Imprints of the LMC on the Milky Way dark matter halo

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GeomGravX, University of Tartu
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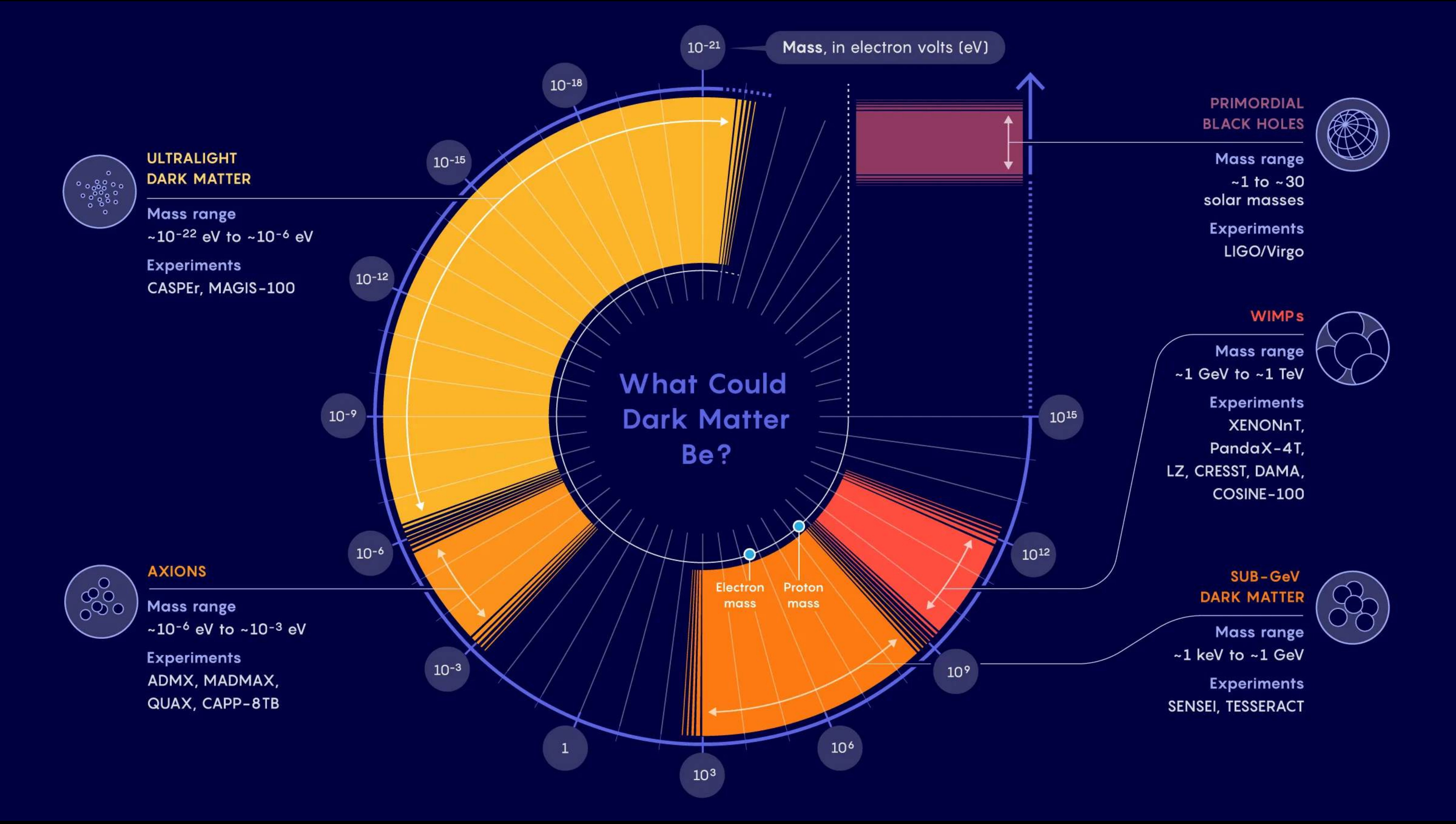
The nature of dark matter



Credit: Samuel Velasco/Quanta Magazine

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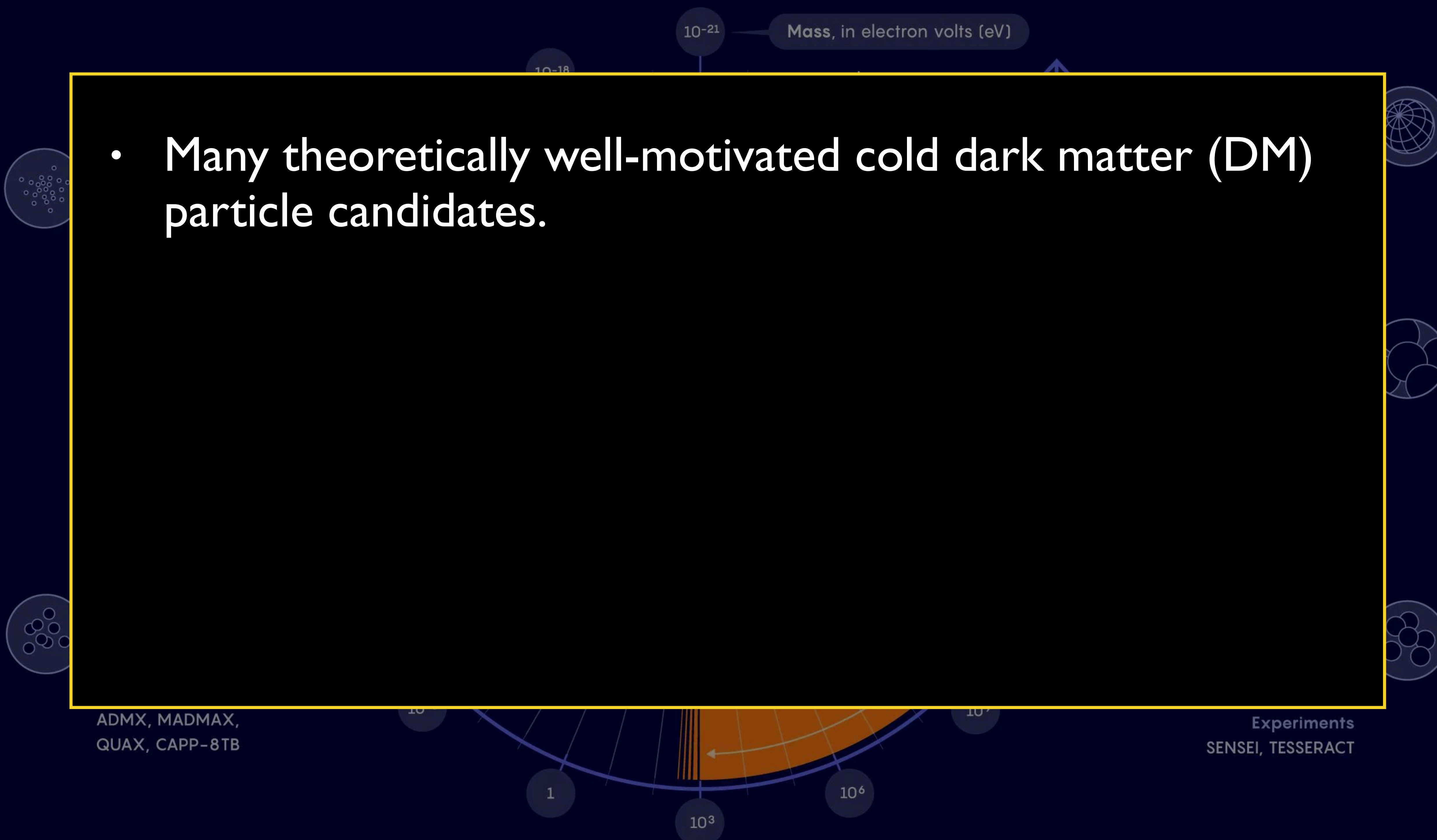

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Credit: Samuel Velasco/Quanta Magazine

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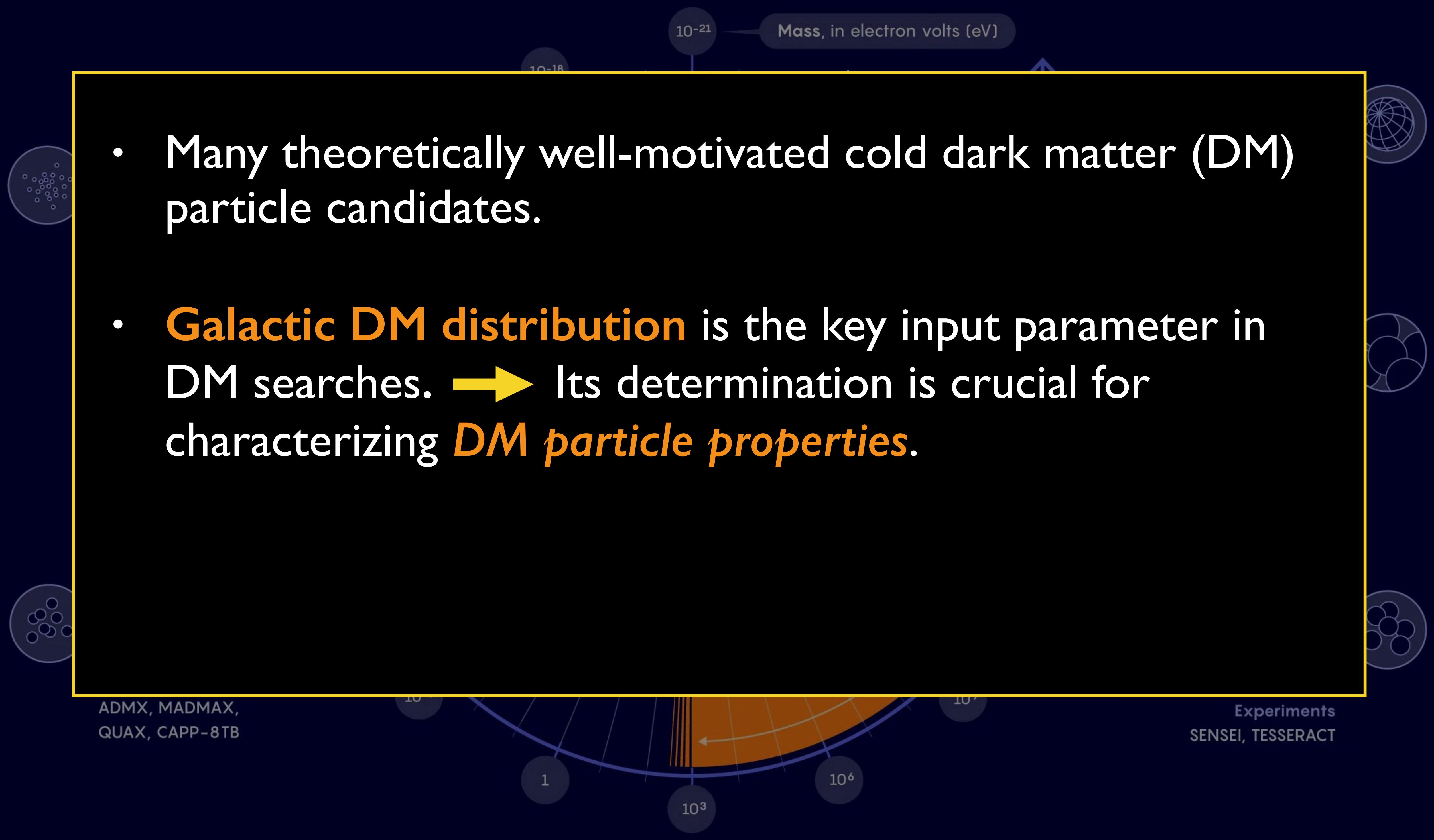
- **Galactic DM distribution** is the key input parameter in DM searches. → Its determination is crucial for characterizing ***DM particle properties***.



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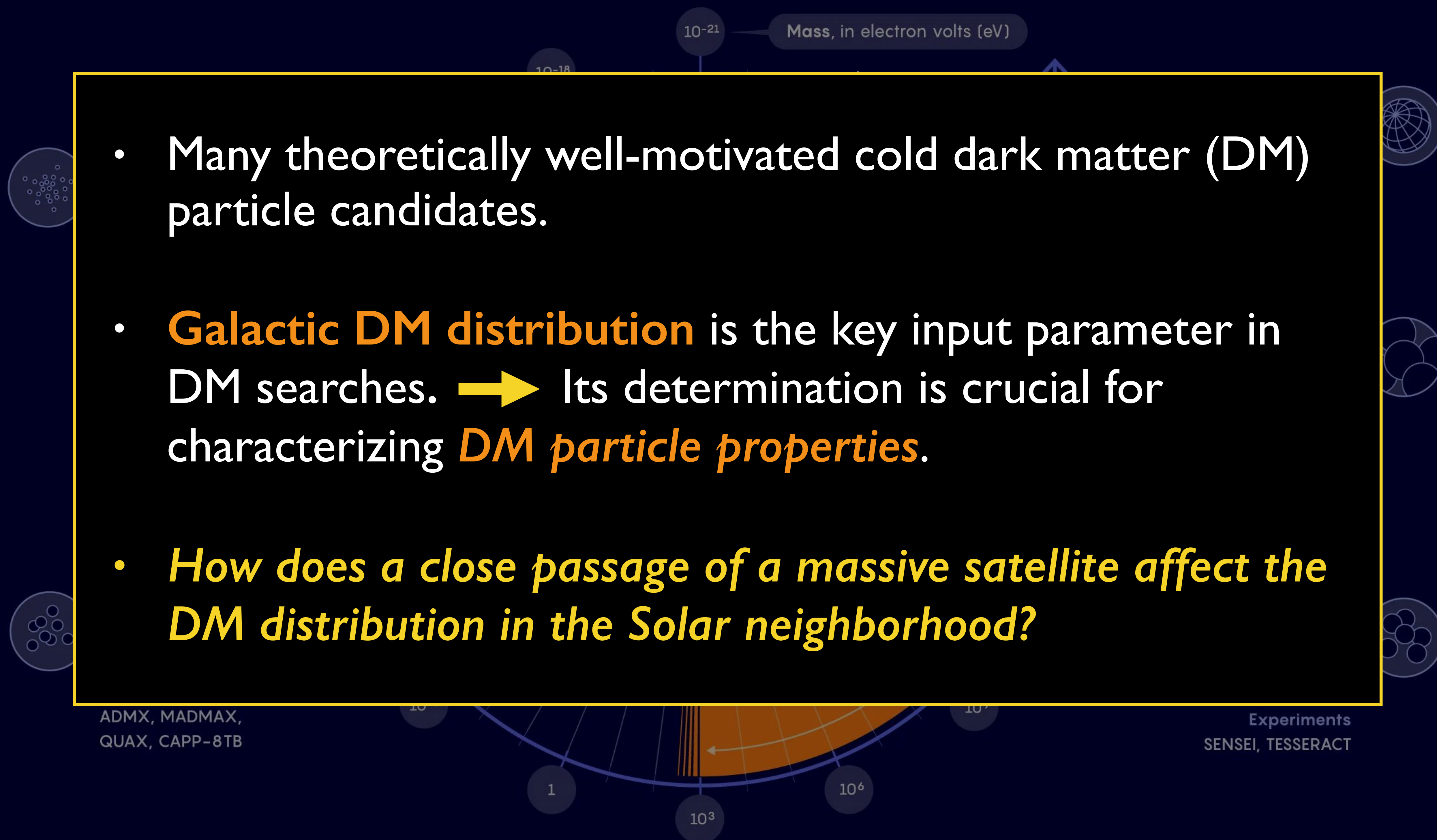

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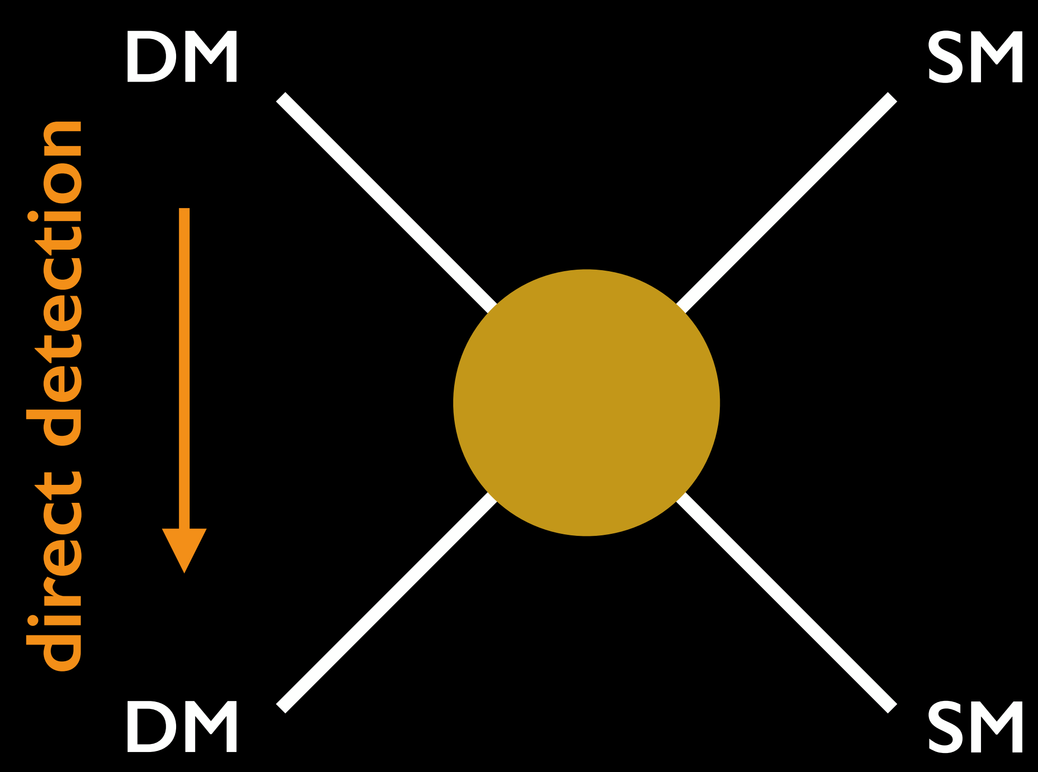
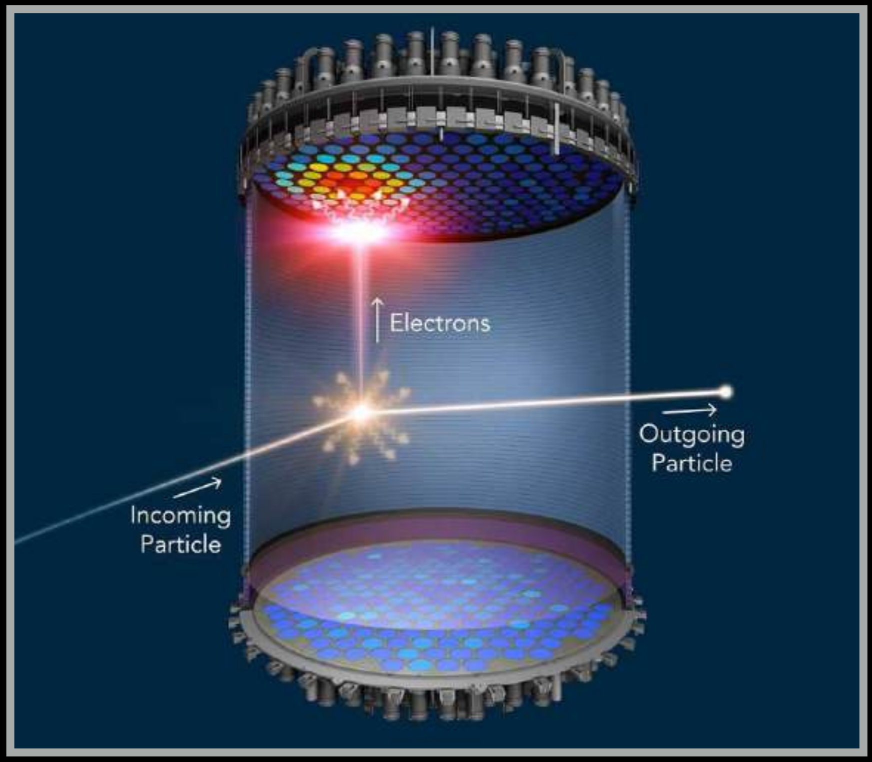
- **Galactic DM distribution** is the key input parameter in DM searches. ➡ Its determination is crucial for characterizing *DM particle properties*.
- *How does a close passage of a massive satellite affect the DM distribution in the Solar neighborhood?*

Credit: Samuel Velasco/Quanta Magazine

Dark matter direct detection





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

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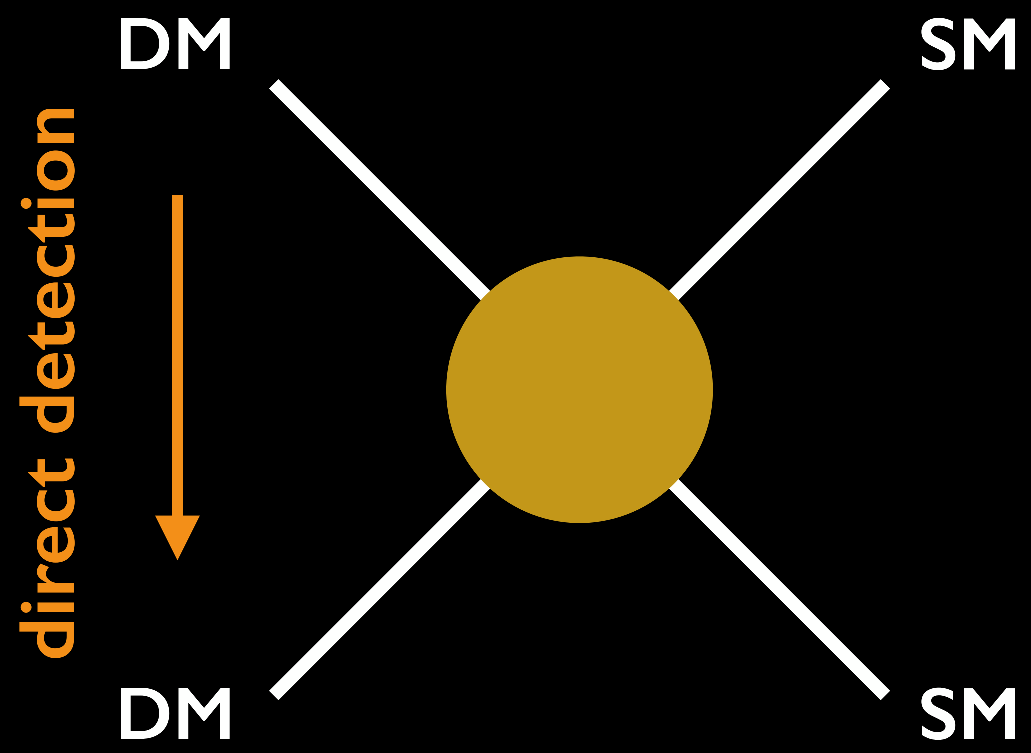

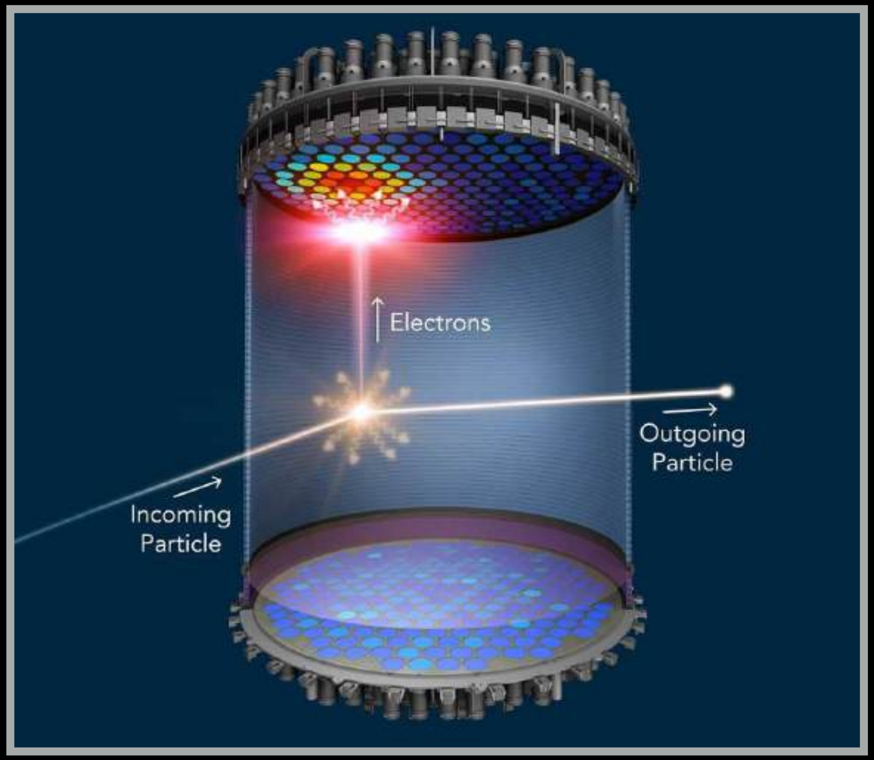

Signals in direct DM searches strongly depend on the DM distribution in the **Solar neighborhood**.

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

Dark matter direct detection

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

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

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astrophysics

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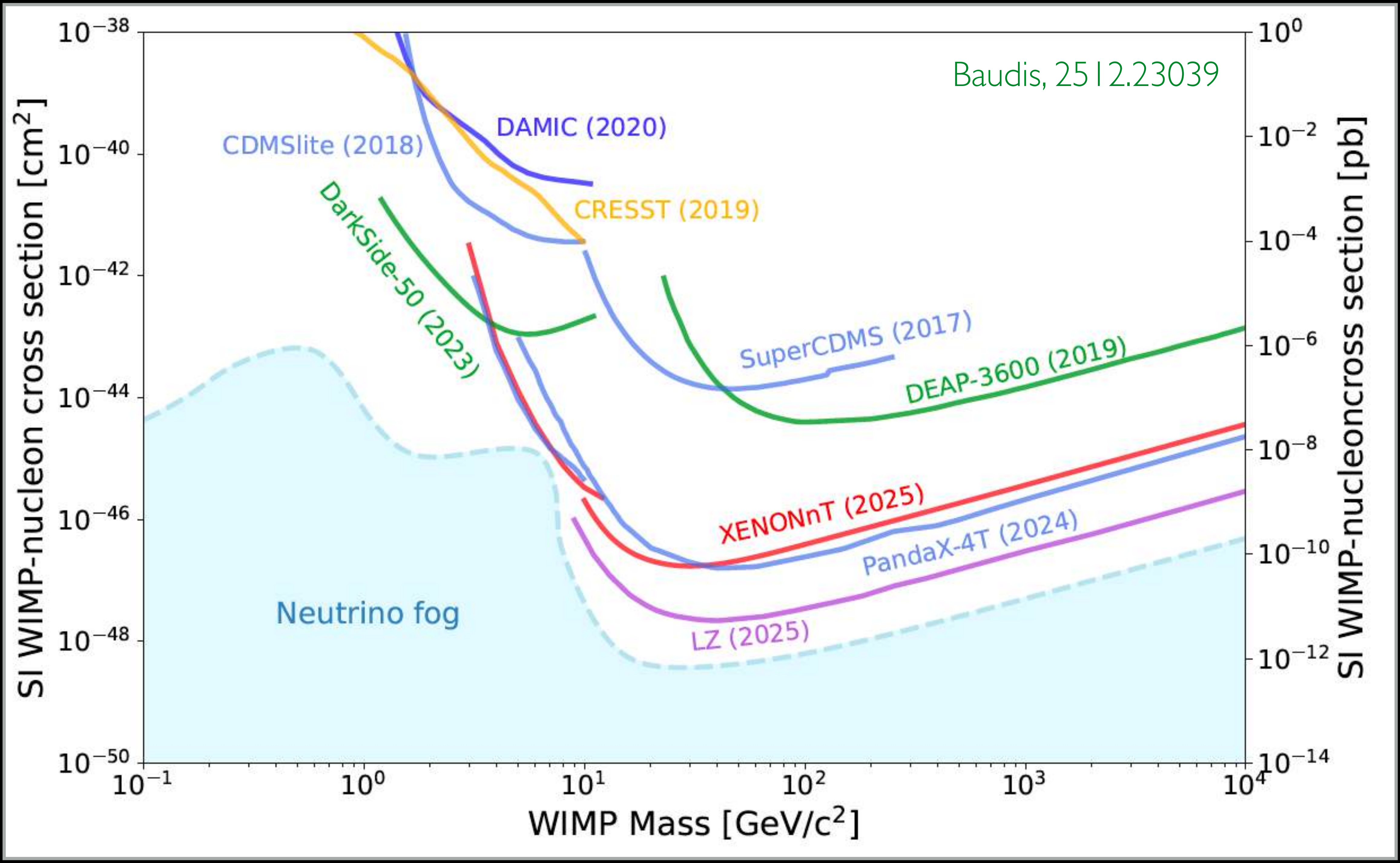
- Astrophysical inputs:
  - **local DM density:** *normalization in event rate.*
  - **local DM velocity distribution:** *enters the event rate through an integration.*

Direct detection exclusion 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

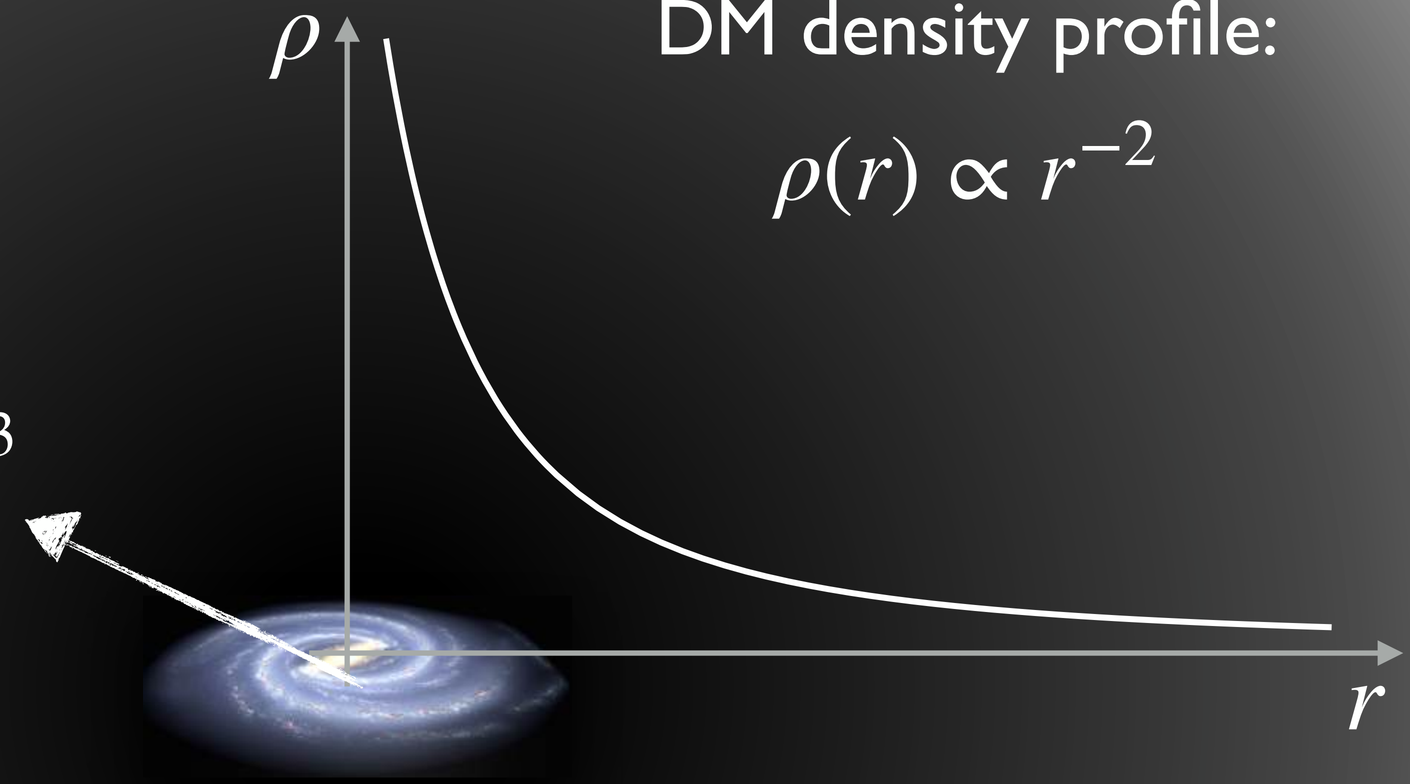
Standard Halo Model

DM density profile:

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

- Local DM density:

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



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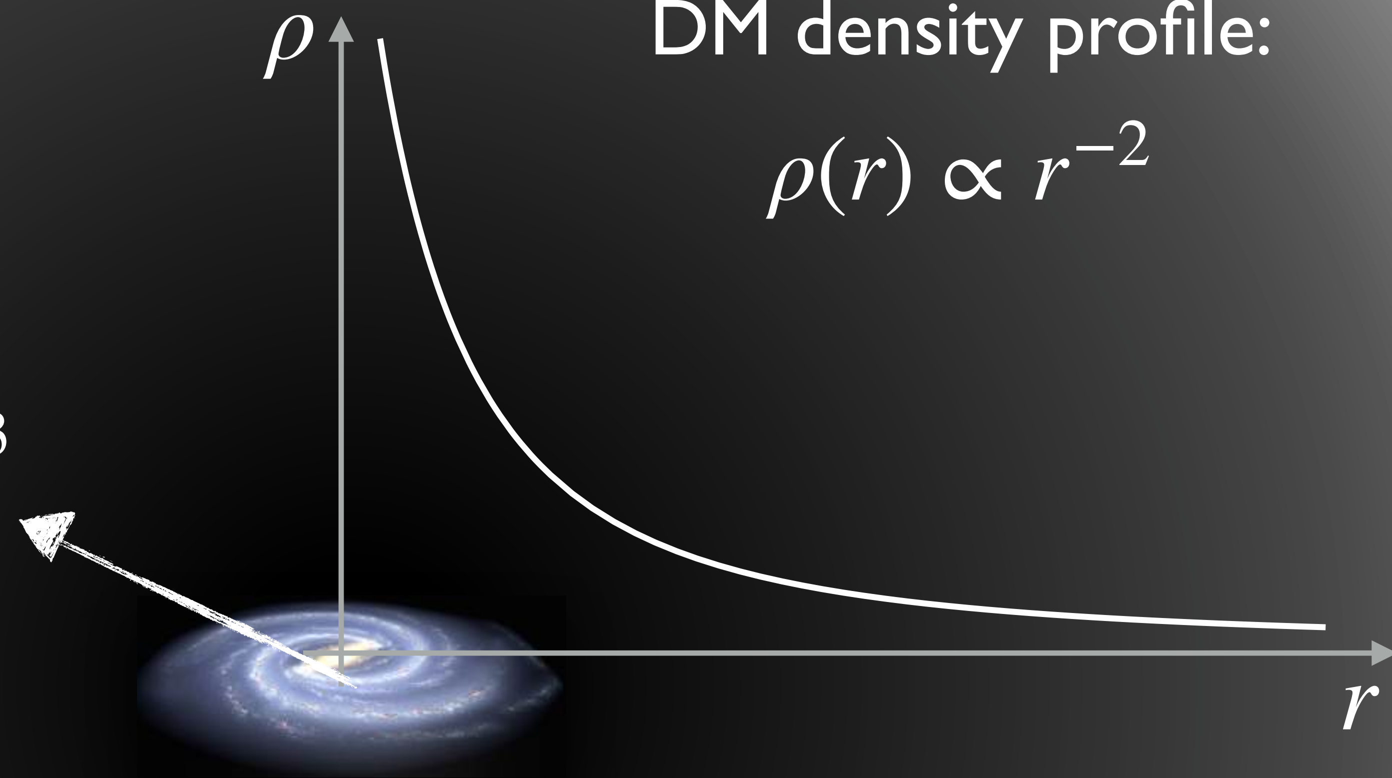

- Local DM density:

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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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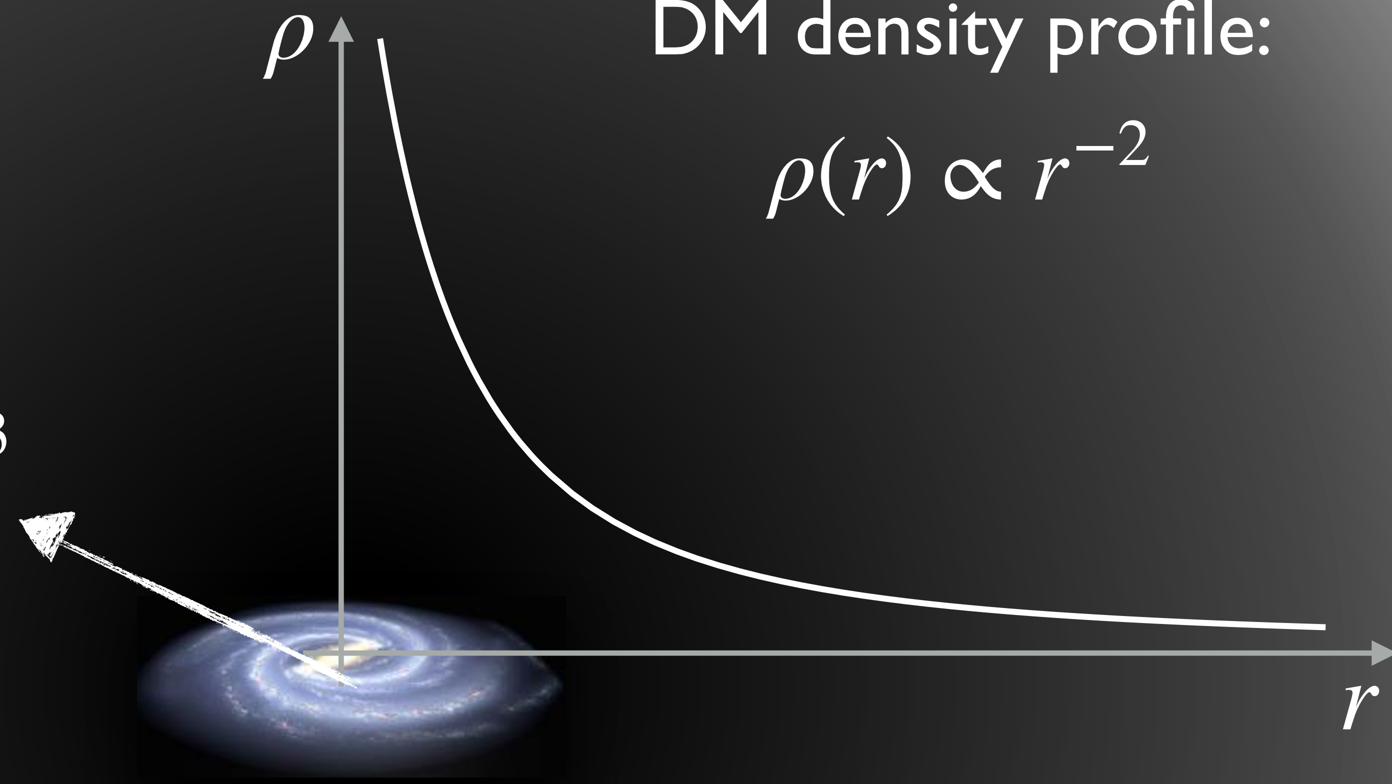

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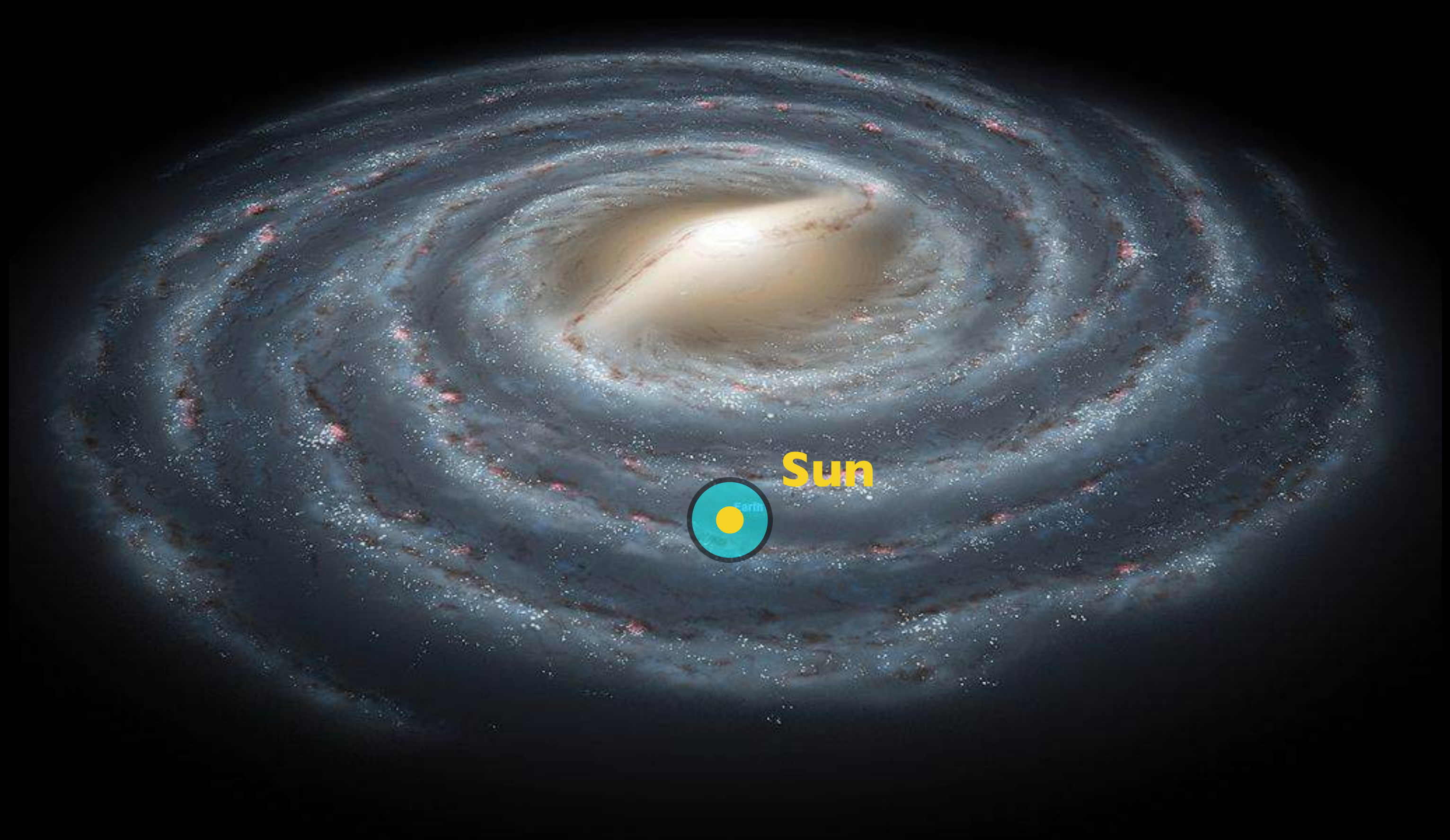
How accurate is this picture?

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

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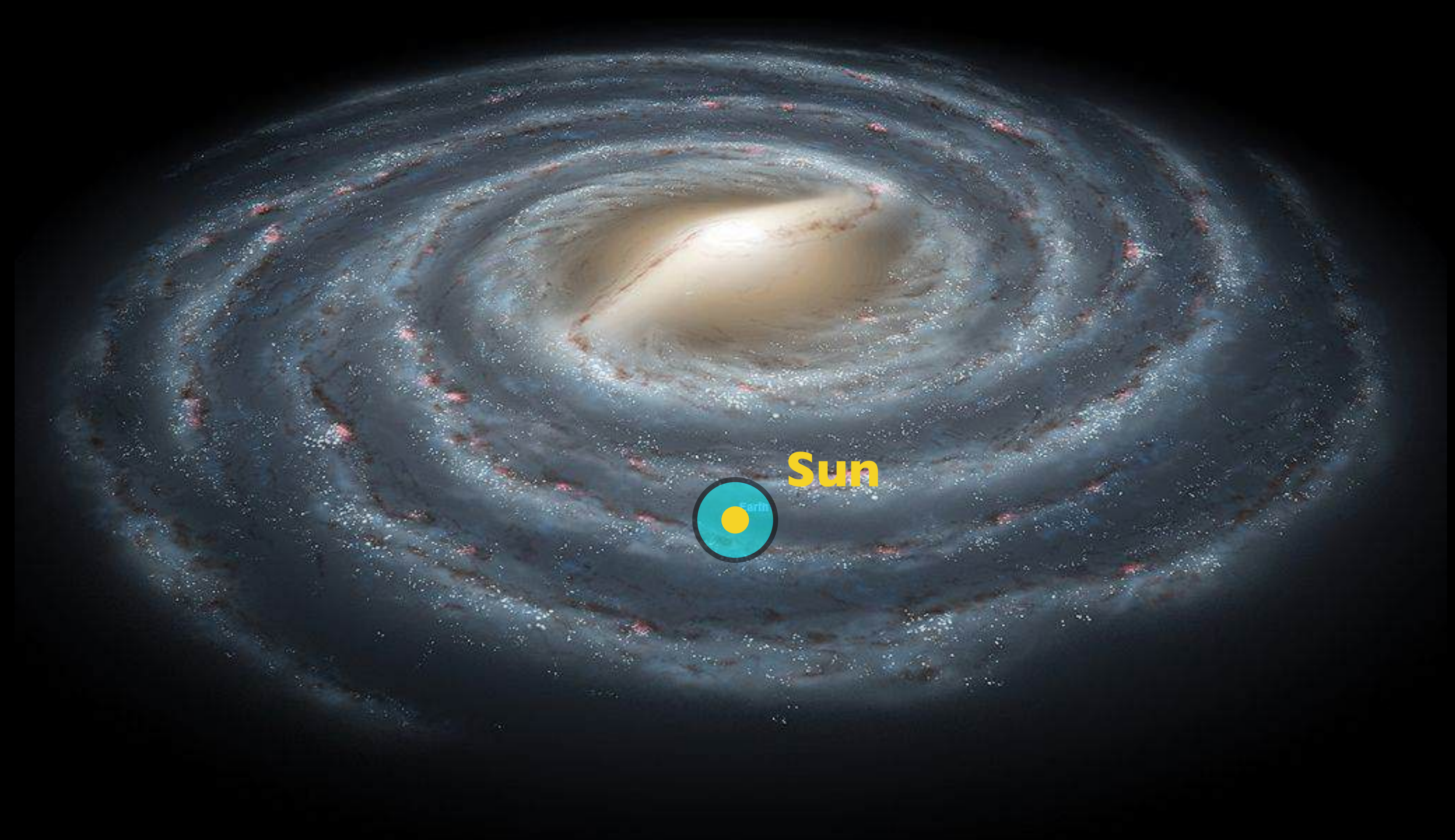
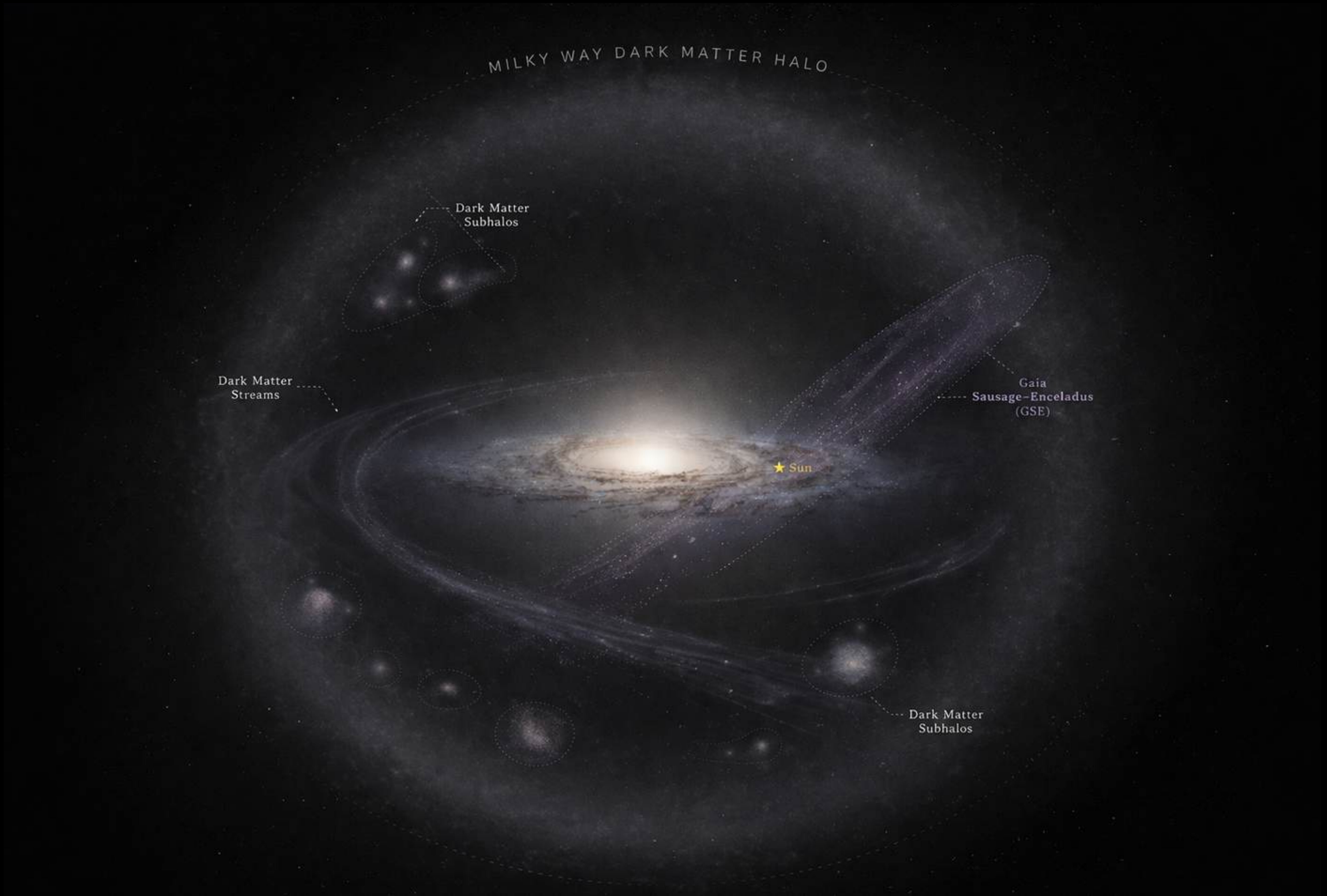
- **Local DM velocity distribution:** *cannot be directly measured, but we can infer it from cosmological simulations and observations.*



The dark matter halo



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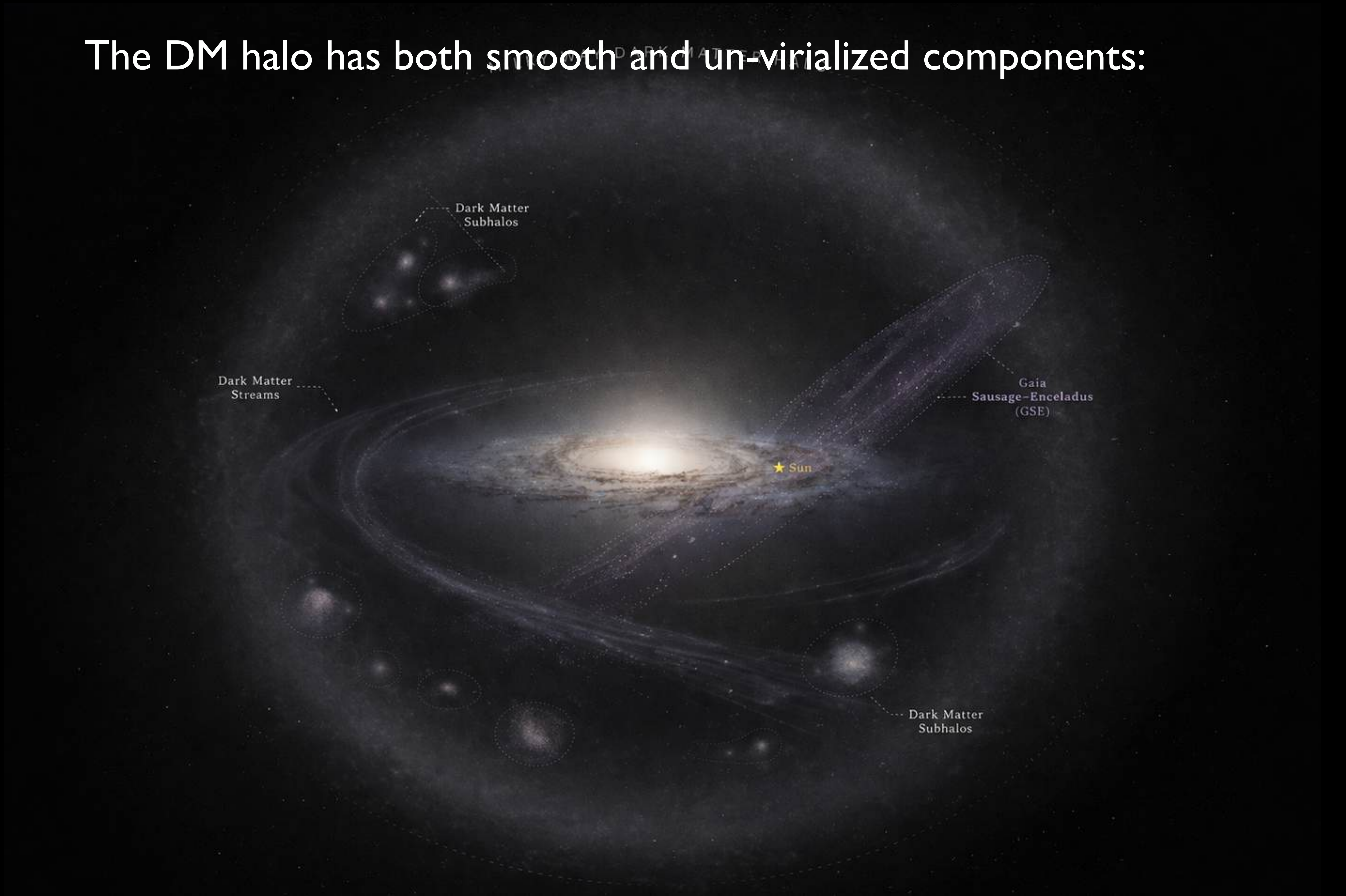
The DM halo has both smooth and un-virialized components:



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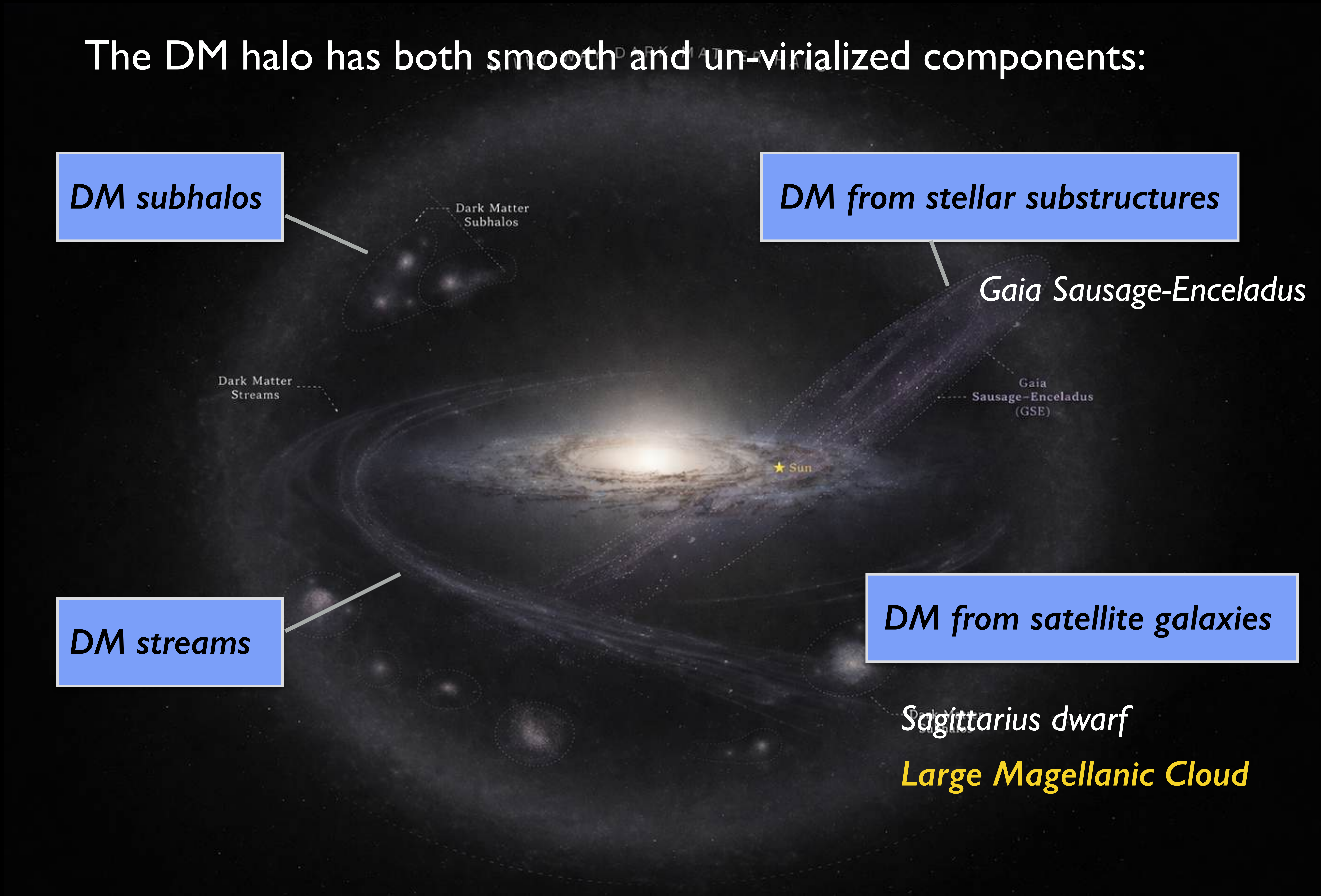
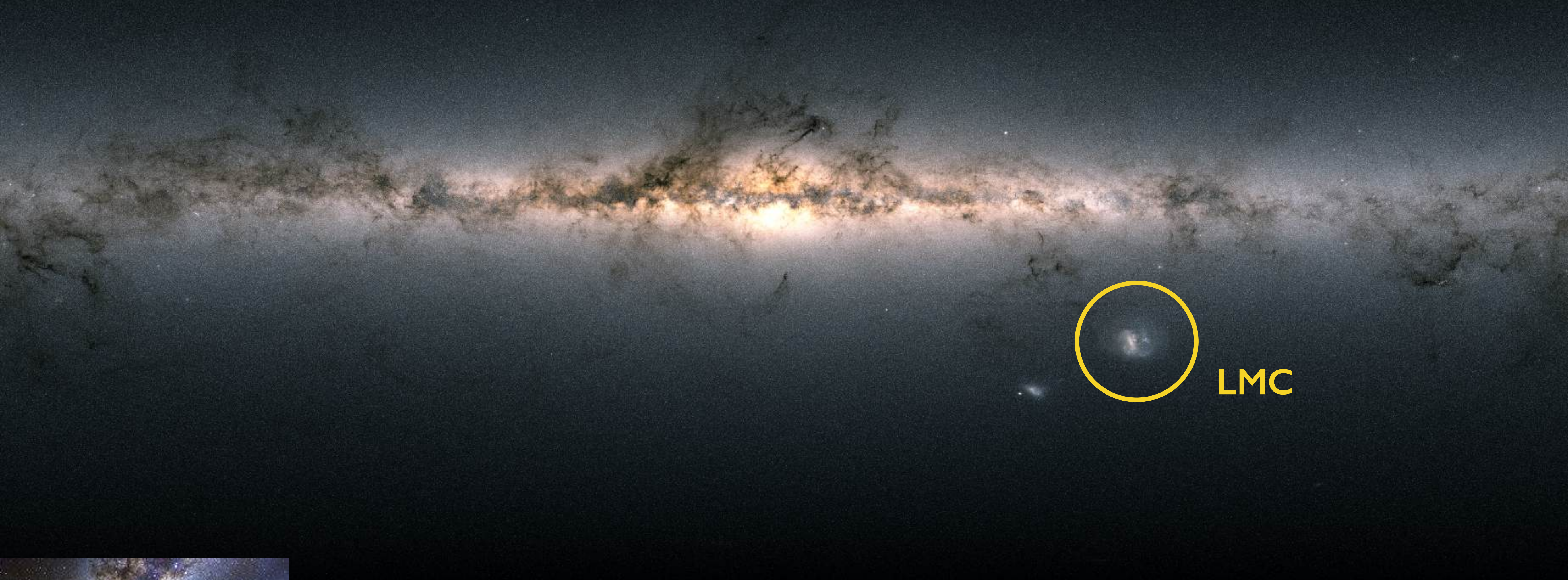
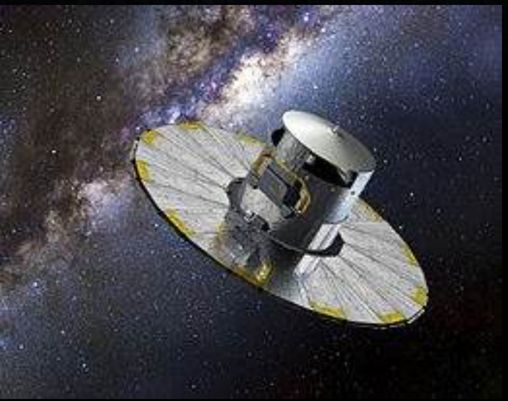


The Large Magellanic Cloud

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



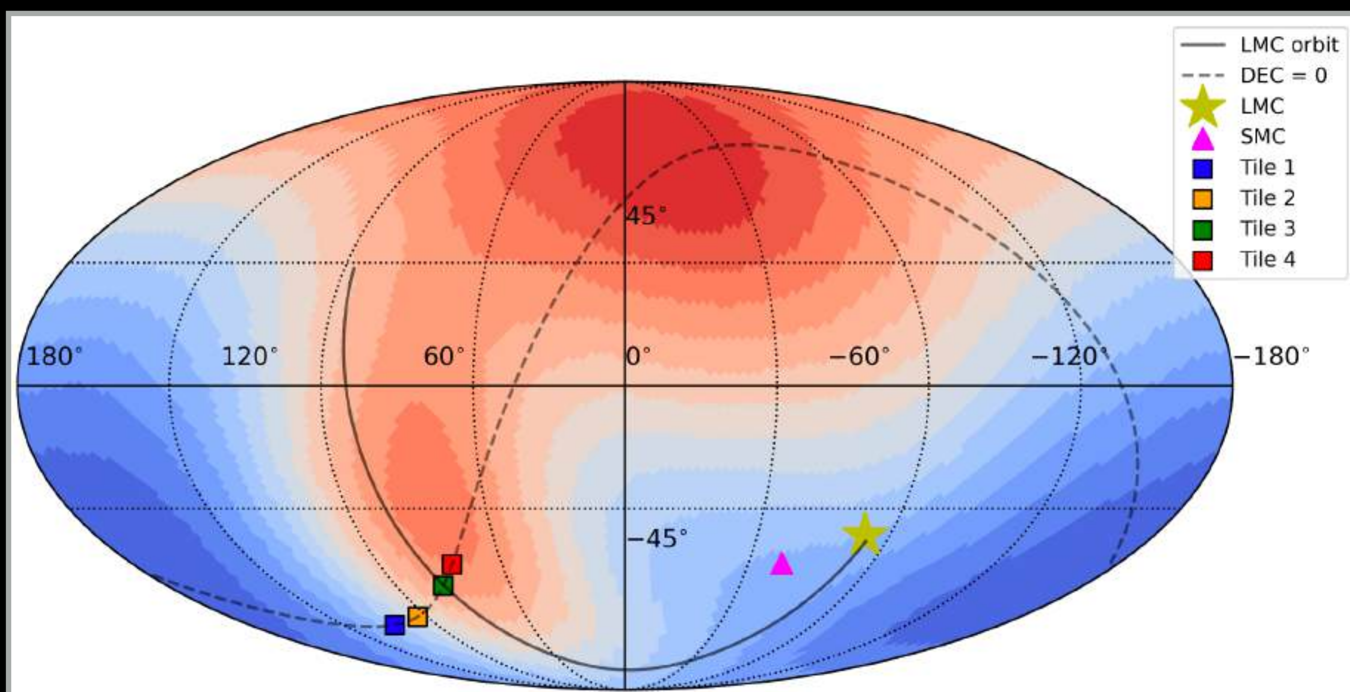


Gaia's EDR3 sky map. Credit: ESA/Gaia/DPAC

The impact of the LMC

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

DM halo



Cavieres et al., ApJ 983, 83 (2025)
Garavito-Camargo et al., ApJ 919, 2, 109 (2021)
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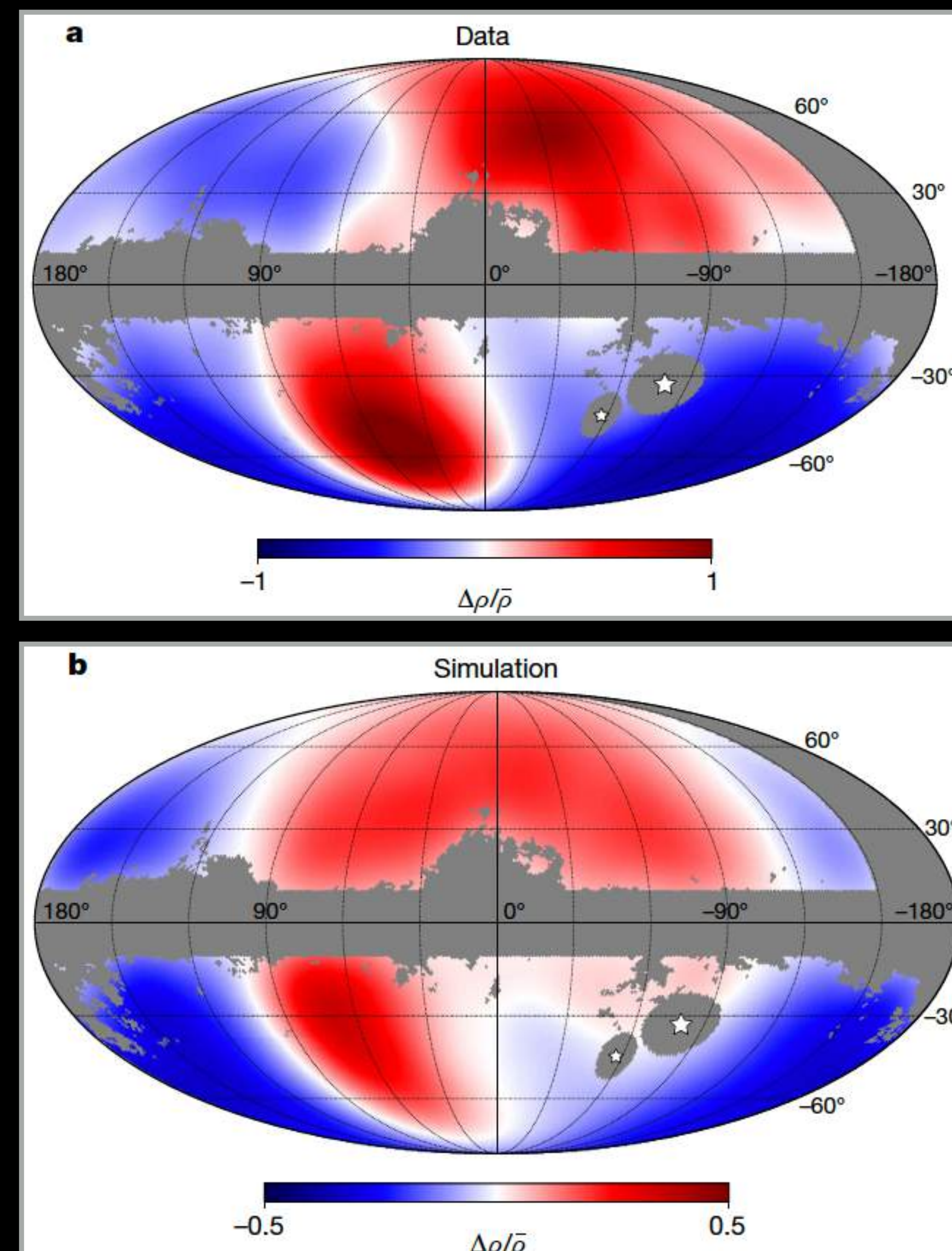
Stellar halo



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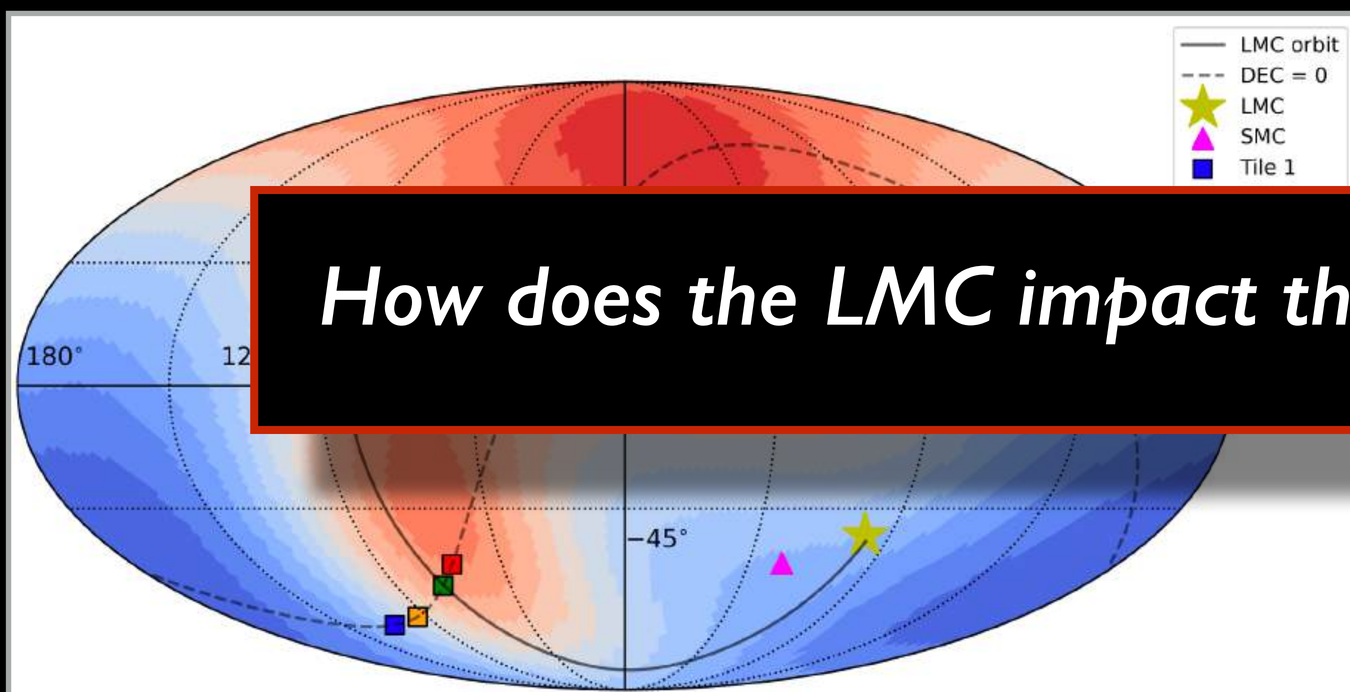

How does the LMC impact the local DM distribution?

Cavieres et al., ApJ 983, 83 (2025)
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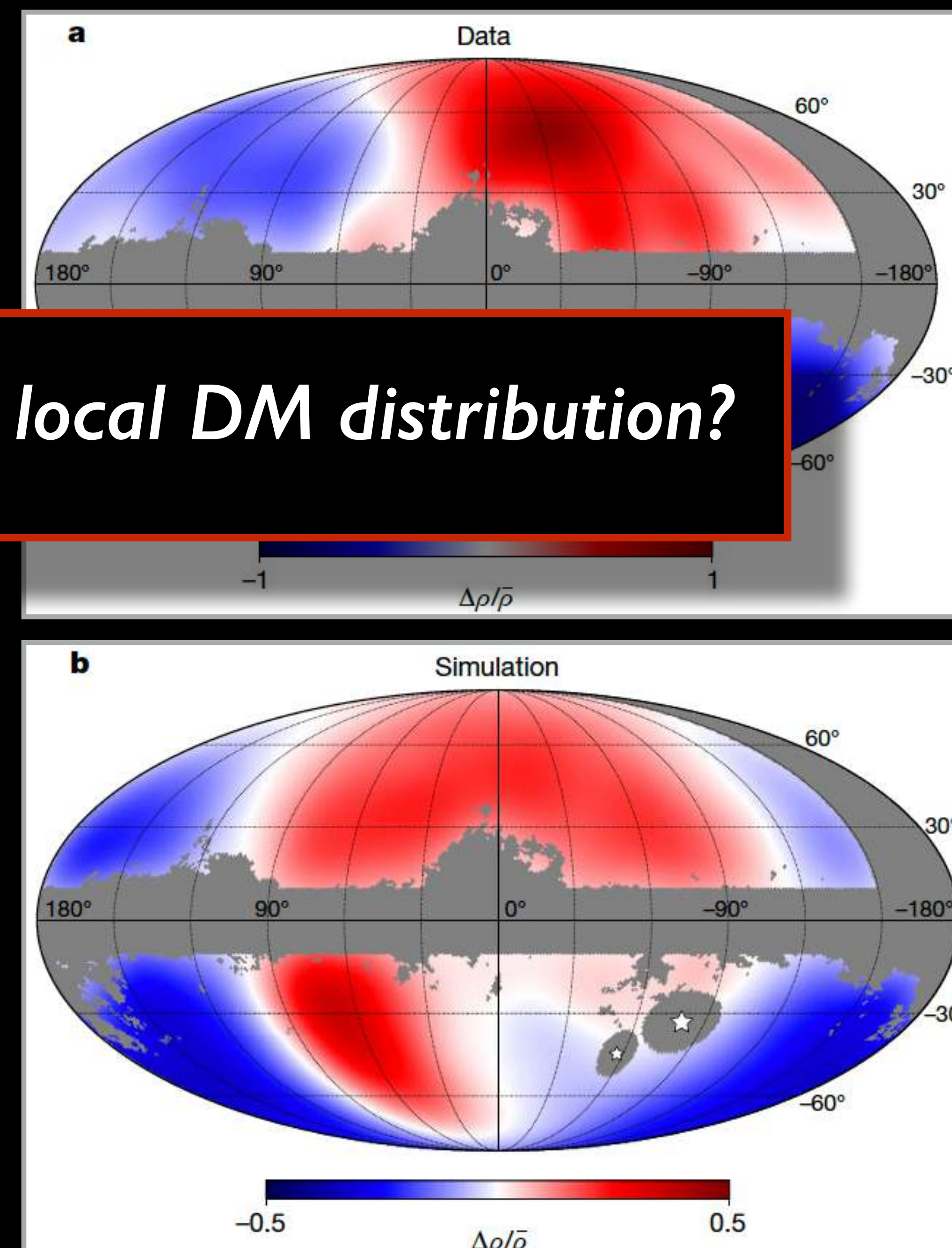

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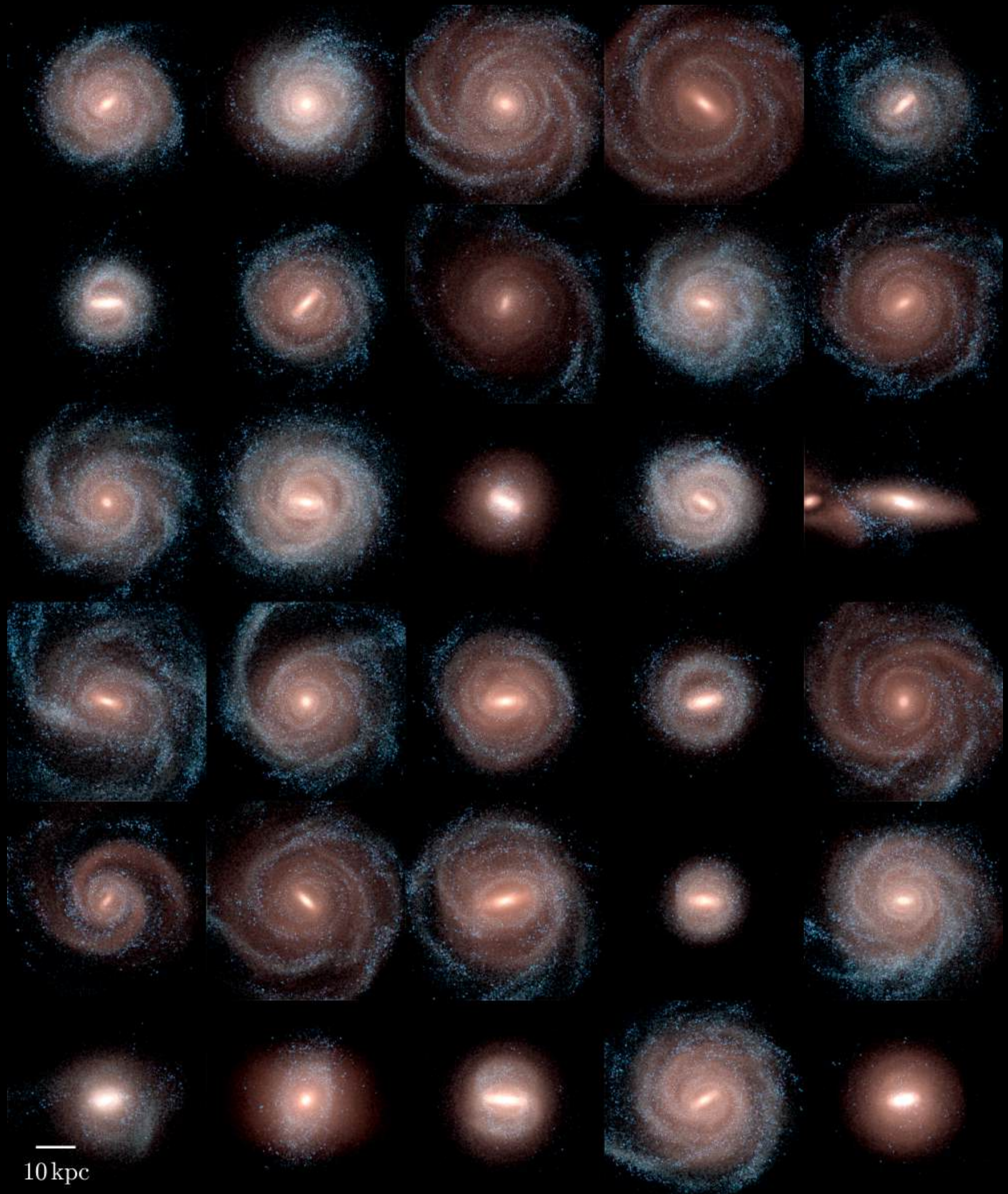
Auriga cosmological simulations

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



Auriga cosmological simulations

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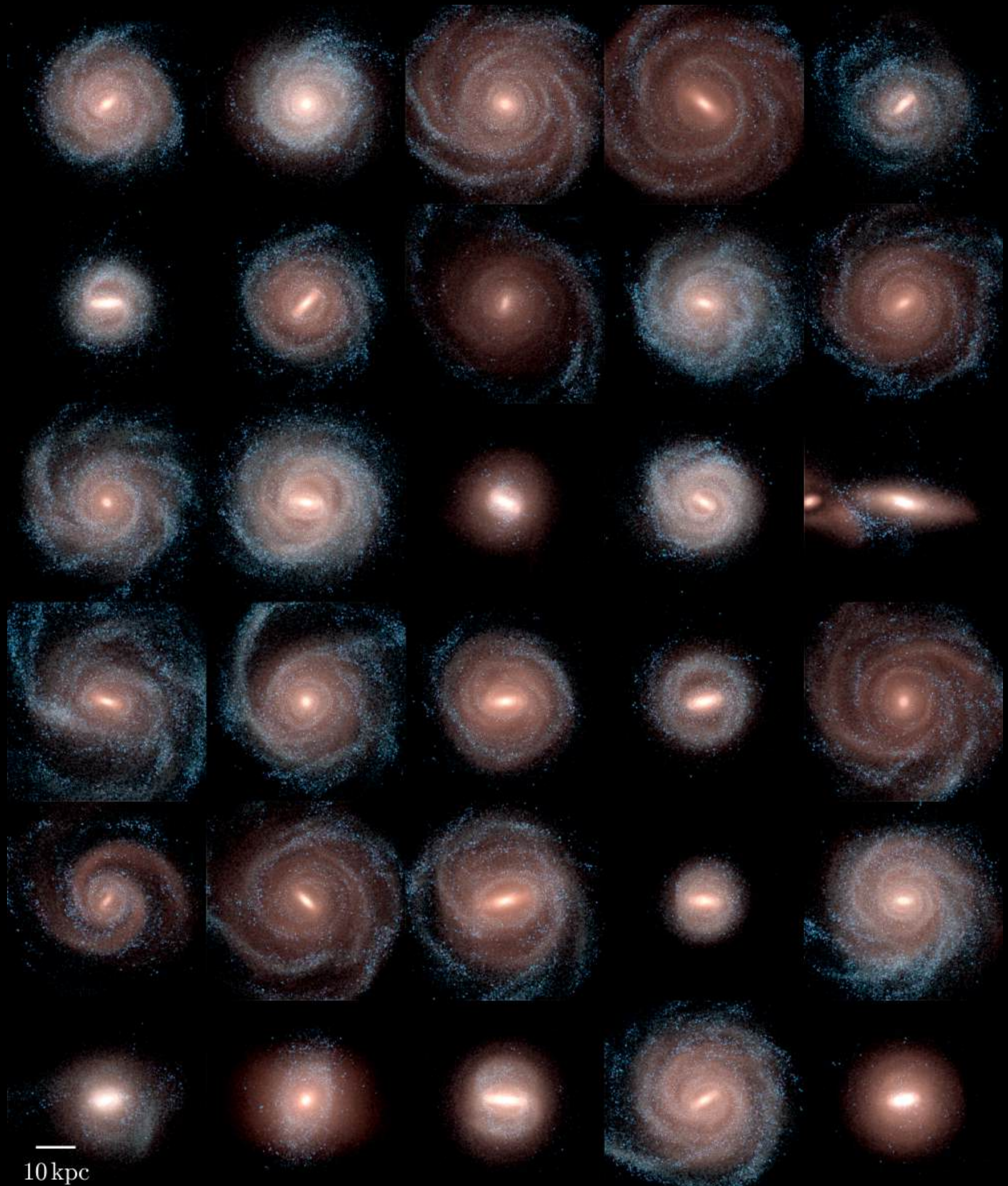
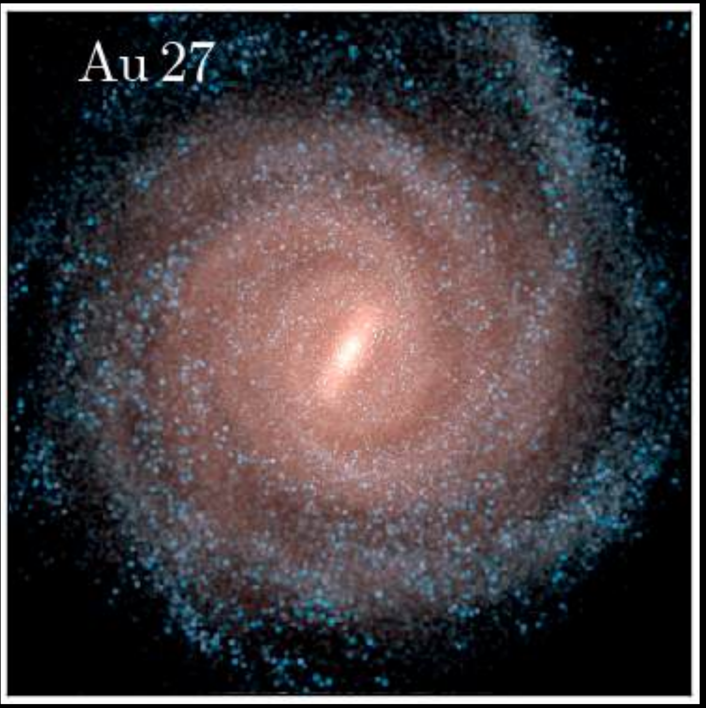
- Identify **Milky Way-LMC analogues** based on **LMC's stellar mass** and **distance from host**.



Auriga cosmological simulations

- Consider one **Milky Way-LMC analogue** and study the impact of the LMC on the local DM distribution at different times (snapshots) in its orbit.



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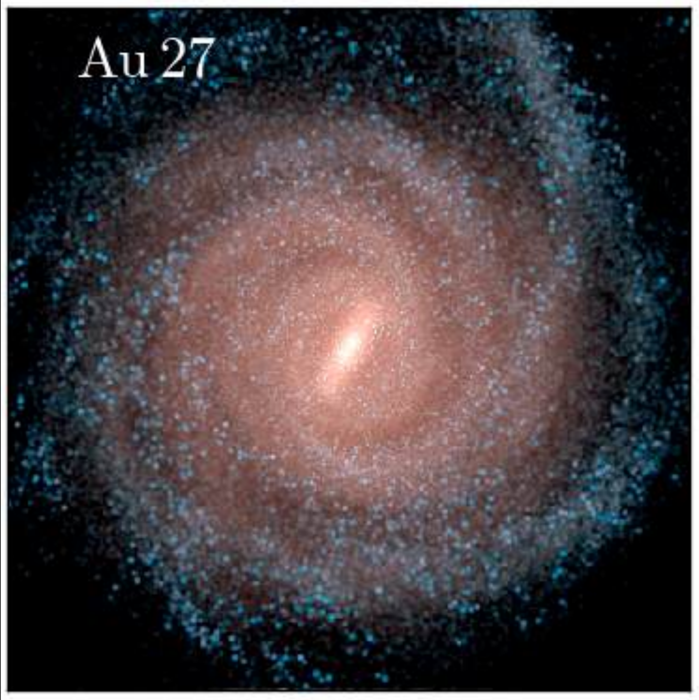

- Compare two representative snapshots:

Snapshot	Description	$t - t_{\mathrm{Pres.}}$ [Gyr]	r_{LMC} [kpc]
Iso.	Isolated MW analogue	-2.83	384
Pres.	Present day MW-LMC analogue	0	50.6

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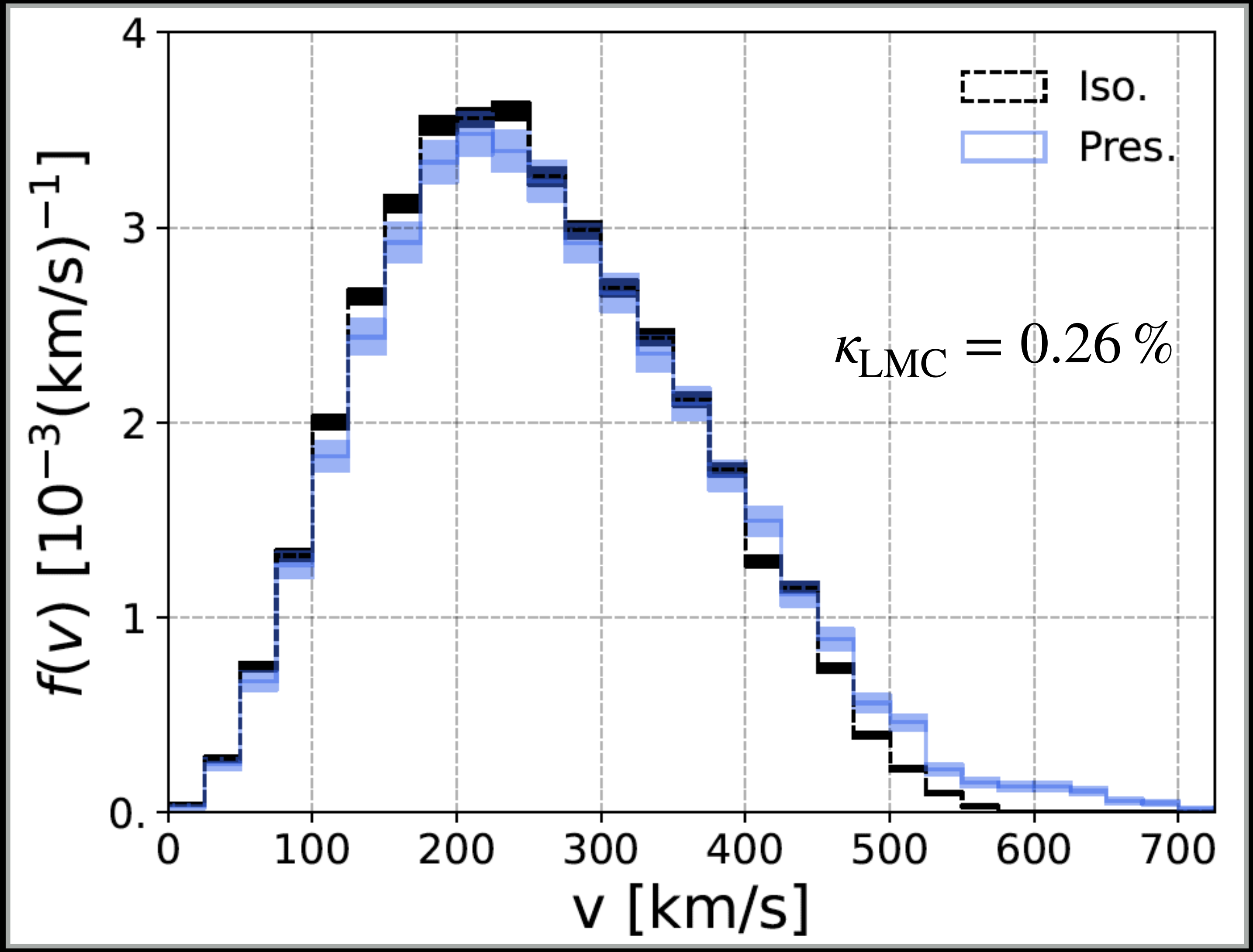
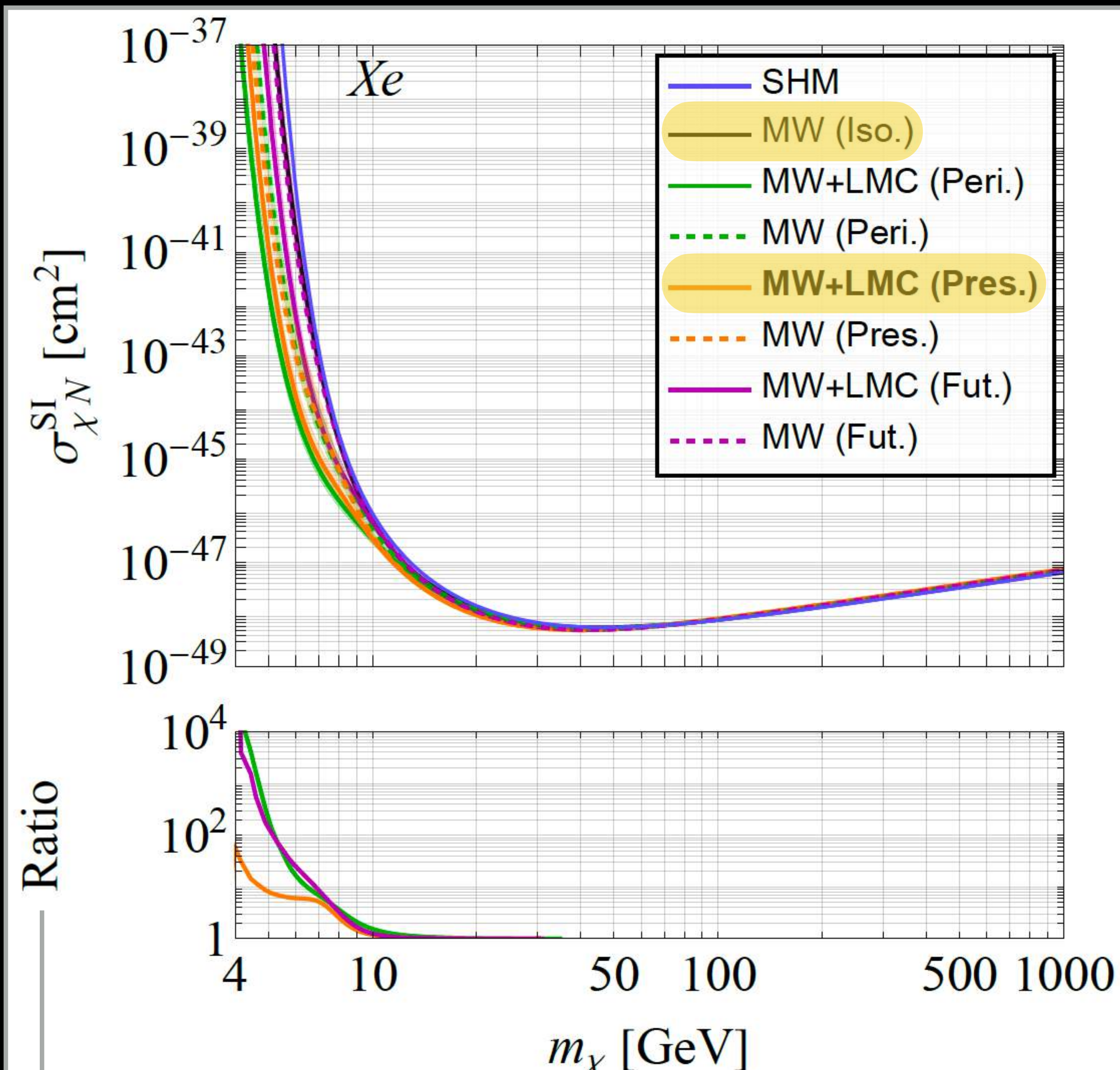


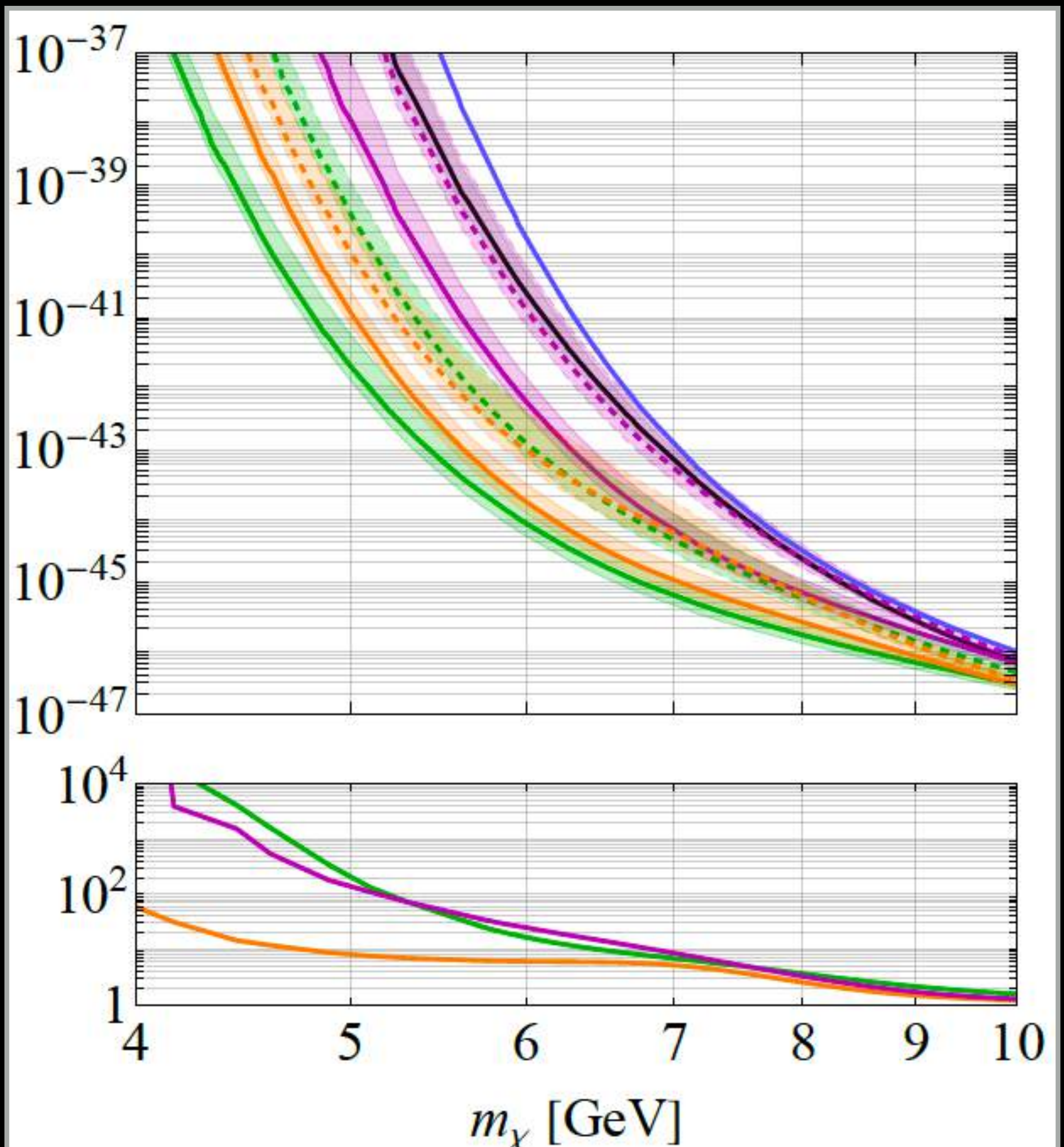
Smith-Orlik, Ronaghi, **NB** et al., JCAP 10, 070 (2023)
Reynoso, **NB**, Piro, JCAP 12, 037 (2024)

See also: Besla et al., JCAP 11, 013 (2019); Donaldson et al., MNRAS 513, 1, 46 (2022)

Implications for direct detection

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





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

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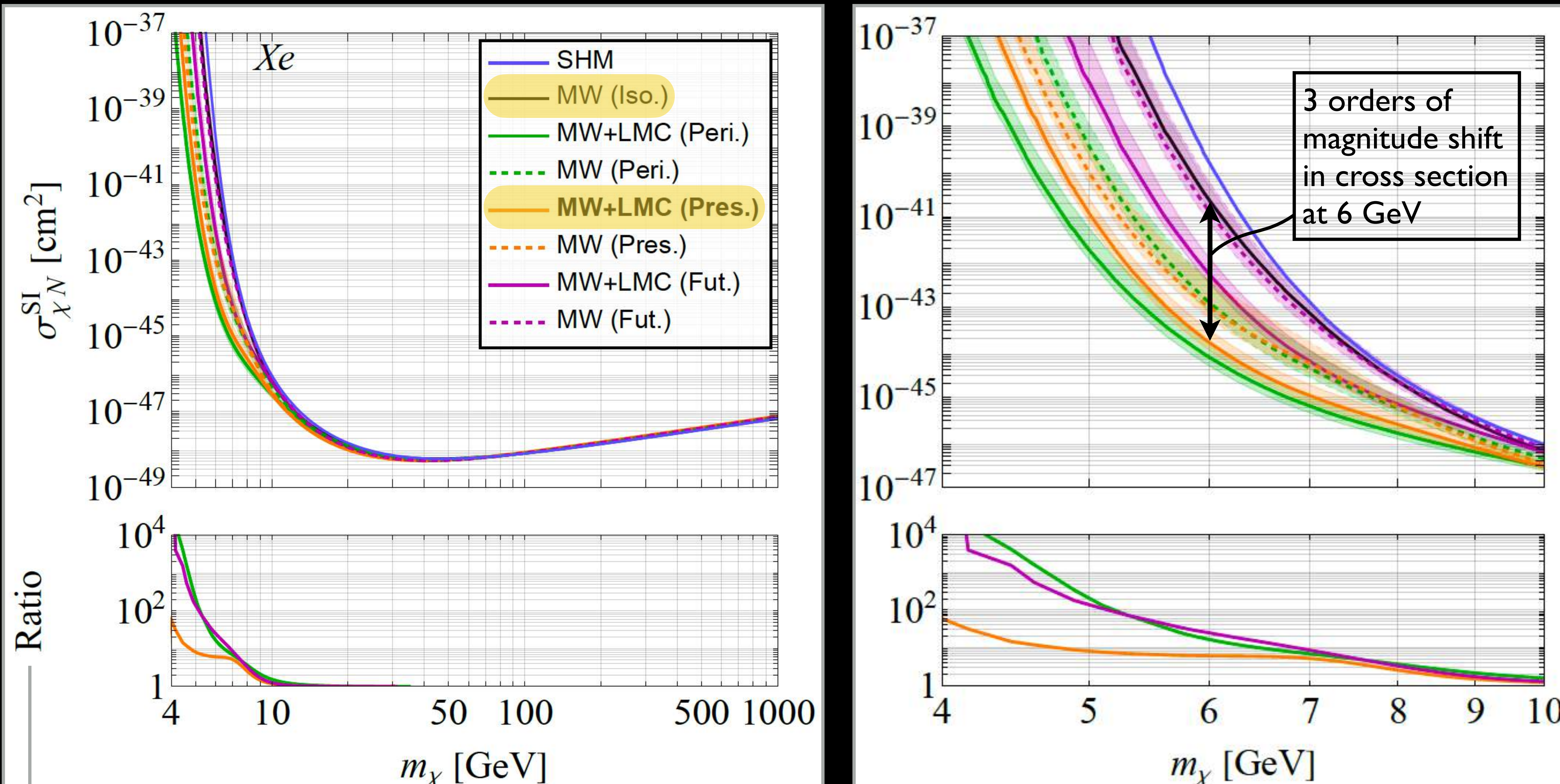

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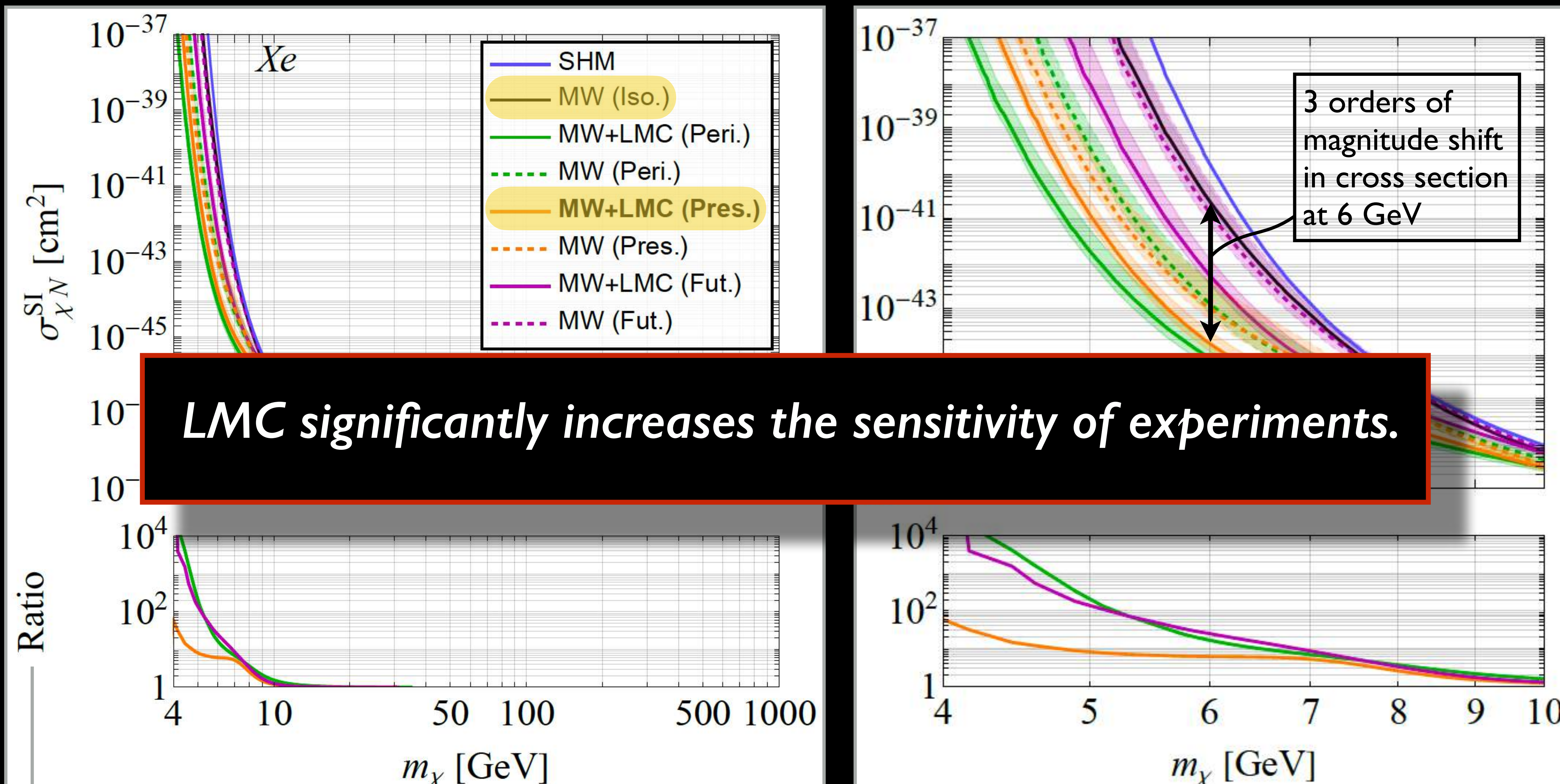

LMC significantly increases the sensitivity of experiments.

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

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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
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$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}/m_N$	q^2
$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp\right)$	$v_\perp^2,\ q^2$
$\mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \vec{v}_\perp\right)\left(\vec{S}_N \cdot \vec{q}/m_N\right)$	$q^2 v_\perp^2,\ q^4$
$\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \vec{q}/m_N\right)\left(\vec{S}_N \cdot \vec{v}_\perp\right)$	$q^2 v_\perp^2$
$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \vec{q}/m_N\right)\left(\left(\vec{S}_N \times \vec{v}_\perp\right) \cdot \vec{q}/m_N\right)$	$q^4 v_\perp^2,\ q^6$

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- 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.

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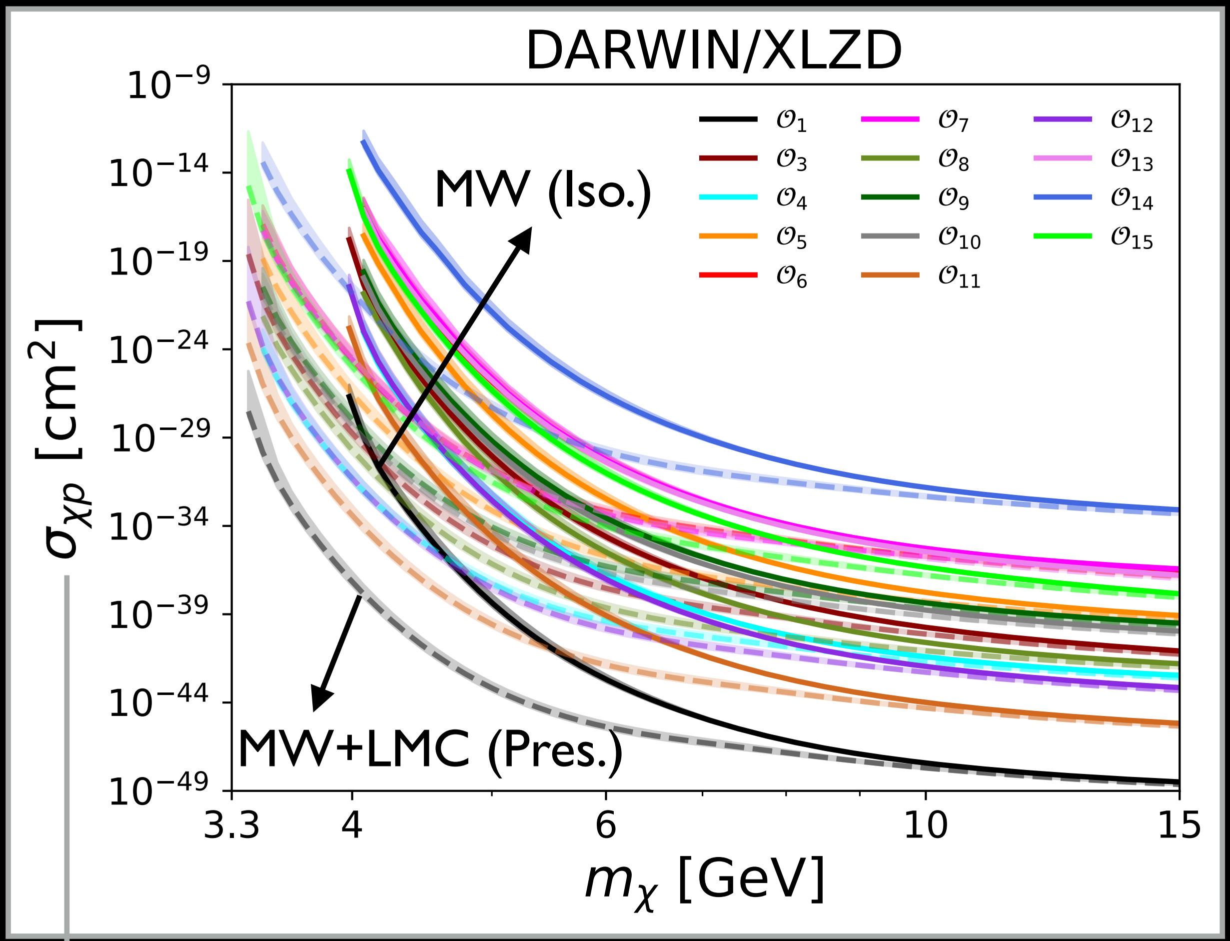
Future Xe-based experiment



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Reynoso, **NB**, Piro, JCAP 12, 037 (2024)

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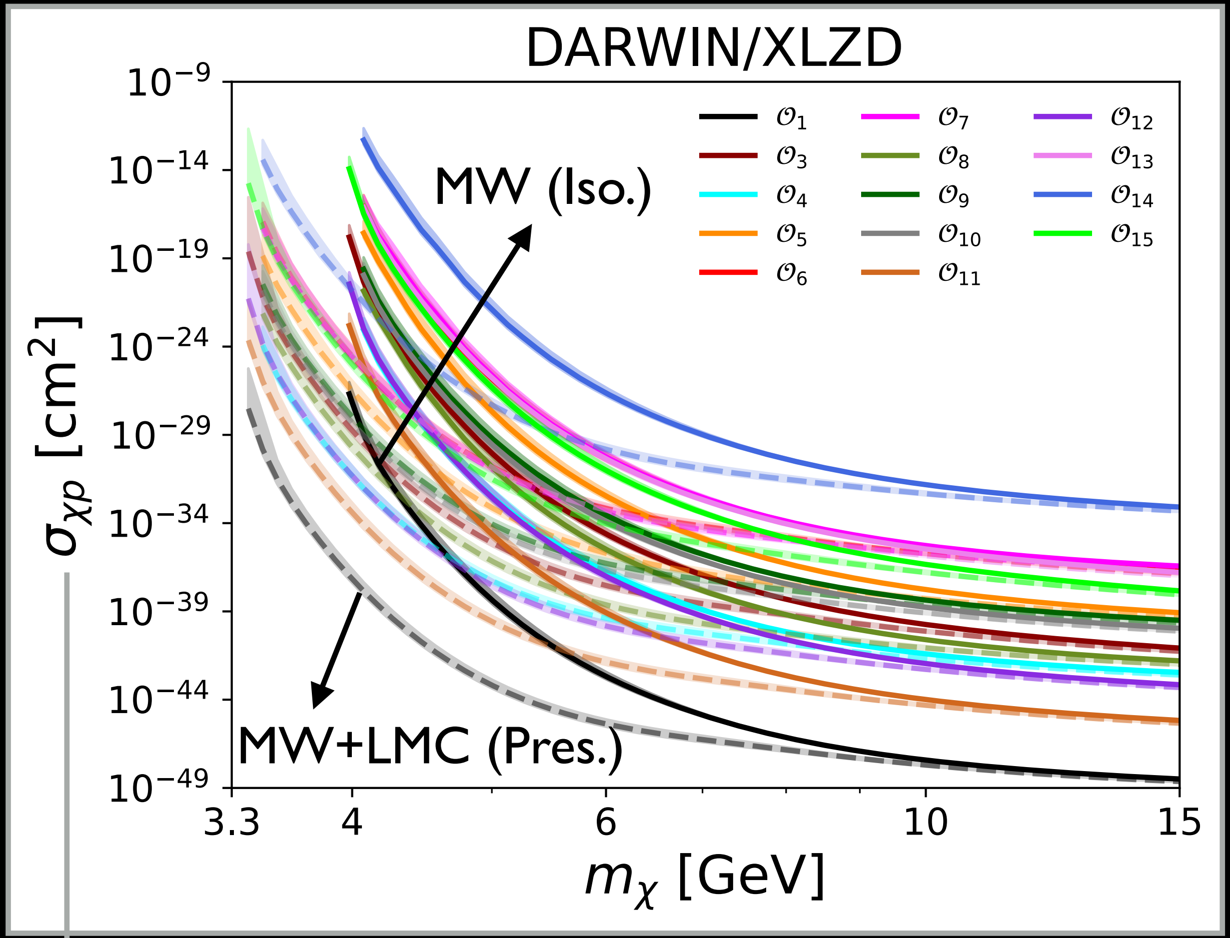

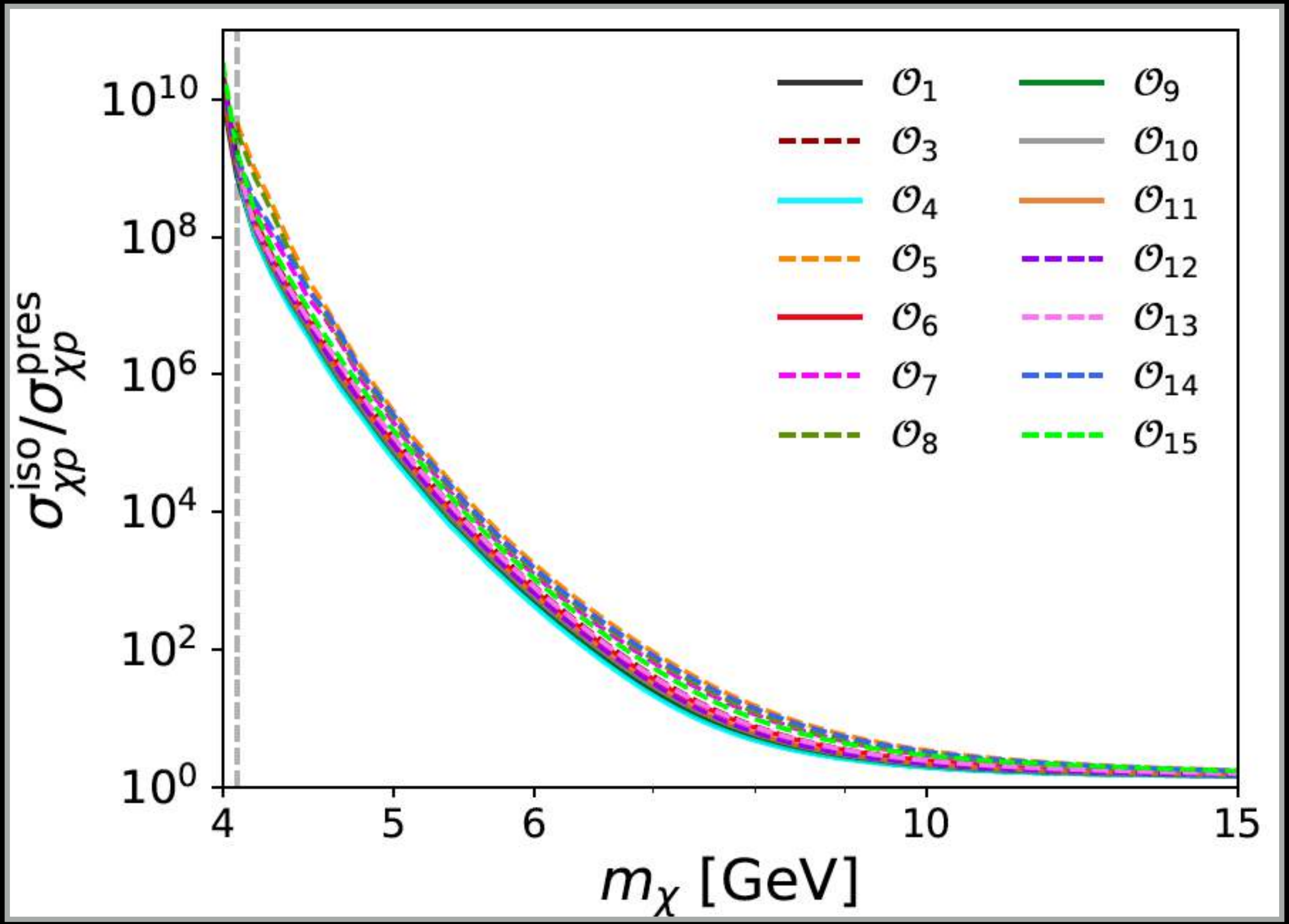

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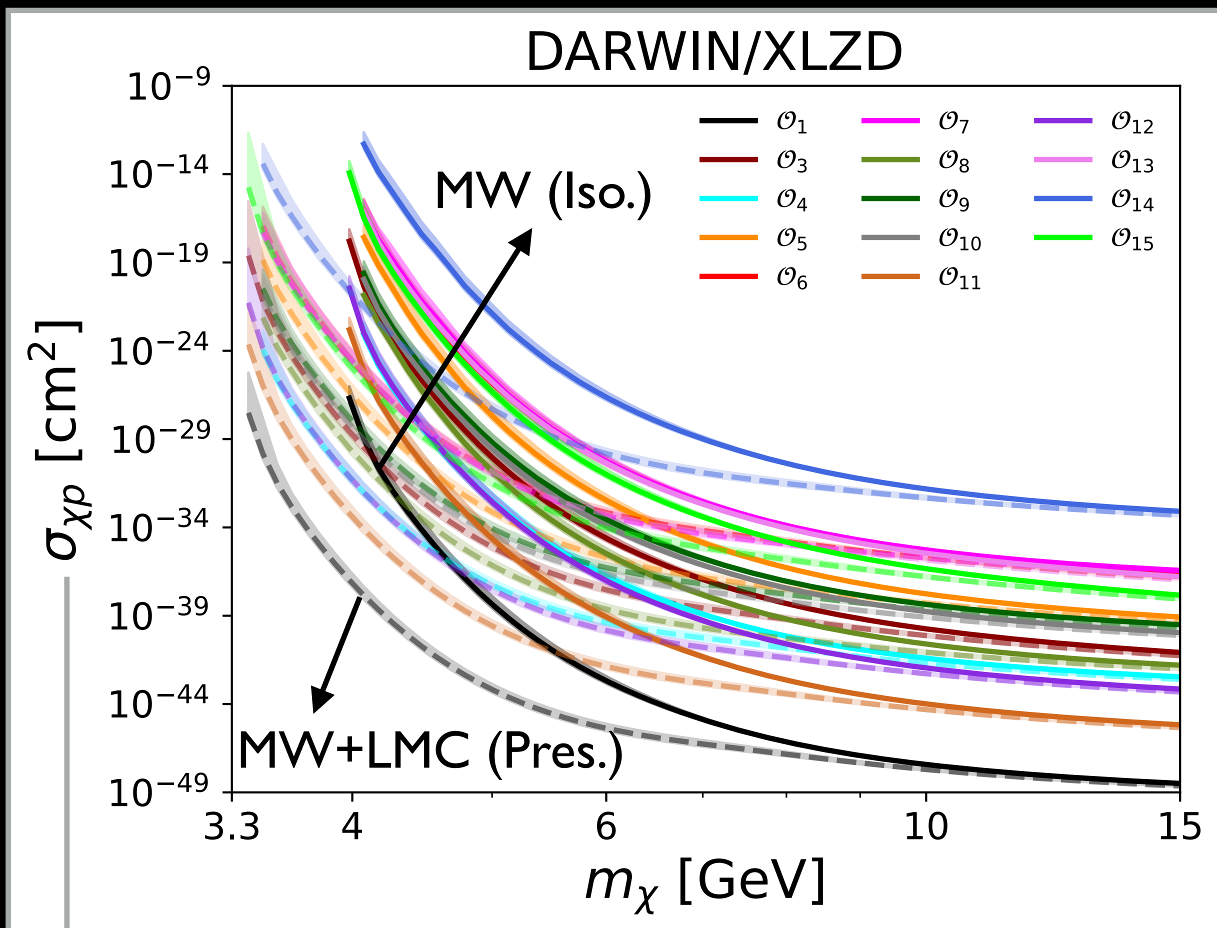

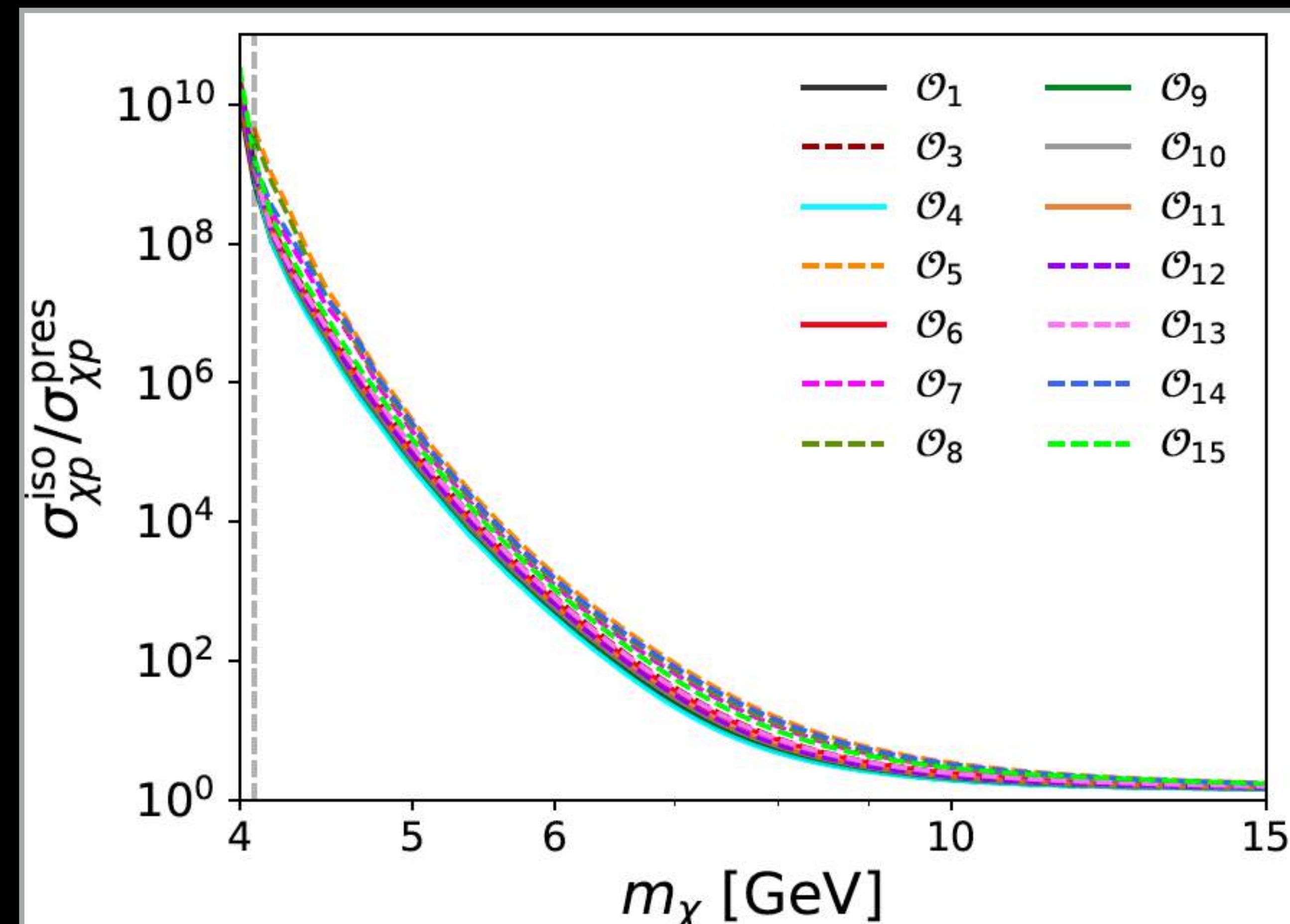

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- The impact of the LMC is larger for operators that lead to a velocity-dependent scaling in the DM-nucleus cross section.

Heavy dark matter

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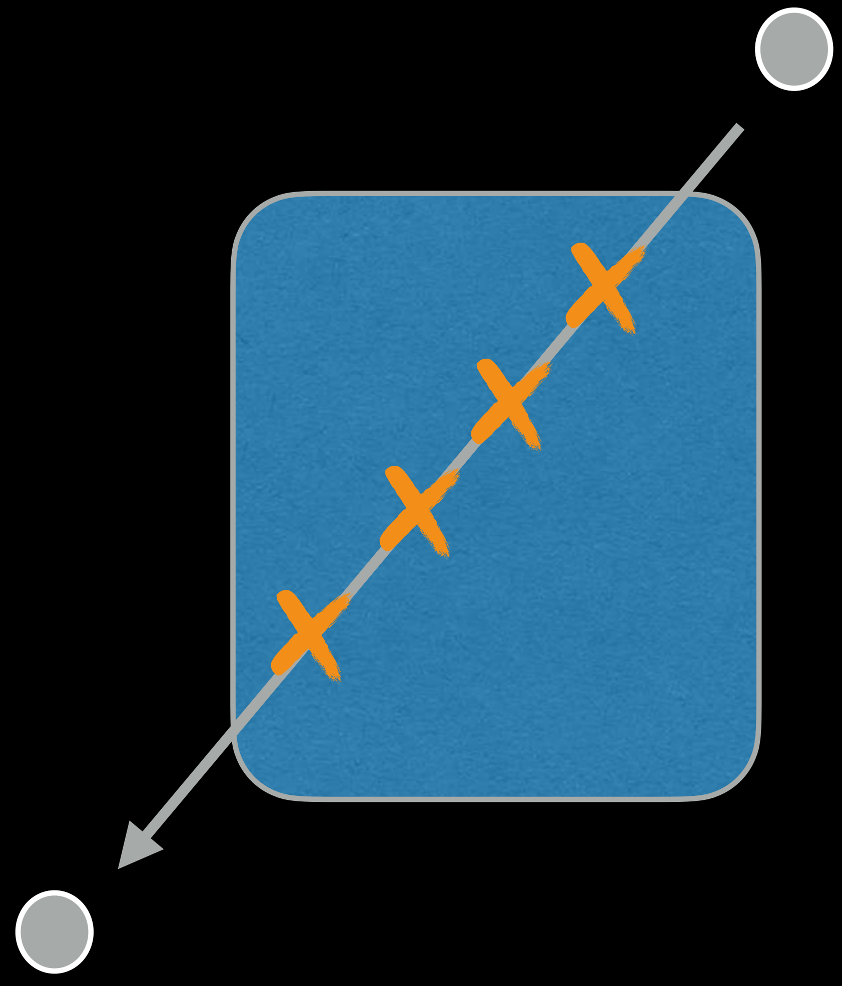

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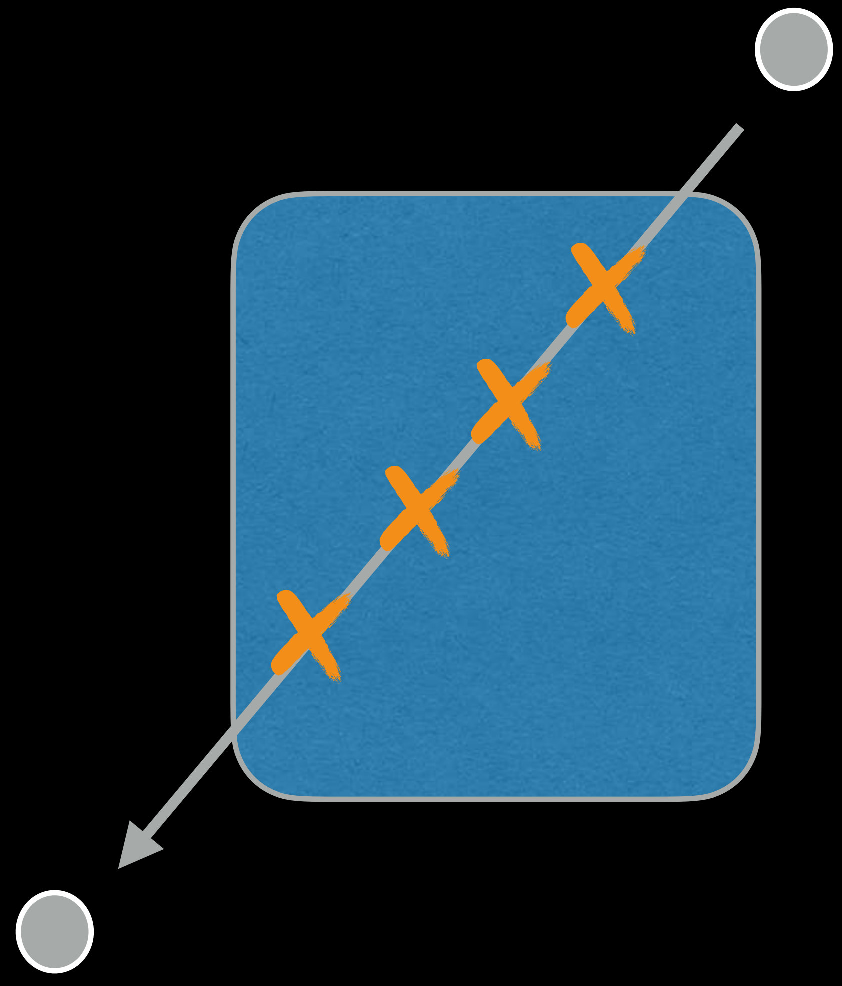
- Energy loss in overburden → motivates near-surface and space-based searches



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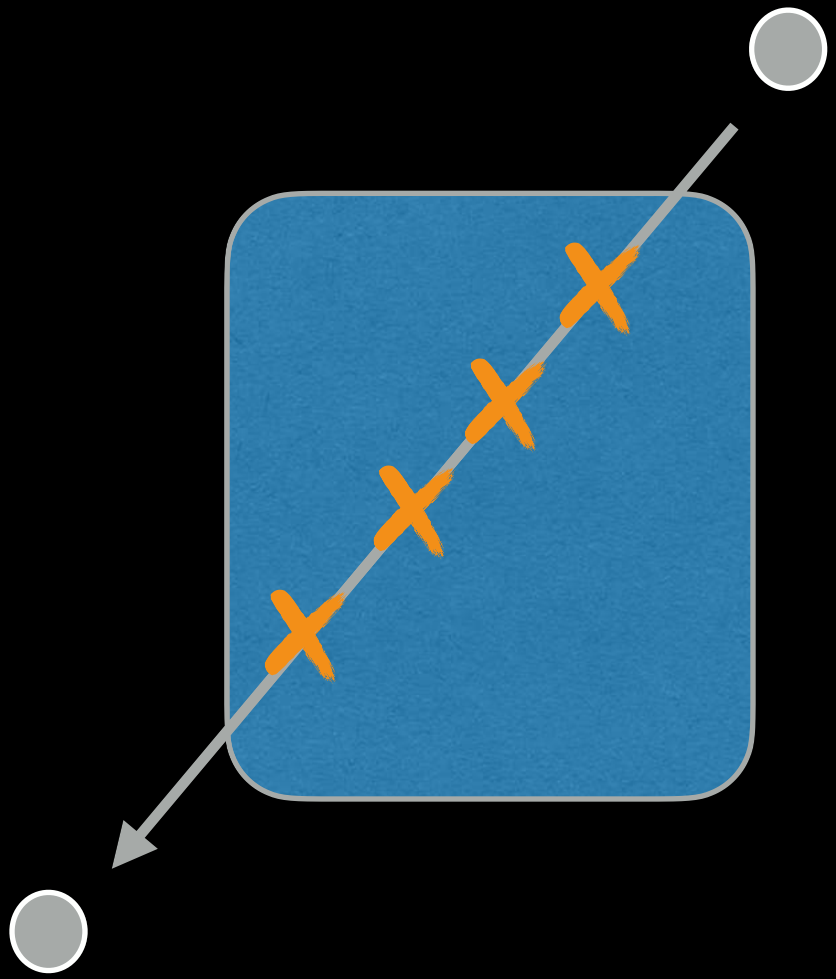
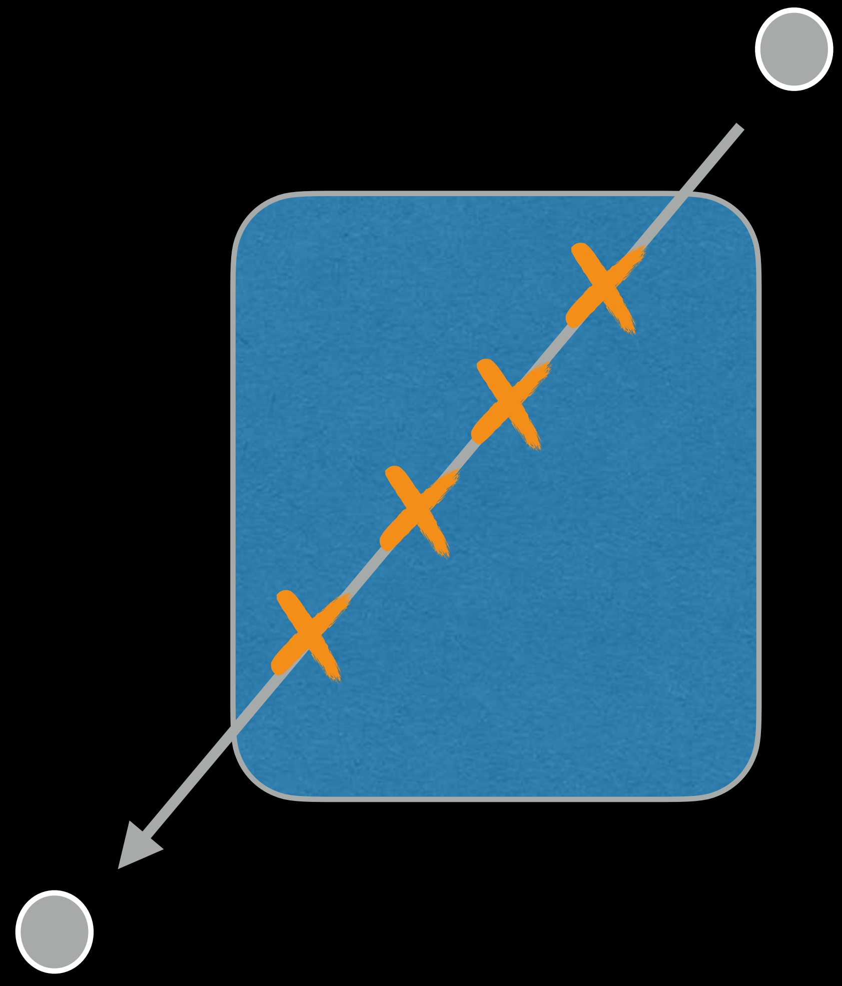
- Energy loss in overburden → motivates near-surface and space-based searches
- *Sensitivity strongly depends on the DM velocity distribution.*



Heavy dark matter

- DM mass: $m_\chi \gg 10\ \mathrm{TeV}$
- Low number density → allows large scattering cross sections without violating existing bounds
- Multiple scatters with little deflection
- Energy loss in overburden → motivates near-surface and space-based searches
- *Sensitivity strongly depends on the DM velocity distribution.*
- *How does the LMC impact the sensitivity of multiscatter searches?*



Plastic etch experiments

Searches for cosmogenic particles in etched plastic track detectors:

Skylab

Skylab space station cosmic ray search (1978)

Ohya Quarry

Underground search for monopoles and exotic particles in Japan (1990)

Plastic etch experiments

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Ohya Quarry

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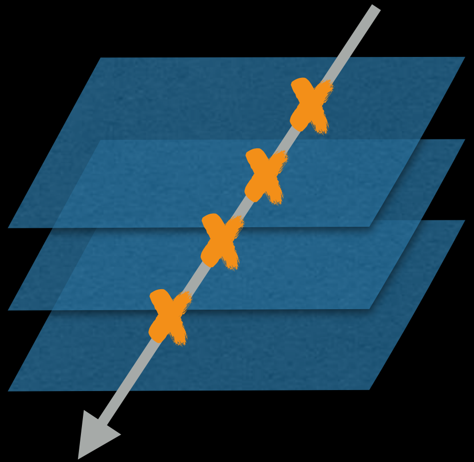
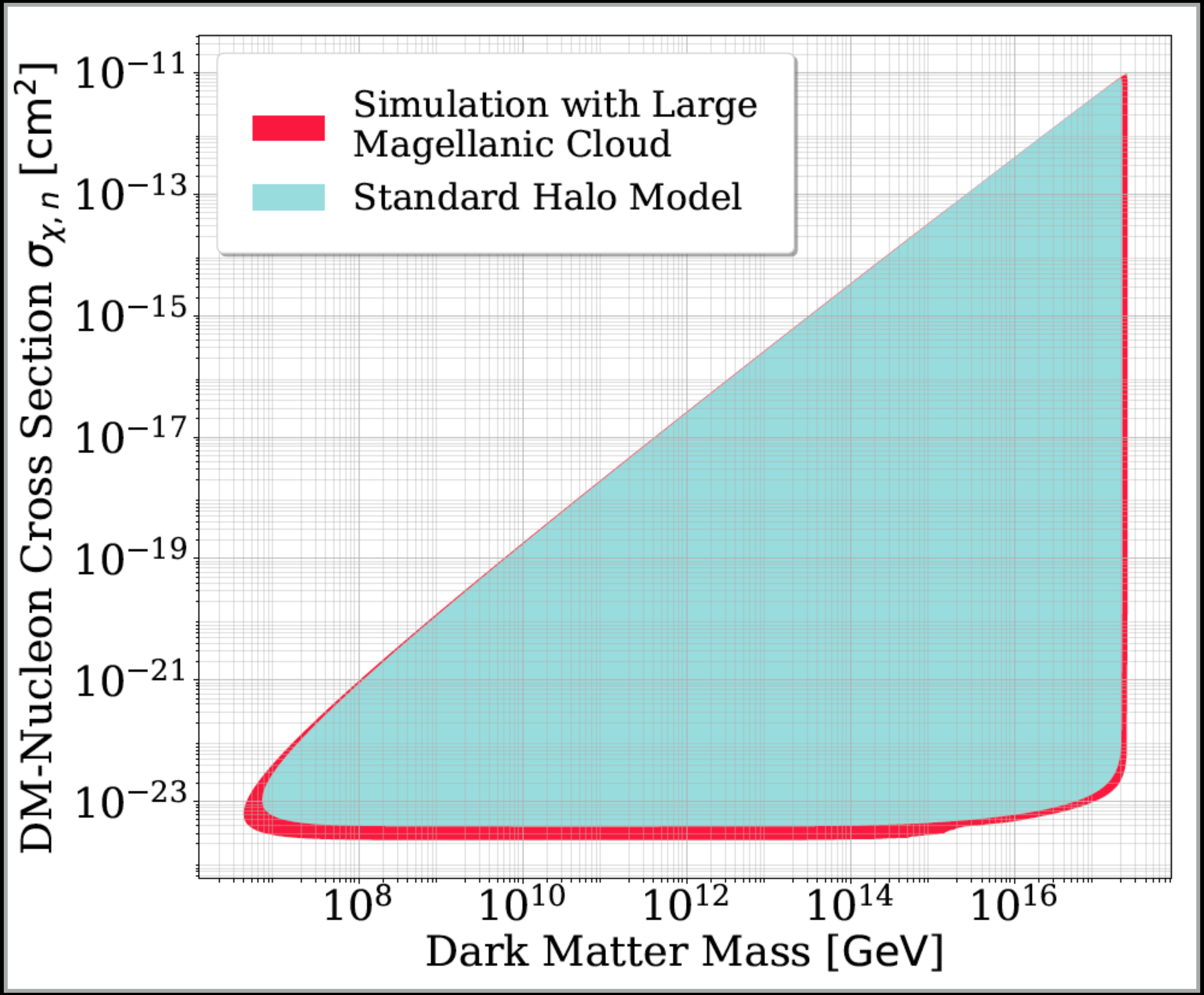
Particle passing through the plastic damages molecular bonds.



Plastic etch searches for dark matter

Skylab



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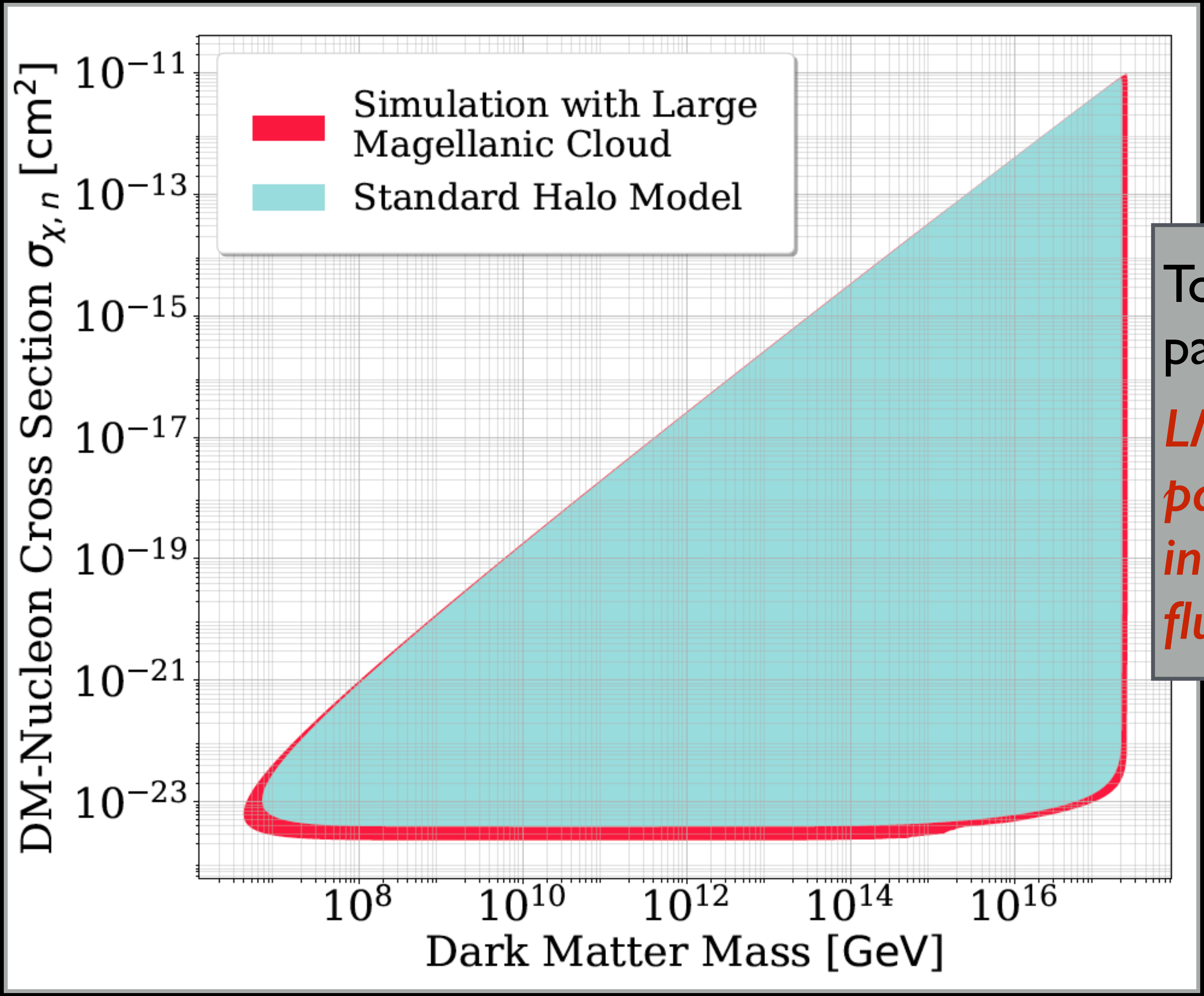
Plastic etch searches for dark matter

Skylab



Too few particles pass the detector

LMC boosts particle speeds, increasing the flux

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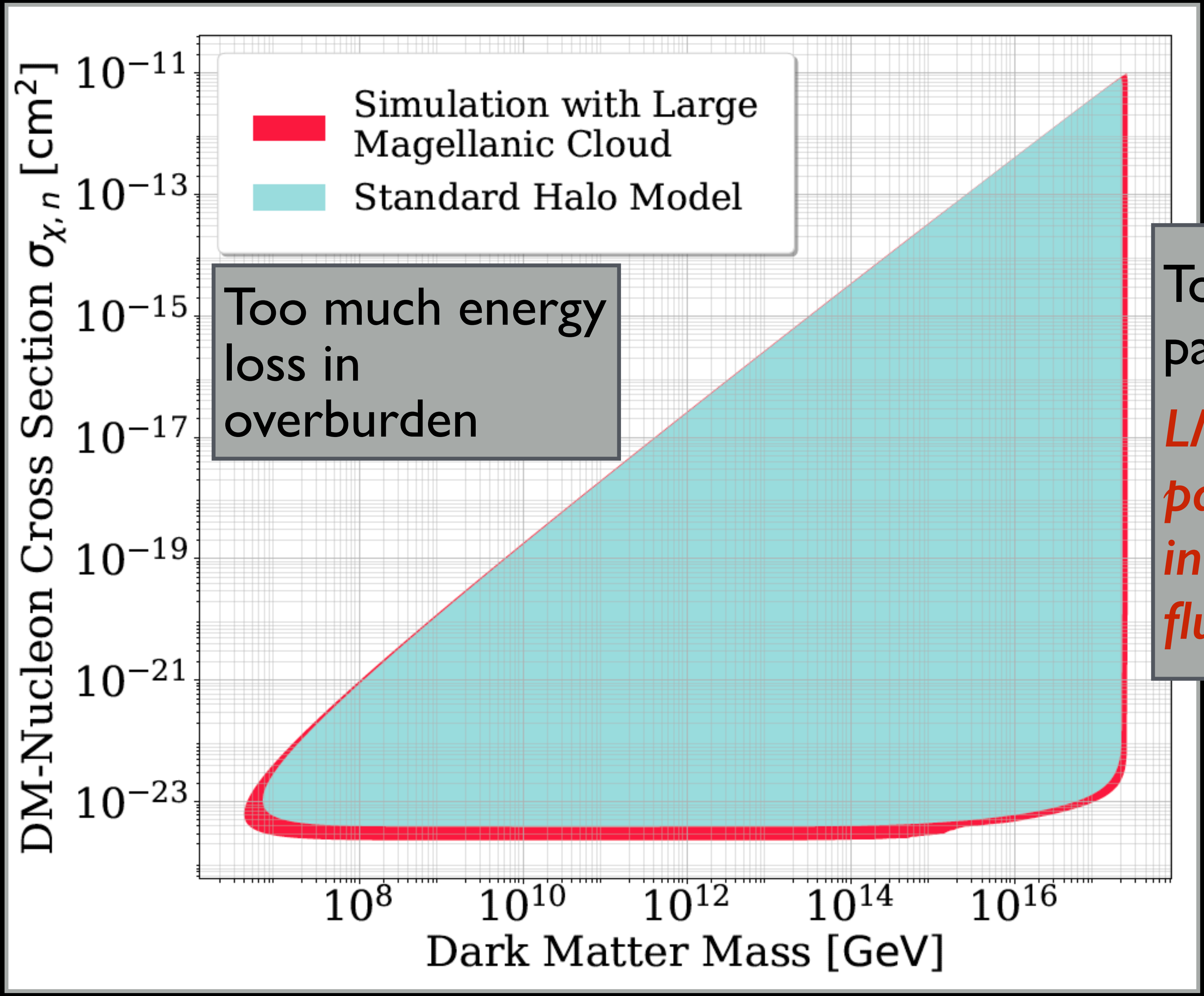
Plastic etch searches for dark matter

Skylab



Too much energy loss in overburden

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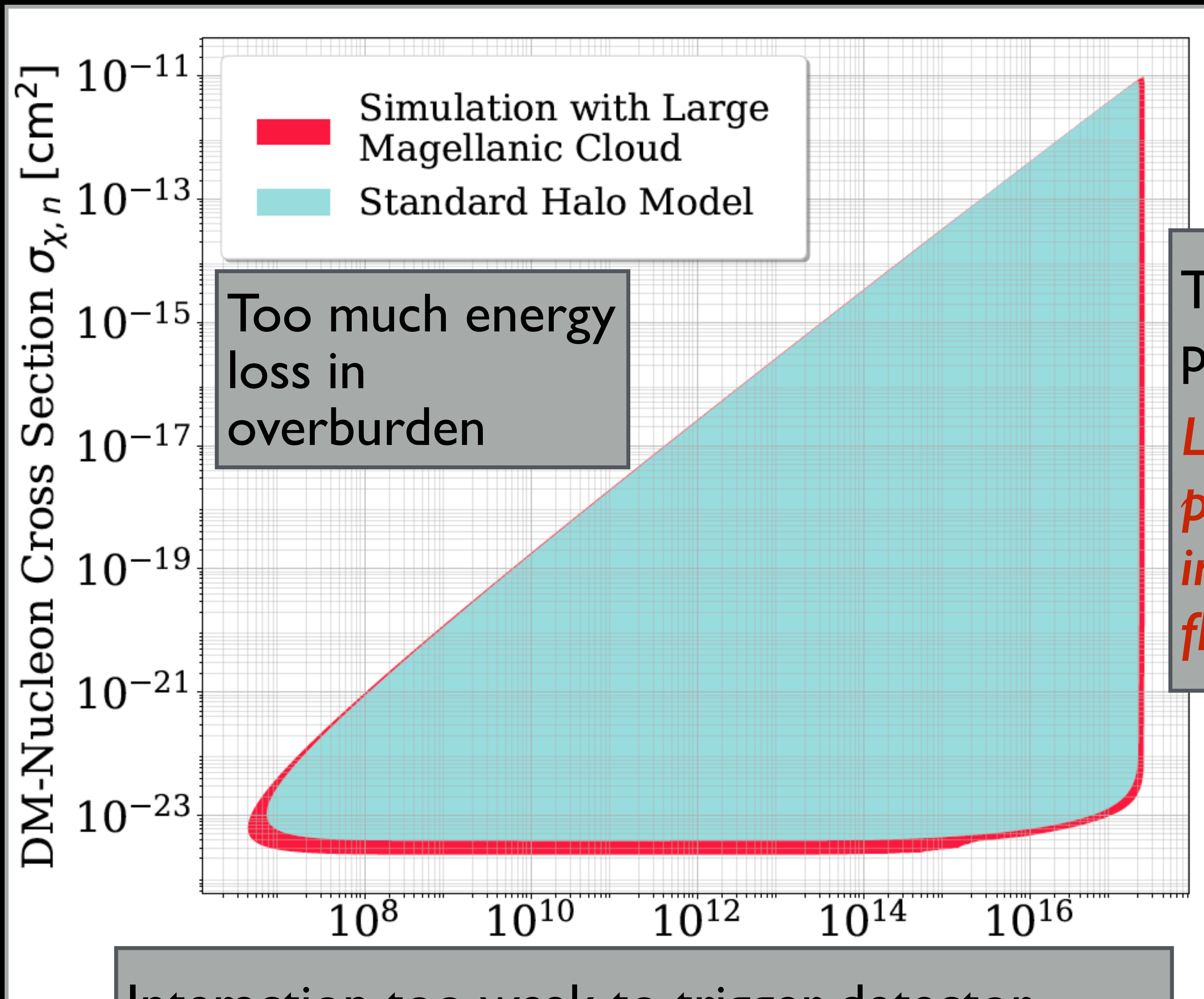
Plastic etch searches for dark matter

Skylab



Too much energy loss in overburden

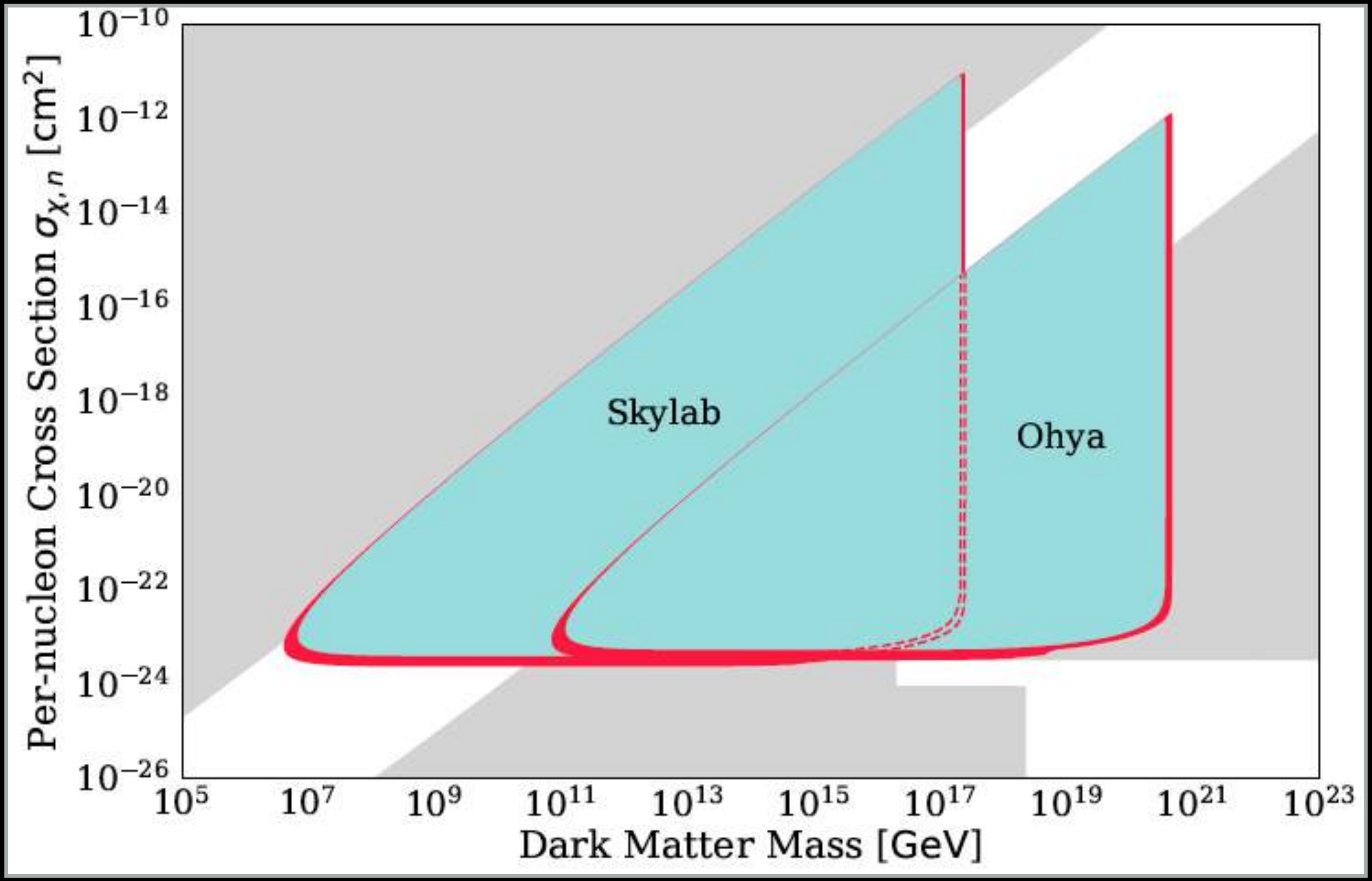
Too few particles pass the detector

LMC boosts particle speeds, increasing the flux

Interaction too weak to trigger detector

Effect of LMC most significant at low masses

Plastic etch searches for dark matter



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- LMC extends the parameter space that can be probed by the heavy DM searches.

Summary

- The LMC boosts the high speed tail of the local DM velocity distribution.

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- **This leads to substantial modifications of DM direct detection signals:**
  - Stronger direct detection limits.
  - An even greater impact for ***velocity-dependent*** interactions.
  - Improved sensitivity to ***heavy DM***.

Summary

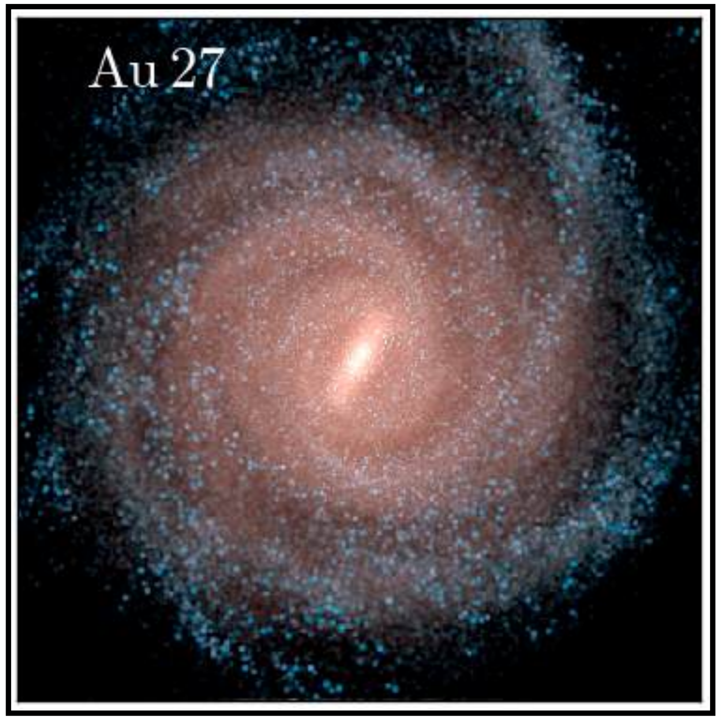
- The LMC boosts the high speed tail of the local DM velocity distribution.
- **This leads to substantial modifications of DM direct detection signals:**
    - Stronger direct detection limits.
    - An even greater impact for ***velocity-dependent*** interactions.
    - Improved sensitivity to *heavy DM*.
- *Highlights the need to move beyond equilibrium models for the DM halo.*

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: ~ 48 kpc

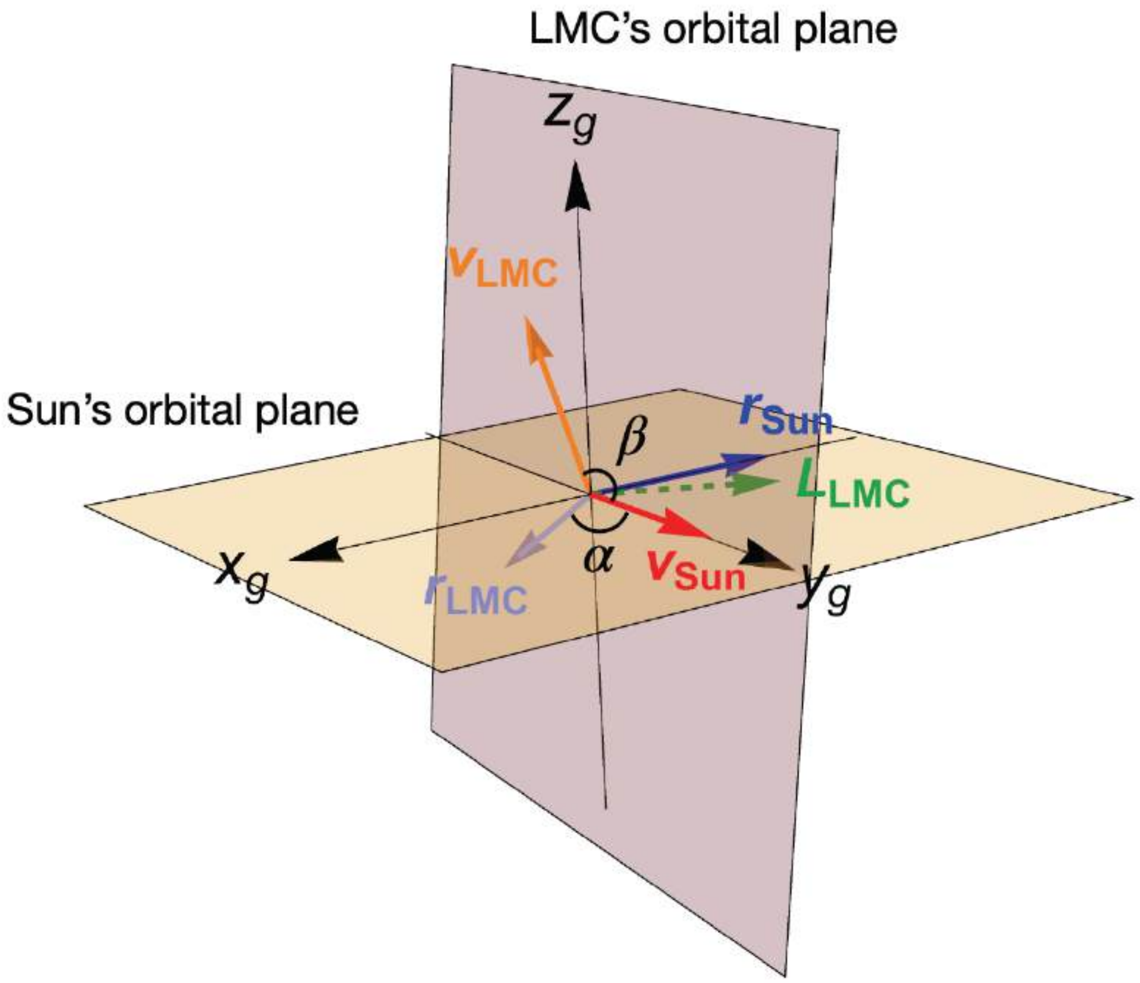
- Difficult to find an exact LMC analogue in cosmological simulations. → Follow the history of the simulated halos within the last 8 Gyrs to find LMC analogues.



- 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 $[40,60]$ kpc.

Matching the Sun-LMC geometry

Steps in matching the Sun-LMC geometry to observations:



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

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

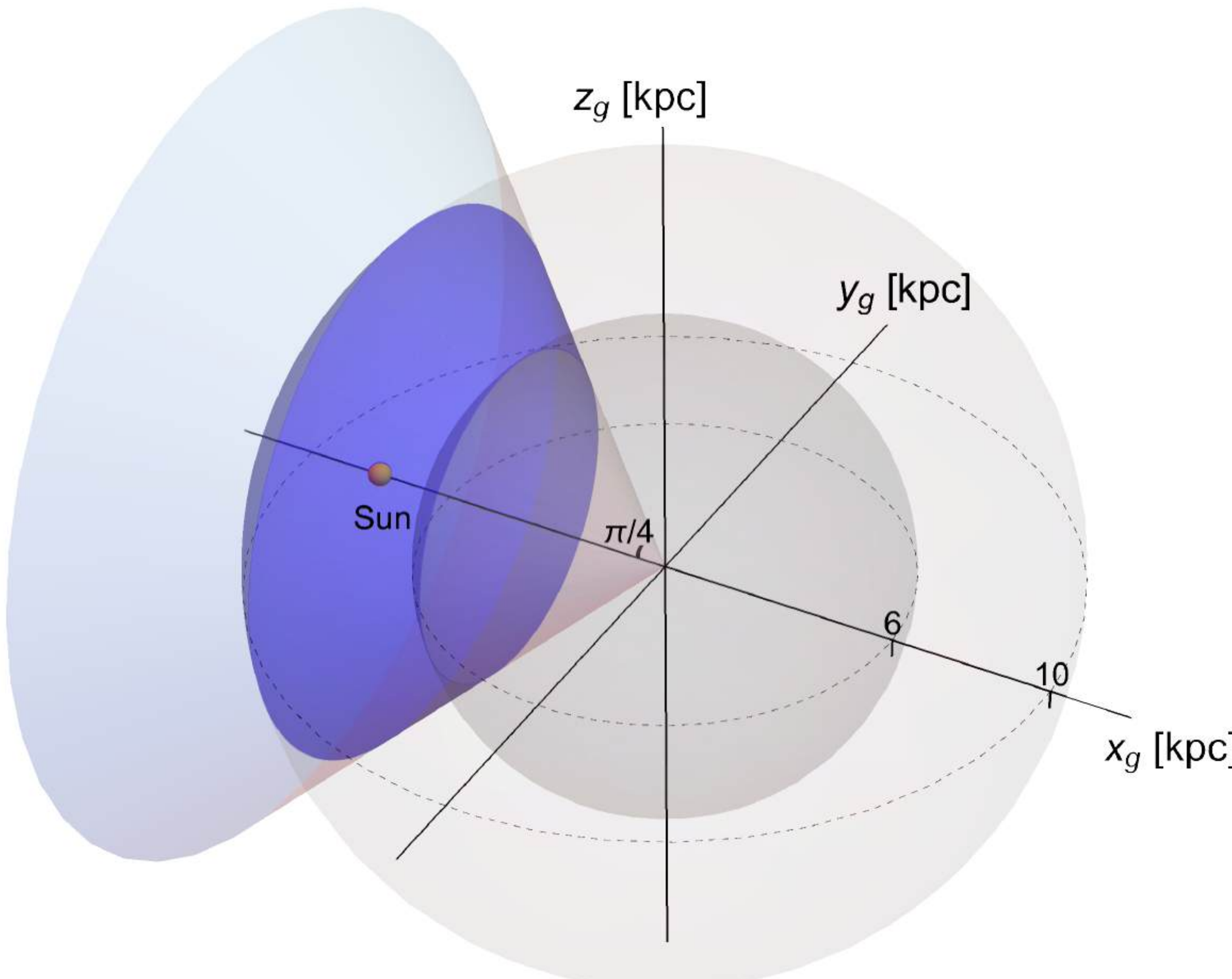
1. Find the stellar disk orientations that make the same angle with the orbital plane of the LMC analogues as in observations.

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 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.

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

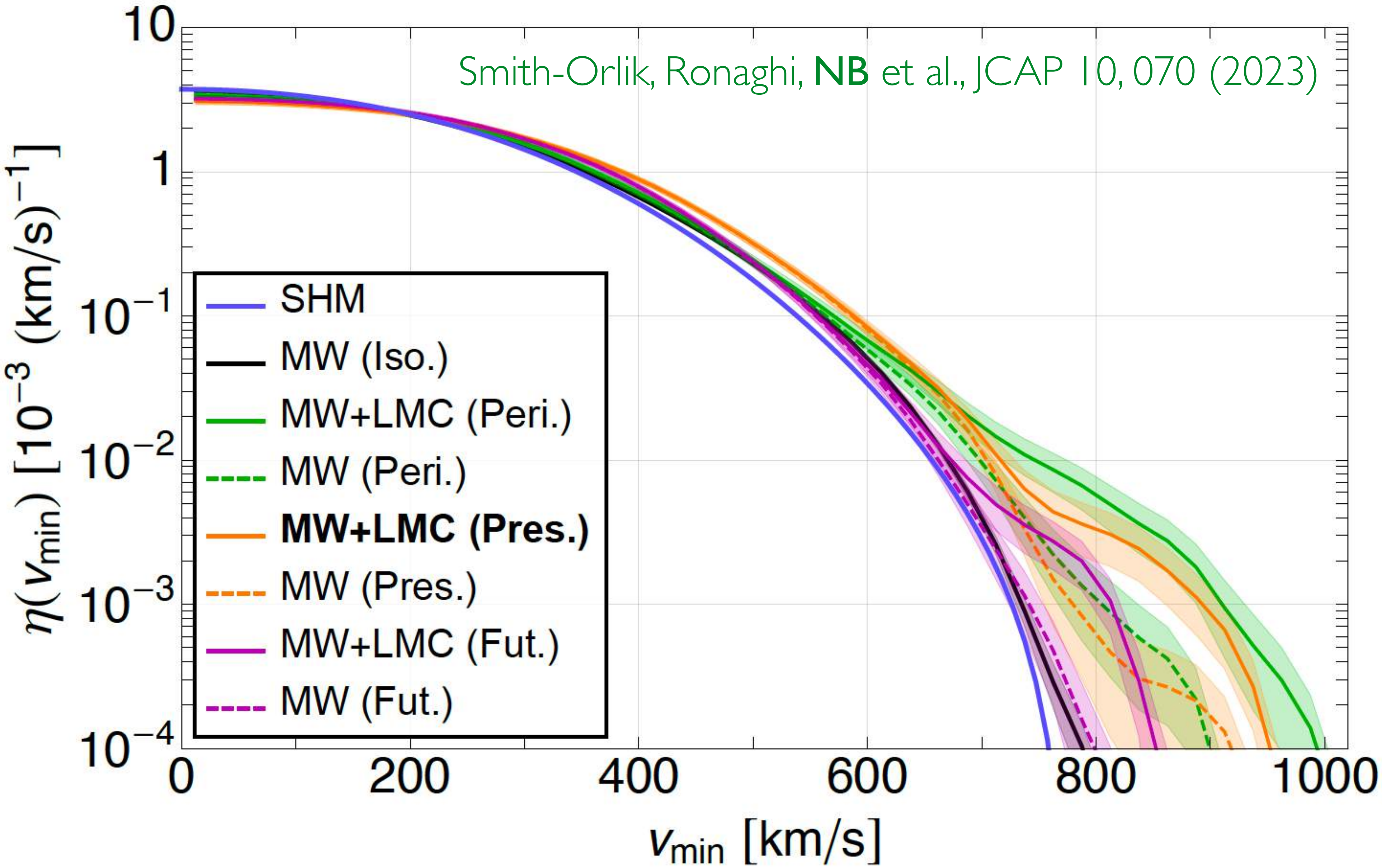
$$\frac{dR}{dE_R} = \frac{\sigma_0 \, F^2(E_R)}{2 m_\chi \mu_{\chi N}^2} \rho_\chi \, \eta(v_{\min}, t)$$

where

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

Halo integral

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

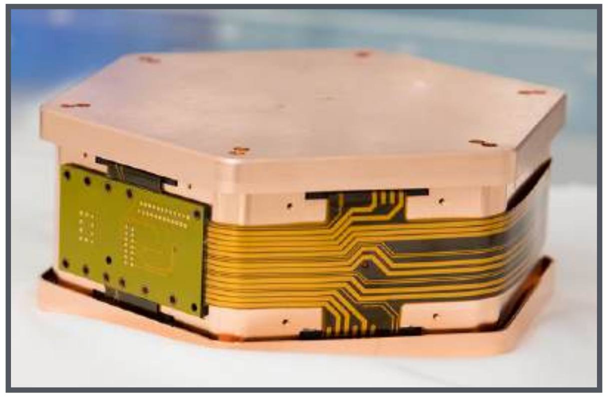
Xenon based

$[2 - 50]$ 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

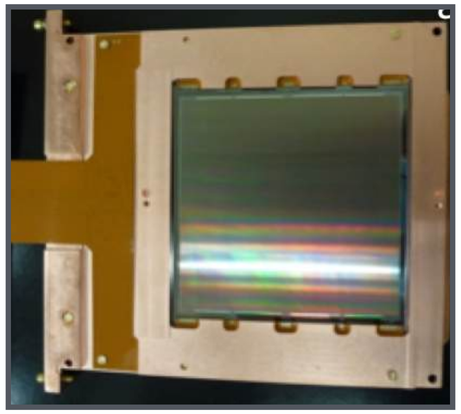
Based on SuperCDMS



Electron recoils

Silicon CCD

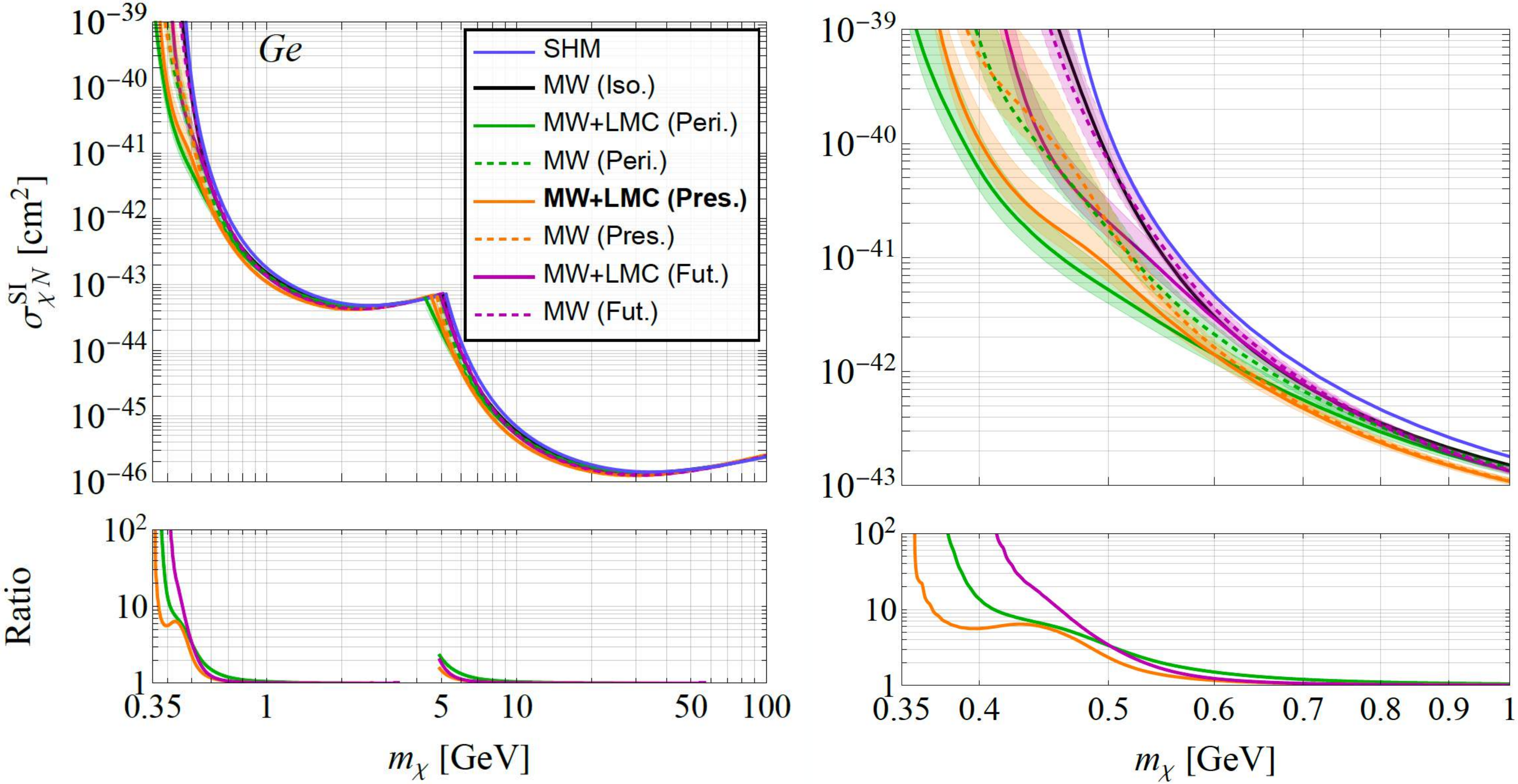
1 electron threshold
1 kg yr
Based on DAMIC



Direct detection: nuclear recoils

Germanium based detector:

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

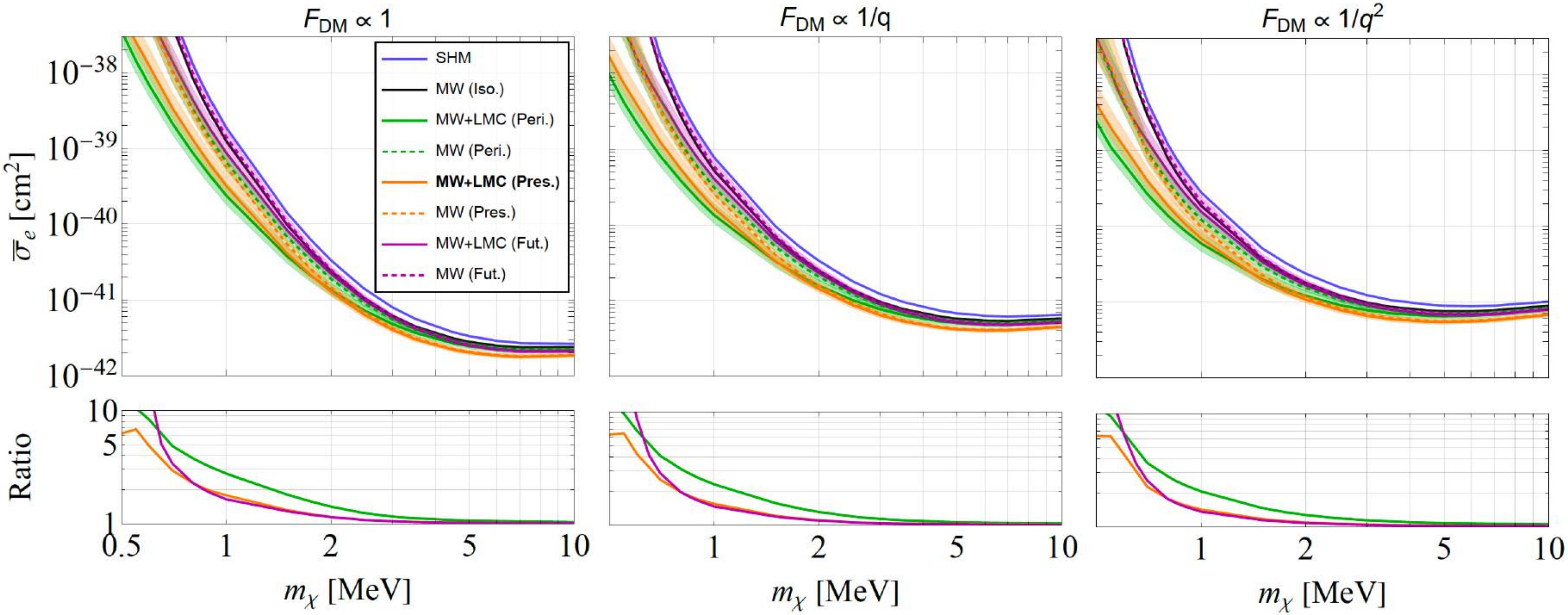


Smith-Orlik, Ronaghi, **NB** et al., JCAP 10, 070 (2023)

Direct detection: electron recoils

Silicon CCD detector:

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



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

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]

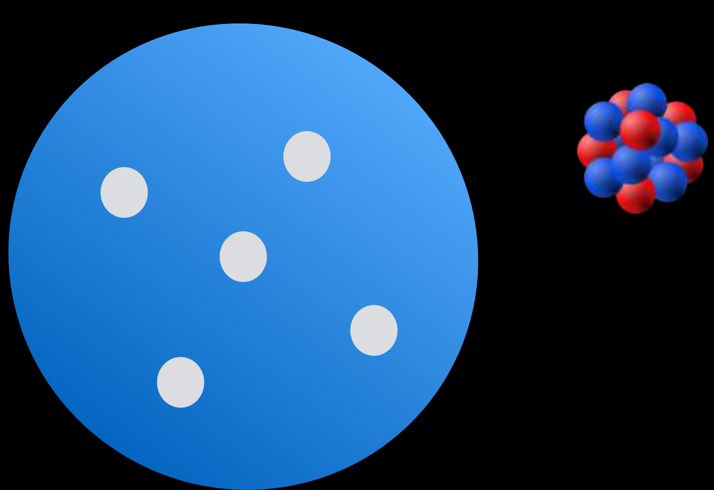
Heavy dark matter

Two models for DM interaction with nuclei:

- **Spin-independent scattering:**

  Loosely-bound composite DM
  → Coherent interaction with all nucleons

$$\sigma_{\chi N} = A^2 \left(\frac{\mu_{\chi N}}{\mu_{\chi n}} \right)^2 \sigma_{\chi n}$$

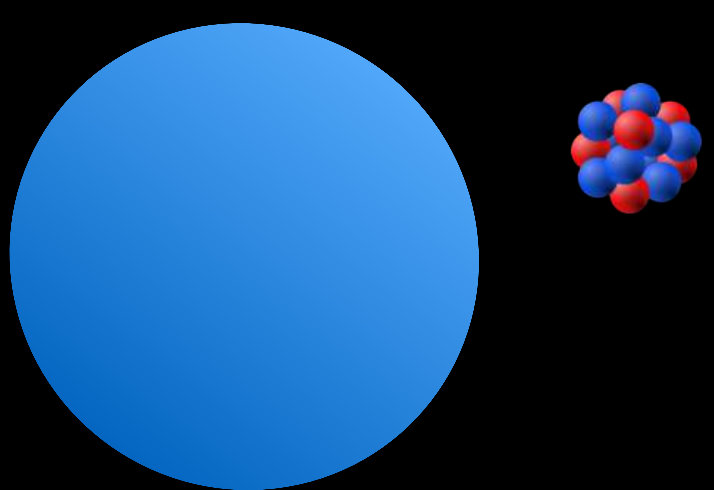


DM

- **Contact interaction:**

  Single large DM particle or tightly-bound composite DM
  → Cross section independent of nucleus

$$\sigma_{\chi N} = \sigma_C$$

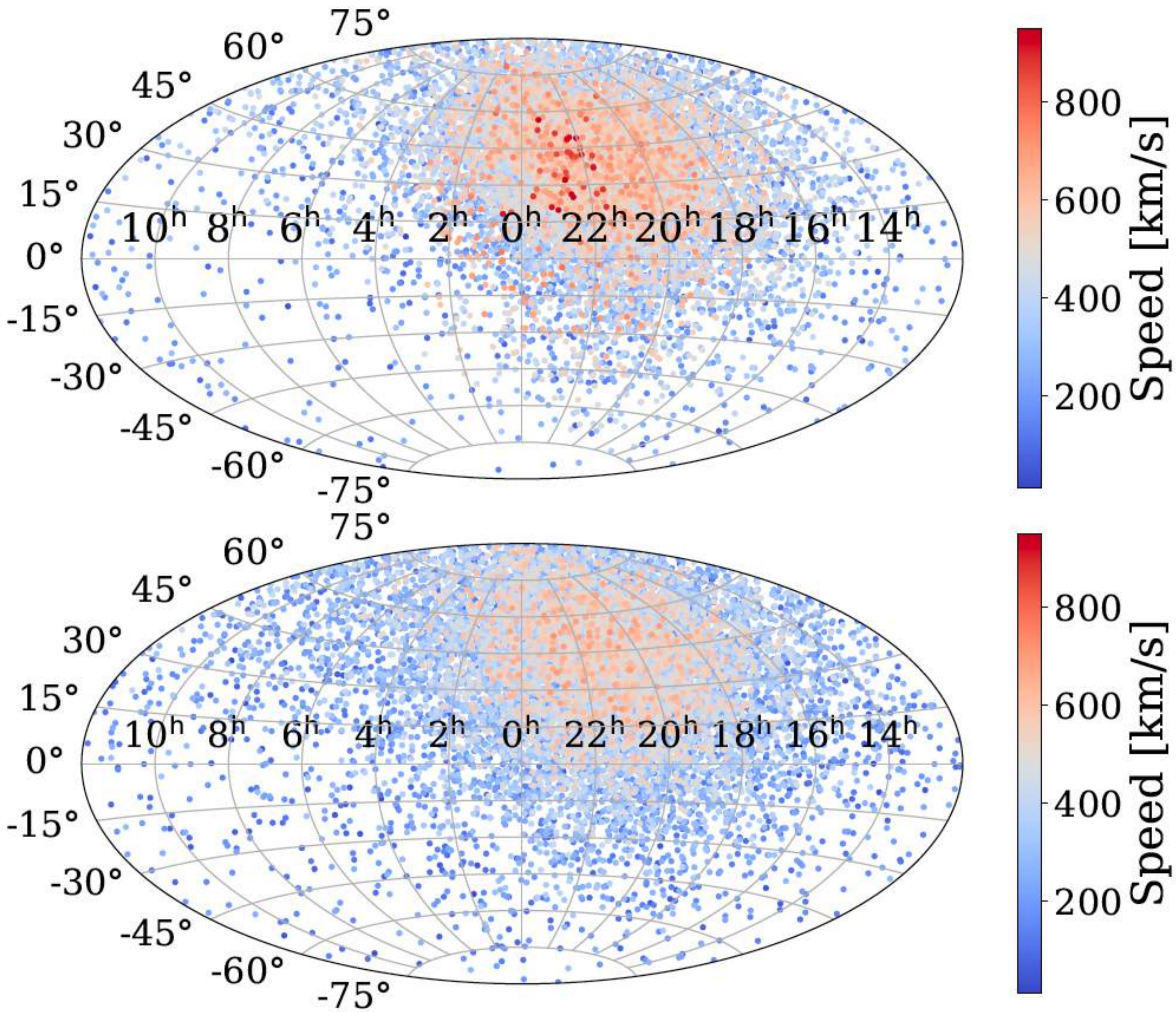


DM

Skylab and Ohya Experiments

	Ohya	**Skylab**
Area A	$2442\,\mathrm{m}^2$	$1.17\,\mathrm{m}^2$
Duration T	$2.1\,\mathrm{yr}$	$0.70\,\mathrm{yr}$
Tolerance Angle θ_{tol}	$18.4°$	$60°$
Overburden Material	Atmosphere + $2.7\,\frac{\mathrm{g}}{\mathrm{cm}^3}$ Crust	$2.7\,\frac{\mathrm{g}}{\mathrm{cm}^3}$ Aluminum
Solid Overburden Length at θ_{tol}	$39\,\mathrm{m}$	$0.74\,\mathrm{cm}$
Column Density of Atmospheric Overburden at θ_{tol}	$960\,\frac{\mathrm{g}}{\mathrm{cm}^2}$	$0\,\frac{\mathrm{g}}{\mathrm{cm}^2}$
Detector Material	$1.2\,\frac{\mathrm{g}}{\mathrm{cm}^3}$ Lexan ($C_{16}H_{14}O_3$)	$1.34\,\frac{\mathrm{g}}{\mathrm{cm}^3}$ CR-39 ($C_{12}H_{18}O_7$)
Detector Length at θ_{tol}	$0.66\,\mathrm{cm}$	$1.6\,\mathrm{cm}$
Detection Threshold E'_{th}	$0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}}$	$0.5\,\frac{\mathrm{GeV}}{\mathrm{cm}}$

Dark matter velocity distribution



NB, Bramante, Buchanan, JCAP 04, 065 (2026)

Dark matter energy loss

Number of DM particles above a given speed v_0, which pass through the detector:

$$N_{\geq v_0}(m_\chi) = \frac{A_d T \rho_\chi}{m_\chi} \int_{v > v_0} d^3 v \, f_{\rm det}(\mathbf{v}) \, I(\mathbf{v})$$

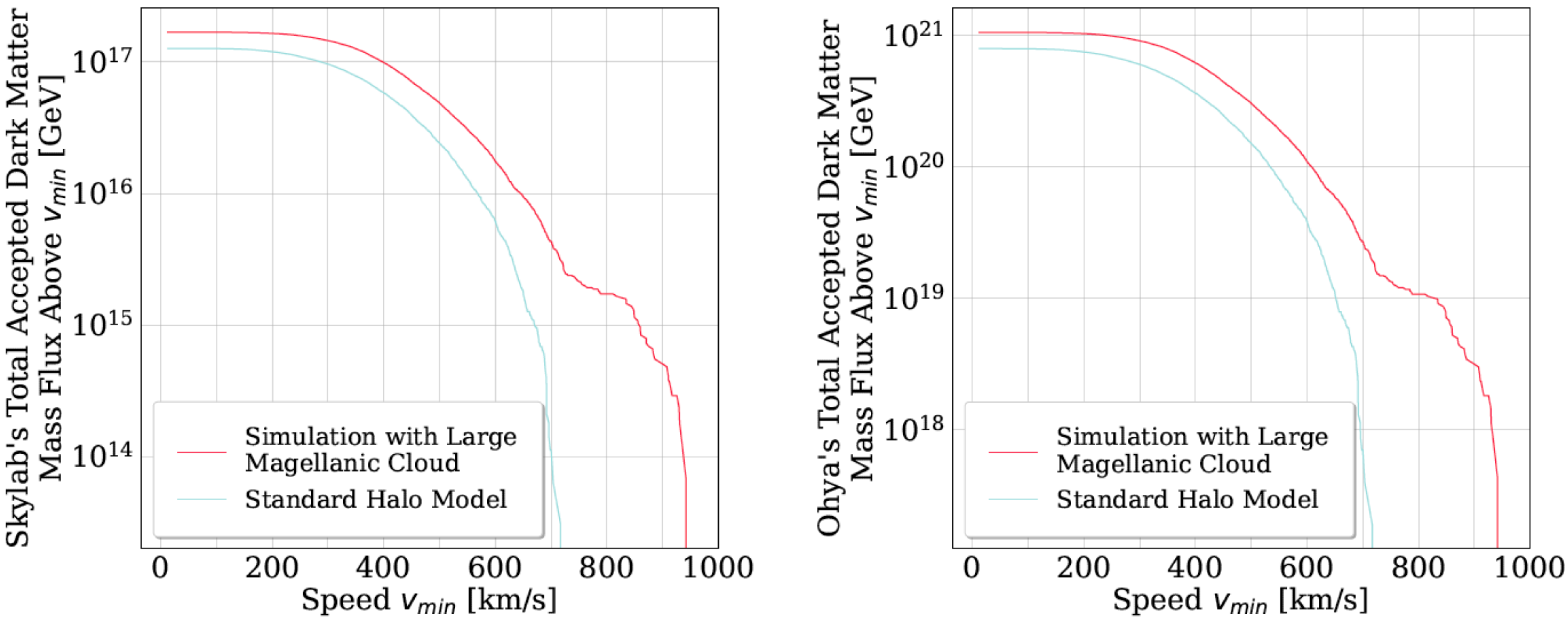
detector quantities

As a DM particle crosses through a medium, it will lose energy to background nuclei at a rate of

$$\frac{dE}{dx} = -\frac{2E}{m_\chi} \sum_{A \in M} \frac{\mu_{\chi A}^2}{m_A} n_A \sigma_{\chi A}$$

where the sum is over all nuclei in the material, with number density n_A.

Integrated dark matter mass flux



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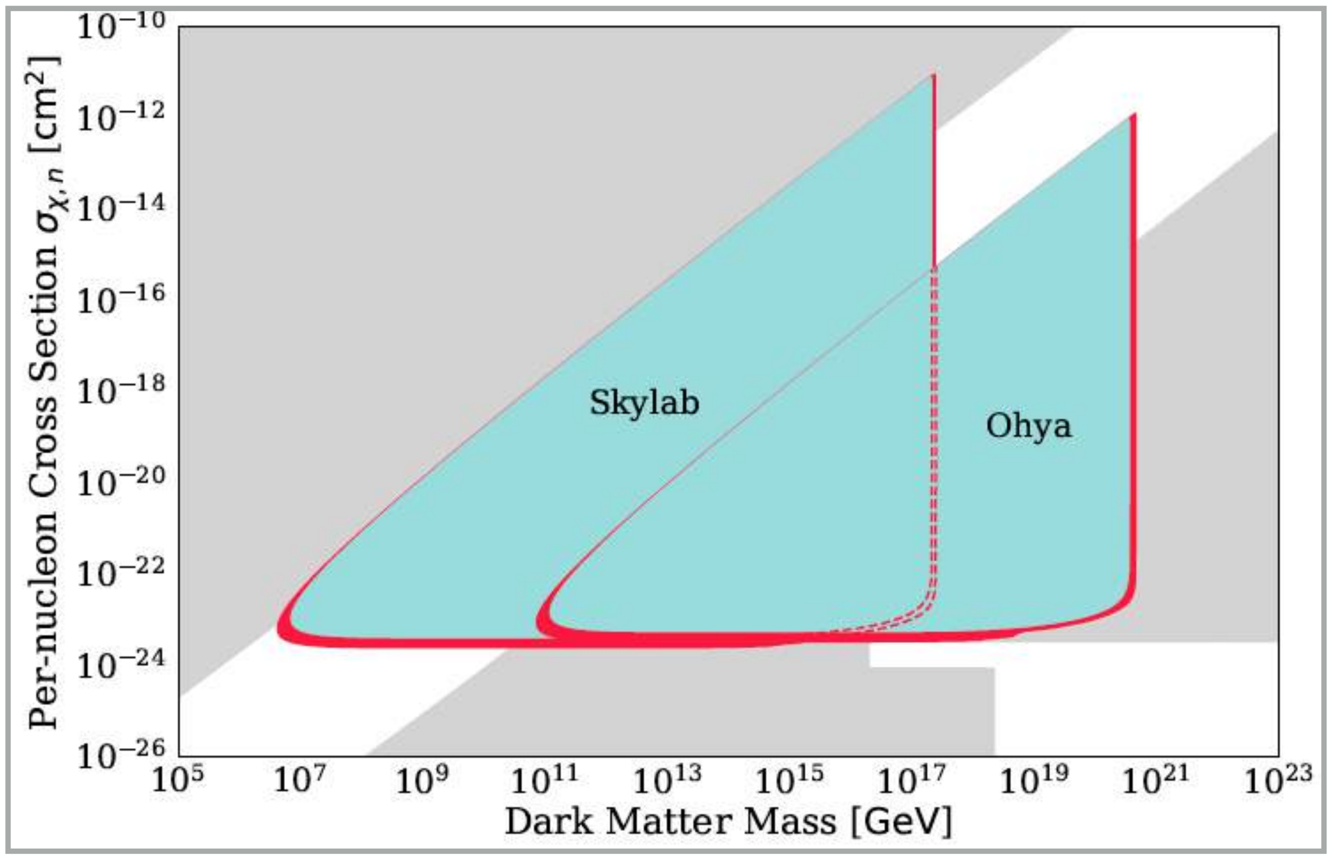
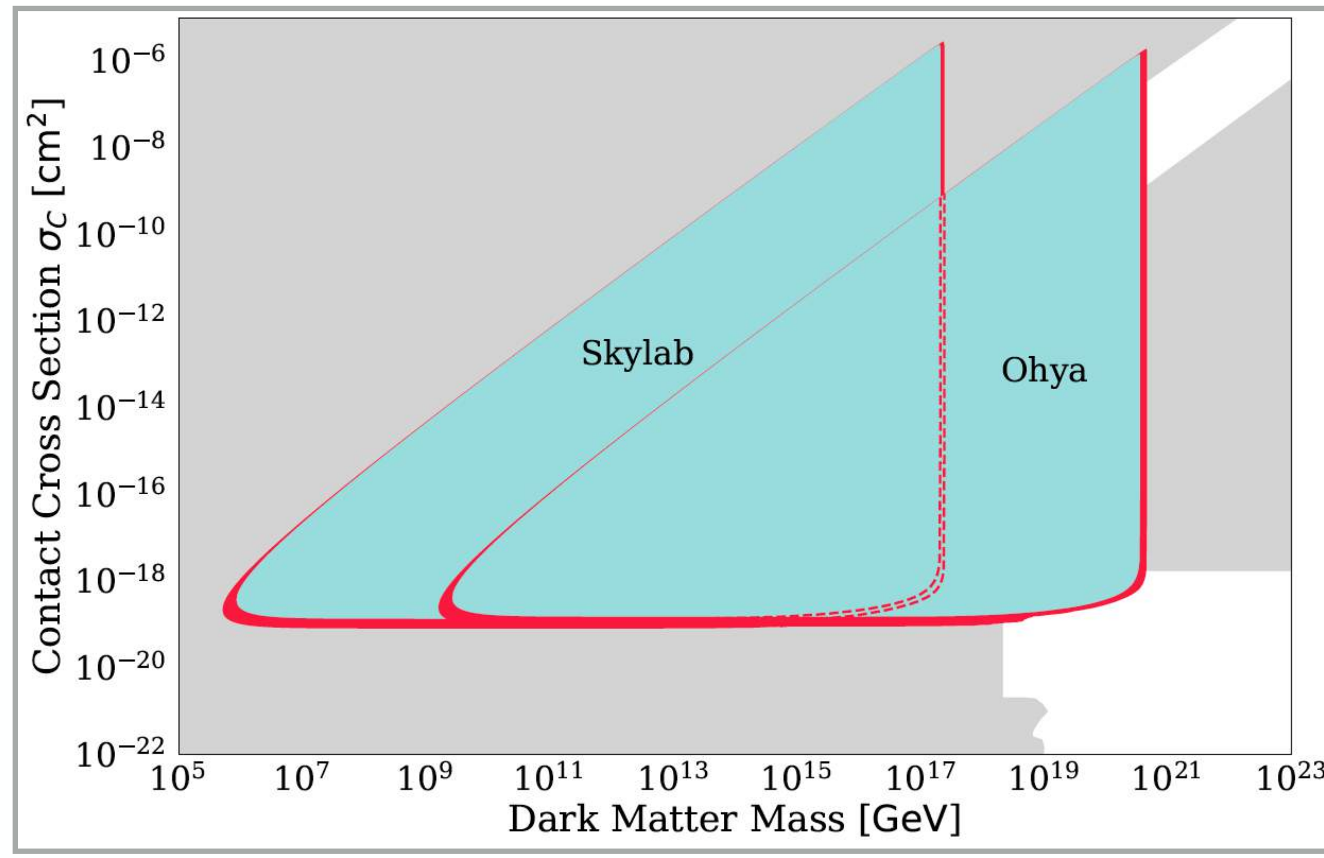
Plastic etch searches for dark matter

Spin-independent



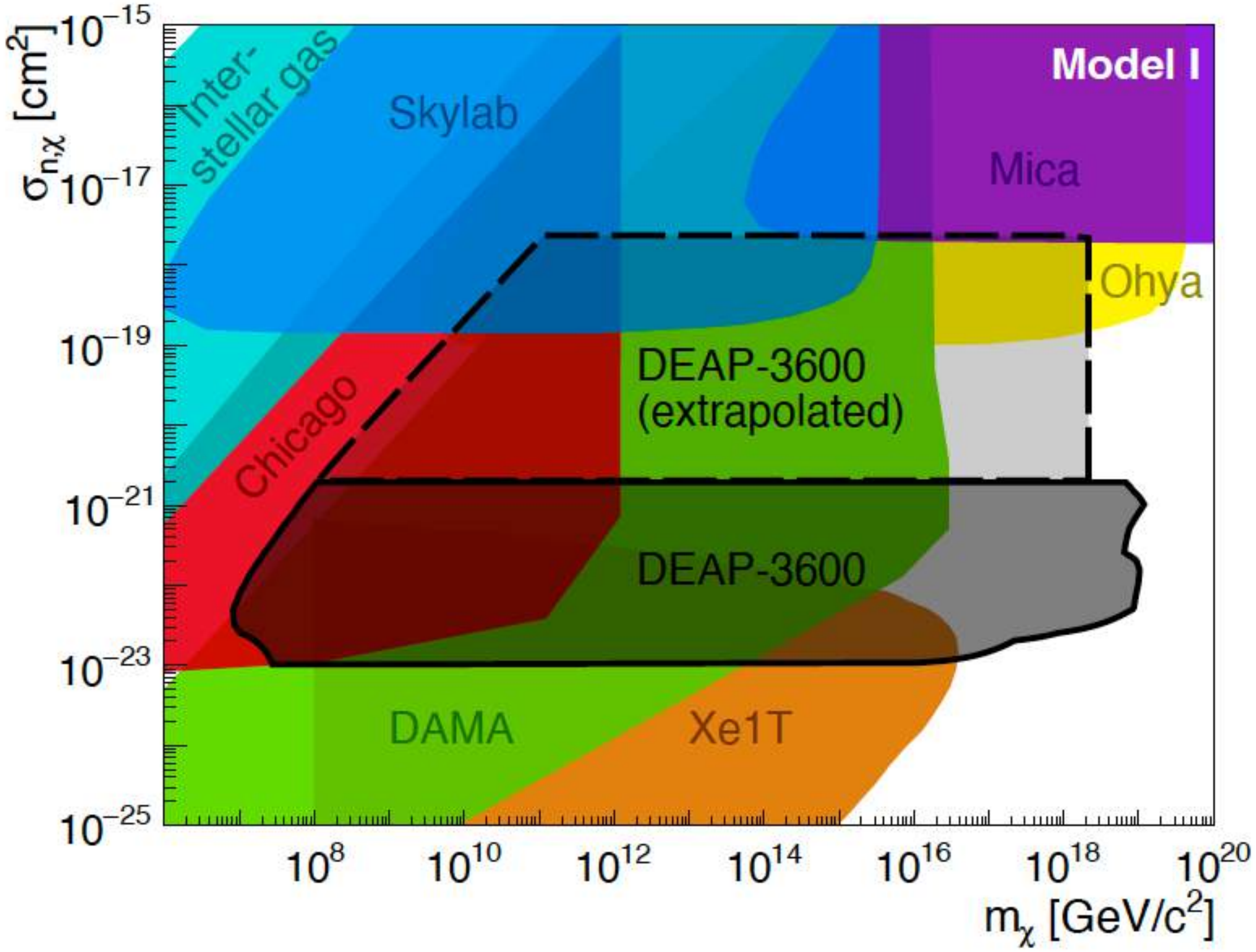
Contact



NB, Bramante, Buchanan, JCAP 04, 065 (2026)

Heavy dark matter bounds

Contact



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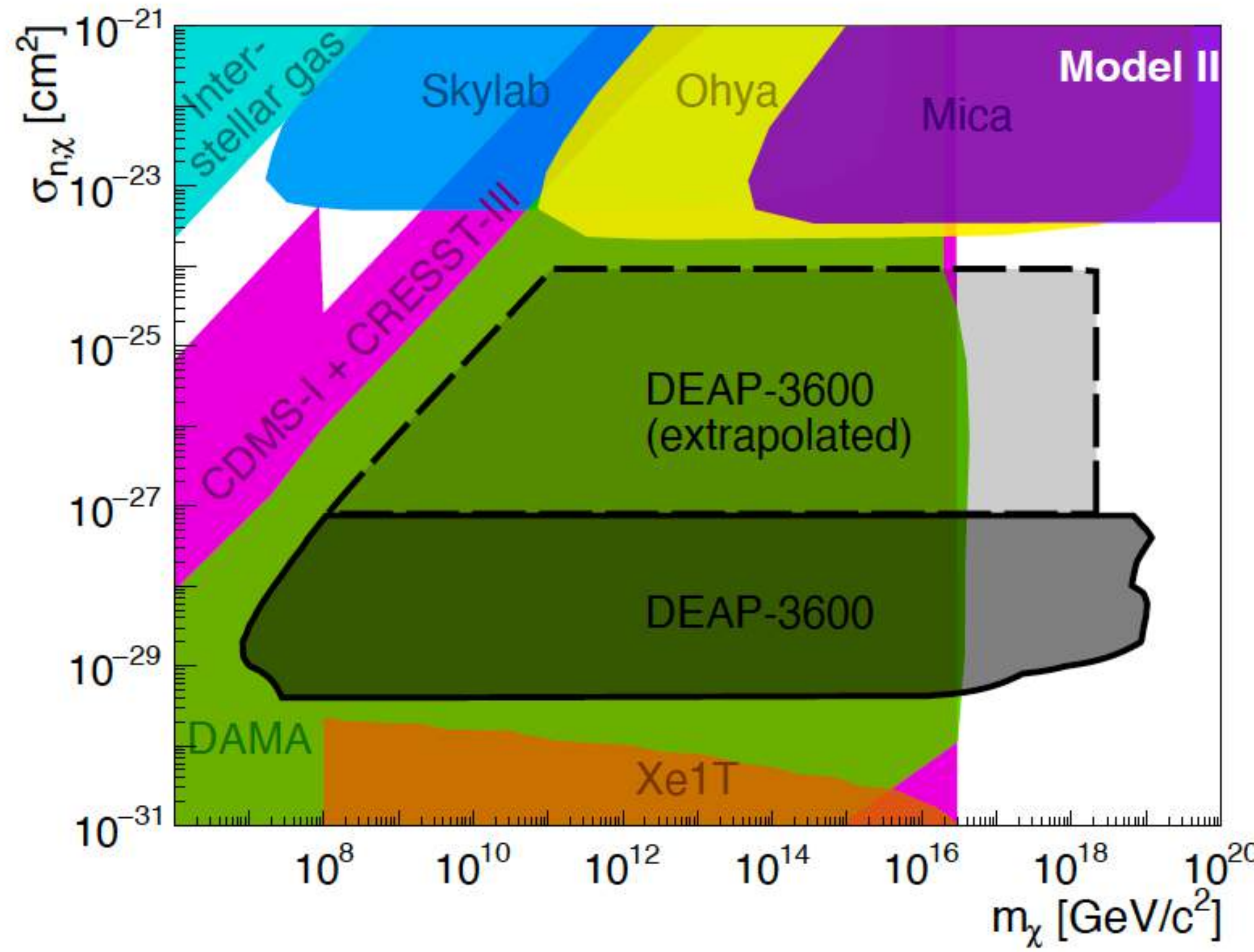

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