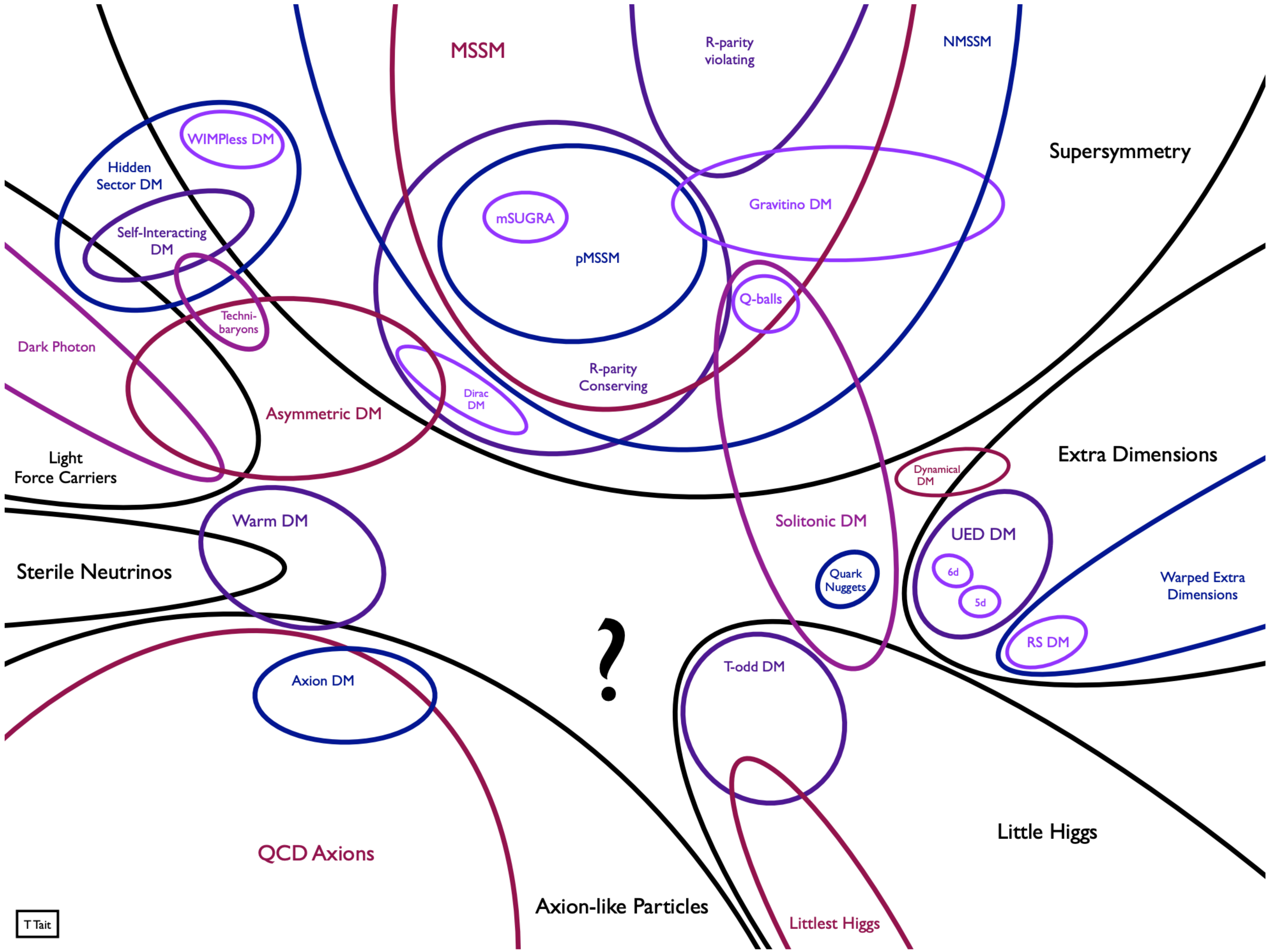
The Faintest Galaxies and their Dark Matter Halos

Ethan Nadler

BCCP Seminar

9/15/2020

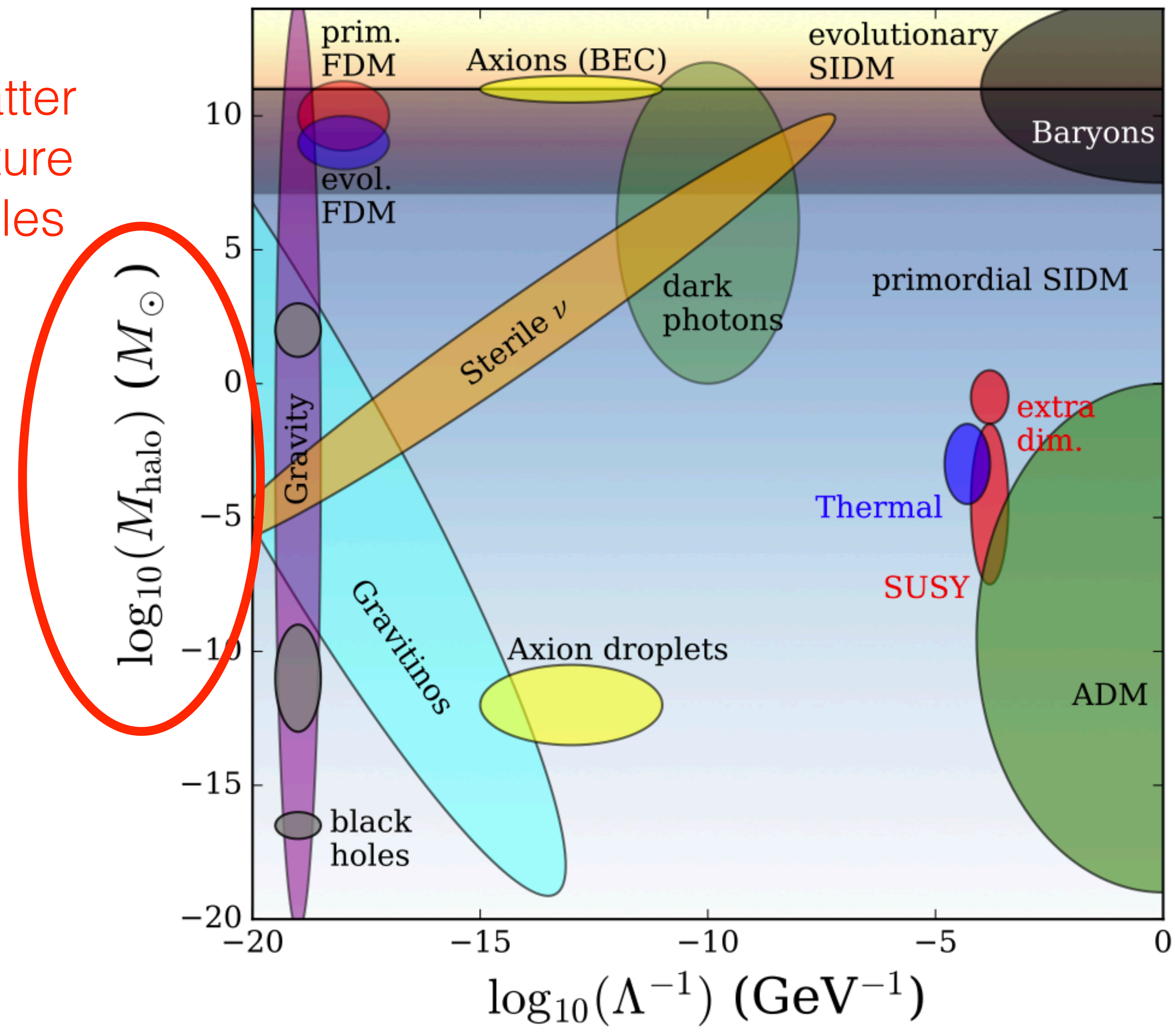
The Dark Matter Landscape



Credit: T. Tait

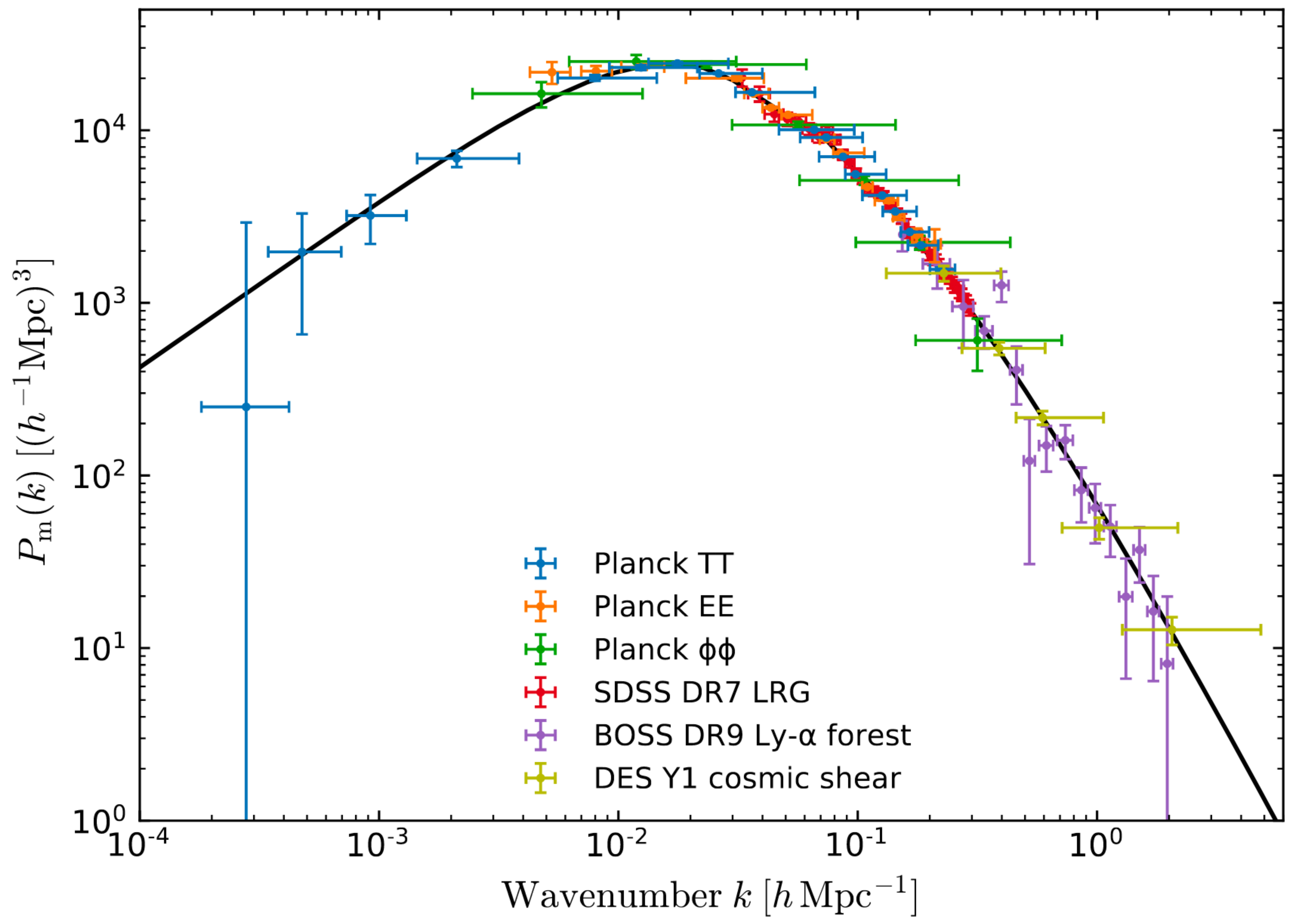
Dark Matter and Structure Formation

Microphysical dark matter properties affect structure formation on small scales

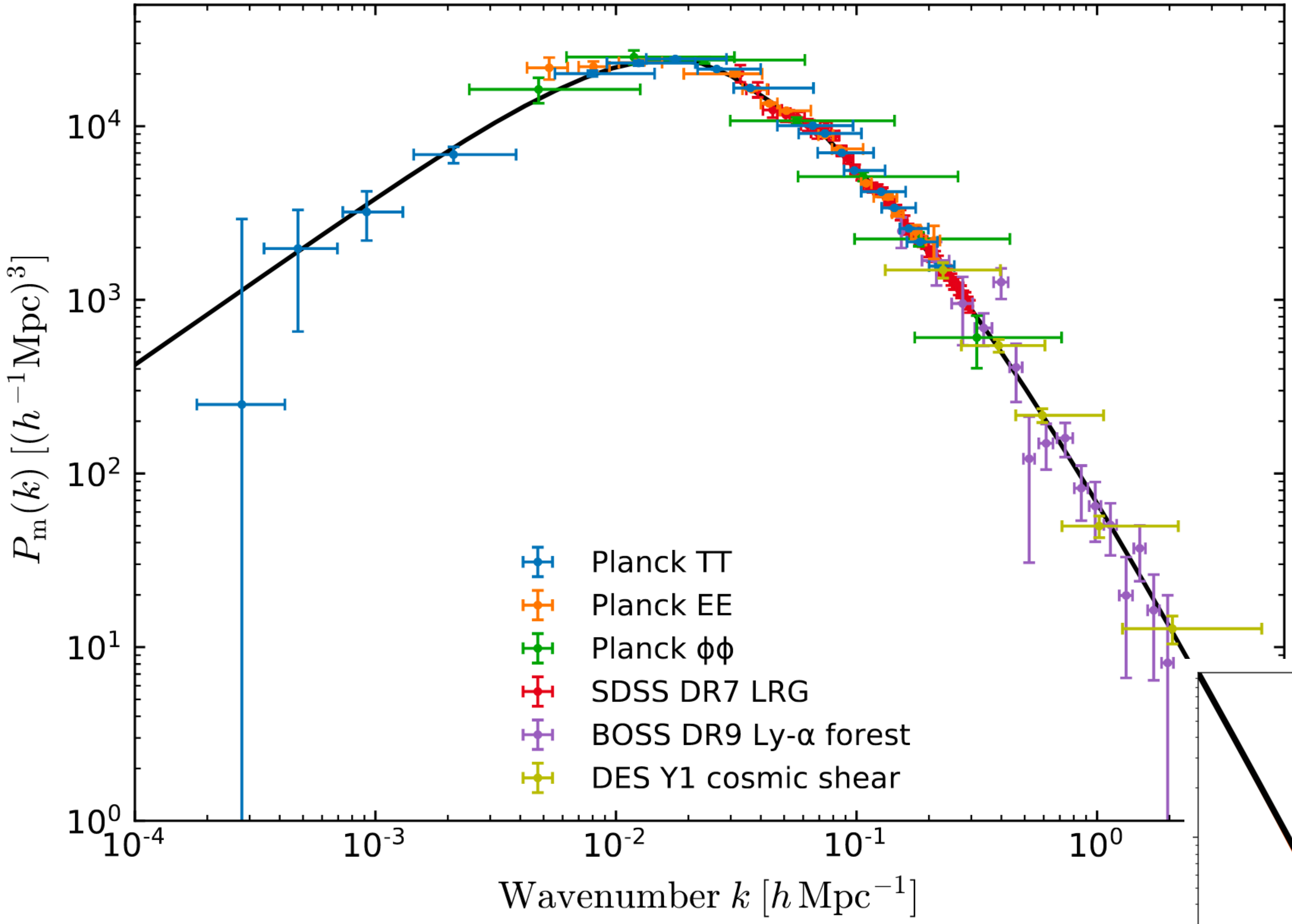


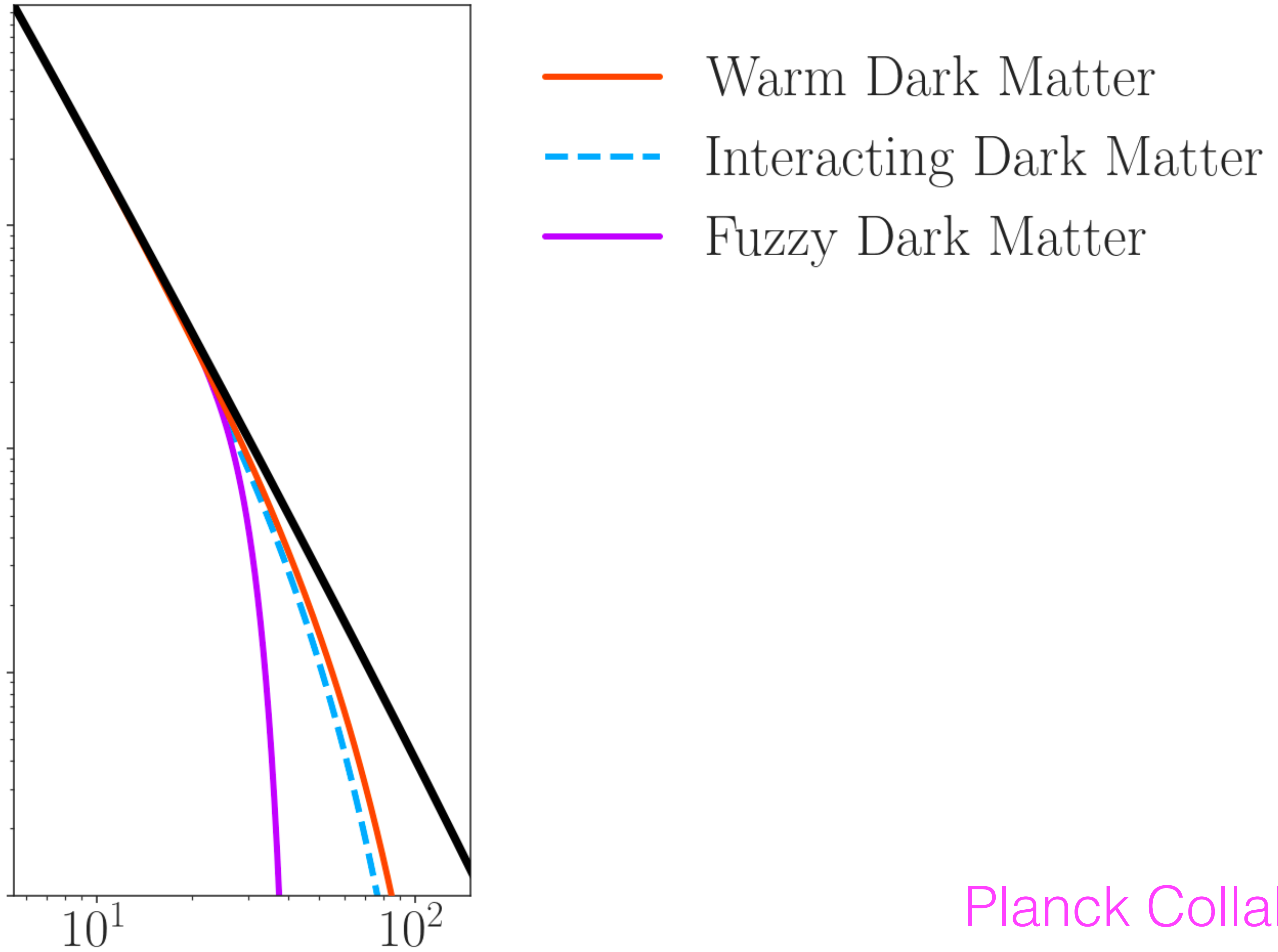
Buckley & Peter 2018

Dark Matter and Structure Formation



Planck Collaboration 2019

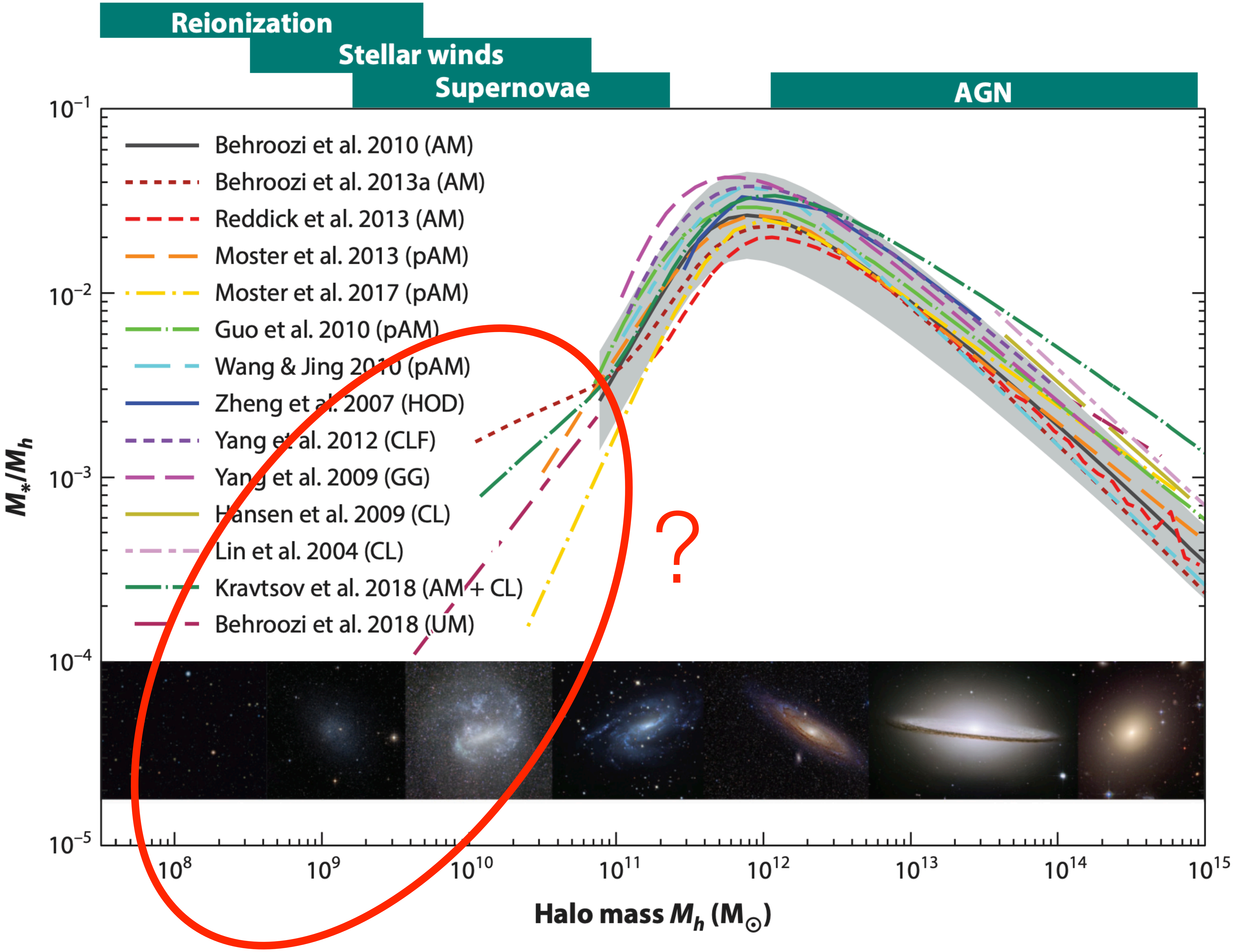




- Small scales contain information about a variety of dark matter physics: we are compelled to search there!
- **What is the luminous content of the smallest halos?**

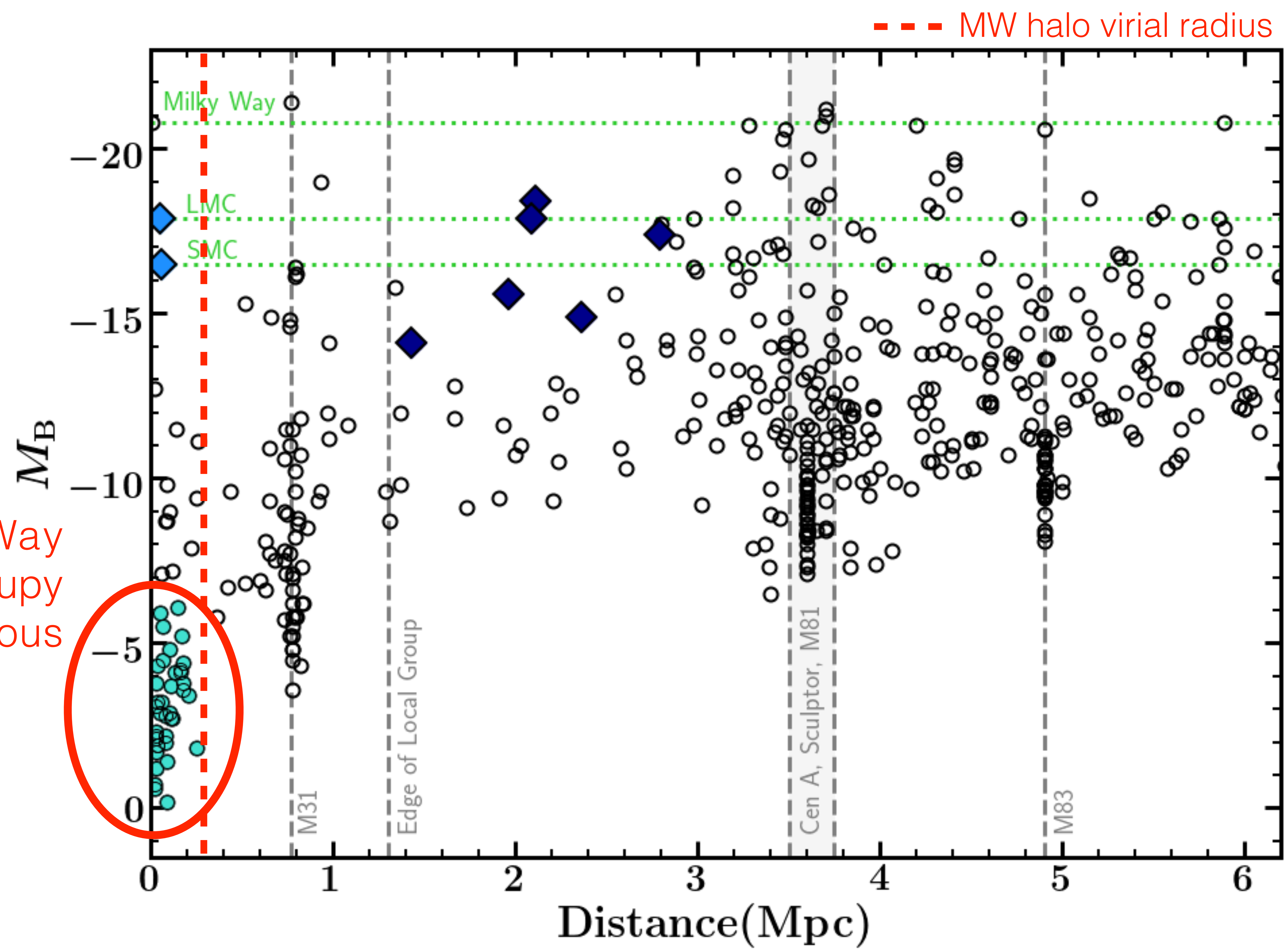
Planck Collaboration 2019

The Galaxy–Halo Connection



Wechsler & Tinker 2018

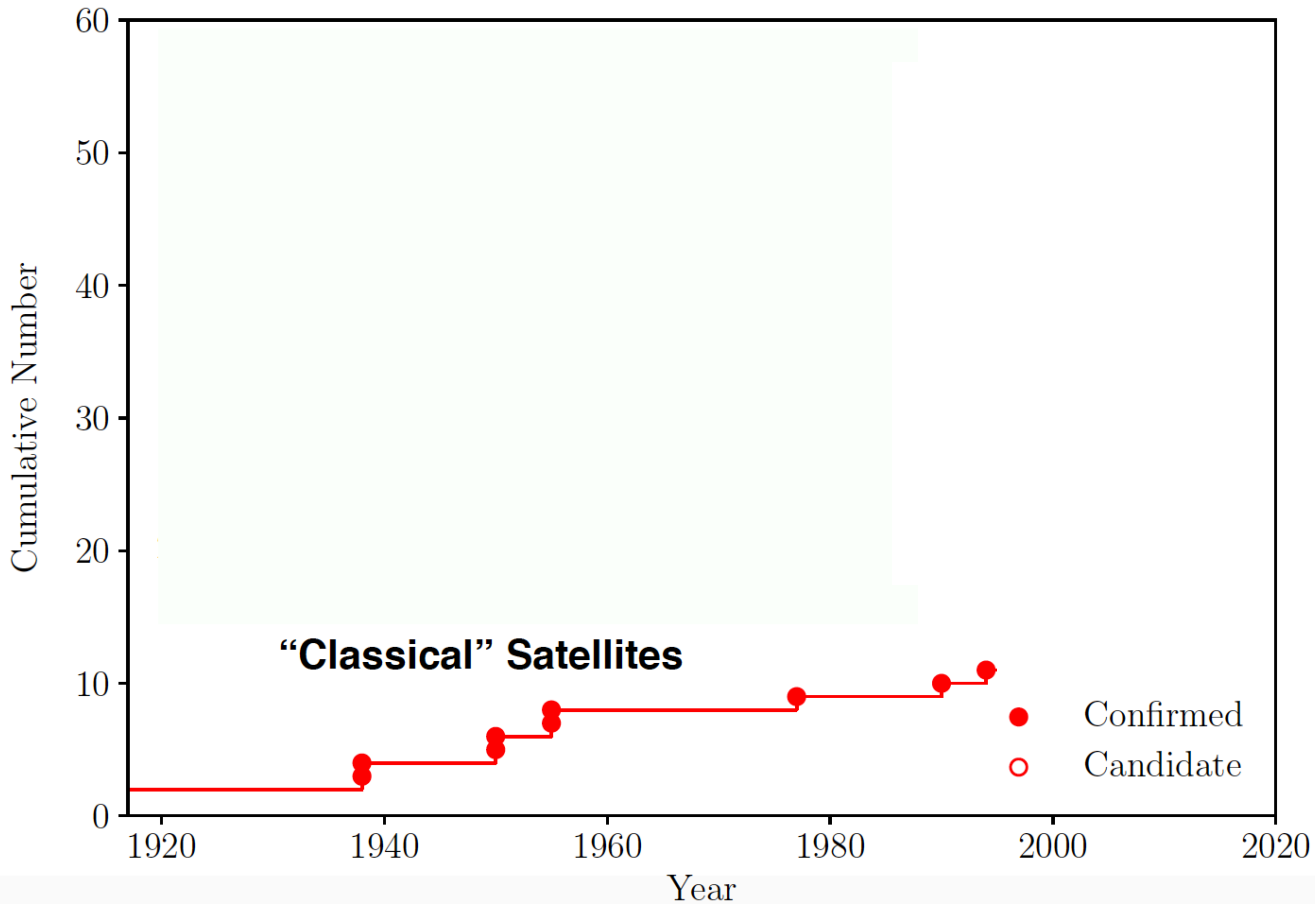
Our Census of the Faintest Galaxies



Ultra-faint Milky Way satellite galaxies occupy the smallest luminous dark matter halos

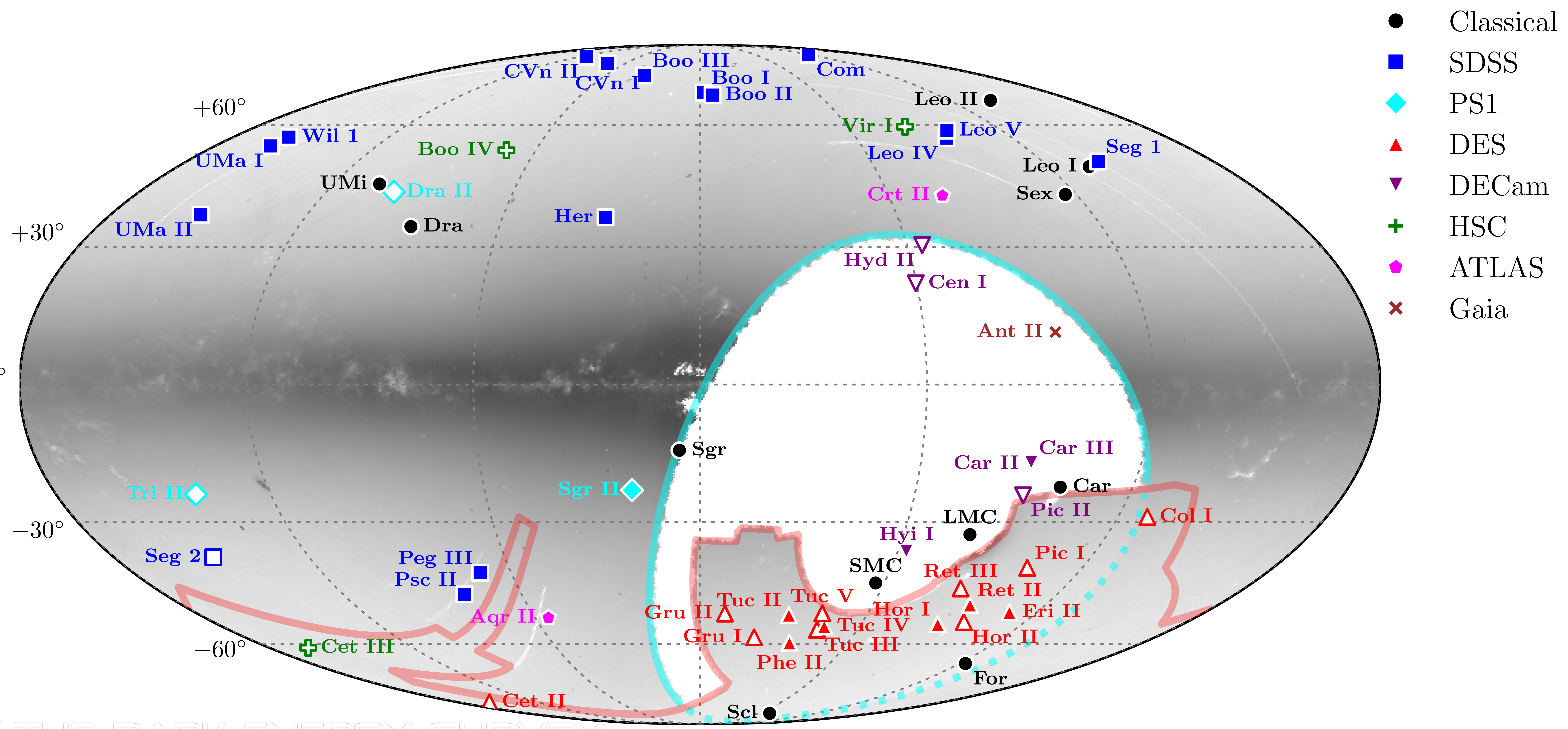
Credit: J. Carlin

The Milky Way Satellite Population



Credit: K. Bechtol

The Milky Way Satellite Population



THE DARK ENERGY SURVEY

Drlica-Wagner & Bechtol et al. 2020

Missing Satellites?

Dwarf galaxy problem

From Wikipedia, the free encyclopedia

“although there seem to be enough observed normal-sized galaxies to match the simulated size distribution, the number of dwarf galaxies is orders of magnitude lower than expected from simulation.”

There is No Missing Satellites Problem

Stacy Y. Kim, Annika H. G. Peter, Jonathan R. Hargis

“We show that there is a match between the observed satellite counts corrected by the detection efficiency of the Sloan Digital Sky Survey … and the number of luminous satellites predicted by CDM, assuming an empirical relation between stellar mass and halo mass. The “missing satellites problem”, cast in terms of number counts, is thus solved.”

Quanta Magazine

The Problem of the Missing Satellite Galaxies Gives Way — Now There's Too Many

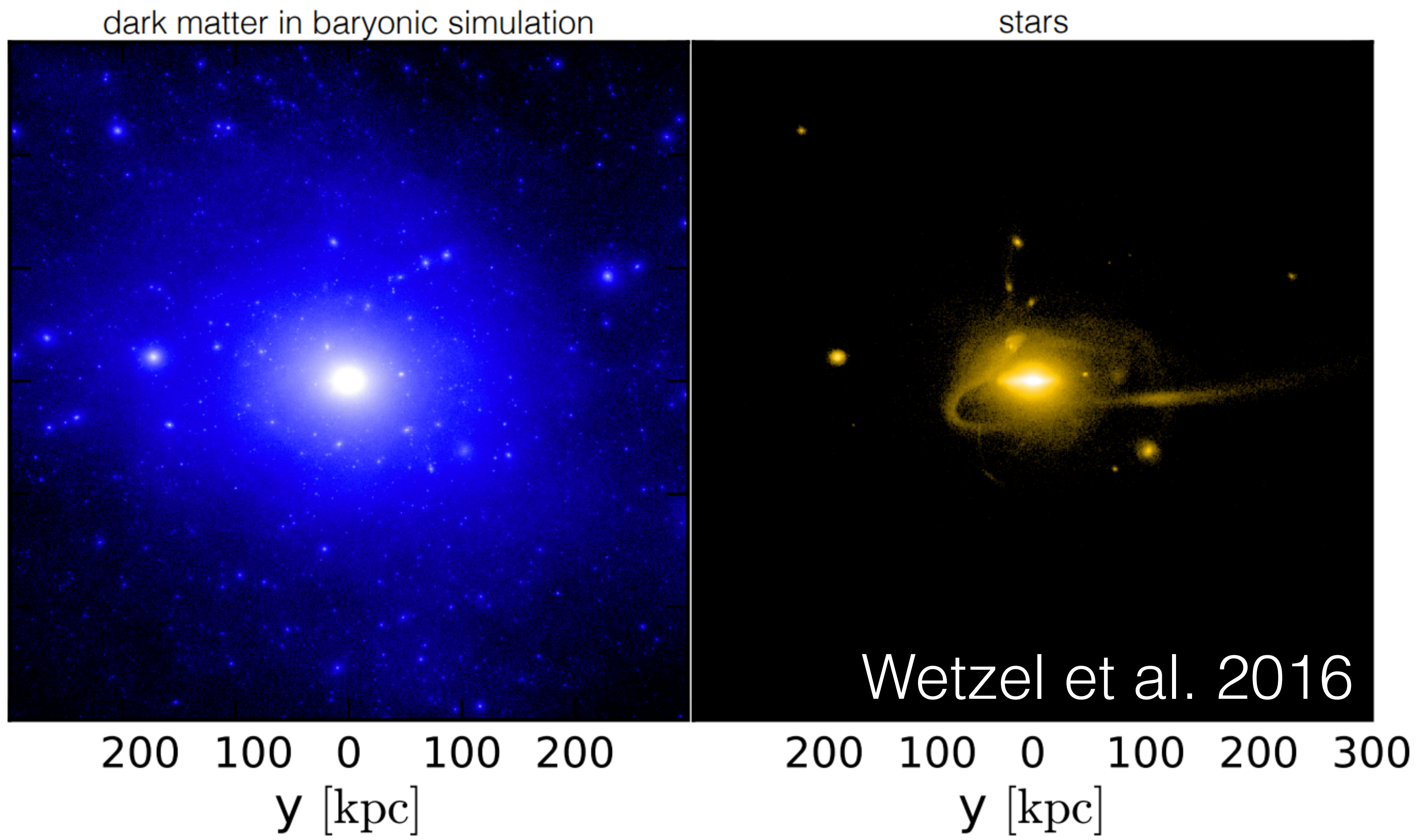
“Astronomers couldn’t find enough satellite galaxies orbiting the Milky Way. Now they have the opposite problem, suggesting that our understanding of how galaxies get built is incomplete.”

🤕

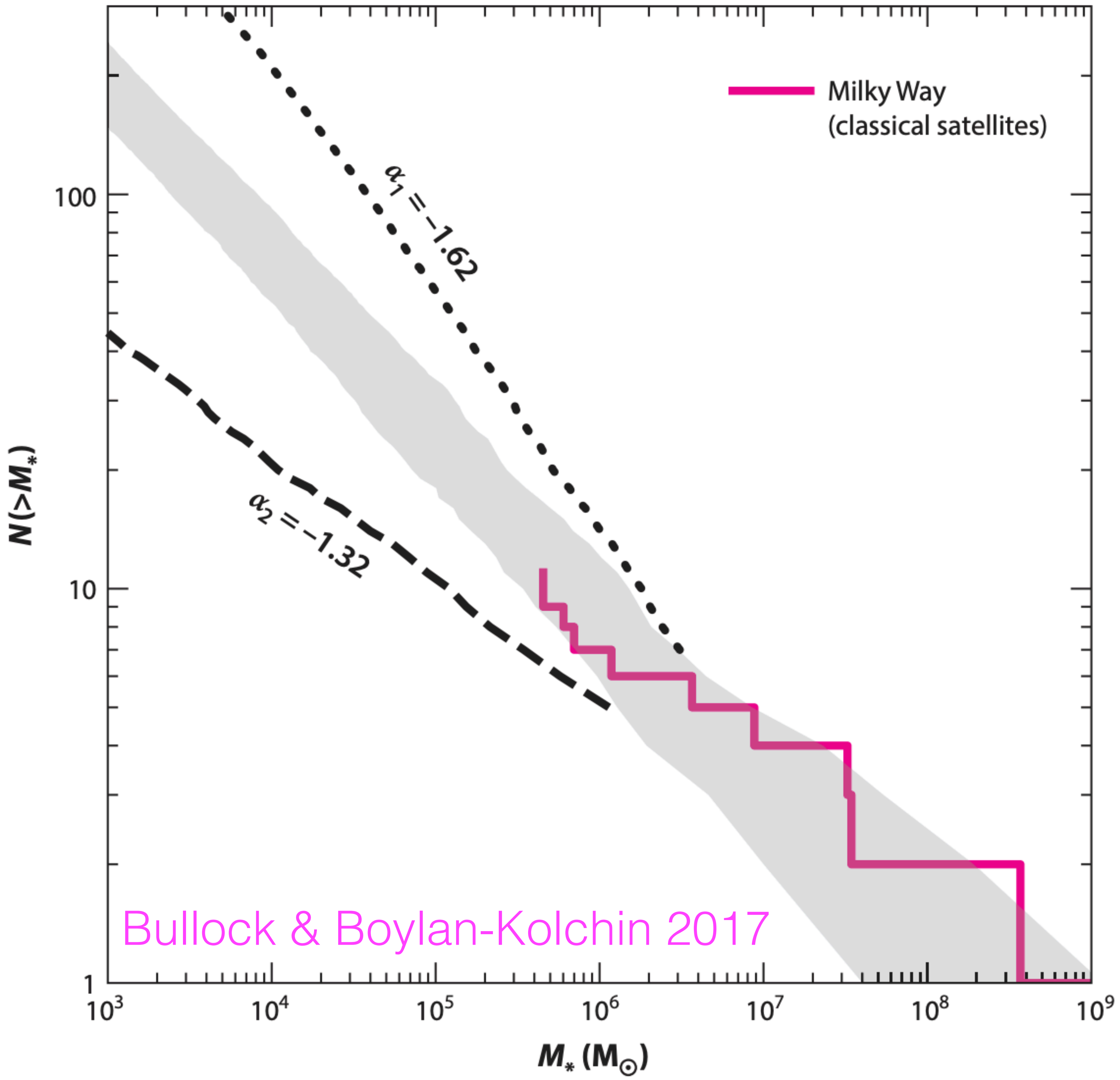
No Missing Satellites?

- No missing satellites after correcting for observational incompleteness and extrapolating standard stellar mass–halo mass relations

- Consistency has only been demonstrated at fixed modeling assumptions, and only for the brightest half of the Milky Way satellite population

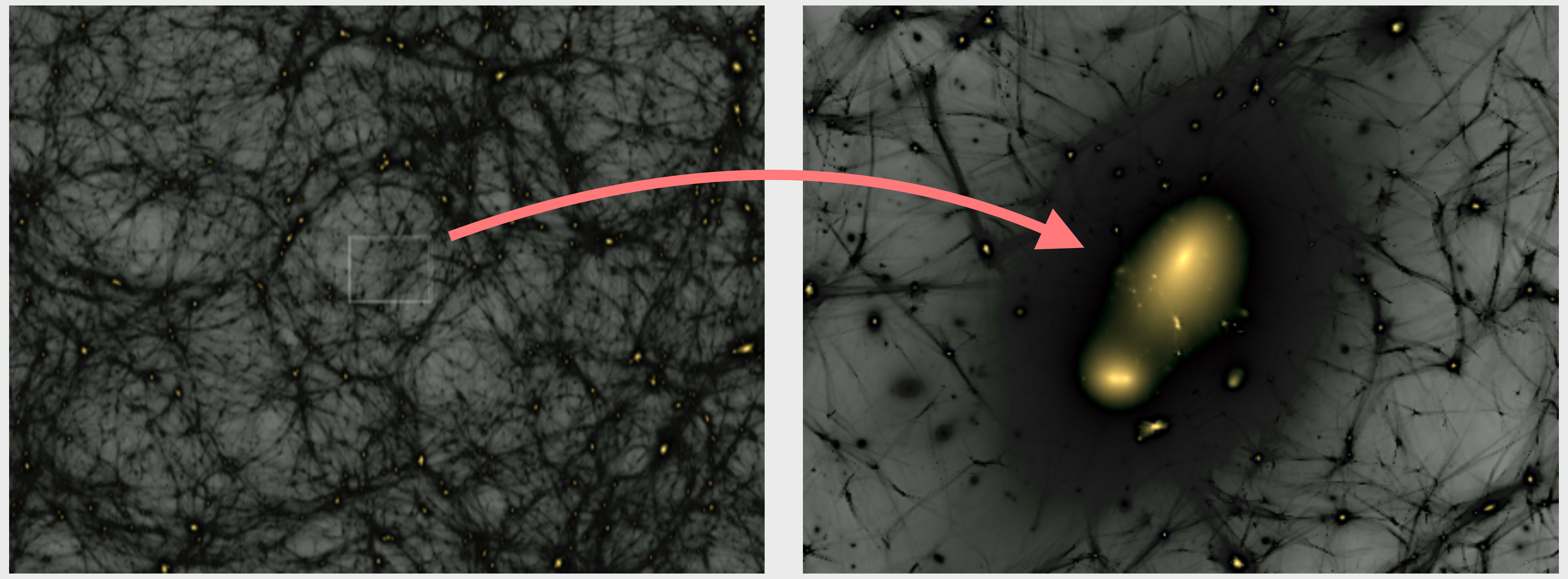


Small-Scale Challenges to the ΛCDM Paradigm

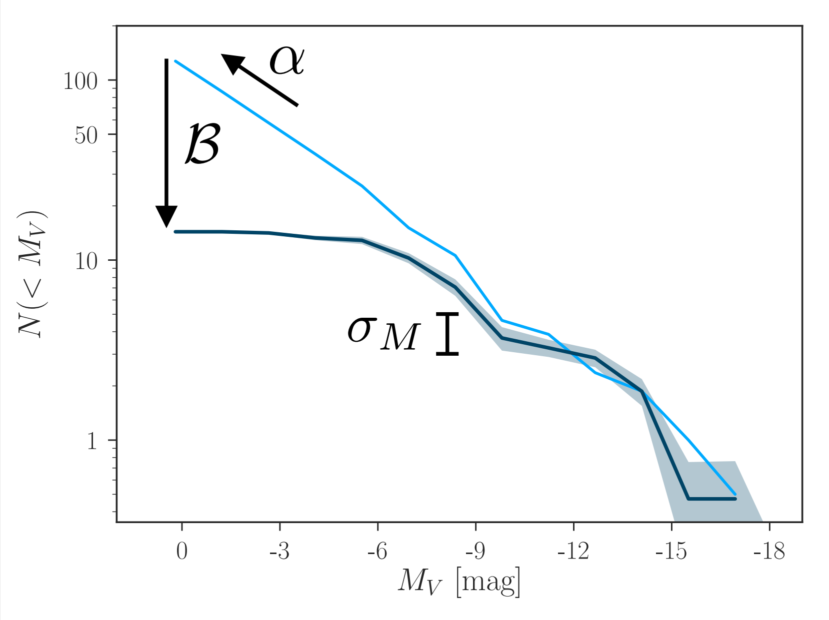


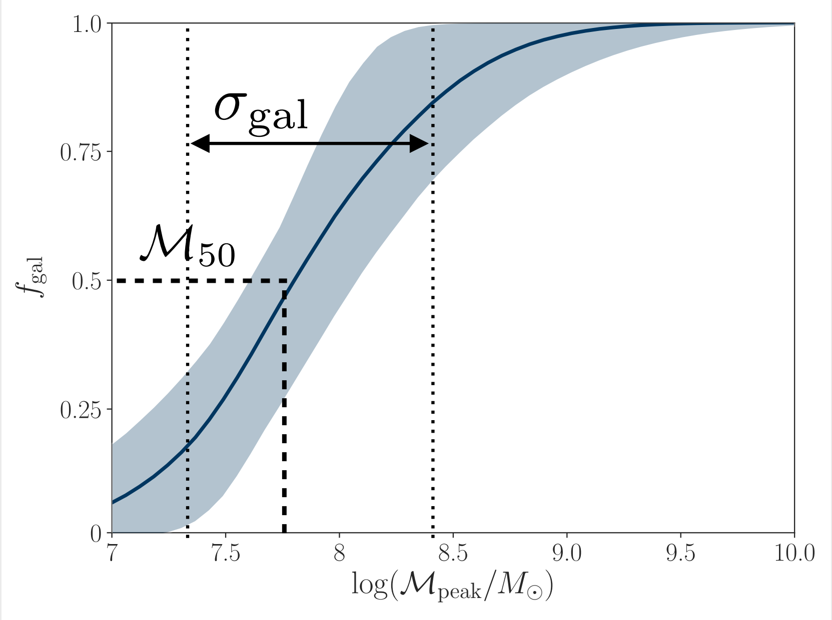
Markov Chain Monte Carlo

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

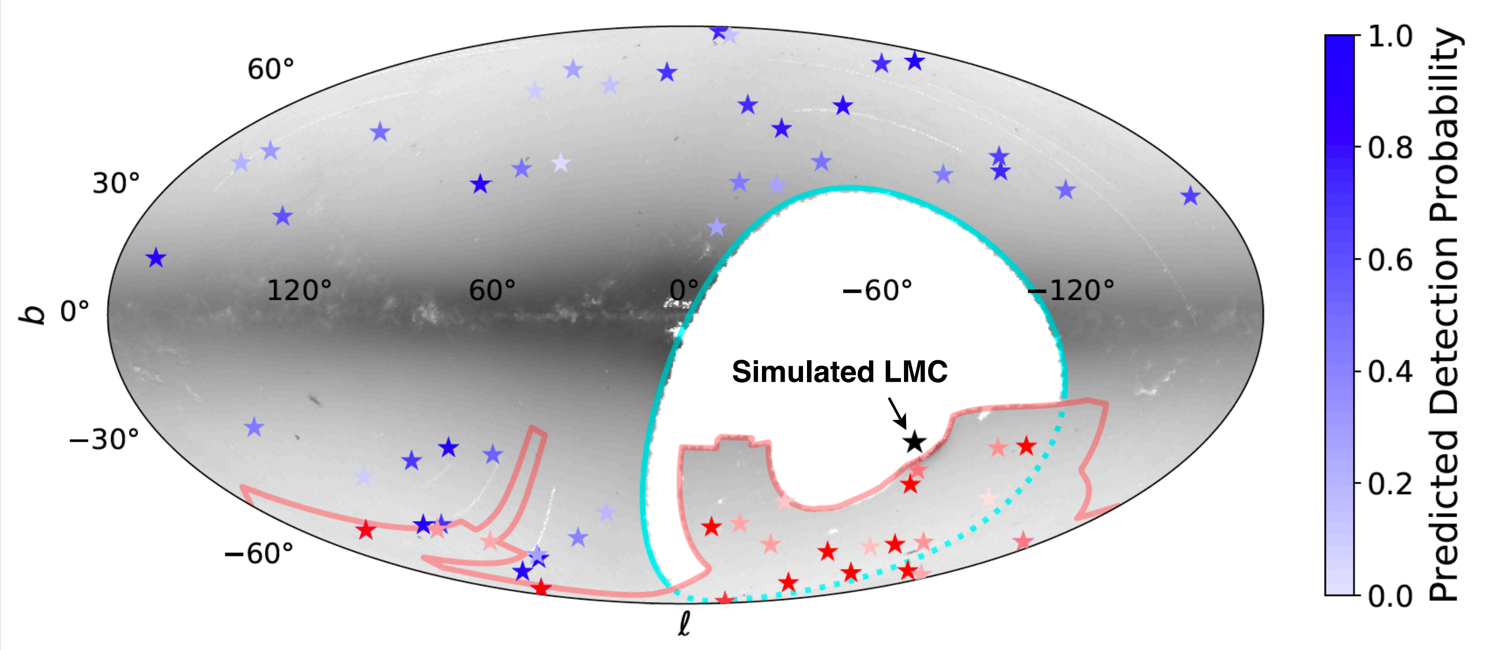


2. Paint satellite galaxies onto subhalos using galaxy—halo model.

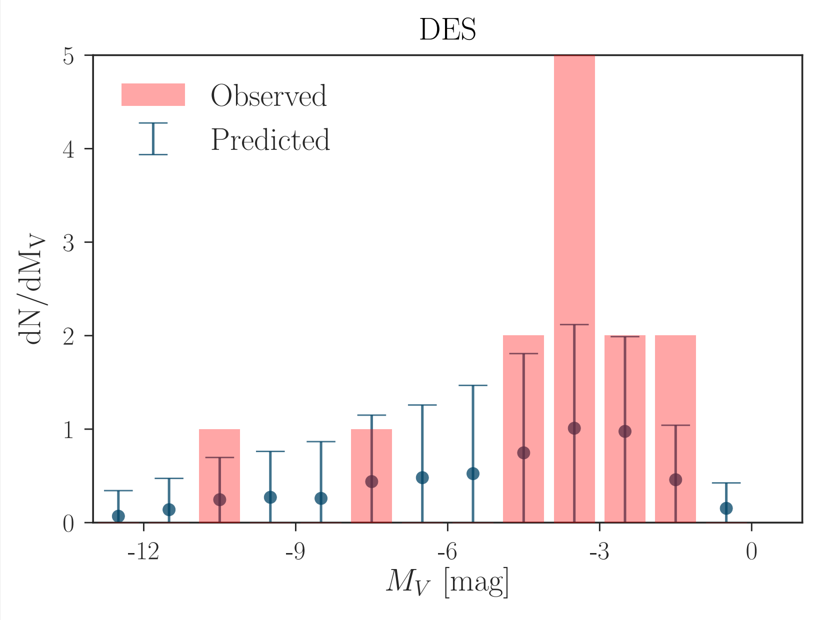


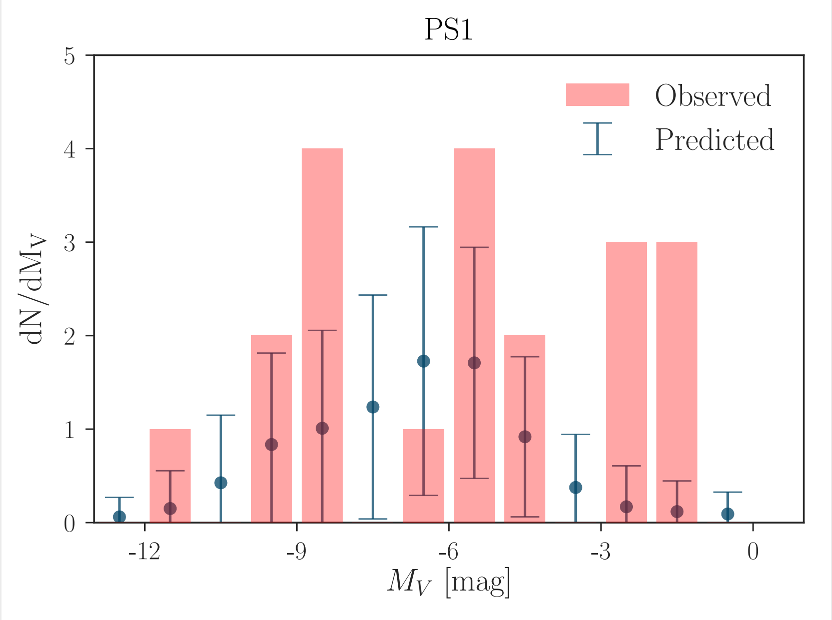


3. Apply observational selection functions based on imaging data.



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





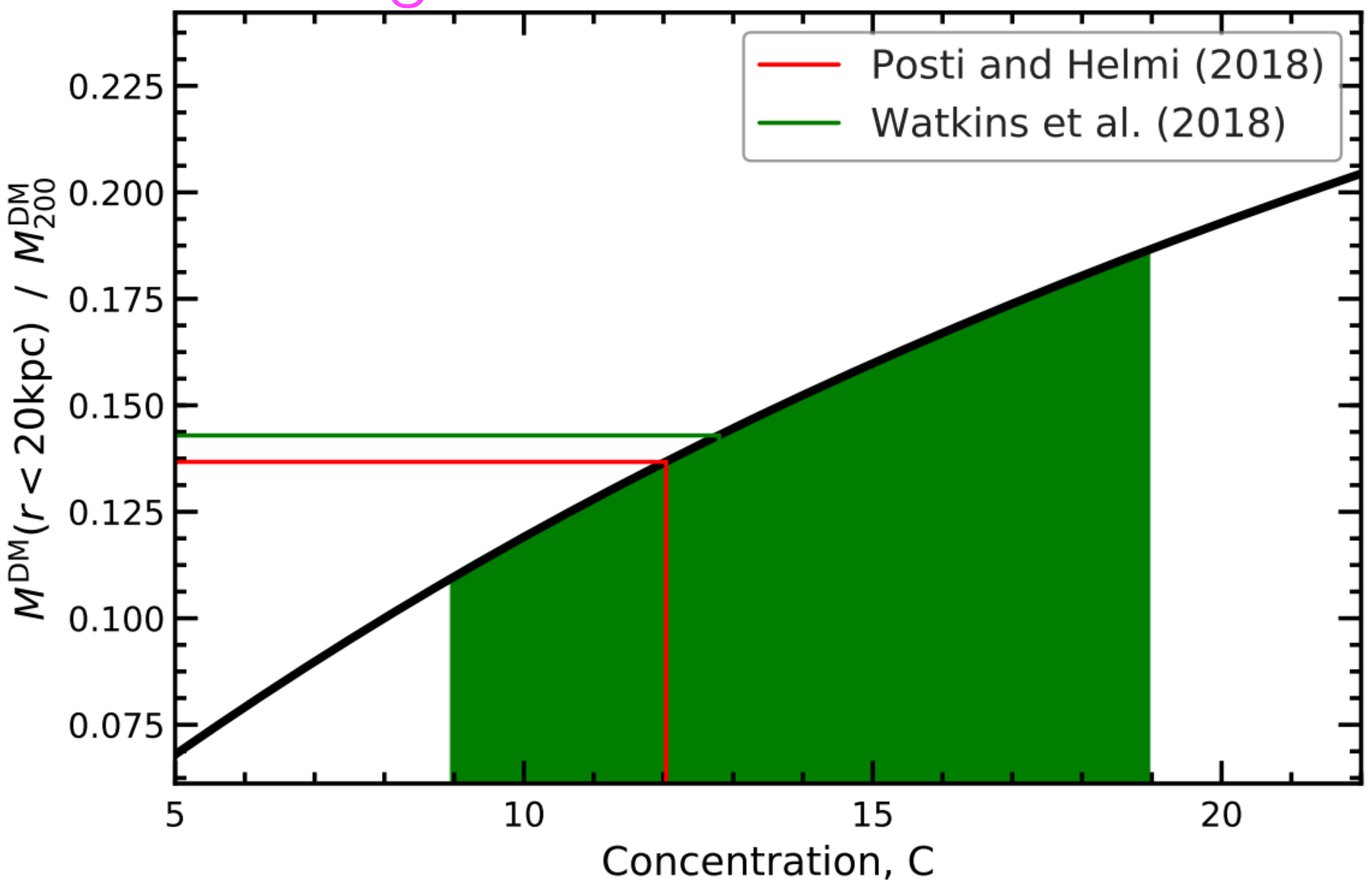
EN & Wechsler et al. 2020

Simulating Milky Way Analogs

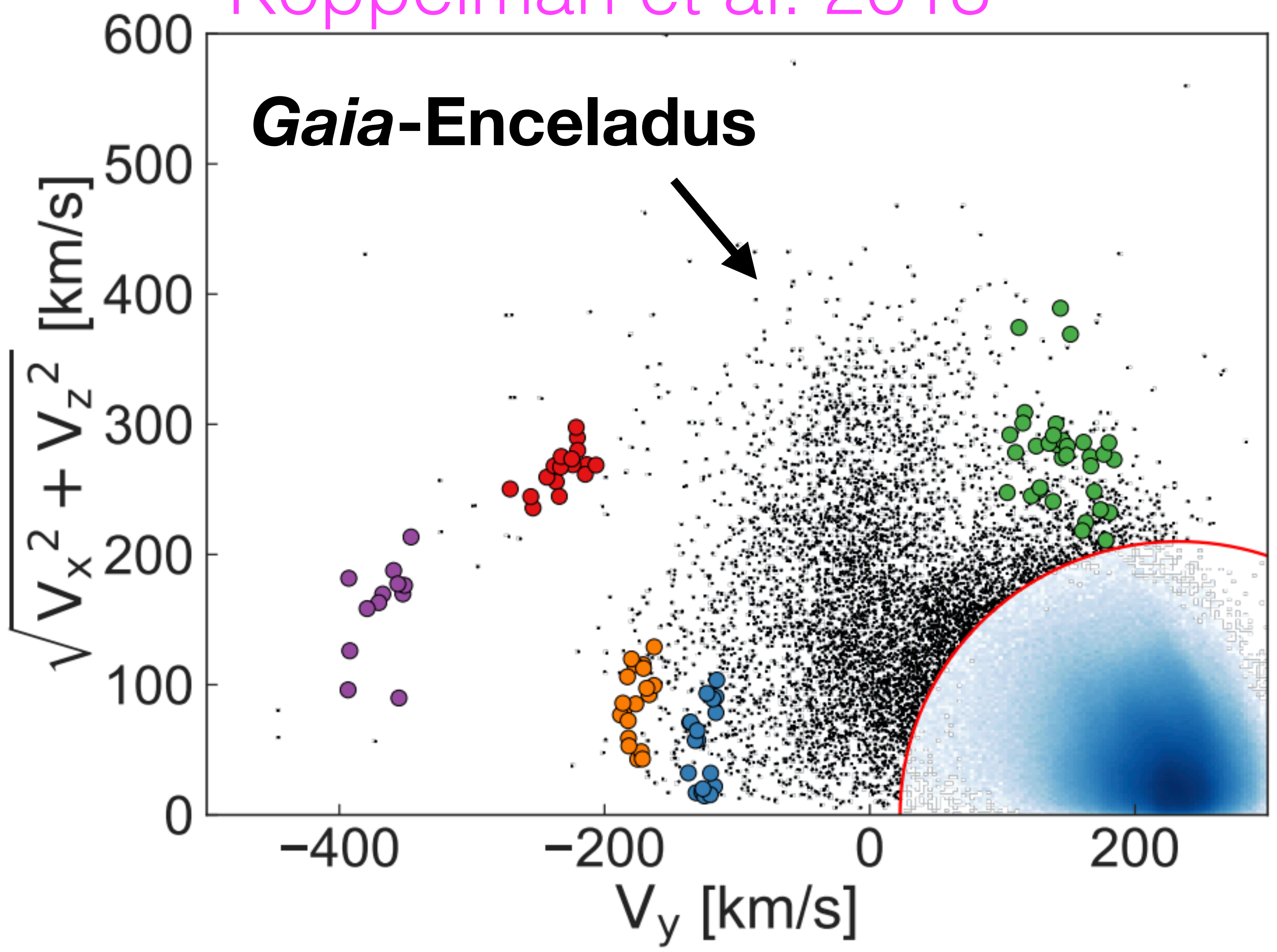
- *Gaia* is revolutionizing our understanding of Milky Way halo properties: mass, concentration, assembly history

- We analyze simulated halos that 1) are consistent with these MW halo properties, 2) experience a *Gaia*-Enceladus merger, and 3) have a realistic Large Magellanic Cloud analog system

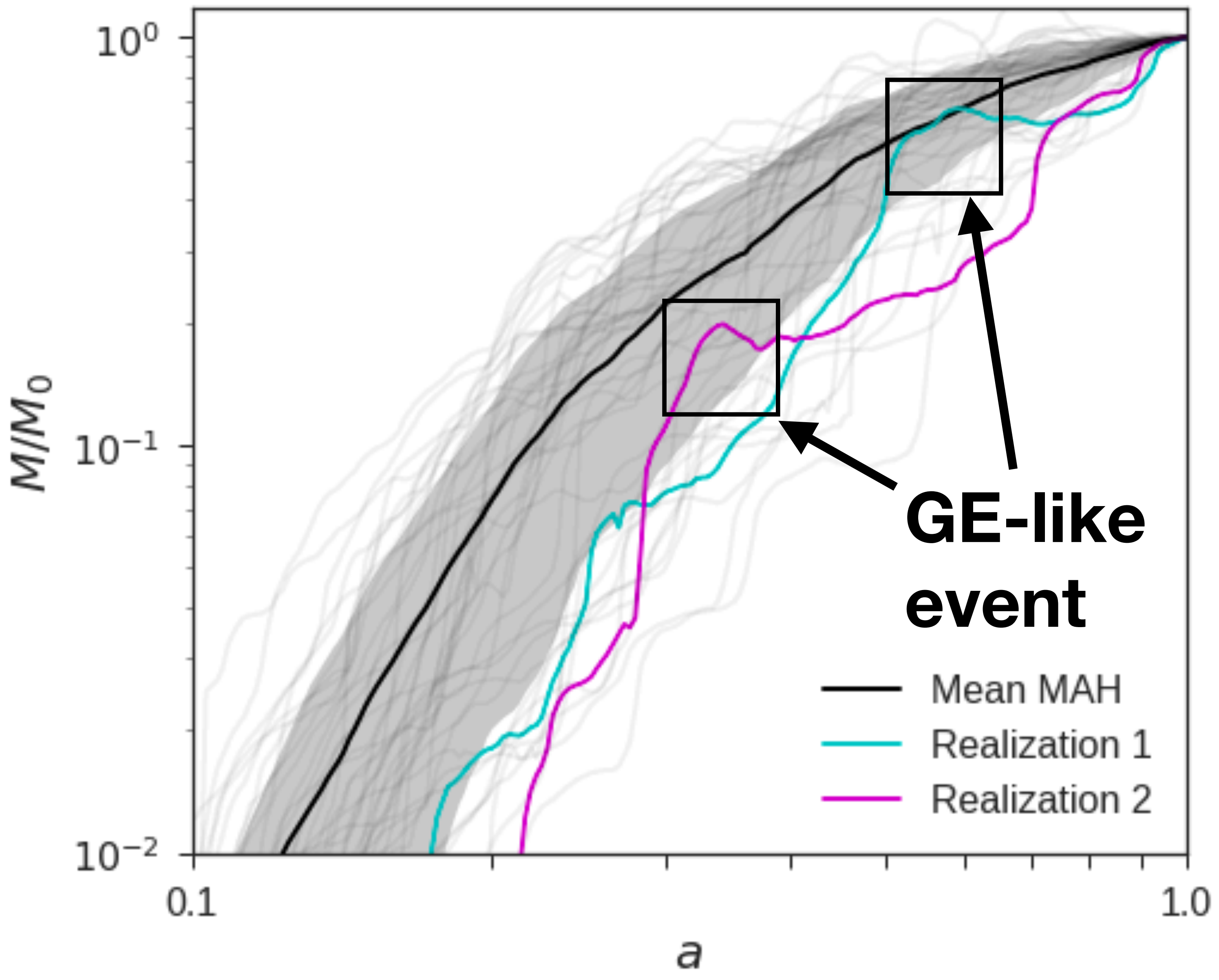
Callingham et al. 2018



Koppelman et al. 2018



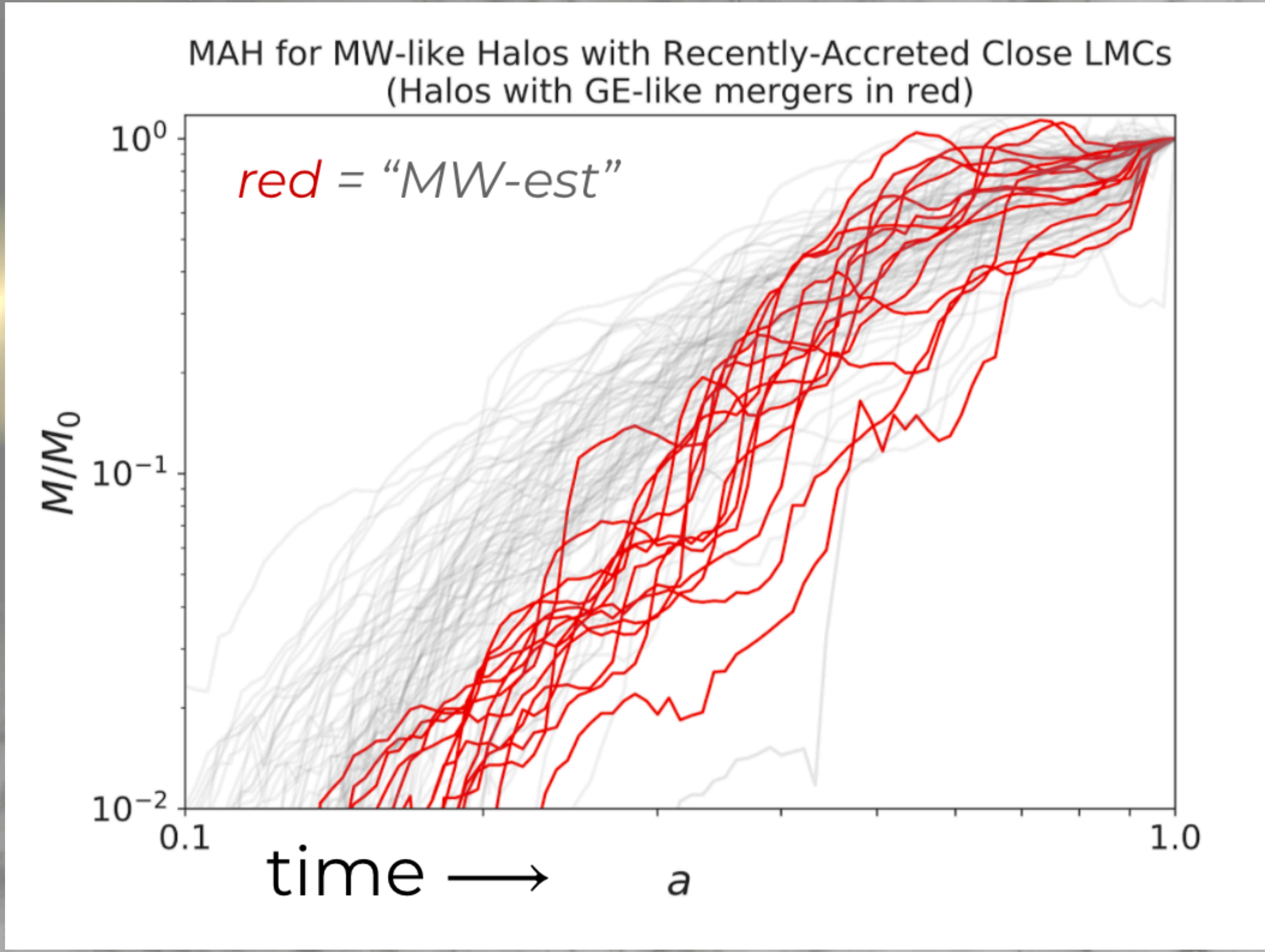
Simulated MWs



Credit: Ralf Kaehler

- In progress: Suite of 14 zoom-in re-simulations of Milky Way-like systems, with *Gaia*-Enceladus mergers and recently-accreted LMCs (started on **XSEDE**)

Deveshi Buch



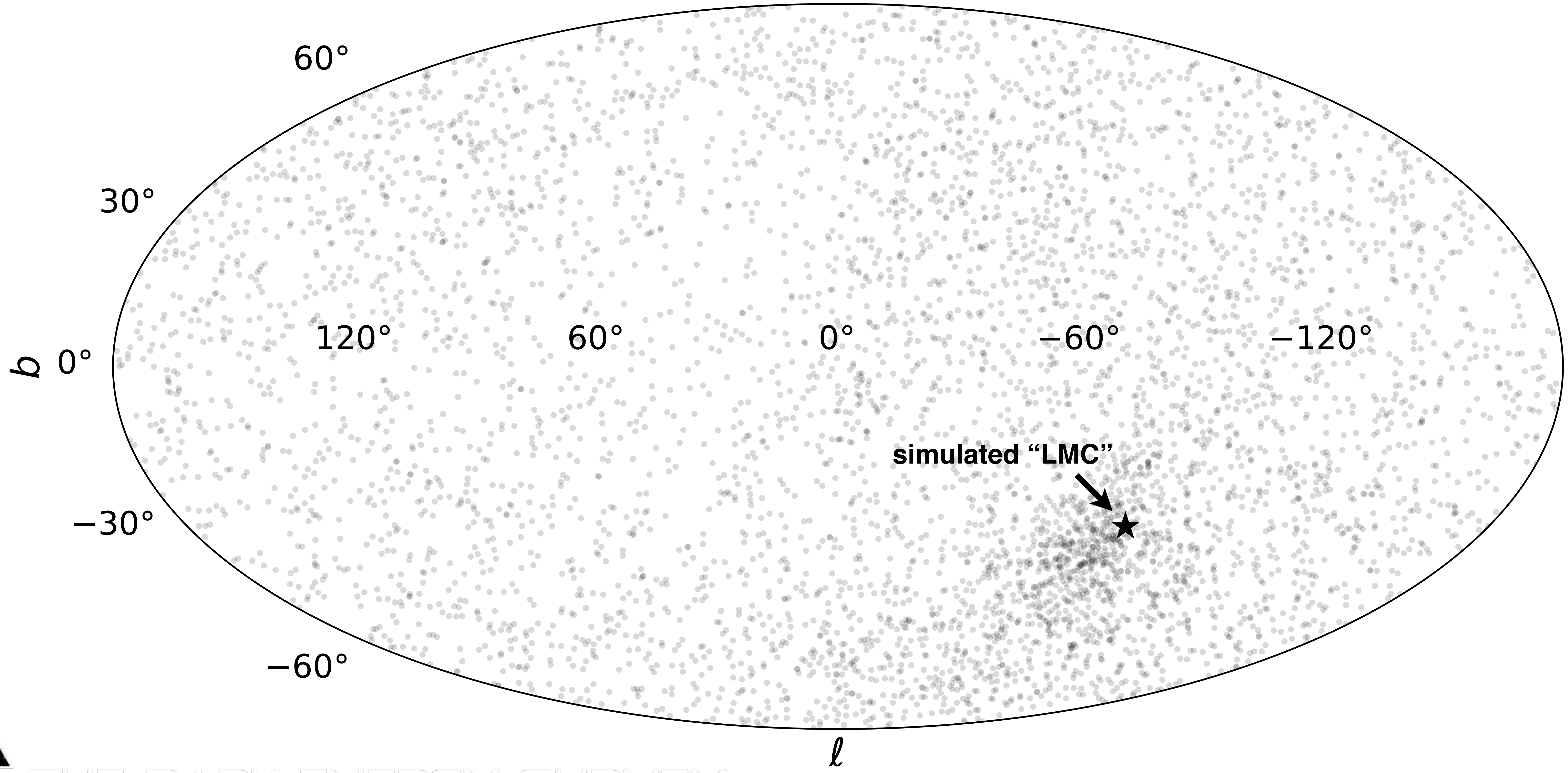
Galaxy–Halo Connection Model

Empirical modeling allows us to marginalize over theoretical uncertainties

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 $(M_V \| V_{\rm peak})$ 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 $(r'_{1/2} \| R_{\rm vir})$ 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, Y.-Y. Mao, G. Green, R. Wechsler 2019

Mock Satellite Observations



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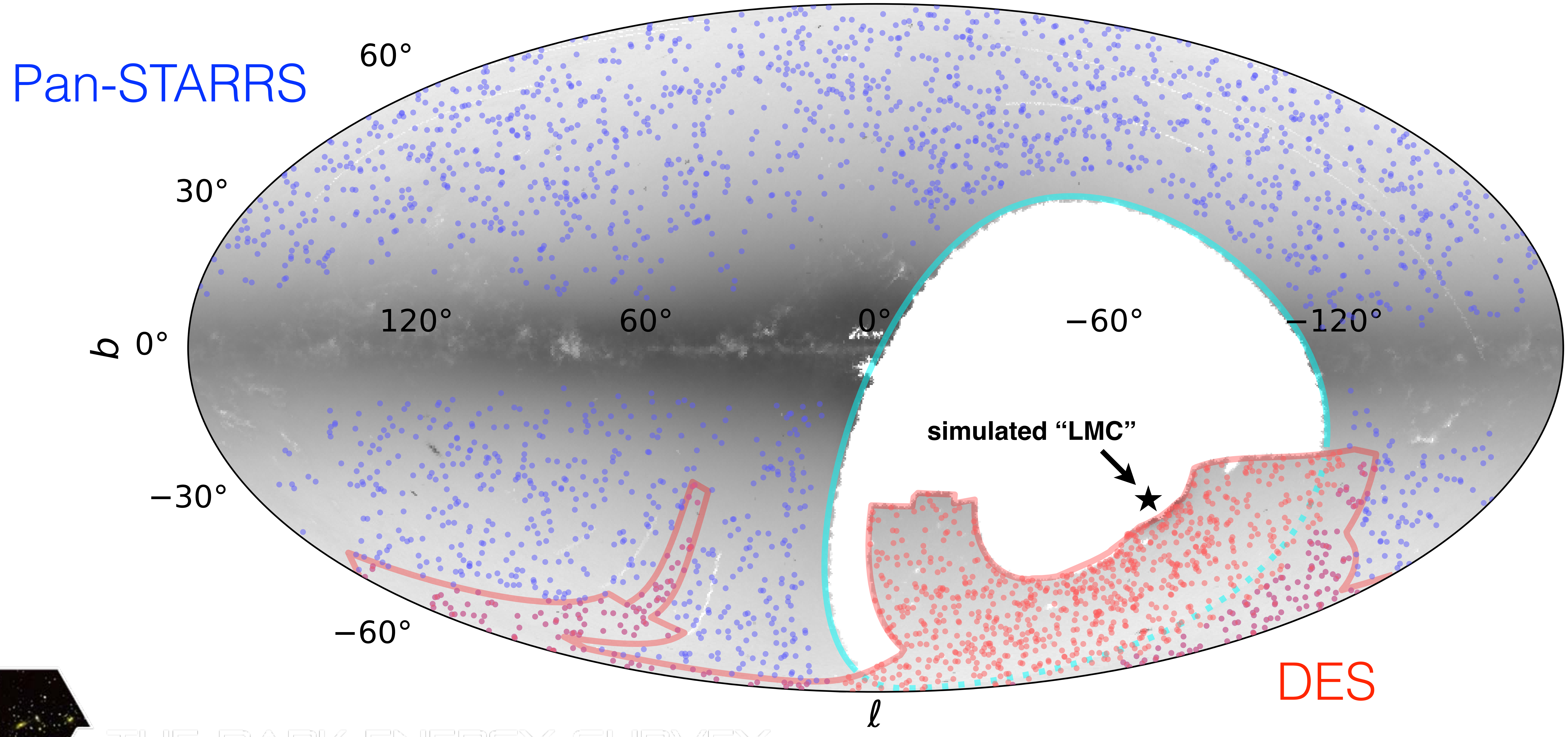
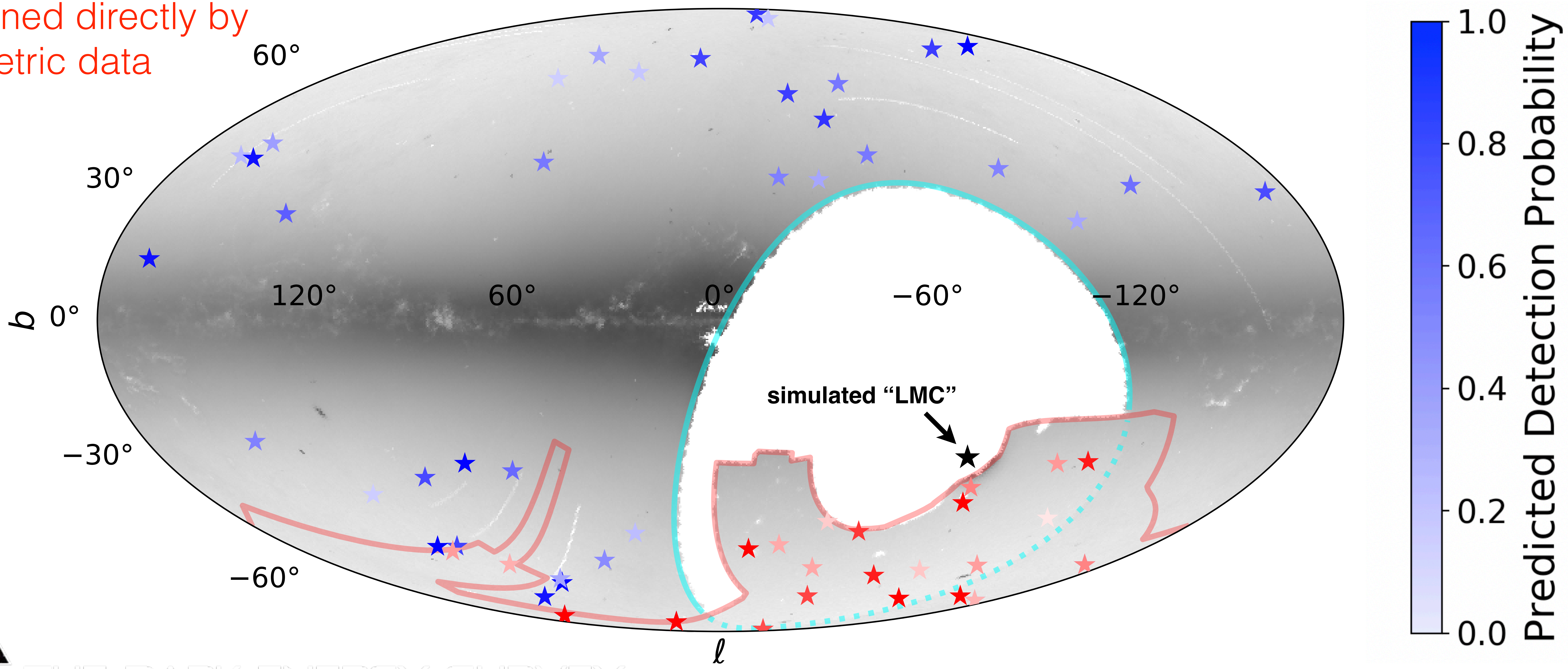
Mock Satellite Observations



Mock Satellite Observations

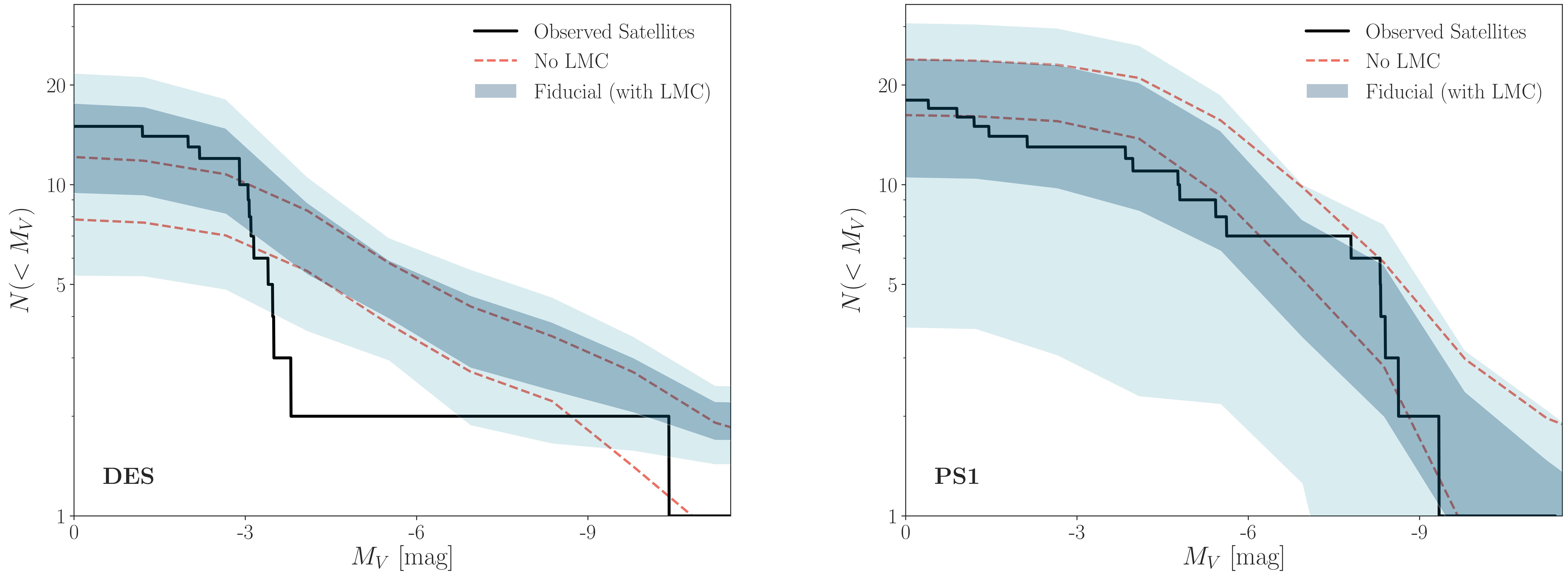
Detection probability is constrained directly by photometric data



Allows for a rigorous statistical comparison to observations

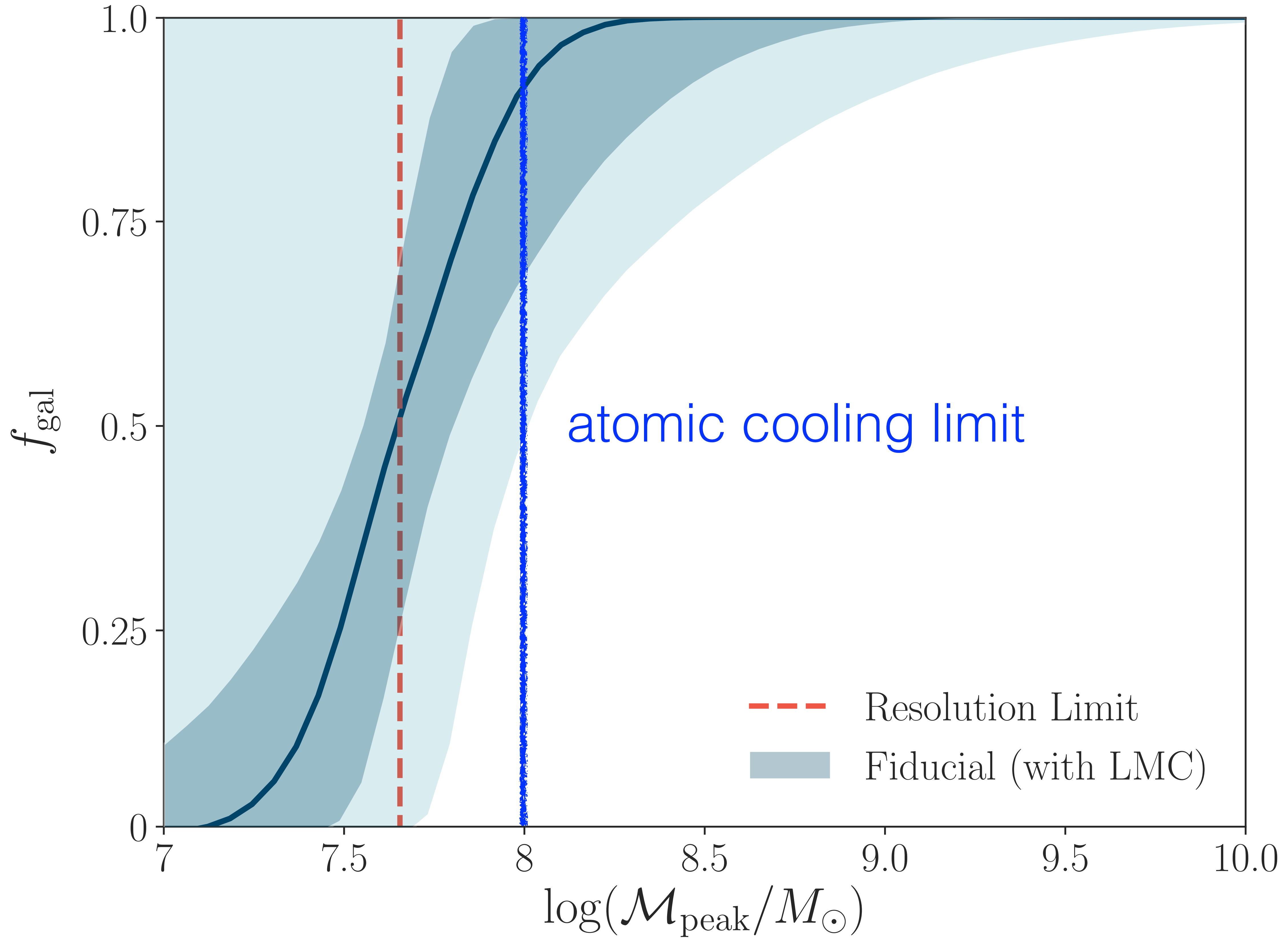
Predicted Satellite Populations

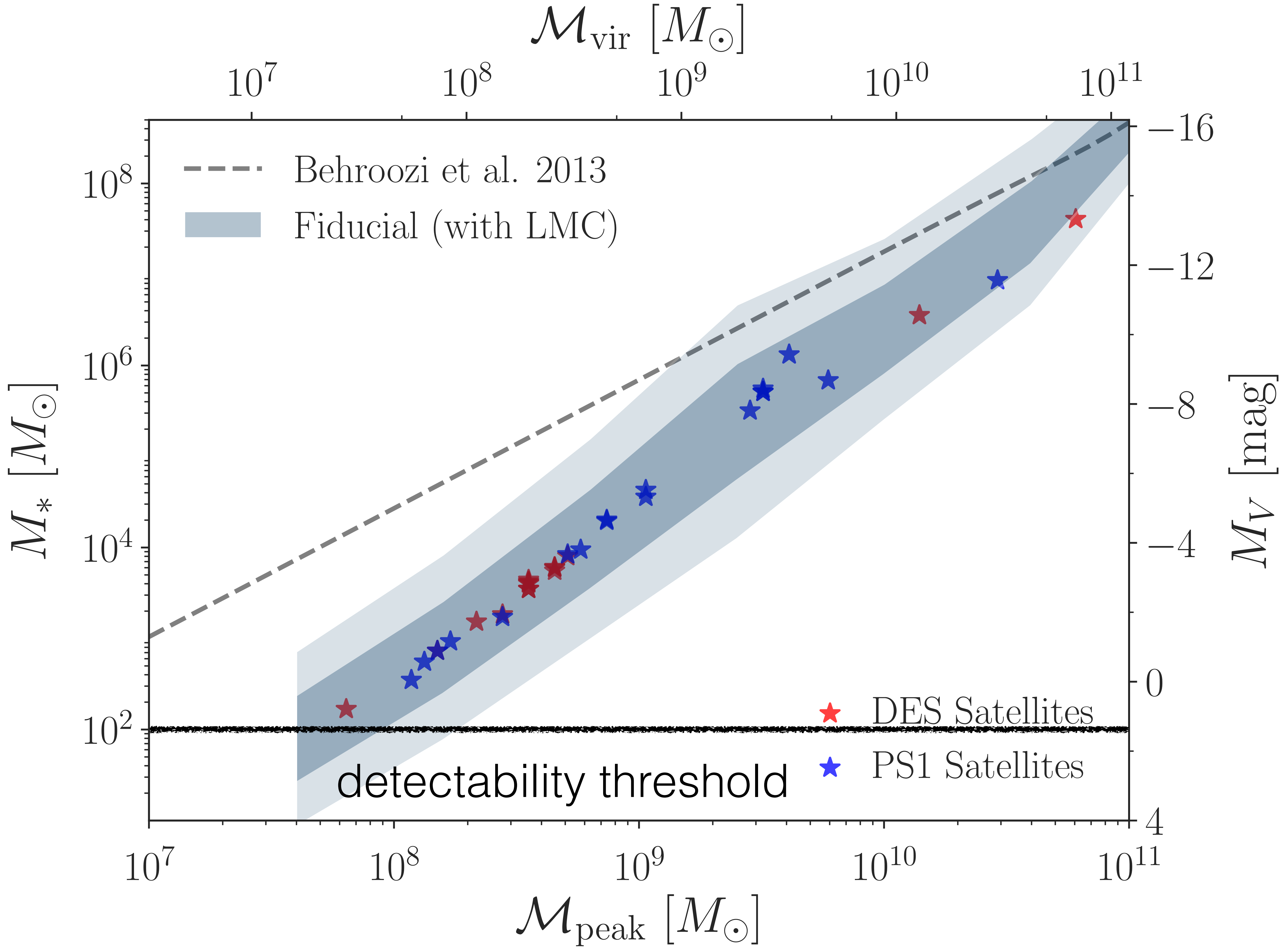
- Recent infall (within last 2 Gyr) of LMC system is **required** to fit the data
- Predict 5 (DES) & 1 (PS1) LMC satellites, consistent with *Gaia* proper motions!



EN & Wechsler et al. 2020

The Faint-End Galaxy–Halo Connection

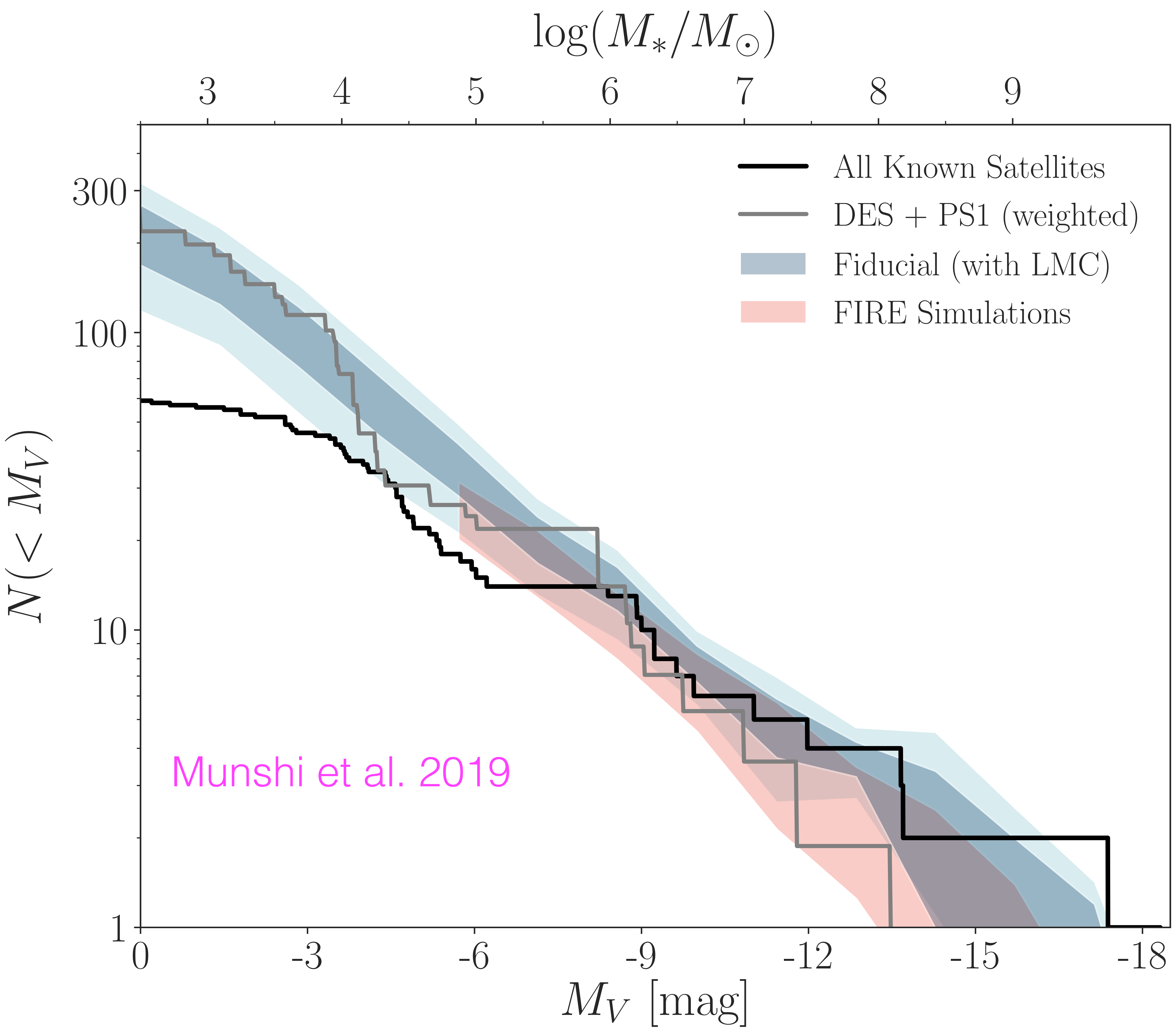




No evidence for a galaxy formation cutoff due to reionization or dark matter physics

The Total MW Satellite Population

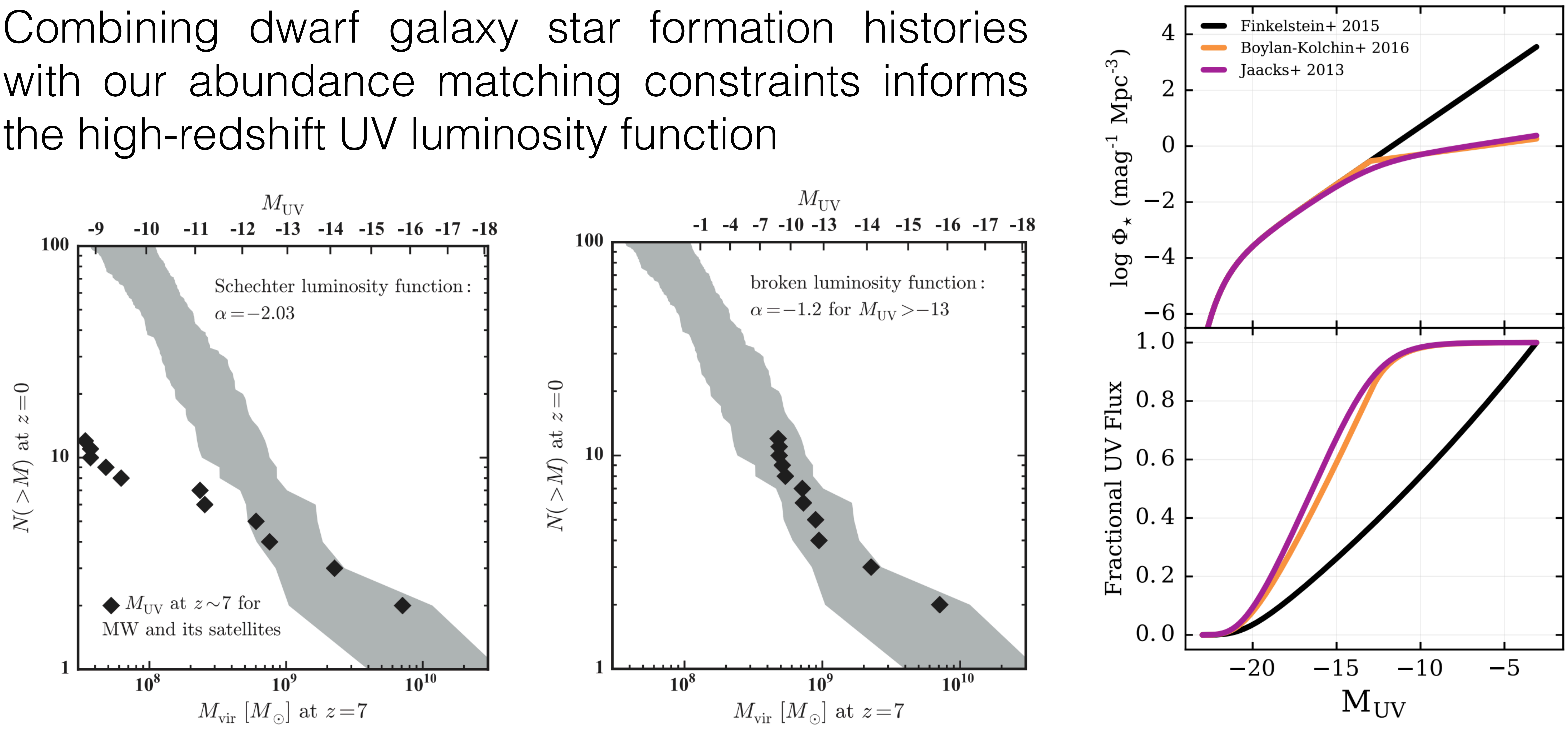
- Predict ~220 total MW satellites, 25% of which are LMC-associated
- Vera C. Rubin Observatory will discover most of these systems
- Spectroscopic confirmation of dark matter-dominated nature is key
- Constraints on faint-end slope and galaxy formation efficiency inform hydrodynamic simulations



EN & Wechsler et al. 2020

Interplay with High-z Galaxy Formation

- Combining dwarf galaxy star formation histories with our abundance matching constraints informs the high-redshift UV luminosity function



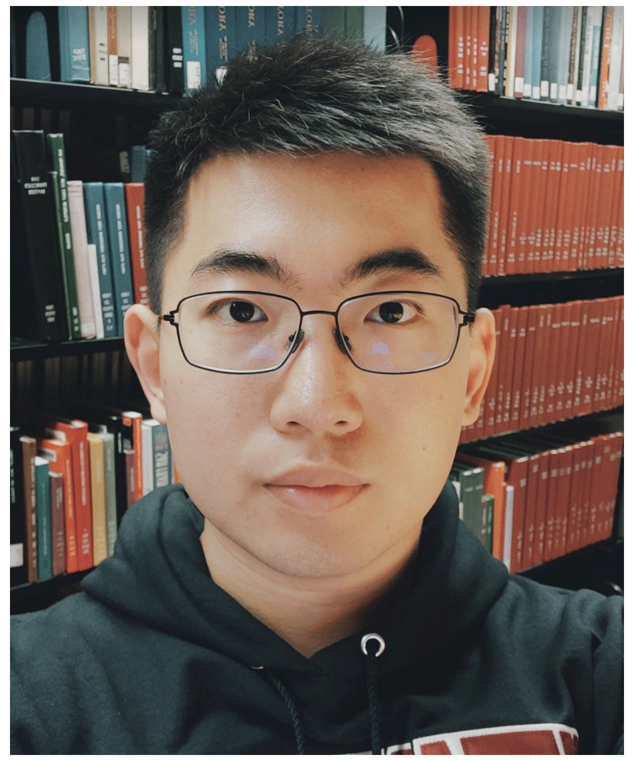
Boylan-Kolchin et al. 2015

Weisz & Boylan-Kolchin 2017

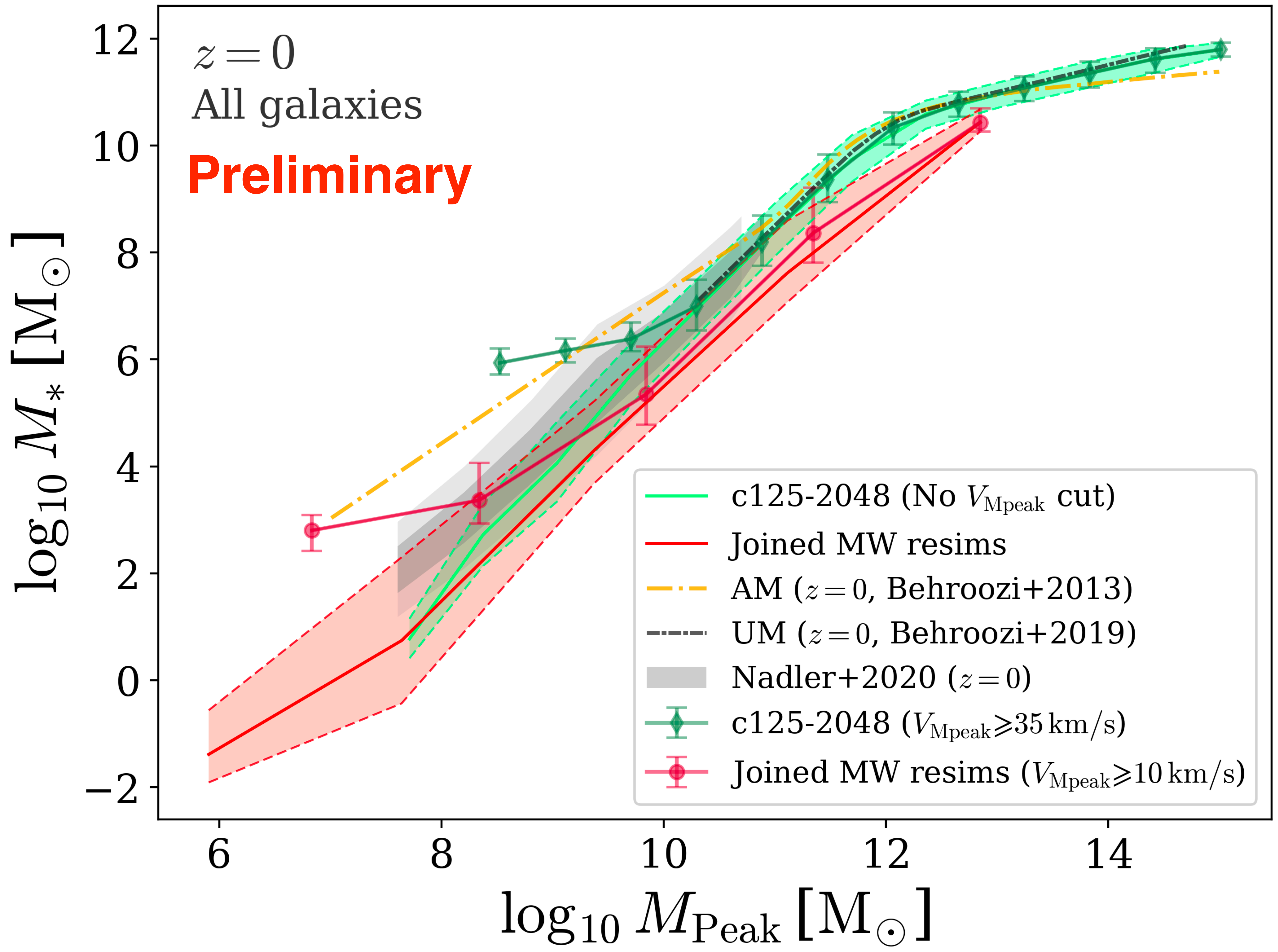
Modeling Satellite Star Formation Histories

- In progress: `UniverseMachine` modeling of star formation histories for satellite systems constrained to match Milky Way observations

- Yields detailed predictions for the progenitors of observed satellites



Yunchong (Richie) Wang



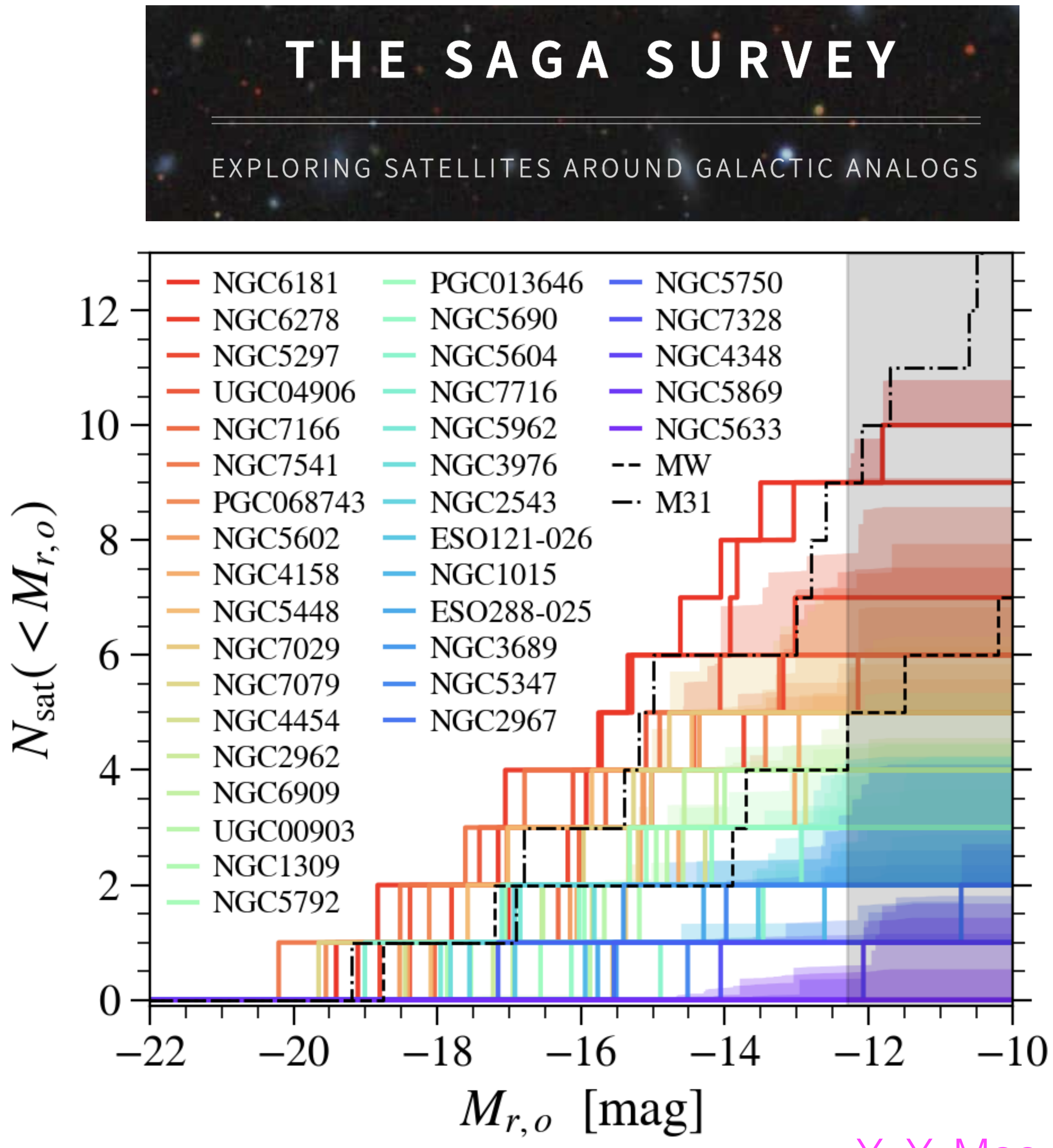
Y. Wang et al. in prep.

Interplay with Milky Way Analog Surveys

- Observations Milky Way analog satellite systems in the nearby universe are rapidly advancing

- The SAGA survey has measured 36 Milky Way analog luminosity functions down to $M_* \sim 10^6\,M_\odot$

- The Milky Way satellite luminosity function is consistent with SAGA and Local Volume observations



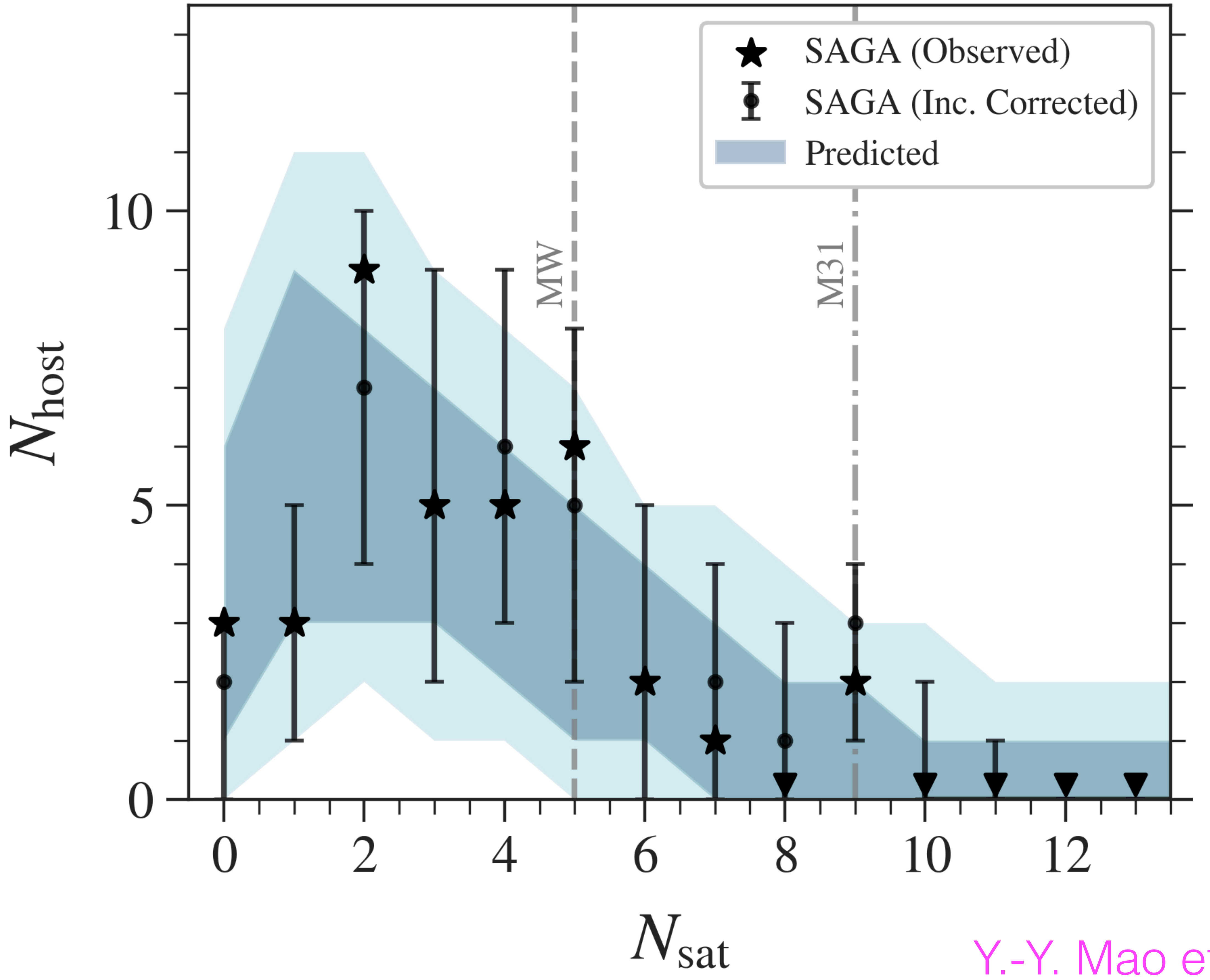
Y.-Y. Mao et al. 2020

Interplay with Milky Way Analog Surveys

- Observations Milky Way analog satellite systems in the nearby universe are rapidly advancing

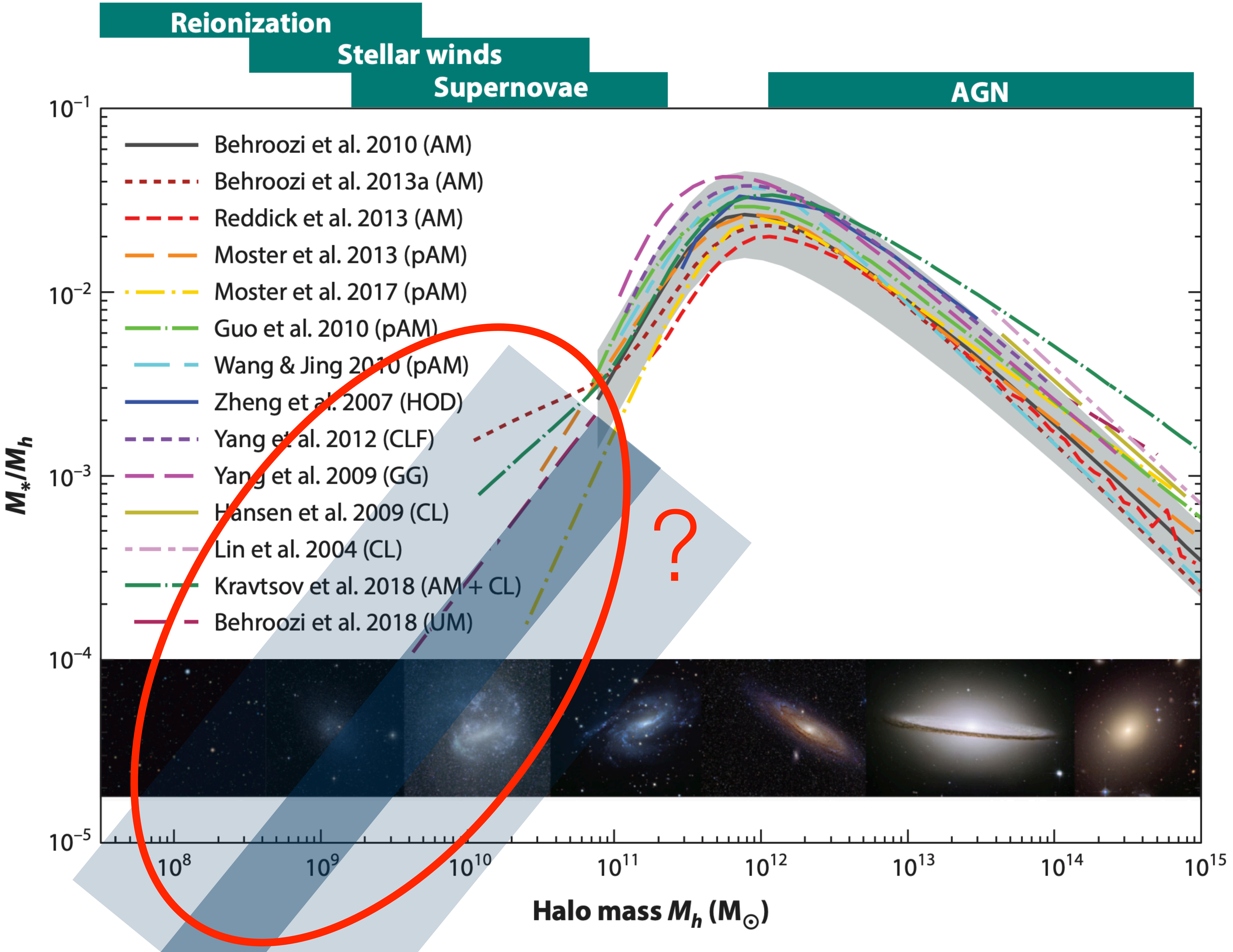
- The SAGA survey has measured 36 Milky Way analog luminosity functions down to $M_* \sim 10^6\,M_\odot$

- Our satellite model predictions (constrained only by Milky Way satellites) are **consistent** with SAGA data



Y.-Y. Mao et al. 2020

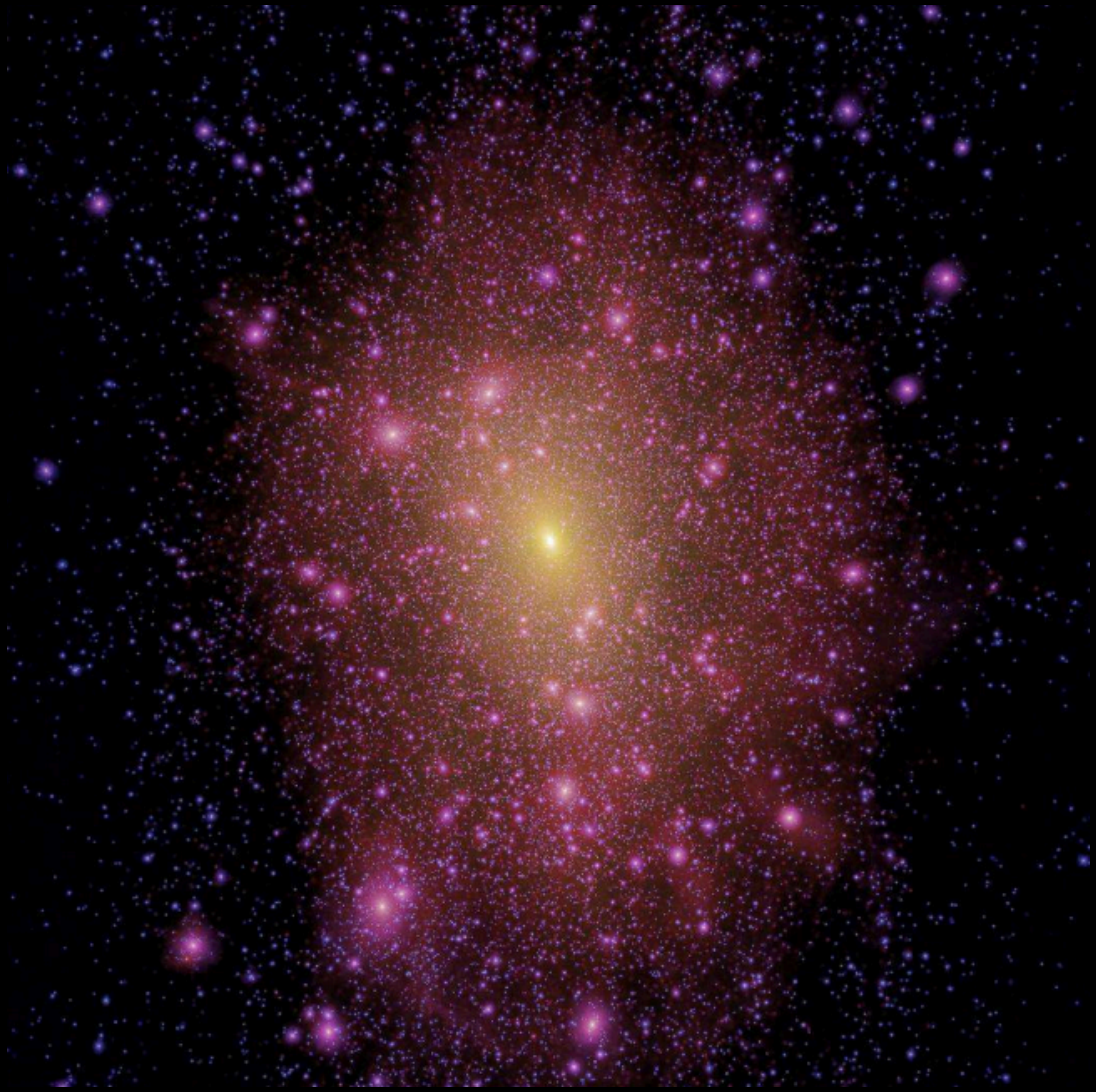
The Faint-End Galaxy–Halo Connection



Wechsler & Tinker 2018

Dark Matter Constraints

CDM

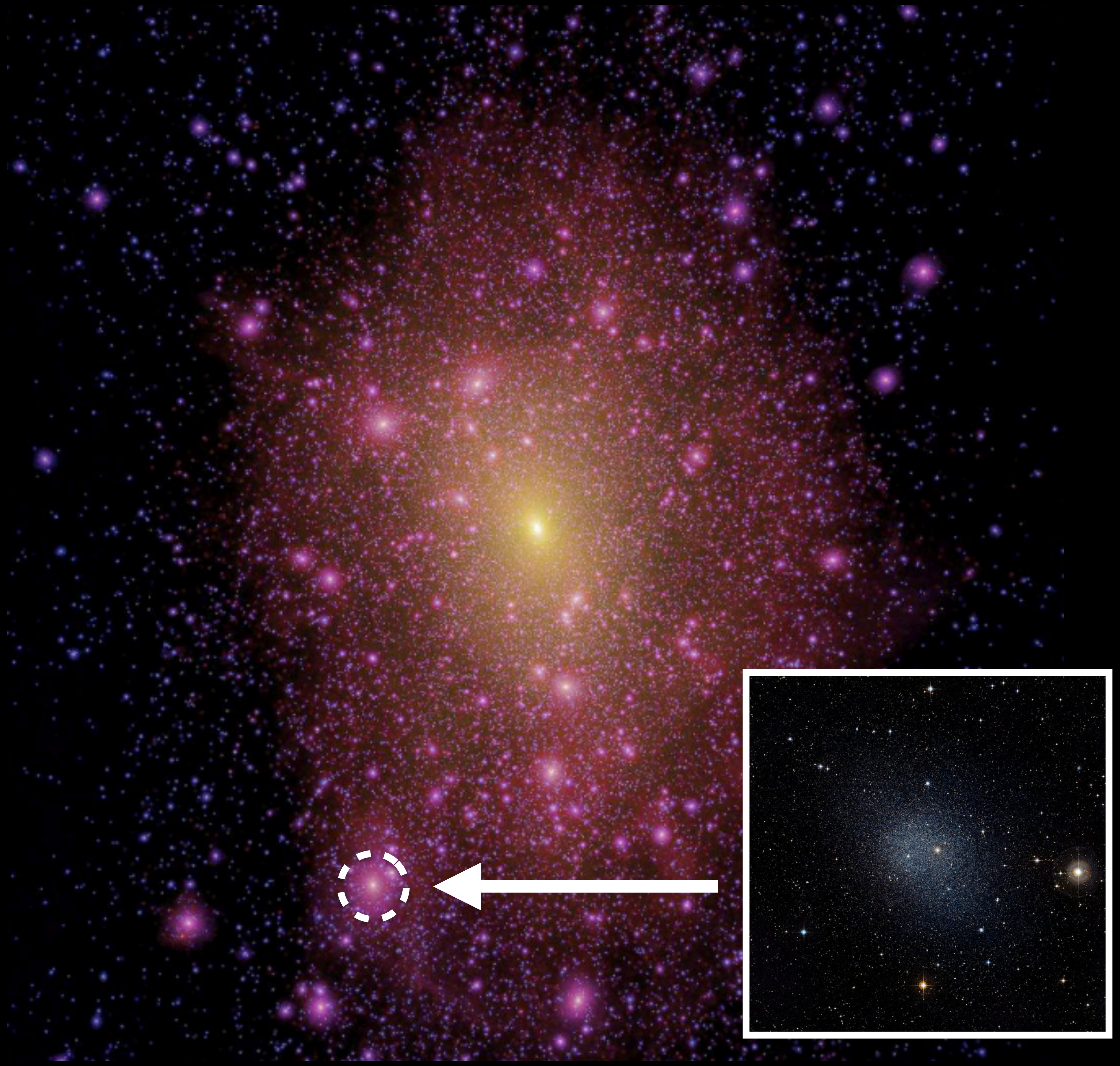


WDM

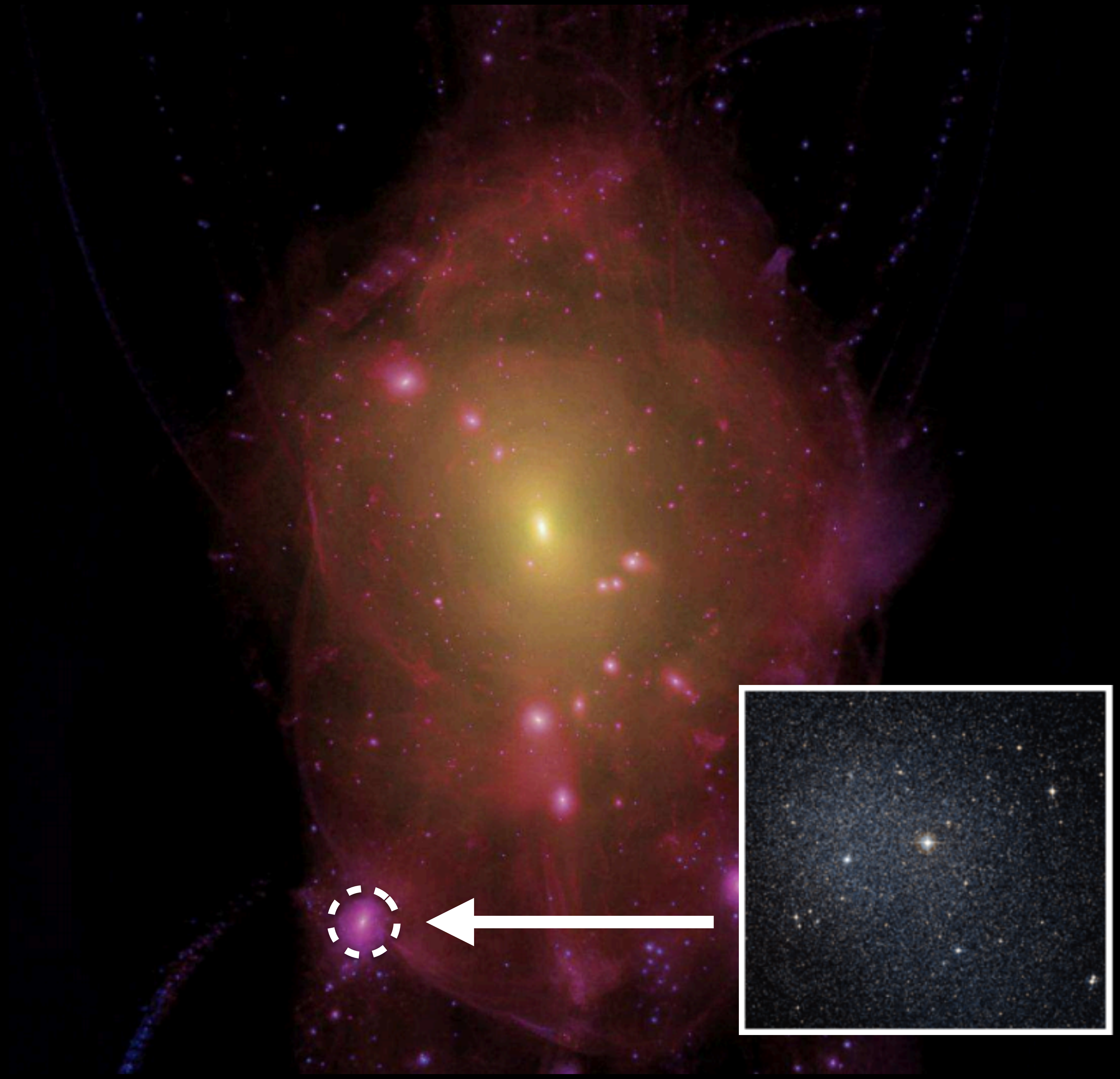
Lovell et al. 2011

Dark Matter Constraints

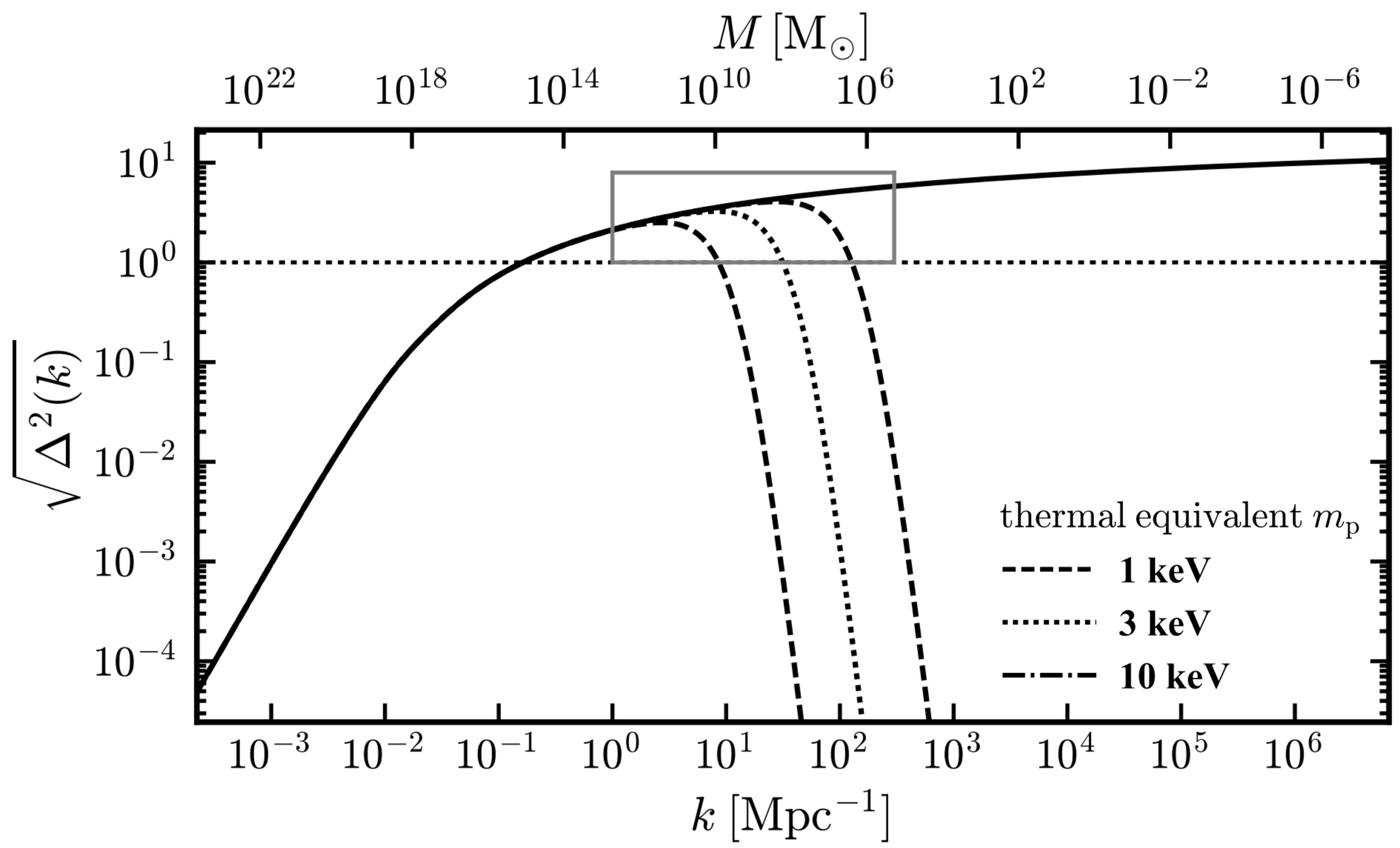
CDM



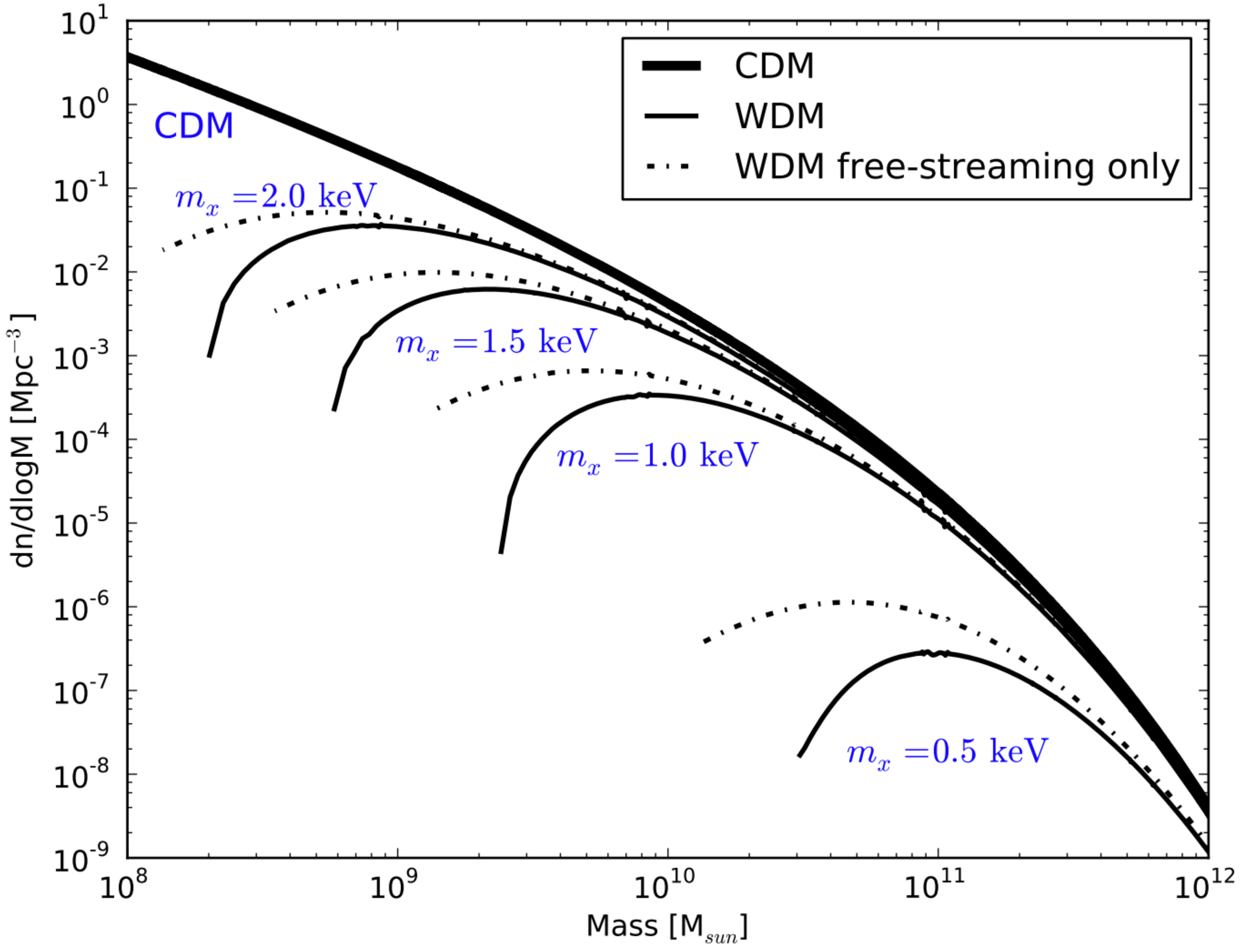
WDM



DM Physics and the Minimum Halo Mass



Bullock & Boylan-Kolchin 2017

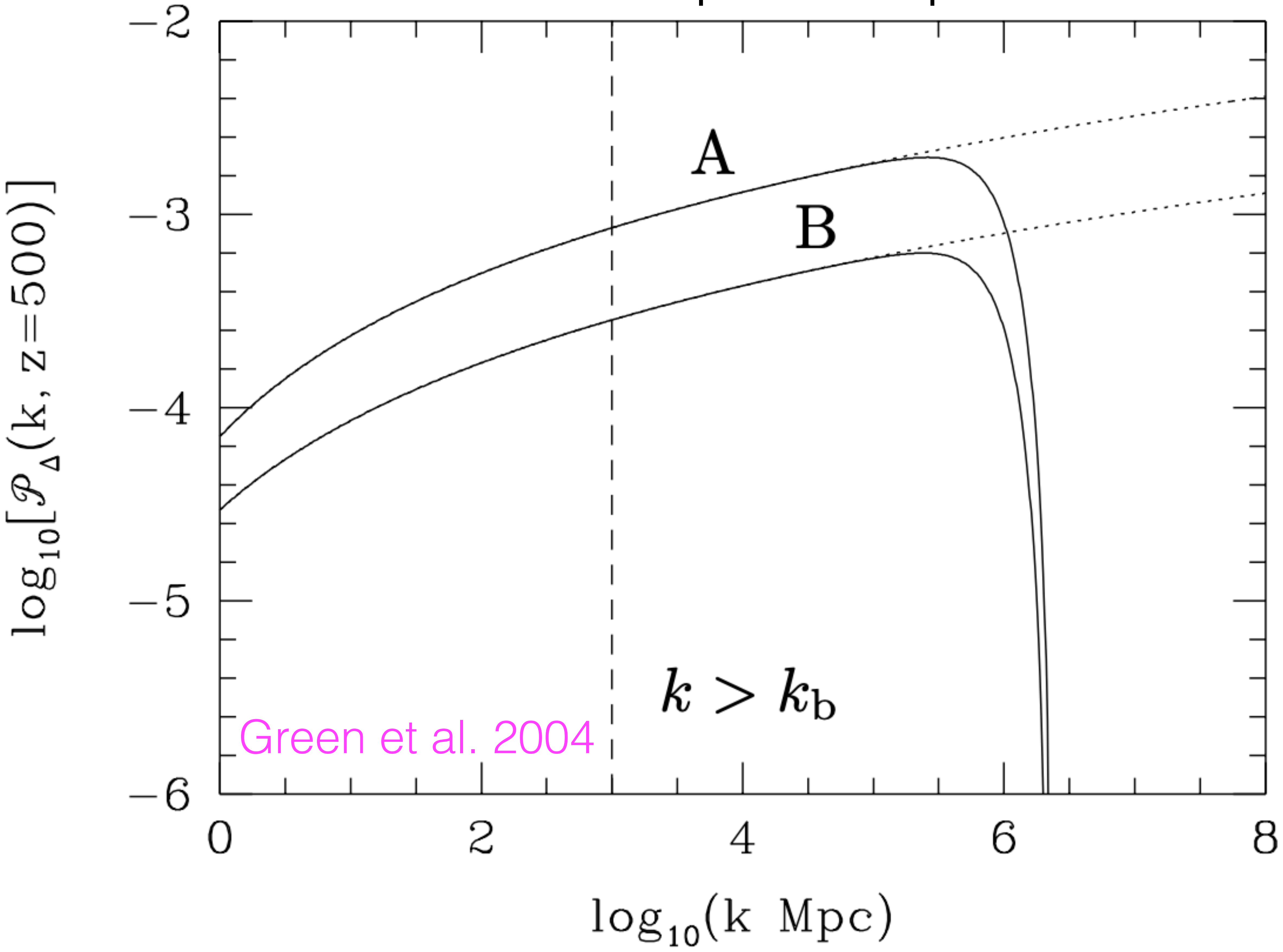


Pacucci et al. 2013

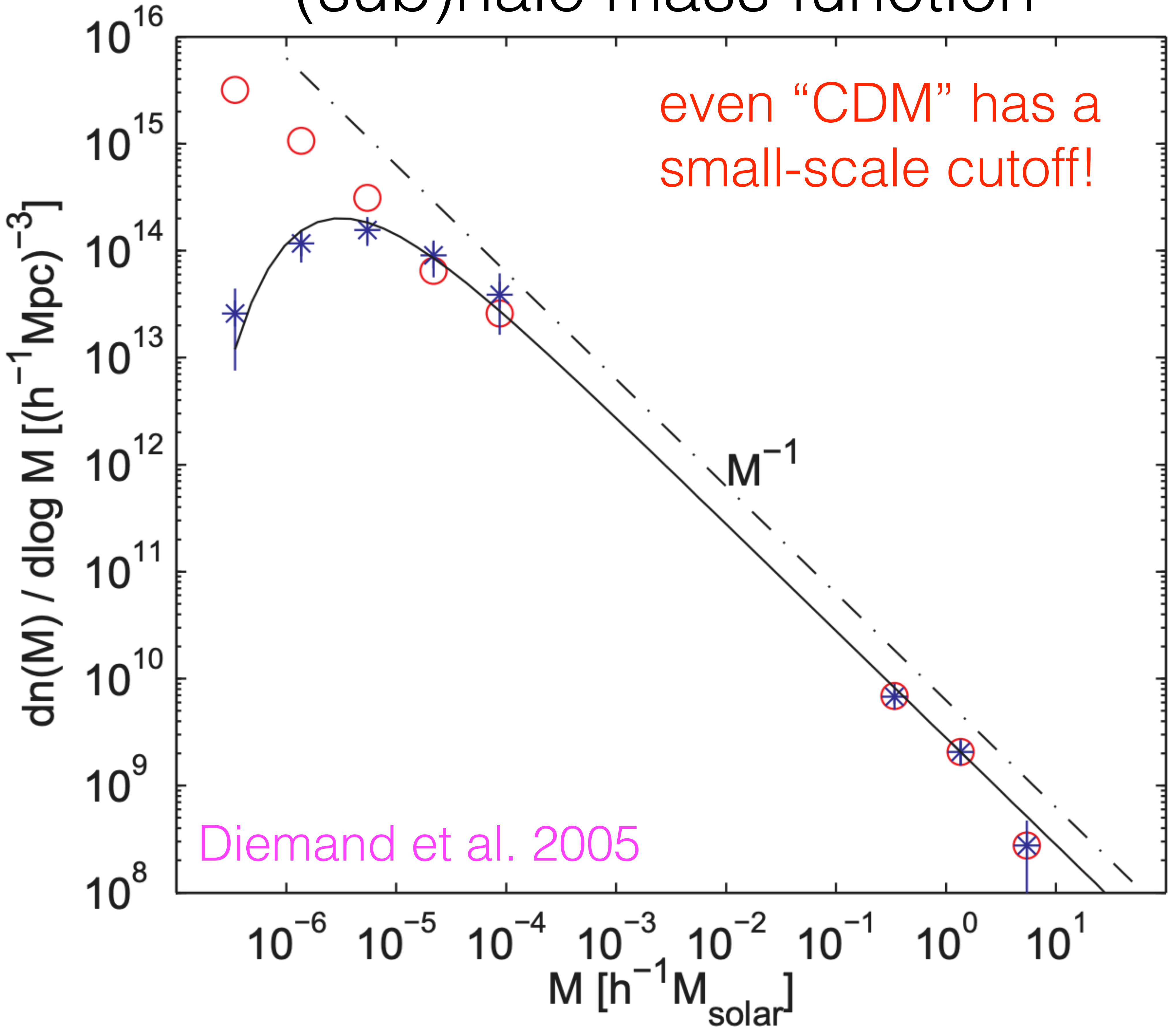
free-streaming due to large primordial velocity dispersion → cutoff in abundance of low-mass halos

DM Physics and the Minimum Halo Mass

linear matter power spectrum

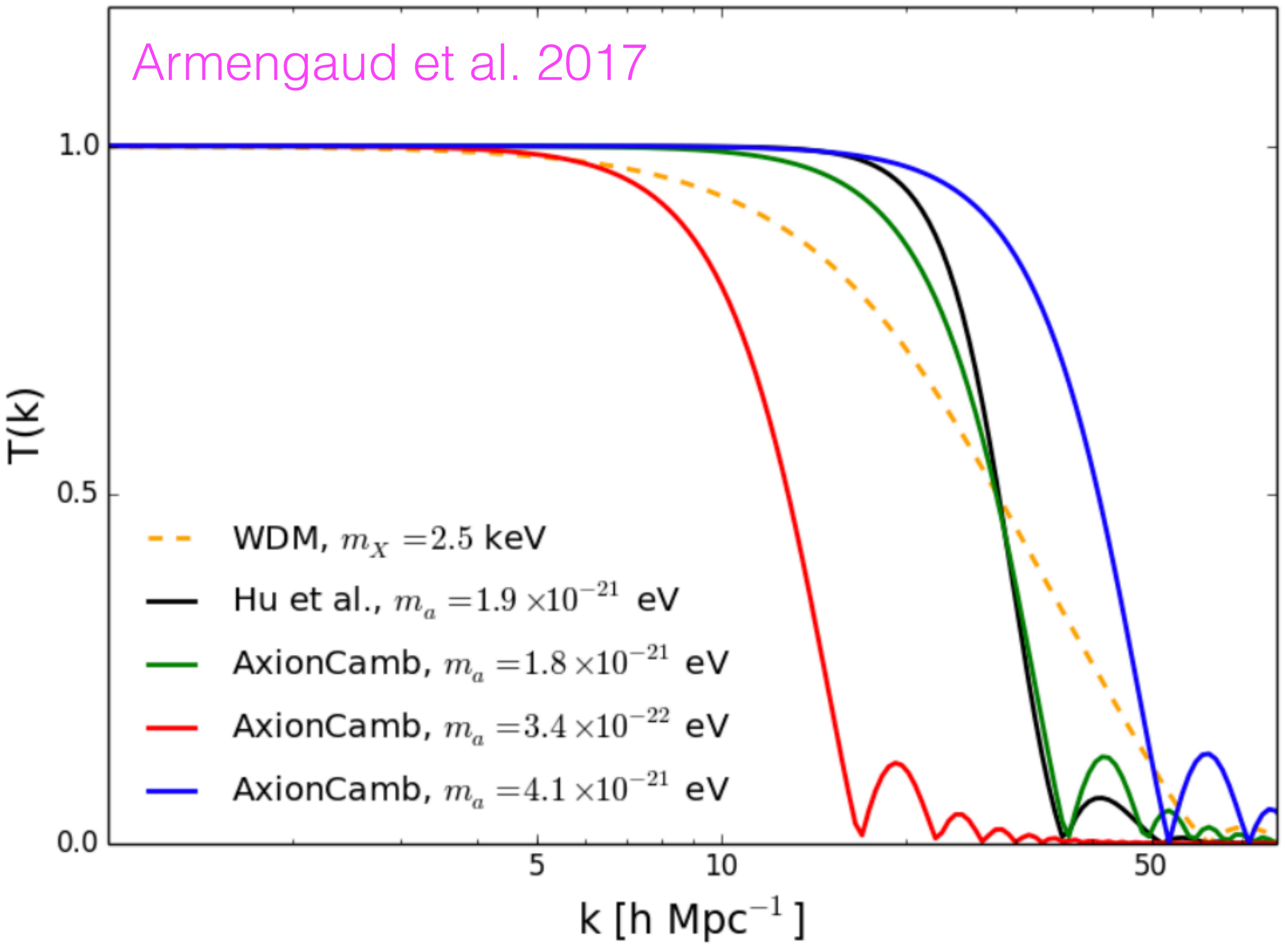


(sub)halo mass function



collisional damping due to DM–SM interactions → cutoff in abundance of low-mass halos

DM Physics and the Minimum Halo Mass



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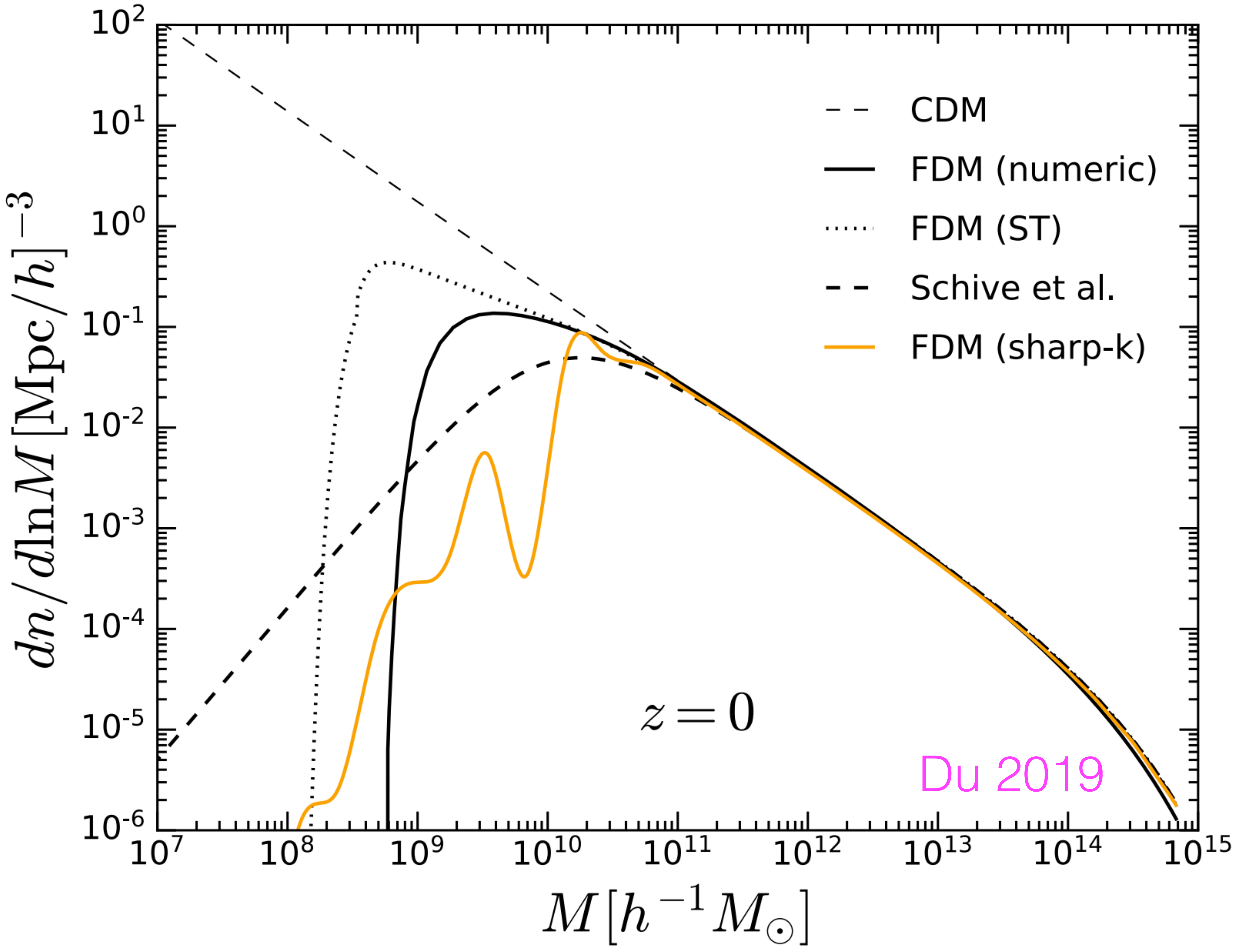
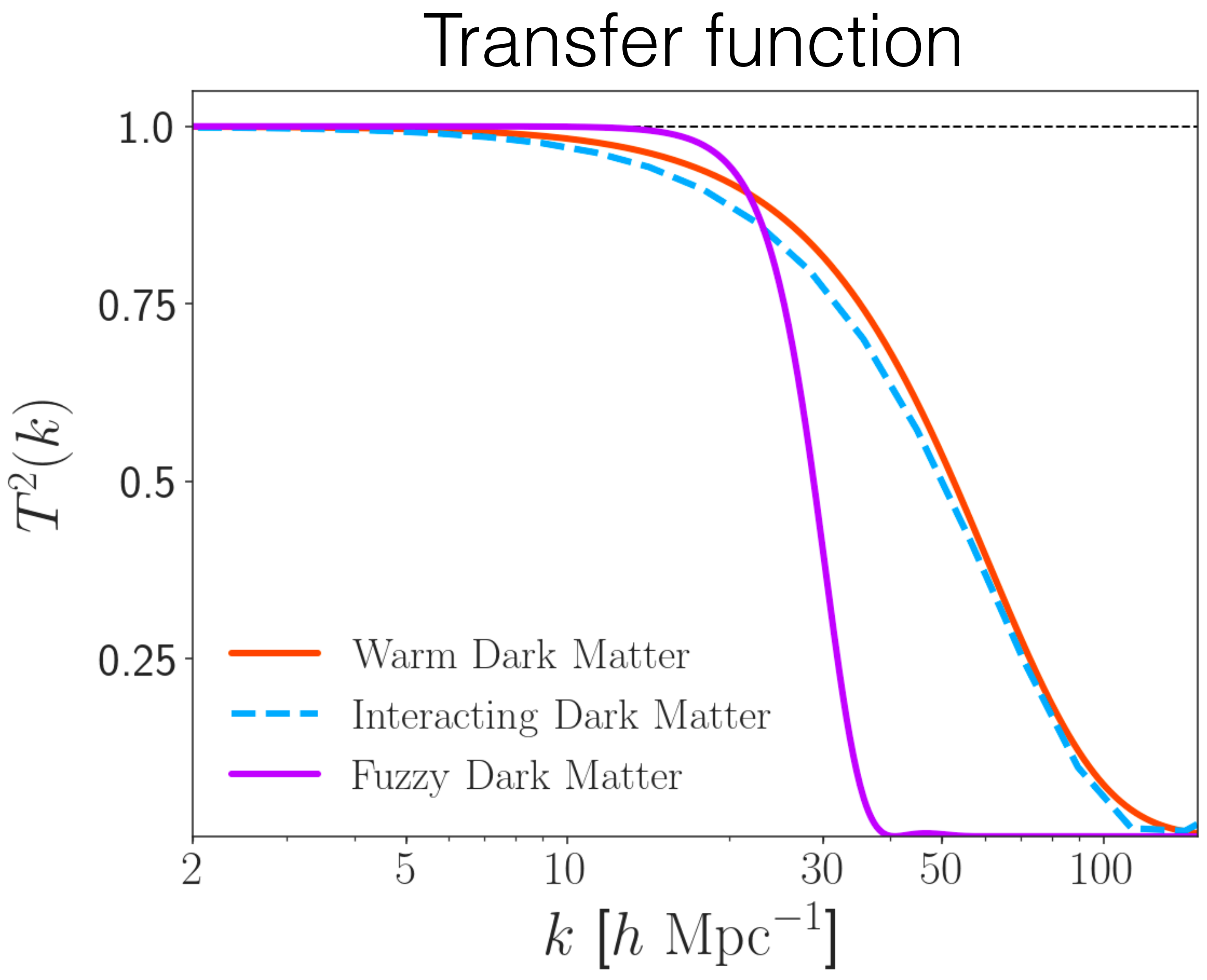
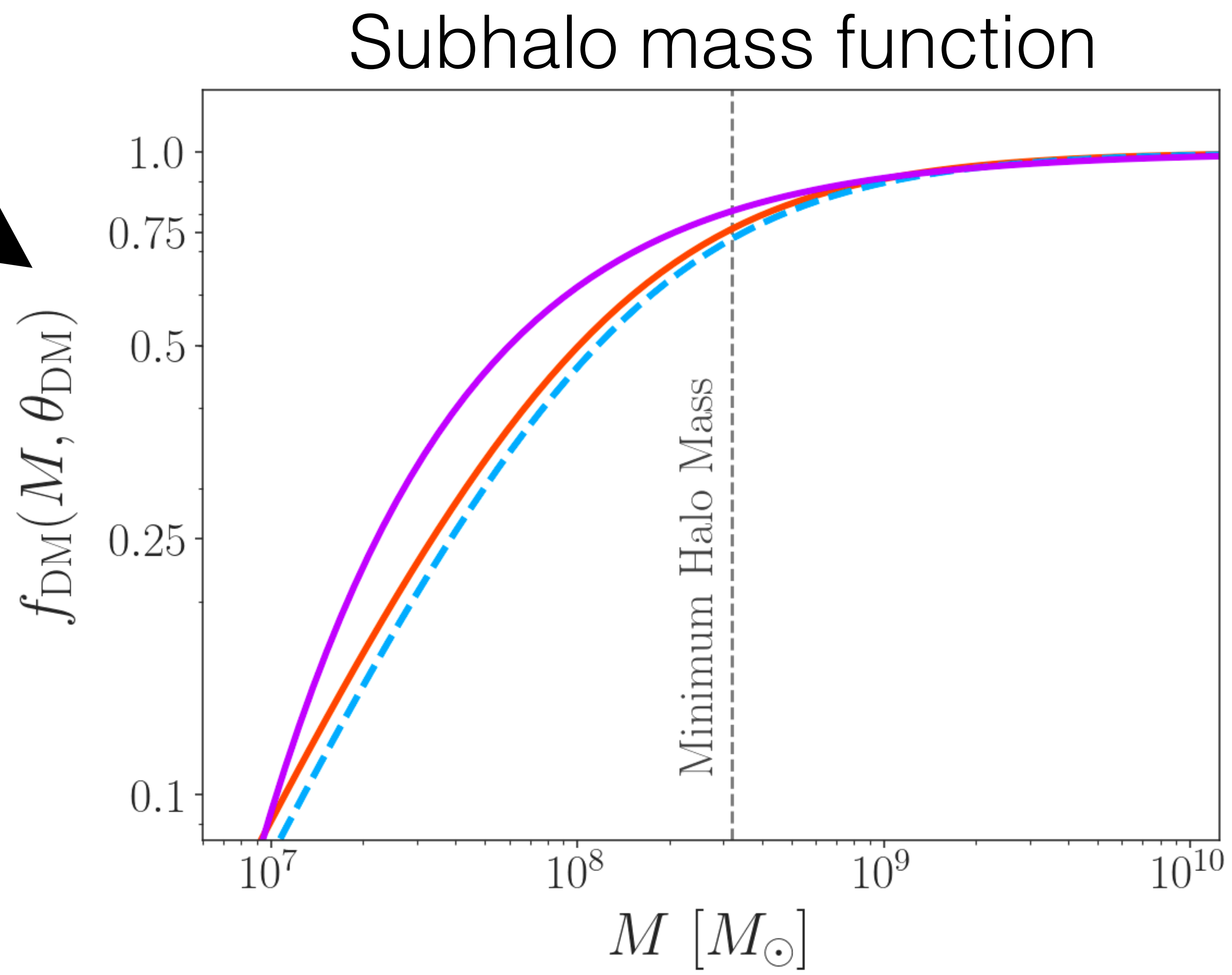
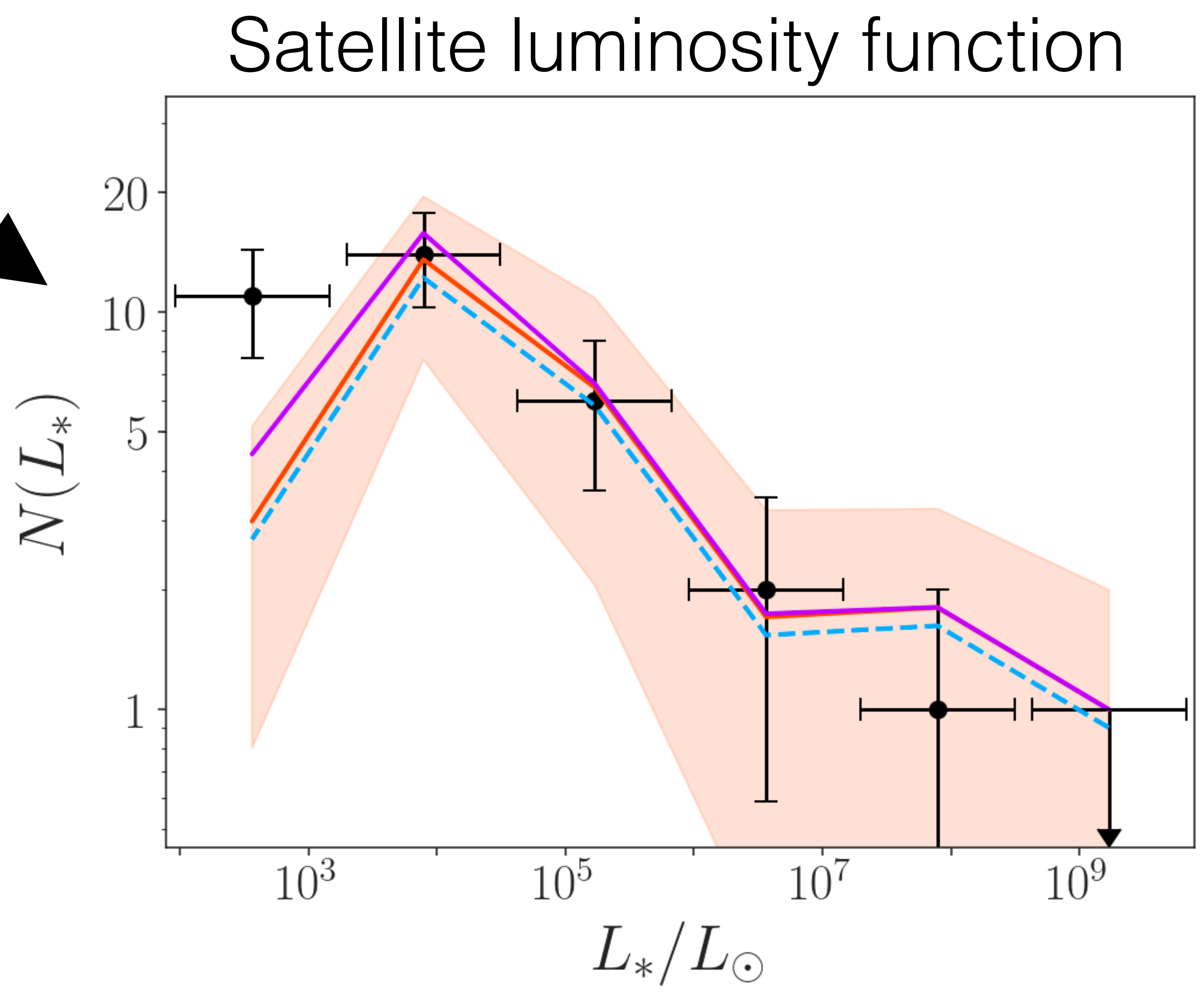


interference due to macroscopic de Broglie wavelength → cutoff in abundance of low-mass halos

Fit the Milky Way satellite population with subhalo mass function suppression, marginalizing over galaxy–halo connection and MW halo properties:







Current satellite observations are sensitive to **~25%** suppression in subhalo abundance relative to CDM

EN & Drlica-Wagner et al. 2020

Dark Matter Constraints

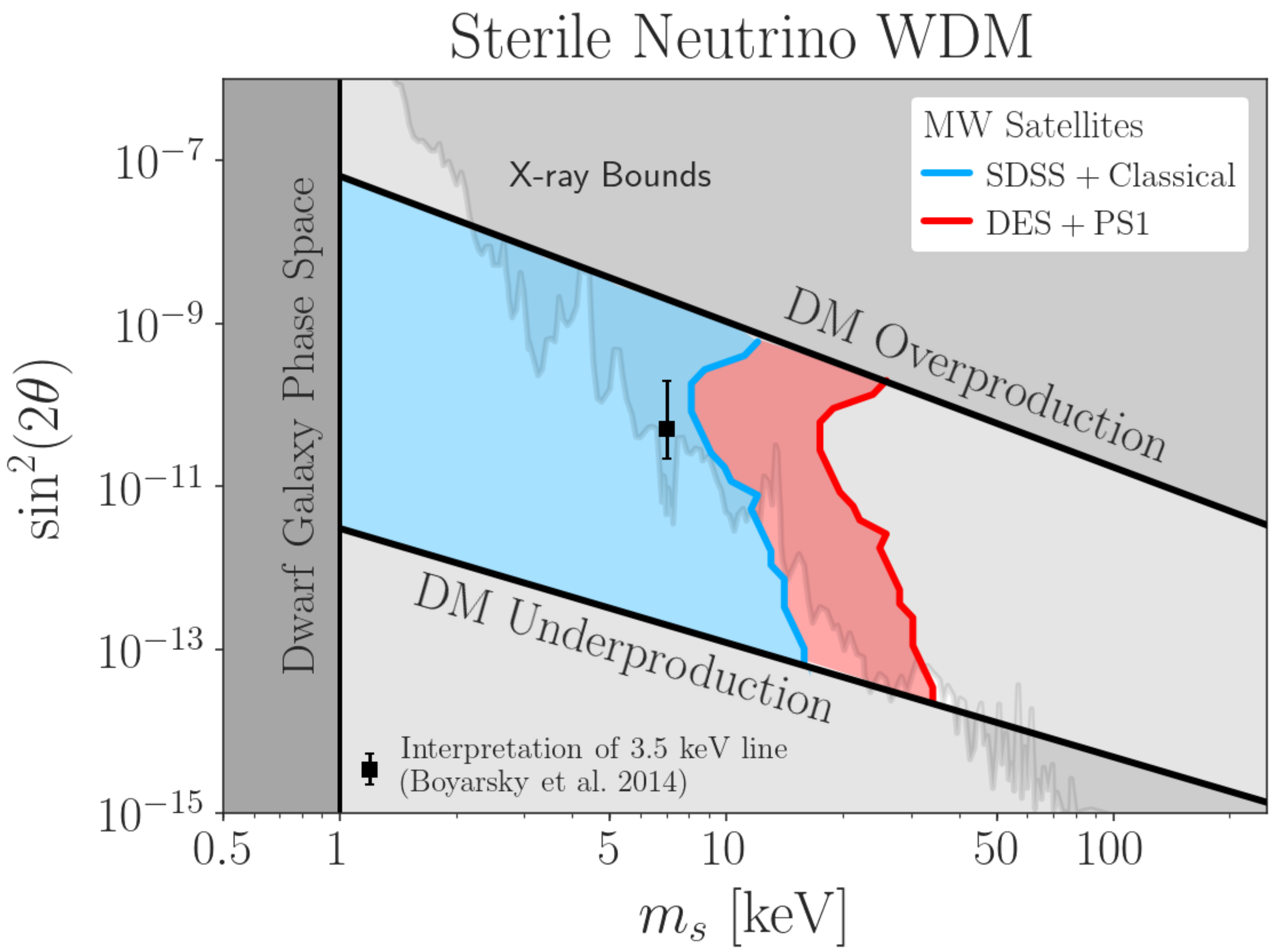
- Our Milky Way satellite analysis yields the strongest astrophysical constraints to date on a variety of dark matter properties and particle models
- For thermal relic WDM: **m_{WDM} > 6.5 keV** at 95% confidence, comparable to limits from the Lyman-α forest, strong gravitational lensing, and stellar streams (with distinct systematics)
- This is the opposite of searching under a lamppost!

Dark Matter Paradigm	Parameter	Constraint	Derived Property	Constraint
Warm Dark Matter	Thermal Relic Mass	$m_{\rm WDM} > 6.5\,{\rm keV}$	Free-streaming Length	$\lambda_{\rm fs} \lesssim 10\,h^{-1}\,{\rm kpc}$
Interacting Dark Matter	Velocity-independent DM–Proton Cross Section	$\sigma_0 < 8.8 \times 10^{-29}\,{\rm cm}^2$	DM–Proton Coupling	$c_p \lesssim (0.3\,{\rm GeV})^{-2}$
Fuzzy Dark Matter	Particle Mass	$m_\phi > 2.9 \times 10^{-21}\,{\rm eV}$	de Broglie Wavelength	$\lambda_{\rm dB} \lesssim 0.5\,{\rm kpc}$

EN & Drlica-Wagner et al. 2020

Warm Dark Matter Constraints

- Nearly all viable parameter space for resonantly-produced sterile neutrino dark matter is ruled out
- The sterile neutrino interpretation of the 3.5 keV X-ray line is ruled out at >> 99% confidence
- The dark matter free-streaming length must be smaller than the sizes of the halos that host ultra-faint dwarf galaxies (~10 kpc)



EN & Drlica-Wagner et al. 2020

Interacting Dark Matter Constraints

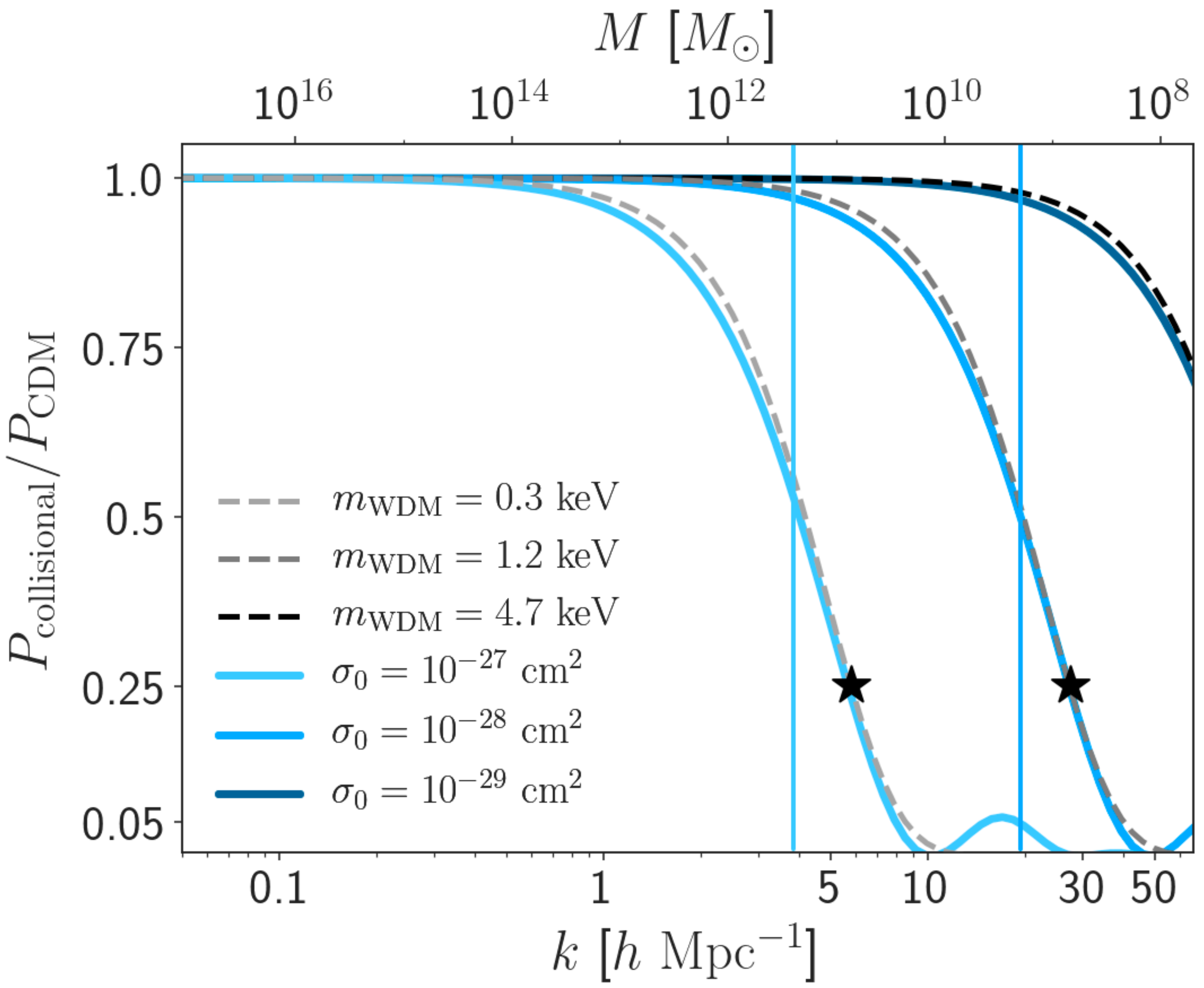
- Collisional damping due to DM–baryon scattering at early times suppresses power on small scales

- Mass of the smallest halo allowed to form corresponds to the size of the horizon when

$$R_\chi \sim aH$$

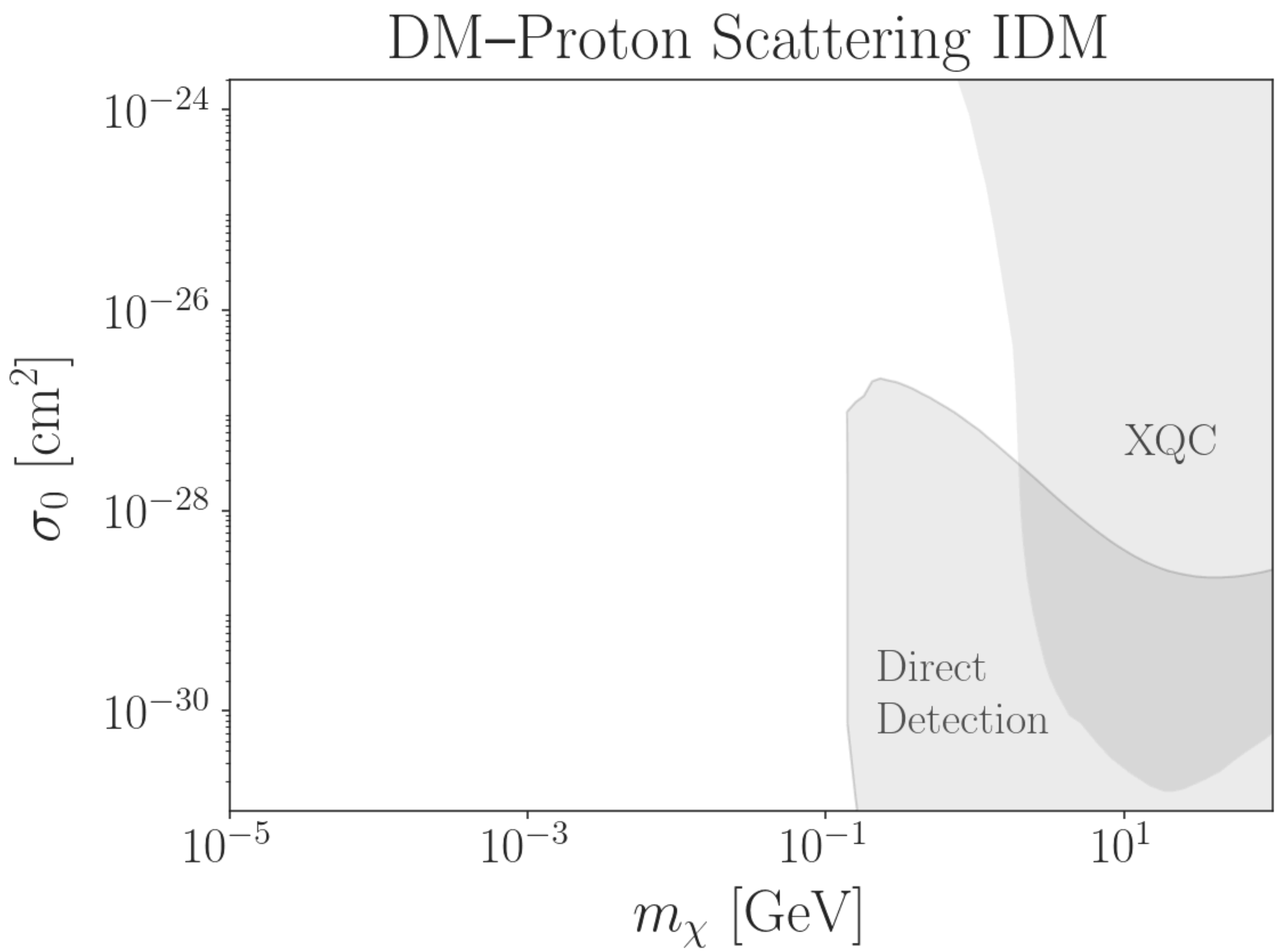
Momentum transfer rate → R_χ; Hubble rate → aH

- Minimum observed halo mass sets cross section limit



EN, V. Gluscevic, K. Boddy, R. Wechsler 2019

Interacting Dark Matter Constraints



EN & Drlica-Wagner et al. 2020

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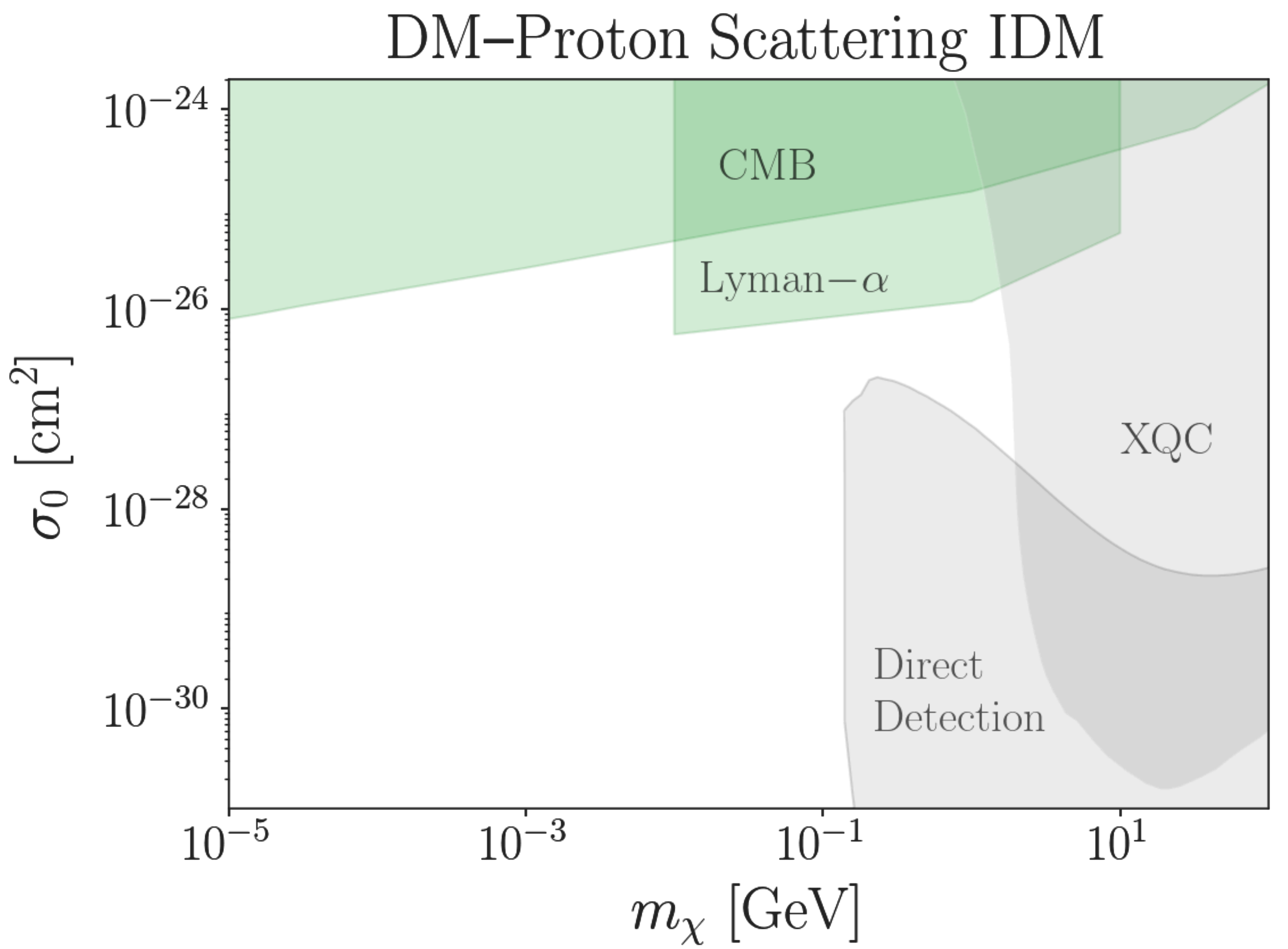

EN & Drlica-Wagner et al. 2020

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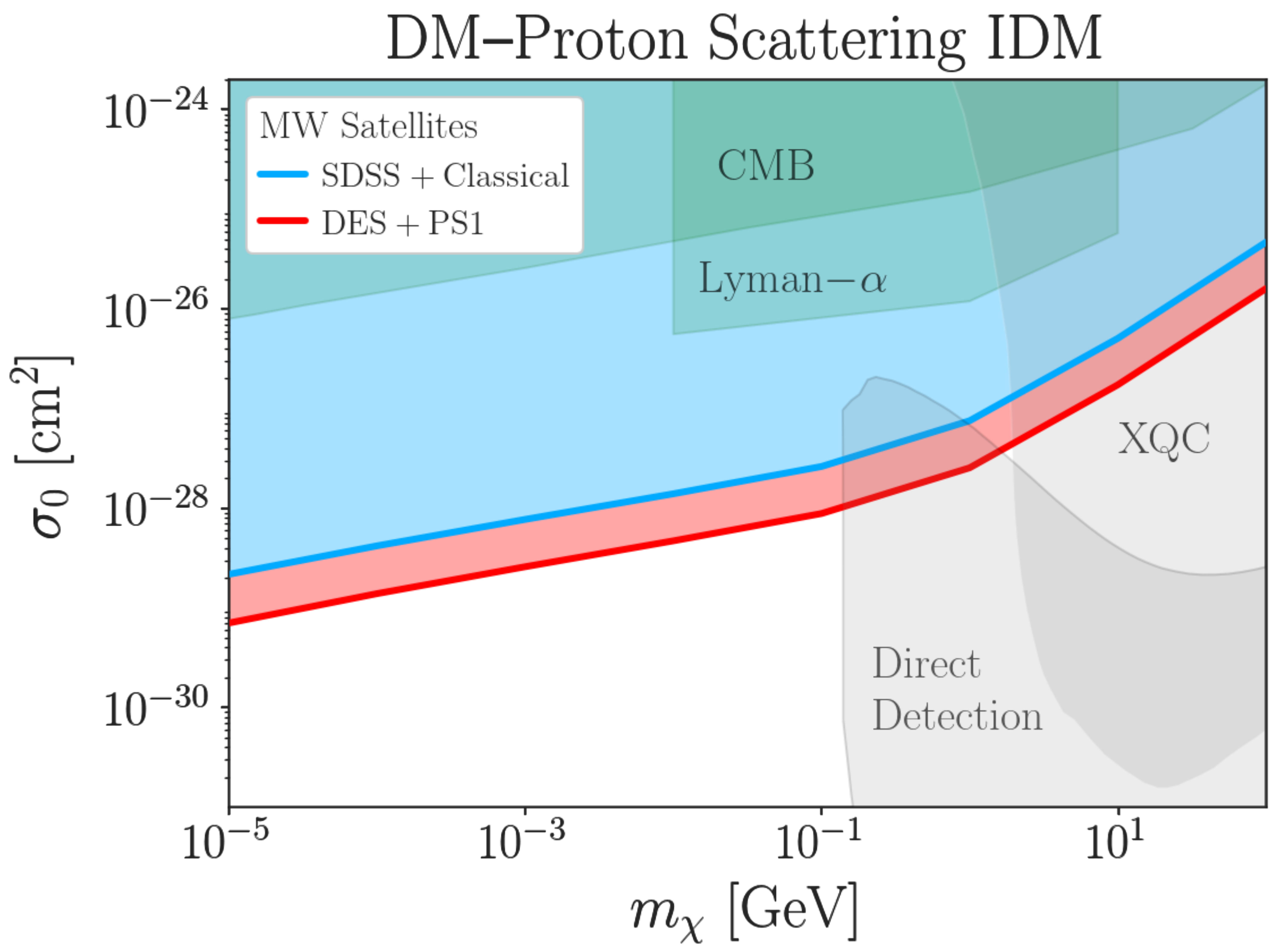
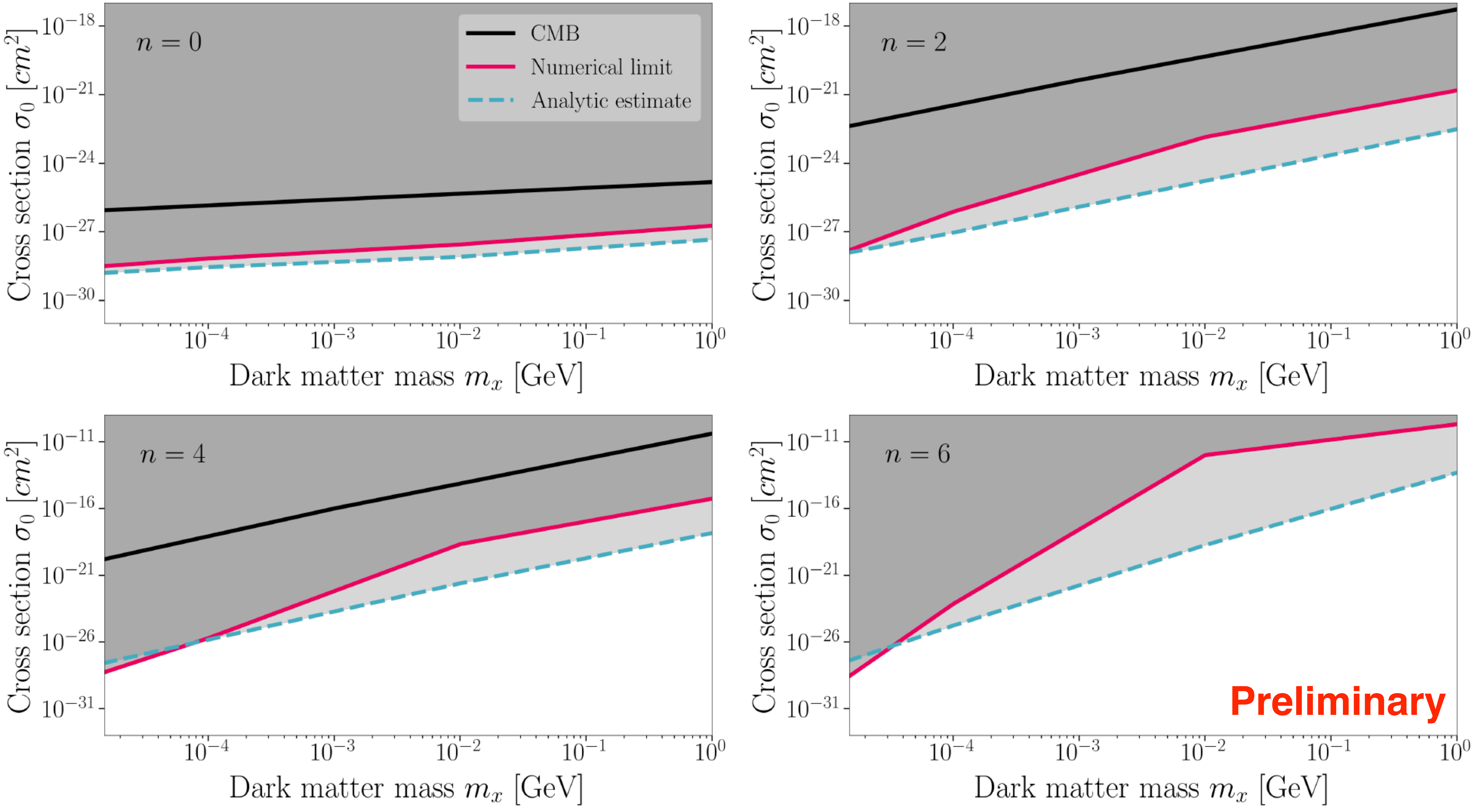


EN & Drlica-Wagner et al. 2020

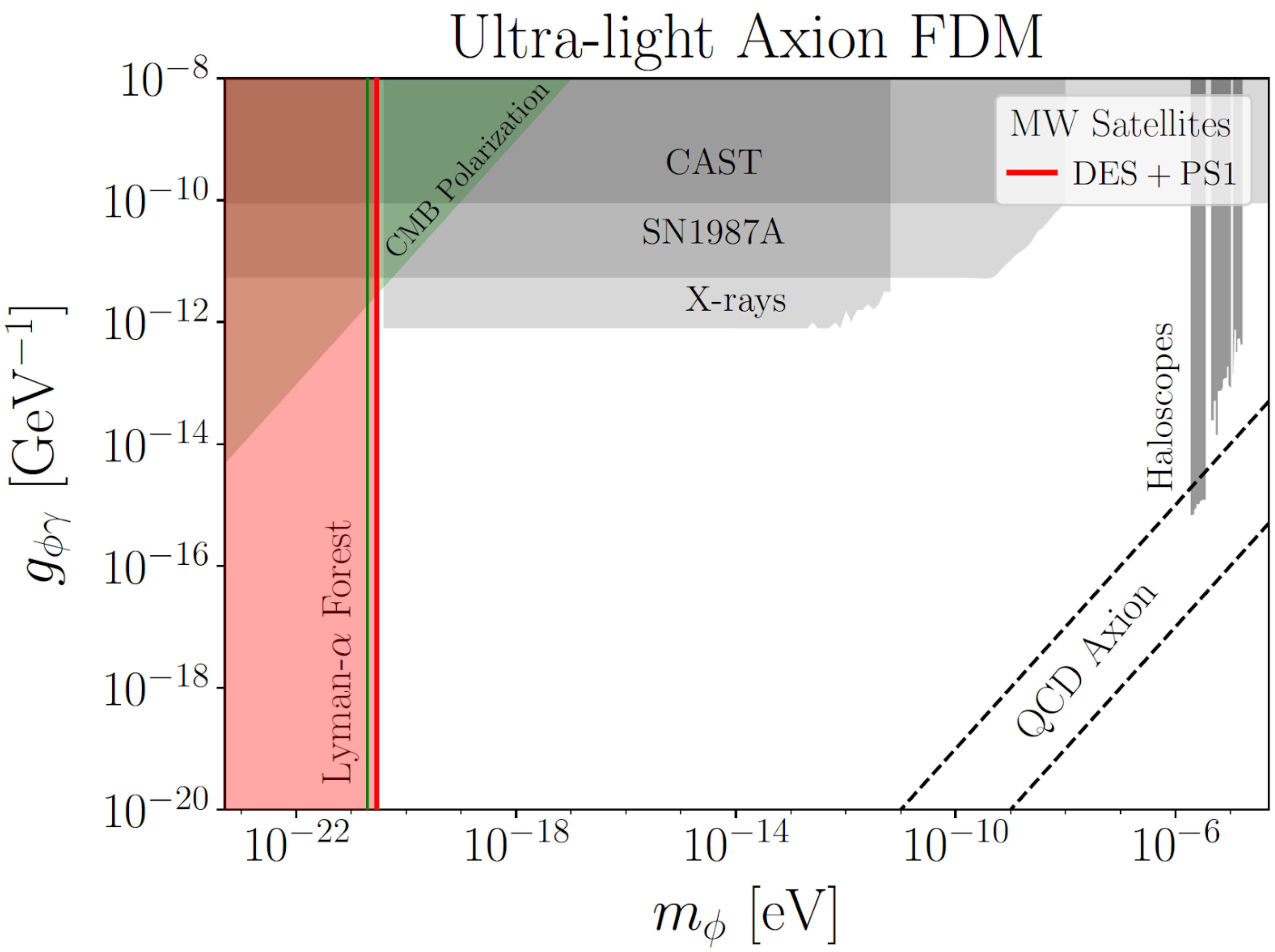
Interacting Dark Matter Constraints



K. Maamari et al. in prep

Fuzzy Dark Matter Constraints

- Fuzzy dark matter masses below 10^{-21} eV are robustly ruled out, with very conservative modeling assumptions
- Can be interpreted as a lower limit on the ultra-light axion mass assuming negligible self and Standard Model couplings
- The dark matter de Broglie wavelength must be smaller than ultra-faint dwarf sizes (~1 kpc)

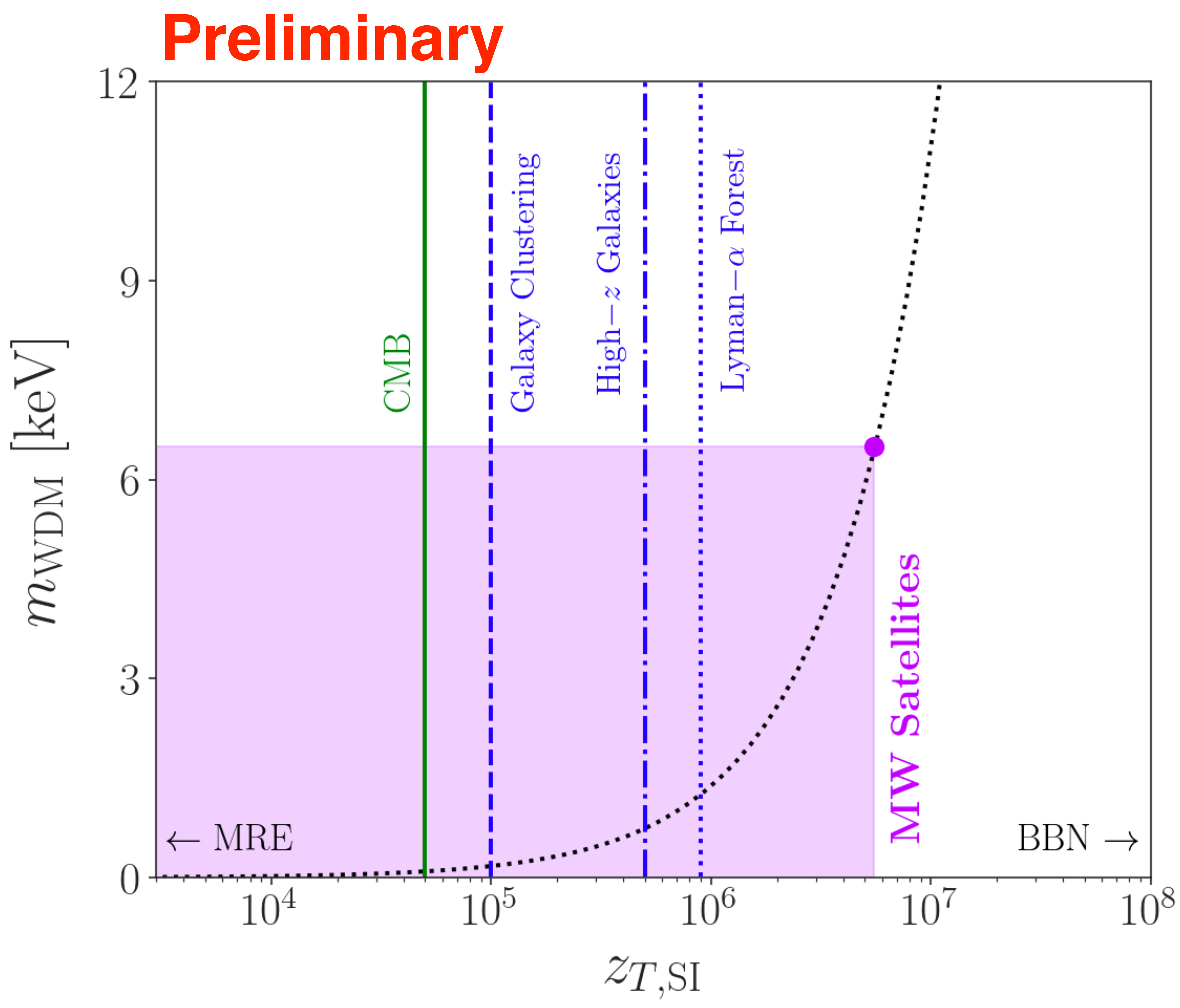


EN & Drlica-Wagner et al. 2020

Late-Forming Dark Matter Constraints

- Dark radiation that transitions to CDM after BBN ("late-forming dark matter") suppresses power on small scales
- Cutoff in halo abundance is set by the LFDM transition redshift
- Milky Way satellite abundances imply that LFDM forms no later than **one week** after the Big Bang:

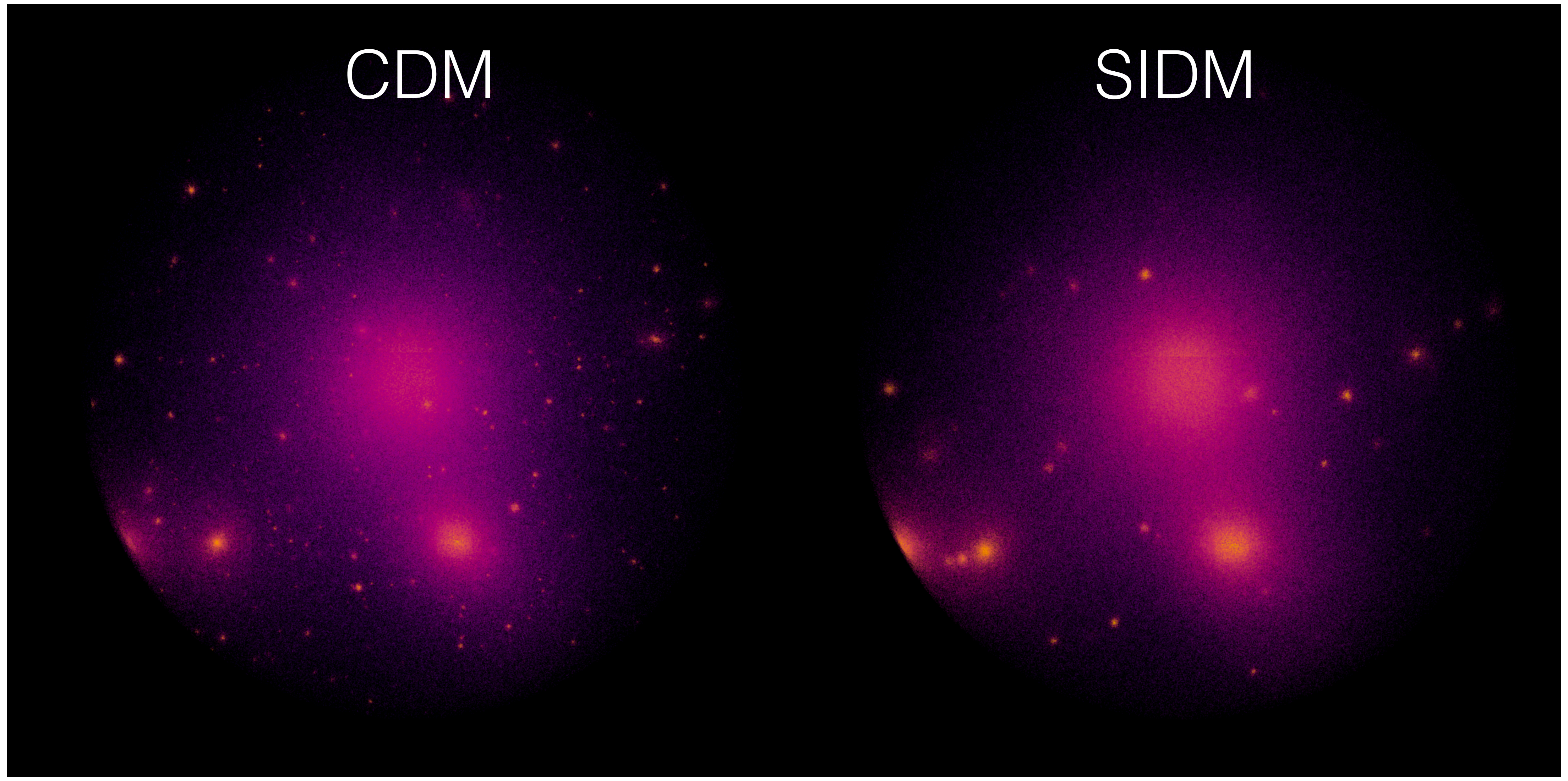
$$z_{\mathrm{LFDM}} > 5.5 \times 10^6 \ (95\% \ \mathrm{C.L.})$$

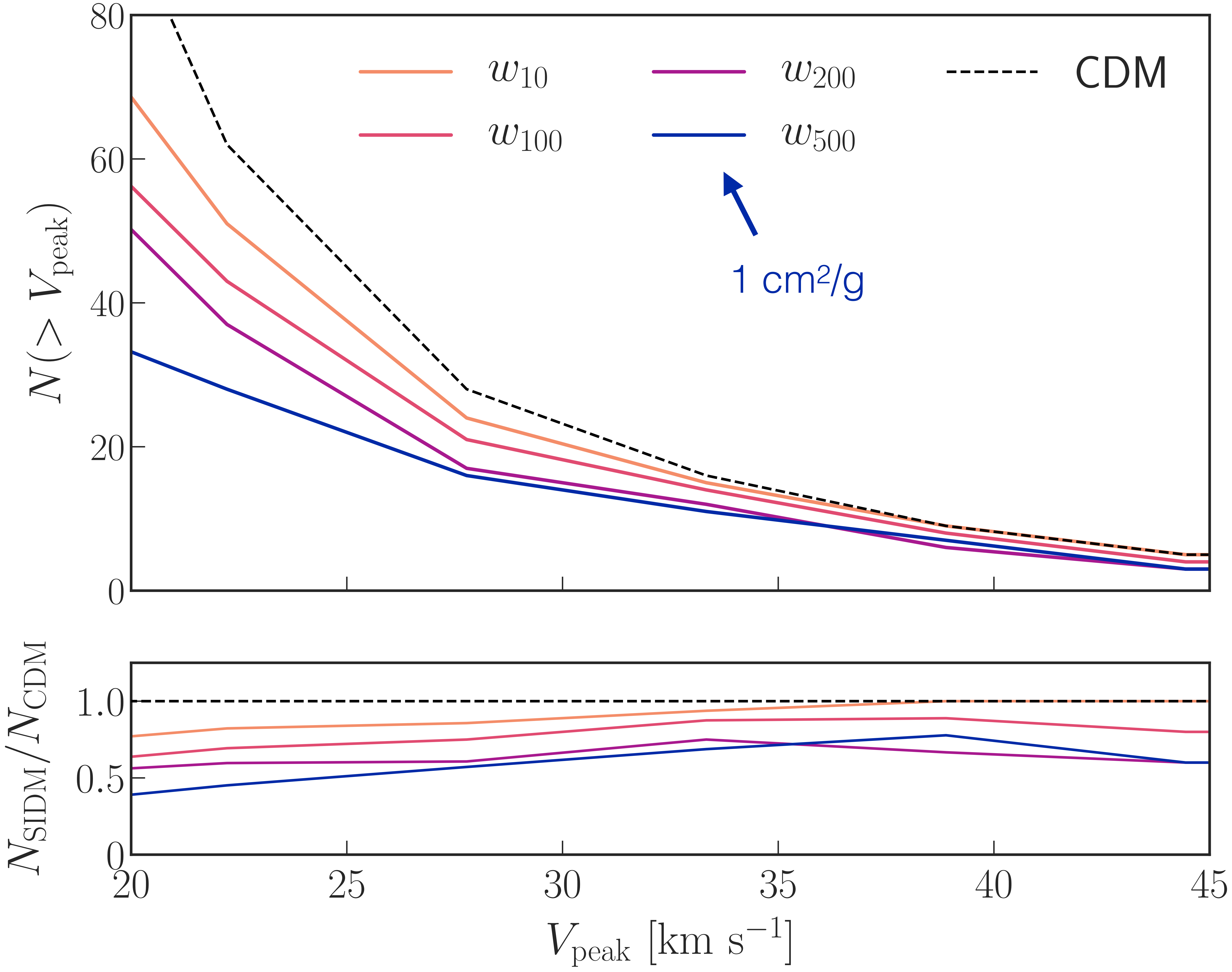


S. Das & EN in prep.

Constraining Late-time DM Physics

- Our framework constrains dark matter physics that suppresses subhalo abundances at late times
- Sensitivity to SIDM cross sections of ~0.1 cm²/g (stay tuned!)



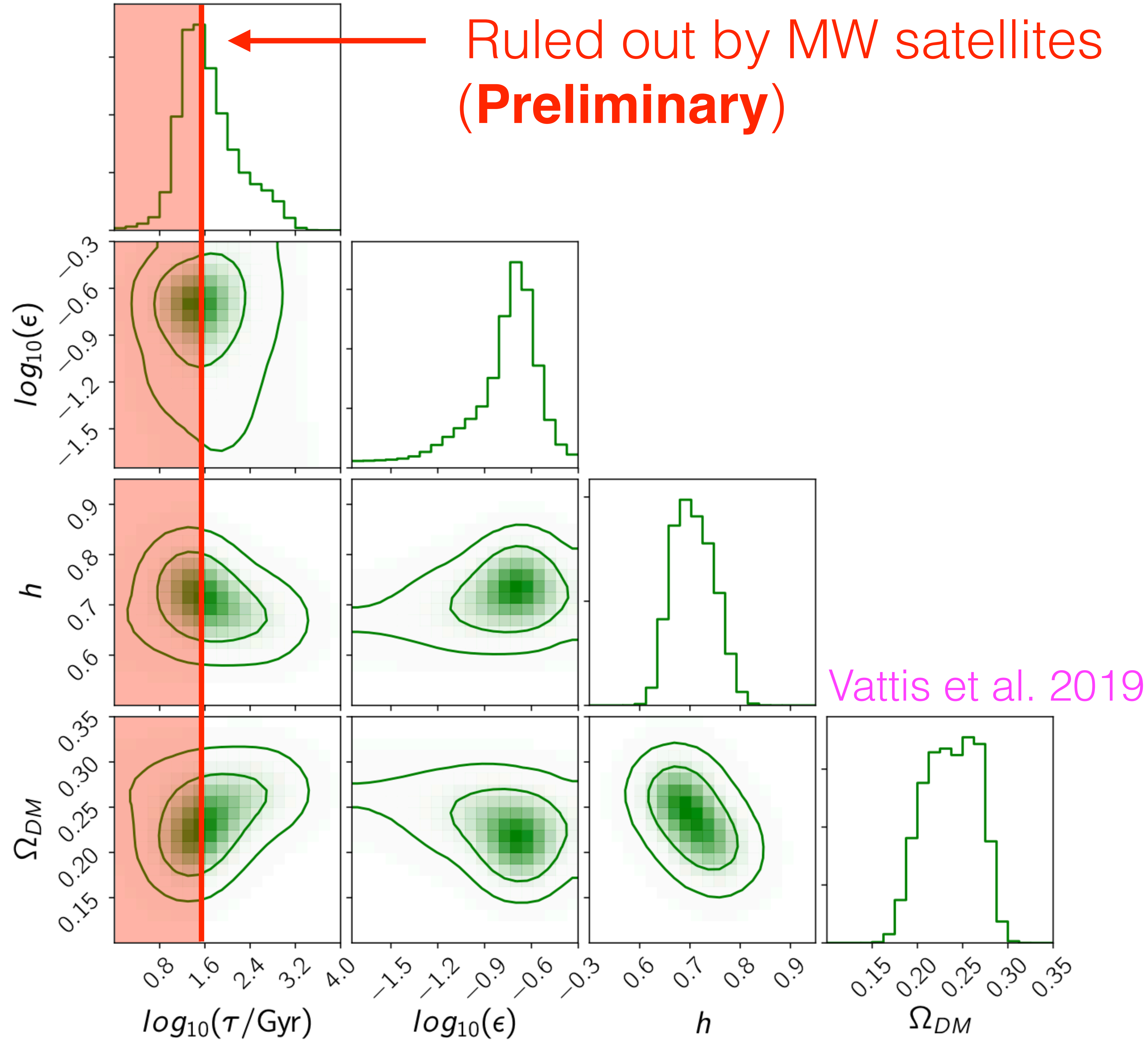


EN, A. Banerjee, S. Adhikari, Y.-Y. Mao, R. Wechsler 2020

Constraining Late-time DM Physics

- Our framework constrains dark matter physics that suppresses subhalo abundances at late times

- Sensitivity to decaying dark matter with a lifetime of ~10 Gyr, which has been claimed to alleviate the Hubble tension (stay tuned!)

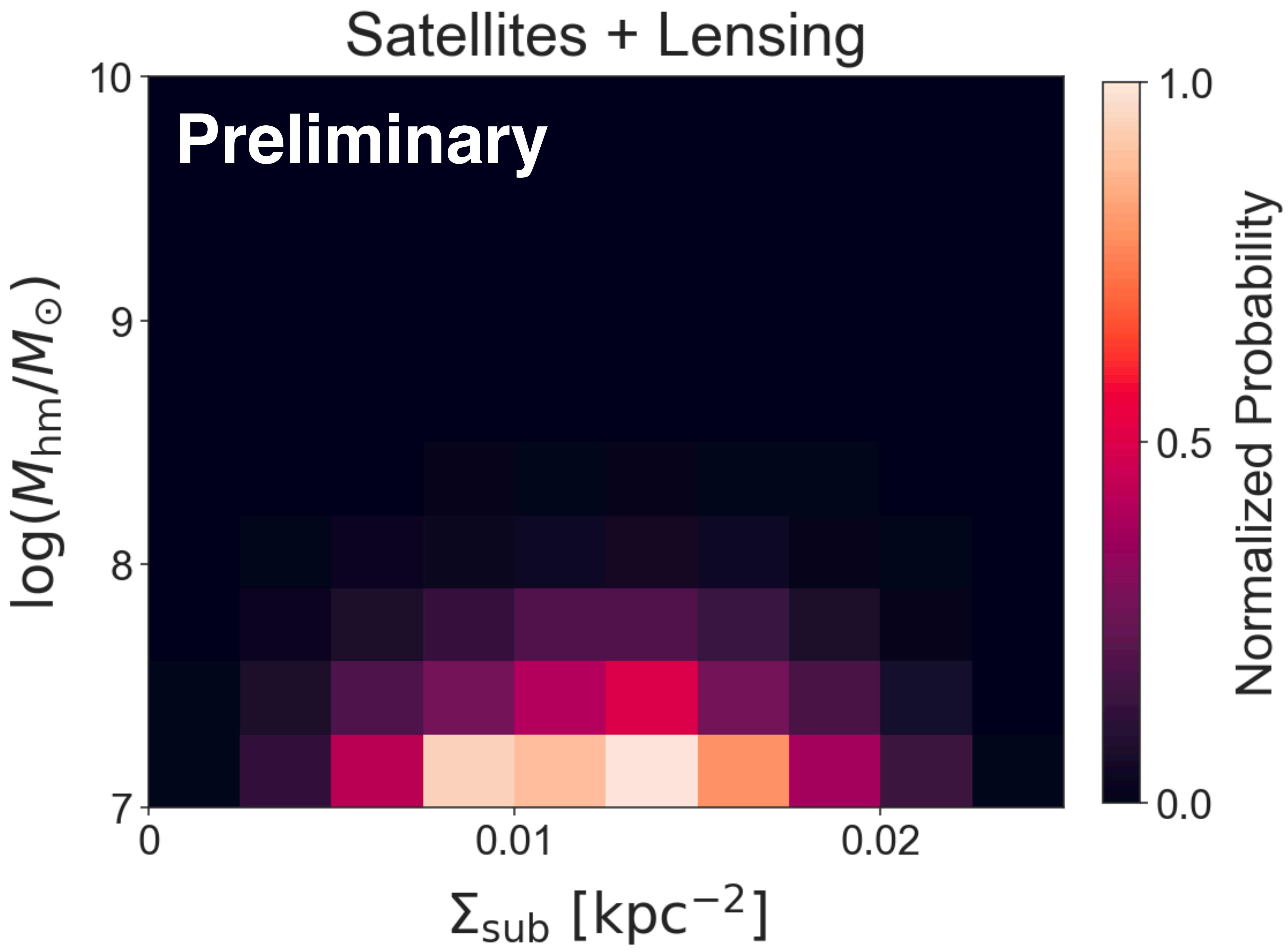


Sidney Mau

S. Mau et al. in prep

Combining Small-Scale Structure Probes

- Recent analyses of the Lyman-α forest, strong gravitational lenses, and stellar streams achieve similar dark matter sensitivity
- Joint models of small-scale probes are key to break degeneracies and robustly detect non-CDM physics
- In progress: combined constraints using subhalo populations inferred from satellite abundances and strong lensing



EN, S. Birrer, D. Gilman et al. in prep.

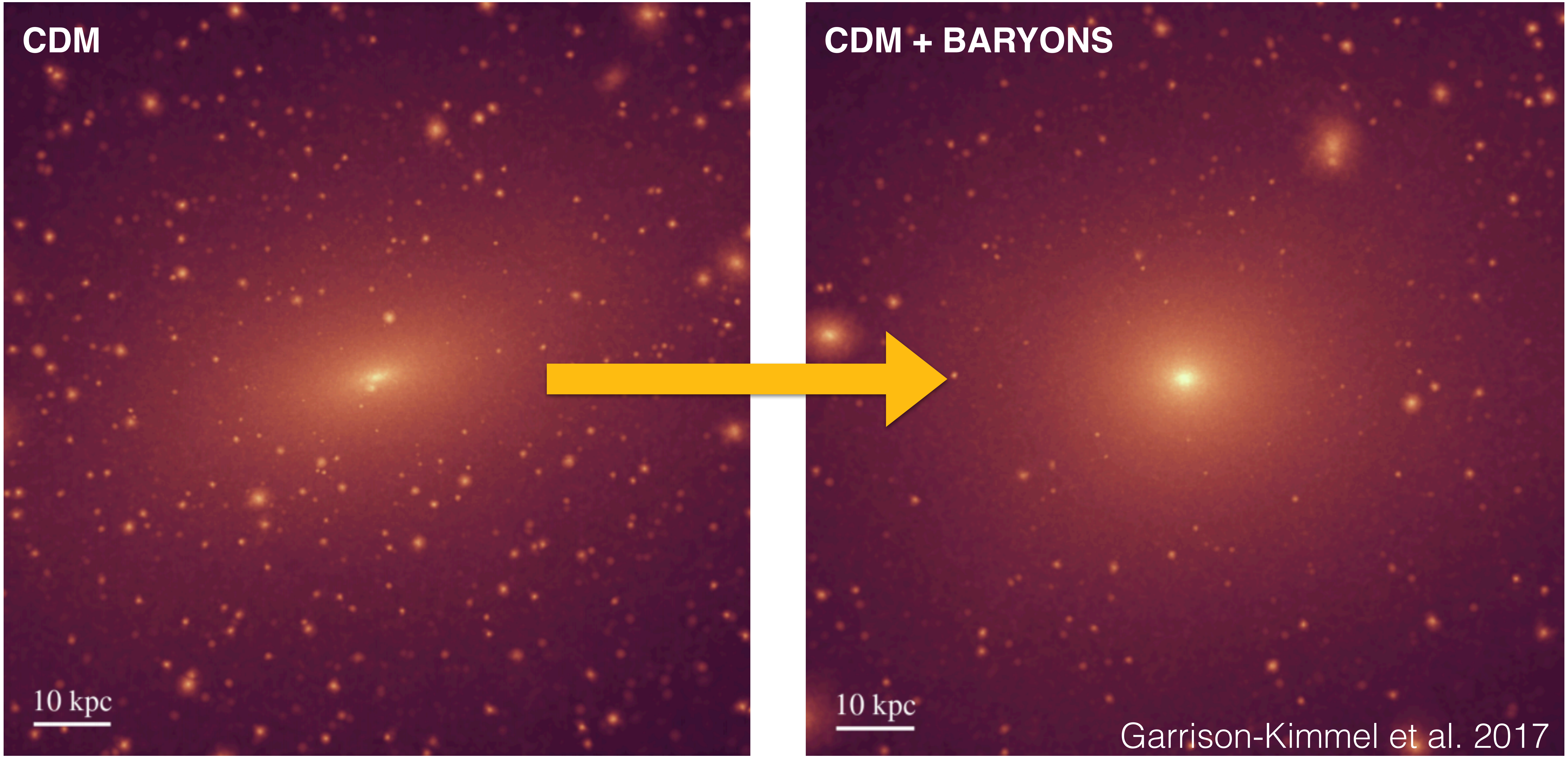
Outlook

- The lack of a cutoff in the abundance of observable ultra-faint galaxies down to halo masses of $\sim 10^8\ M_\odot$ yields stringent constraints on the galaxy–halo connection and dark matter physics
- These constraints will **continue to improve** with advances in (currently conservative) galaxy–halo modeling and LSST satellite discoveries
- Our analysis informs a variety of dark matter properties: free-streaming length, coupling to the Standard Model, de Broglie wavelength, self-interaction cross section, formation epoch, particle lifetime
- Joint modeling of small-scale structure probes is an important area for future work, starting with satellites, stellar streams, and strong lenses

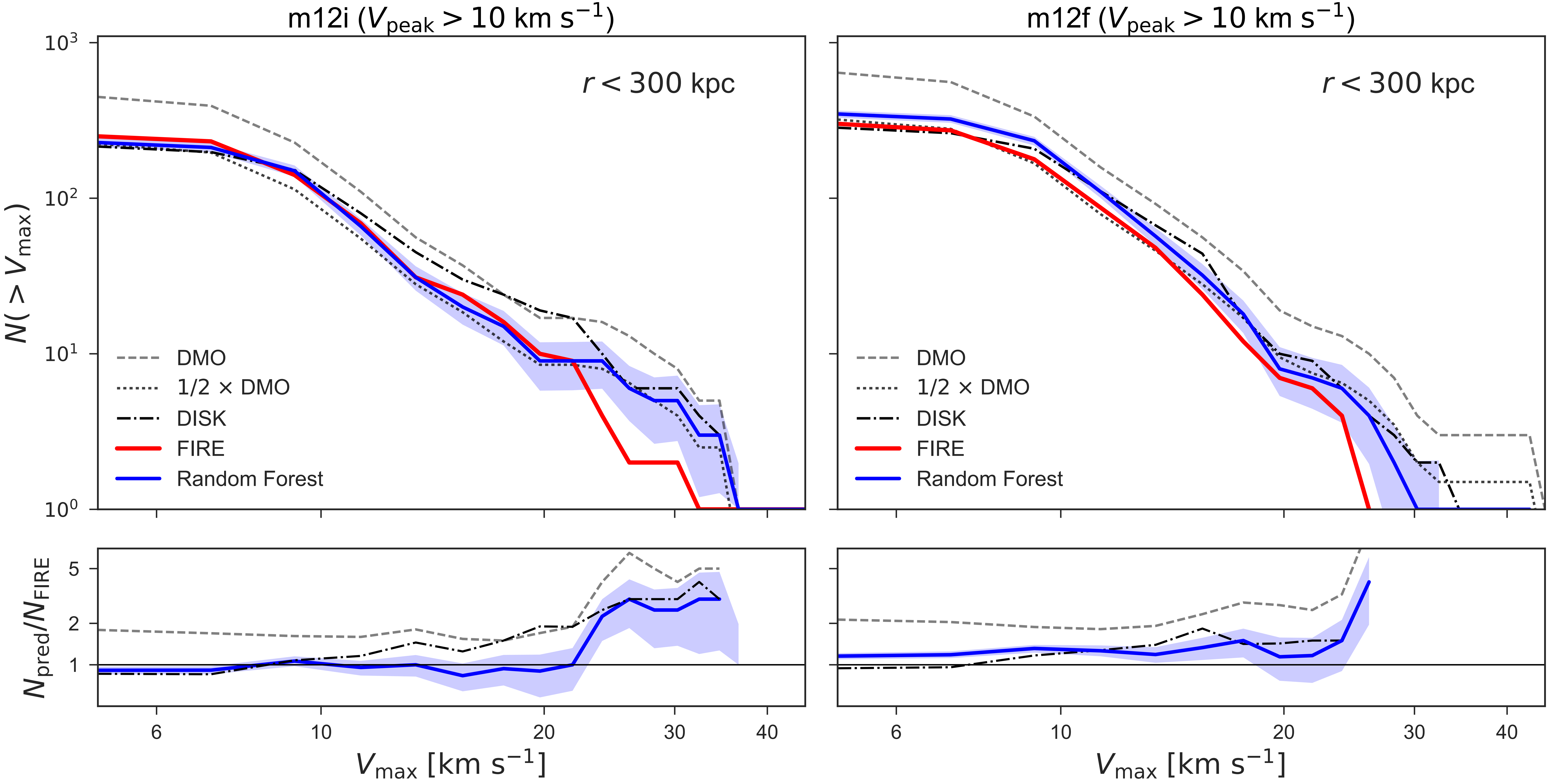
Thanks!

Susmita Adhikari, Arka Banerjee, Keith Bechtol, Kimberly Boddy,
Subinoy Das, Alex Drlica-Wagner, Vera Gluscevic, Greg Green,
Yao-Yuan Mao, Sidney Mau, Mitch McNanna, Risa Wechsler

Baryonic Subhalo Disruption



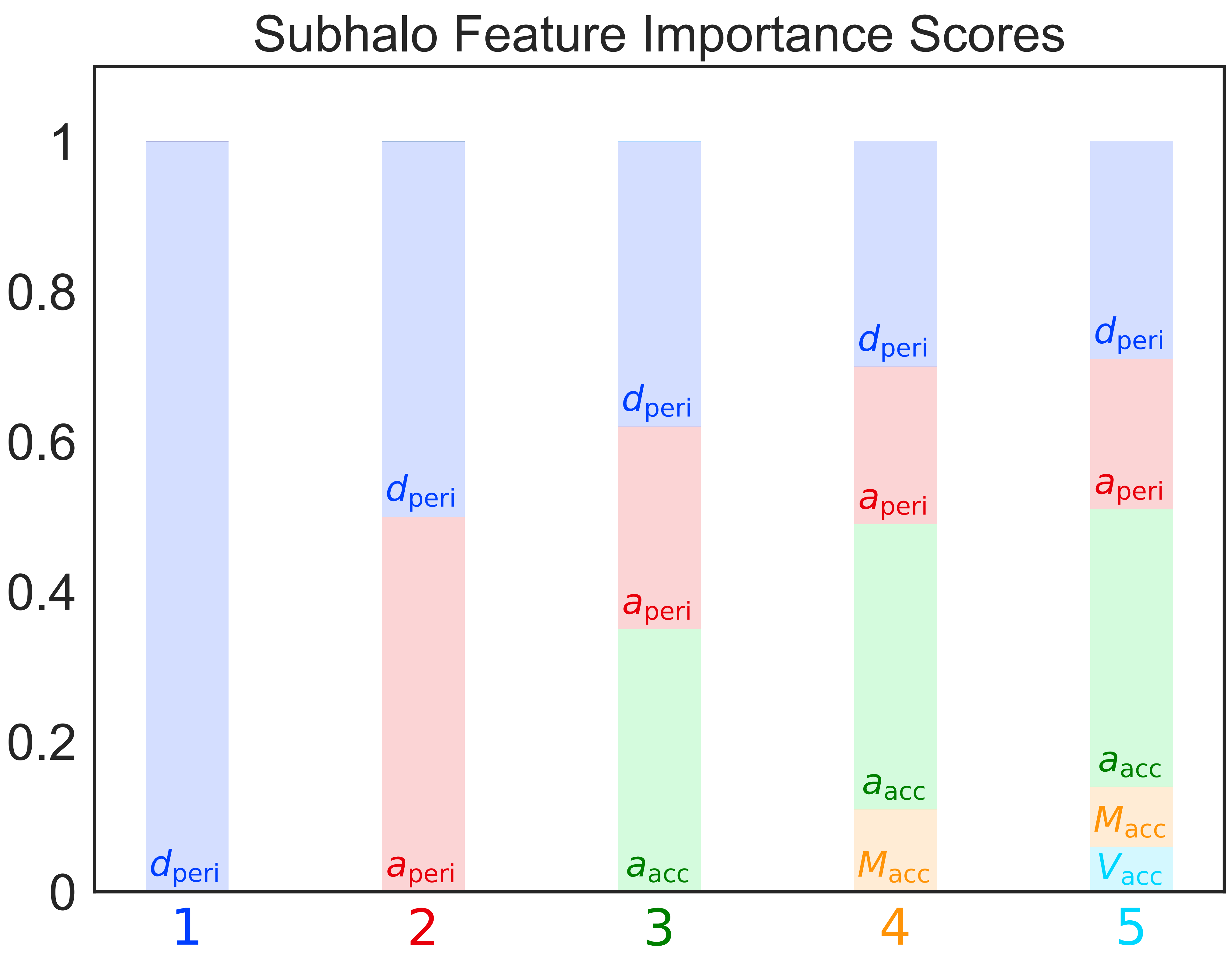
Baryonic Subhalo Disruption

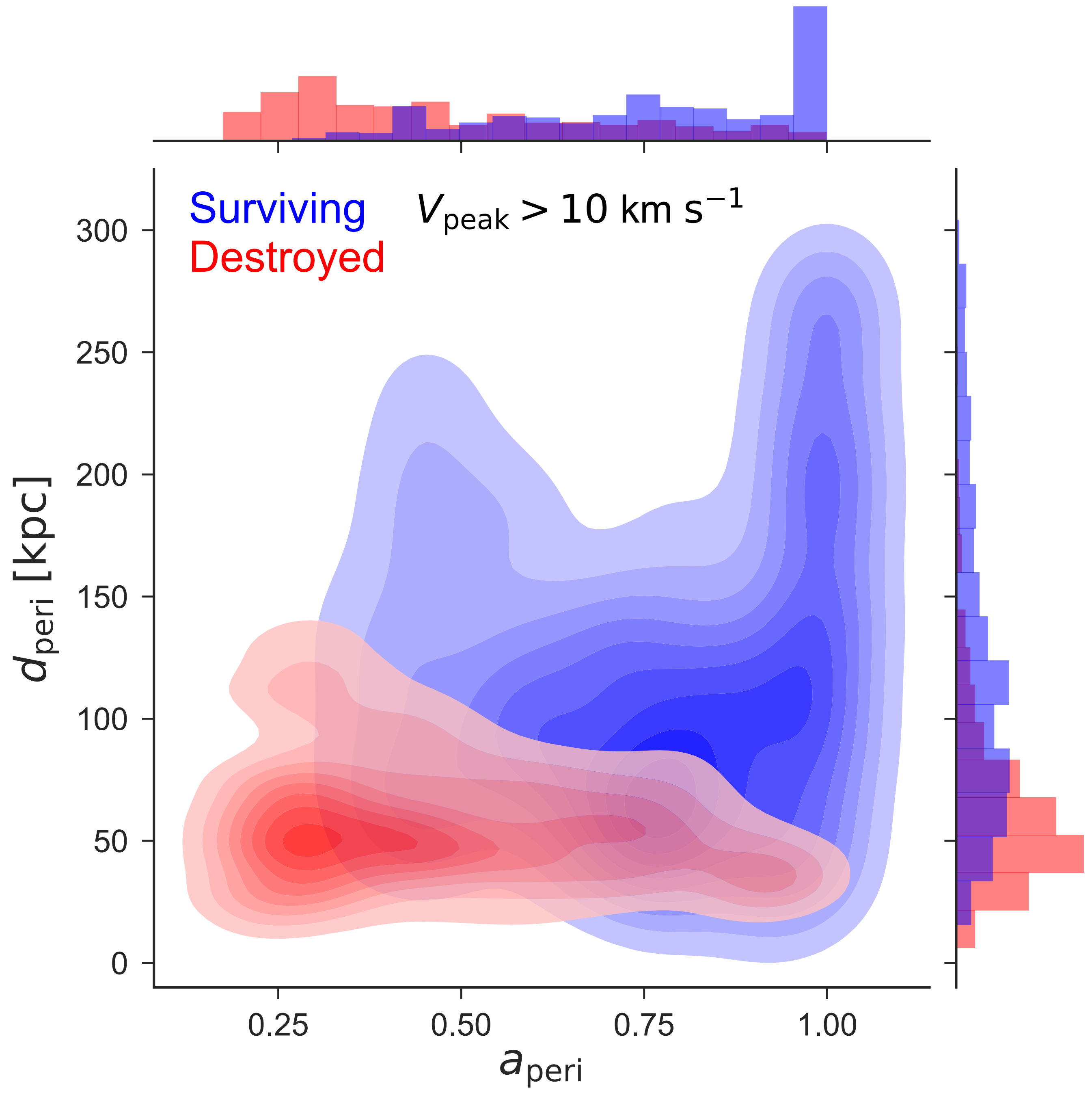


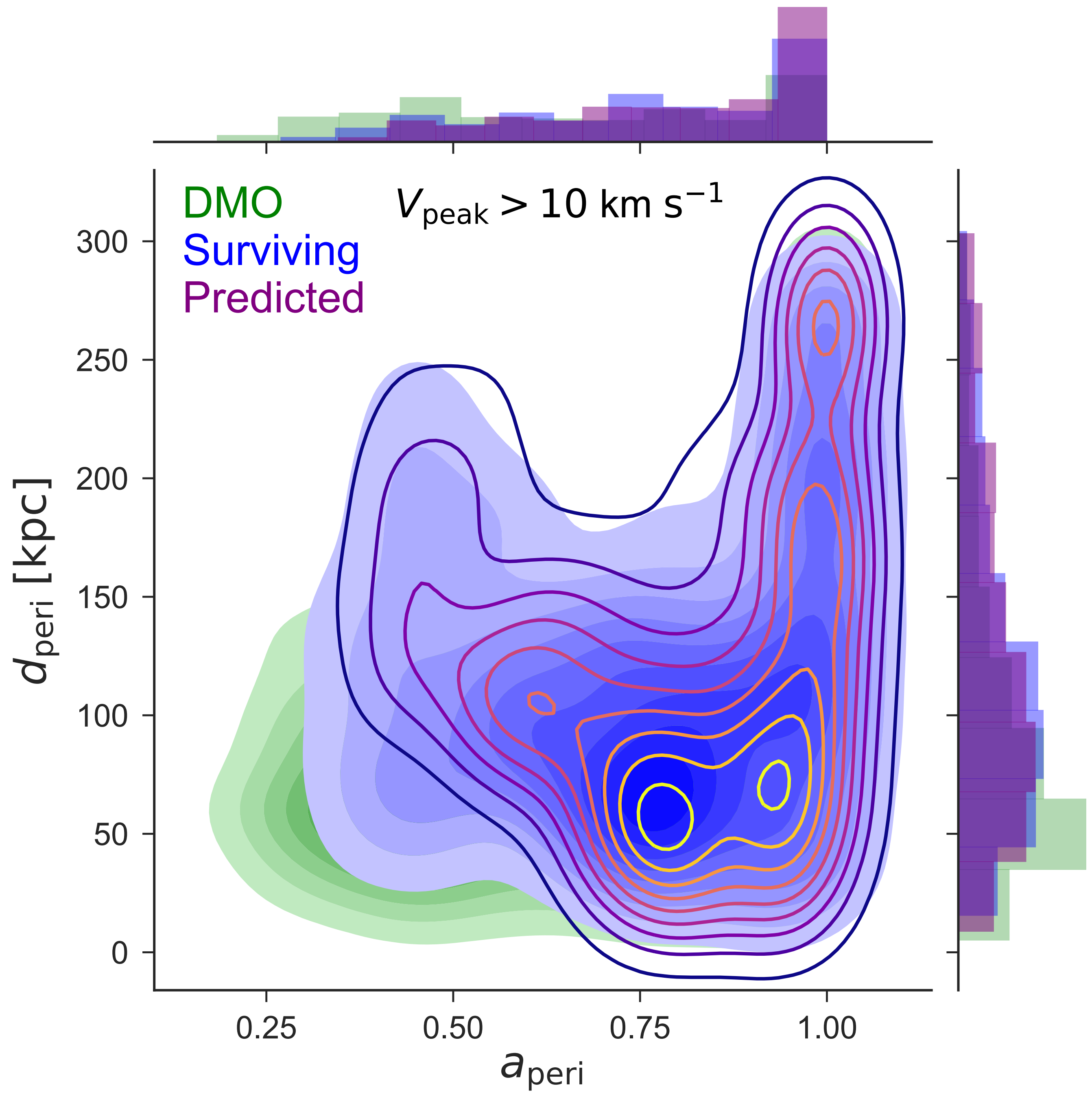
EN, Y.-Y. Mao, R. Wechsler et al. 2018

Baryonic Subhalo Disruption

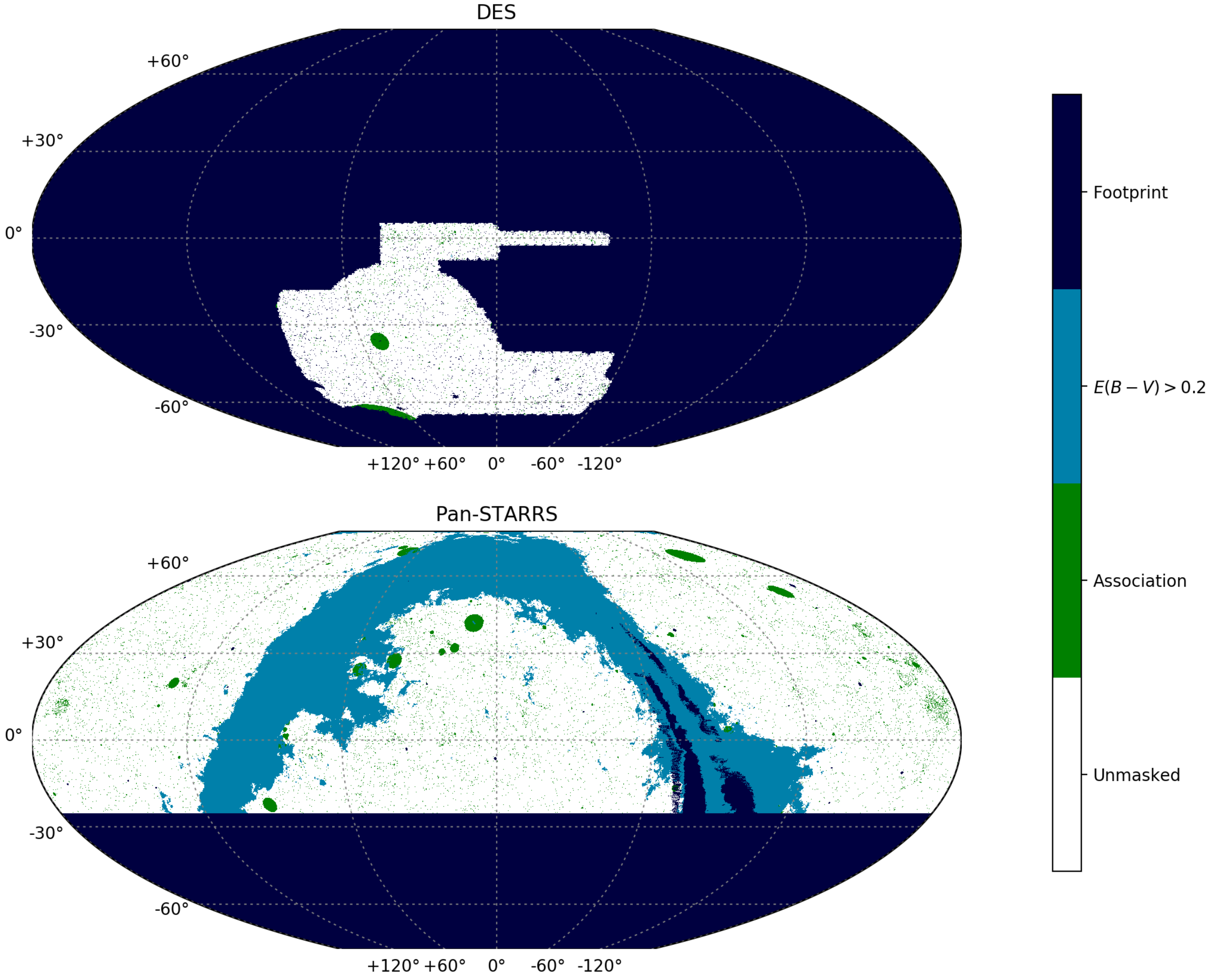
- Five subhalo features encode ~90% of disruption
- Predicted subhalo populations consistent with FIRE







EN, Y.-Y. Mao, R. Wechsler et al. 2018

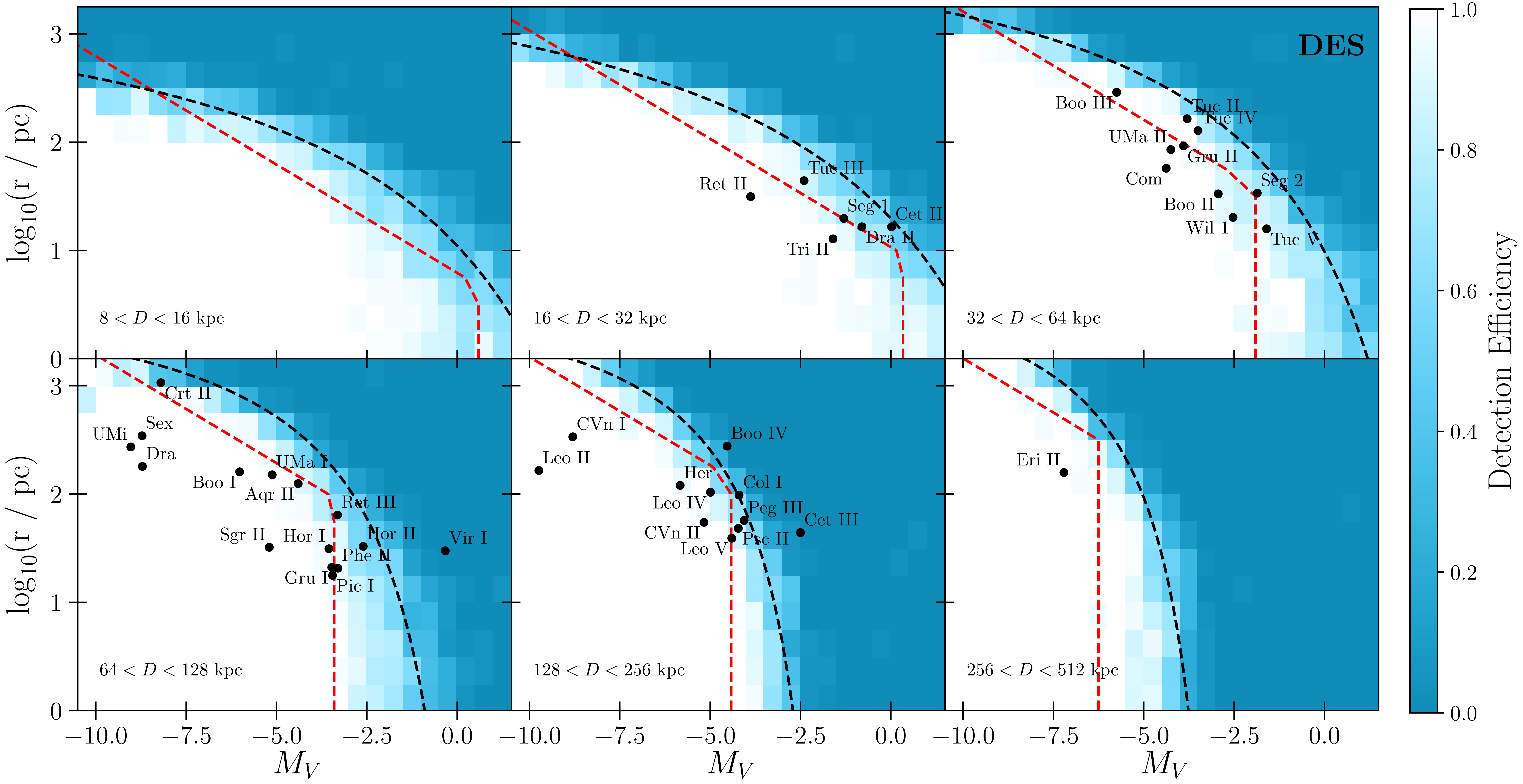


DES & Pan-STARRS Survey Selection Functions

- Rigorous satellite search over ~75% of the sky
- Masks for dusty regions, background galaxies, etc.
- 17/18 (DES), 19/31 (PS1) satellites recovered by two search algorithms
- Selection functions from catalog-level searches for simulated satellites

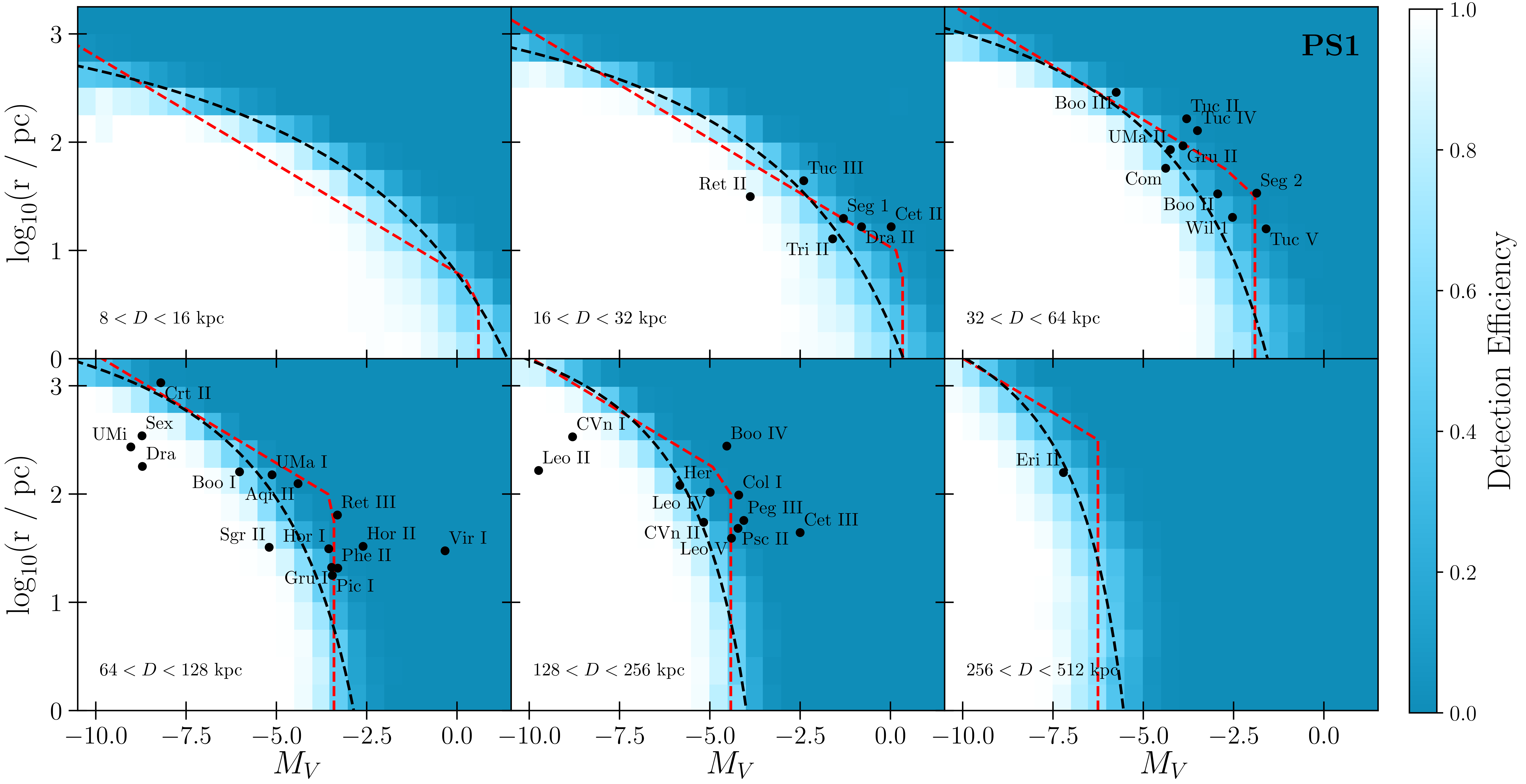
Drlica-Wagner & Bechtol et al. 2020

Observational Selection Functions



Drlica-Wagner & Bechtol et al. 2020

Observational Selection Functions



Drlica-Wagner & Bechtol et al. 2020

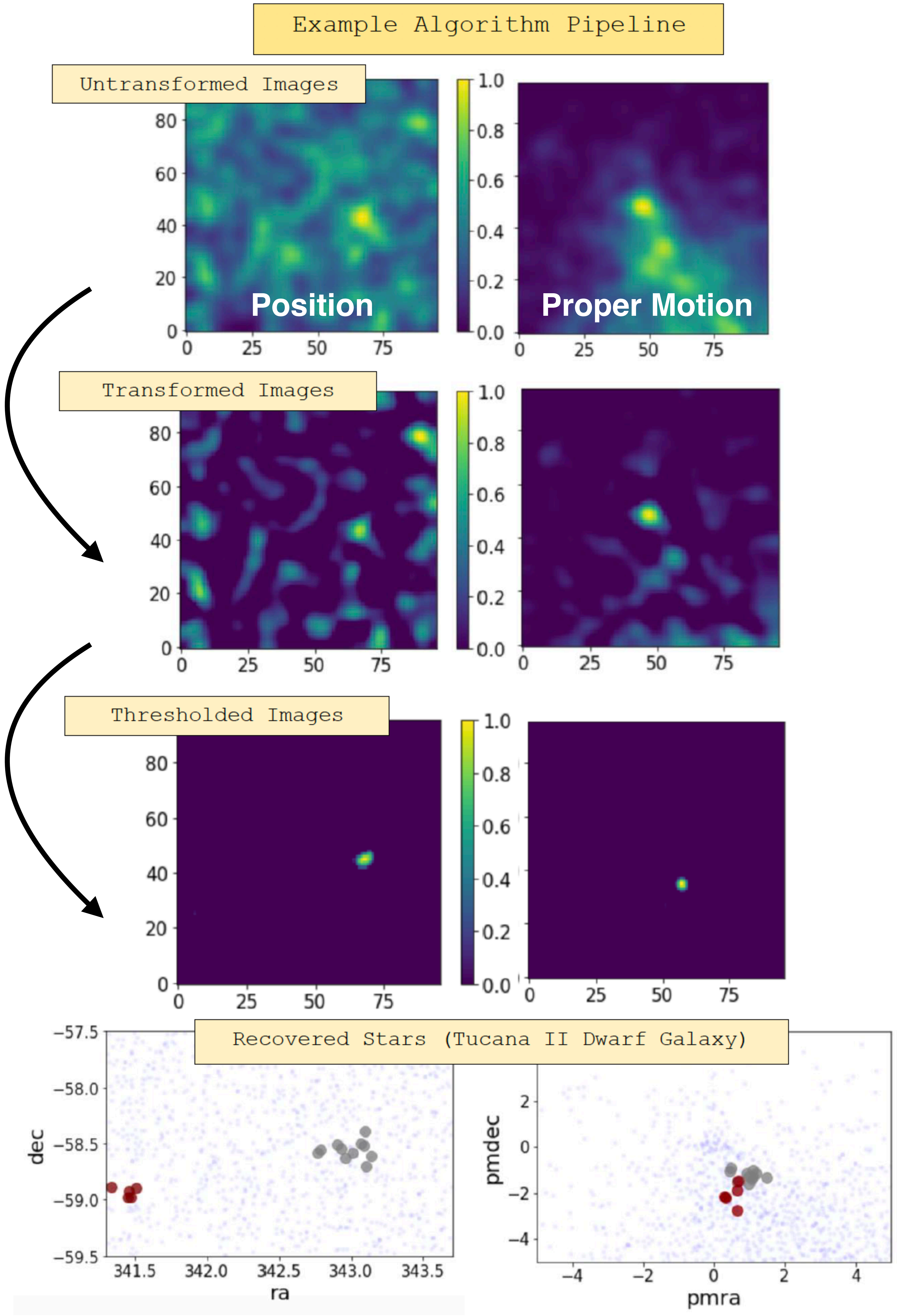
Satellite Searches in *Gaia*

- In progress: search for satellites in phase space using *Gaia* proper motion measurements
- Calibrate detection significance on mock dwarf galaxies

Elise Darragh-Ford

wavelet transform

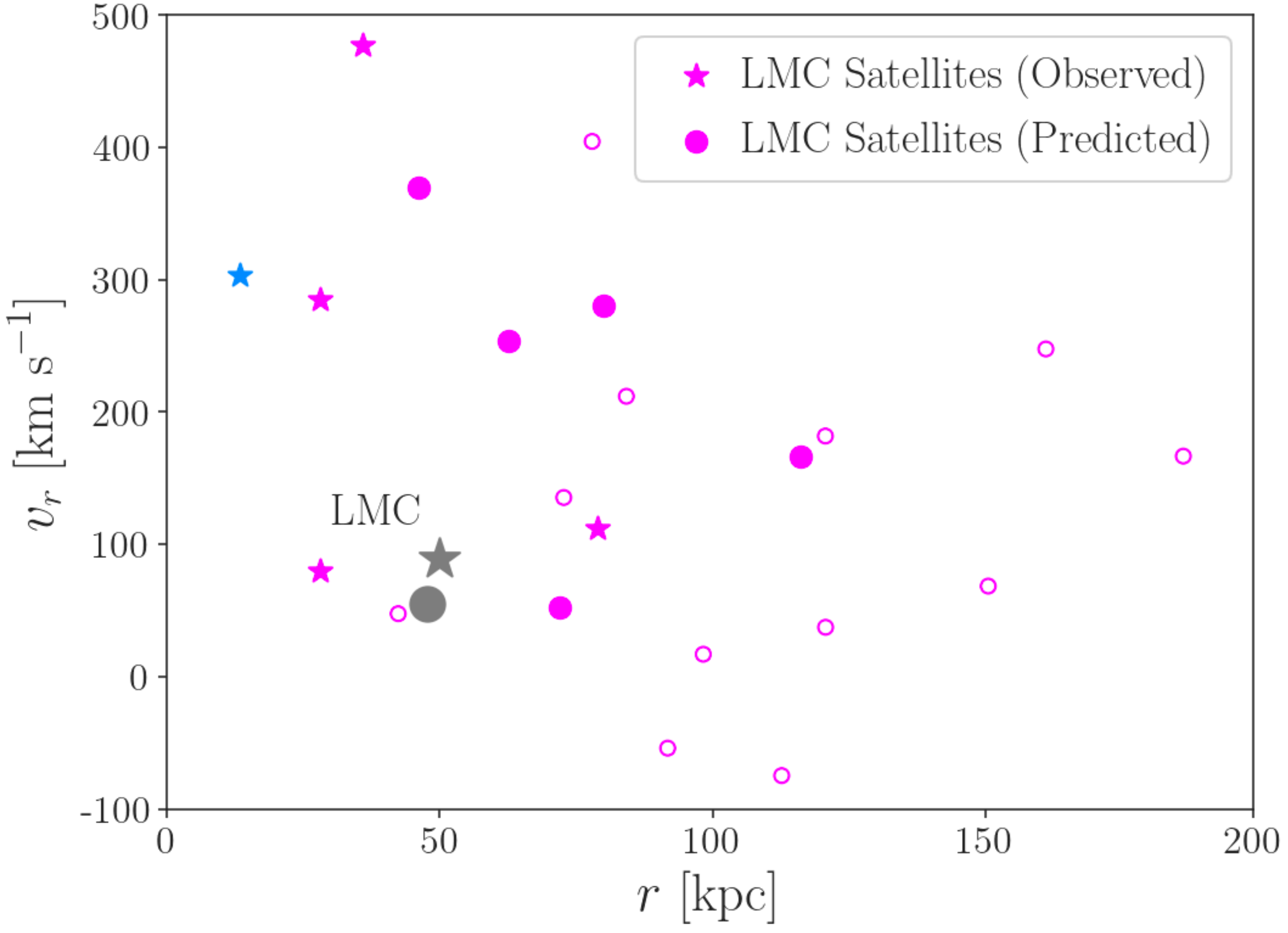
significance threshold

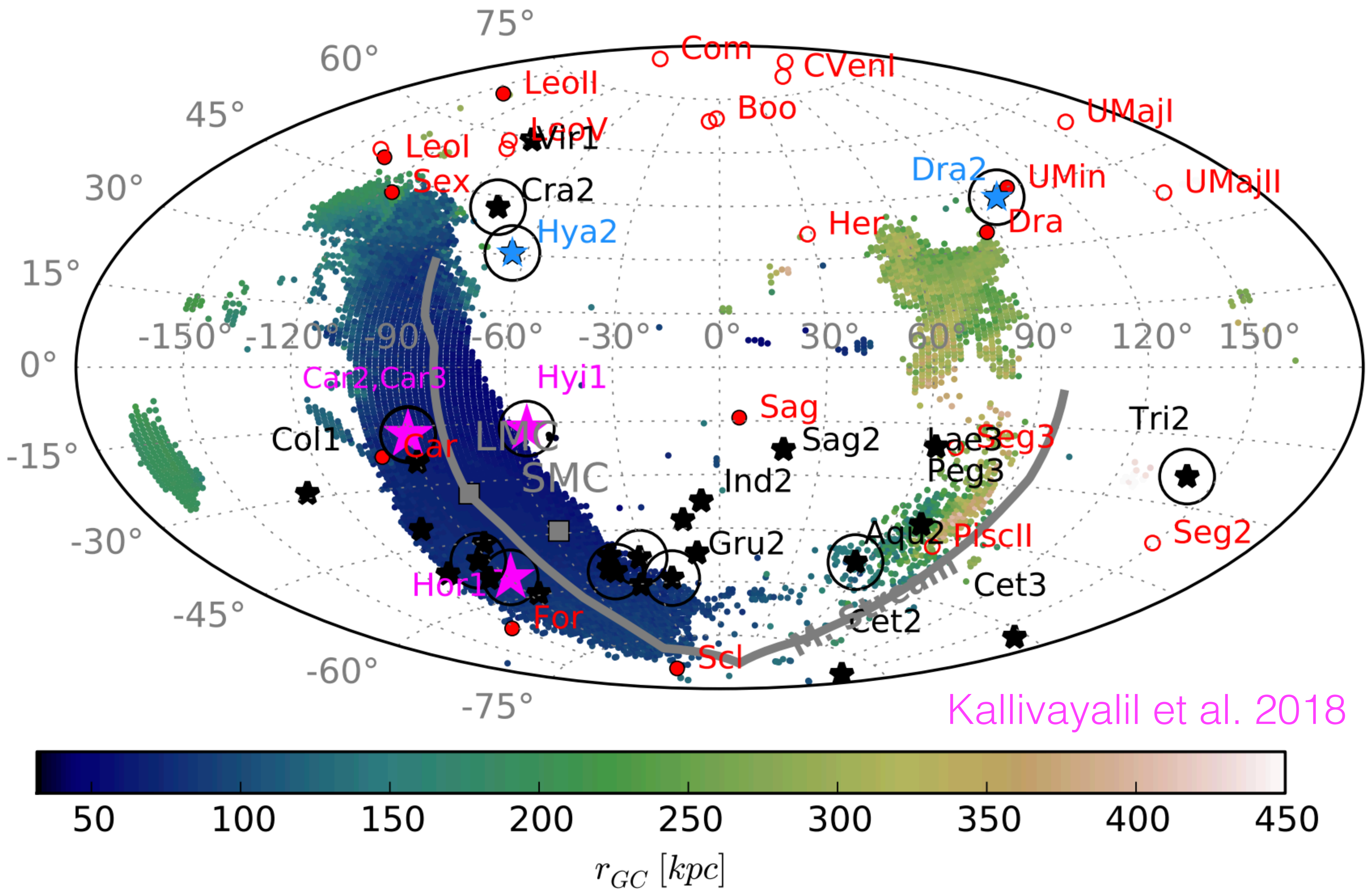


E. Darragh-Ford et al. in prep.

Satellites of the LMC

Also see Patel et al. 2020!

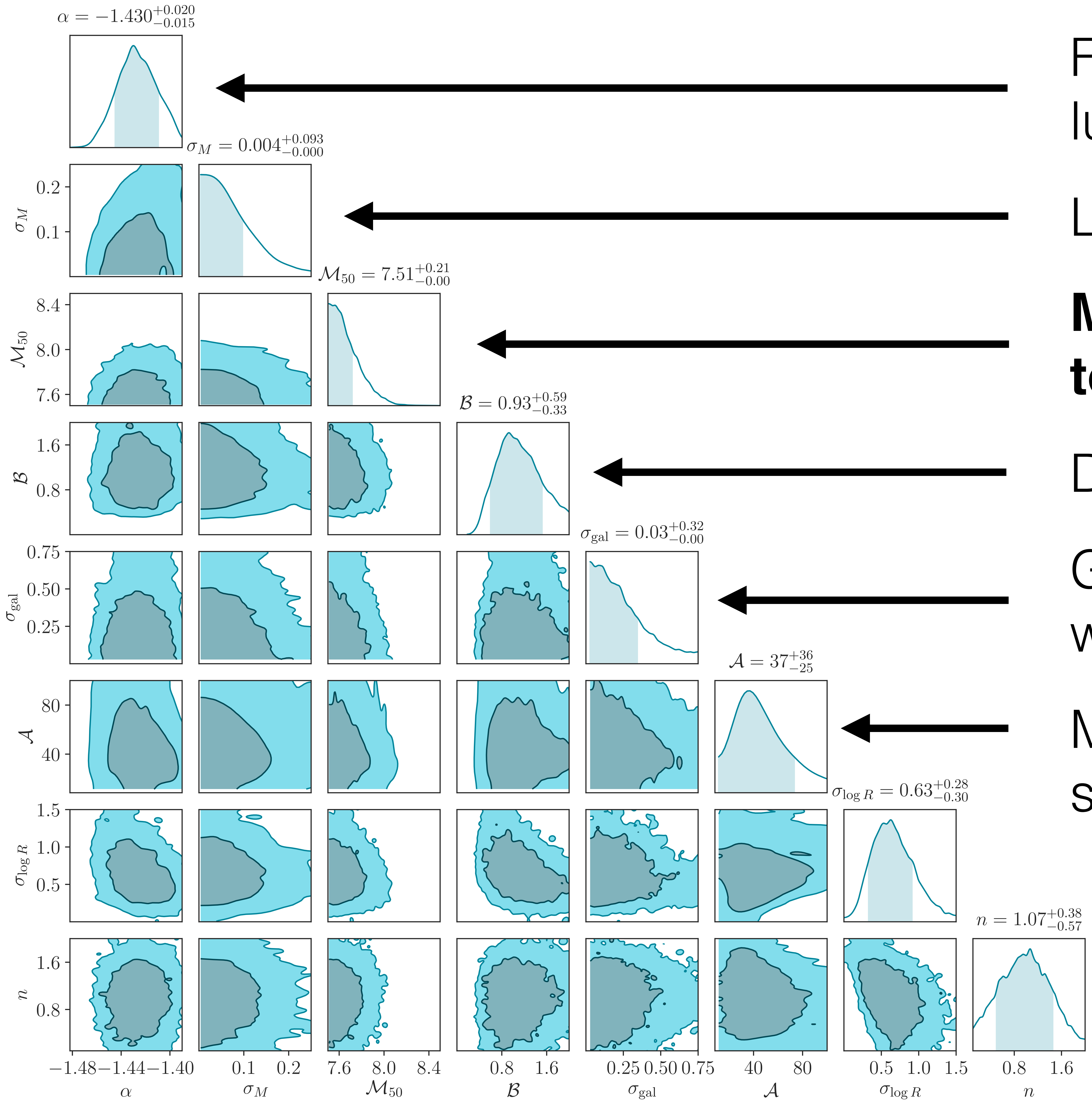




Kallivayalil et al. 2018

Predict 5 (1) currently observed LMC-associated satellites in DES (PS1), consistent with *Gaia* PMs!

EN & Wechsler et al. 2020



Faint-end slope consistent with global luminosity function

Luminosity scatter < 0.2 dex

Minimum halo mass corresponding to observed satellites < 3 x10^8 $M_\odot$

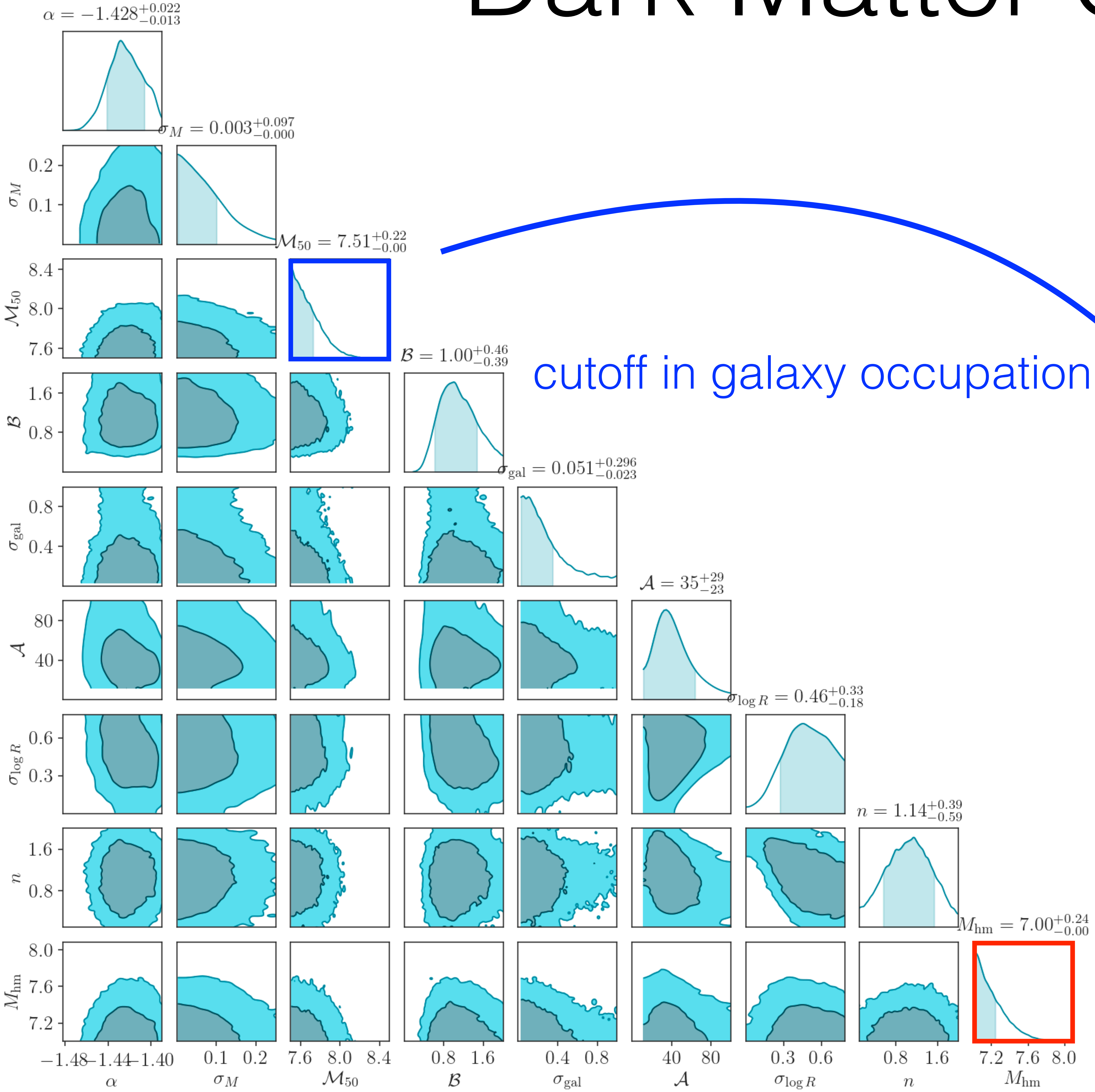
Disruption consistent with FIRE sims

Galaxy occupation fraction consistent with step function

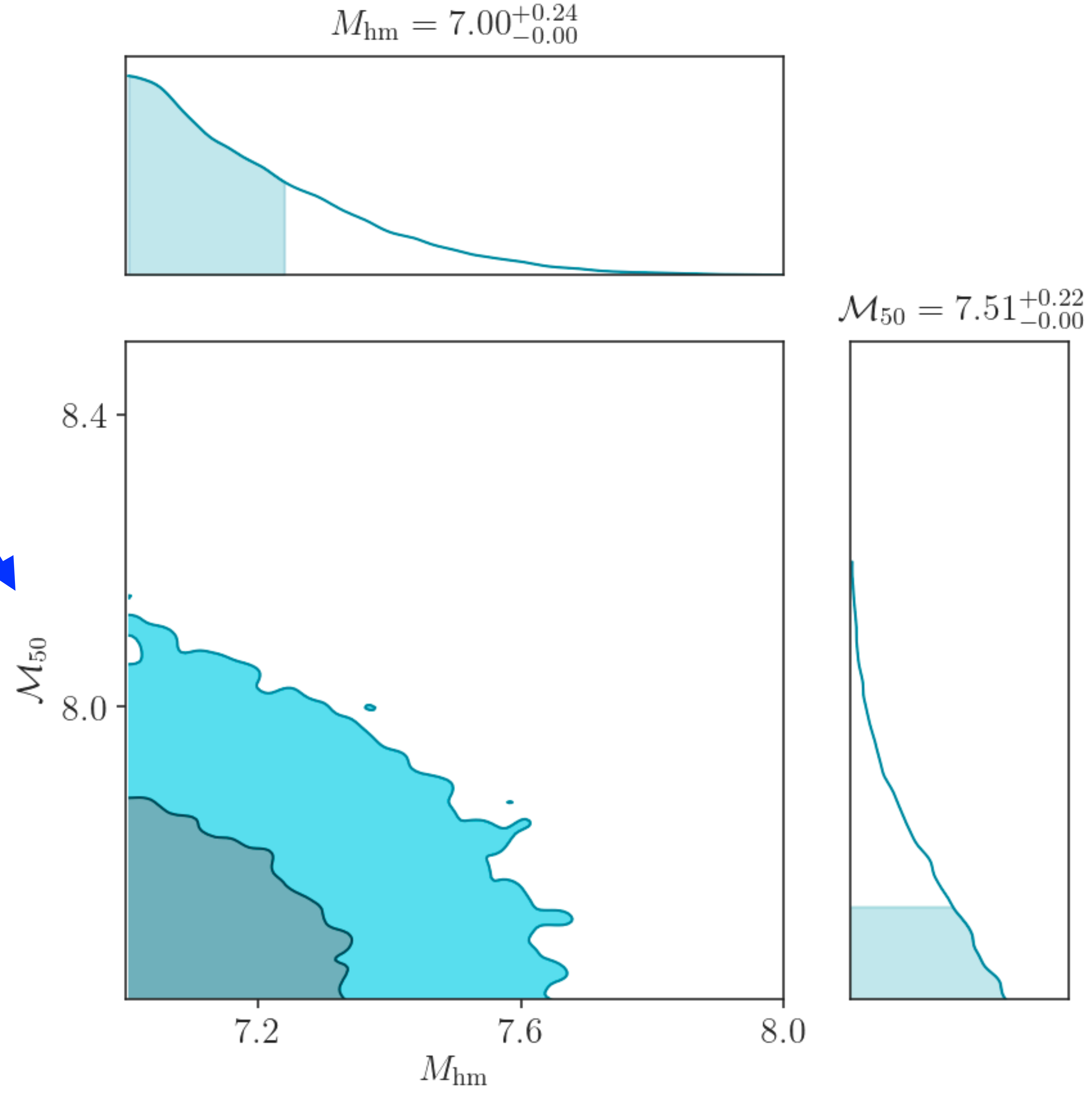
Measurement of amplitude, scatter, slope of galaxy-halo size relation

EN & Wechsler et al. 2020

Dark Matter Constraints



cutoff in galaxy occupation



mass scale of suppression
due to dark matter physics

EN & Drlica-Wagner et al. 2020