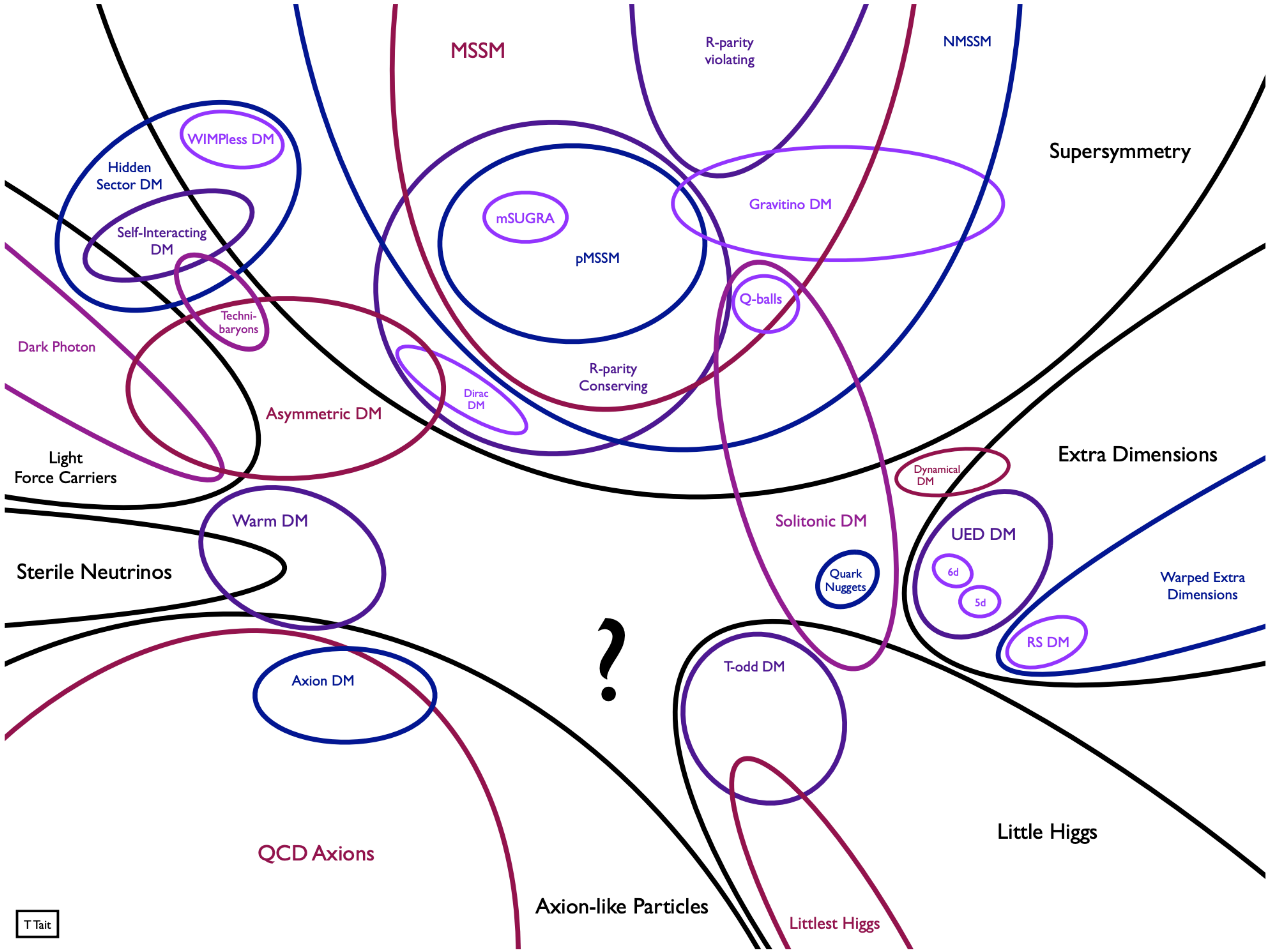
Constraints on Dark Matter Microphysics from Dwarf Galaxies

Ethan Nadler

BSM PANDEMIC

6/3/2020

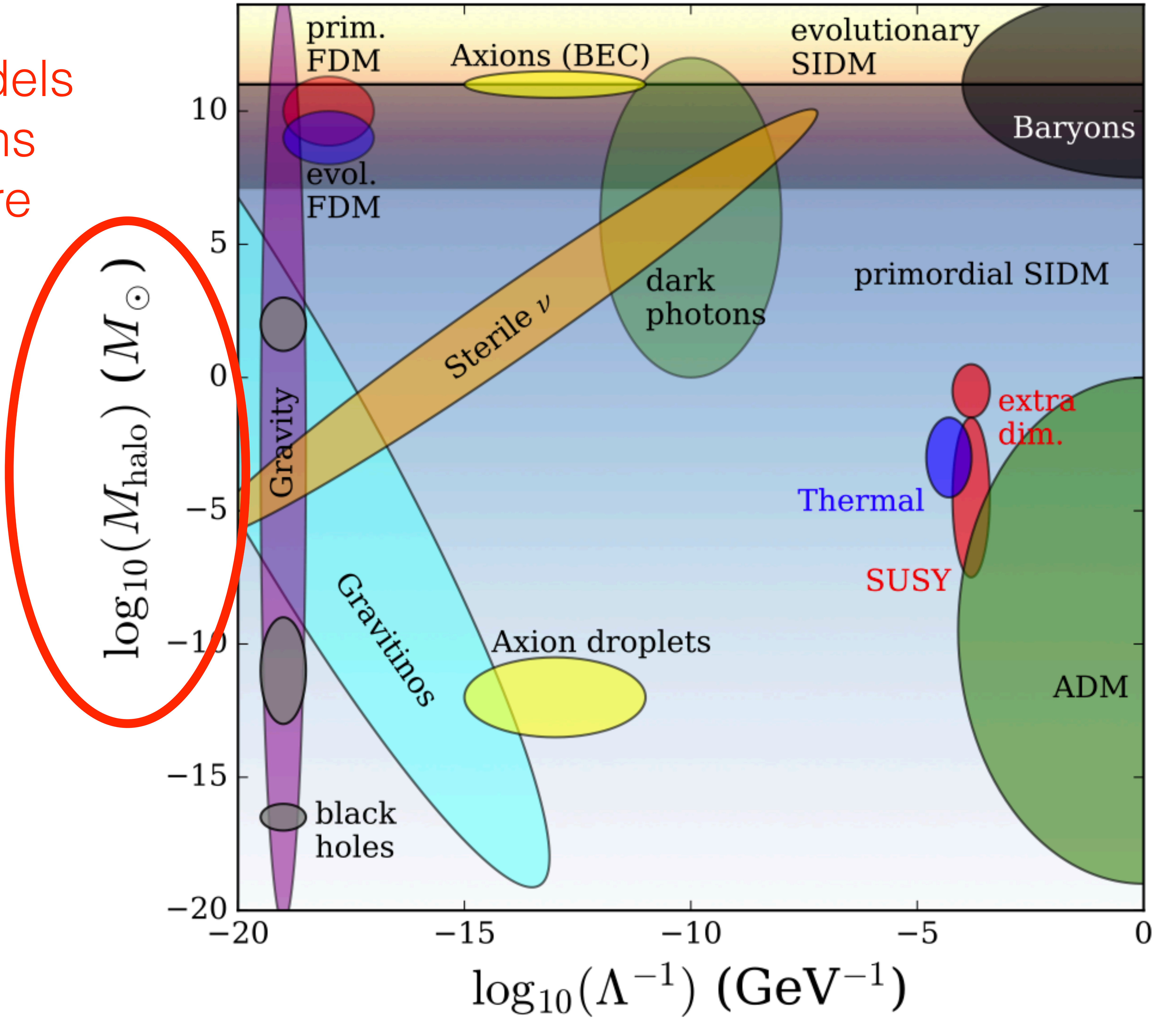
The Dark Matter Landscape



Credit: T. Tait

DM Physics from Structure Formation

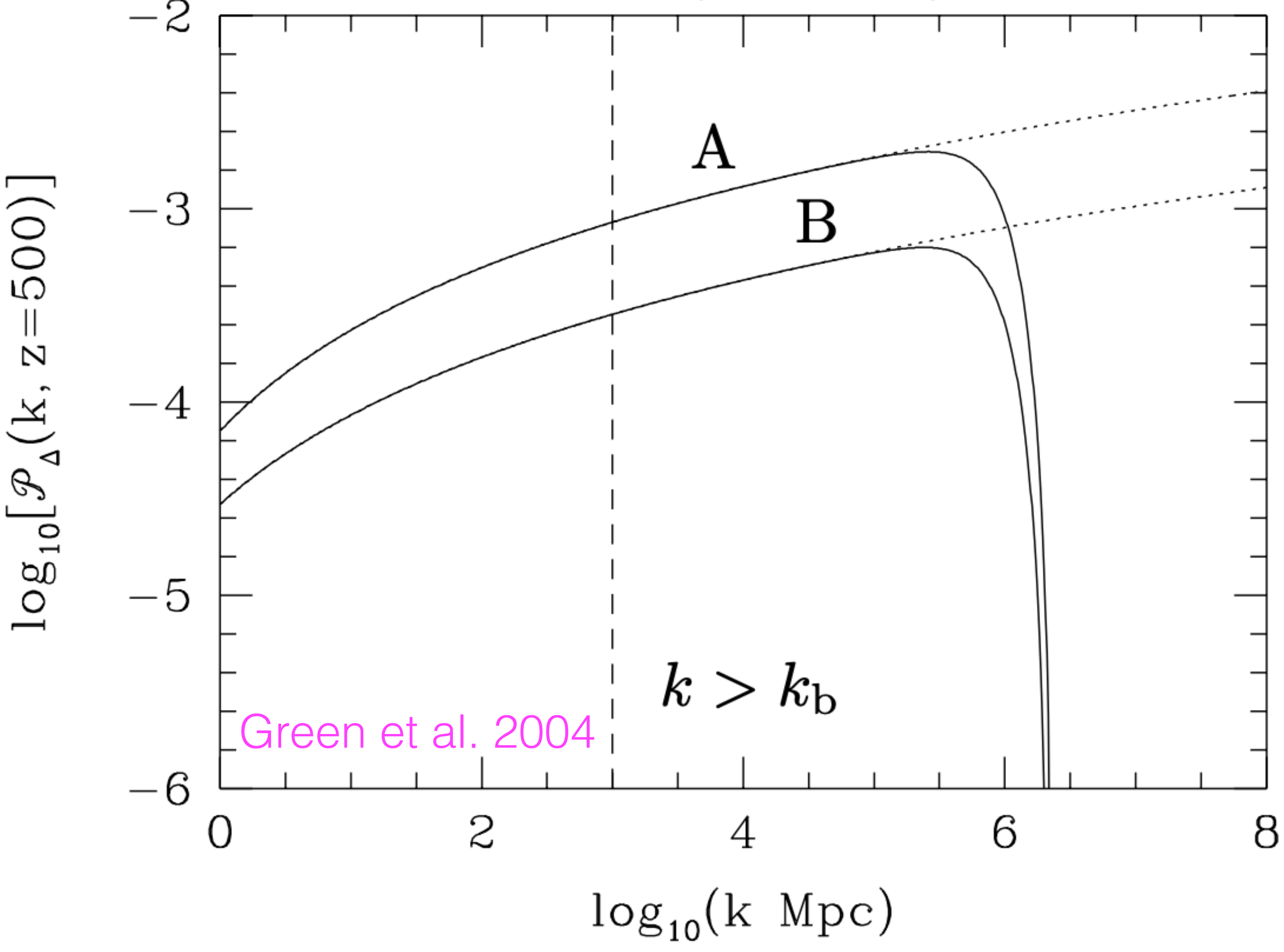
Many popular DM models differ in their predictions for small-scale structure



Buckley & Peter 2018

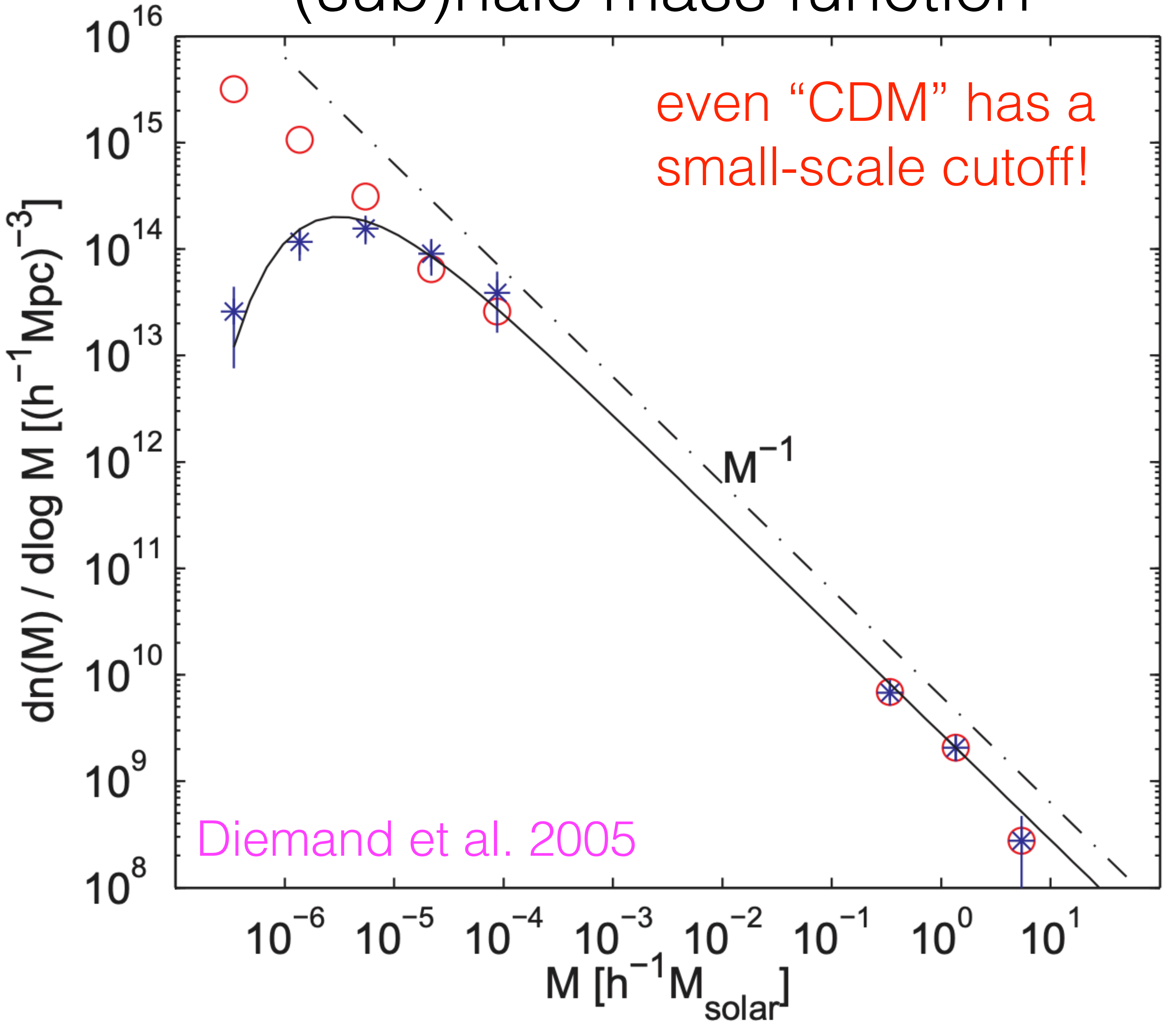
DM Physics from Structure Formation

linear matter power spectrum



Green et al. 2004

(sub)halo mass function

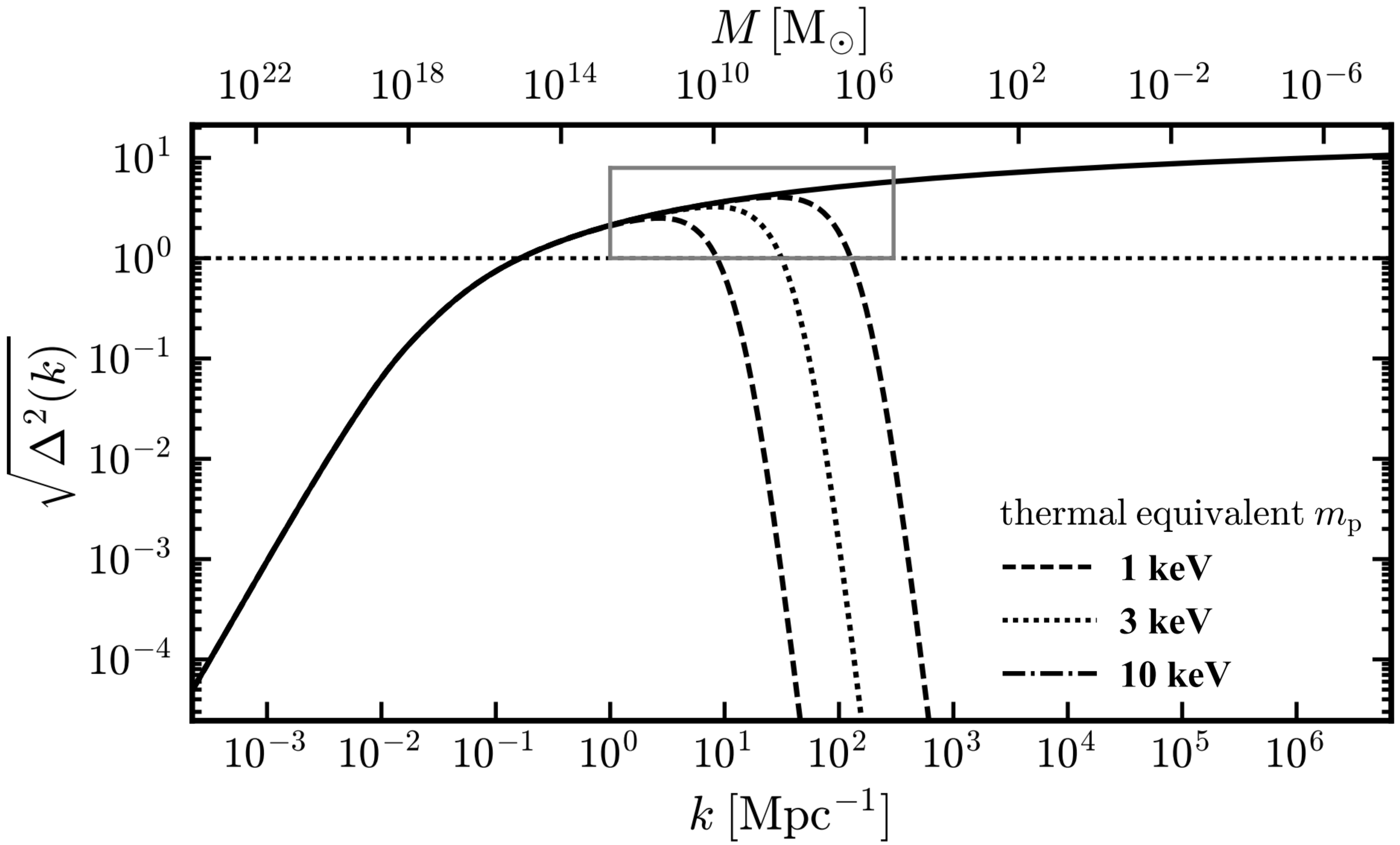


even “CDM” has a small-scale cutoff!

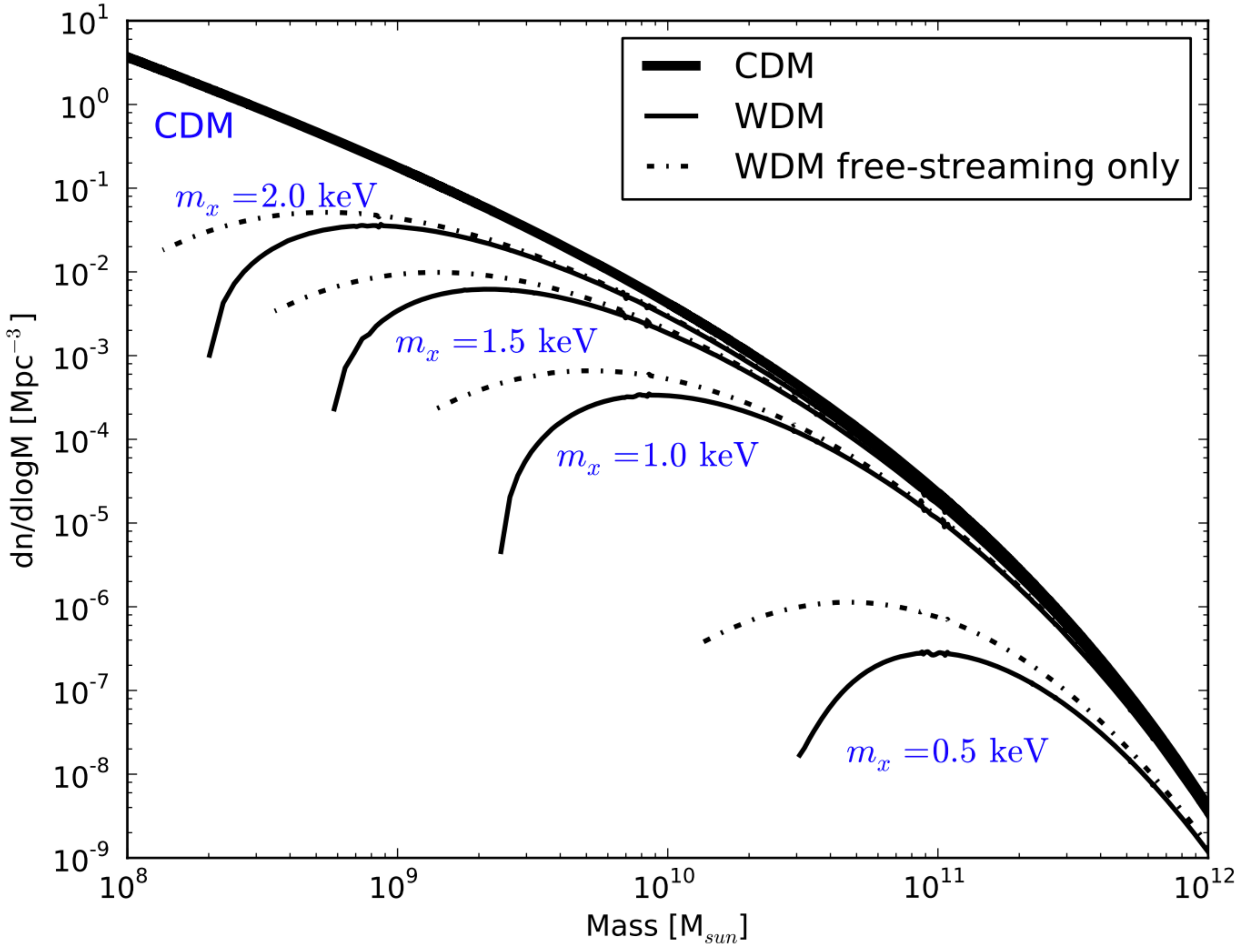
Diemand et al. 2005

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

DM Physics from Structure Formation



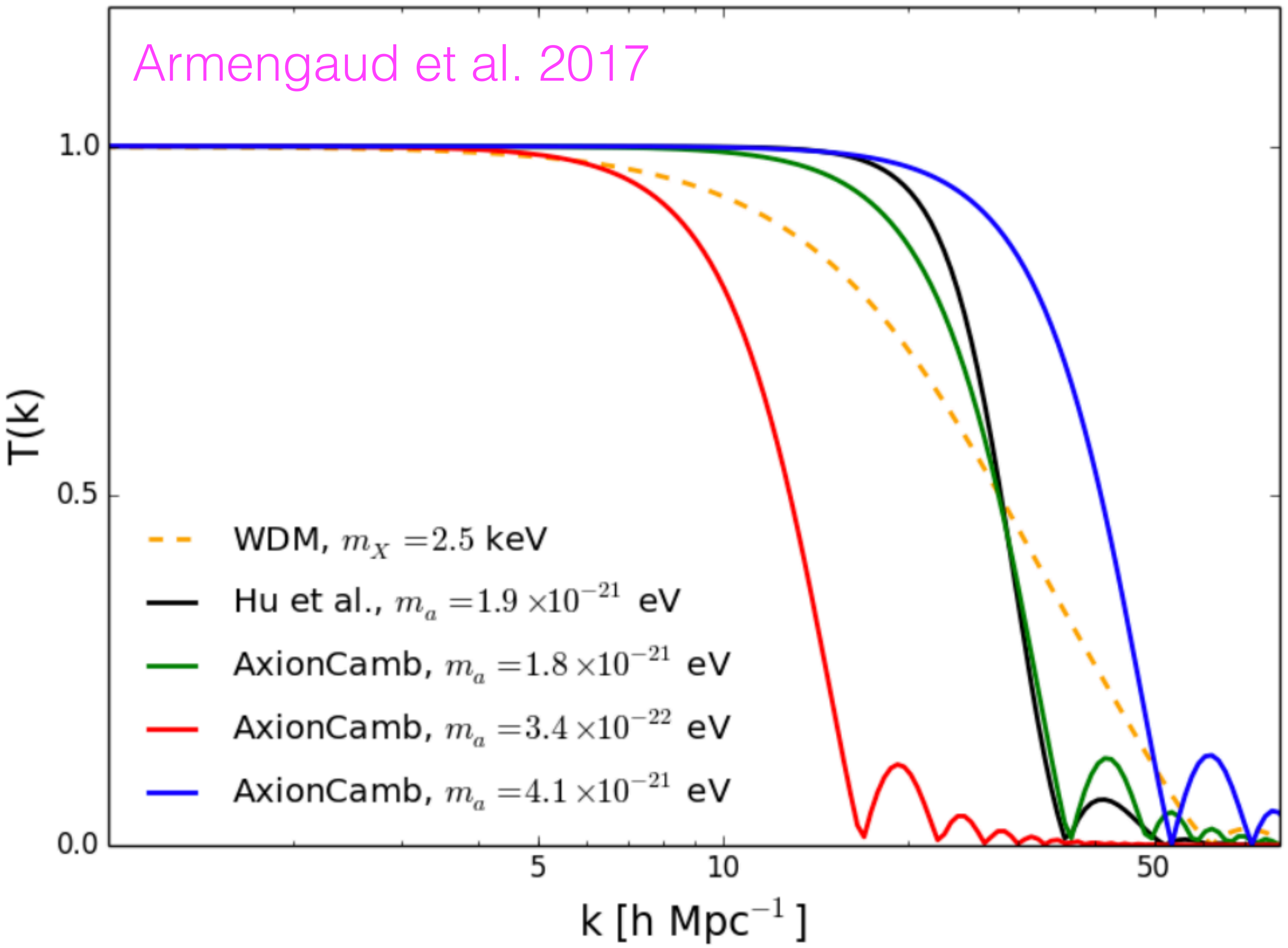
Bullock & Boylan-Kolchin 2017

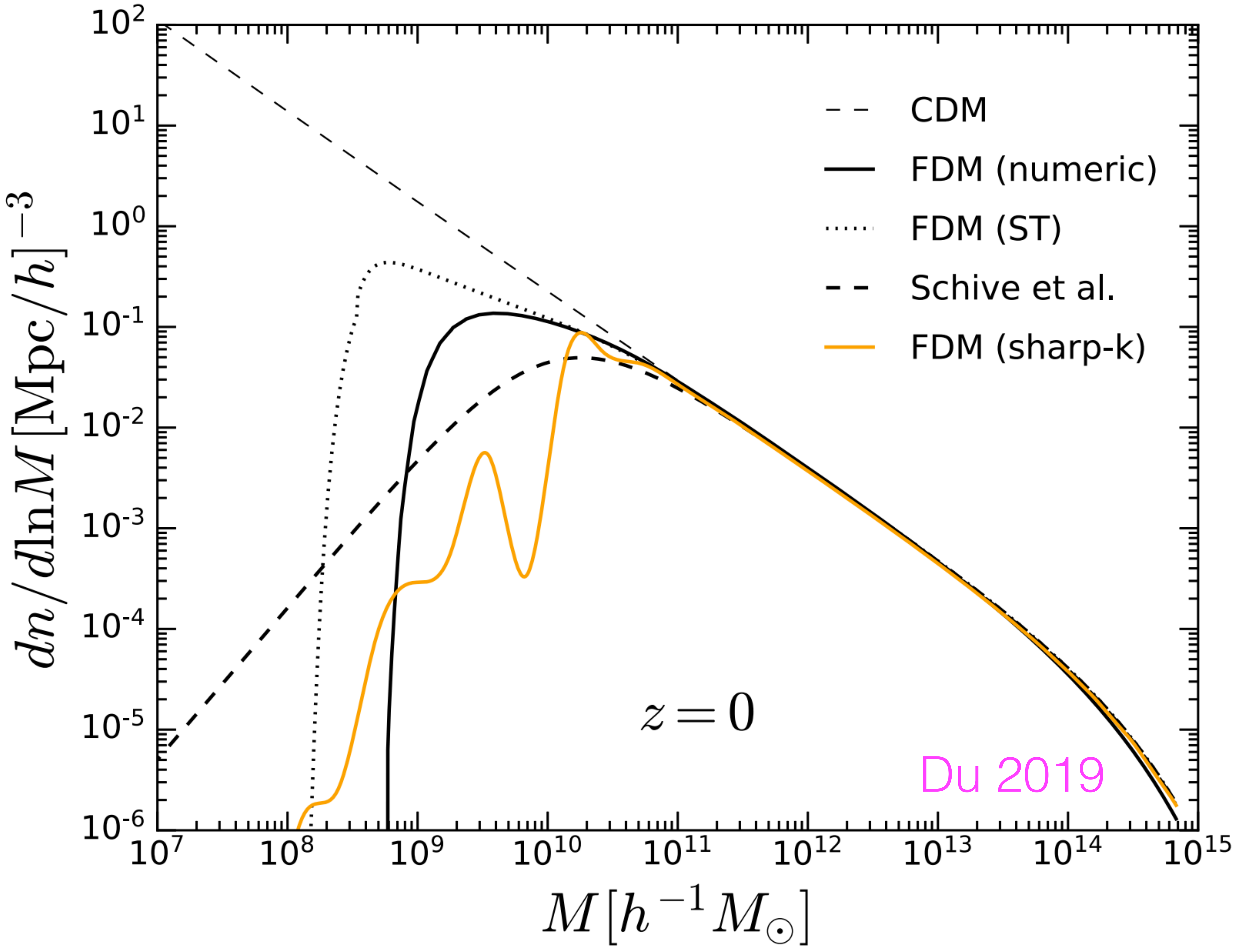


Pacucci et al. 2013

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

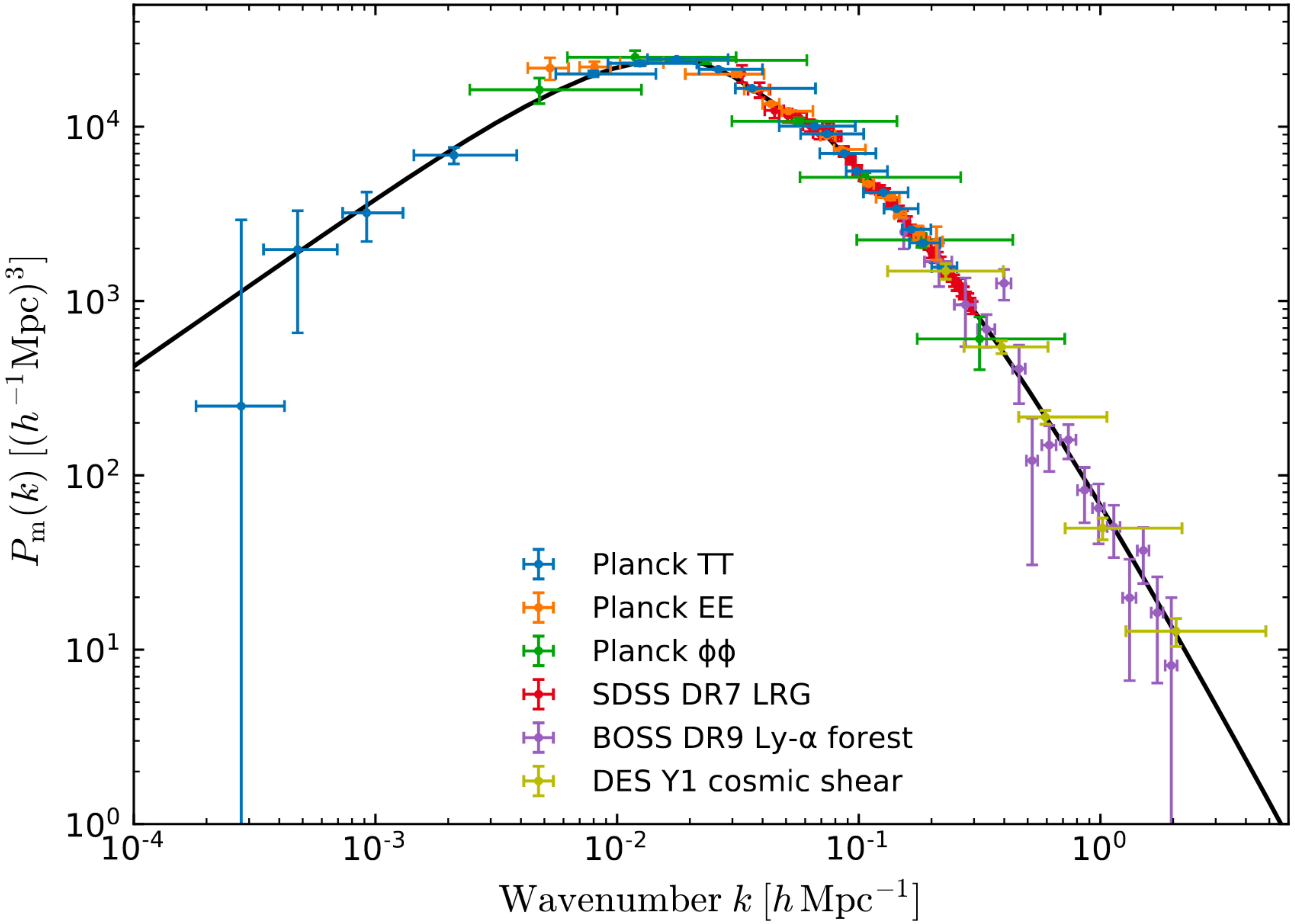
DM Physics from Structure Formation





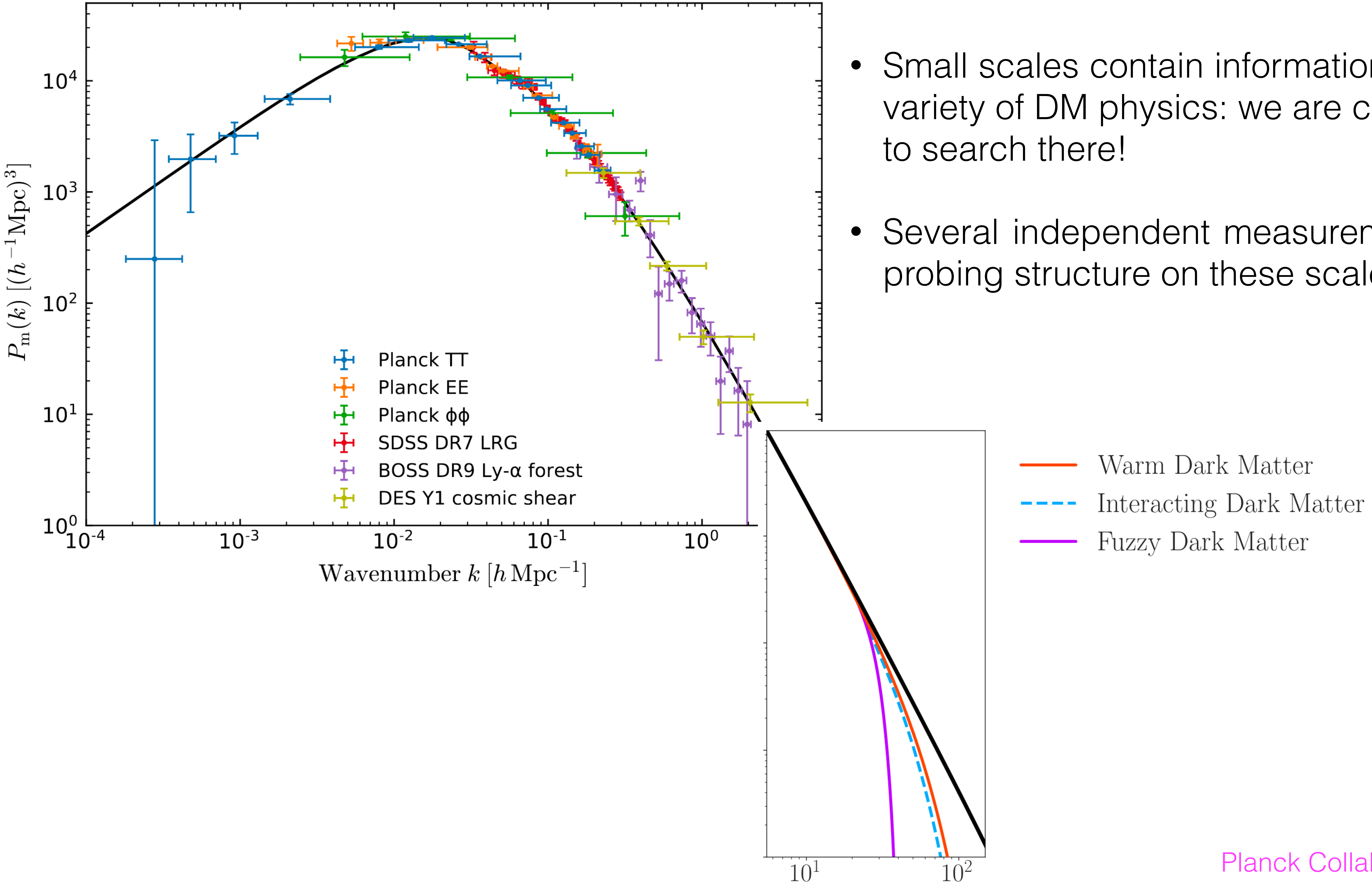
interference due to macroscopic de Broglie wavelength → cutoff in abundance of low-mass halos

DM Physics from Structure Formation



Planck Collaboration 2019

- Small scales contain information about a variety of DM physics: we are compelled to search there!
- Several independent measurements are probing structure on these scales …

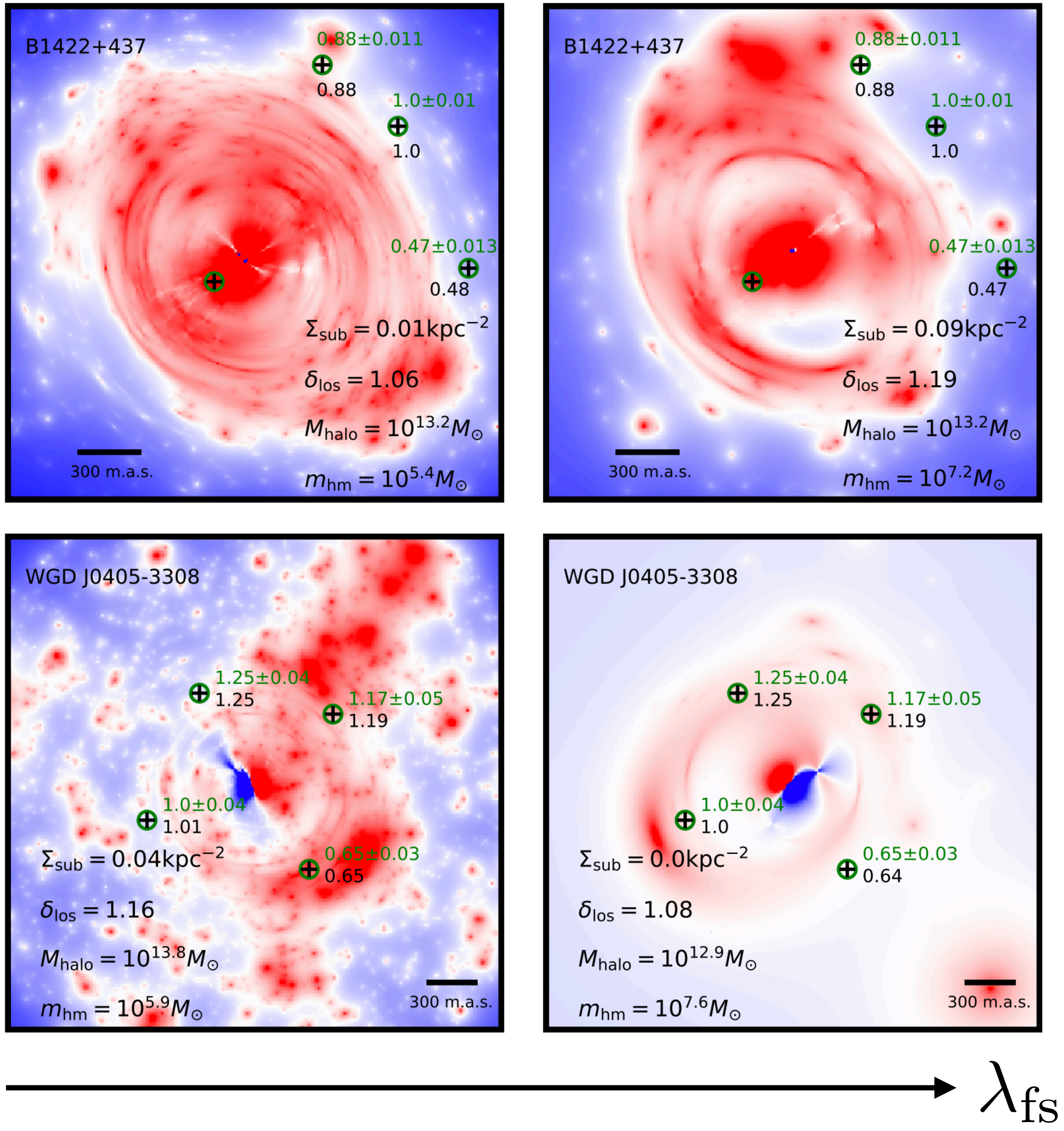


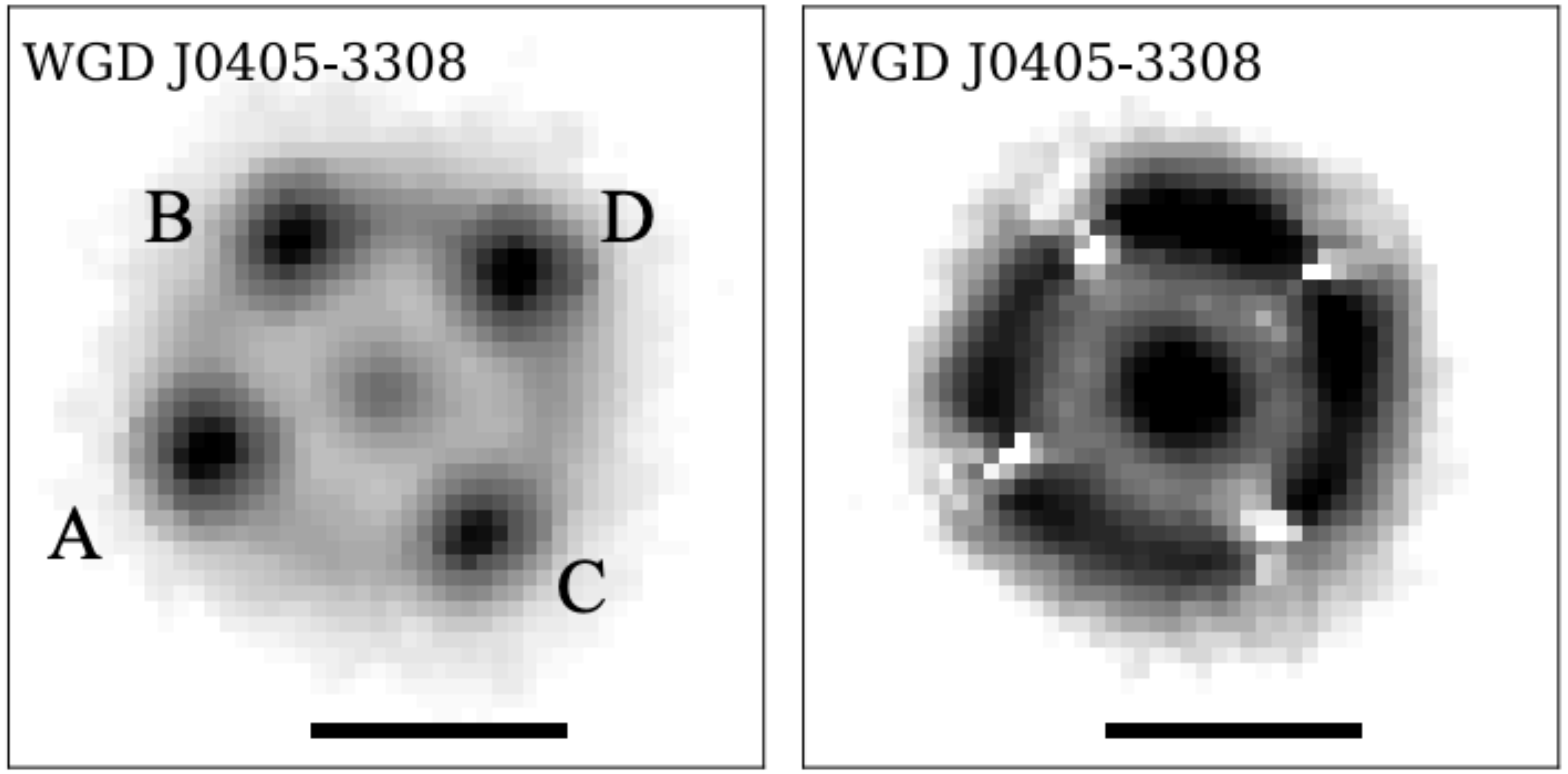
Planck Collaboration 2019

DM Physics from Strong Lenses

- Flux ratios in strongly-lensed systems (often using quadruply-imaged quasars) constrain small-scale cutoff
- Recent analyses use ~10 lenses with a range of redshifts and halo properties

Gilman et al. 2020

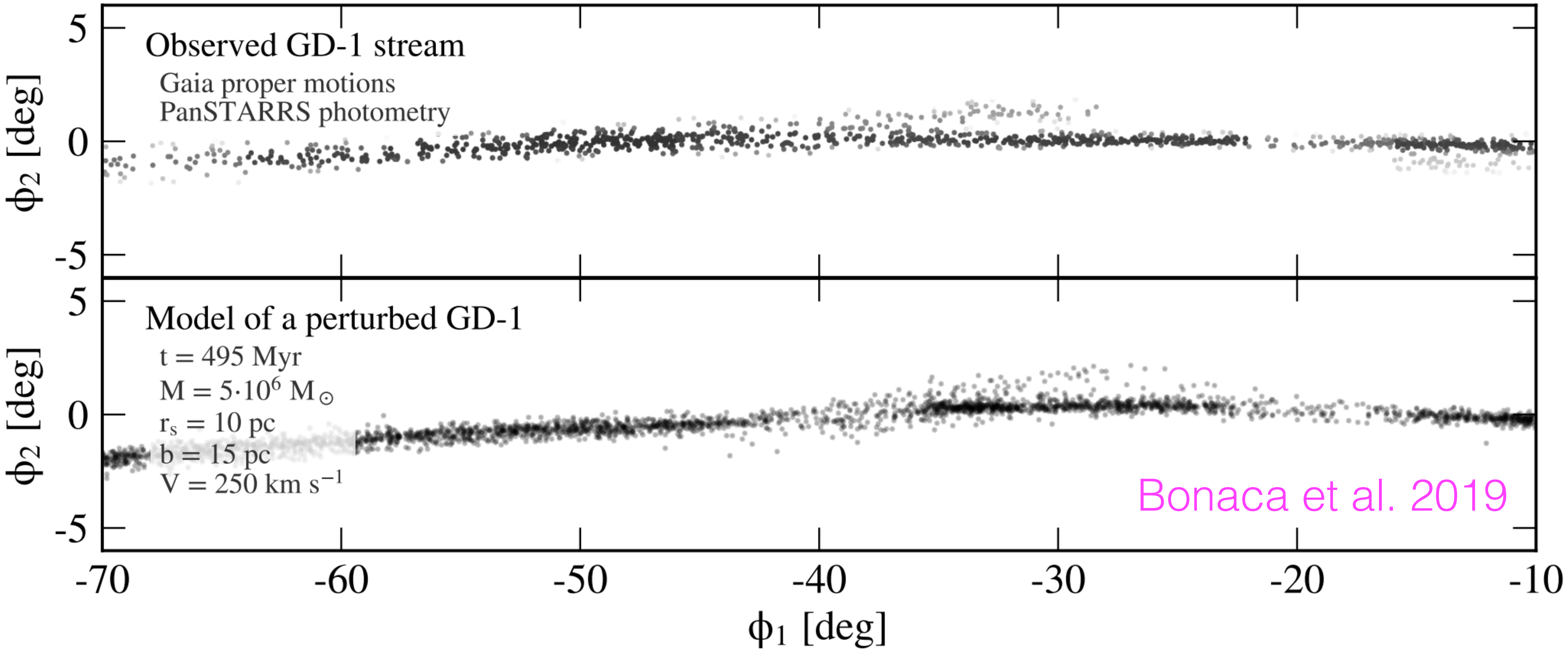




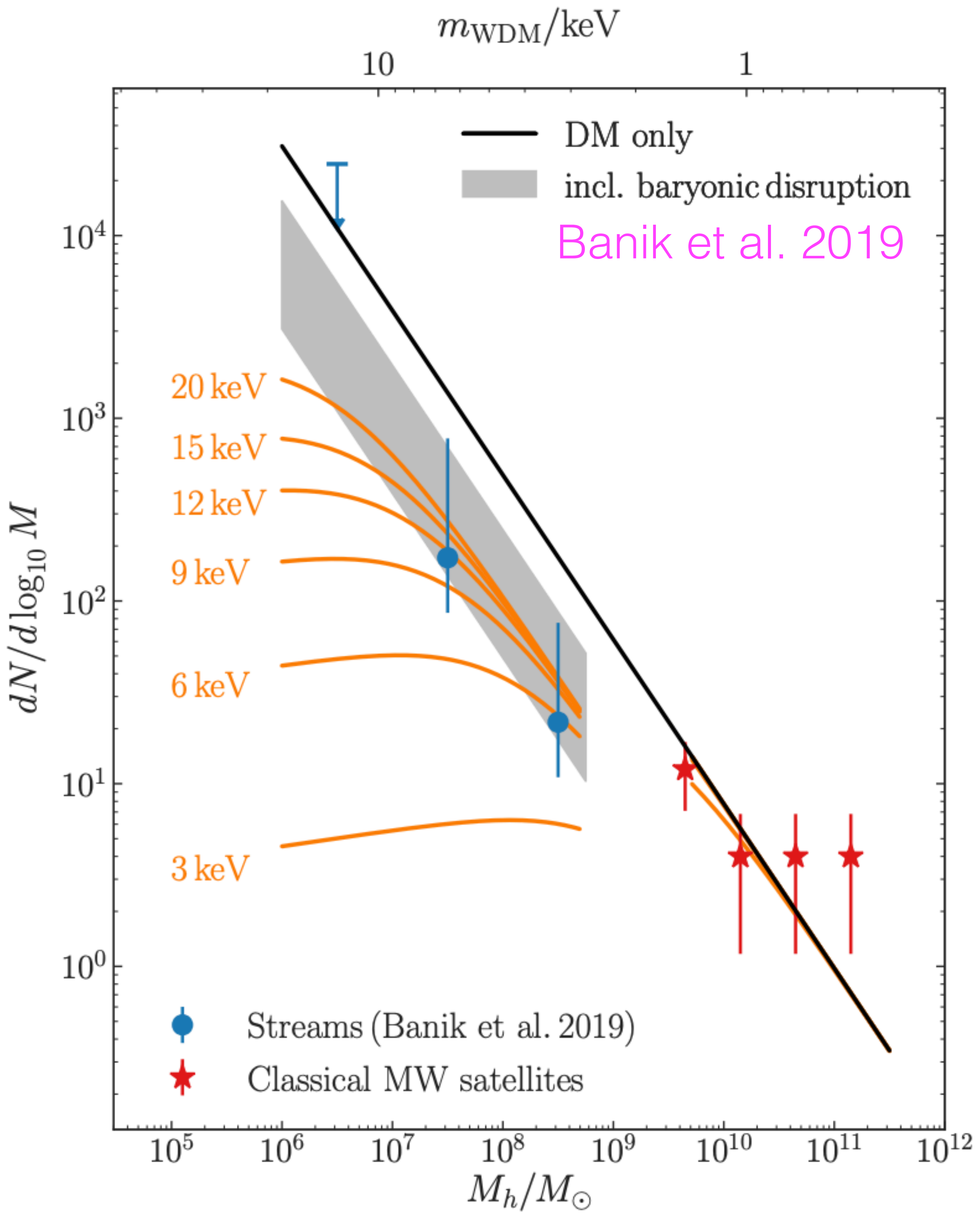
Nierenberg et al. 2019

DM Physics from Stellar Streams

- Density perturbations and gaps in Galactic stellar streams constrain small-scale cutoff
- Analyses of GD-1 and Pal 5 (two nearby streams) based on *Gaia* data indicate consistency with CDM

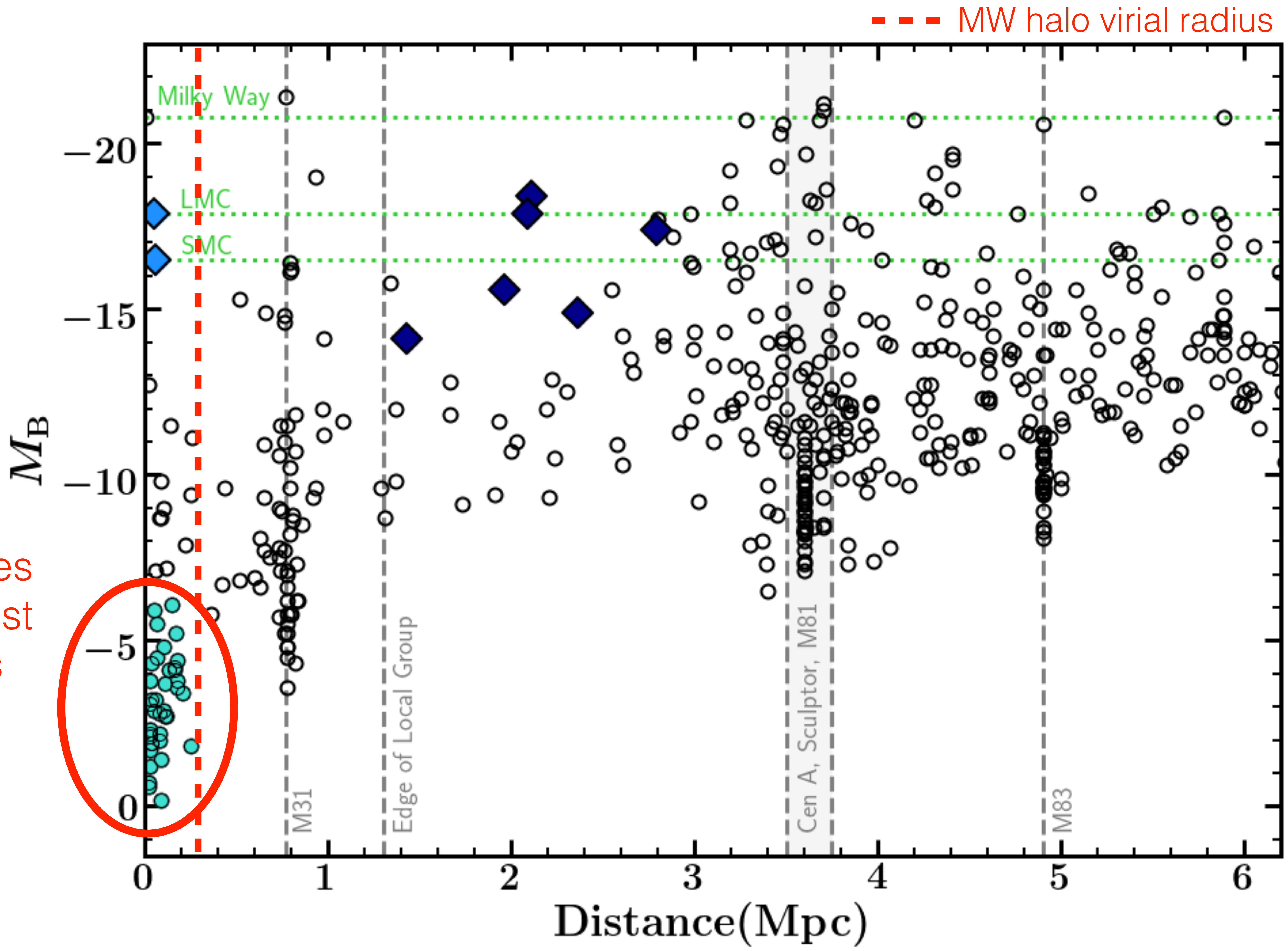


Bonaca et al. 2019



Banik et al. 2019

DM Physics from Milky Way Satellites

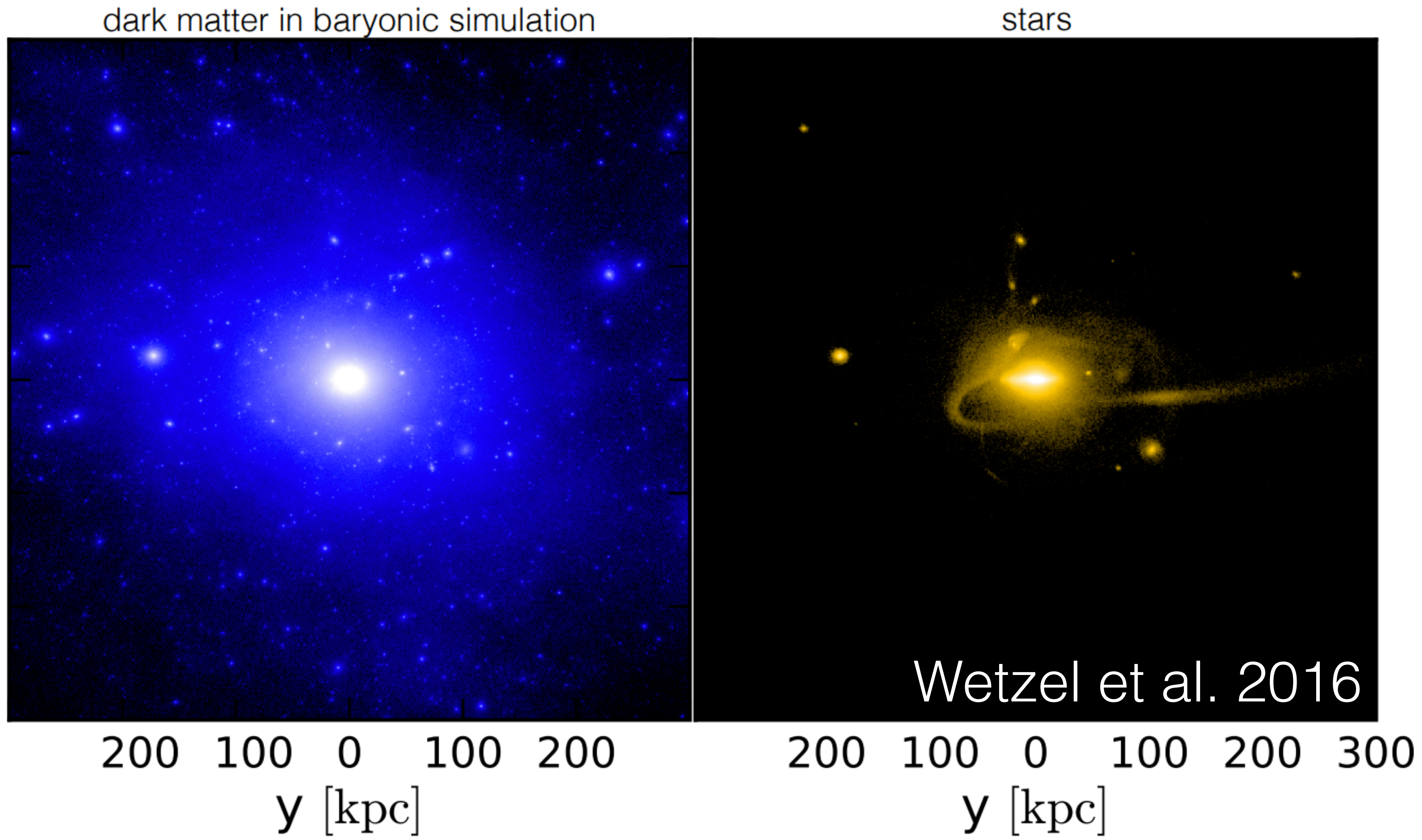


Milky Way satellites inhabit the smallest luminous DM halos

Credit: A. Drlica-Wagner, K. Bechtol

DM Physics from Milky Way Satellites

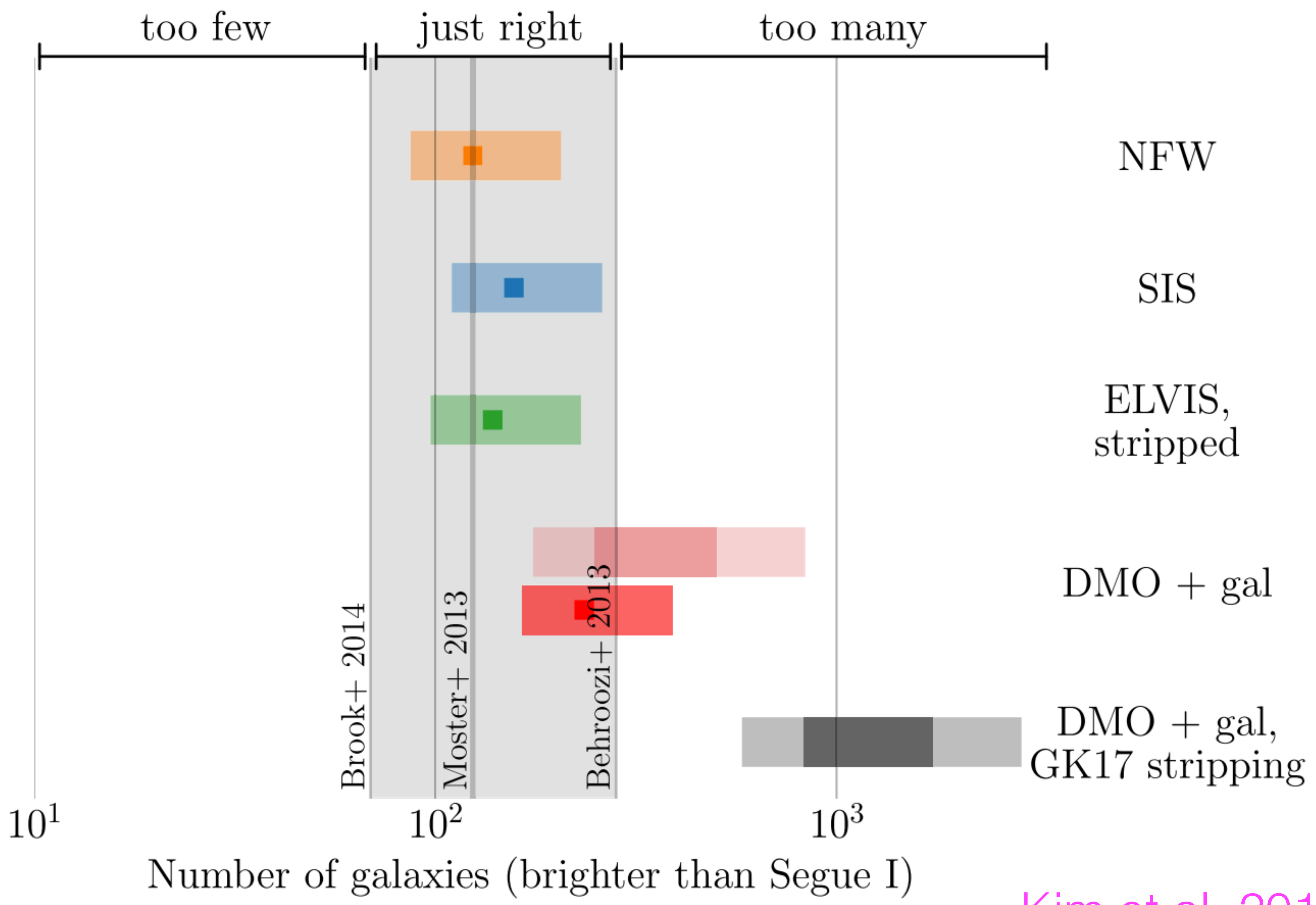
- Abundance of Milky Way satellite galaxies “directly” traces subhalo abundance
- Simulations and semi-analytic models show that the abundance of classical and SDSS satellites is consistent with CDM



Wetzel et al. 2016

There is No Missing Satellites Problem

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



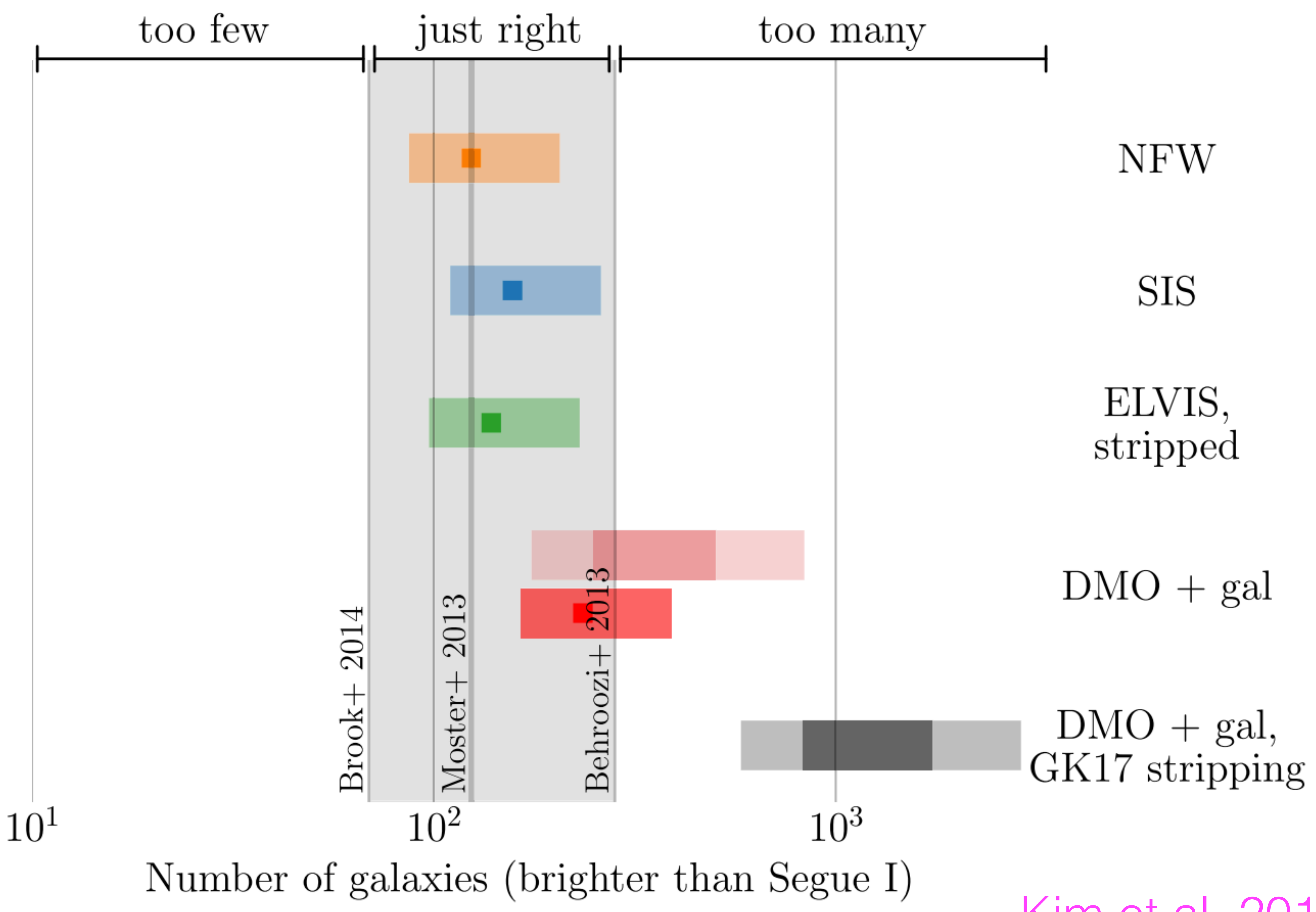
Kim et al. 2018

DM Physics from Milky Way Satellites

- Abundance of Milky Way satellite galaxies “directly” traces subhalo abundance
- Simulations and semi-analytic models show that the abundance of classical and SDSS satellites is consistent with CDM
- Most of these studies only consider limiting cases to address the impact of theoretical uncertainties …
- And they use data that is ~15 years old!

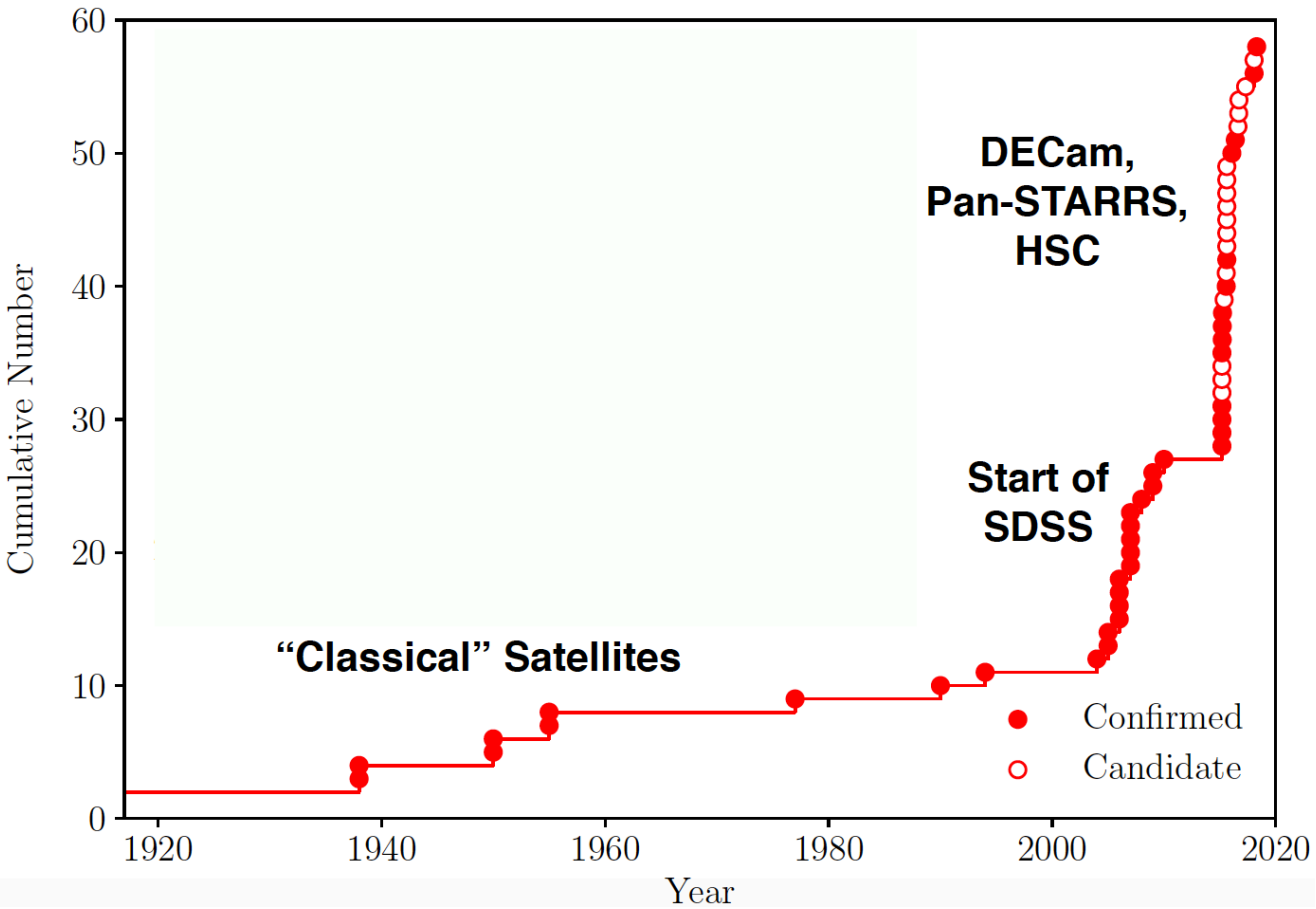
There is No Missing Satellites Problem

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



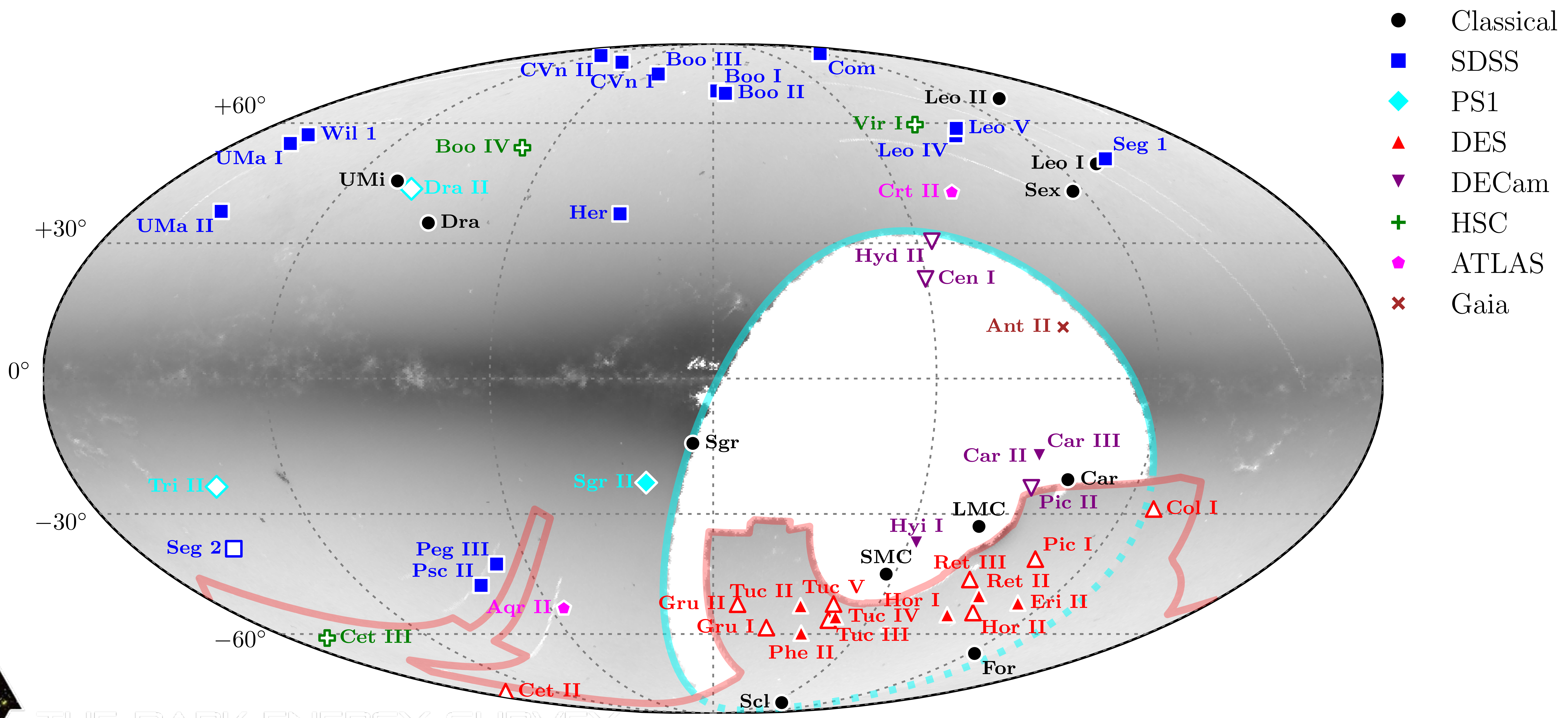
Kim et al. 2018

The Milky Way Satellite Population



Credit: K. Bechtol

The Milky Way Satellite Population

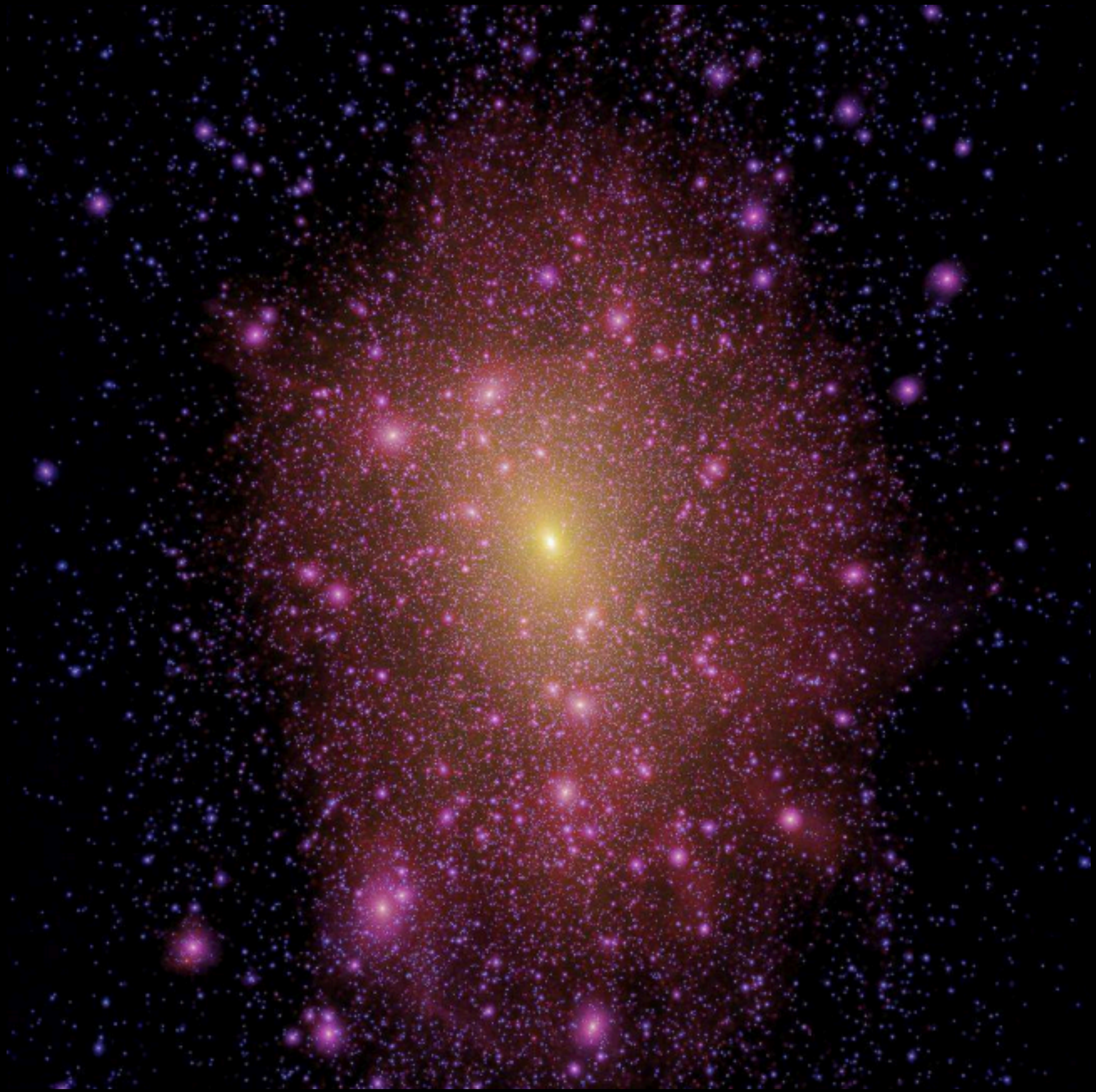


THE DARK ENERGY SURVEY

Drlica-Wagner & Bechtol et al. 2020

DM Physics from Milky Way Satellites

CDM

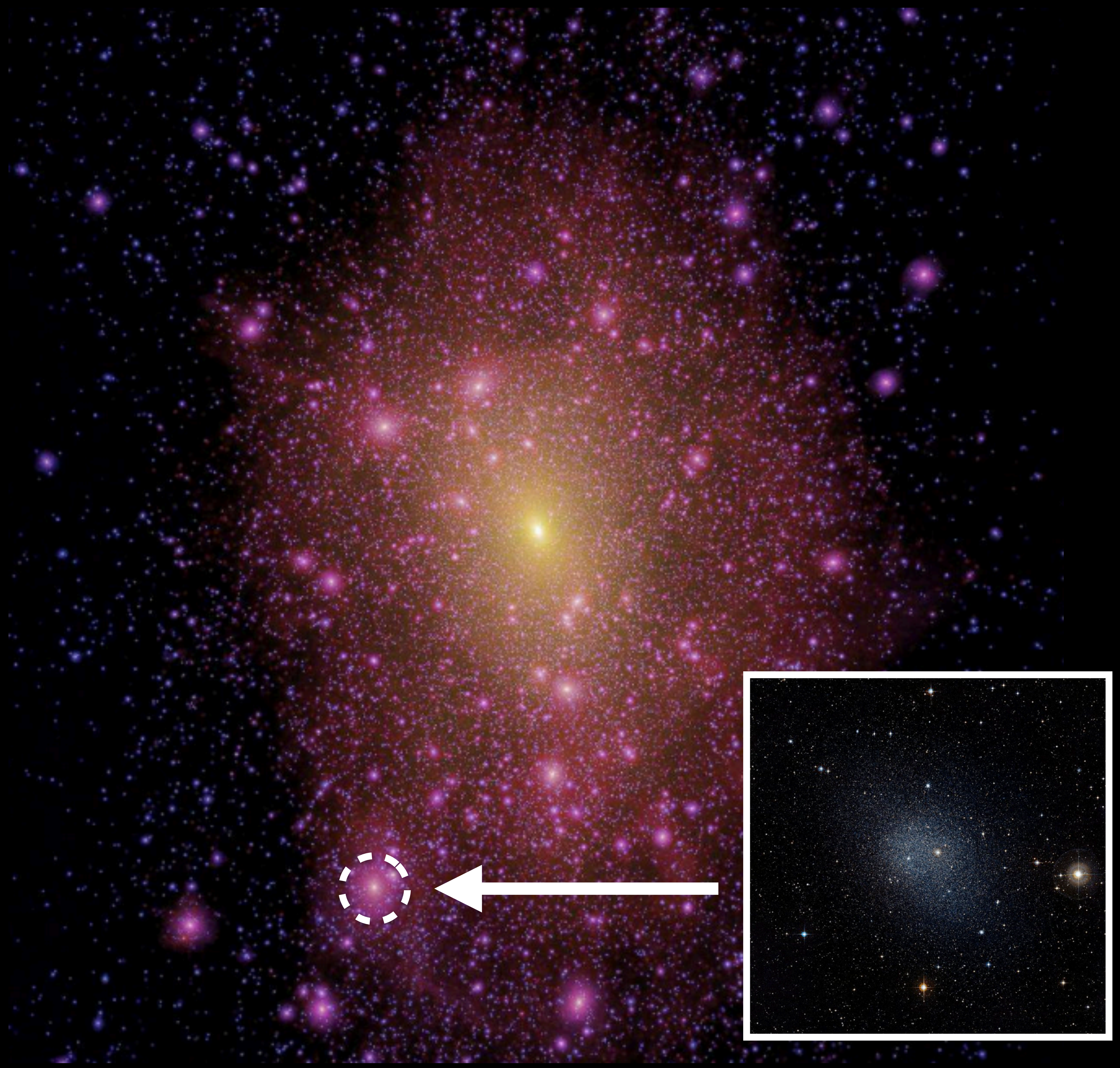


WDM

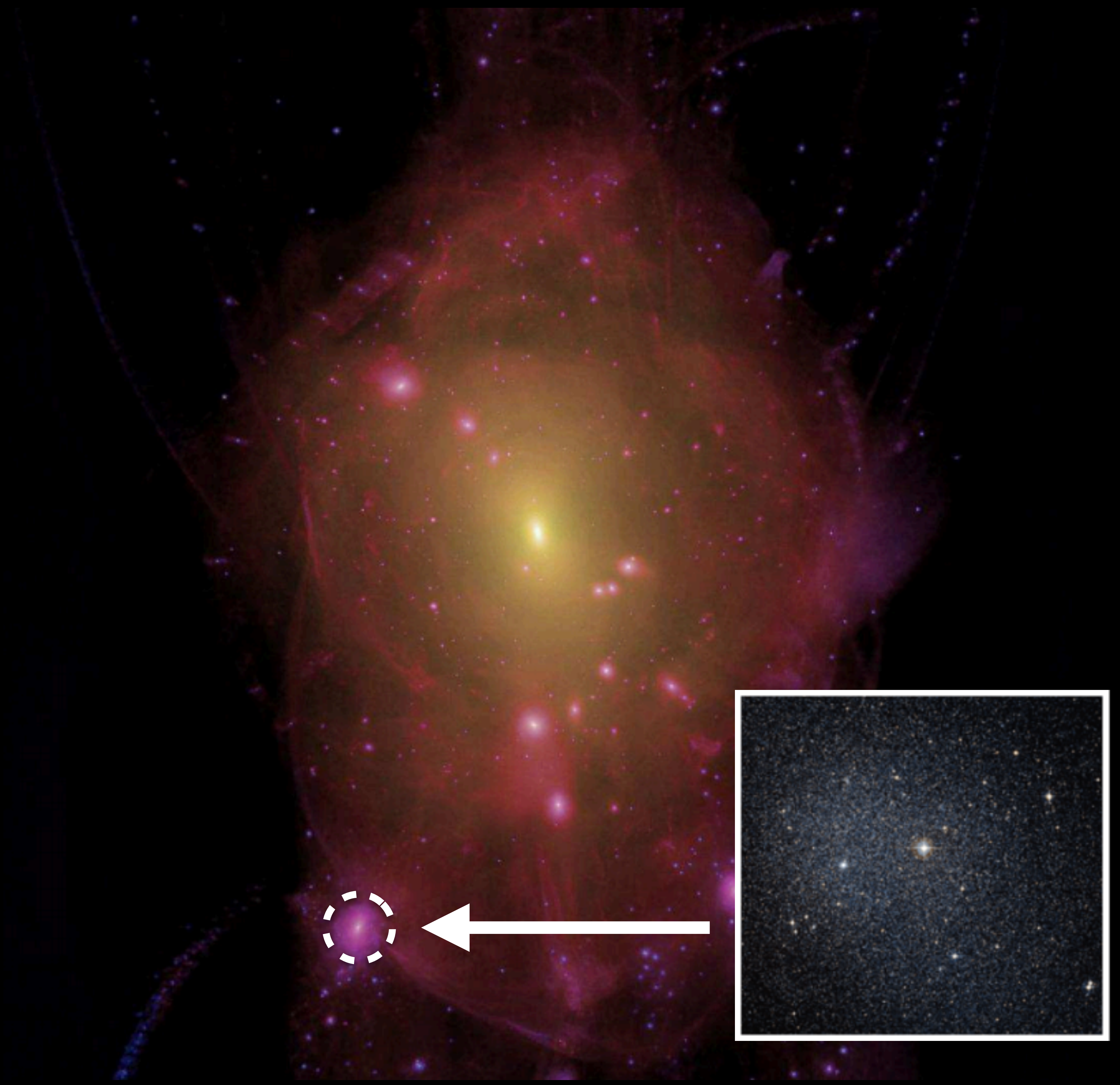
Lovell et al. 2011

DM Physics from Milky Way Satellites

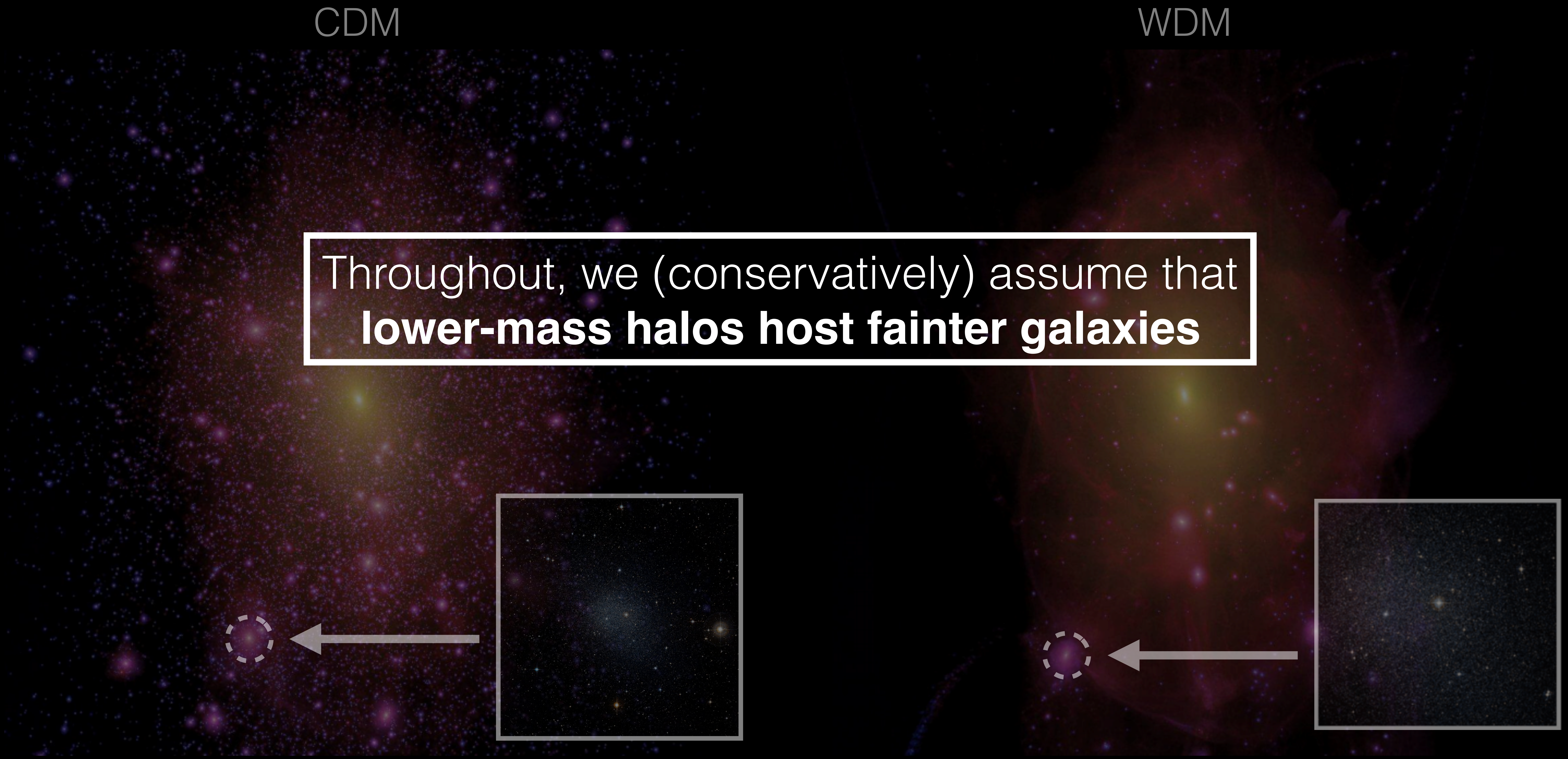
CDM



WDM



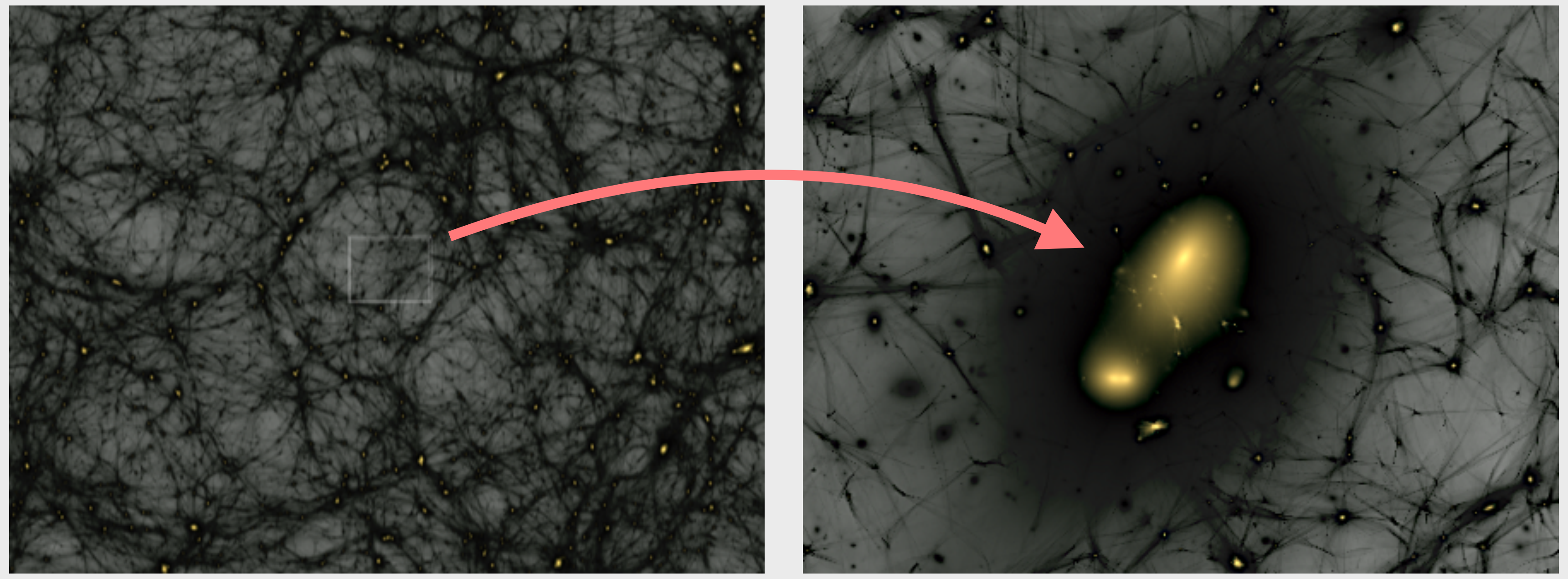
DM Physics from Milky Way Satellites



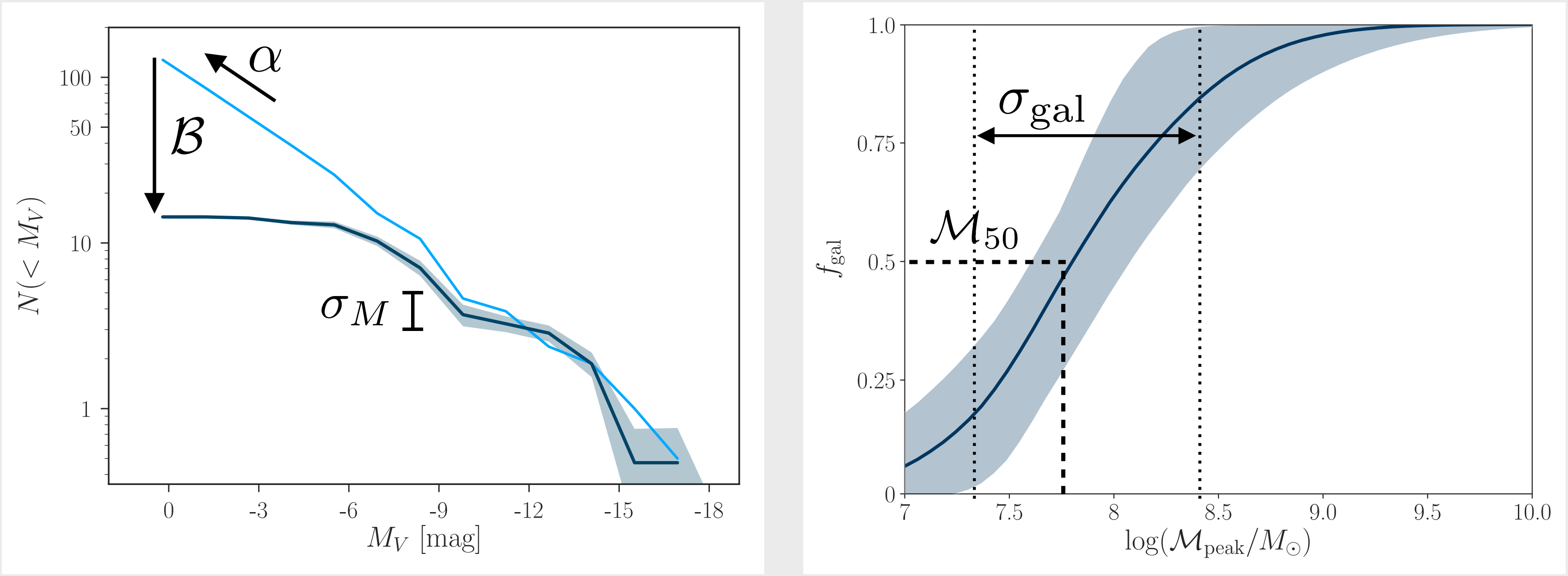
Throughout, we (conservatively) assume that **lower-mass halos host fainter galaxies**

Markov Chain Monte Carlo

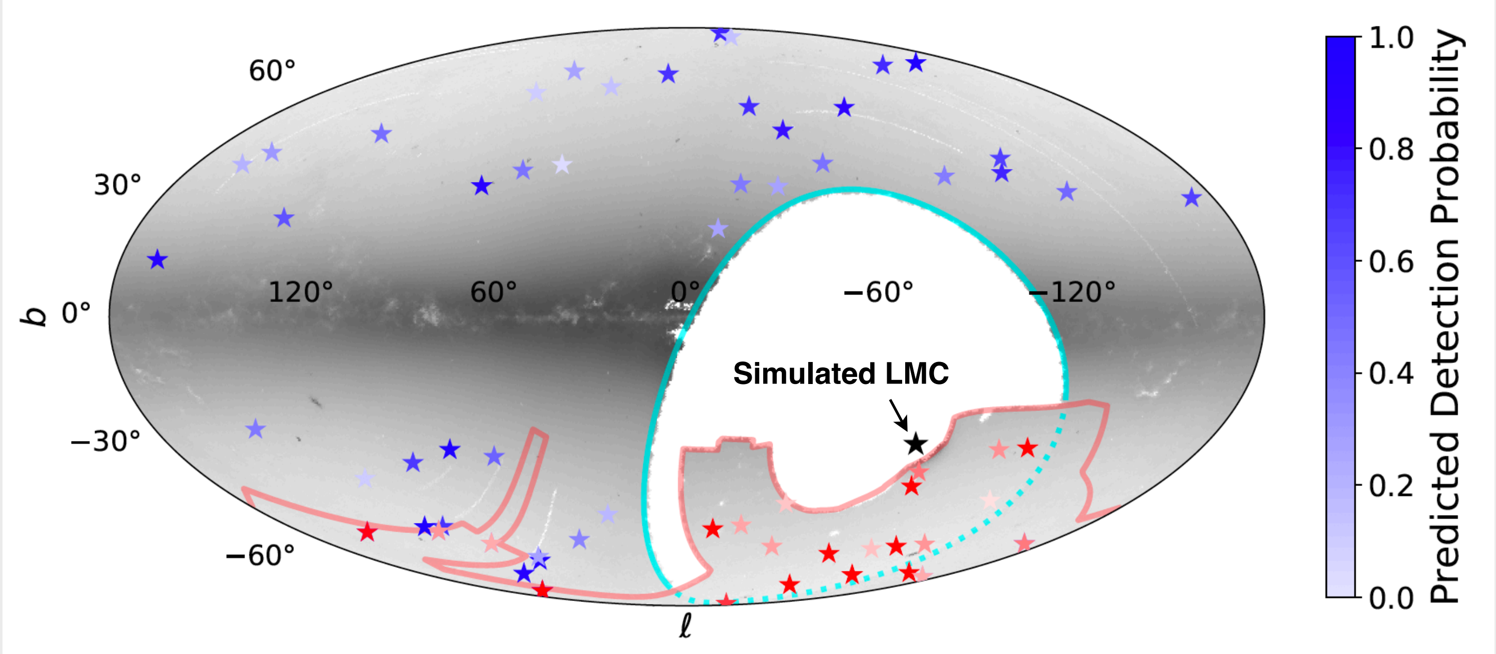
1. **Resimulate Milky Way-like halos from large cosmological volume.**



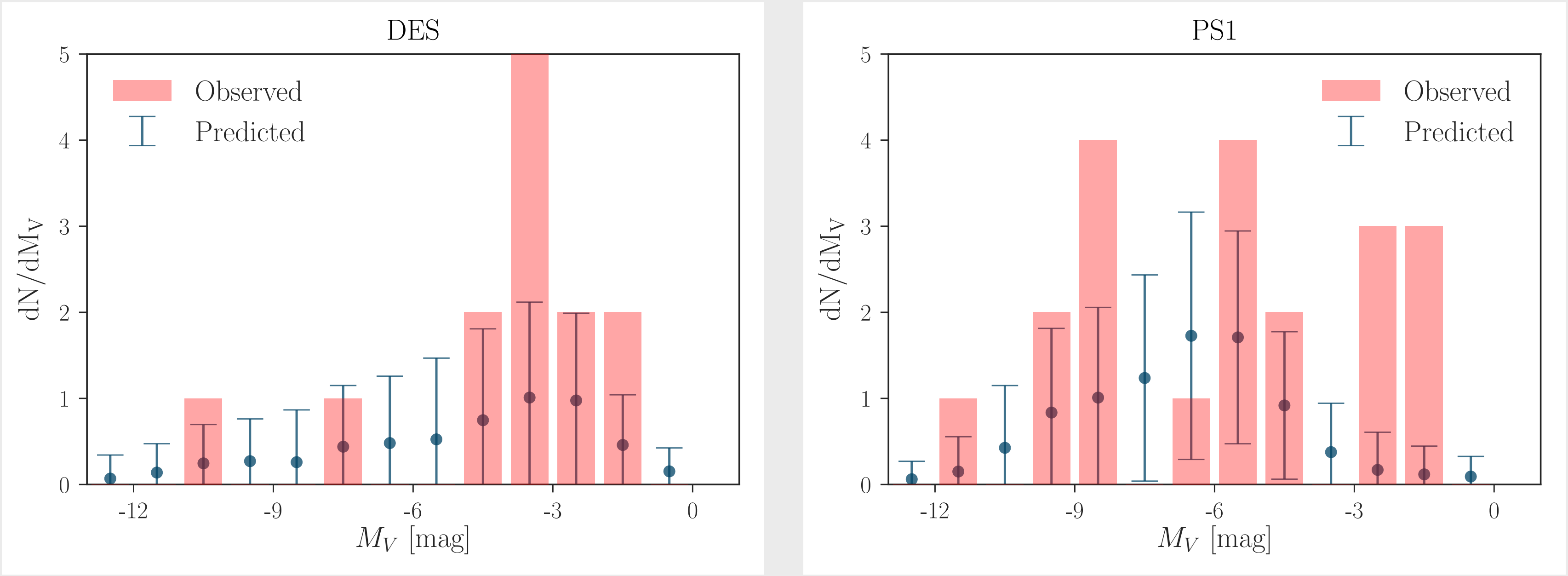
2. **Paint satellite galaxies onto subhalos using galaxy—halo model.**



3. **Apply observational selection functions based on imaging data.**



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

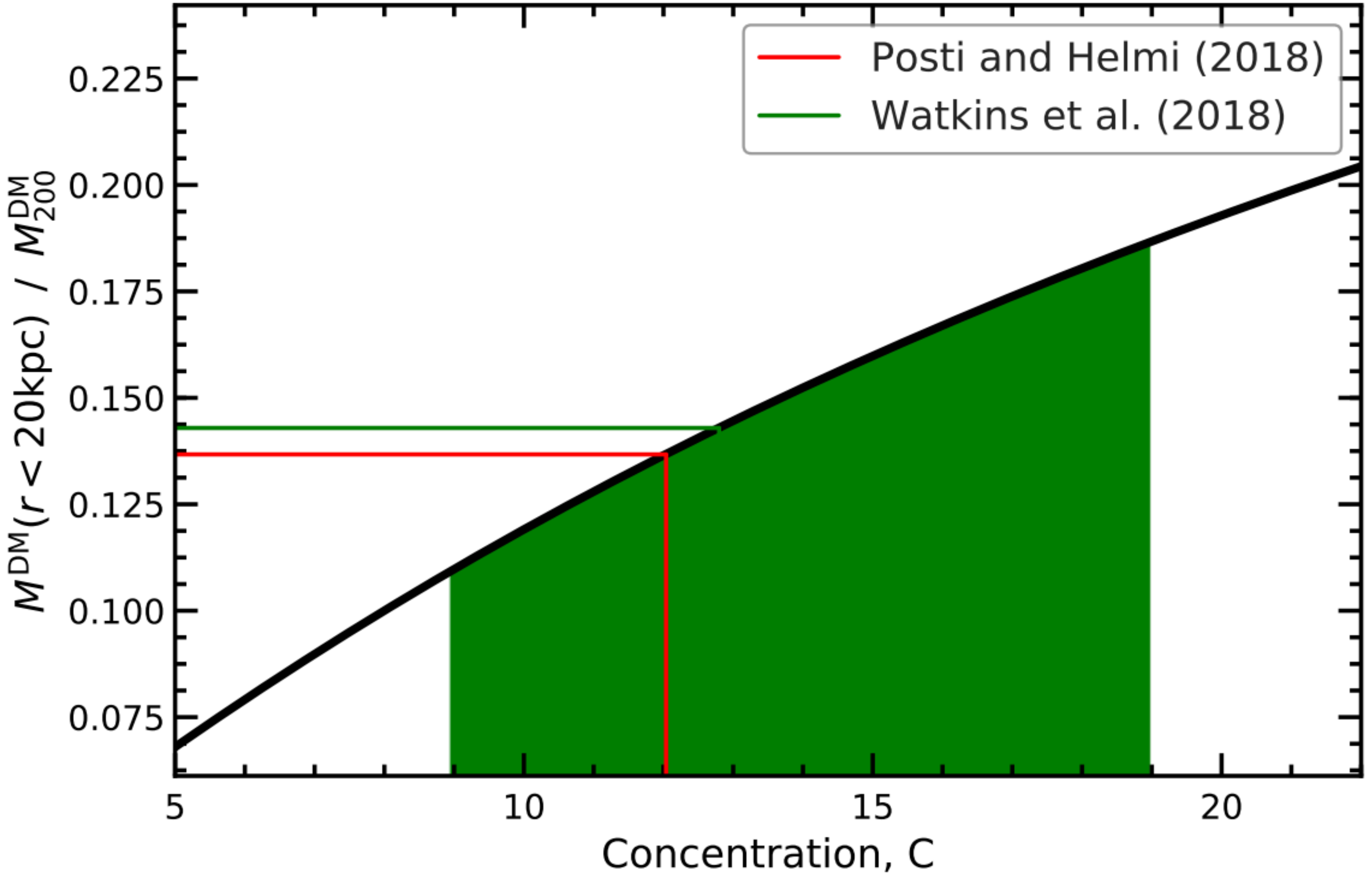


EN & Wechsler et al. 2020

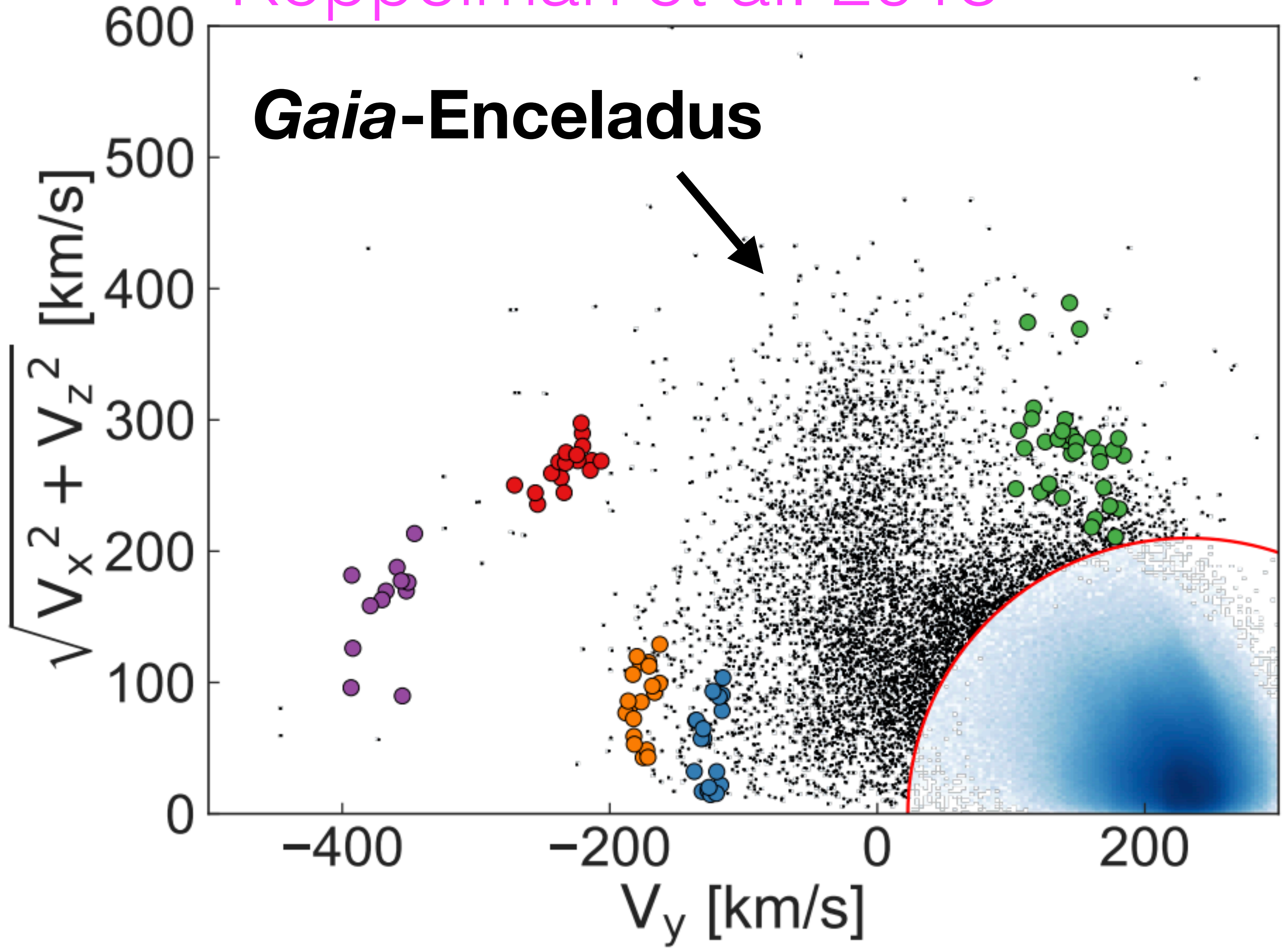
Simulating Milky Way Analogs

- *Gaia* is revolutionizing our understanding of Milky Way halo properties: mass, concentration, assembly history (and satellite proper motions)

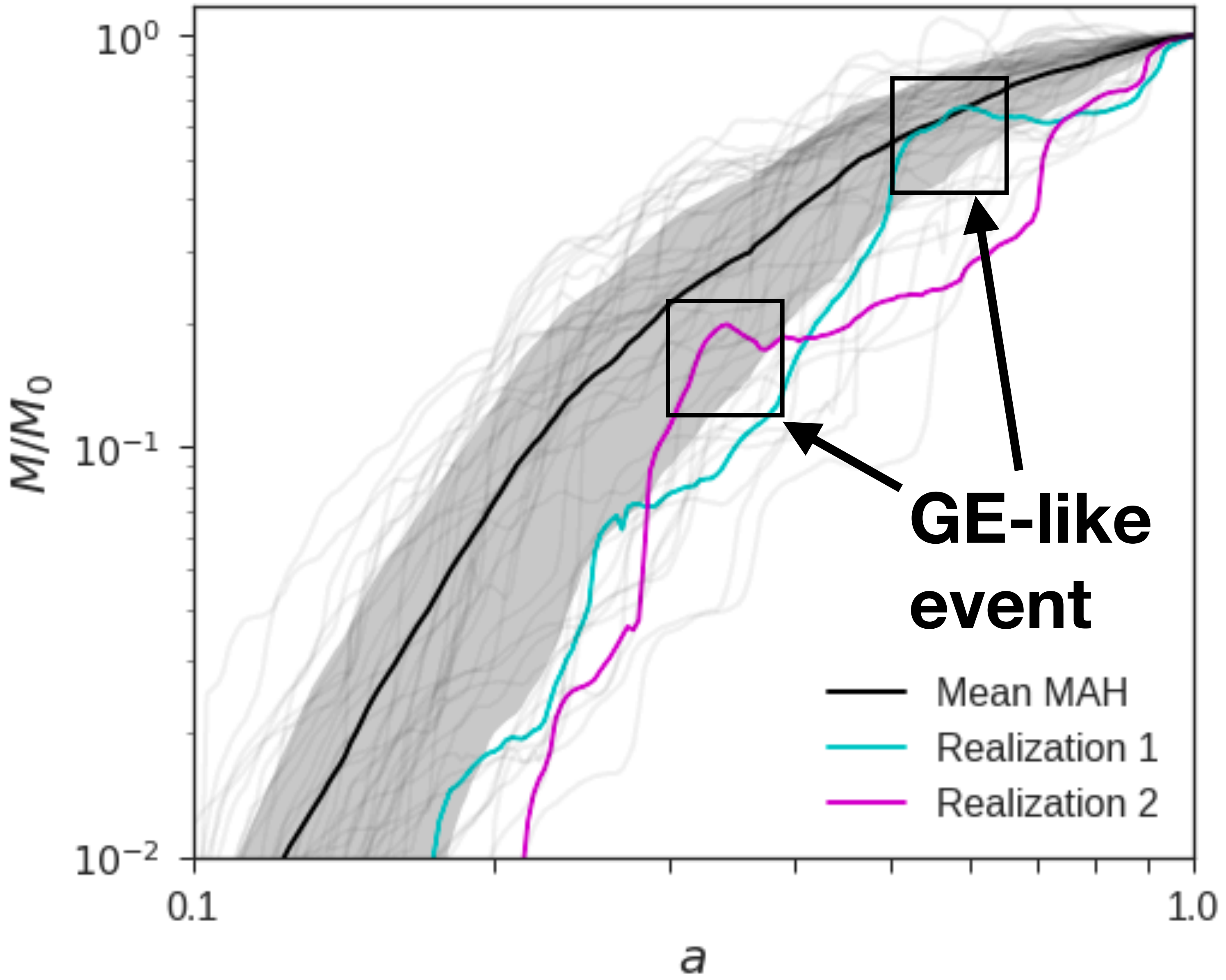
- We analyze simulations constrained to match the MW halo in these properties **and** in the existence of a Large Magellanic Cloud analog



Callingham et al. 2018



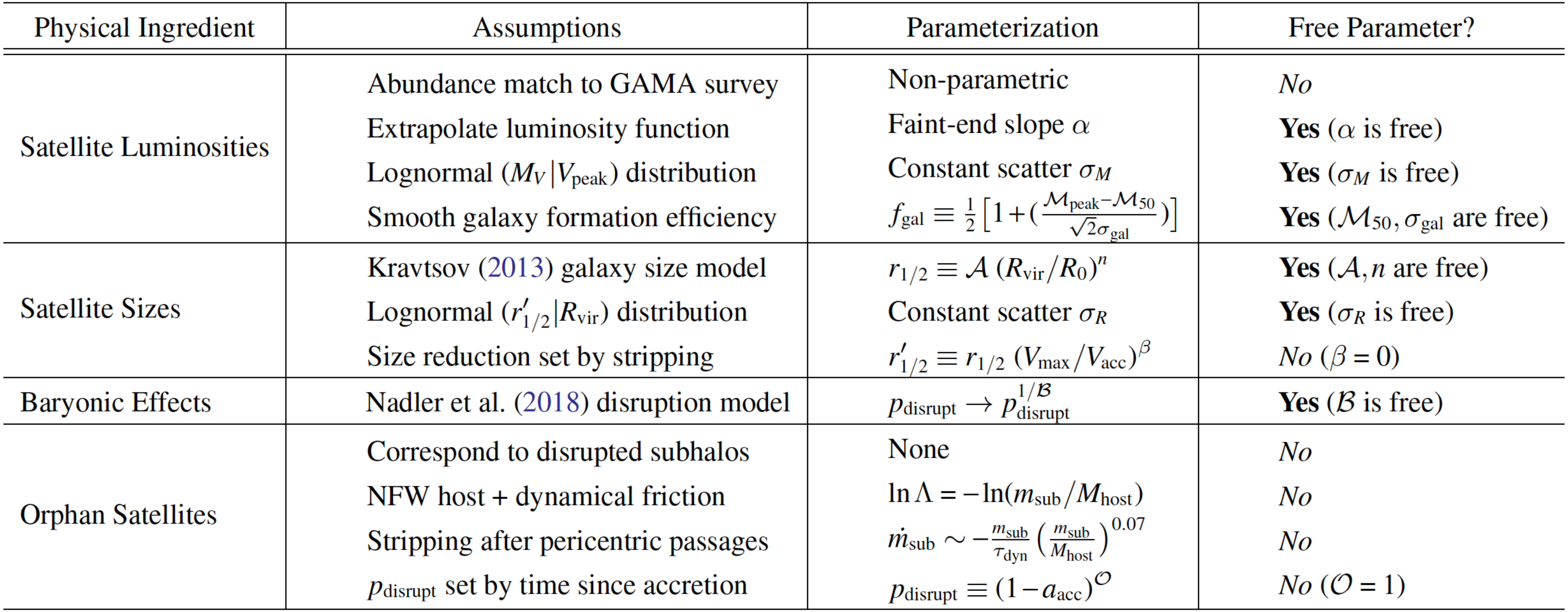
Koppelman et al. 2018



Simulated MWs

Galaxy–Halo Connection Model

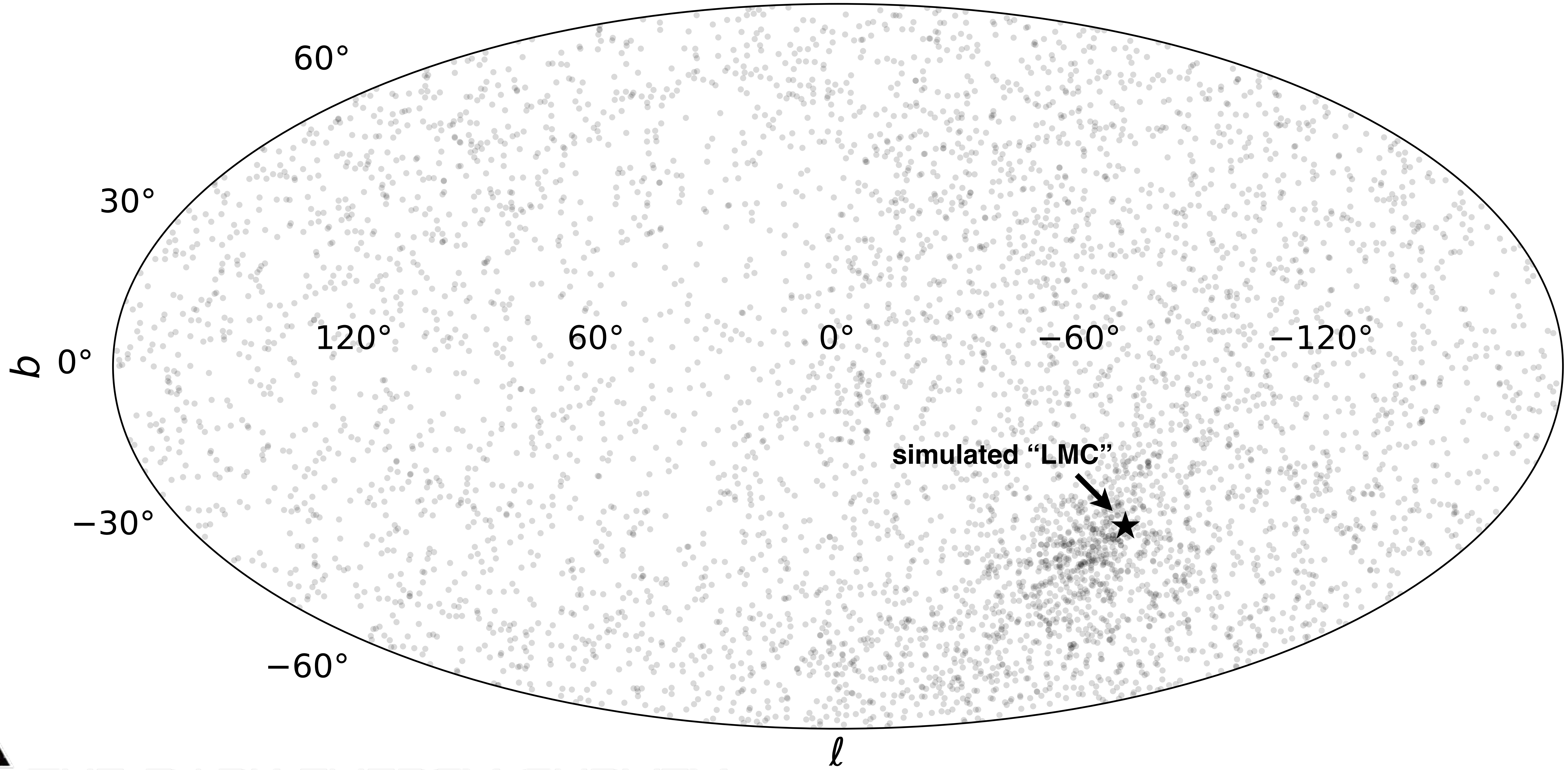
Empirical modeling allows us to marginalize over theoretical uncertainties



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 $(M_V\,\vert V_{\rm peak})$ 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* ($\mathcal{O} = 1$)

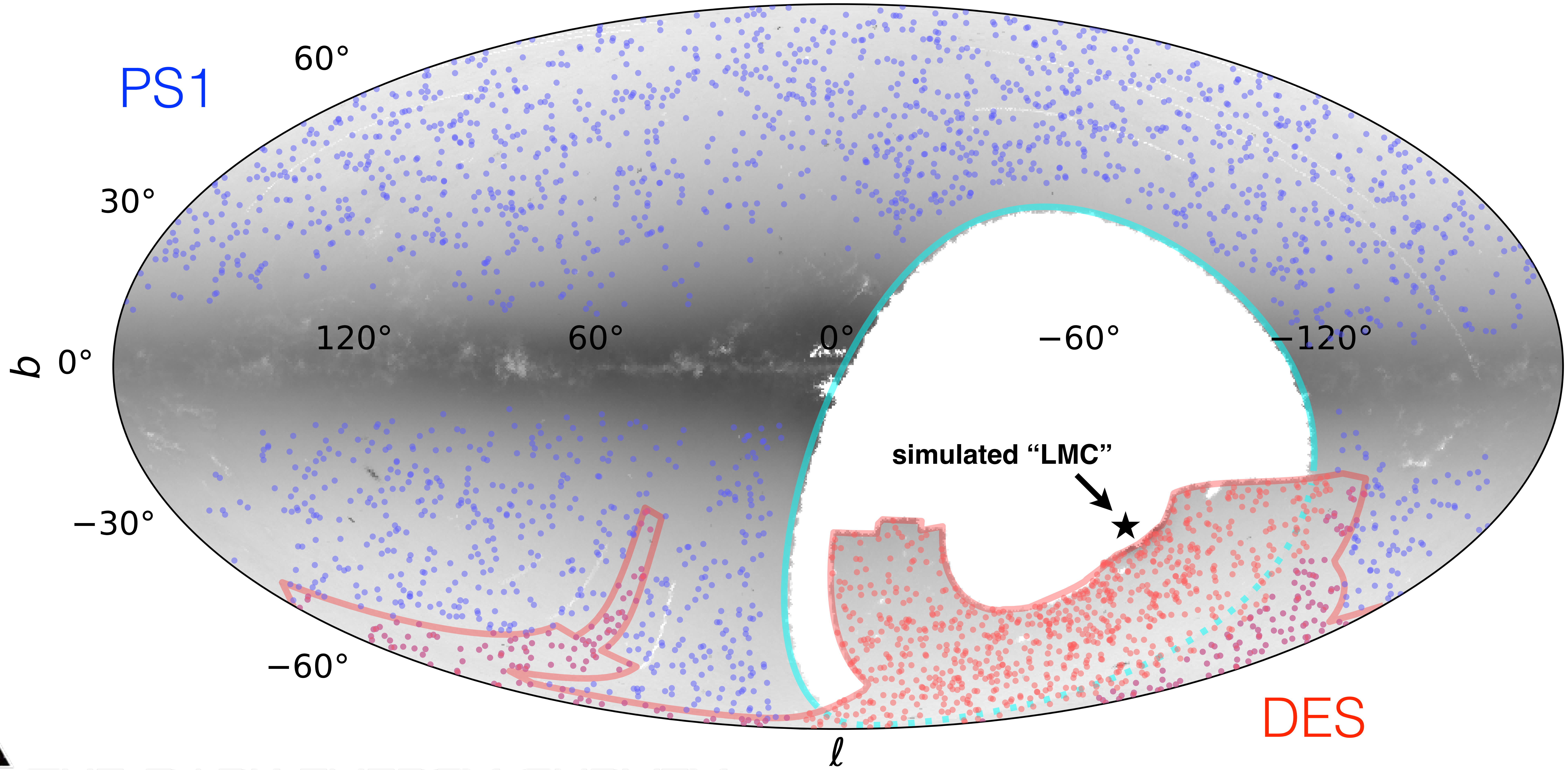
EN, Y.-Y. Mao, G. Green, R. Wechsler 2019

Mock Satellite Observations



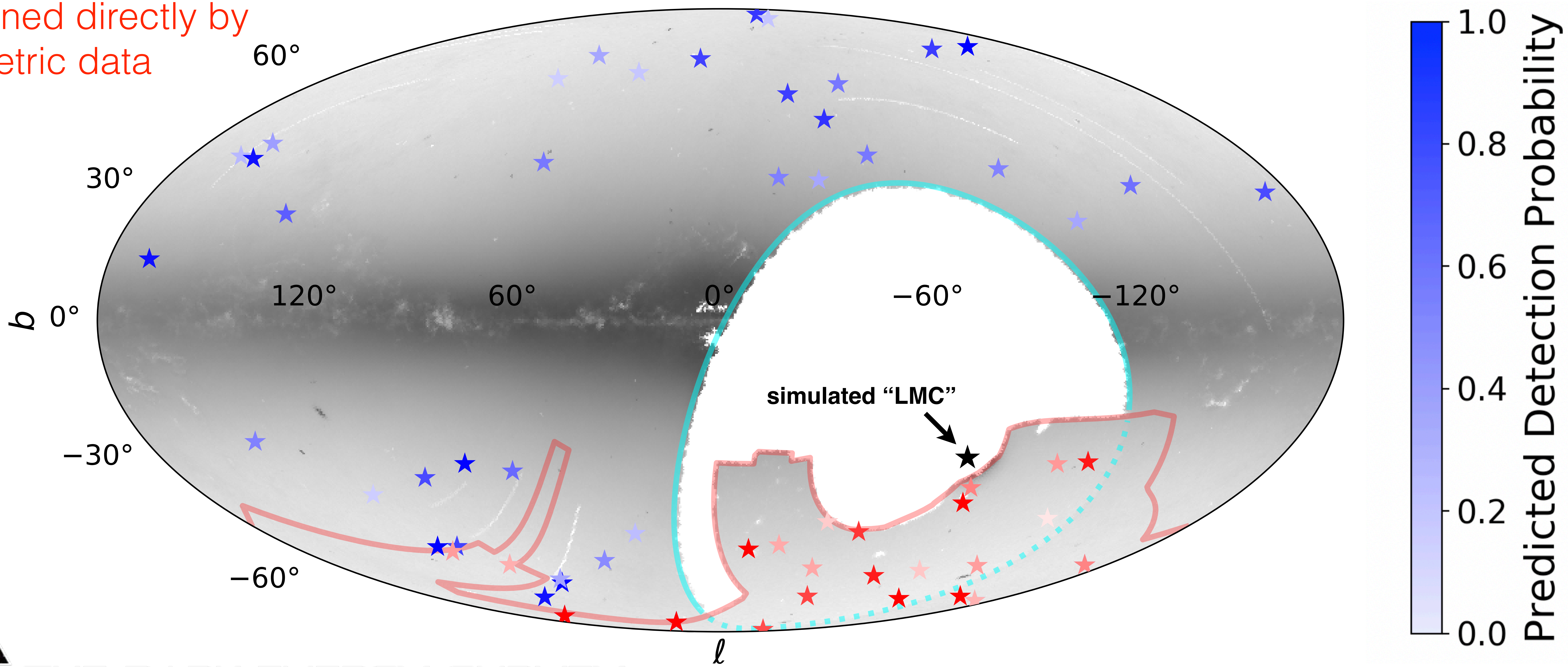
THE DARK ENERGY SURVEY

Mock Satellite Observations



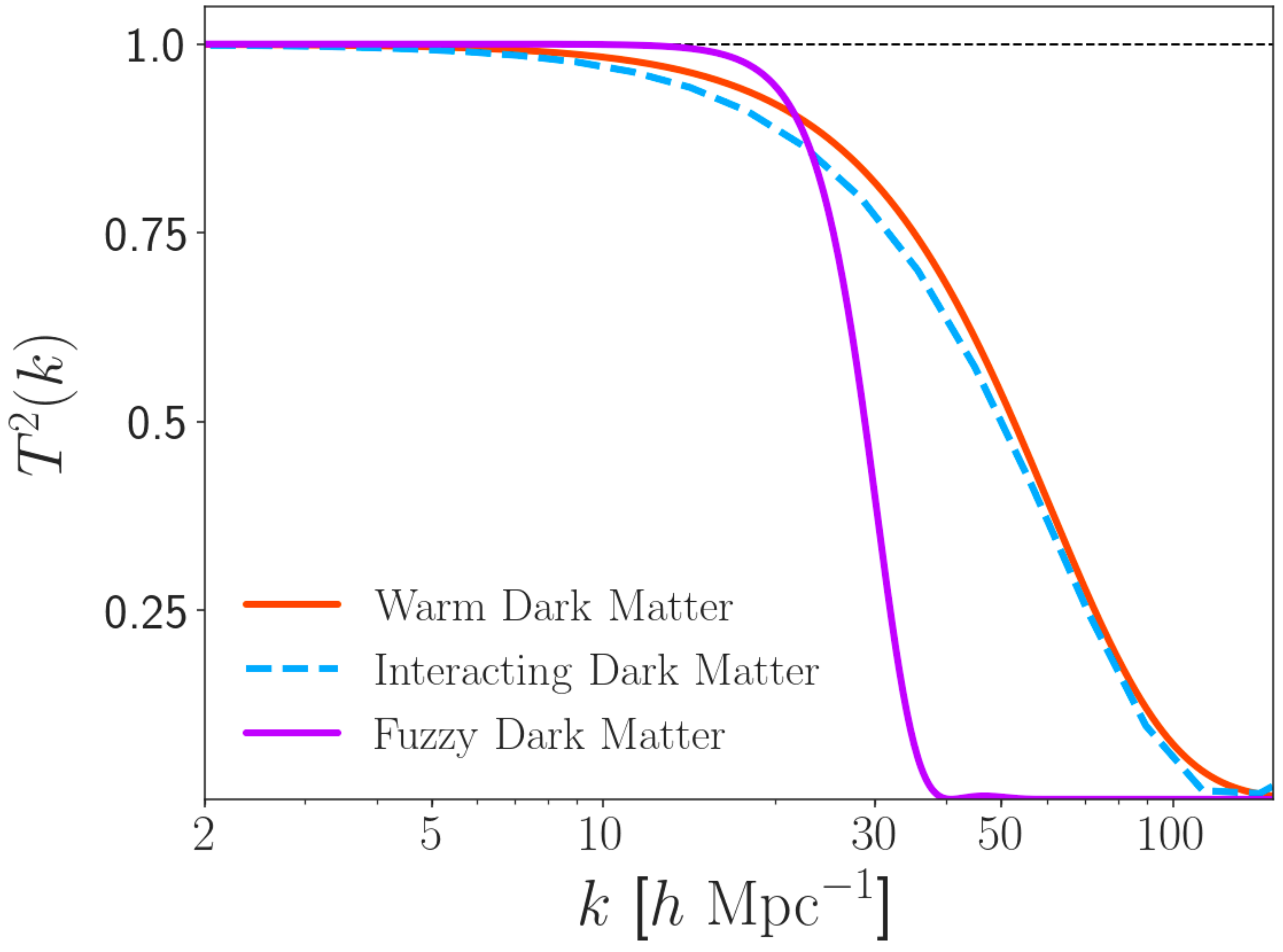
Mock Satellite Observations

Detection probability is constrained directly by photometric data



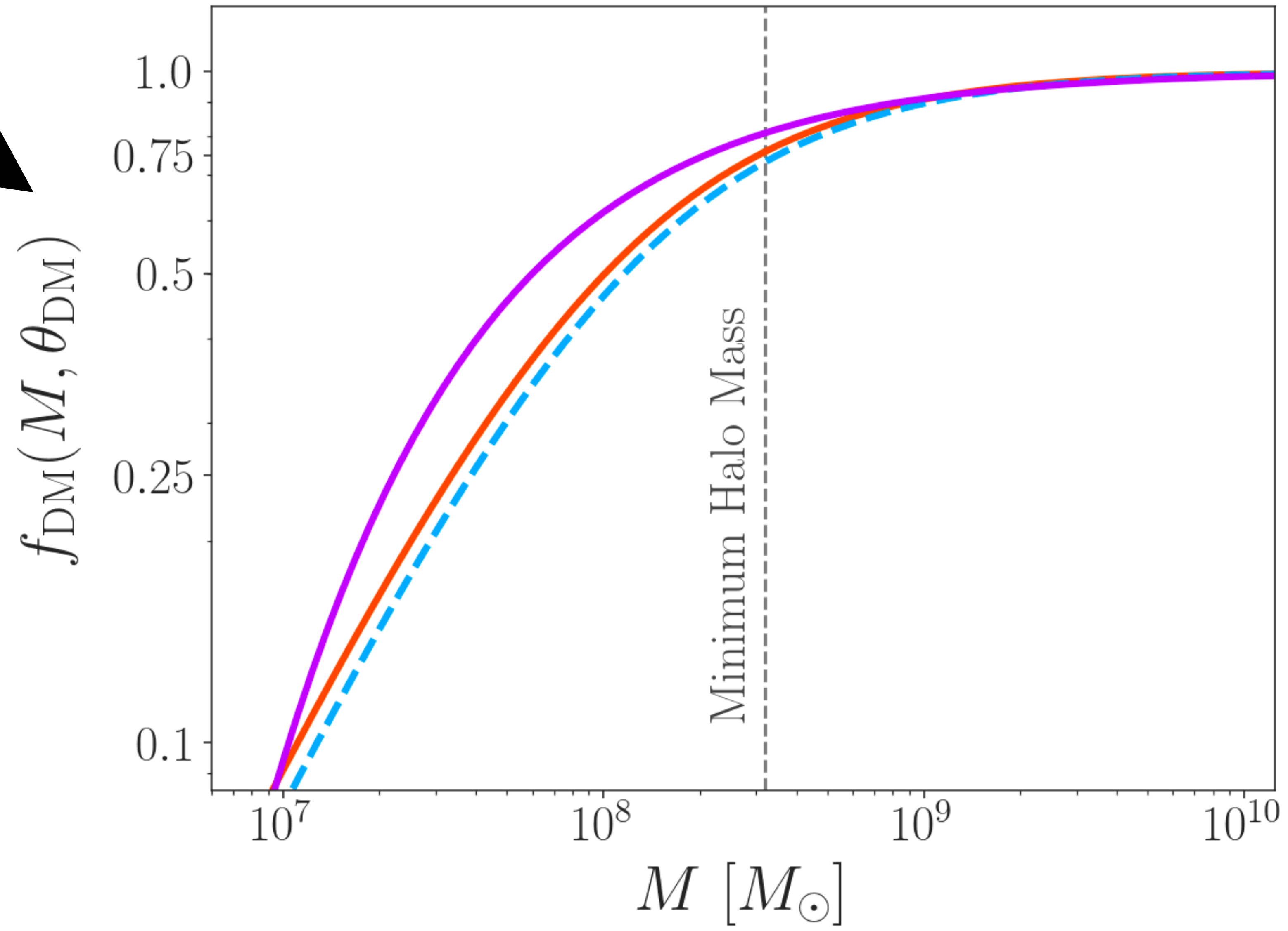
Allows for a rigorous statistical comparison to observations

Transfer function

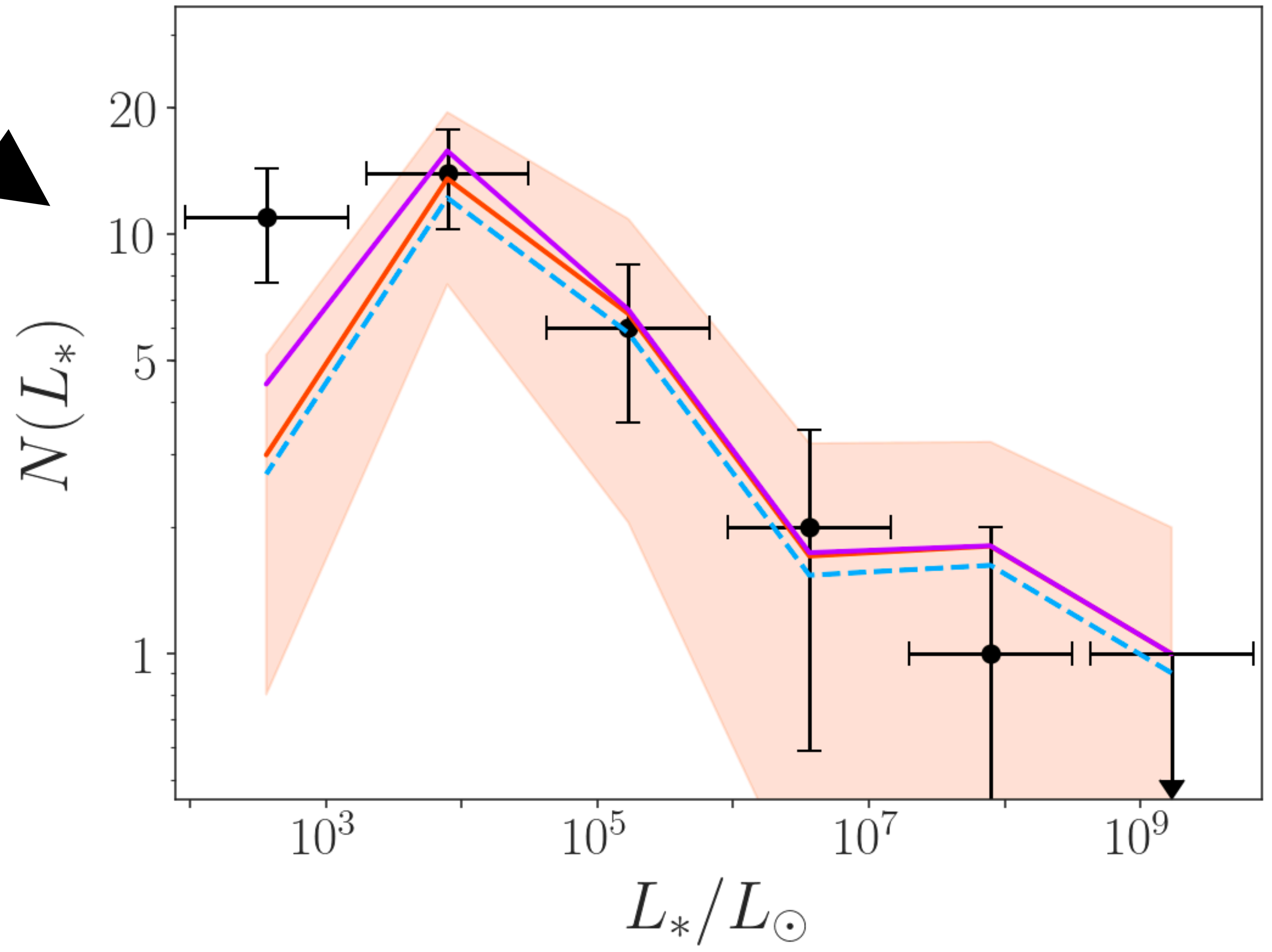


Fit the data with SHMF suppresssion, marginalizing over galaxy–halo connection and MW properties:

Subhalo mass function



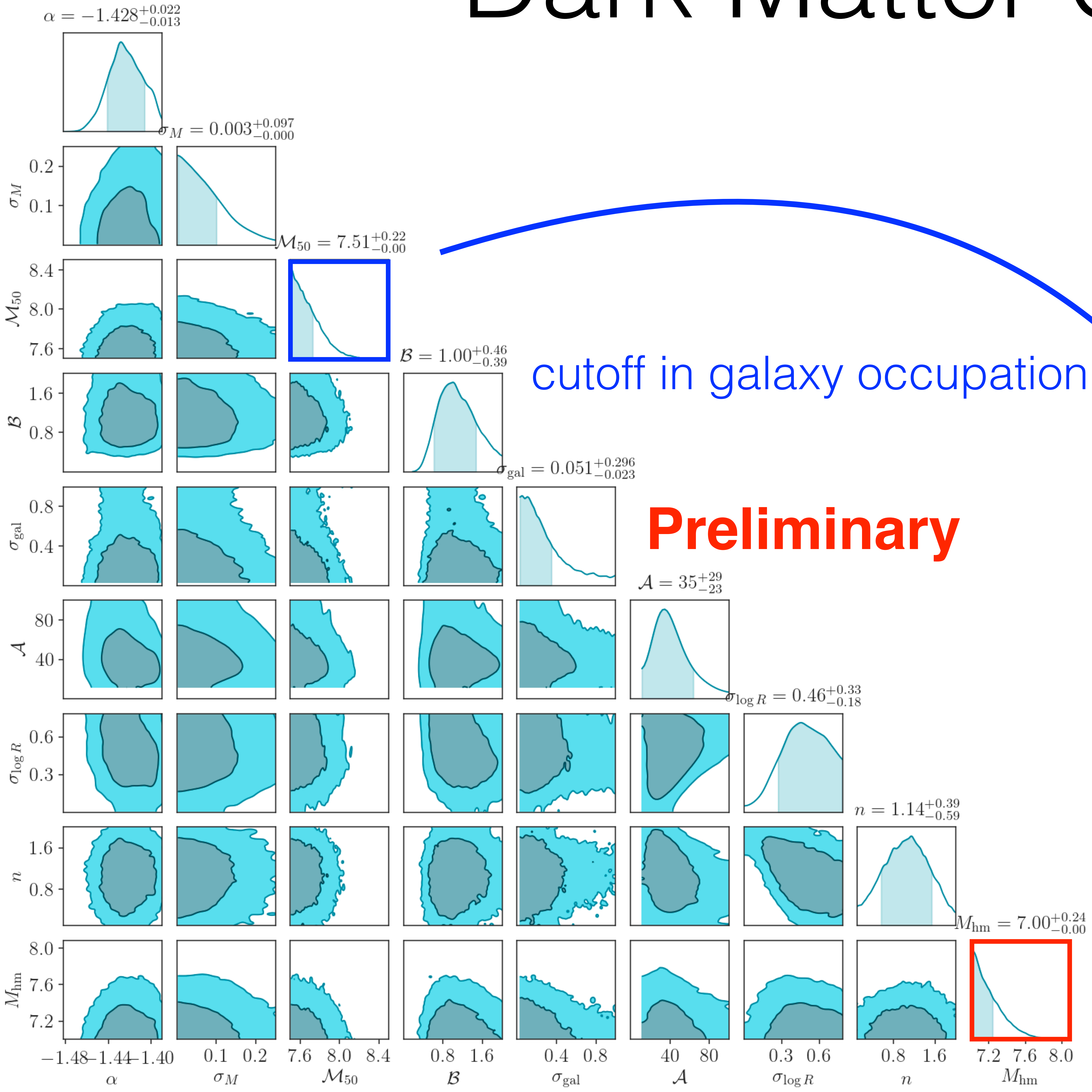
Satellite luminosity function



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

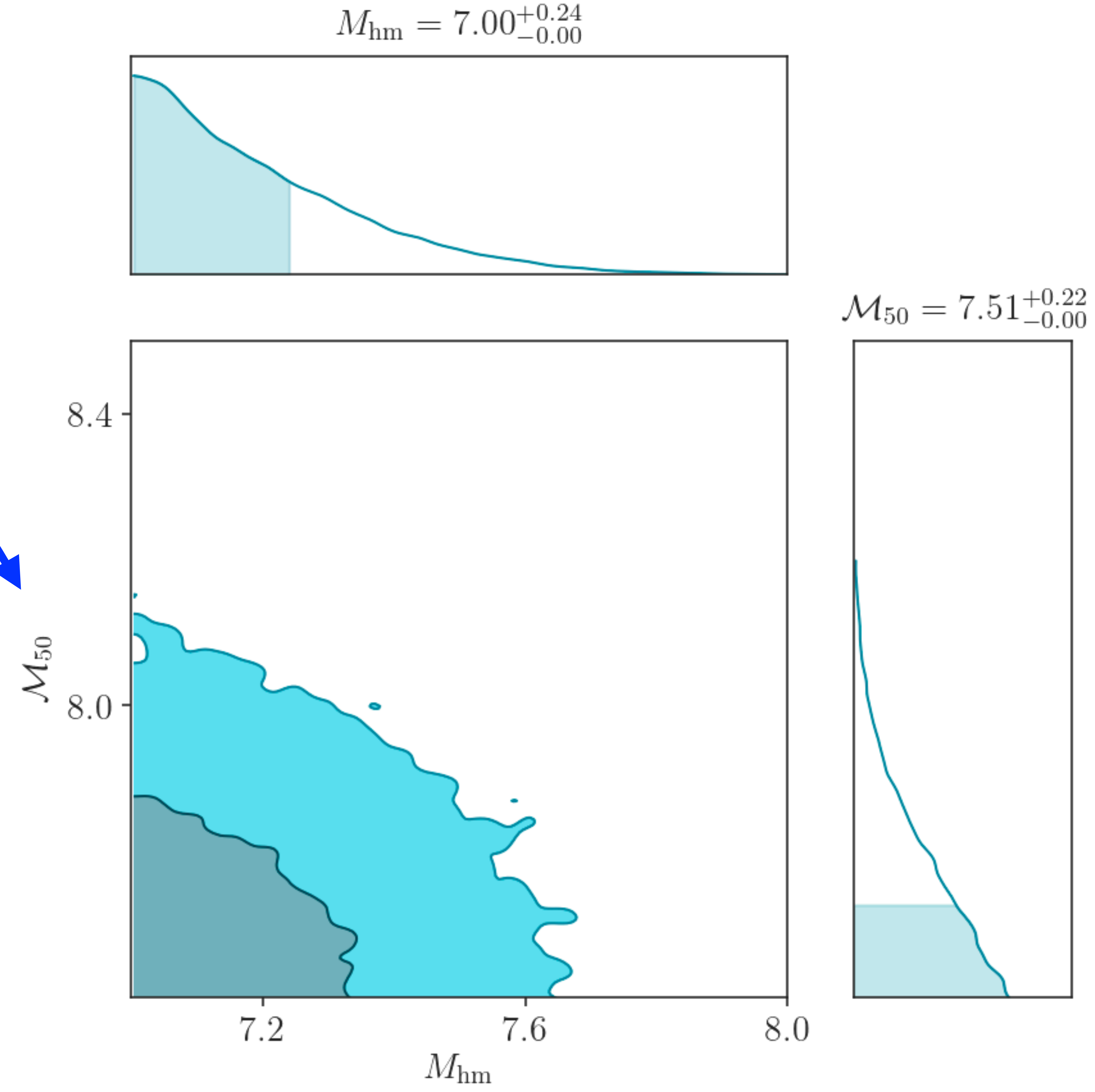
DES Collaboration in prep.

Dark Matter Constraints



cutoff in galaxy occupation

Preliminary



mass scale of suppression due to DM physics

DES Collaboration in prep.

Dark Matter Constraints

- MW satellites yield the strongest astrophysical constraints to date on a variety of DM properties, setting stringent limits on specific models
- For thermal relic WDM: m_{WDM} > 6.5 keV (95% confidence), comparable to limits from the Lyman-alpha forest (modulo IGM assumptions) and strong lensing (modulo subhalo density profile assumptions)
- This is the opposite of searching under a lamppost!

Dark Matter Paradigm	Parameter	Constraint	Derived Property	Constraint
Warm Dark Matter	Thermal Relic Mass	$m_{\mathrm{WDM}} > 6.5\,\mathrm{keV}$	Free-streaming Length	$\lambda_{\mathrm{fs}} \lesssim 10\,h^{-1}\,\mathrm{kpc}$
Interacting Dark Matter	Velocity-independent DM–Proton Cross Section	$\sigma_0 < 2.2 \times 10^{-29}\,\mathrm{cm}^2$	DM–Proton Coupling	$c_p \lesssim (0.5\,\mathrm{GeV})^{-2}$
Fuzzy Dark Matter	Particle Mass	$m_\phi > 3.2 \times 10^{-21}\,\mathrm{eV}$	de Broglie Wavelength	$\lambda_{\mathrm{dB}} \lesssim 0.5\,\mathrm{kpc}$

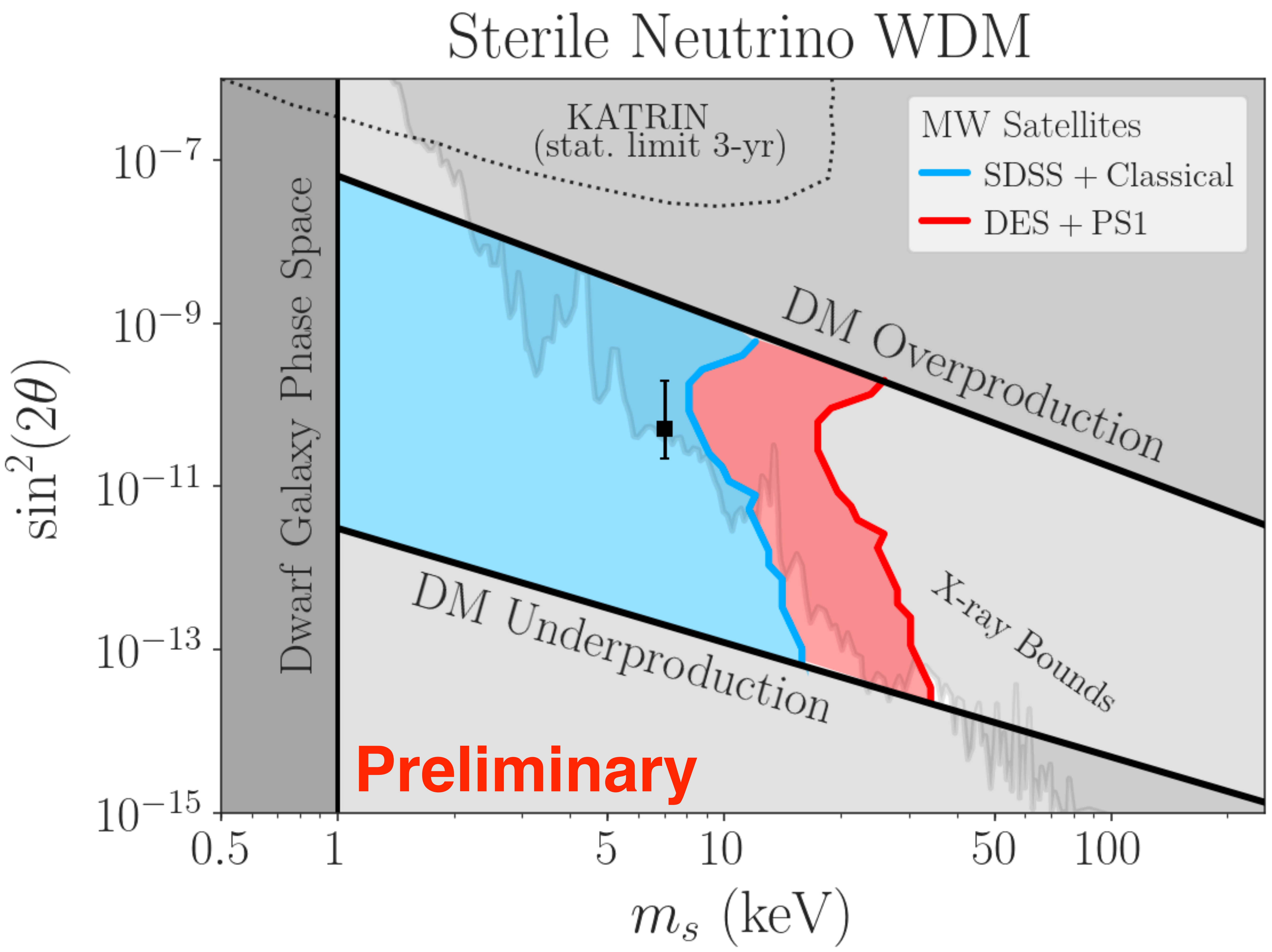
DES Collaboration in prep.

Warm Dark Matter Constraints

- Our analysis excludes nearly all remaining parameter space for resonantly-produced Shi-Fuller sterile neutrinos

- Sterile neutrino interpretation of the 3.5 keV X-ray line is robustly ruled out (> 99% confidence)

- Interpretation: DM free-streaming length must be smaller than the sizes of the halos that host ultra-faint dwarf galaxies



DES Collaboration in prep.

Interacting Dark Matter Constraints

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

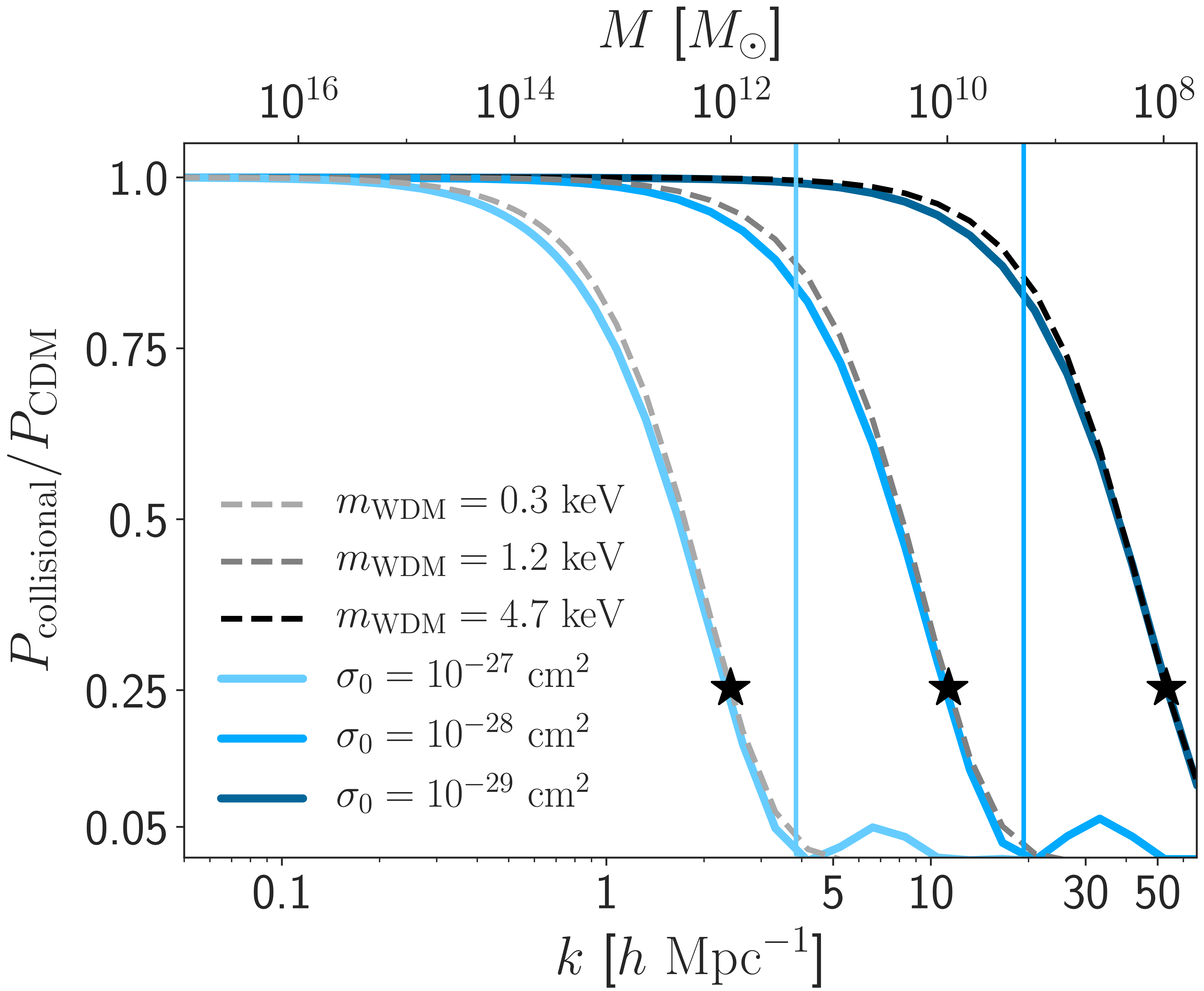
- Mass of the smallest halo allowed to form corresponds to the size of the horizon when

Momentum transfer rate

$$R_\chi \sim aH$$

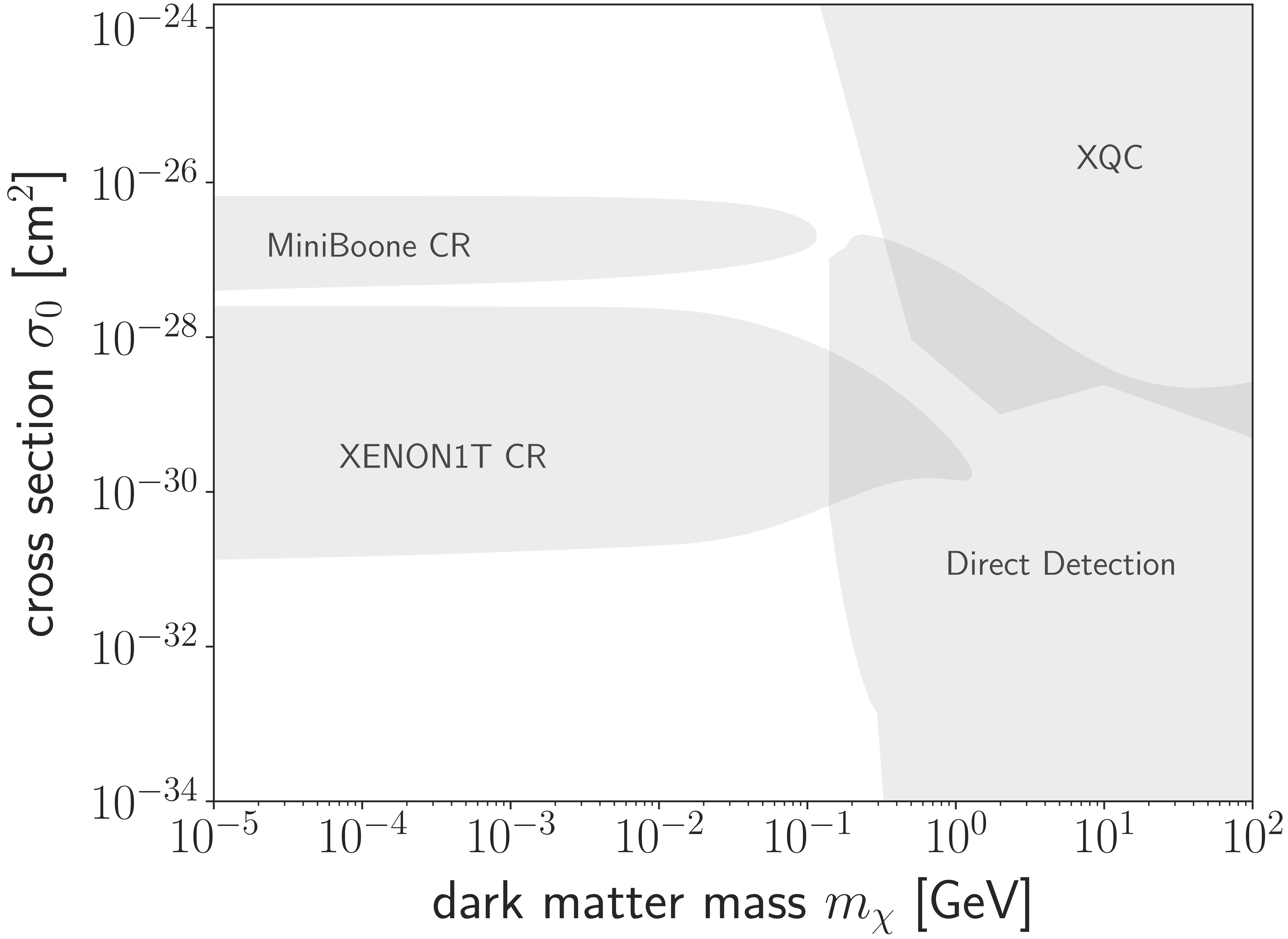
Hubble rate

- Minimum observed halo mass yields analytic cross section



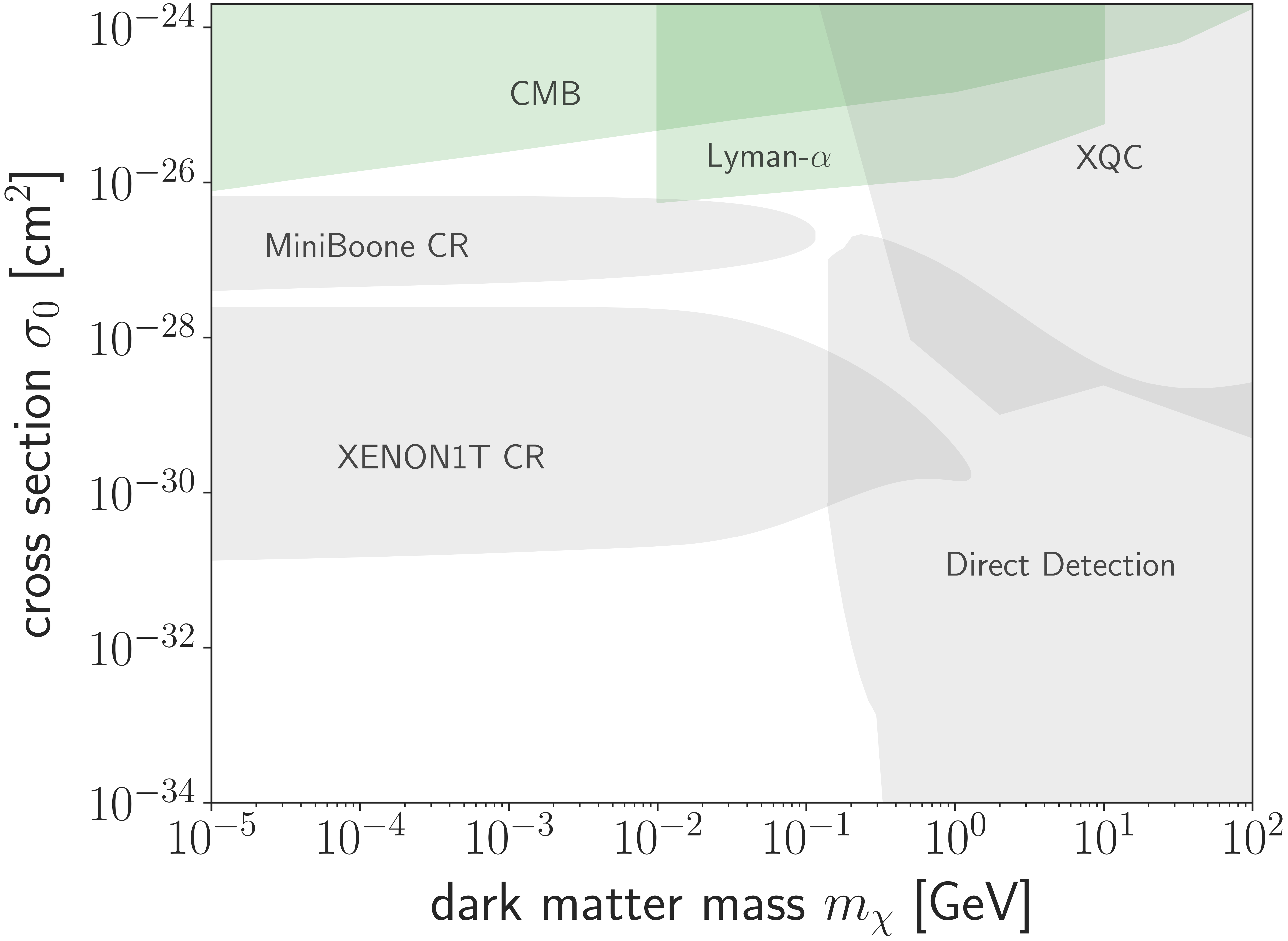
EN, V. Gluscevic, K. Boddy, R. Wechsler 2019

Interacting Dark Matter Constraints



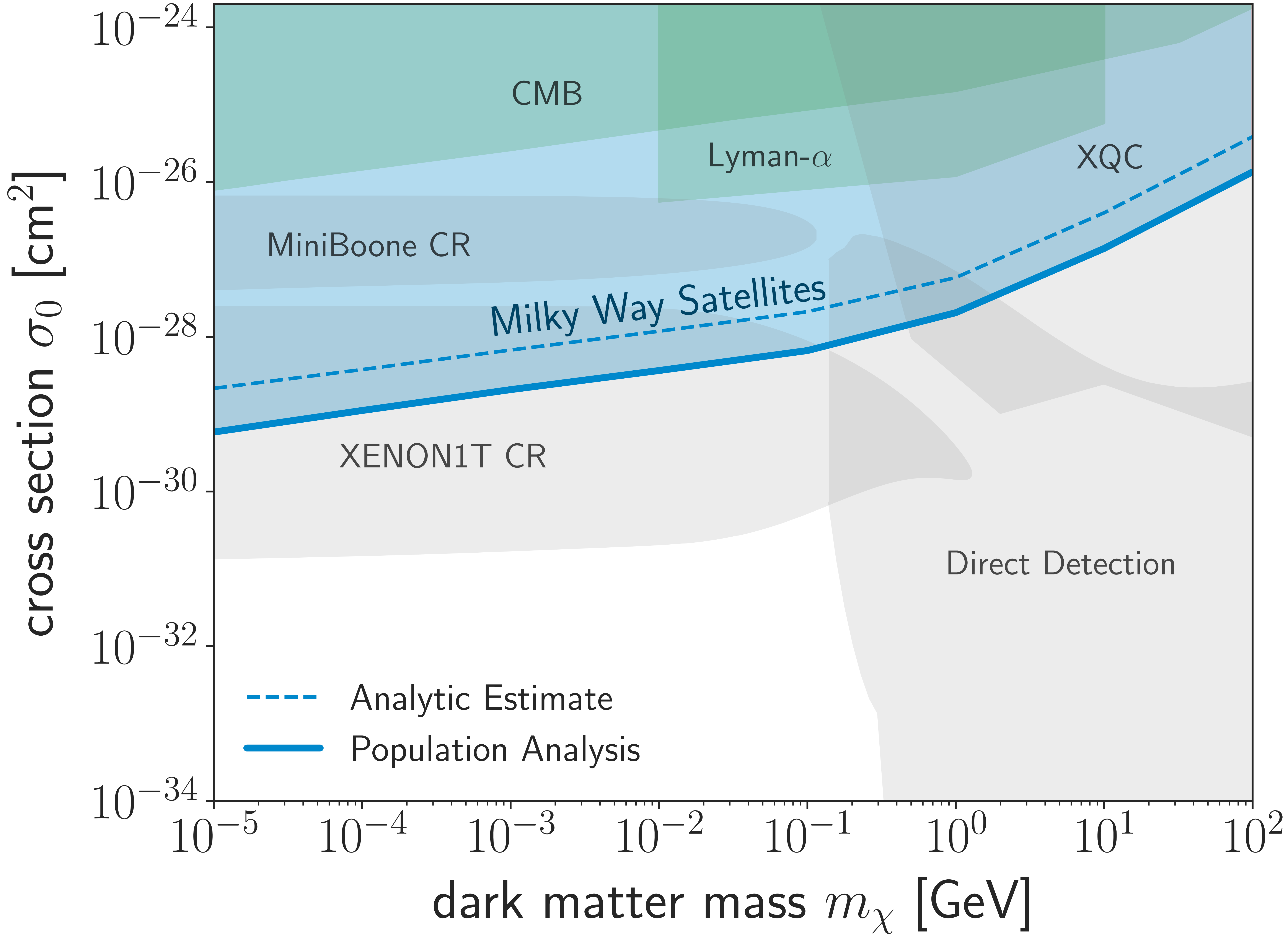
EN, V. Gluscevic, K. Boddy, R. Wechsler 2019

Interacting Dark Matter Constraints



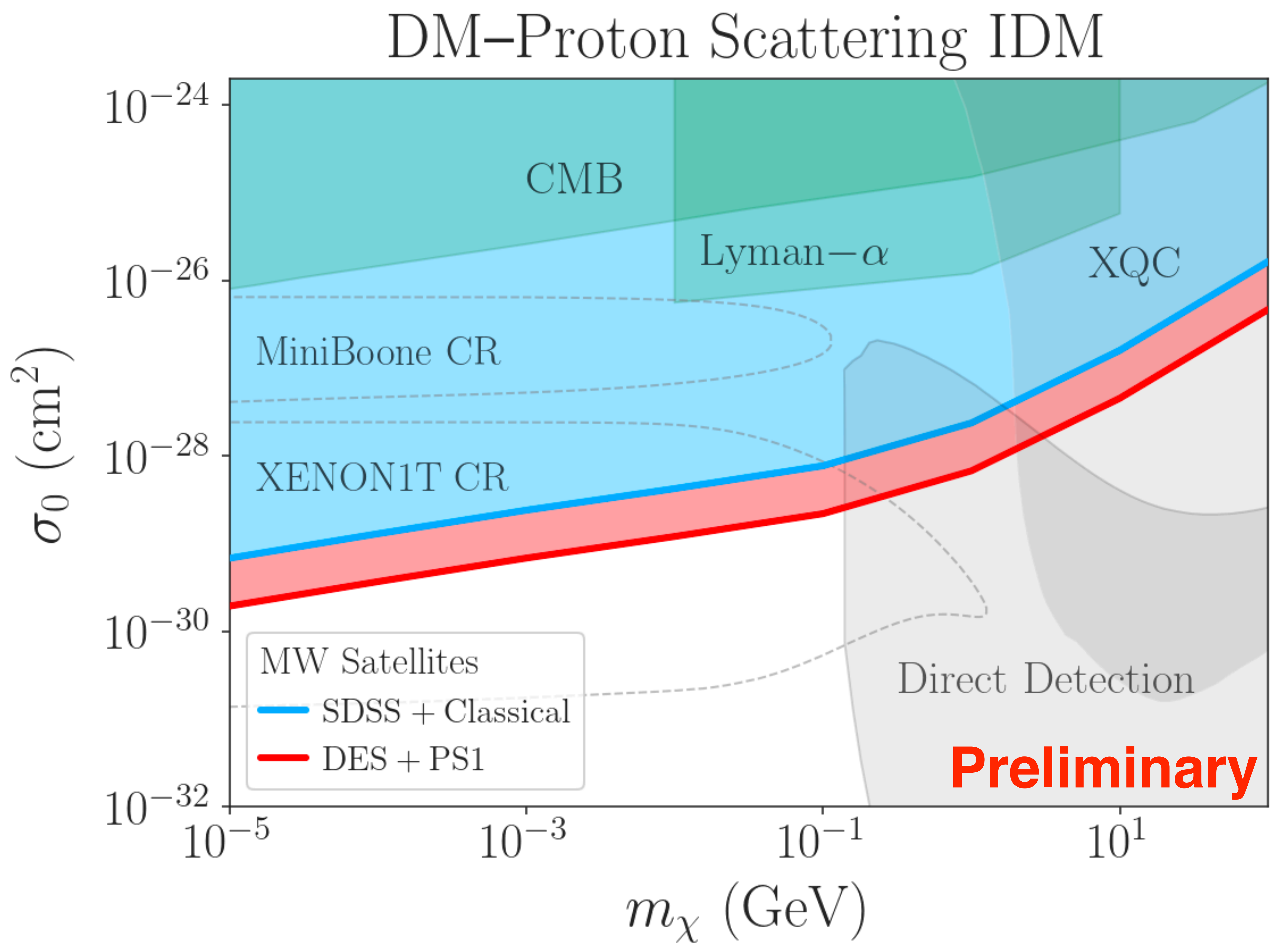
EN, V. Gluscevic, K. Boddy, R. Wechsler 2019

Interacting Dark Matter Constraints



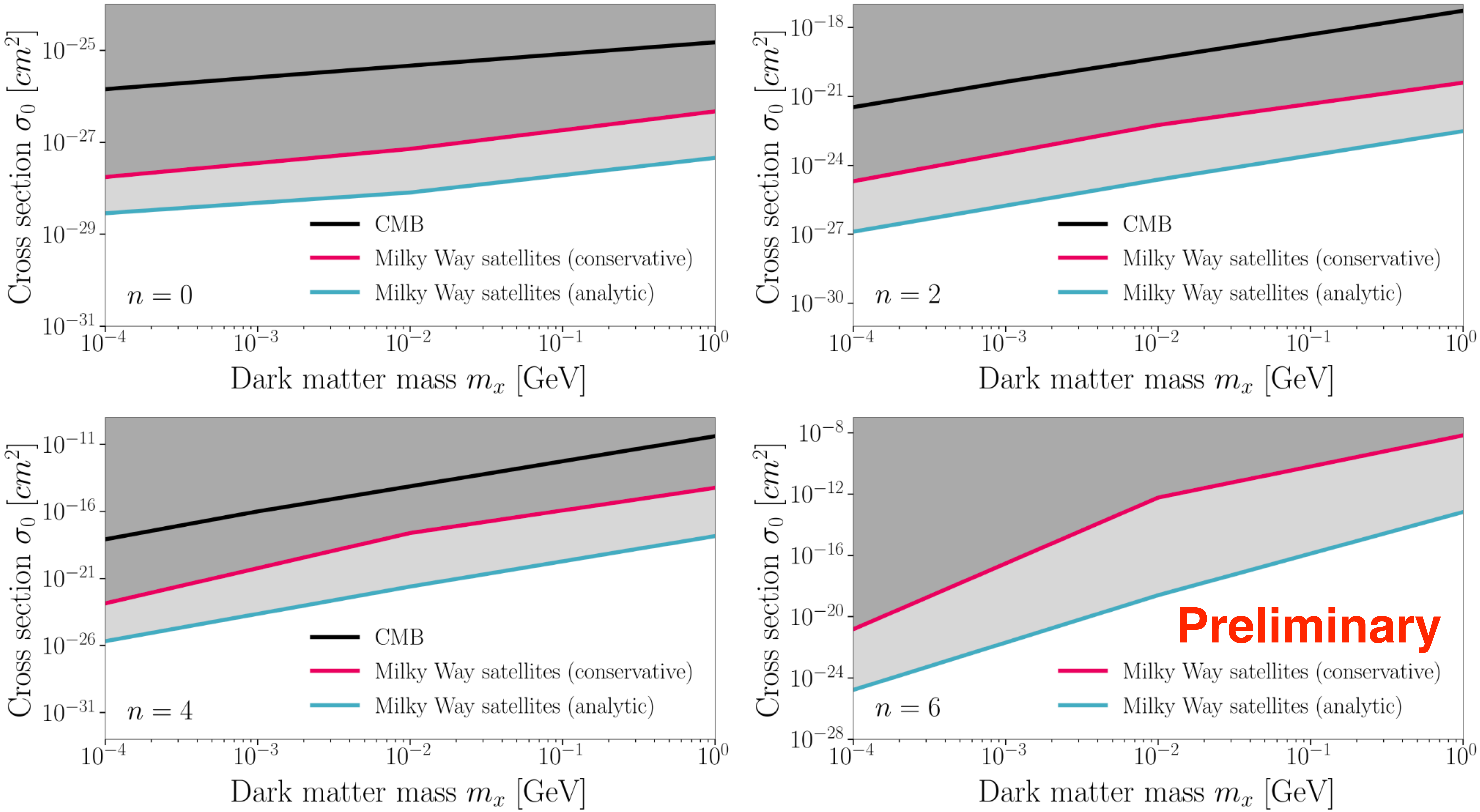
EN, V. Gluscevic, K. Boddy, R. Wechsler 2019

Interacting Dark Matter Constraints



DES Collaboration in prep.

Interacting Dark Matter Constraints

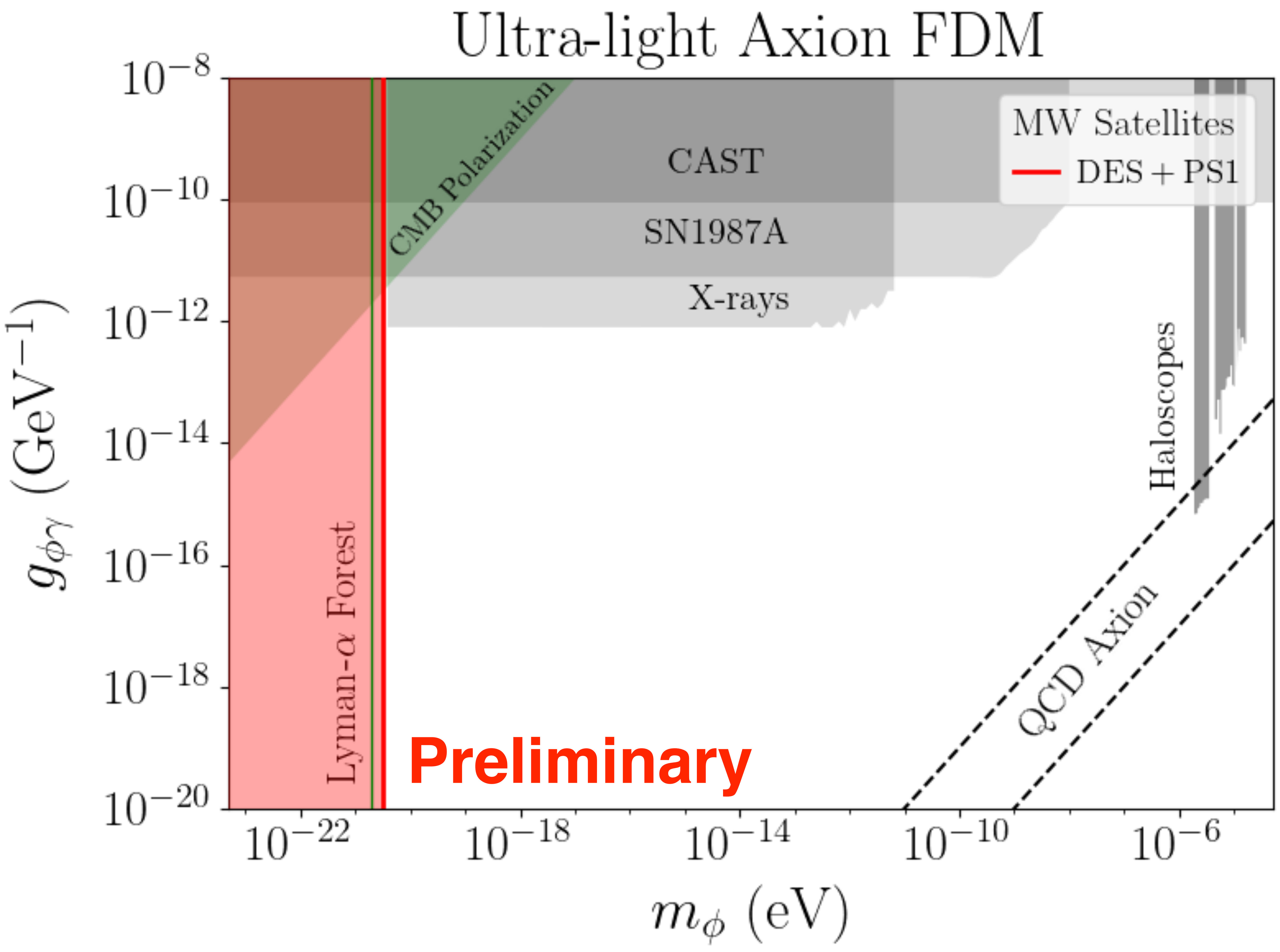


Preliminary

K. Maamari et al. in prep

Fuzzy Dark Matter Constraints

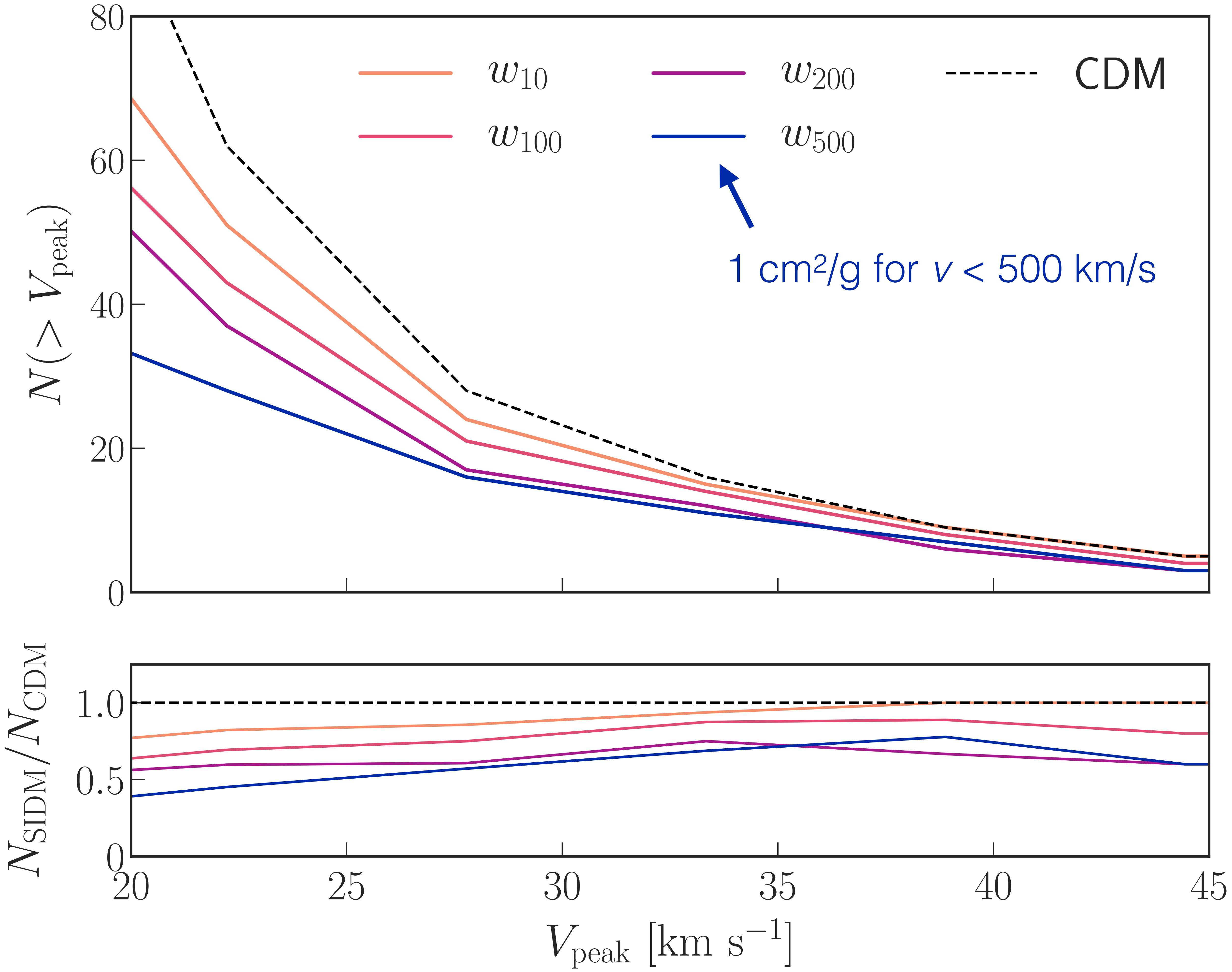
- Our analysis robustly rules out 10^{-22} eV fuzzy DM, even with conservative SHMF assumptions
- This is a limit on ultra-light scalar field DM with no self- or SM-coupling; including interactions is an active area of research!
- Interpretation: DM de Broglie wavelength must be smaller than the sizes of ultra-faint dwarfs



DES Collaboration in prep.

Constraining Late-time DM Physics

- Our framework also constrains DM properties that suppress subhalo abundances at late times (e.g. DM self-interactions, decays)
- Self-interactions: Sensitivity to SIDM cross sections of ~1 cm²/g at low velocity scales (stay tuned!)

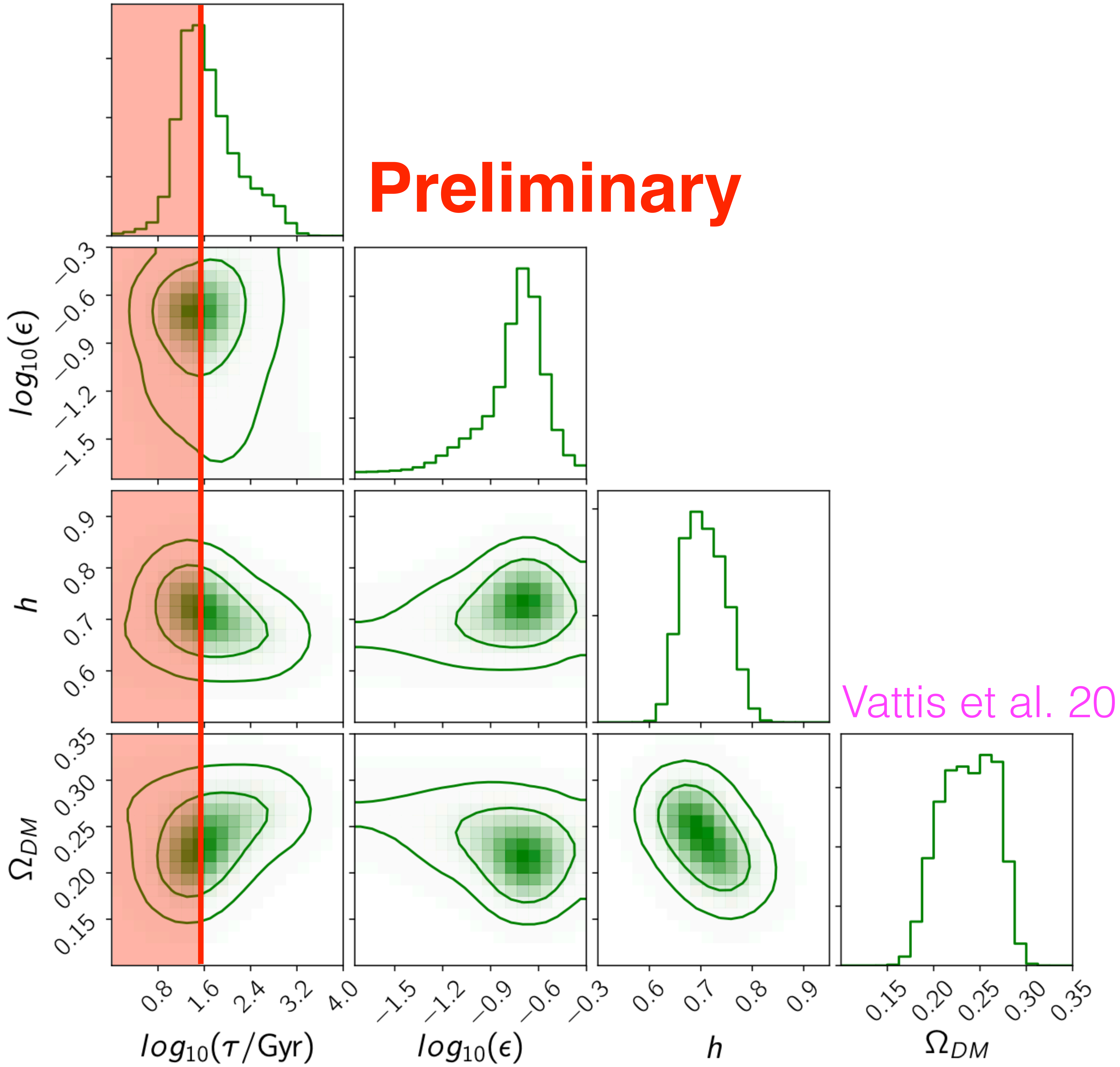


EN, A. Banerjee, S. Adhikari, Y.-Y. Mao, R. Wechsler 2020

Constraining Late-time DM Physics

- Our framework also constrains DM properties that suppress subhalo abundances at late times (e.g. DM self-interactions, decays)

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



Preliminary

Vattis et al. 2019

S. Mau et al. in prep

Outlook

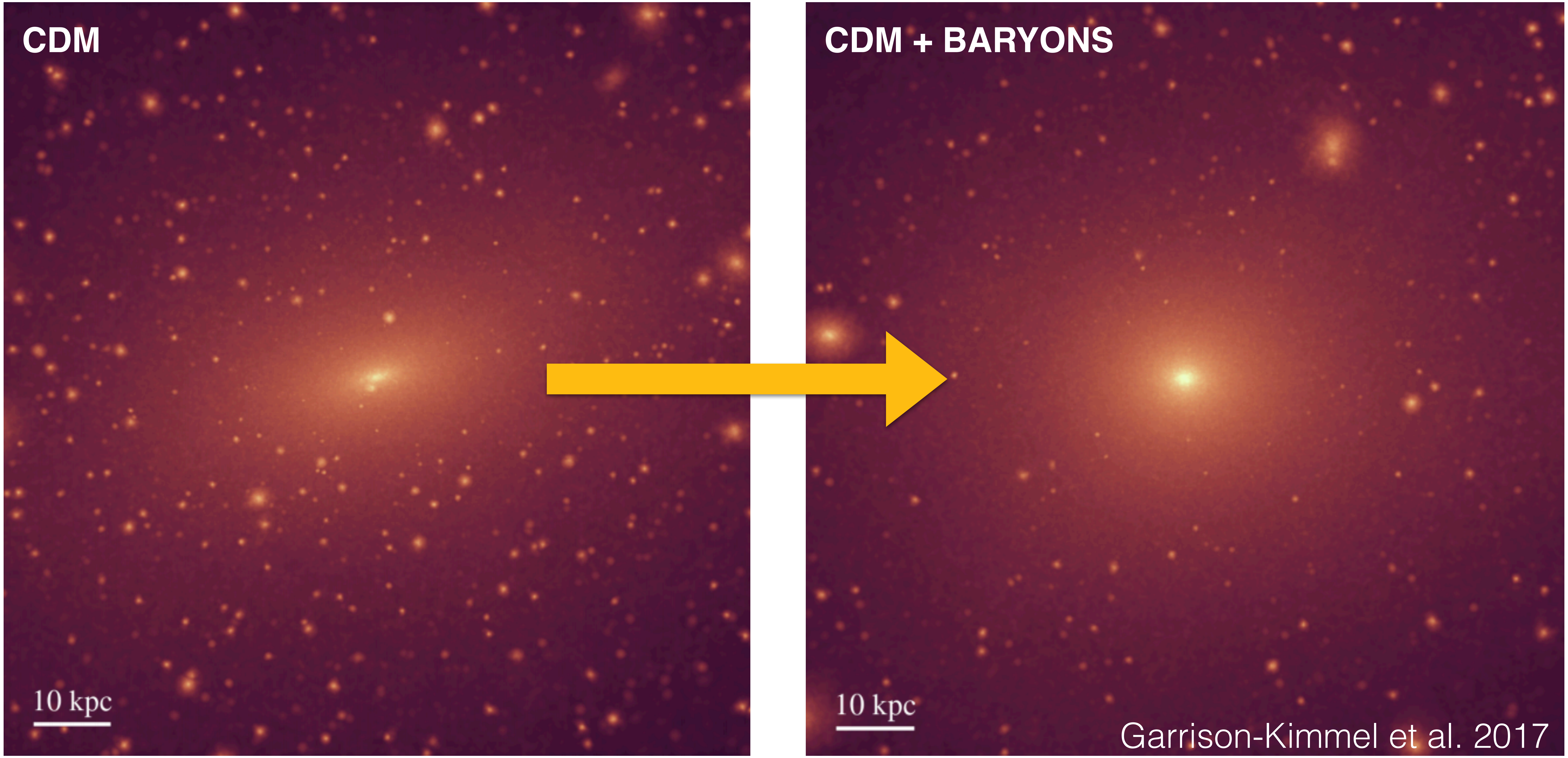
- MW satellite abundances are consistent with CDM predictions down to halo masses of ~10^8 $M_\odot$, yielding the strongest astrophysical constraints to date on the (lack of) a small-scale cutoff
- These constraints will **continue to improve** with advances in (currently conservative) galaxy–halo modeling and LSST satellite discoveries
- Our analysis informs a variety of DM properties: free-streaming scale, de Broglie wavelength, coupling to the Standard Model, self-interactions, particle lifetime, production mechanism, and more …
- Joint modeling of various small-scale structure probes is an important area for future work, starting with satellites + streams + 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

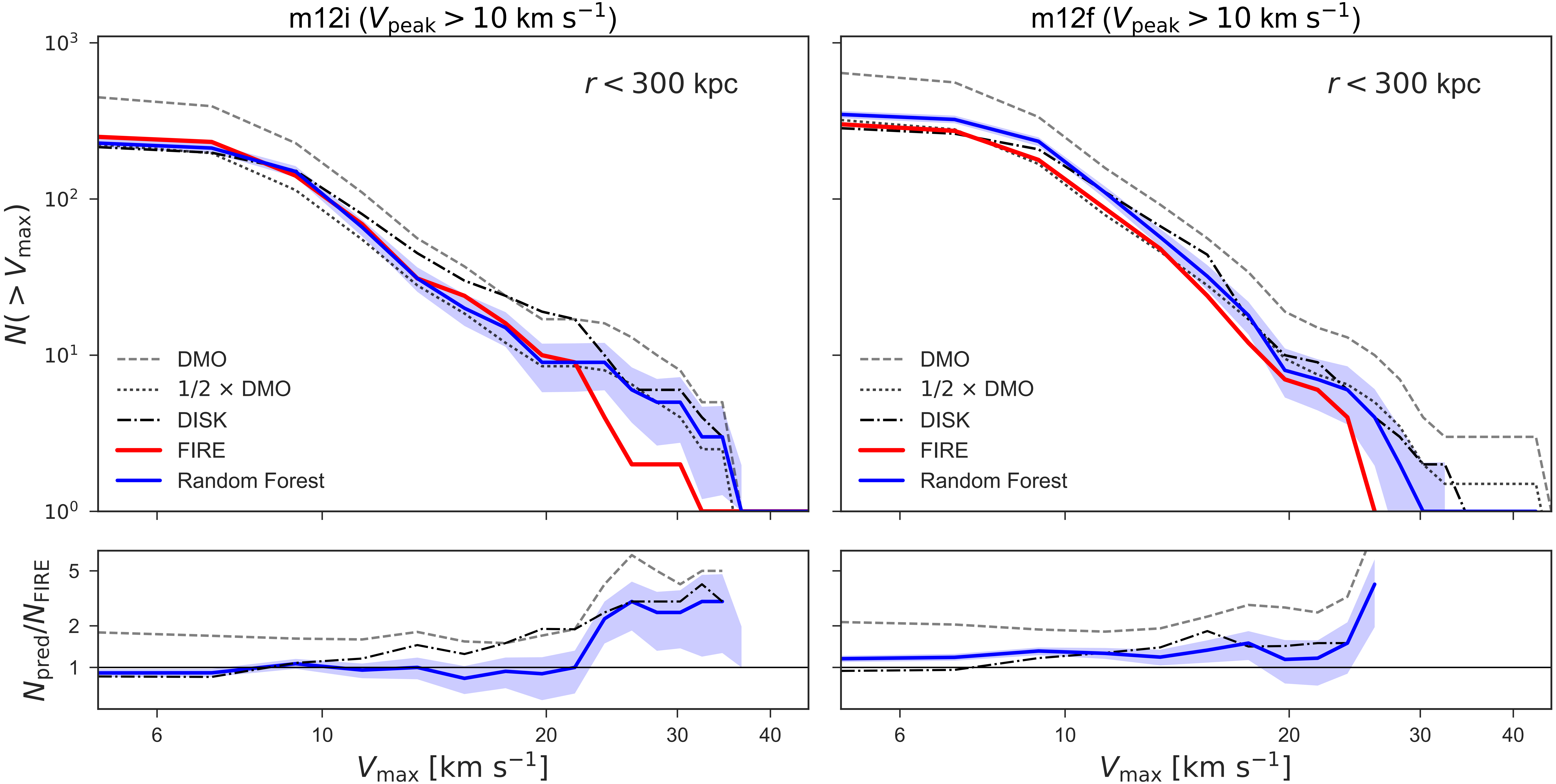

Gaia-Enceladus
LMC
MW

Baryonic Subhalo Disruption



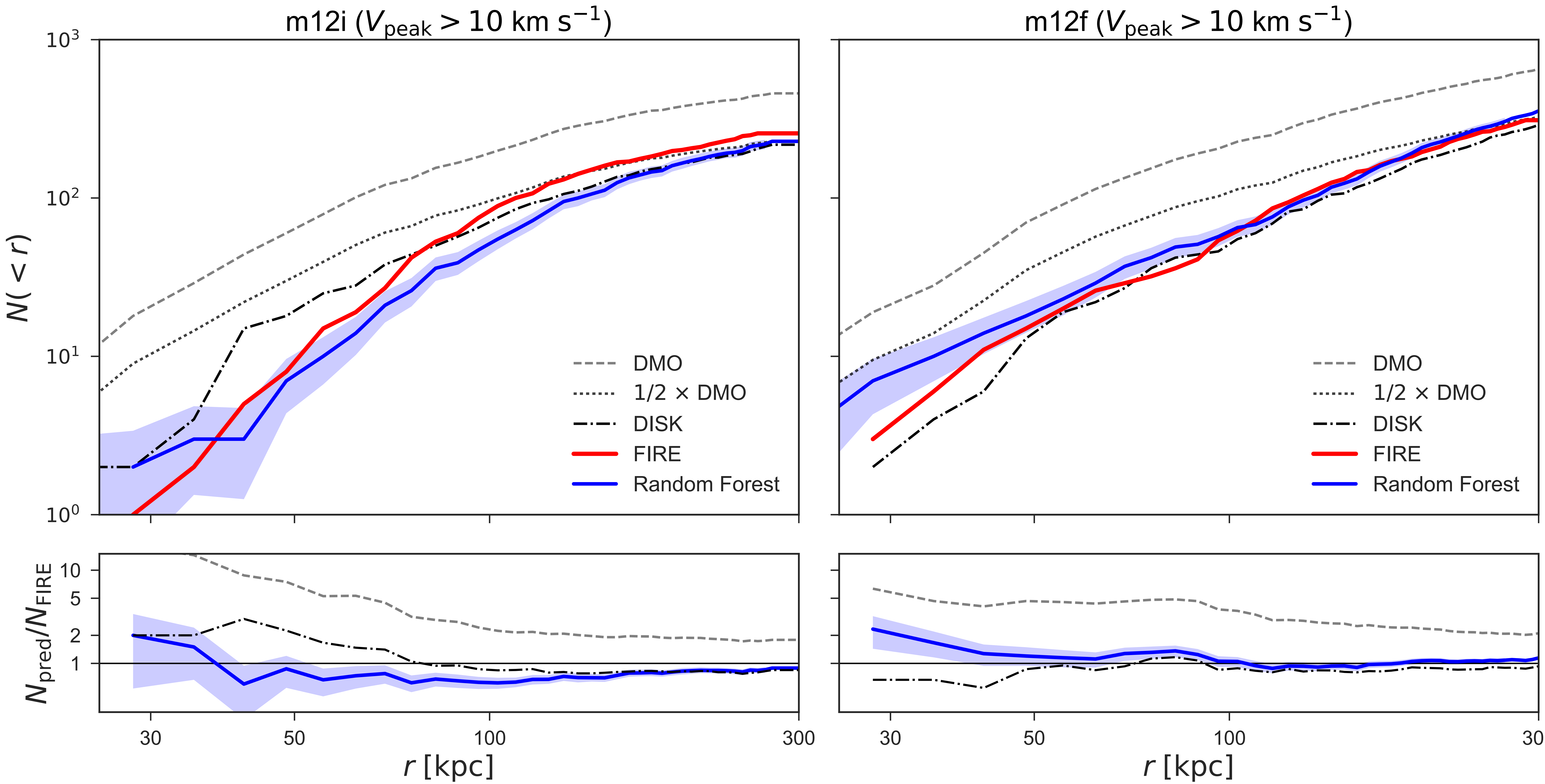
Garrison-Kimmel et al. 2017

Baryonic Subhalo Disruption



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

Baryonic Subhalo Disruption



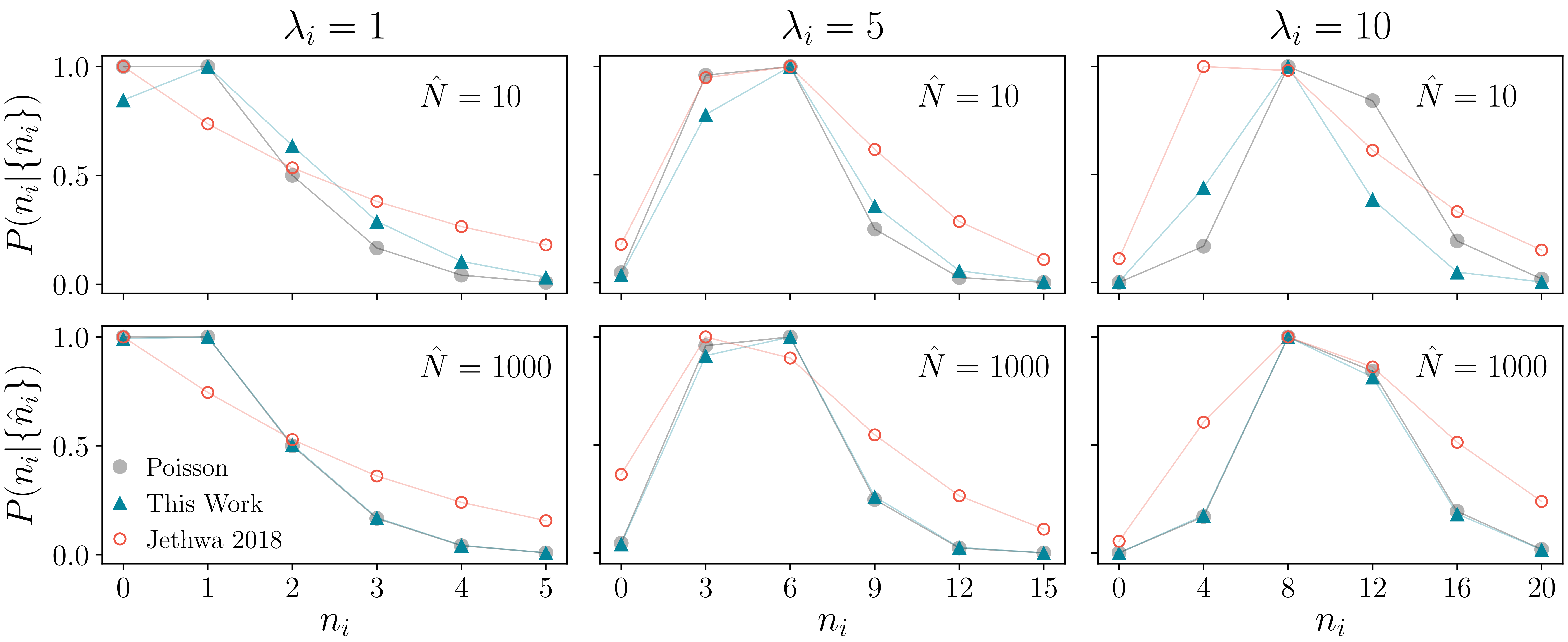
EN, Y.-Y. Mao, R. Wechsler et al. 2018

Satellite Population Likelihood

- Assume that mock and observed satellites are Poisson distributed
- Marginalize over unknown rate λ_i

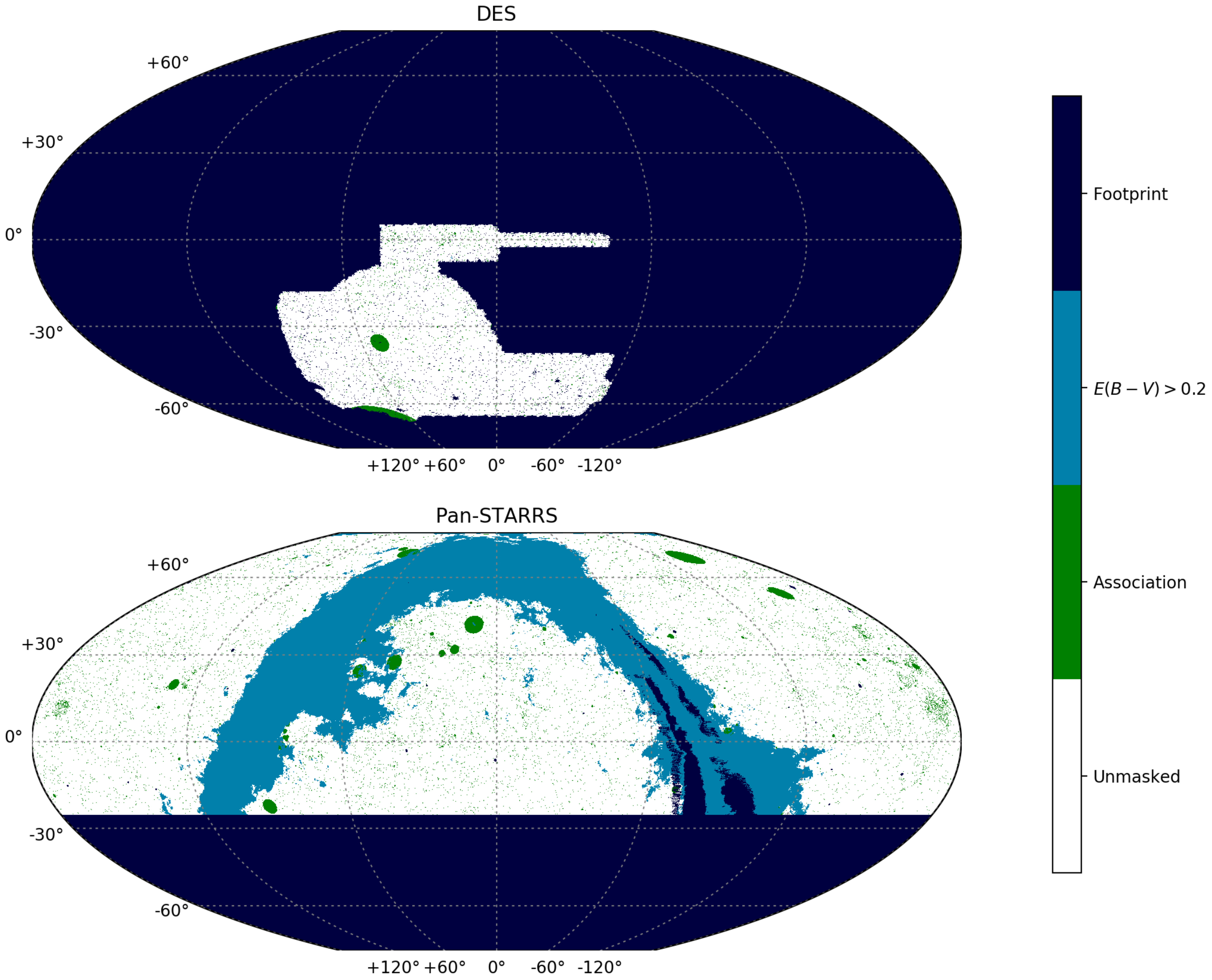
$$P(n_i|\hat{n}_{i,1},\ldots,\hat{n}_{i,\hat{N}}) = \int P(n_i|\lambda_i)P(\lambda_i|\hat{n}_{i,1},\ldots,\hat{n}_{i,\hat{N}})\,\mathrm{d}\lambda_i$$

$$= \left(\frac{\hat{N}+1}{\hat{N}}\right)^{-(\hat{n}_{i,1}+\cdots+\hat{n}_{i,\hat{N}}+1)} (\hat{N}+1)^{-n_i} \frac{(\hat{n}_{i,1}+\cdots+\hat{n}_{i,\hat{N}}+n_i)!}{n_i!(\hat{n}_{i,1}+\cdots+\hat{n}_{i,\hat{N}})!},$$



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

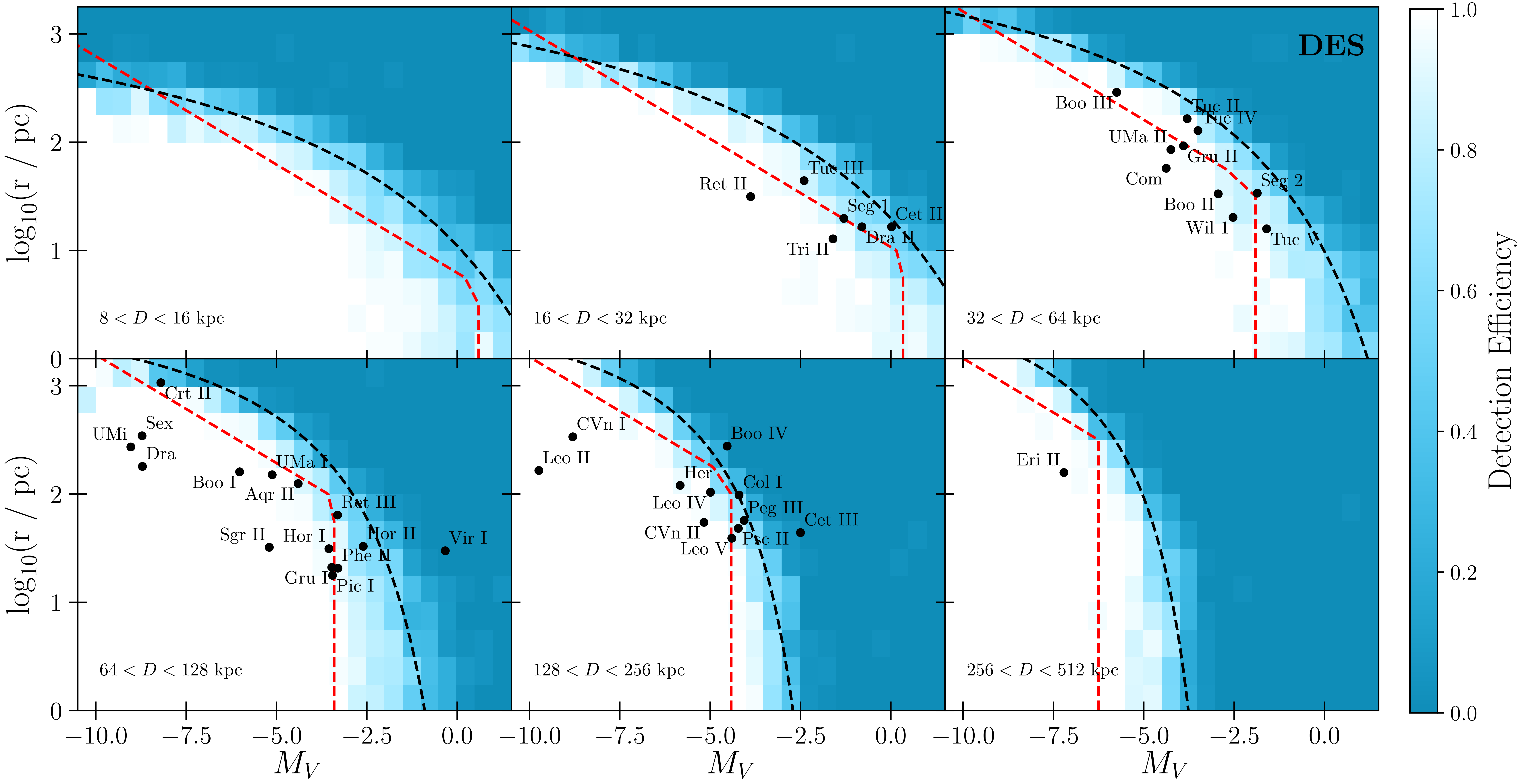
DES & Pan-STARRS
Survey Selection Functions



- 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

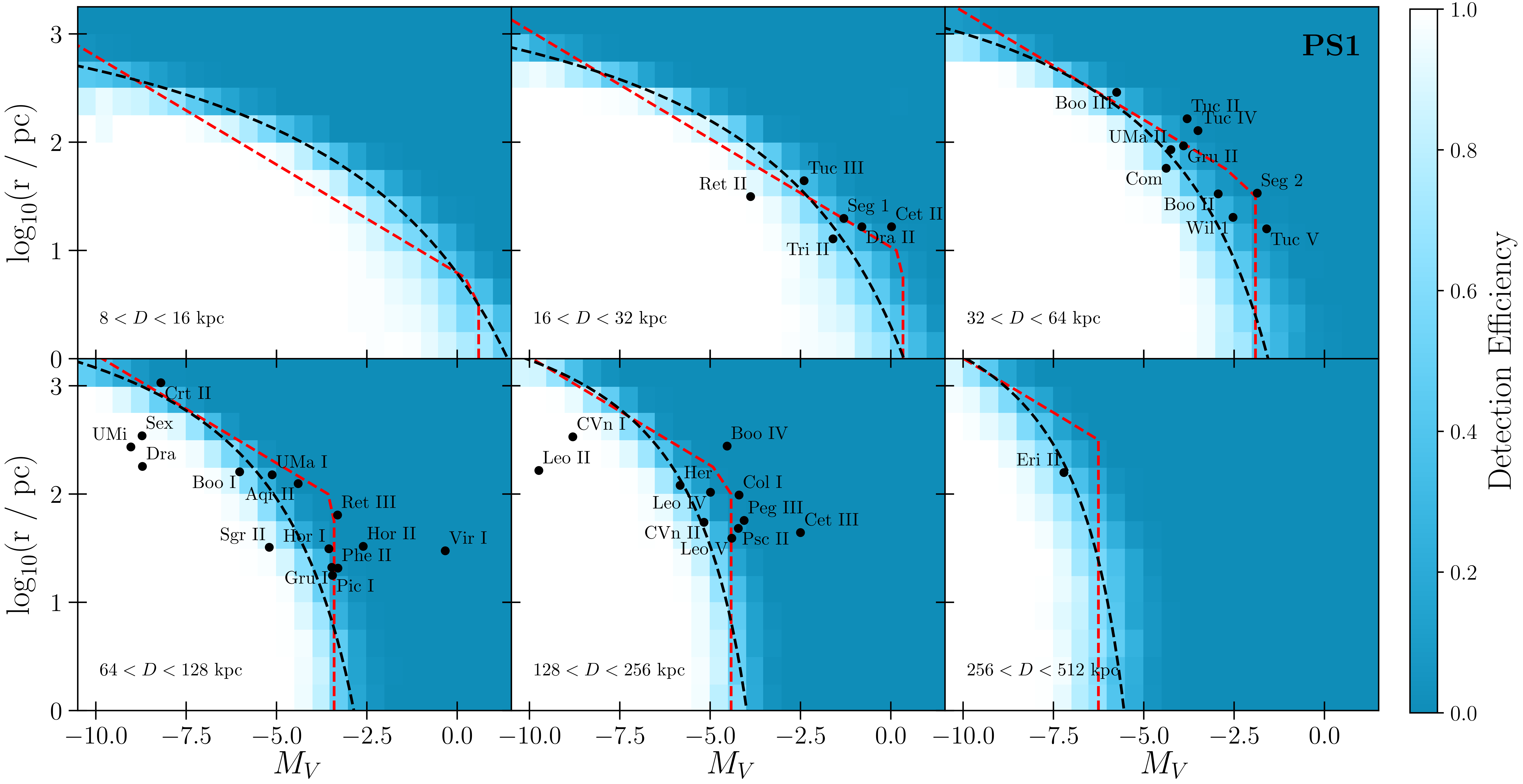
Drlica-Wagner & Bechtol et al. 2020

Observational Selection Functions



Drlica-Wagner & Bechtol et al. 2020

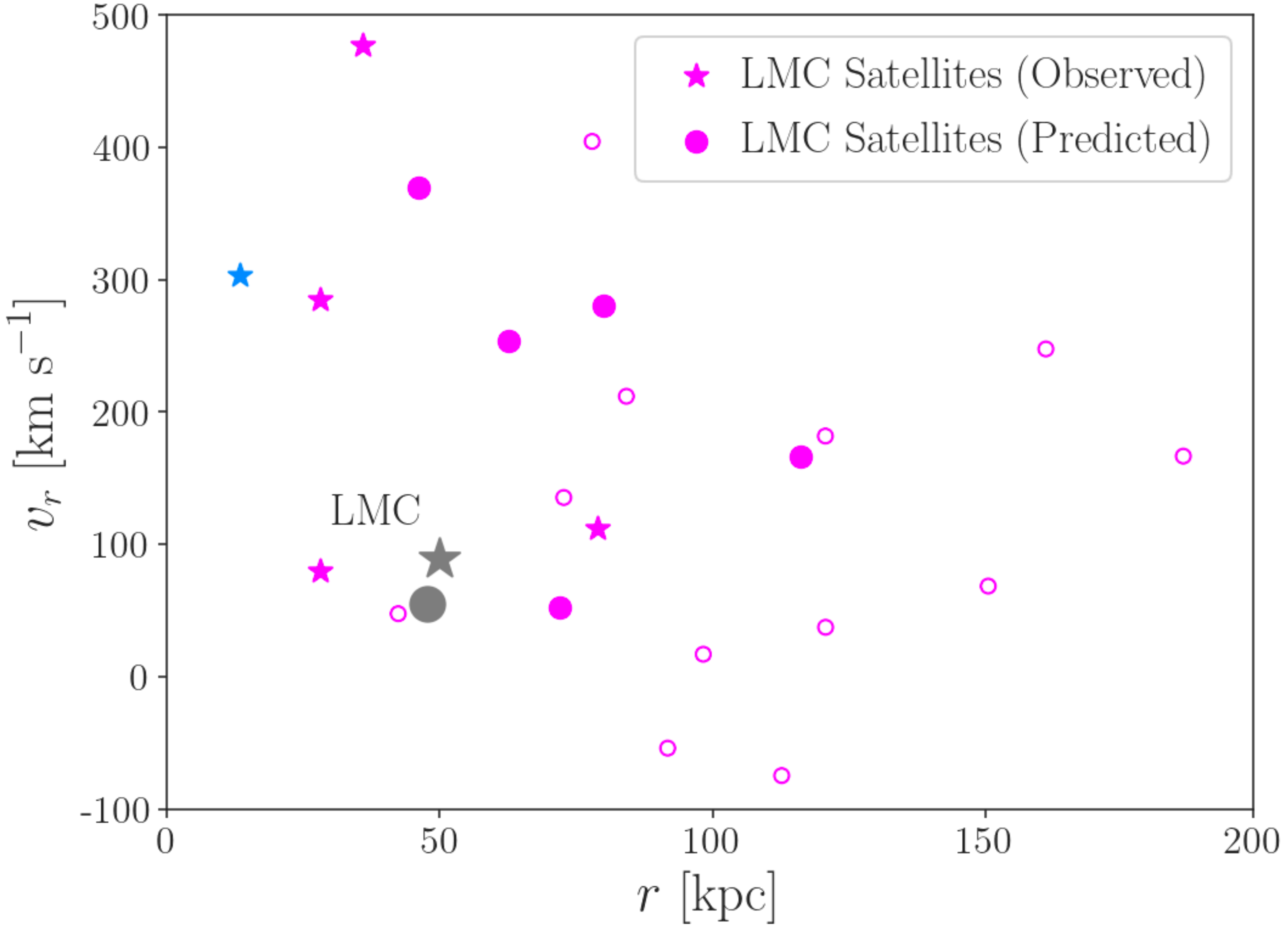
Observational Selection Functions

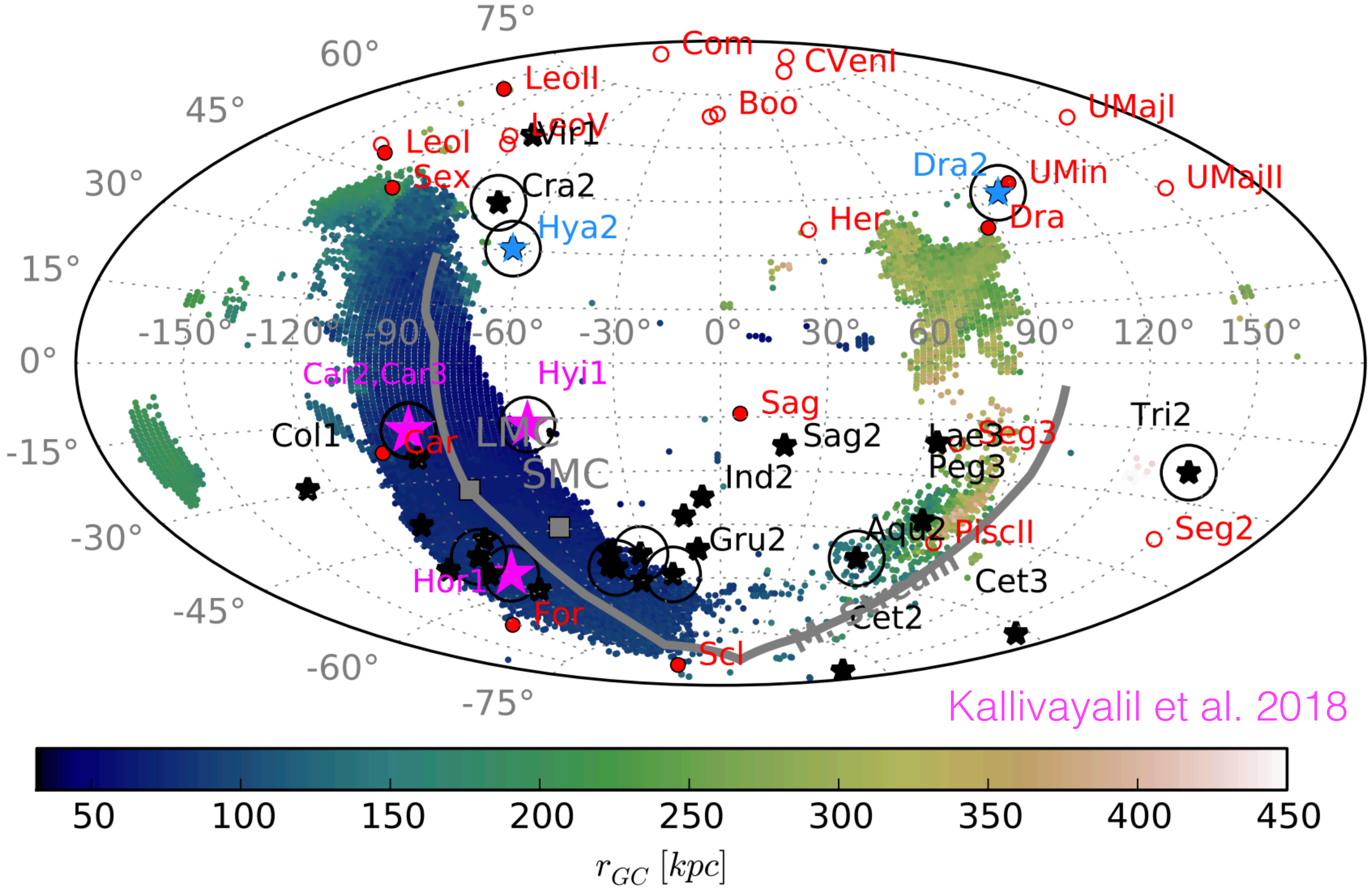


Drlica-Wagner & Bechtol et al. 2020

Satellites of the LMC

Also see Patel et al. 2020!

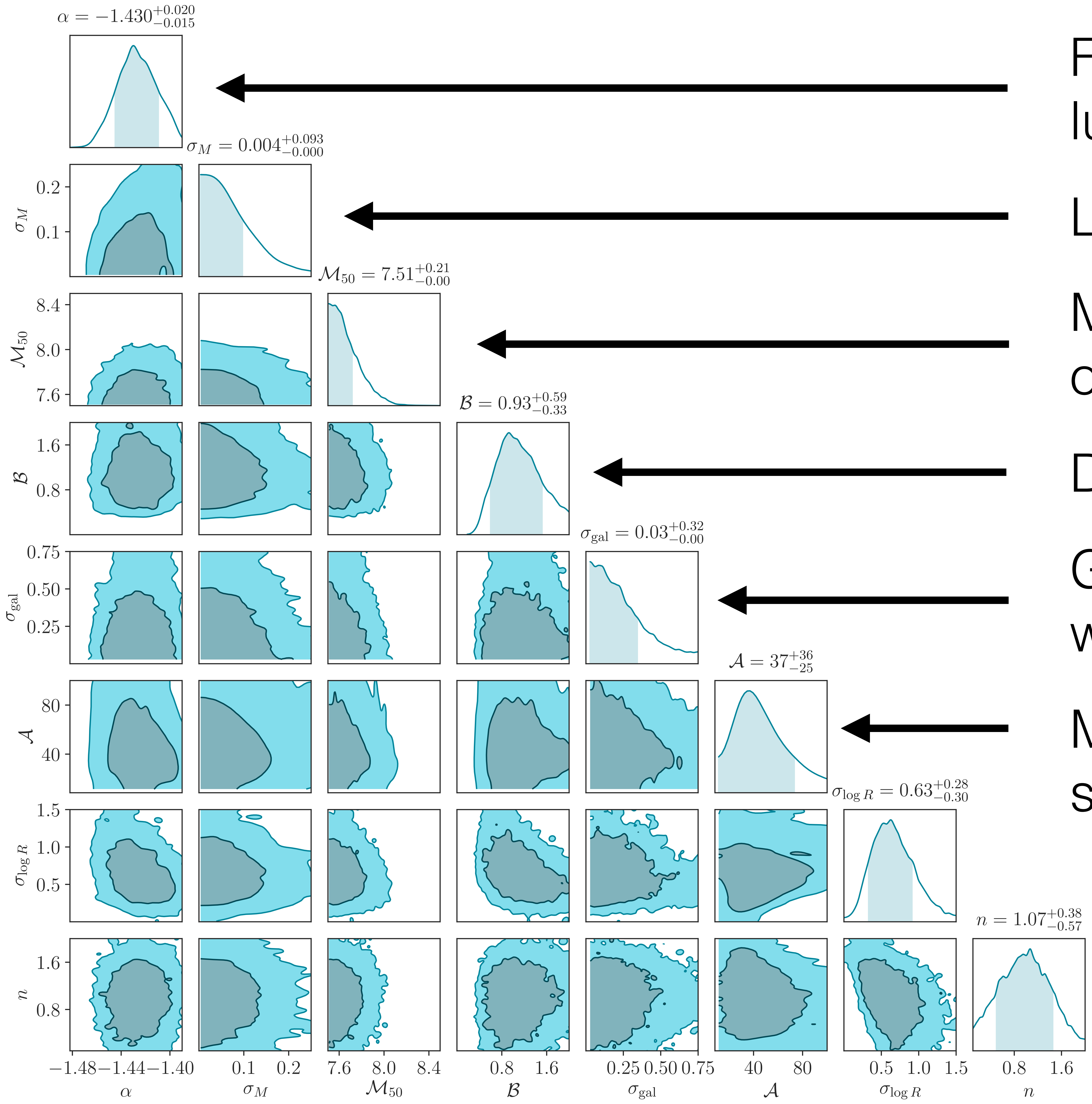




Kallivayalil et al. 2018

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 from GAMA

Luminosity scatter < 0.2 dex

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

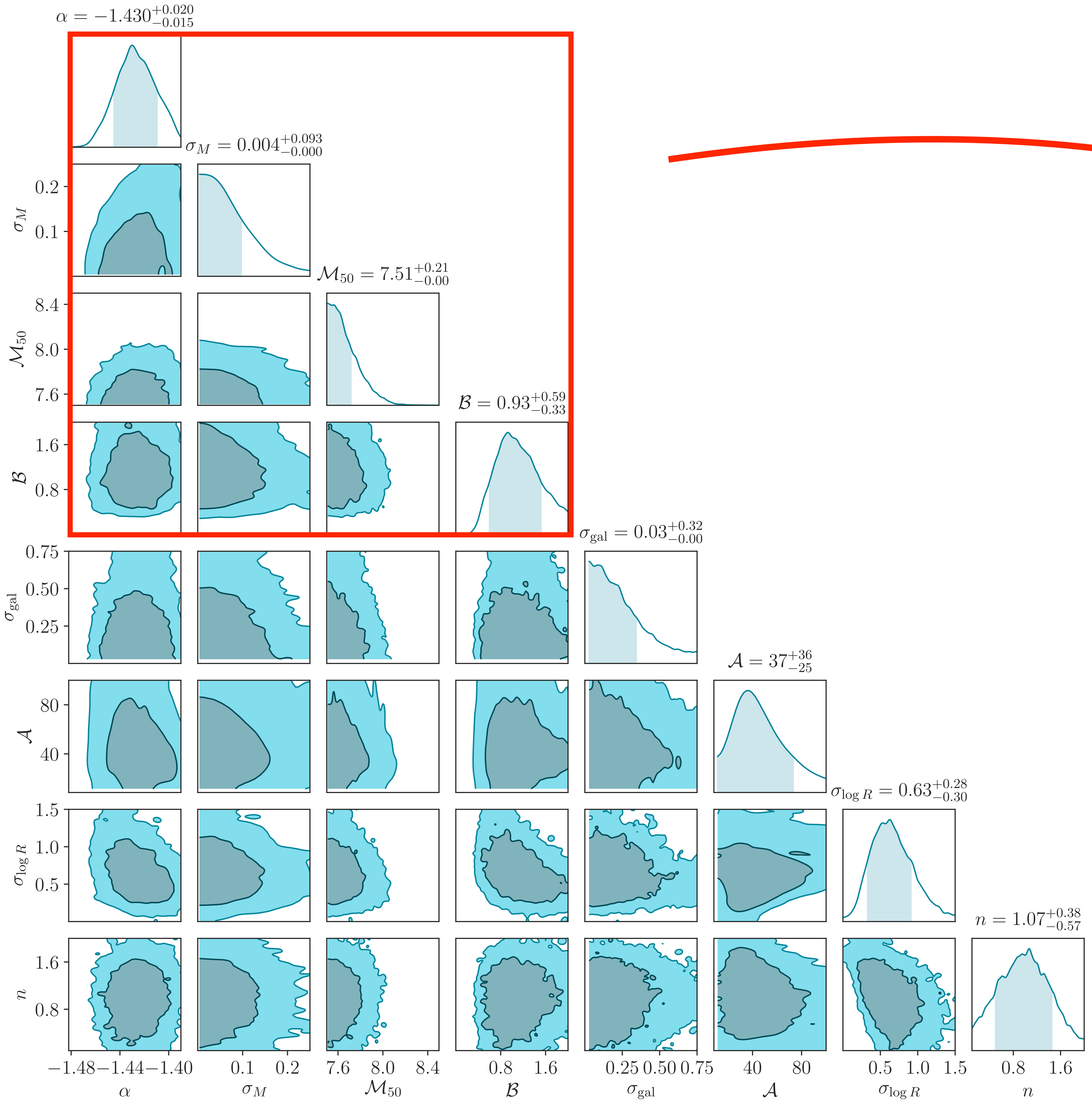
Disruption consistent with FIRE sims

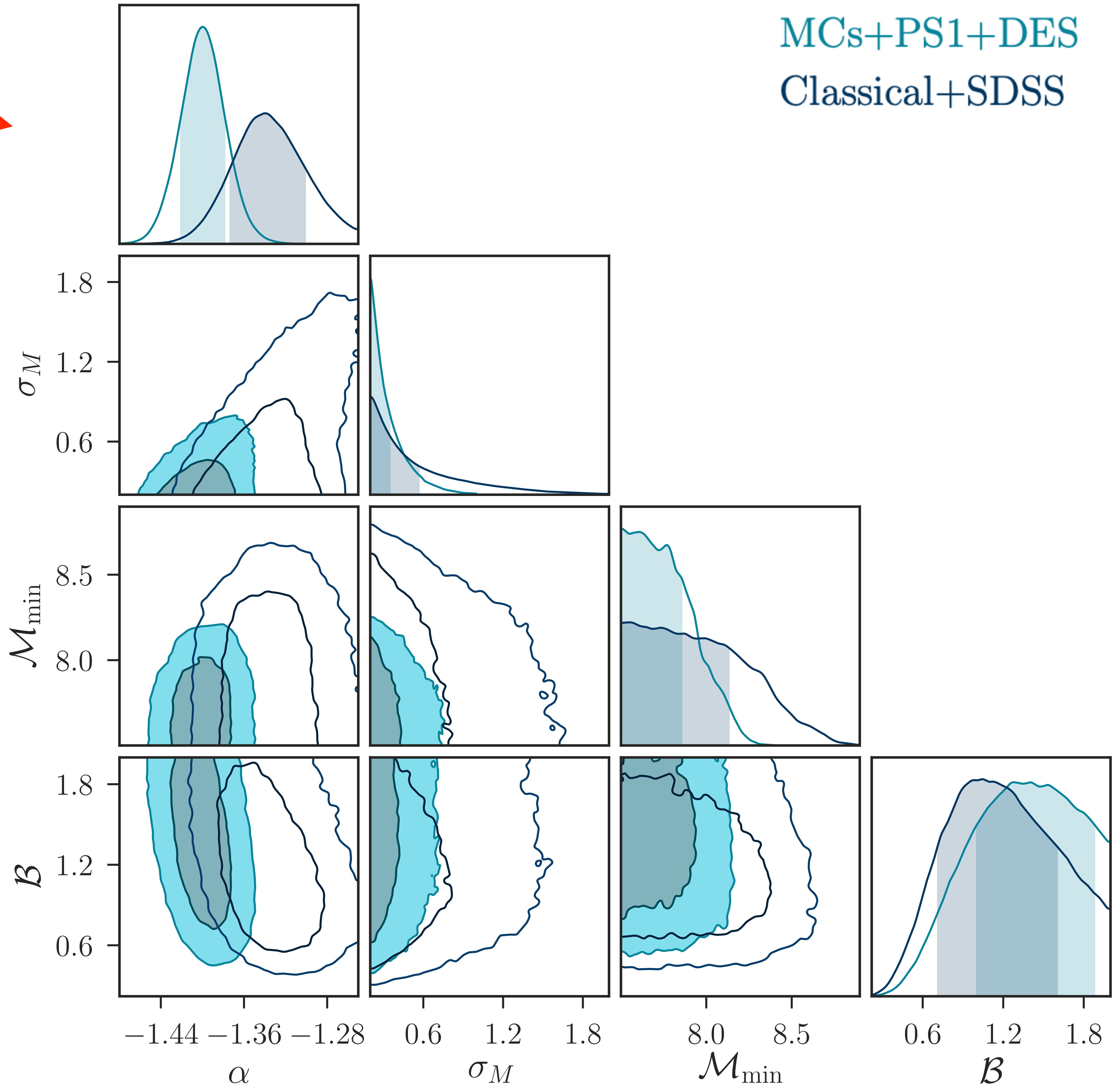
Galaxy occupation fraction consistent with step function

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

EN & Wechsler et al. 2020

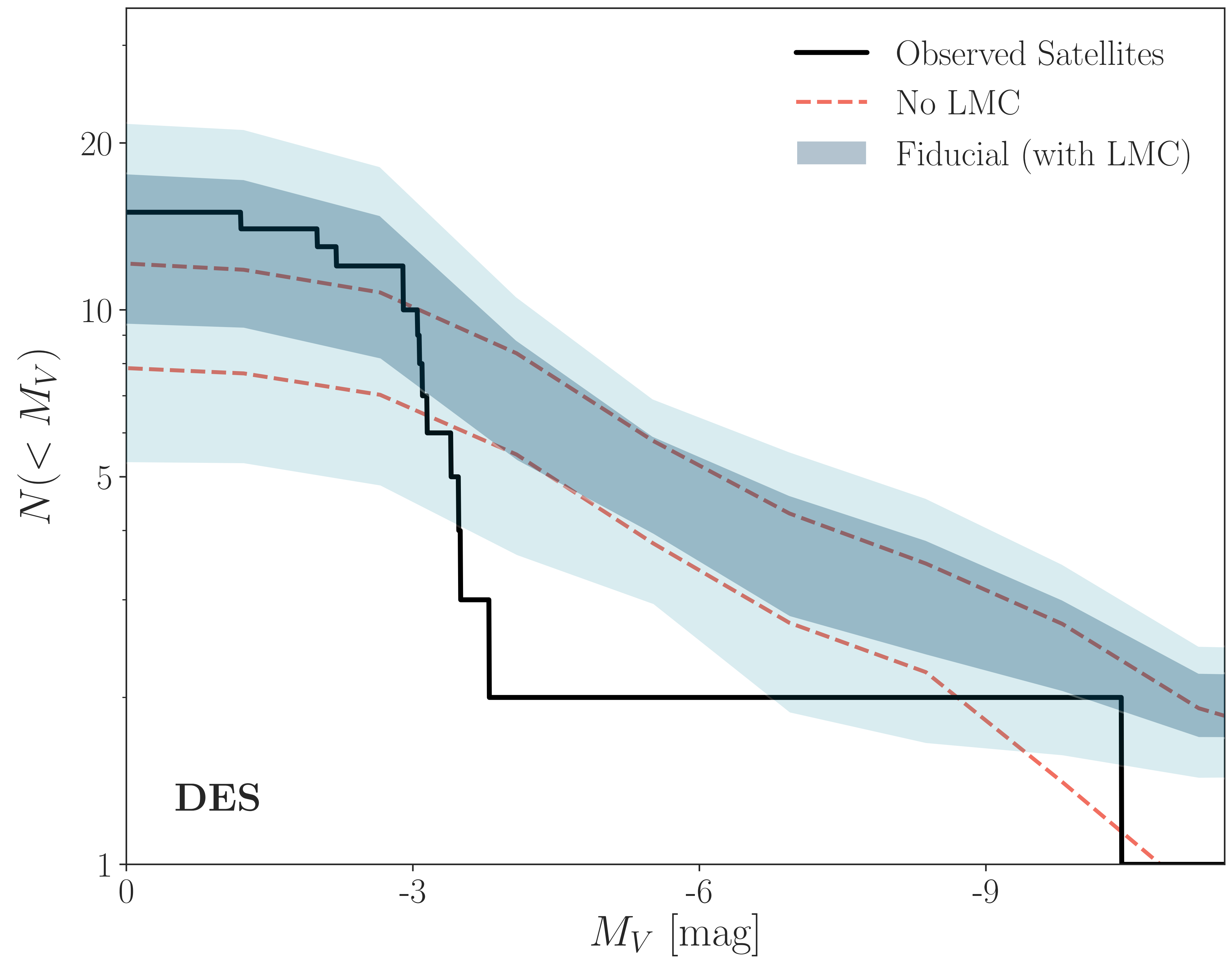
Galaxy–Halo Connection Constraints

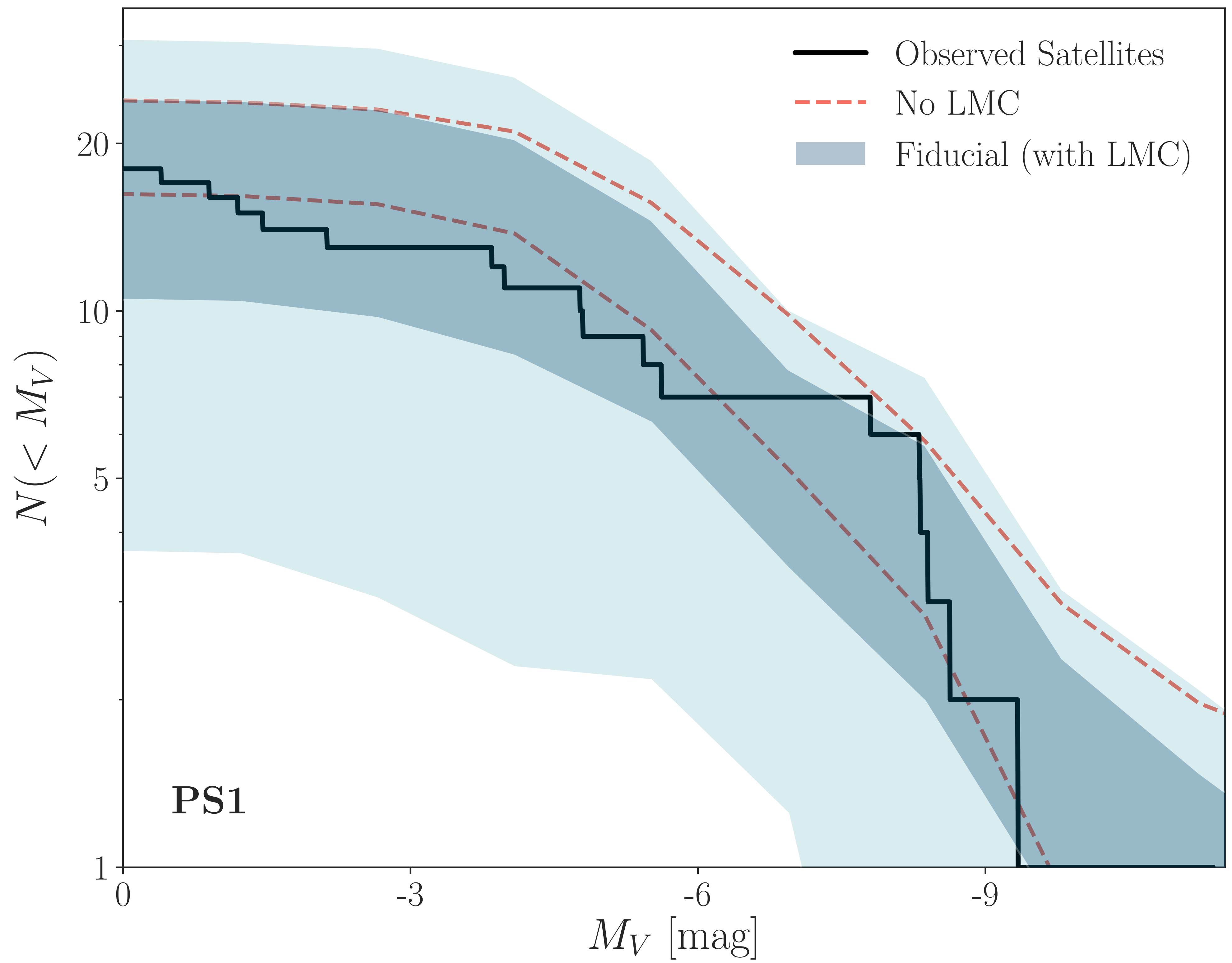




Predicted Satellite Populations

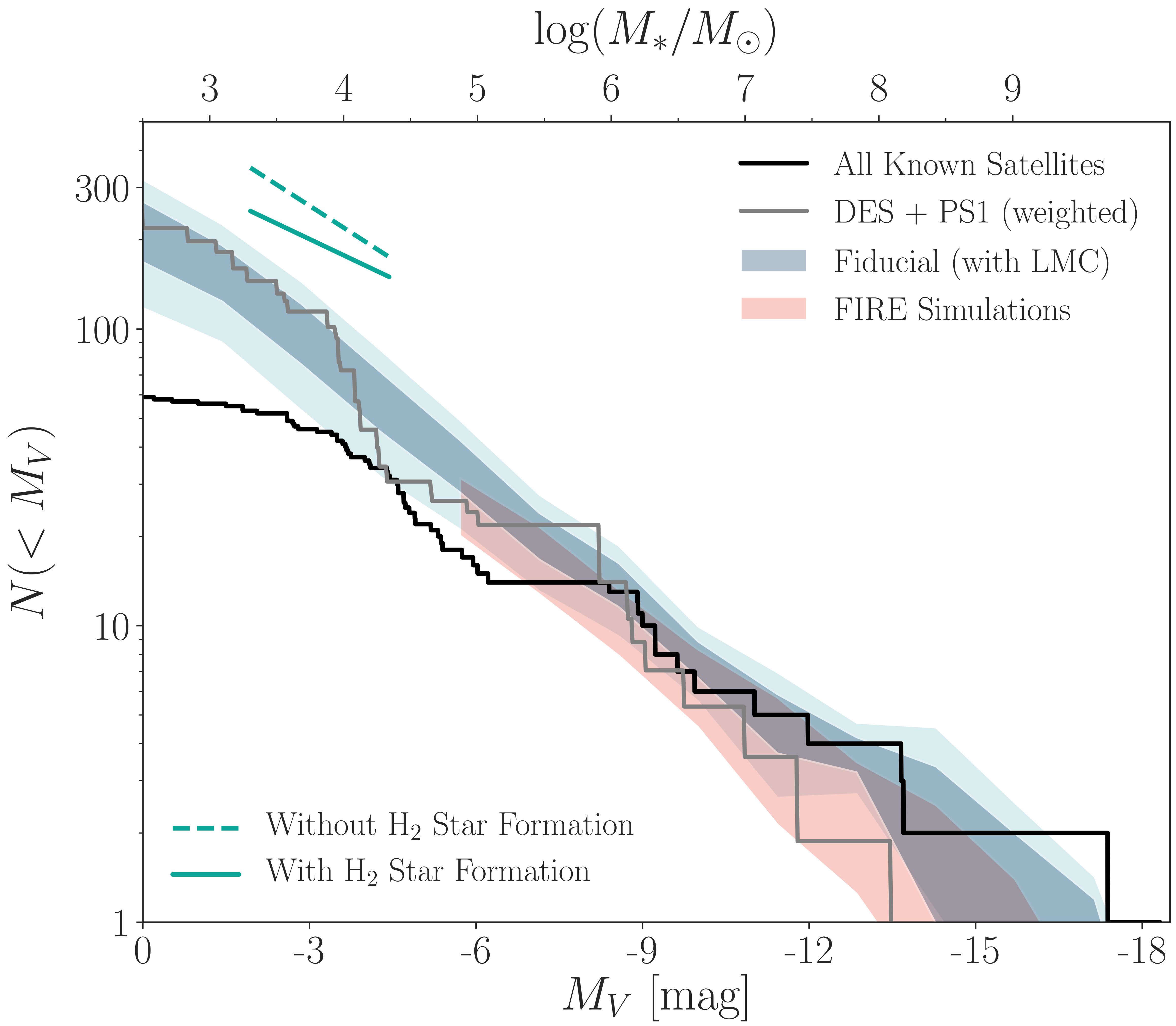
- Recent infall (within last 2 Gyr) of LMC system **required** to fit the data
- Predict 5 (DES) & 1 (PS1) observed LMC satellites, consistent with *Gaia* PMs!

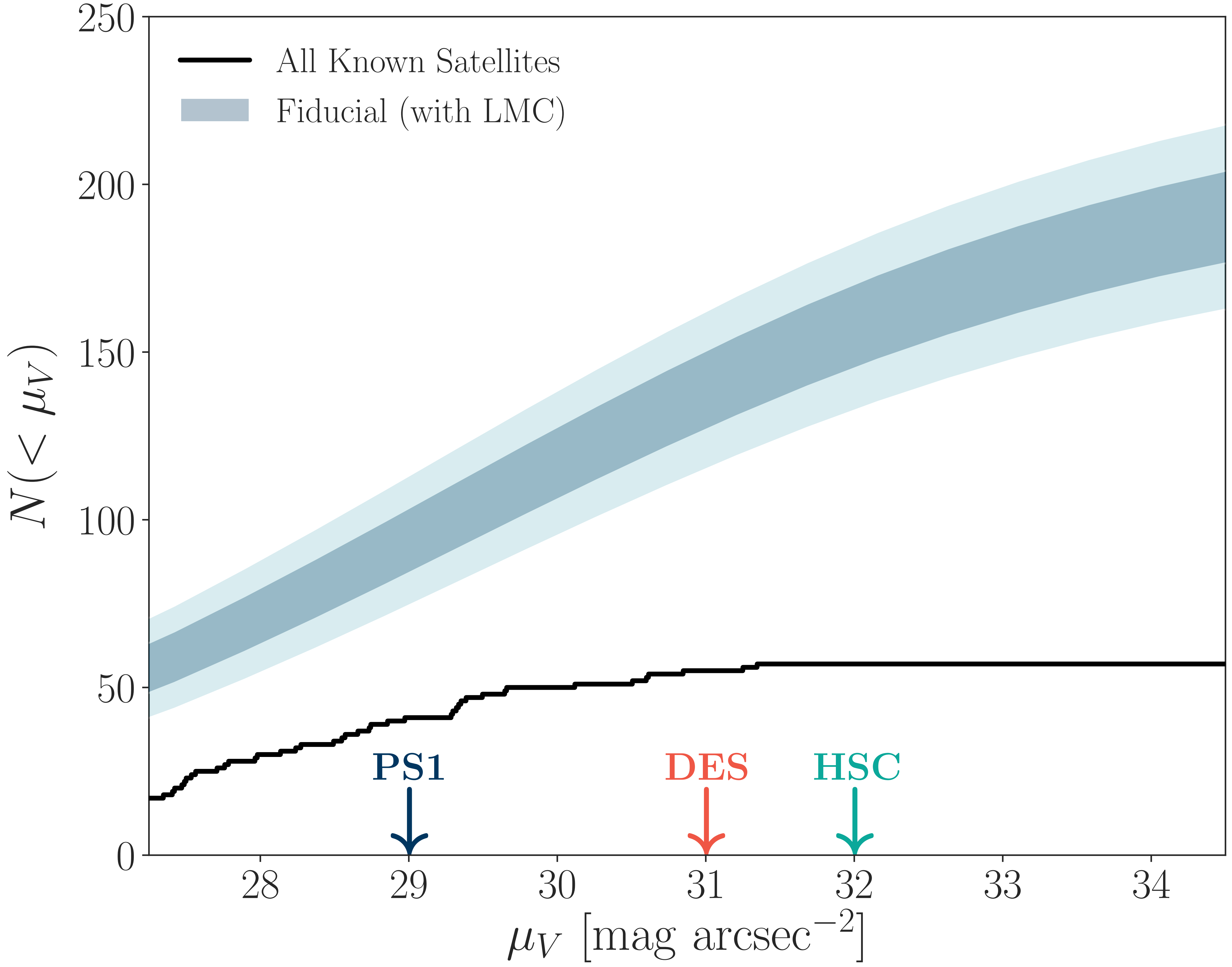




EN & Wechsler et al. 2020

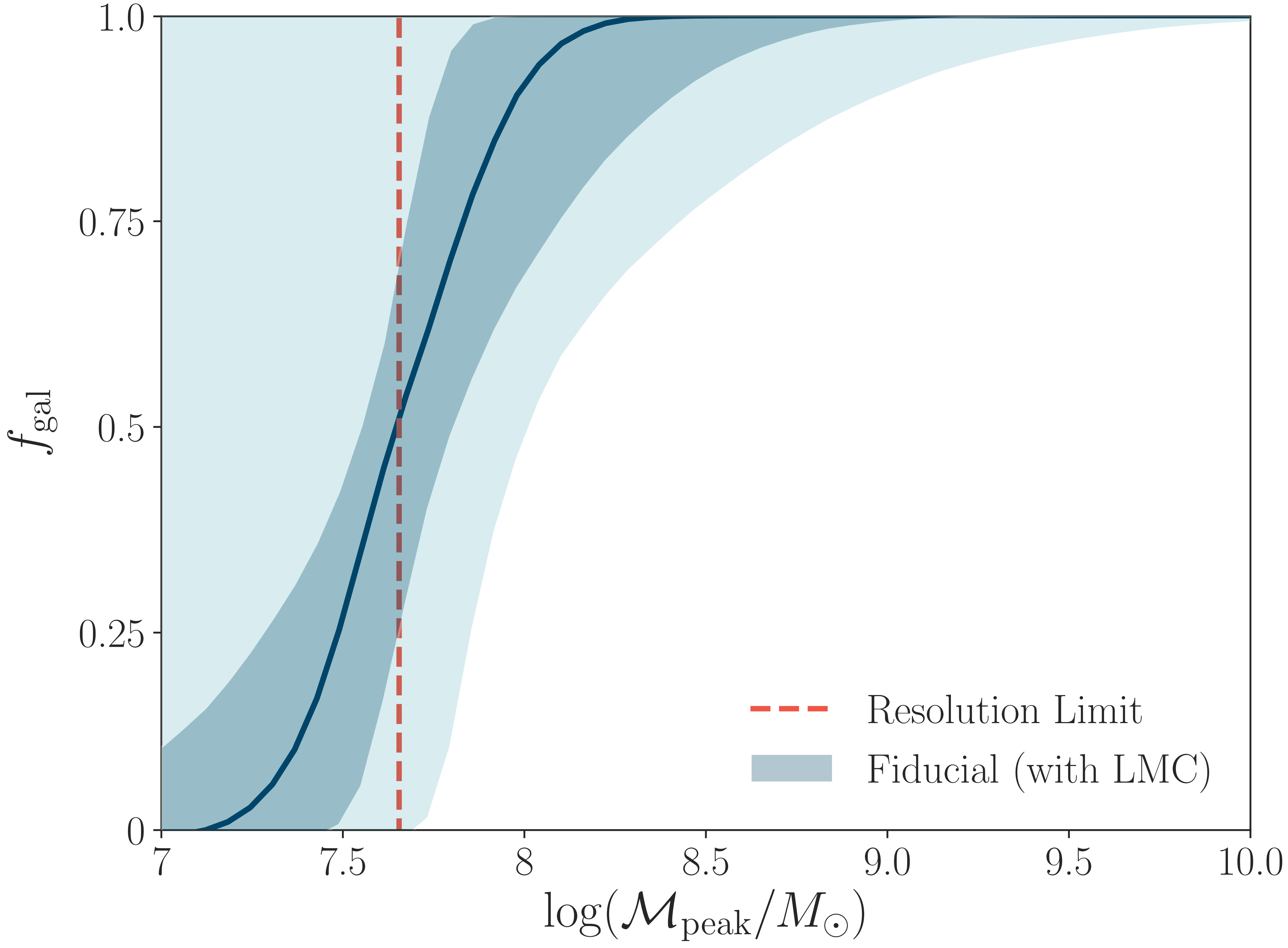
Predictions for Future Surveys

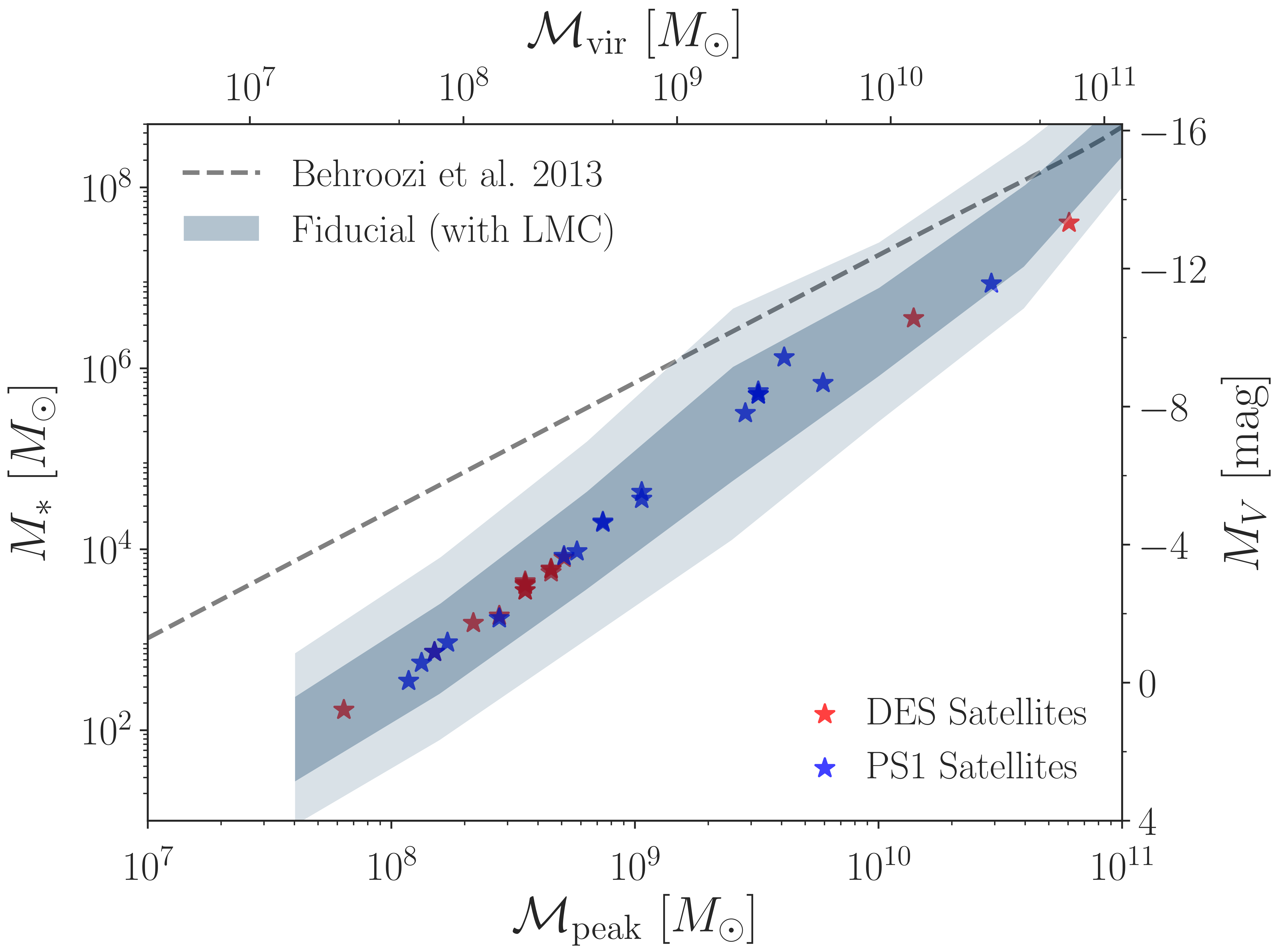




EN & Wechsler et al. 2020

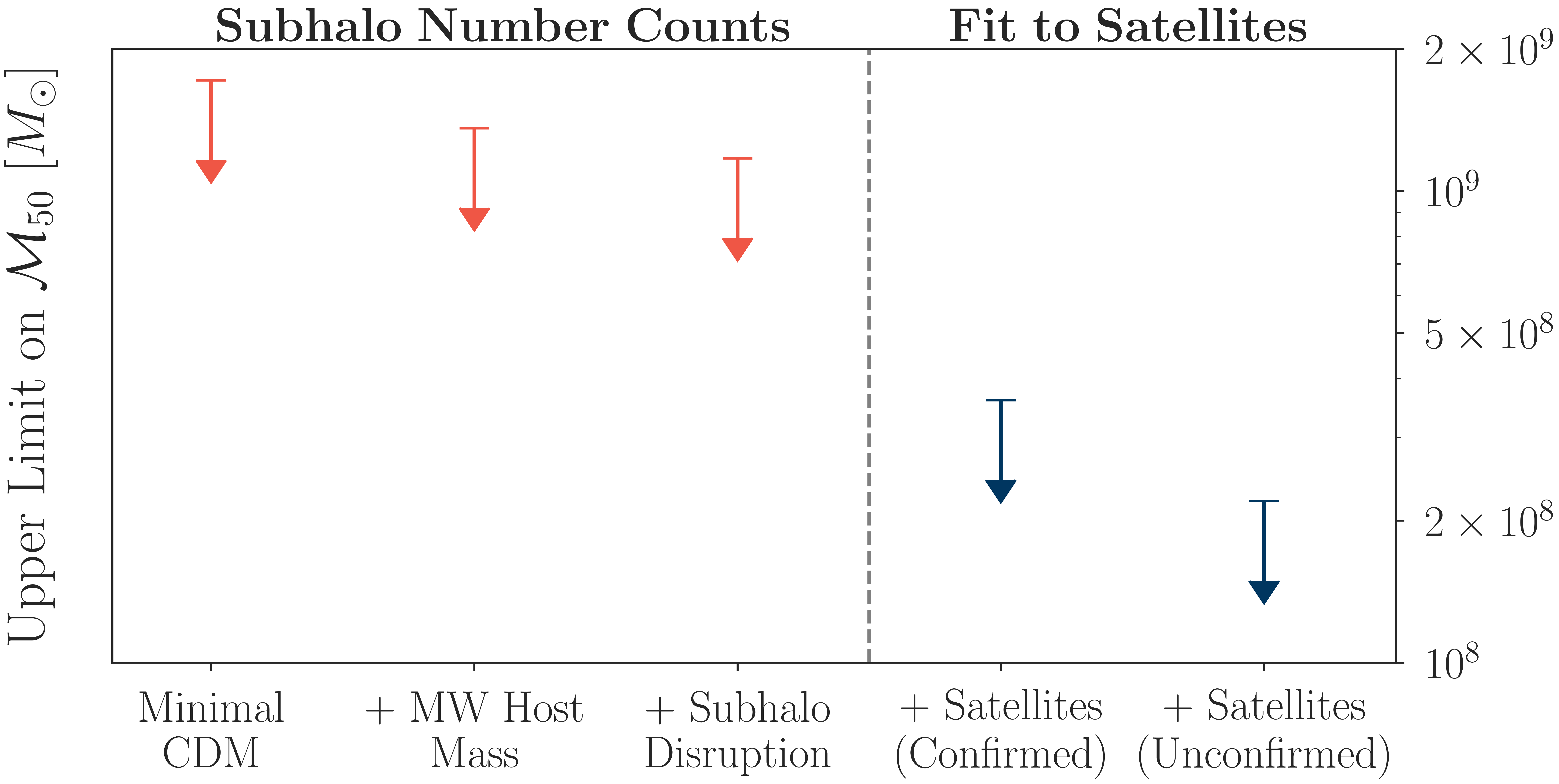
The Faint-End Galaxy–Halo Connection





EN & Wechsler et al. 2020

Theoretical Uncertainties



EN & Wechsler et al. 2020

DM–Proton Scattering Constraints

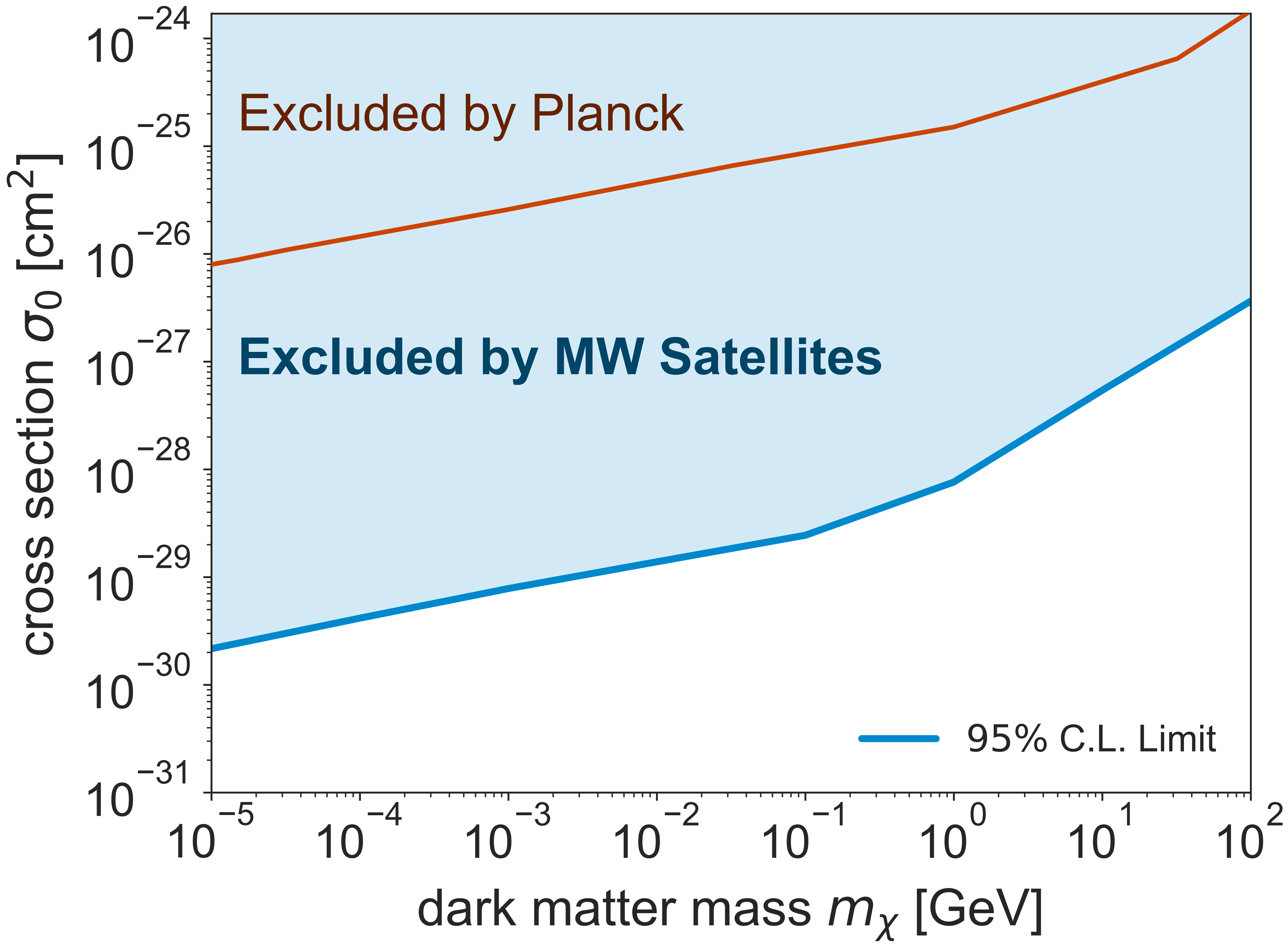
Evolution of DM density fluctuations:

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}$$

$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)$$

Evolution of DM temperature:

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + 2R'_\chi(T_b - T_\chi)$$



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

DM–Proton Scattering Constraints

Evolution of DM density fluctuations:

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}$$

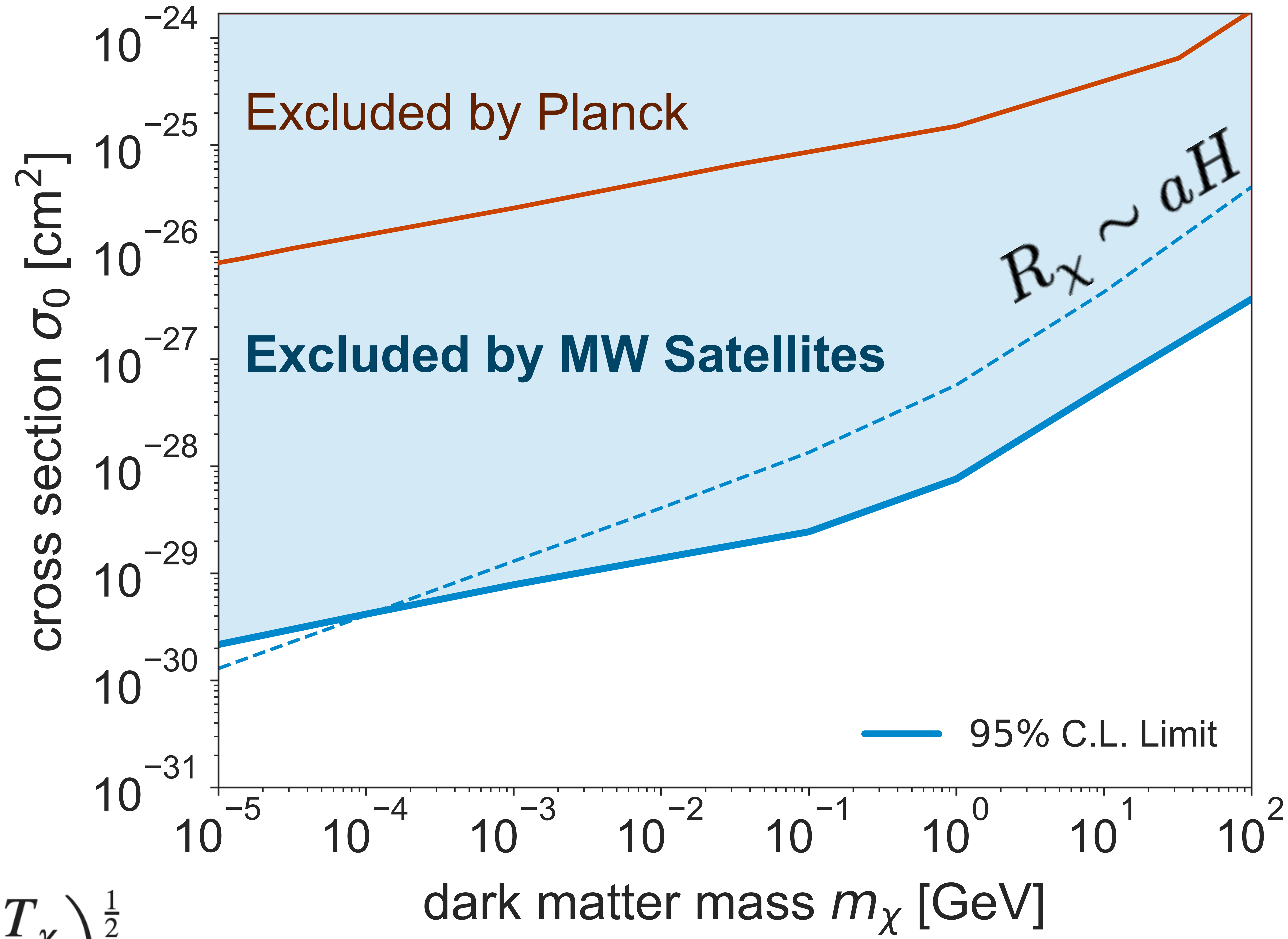
$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)$$

Evolution of DM temperature:

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + 2R'_\chi(T_b - T_\chi)$$

Momentum transfer rate:

$$R_{\chi p}^{(\mathrm{SI/SD})} = \mathcal{N}_0 a \rho_b (1 - Y_{\mathrm{He}}) \frac{\sigma_p^{(\mathrm{SI/SD})}}{m_\chi + m_p} \left(\frac{T_b}{m_p} + \frac{T_\chi}{m_\chi}\right)^{\frac{1}{2}}$$



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

DM–Proton Scattering Constraints

Evolution of DM density fluctuations:

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}$$

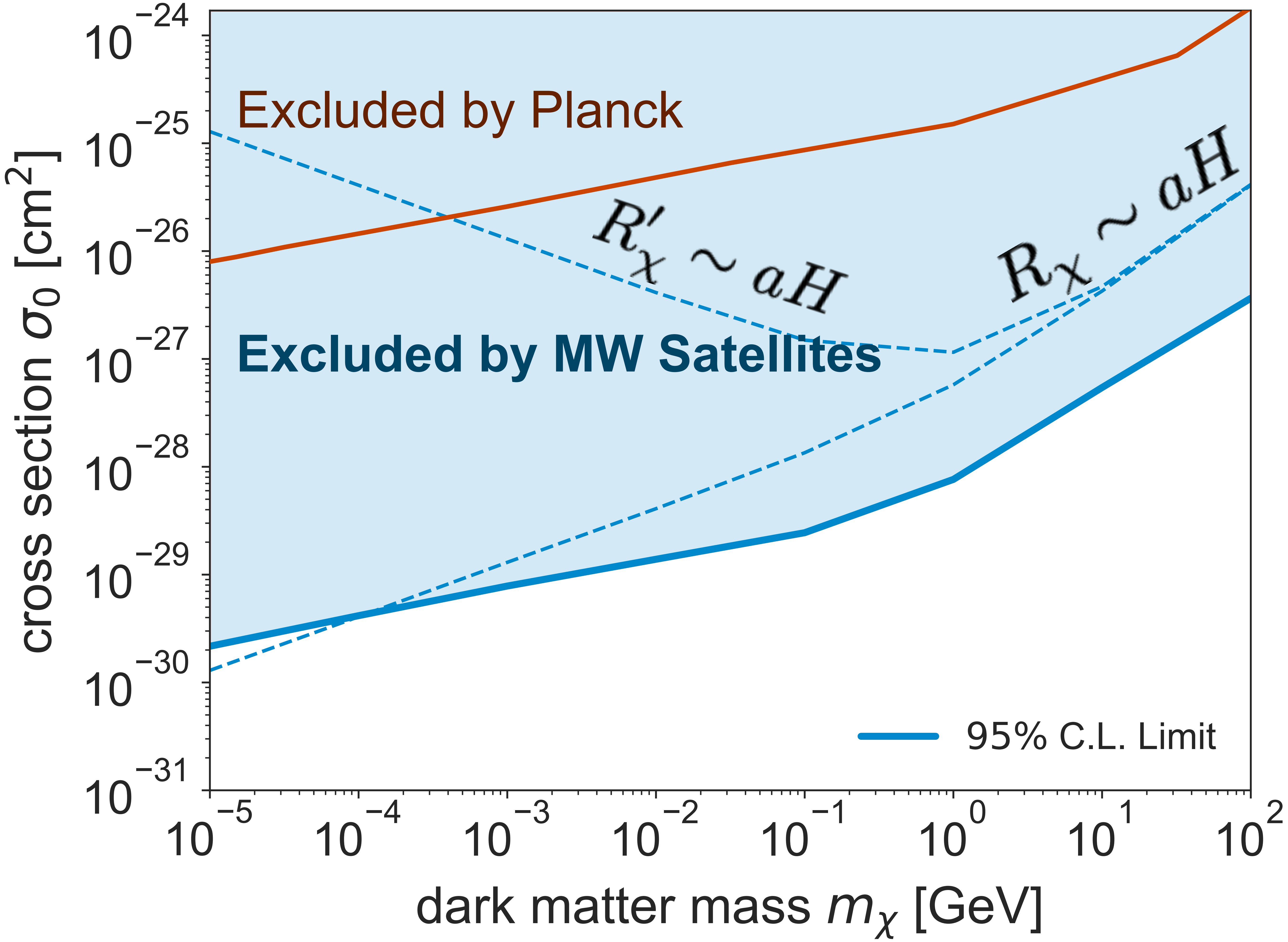
$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)$$

Evolution of DM temperature:

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + 2R'_\chi(T_b - T_\chi)$$

Heat transfer rate:

$$R'^{(\mathrm{SI})}_\chi = \frac{m_\chi}{m_\chi + m_p} R^{(\mathrm{SI})}_{\chi p}$$



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

DM–Proton Scattering Constraints

Evolution of DM density fluctuations:

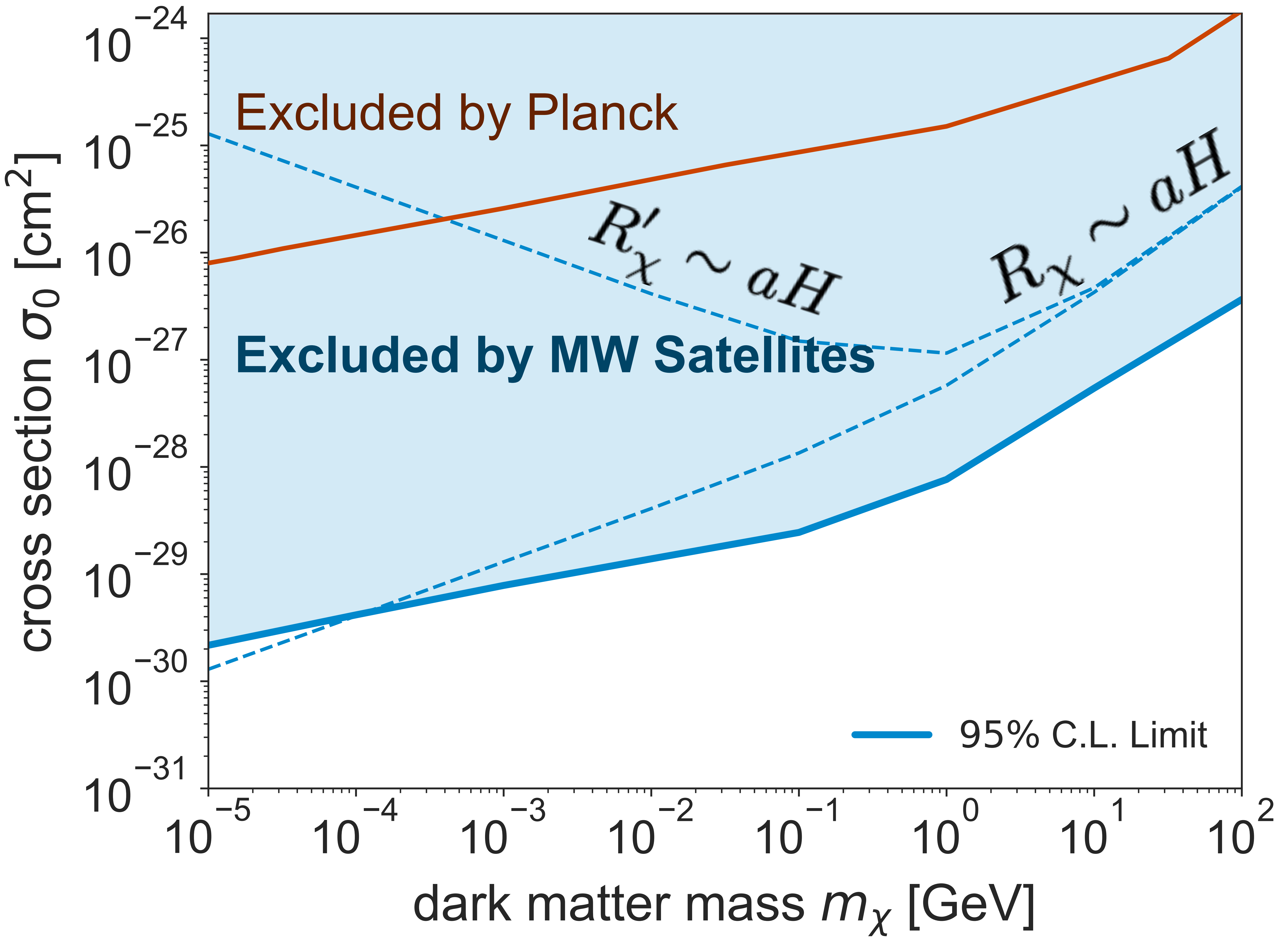
$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}$$

$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)$$

Evolution of DM temperature:

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + 2R'_\chi(T_b - T_\chi)$$

- Find thermal decoupling redshift
- Evolve DM temp. adiabatically to find kinetic decoupling redshift



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

DM–Proton Scattering Constraints

Evolution of DM density fluctuations:

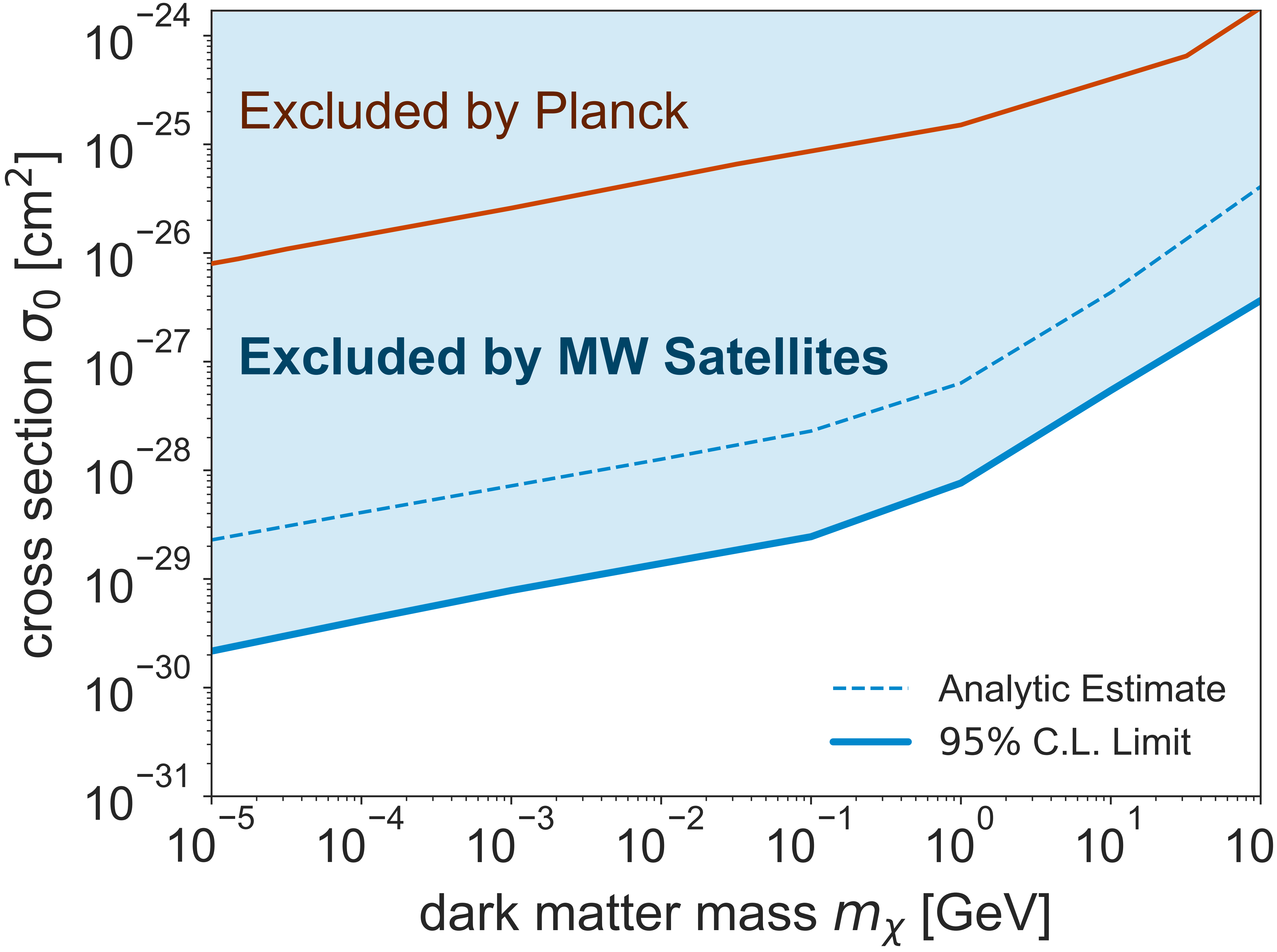
$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}$$

$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)$$

Evolution of DM temperature:

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + 2R'_\chi(T_b - T_\chi)$$

- Find thermal decoupling redshift
- Evolve DM temp. adiabatically to find kinetic decoupling redshift

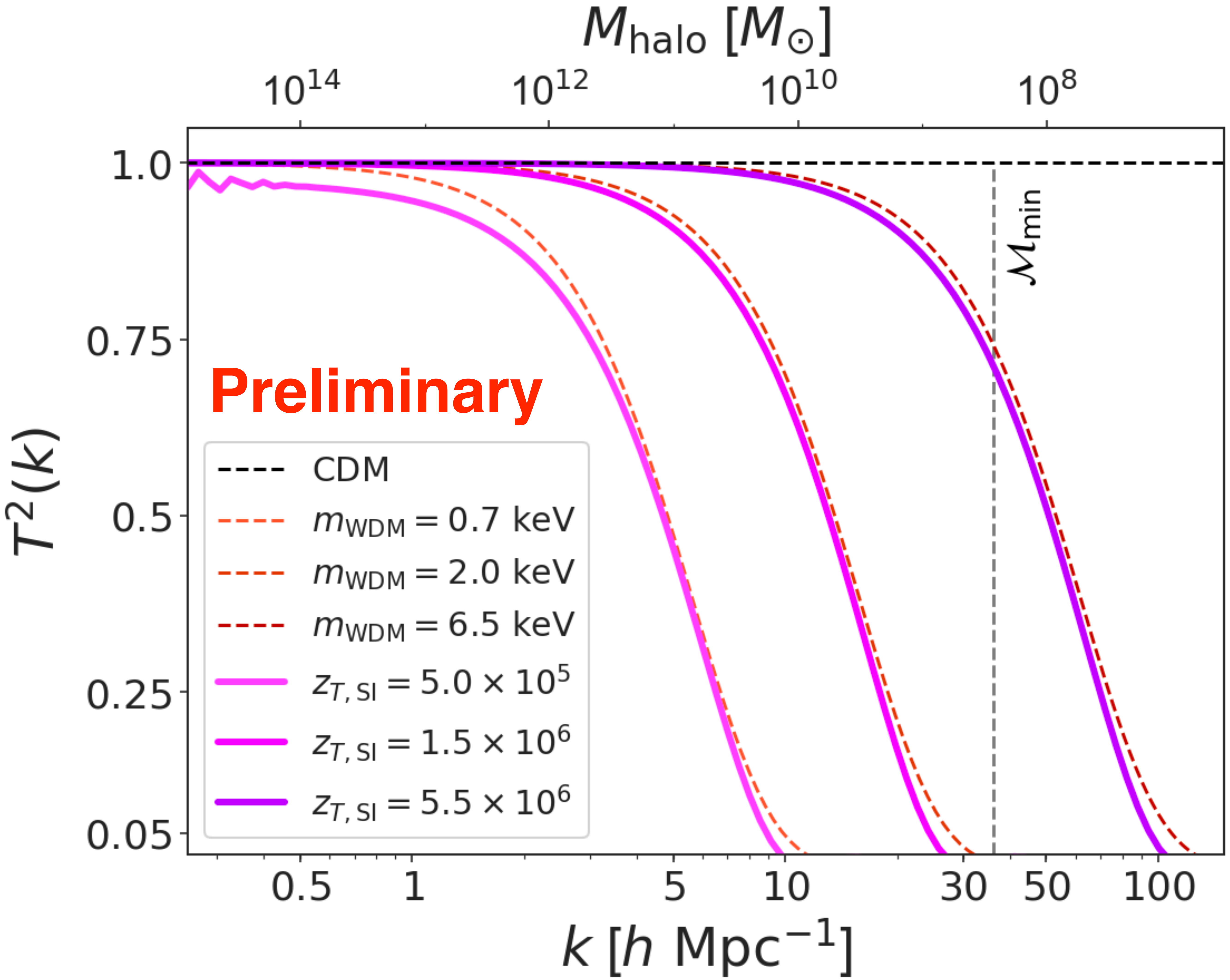


EN, V. Gluscevic, K. Boddy, R. Wechsler 2019

Late-Forming DM Constraints

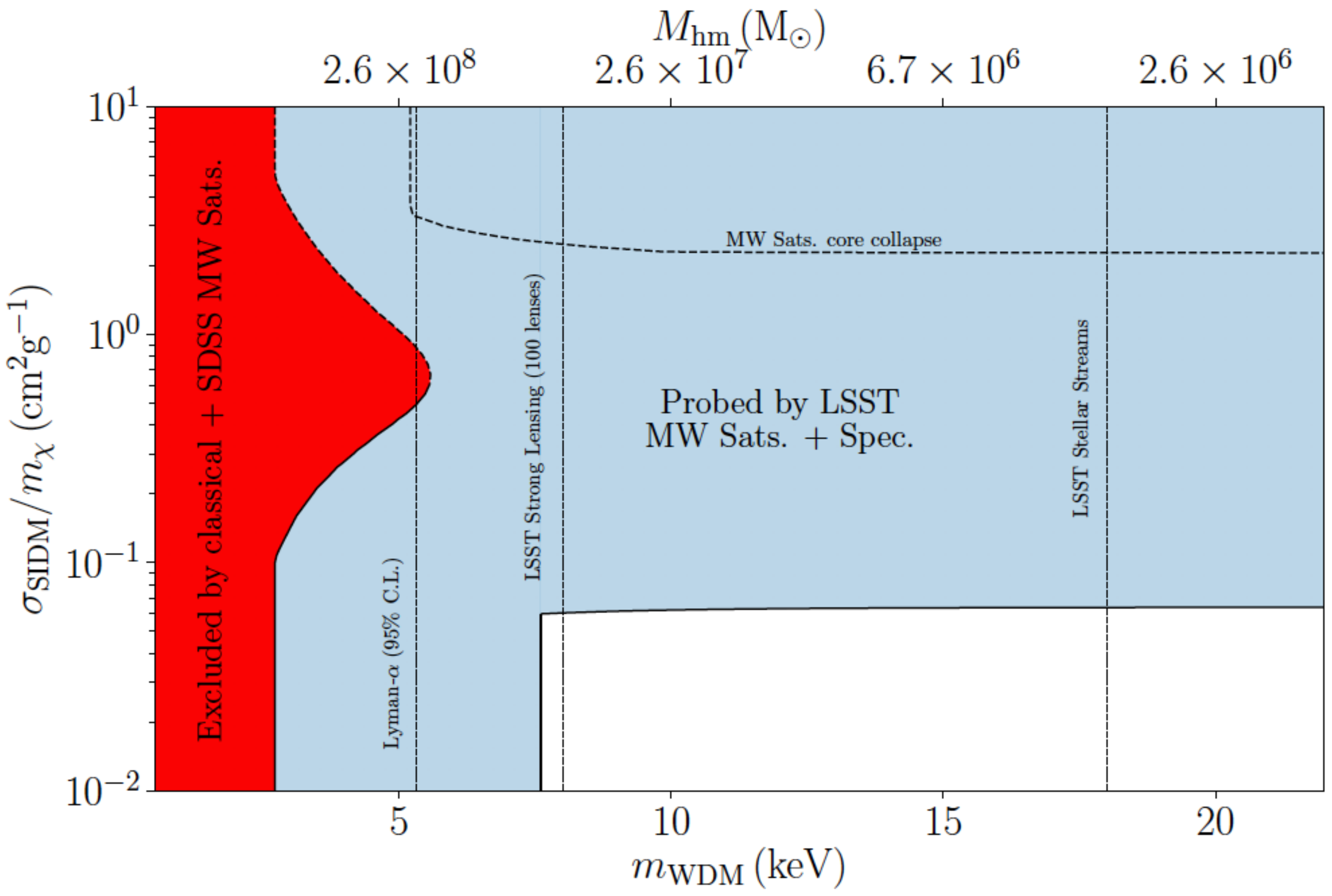
- Excess radiation that decays to DM after BBN ("late-forming DM") suppresses power on small scales
- Cutoff in halo abundance is set by the LFDM phase transition redshift
- Our MW satellite analysis yields order-of-magnitude improvement relative to Lyman-alpha forest:

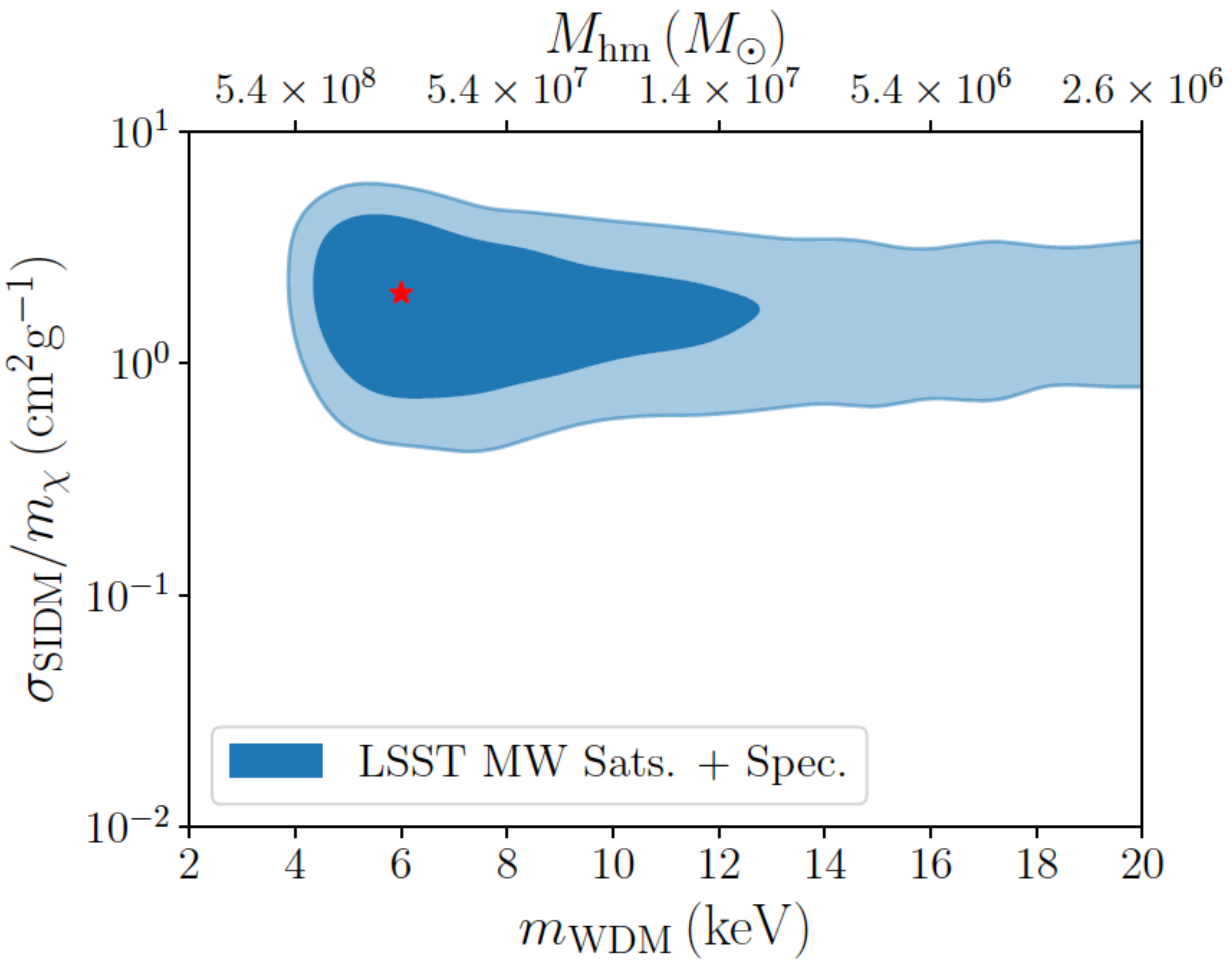
$$z_{\mathrm{LFDM}} > 5.5 \times 10^6 \ (95\% \ \mathrm{C.L.})$$



S. Das & EN in prep.

Joint DM Physics Constraints

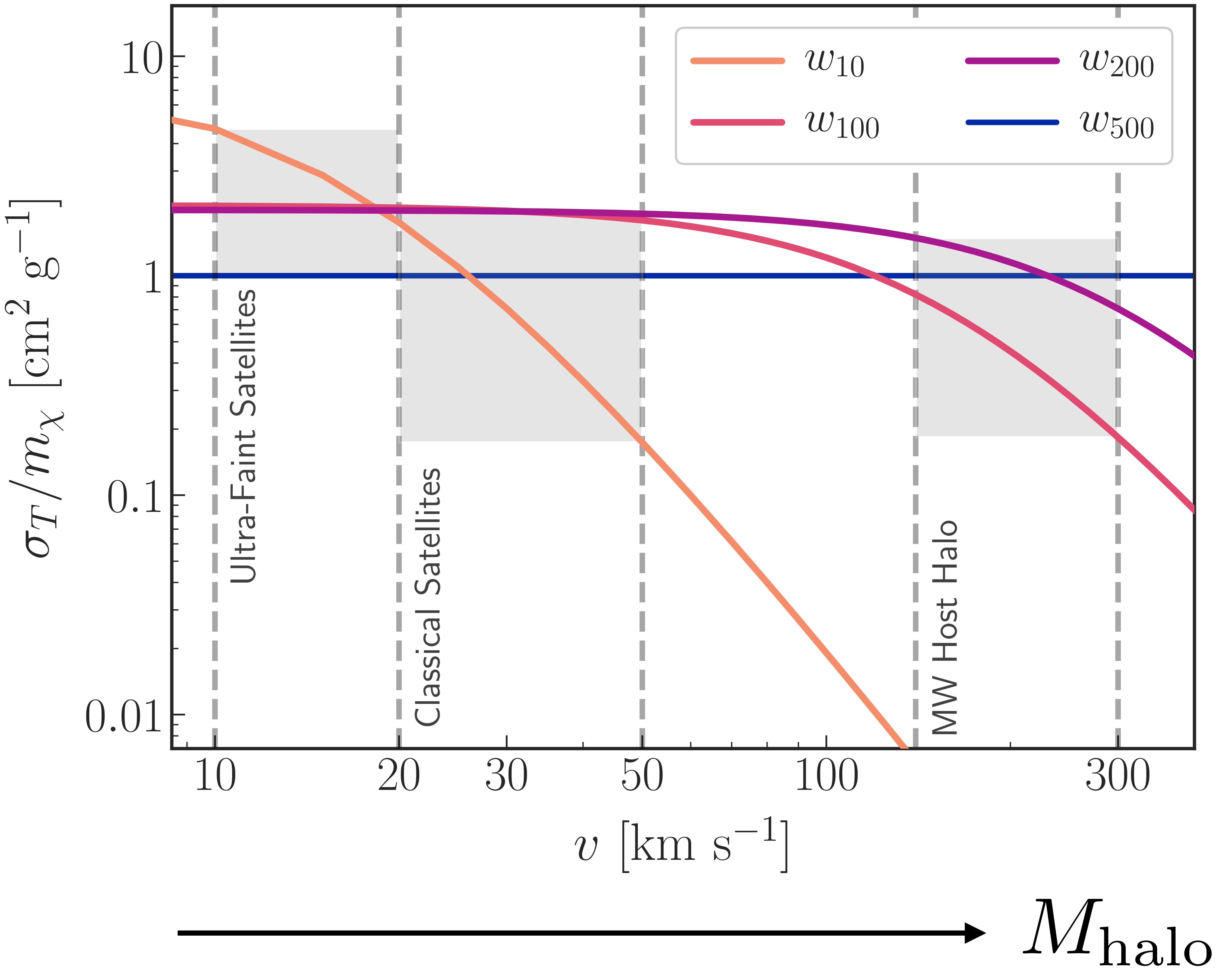




Drlica-Wagner et al. 2019

Self-Interacting Dark Matter

- Halo mass scale imposes typical relative scattering velocity
- Probing velocity-dependence of the SIDM cross section therefore requires observations over a range of halo masses
- The Milky Way's DM halo and its subhalos provide a testbed for this kind of physics!



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

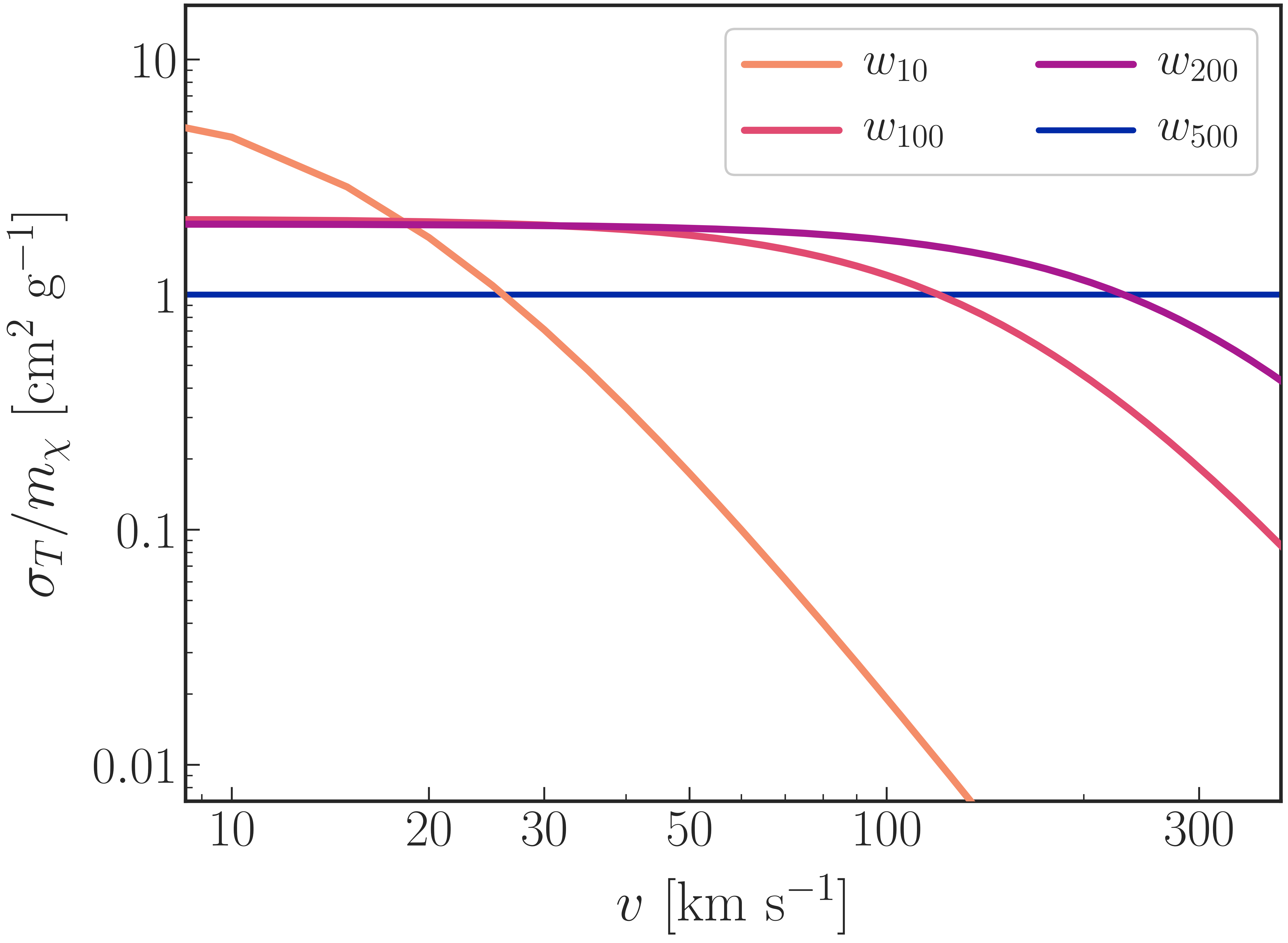
Self-Interacting Dark Matter

- Simple self-interacting Lagrangian:

$$\mathcal{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\chi\phi, & \text{scalar mediator} \\ g_\chi \bar{\chi}\gamma^\mu\chi\phi_\mu, & \text{vector mediator.} \end{cases}$$

- For sufficiently light mediator, interactions can be dealt with in Born approximation, leading to the differential cross section

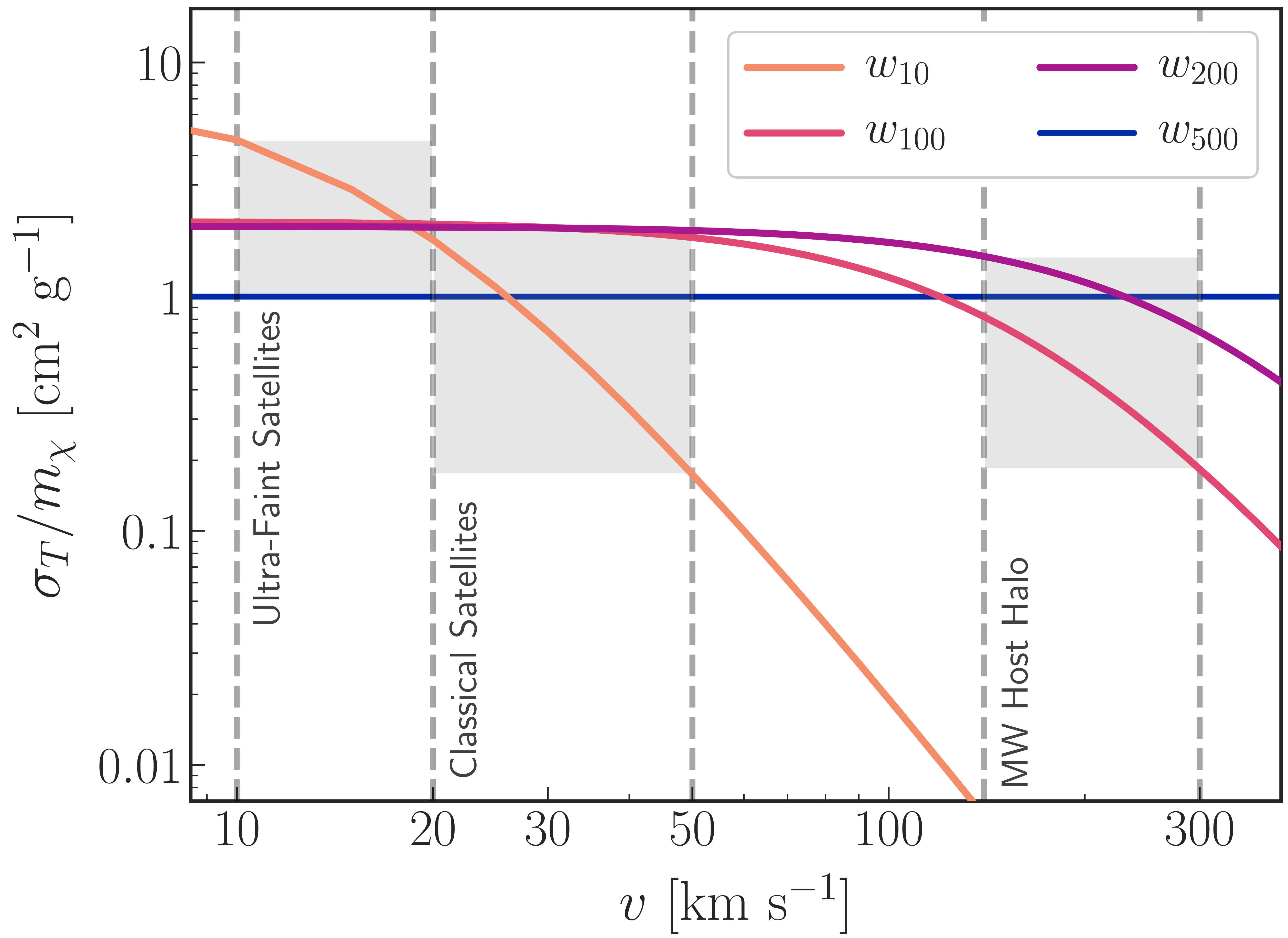
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{2\left[1+\frac{v^2}{w^2}\sin^2(\frac{\theta}{2})\right]}, \qquad w \equiv m_\phi/m_\chi$$

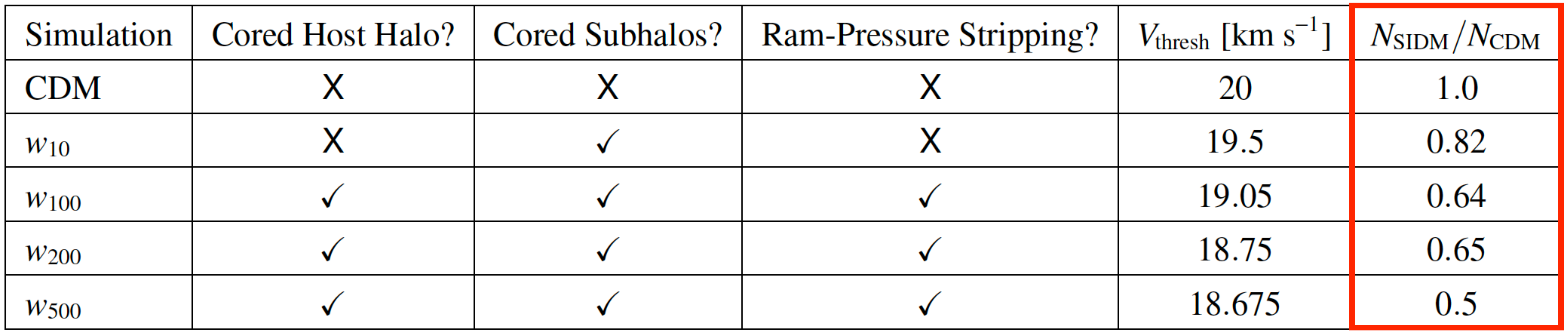


EN, A. Banerjee, S. Adhikari, Y.-Y. Mao, R. Wechsler 2020

Overview

- Zoom-in simulations of a MW host analyzed at representative points in SIDM parameter space
- Number of surviving subhalos relative to CDM is set by the SIDM cross section at the MW halo velocity scale (~200 km/s)

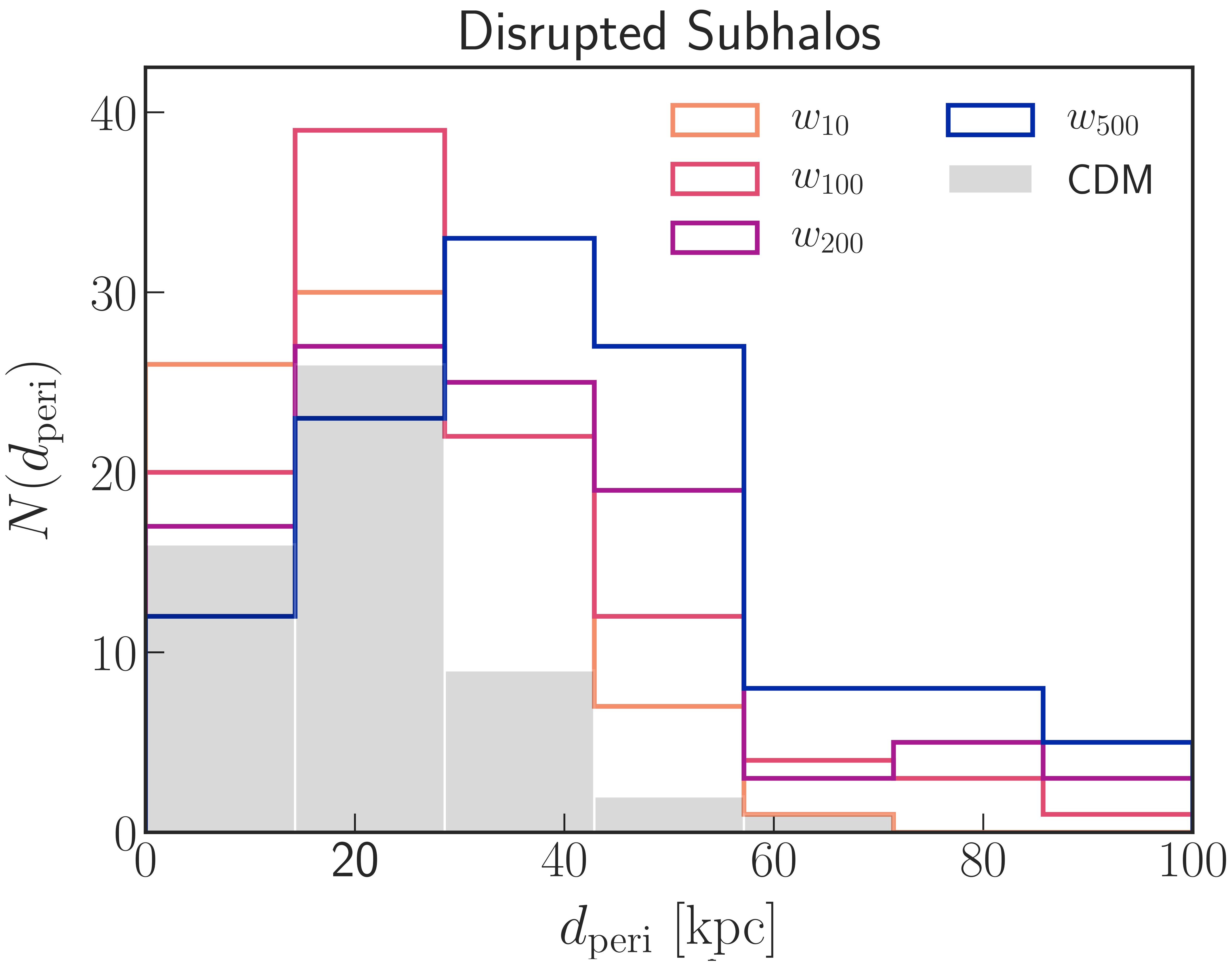


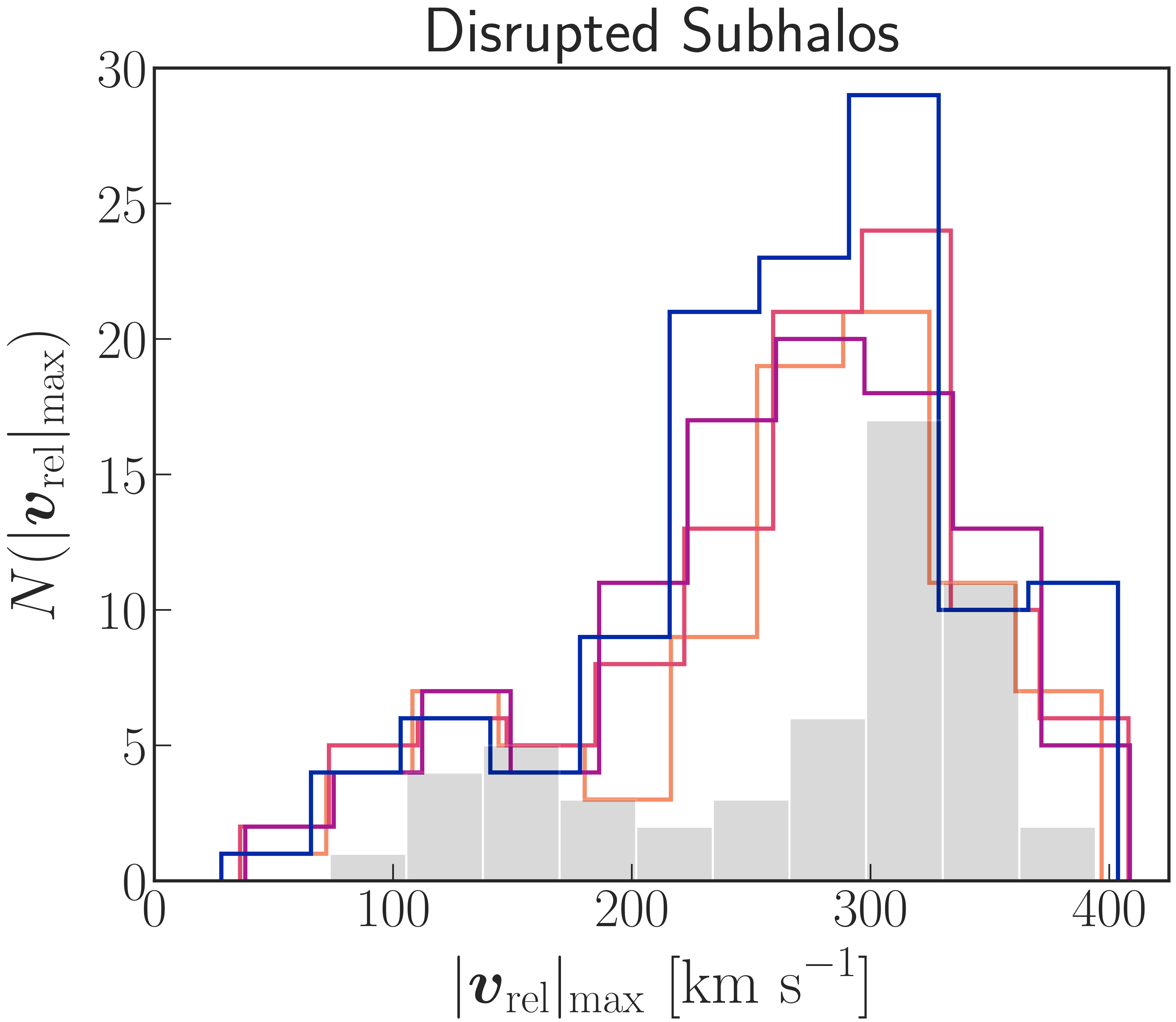


Simulation	Cored Host Halo?	Cored Subhalos?	Ram-Pressure Stripping?	V_{thresh} [km s^{-1}]	$N_{\mathrm{SIDM}}/N_{\mathrm{CDM}}$
CDM	X	X	X	20	1.0
w_{10}	X	✓	X	19.5	0.82
w_{100}	✓	✓	✓	19.05	0.64
w_{200}	✓	✓	✓	18.75	0.65
w_{500}	✓	✓	✓	18.675	0.5

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

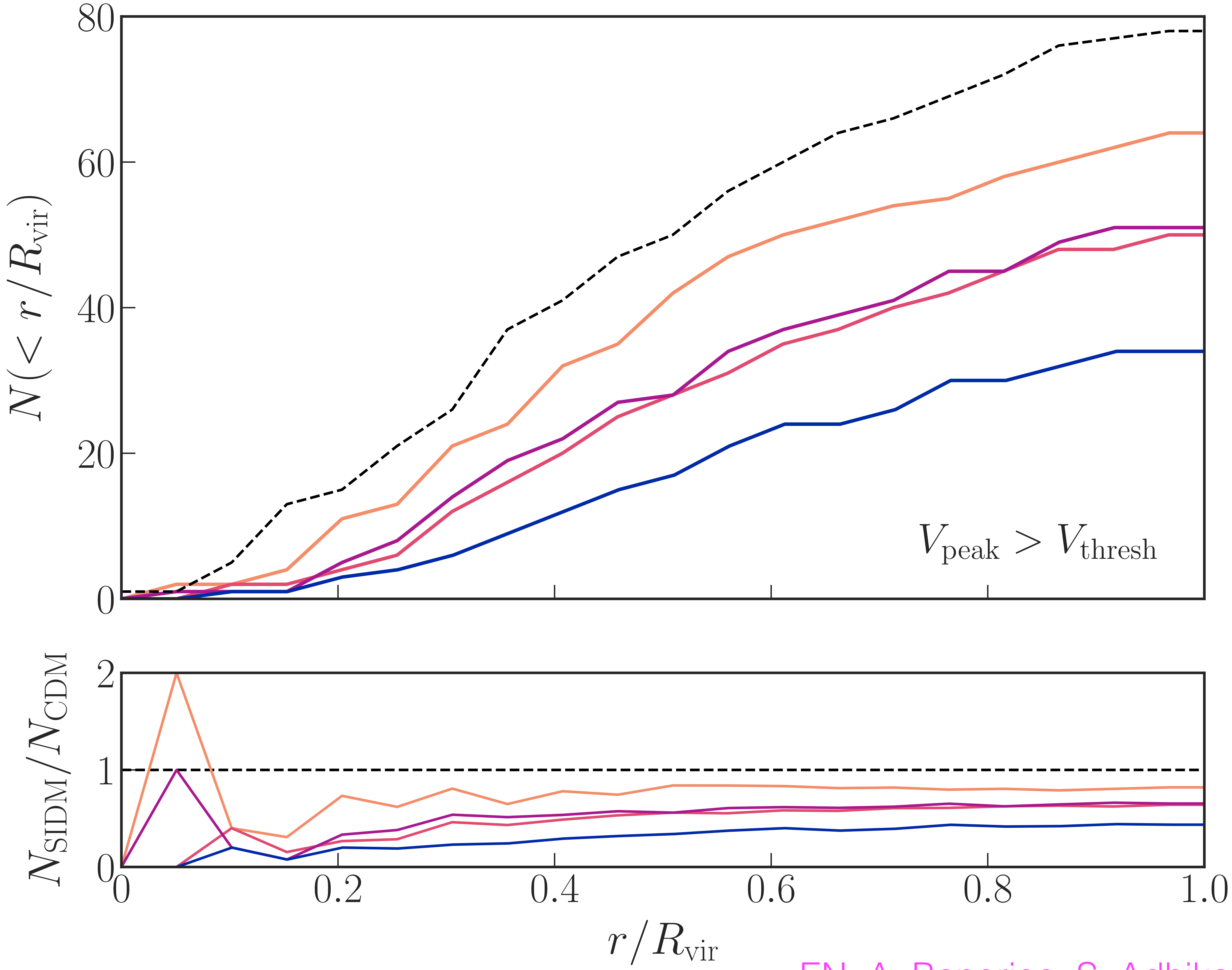
Subhalo Disruption





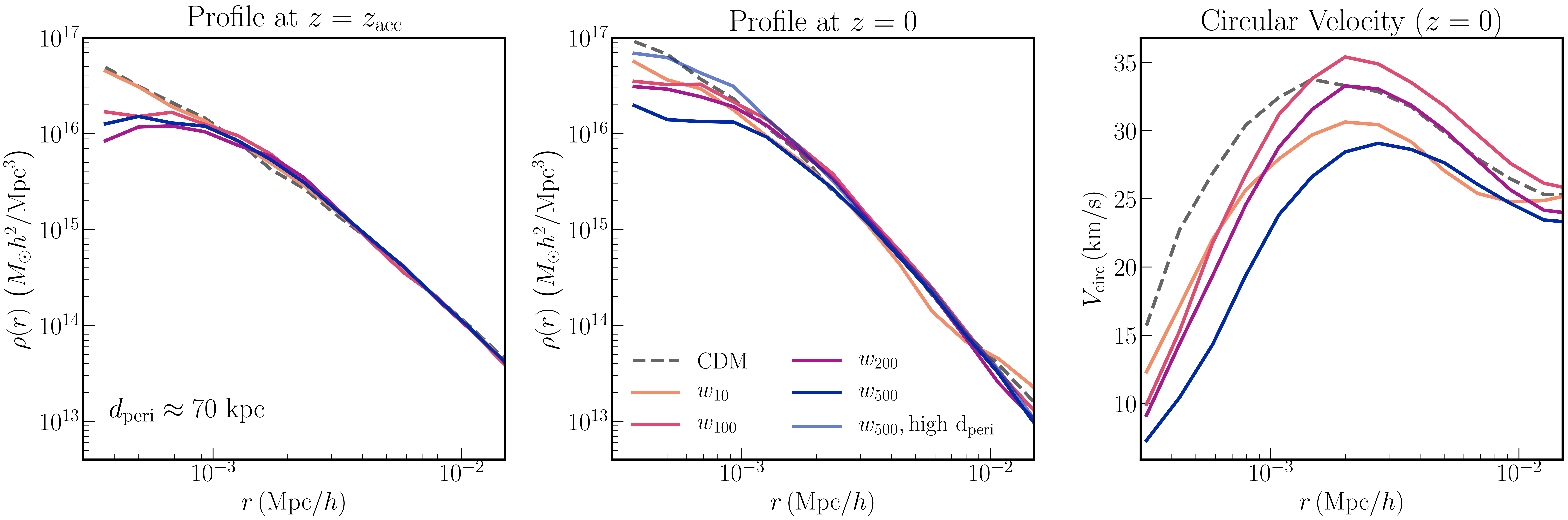
EN, A. Banerjee, S. Adhikari, Y.-Y. Mao, R. Wechsler 2020

Subhalo Radial Distribution



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

Subhalo Density Profiles

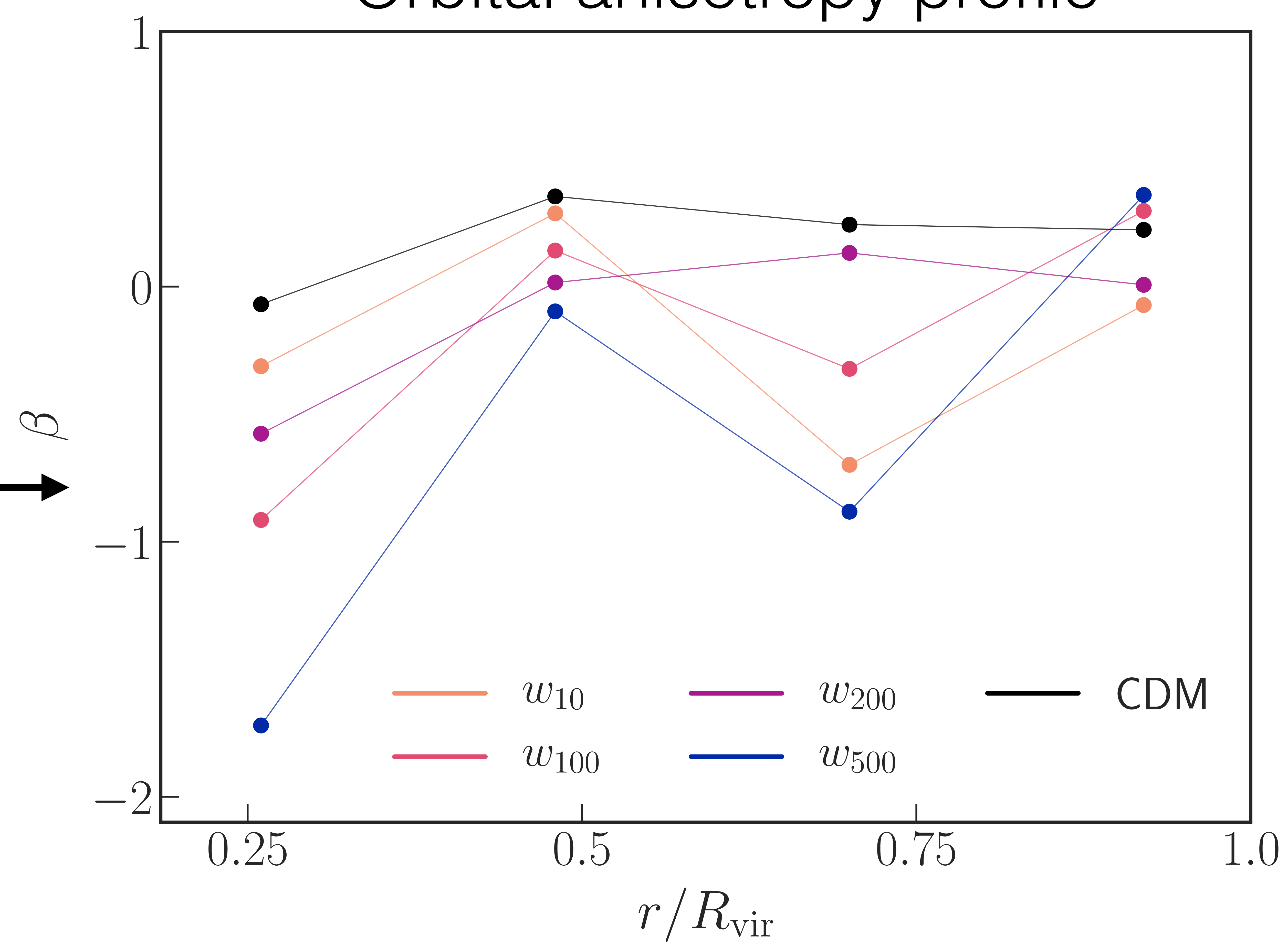


EN, A. Banerjee, S. Adhikari, Y.-Y. Mao, R. Wechsler 2020

Implications

- Abundance of surviving subhalos relative to CDM is sensitive to the SIDM cross section at ~200 km/s
- Surviving subhalos preferentially have tangential orbits (implications for stellar streams) →
- Observables probing a range of velocity scales (e.g. satellite abundances *and* density profiles) are needed to constrain velocity-dependent SIDM models

Orbital anisotropy profile



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