KICP Seminar
Nov 20, 2025

Dwarfs: Near and Far

Jiaxuan Li 李嘉轩 (Princeton)

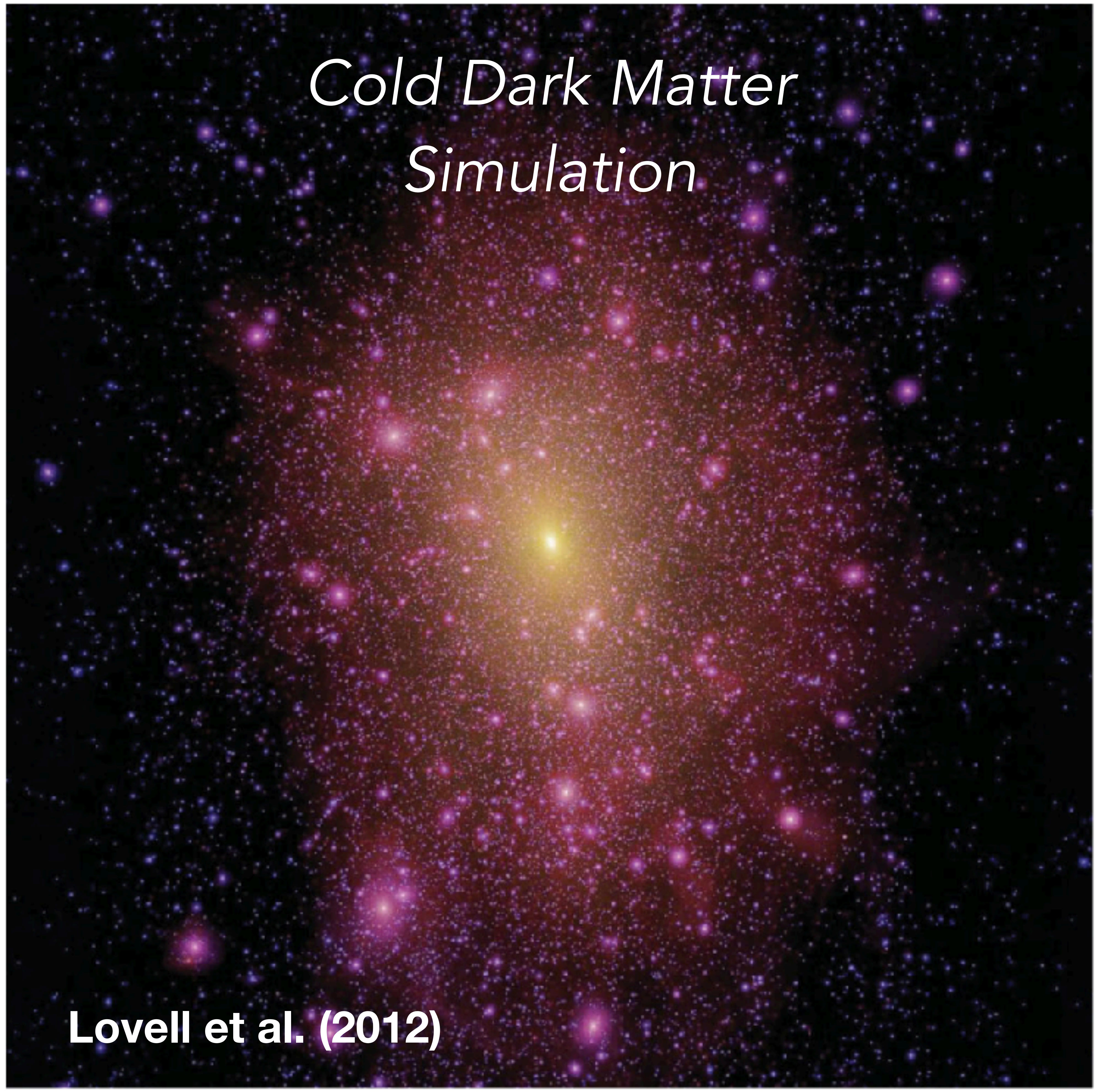
Dwarf Galaxy:
Jenny Greene, Shany Danieli, Marla Geha, Scott Carlsten, Risa Wechsler, Yao-Yuan Mao, Masayuki Tanaka, Fangzhou Jiang, Rachael Beaton

Dwarf Planet:
Sihao Cheng and Eritas Yang

arXiv:2511.01733
arXiv:2504.08030
arXiv:2406.00101
arXiv:2505.15806


LMC
$M_* = 3 \times 10^9\,M_\odot$
200 pc
Fornax
$4 \times 10^7\,M_\odot$
200 pc
WLM
$2 \times 10^7\,M_\odot$
200 pc
Pegasus
$M_* = 6 \times 10^6\,M_\odot$
200 pc
Sculptor
$4 \times 10^6\,M_\odot$
200 pc
Phoenix
$2 \times 10^6\,M_\odot$
200 pc
Draco
$M_* = 4 \times 10^5\,M_\odot$
200 pc
Eridanus II
$6 \times 10^4\,M_\odot$
200 pc
Pictoris I
$3 \times 10^3\,M_\odot$
200 pc
Milky Way
Large Magellanic Cloud
Small Magellanic Cloud
Bullock & Boylan-Kolchin (2017)

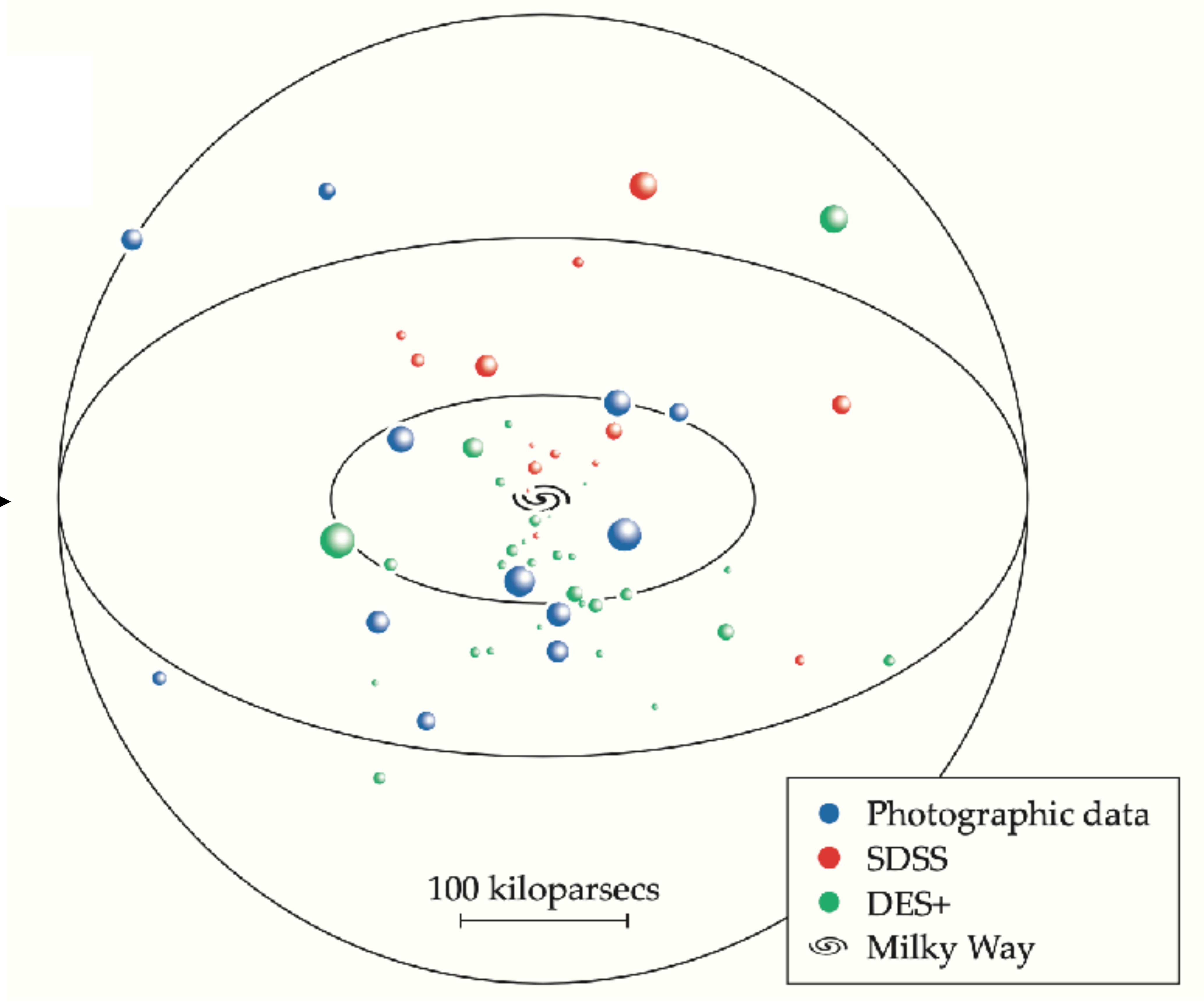
Dwarf galaxies challenged CDM model



Missing

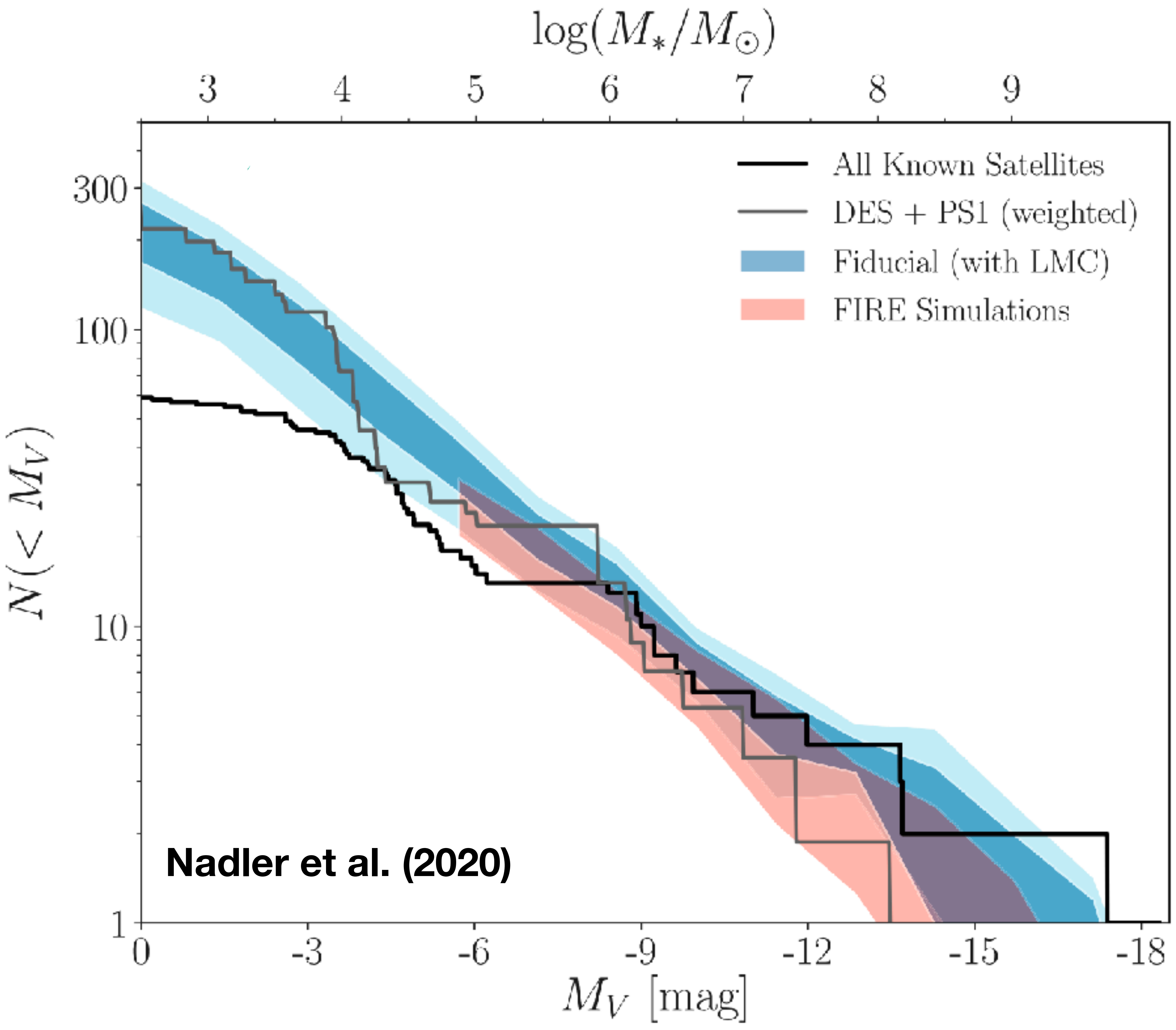
satellites?

Observed Milky Way satellites



Simon & Geha (2021)

Dwarf galaxies challenged CDM model

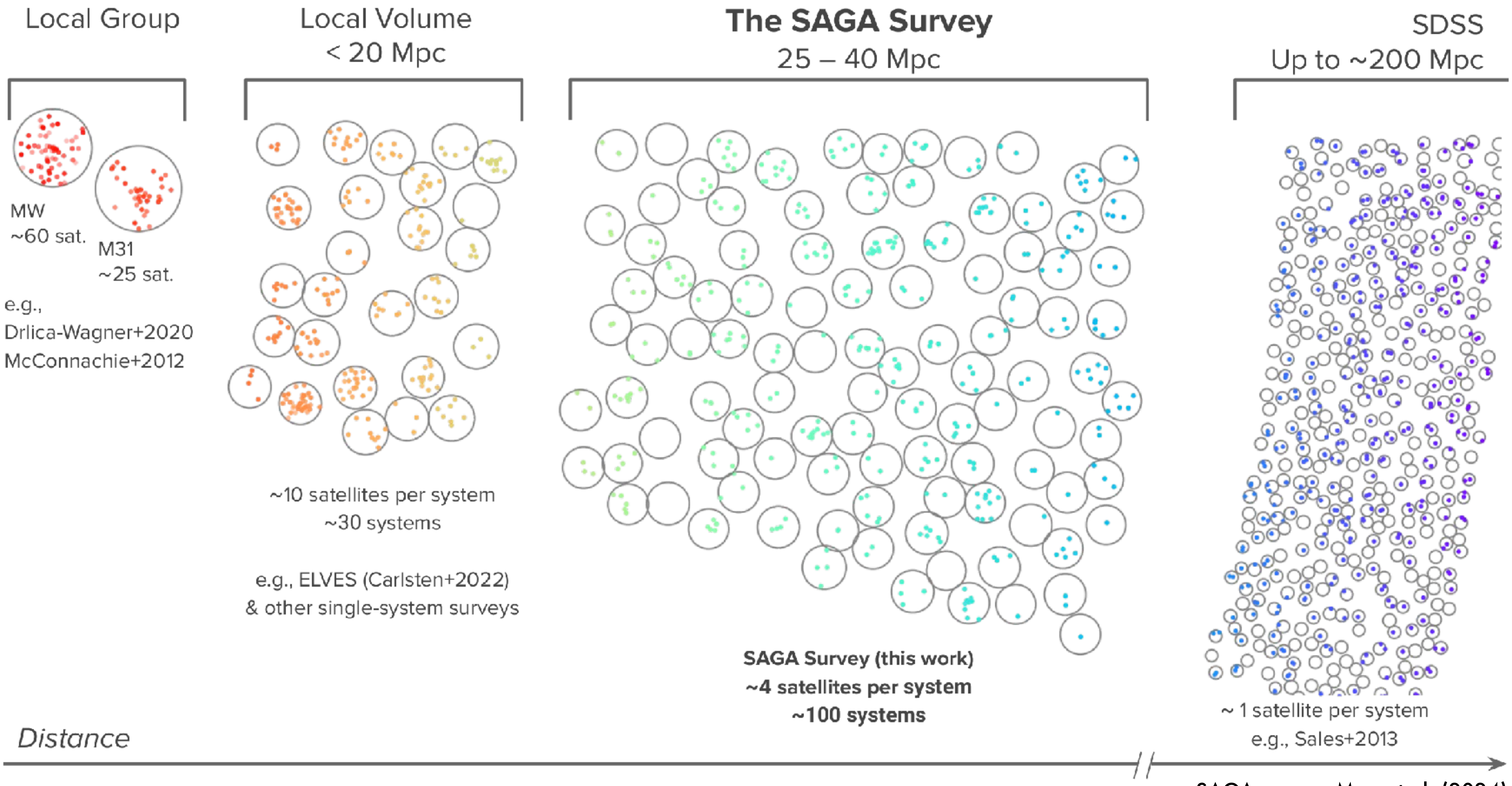


Problem solved:

- Not all subhalos can host galaxy formation ($M_h > 10^9\, M_\odot$)
- Our **galaxy formation models** (hydrodynamical simulation and semi-analytical models) now agree with observation quite well

This is mostly tested against satellites of our own Milky Way!

... and satellites of MW analogs



SAGA survey; Mao et al. (2024)

Dwarf galaxies should also have satellites

(10-1000x smaller than MW)

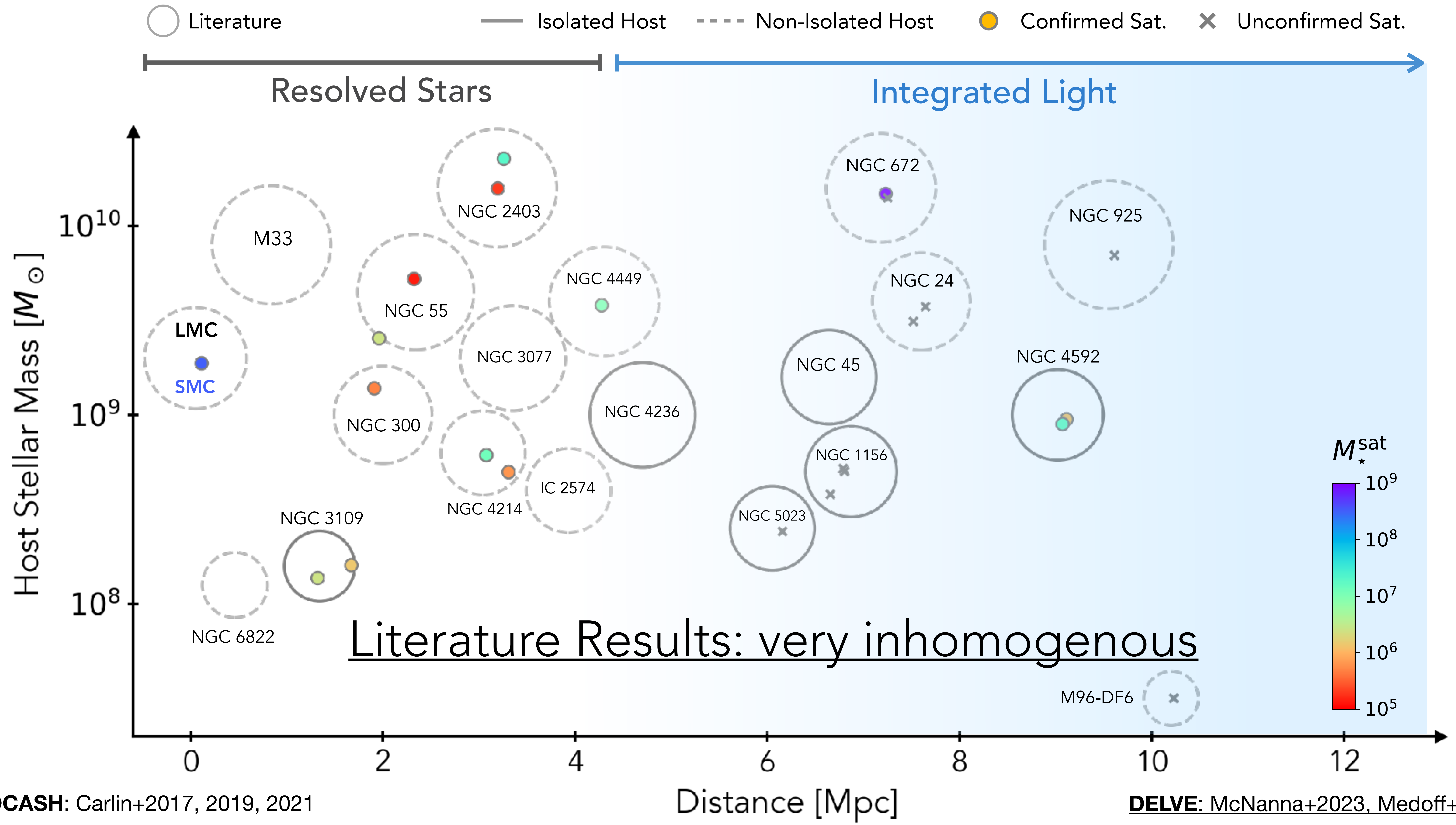
Symphony simulations: Nadler et al. (2023)

Do satellites of dwarf galaxies follow CDM prediction?

We need:

- A sample of “satellites of dwarfs”

*Only showing classical dwarfs



MADCASH: Carlin+2017, 2019, 2021

LBT-SONG: Davis+2020, Garling+2021, 2024

DELVE: McNanna+2023, Medoff+2025

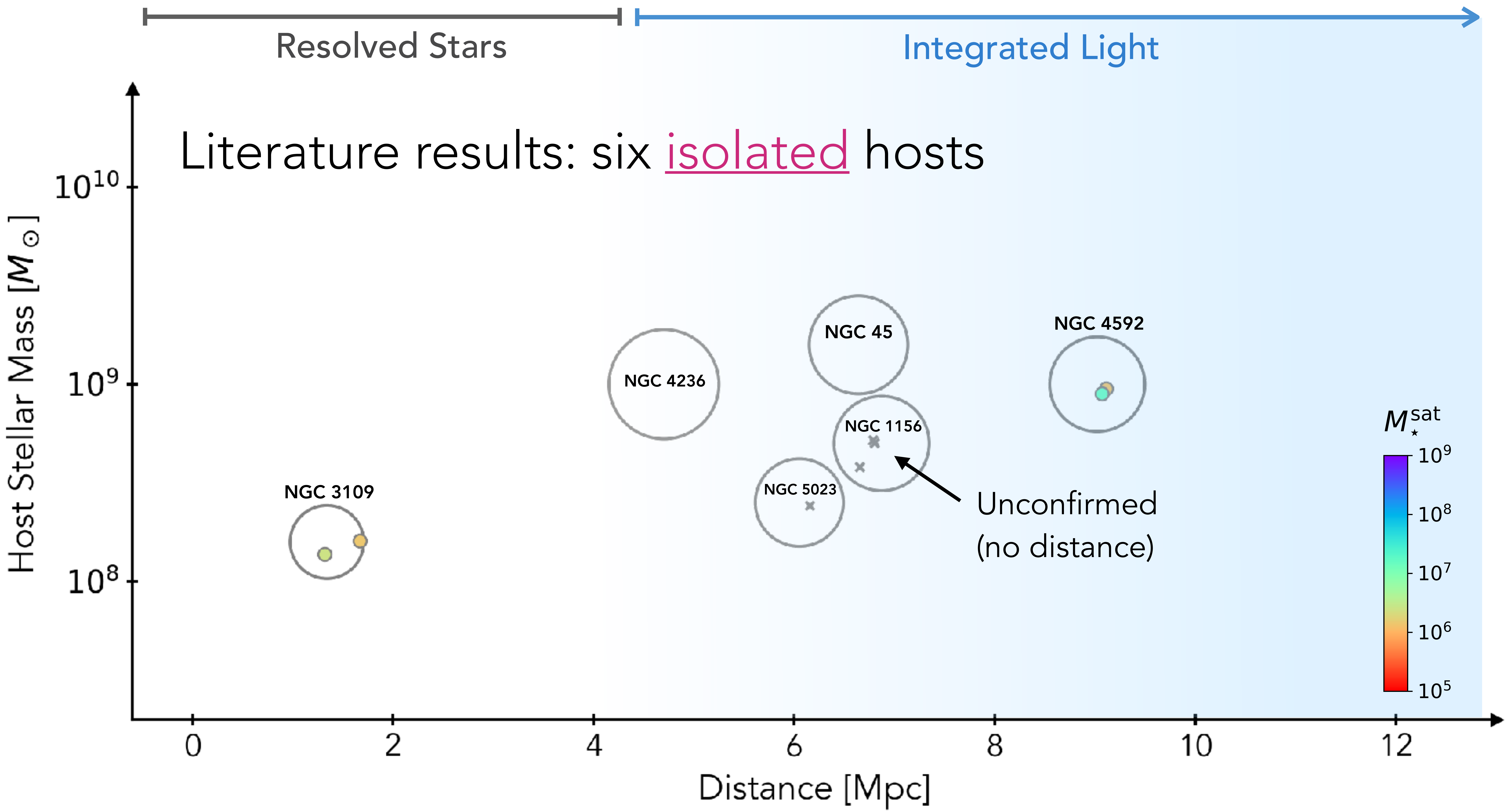
ID-MAGE: Hunter+2025

Do satellites of dwarf galaxies follow CDM prediction?

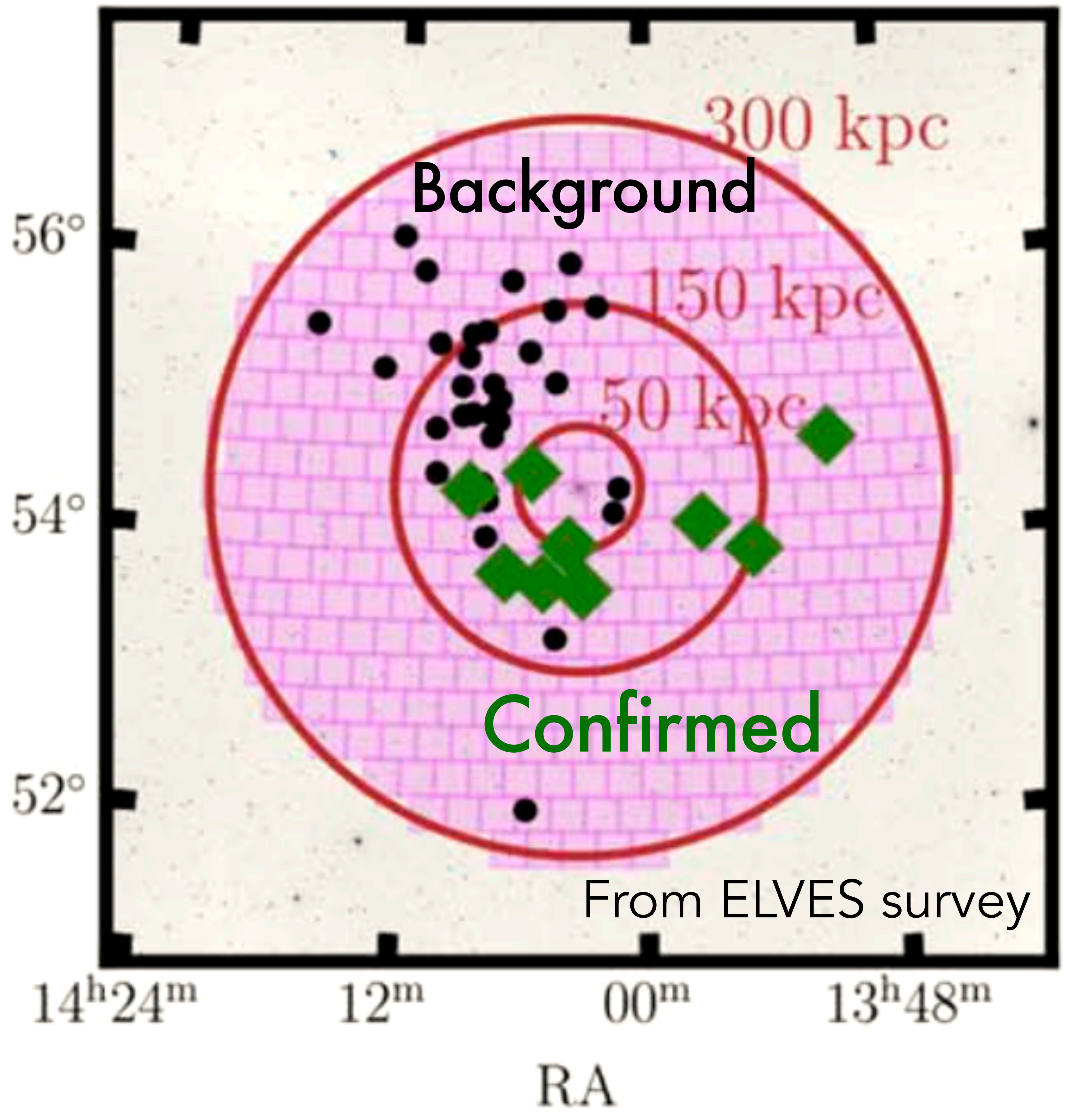
We need:

- *isolated* systems
  - ✦ Unambiguously assign satellites to the host (bad example: MW+LMC)
  - ✦ Easier to compare with theory/simulations

Only showing classical dwarfs



Distance is crucial!



A large fraction of candidates can be background galaxies

We need:

- **more *isolated* systems**
  - ✦ Unambiguously assign satellites to the host (bad example: MW+LMC)
  - ✦ Easier to compare with theory/simulations
- **Distances to satellite candidates**
  - ✦ Distance doesn’t come for free at > 2 Mpc
  - ✦ Spectroscopic surveys might not be the most efficient way

Milky Way

Large Magellanic Cloud

Small Magellanic Cloud

ELVES-DWARF Survey

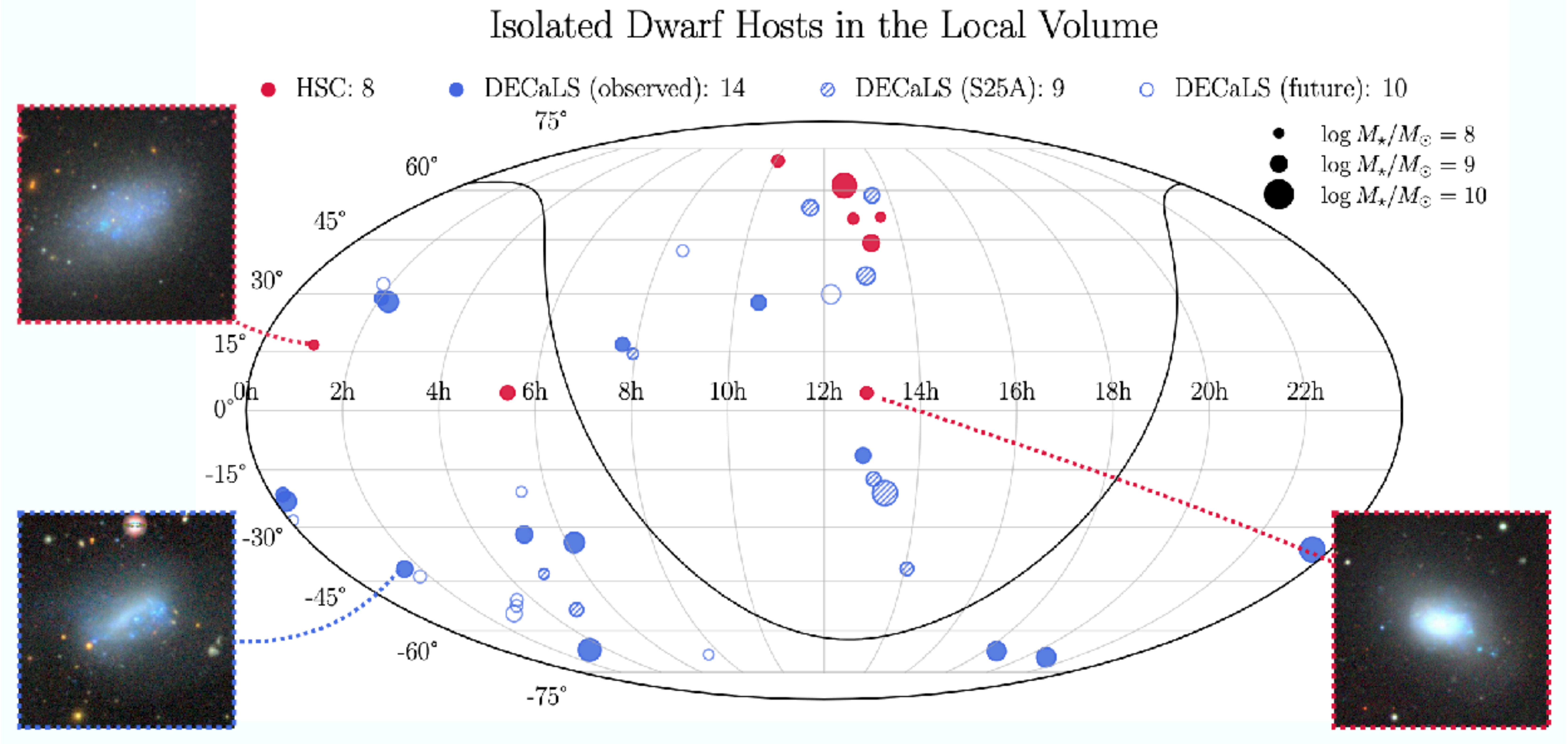
Goal: survey 30-40 ***isolated*** dwarf hosts at 4-12 Mpc

Hosts: $M_\star = 10^{8-10}\,M_\odot$, selected from Karachentsev's Nearby Galaxy Catalog

Satellite search: ground-based wide surveys (DECaLS).

Complete to $M_g \approx -9\,\mathrm{mag}$

Distance: **S**urface **B**rightness **F**luctuation (SBF) from imaging data

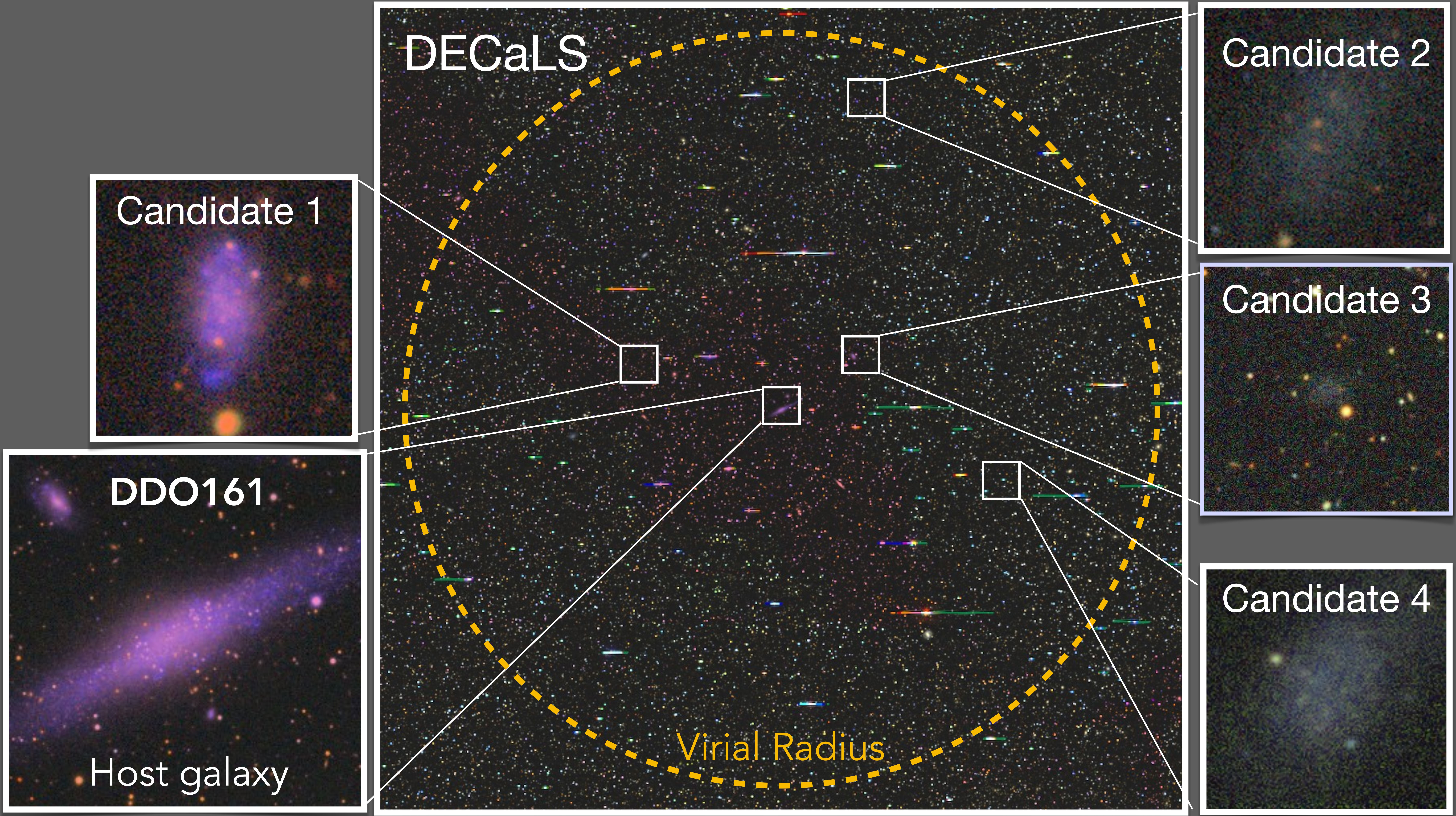


J. Li et al. (2025)

Magellan/IMACS

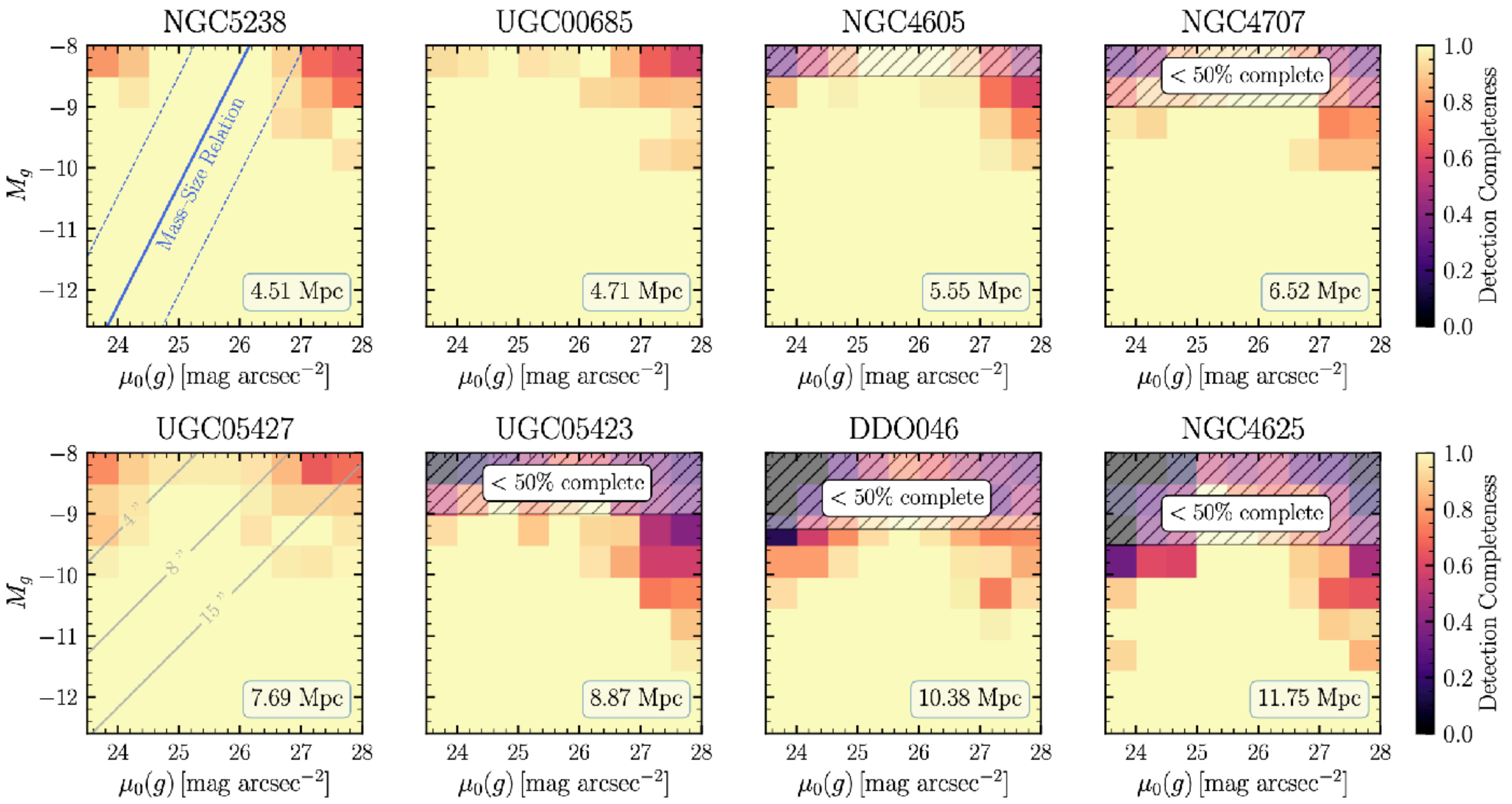
Gemini-N/GMOS

Subaru/HSC


DECaLS
Candidate 1
Candidate 2
Candidate 3
Candidate 4
DDO161
Host galaxy
Virial Radius

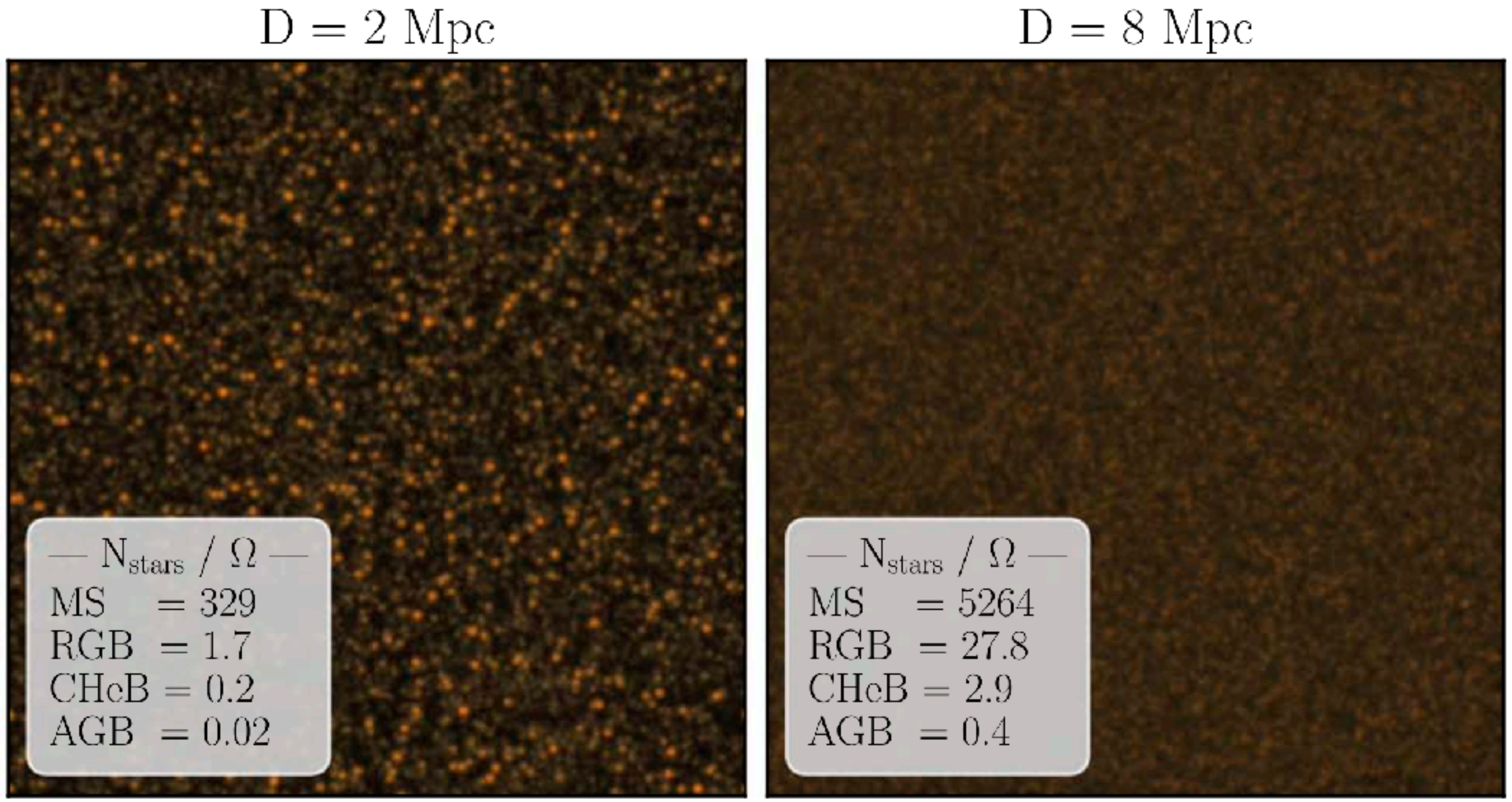
Satellite Search Completeness

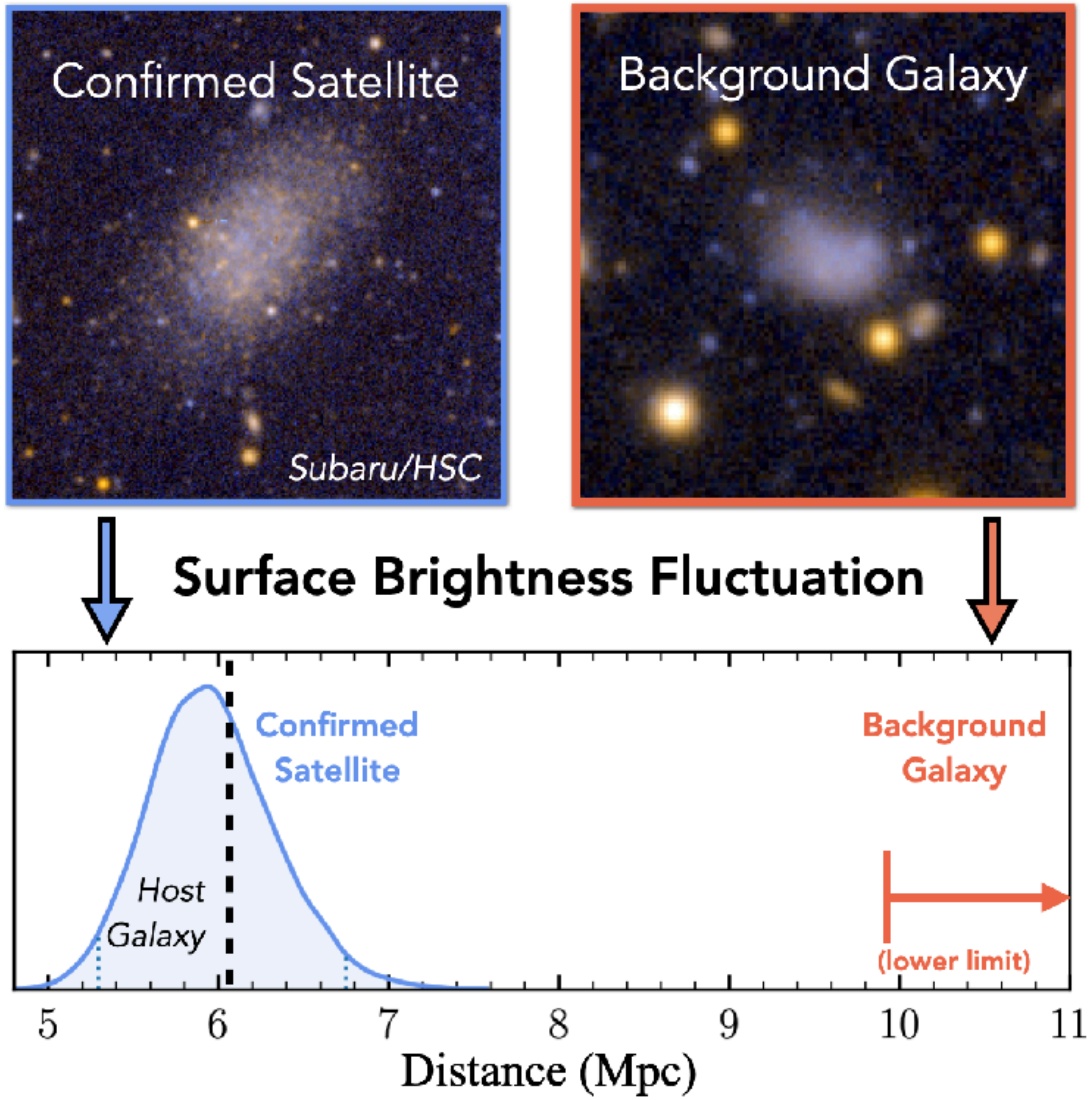
- Complete down to $M_g \approx -9$ mag for most hosts



Surface Brightness Fluctuation contains distance information

*SBF is an **OLD** technique!! (Tonry & Schneider 1988)*

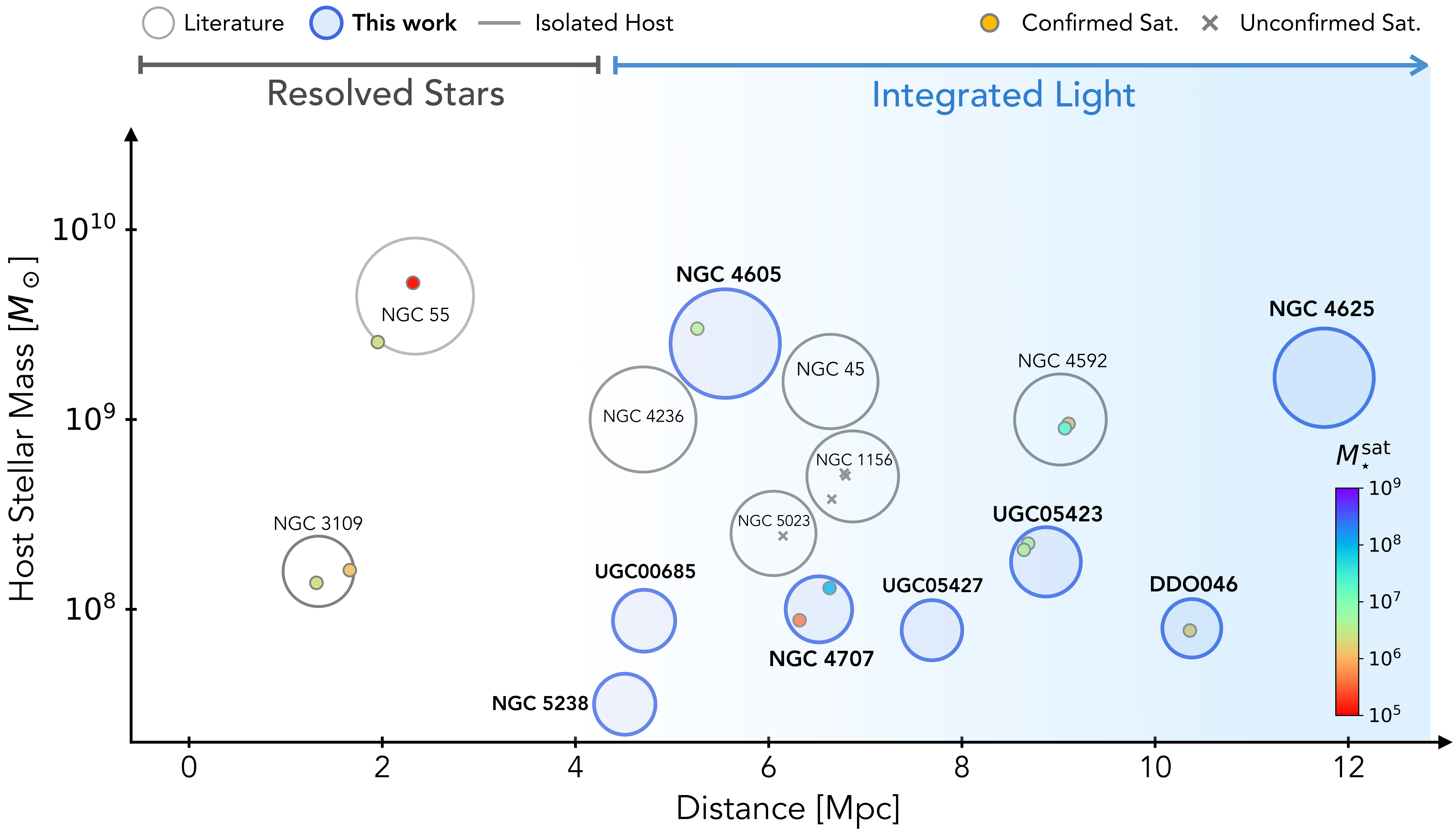




- Ground-based SBF reaches 10–12 Mpc for $M_\star > 10^{5.5}\ M_\odot$
- Not biased towards blue dwarfs (compared with spectroscopic surveys)

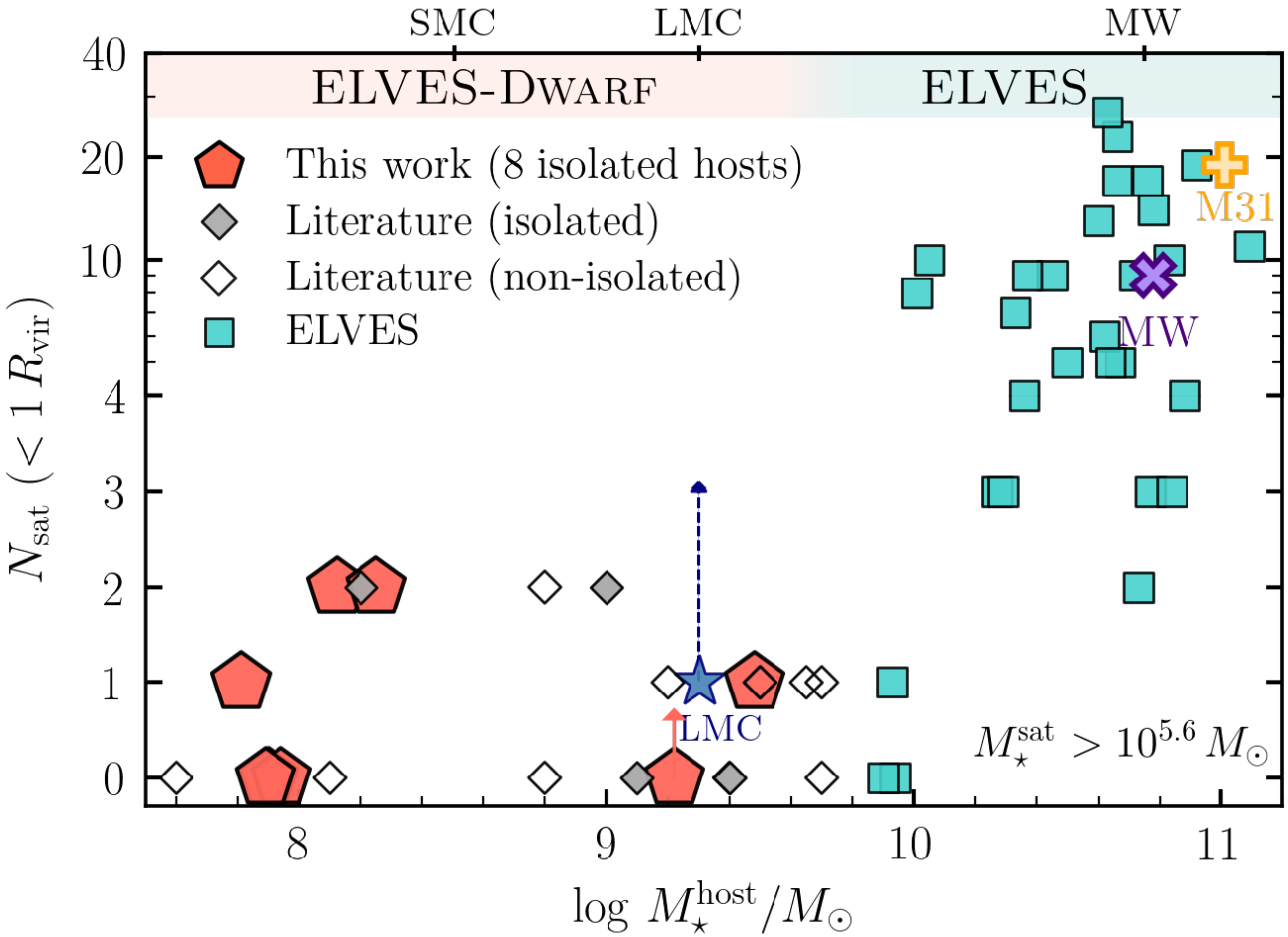
ELVES-DWARF: First results using HSC

J. Li et al. (2025)
arXiv:2504.08030

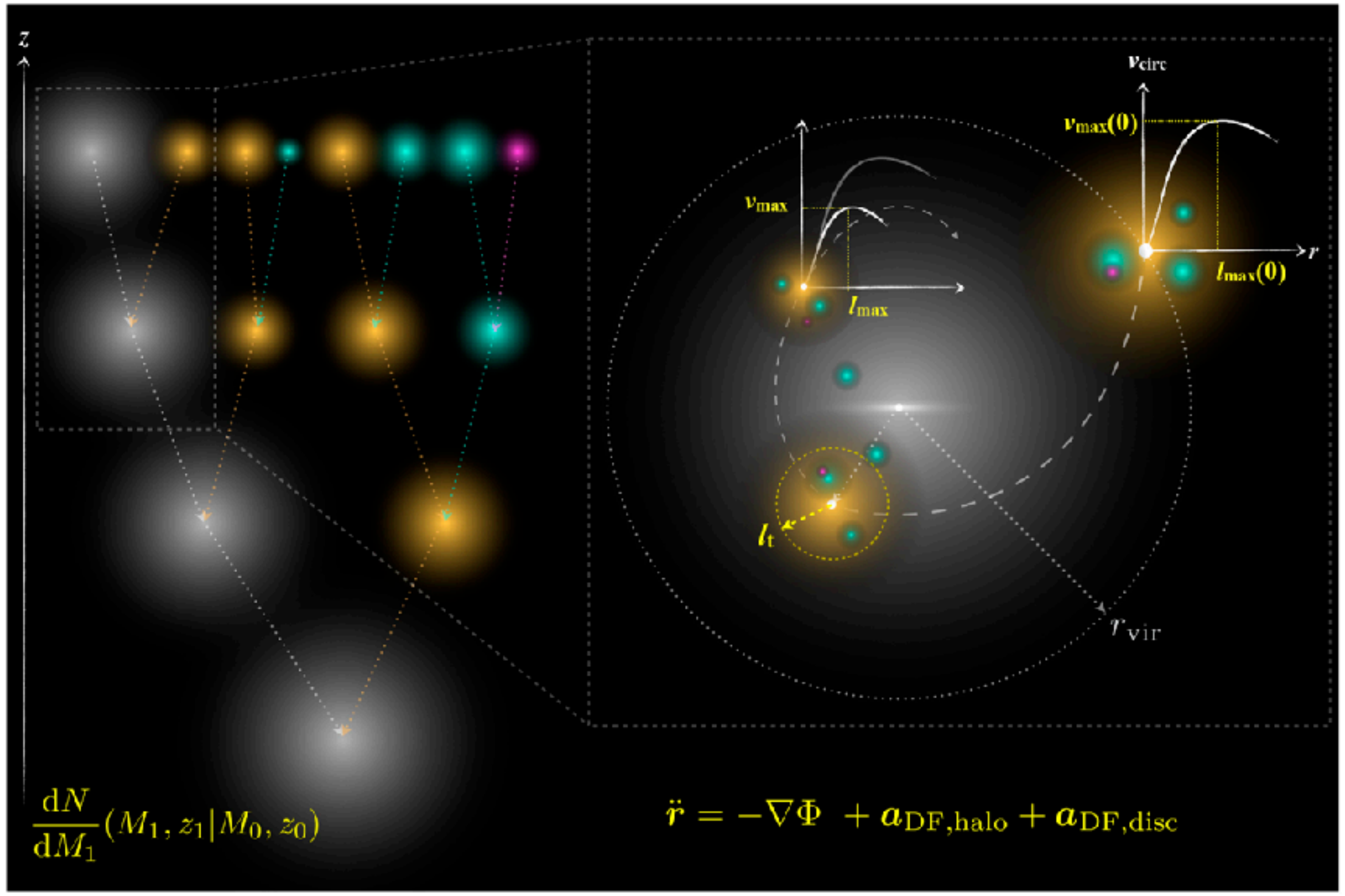


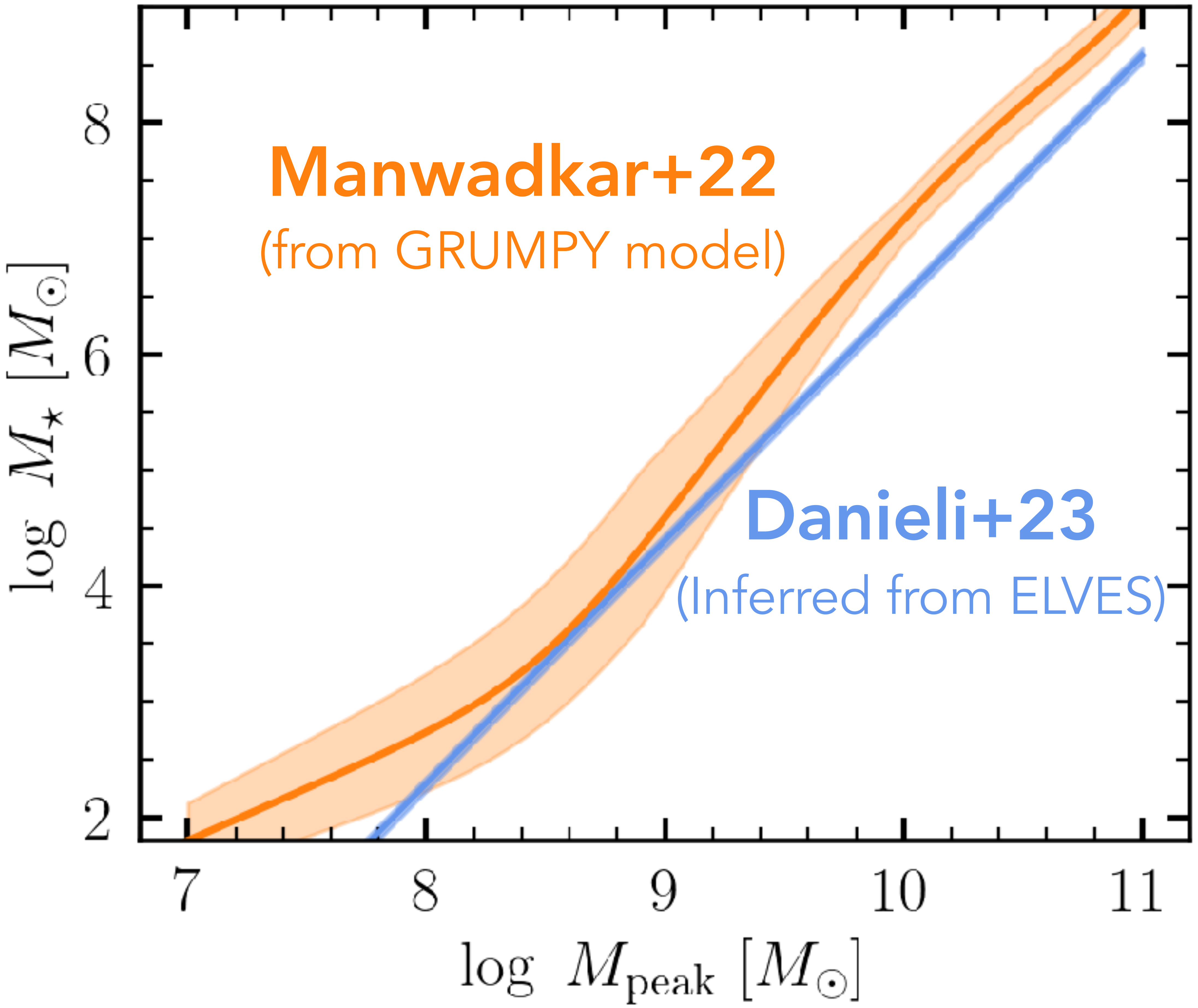
Images of confirmed satellites

Satellite Abundance



Satellite Abundance: SatGen prediction

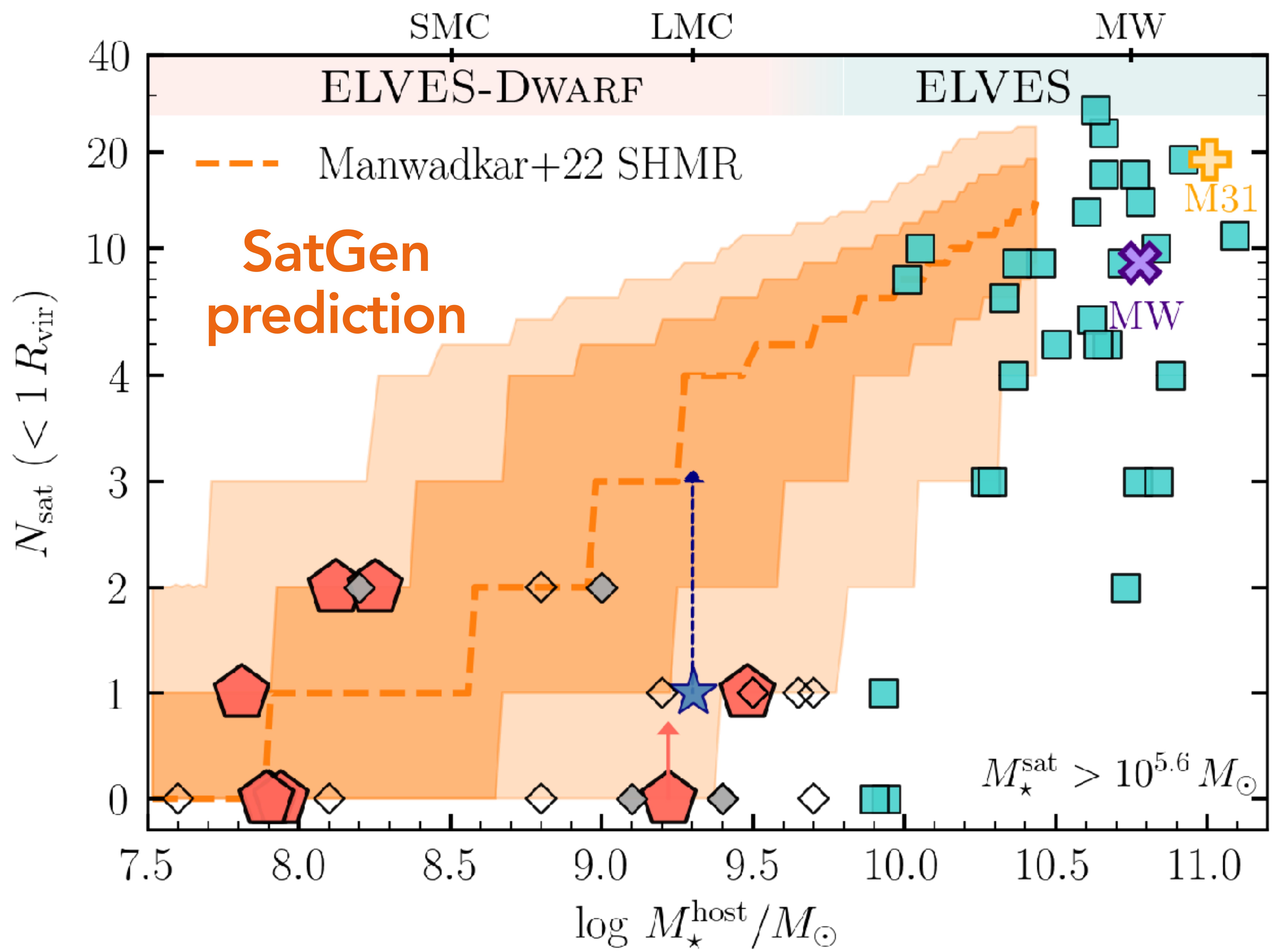




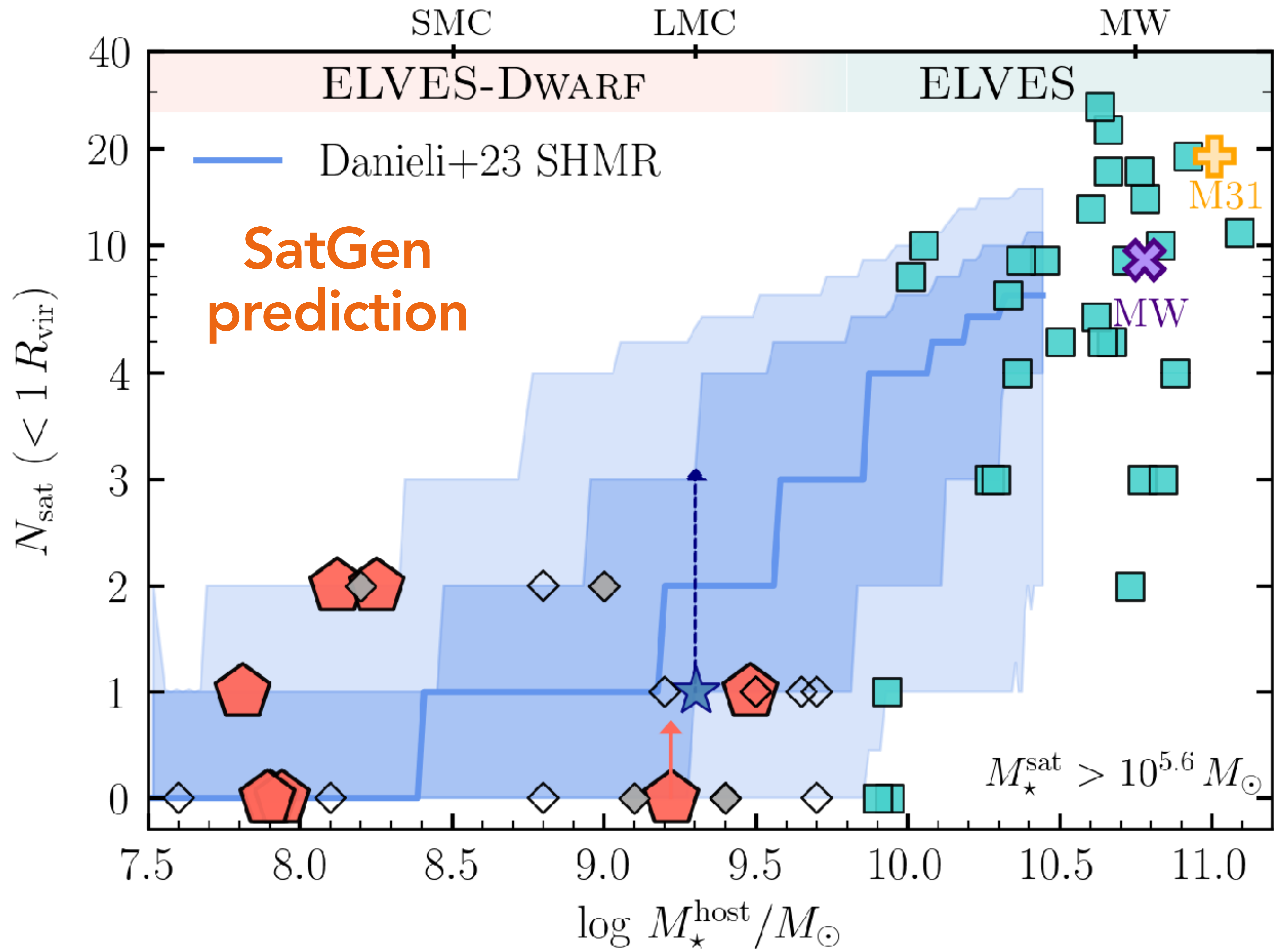
- *SatGen*: Semi-analytical model for satellites
- Includes tidal stripping; emulates baryonic processes

- We populate dark matter halos using galaxy-halo connection models

No “Missing satellite problem”

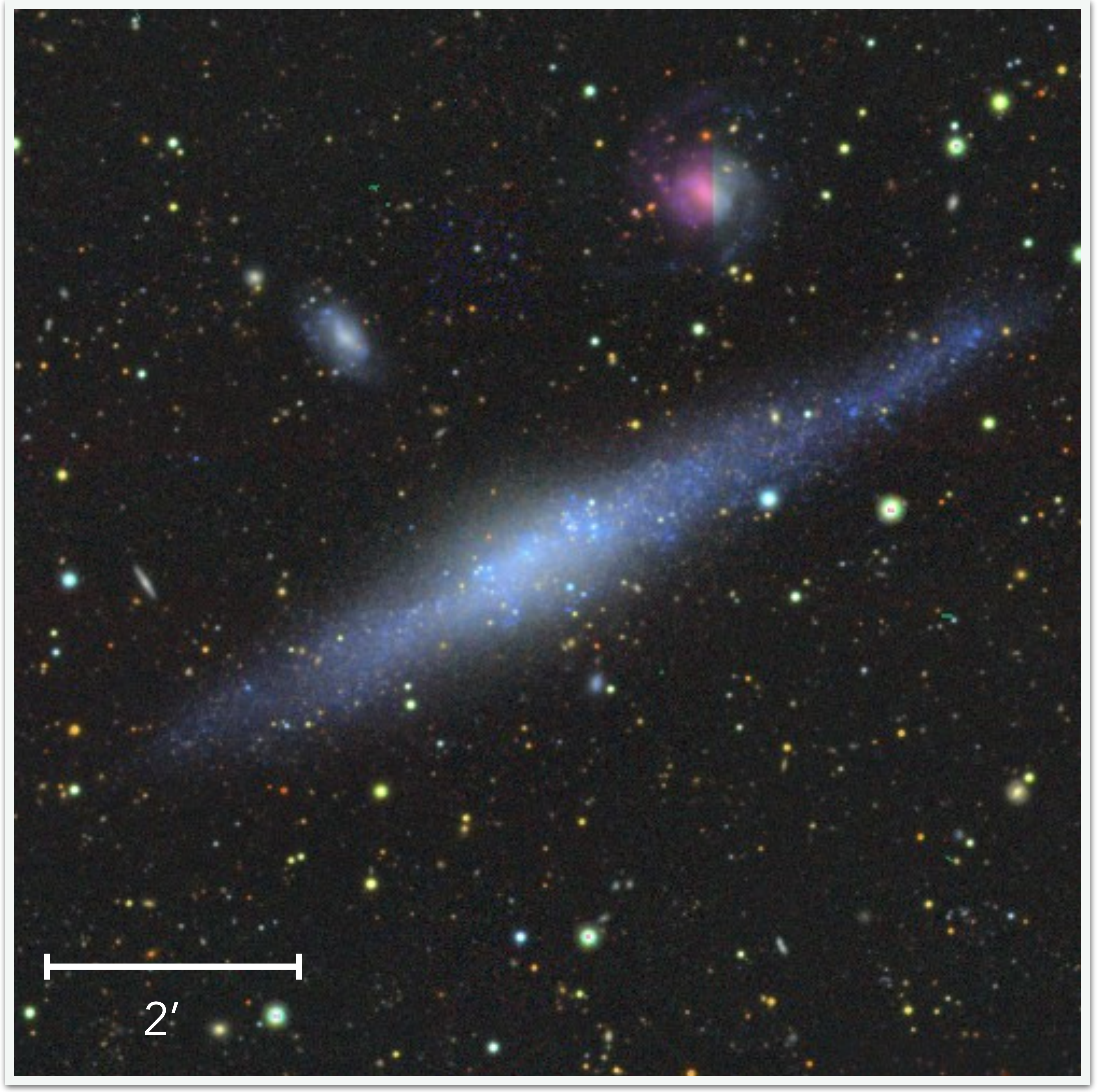


No “Missing satellite problem”

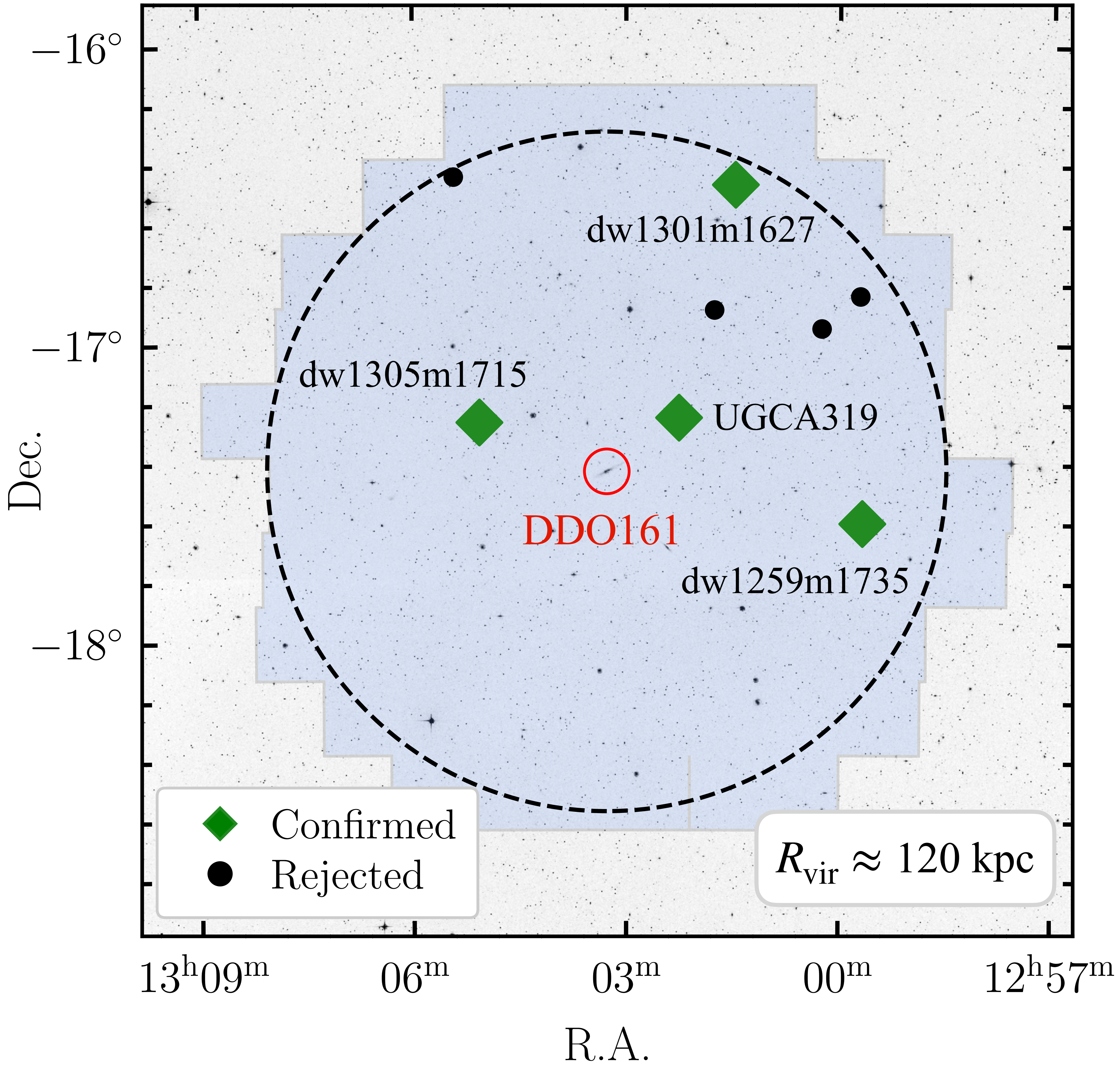


But a "too-many-satellites" problem?

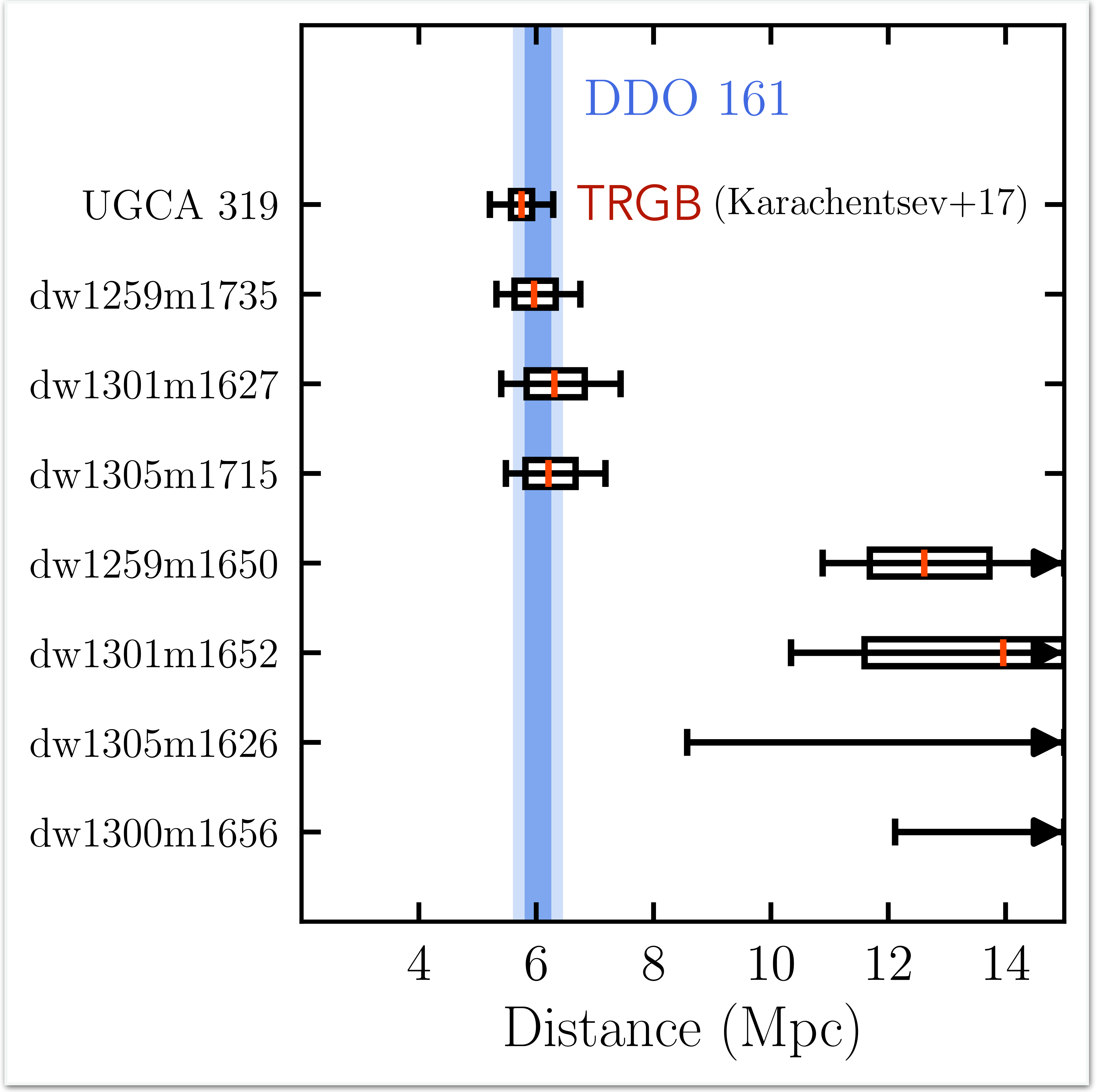
Li et al. (2025b)

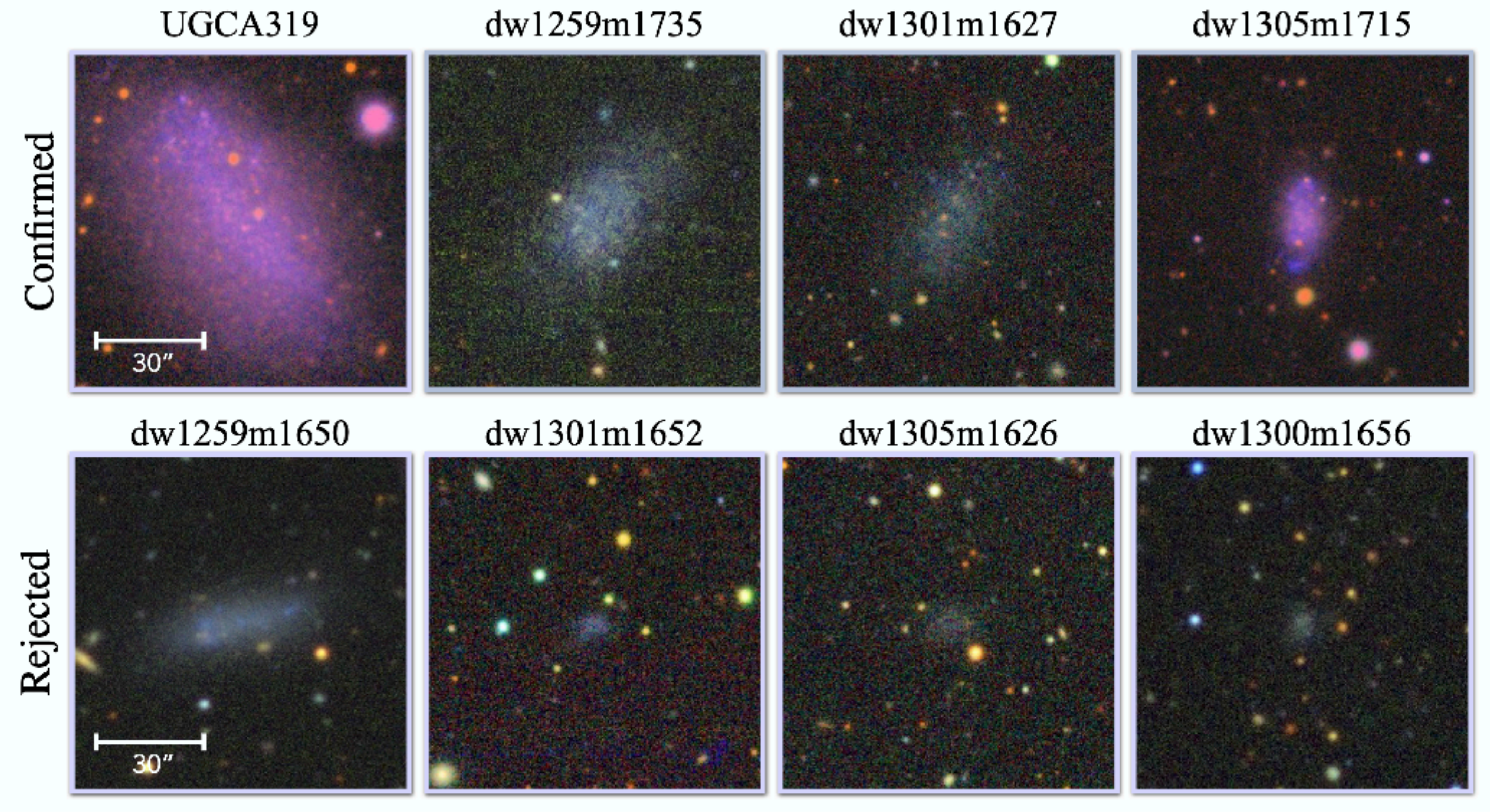


DDO161: an SMC analog at 6 Mpc

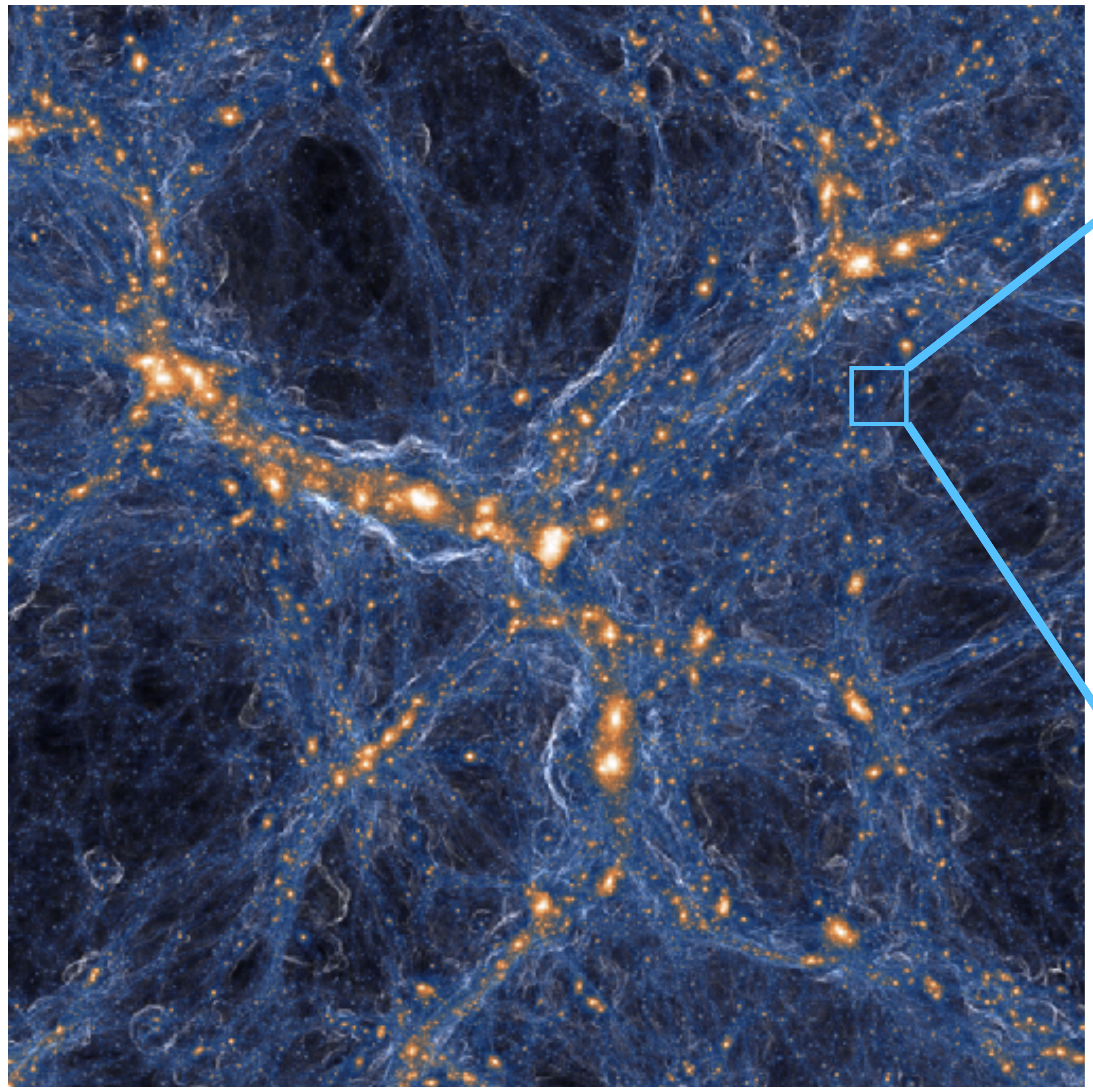


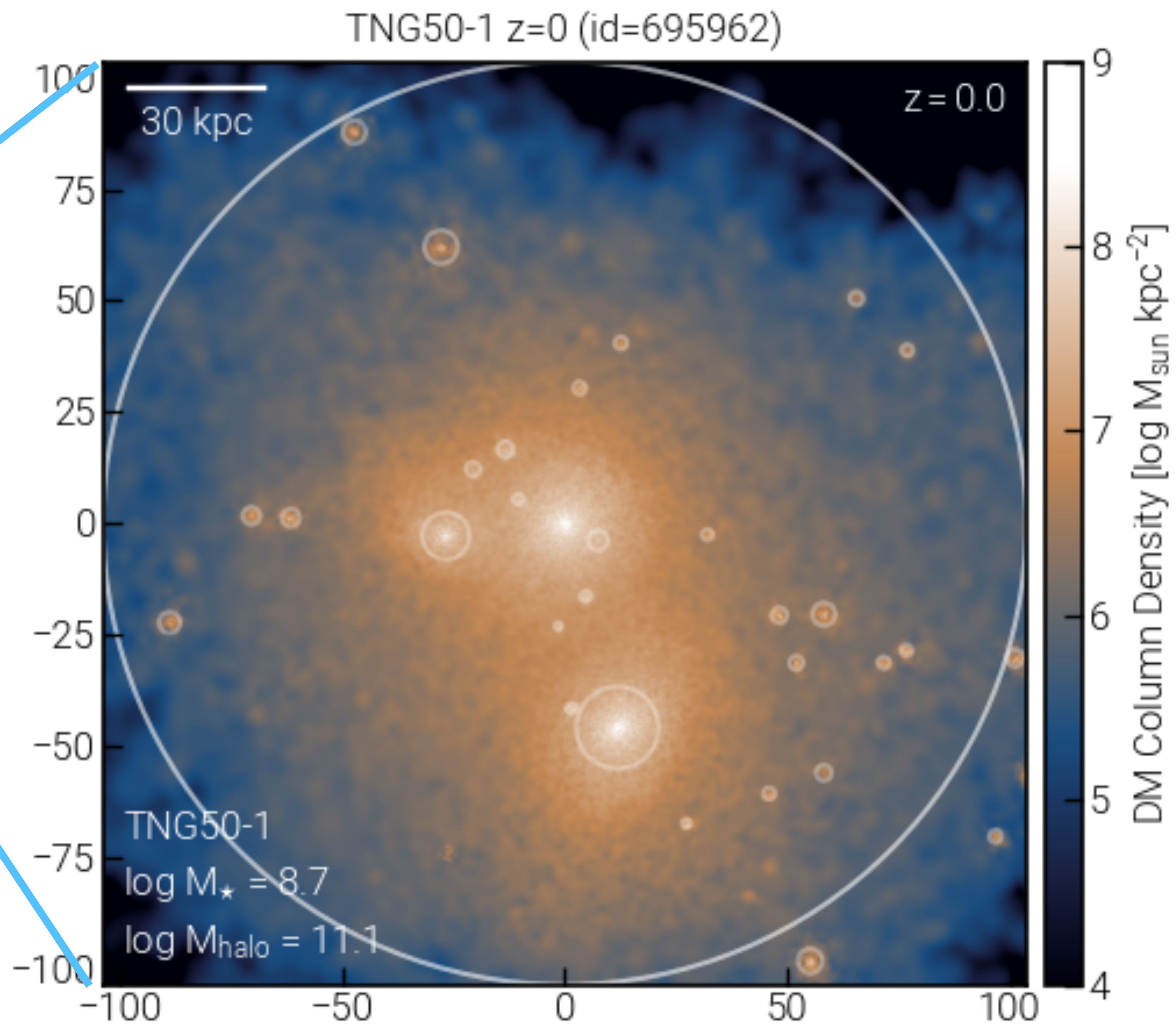
DDO 161 is very rich!

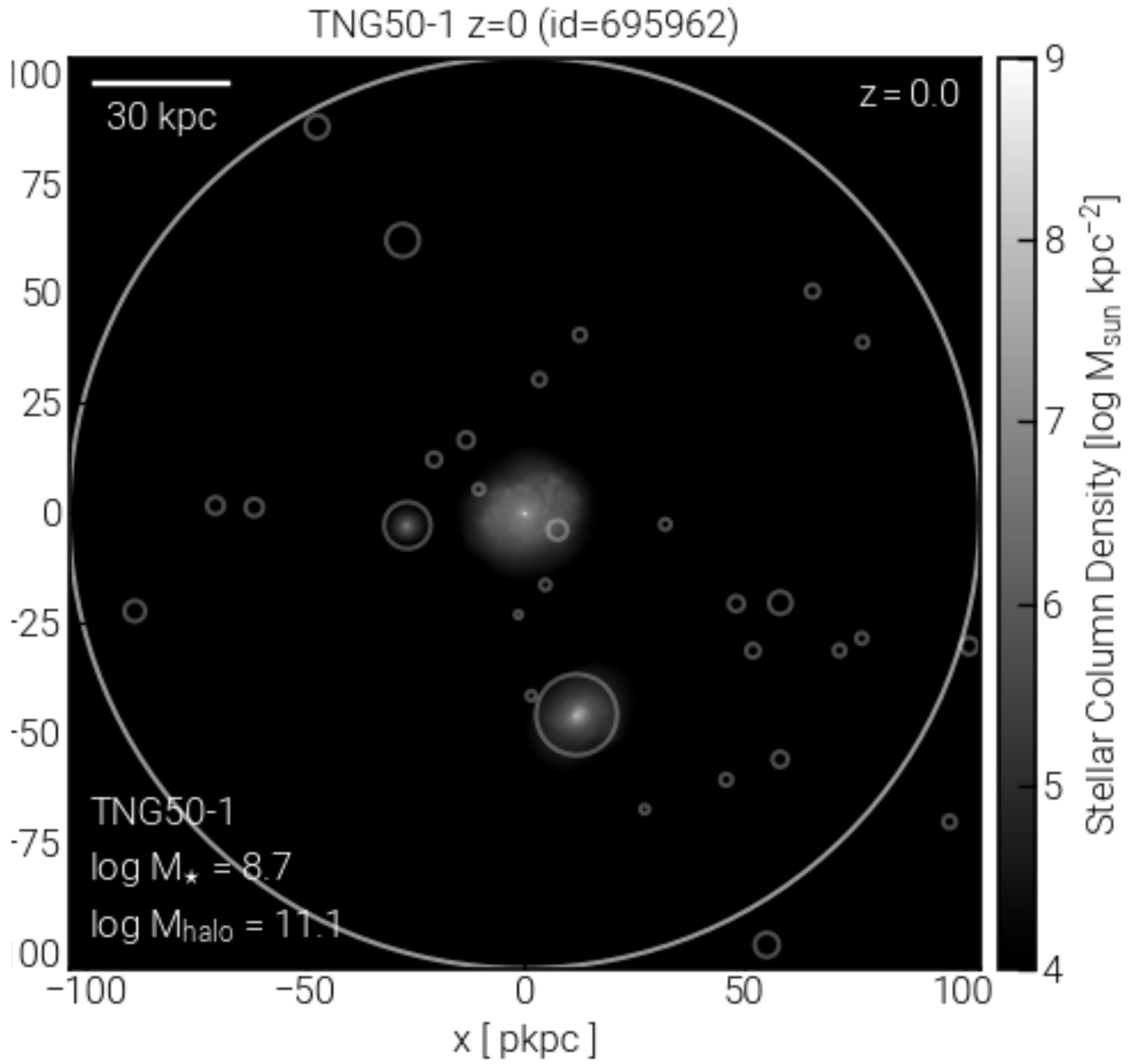




What’s the chance of finding such a system?





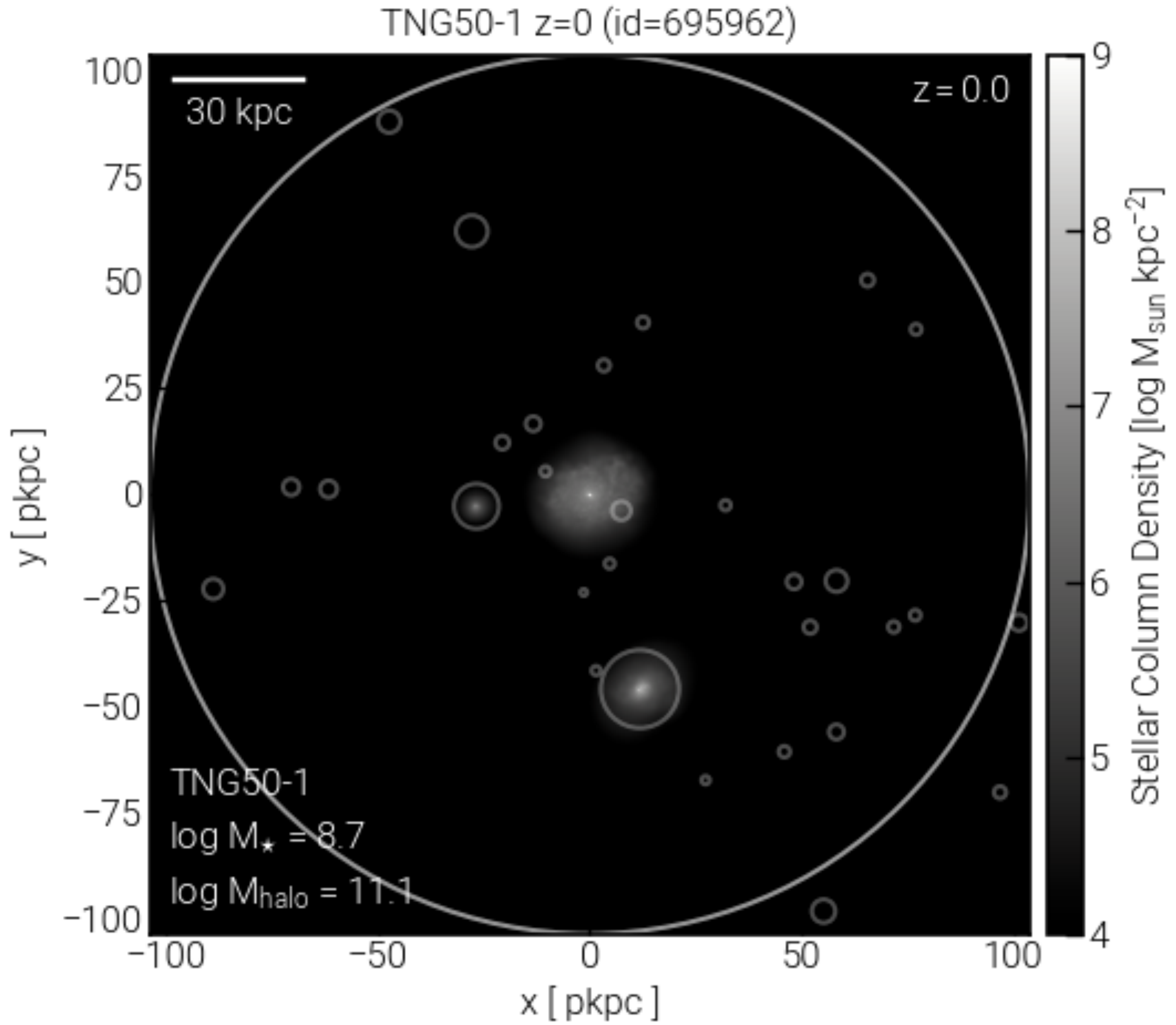


TNG50 simulation

Select hosts similar to DDO161 in stellar mass and environment

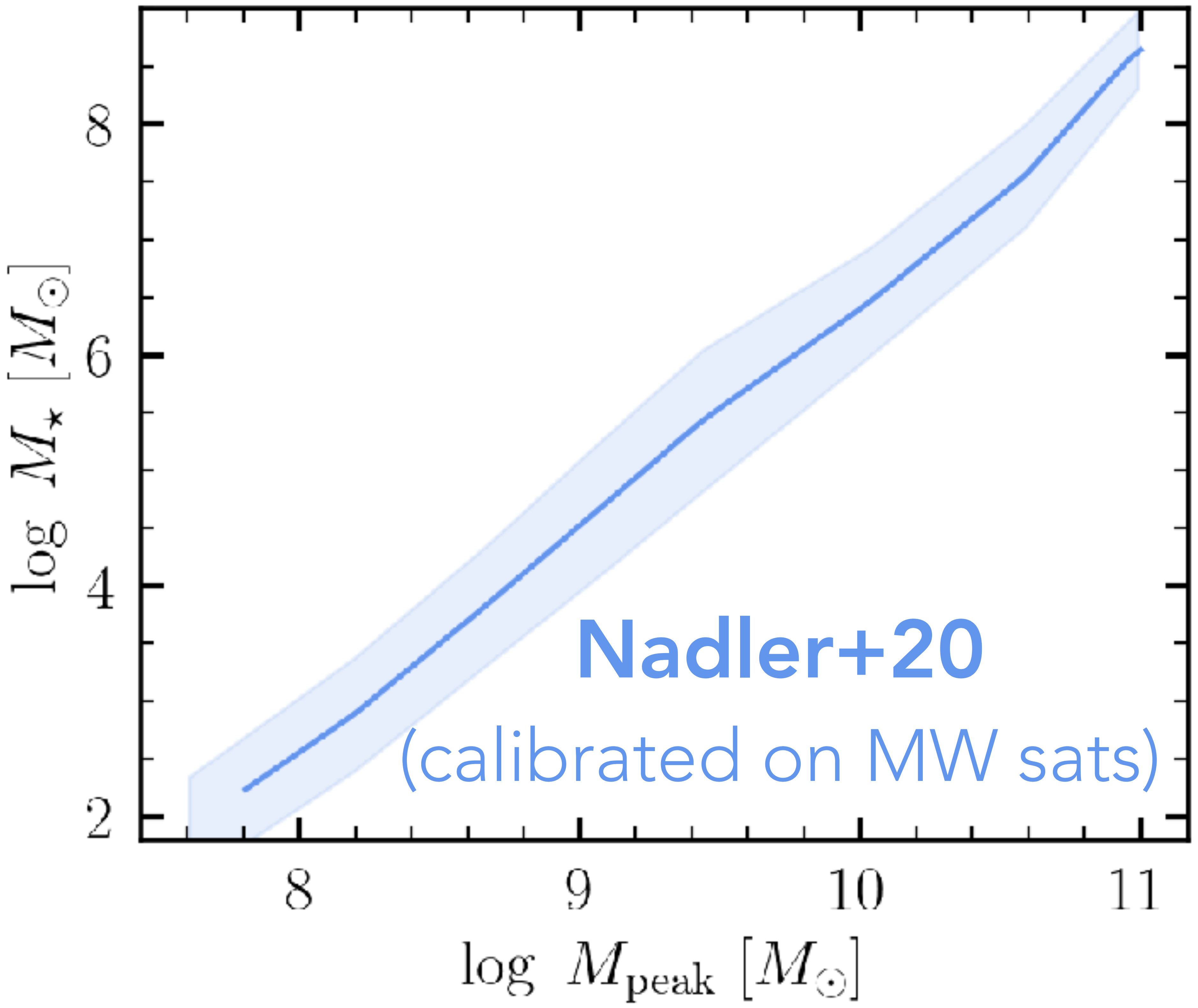
Populate subhalos with galaxies

What's the chance of finding such a system?

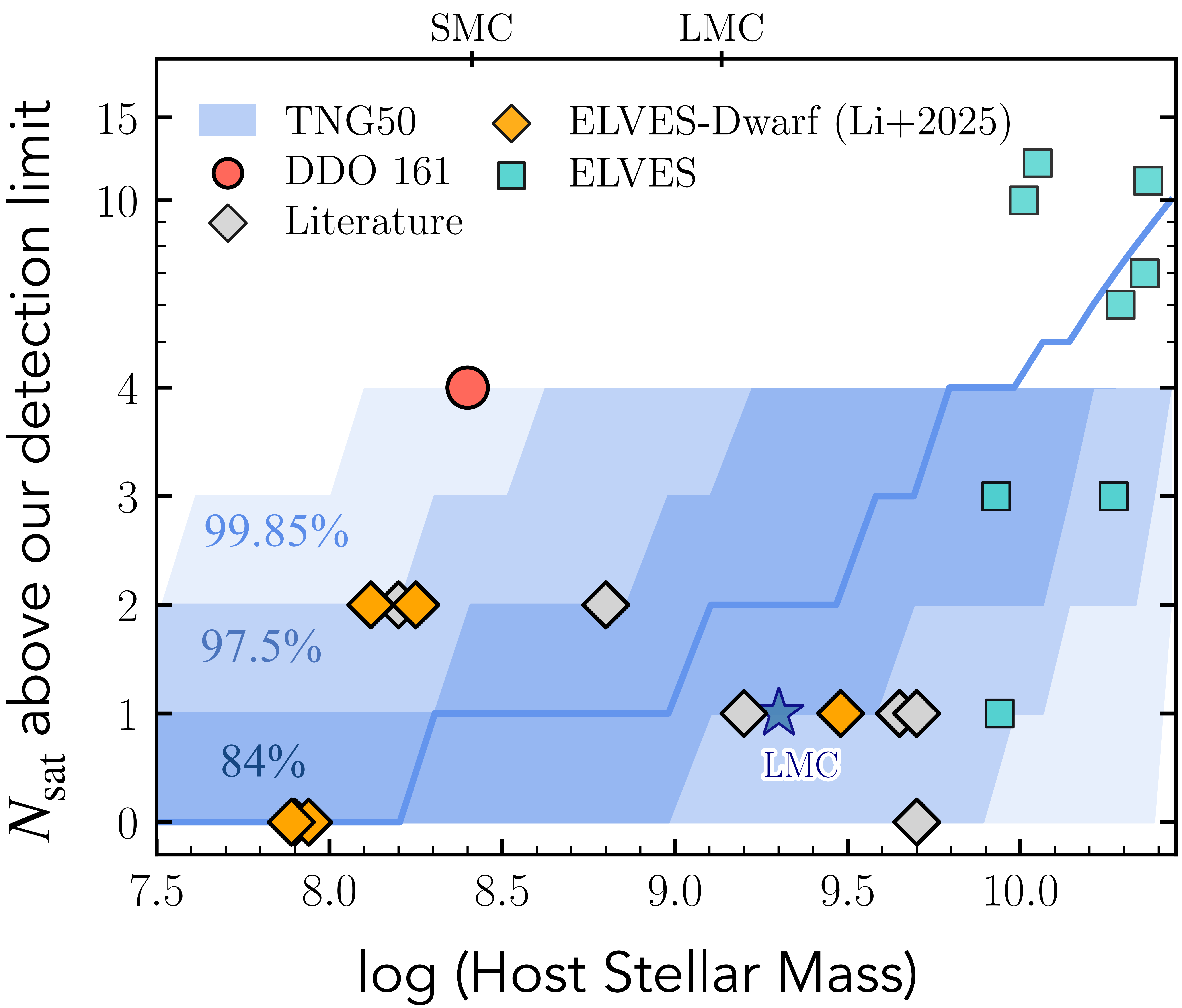


Populate subhalos with galaxies

- TNG50's resolution makes it only reliable for $M_\star > 10^7\,M_\odot$ (our detection limit is $10^{5.4}\,M_\odot$)
- We use empirical galaxy-halo connection models (stellar-to-halo mass relations)

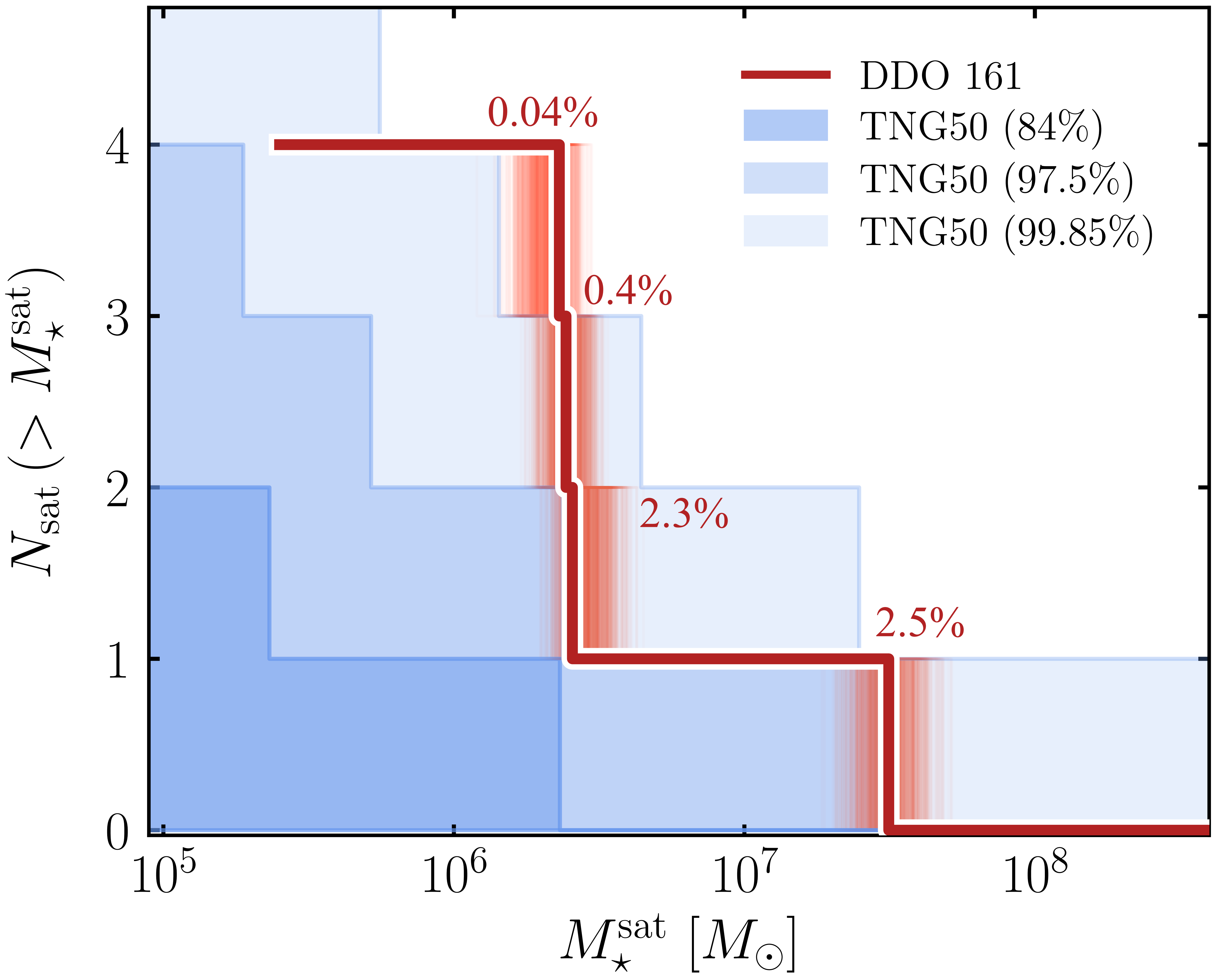


Such satellite-rich systems are very rare



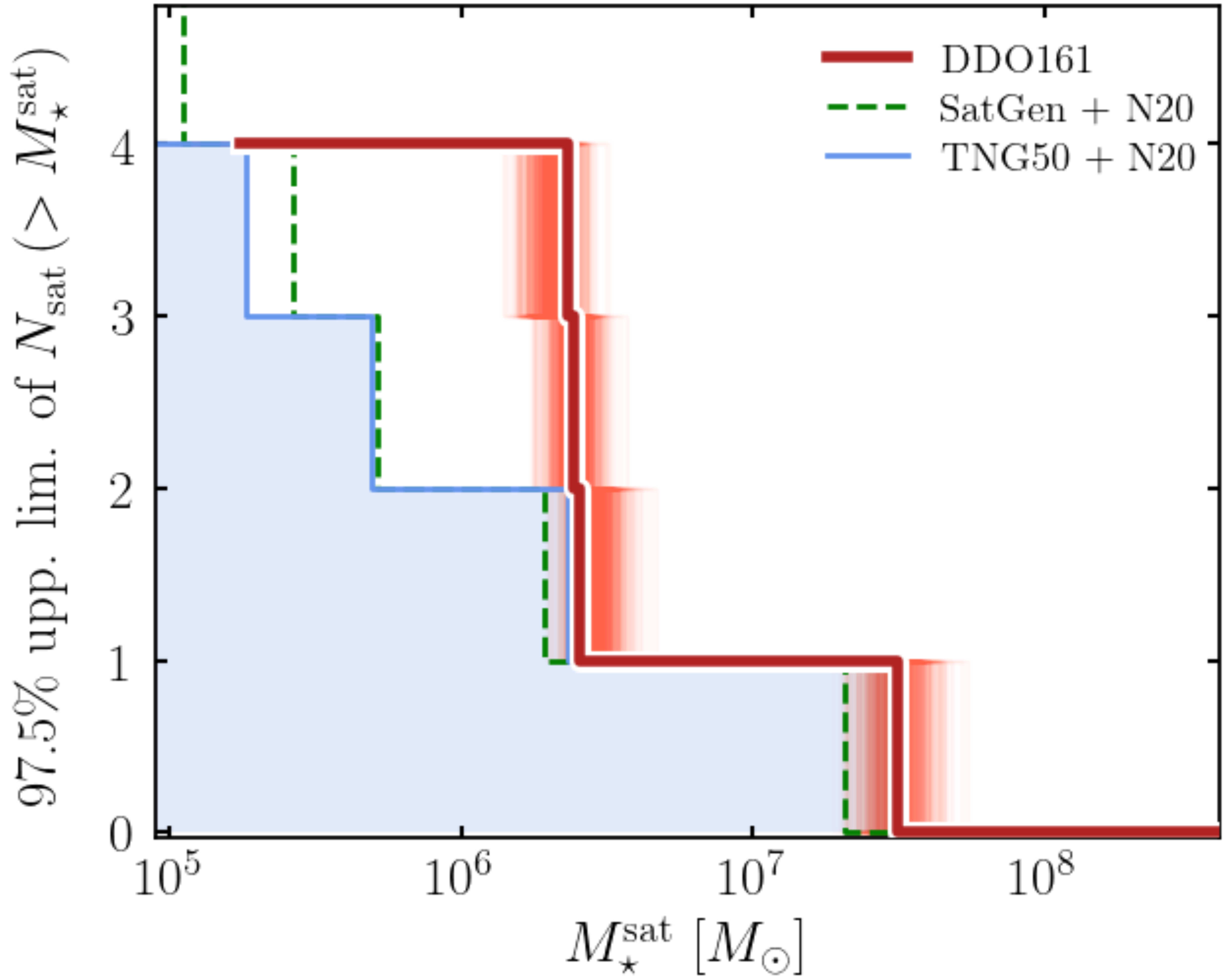
Such satellite-rich systems are very rare

The chance of finding 4 satellites more massive than $M_\star > 10^{6.2}\,M_\odot$ is only 0.04%



- Is this **numerical issue**? (simulations suffer from artificial disruption for subhalos)

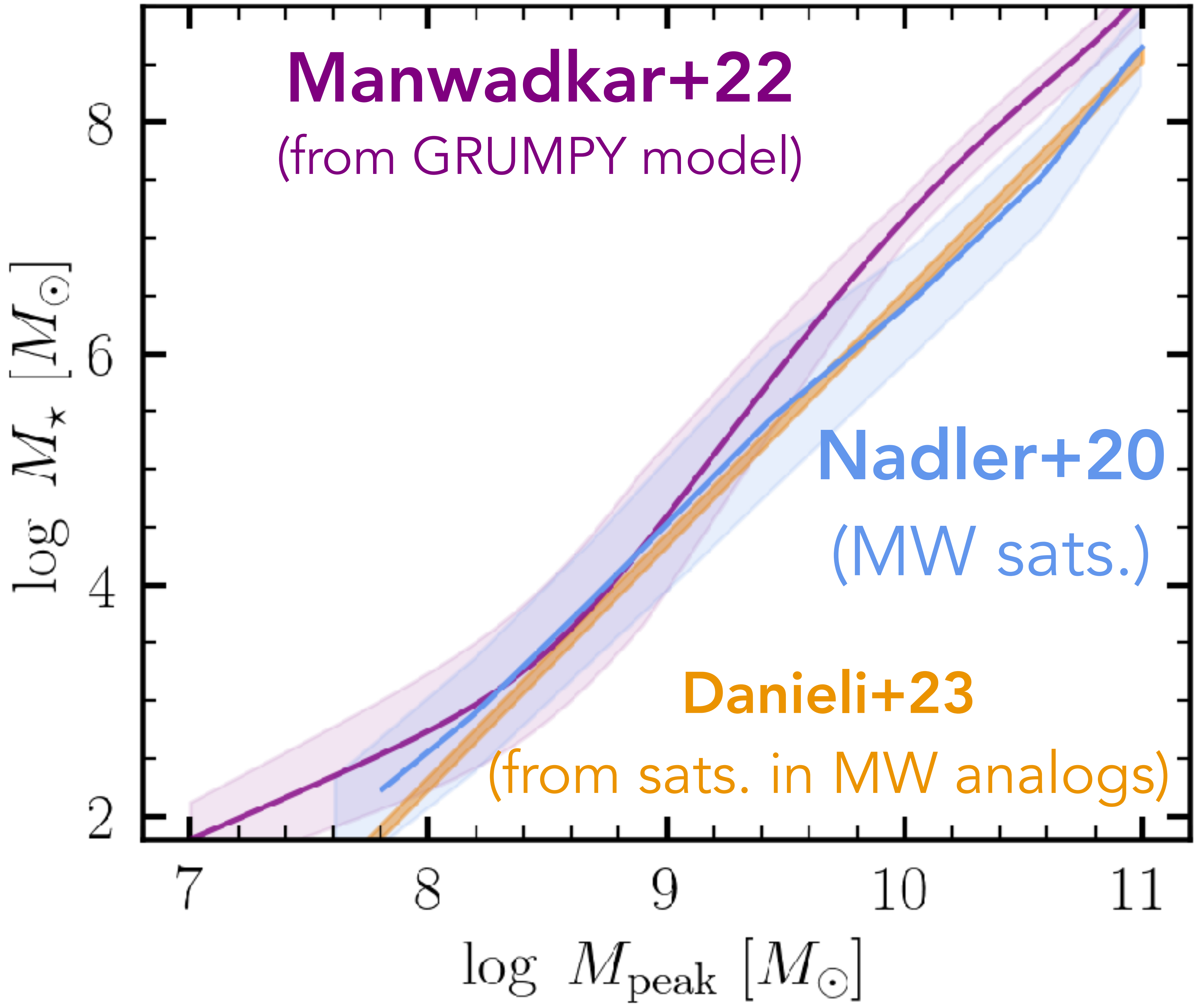
Such satellite-rich systems are very rare



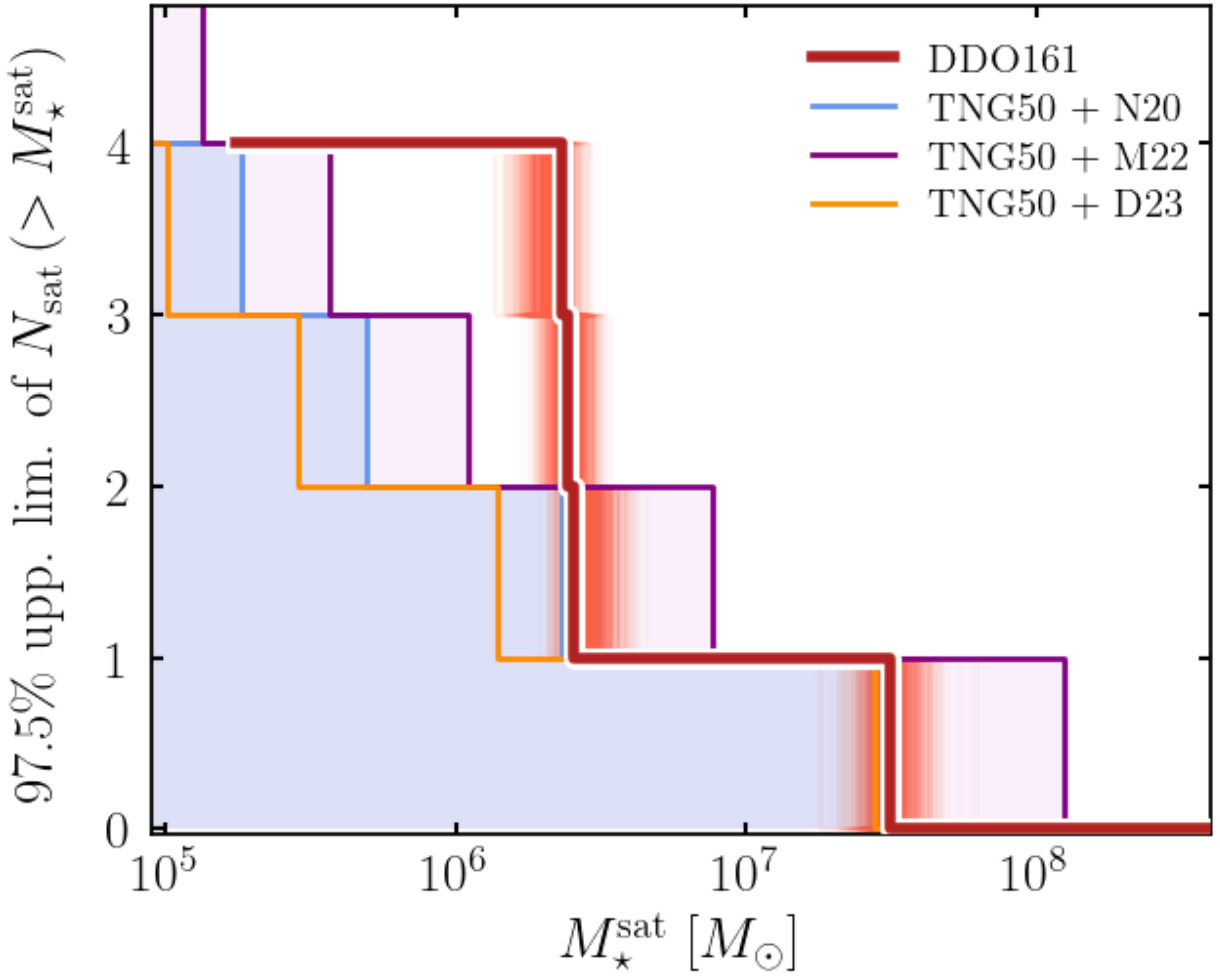
- Is this **numerical issue**? No!
- We only used a **specific galaxy-halo connection** model
  (Try a few others!)

Such satellite-rich systems are very rare

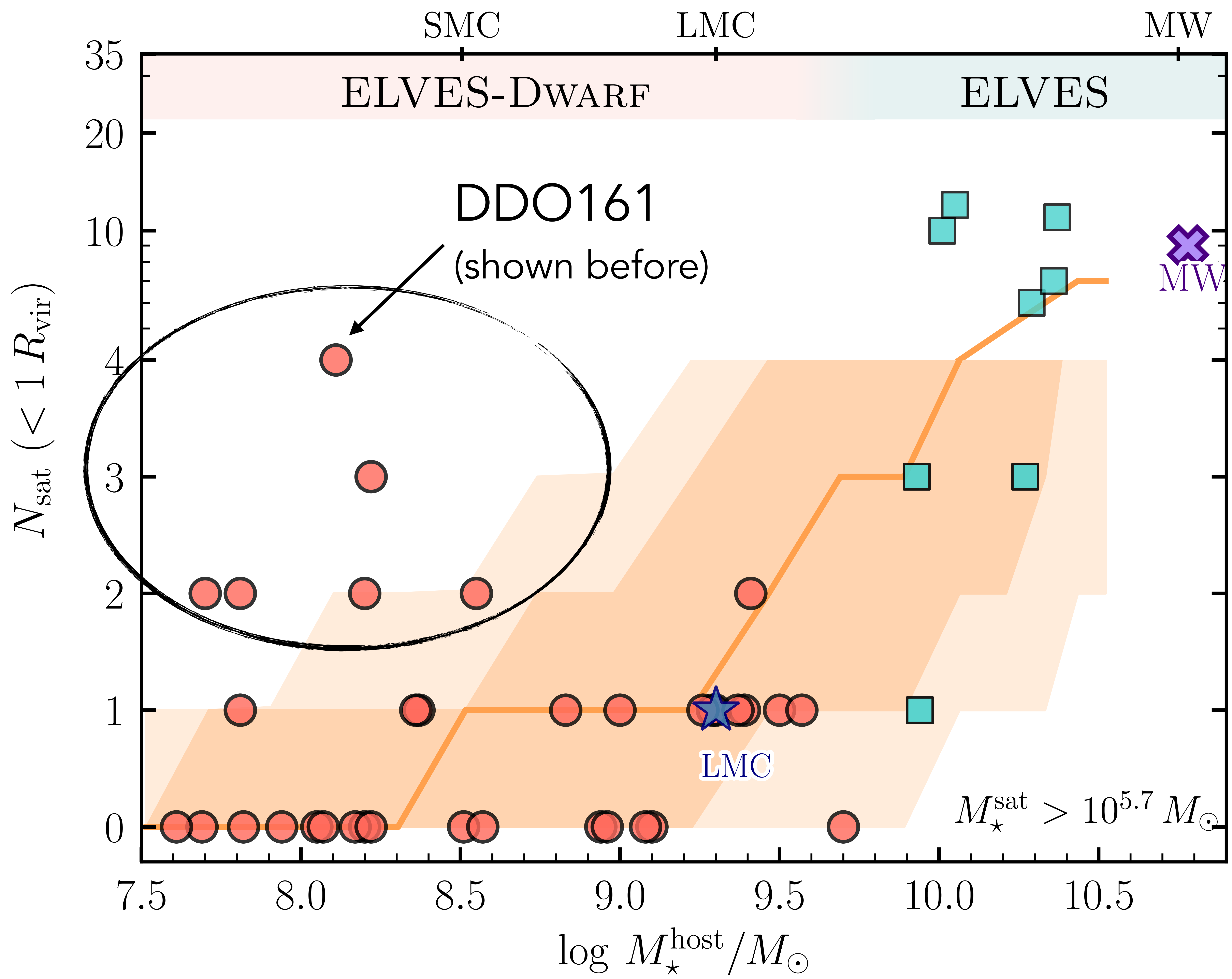
These models are calibrated on satellites in MW-like groups



None of these models could resolve this "too-many-satellites" tension



Probing the limit of galaxy formation model



30 hosts

Li et al. (in prep)

Maybe… for low-mass galaxies,

Galaxy-halo connection

(i.e., galaxy formation efficiency and stochasticity)

depends on environment ?

(MW-group → dwarf group → field)

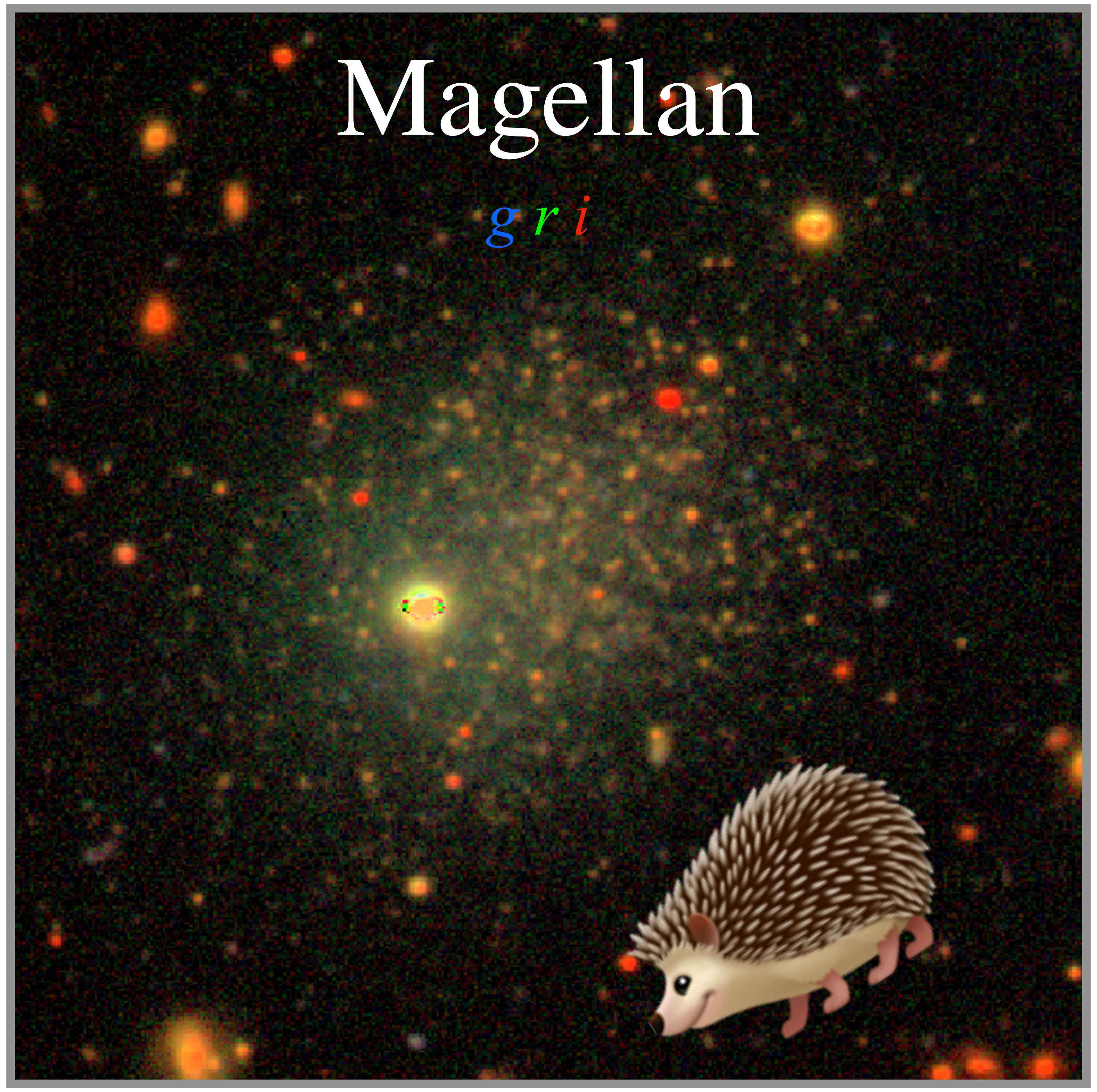
An intriguing dwarf in isolation:

Hedgehog

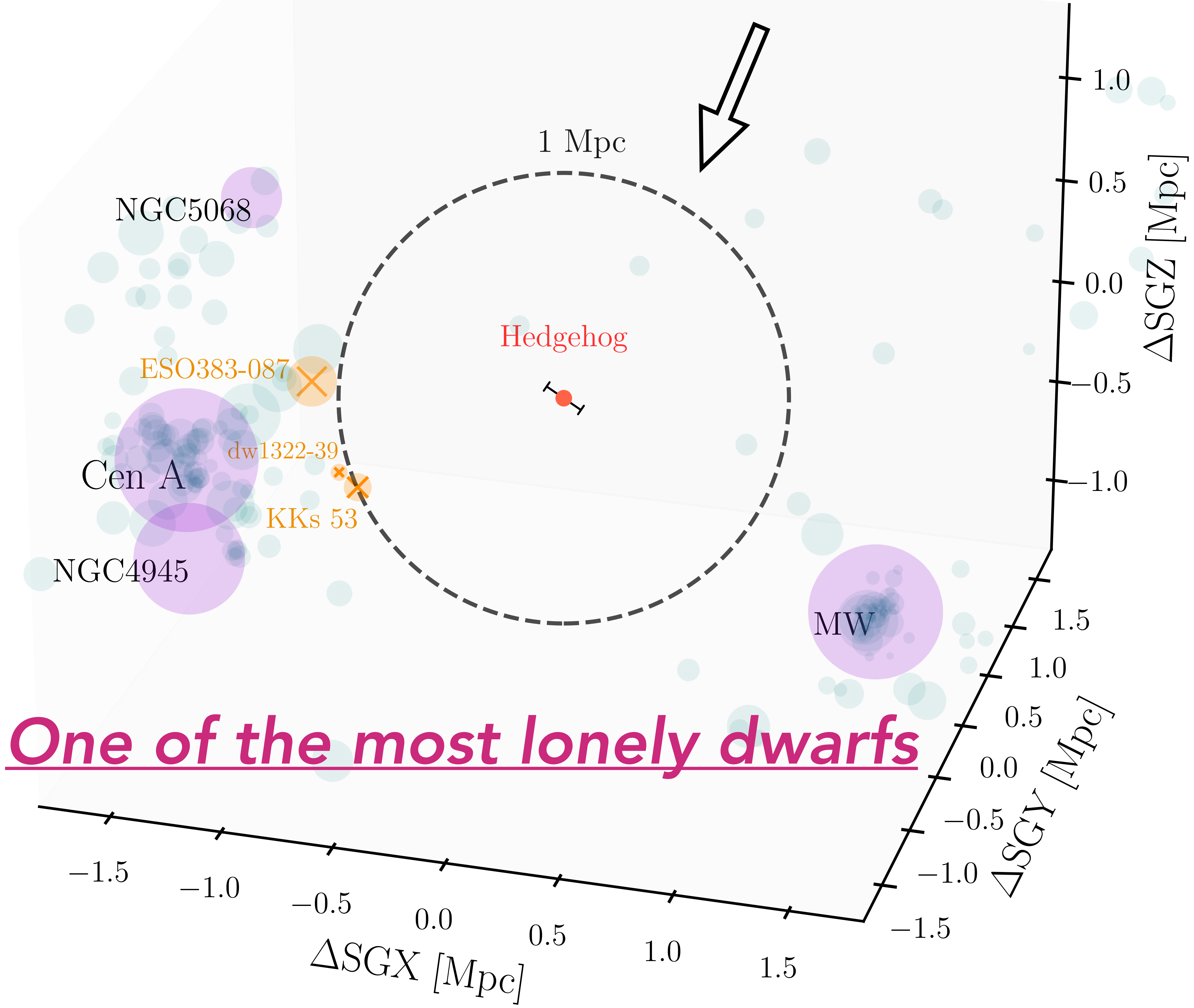
J. Li et al. (2024)
arXiv:2406.00101

A (serendipitously found) quiescent dwarf at 2.4 Mpc

$M_\star \approx 10^{5.8}\ M_\odot \quad M_V \approx -9.8$



No known neighbors within 1 Mpc



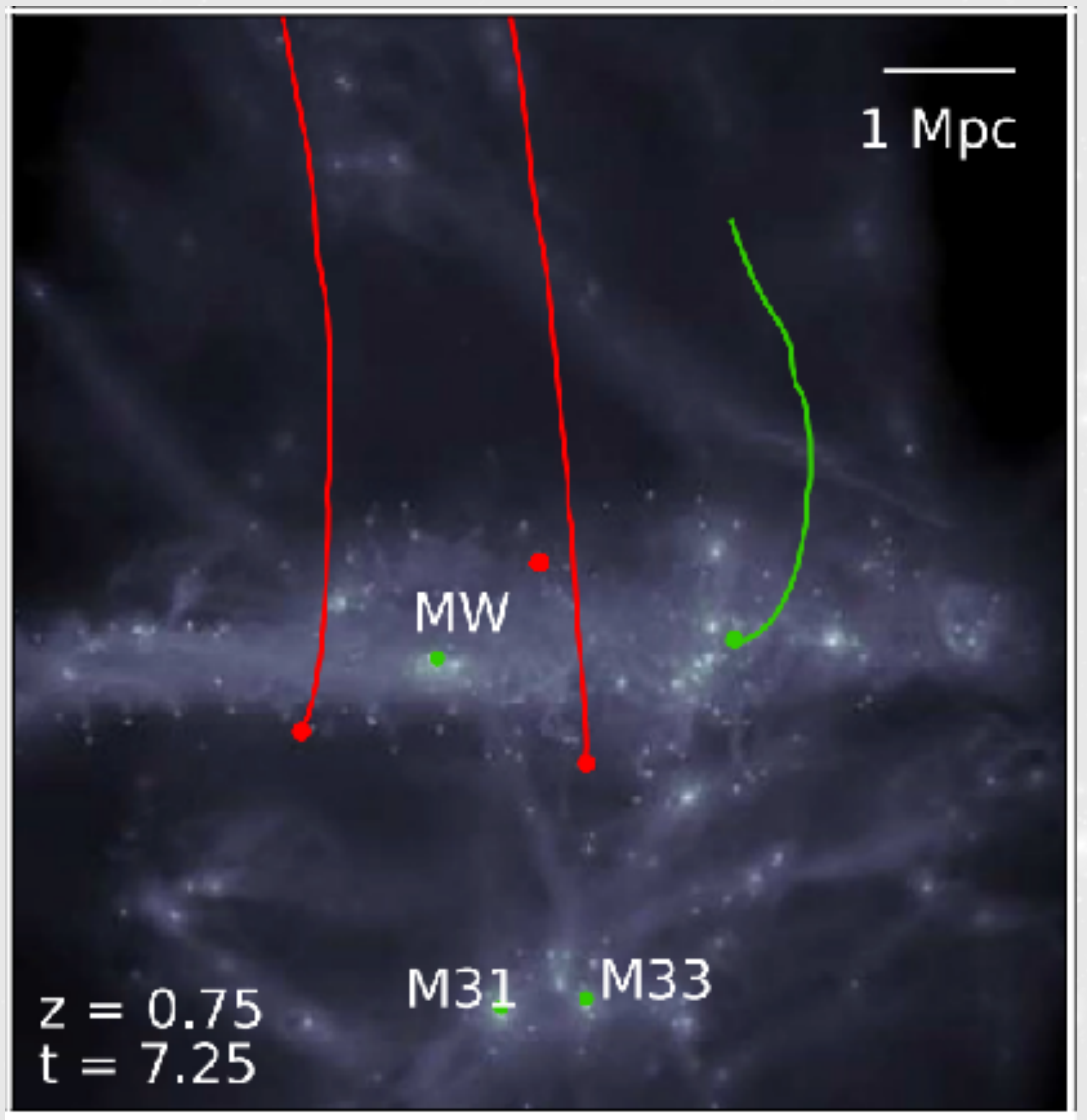
One of the most lonely dwarfs

Red dSph ⇨ Quiescent ⇦ NO UV and HI

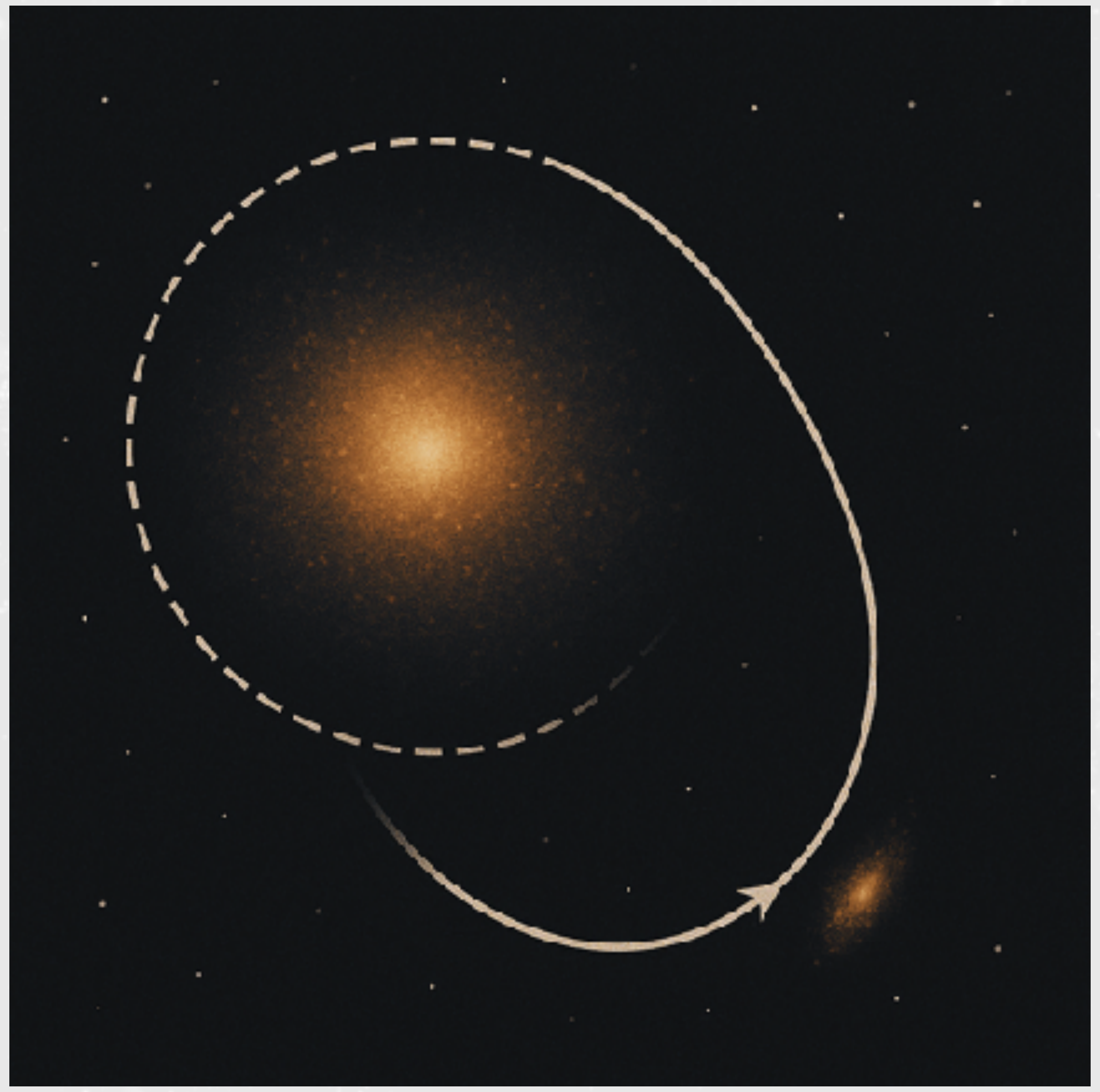
Field Dwarfs: How are they quenched?

Isolated **quiescent** dwarfs are very rare at $M_\star \approx 10^{7-9}\,M_\odot$ (<0.06%, Geha+12)

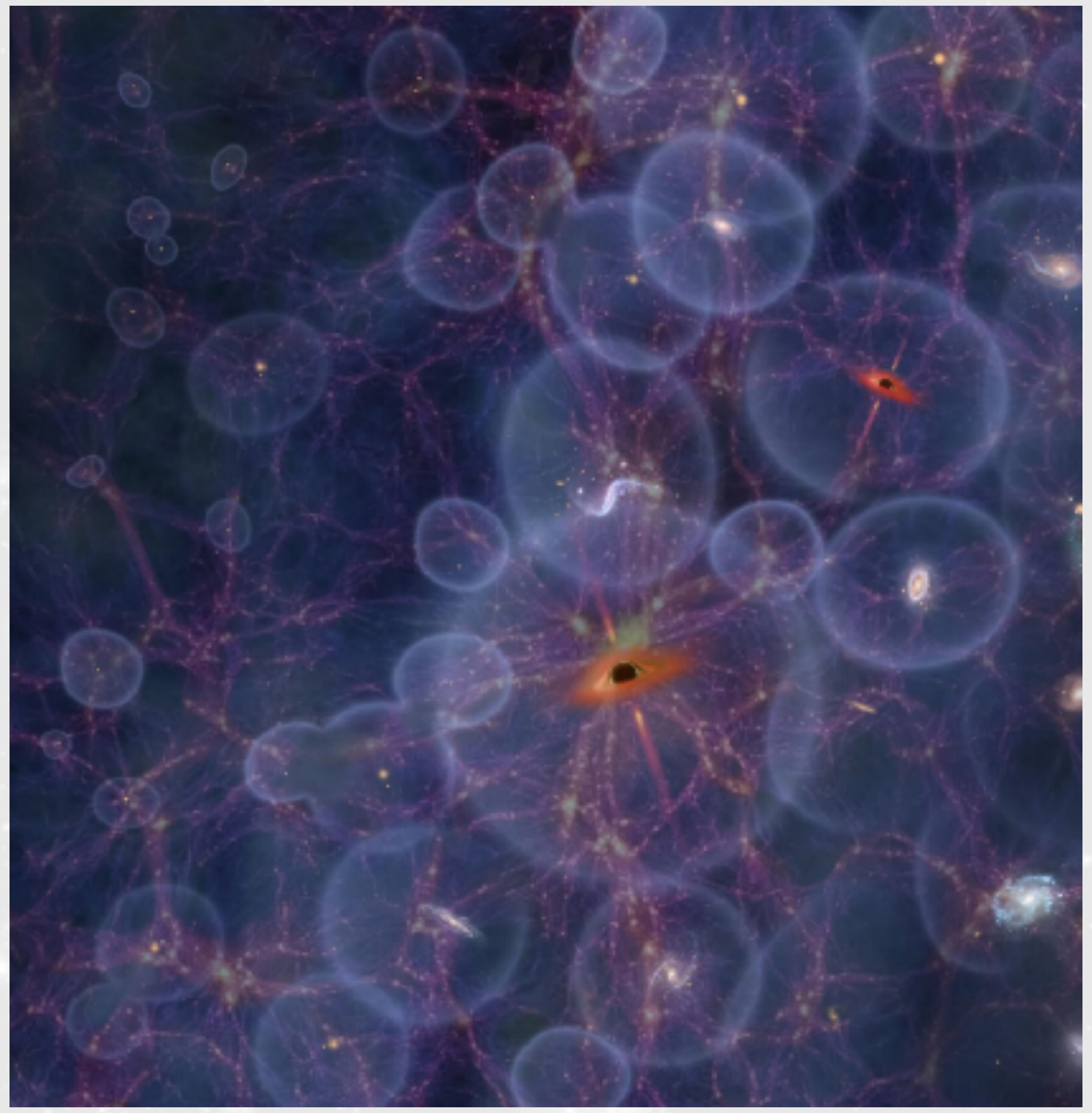
Only a handful of such objects known (including Ava Polzin's COSMOS-dw1)



Cosmic web stripping

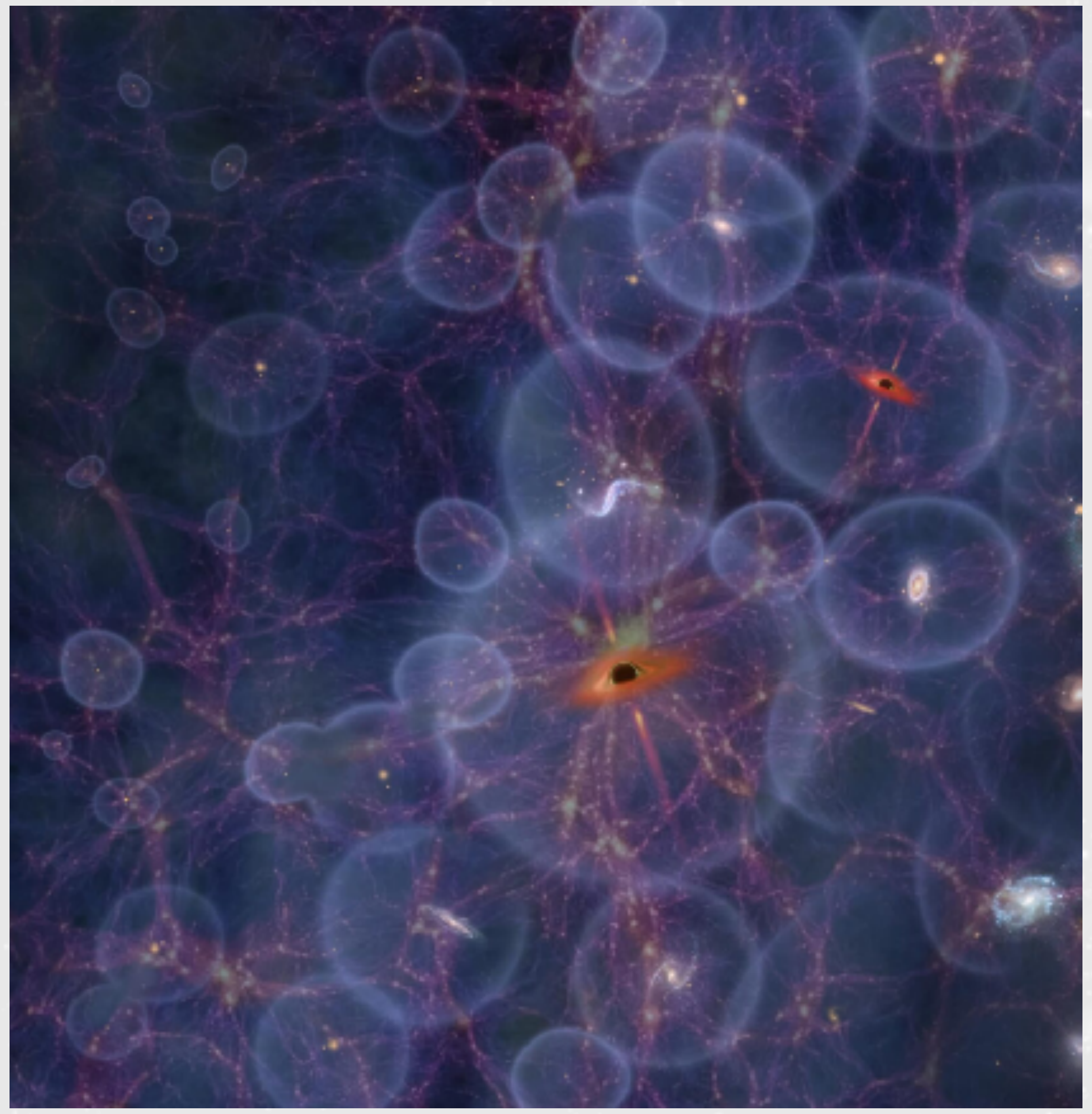


Backsplash dwarf



Reionoization

Hedgehog be a clean test for Reionization Quenching



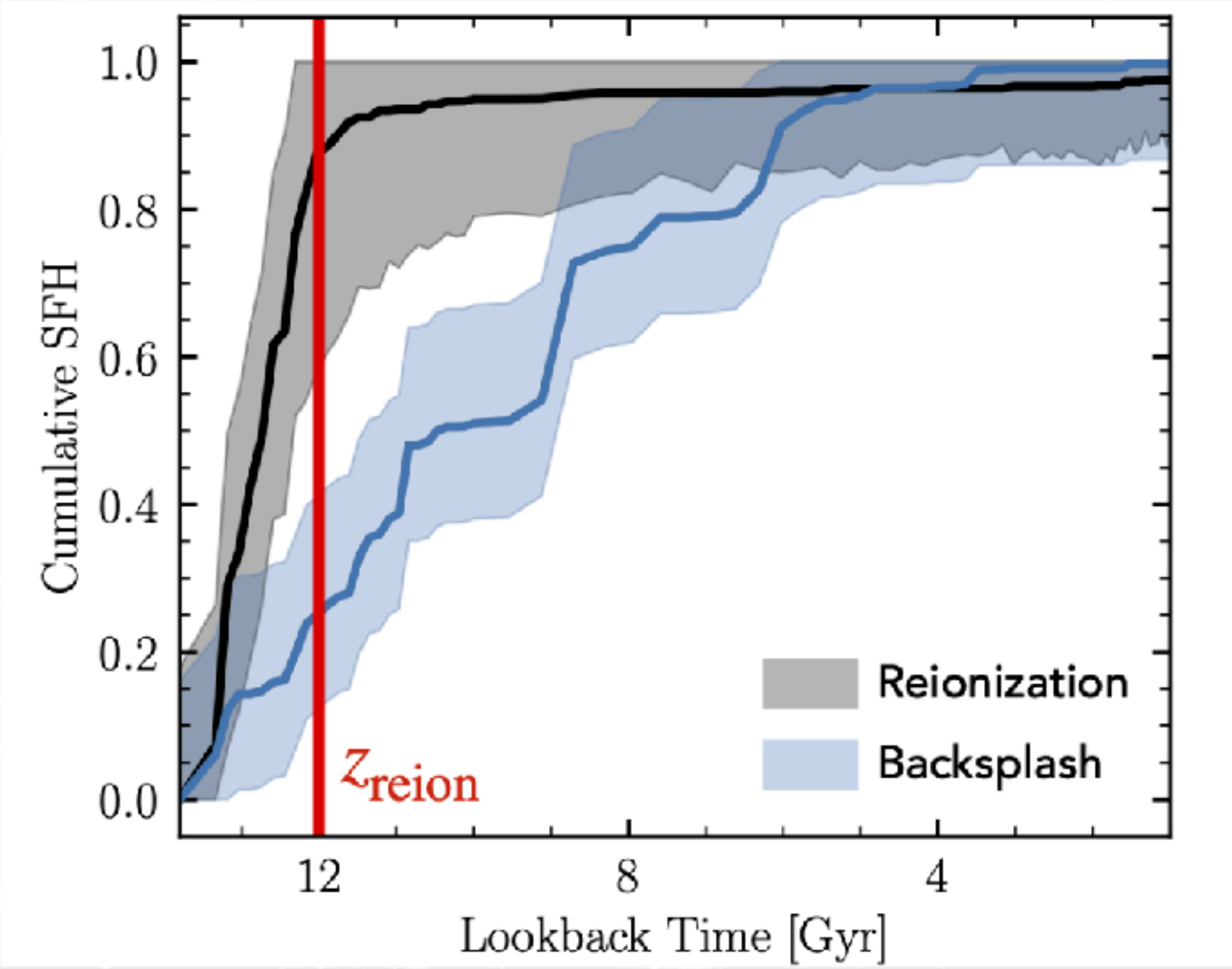
Reionoization

Reionization at z=6 is believed to quench dwarfs $M_\star < 10^5\,M_\odot$ (e.g., Savino+23)

This threshold is unknown, and it must be a halo mass threshold

If Hedgehog lives in a small dark matter halo, it can still be quenched by reionization

With 30 orbits on HST (PI: Li), we will know the answer



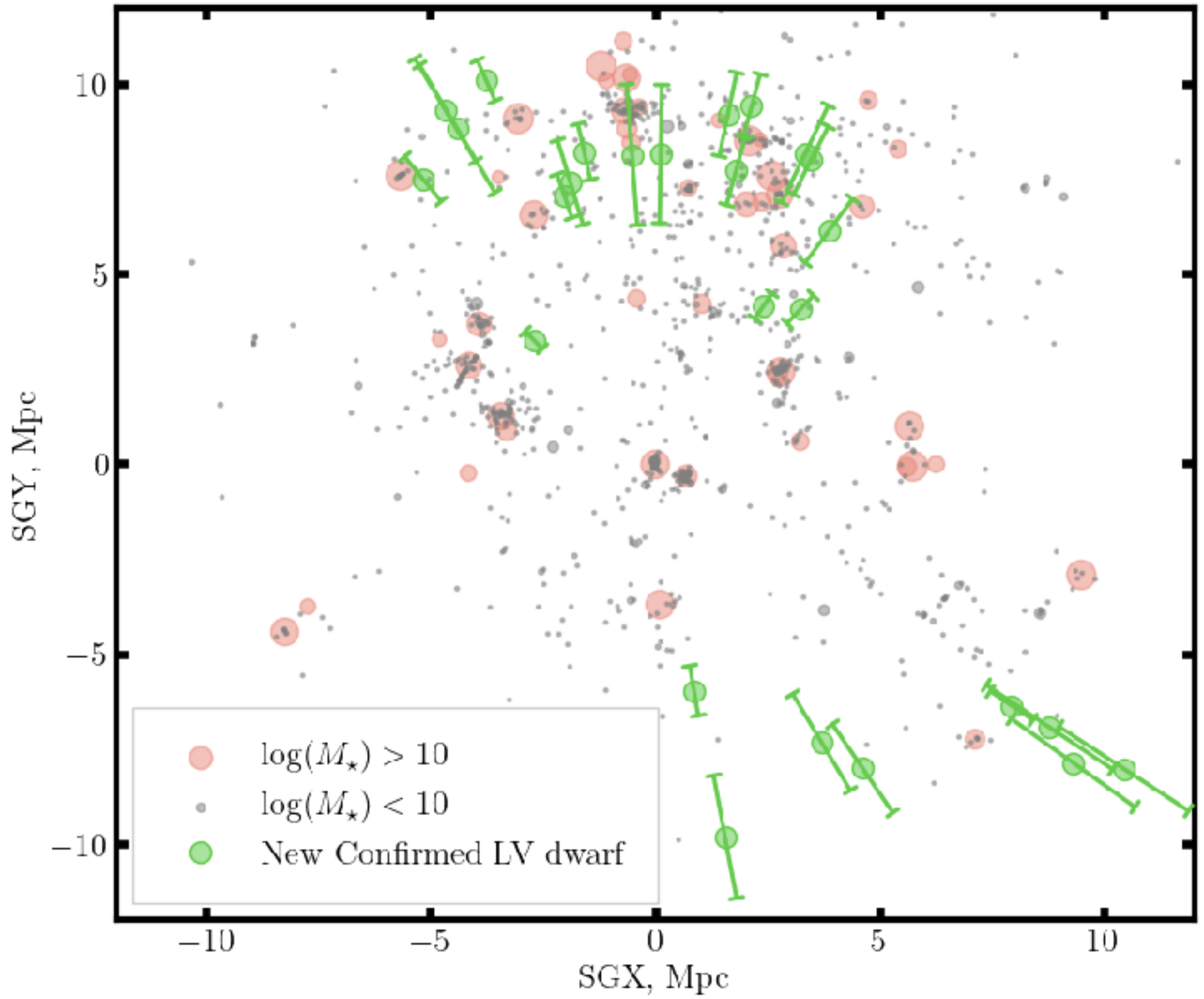
ELVES-Field: systematic search for field dwarfs

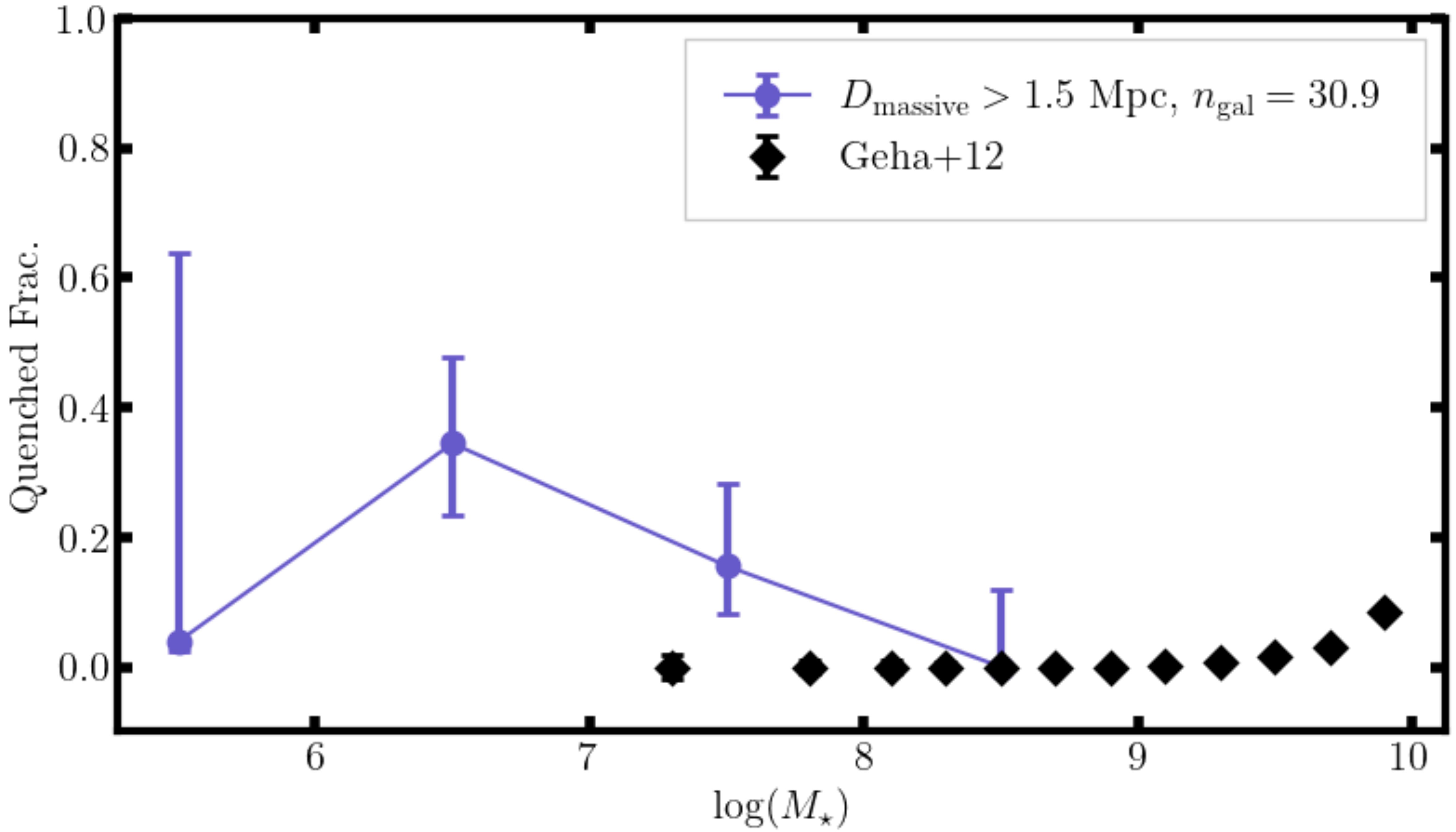
Field dwarf search is more difficult because you don't know where to look!

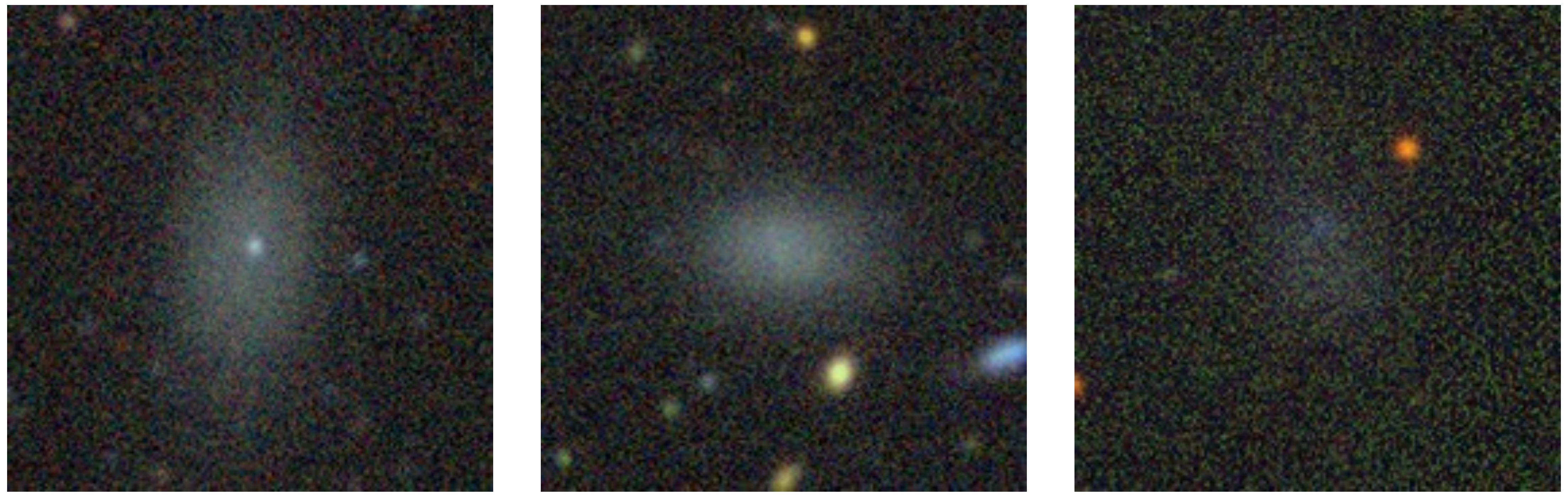
Led by Scott Carlsten

3000 sq deg in DECaLS+HSC

41 dwarfs, ~14 are new

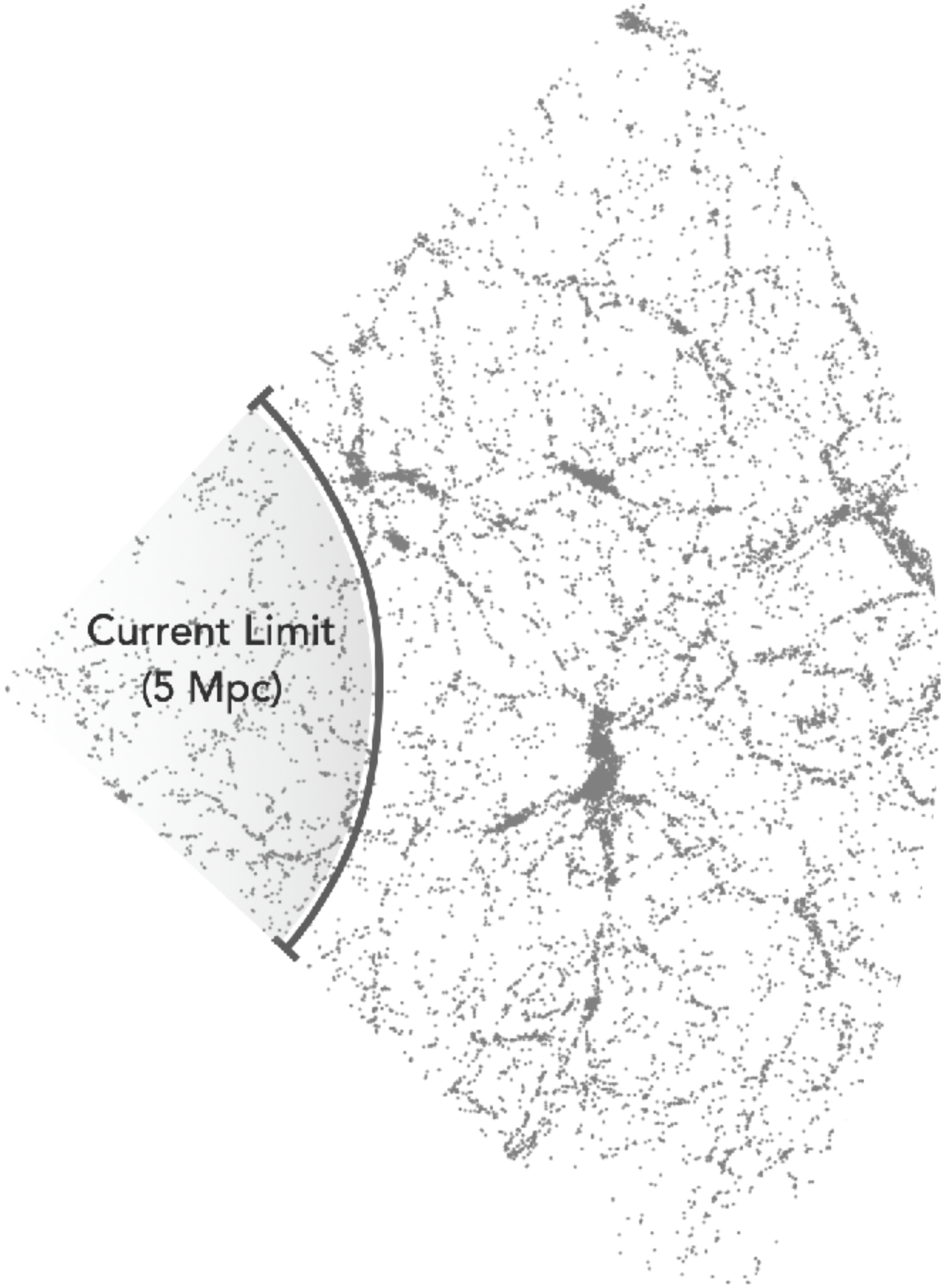




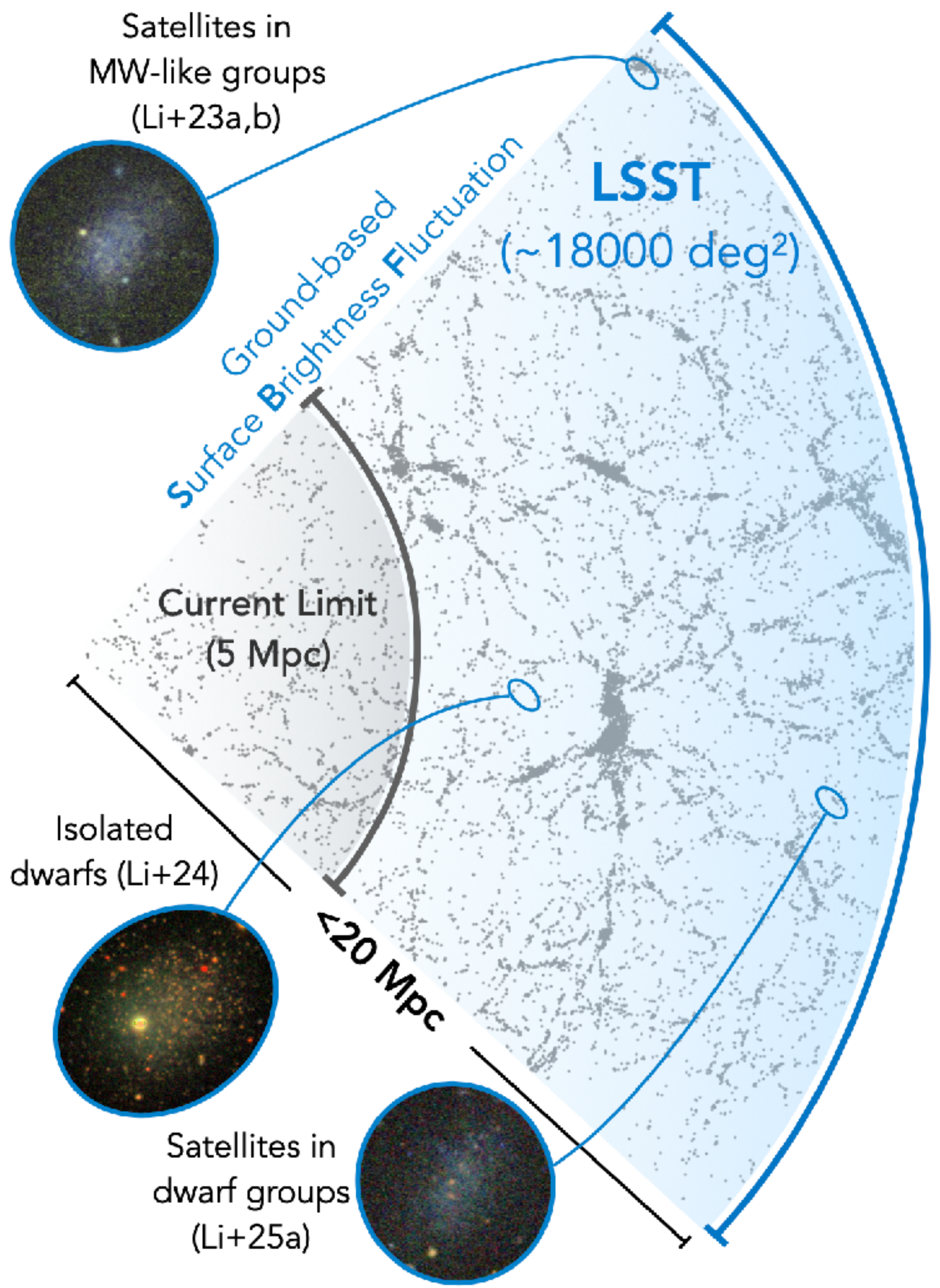


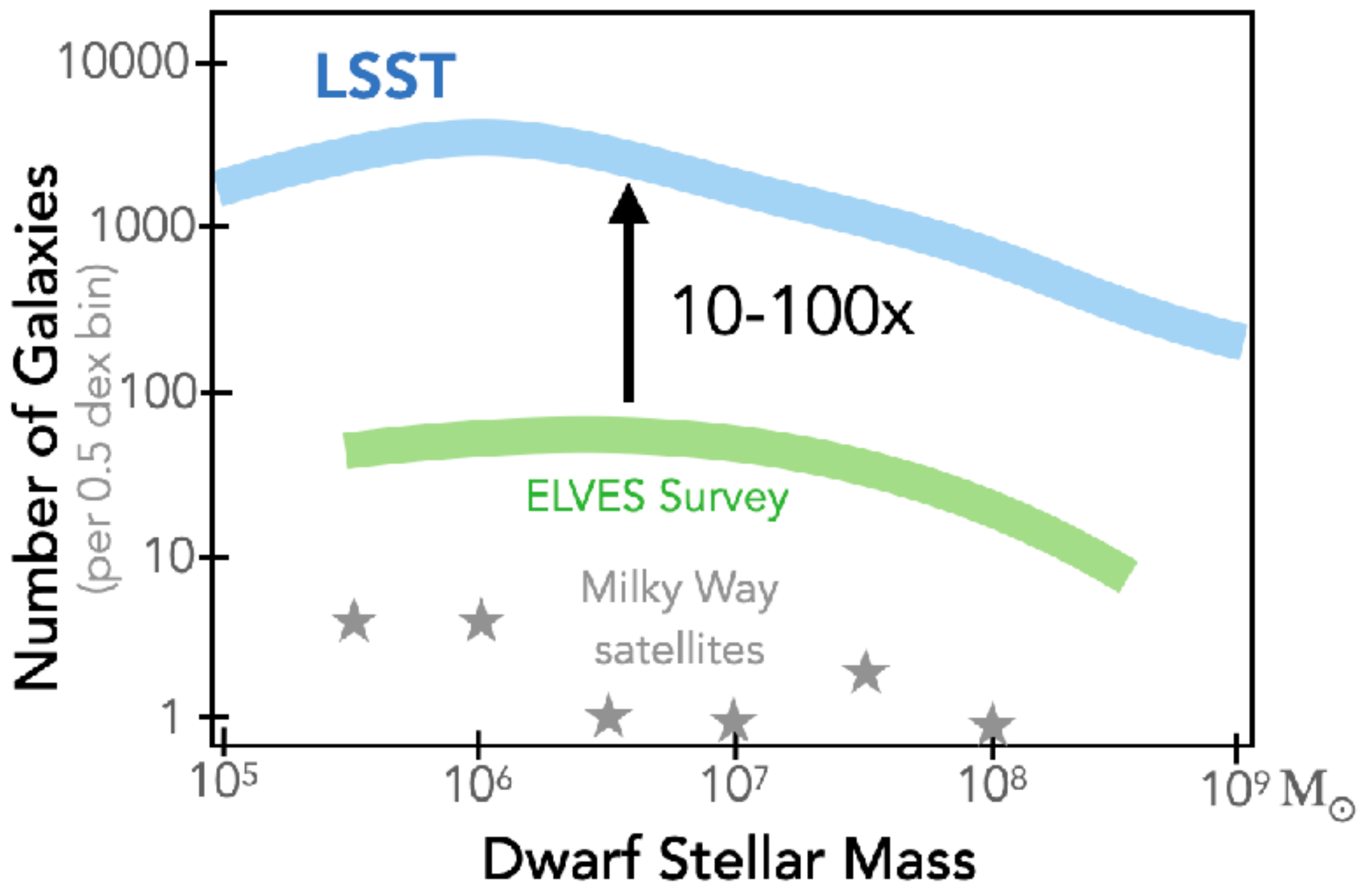
We still don't quite **understand galaxy formation** in low-mass regime because:

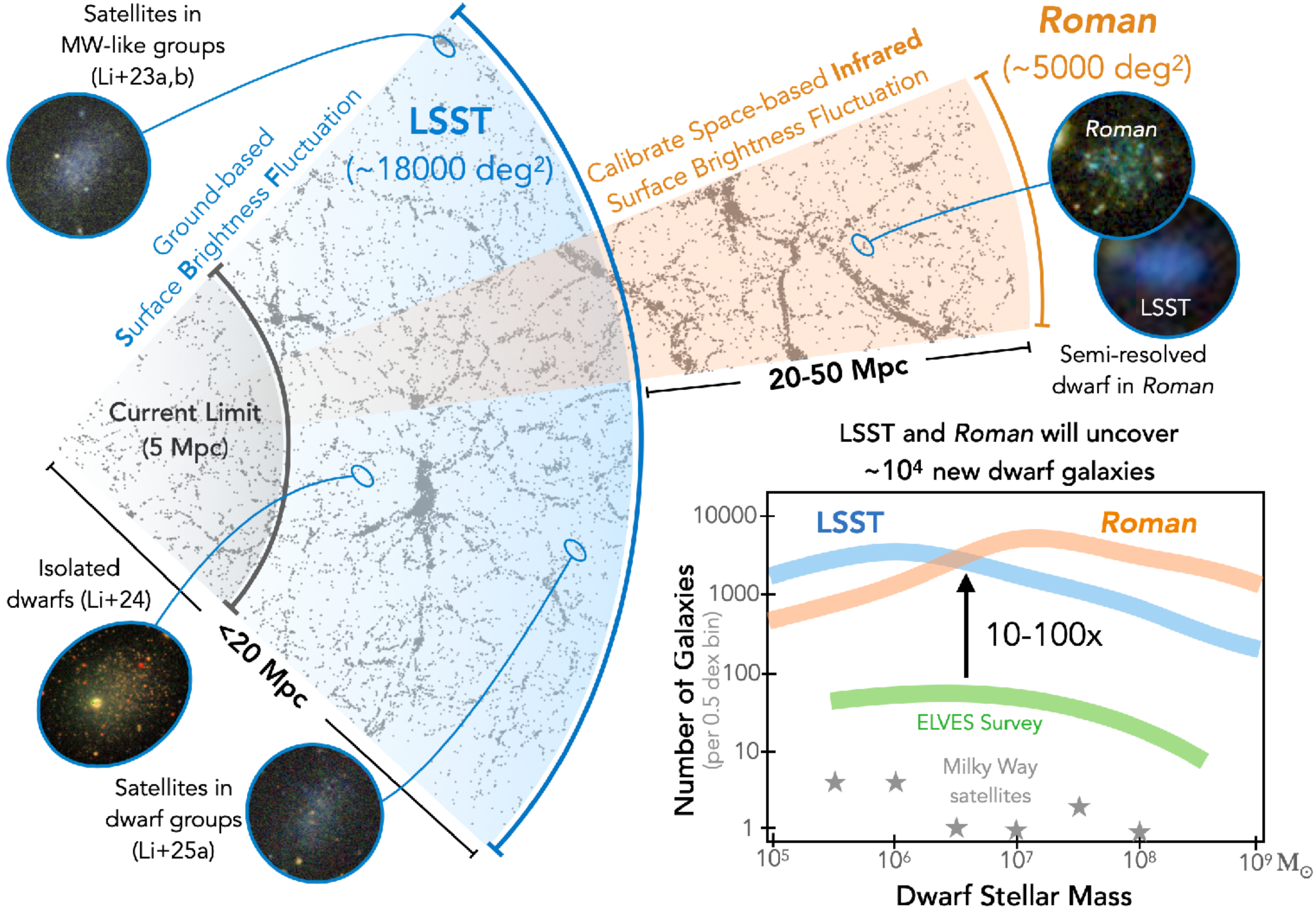
- We've mostly focused on **satellites** of MW groups
- We are **incomplete** at $M_\star \approx 10^6\, M_\odot$ even within a few Mpc



In the next 5 years…



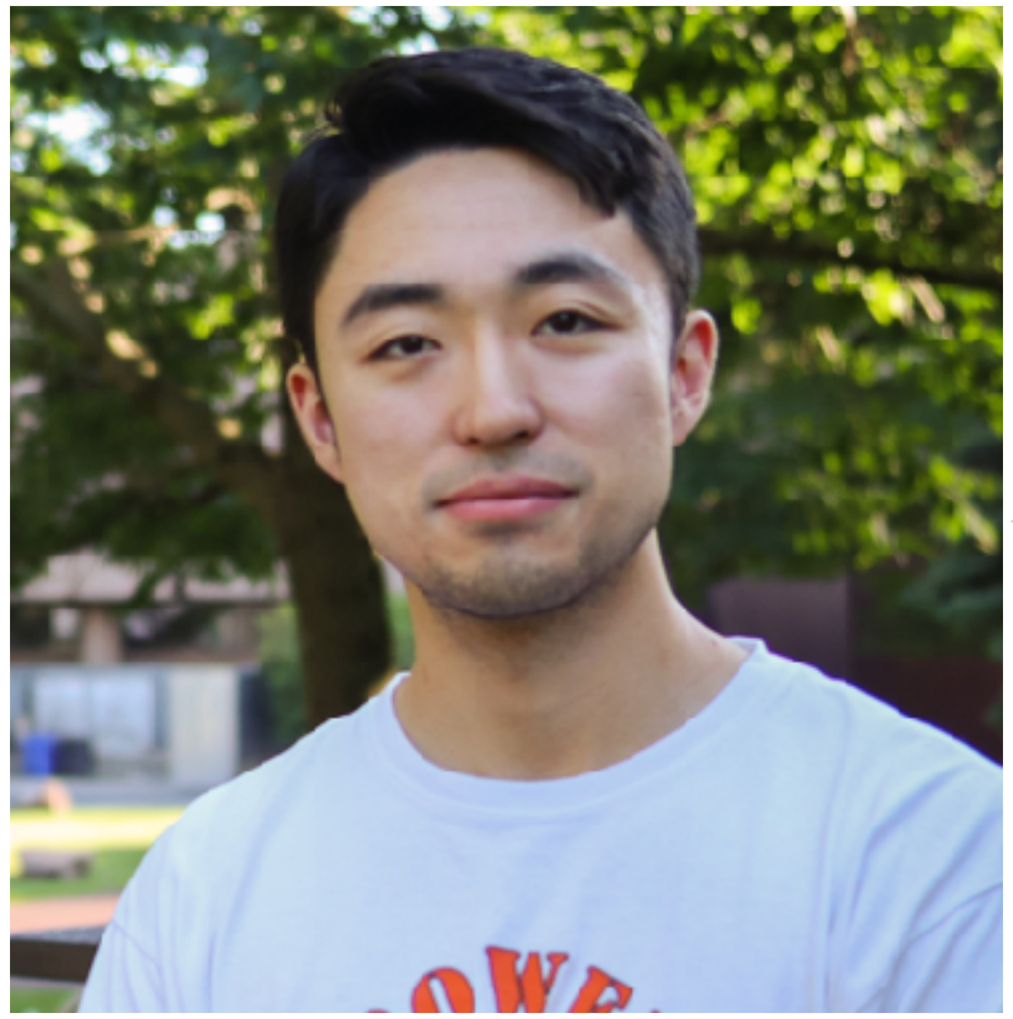



Satellites in
MW-like groups
(Li+23a,b)
LSST
(~18000 deg²)
Ground-based
Surface Brightness Fluctuation
Calibrate Space-based Infrared
Surface Brightness Fluctuation
Roman
(~5000 deg²)
Roman
LSST
Semi-resolved
dwarf in Roman
20-50 Mpc
Current Limit
(5 Mpc)
<20 Mpc
Isolated
dwarfs (Li+24)
Satellites in
dwarf groups
(Li+25a)
LSST and Roman will uncover
~10⁴ new dwarf galaxies
LSST
Roman
10-100x
ELVES Survey
Milky Way
satellites
Number of Galaxies
(per 0.5 dex bin)
10000
1000
100
10
1
10⁵
10⁶
10⁷
10⁸
10⁹ M☉
Dwarf Stellar Mass

Discovery of a new **Dwarf Planet** candidate

Sihao Cheng (IAS)

I want to search for Planet 9, but what's the best dataset?



Me

Try Dark Energy Camera Legacy Surveys?

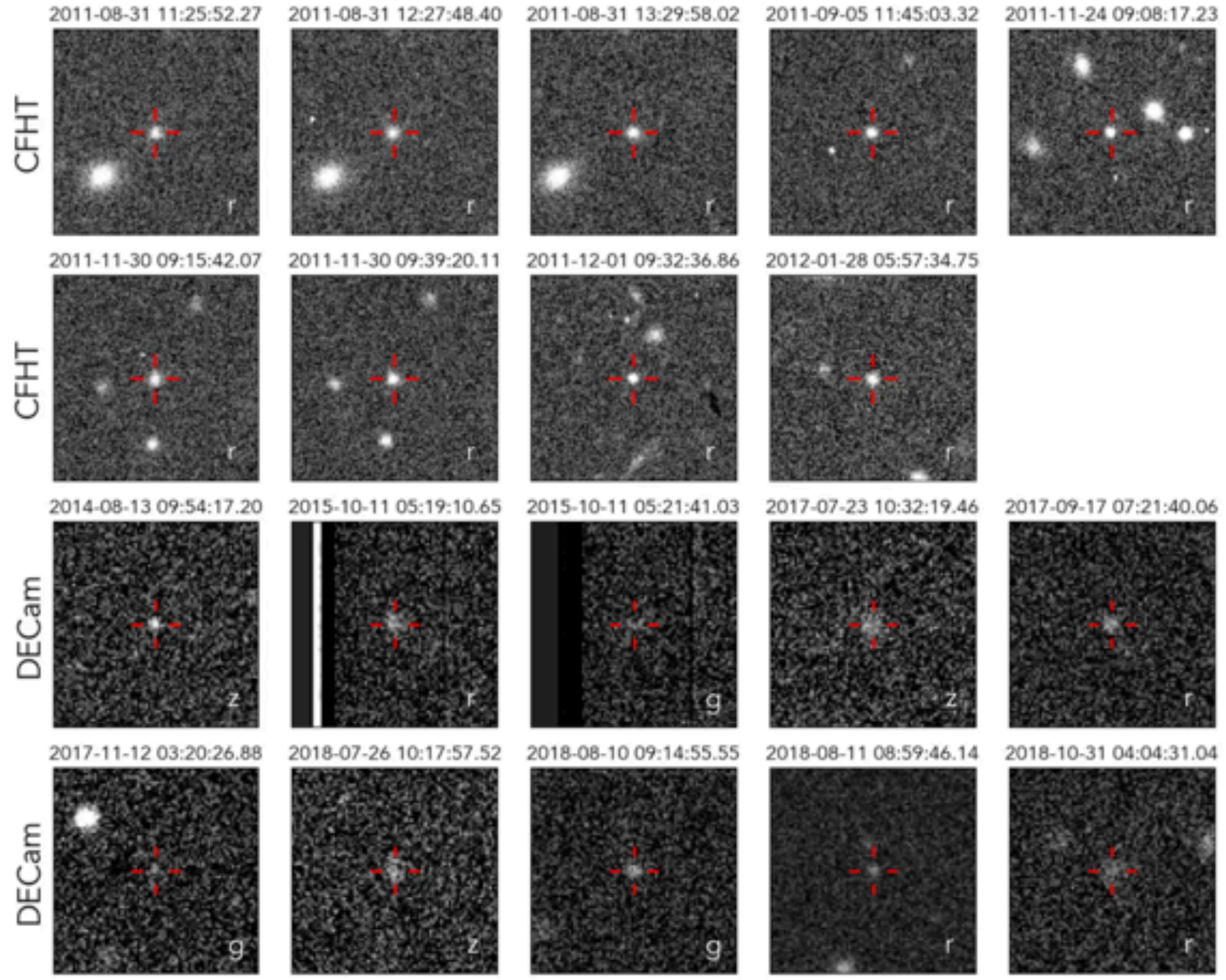
The New York Times

Scientists Say They've Found a Dwarf Planet Very Far From the Sun

The small world was found during a search for the hypothetical Planet Nine, and astronomers say the next time it will reach its closest point to the sun is in the year 26186.

Listen to this article · 8:10 min Learn more

Share full article

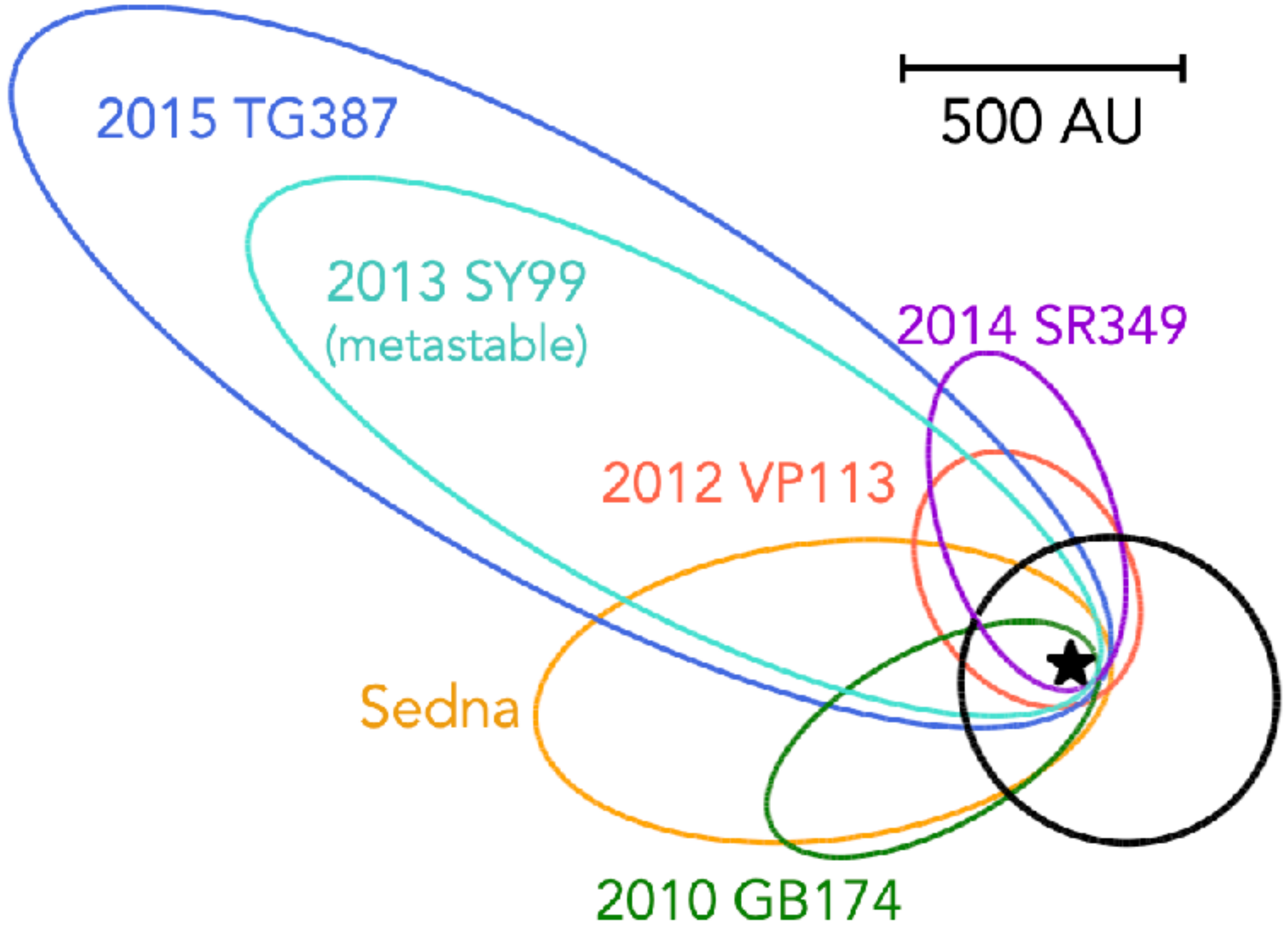


All 19 detections of the dwarf planet 2017 OF201, from August 2011 to October 2018.
Cheng et al., arxiv.org, 2025

Planet 9 (or X) Hypothesis

Orbital clustering
caused by Planet 9

We need to find slow-moving and bright object!

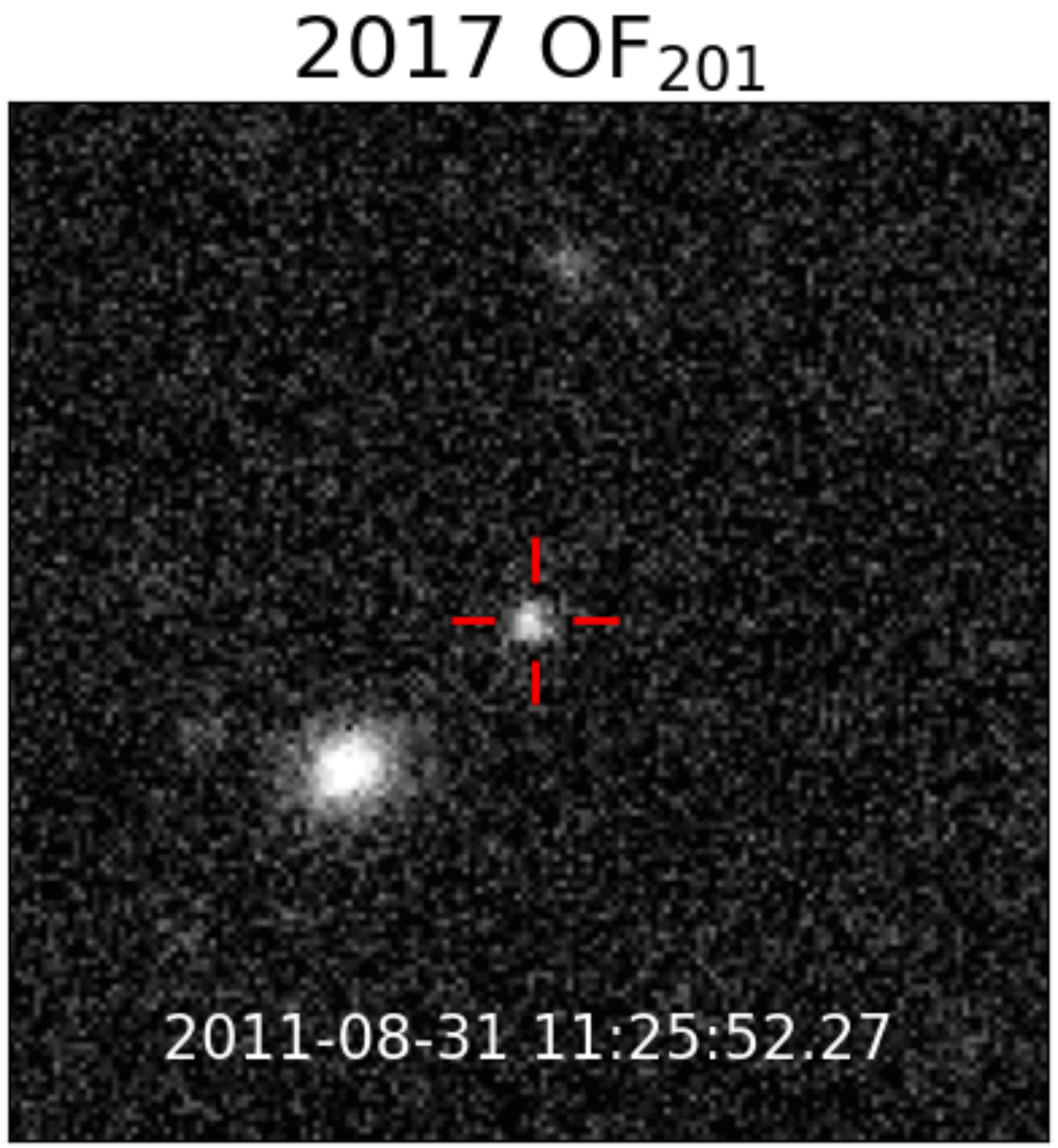


Planet X at 300 AU, $4\,M_\oplus$

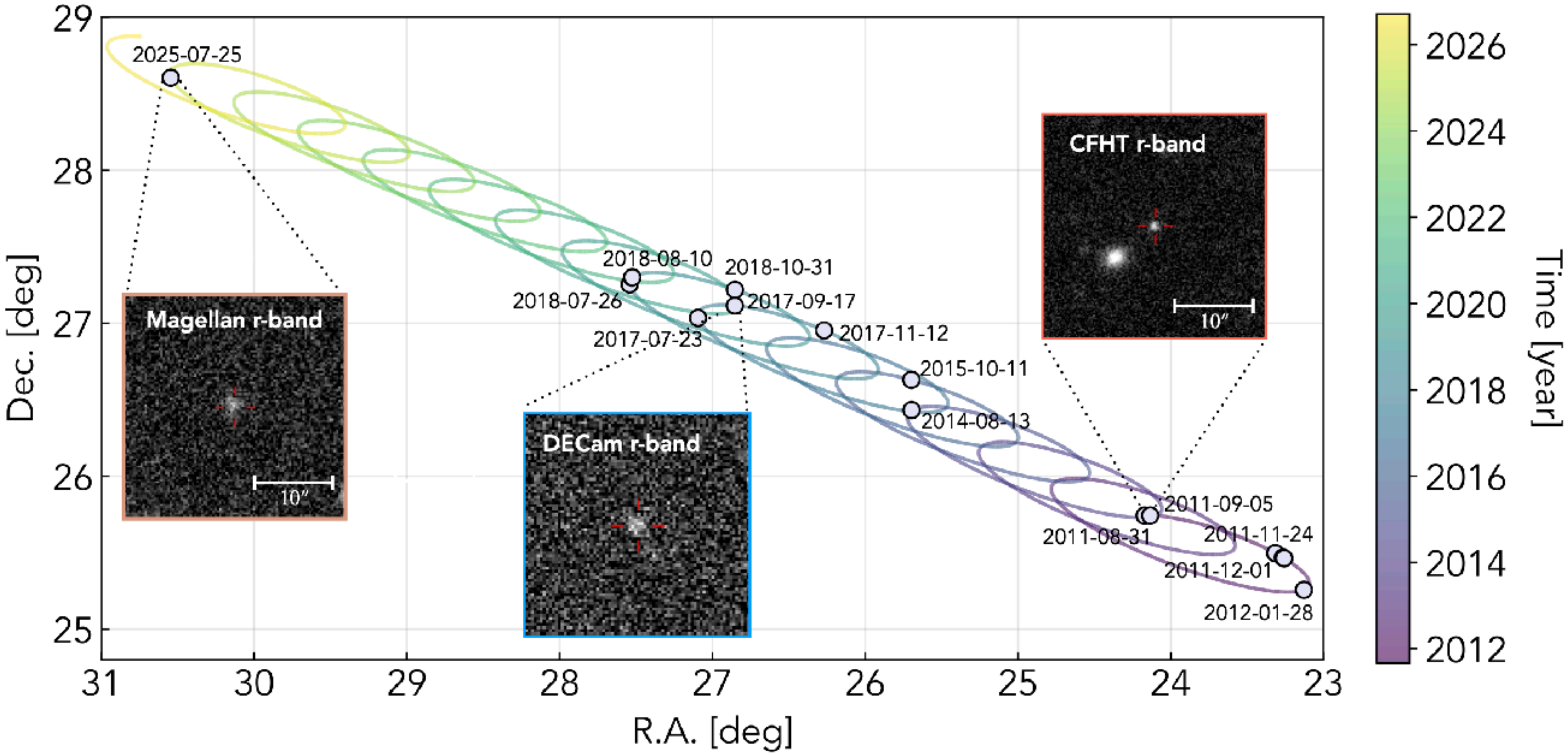
(Siraj+25)

Discovery of a **Dwarf Planet** candidate

Led by Sihao Cheng (IAS)

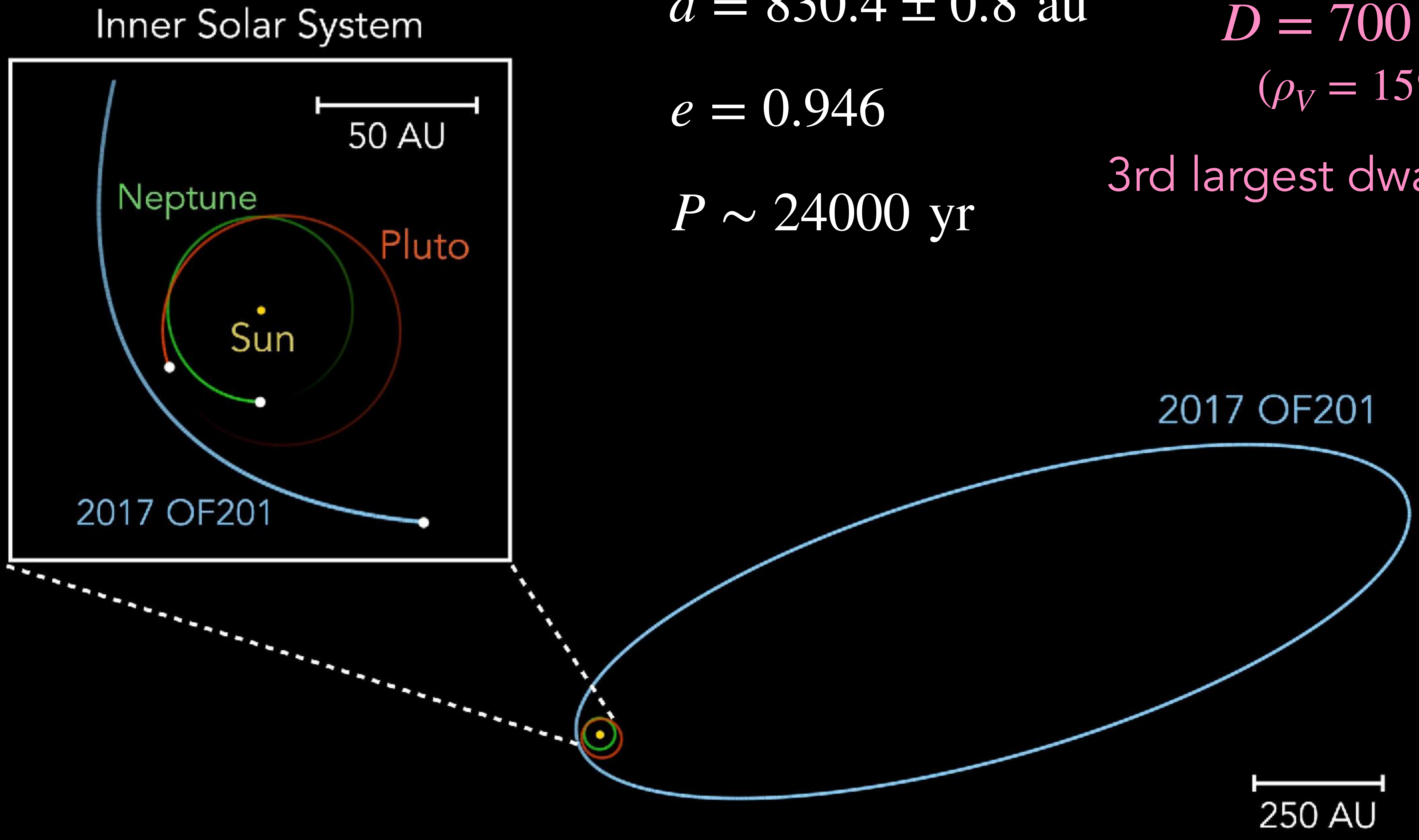


Bright and slow-moving



22 detections spanning 20 years, enabling very precise orbit determination (<0.1%)

Cheng, Li, Yang (2025)



$a = 830.4 \pm 0.8$ au

$e = 0.946$

$P \sim 24000$ yr

$D = 700$ km

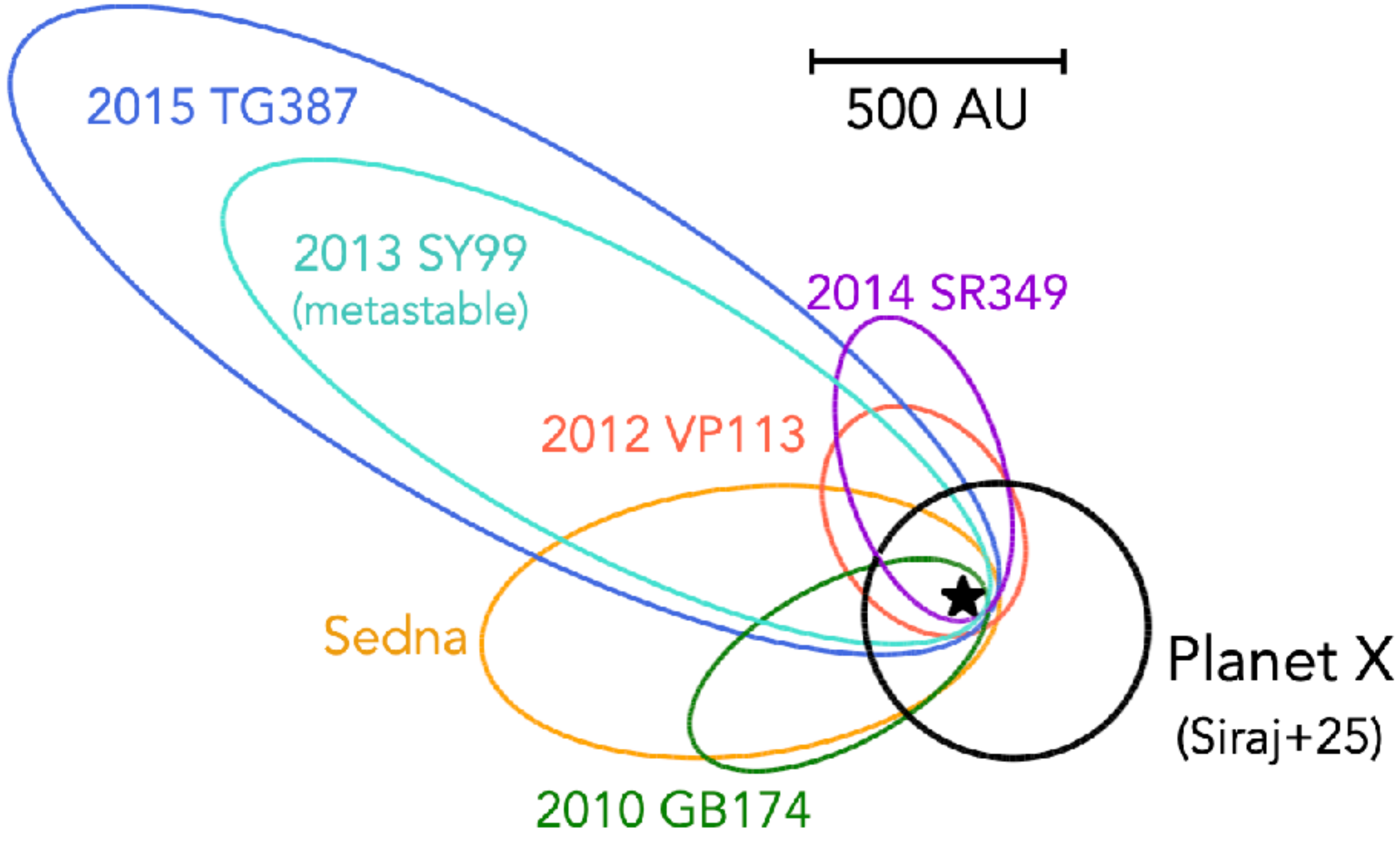
$(\rho_V = 15\%)$

3rd largest dwarf planet

Planet 9 (or X) Hypothesis

Orbital clustering caused by Planet 9

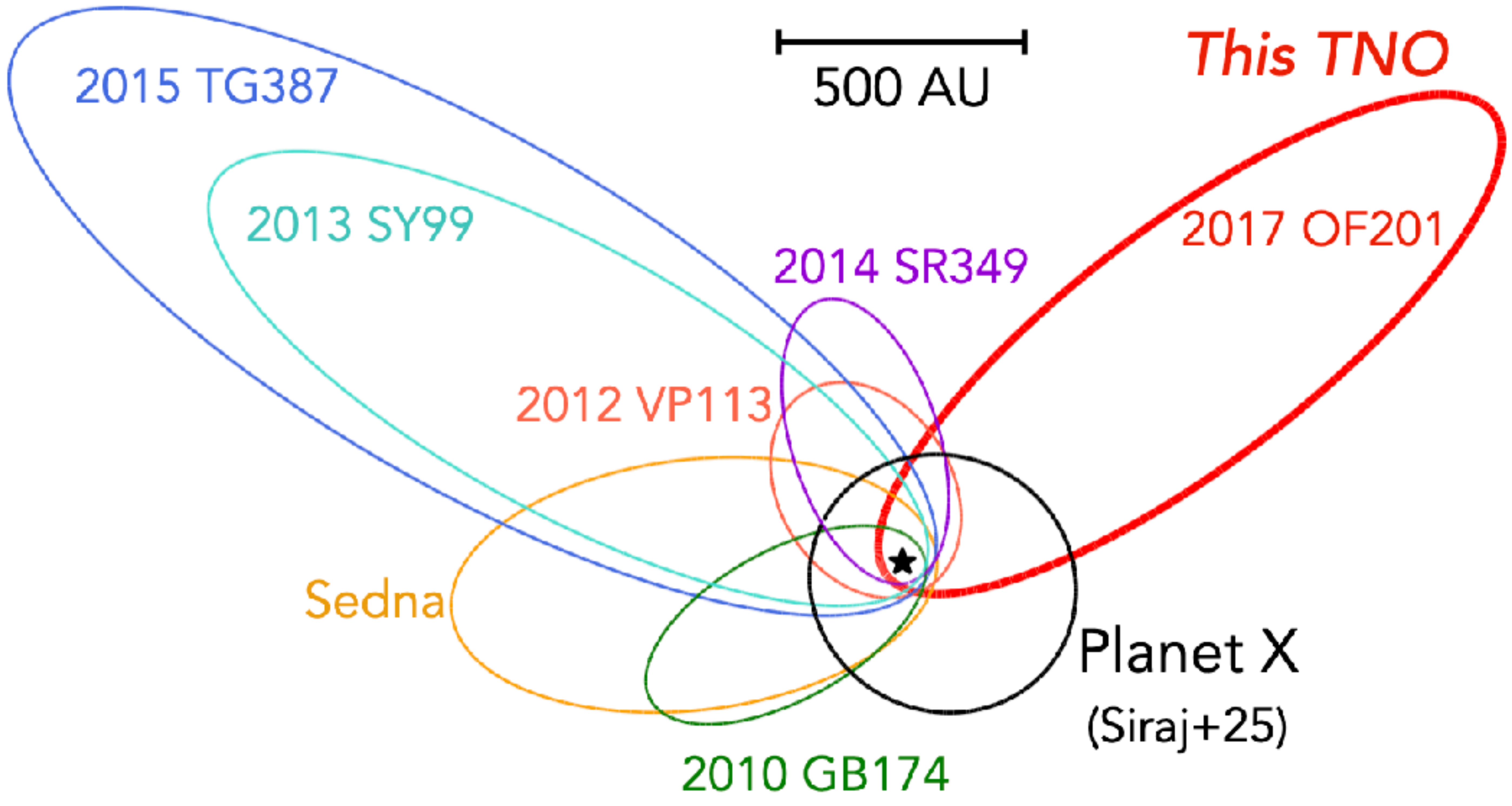
We need to find slow-moving and bright object!

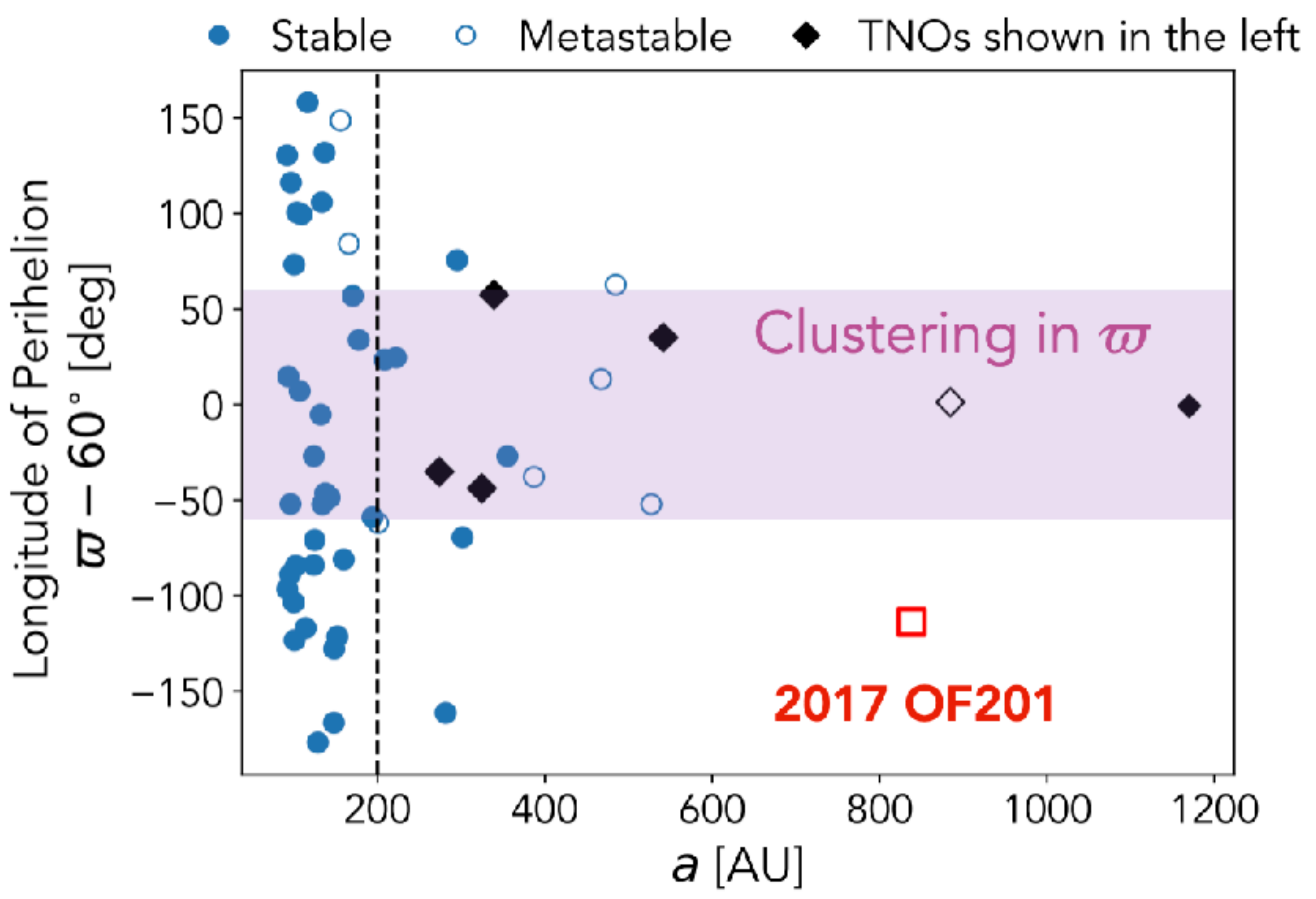


300 AU, $4\,M_{\oplus}$

Implication for **Planet 9** Hypothesis

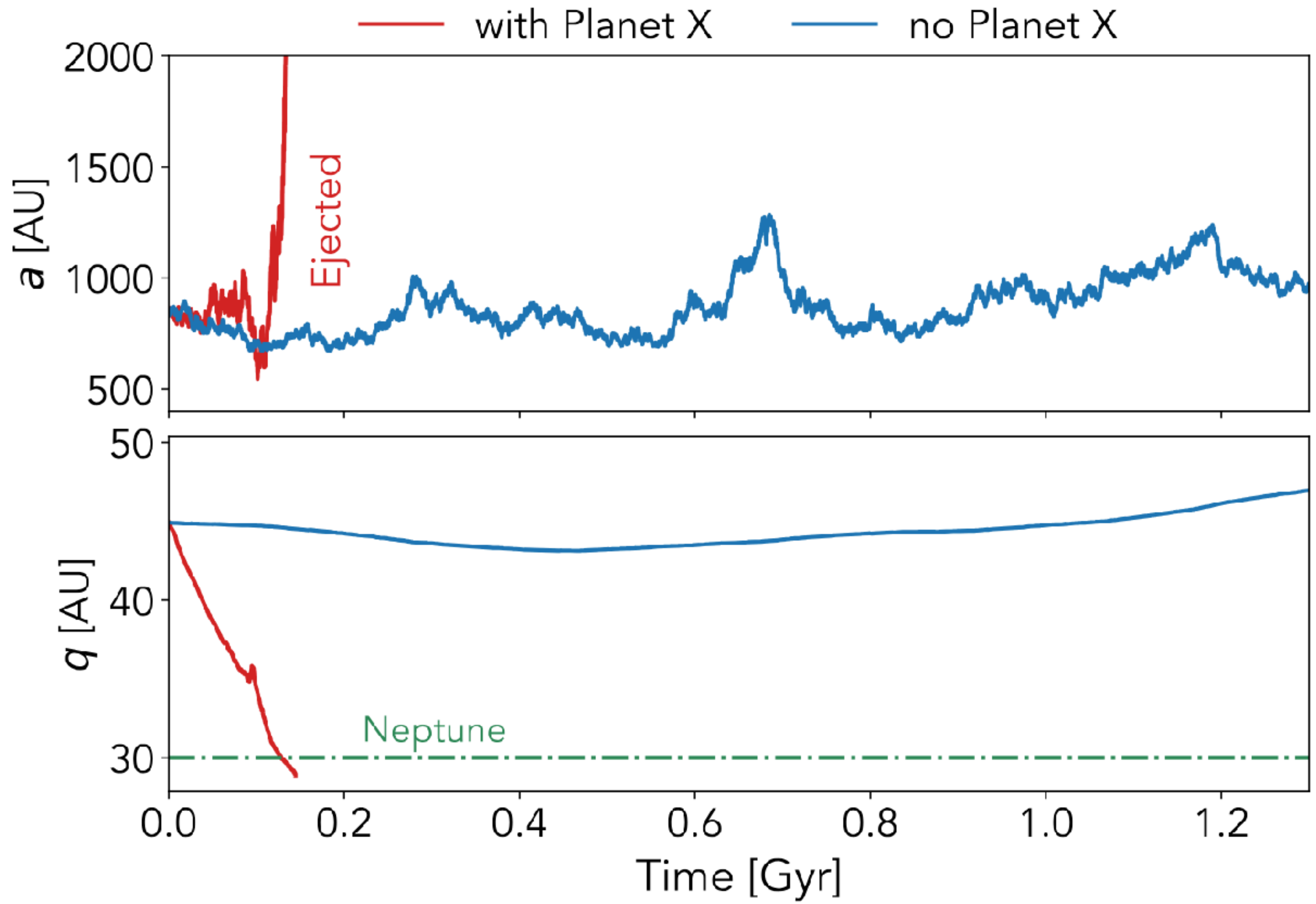
This TNO is outside of the orbital cluster, which is the evidence of P9





Implication for Planet 9 Hypothesis

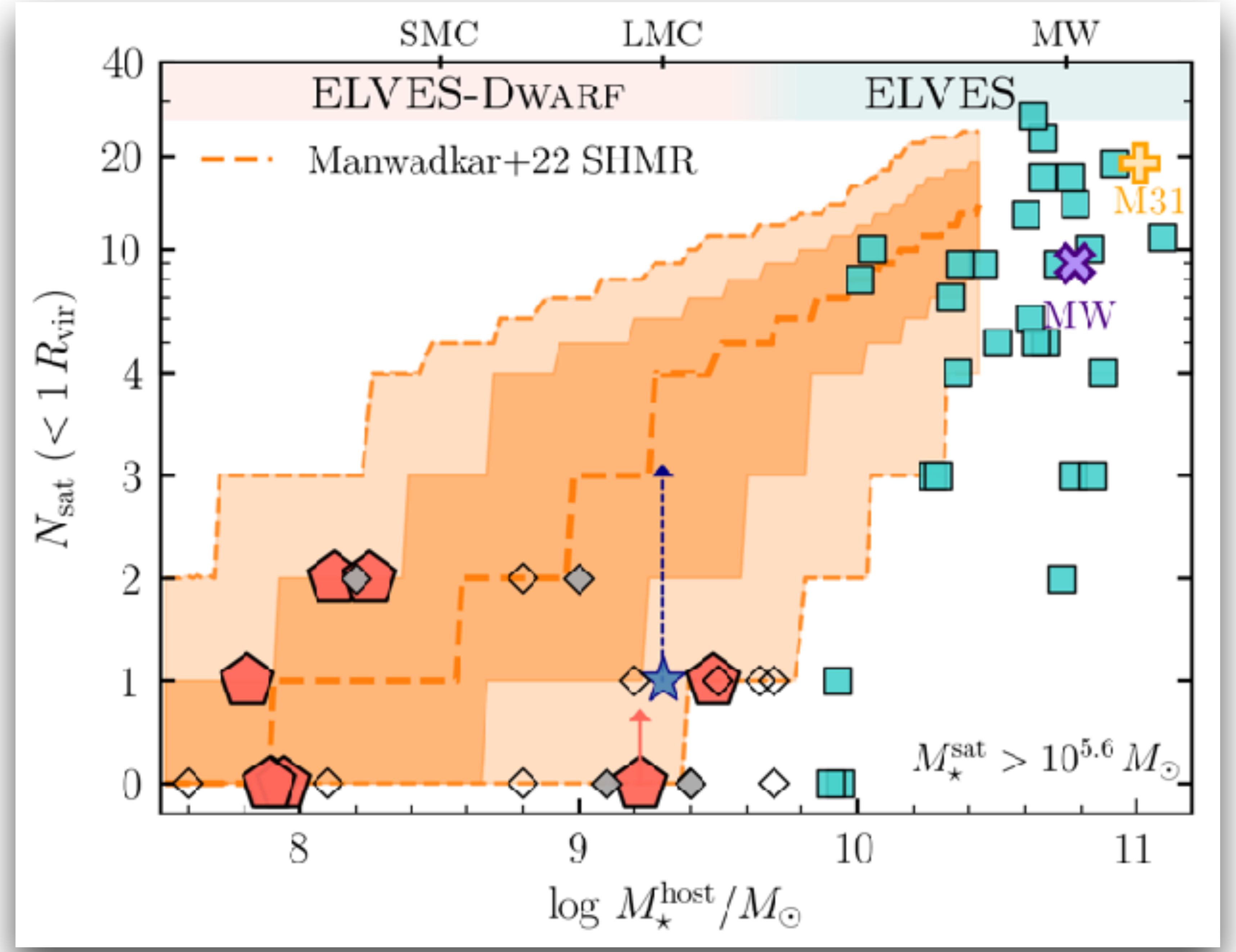
With Planet 9, this TNO will be ejected very quickly



Summary

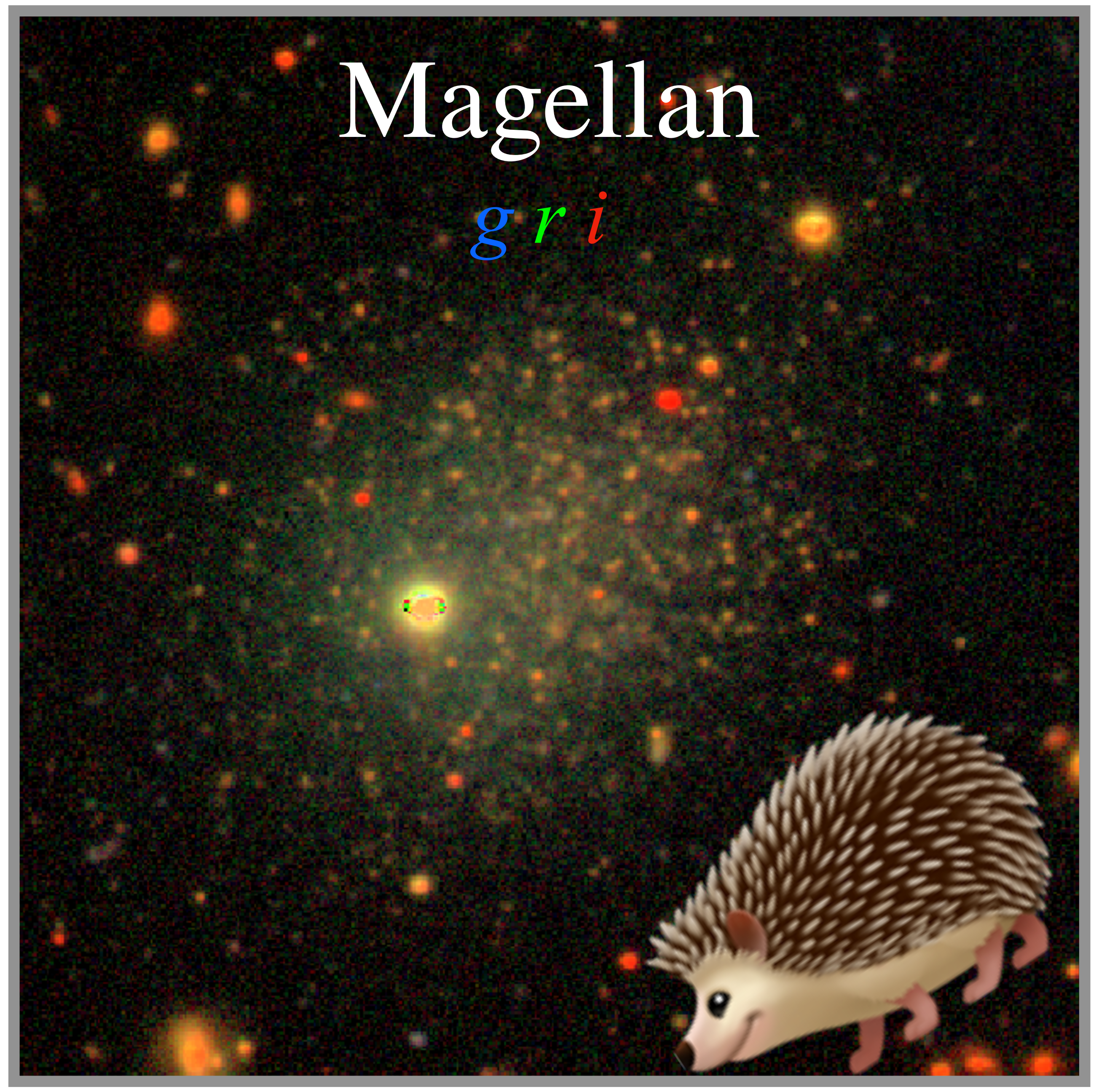
ELVES-Dwarf

Satellites of Dwarfs



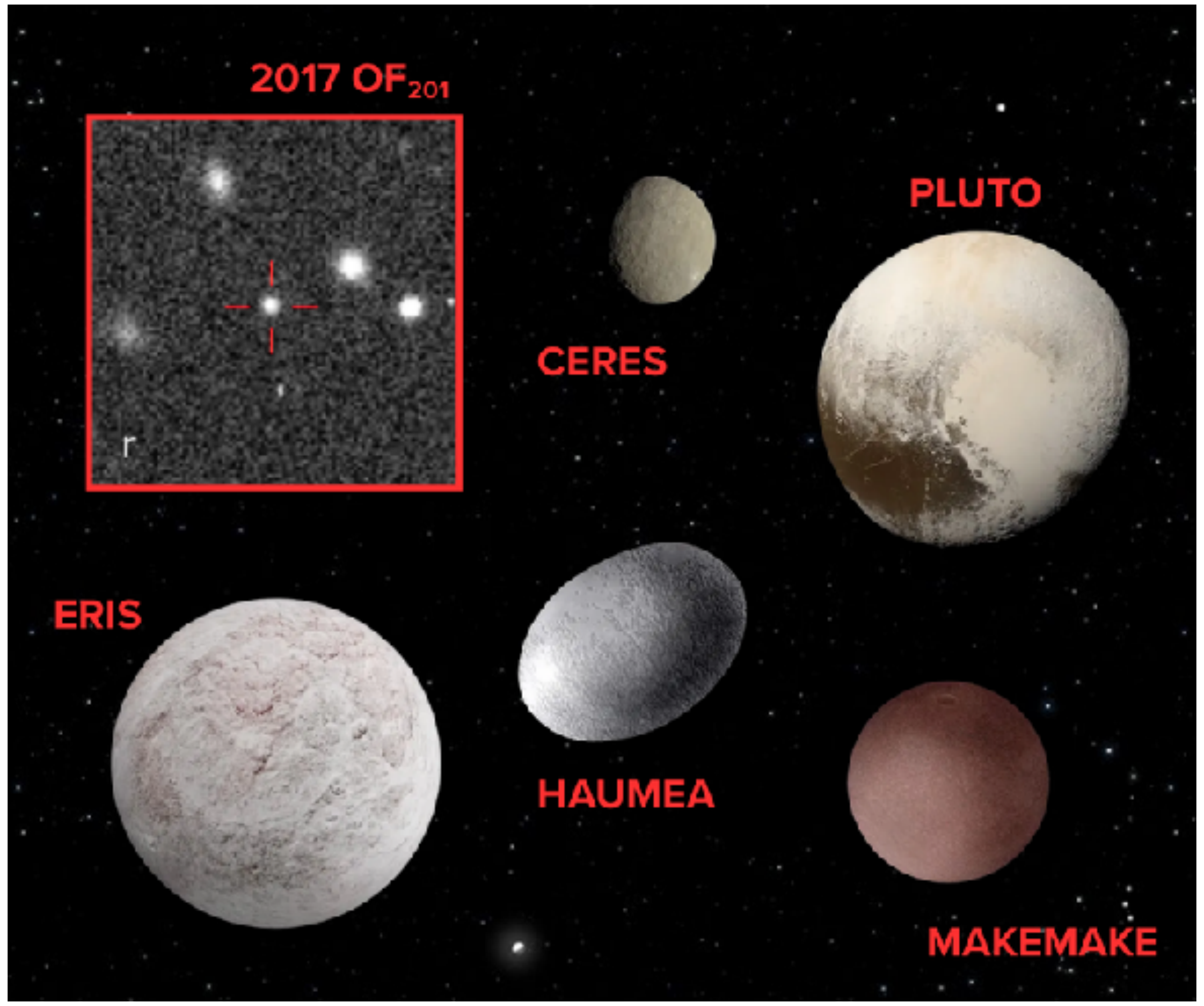
Hedgehog

Isolated Quiescent Dwarf



New Dwarf Planet

Does Planet 9 exist?



Interested in chatting more?

SBF for future surveys

Ultra-Diffuse Galaxies

Finding dwarfs in LSST

ML for SED fitting

Jiaxuan Li