Ultra-Puffy Galaxies™ Among Satellites of Milky Way Analogs

From Definition to their Environmental Quenching

Li et al. (2022b)
Li et al. (2023)

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with Jenny Greene, Johnny Greco, Shany Danieli
Song Huang, Erin Kado-Fong, Rachael Beaton, et al.

2023.06.12, KIAA

Image credit: Subaru/HSC

Bullock & Boylan-Kolchin (2017)

Why study dwarf galaxies?

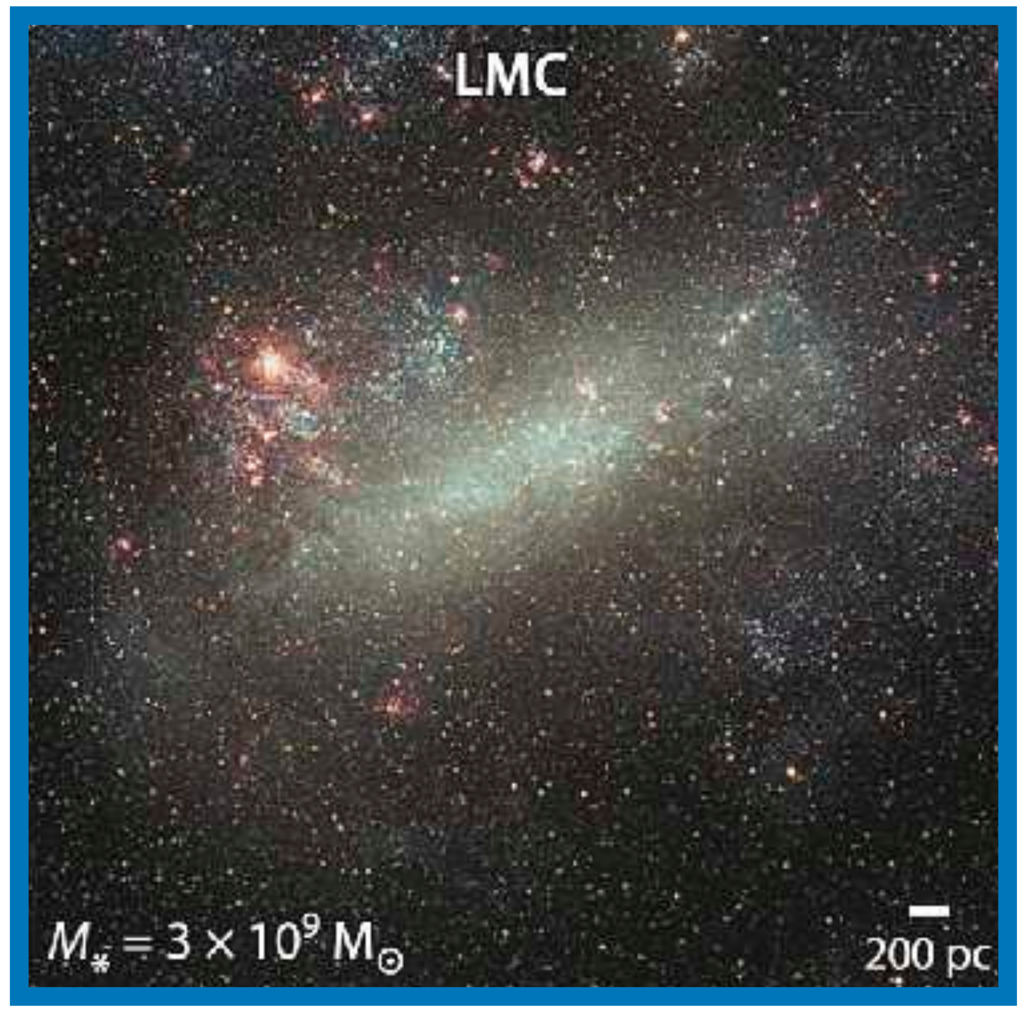
Dwarf galaxies: everything below $M_\star < 10^9\ M_\odot$.

They are ideal probes for

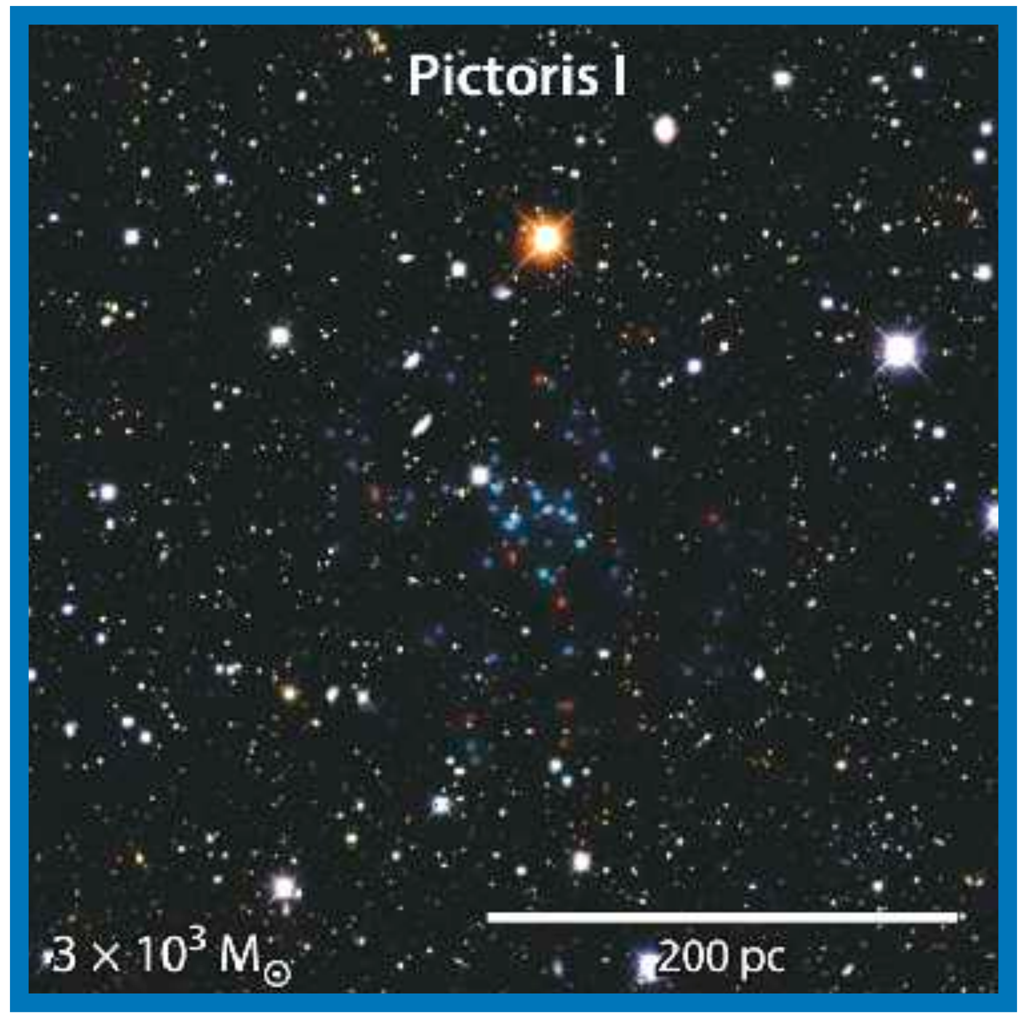
- Testing ΛCDM model ("small scale challenges", e.g., core-cusp, satellite plane, etc.) and alternative dark matter models (e.g., SIDM).
- Understand baryonic processes (e.g., star formation, stellar feedback)
- Probing reionization physics

Pros: they are in our backyard! Resolved stellar population!

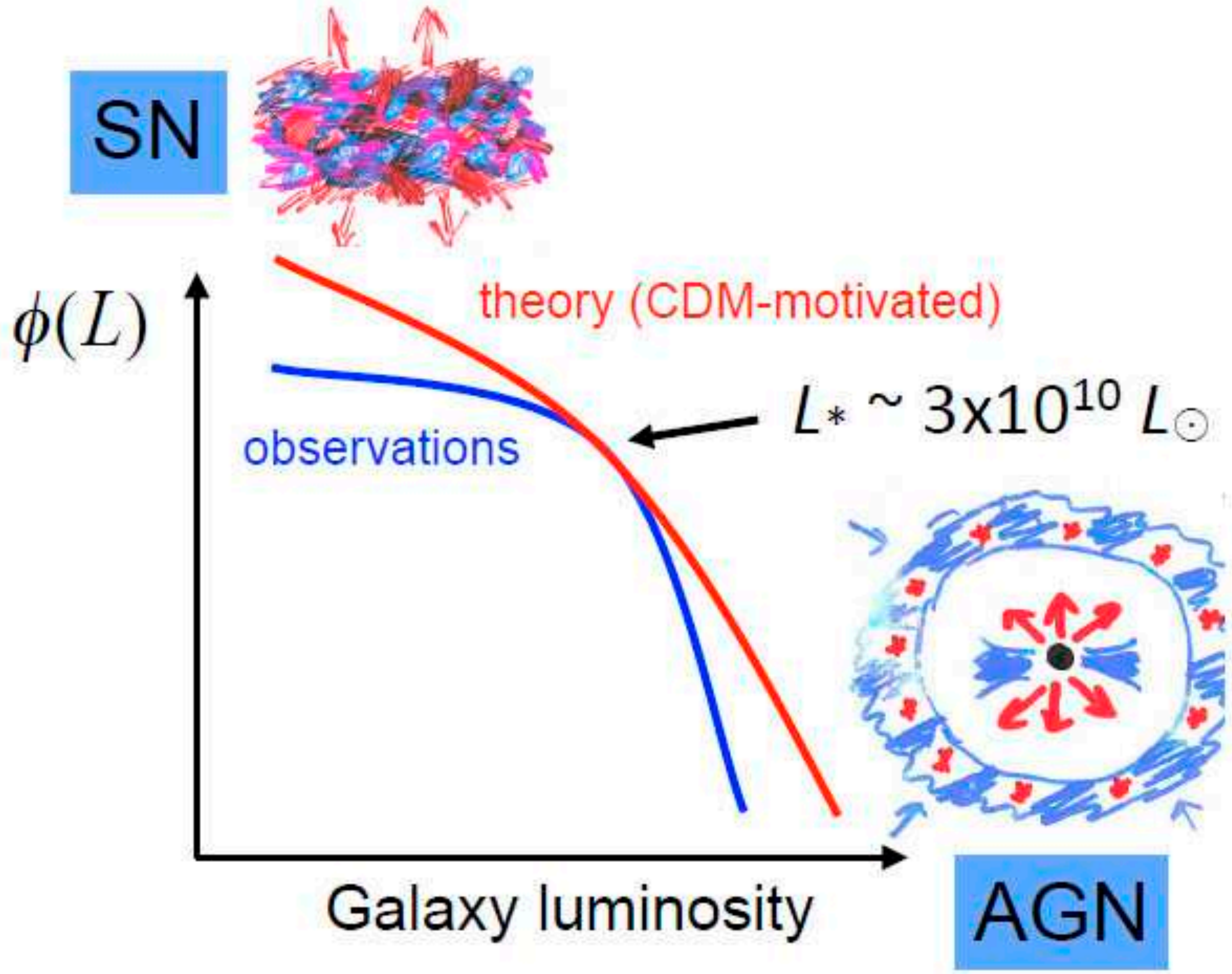
Cons: they are faint, difficult to find and measure distances.



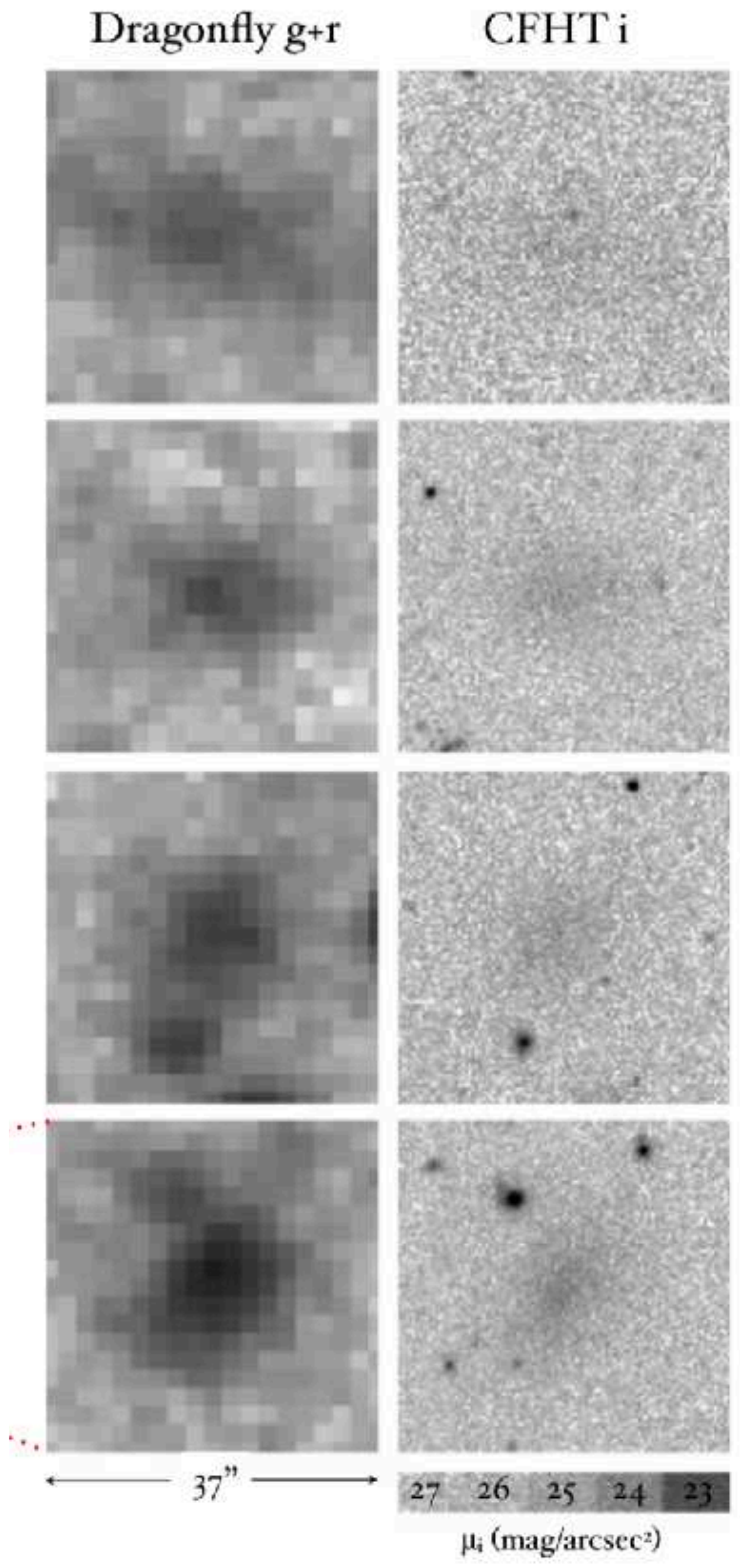
$M_\star \approx 3 \times 10^9\ M_\odot$



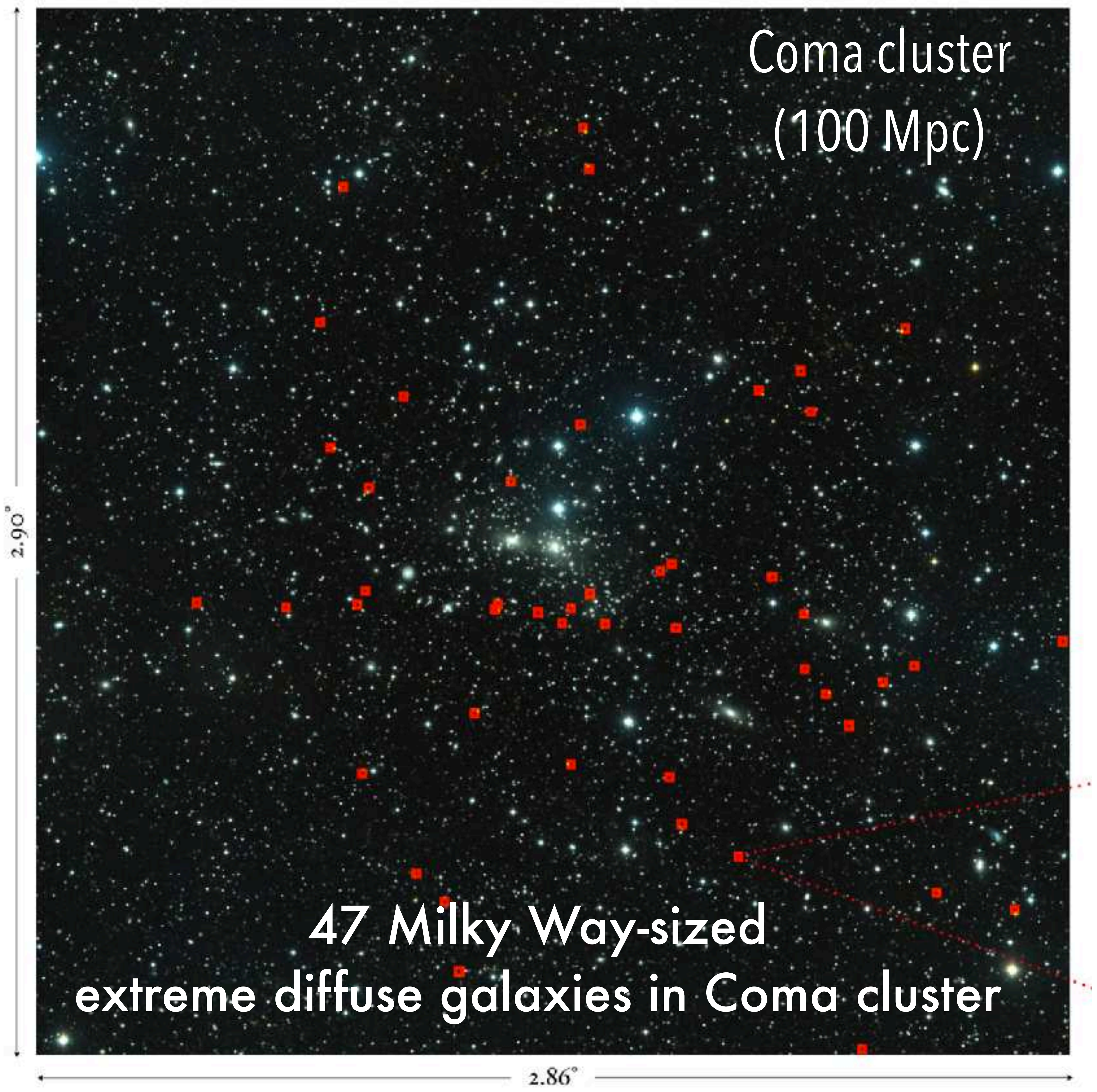
$M_\star \approx 3 \times 10^3\ M_\odot$



An intriguing type of dwarfs: Ultra-Diffuse Galaxy



van Dokkum et al. (2015)



Dragonfly Telescope
Abraham & van Dokkum (2013)

An intriguing type of dwarfs: Ultra-Diffuse Galaxy

Ultra-diffuse galaxies (UDGs) in vD+15 are defined to have $r_e > 1.5$ kpc and $\mu_0(g) > 24$ mag arcsec^{-2}

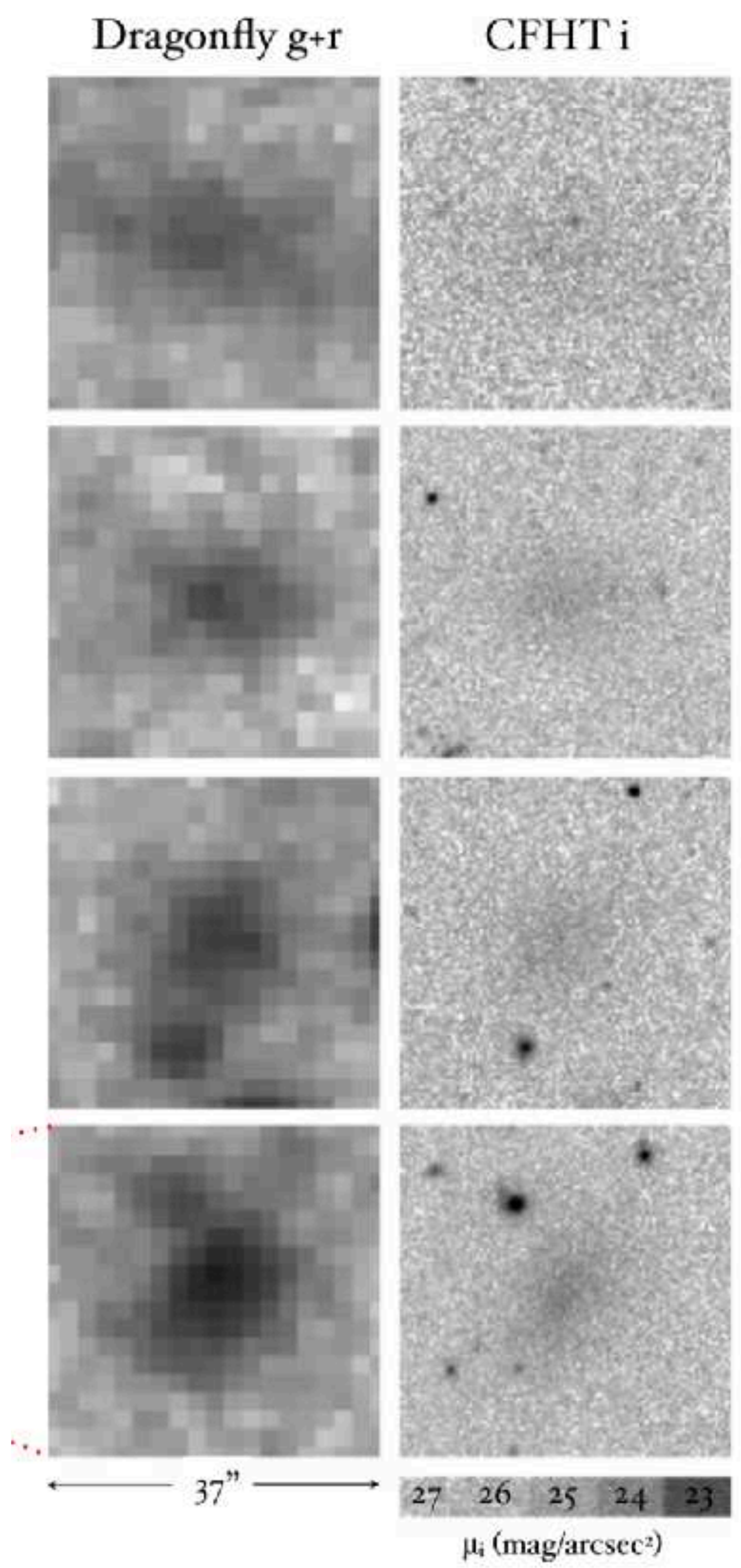
UDGs are found primarily in galaxy clusters: $N_{\rm UDG} \propto M_{\rm halo}$

UDGs in clusters are quenched, whereas field UDGs are star-forming (with exceptions)

Two UDGs have no dark matter (NGC1052-DF2, DF4)

Some UDGs can have many globular clusters (Danieli+20)

Question: are UDGs really a distinct population?



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Ultra-Diffuse Galaxy: a closer look at the definition

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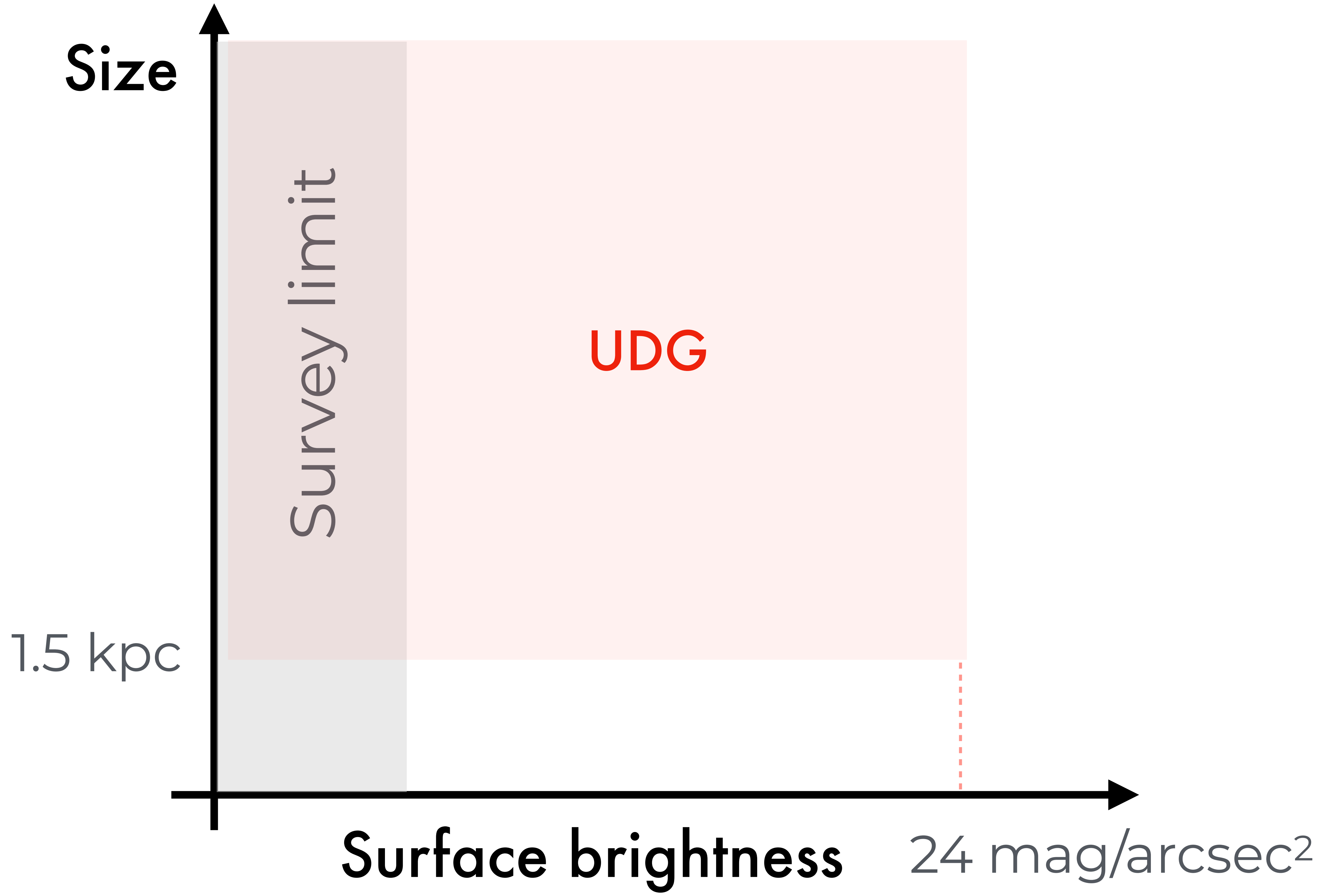

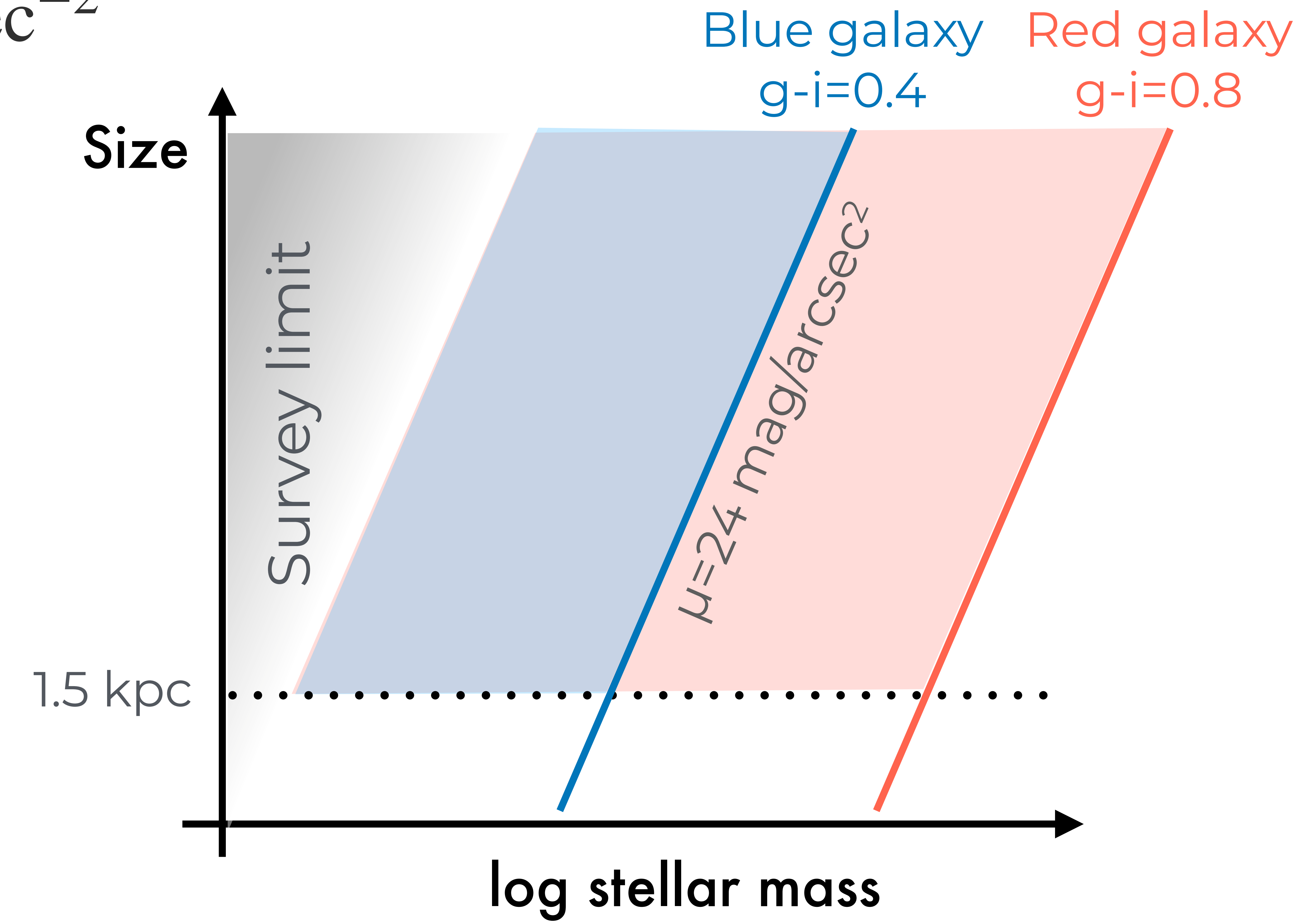

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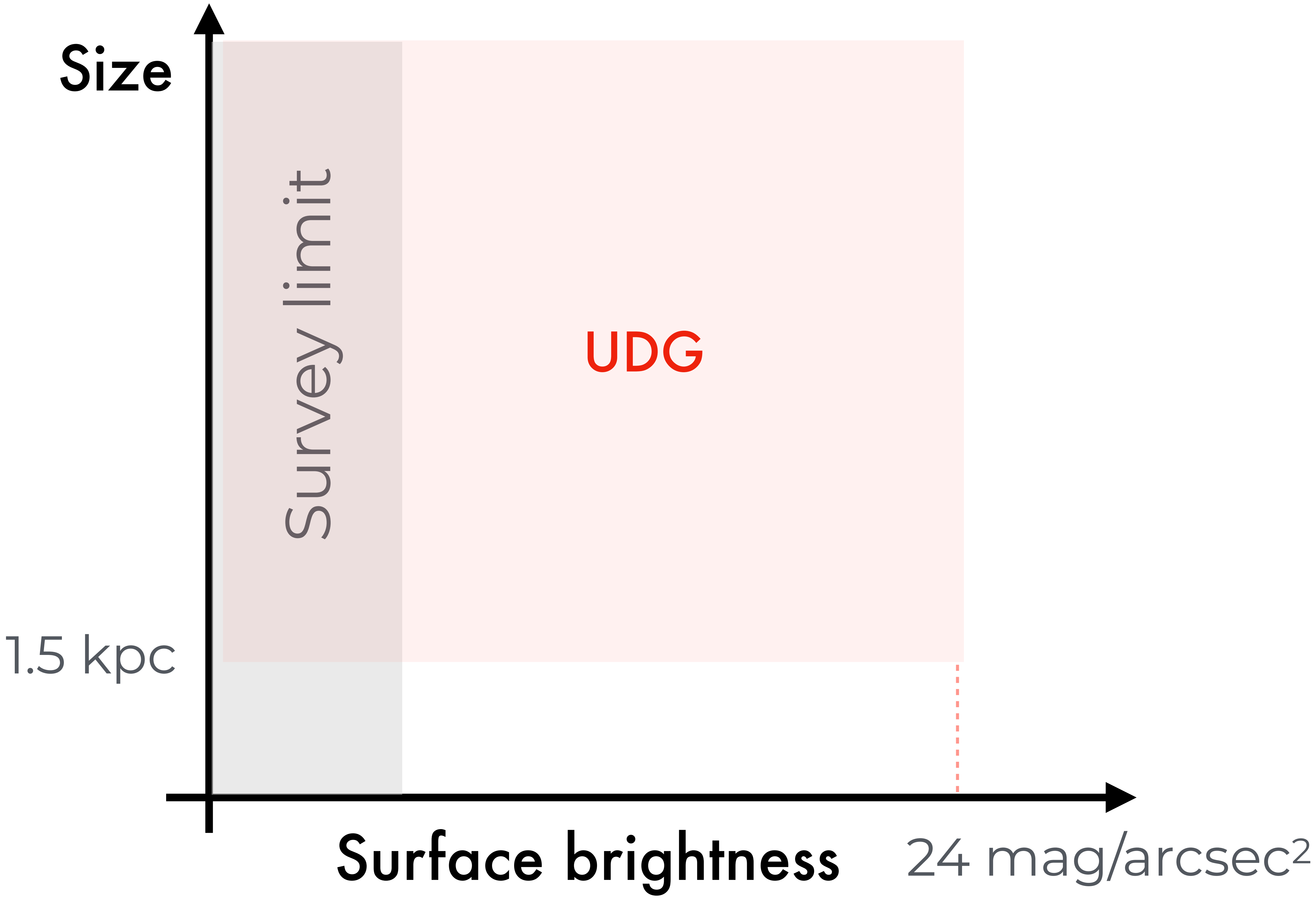
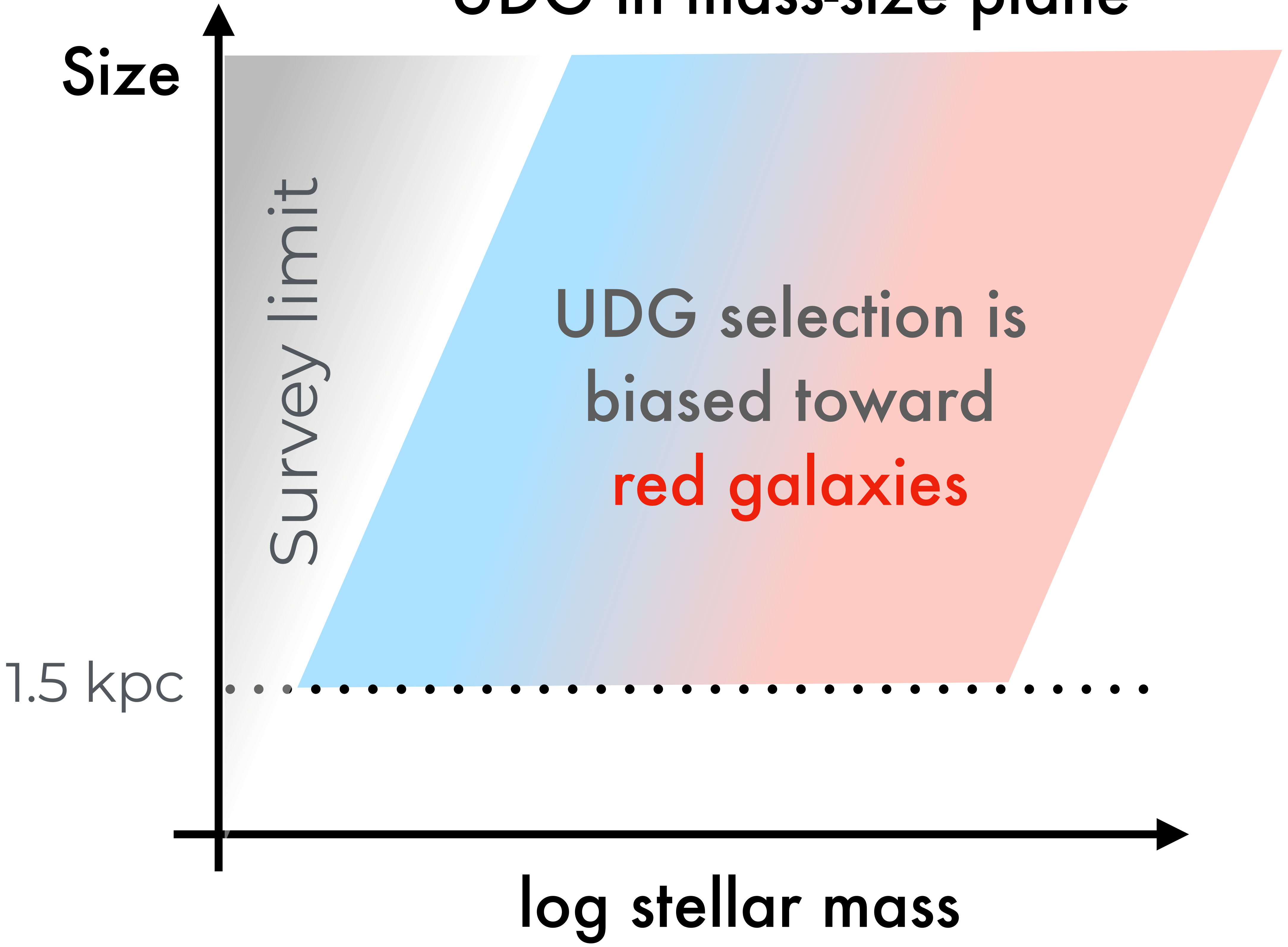


UDG in mass-size plane



Problem 1: UDGs are preferentially selected to be red

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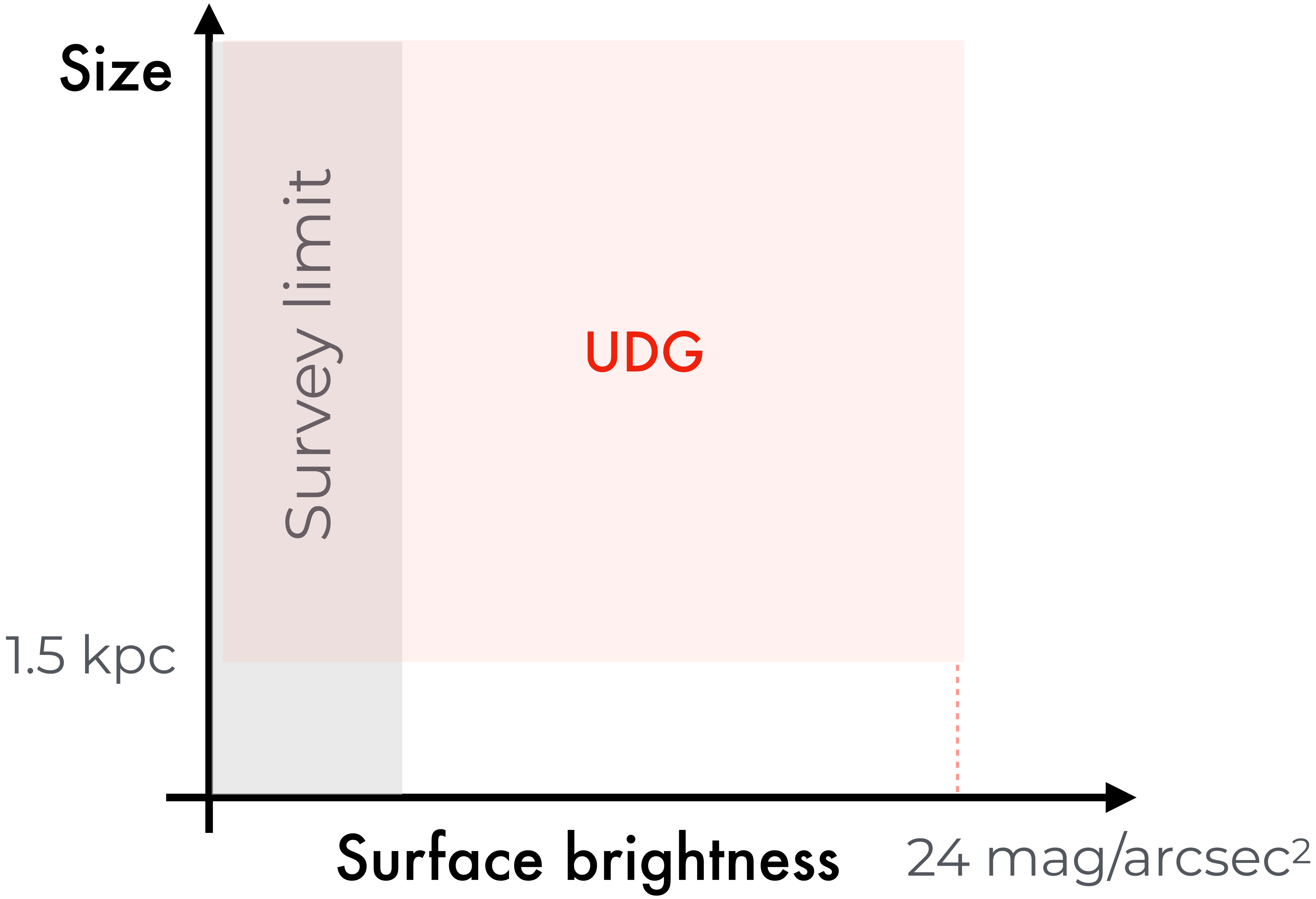

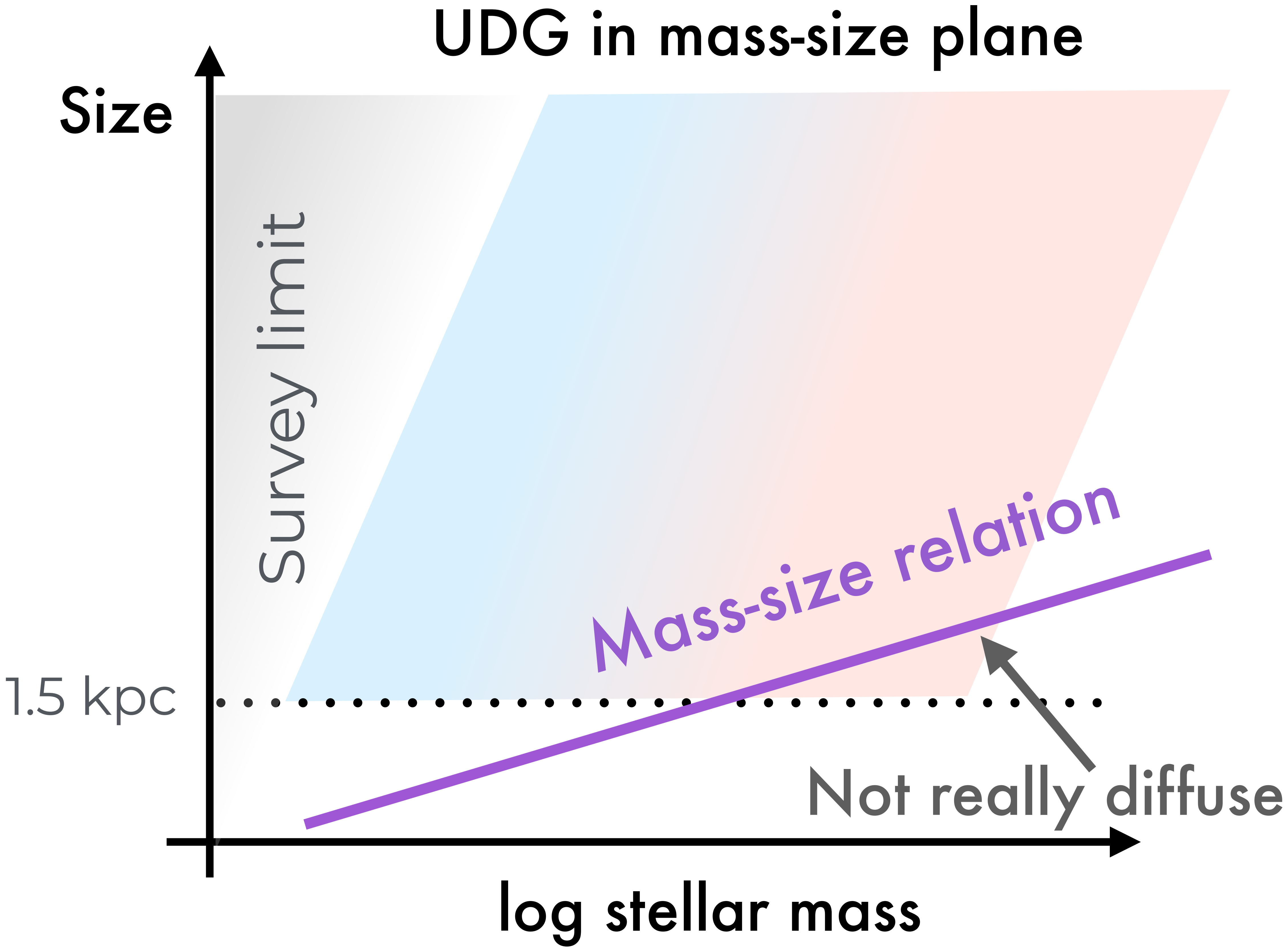

Problem 2: UDGs are not necessarily "diffuse"

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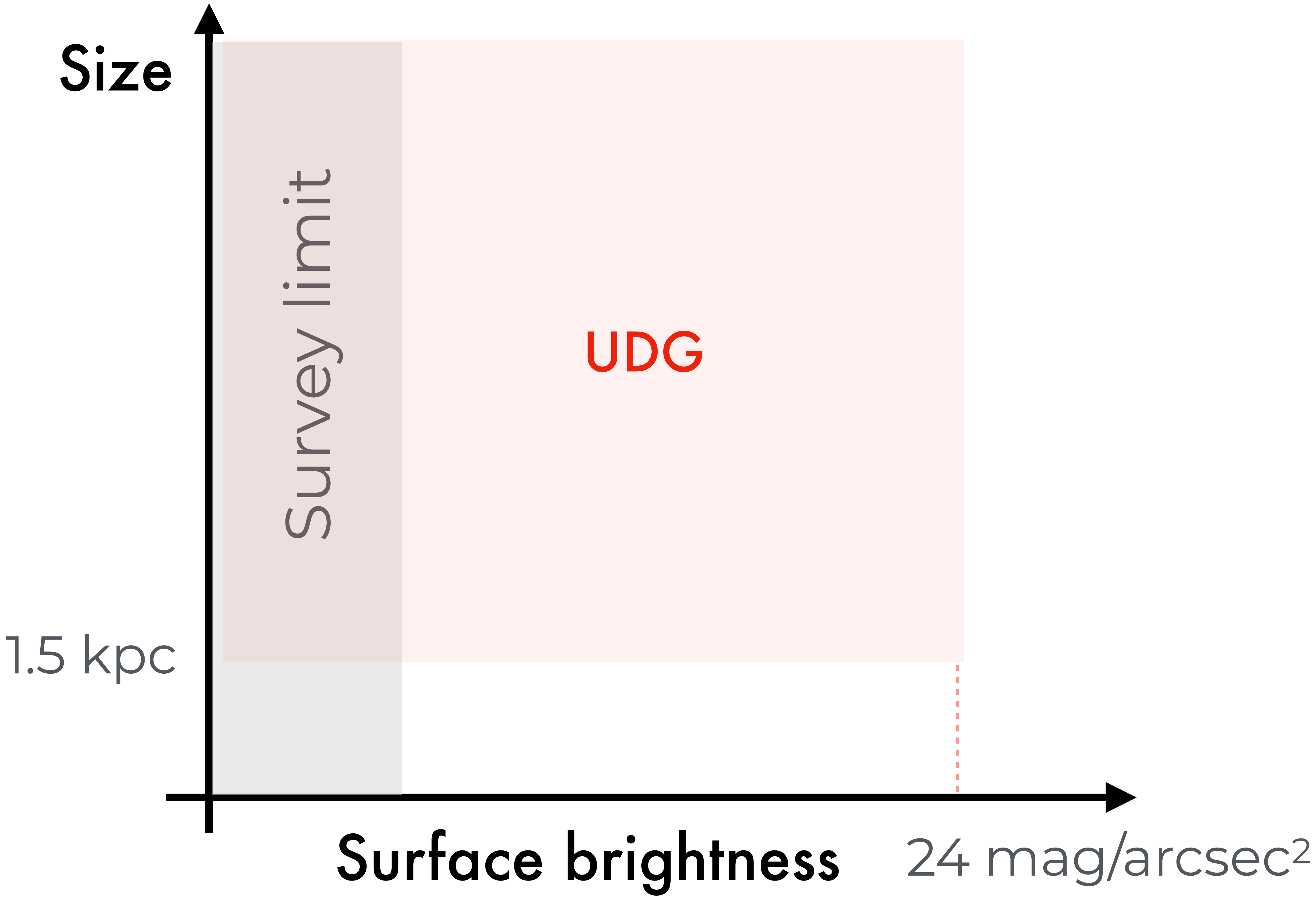
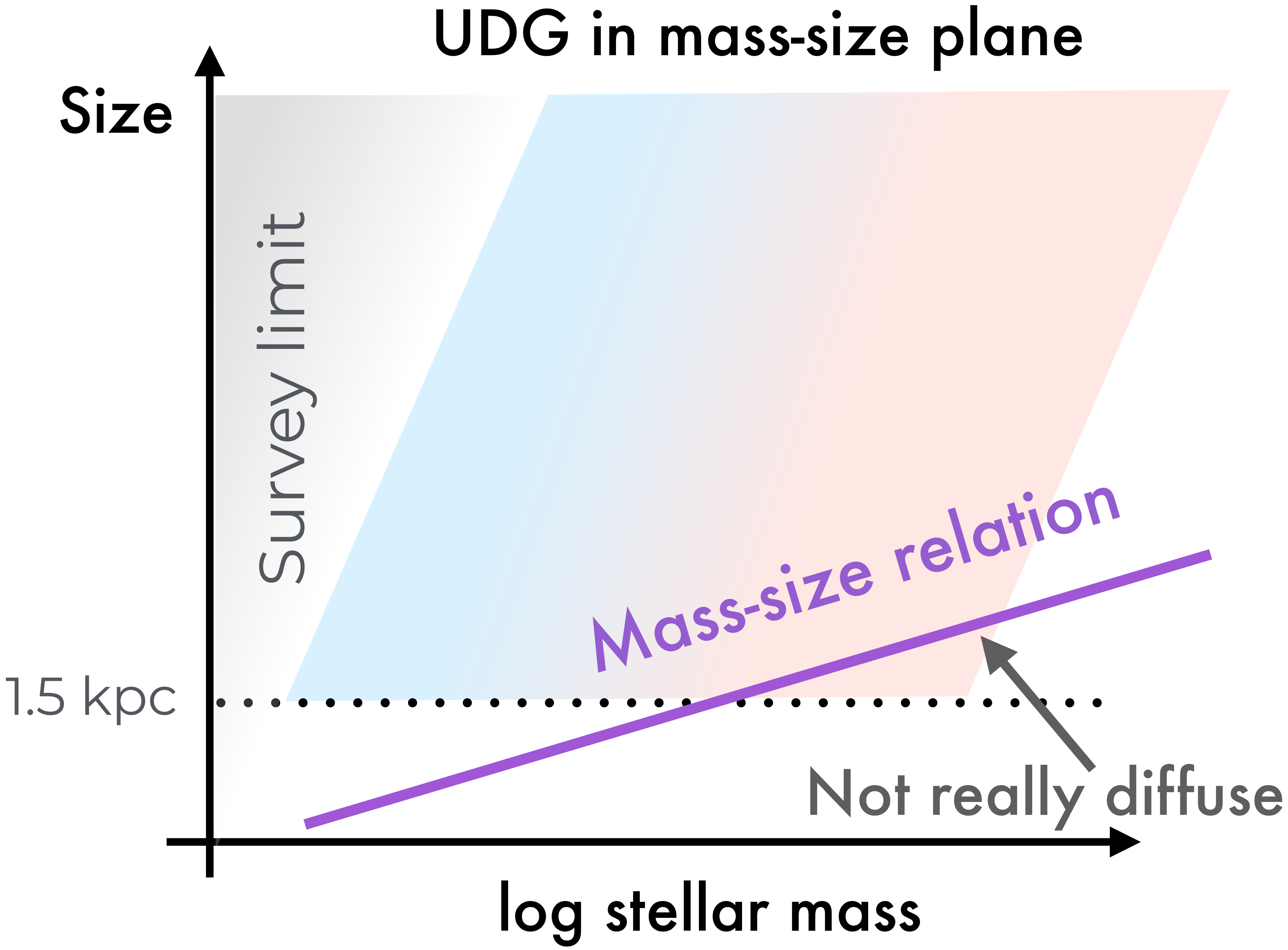
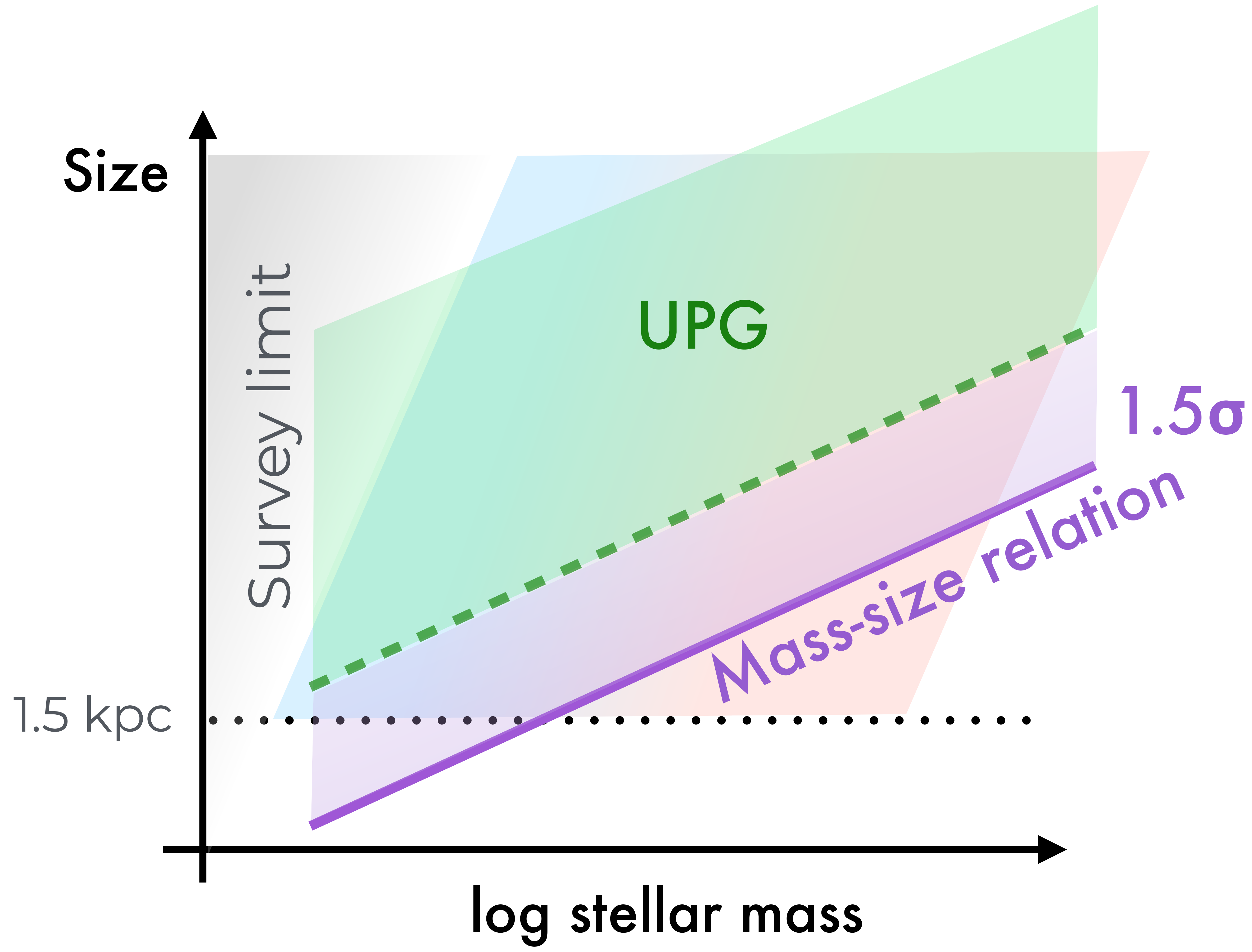




Is there a better way to define a diffuse population?

Ultra-Puffy Galaxy: mass-size outlier

We define Ultra-Puffy Galaxies (UPGs) as dwarfs being 1.5-sigma above the average mass-size relation. This is physically motivated and better represents the mass-size outliers.



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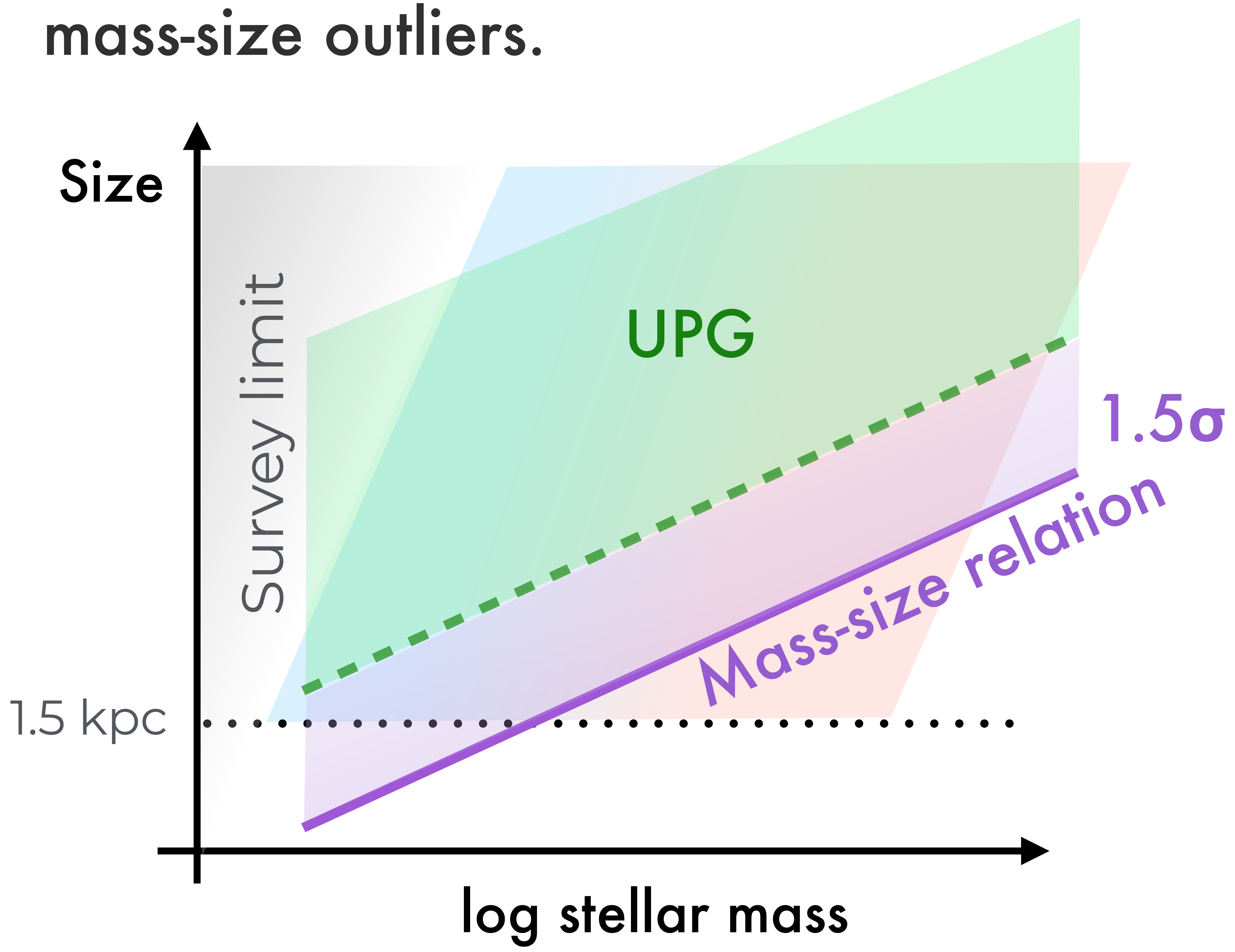

UPGs are the size outliers for a given stellar mass.

UPG selection directly works on the mass-size plane.

This idea has been applied to simulations (Benavides+22) and clusters (Lim+20)

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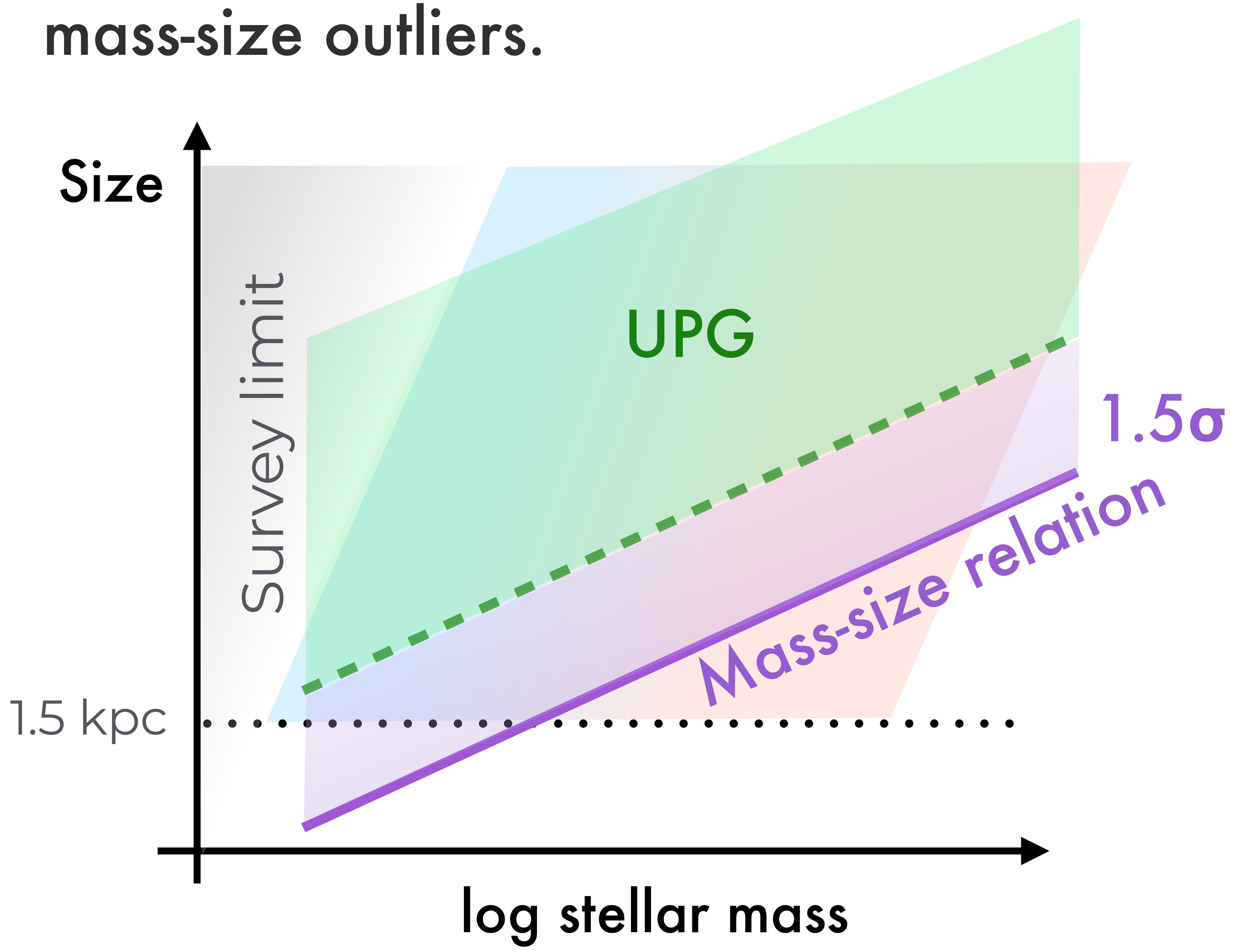

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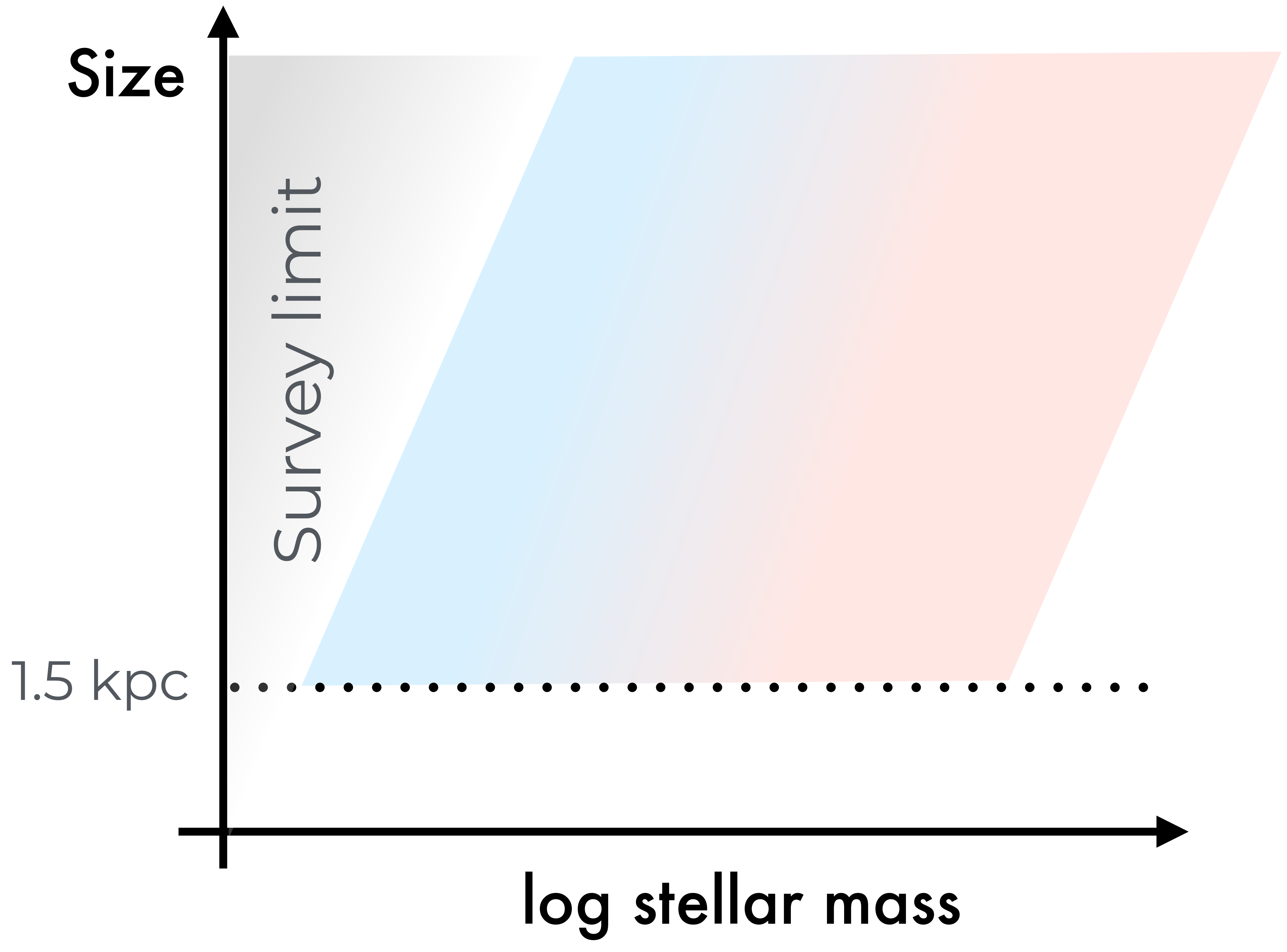

Could UPGs help us better understand the population of diffuse dwarf galaxies?

Yes! Let's find some UDGs/UPGs in the data. We need an environment where the UPG has unfair advantages.

We might not want to survey clusters (satellites are all red) or the field (dwarfs are all blue).

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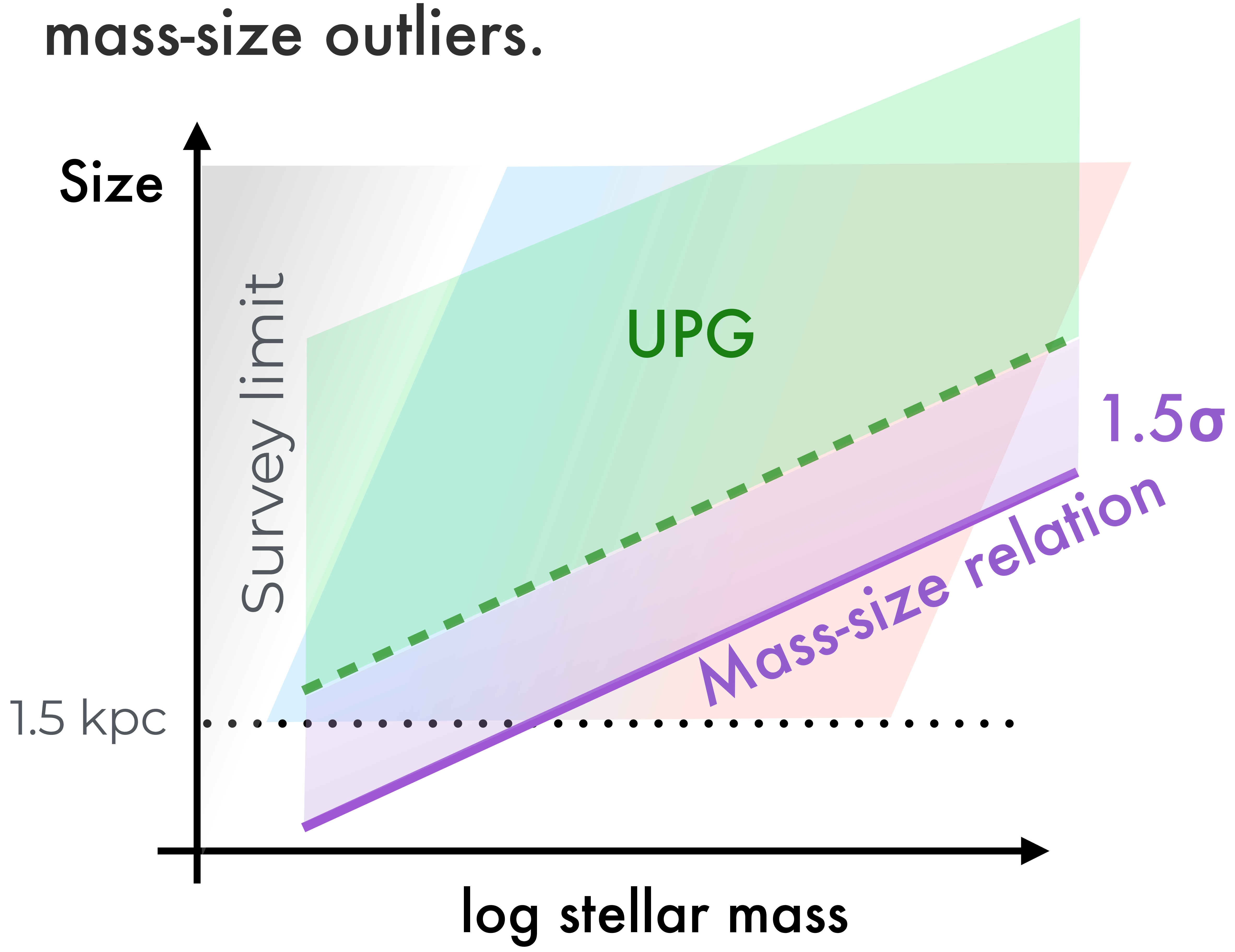


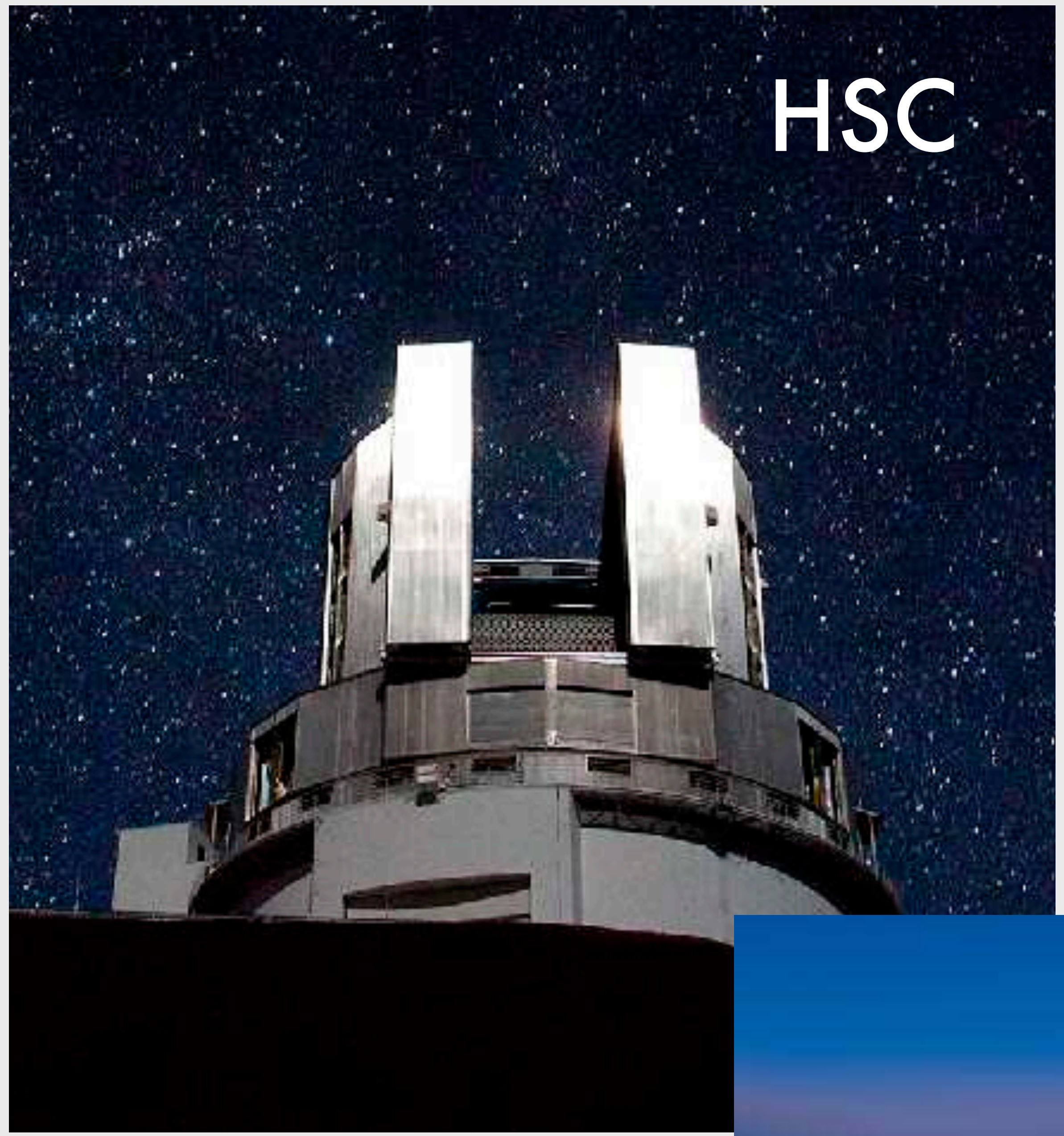
How about Milky Way-like galaxies?
We understand their satellites!

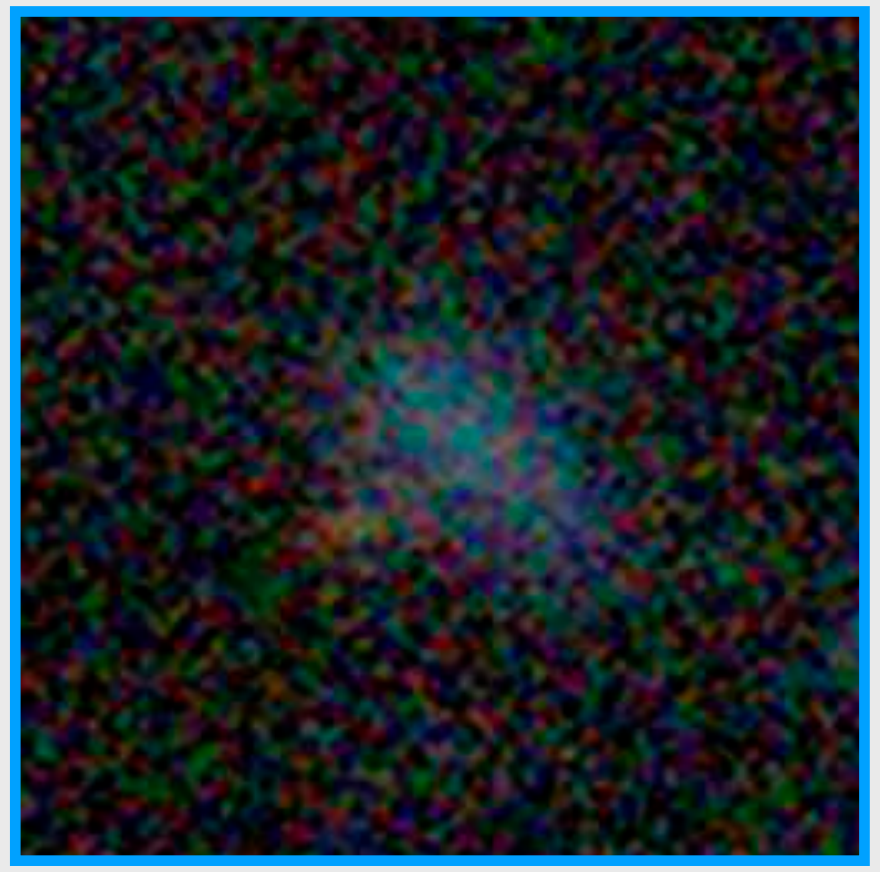
Low surface brightness galaxies in HSC

In order to find UDGs/UPGs, we search for low surface brightness galaxies in the Hyper Suprime-Cam (HSC) survey.

HSC: 1000 deg^2 in grizy using 8-m Subaru. Prototype for Rubin/LSST. PDR2 covers 300 deg^2.

Deep ($r \approx 26$ mag) and clear (0.6″ seeing)



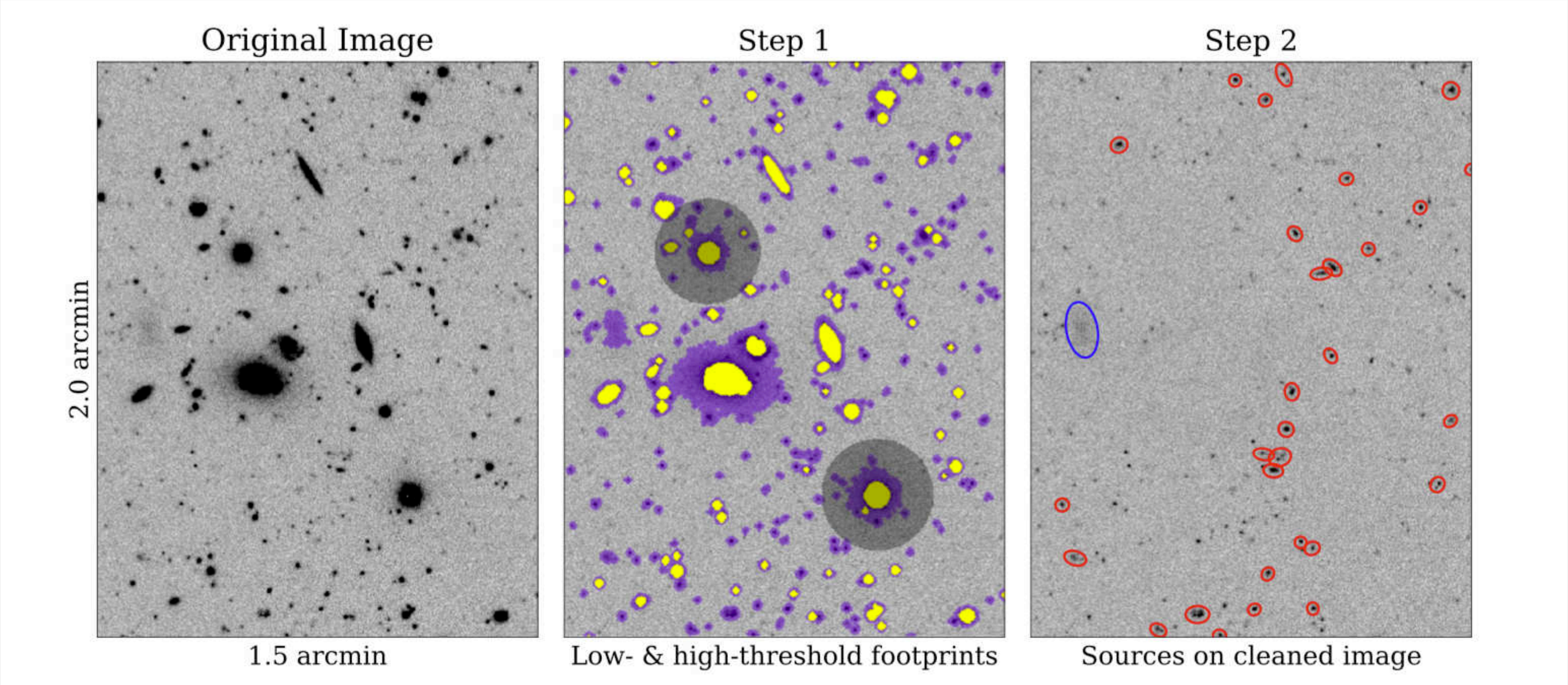


SDSS

DECaLS

HSC

Low surface brightness galaxies in HSC



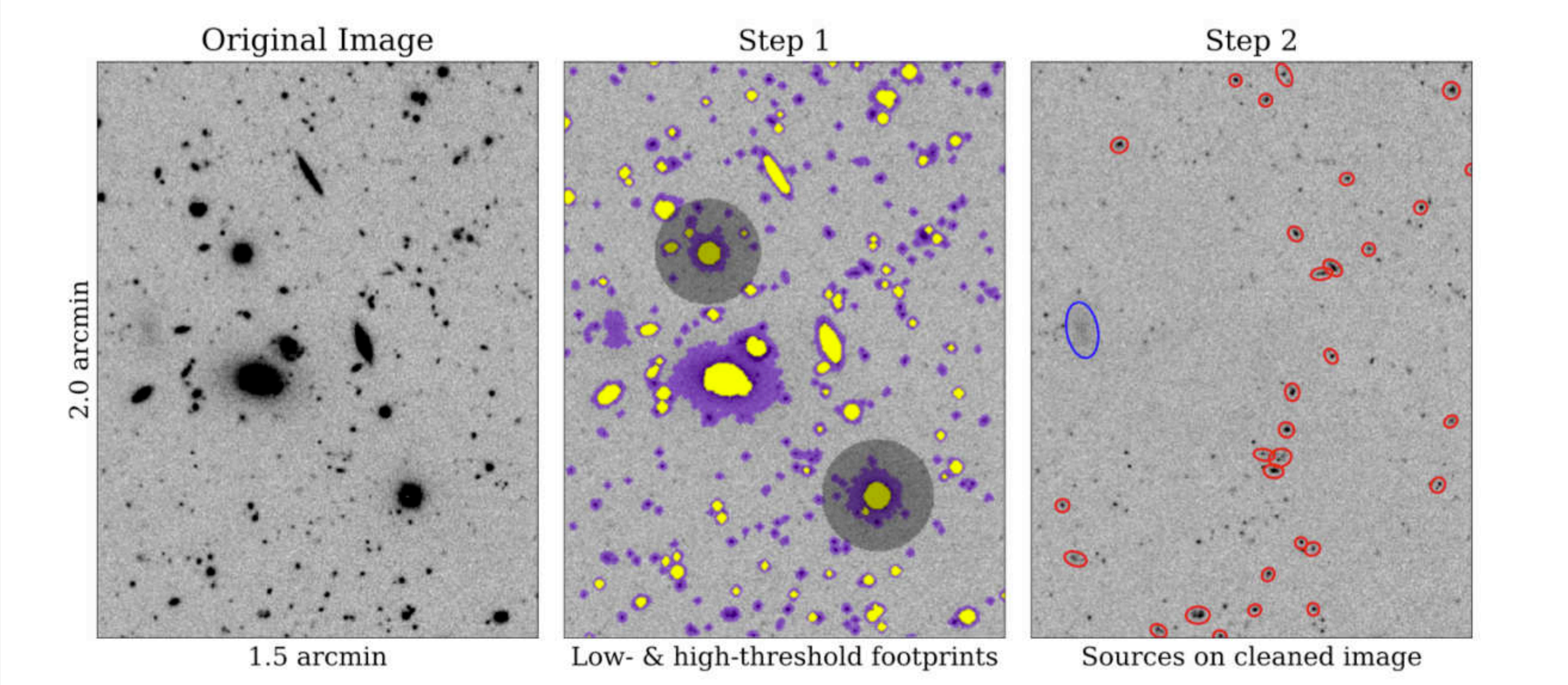
Greco et al. (2018), Li et al. (2022b)

Low surface brightness galaxies in HSC

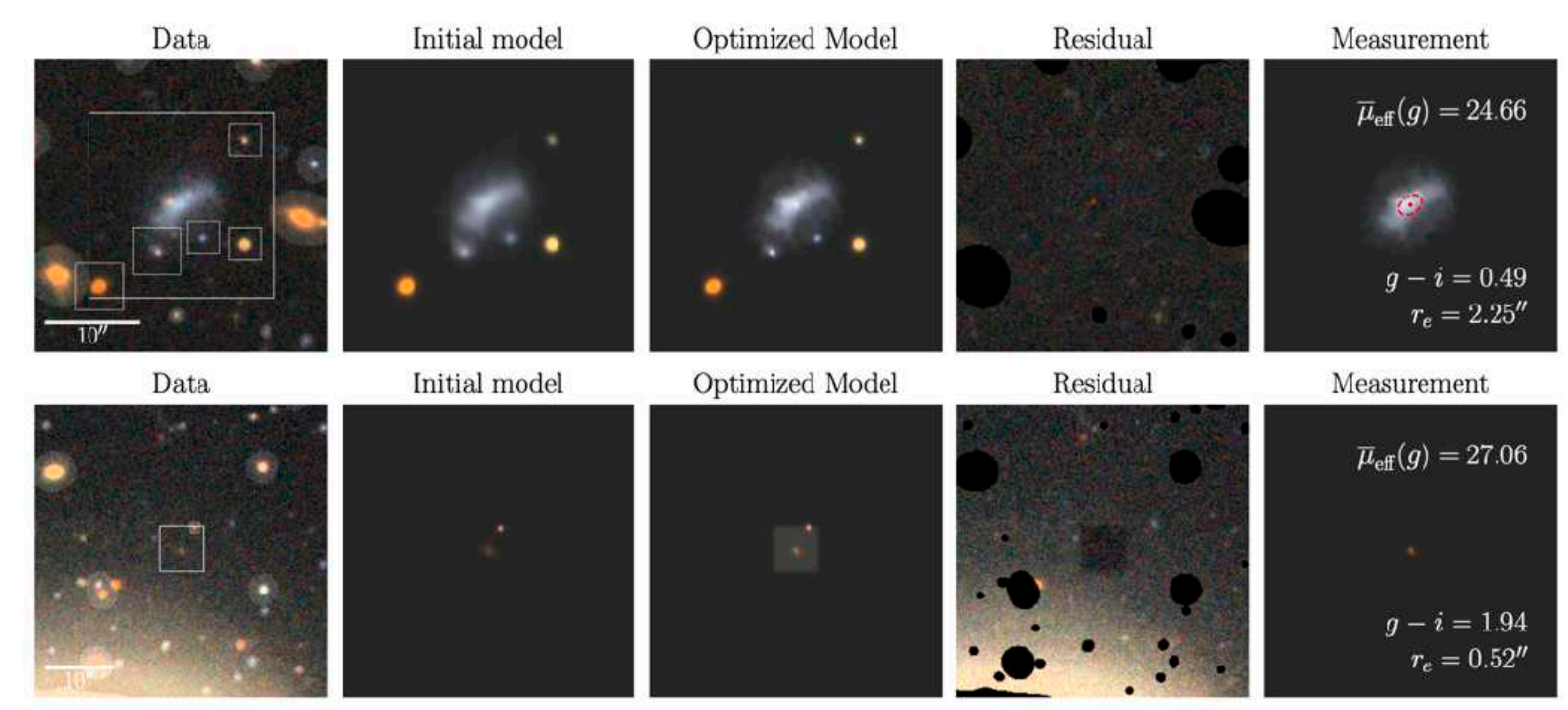
After initial detection, we model each source with a non-parametric method (scarlet).

Then we remove junks by apply a cut based on size, color, surface brightness, Gini coeff, etc.

We characterize the remaining LSBGs by fitting a Spergel model to them, then measure size, surface brightness, etc.



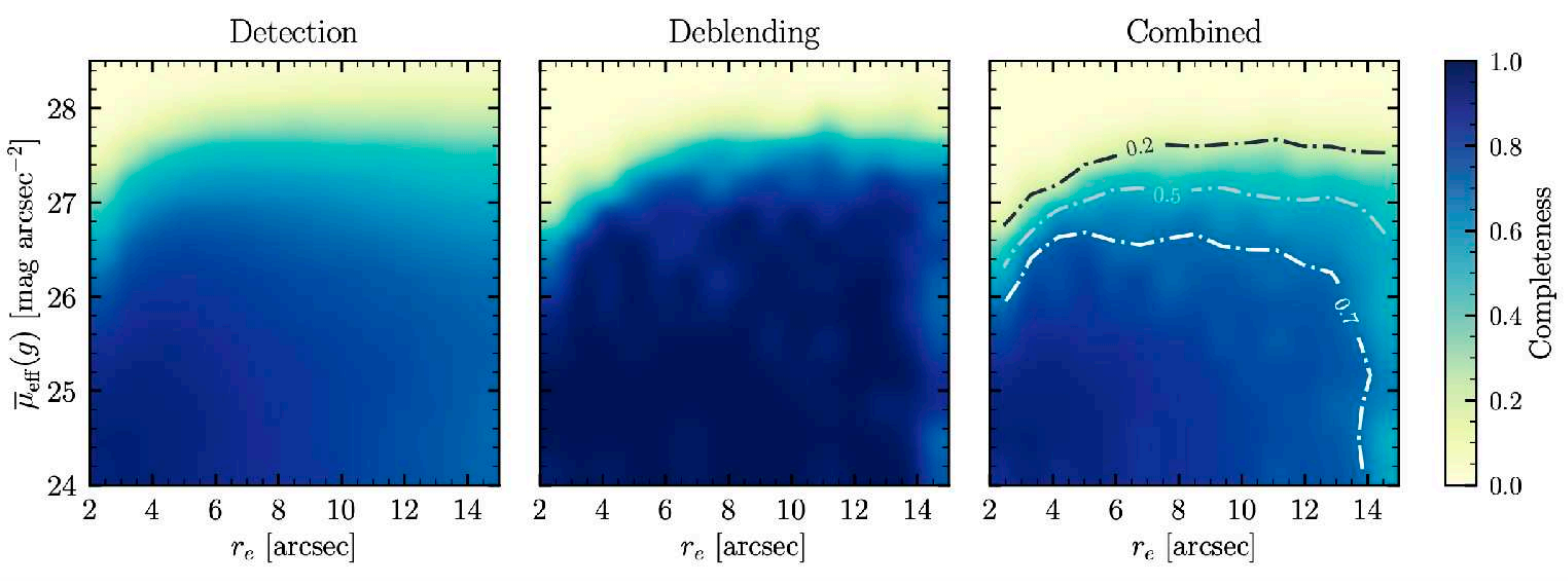
Initial Detection



Junk removal using scarlet

Low surface brightness galaxies in HSC

We are >50% complete to $\mu_{\rm eff}(g) = 27\ \mathrm{mag\,arcsec^{-2}}$, very high compared to other similar searches (e.g., using DES, DECaLS). Dragonfly beats us by sacrificing spatial resolution.



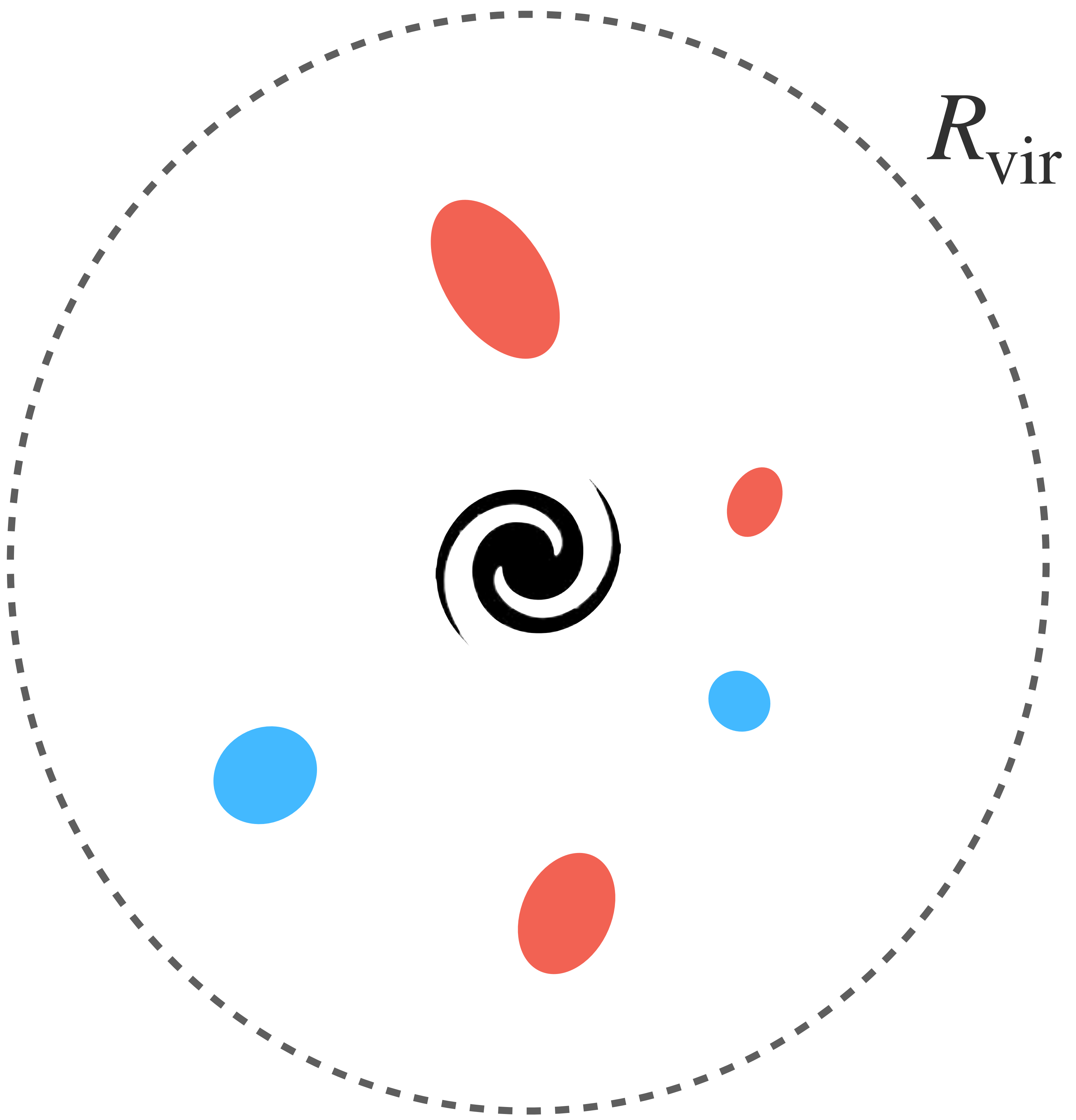
Completeness as a function of size and surface brightness

UDGs/UPGs among the satellites of Milky Way analogs

We select 922 MW analogs at 0.01 < z < 0.04 in HSC footprint, match LSBGs to them in projection ($r < R_{\rm vir}$). MW analogs are from the NASA-Sloan Atlas:
$10.2 < \log(M_\star/M_\odot) < 11.2$

We do not know distances to the matched LSBGs, so we assume they are at the same distance as the host. Once the distance is known, it is straightforward to select UDGs and UPGs.

We obtain 412 UDGs and 337 UPGs.



MW analog

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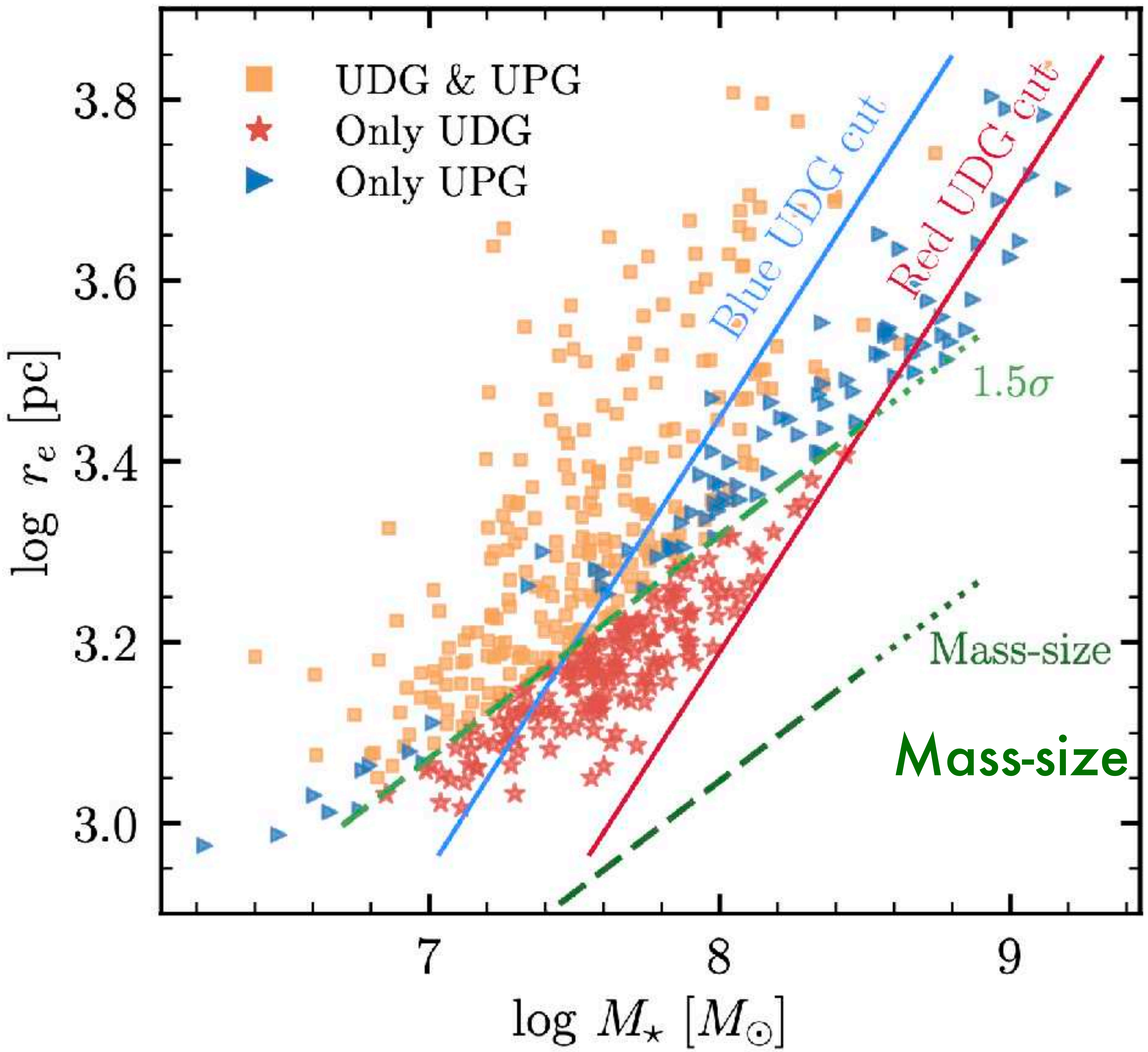

Mass-size relation is from ELVES

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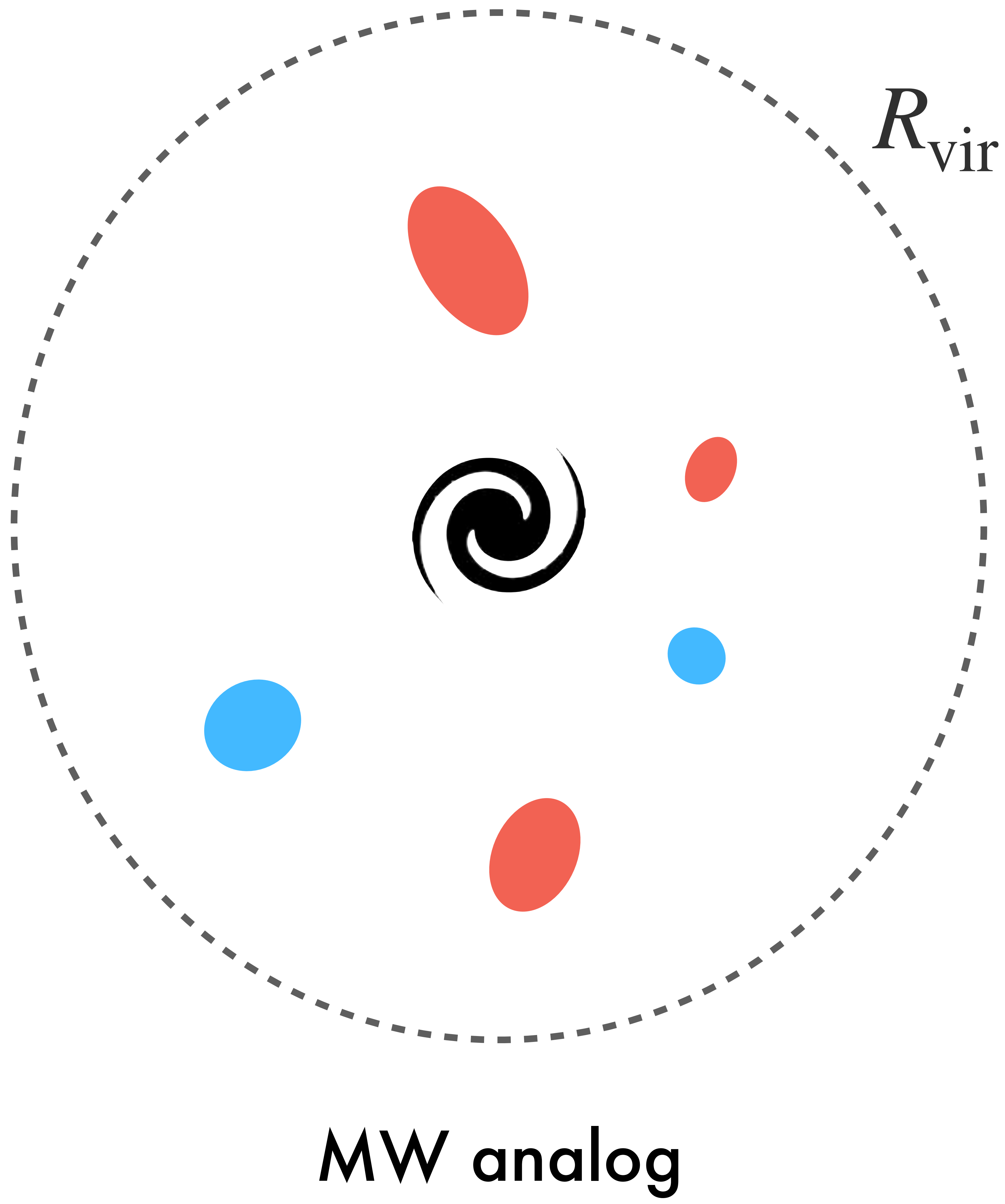

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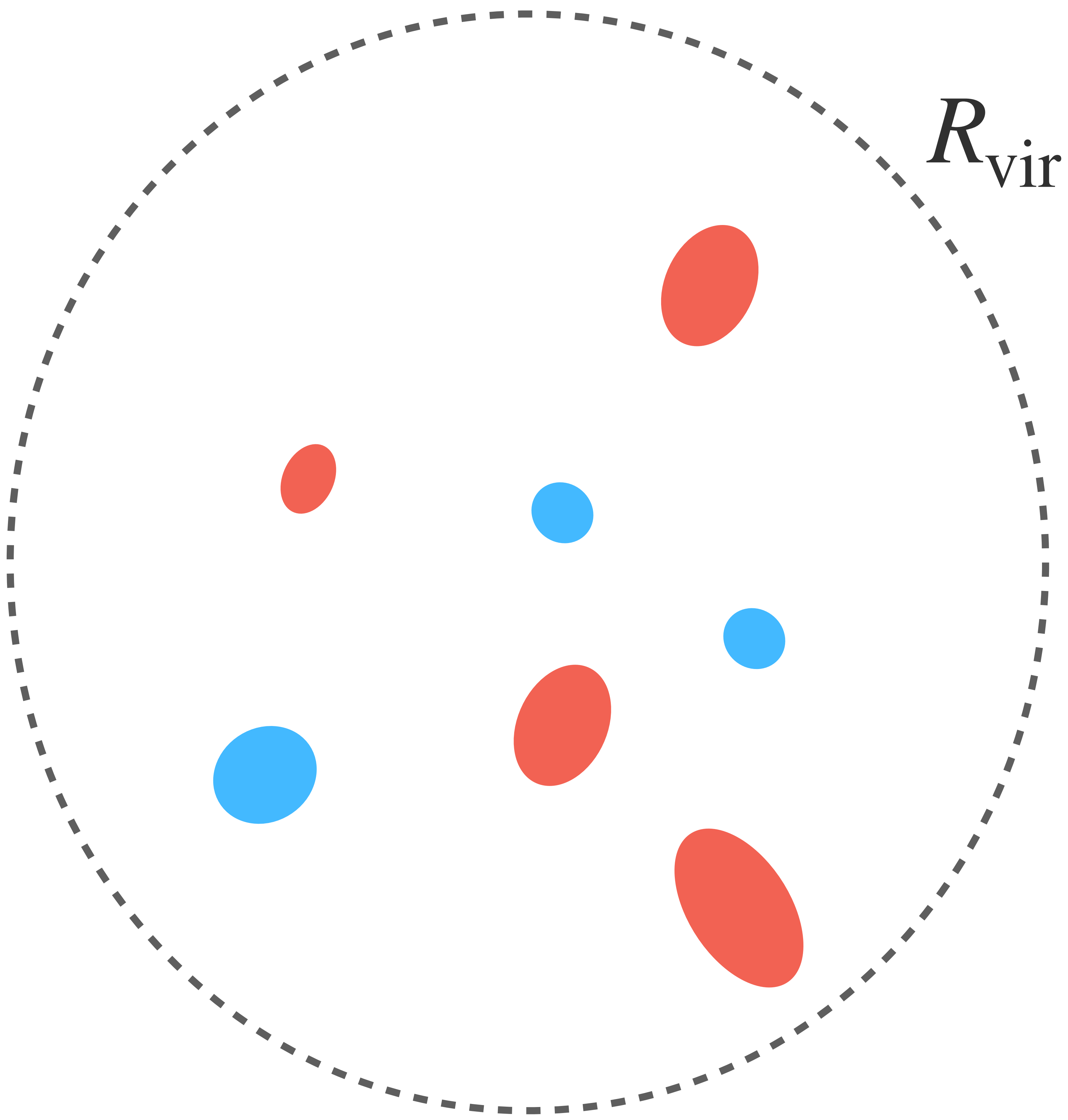

Random field

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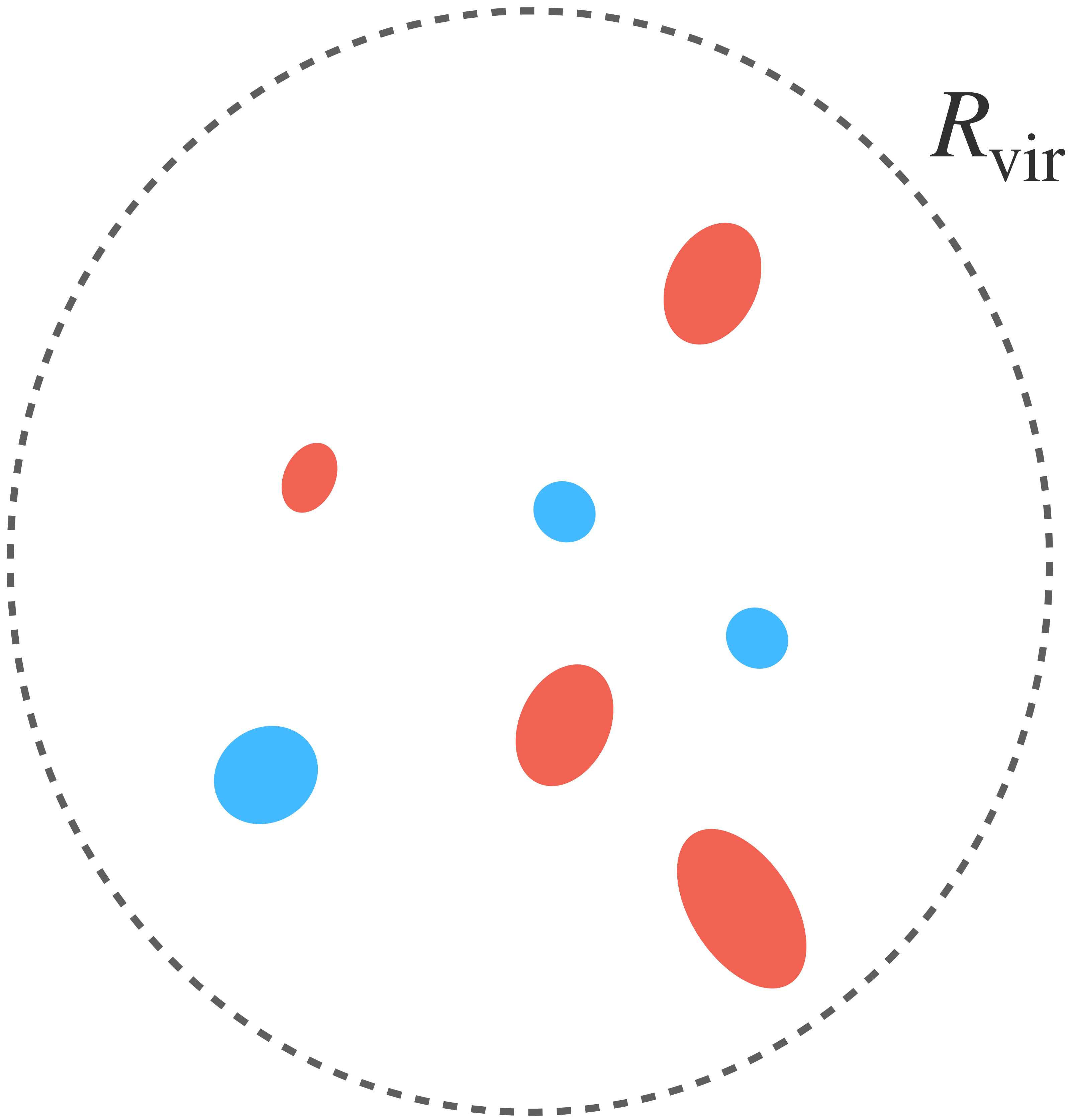

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Surface density of "artificial" UDG/UPG:
$S_{\rm UDG} = 1.6\ \mathrm{deg}^{-2}$, $S_{\rm UPG} = 1.7\ \mathrm{deg}^{-2}$

35% of UDGs and 45% of UPGs are interlopers!

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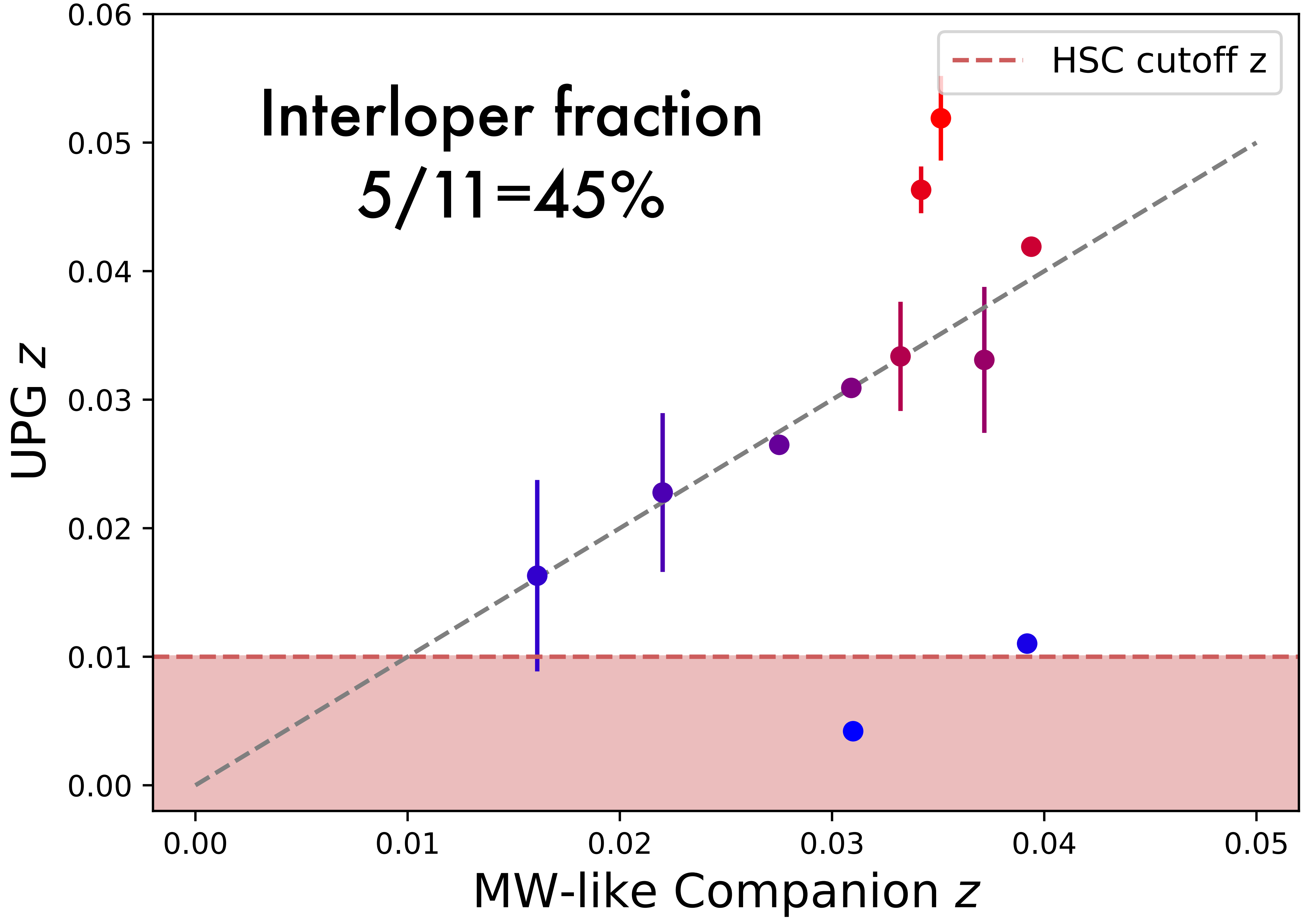

Spec-zs of 11 bright UPGs using SALT

Kelly Whalen, Ryan Hickox (Dartmouth College)

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Spectroscopic follow-ups confirm this

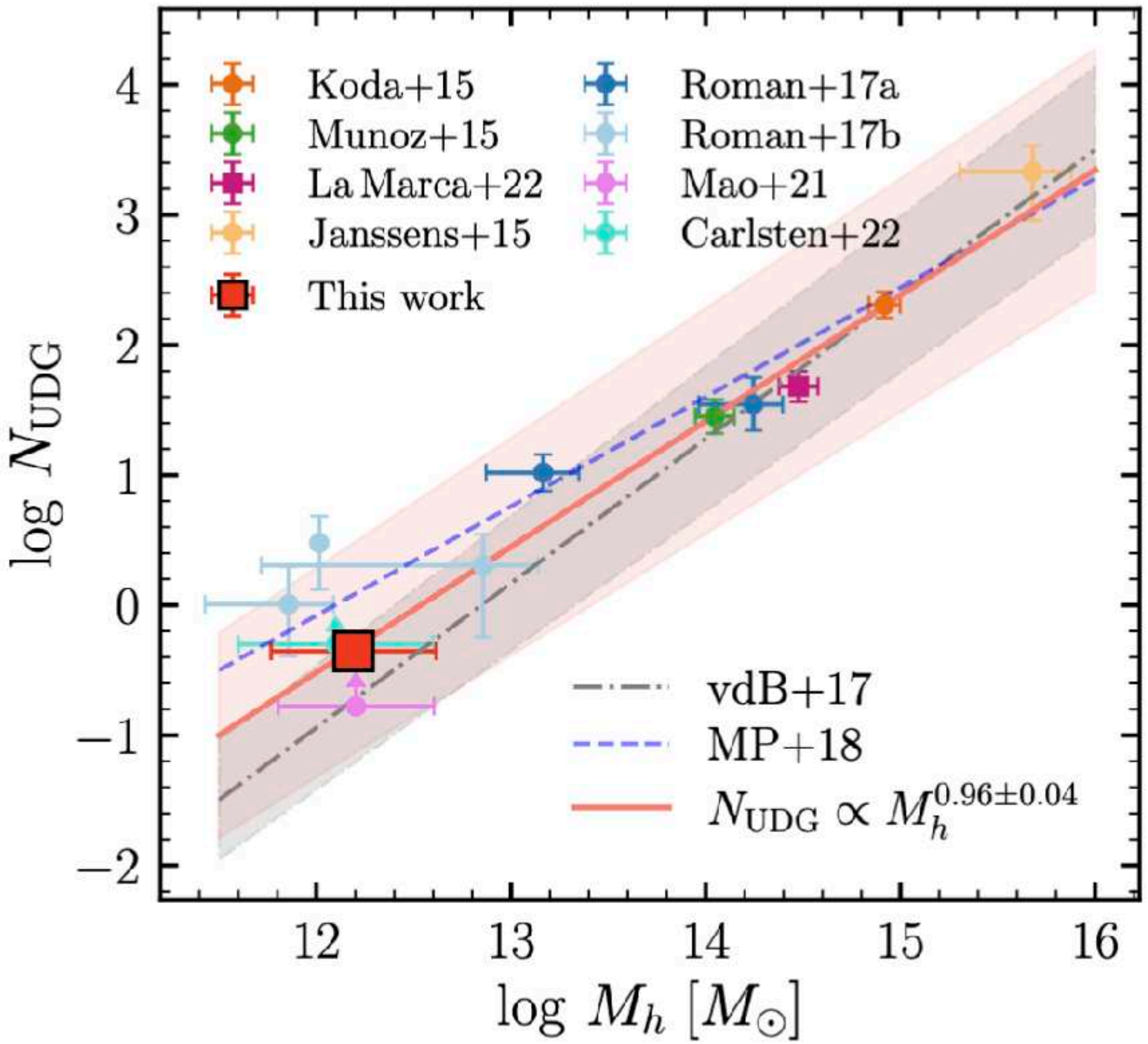
Abundances of UDGs and UPGs

UDG abundance: 0.44 ± 0.05 per host

UPG abundance: 0.31 ± 0.04 per host

Agrees with ELVES and SMUDGES results

We revisit the N(UDG) v.s. Halo mass relation: $N_{\rm UDG} \propto M_h^{0.96\pm0.04}$



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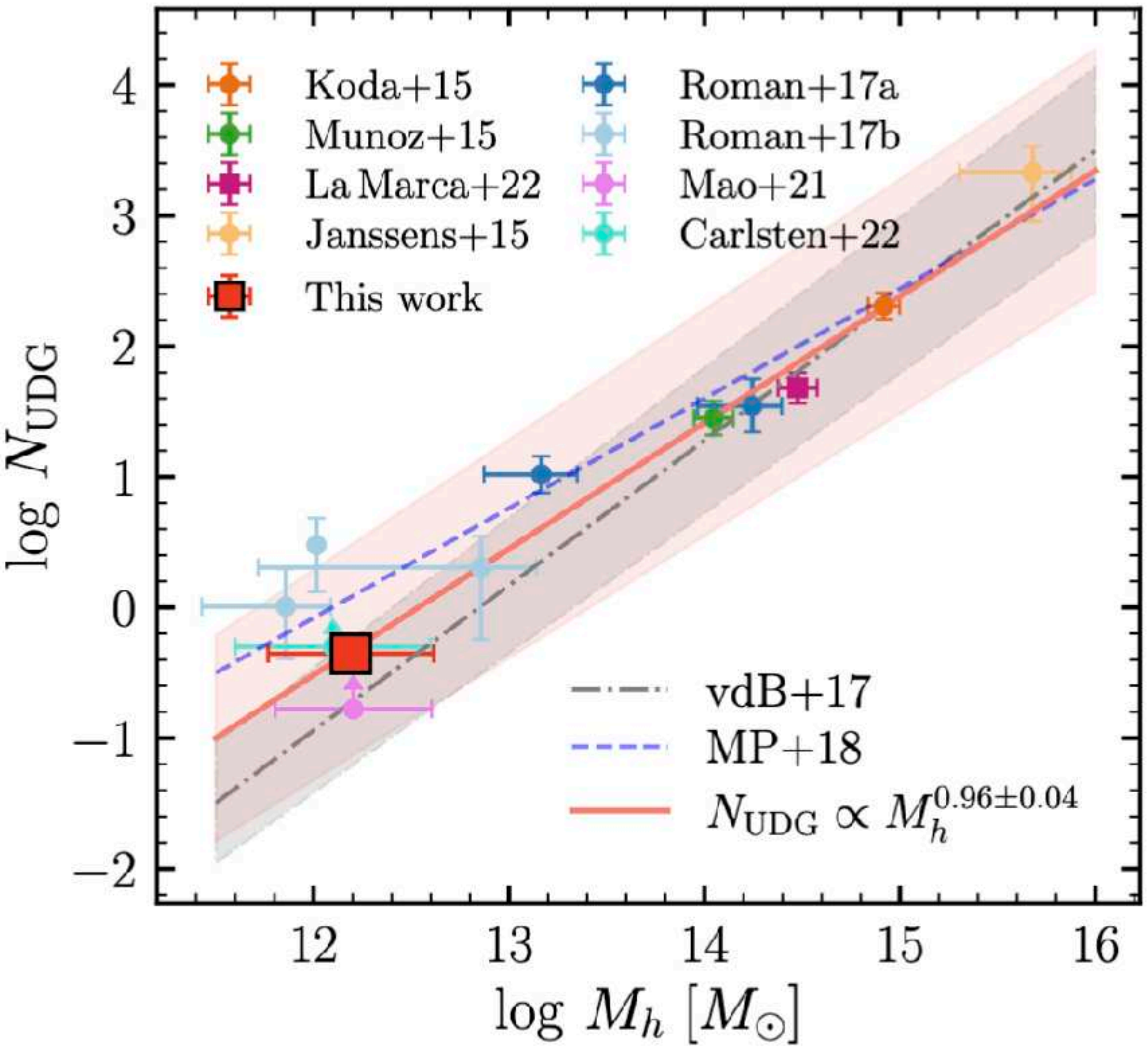
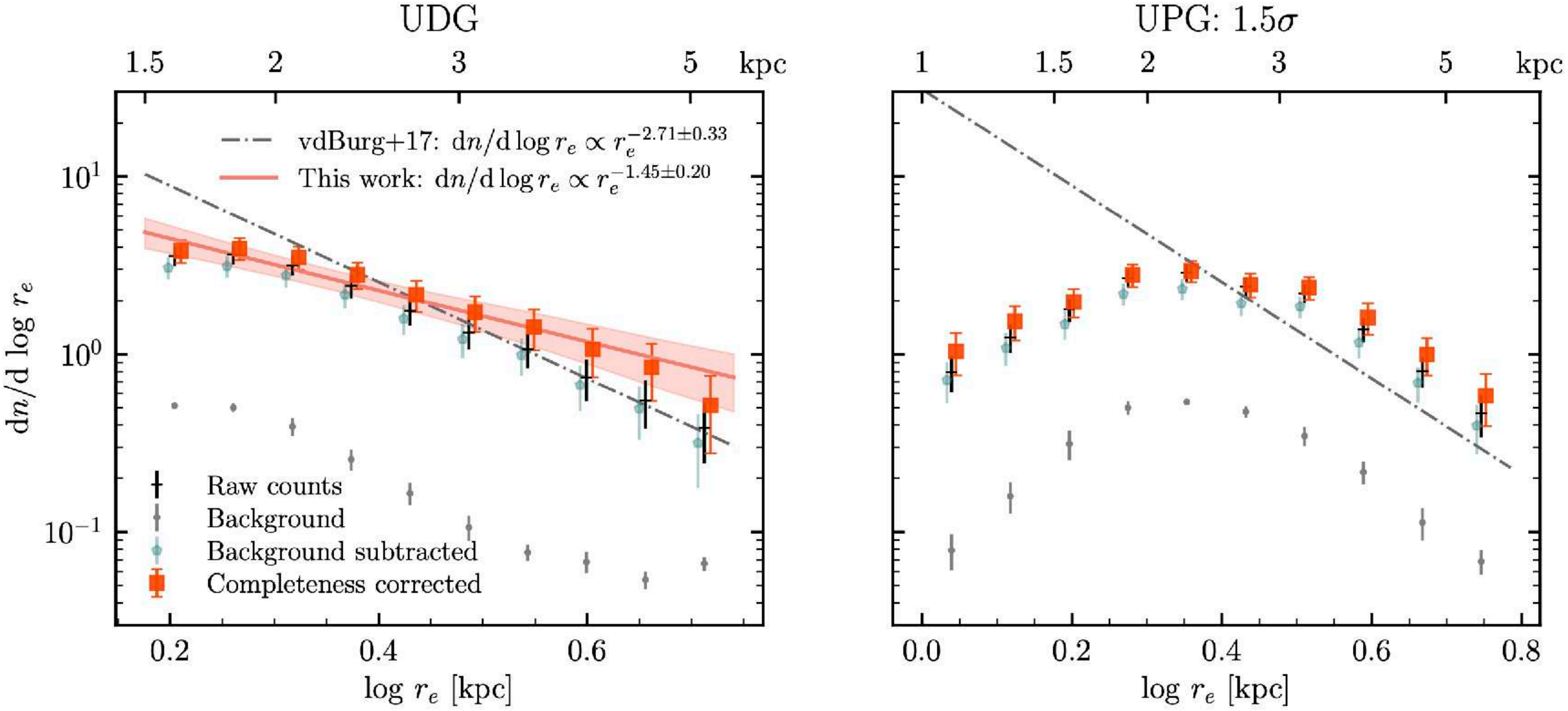
The fraction of UDG among satellites: 7% ±2%

The fraction of UPG among satellites: 5% ±2%

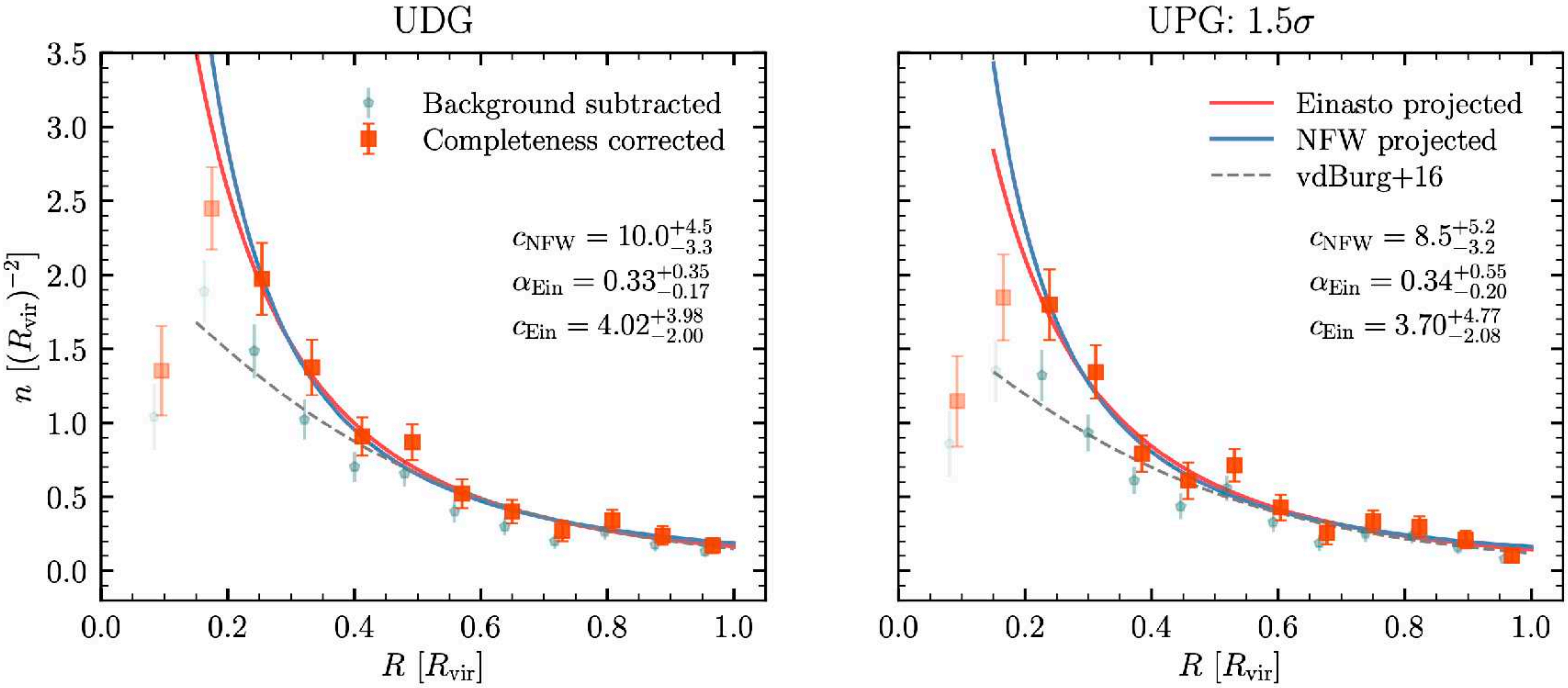
Gaussian CDF F(1.5σ)=0.93



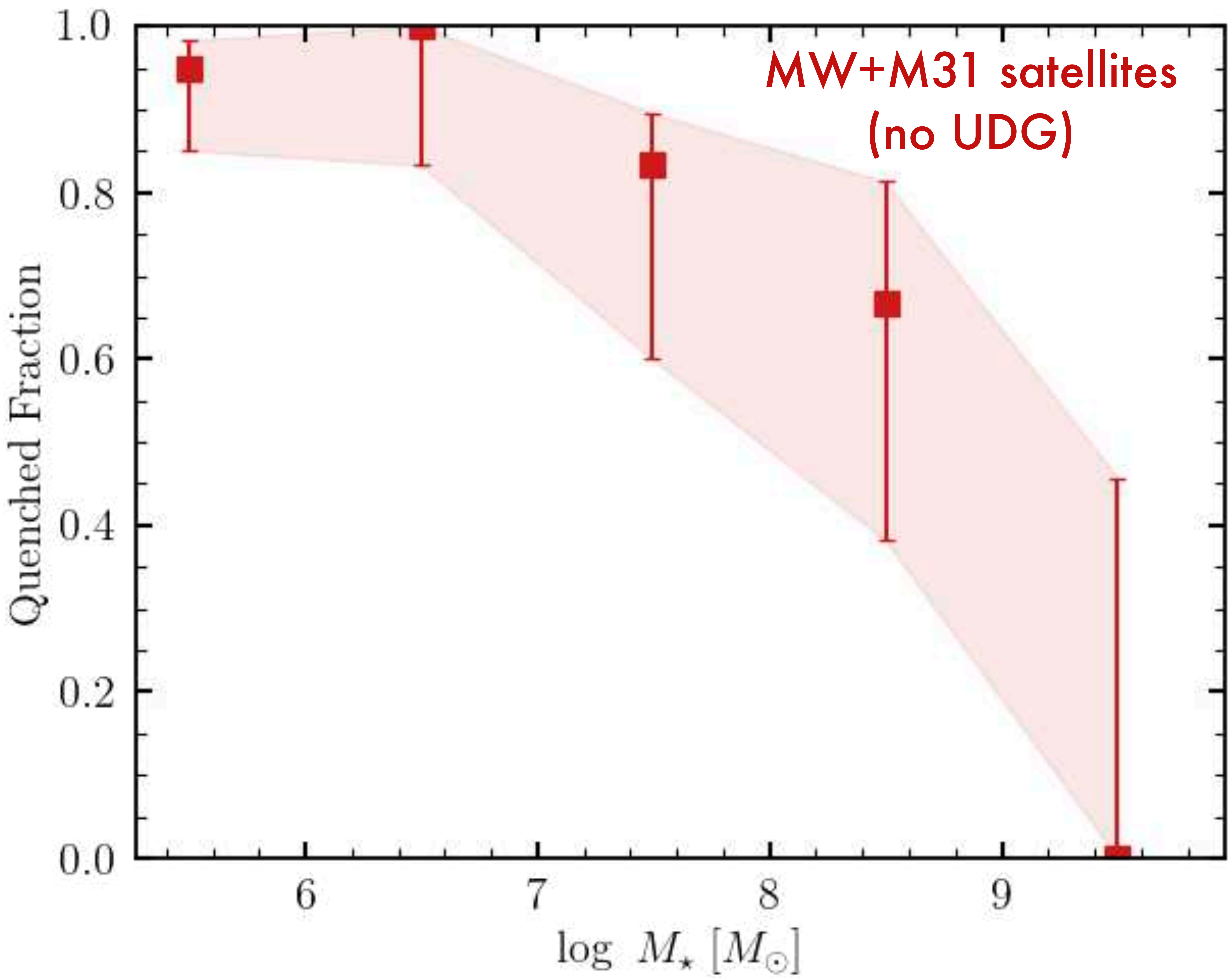
Size distribution of UDGs and UPGs



Spatial distribution of UDGs and UPGs



Quenching of satellites, UDGs, and UPGs



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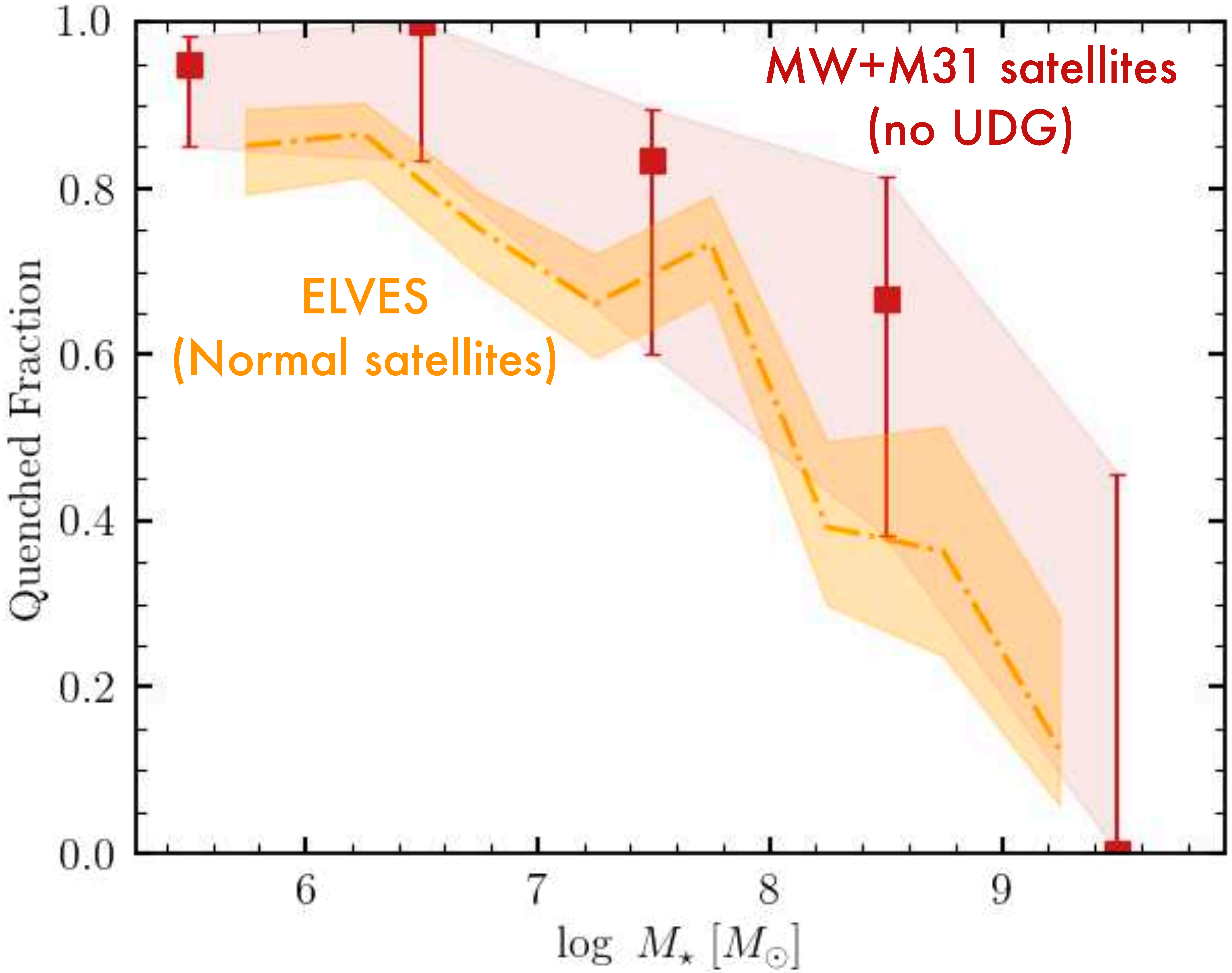
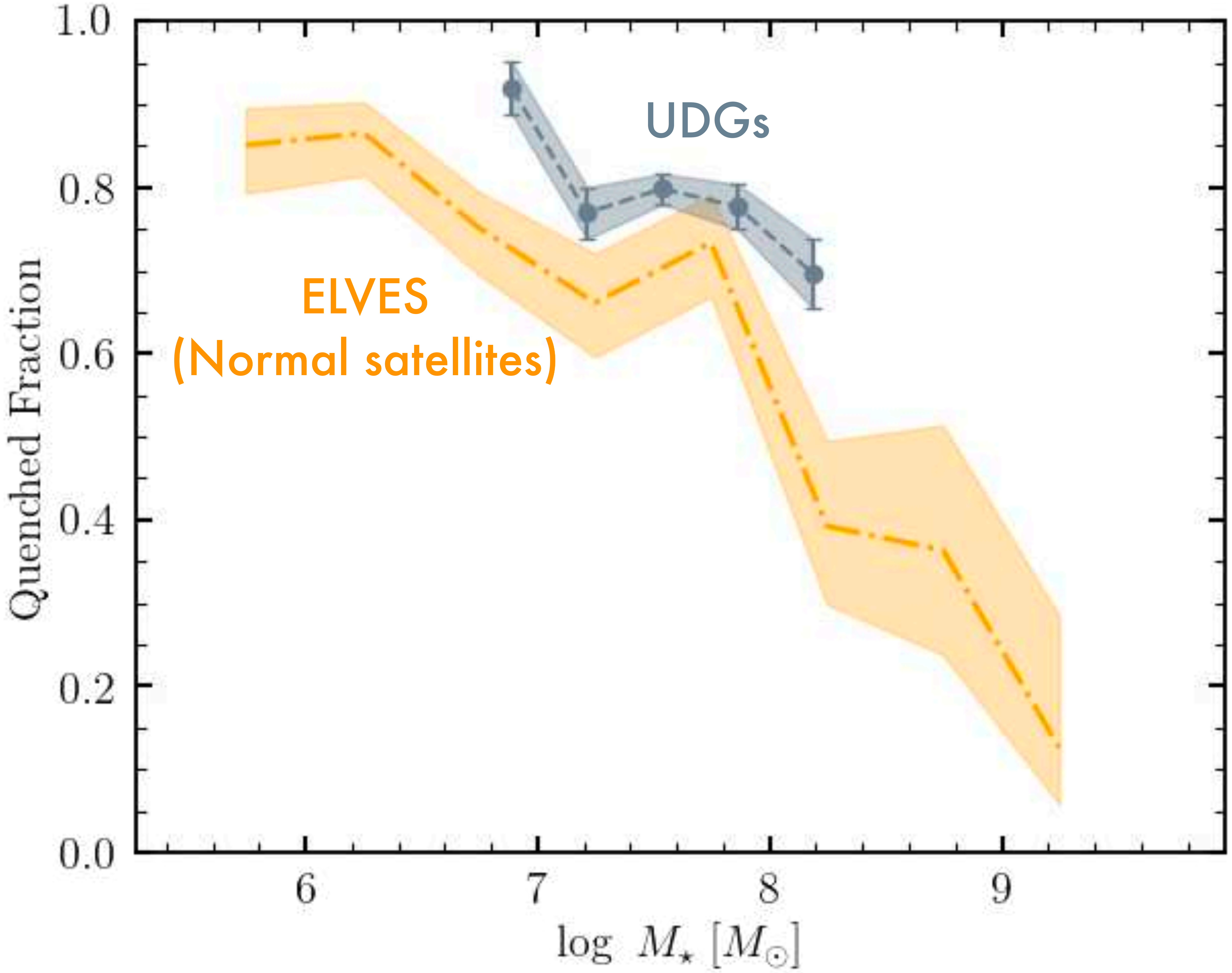


ELVES (Exploration of Local VolumE Satellites): photometric survey for satellites of MW analogs within 12 Mpc. Distances measured using *surface brightness fluctuation*.

Quenching of satellites, UDGs, and UPGs



UDGs have a higher and constant quenched fraction

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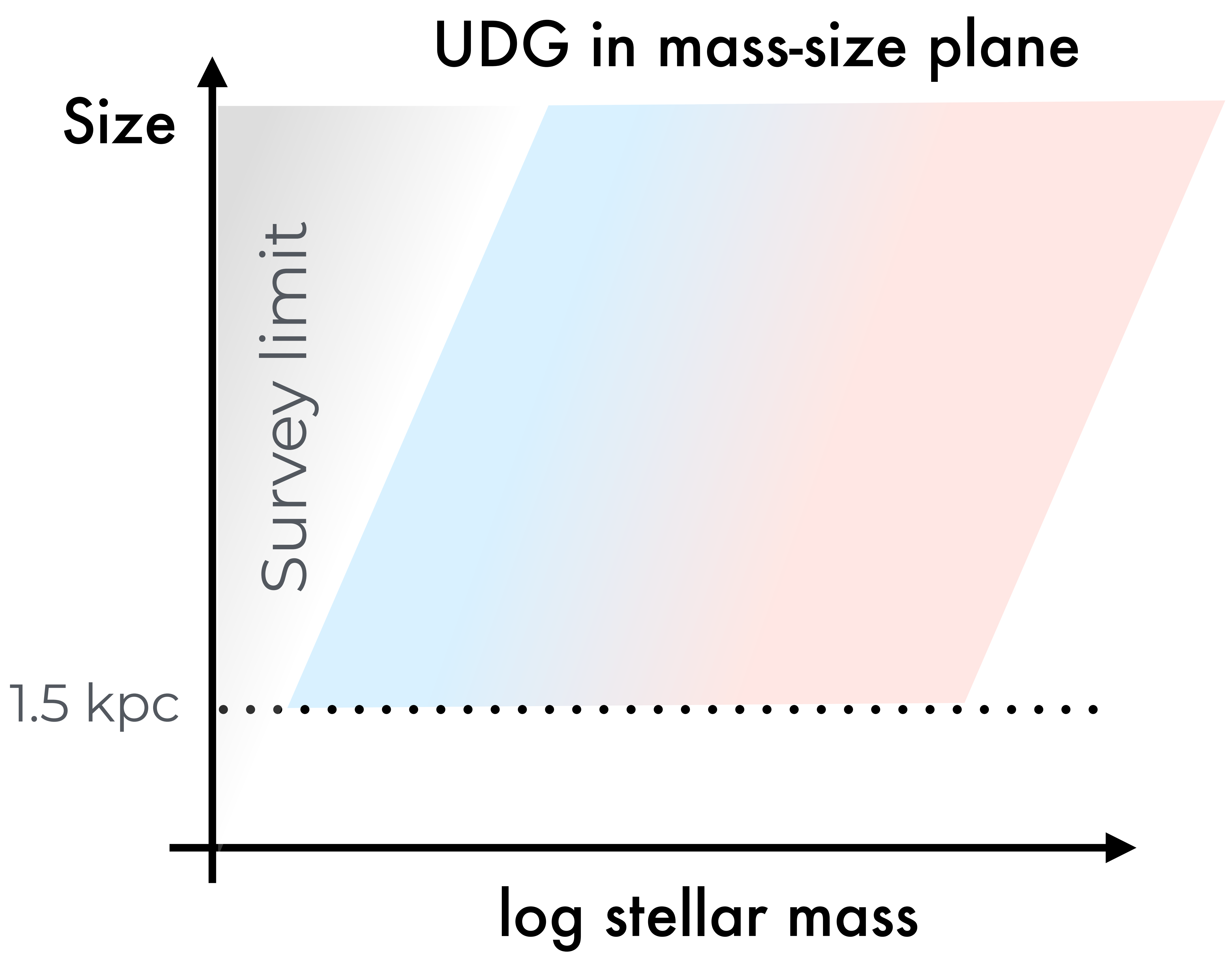

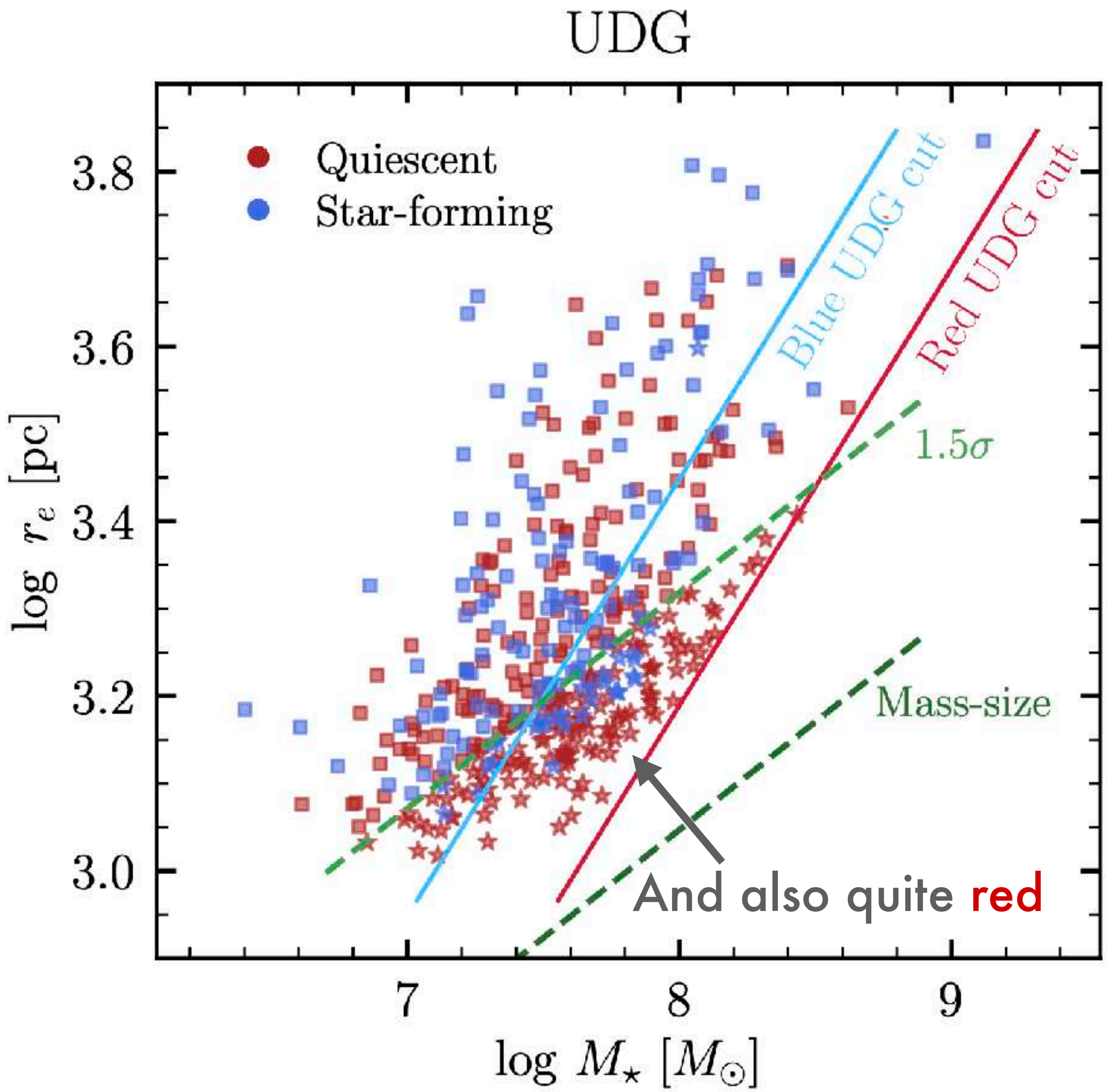

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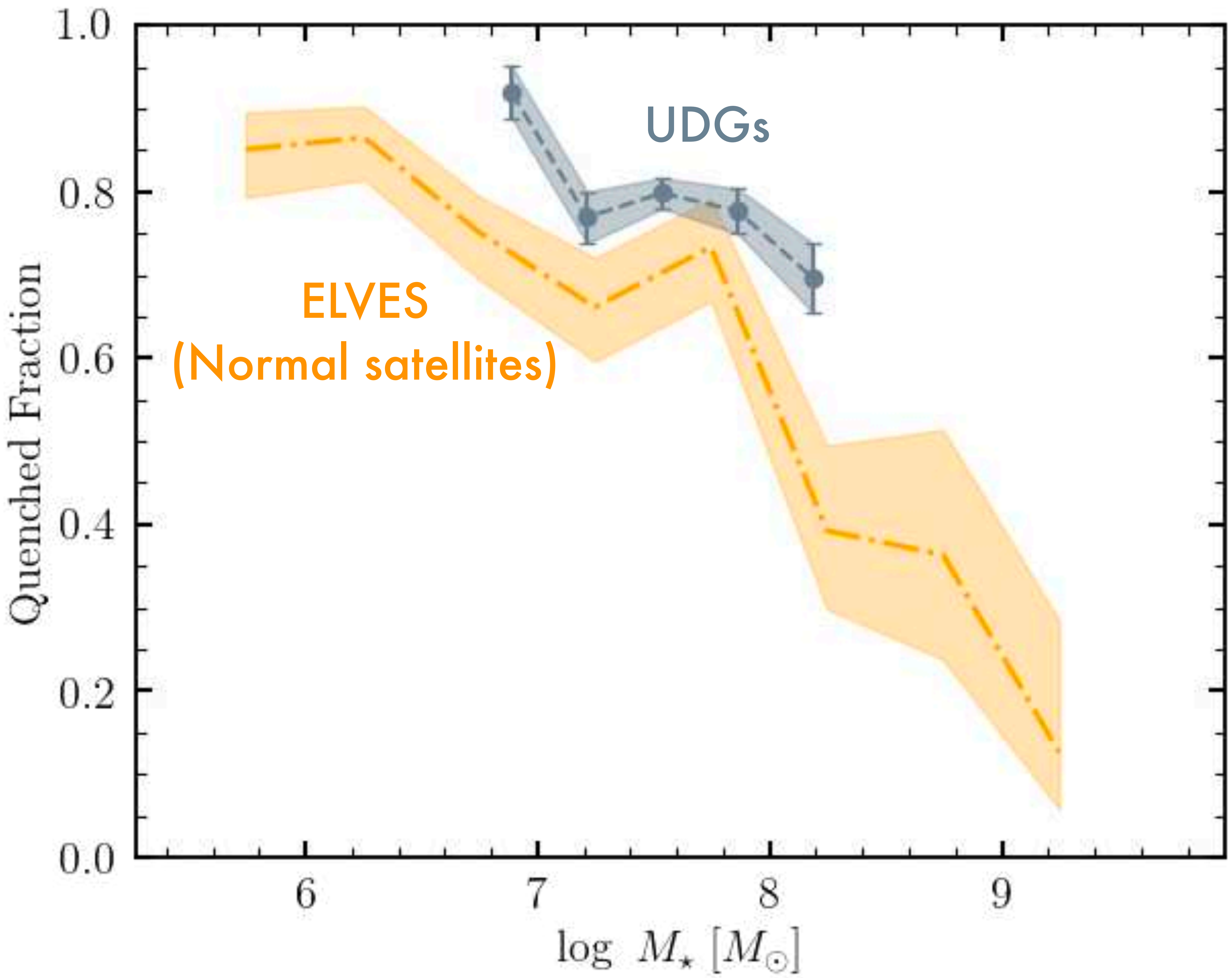
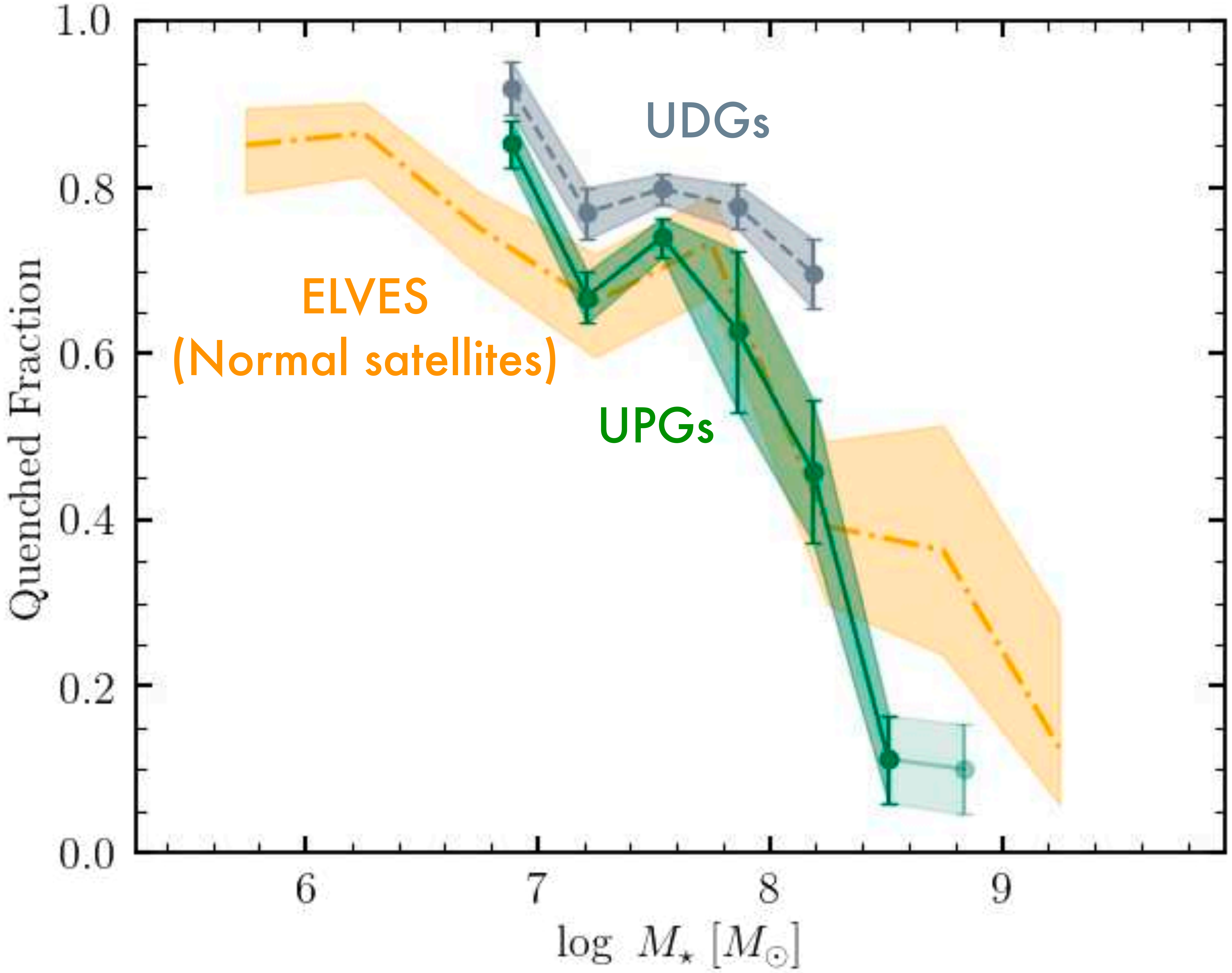


UDGs have a higher and constant quenched fraction

<u>High quenched fraction of UDGs is merely an artifact of the definition</u>

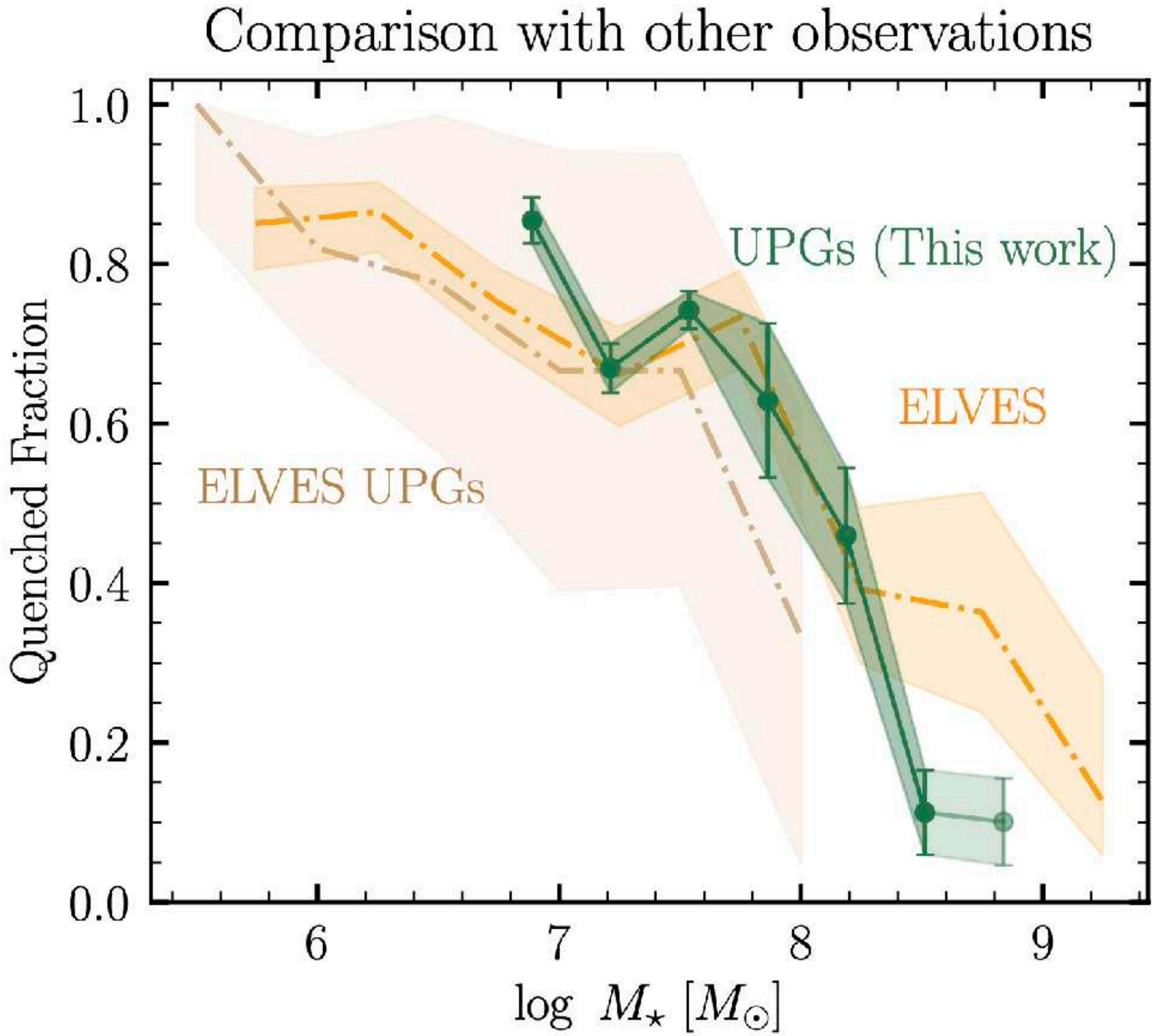
Quenching of satellites, UDGs, and UPGs



UDGs have a higher quenched fraction

UPGs have a similar quenched fraction as normal satellites, although UPGs are puffy!

Quenching of satellites, UDGs, and UPGs



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UPGs in ELVES also show similar quenched fraction

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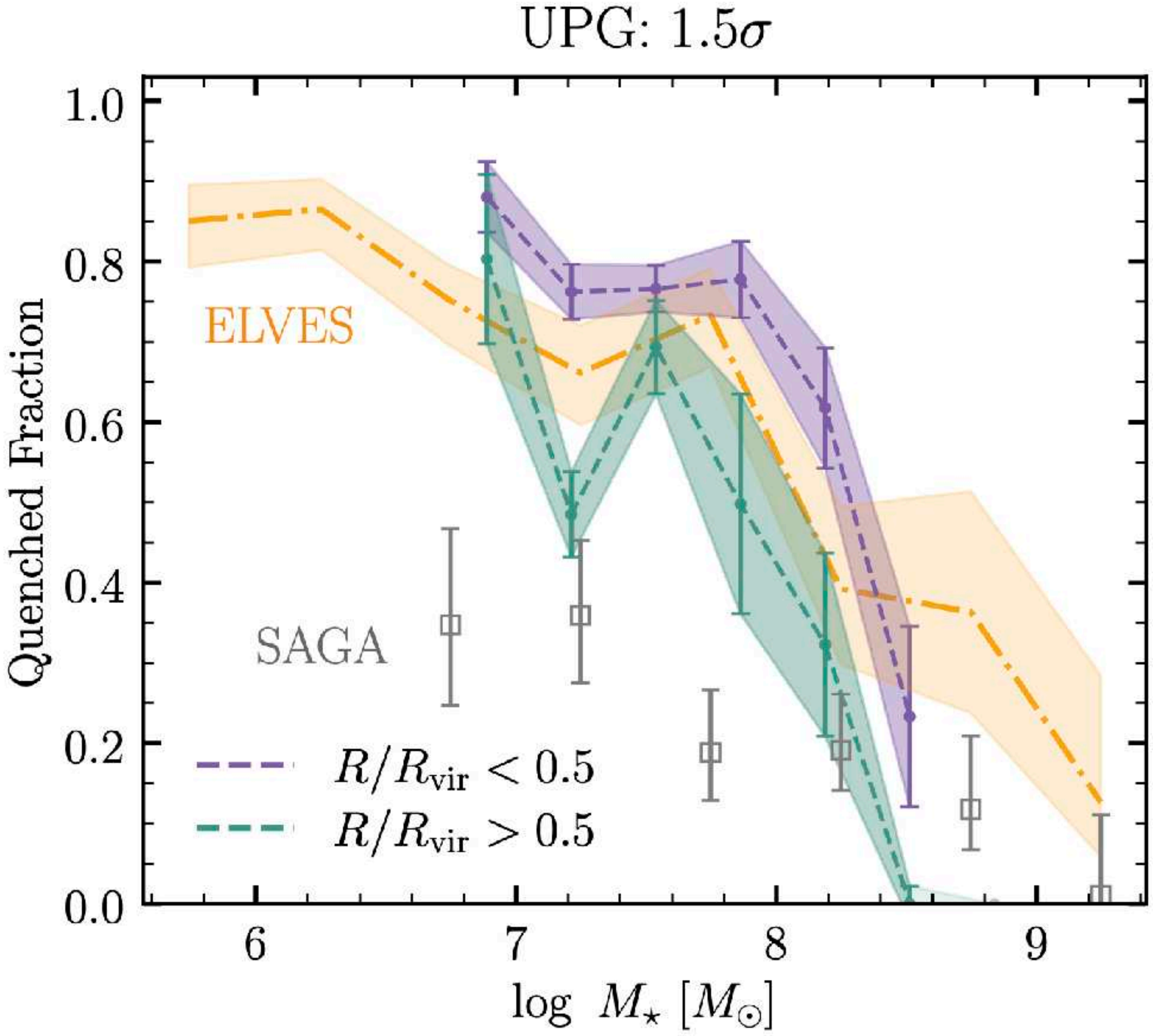

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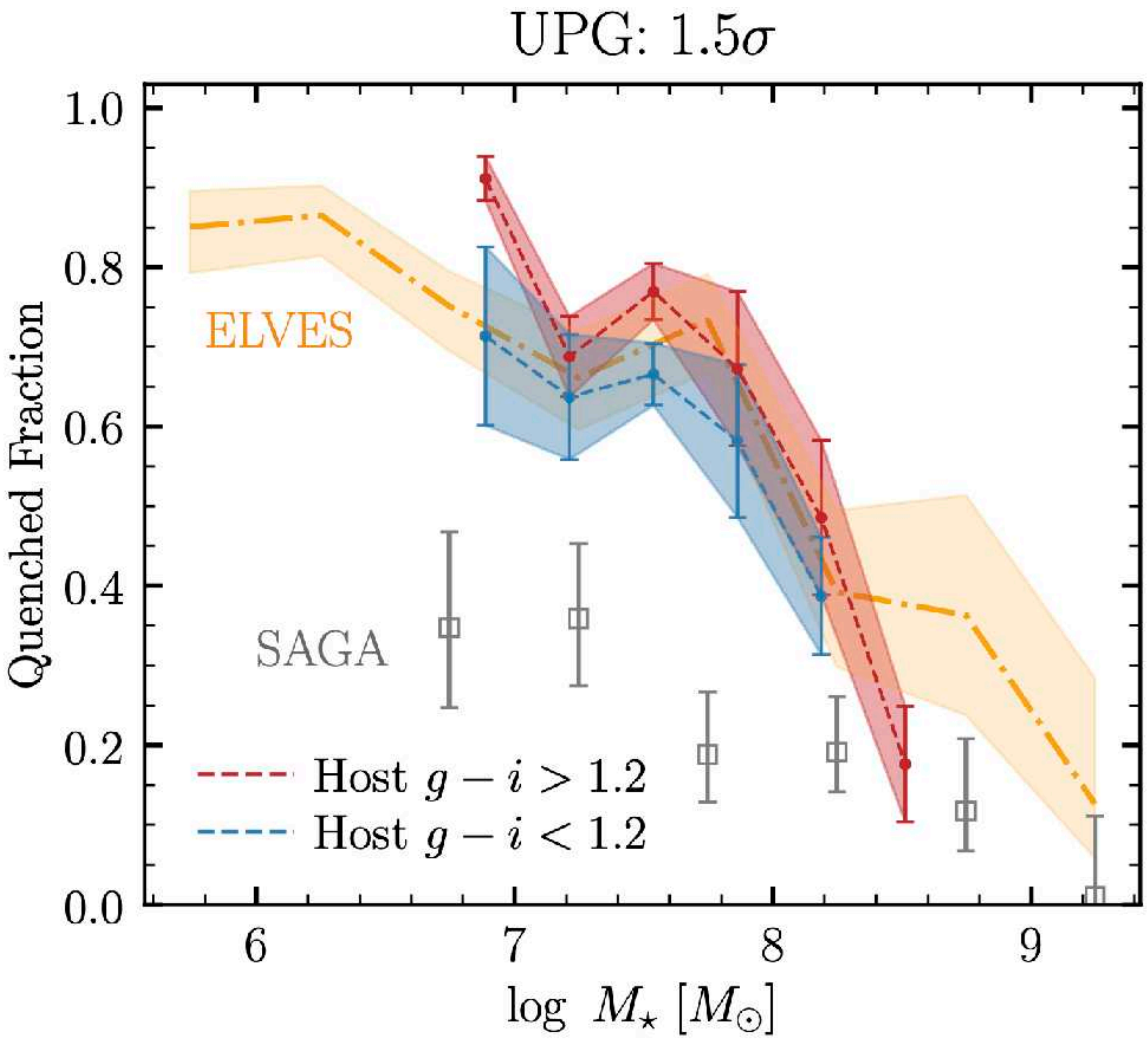

UPGs closer to the host are more quenched

UPGs with red hosts are more quenched (galaxy conformity)

Group UPG origins

Puffed-up during infall	50%
Accreted as field UPG	50%
	Jiang+18

Quench a dwarf

- Bursty stellar feedback (El-Badry+18)
- Ram-pressure stripping by the CGM (e.g., Simpson+18)
- Tidal stripping (e.g., Simpson+18)
- Strangulation (e.g., Fillingham+18)

Puff up a dwarf

Internal

- Bursty stellar feedback (Di Cinto+17)
- High-spin halo (Amorisco+16, Rong+17)

External

- Tidal heating (Jiang+19)
- Merger (Wright+21)

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Accreted as field UPG

Quench a dwarf

Bursty stellar feedback (El-Badry+18)

Ram-pressure stripping by the CGM (e.g., Simpson+18)

Tidal stripping (e.g., Simpson+18)

Strangulation (e.g., Fillingham+18)

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→ More quenched than normal satellites 😢

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→ More similar to normal satellites 🙂

UPGs' Origin:

Accreted as field UPGs

Puffed-up by:

Bursty stellar feedback (Di Cinto+17)

High-spin halo (Amorisco+16, Rong+17)

Merger (Wright+21)

Quenched by:

Ram-pressure stripping by the CGM

How to better understand puffy dwarfs?

Simulations

Studying the SFH of UPGs in high-res zoom-in simulations

(w/ Alyson Brooks, Anna Wright)

Distances

How to measure the distances to UPGs in a cheap way?

Surface Brightness Fluctuation

Surface Brightness Fluctuation

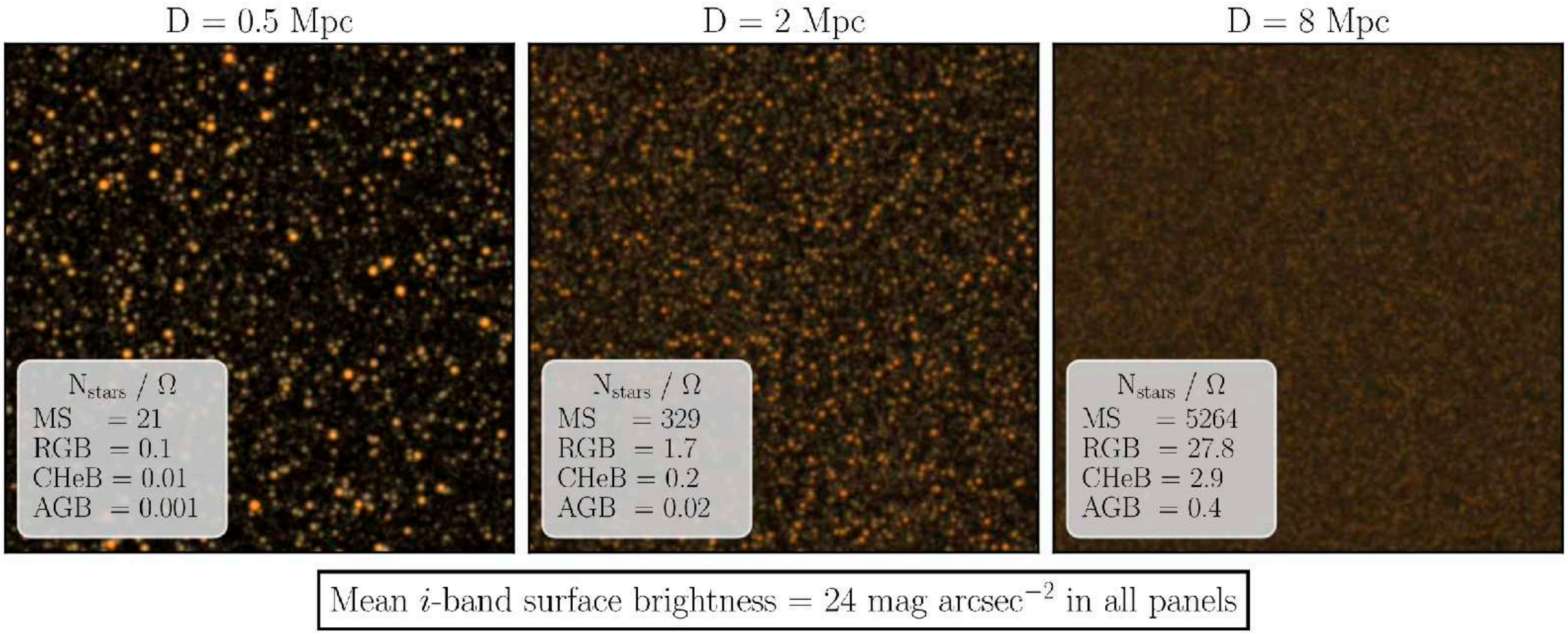
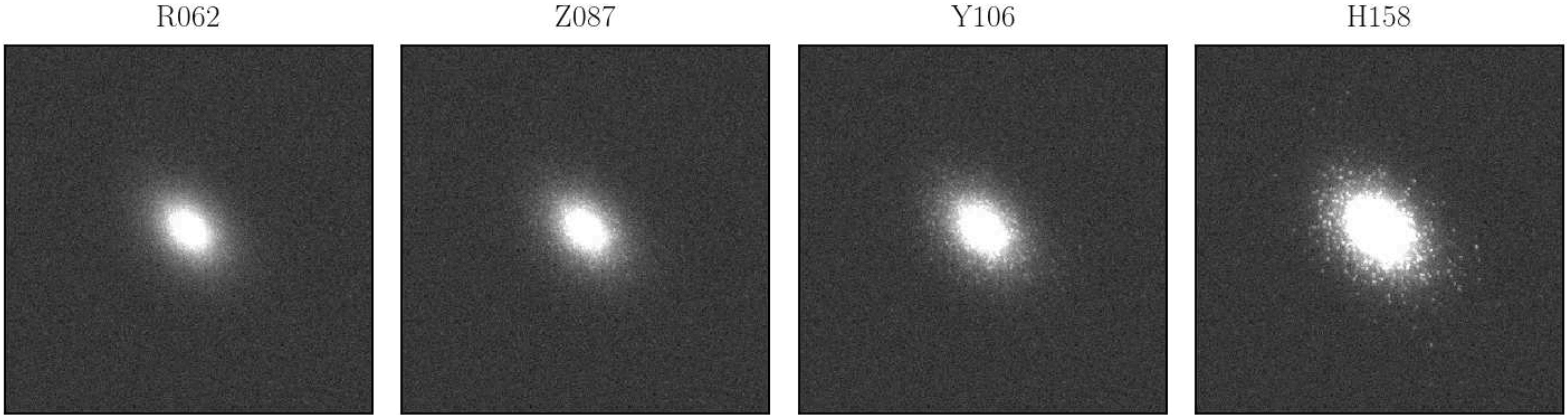


Figure 1. Illustration of the decreasing amplitude of SBFs as a function of distance, at fixed surface brightness. Each panel shows a *gri*-composite image of a simple stellar population of age 3 Gyr, metallicity [Fe/H] = −1.5, and mean *i*-band surface brightness 24 mag arcsec^{-2}. The simulations assume a ground-based observatory with $0\farcs6$ seeing and a pixel scale of $0\farcs2$ pixel^{-1}. The text box in each panel lists the number of stars per resolution element (Ω) for stars on the main sequence (MS), red giant branch (RGB), core helium-burning (CHeB) phase, and asymptotic giant branch (AGB). The images are 500 pixels on a side.

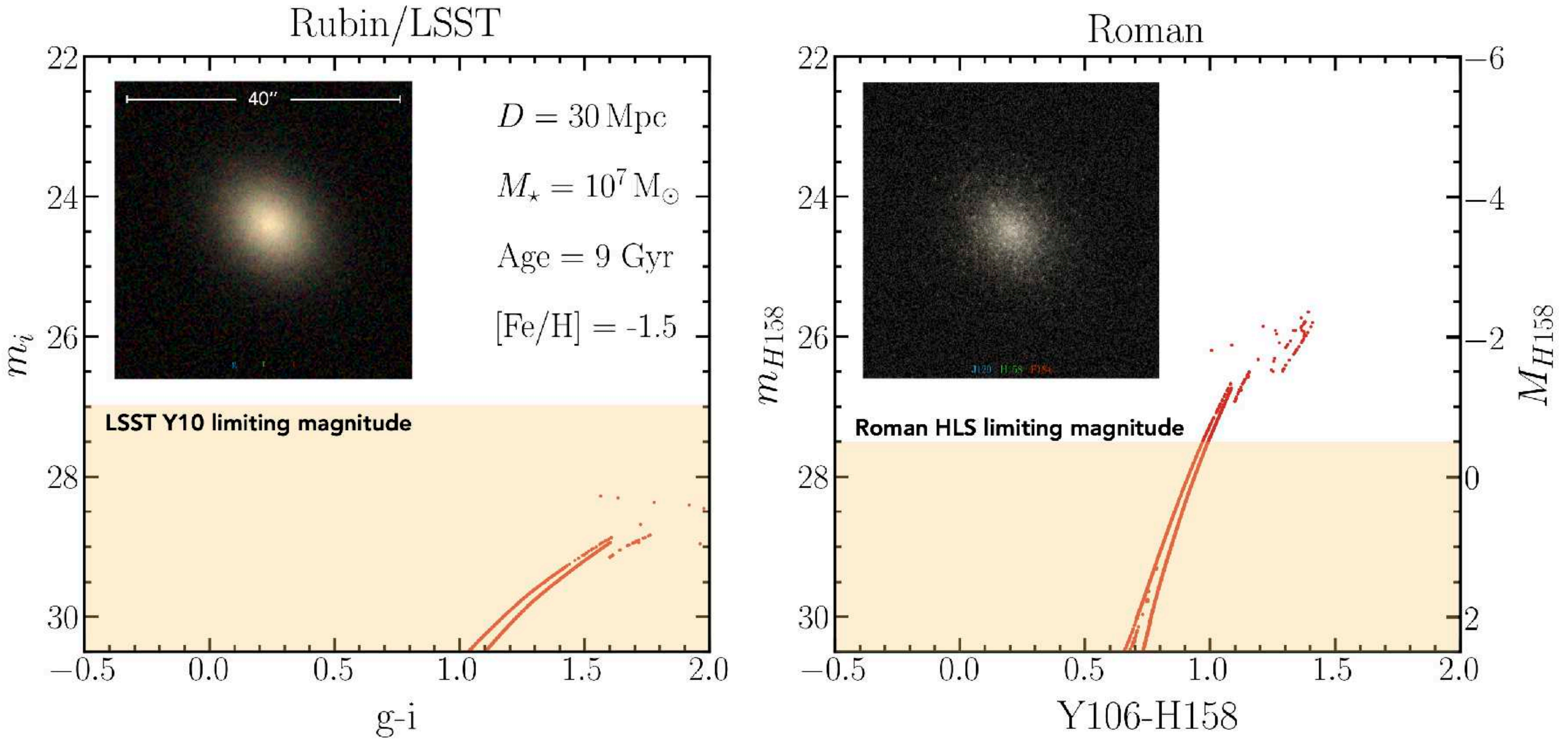
Greco+21

SBF in NIR is much brighter!



Simulated Roman image of a dwarf galaxy at 50 Mpc

SBF in NIR is much brighter!



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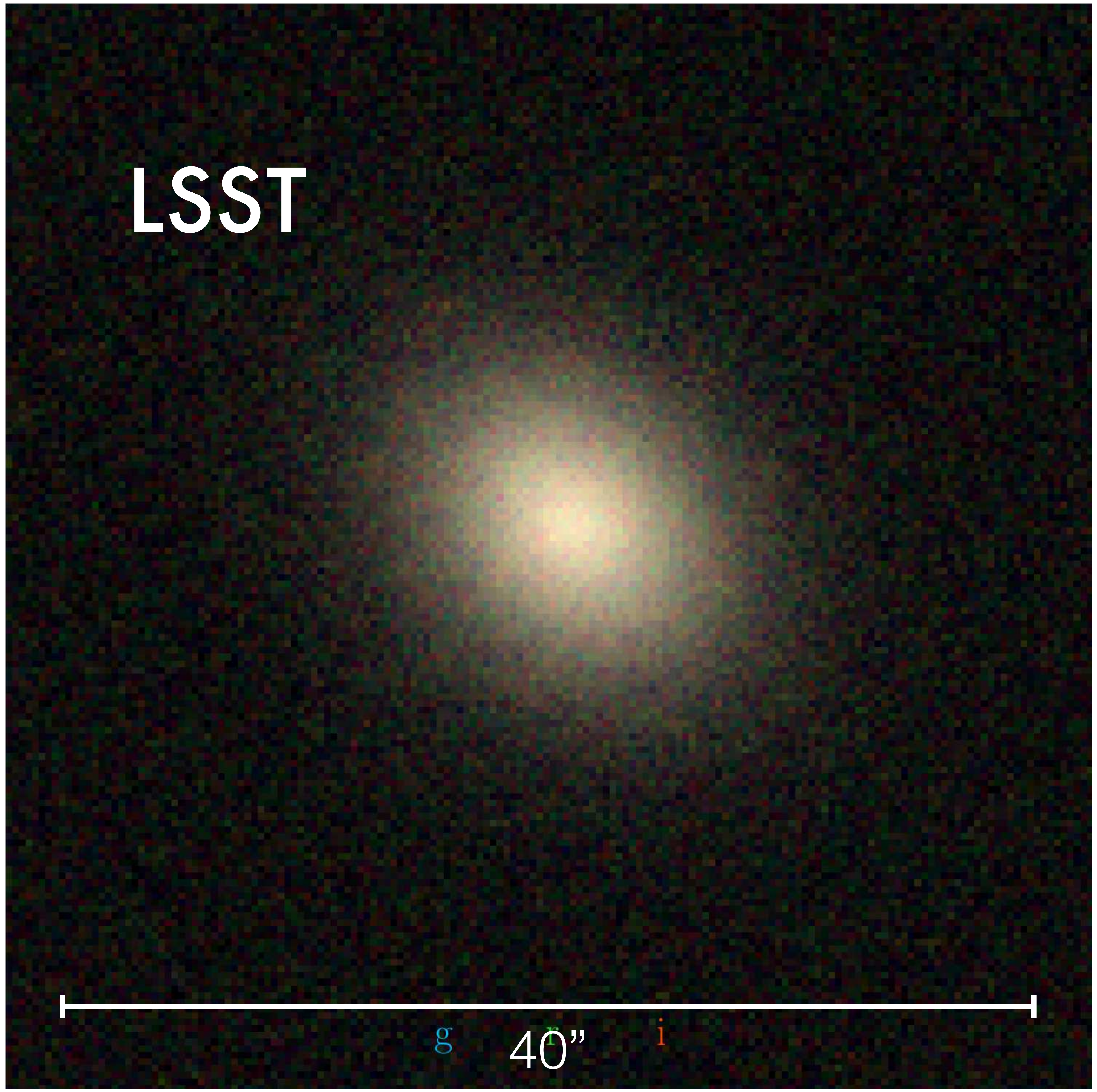
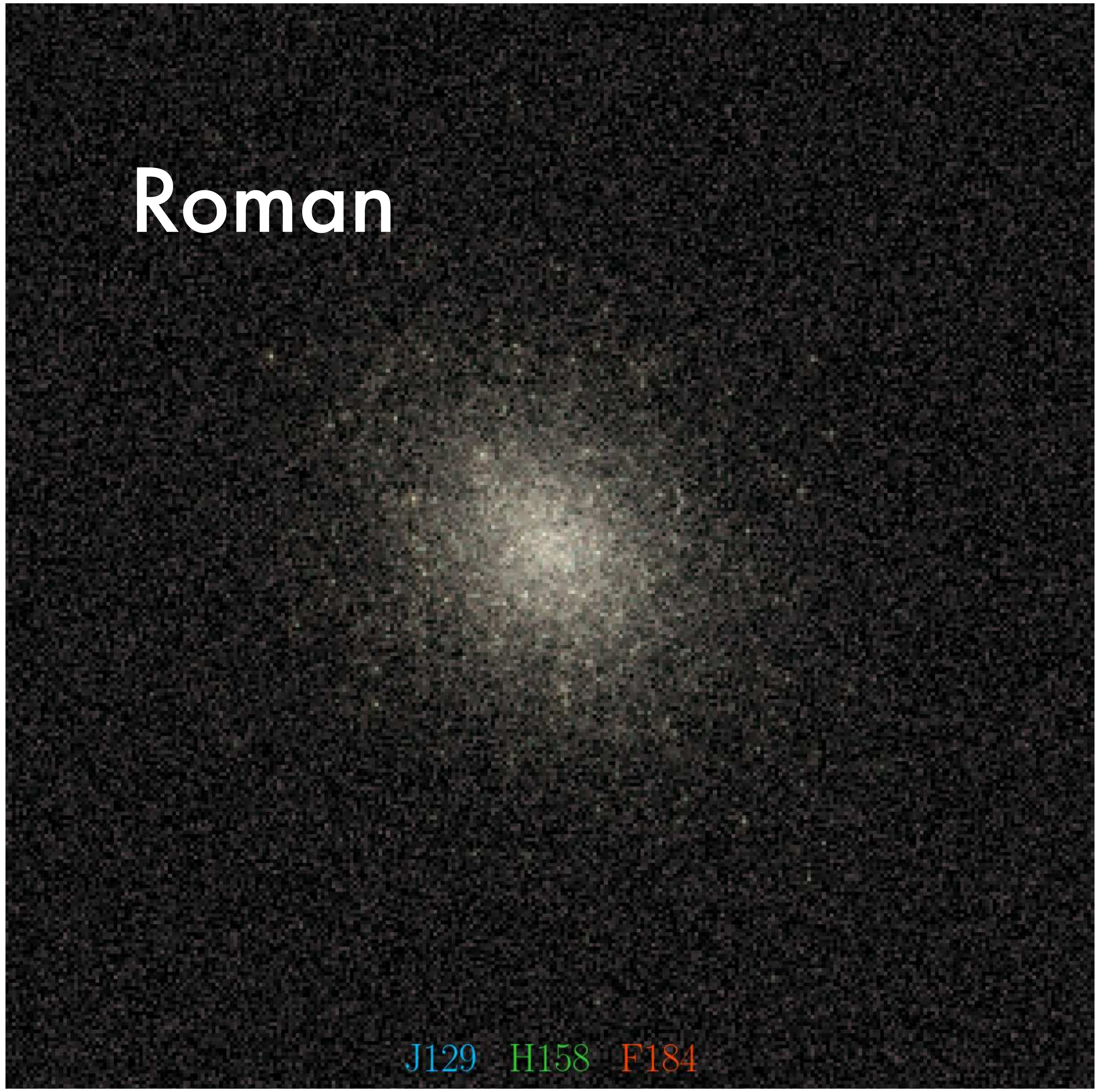
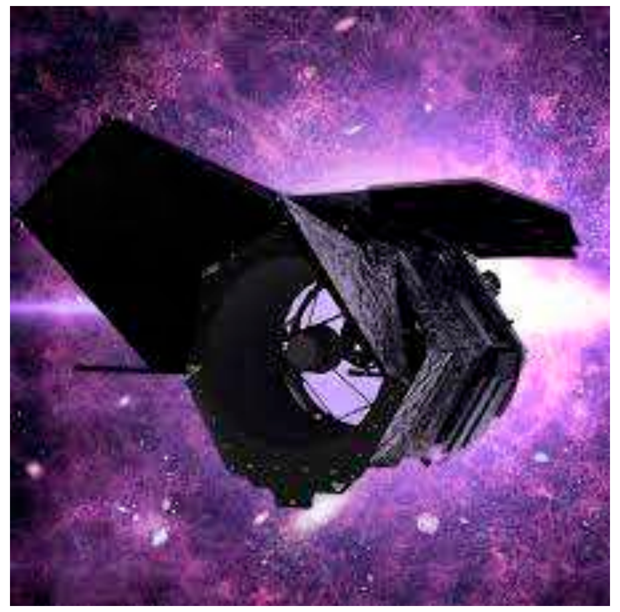
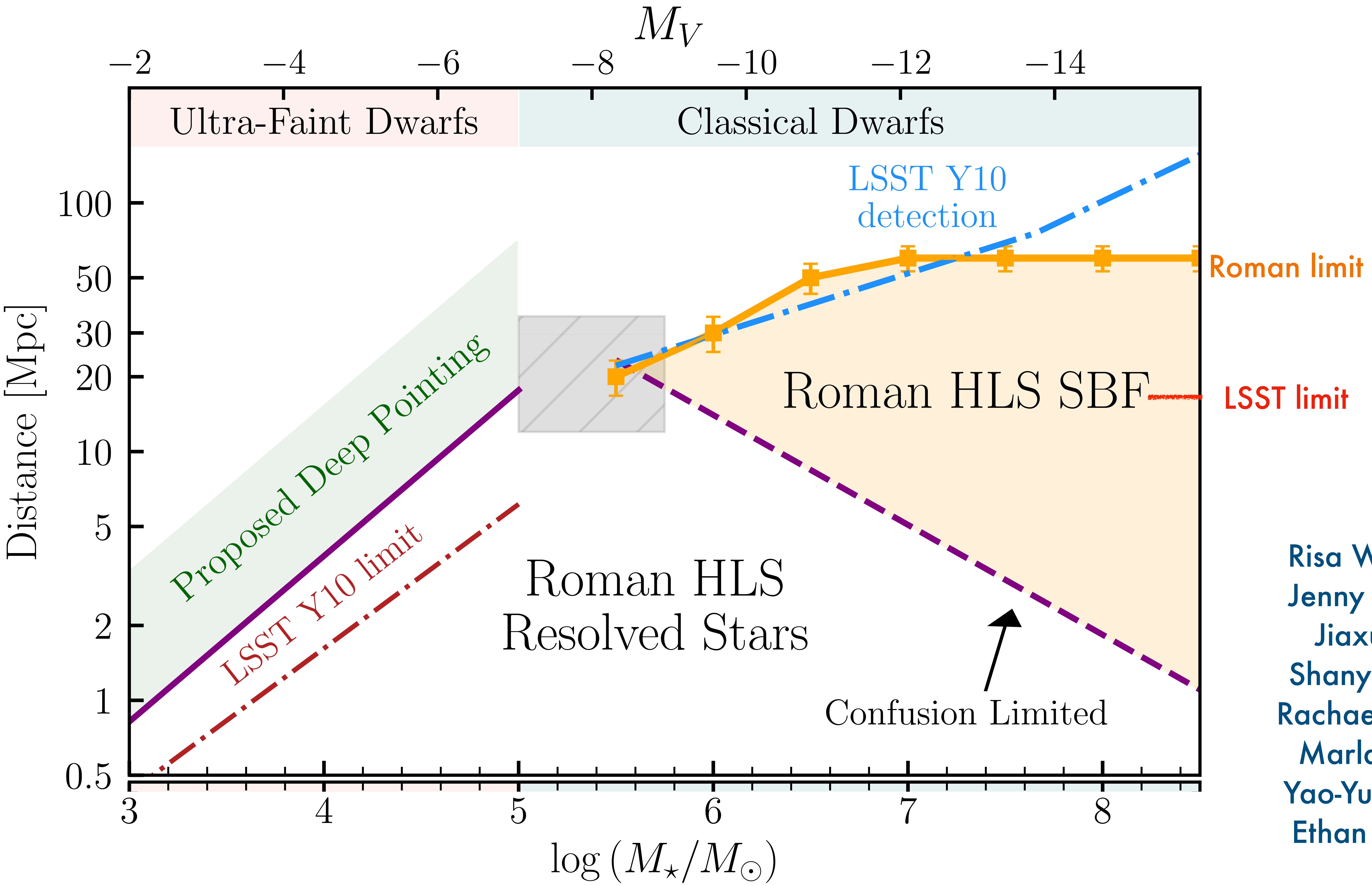




An old stellar population at 30 Mpc

Roman as a dwarf galaxy machine





Risa Wechsler
Jenny Greene
Jiaxuan Li
Shany Danieli
Rachael Beaton
Marla Geha
Yao-Yuan Mao
Ethan Nadler

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Star formation

How to better understand the star formation of dwarfs?

The Merian survey

The Merian Survey

Mapping the Population of Classical Dwarf Galaxies at z=0.05-0.1 with an HSC-SSP + Blanco/DECam Survey

Blanco Telescope @ Chile

PIs: Jenny Greene and Alexie Leauthaud

Co-Is:

Yifei Luo
Song Huang
Erin Kado-Fong
Shany Danieli
Jiaxuan Li
Alyson Brooks
Annika Peter
Ting Li
Vivienne Baldassare

Jim Gunn
Robert Lupton
Lee Kelvin
Zheng Cai
X. Prochaska
Arka Banerjee
Sean Johnson
Diana Blanco
Erik Wasleske
Joseph Wick

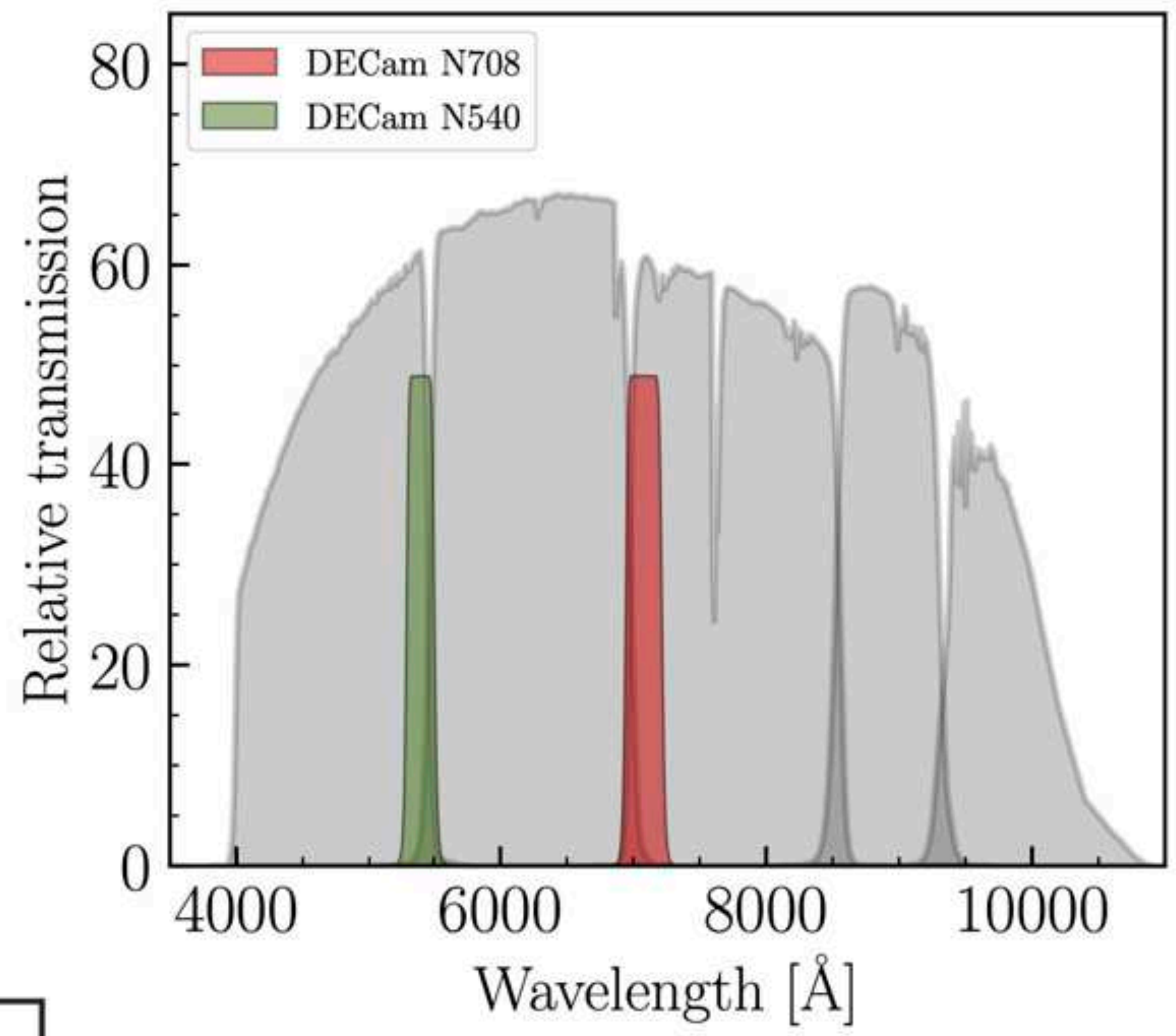
The Merian Survey

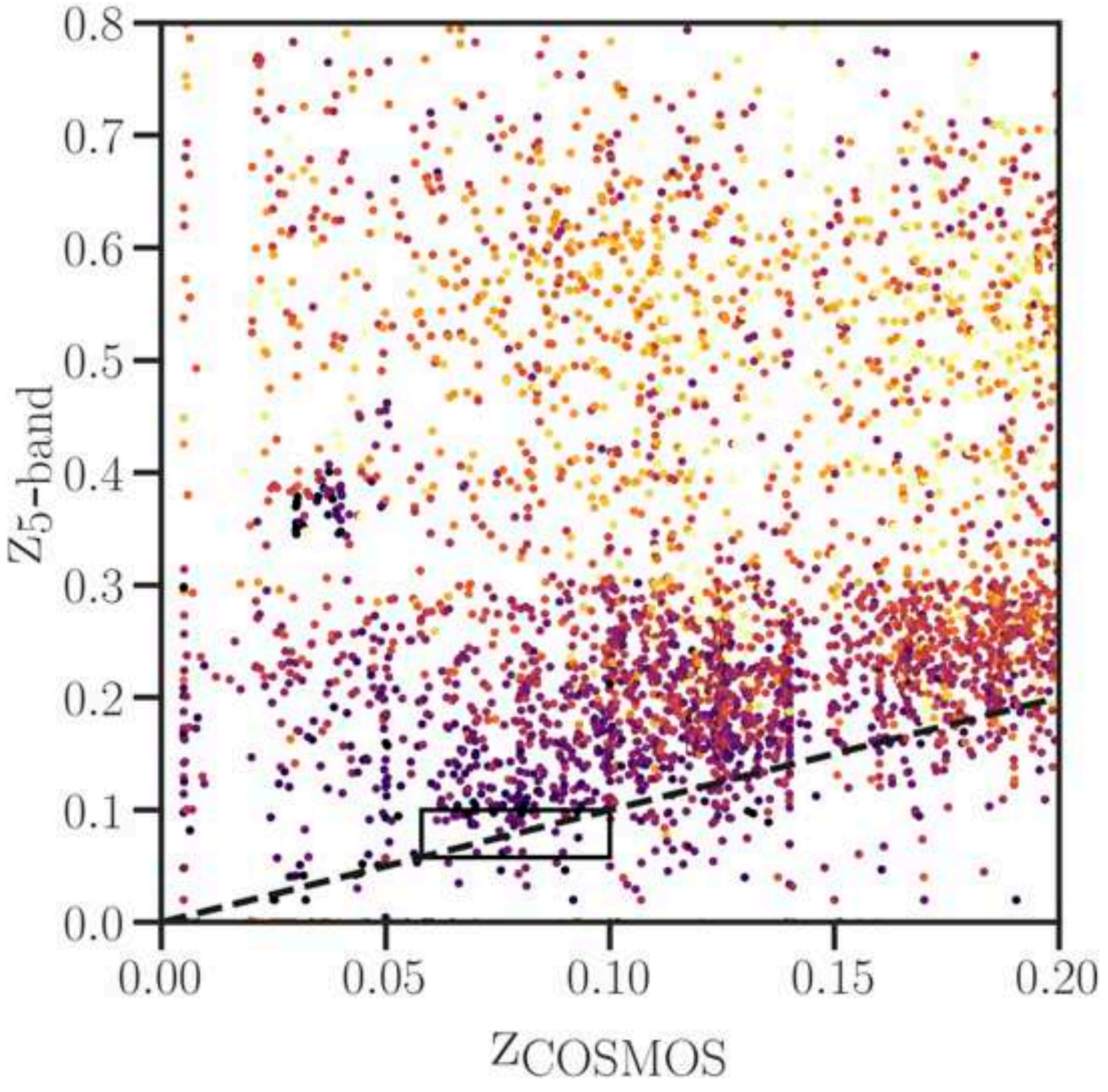
Targeting star-forming dwarfs at 0.05 < z < 0.10, 8 < logM*< 9

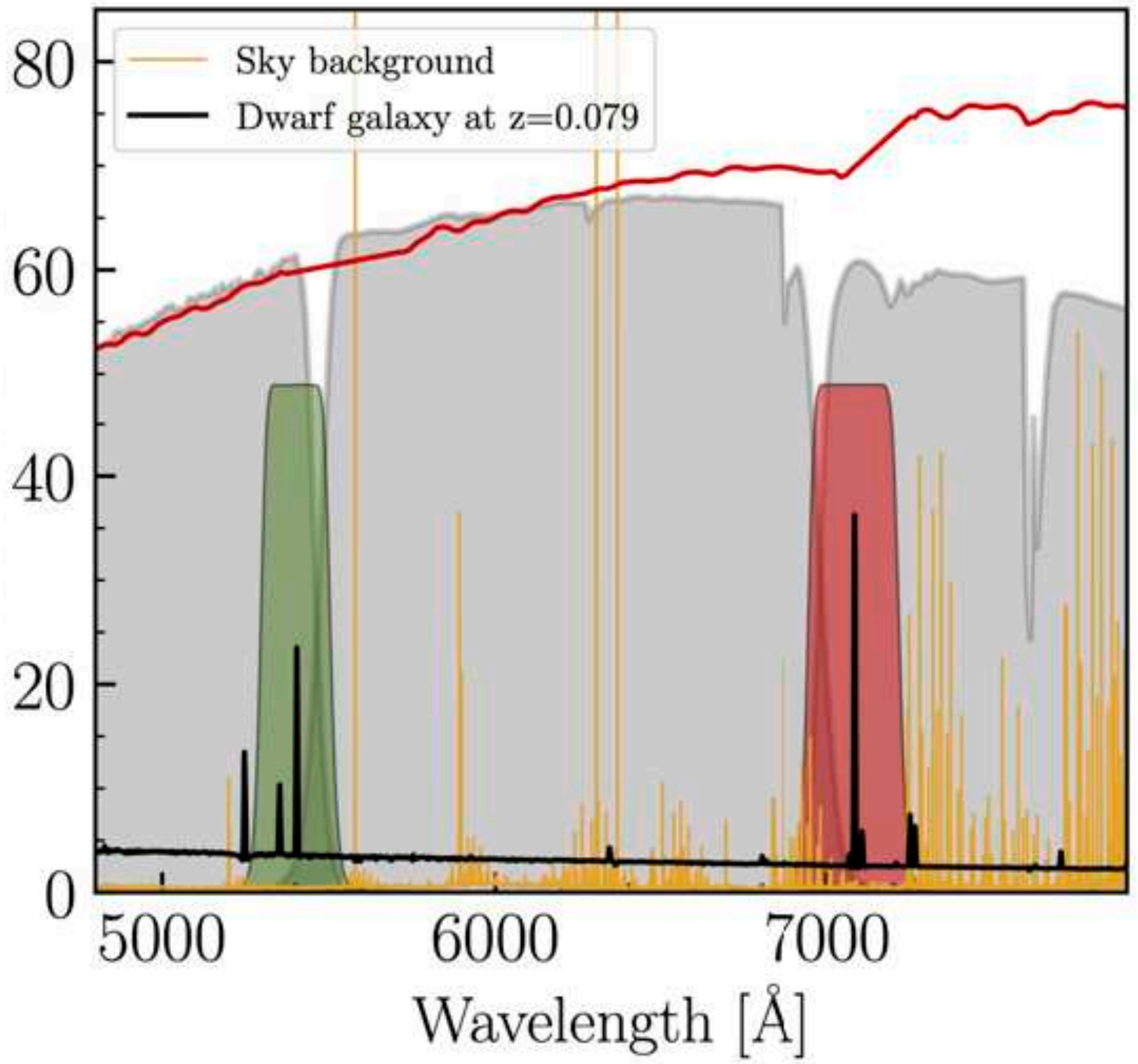
1000 sq. deg high-quality imaging in *grizy*+Ha+[OIII], enables selection based on photo-z and studies of SEDs

Main science goals:

- Weak lensing around dwarfs







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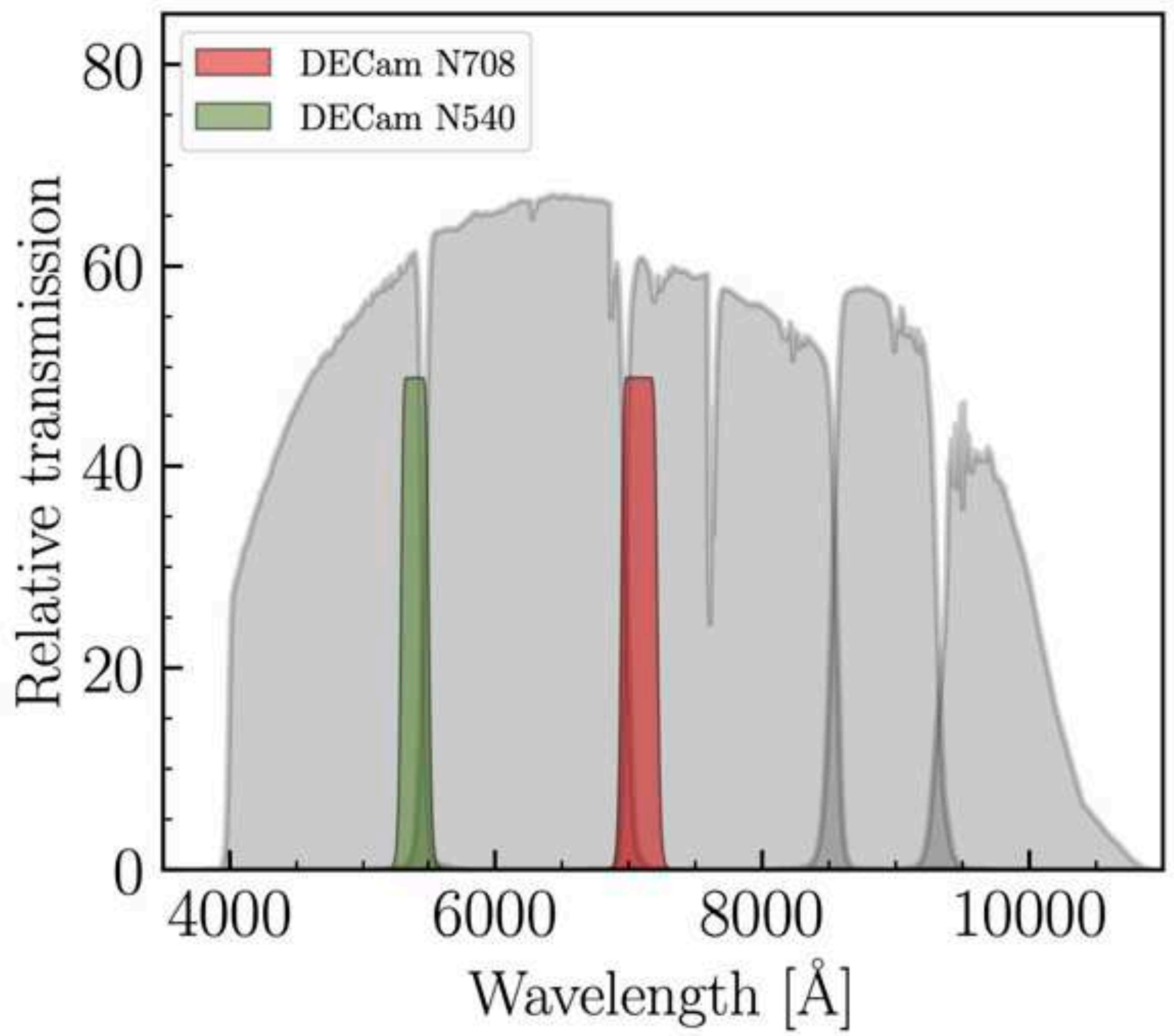
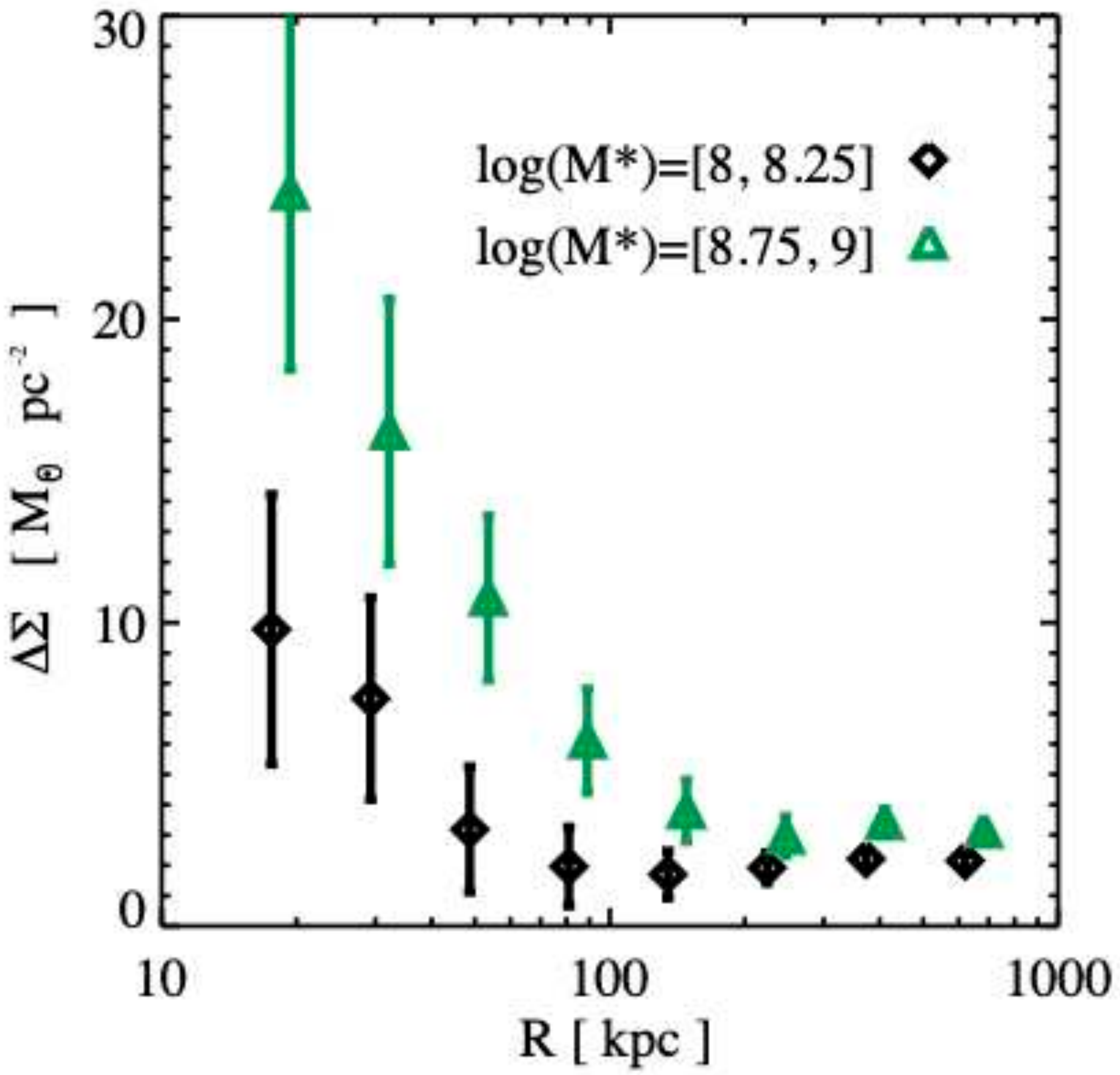
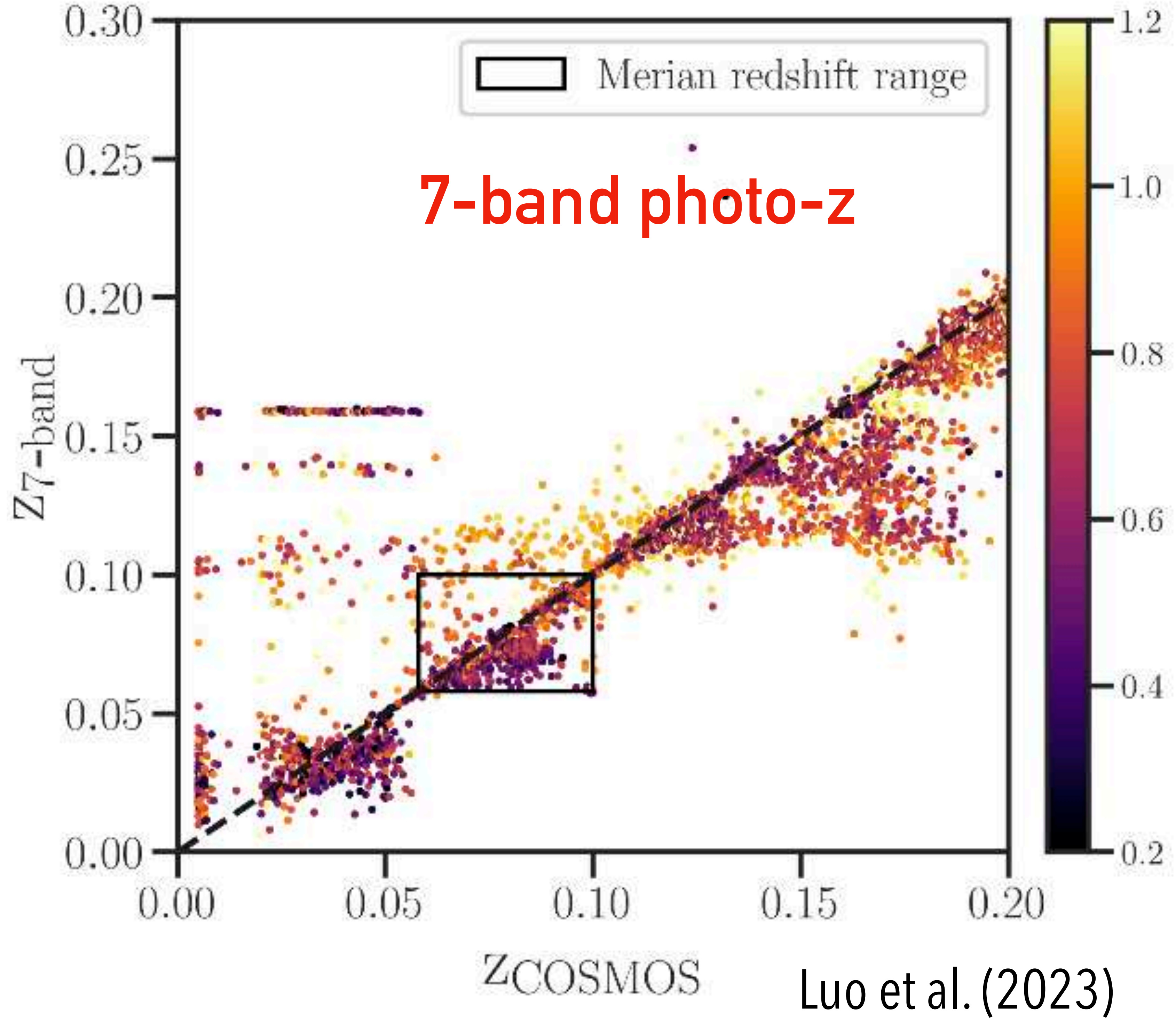
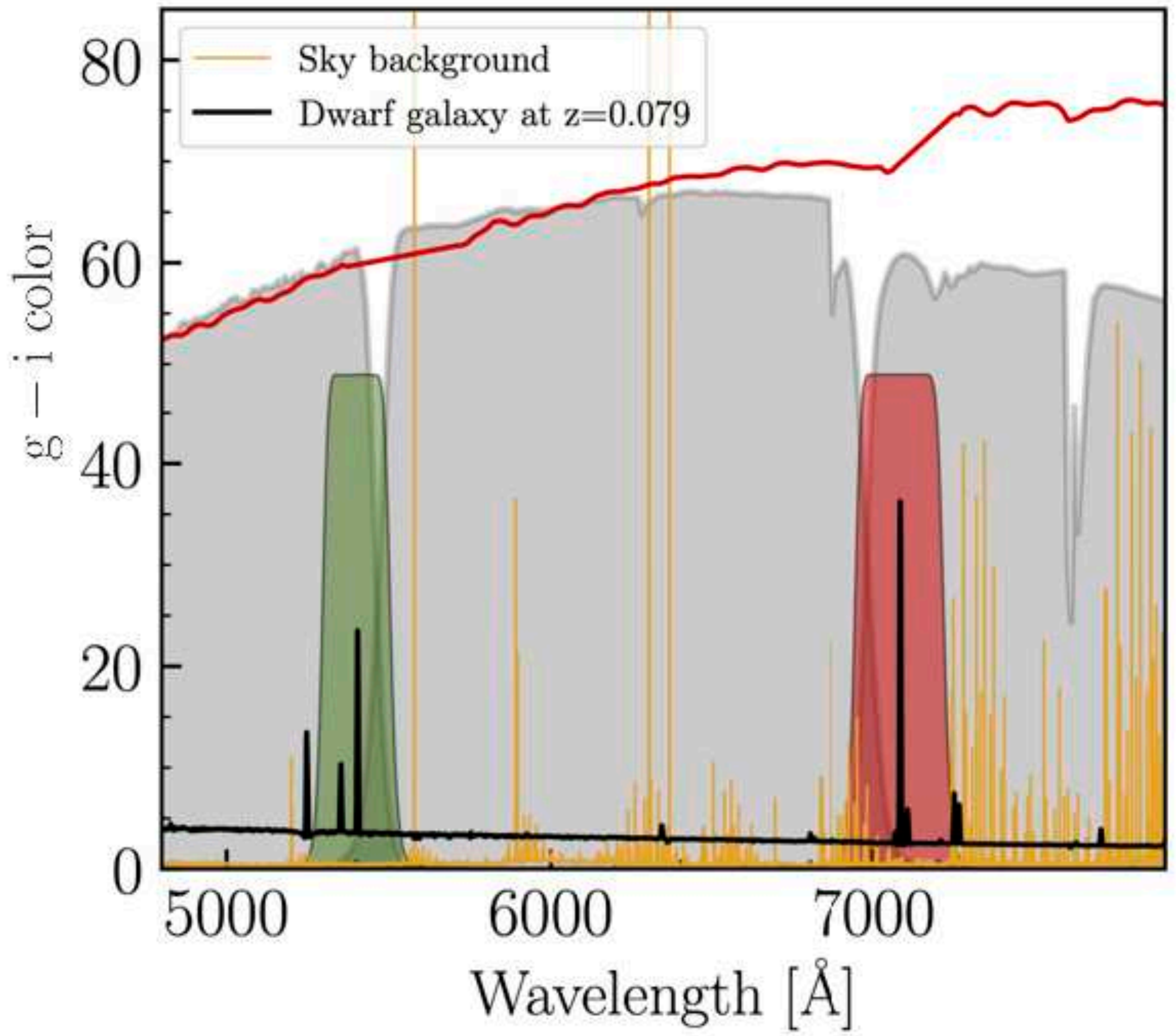


Predicted WL





Luo et al. (2023)



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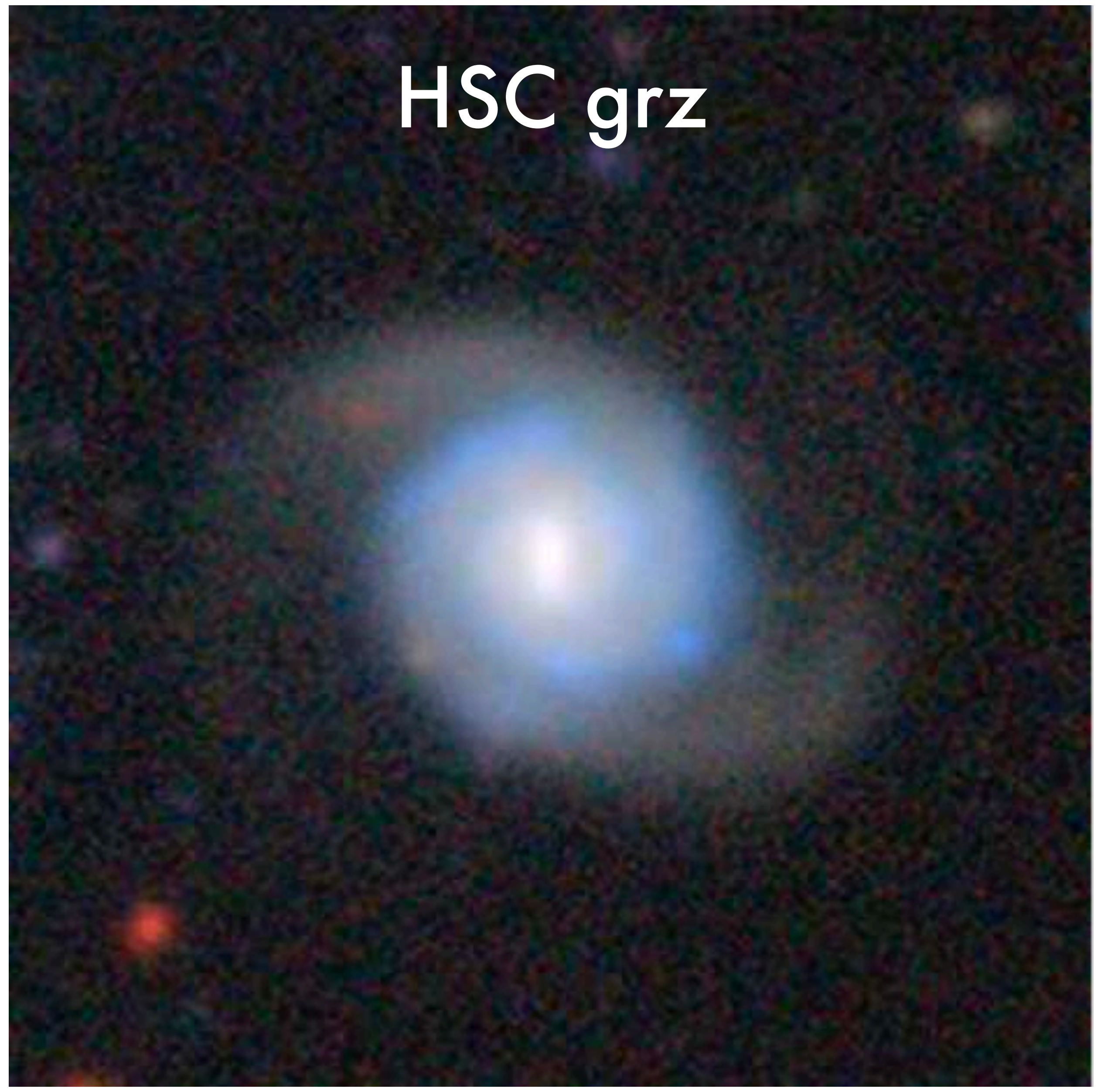
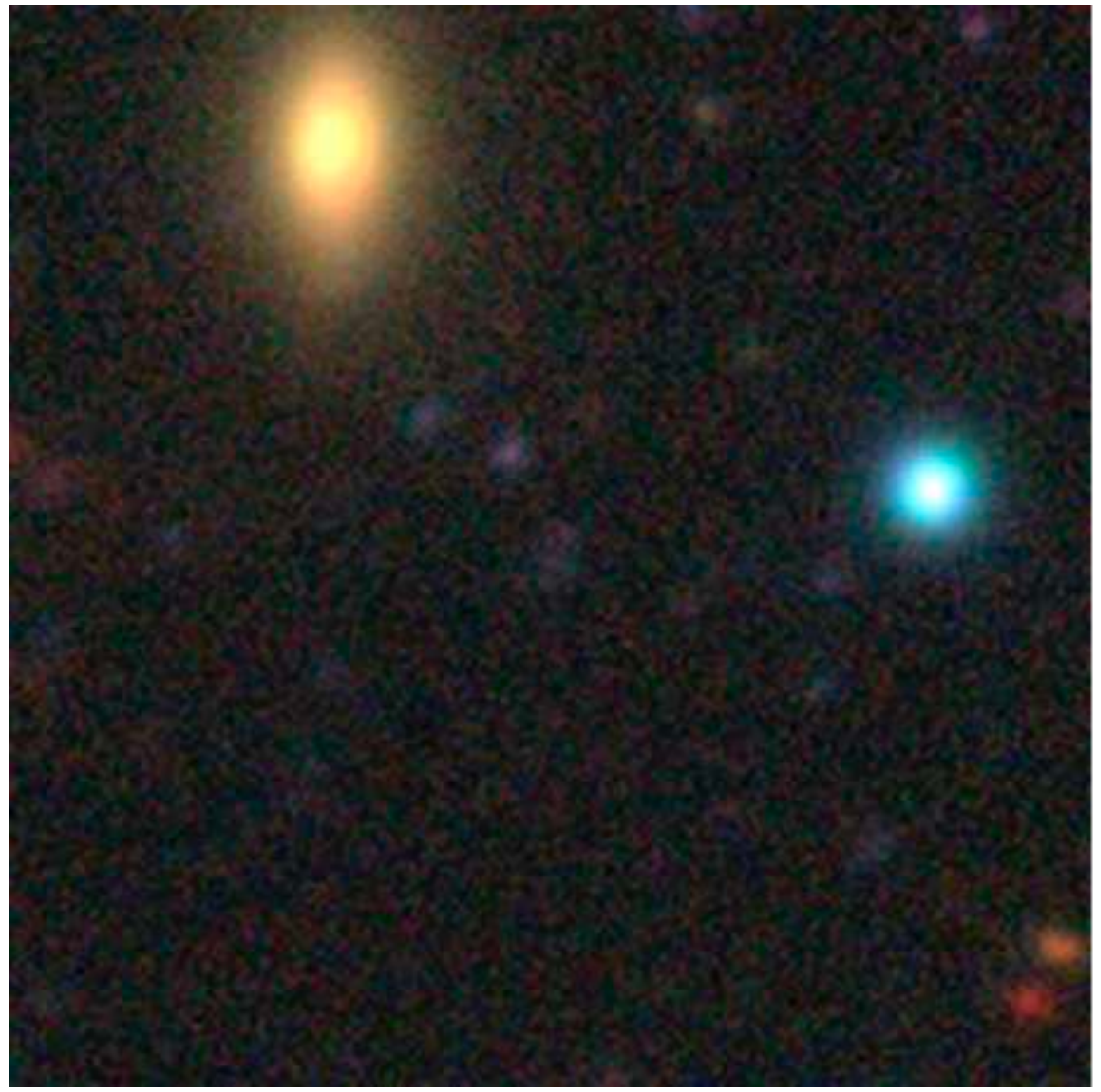
  - H-alpha luminosity function, SFR, SFH from SED fitting





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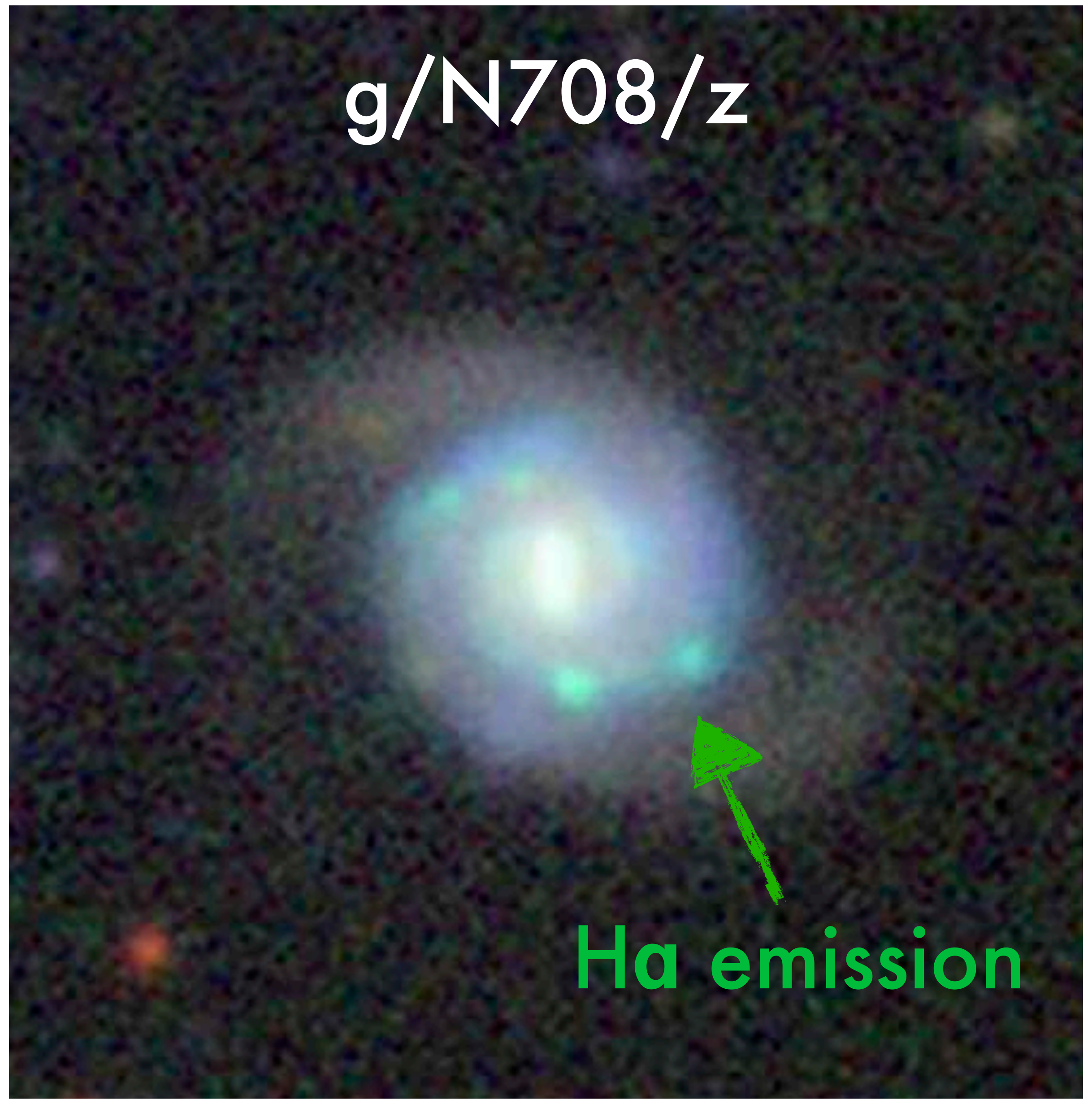

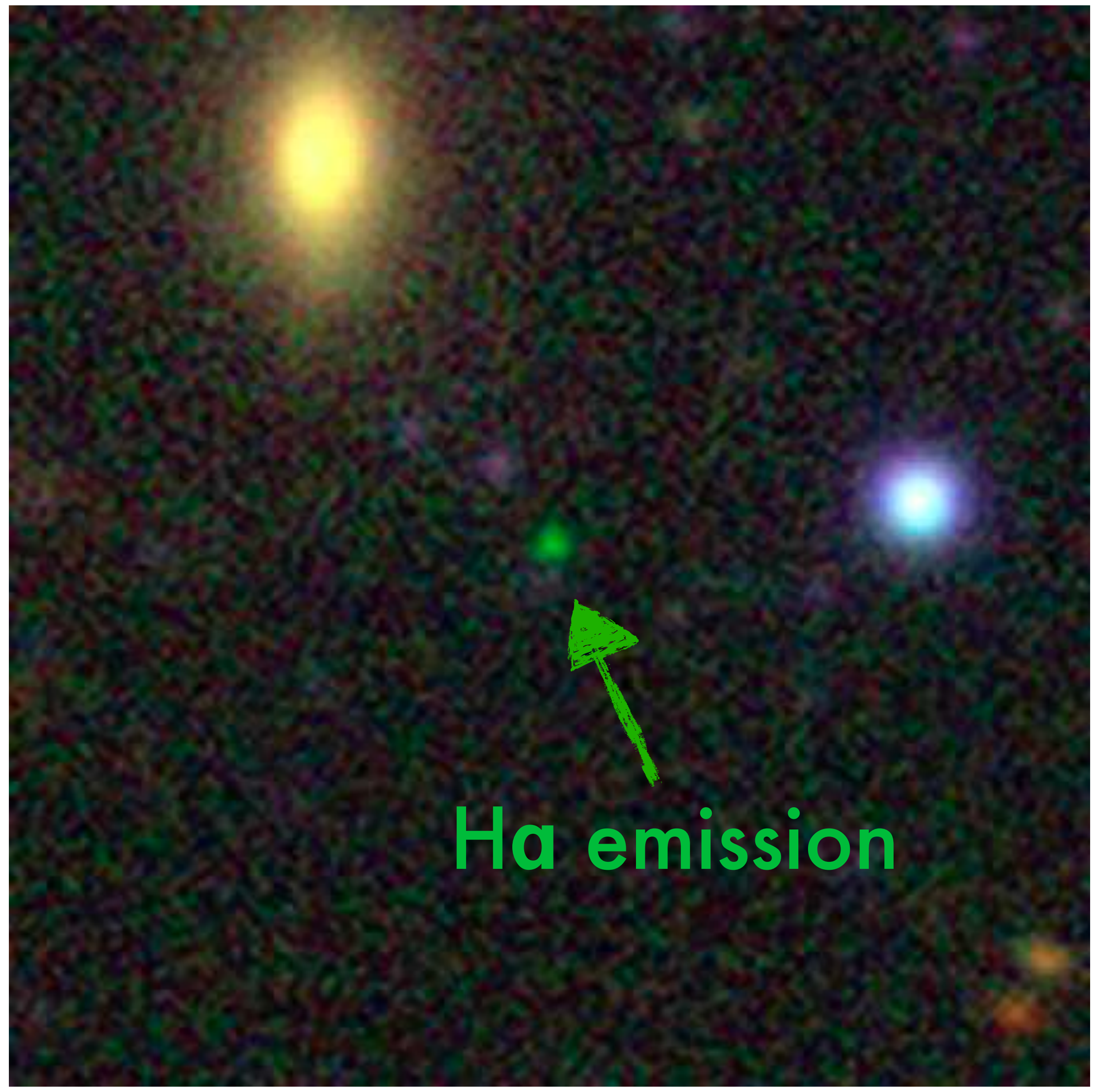

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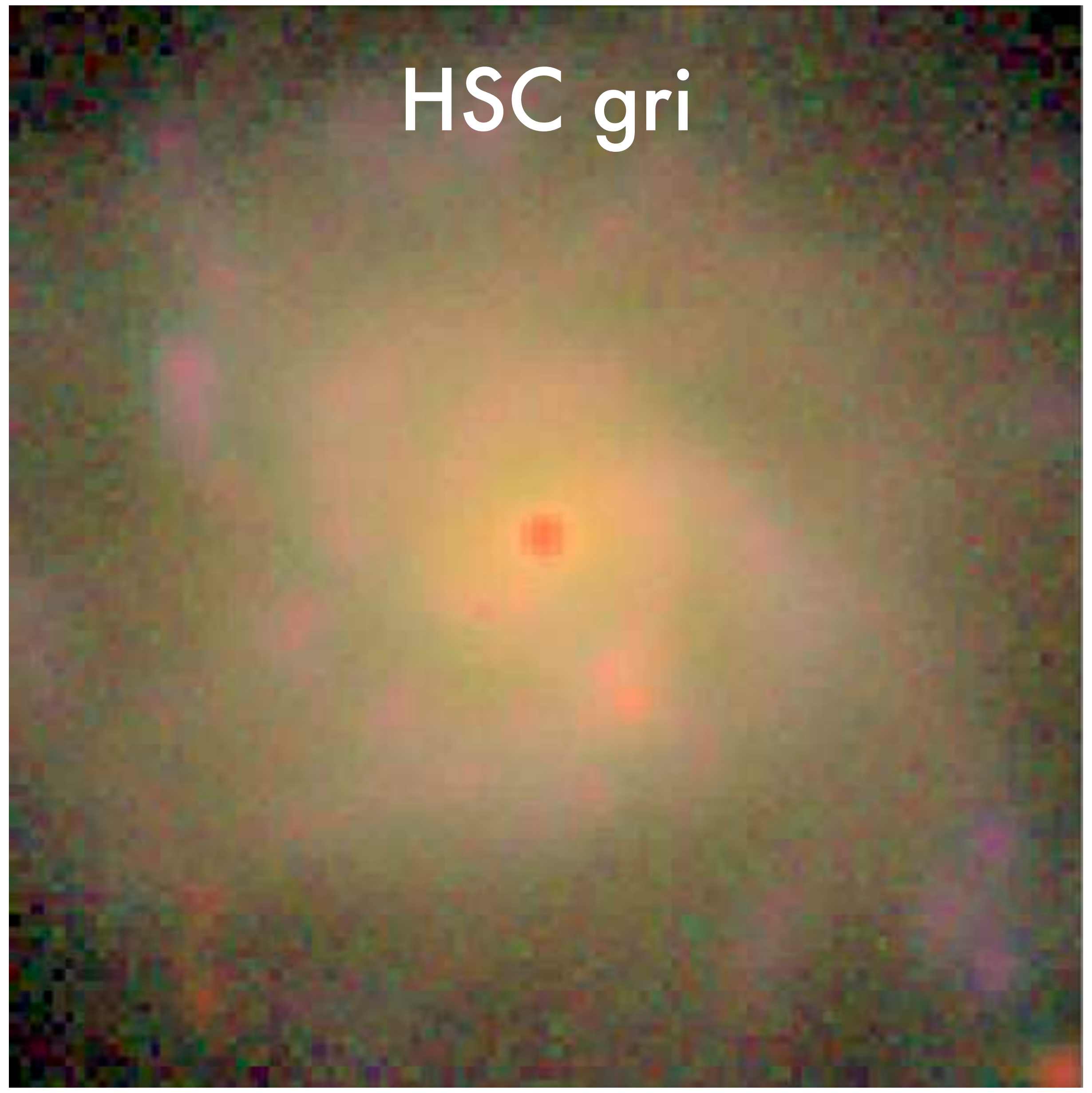
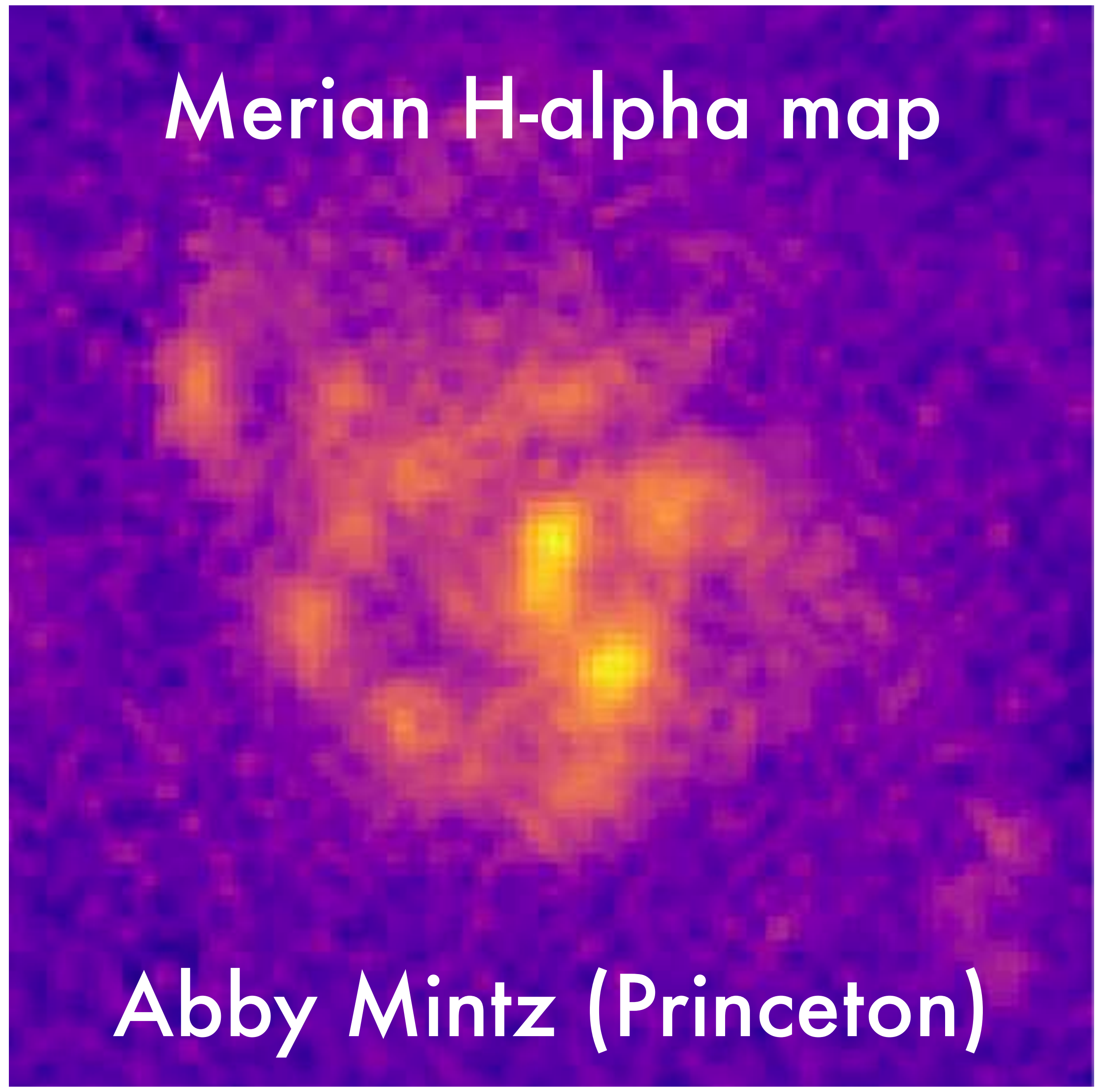
Main science goals:

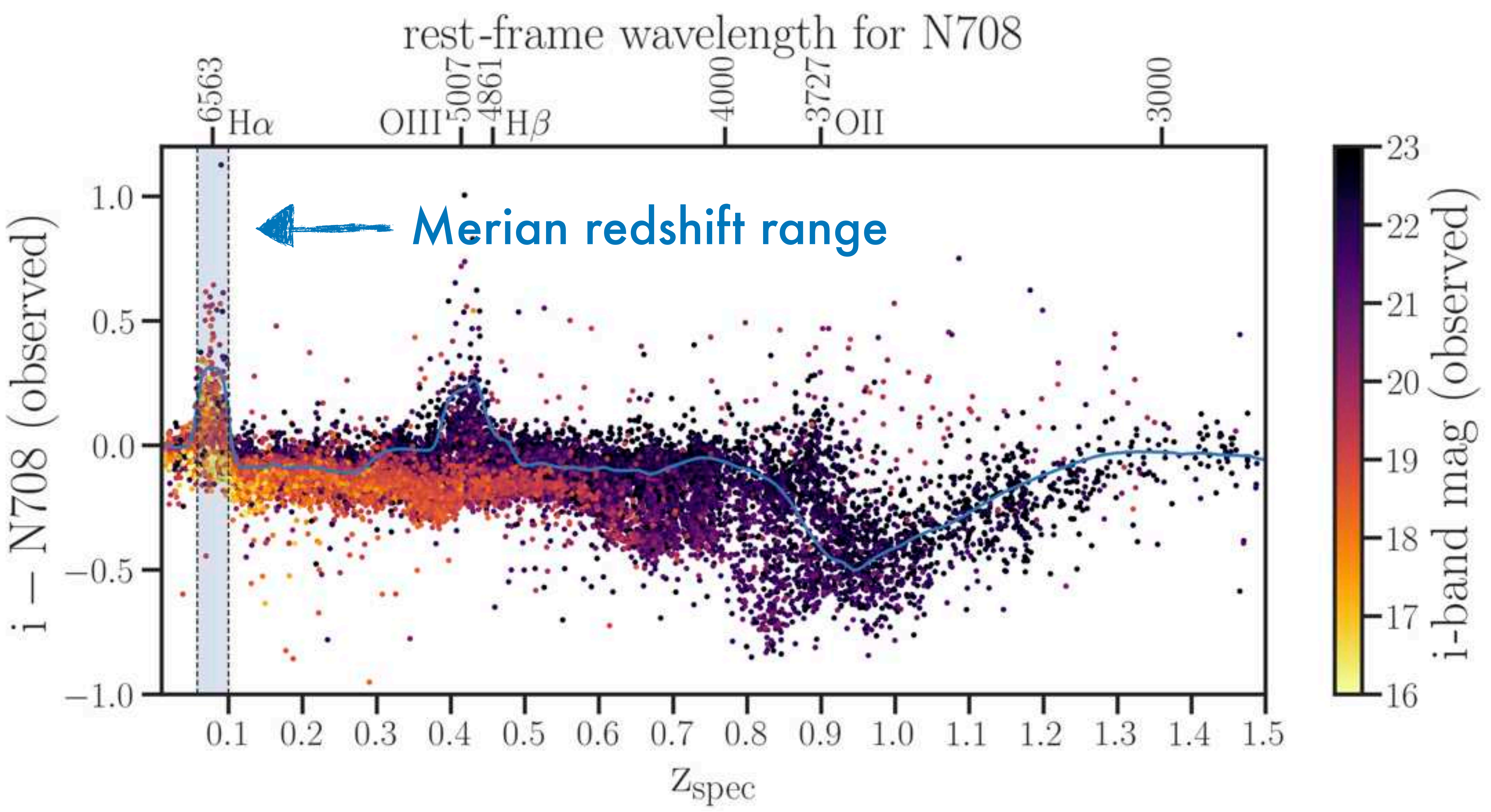
- Weak lensing around dwarfs
- Comprehensive understanding of dwarfs
- Legacy: SF in more massive galaxies, Lyman-alpha emitter, jellyfish galaxy, etc.



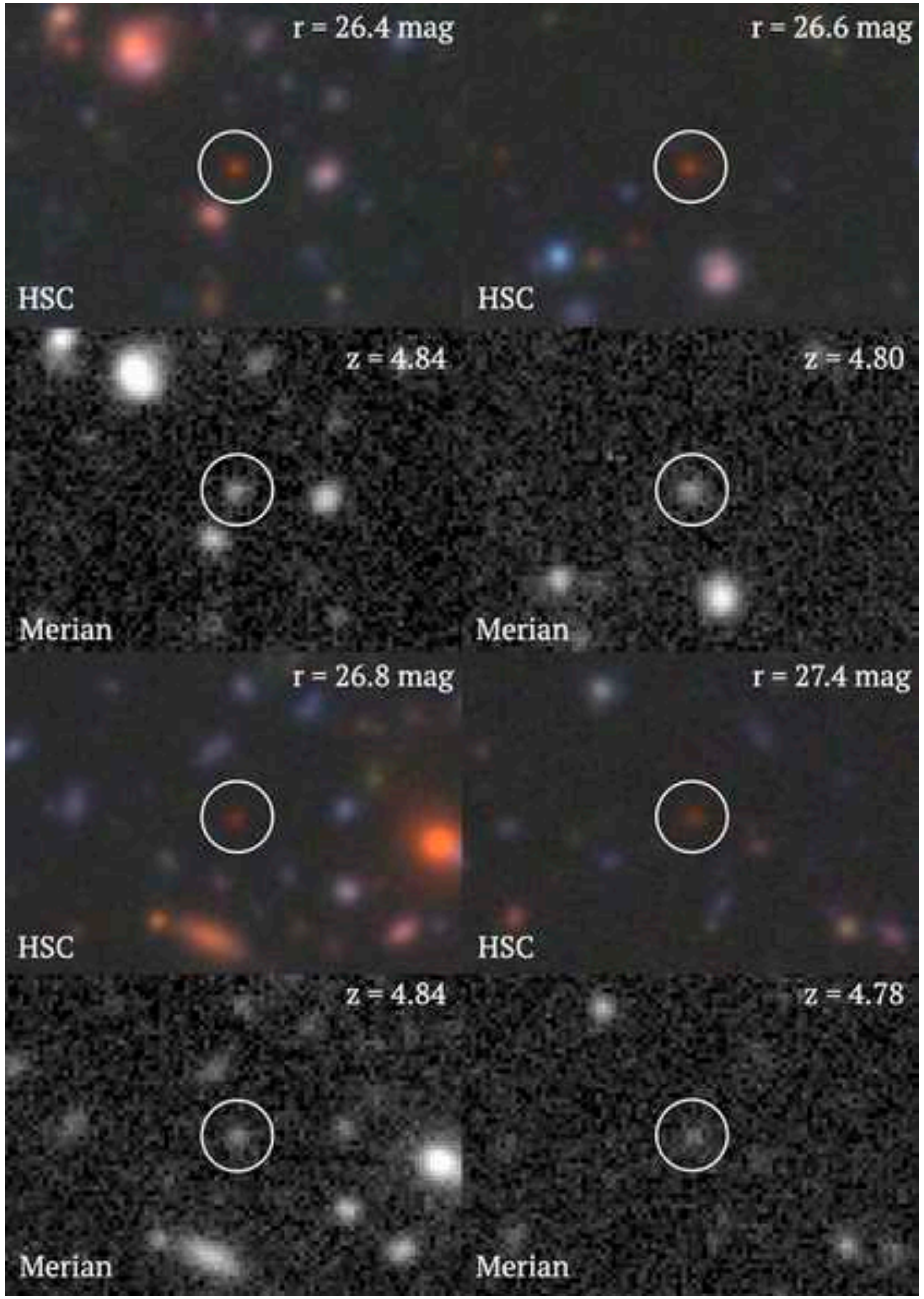


The Merian Survey

Started in 2021, 62 nights on 4-m Blanco telescope. Now >50% completed. DR1 (200 sq. deg) is almost done.



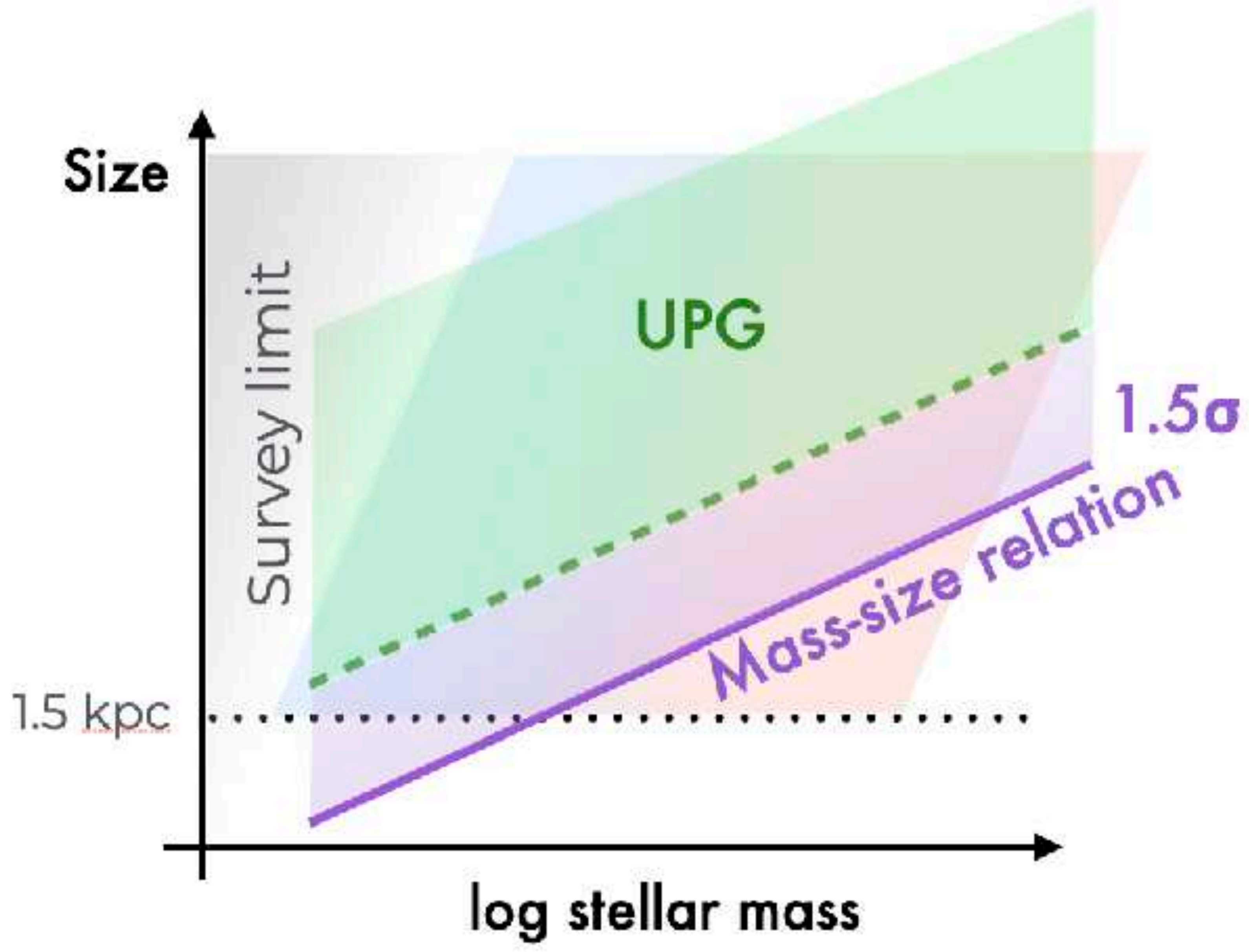
The filters & photometry work as expected!

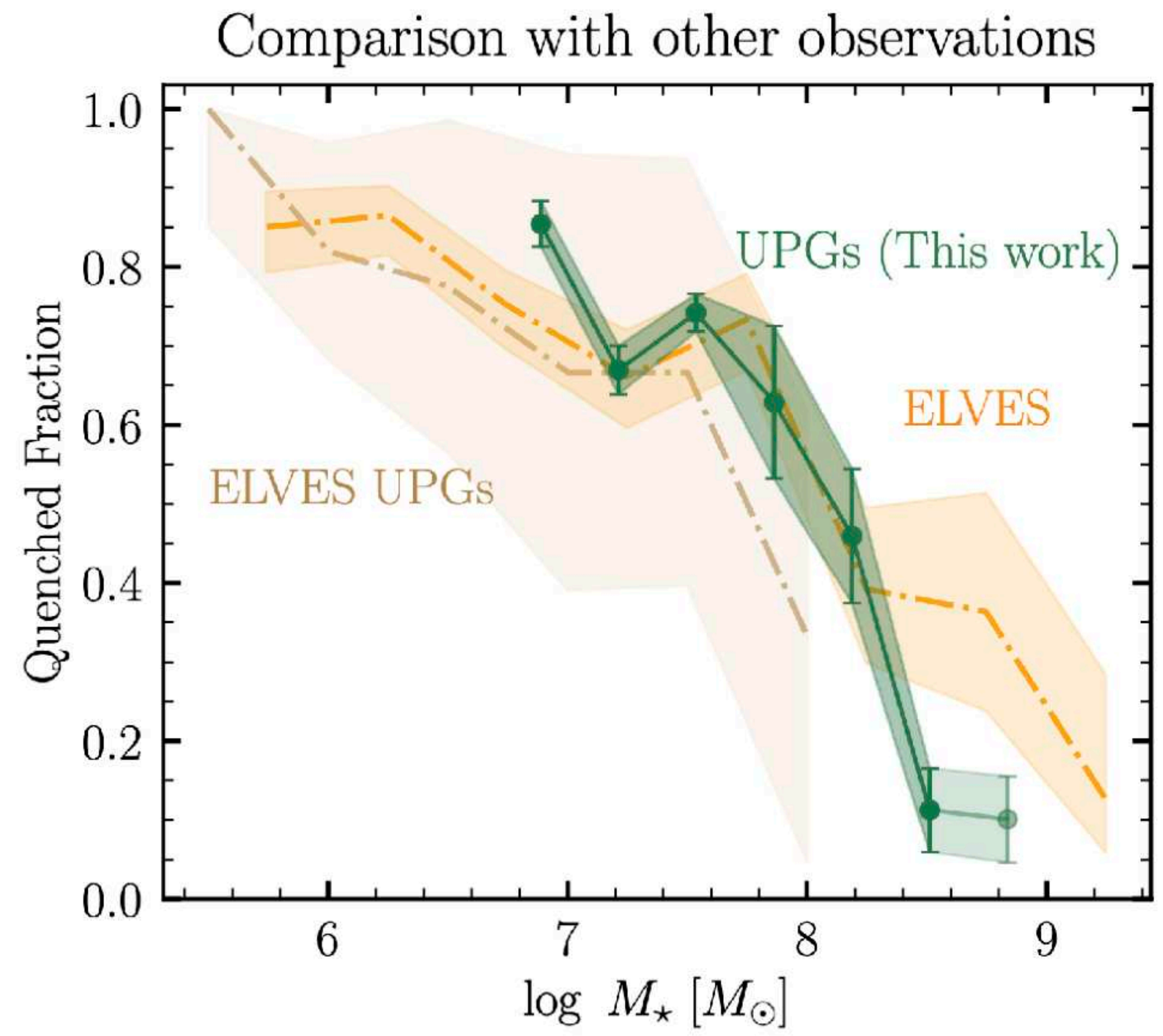


Lyman-alpha Emitters in Merian
(Mingyu Li, Xiaojing Lin, Zheng Cai)

Summary

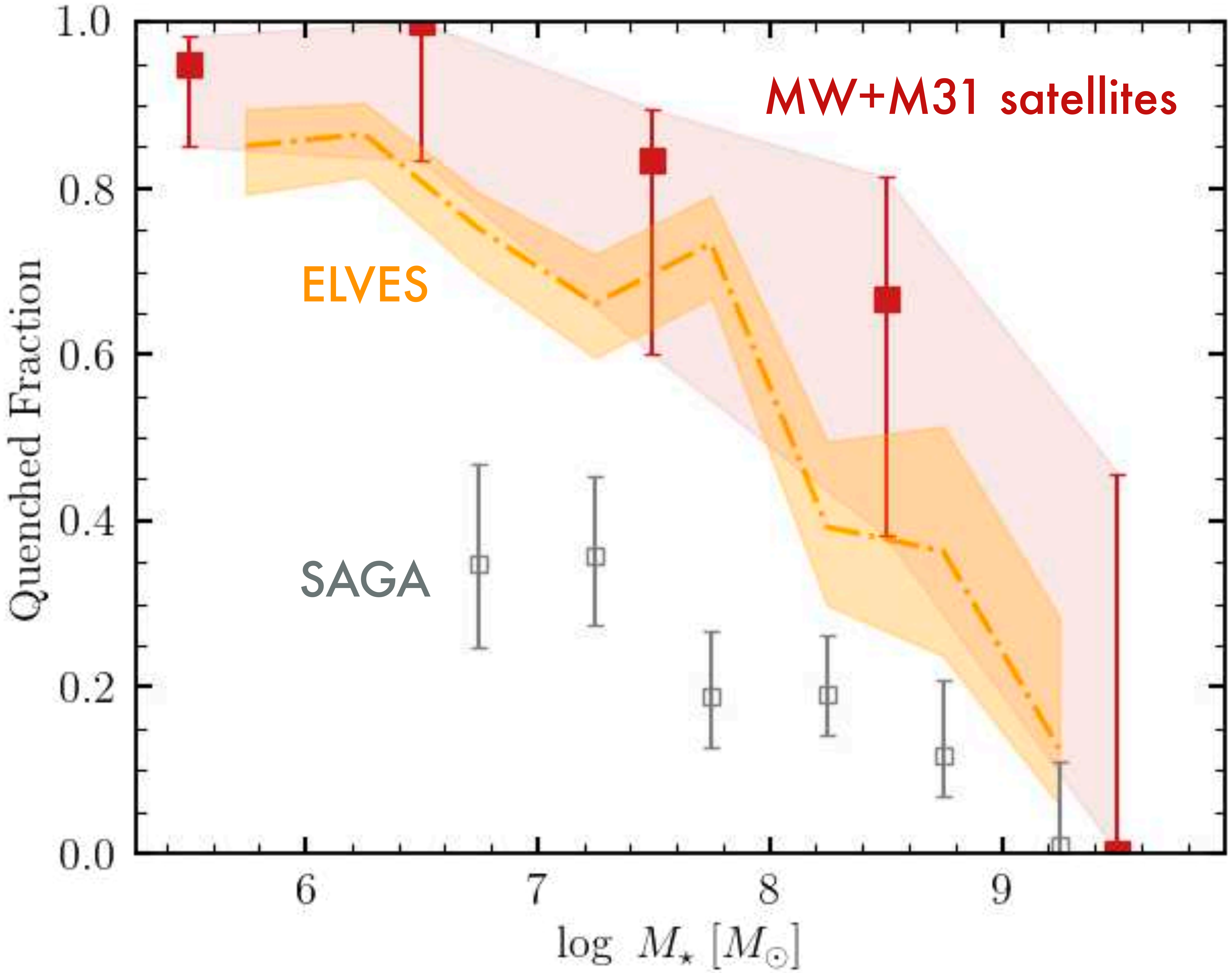
- The definition of Ultra-Diffuse Galaxy makes it NOT ideal for understanding the diffuse dwarf population.
- Ultra-Puffy Galaxy, defined the mass-size outliers, is better suited to study the population, especially quenching.
- Despite being size outliers, UPGs have similar quenched fraction as normal satellites of MW analogs.
- They might be puffed up before infall, and quenched together with normal sat. due to ram pressure stripping.





Thank you!

Quenching of satellites, UDGs, and UPGs



ELVES: photometric survey for MW analogs within 12 Mpc. Distances measured using *surface brightness fluctuation*.

SAGA: spectroscopic survey for satellites of 100 MW analogs at z=0.01