High speed dark matter particles in our Solar vicinity

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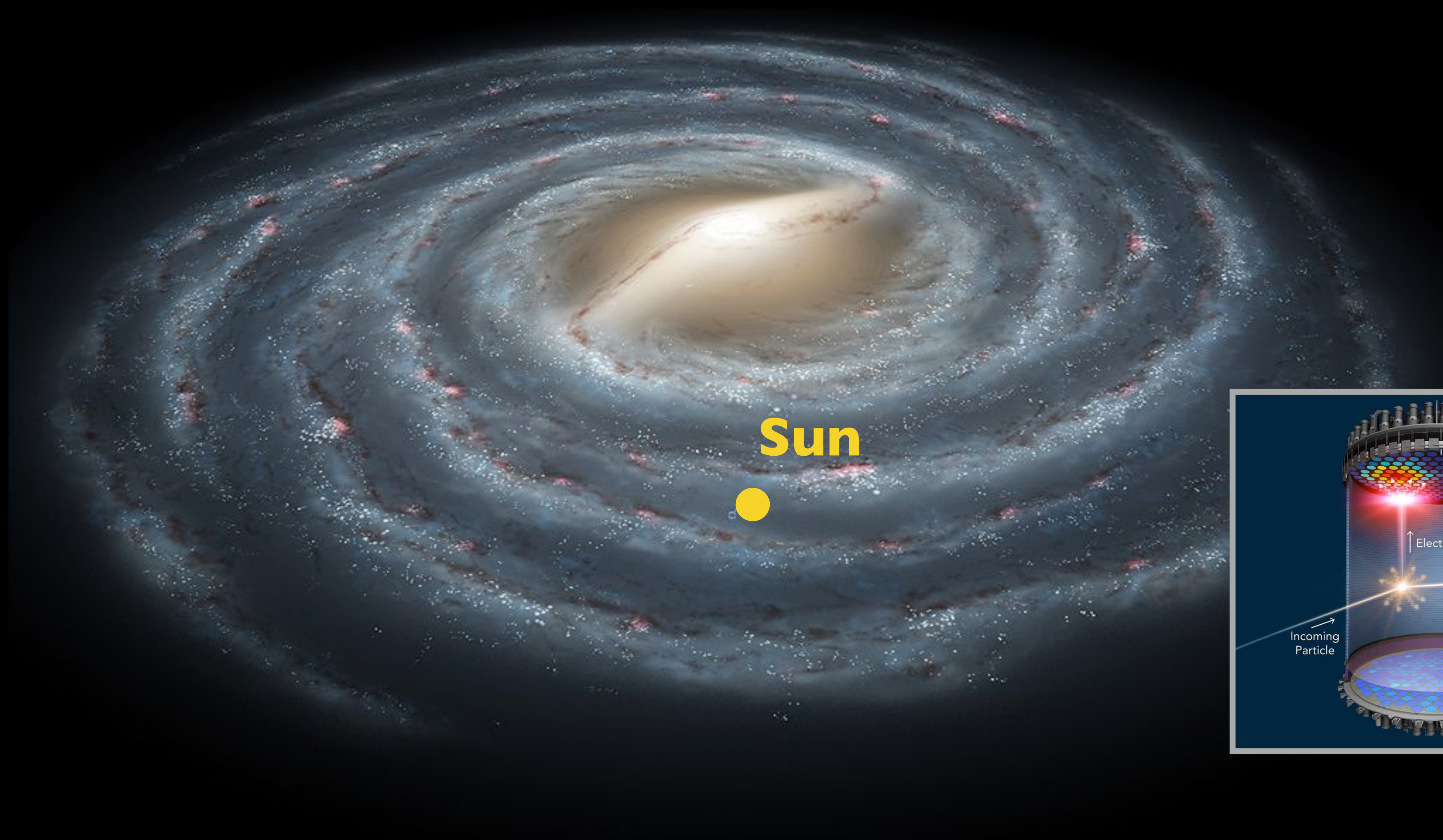
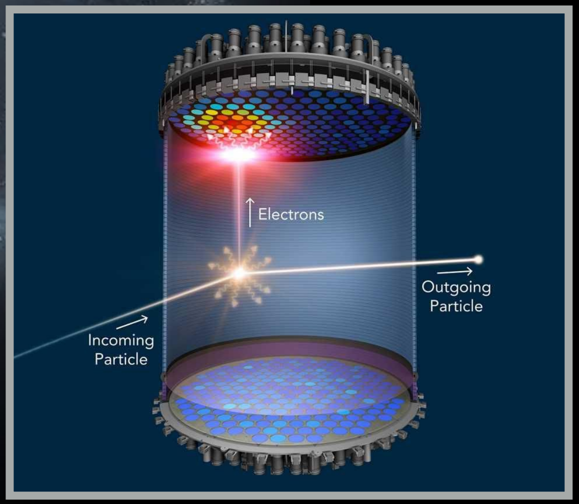
Local dark matter distribution

Signals in direct dark matter (DM) searches strongly depend on the DM distribution in the ***Solar neighborhood****.*





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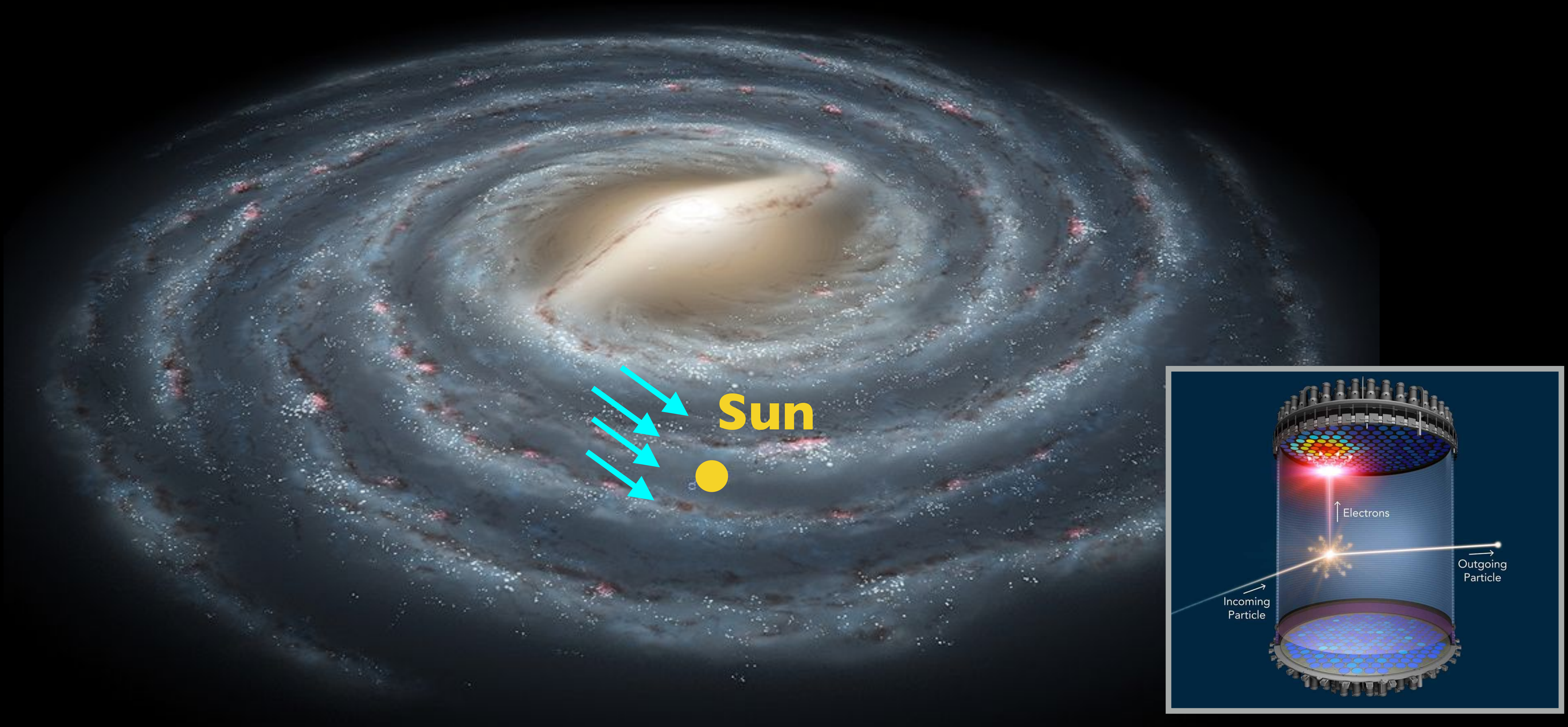

A population of high speed DM particles in our Solar vicinity can *significantly change the interpretation of direct detection data.*

Direct detection event rate

- The differential event rate (per unit detector mass):

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v > v_{\min}} d^3v \; \frac{d\sigma_{\chi N}}{dE_R} \; v \, f_{\rm det}(\mathbf{v}, t)$$

$v_{\min} = \sqrt{m_N E_R / (2\mu_{\chi N}^2)}$: minimum DM speed required to produce a recoil energy E_R.

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astrophysics

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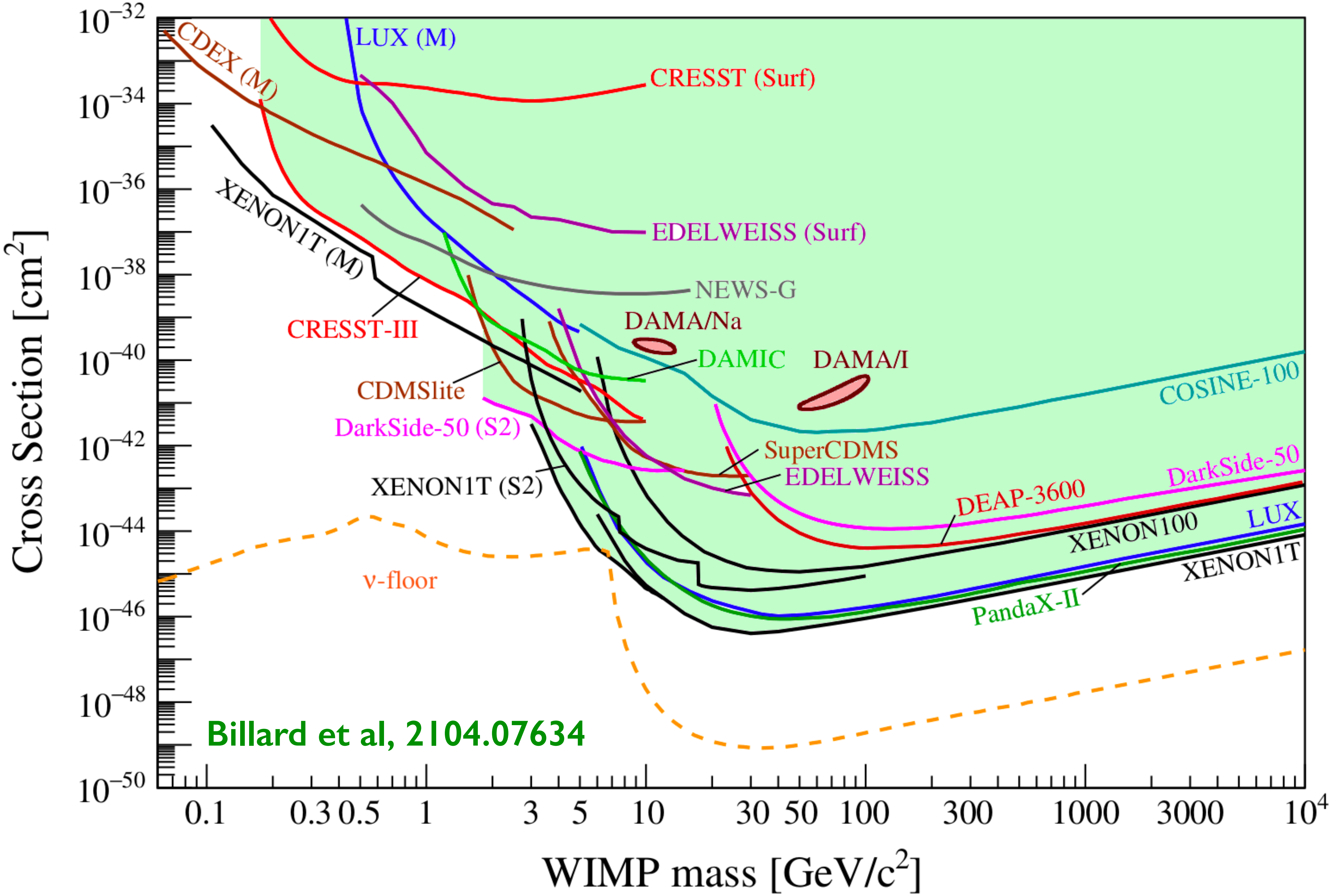
- **Astrophysical inputs:**
  - **local DM density:** *normalization in event rate.*
  - **local DM velocity distribution:** *enters the event rate through an integration.*

Direct detection status

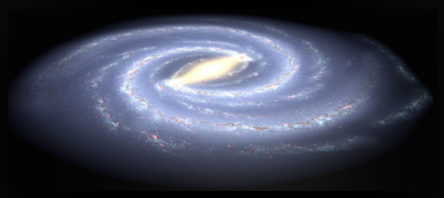


Assumption for the DM distribution: **Standard Halo Model**

Standard Halo Model

- The simplest model for the DM distribution in our Galaxy is the **Standard Halo Model (SHM)**: isothermal sphere with an isotropic Maxwell-Boltzmann velocity distribution.

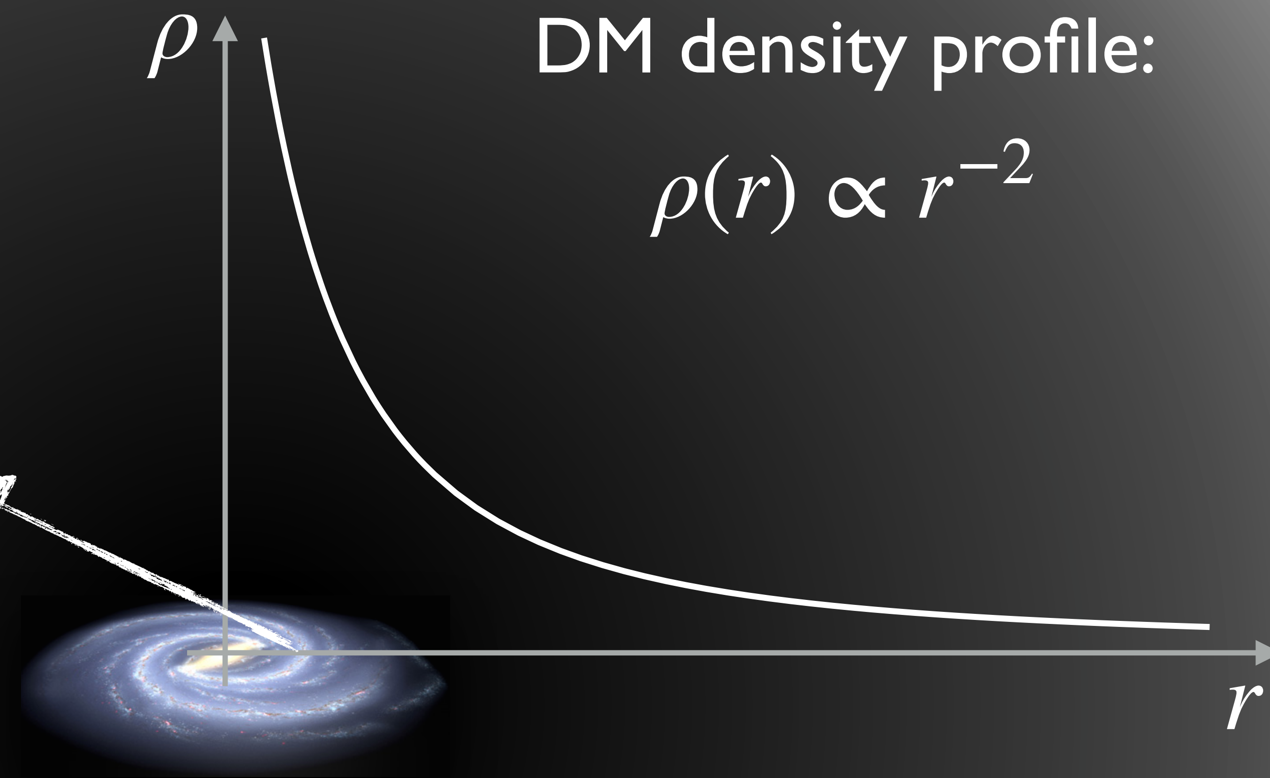
Drukier, Freese, Spergel, 1986



Standard Halo Model

- Local DM density:

$$\rho_\chi = 0.3 \text{ GeV/cm}^3$$



DM density profile:

$$\rho(r) \propto r^{-2}$$

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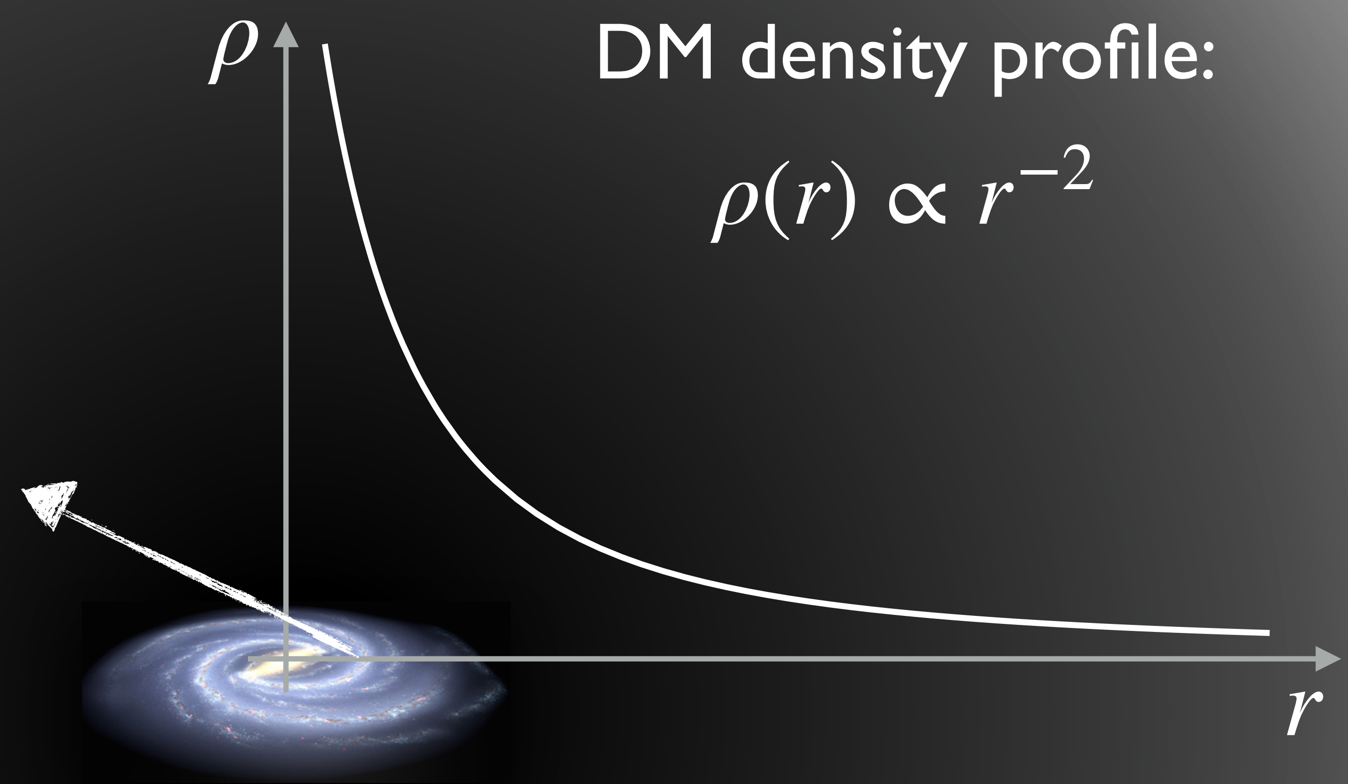

- Most probable DM speed: $v_c = 220\ \mathrm{km/s}$
- Local DM velocity distribution:

$$f_{\mathrm{gal}}(\mathbf{v}) = \begin{cases} N \exp\left(-\mathbf{v}^2/v_c^2\right) & v < v_{\mathrm{esc}} \\ 0 & v \geq v_{\mathrm{esc}} \end{cases}$$

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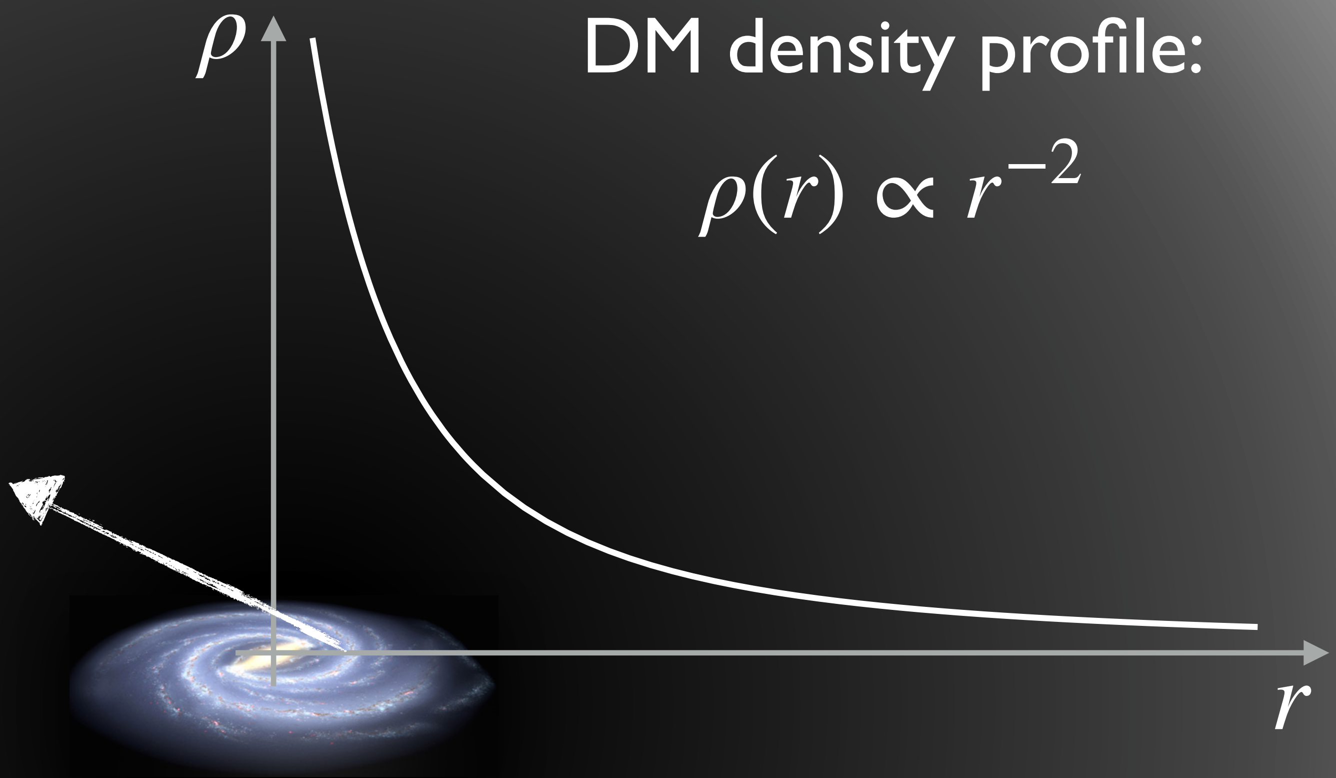

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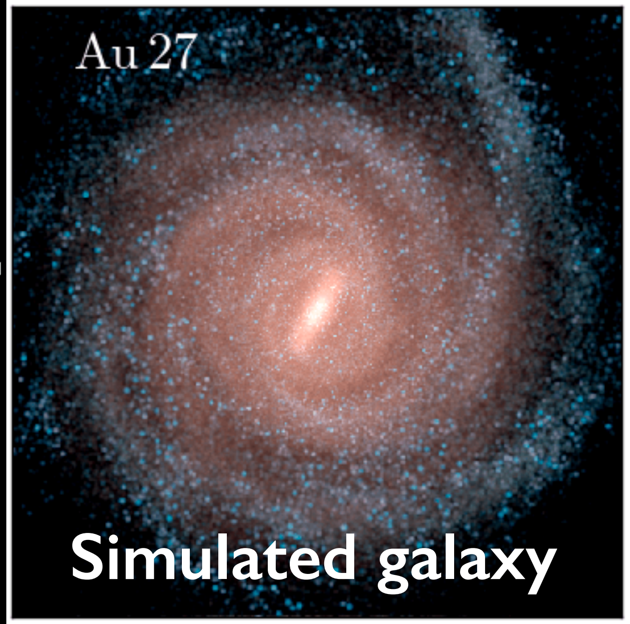
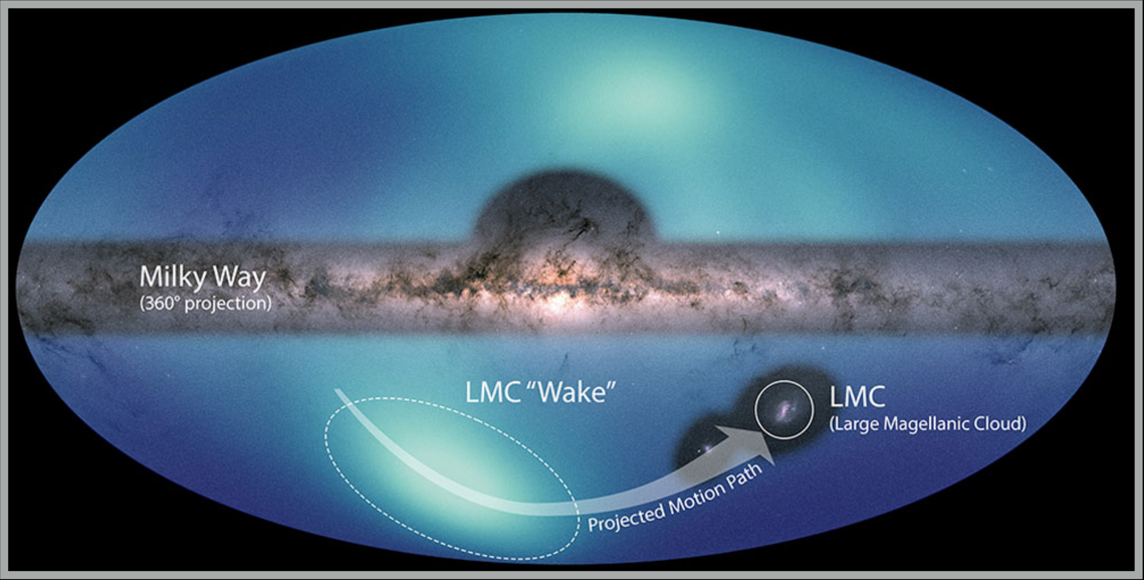
How does a massive satellite or extragalactic DM particles change this picture?

Dark matter velocity distribution

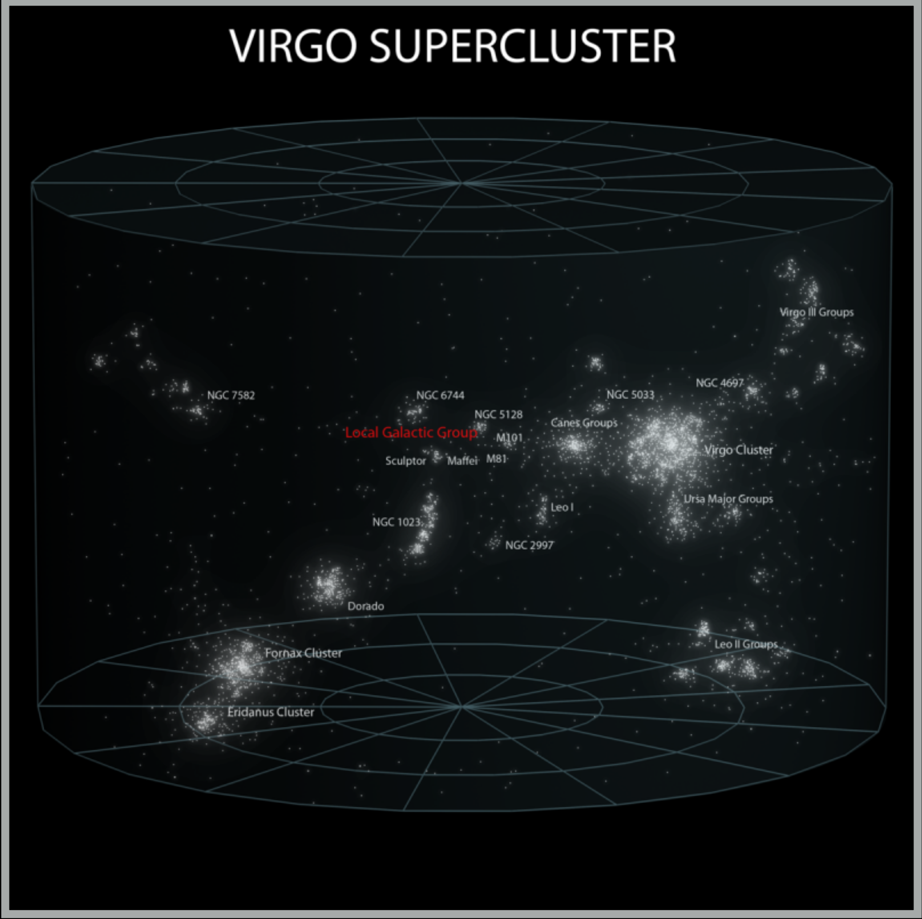
Extract the DM distribution from cosmological simulations:



Large Magellanic Cloud (LMC)



Extragalactic DM particles



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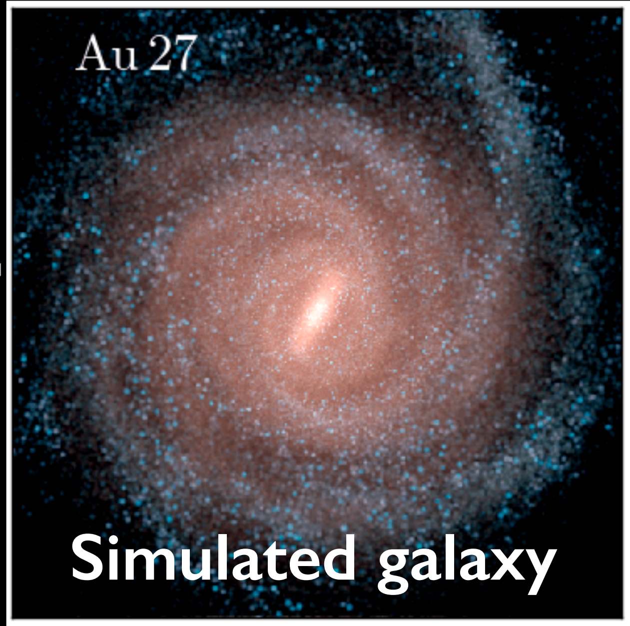

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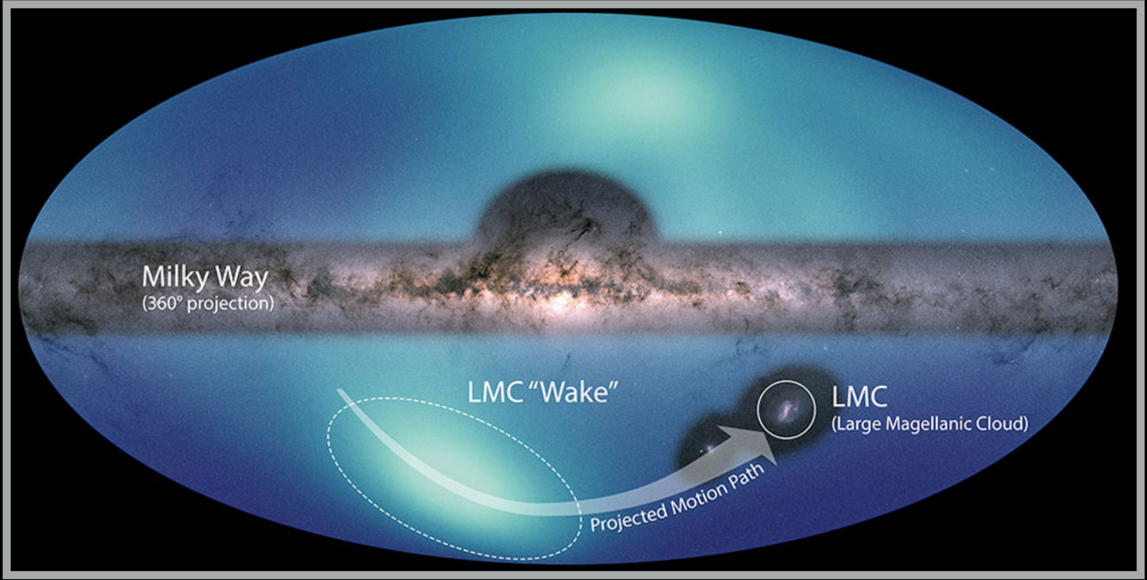

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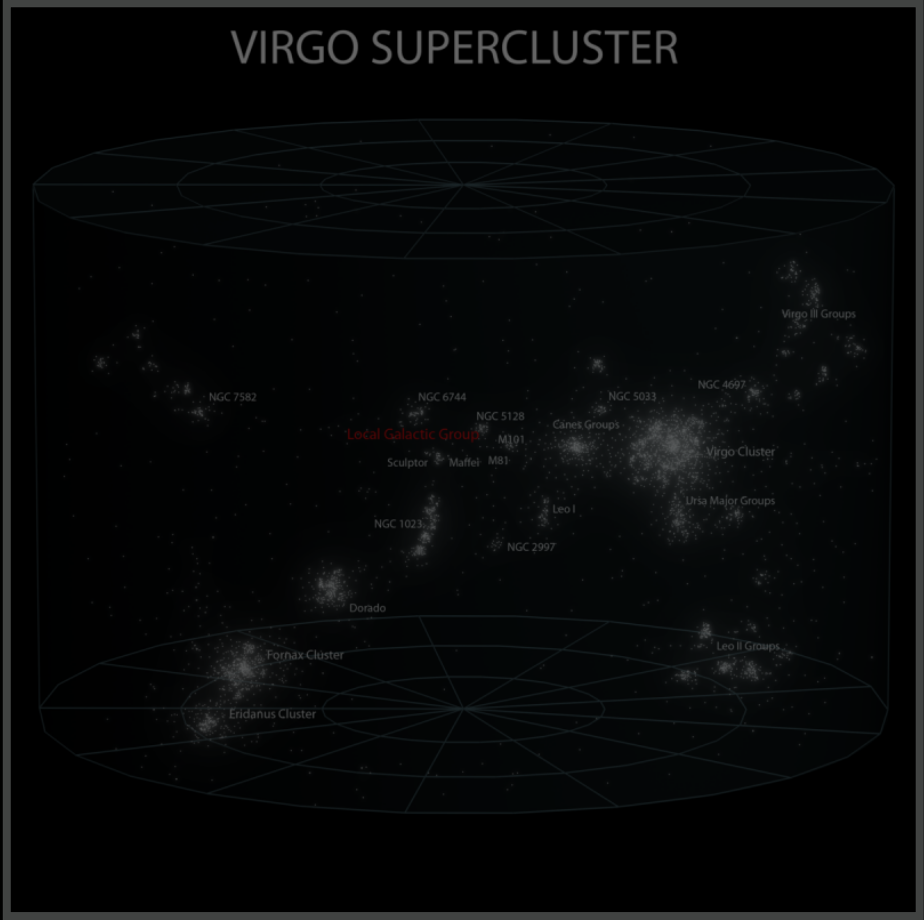
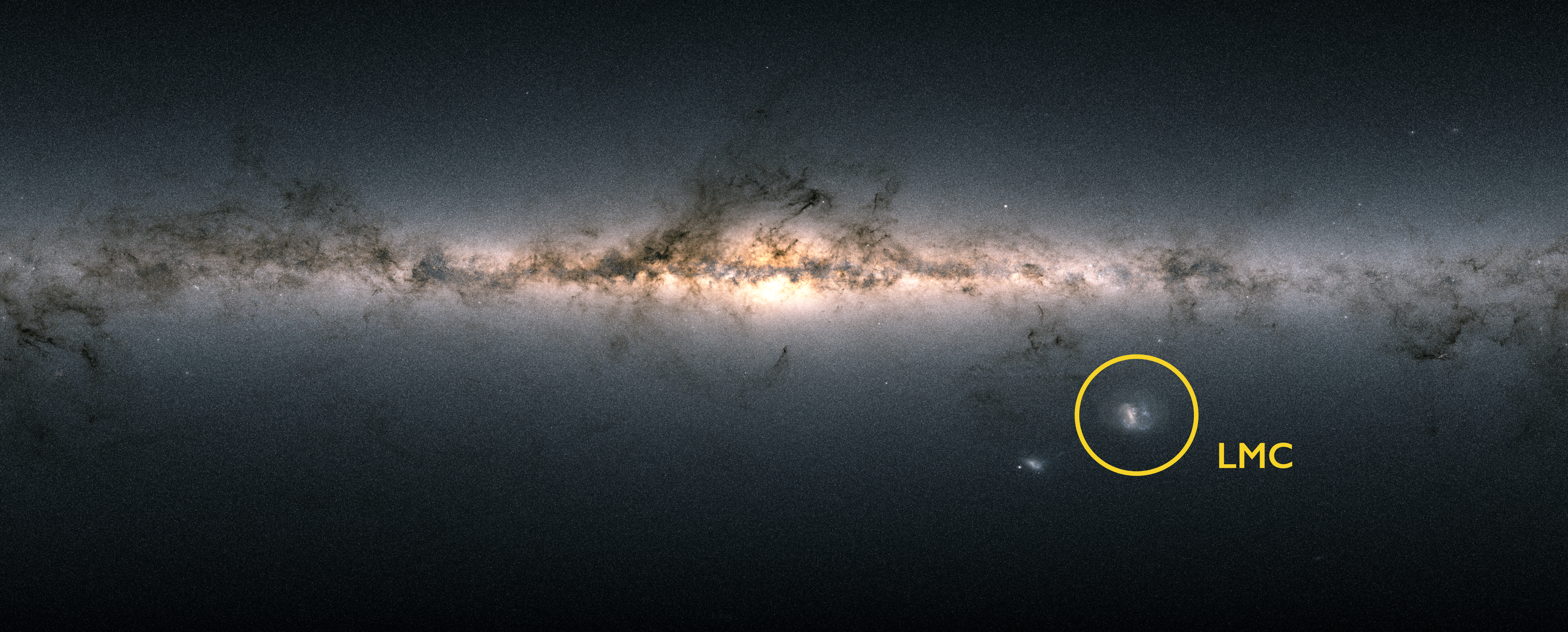
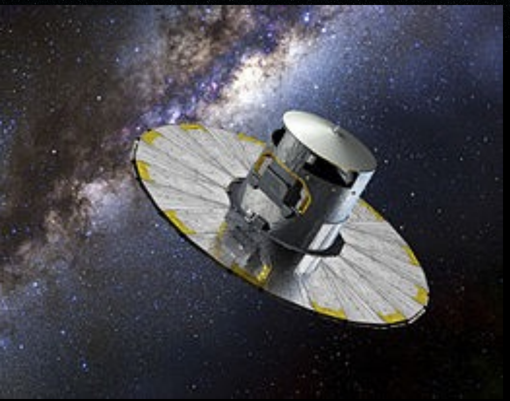


The Large Magellanic Cloud

The **LMC** is the most massive satellite of the Milky Way and likely on its first passage around the Galaxy.



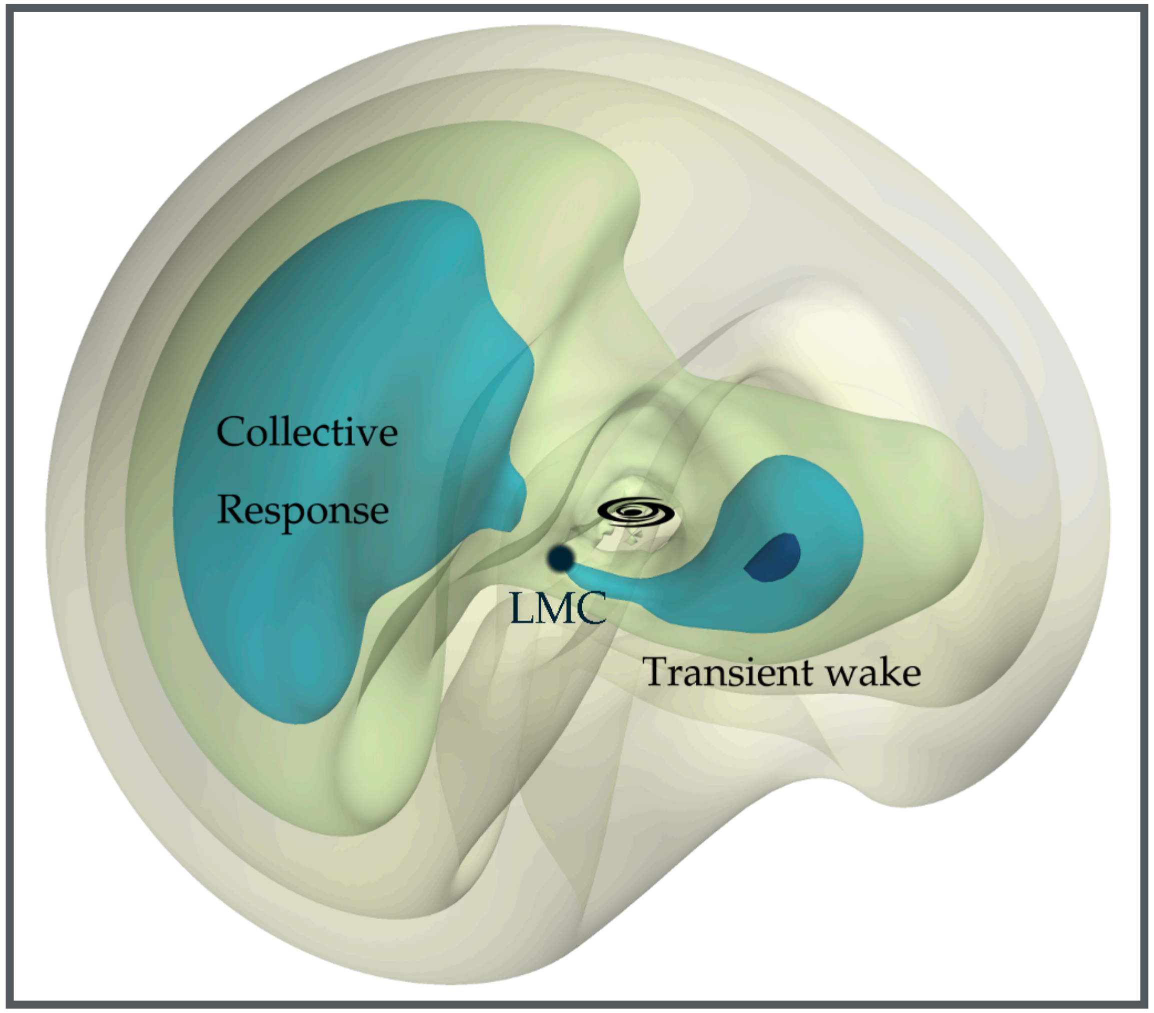


Gaia's EDR3 sky map. *Credit: ESA/Gaia/DPAC*

The effect of the LMC

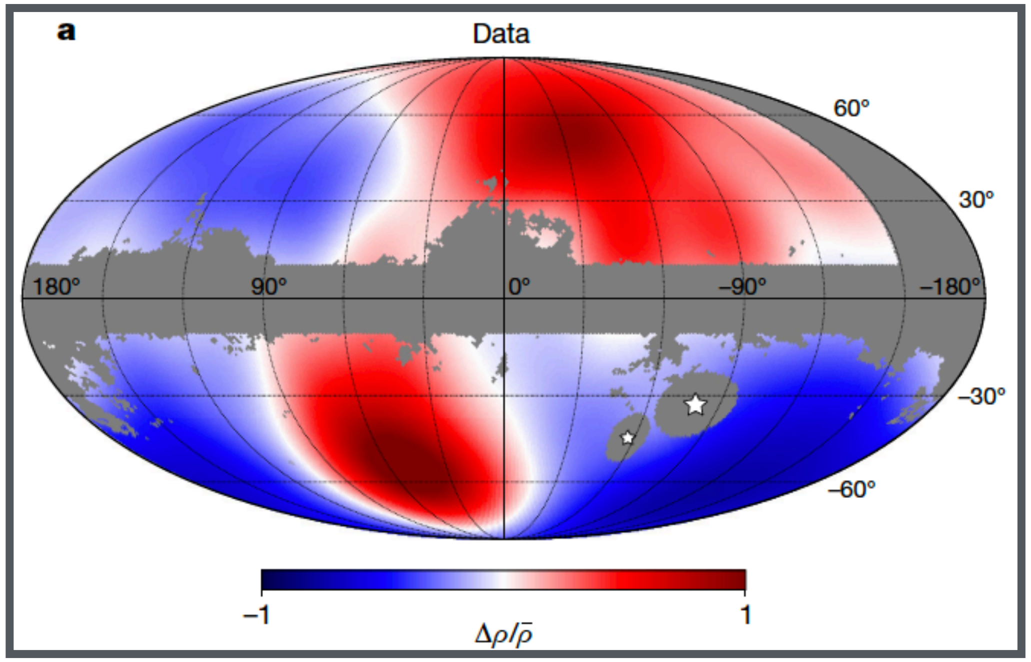
The **LMC** introduces perturbations in the DM and stellar halo.

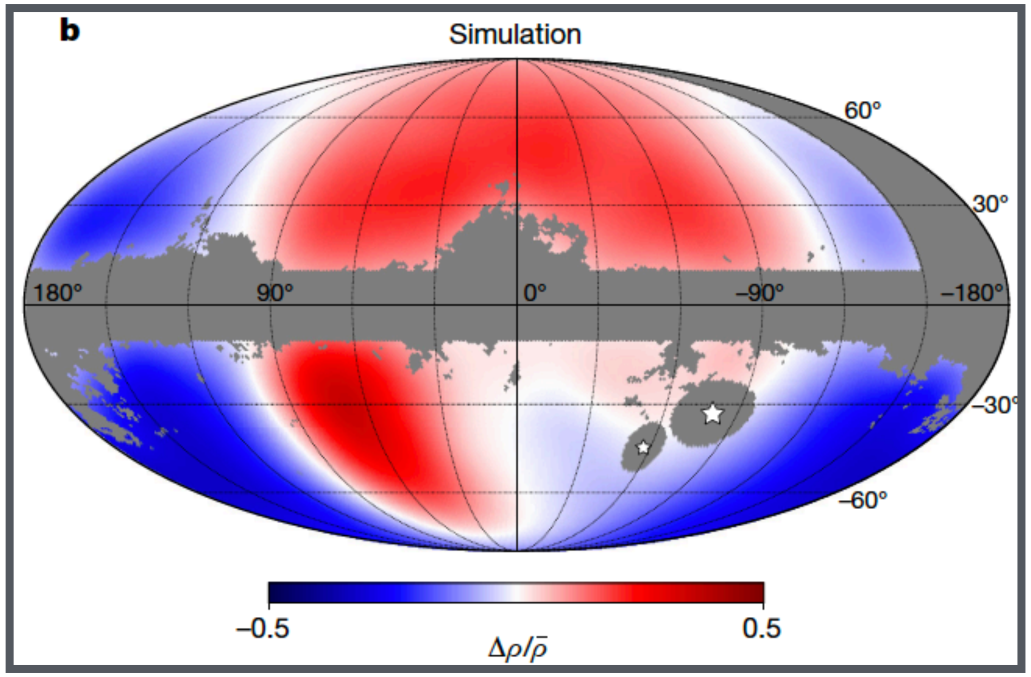
DM halo



Garavito-Camargo et al, ApJ 919, 2, 109 (2021)
Garavito-Camargo et al, ApJ 884, 51 (2019)

Stellar halo





Conroy et al, Nature 592, 534–536 (2021)

Effect of LMC on direct detection

- The **LMC** could also perturb the high speed tail of the local DM velocity distribution. → ***Affects direct detection implications for low mass DM.***

Besla et al, JCAP 11, 013 (2019)
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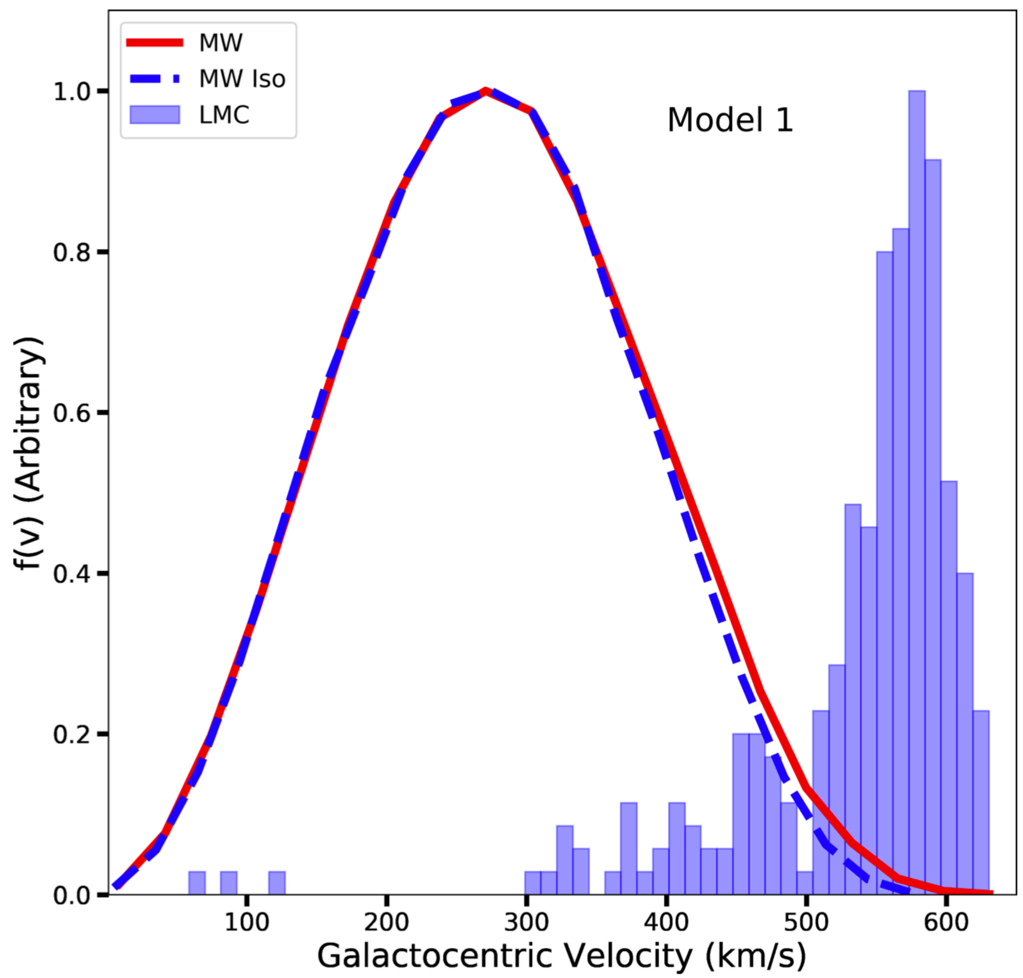

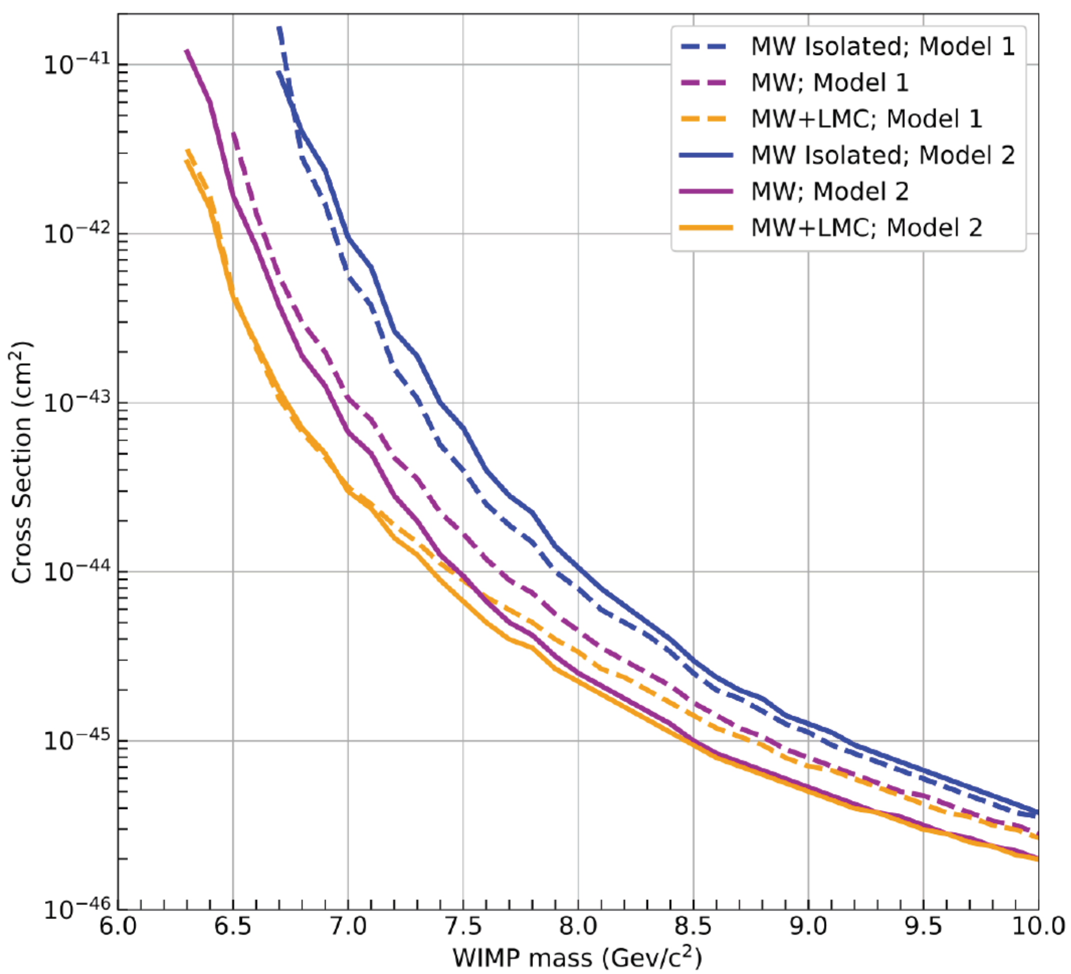

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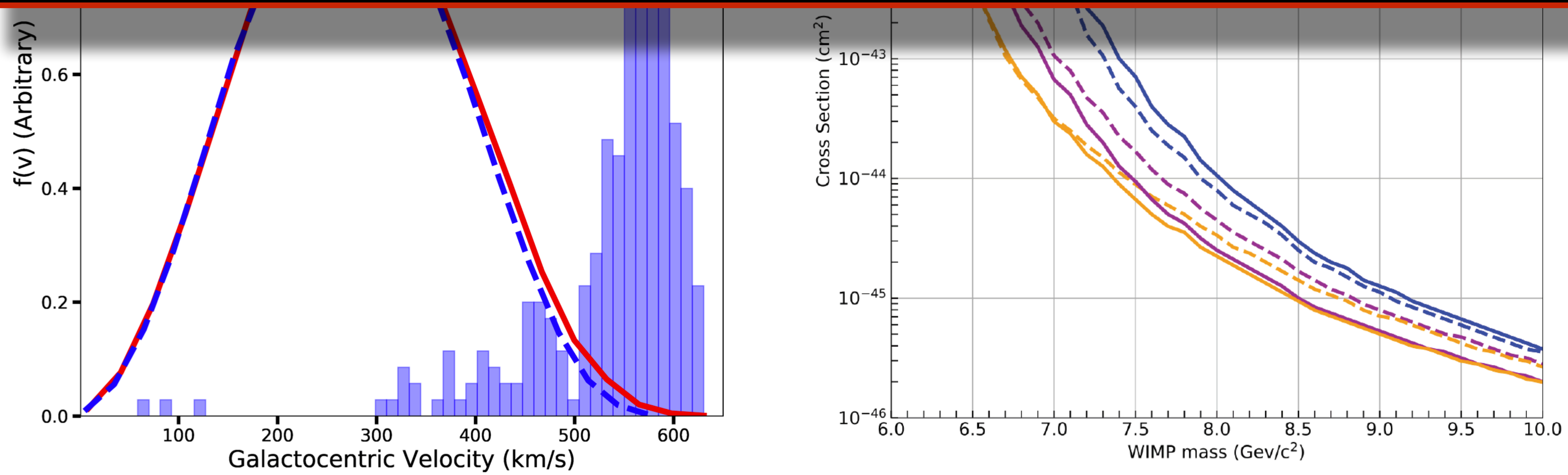
Are these findings valid for fully cosmological halos with multiple accretion events over their formation history?



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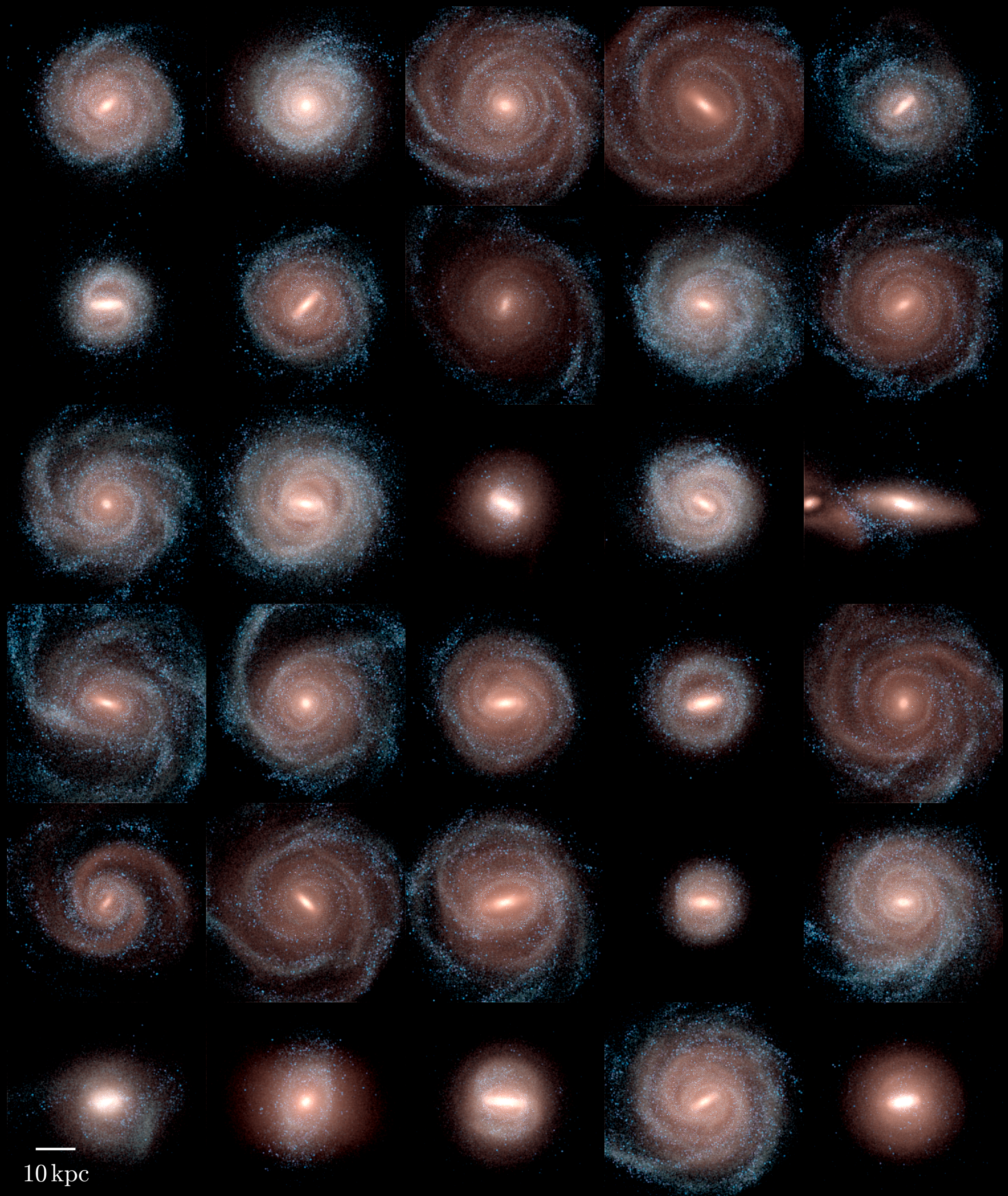
Auriga cosmological simulations

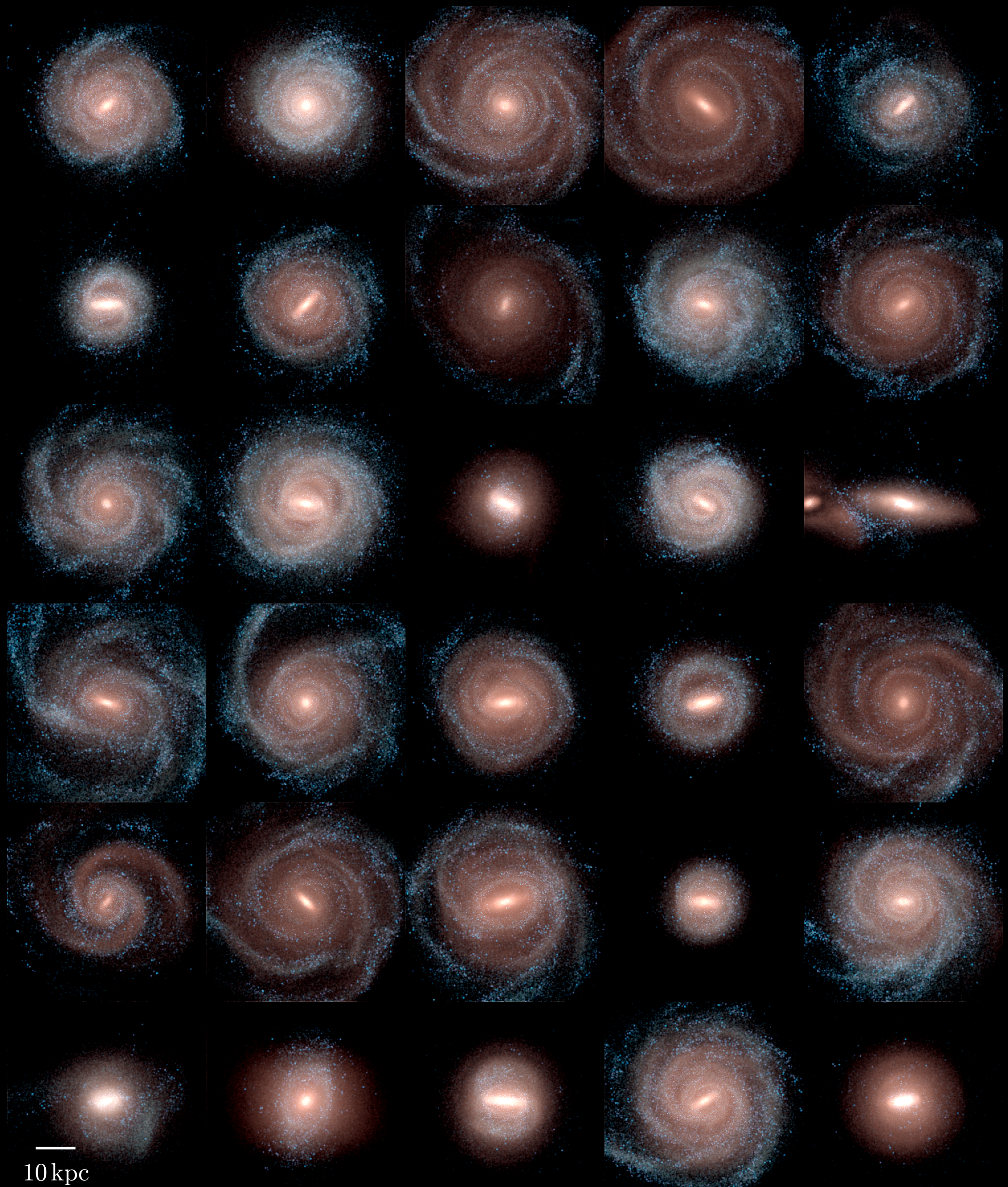
- State-of-the-art cosmological magneto-hydrodynamical zoom-in simulations of Milky Way size halos.



Auriga cosmological simulations

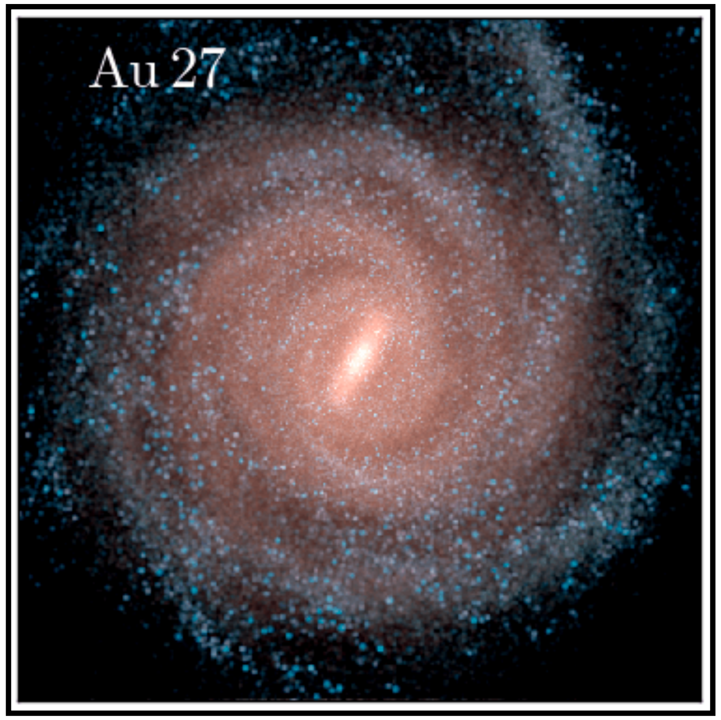
- State-of-the-art cosmological magneto-hydrodynamical zoom-in simulations of Milky Way size halos.
- 30 halos at the standard resolution:

$m_{\rm DM}$ [$M_\odot$]	$m_{\rm b}$ [$M_\odot$]	ϵ [pc]
3×10^5	5×10^4	369



Auriga cosmological simulations

- Identify **15 Milky Way-LMC analogues** based on **LMC's stellar mass** and **distance from host** at first pericenter approach.



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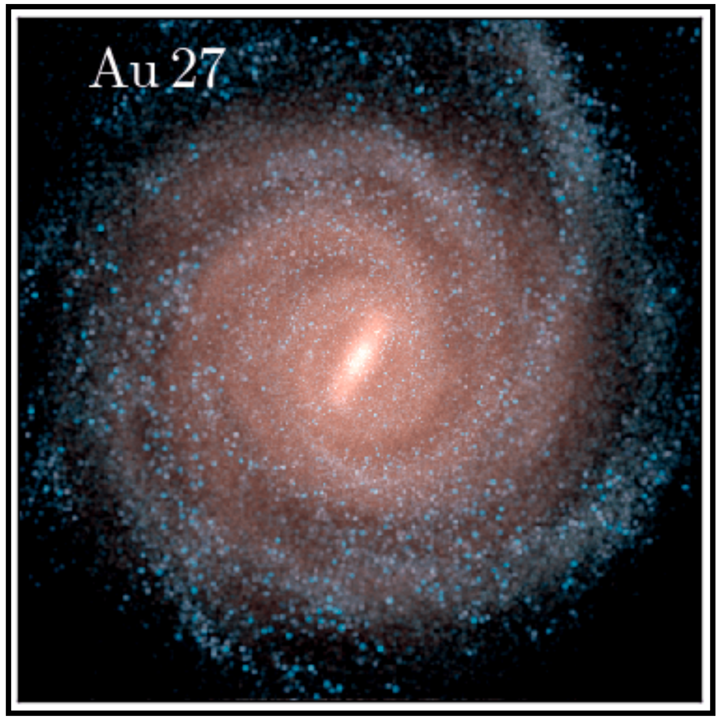

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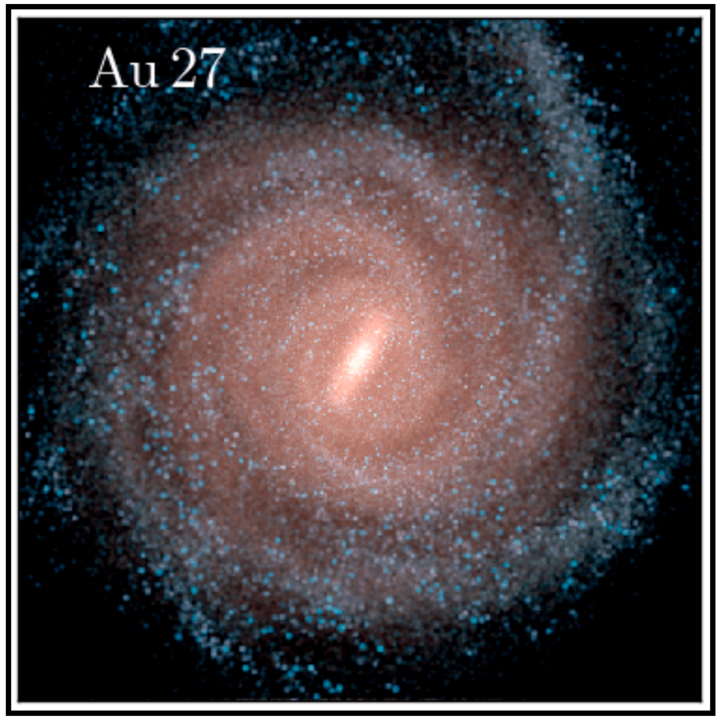
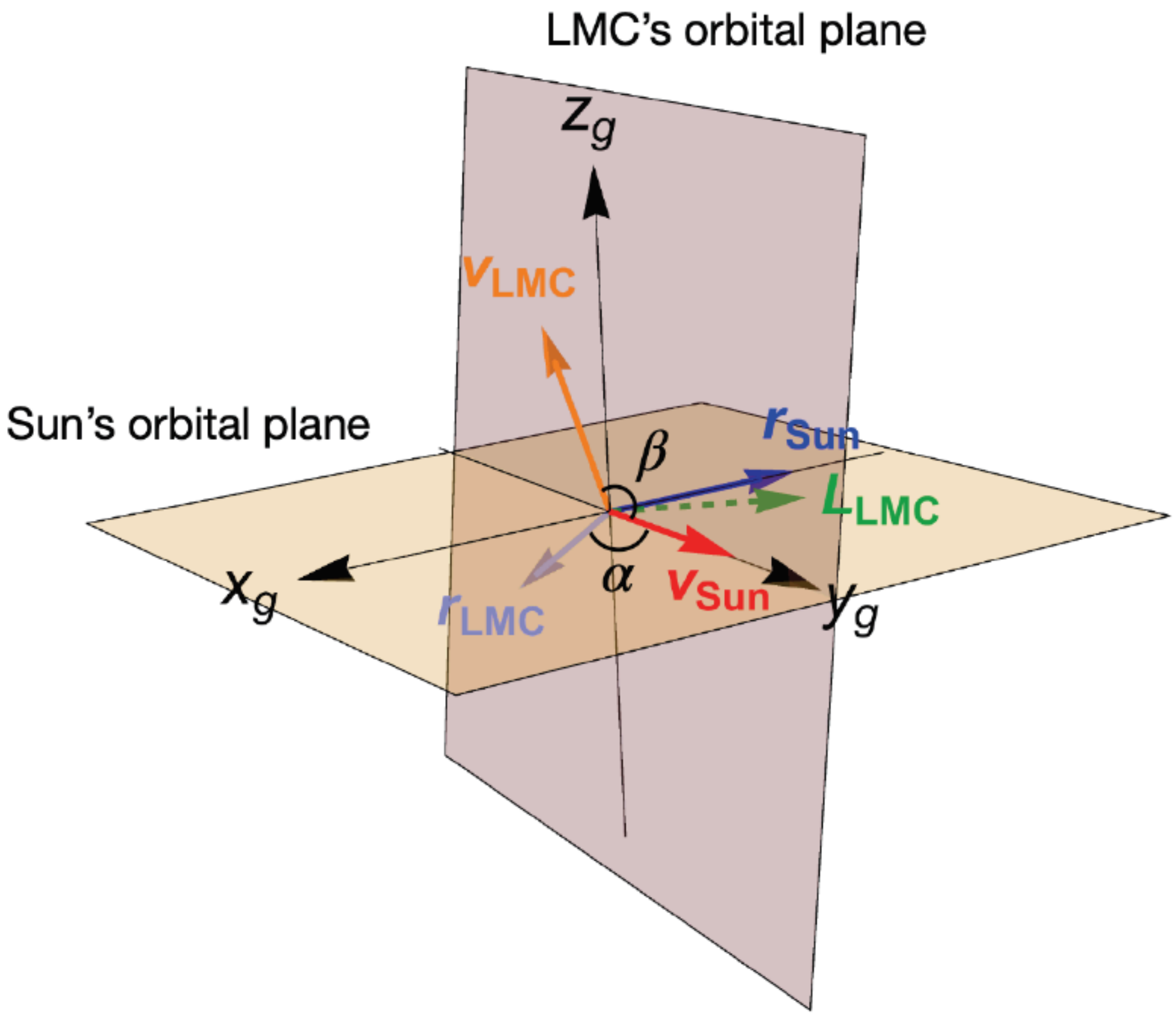


- Consider four representative snapshots:

Snapshot	Description	$t - t_{\rm Pres.}$ [Gyr]	$r_{\rm LMC}$ [kpc]
Iso.	Isolated MW analogue	-2.83	384
Peri.	LMC's 1st pericenter approach	-0.133	32.9
Pres.	Present day MW-LMC analogue	0	50.6
Fut.	Future MW-LMC analogue	0.175	80.3

Matching the Sun-LMC geometry

- The LMC is predominately moving in the opposite direction of the Solar motion. → Large relative speeds of DM particles originating from the LMC with respect to the sun.



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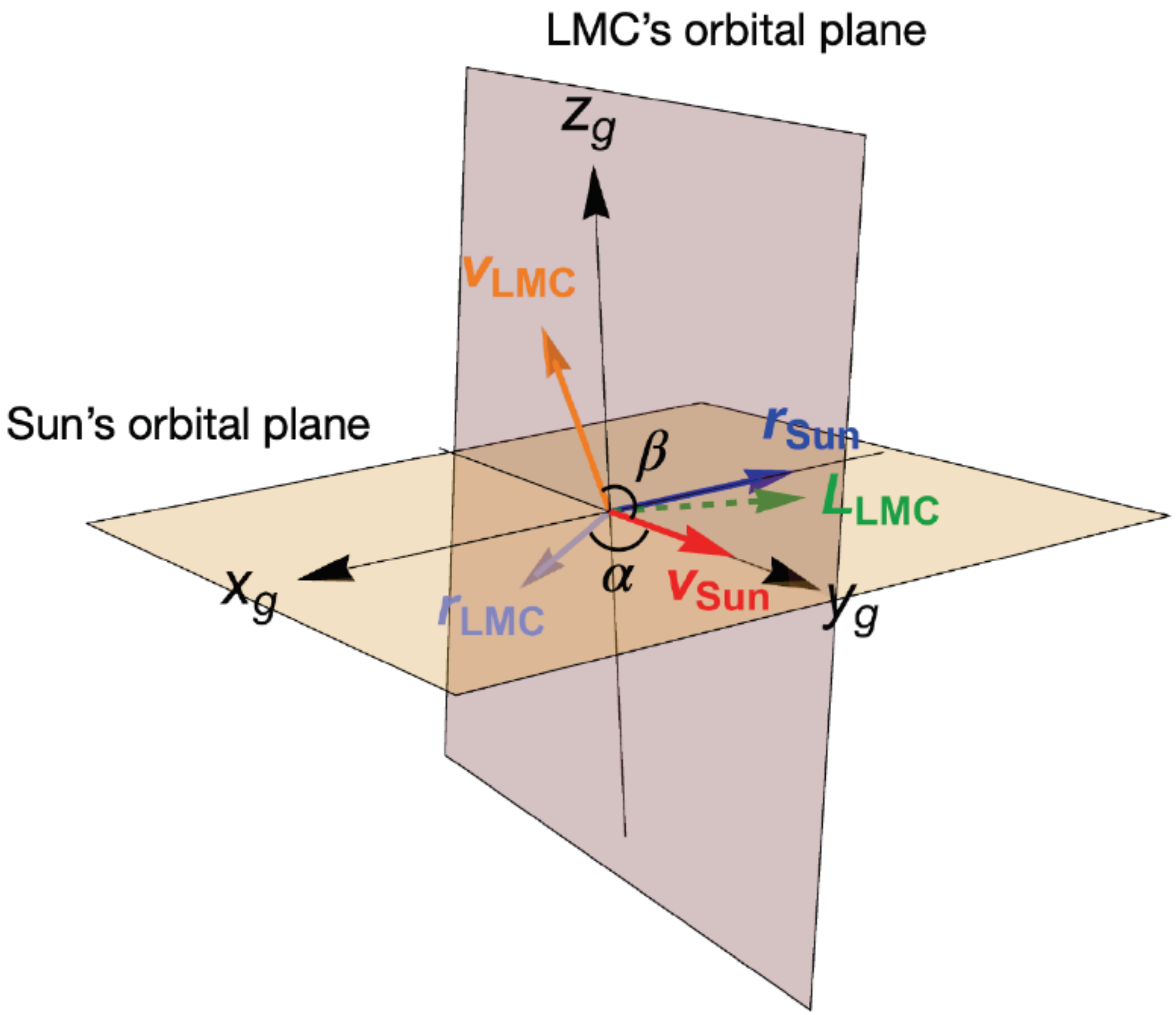


- Choose the position of the Sun in the simulations such that it matches the observed Sun-LMC geometry.

Local dark matter density

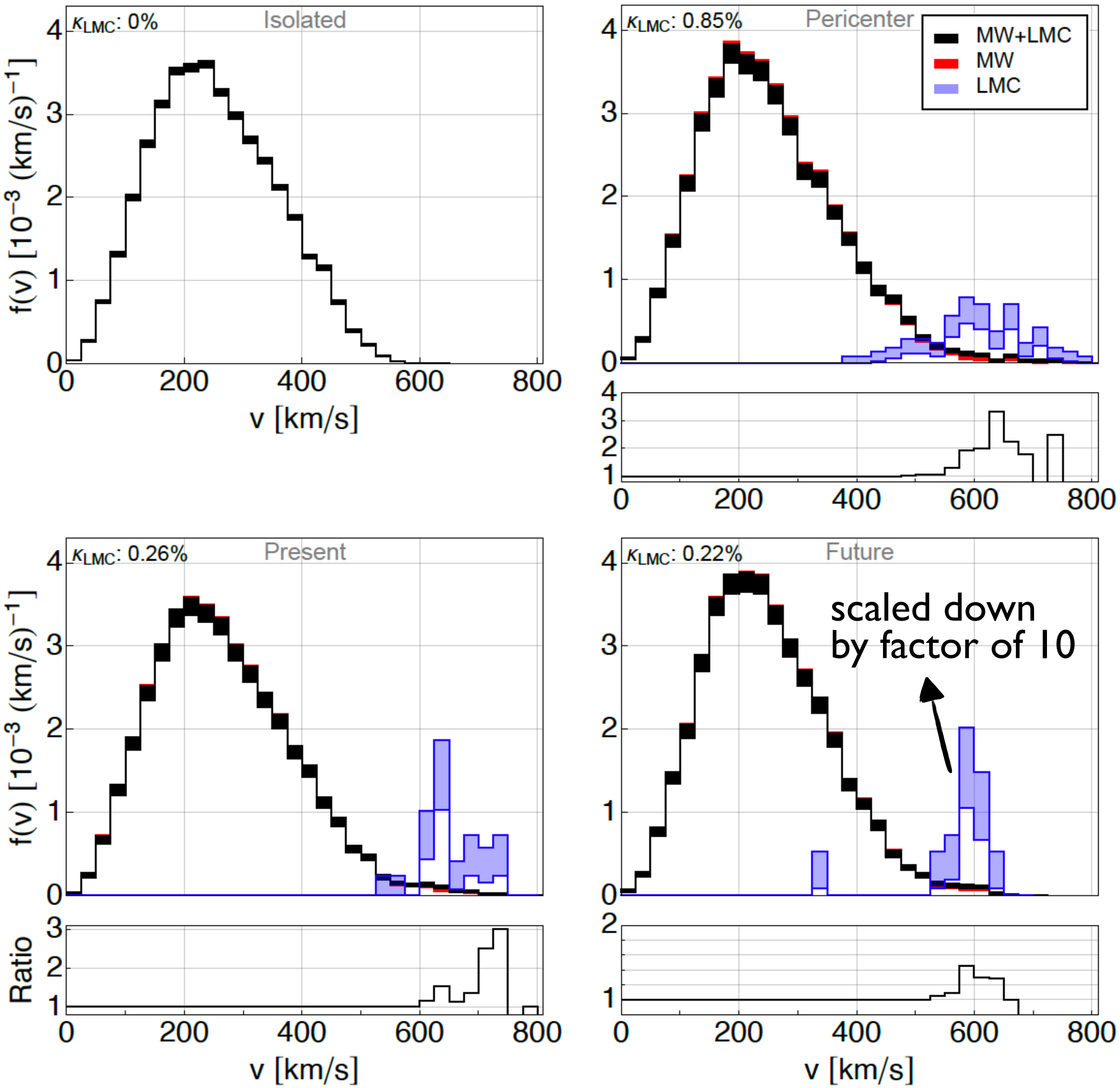
Halo ID	$M_{\rm Infall}^{\rm LMC}$ [10^{11} $M_{\odot}$]	ρ_{χ} [GeV/cm^3]	$\kappa_{\rm LMC}$ [%]
1	0.31	0.21	0.14
2	0.31	0.23	0.64
3	0.34	0.35	0.026
4	0.82	0.34	0.096
5	1.84	0.24	1.5
6	1.10	0.38	0.038
7	0.32	0.53	0.032
8	0.36	0.38	0.0077
9	0.73	0.36	0.10
10	3.28	0.39	2.8
11	1.45	0.43	0.028
12	1.43	0.53	0.17
13	3.18	0.34	2.3
14	0.84	0.60	0.26
15	1.15	0.32	1.2

Percentage of DM particles in the Solar region originating from the LMC

- The percentage of DM particles in the Solar neighborhood originating from the LMC is small.

Local dark matter speed distribution

In the galactic rest frame



Smith-Orlik et al., JCAP 10, 070 (2023)

Local dark matter speed distribution

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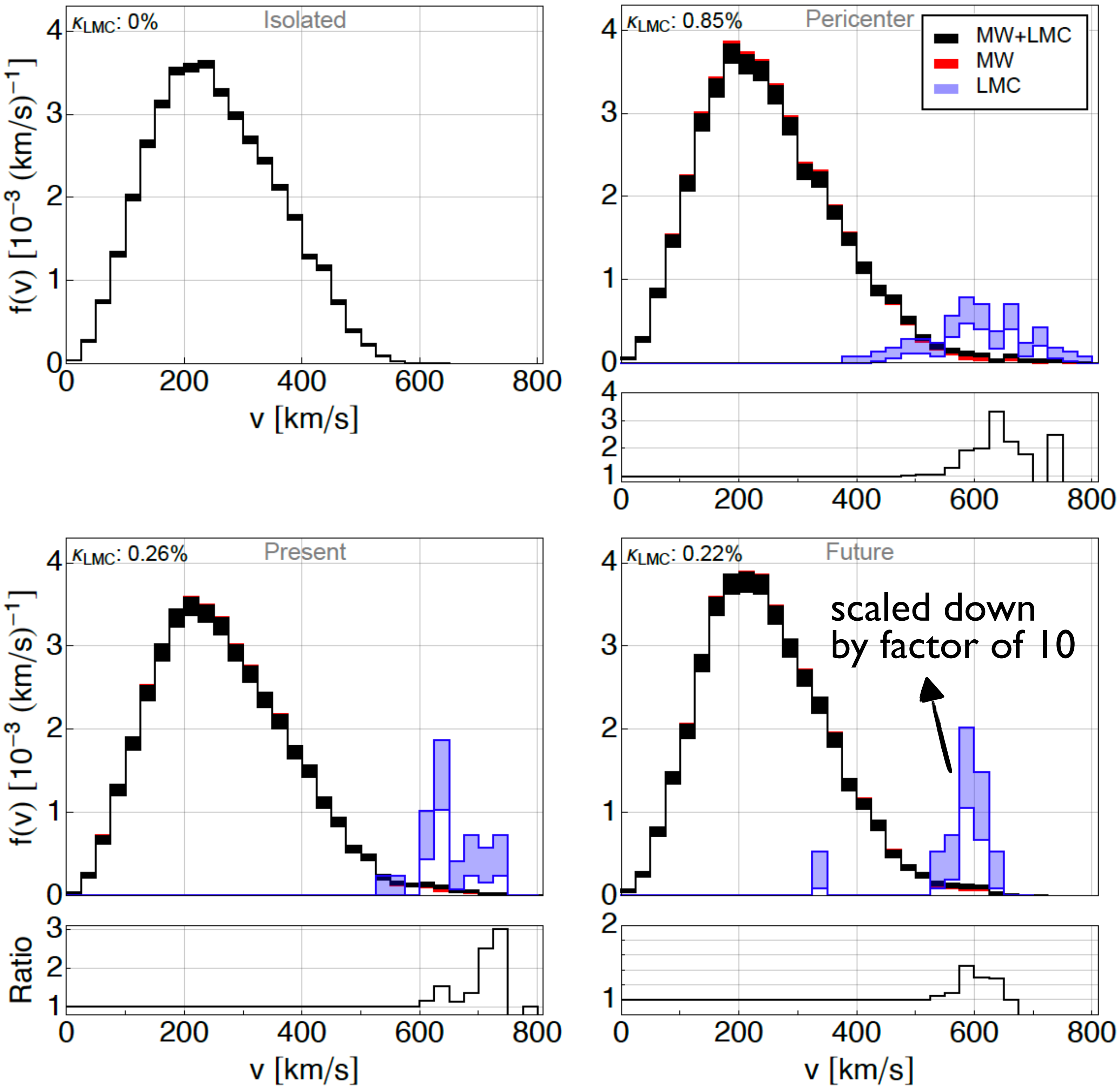

Smith-Orlik et al., JCAP 10, 070 (2023)

The LMC impacts the high speed tail of the DM speed distribution not only at its **pericenter approach** and the **present day**, but also up to **~175 Myr after the present day**.

Direct detection event rate

- The differential event rate (per unit detector mass):

astrophysics

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v>v_{\rm min}} d^3v \, \frac{d\sigma_{\chi N}}{dE_R} \, v \, f_{\rm det}(\mathbf{v}, t)$$

- For standard spin-independent and spin-dependent interactions:

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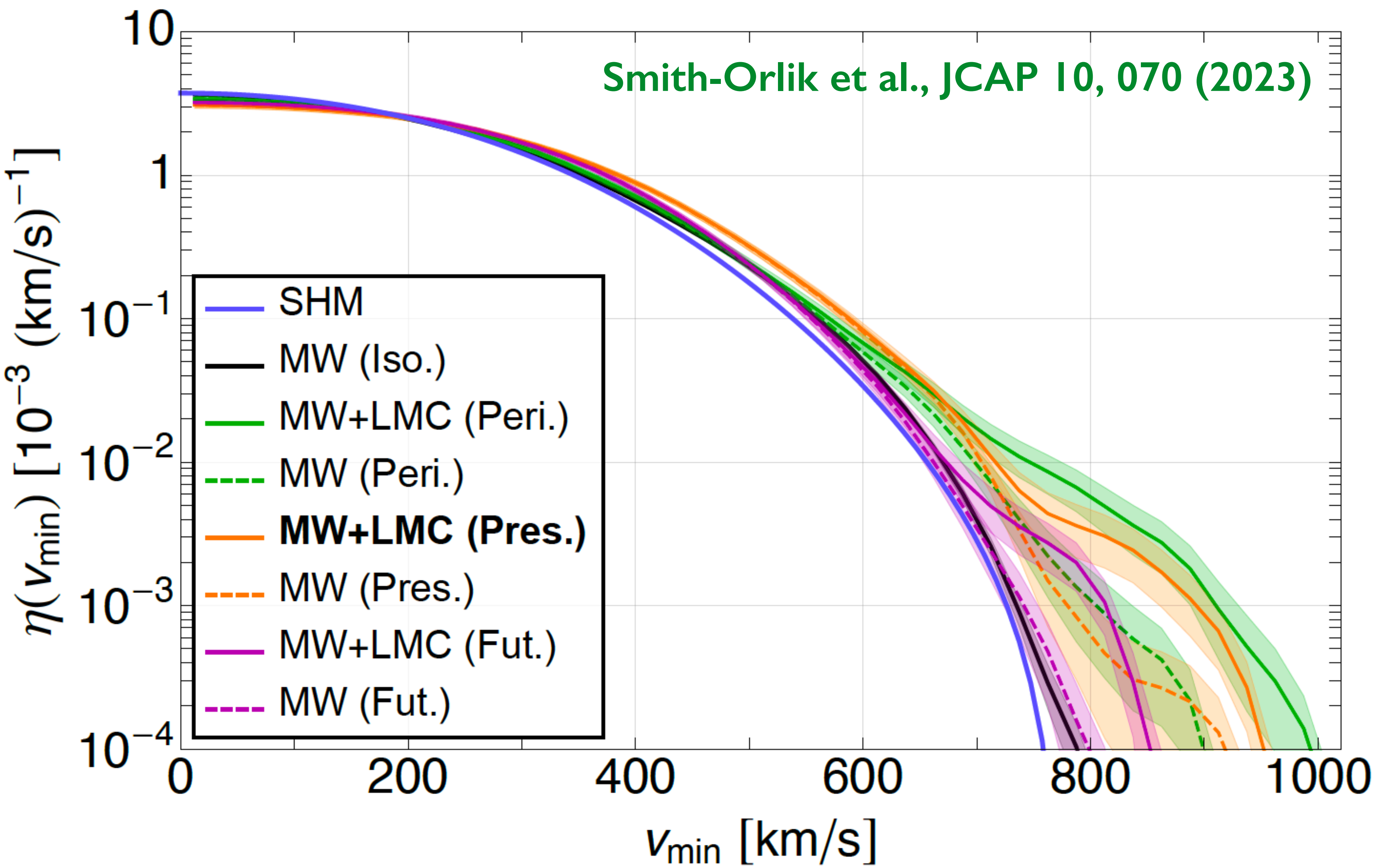
$$\eta(v_{\min}, t) \equiv \int_{v>v_{\min}} d^3v \, \frac{f_{\text{det}}(\mathbf{v}, t)}{v}$$

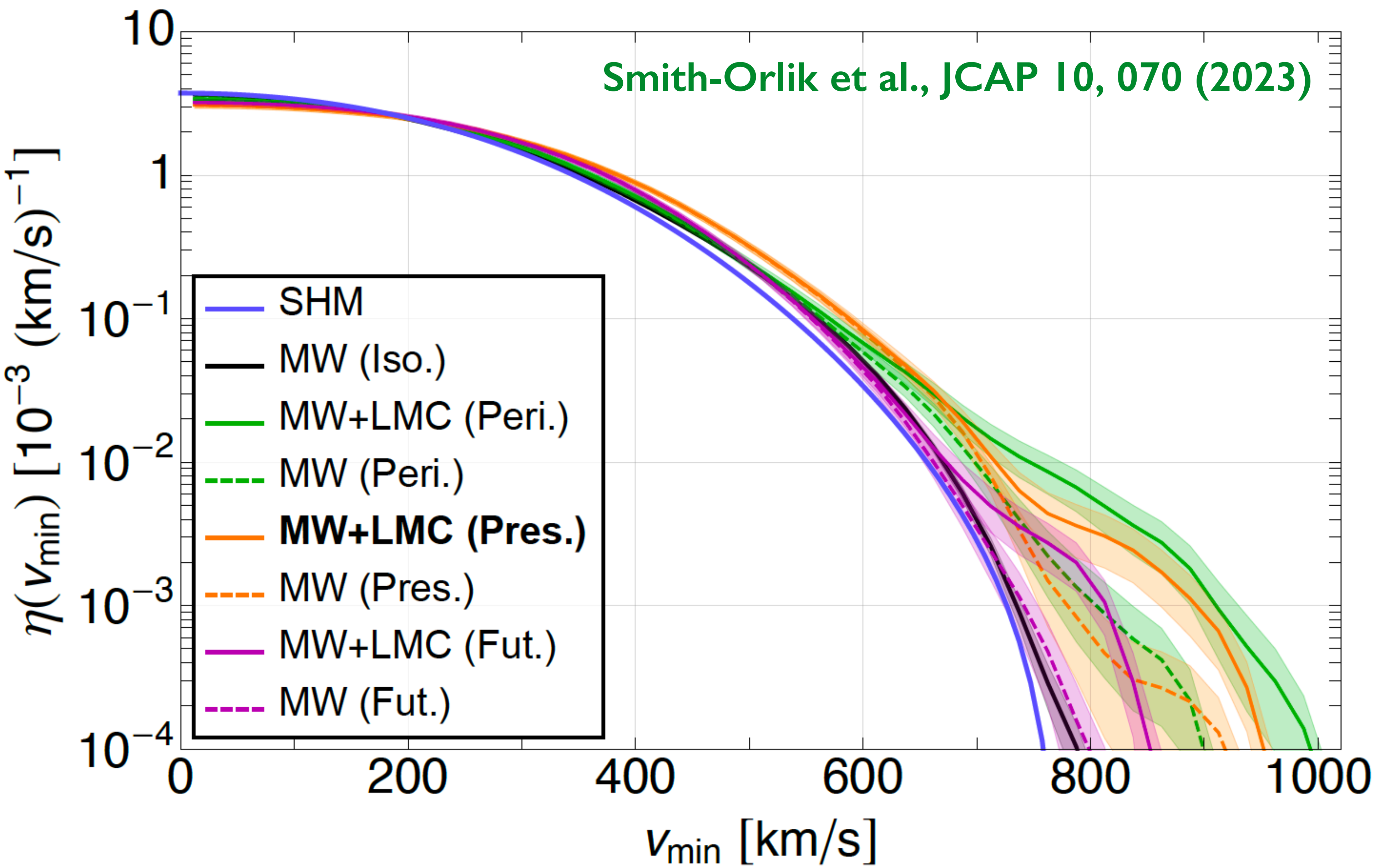
Halo integral

Halo integrals



- **Two effects:** High speed LMC particles in the Solar region + Milky Way's response to the LMC.

Halo integrals



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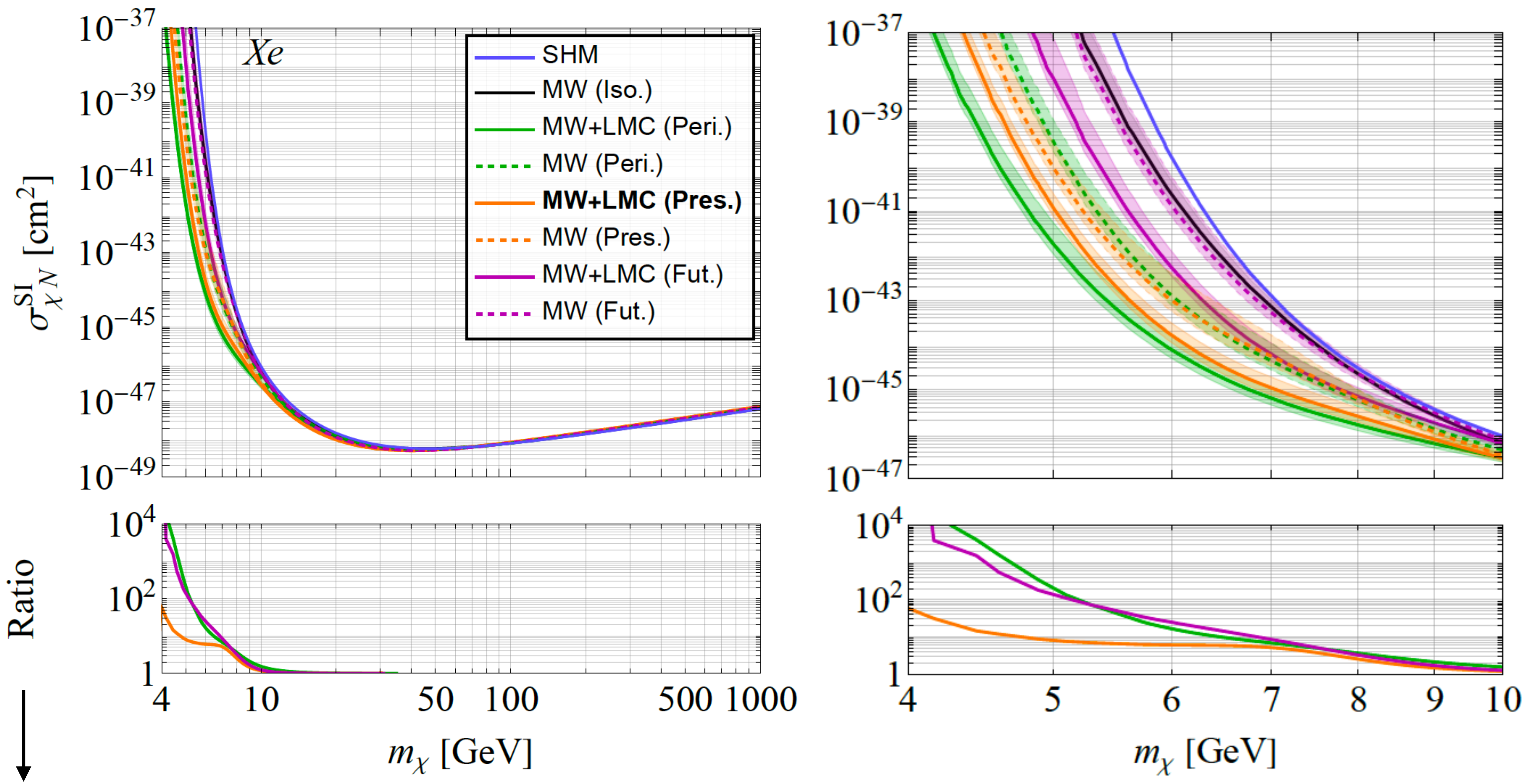
  ➡ *Shift of $> 150\ {\rm km/s}$ in the high speed tail of the halo integrals at the present day.*

Direct detection: nuclear recoils

Simulate the signal in an idealized near future **Xe-based detector:**



$$\text{Ratio} = \frac{\sigma^{\rm SI}_{\chi,\rm MW}}{\sigma^{\rm SI}_{\chi,\rm MW+LMC}}$$

Smith-Orlik et al., JCAP 10, 070 (2023)

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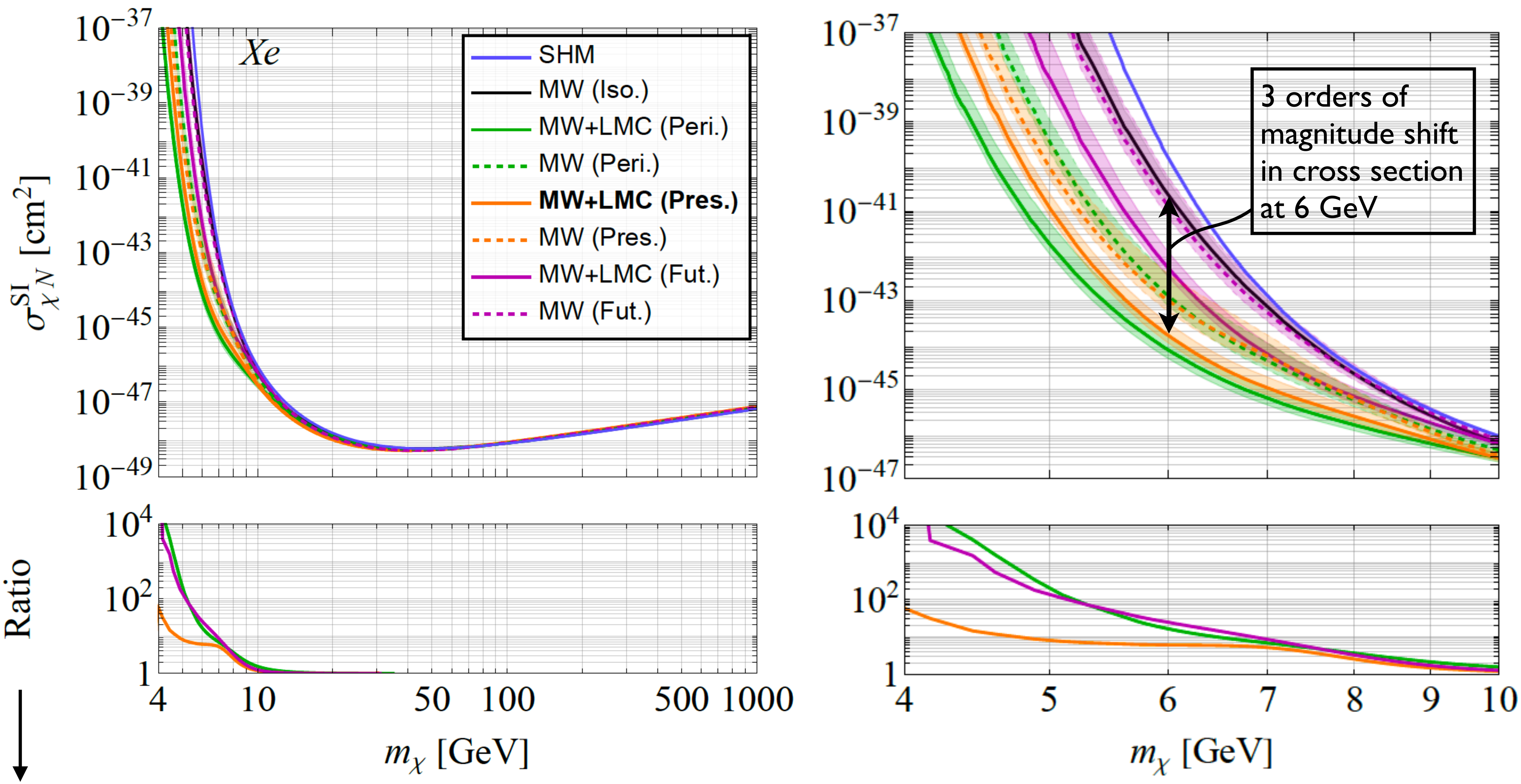

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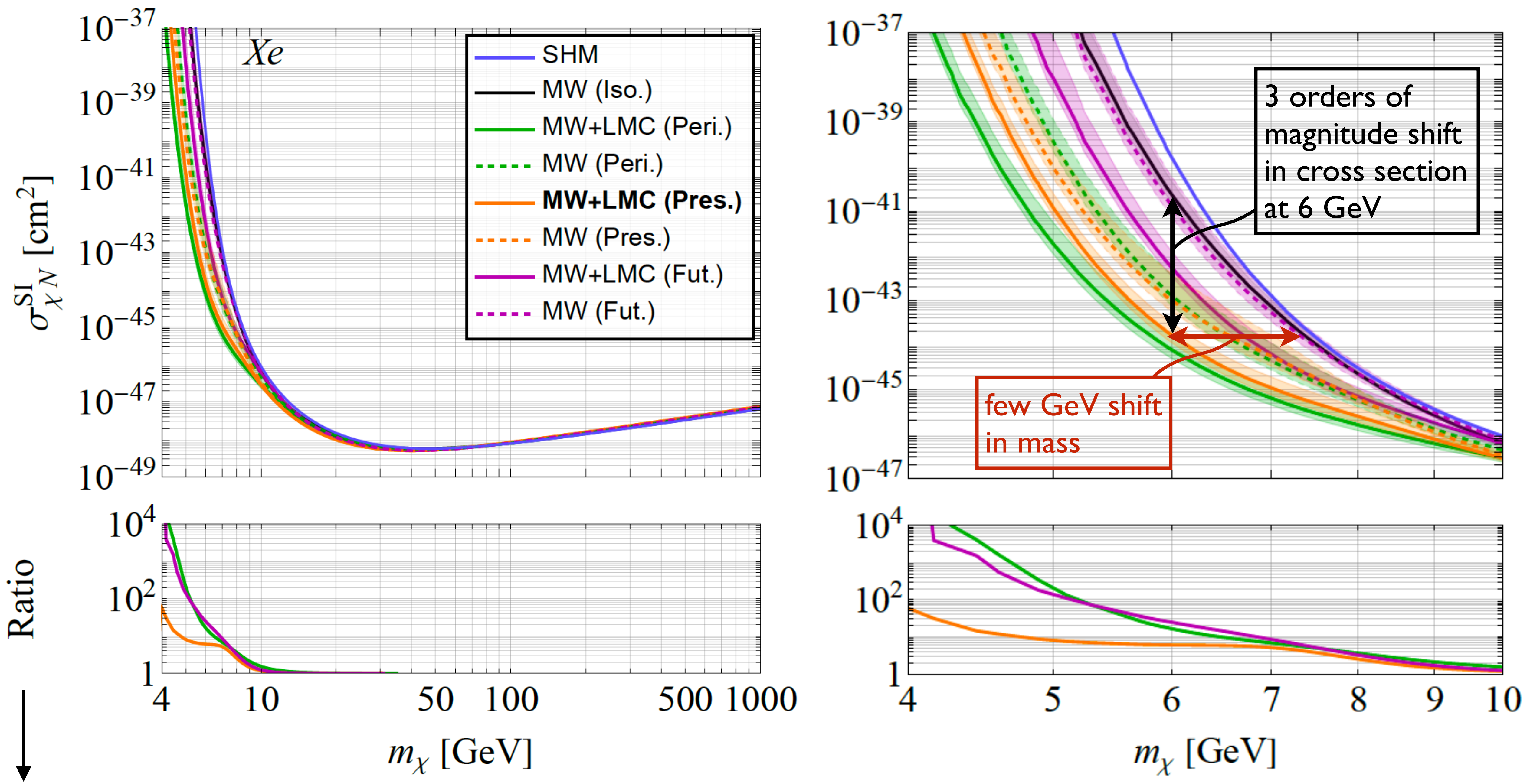

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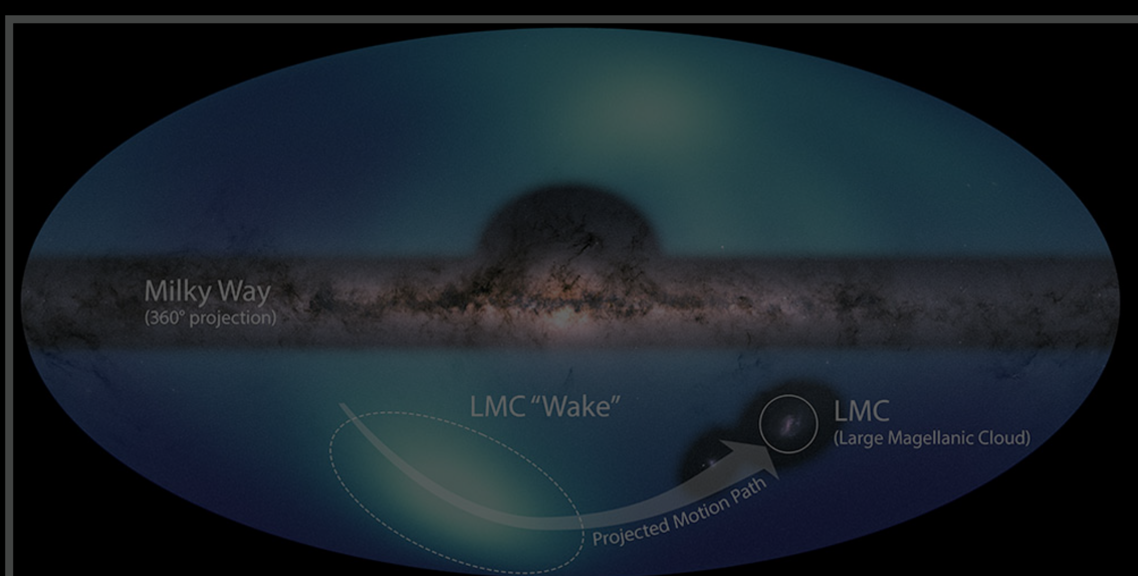
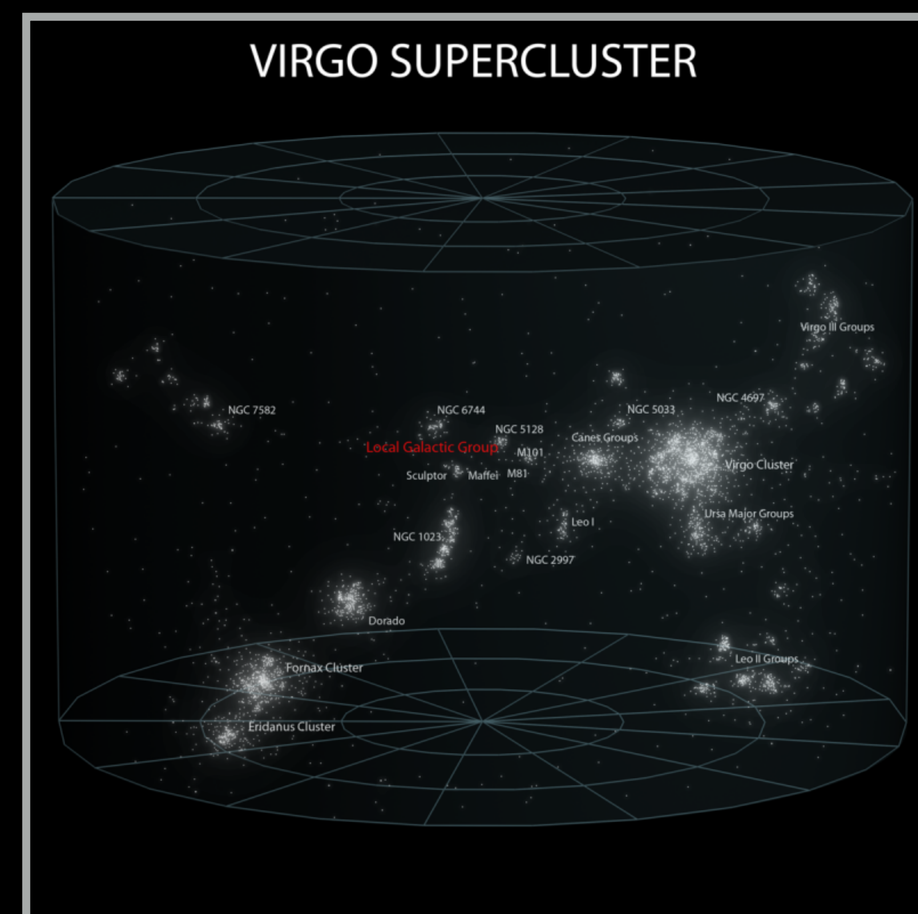


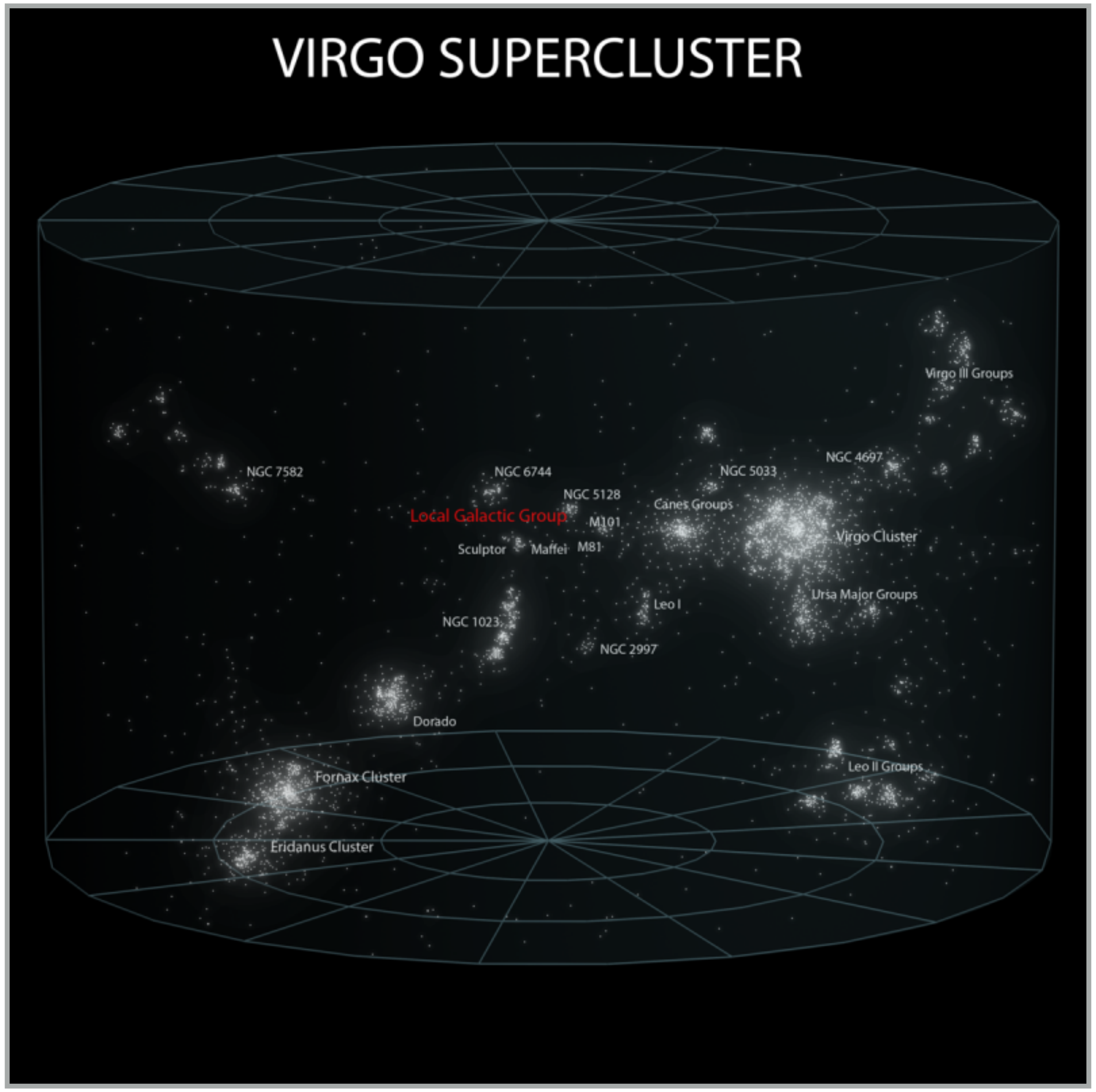
Extragalactic DM particles



High speed extragalactic DM particles

- Extragalactic DM particles from the **Local Group** or the **Virgo Supercluster** may contribute to the high speed tail of local DM velocity distribution.

  Freese et al, PRD 64, 123502 (2001)
  Baushev, ApJ 771, 117 (2013)
  Herrera & Ibarra, PLB 820, 136551 (2021)



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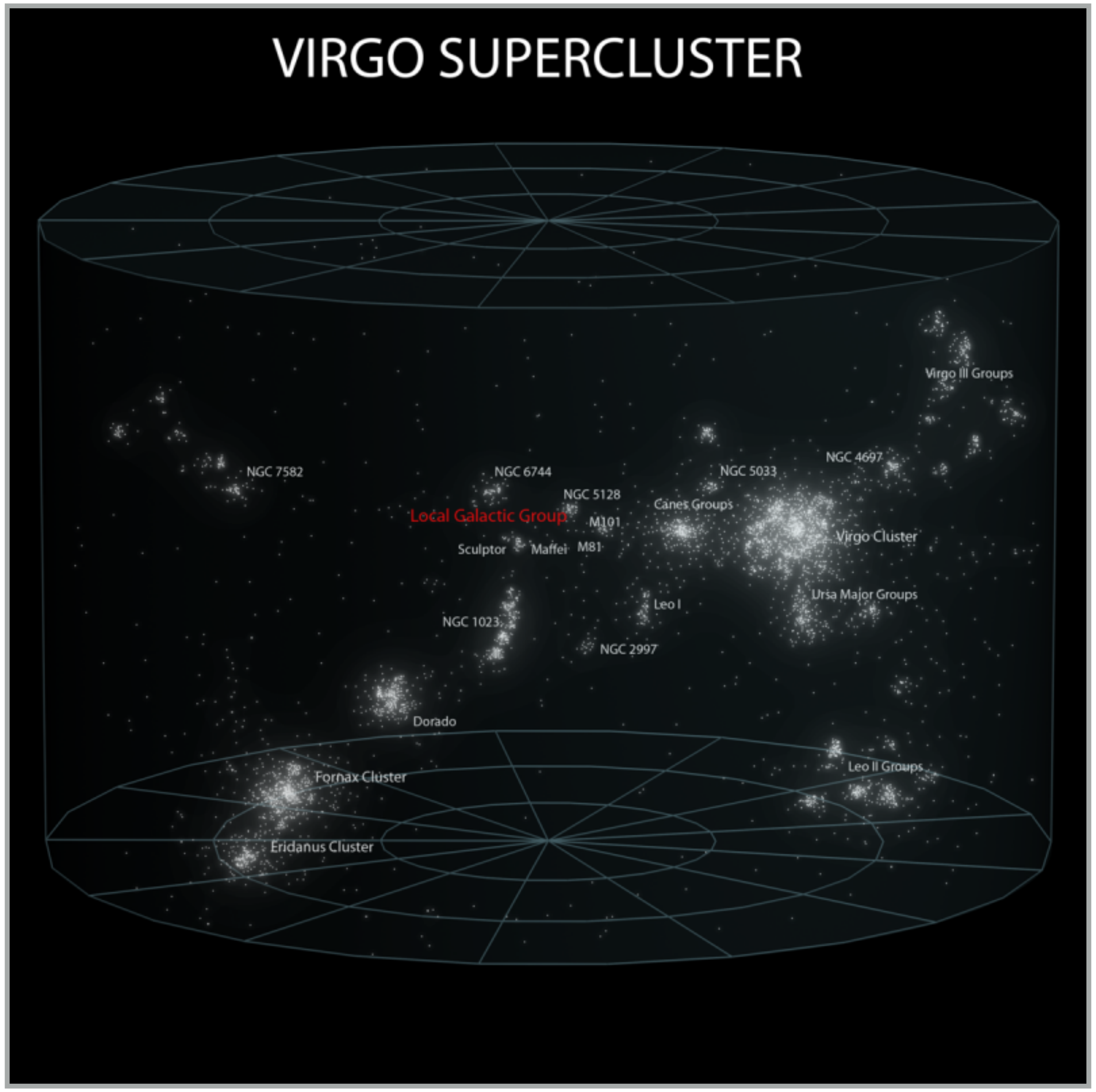

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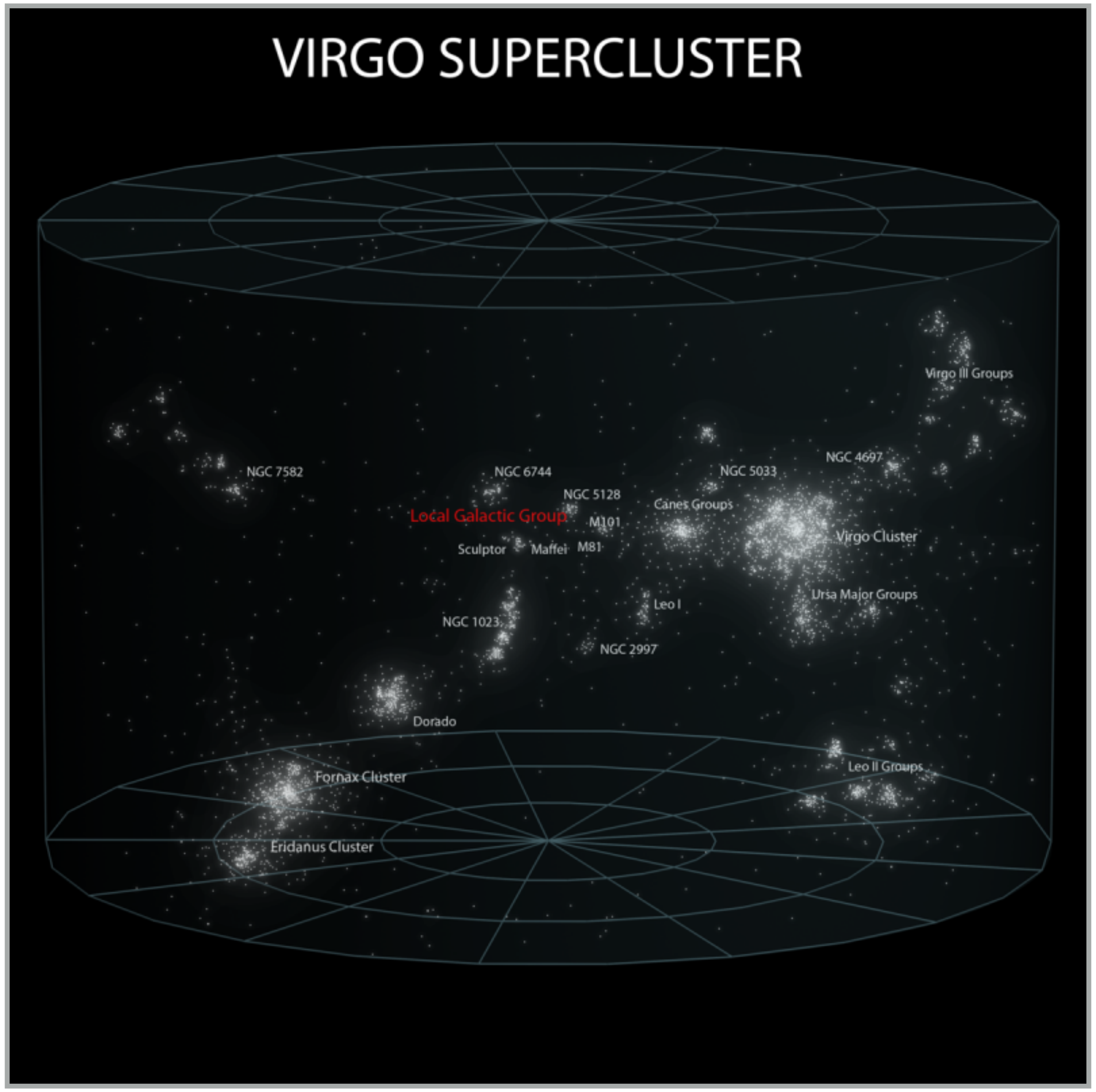
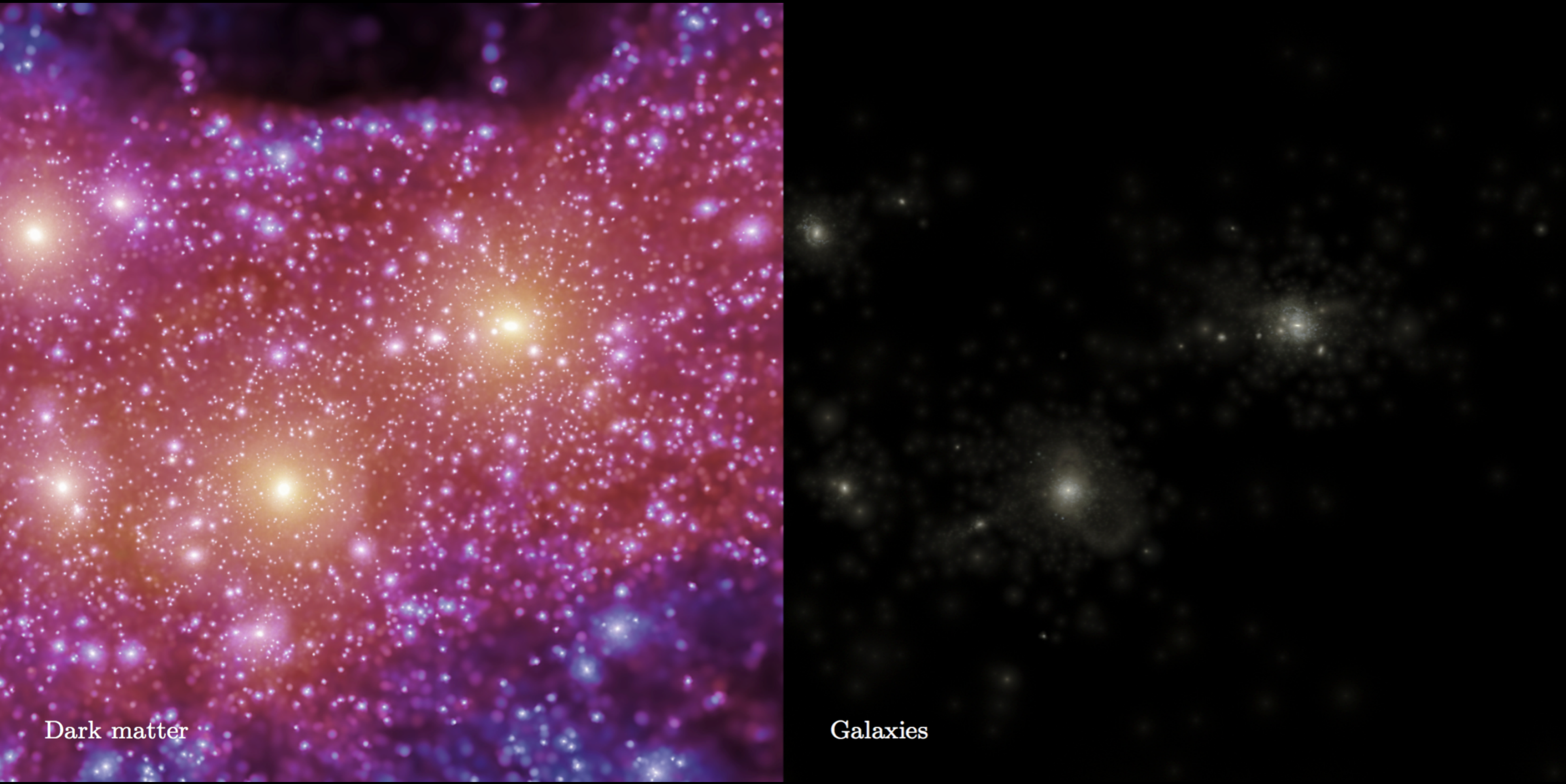


- If such component exists, it should be present in cosmological simulations of the Local Group. → Investigate this using the **APOSTLE** hydrodynamical simulations.

APOSTLE simulations

Zoomed simulations of Local Group analogue systems, identified based on the kinematic properties of the Milky Way-M31 pair and the surrounding Hubble flow.



APOSTLE simulations

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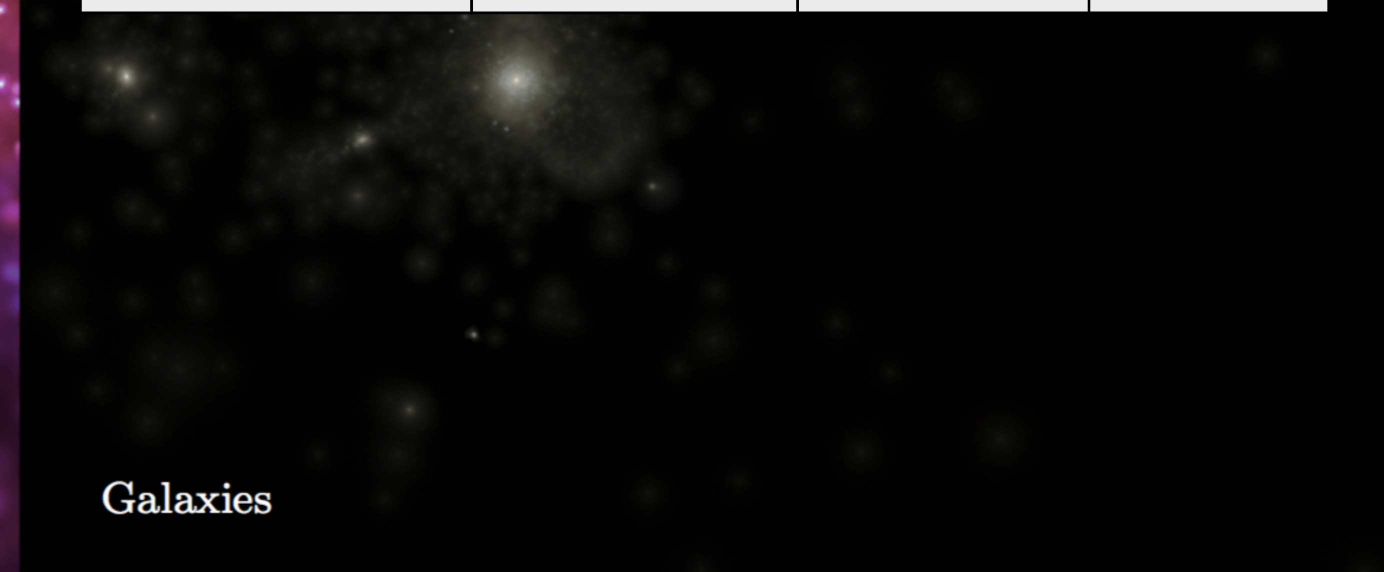
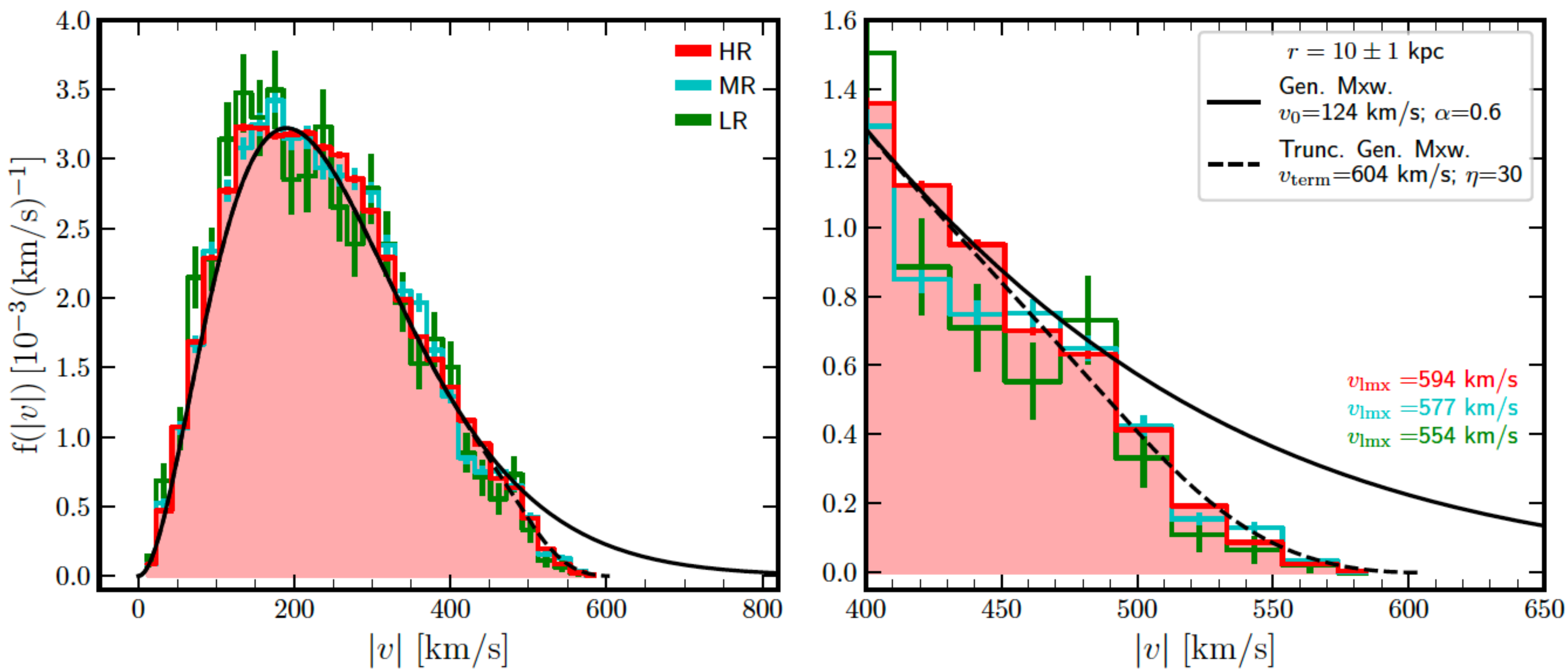
Study 4 Local Group-like volumes simulated at three resolution levels:

Resolution	m_{DM} $[\mathrm{M}_\odot]$	m_{b} $[\mathrm{M}_\odot]$	ϵ [pc]
High (HR)	5×10^4	10^4	134
Medium (MR)	5×10^5	10^5	307
Low (LR)	5×10^6	10^6	711



Local dark matter speed distribution



Santos-Santos et al., JCAP 03, 046 (2024)

- The local DM speed distribution vanishes beyond a maximum speed of $\sim 600\ \mathrm{km/s}$, regardless of the resolution.

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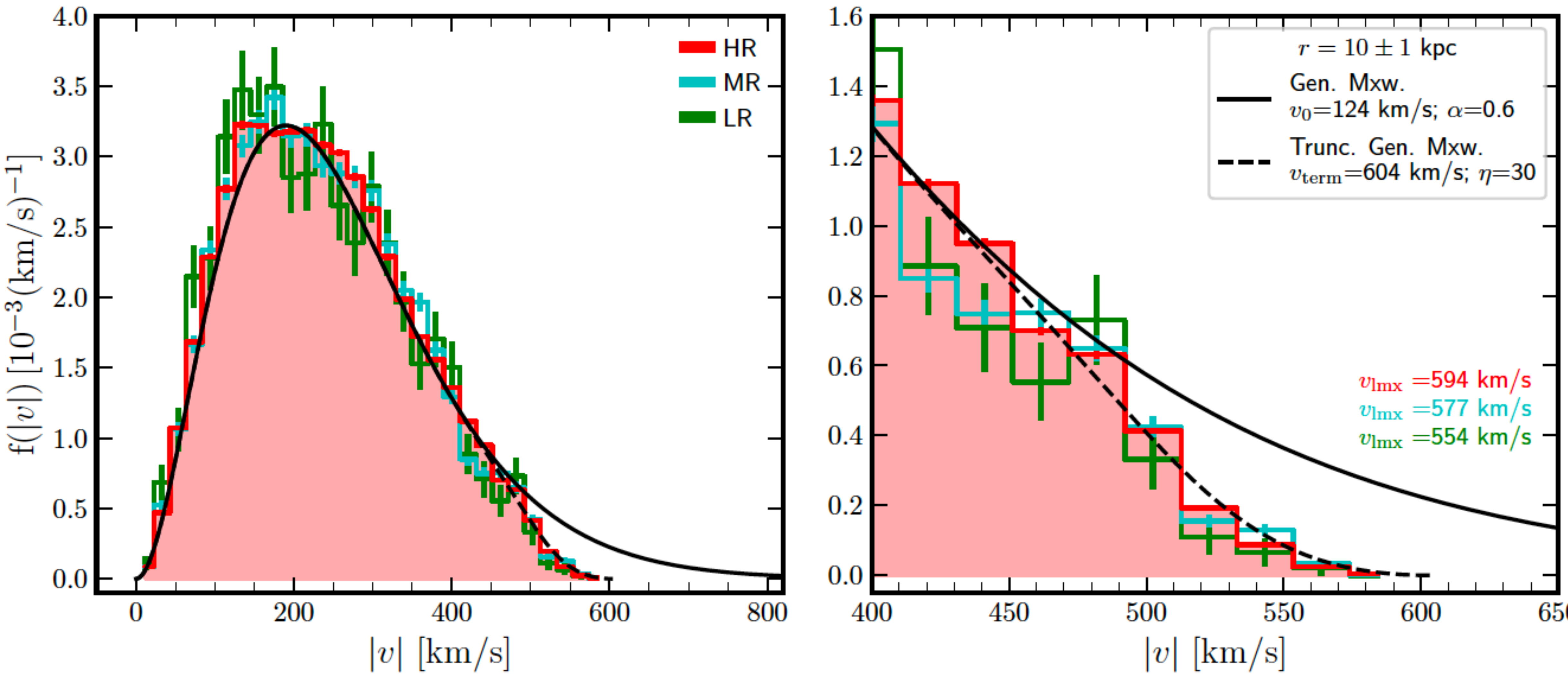

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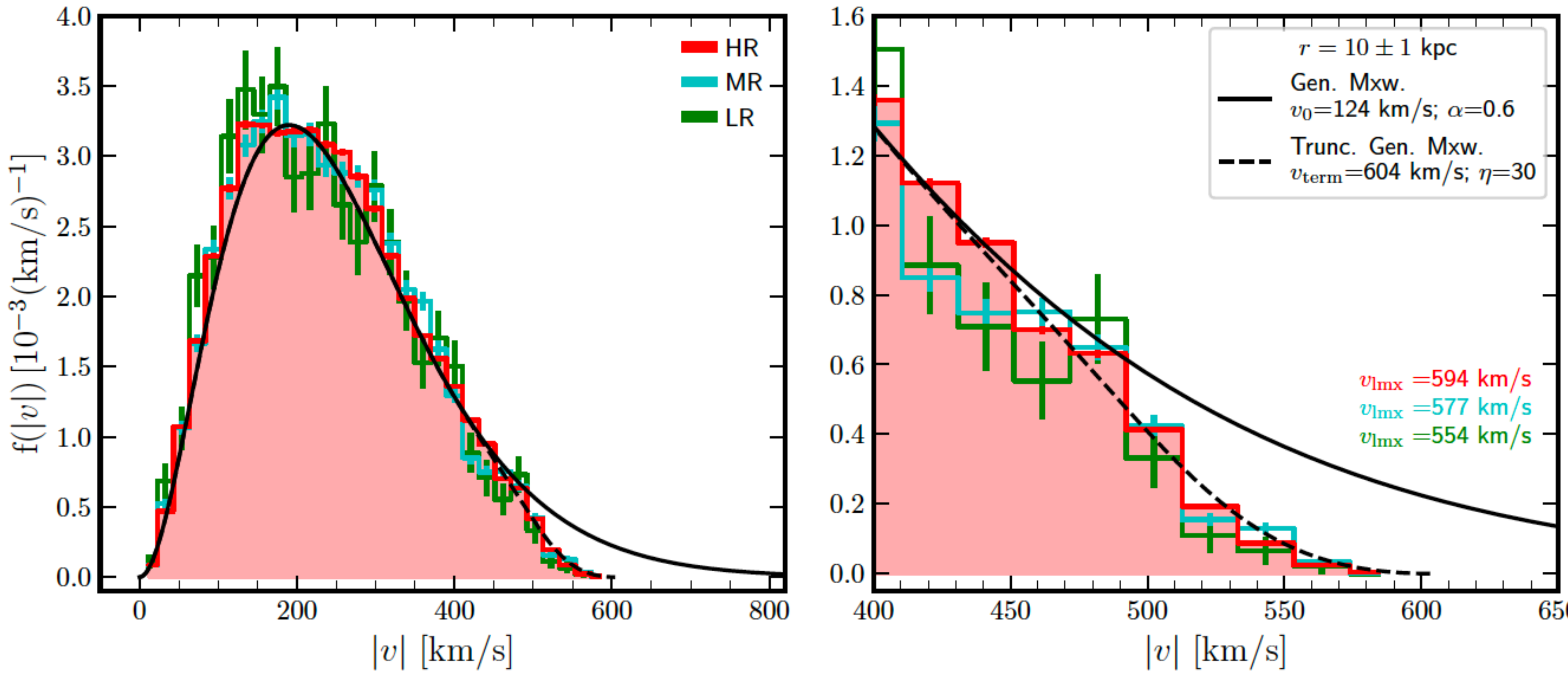
- The local DM speed distribution vanishes beyond a maximum speed of ~ 600 km/s, regardless of the resolution.
- No hint of an excess of high-speed extragalactic DM particles.

Local dark matter speed distribution



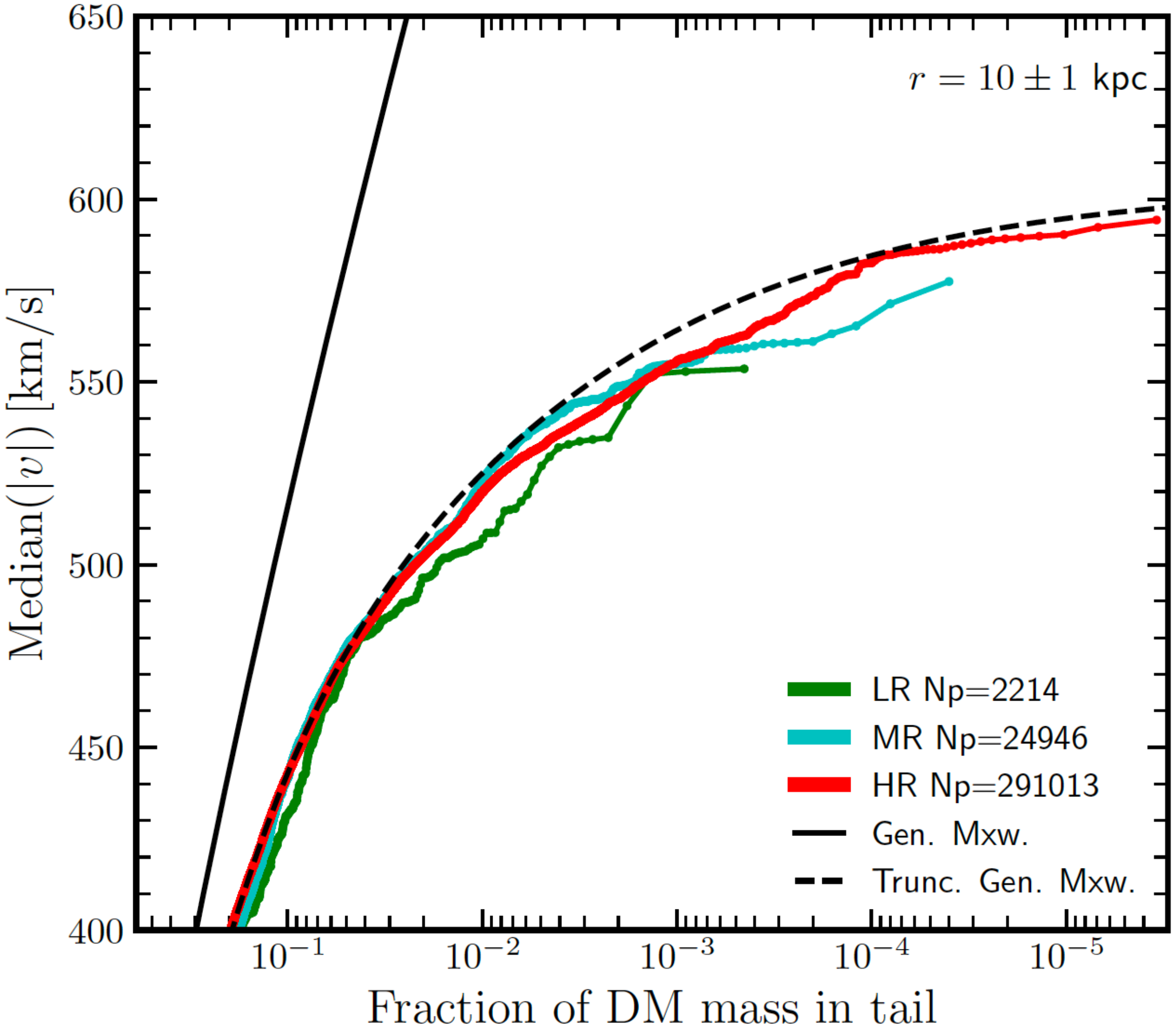
Santos-Santos et al., JCAP 03, 046 (2024)

- A **truncated generalized Maxwellian** accurately models the local DM velocity distribution:

$$f(|\mathbf{v}|) \propto g(|\mathbf{v}|)|\mathbf{v}|^2 \exp\left[-(|\mathbf{v}|/v_0)^{2\alpha}\right] \quad , \quad g(|\mathbf{v}|) = \tanh\left(\eta\left[1 - |\mathbf{v}|/v_{\mathrm{term}}\right]^2\right)$$

Impact of numerical resolution

Is this maximum speed just the result of limited numerical resolution, or is it a physically meaningful local characteristic of the halo?



Santos-Santos et al., JCAP 03, 046 (2024)

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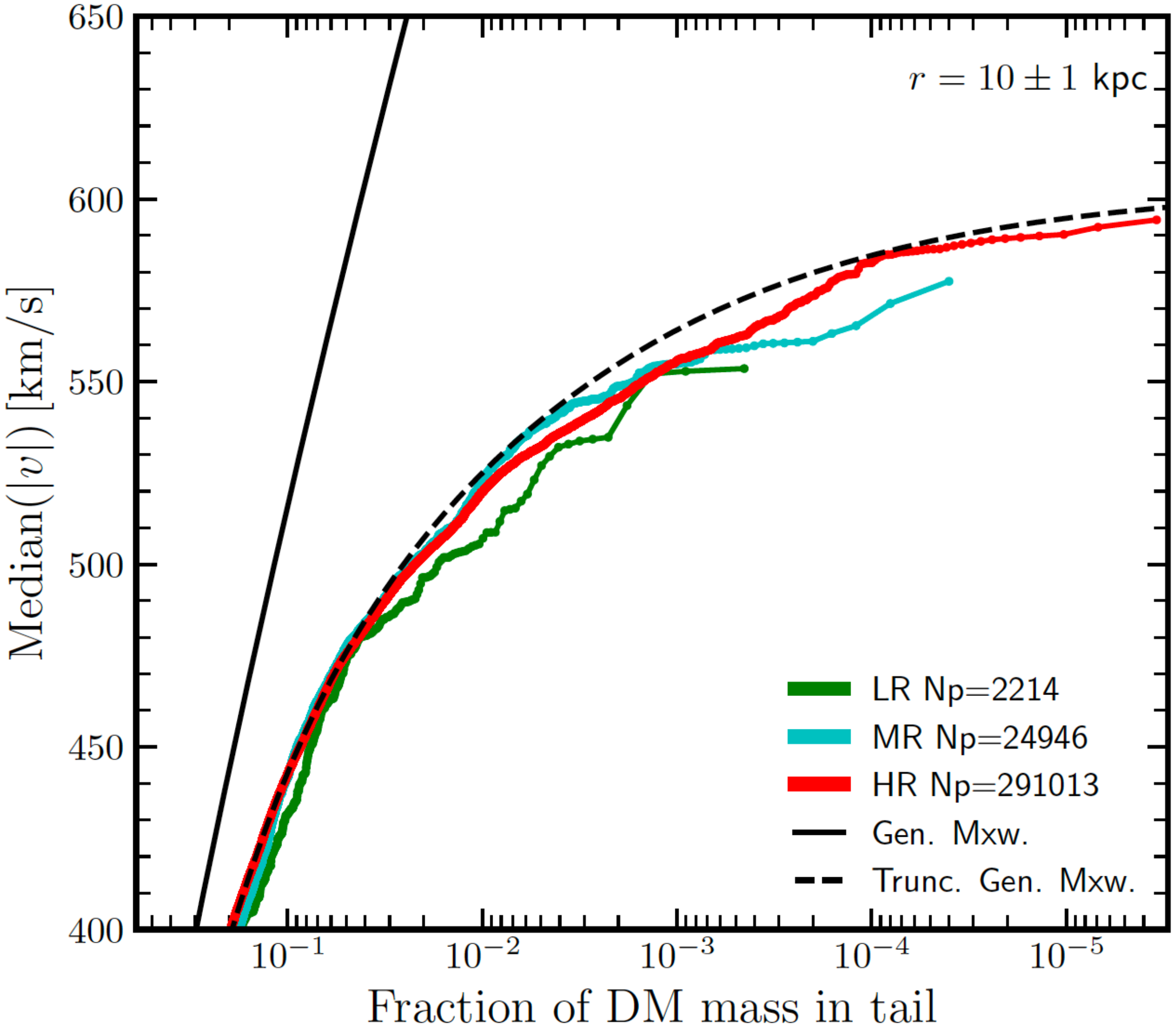
- Median speed of particles in the high-speed tail follows the truncated generalized Maxwellian and agrees between different resolutions.

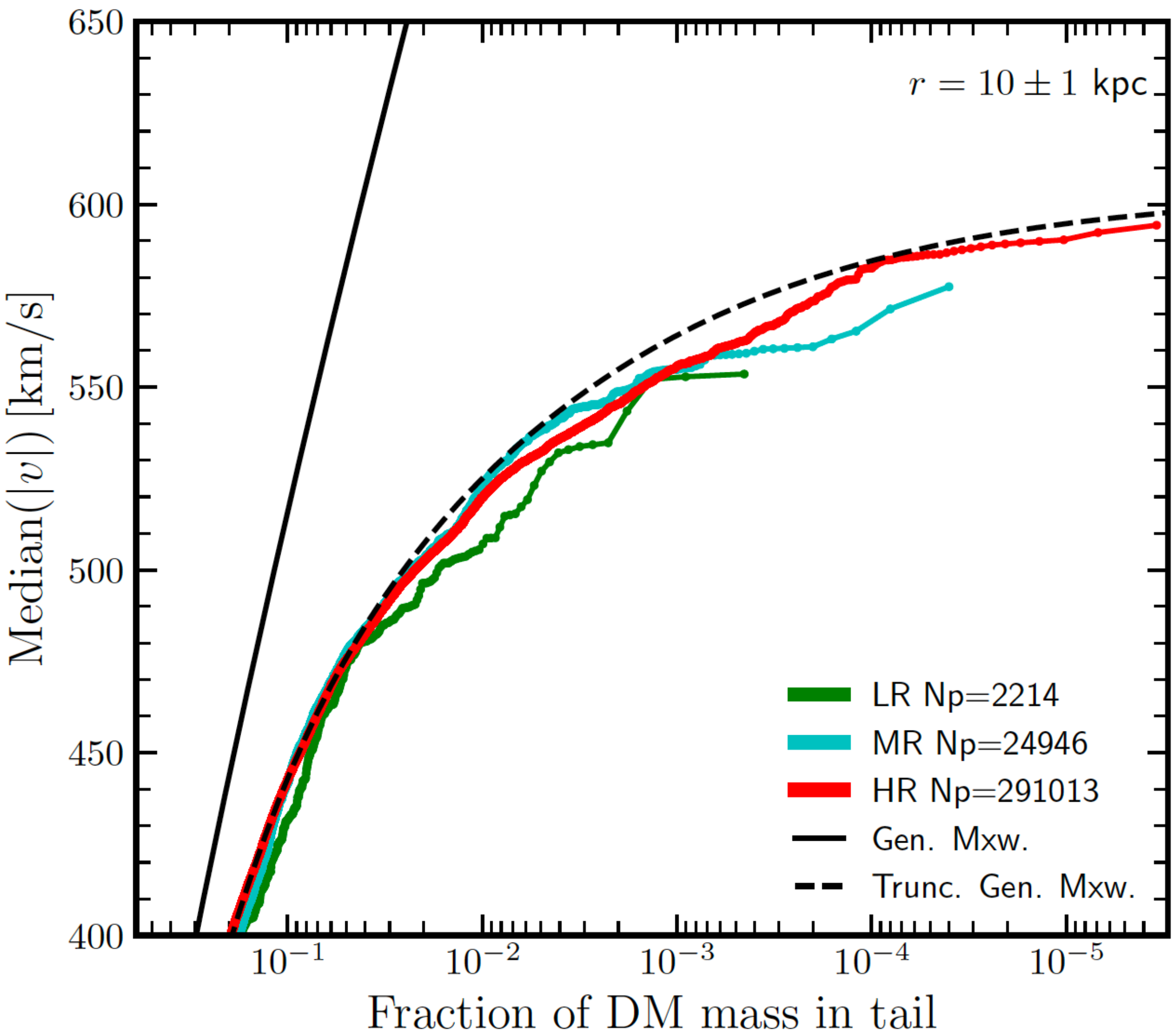


Santos-Santos et al., JCAP 03, 046 (2024)

Impact of numerical resolution

Is this maximum speed just the result of limited numerical resolution, or is it a physically meaningful local characteristic of the halo?

- Median speed of particles in the high-speed tail follows the truncated generalized Maxwellian and agrees between different resolutions. ➡ ***Max speed of*** ~ 600 km/s ***is a true physical property of the halos.***



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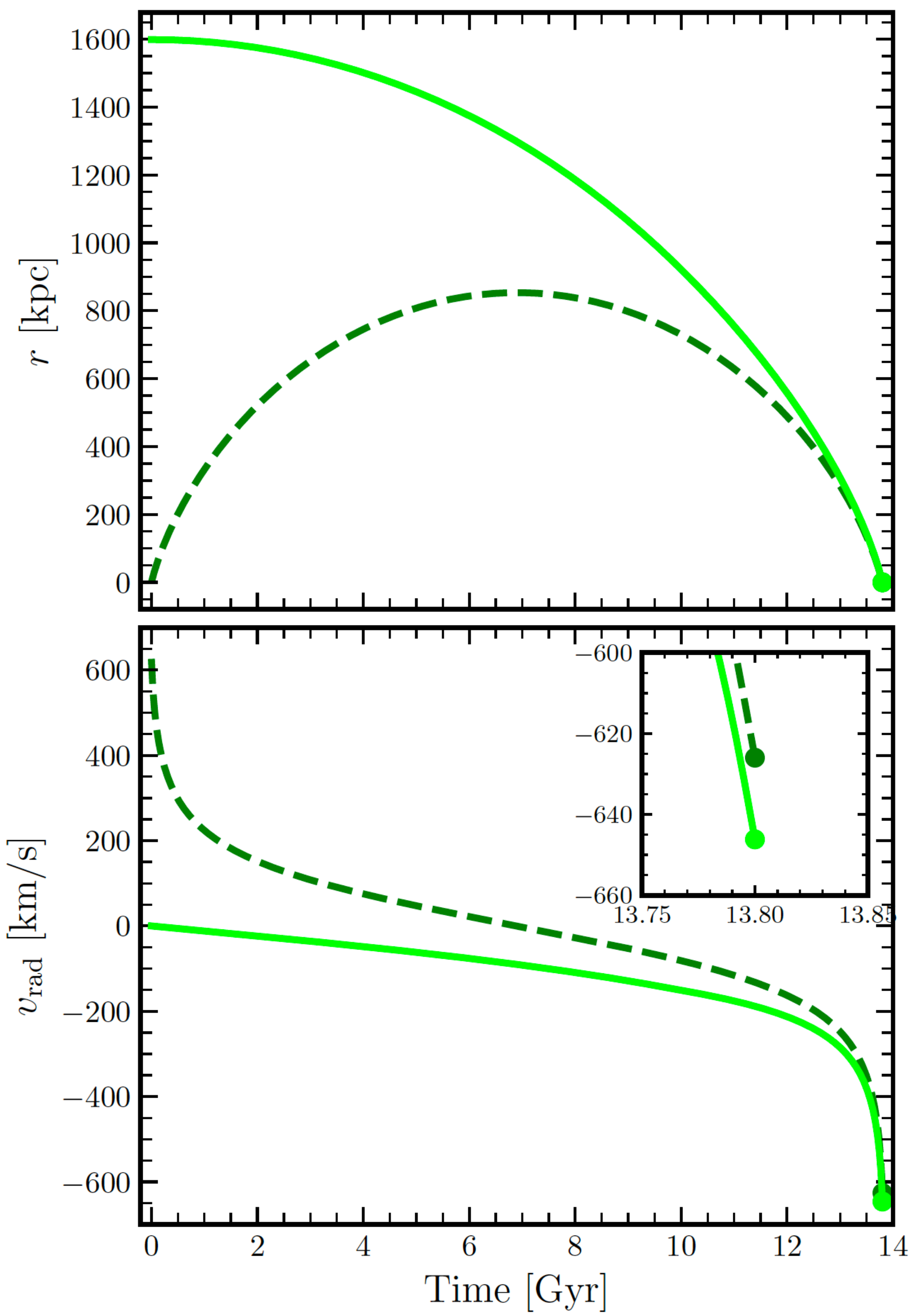
- In this case, maximum speeds result from the *depth of the potential well* + *the finite age of the Universe*, which restricts the maximum radius from where a particle could have been accreted by the present time.
- Particles from outside the Local Group have not yet had time to reach the Solar neighborhood in the finite age of the Universe.

Origin of the maximum speed

What sets this maximum speed?

- Simple estimate of the maximum speed expected at any radius of a halo using its ***present day mass distribution*** and the ***age of the Universe***.



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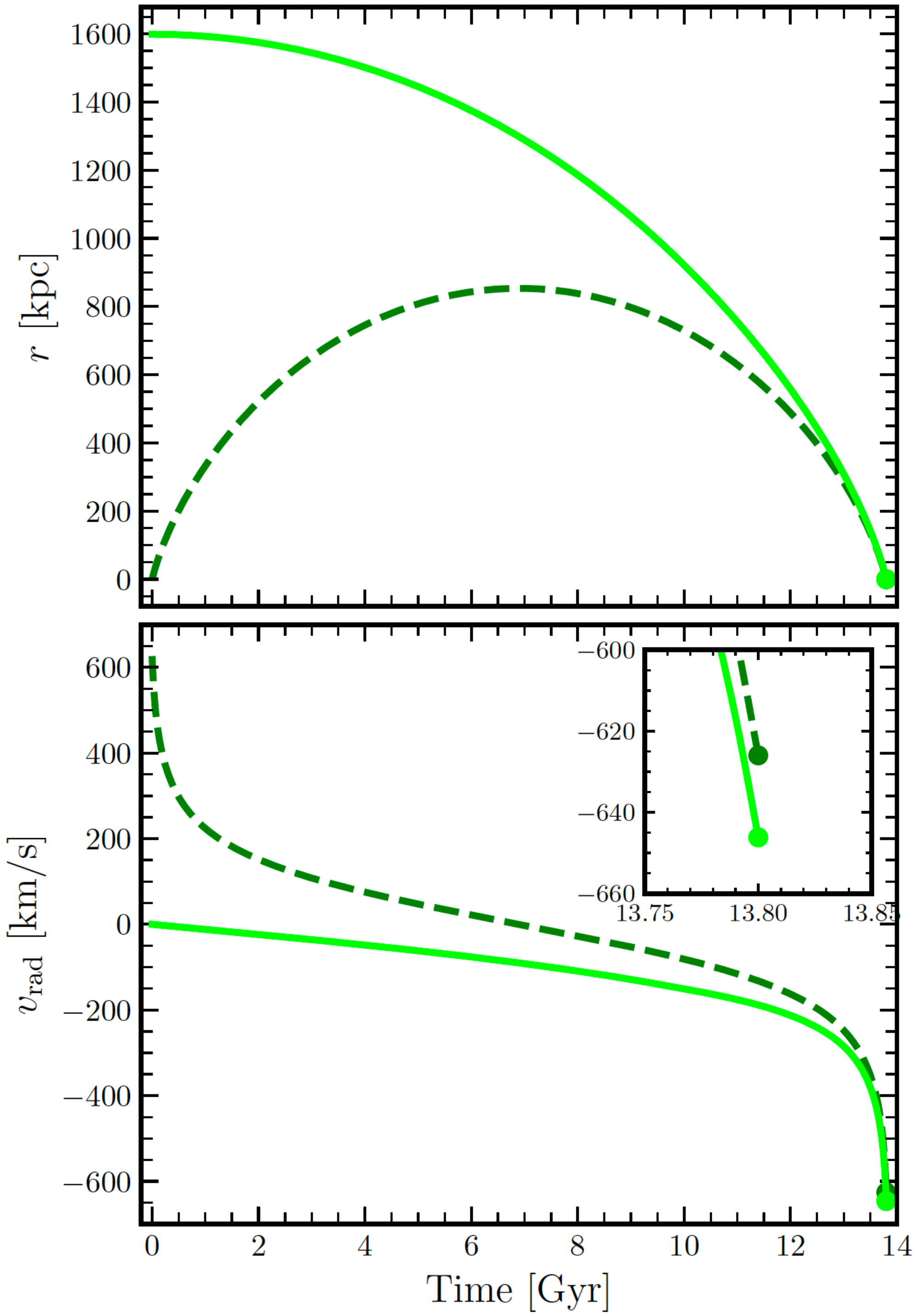

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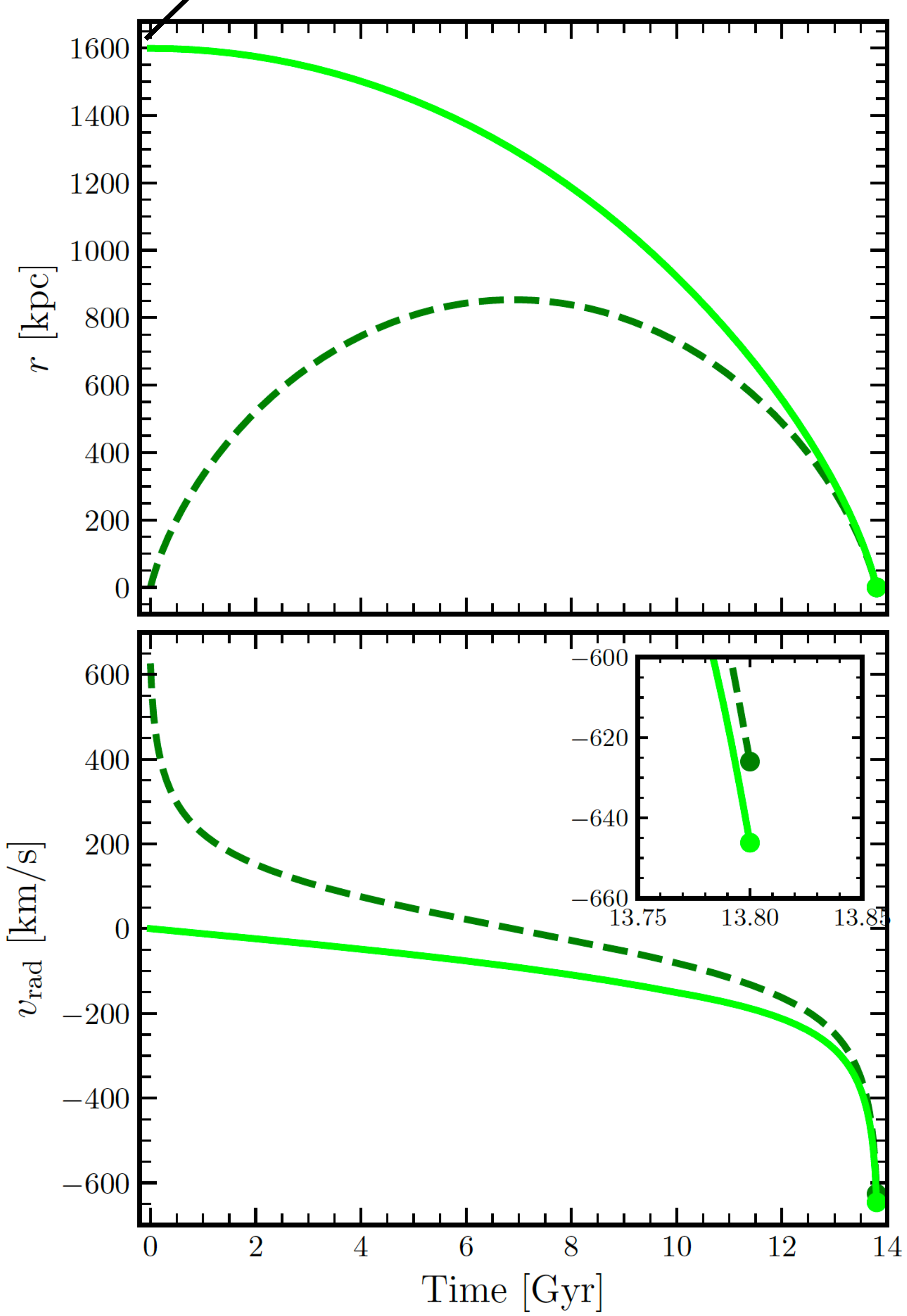
max radius that the particle can start from to reach the center by present day



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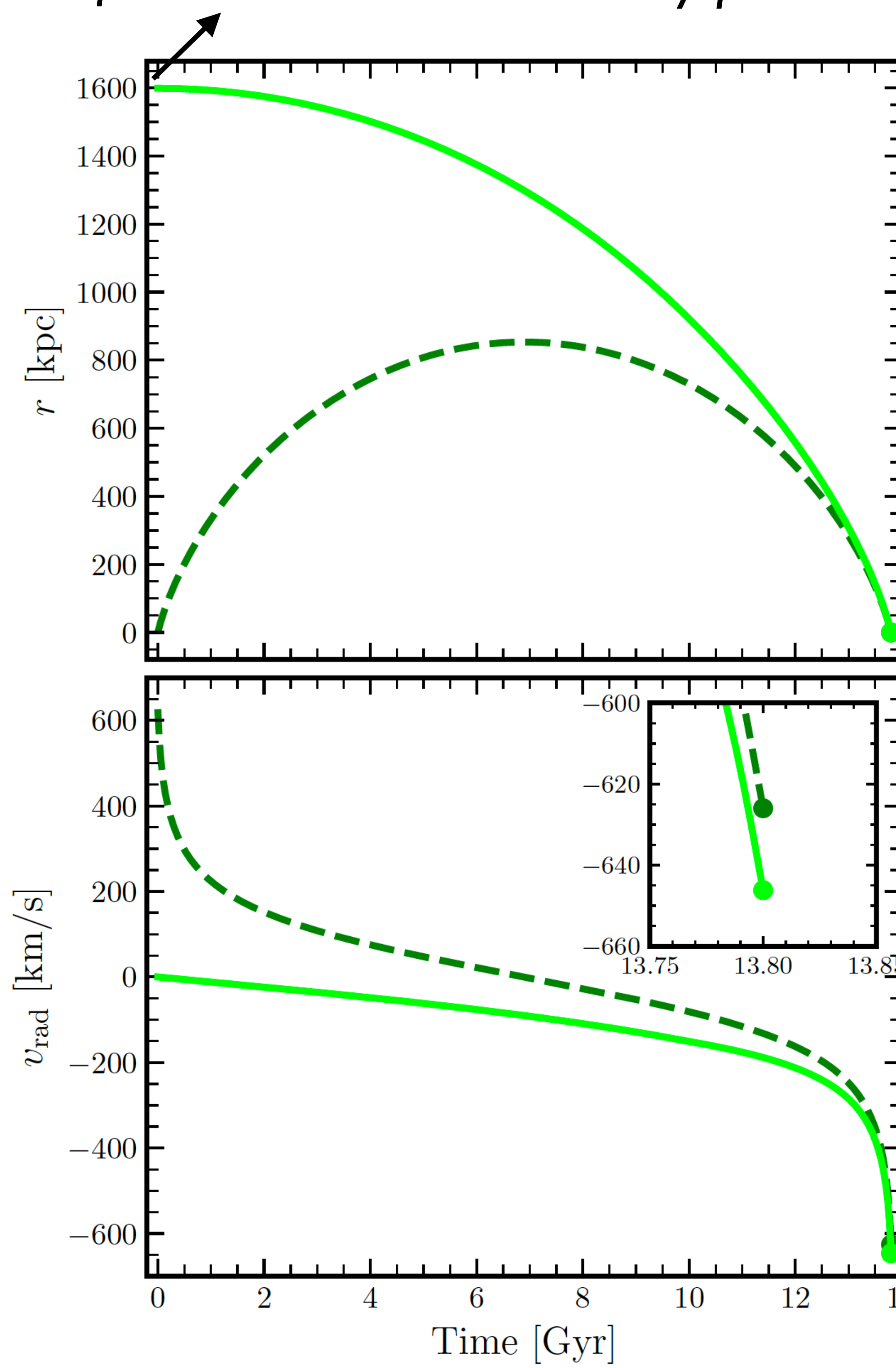
- Test particle on a radial orbit that reaches the Solar vicinity at the present day after evolving for 13.8 Gyr, reaches a terminal velocity of ~ 600 km/s.
- ***The model reproduces remarkably well the maximum speeds obtained at all radii from the simulations.***

max radius that the particle can start from to reach the center by present day



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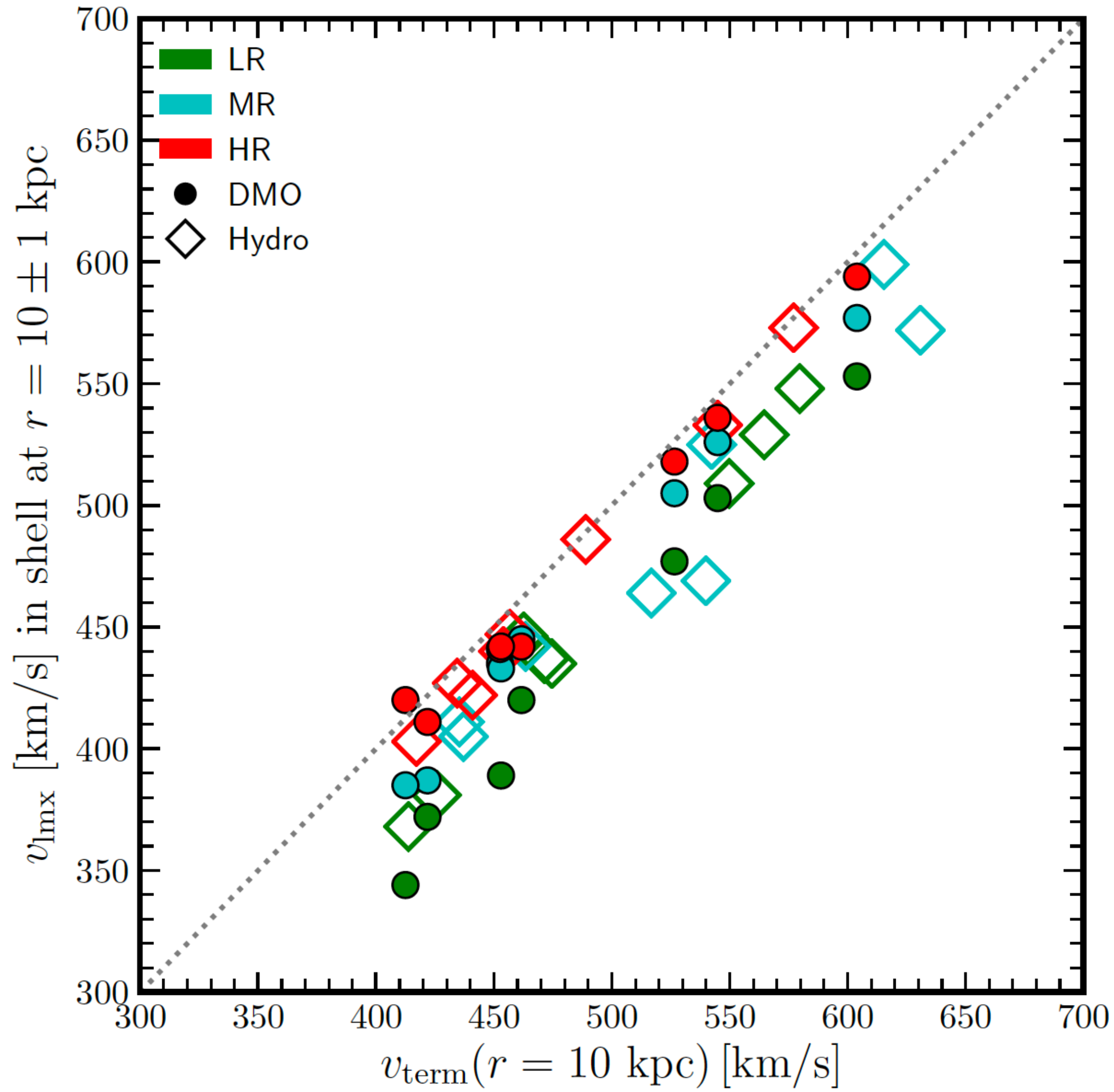
Halo-to-halo scatter



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- Excellent agreement between the maximum speeds of DM particles in the Solar neighborhood and the terminal velocity model for all HR halos.

Summary

Cosmological simulations provide important insight on the local DM distribution. → *Crucial for the interpretation of direct detection data.*

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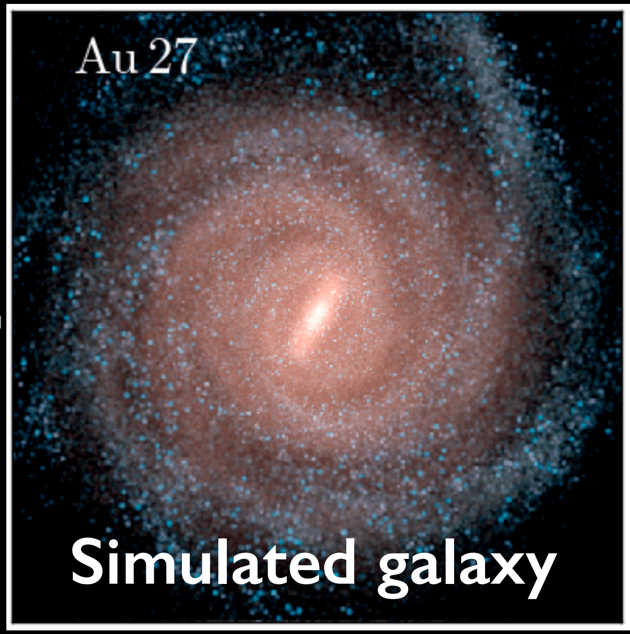

Large Magellanic Cloud

The LMC boosts the high speed tail of the local DM velocity distribution. → *Significant shifts in direct detection limits.*

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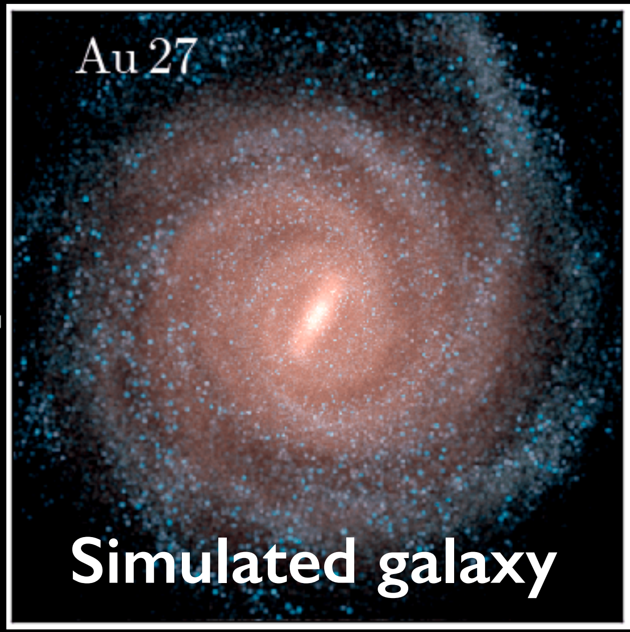


Large Magellanic Cloud

The LMC boosts the high speed tail of the local DM velocity distribution. → *Significant shifts in direct detection limits.*

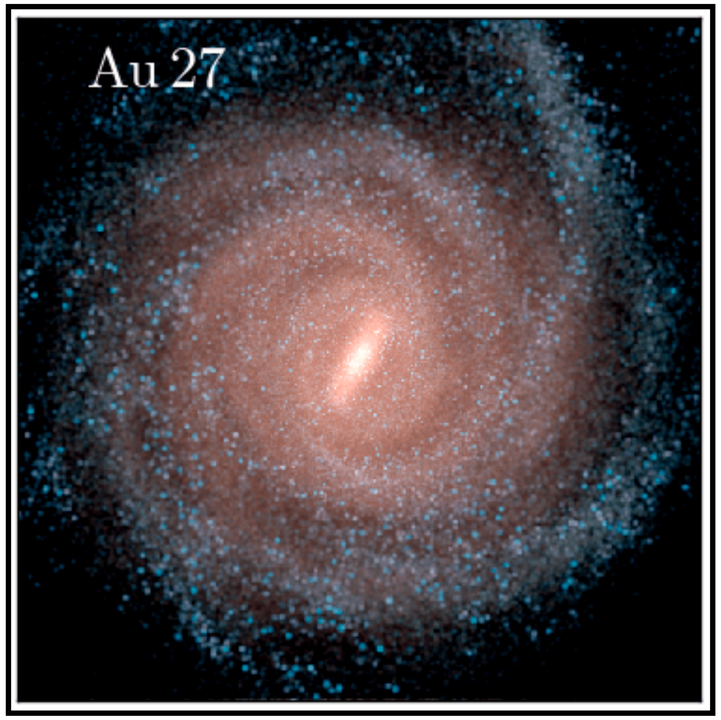
Extragalactic DM particles

Particles from outside the Local Group have not had time to reach the Solar vicinity. → *No evidence for a separate extragalactic high speed DM component.*

Backup Slides

Identifying LMC analogues

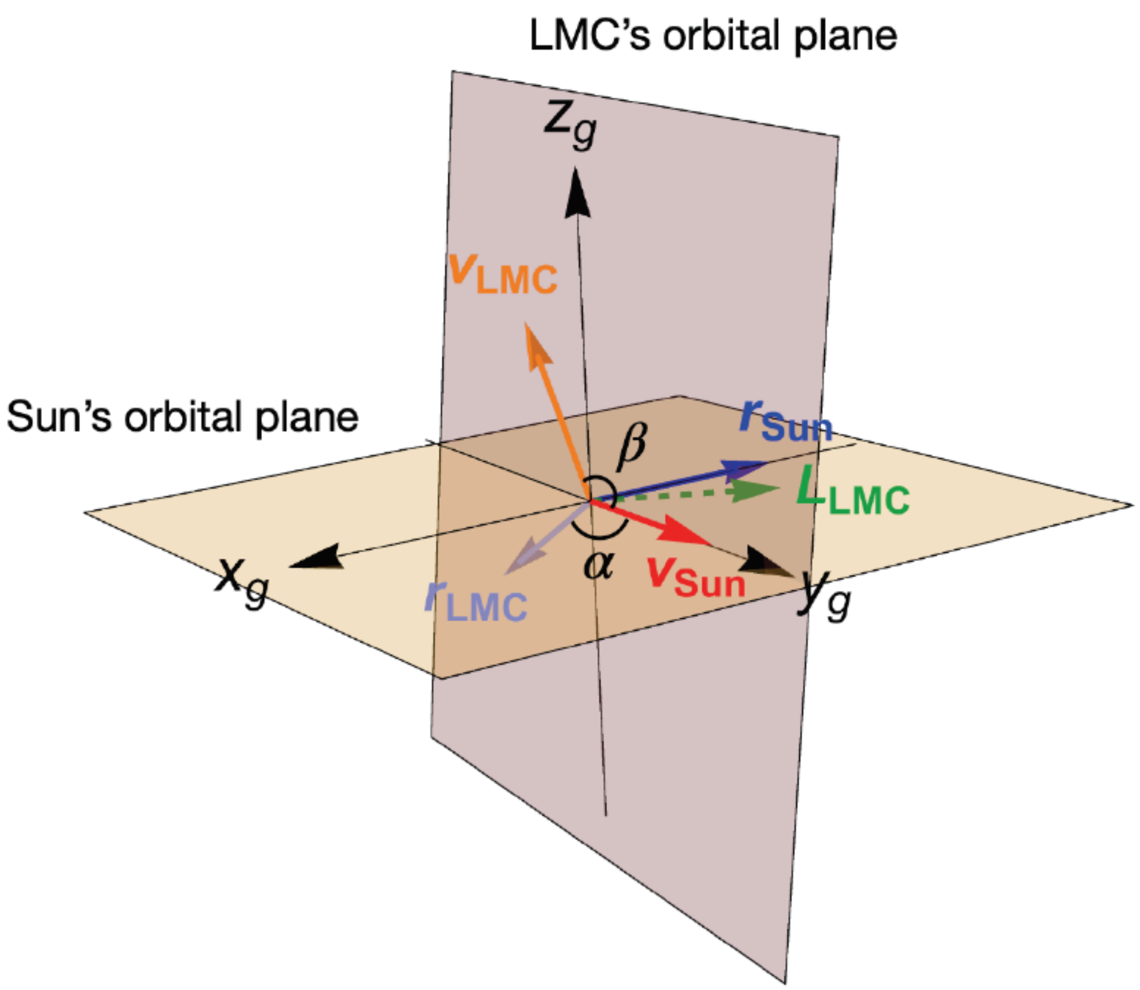
- Select simulated LMC analogues that have properties similar to the observed LMC:
  - Present day stellar mass of the LMC: $\sim 2.7 \times 10^9 \ \mathrm{M}_\odot$
  - LMC's first pericenter distance: $\sim 48 \ \mathrm{kpc}$
- Difficult to find an exact LMC analogue in cosmological simulations. → Follow the history of the simulated halos within the last 8 Gyrs to find LMC analogues.



- Identify 15 LMC analogues based on two criteria:
  - LMC's stellar mass is $> 5 \times 10^8 \ \mathrm{M}_\odot$.
  - Distance from host at first pericenter is in the range of $[40,60] \ \mathrm{kpc}$.

Matching the Sun-LMC geometry

Steps in matching the Sun-LMC geometry to observations:



$$\cos\alpha \equiv \hat{\mathbf{v}}^{\rm sim}_{\rm Sun} \cdot \hat{\mathbf{r}}^{\rm sim}_{\rm LMC} = -0.835$$

$$\cos\beta \equiv \hat{\mathbf{v}}^{\rm sim}_{\rm Sun} \cdot \hat{\mathbf{v}}^{\rm sim}_{\rm LMC} = -0.709$$

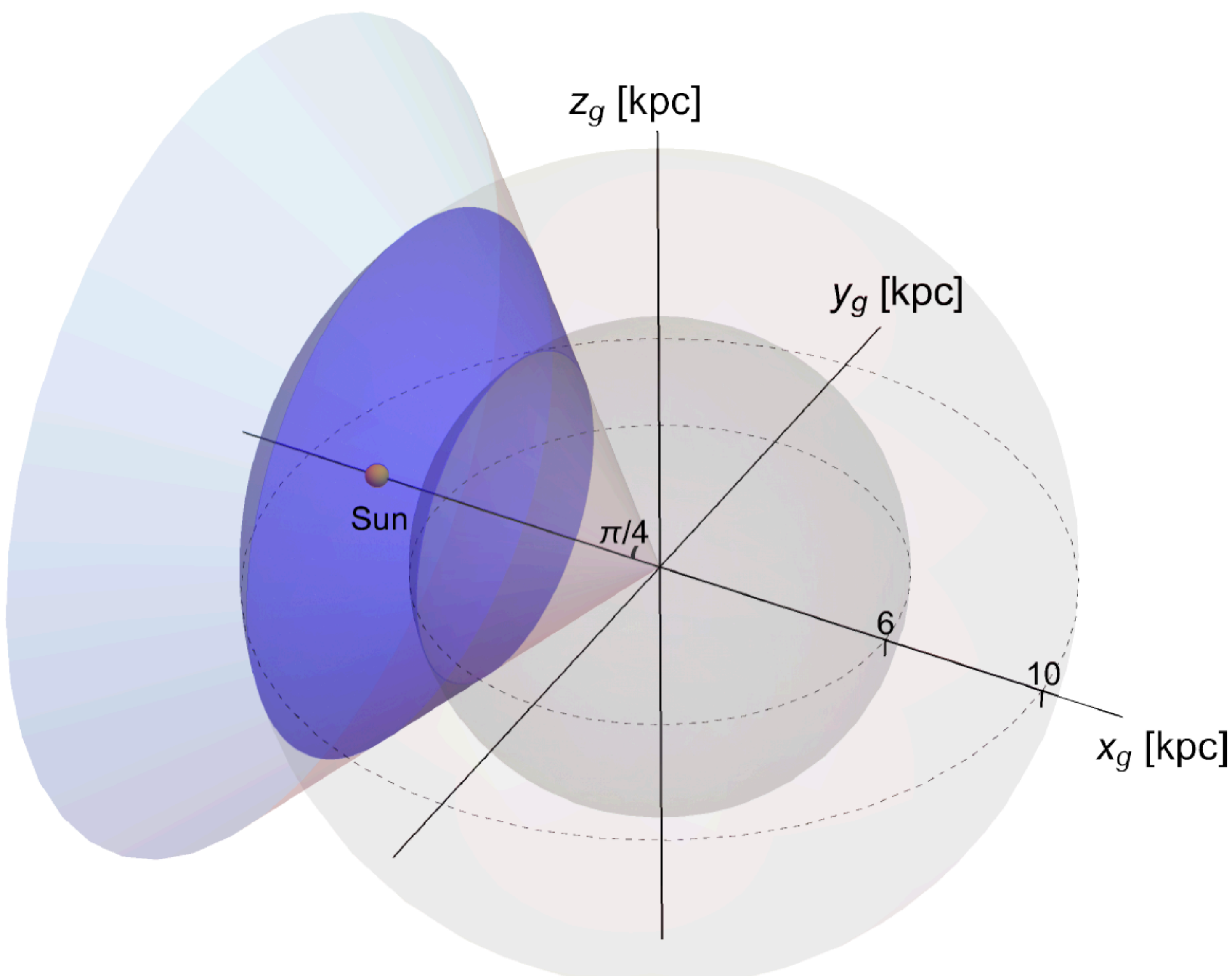
1. Find the stellar disk orientations that make the same angle with the orbital plane of the LMC analogues as in observations.

2. Find the position of the Sun for each allowed disk by matching the angles between the angular momentum of the LMC and the Sun's position and velocity in the simulations to their observed values.

3. The best fit Sun's position is the one that leads to the closest match of the angles between the Sun's velocity and the LMC's position and velocity with observations.

Defining the Solar region

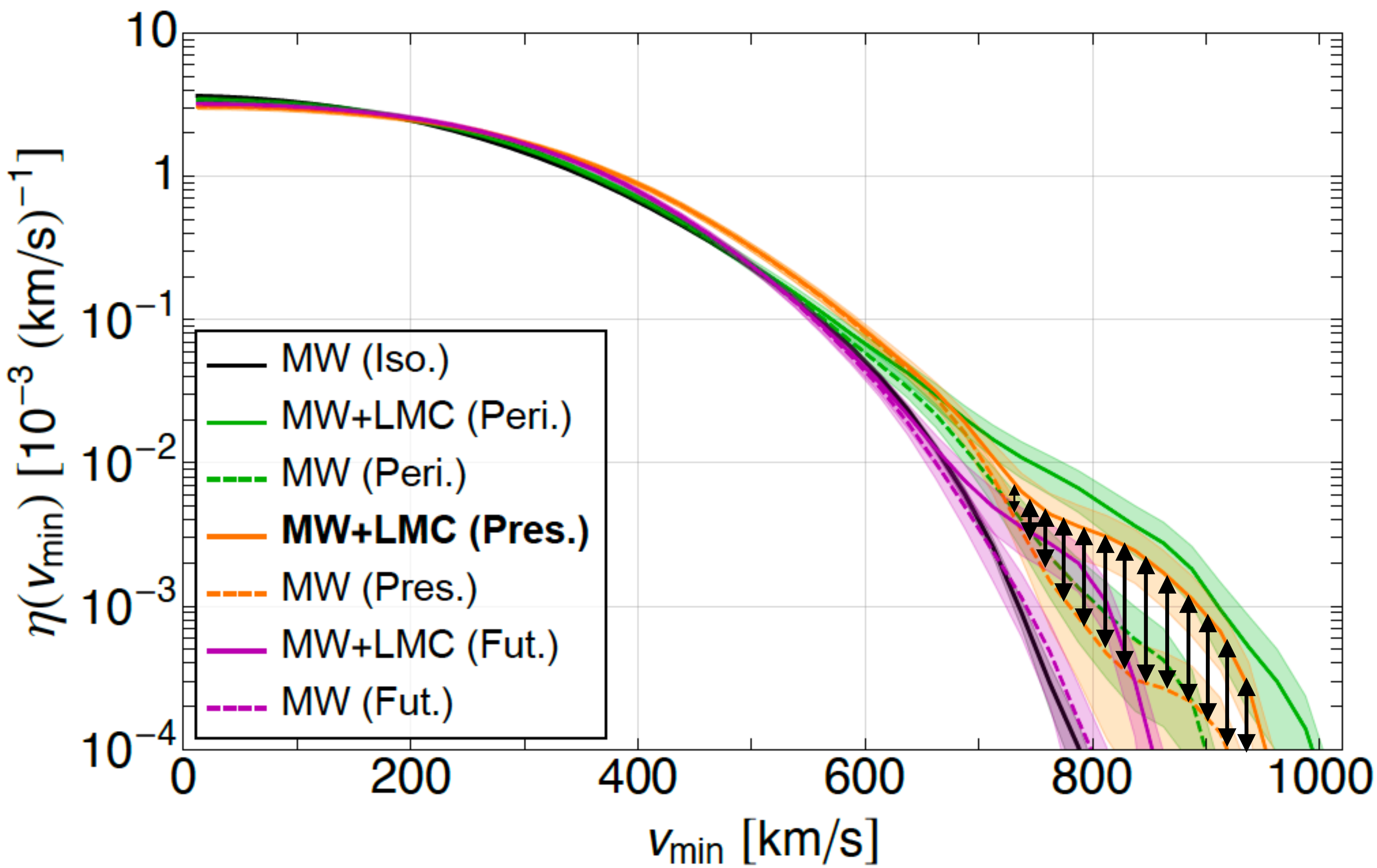
Solar region: overlap of a **spherical shell** with radius between $6-10$ kpc and a **cone** with opening angle $\pi/4$ with its axis aligned with the position of the Sun.



Changes in the halo integrals

Quantify the changes in the tails of the halo integrals by:

$$\Delta\eta = \sum_{v^i_{\rm min} \geq 0.7 v^{\rm det}_{\rm esc}} \left[\eta_{\rm MW+LMC}(v^i_{\rm min}) - \eta_{\rm MW}(v^i_{\rm min})\right] \Delta v_{\rm min}$$



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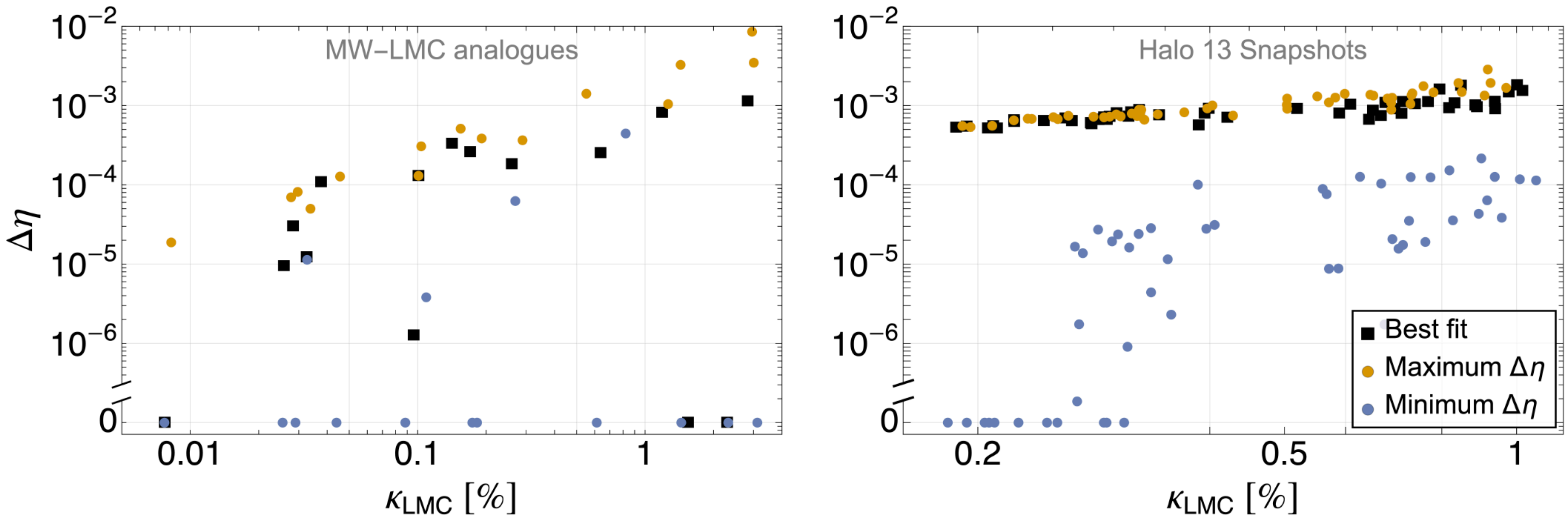
Factors that contribute to changes in the tail of the halo integrals:

1. Percentage of DM particles originating from the LMC in the Solar region.
2. The Sun's position in the simulations.
3. The Milky Way response due to the motion of the LMC.

Impact of the DM particles from the LMC

Correlations between the **percentage of LMC DM particles in the Solar region** (κ_{LMC}) and $\Delta\eta$:

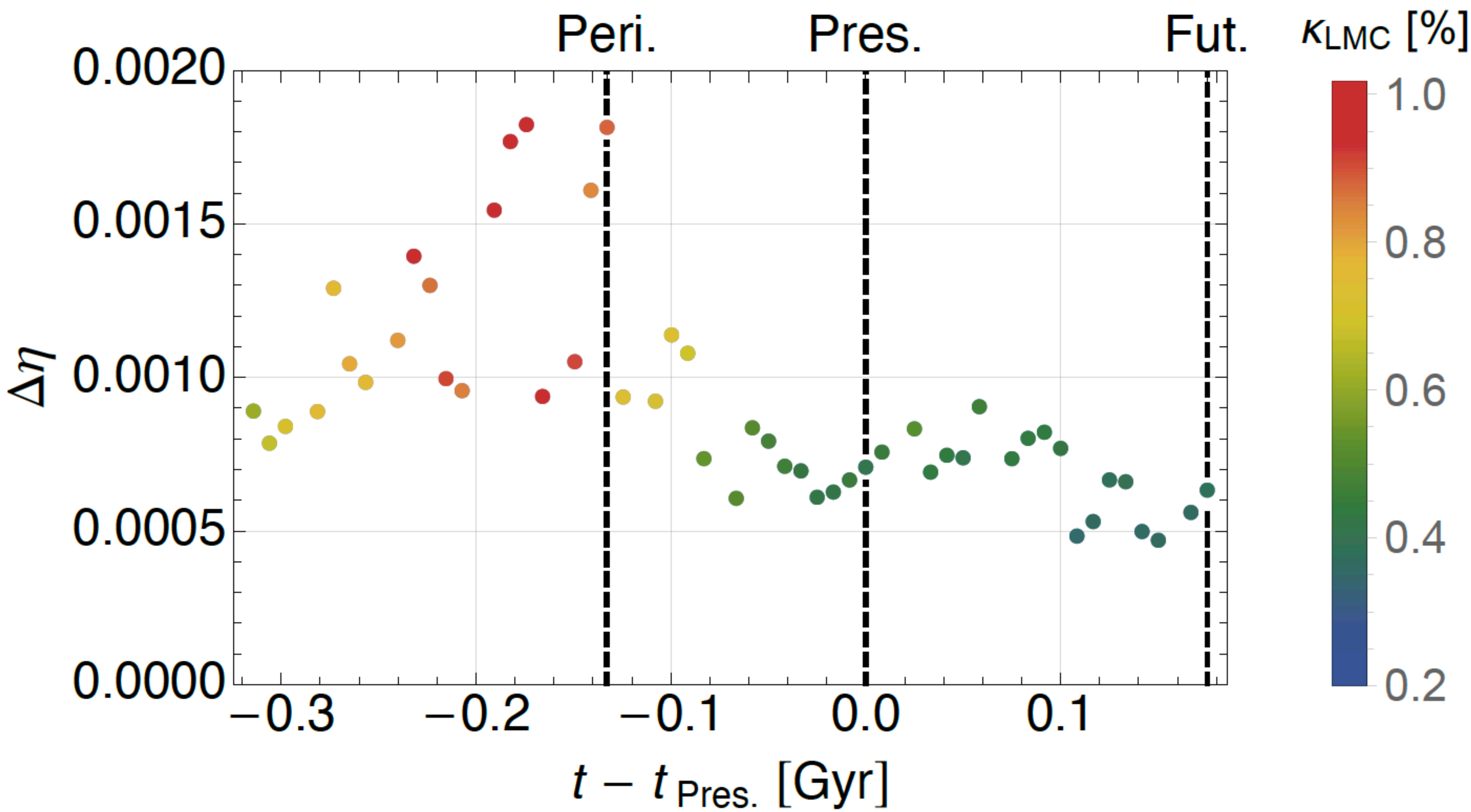


Smith-Orlik et al., JCAP 10, 070 (2023)

- $\Delta\eta$ for best fit Sun's position close to max $\Delta\eta$, and increases with κ_{LMC}.
- Scatter in $\Delta\eta$ for halos with similar κ_{LMC}, due to the **choice of the Sun's position** for specifying the Solar region.

Impact of the DM particles from the LMC

$\Delta\eta$ for best fit Sun's position for different snapshots in one halo:

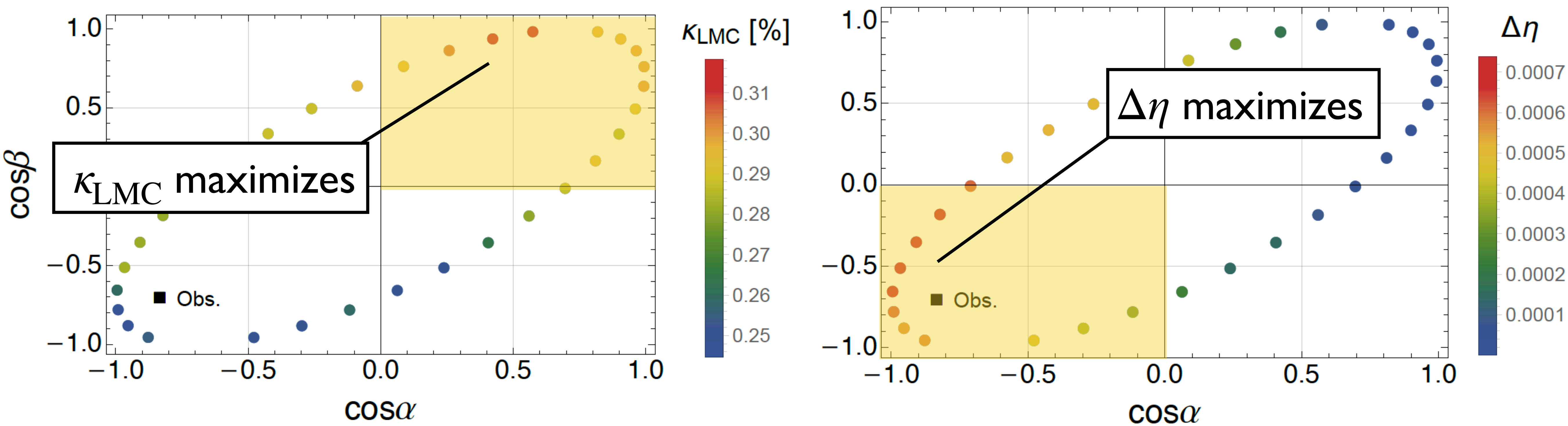


Smith-Orlik et al., JCAP 10, 070 (2023)

Variation with the Sun-LMC geometry

Cosine angles that parametrize the Sun-LMC geometry:

$$\cos\alpha \equiv \hat{\mathbf{v}}^{\text{sim}}_{\text{Sun}} \cdot \hat{\mathbf{r}}^{\text{sim}}_{\text{LMC}}$$
$$\cos\beta \equiv \hat{\mathbf{v}}^{\text{sim}}_{\text{Sun}} \cdot \hat{\mathbf{v}}^{\text{sim}}_{\text{LMC}}$$



Smith-Orlik et al., JCAP 10, 070 (2023)

The best fit Sun's position is in a privileged position with respect to maximizing $\Delta\eta$. ➡ ***For the actual Milky Way, we expect the LMC to maximally affect the tail of the halo integral.***

Direct detection exclusion limits

- Simulate the signals in 3 idealized near future direct detection experiments that would search for nuclear or electron recoils.

Nuclear recoils

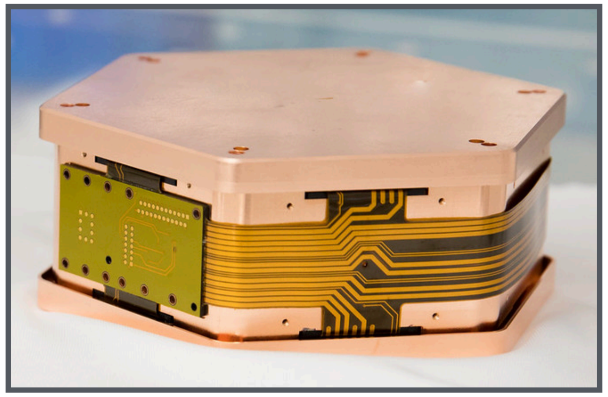
Xenon based

[2 – 50] keV
5.6×10^6 kg days
Based on LZ

Germanium based

- [40 – 300] eV, 1.6×10^4 kg days
- [3 – 30] keV, 2.04×10^4 kg days

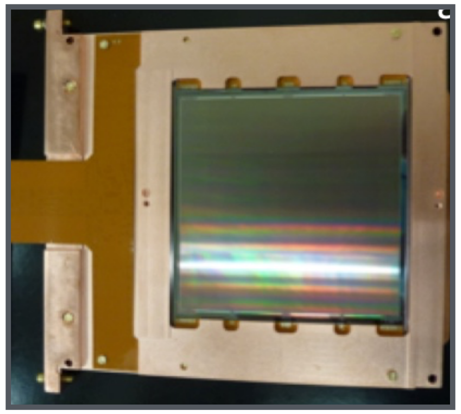
Based on SuperCDMS



Electron recoils

Silicon CCD

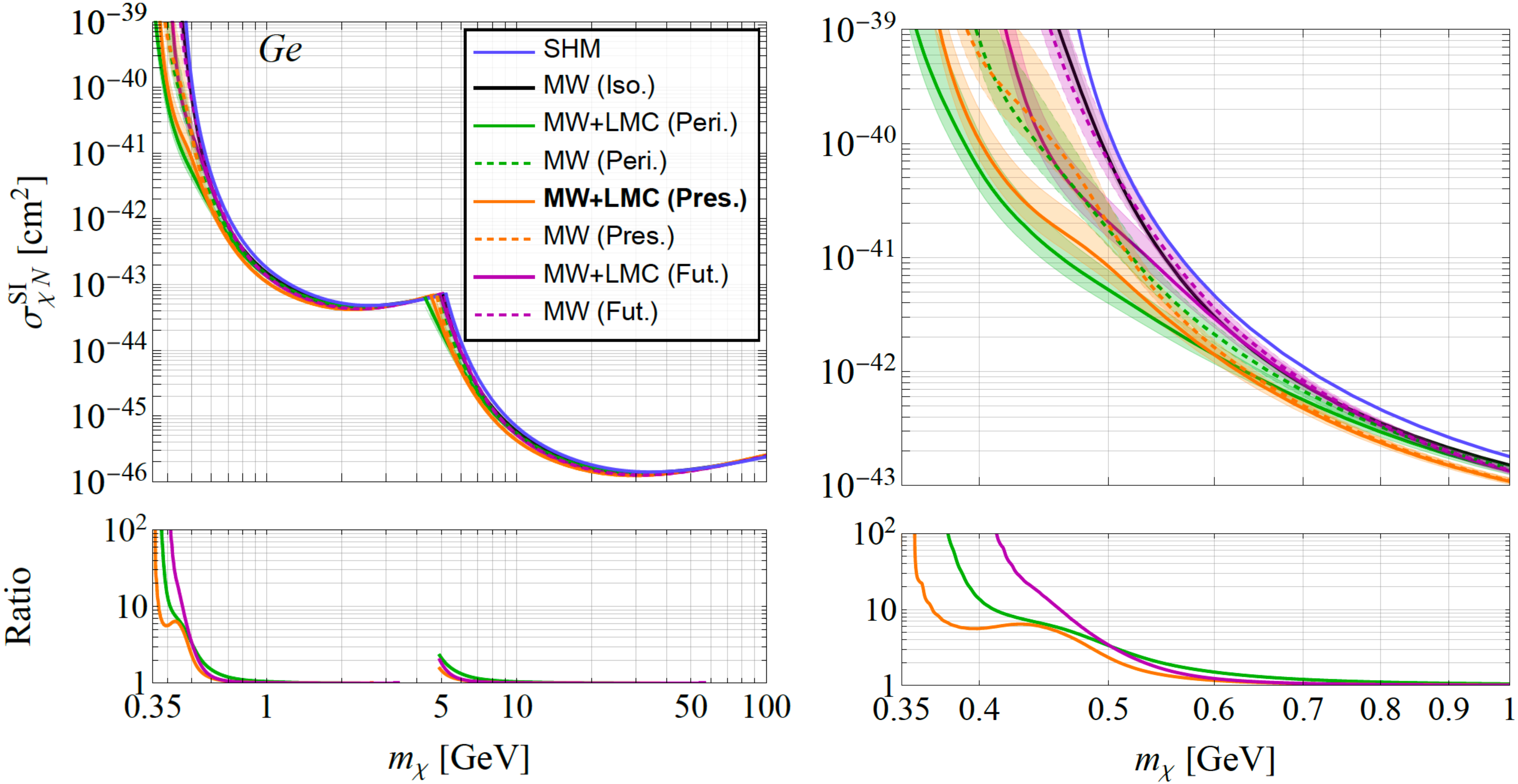
1 electron threshold
1 kg yr
Based on DAMIC



Direct detection: nuclear recoils

Germanium based detector:

Fix $\rho_\chi = 0.3\ \mathrm{GeV/cm^3}$



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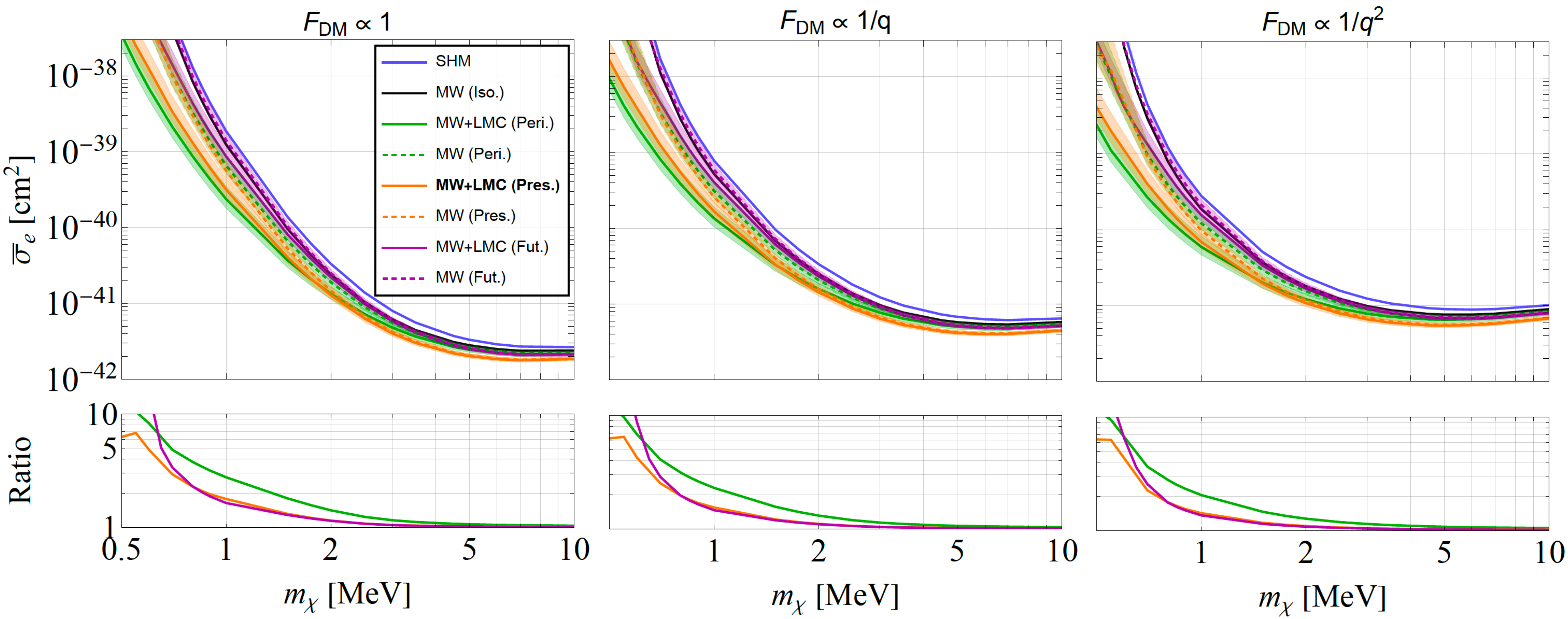

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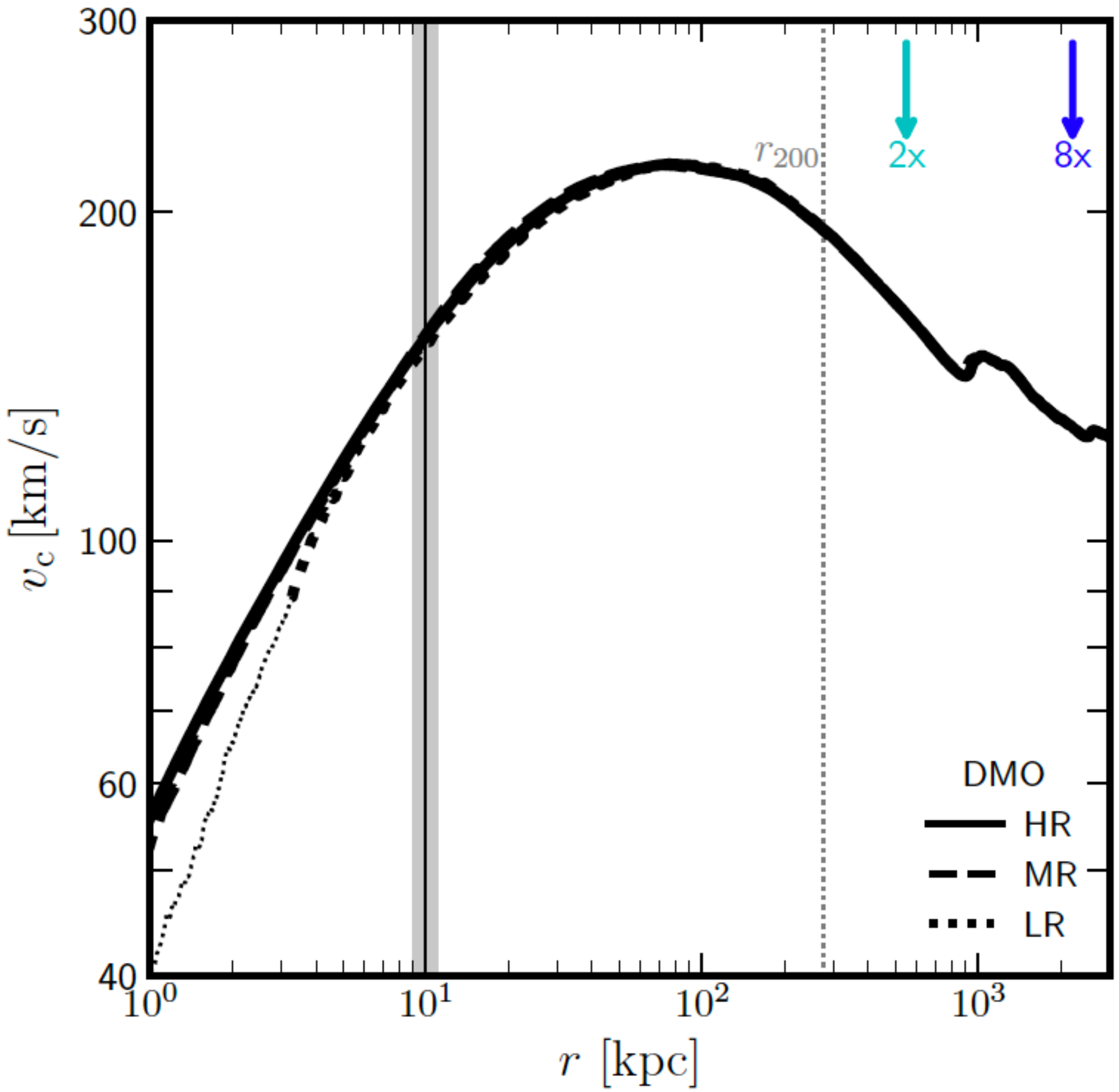
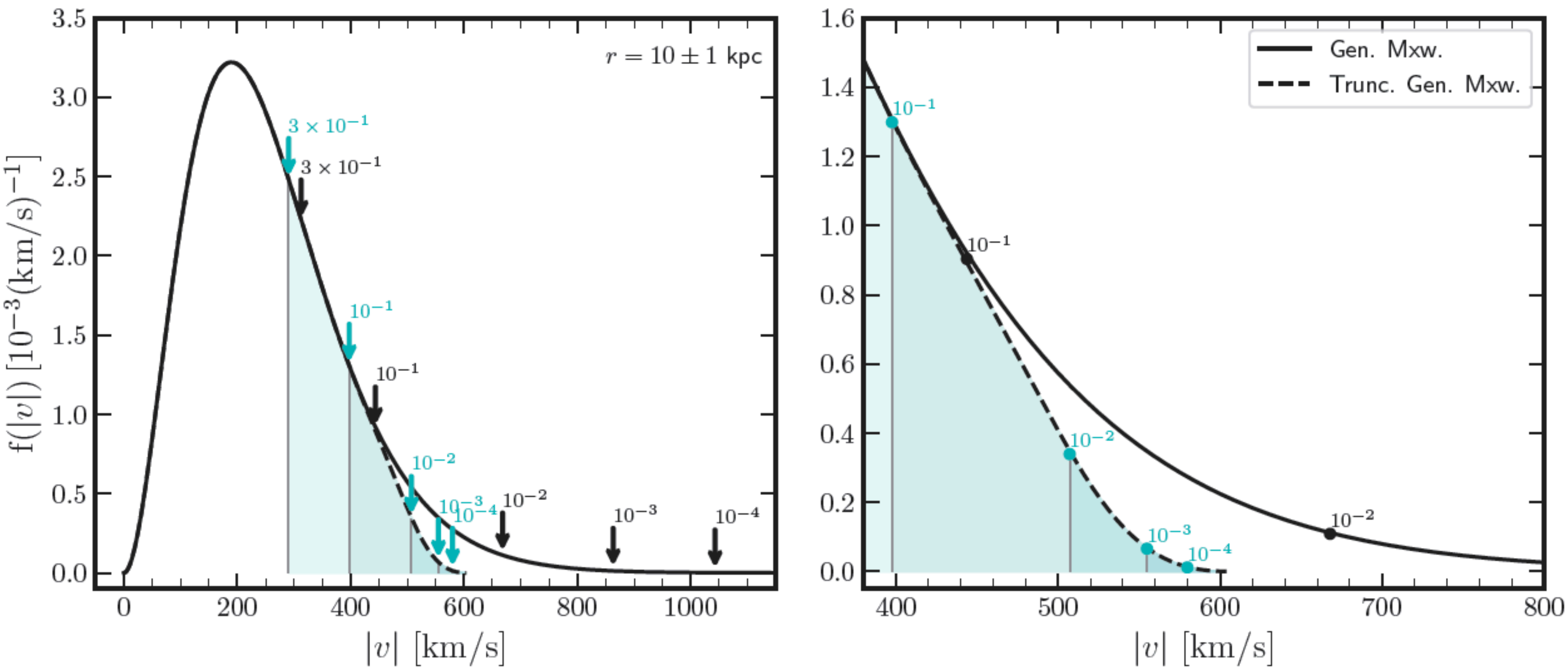
Circular velocities



Santos-Santos et al., JCAP 03, 046 (2024)

Circular velocity profiles show excellent agreement between the different resolution simulations, except for the inner most radii of the lowest resolution run.

Mass fraction in the tails



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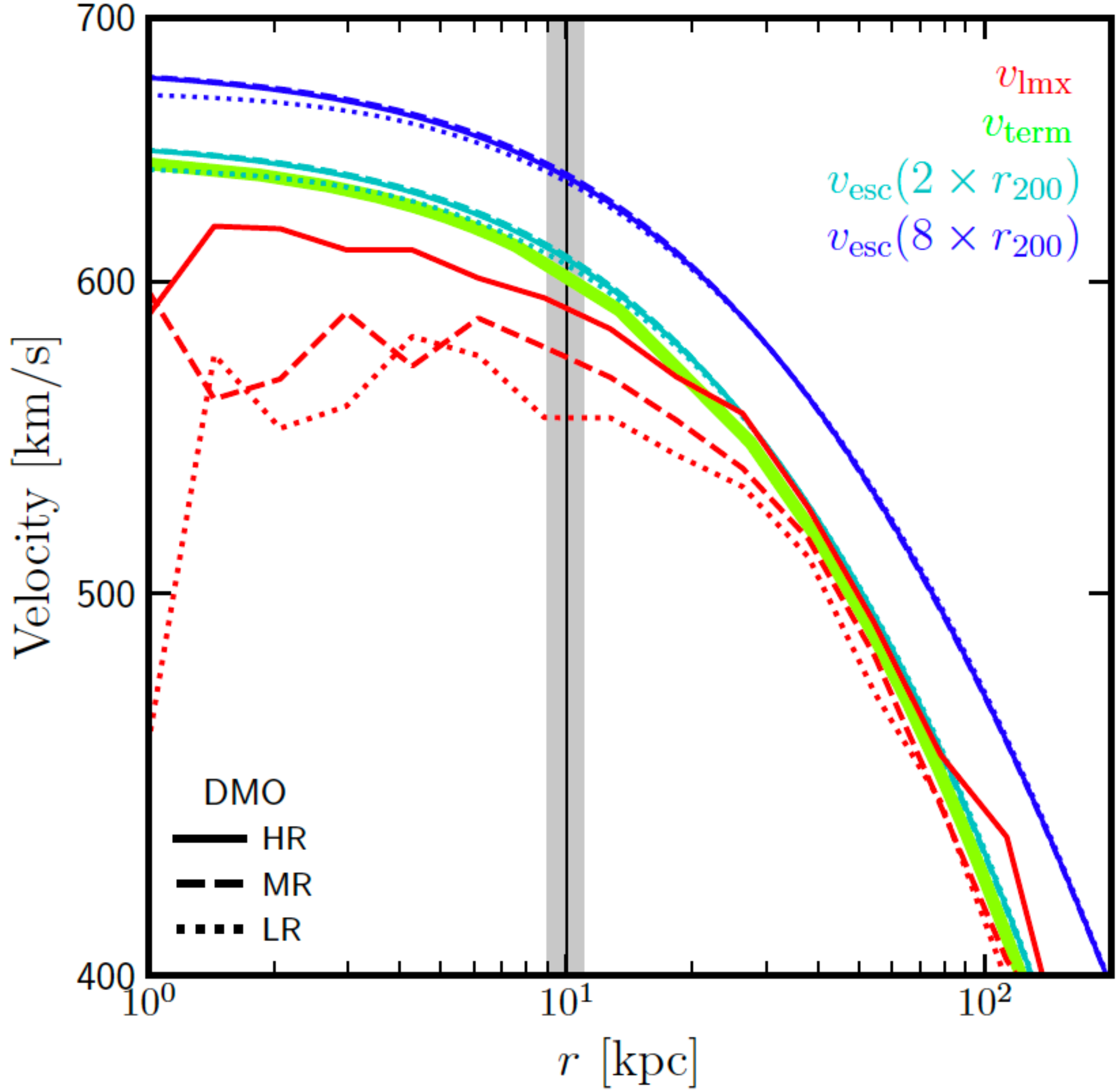
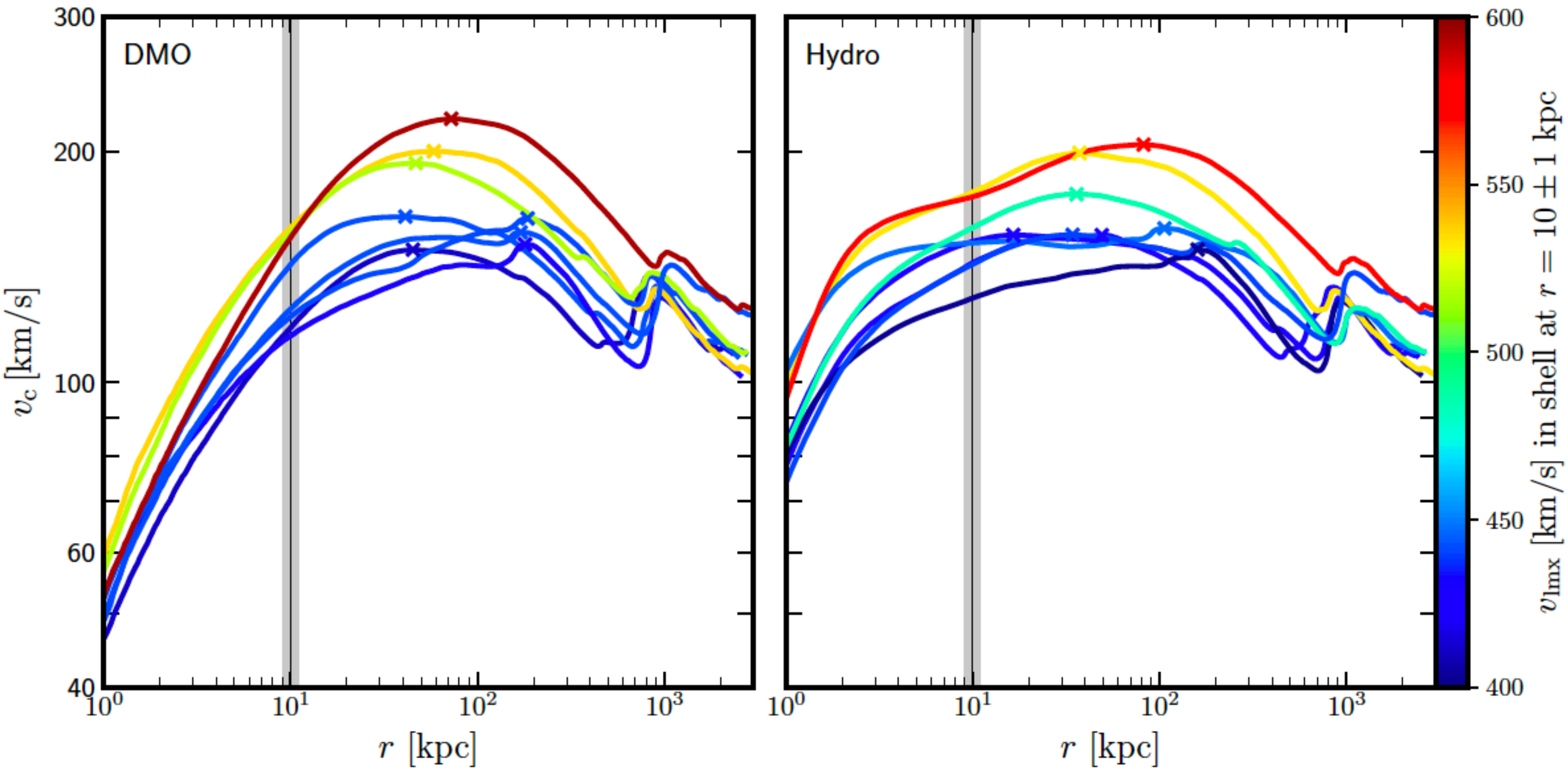
Maximum speeds



Santos-Santos et al., JCAP 03, 046 (2024)

The model reproduces very well the maximum speeds at all radii.

Circular velocity profiles



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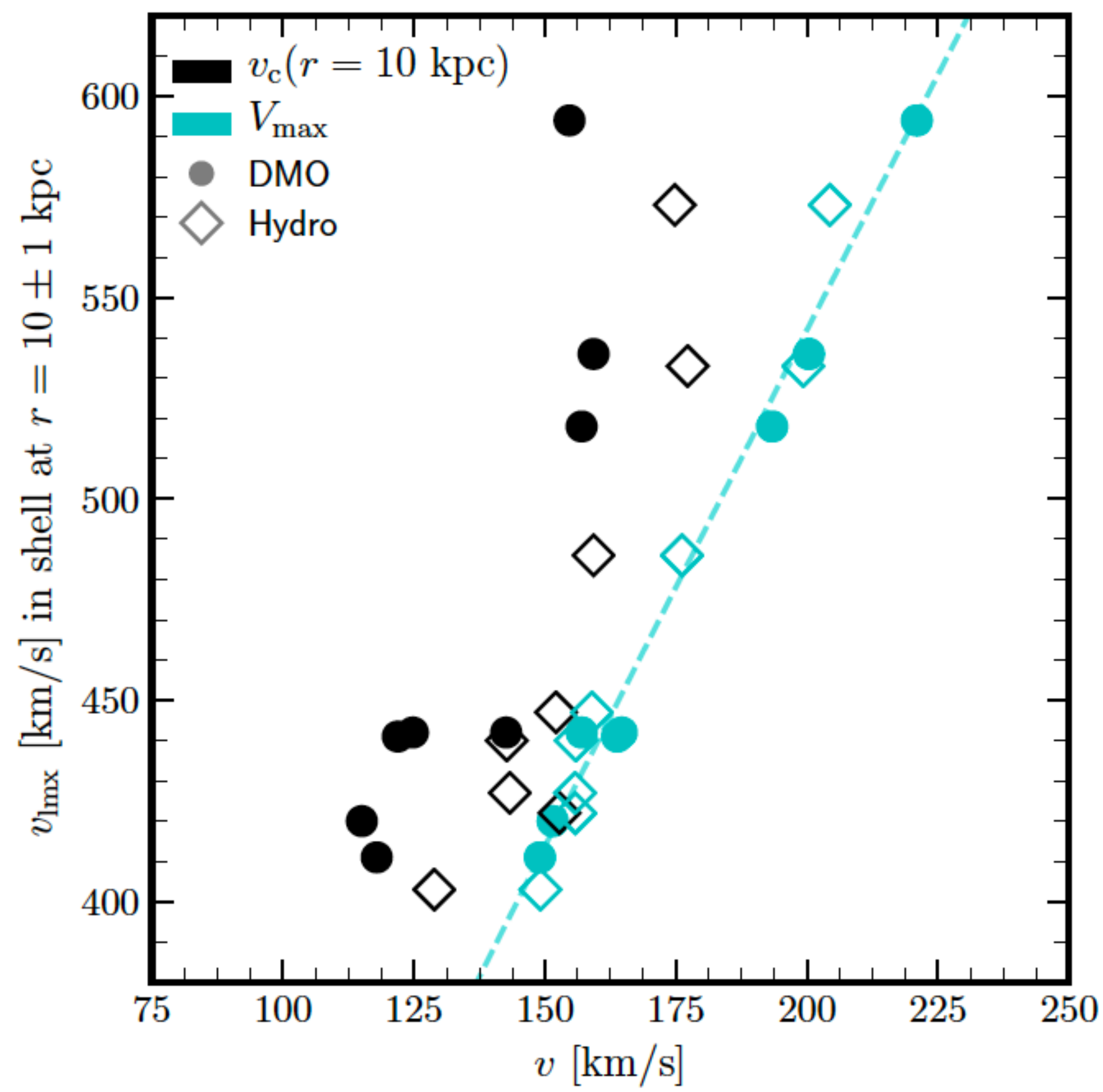
Maximum speeds are in the range $\sim [350 - 600]$ km/s, which is much greater than the spread in local circular velocities.

Circular velocity profiles

- The correlation between the local maximum DM speed and circular velocity is poor.
- Terminal velocities depend on the total halo mass, whereas circular velocities depend only on the enclosed mass.
- Even small variations in circular velocity may be accompanied by large changes in the terminal velocity at the same radius.

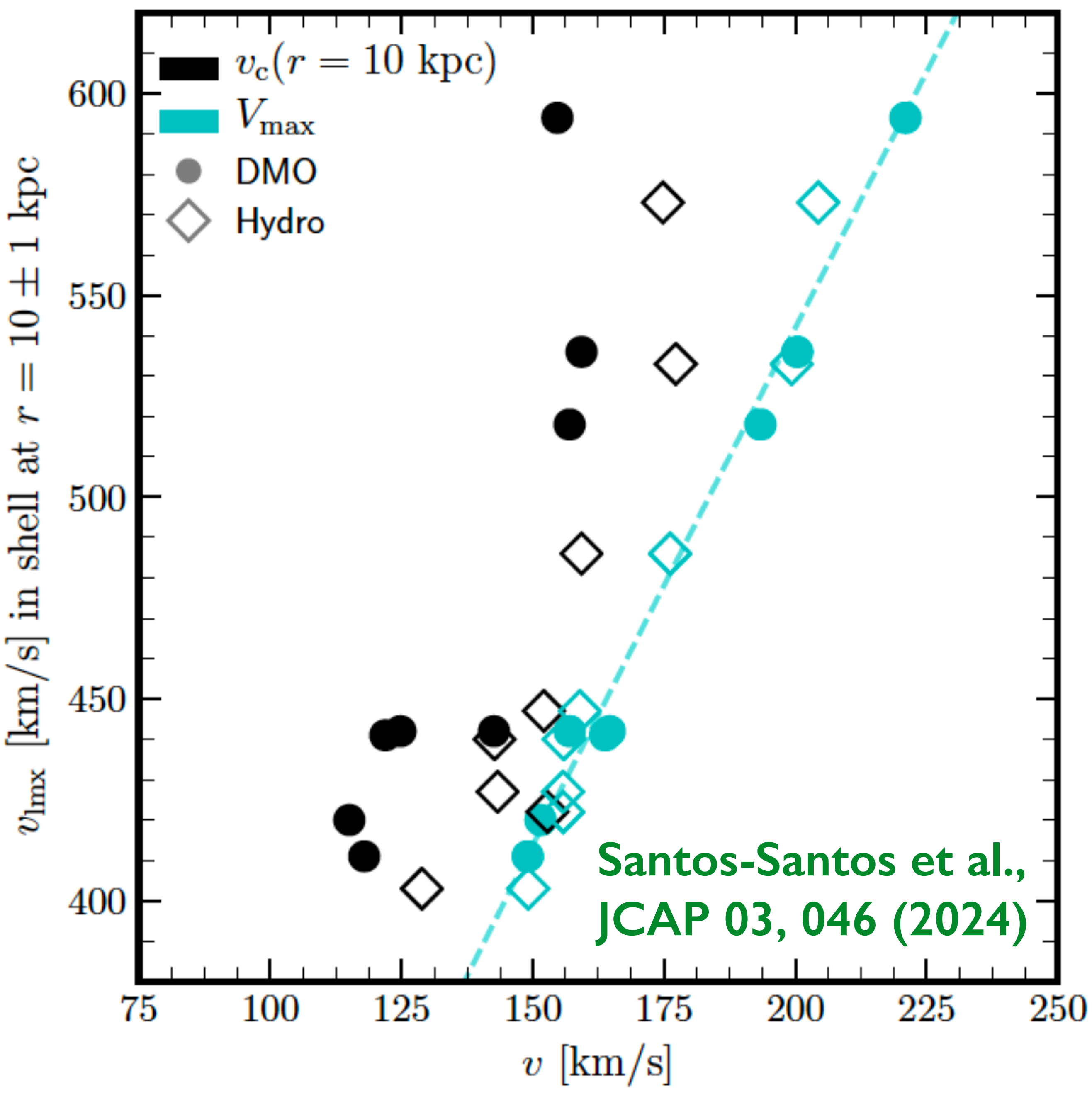


Santos-Santos et al., JCAP 03, 046 (2024)

Circular velocity profiles

- Correlation between the local maximum DM speed and the maximum circular velocity, $V_{\rm max}$ is excellent.
- The maximum circular velocities probe better the outskirts of the halos, which are responsible for accelerating infalling particles to the highest speeds.
- Find a simple relation:

$$v_{\rm lmx} \sim 3.75\, V_{\rm max}^{0.94}$$



Tight constraints on $V_{\rm max}$ are needed to accurately predict the local maximum DM speed.