Impact of massive satellites on direct dark matter searches

Nassim Bozorgnia

University of Alberta

EDSU-Tools, Île de Noirmoutier
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Canada Research Chairs
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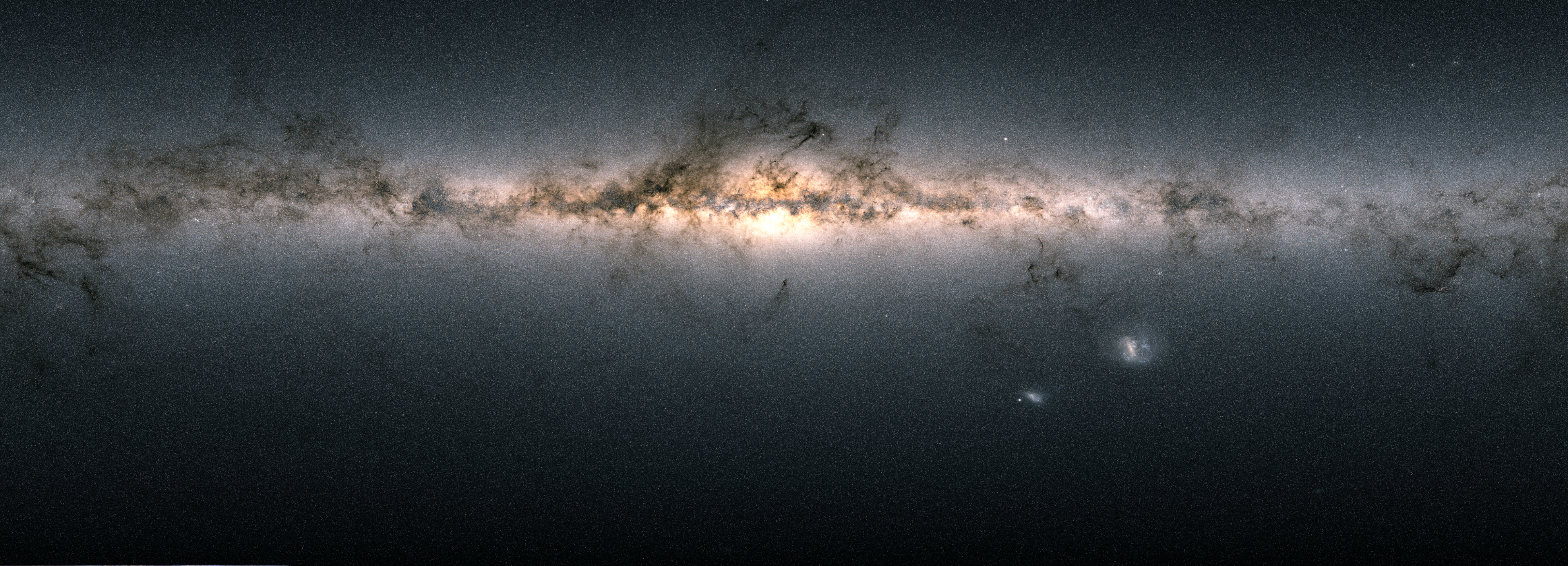
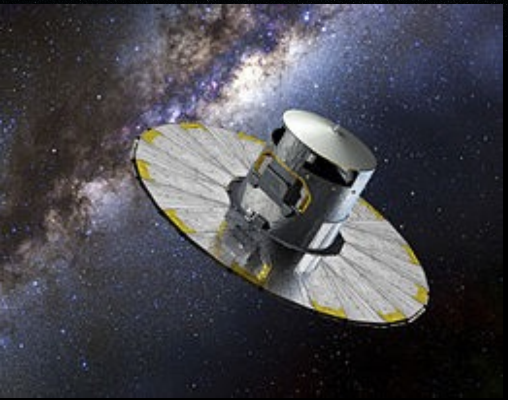
A massive satellite encounter

Could a** recent ($\lesssim 100$ Myr) **and** close ($\lesssim 100$ kpc) **approach of a massive satellite significantly impact the dark matter (DM) distribution in the Solar neighborhood?

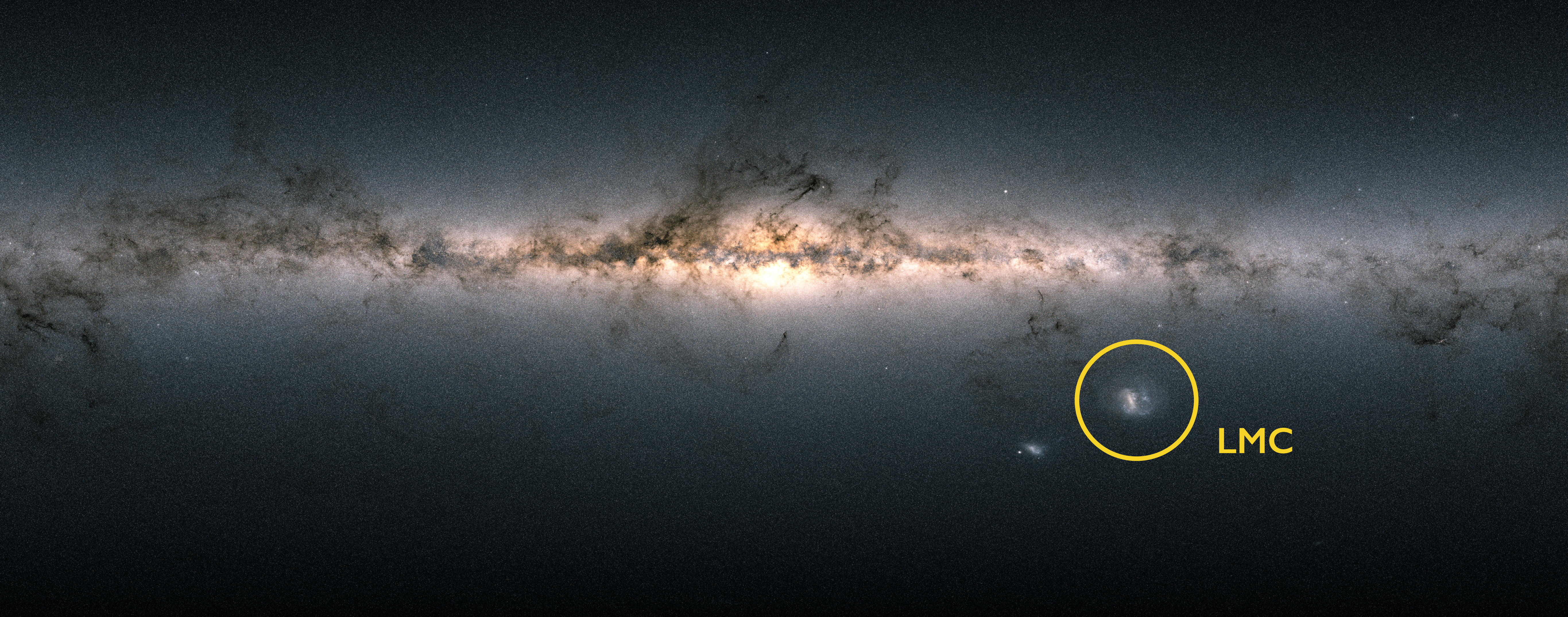


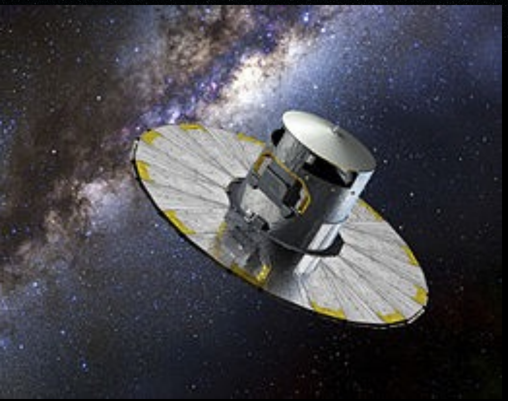


Gaia's EDR3 sky map. *Credit: ESA/Gaia/DPAC*

The Large Magellanic Cloud

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



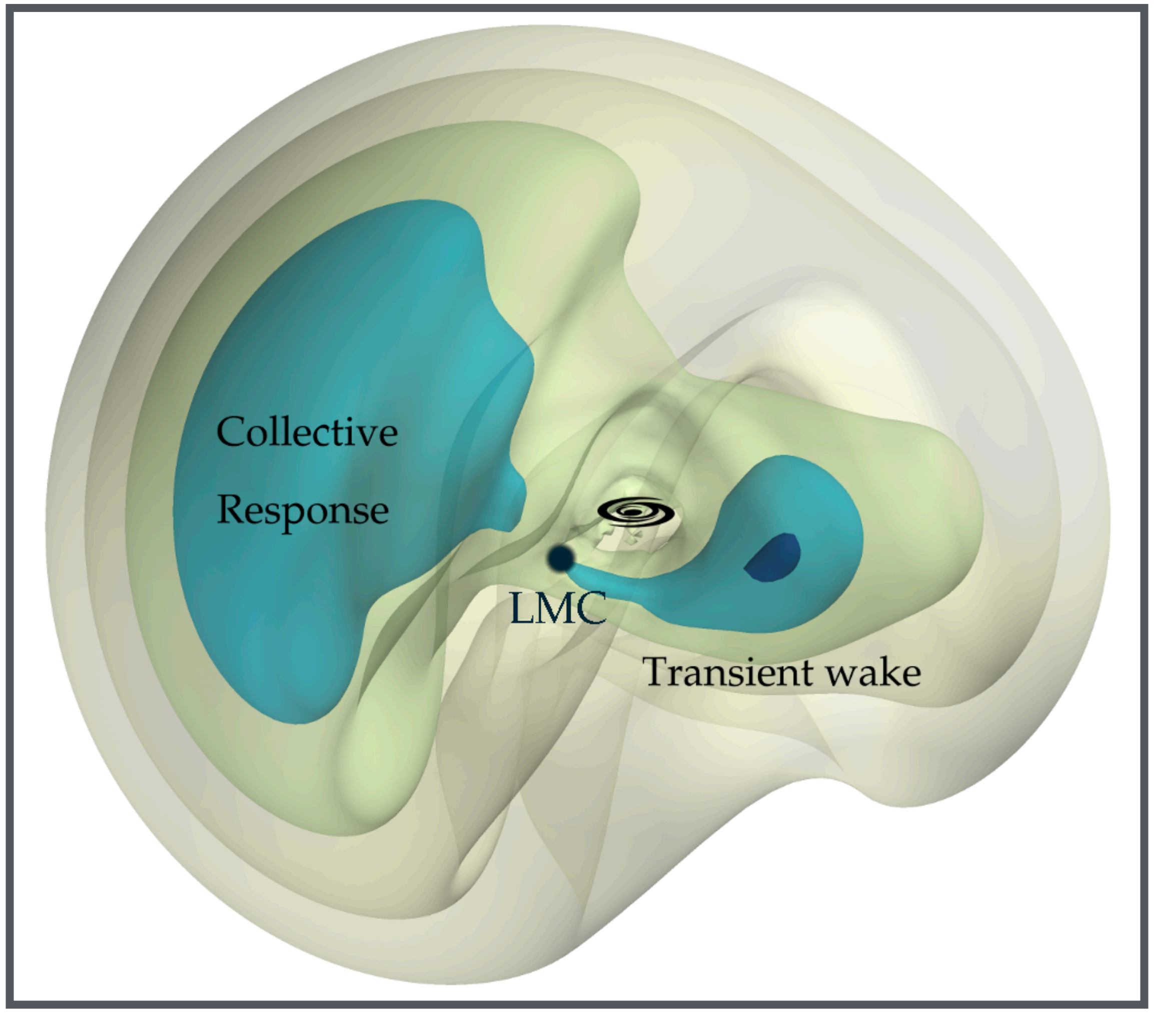


Gaia's EDR3 sky map. *Credit: ESA/Gaia/DPAC*

The effect of the LMC

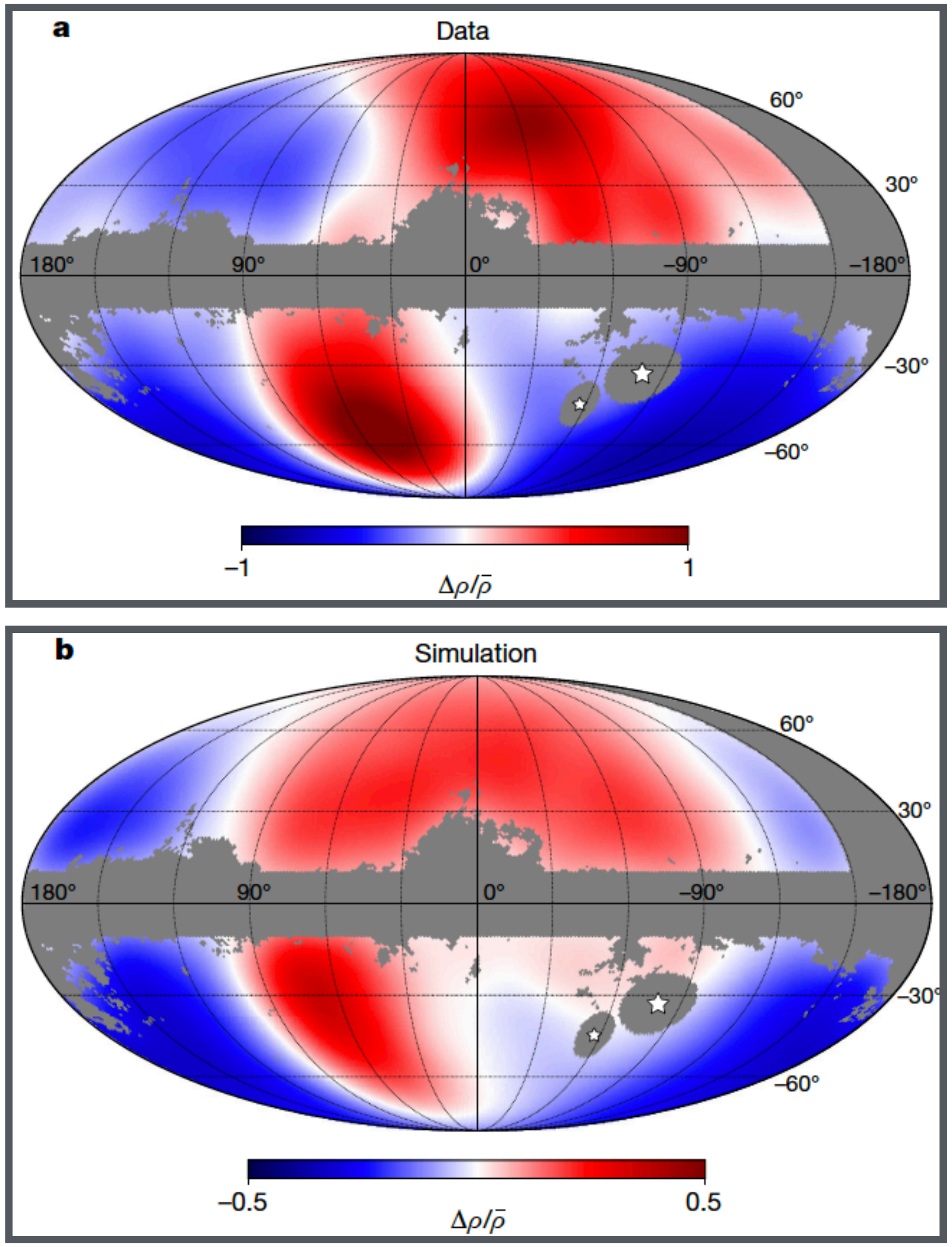
The **LMC** introduces perturbations in the DM and stellar halo.

DM halo



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

Stellar halo



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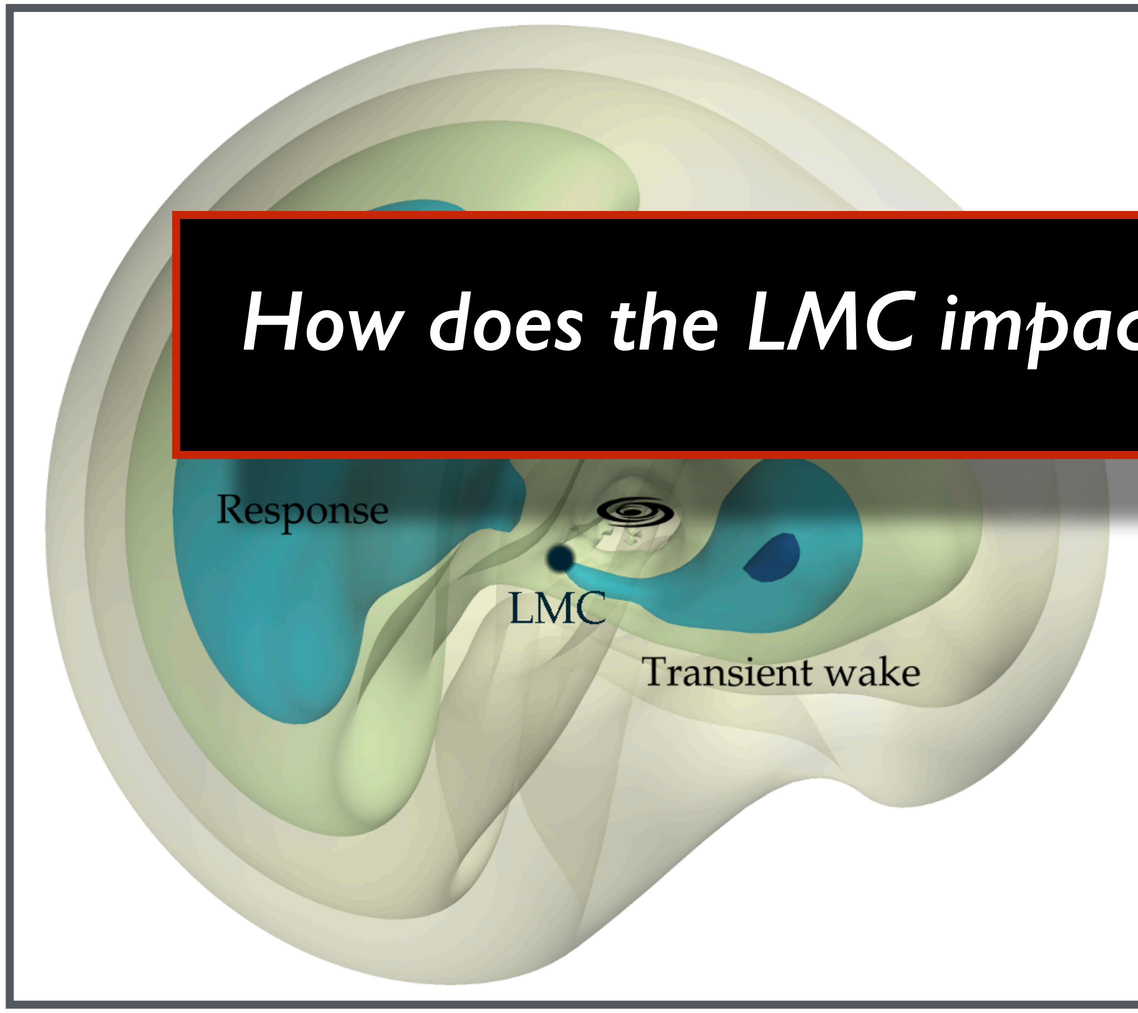

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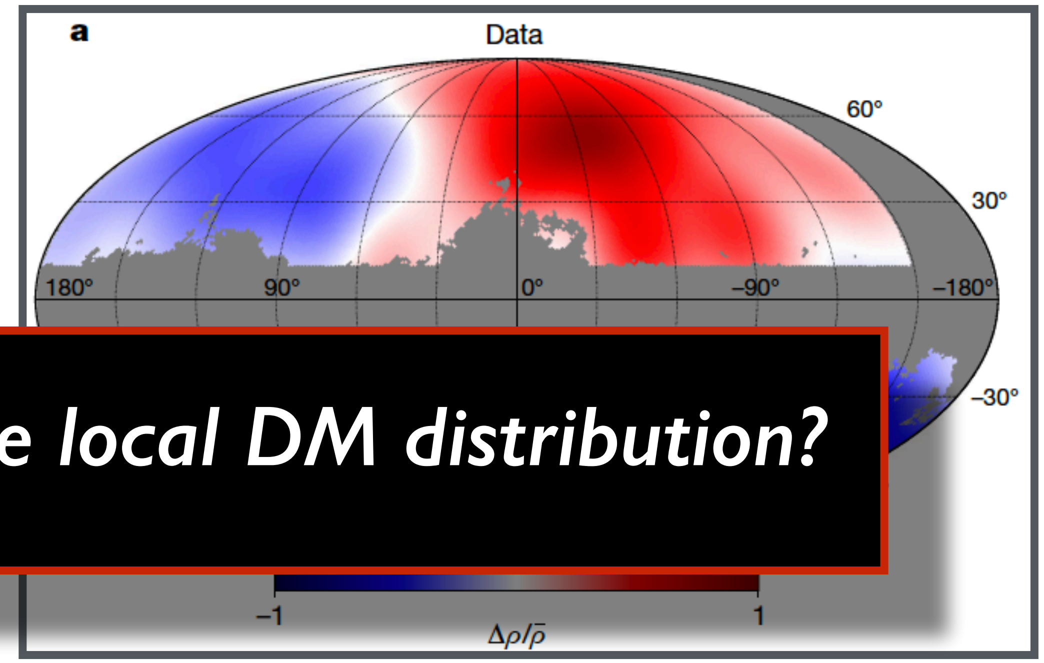
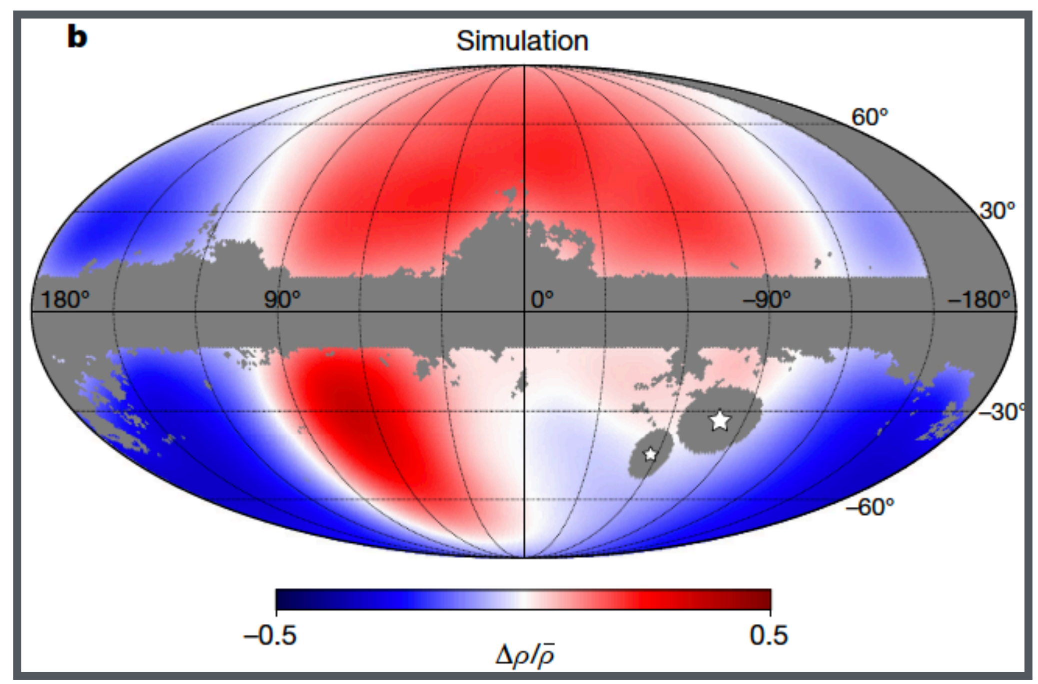
How does the LMC impact the local DM distribution?

Stellar halo





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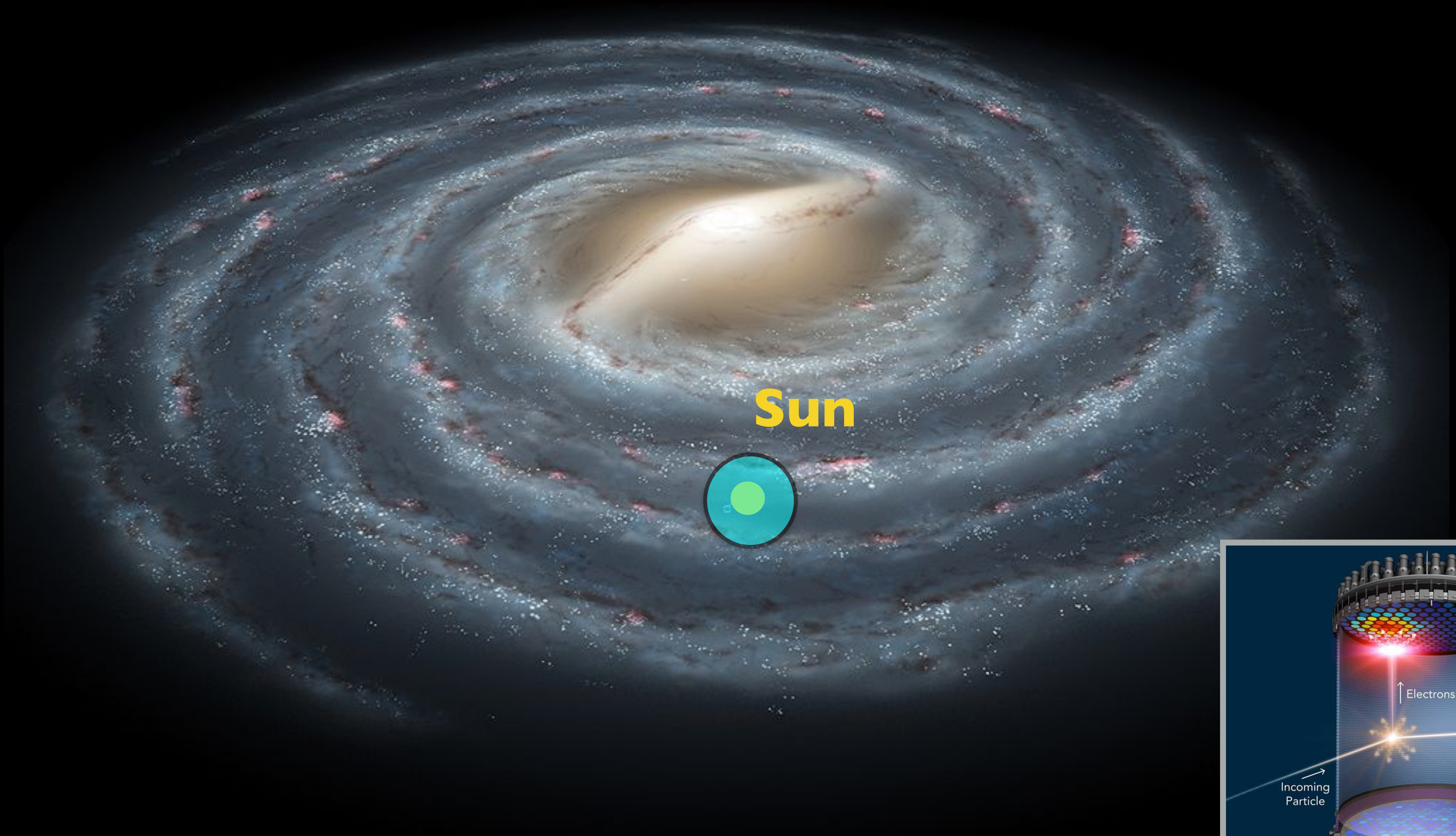
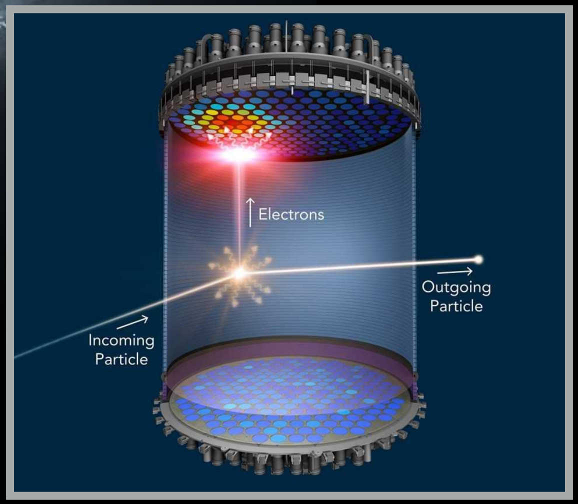
Local dark matter distribution

*Signals in direct DM searches strongly depend on the DM distribution in the **Solar neighborhood**.*





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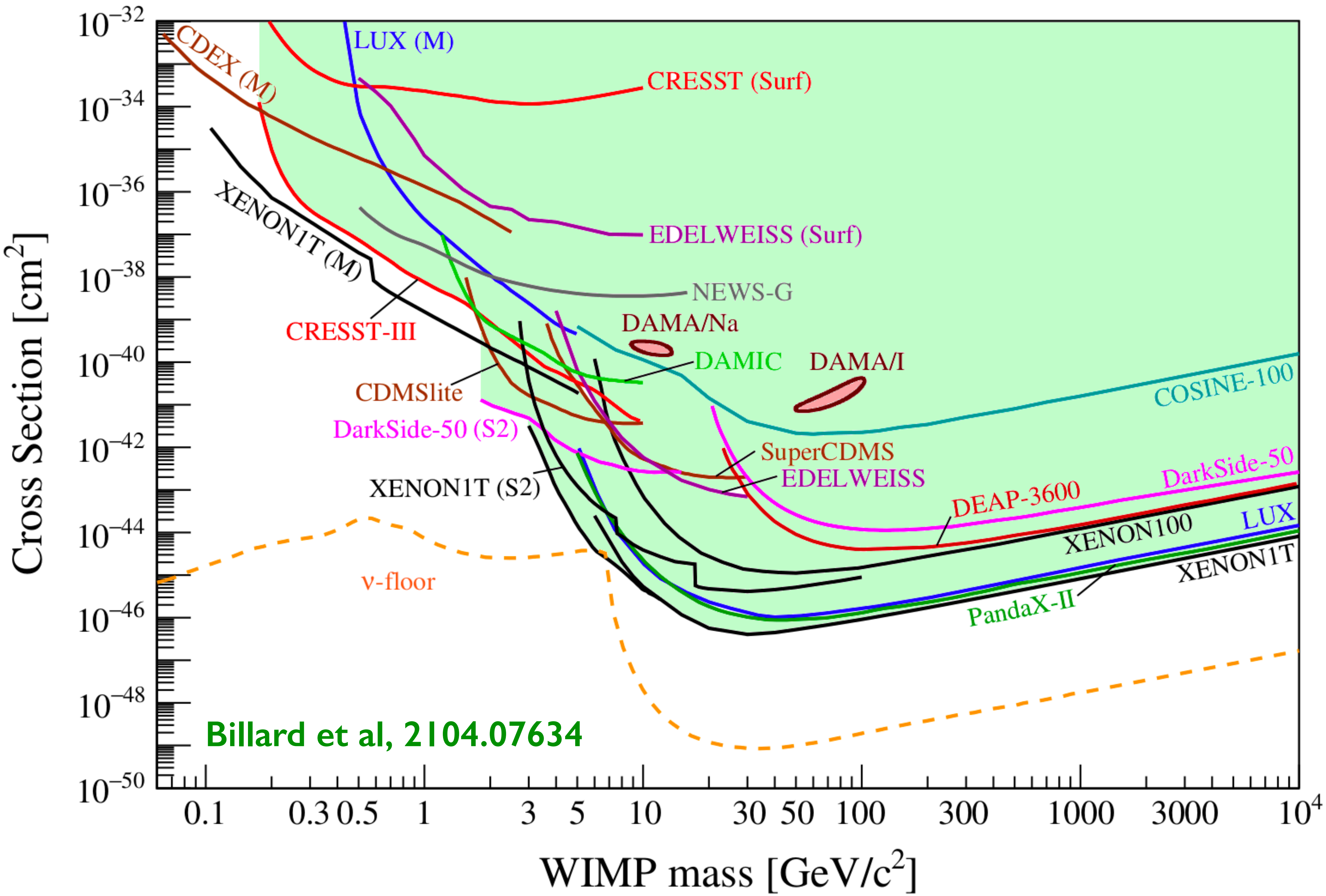
- **Astrophysical inputs:**
  - **local DM density:** *normalization in event rate.*
  - **local DM velocity distribution:** *enters the event rate through an integration.*

Direct detection limits

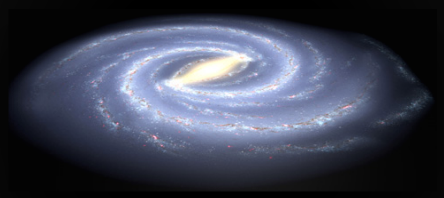


Assumption for the DM distribution: **Standard Halo Model**

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



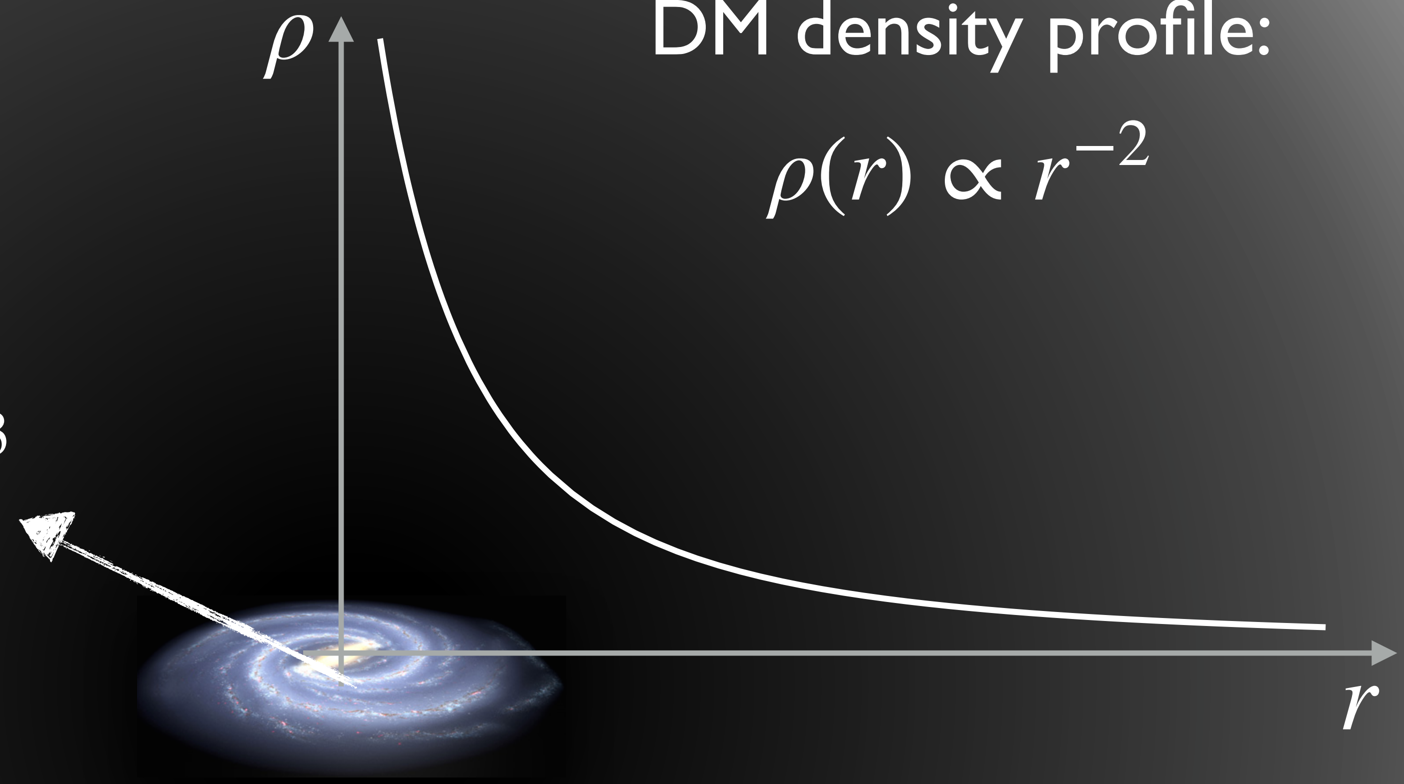
Standard Halo Model

DM density profile:

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

- Local DM density:

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



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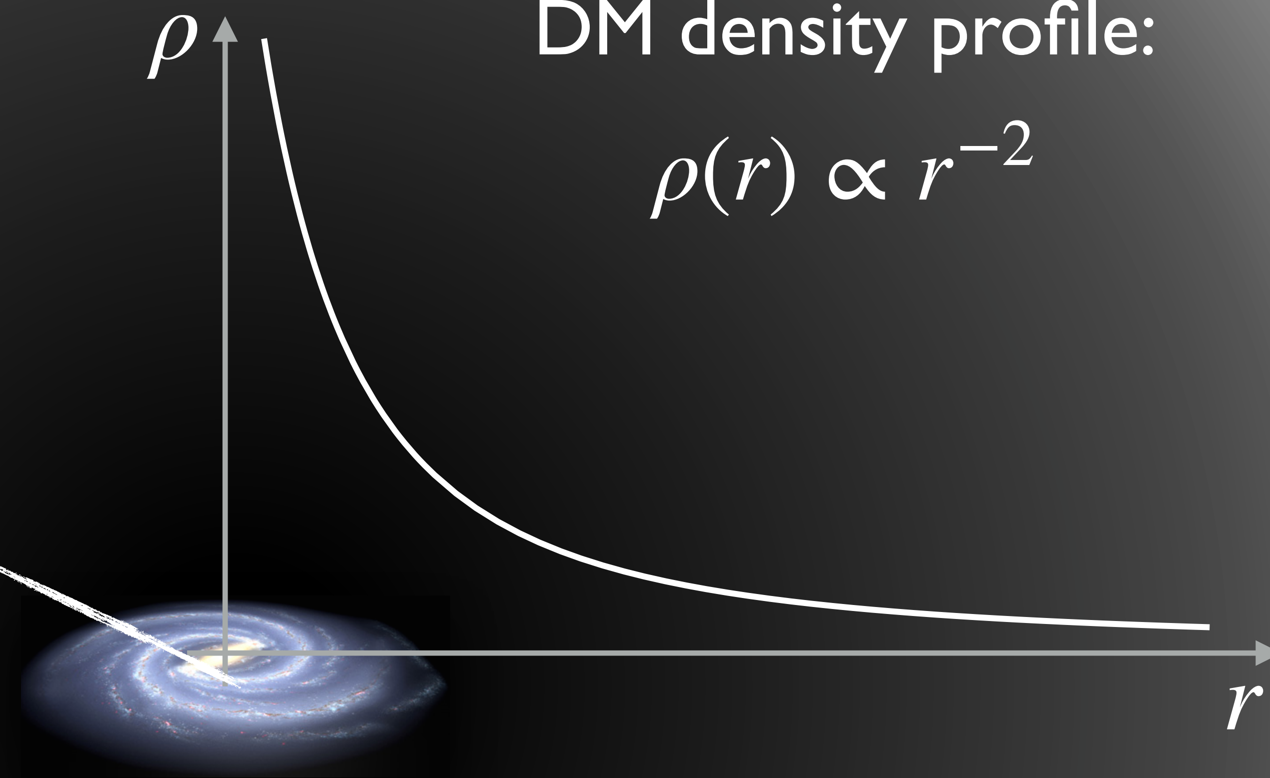

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- Local DM density:

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

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

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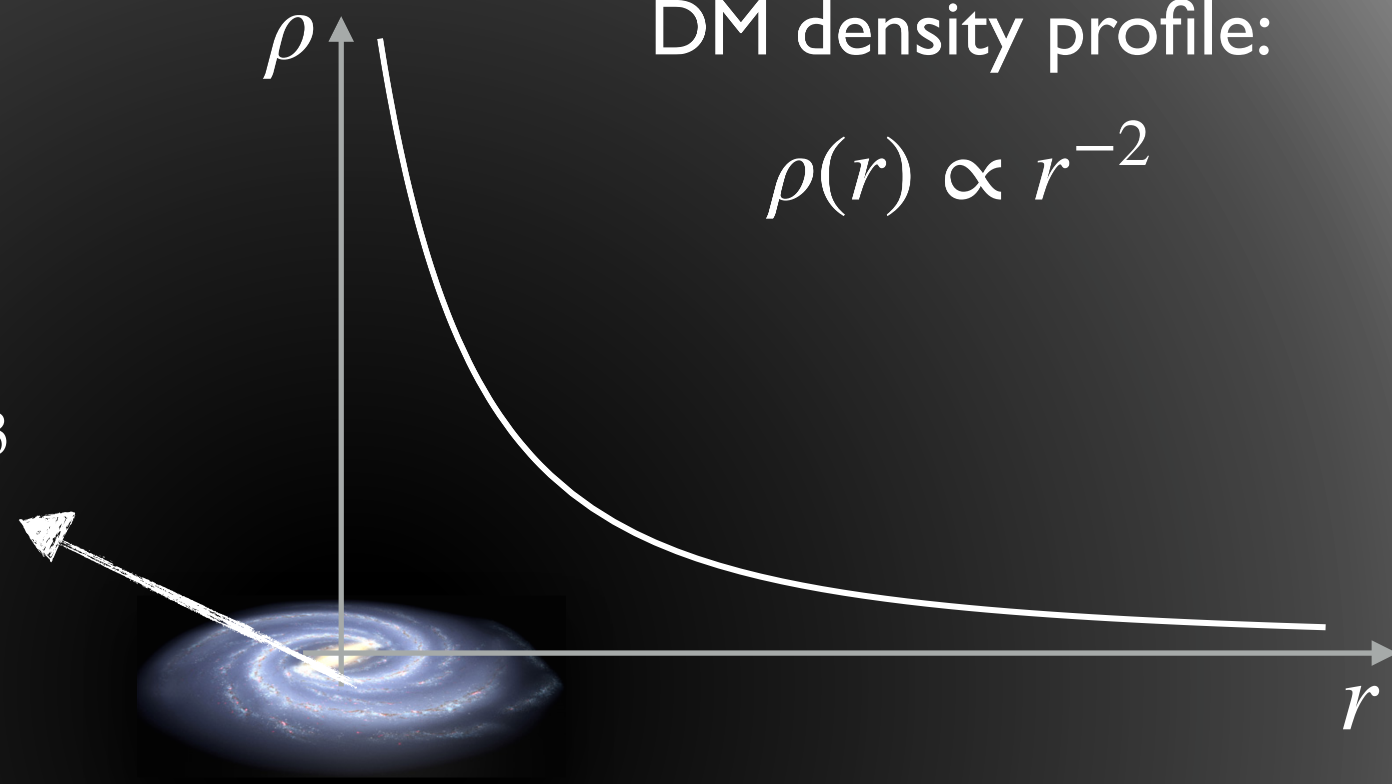

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How does the LMC change this picture?

Effect of LMC on direct detection

- The **LMC** could 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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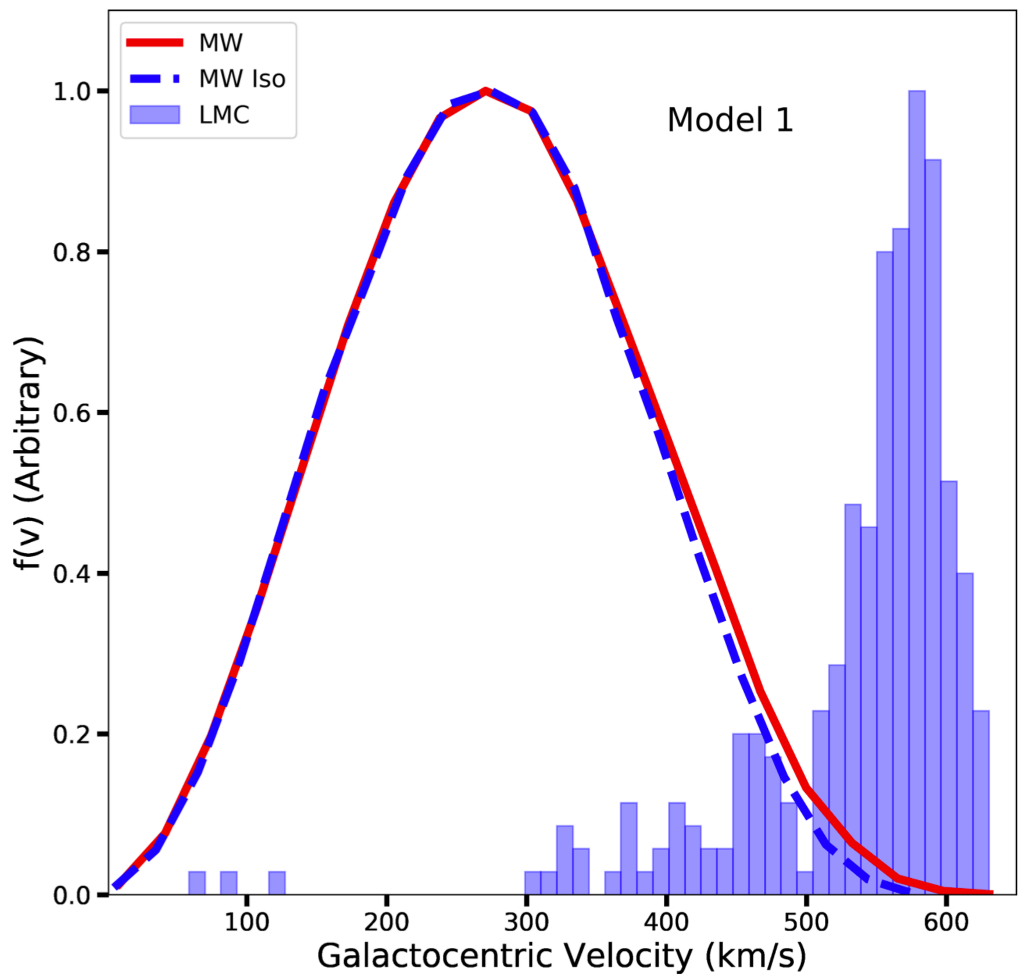
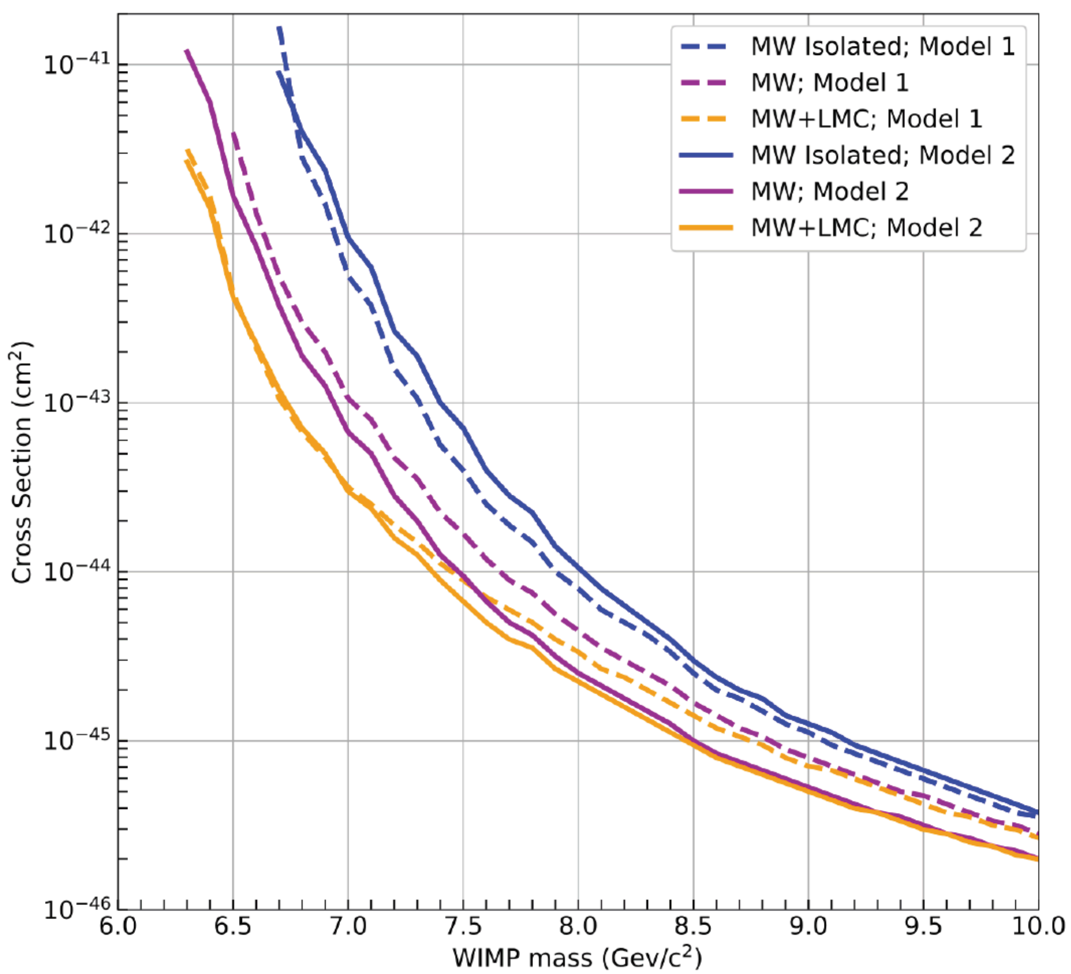
- Studied in specially designed idealized simulations.





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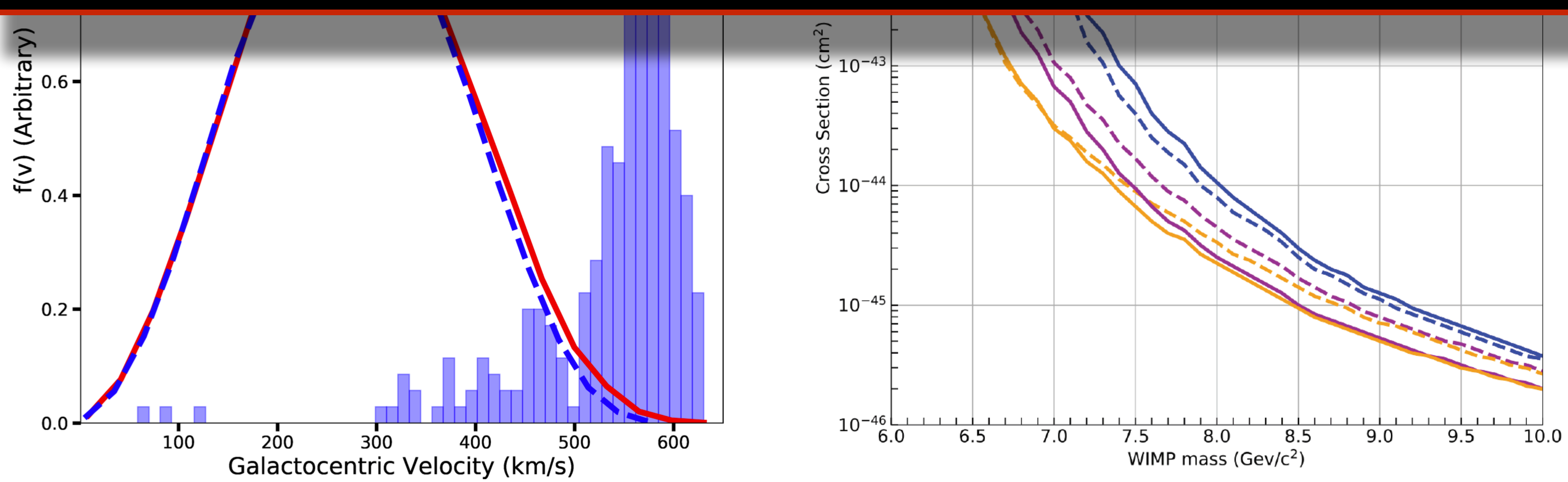
Are these findings valid for fully cosmological halos with multiple accretion events over their formation history?



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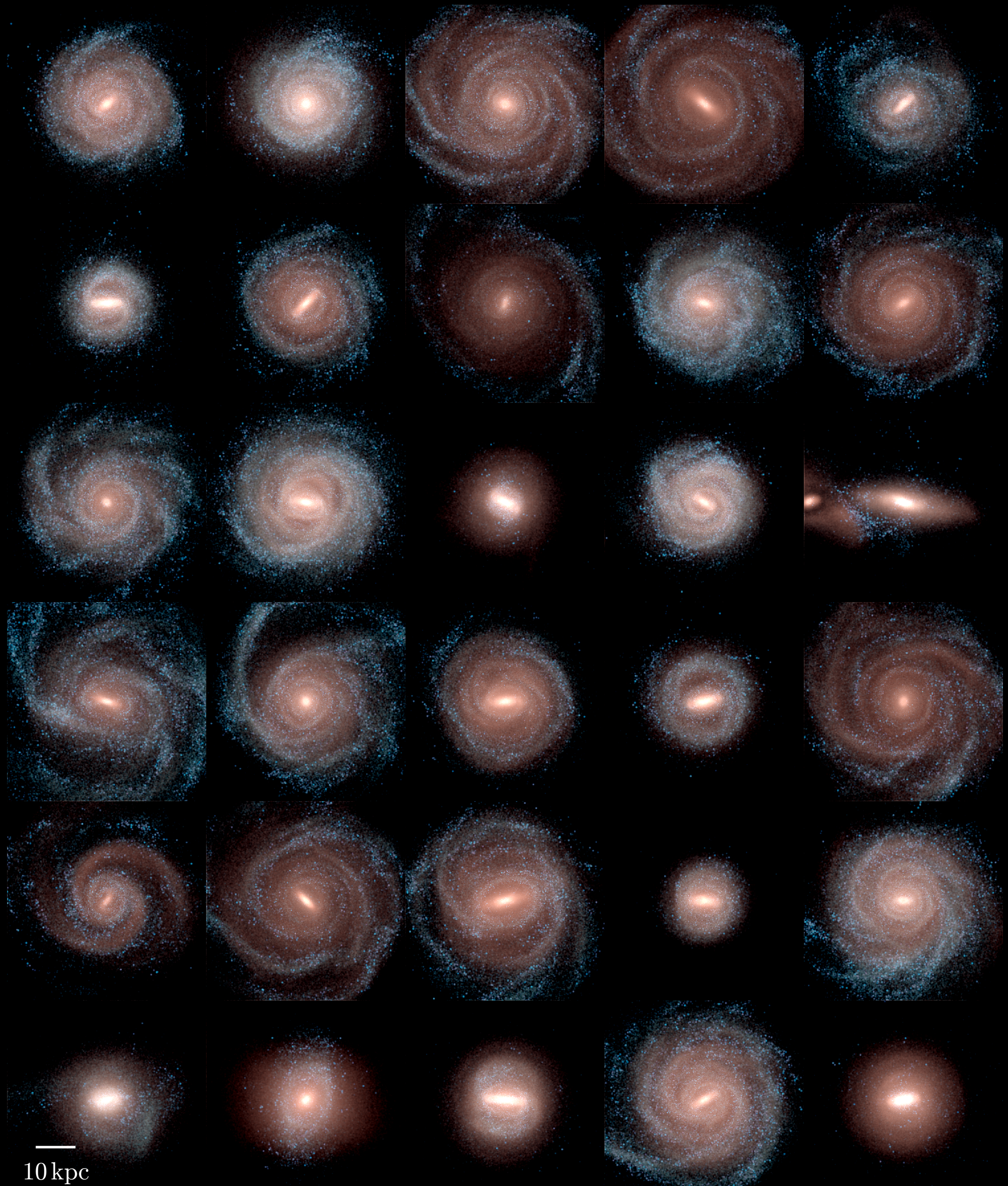
Auriga cosmological simulations

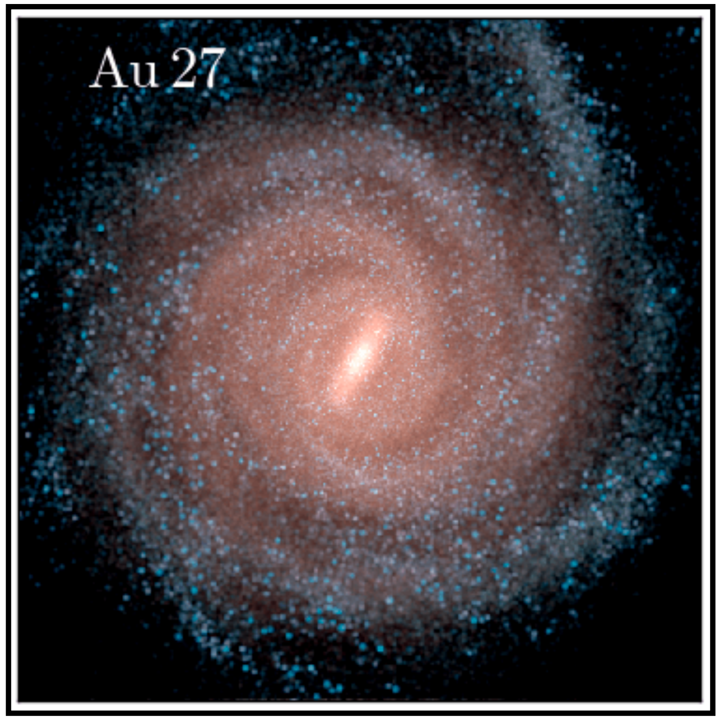
- State-of-the-art cosmological magneto-hydrodynamical zoom-in simulations of Milky Way size halos.
- 30 halos at the standard resolution:

$m_{\rm DM}$ [$M_\odot$]	$m_{\rm b}$ [$M_\odot$]	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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- Identify **15 Milky Way-LMC analogues** based on **LMC's stellar mass** and **distance from host** at first pericenter approach.

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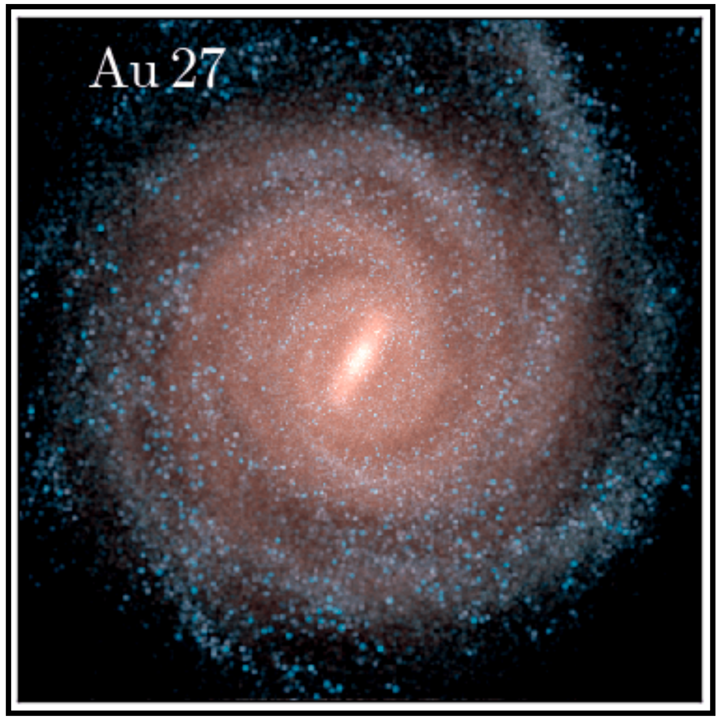

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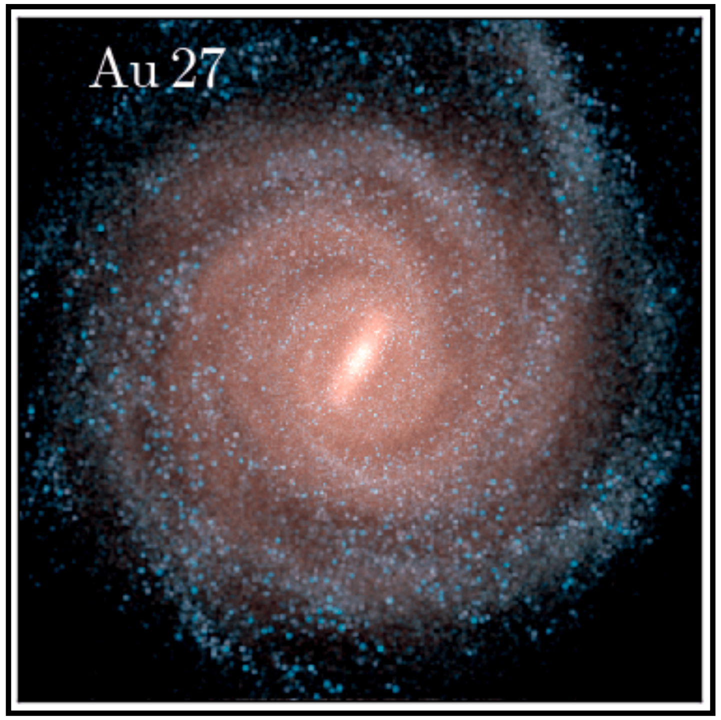
- Consider four representative snapshots:



Snapshot	Description	$t - t_{\mathrm{Pres.}}$ [Gyr]	r_{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

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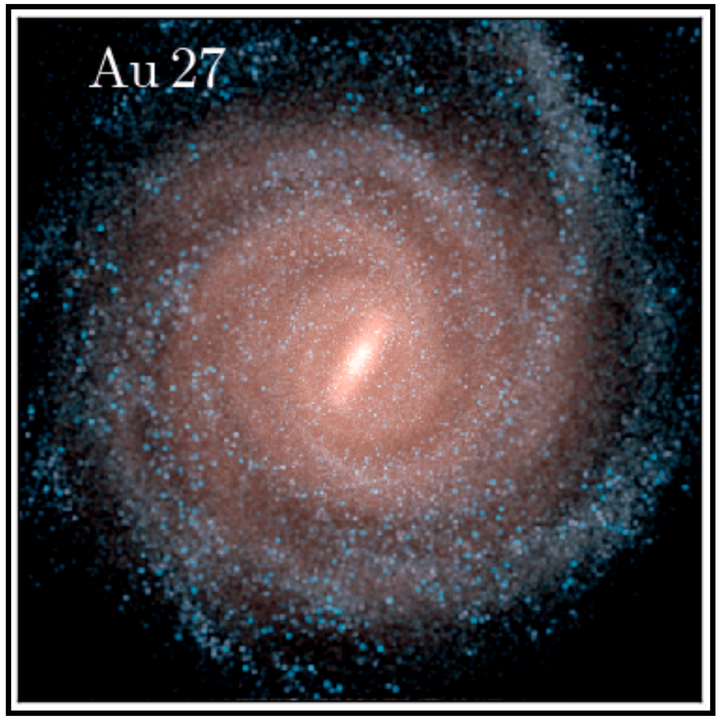

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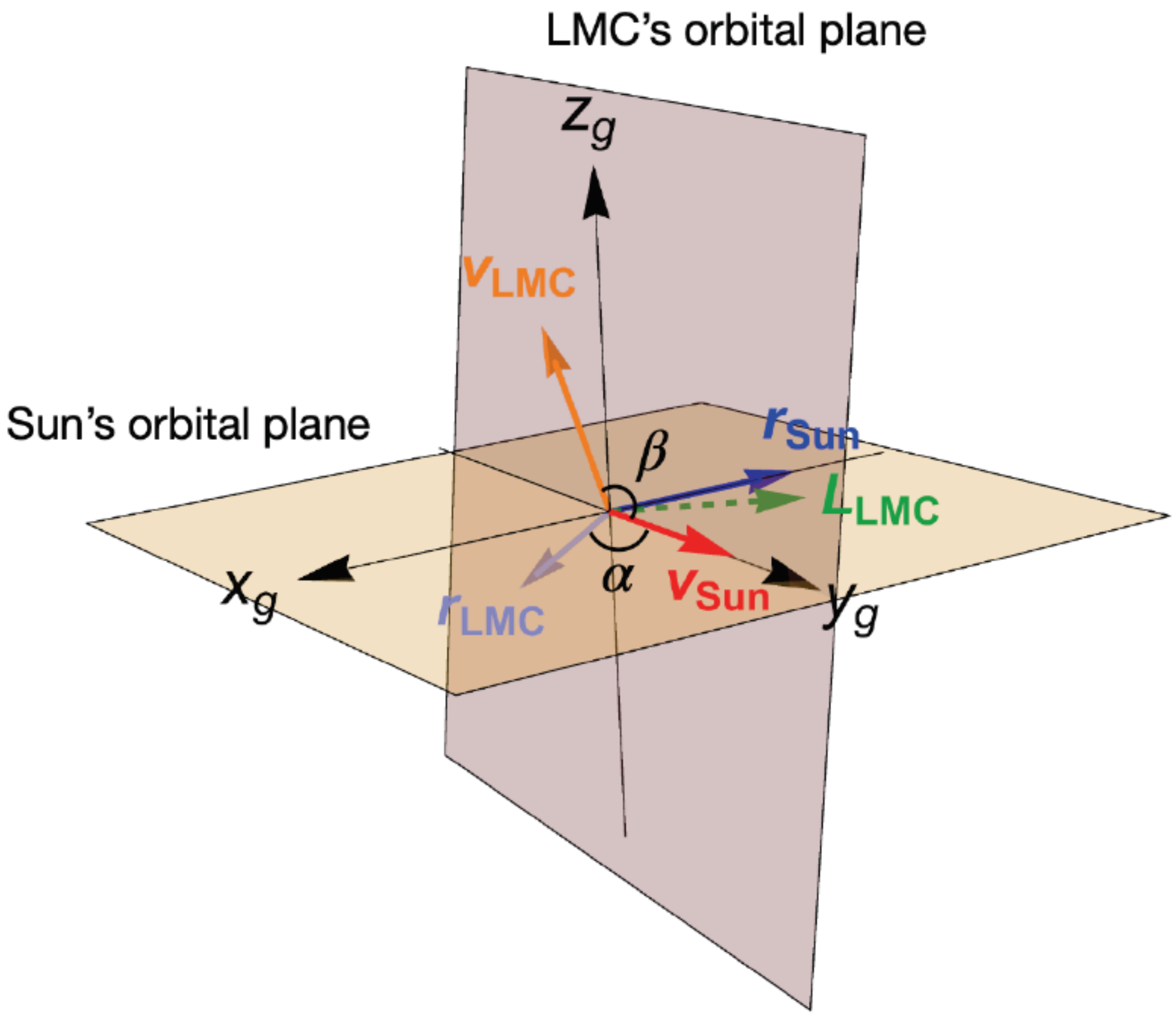
Matching the Sun-LMC geometry

- 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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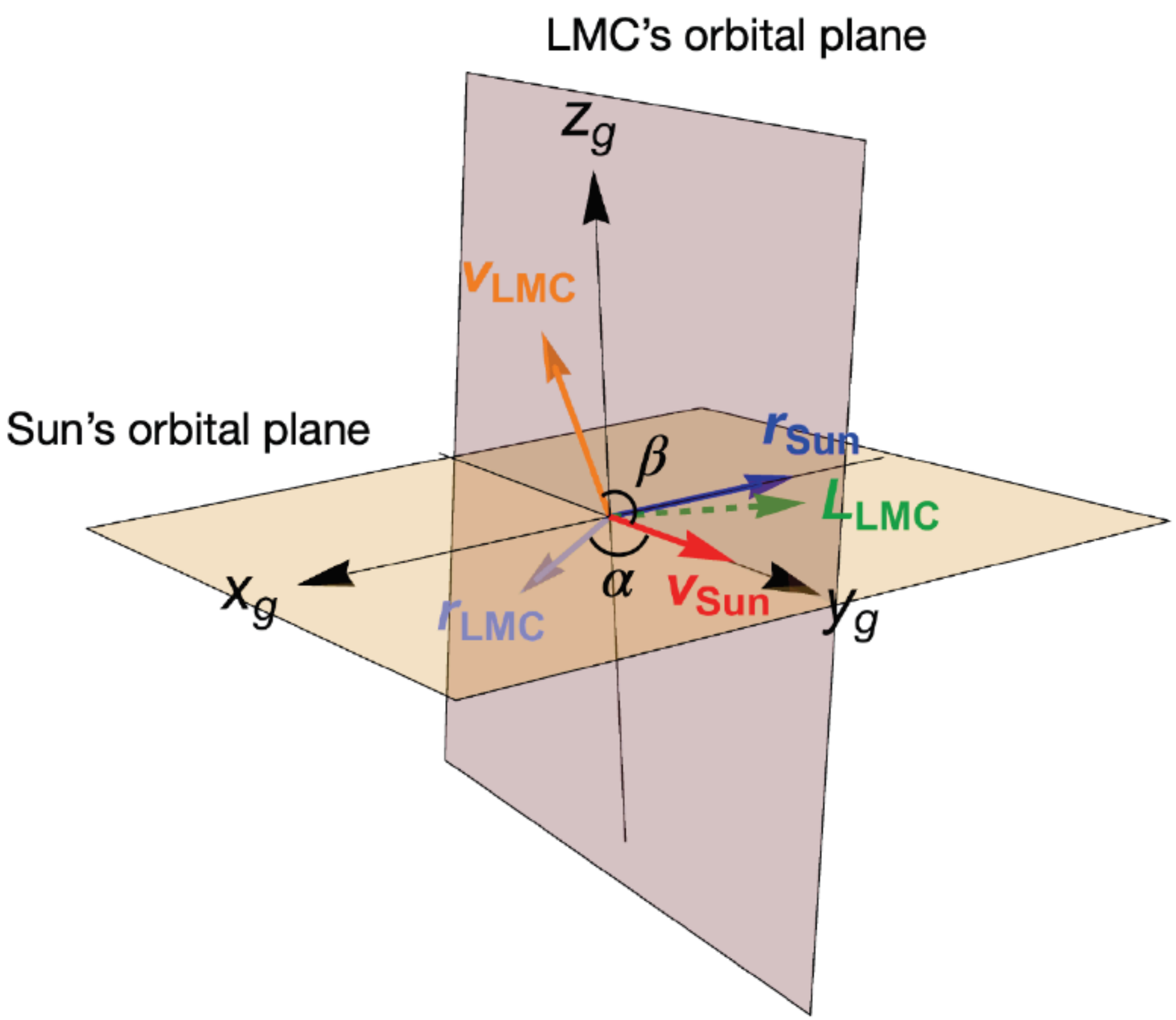


- Choose the position of the Sun in the simulations such that it matches the observed Sun-LMC geometry.

Local dark matter density

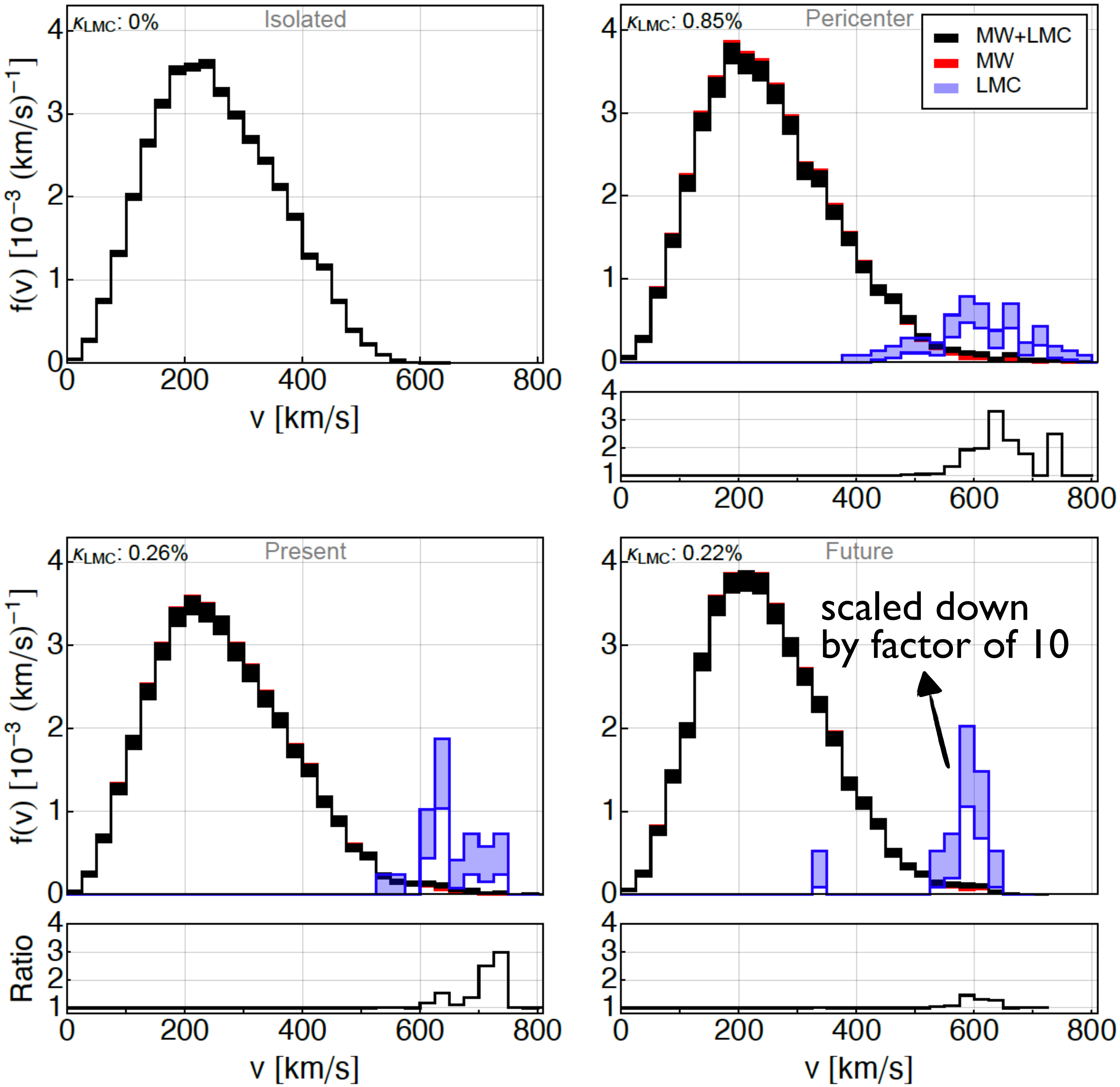
Halo ID	$M_{\rm Infall}^{\rm LMC}$ [10^{11} M$_\odot$]	ρ_χ [GeV/cm^3]	$\kappa_{\rm LMC}$ [%]
1	0.31	0.21	0.14
2	0.31	0.23	0.64
3	0.34	0.35	0.026
4	0.82	0.34	0.096
5	1.84	0.24	1.5
6	1.10	0.38	0.038
7	0.32	0.53	0.032
8	0.36	0.38	0.0077
9	0.73	0.36	0.10
10	3.28	0.39	2.8
11	1.45	0.43	0.028
12	1.43	0.53	0.17
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)

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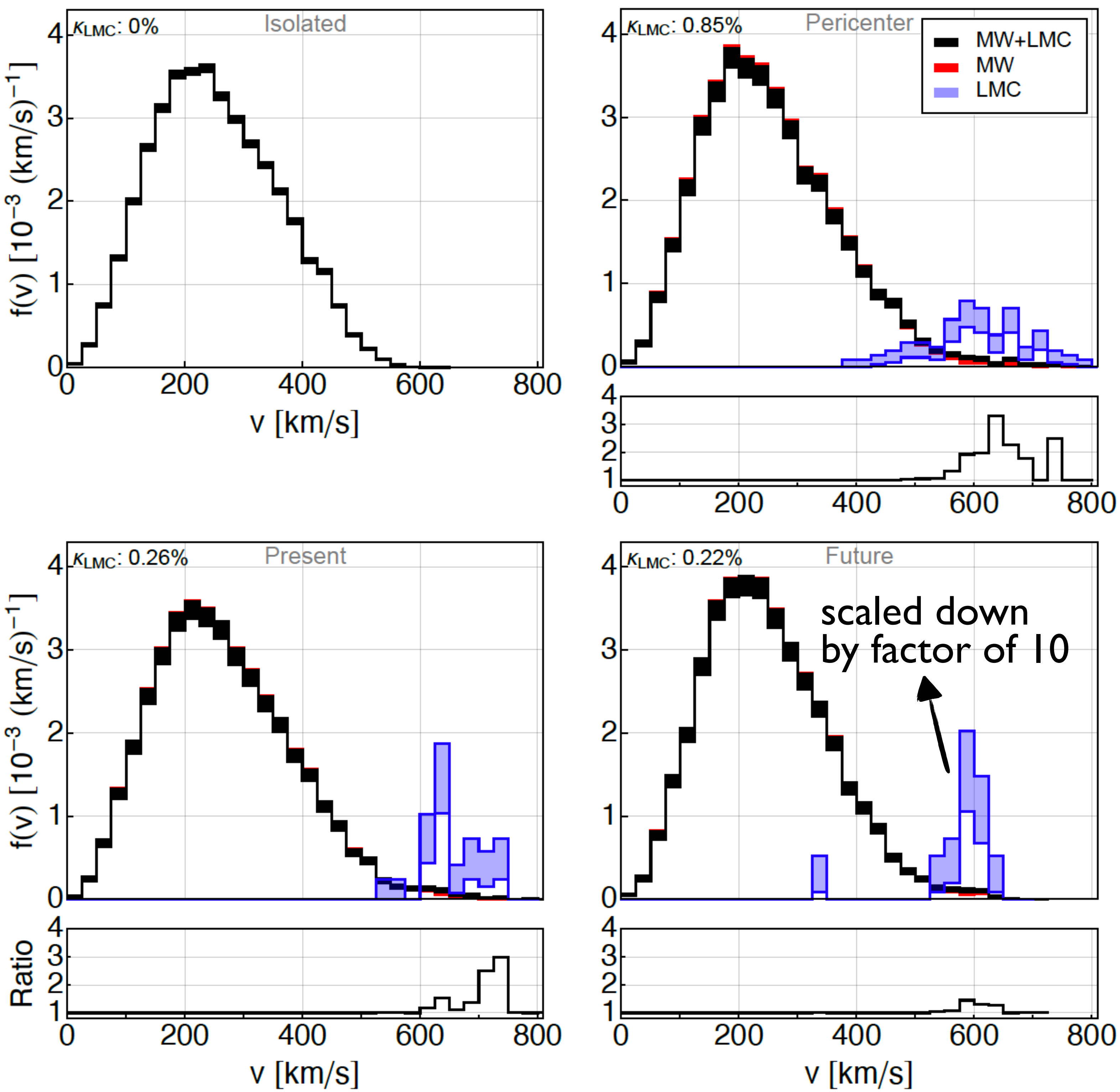

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The LMC impacts the high speed tail of the DM speed distribution not only at its **pericenter approach** and the **present day**, but also up to **~175 Myr after the present day**.

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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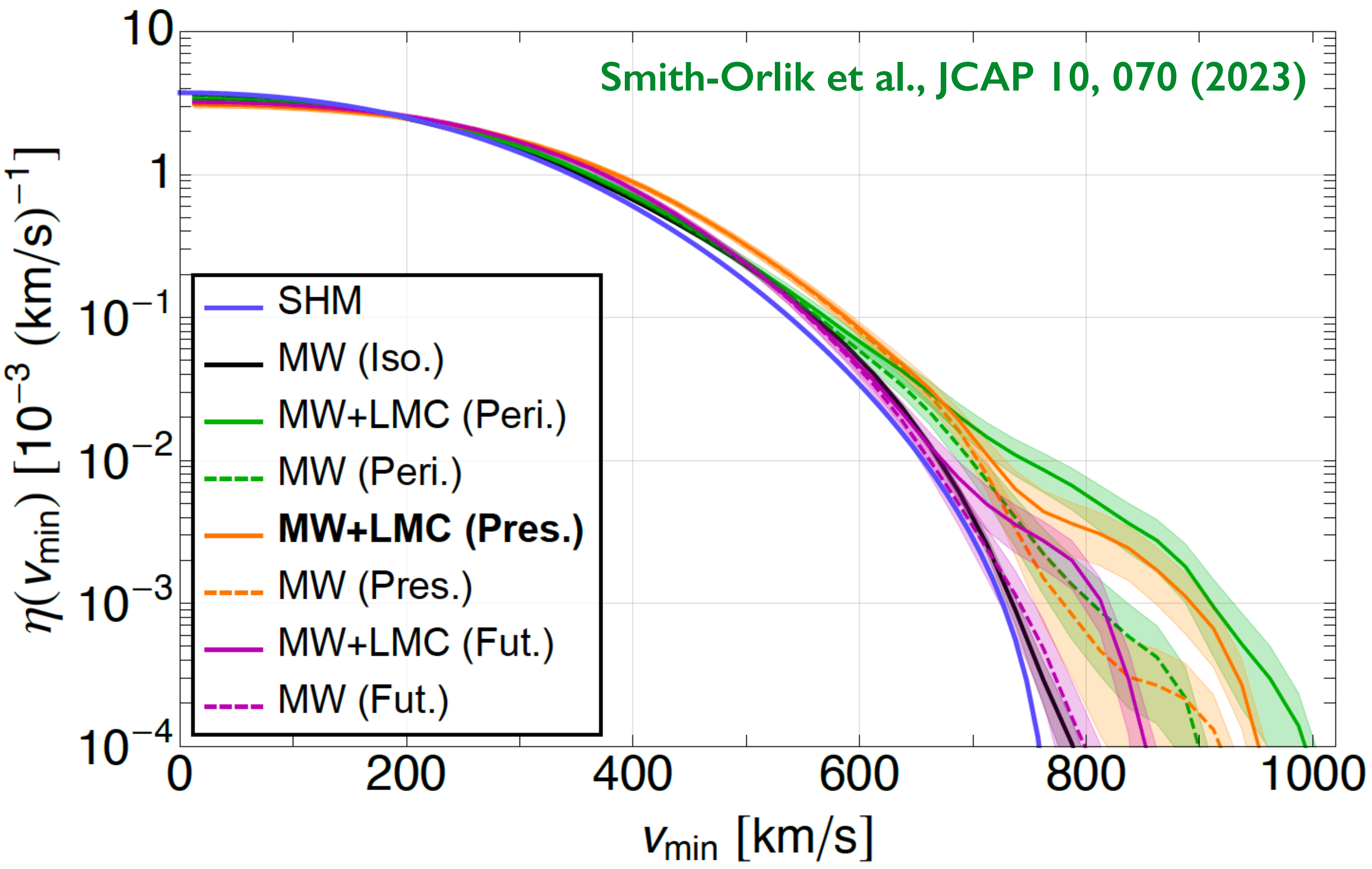
where

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

Halo integral

Halo integrals



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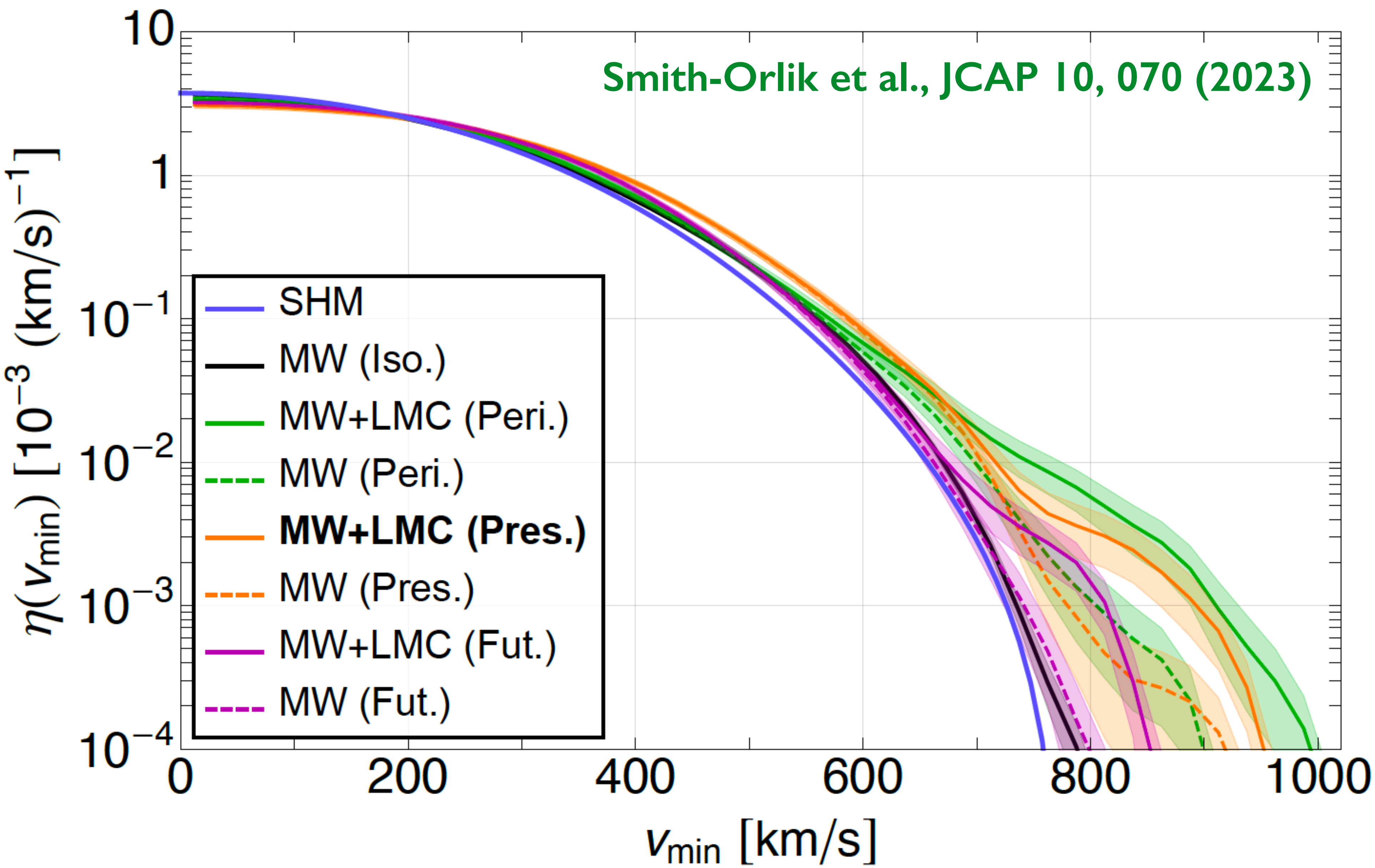
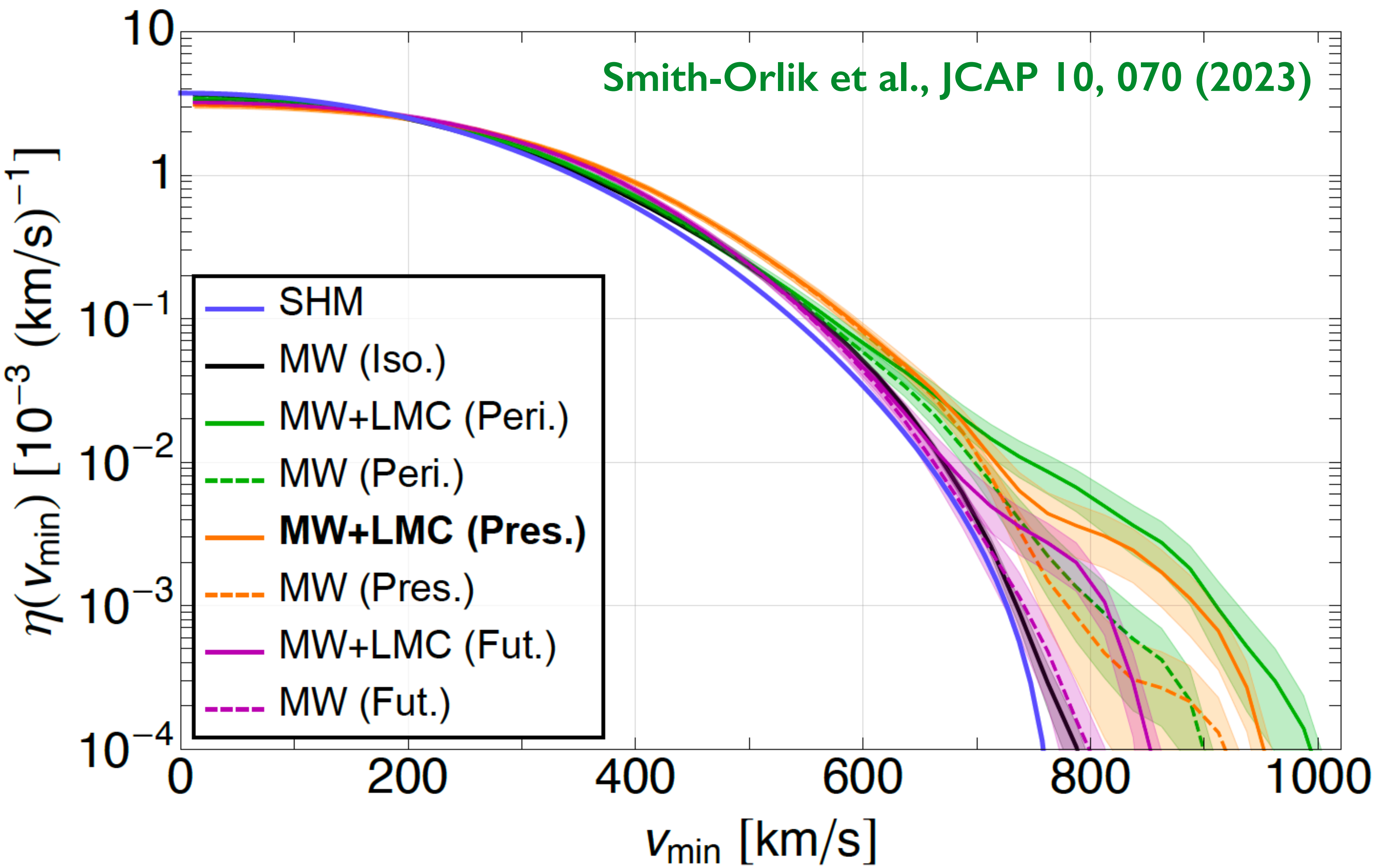


- **Two effects:** High speed LMC particles in the Solar region + Milky Way's response to the LMC.

Halo integrals



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

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

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

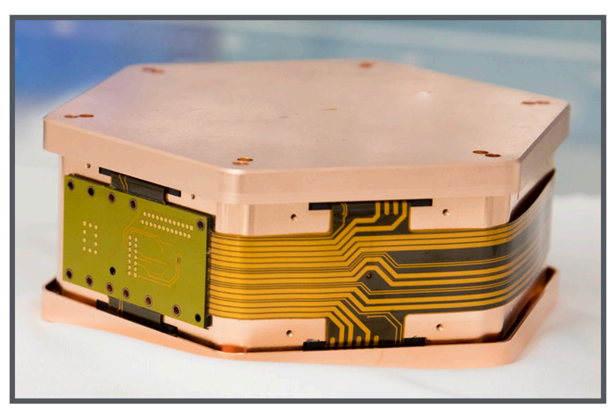
Xenon based

$[2-50]$ 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

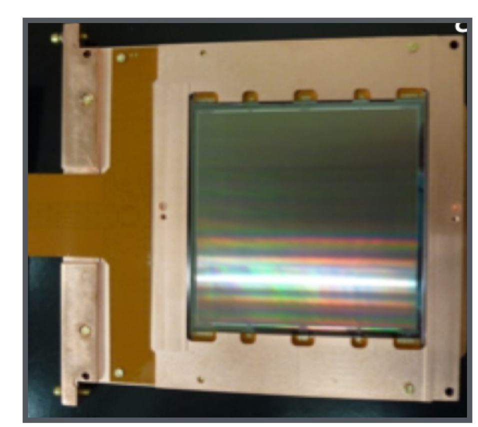
Based on SuperCDMS



Electron recoils

Silicon CCD

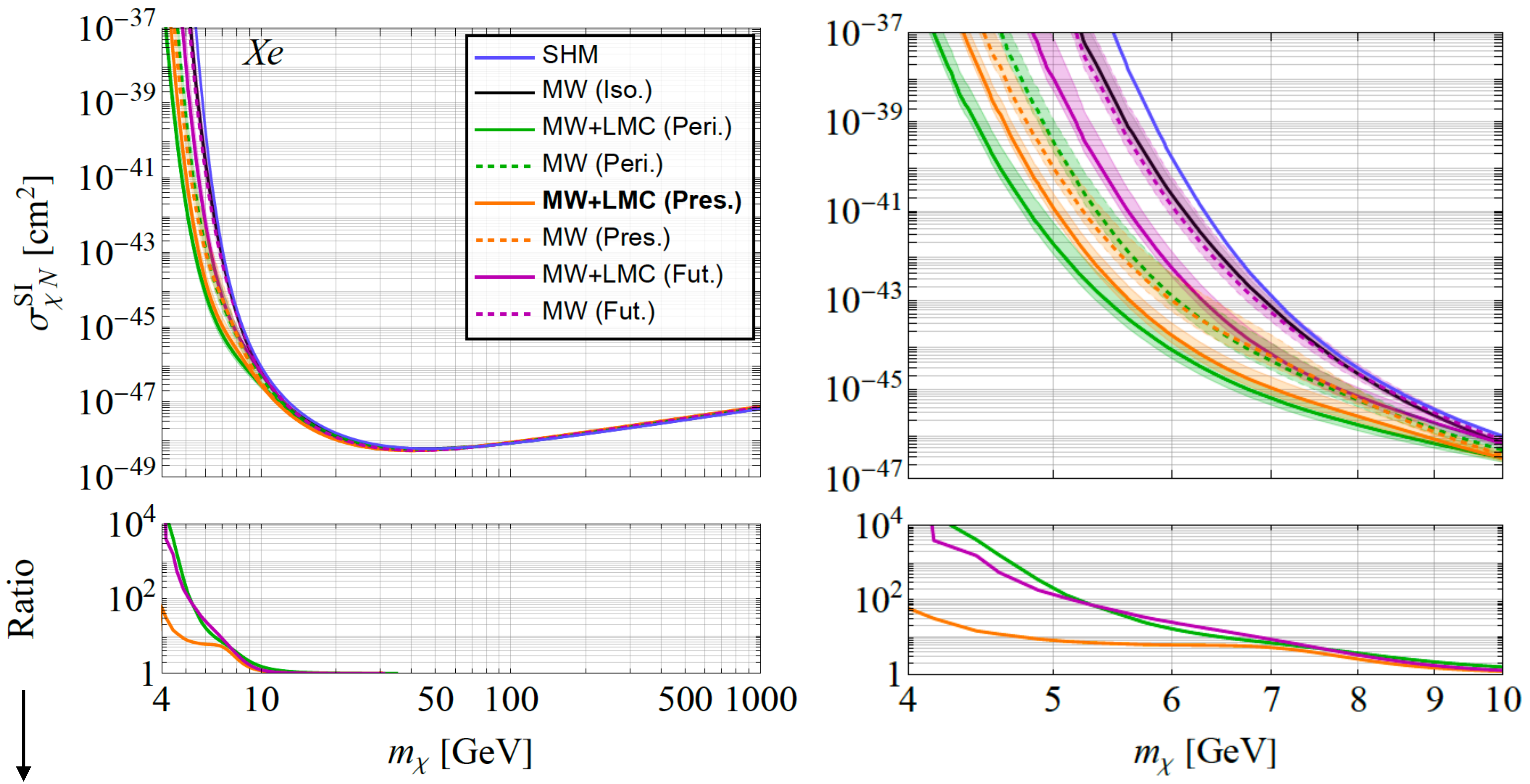
1 electron threshold
1 kg yr
Based on DAMIC



Direct detection: nuclear recoils

Xenon based detector:

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



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

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

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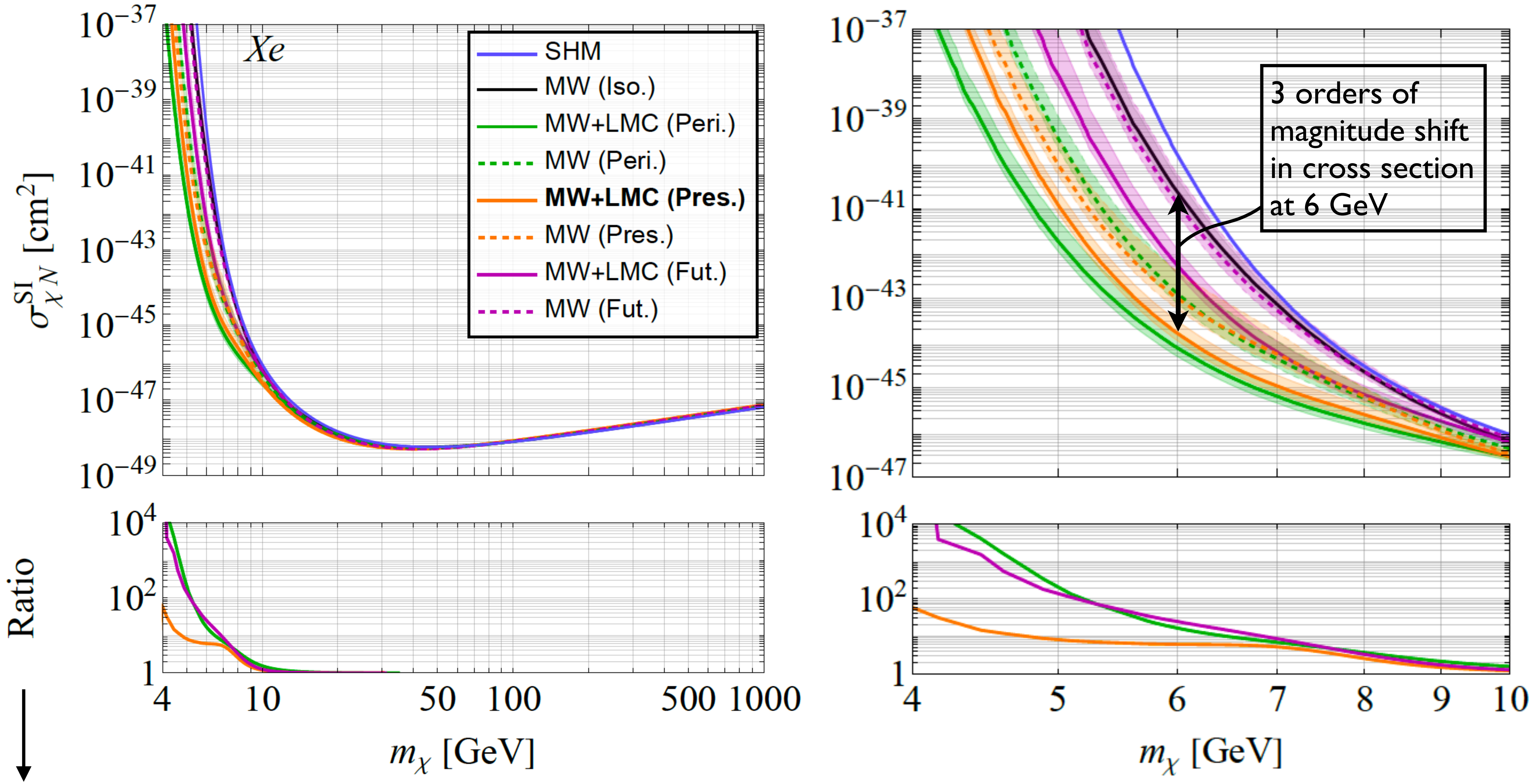

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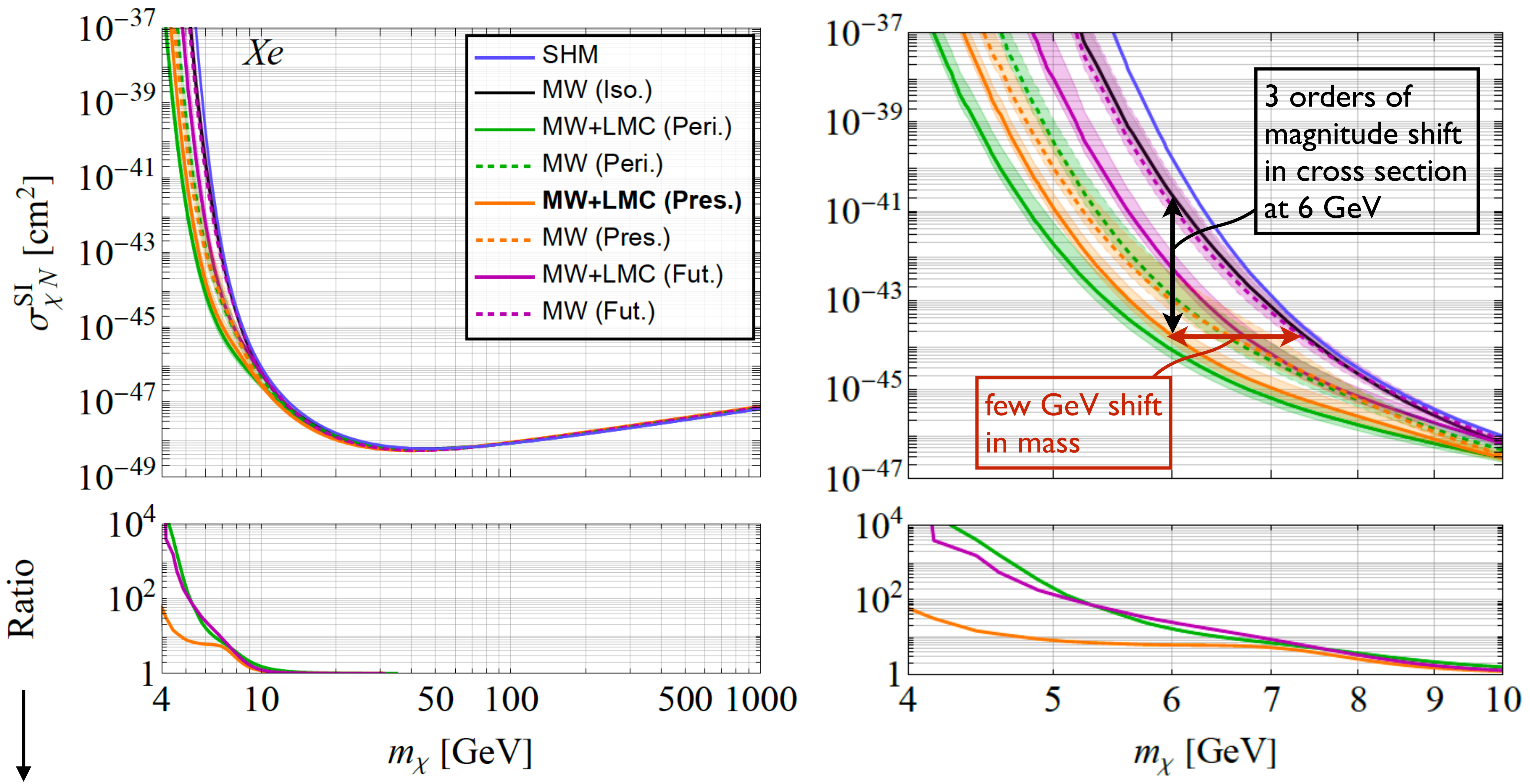

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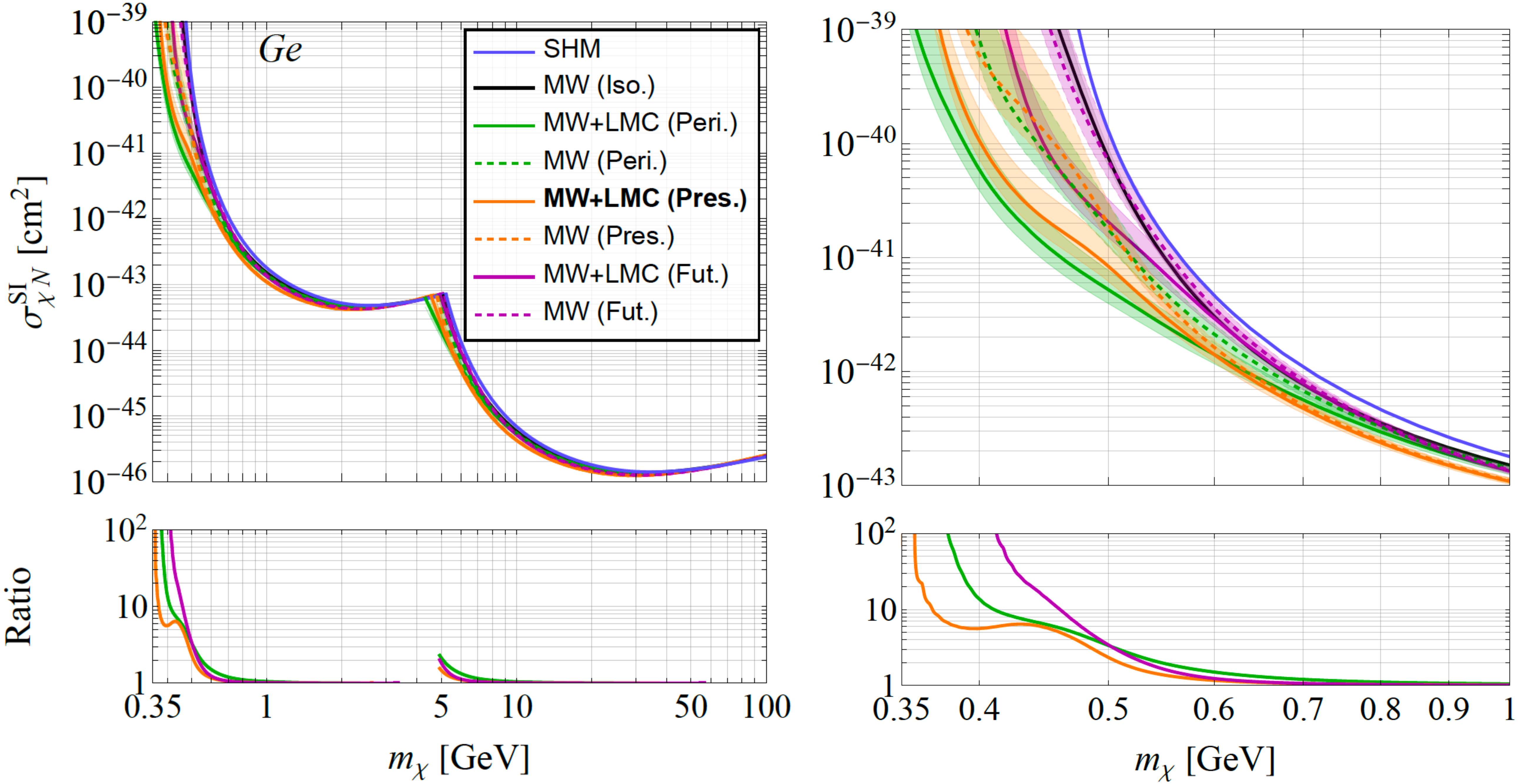
Direct detection: nuclear recoils

Germanium based detector:

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



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Direct detection: electron recoils

Silicon CCD detector:

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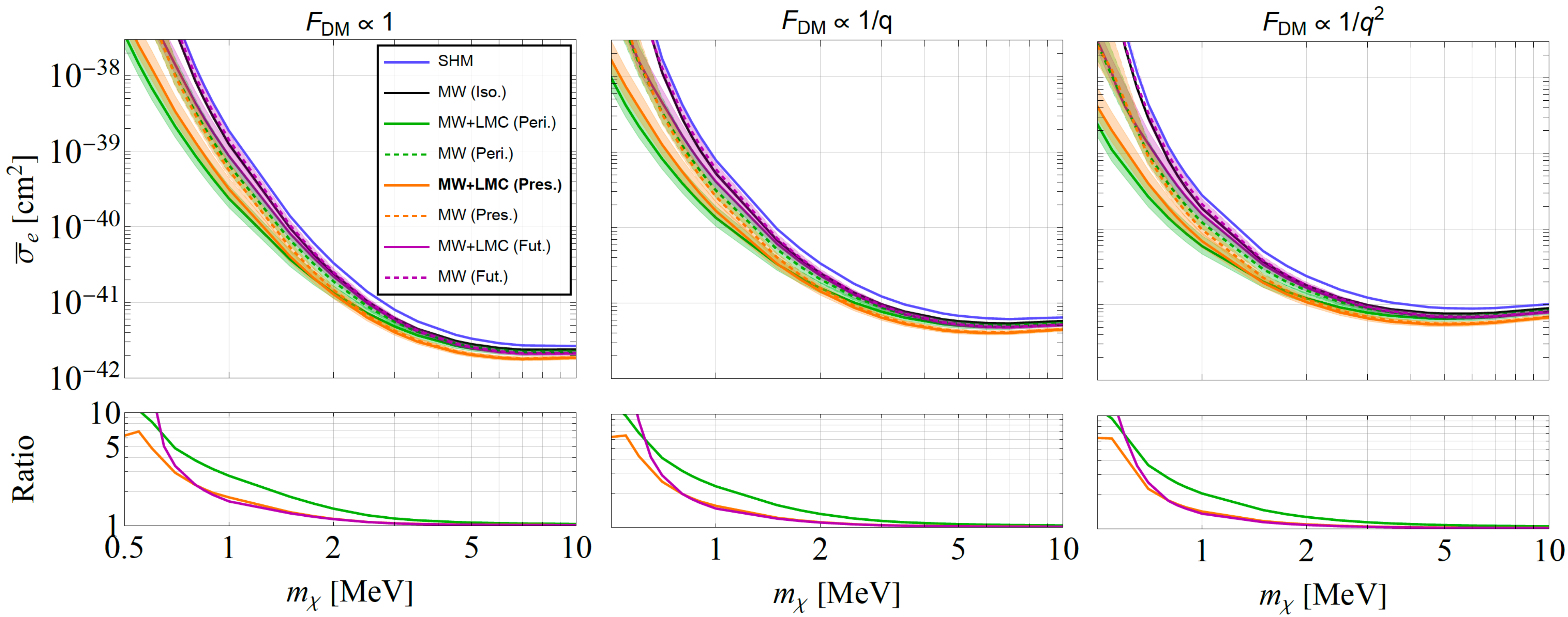

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Beyond standard interactions

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- Consider an **argon based detector** (*based on DarkSide-20k*):

$$\mathcal{O}_1 = 1_\chi 1_N \longrightarrow \textbf{SI}$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right)$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right)$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = v_\perp \cdot \left(\vec{S}_\chi \times \vec{S}_N\right)$$

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$\mathcal{O}_1 = 1_\chi 1_N$ → **SI**	1
$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}_\perp)$	q^4
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}_\perp)$	$q^2 v_\perp^2$
$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp$	$v_\perp^2$
$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$	q^2
$\mathcal{O}_{12} = v_\perp \cdot (\vec{S}_\chi \times \vec{S}_N)$	q^2

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- Consider an **argon based detector** (*based on DarkSide-20k*):

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$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp$	$v_\perp^2$
$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$	q^2
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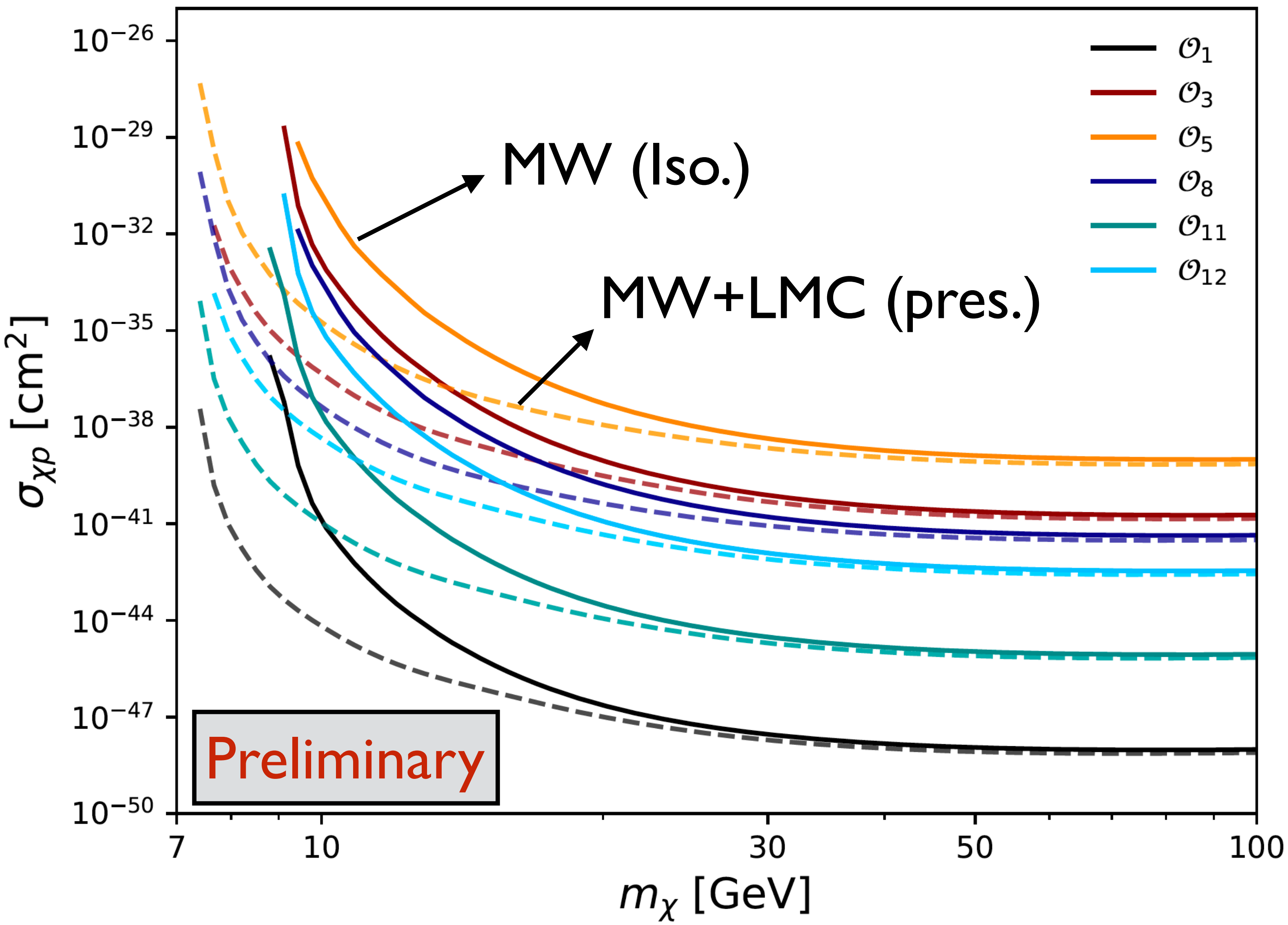

Bozorgnia, Reynoso, Piro, *in preparation*

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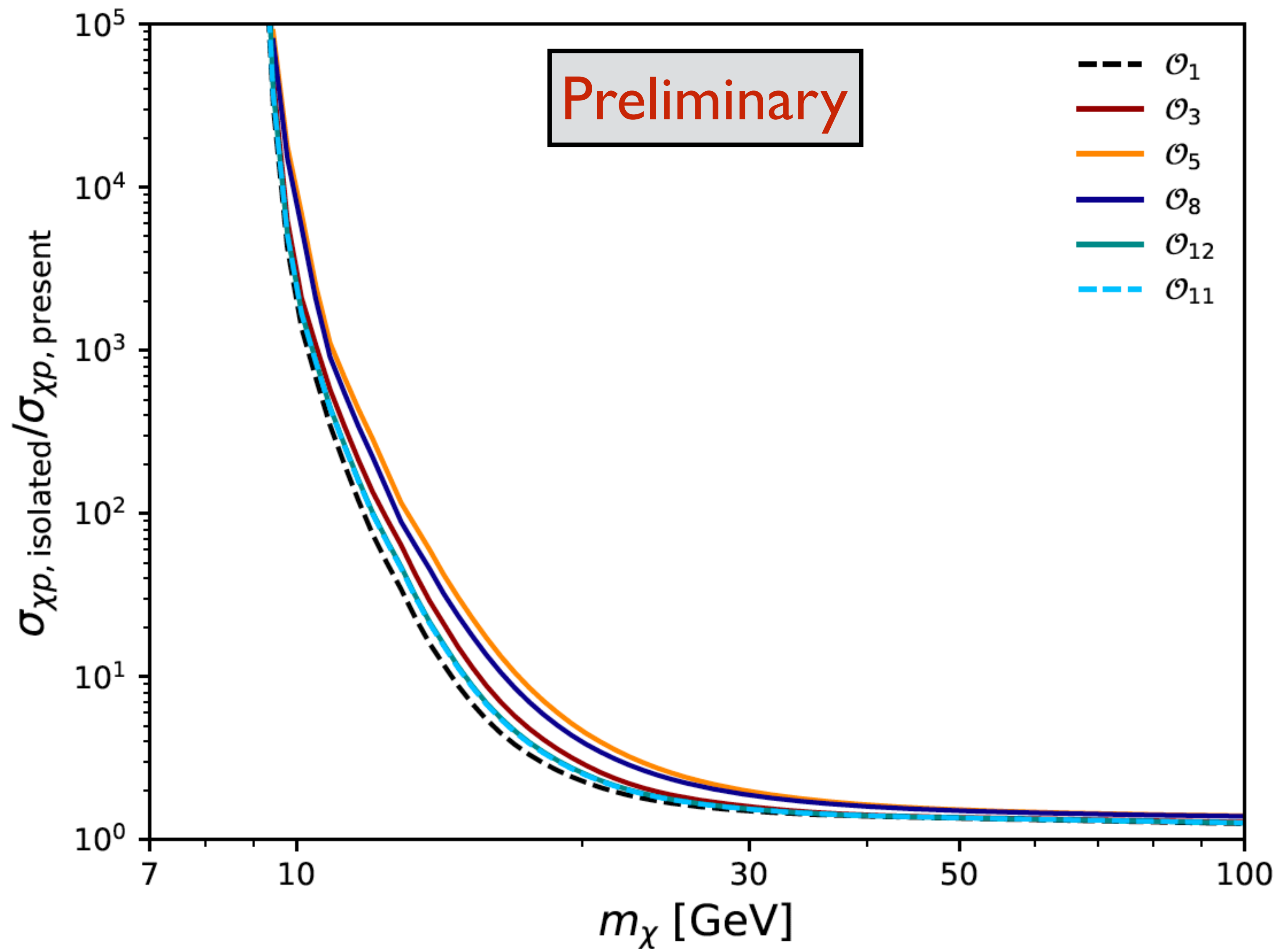

Bozorgnia, Reynoso, Piro, *in preparation*

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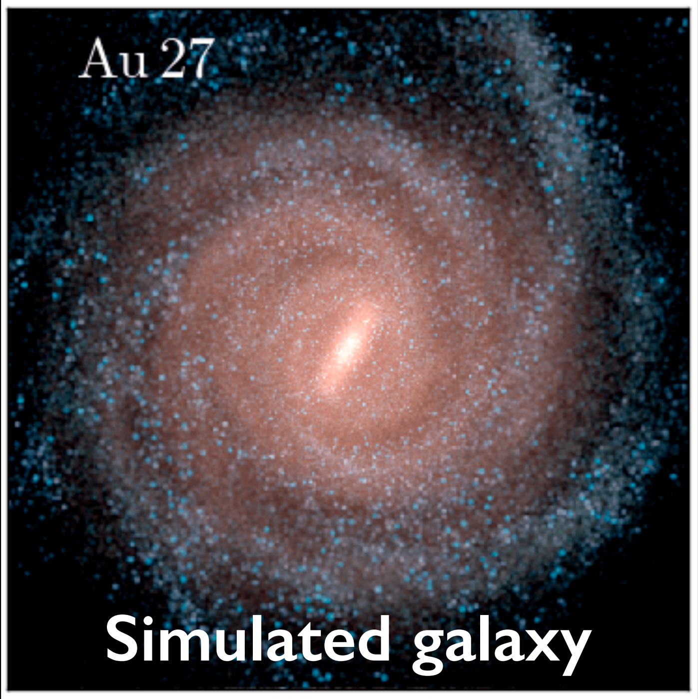
  - Response of the Milky Way DM particles to the LMC

  → *Significant shifts in direct detection limits*
- LMC's impact even more significant for velocity-dependent effective operators.

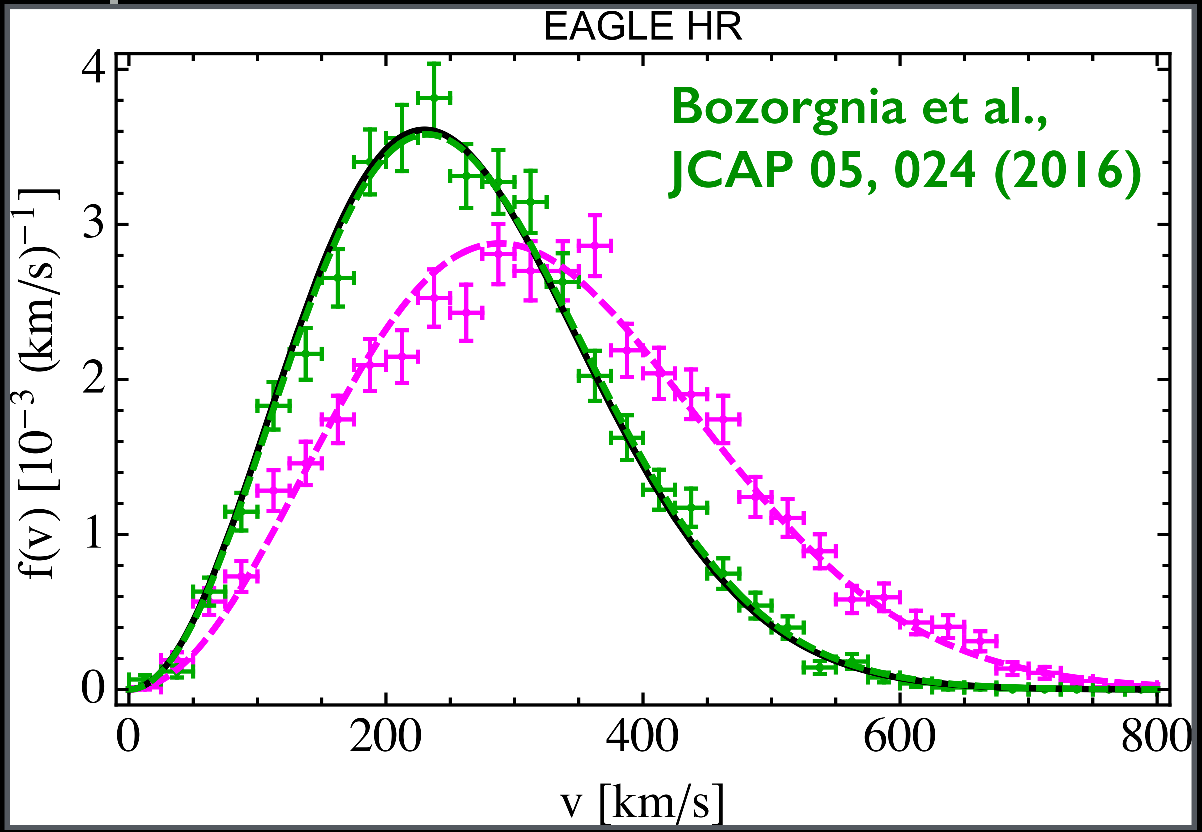
Backup Slides

Dark matter velocity distribution

Extract the DM distribution from cosmological simulations:



Smooth halo



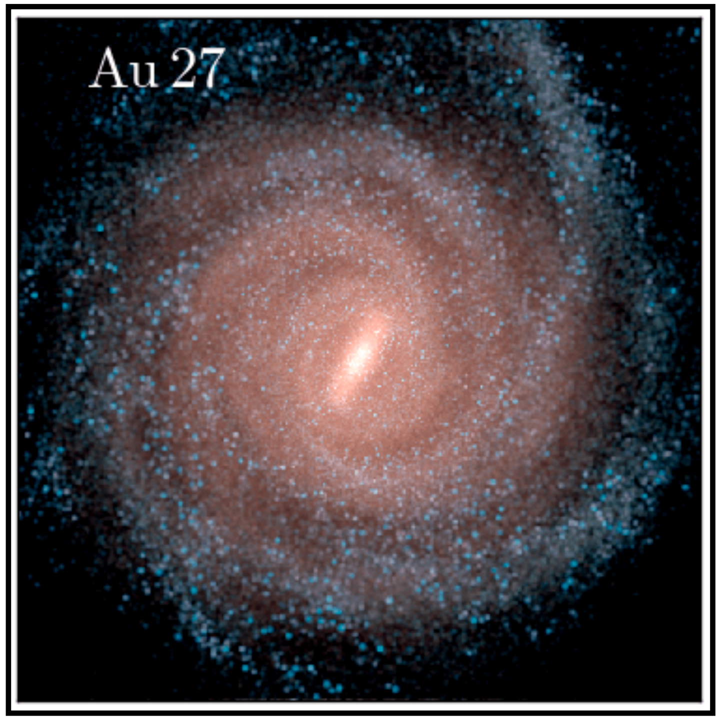
Bozorgnia et al., 2016 (EAGLE & APOSTLE)
Kelso et al., 2016 (MaGICC)
Sloane et al., 2016
Bozorgnia & Bertone, 2017
Bozorgnia et al., 2020 (Auriga)
Poole-McKenzie et al., 2020 (ARTEMIS)
Rahimi, Vienneau, Bozorgnia, Robertson, 2023 (SIDM EAGLE)

Maxwellian distribution provides a good fit to the DM velocity distribution of Milky Way-like halos in cosmological simulations.

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: $\sim 48\ \mathrm{kpc}$

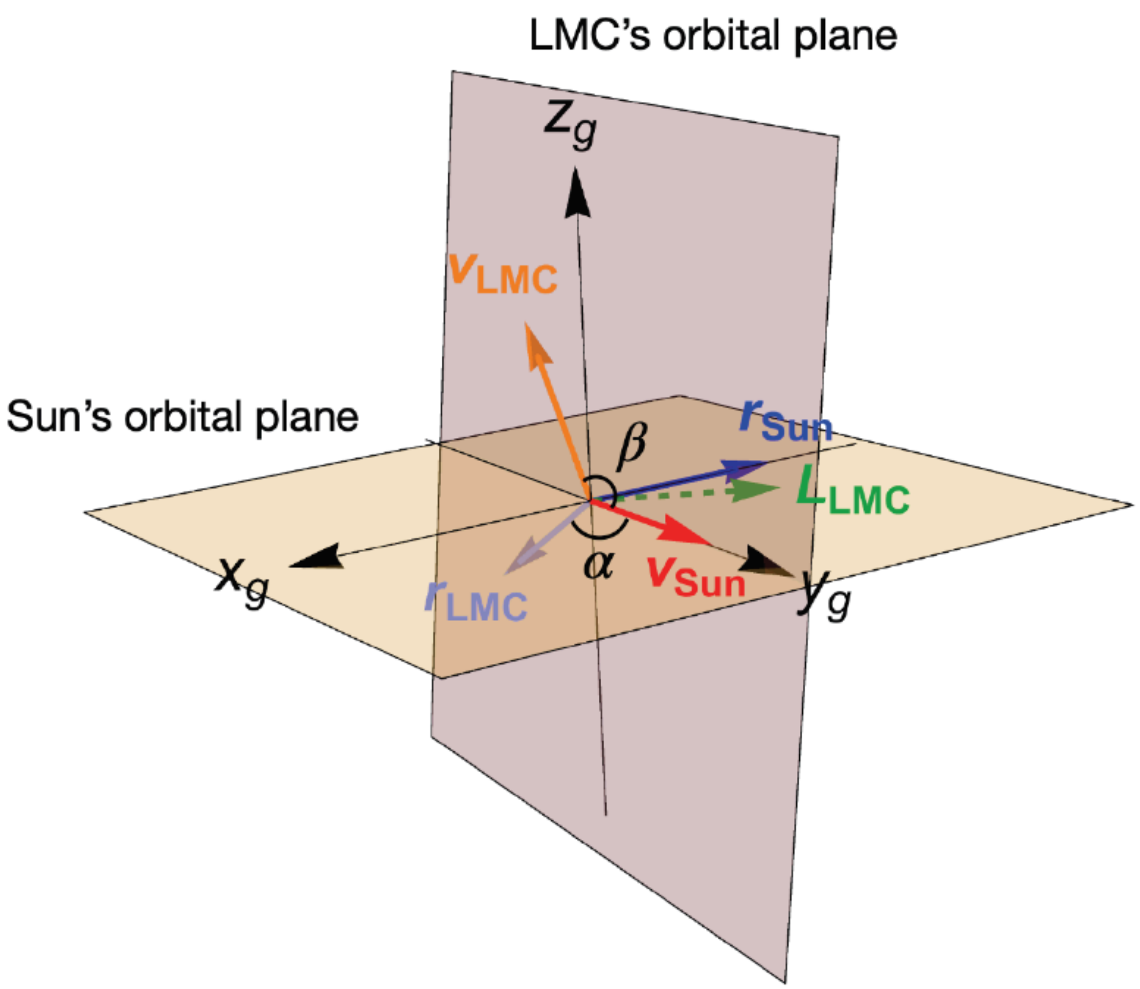
- Difficult to find an exact LMC analogue in cosmological simulations. → Follow the history of the simulated halos within the last 8 Gyrs to find LMC analogues.



- 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:



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

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

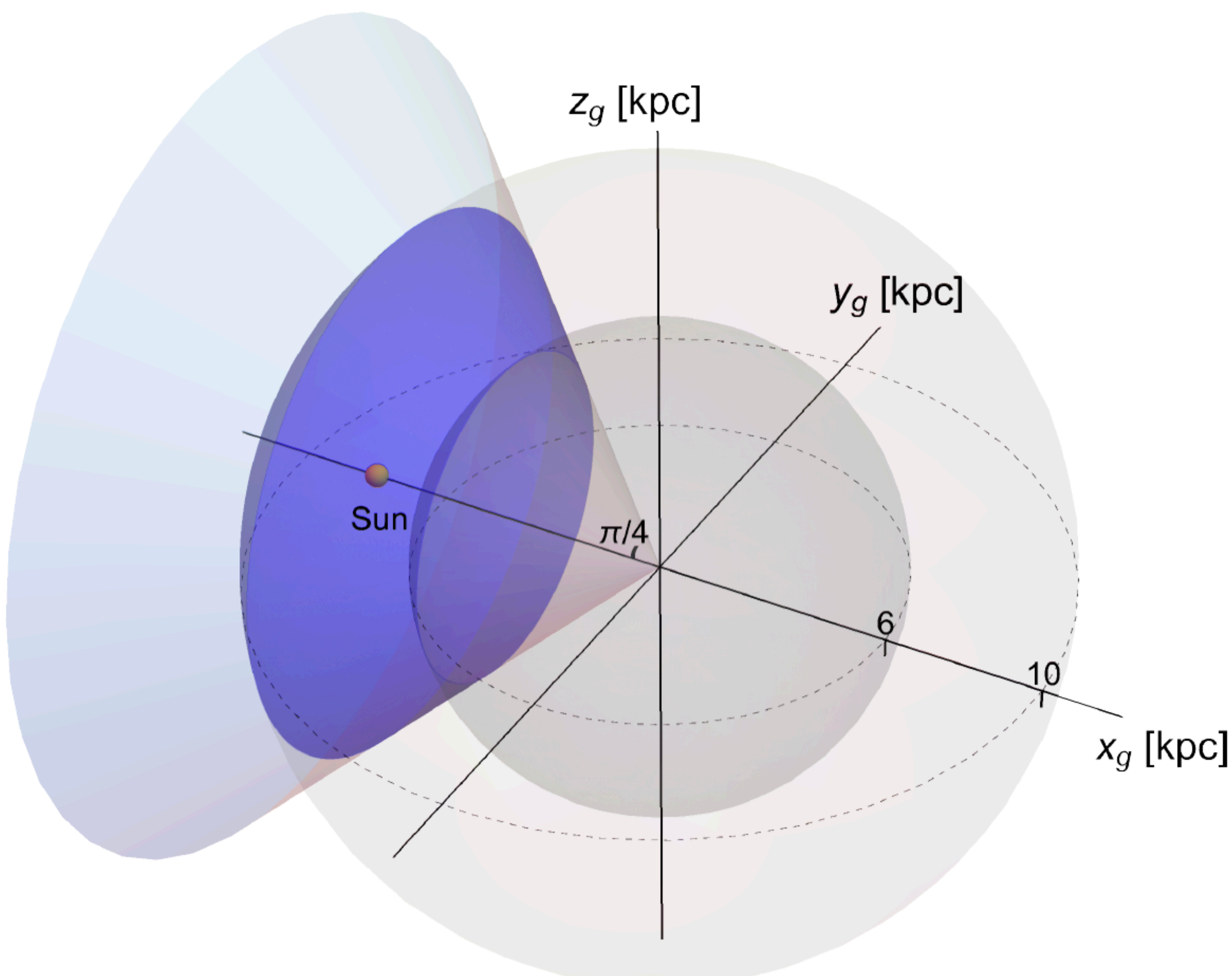
1. Find the **stellar disk orientations** that make the same angle with the orbital plane of the LMC analogues as in observations.

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.

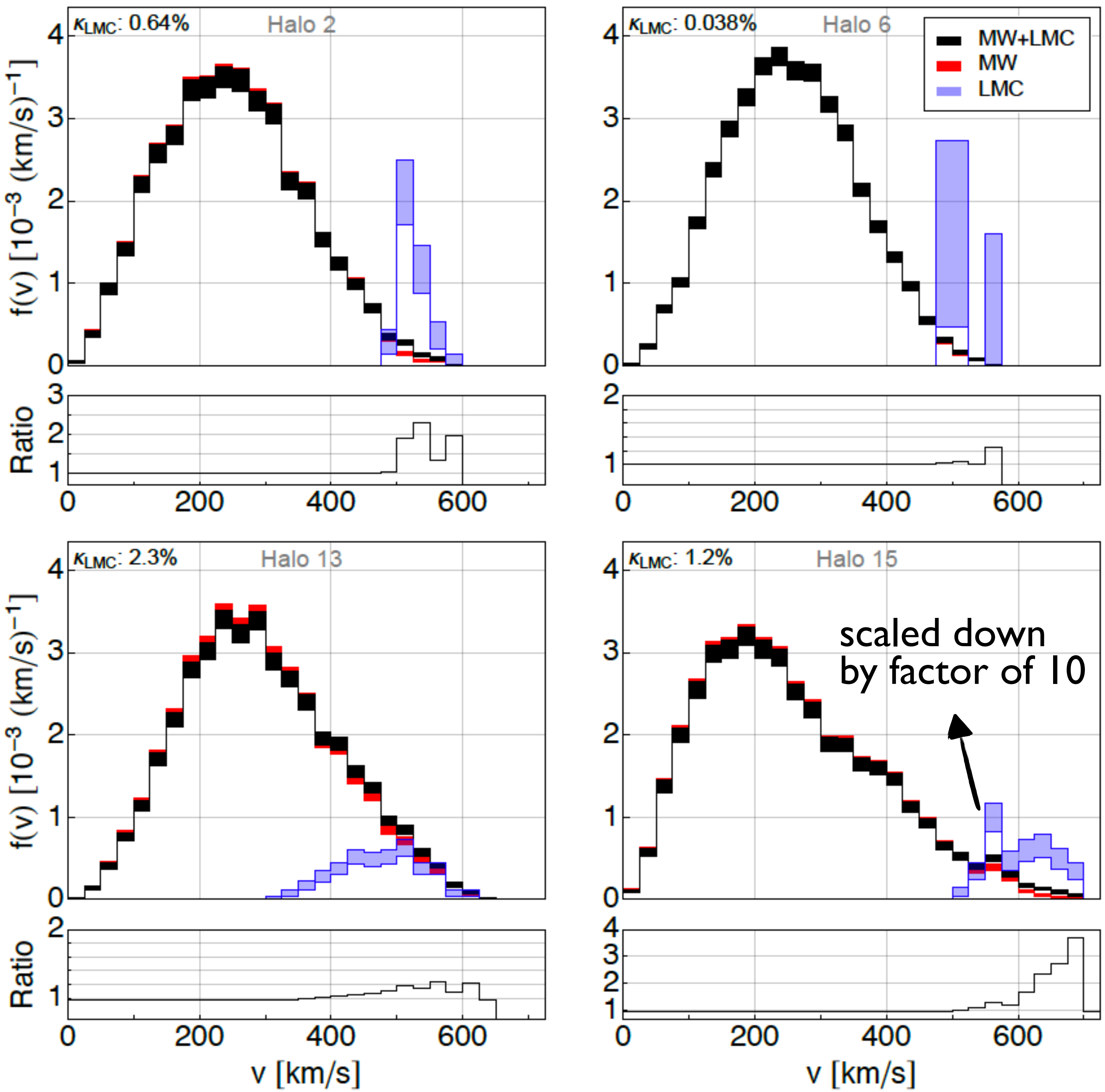
Defining the Solar region

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.



Local dark matter speed distribution

In the galactic rest frame (present day)



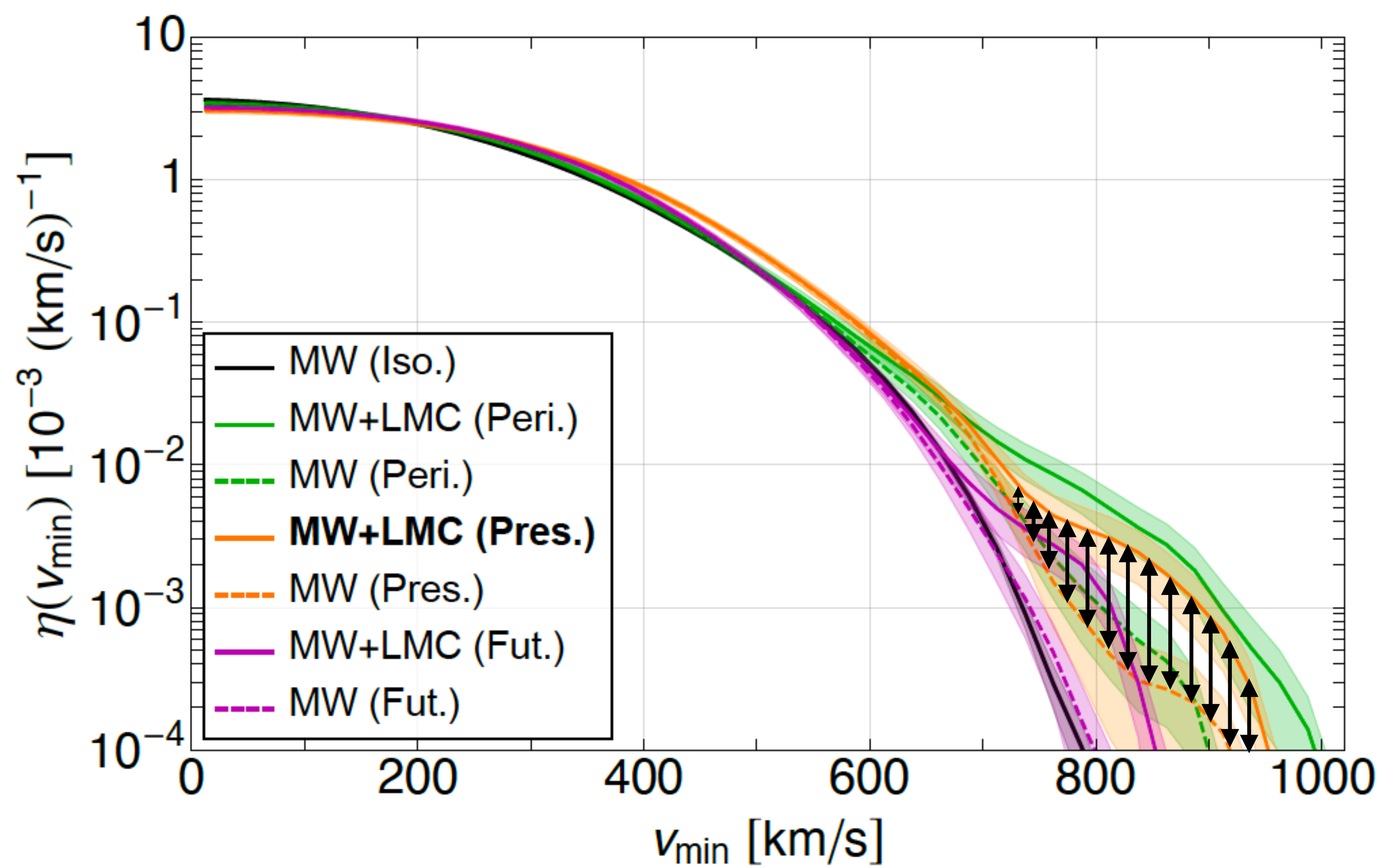
Smith-Orlik et al., 2302.04281

- The speed distribution of DM particles originating from the LMC **peaks at the high speed tail** of the Milky Way's DM distribution.
- Large halo-to-halo scatter in the results.

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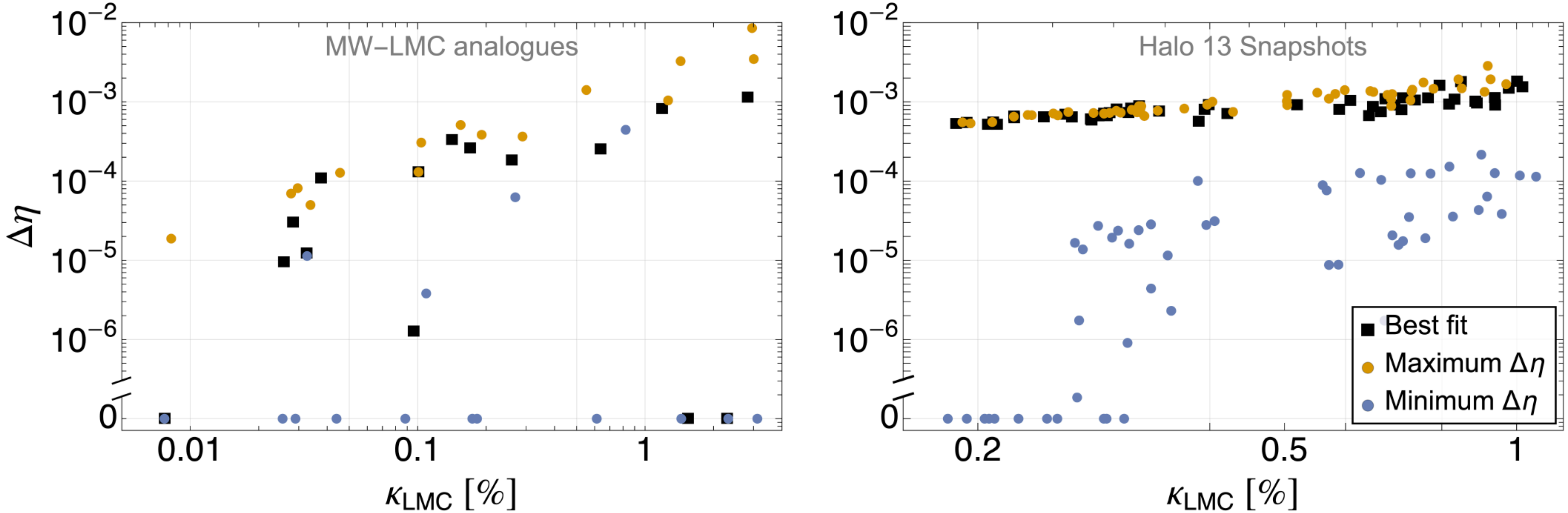
Factors that contribute to changes in the tail of the halo integrals:

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** ($\kappa_{\rm LMC}$) and $\Delta\eta$:

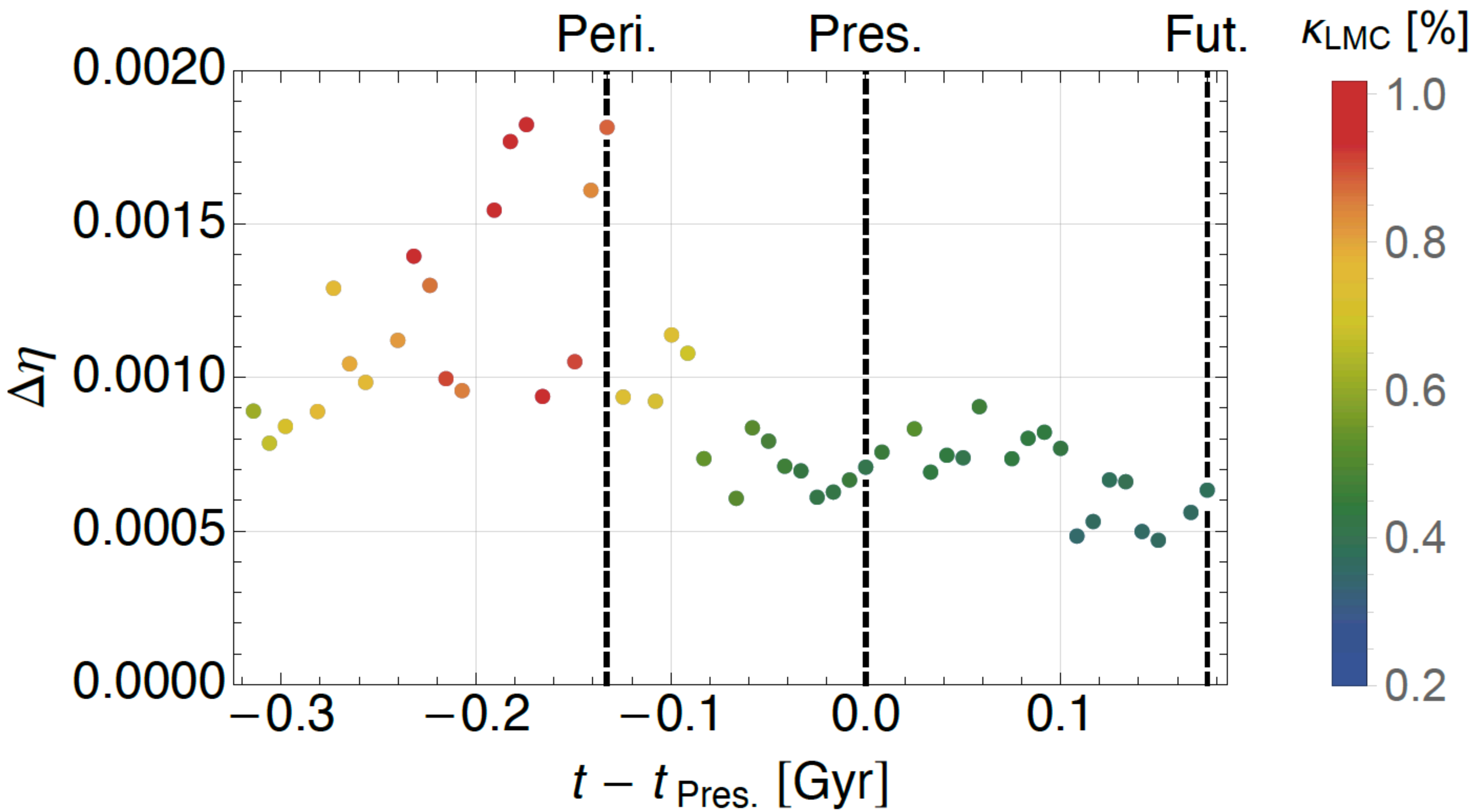


Smith-Orlik et al., 2302.04281

- $\Delta\eta$ for best fit Sun's position close to max $\Delta\eta$, and increases with $\kappa_{\rm LMC}$.
- Scatter in $\Delta\eta$ for halos with similar $\kappa_{\rm LMC}$, 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., 2302.04281

Variation with the Sun-LMC geometry

Cosine angles that parametrize the Sun-LMC geometry:

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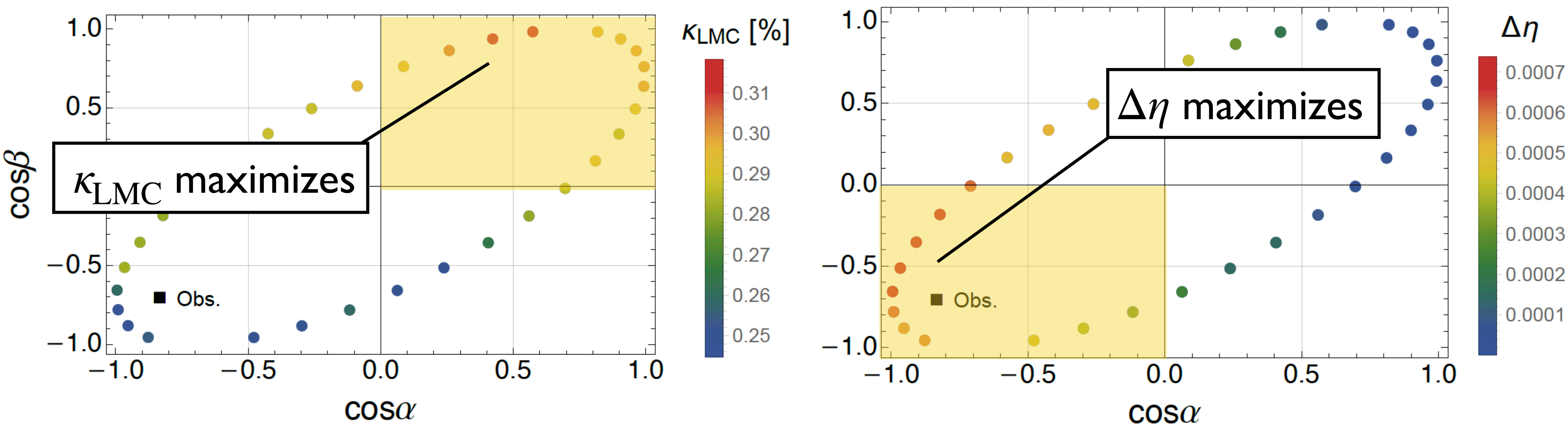
$$\cos\beta \equiv \hat{\mathbf{v}}^{\rm sim}_{\rm Sun} \cdot \hat{\mathbf{v}}^{\rm sim}_{\rm LMC}$$



Smith-Orlik et al., 2302.04281

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.*