Forecasts for Galaxy Formation and Dark Matter Physics from Dwarf Galaxy Surveys

Ethan Nadler

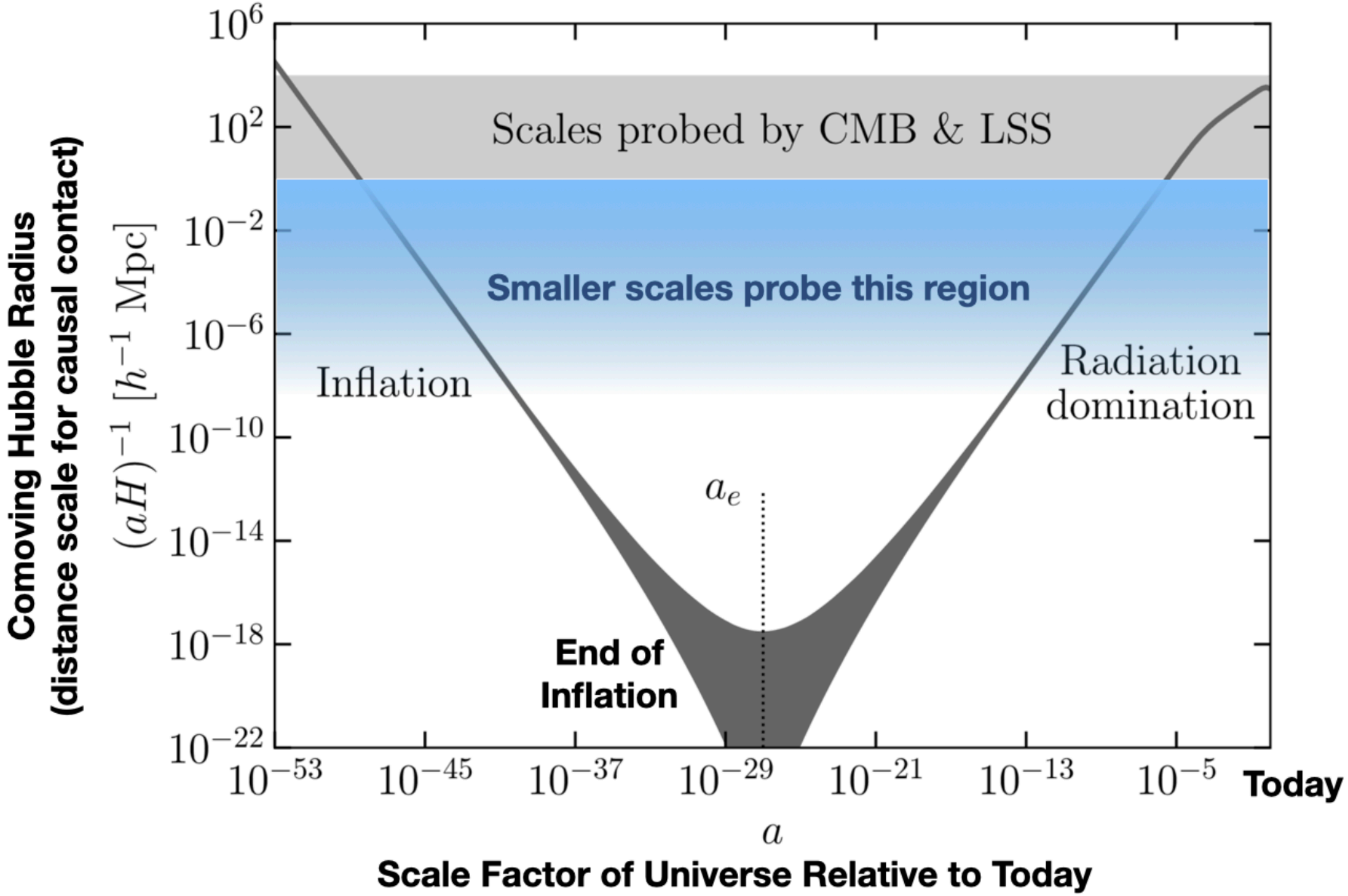
Fundamental Physics from Spectroscopic Surveys

5/8/2024

Carnegie Science

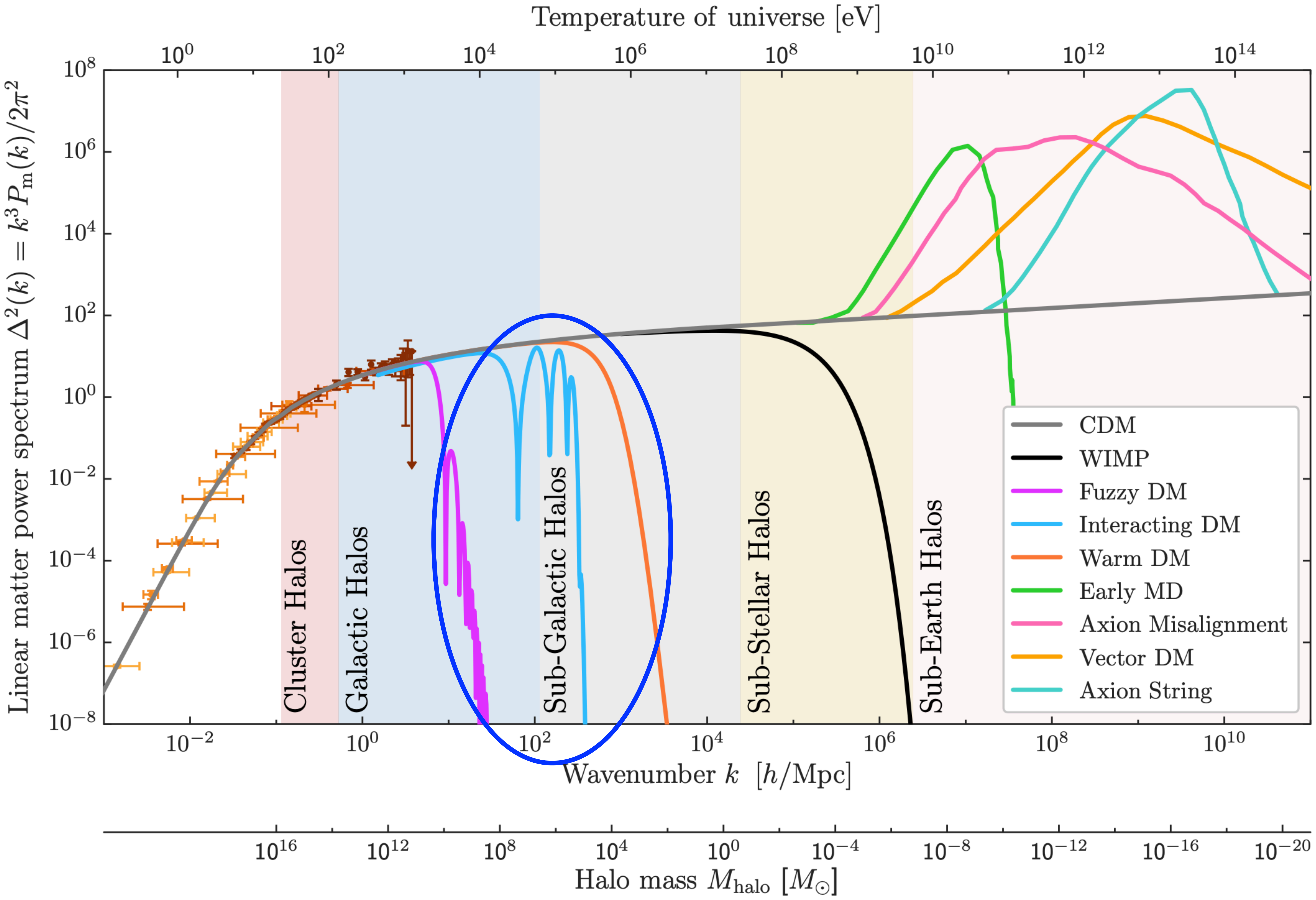
USC

Fundamental Physics on Small Scales



Credit: K. Bechtol

Fundamental Physics on Small Scales



- Dark matter physics affects structure formation throughout cosmic history
- Matter distribution on scales smaller than ~1 Mpc is mostly unconstrained
- New surveys will probe clustering on dwarf and sub-galactic scales

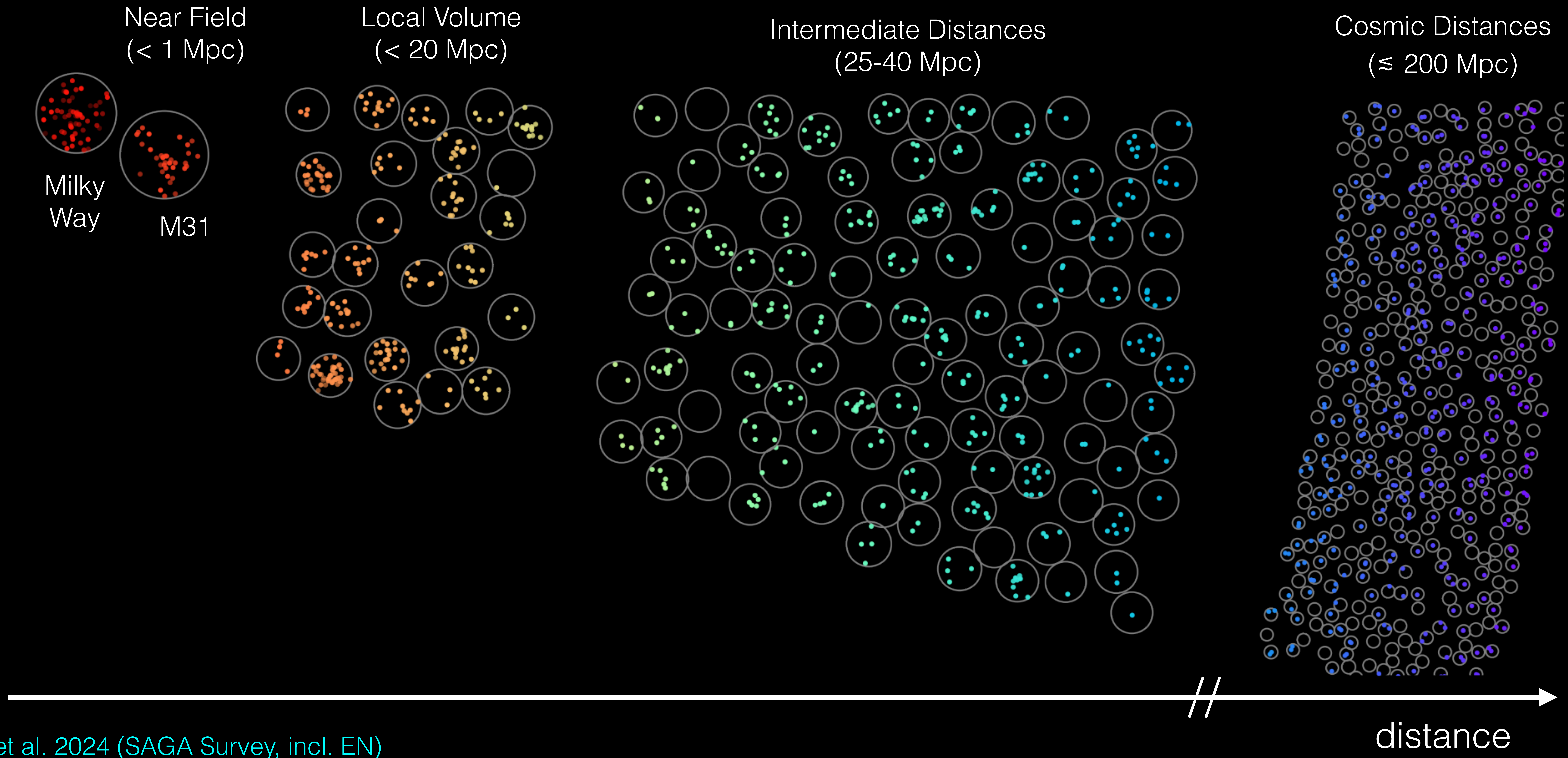
Pathways to Innovation and Discovery in Particle Physics

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Snowmass Cosmic Probes of Dark Matter Report (2209.08215, incl. EN)

Census of the Faintest Galaxies

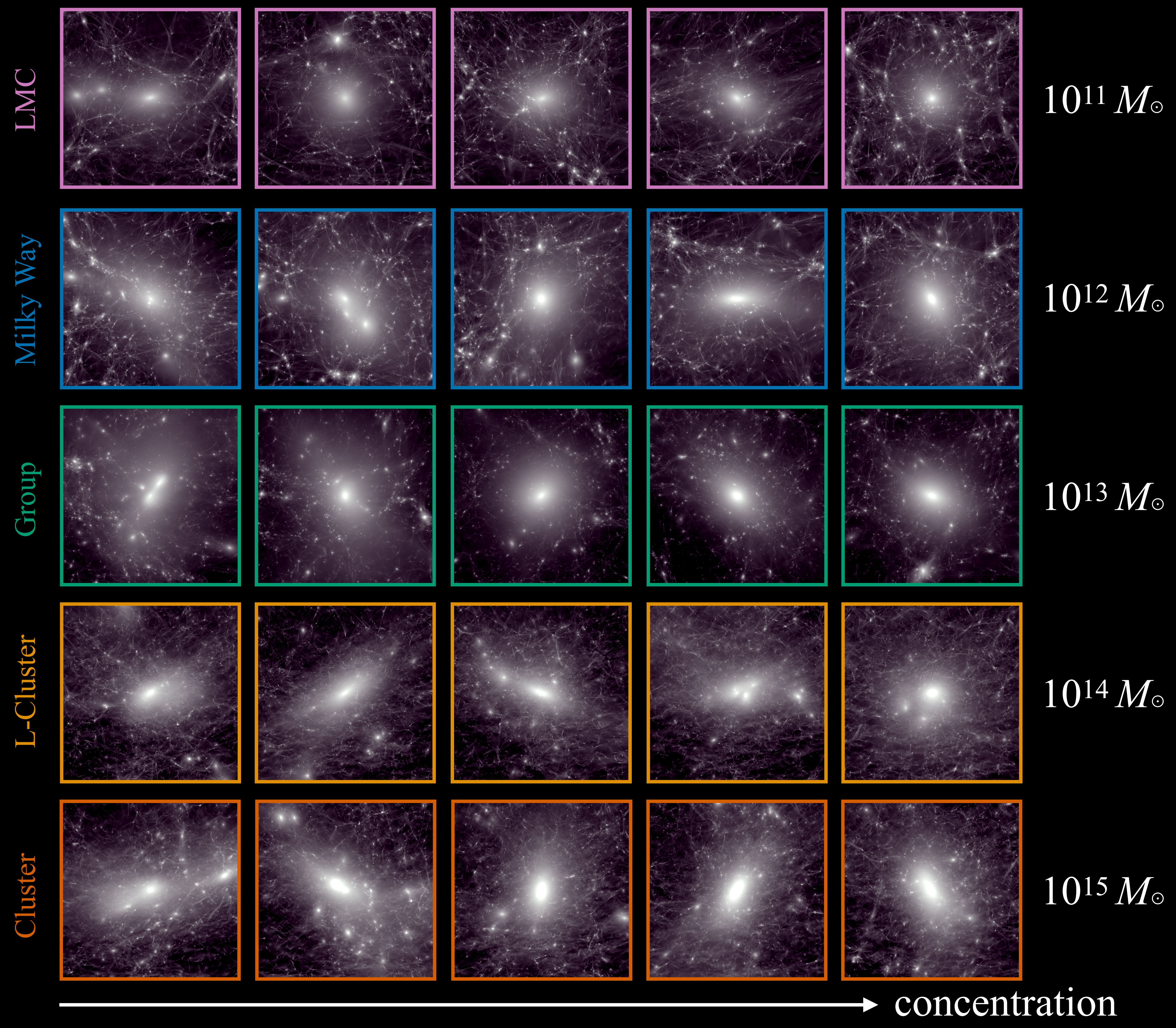


Mao et al. 2024 (SAGA Survey, incl. EN)

Symphony Zoom-in Simulation Suites

- **262** cosmological DMO zoom-in simulations spanning four decades of host halo mass
- Includes the first large suites of **LMC** and **strong lens** analog host halos
- Run with a unified simulation and analysis code pipeline; all data is **publicly available!**

web.stanford.edu/group/gfc/symphony

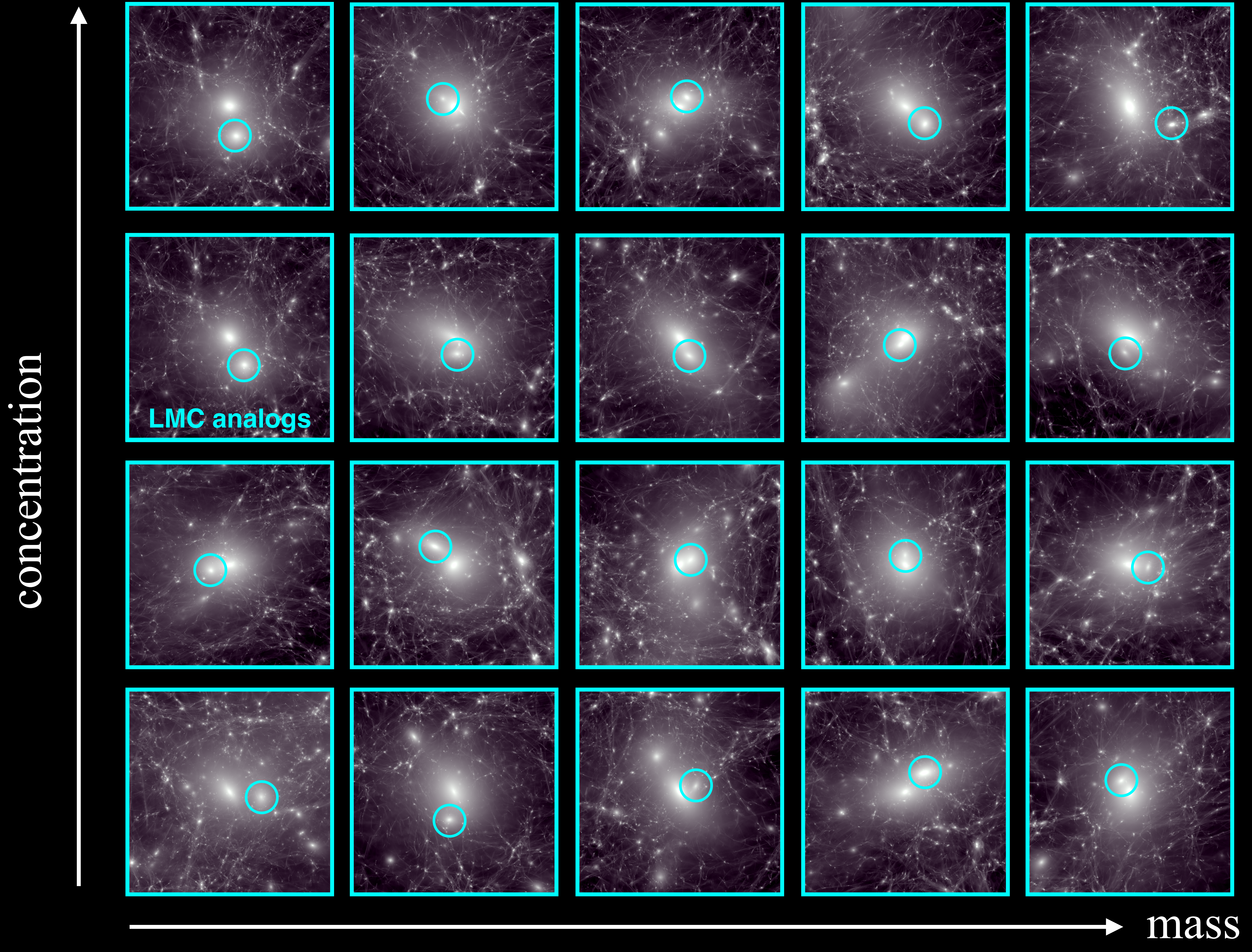


EN et al. 2023 (Symphony Team, 2209.02675)

Milky Way-est Zoom-in Simulations

- 20 high-resolution cosmological zoom-in simulations of Milky Way-like systems
- All realizations include analogs of the LMC and Gaia-Sausage-Enceladus
- Provides high-fidelity predictions for the Milky Way subhalo population in CDM

Deveshi Buch
(Stanford)



Buch, EN, Wechsler, Mao (2404.08043)

Empirically Modeling the Galaxy–Halo Connection

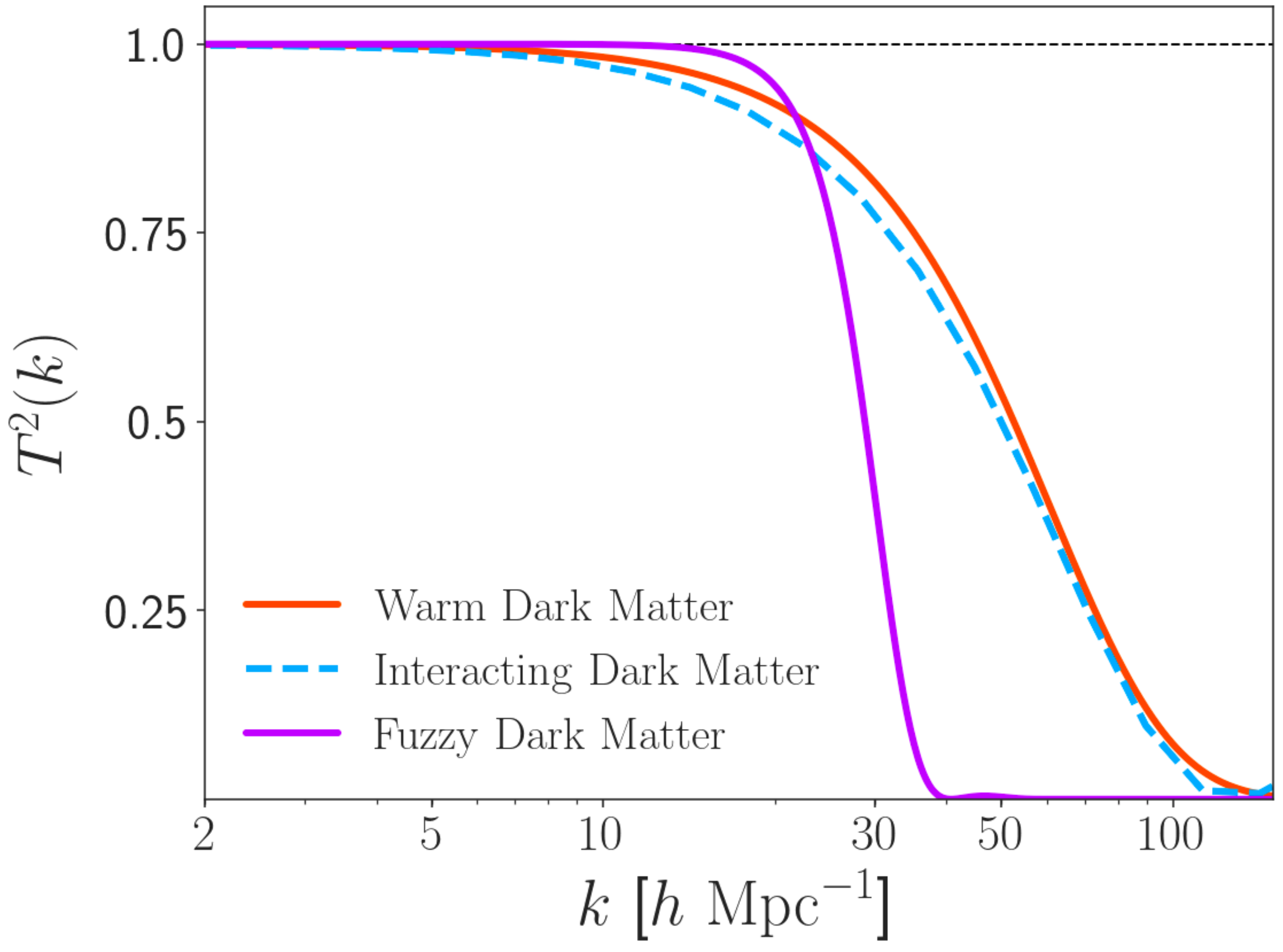
Theoretical uncertainties parameterized and fit to the data:

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	$f_{\rm gal} \equiv \frac{1}{2}\left[1+\left(\frac{\mathcal{M}_{\rm peak}-\mathcal{M}_{50}}{\sqrt{2}\sigma_{\rm gal}}\right)\right]$	**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	$p_{\rm disrupt} \rightarrow p_{\rm disrupt}^{1/\mathcal{B}}$	**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* ($\mathcal{O} = 1$)

EN et al. 2019 (1809.05542), 2020 (1912.03303), 2021 (2008.00022), 2024 (2401.10318)

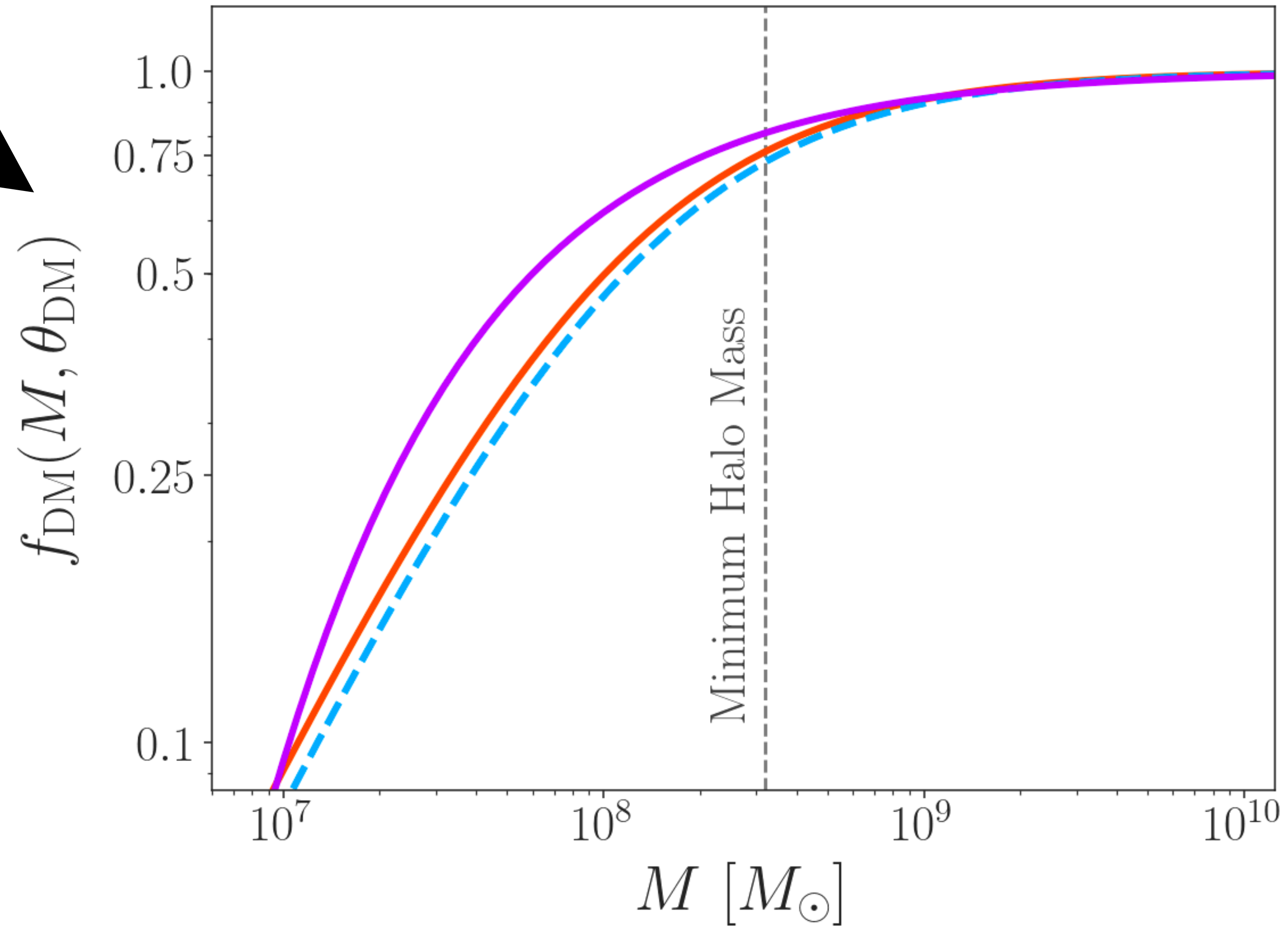
Constraints on Dark Matter Physics

Linear matter power spectrum

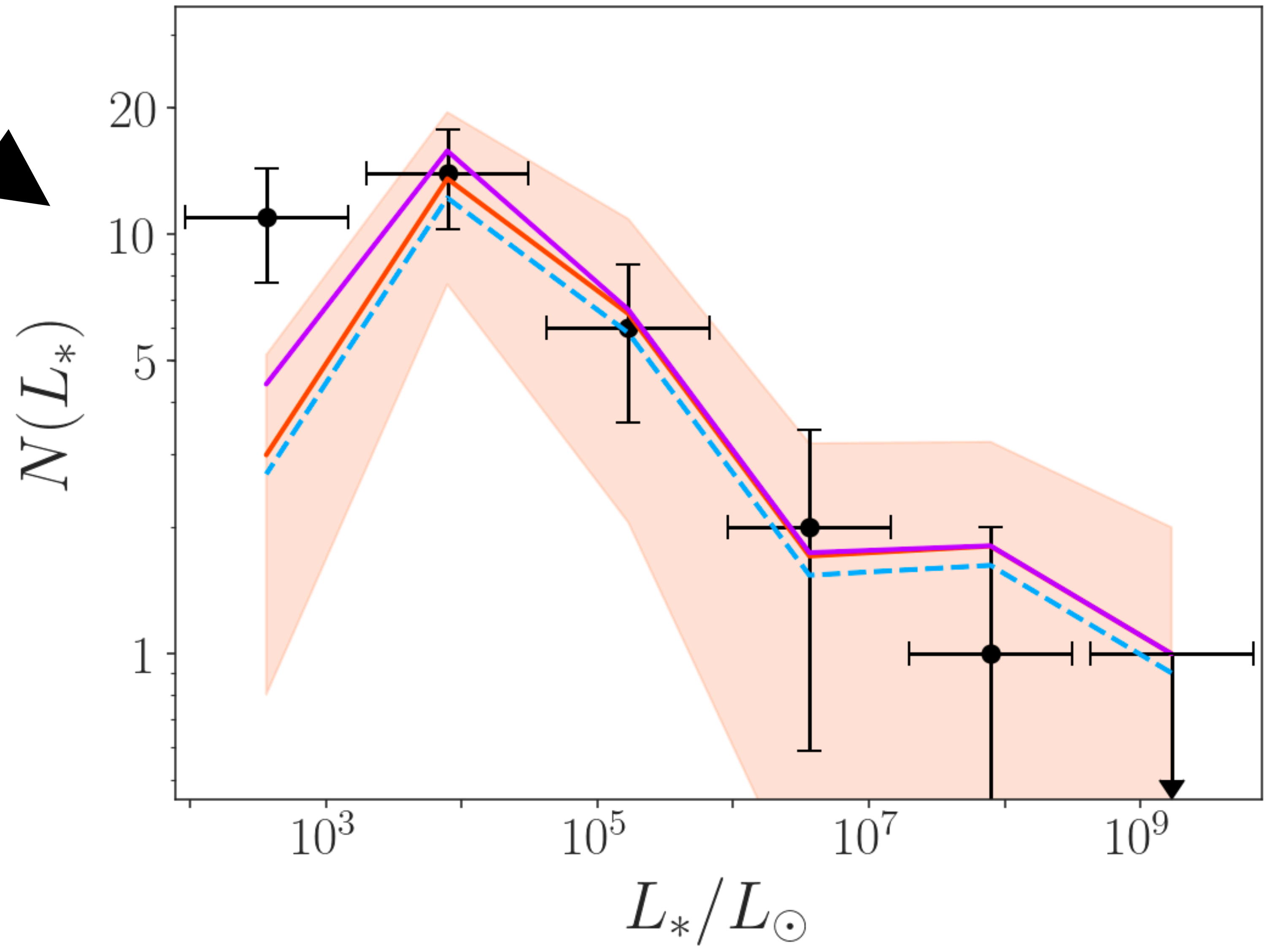


Simultaneously infer subhalo mass function suppression and galaxy-halo connection to constrain dark matter properties

Subhalo mass function



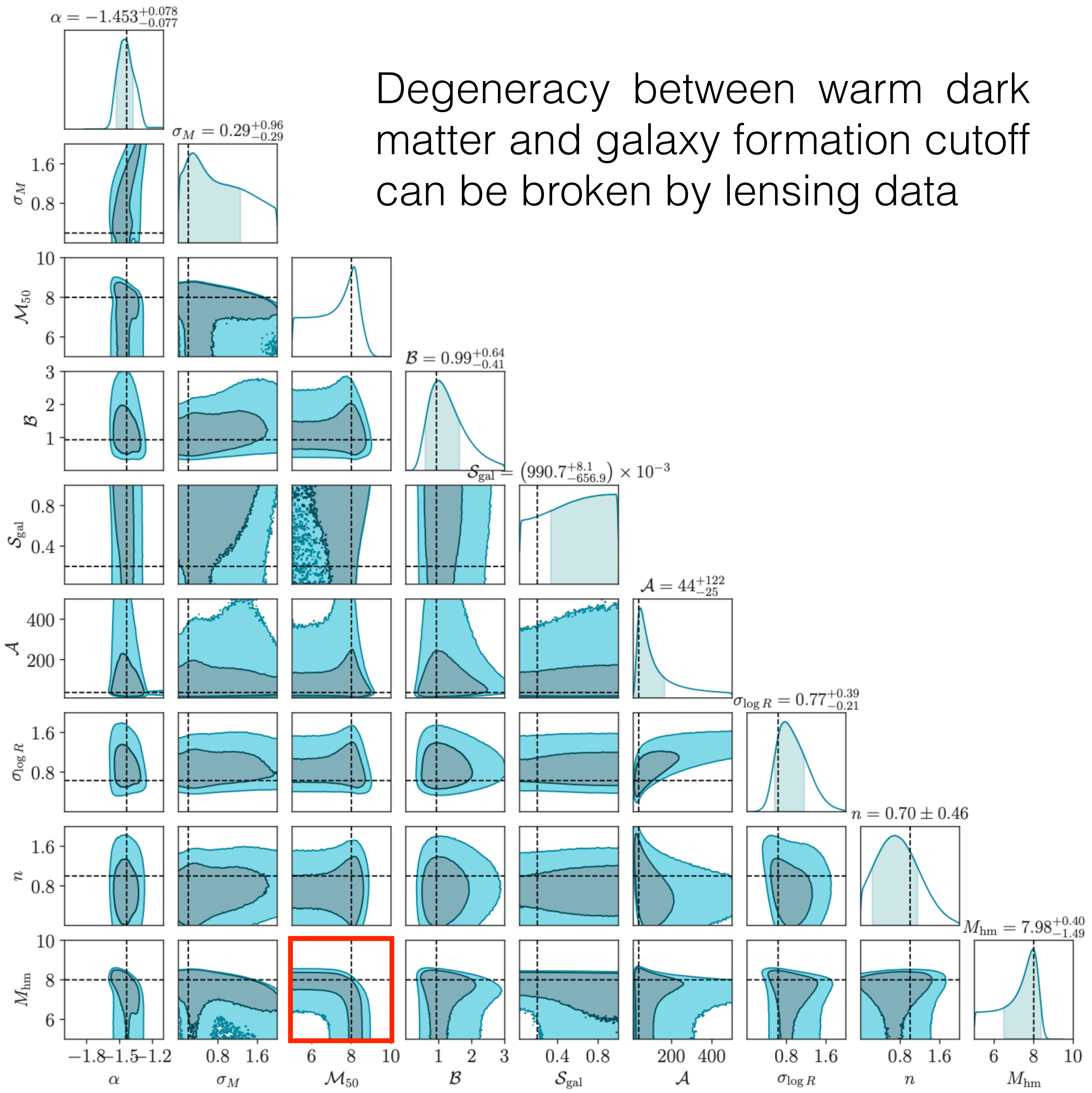
Satellite luminosity function



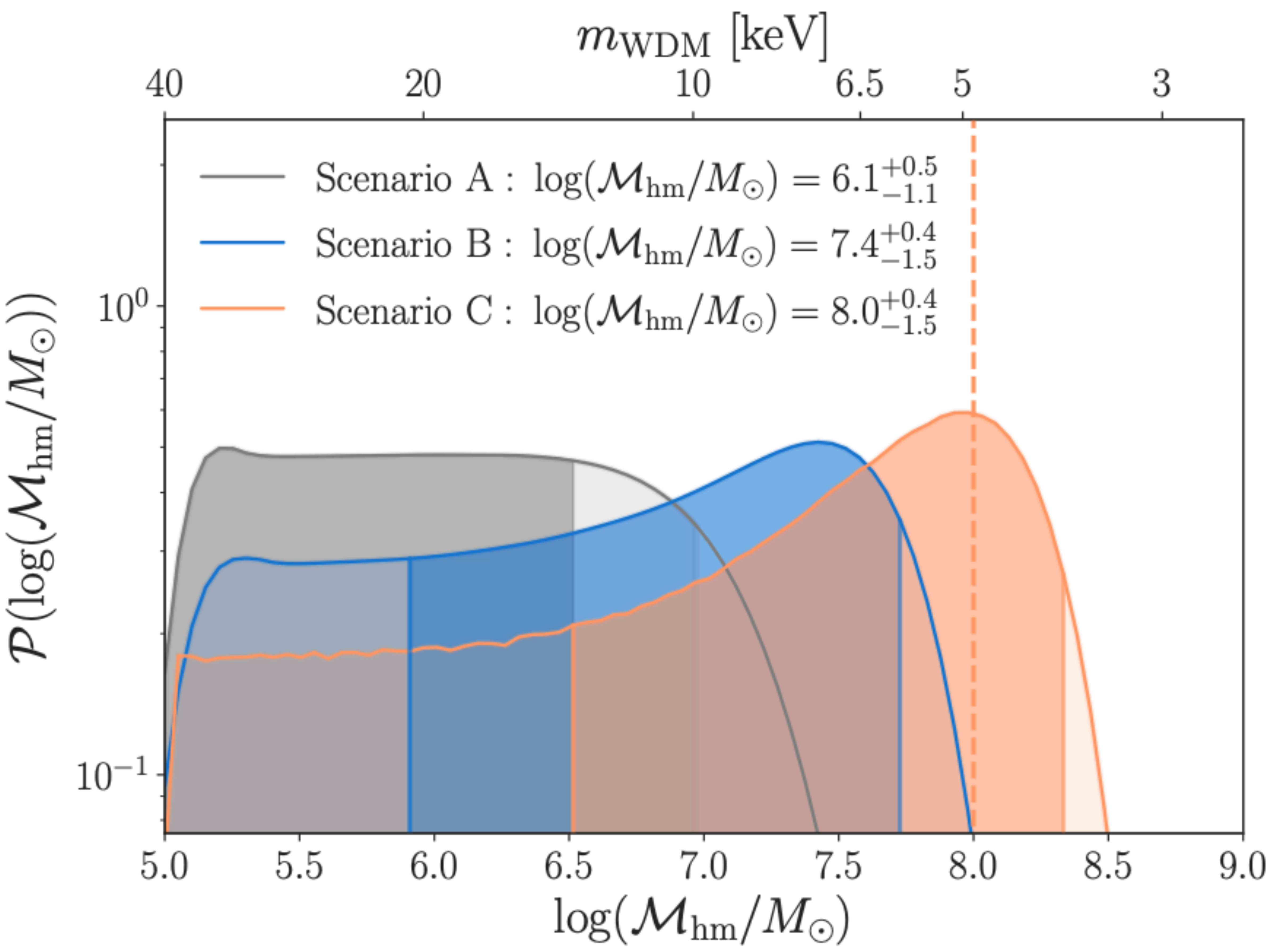
Current Milky Way satellite population data yields ***$m_{\rm WDM}$* > 6.5 keV** (95% CL), complementary to limits from Lyman-α forest, strong lensing

EN et al. 2021 (DES Collaboration, 2008.00022)

Warm Dark Matter Forecsasts



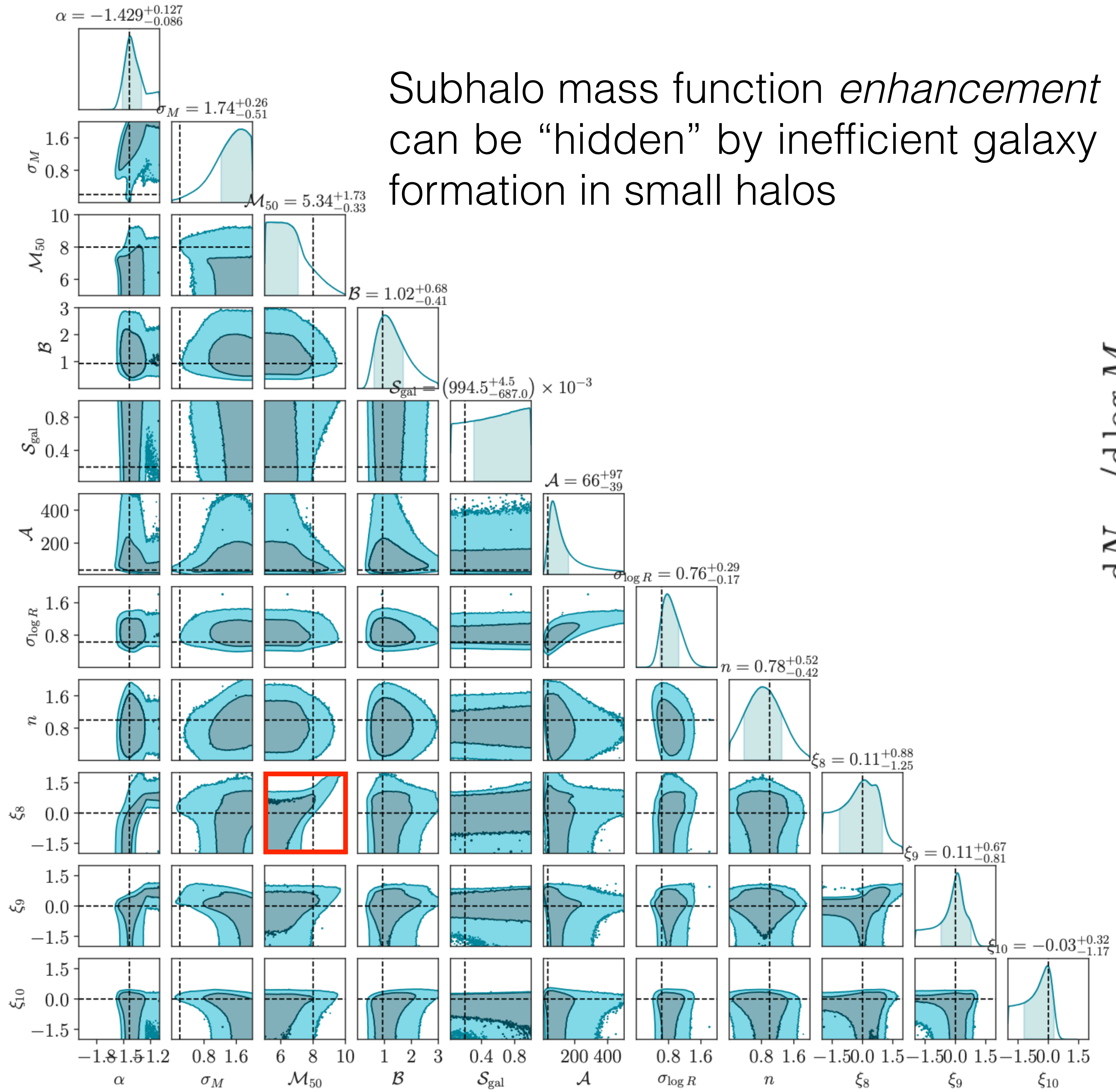
Degeneracy between warm dark matter and galaxy formation cutoff can be broken by lensing data



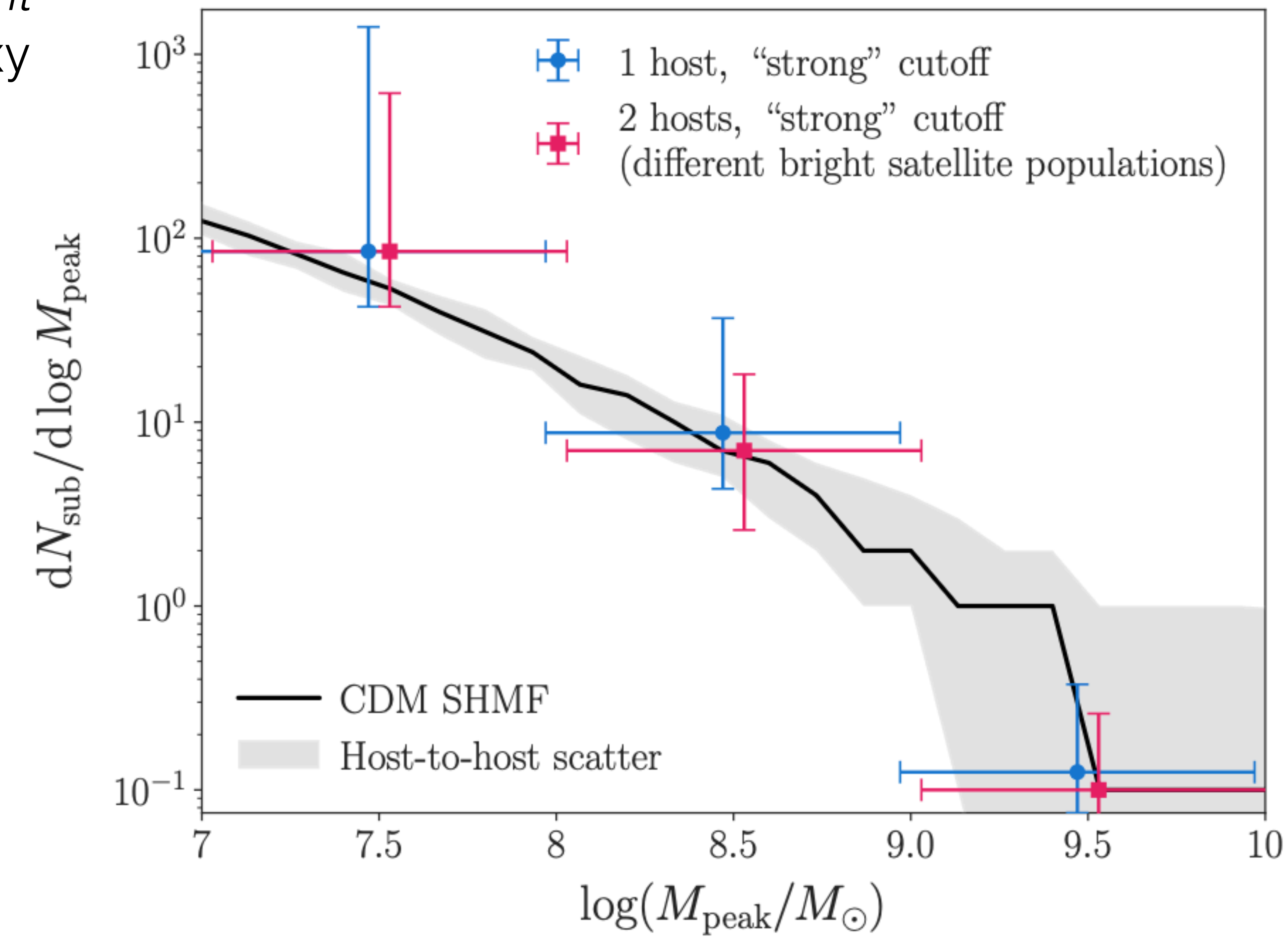
Two complete satellite populations probe ~**20 keV** WDM, or linear matter power spectrum suppression of ~10% at k ~ 50 Mpc^{-1}

EN et al. 2024 (2401.10318)

Subhalo Mass Function Forecasts



Subhalo mass function *enhancement* can be "hidden" by inefficient galaxy formation in small halos

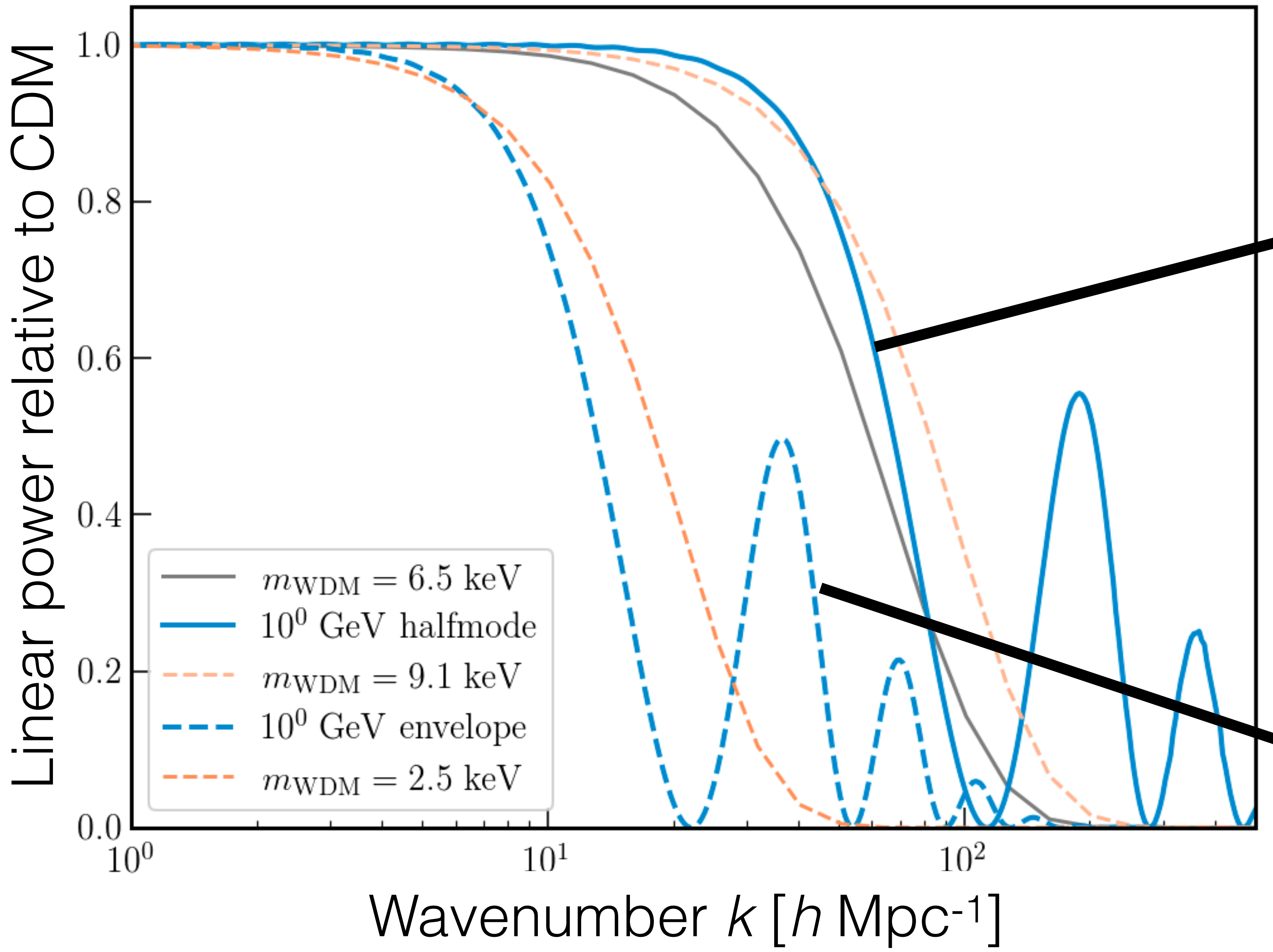


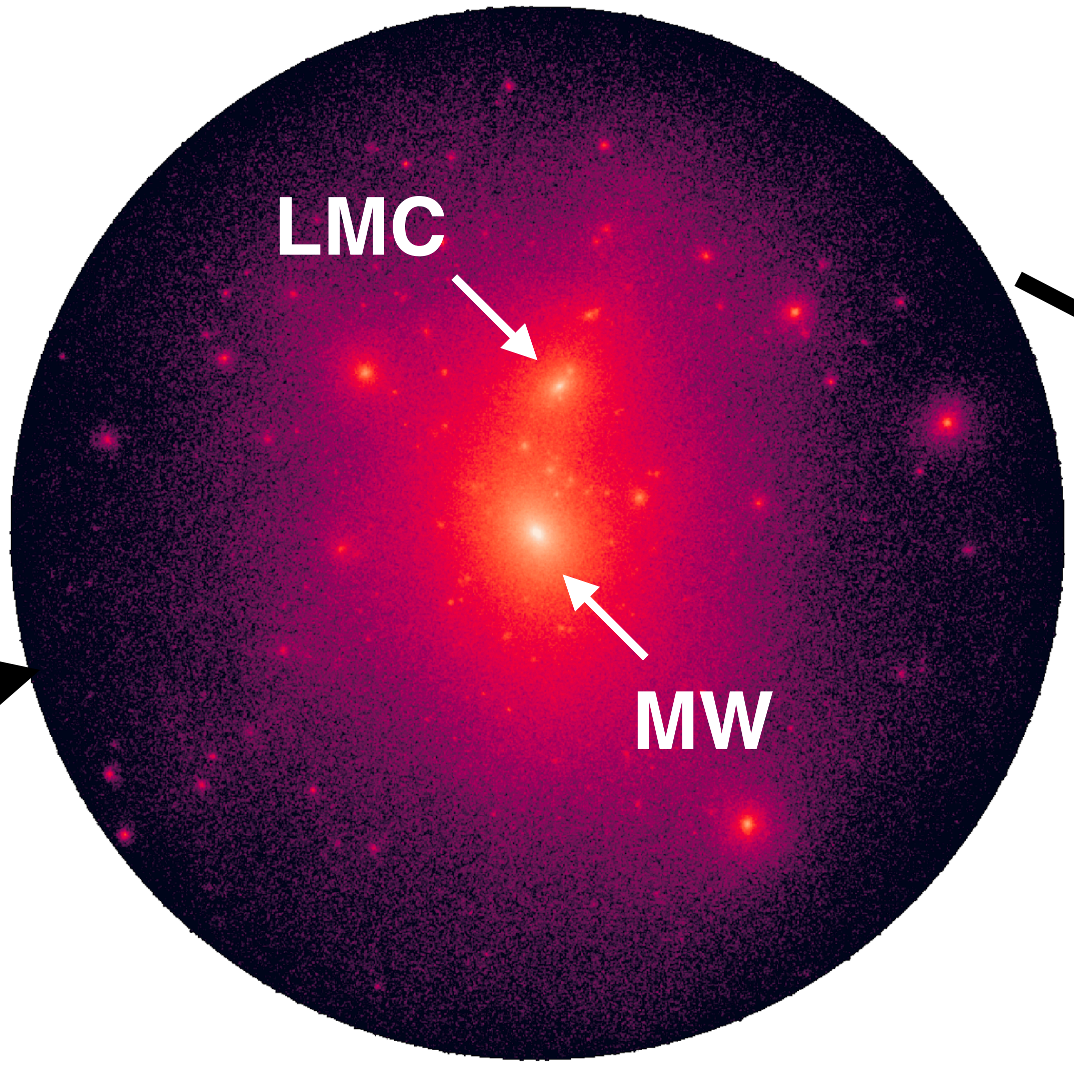
Two satellite populations probe subhalo mass function *suppression* of ~20% relative to CDM

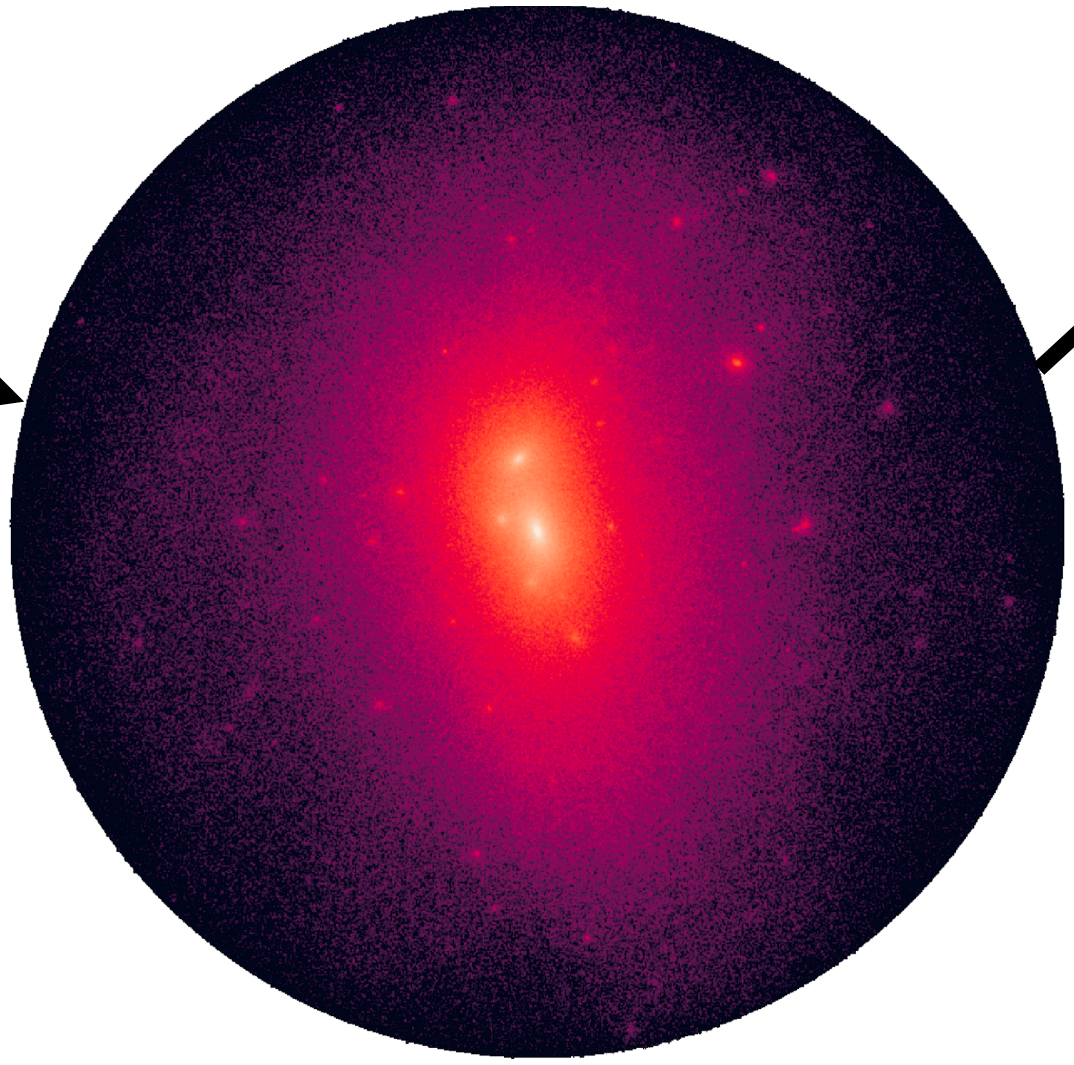
EN et al. 2024 (2401.10318)

Beyond-CDM Zoom-in Simulations

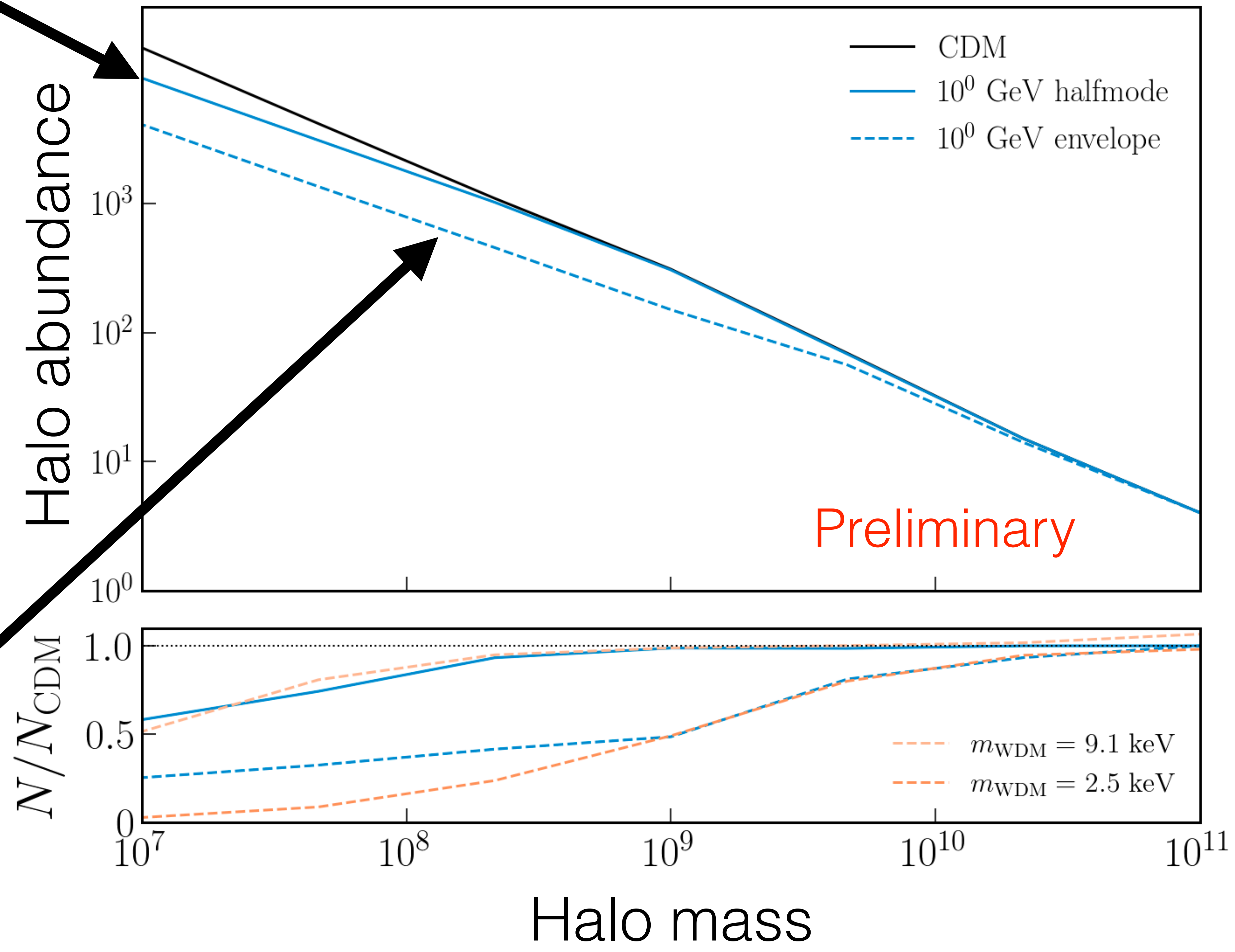
Initial conditions from linear theory





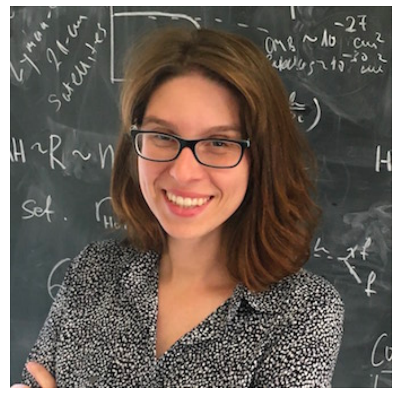


Halo and subhalo populations



Rui An
(USC)

Andrew Benson
(Carnegie)

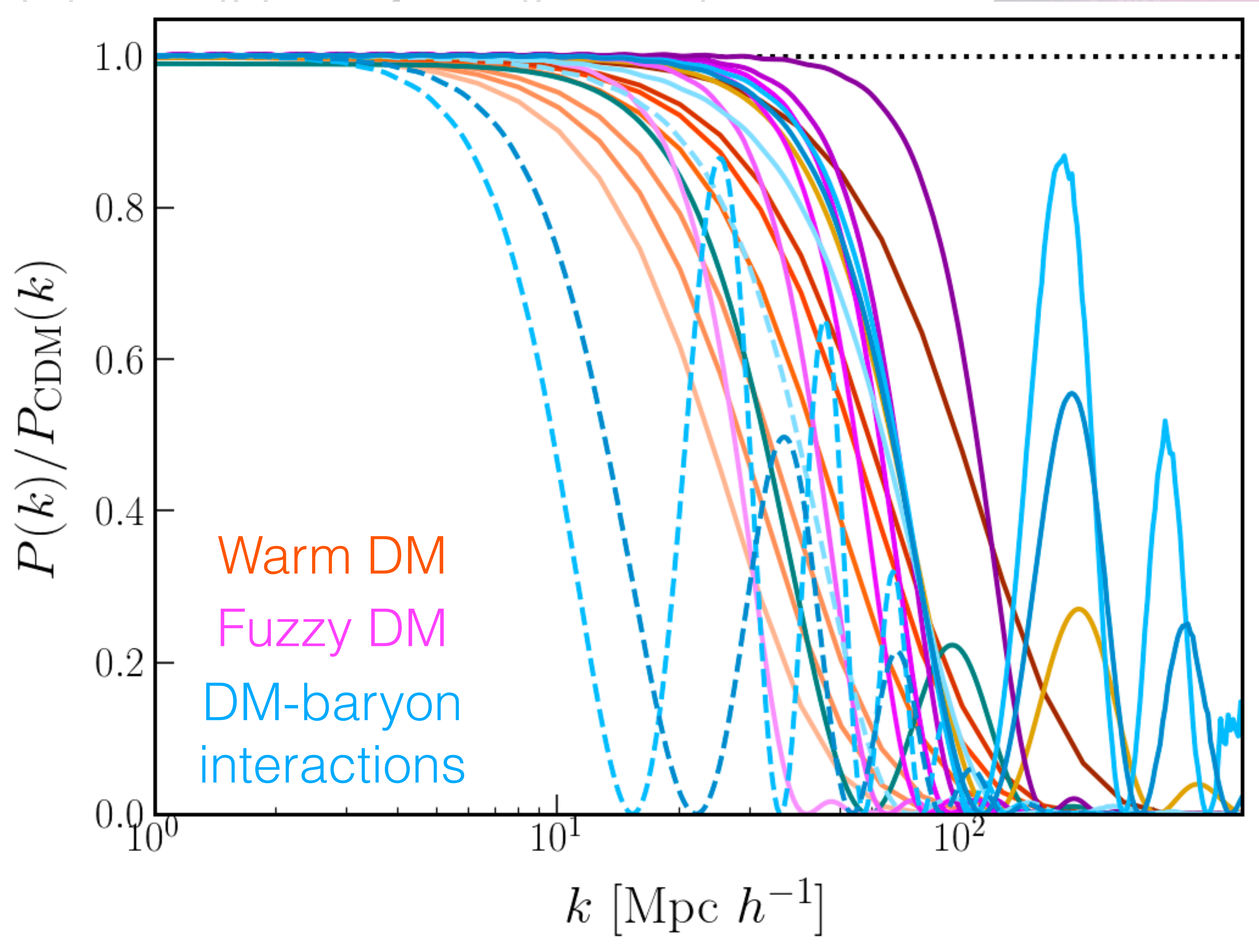


Vera Gluscevic
(USC)

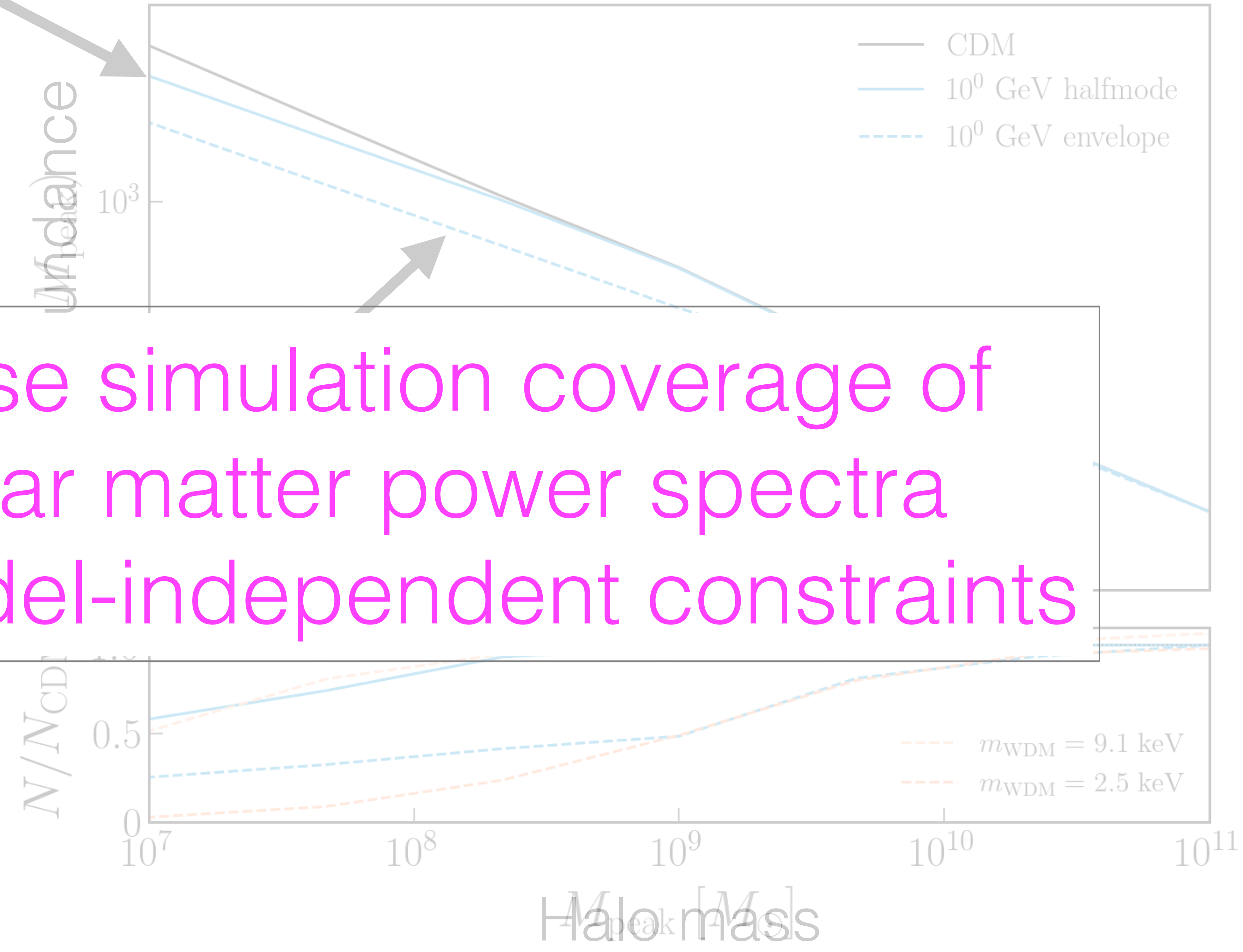
100+ cosmological DMO zoom-in simulations of Milky Way analogs in **warm**, **fuzzy**, **interacting** DM models

EN et al., in prep.

Beyond-CDM Zoom-in Simulations



Halo and subhalo populations



Dense simulation coverage of linear matter power spectra → model-independent constraints

100+ cosmological DMO zoom-in simulations of Milky Way analogs in **warm**, **fuzzy**, **interacting** DM models

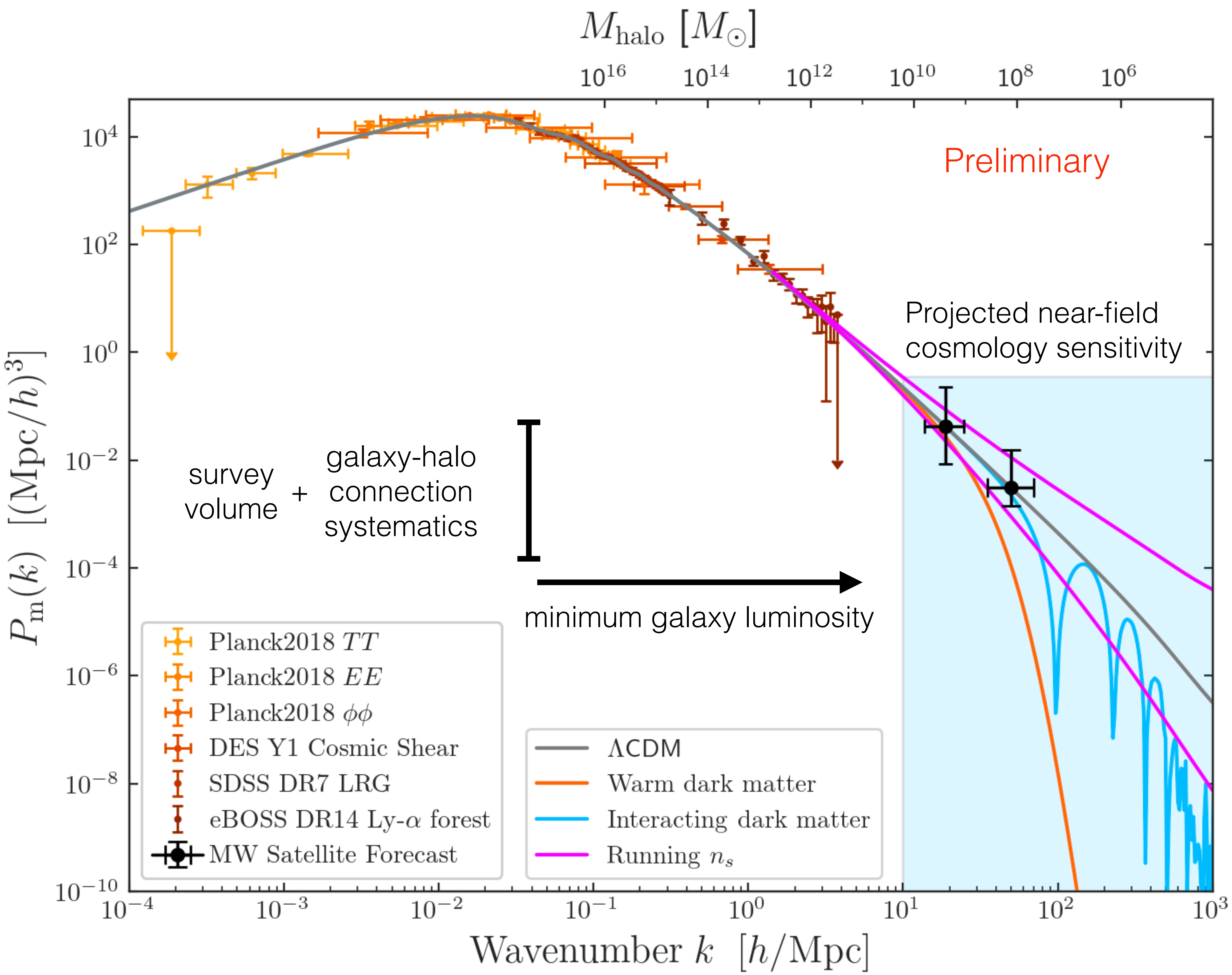
Rui An (USC)

Andrew Benson (Carnegie)

Vera Gluscevic (USC)

EN et al., in prep.

Linear Matter Power Spectrum Forecasts

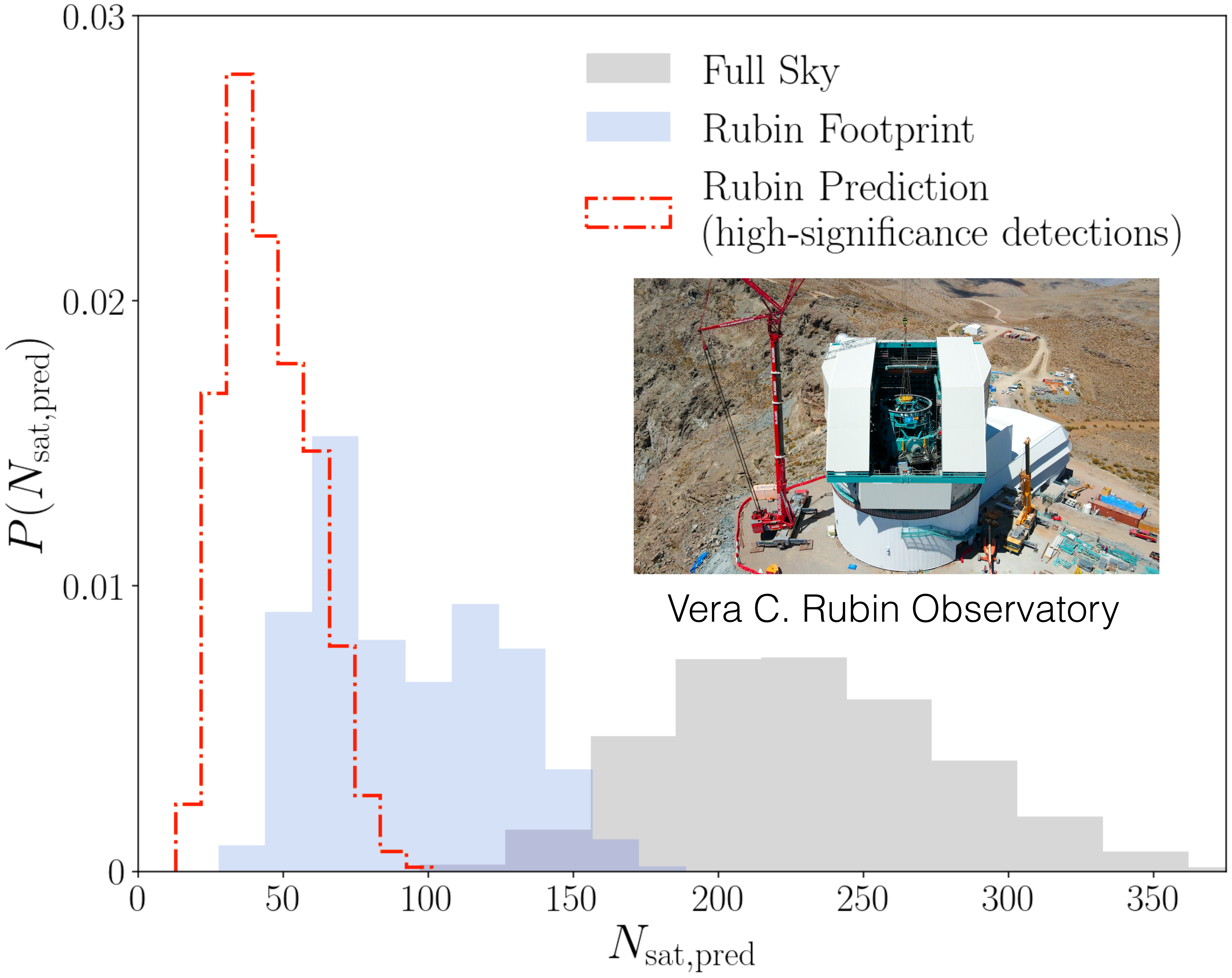


- For the first time, linear matter power spectrum reconstruction using dwarf galaxy populations is within reach
- Projected dwarf sensitivity to running n_s complements LSS on small scales
- Upcoming surveys will deliver large samples of low-z dwarfs, improving sub-Mpc clustering measurements

EN, et al., in prep.

Predictions for Upcoming Surveys

- Rubin LSST will detect most remaining Milky Way satellites in the South
- Star-galaxy separation using Roman and Euclid will increase purity
- Continued spectroscopic follow-up is crucial to obtain dynamical masses
- Spectroscopic surveys are already complementing this effort (e.g., DESI LOW-Z: ~20k dwarf redshifts, $z < 0.03$)



Tsiane et al. in prep. (DESC Collaboration, incl. EN)

- Dwarf galaxies are a key small-scale test of galaxy formation, dark matter, and inflation
- Understanding the dwarf galaxy–halo connection is a step toward discovery of new physics
- First linear matter power spectrum reconstruction using dwarf galaxies is within reach
- Smallest scale set by minimum galaxy luminosity; statistical error set by survey volume
- Robust theoretical modeling of dwarf galaxy data will bridge LSS and near-field cosmology

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