Dark matter direct detection in the presence of the LMC

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The Large Magellanic Cloud

The **Large Magellanic Cloud (LMC)** is the most massive satellite of the Milky Way and on its first passage around the Galaxy.
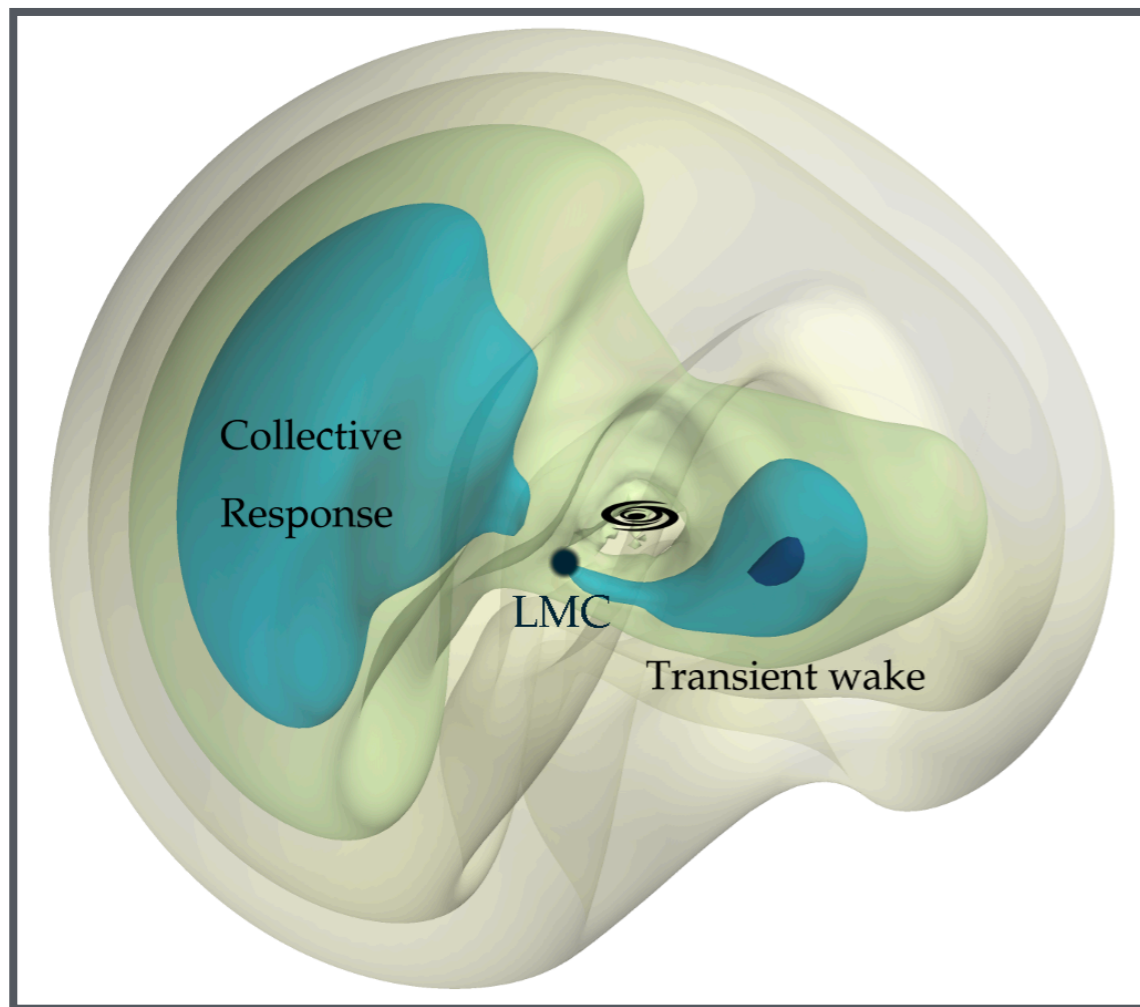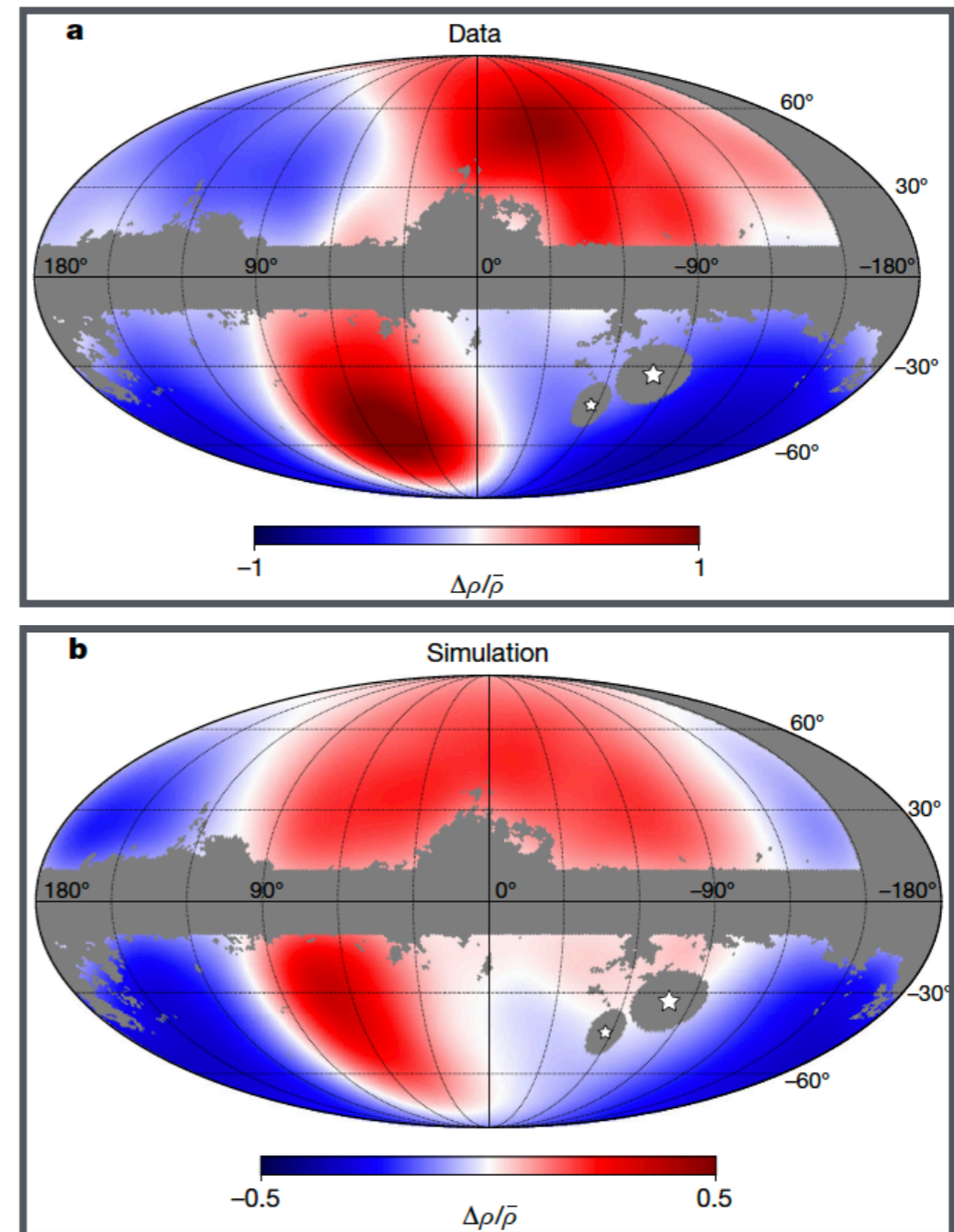

Large Magellanic Cloud

Gaia's EDR3 sky map. *Credit: ESA/Gaia/DPAC*
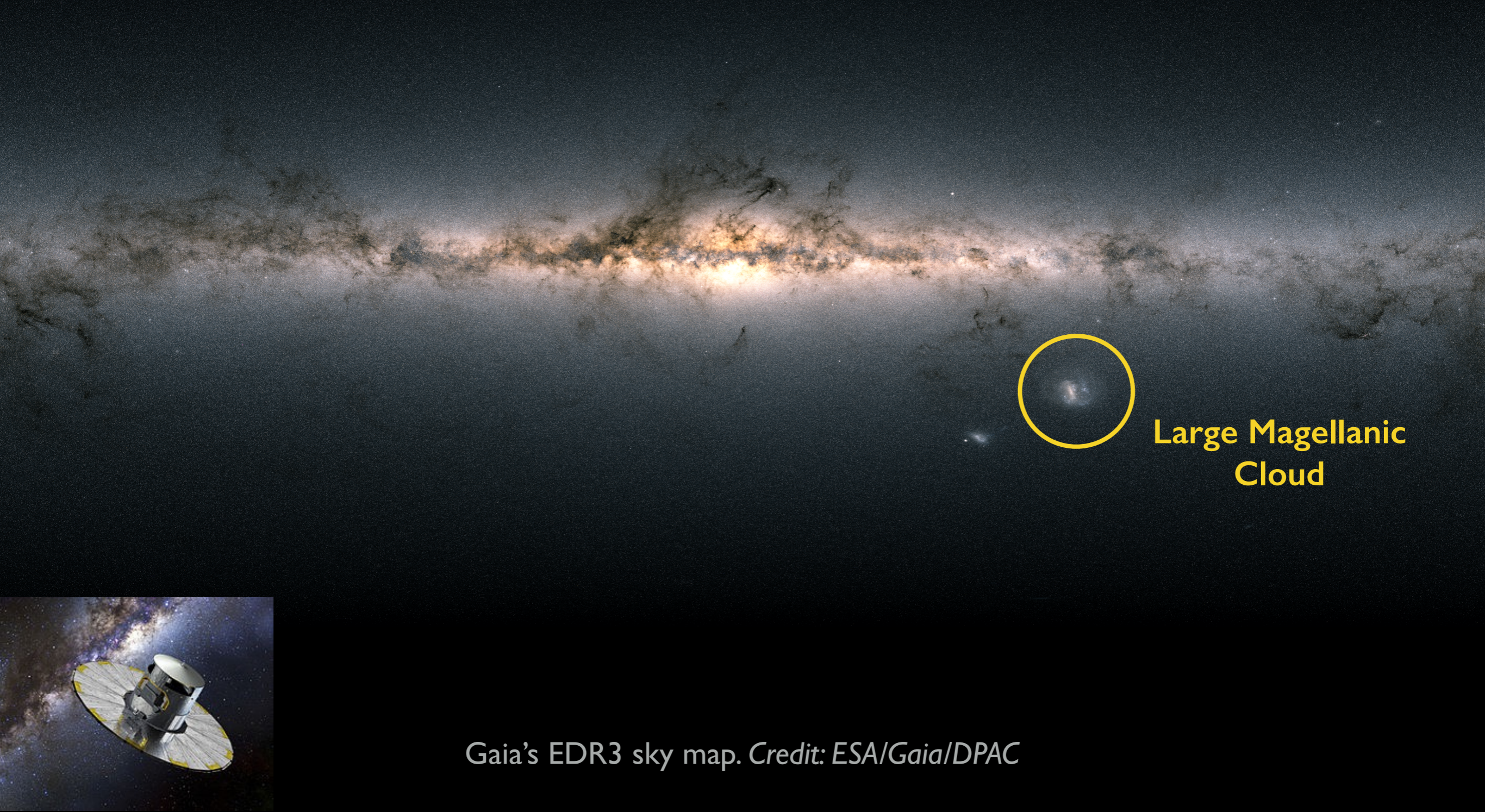
The effect of the LMC

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

DM halo

Collective Response

LMC

Transient wake

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 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)
Donaldson et al, MNRAS 513, 1, 46 (2022)

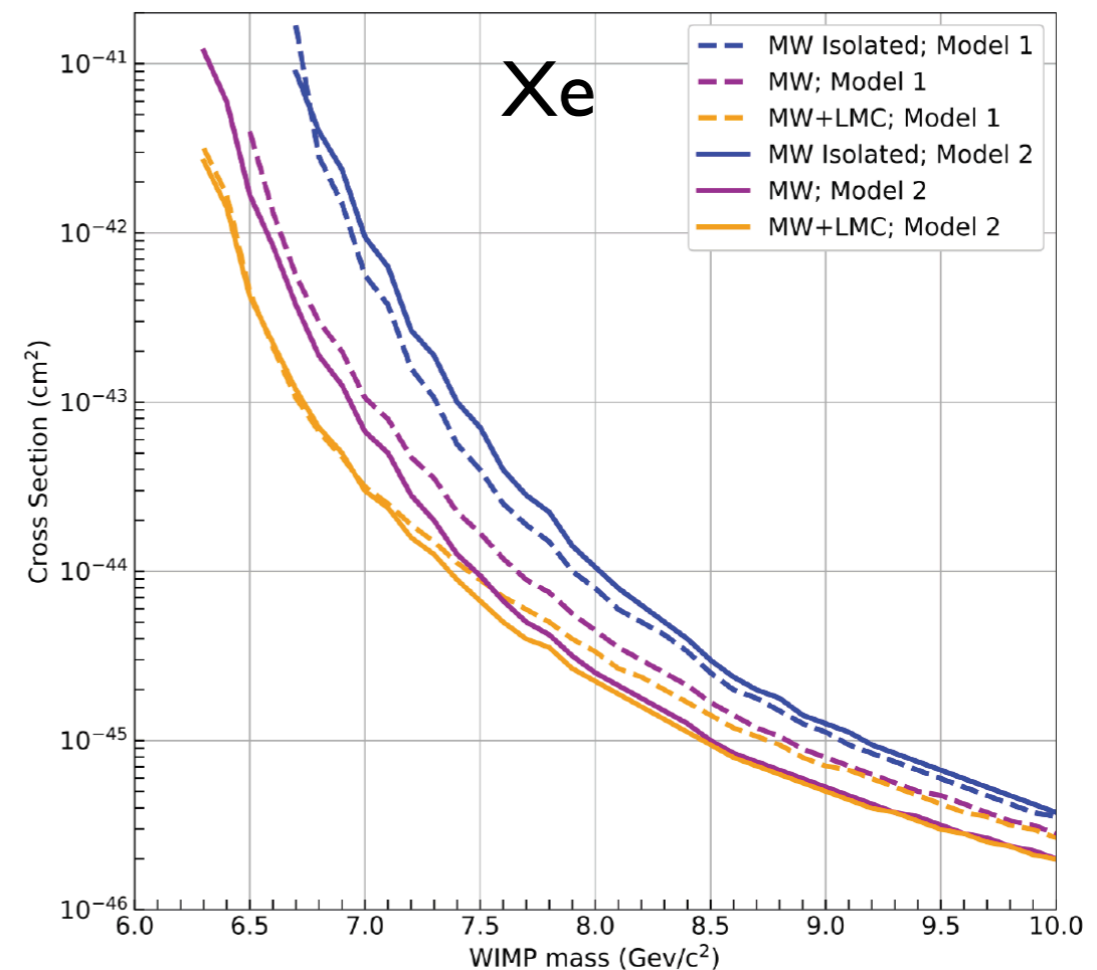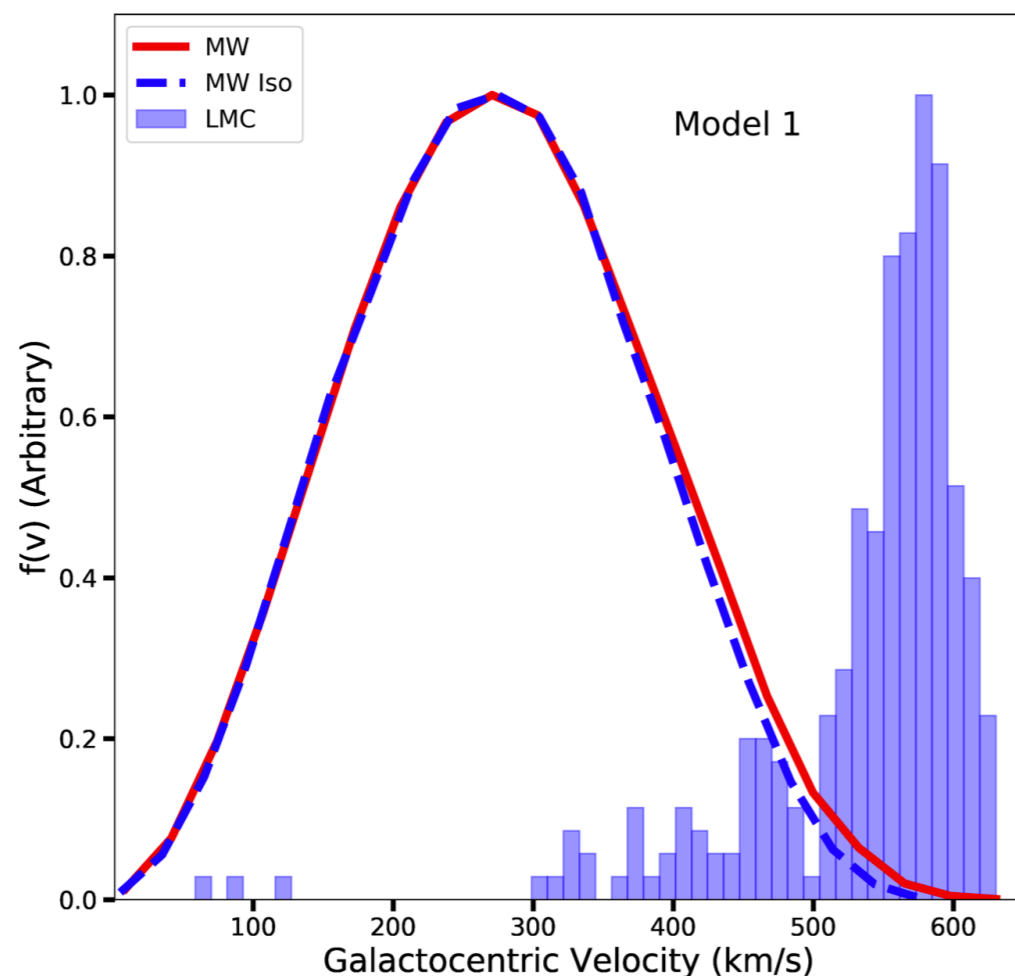# Effect of LMC on direct detection

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- Studied in specially designed idealized simulations.

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- Studied in specially designed idealized simulations.

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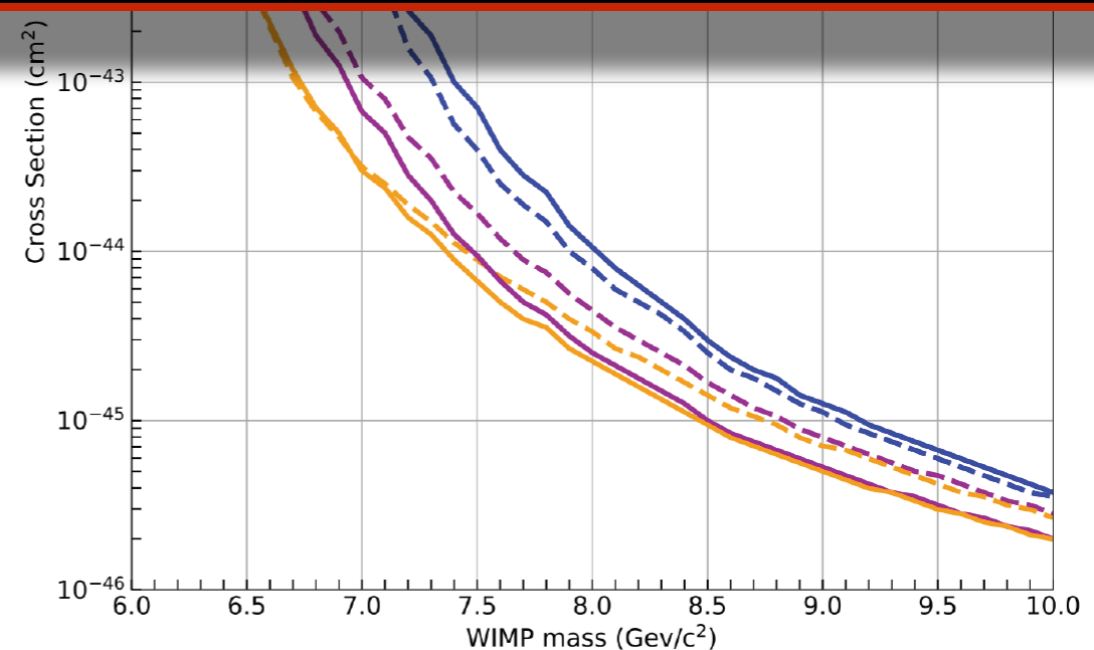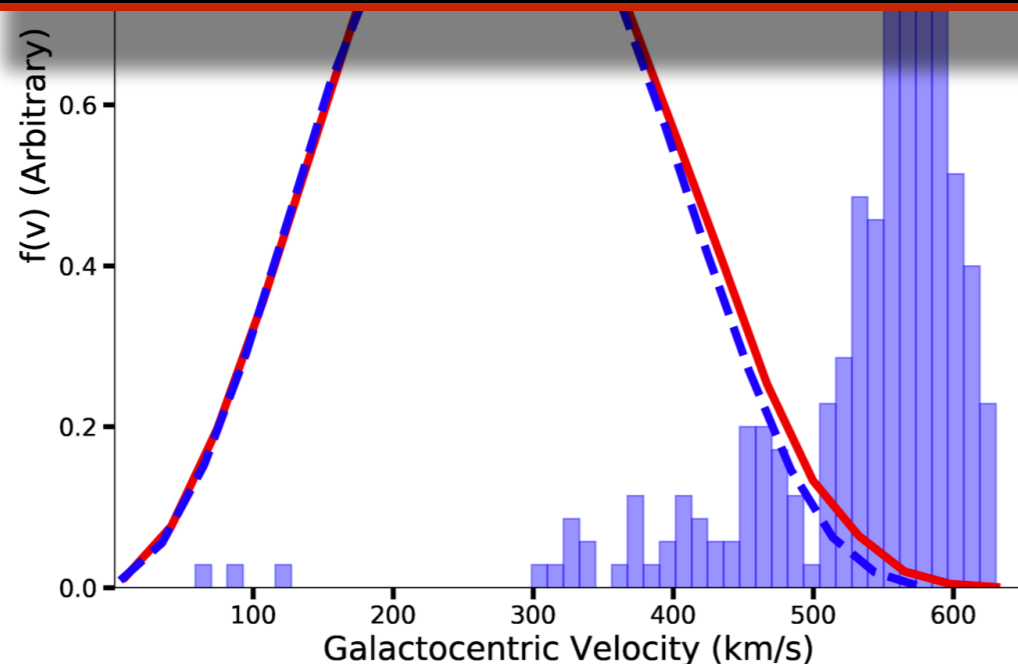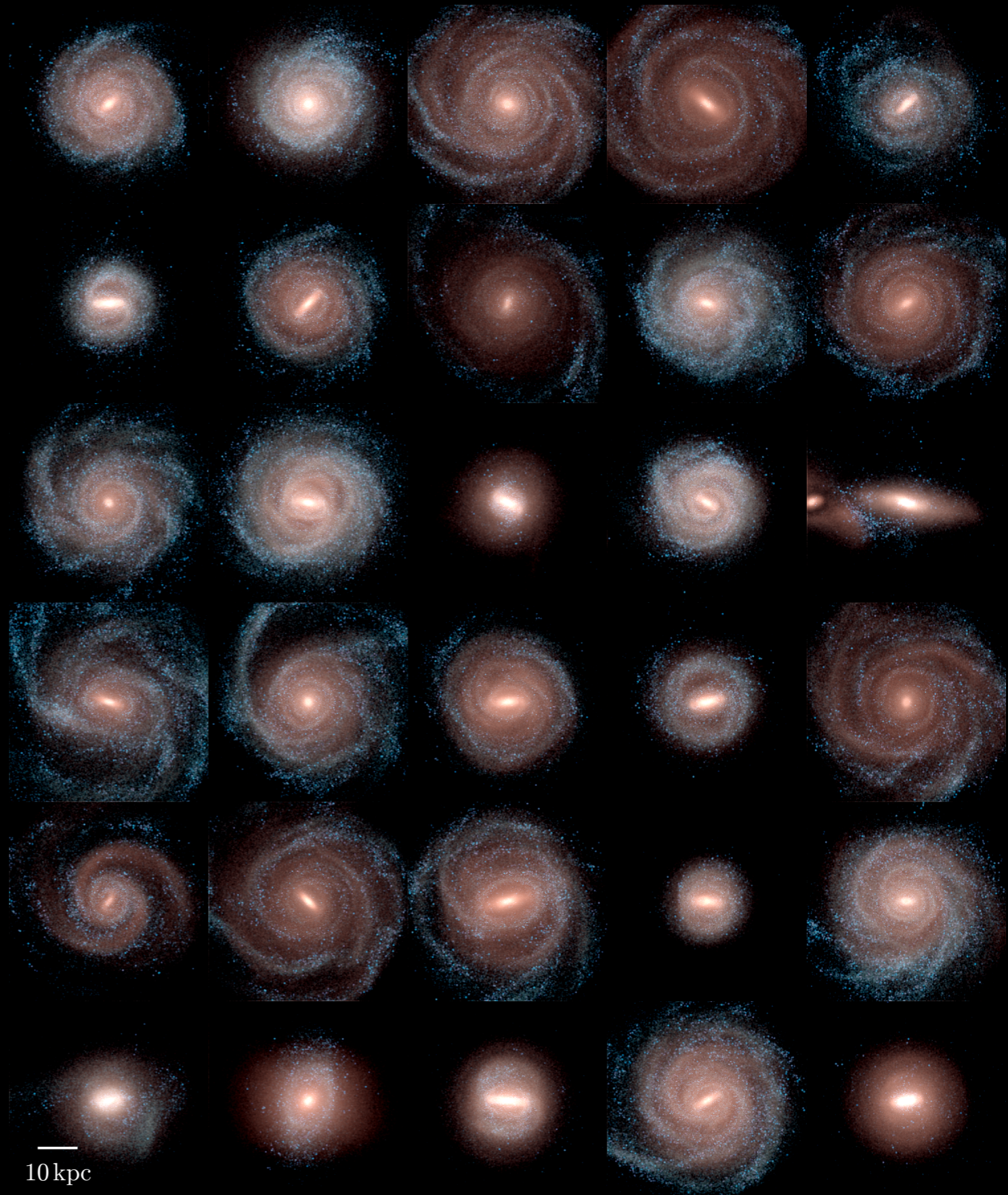

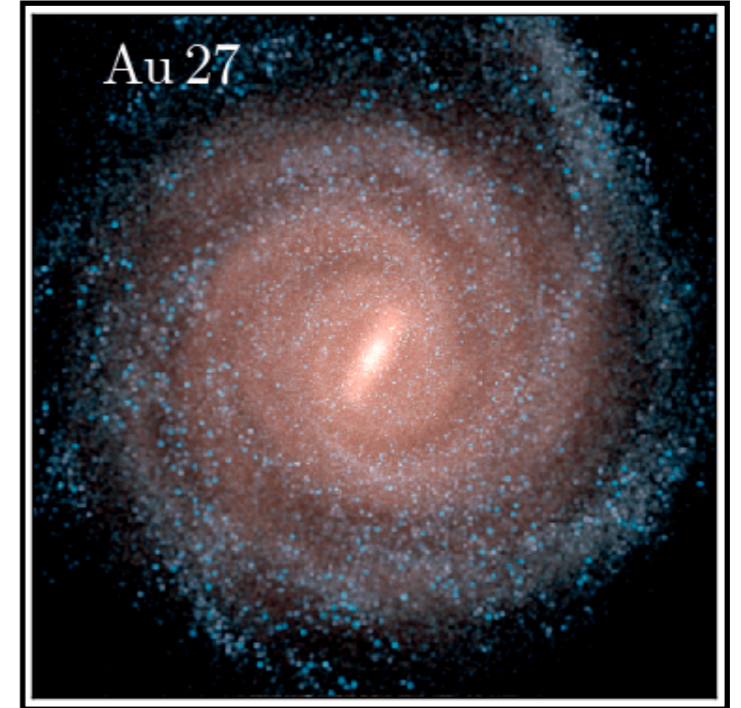Besla et al, JCAP 11, 013 (2019)

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

10 kpc

Auriga cosmological simulations

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

Au 27

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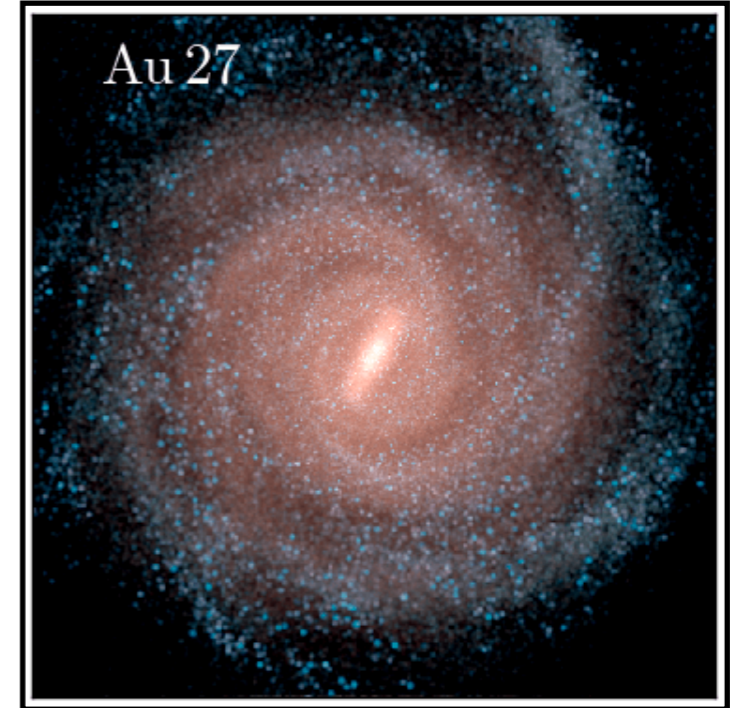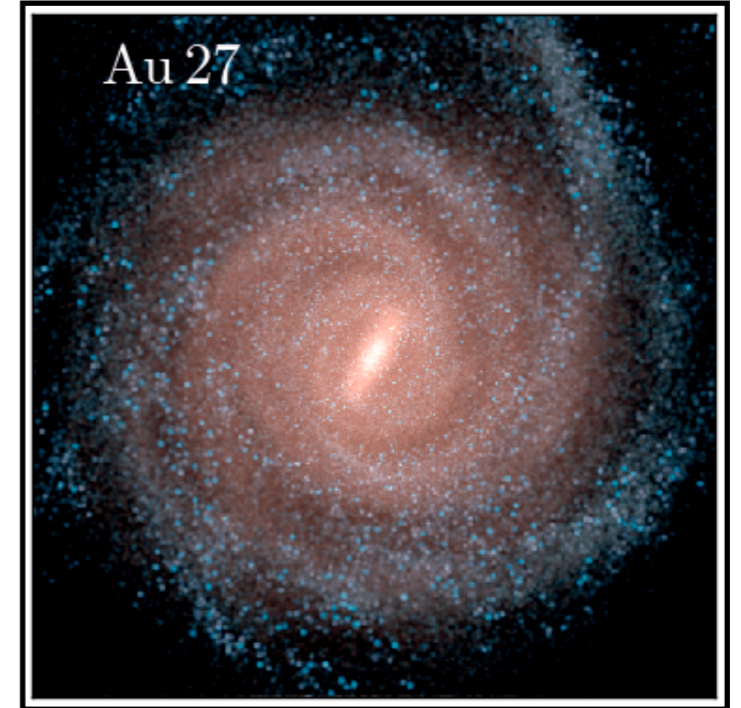

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- Consider four representative snapshots:

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

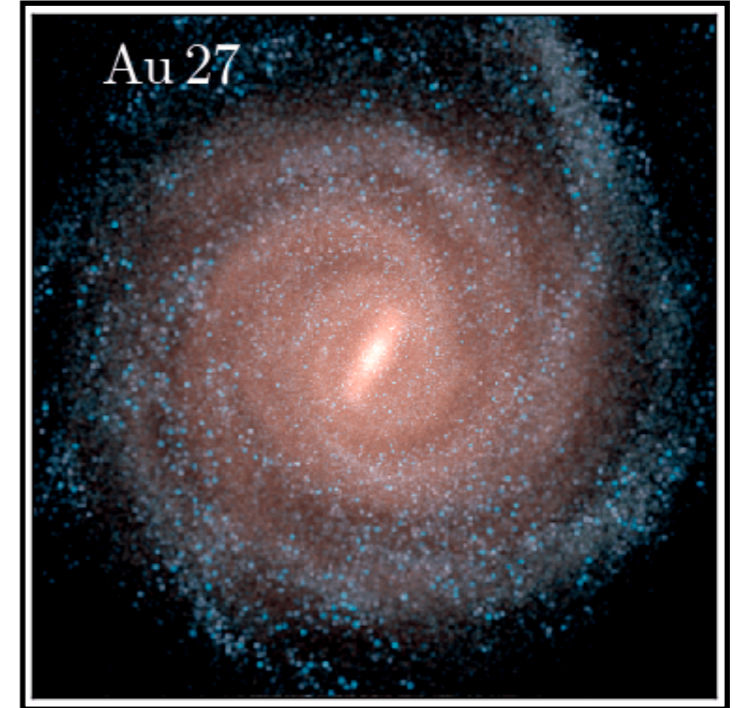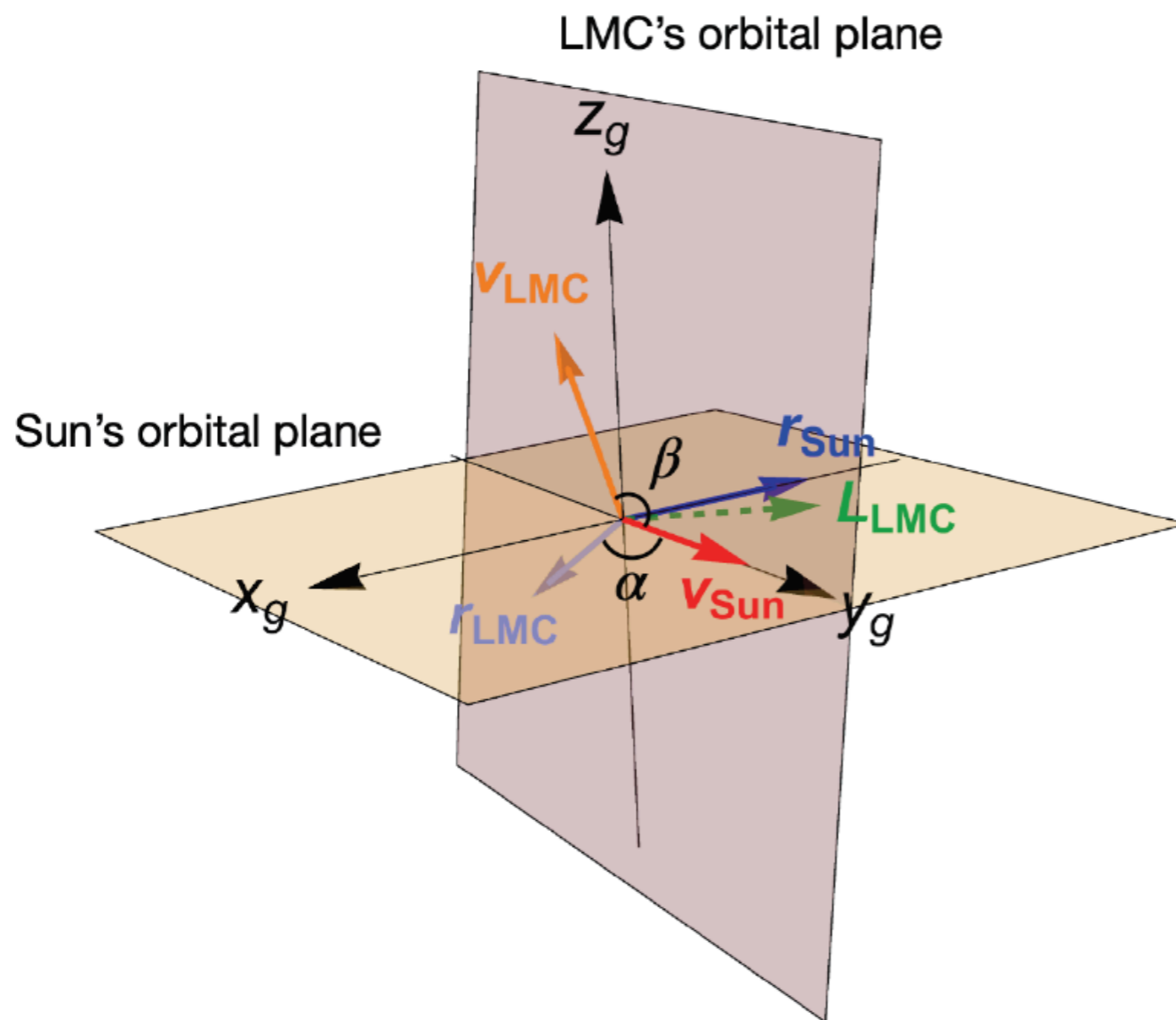# Auriga cosmological simulations

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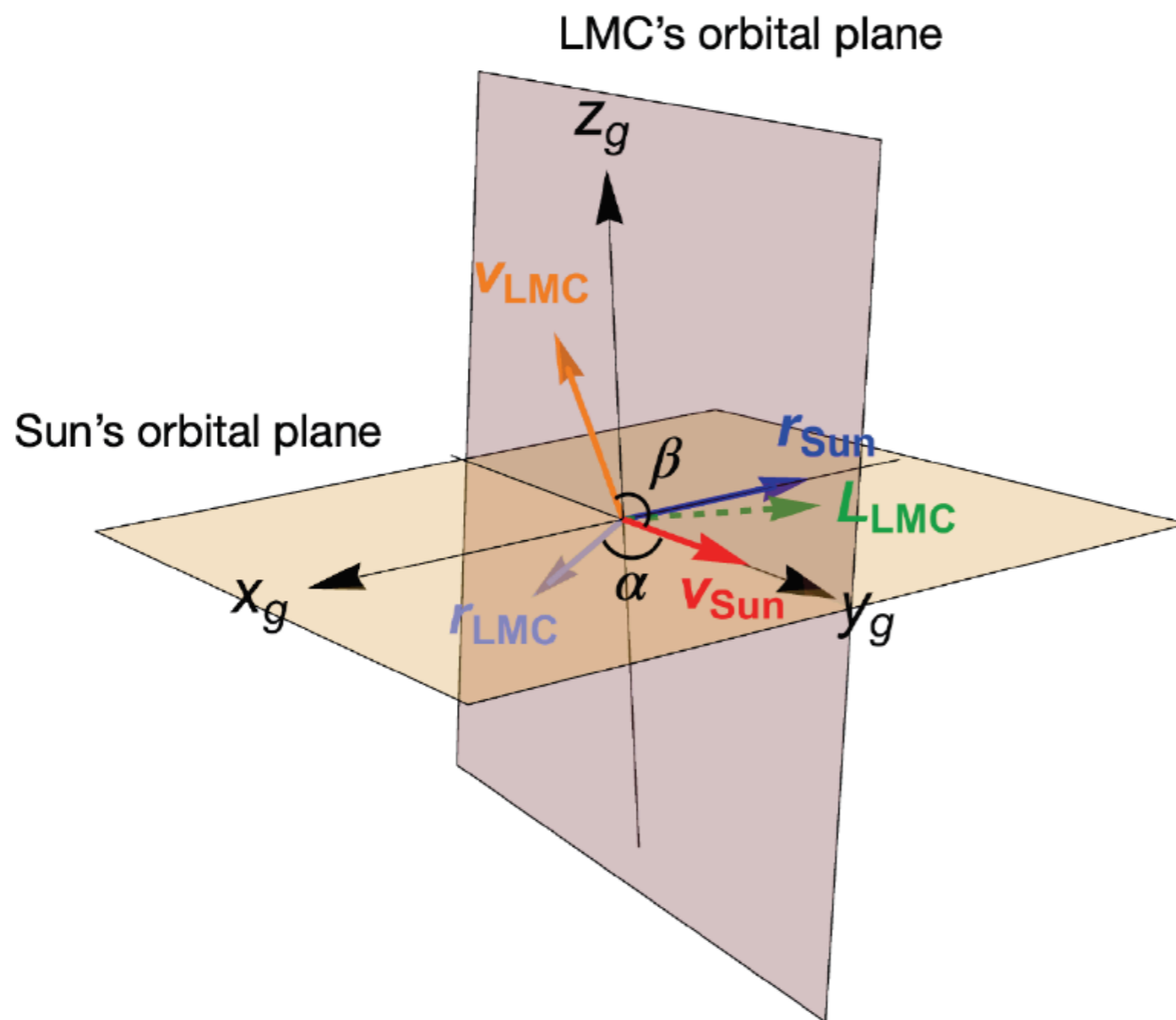
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- Choose the position of the Sun in the simulations such that it matches the observed Sun-LMC geometry.
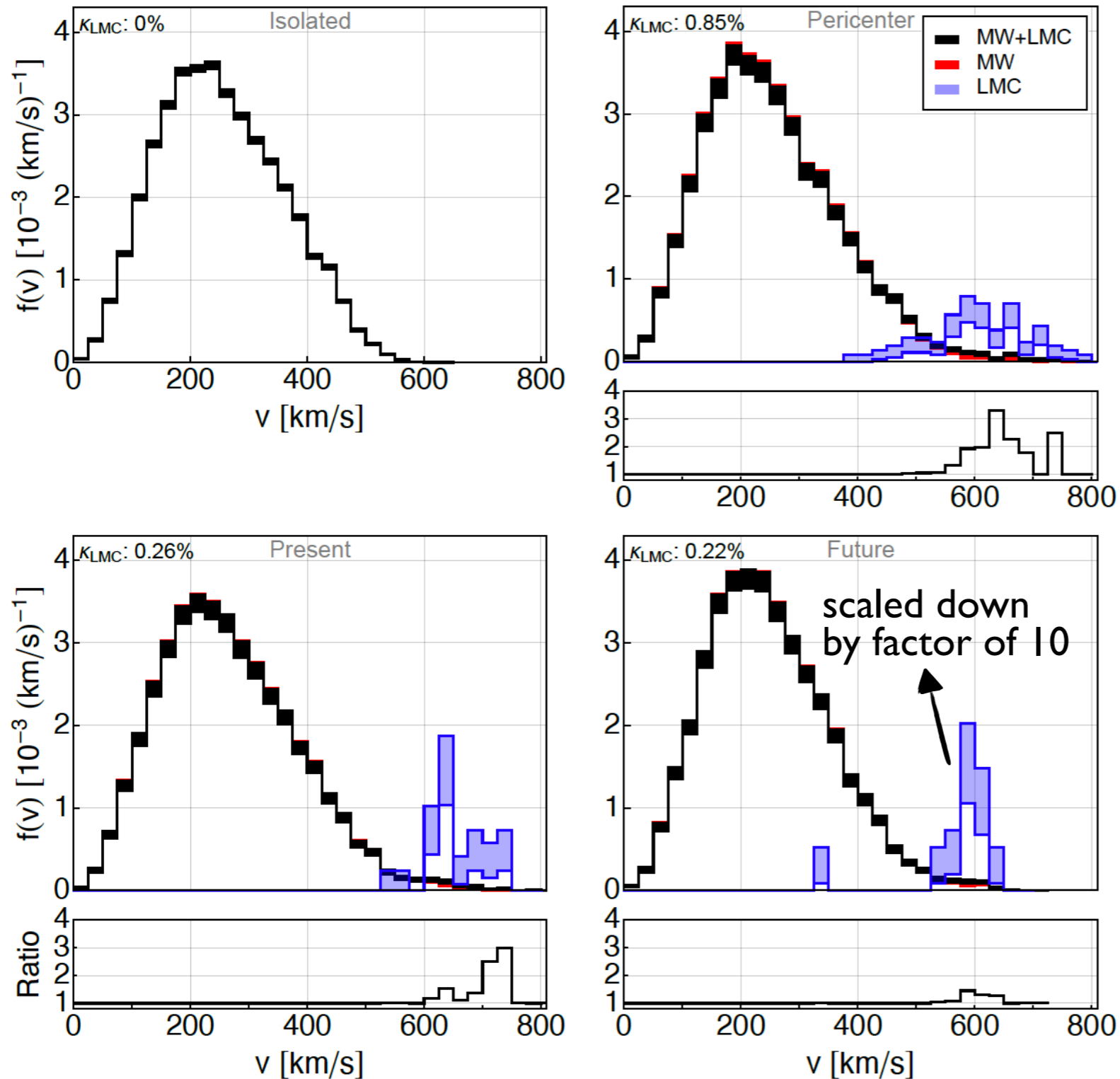
Local dark matter density

Halo ID	$M_{\text{Infall}}^{\text{LMC}}$ [10^{11} M$_\odot$]	ρ_χ [GeV/cm^3]	κ_{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.
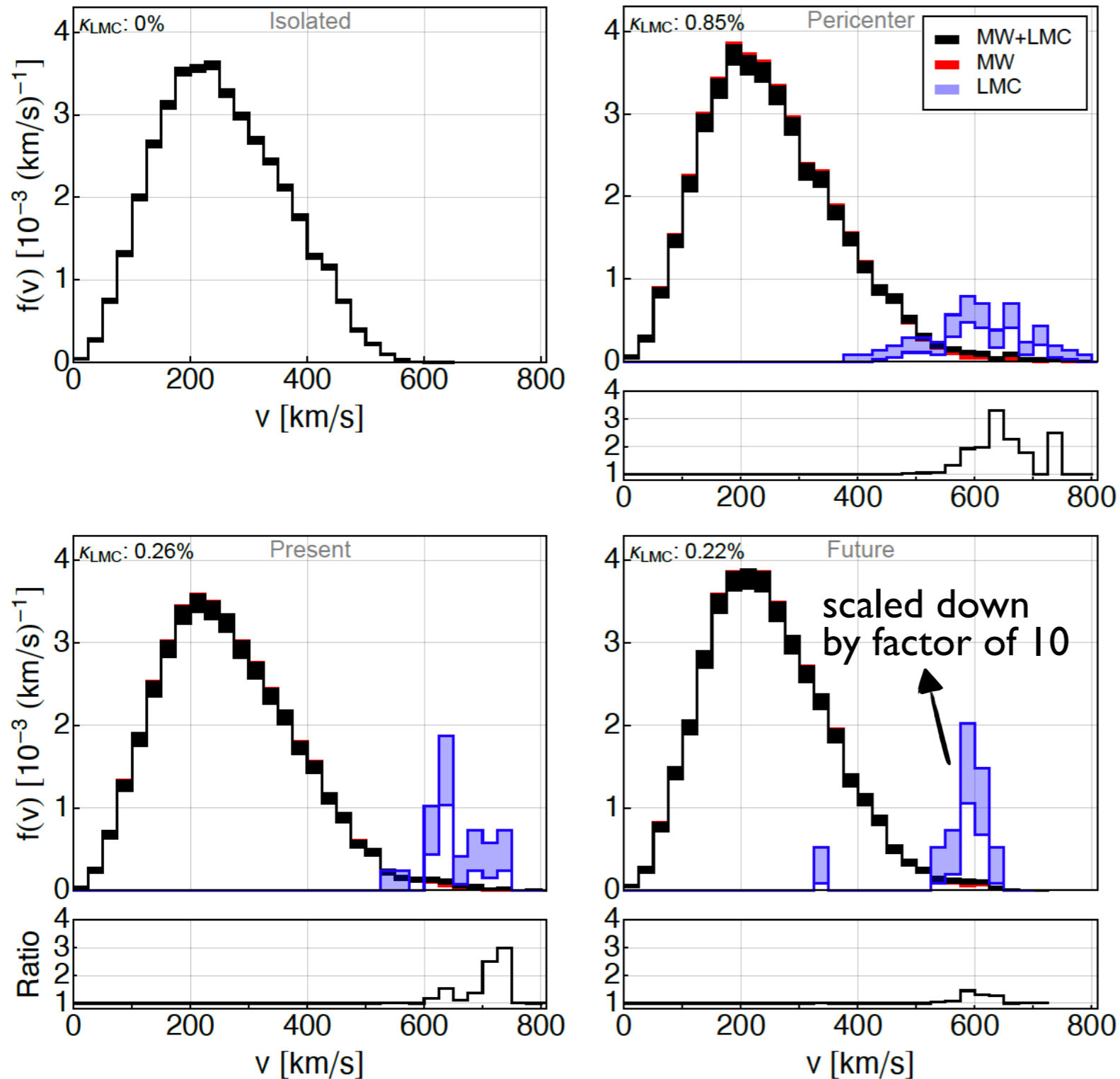
Local dark matter speed distribution

In the galactic rest frame
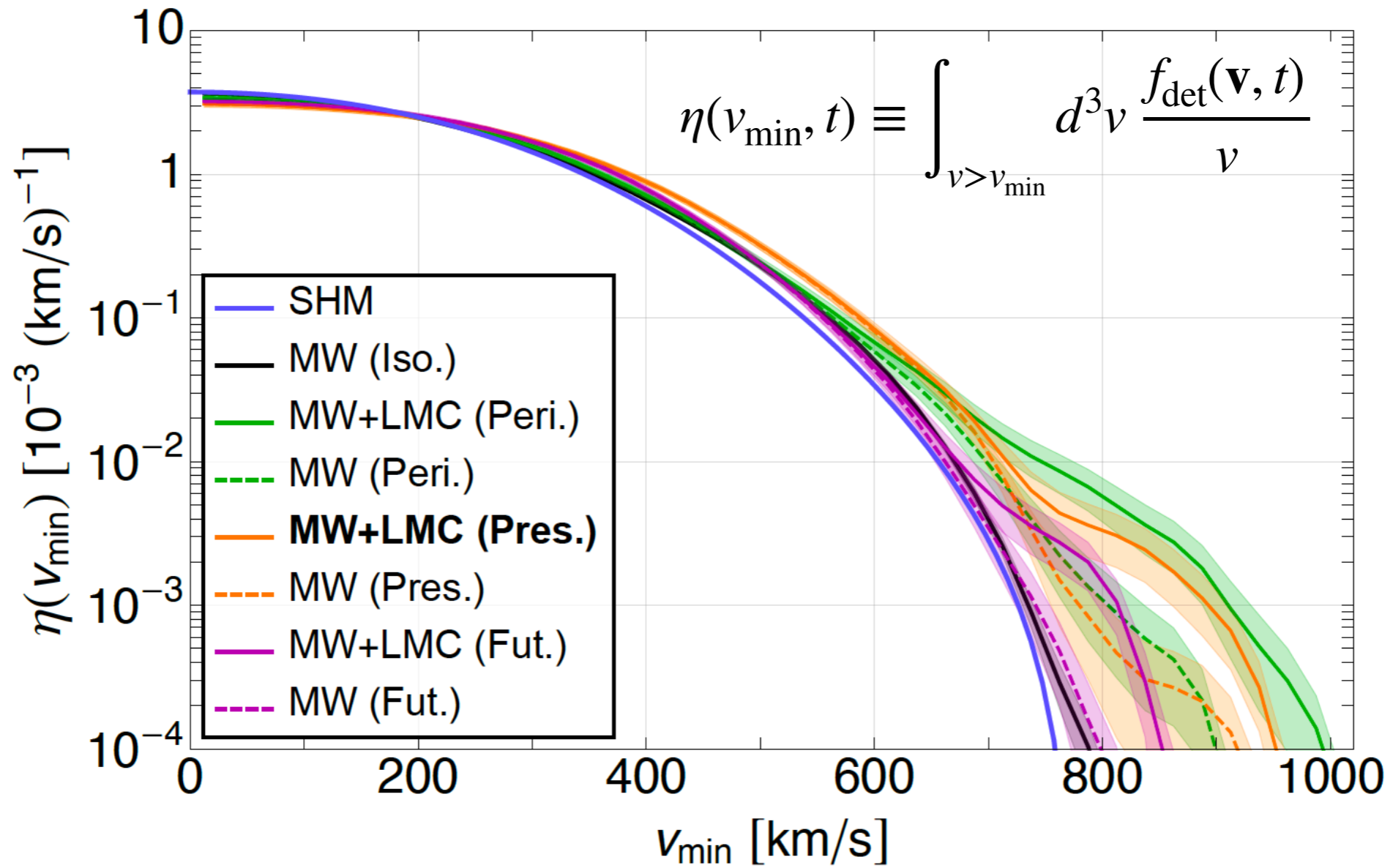
Local dark matter speed distribution

In the galactic rest frame

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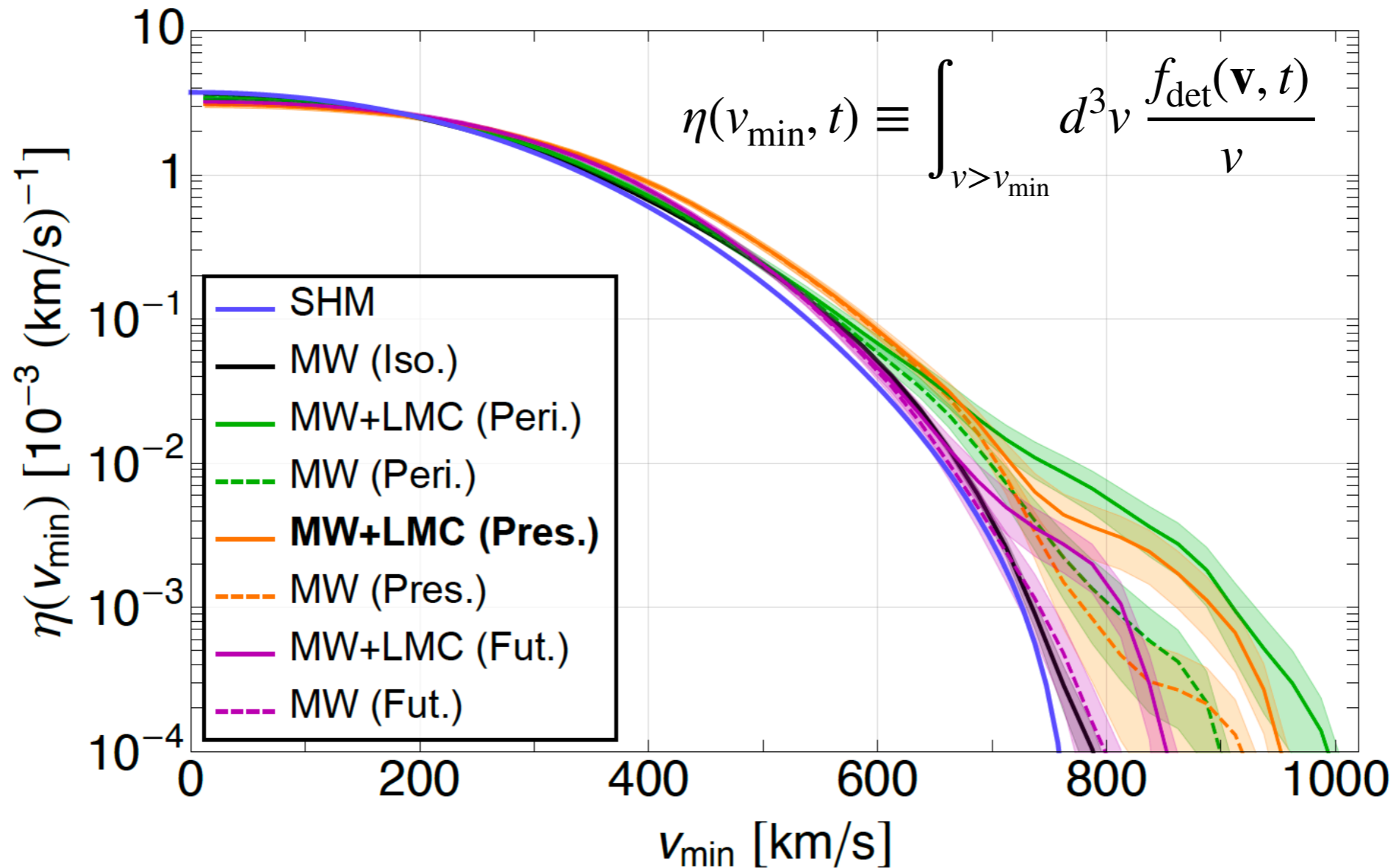
Smith-Orlik et al., JCAP 10, 070 (2023)

Halo integrals

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

Legend:
- SHM
- MW (Iso.)
- MW+LMC (Peri.)
- MW (Peri.)
- **MW+LMC (Pres.)**
- MW (Pres.)
- MW+LMC (Fut.)
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Axes: $\eta(v_{\min})$ [10^{-3} (km/s)$^{-1}$] versus $v_{\min}$ [km/s]

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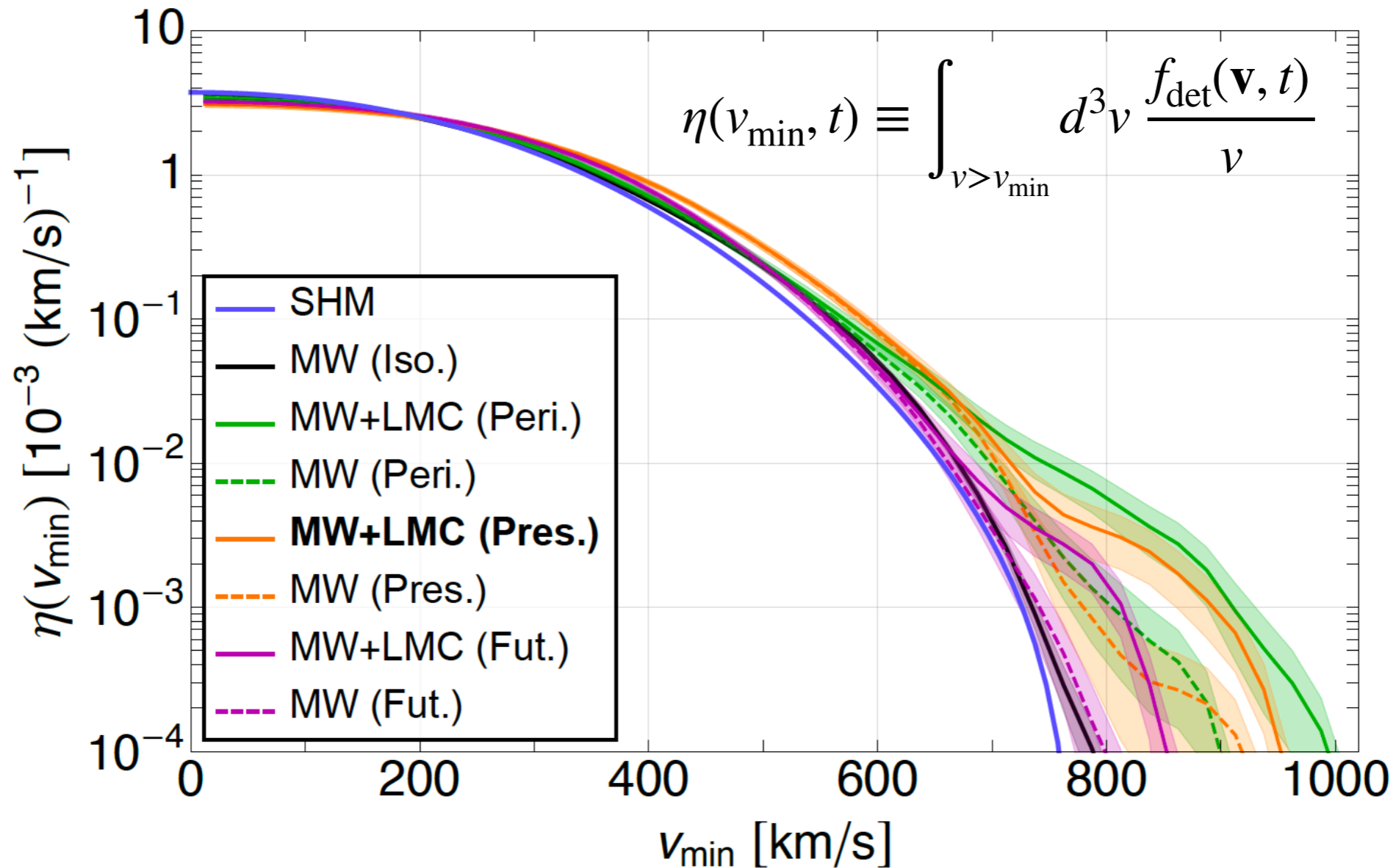
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- **Two effects:** High speed LMC particles in the Solar region + Milky Way's response to the LMC.

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

- **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.
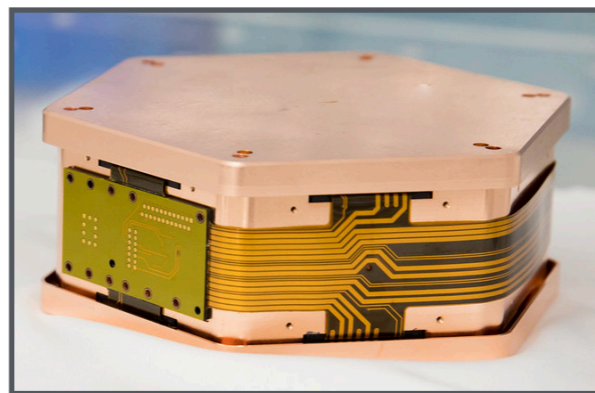
Nuclear recoils

Electron recoils

Xenon based

Germanium based
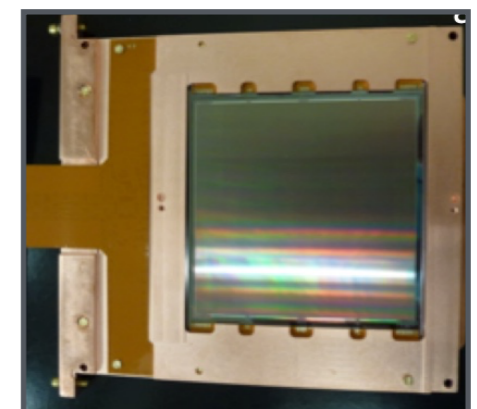
Silicon CCD

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

- $[40 - 300]$ eV, 1.6×10^4 kg days
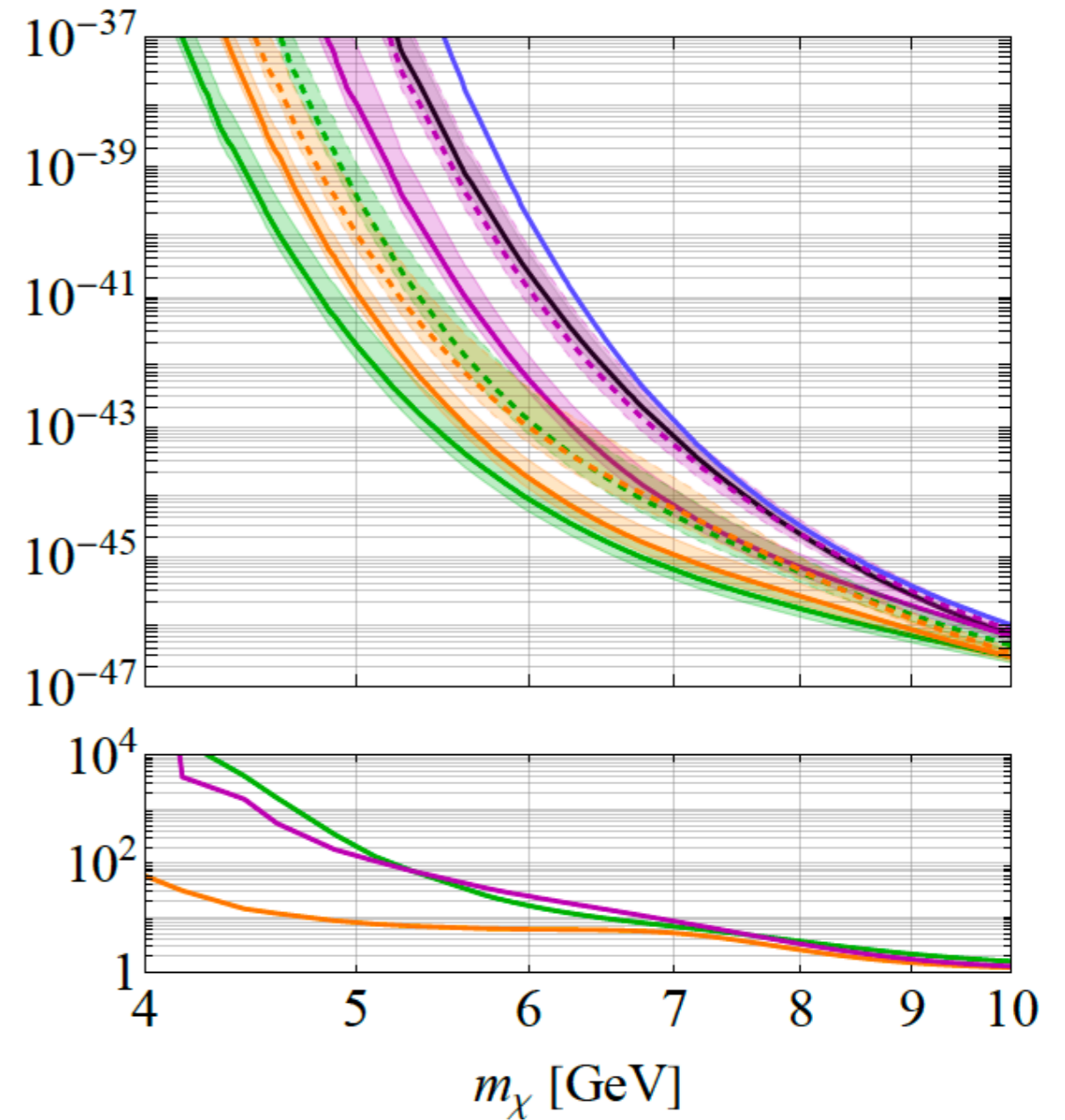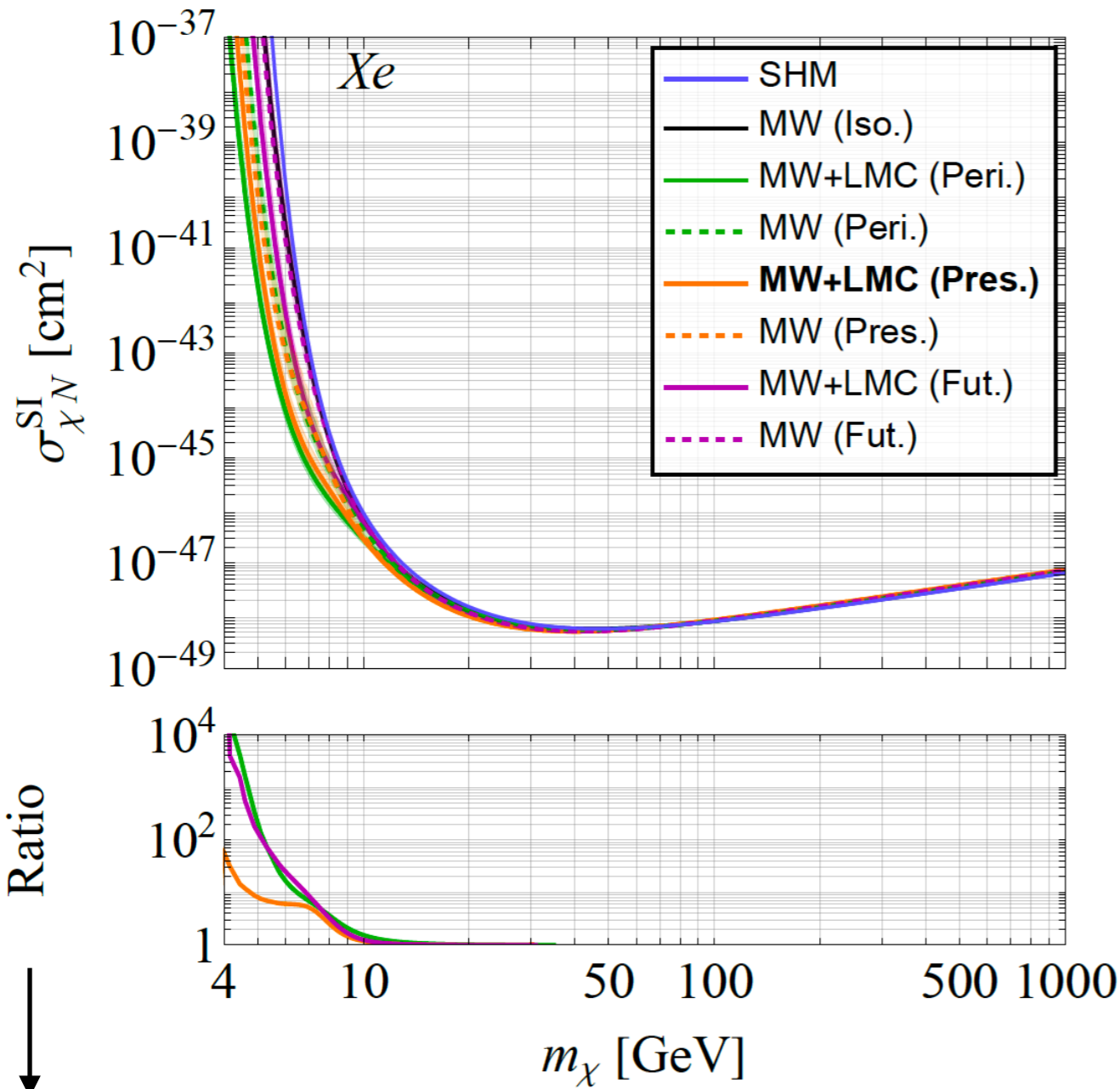- $[3 - 30]$ keV, 2.04×10^4 kg days
Based on SuperCDMS

1 electron threshold
1 kg yr
Based on DAMIC

Direct detection: nuclear recoils

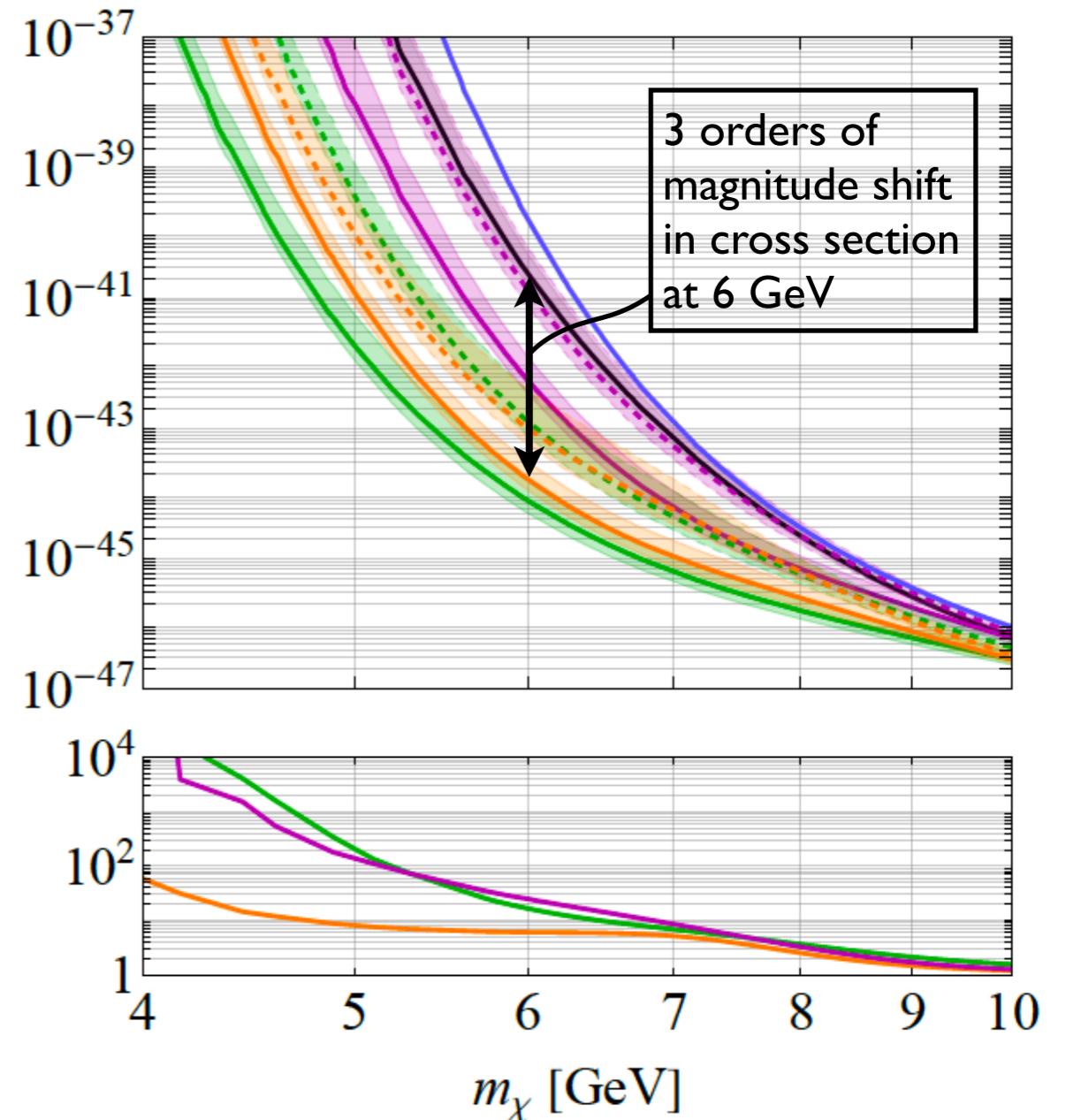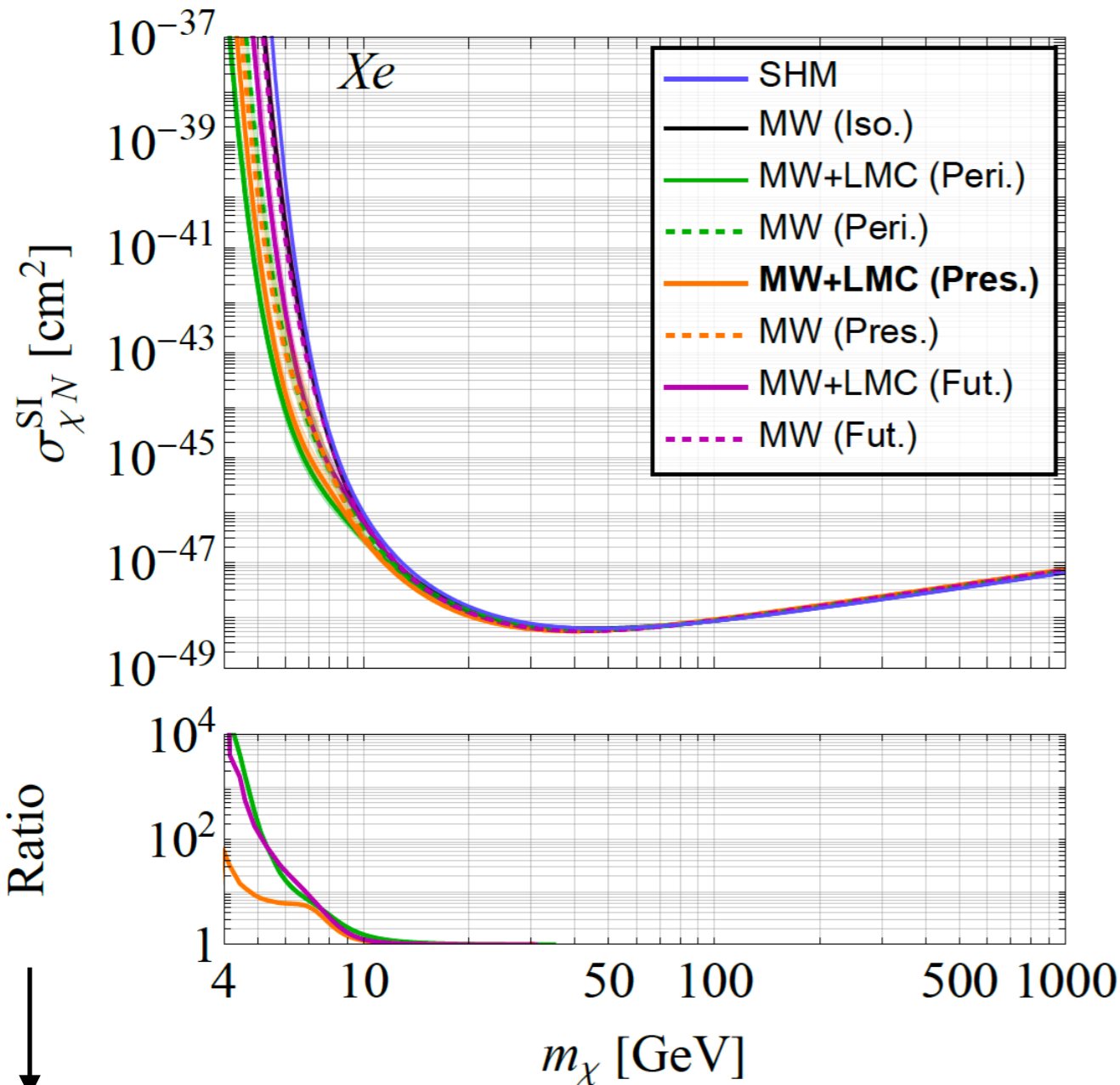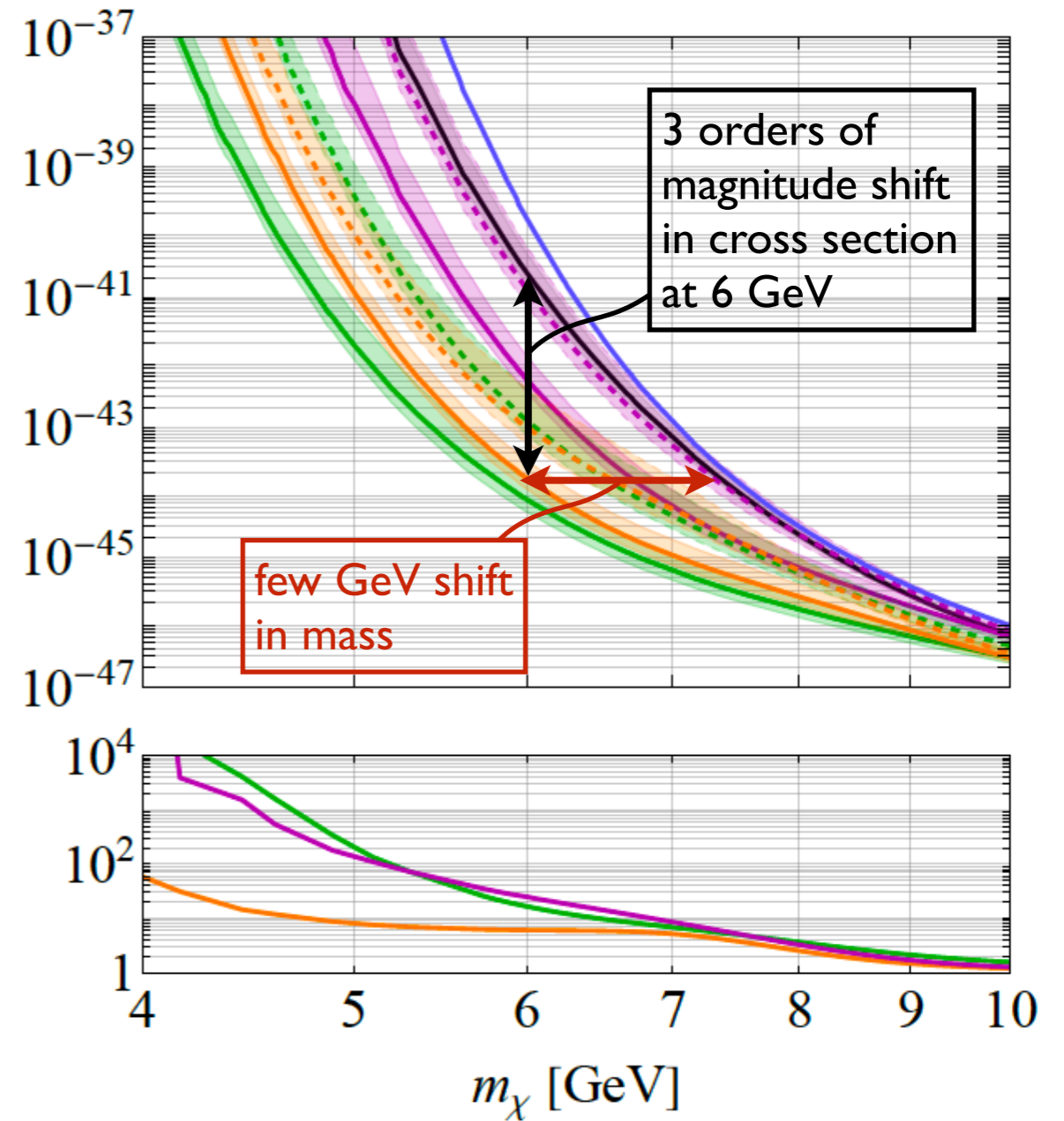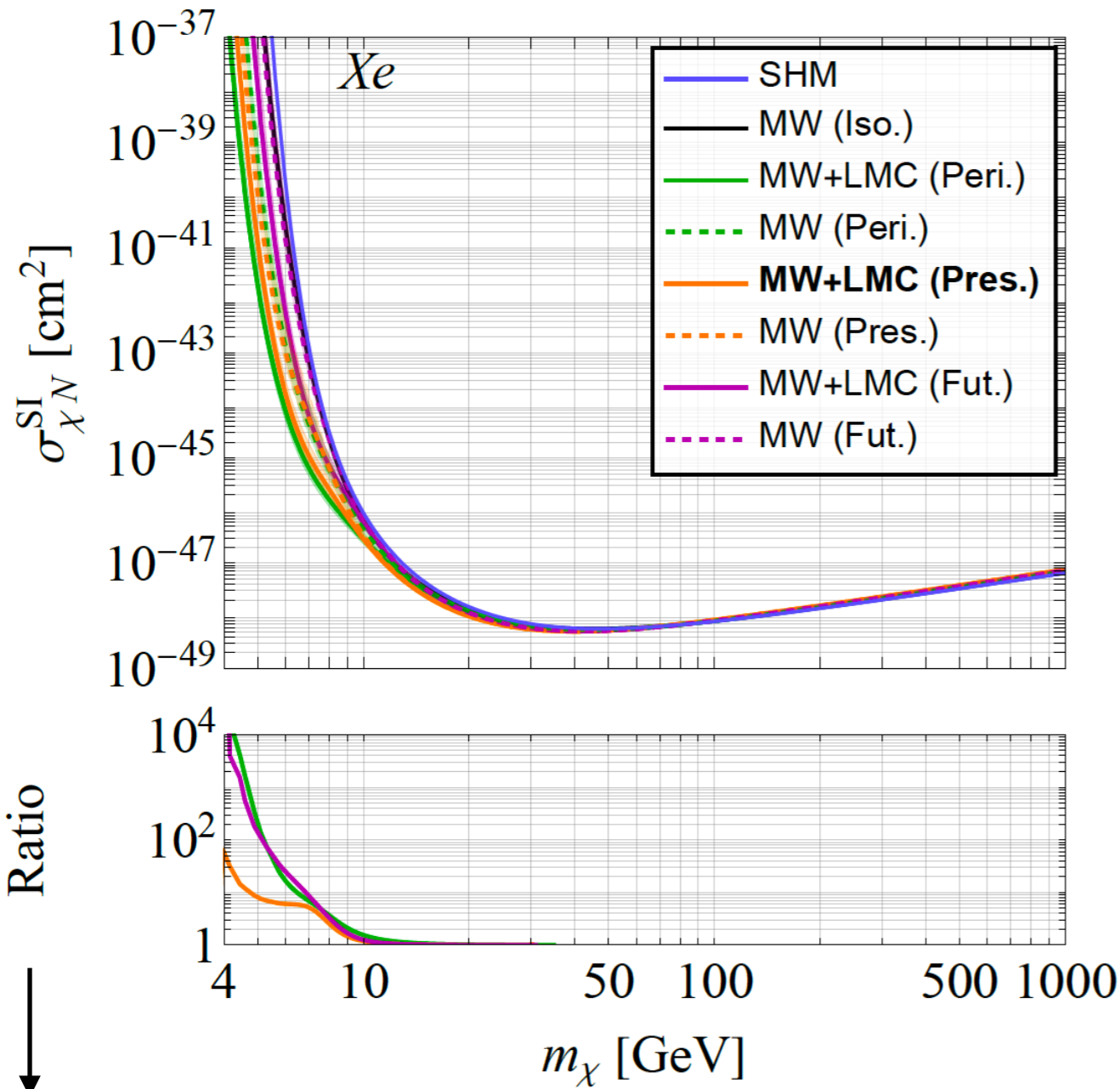**Xenon based detector:**

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

$$\text{Ratio} = \frac{\sigma_{\chi,\text{MW}}^{\text{SI}}}{\sigma_{\chi,\text{MW+LMC}}^{\text{SI}}}$$

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

Direct detection: nuclear recoils

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3 orders of magnitude shift in cross section at 6 GeV

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3 orders of magnitude shift in cross section at 6 GeV

few GeV shift in mass

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

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

Direct detection: nuclear recoils

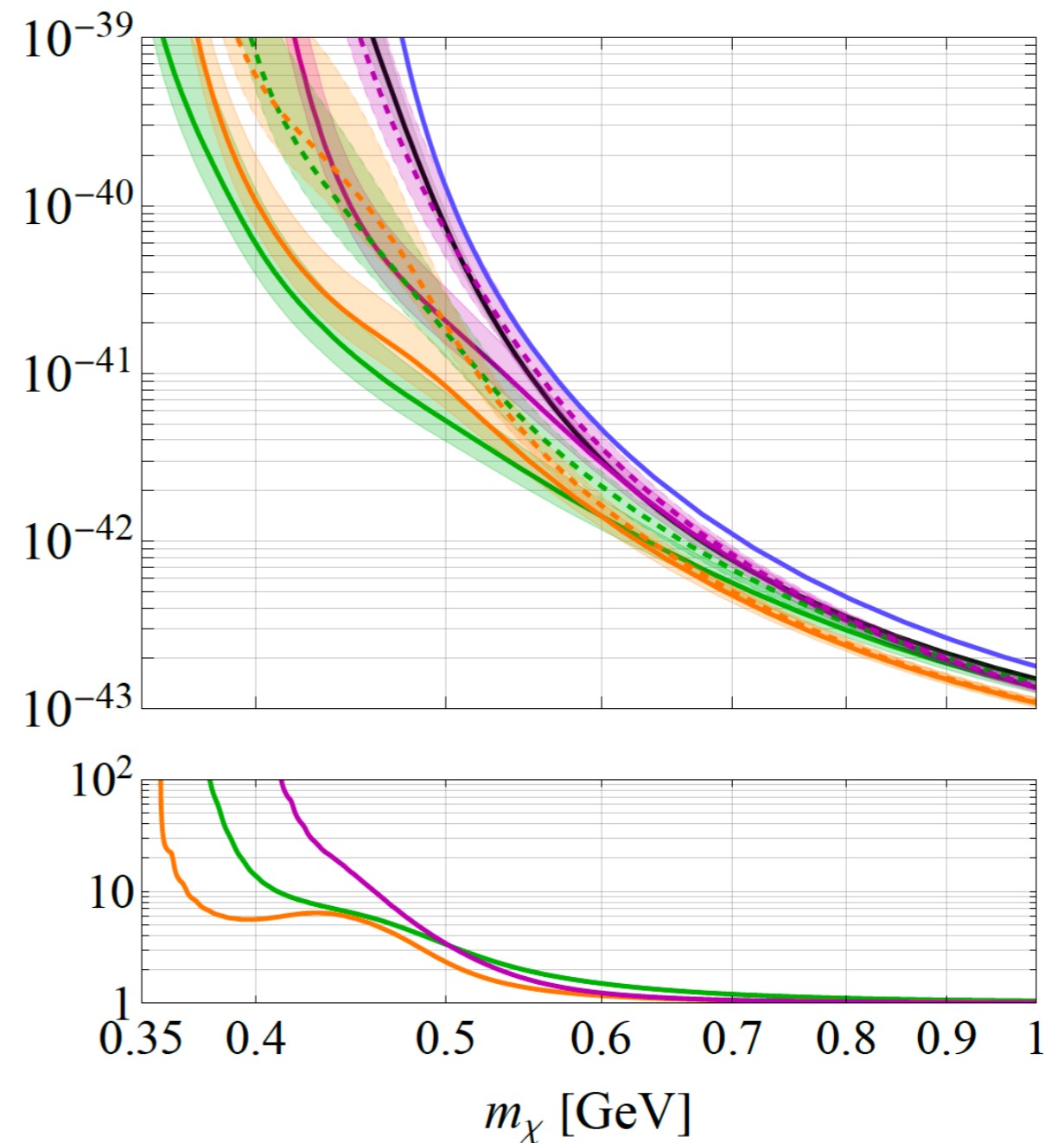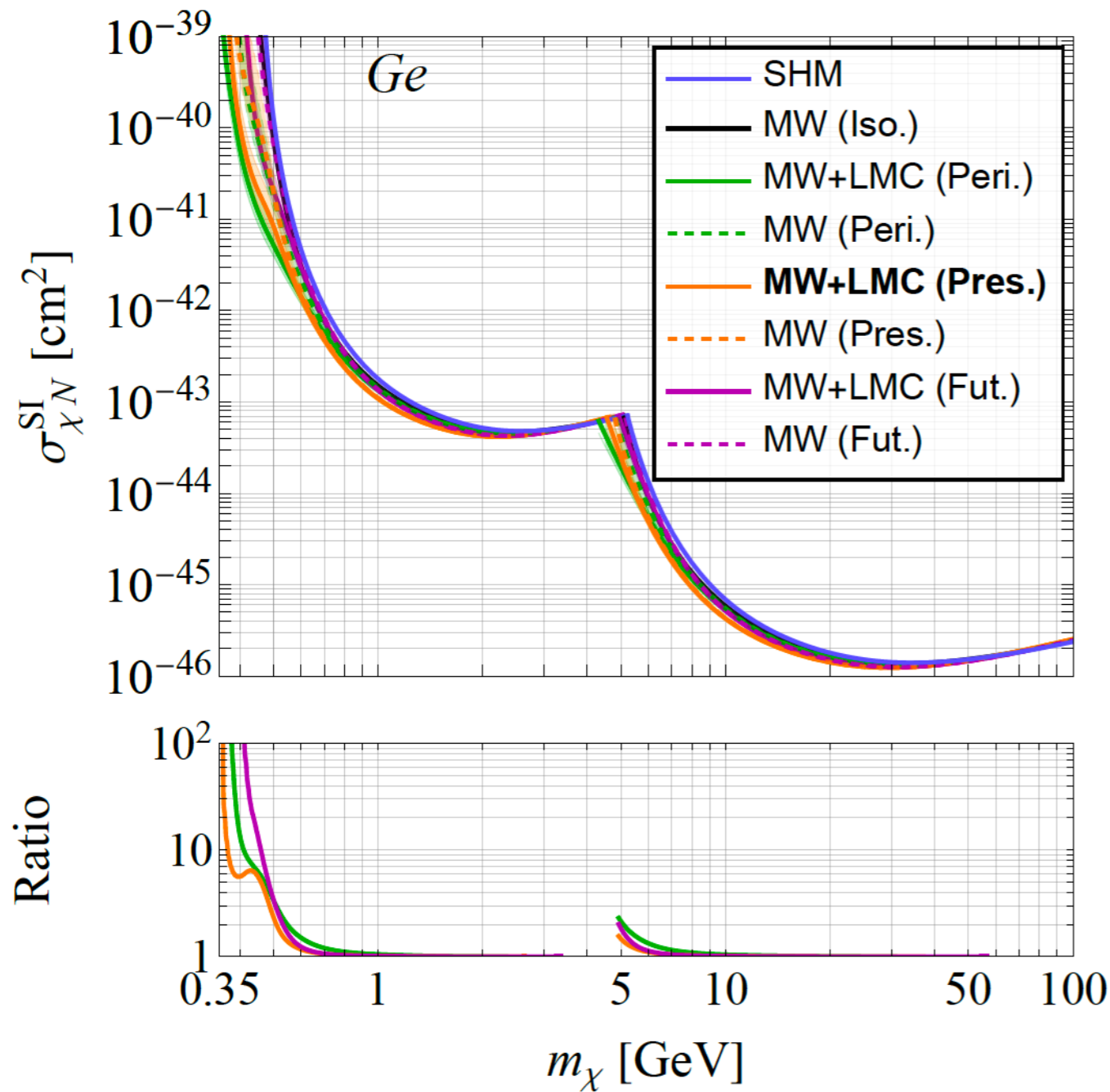**Germanium based detector:**

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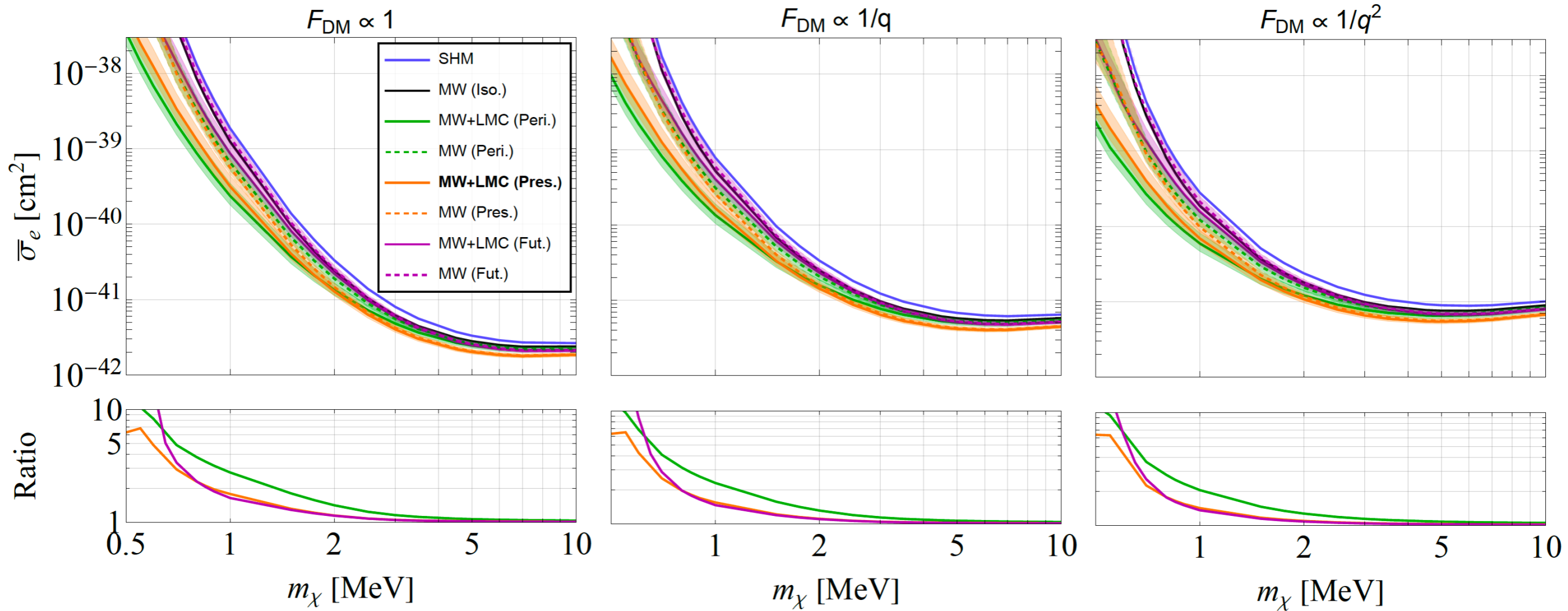

Smith-Orlik et al., JCAP 10, 070 (2023)

Direct detection: electron recoils

Silicon CCD detector:

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

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

Summary

- **LMC's influence on the local DM distribution is significant even in a fully cosmological simulation.**

- Our particular Sun-LMC geometry maximizes the impact.

- **Two effects** boost the tail of the DM velocity distribution:

  - High speed DM particles from the LMC

  - Response of the Milky Way DM particles to the LMC

  ➡️ *Significant shifts in direct detection limits towards lower cross sections and smaller DM masses.*

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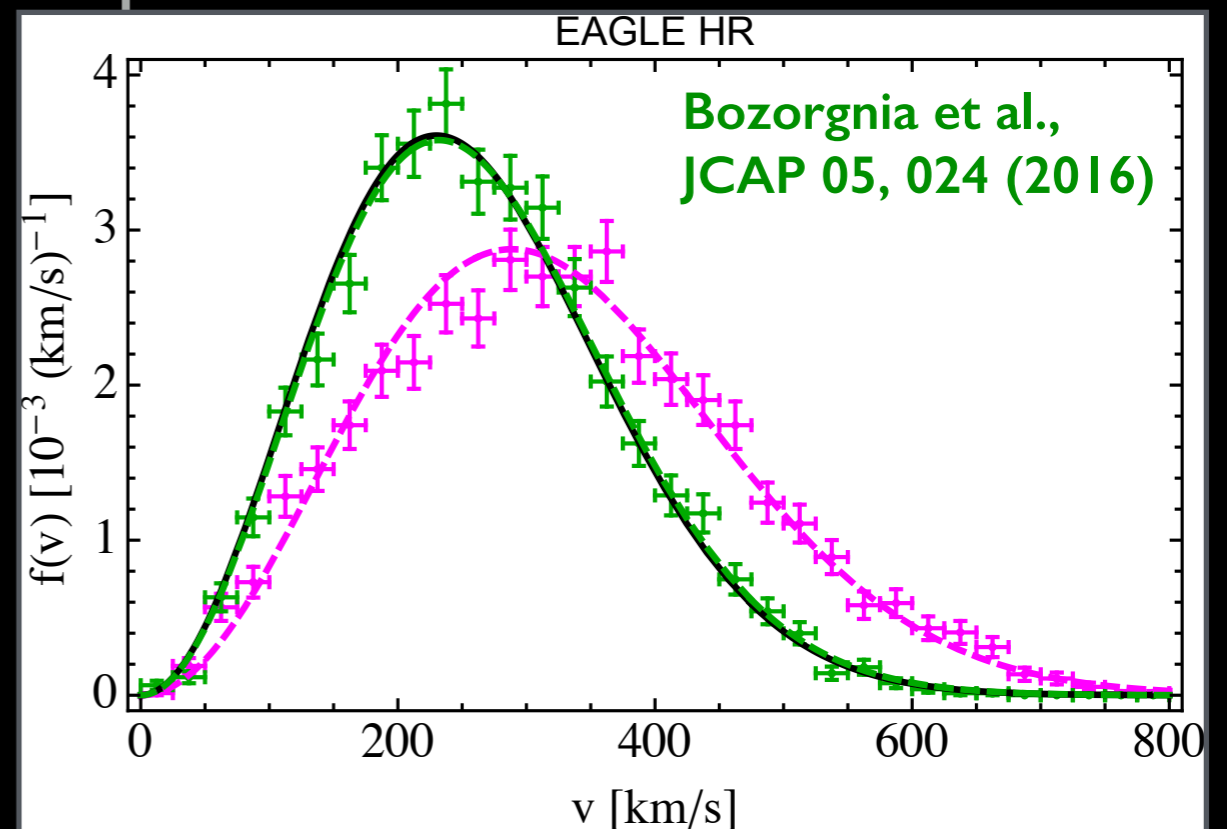*See next talk by **Javier Reynoso** on LMC and non-standard DM interactions.*

Backup Slides

Dark matter velocity distribution

Extract the DM distribution from cosmological simulations:

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Simulated galaxy
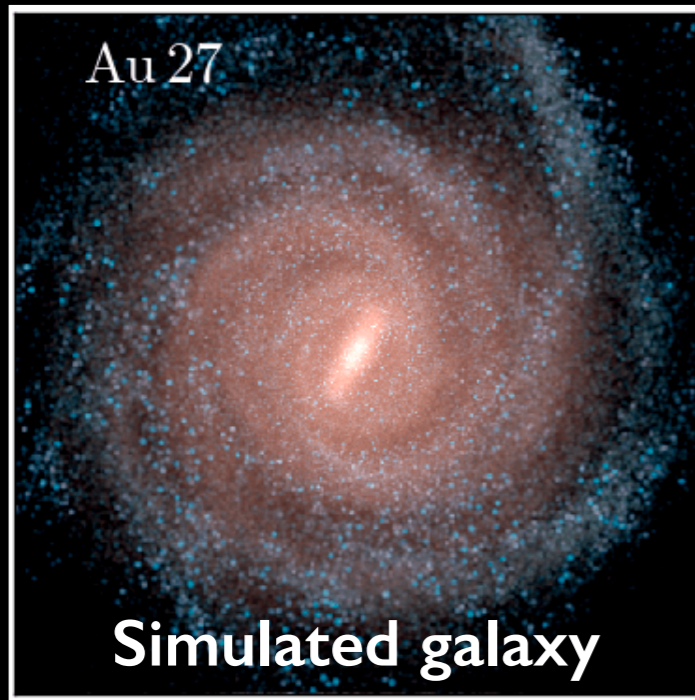
Smooth halo

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)

EAGLE HR

Bozorgnia et al.,
JCAP 05, 024 (2016)

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

- 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 $[40,60] \ \mathrm{kpc}$.

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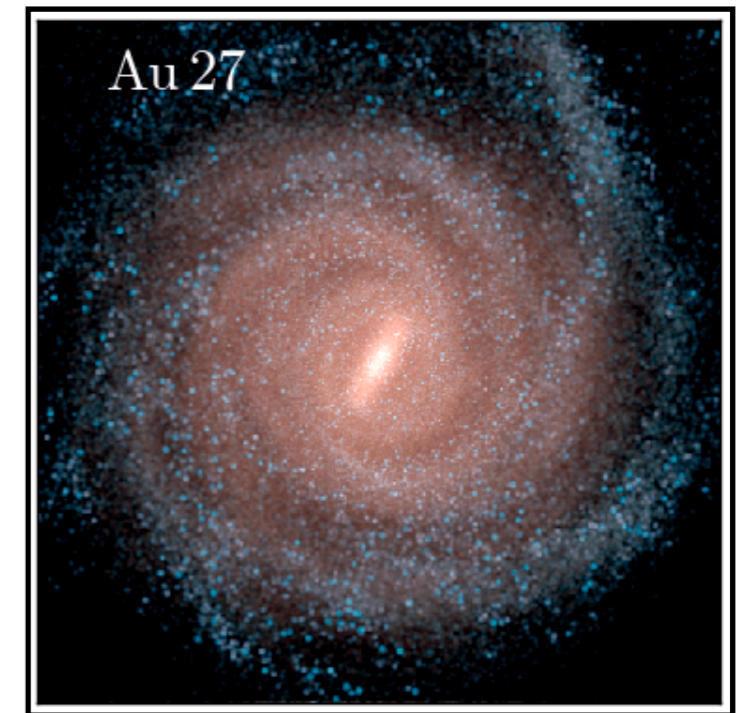
**Steps in matching the Sun-LMC geometry to observations:**

$$\cos\alpha \equiv \hat{\mathbf{v}}^{\text{sim}}_{\text{Sun}} \cdot \hat{\mathbf{r}}^{\text{sim}}_{\text{LMC}} = -0.835$$
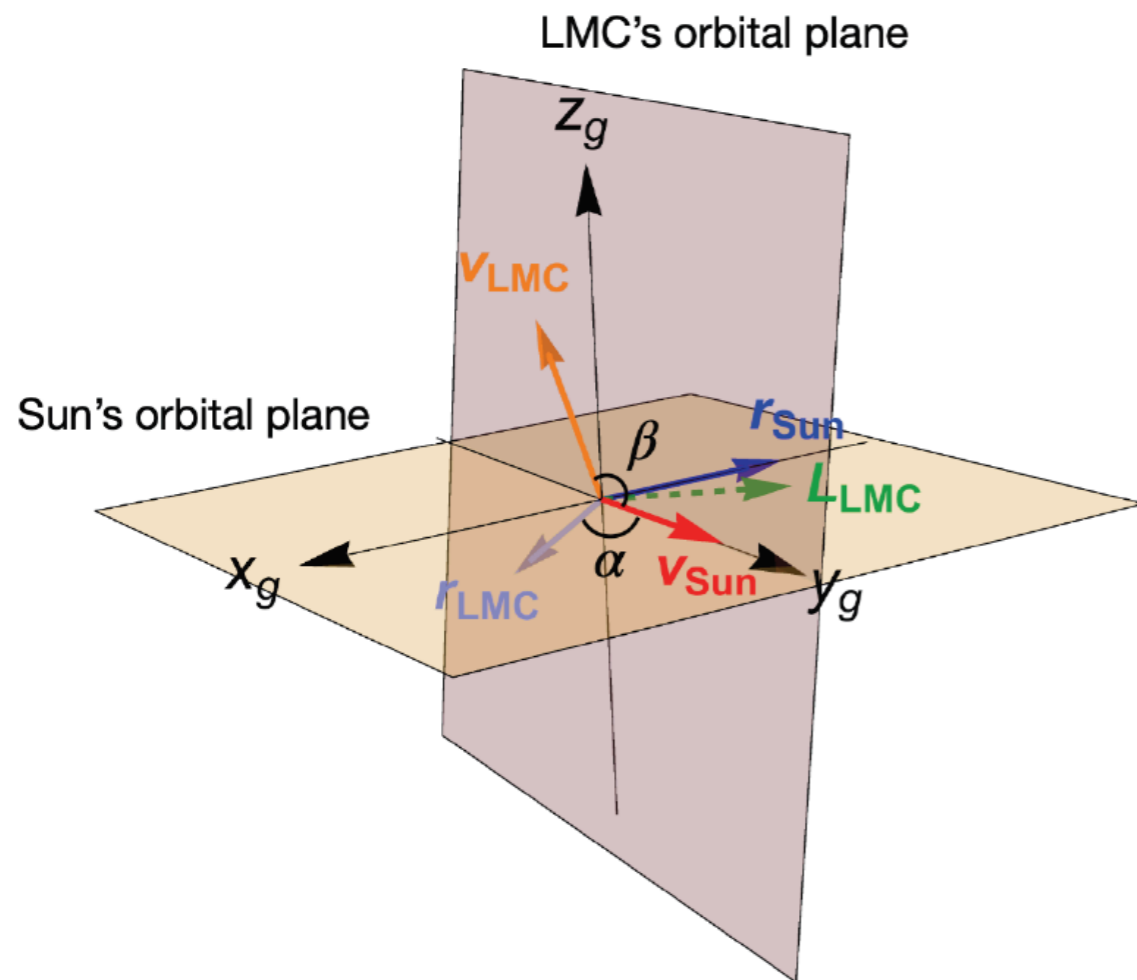
$$\cos\beta \equiv \hat{\mathbf{v}}^{\text{sim}}_{\text{Sun}} \cdot \hat{\mathbf{v}}^{\text{sim}}_{\text{LMC}} = -0.709$$

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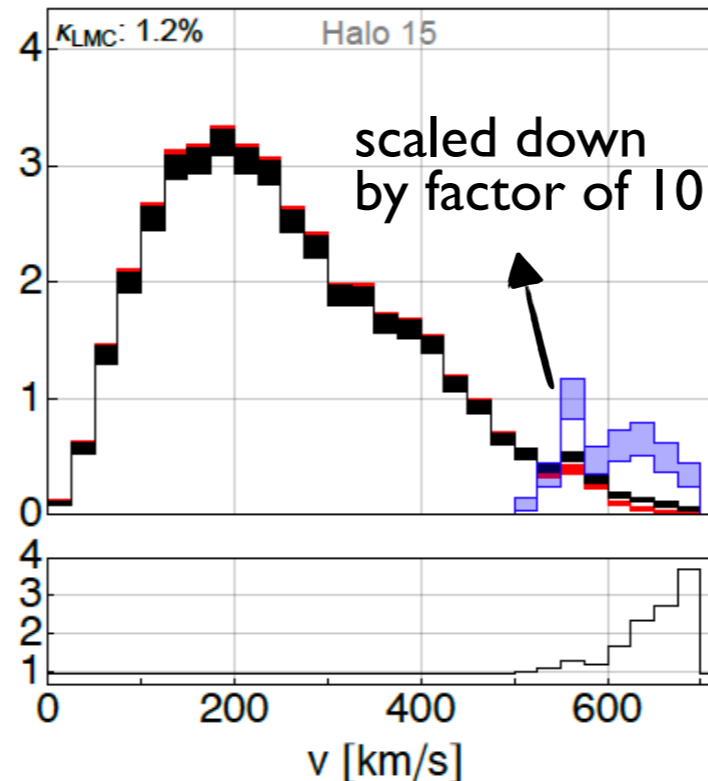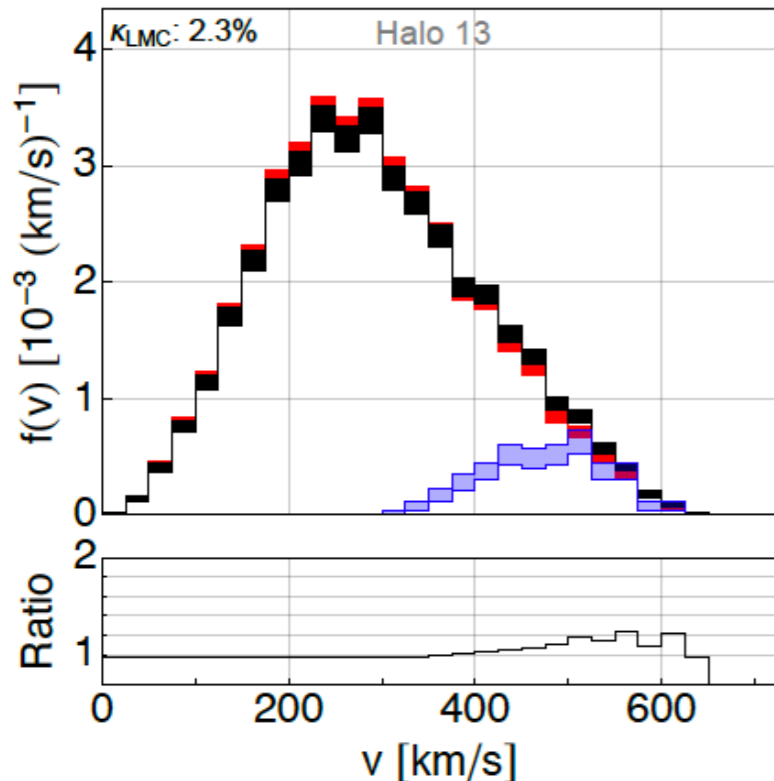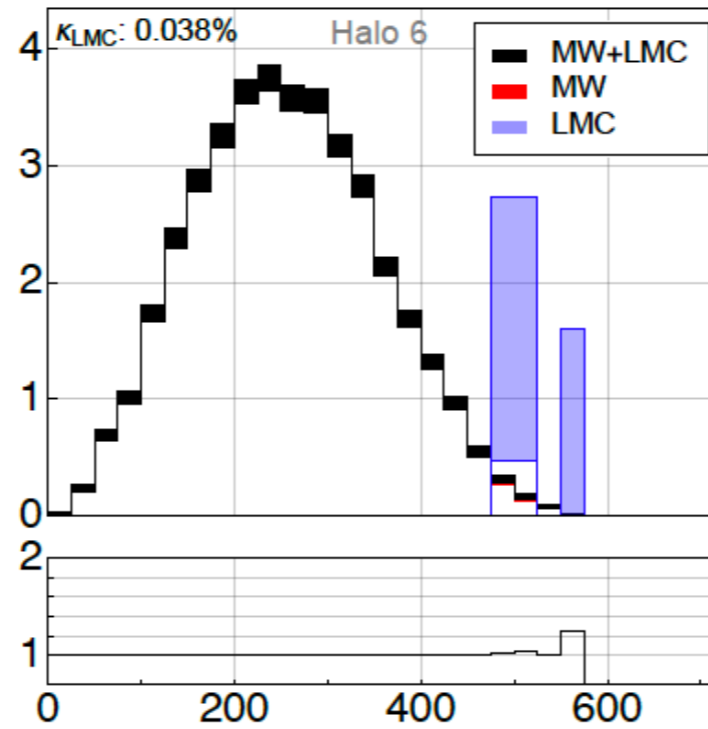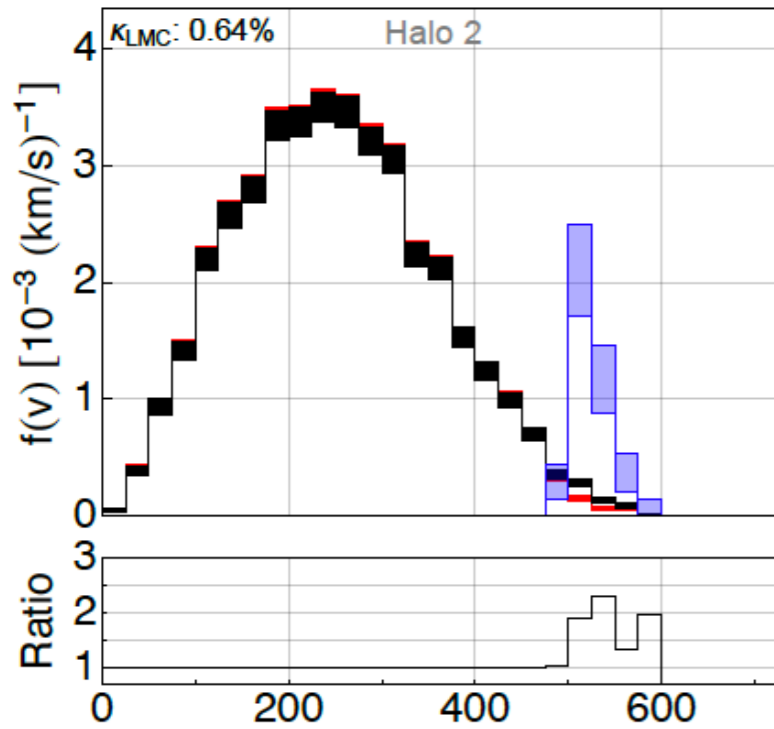
Solar region: overlap of a **spherical shell** with radius between $6 - 10 \text{ kpc}$ and a **cone** with opening angle $\pi/4$ with its axis aligned with the position of the Sun.
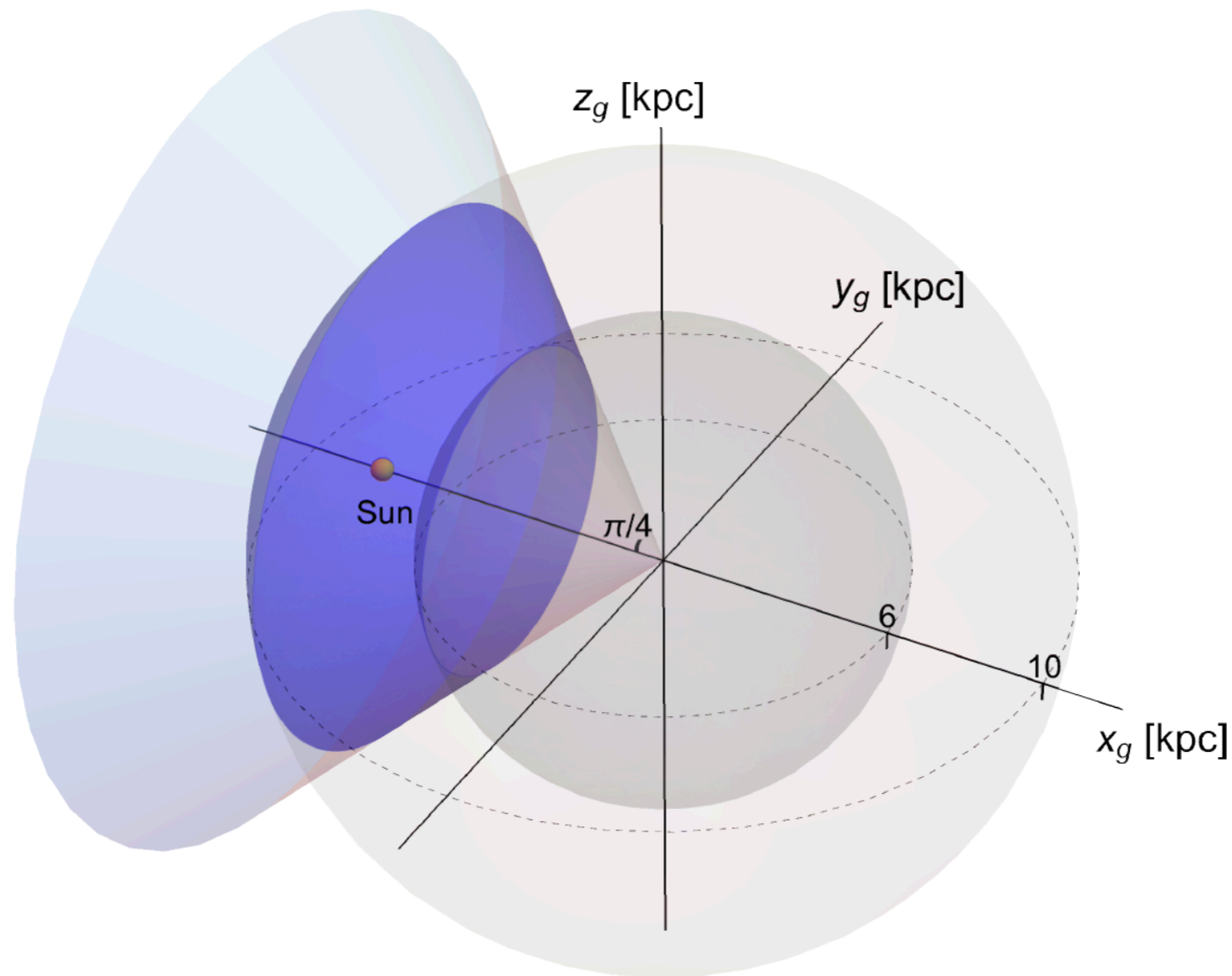
Local dark matter speed distribution

In the galactic rest frame (present day)

- 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.

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

Direct detection event rate

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

astrophysics

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

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

astrophysics

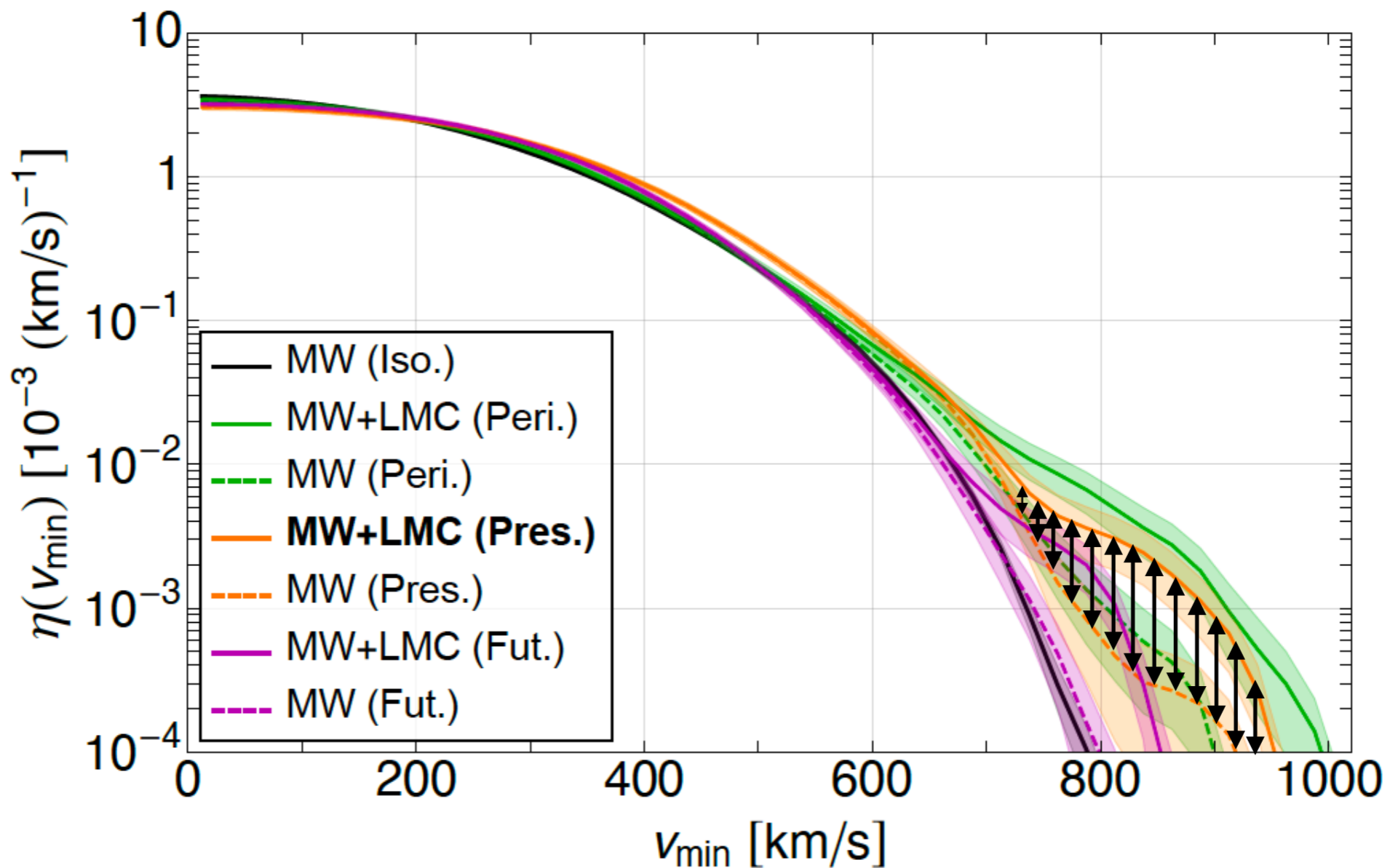$$\frac{dR}{dE_R} = \frac{\sigma_0 \, F^2(E_R)}{2 m_\chi \mu_{\chi N}^2} \rho_\chi \, \eta(v_{\min}, t)$$

where

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

Halo integral

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

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

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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.

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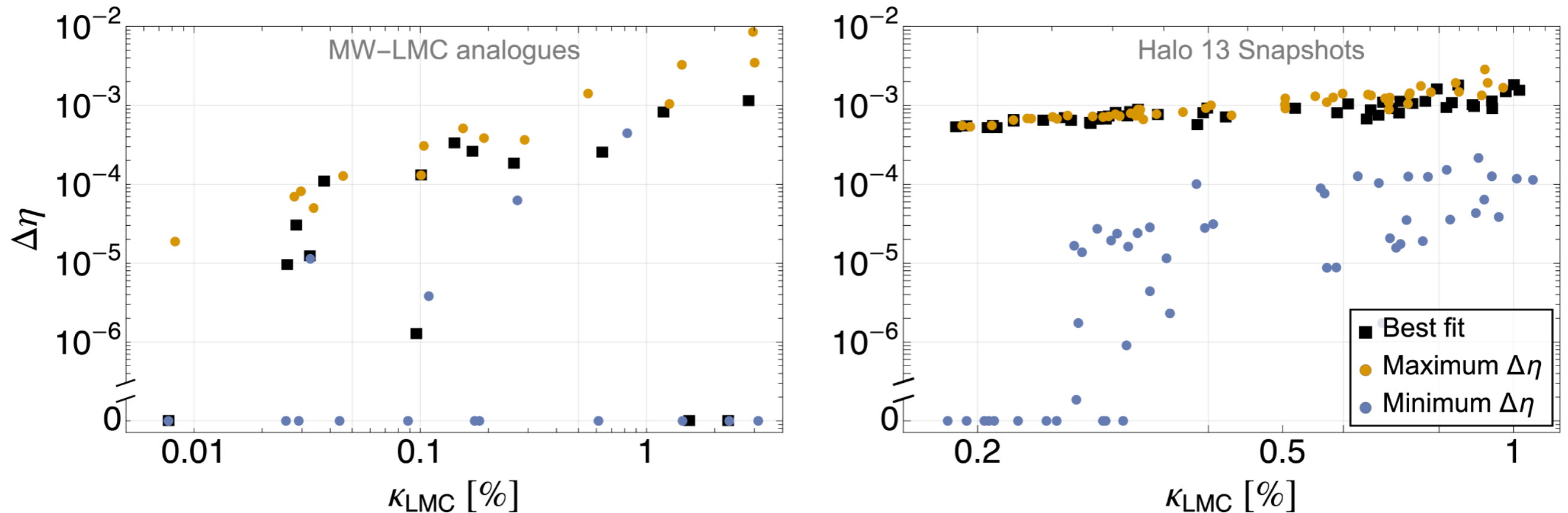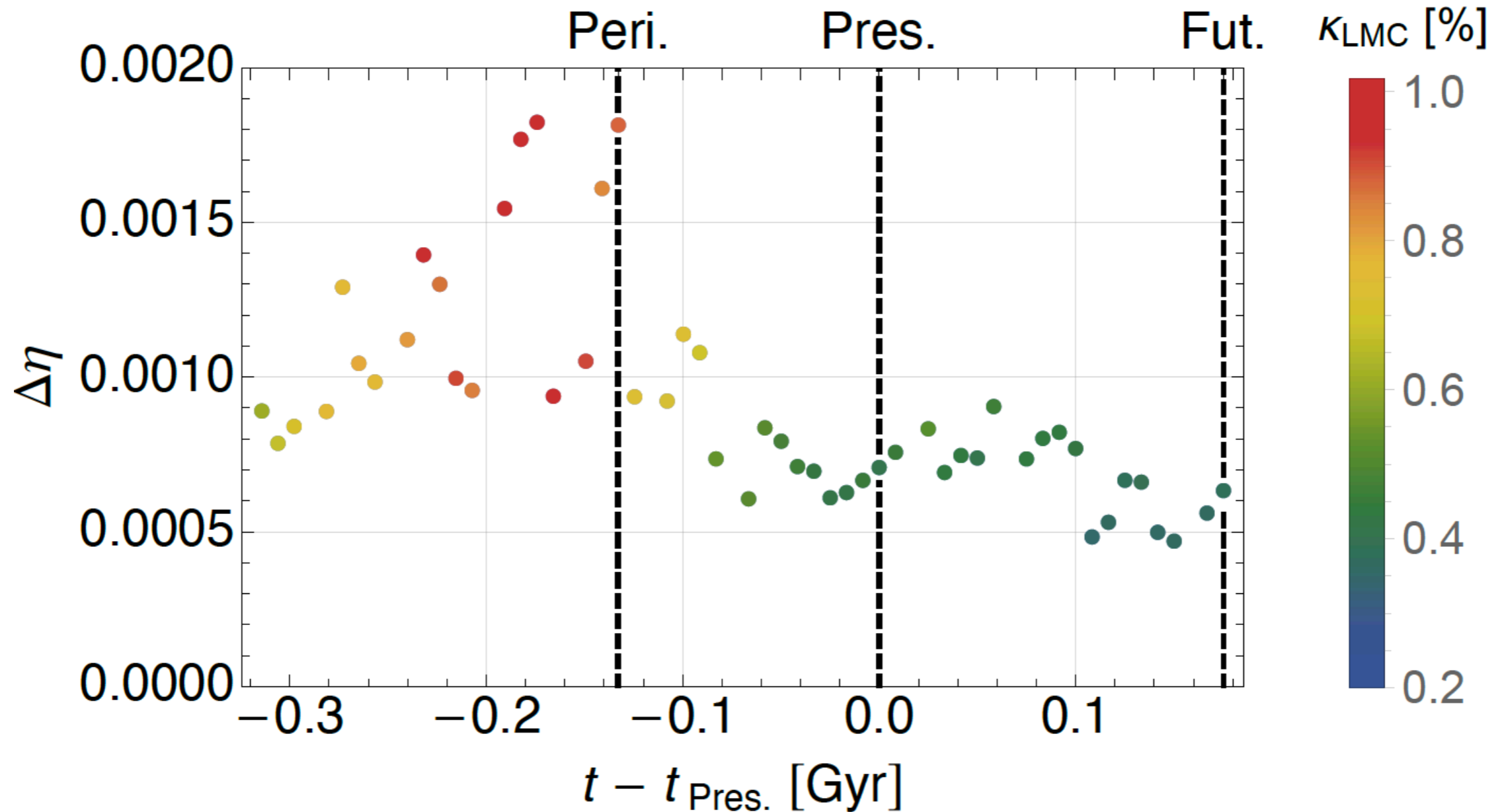

Smith-Orlik et al., JCAP 10, 070 (2023)

- $\Delta\eta$ 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

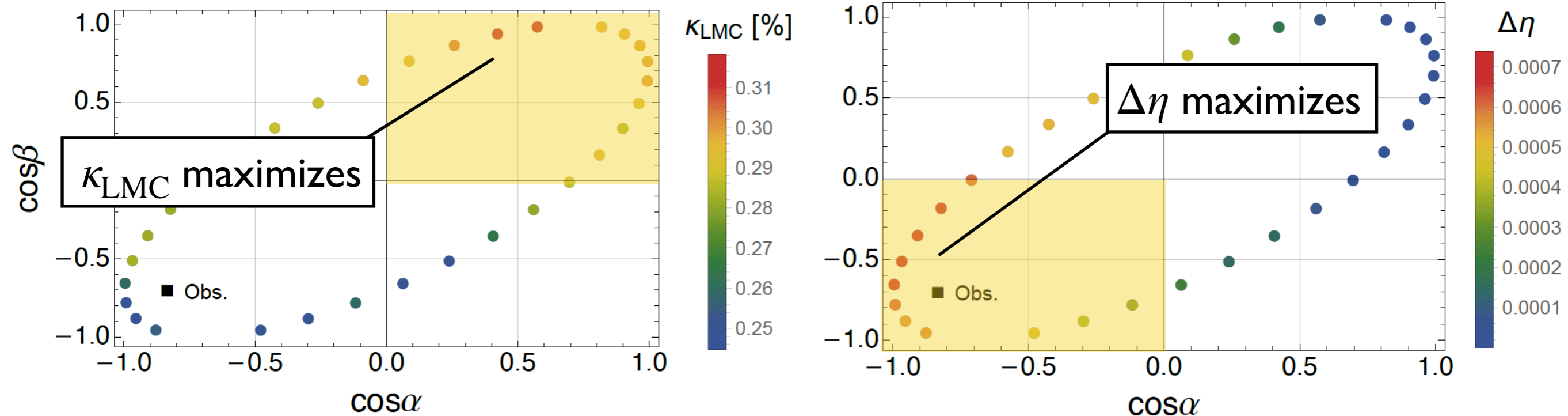$\Delta\eta$ for best fit Sun's position for different snapshots in one halo:

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

Cosine angles that parametrize the Sun-LMC geometry:

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

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

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.*