The Faint End of the Galaxy-Halo Connection

Ethan Nadler

KITP GalEvo 2023

1/27/2023
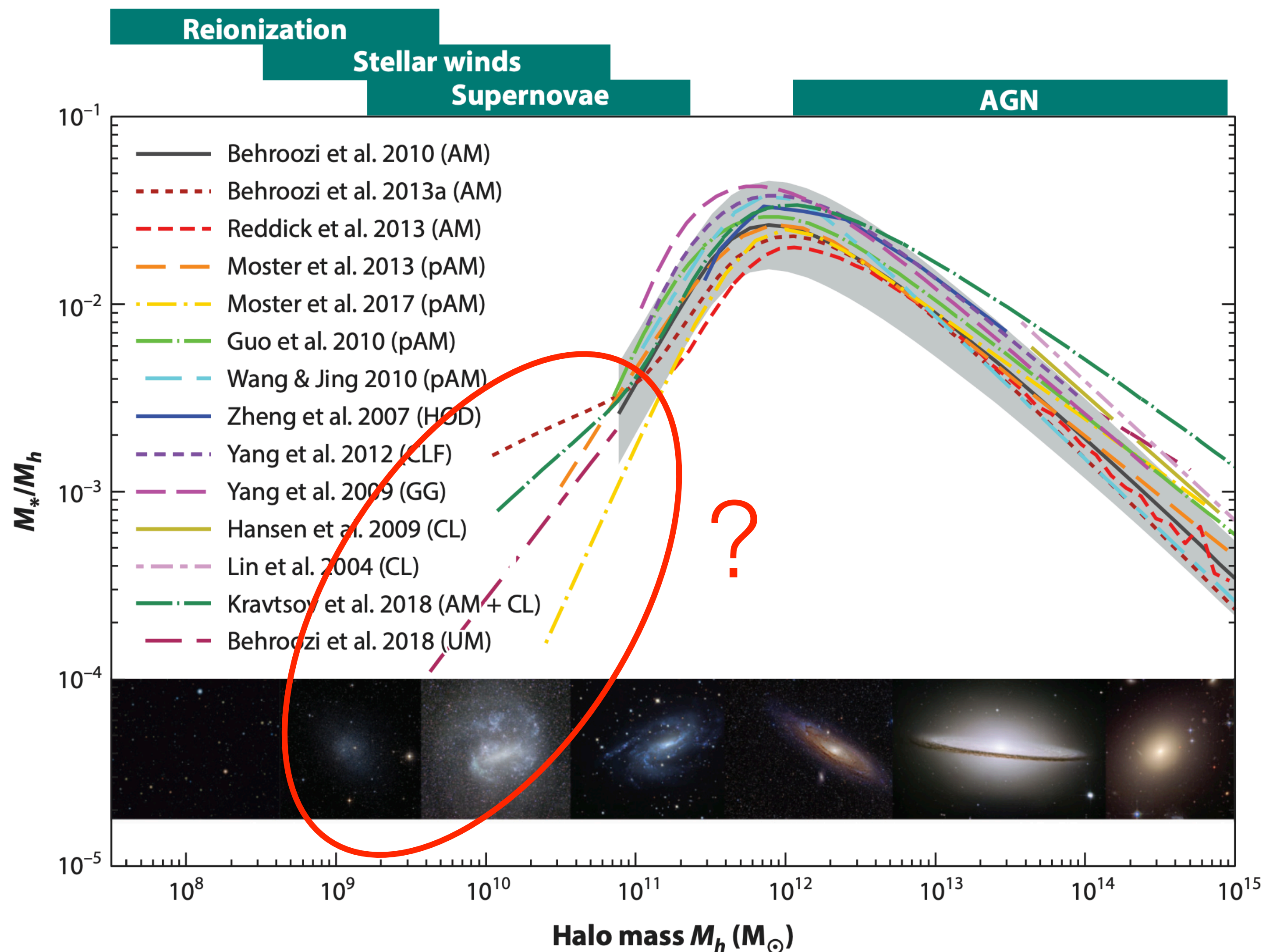
CARNEGIE SCIENCE
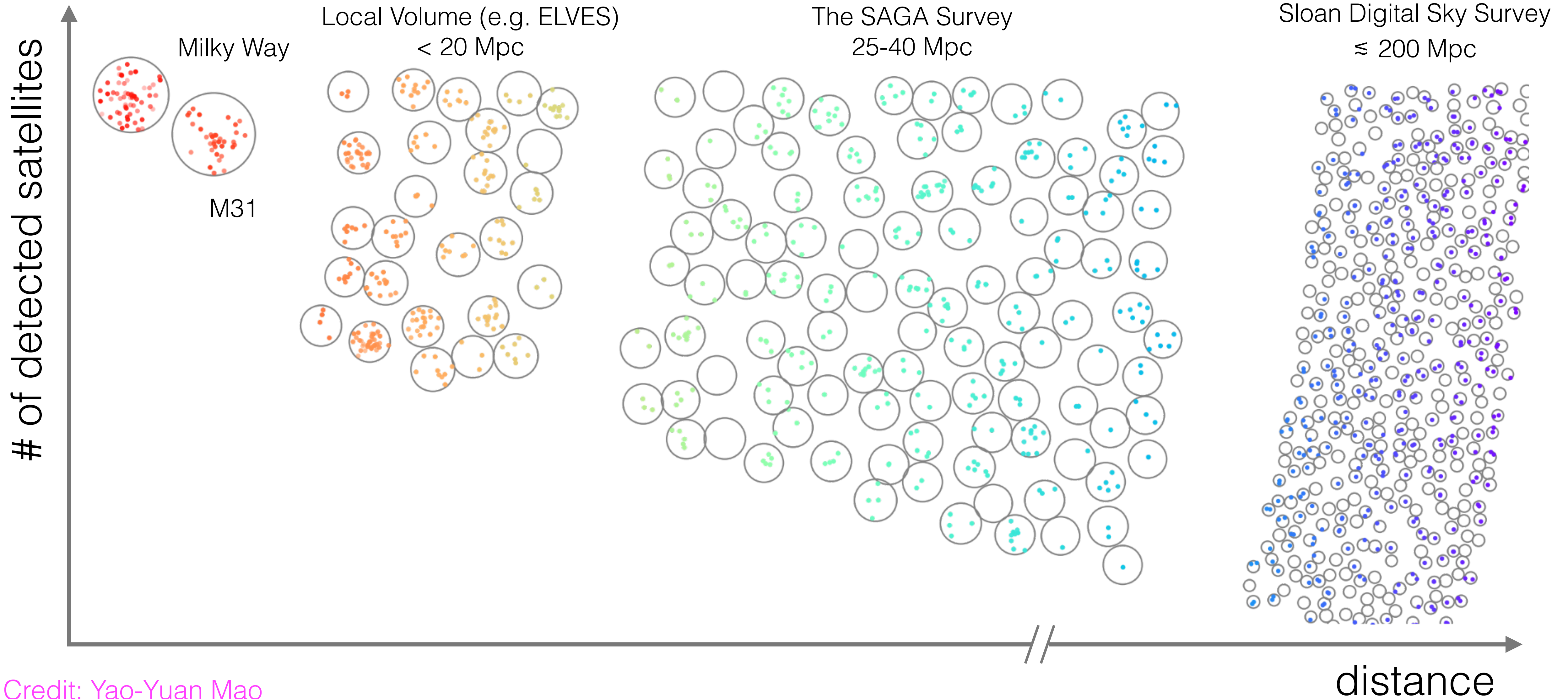
USC University of Southern California

Key Questions

- What is the relation between halo and dwarf galaxy properties?

- Does scatter in stellar mass at fixed halo mass grow at the faint end?

- What fraction of low-mass halos host galaxies? Where is the cutoff?

- Below what halo mass is quenching primarily driven by reionization?

- Is H_2 cooling required to explain the properties of known ultra-faint dwarfs?

Reionization

Stellar winds

Supernovae

AGN

Legend:
- Behroozi et al. 2010 (AM)
- Behroozi et al. 2013a (AM)
- Reddick et al. 2013 (AM)
- Moster et al. 2013 (pAM)
- Moster et al. 2017 (pAM)
- Guo et al. 2010 (pAM)
- Wang & Jing 2010 (pAM)
- Zheng et al. 2007 (HOD)
- Yang et al. 2012 (CLF)
- Yang et al. 2009 (GG)
- Hansen et al. 2009 (CL)
- Lin et al. 2004 (CL)
- Kravtsov et al. 2018 (AM + CL)
- Behroozi et al. 2018 (UM)

Axis labels: M_*/M_h (vertical), Halo mass M_h ($M_\odot$) (horizontal)

Wechsler & Tinker 2018

Current Census of the Faintest Galaxies

# of detected satellites

Milky Way

M31

Local Volume (e.g. ELVES)
< 20 Mpc

The SAGA Survey
25-40 Mpc

Sloan Digital Sky Survey
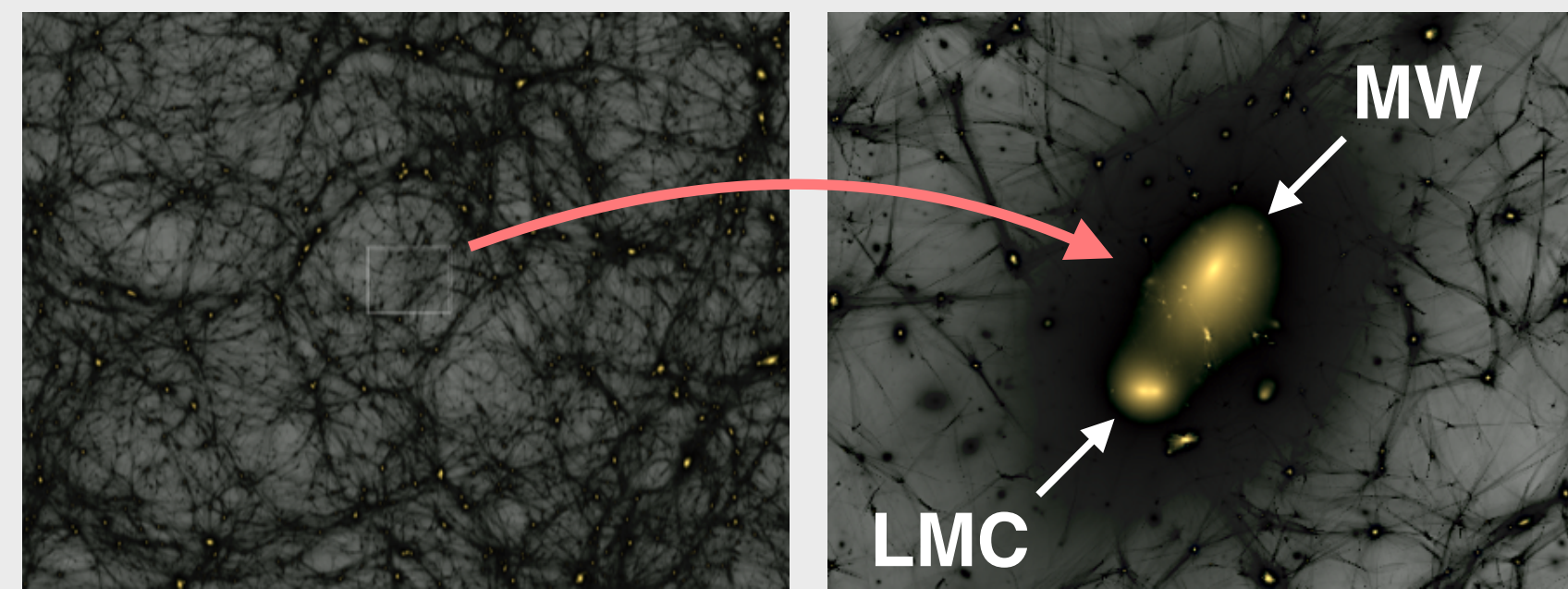≲ 200 Mpc
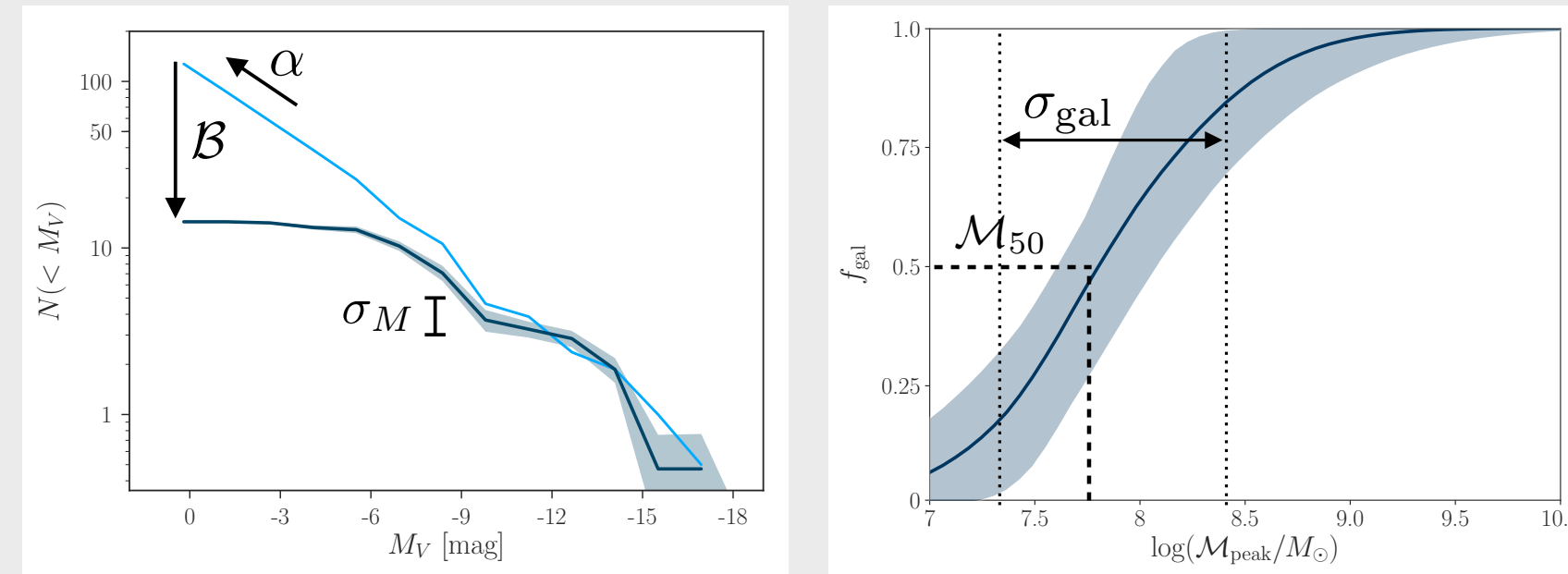
distance

Credit: Yao-Yuan Mao

Empirically Modeling the Faint End

Theoretical uncertainties parameterized and fit to the data!

Physical Ingredient	Assumptions	Parameterization	Free Parameter?
Satellite Luminosities	Abundance match to GAMA survey	Non-parametric	*No*
	Extrapolate luminosity function	Faint-end slope α	**Yes** (α is free)
	Lognormal ($M_V \vert V_{\rm peak}$) distribution	Constant scatter σ_M	**Yes** (σ_M is free)
	Smooth galaxy formation efficiency	$f_{\rm gal} \equiv \frac{1}{2} \left[1 + (\frac{\mathcal{M}_{\rm peak} - \mathcal{M}_{50}}{\sqrt{2}\sigma_{\rm gal}}) \right]$	**Yes** ($\mathcal{M}_{50}, \sigma_{\rm gal}$ are free)
Satellite Sizes	Kravtsov (2013) galaxy size model	$r_{1/2} \equiv \mathcal{A} \, (R_{\rm vir}/R_0)^n$	**Yes** ($\mathcal{A}, n$ are free)
	Lognormal ($r'_{1/2} \vert R_{\rm vir}$) distribution	Constant scatter σ_R	**Yes** (σ_R is free)
	Size reduction set by stripping	$r'_{1/2} \equiv r_{1/2} \, (V_{\rm max}/V_{\rm acc})^\beta$	*No* ($\beta = 0$)
Baryonic Effects	Nadler et al. (2018) disruption model	$p_{\rm disrupt} \to p_{\rm disrupt}^{1/\mathcal{B}}$	**Yes** ($\mathcal{B}$ is free)
Orphan Satellites	Correspond to disrupted subhalos	None	*No*
	NFW host + dynamical friction	$\ln \Lambda = -\ln(m_{\rm sub}/M_{\rm host})$	*No*
	Stripping after pericentric passages	$\dot{m}_{\rm sub} \sim -\frac{m_{\rm sub}}{\tau_{\rm dyn}} \left(\frac{m_{\rm sub}}{M_{\rm host}}\right)^{0.07}$	*No*
	$p_{\rm disrupt}$ set by time since accretion	$p_{\rm disrupt} \equiv (1 - a_{\rm acc})^{\mathcal{O}}$	*No* ($\mathcal{O} = 1$)

Markov Chain Monte Carlo

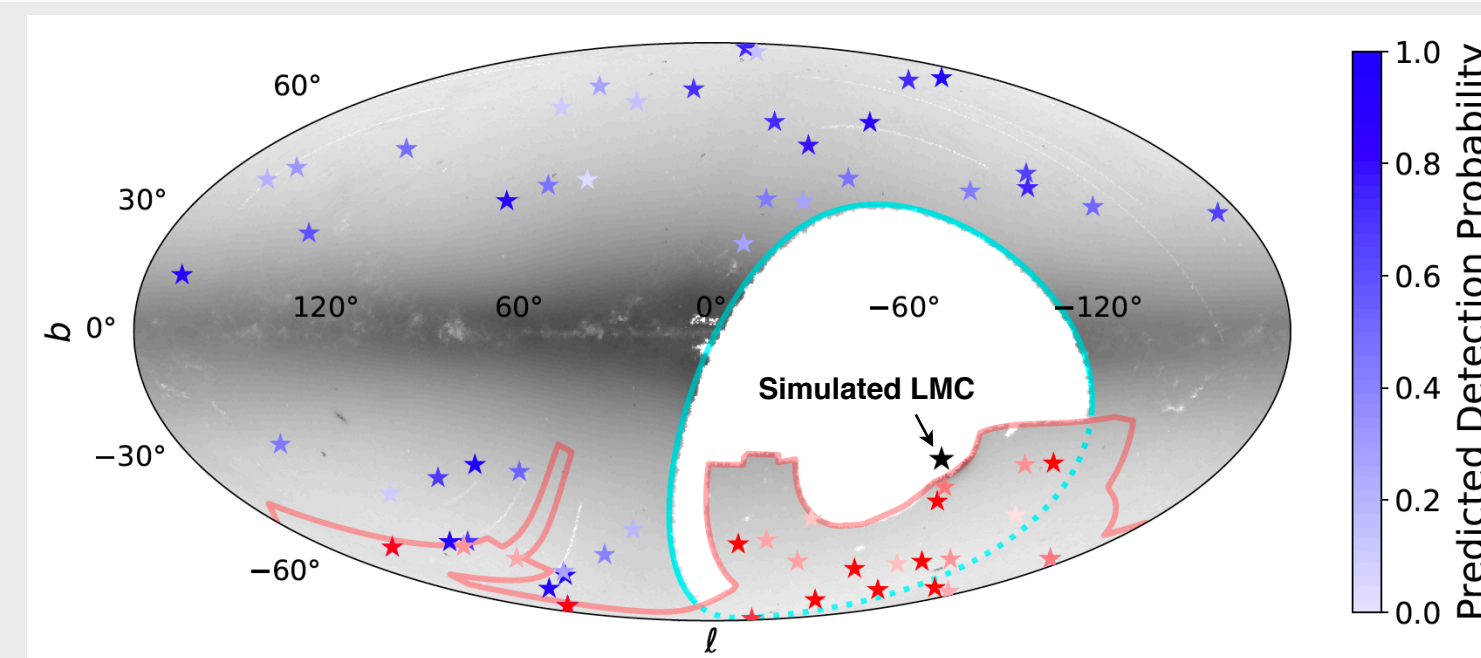**1. Resimulate Milky Way-like halos from large cosmological volume.**

MW

LMC

2. Paint satellite galaxies onto subhalos using galaxy—halo model.

α

$\mathcal{B}$

$N(<M_V)$

σ_M

M_V [mag]

$f_{\rm gal}$

$\sigma_{\rm gal}$

$\mathcal{M}_{50}$

$\log(\mathcal{M}_{\rm peak}/M_\odot)$

3. Apply observational selection functions based on imaging data.

60°

30°

b 0°

120° 60° 0° −60° −120°

−30°

−60°

ℓ

Simulated LMC

Predicted Detection Probability

4. Calculate likelihood of observed satellites given galaxy—halo connection parameters.

DES

Observed
Predicted

dN/dM_V

M_V [mag]

PS1

Observed
Predicted

dN/dM_V

M_V [mag]

Empirically modeling the Milky Way satellite population

• Calibrate halo abundances and properties on simulations of MW analogs with realistic LMCs and merger histories

• Model satellite detectability as a function of luminosity, size, and 3-d position

• Probabilistically infer the faint-end galaxy-halo connection (priors informed by brighter systems and hydrodynamic simulations)

$\alpha = -1.430^{+0.020}_{-0.015}$

$\sigma_M = 0.004^{+0.093}_{-0.000}$

$\mathcal{M}_{50} = 7.51^{+0.21}_{-0.00}$

$\mathcal{B} = 0.93^{+0.59}_{-0.33}$

$\sigma_{\text{gal}} = 0.03^{+0.32}_{-0.00}$

$\mathcal{A} = 37^{+36}_{-25}$

$\sigma_{\log R} = 0.63^{+0.28}_{-0.30}$

$n = 1.07^{+0.38}_{-0.57}$

Faint-end slope consistent with GAMA luminosity function

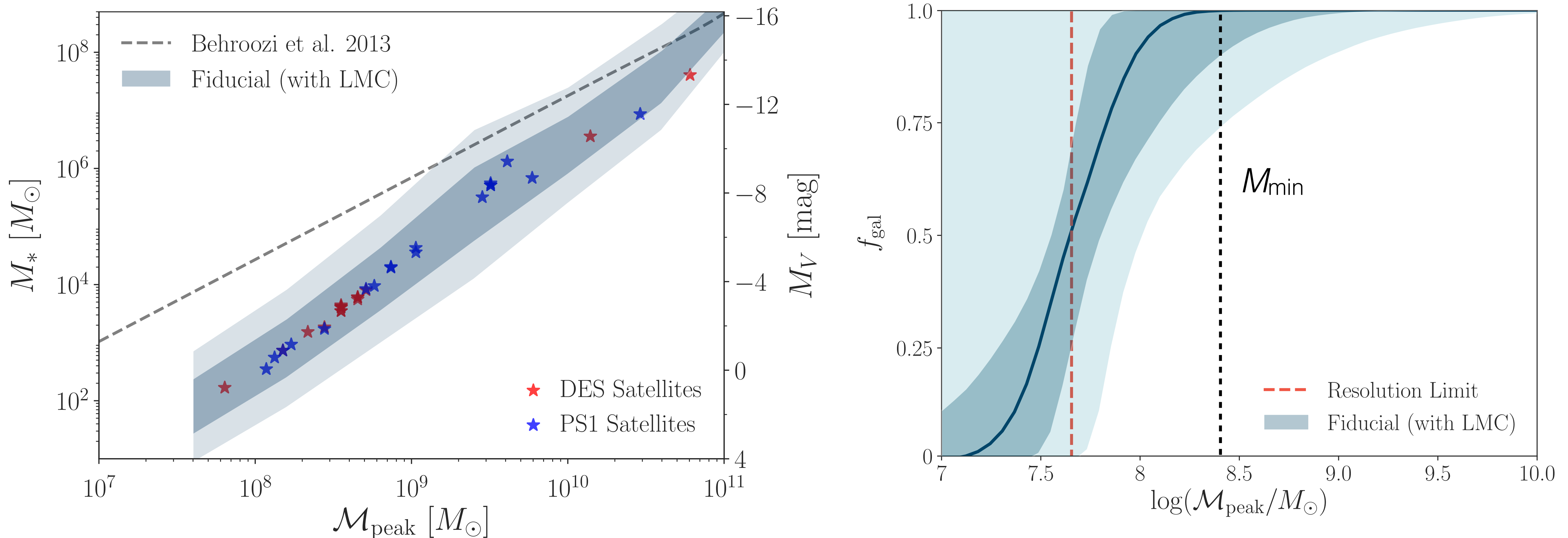Scatter in luminosity at fixed $V_{\text{peak}} < 0.2$ dex (!)

Minimum peak halo mass corresponding to observed MW satellites $< 3 \times 10^8 \, M_\odot$

Satellite disruption consistent with FIRE sims

Galaxy occupation fraction consistent with 100% down to the minimum halo mass

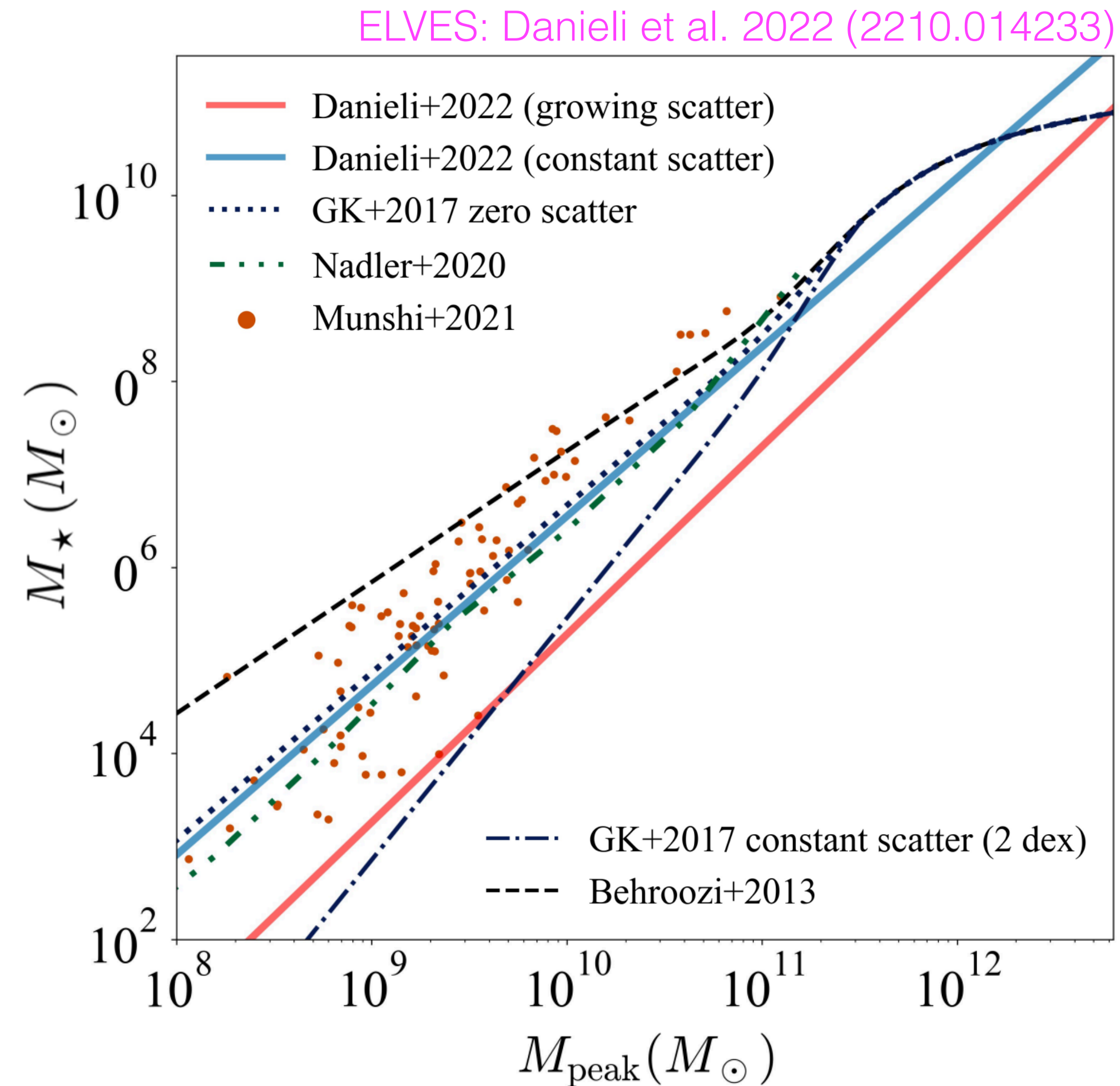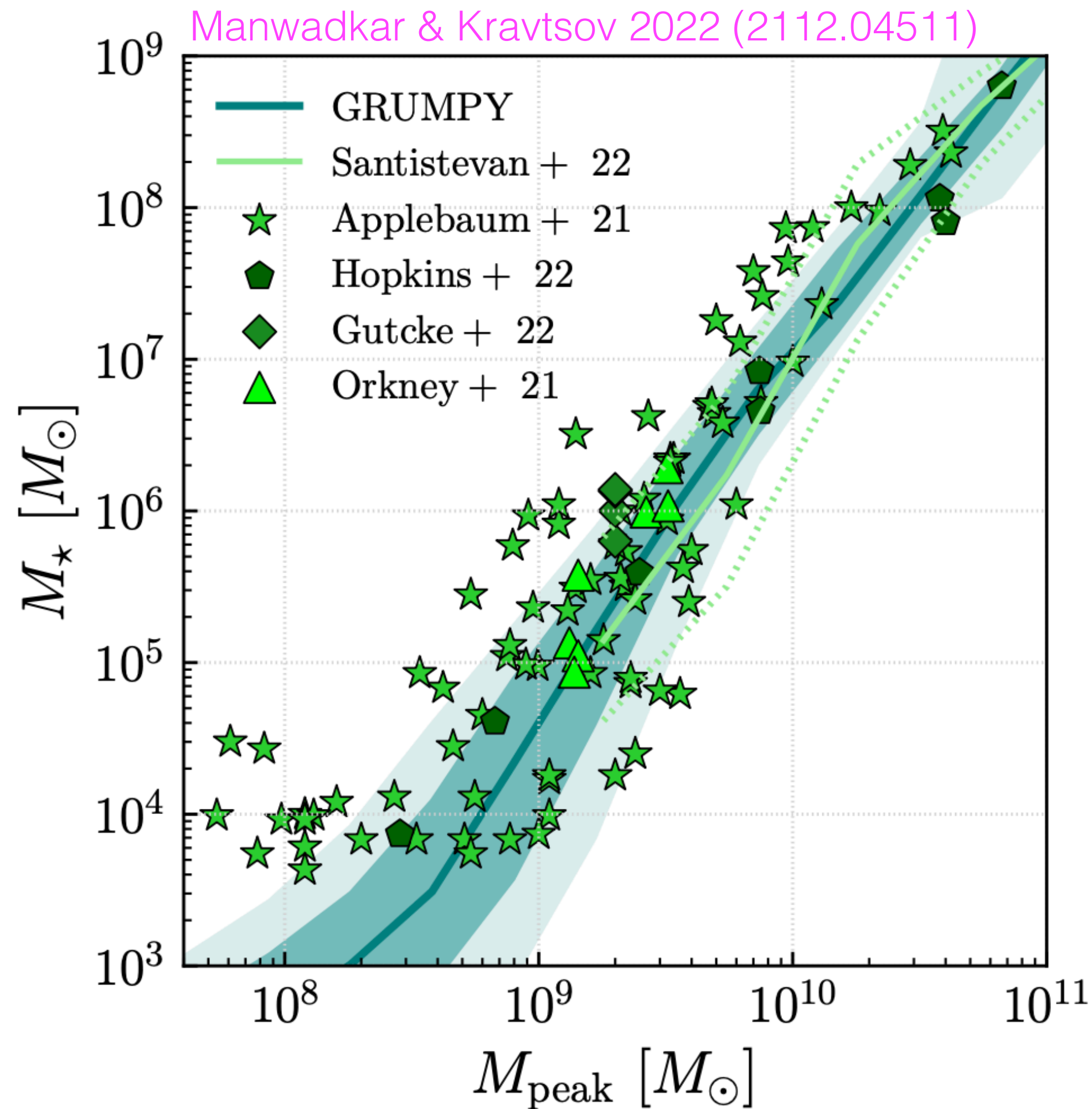Measurements of amplitude, scatter, & slope of galaxy-halo size relation

Faint-End Constraints from Empirical Models

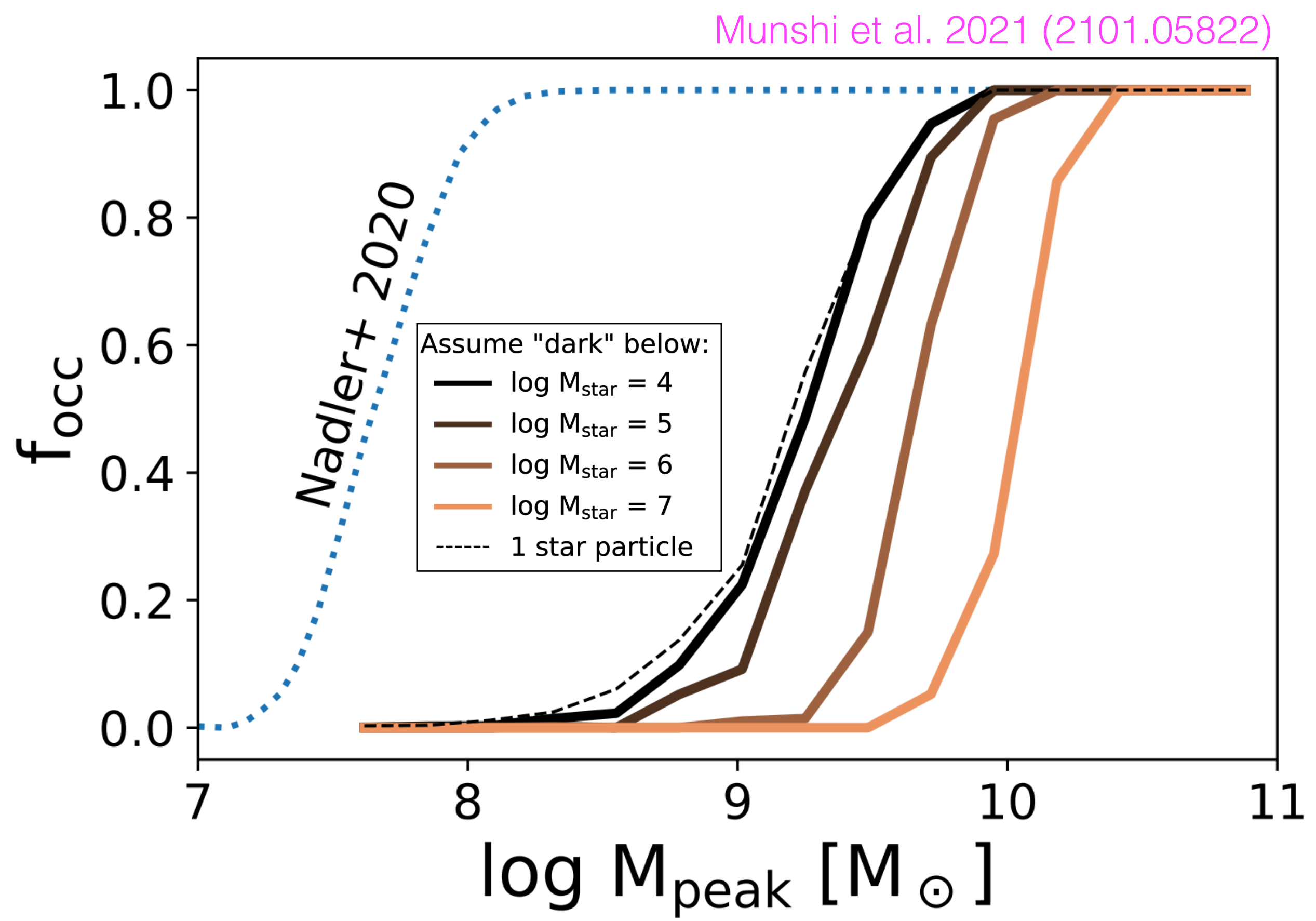Current Milky Way satellite data are consistent with:
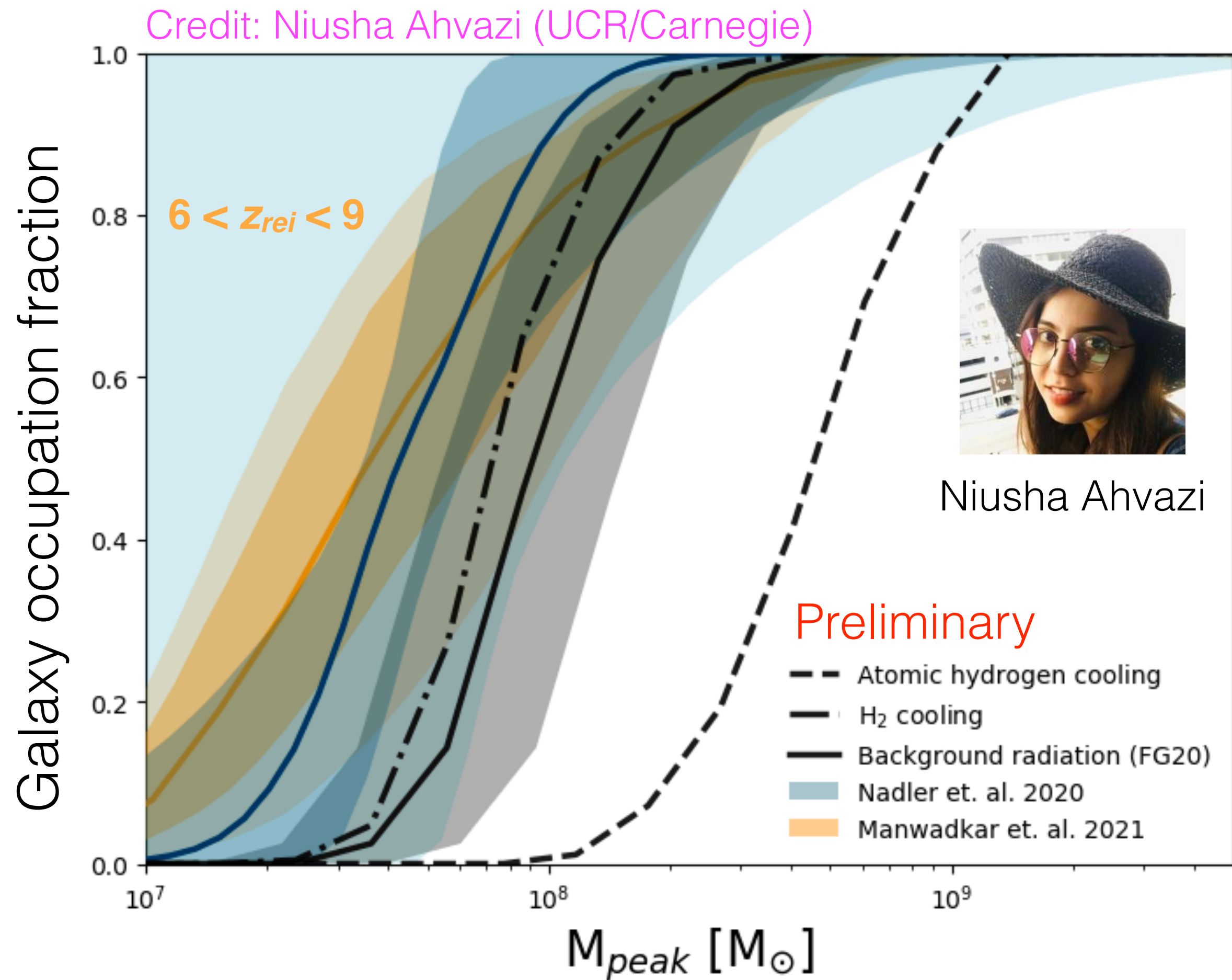
- A power-law faint-end SMHM relation, with a steeper slope than the bright end

- 100% halo occupation down to peak virial masses of $M_{min} \sim 3 \times 10^8$ $M_\odot$

The Faint-End Stellar Mass-Halo Mass Relation

- Semi-analytic models and hydro sims often predict flattening & growing scatter in the SMHM relation
- ELVES and MW-inferred SMHM relations are consistent; mild preference for growing scatter in ELVES

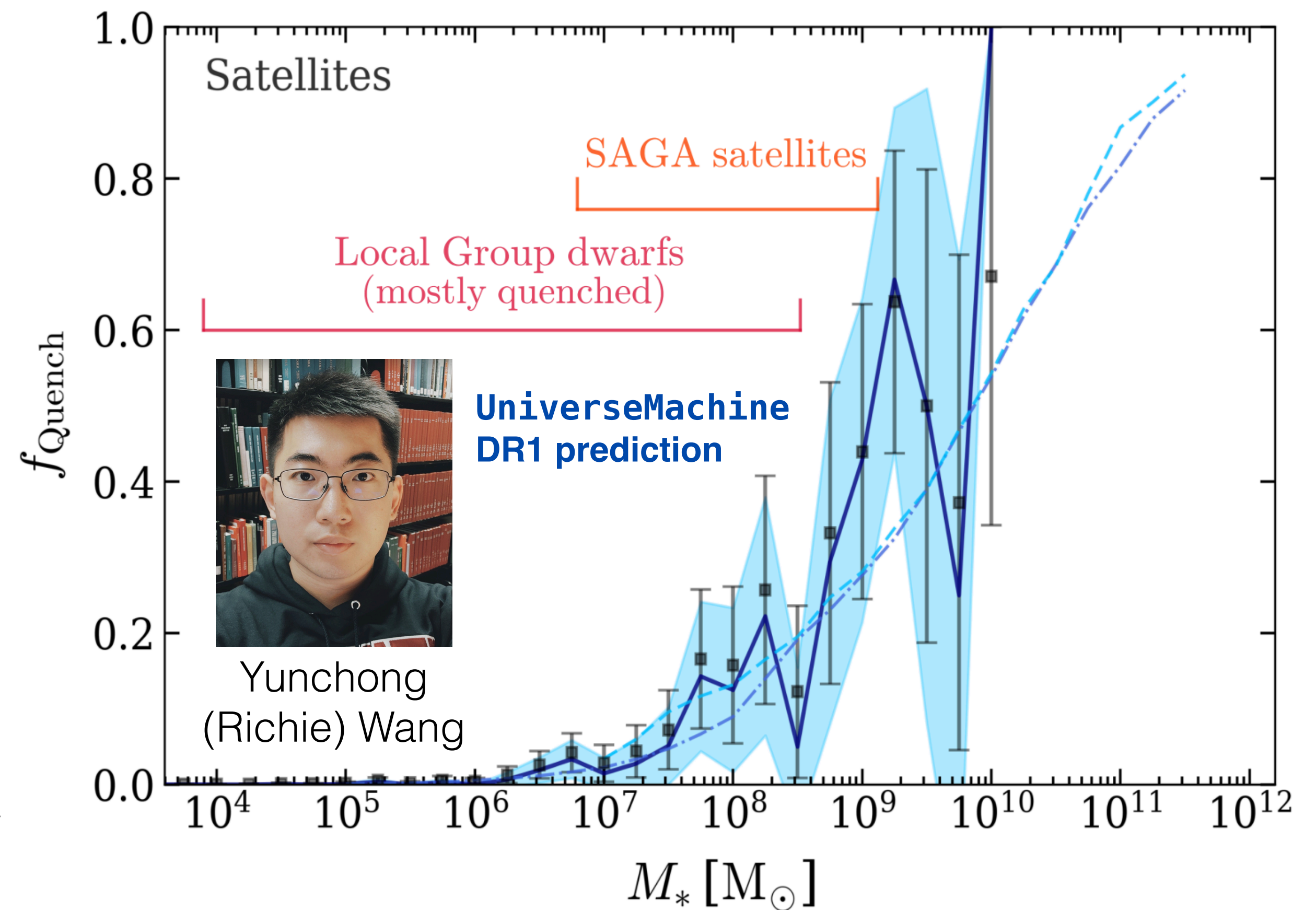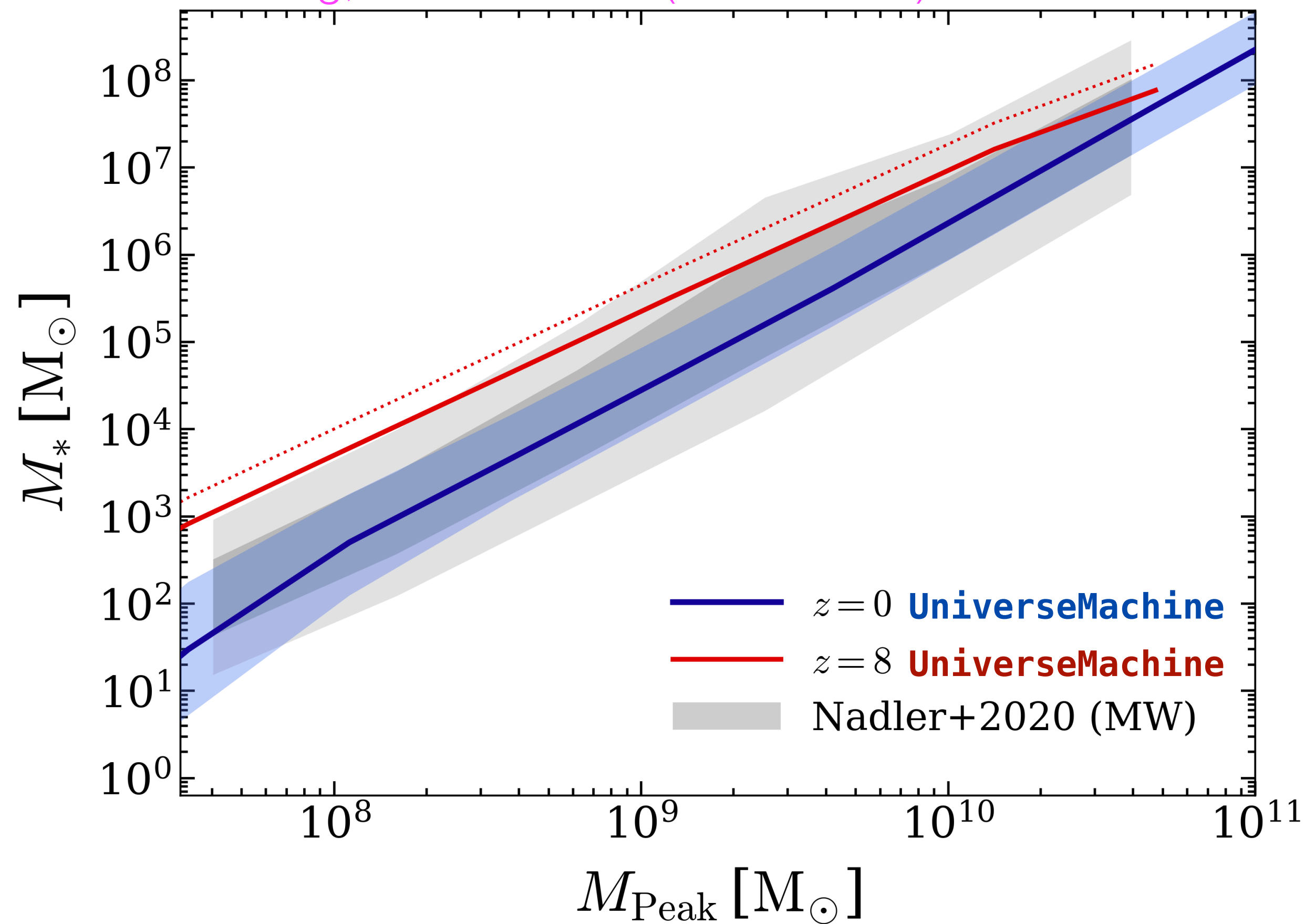# The Galaxy Occupation Fraction

Credit: Niusha Ahvazi (UCR/Carnegie)

$6 < z_{rei} < 9$

Galaxy occupation fraction

M_{peak} [$M_\odot$]

Niusha Ahvazi

Preliminary

- - - Atomic hydrogen cooling
- · - H$_2$ cooling
—— Background radiation (FG20)
Nadler et. al. 2020
Manwadkar et. al. 2021

Munshi et al. 2021 (2101.05822)

f_{occ}

Nadler+ 2020

Assume "dark" below:
—— log M_{star} = 4
—— log M_{star} = 5
—— log M_{star} = 6
—— log M_{star} = 7
- - - 1 star particle

log M_{peak} [$M_\odot$]

- In certain SAMs (e.g., `Galacticus`), H$_2$ cooling is required to fit the inferred galaxy occupation fraction
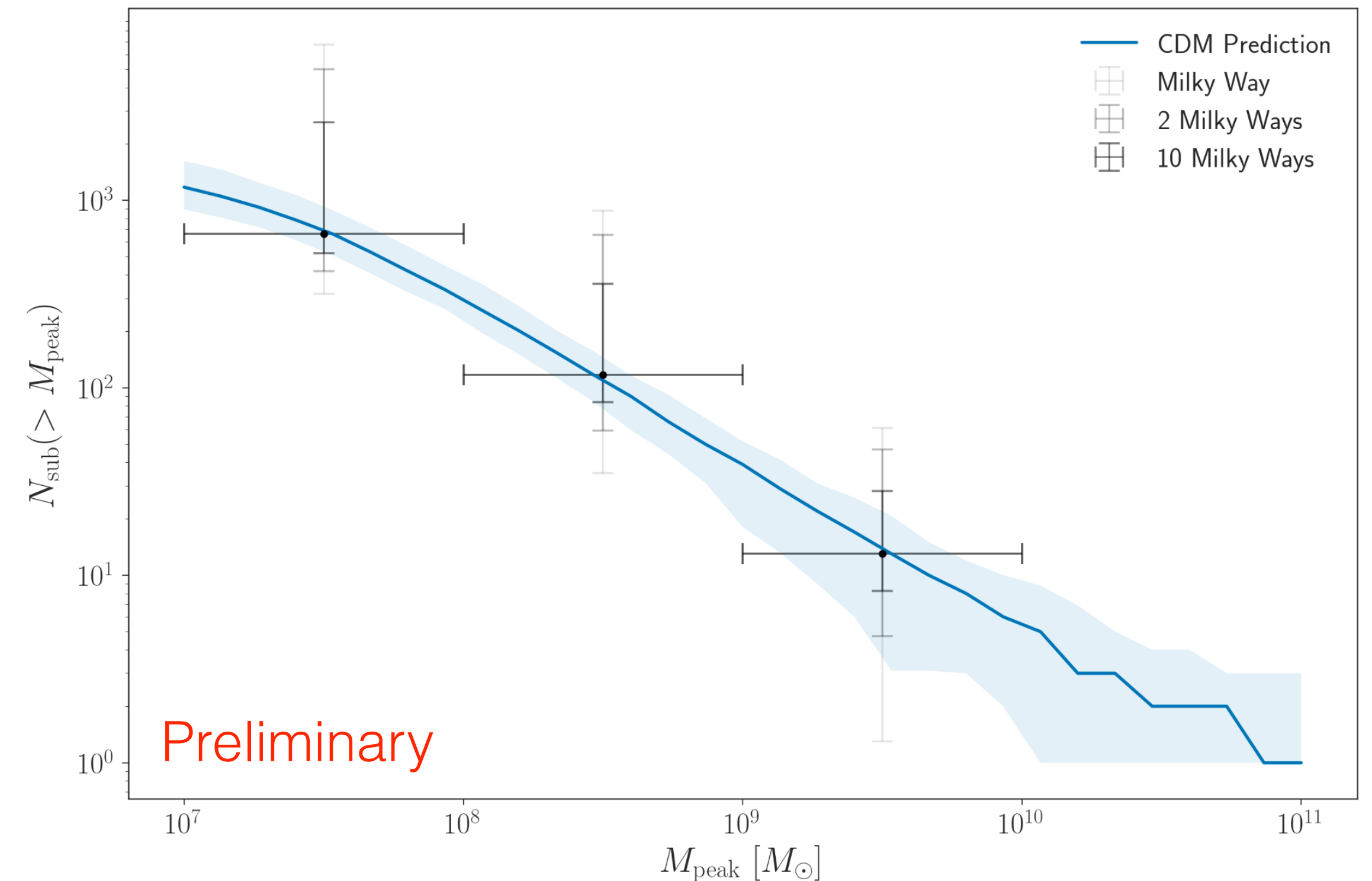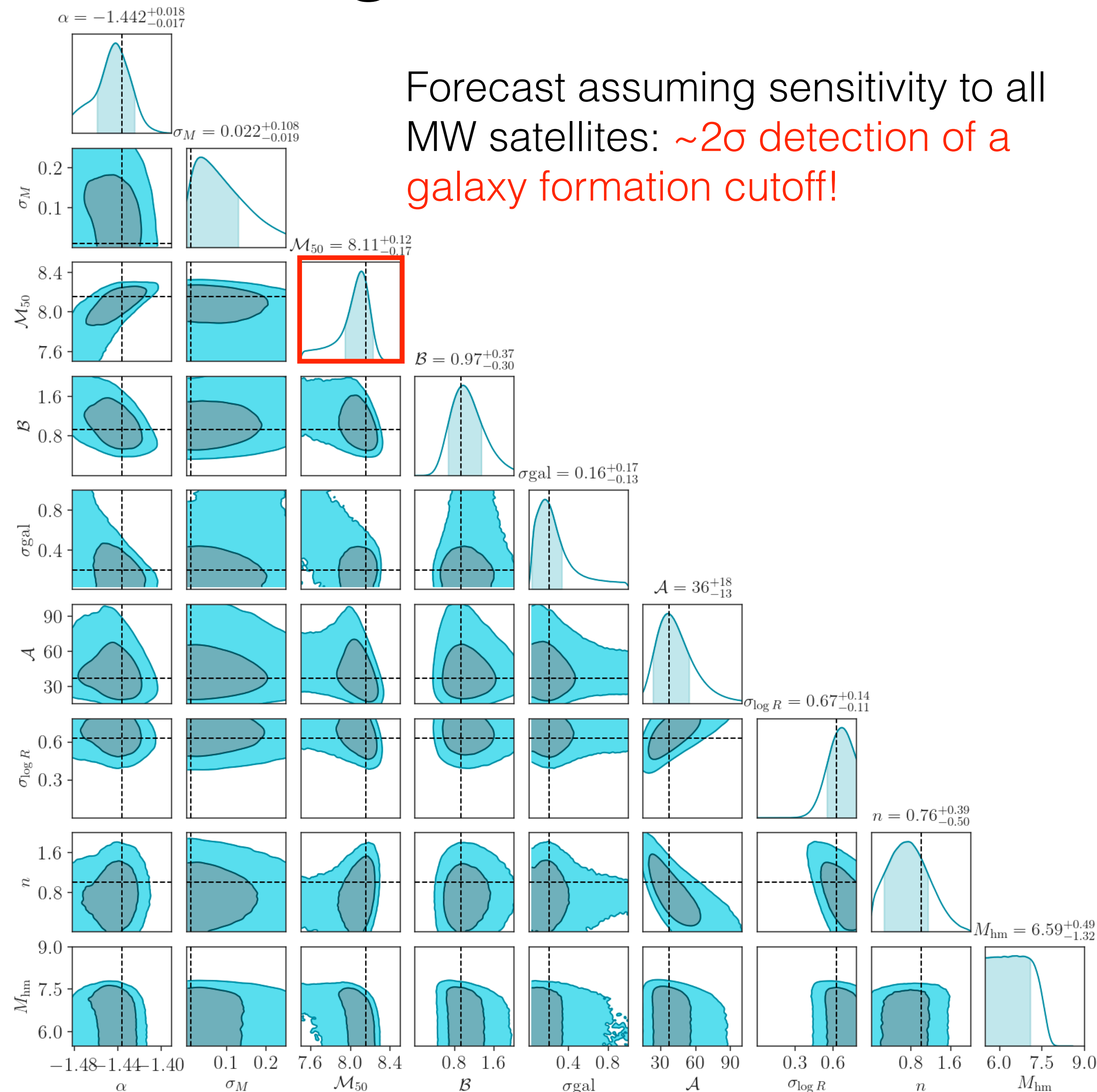- In simulations, the occupation fraction is definition & resolution-dependent; interpret with caution!

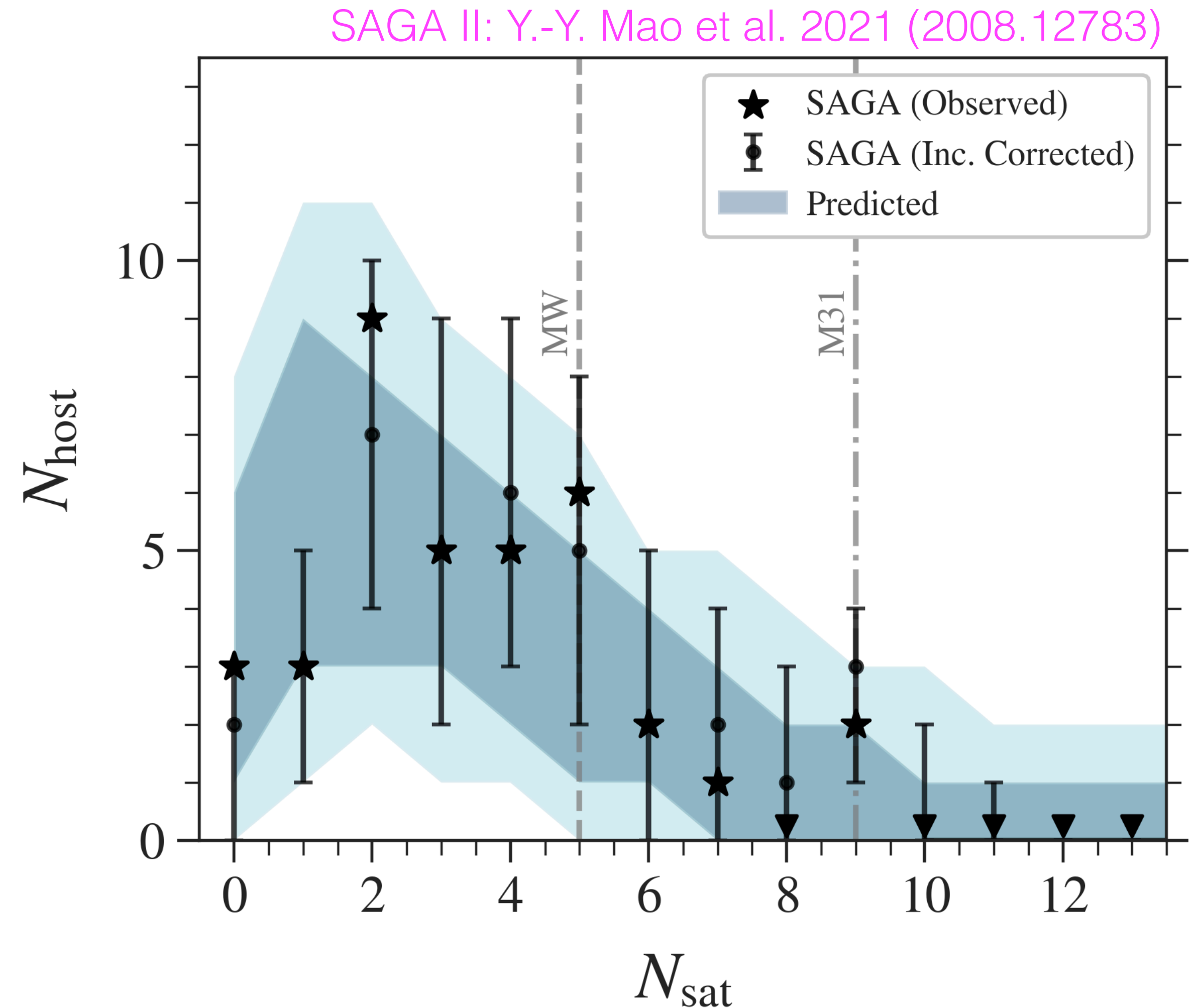# Star Formation History Constraints

Y. Wang, EN et al. 2021 (2102.11876)
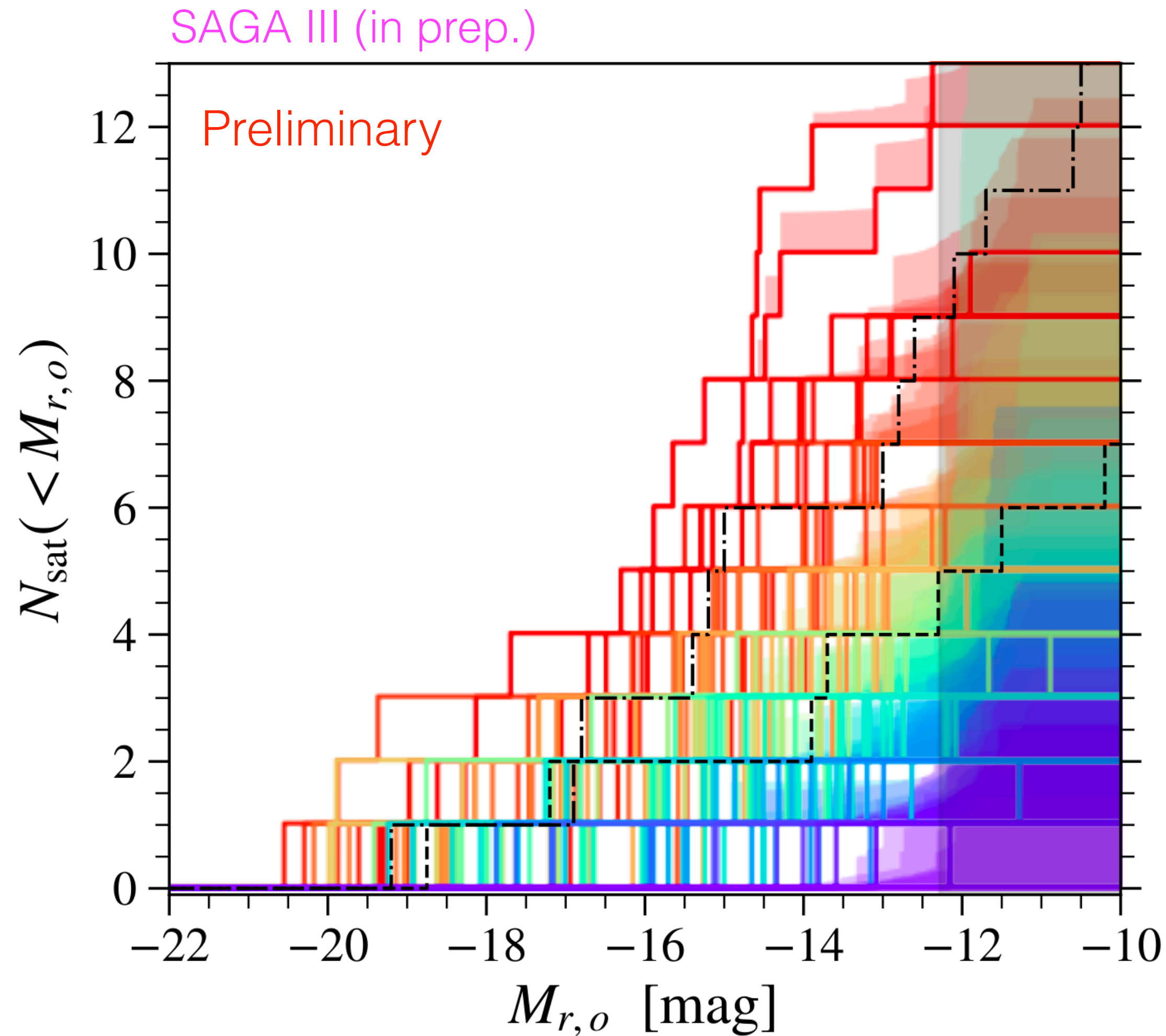
- `UniverseMachine`: an empirical model that connects dark matter accretion to star formation
- Consistent with MW-inferred SMHM, despite lack of low-mass quenching; faint-end calibration in prep.

Looking Forward: Next-Generation Discoveries

Forecast assuming sensitivity to all MW satellites: ~2σ detection of a galaxy formation cutoff!

Preliminary

- Complete observations of ~10 MW analog satellite populations are needed to overcome host-to-host subhalo mass function scatter

- Rubin and Roman dwarf observations will provide crucial complementary information

Looking Forward: The Milky Way in Context

- SAGA III observations of ~100 MW-analog satellite systems, down to $M_\star \sim 10^6\,\mathrm{M_\odot}$, in prep.
- MW-inferred galaxy-halo model is consistent with SAGA II; hints of tension at bright end, as in ELVES

- Are faint-end SMHM relations with **flattening** & **growing scatter** consistent with current data? What future observations most incisively test these predictions?

- How best to measure and mode the **cutoff in galaxy occupation**? Can this be tested outside the Milky Way?

- Can evidence of the need for H_2 **cooling** to form ultra-faints be tested directly?

- Why is the **Local Group quenched fraction** anomalous?

- How does the faint-end galaxy-halo connection vary with **host system** and **environment**?

CARNEGIE SCIENCE

USC University of Southern California