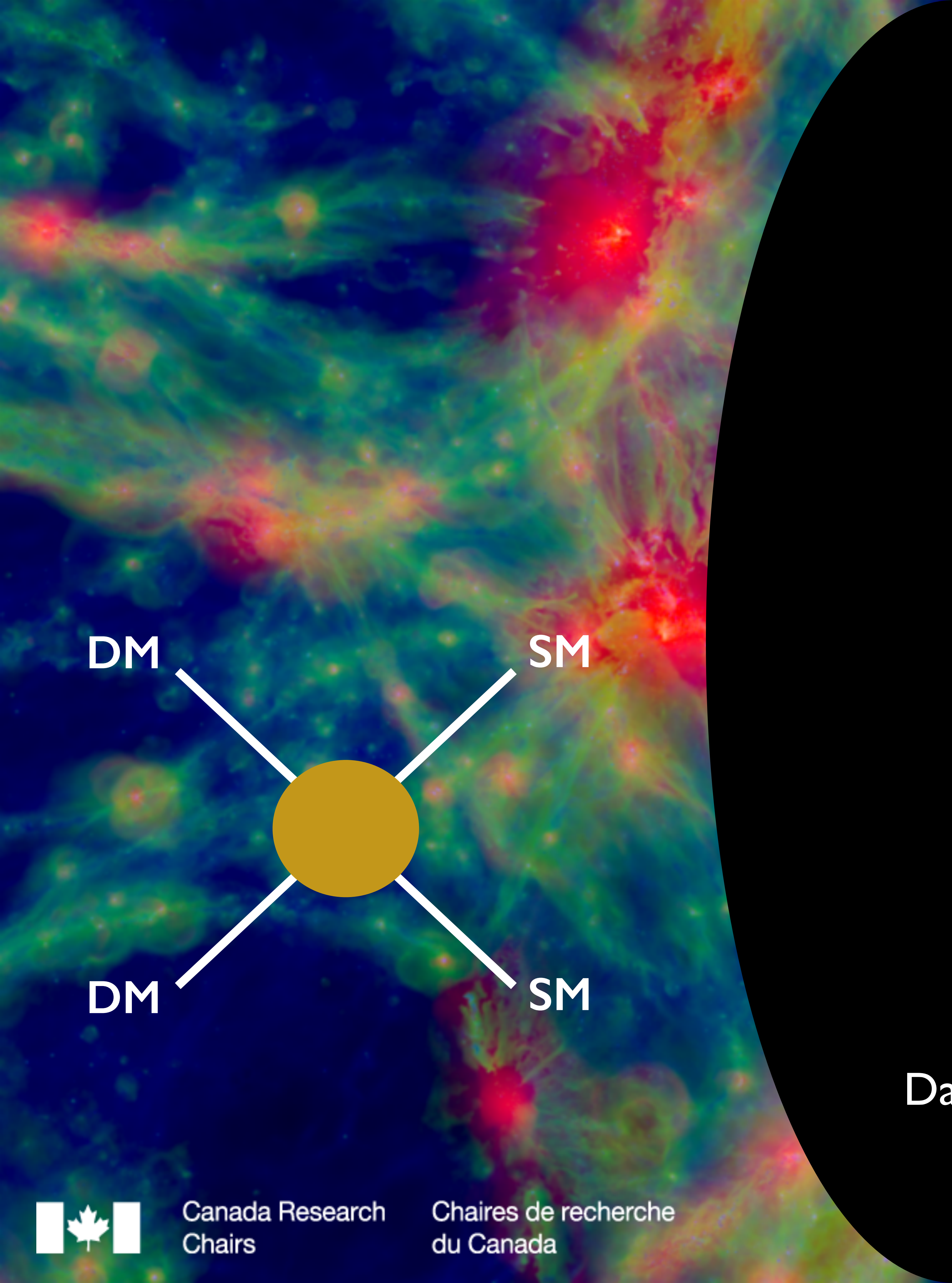


Astrometric probes of dark matter

Nassim Bozorgnia

UNIVERSITY OF ALBERTA

Dark Interactions 2024, Vancouver
18 October 2024

Canada Research Chairs
Chaires de recherche du Canada

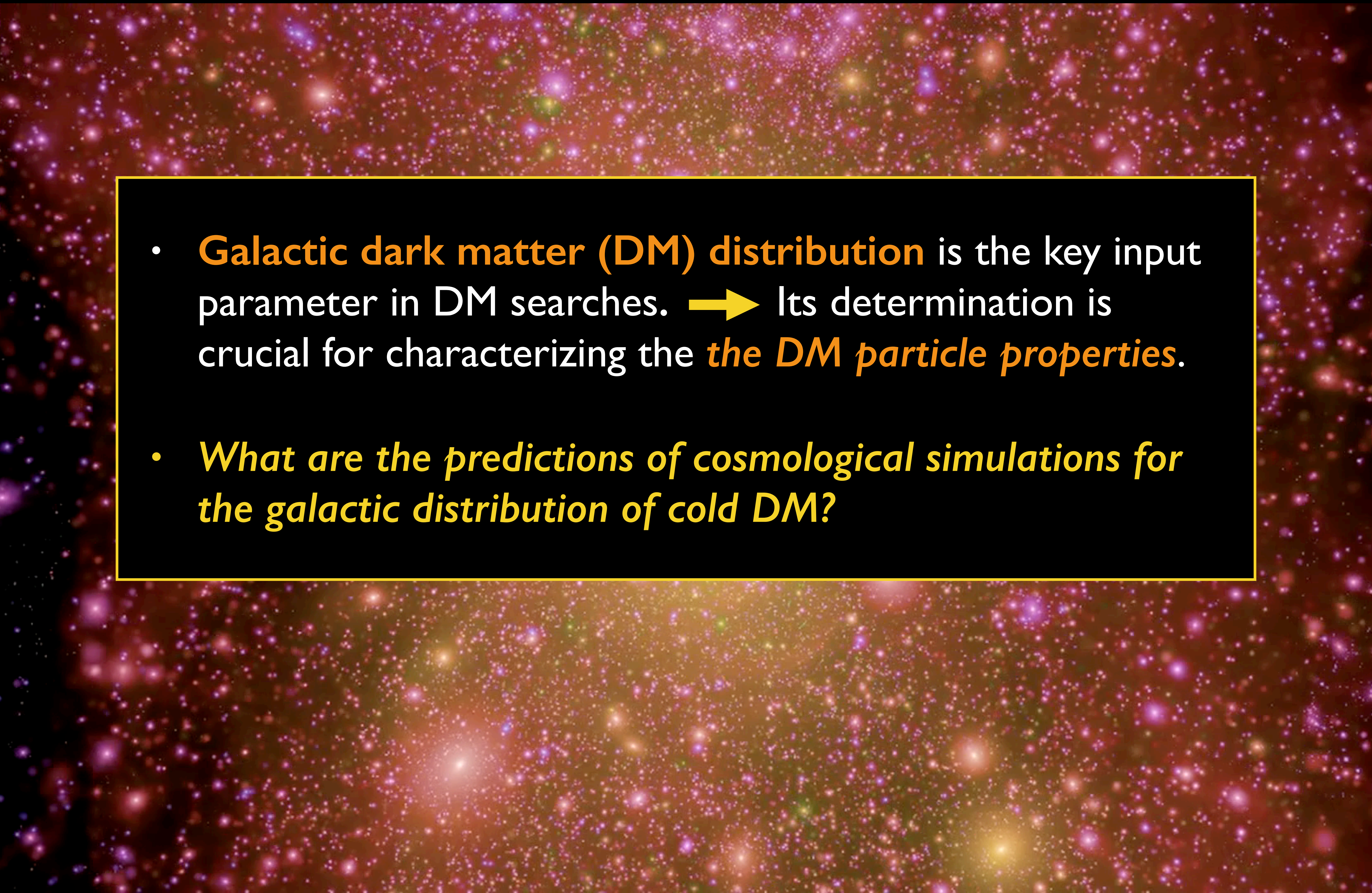
NSERC
CRSNG

Dark matter in the galaxy

Dark matter in the galaxy

- **Galactic dark matter (DM) distribution** is the key input parameter in DM searches. → Its determination is crucial for characterizing the ***the DM particle properties***.

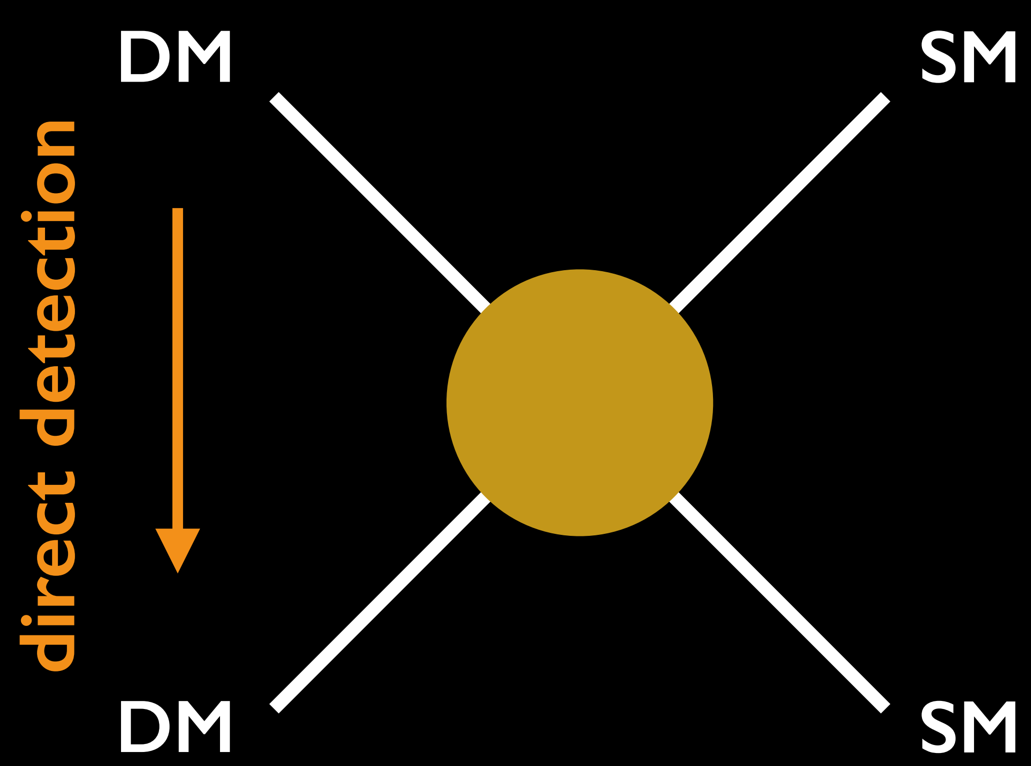
Dark matter in the galaxy

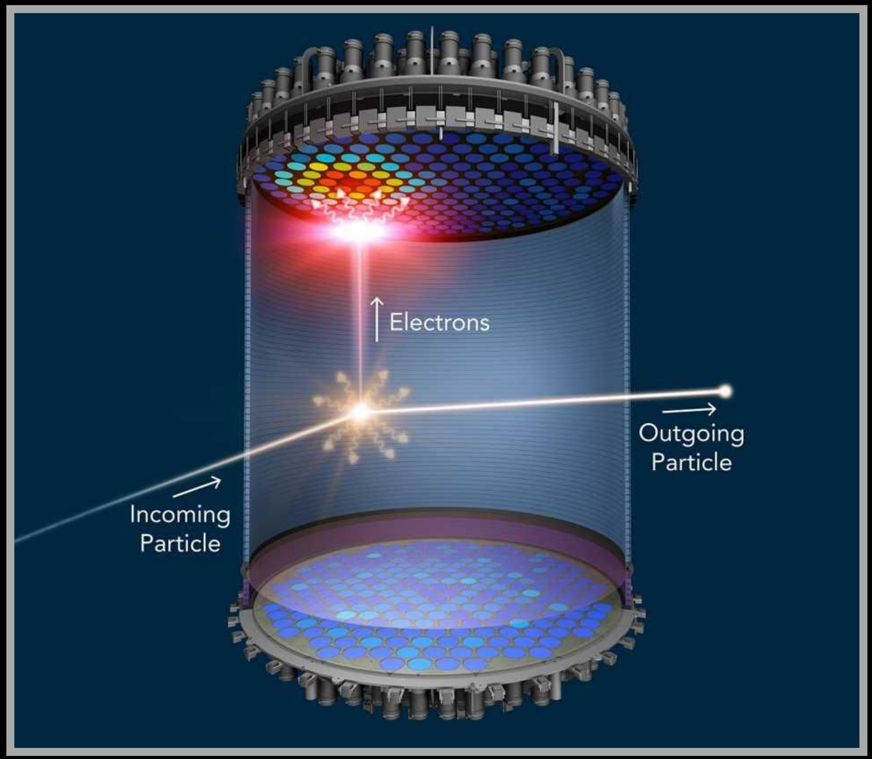


- **Galactic dark matter (DM) distribution** is the key input parameter in DM searches. → Its determination is crucial for characterizing the *the DM particle properties*.

- *What are the predictions of cosmological simulations for the galactic distribution of cold DM?*

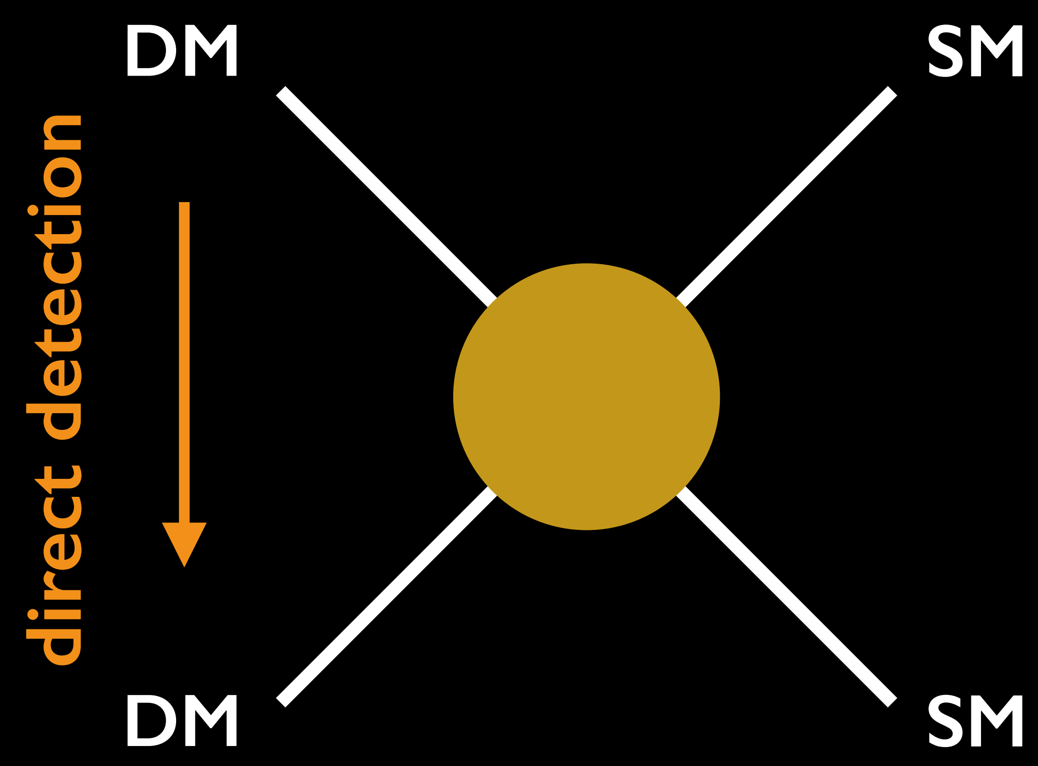
Dark matter direct detection

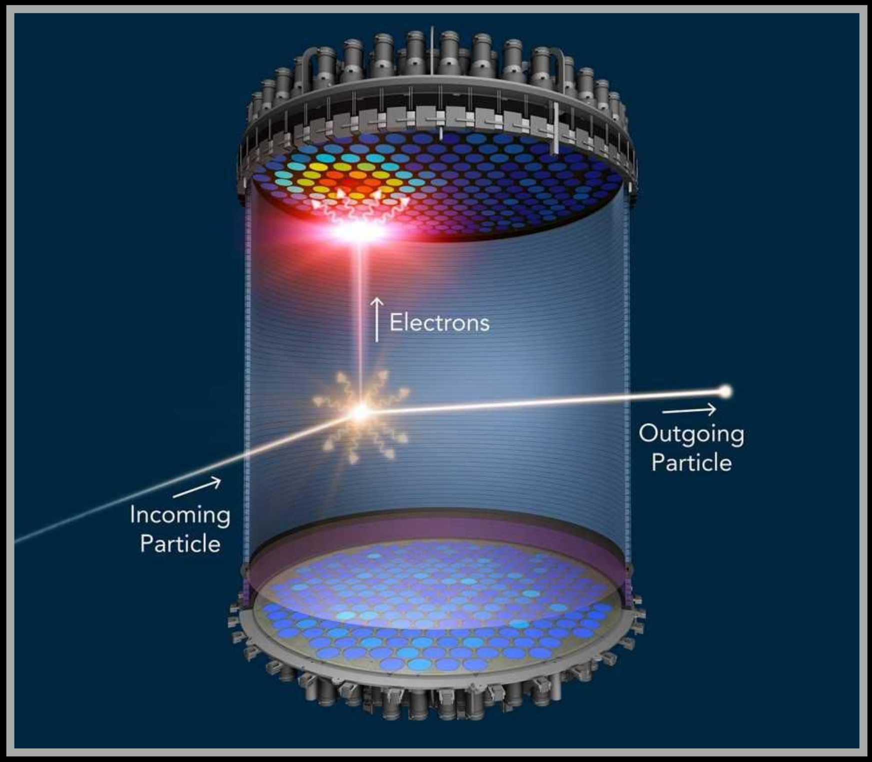




Signals in direct DM searches strongly depend on the DM distribution in the **Solar neighborhood**.

Dark matter direct detection





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

Uncertainties in the local DM distribution → ***large uncertainties in the interpretation of direct detection data.***

Direct detection event rate

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

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

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

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astrophysics

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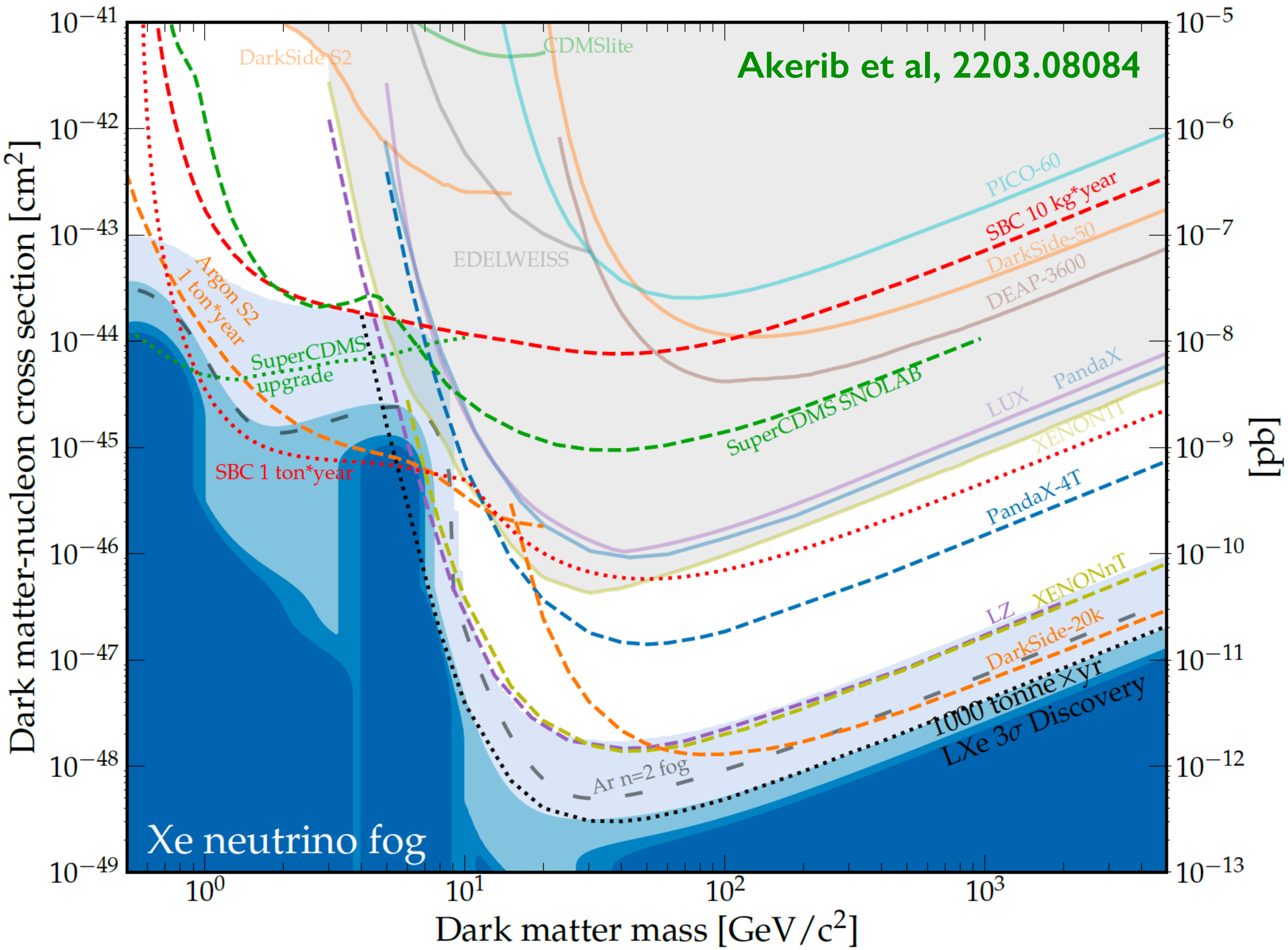
$v_{\min} = \sqrt{m_N E_R/(2\mu_{\chi N}^2)}$: minimum DM speed required to produce a recoil energy E_R.

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

Direct detection limits

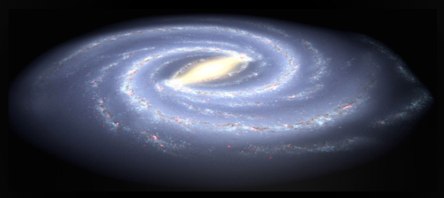


Assumption for the DM distribution: **Standard Halo Model**

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



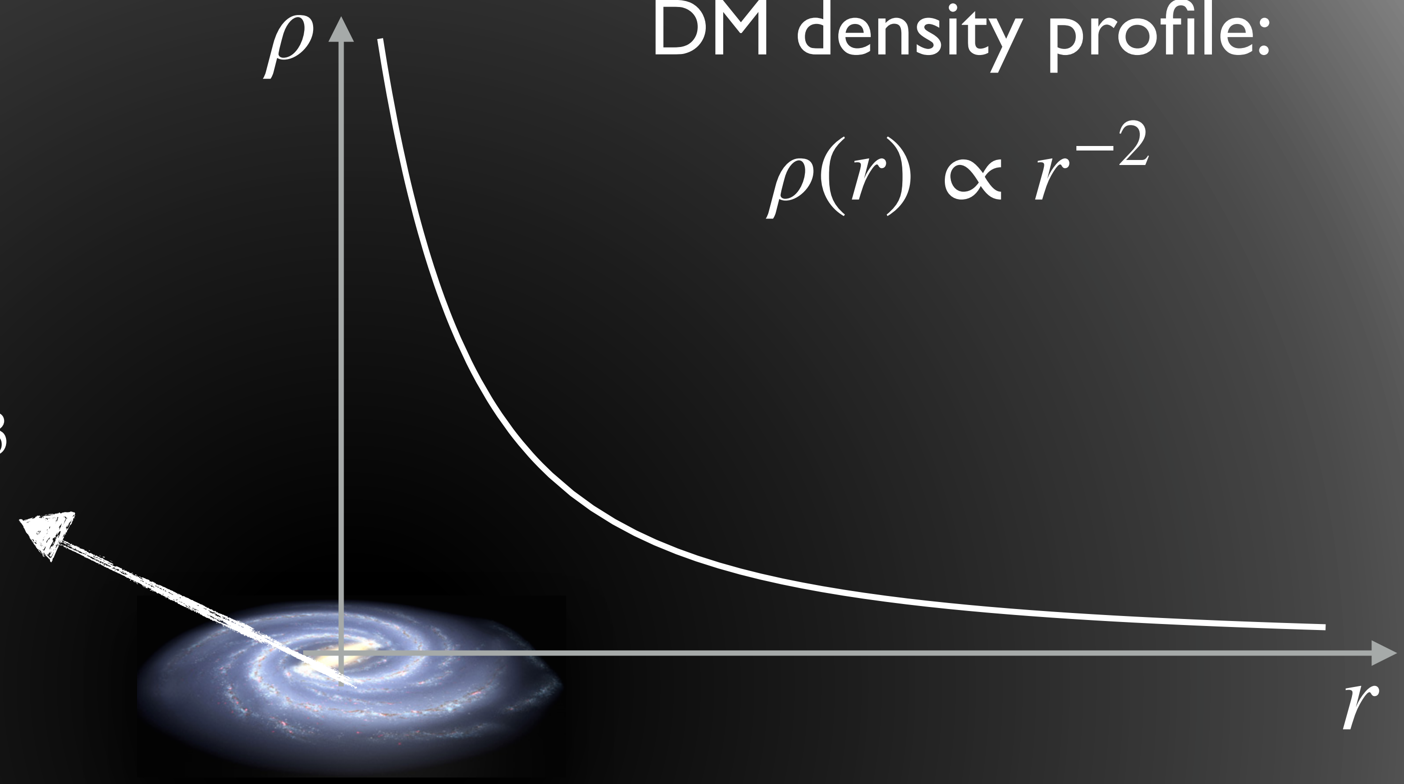
Standard Halo Model

DM density profile:

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

- Local DM density:

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



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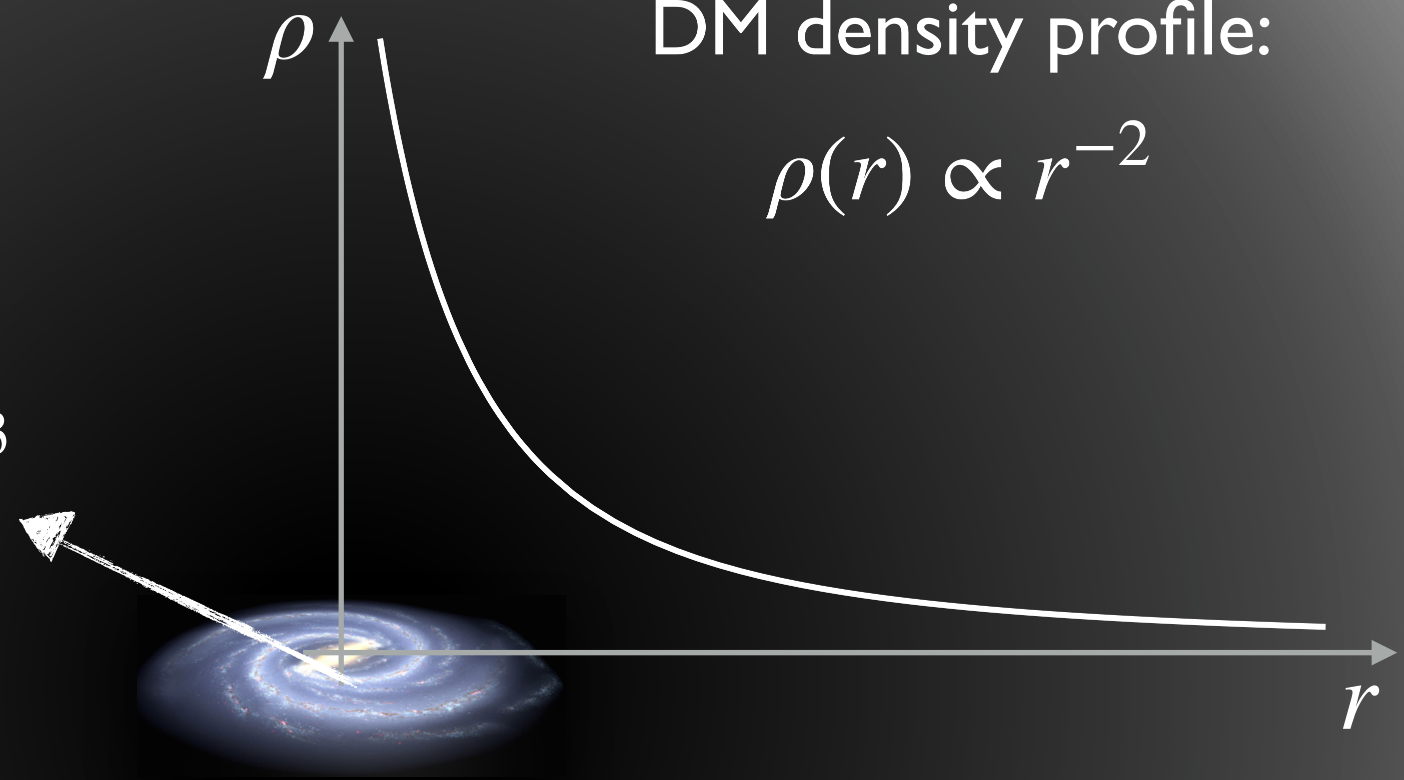

- Local DM density:

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

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

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

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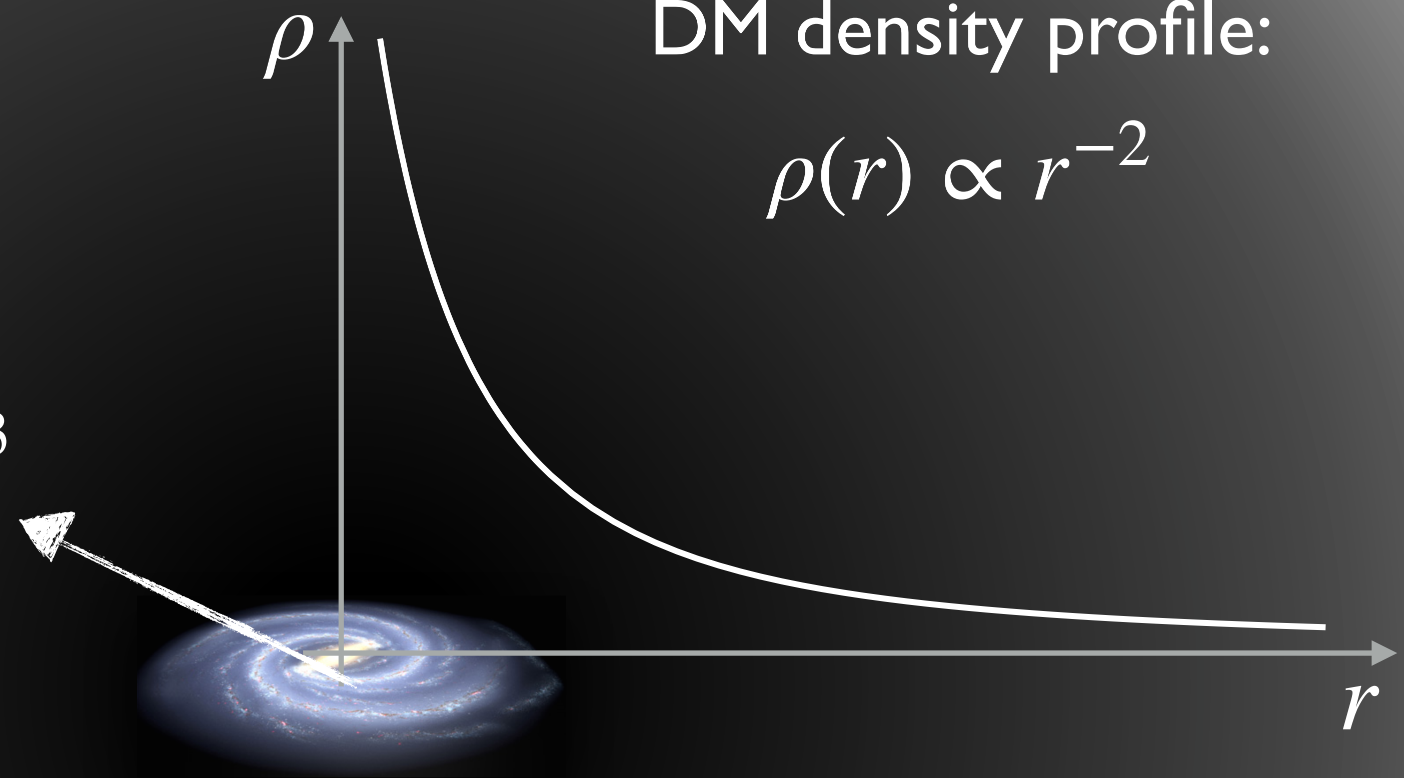

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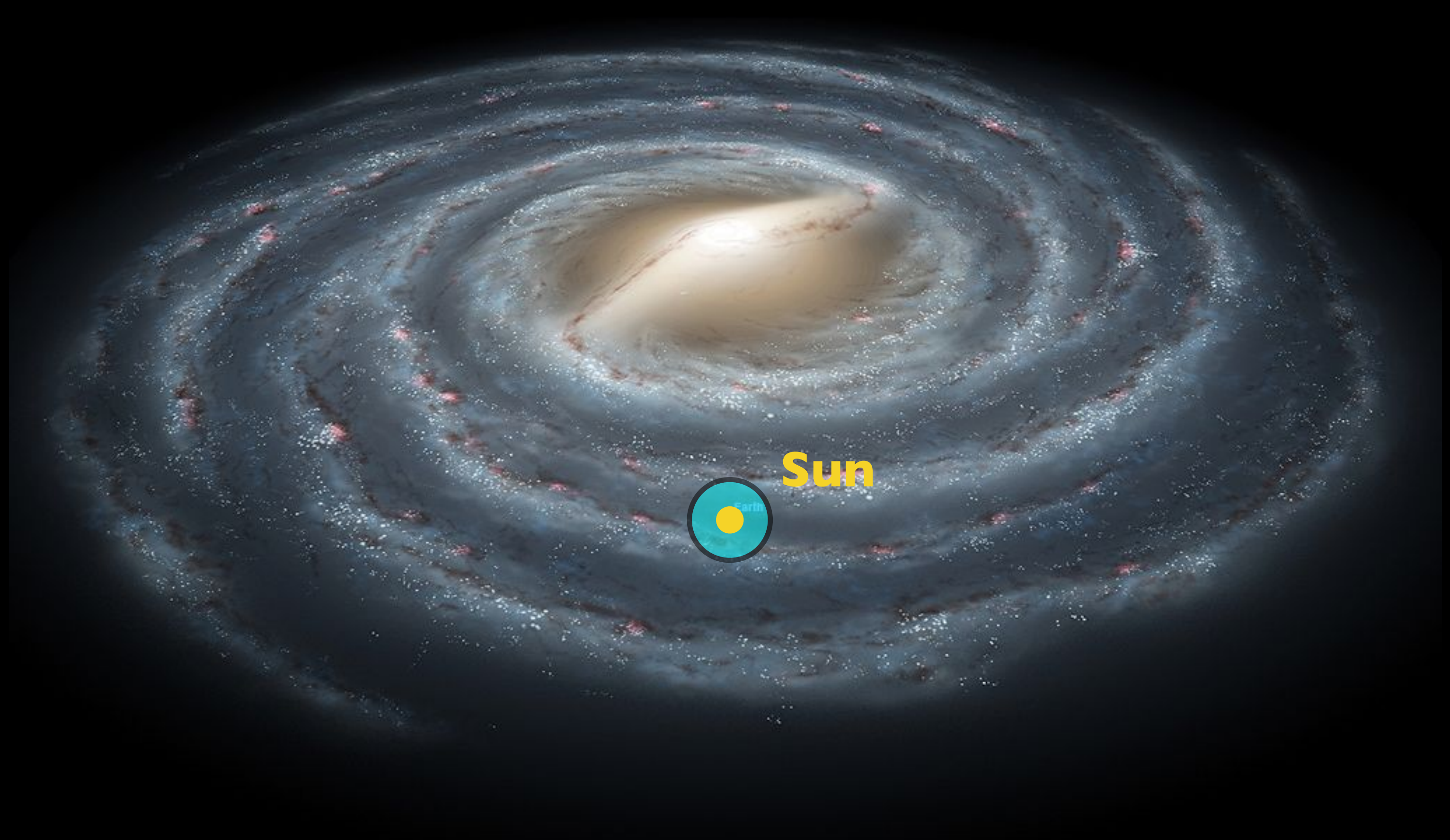
How accurate is this picture?

Astrophysical uncertainties

- **Local DM density:** *Estimates from observations are model dependent and vary in the literature:*

$$\rho_\chi = (0.2 - 0.8)\ \mathrm{GeV/cm^3}$$

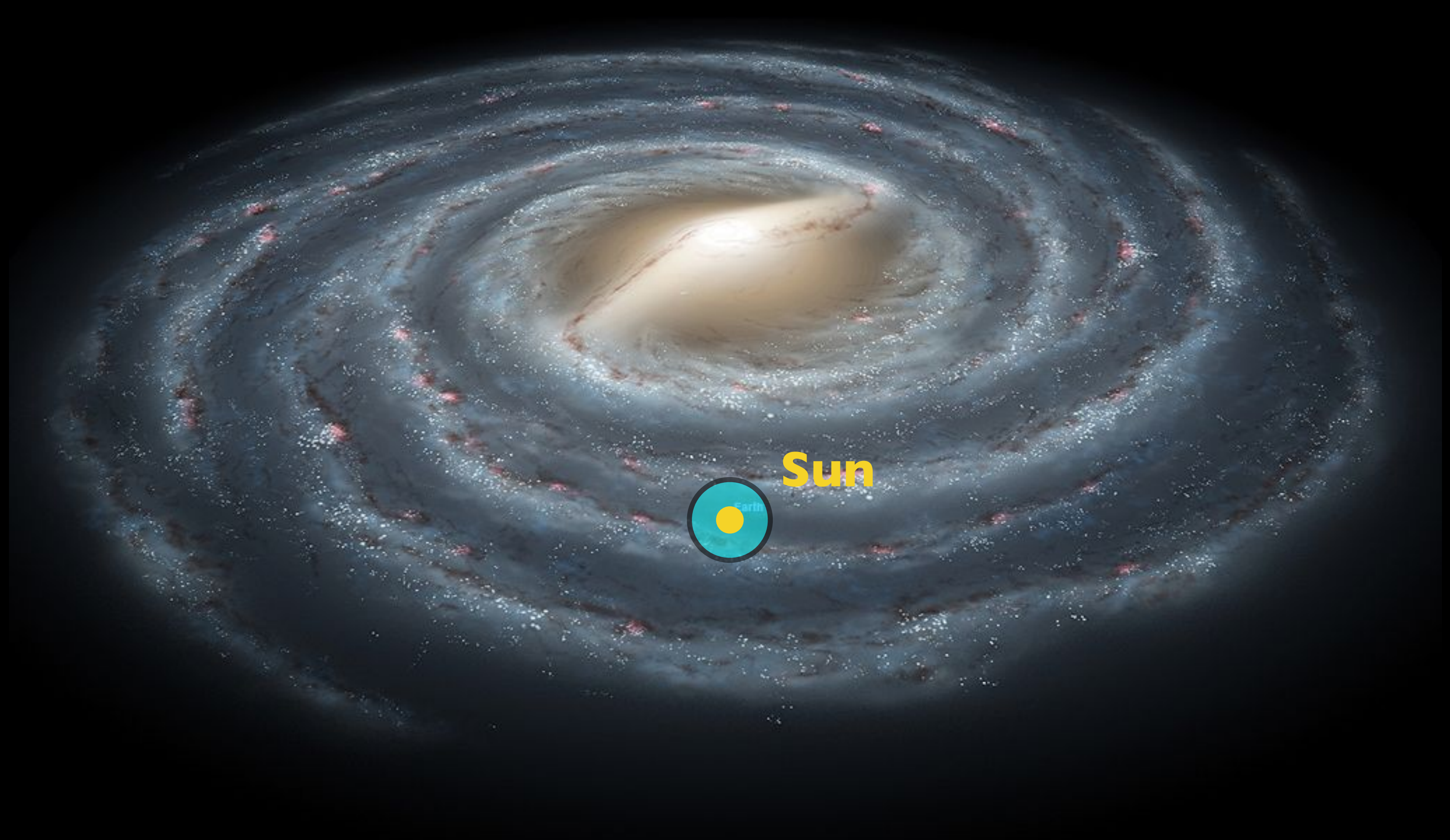


Astrophysical uncertainties

- **Local DM density:** *Estimates from observations are model dependent and vary in the literature:*

$$\rho_\chi = (0.2 - 0.8)\ \mathrm{GeV/cm^3}$$

- **Local DM velocity distribution:** *cannot be directly measured, but we can infer it from cosmological simulations and observations.*



Dark matter velocity distribution

The DM halo has both smooth and un-virialized components:

Smooth halo

Does the smooth component have a Maxwellian velocity distribution?

Dark matter velocity distribution

The DM halo has both smooth and un-virialized components:

Smooth halo

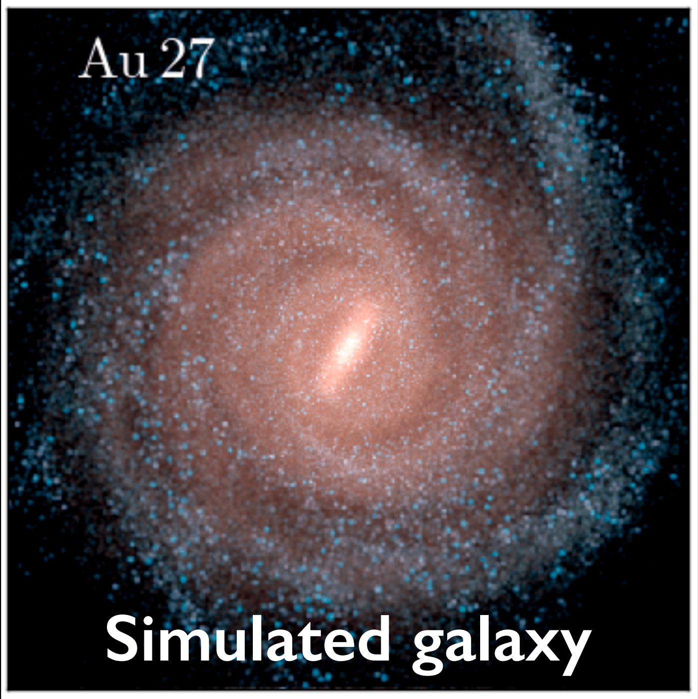
- *Does the smooth component have a Maxwellian velocity distribution?*

Substructure

- *DM subhalos*
- *DM from satellite galaxies* — *Sagittarius dwarf*, *Large Magellanic Cloud*
- *DM streams* — *Nyx, S1, S2, …*
- *DM from stellar substructures* — *Gaia Sausage-Enceladus*

Dark matter velocity distribution

Extract the DM distribution from cosmological simulations:



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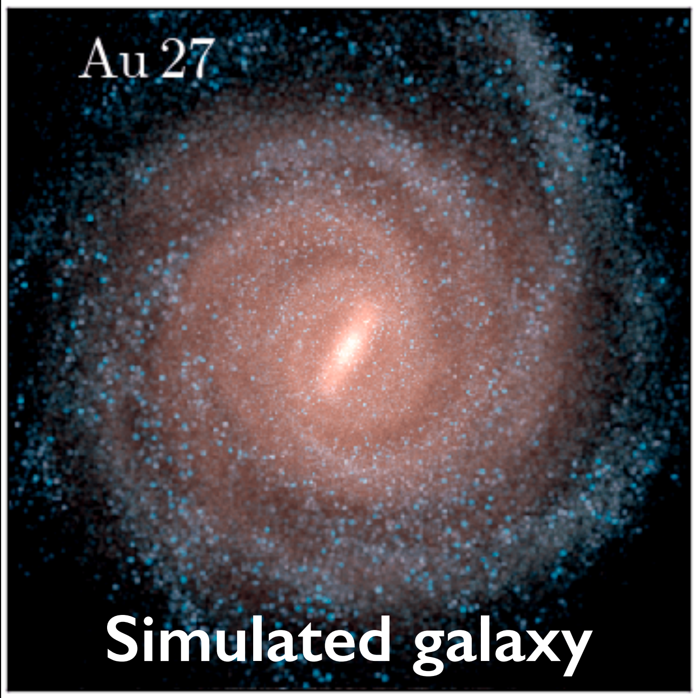
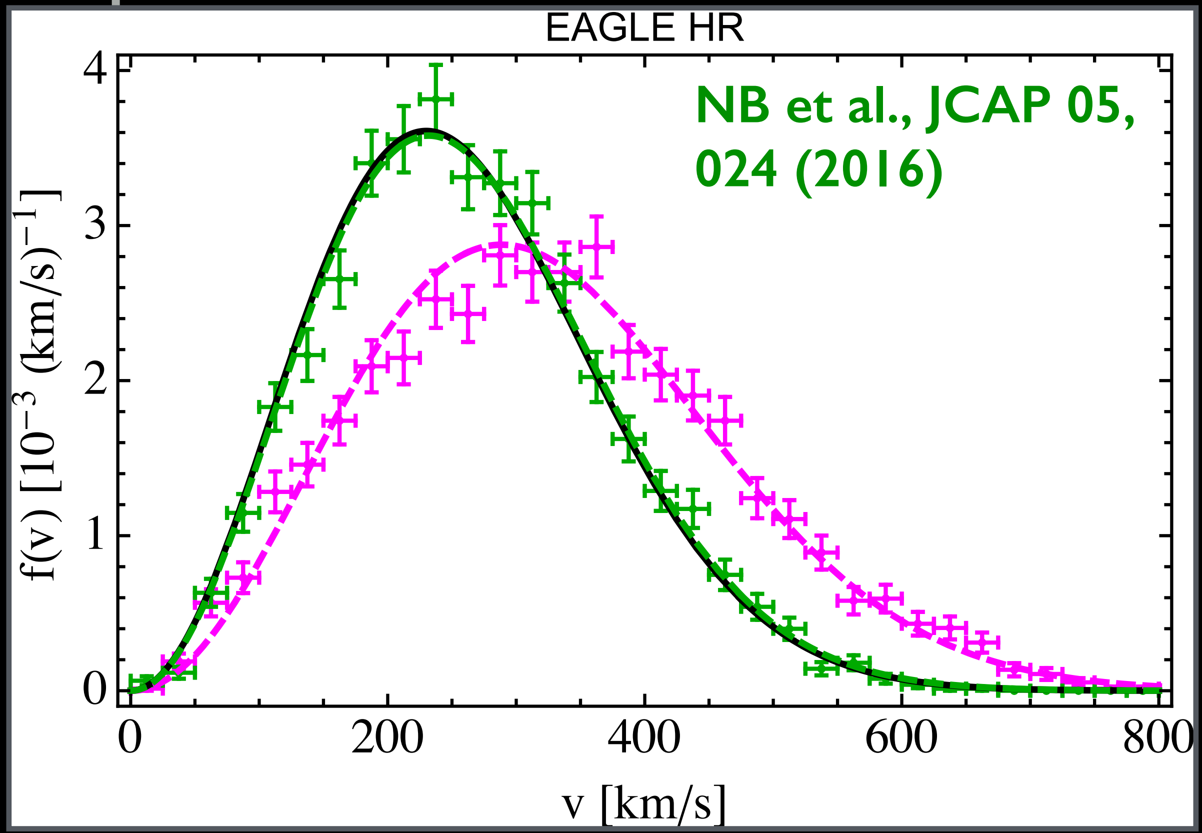


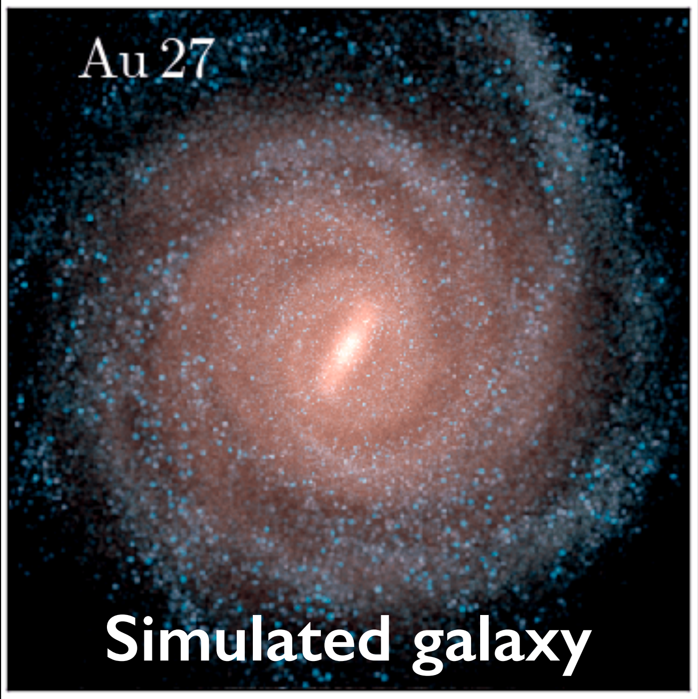
Smooth halo



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

Dark matter velocity distribution

Extract the DM distribution from cosmological simulations:



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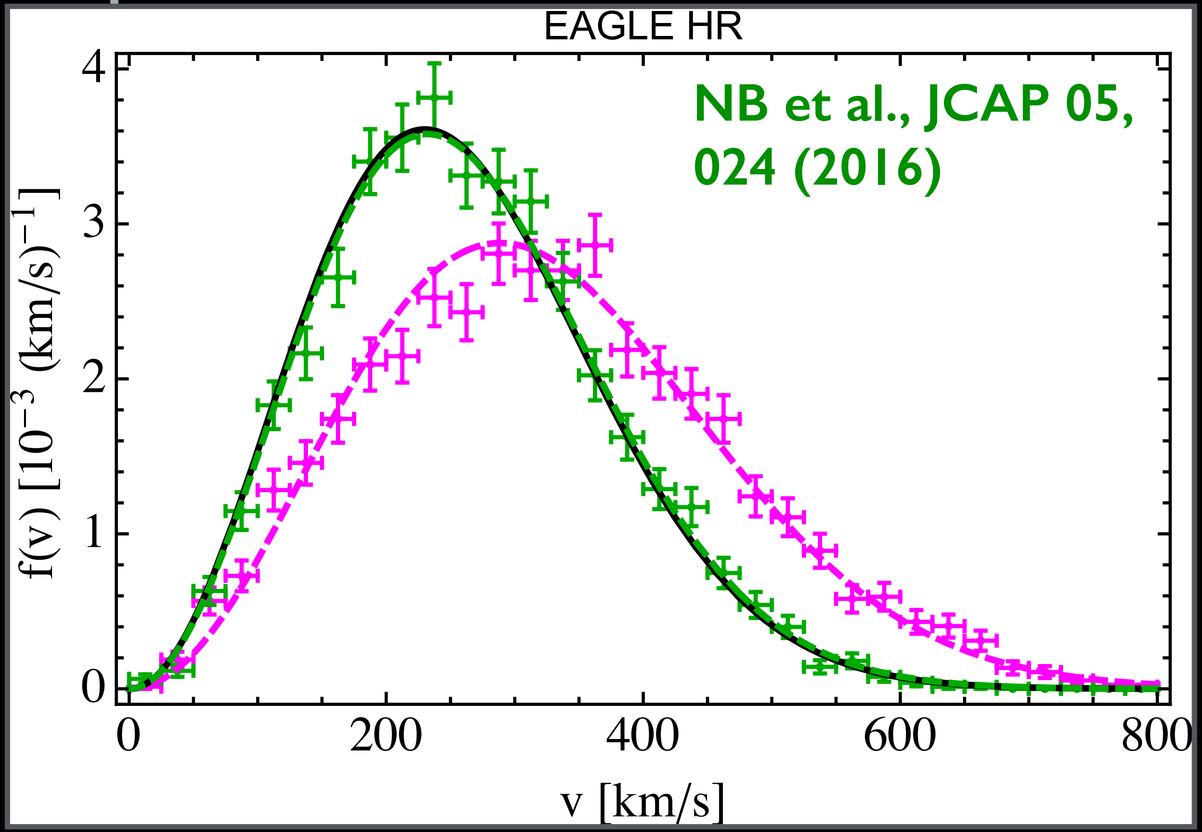

NB et al., 2016 (EAGLE & APOSTLE)
Kelso et al., 2016 (MaGICC)
Sloane et al., 2016
NB & Bertone, 2017
NB et al., 2020 (Auriga)
Poole-McKenzie et al., 2020 (ARTEMIS)
Rahimi, Vienneau, NB, Robertson, 2023 (SIDM EAGLE)

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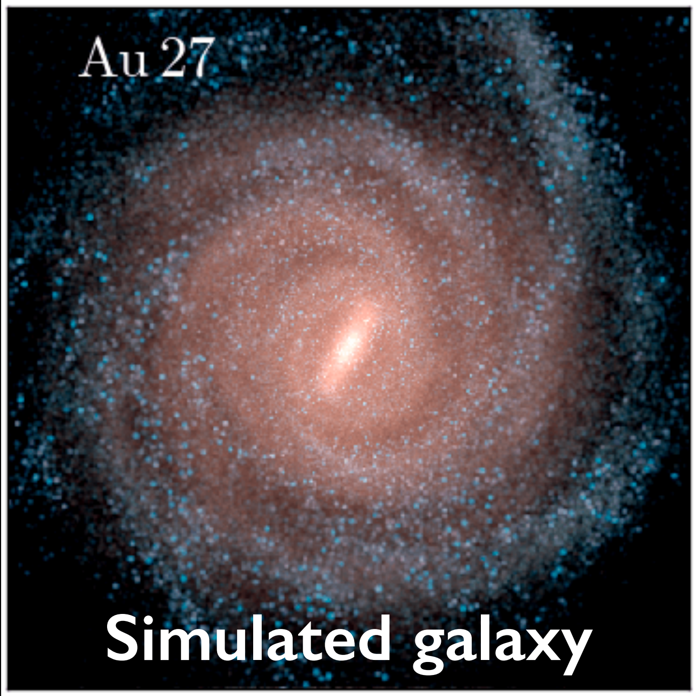
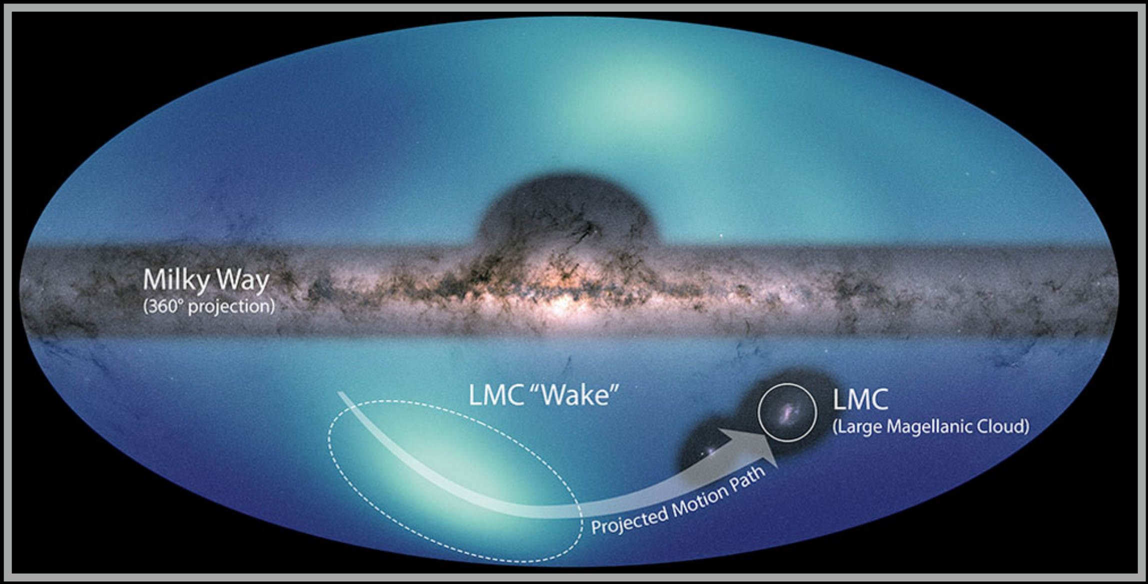


Smooth halo

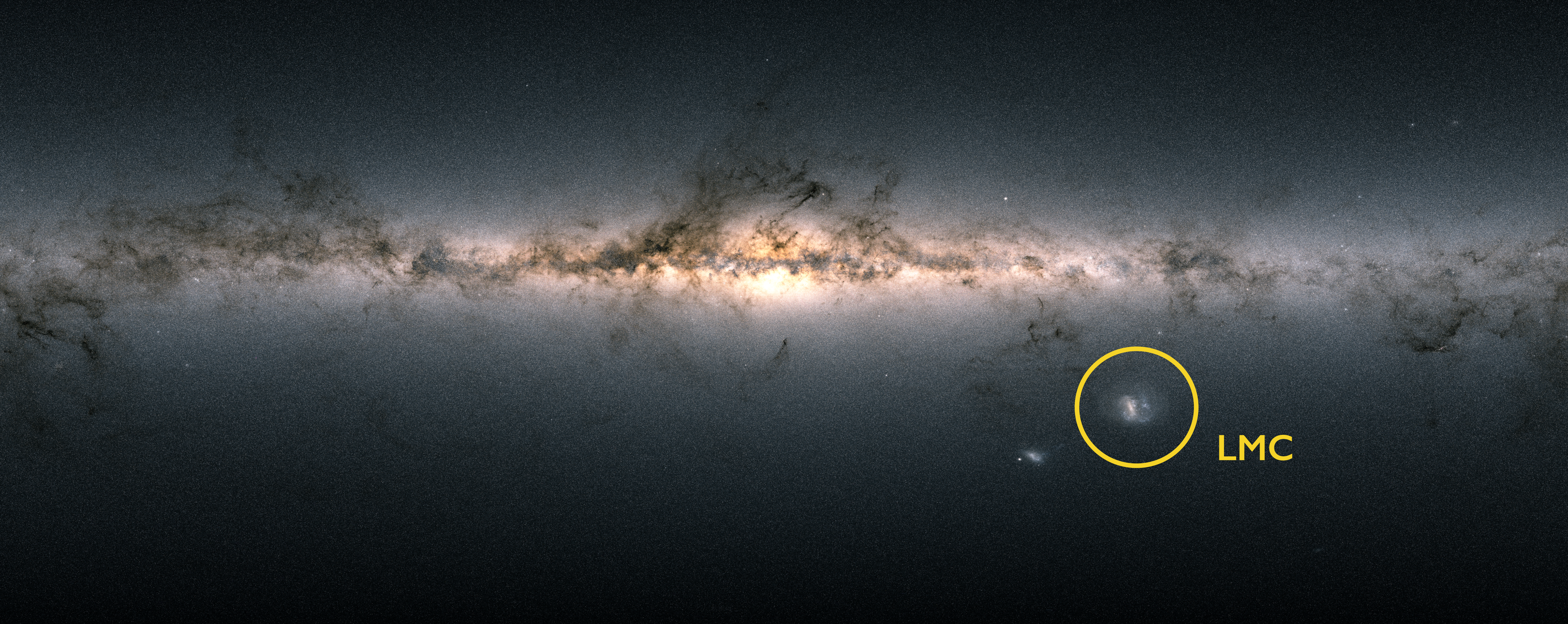
Substructure

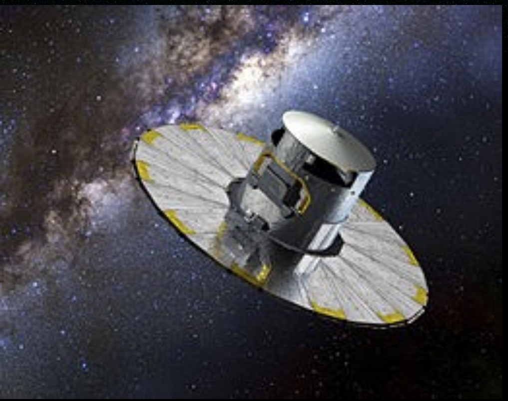
Large Magellanic Cloud (LMC)



The Large Magellanic Cloud

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



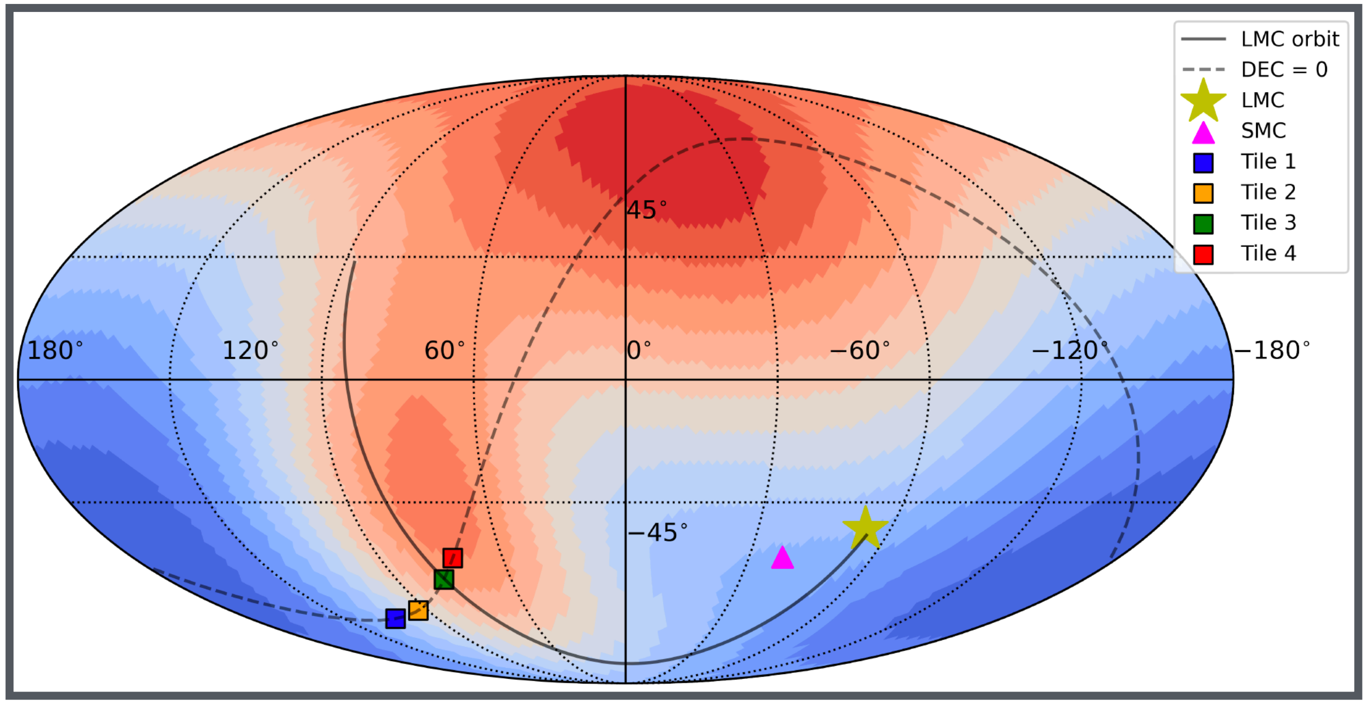


Gaia's EDR3 sky map. *Credit: ESA/Gaia/DPAC*

The effect of the LMC

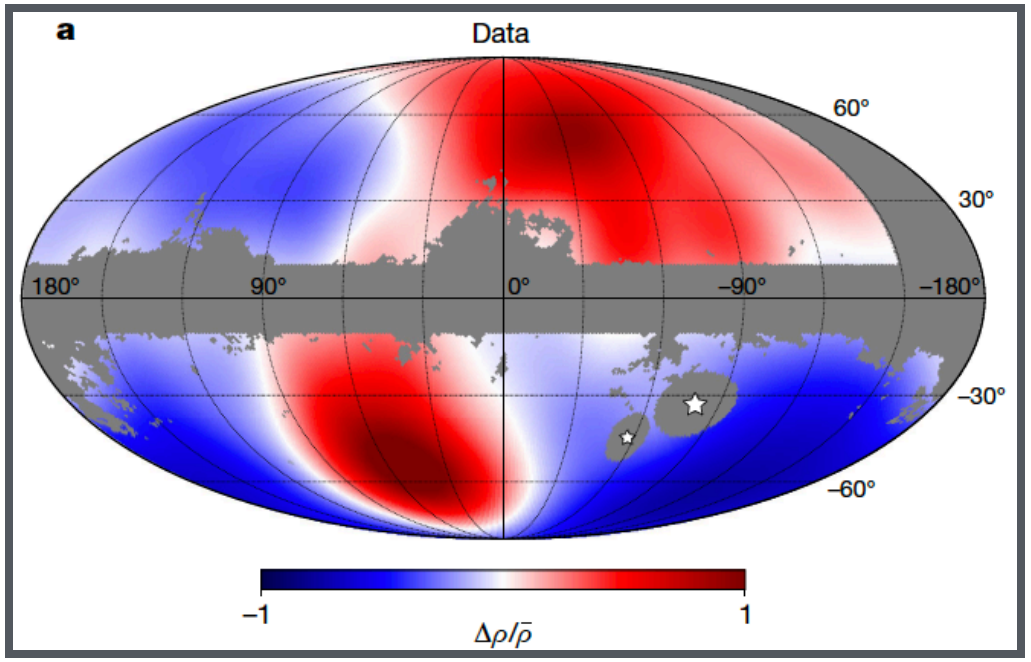
The **LMC** introduces perturbations in the DM and stellar halo.

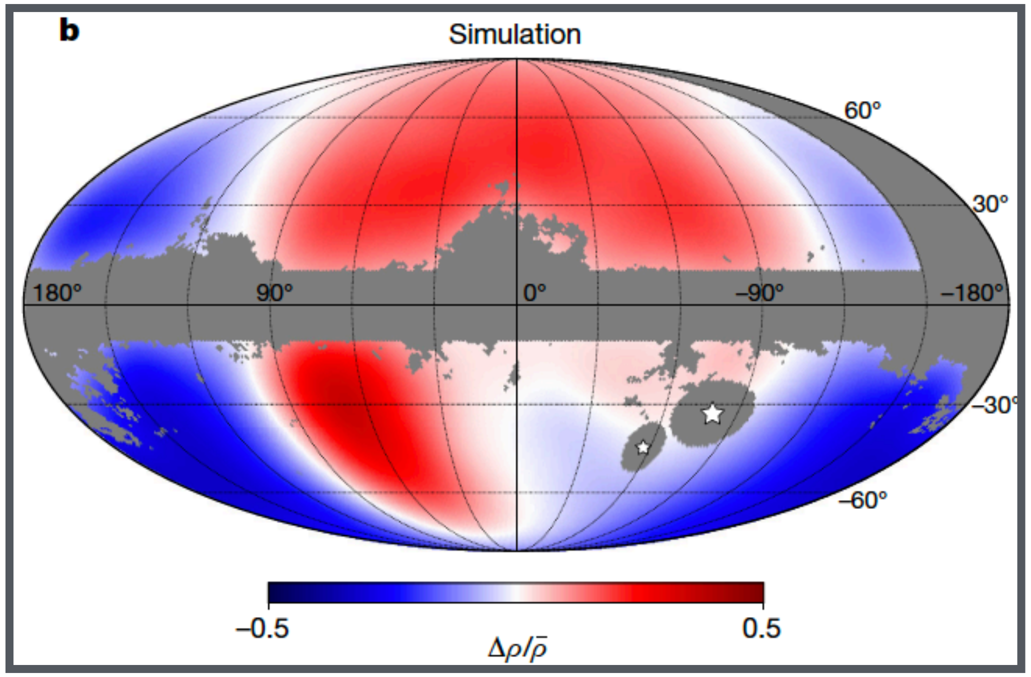
DM halo



Cavieres et al, arXiv:2410.00114
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)

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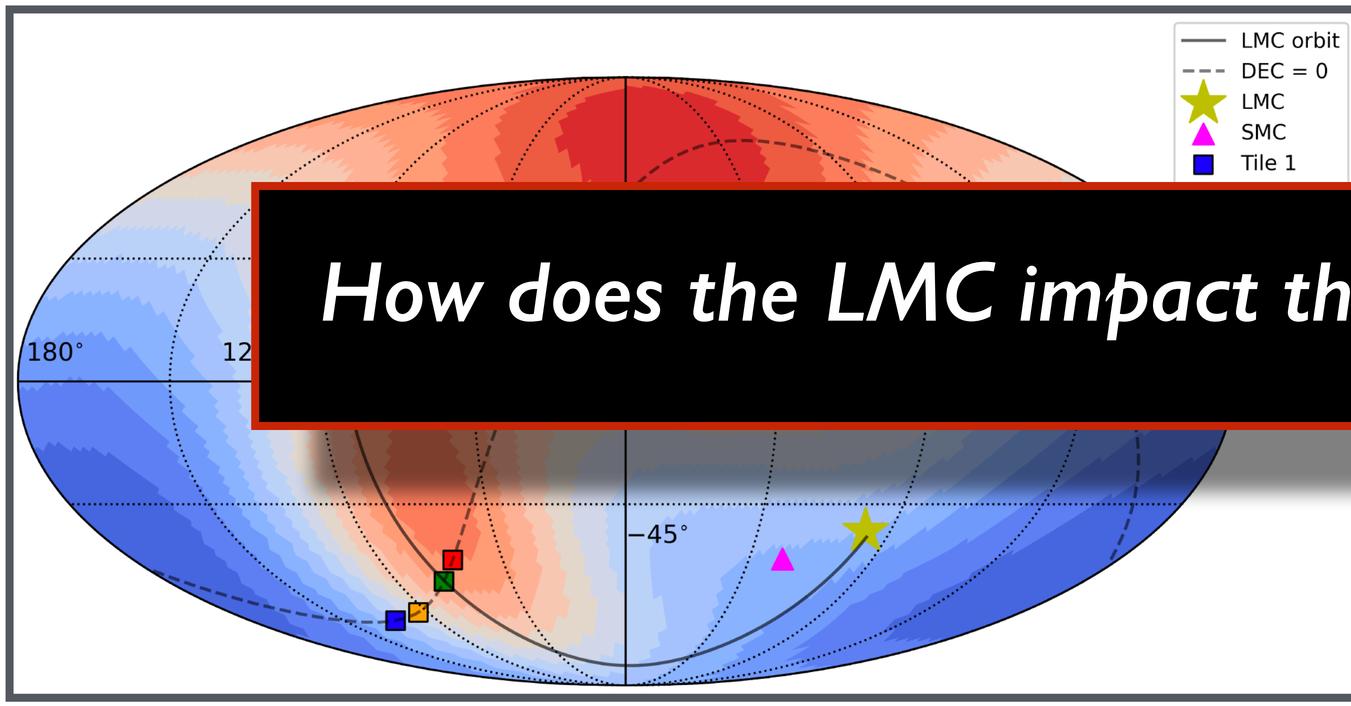
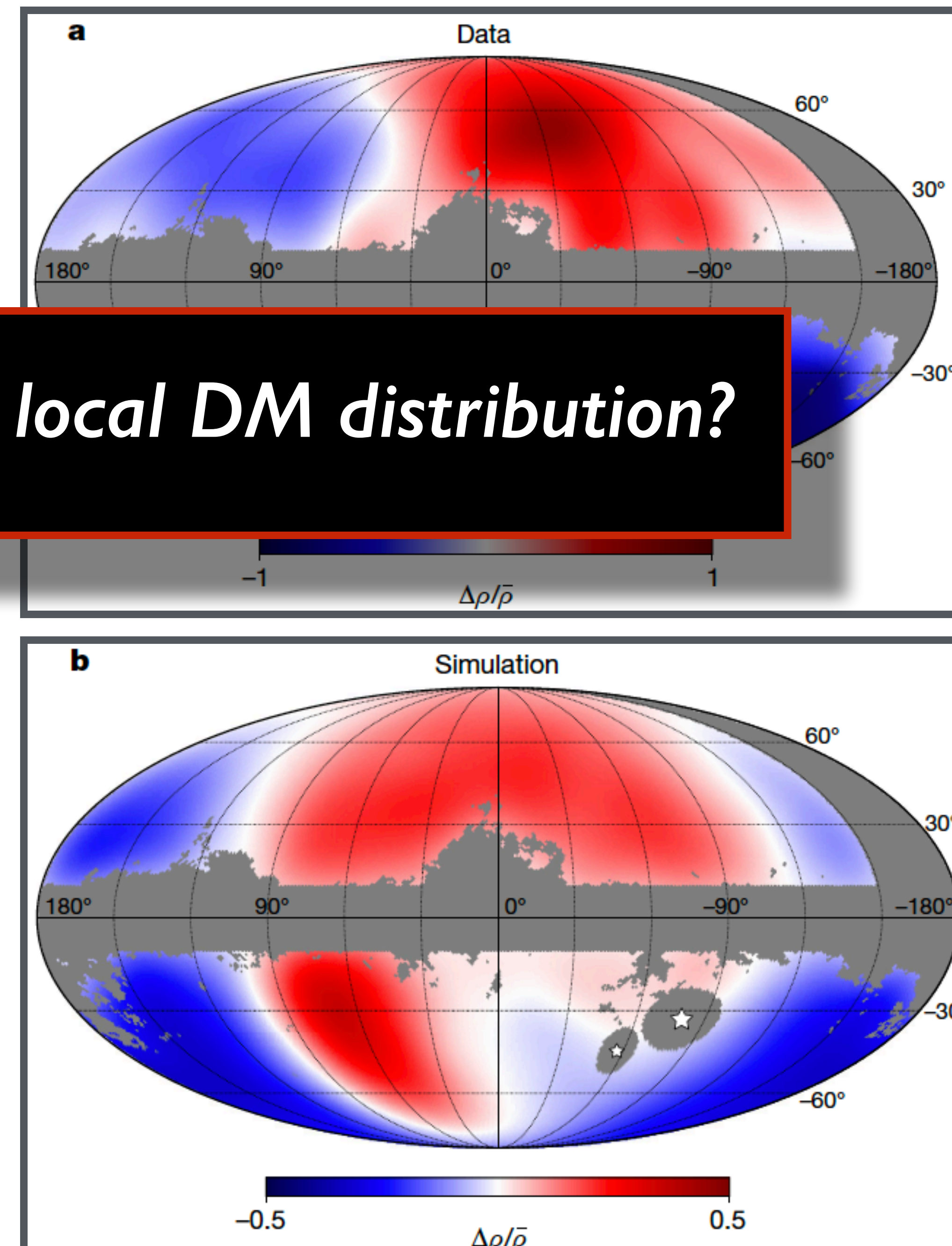


Stellar halo



How does the LMC impact the local DM distribution?

Cavieres et al, arXiv:2410.00114
Garavito-Camargo et al, ApJ 919, 2, 109 (2021)
Garavito-Camargo et al, ApJ 884, 51 (2019)

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)

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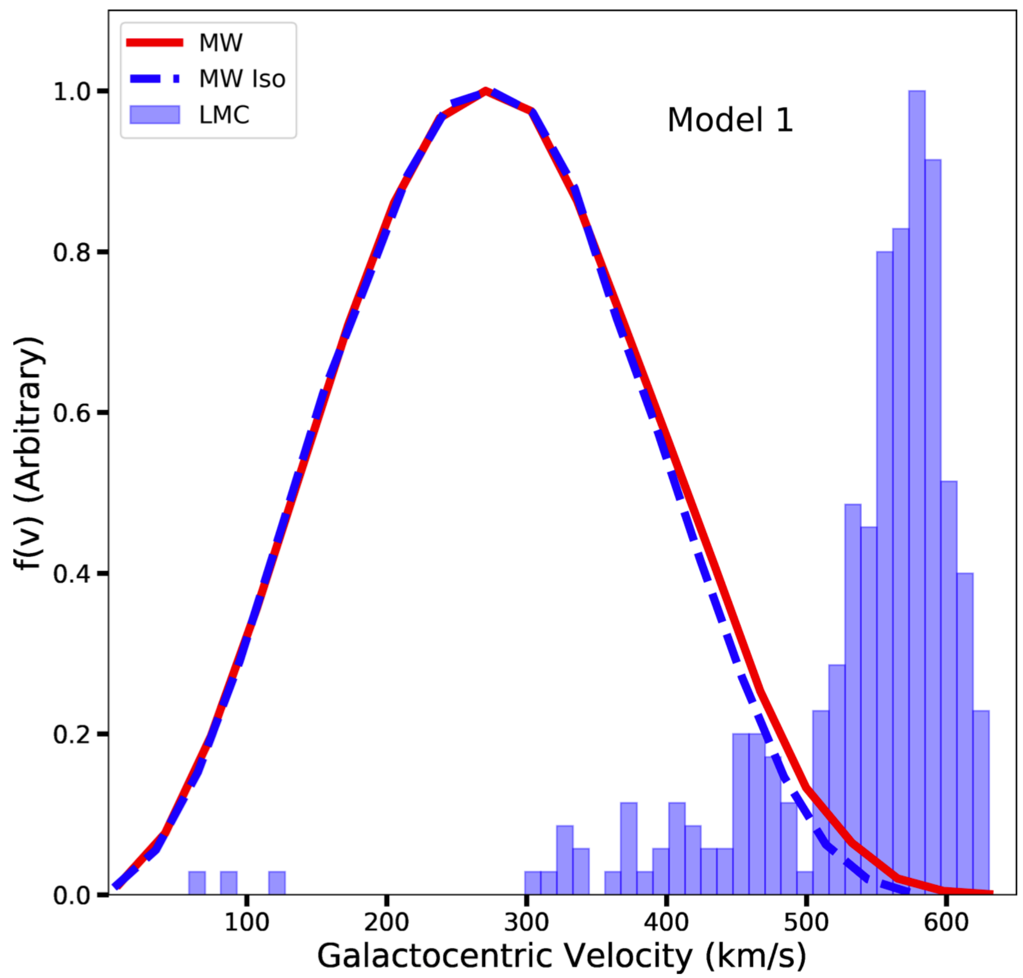

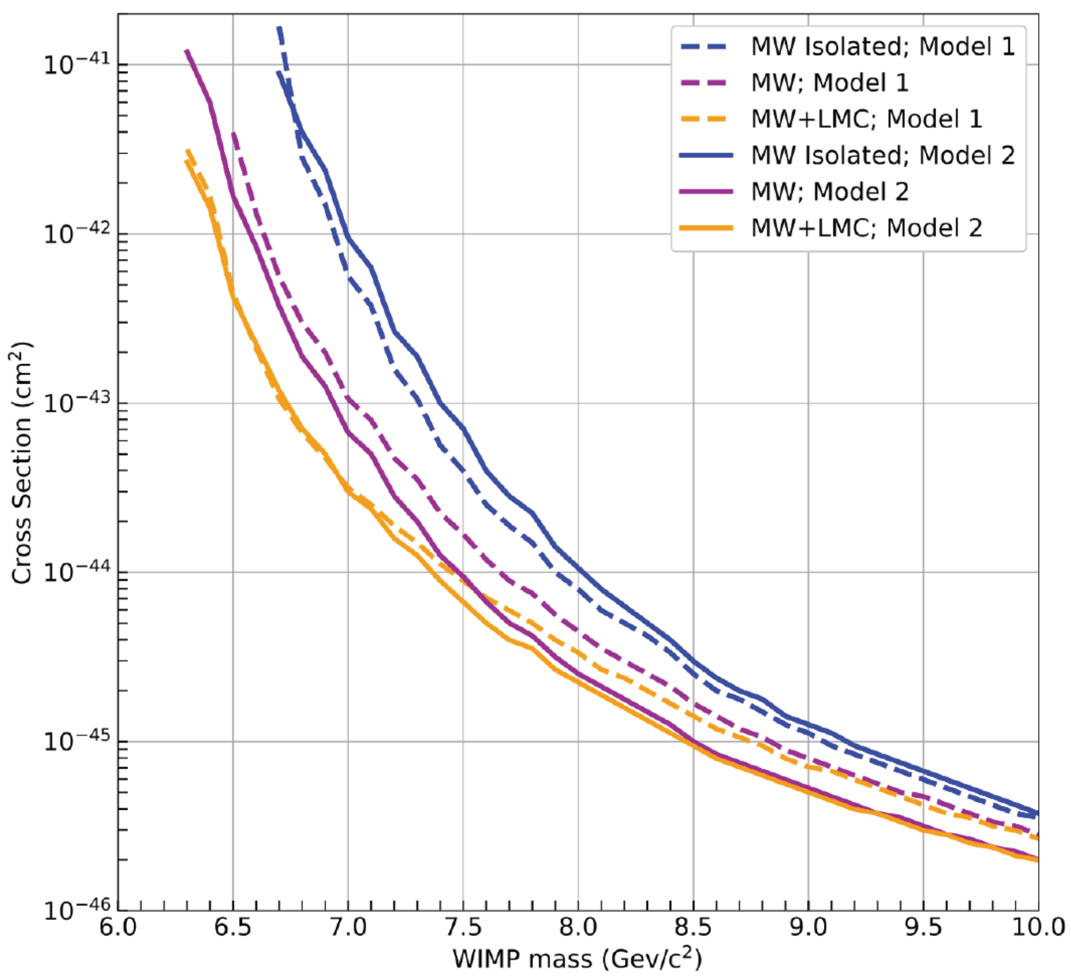

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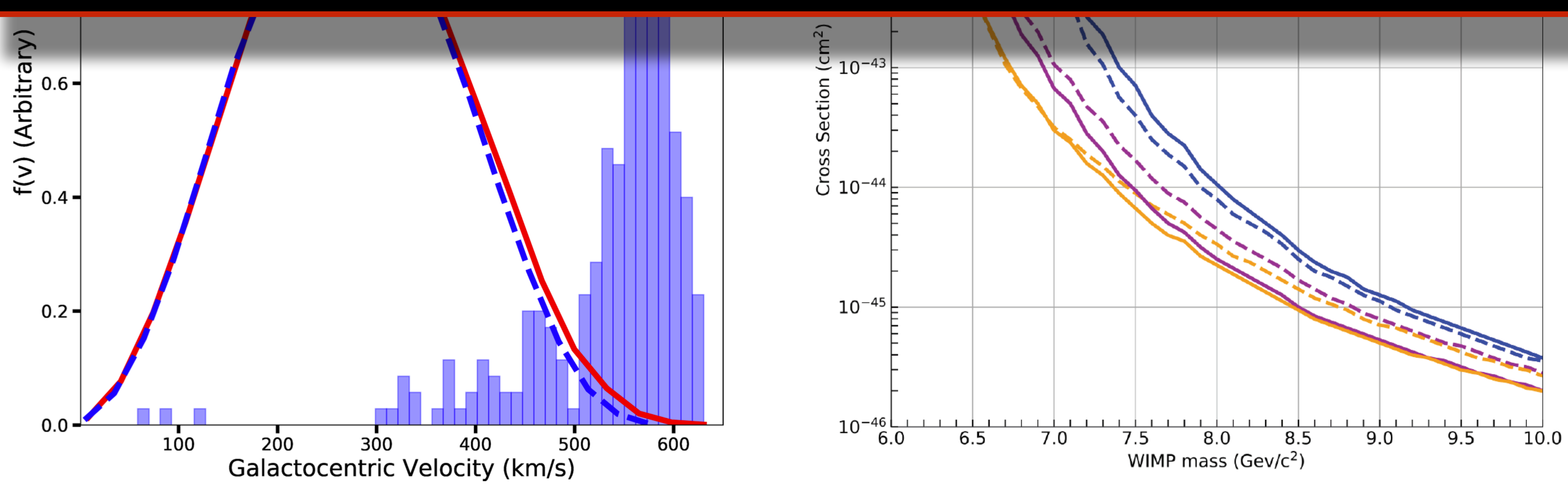
Are these findings valid for fully cosmological halos with multiple accretion events over their formation history?

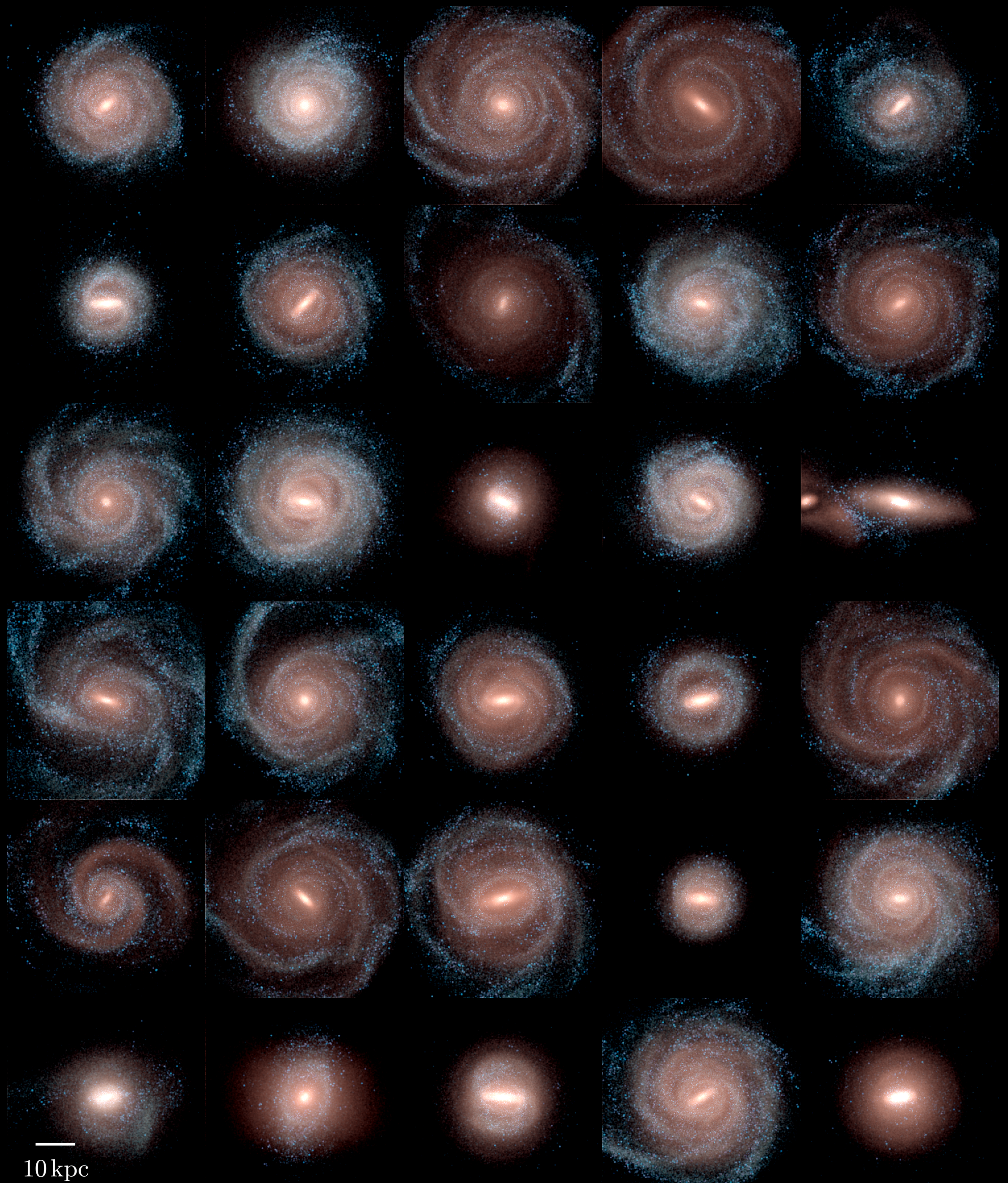


Besla et al, JCAP 11, 013 (2019)

Auriga cosmological simulations

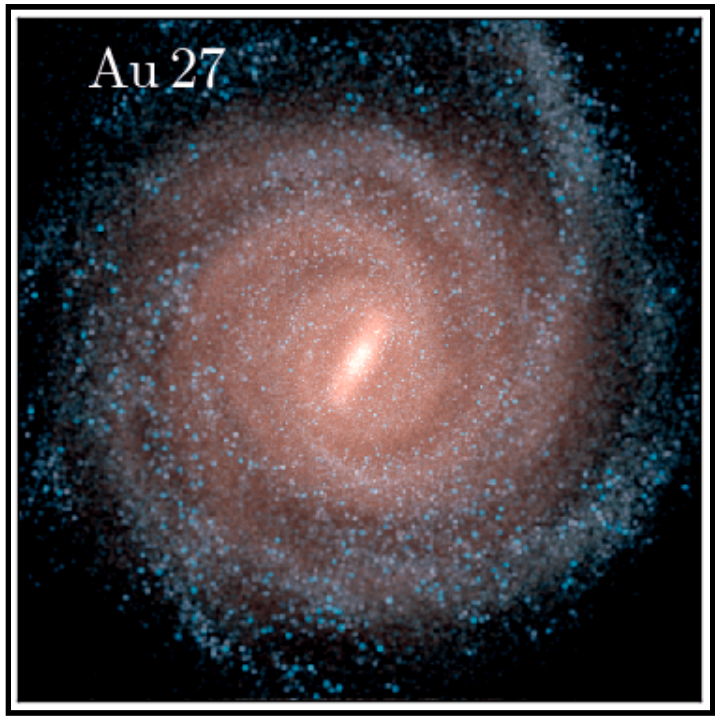
- State-of-the-art cosmological magneto-hydrodynamical zoom-in simulations of Milky Way size halos.
- 30 halos at the standard resolution:

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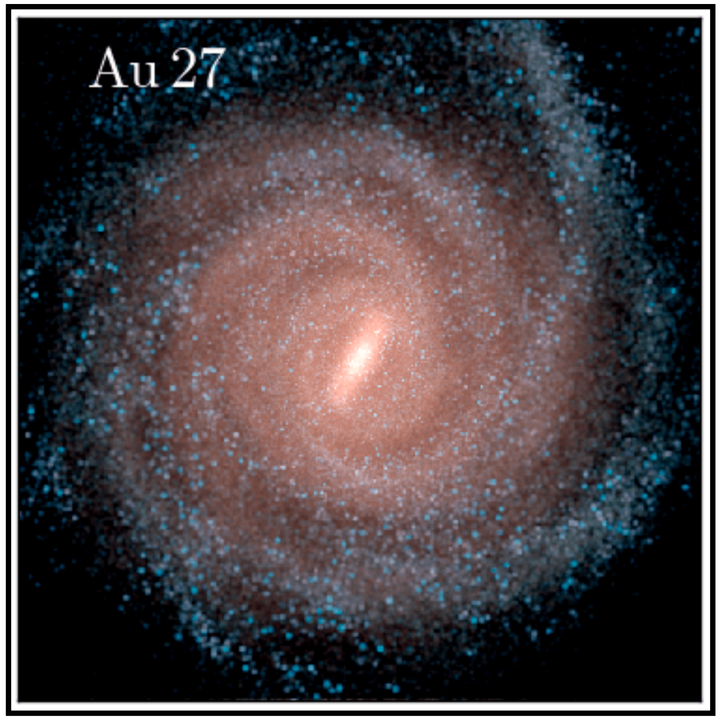
- Identify **15 Milky Way-LMC analogues** based on **LMC's stellar mass** and **distance from host** at first pericenter approach.

- Focus on one halo and study the impact of the LMC on the local DM distribution at different times (snapshots) in its orbit.



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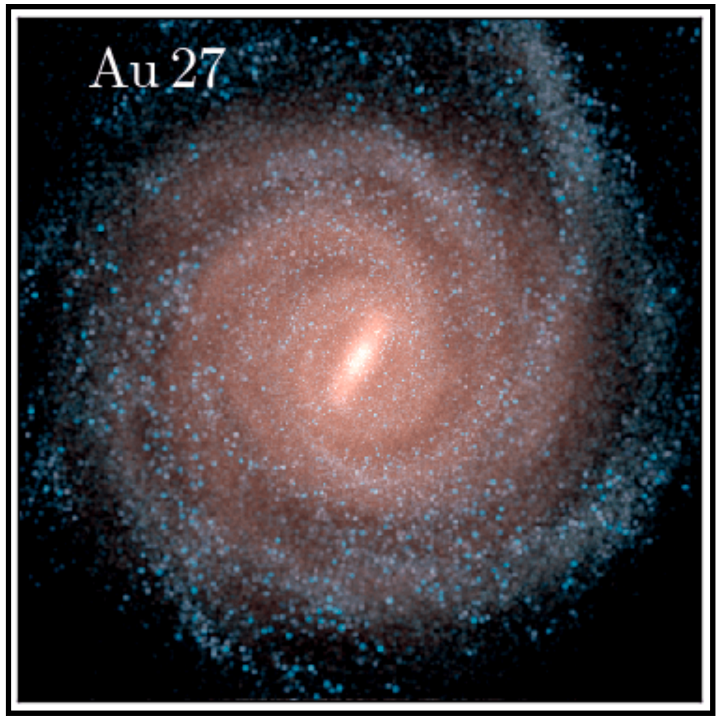

- Consider four representative snapshots:

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

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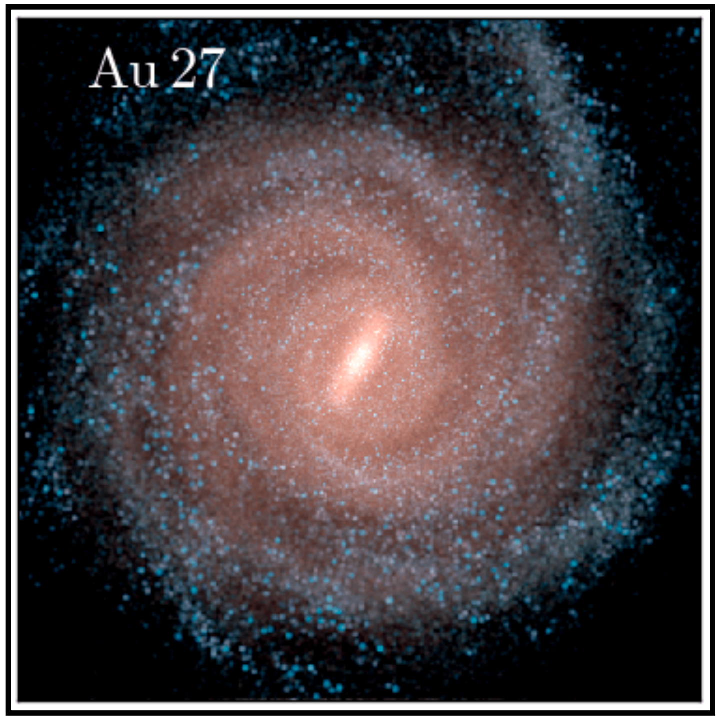

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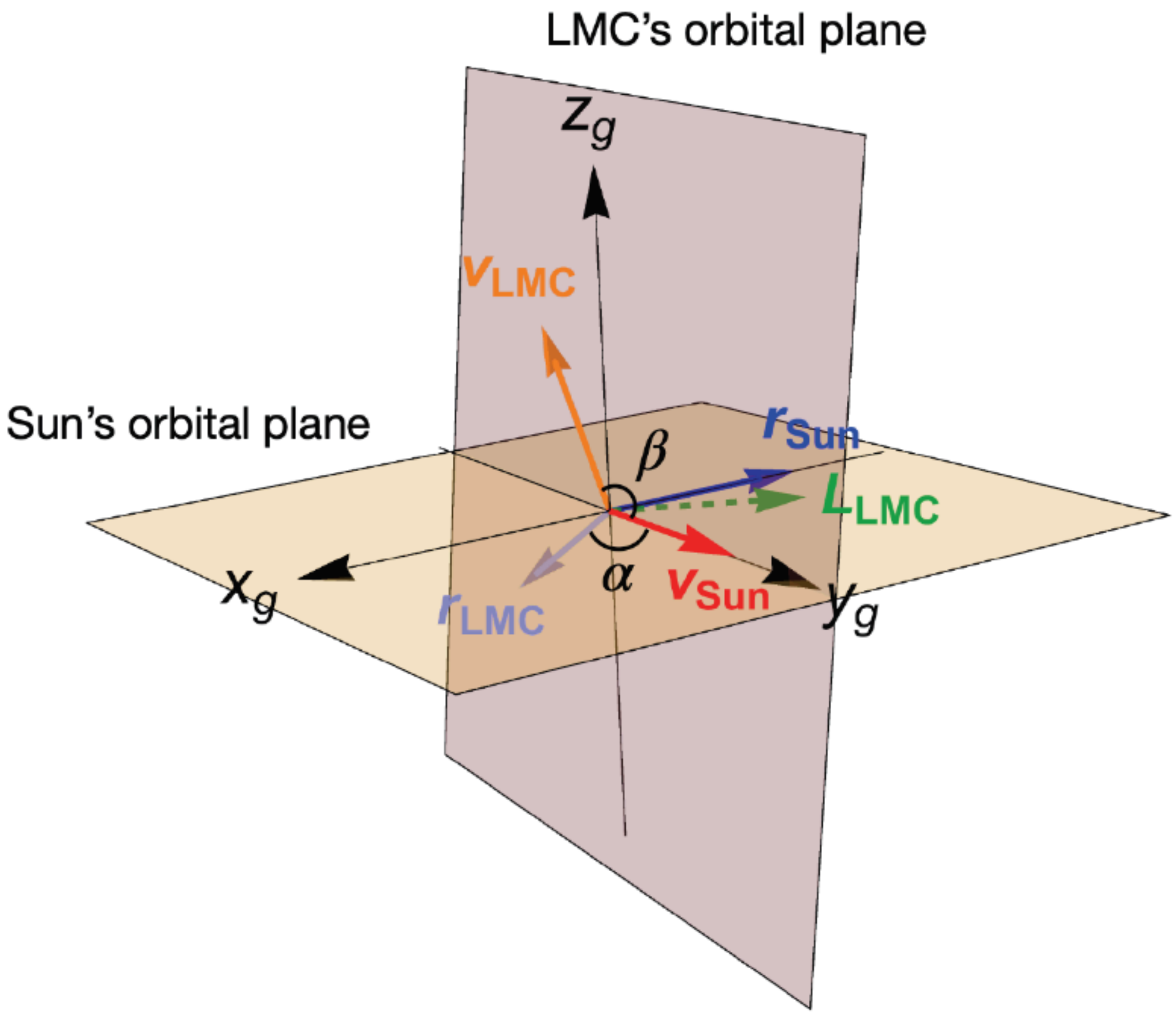
Matching the Sun-LMC geometry

- 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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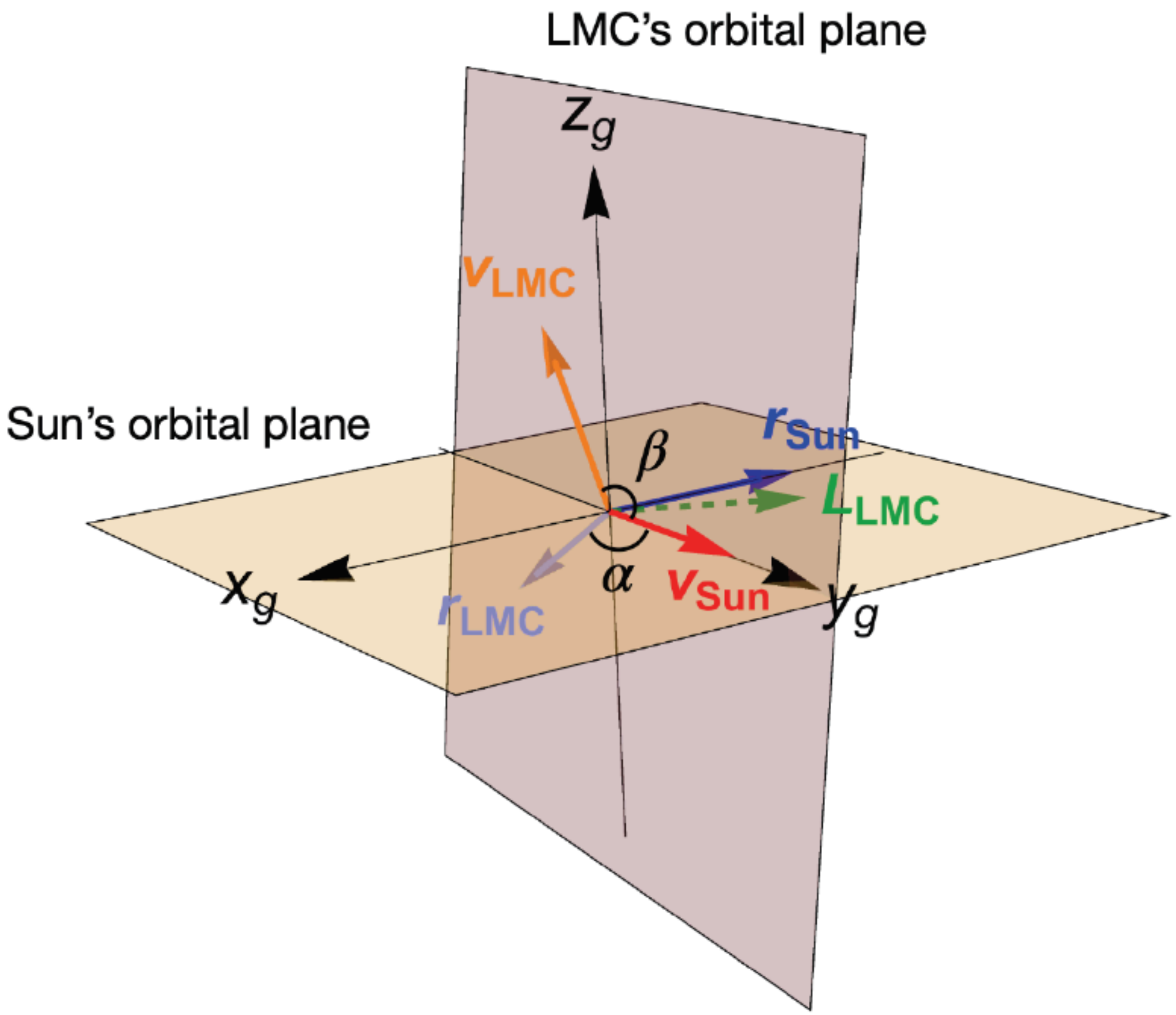


- Choose the position of the Sun in the simulations such that it matches the observed Sun-LMC geometry.

Local dark matter density

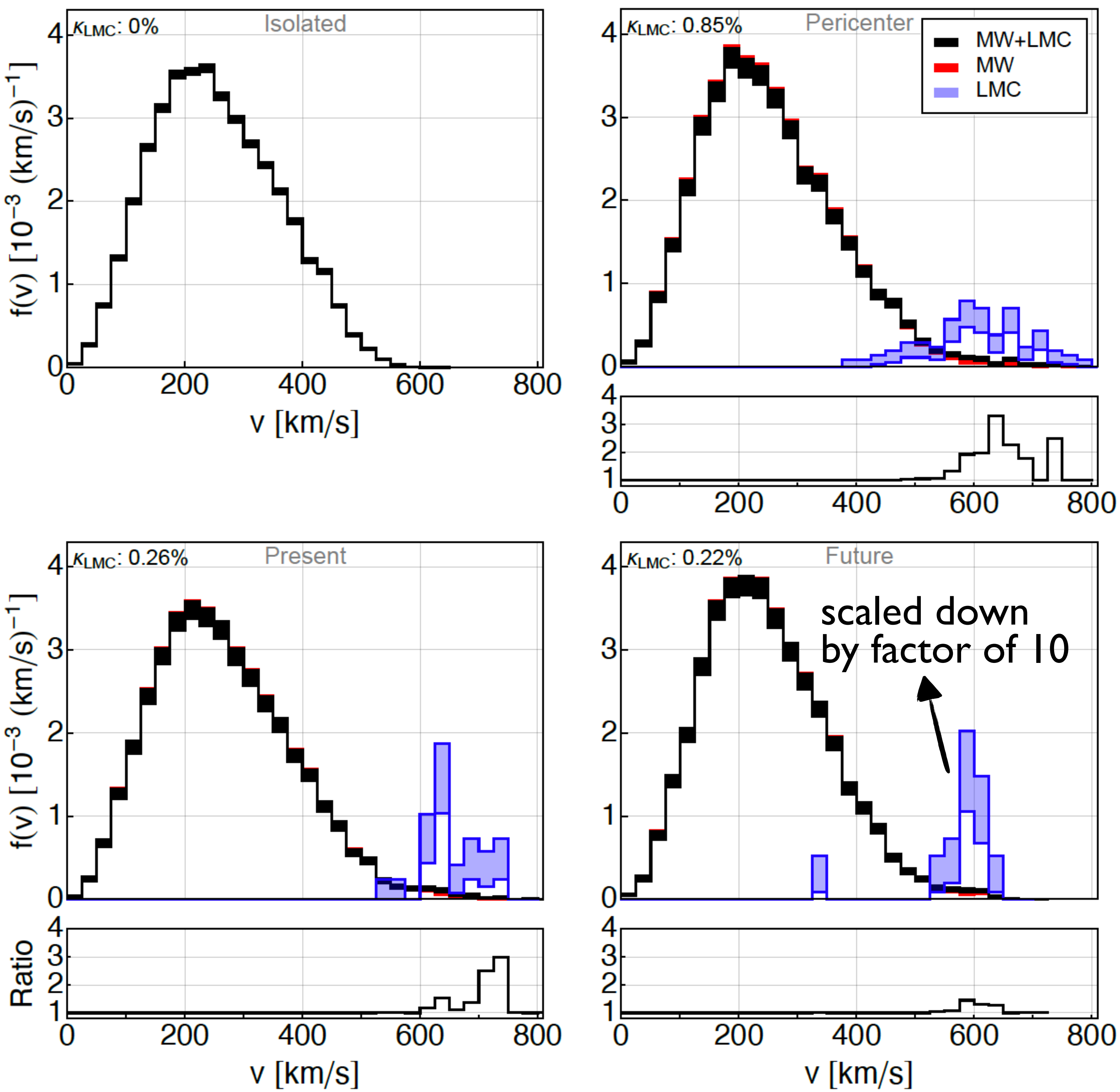
Halo ID	$M_{\rm Infall}^{\rm LMC}$ [10^{11} $M_\odot$]	ρ_χ [GeV/cm^3]	$\kappa_{\rm LMC}$ [%]
1	0.31	0.21	0.14
2	0.31	0.23	0.64
3	0.34	0.35	0.026
4	0.82	0.34	0.096
5	1.84	0.24	1.5
6	1.10	0.38	0.038
7	0.32	0.53	0.032
8	0.36	0.38	0.0077
9	0.73	0.36	0.10
10	3.28	0.39	2.8
11	1.45	0.43	0.028
12	1.43	0.53	0.17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

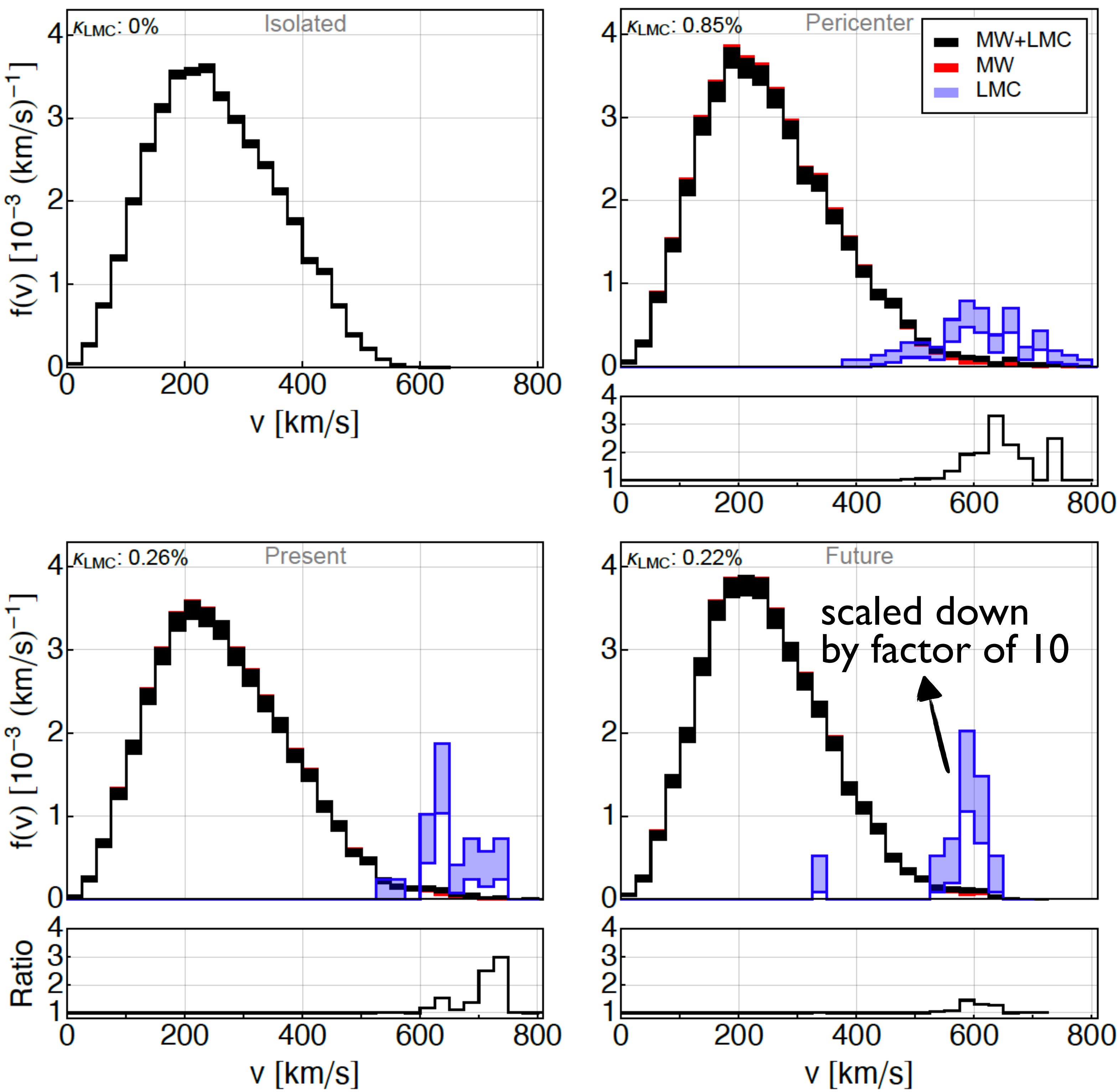
In the galactic rest frame



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

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, Ronaghi, NB et al., JCAP 10, 070 (2023)

Direct detection event rate

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

astrophysics

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

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

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

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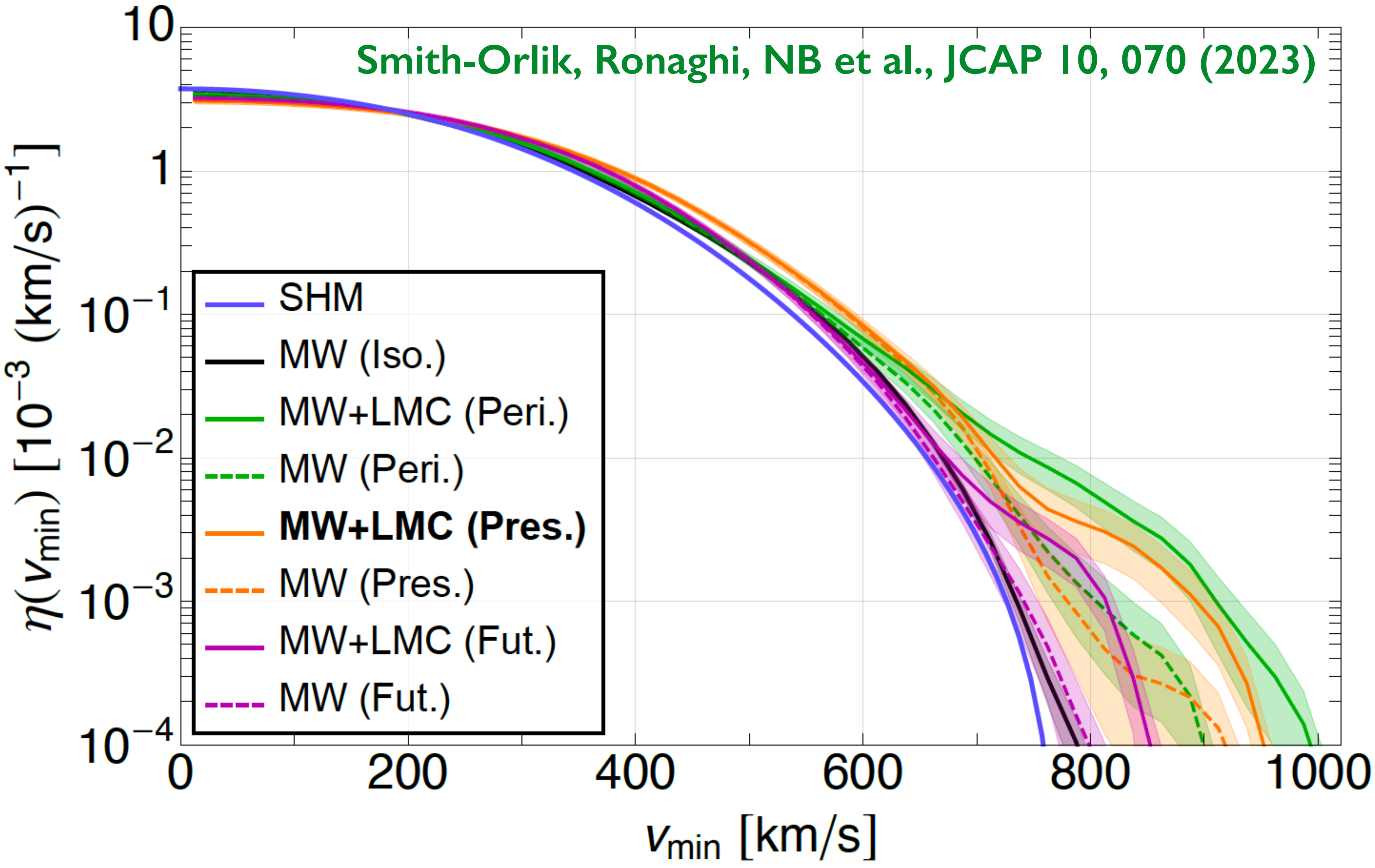
where

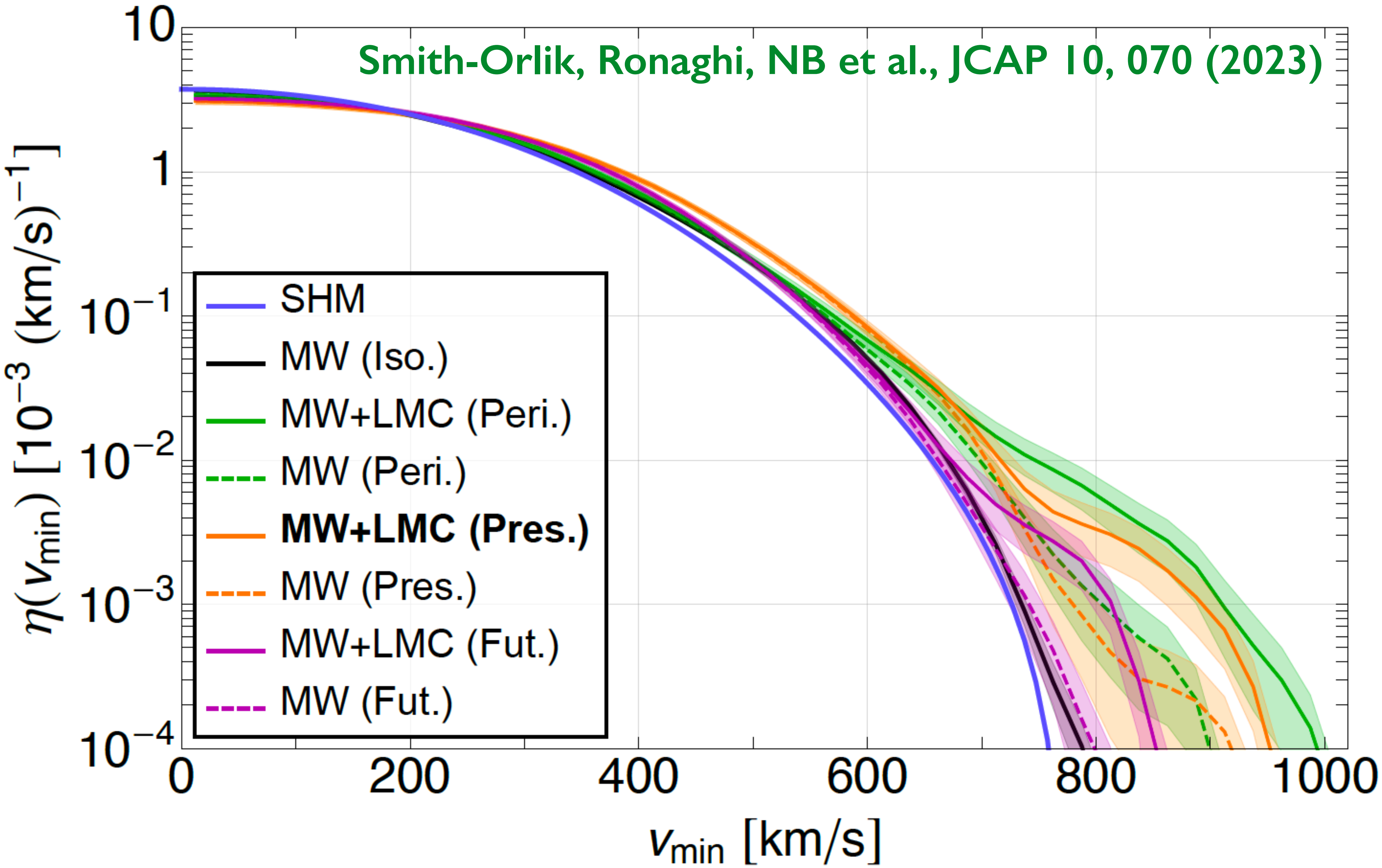
$$\eta(v_{\rm min}, t) \equiv \int_{v > v_{\rm min}} d^3v \, \frac{f_{\rm det}(\mathbf{v}, t)}{v}$$

Halo integral

Halo integrals

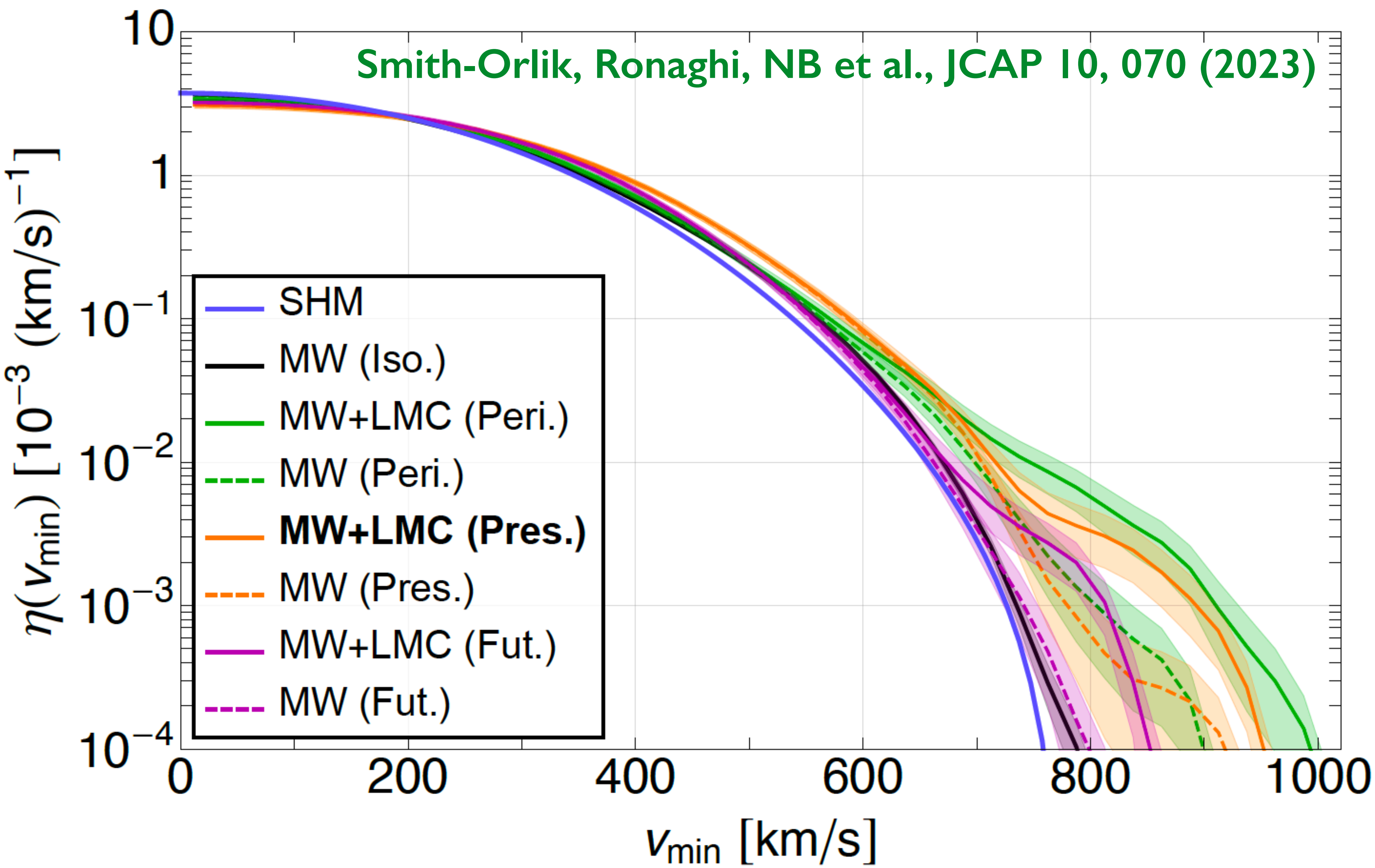


Halo integrals



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

Halo integrals

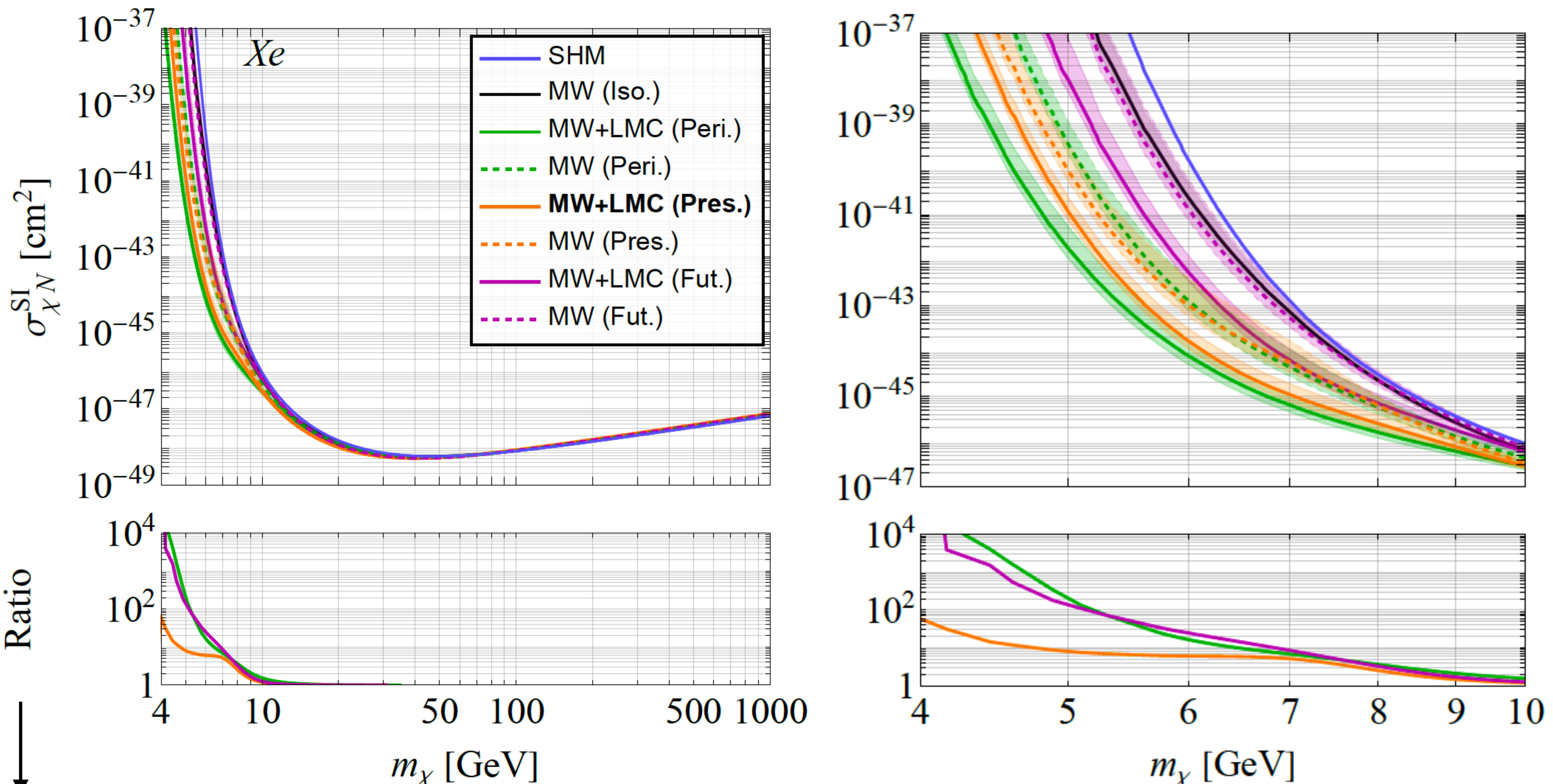


- **Two effects:** High speed LMC particles in the Solar region + Milky Way's response to the LMC.

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

Direct detection limits

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, Ronaghi, NB et al., JCAP 10, 070 (2023)

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

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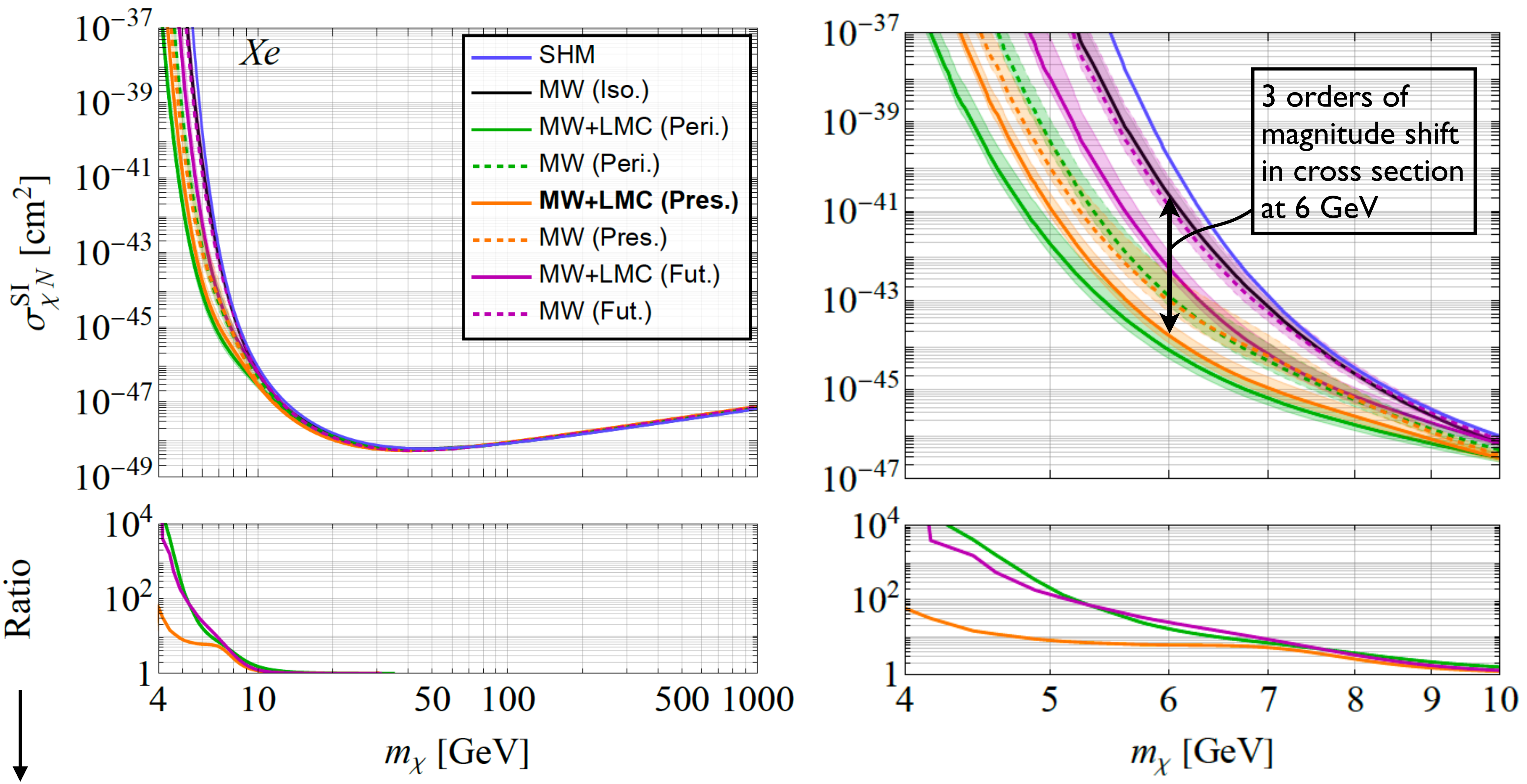

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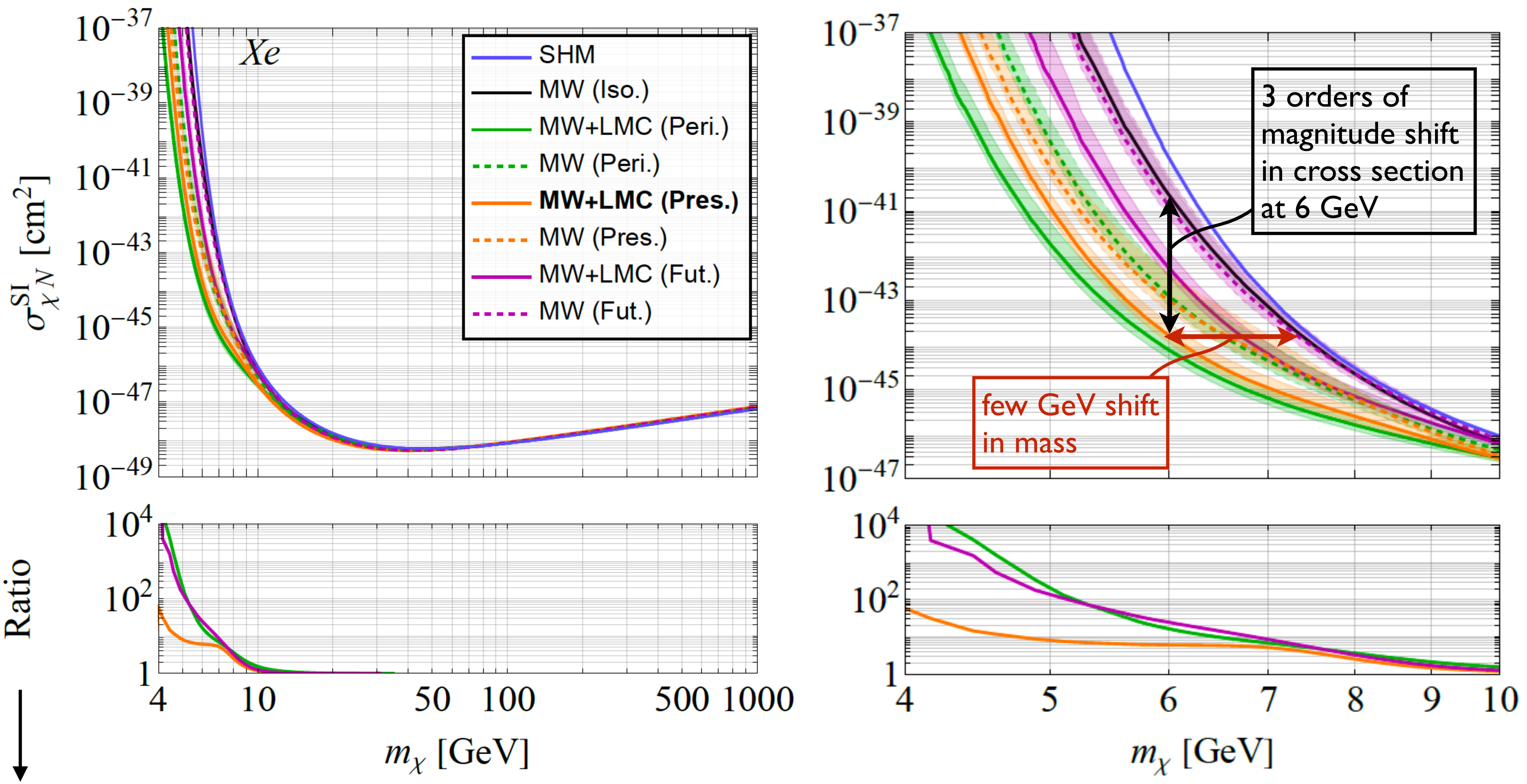

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Smith-Orlik, Ronaghi, NB et al., JCAP 10, 070 (2023)

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

Beyond standard interactions

- Parametrize possible DM-nucleon contact interactions using nonrelativistic effective field theory.

Operator	Scaling factor
$\mathcal{O}_1 = 1_\chi 1_N$	1
$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q}/m_N \times \vec{v}_\perp)$	$q^2 v_\perp^2,\ q^4$
$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	1
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q}/m_N \times \vec{v}_\perp)$	$q^2 v_\perp^2,\ q^4$
$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \vec{q}/m_N\right)\left(\vec{S}_N \cdot \vec{q}/m_N\right)$	q^4
$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}_\perp$	$v_\perp^2$
$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp$	$v_\perp^2,\ q^2$
$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{q}/m_N\right)$	q^2
$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}/m_N$	q^2
$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}/m_N$	q^2
$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp\right)$	$v_\perp^2,\ q^2$
$\mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \vec{v}_\perp\right)\left(\vec{S}_N \cdot \vec{q}/m_N\right)$	$q^2 v_\perp^2,\ q^4$
$\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \vec{q}/m_N\right)\left(\vec{S}_N \cdot \vec{v}_\perp\right)$	$q^2 v_\perp^2$
$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \vec{q}/m_N\right)\left(\left(\vec{S}_N \times \vec{v}_\perp\right) \cdot \vec{q}/m_N\right)$	$q^4 v_\perp^2,\ q^6$

Beyond standard interactions

- Parametrize possible DM-nucleon contact interactions using nonrelativistic effective field theory.
- Study the impact of the LMC on expected results from several near-future experiments.

Operator	Scaling factor
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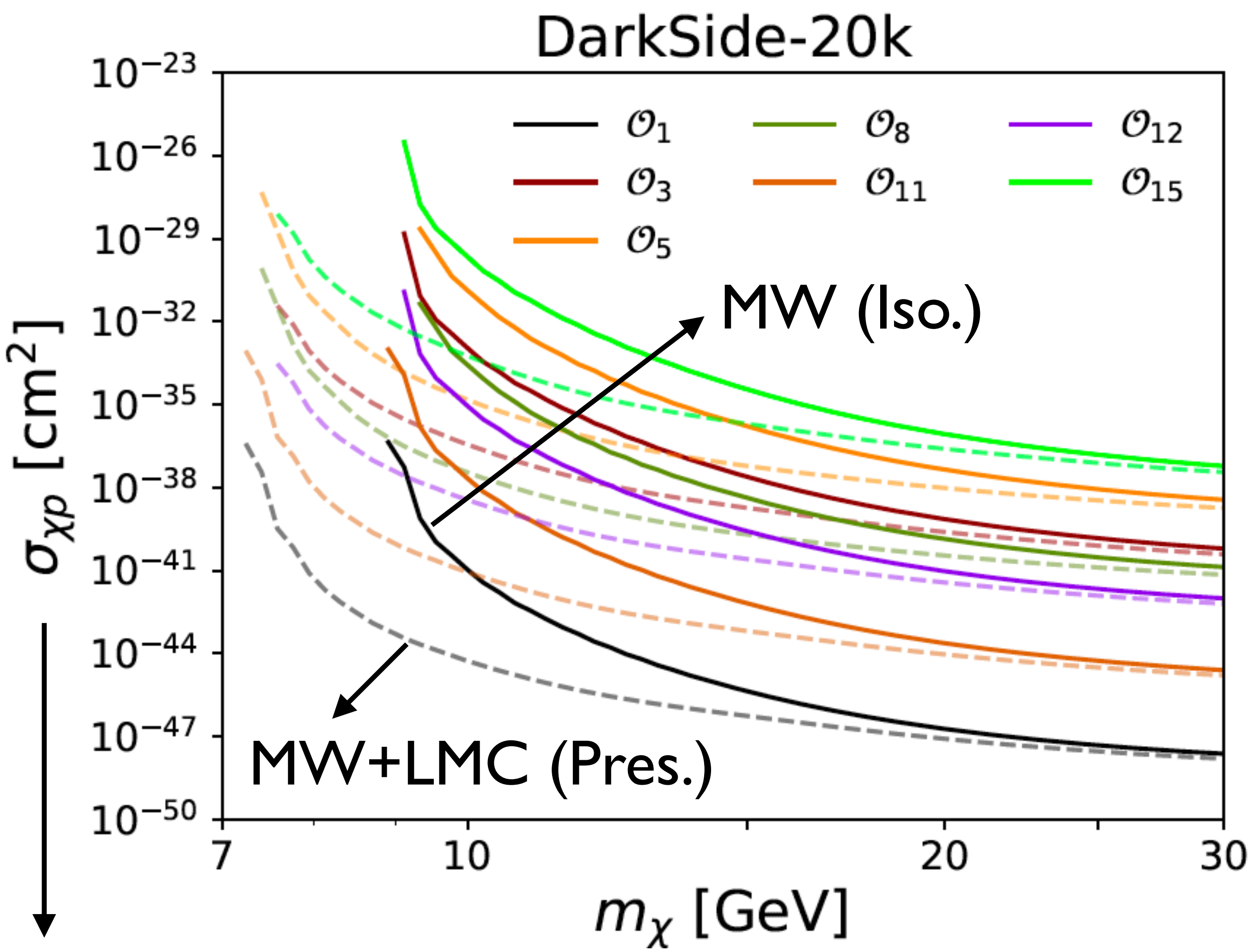
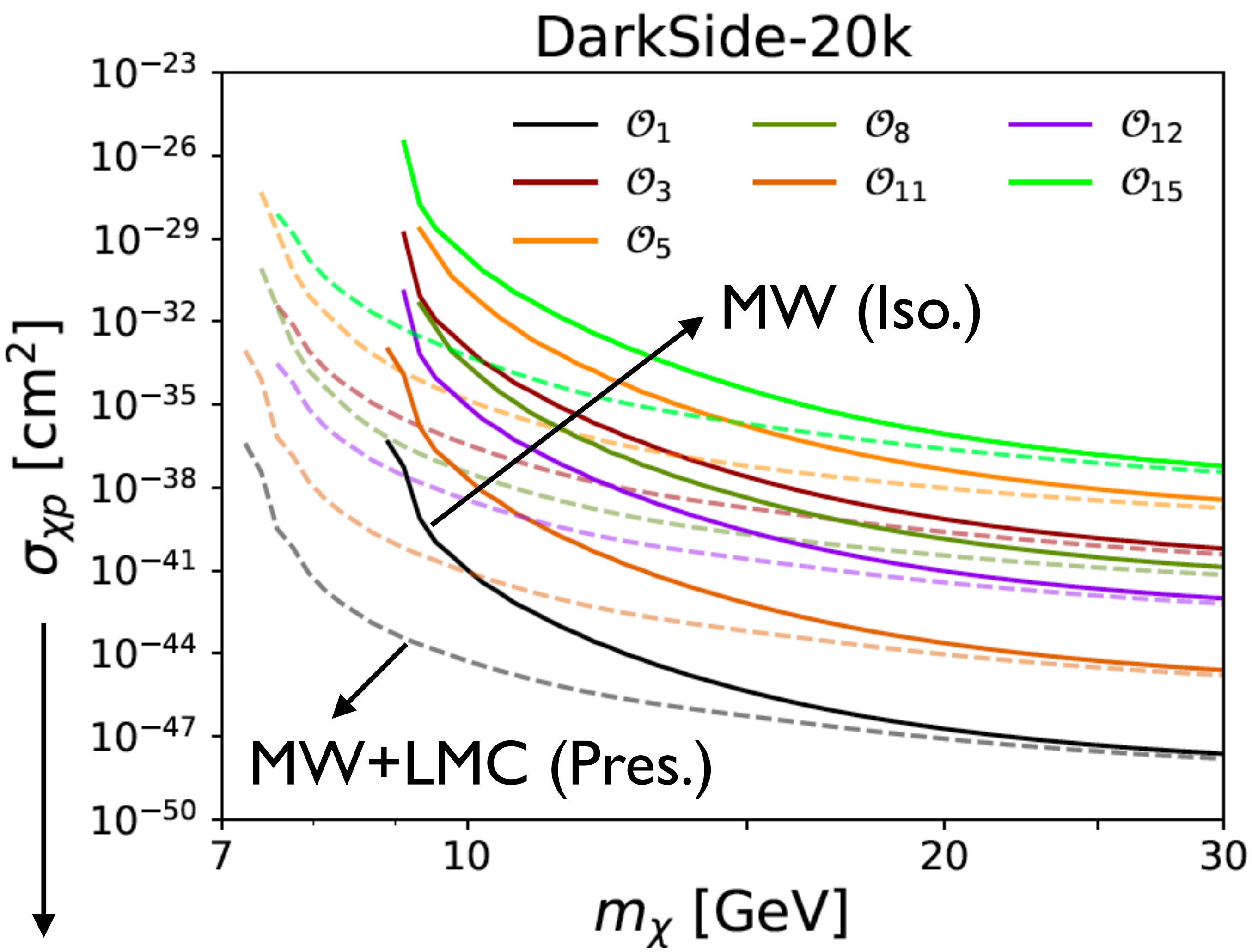
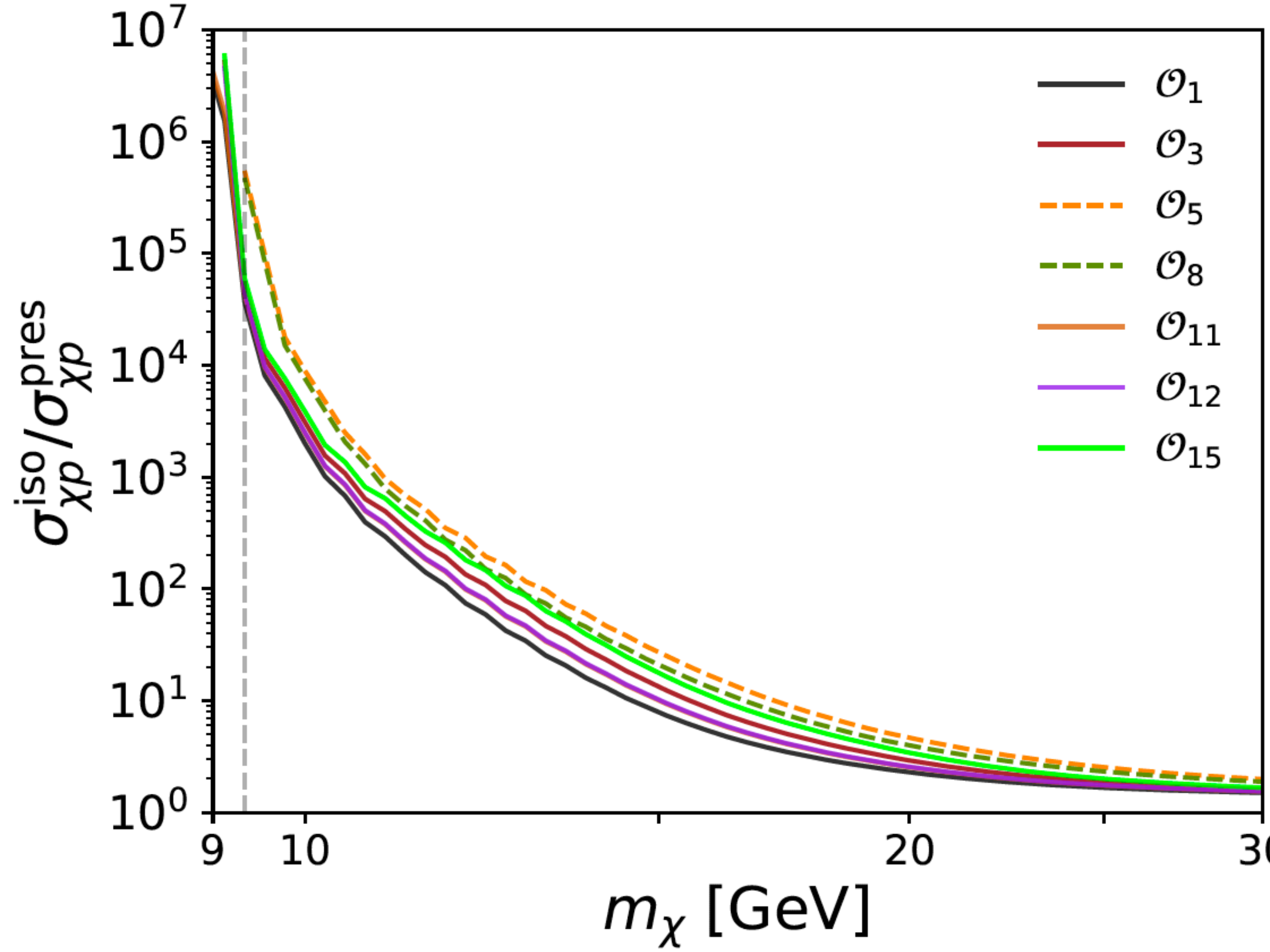
DarkSide-20k



$$\sigma_{\chi p} \equiv \frac{(c_i^p \mu_p)^2}{\pi}$$

DarkSide-20k





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Reynoso, NB, Piro, arXiv:2409.09119

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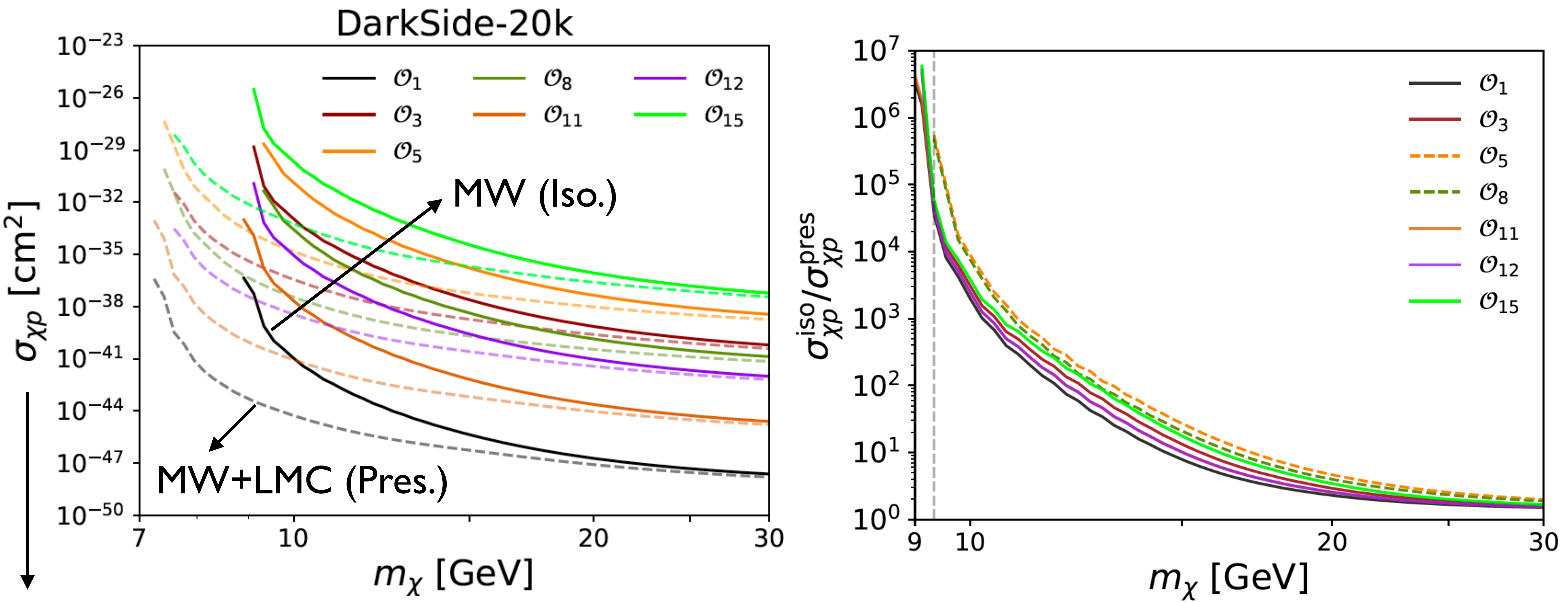
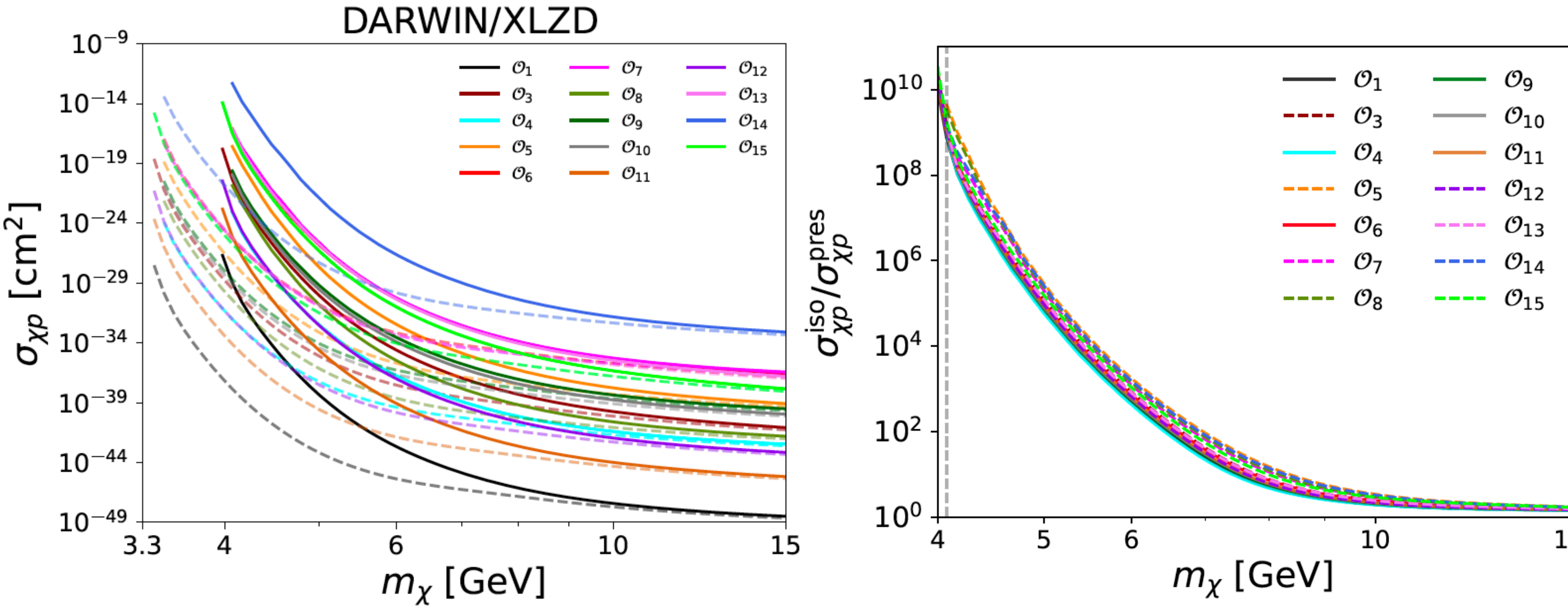


$$\sigma_{\chi p} \equiv \frac{(c_i^p \mu_p)^2}{\pi}$$

Reynoso, NB, Piro, arXiv:2409.09119

- The impact of the LMC is larger for operators that lead to a velocity-dependent scaling in the DM-nucleus cross section.

DARWIN/XLZD



Reynoso, NB, Piro, arXiv:2409.09119

Inelastic dark matter

- DM particle χ scatters to an excited state χ^* with $\delta = m_{\chi^*} - m_\chi$.

Inelastic dark matter

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- Minimum DM speed required to produce a recoil energy E_R:

$$v_{\min} = \sqrt{\frac{1}{2m_N E_R}}\left(\frac{m_N E_R}{\mu_{\chi N}} + \delta\right)$$

Inelastic dark matter

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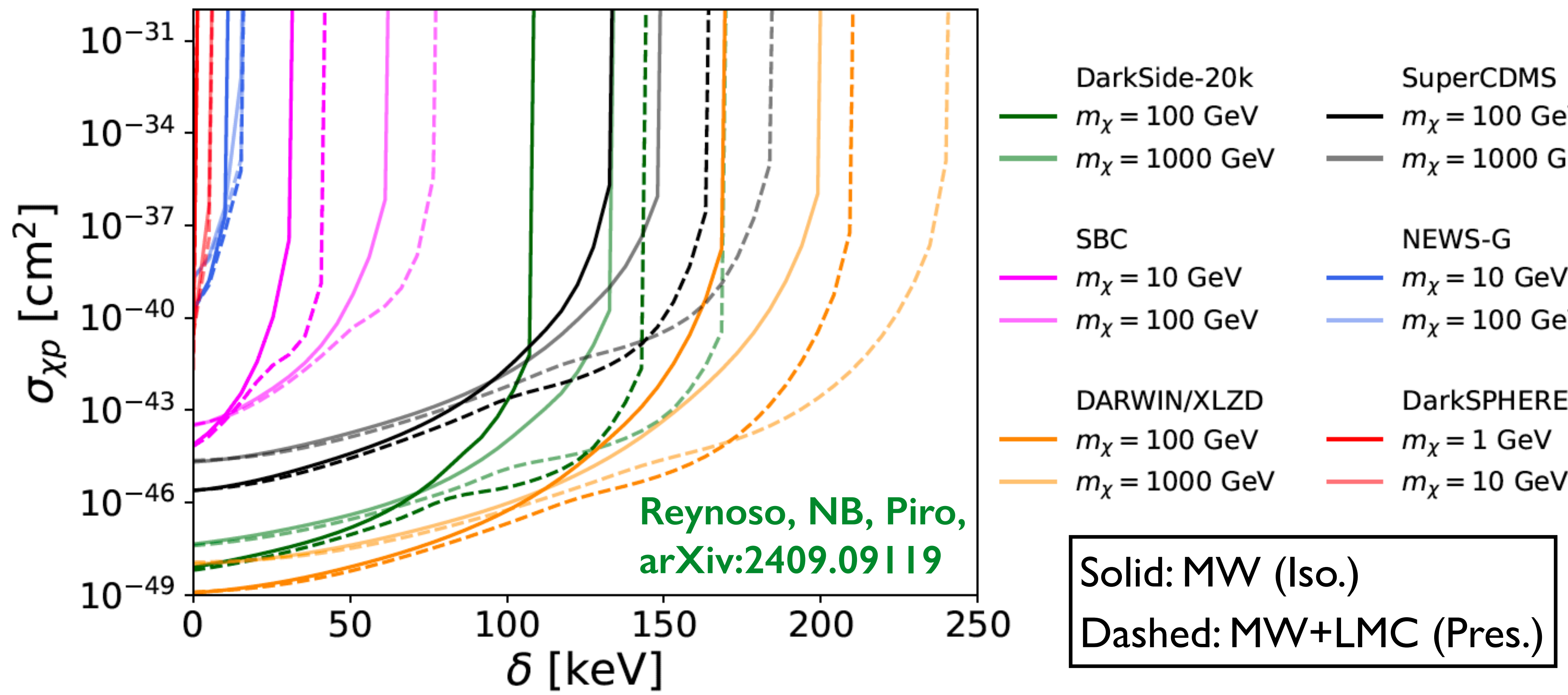

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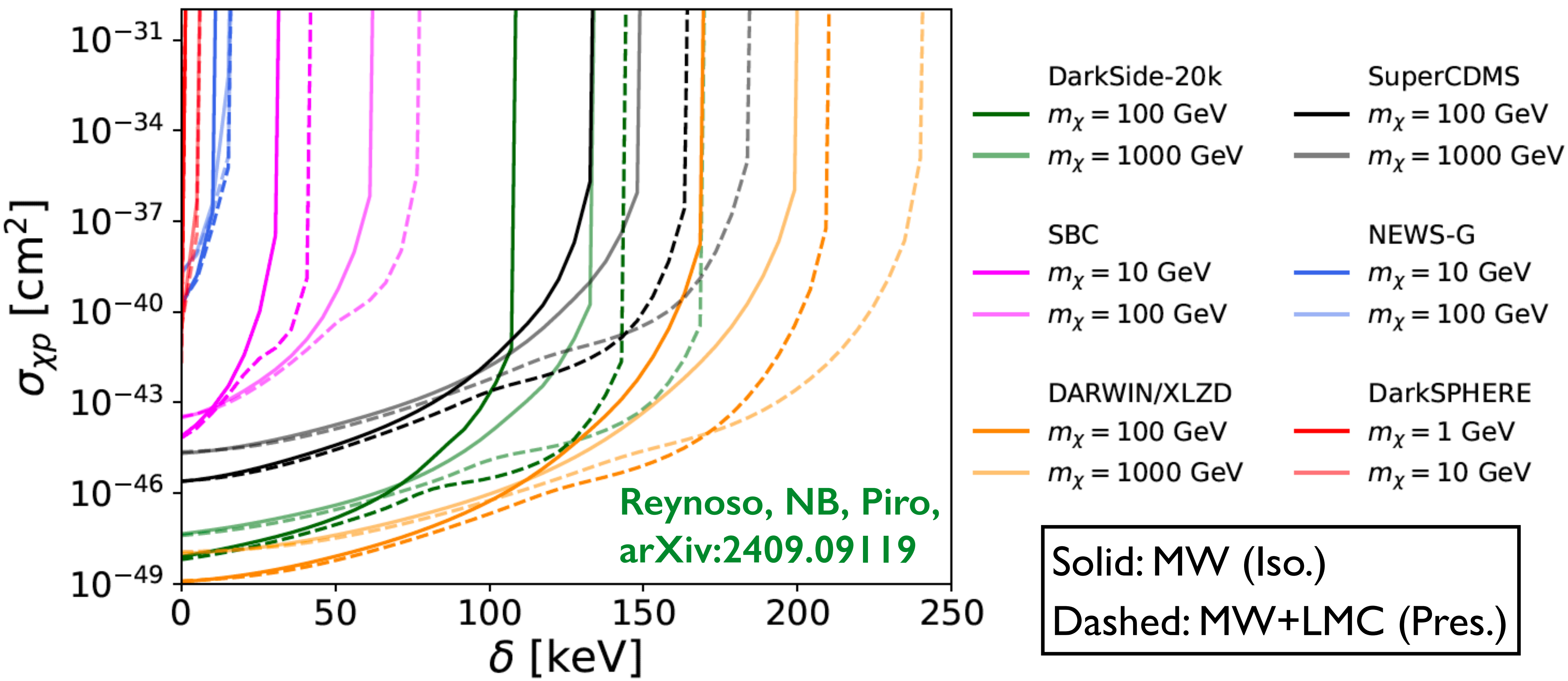

- The LMC shifts the exclusion limits towards larger δ and smaller $\sigma_{\chi p}$. ➡ ***The LMC increases the sensitivity of the experiments for probing larger values of δ.***

Summary

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

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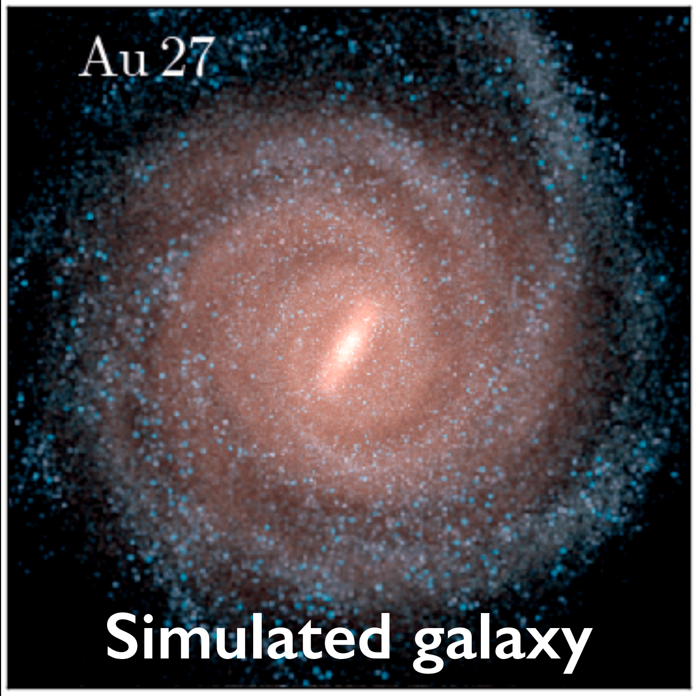


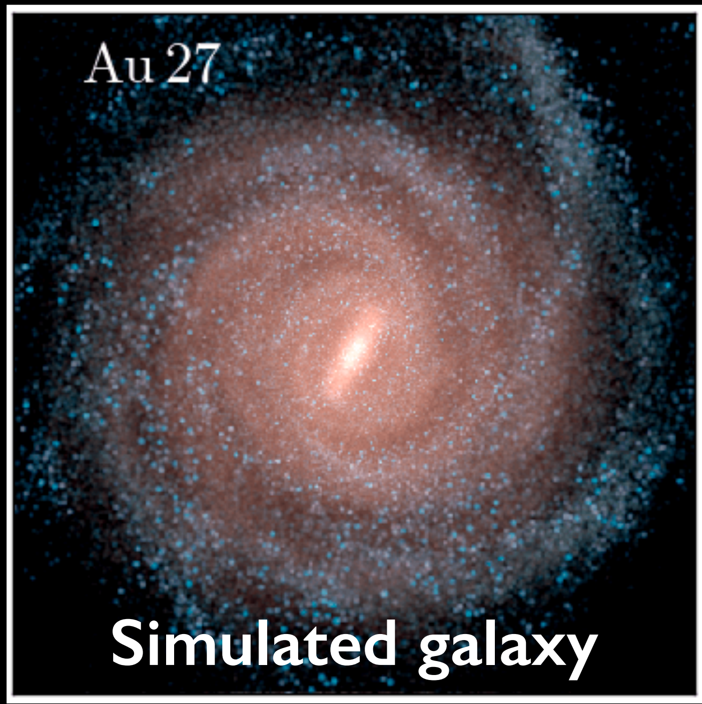
Simulated galaxy

Smooth halo

Local DM velocity distribution consistent with a Maxwellian.

Summary

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



Smooth halo

Local DM velocity distribution consistent with a Maxwellian.

Substructure

Large Magellanic Cloud

- LMC boosts the tail of the DM velocity distribution. → *Significantly increases the sensitivity of direct detection experiments.*

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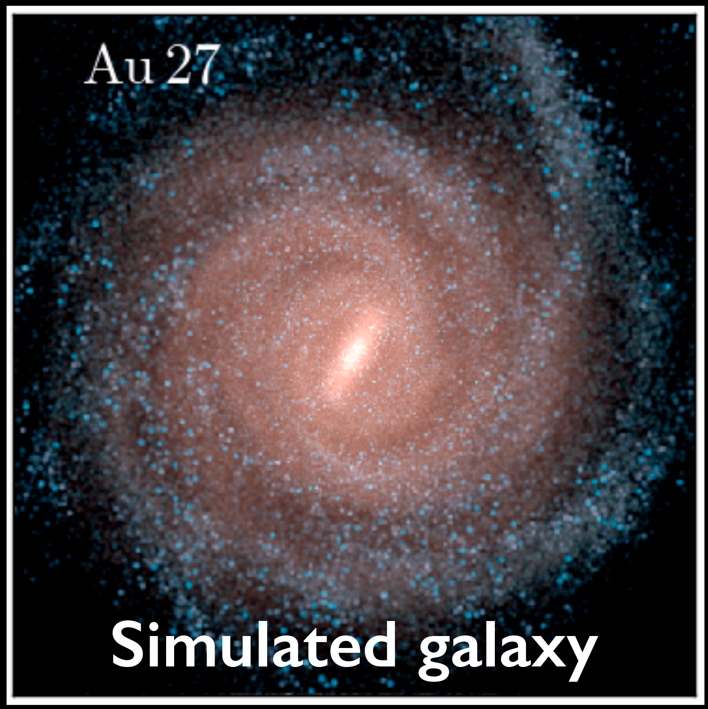
Cosmological simulations provide important insight on the local DM distribution. → *Crucial for the interpretation of direct detection data.*



Smooth halo

Local DM velocity distribution consistent with a Maxwellian.

Substructure

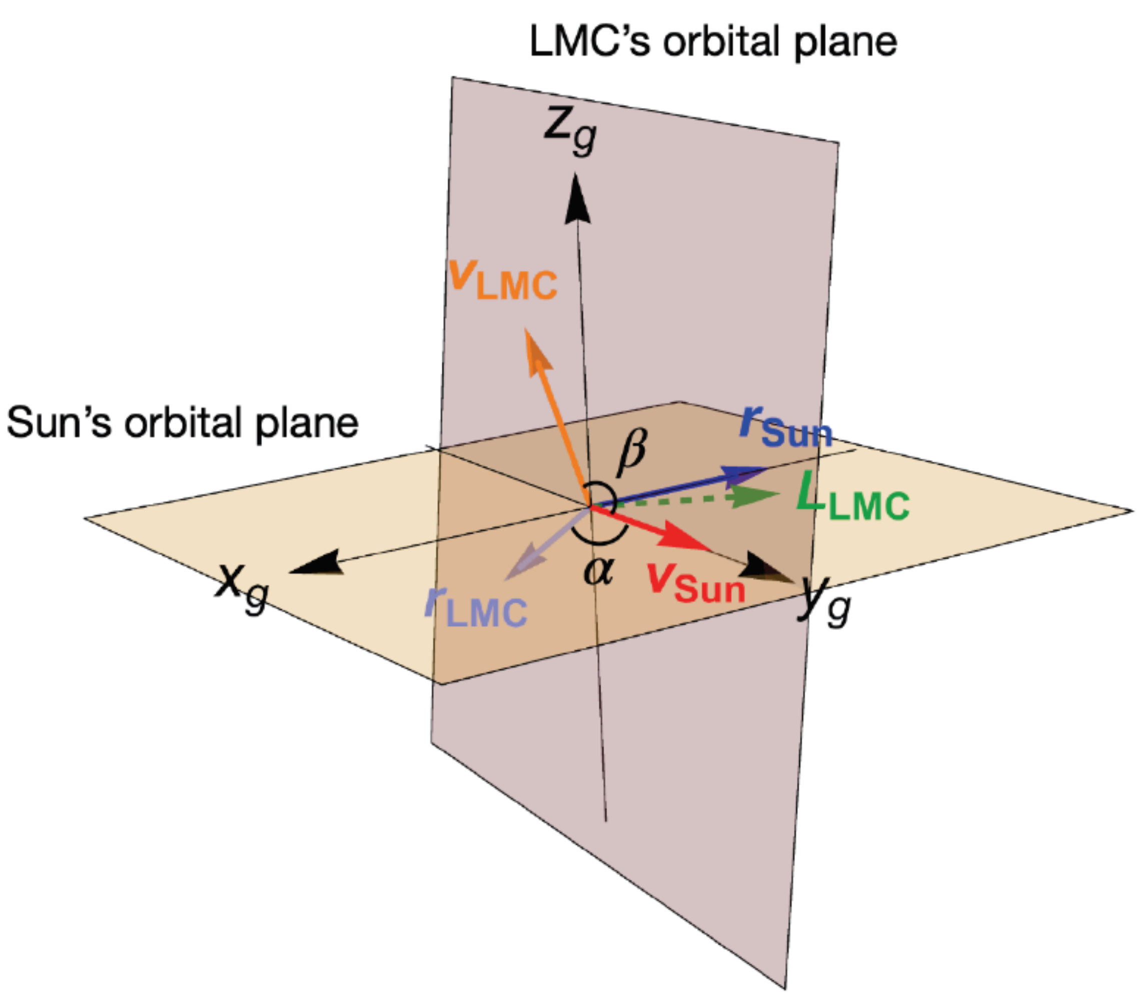
Large Magellanic Cloud

- LMC boosts the tail of the DM velocity distribution. → ***Significantly increases the sensitivity of direct detection experiments.***
- Impact even more significant for ***velocity-dependent*** operators and ***inelastic DM***.

Backup Slides

Matching the Sun-LMC geometry

Steps in matching the Sun-LMC geometry to observations:



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

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

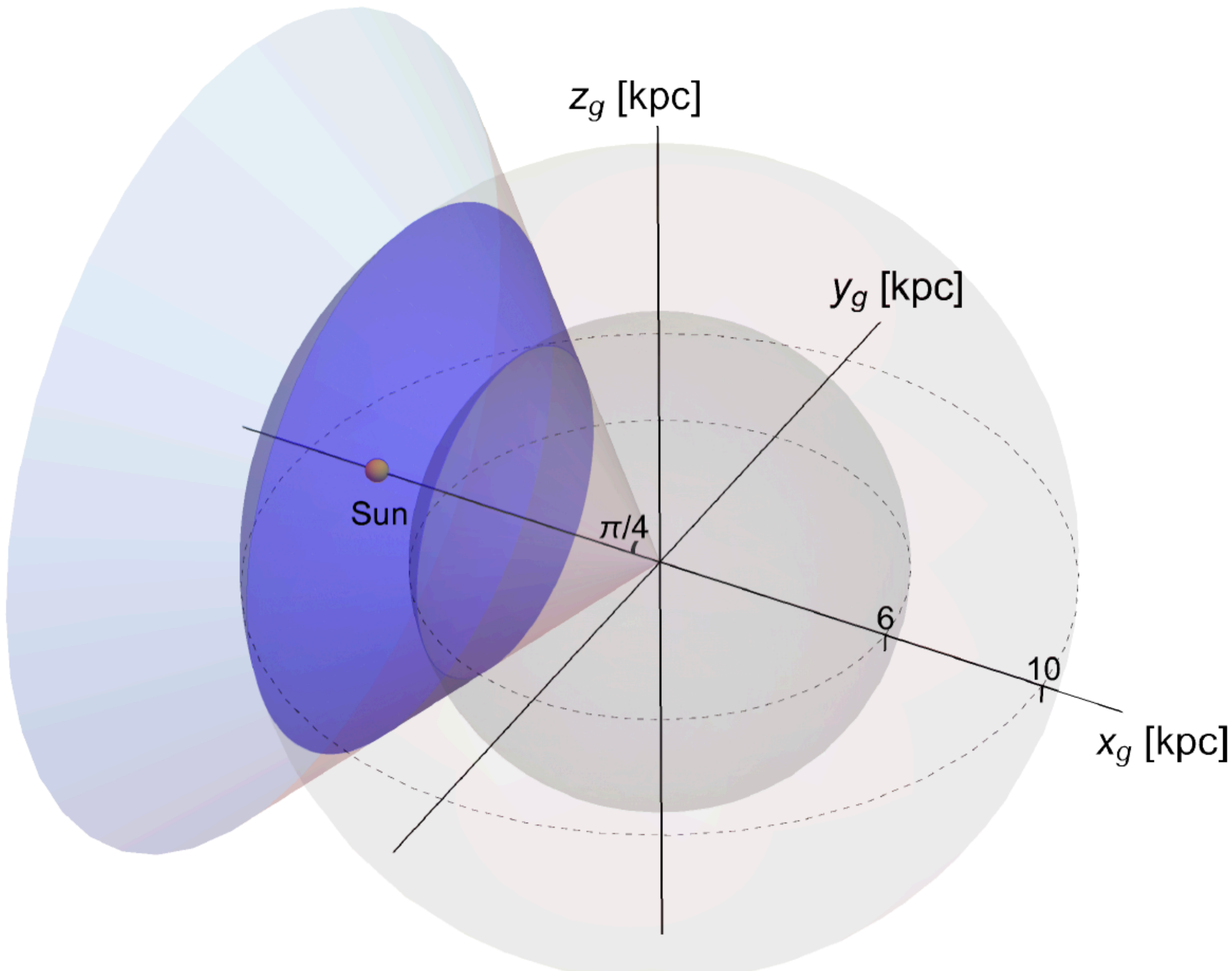
1. Find the stellar disk orientations that make the same angle with the orbital plane of the LMC analogues as in observations.

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.

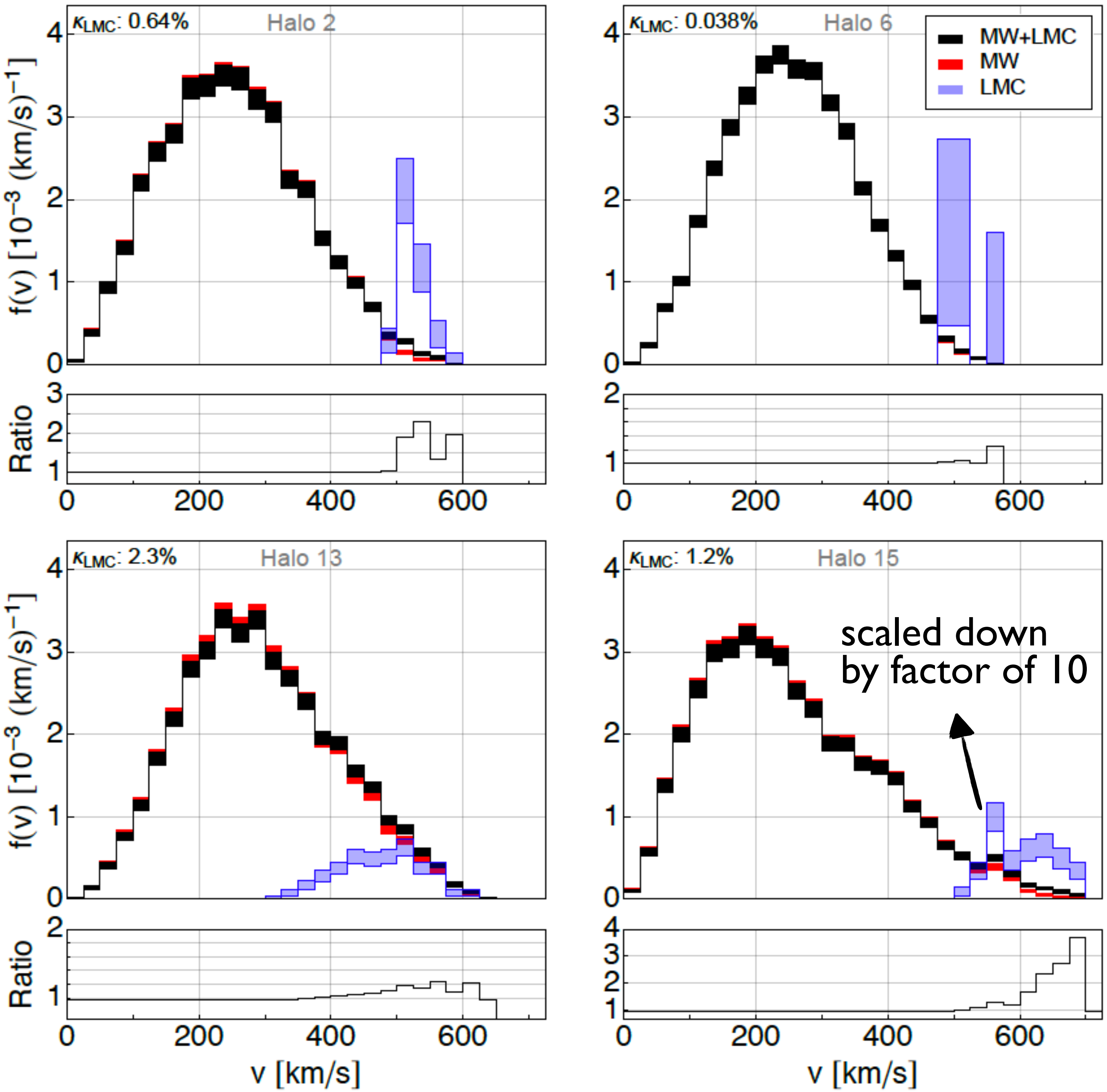
Defining the Solar region

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)



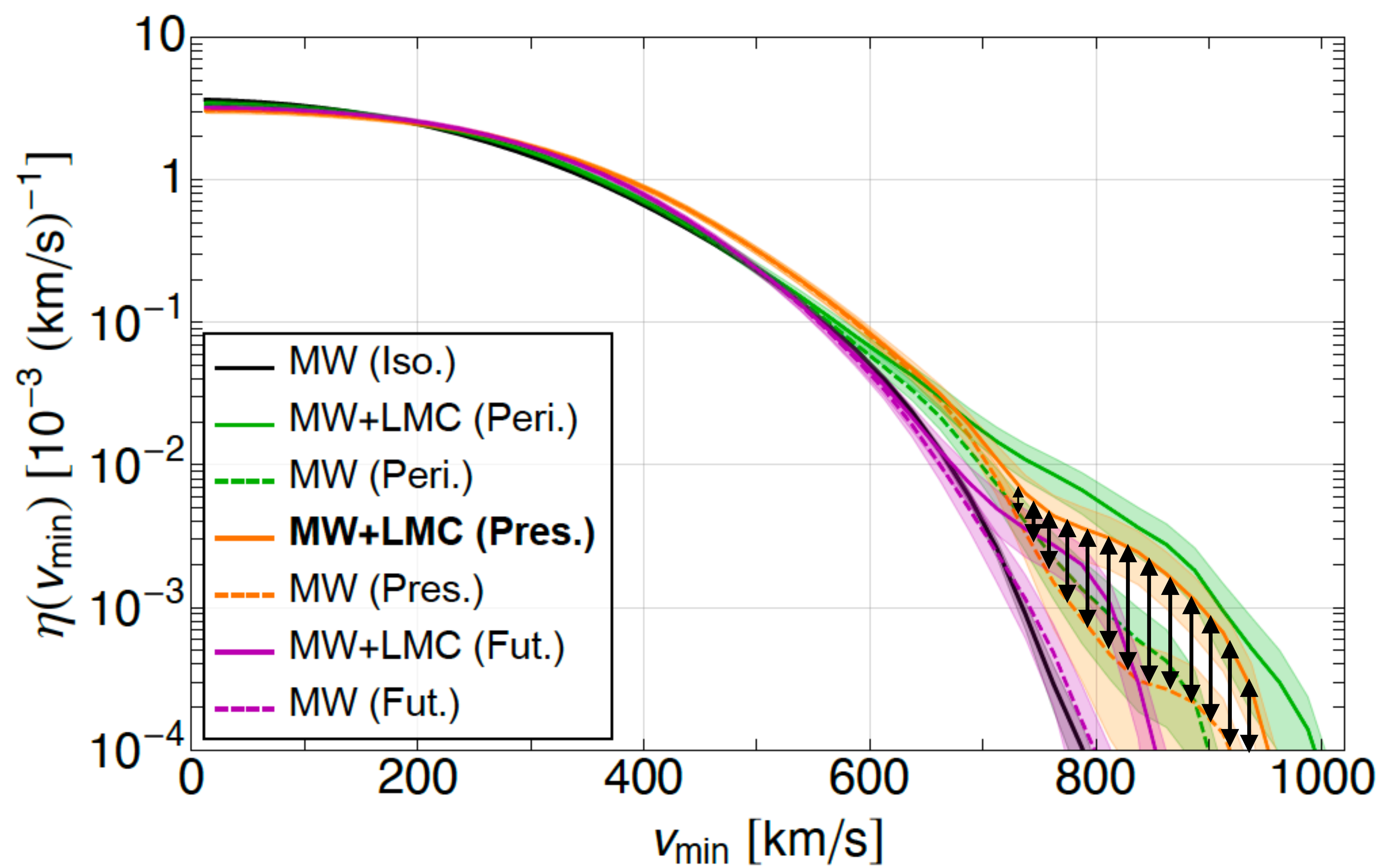
Smith-Orlik et al., JCAP 10, 070 (2023)

- 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

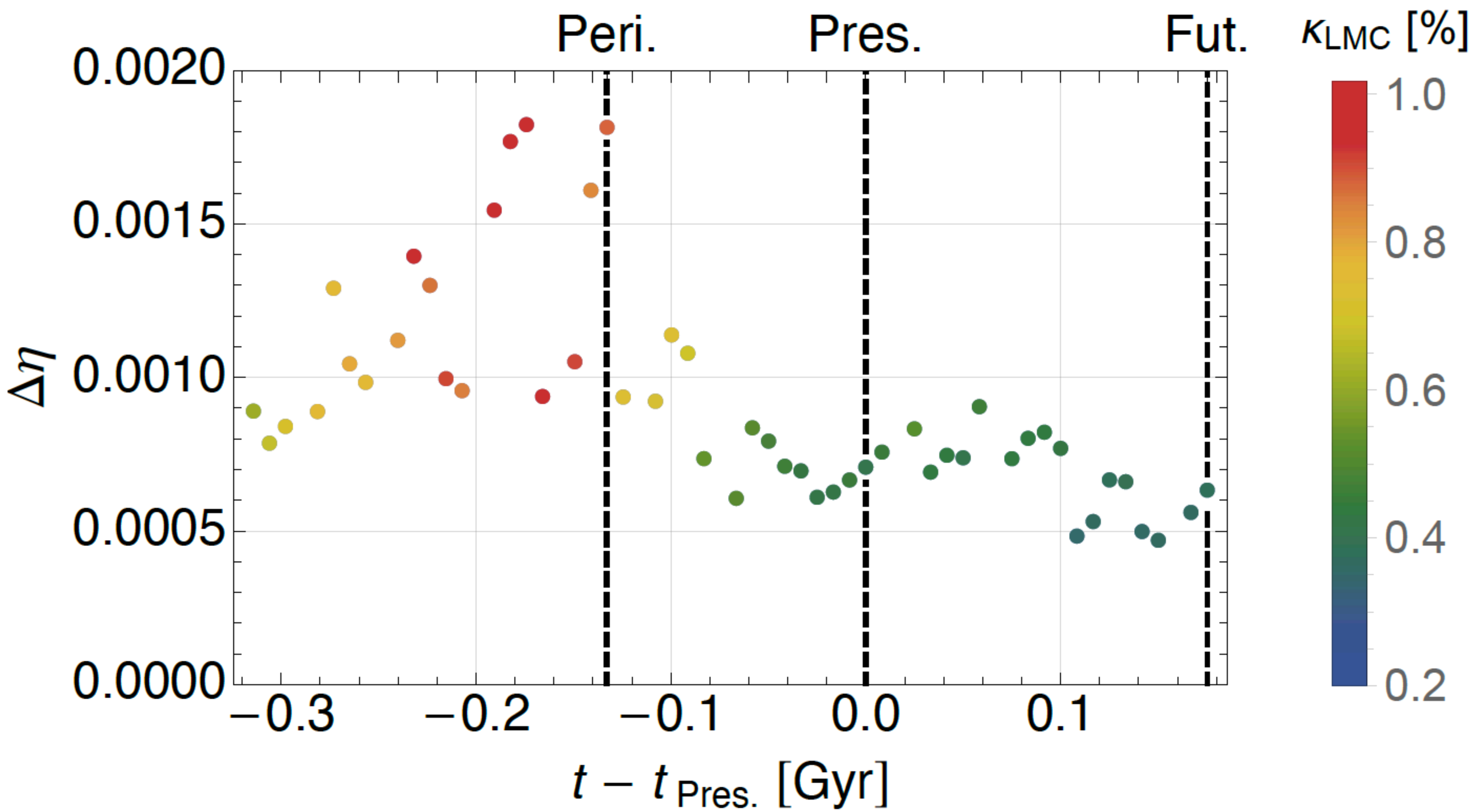
Quantify the changes in the tails of the halo integrals by:

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



Impact of the DM particles from the LMC

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

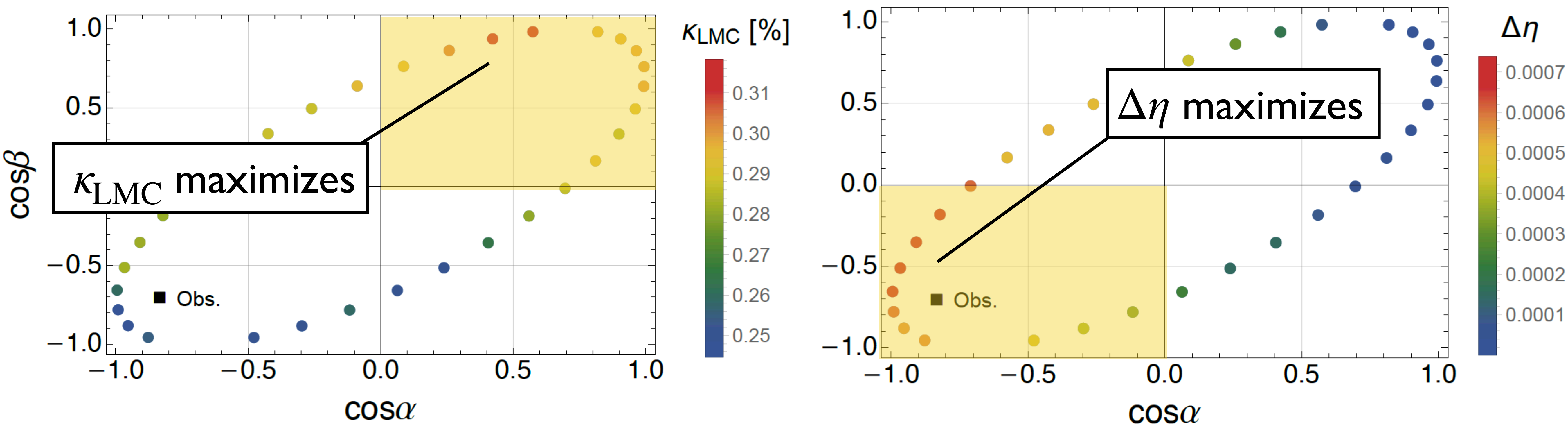


Smith-Orlik et al., JCAP 10, 070 (2023)

Variation with the Sun-LMC geometry

Cosine angles that parametrize the Sun-LMC geometry:

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



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.*

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

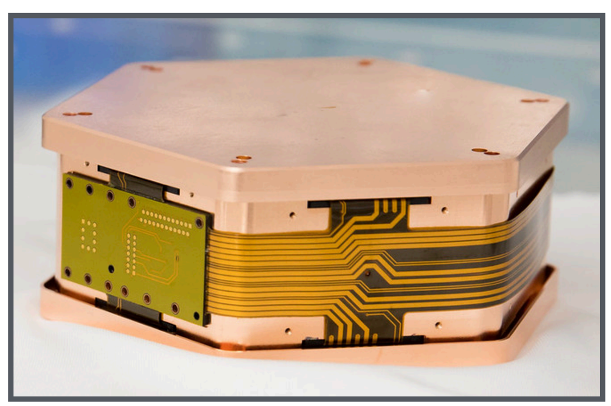
Xenon based

$[2-50]$ 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

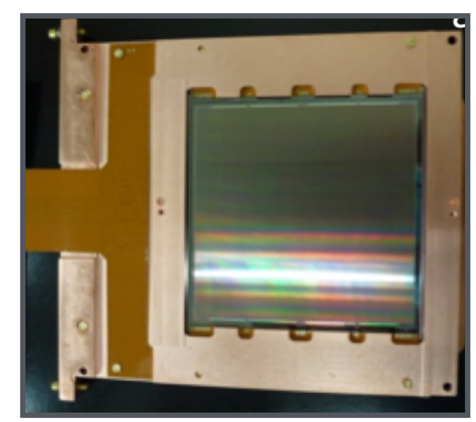
Based on SuperCDMS



Electron recoils

Silicon CCD

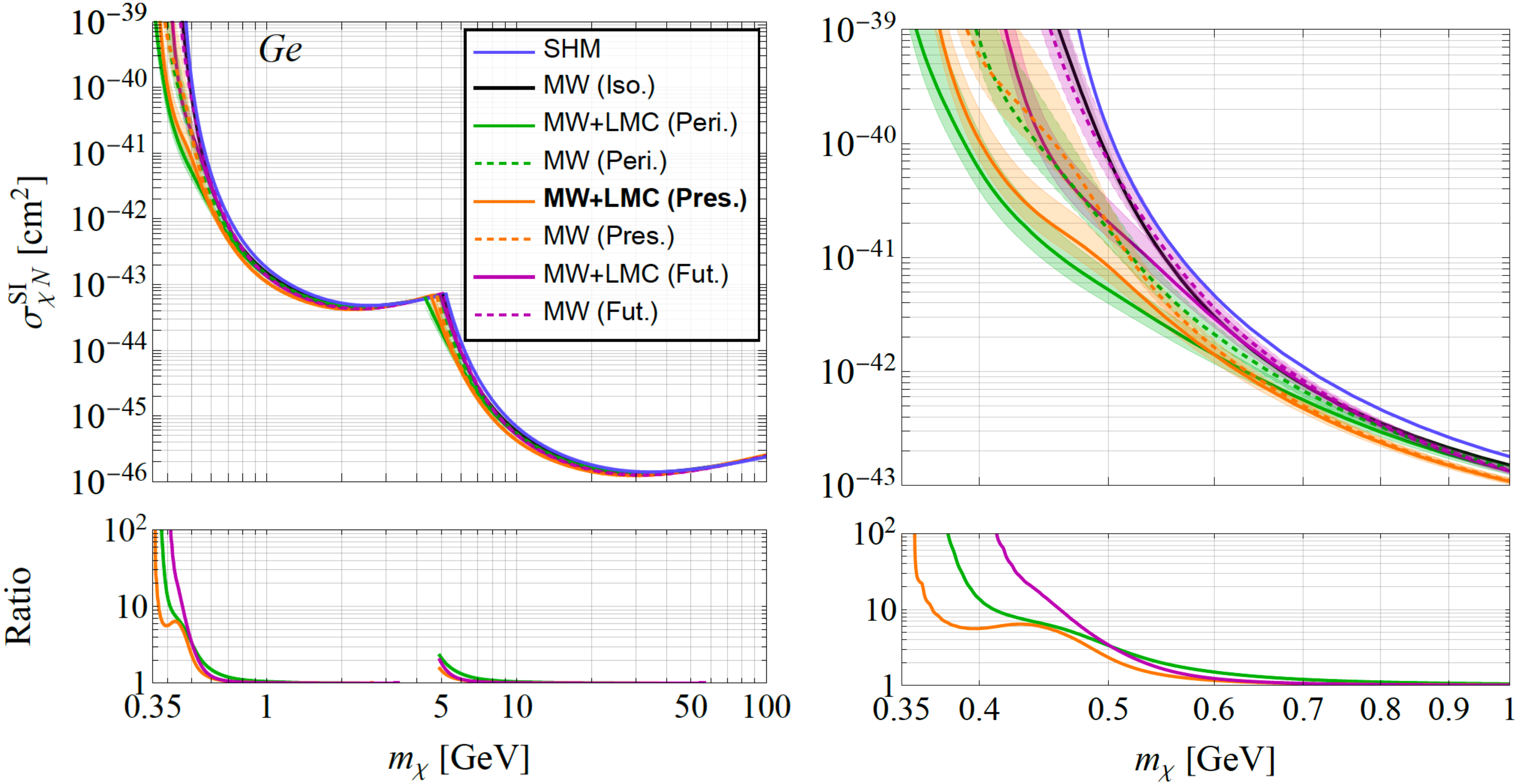
1 electron threshold
1 kg yr
Based on DAMIC



Direct detection: nuclear recoils

Germanium based detector:

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



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

Direct detection: electron recoils

Silicon CCD detector:

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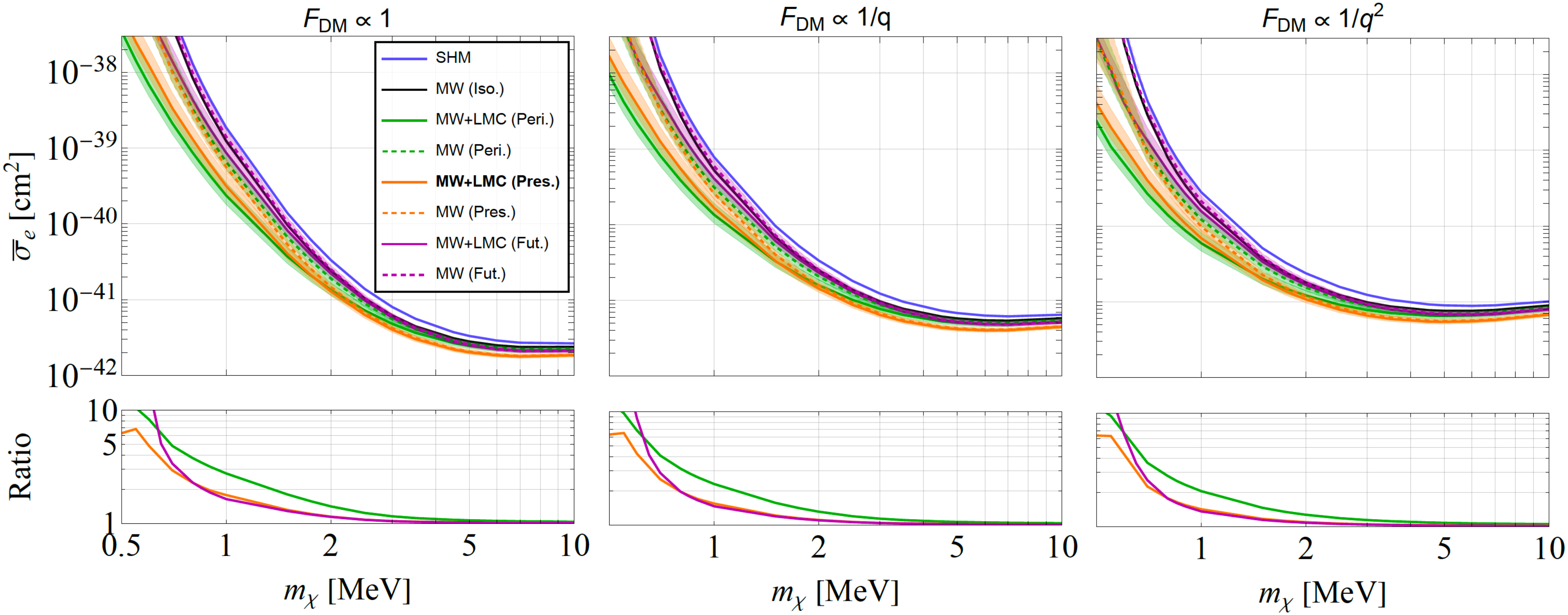


Smith-Orlik et al., JCAP 10, 070 (2023)

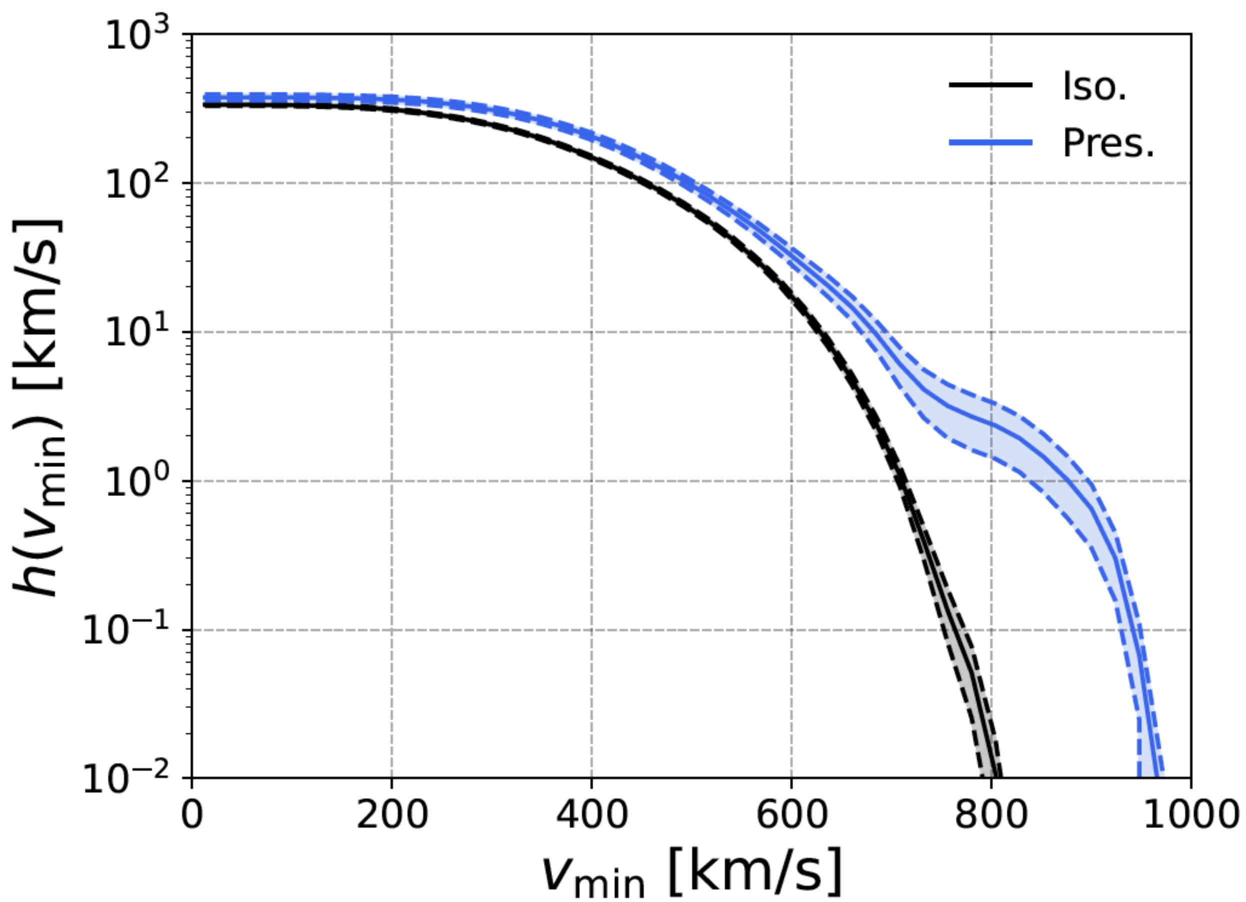
Beyond standard interactions

- For a very general set of non-relativistic effective operators:

Kahlhoefer & Wild, JCAP 11, 016 (2017)

$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{d\sigma_1}{dE_R}\frac{1}{v^2} + \frac{d\sigma_2}{dE_R}$$

$$\eta(v_{\rm min}, t) \qquad h(v_{\rm min}, t) = \int_{v>v_{\rm min}} d^3v\, v\, f_{\rm det}(\mathbf{v}, t)$$



Reynoso, NB, Piro, arXiv:2409.09119

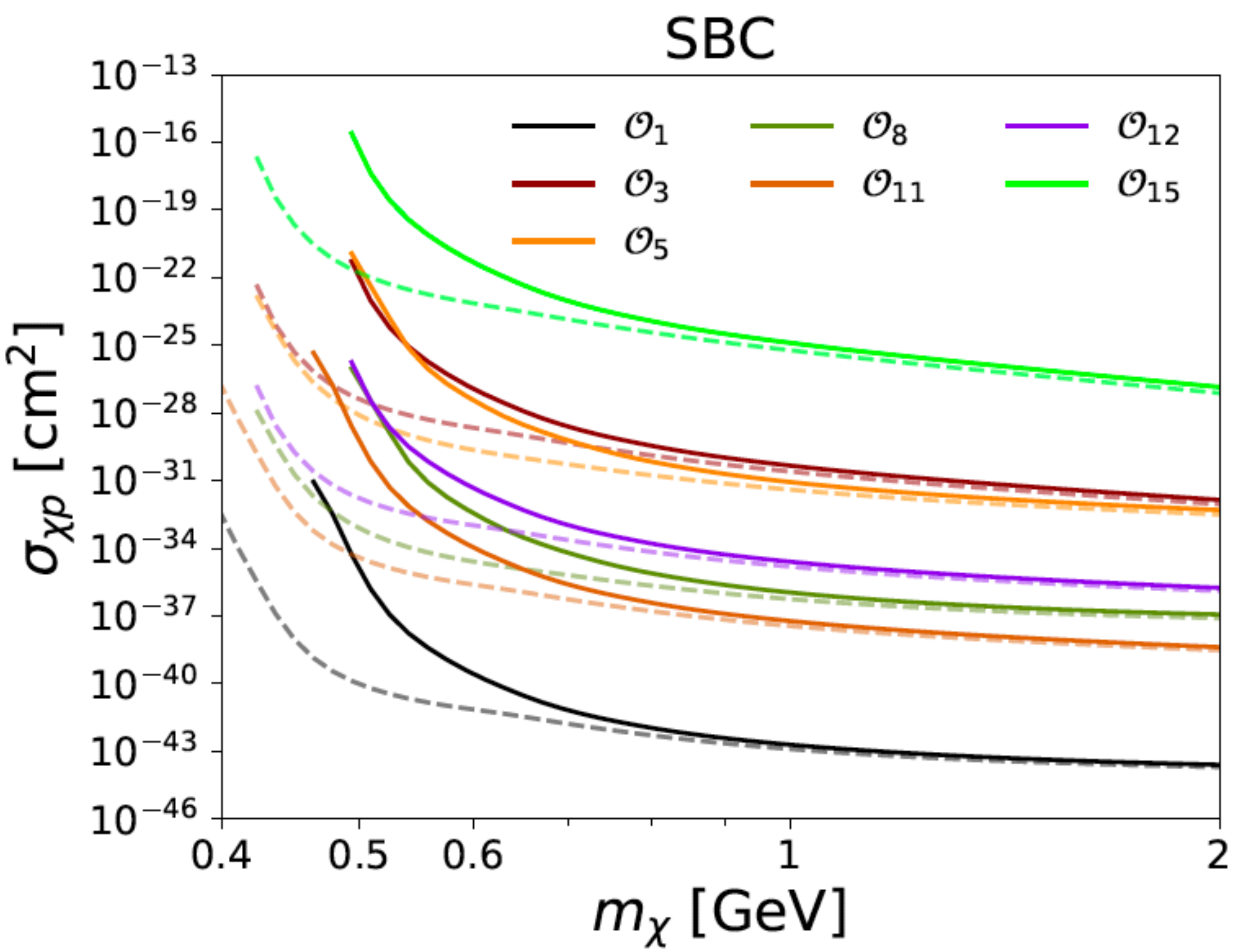
- The LMC leads to a Shift of > 160 km/s in the high speed tail of $h(v_{\rm min})$ at the present day.

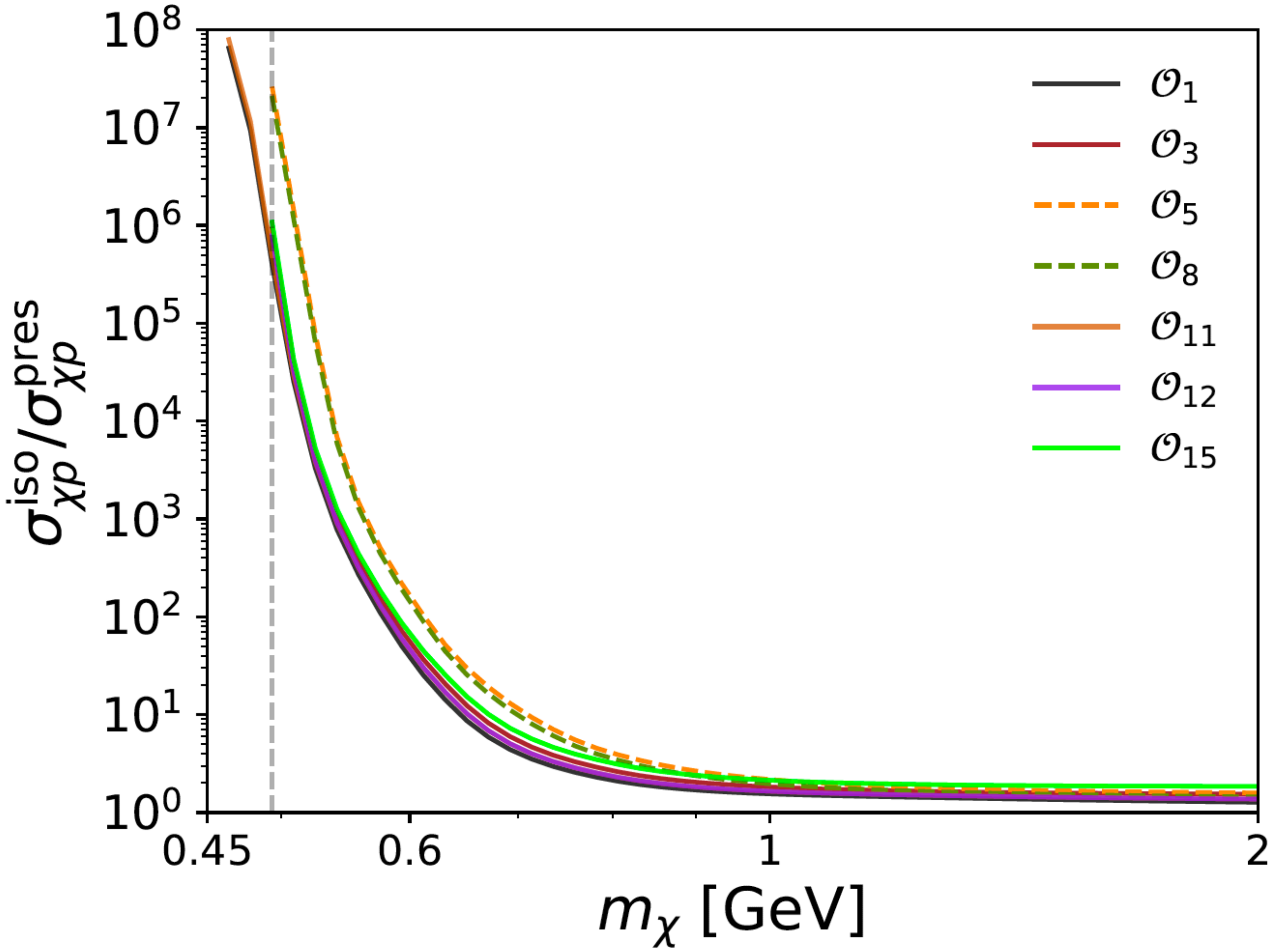
Direct detection exclusion limits

- Simulate the signals in 6 near-future direct detection experiments, which use different detector technology and target nuclei:

Experiment	Target Nucleus	Exposure [kg.day]	Energy range [keVnr]
DarkSide-20k	^{40}Ar	3.65×10^7	[30 - 200]
SBC	^{40}Ar	3.65×10^3	[0.1 - 10]
DARWIN/XLZD	Xe	7.3×10^7	[5 - 21]
SuperCDMS	Ge	1.6×10^4	[0.04 - 0.3]
NEWS-G	^{20}Ne	18	[0.03 - 1]
DarkSPHERE	^{4}He	7.4×10^3	[0.03 - 1]

SBC





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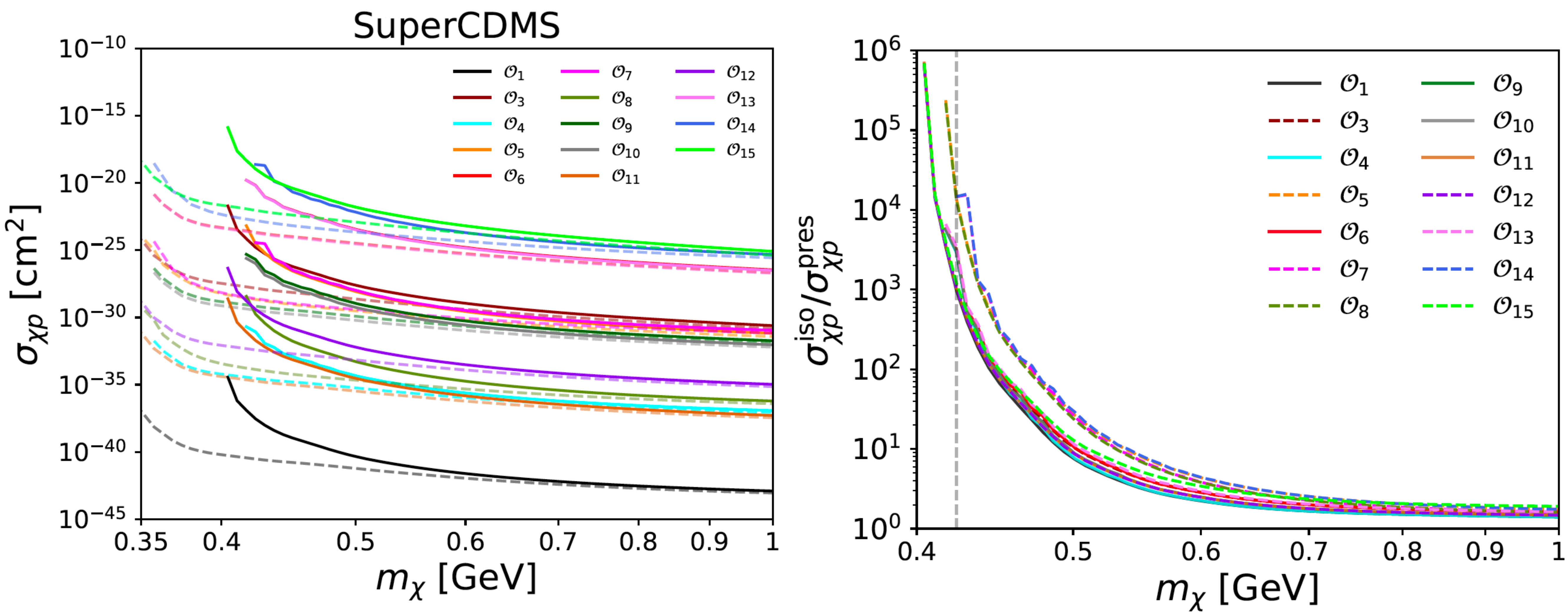
SuperCDMS



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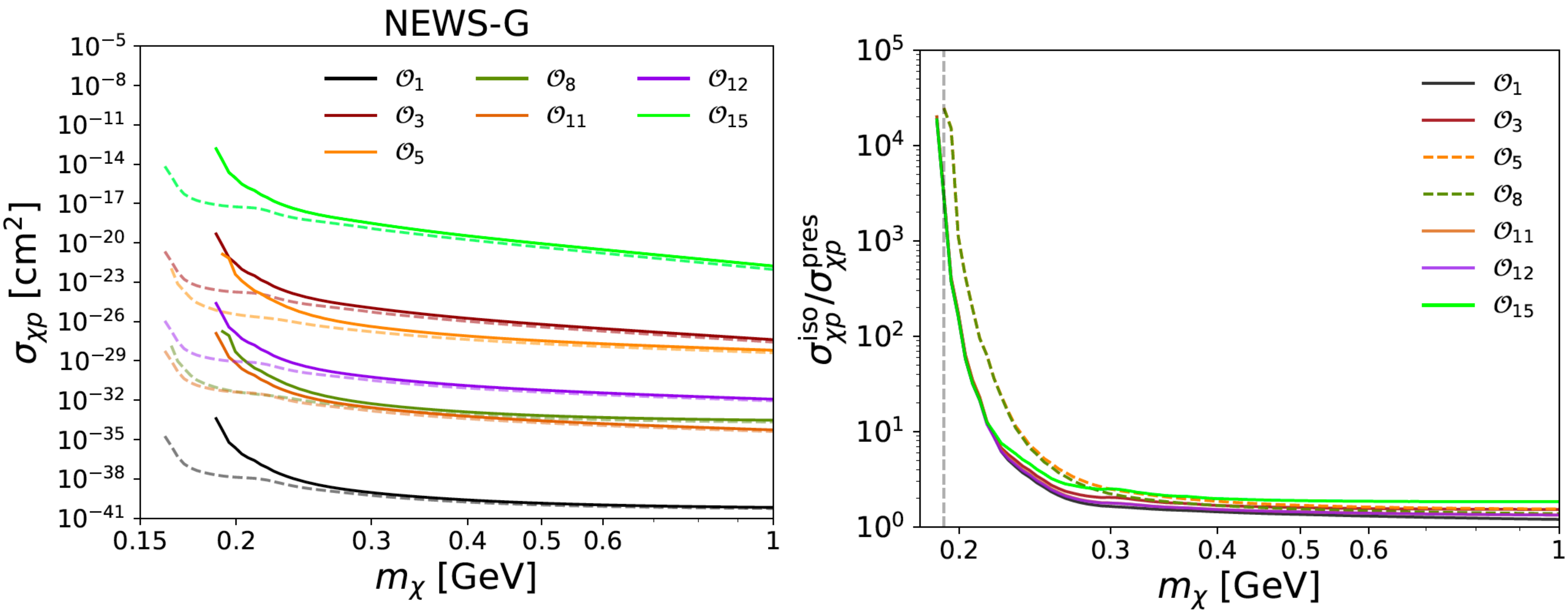
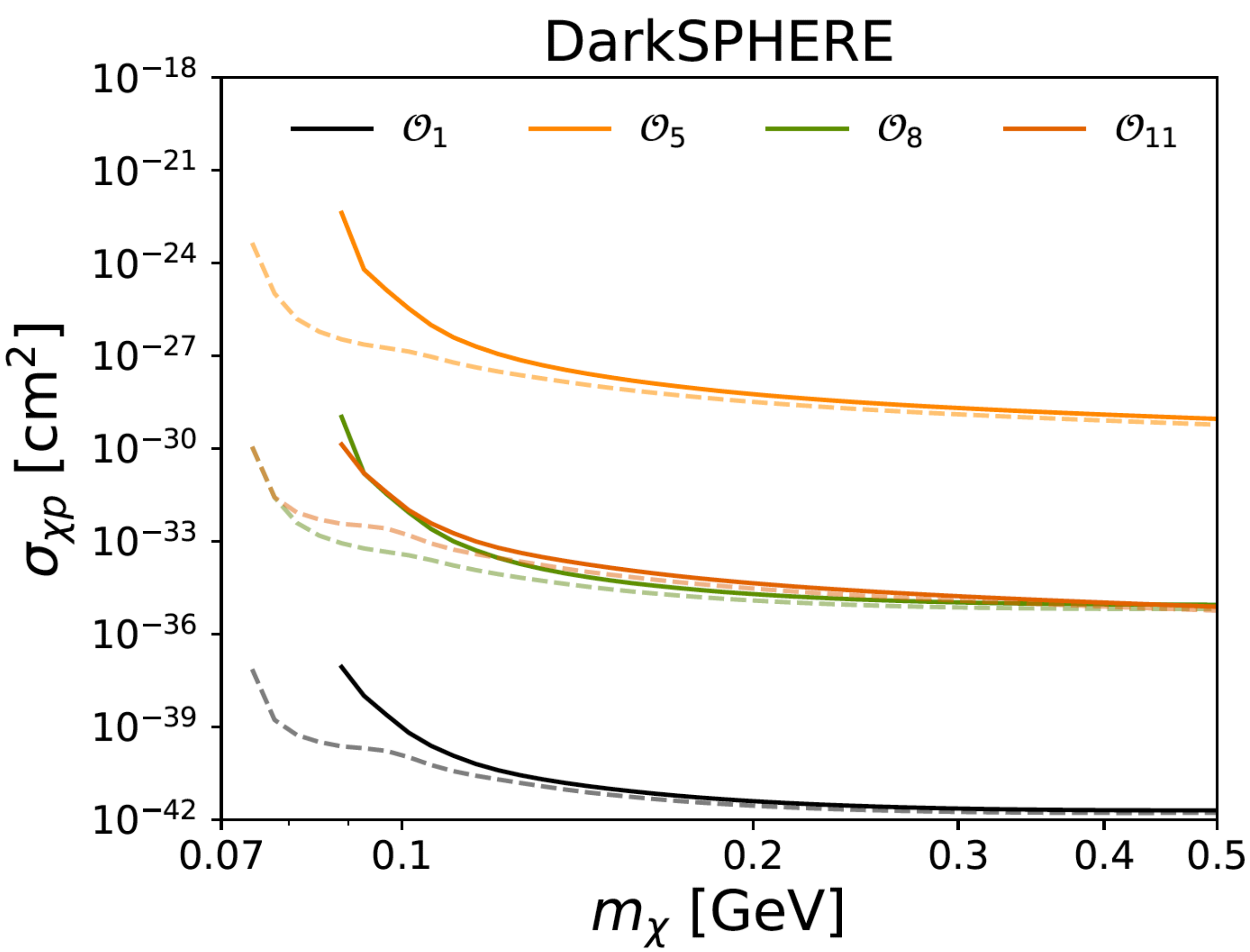
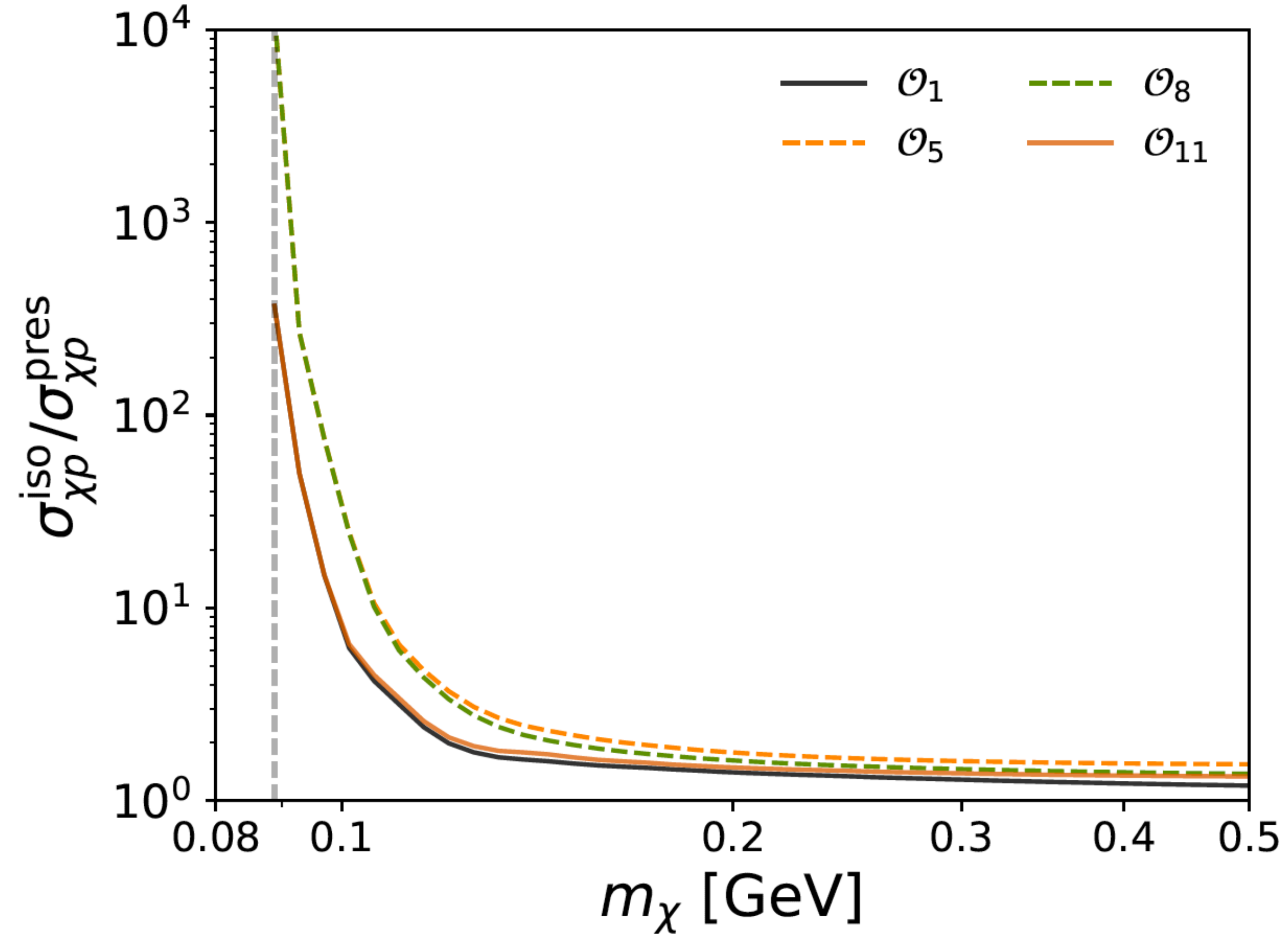
NEWS-G



Reynoso, NB, Piro, arXiv:2409.09119

DarkSPHERE





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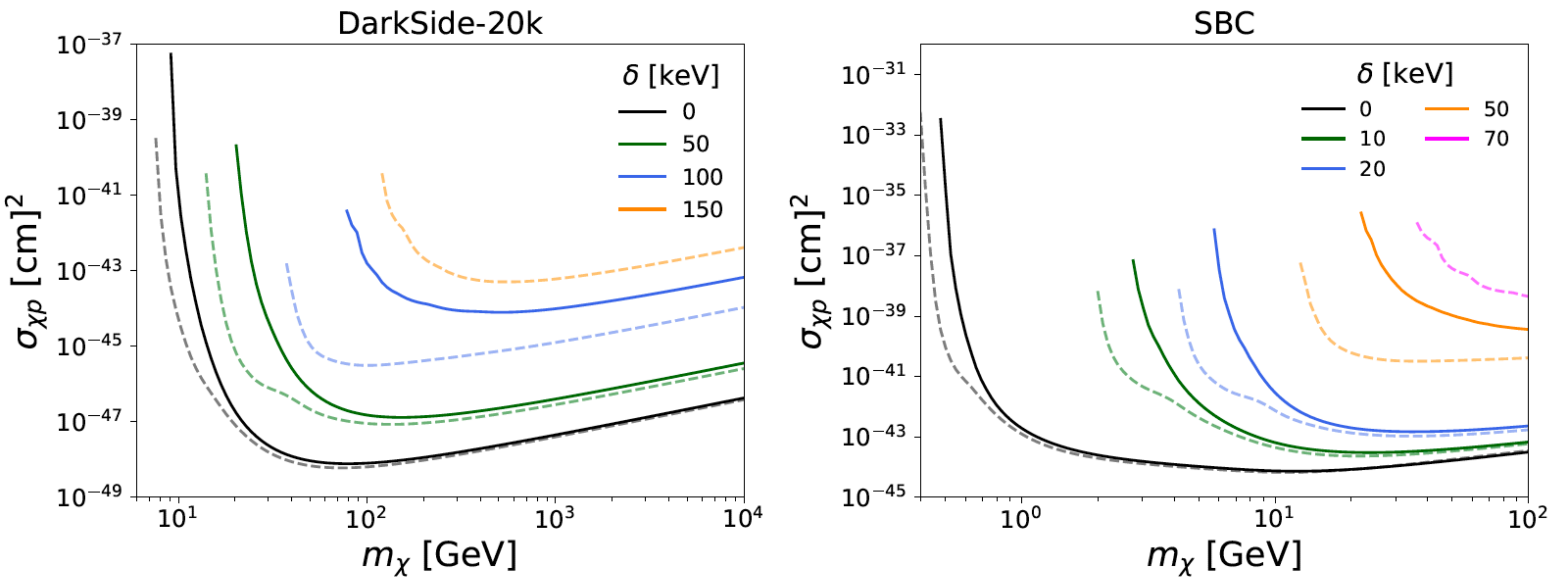
Inelastic dark matter



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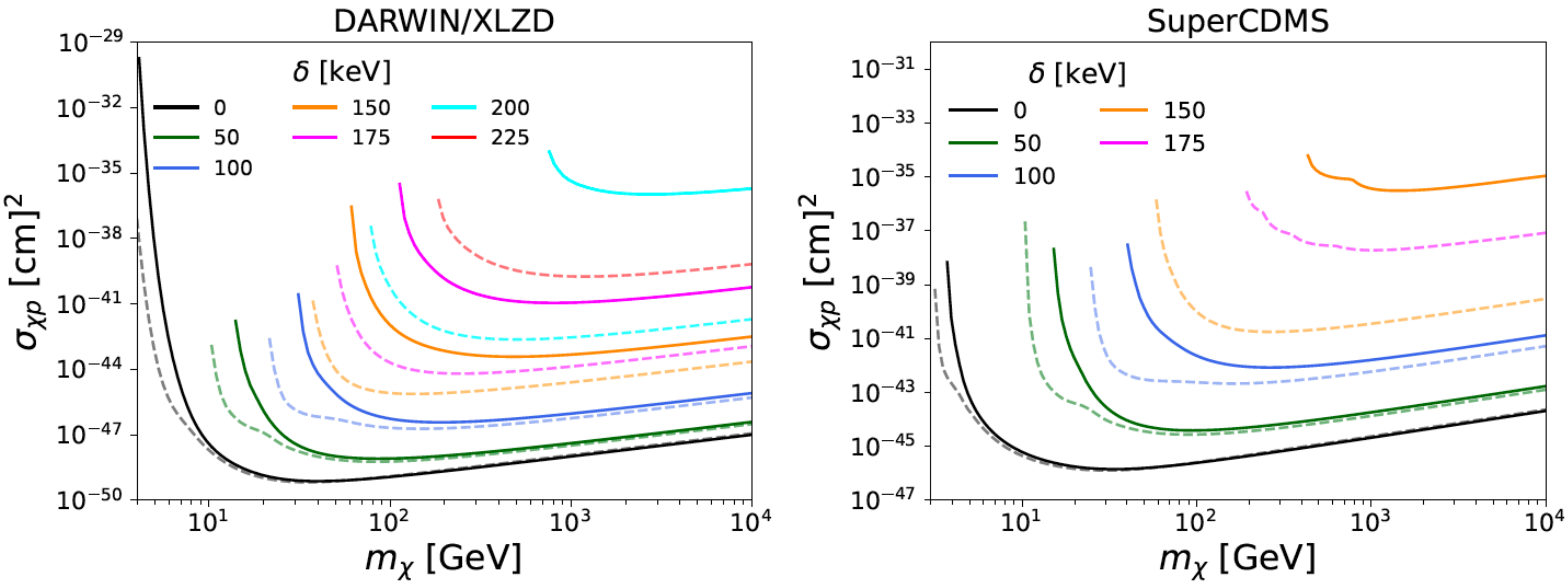

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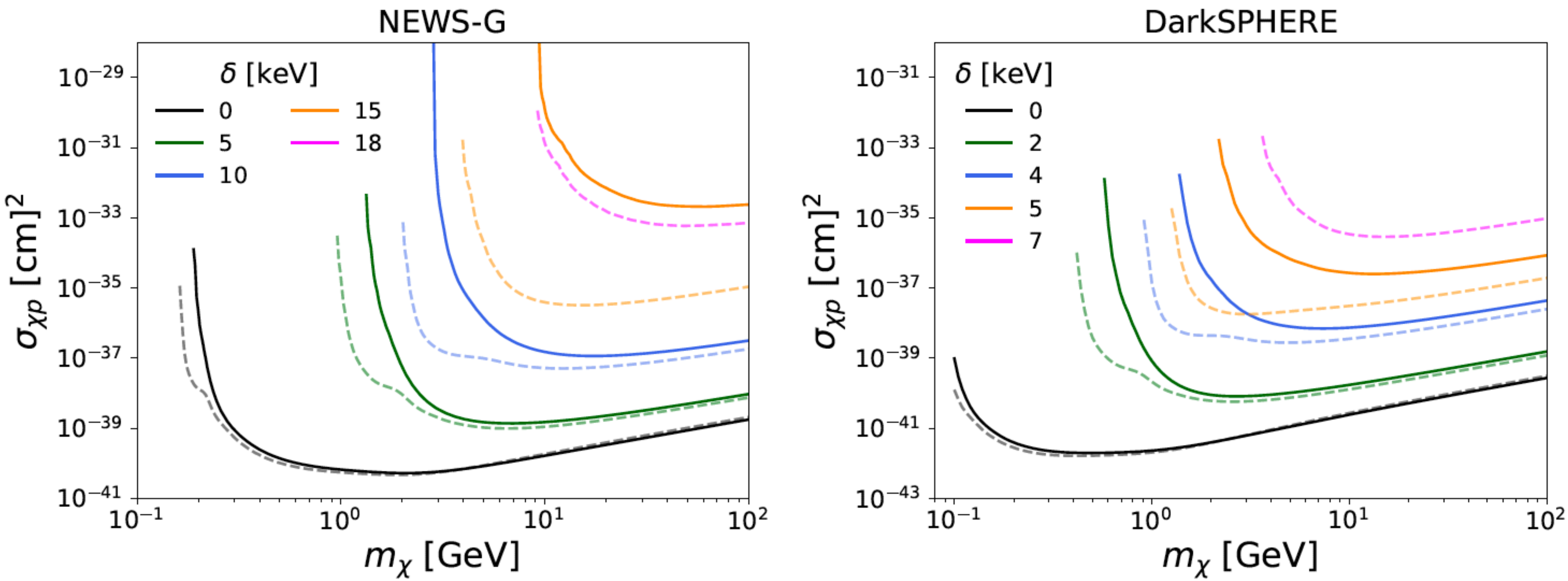

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