Constraints on (Fuzzy) Dark Matter Microphysics from Dwarf Galaxies

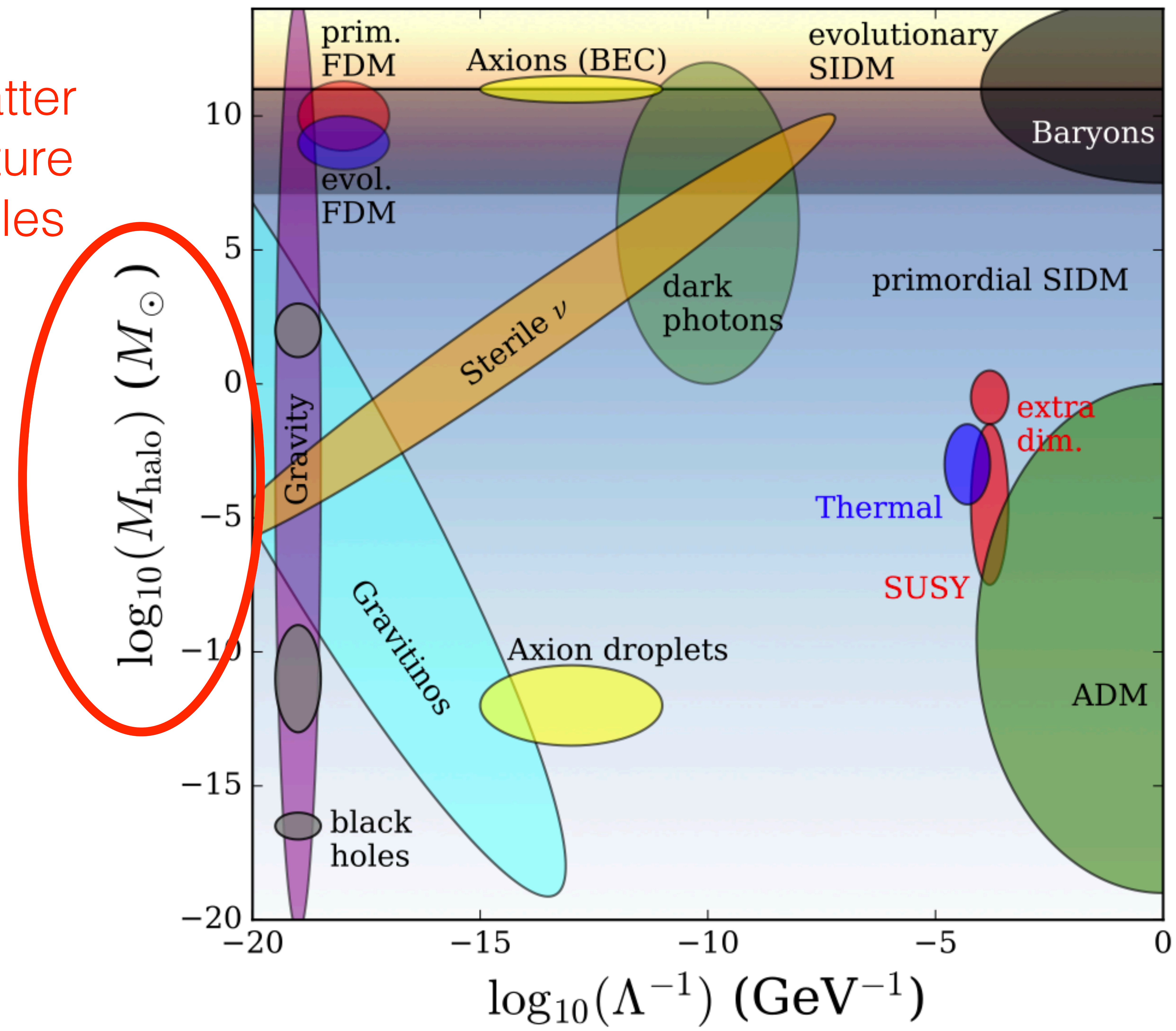
Ethan Nadler

Less Travelled Path of Dark Matter (ICTS)

11/12/2020

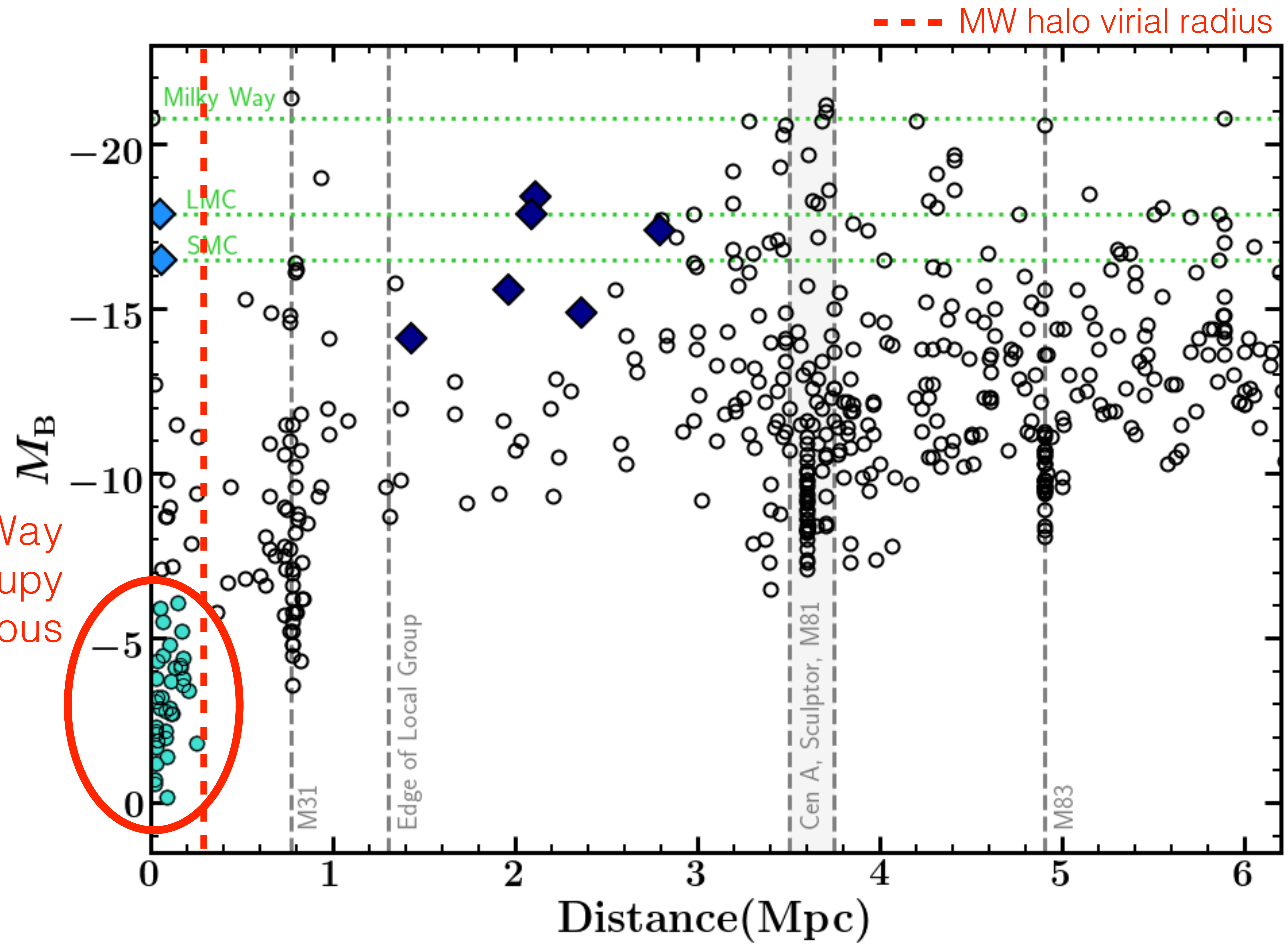
Dark Matter and Structure Formation

Microphysical dark matter properties affect structure formation on small scales



Buckley & Peter 2018

Our Census of the Faintest Galaxies



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

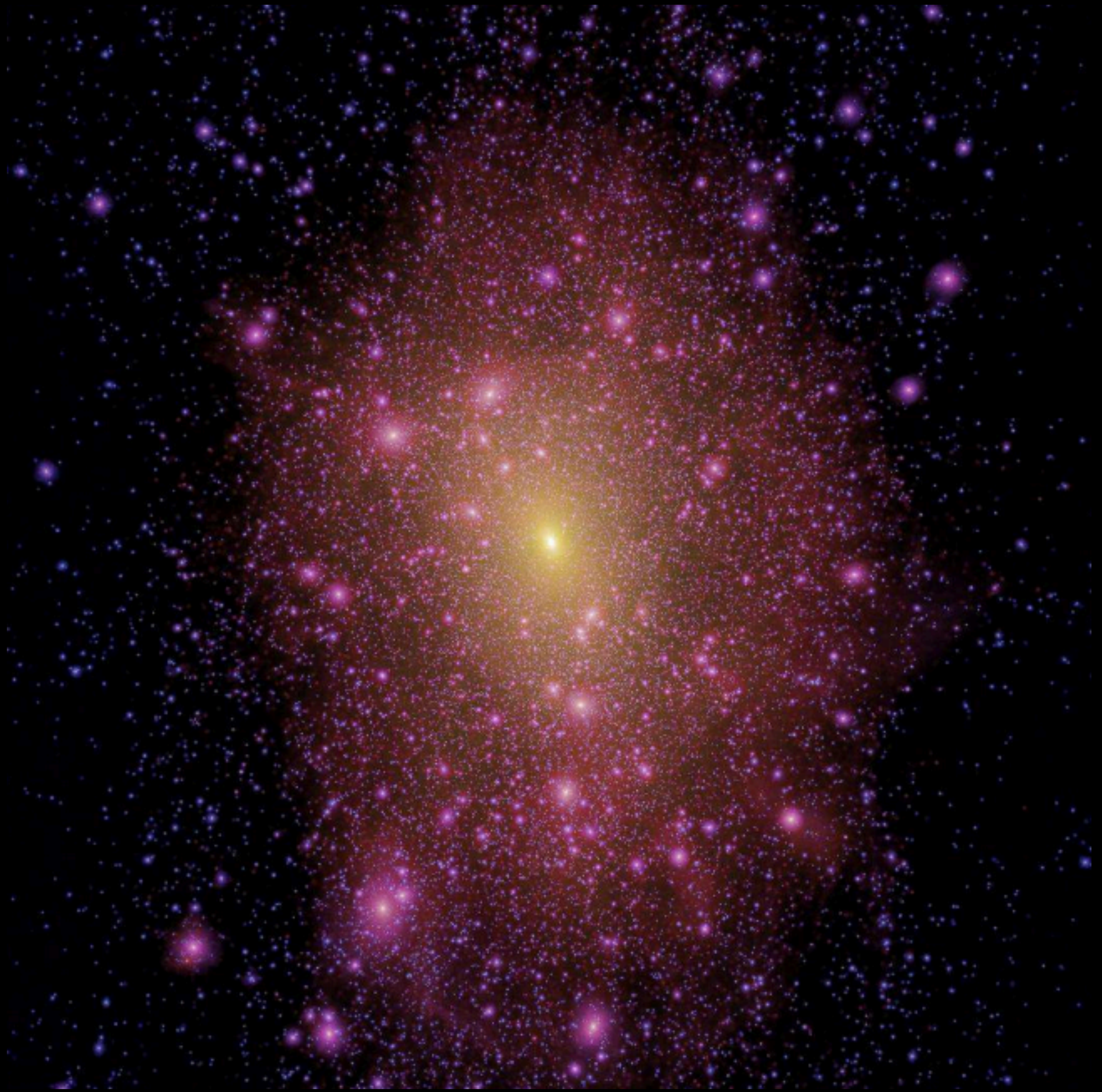
Credit: J. Carlin

The Milky Way Satellite Population

Drlica-Wagner & Bechtol et al. 2020

Small Halos as Dark Matter Probes

CDM

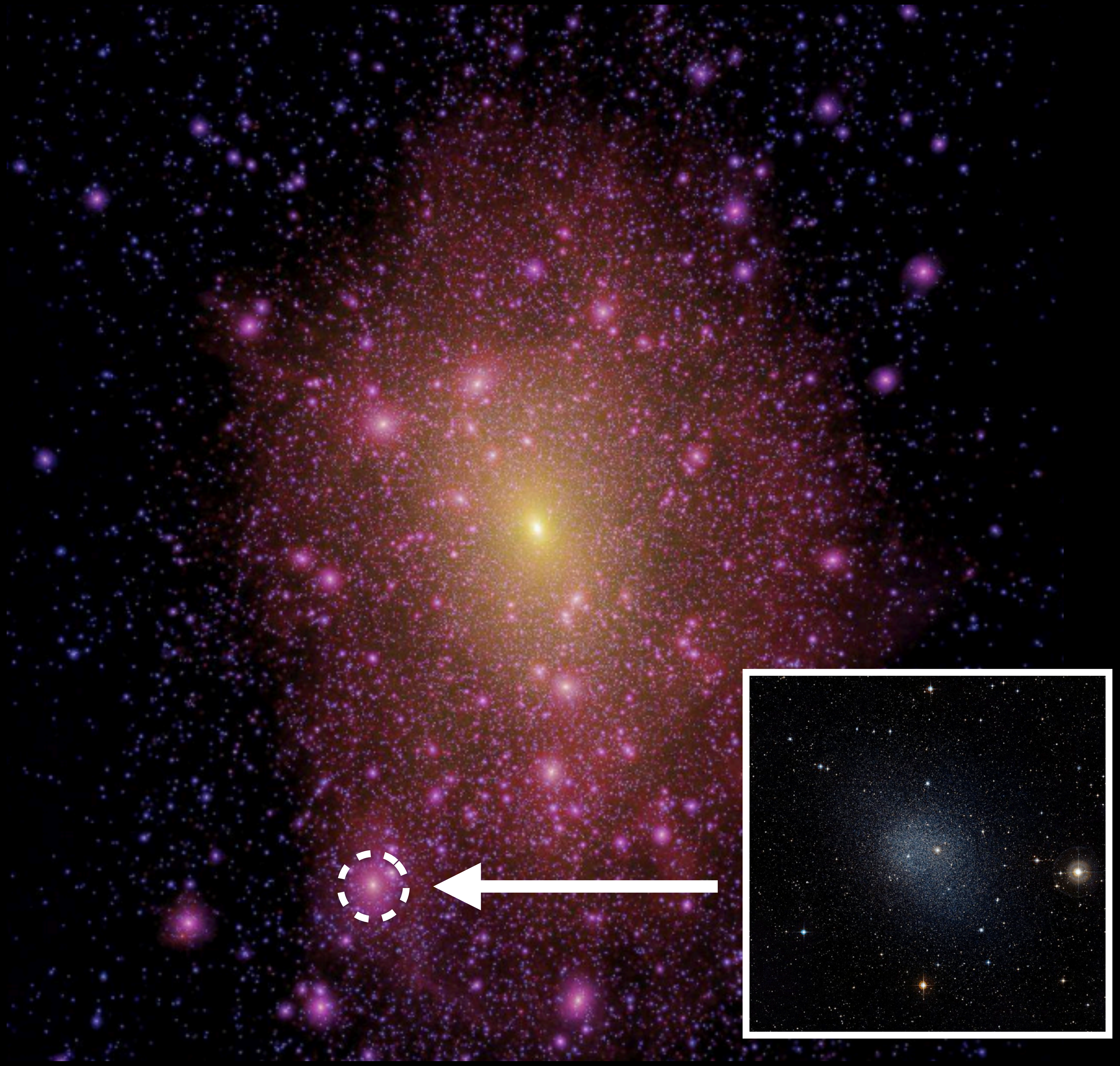


WDM

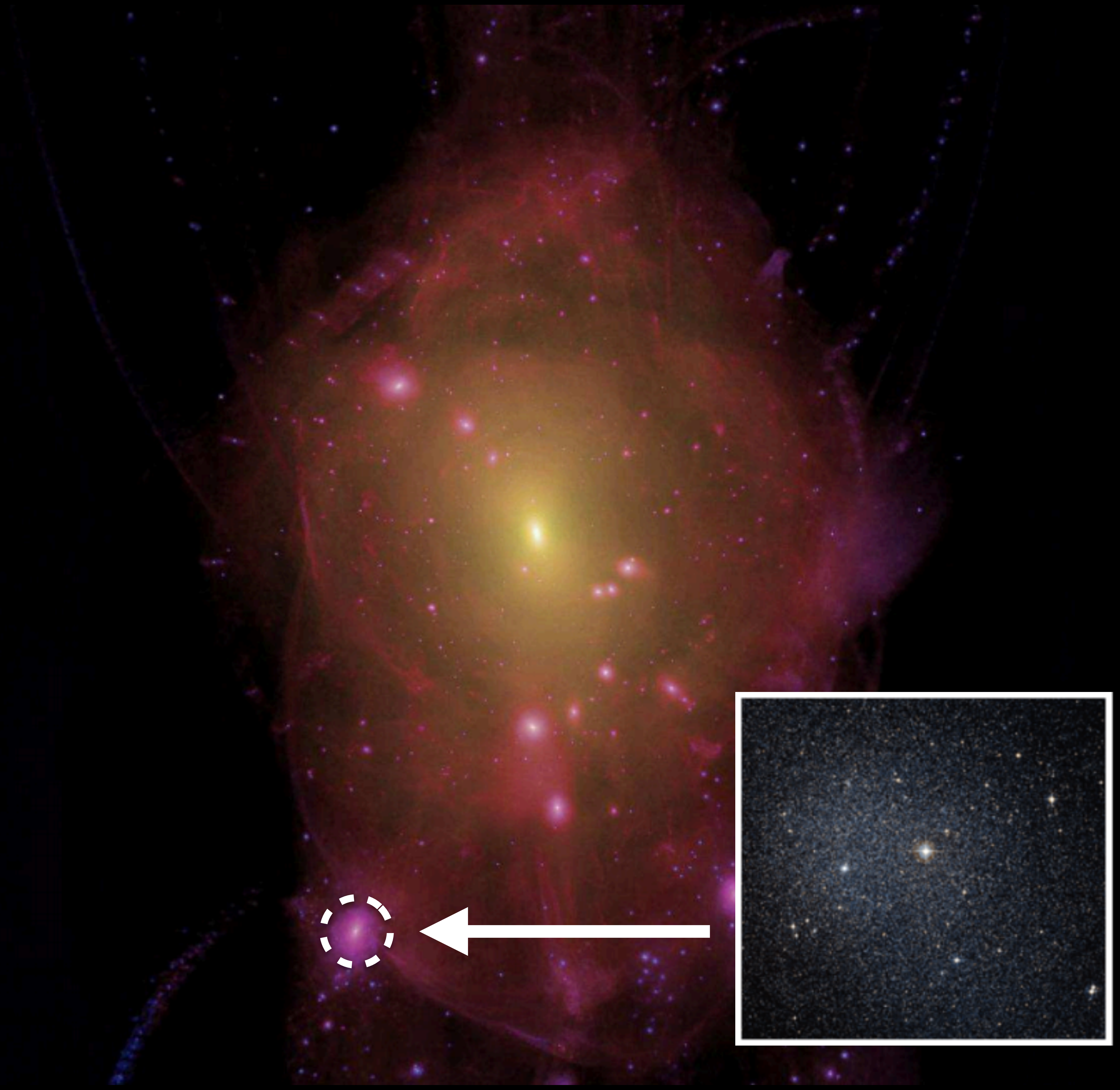
Lovell et al. 2011

Faint Galaxies as Dark Matter Probes

CDM

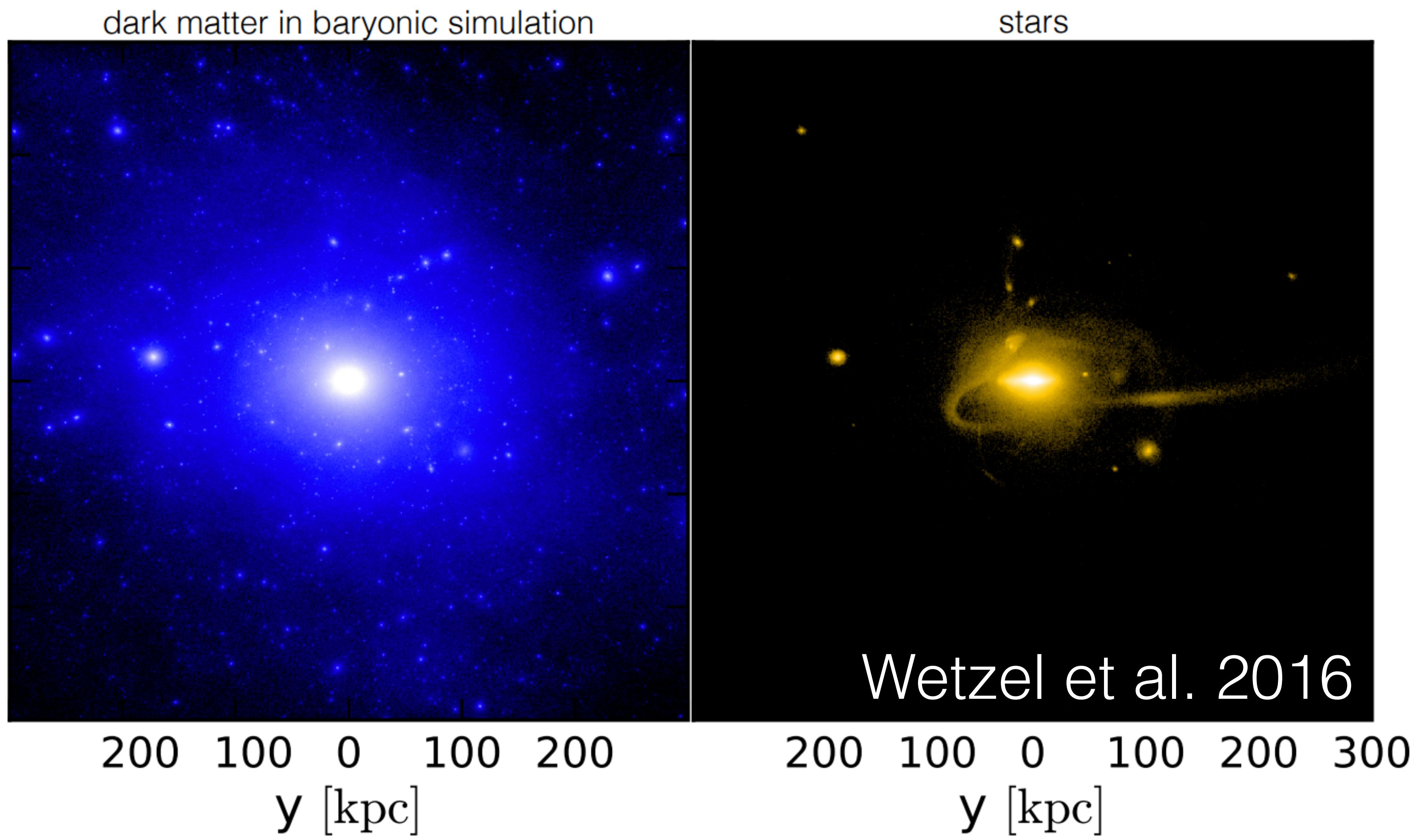


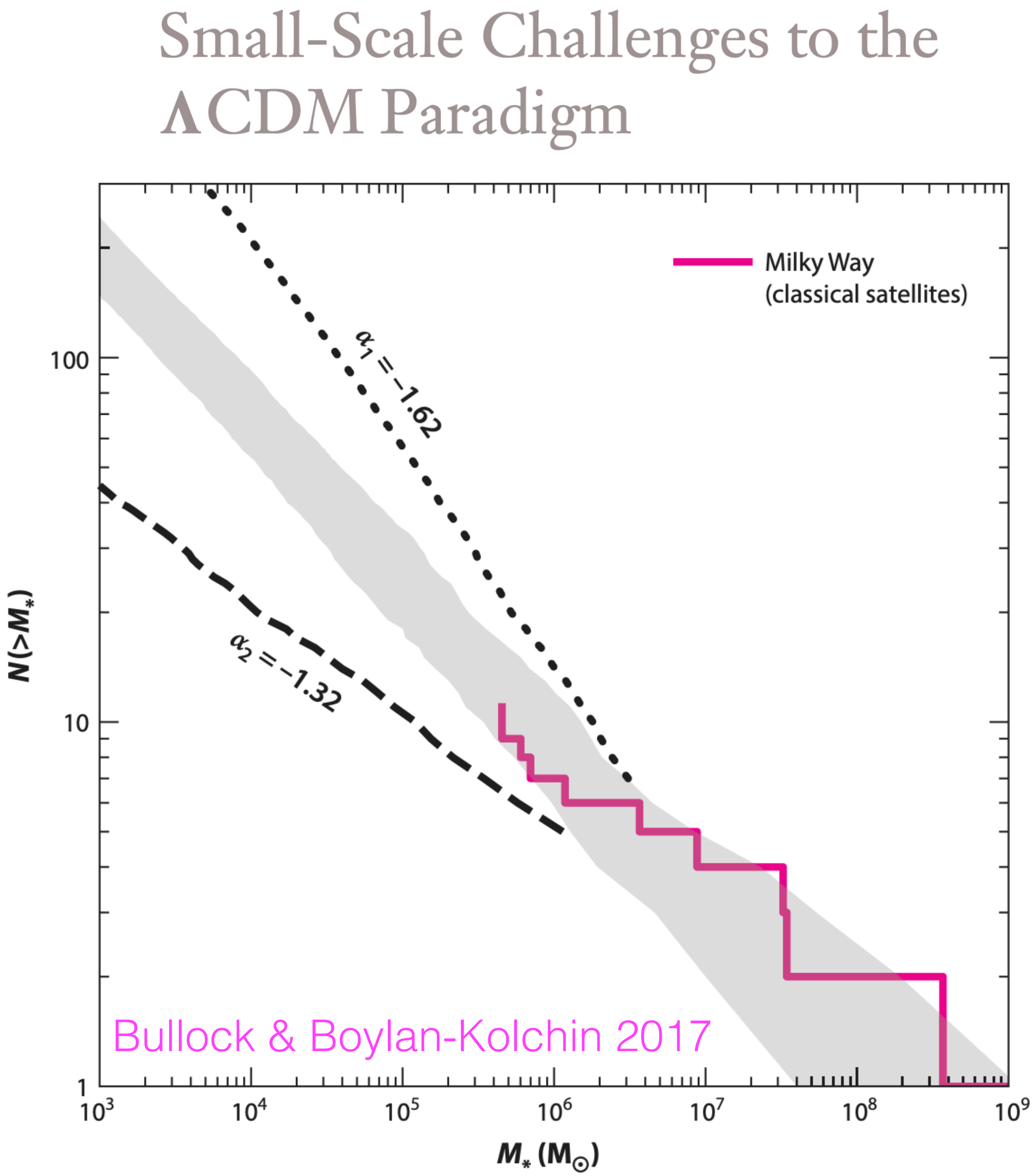
WDM



There is No Missing Satellites Problem

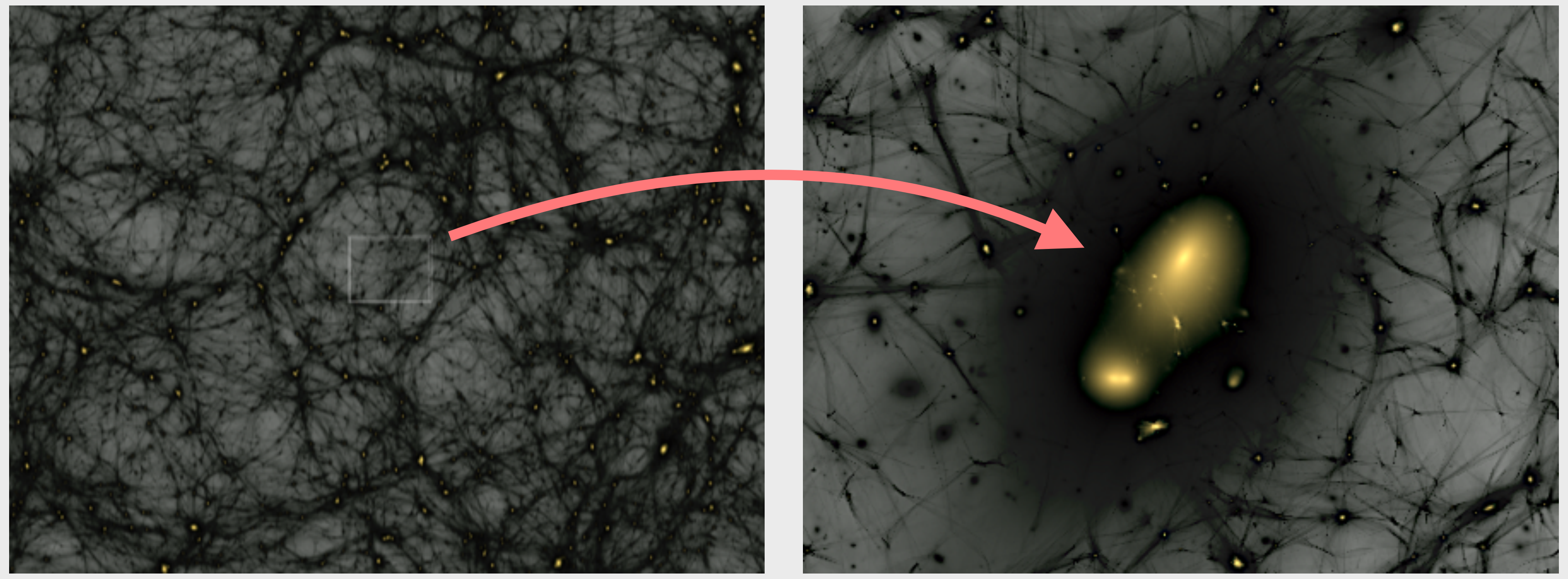
- **No missing satellites problem** after correcting for incomplete observations and extrapolating standard stellar mass–halo mass relations
- Consistency has only been demonstrated at fixed modeling assumptions, and only for the brightest half of the Milky Way satellite population



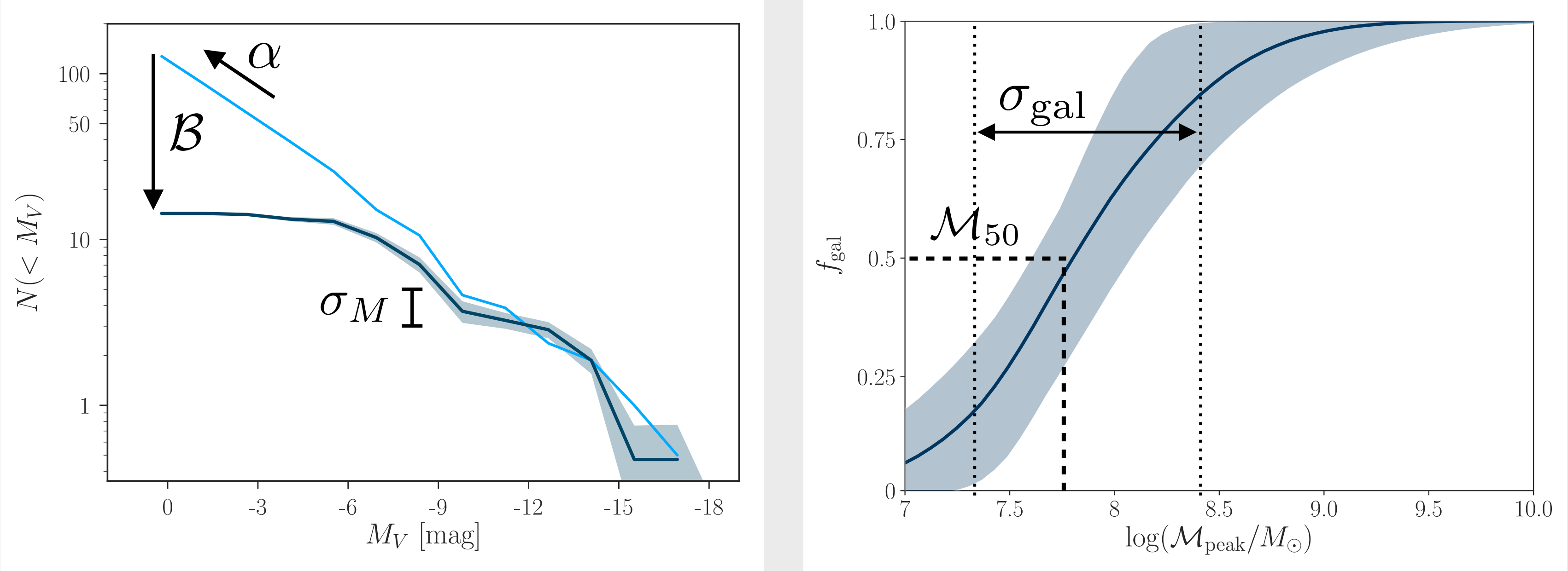


Markov Chain Monte Carlo

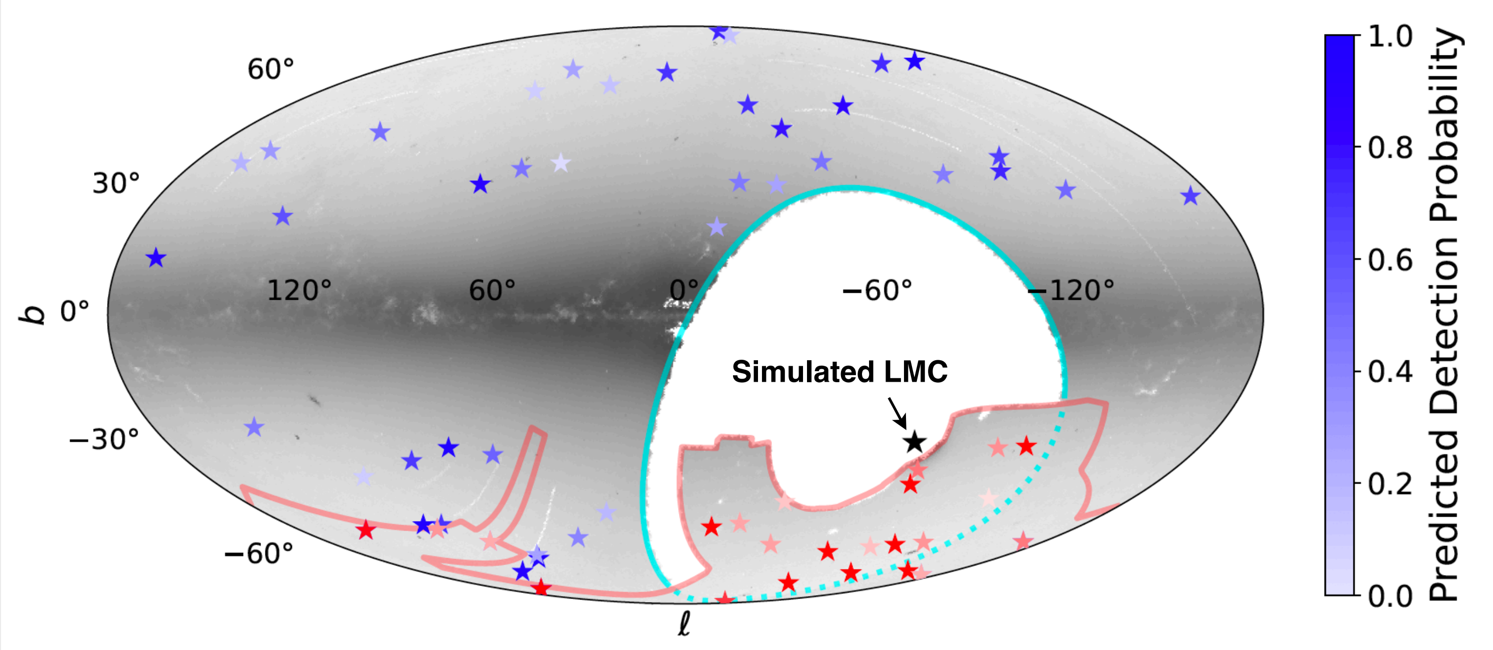
1. Resimulate Milky Way-like halos from large cosmological volume.



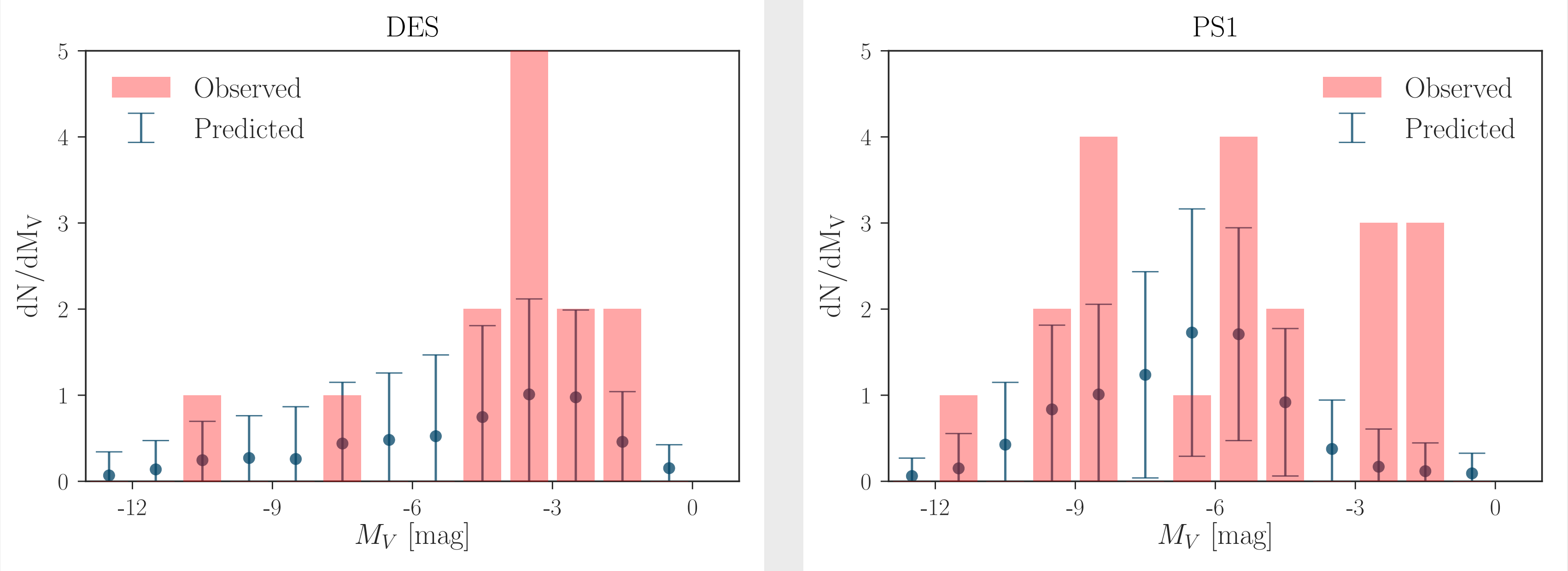
2. Paint satellite galaxies onto subhalos using galaxy—halo model.



3. Apply observational selection functions based on imaging data.

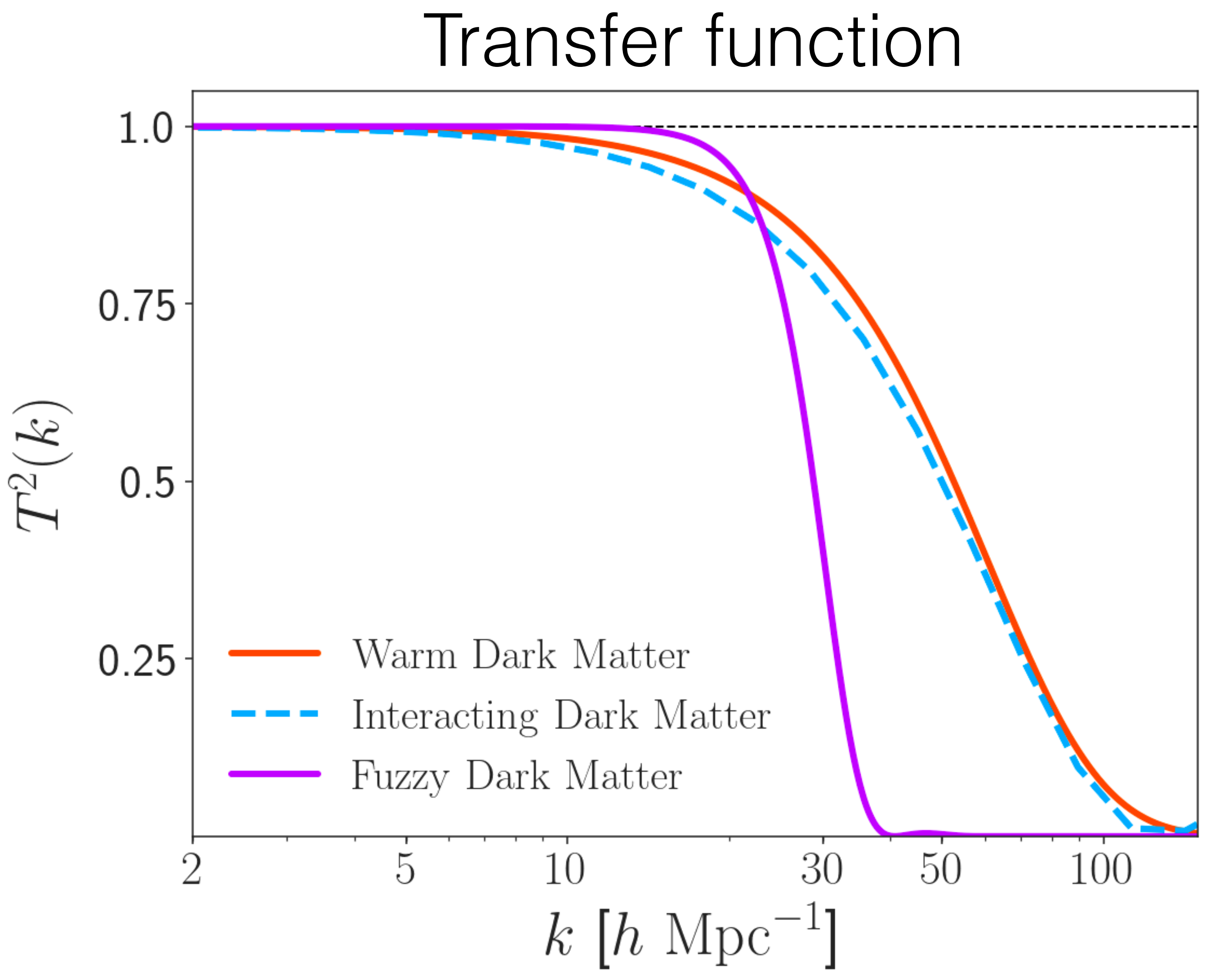


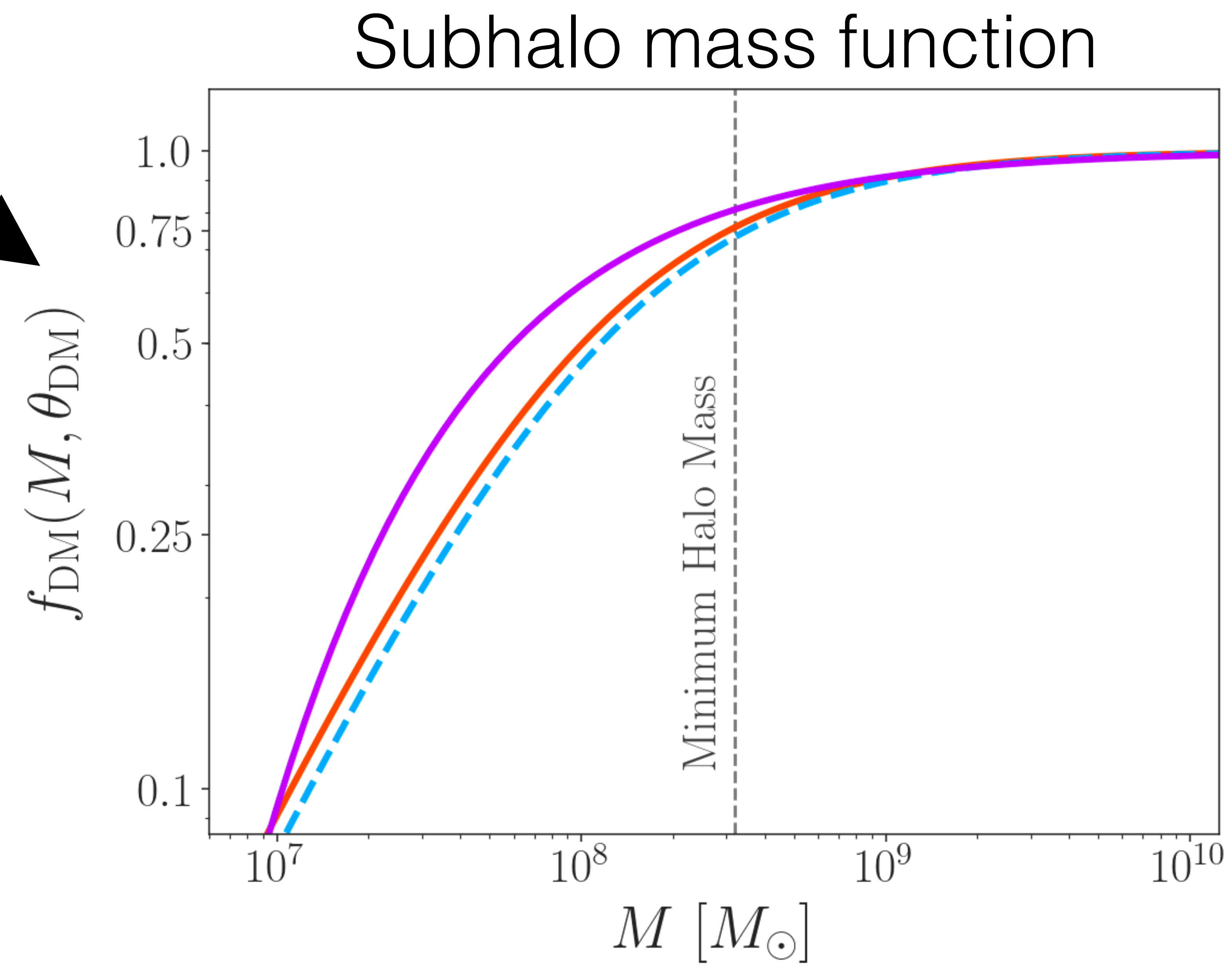
4. Calculate likelihood of observed satellites given galaxy—halo connection parameters.

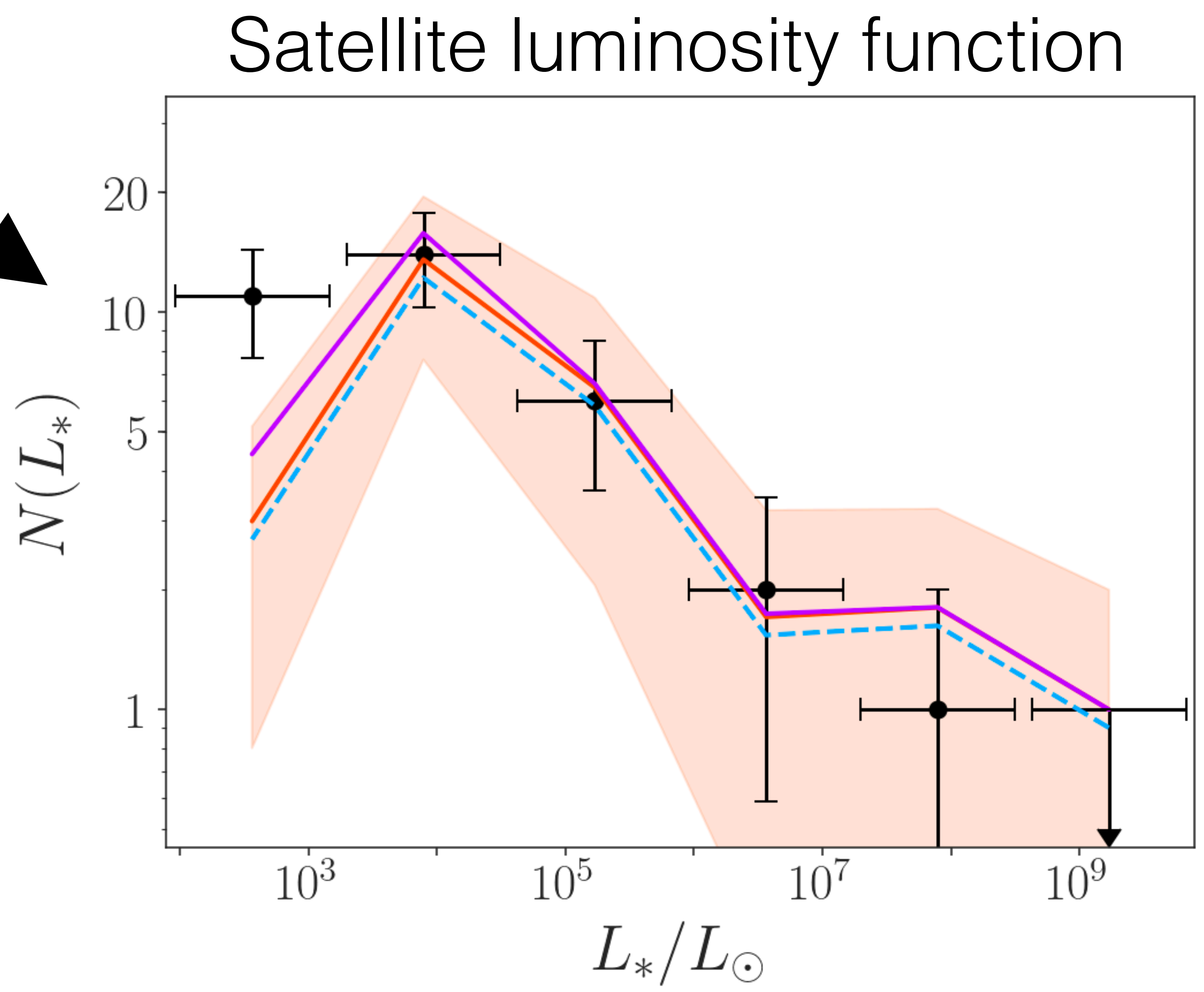


EN & Wechsler et al. 2020

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



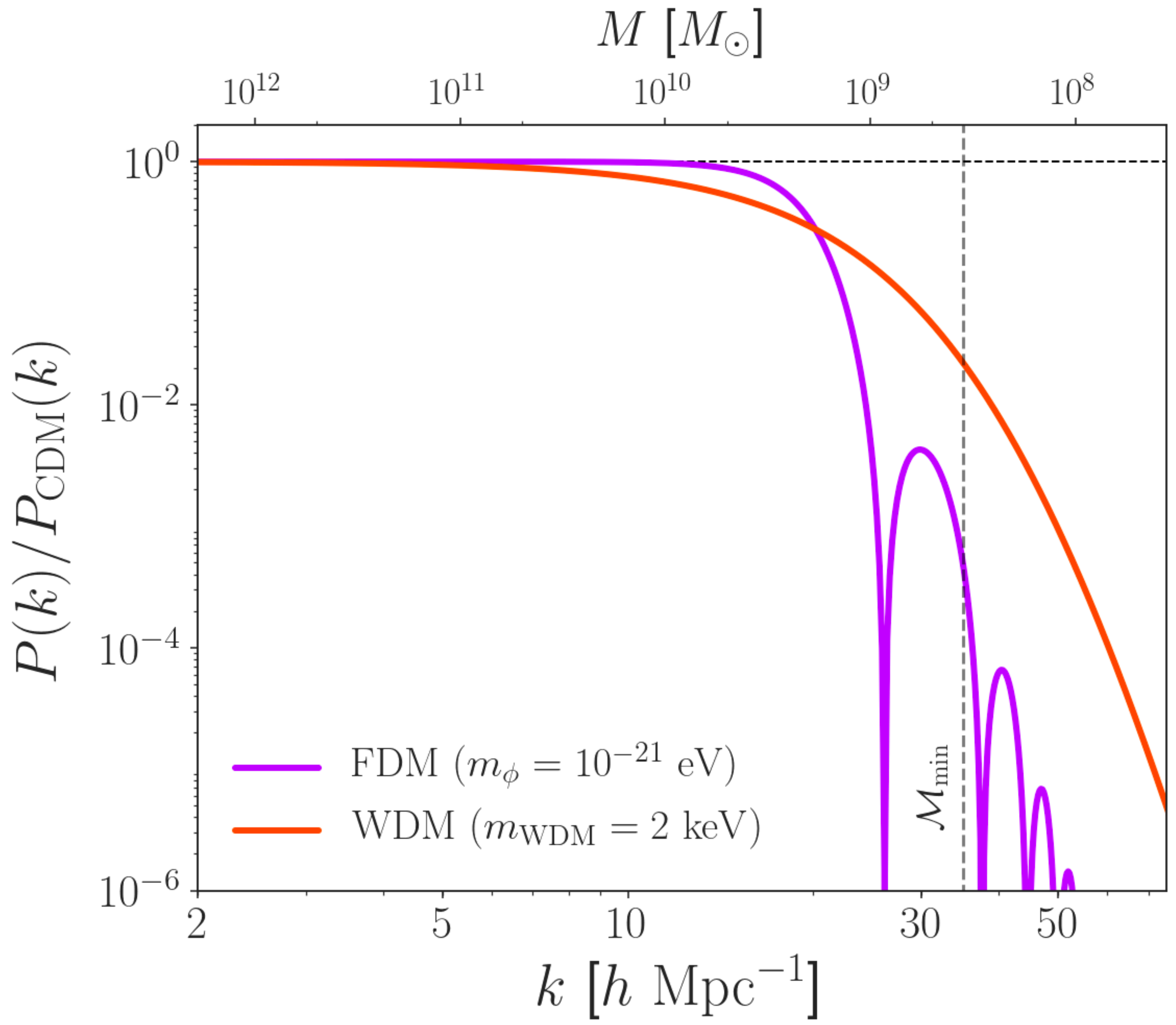


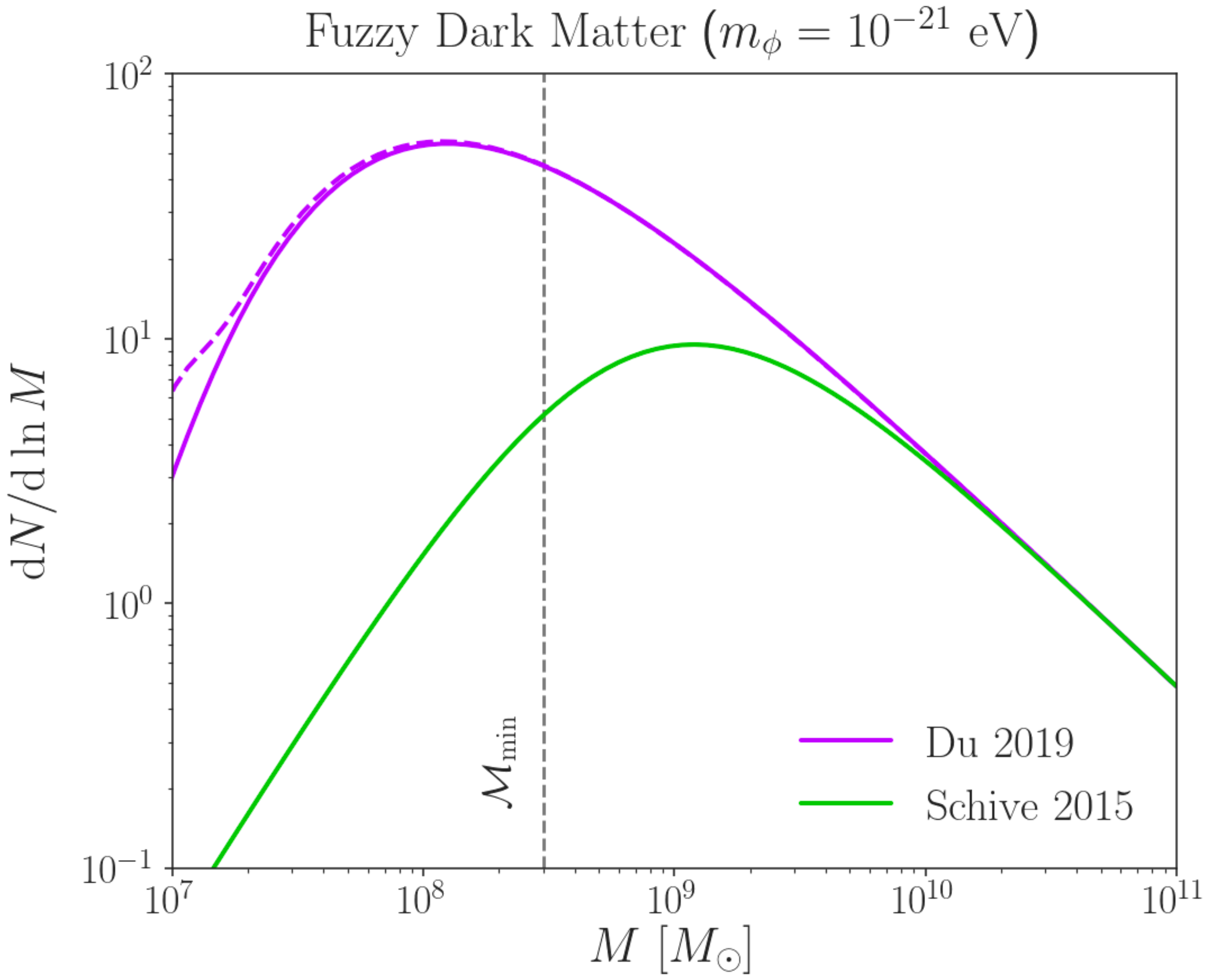


Current satellite observations are sensitive to **~25%** suppression in subhalo abundance relative to CDM

EN & Drlica-Wagner et al. 2020

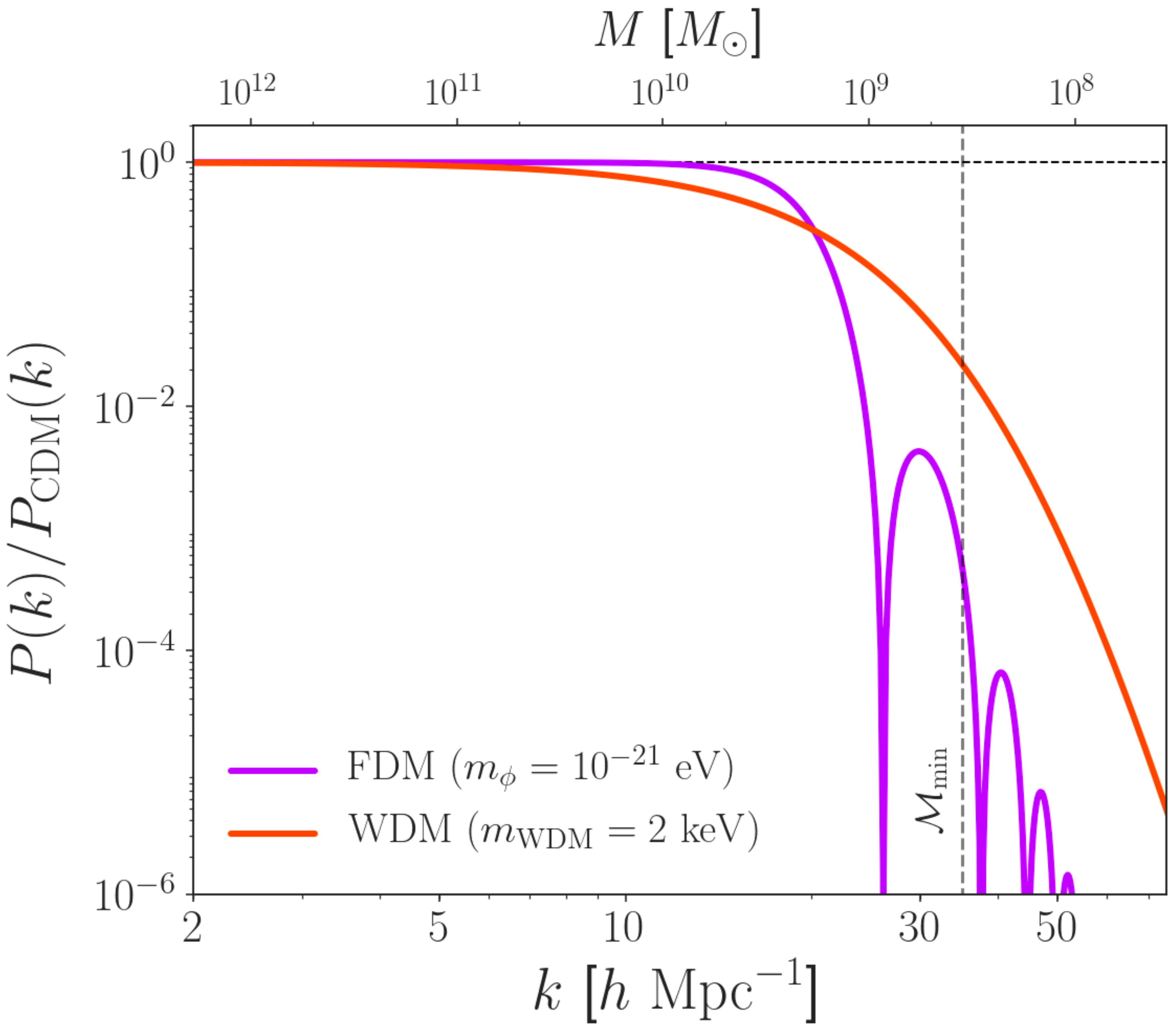
Fuzzy Dark Matter Subhalo Mass Function

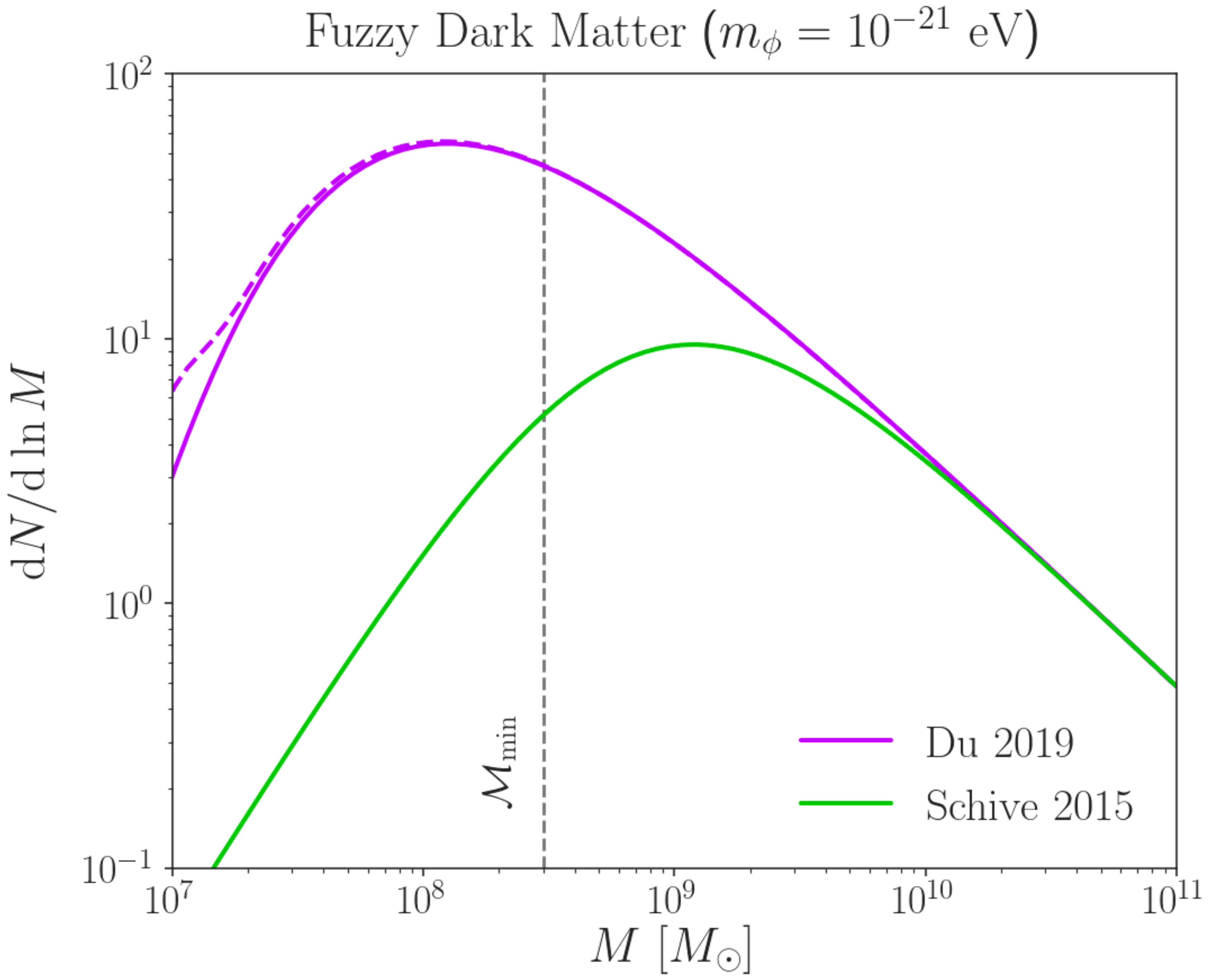




interference due to macroscopic de Broglie wavelength → cutoff in abundance of low-mass halos

Fuzzy Dark Matter Subhalo Mass Function





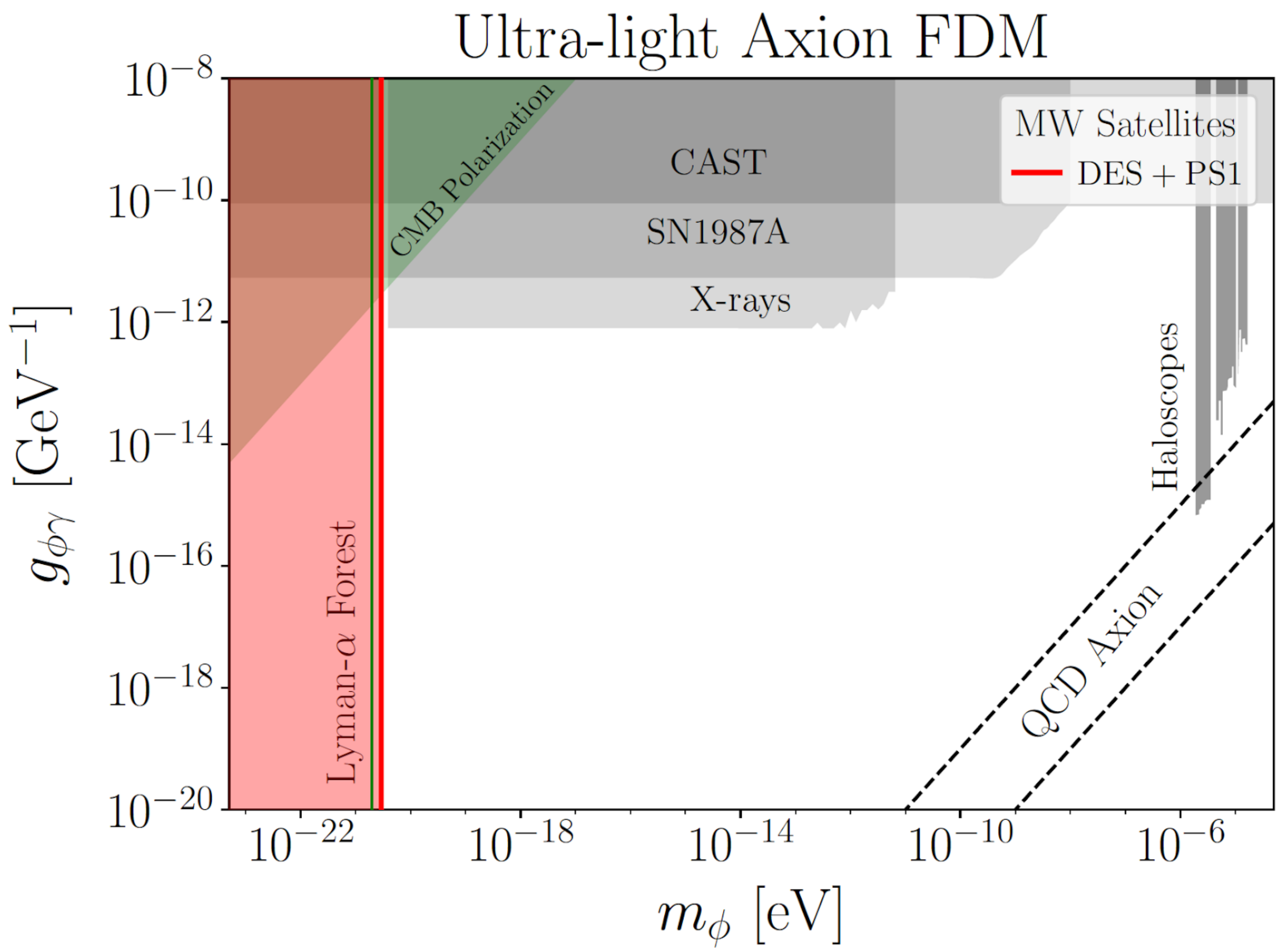
Order of magnitude uncertainty in FDM SHMF!

Fuzzy Dark Matter Constraints

- Fuzzy dark matter lighter than **10^{-21} eV** is robustly ruled out by MW satellite observations

- Strongly disfavors FDM models that solve the core/cusp problem

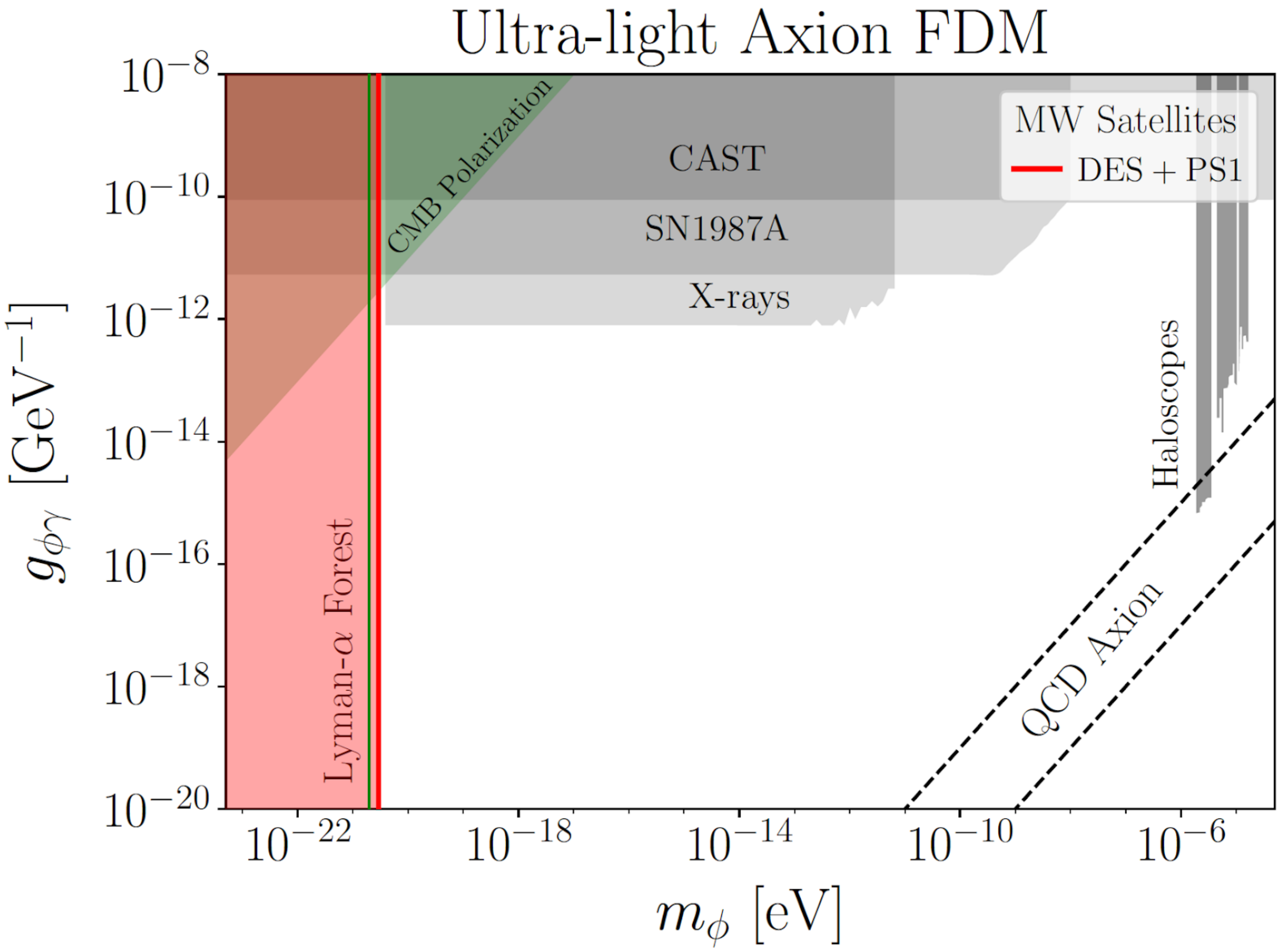
- Sets a lower limit on ULA mass *for negligible self-interactions*



EN & Drlica-Wagner et al. 2020

Fuzzy Dark Matter Constraints

- Fuzzy dark matter lighter than **10^{-21} eV** is robustly ruled out by MW satellite observations
- Strongly disfavors FDM models that solve the core/cusp problem
- Subhalo evolution with ULA-like self-interactions is an important area for simulation work!



EN & Drlica-Wagner et al. 2020

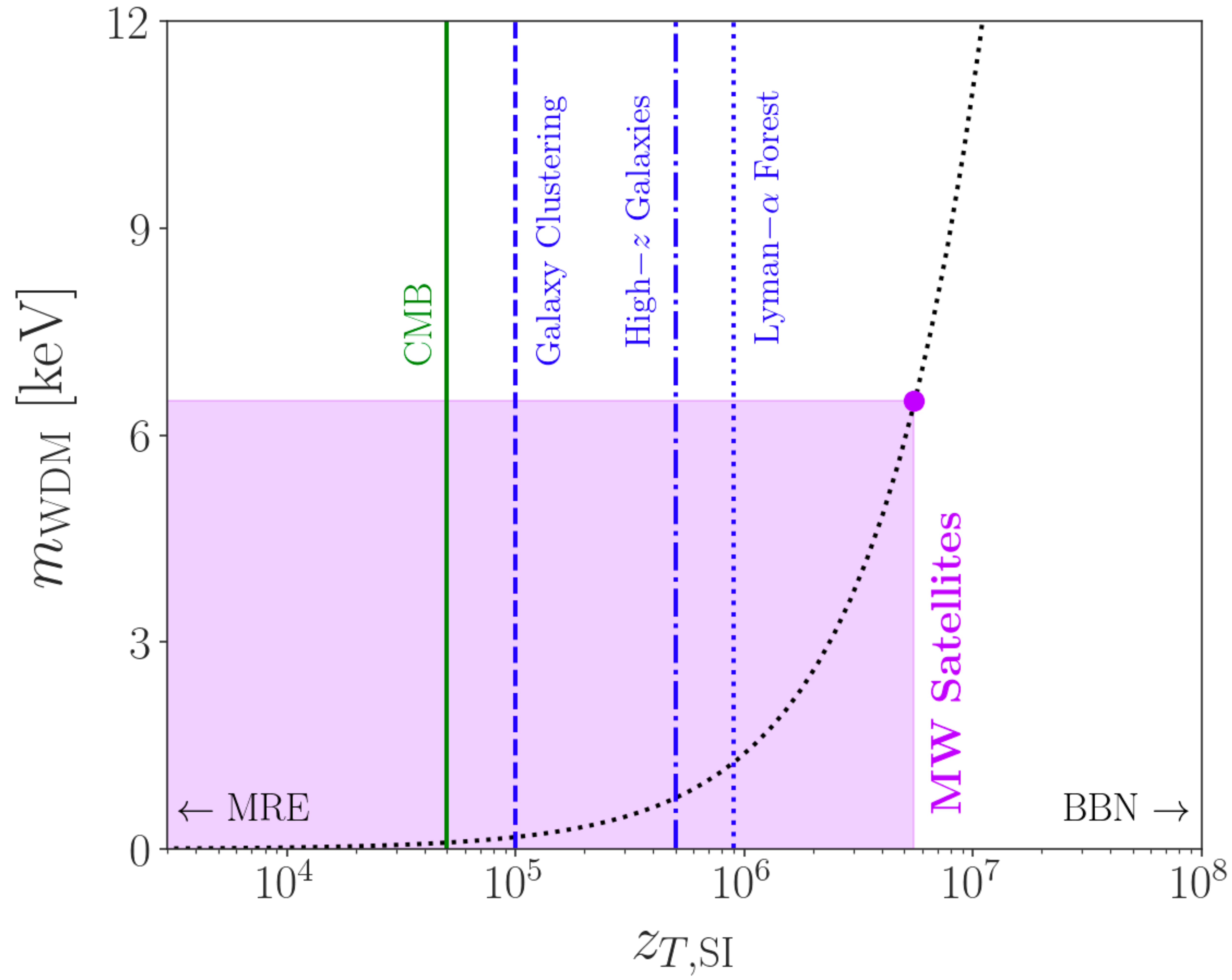
Late-Forming Dark Matter Constraints

- Dark radiation that transitions to CDM ("late-forming dark matter") suppresses power on small scales

- Cutoff in halo abundance is set by the LFDM transition redshift

- From MW satellites, dark radiation can transition to CDM **no later than 1 week** after the Big Bang:

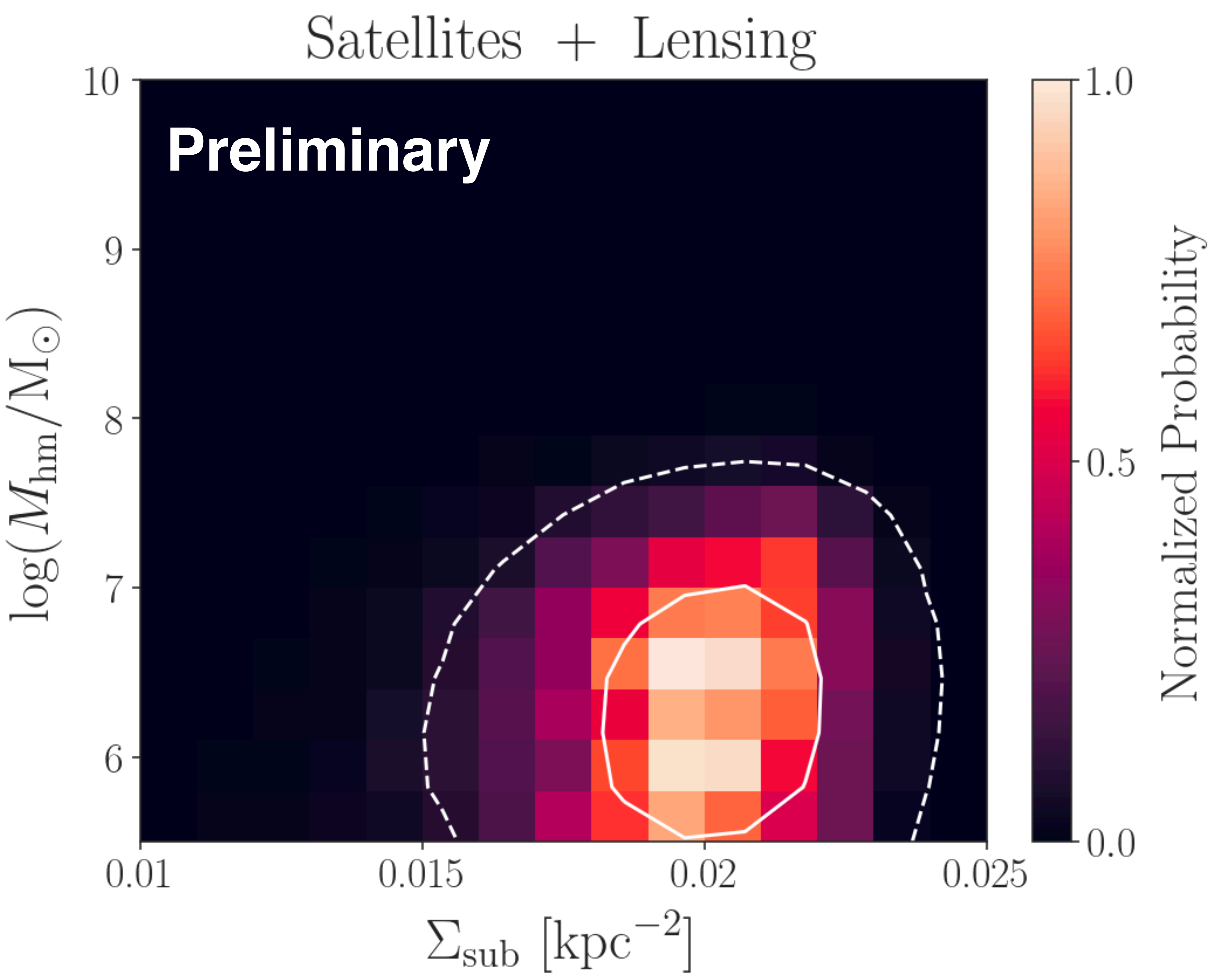
$$z_{\mathrm{LFDM}} > 5.5 \times 10^6 \ (95\% \ \mathrm{C.L.})$$



Das & EN 2020

Combining Small-Scale Structure Probes

- Lyman-α forest, strong gravitational lensing, and stellar streams yield similar dark matter constraints
- Joint models of small-scale probes are key to break degeneracies and robustly detect non-CDM physics
- In progress: combined constraints using MW satellite abundances and strong gravitational lensing



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

Outlook

- The lack of a cutoff in the abundance of Milky Way satellites down to halo masses of $\sim 10^8\ M_\odot$ yields **stringent constraints** on dark matter physics

- These constraints will **continue to improve** with next-generation data from the Vera C. Rubin Observatory (LSST) and simulation advances

- Fuzzy dark mater lighter than **10^{-21} eV** is robustly ruled out despite SHMF uncertainty (for ULAs, simulations with self-interactions are crucial)

- **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

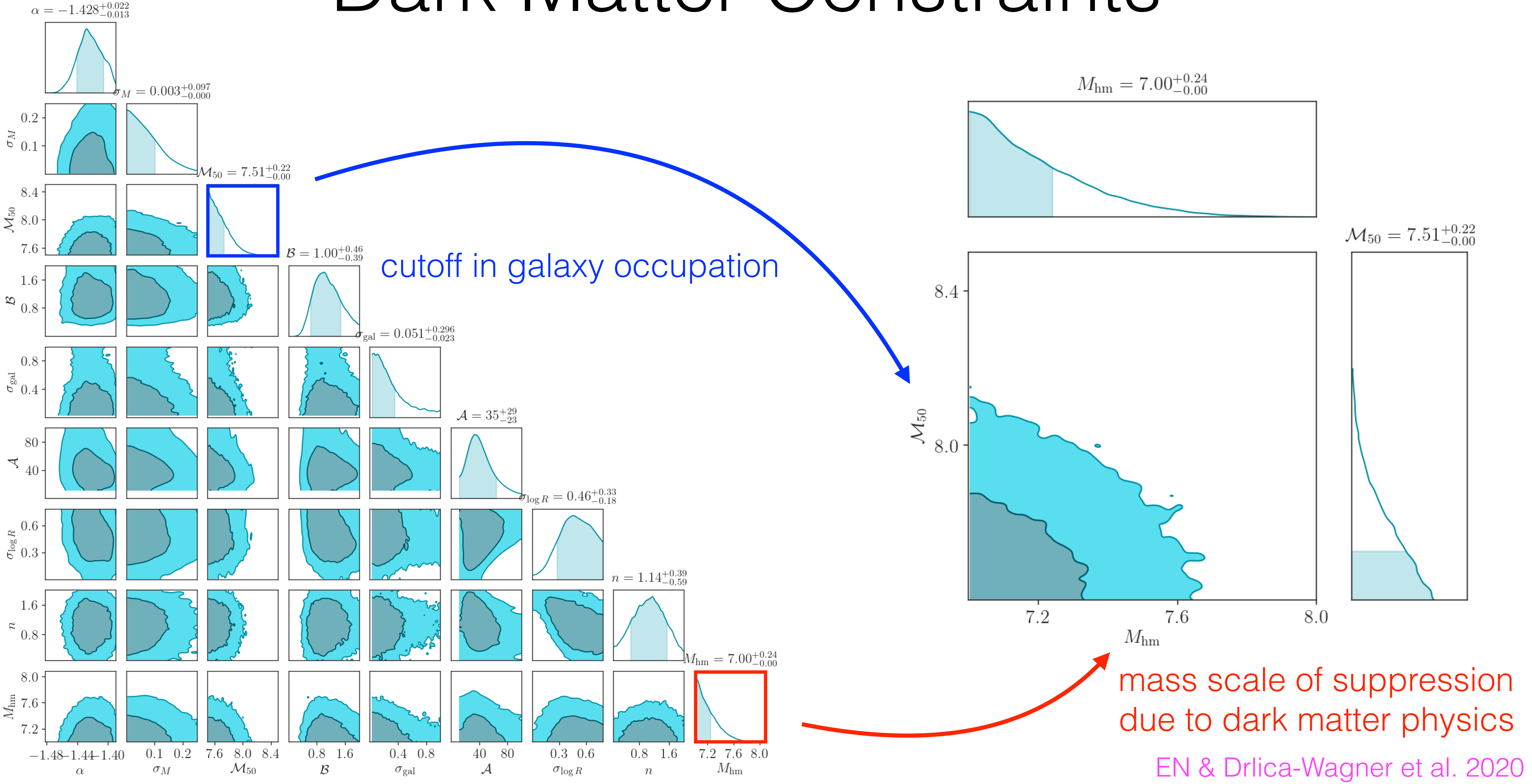
Galaxy–Halo Connection Model

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

EN, Y.-Y. Mao, G. Green, R. Wechsler 2019

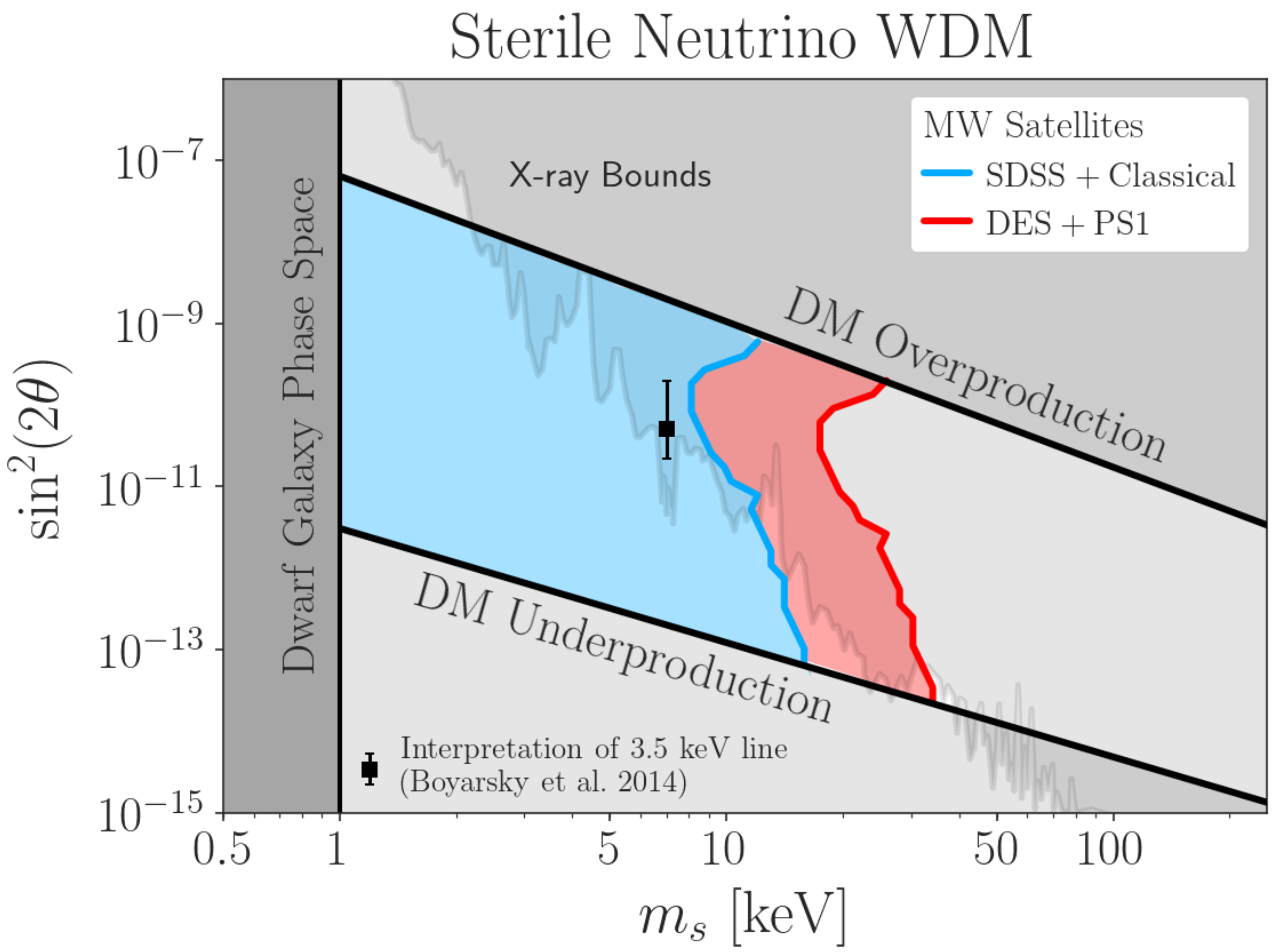
Dark Matter Constraints



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

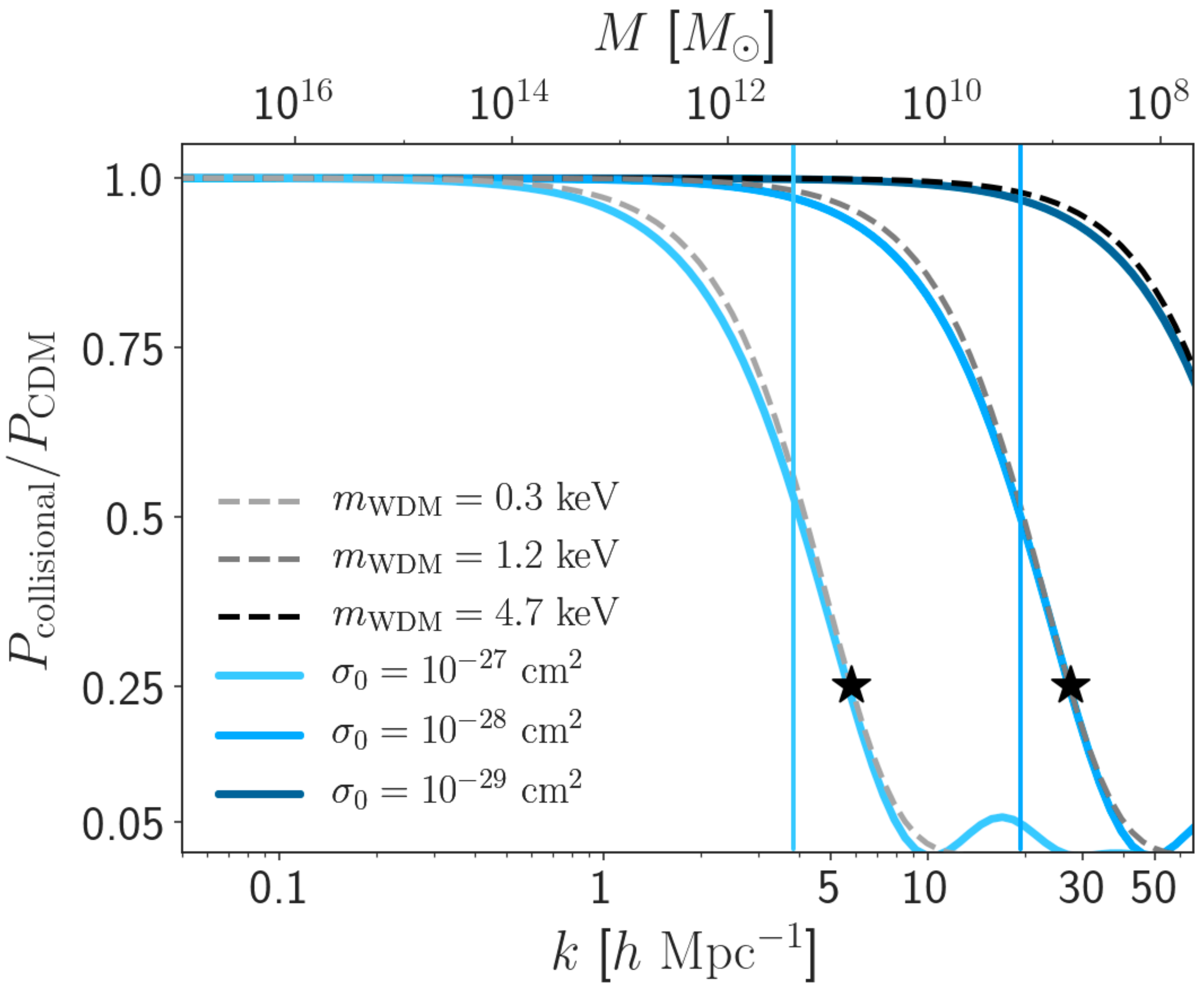
- Mass of the smallest halo allowed to form corresponds to the size of the horizon when

$$R_\chi \sim aH$$

Momentum transfer rate

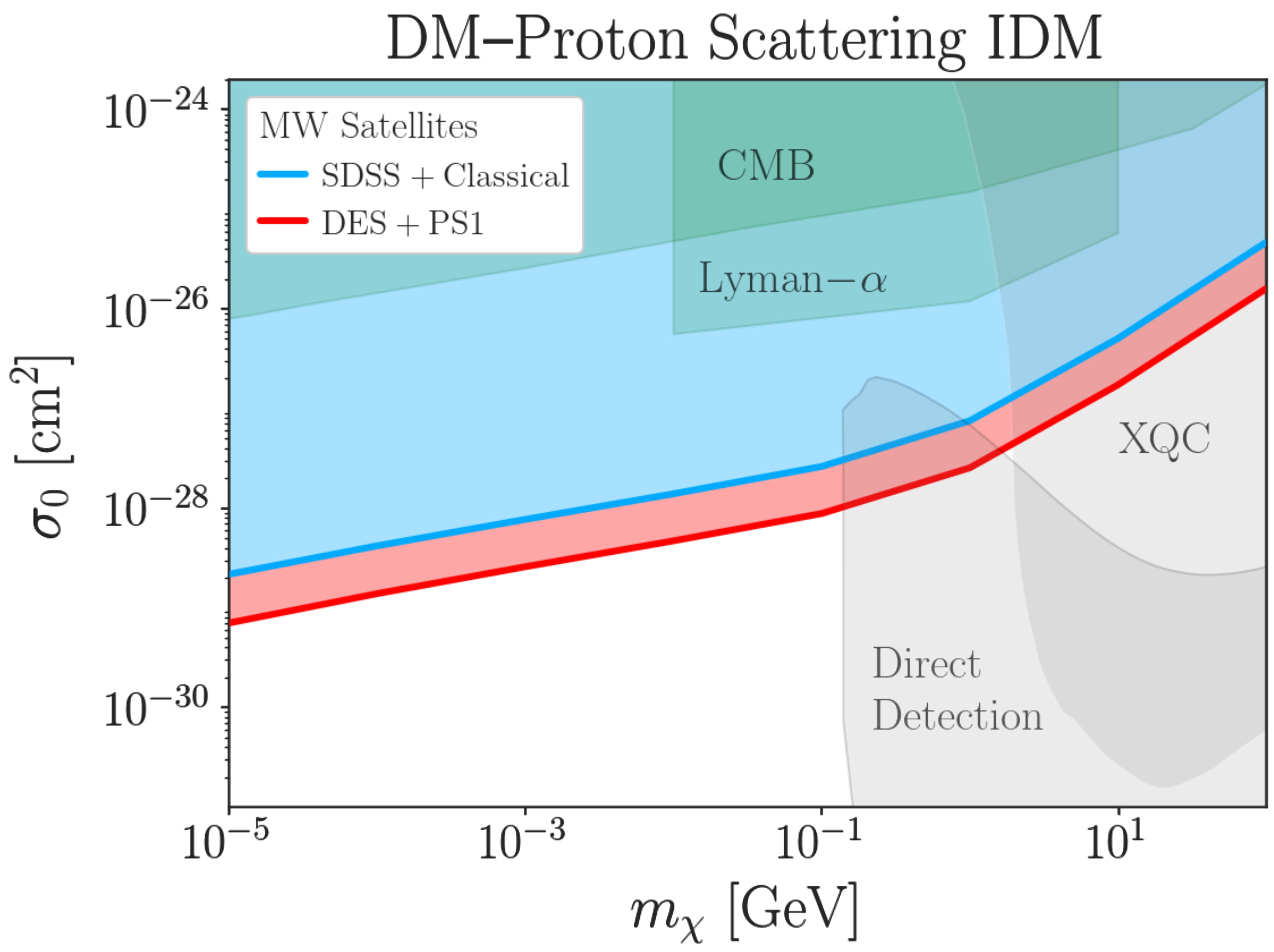
Hubble rate

- 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