Constraints on Dark Matter Microphysics from Dwarf Galaxies

Ethan Nadler

PPC 2021

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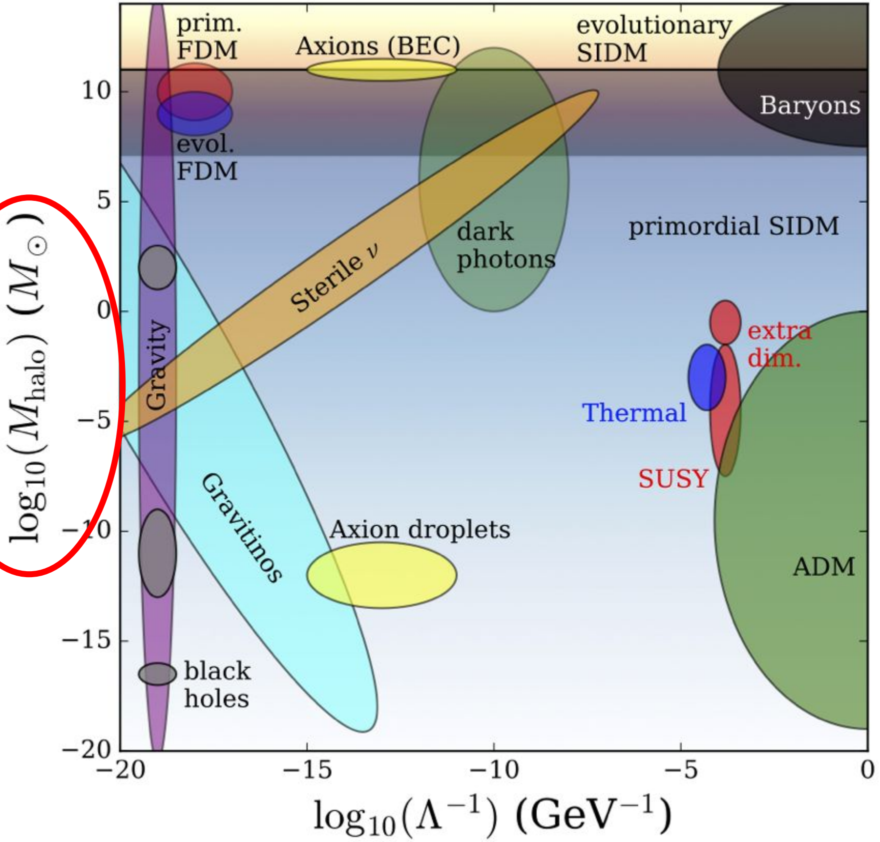
KIPAC

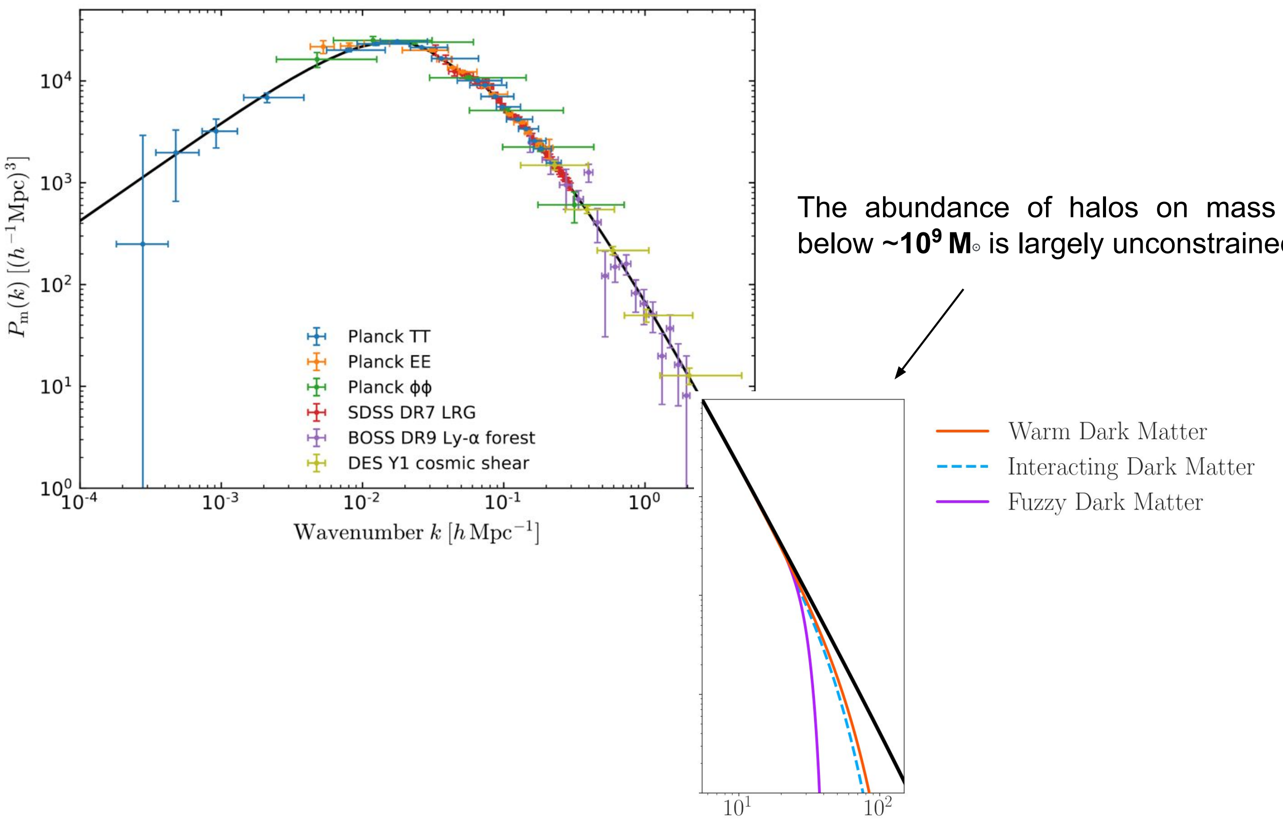
Dark Matter Physics and Structure Formation

Microphysical dark matter properties affect structure formation on small scales



Buckley & Peter 2018

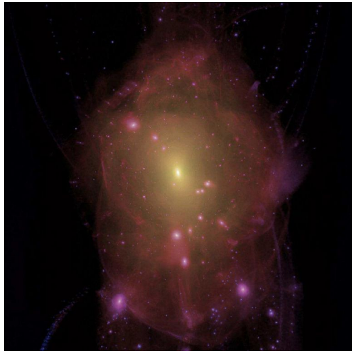
Dark Matter Physics and Structure Formation



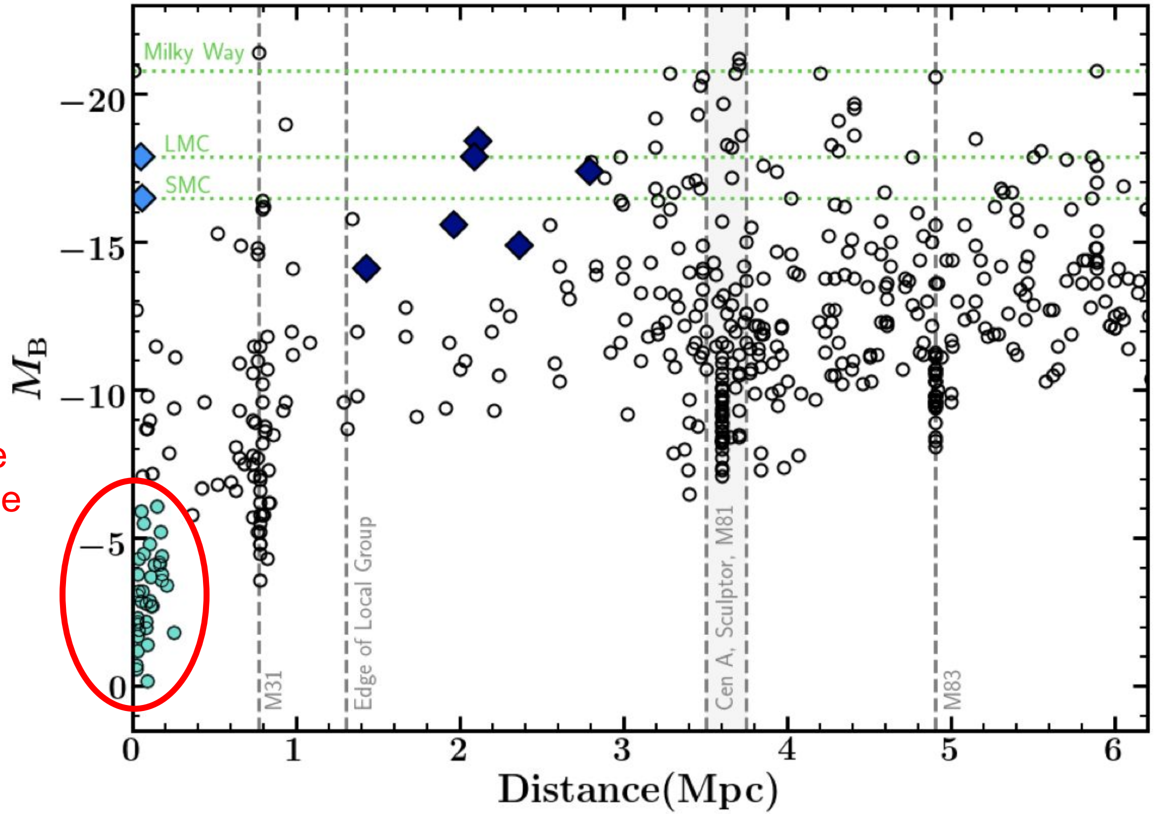
The abundance of halos on mass scales below **~10^9 M$_\odot$** is largely unconstrained

CDM

WDM



Ultra-Faint Galaxies as Dark Matter Probes



Milky Way satellite galaxies inhabit the smallest luminous dark matter halos

Credit: J. Carlin

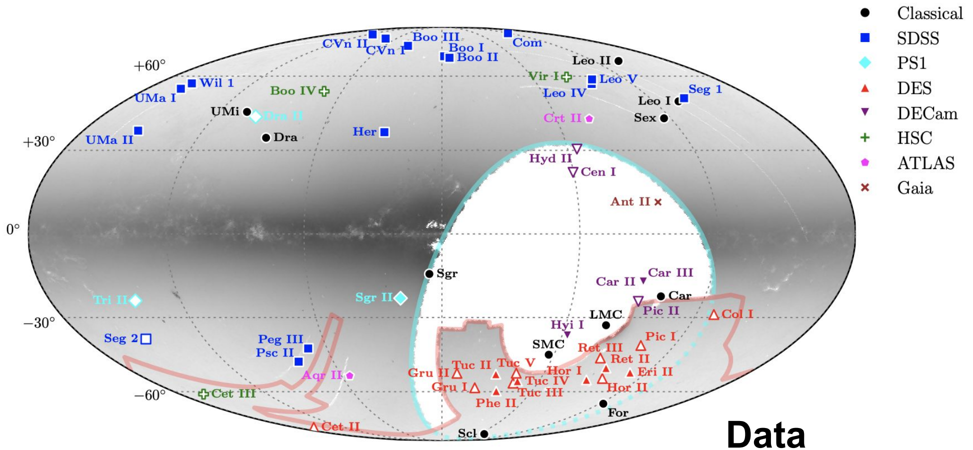
DES Y3 Milky Way Satellite Analyses

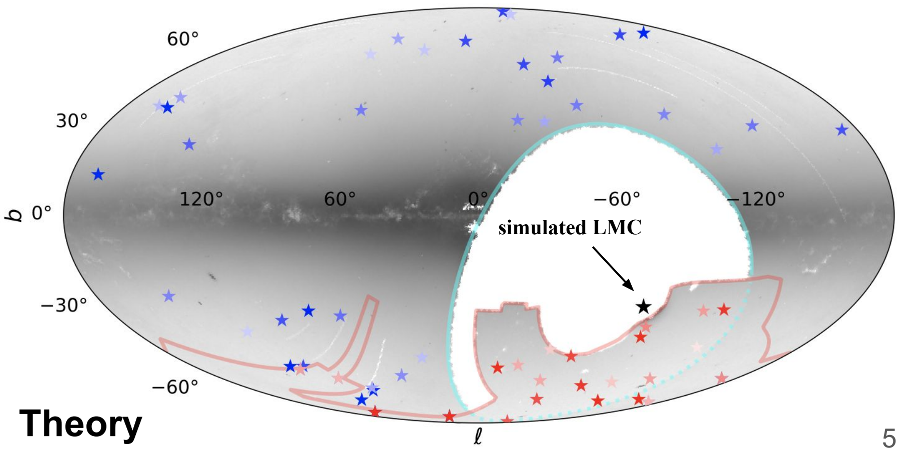
Drlica-Wagner & Bechtol et al. 2020

- Rigorous satellite search in DES Y3 & Pan-STARRS data over ~75% of the sky
- Satellite detection sensitivity characterized vs. luminosity, size, distance, local stellar density

EN & Wechsler et al. 2020

- Forward model of the Milky Way satellite population, including the LMC
- Galaxy–halo connection interpretation: the faintest observed satellites occupy halos down to **~10^8 M$_\odot$**

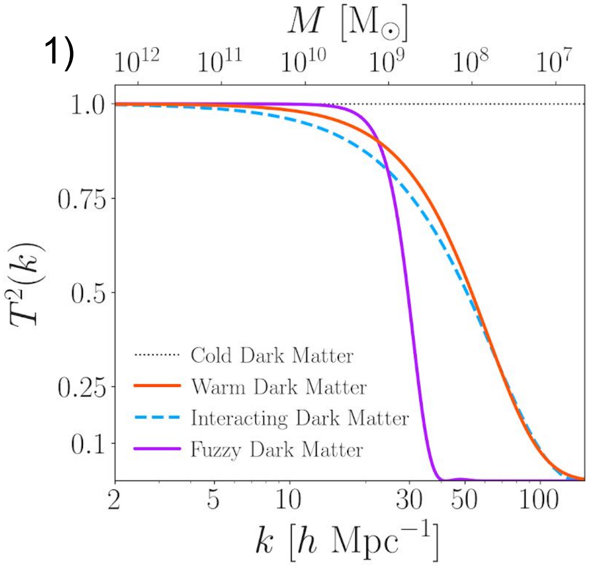




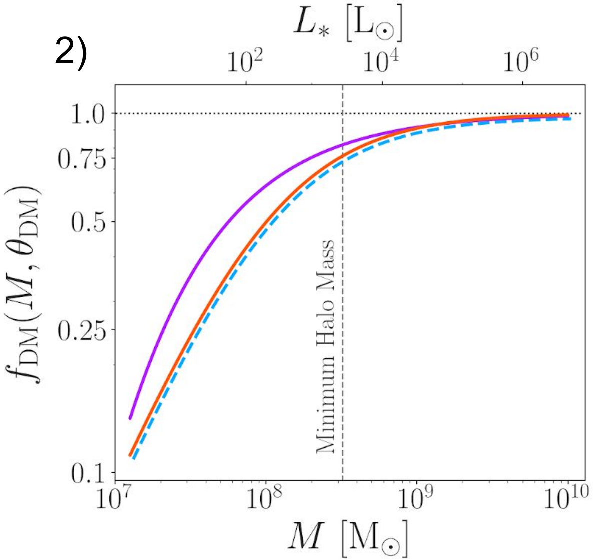
Constraints on Dark Matter Properties

1) Non-gravitational dark matter physics imprints as a cutoff in the **linear matter power spectrum**
2) Structure formation processes this cutoff into a suppression of the **subhalo mass function**
3) This manifests as a suppression in the **abundance of observable satellites**

1)



2)



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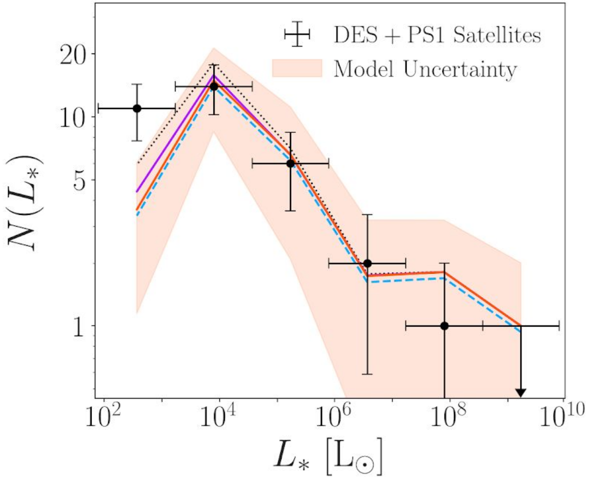
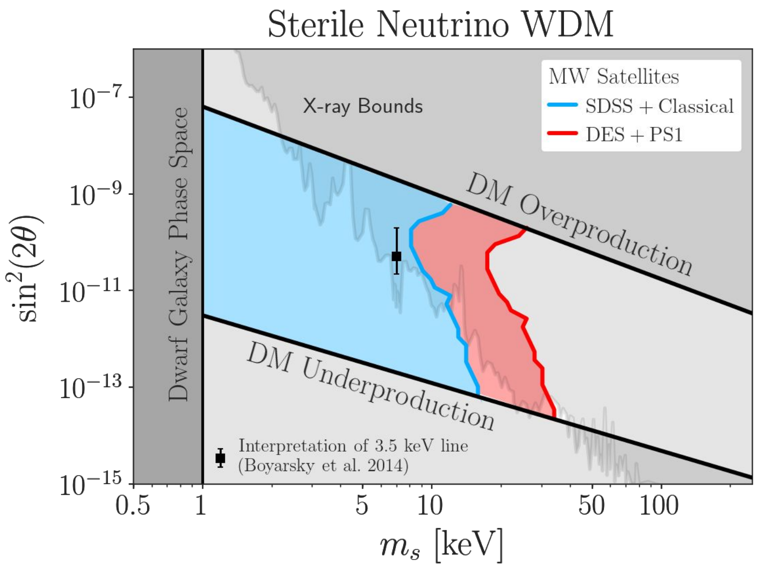


EN & Drlica-Wagner et al. 2021

Warm Dark Matter Constraints

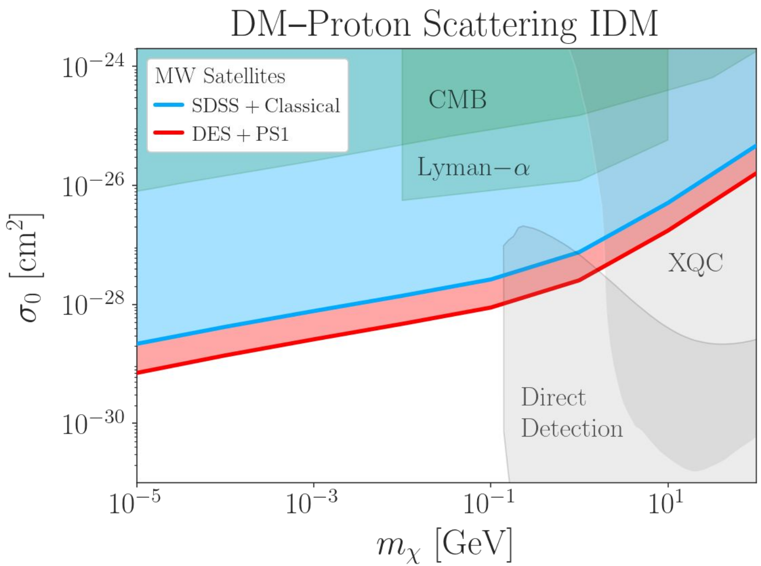
- Thermal relic warm dark matter lighter than **6.5 keV** is ruled out at 95% confidence
- This constraint excludes nearly all remaining parameter space for 100% resonantly-produced sterile neutrino dark matter
- The dark matter free-streaming length must be smaller than the sizes of halos that host ultra-faint dwarf galaxies (~10 kpc)



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	$\sigma_0 < 8.8 \times 10^{-29}\,\mathrm{cm}^2$	DM–Proton Coupling	$c_p \lesssim (0.3\,\mathrm{GeV})^{-2}$
Fuzzy Dark Matter	Particle Mass	$m_\phi > 2.9 \times 10^{-21}\,\mathrm{eV}$	de Broglie Wavelength	$\lambda_{\mathrm{dB}} \lesssim 0.5\,\mathrm{kpc}$

Interacting Dark Matter Constraints

- Dark matter–baryon scattering suppresses power on small scales by transferring momentum to dark matter before recombination
- Constraints derived by conservatively comparing to WDM complement direct detection experiments
- These limits improve those from other cosmological probes by several orders of magnitude



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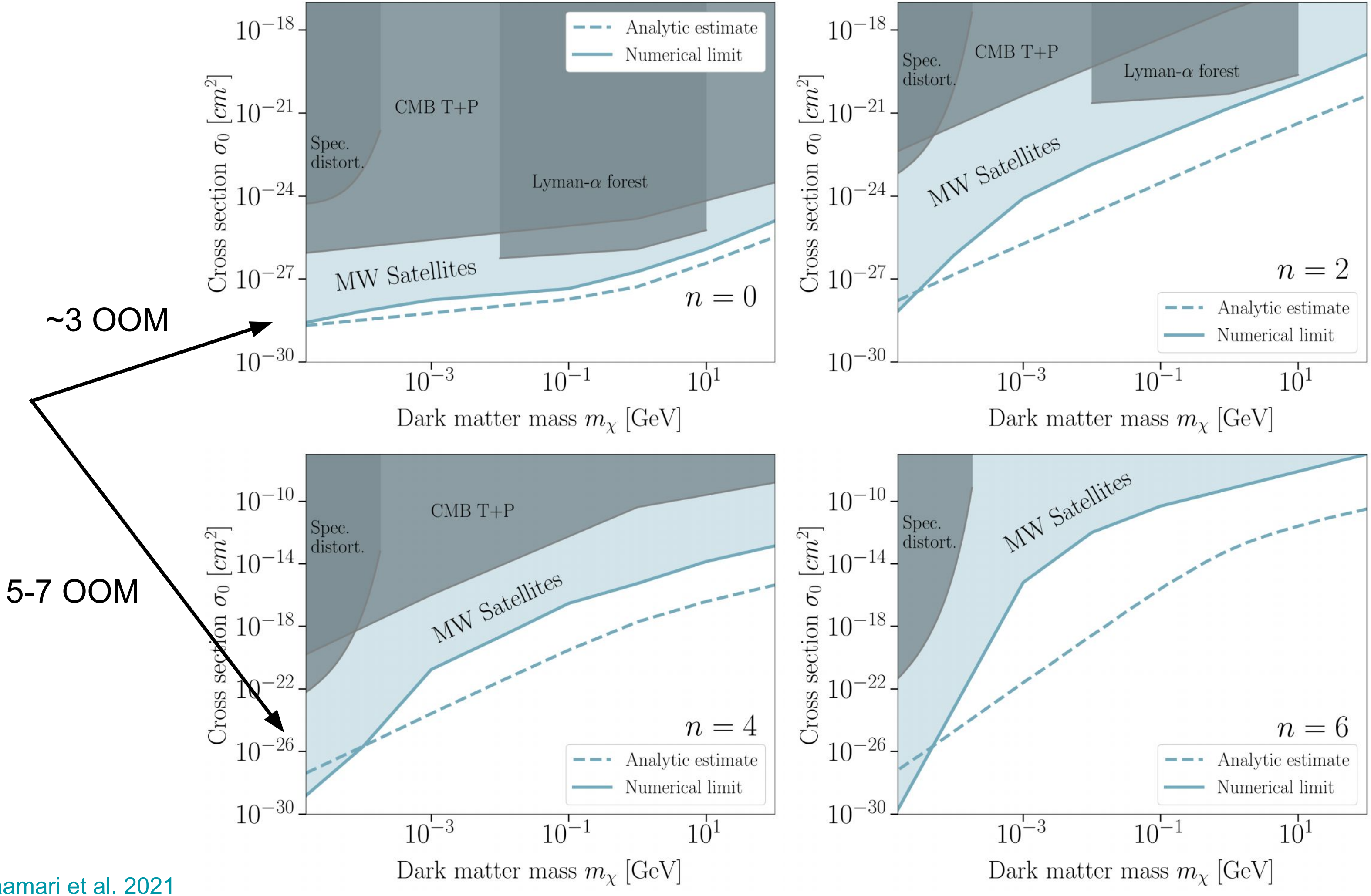


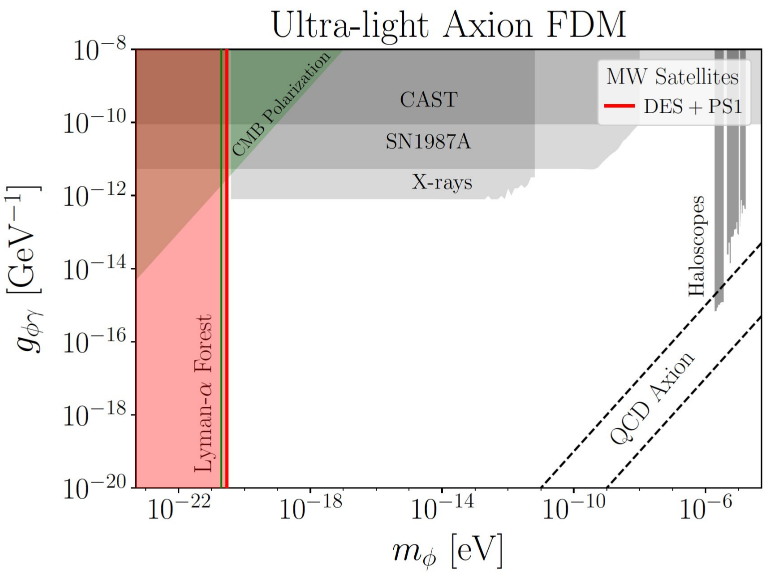
Maamari et al. 2021

Fuzzy Dark Matter Constraints

- Dark matter must be heavier than **3×10^{-21} eV** at 95% confidence to fit Milky Way satellite abundances

- This constraint can be interpreted as a lower limit on the ultra-light axion mass, assuming negligible self-interactions (more detailed work with N. Glennon & C. Prescod-Weinstein in prep.)

- The dark matter de Broglie wavelength must be smaller than the sizes of ultra-faint dwarfs (~1 kpc)



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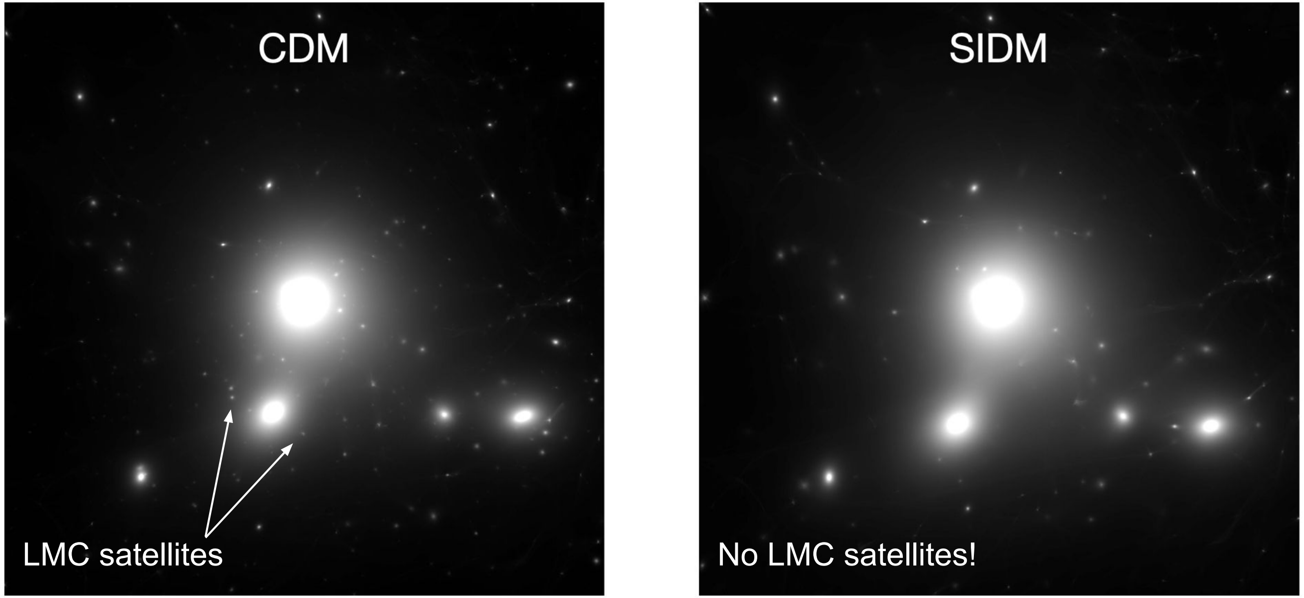
Subhalos and Dark Matter Self-interactions

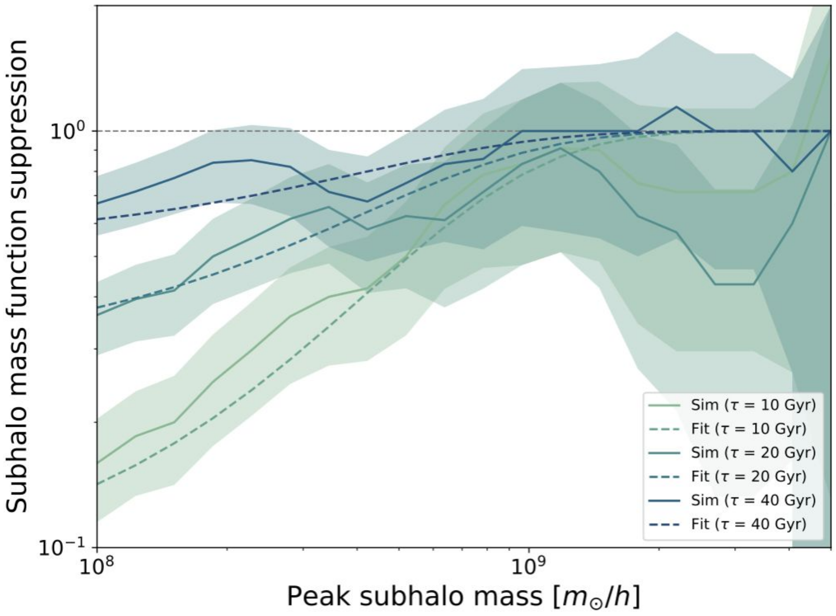
- Dark matter self-interactions can disrupt subhalos via ram-pressure stripping
- Large Magellanic Cloud satellites are preferentially disrupted due to their high-velocity infall
- Milky Way satellite abundances are sensitive to cross sections of ~0.1 cm^2/g at 200 km/s

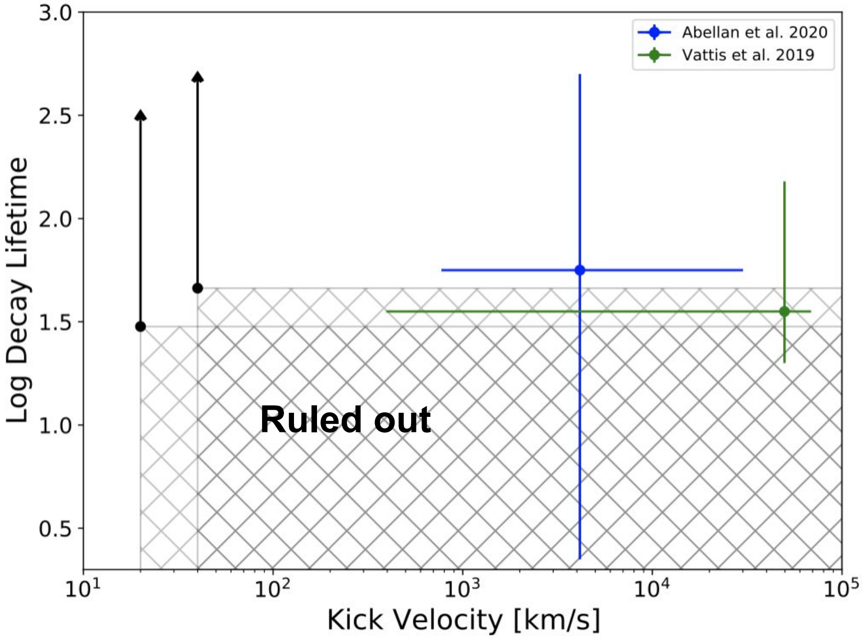


EN, A. Banerjee, S. Adhikari et al. 2020

Decaying Dark Matter Constraints

- Late-time dark matter decays unbind halos, suppressing the subhalo mass function
- Milky Way satellite abundances rule out two-body decay lifetimes shorter than ~20 Gyr, even for small parent-daughter mass splittings

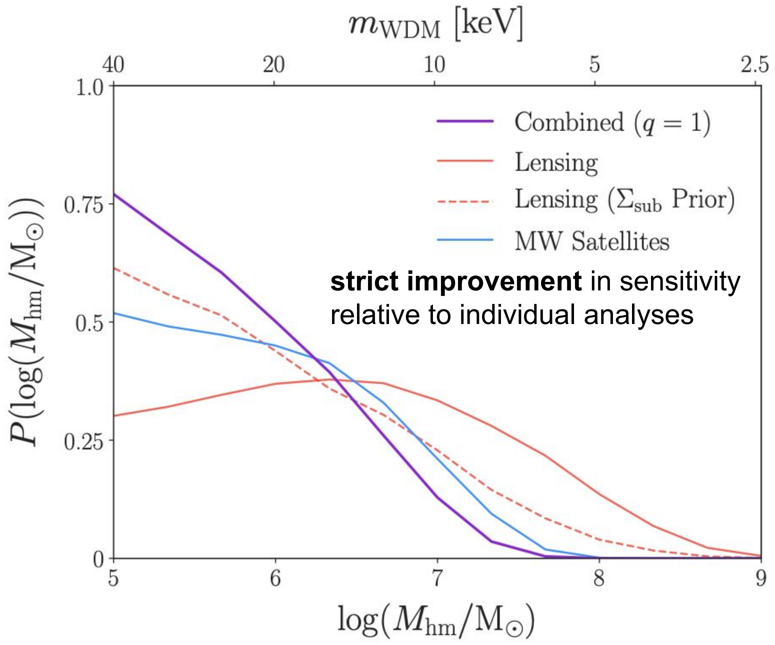




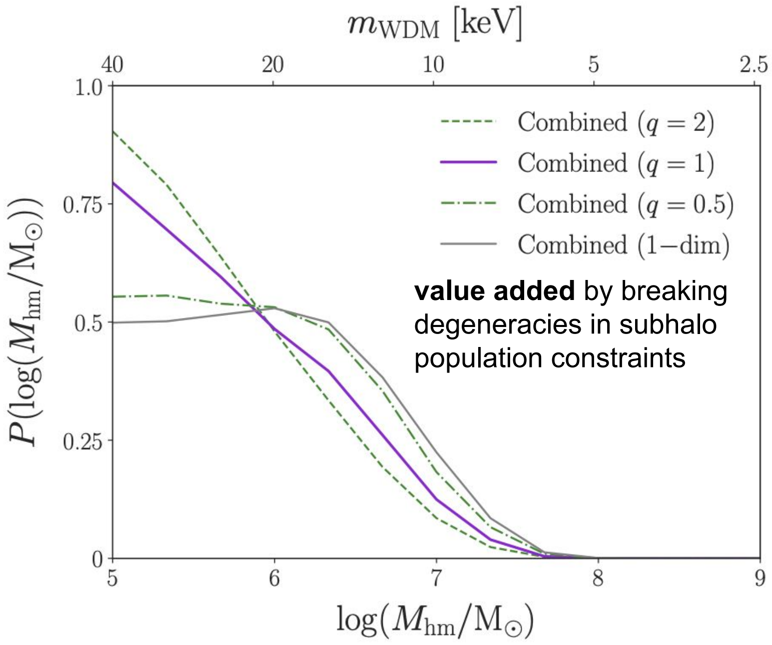
S. Mau, EN et al. in prep.

Combining Satellites and Strong Lensing

- Strong gravitational lensing flux ratio statistics and Milky Way satellite galaxies probe low-mass halo populations in complementary ways
- Combining these probes improves the lower limit on WDM mass to **9.7 keV** (95% CL)



strict improvement in sensitivity relative to individual analyses



value added by breaking degeneracies in subhalo population constraints

EN, S. Birrer, D. Gilman et al. 2021

Conclusions and Outlook

- The abundance of Milky Way satellite galaxies is consistent with cold dark matter predictions down to halo mass scales of $\mathbf{\sim 10^8\, M_\odot}$

- Combining cosmological simulations and galaxy–halo connection modeling in a rigorous statistical framework yields **stringent constraints** on warm, interacting, fuzzy, dark matter models that inhibit the formation of small halos

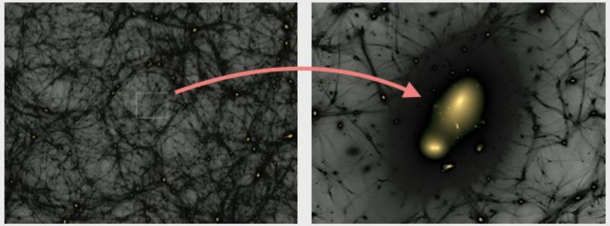
- Our analysis informs dark matter physics that impacts subhalo abundances at late times, including dark matter **self-interactions** and **decays** (constraints in progress!)

- The sensitivity of these dark matter measurements will **continue to improve** with future dwarf galaxy discoveries, including from the Vera C. Rubin Observatory, and advances in joint modeling of small-scale structure probes

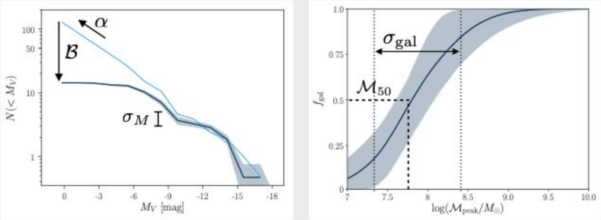
The Galaxy–Halo Connection Inferred from Milky Way Satellites

Markov Chain Monte Carlo

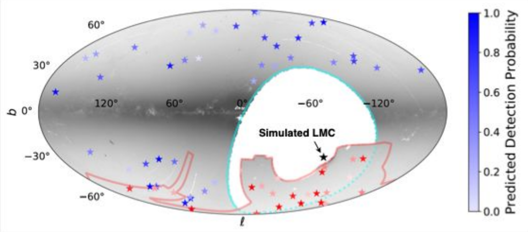
1. Resimulate Milky Way-like halos from large cosmological volume.



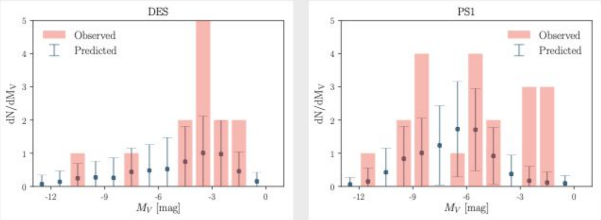
2. Paint satellite galaxies onto subhalos using galaxy—halo model.



3. Apply observational selection functions based on imaging data.



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



- An LMC system on recent infall is **required** to fit the anisotropy of the MW satellite population;
- The number and kinematics of predicted LMC satellites are **consistent** with *Gaia* data;
- The faintest satellites occupy halos with peak virial mass below **3×10^8 $M_\odot$** (95% CL);
- DES & Pan-STARRS data are consistent with **100%** of halos hosting observable satellites down to this mass.

EN & Wechsler et al. 2020

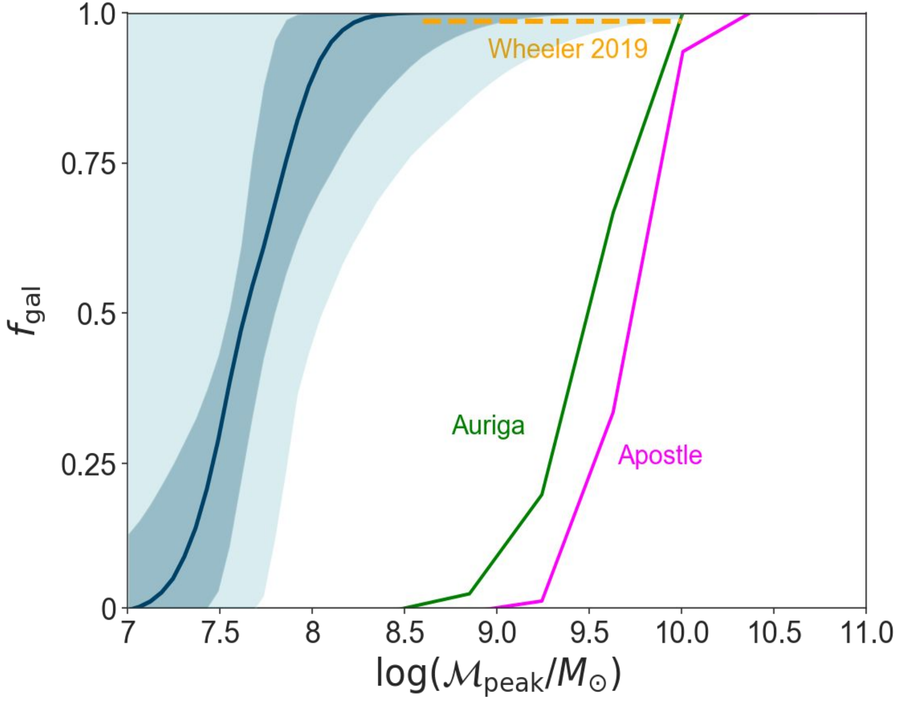
Empirically Modeling the Faint End

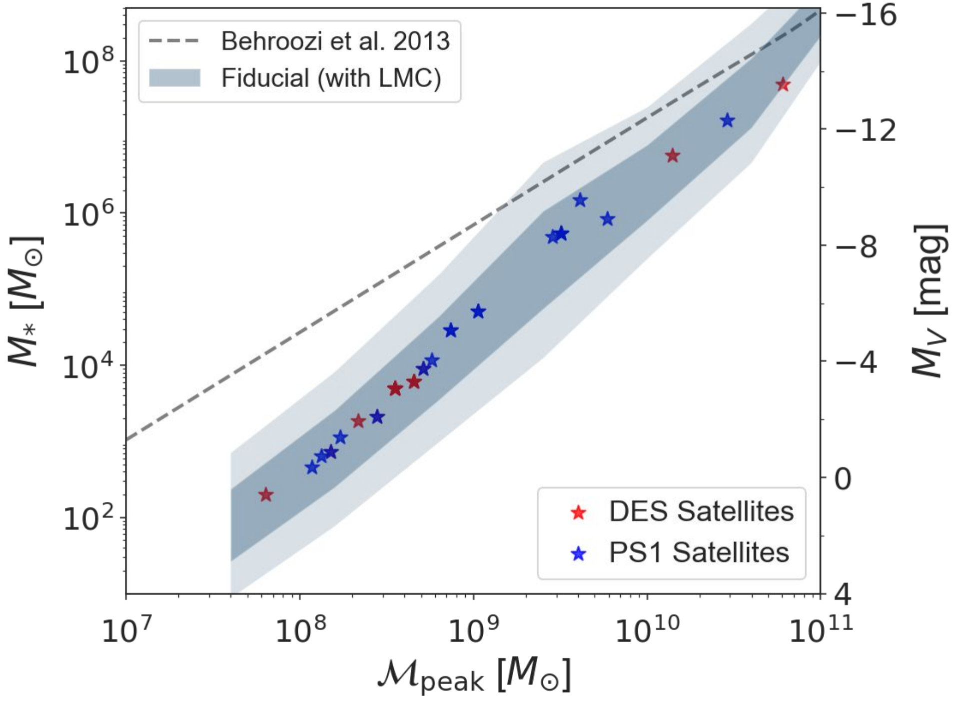
Physical Ingredient	Assumptions	Parameterization	Free Parameter?
Satellite Luminosities	Abundance match to GAMA survey	Non-parametric	*No*
	Extrapolate luminosity function	Faint-end slope α	**Yes** (α is free)
	Lognormal $(M_V\|V_{\rm peak})$ distribution	Constant scatter σ_M	**Yes** (σ_M is free)
	Smooth 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	$p_{\rm disrupt} \to p_{\rm disrupt}^{1/\mathcal{B}}$	**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* ($\mathcal{O} = 1$)

Also see SatGen (Jiang et al. 2020)

EN, Mao, Green, Wechsler 2019

The Faint-End Galaxy–Halo Connection

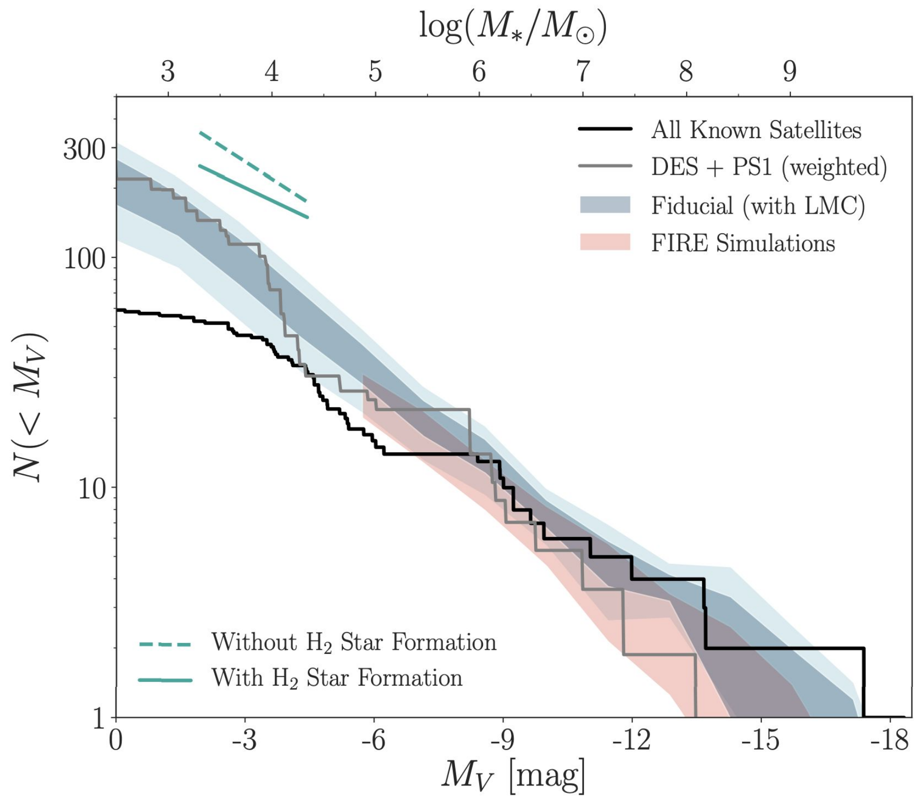




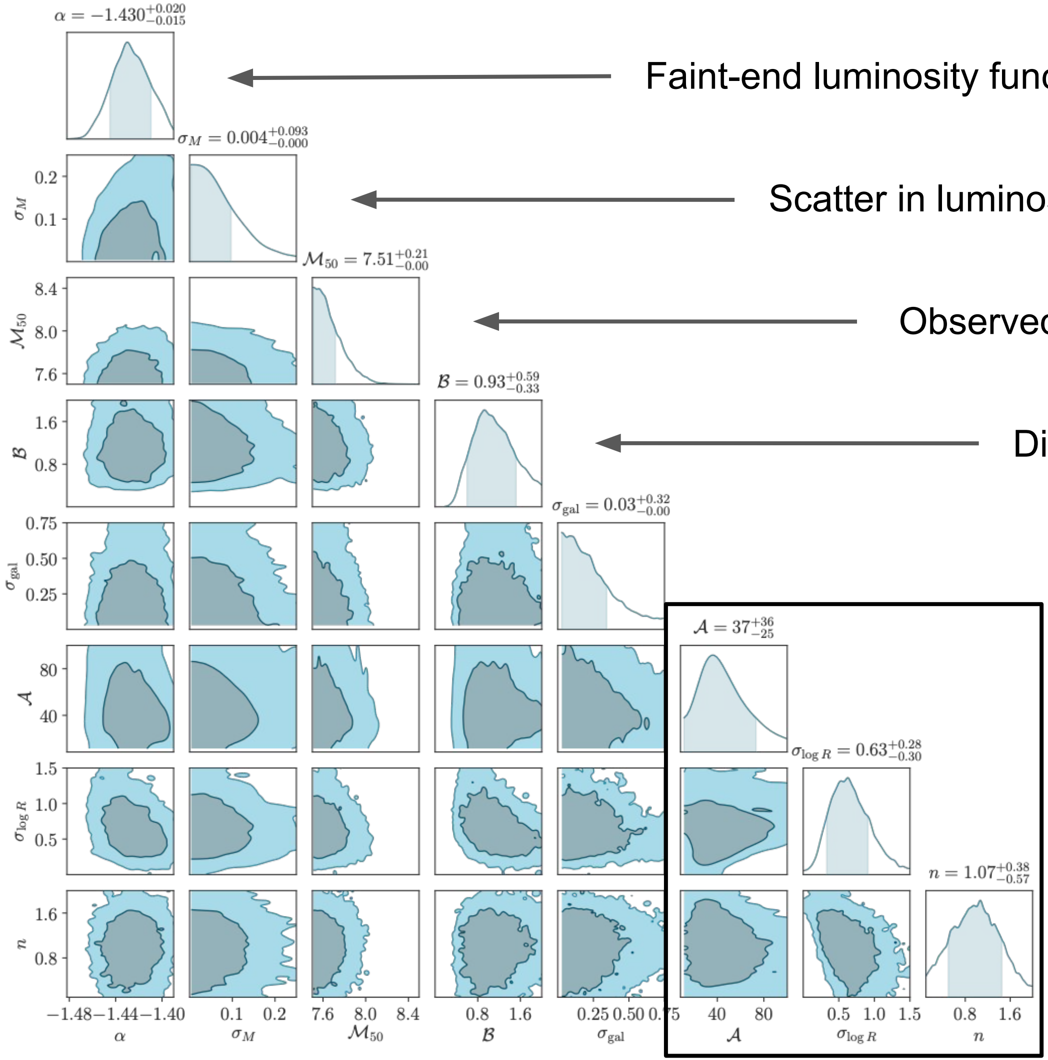
No evidence for a cutoff in galaxy formation due to reionization or dark matter physics.

The Total Milky Way Satellite Population

- Predict ~200 ± 50 total satellites, consistent with other empirical models (Jethwa et al. 2018, Newton et al. 2018, Kim et al. 2018) and hydrodynamic simulations;
- Most of the remaining population will be discovered by the Rubin Observatory Legacy Survey of Space and Time;
- Measurements of the faint-end luminosity function slope can potentially inform star formation and feedback prescriptions (e.g. Munshi et al. 2019).



EN & Wechsler et al. 2020



Faint-end luminosity function slope consistent with GAMA;

Scatter in luminosity at fixed V_{peak} < 0.2 dex;

Observed satellites occupy $M_{peak} < 3 \times 10^8\ M_\odot$ halos;

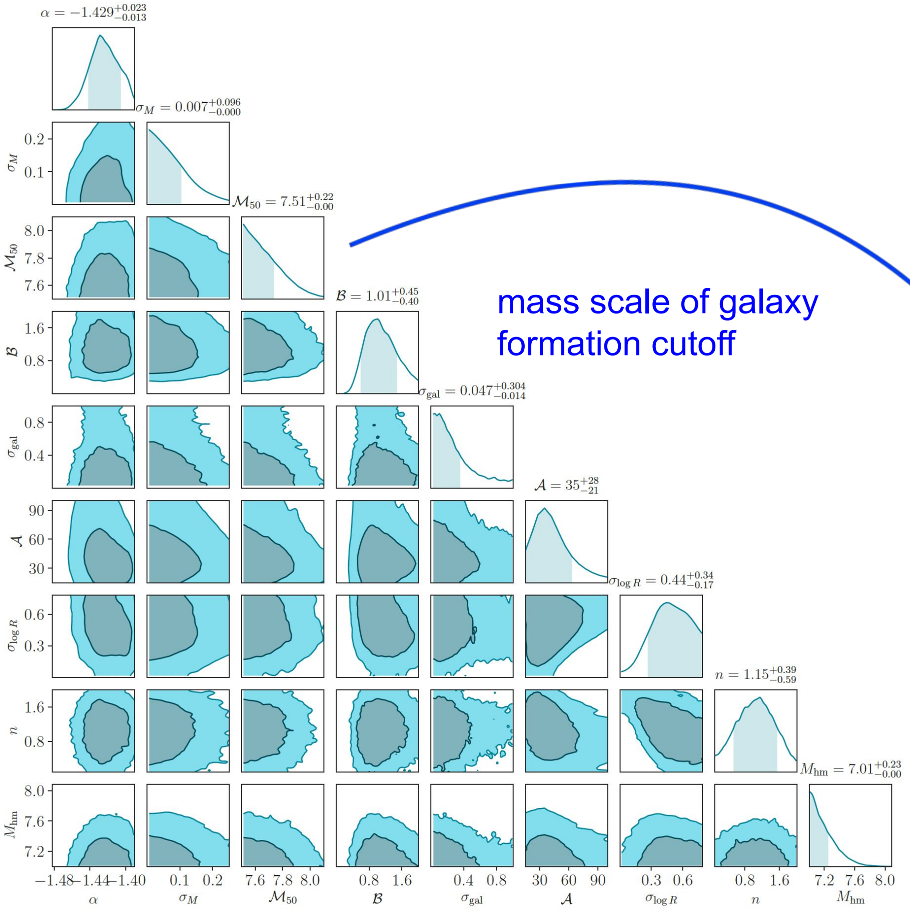
Disruption consistent with FIRE simulations;

Amplitude, scatter, and power-law slope of size relation consistent with Kravtsov 2013.*

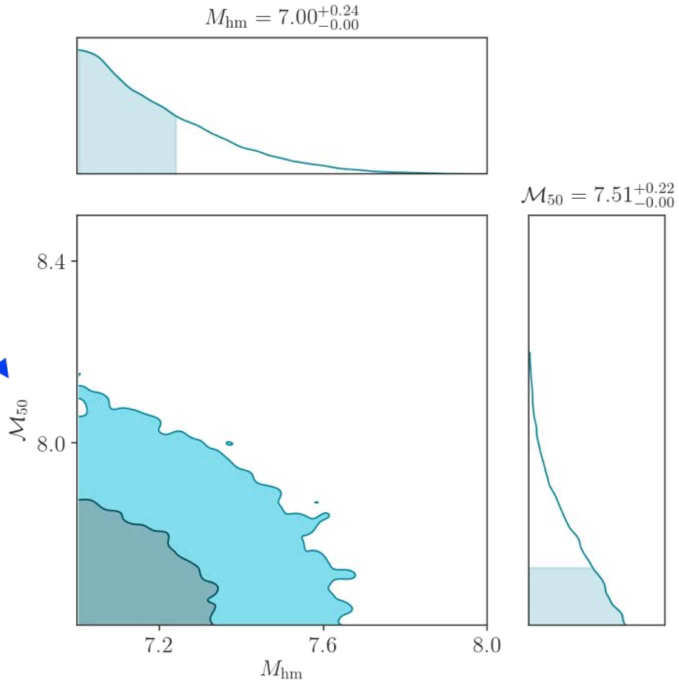
*Concentration-dependence of the size-virial radius relation (e.g. Jiang et al. 2019, Zanisi et al. 2020) is degenerate with the power-law index for these faint systems.

EN & Wechsler et al. 2020

Dark Matter Physics and Galaxy Formation



mass scale of galaxy formation cutoff



mass scale of SHMF suppression due to dark matter physics

Self-interacting Dark Matter Constraints

- Halo mass scale imposes typical relative velocity of self-interacting dark matter particles
- SIDM models with large cross sections at subhalo infall velocity scale disrupt subhalos efficiently