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DARK MATTER CONSTRAINTS FROM THE KINEMATICS, STRUCTURE, AND LIGHT OF SDSS SATELLITE GALAXIES

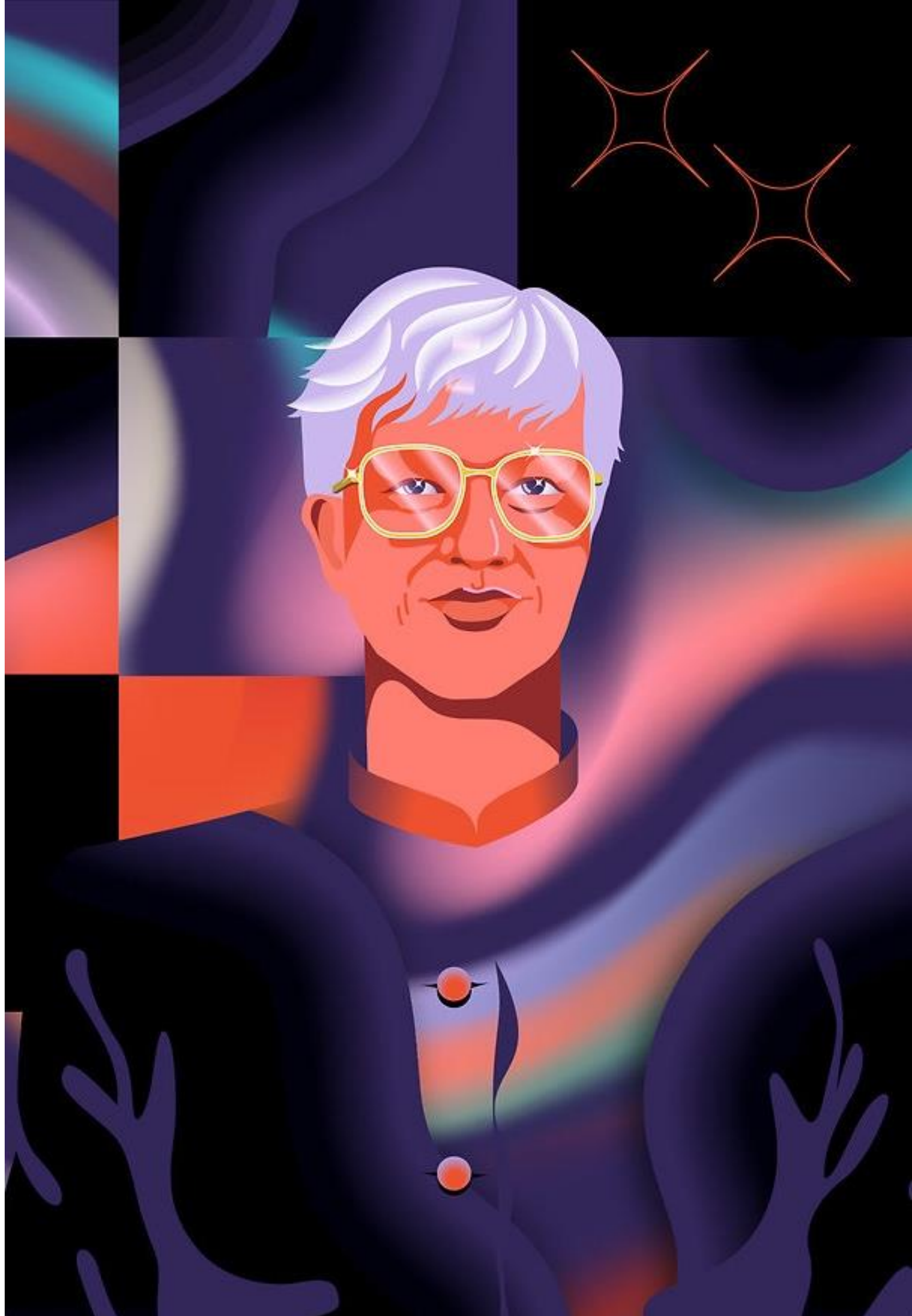
Nicole Marcelina Gountanis
Les Houches | July 24, 2025

THE OHIO STATE UNIVERSITY

DARK MATTER EXISTS— BUT WHAT *IS* IT?

Established: Dark Matter's Macroscopic Role

- **Galaxy dynamics**: Flat rotation curves indicate mass distributions extending beyond visible disks (Rubin & Ford 1970).
- **Galaxy cluster kinematics**: Discrepancy between luminous mass and velocity dispersions implies substantial unseen mass (Zwicky 1933).
- **Gravitational lensing**: Weak and strong lensing reveal dark matter distributions independent of luminous tracers (e.g., Bullet Cluster).
- **Structure formation**: Hierarchical formation of cosmic structure requires an early, pressureless component.
- **CMB anisotropies**: Acoustic peak structure requires a non-baryonic, pressureless matter component to fit early-universe density fluctuations.



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DARK MATTER EXISTS—BUT WHAT *IS* IT?

Unresolved: Dark Matter's Microphysical Properties

- **Beyond the Standard Model**: No Standard Model particle accounts for dark matter; current evidence is solely gravitational.
- **Mass scale**: Viable candidates span from ultralight axions ($\sim 10^{-22}$ eV) to weak-scale WIMPs (~TeV).
- **Spin/statistics**: Fermionic (e.g., sterile neutrinos) vs. bosonic (e.g., axions).
- **Self-interactions**: Viable cross sections $\sigma/m \sim 0.1\text{–}1$ cm^2/g could resolve small-scale tensions.
- **Non-gravitational couplings**: Possibility of interactions with baryons, photons, or hidden-sector fields.
- **Thermal origin and production mechanism**:
  - **Freeze-out** (thermal relics, e.g., WIMPs)
  - **Freeze-in**, **misalignment** (e.g., axions), or decay from heavier species

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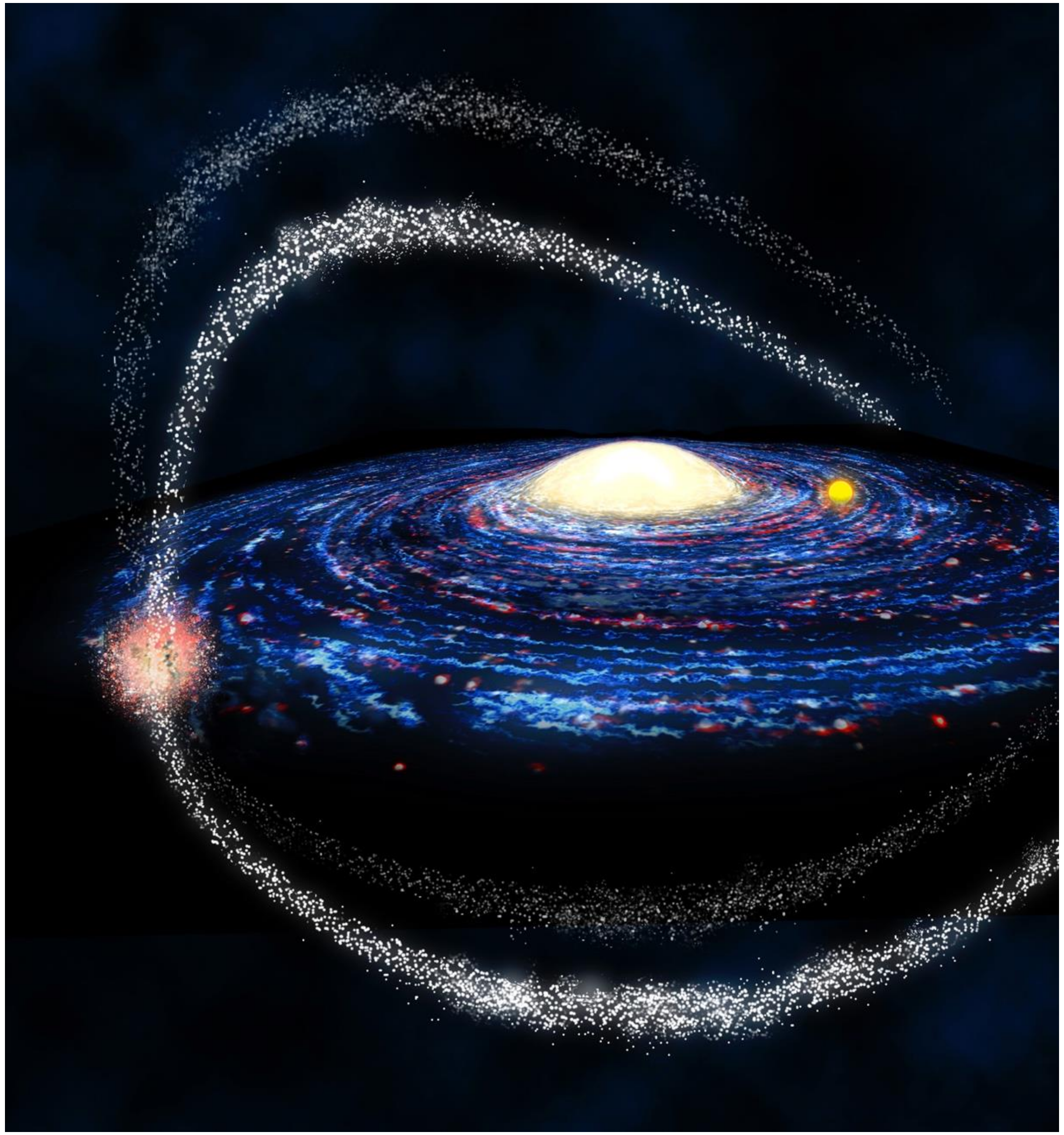
PROBING DARK MATTER WITH SMALL-SCALE STRUCTURE

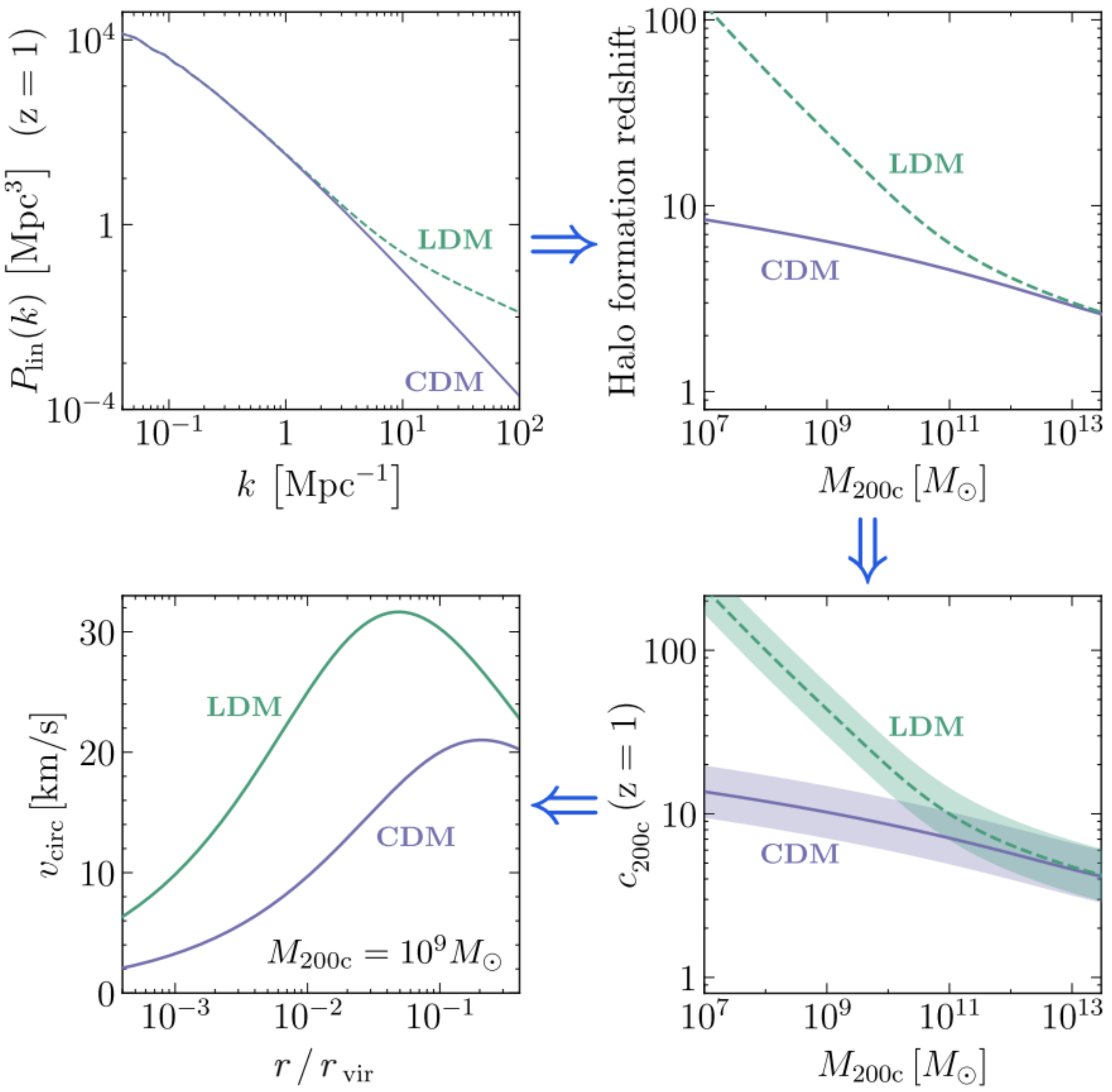
- Small halos form earlier and are more sensitive to initial conditions and DM properties
- Suppression or modification of low-mass structure encodes information on DM particle mass, interactions, and production
- Non-gravitational effects (e.g., self-interactions, free-streaming) imprint measurable deviations from cold, collisionless DM predictions
- **Examples of Observables:**
  - Satellite galaxy counts and spatial distributions
  - Internal dynamics of dwarf galaxies
  - Subhalo signatures in lensing and stellar stream perturbations



Amanda Smith, Institute of Astronomy, University of Cambridge

HOW THE POWER SPECTRUM SHAPES GALAXY AND HALO PROPERTIES

- Small-scale features in the power spectrum determine when low-mass halos form.
- **Blue-tilted models** (enhanced power at small scales):
    - Boost small-scale fluctuations without altering large scales.
    - Lead to earlier halo collapse, when the universe is denser.
    - Result in more concentrated halos with higher internal velocities.
- **Key takeaway**:
  The **shape and amplitude** of the small-scale matter power spectrum leaves **imprints in halo structure.**



Esteban, Peter, & Kim (2024), arXiv:2306.04674

CONSTRAINING DARK MATTER VIA THE SMALL-SCALE POWER SPECTRUM

- Perform a likelihood-based inference using internal velocities and sizes of Milky Way satellite galaxies
- Target deviations in the linear matter power spectrum over $4 \lesssim k \lesssim 37$ Mpc^{-1}
- Fit model-agnostic modifications to the power spectrum and compare with predictions from CDM and blue-tilted alternatives
- Incorporate baryonic and observational systematics through a forward model of galaxy–halo connection and tidal evolution
- Demonstrates that current satellite data already constrain power spectrum features at subgalactic scales
- Reference: *Esteban, Peter, & Kim (2024)*, arXiv:2306.04674

Milky Way satellite velocities reveal the Dark Matter power spectrum at small scales

Ivan Esteban [1,2,*], Annika H. G. Peter [1,2,3,4,†] and Stacy Y. Kim [5,‡]

[1] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, Ohio 43210*
[2] *Department of Physics, Ohio State University, Columbus, Ohio 43210*
[3] *Department of Astronomy, Ohio State University, Columbus, Ohio 43210*
[4] *School of Natural Sciences, Institute for Advanced Study, 1 Einstein Drive, Princeton, New Jersey 08540*
[5] *Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom*

(Dated: November 1, 2024)

Ivan Esteban
University of the Basque Country

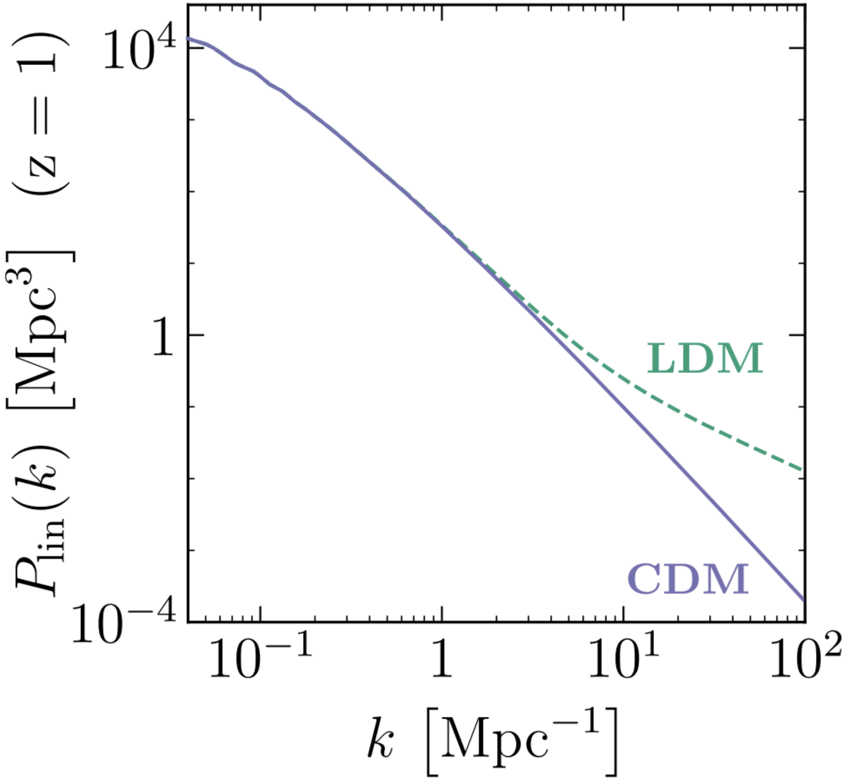
Annika Peter
Ohio State University

Stacy Kim
Carnegie Theoretical Astrophysics Center

POWER SPECTRUM PARAMETERIZATION

$$\mathcal{P}_{\mathcal{R}}(k) \propto k^{n_s-1}\left[1+\left(\frac{k}{k_{\rm cut}}\right)^{n_{\rm cut}-n_s}\right]$$

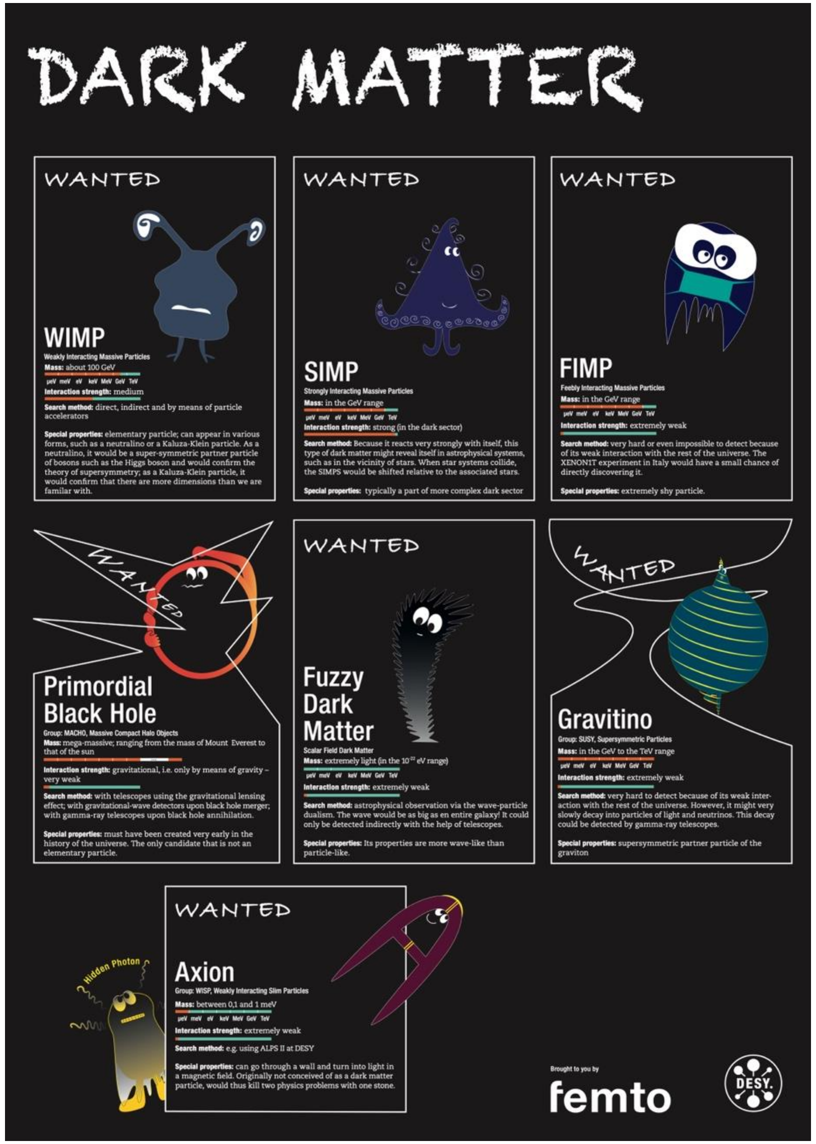
- **Motivation**: To test for deviations from ΛCDM at subgalactic scales without committing to a specific dark matter model.
- **Approach**: Parametrize the primordial power spectrum:
  - $n_s \simeq 0.97$: standard CDM spectral index
  - k_{cut}: scale at which power begins to enhance
  - $n_{cut} > n_s$: spectral index after k_{cut}
- **Interpretation**:
  - Reduces to ΛCDM when $n_{cut} = n_s$
  - Allows smooth enhancements in power at small scales
  - Can mimic the effects from a range of alternative DM theories
- **Assumption:**
  Linear perturbation growth follows CDM evolution →only initial conditions are modified.



Esteban, Peter, & Kim (2024), arXiv:2306.04674

WHY USE A MODEL-AGNOSTIC POWER SPECTRUM?

- **Theoretical Scope**
  Encompasses diverse scenarios including blue-tilted inflation, DM–radiation interactions, and non-thermal production channels.
- **Flexible Parameterization**
  Captures both smooth and sharp features in the linear matter power spectrum, allowing for unknown or complex small-scale physics.
- **Direct Observational Mapping**
  Forward-models initial conditions to galaxy observables (abundance, structure, kinematics), enabling constraints on small-scale structure independent of microphysical details.
- **Minimal Assumptions on Evolution**
  Modifies only initial perturbations, assumes standard CDM growth and late-time dynamics remain unaltered.
- **Applicability**
  Valid when late-time physics (gravity, expansion) are unchanged and enhanced power is sourced from early-universe processes (e.g., inflation). Commonly employed in dwarf galaxy formation models.

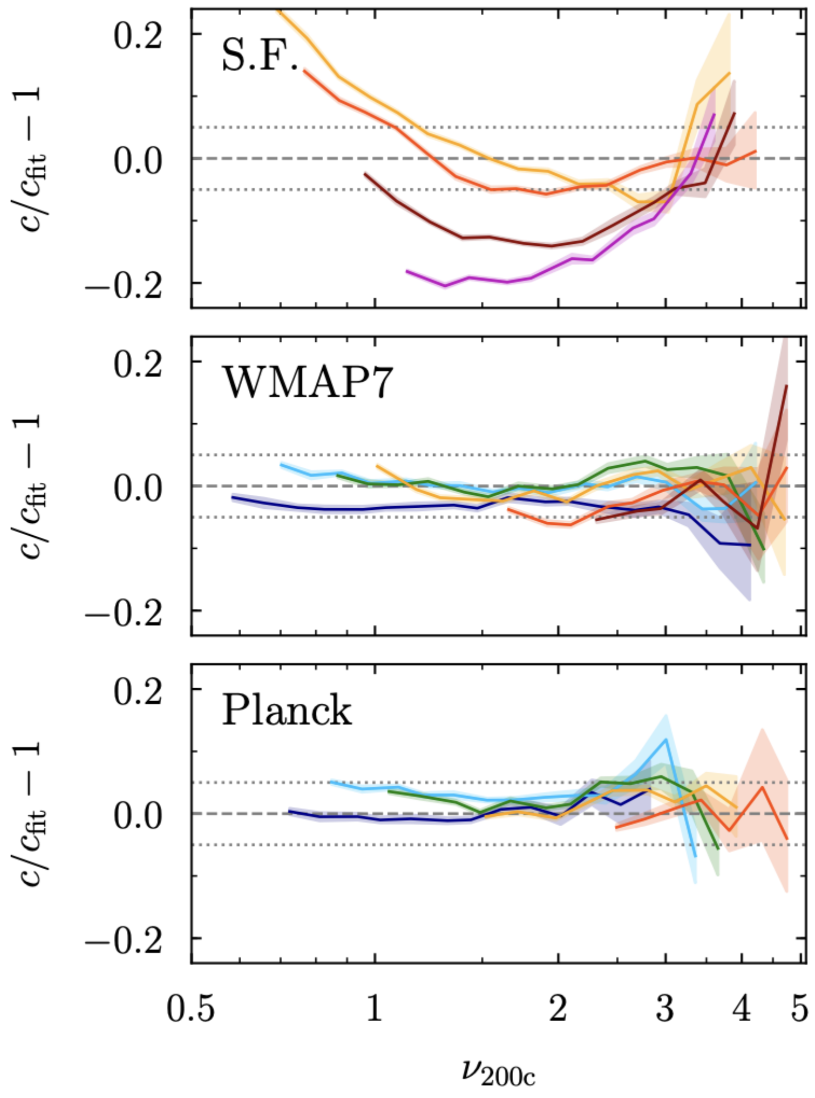


Esteban, Peter, & Kim (2024), arXiv:2306.04674

HALO MASS FUNCTION & CONCENTRATION MODELING

- **Halo Mass Function** from extended Press-Schechter theory with Sheth–Tormen correction for ellipsoidal collapse.
  - Variance σ(R,z) computed from the linear power spectrum using a sharp k-space filter.
  - **Subhalos** generated via merger trees, including a 20% baryonic suppression for $M<10^{11}M_{\odot}$.
- **Concentration–Mass Relation** from Diemer & Joyce (2019):
  - Physically motivated by the link between halo **formation redshift** and **present-day concentration**.
  - Depends on halo mass, local slope of the power spectrum, and formation time.
  - **Cosmology-independent** and validated across N-body simulations for varied power spectra and redshifts.
  - Scatter modeled as a **lognormal distribution** with σ log c=0.16 dex.
- All quantities computed using the **Galacticus** semi-analytic framework

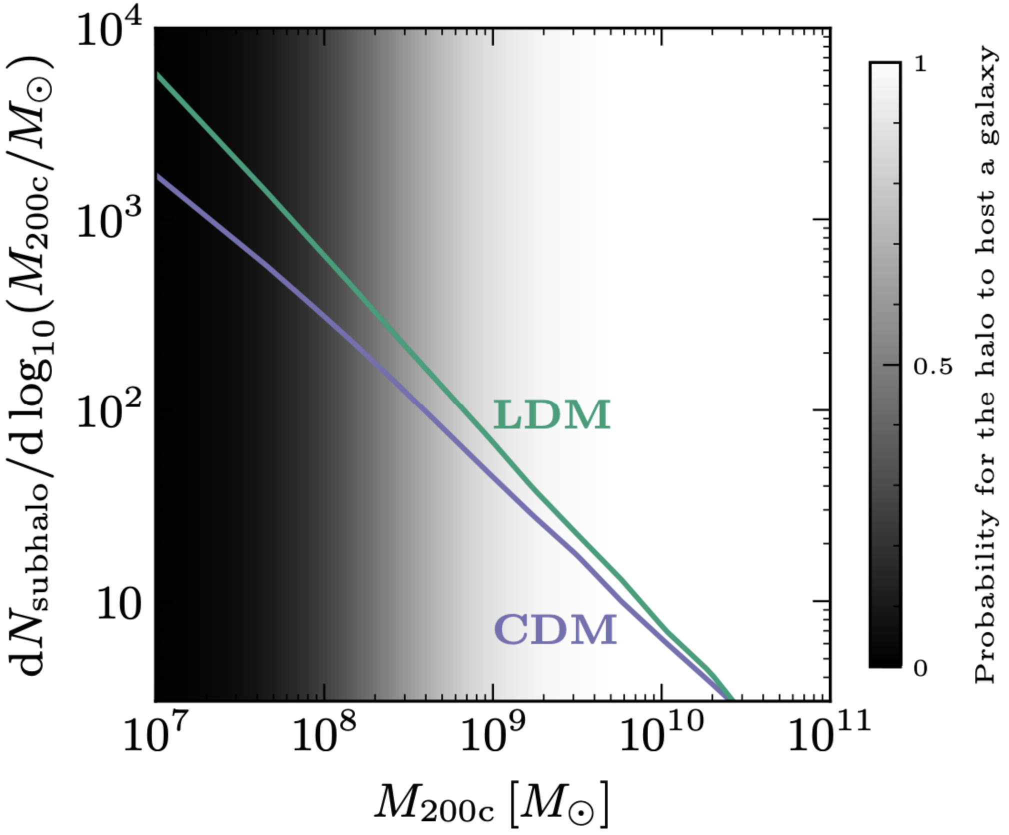
Diemer & Joyce (2019), arXiv:1809.07326



Esteban, Peter, & Kim (2024), arXiv:2306.04674

SUBHALO MASS FUNCTION IN LDM MODELS

- **Figure: Impact of LDM on subhalo mass function (z = 0)**
- Milky Way–mass host, computed with *Galacticus*
- LDM parameters: k_{cut}=8 Mpc^{-1}, n_{cut}=2.6
- **Visible subhalo abundance is only mildly enhanced** in LDM models.
  - ~35% increase at 10^9 $M_\odot$, ~50% at 10^8 $M_\odot$, but these halos are typically dark.
  - Halo occupation fraction (gray background) shows which halos are likely to host galaxies.
  - The HOD model is fixed here for illustration, but is marginalized over in the full analysis.
- **Key takeaway**:
  - The main observational signature of LDM models is not in total subhalo abundance but in enhanced concentrations.



Esteban, Peter, & Kim (2024), arXiv:2306.04674

GALAXY–HALO CONNECTION MODEL

- **Goal:** Bridge dark matter halo structure to observable galaxy properties, so we can test DM models against real data.
- **Why do this?**
  - LDM alters halo internal structure, not just counts.
  - Observables like galaxy sizes and velocity dispersions depend on halo density profiles.
  - Need a model to translate from halo-scale predictions to what telescopes see.
- **What we gain:**
  - A way to forward model galaxy observables from LDM power spectra
  - Robust constraints on DM physics, independent of uncertain galaxy formation details

The Galaxy–Halo Connection is our recipe book for producing satellite populations!

THE RECIPE FOR A GALAXY

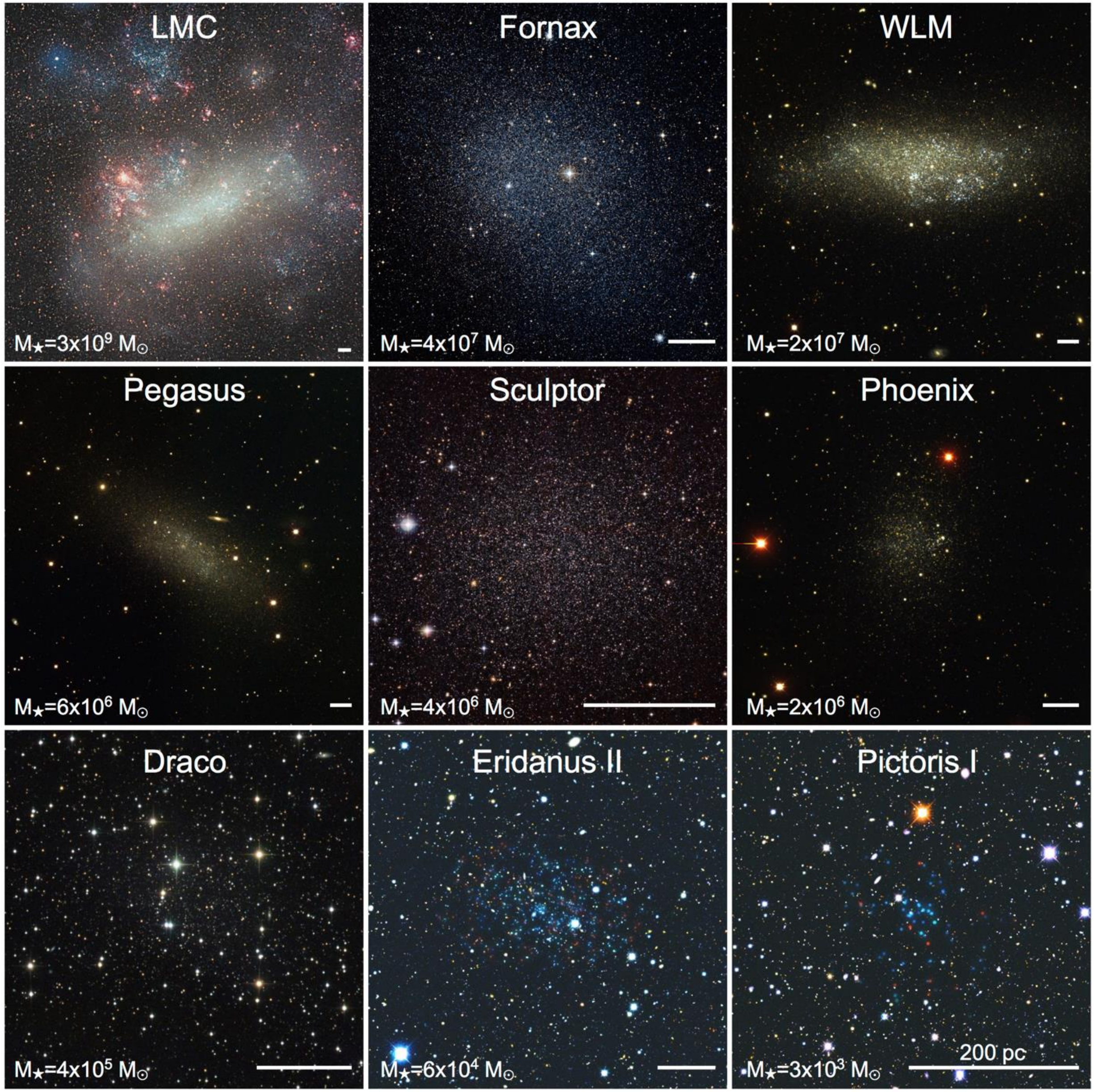
Ingredient	Role
Halo mass & concentration	Sets the base gravitational structure
SMHM relation	Assigns stellar mass to each halo
Size relation	Converts stellar mass into galaxy size
Kinematics model	Adds internal motion (velocity dispersion)
Occupation fraction	Determines which halos host galaxies
Completeness & radial dist.	Filters what we observe in surveys

This recipe lets us predict observable galaxy properties from any underlying dark matter model.




OBSERVED DWARF SATELLITE SAMPLE

- **Data source**: SDSS satellite galaxies
- **Observables used**:
  - Line-of-sight velocity dispersion (σ_{los})
  - Projected half-light radius (R_{eff})
  - Satellite count (N_{obs})
- **Excluded objects**:
  - **Magellanic Clouds**, **Pisces II**, **Sagittarius**
    ↳ affected by baryonic effects and tidal stripping
  - **DES and Pan-STARRS satellites**
    ↳ would require modeling the LMC contribution
- Sample chosen to minimize bias from tidal disruption and baryonic physics



Crnojević & Mutlu-Pakdil, *Nat Astron* **5**, 1191–1194 (2021)

LIKELIHOOD FRAMEWORK: TESTING DM MODELS WITH SATELLITES

- **Goal:** Quantify how well DM models reproduce Milky Way satellite properties.
- **Data Inputs:**
  - Stellar velocity dispersion σ_{los}
  - Half-light radius R_{eff}
  - Total satellite count N_{obs}
- **Likelihood** →

$$-2\ln\mathcal{L} = -2\sum_i \ln\mu(\sigma_{\rm los}^{*\,{\rm obs},\,i}, R_{\rm eff}^{{\rm obs},\,i}) - 2\ln\mathcal{P}(N_{\rm obs})$$

- **Free Parameters (10 total):**
  - **DM**: $\{n_{cut}, k_{cut}\}$
  - **Galaxy**: $\{M_{0hof}, \alpha_{hof}, \beta^*, \sigma^*, \gamma^*, M_{corethres}, \sigma_{C\Omega}, y\}$
- **Inference:**
  - Maximize likelihood over nuisance parameters
  - Use $\Delta 2\ln\mathcal{L}$ and Wilks' theorem for confidence intervals

VELOCITY DISPERSION–SIZE RELATION AS A PROBE OF DARK MATTER

Figure 4

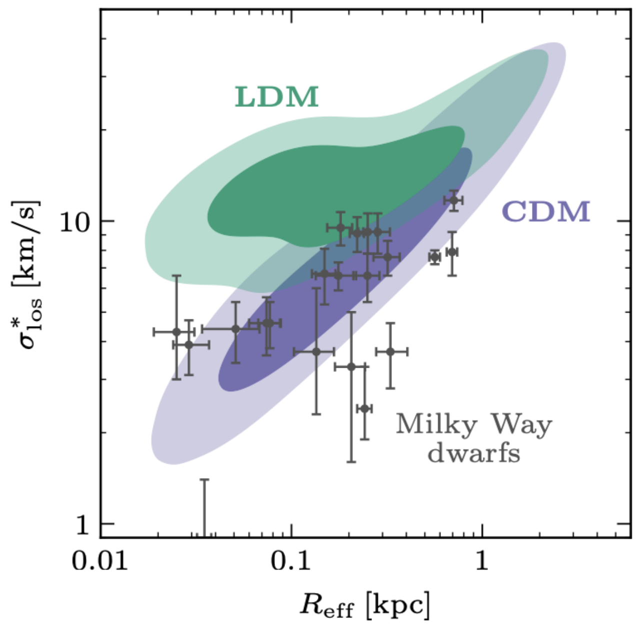
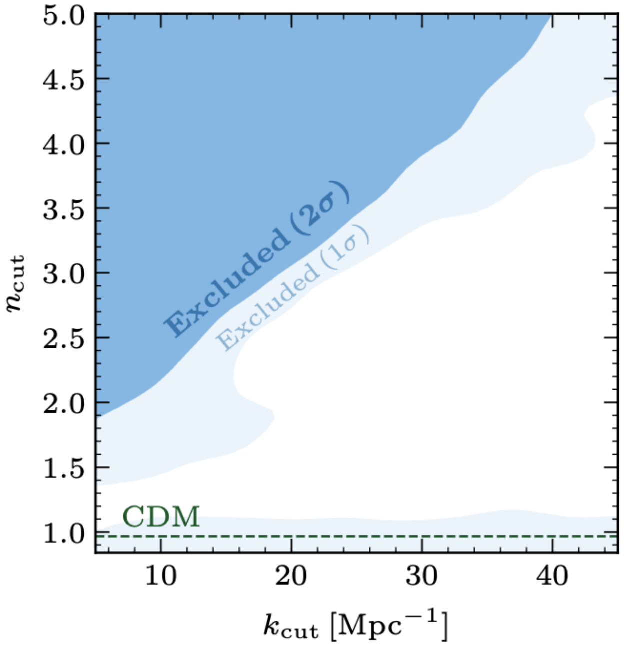


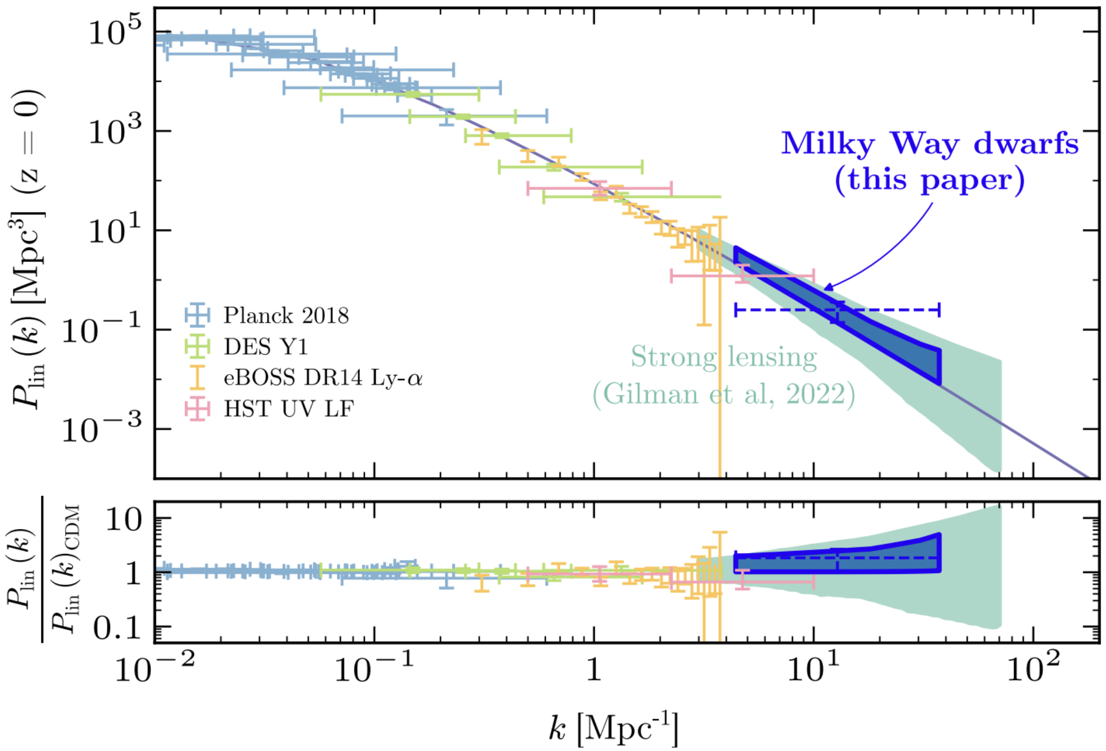
Figure 7



- Observed correlation between velocity dispersion (σ_{los}) and half-light radius ($R_e$ff) in MW satellites provides a sensitive test of the DM power spectrum.
- **Figure 4**: Lumpy DM models predict higher σ_{los} at fixed R_{eff} due to increased halo concentrations: can overshoot observed values.
- **Figure 7**: Likelihood analysis excludes models with strong power enhancements between k ≈ 5–40 Mpc^{-1}.
- Large n_{cut} values are disfavored at 2σ.
- Slight ~1σ preference for enhancement is driven by the mild upturn in σ_{los} at low R_{eff} → not statistically significant.
- **Result**: Kinematic–structural correlations of satellites place tight constraints on small-scale DM power, ruling out overly "lumpy" models.

Esteban, Peter, & Kim (2024), arXiv:2306.04674

CONSTRAINTS ON THE PRIMORDIAL POWER SPECTRUM



- This analysis constrains the shape and amplitude of the primordial matter power spectrum on small scales, leveraging dwarf galaxy kinematics and sizes.
- Sensitivity peaks at 5 $\text{Mpc}^{-1} \lesssim k_{cut} \lesssim 40\ \text{Mpc}^{-1}$
- **Key result:** $\frac{P_{lin}}{P_{lin}^{CDM}} = 1.81 \pm 0.80$

⇨Mild deviation from CDM at small scales, but within uncertainties.

- **Degeneracies:**
  Power spectrum shape is partially degenerate with baryonic core threshold $M_{corethres}$ but lumpy DM-like velocity–size relations can't fully mimic CDM.
- **Conclusion:**
  MW satellite kinematics and sizes yield powerful constraints on the small-scale primordial power spectrum and structure formation.

Esteban, Peter, & Kim (2024), arXiv:2306.04674

CURRENT WORK

- **Expanded Galaxy Observables:**
- Add **satellite luminosities** to better constrain the stellar mass–halo mass relation and satellite occupation fraction.
    - This enhances constraints on the galaxy–halo connection and informs models of star formation efficiency.
    - Joint analysis of **luminosities, abundances, sizes, and kinematics** will provide a more comprehensive probe of dark matter microphysics and galaxy formation.
- **Modeling Improvements:**
- Implement and compare **three different completeness corrections prescriptions.**
- Incorporate **warm dark matter (WDM)** models to extend the parameter space of small-scale structure suppression.

Nicole Gountanis
Ohio State University

Zavier Kamath
Ohio State University

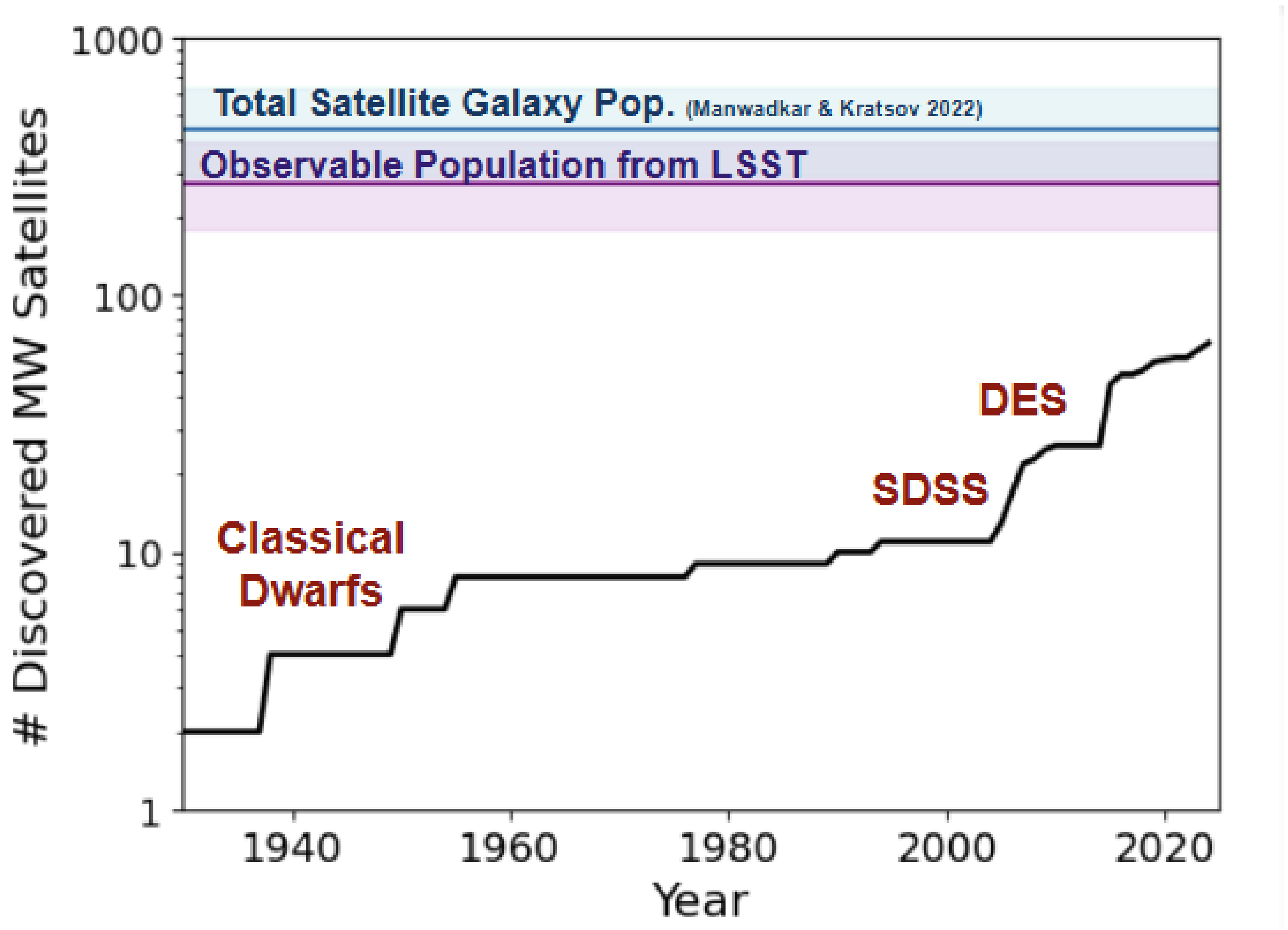
FUTURE WORK

- **Observational Extensions:**
- Incorporate new Milky Way satellites from DES, DELVE, and Pan-STARRS, which now have improving kinematic data and well-characterized completeness corrections.
- Add M31 satellites to test for host-to-host variance and mitigate concerns about the Milky Way being an outlier.
- Include field dwarf galaxies to probe environments unaffected by tidal interactions, though modeling completeness is more challenging.
- Utilize upcoming Rubin Observatory discoveries to map the spatial distribution of dwarfs and quantify tidal disruption.
- Add a **LMC halo** to properly model satellites discovered in DES and Pan-STARRS footprints.

CONCLUSIONS

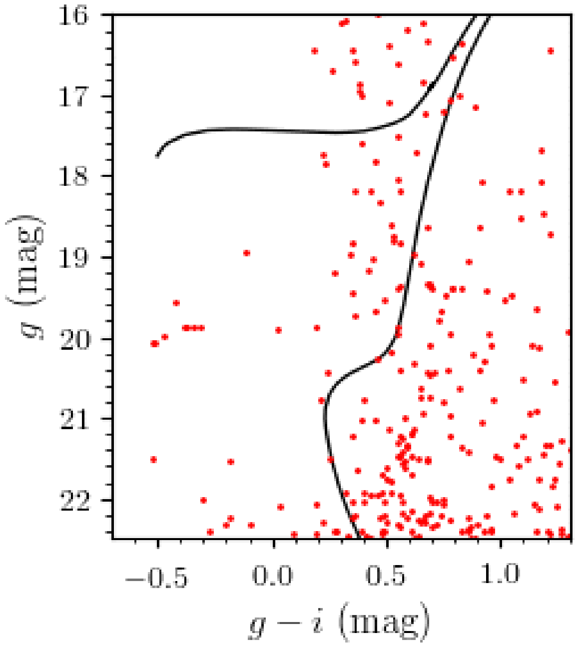
- MW satellite sizes and kinematics provide precise probes of small-scale dark matter structure and the primordial power spectrum.
- Modeling velocity dispersion–size correlations distinguishes CDM from models with enhanced small-scale power.
- Our likelihood approach accounts for observational uncertainties, completeness, and baryonic effects, yielding strong constraints on DM at dwarf galaxy scales.
- Data exclude strong enhancements in the power spectrum at 5–40 Mpc^{-1}.
- Future observations of new satellites, M31 dwarfs, and field galaxies will tighten constraints and improve galaxy–halo connections.
- Adding luminosities and high-redshift data will deepen understanding of dark matter and galaxy formation.

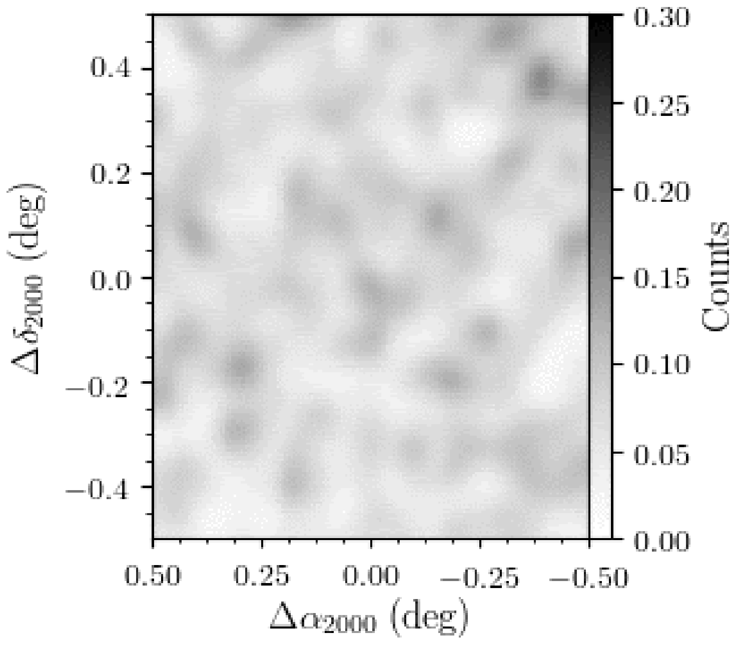
BACK UP SLIDES



Total Satellite Galaxy Pop. (Manwadkar & Kratsov 2022)
Observable Population from LSST
Classical Dwarfs
SDSS
DES
Discovered MW Satellites
1000
100
10
1
1940
1960
1980
2000
2020
Year

ISOCHRONE FITTING





TIDAL STRIPPING

In the main text, we neglect tidal stripping of subhalos by the Milky Way.

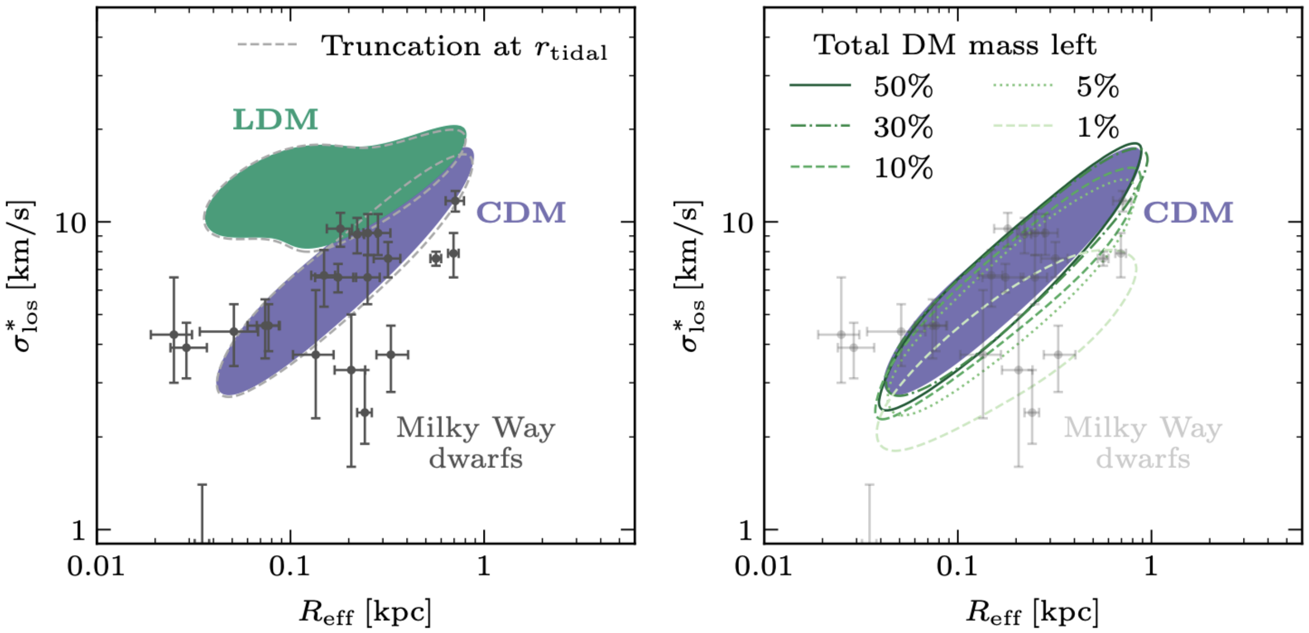


FIG. A1. Same as Fig. 4, but the dashed lines include tidal effects. To avoid crowding the figure, colored regions show 68% of the enclosed population. In the left panel, we truncate DM density profiles at the tidal radius. In the right panel, we include tidal shocking and heating by changing the halo structural parameters, following the "tidal tracks" in Ref. [130]. *Tidal effects would have a subleading impact on our error budget.*

INFALL TIME

In the main text, we evaluate all Milky Way satellite properties at median infall redshift $z_{\rm infall} = 1$ [36–38].

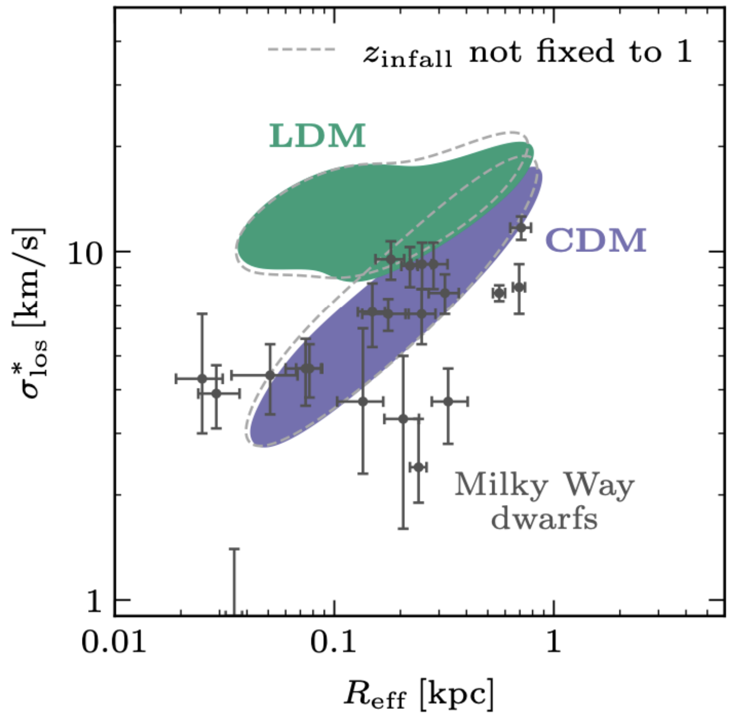


FIG. A2. Same as Fig. 4, but the dashed lines include the different satellite infall times. To avoid crowding the figure, colored regions show 68% of the enclosed population. *Different infall times would have a subleading impact on our error budget.*

DM HALO PROFILE

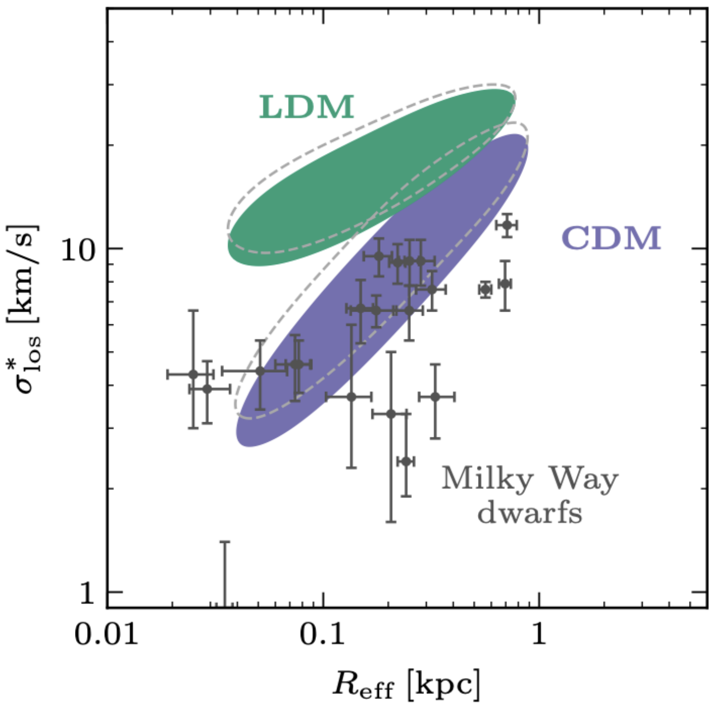


FIG. A4. Same as Fig. 4, but the dashed lines assume an Einasto profile and the solid region an NFW profile. To avoid crowding the figure, colored regions show 68% of the enclosed population. *Assuming an Einasto profile would have a subleading impact on our error budget.*

BARYONIC FEEDBACK

Here, we illustrate the effects of some parameters that we set free in our analysis: baryonic feedback that turns NFW "cusps" into "cores", the uncertain stellar mass-halo mass relation, and the uncertain halo occupation fraction. As discussed in the main text, the first effect is the most degenerate with our determination of the power spectrum.

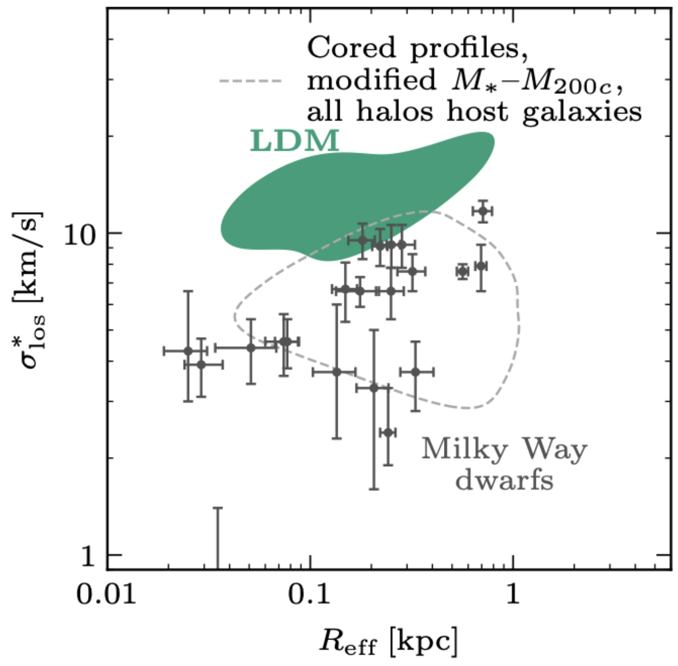


FIG. A5. Same as Fig. 4, but for the dashed line we change our free parameters. To avoid crowding the figure, colored regions show 68% of the enclosed population for the LDM case. *Our error budget is dominated by the parameters we set free.*

	$k_{cut}/\mathrm{Mpc}^{-1}$	n_{cut}	$M_0^{hof}/M_\odot$	α^{hof}	β^{M_*}
Meaning	Scale above which $P(k)$ is enhanced	Slope of the enhanced $P(k)$	Halo mass above which halos host galaxies	Steepness of the halo occupation fraction	Slope of the stellar mass-halo mass relation
Definition	Eq. (1)	Eq. (1)	Eq. (13)	Eq. (13)	Eq. (10)
Value in Fig. 4	8	2.6	$10^{8.35}$ [37, 143]	1.31 [37, 143]	0.963 [102]
Scan range	(4, 45)	(1, 5)	$(10^7, 10^{11})$	(1, 10) [34, 69]	(0, 3)
1σ range	(4, 45)*	(1, 5)*	$(10^7, 10^{7.9})$	(1, 10)	(1.0, 1.7)

	$\sigma^{M_*}/\mathrm{dex}$	$\gamma^{M_*}/\mathrm{dex}$	$M_{thres}^{core}/M_\odot$	$\mathcal{Y}_C$	$\sigma_{\mathcal{C}_\Omega}$
Meaning	Stellar mass-halo mass scatter at $10^{11}\ M_\odot$	Mass dependence of stellar mass-halo mass scatter	Halo mass below which DM profiles are cored	Amount of tidal halo disruption	Anisotropy in the satellite distribution
Definition	Eq. (11)	Eq. (11)	Below Eq. (12)	Eq. (17)	Below Eq. (17)
Value in Fig. 4	0.15 [102]	0 [102]	$10^9\ M_\odot$ [22]	1	1
Scan range	(0, 2) [69, 106]	(-2, 0)	$(10^7, 10^{11})$	(0, 1)	(0, 2)
1σ range	(0, 1.5)	(-0.6, -0.2)	$(10^7, 10^{7.2})$	(0.4, 1)	(0.87, 1.14)

TABLE I. Parameters in our analysis. The parameters whose 1σ range has a * are strongly correlated with other parameters (see Fig. C1); meaningful constraints can be derived when other parameters are fixed. For the theoretical population in Fig. 4, we use illustrative galaxy-halo connection parameters (see references). Some scan ranges are physics-motivated (see references).

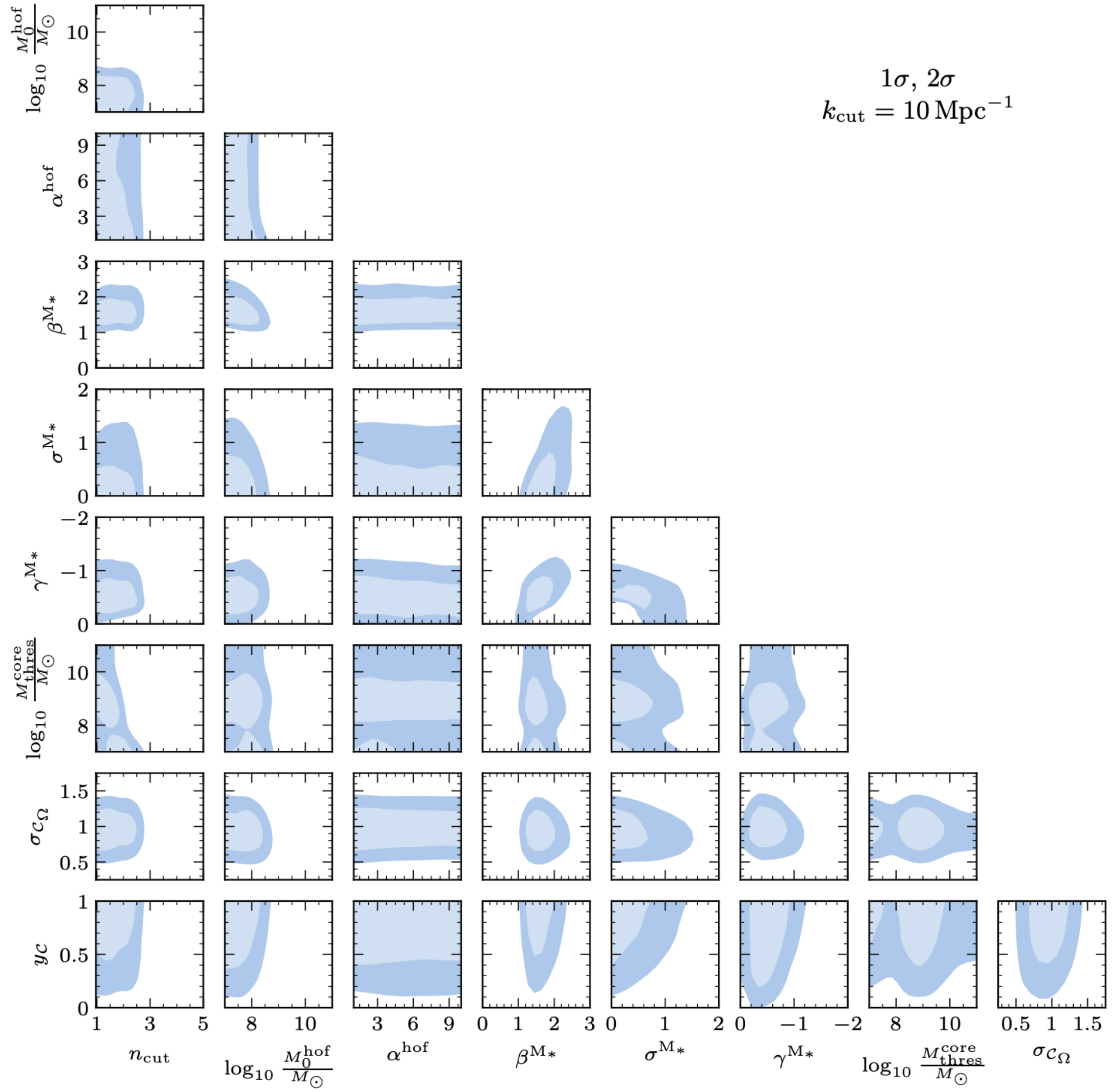


FIG. C1. Allowed regions within 1σ and 2σ for all parameters in our analysis. For each pair of parameters shown, all other parameters are minimized over in the likelihood. To visualize correlations with our determination of the power spectrum, we fix $k_{\rm cut} = 10\,{\rm Mpc}^{-1}$. *Parameters controlling galaxy-halo connection and baryonic feedback are mostly independent of the DM power spectrum.*

DWARF GALAXIES

Galaxy	$\sigma^*_{\rm los}$ [km/s]	$R_{\rm eff}$ [kpc]
Fornax	11.7 ± 0.9	0.710 ± 0.077
Leo I	9.2 ± 1.4	0.251 ± 0.027
Sculptor	9.2 ± 1.4	0.283 ± 0.045
Leo II	6.6 ± 0.7	0.176 ± 0.042
Sextans I	7.9 ± 1.3	0.695 ± 0.044
Carina	6.6 ± 1.2	0.250 ± 0.039
Draco	9.1 ± 1.2	0.221 ± 0.019
Ursa Minor	9.5 ± 1.2	0.181 ± 0.027
Canes Venatici I	7.6 ± 0.4	0.564 ± 0.036
Hercules	3.7 ± 0.9	$0.330^{+0.075}_{-0.052}$

Galaxy	$\sigma^*_{\rm los}$ [km/s]	$R_{\rm eff}$ [kpc]
Bootes I	$2.4^{+0.9}_{-0.5}$	0.242 ± 0.021
Leo IV	3.3 ± 1.7	0.206 ± 0.037
Ursa Major I	7.6 ± 1.0	0.319 ± 0.050
Leo V	$3.7^{+2.3}_{-1.4}$	0.135 ± 0.032
Canes Venatici II	4.6 ± 1.0	0.074 ± 0.014
Ursa Major II	6.7 ± 1.4	0.149 ± 0.021
Coma Berenices	4.6 ± 0.8	0.077 ± 0.010
Bootes II	4.4 ± 1.0	0.051 ± 0.017
Willman 1	$4.3^{+2.3}_{-1.3}$	0.025 ± 0.006
Segue II	< 1.4	0.035 ± 0.003
Segue I	3.9 ± 0.8	$0.029^{+0.008}_{-0.005}$

TABLE II. List of data used in the analysis

SEGUE II

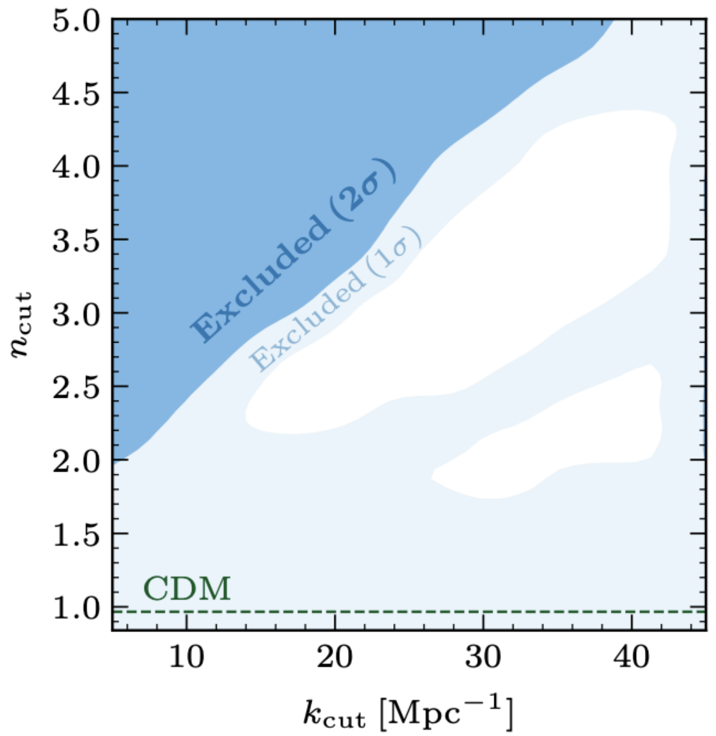


FIG. D1. Excluded values of LDM parameter space in our analysis, if the original determination of $\sigma^*_{\rm los}$ for Segue II is used