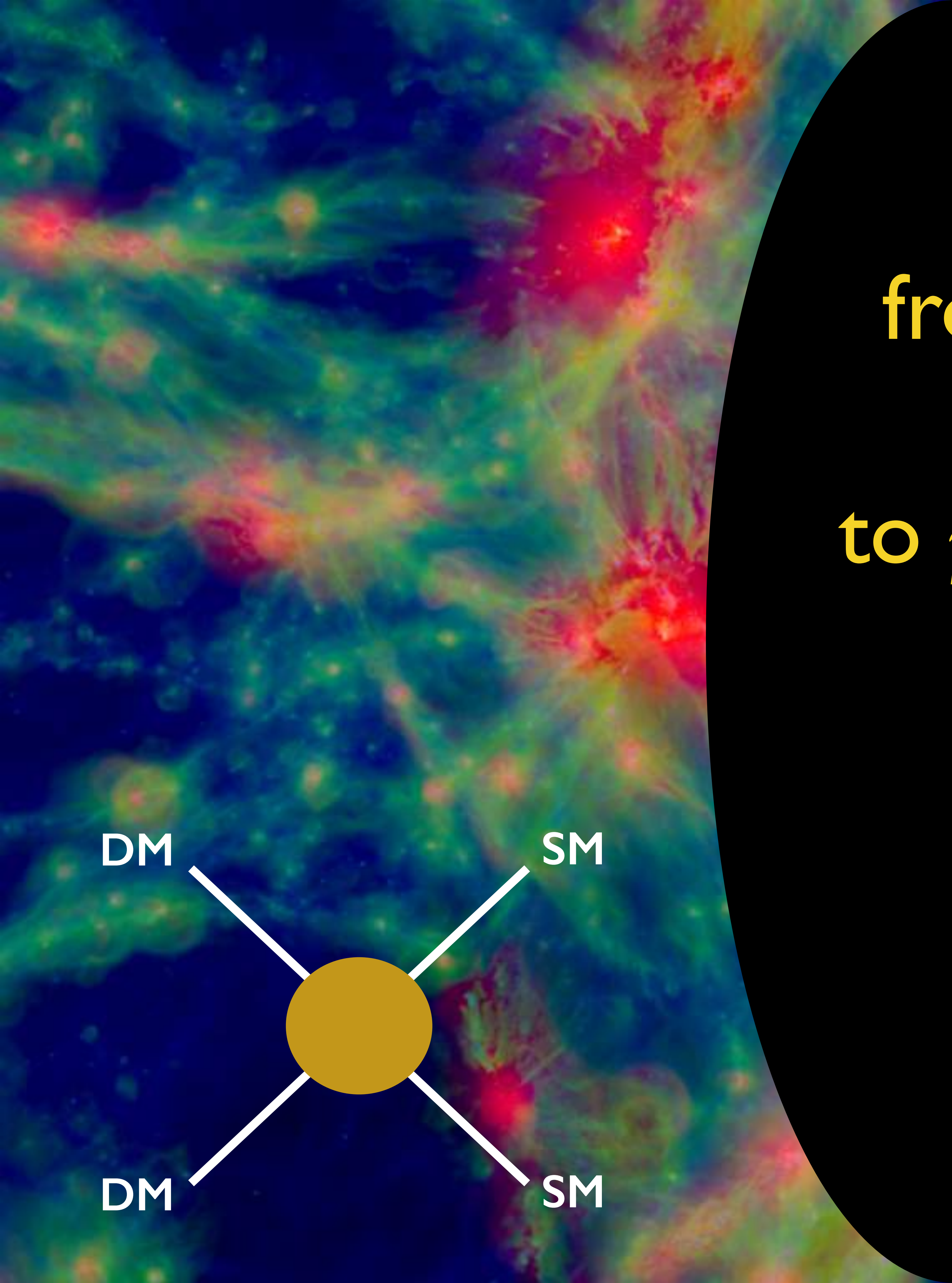


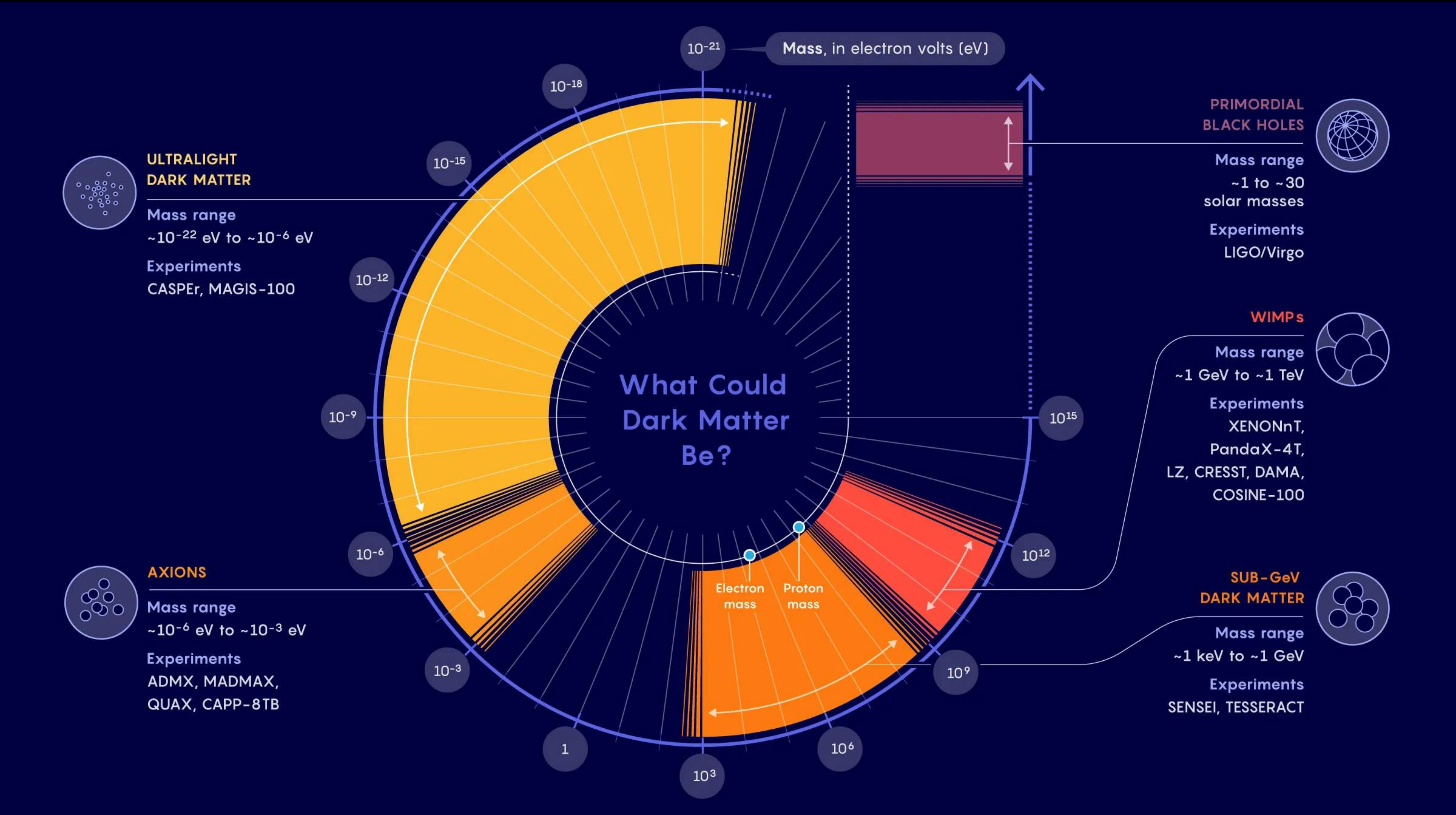
Dark matter: from *cosmological simulations* to *particle detection*

Nassim Bozorgnia

UNIVERSITY OF ALBERTA

Lake Louise Winter Institute
20 February 2023

The nature of dark matter



Credit: Samuel Velasco/Quanta Magazine

The nature of dark matter

- Many theoretically well-motivated dark matter (DM) particle candidates.

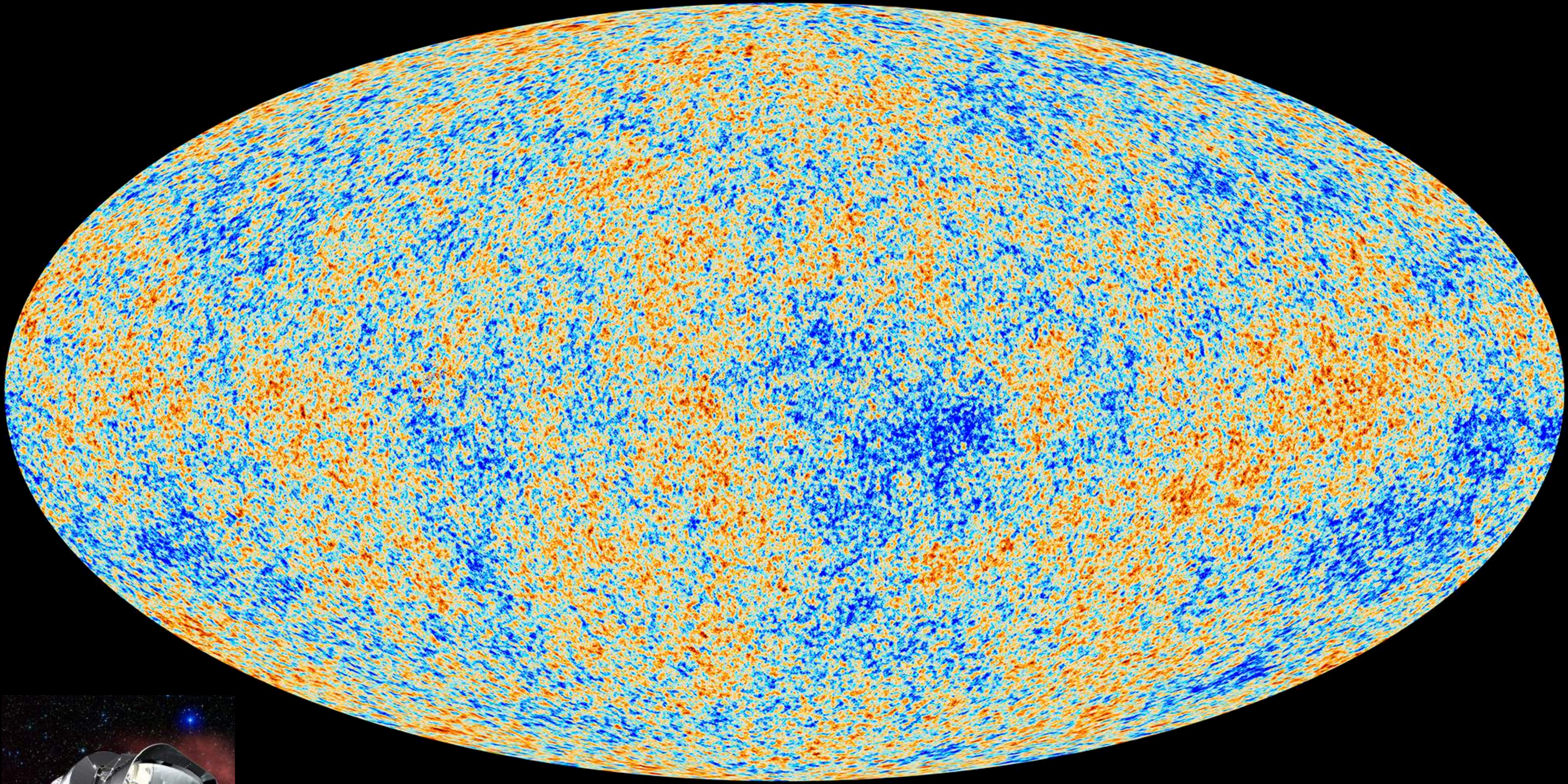
- **Key input parameter in particle DM searches:** galactic DM distribution.

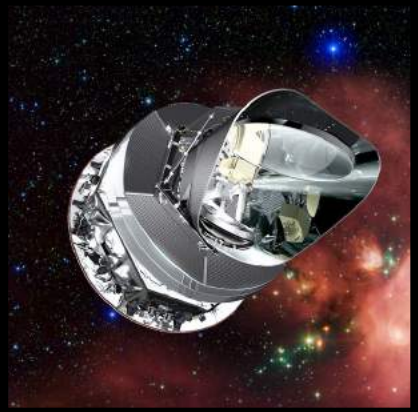
  Determining the DM distribution in the galaxy crucial for extracting the properties of the DM particle.

- *What are the predictions of cosmological simulations for particle DM detection?*

Cosmic Microwave Background

Snapshot of the baby Universe!

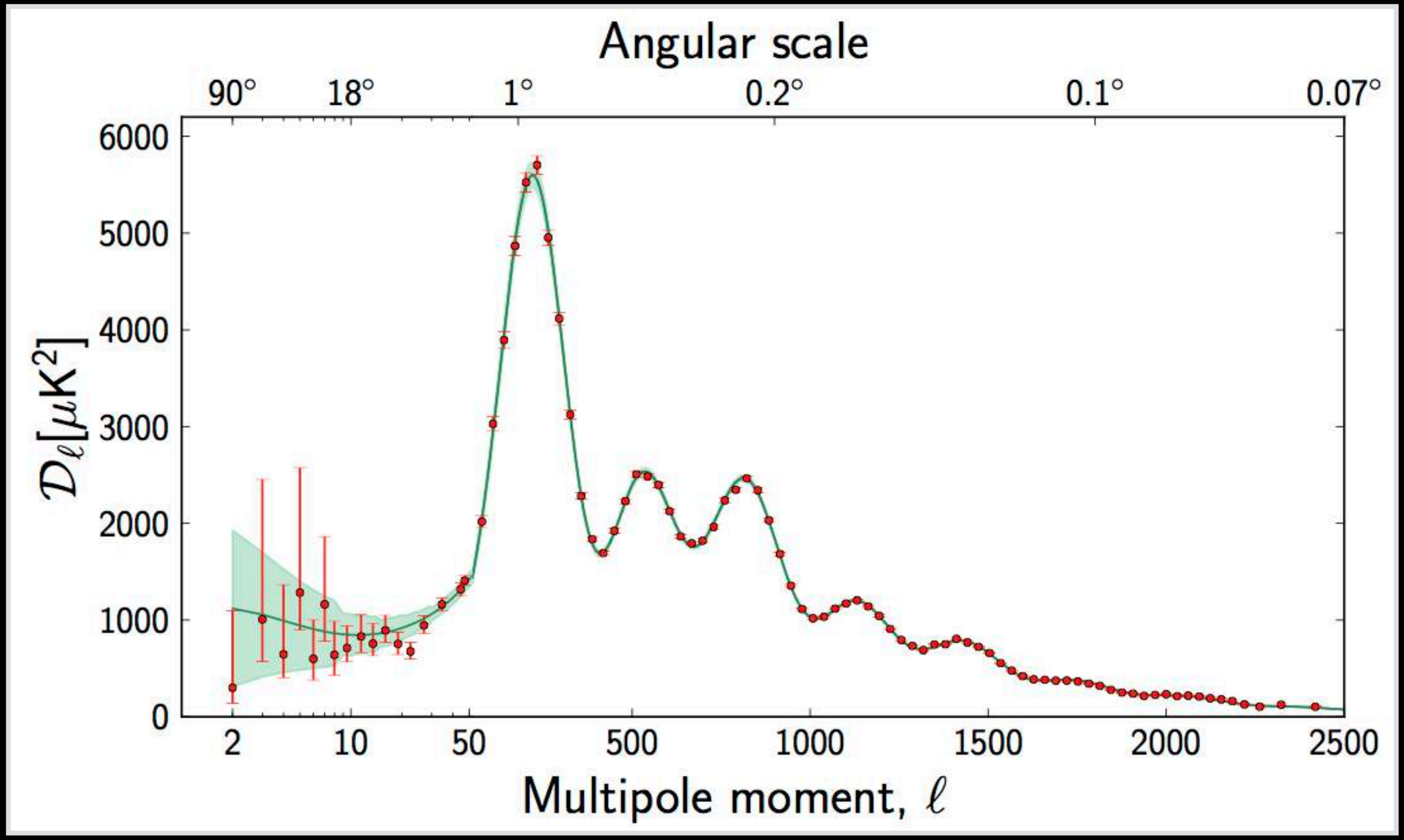


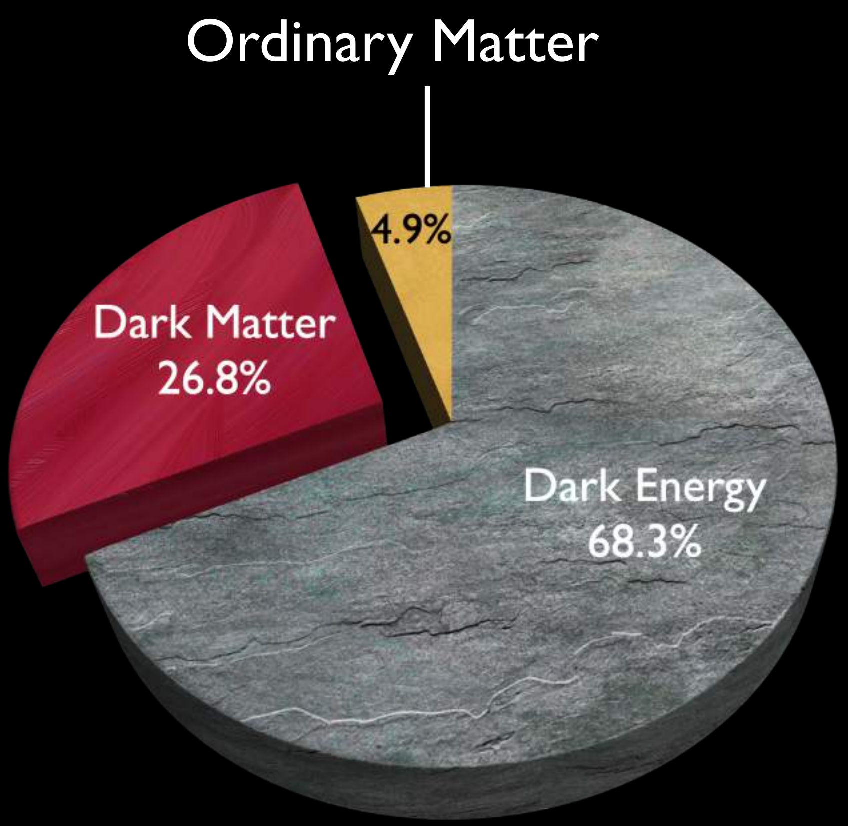


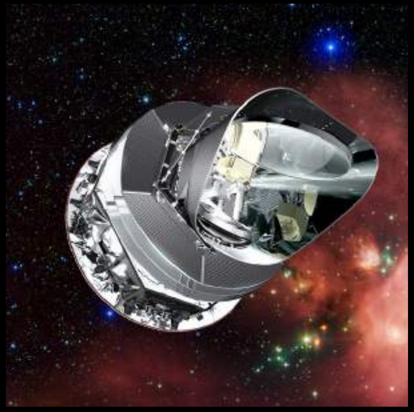
Planck CMB

Cosmic Microwave Background

Measurements of temperature fluctuations in the CMB provide a precise determination of the DM density in the Universe.





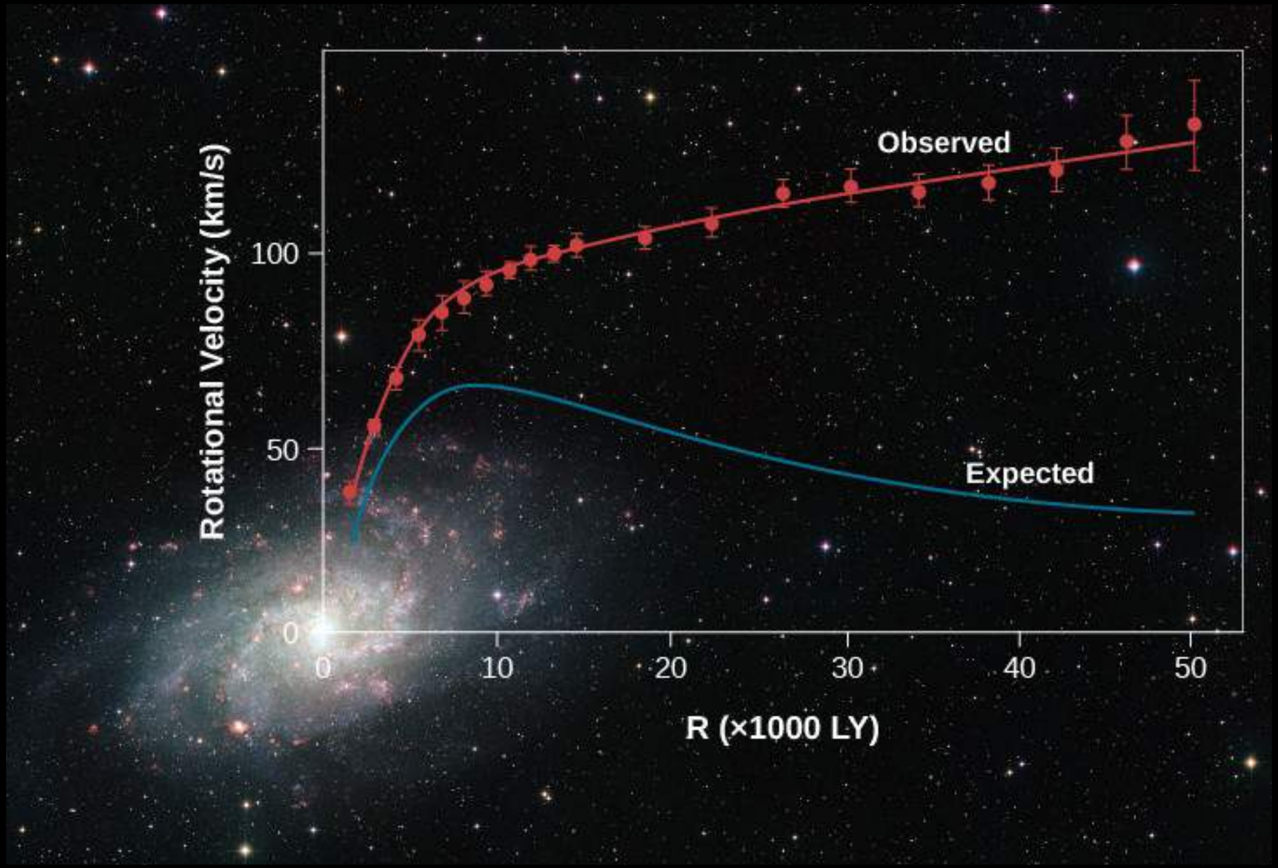


Planck 2015

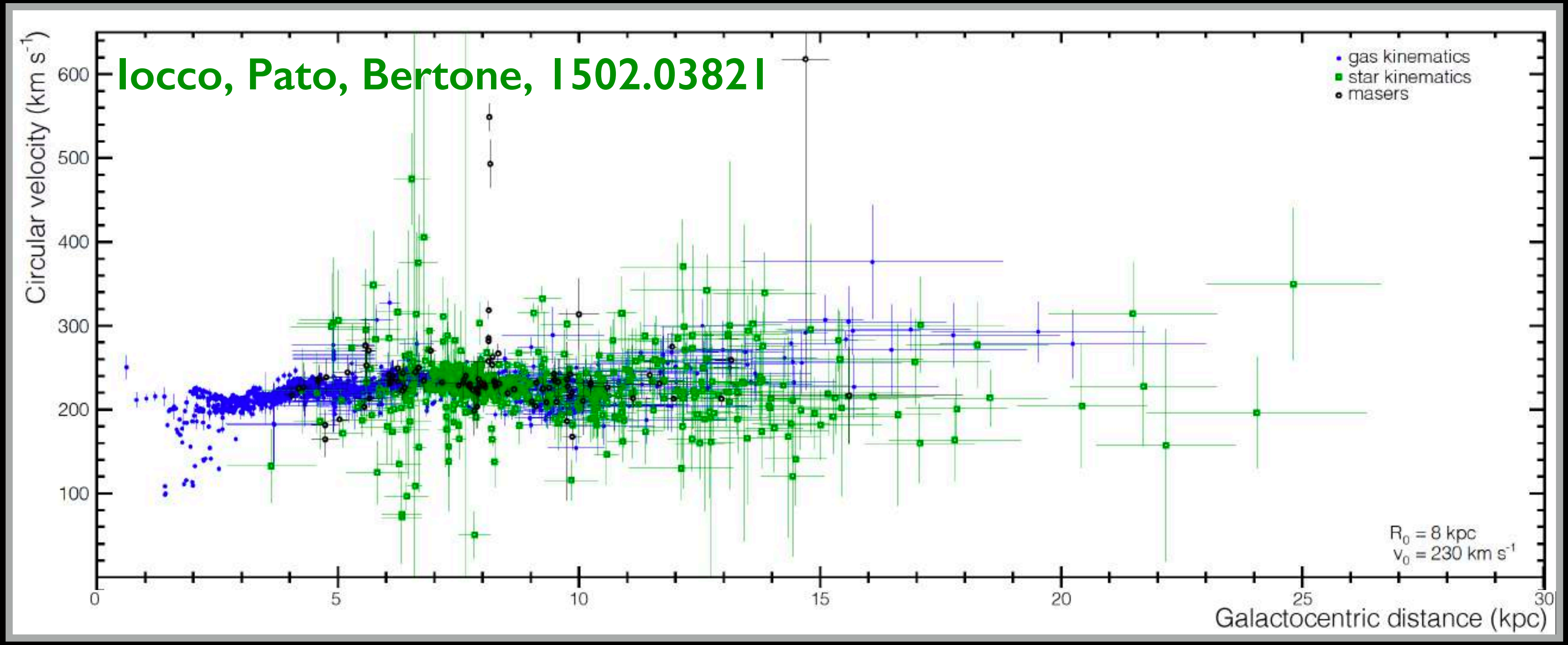
Our simulated Universe

Our simulated Universe

Galaxy rotation curves

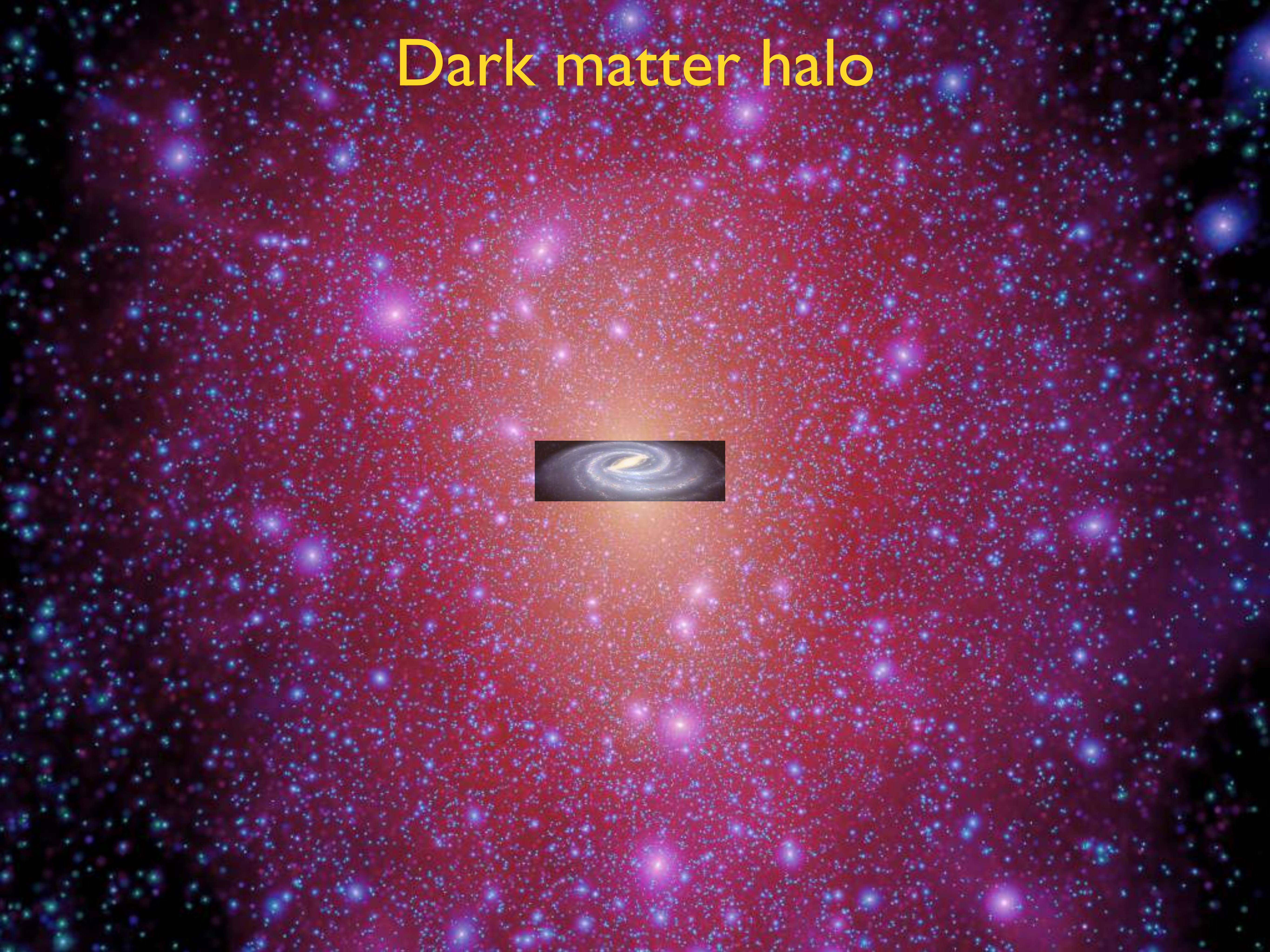


Compilation of Milky Way rotation curve observations



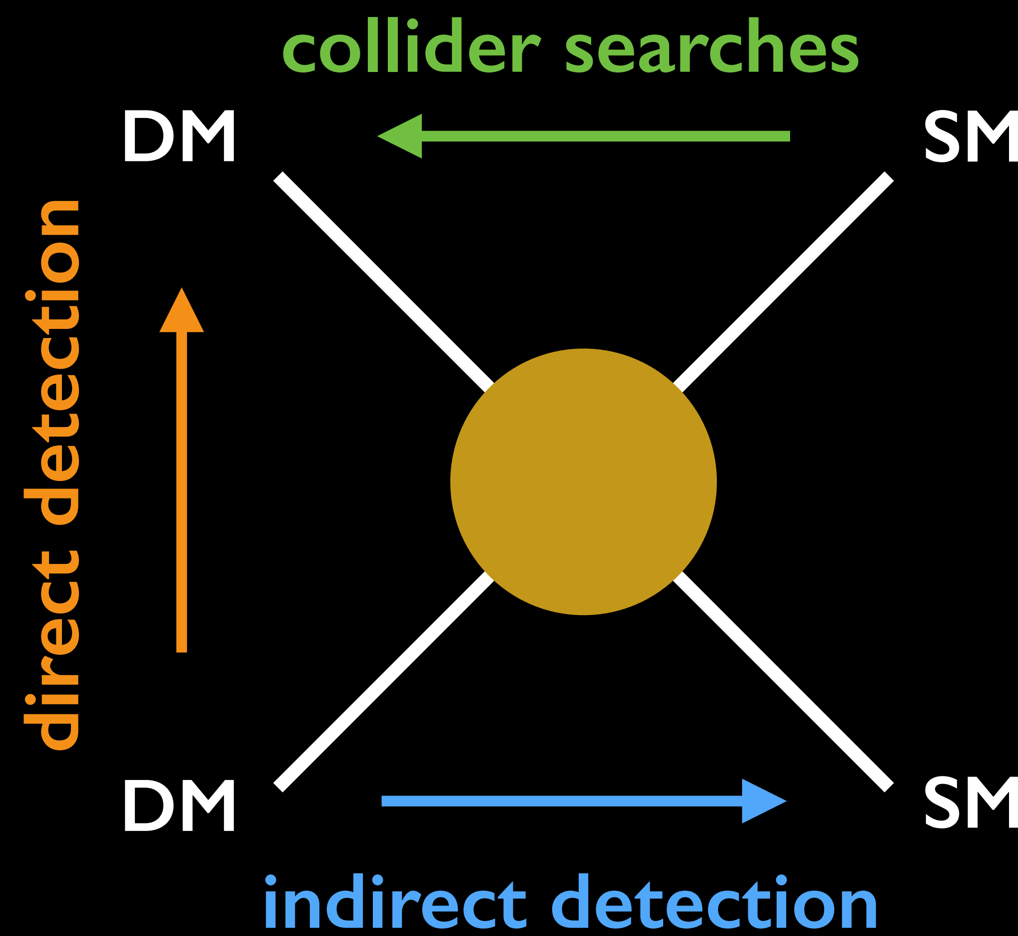
Dark matter halo

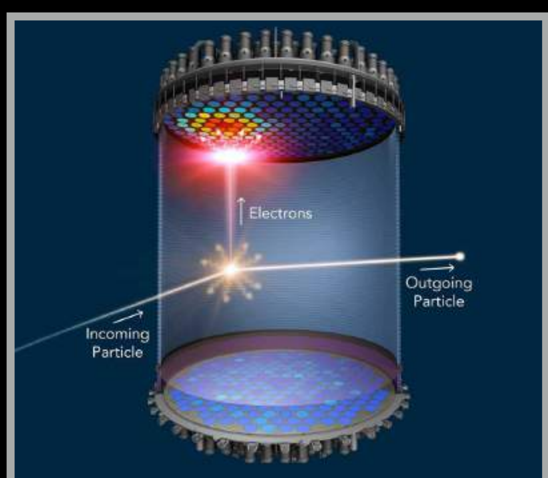
Dark matter halo

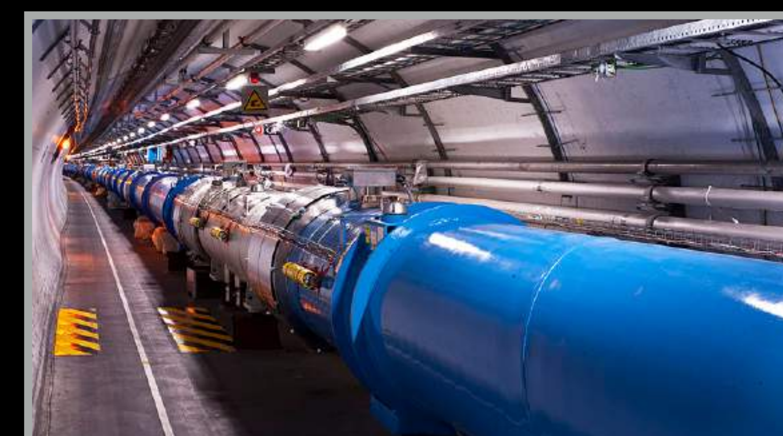


Dark matter searches

Searching for DM particles in three complementary ways:







Dark matter searches

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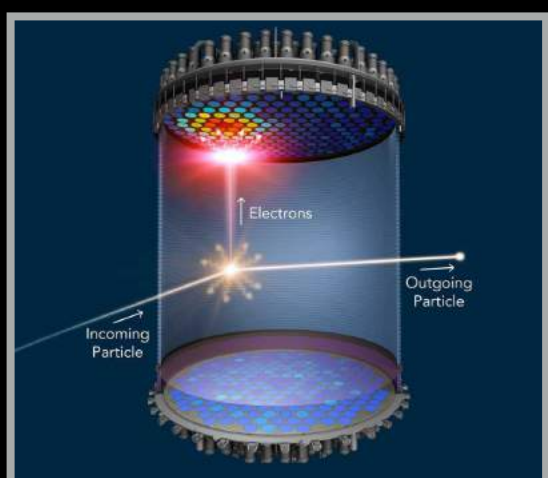
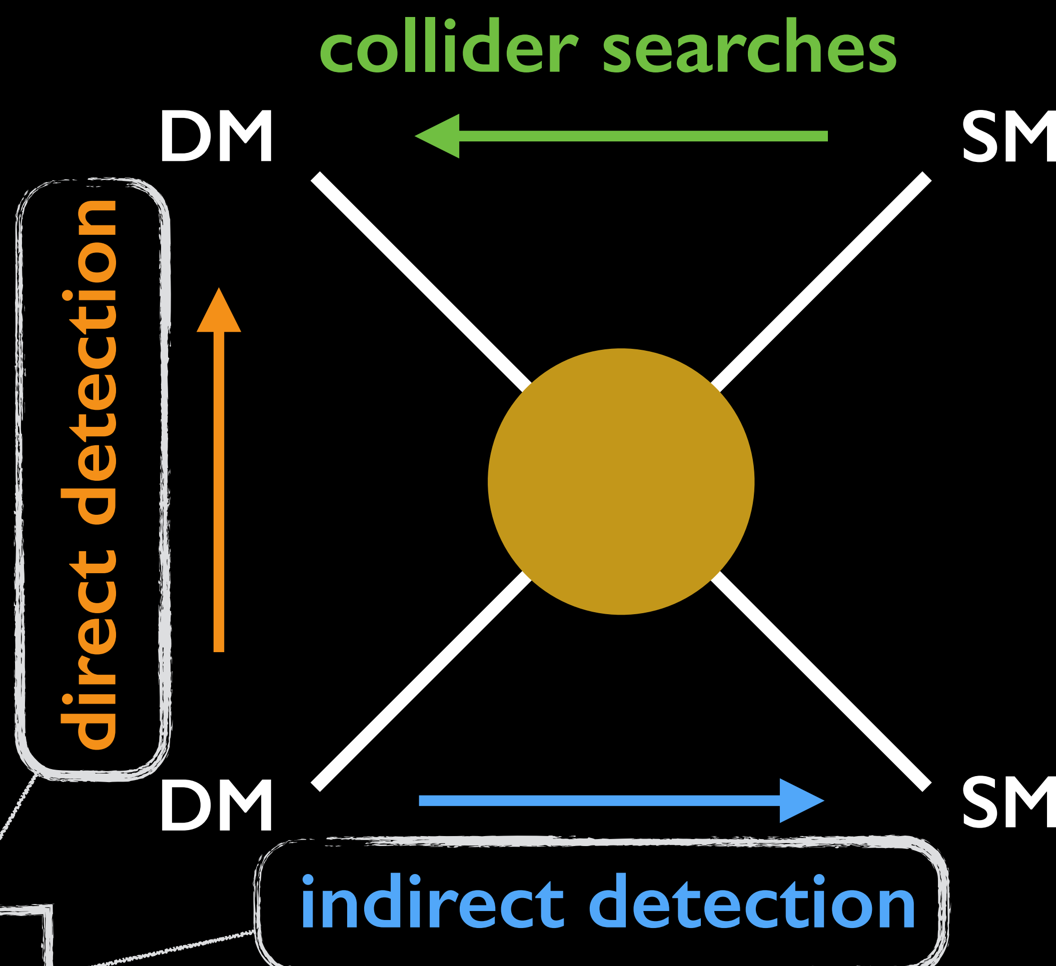
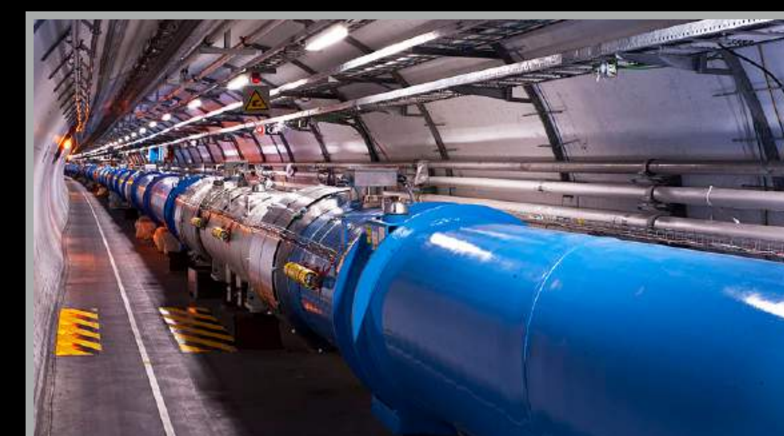


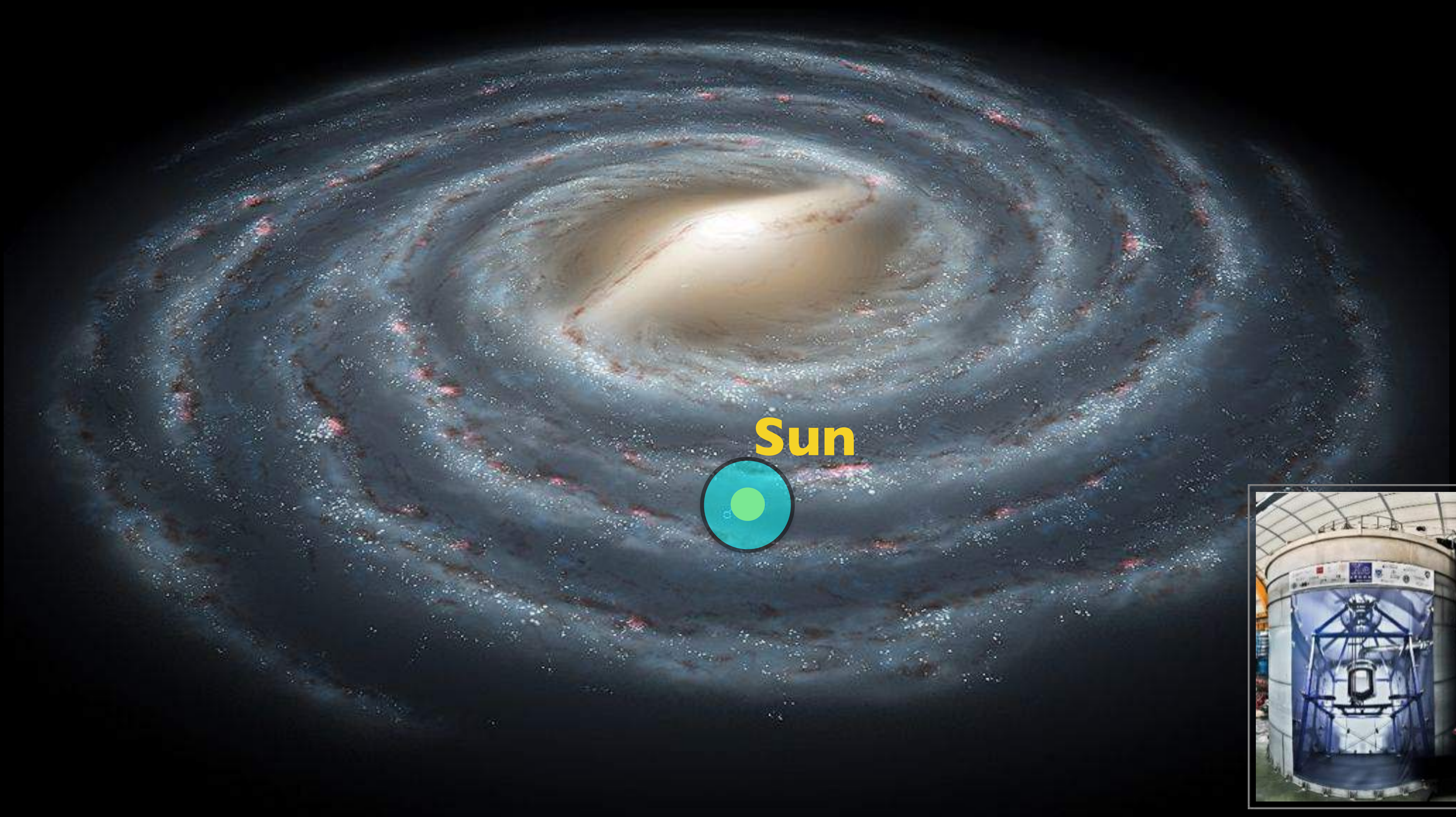




Signals strongly depend on the DM distribution in the Milky Way

Local dark matter distribution

*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):

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

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

Direct detection event rate

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

astrophysics

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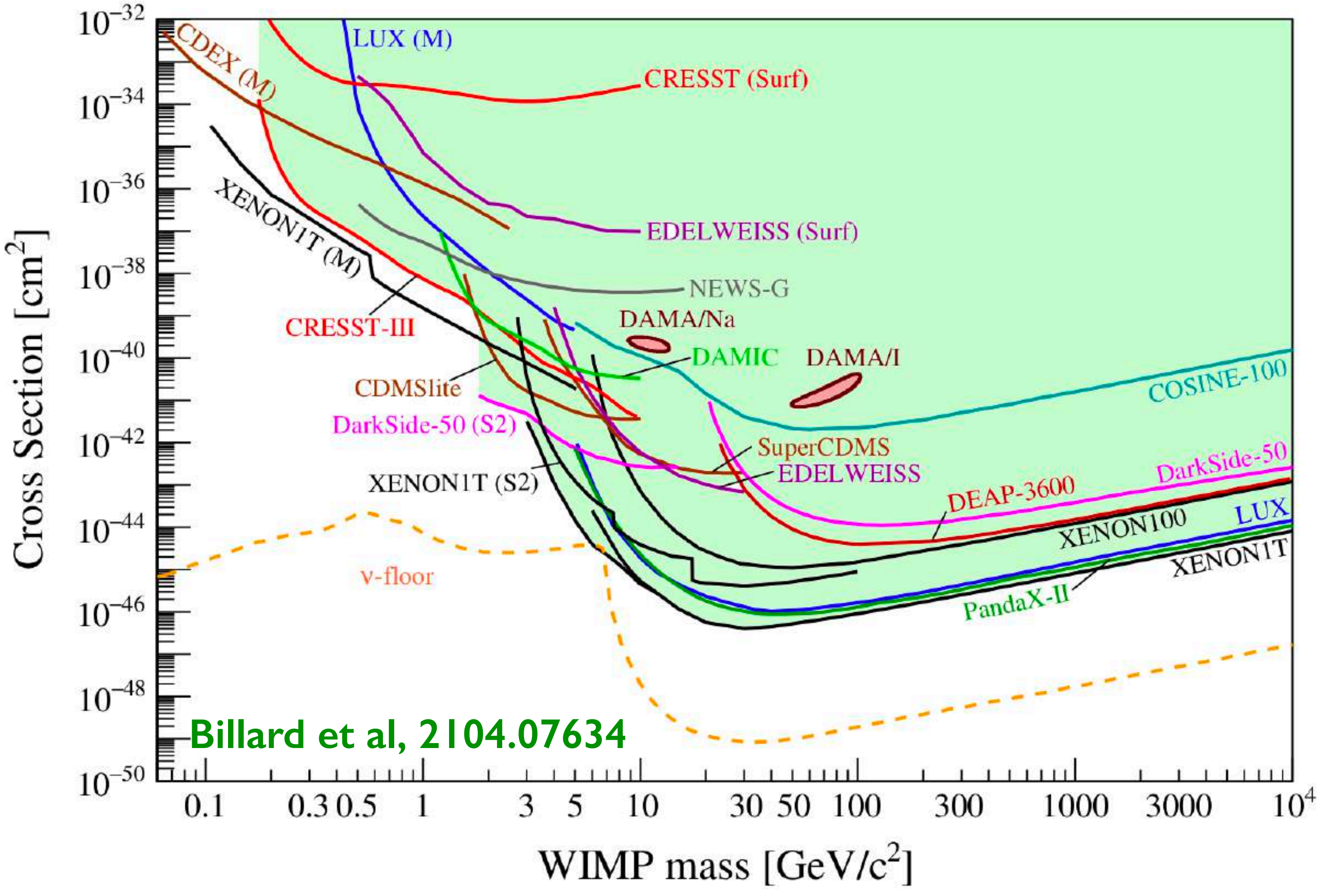
$v_{\min} = \sqrt{m_N E_R/(2\mu_{\chi N}^2)}$: minimum DM speed required to produce a recoil energy E_R.

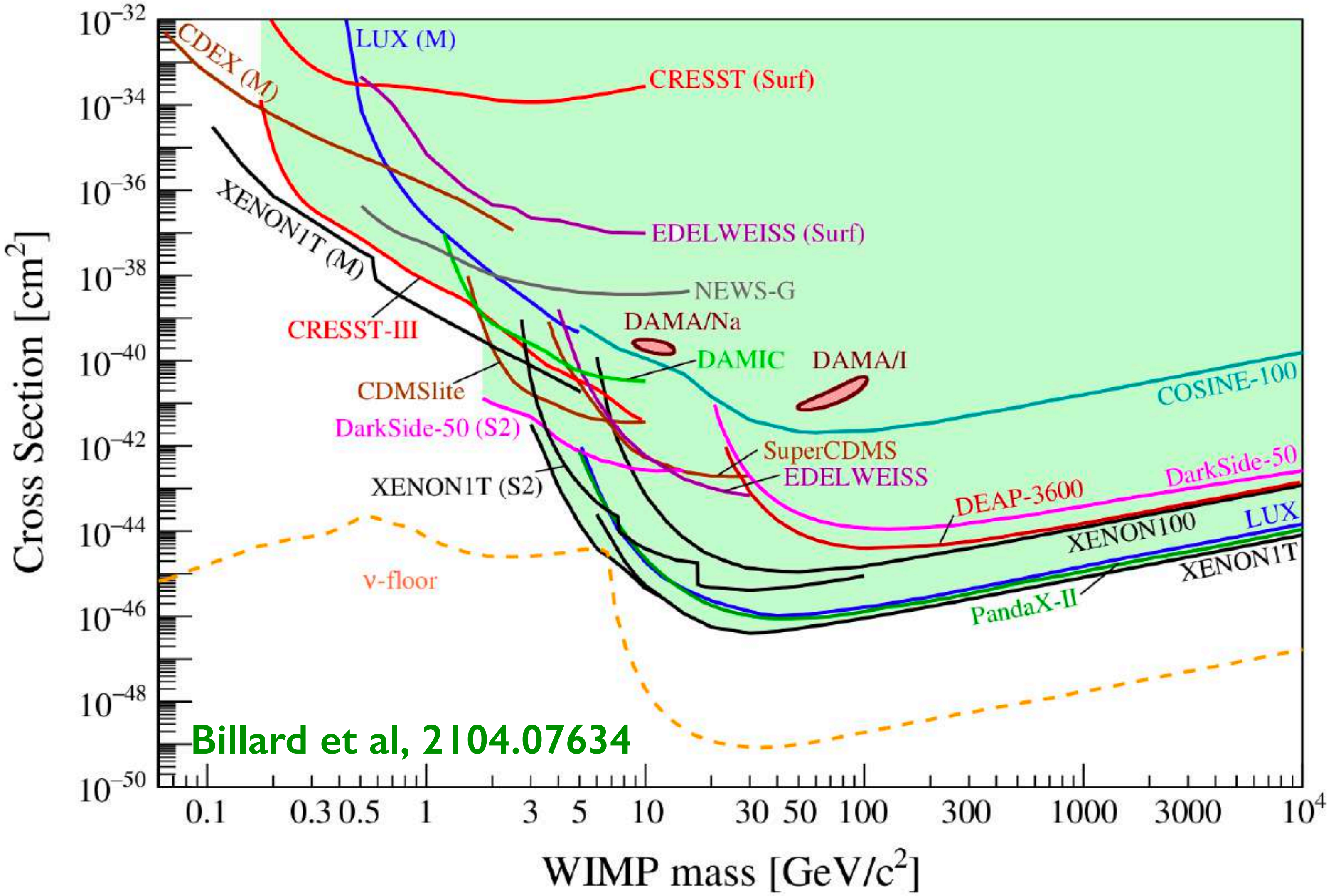
- **Astrophysical inputs:**
  - **local DM density:** *normalization in event rate.*
  - **local DM velocity distribution:** *enters the event rate through an integration.*

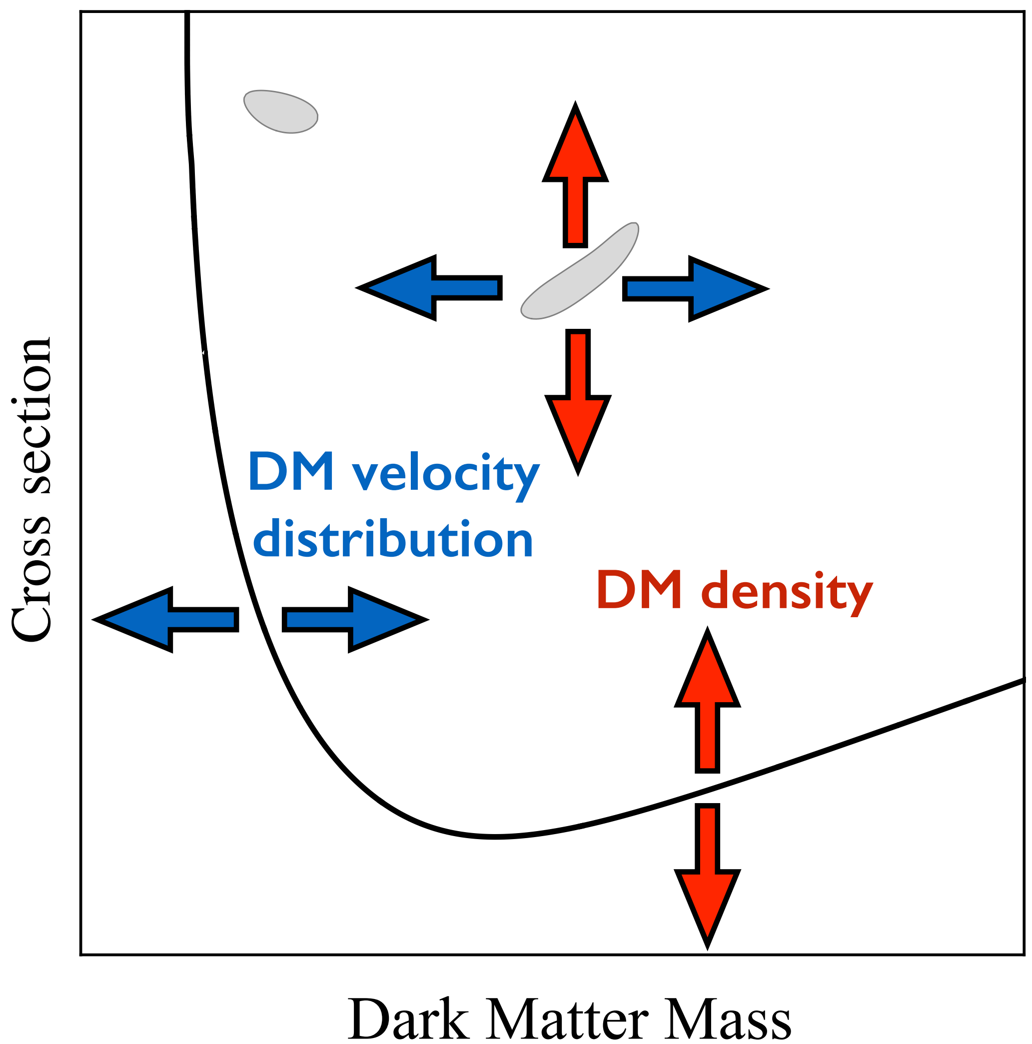
Astrophysical uncertainties



Assumption: **Standard Halo Model**

Astrophysical uncertainties





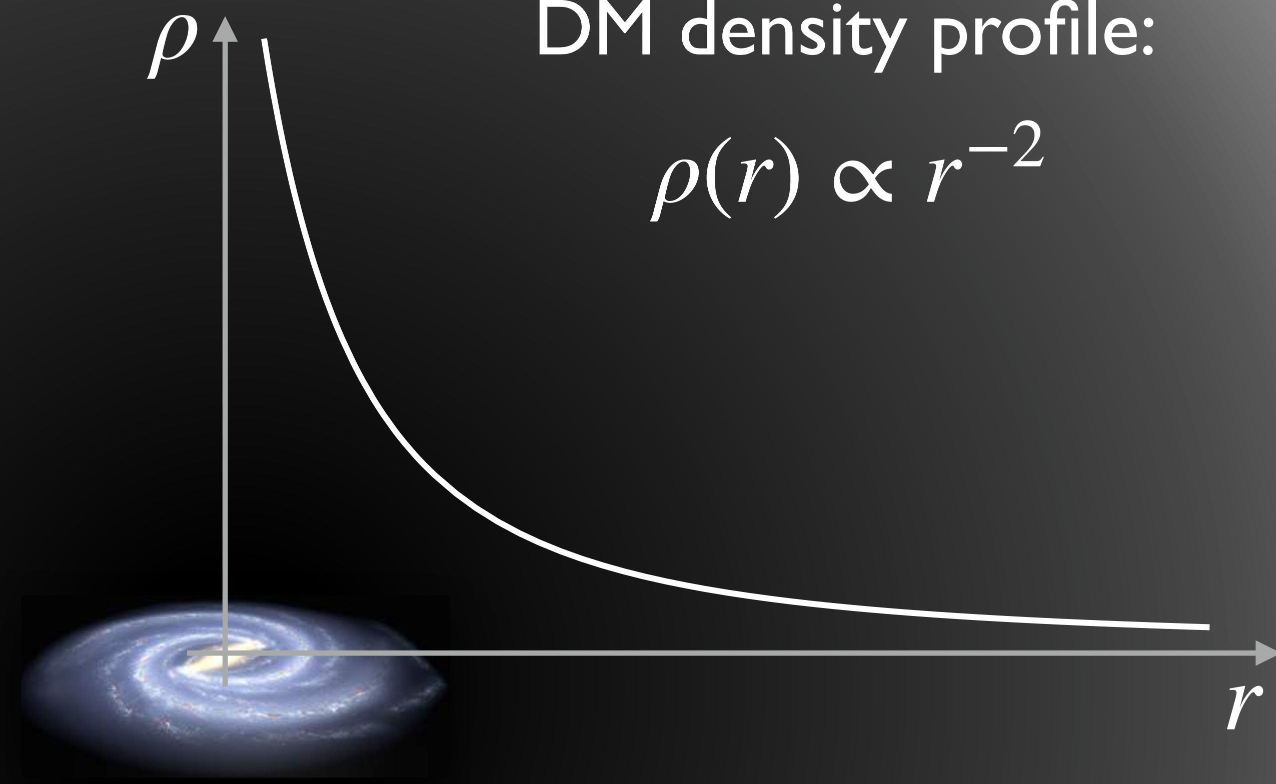
Assumption: **Standard Halo Model**

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

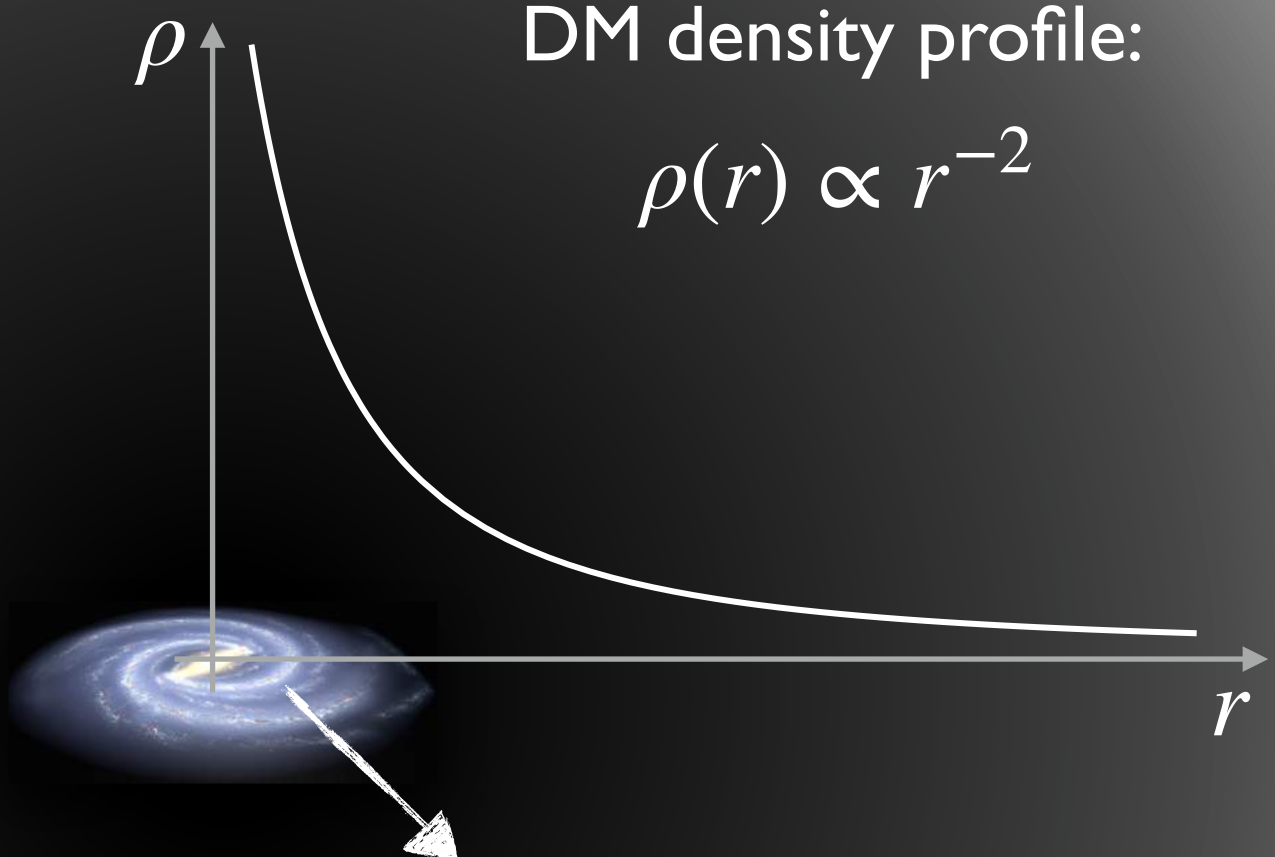
Standard Halo Model



DM density profile:

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

Standard Halo Model

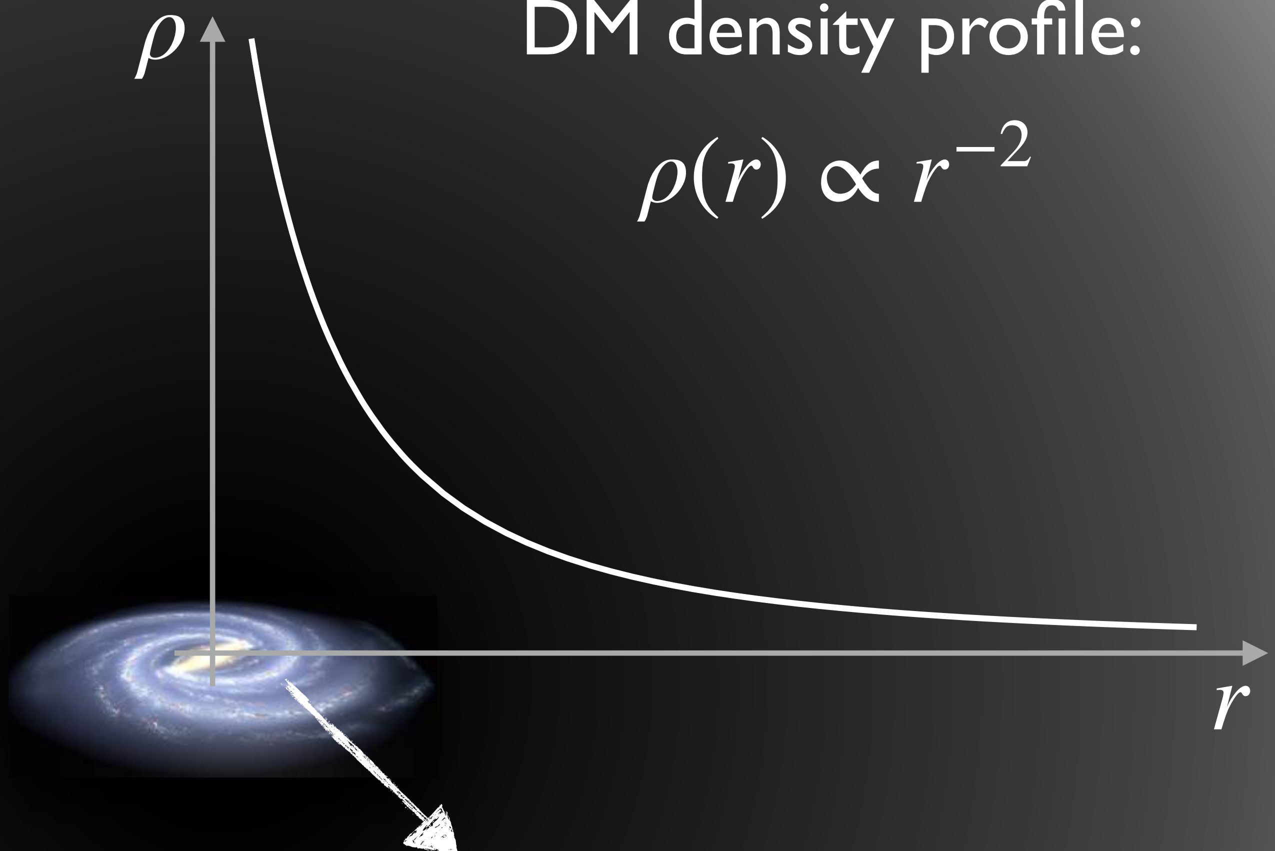


DM density profile:

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

- DM density in the Solar System: $\rho_\chi = 0.3\ \mathrm{GeV/cm^3}$
- Most probable DM speed: $v_c = 220\ \mathrm{km/s}$

Standard Halo Model



DM density profile:

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

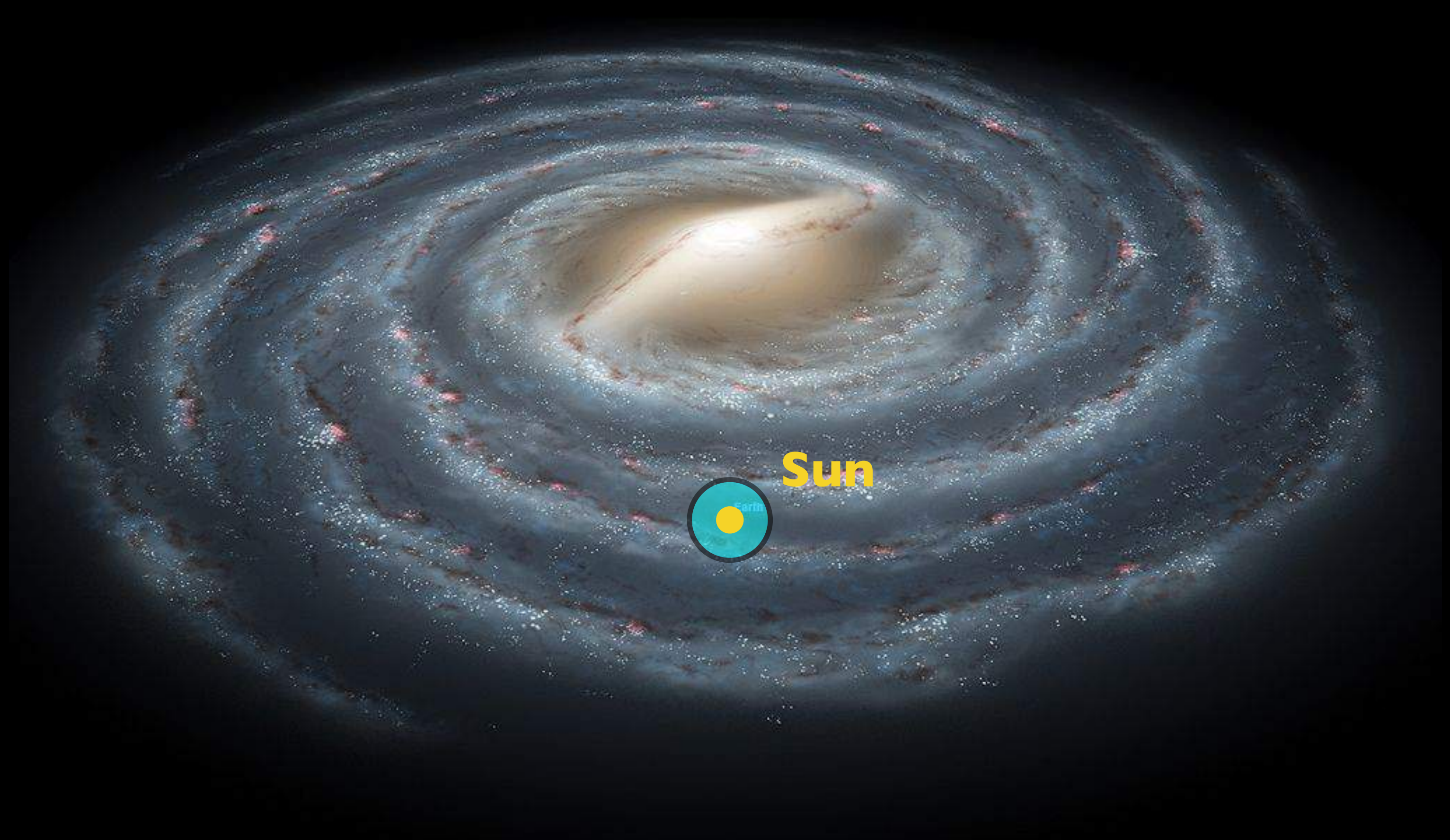
- DM density in the Solar System: $\rho_\chi = 0.3\ \mathrm{GeV/cm^3}$
- Most probable DM speed: $v_c = 220\ \mathrm{km/s}$

*The actual DM distribution may **deviate substantially** from the SHM.*

Astrophysical uncertainties

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

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

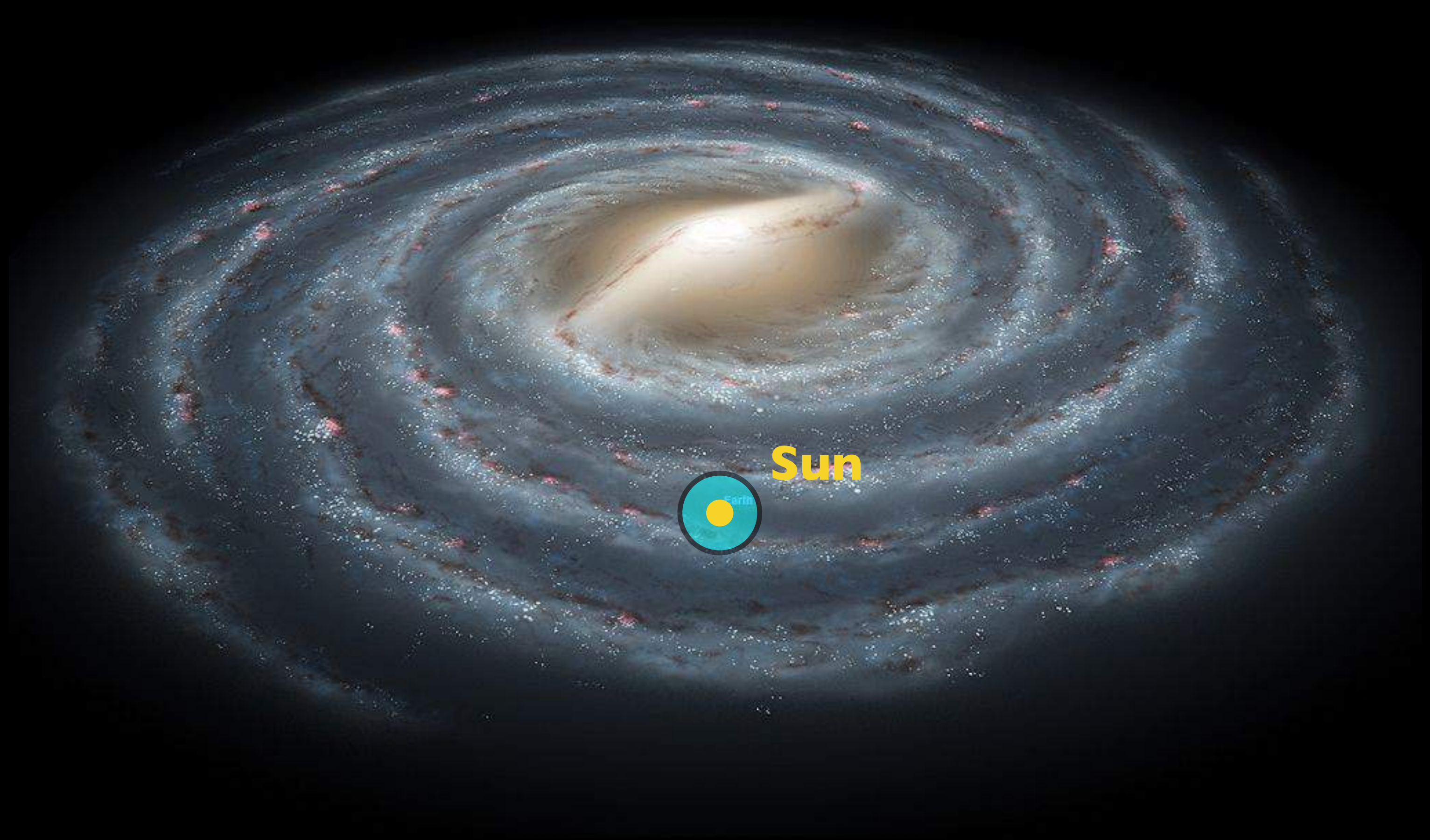


Astrophysical uncertainties

- **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 local DM halo has both smooth and un-virialized components:

Dark matter velocity distribution

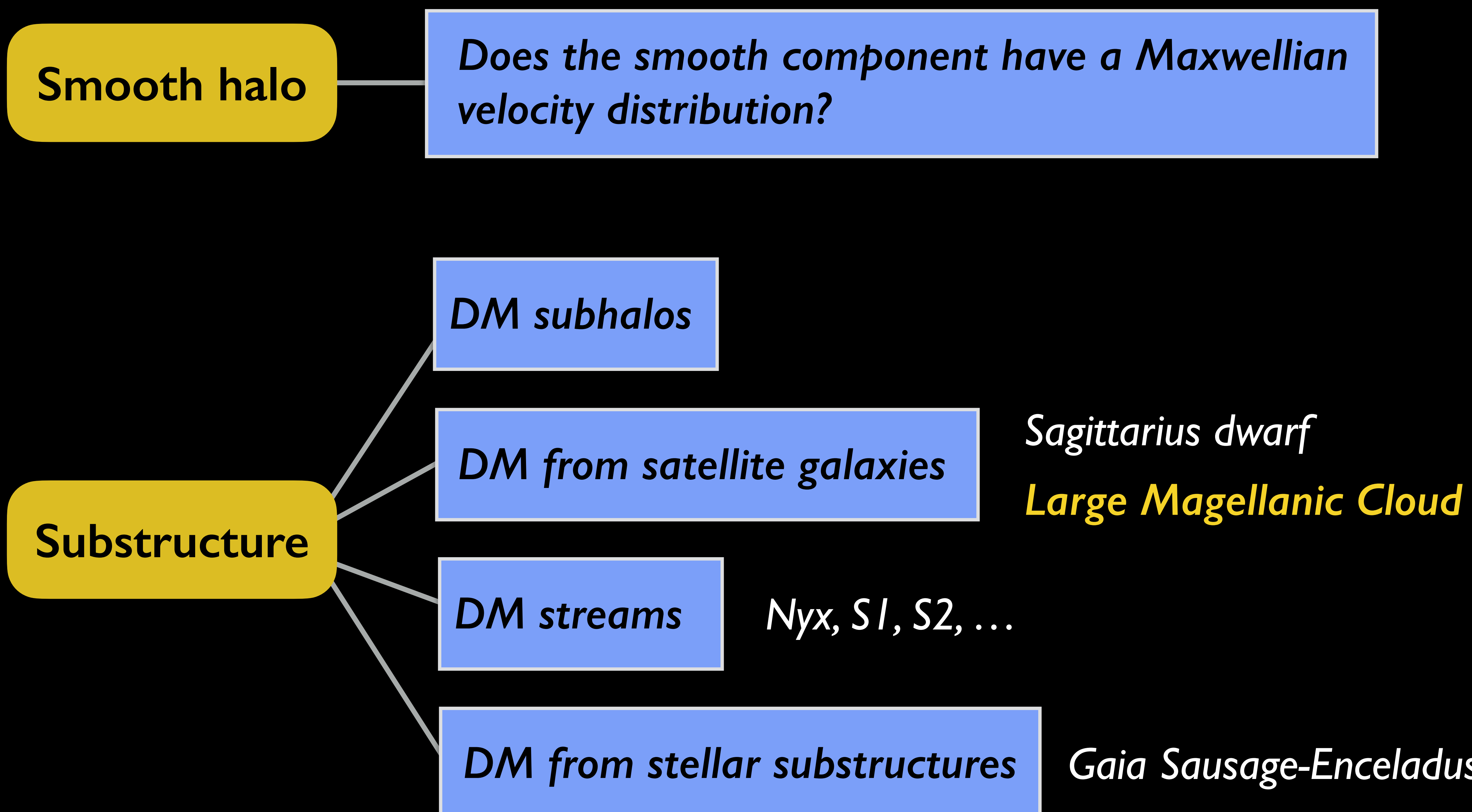
- The local DM halo has both smooth and un-virialized components:

Smooth halo

Does the smooth component have a Maxwellian velocity distribution?

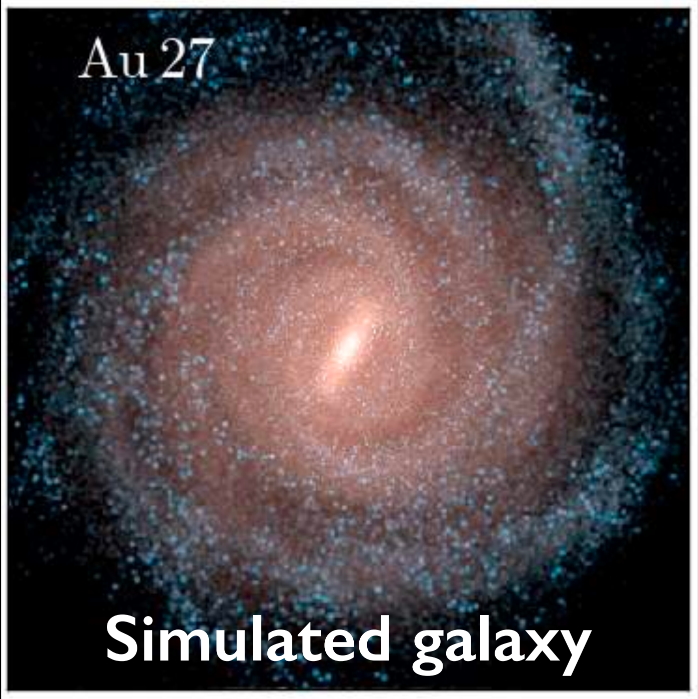
Dark matter velocity distribution

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



Dark matter velocity distribution

Extract the DM distribution from cosmological simulations:



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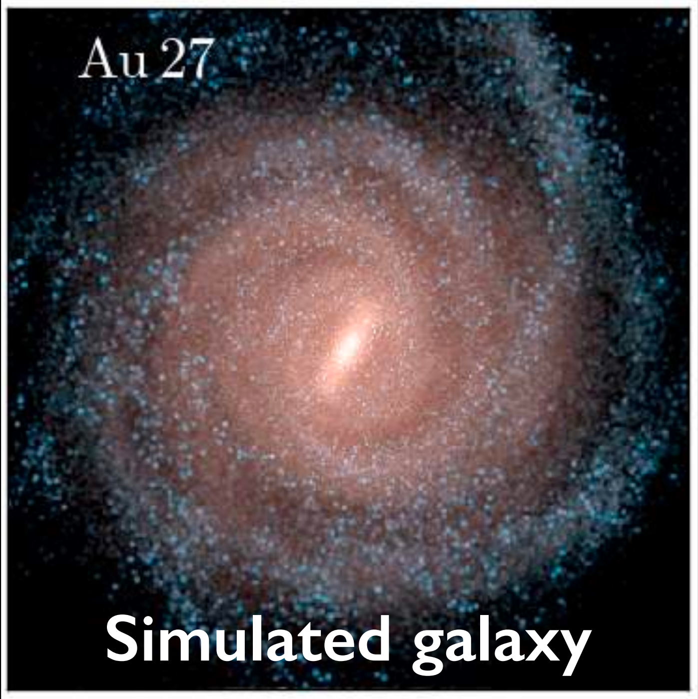
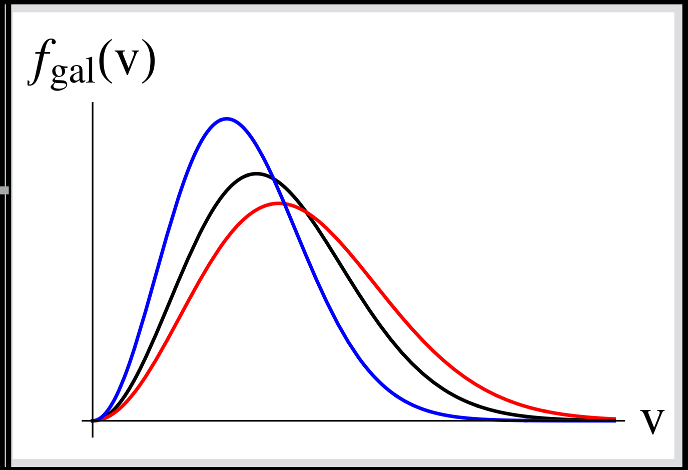


Smooth halo



Dark matter velocity distribution

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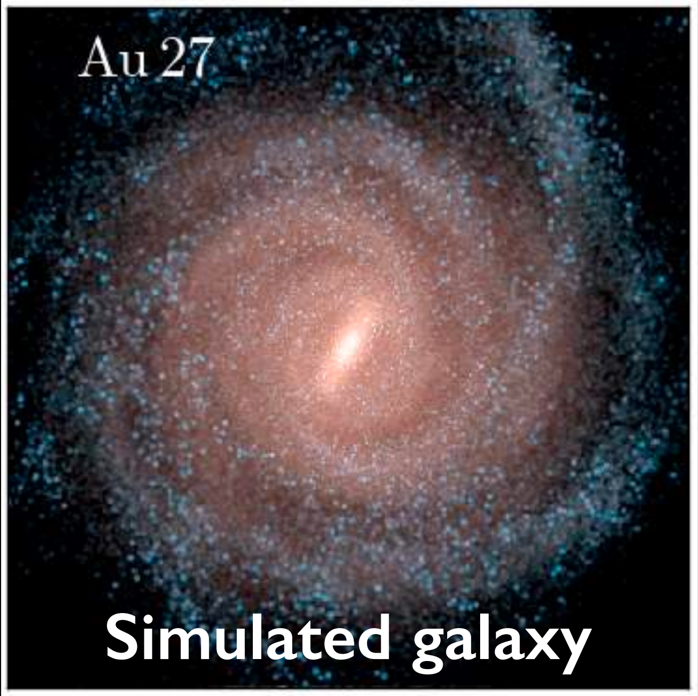

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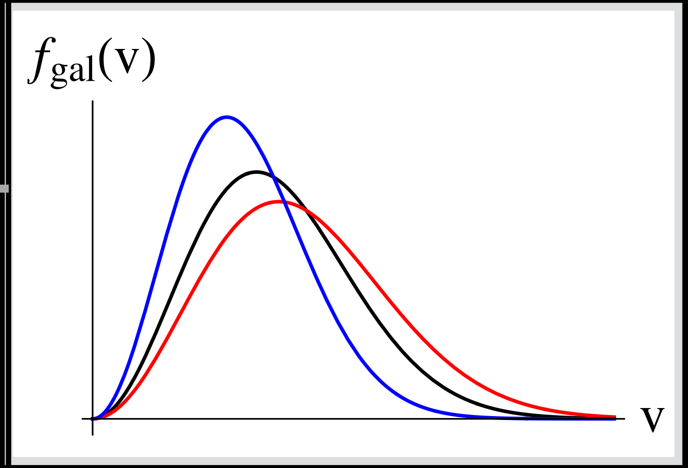
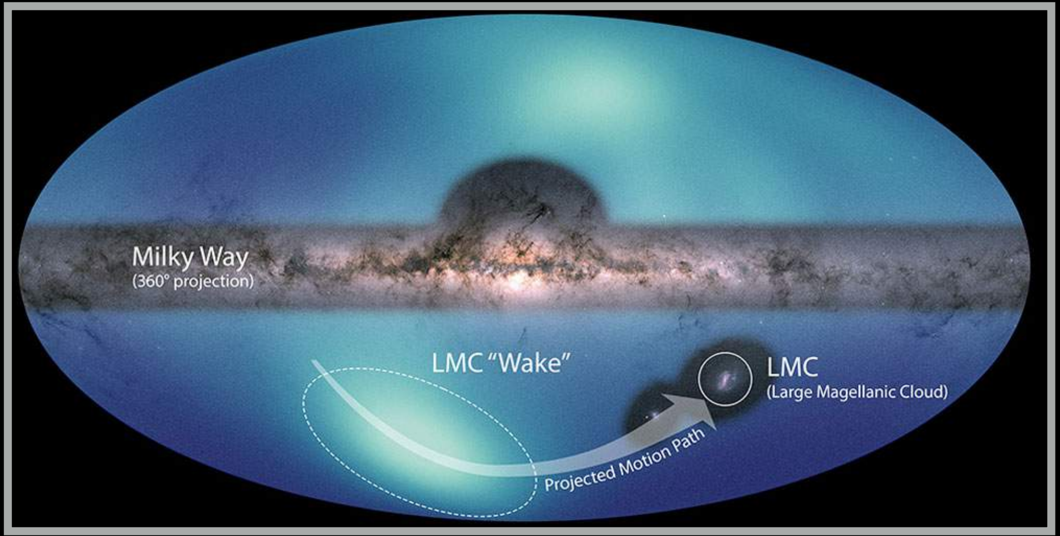


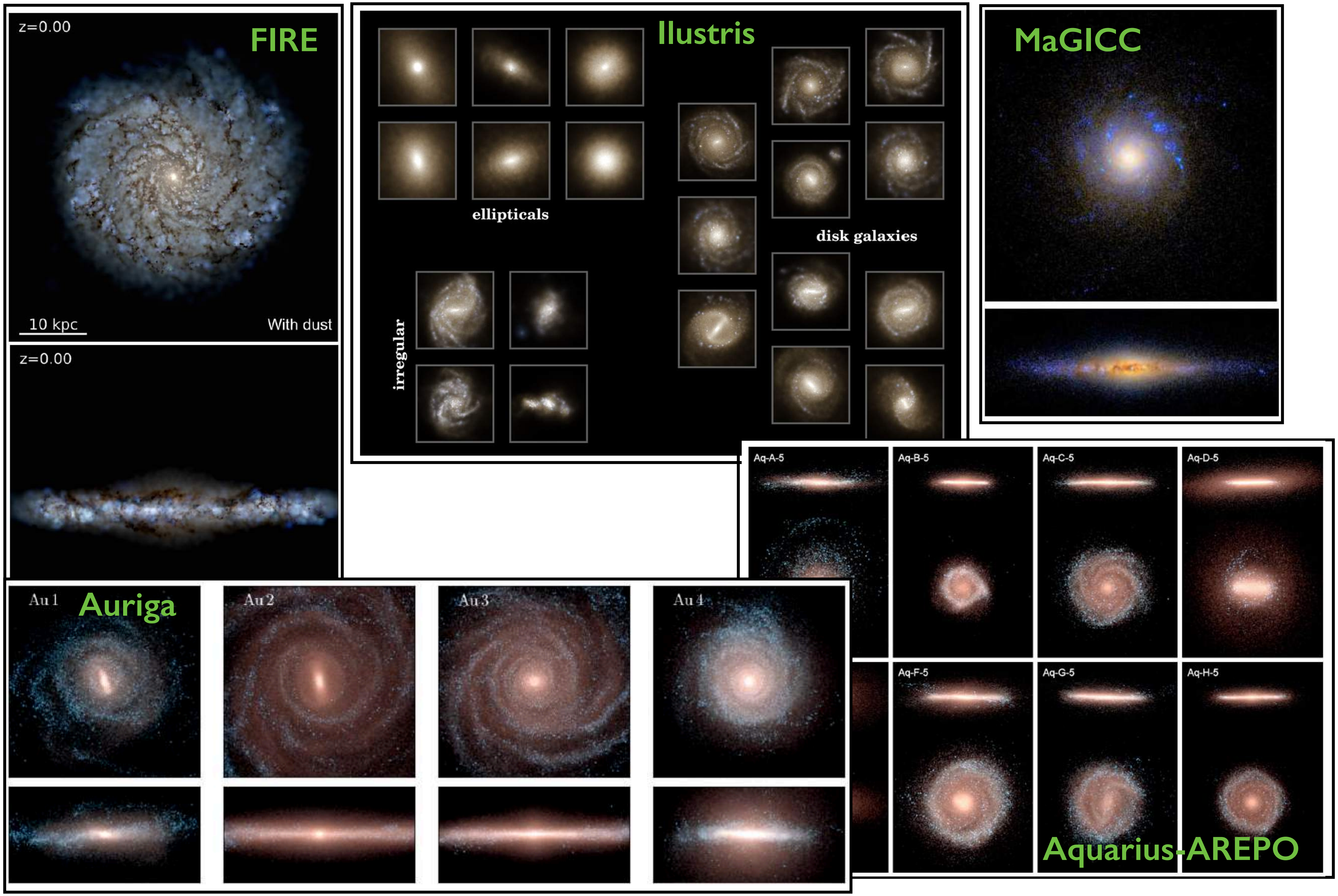
Substructure

Large Magellanic Cloud (LMC)



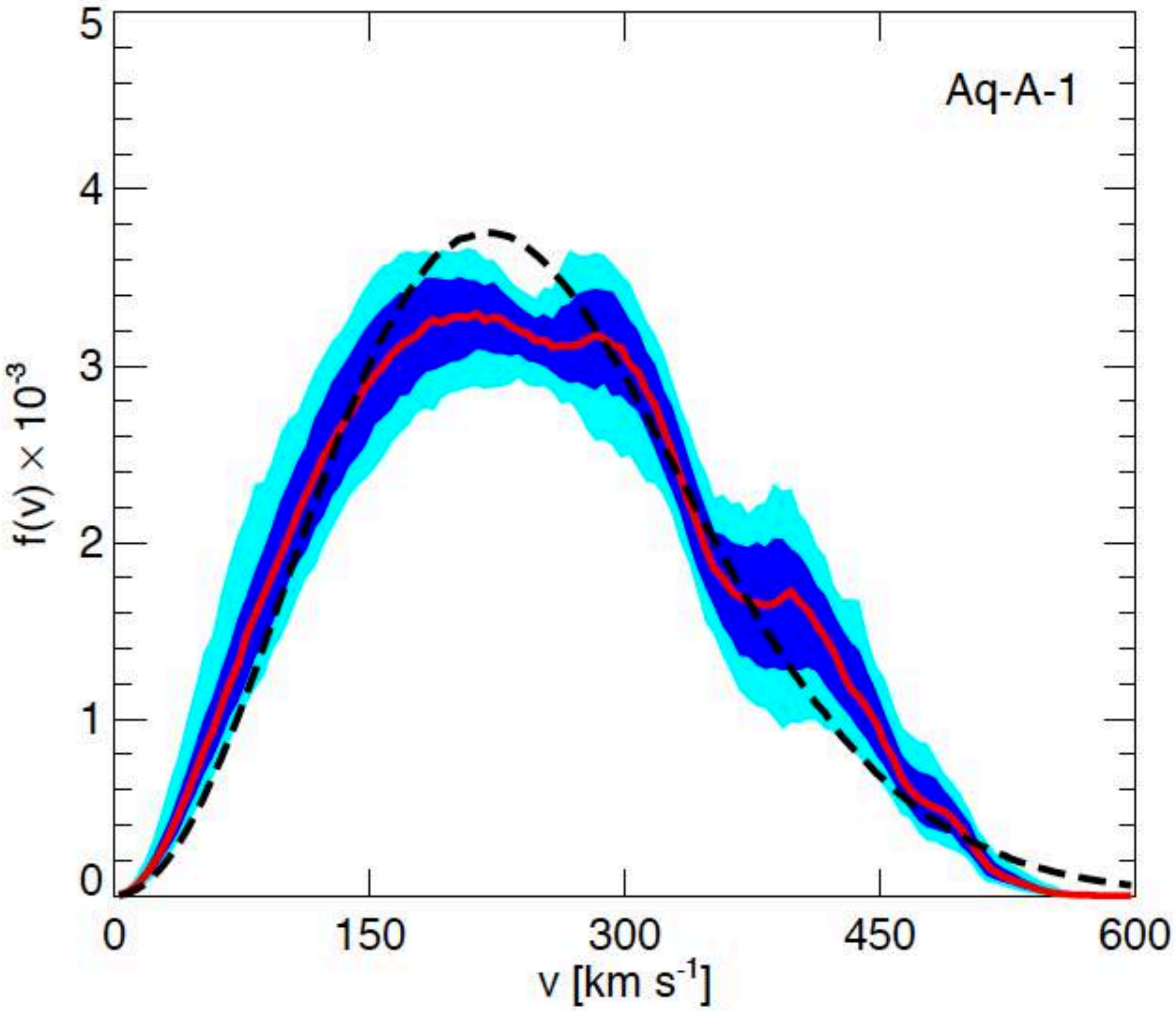
Cosmological simulations

Cosmological simulations can produce realistic galaxies like our own.



Dark matter only simulations

- DM speed distributions from cosmological N-body simulations **without baryons** deviate substantially from a Maxwellian.



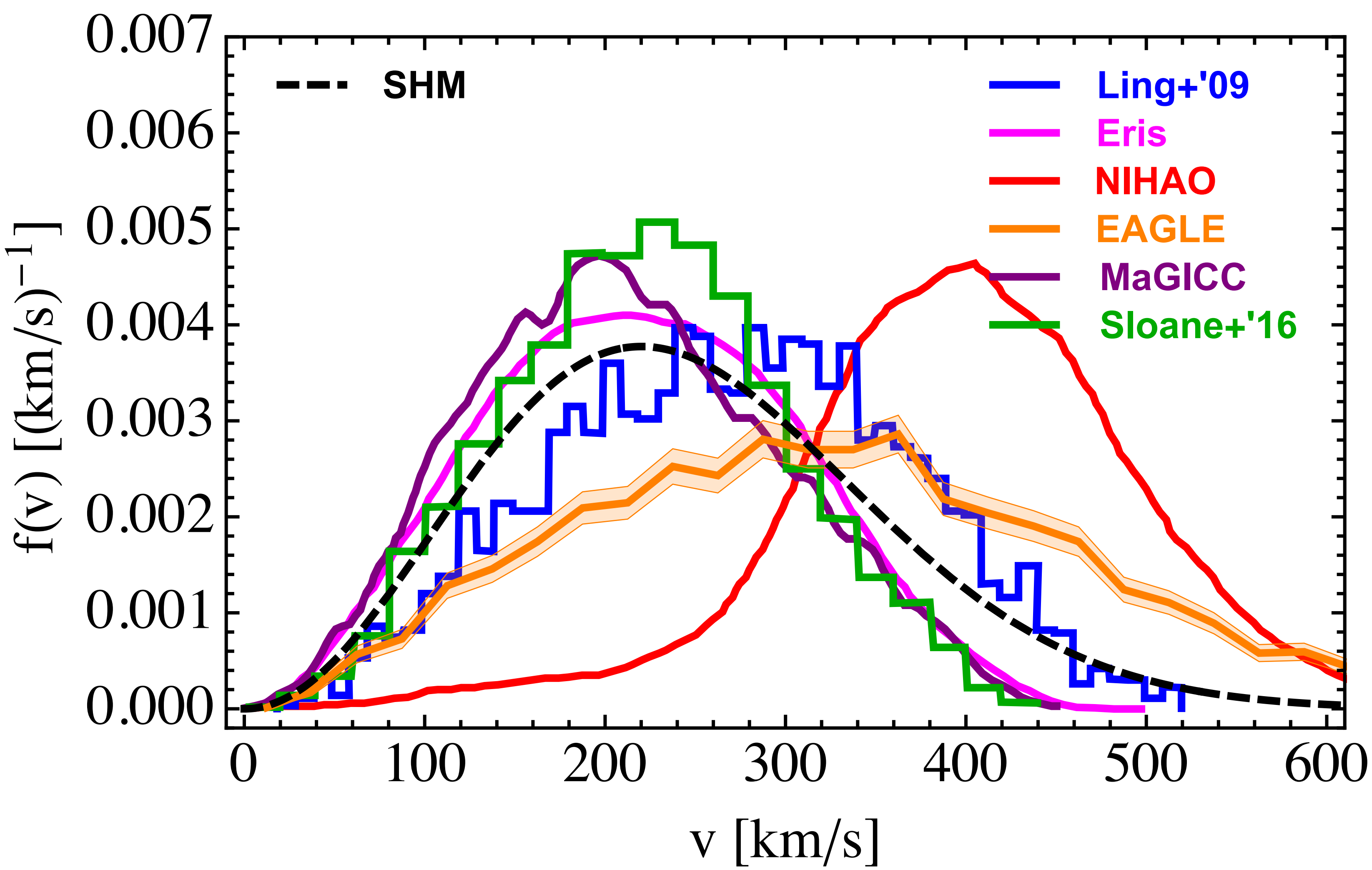
$$f(|\mathbf{v}|) = v^2 \int d\Omega_{\mathbf{v}} f(\mathbf{v})$$

Vogelsberger et al., MNRS 395, 797 (2009)

- *Significant systematic uncertainty since the impact of baryons neglected.*

Hydrodynamical simulations

- Each hydrodynamical (**DM + baryons**) simulation adopts a different *galaxy formation model*, *spatial resolution*, *DM particle mass*.



Bozorgnia & Bertone, IJMPA 32, 1730016 (2017)

- Large variation in DM speed distributions between the results of different simulations.

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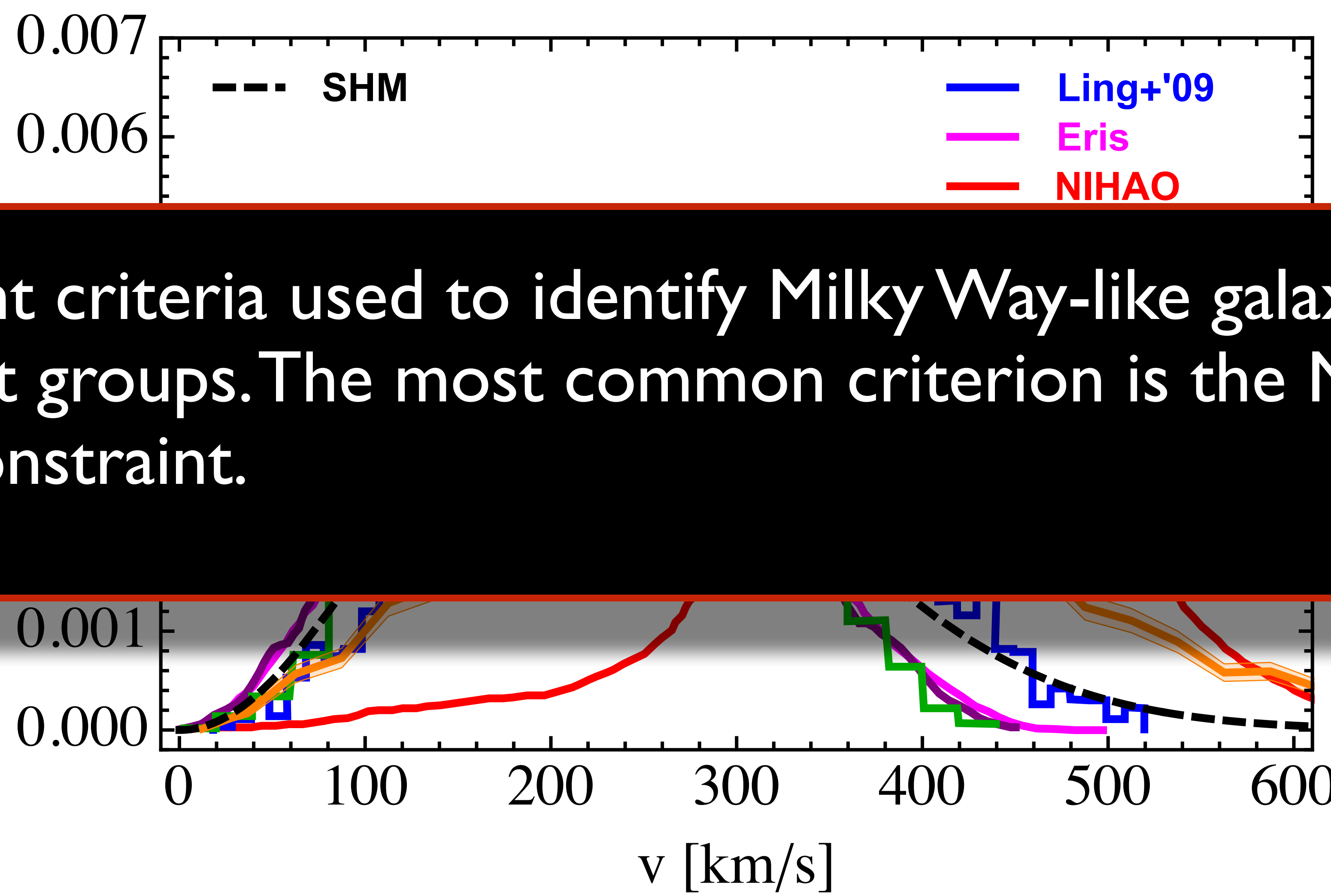


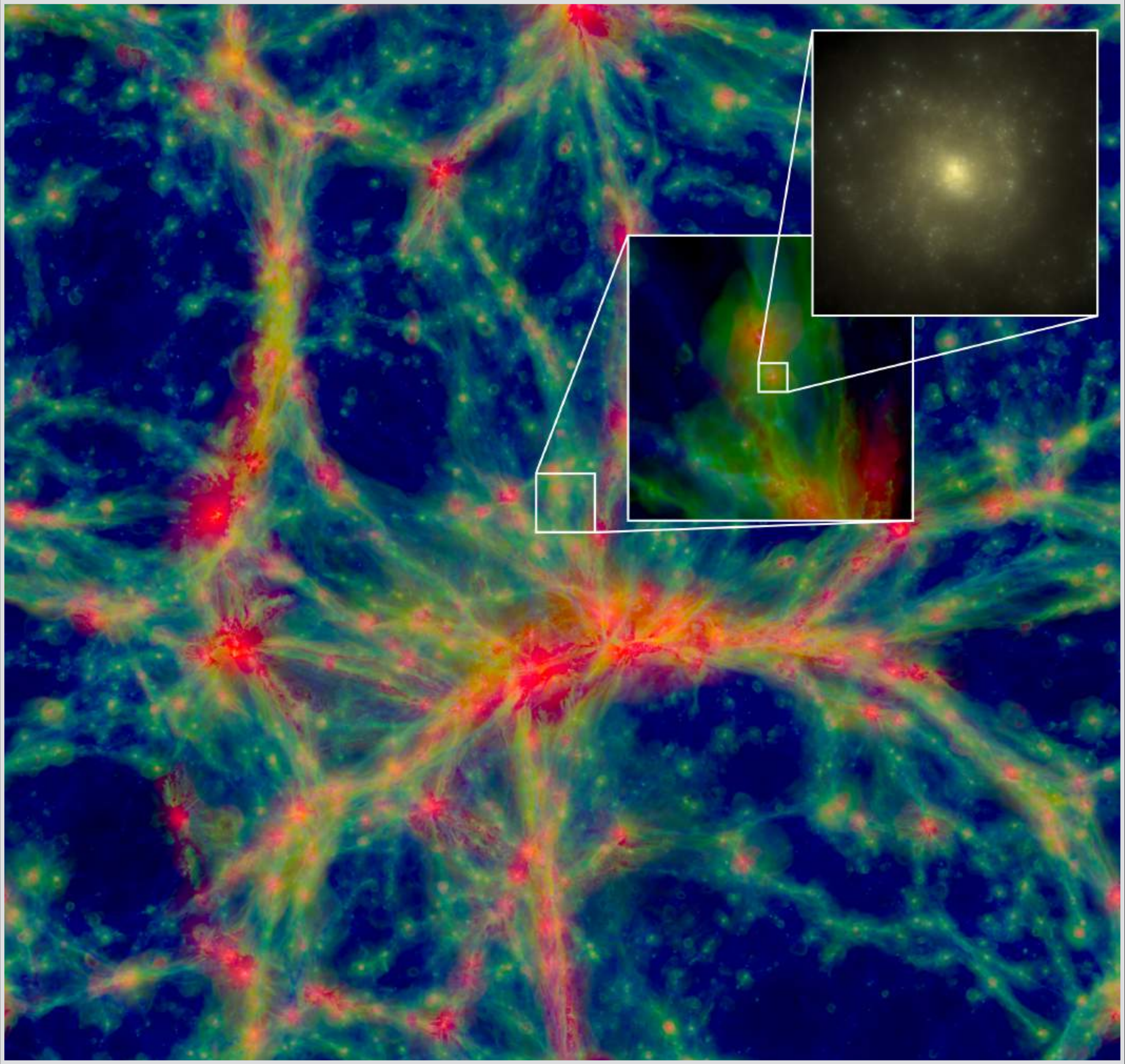
Different criteria used to identify Milky Way-like galaxies among different groups. The most common criterion is the Milky Way mass constraint.

Bozorgnia & Bertone, IJMPA 32, 1730016 (2017)

- Large variation in DM speed distributions between the results of different simulations.

EAGLE simulations

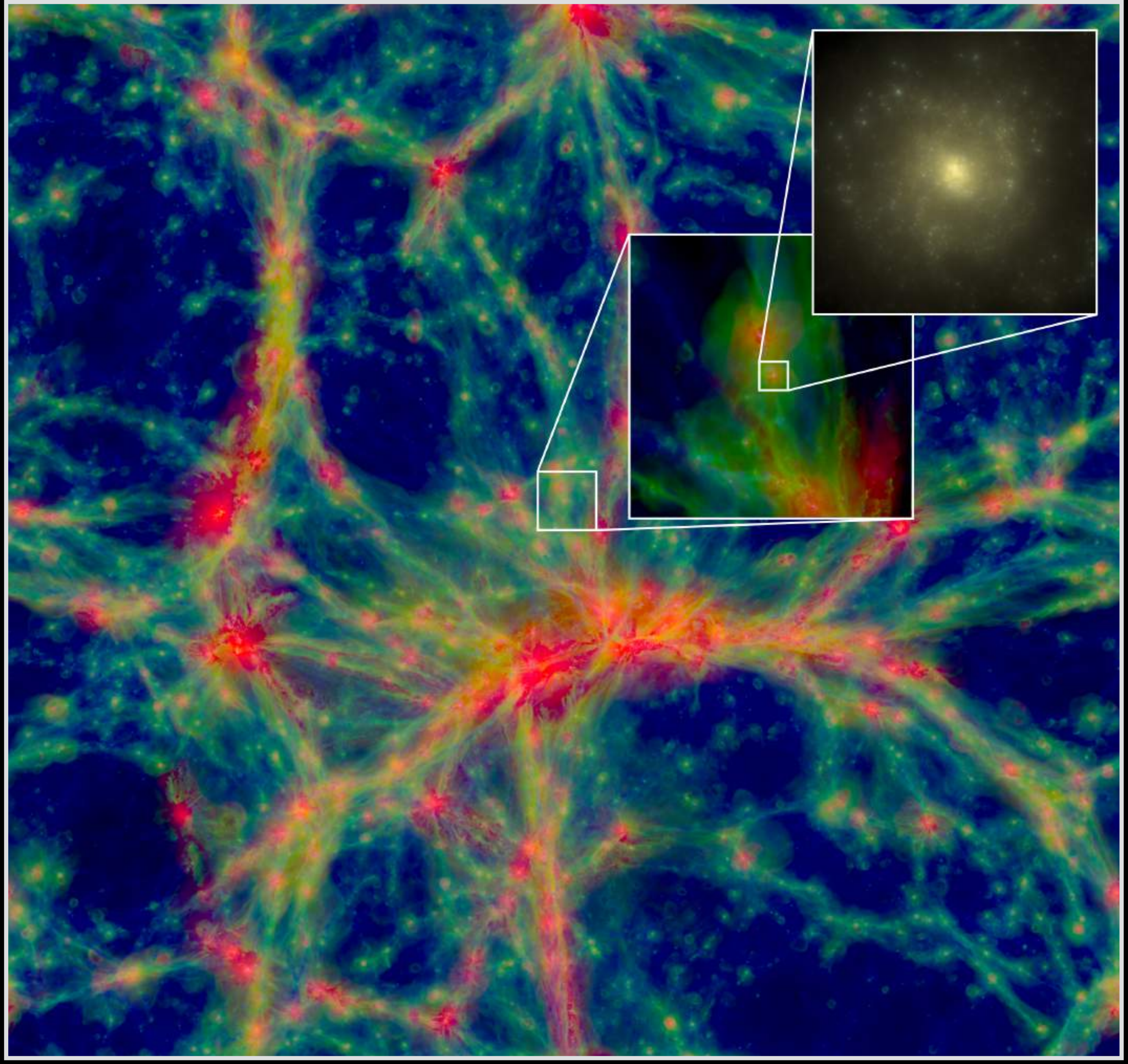
- *Calibrated to reproduce the observed distribution of stellar masses and sizes of low-redshift galaxies.*



EAGLE simulations

- *Calibrated to reproduce the observed distribution of stellar masses and sizes of low-redshift galaxies.*

m_{DM} [$M_\odot$]	m_b [$M_\odot$]	ϵ [pc]
1.2×10^6	2.3×10^5	350



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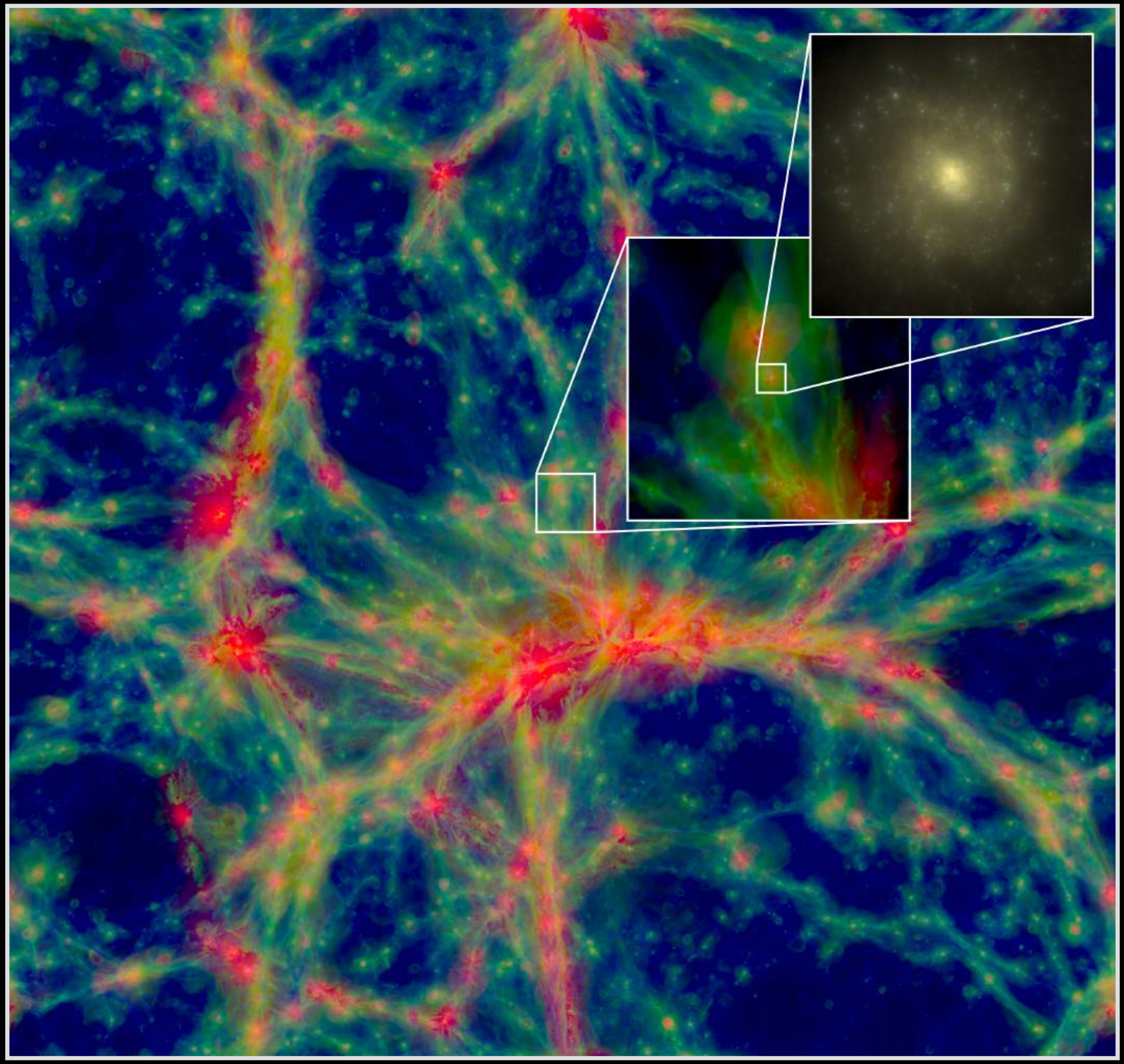
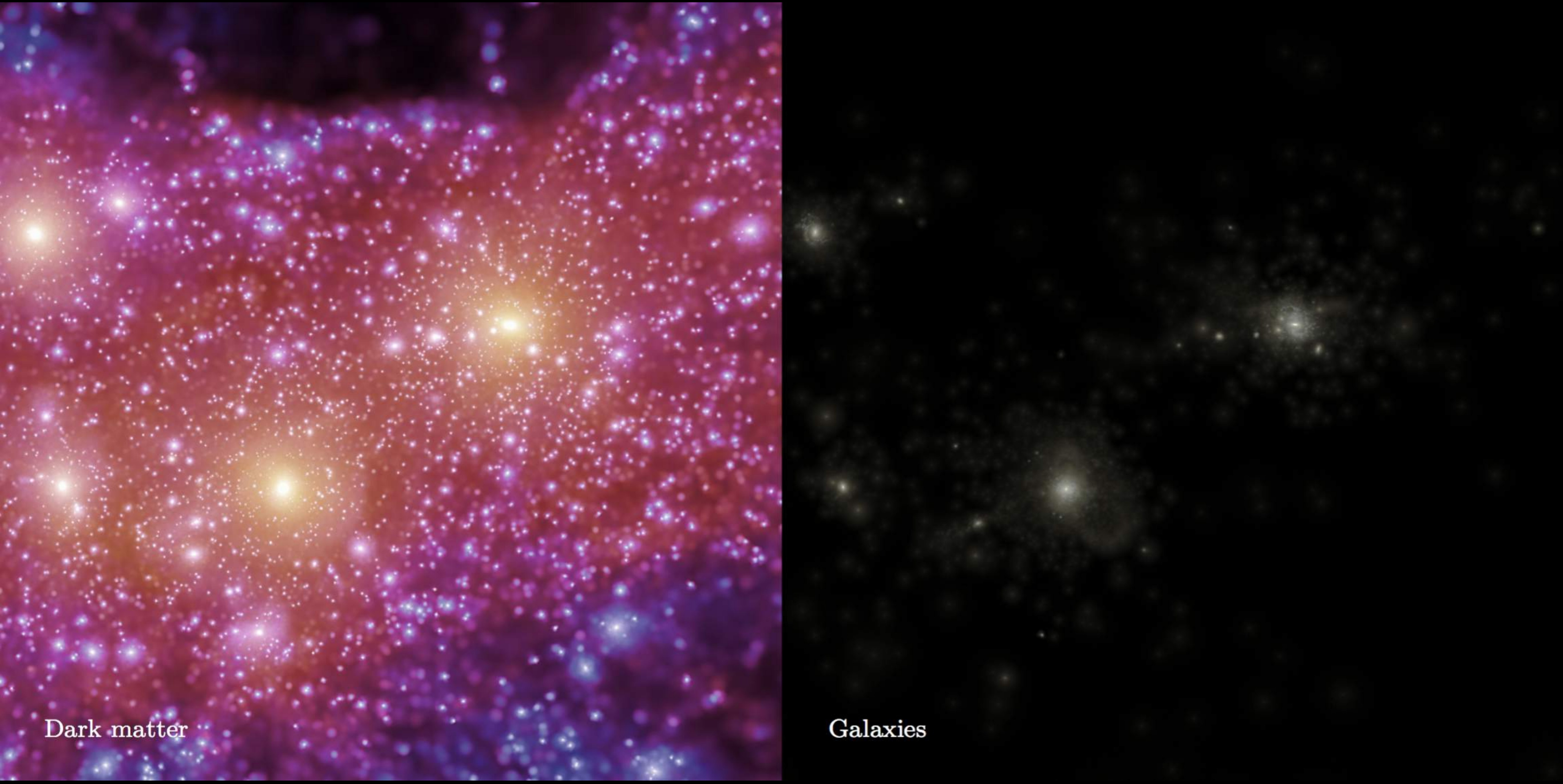
$m_{\rm DM}$ [$M_\odot$]	$m_{\rm b}$ [$M_\odot$]	ϵ [pc]
1.2×10^6	2.3×10^5	350

- Companion DM-only **(DMO)** simulations were run assuming all the matter content is collisionless.

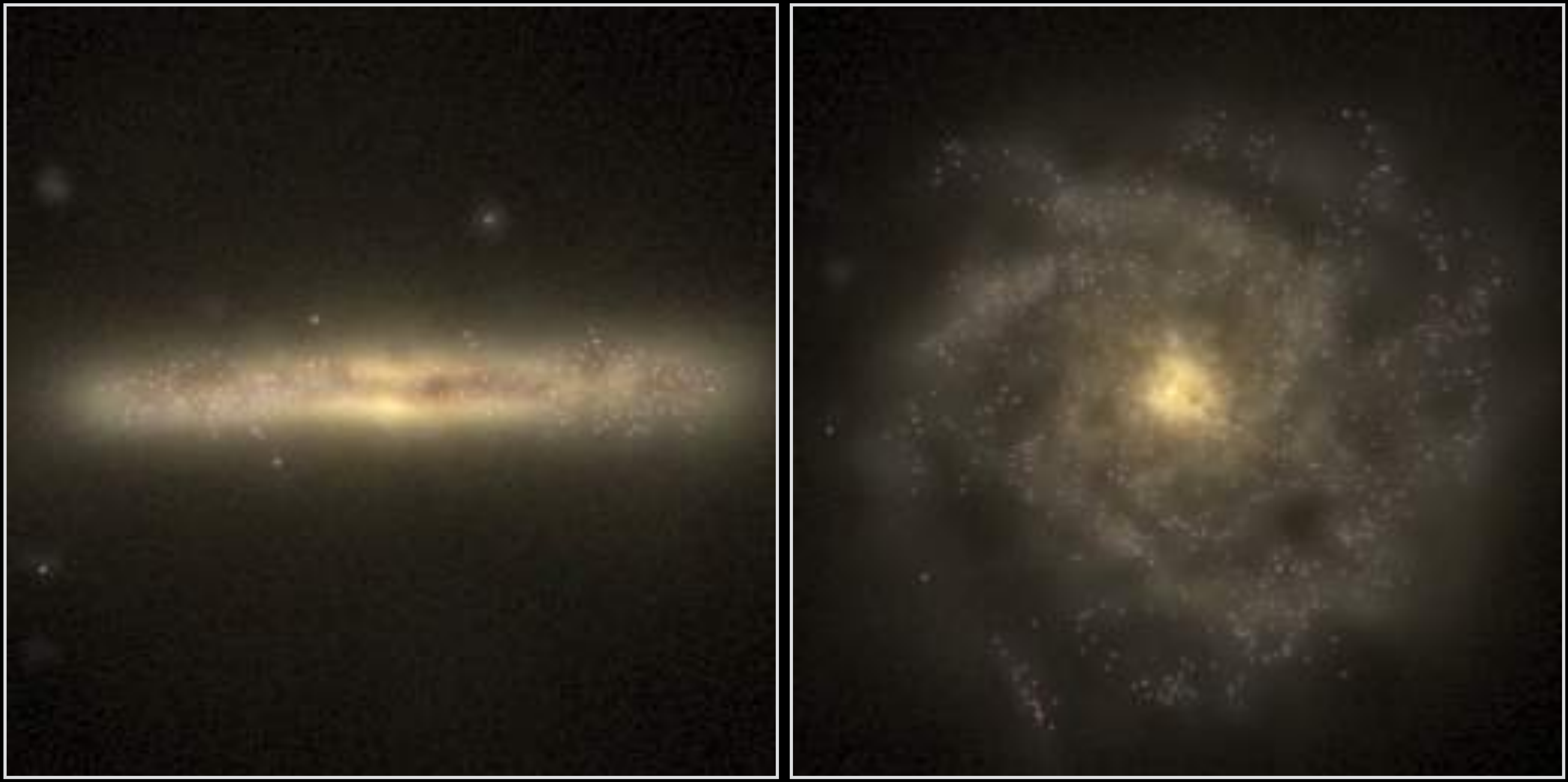


APOSTLE simulations

Zoomed simulations of Local Group analogue systems, comparable in resolution to **EAGLE**.



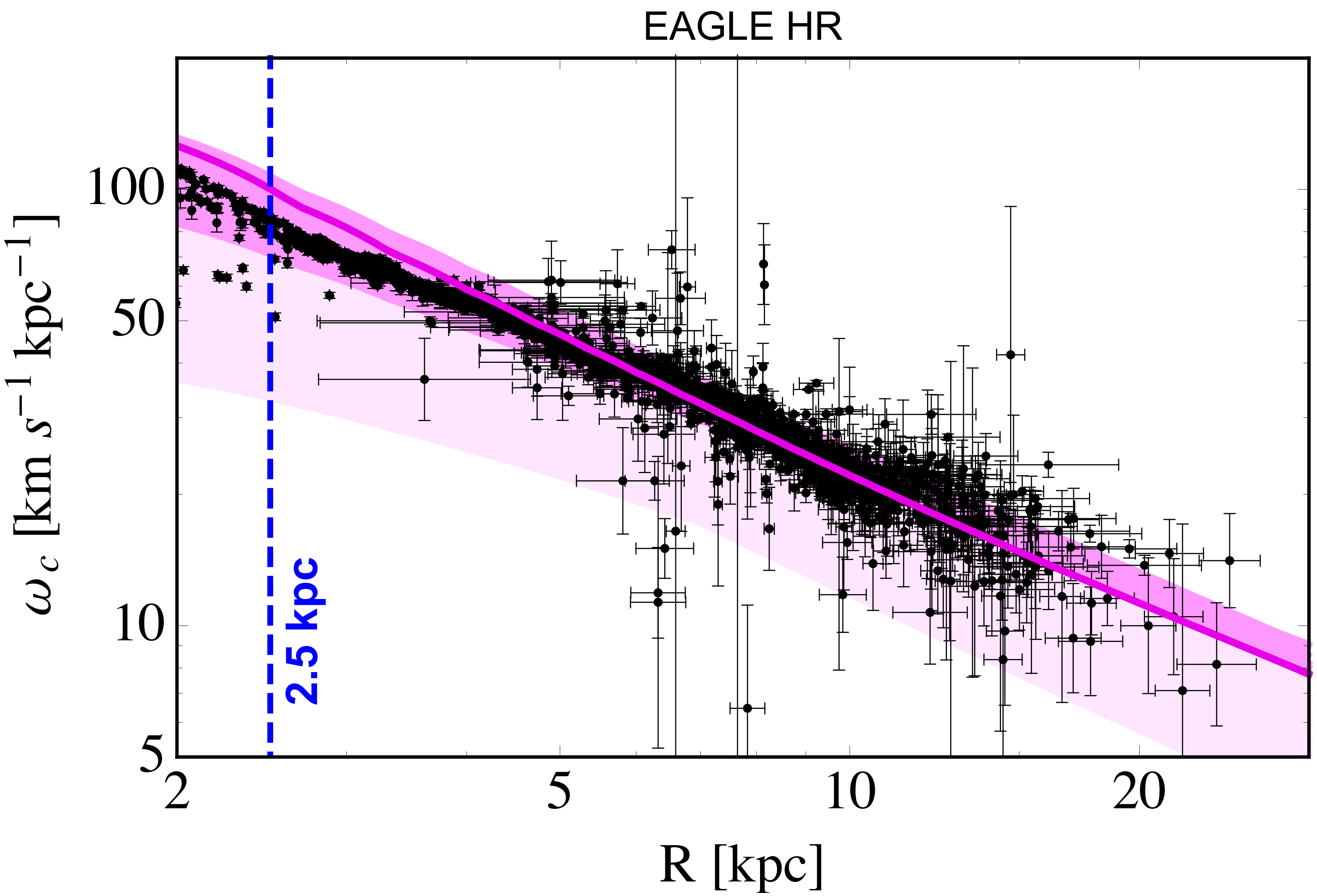
Simulated Milky Way analogues



EAGLE Simulations

Identifying Milky Way analogues

- Identify Milky Way analogues by taking into account observed Milky Way kinematical data: **rotation curves, total stellar mass.**



Bozorgnia et al., JCAP 05, 024 (2016)
Calore, Bozorgnia et al., JCAP 12, 053 (2015)

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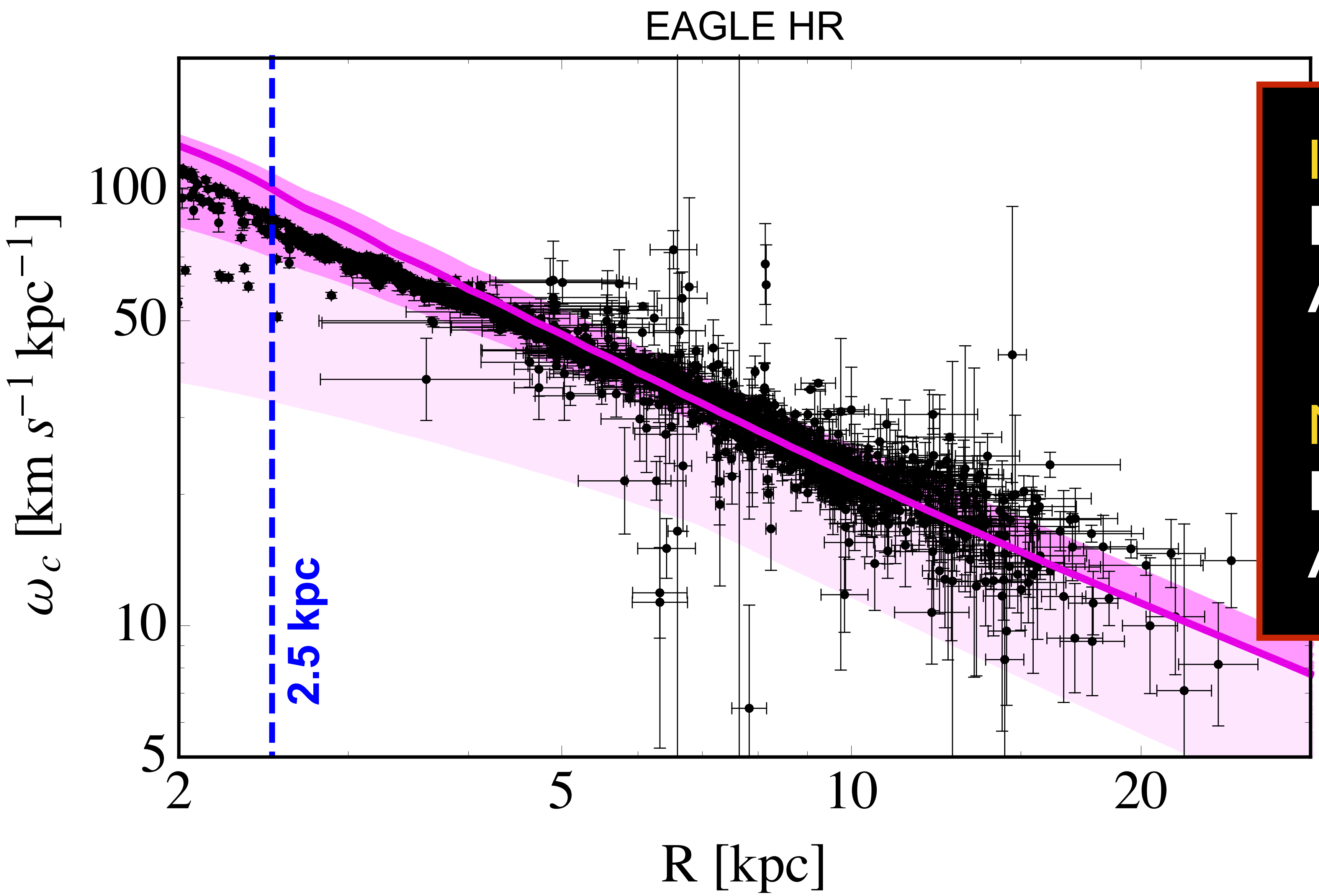


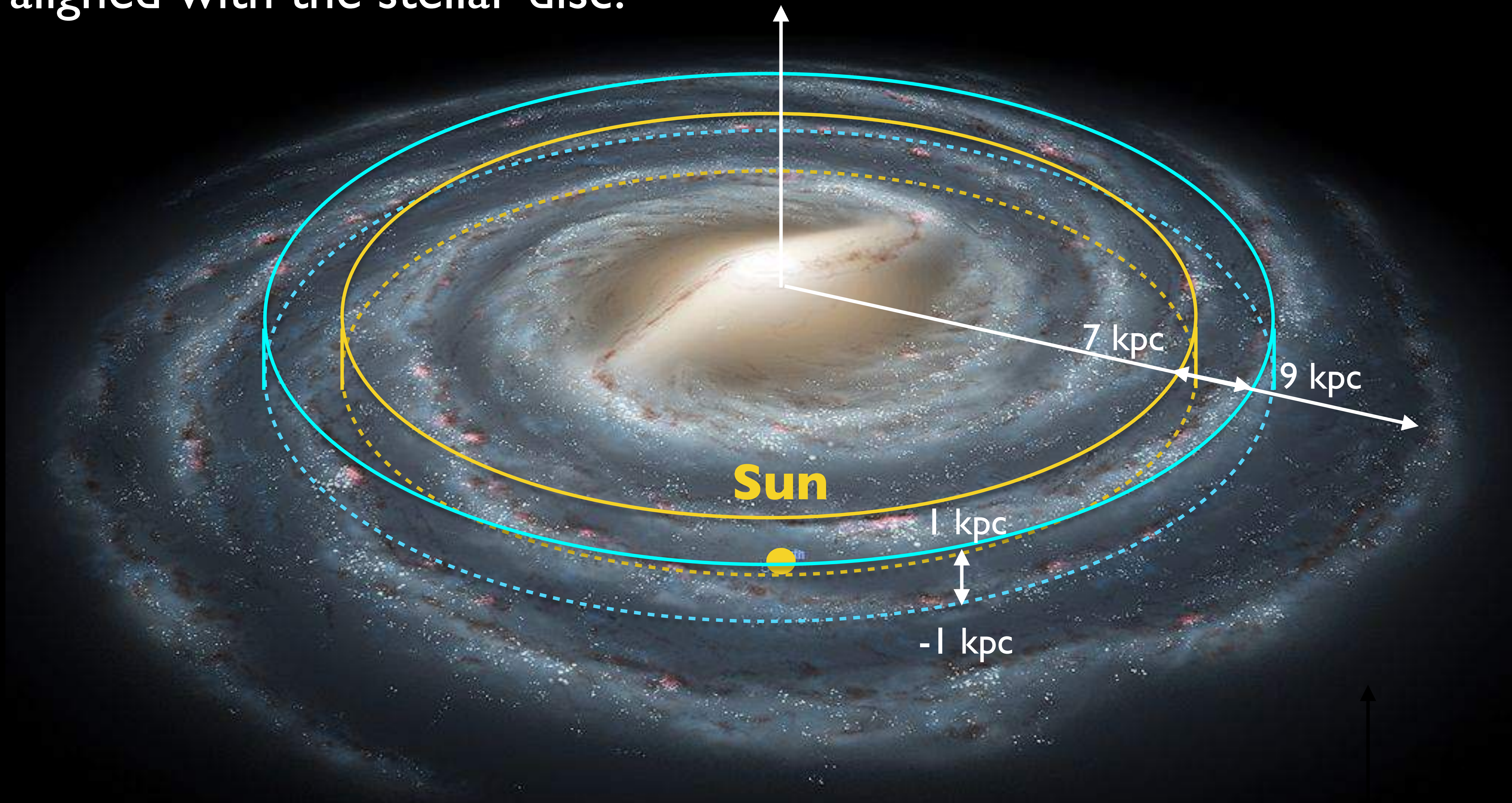
Initial halos:
EAGLE: 61
APOSTLE: 24

Milky Way-like:
EAGLE: 12
APOSTLE: 2

Bozorgnia et al., JCAP 05, 024 (2016)
Calore, Bozorgnia et al., JCAP 12, 053 (2015)

Local dark matter density

To find the DM density at the position of the Sun, consider a torus aligned with the stellar disc.

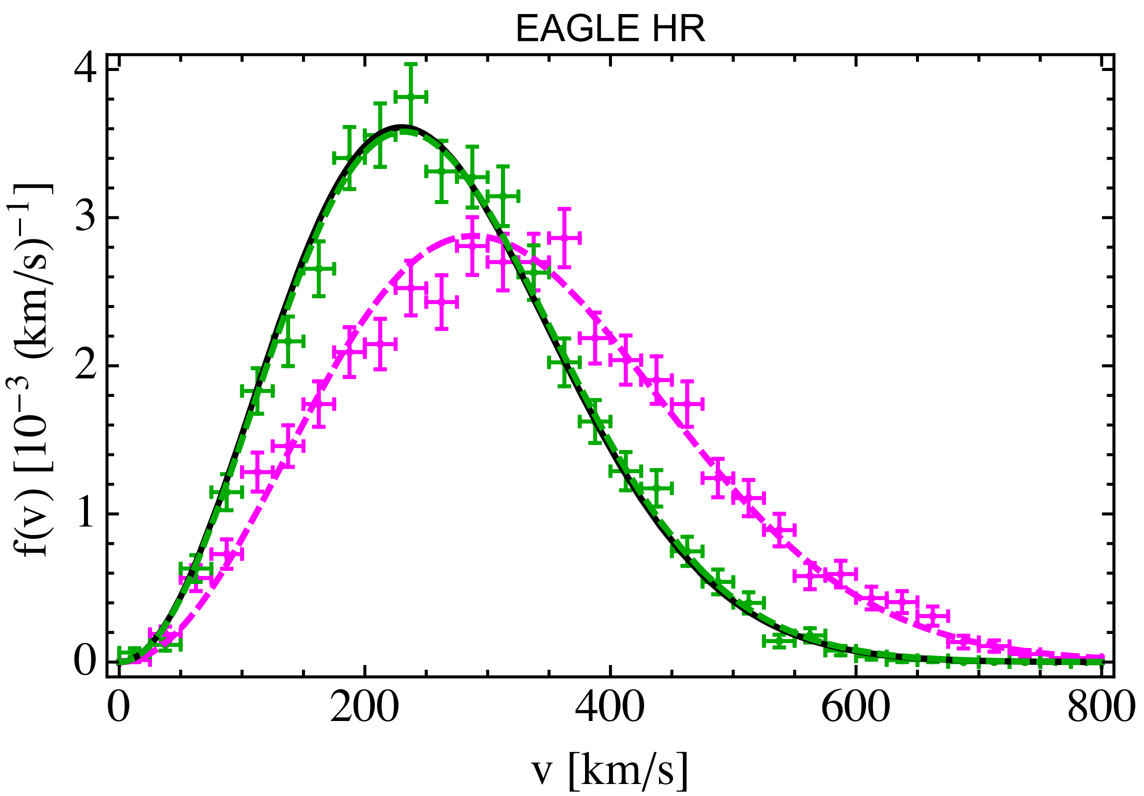


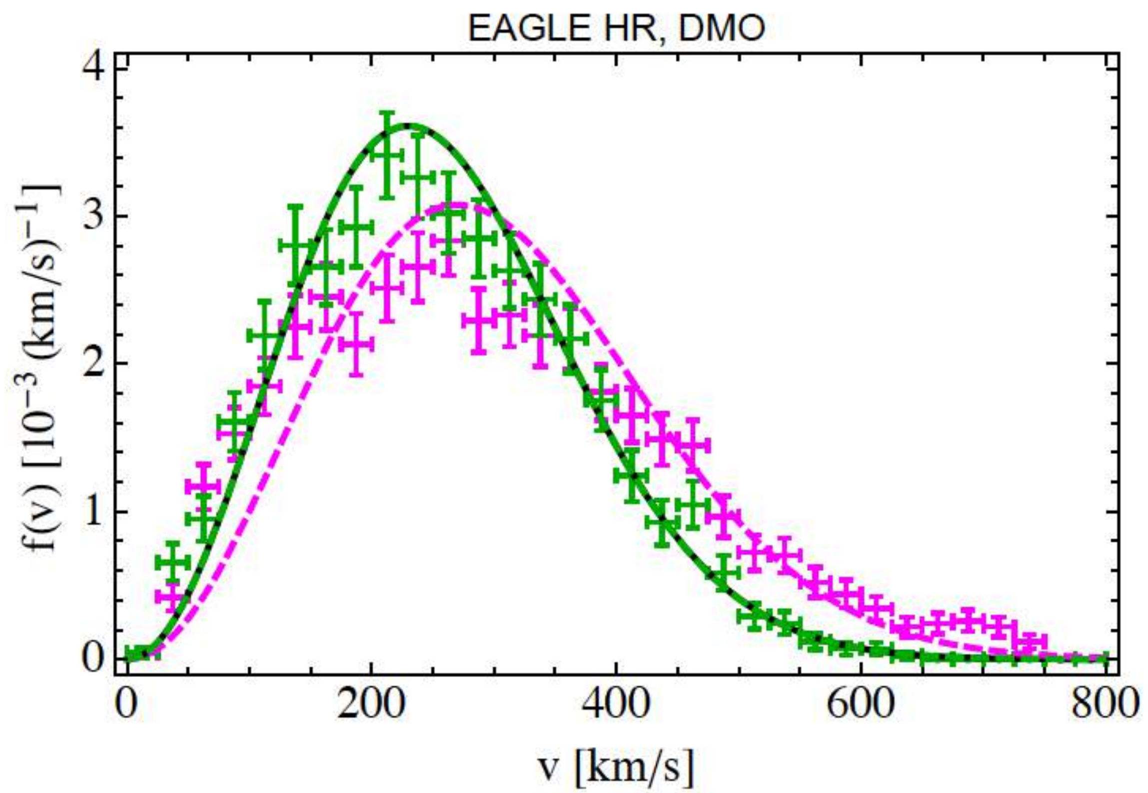
$$\rho_\chi = 0.41 - 0.73\ \mathrm{GeV/cm^3}$$

Local DM speed distributions

In the galactic rest frame:

DMO simulations





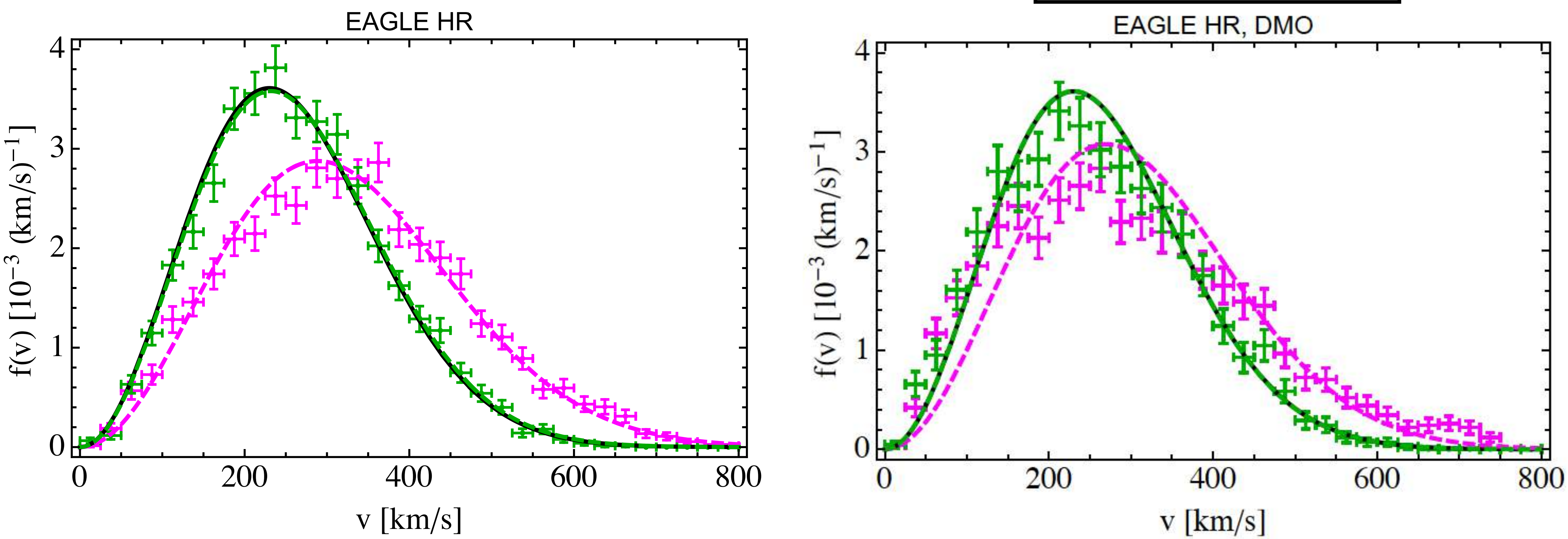
Bozorgnia et al., JCAP 05, 024 (2016)

- Maxwellian distribution with a free peak provides a better fit to halos in the hydrodynamical simulations compared to their DMO counterparts.

Local DM speed distributions

In the galactic rest frame:

DMO simulations



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

- Maxwellian distribution with a free peak provides a better fit to halos in the hydrodynamical simulations compared to their DMO counterparts.

- Best fit peak speed: $v_{\rm peak} = 223 - 289 \text{ km/s}$

Local DM speed distributions

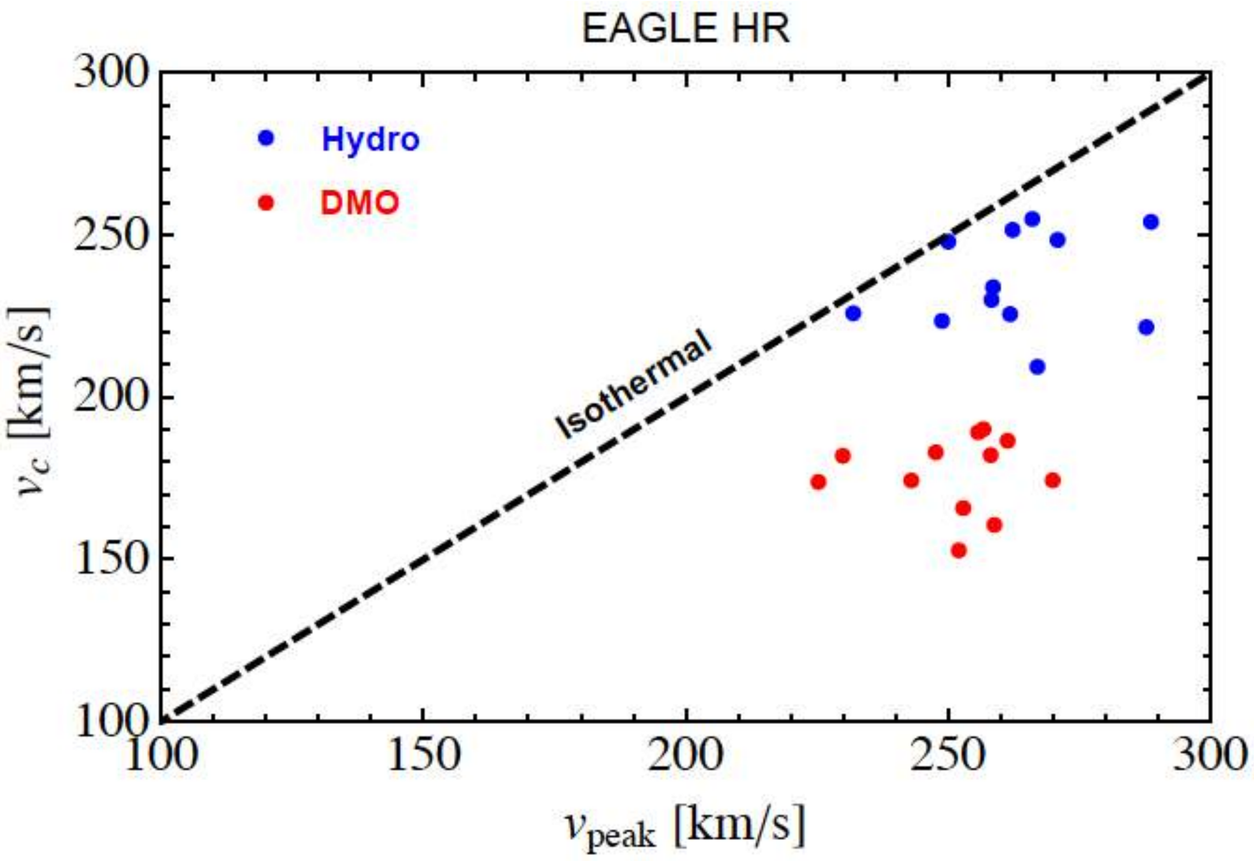
Common trends in different hydrodynamical simulations:

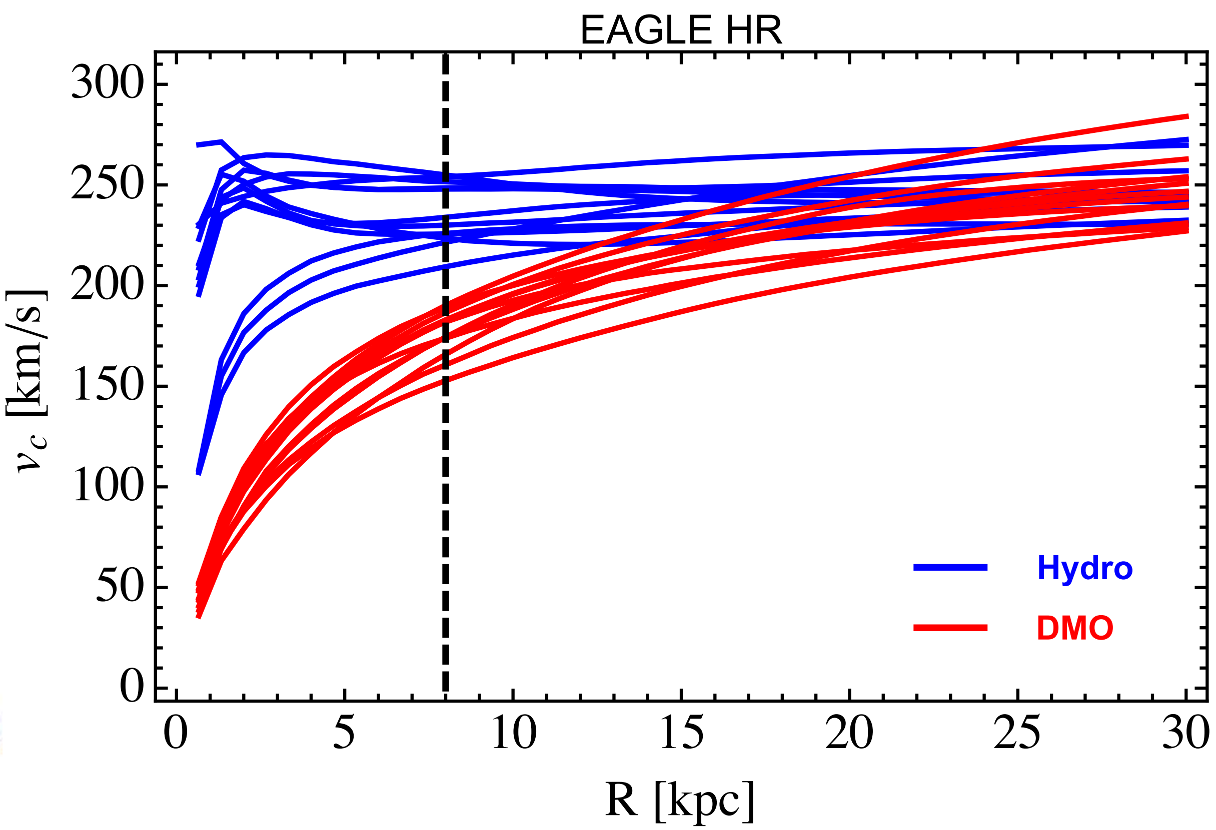
- Baryons deepen the gravitational potential in the inner halo, shifting the peak of the DM speed distribution to *higher speeds.*

- In most cases, baryons appear to make the local DM speed distribution ***more Maxwellian***.

Bozorgnia et al., JCAP 05, 024 (2016) (EAGLE & APOSTLE)
Kelso et al., JCAP 08, 071 (2016) (MaGICC)
Sloane et al., ApJ 831, 93 (2016)
Bozorgnia & Bertone, IJMPA 32, 1730016 (2017)
Bozorgnia et al., JCAP 07, 036 (2020) (Auriga)
Poole-McKenzie et al., JCAP 11, 016 (2020) (ARTEMIS)
Rahimi, Vienneau, Bozorgnia, Robertson, 2210.06498 (SIDM EAGLE)

Departure from isothermal





Bozorgnia & Bertone, IJMPA 32, 1730016 (2017)

- At the Solar circle, halos in the hydrodynamical simulation are closer to isothermal than their DMO counterparts.

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

astrophysics

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astrophysics

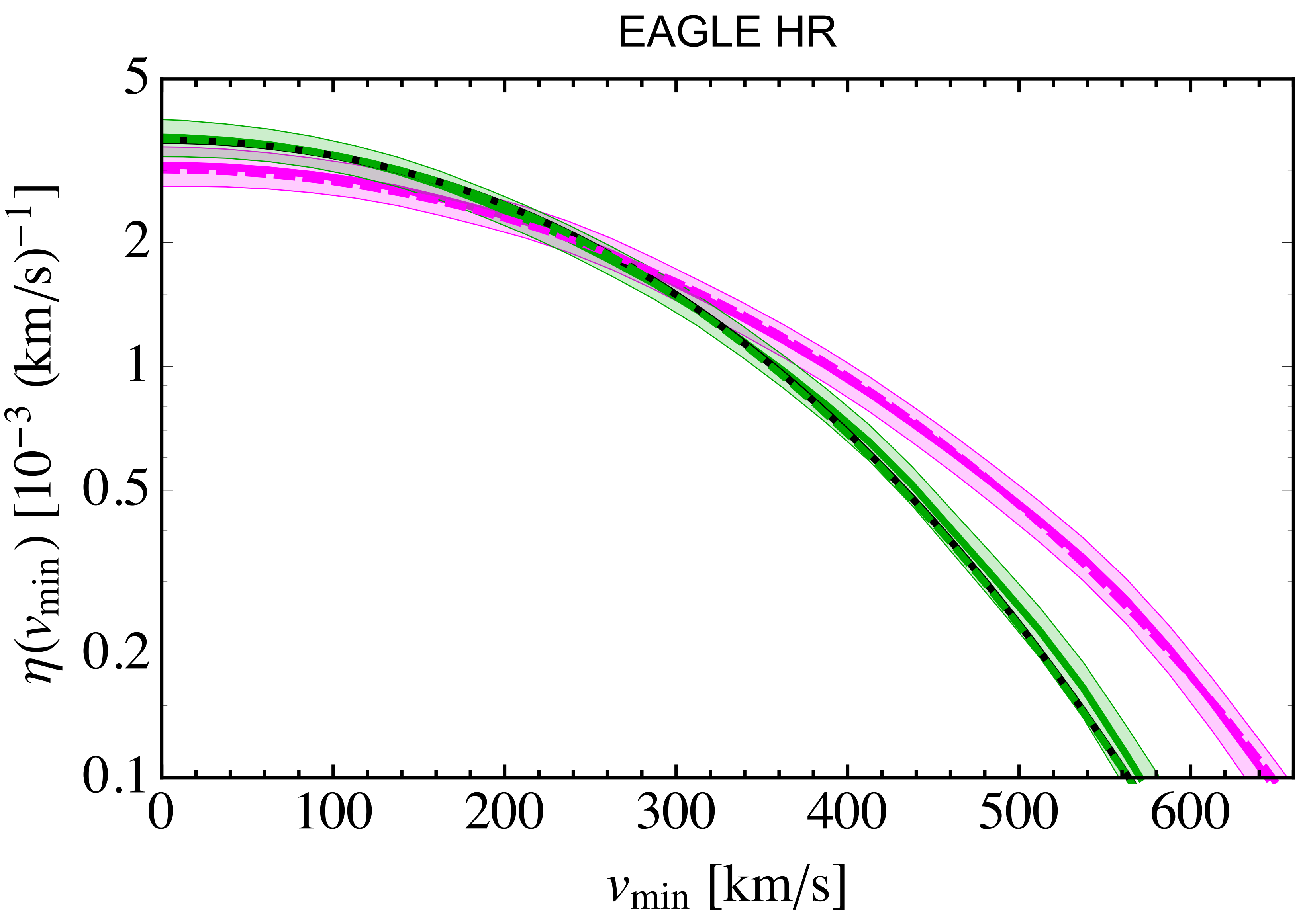
$$\frac{dR}{dE_R} = \frac{\sigma_0 \, F^2(E_R)}{2 m_\chi \mu_{\chi N}^2} \rho_\chi \, \eta(v_{\min}, t)$$

where

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

Halo integral

The halo integral



- Halo integrals for the best fit Maxwellian velocity distribution (*peak speed 223 - 289 km/s*) fall within the 1σ uncertainty band of the halo integrals of the simulated halos.

The halo integral

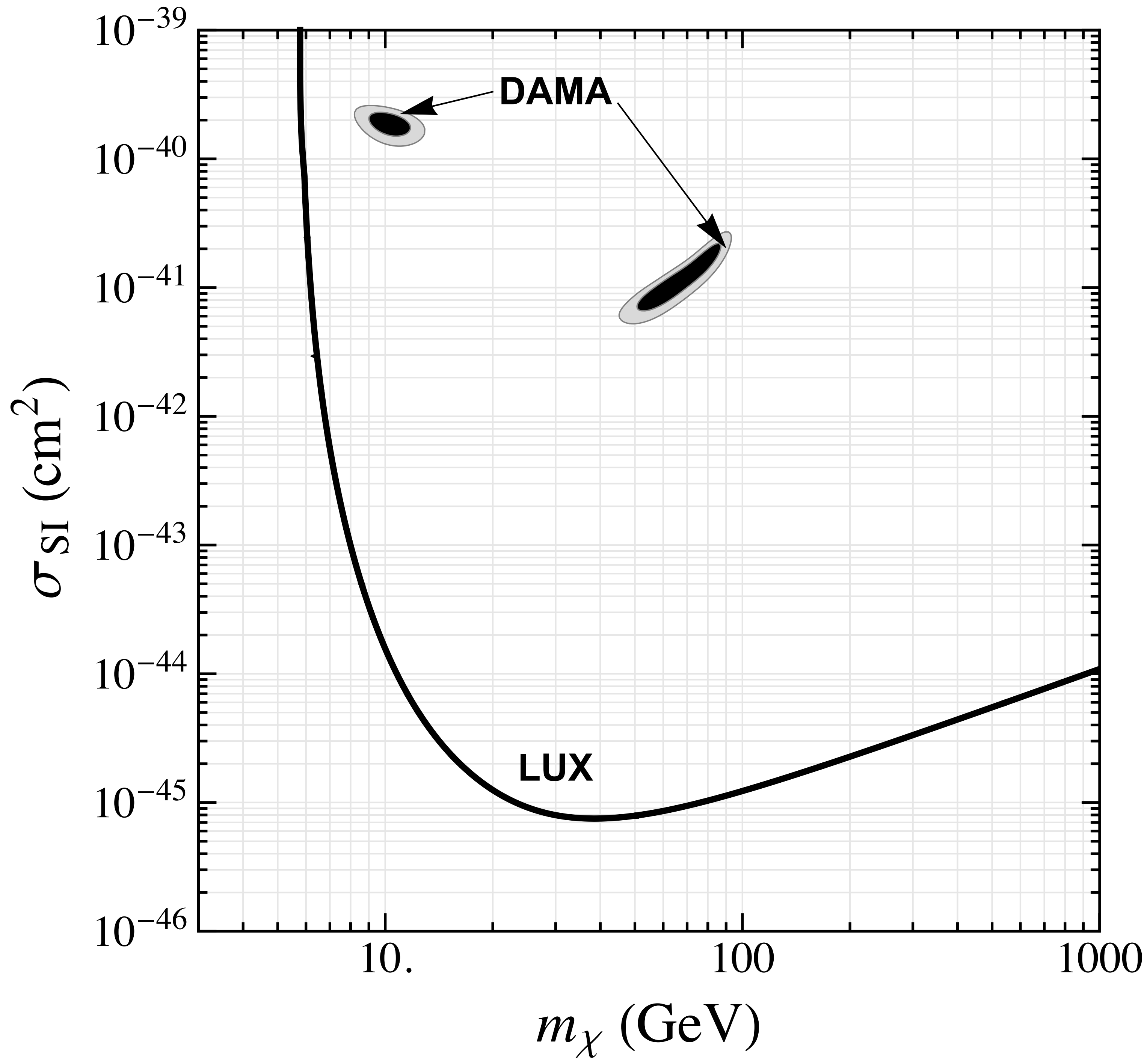
Common trend in different hydrodynamical simulations:

- Halo integrals and hence direct detection event rates obtained from a Maxwellian velocity distribution with a free peak are similar to those obtained directly from the simulated halos.

Bozorgnia et al., JCAP 05, 024 (2016) (EAGLE & APOSTLE)
Kelso et al., JCAP 08, 071 (2016) (MaGICC)
Sloane et al., ApJ 831, 93 (2016)
Bozorgnia & Bertone, IJMPA 32, 1730016 (2017)

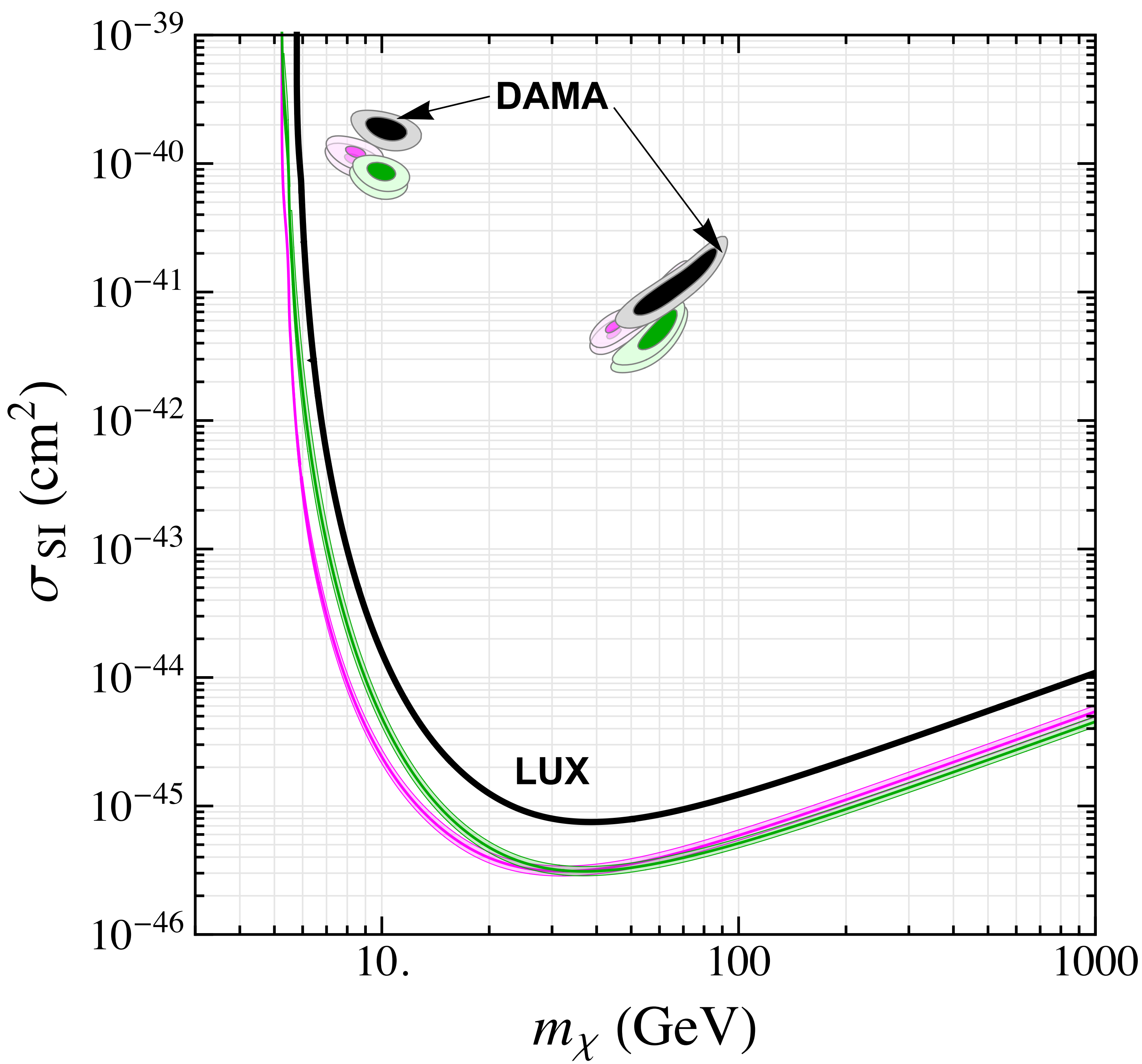
Implications for direct detection

- Assuming the **SHM**:



Implications for direct detection

- Compare with simulated Milky Way-like halos:



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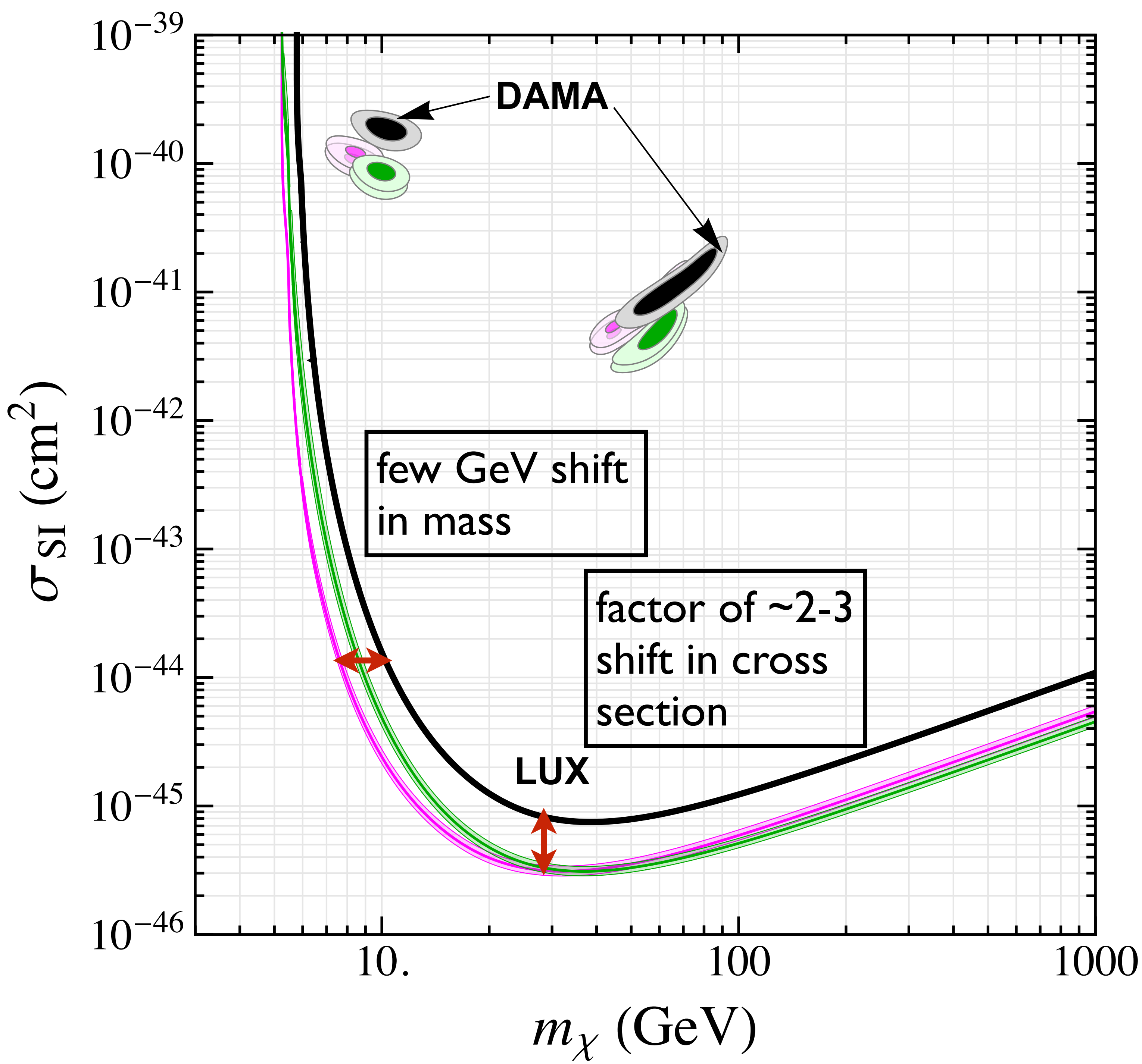
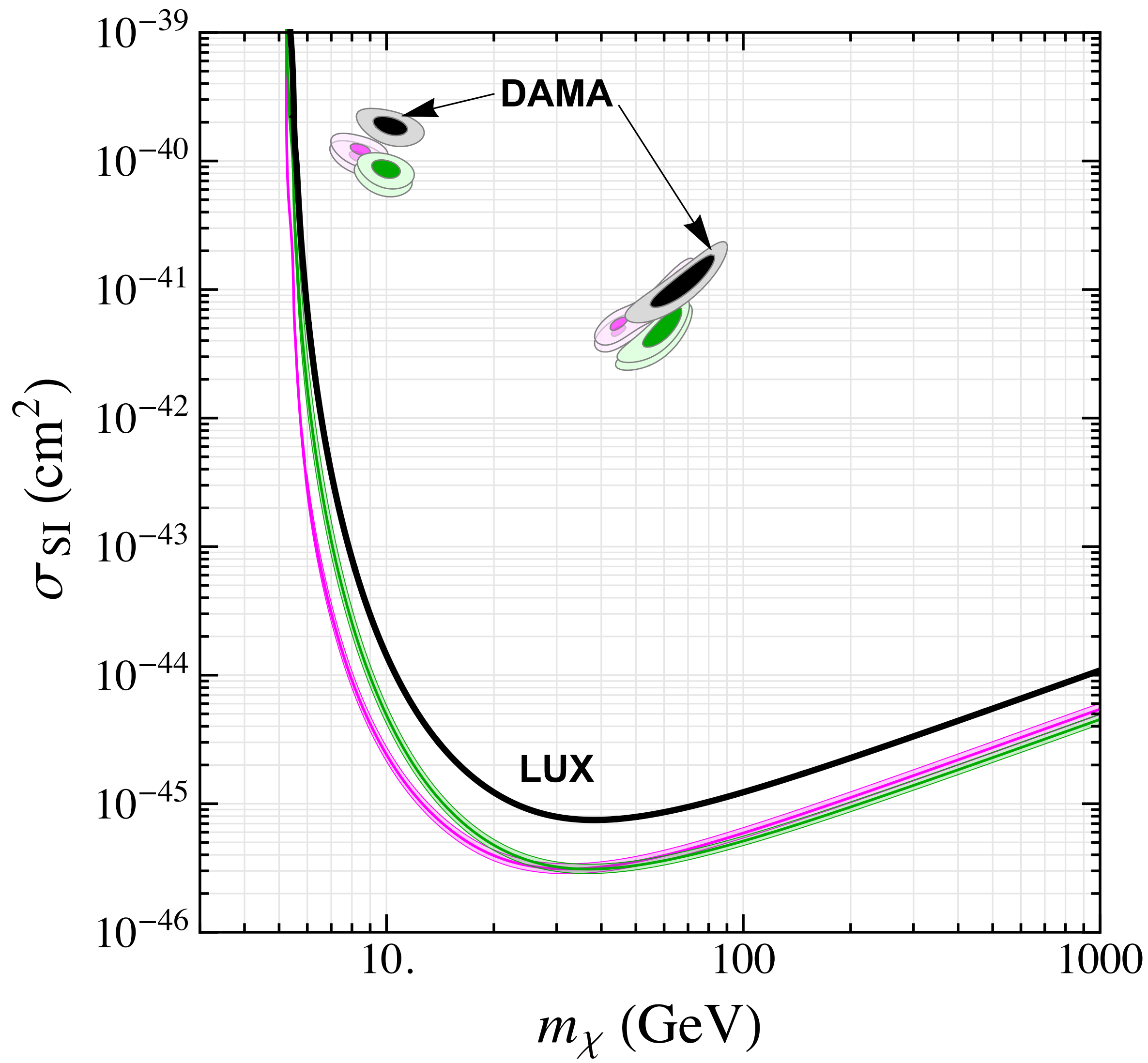
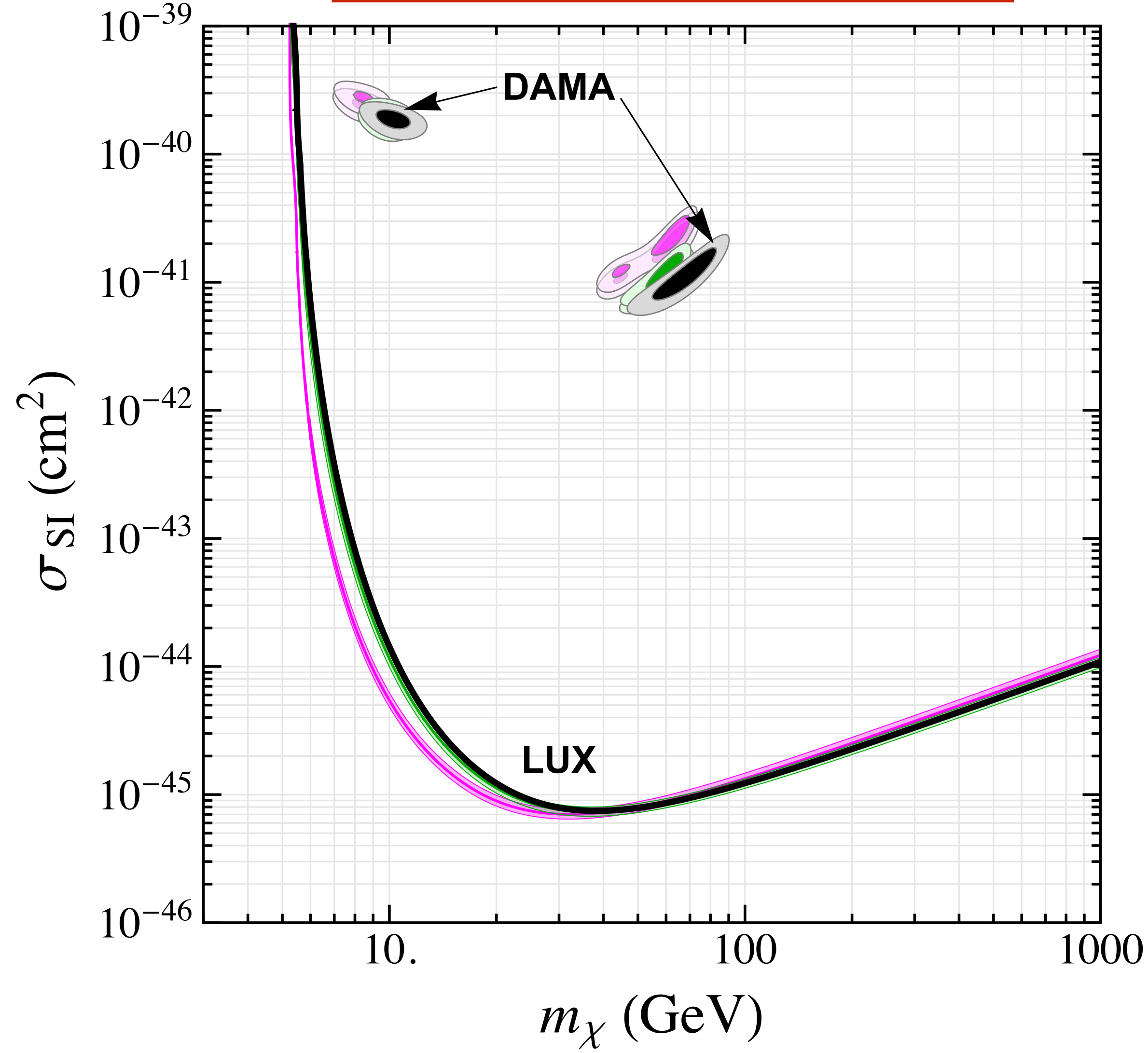


Implications for direct detection



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

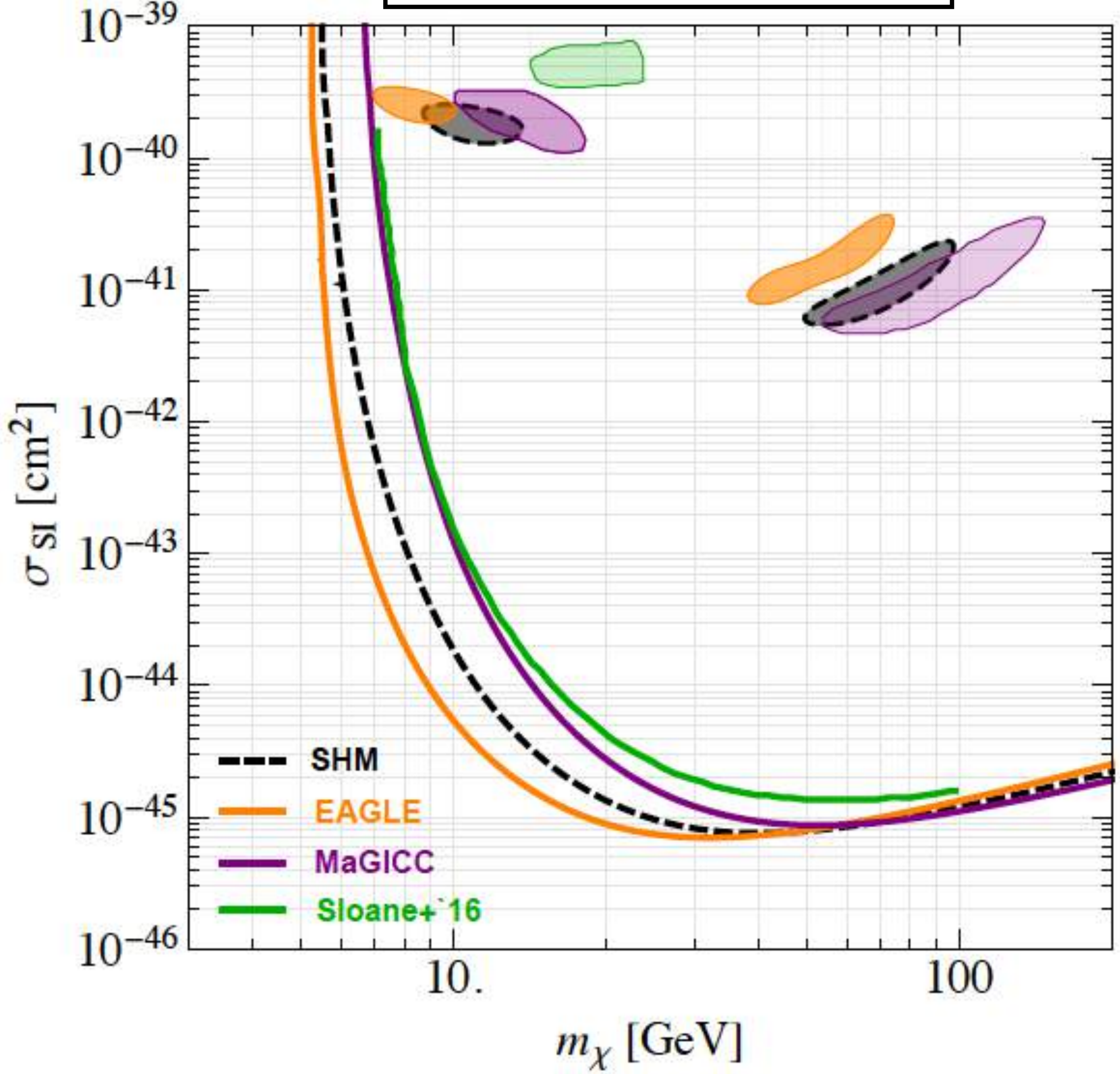


- Difference in the local DM density → overall difference with the SHM.
- Shift of the DM speed distributions to higher speeds → shift in the low mass region.

Implications for direct detection

Comparison to other hydrodynamical simulations:

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



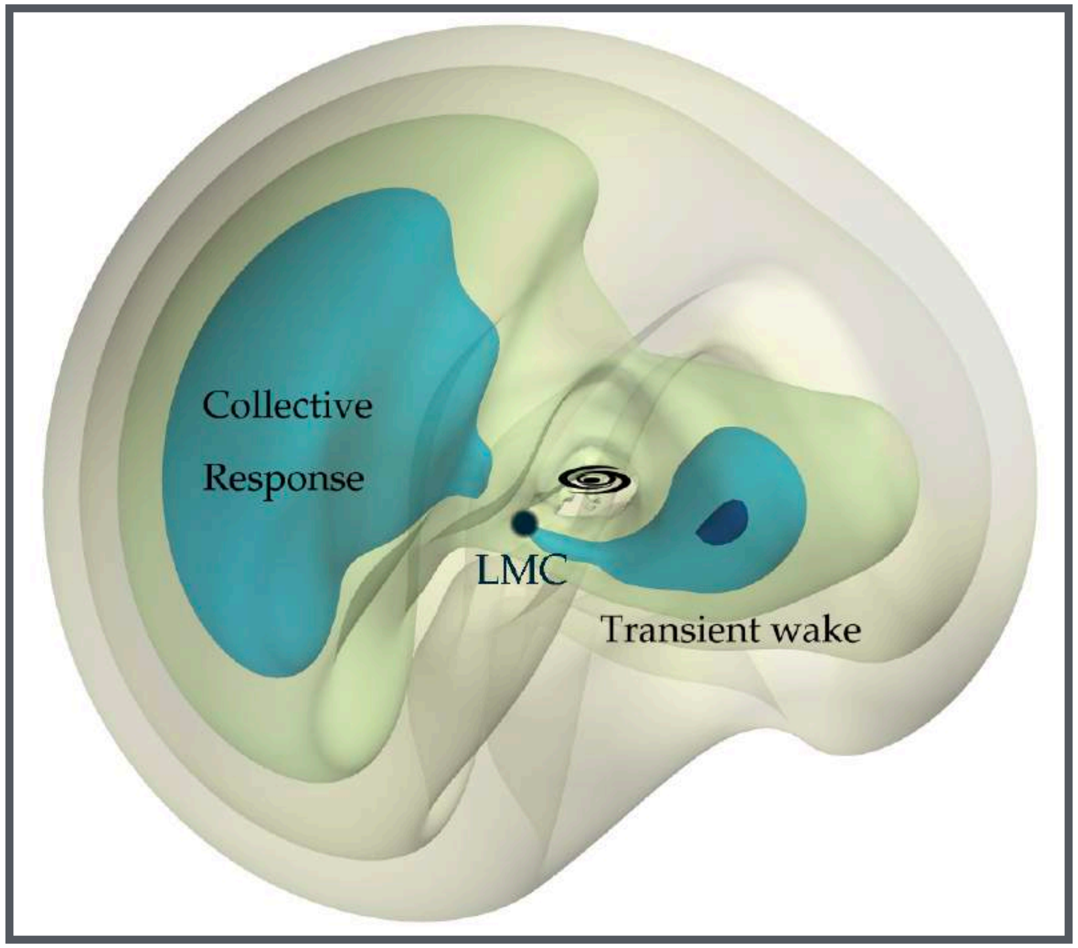
Bozorgnia & Bertone, IJMPA 32, 1730016 (2017)

Effect of the LMC

The effect of the LMC

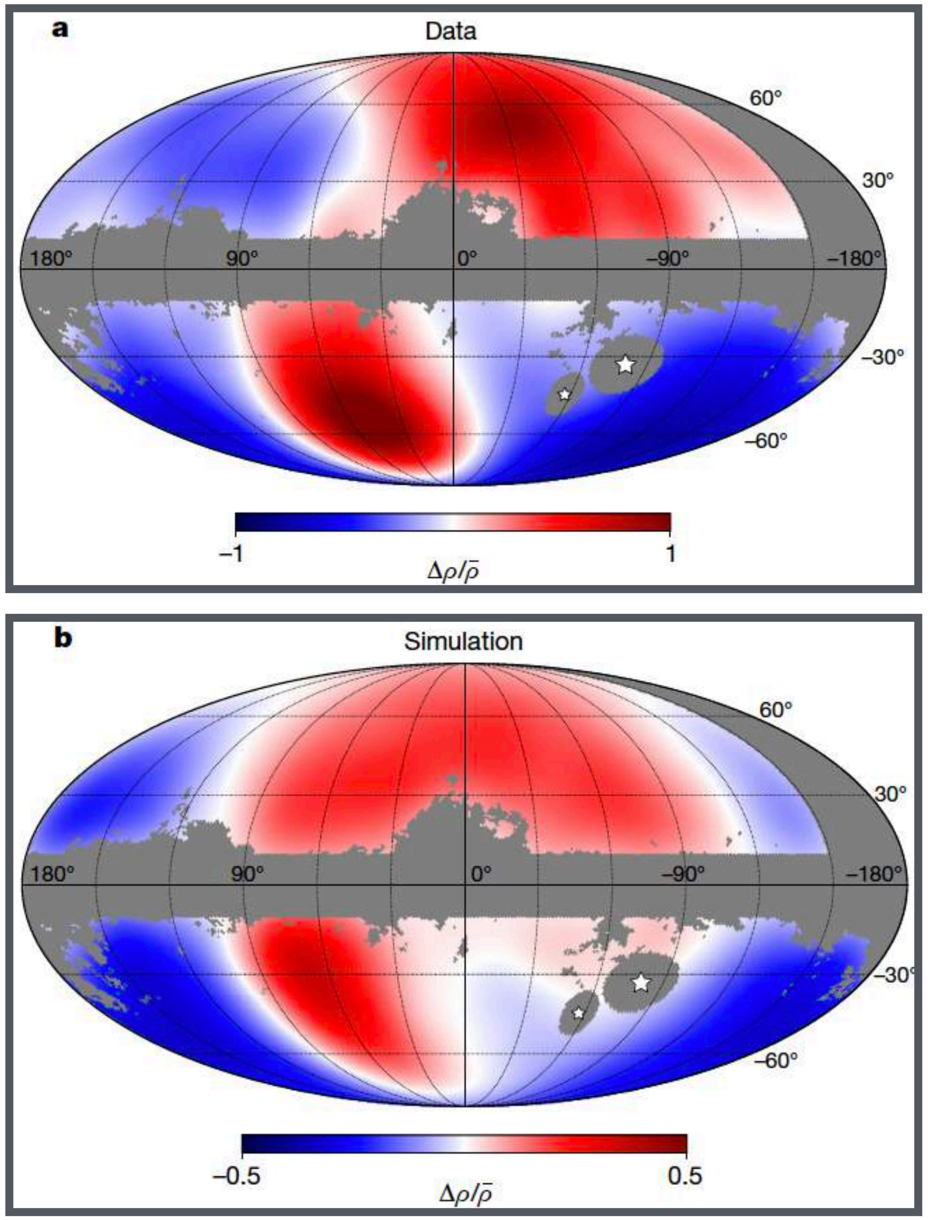
The **LMC** is the most massive satellite of the Milky Way and on its first passage around the Galaxy. → *Introduces perturbations in the DM and stellar halo.*

DM halo



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

Stellar halo



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

Effect of LMC on direct detection

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

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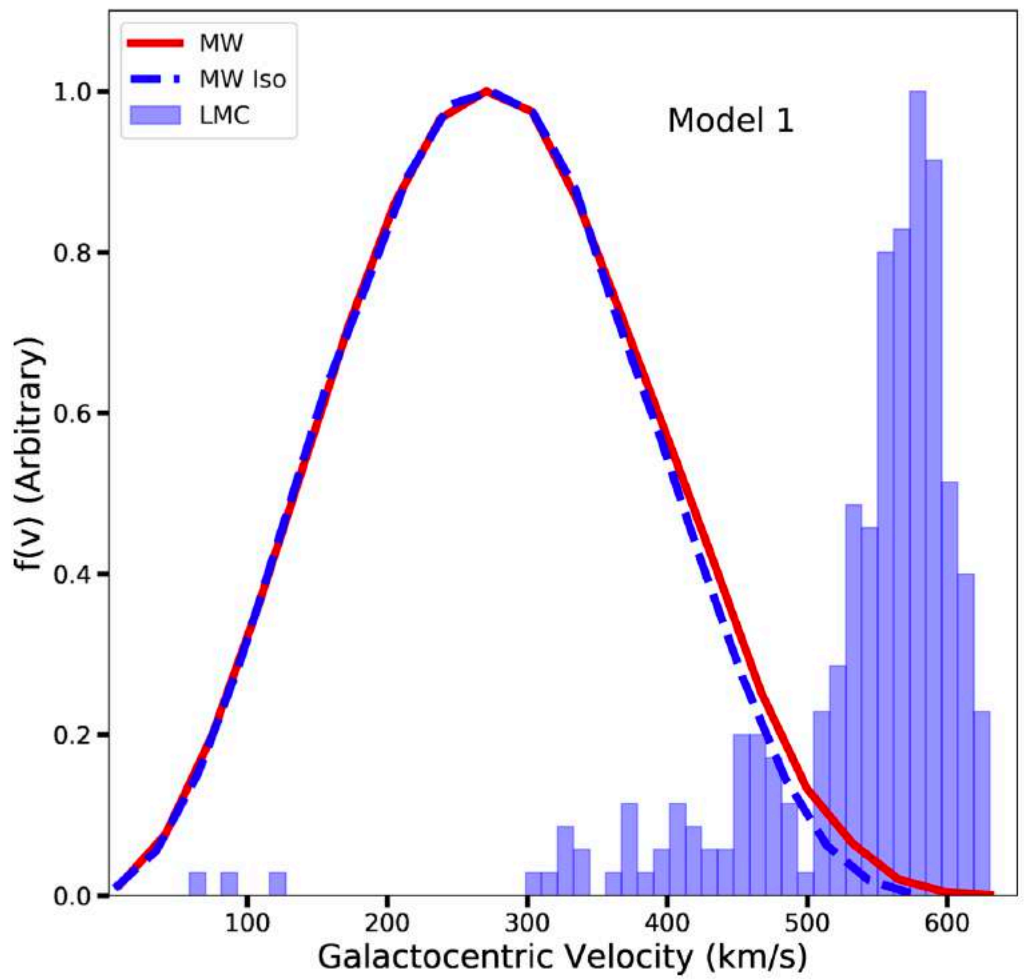

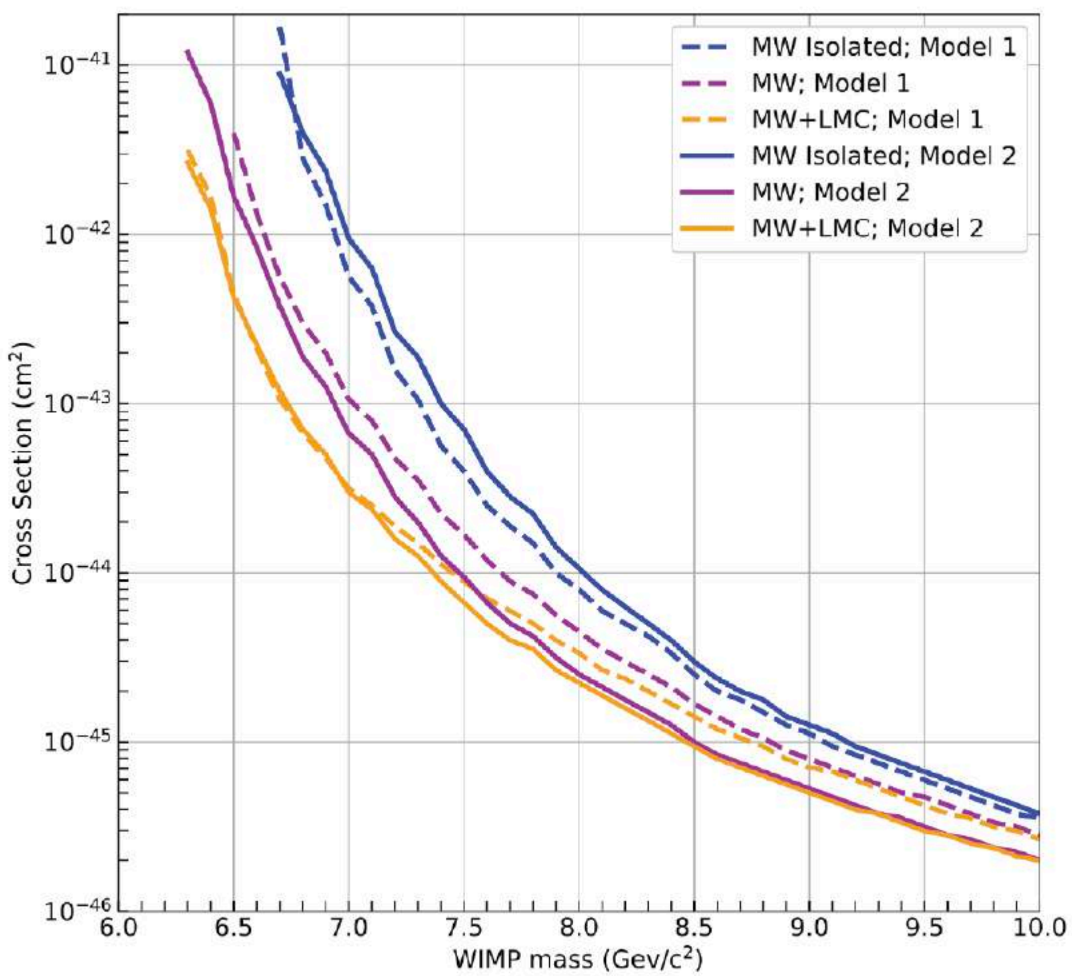

Besla et al, JCAP 11, 013 (2019)

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

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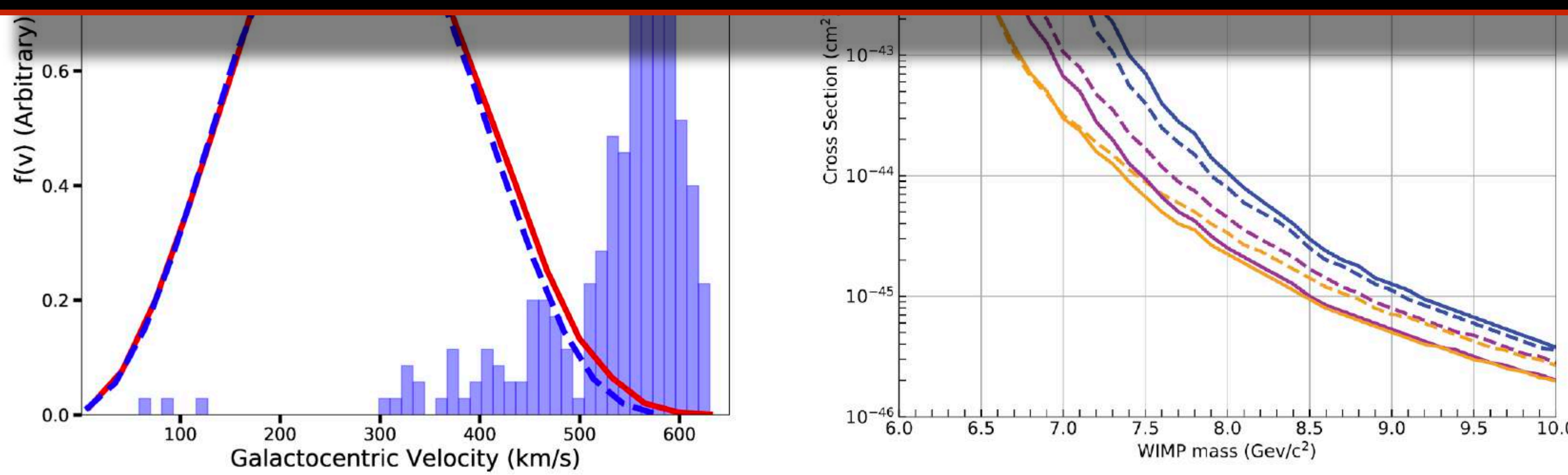
Are these findings valid for fully cosmological halos with multiple accretion events over their formation history?

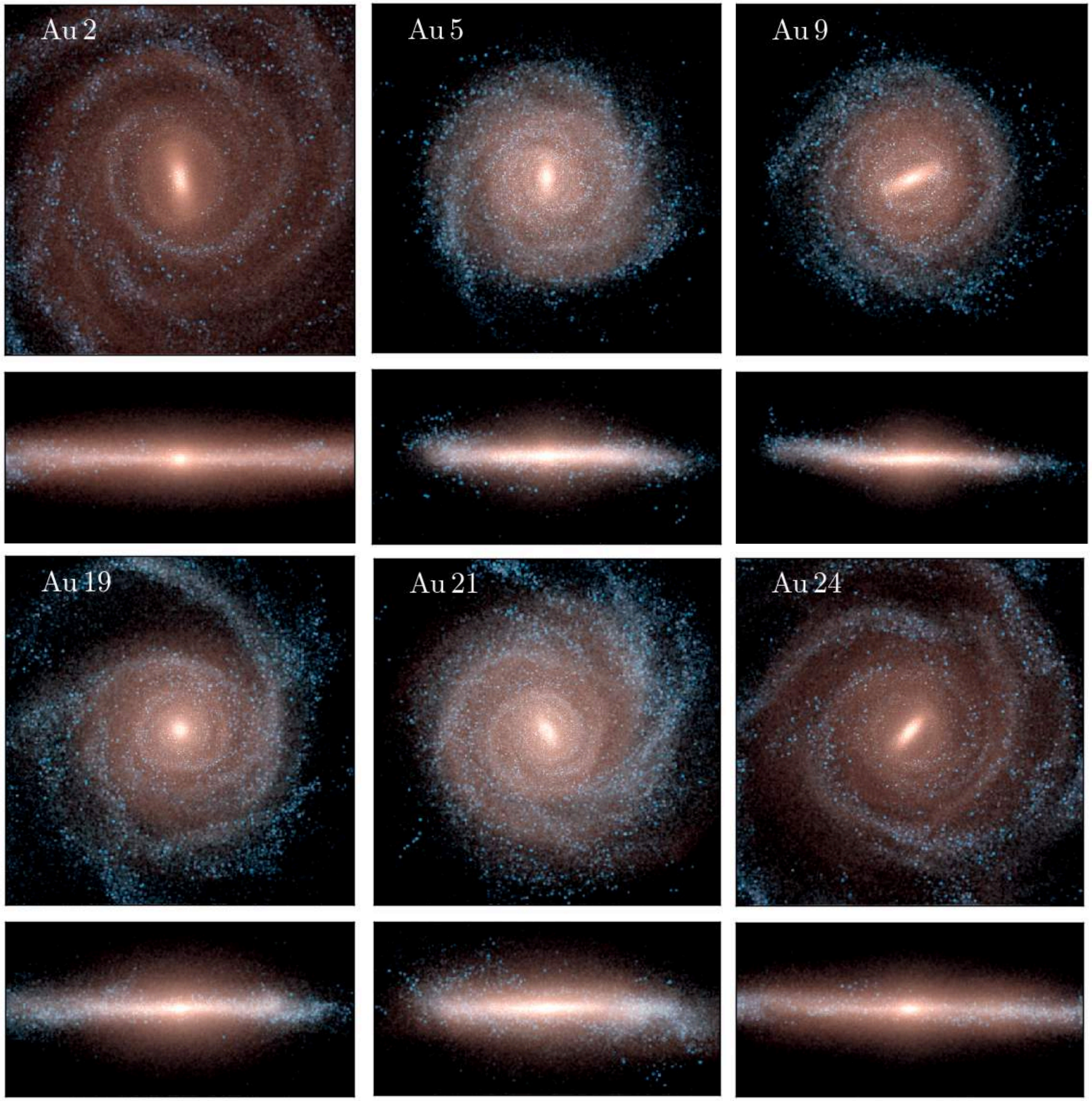


Besla et al, JCAP 11, 013 (2019)

Auriga cosmological simulations

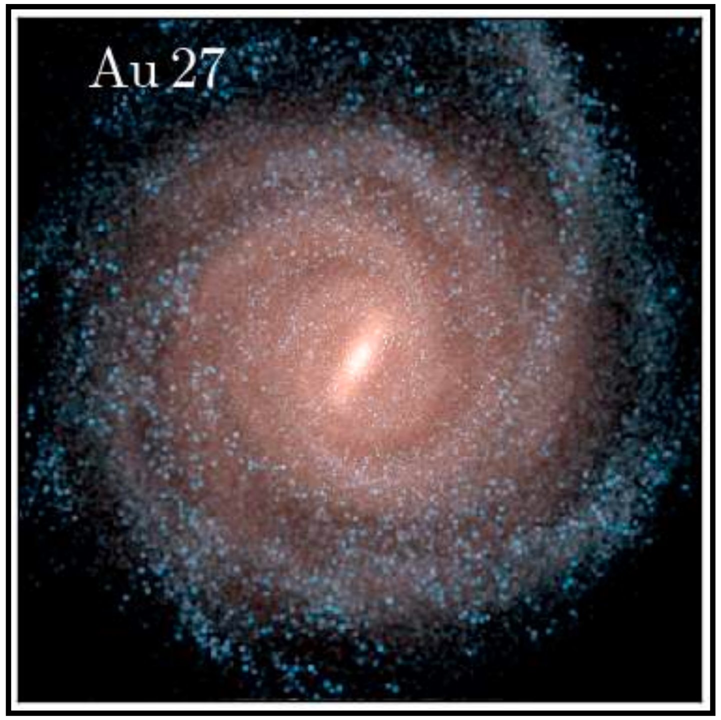
- State-of-the-art cosmological magneto-hydrodynamical zoom-in simulations of Milky Way size halos.
- 30 halos at the standard resolution:

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



Auriga cosmological simulations

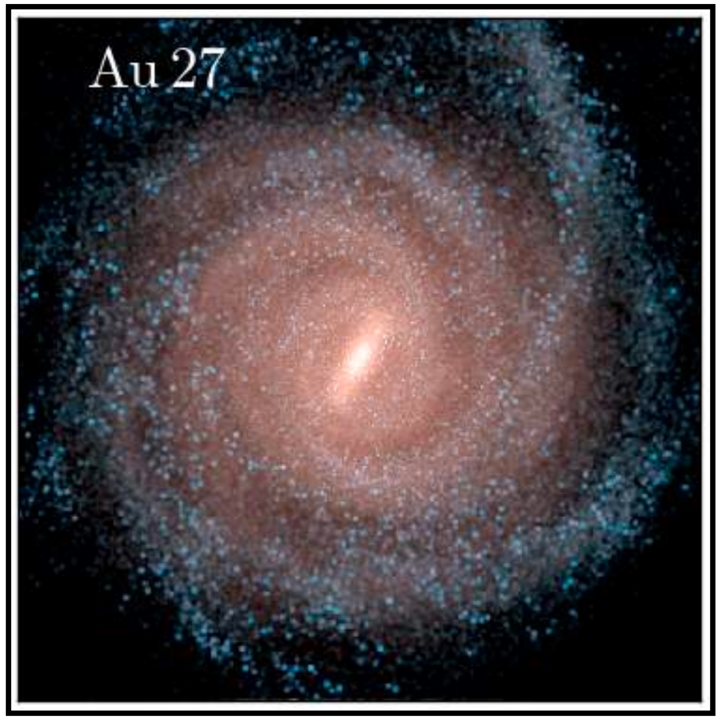
- Identify **15 Milky Way-LMC analogues** based on **LMC's stellar mass** and **distance from host** at first pericenter approach.



Auriga cosmological simulations

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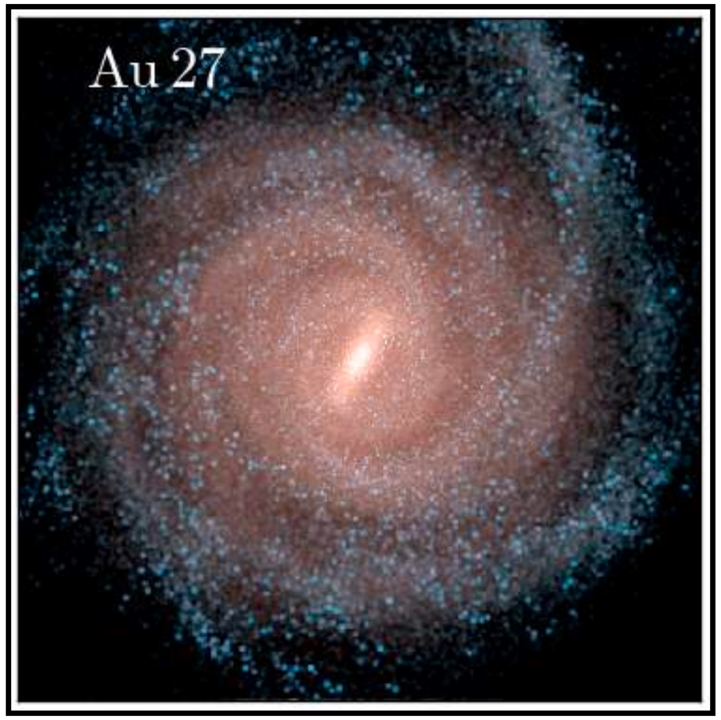
- Focus on one halo and study the impact of the LMC on the local DM distribution at different times (snapshots) in its orbit.

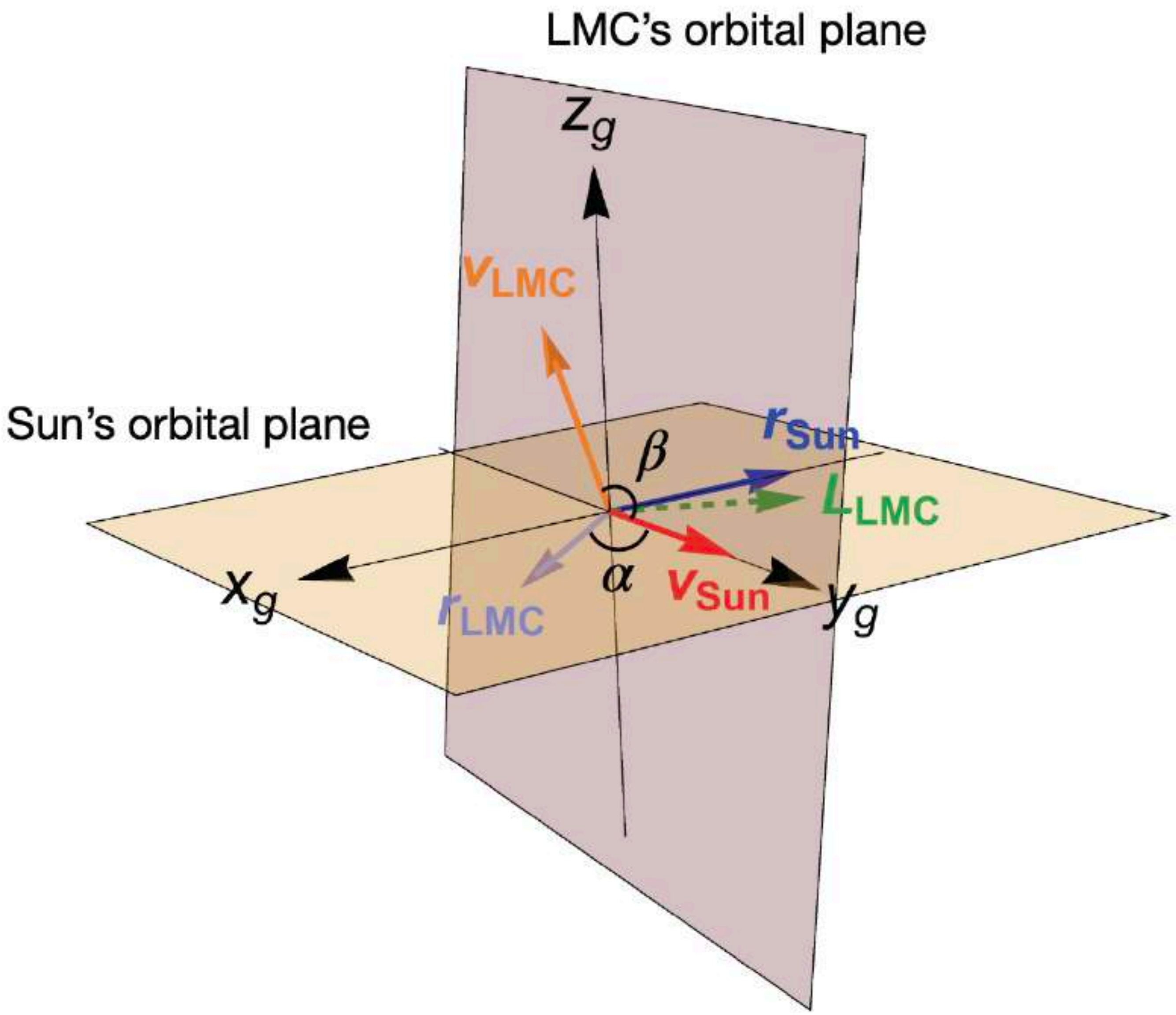
- Consider four representative snapshots:



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

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.



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

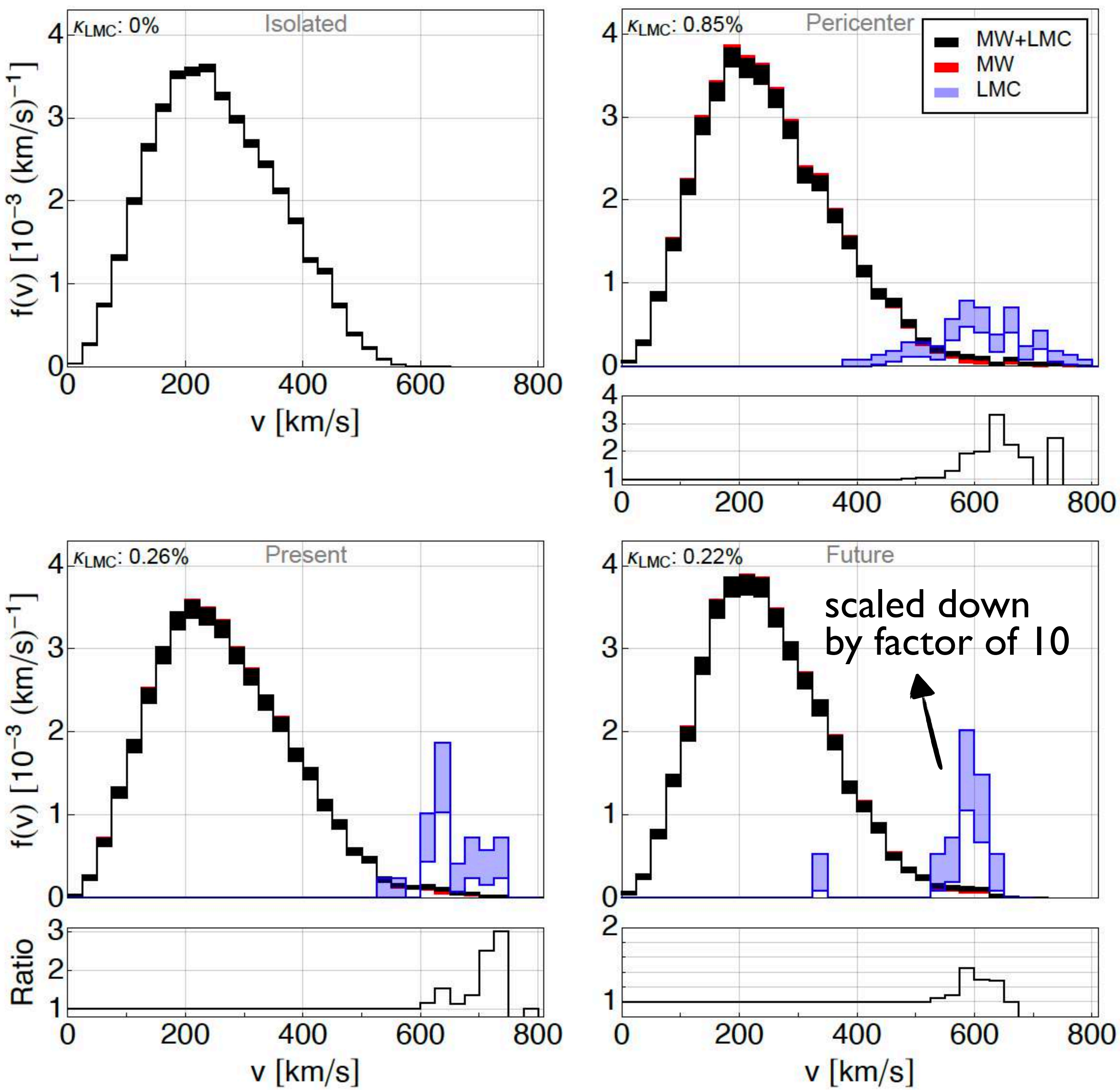
Local dark matter density

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.

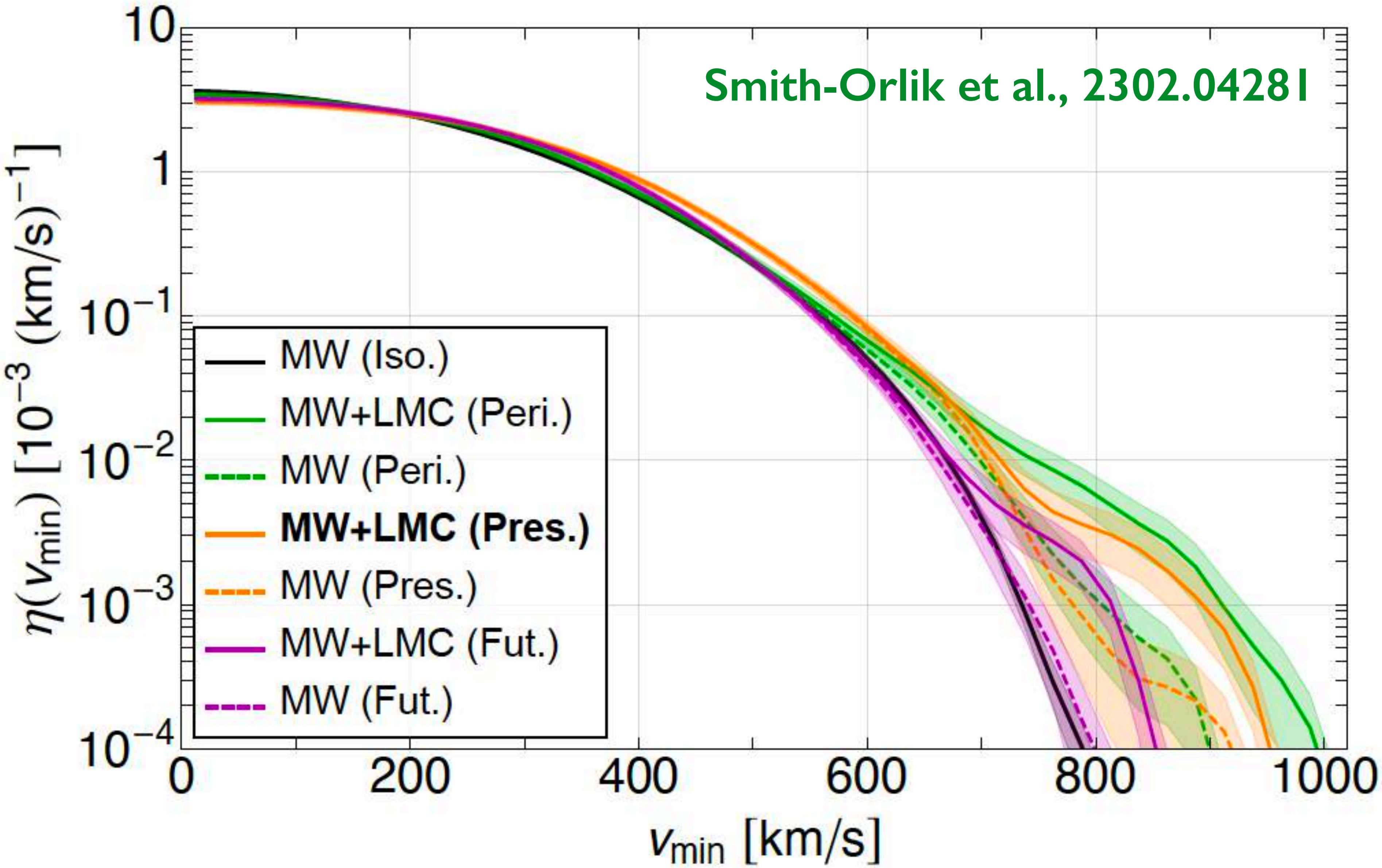
Local DM speed distribution



The LMC impacts the high speed tail of the local 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., 2302.04281

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

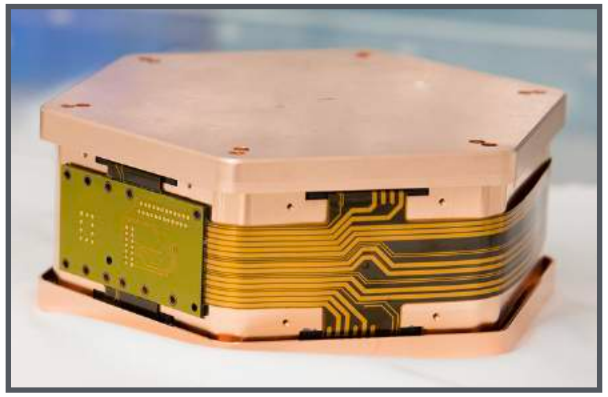
Xenon based

[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

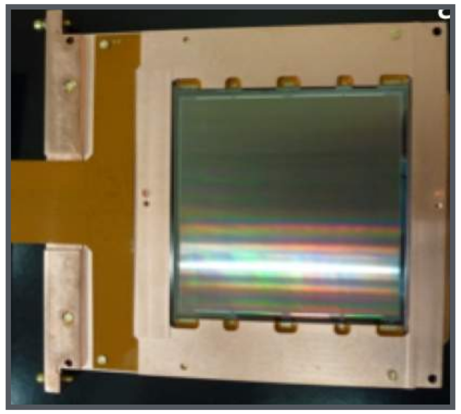
Based on SuperCDMS



Electron recoils

Silicon CCD

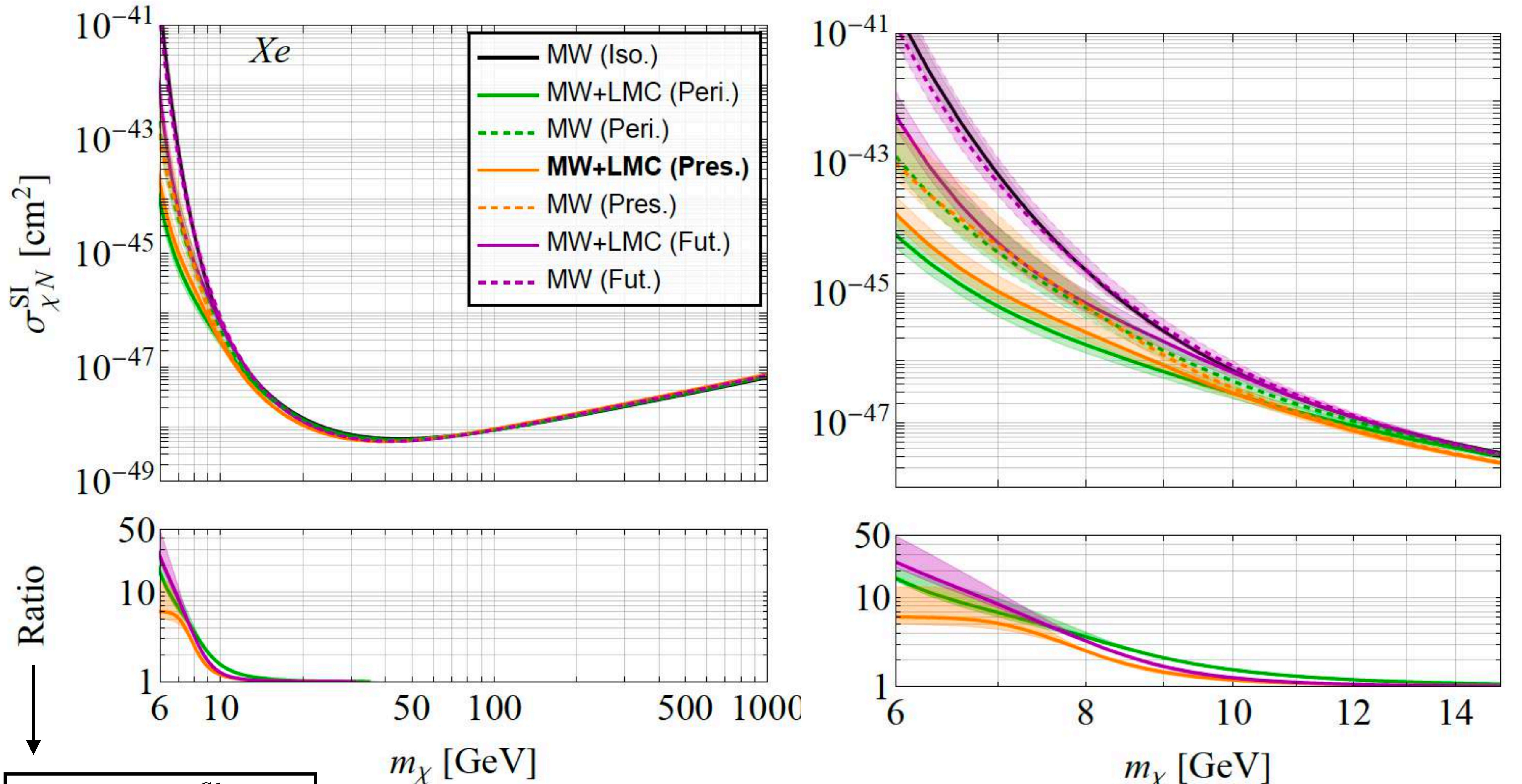
1 electron threshold
1 kg yr
Based on DAMIC



Direct detection: nuclear recoils

Xenon based detector:

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



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

Smith-Orlik et al., 2302.04281

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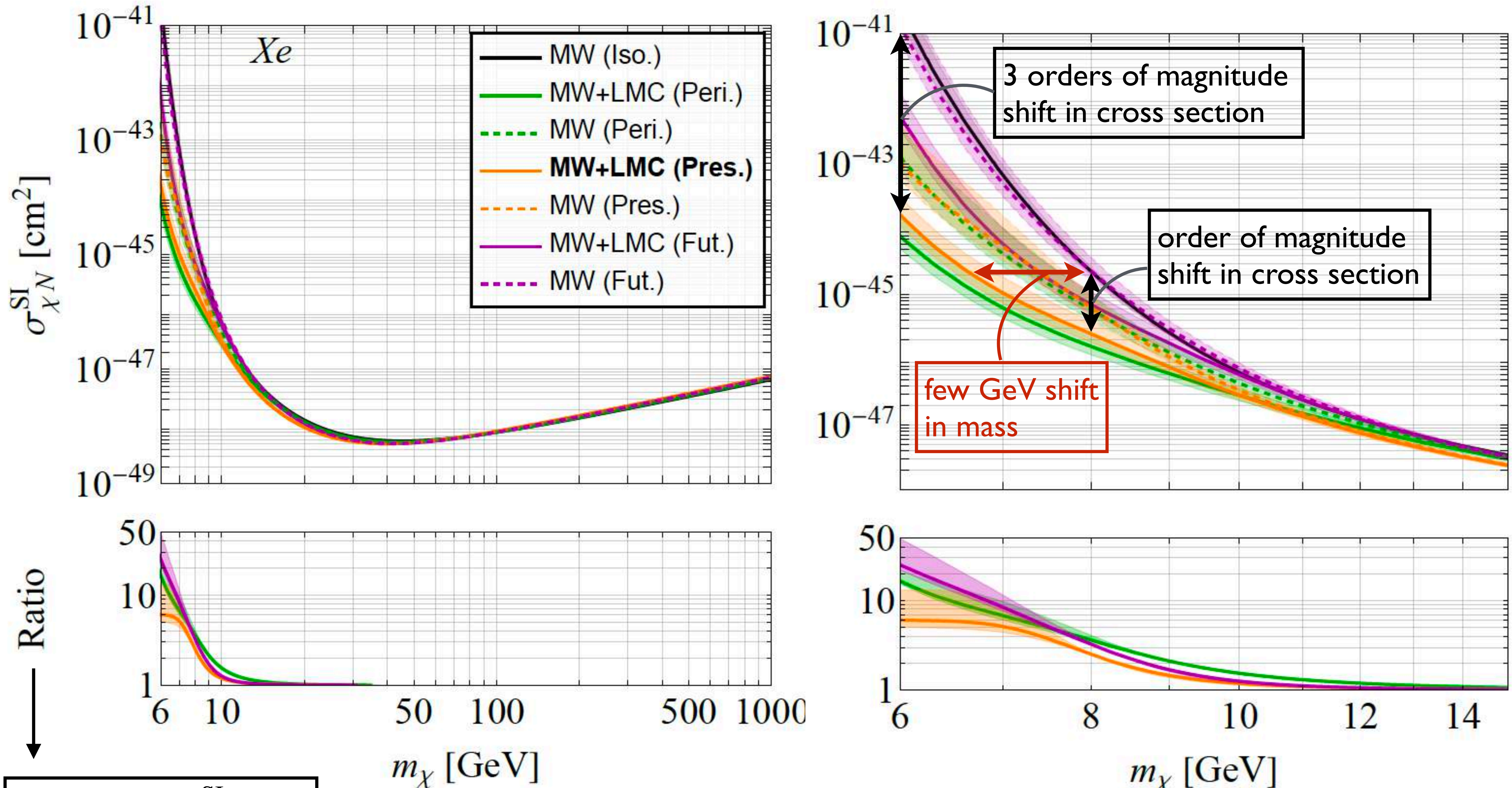


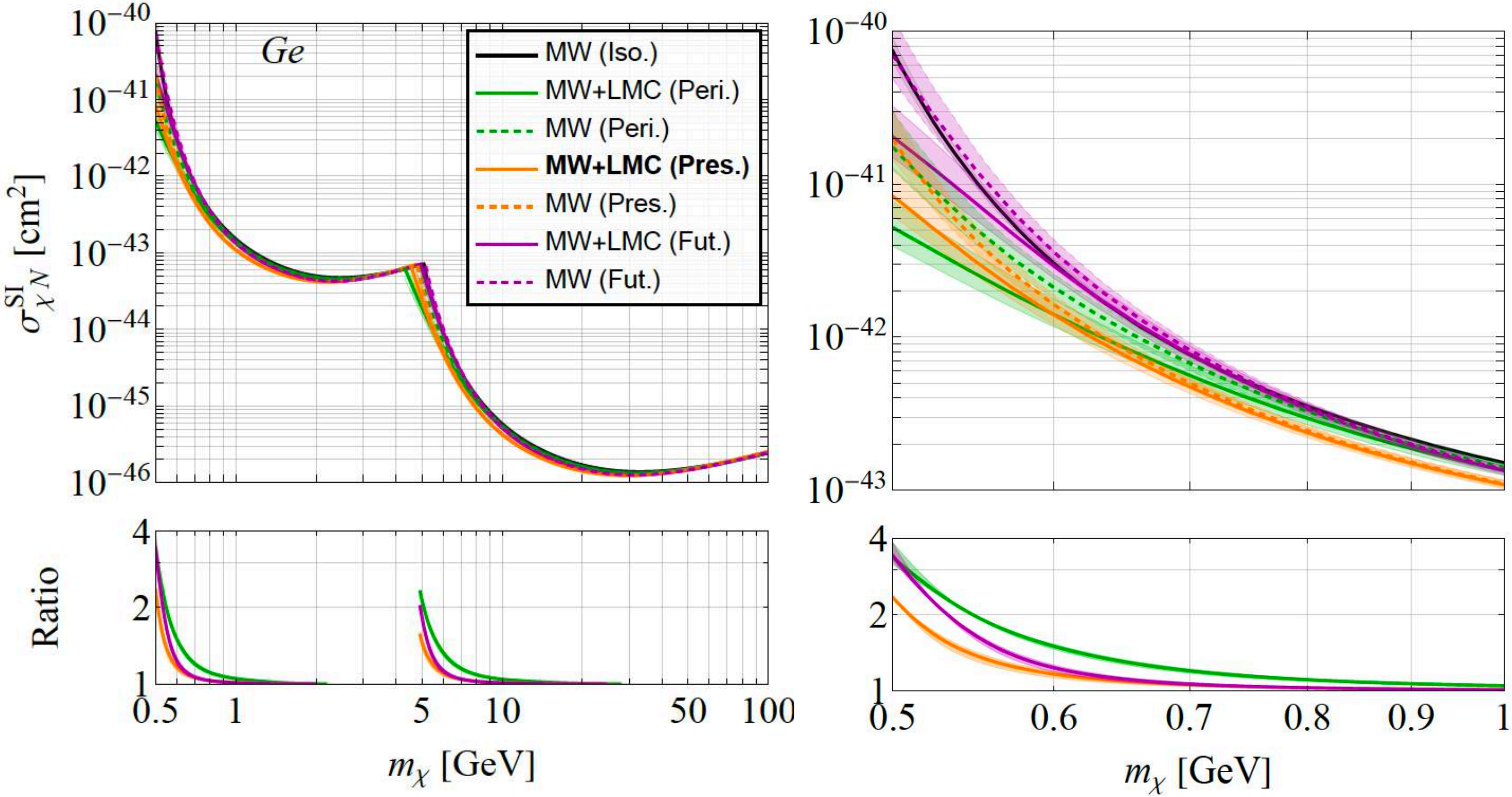
$$\mathrm{Ratio} = \frac{\sigma^{\mathrm{SI}}_{\chi,\mathrm{MW}}}{\sigma^{\mathrm{SI}}_{\chi,\mathrm{MW+LMC}}}$$

Smith-Orlik et al., 2302.04281

Direct detection: nuclear recoils

Germanium based detector:

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

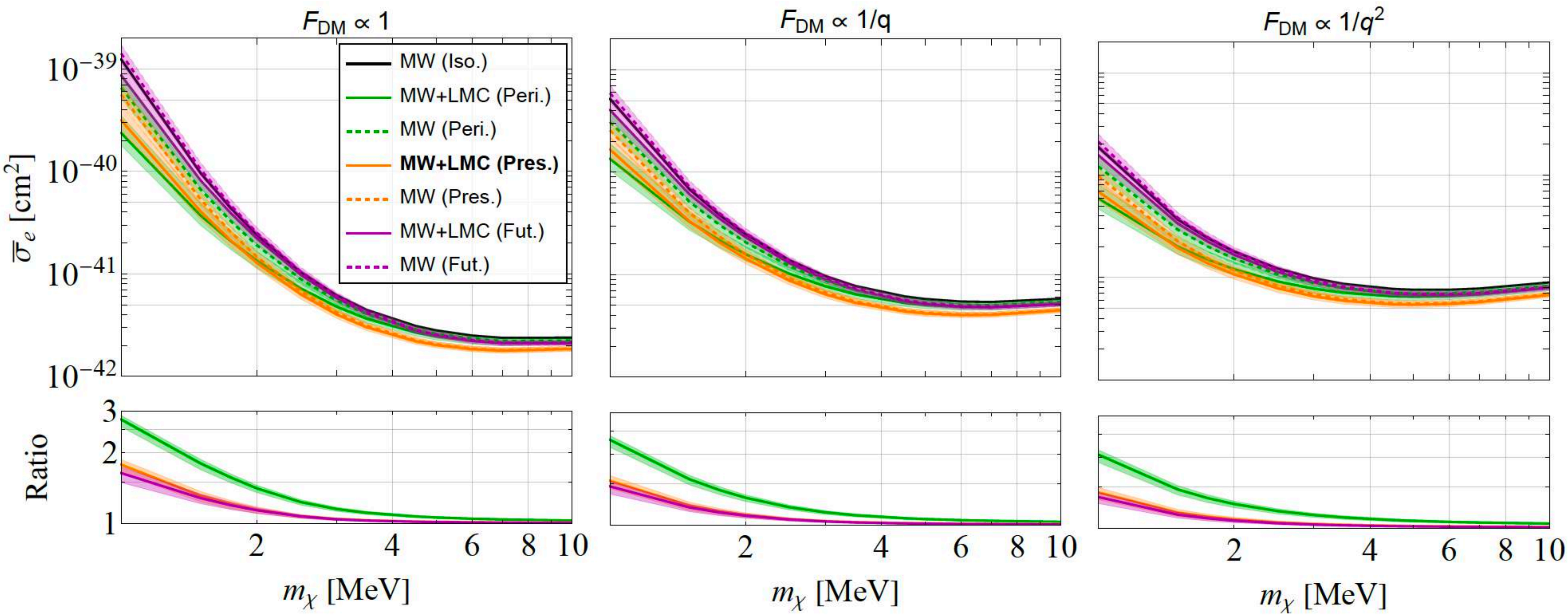


Smith-Orlik et al., 2302.04281

Direct detection: electron recoils

Silicon CCD detector:

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



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Summary

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

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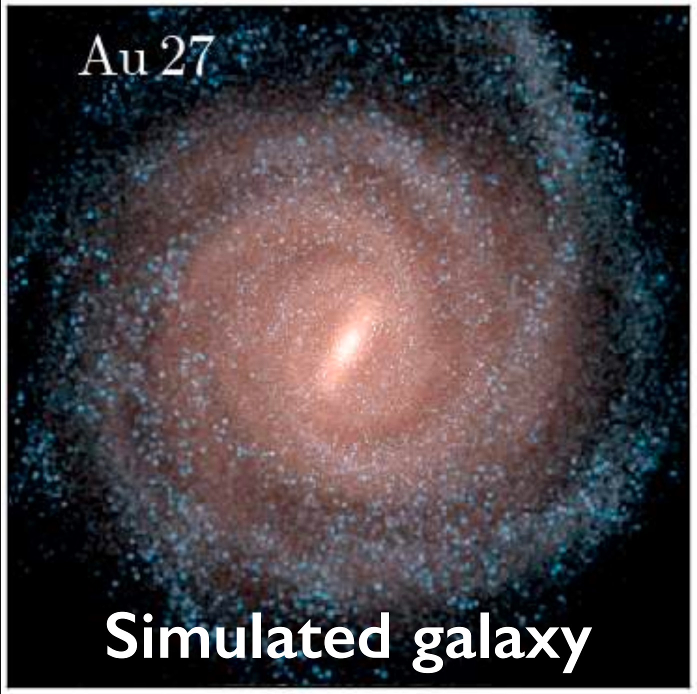

Smooth halo

- Local DM density agrees with estimates from observations.
- Local DM velocity distribution consistent with a Maxwellian distribution.

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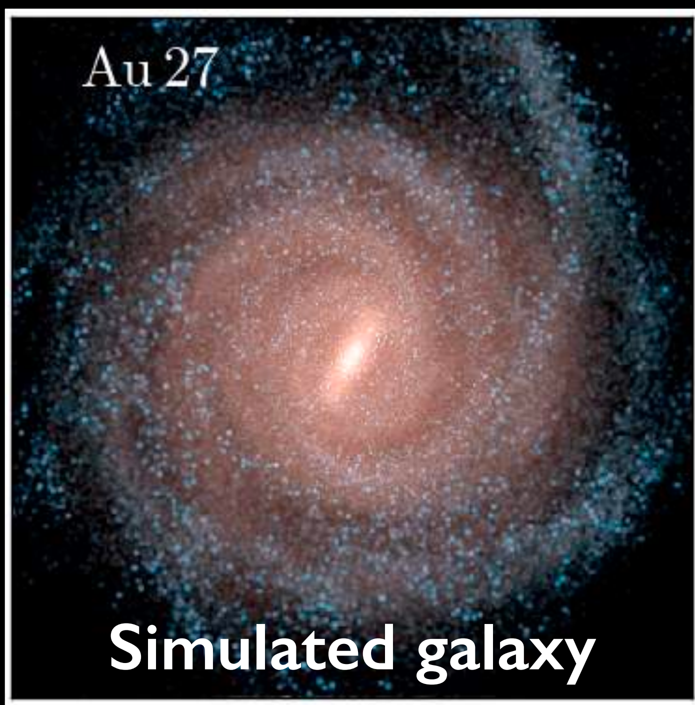
Cosmological simulations provide important insight on the local DM distribution. → *Crucial for the interpretation of direct detection data.*



Smooth halo

Substructure

Local DM density agrees with estimates from observations.

Local DM velocity distribution consistent with a Maxwellian distribution.

Large Magellanic Cloud

The LMC significantly boosts the high speed tail of the local DM velocity distribution. → Considerable shifts in direct detection limits towards lower cross sections and smaller DM masses.