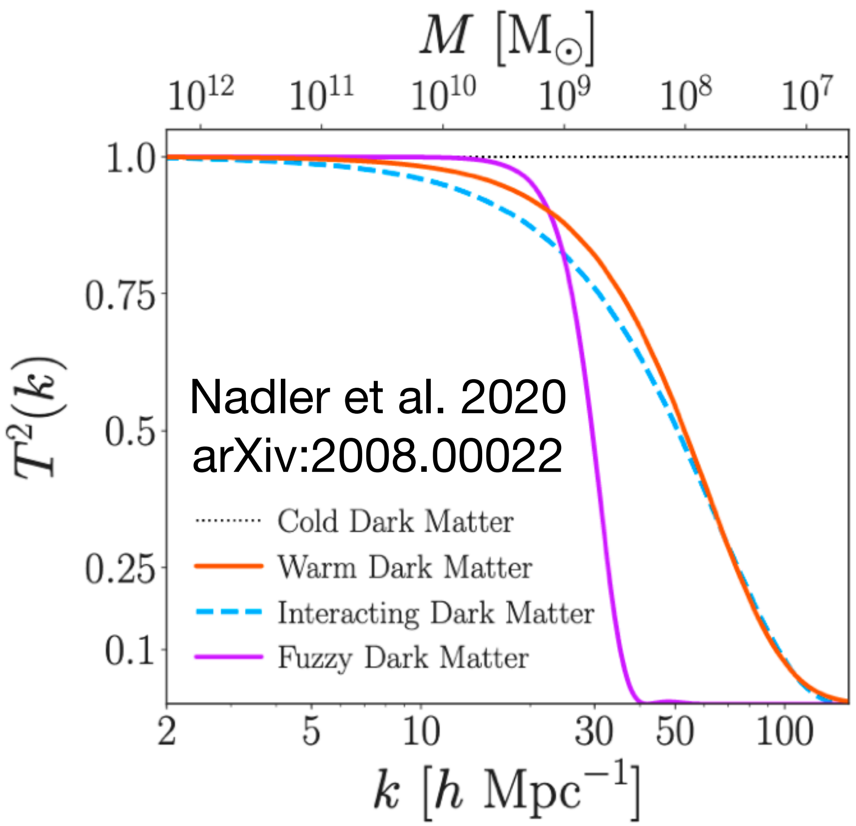
Dark Matter Microphysics



Nadler et al. 2020
arXiv:2008.00022

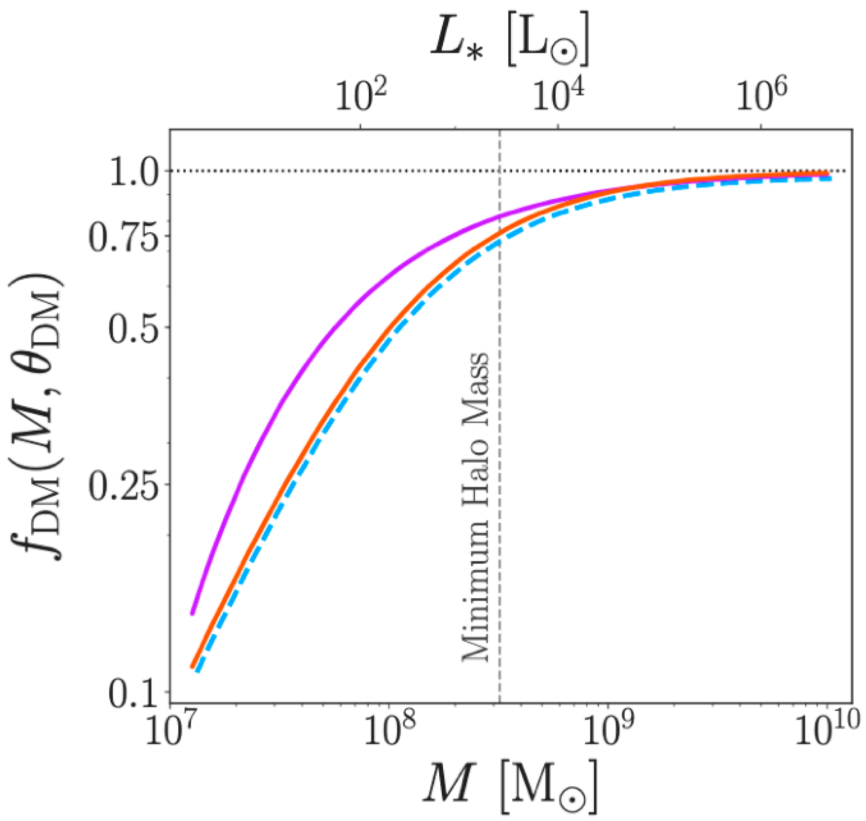
Dark Matter Microphysics

Matter Power Spectrum

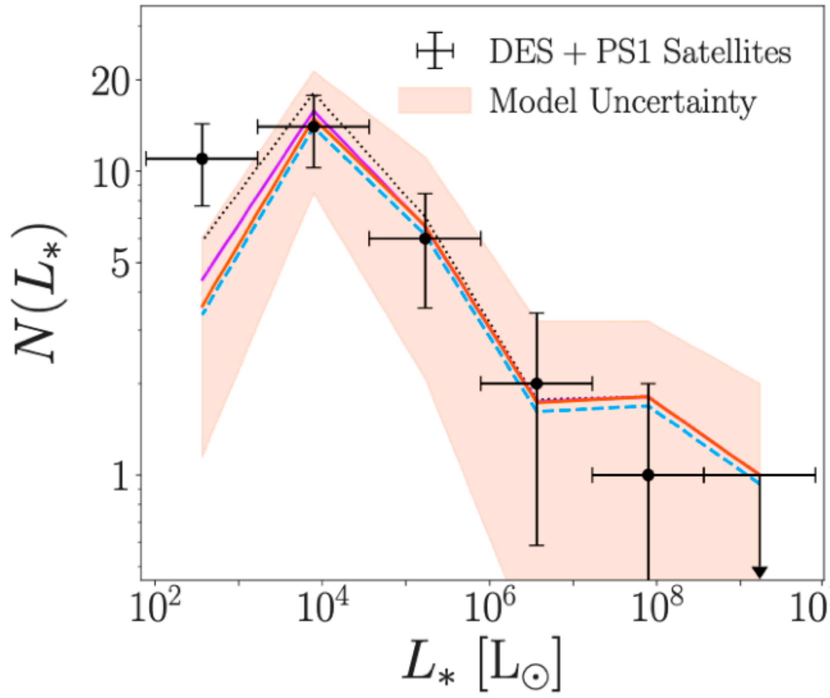


Nadler et al. 2020
arXiv:2008.00022

Subhalos



Luminous Galaxies



Dark Matter Paradigm	Parameter	Constraint	Derived Property	Constraint
Warm Dark Matter	Thermal Relic Mass	$m_{\mathrm{WDM}} > 6.5\,\mathrm{keV}$	Free-streaming Length	$\lambda_{\mathrm{fs}} \lesssim 10\,h^{-1}\,\mathrm{kpc}$
Interacting Dark Matter	Velocity-independent DM–Proton Cross Section	$\sigma_0 < 8.8 \times 10^{-29}\,\mathrm{cm}^2$	DM–Proton Coupling	$c_p \lesssim (0.3\,\mathrm{GeV})^{-2}$
Fuzzy Dark Matter	Particle Mass	$m_\phi > 2.9 \times 10^{-21}\,\mathrm{eV}$	de Broglie Wavelength	$\lambda_{\mathrm{dB}} \lesssim 0.5\,\mathrm{kpc}$

Constraints on many other broad classes of models self-interacting dark matter, late-forming dark matter, decaying dark matter as well as early Universe physics

Dark Matter Microphysics

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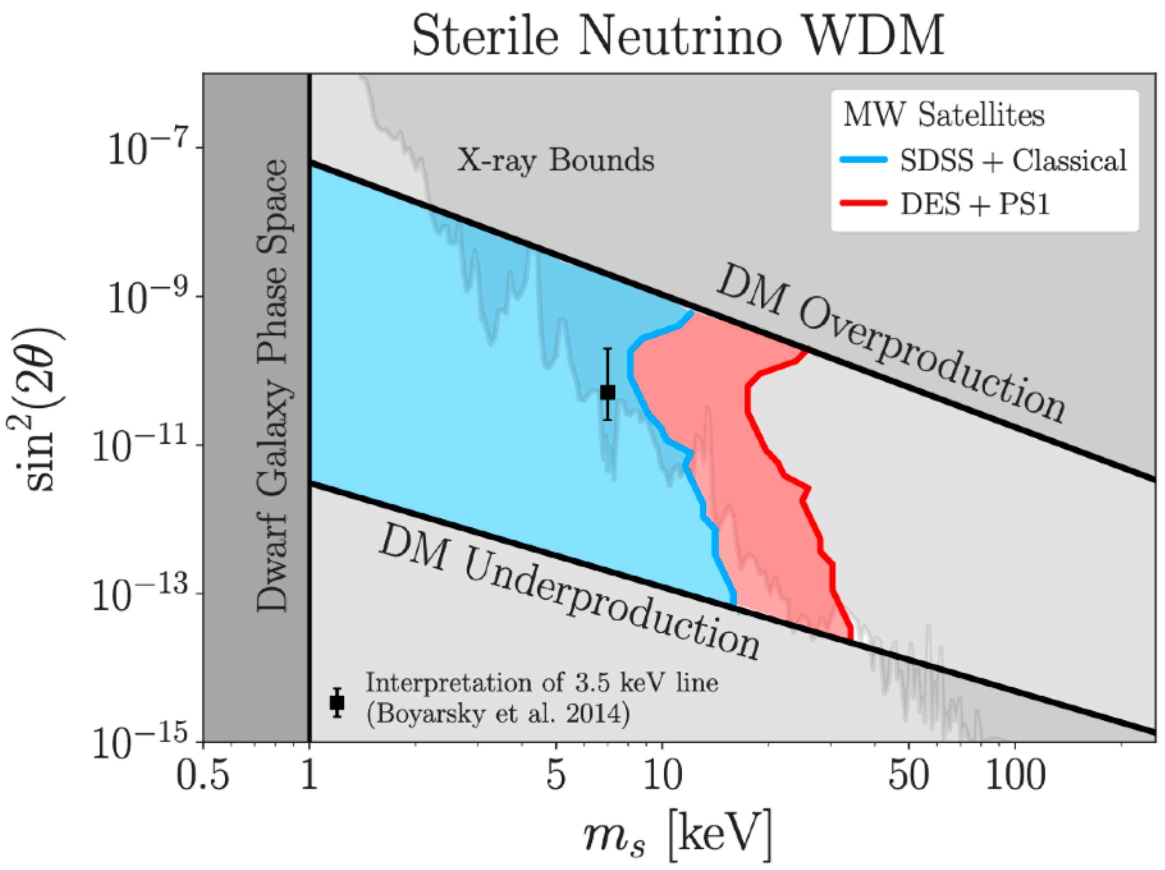
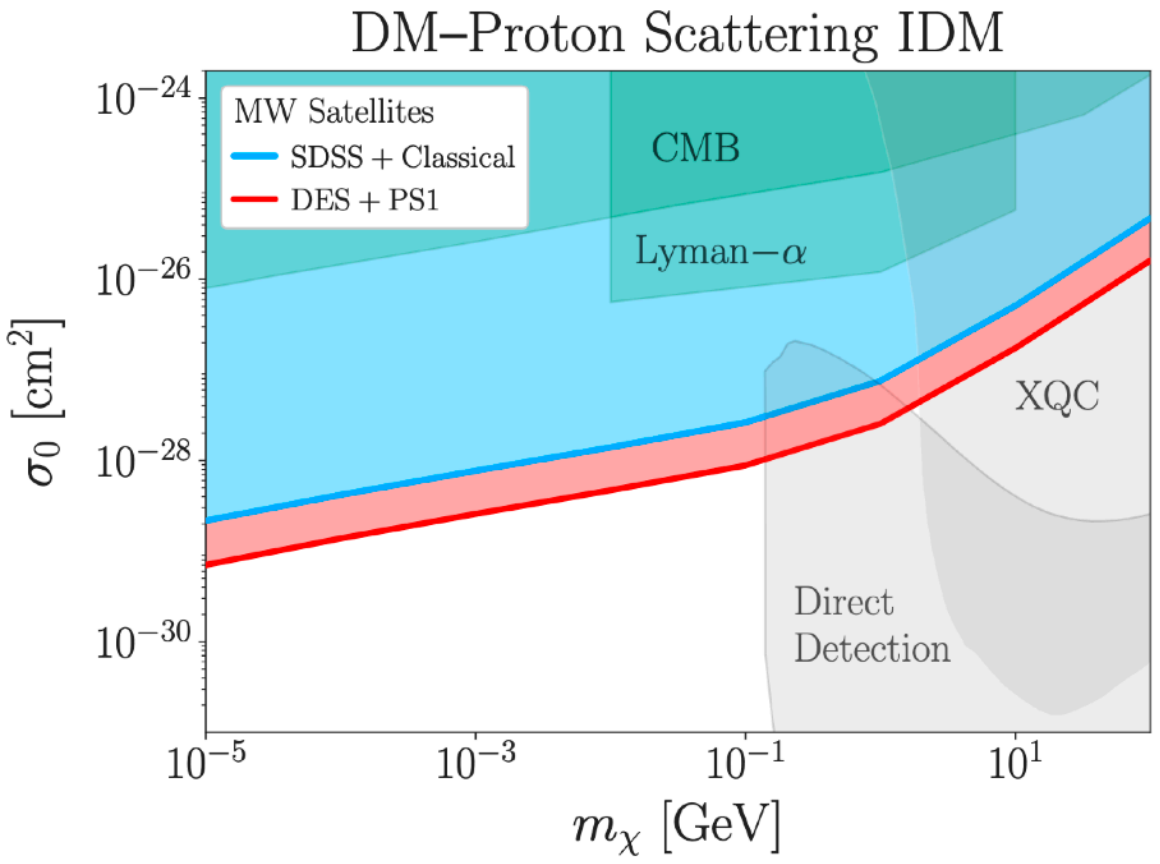
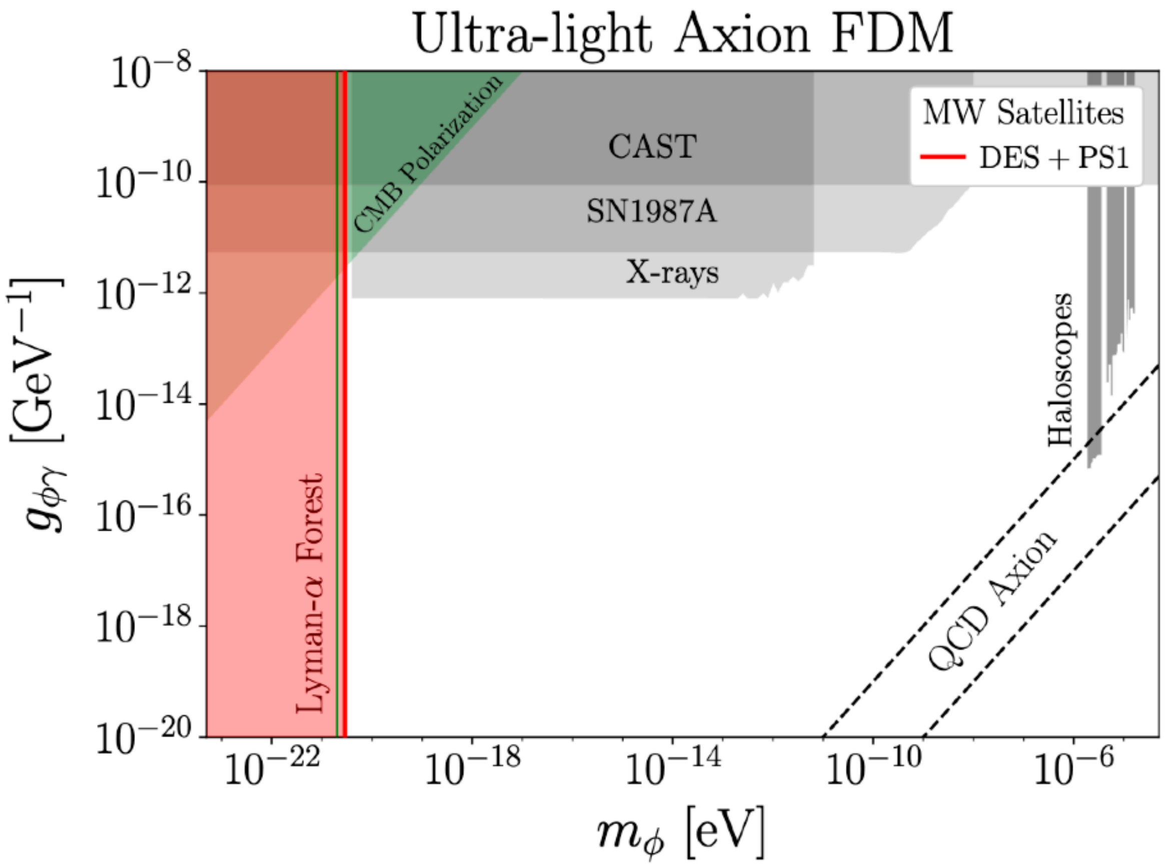
Application of Milky Way satellite population constraints to specific dark matter models

Nadler et al. 2020
arXiv:2008.00022







Milky Way Satellites: Decisive Statistical Evidence that…

- The LMC impacts the observed MW satellite population, contributing 4.8 ± 1.7 (1.1 ± 0.9) 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 $3.2 \times 10^8 M_\odot$ (95% CL)
  - *Approaching the atomic cooling limit* $v_{peak} \sim 21 \text{ km s}^{-1}$
  - *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*

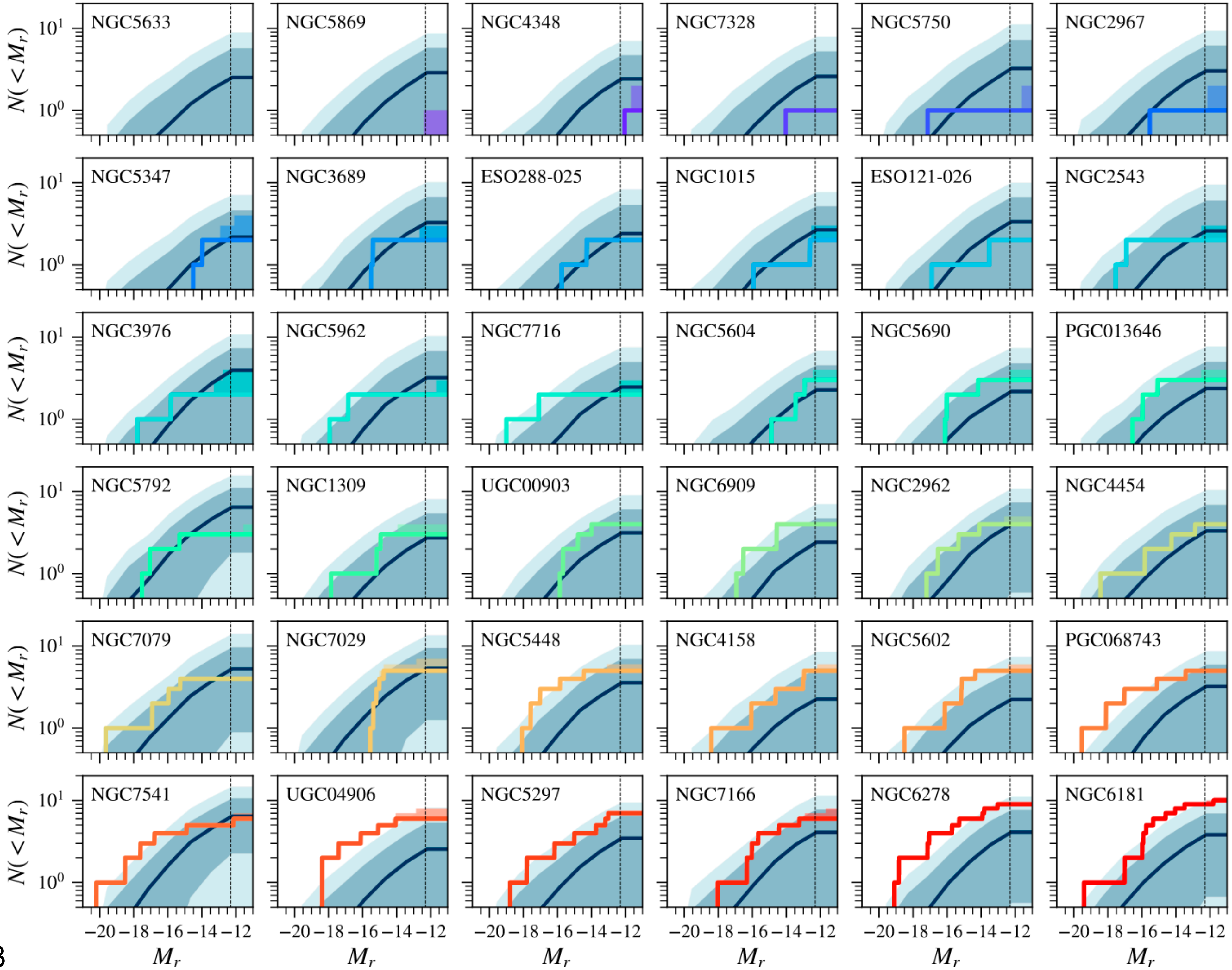
Beyond the Milky Way: SAGA Results

127 satellites around 36 Milky Way analogs at distances of 25 to 40 Mpc (z ~ 0.01)
Satellites have stellar masses 10^6 to 10^9 $M_\odot$

Mao et al. 2020 arXiv:2008.12783

Beyond the Milky Way:
SAGA Results

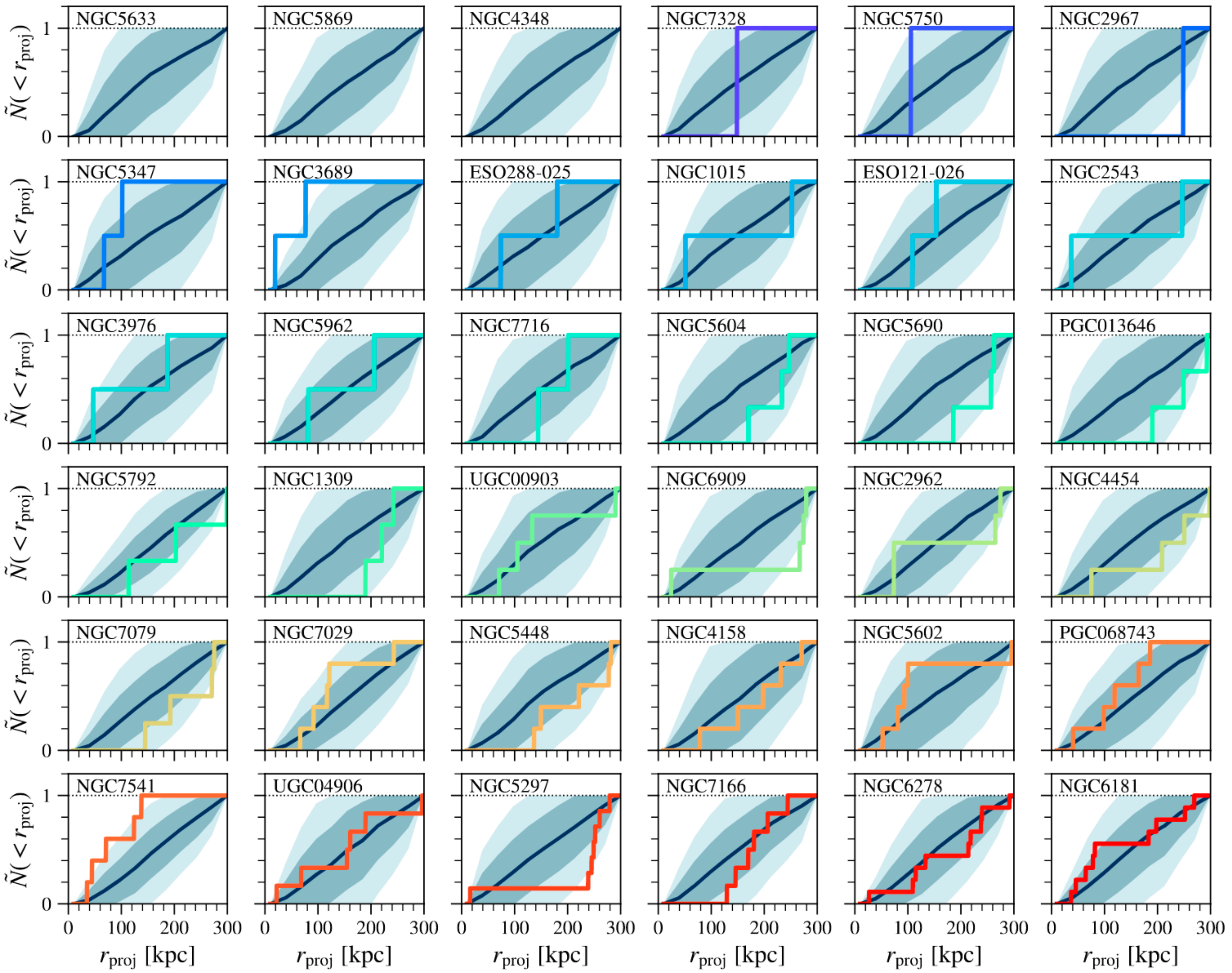
Luminosity distributions of SAGA Satellites Consistent with fit to Milky Way population



Mao et al. 2020
arXiv:2008.12783

Beyond the Milky Way: SAGA Results

Radial distributions of SAGA Satellites Consistent with fit to Milky Way population



Mao et al. 2020
arXiv:2008.12783

- Milky Way stellar halo is rich with structure; satellites, streams, and more are revealed though spatial overdensities, dynamics, and chemistry
- DES produces large high-quality public datasets, made even more powerful in combination with Gaia, VHS, etc.
  - DES DR2 coming January 2021!
- Evidence for hierarchical structure formation on the scale of dwarf galaxies and new constraints on the particle nature of dark matter

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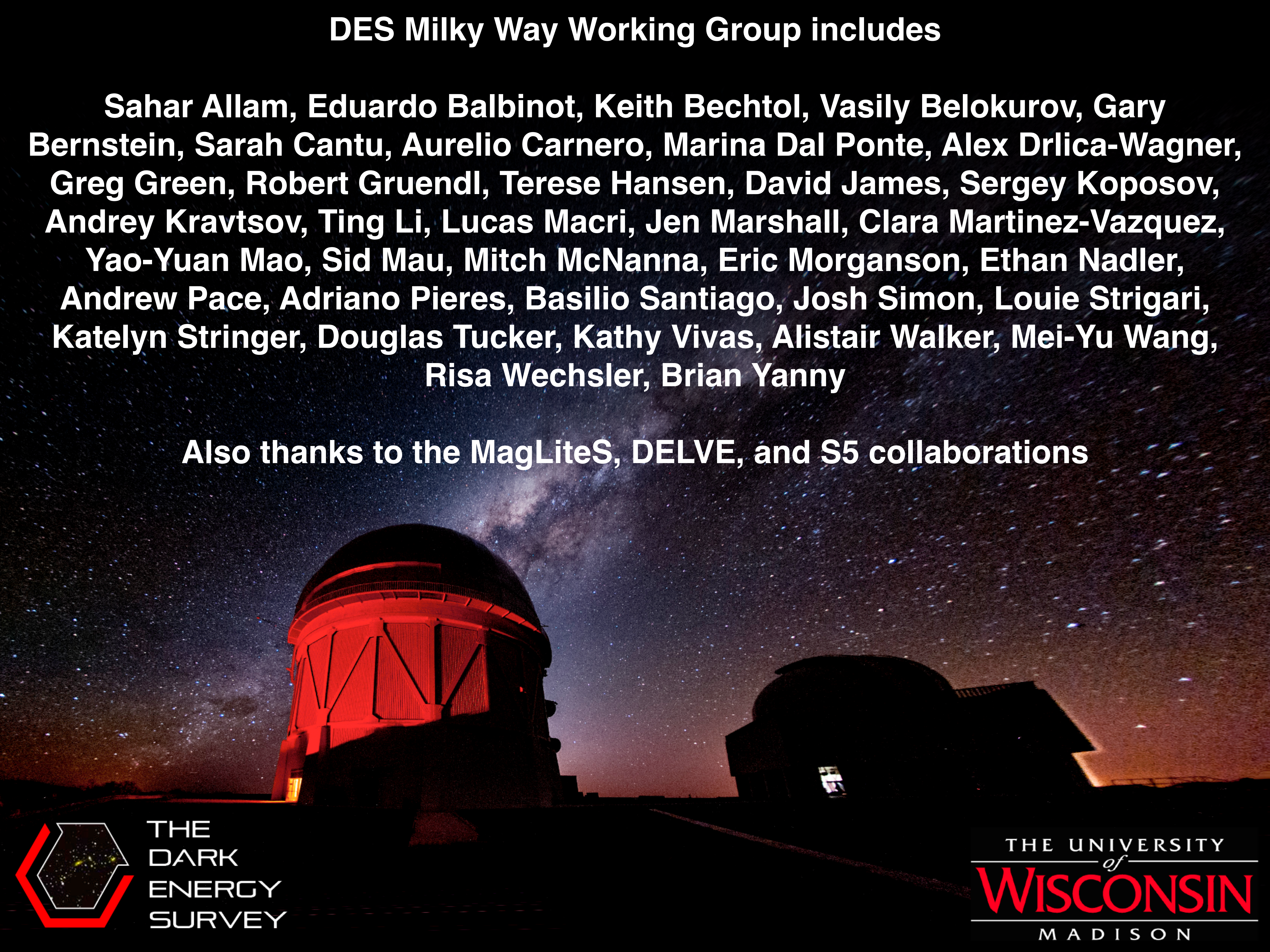
THE UNIVERSITY *of* WISCONSIN MADISON



DES Milky Way Working Group includes

Sahar Allam, Eduardo Balbinot, Keith Bechtol, Vasily Belokurov, Gary Bernstein, Sarah Cantu, Aurelio Carnero, Marina Dal Ponte, Alex Drlica-Wagner, Greg Green, Robert Gruendl, Terese Hansen, David James, Sergey Koposov, Andrey Kravtsov, Ting Li, Lucas Macri, Jen Marshall, Clara Martinez-Vazquez, Yao-Yuan Mao, Sid Mau, Mitch McNanna, Eric Morganson, Ethan Nadler, Andrew Pace, Adriano Pieres, Basilio Santiago, Josh Simon, Louie Strigari, Katelyn Stringer, Douglas Tucker, Kathy Vivas, Alistair Walker, Mei-Yu Wang, Risa Wechsler, Brian Yanny

Also thanks to the MagLiteS, DELVE, and S5 collaborations

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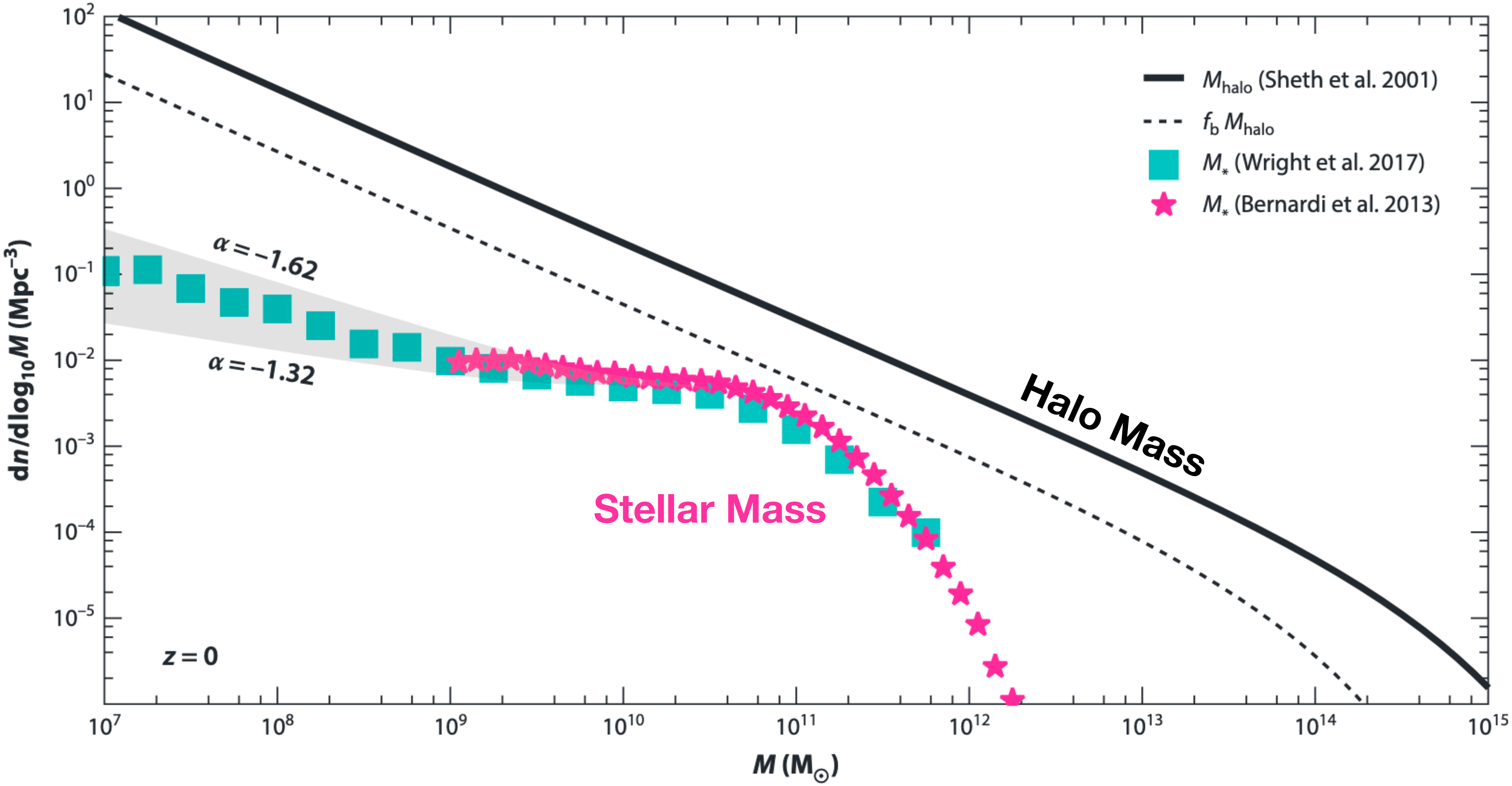
Galaxy-Halo Connection

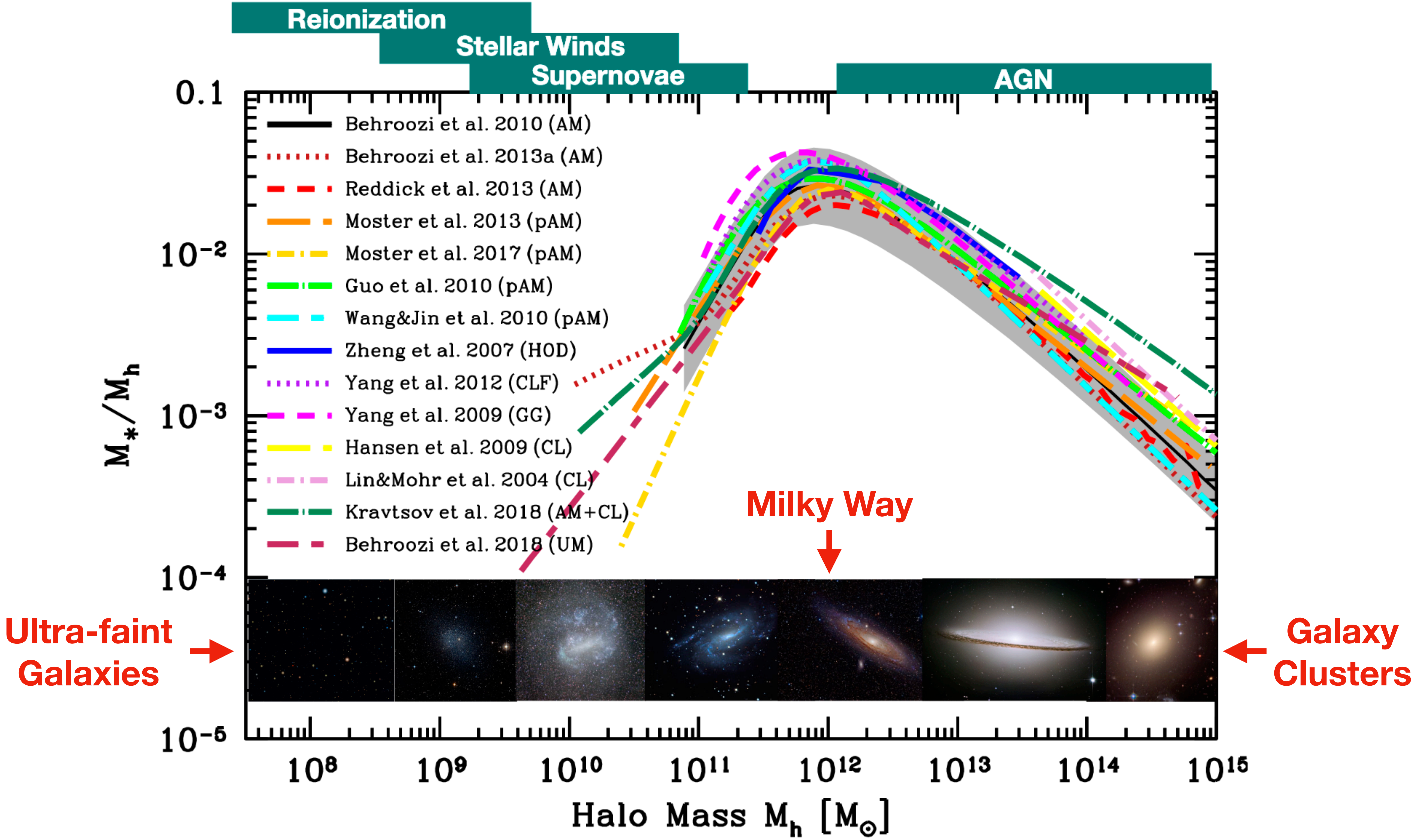
Abundance Matching (simplified):

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

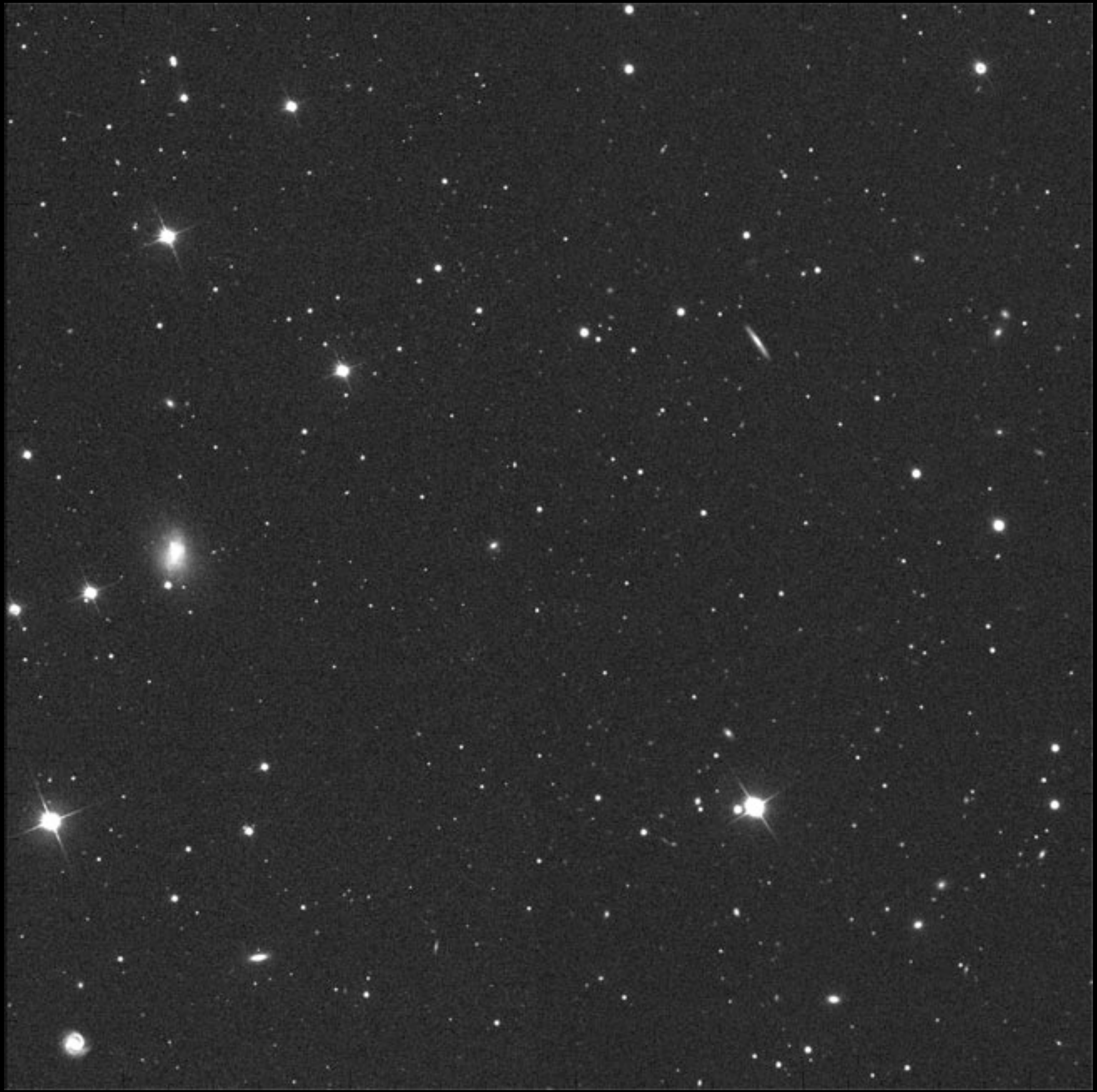


Bullock & Boylan-Kolchin 2017

Galaxy-Halo Connection



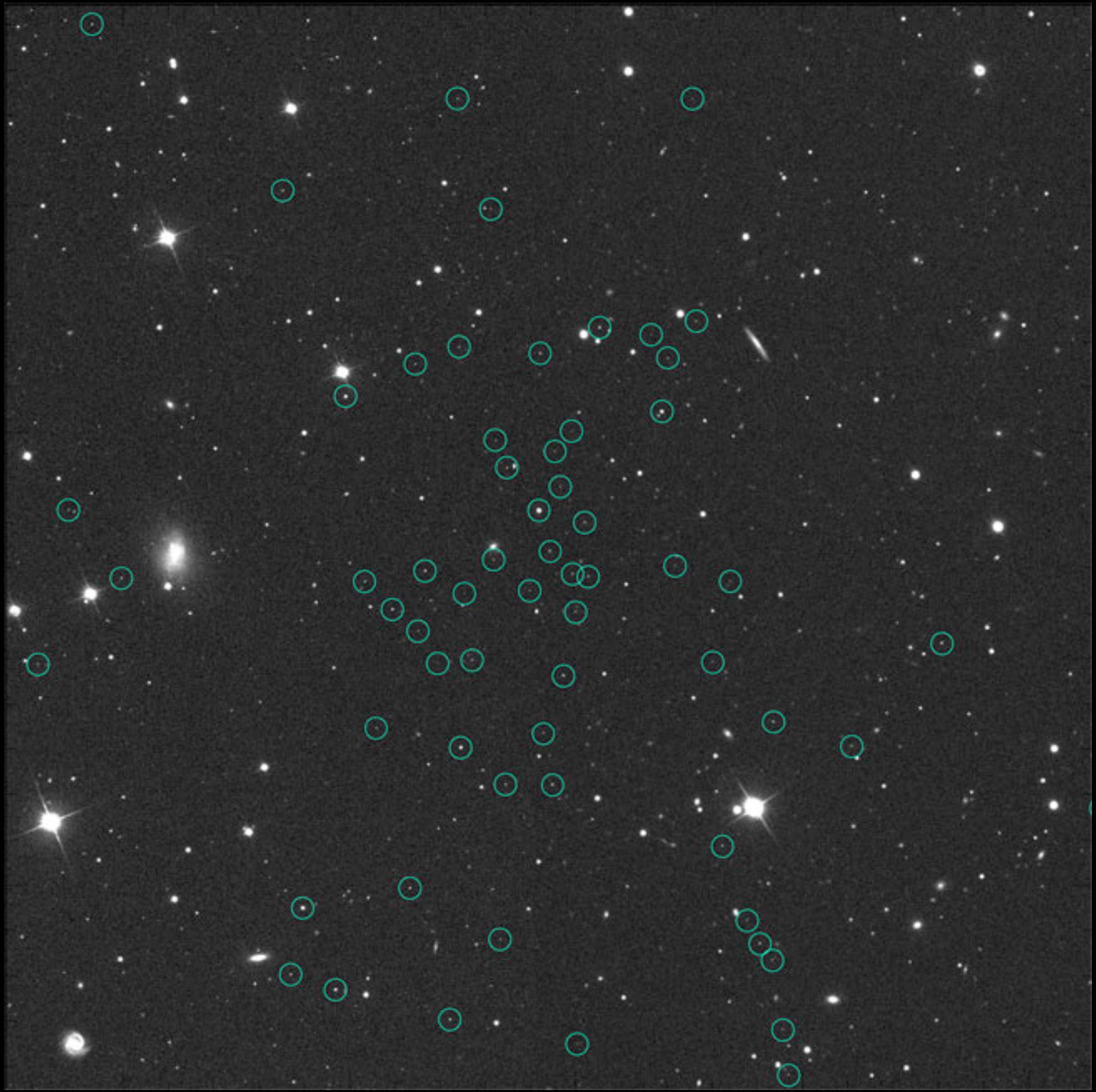
Wechsler & Tinker 2018
arXiv:1804.03097



Segue 1

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

Credit: Marla Geha



Segue 1

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

Credit: Marla Geha

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

Segue 1

$M_{☆} = \sim 300\ M_{O}$

Credit: Marla Geha