Ultra Diffuse Galaxies as Probes for Dark Matter

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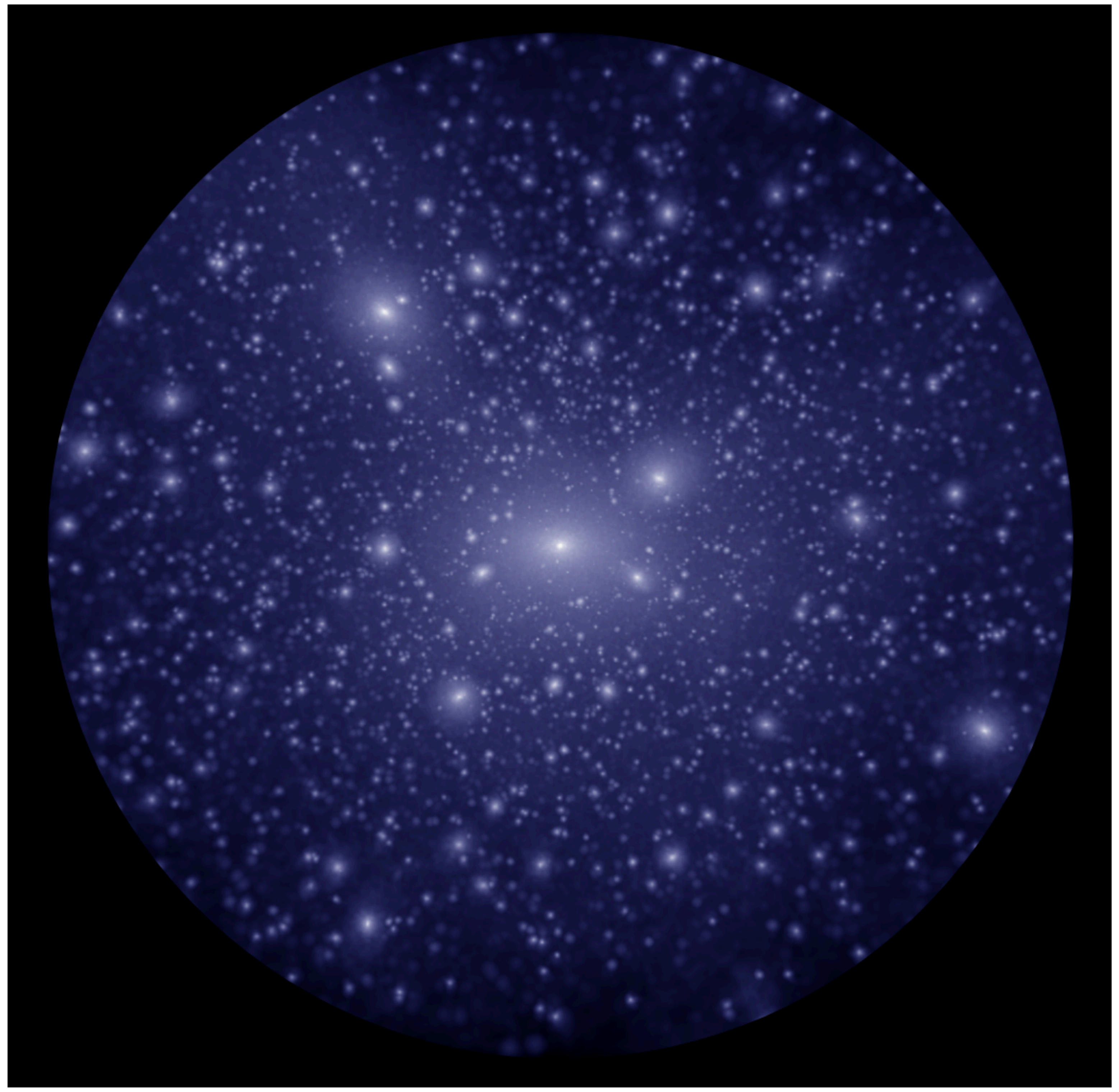
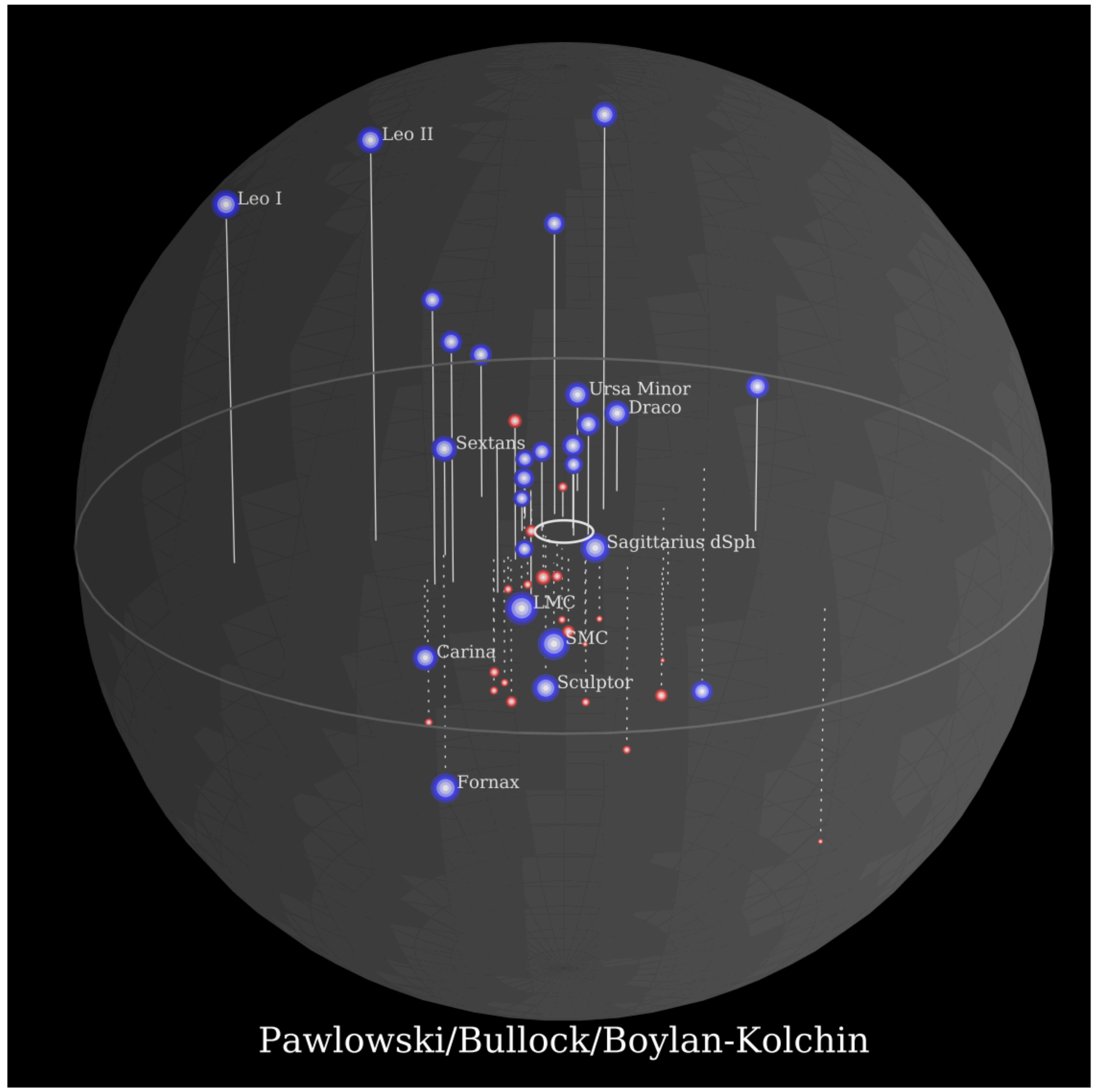
LOW-MASS GALAXIES ($M_* < 10^9\ M_\odot$) ARE ESSENTIAL FOR TESTING DARK MATTER (AND GALAXY FORMATION) MODELS ON SMALL SCALES - I

In galaxy groups: they trace dark matter sub-structure



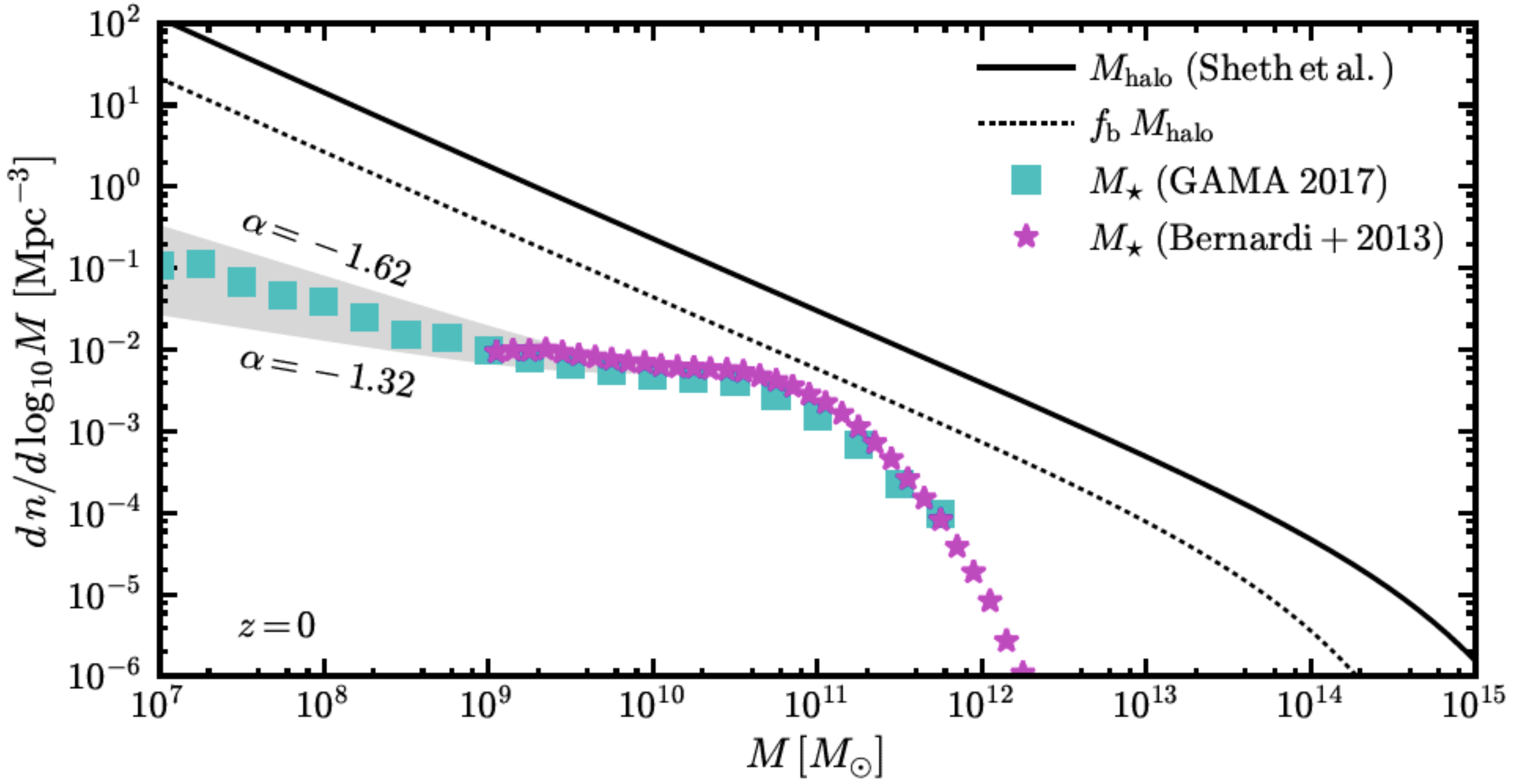


Bullock & Boylan-Kolchin 2019

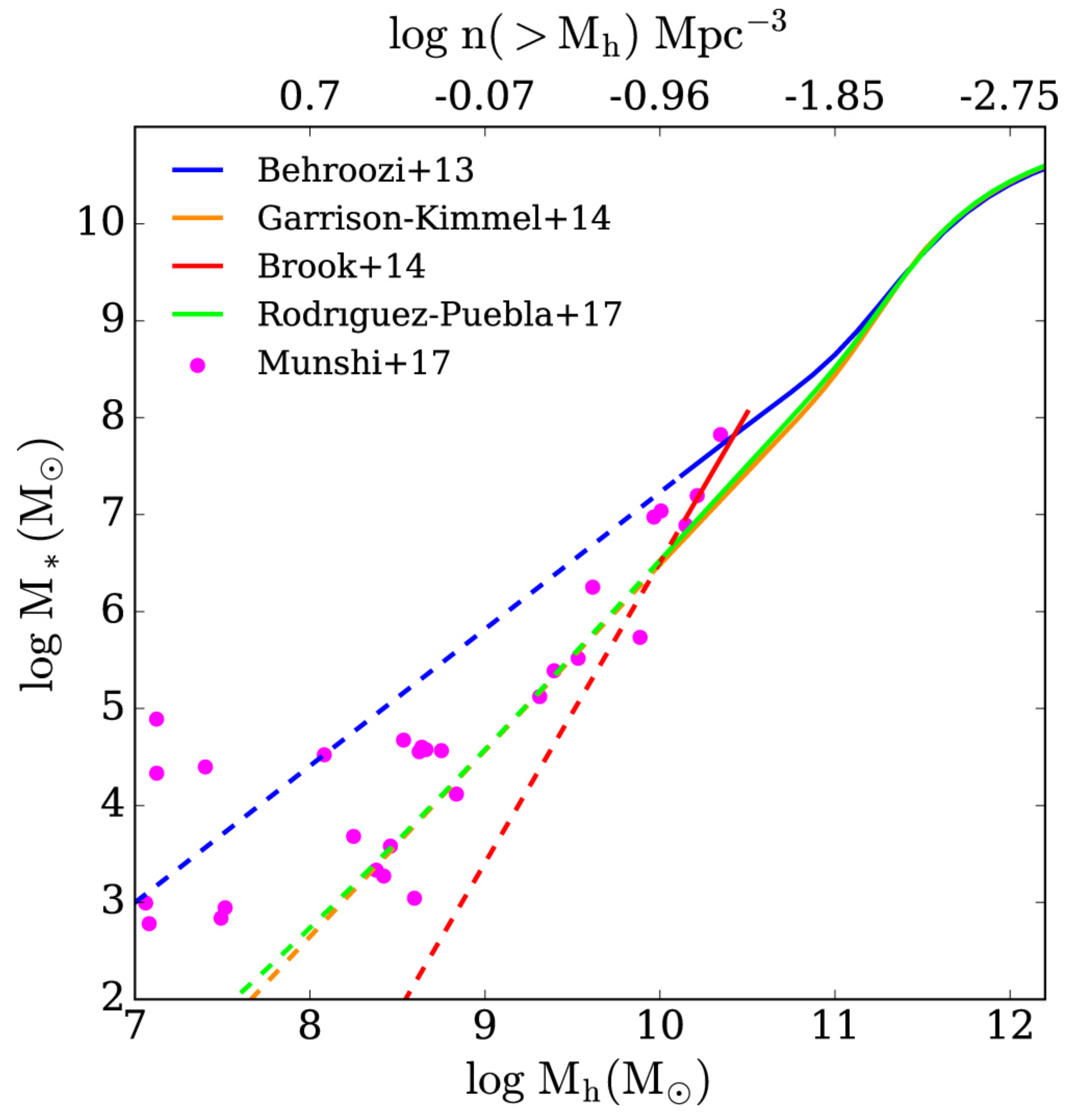
Low-mass galaxies ($M_* < 10^9\ M_\odot$) are essential for testing dark matter (and galaxy formation) models on small scales - II

In the field:

- **Constraints on the field luminosity function**
- **Galaxy-halo connection**



Bullock & Boylan-Kolchin 2019

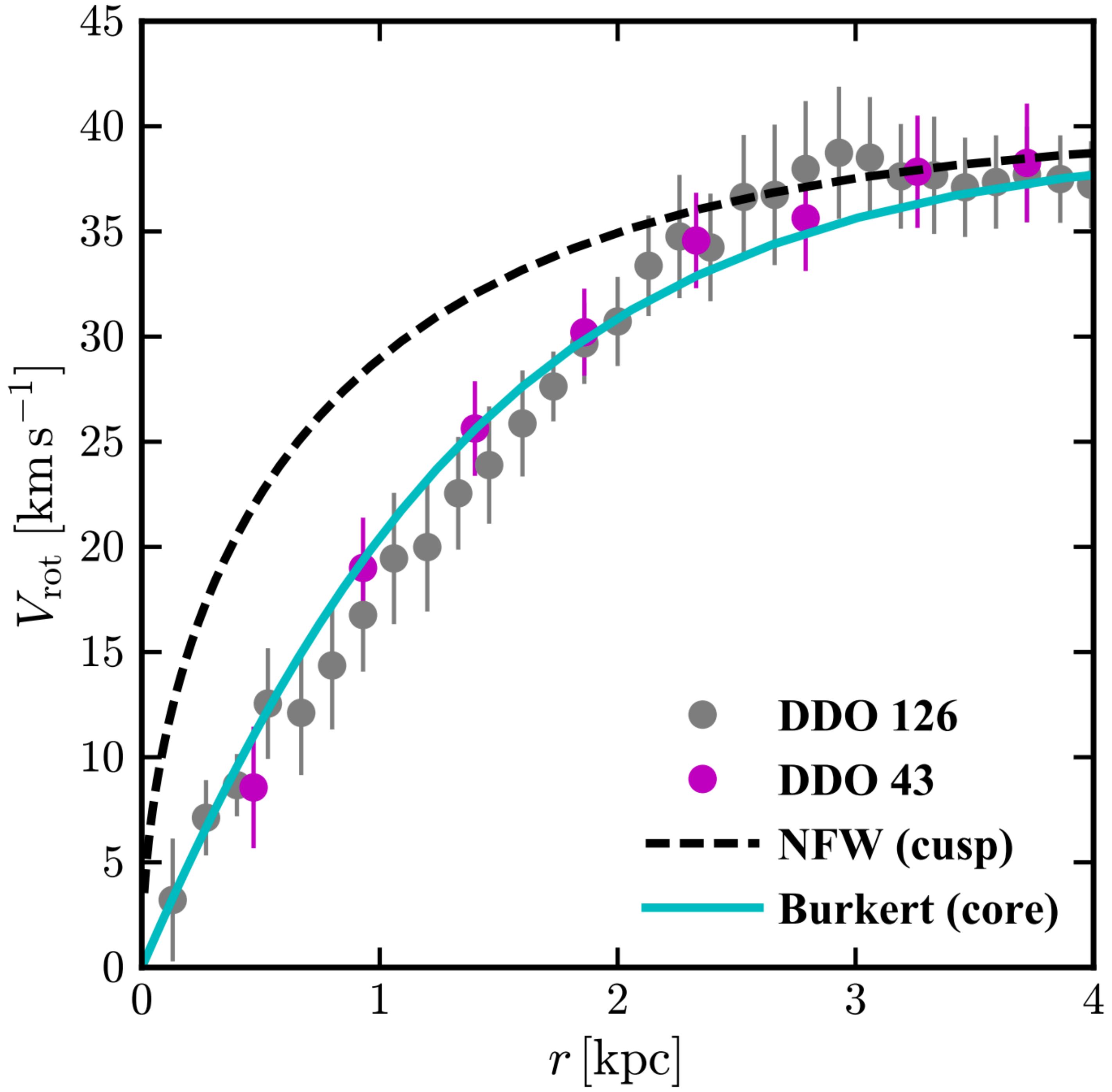


Danieli et al. 2018

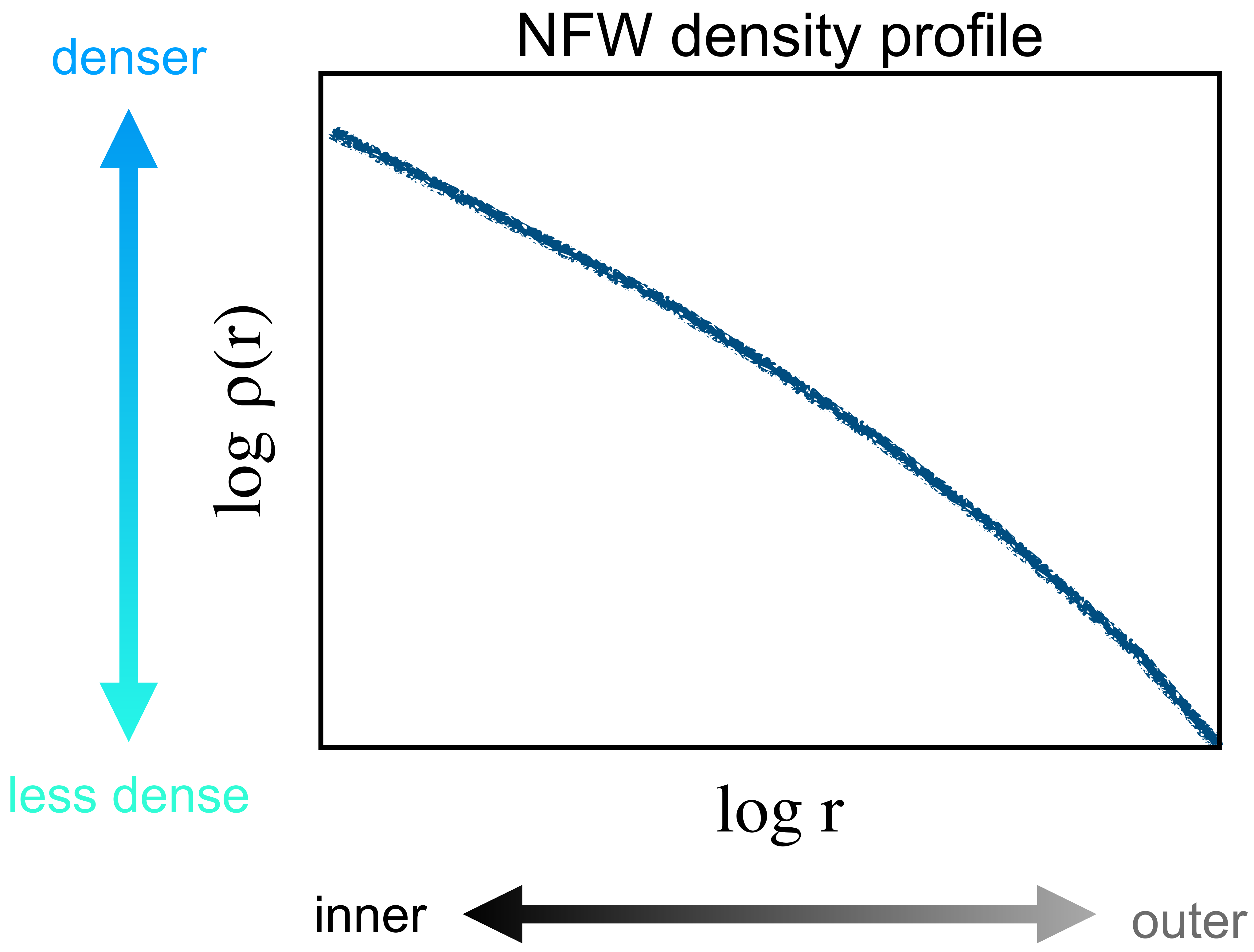
The sub-structure of individual dark matter halos - <u>Core or cusp</u>?

*In dark matter-only N-body simulations, **halos have a cuspy** profile, inner 1/r cusp to an outer 1/r³ profile (Dubinski et al. 1991, Navarro et al. 1996, 1997)*

Observations reveal a constant “cored” density profile

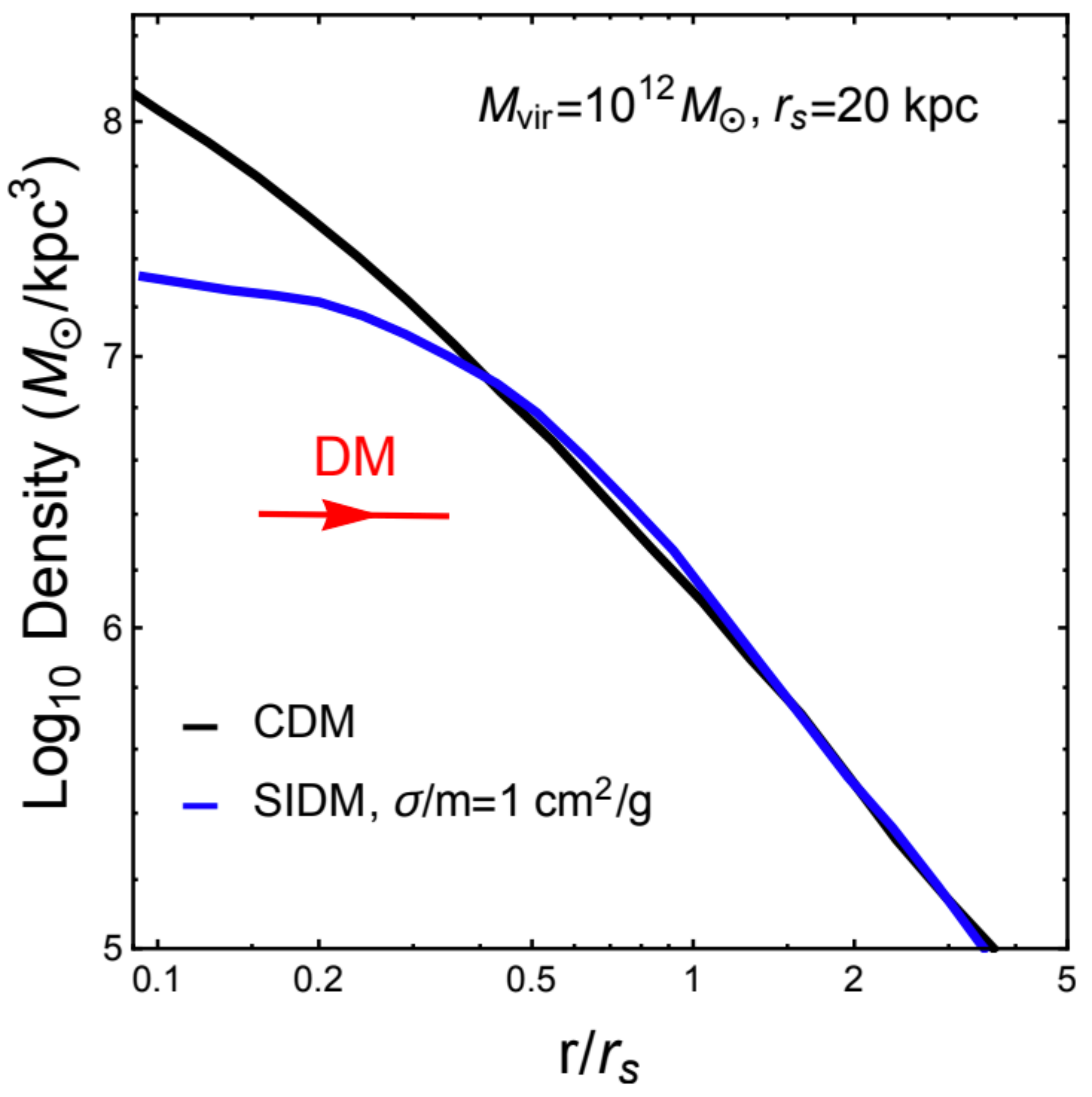


Bullock & Boylan-Kolchin 2019



THE SUB-STRUCTURE OF INDIVIDUAL DARK MATTER HALOS - <u>CORE OR CUSP</u>?

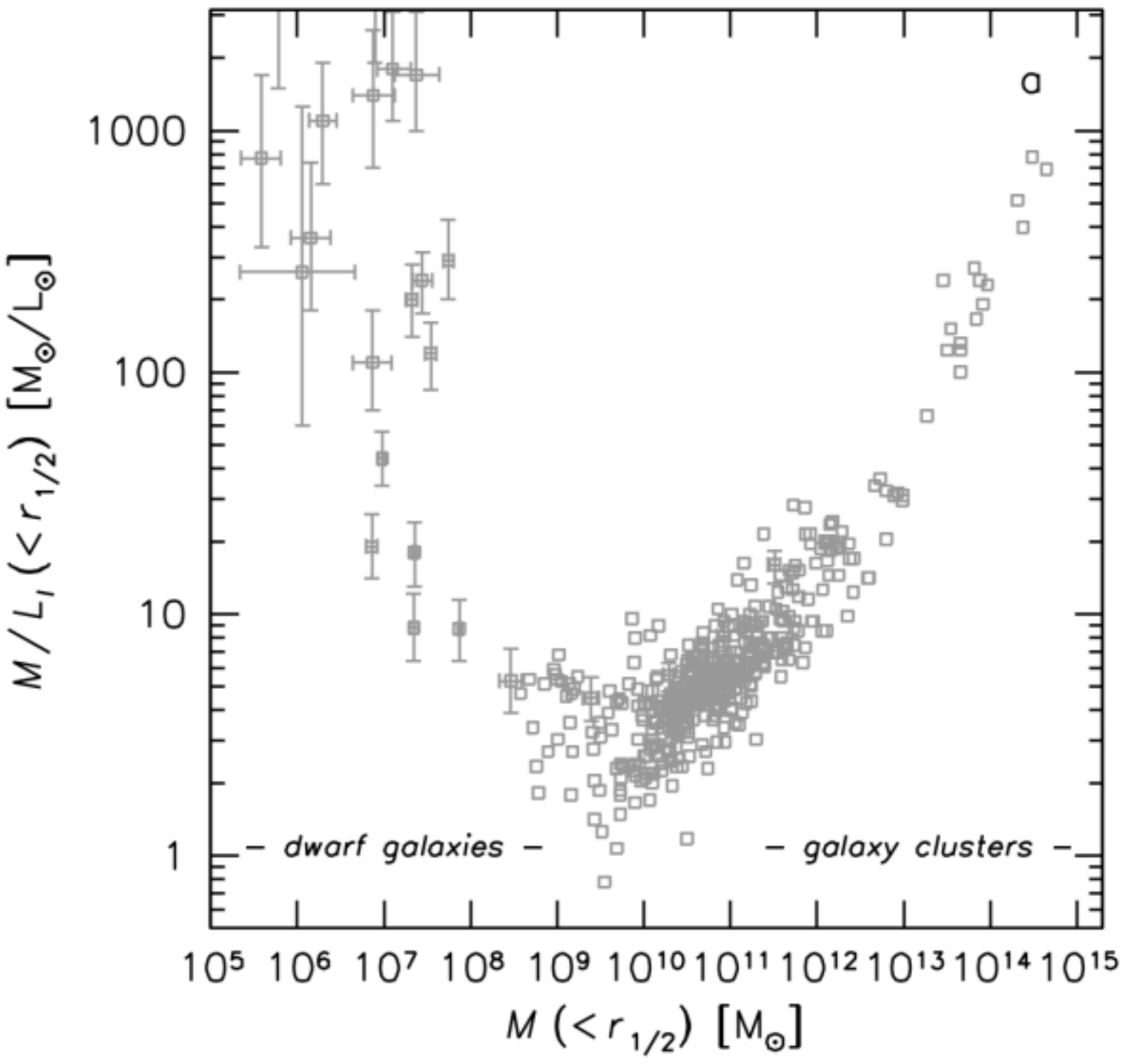
Self Interacting Dark Matter (SIDM; Spergel & Steinhardt 2000) predicts reduced central density



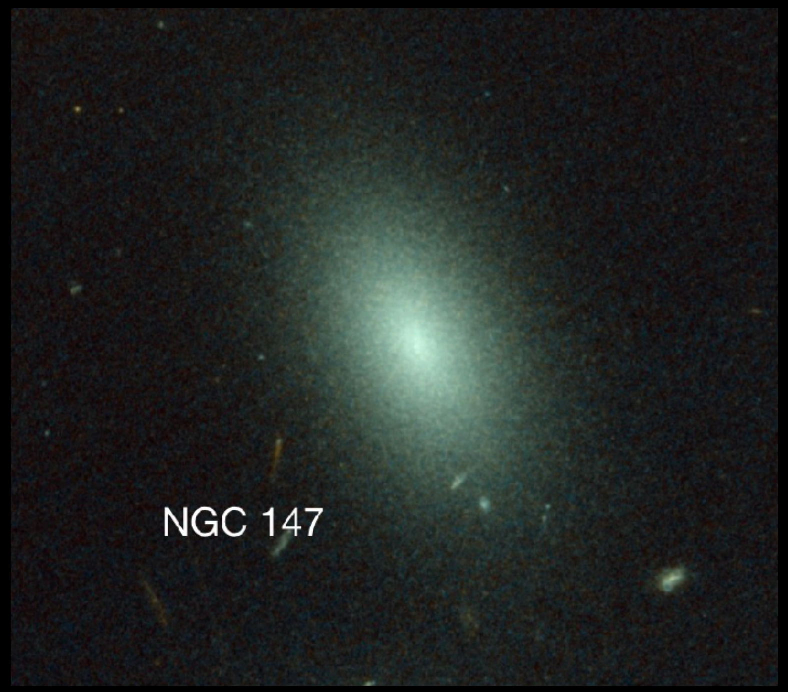
Tulin & Yu 2017

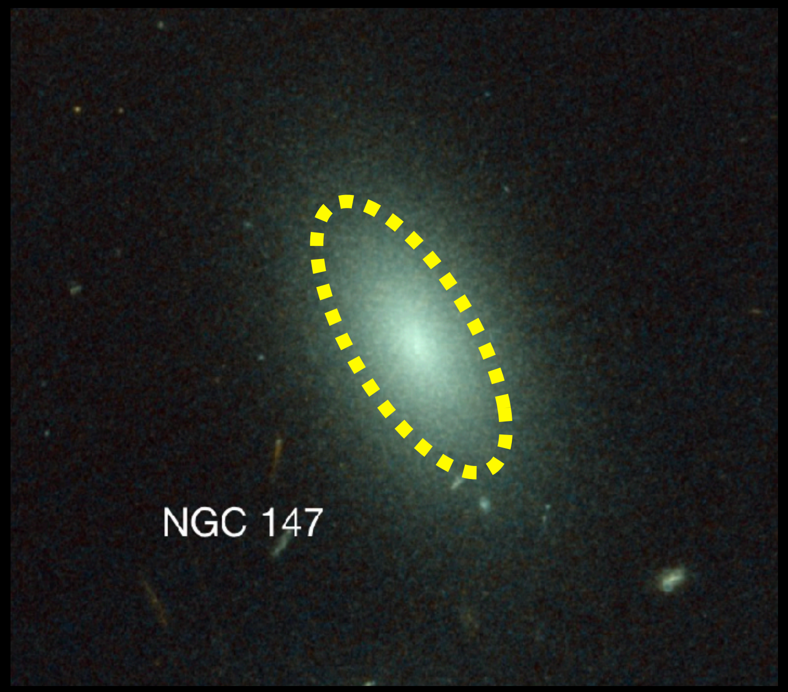
Low-mass galaxies ($M_* < 10^9\ M_\odot$) are essential for testing dark matter (and galaxy formation) models on small scales - III

In the Local Group, they are dark matter dominated (high mass-to-light ratios)

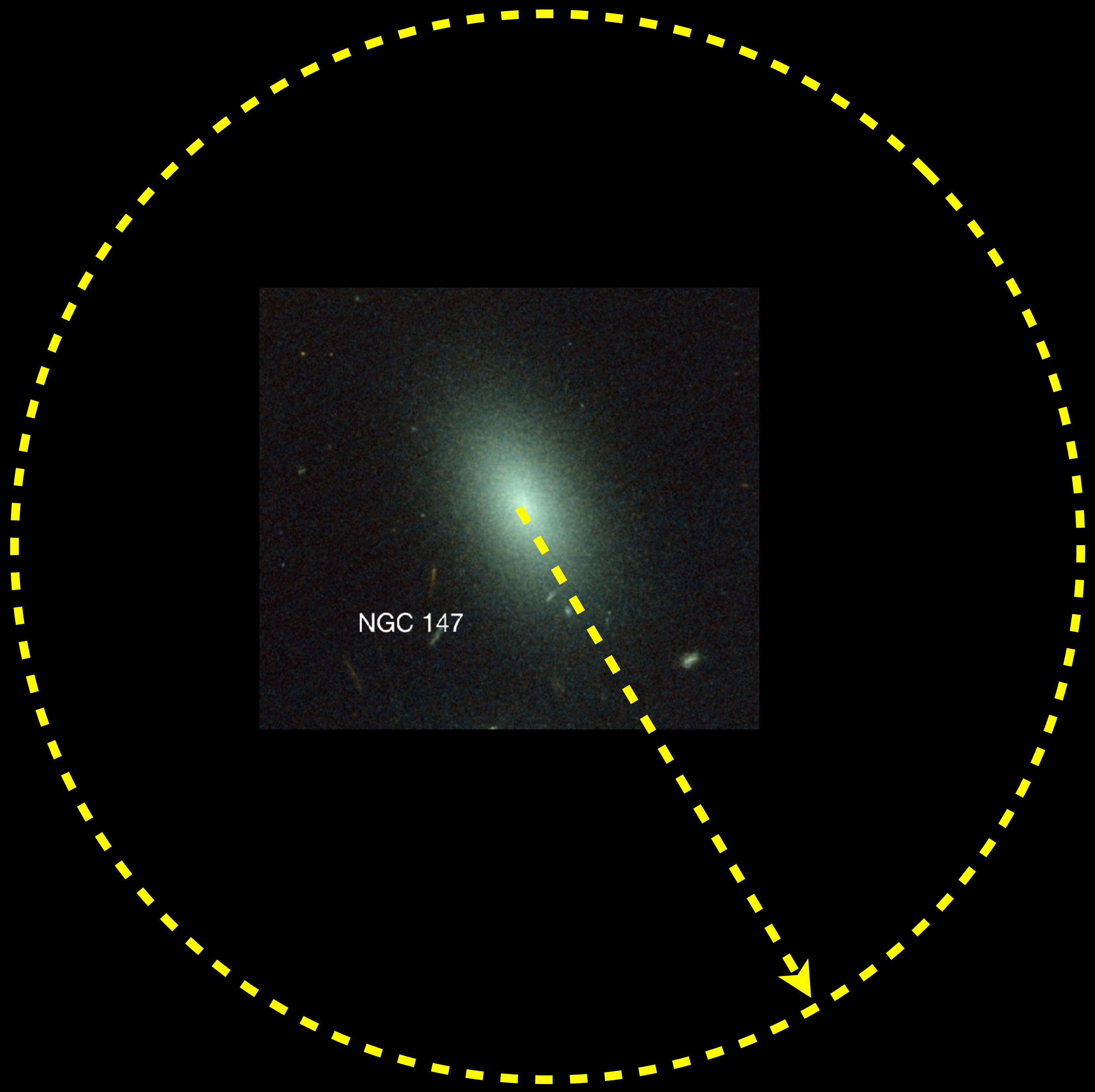


van dokkum et al. 2016

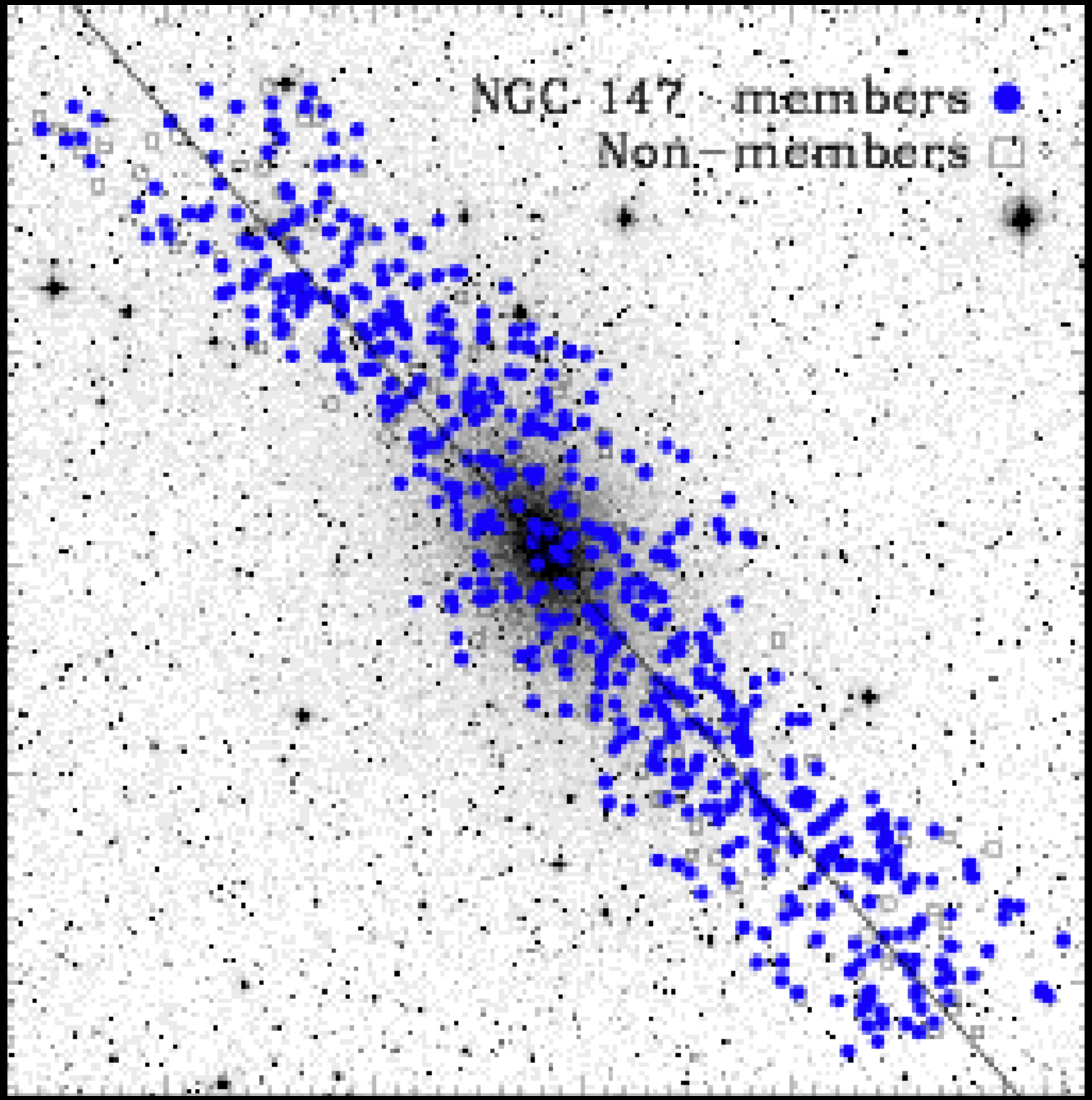

NGC 147



r_{eff} ~ 0.3 kpc



kinematic profile out to $8r_{eff}$ = 2.4 kpc (Geha et al. 2010)



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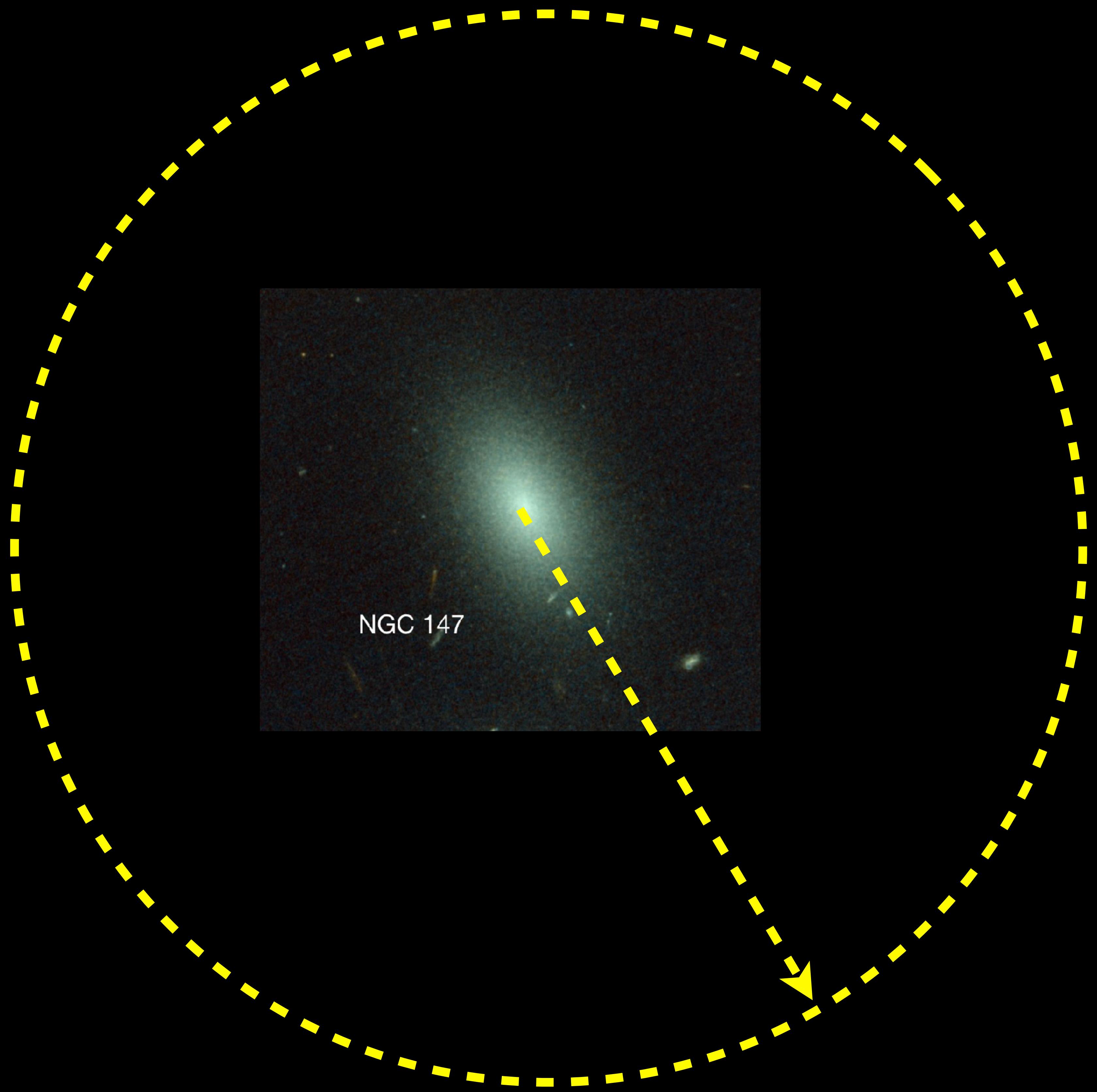

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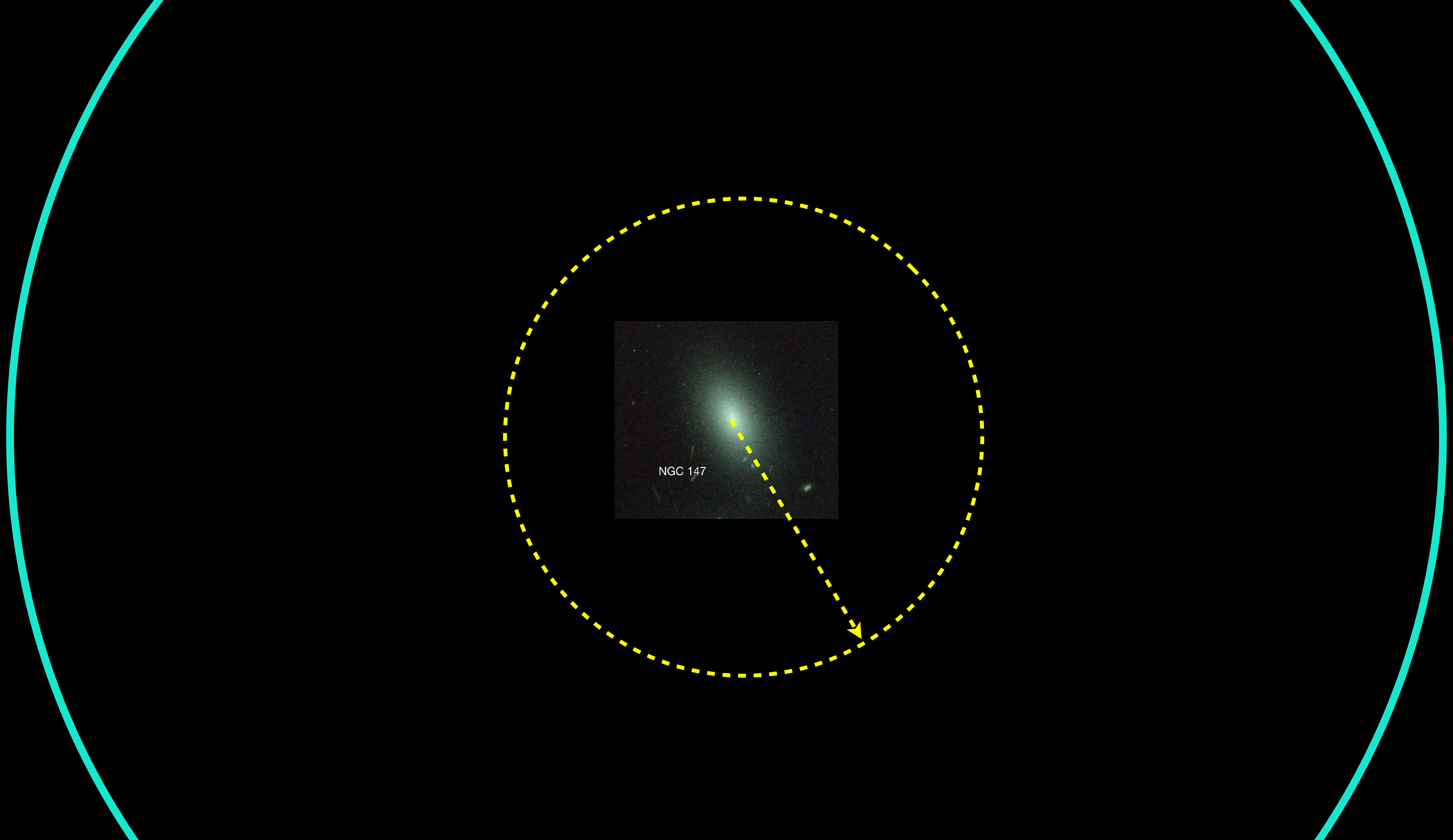
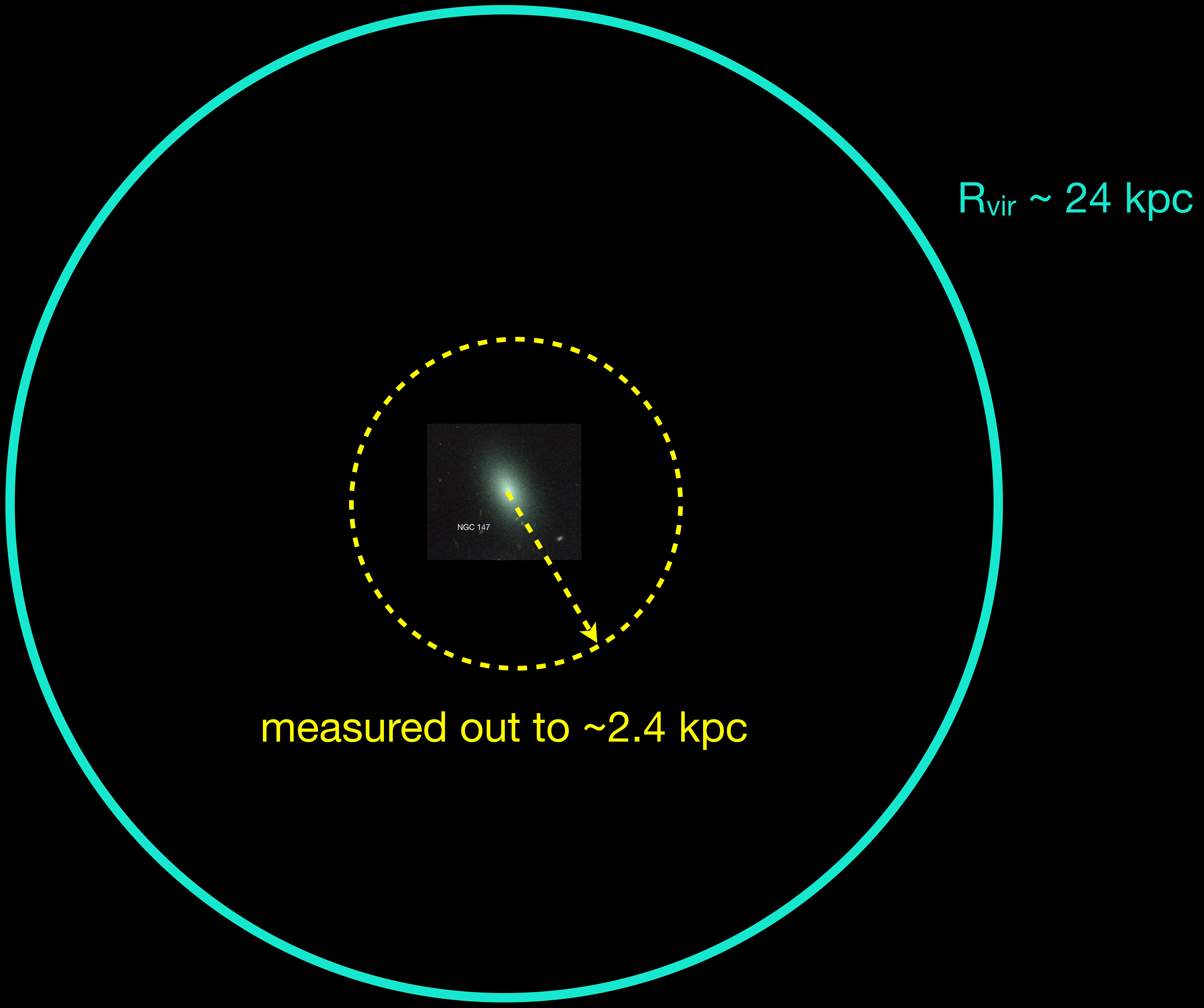
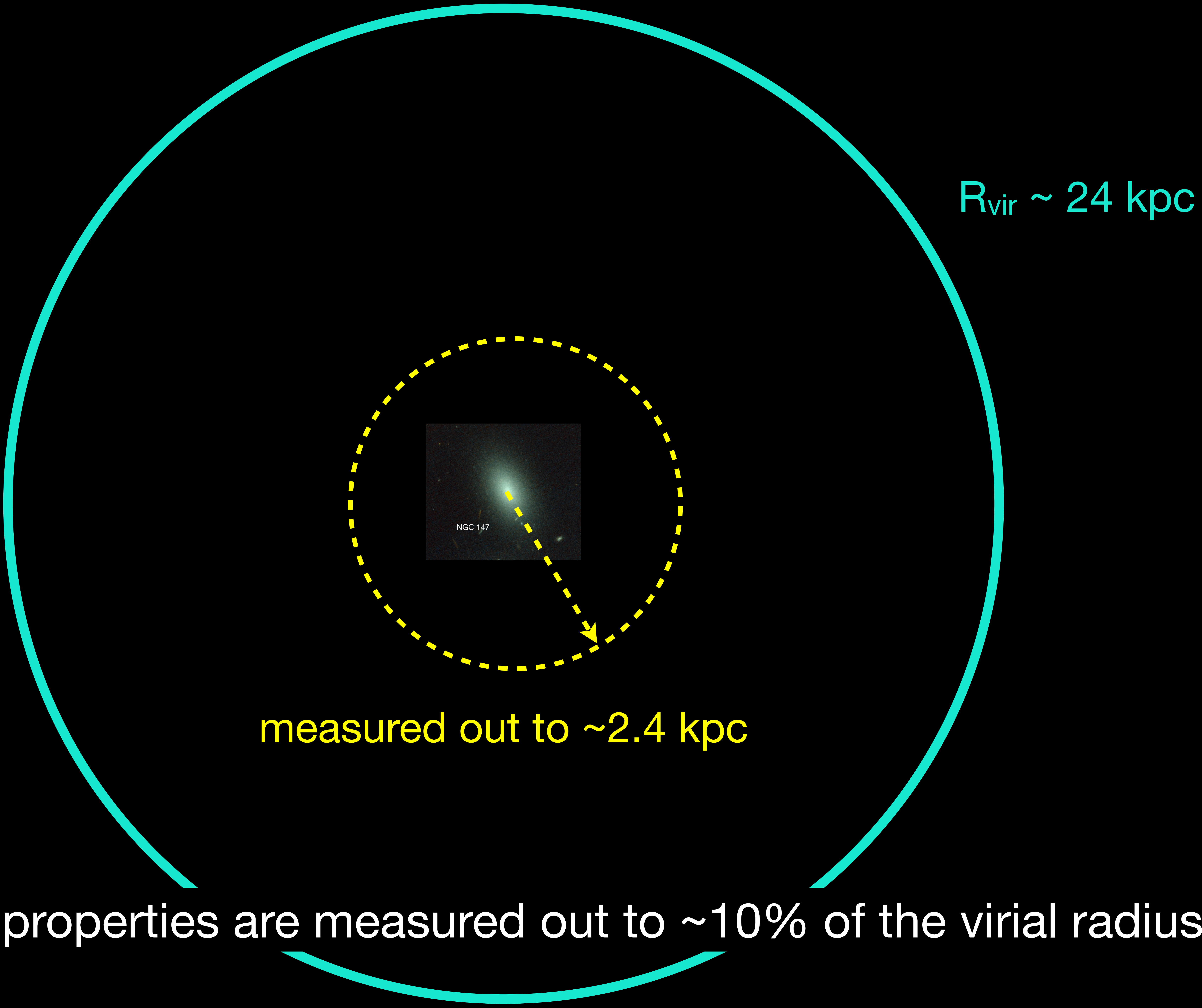

NGC 147

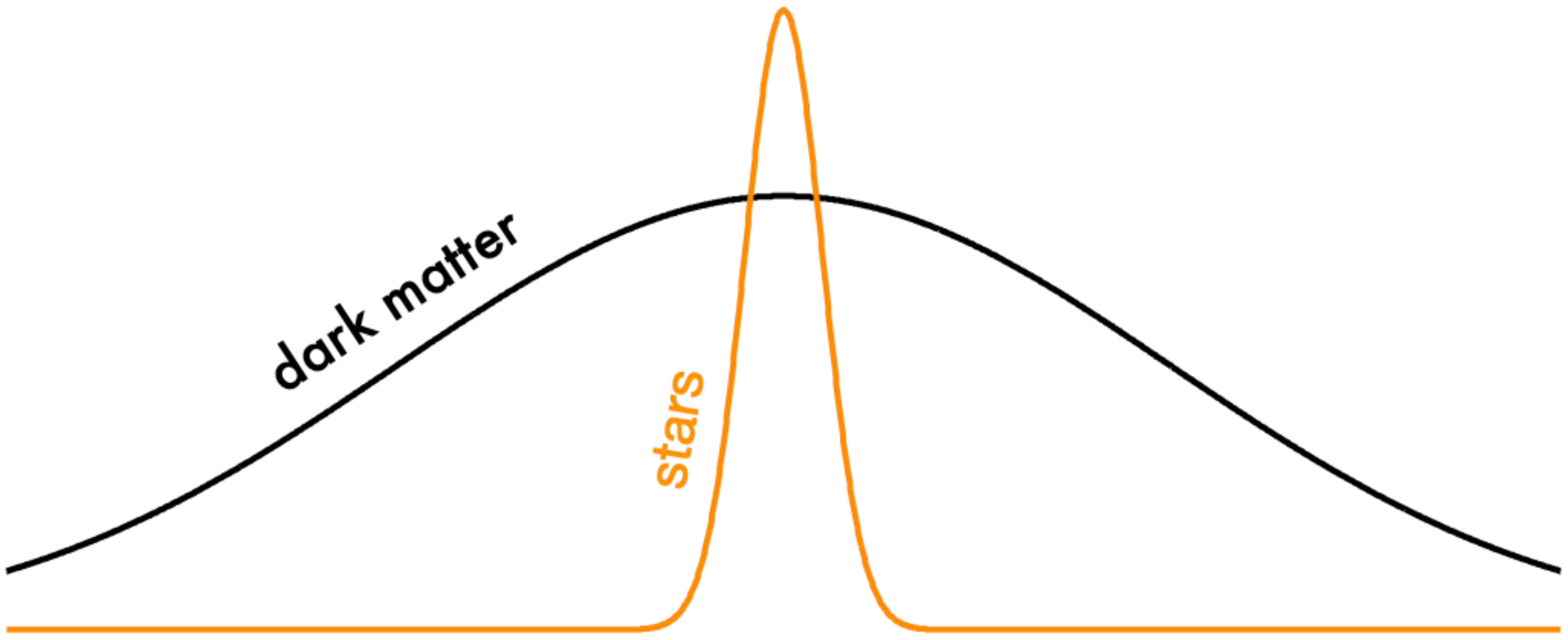


Rvir ~ 24 kpc
NGC 147
measured out to ~2.4 kpc



The halo properties are measured out to ~10% of the virial radius

In “normal” dwarf galaxies



- stars contribute significantly in central regions
- stellar distribution does not extend much beyond those regions

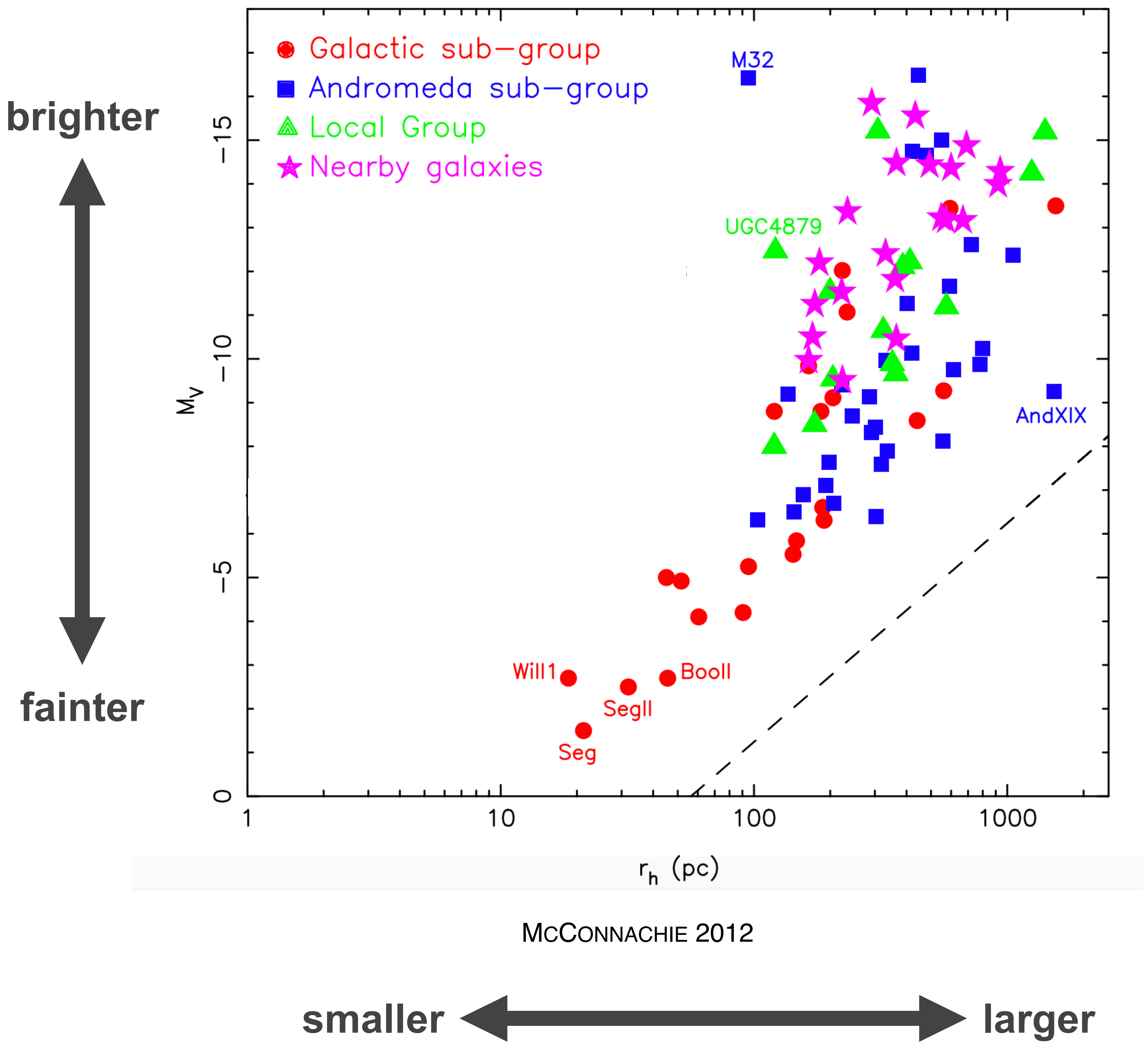
The halo properties are measured out to ~10% of the virial radius

Limitations in studying the dynamics of dwarf galaxies

1. Observationally very difficult and expensive (Geha et al. 2010)
2. The fraction of the halo we can measure is limited (~10% of the virial radius)
3. Extremely sensitive to the number of tracers used to estimate the velocity dispersion (e.g. Collins et al. 2019 - And XIX, from 4.7 km/s to 7.8 km/s when increasing the number of tracers from ~25 stars to ~100 stars)

Galaxies are thought to follow a tight relation between their sizes and total luminosity/mass

In the Local Group, smaller galaxies have lower total magnitude



McCONNACHIE 2012

THE ASTRONOMICAL JOURNAL VOLUME 89, NUMBER 7 JULY 1984

STUDIES OF THE VIRGO CLUSTER. III. A CLASSIFICATION SYSTEM AND AN ILLUSTRATED ATLAS OF VIRGO CLUSTER DWARF GALAXIES

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ABSTRACT

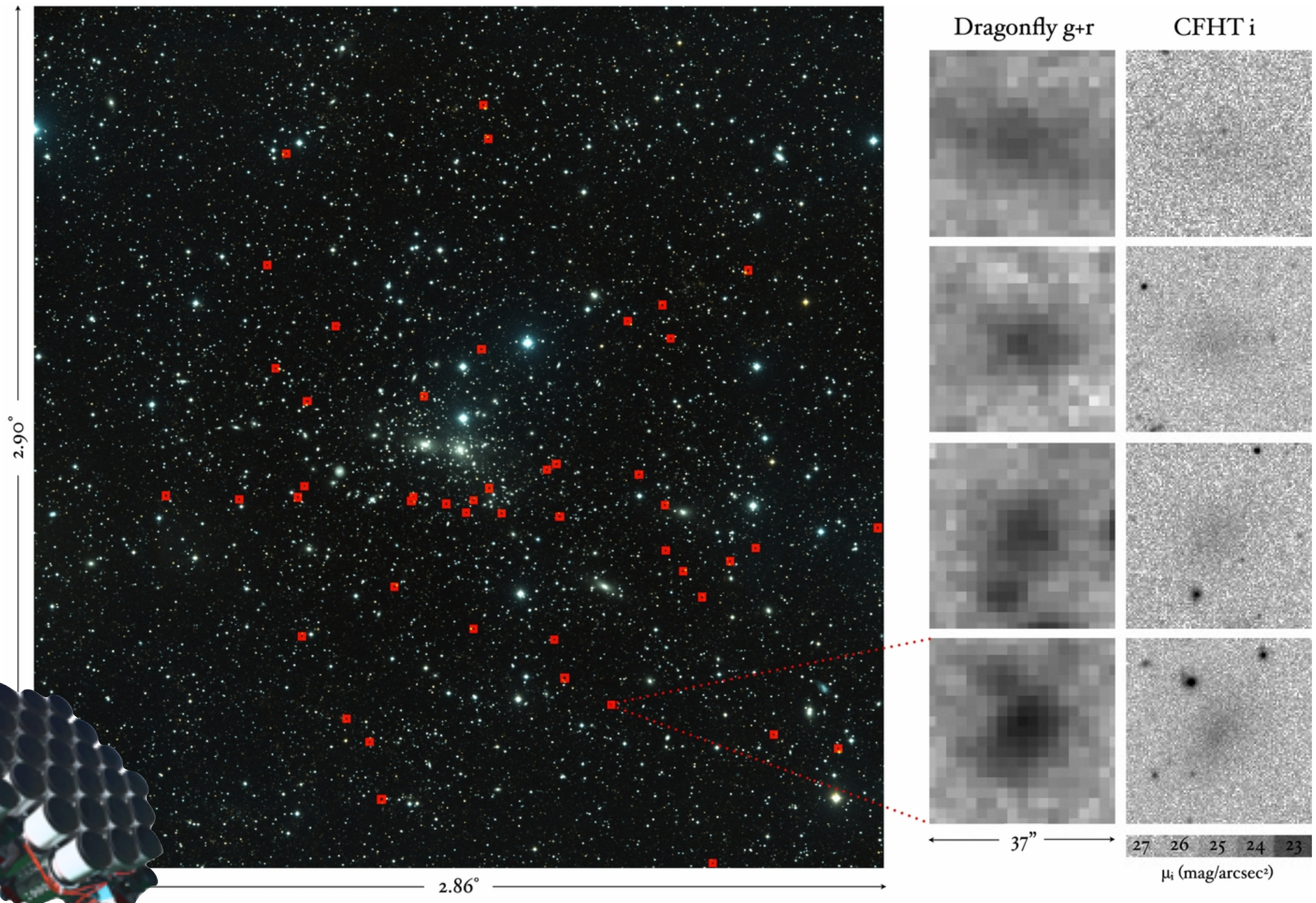
Photographs enlarged to a common scale are given for 138 dwarf galaxies in the region of the Virgo cluster. Most are cluster members, as judged either from their uniquely low surface brightness and/or morphology, or occasionally from velocity data. All known Hubble galaxy types have been found in the Virgo cluster, ranging in absolute magnitude from the brightest known giant ellipticals and spirals to all the types of dwarfs that were expected from prior knowledge of the dE, Sm, Im, and blue compact dwarfs (BCD) in the Local Group and its environs. A new type of very large diameter (10 000 pc), low central surface brightness ($\gtrsim 25$ B mag/arcsec) galaxy, that comes in both early (i.e., dE) and late (i.e., Im V) types, has been isolated, but there are, as yet, no known examples in the local neighborhood. The Atlas is organized in a way that recognizes the continuum between the giant and the dwarf ellipticals on the one hand, and the linear progression which, in order, connects the high luminosity Sc and Sd galaxies, the Magellanic Cloud Sm types, and the SMC Im galaxies of decreasing average surface brightness. This sequence among the late-type galaxies is one of ever-decreasing absolute luminosity. It is emphasized that, unlike the continuum that exists between giant and dwarf E galaxies, there are no connectives from the giant Sa, Sb, and Sc galaxies to a sequence of *very-low-luminosity spirals*. Dwarf Sa, Sb, and Sc galaxies (i.e., fainter than, say $M_B = -17$) are not present in the Virgo cluster, and we surmise that they *do not exist*. This Atlas and its descriptions are meant to form a preliminary classification system that organizes all known types of low-luminosity galaxies into a coherent scheme. It is also meant as a preliminary candidate list of late-type, low-SB dwarfs that can be usefully observed with Space Telescope to resolve the brightest stars in a next step to establish the extragalactic distance scale.

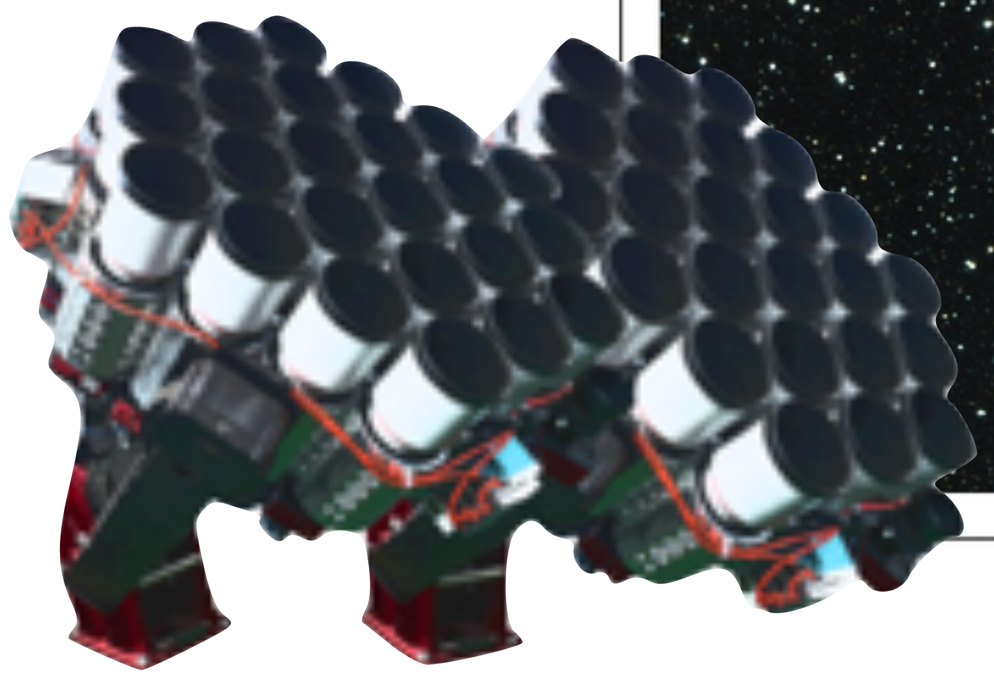
THE DRAGONFLY TELEPHOTO ARRAY

- 2x24 Canon Telephoto lenses
- Effectively a **1.0m f/0.4 refractor**

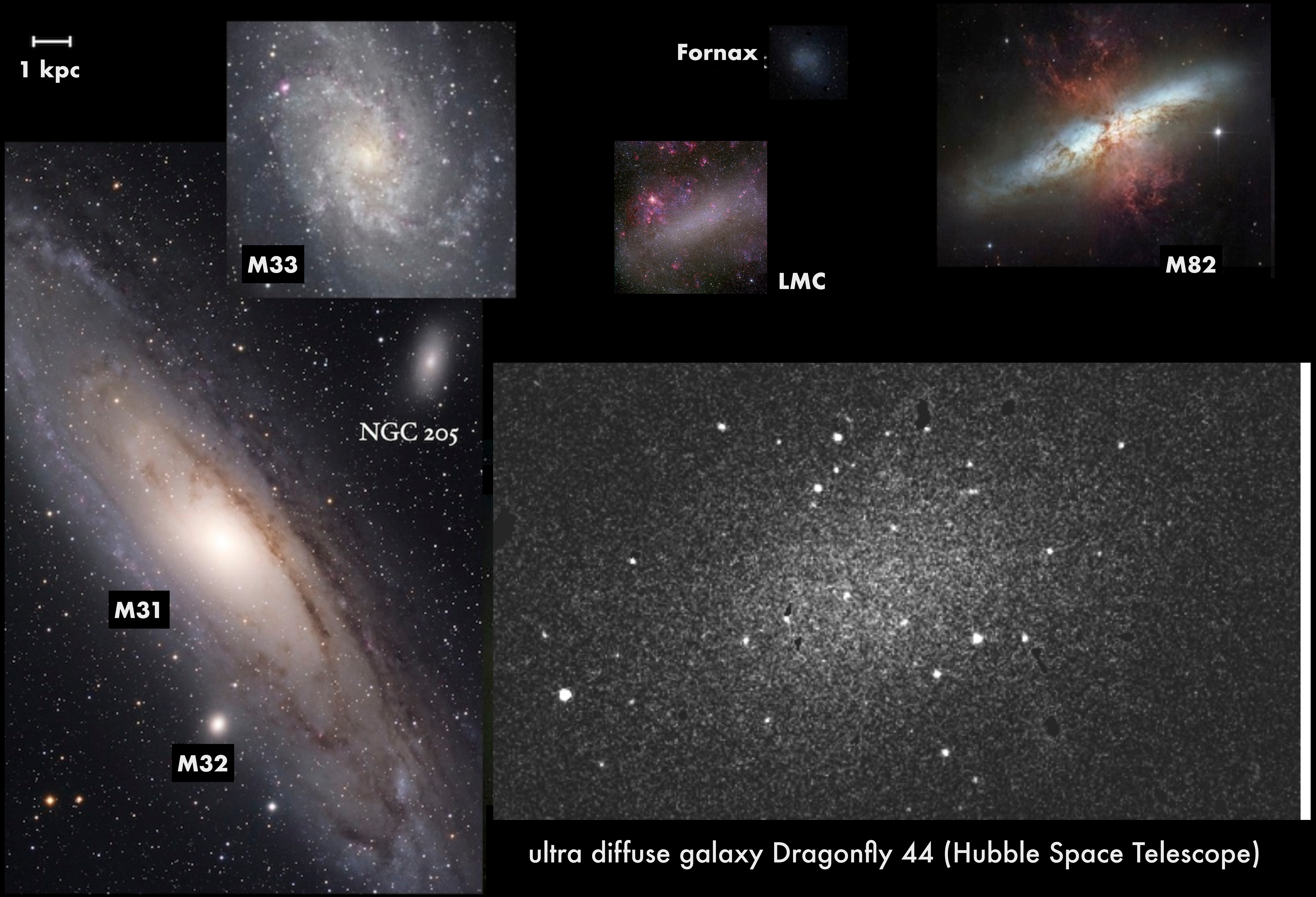
- 2x3 degree^2 field of view
- 2.9″ pixels

IMAGING OF THE **COMA CLUSTER** WITH DRAGONFLY DEMONSTRATED THAT LARGE, LOW SURFACE BRIGHTNESS GALAXIES ARE VERY COMMON





VAN DOKKUM ET AL. 2015

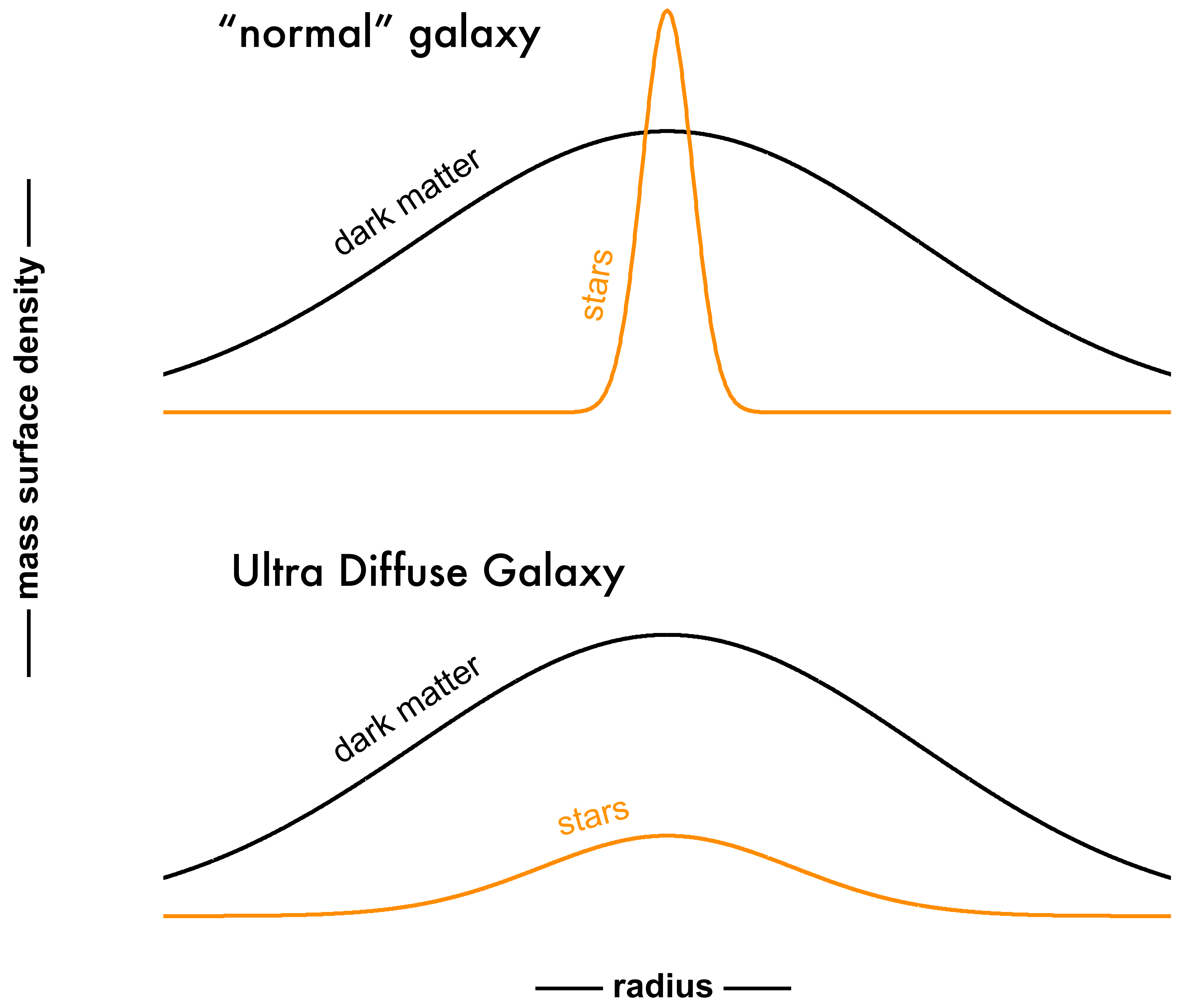


ultra diffuse galaxy Dragonfly 44 (Hubble Space Telescope)

UDGs are observed in very large numbers and in all environments

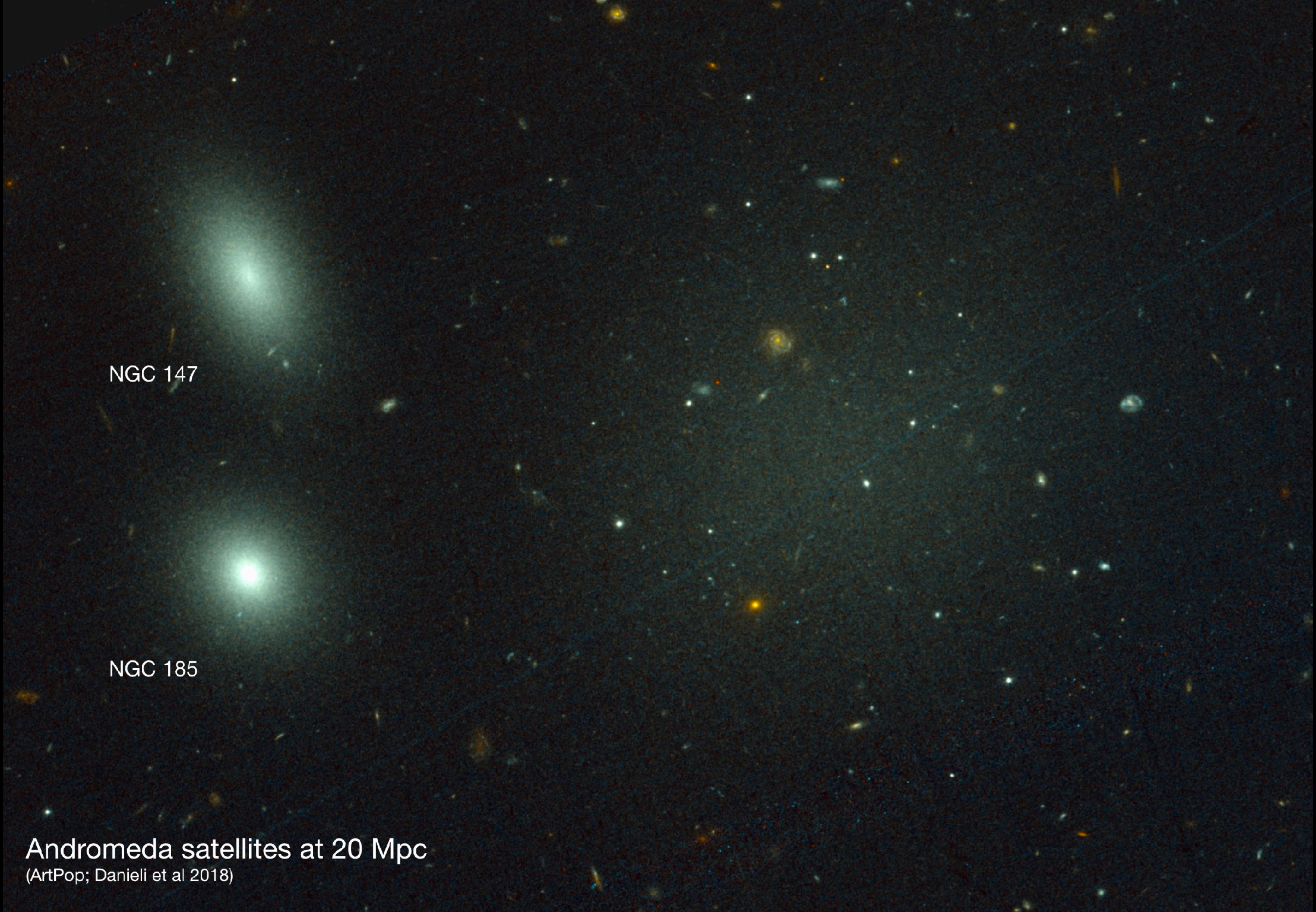
- 1000s in galaxy clusters (Koda et al 2015, Mihos et al 2015, van der Burg et al. 2017, Janssens et al. 2017, Lee et al. 2020, Alabi et al. 2020, Iodice et al. 2020, Liu et al. 2020)
- Associated with galaxy groups or low-density field (Merritt et al. 2016, Habas et al. 2019, Forbes et al. 2020, Tanoglidis et al 2020)
- ~ 800 in 200 deg^2 of the HSC-SSP Survey (Greco et al. 2018)
- ~ 300 in 290 deg^2 around the coma cluster with DECam (Zaritsky et al. 2019)
- In the field (Barbosa et al. 2020)
- HI observations (Papastergis et al. 2017, Leisman et al. 2017, Karunakaran et al. 2020, He et al. 2020)

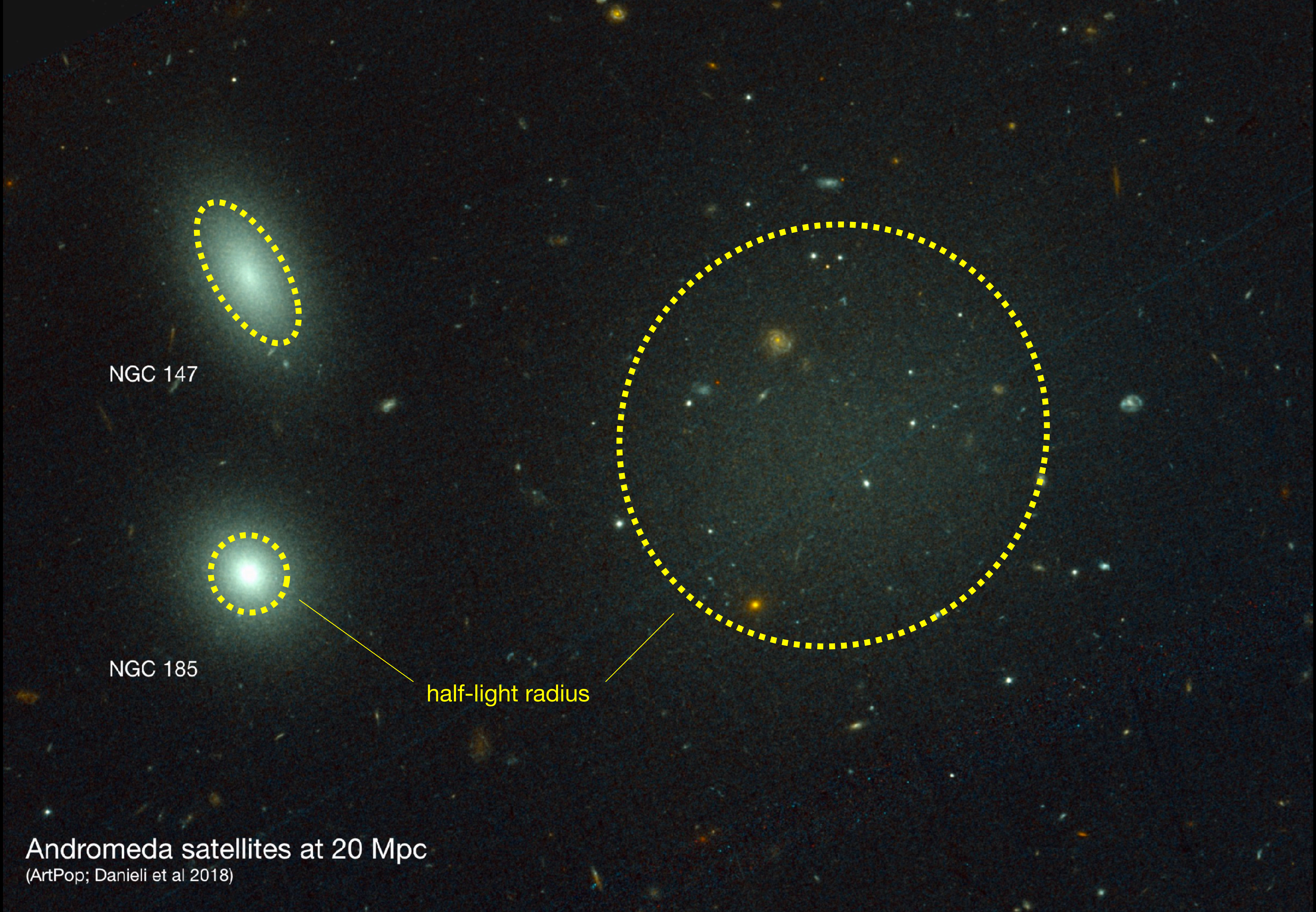
The large size of Ultra Diffuse Galaxies



- stars contribute significantly in central regions
- stellar distribution does not extend much beyond those regions

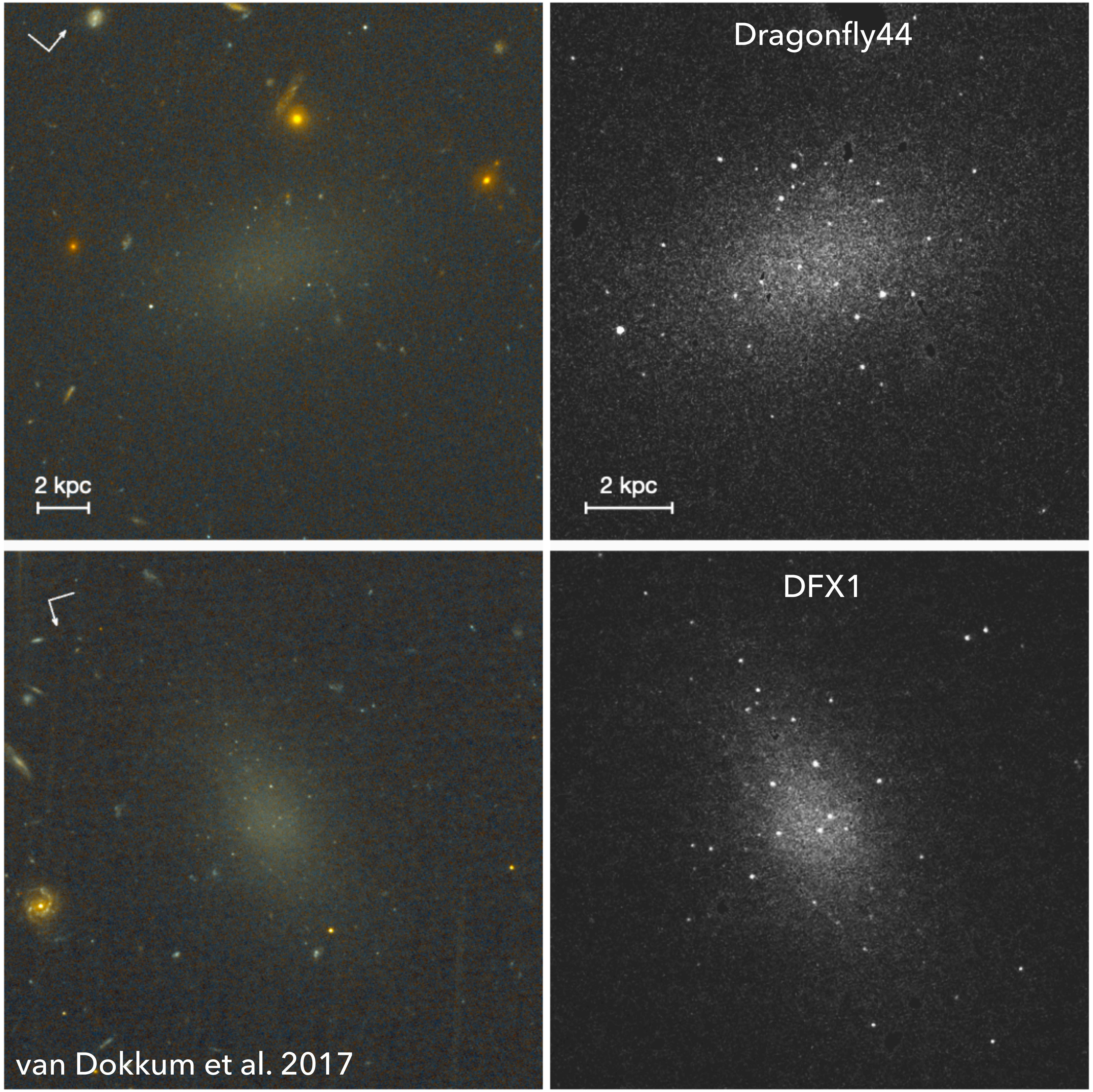
- dark matter dominates (or should dominate) on all scales
- dark matter can be traced to large radii


NGC 147
NGC 185
Andromeda satellites at 20 Mpc
(ArtPop; Danieli et al 2018)

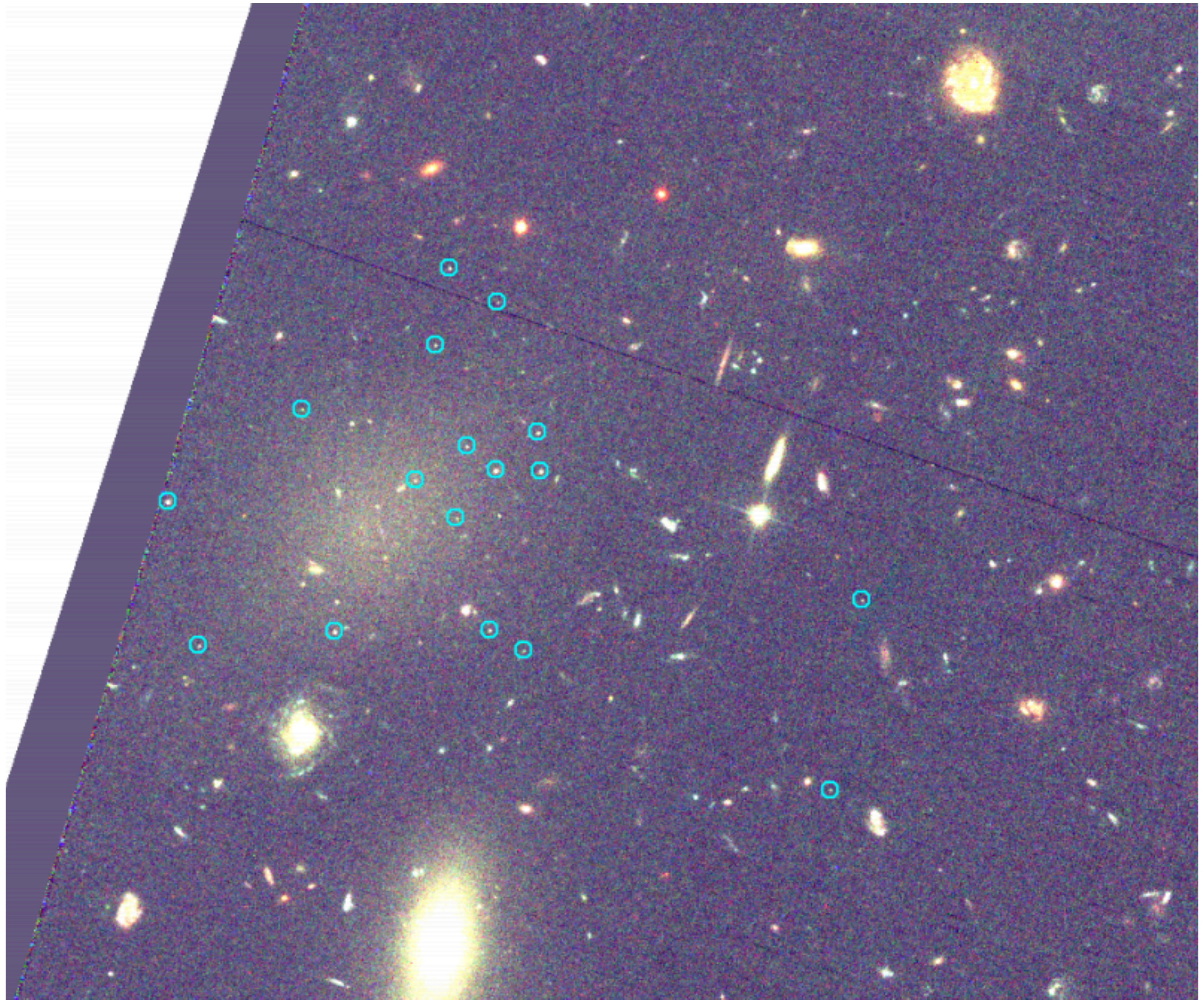

NGC 147
NGC 185
half-light radius
Andromeda satellites at 20 Mpc
(ArtPop; Danieli et al 2018)

Globular clusters in Ultra Diffuse galaxies

- High specific frequency (high number of globular clusters for their stellar mass)



van Dokkum et al. 2017



Peng & Lim 2016

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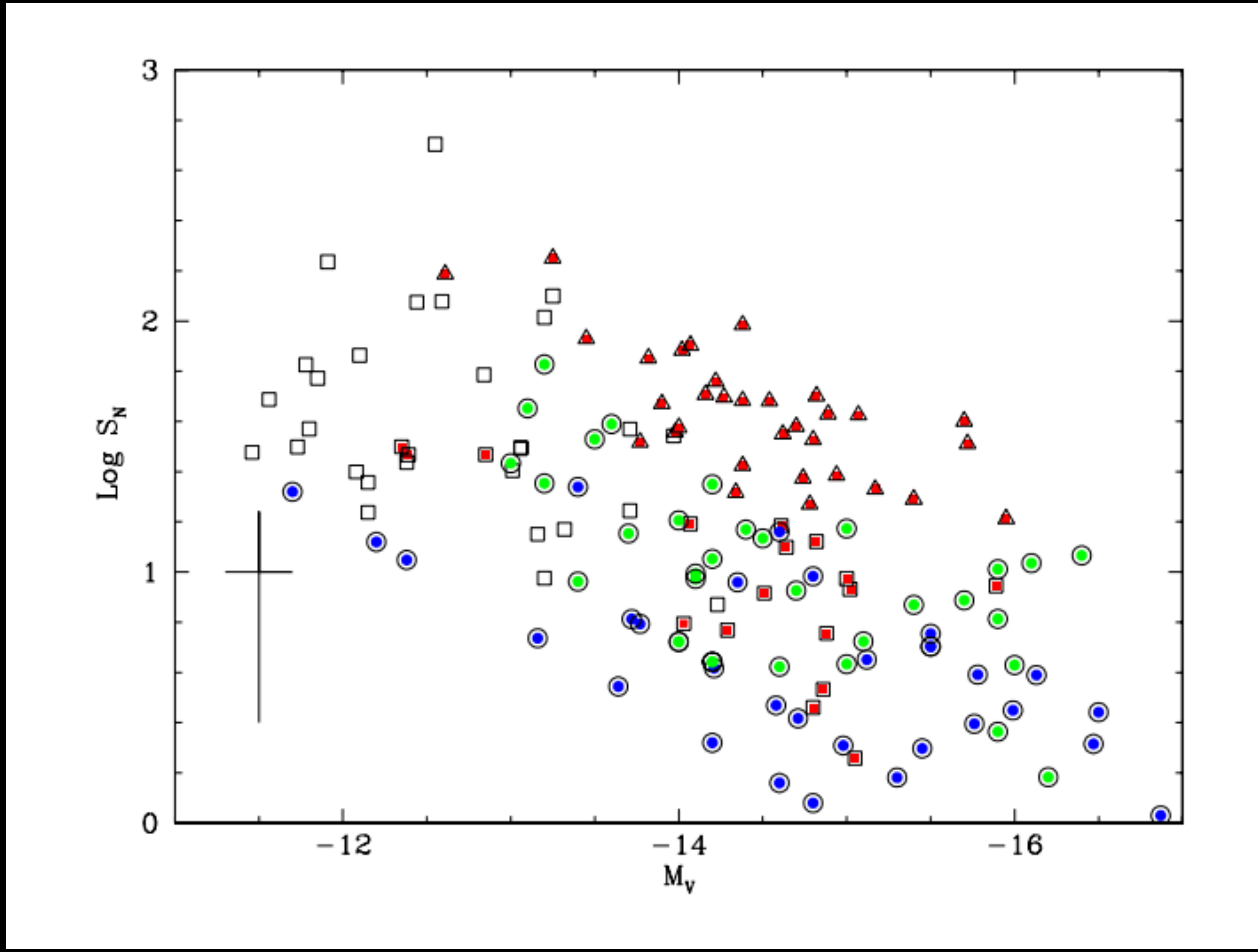


Coma UDGs

Coma LSBs dwarfs

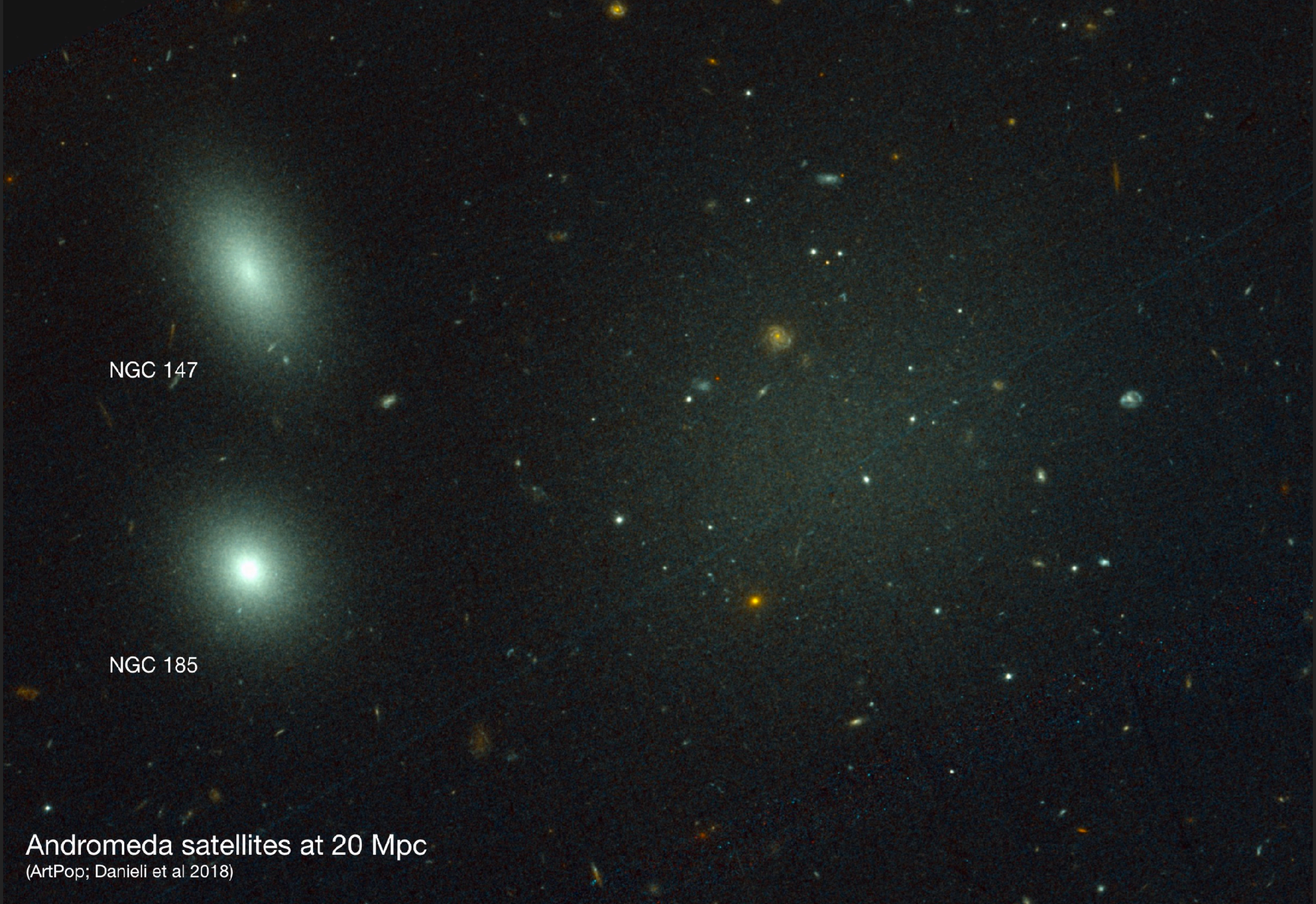
Coma early-type dwarfs

Local dwarfs

Forbes et al. 2020

Globular clusters in Ultra Diffuse galaxies

- High specific frequency (high number of globular clusters for their stellar mass)
- Excellent tracers of the dynamics - make dynamical constraints much easier and in some cases possible


NGC 147
NGC 185
Andromeda satellites at 20 Mpc
(ArtPop; Danieli et al 2018)


Globular clusters trace mass out to R ~ 8 kpc
NGC 147
NGC 185
Andromeda satellites at 20 Mpc
(ArtPop; Danieli et al 2018)

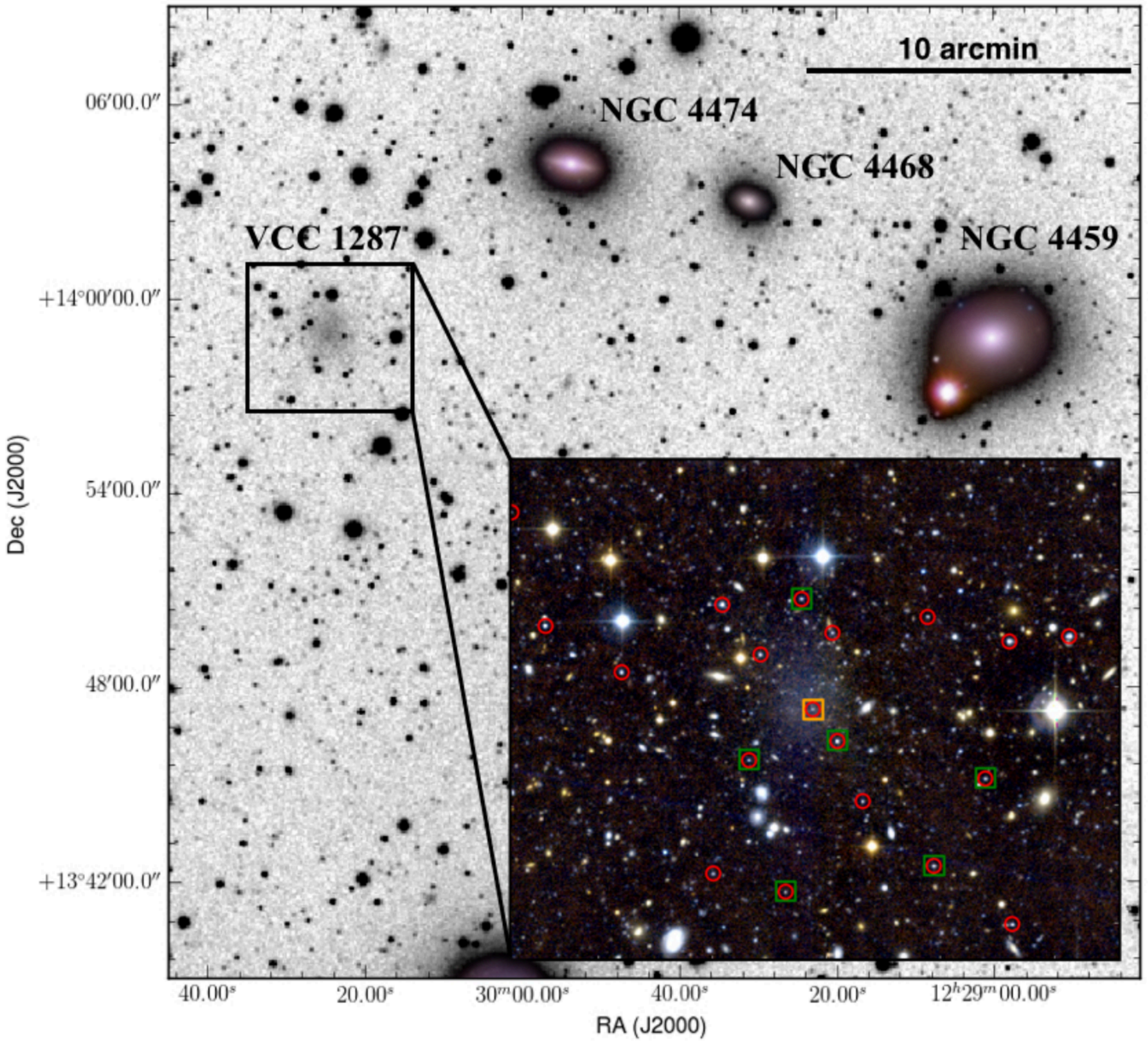
The Dark Matter Halo of Ultra Diffuse Galaxies

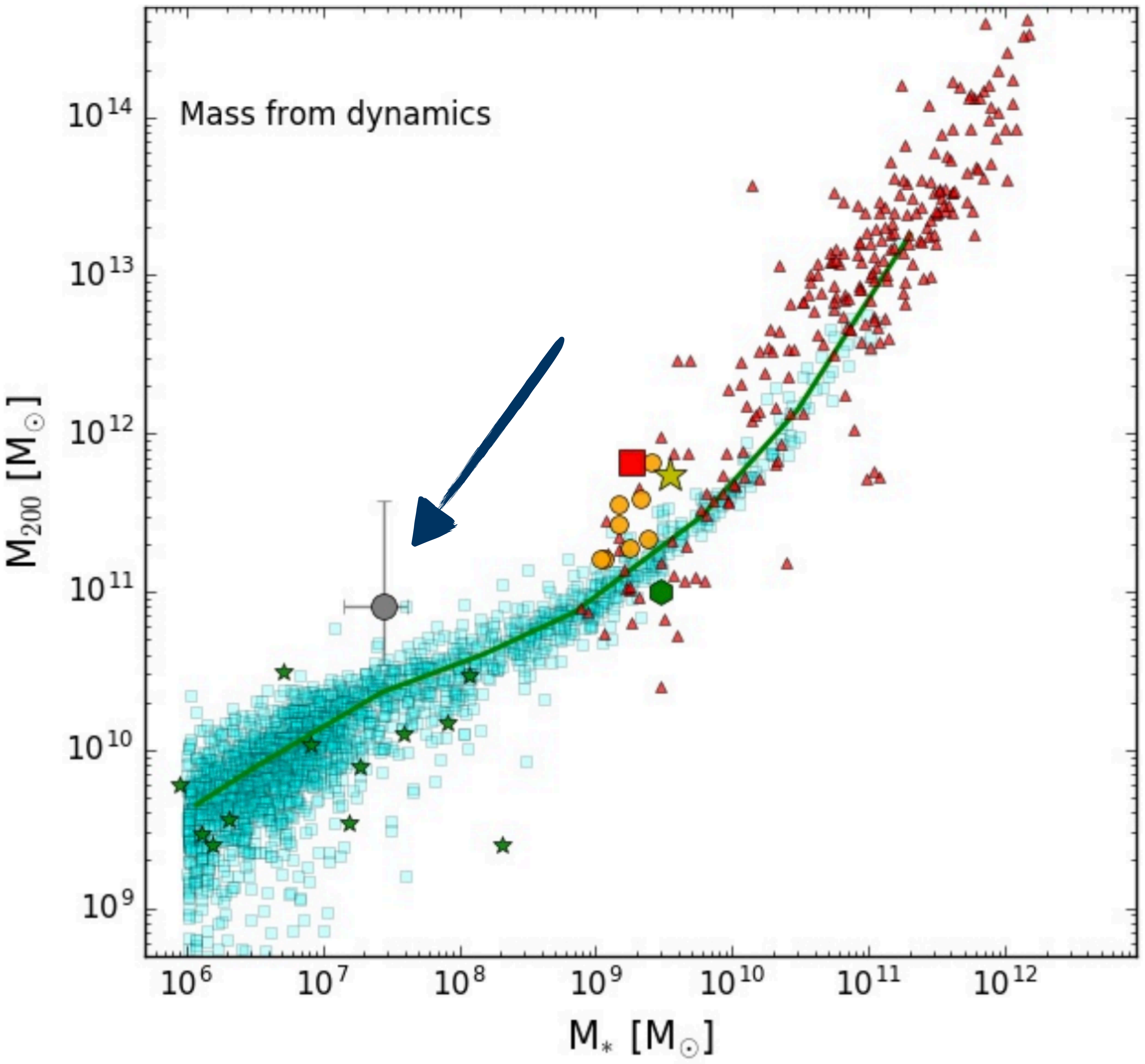
Can be measured through:

1. Globular clusters dynamics
2. Stellar kinematics

VCC 1287 (Beasley et al. 2016)

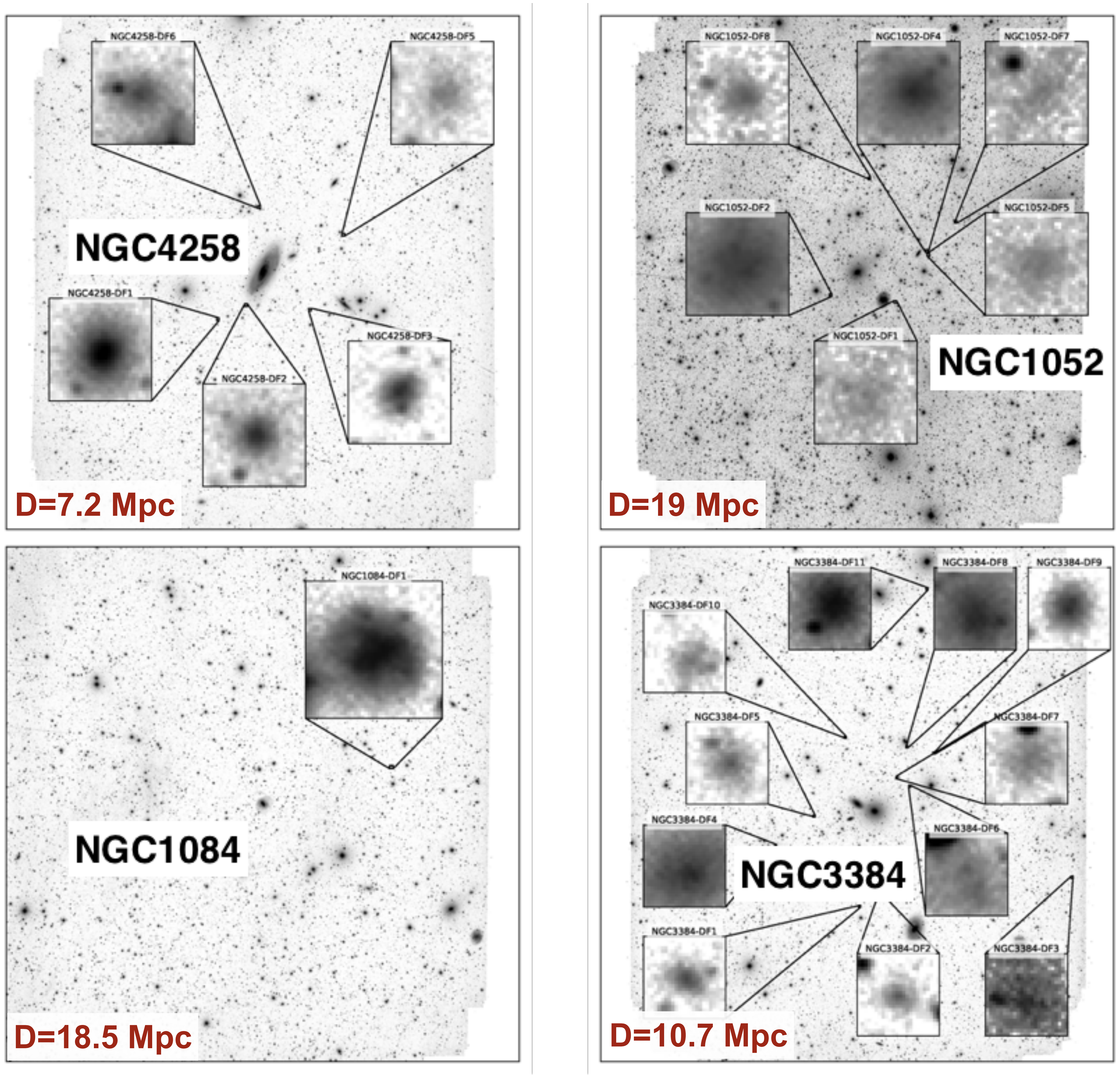
measured from seven globular clusters: σ = 33 km/s within 8.1 kpc



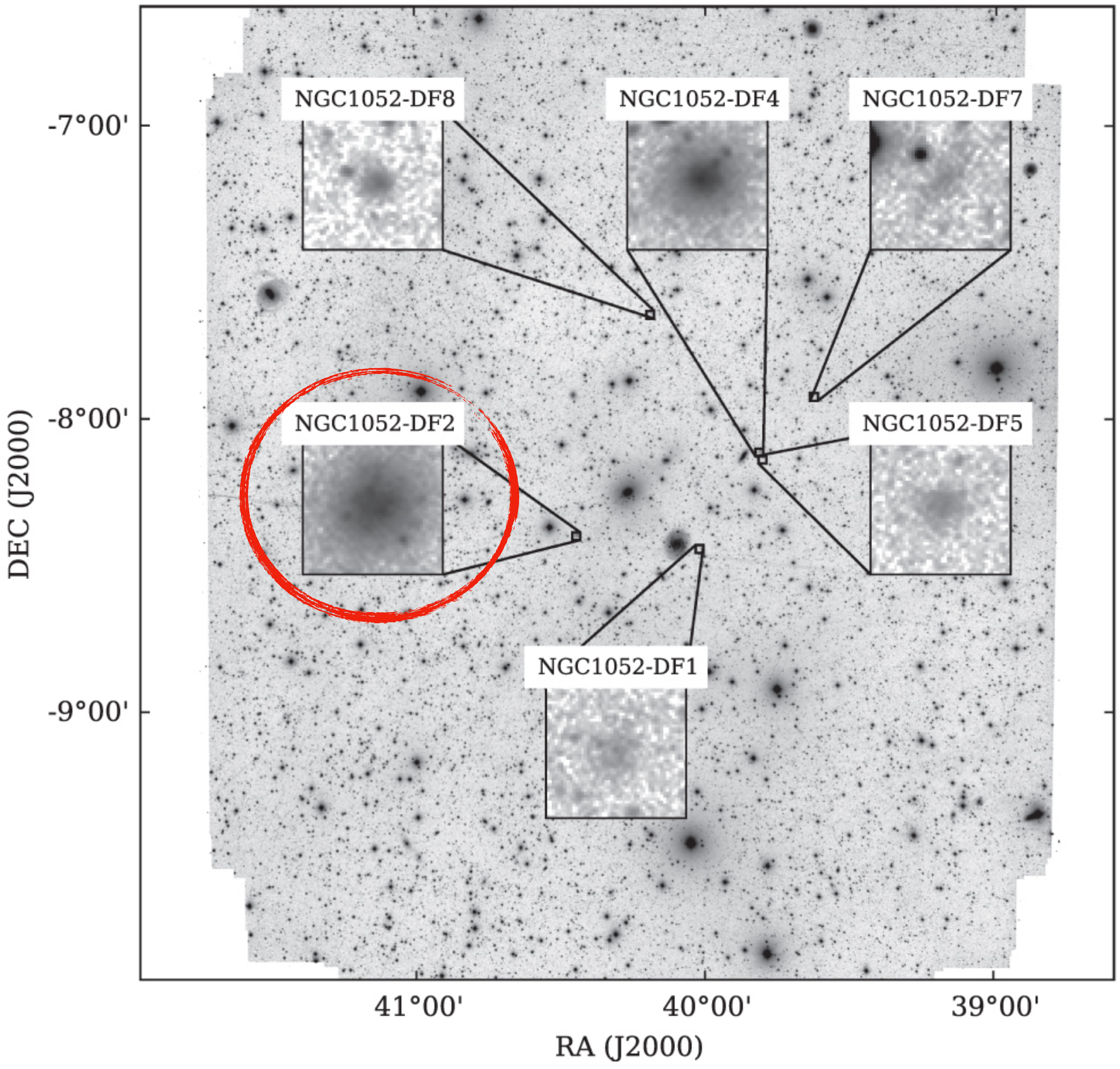


The Dragonfly Nearby Galaxies Survey

- Deep optical imaging of four nearby galaxy groups
- 23 very low surface brightness ($\mu_{e,V}$ ~ 25-27.5 mag/arcsec^2) galaxies were imaged with the Hubble Space Telescope
- 4/23 fall in the class of Ultra Diffuse Galaxies



Merritt et al. 2016, Danieli et al. 2017, Cohen et al. 2018



COHEN ET AL. 2018

Stellar mass of a dwarf galaxy

but big

M_{stars}=2x10^8 $M_{\odot}$, R_{eff} = 2.2 kpc,
μ_V = 24.4 mag $arcsec^{-2}$

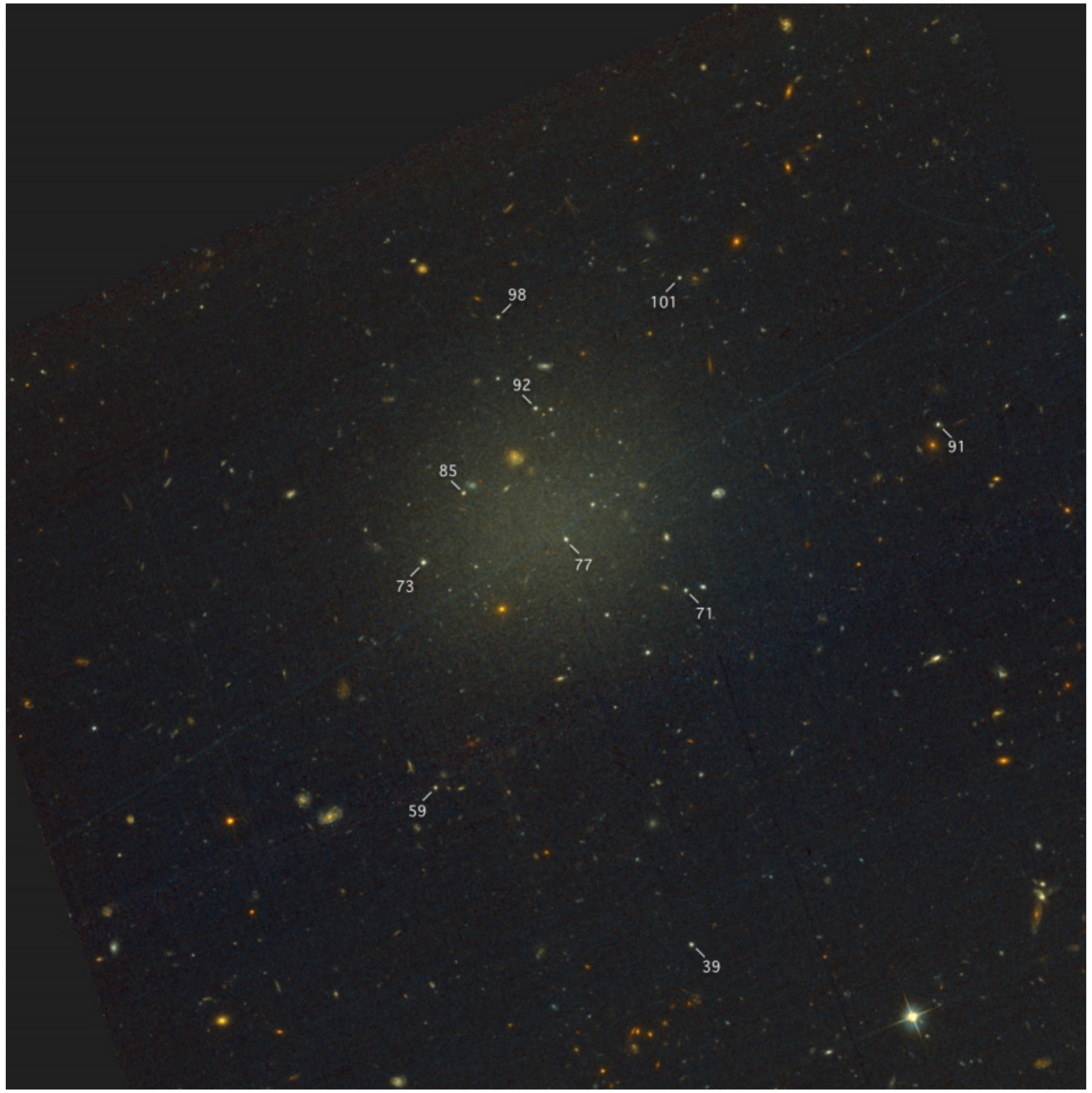
The diffuse light is accompanied

by many compact sources

Population of extraordinary

globular clusters

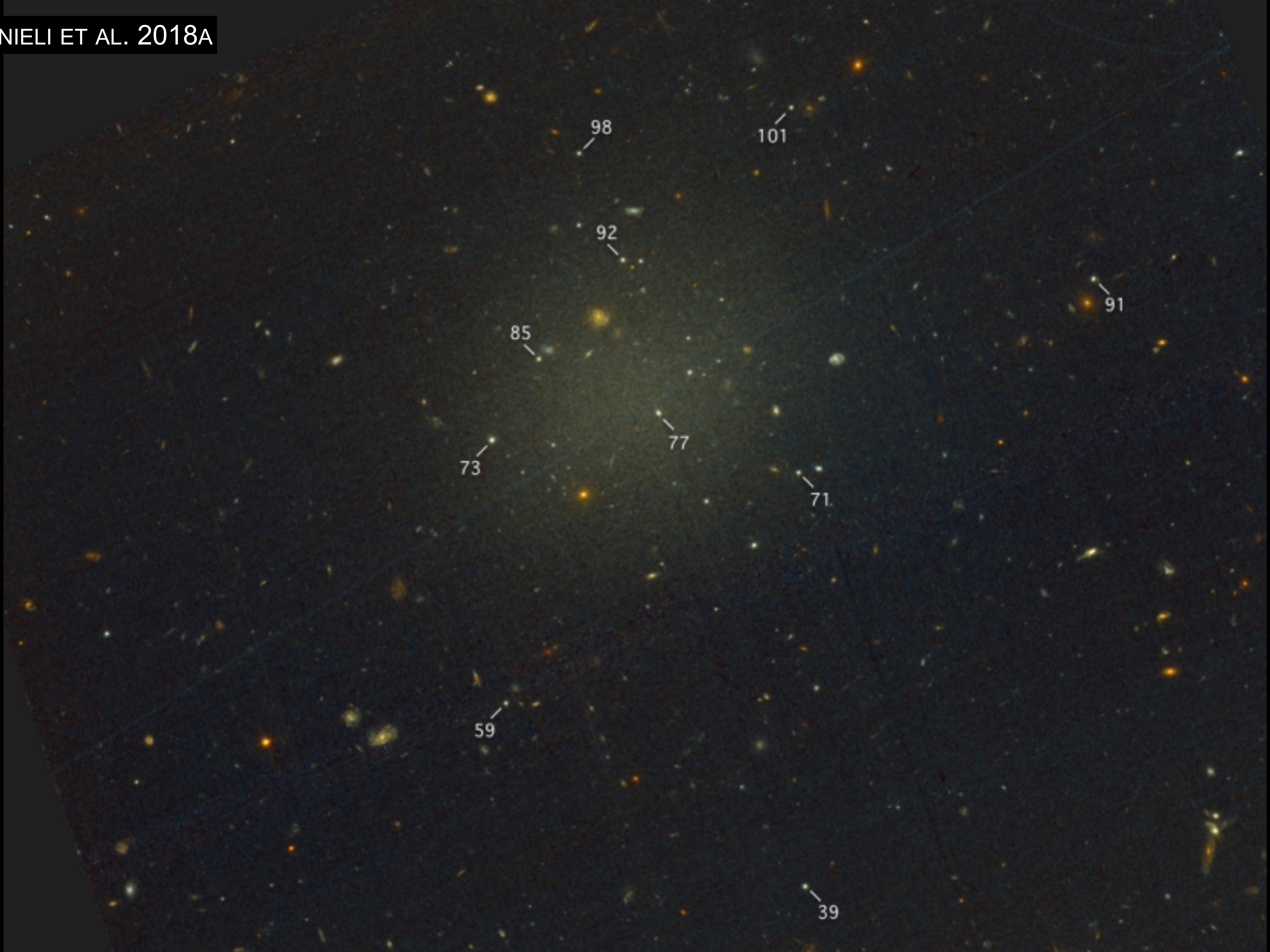
NGC1052-DF2



HST/ACS

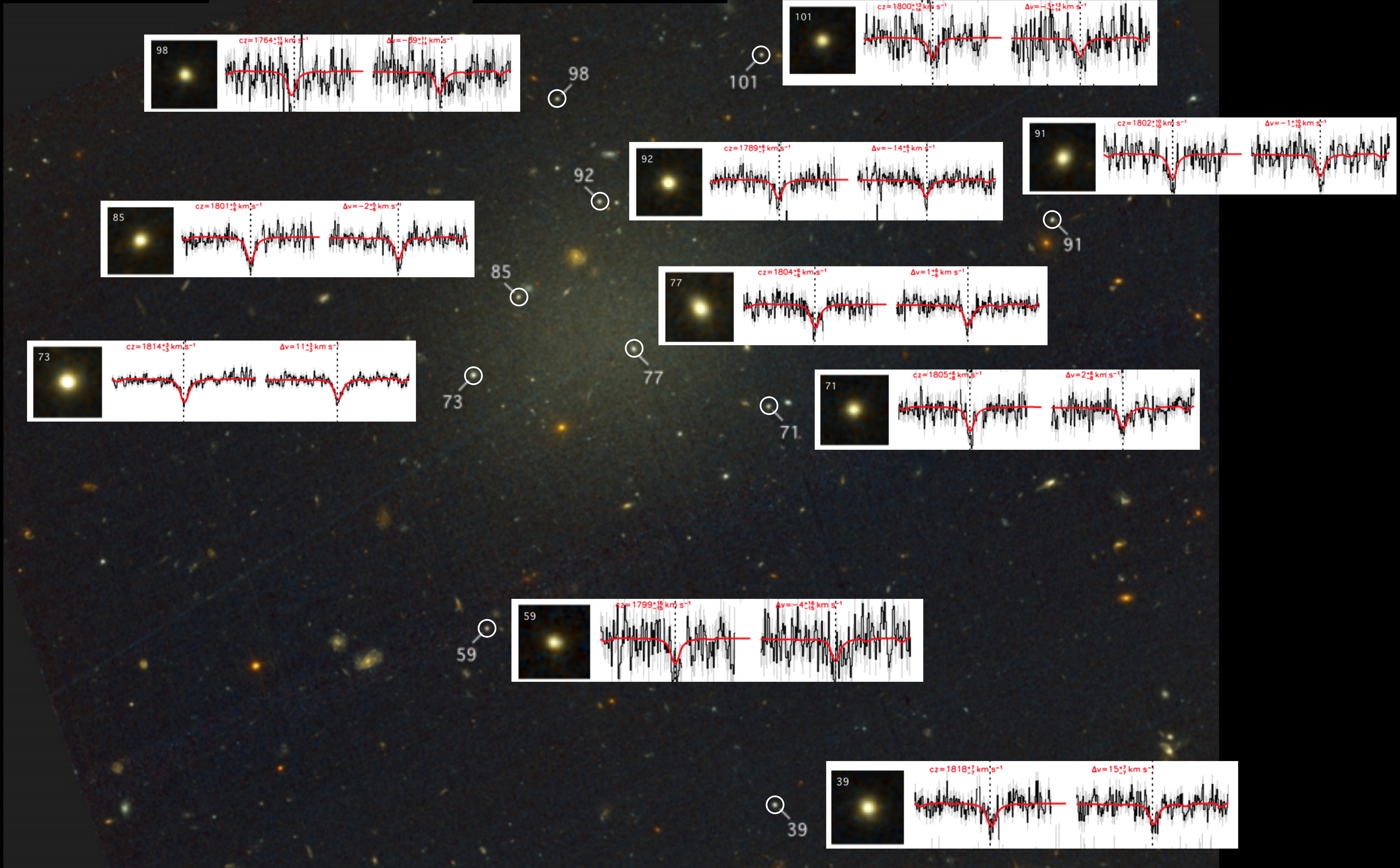
VAN DOKKUM, DANIELI ET AL. 2018

VAN DOKKUM, DANIELI ET AL. 2018A



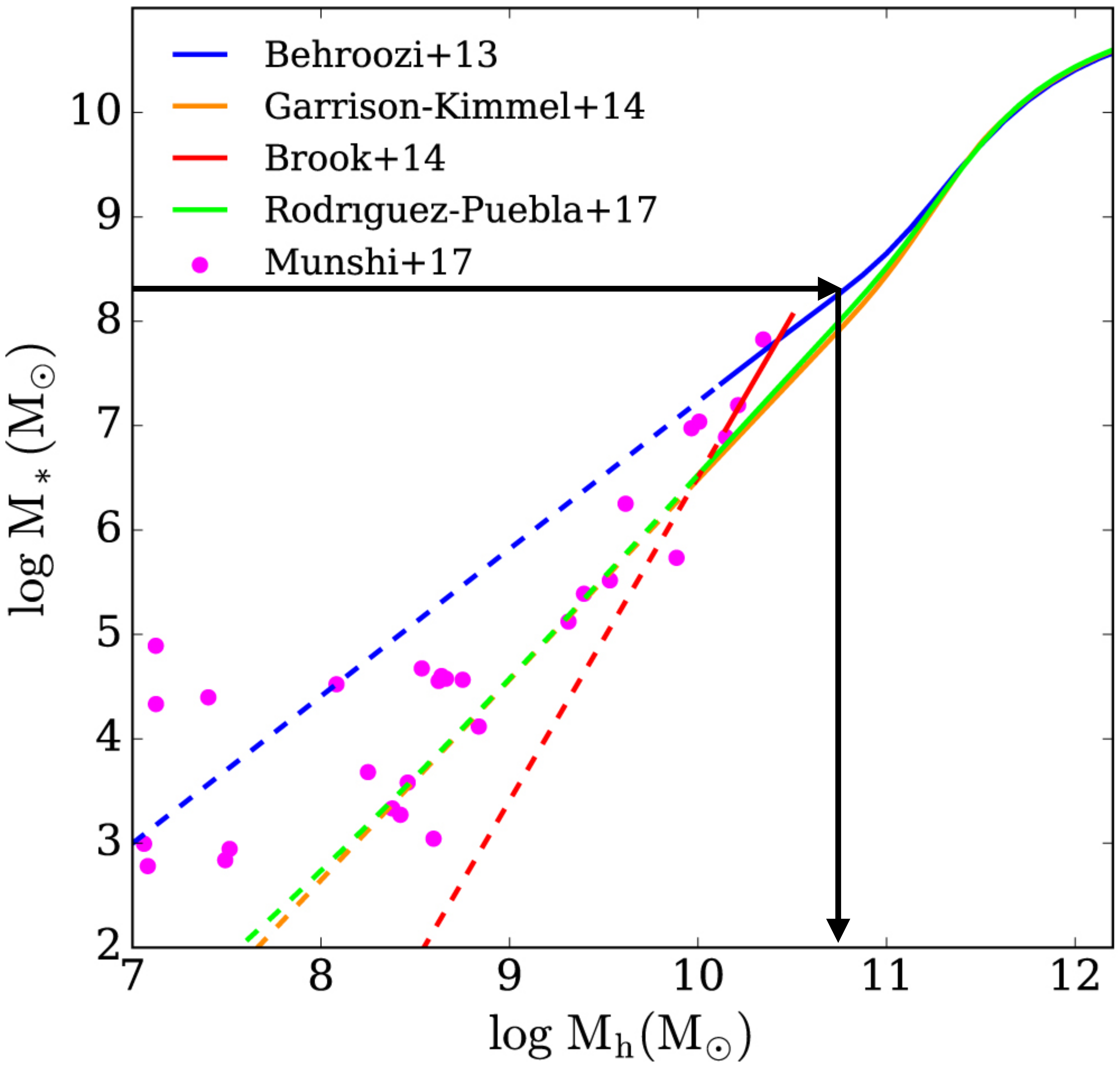
VAN DOKKUM, DANIELI ET AL. 2018A

KECK SPECTROSCOPY



Stellar mass-halo mass relation

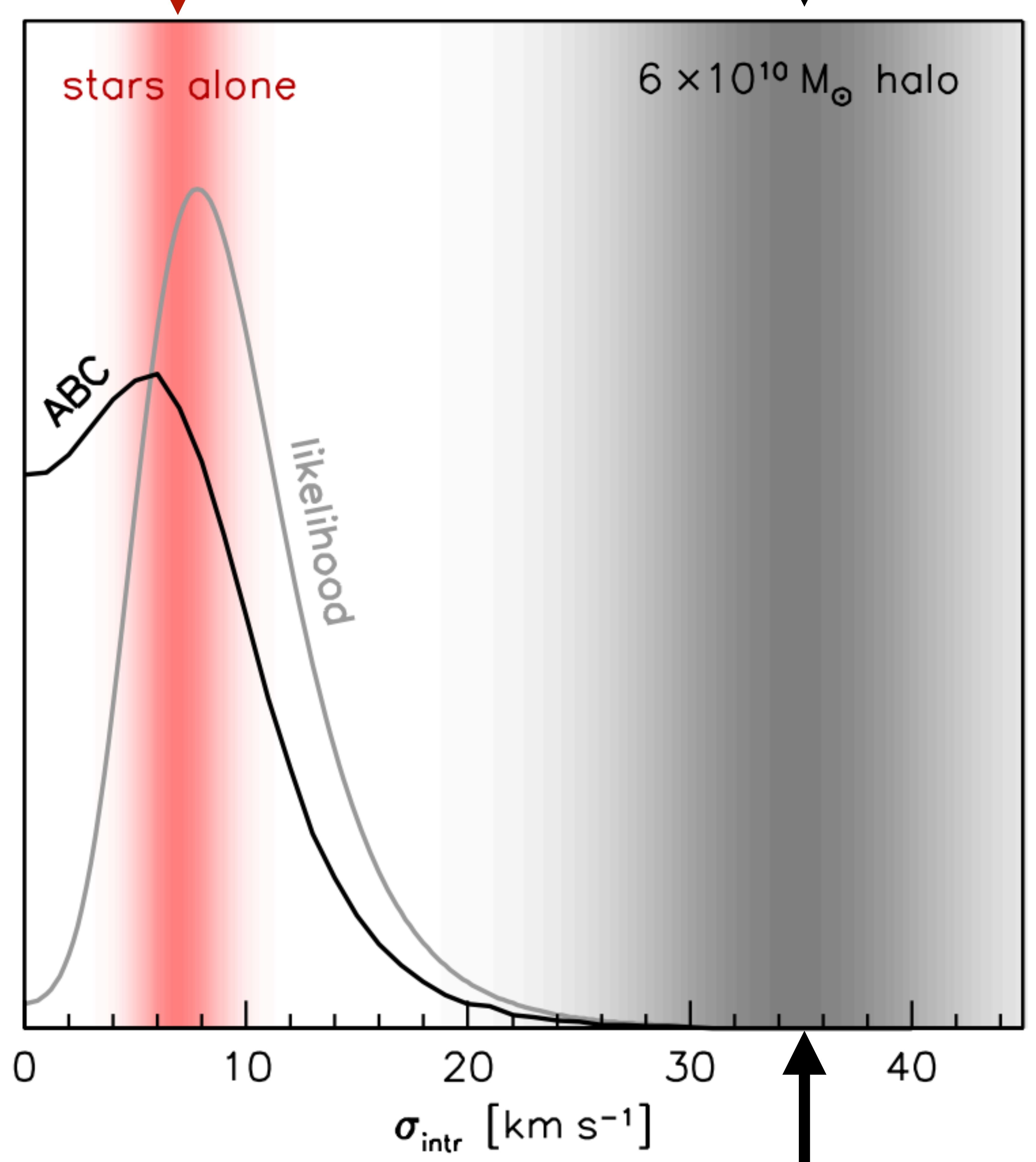
For a stellar mass of $2 \times 10^8\ M_\odot$



we expect a $6 \times 10^{10}\ M_\odot$ halo

The expected dispersion from the stars alone is σ_{stars}= 7.0 km/s

If the galaxy had a halo according to the stellar-to-halo mass relation



we expect a velocity dispersion of 35 km/s

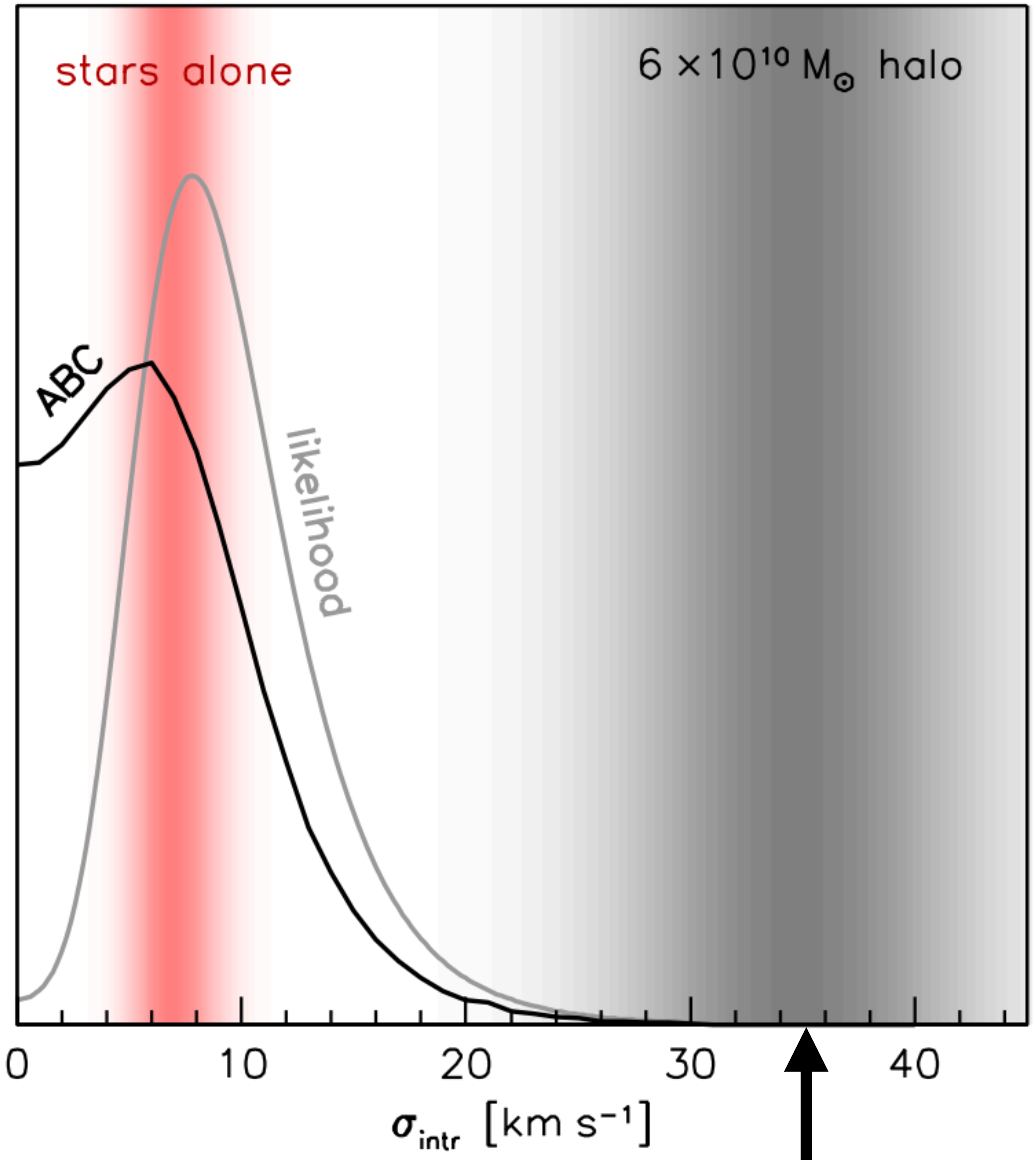
VAN DOKKUM, DANIELI ET AL. 2018C

If the galaxy had a halo according to the stellar-to-halo mass relation

The expected dispersion from the stars alone is σ_{stars}= 7.0 km/s

We measured a velocity dispersion of $\sigma_{DF2,int} = 7.8^{+5.5}_{-2.3}$ km/s

Consistent with the galaxy having little to no dark matter within the half-light radius



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VAN DOKKUM, DANIELI ET AL. 2018C

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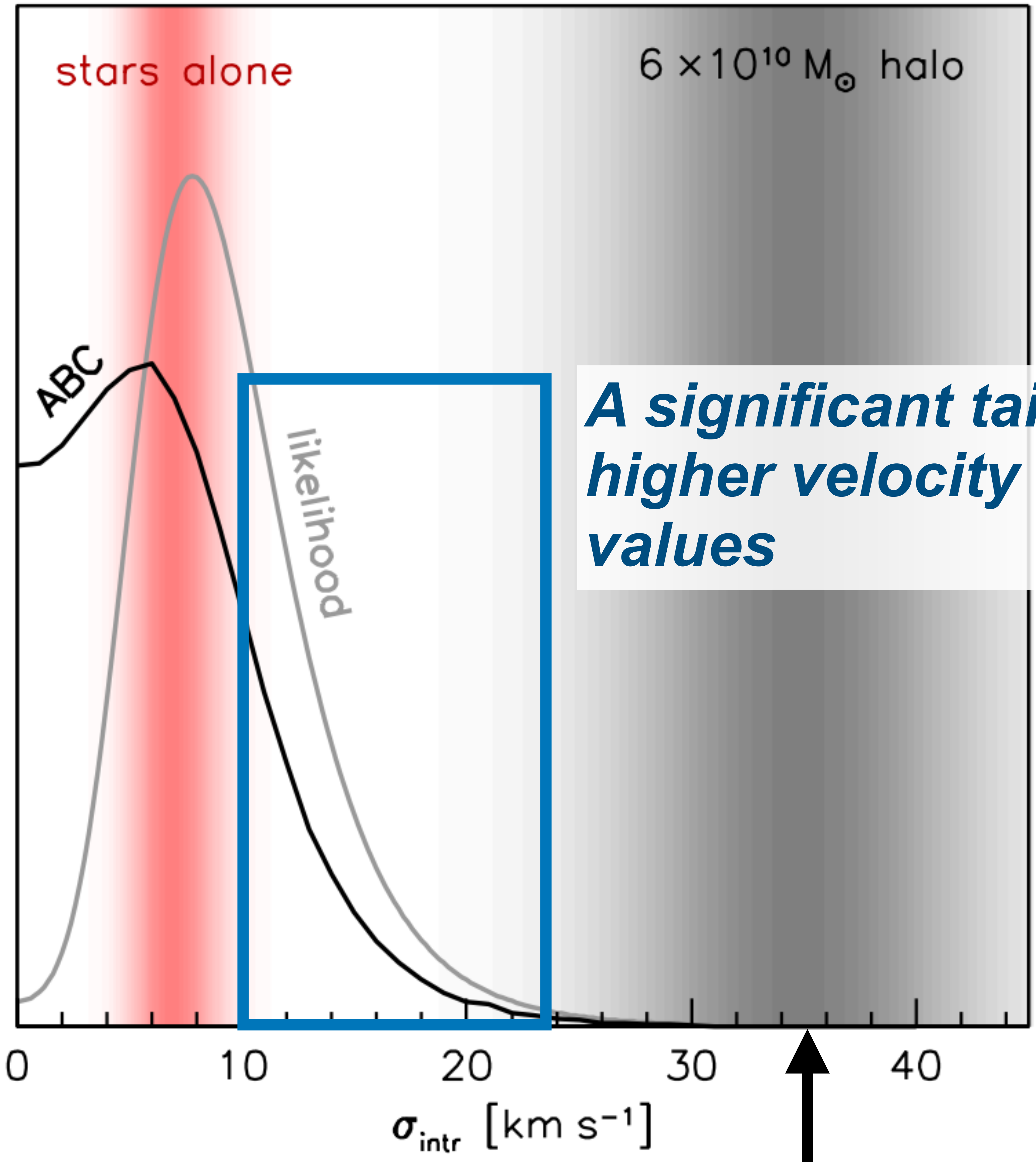


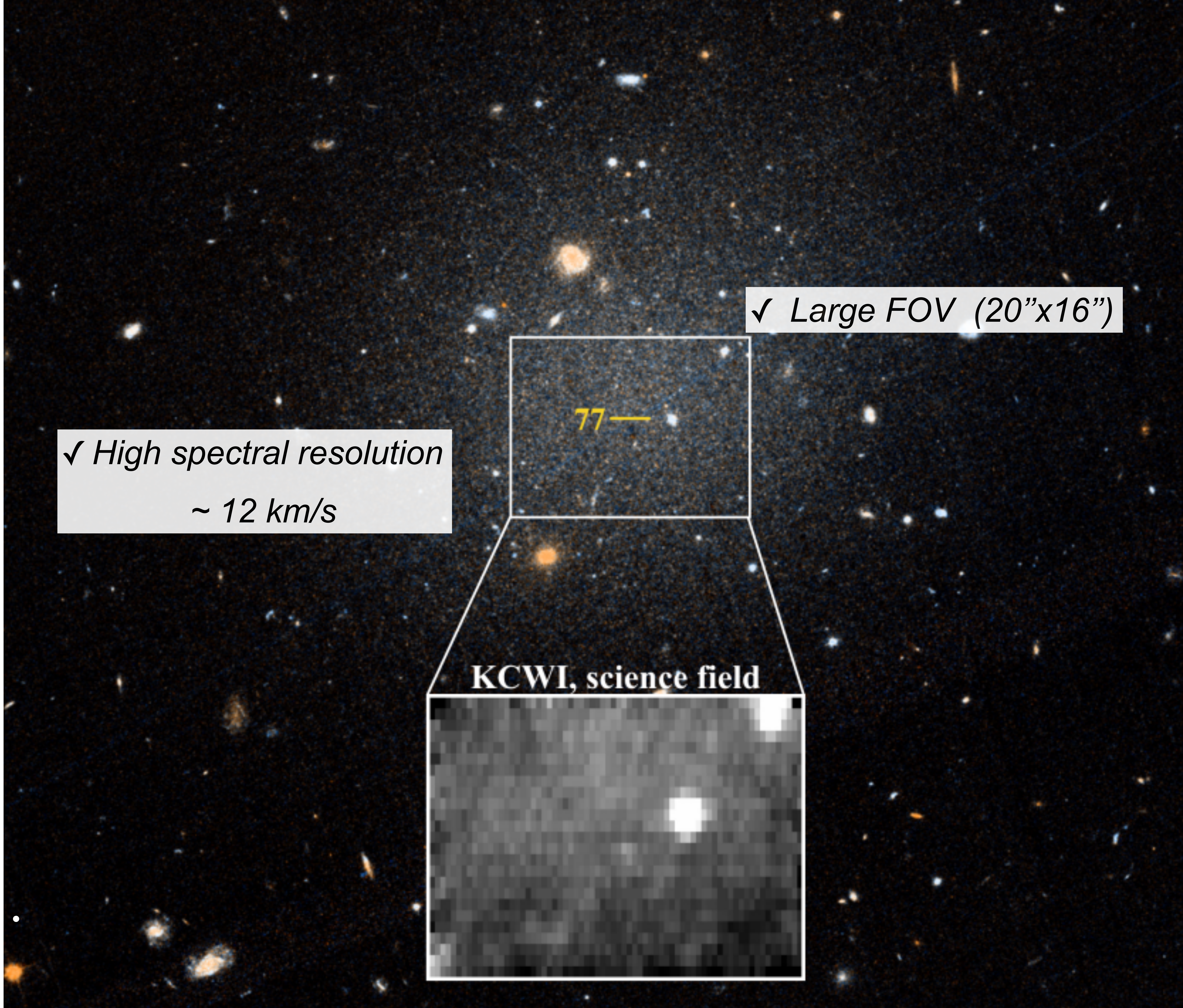
A significant tail allows for higher velocity dispersion values

we expect a velocity dispersion of 35 km/s

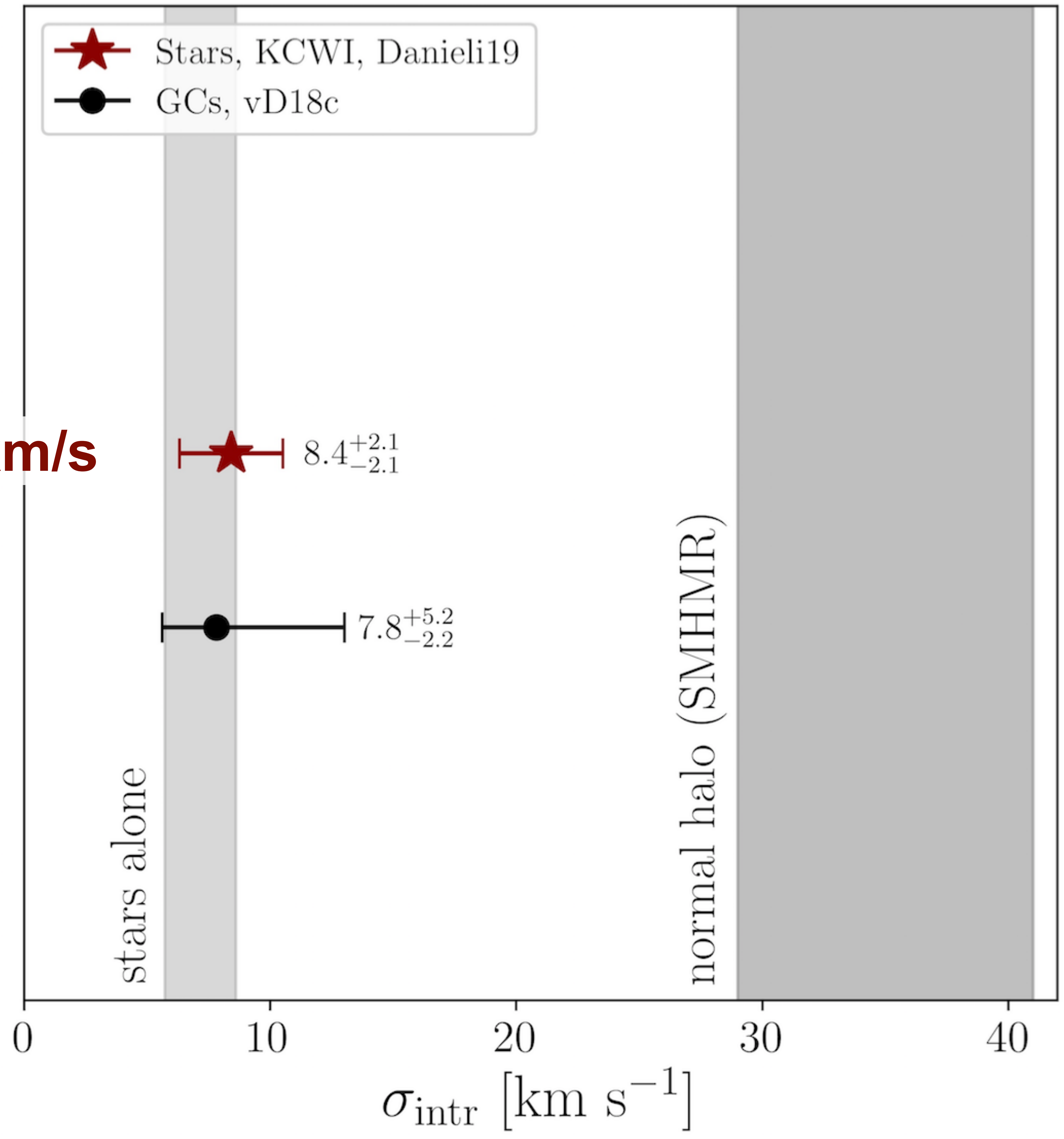
VAN DOKKUM, DANIELI ET AL. 2018C

- The low velocity dispersion requires a verification
- Measure **Stellar** velocity dispersion with an IFU, high spectral resolution

- Keck Cosmic Web Imager (KCWI) Spectrocopy
- On target + sky integration time of 5.6 hrs



Danieli et al. 2019



$\sigma_{DF2,int}$ = **8.4±2.1 km/s**

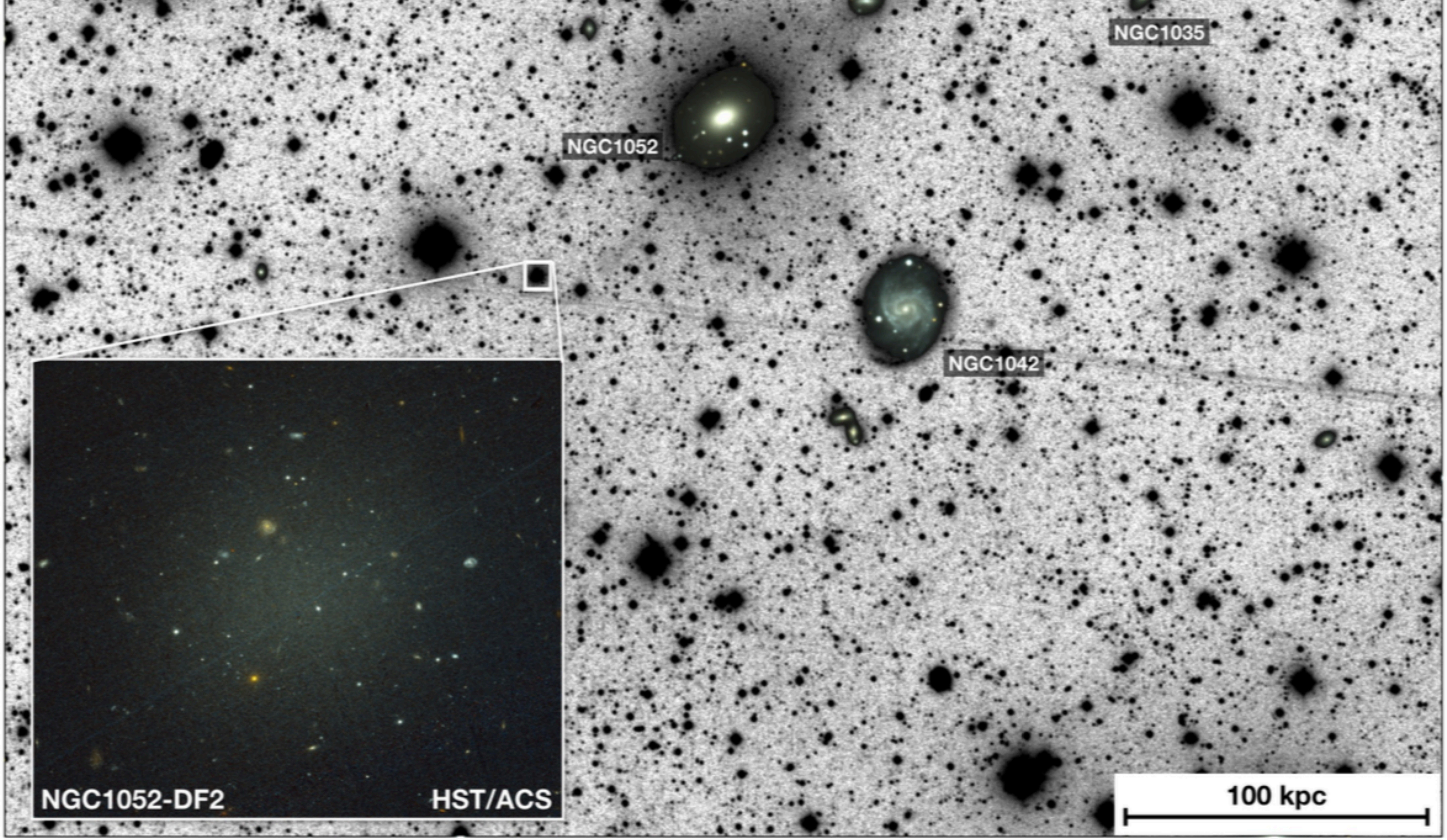
The dynamical mass within the half-light radius is

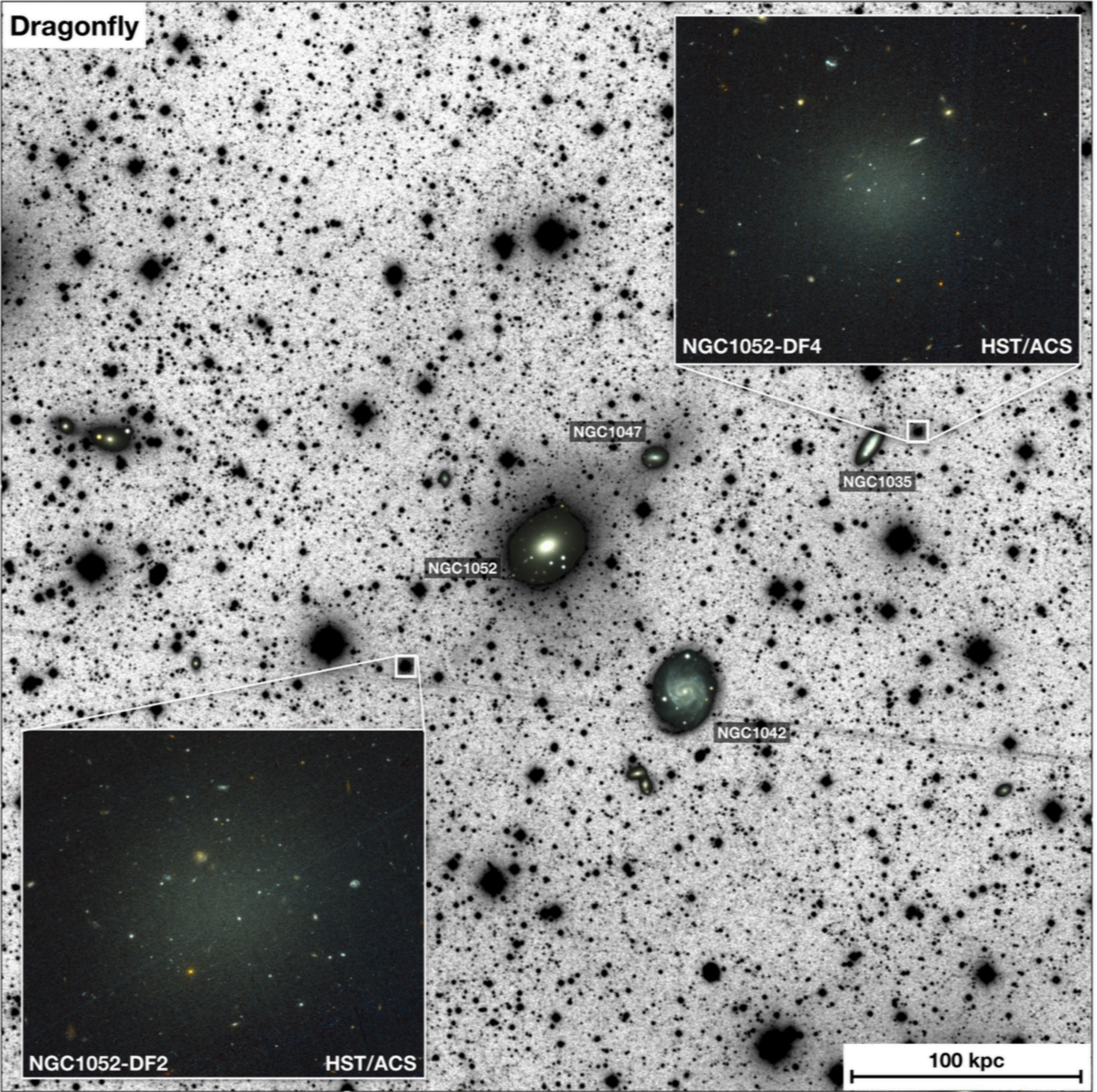
M_{dyn}=1.3±0.8x10^8 $M_\odot$

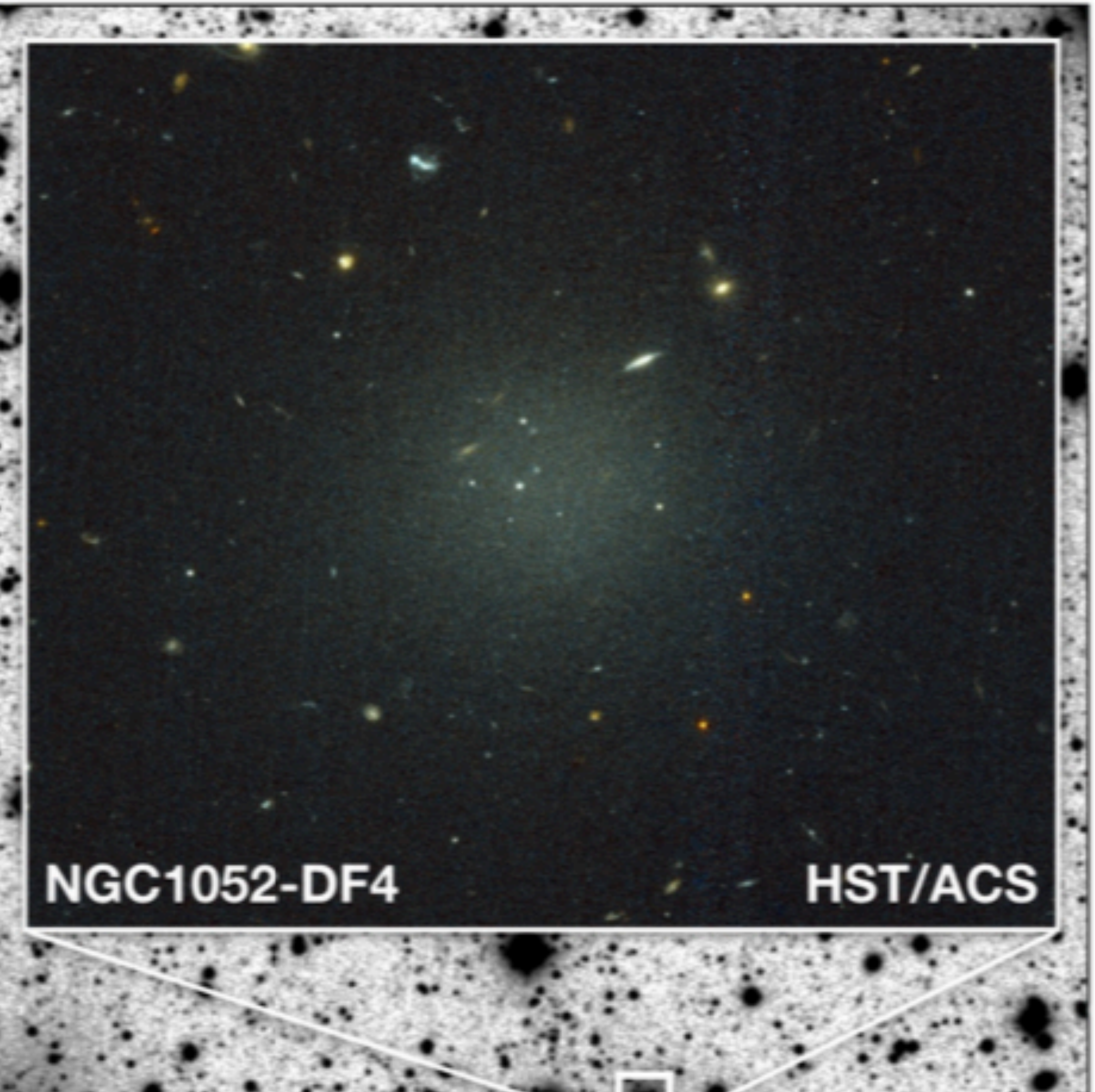
with a stellar mass of

M_{stars}=1.0±0.2x10^8 $M_\odot$

DANIELI ET AL. 2019

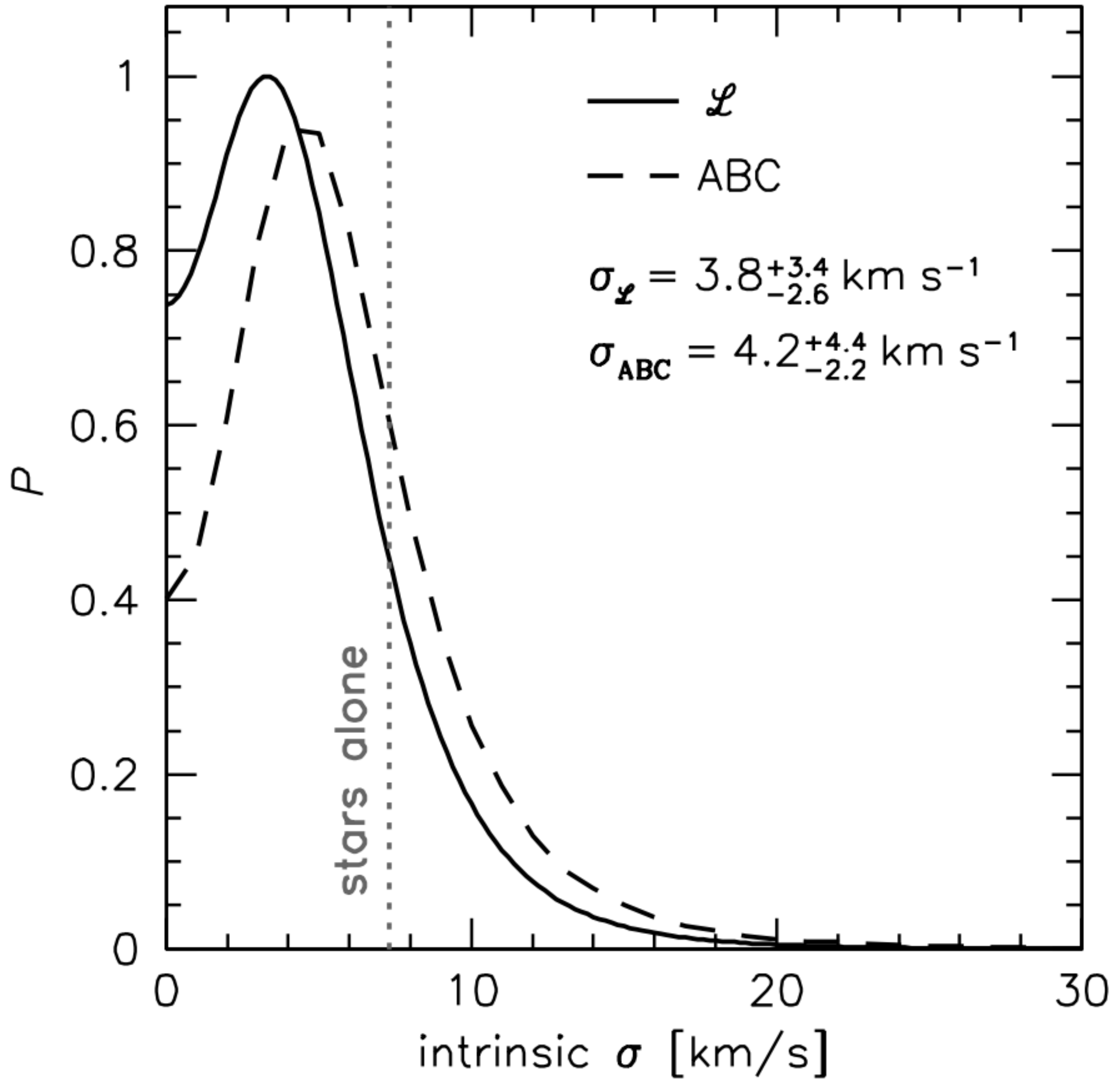

NGC1035
NGC1052
NGC1042
NGC1052-DF2
HST/ACS
100 kpc

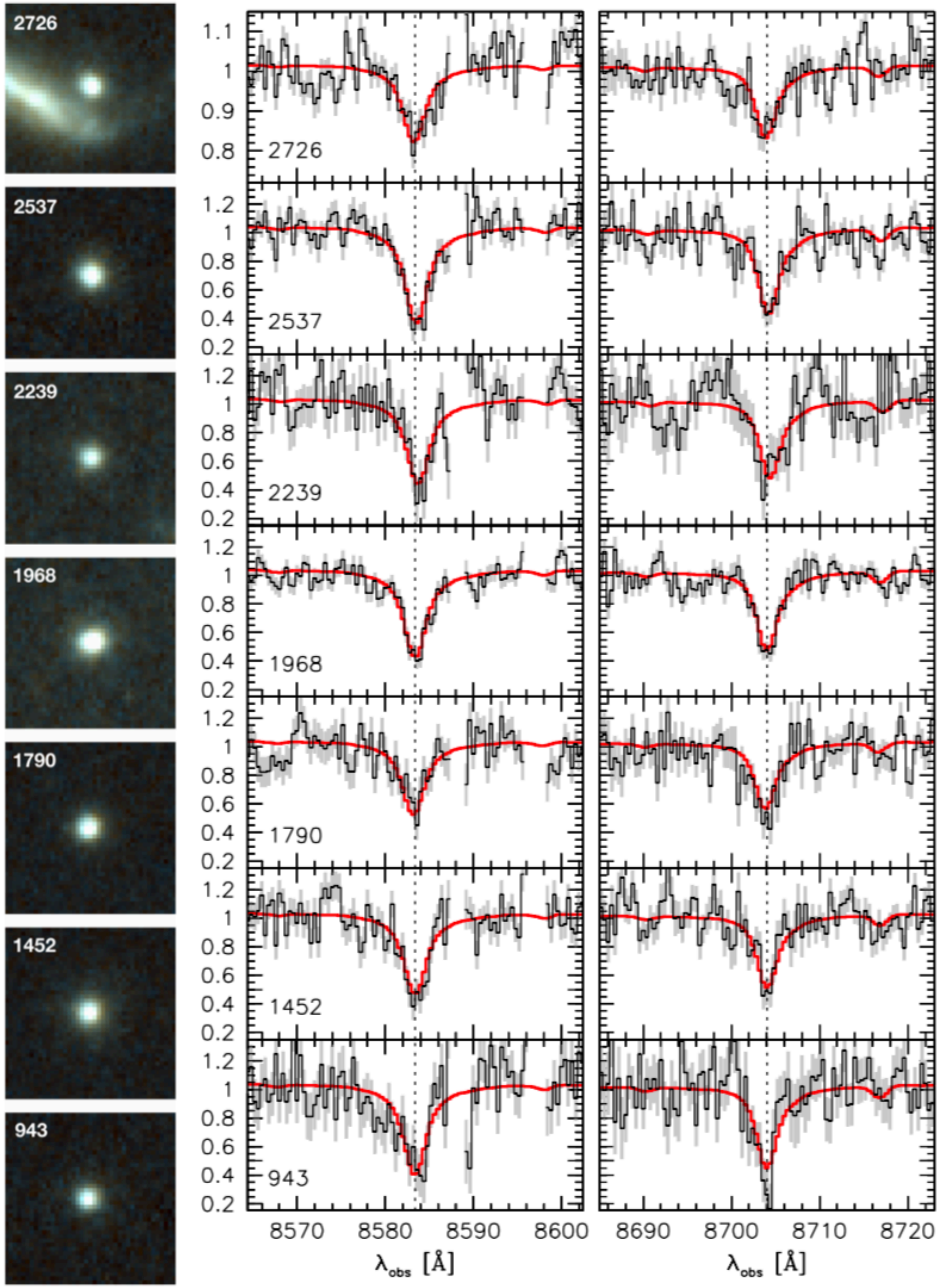

Dragonfly
NGC1052-DF4
HST/ACS
NGC1047
NGC1035
NGC1052
NGC1042
NGC1052-DF2
HST/ACS
100 kpc


NGC1052-DF4
HST/ACS

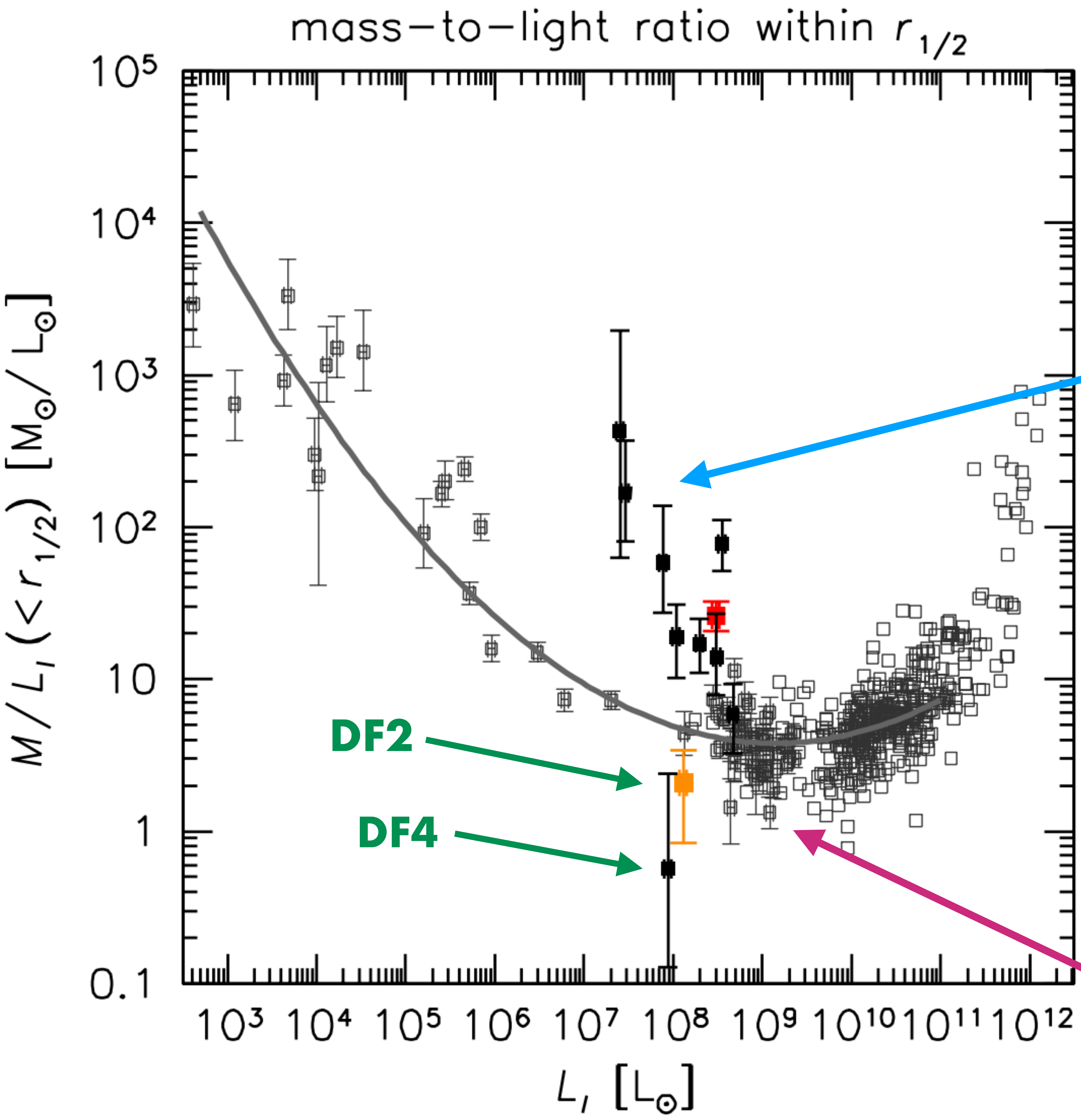
NGC1052-DF4
HST/ACS
2726
2537
2239
1968
1790
1452
943
λobs [Å]
λobs [Å]

A SECOND GALAXY LACKING DARK MATTER - NGC1052-DF4





VAN DOKKUM, DANIELI ET AL. 2019B



<u>ULTRA DIFFUSE GALAXIES</u>

BEASLEY ET AL. 2016

TOLOBA ET A. 2018

MARTIN-NAVARRO ET AL. 2019

CHILINGARIAN ET AL. 2019

VAN DOKKUM ET AL. 2019

DANIELI ET AL. 2019

VAN DOKKUM ET AL. 2020

<u>"NORMAL" DWARF GALAXIES</u>

ZARITSKY, GONZALEZ, & ZABLUDOFF 2006

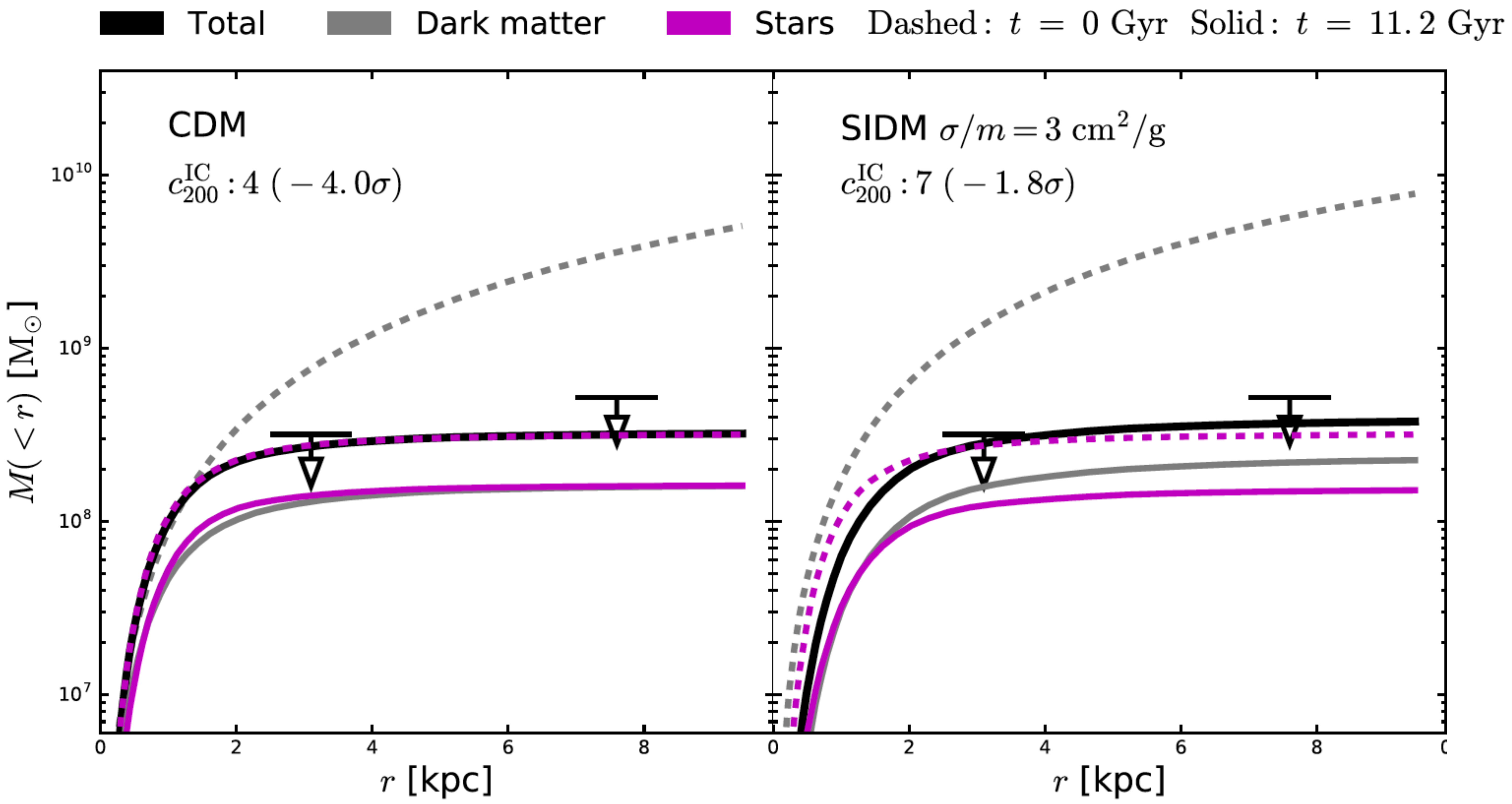
WOLF ET AL. 2010

TOLOBA ET AL. 2015

- THE DARK MATTER CONTENT OF ULTRA DIFFUSE GALAXIES SPANS 4 ORDERS OF MAGNITUDE
- THE ESPECIALLY DARK MATTER-DOMINATED AND DARK MATTER-DEFICIENT GALAZXIES, AS WELL AS THE SCATTER IN THE TOTAL MASS-TO-LIGHT RATIO FOR ULTRA DIFFUSE GALAXIES PRESENTS AN OPPORTUNITY FOR TESTING DARK MATTER MODELS

Example #1: Self-Interacting Dark Matter

- Yang, Yu & An 2020 studies DF2 and DF4-like galaxies in the SIDM scenario.
- Using controlled N-body simulation, they show that SIDM is more likely (than CDM) to result in DF2 and DF4-like galaxies, through tidal stripping
- The SIDM simulation also predict more diffuse stellar distributions, in better agreement with the observations

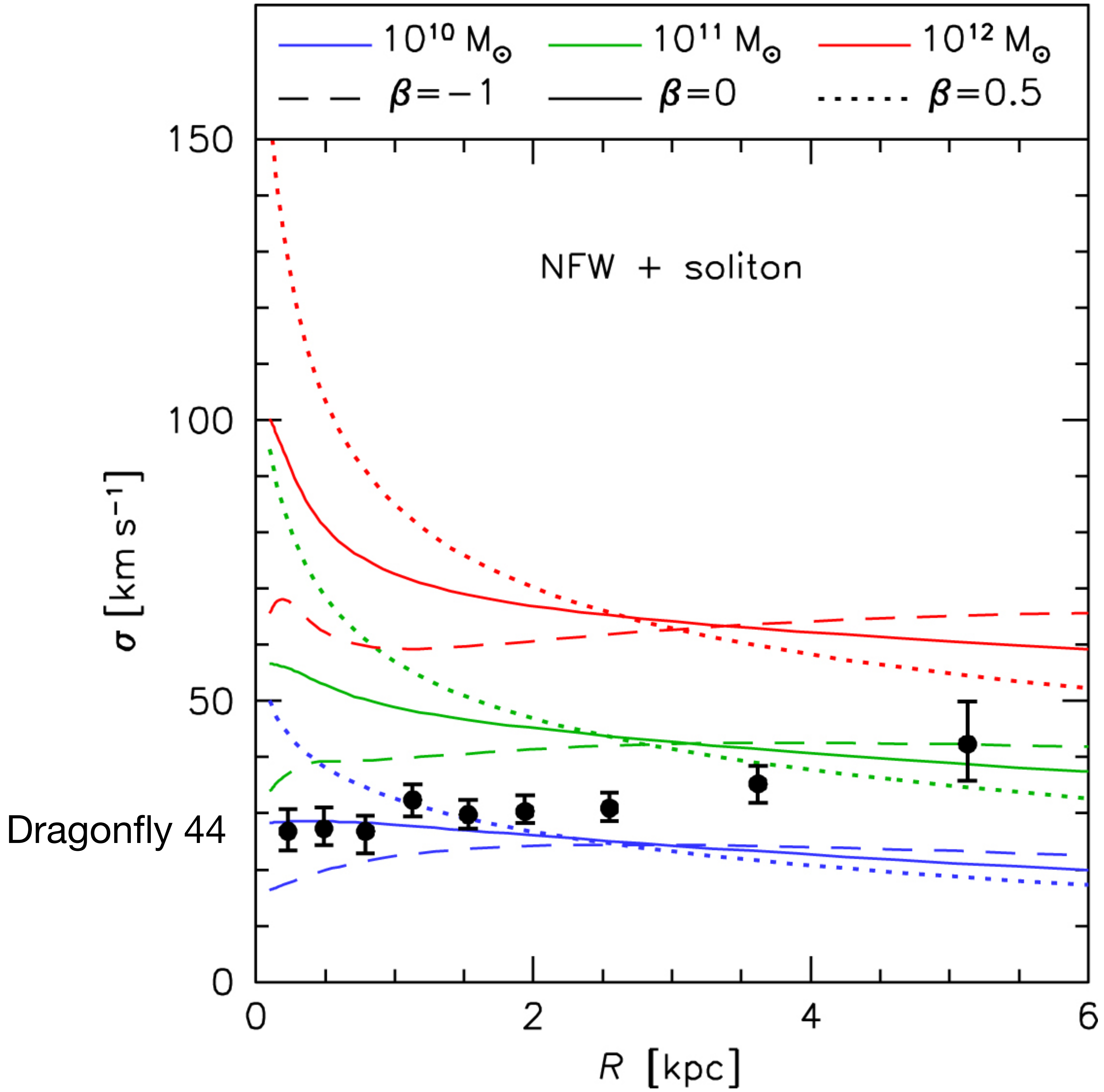


Yang, Yu & An 2020

- THE DARK MATTER CONTENT OF ULTRA DIFFUSE GALAXIES SPANS 4 ORDERS OF MAGNITUDE
- THE ESPECIALLY DARK MATTER-DOMINATED AND DARK MATTER-DEFICIENT GALAZXIES, AS WELL AS THE SCATTER IN THE TOTAL MASS-TO-LIGHT RATIO FOR ULTRA DIFFUSE GALAXIES PRESENTS AN OPPORTUNITY FOR TESTING DARK MATTER MODELS

Example #2: Ultralight Axion ("fuzzy") dark matter

- For sufficiently high halo masses these models predict a characteristic bump in the profile at small (~500 pc) scales, indicating the presence of a soliton core
- UDGs with higher central dispersions may exist, and they could provide a direct test of these predictions.



van Dokkum et al. 2020

Summary

- Ultra Diffuse Galaxies are common and have unusual properties
- Thanks to the large extent of their stellar distributions, the properties of their dark matter halos can be traced out to larger radii
- Many seem to host a large population of globular clusters which help to measure their dynamical mass
- The dark matter content of Ultra Diffuse Galaxies spans 4 orders of magnitude
  - Some have massive dark matter halos
  - Some have little to no dark matter
- UDGs provide an opportunity to test and constrain dark matter models in interesting regimes