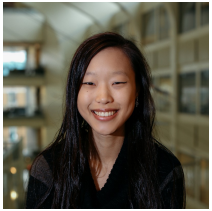
Milky Way satellite velocities reveal Dark Matter properties



Ivan Esteban

28th May 2025

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

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The Dark Matter puzzle is central to

- Fundamental physics
- Astrophysics

We do not fully understand the second most abundant component of the Universe, key for structure formation!

Introduction

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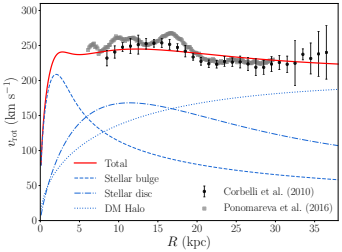
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

Some evidence

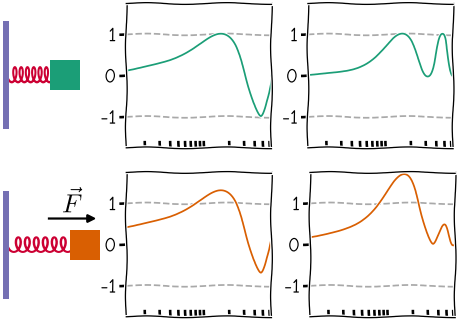


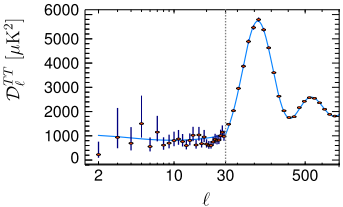
More matter than stars

M31. From arXiv:2111.05343

Structure at $z \sim 10$.

Inhomogeneities grow by $\sim 10^2$ since CMB!





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Making progress

We robustly know that Dark Matter,

- Exists
- Is abundant
- Is cold (on large scales)

This is already a big step. **How do we make further progress?**

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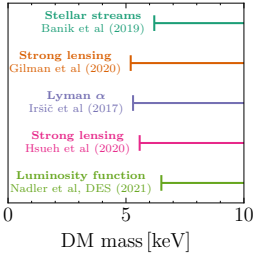
Making progress

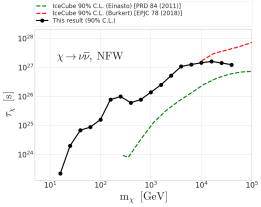
How do we make progress?

Progress is sometimes hard to define, but in my humble opinion from the observational/pheno point of view **pushing boundaries** is a good idea.

Mass?

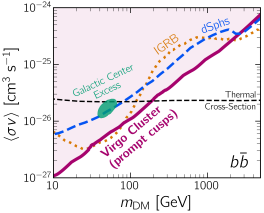


Lifetime?



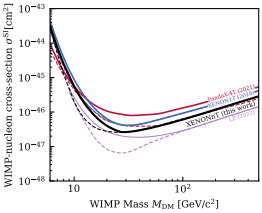
IceCube, 2303.13663

Annihilation?



Crnogorcevic et al, 2501.14865

Interactions?



XENONnT, 2303.14729

. . . ?

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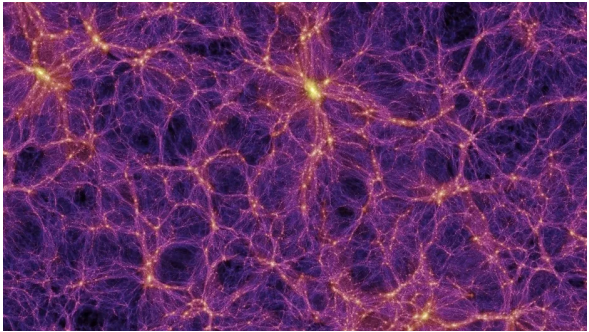
My focus in this talk

How does DM cluster at small scales? How can we probe it?



TL;DR: *Abundances, internal velocities, and sizes of dwarf galaxies*

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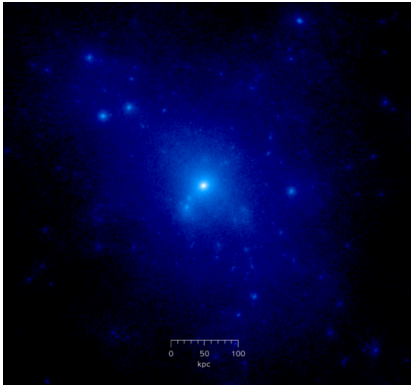
DM at dwarf scales

DM perturbations, in principle seeded by inflation, grow gravitationally. When $\delta\rho/\rho \sim 1$, they *virialize* into **DM halos**.



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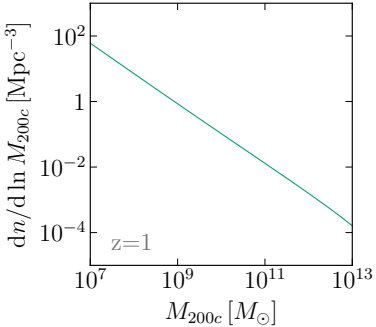
DM at dwarf scales

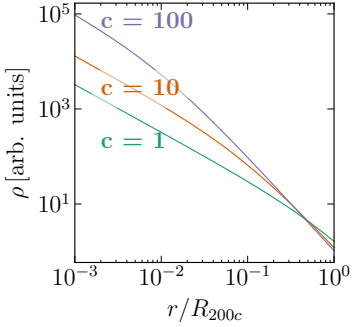
DM perturbations, in principle seeded by inflation, grow gravitationally. When $\delta\rho/\rho \sim 1$, they *virialize* into **DM halos**. Characterized by

Mass (equivalently, "virial" radius: $M_{200c} \equiv 200\,\rho_c \times 4/3\pi\, R_{200c}^3$)



Concentration ($\rho \propto r^{-1}(1 + r/r_s)^{-2}$)

$c_{200c} \equiv R_{200c}/r_s$



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Semianalytic methods

How do we predict halo masses and concentrations?

- *N-body simulations*: accurate. Expensive and still miss some physics.
- *Semi-analytic methods*: faster and easier to understand, good first step. Need calibration and are not the last word.

As a 1st step, the standard approach is start with semi-analytic methods.

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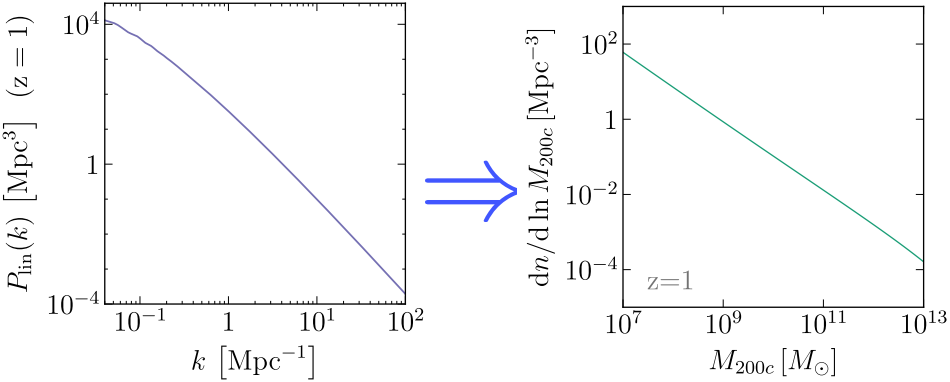
Semianalytic methods in practice: halo mass distribution

Rough idea: *study halo formation as a consequence of random fluctuations of density perturbations*. **The main input is the linear matter power spectrum $P(k)$.** Sheth & Tormen, 2002



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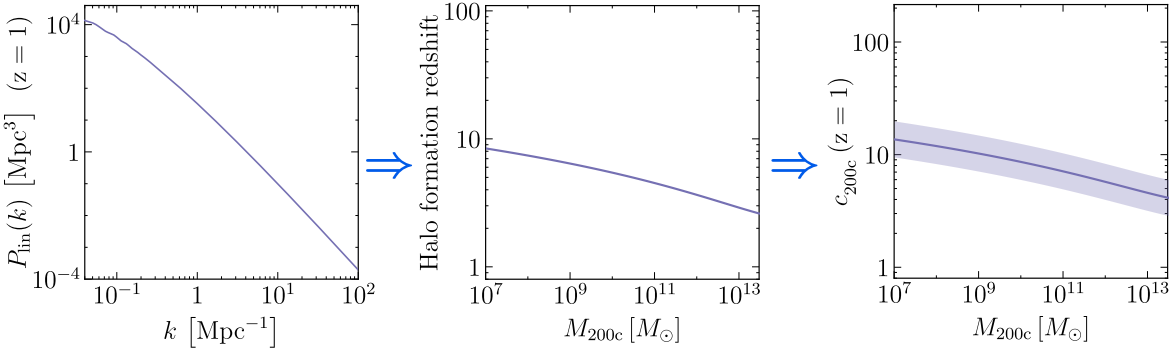
Semianalytic methods in practice: halo concentration

Rough idea: *study halo formation as a consequence of random fluctuations of density perturbations*. **Halos formed earlier have higher concentrations**. Diemer & Joyce, 2019



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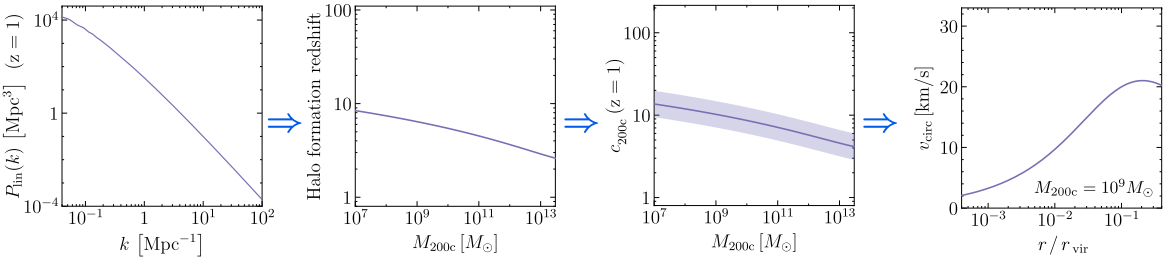
Semianalytic methods in practice: halo concentration

Rough idea: *study halo formation as a consequence of random fluctuations of density perturbations.* **Halos formed earlier have higher concentrations. This impacts internal velocities**. Kim & Peter, 2022



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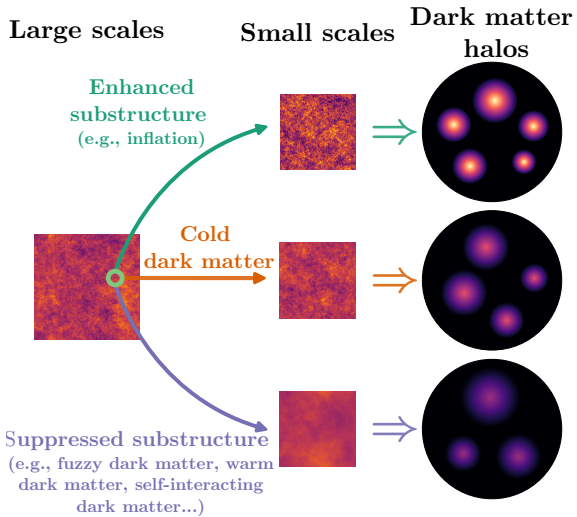
Probing Dark Matter properties

The basic idea of

$$P(k)$$
$$\Downarrow$$
Abundances & Concentrations
$$\Updownarrow$$
Abundances & Internal velocities

Can be used to study how DM clusters, $P(k)$.



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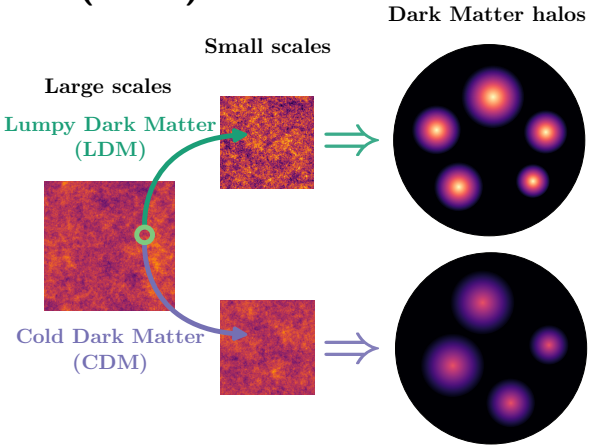
Introduction

For concreteness, we focused on models with *enhanced substructure*: **Lumpy Dark Matter (LDM)**.



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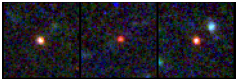
Why LDM?

From an observational/pheno point of view,

- Most of the models in the literature (warm dark matter, fuzzy dark matter...) have suppressed substructure. *What are the consequences of enhanced substructure?*
- Some simulations/datasets suggest "too many satellites" Kim et al, 2018; Graus et al, 2019.
- JWST! 

Why LDM?

From a theory point of view, several theories predict enhanced substructure

- Production out of fluctuations during inflation (DM can have zero interactions with baryons, i.e., "nightmare scenario") Graham et al, 2016; Alonso-Álvarez & Jaeckel, 2018; Tenkanen, 2019.
- Primordial magnetic fields. Subramanian, 2016
- Deviations from single-field, slow-roll inflation. Zentner & Bullock, 2002; Zentner & Bullock, 2002; Achúcarro et al, 2022.

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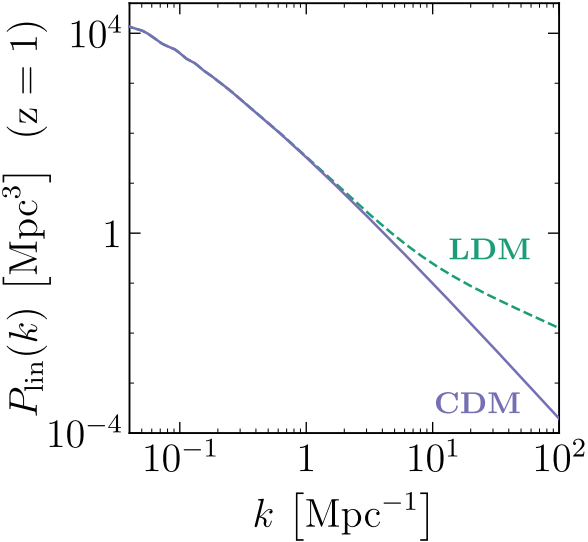
LDM in a nutshell



Phenomenologically, parametrized as

- Scale below which power is enhanced, $\equiv k_{\rm cut}$
- Enhanced spectral index, $\equiv n_{\rm cut}$

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

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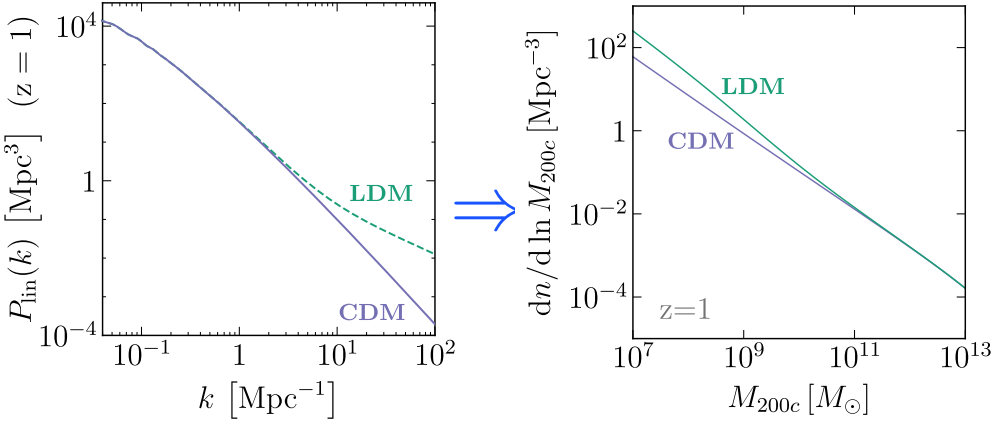
Consequences: halo masses

Exactly as before, we can use semi-analytic theory to predict halo masses (checked against simulation!) Hirano et al, 2015



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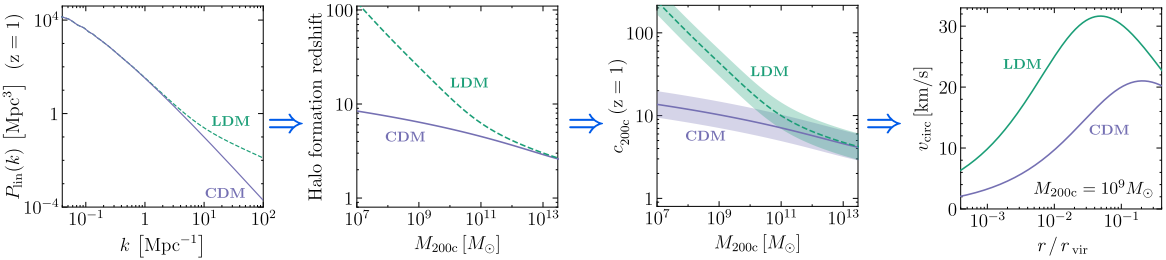
Consequences: concentrations and circular velocities



Large differences in halo formation redshift and concentration! Zentner & Bullock, 2002; Hirano et al, 2015

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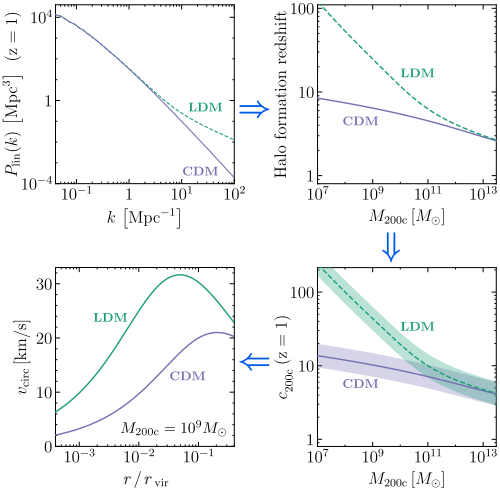
Consequences: concentrations and circular velocities

It's worth to pause and get some analytic understanding



The key quantity for halo formation is not really the linear power spectrum, $P(k)$; but the *variance of the density field*

$$\sigma^2(R(M),z) \equiv \int \frac{\mathrm{d}^3 k}{(2\pi)^3} P(k,z)|W(k,R)|^2$$

$W(k,R)$ picks out $k \sim 1/R$.

Scale invariance: $P(k) \propto k^{-3}$, $\sigma \sim \ln 1/R$.

LDM breaks cancellation. **Small scales collapse much earlier**.

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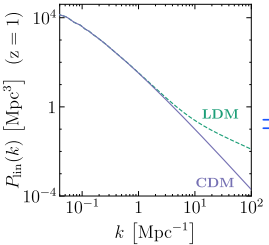
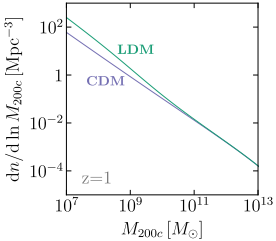
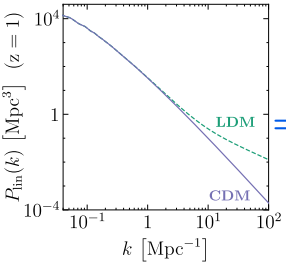
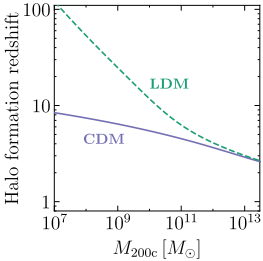
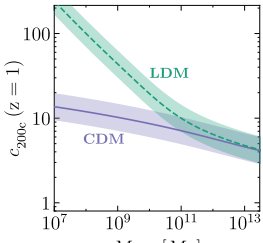
Consequences in a nutshell

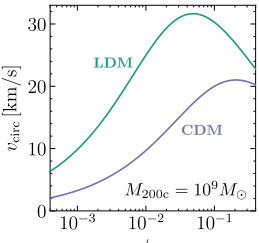












More halos, higher velocities.

If we could directly detect DM halos and their internal velocities, this would be the end of the talk.

Dwarf galaxies

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See arXiv:2306.04674, with A. Peter and S. Y. Kim!

To probe LDM, we need to look at small-scale halos. These halos host **dwarf galaxies**.

- **Small** compared to $M_{\rm MW} \simeq 10^{12}\, M_\odot$ ($10^8\, M_\odot \lesssim M \lesssim 10^{10}\, M_\odot$; $10\,{\rm Mpc}^{-1} \lesssim 1/R \lesssim 50\,{\rm Mpc}^{-1}$)
- **DM dominated** ($M_*/M < 10^{-2}$)
- **Many!** ($>$ 50 orbiting MW)
- Stars are near the **halo center**!

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Wrapping up

To summarize, we start halo **masses** and **concentrations** (computed semi-analytically with Galacticus). This encodes DM physics.

To convert to observable galaxy properties, we use

- Halo occupation fraction (Number of halos $\Rightarrow$ Number of galaxies)
- Stellar mass–halo mass relation ($M_{200c} \Rightarrow M_*$)
- Stellar mass–half-light radius relation ($M_* \Rightarrow R_{\rm eff}$)
- Line-of-sight stellar velocity dispersion ($c \Rightarrow \sigma^*_{\rm los}$)
- Baryonic feedback (cores, tidal disruption)
- Selection effects

that we can compare with observations!

Including data

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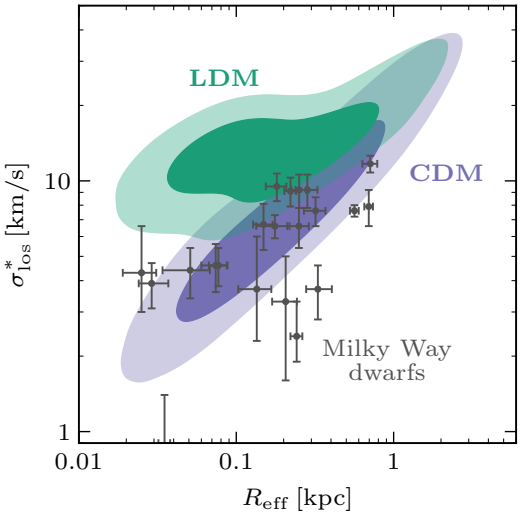

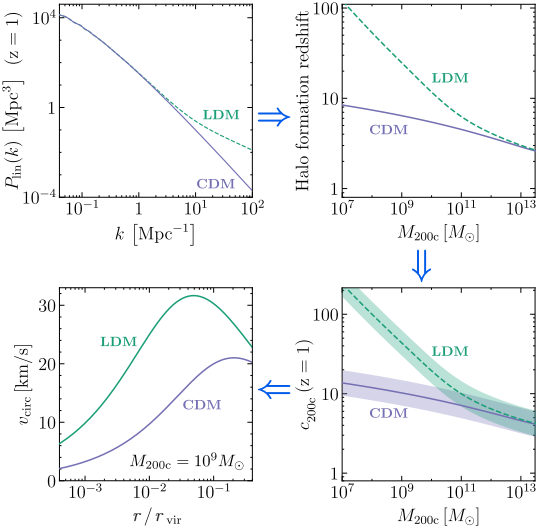

Including data

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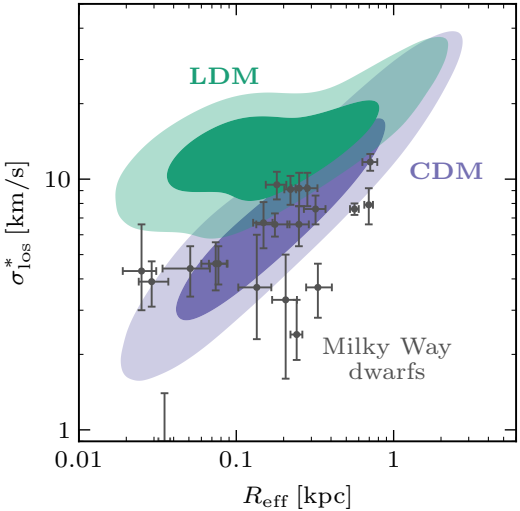
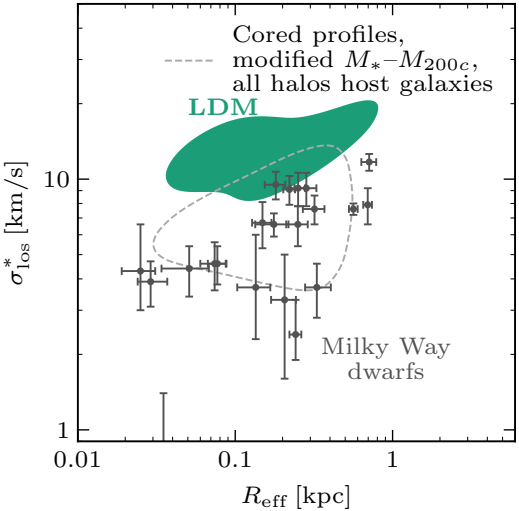
What about uncertain galaxy-halo connection?





Dark Matter power spectrum

Let's get back to the opening question:

How does DM cluster at small scales?

Results

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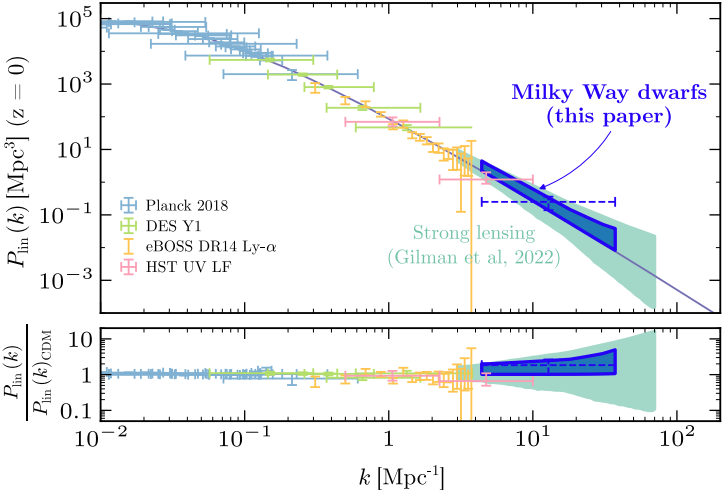
Dark Matter power spectrum



- Leading-precision at small scales!
- Determined by the velocity-size *correlation* (i.e., concentration-mass): robust against uncertain galaxy-halo connection!

  The strongest degeneracy we find is with cores.
- For consistency, we have explored enhanced and suppressed $P(k)$.

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Conclusions

- I think that a way to make progress in characterizing DM is by pushing boundaries (mass, lifetime, . . .)
- One example is *how does DM cluster at smaller scales*?
- Several theory models (e.g., inflation) predict **Lumpy Dark Matter**.
- Using it as a benchmark, we have shown that **the correlation between dwarf galaxy sizes and stellar velocities is a sharp probe of DM properties**. It reflects the mass–concentration relation, i.e., *the halo formation times* ("fine-tuned" in CDM).
- Factor-of-2 determination of small-scale power spectrum.

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Future directions

We just scratched the surface of the method

- More data
- Other DM models (WDM, SIDM, FDM...)
- More detailed simulation/modeling (on the DM side or the galaxy side)
- Test galaxy formation models!
- Reionization? High-redshift galaxy luminosities? JWST?

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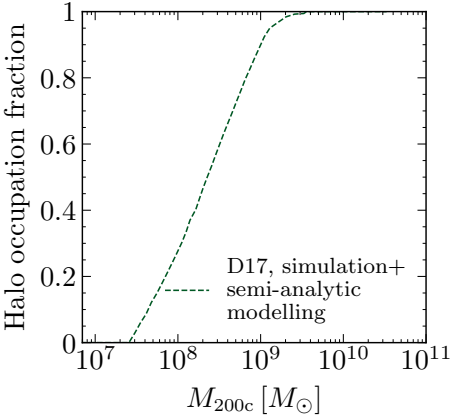
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

From halos to dwarfs: halo occupation fraction

Only halos massive enough by reionization are expected to host galaxies.



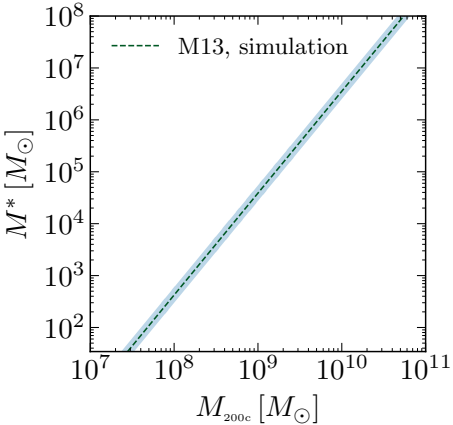
Dooley et al, 2017

Not well understood, **we leave it free in our analysis**.

Ivan Esteban, Basque University, ivan-esteban.com, ivan.esteban@ehu.eus
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

From halos to dwarfs: stellar mass-halo mass relation

Halos are characterized by **mass** and **concentration**. But we measure stellar masses, not DM halo masses.



Moster et al, 2013

Not well understood, **we leave it free in our analysis**.

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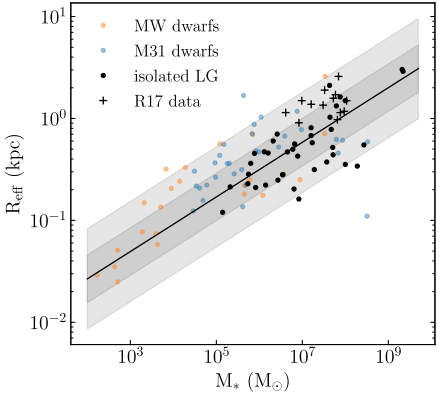
From halos to dwarfs: stellar mass–half-light radius relation

Dwarf galaxies are usually better characterized by the half-light radius, $R_{\rm eff}$. Observationally determined.



Kim & Peter, 2021

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See arXiv:2306.04674, with A. Peter and S. Y. Kim!

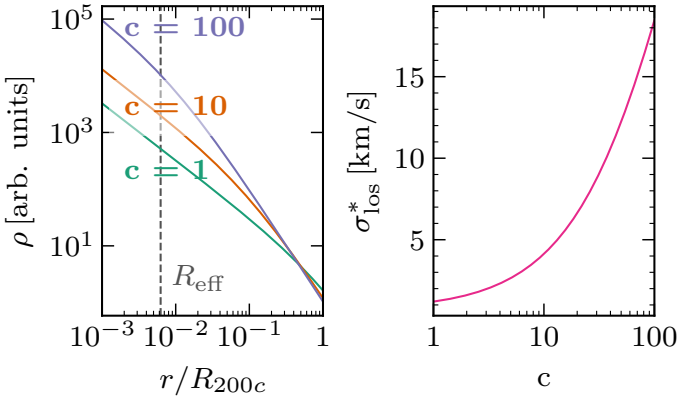
From halos to dwarfs: stellar mass-halo mass relation

Halos are characterized by **mass** and **concentration**. But we measure stellar kinematics, not halo concentrations.

$$\sigma^*_{\rm los} = \sqrt{\frac{G}{4}\frac{M(< R_{\rm eff}/0.75)}{R_{\rm eff}}}$$

Wolf et al, 2010

Derived from Jeans equation with minimal assumptions, robust against velocity anisotropy, halo profile shape, and how deeply stars are embedded in the halo



Median relations, $M_{200c} = 10^9\ M_\odot$

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Up to now

The

- Halo occupation fraction
- Stellar mass–halo mass relation
- Stellar mass–half-light radius relation
- Line-of-sight velocity dispersion

allow us to convert **mass** and **concentration** (predictable but not observable) to **velocity dispersion** and **half-light radius** (observable).

Are we done? Not yet! Baryons and selection effects!

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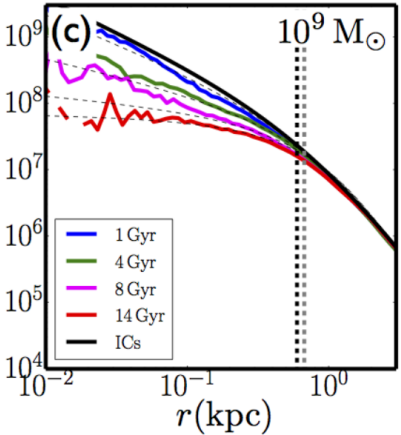
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

Baryons: cusps vs cores

Baryons (e.g., supernova explosions) can "soften" central densities, at least for high-mass halos.



Read et al, 2015, simulation- and observation-constrained.

The smallest mass with cored profiles is not well understood, **we leave it free in our analysis** (Including the unrealistic possibility of cores for all halos).

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Baryons: tidal effects and selection

We will analyze Milky Way satellites, which are not isolated! The Milky Way and its disk can,

1. Tidally strip mass from the halo outskirts.
2. Modify the halo density profile (*tidal shocking and heating*).
3. Tidally disrupt (i.e., destroy) the halo.

We have checked that #1 and #2 are negligible for us, because

- The halo density profile only enters in $\sigma^*_{\rm los}$, *sensitive to the innermost part of the halo*.
- Galaxies remain unaffected until halos lose 90%–99% of their mass.

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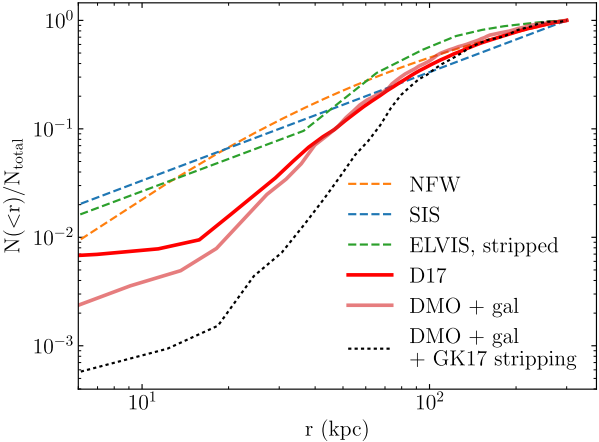
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

Baryons: tidal effects and selection (cont.)

Tidal disruption *is* relevant. It is connected with the selection function, as halos closer to the galactic center (easy to observe) will be easy to disrupt.



Kim, Peter, Hargis, 2018

There is large variance among different models.

We leave this free in our analysis

Cross-checks

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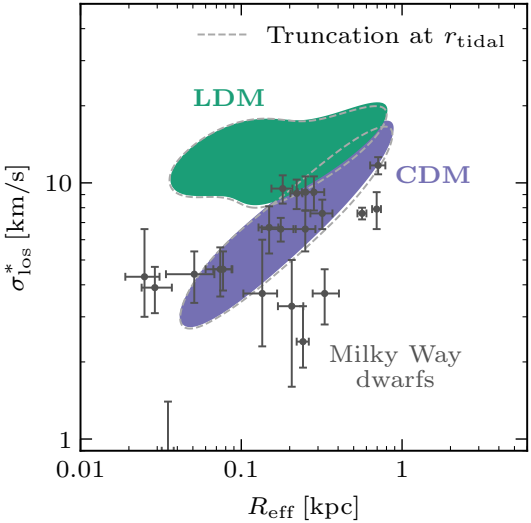
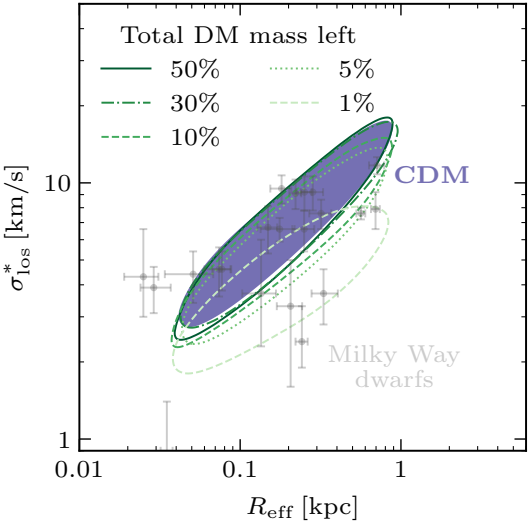
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

Tidal stripping and heating





Cross-checks

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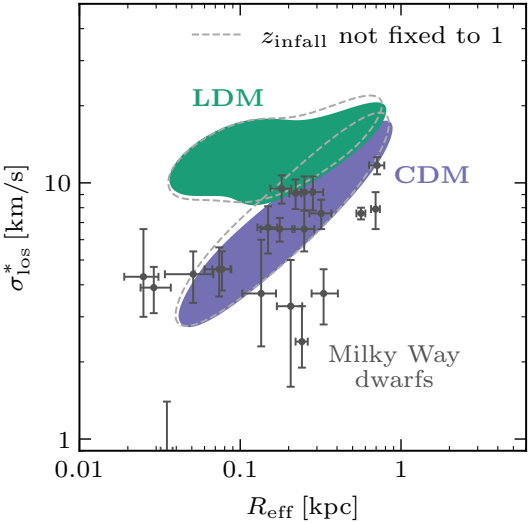
Infall times



Cross-checks

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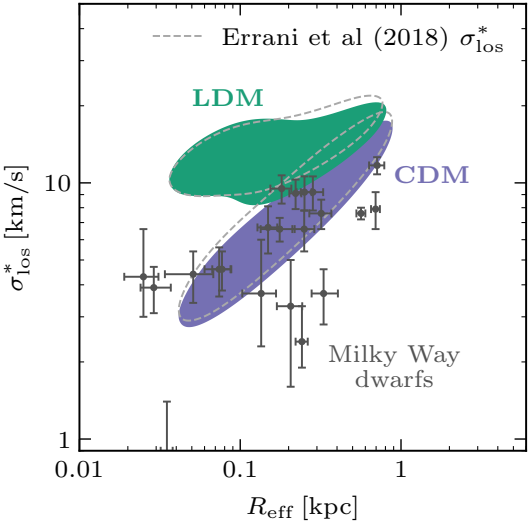
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

Velocity estimator



Cross-checks

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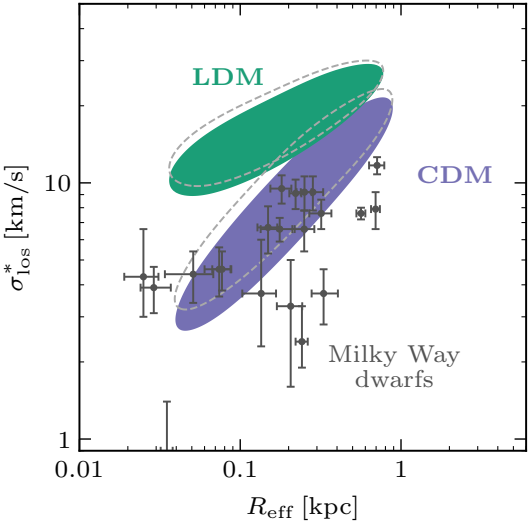
DM profile



Full results

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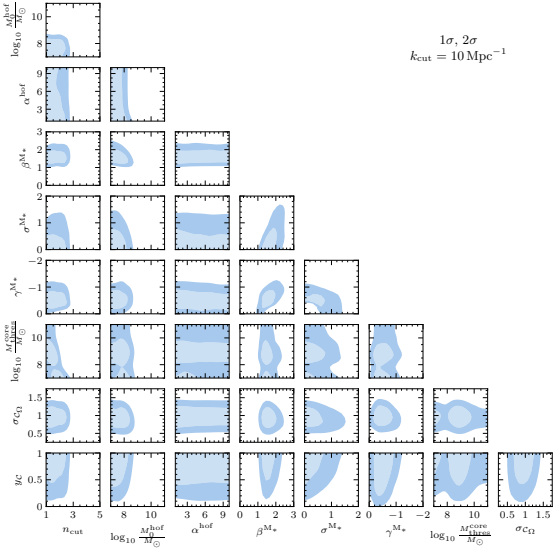
See arXiv:2306.04674, with A. Peter and S. Y. Kim!



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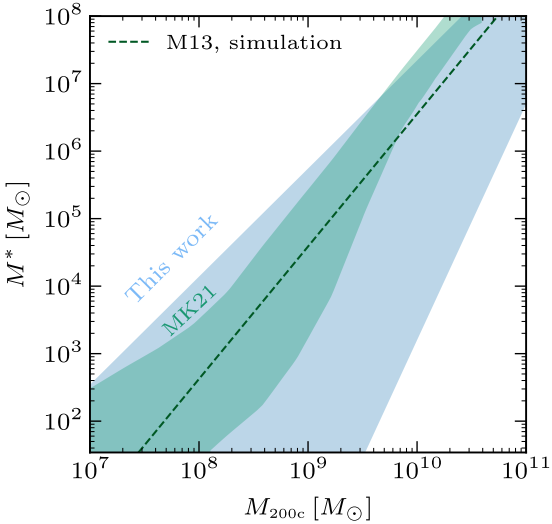
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

Galaxy–halo connection: stellar mass–halo mass relation



Compatible with previous work: Moster et al, 2013 (simulation), Mandwadkar and Kravtsov, 2021 (more satellites, using luminosity, fixed halo occupation and DM power spectrum).

- *Upper end*: avoid overproducing visible galaxies.
- *Lower end*: degenerate with halo occupation.

Should be easy to improve by including galaxy luminosities!

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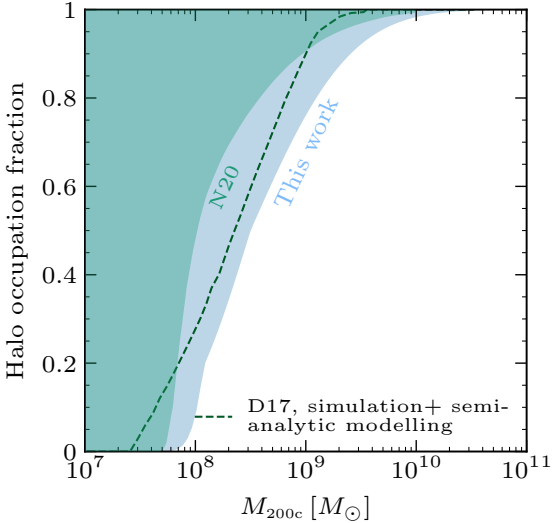
See arXiv:2306.04674, with A. Peter and S. Y. Kim!

Galaxy–halo connection: halo occupation fraction



Compatible with previous work: Dooley et al, 2017 (simulation + semi-analytic modelling), Nadler et al, 2020 (more satellites, using luminosity).

- Very massive halos *must* host galaxies: otherwise, *too many satellites*!
- Low-massive halos: degenerate with stellar mass-halo mass relation.

Should be easy to improve by including galaxy luminosities!