Dwarfs: Near and Far

Jiaxuan Li 李嘉轩 (Princeton)

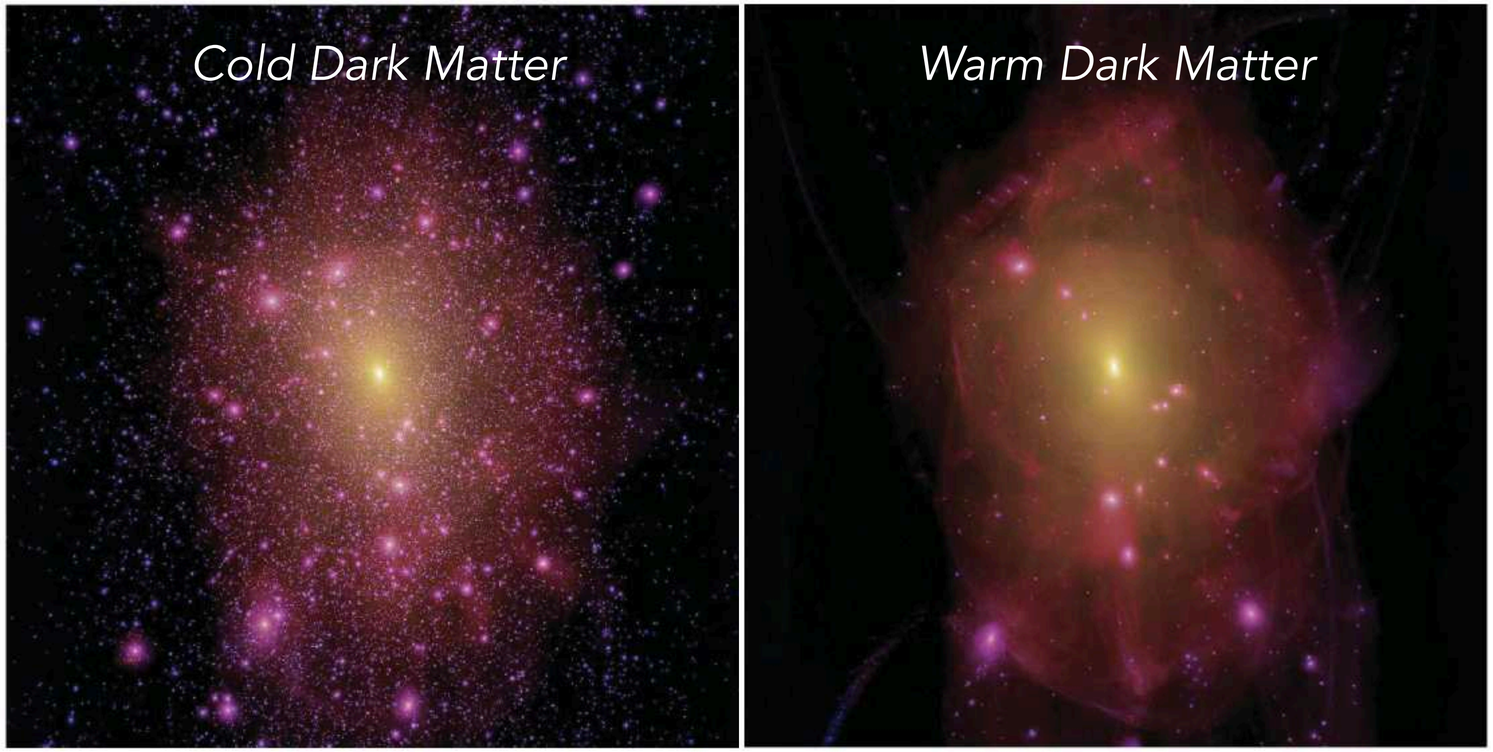
Dwarf Galaxy:
Jenny Greene, Shany Danieli, Marla Geha, Scott Carlsten, Risa Wechsler, Yao-Yuan Mao, Masayuki Tanaka, Fangzhou Jiang, Rachael Beaton, Marcelo Alvarez

Dwarf Planet:
Sihao Cheng and Eritas Yang

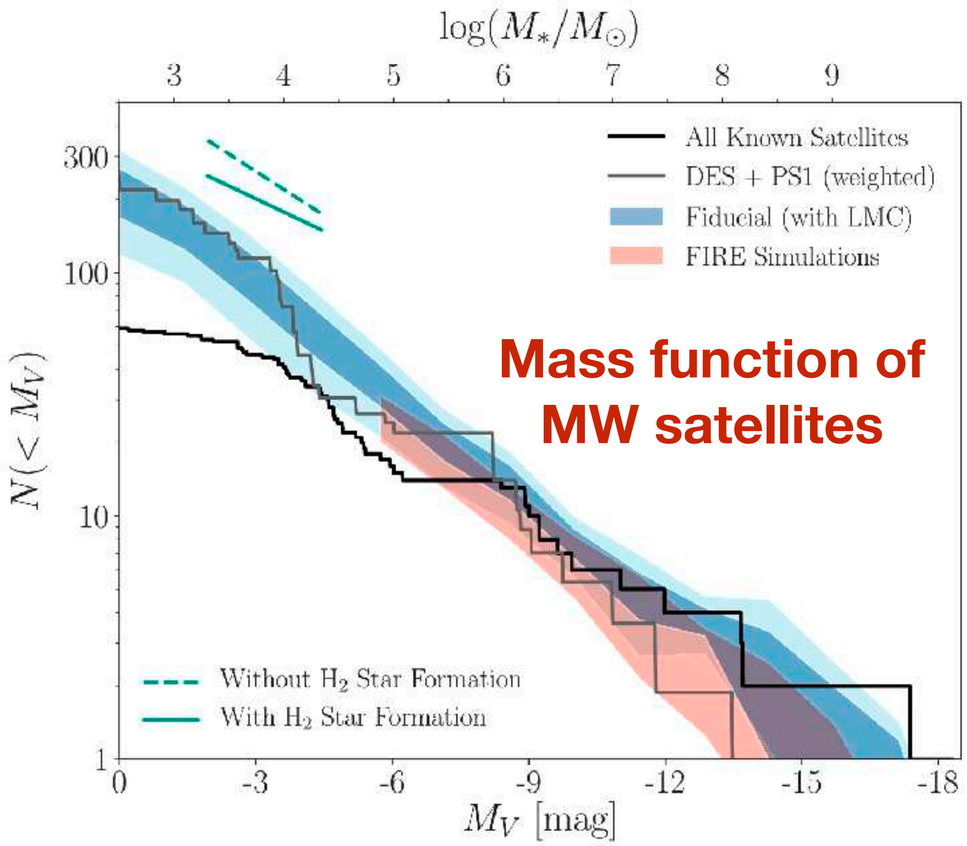
arXiv:2504.08030
arXiv:2406.00101
arXiv:2505.15806

Dwarf galaxies are important

- Dwarf galaxies ($M_\star < 10^9\ M_\odot$) live in small halos
- Their abundance can be used to directly test ΛCDM model

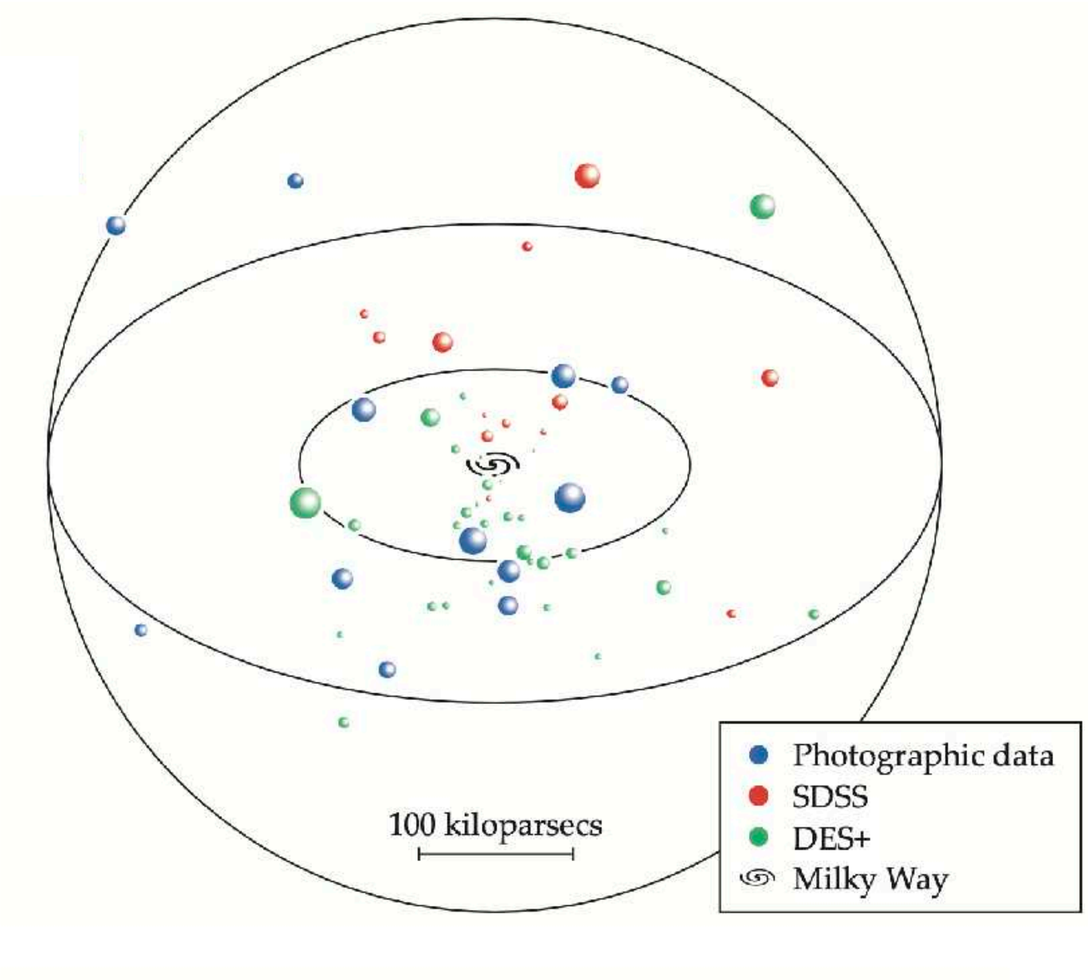


Lovell et al. (2012)

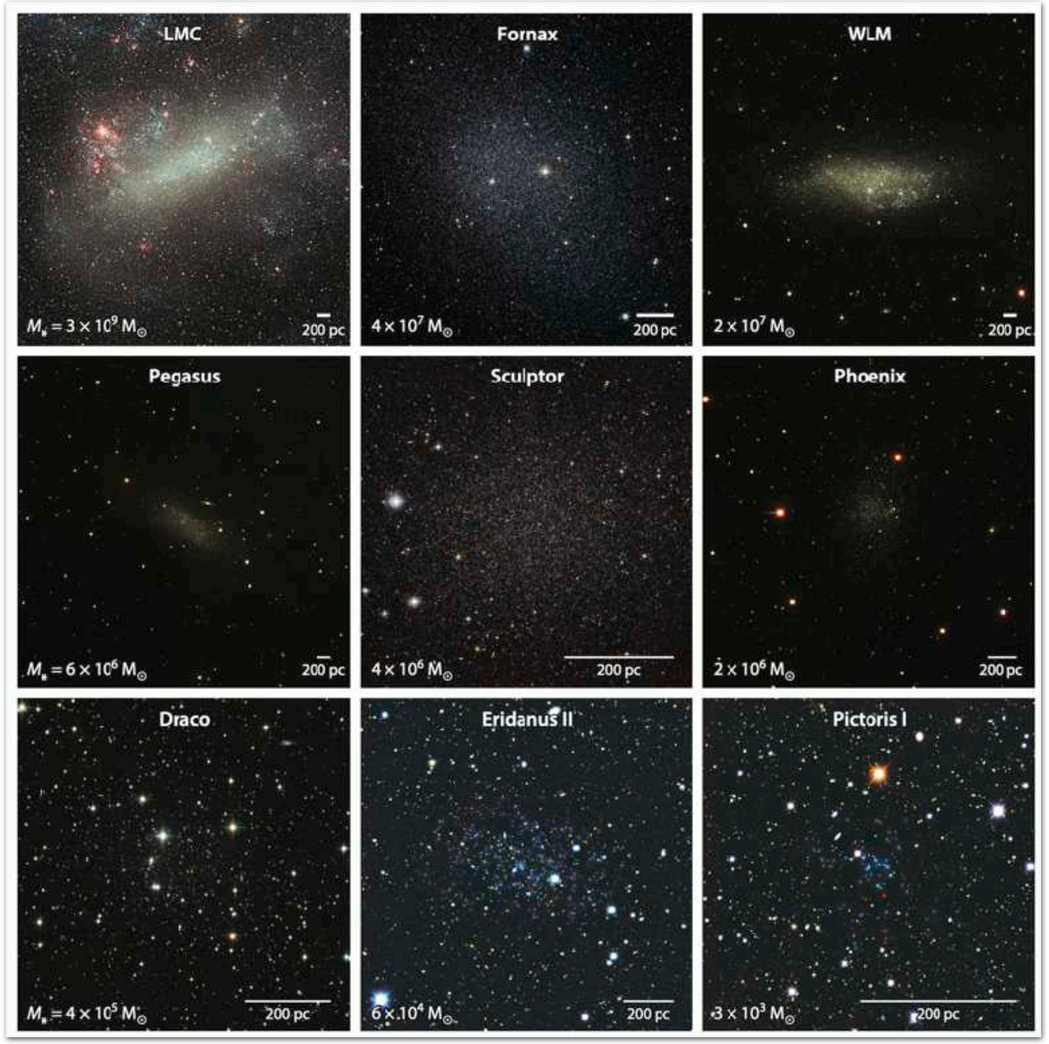


Nadler et al. (2020)

Our best knowledge of dwarf is from MW satellites

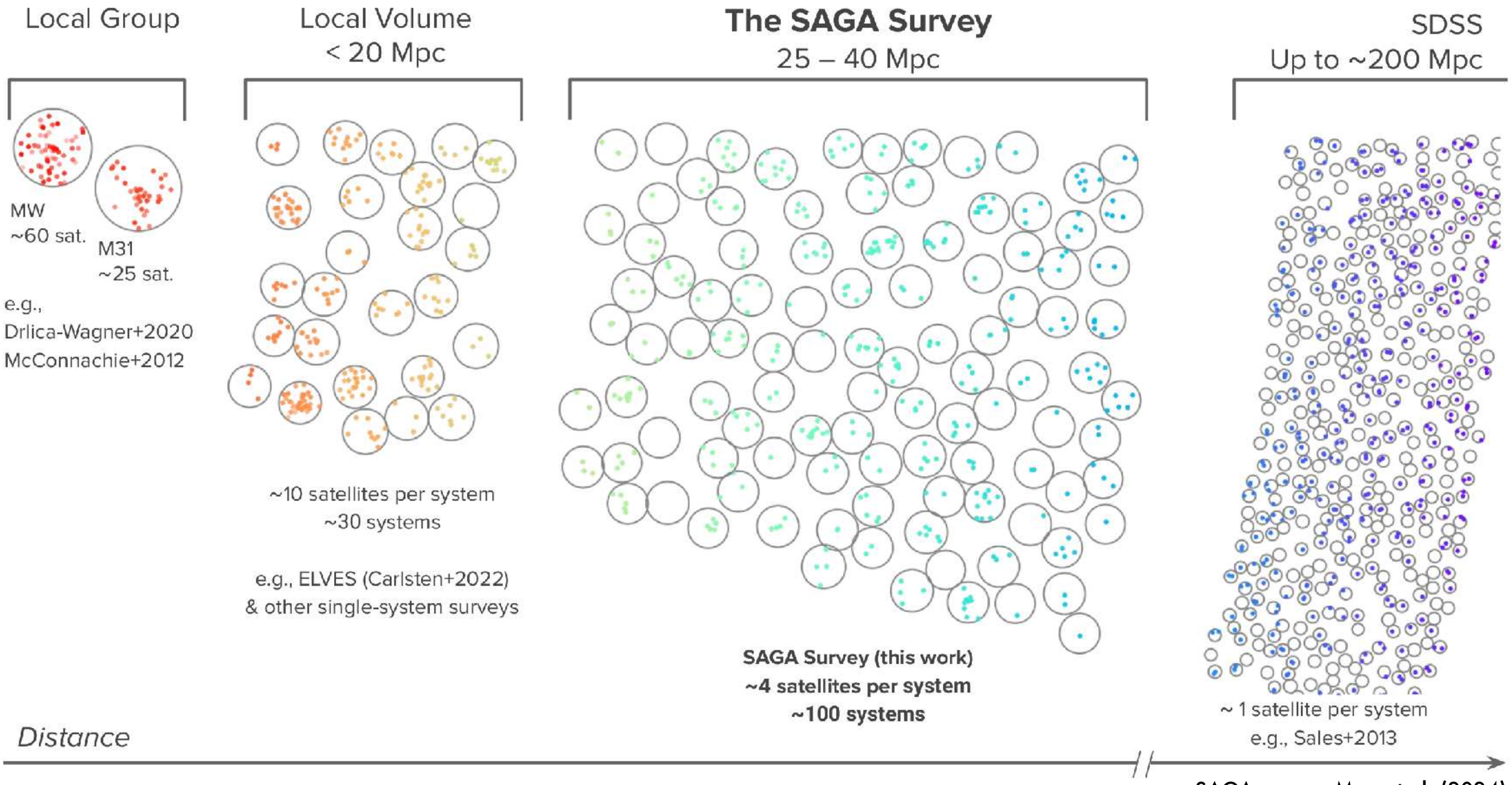


Simon & Geha (2021)



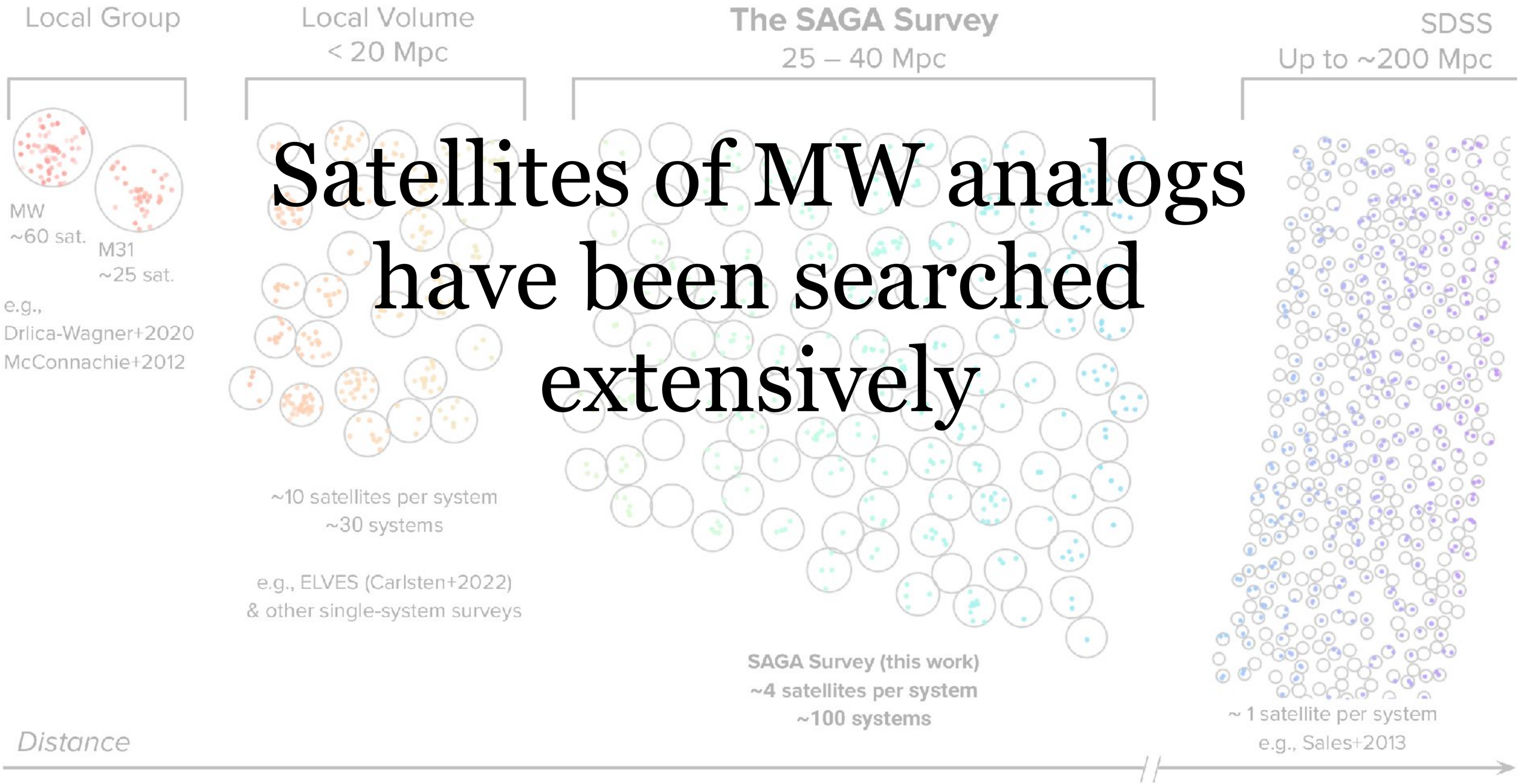
Bullock & Boylan-Kolchin (2017)

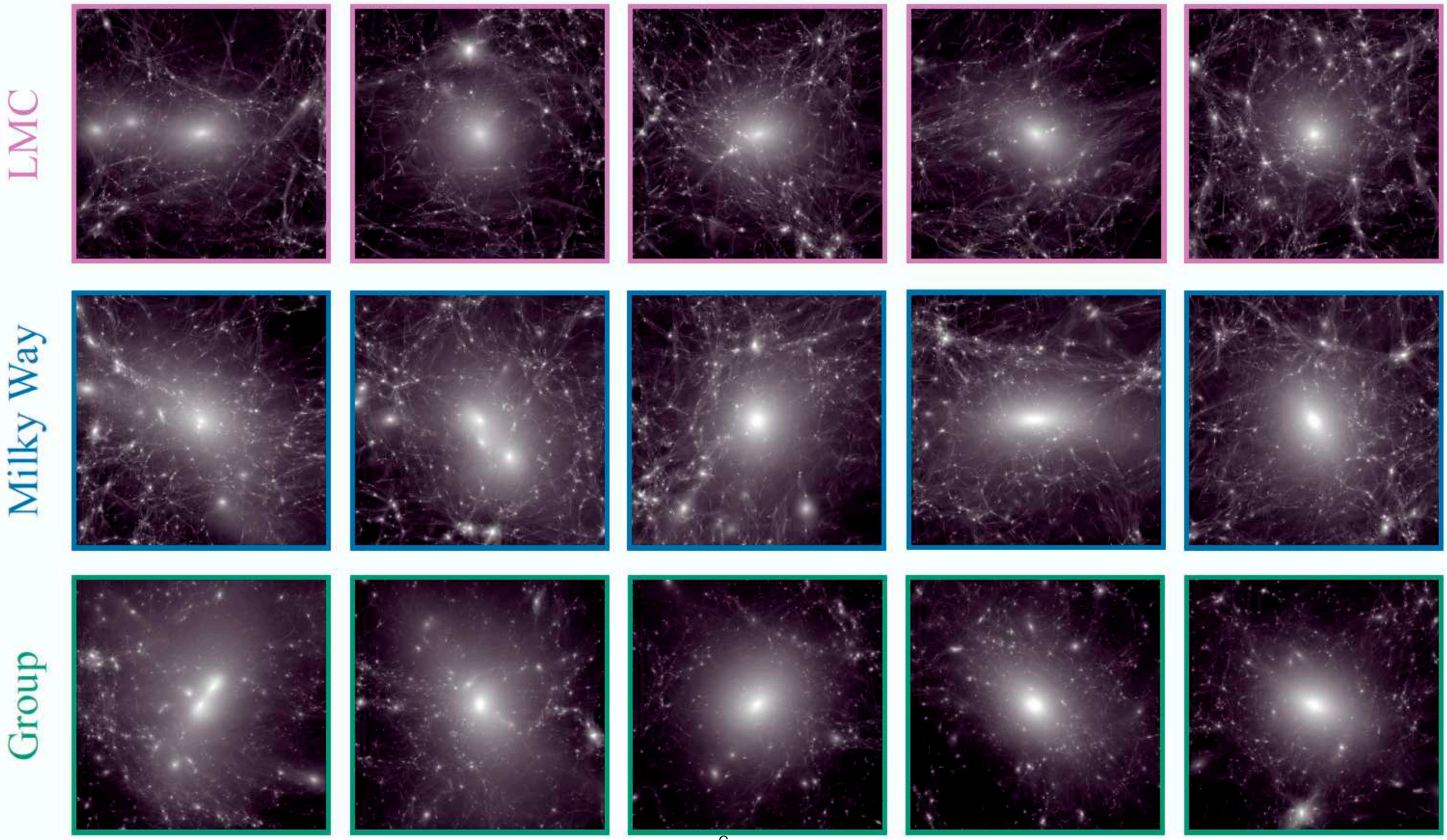
… and satellites of MW analogs



SAGA survey; Mao et al. (2024)

Satellites of MW analogs have been searched extensively



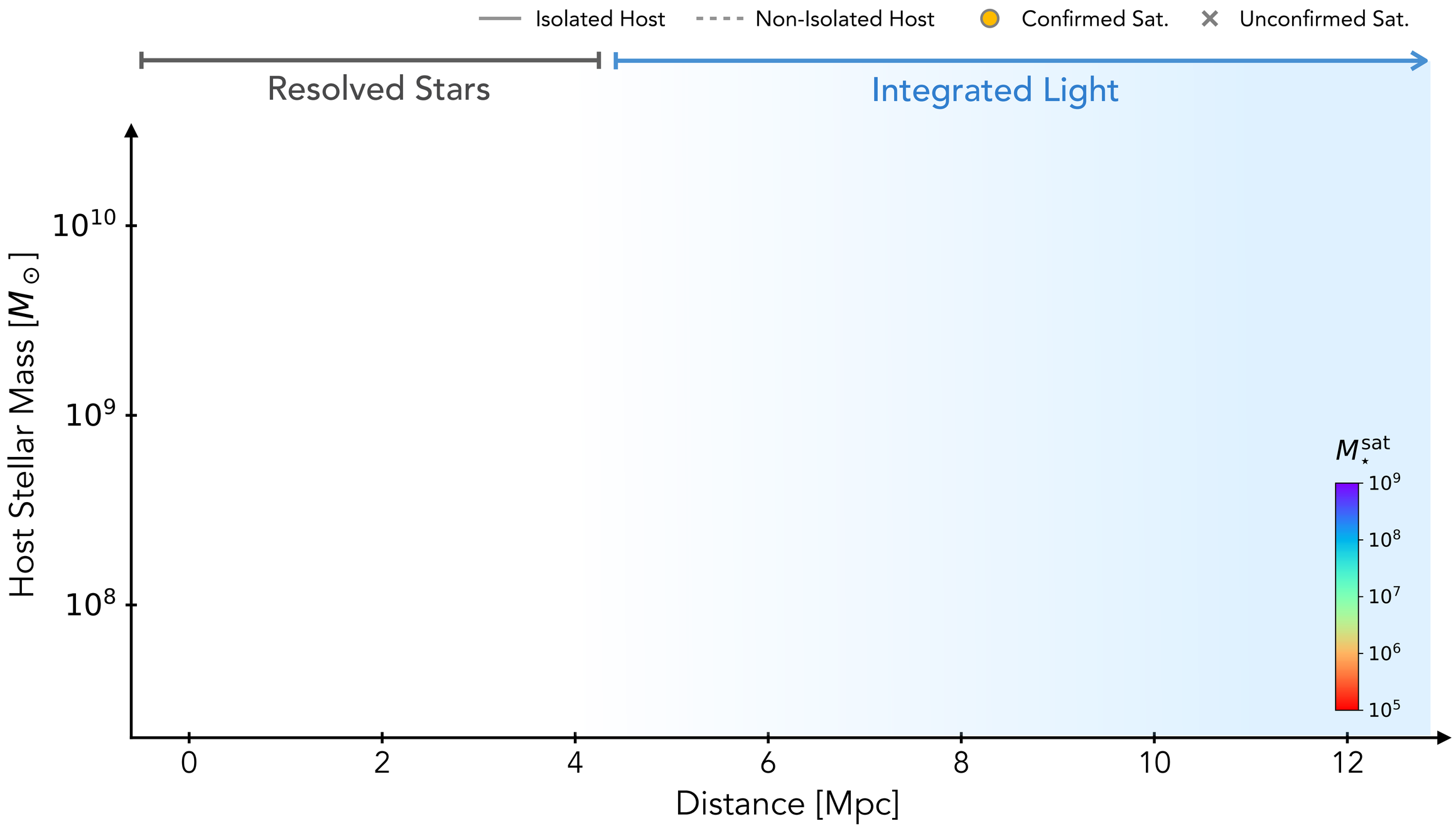


Symphony simulations: Nadler et al. (2023)

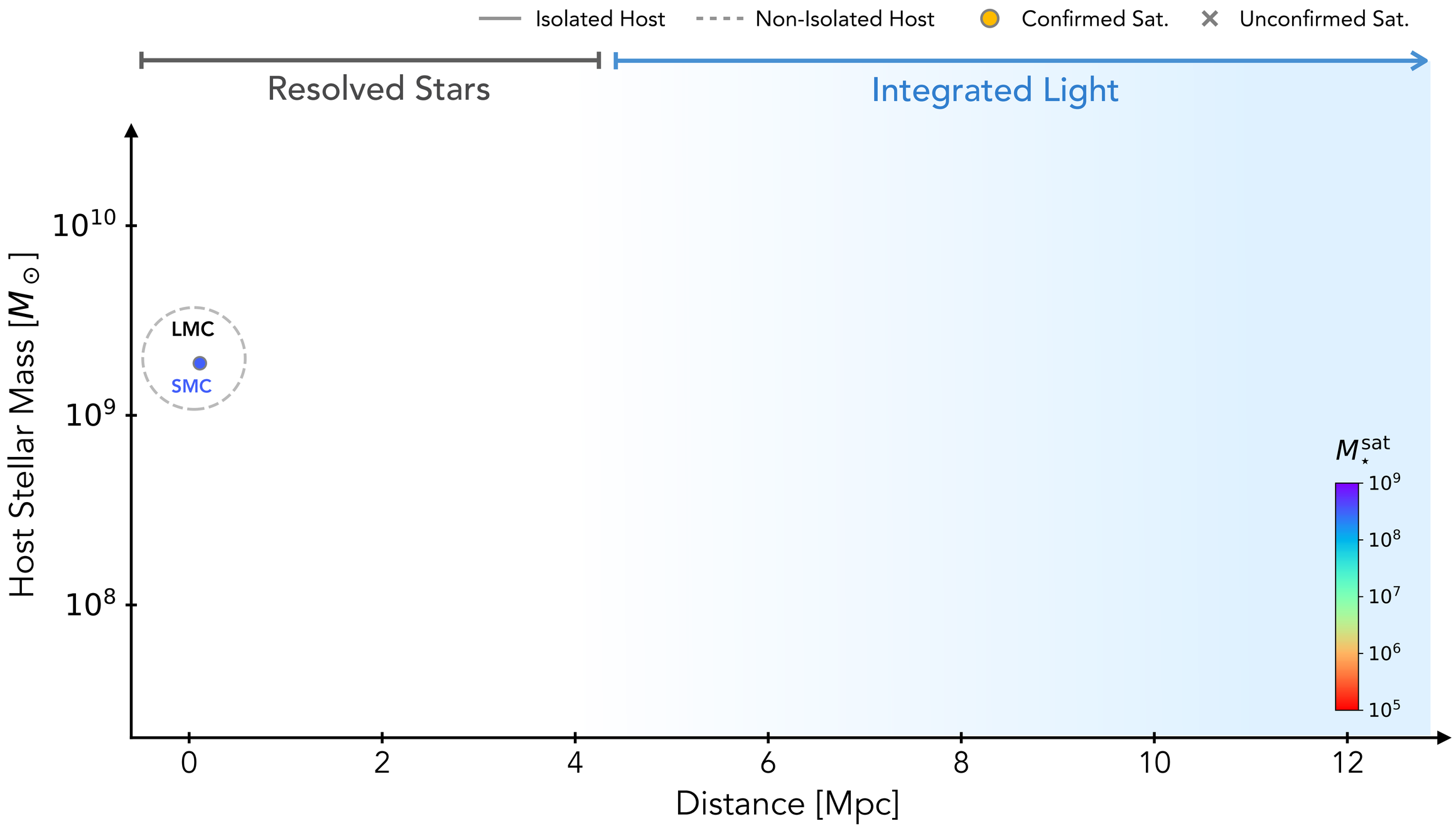
Dwarf galaxies also have satellites

Symphony simulations: Nadler et al. (2023)

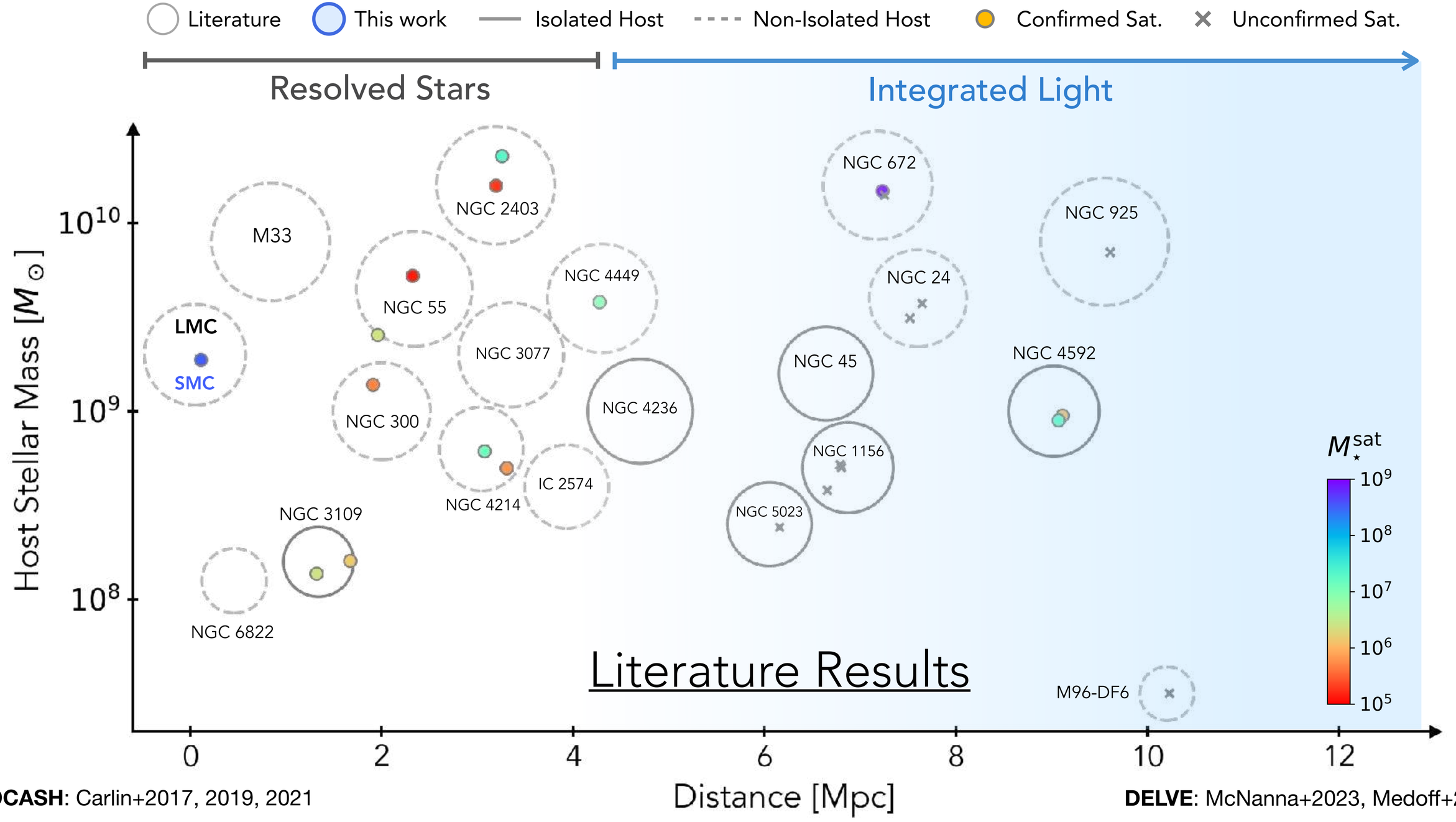
*Only showing classical dwarfs



*Only showing classical dwarfs



*Only showing classical dwarfs



MADCASH: Carlin+2017, 2019, 2021

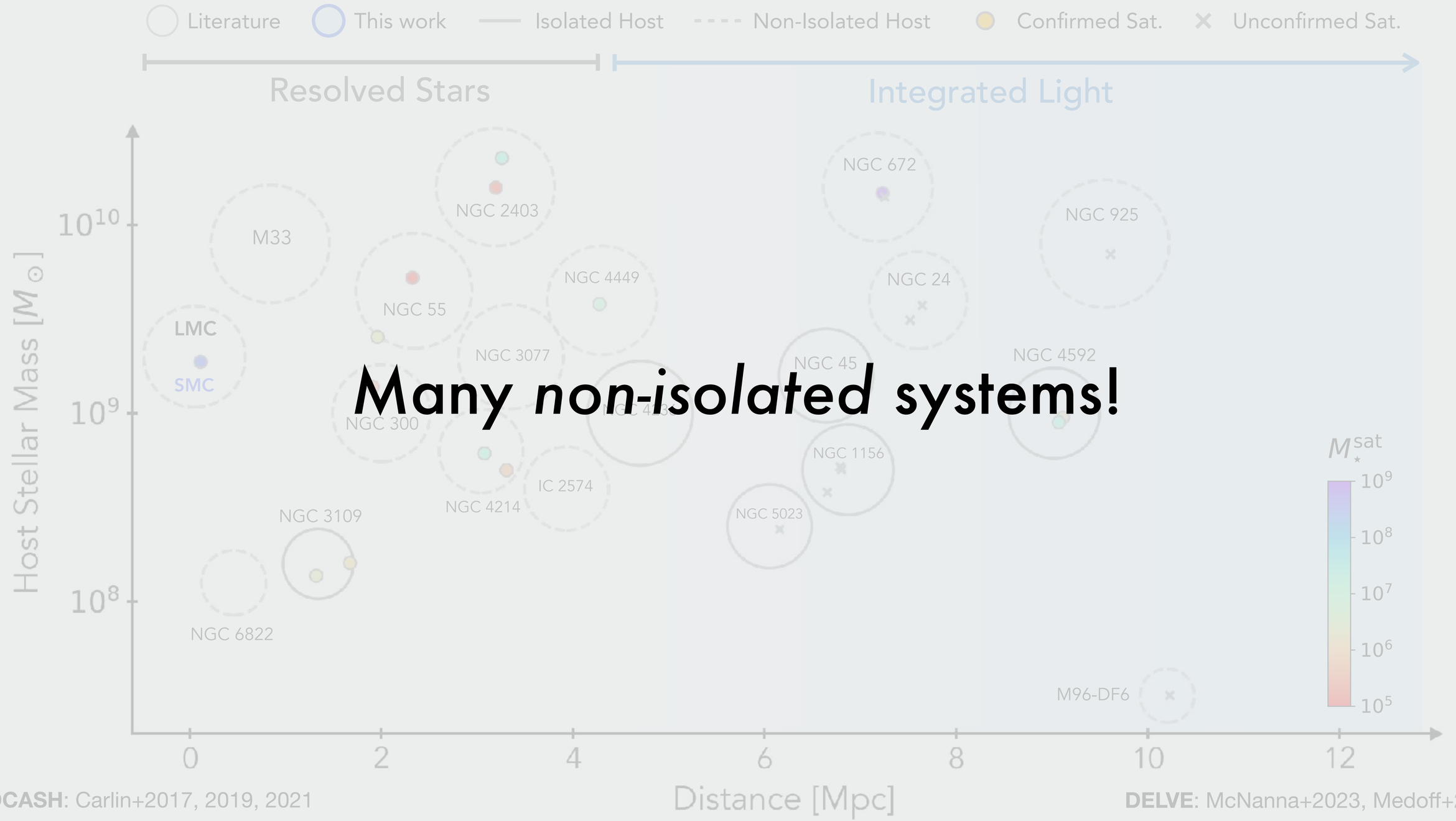
LBT-SONG: Davis+2020, Garling+2021, 2024

DELVE: McNanna+2023, Medoff+2025

ID-MAGE: Hunter+2025

*Only showing classical dwarfs

J. Li et al. (2025)

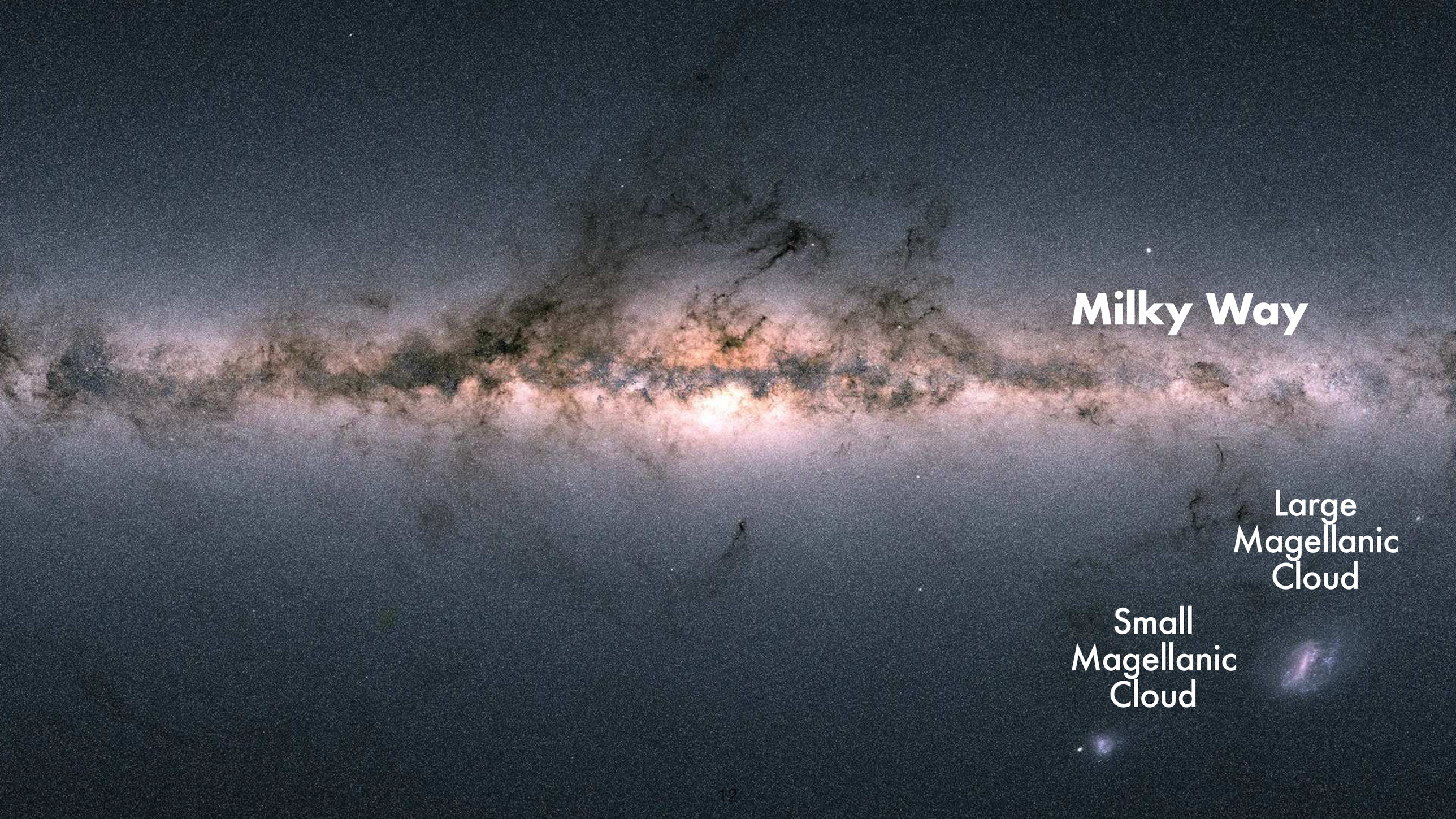


Many *non-isolated* systems!

MADCASH: Carlin+2017, 2019, 2021

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

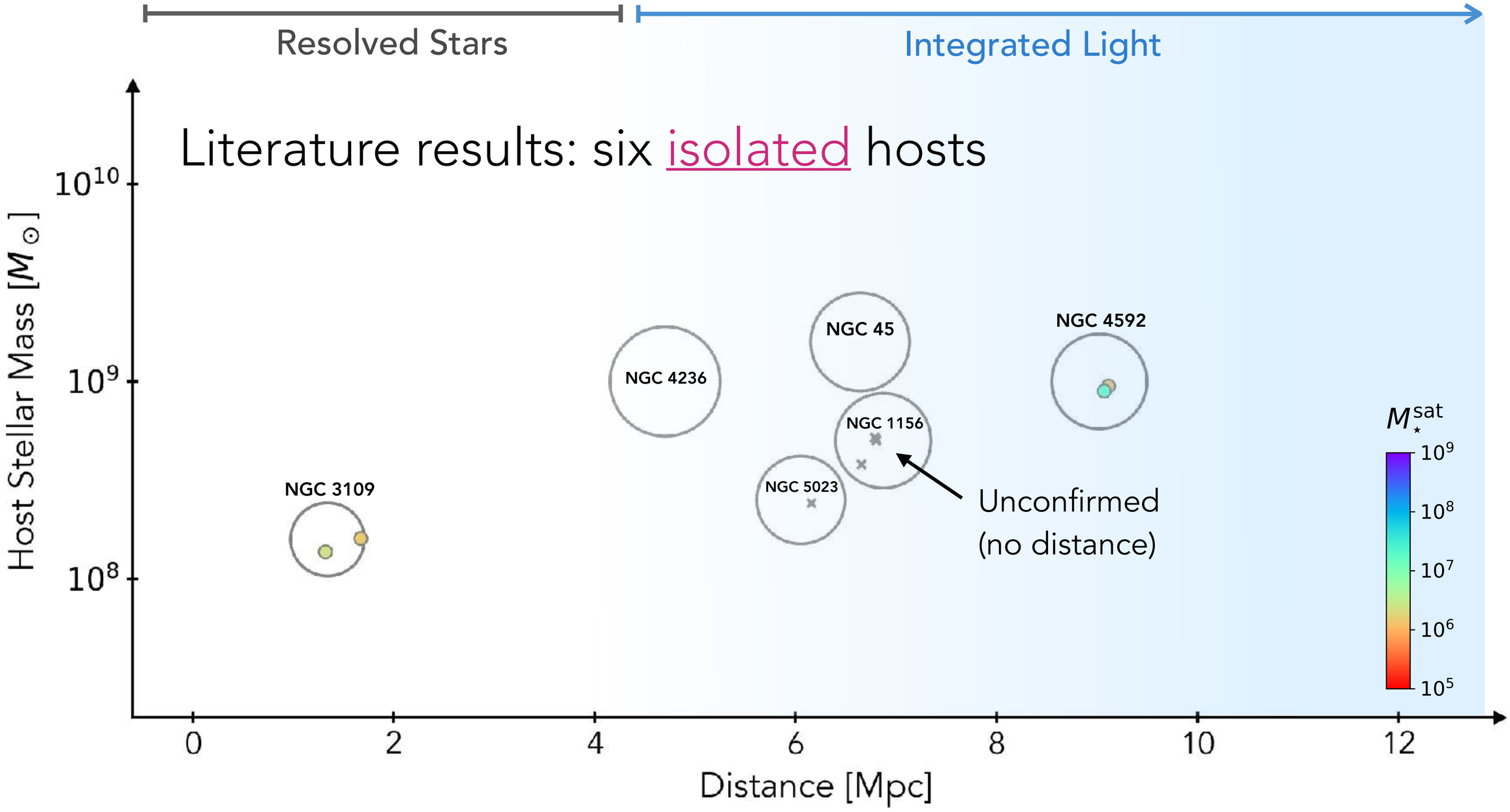
DELVE: McNanna+2023, Medoff+2025


Milky Way
Large Magellanic Cloud
Small Magellanic Cloud

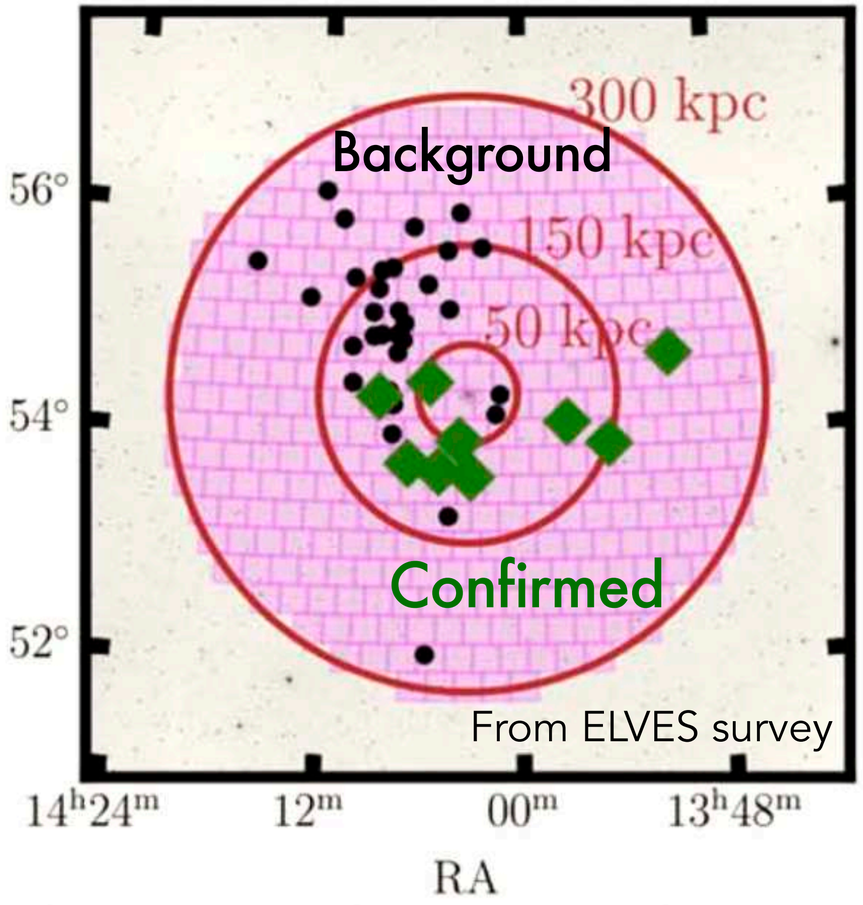
We need:

- *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

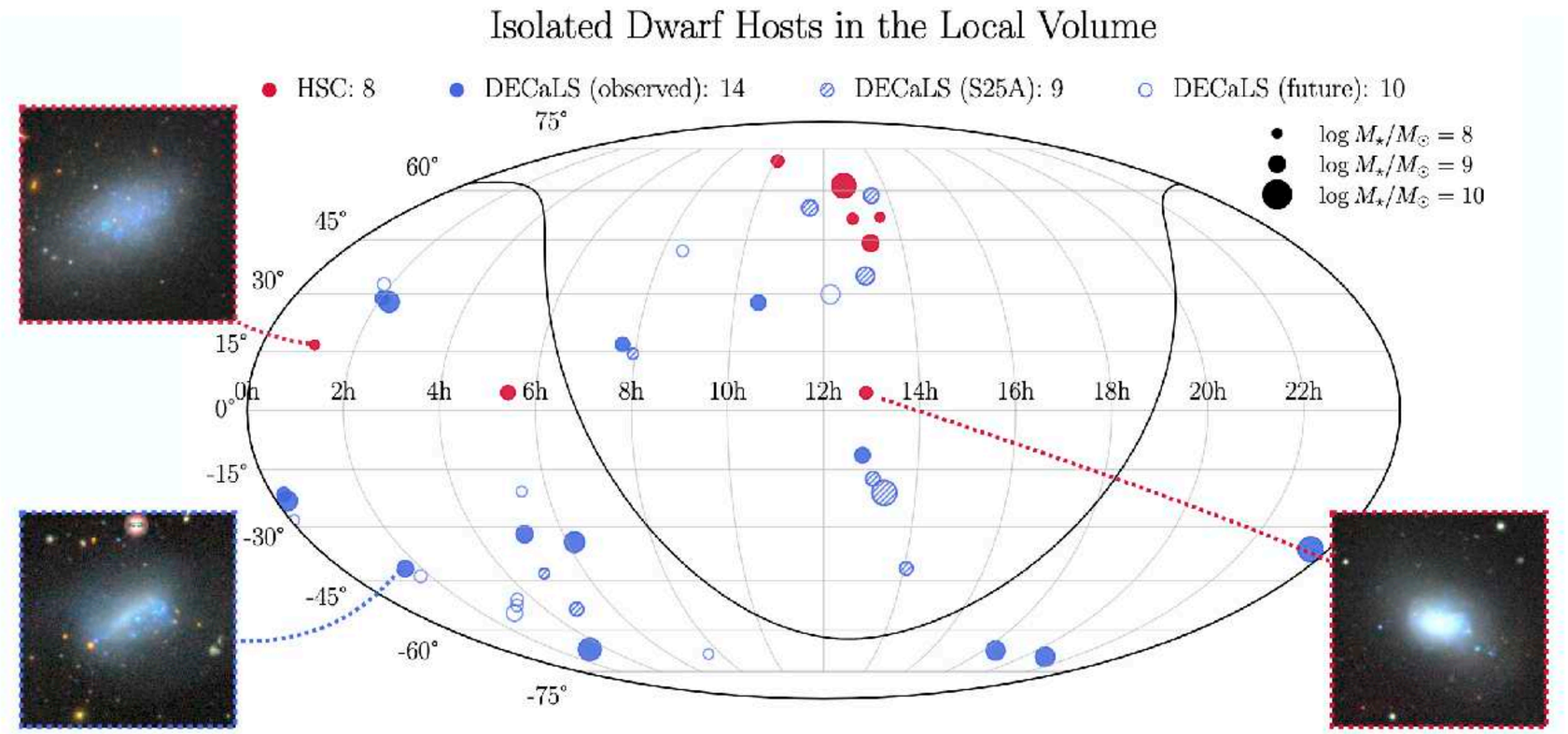
Goal: survey 30-40 ***isolated*** dwarf hosts at 4-12 Mpc

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 <u>imaging data</u>



J. Li et al. (2025)

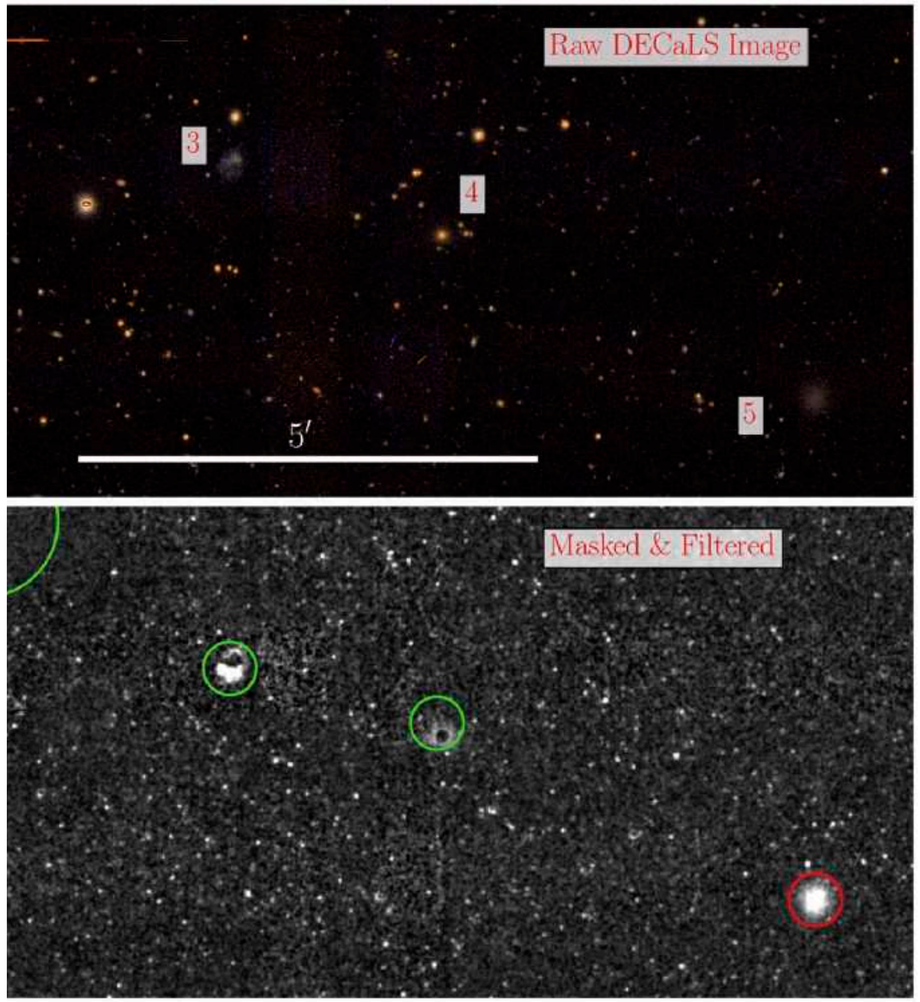
Magellan/IMACS

Gemini-N/GMOS

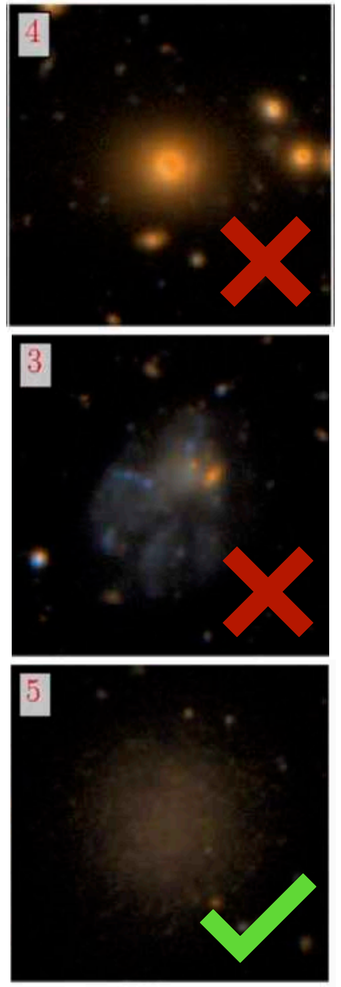
Subaru/HSC

Satellite Search

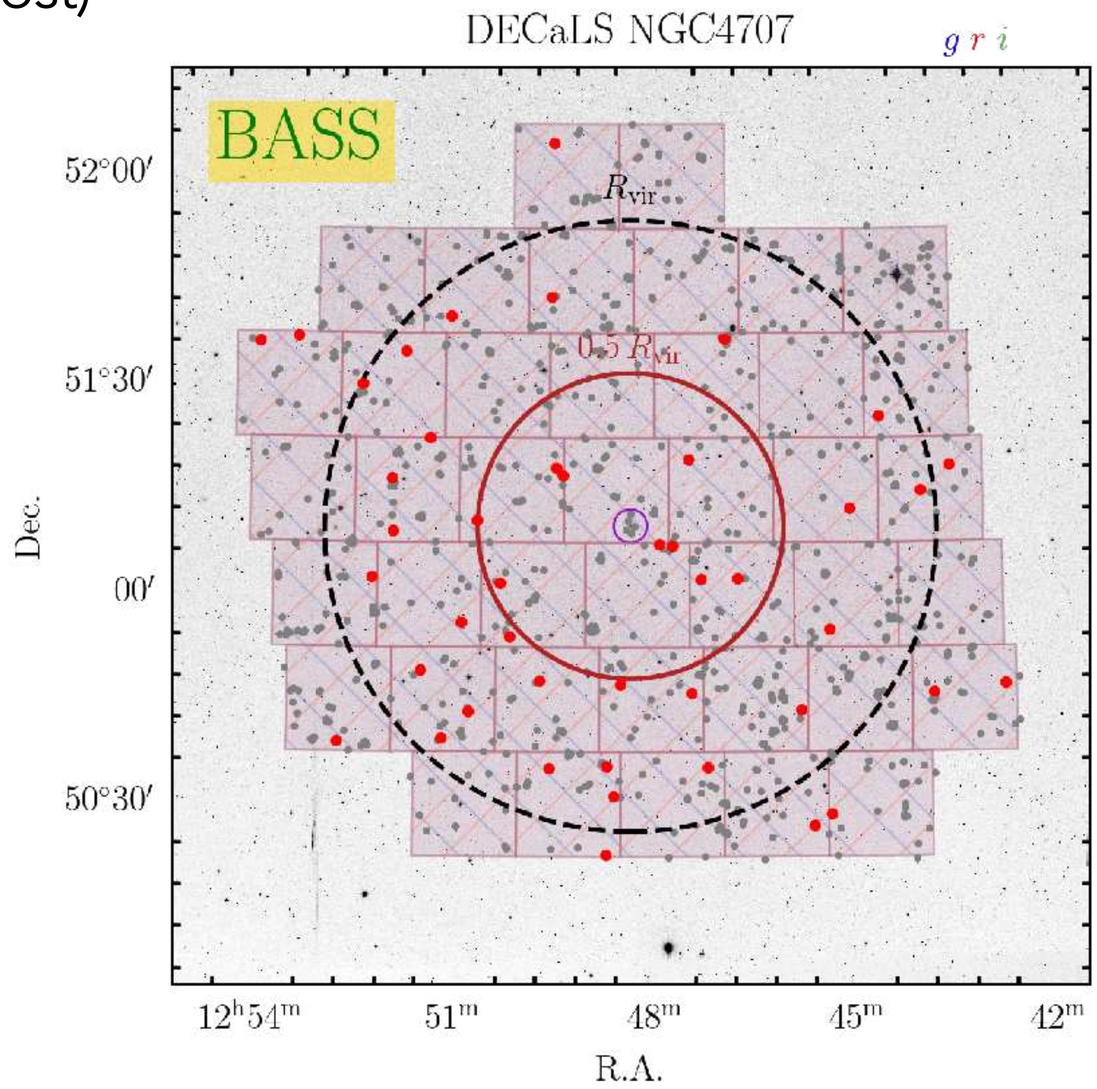
Detection on smoothed images
(Greco+18, Carlsten+22)



Visual inspection
(500-2000 per host)

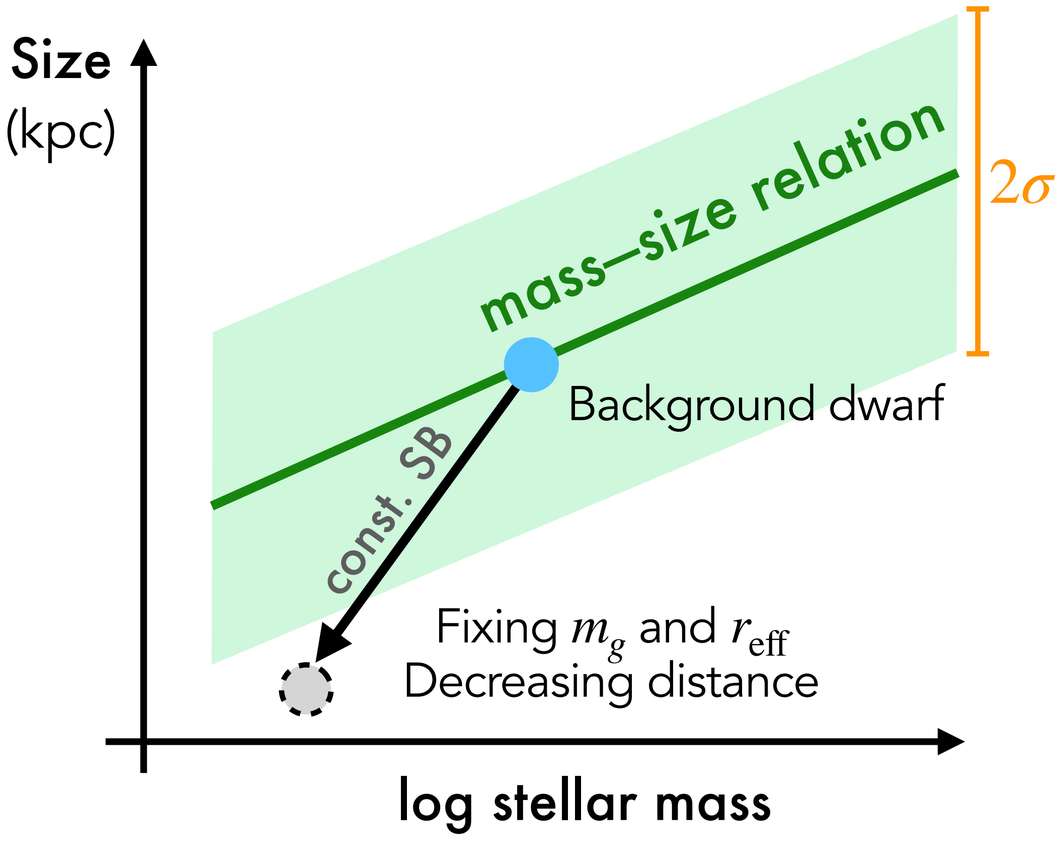


Satellite candidates
(~20-50 per host)



Satellite Search

Use mass-size relation to remove background galaxies

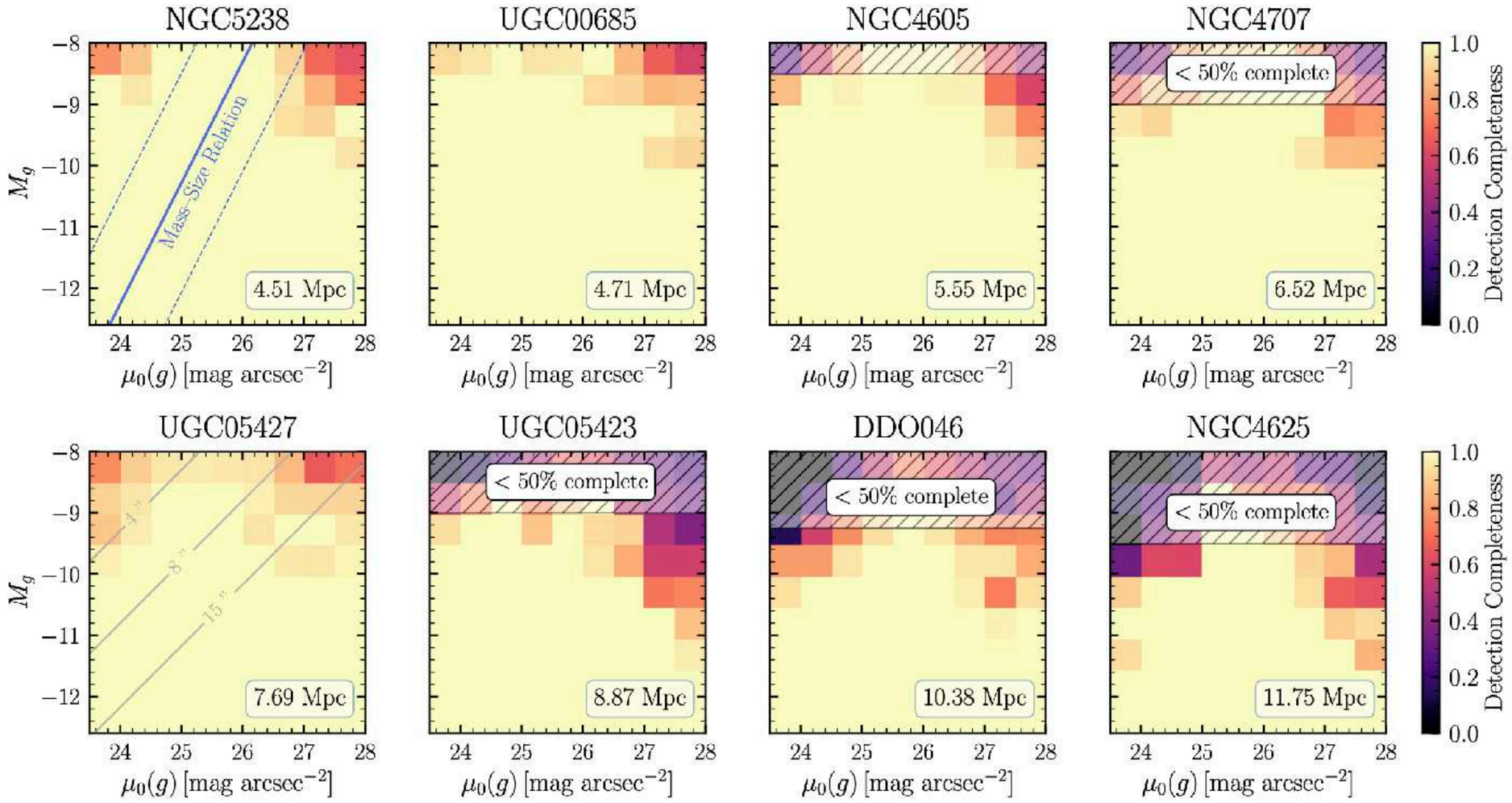


- Sersic fitting for satellite candidates
- Assuming satellite candidates are at the host distance
- Mass-size relation from ELVES
- Background galaxies will be too small

2-15 candidates per host remains

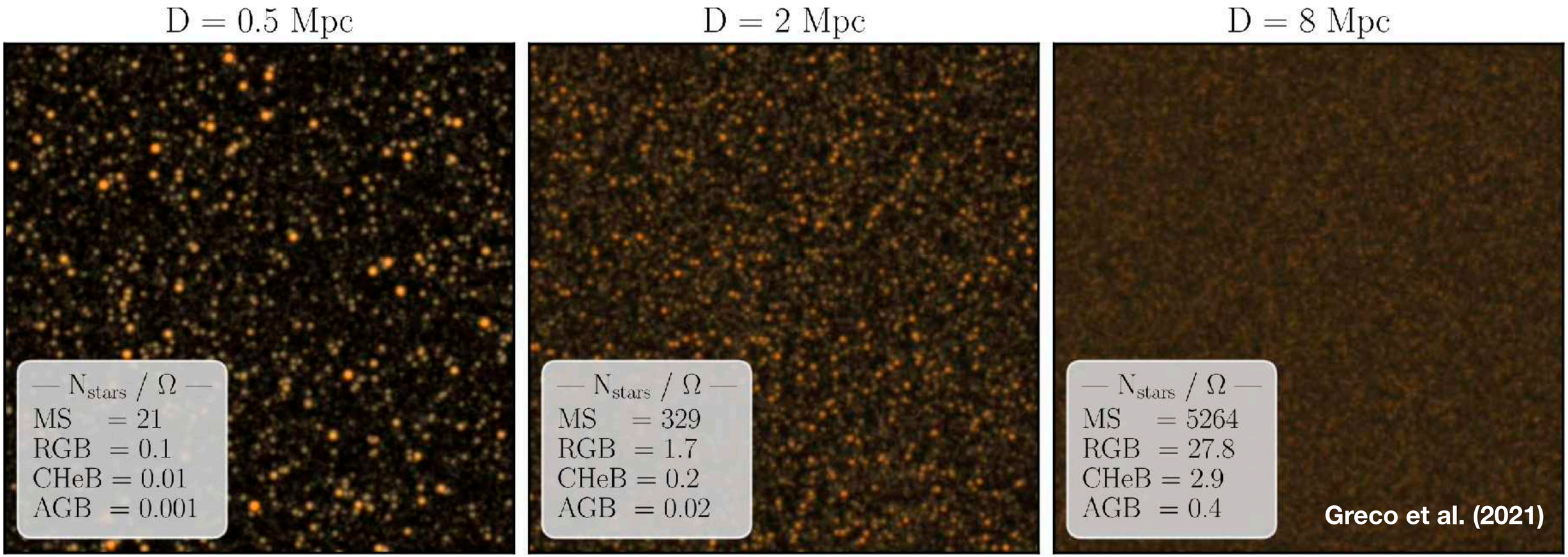
Satellite Search Completeness

- Injected mock Sersic galaxies with a range of colors
- Complete down to $M_g \approx -9$ mag for most hosts



Pixel-to-pixel variation contains distance information

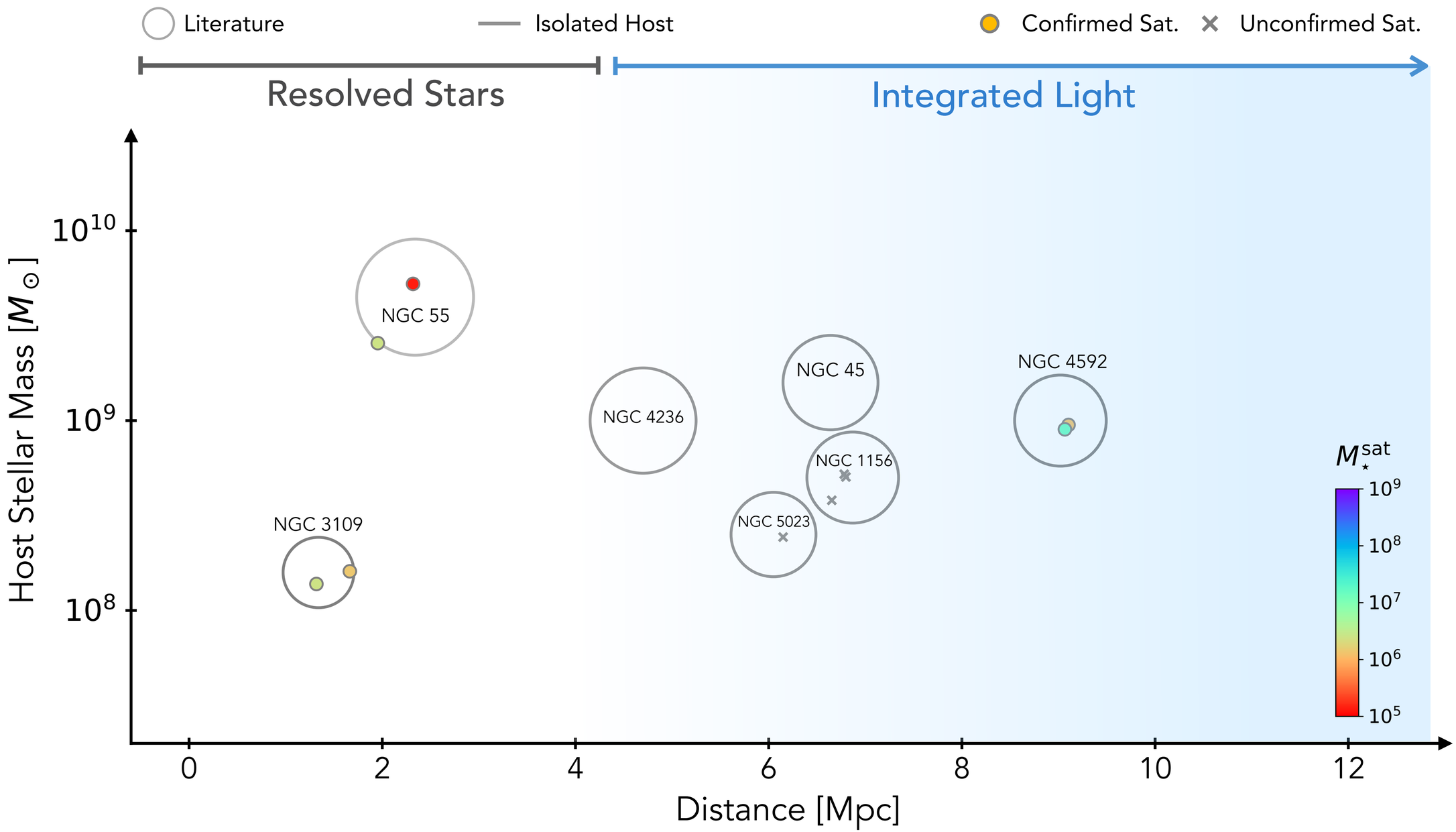
*SBF is an **OLD** technique!! (Tonry & Schneider 1988)*



- 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



ELVES-DWARF: First results using HSC

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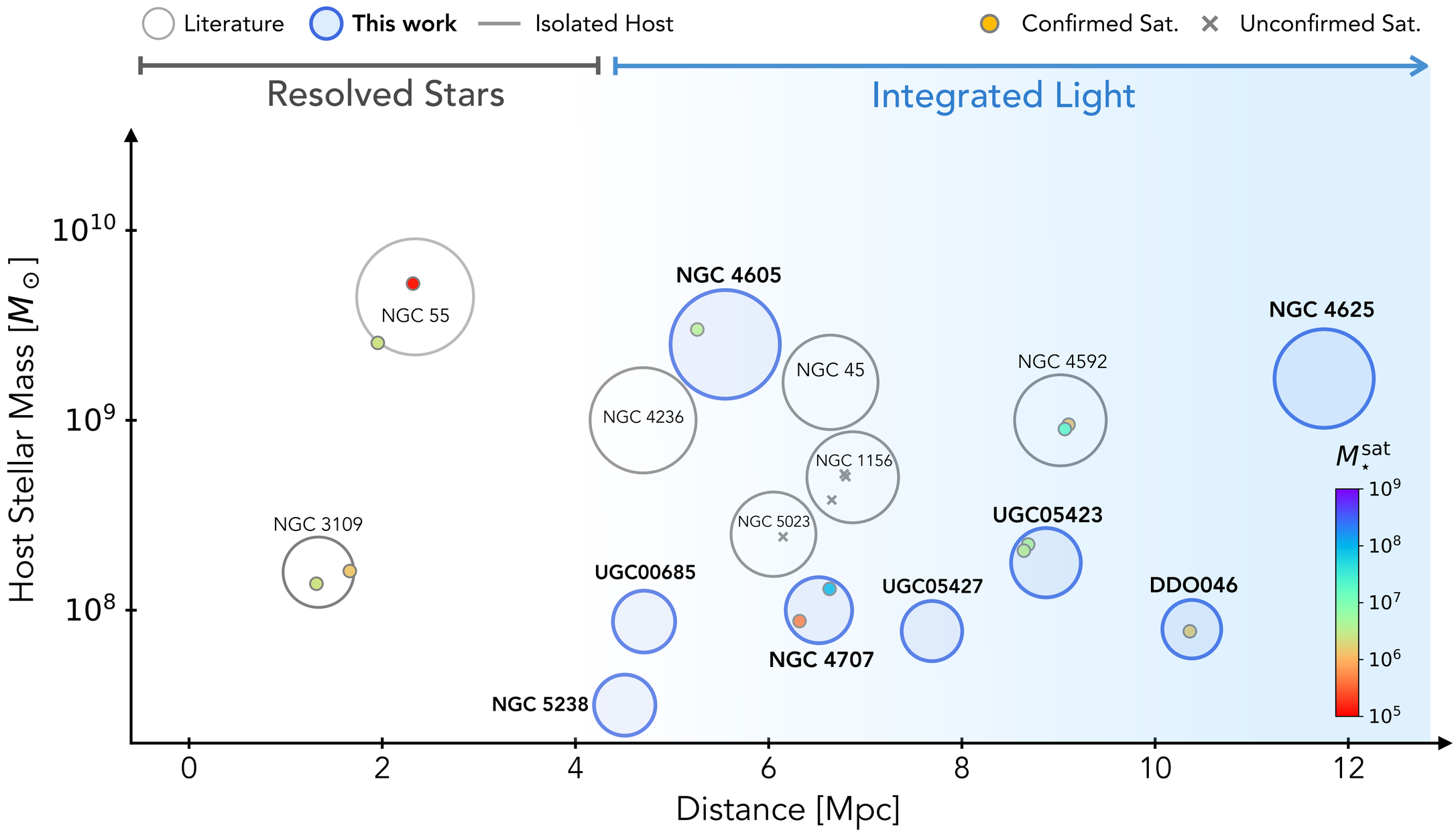
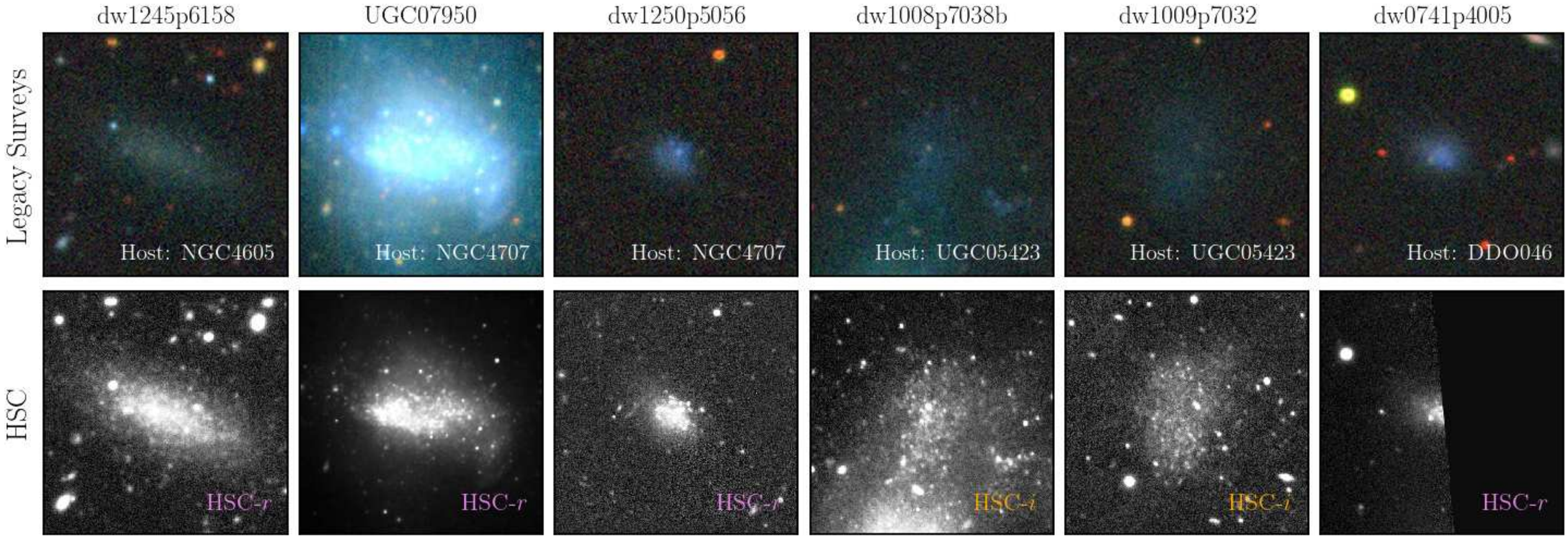
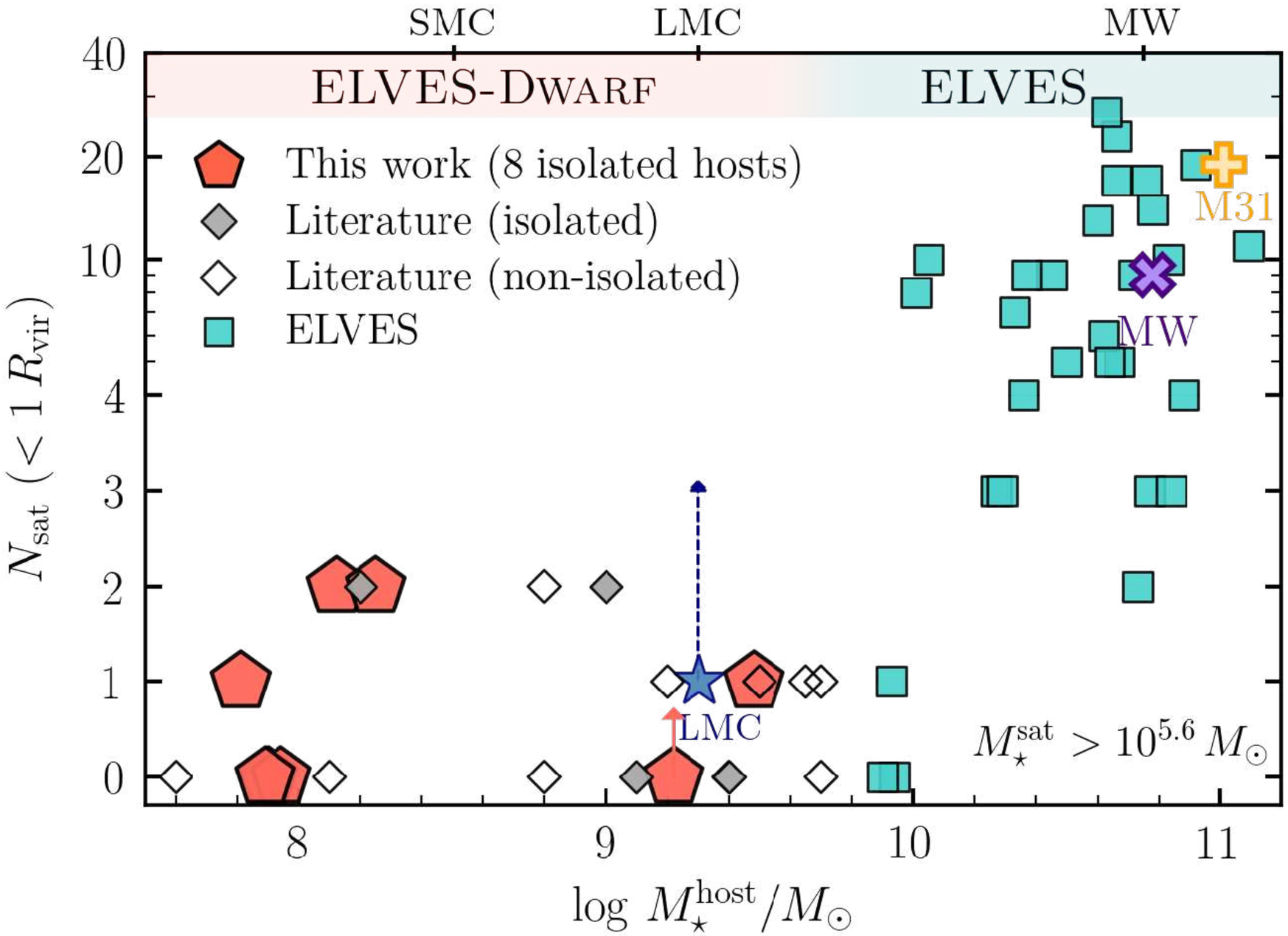


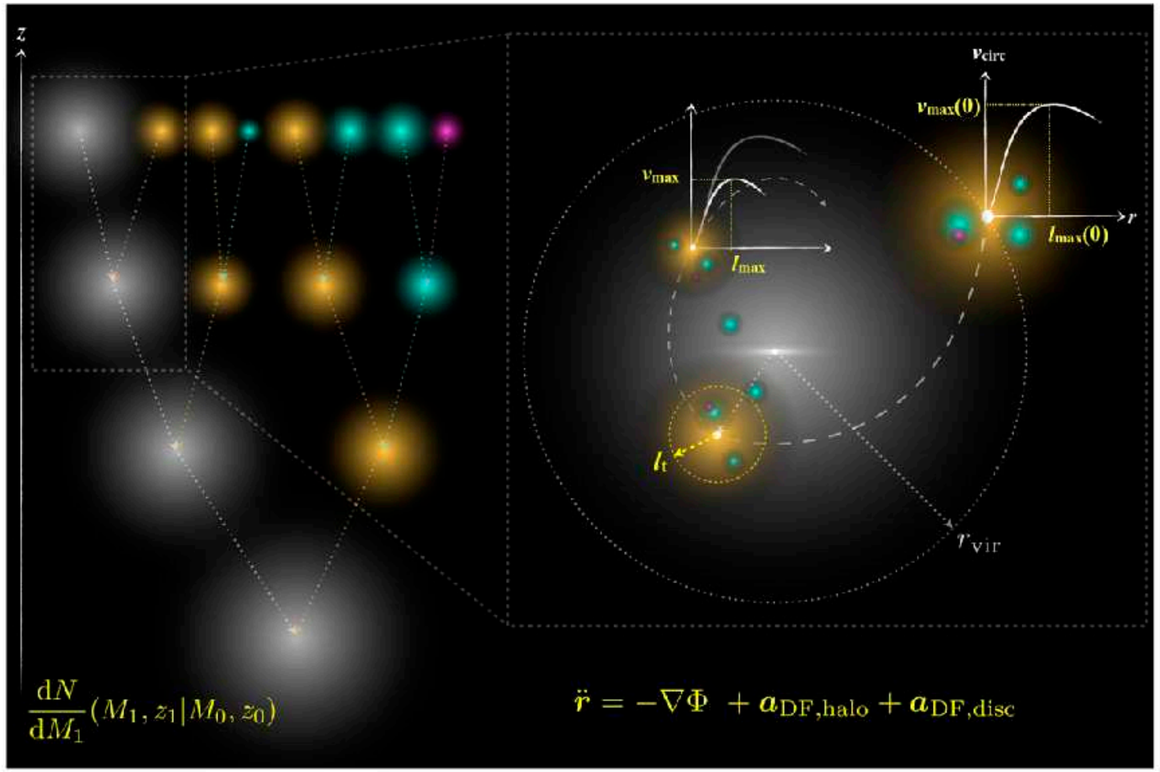
Images of confirmed satellites

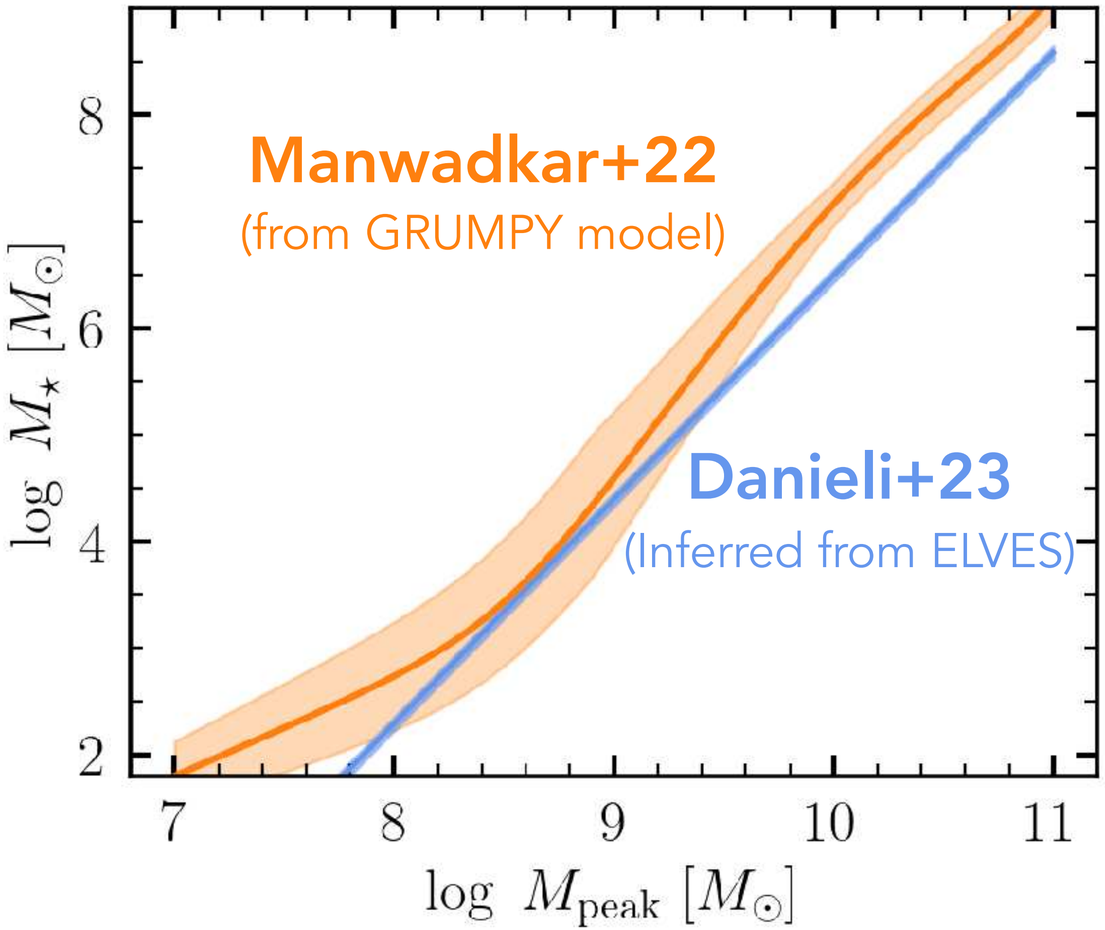


Satellite Abundance



Satellite Abundance: SatGen prediction

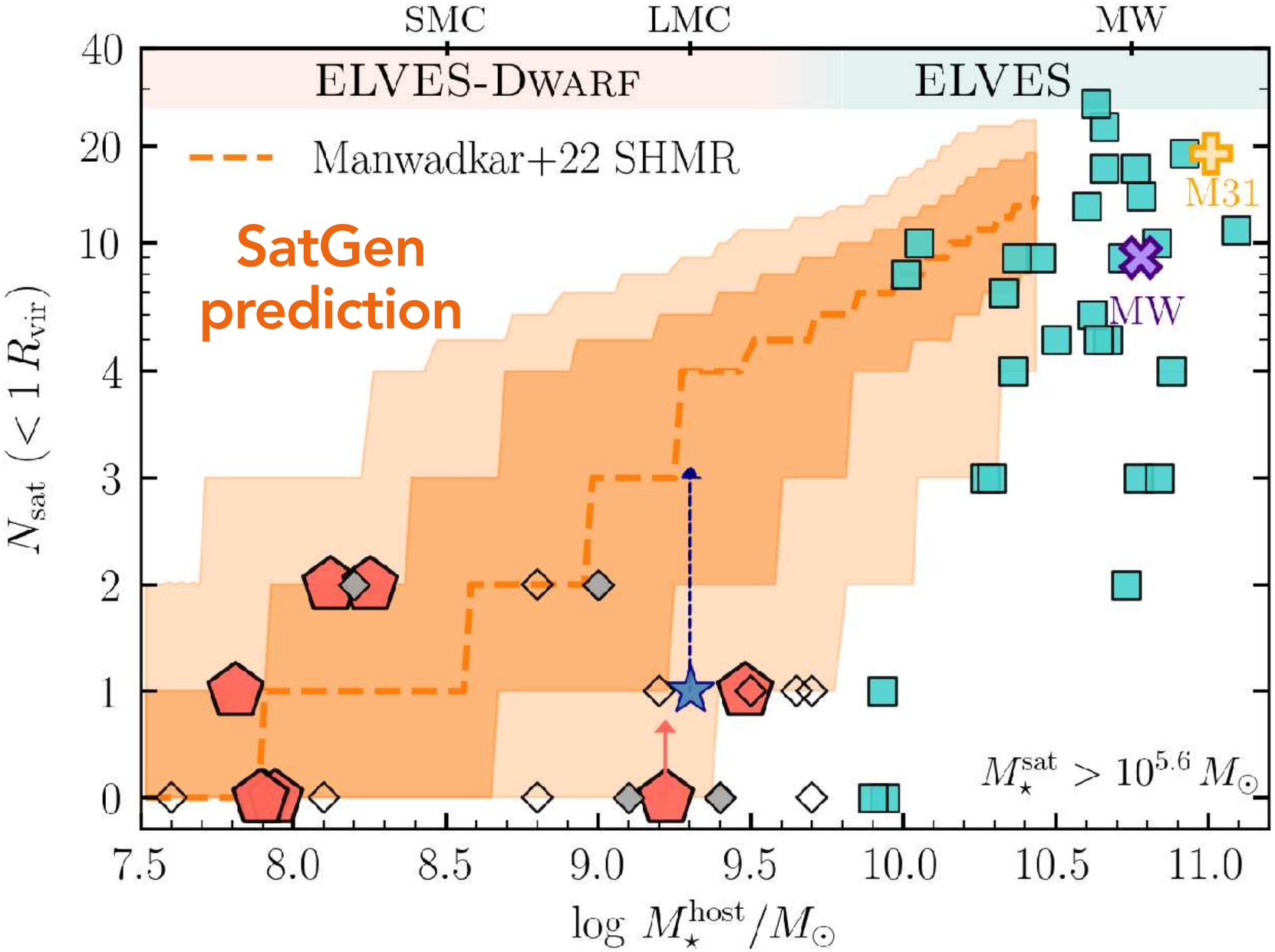




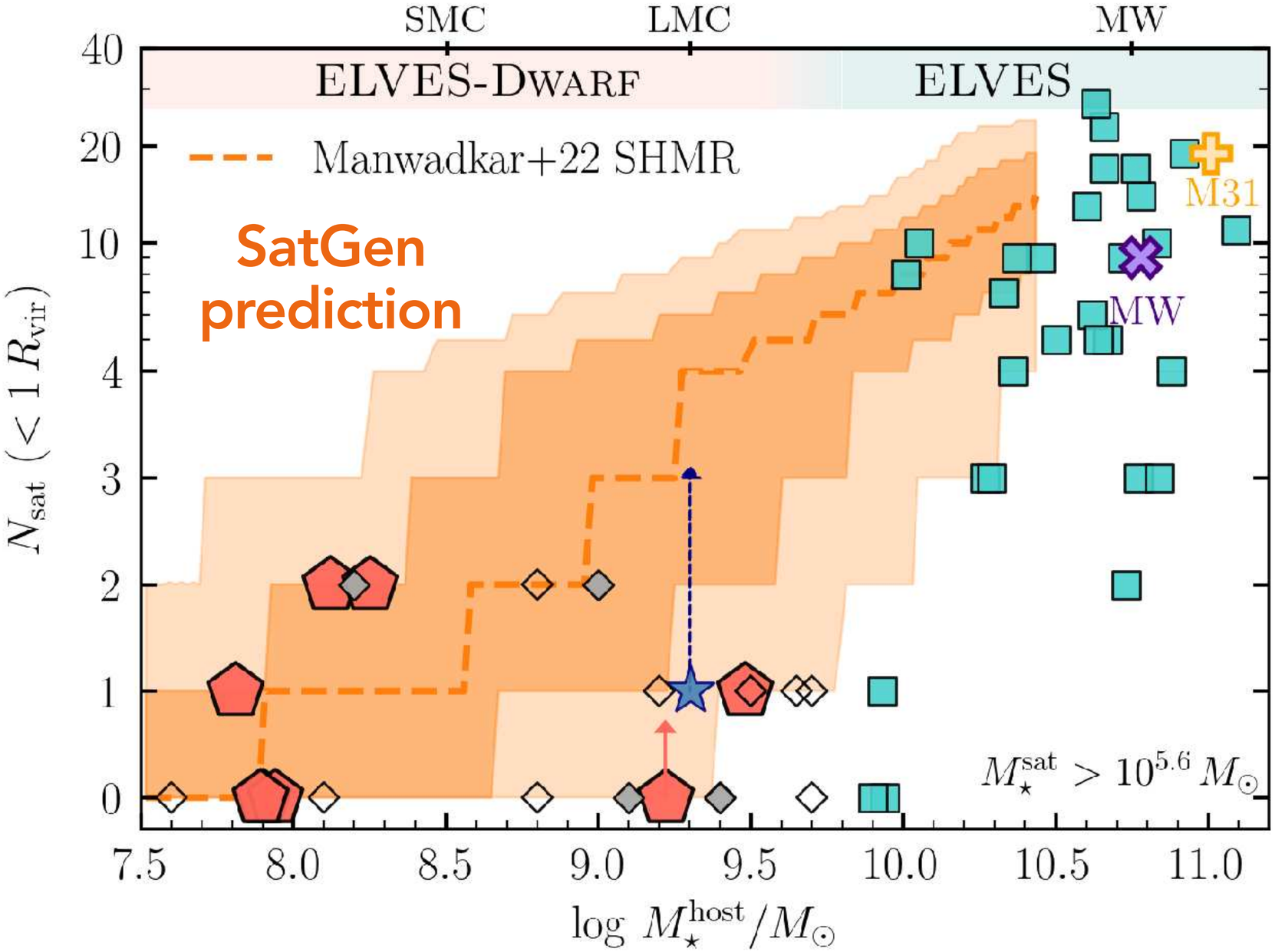
- *SatGen*: Semi-analytical model for satellites
- Includes tidal stripping; emulates baryonic processes
- We do not include a disk component

- Assign stellar mass based on peak subhalo mass using SHMRs

No “Missing satellite problem”



No “Missing satellite problem”



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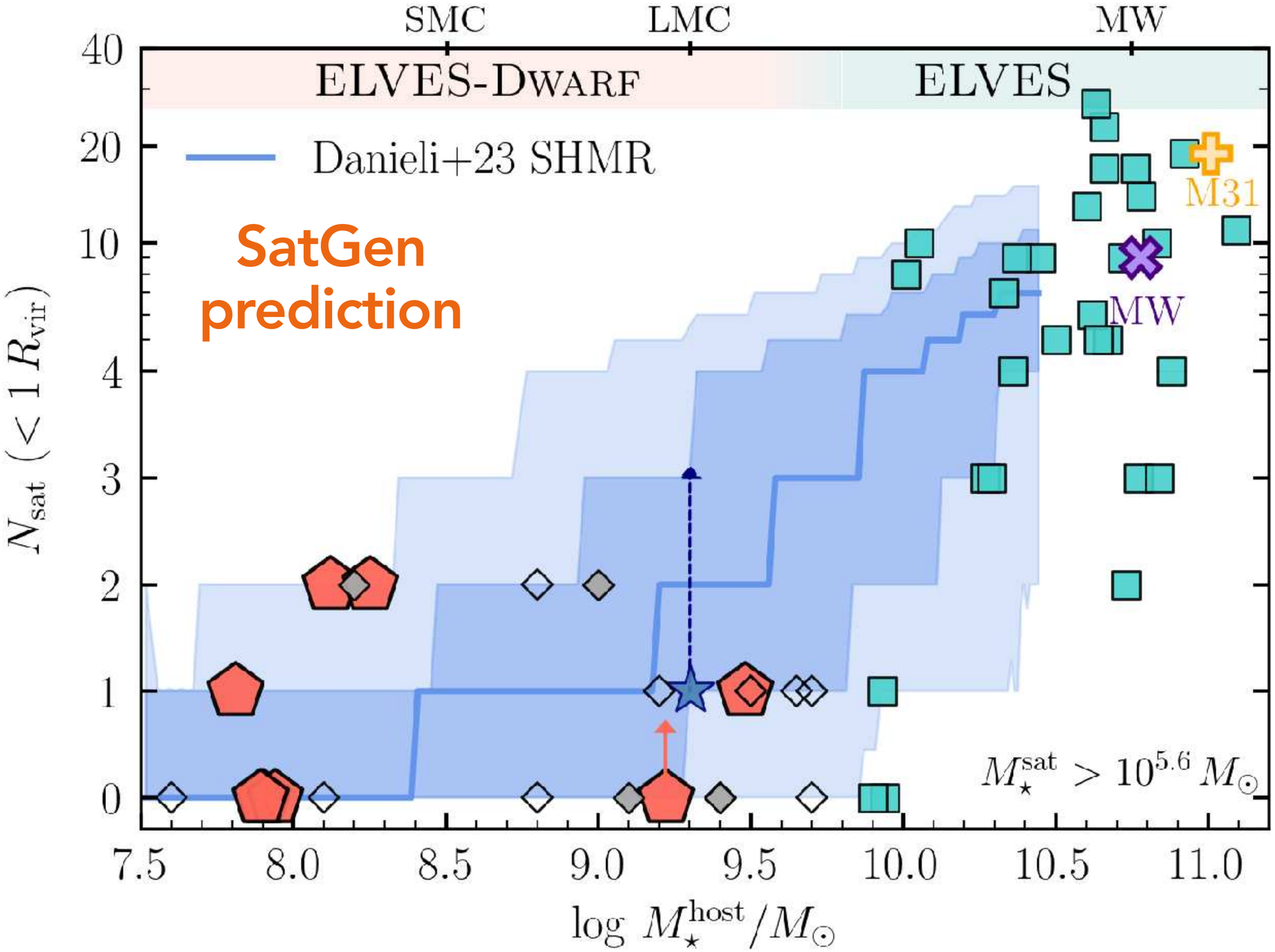
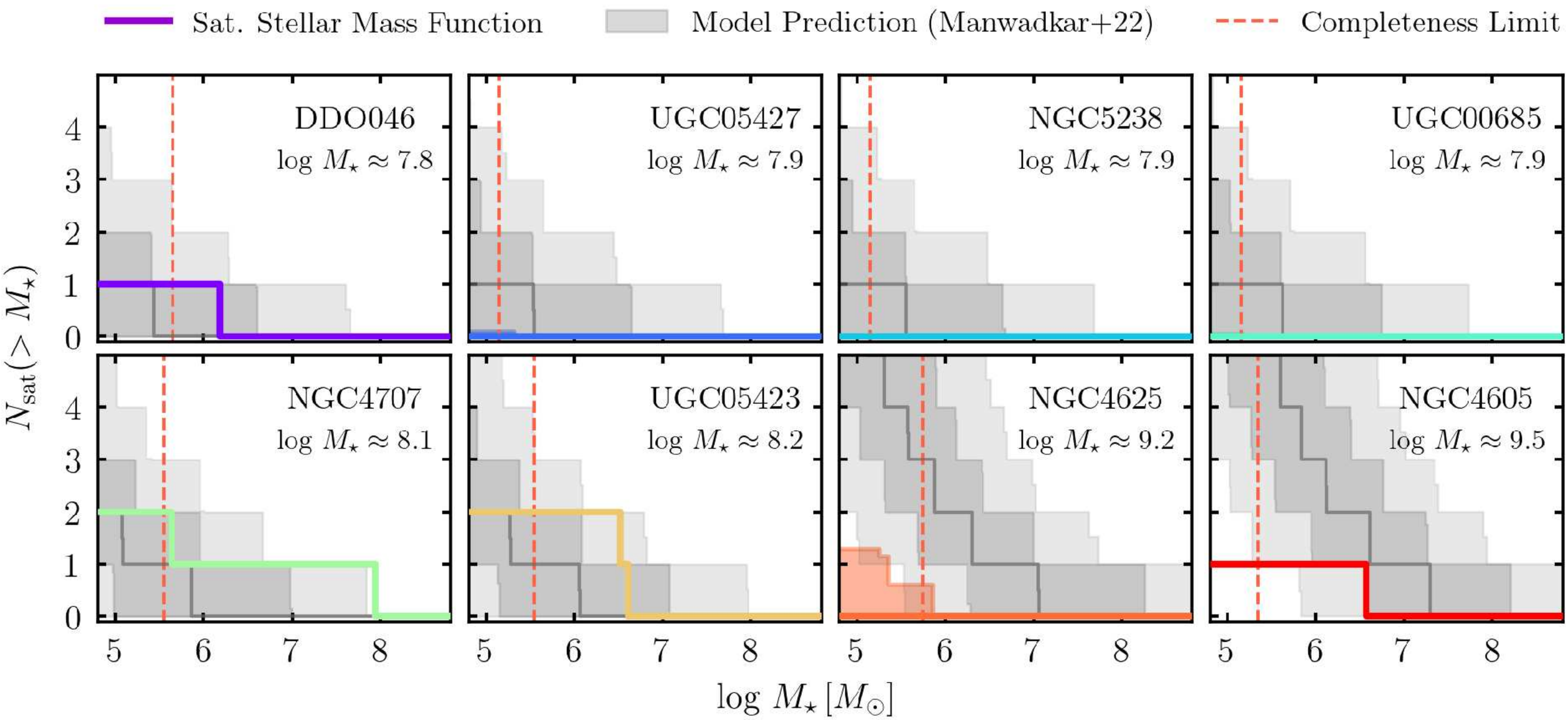
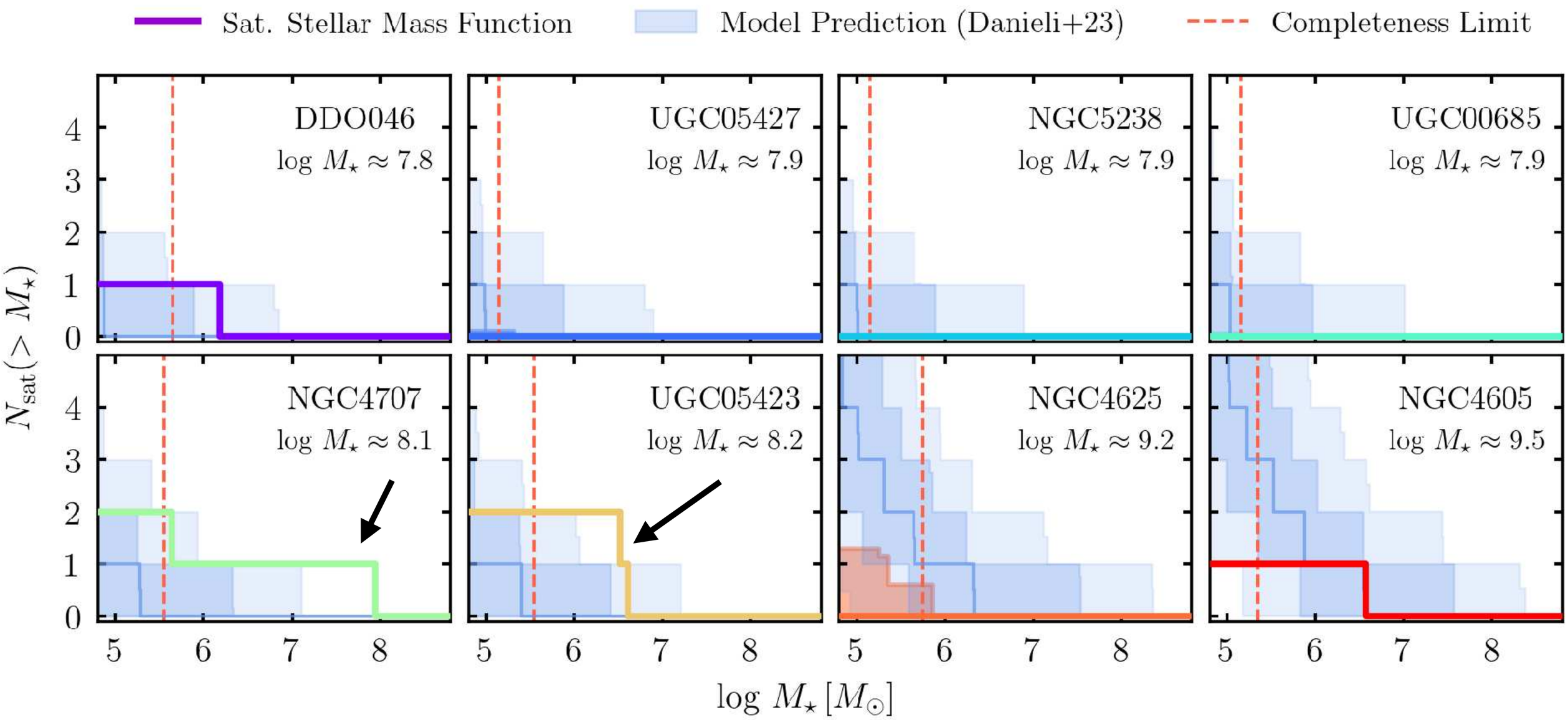


Satellite stellar mass function



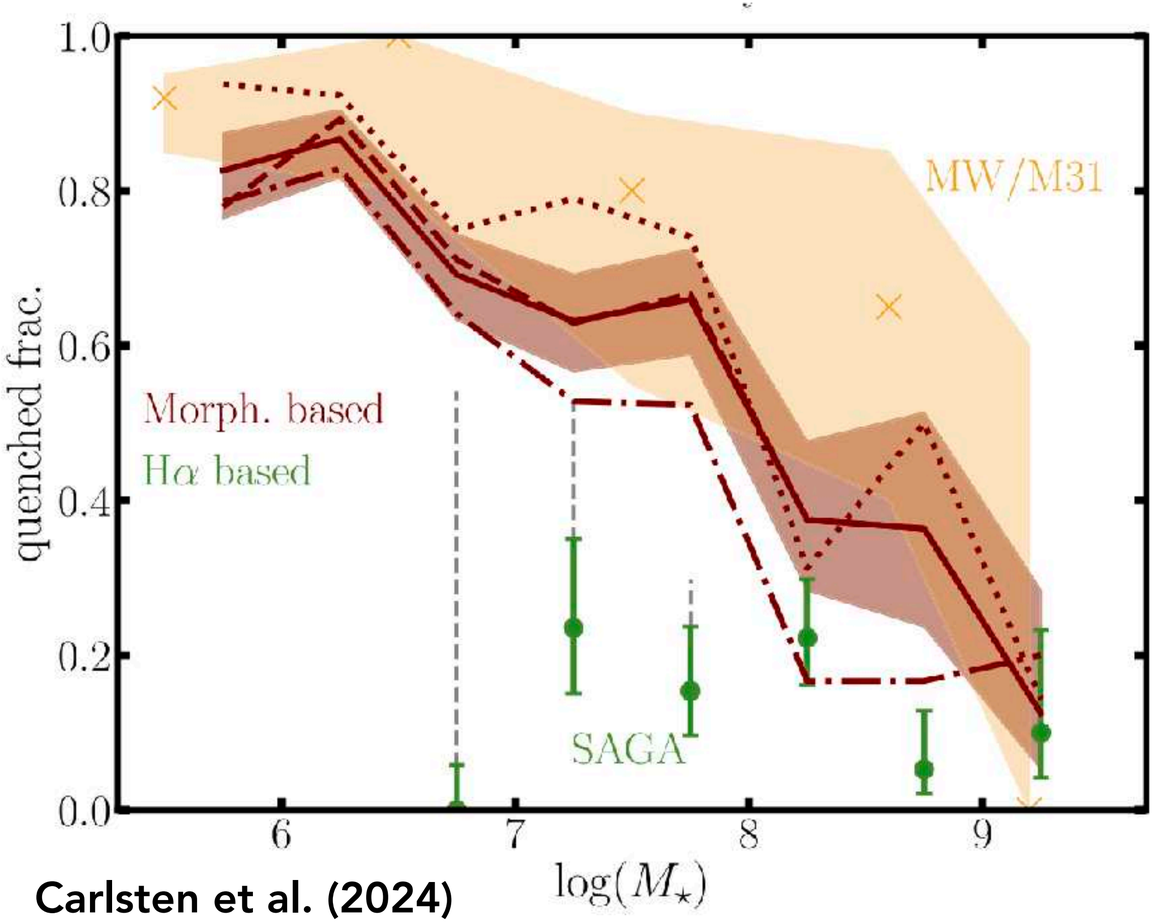
Satellite mass function



Satellite Quenched Fraction

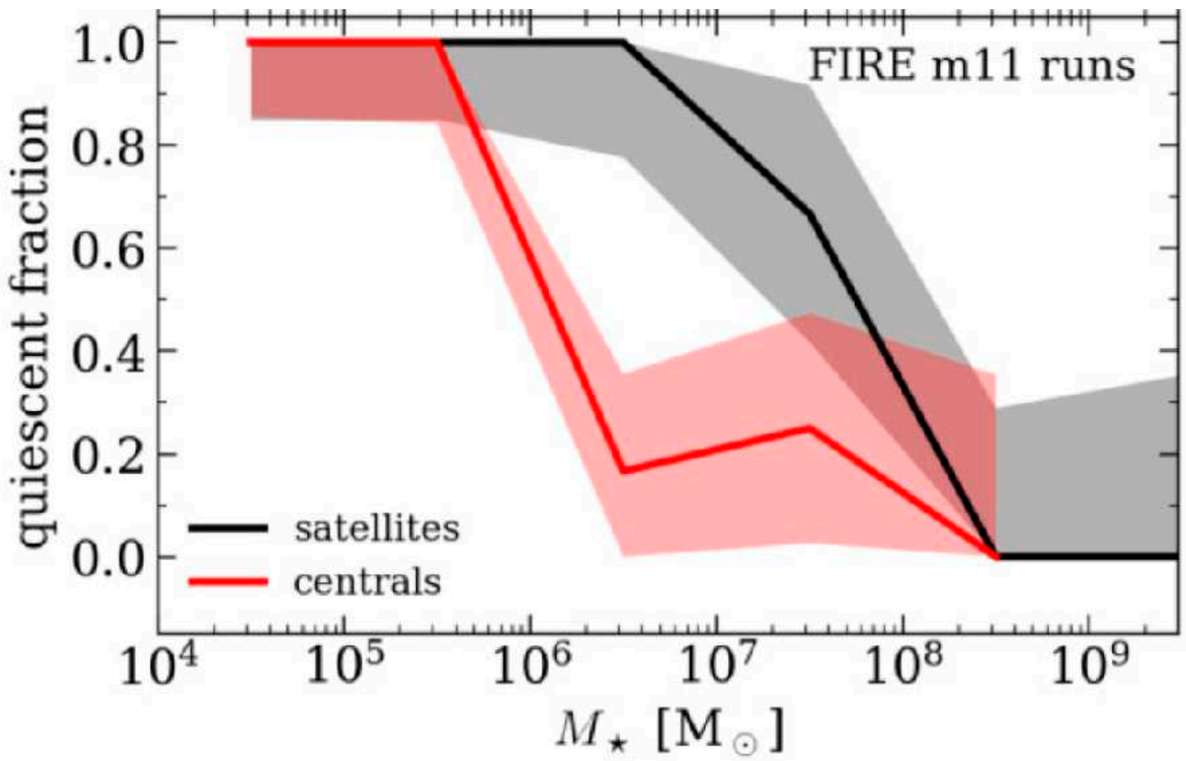
How does the quenching depend on environment -- from large groups to the field?

MW analogs (SAGA+ELVES)



Carlsten et al. (2024)

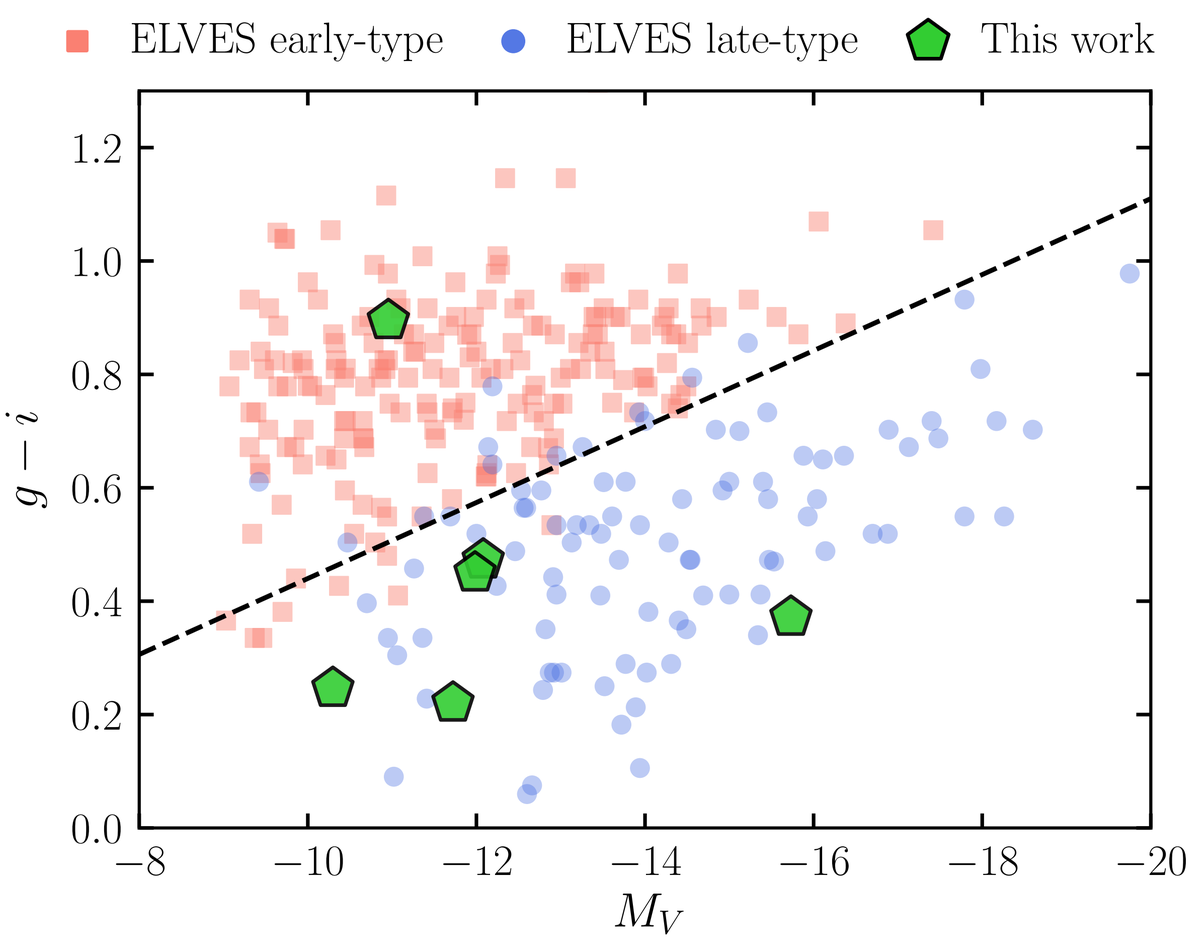
LMC analogs (FIRE simulation)



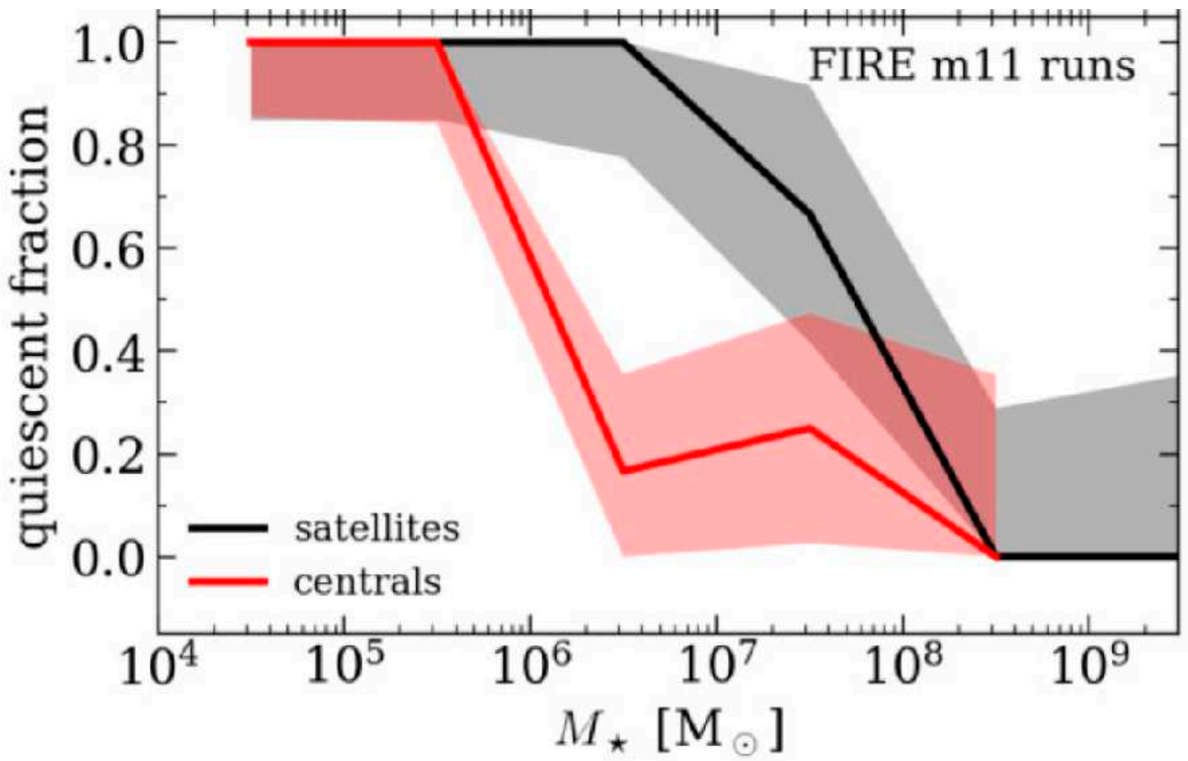
Jahn et al. (2022)

Satellite Quenched Fraction

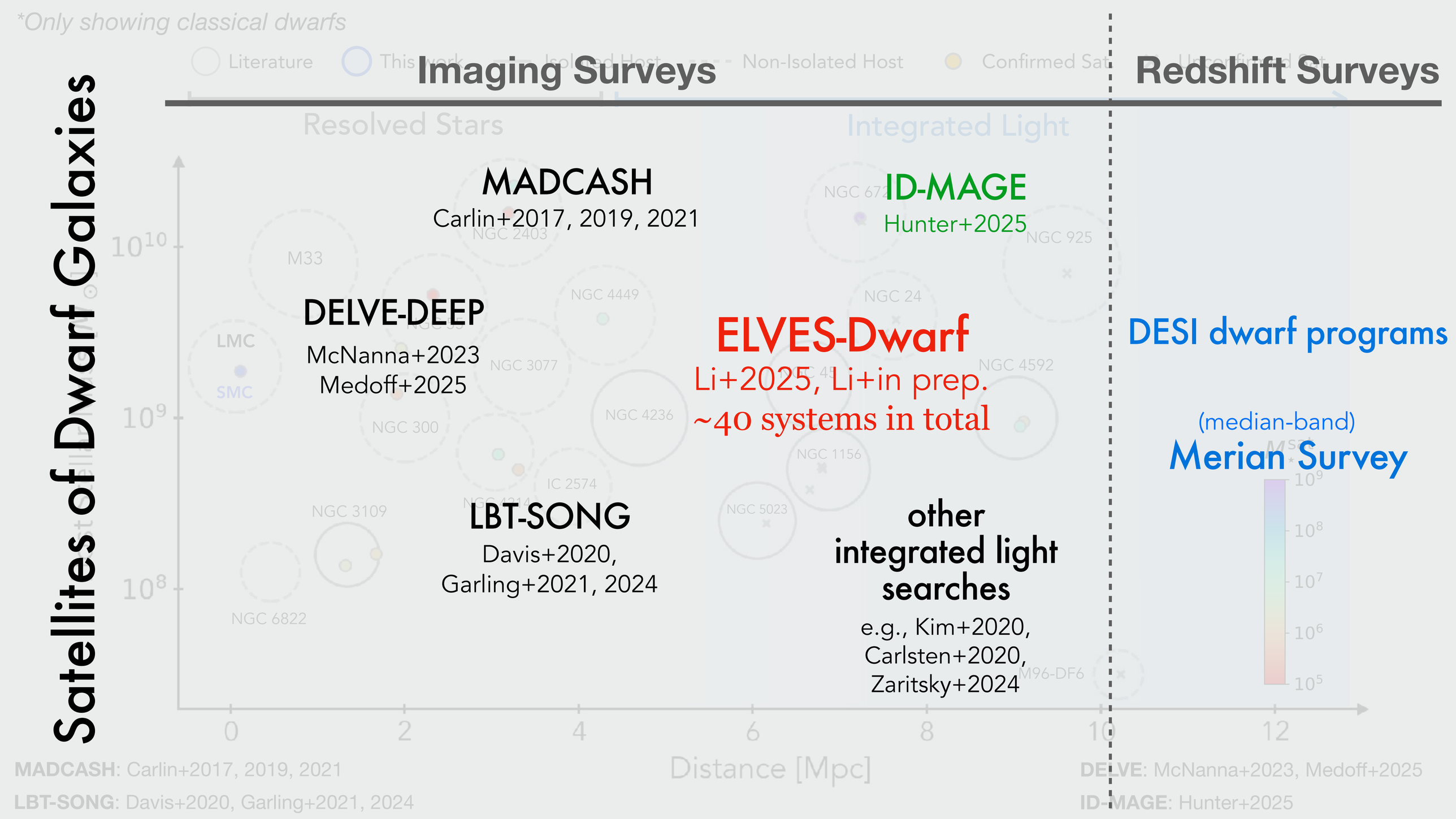
Satellites of LMC-mass dwarfs are quenched to a similar degree as satellites of MW-analogs? Probably not!



LMC analogs (FIRE simulation)



Jahn et al. (2022)


*Only showing classical dwarfs
Literature
This work
Isolated Host
Non-Isolated Host
Confirmed Sat
Unconfirmed Sat
Imaging Surveys
Redshift Surveys
Resolved Stars
Integrated Light
Satellites of Dwarf Galaxies
MADCASH
Carlin+2017, 2019, 2021
ID-MAGE
Hunter+2025
DELVE-DEEP
McNanna+2023
Medoff+2025
ELVES-Dwarf
Li+2025, Li+in prep.
~40 systems in total
DESI dwarf programs
(median-band)
Merian Survey
LBT-SONG
Davis+2020,
Garling+2021, 2024
other
integrated light
searches
e.g., Kim+2020,
Carlsten+2020,
Zaritsky+2024
M33
LMC
SMC
NGC 2403
NGC 4449
NGC 3077
NGC 300
NGC 4236
NGC 3109
NGC 6822
IC 2574
NGC 5023
NGC 1156
NGC 24
NGC 925
NGC 4592
M96-DF6
10^{10}
10^{9}
10^{8}
0
2
4
6
8
10
12
Distance [Mpc]
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
MADCASH: Carlin+2017, 2019, 2021
LBT-SONG: Davis+2020, Garling+2021, 2024
DELVE: McNanna+2023, Medoff+2025
ID-MAGE: Hunter+2025

Satellites in Galaxy Groups
Field Dwarfs

Field Dwarfs

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 are known in the Local Volume

What's the quenched fraction at $10^5 \lesssim M_\star < 10^7\,M_\odot$ and what quenched them?

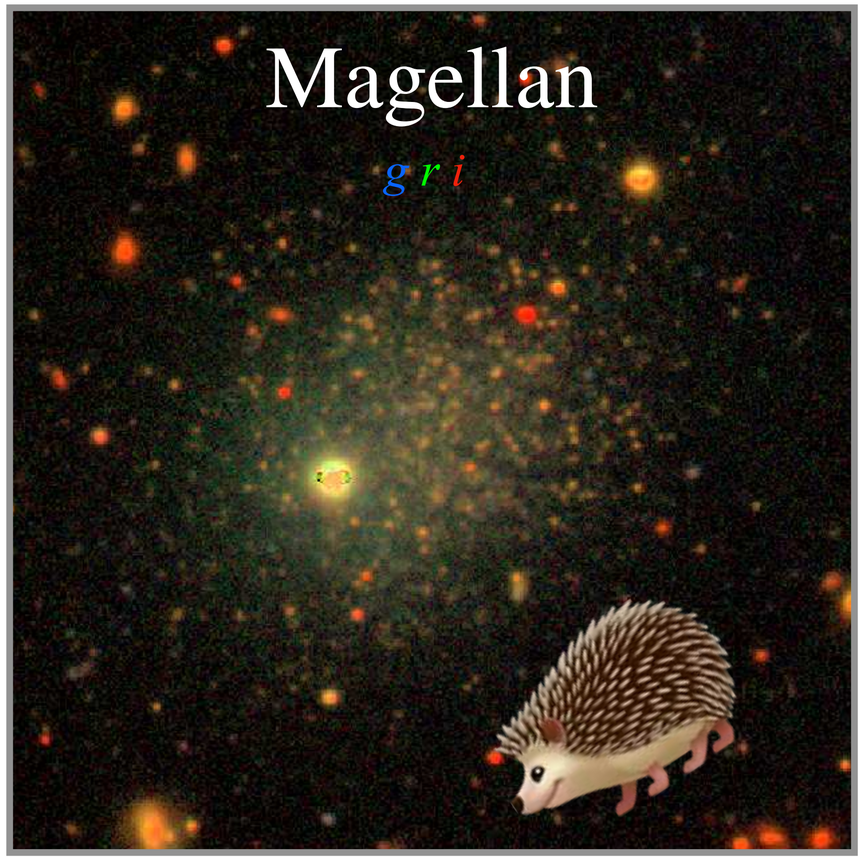
Reionization quenching: what's the upper mass limit for reionization quenching?

Hedgehog

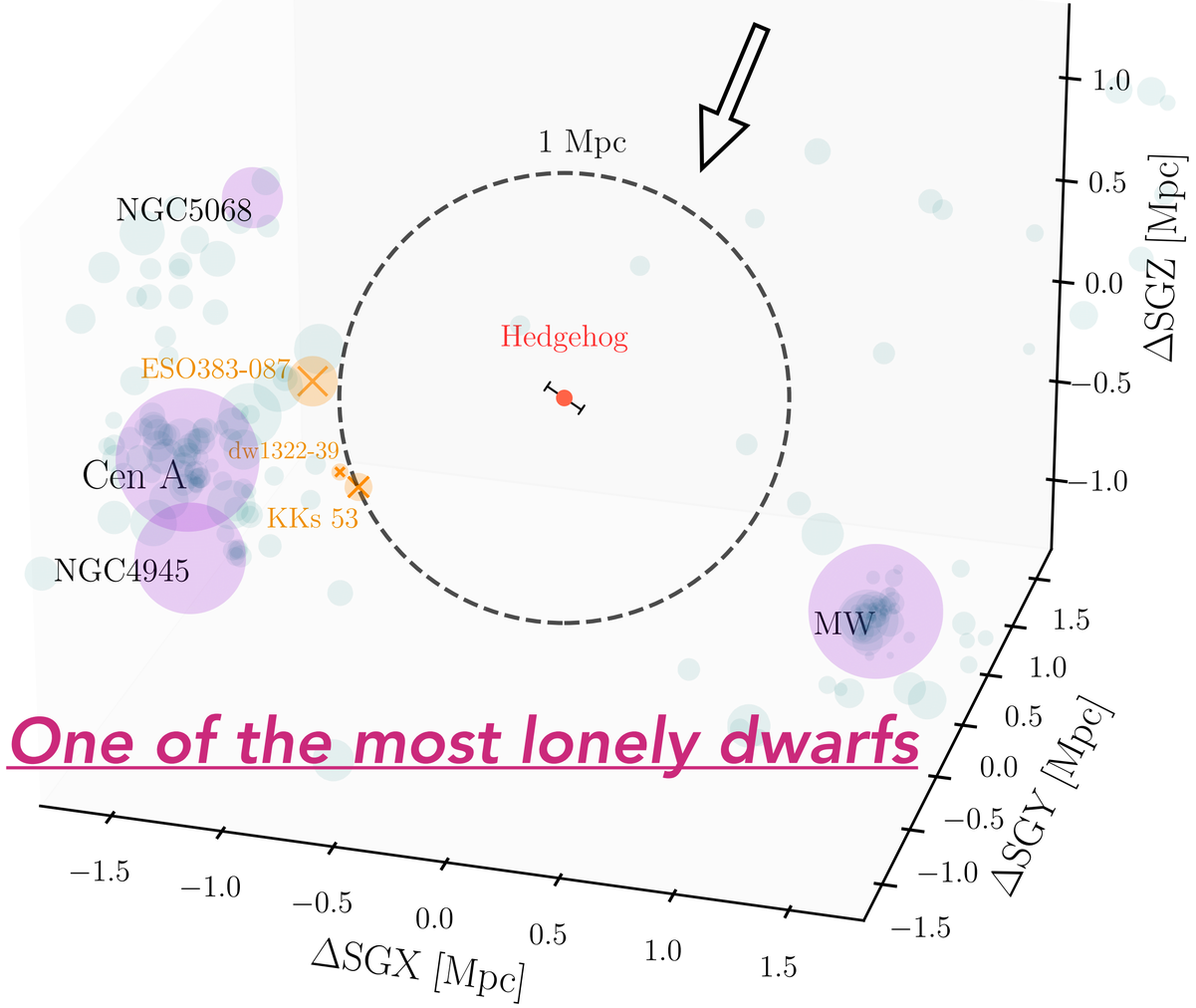
An isolated quiescent dwarf at 2.4 Mpc

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

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



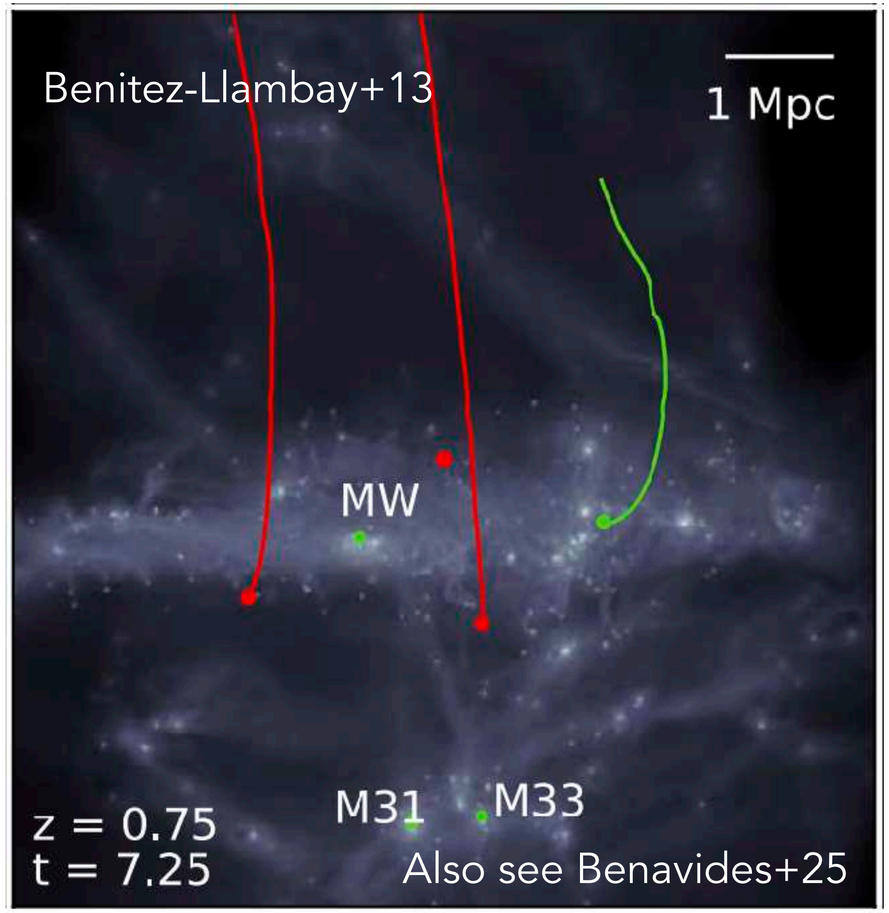
No known neighbors within 1 Mpc



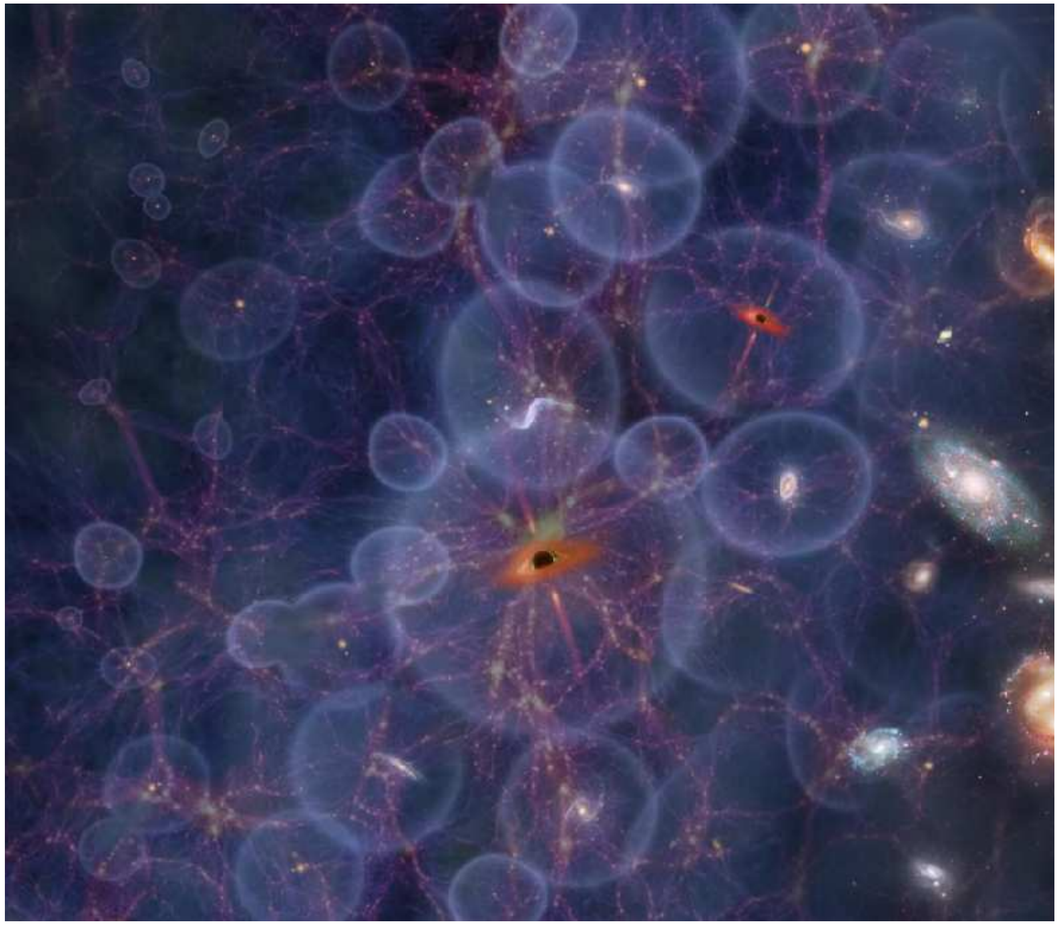
One of the most lonely dwarfs

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

Quenching Mechanism



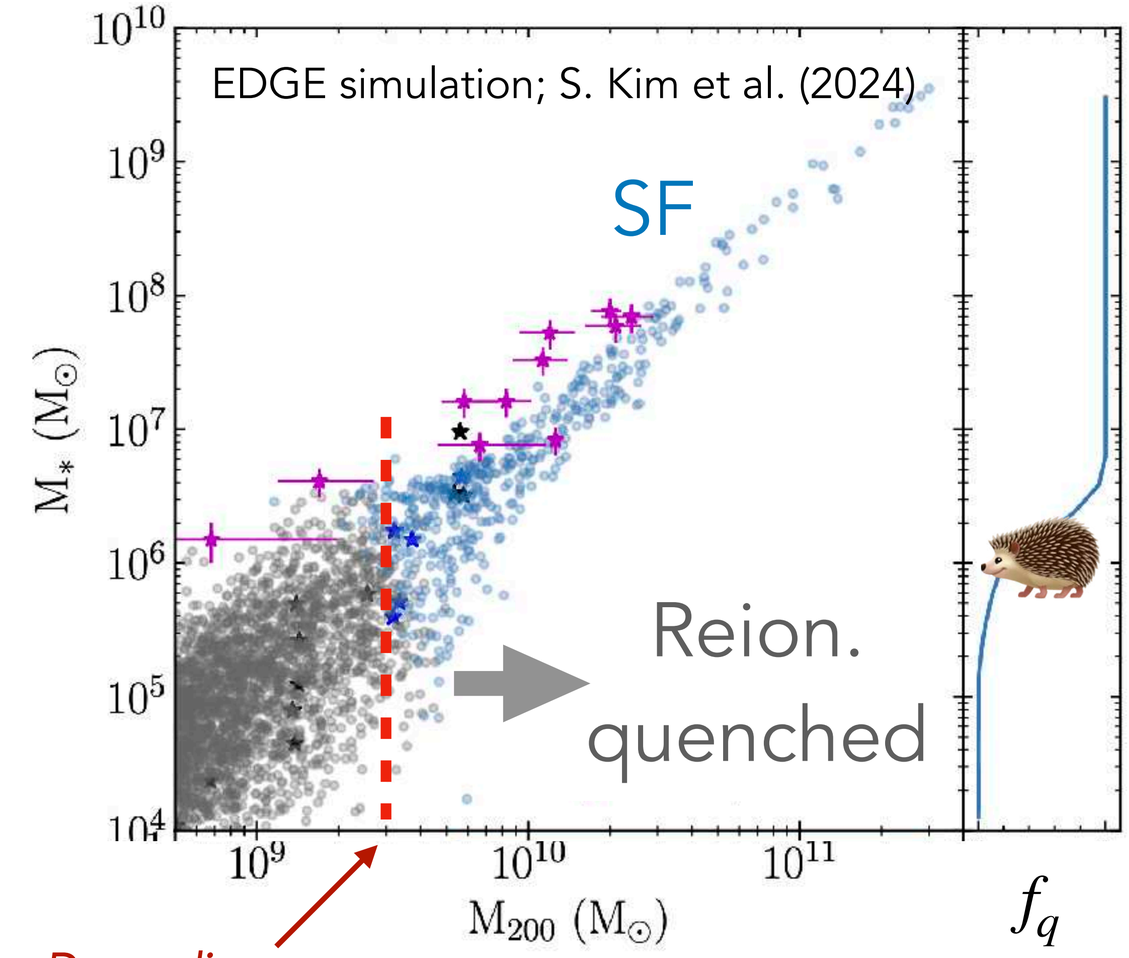
Cosmic web stripping



Reionization quenching (z~6)

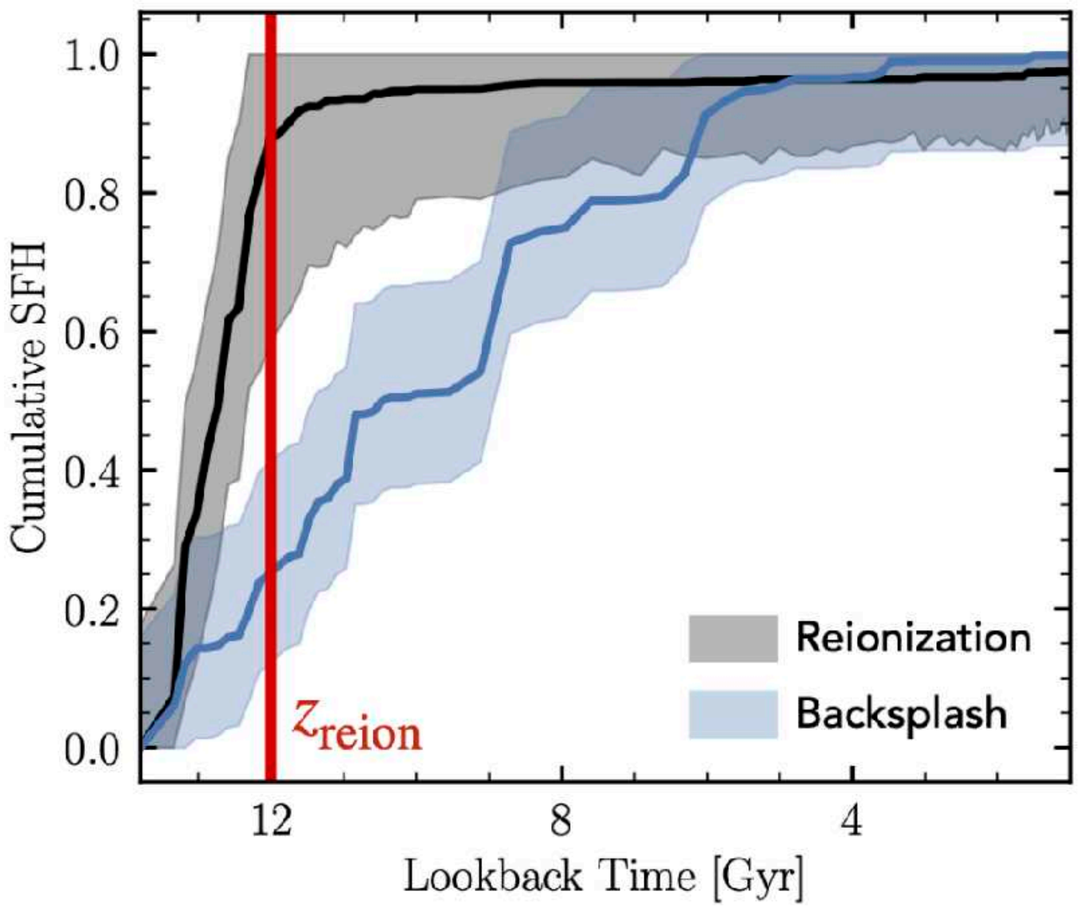
What's the mass upper lim?

Most Massive Reionization Fossil?



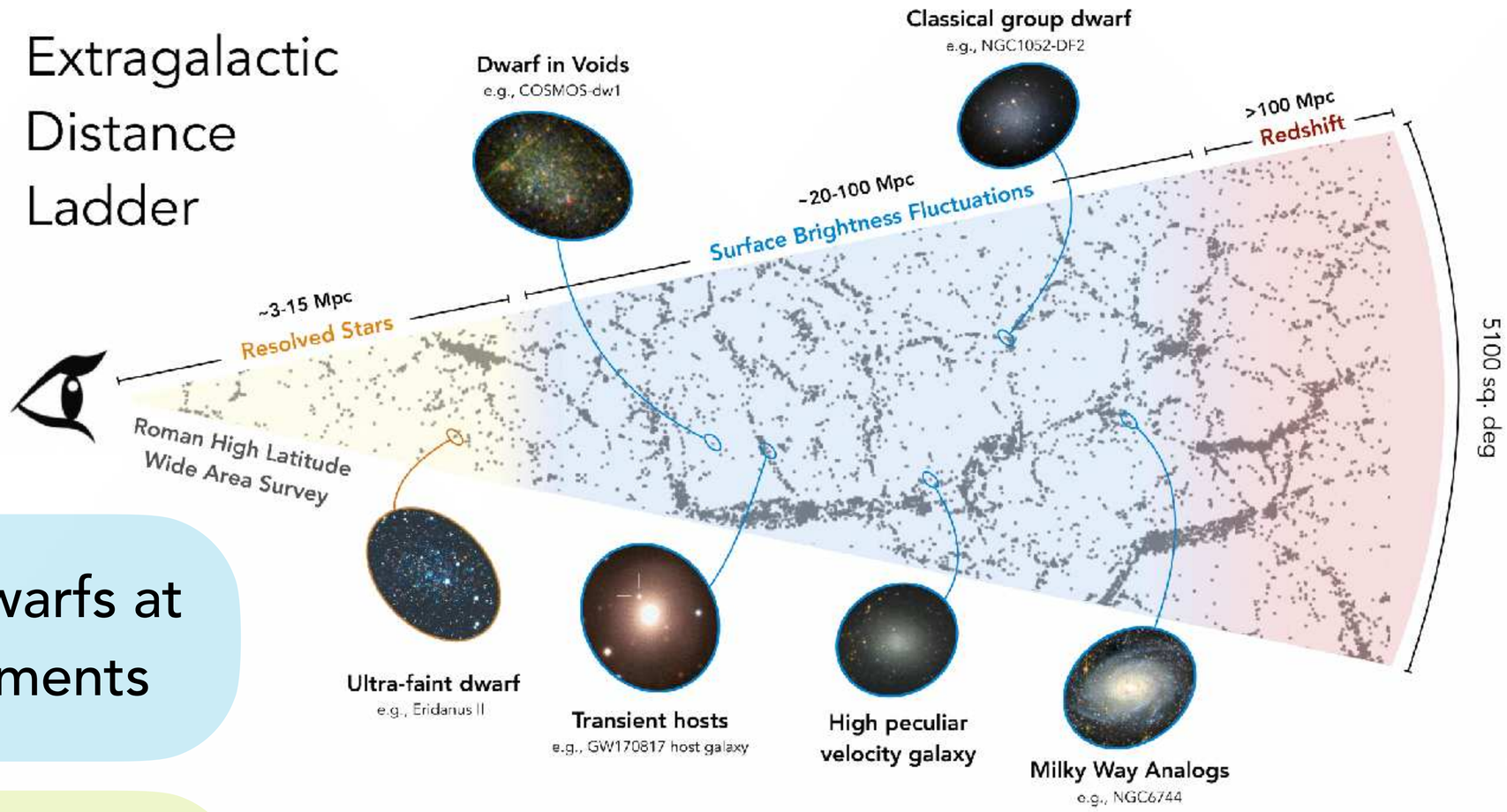
Depending on reionization epoch

Upcoming 30 orbits on HST will tell us:



HST GO-18046 (PI Li)

Future Dwarf Galaxy Surveys



LSST: characterizing all dwarfs at <20 Mpc across environments

Roman: pushing Local Volume to 100 Mpc with SBF in NIR

We need image simulation to understand how far can we push SBF for dwarfs in Roman

RoSESim: Roman semi-resolved galaxy simulator

Artpop

Sample stars from stellar population (Greco & Danieli 23)

Background Galaxies

Drawn from mock galaxy catalogs or simulations

Foreground Stars

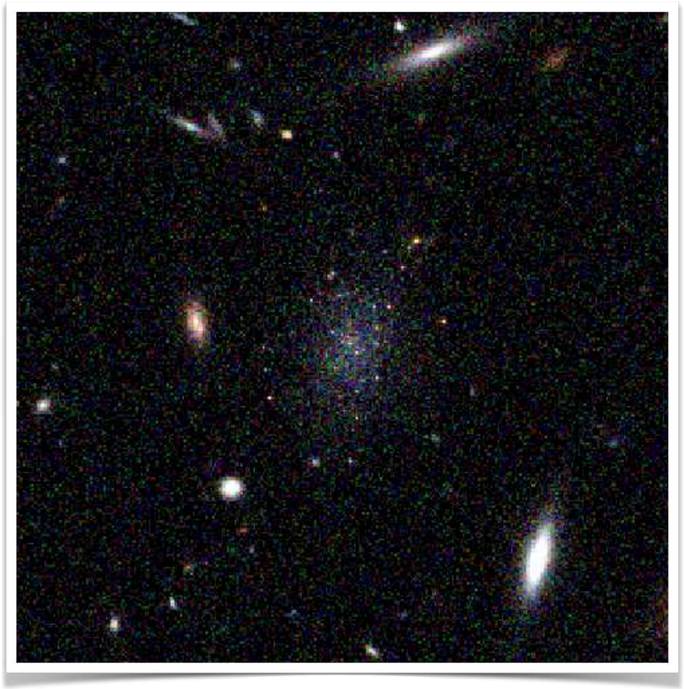
Drawn from Gaia

Roman-I-sim

Exptime, N_exp, RA, Dec

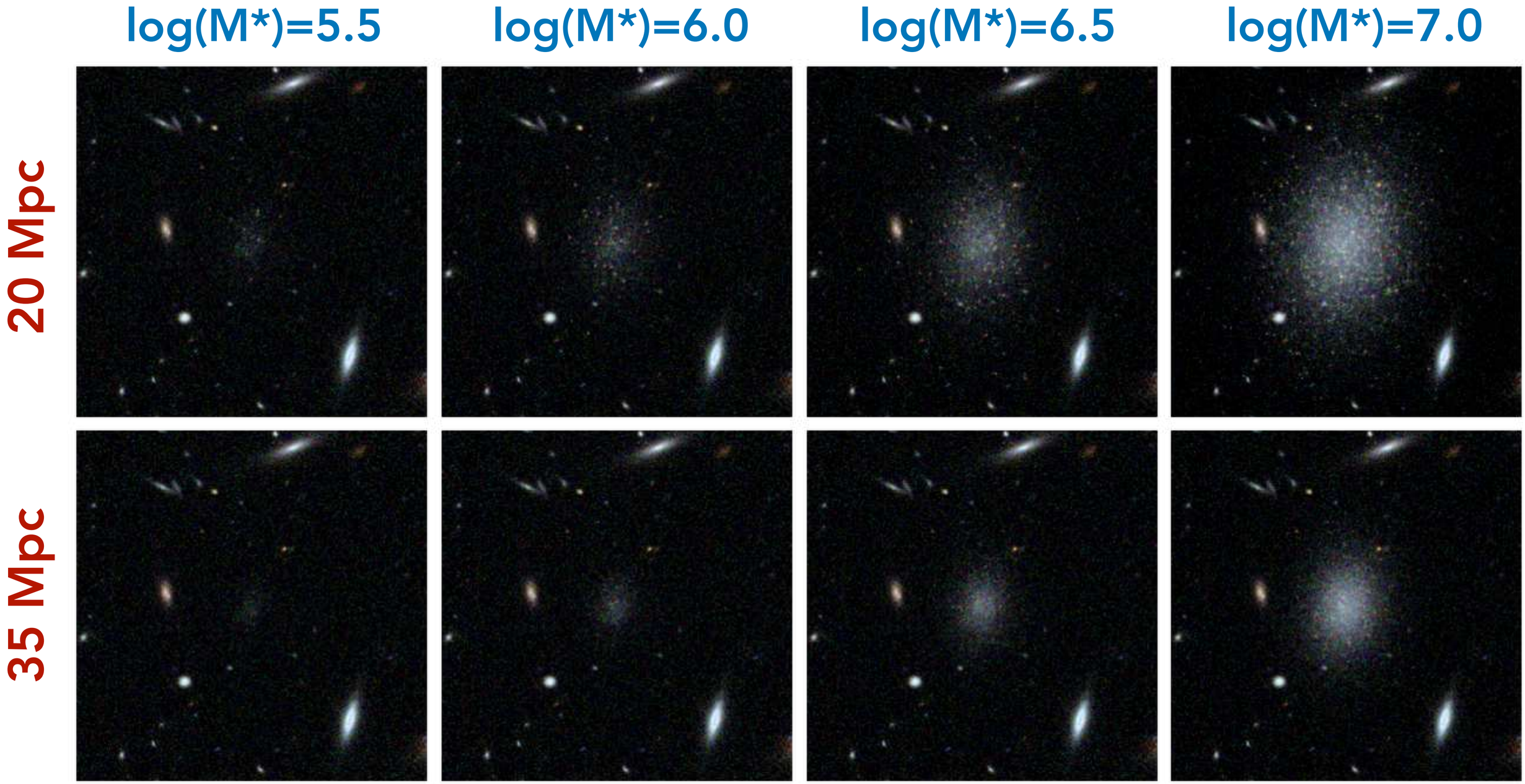
Dither pattern (future)

10^6 solar mass at 25 Mpc



HLWAS depth
F106+F129+F158

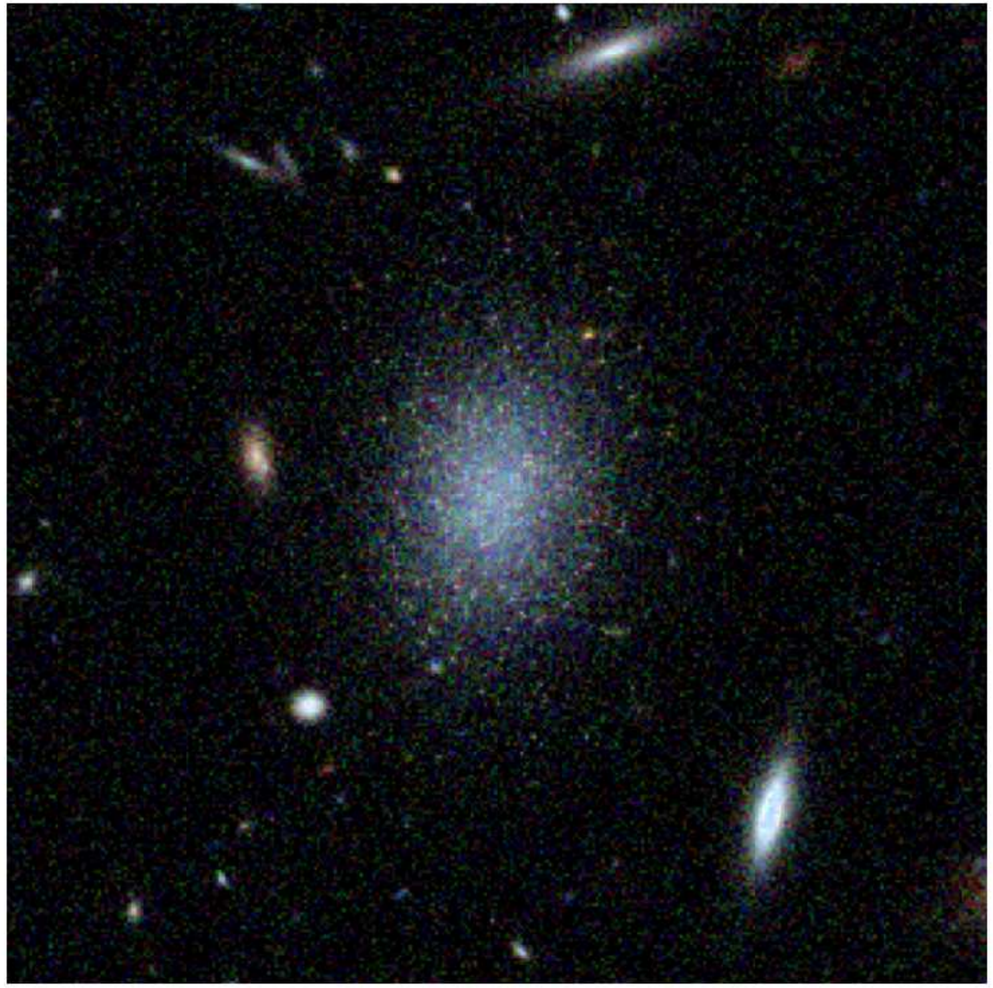
https://github.com/AstroJacobLi/Rosesim



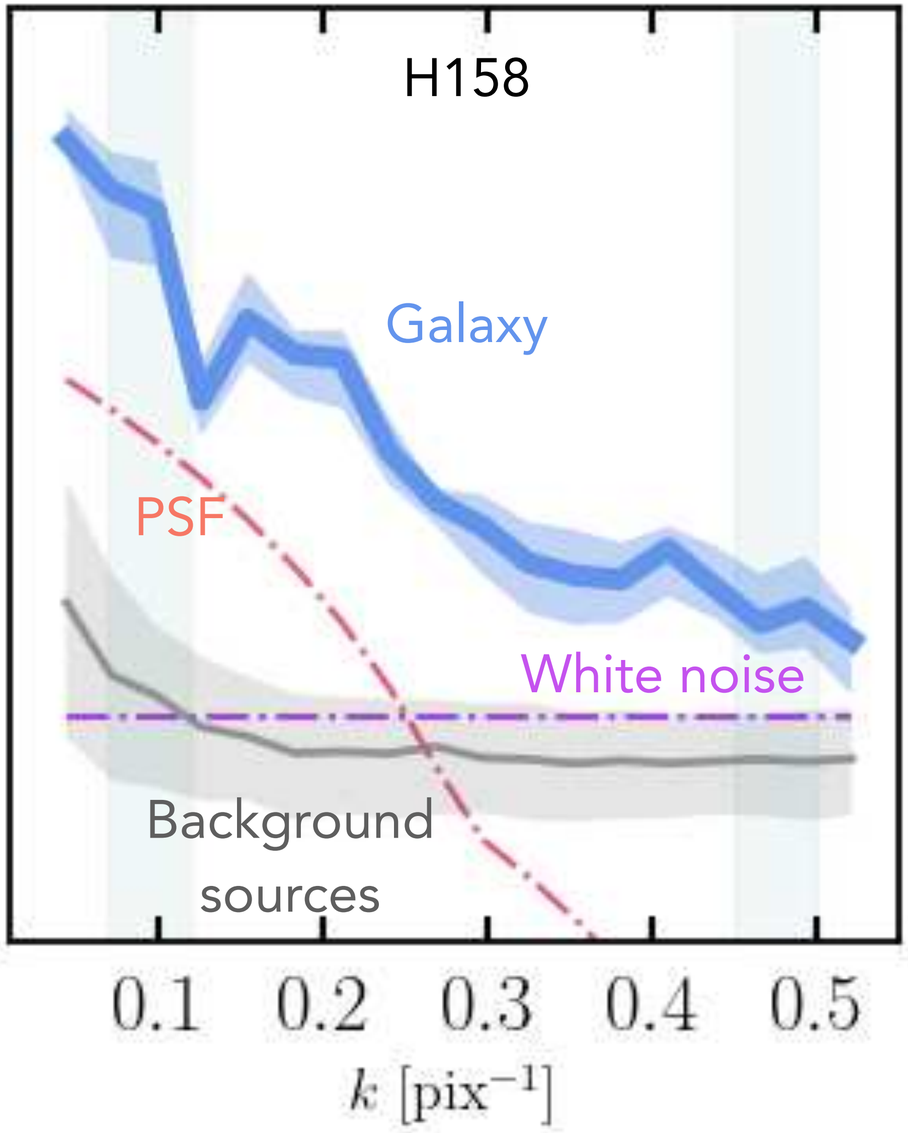
All are SSPs with 1 Gyr, [Fe/H]=-1.5

SBF measurements

SBF can be measured at 40-50 Mpc for log(M*)=7



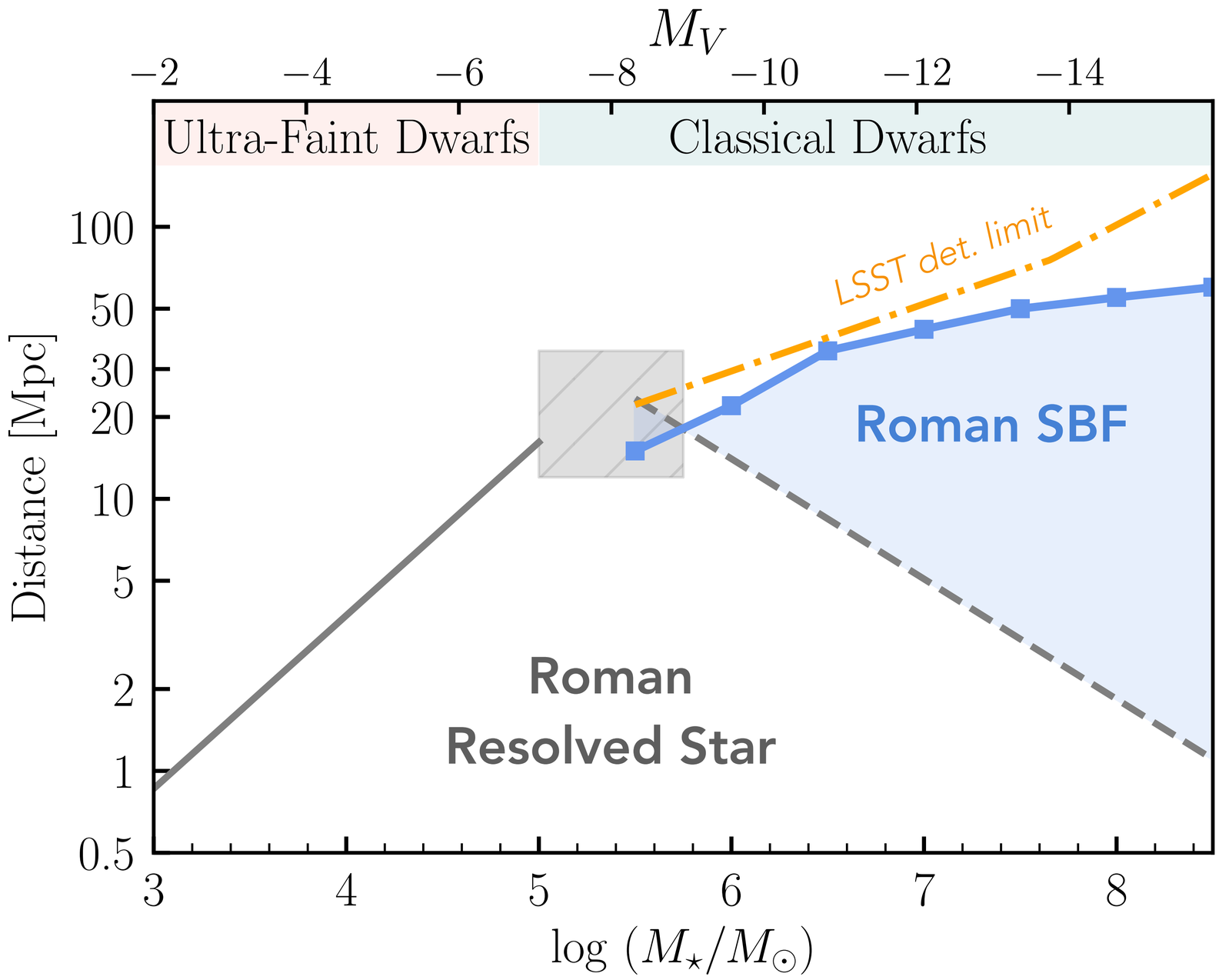
log(M*)=7.0, D=35 Mpc
Age = 0.4 Gyr, [Fe/H]=-1.5



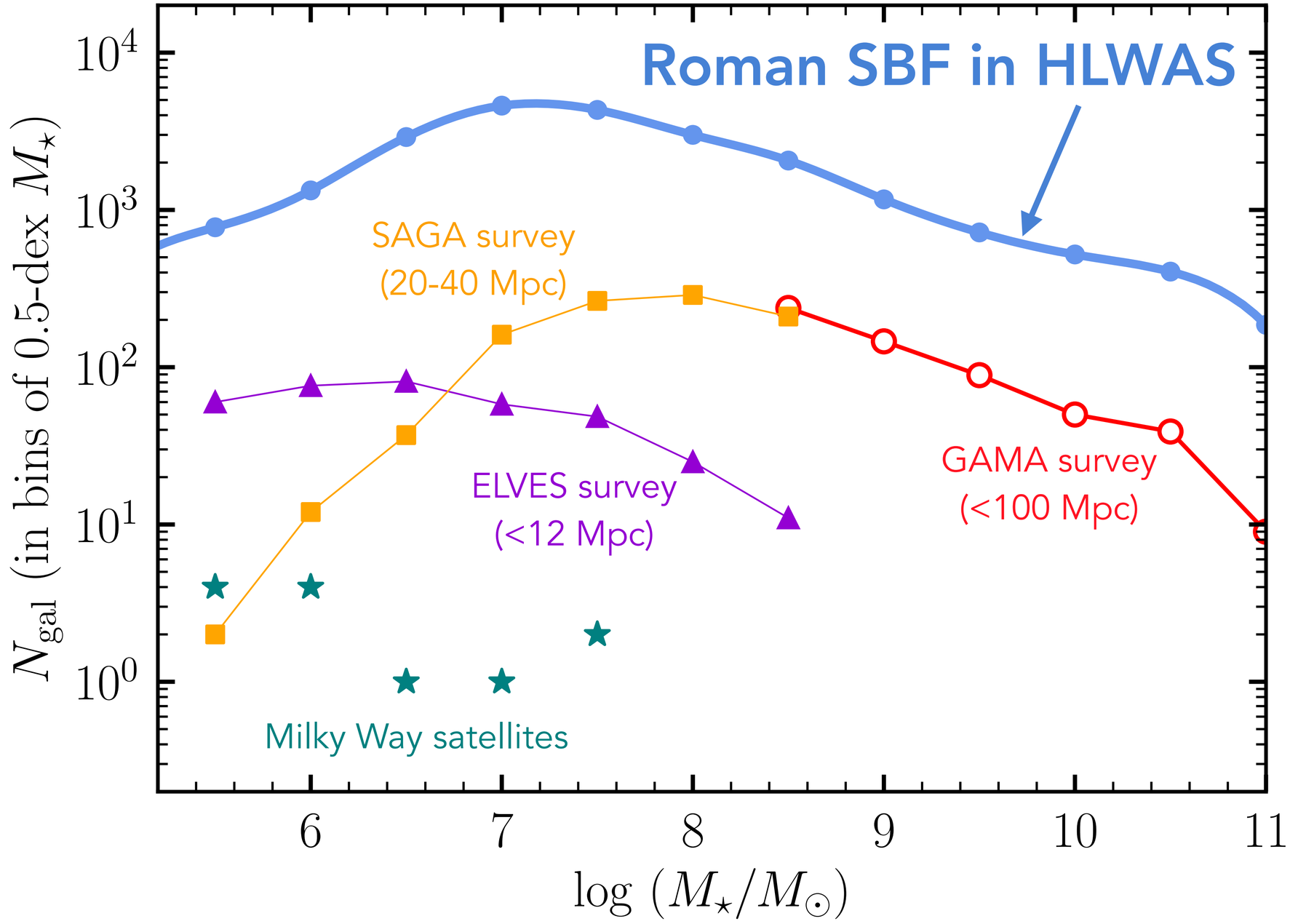
Preliminary!!

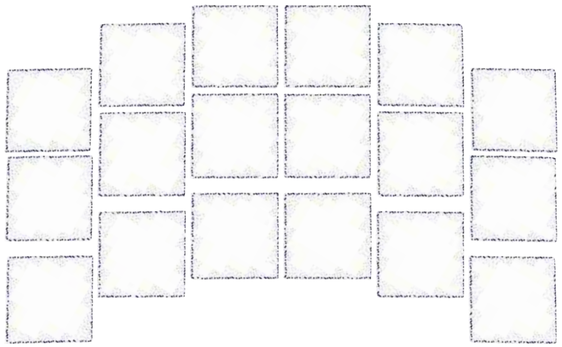
Li+ (in prep)

Forecast for Roman HLWAS



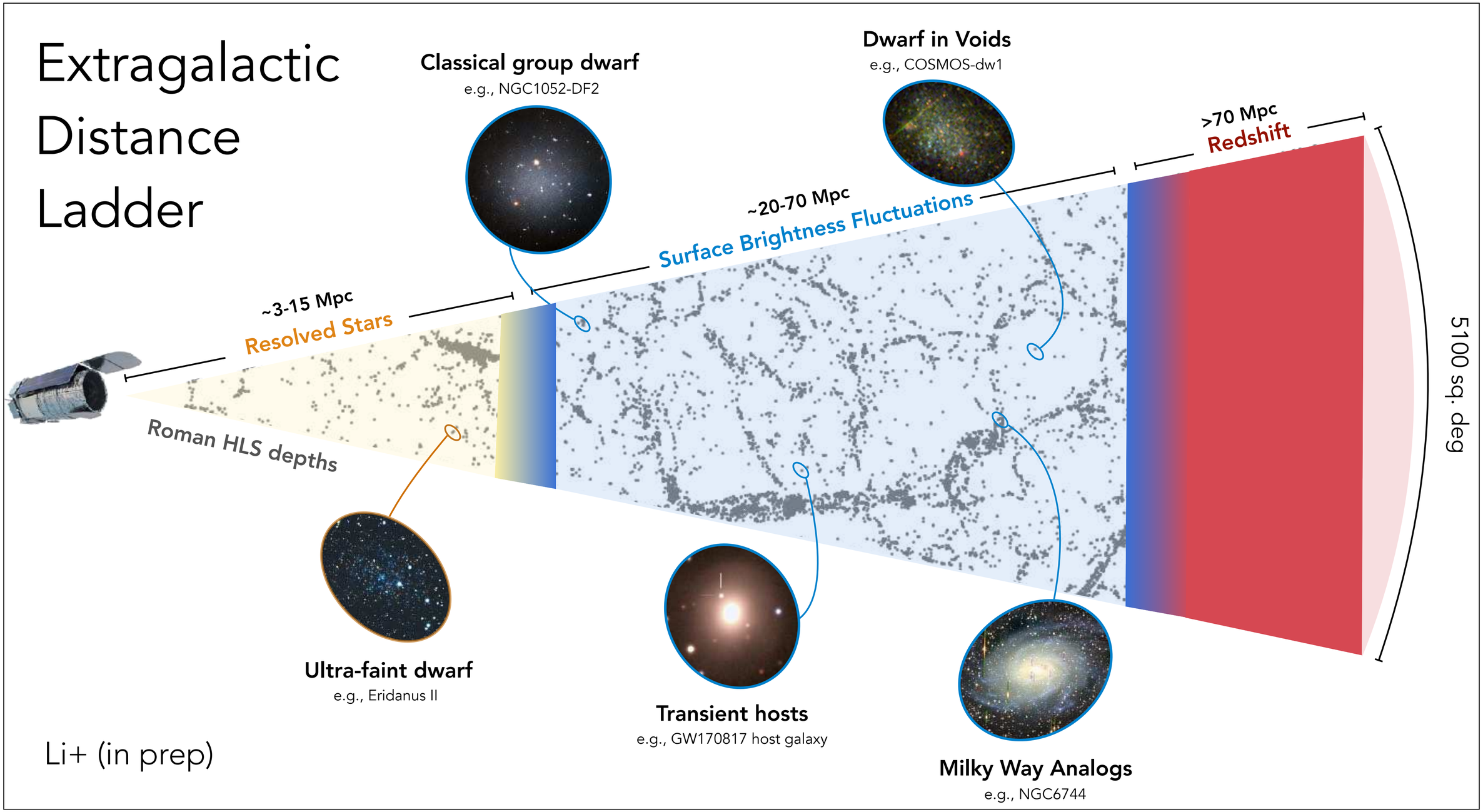
Preliminary!! Li+ (in prep)





~1 SBF-able galaxy per pointing

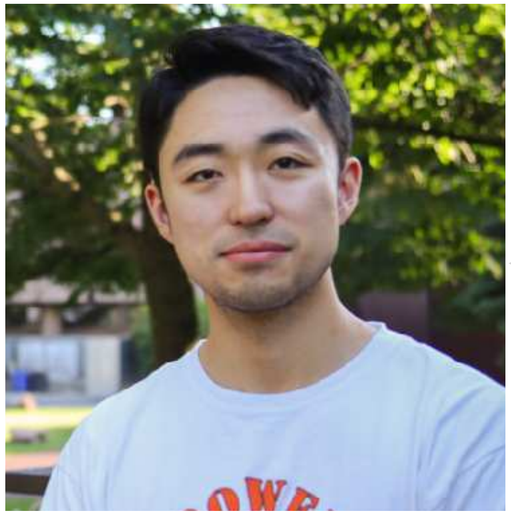
Roman will discover new lovely dwarfs in the deep fields


Extragalactic Distance Ladder
Classical group dwarf
e.g., NGC1052-DF2
Dwarf in Voids
e.g., COSMOS-dw1
>70 Mpc
Redshift
~20-70 Mpc
Surface Brightness Fluctuations
~3-15 Mpc
Resolved Stars
Roman HLS depths
5100 sq. deg
Ultra-faint dwarf
e.g., Eridanus II
Transient hosts
e.g., GW170817 host galaxy
Milky Way Analogs
e.g., NGC6744
Li+ (in prep)

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?

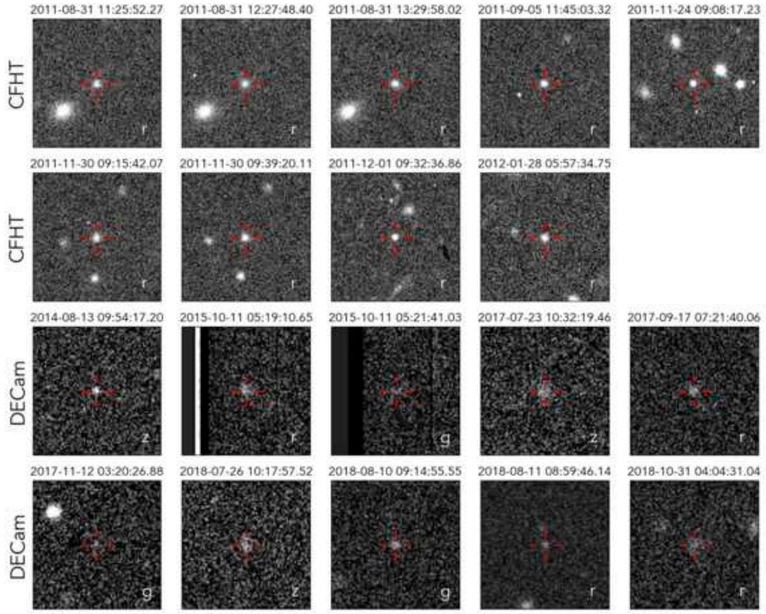
The New York Times

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.

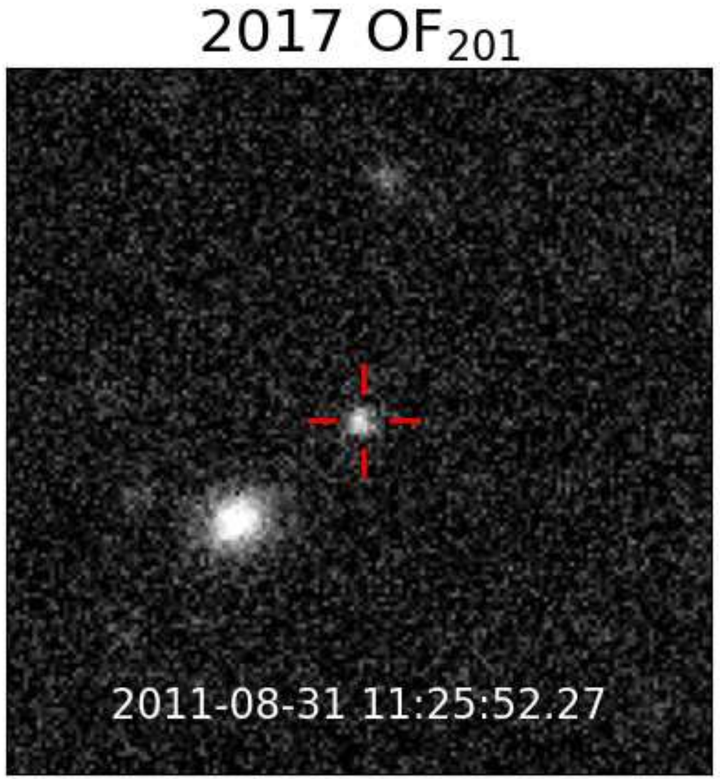
Listen to this article · 8:10 min Learn more

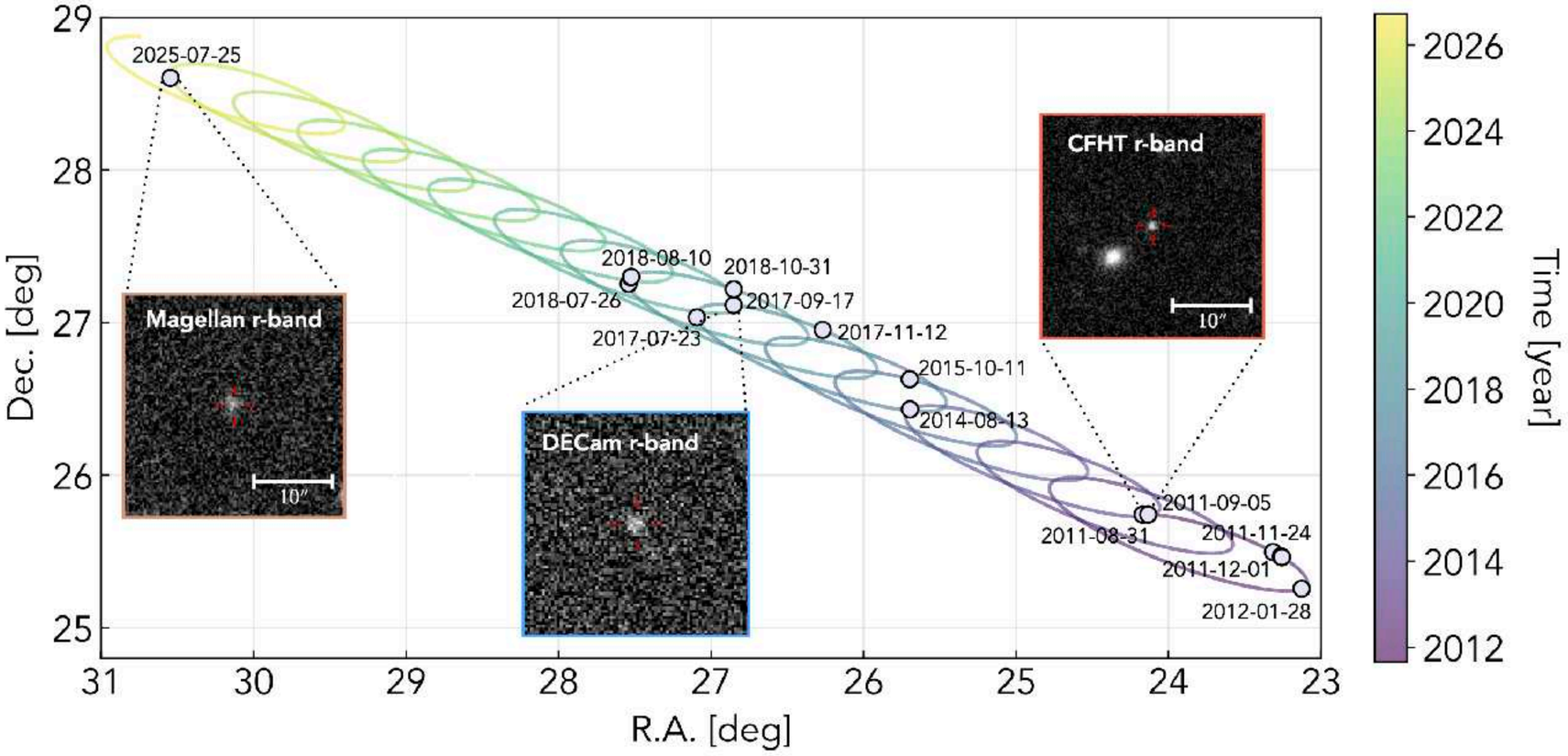
Share full article



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

Discovery of a new **Dwarf Planet** candidate



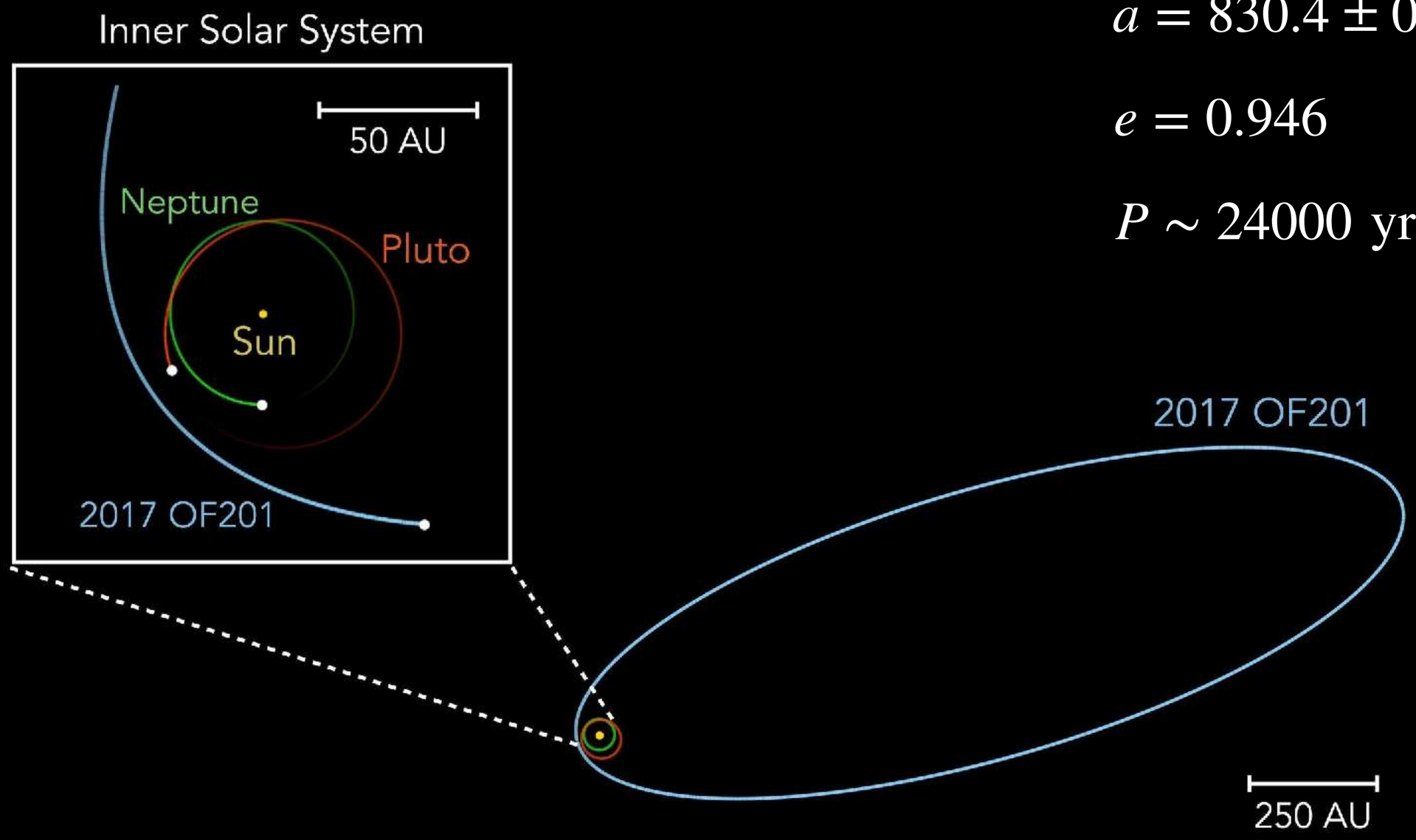


20 detections spanning 13 years, enabling very precise orbit determination (<0.1%)

$a = 830.4 \pm 0.8$ au

$e = 0.946$

$P \sim 24000$ yr



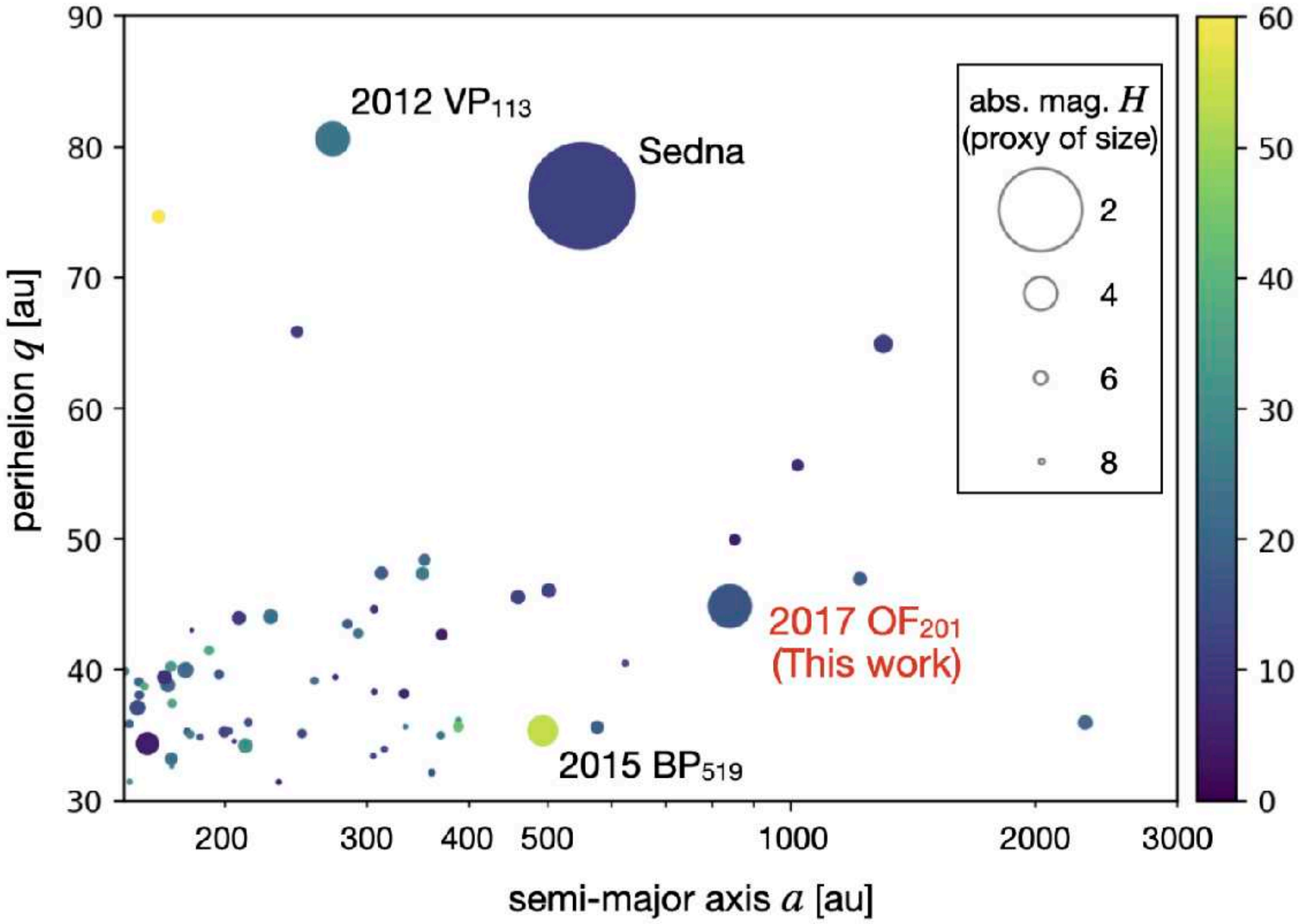
Discovery of a new **Dwarf Planet** candidate

$$H_V = 3.5 \text{ mag}$$

$$D = 700 \text{ km}$$

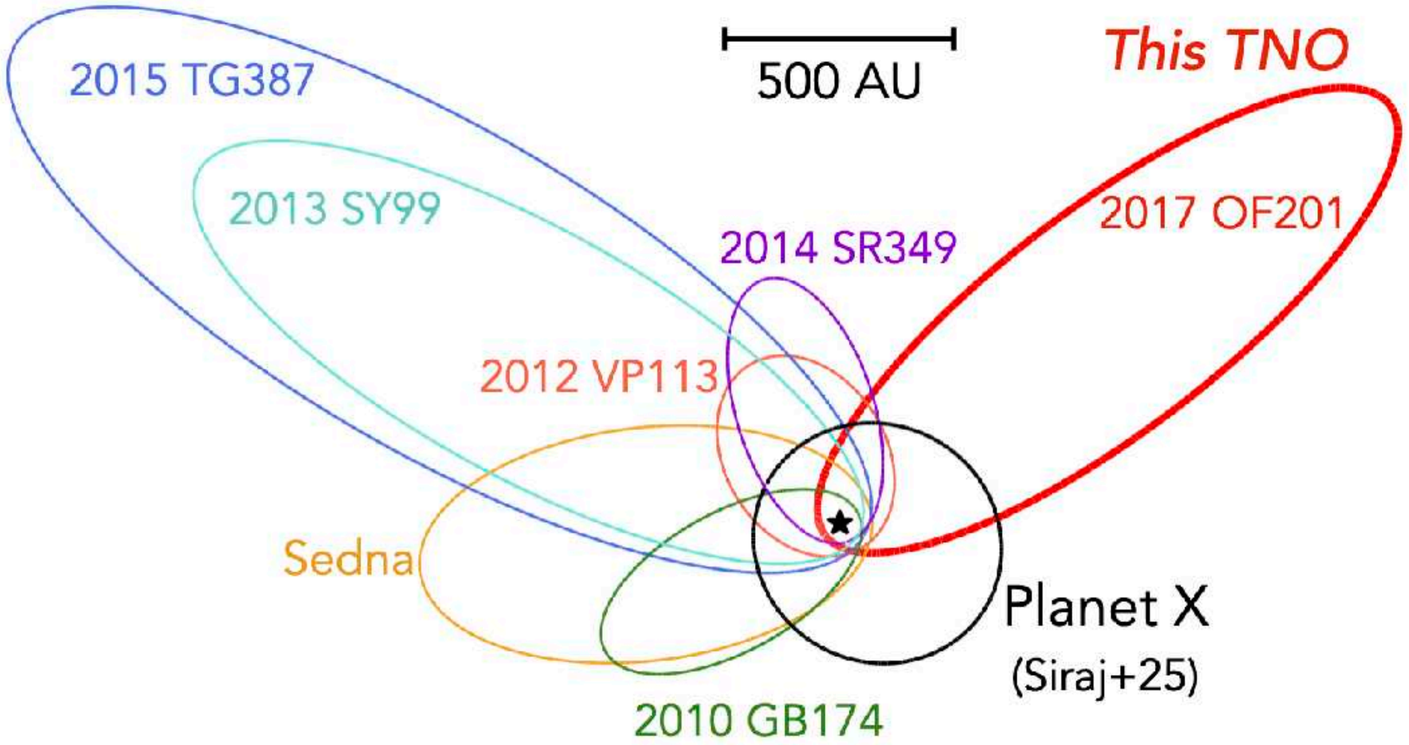
$$(\rho_V = 15\%)$$

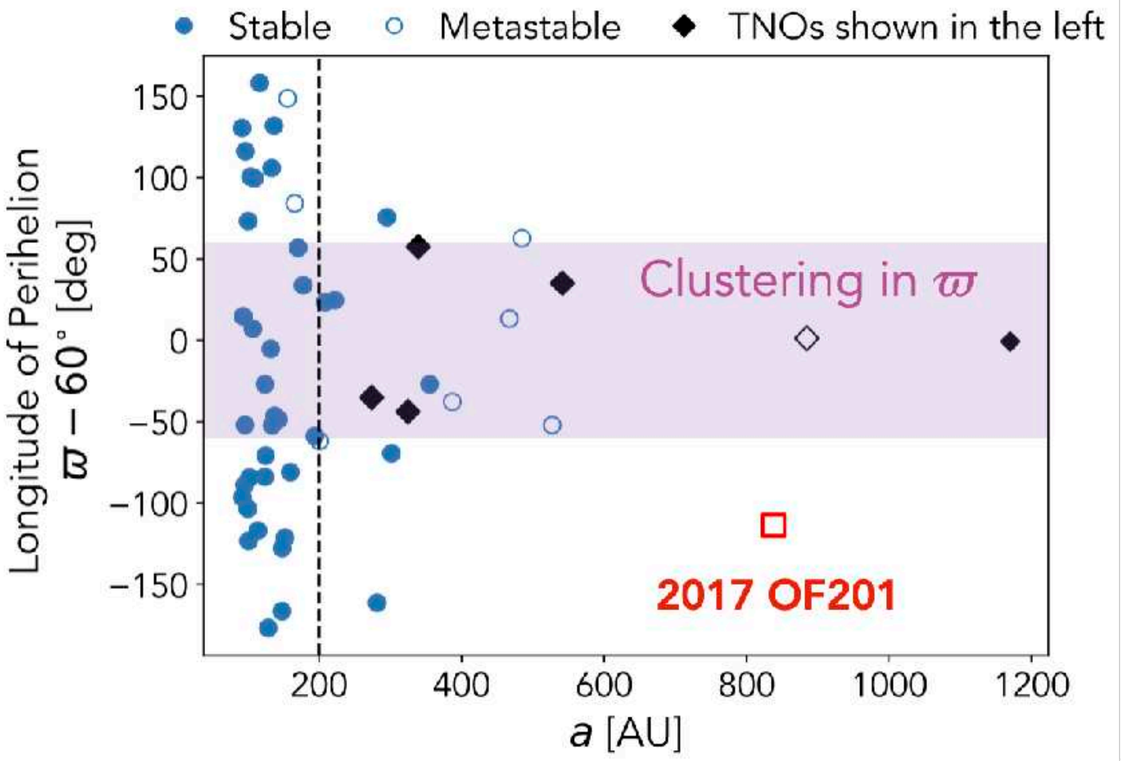
Third largest dwarf planet!



Implication for **Planet 9** Hypothesis

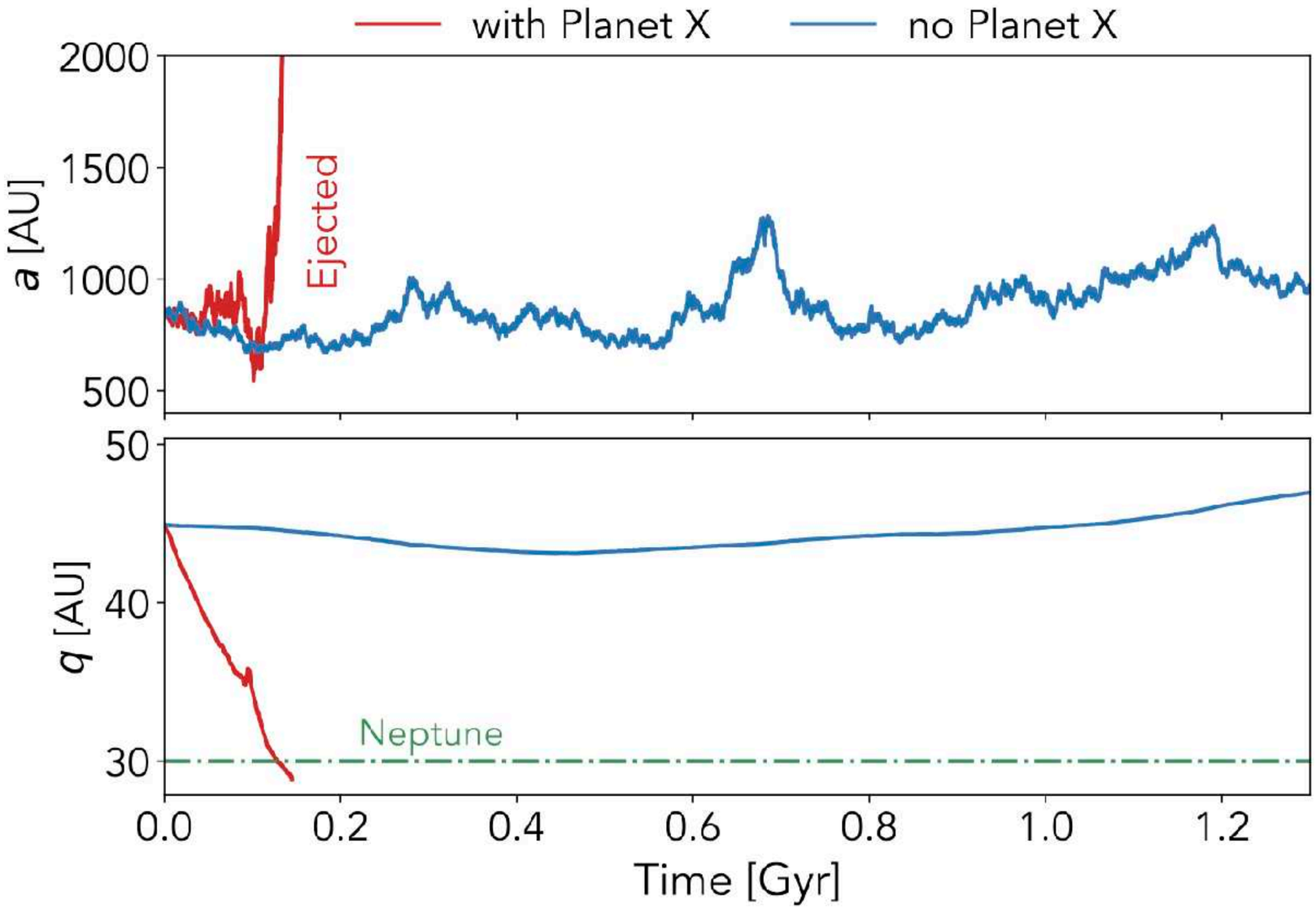
This TNO is outside of the orbital cluster, which is the evidence of P9





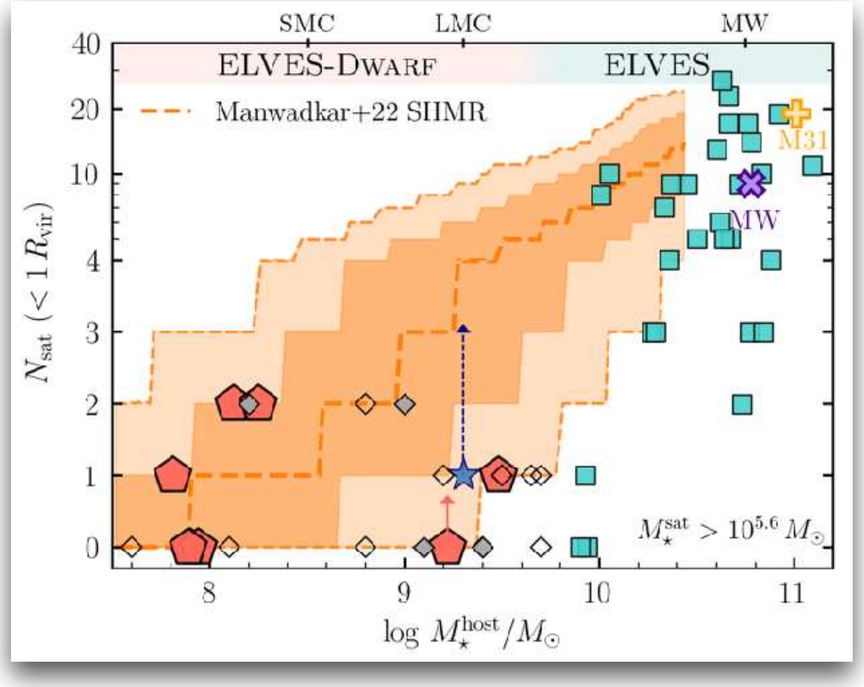
Implication for Planet 9 Hypothesis

With Planet 9, this TNO will be ejected very quickly

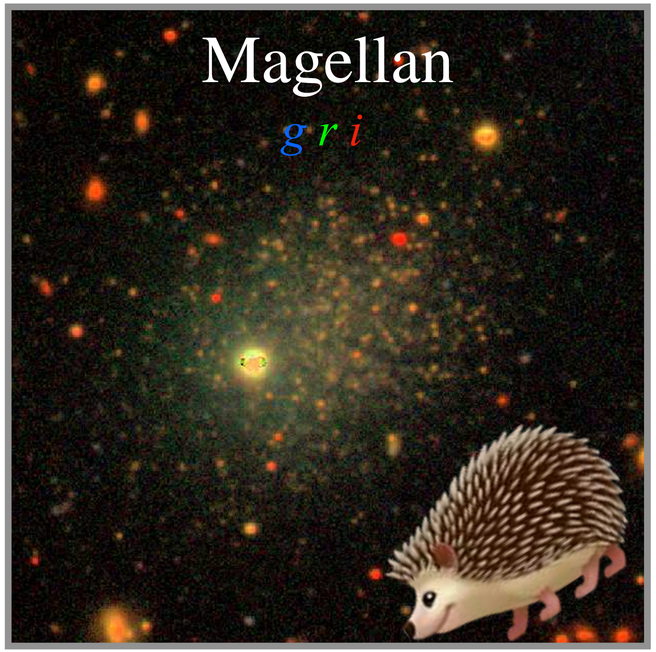


Summary

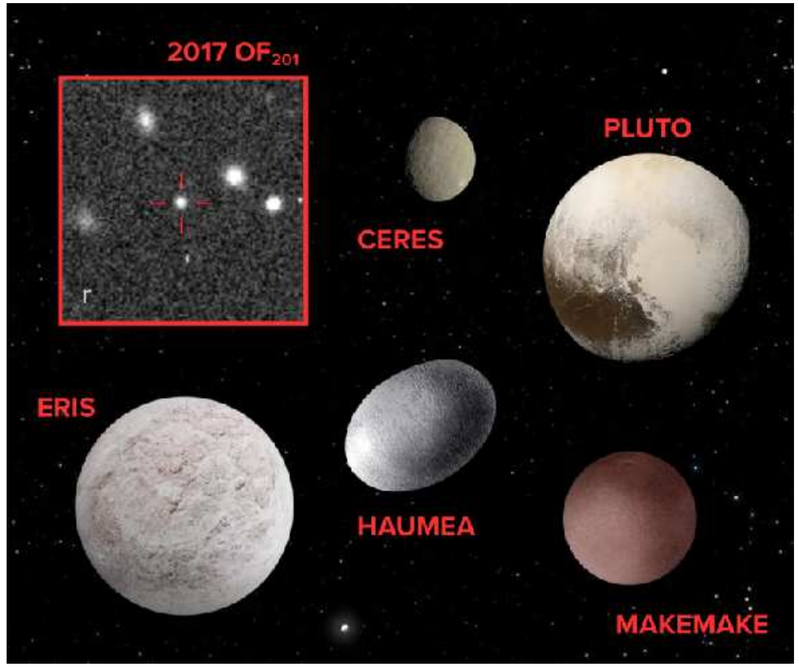
ELVES-Dwarf
Satellites of Dwarfs



Hedgehog
Isolated Quiescent Dwarf



New Dwarf Planet
Does Planet 9 exist?



Interested in chatting more?

SBF for future surveys

Finding dwarfs in LSST

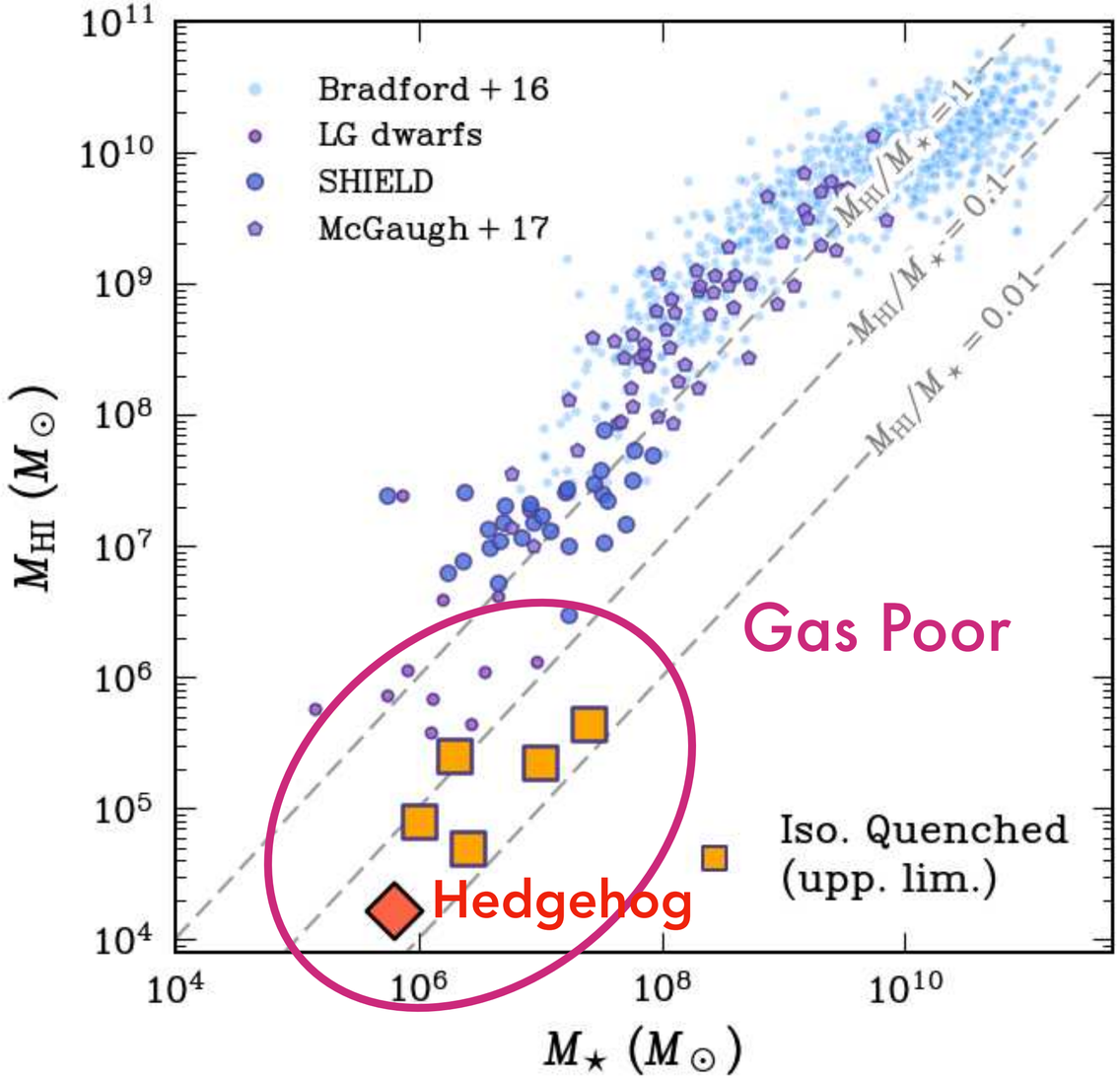
Ultra-Diffuse Galaxies

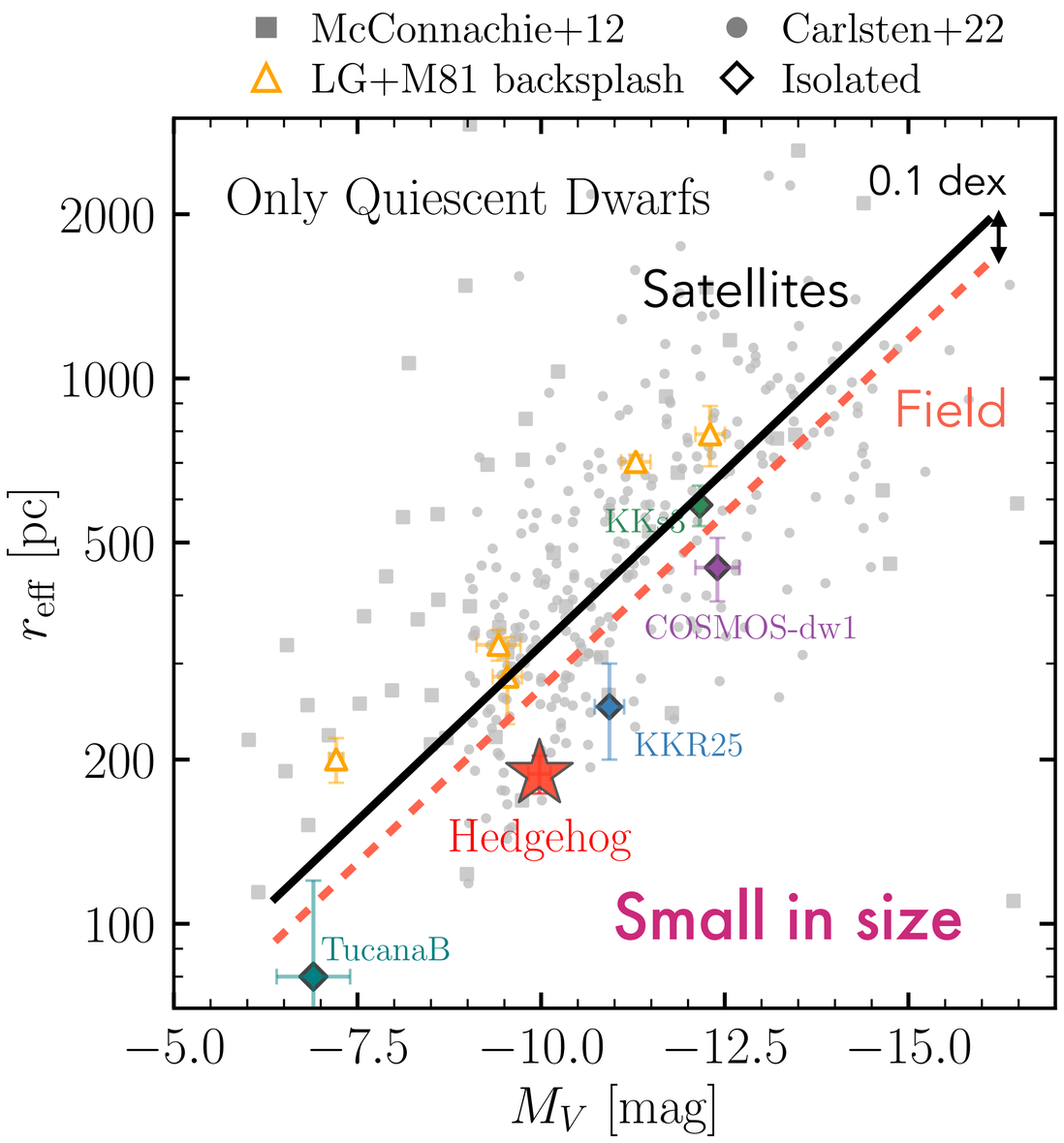
Jiaxuan Li

Backup

Isolated Quenched Dwarfs

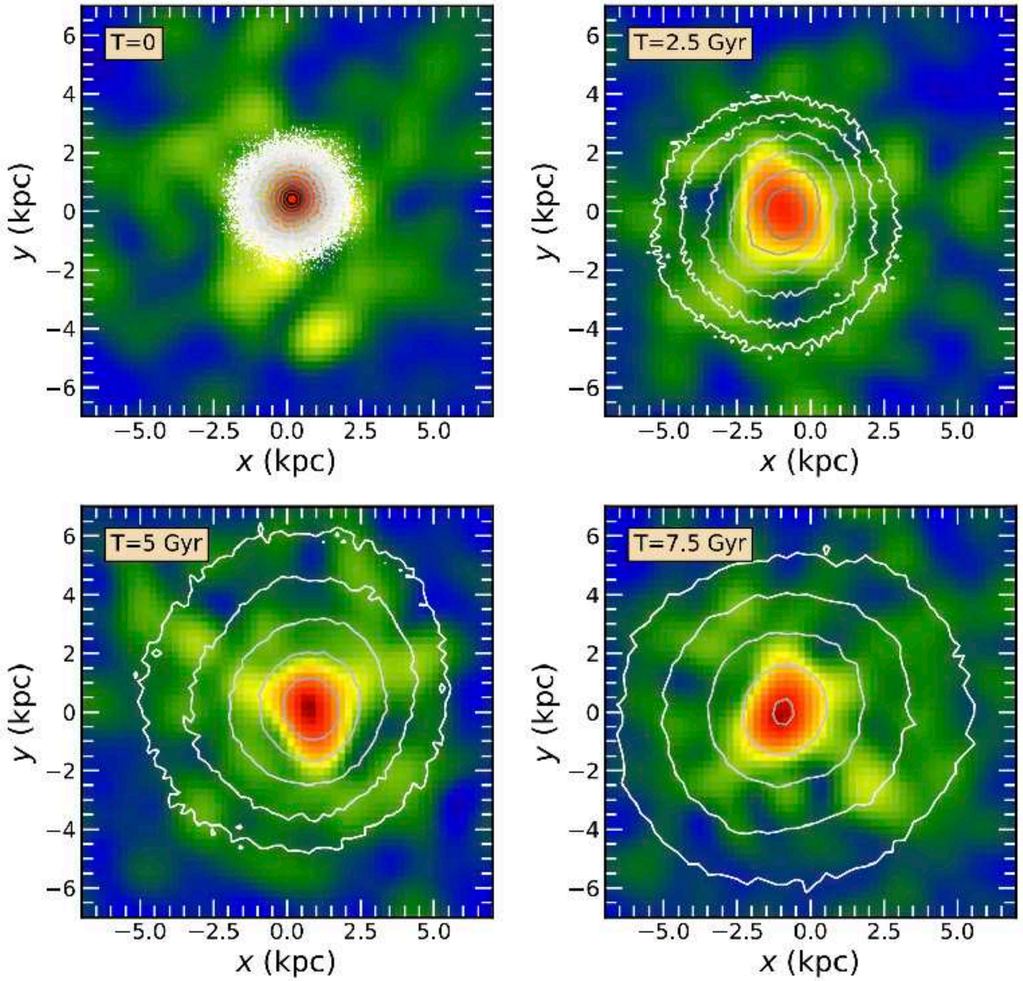
Neutral Gas Content

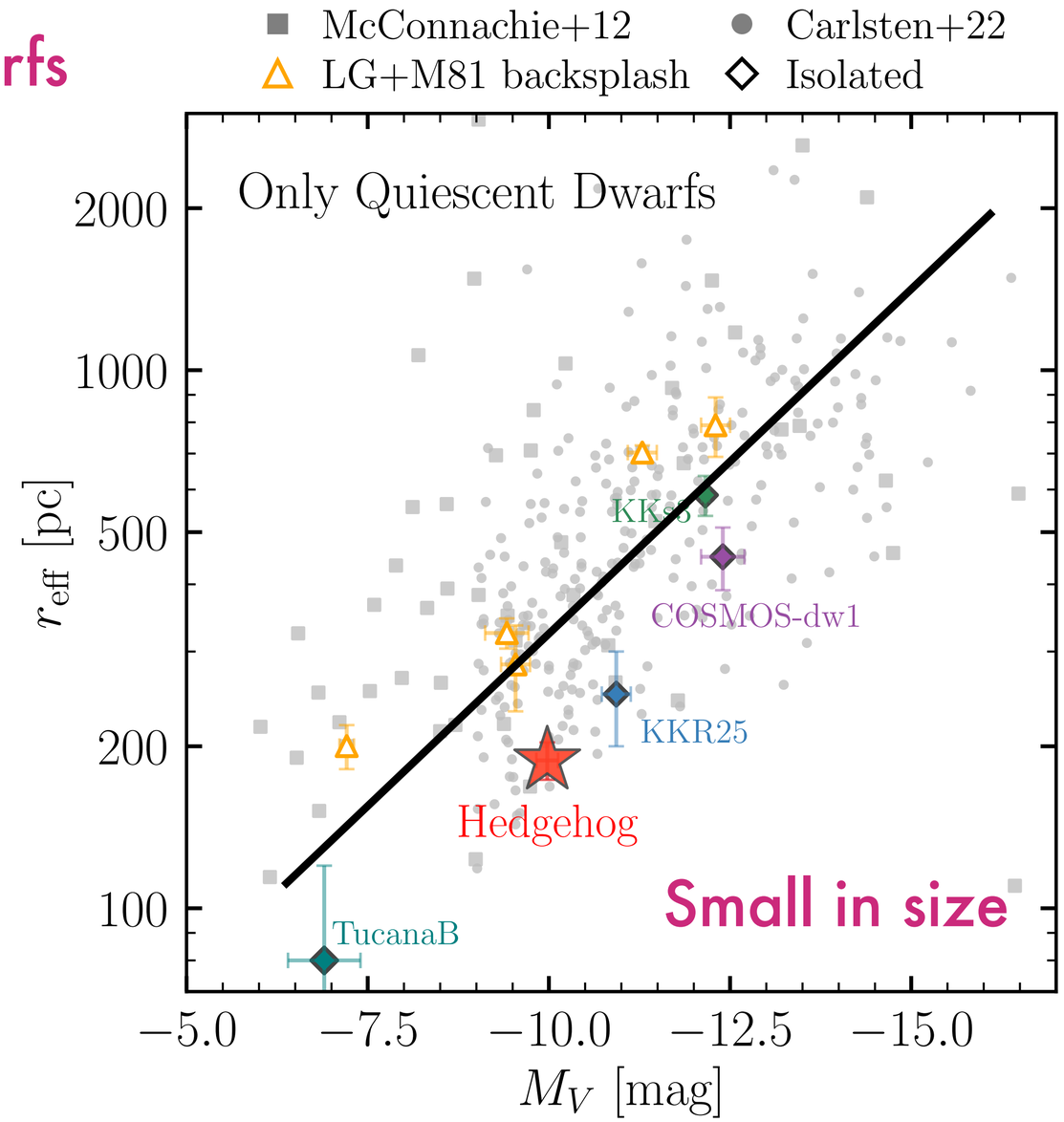




Implication for Fuzzy Dark Matter

Fuzzy DM will puff up isolated old dwarfs





Chowdhury, van den Bosch et al. (2023) $M_\star \approx 10^6\, M_\odot$