KICP Seminar
Nov 20, 2025

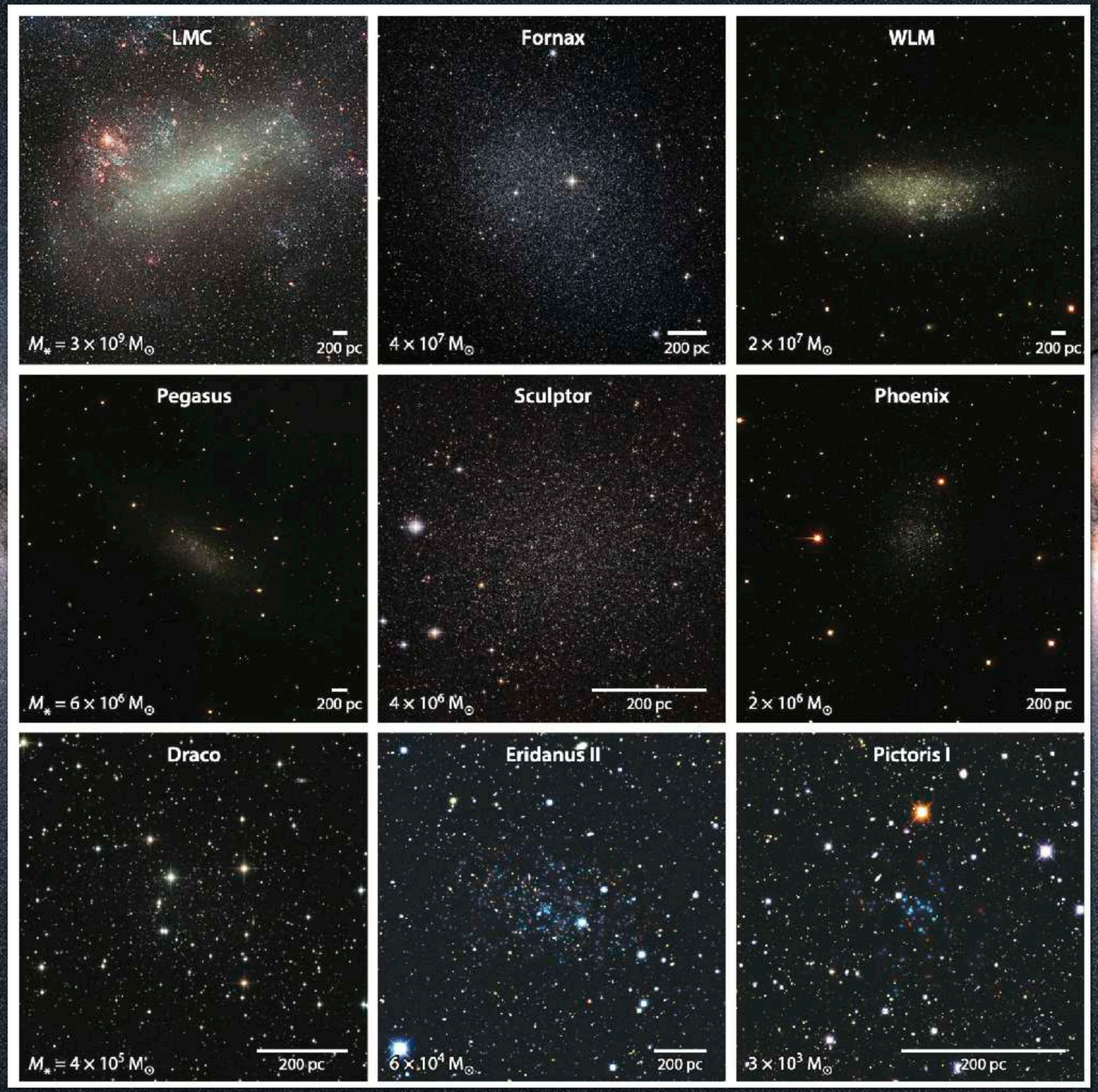
# Dwarfs: Near and Far


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



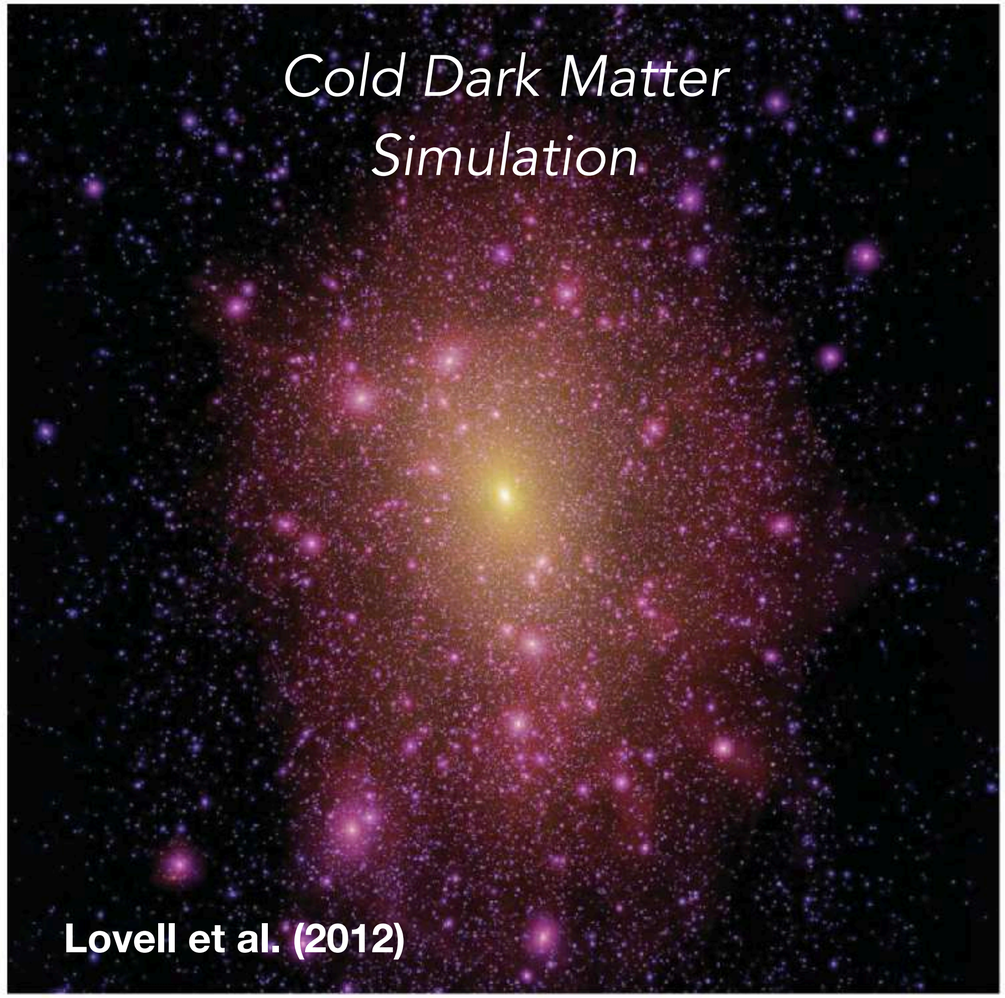

Bullock & Boylan-Kolchin (2017)

# Milky Way

Large Magellanic Cloud

Small Magellanic Cloud

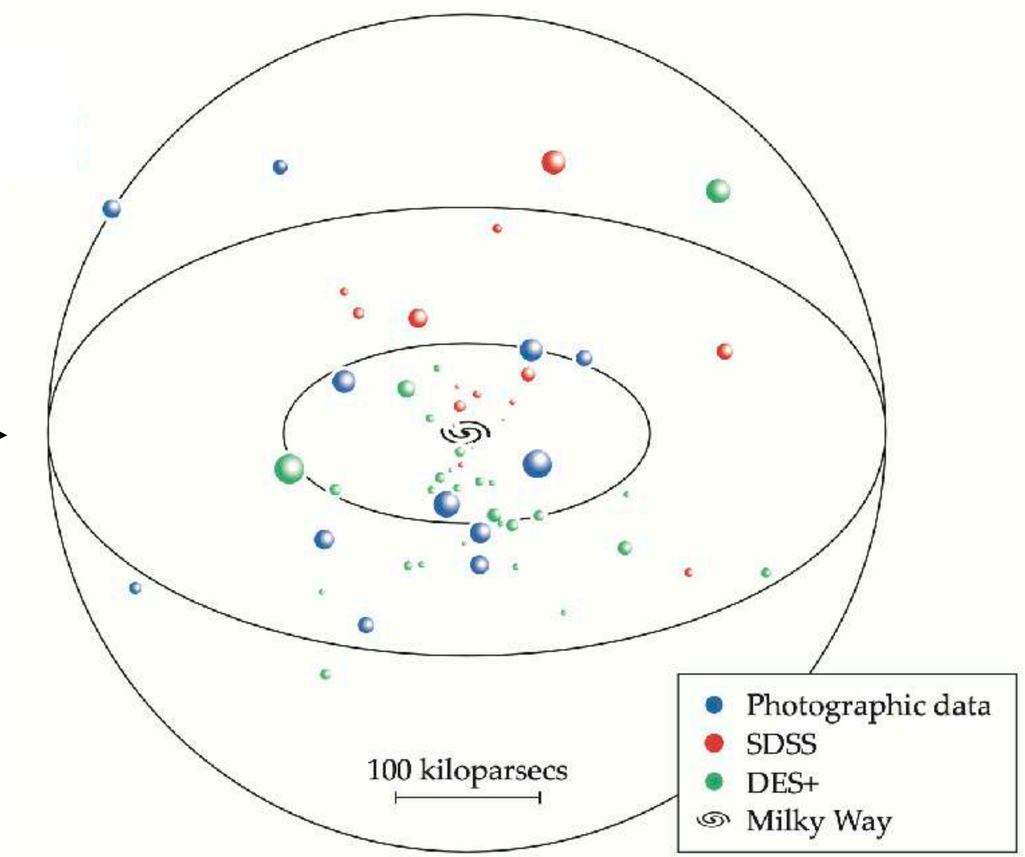
# Dwarf galaxies challenged CDM model




Lovell et al. (2012)

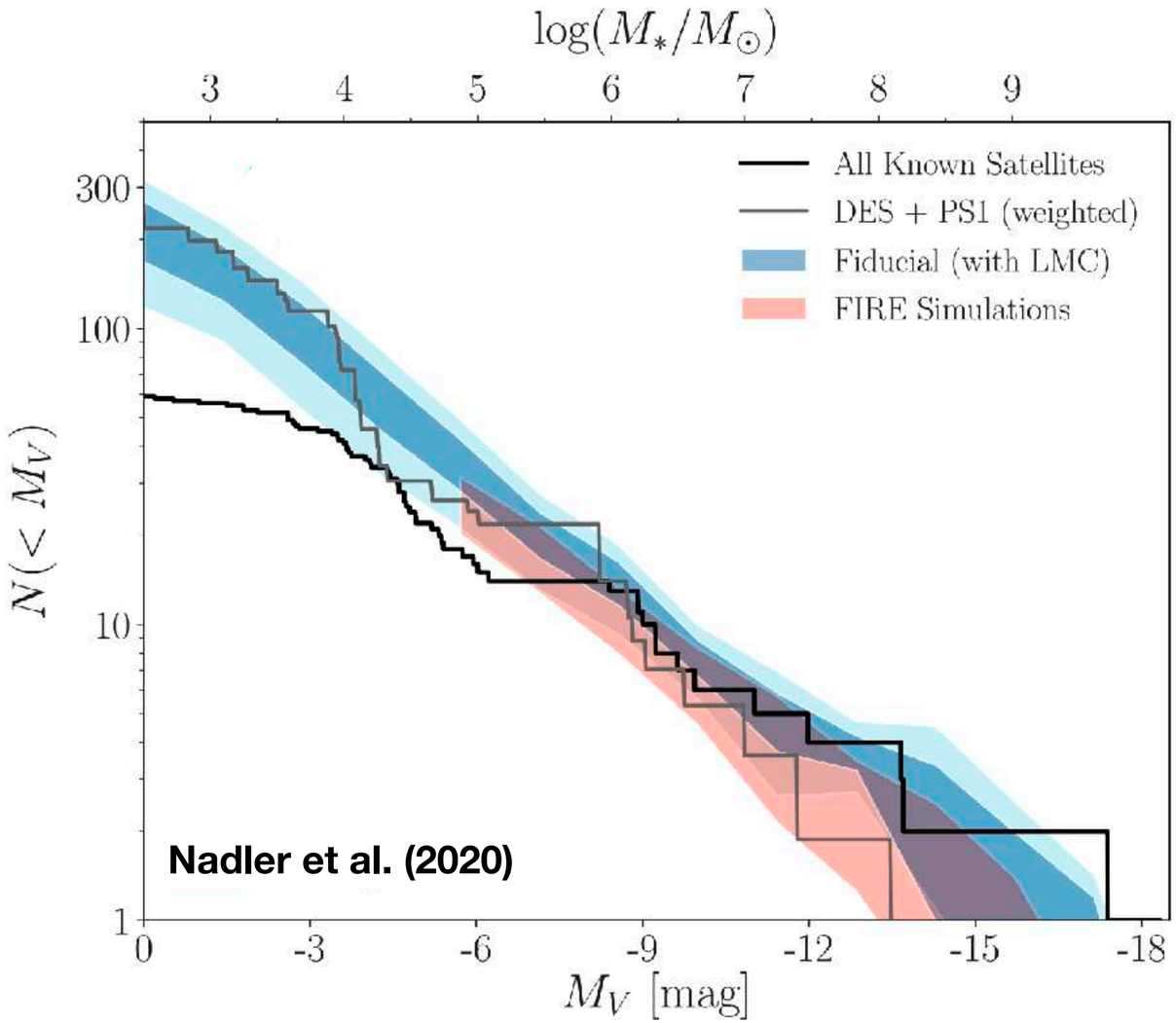
**Missing satellites?**

*Observed Milky Way satellites*




**Simon & Geha (2021)**

# Dwarf galaxies challenged CDM model

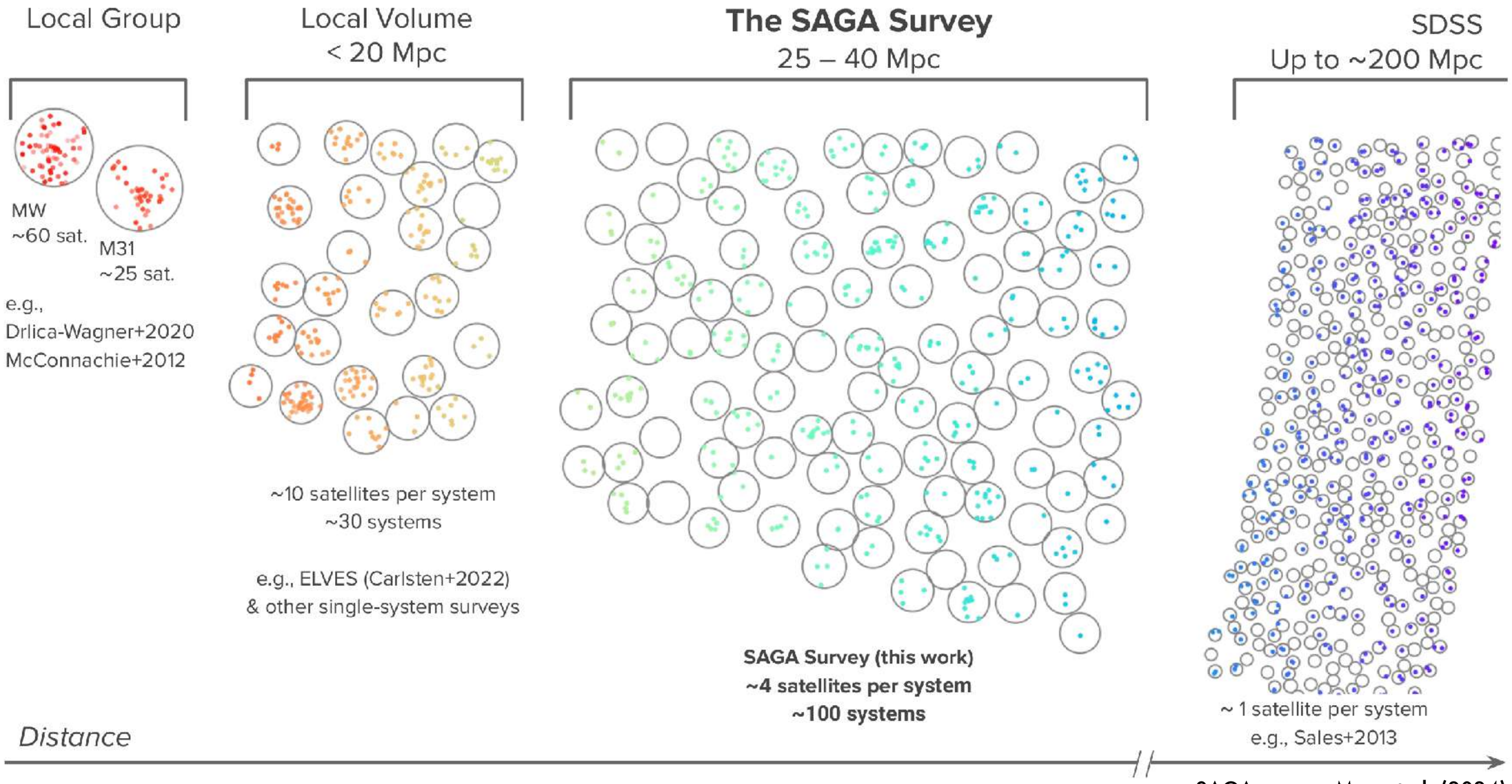



**Problem solved:**

- 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!***

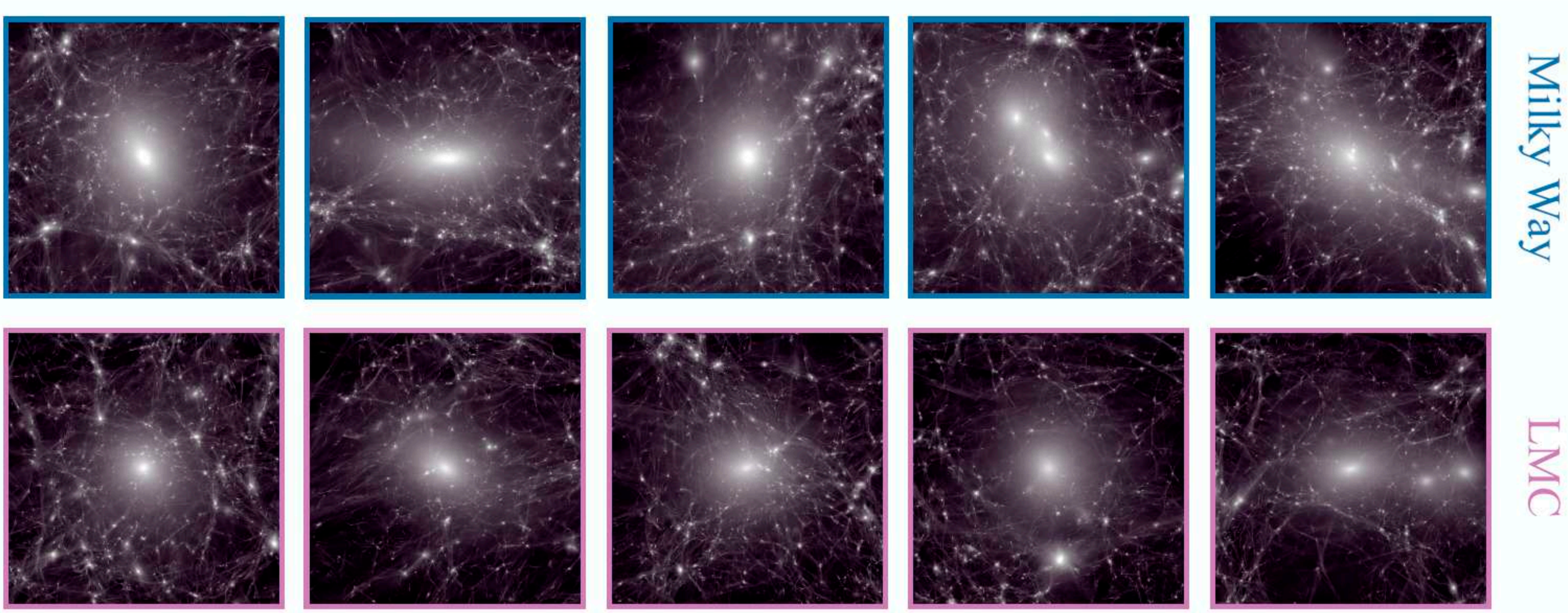
# … and satellites of MW analogs




SAGA survey; Mao et al. (2024)

# Dwarf galaxies should also have satellites

(10-1000x smaller than MW)





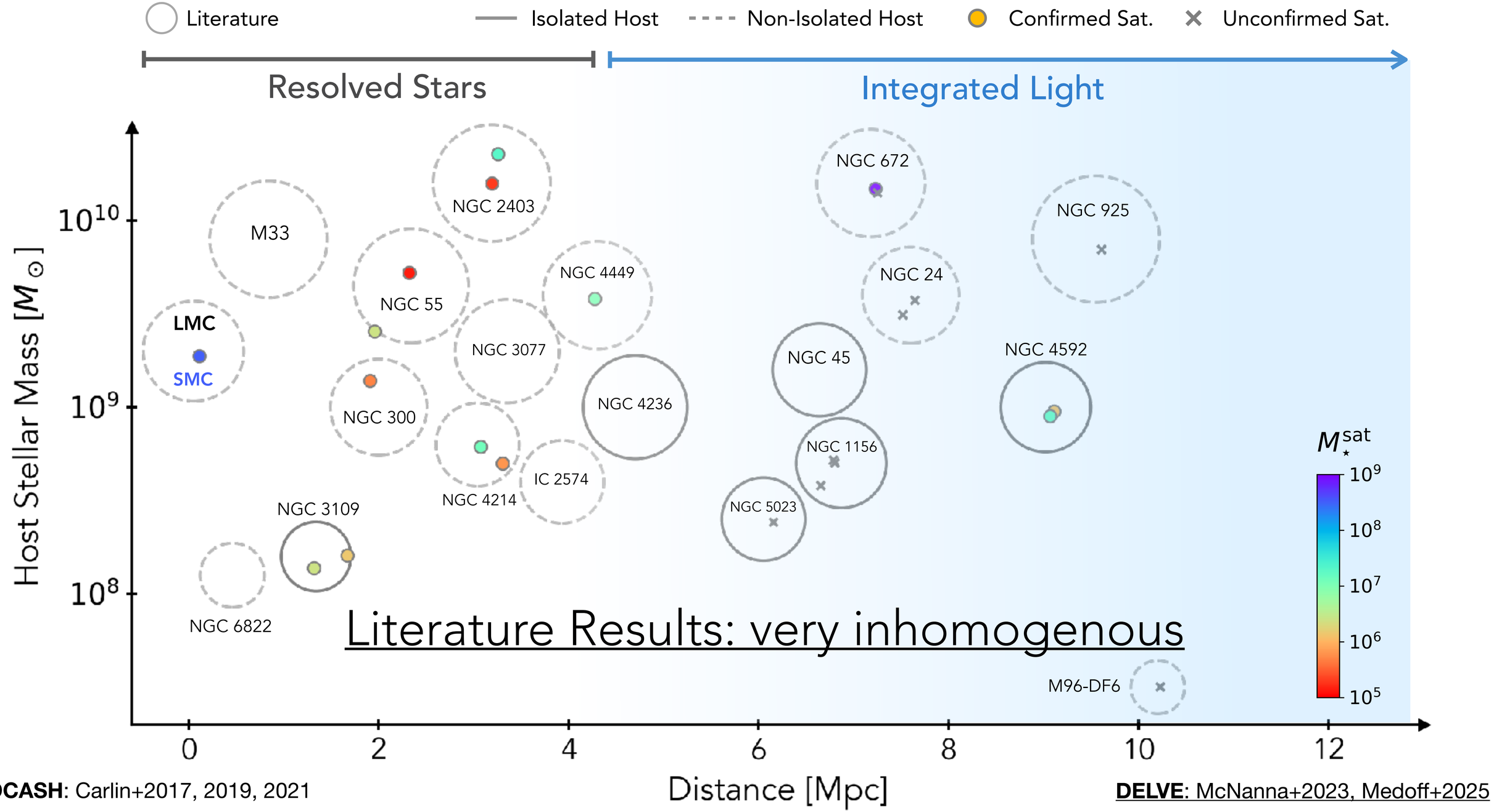

*Symphony simulations: Nadler et al. (2023)*

# Do satellites of dwarf galaxies follow CDM prediction?

We need:

- A sample of “satellites of dwarfs”

**Only showing classical dwarfs*



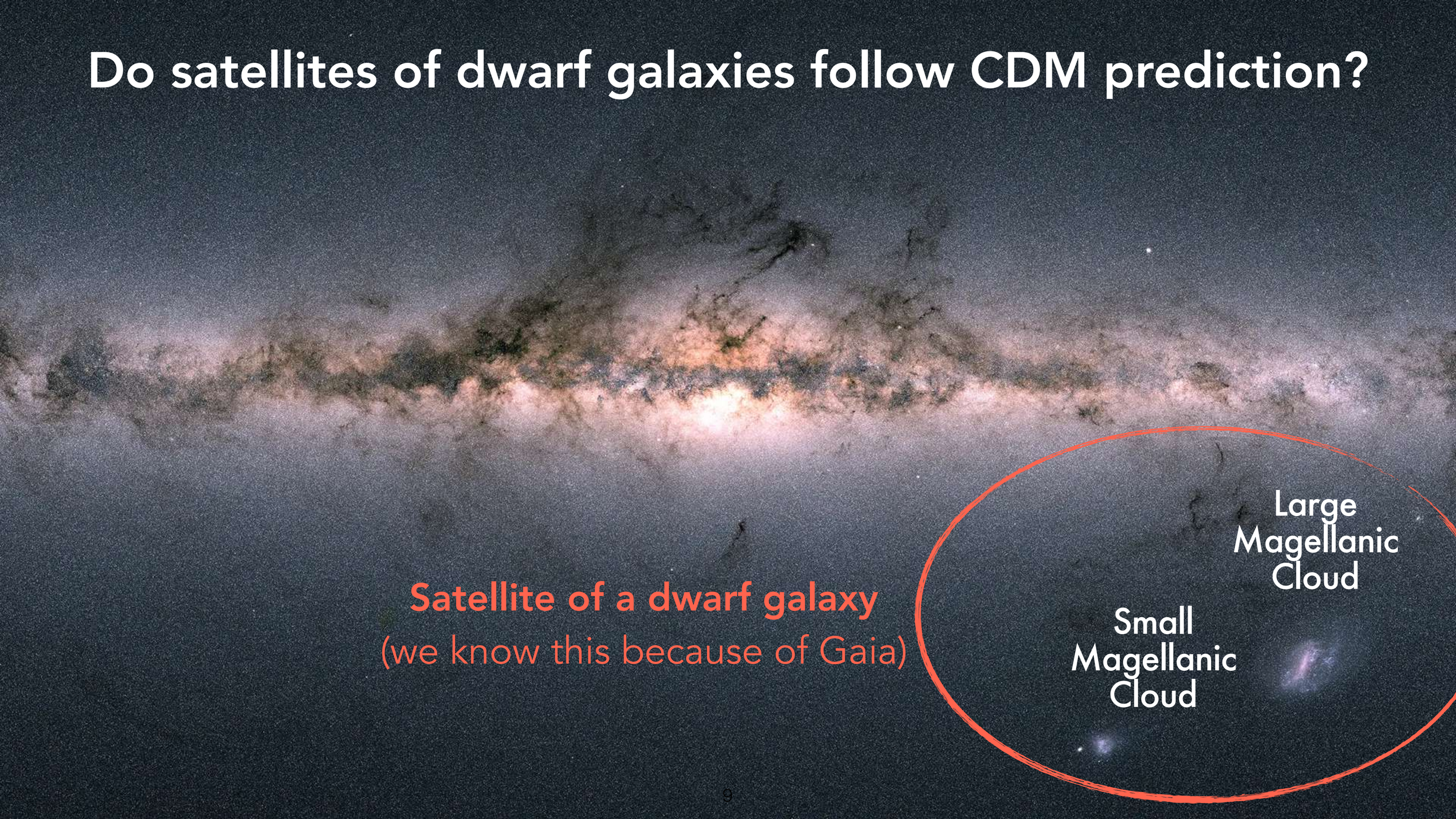

**MADCASH**: Carlin+2017, 2019, 2021

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

**DELVE**: McNanna+2023, Medoff+2025

**ID-MAGE**: Hunter+2025

# Do satellites of dwarf galaxies follow CDM prediction?

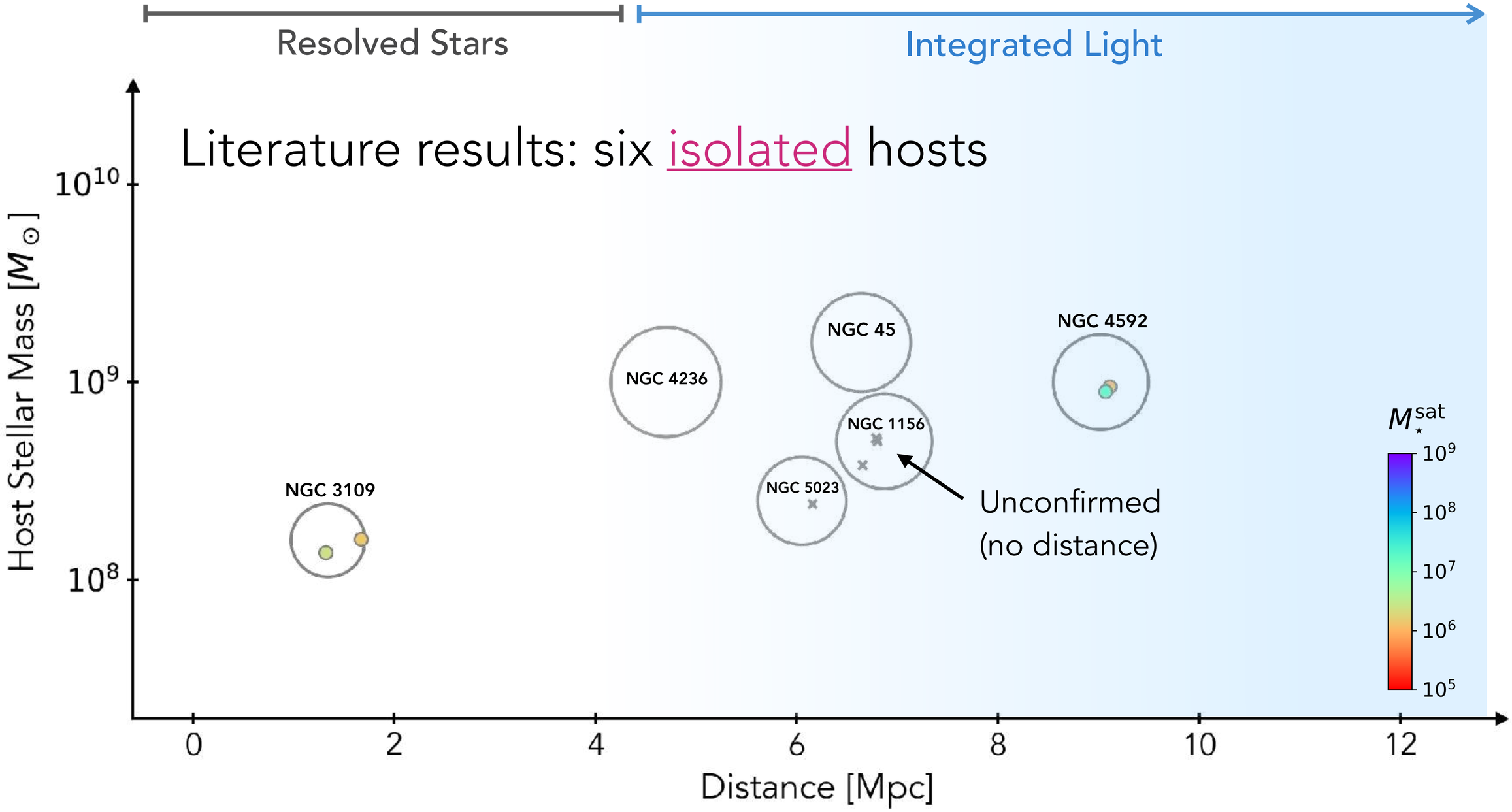



**Satellite of a dwarf galaxy**
(we know this because of Gaia)

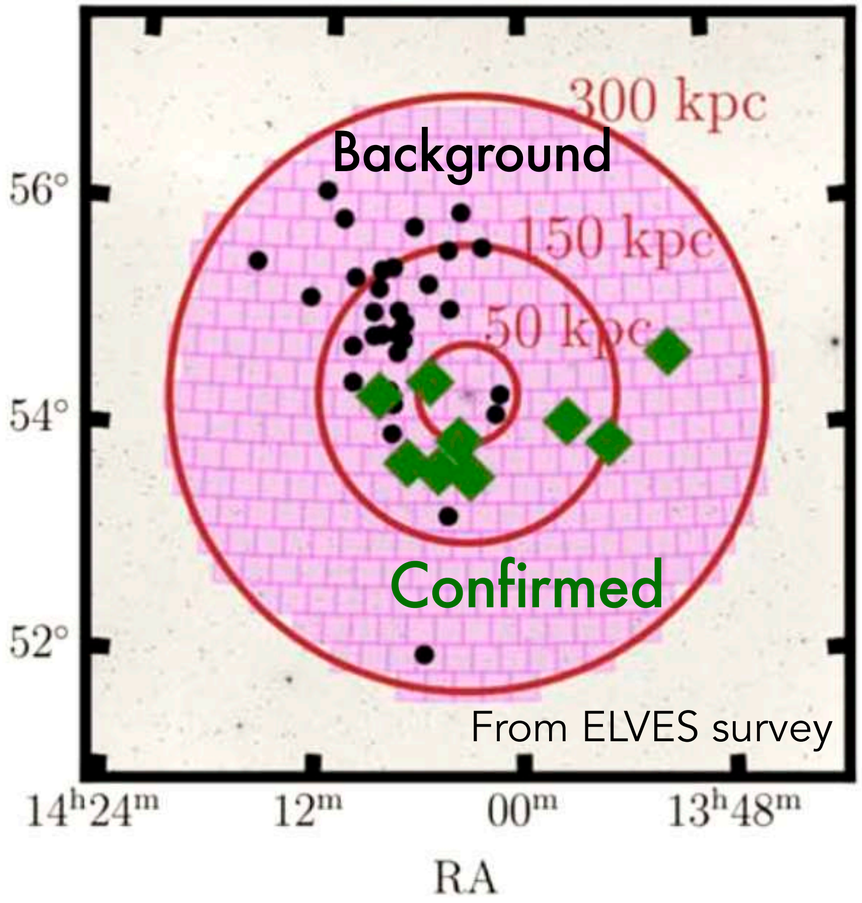
# We need:

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

*Only showing classical dwarfs



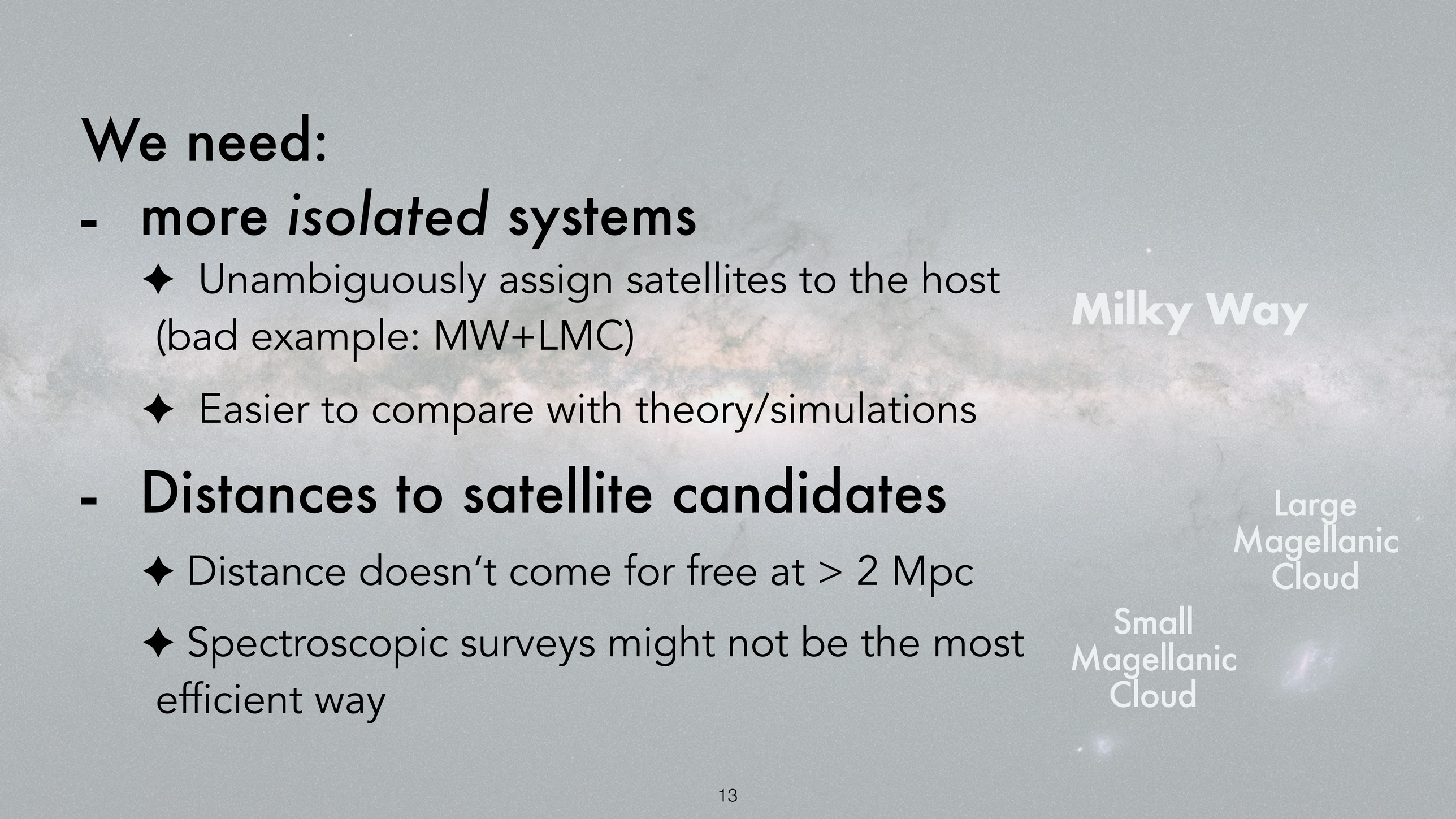
# Distance is crucial!




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



# ELVES-DWARF Survey

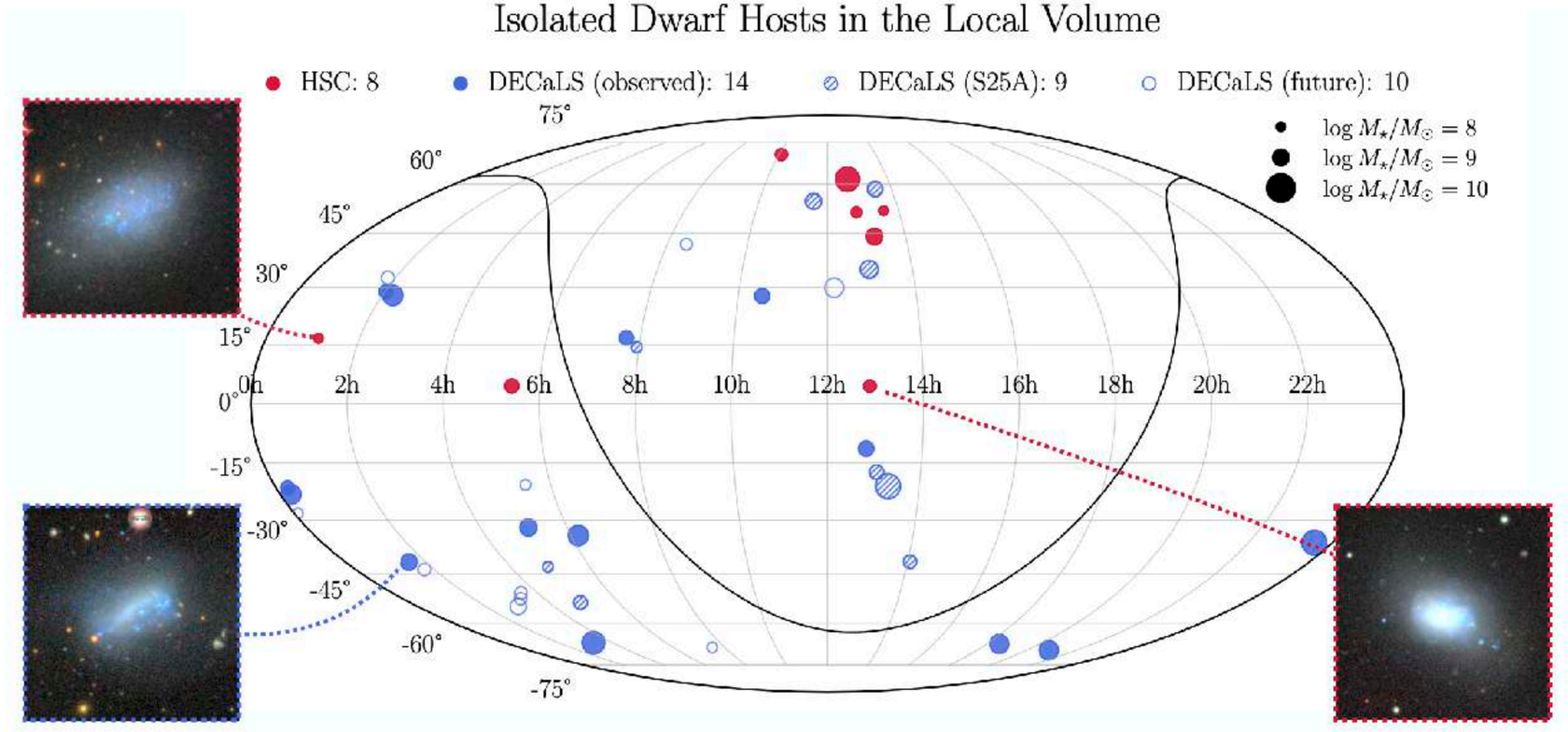
**Goal:** survey 30-40 ***isolated*** dwarf hosts at 4-12 Mpc

**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

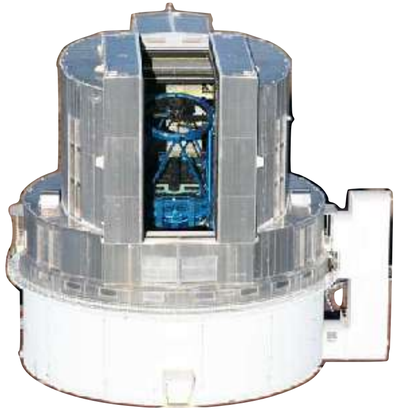


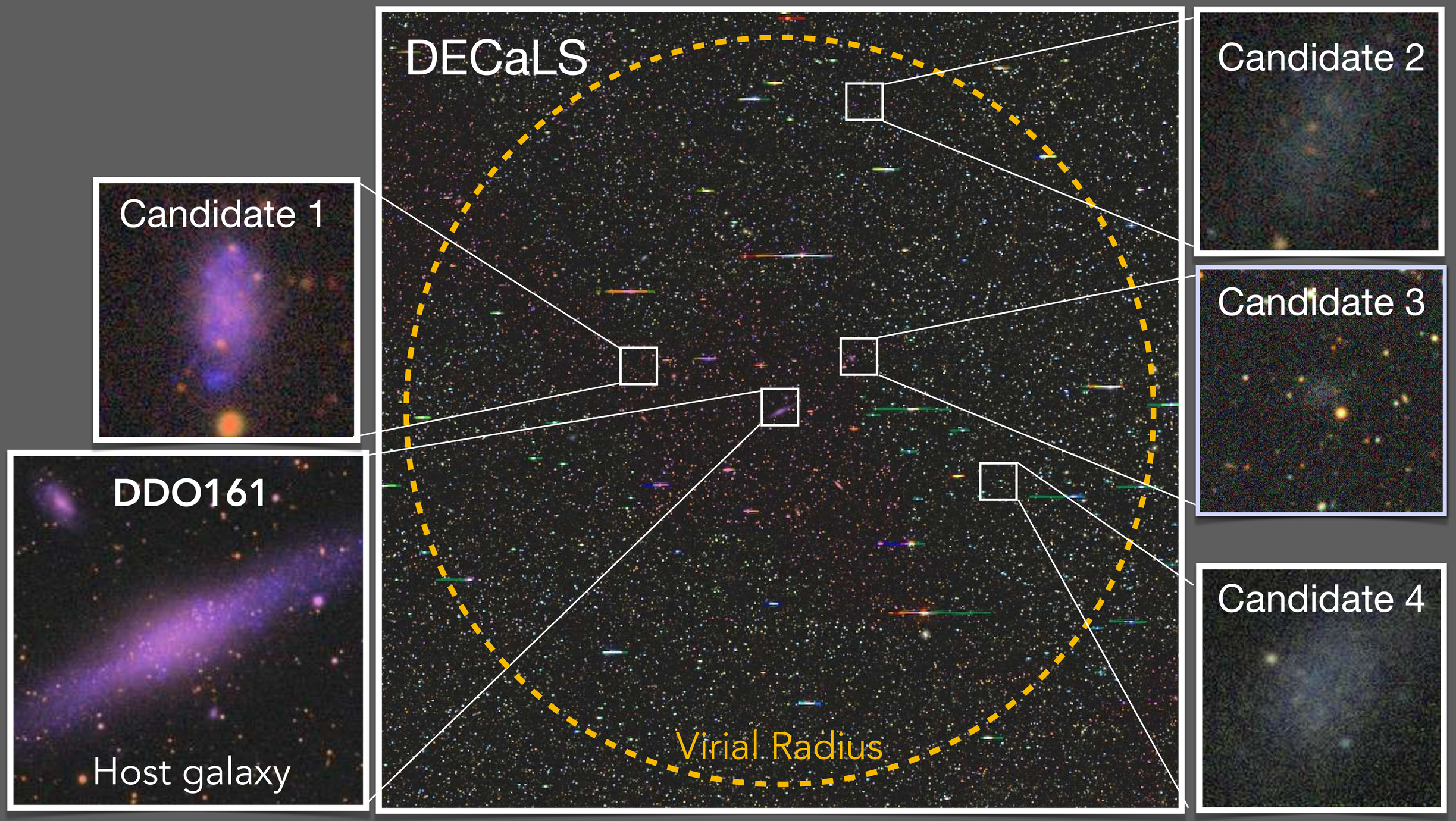

J. Li et al. (2025)

Magellan/IMACS

Gemini-N/GMOS

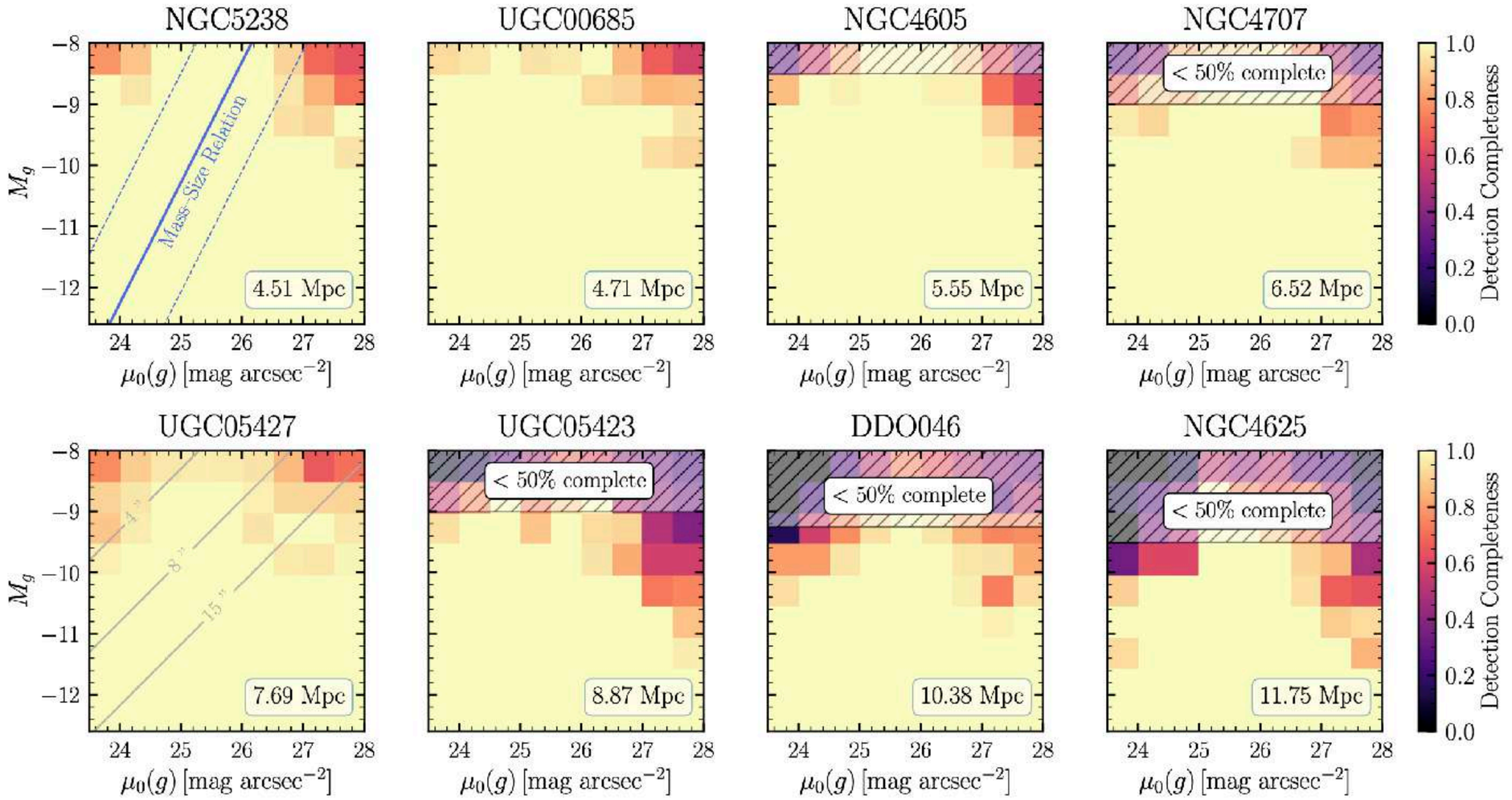
Subaru/HSC




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

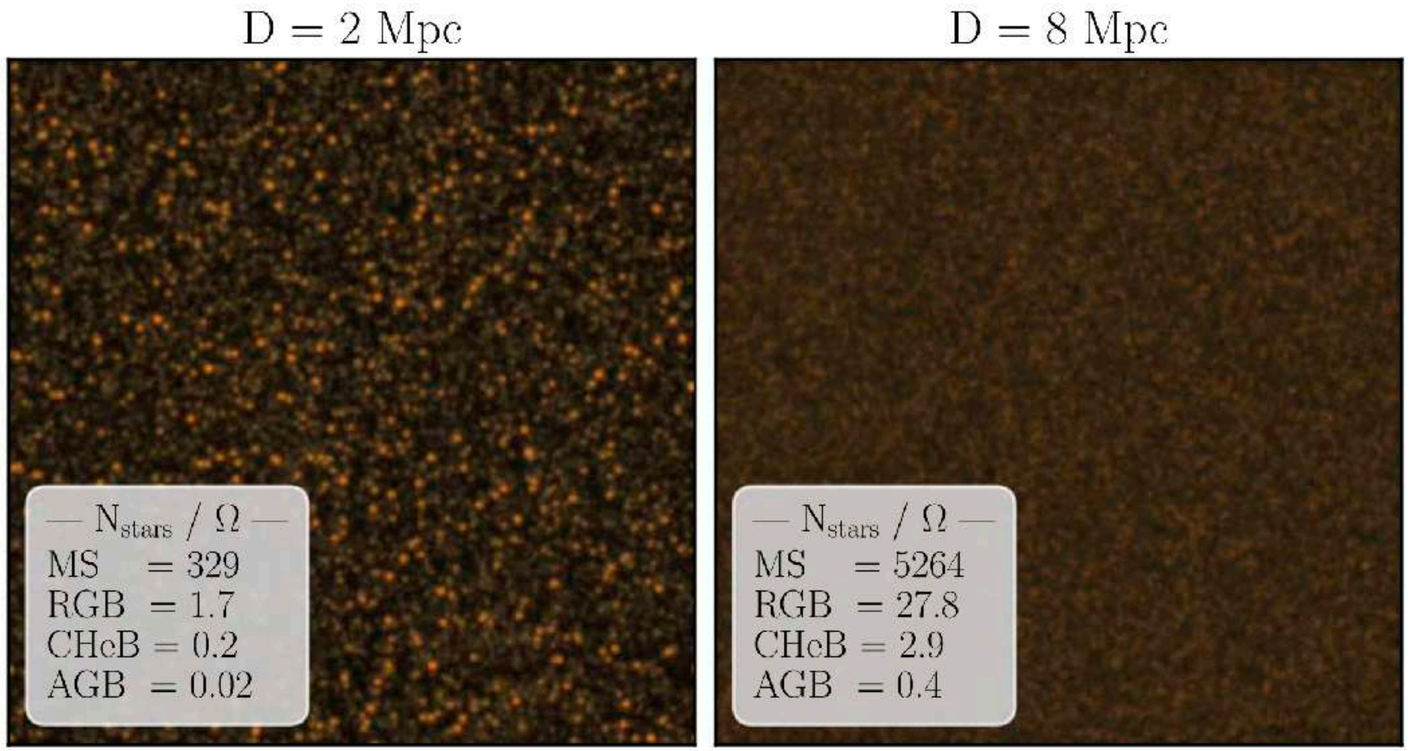
# Satellite Search Completeness

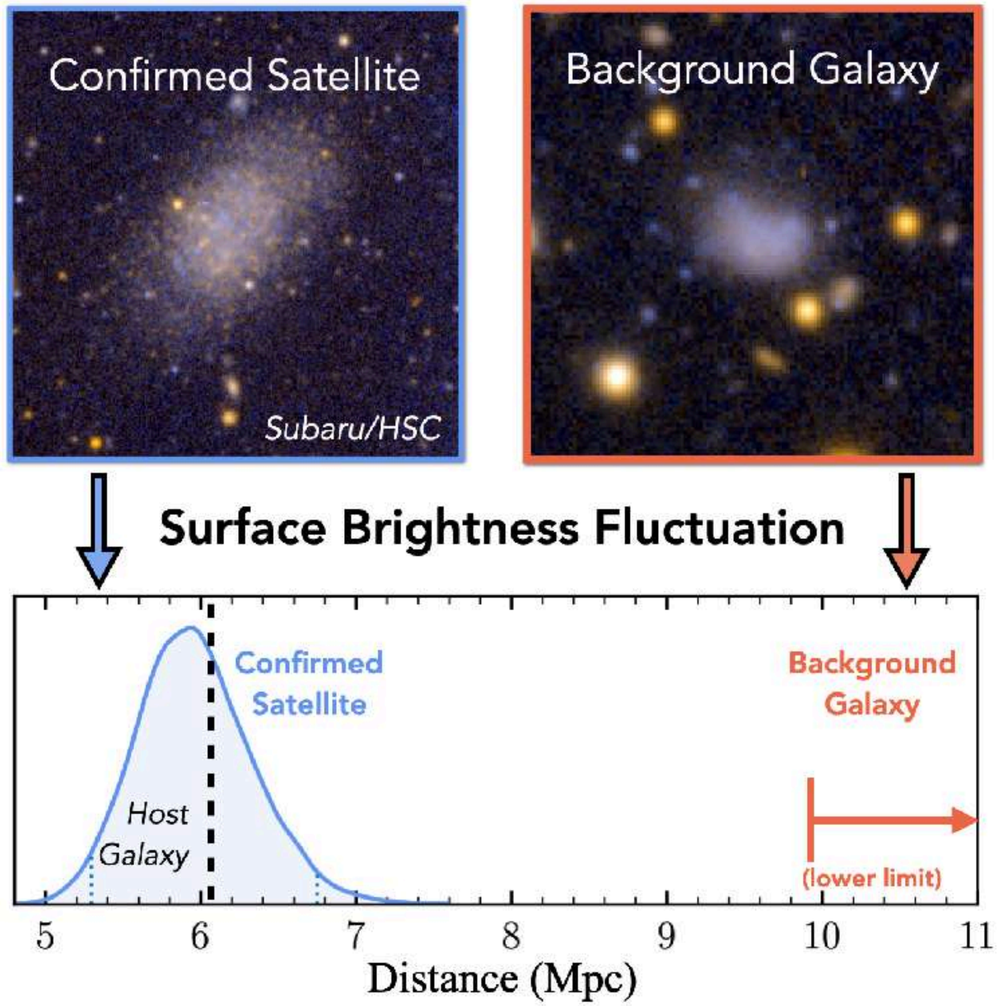
- Complete down to $M_g \approx -9$ mag for most hosts



# Surface Brightness Fluctuation contains distance information

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

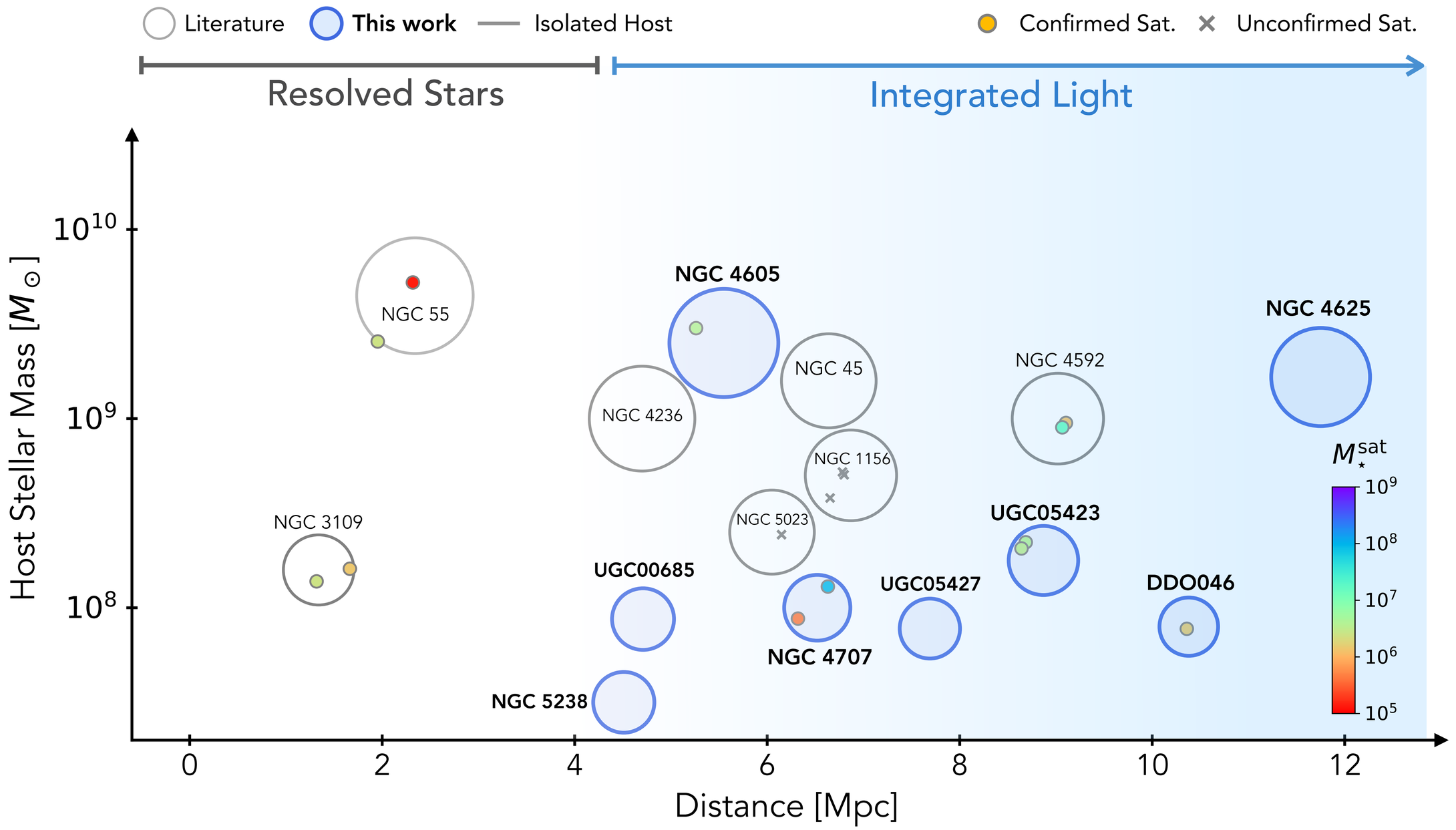


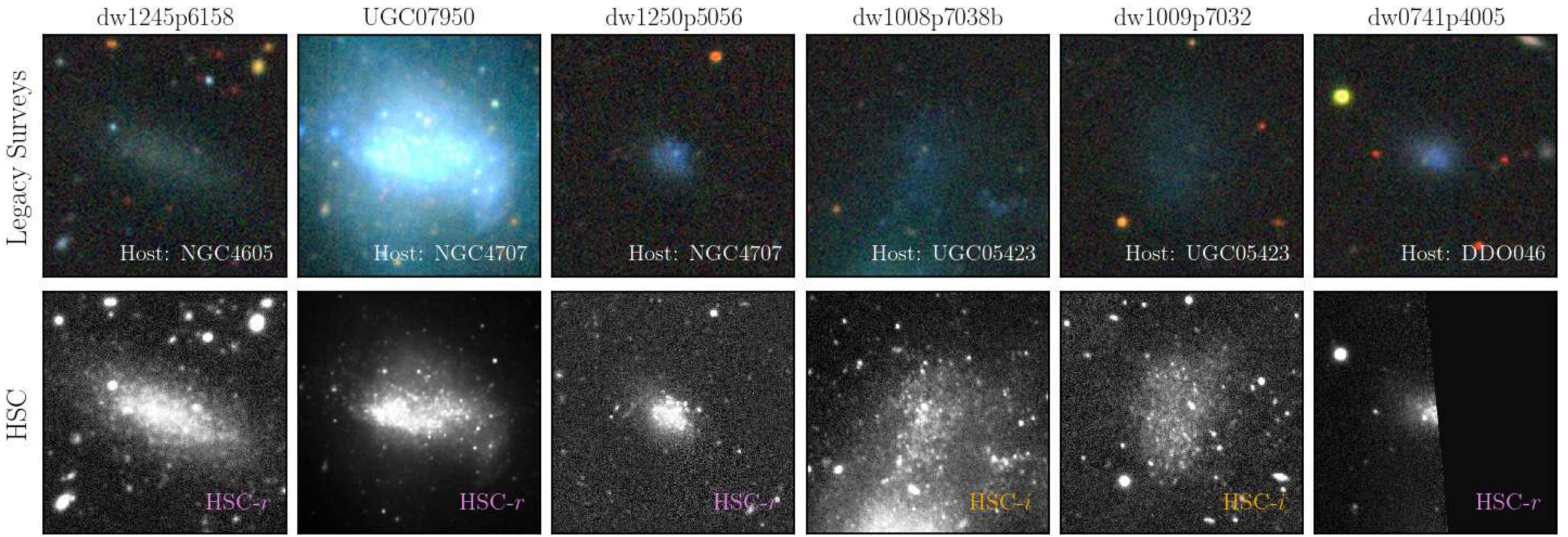

- Ground-based SBF reaches 10–12 Mpc for $M_\star > 10^{5.5}\ M_\odot$
- Not biased towards blue dwarfs (compared with spectroscopic surveys)

# ELVES-DWARF: First results using HSC

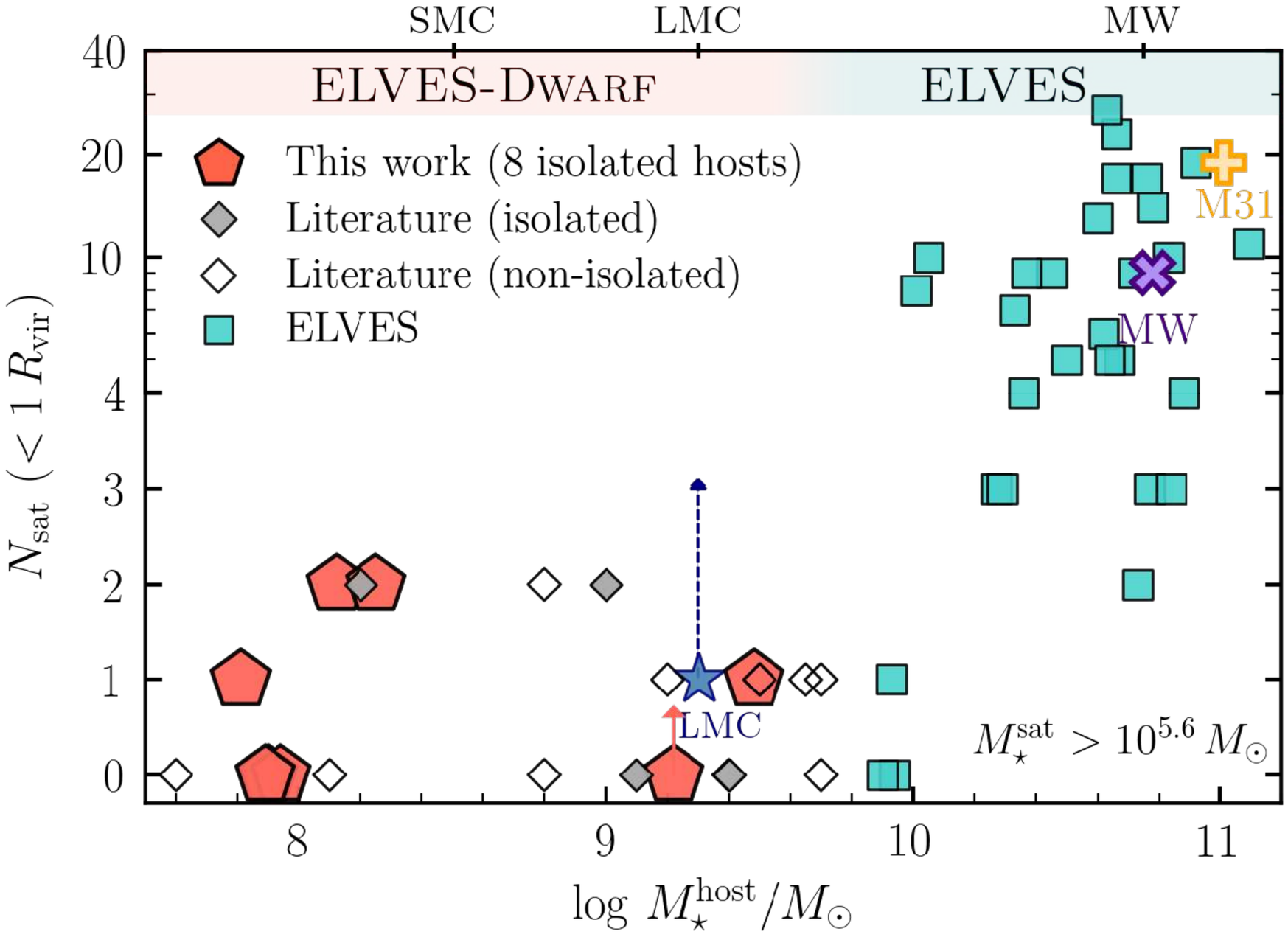
J. Li et al. (2025)
arXiv:2504.08030



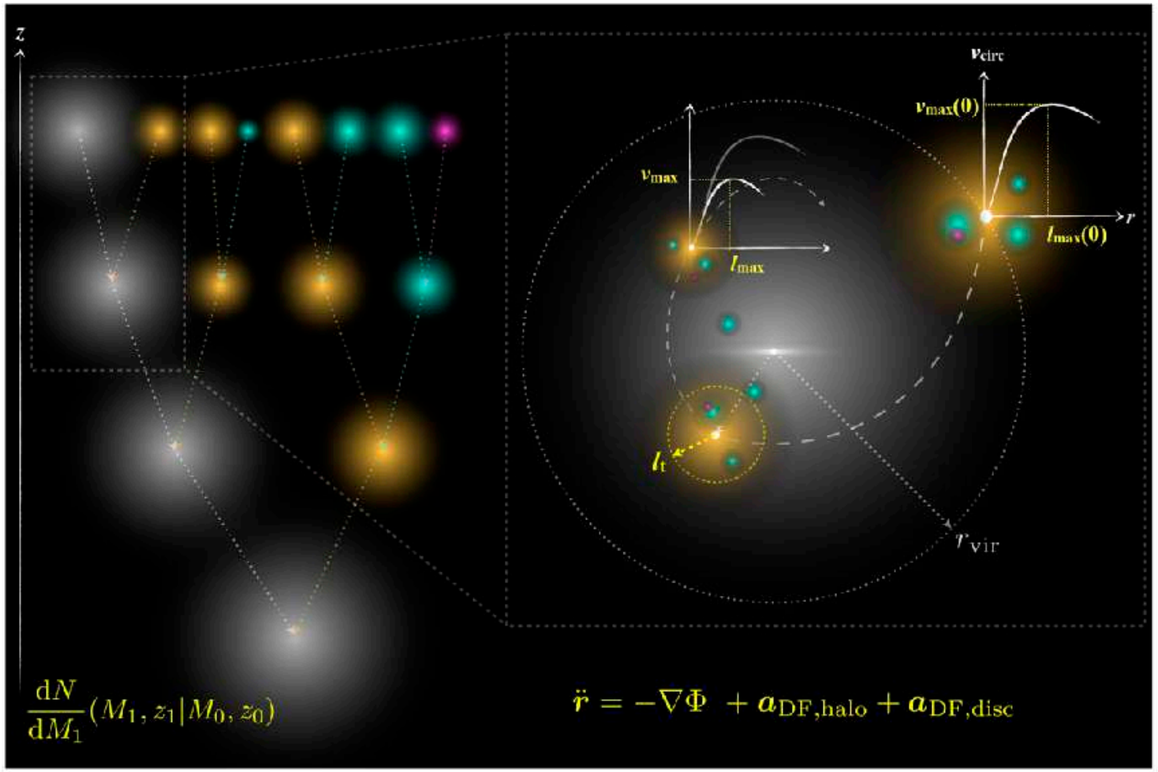
# Images of confirmed satellites

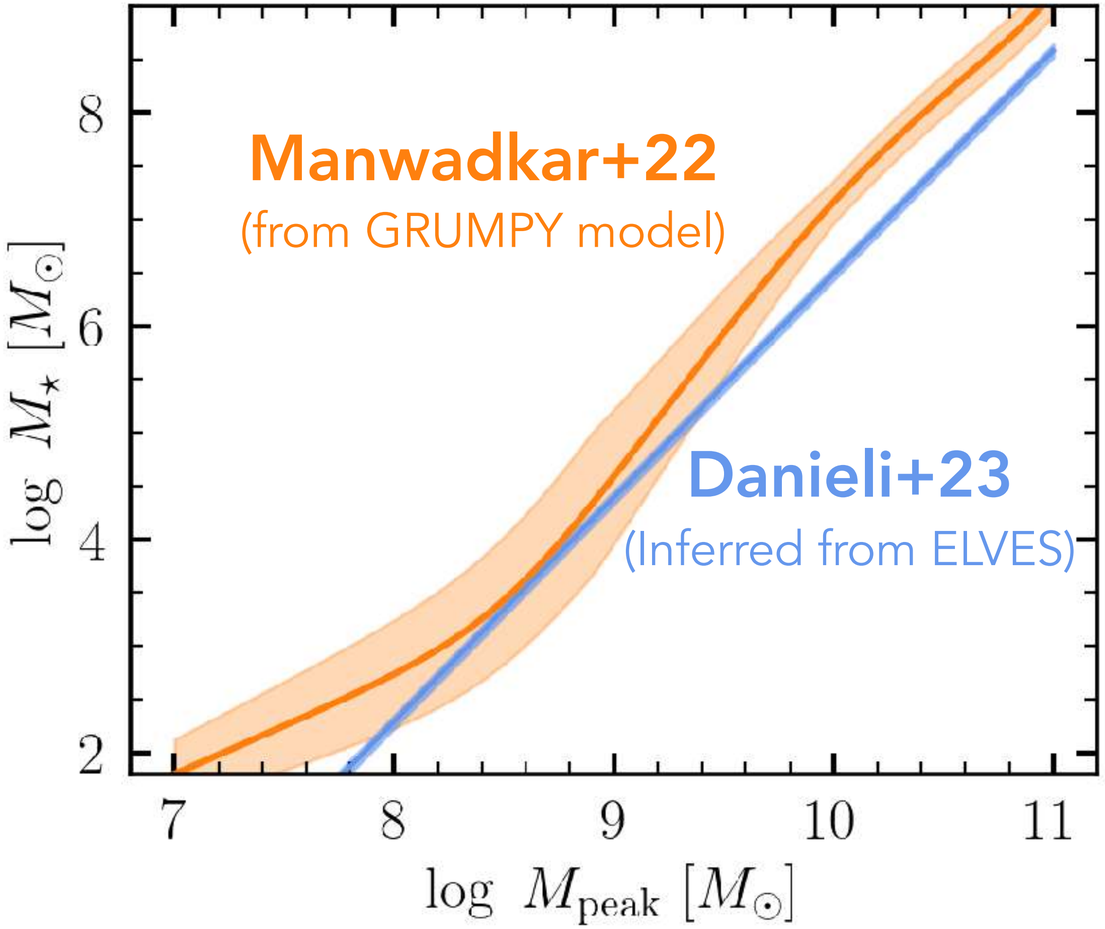


# Satellite Abundance



# Satellite Abundance: SatGen prediction

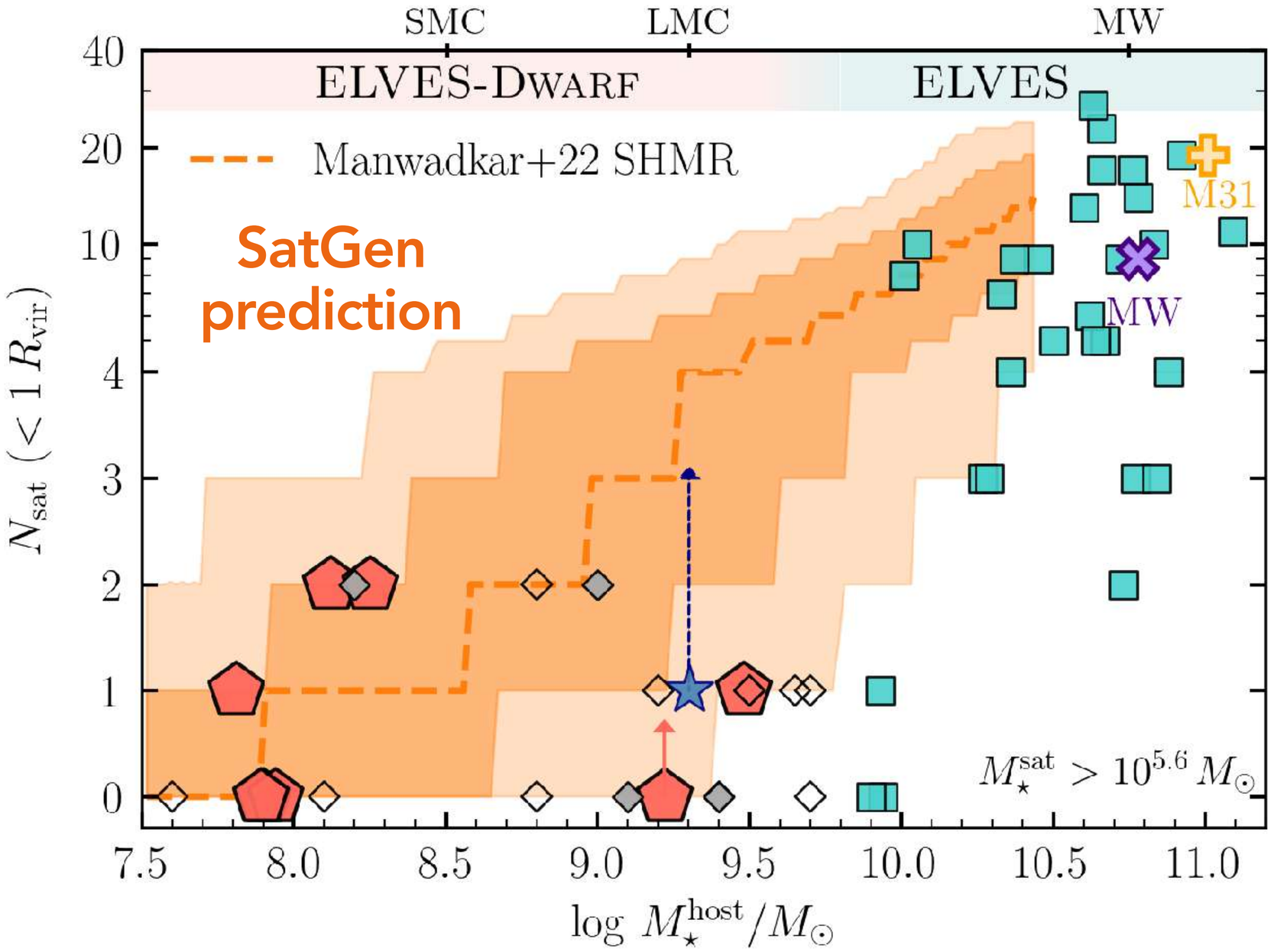


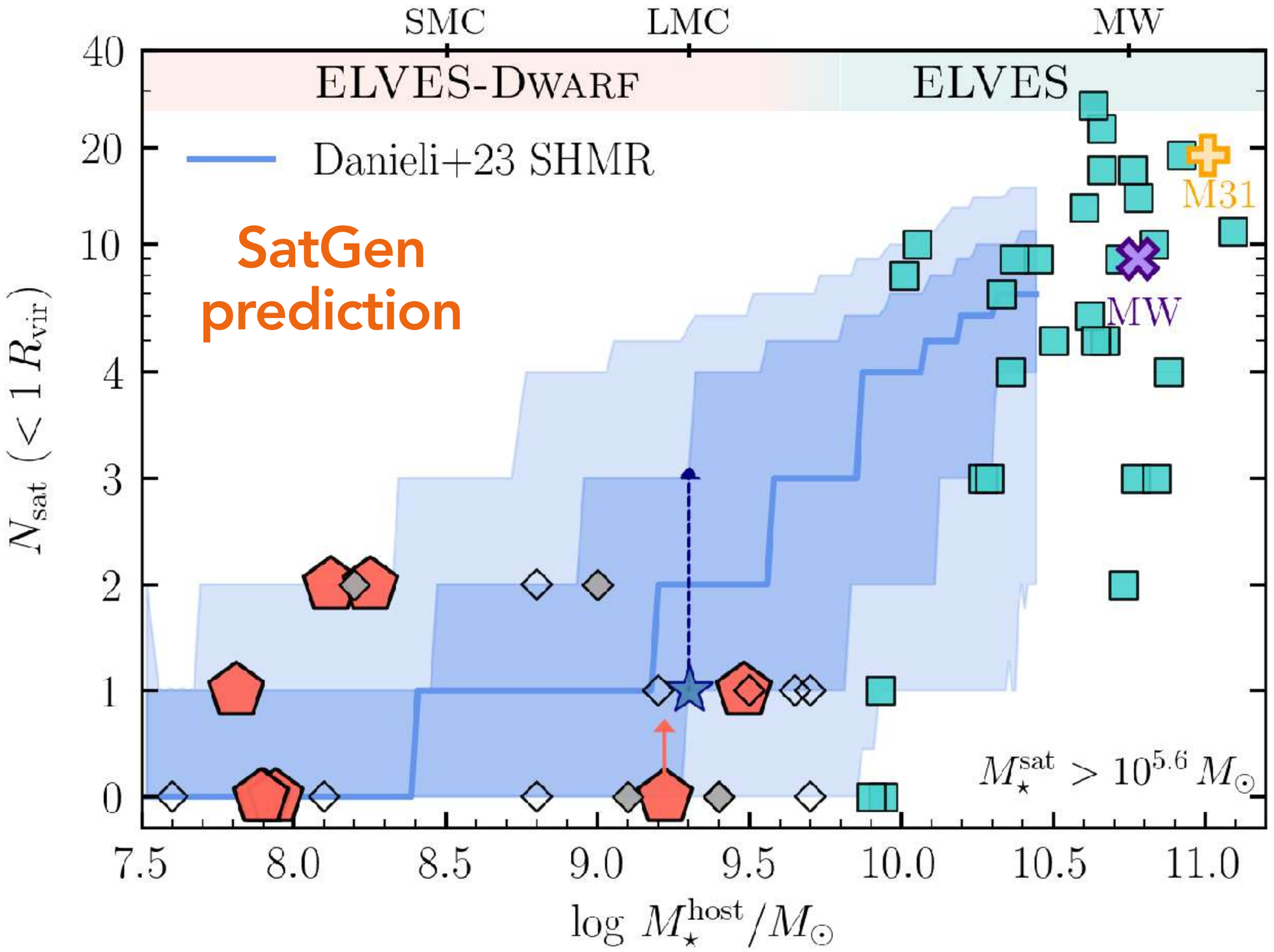

- *SatGen*: Semi-analytical model for satellites
- Includes tidal stripping; emulates baryonic processes

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

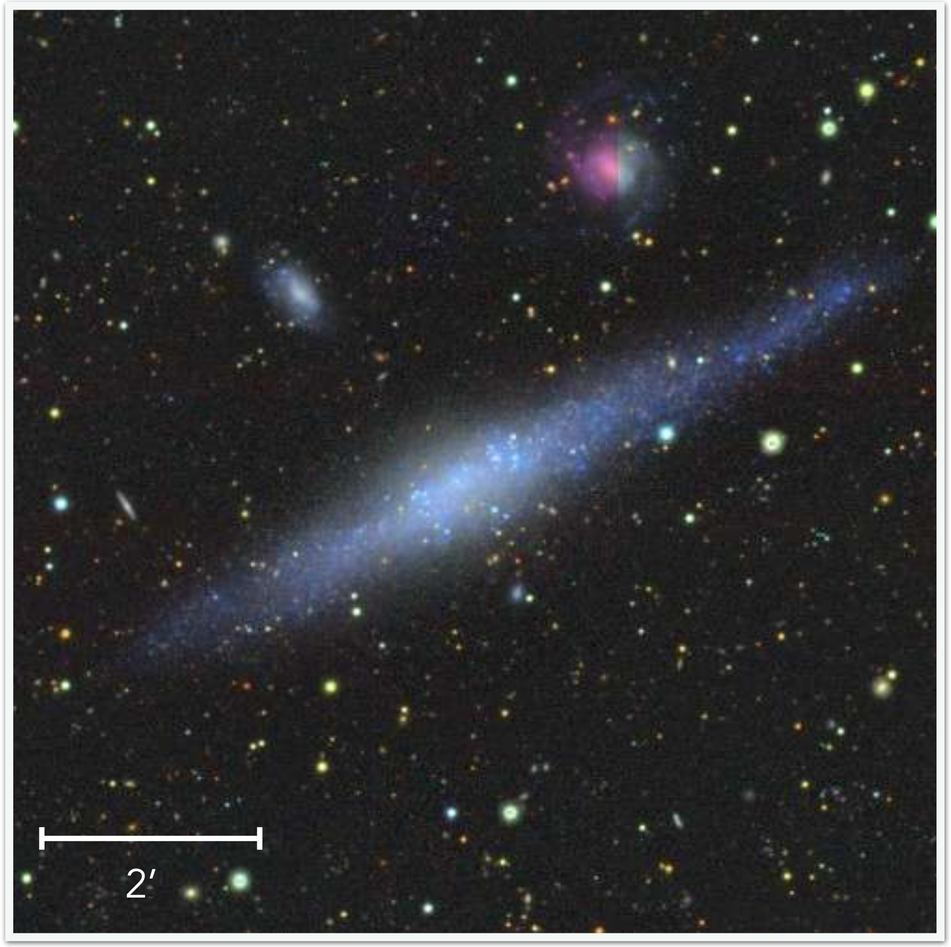
# No “Missing satellite problem”



# No “Missing satellite problem”

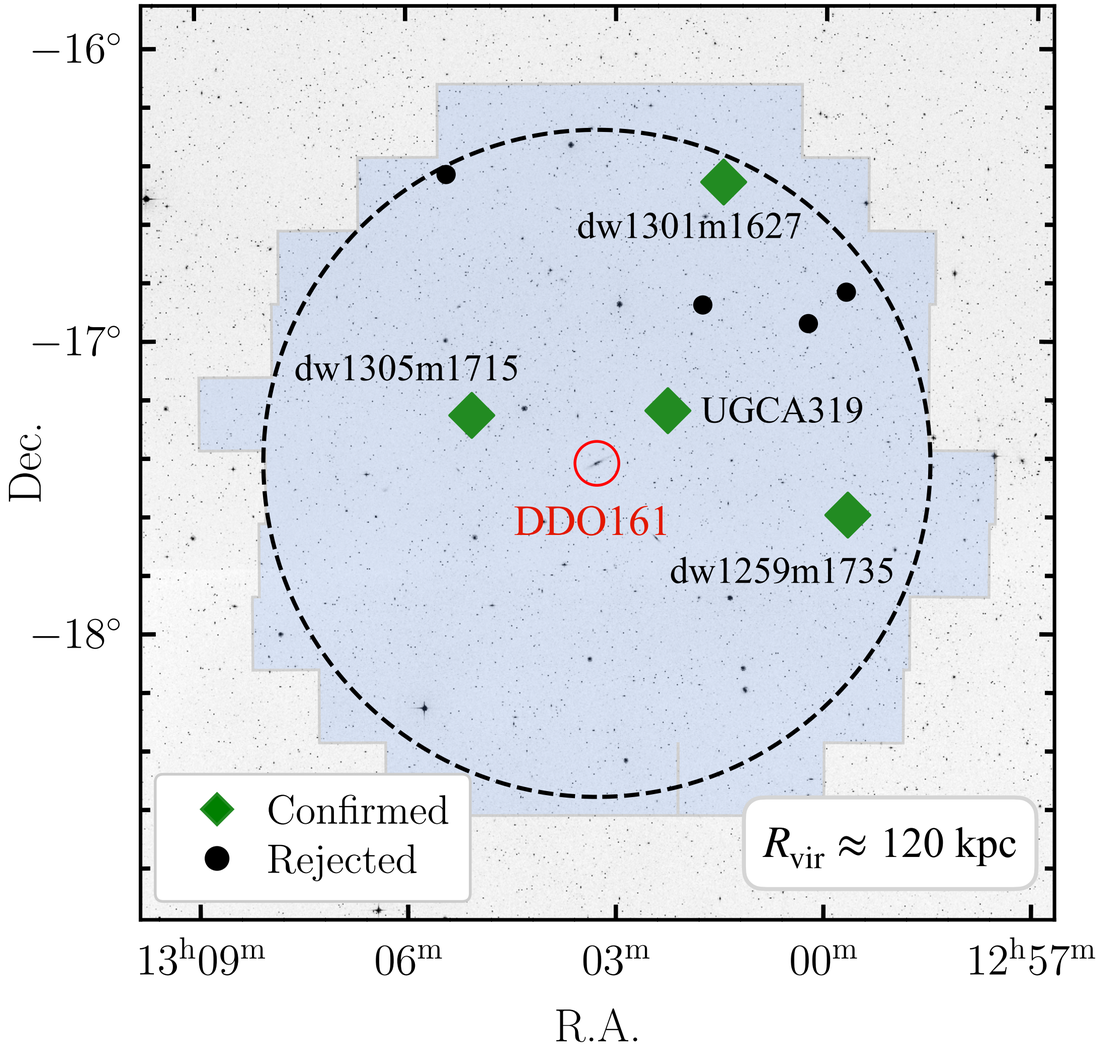


# But a “too-many-satellites” problem?

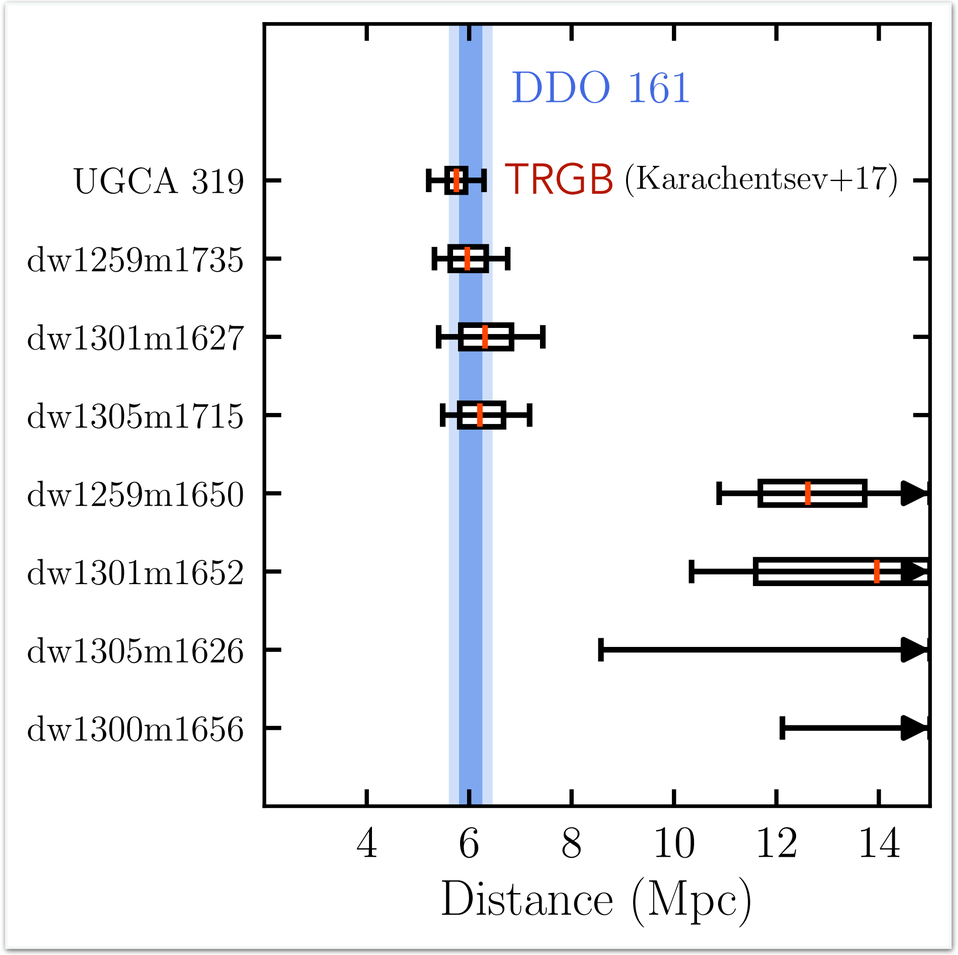


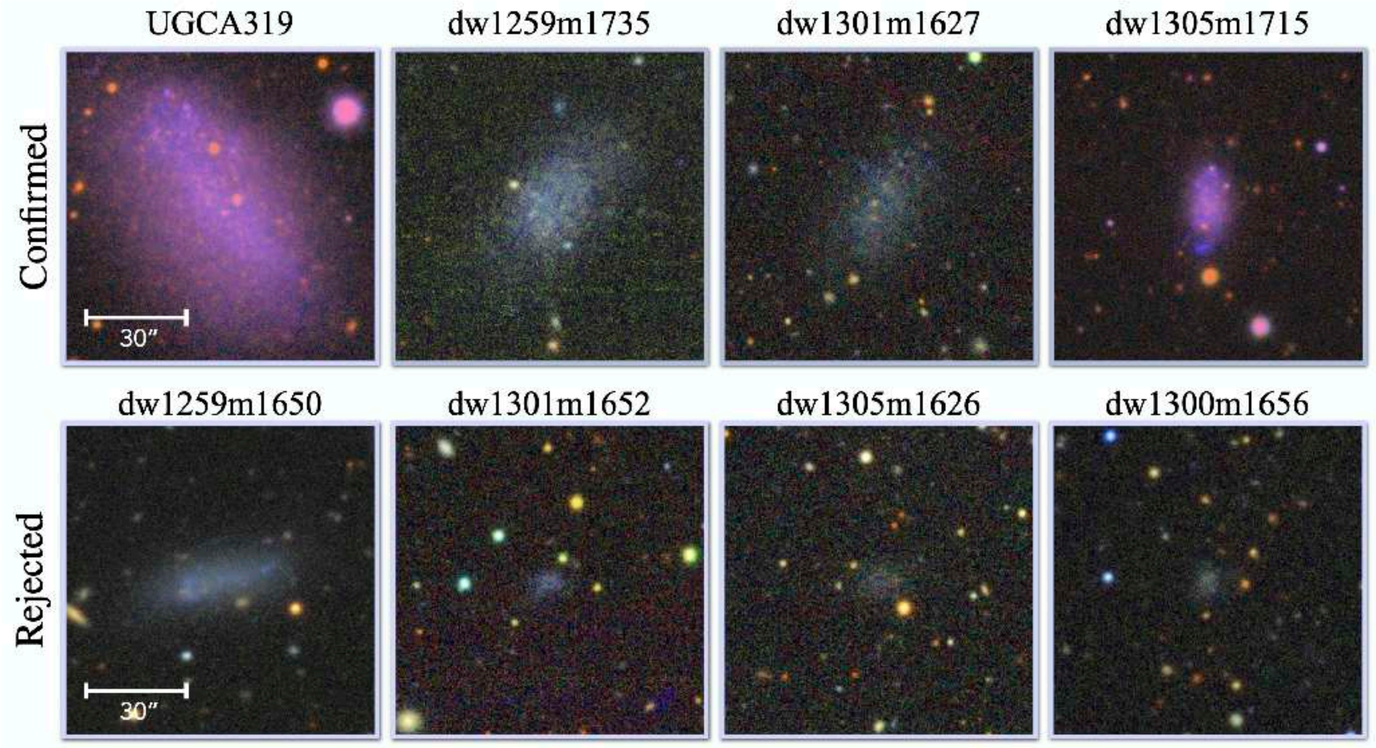

DDO161: an SMC analog at 6 Mpc

Li et al. (2025b)

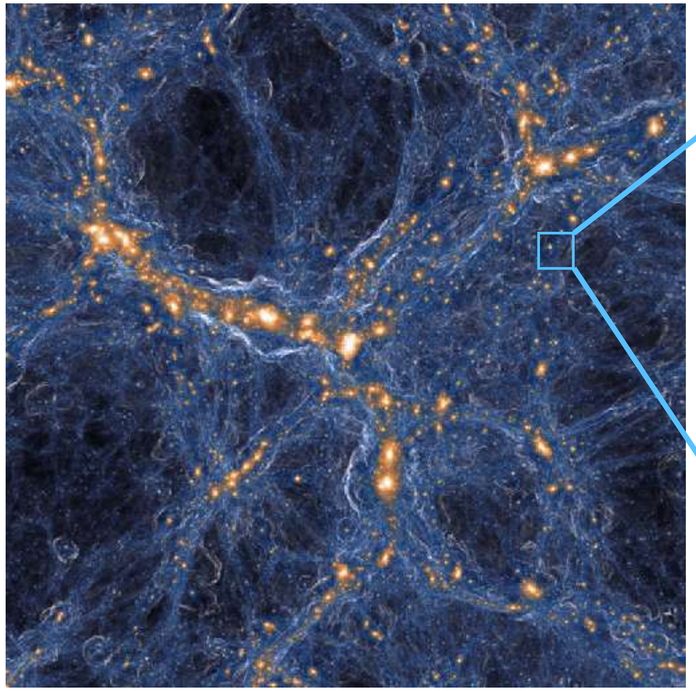


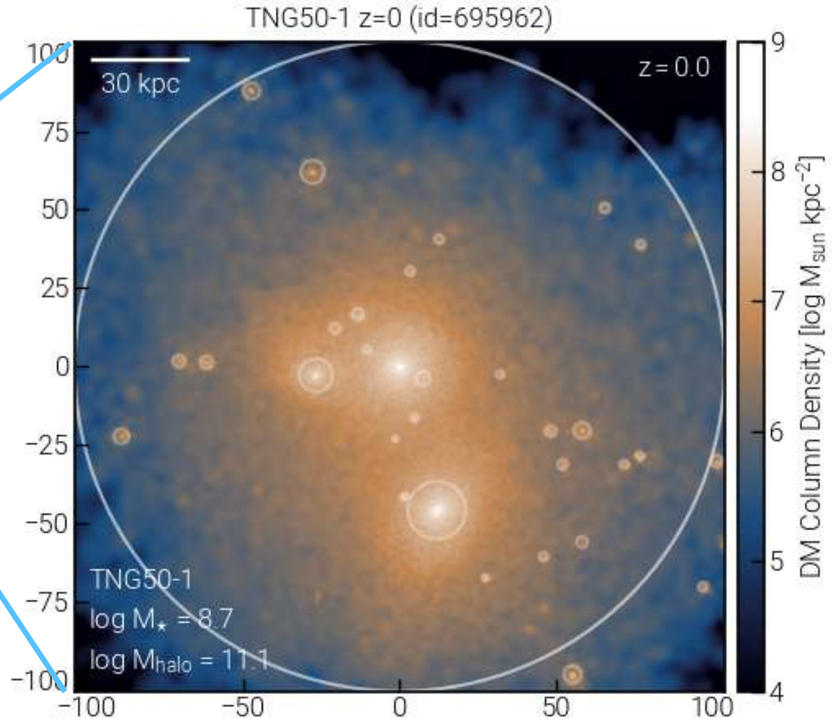
# DDO 161 is very rich!

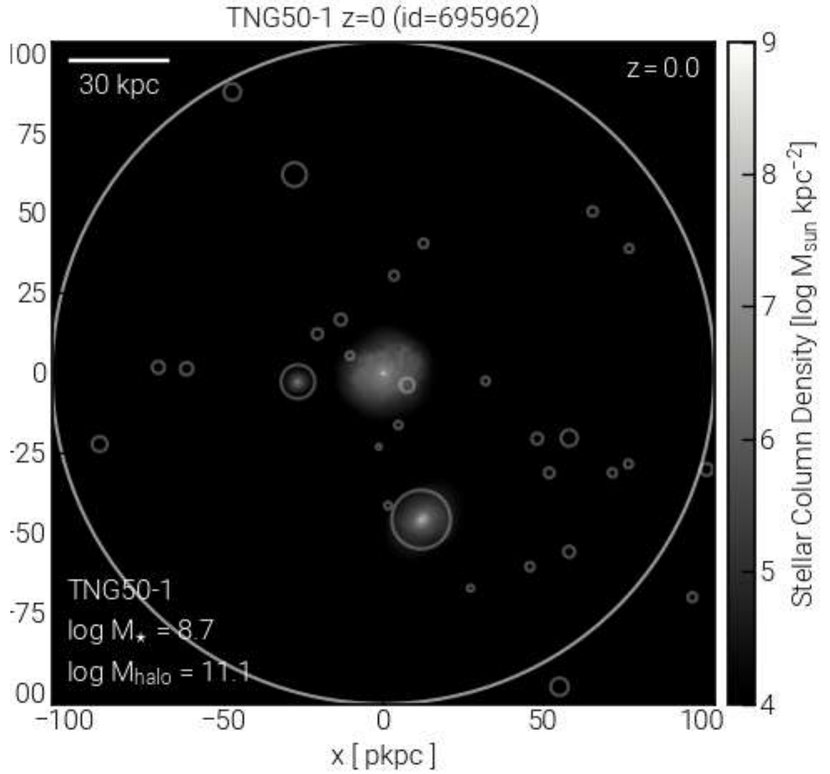


# What's the chance of finding such a system?

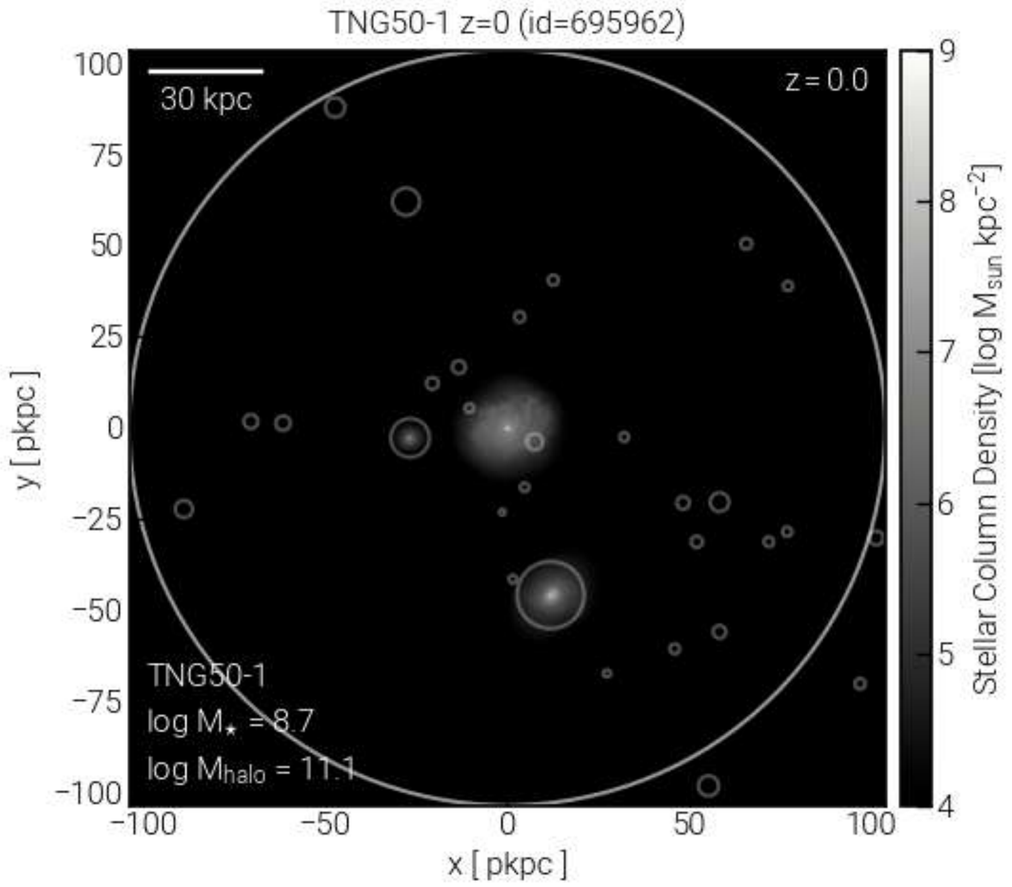




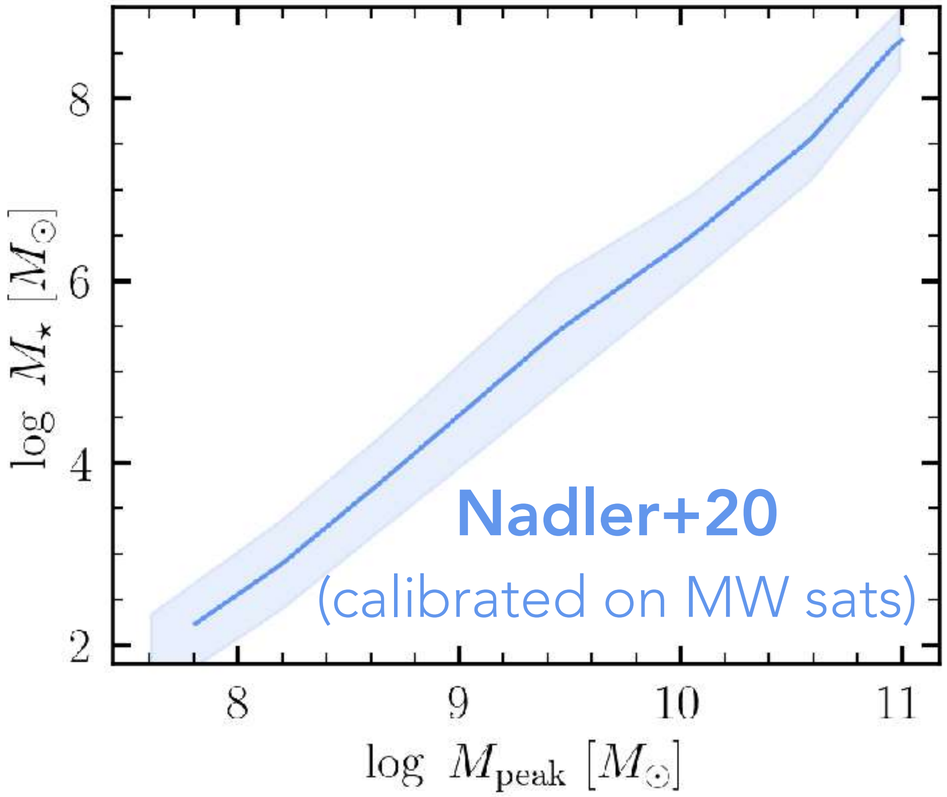

TNG50 simulation → Select hosts similar to DDO161 in stellar mass and environment → Populate subhalos with galaxies

# What's the chance of finding such a system?

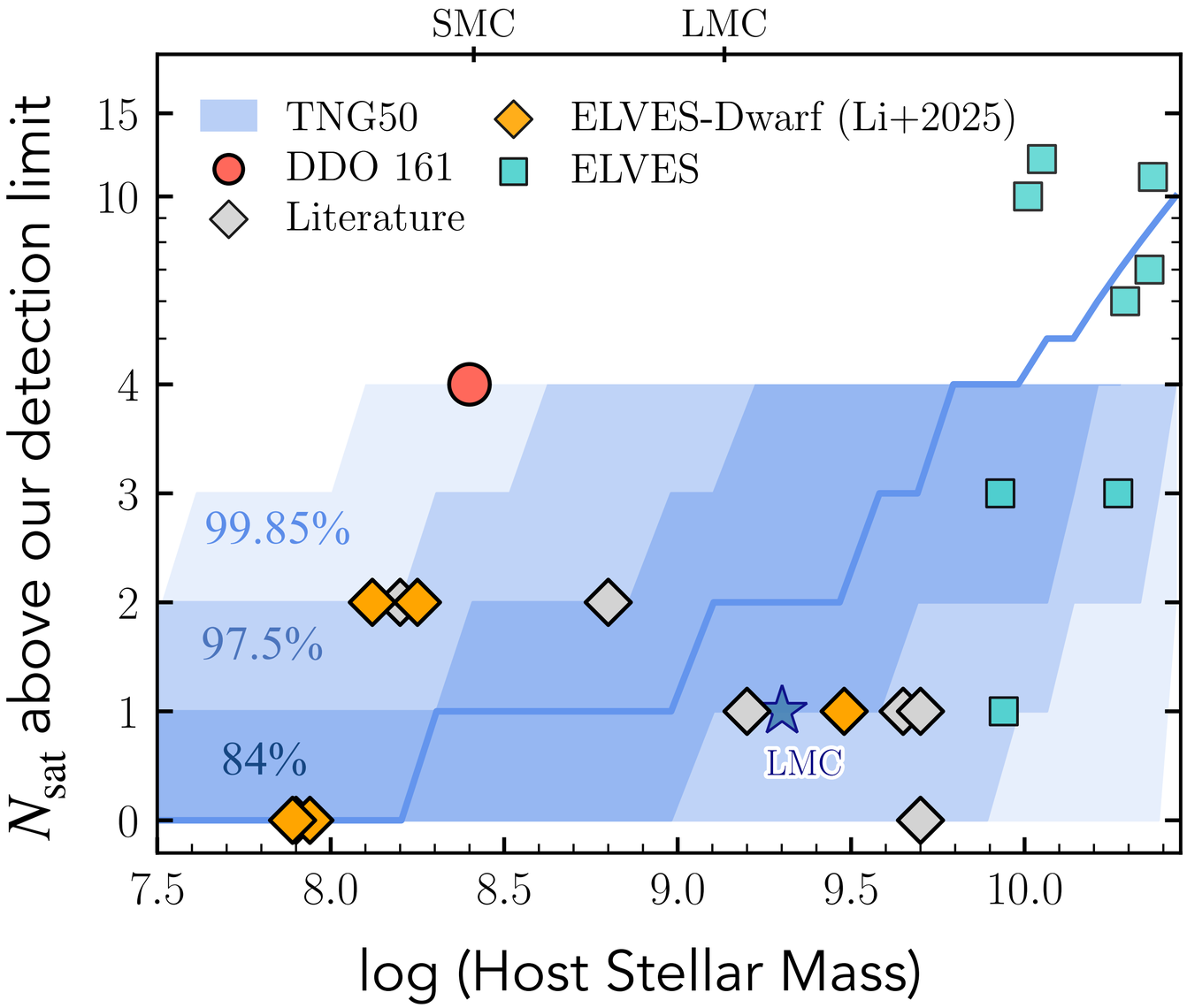



Populate subhalos with galaxies

- 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)

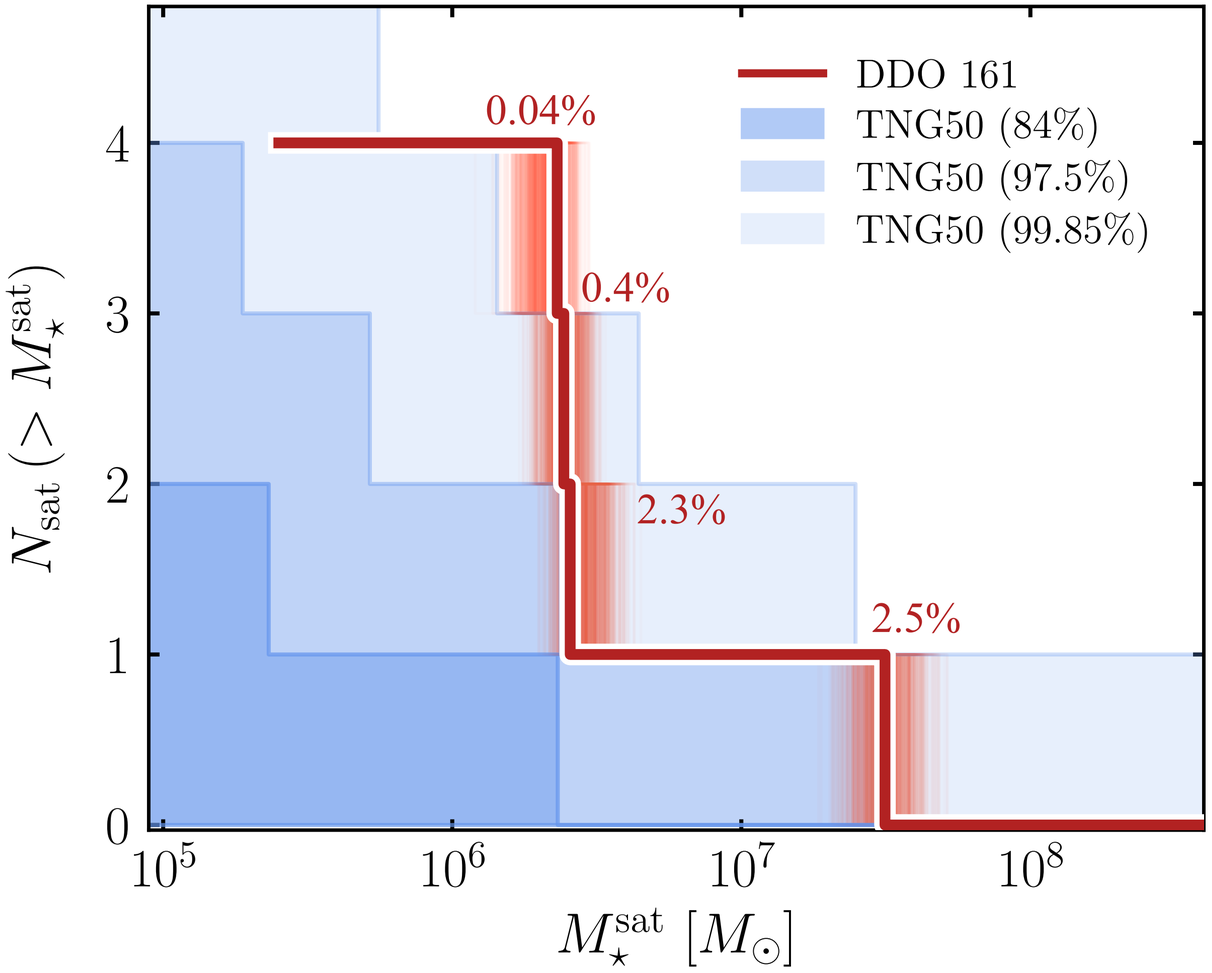


# Such satellite-rich systems are very rare



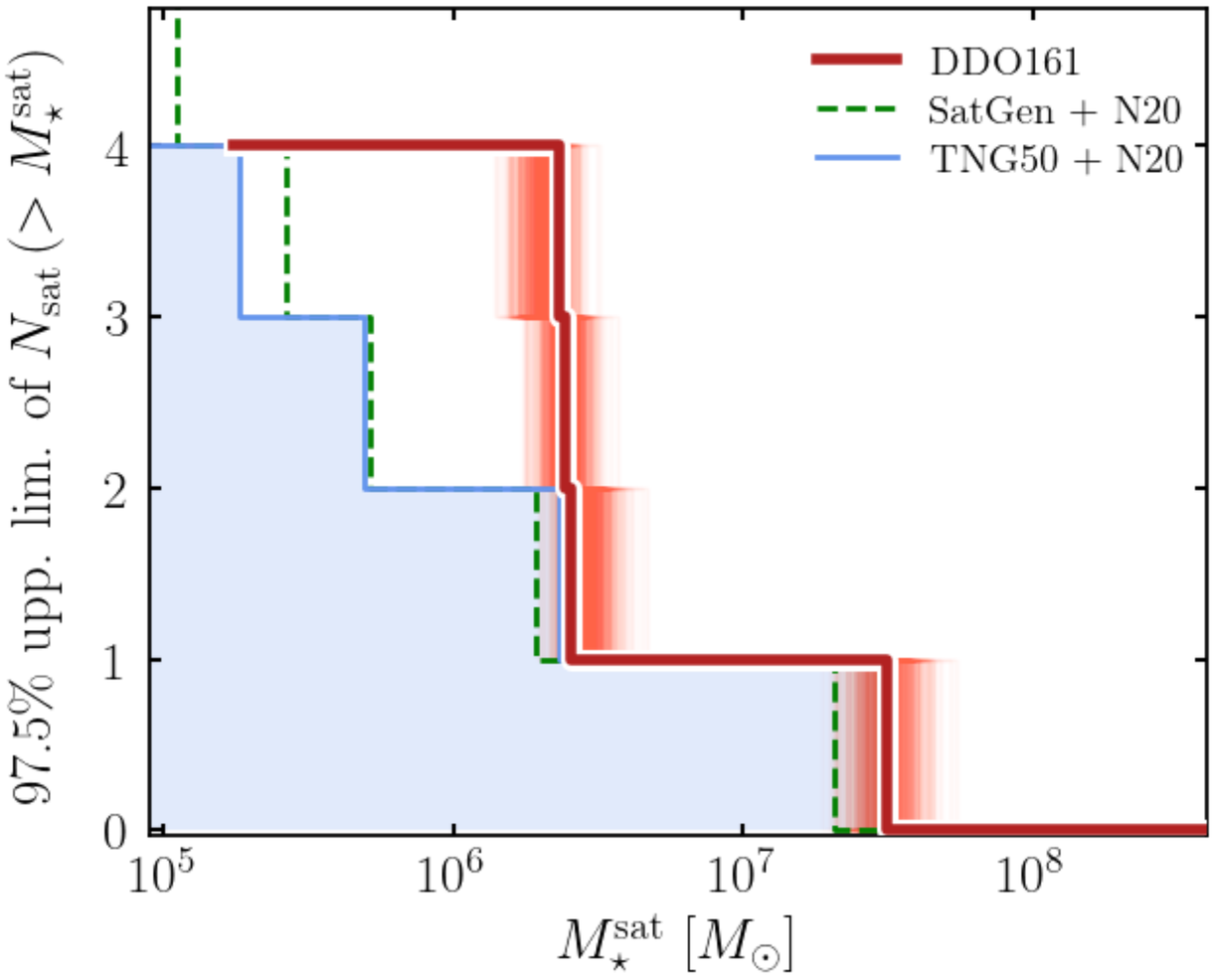
# Such satellite-rich systems are very rare

***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

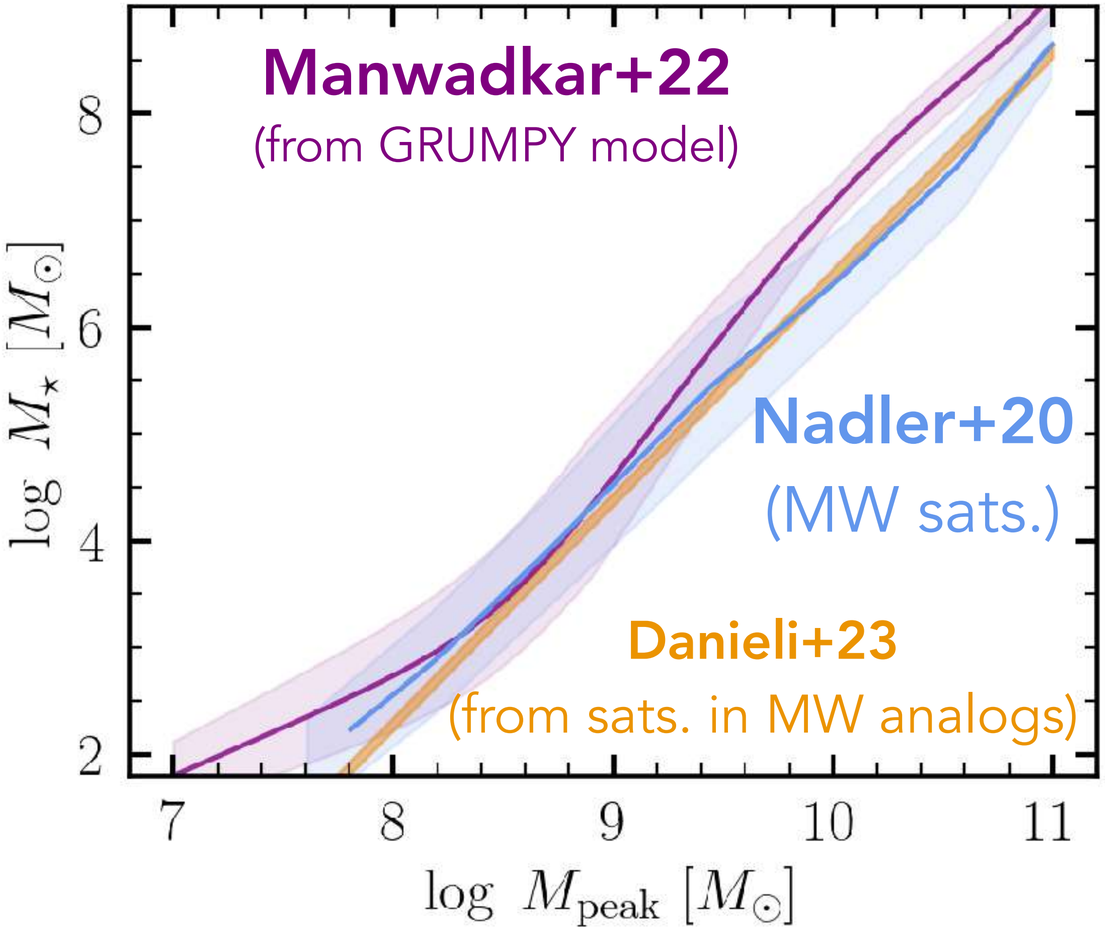



- Is this **numerical issue**? No!

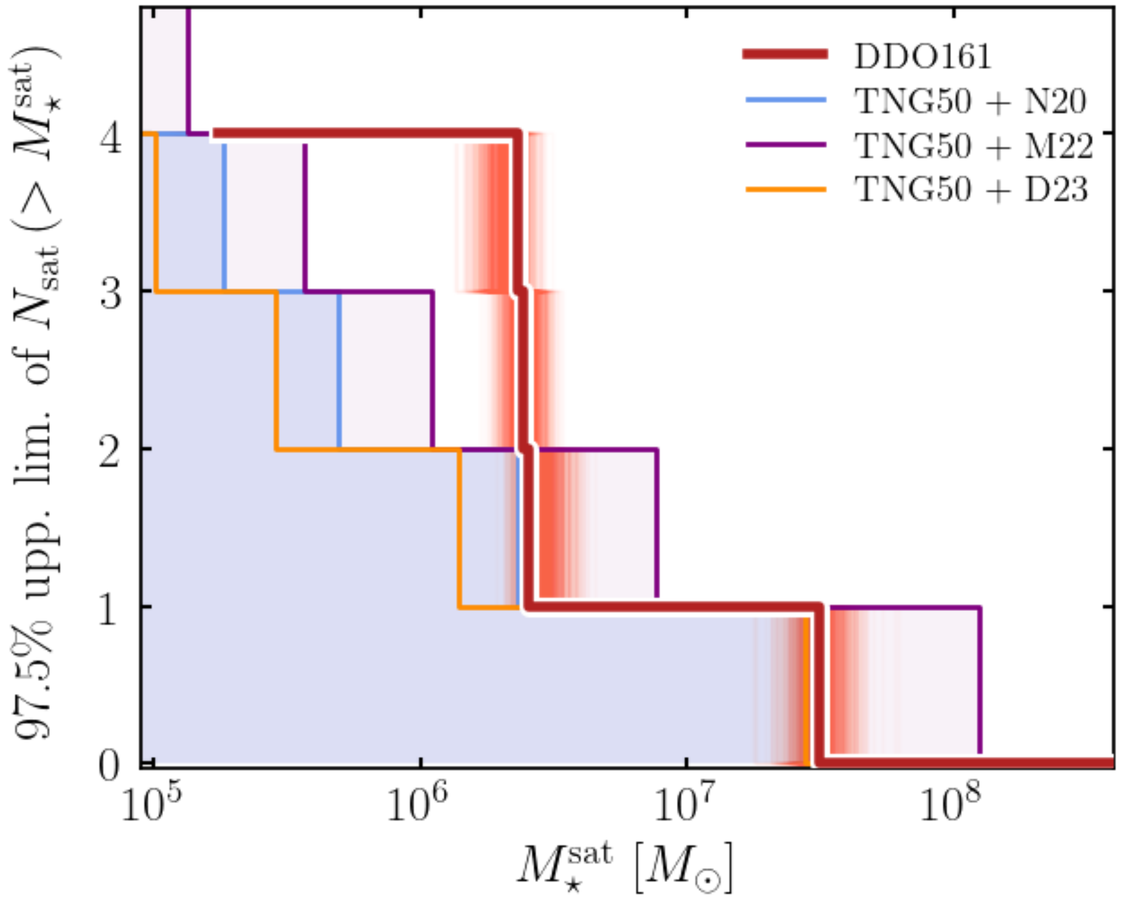
- We only used a **specific galaxy-halo connection** model
  (Try a few others!)

# Such satellite-rich systems are very rare

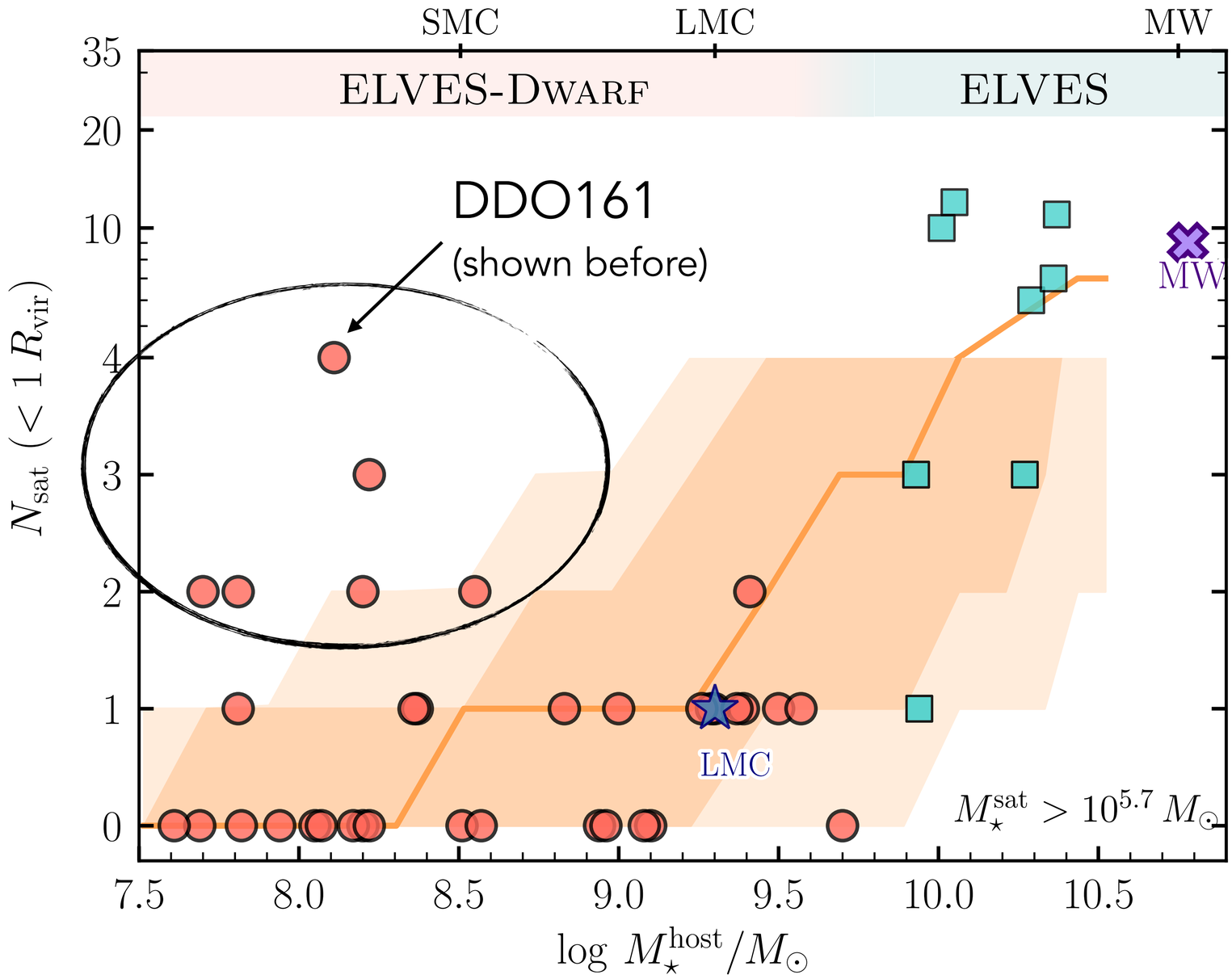
***These models are calibrated on satellites in MW-like groups***




***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)

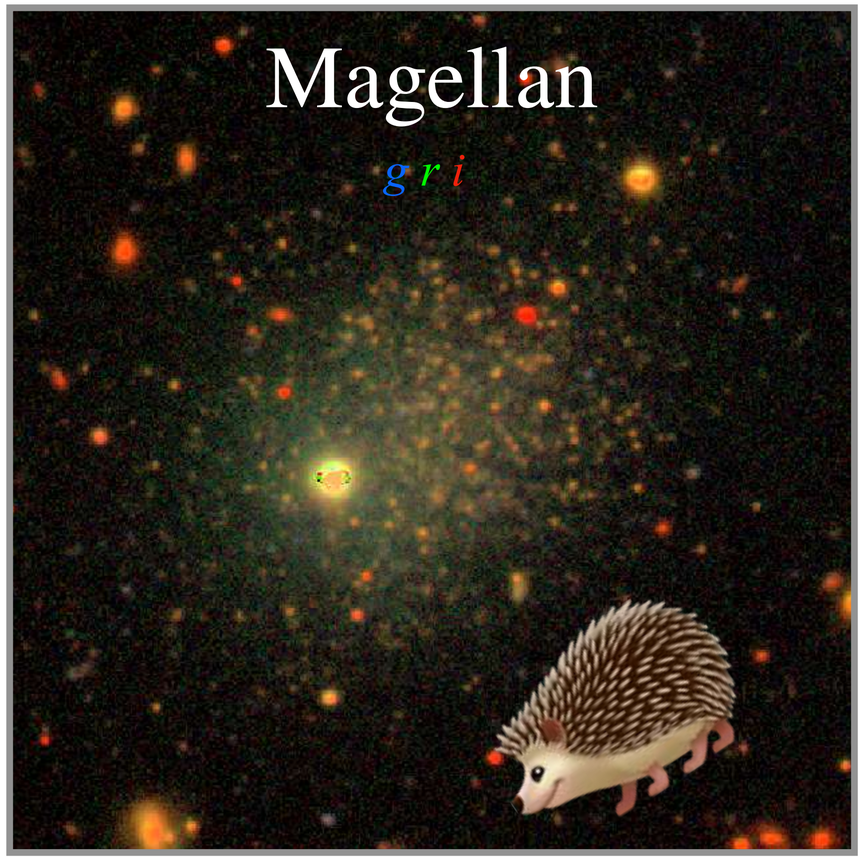
# An intriguing dwarf in isolation:

# Hedgehog

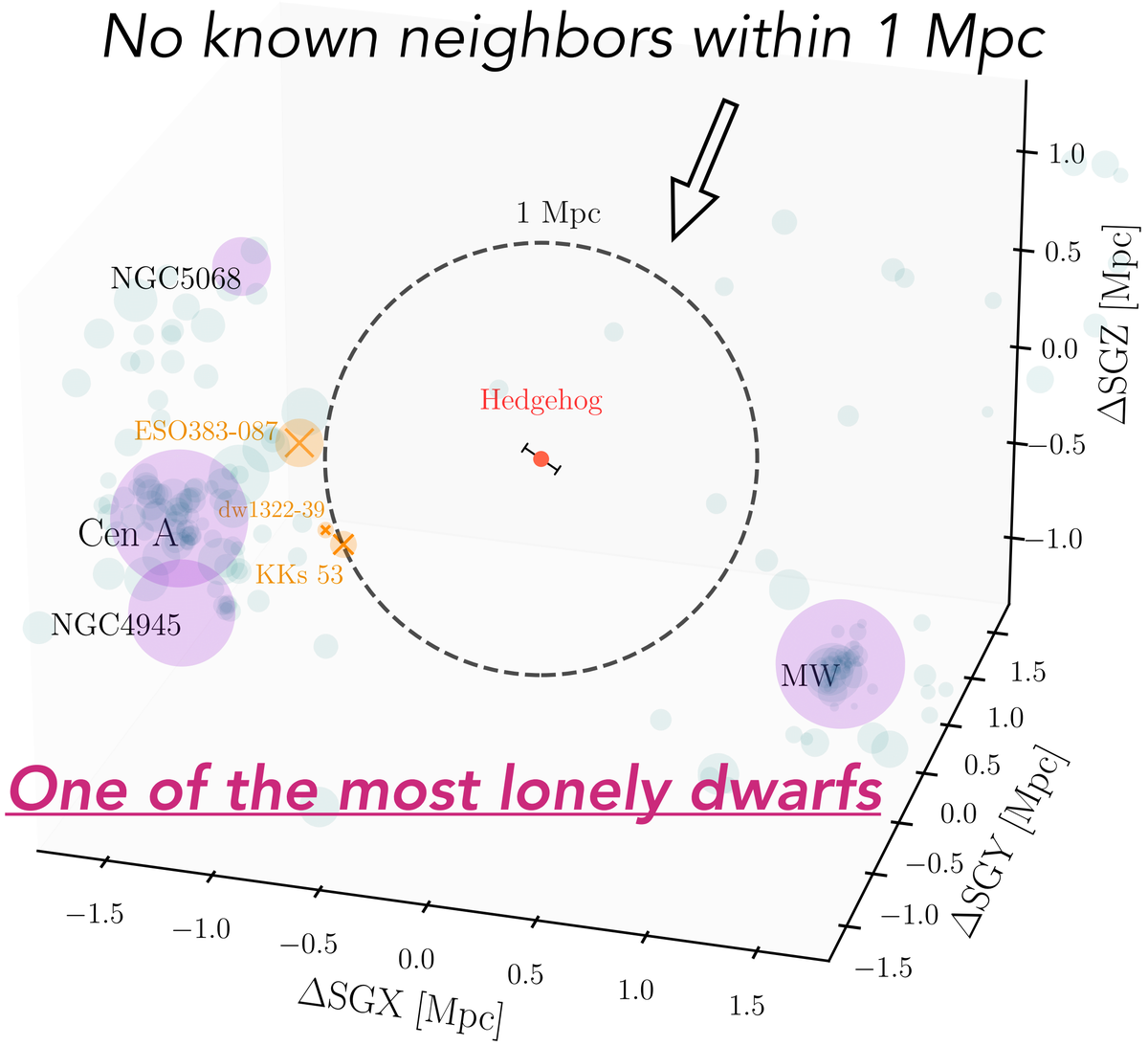
J. Li et al. (2024)
arXiv:2406.00101

## 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*



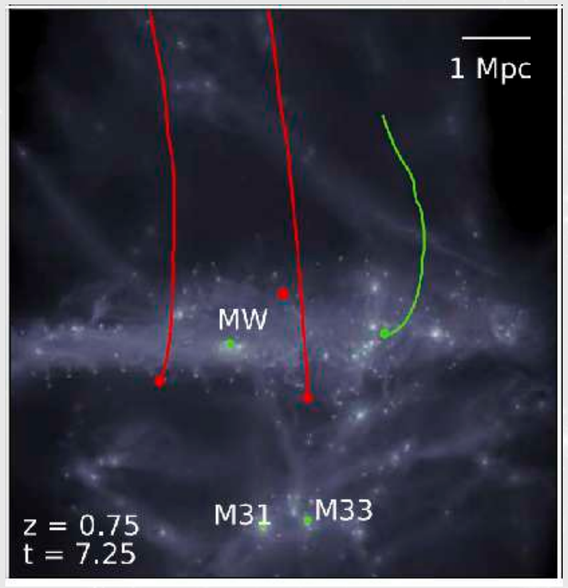

***One of the most lonely dwarfs***

Red dSph ⇨ Quiescent ⇦ **NO** UV and HI

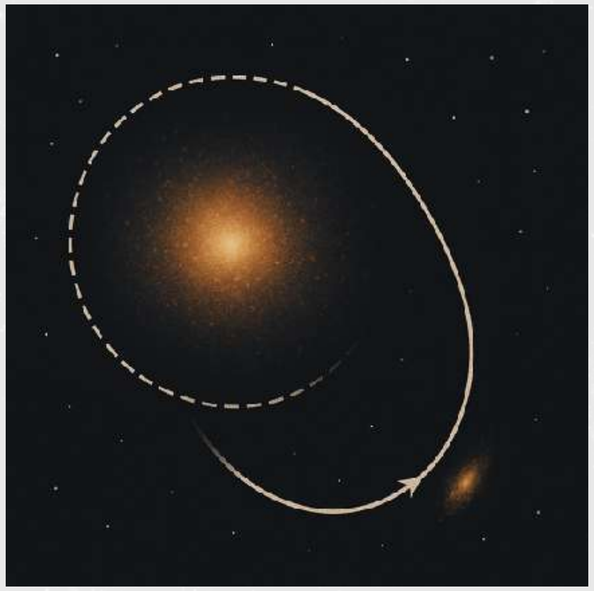
# Field Dwarfs: How are they quenched?

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

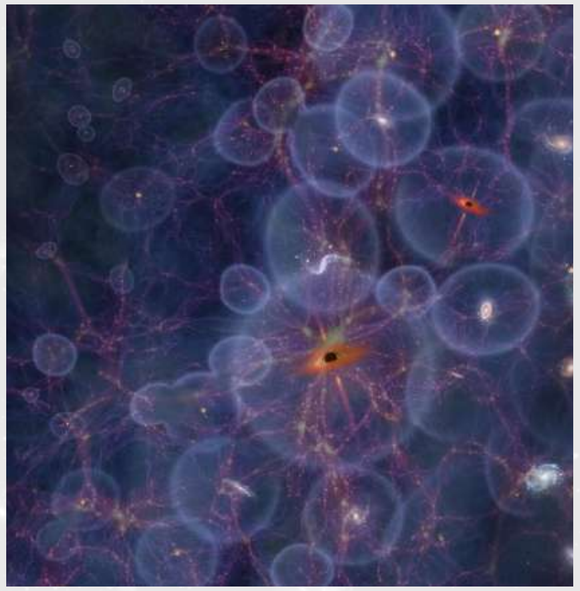
Only a handful of such objects known (including Ava Polzin's COSMOS-dw1)




Cosmic web stripping

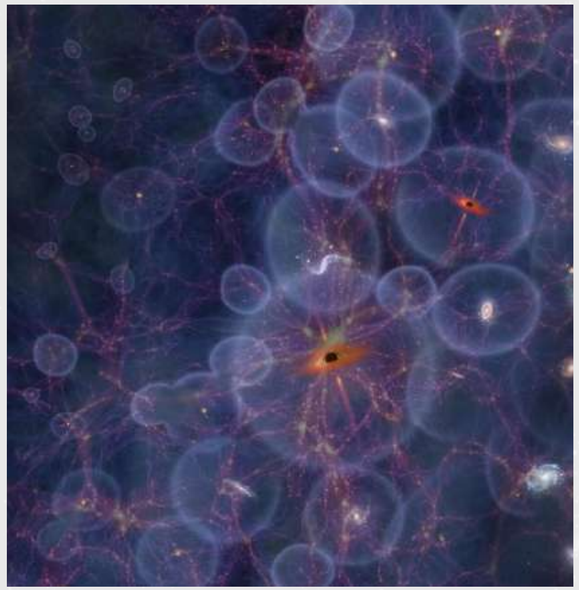


Backsplash dwarf



Reionoization

# Hedgehog be a clean test for Reionization Quenching



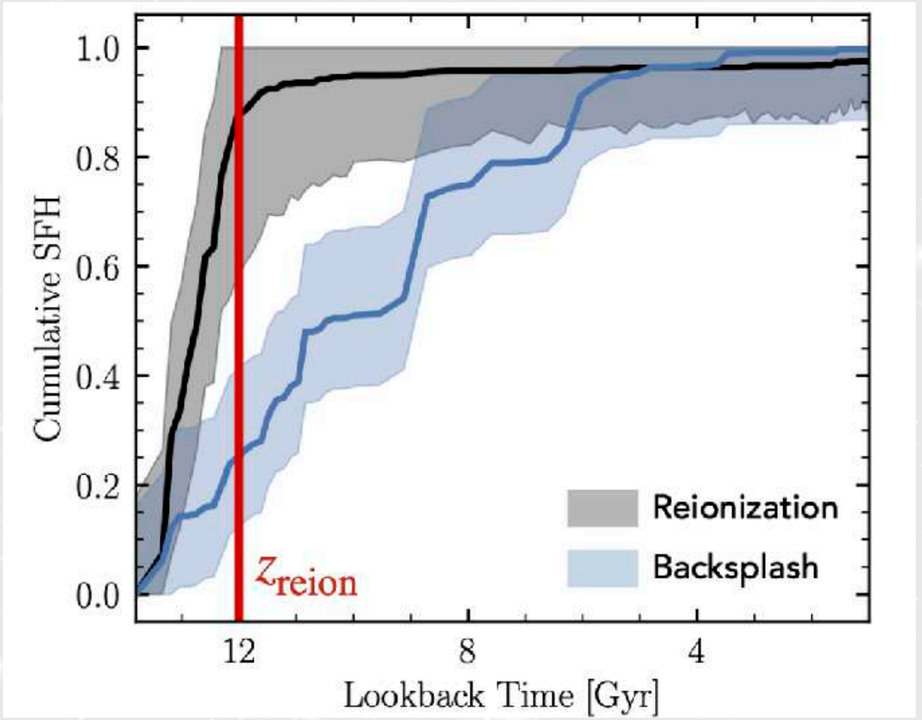
Reionoization

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



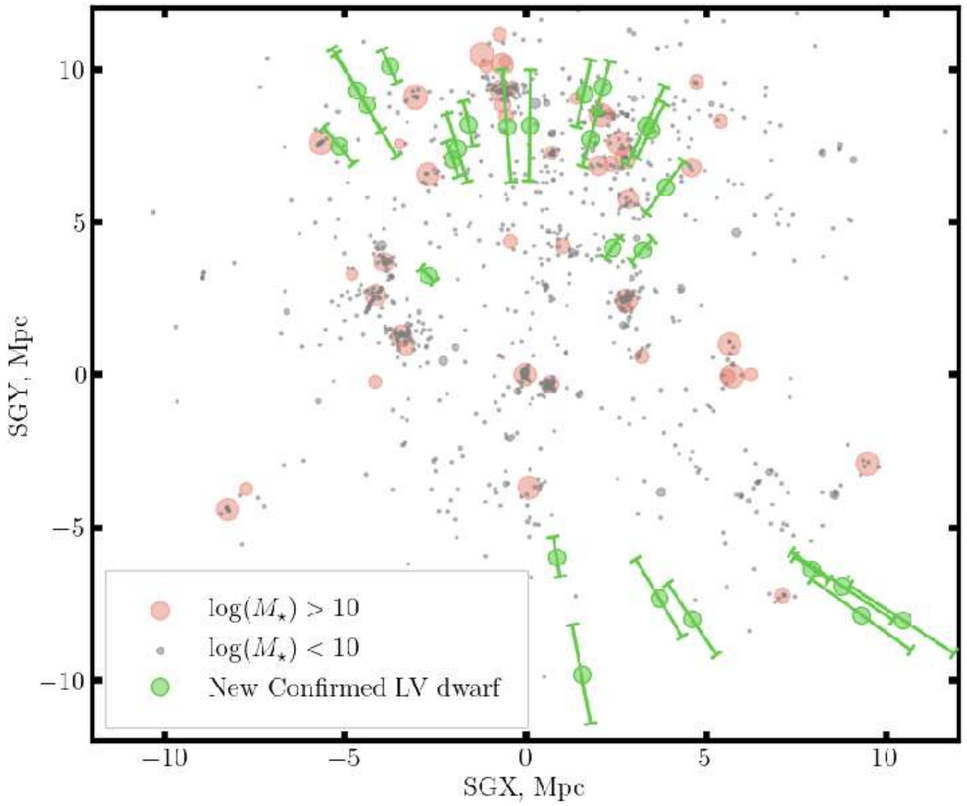
# ELVES-Field: systematic search for field dwarfs

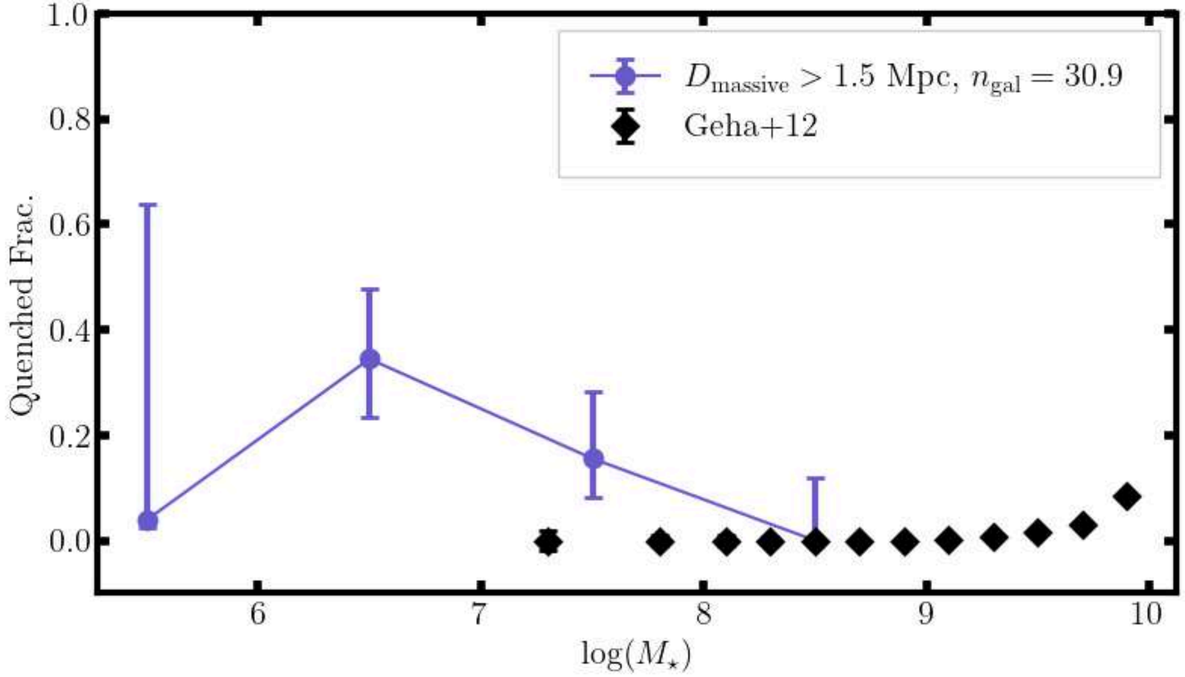
Field dwarf search is more difficult because you don't know where to look!

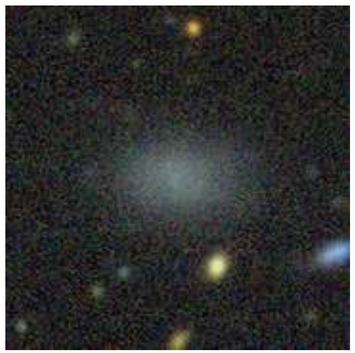
Led by **Scott Carlsten**

3000 sq deg in DECaLS+HSC

41 dwarfs, ~14 are new

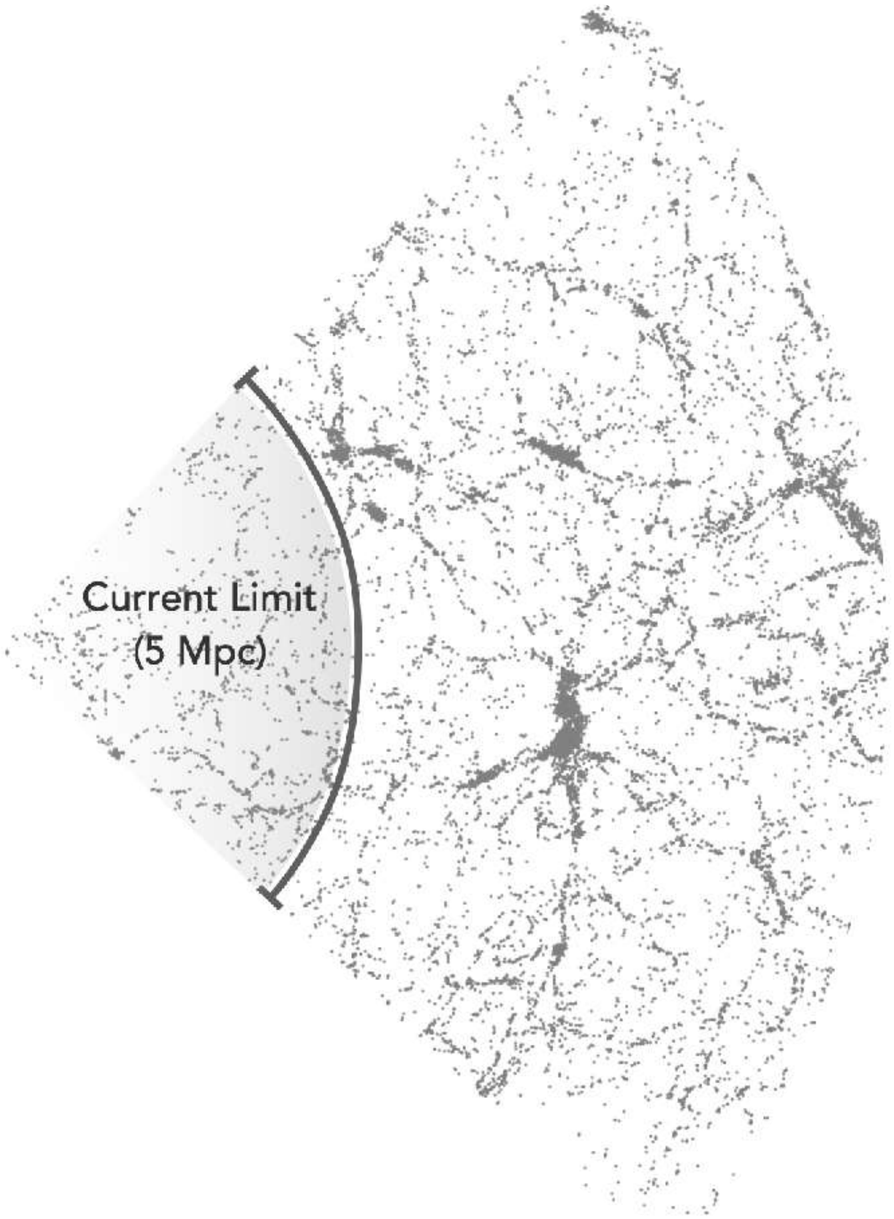


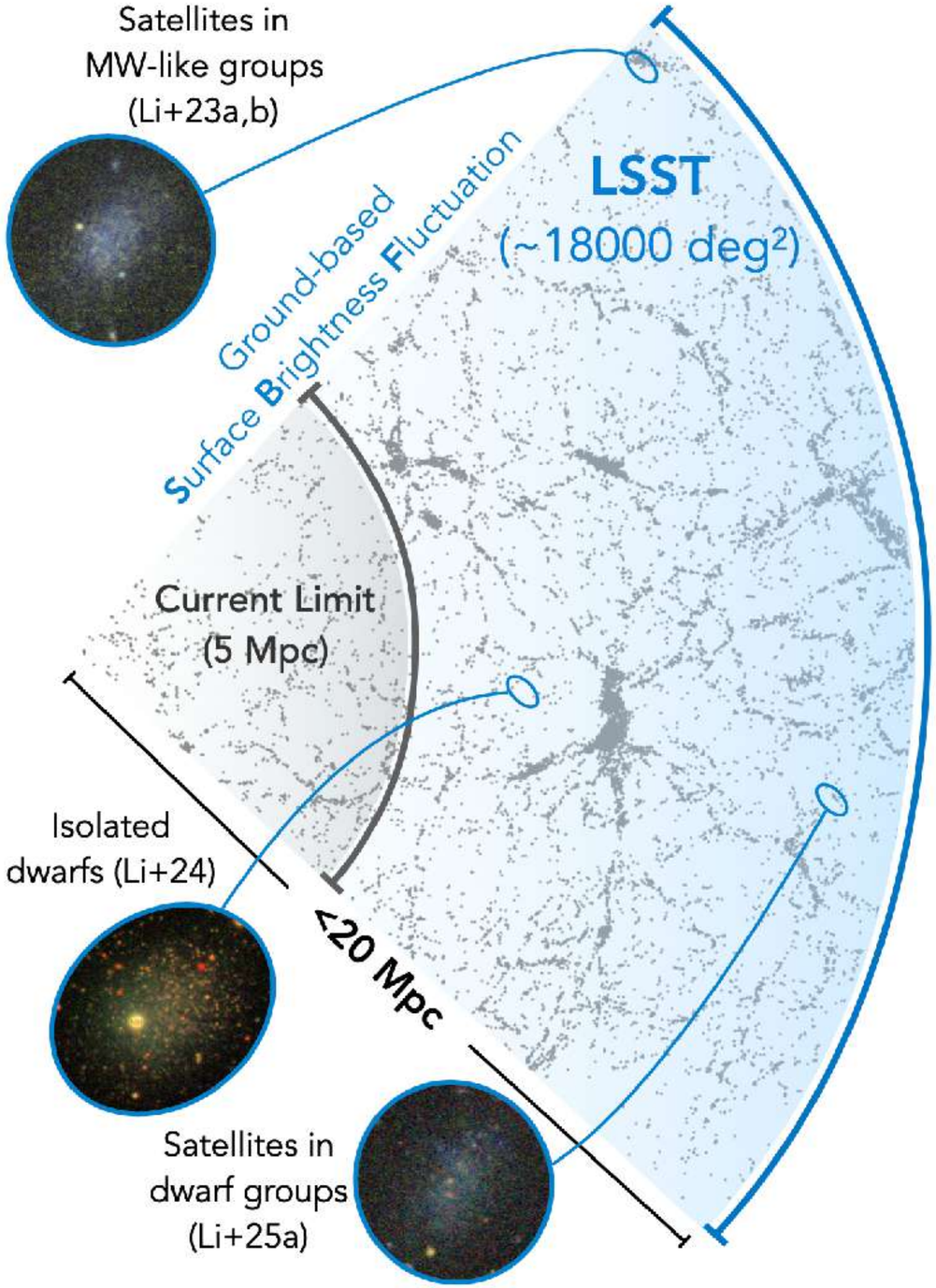



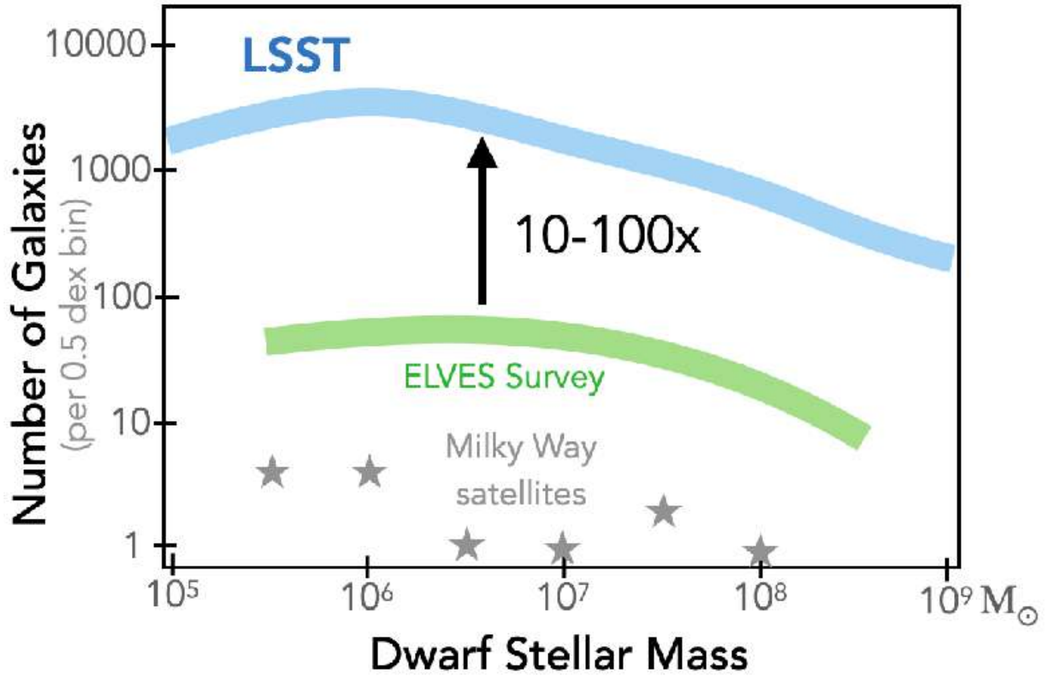
We still don't quite **understand galaxy formation** in low-mass regime because:

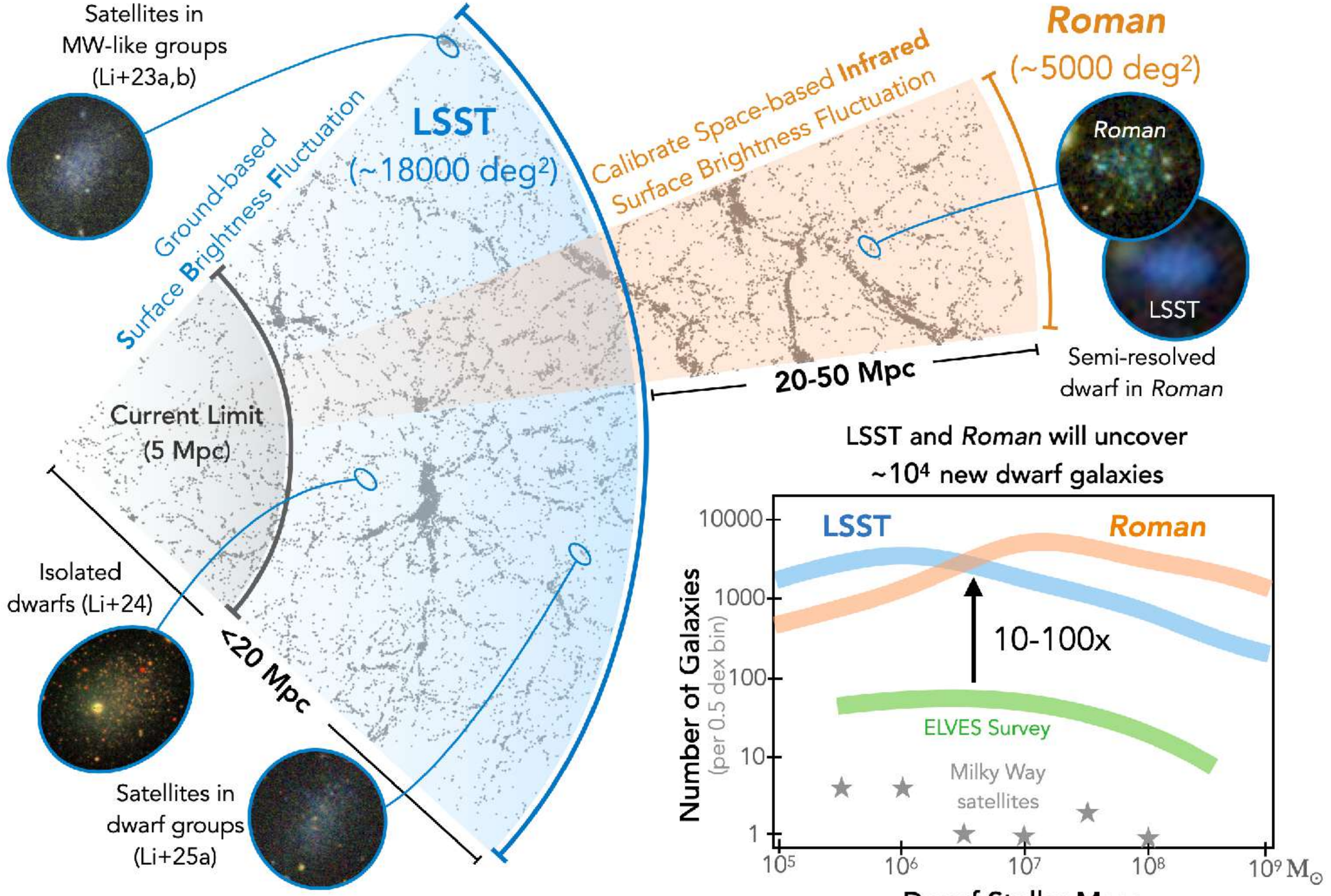
- We've mostly focused on **satellites** of MW groups
- We are **incomplete** at $M_\star \approx 10^6\, M_\odot$ even within a few Mpc



# In the next 5 years…



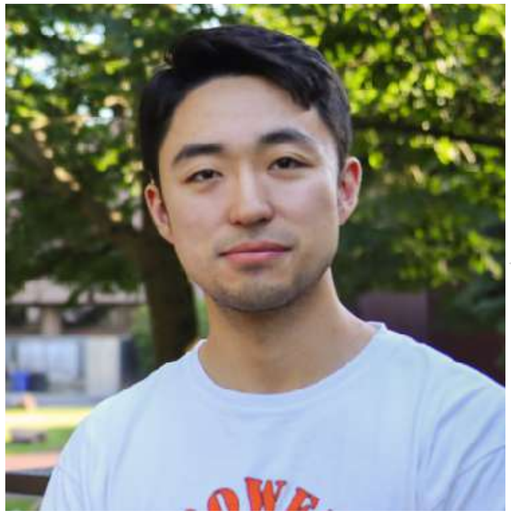




Satellites in
MW-like groups
(Li+23a,b)
Ground-based
Surface Brightness Fluctuation
LSST
(~18000 deg²)
Current Limit
(5 Mpc)
Isolated
dwarfs (Li+24)
~20 Mpc
Satellites in
dwarf groups
(Li+25a)
Calibrate Space-based Infrared
Surface Brightness Fluctuation
Roman
(~5000 deg²)
Roman
LSST
20-50 Mpc
Semi-resolved
dwarf in Roman
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?

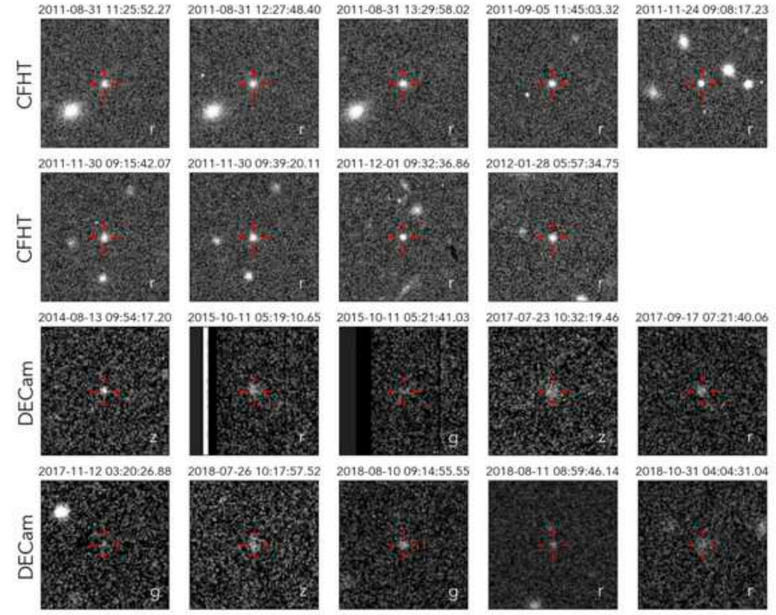
The New York Times

## *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

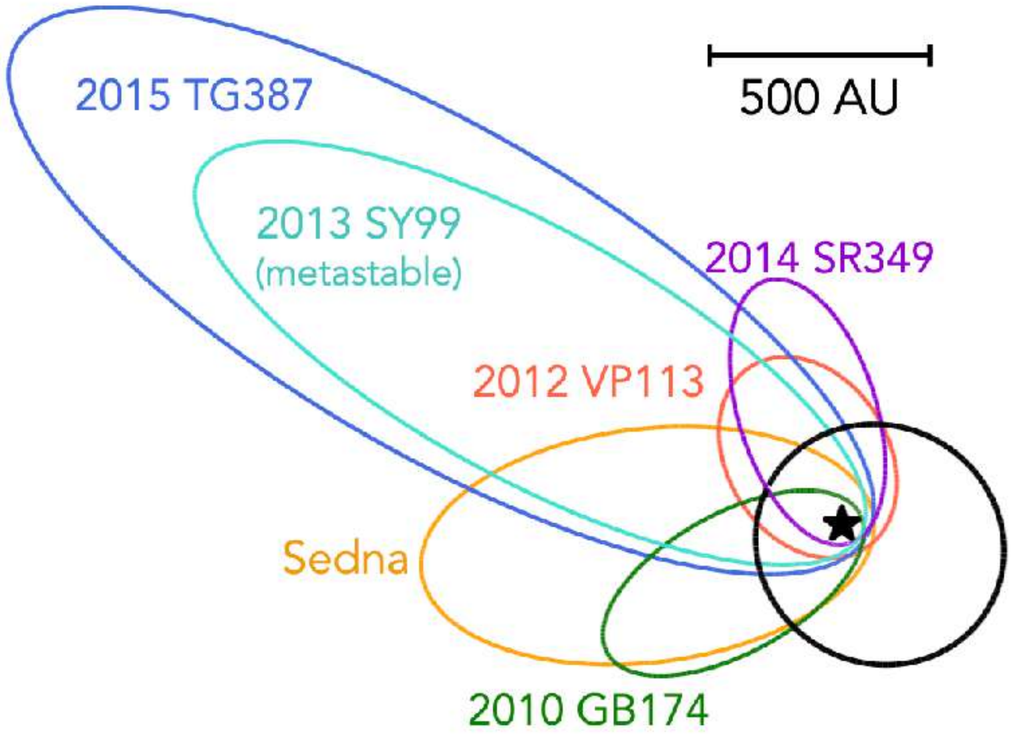



All 19 detections of the dwarf planet 2017 OF201, from August 2011 to October 2018.
Cheng et al., arxiv.org, 2025

# **Planet 9 (or X)** Hypothesis

Orbital clustering caused by Planet 9

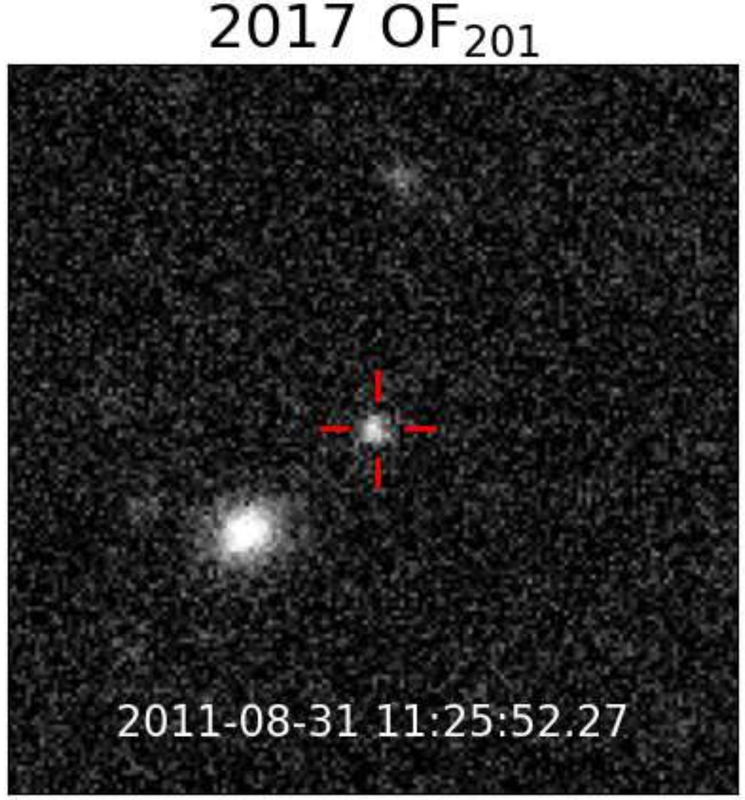
We need to find slow-moving and bright object!



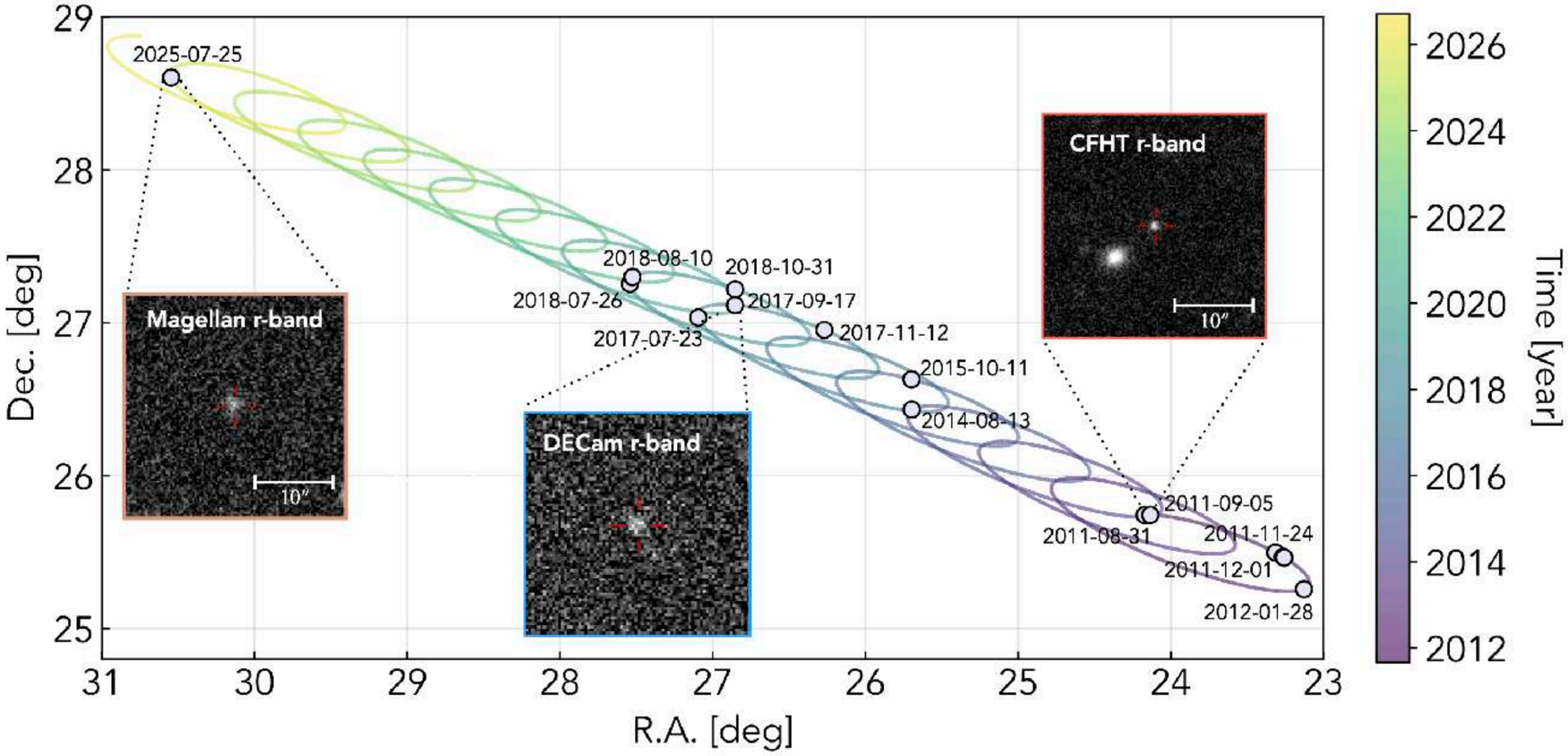

Planet X at 300 AU, $4\,M_\oplus$
(Siraj+25)

# Discovery of a **Dwarf Planet** candidate

Led by Sihao Cheng (IAS)

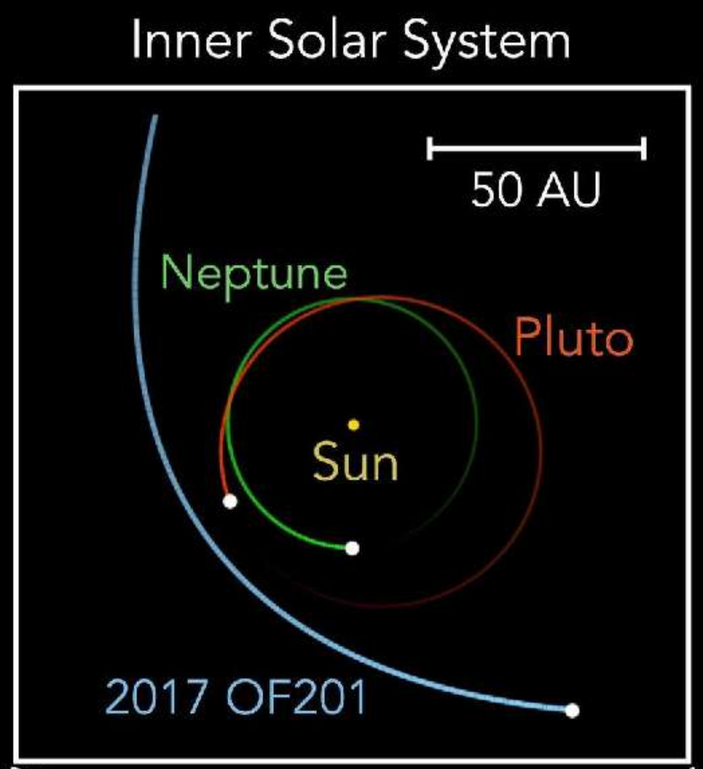



**Bright and slow-moving**




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

Cheng, Li, Yang (2025)




$a = 830.4 \pm 0.8$ au

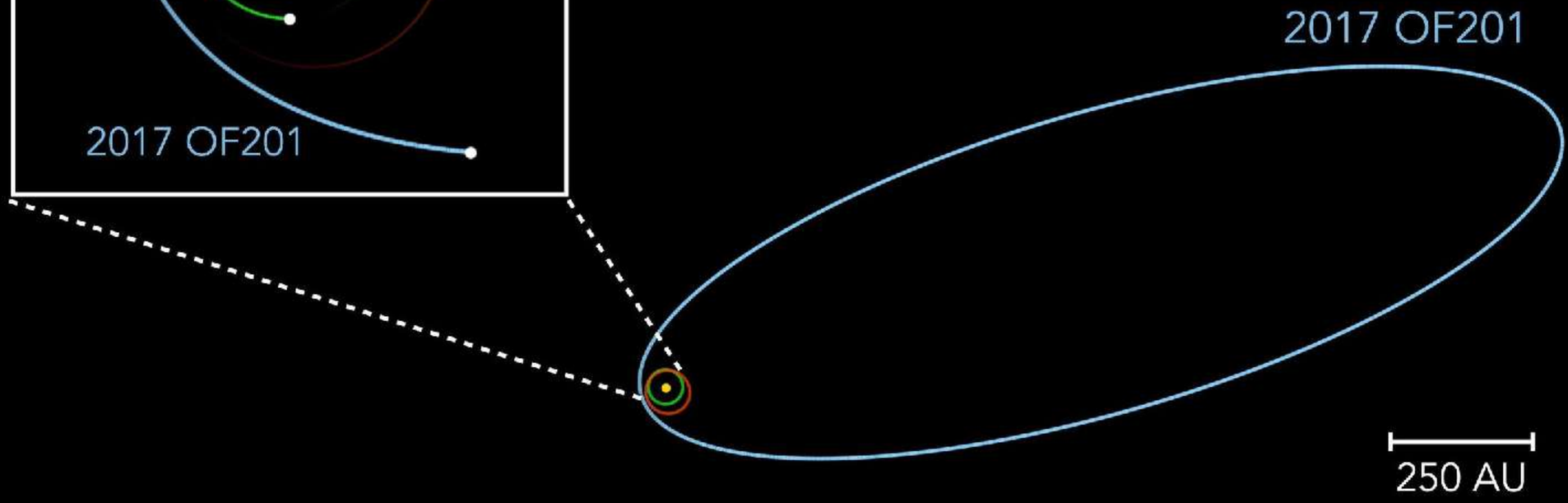
$e = 0.946$

$P \sim 24000$ yr

$D = 700$ km

$(\rho_V = 15\%)$

3rd largest dwarf planet



# **Planet 9 (or X)** Hypothesis

Orbital clustering
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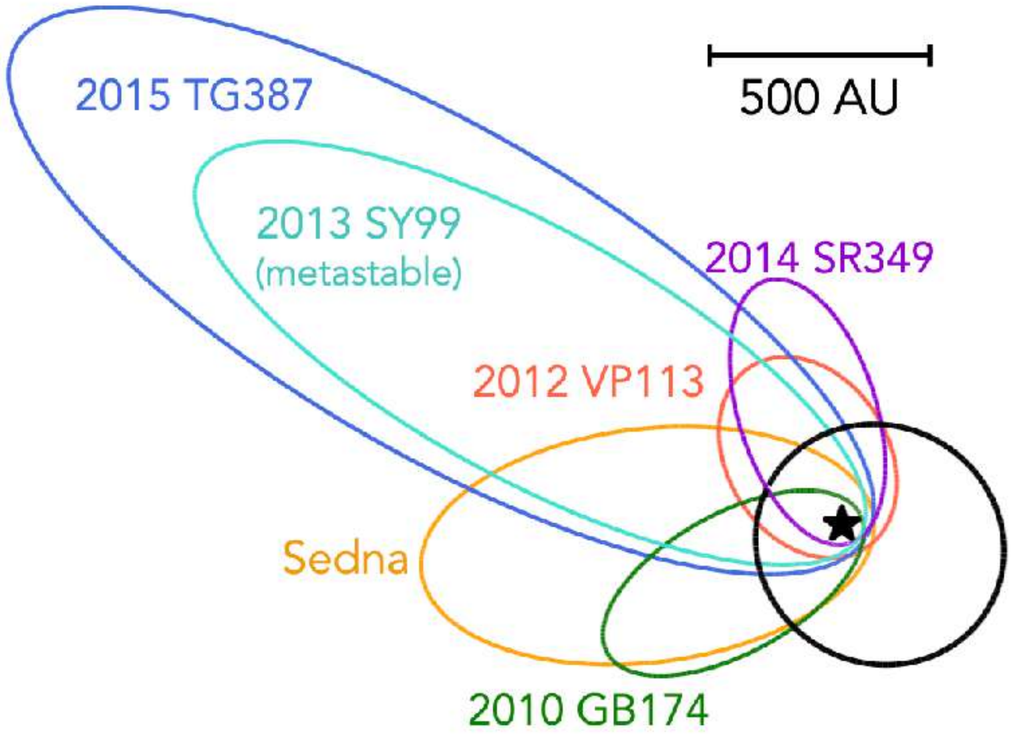
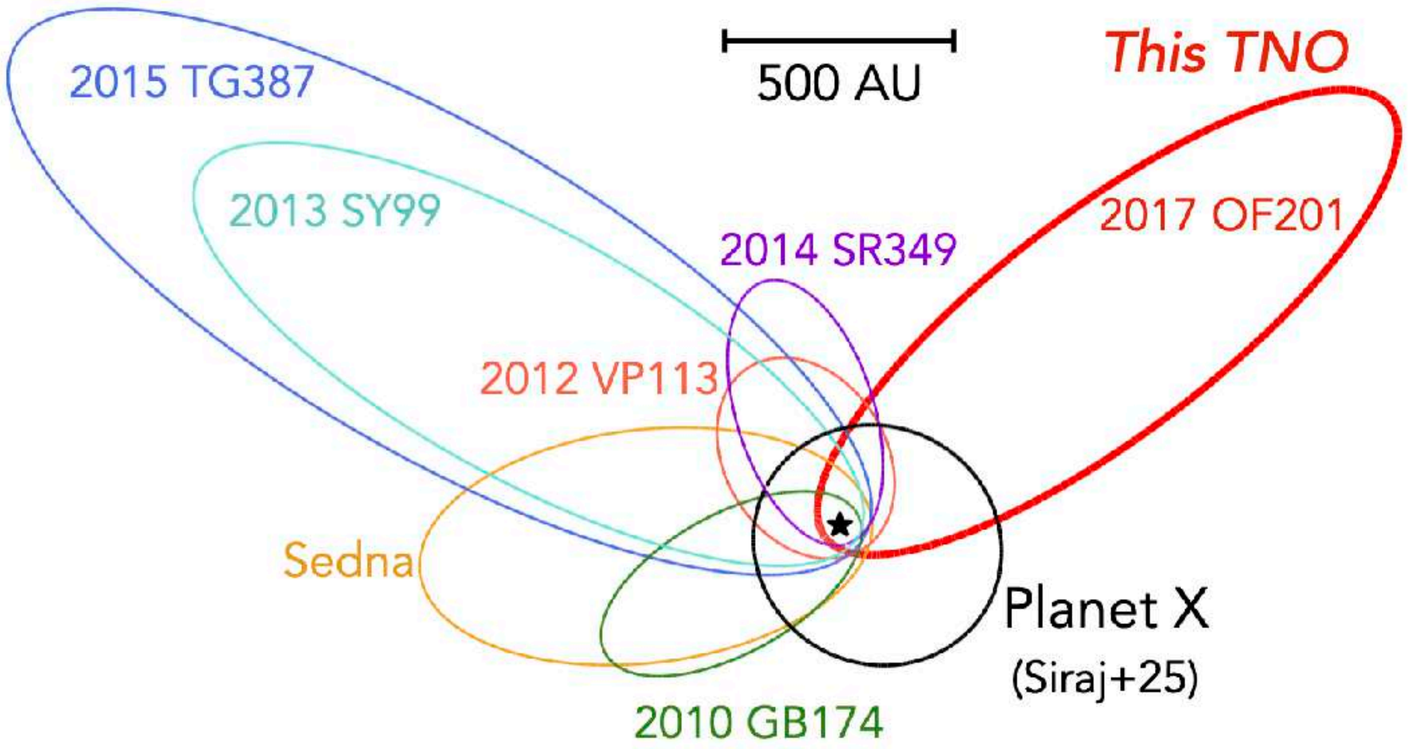
We need to find slow-moving and bright object!

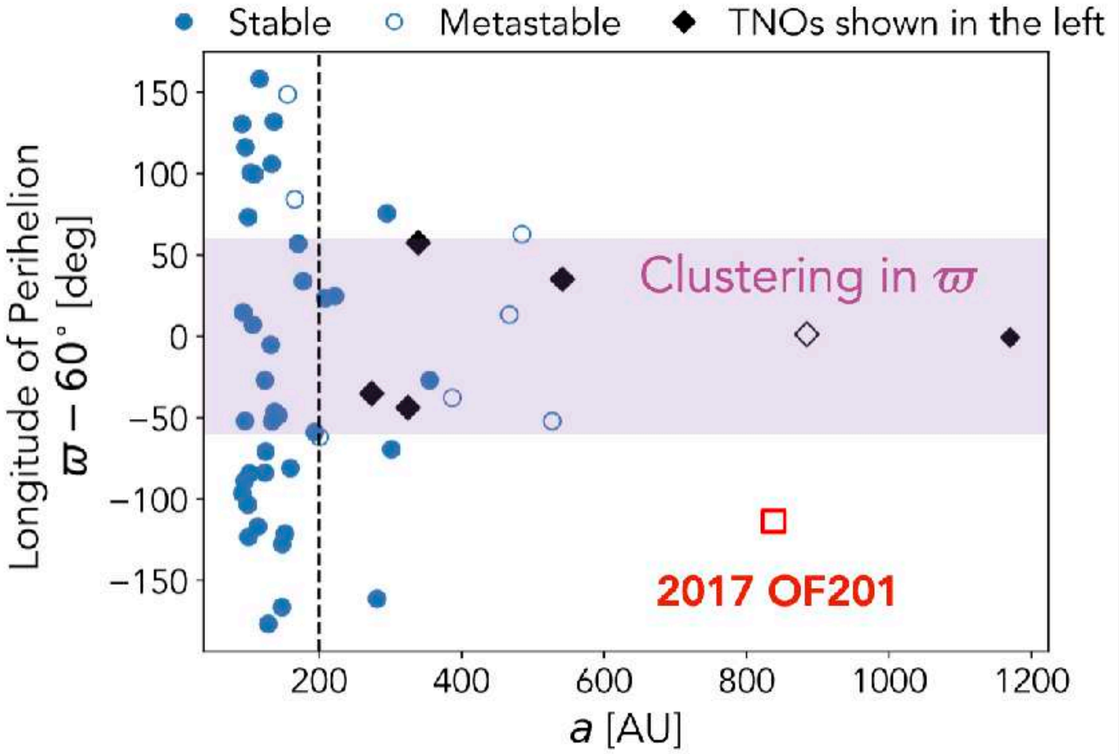



300 AU, $4\,M_{\oplus}$

# Implication for **Planet 9** Hypothesis

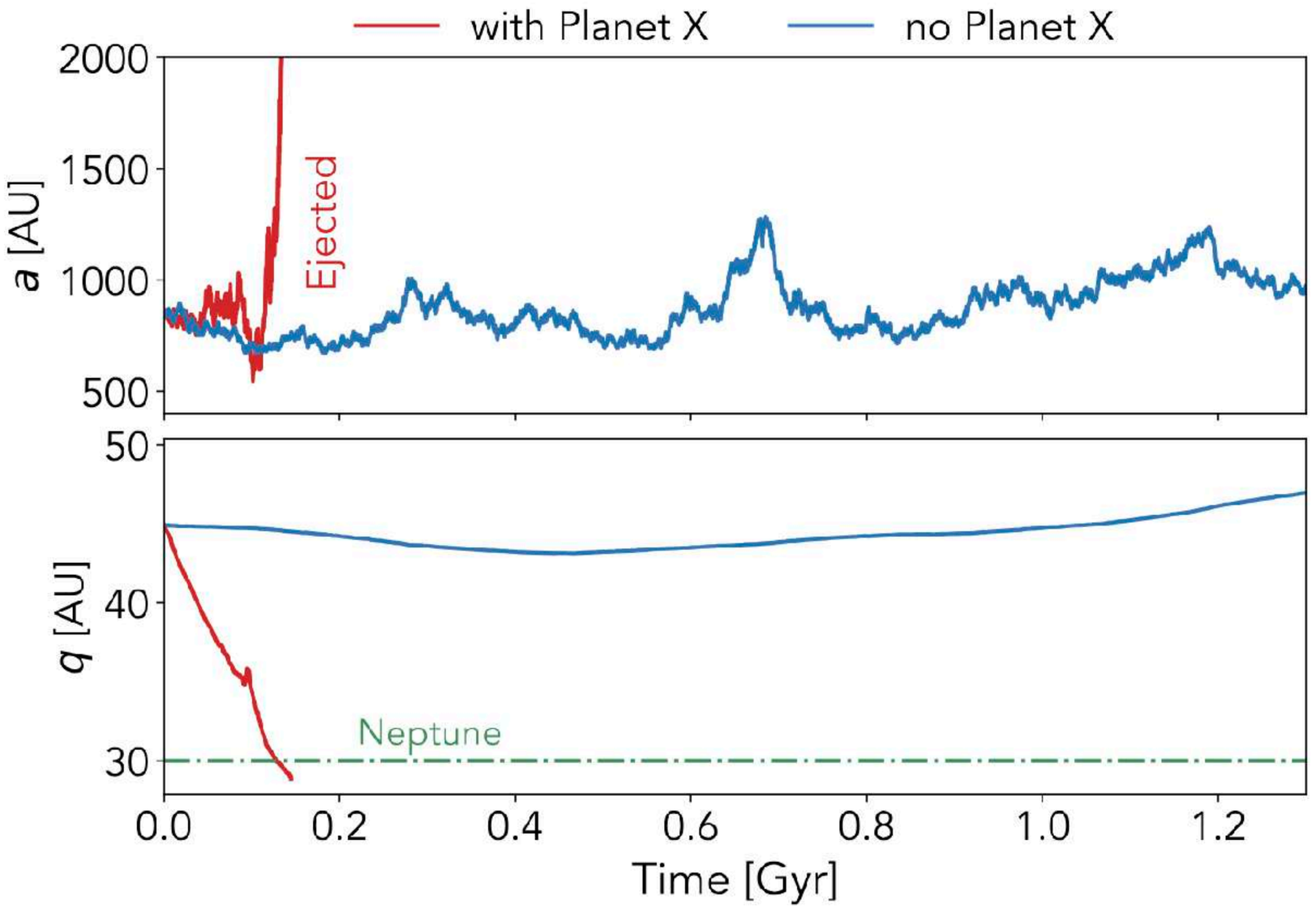
**This TNO is outside of the orbital cluster, which is the evidence of P9**



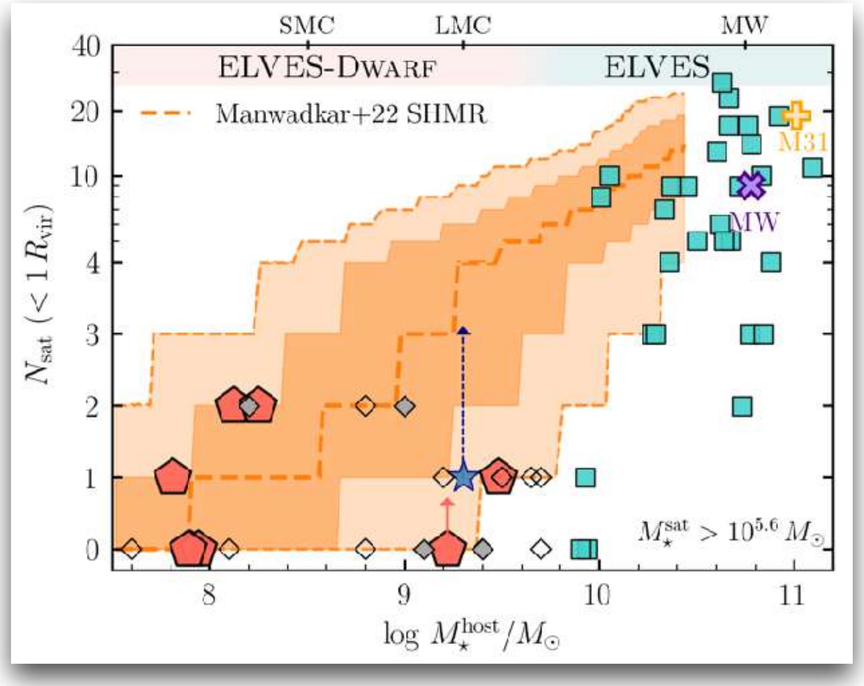
# Implication for Planet 9 Hypothesis

**With Planet 9, this TNO will be ejected very quickly**

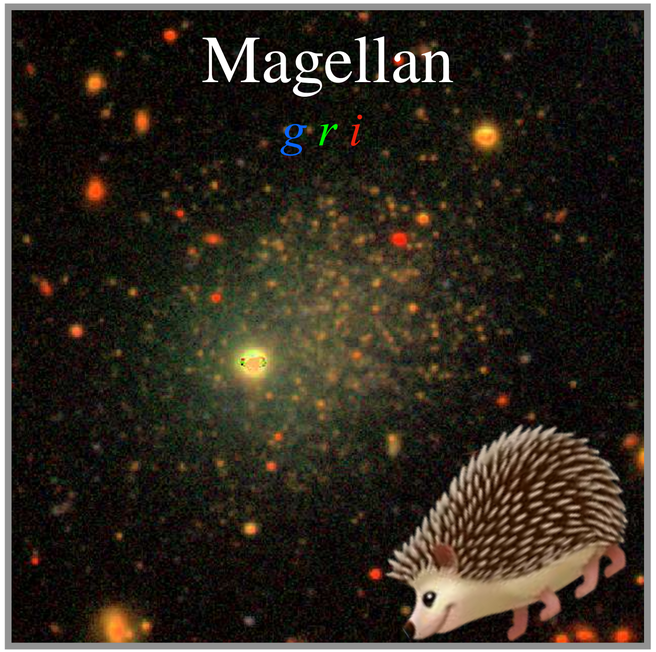


# Summary

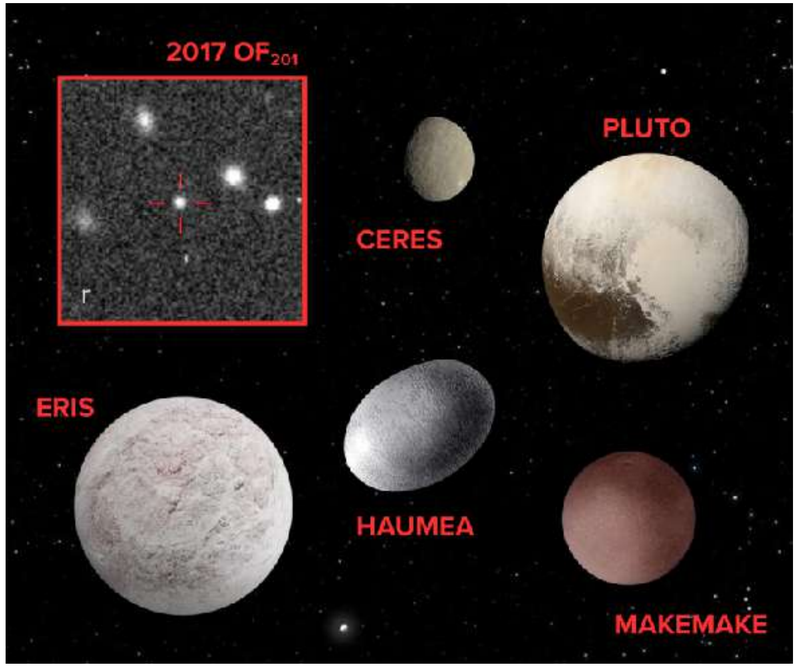
## ELVES-Dwarf
Satellites of Dwarfs




## 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