The dark matter distribution of *Milky Way-like* galaxies

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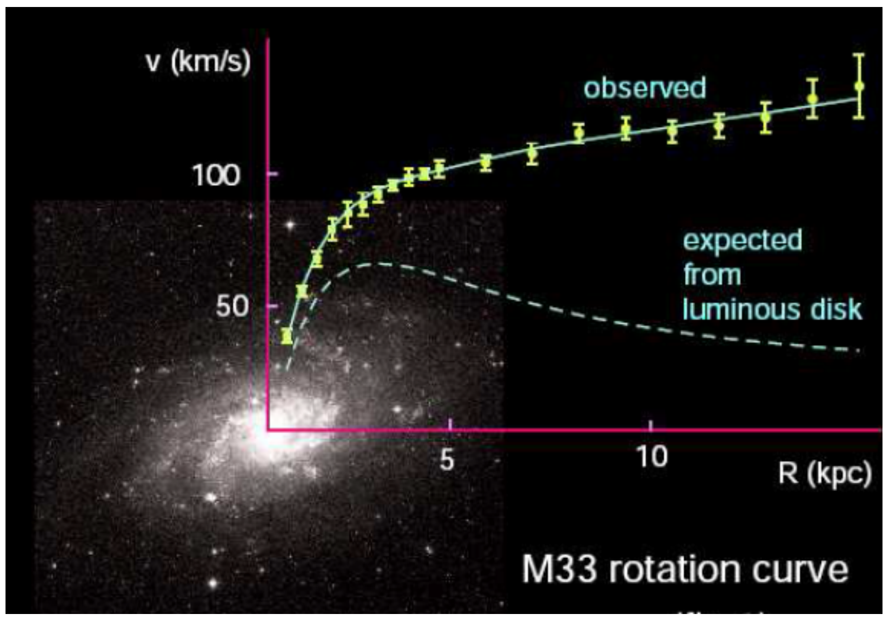
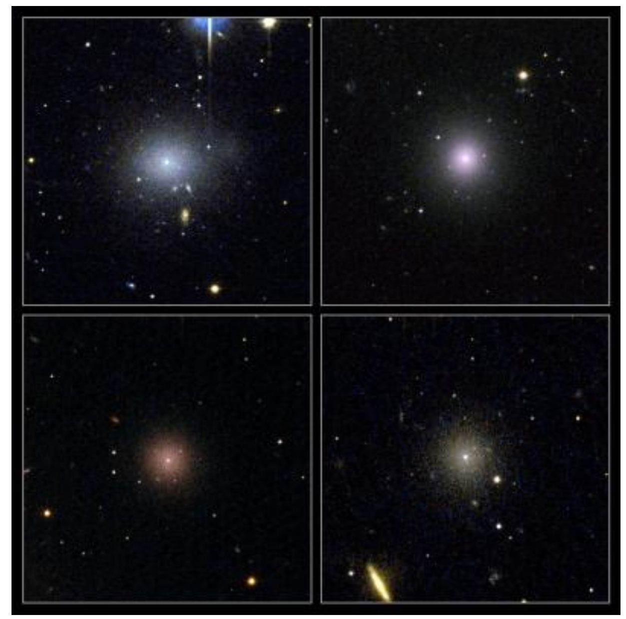
Evidence for Dark Matter

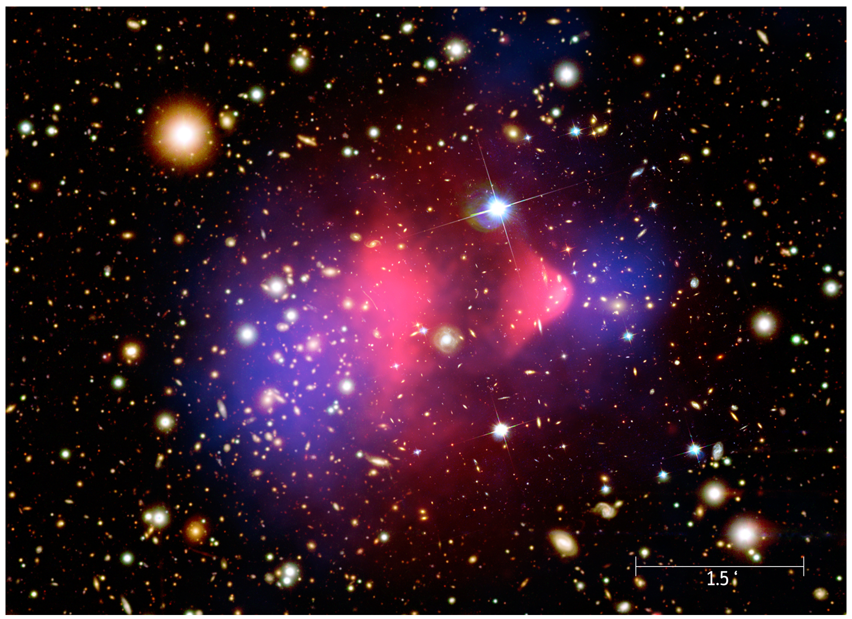
Galaxy rotation curves



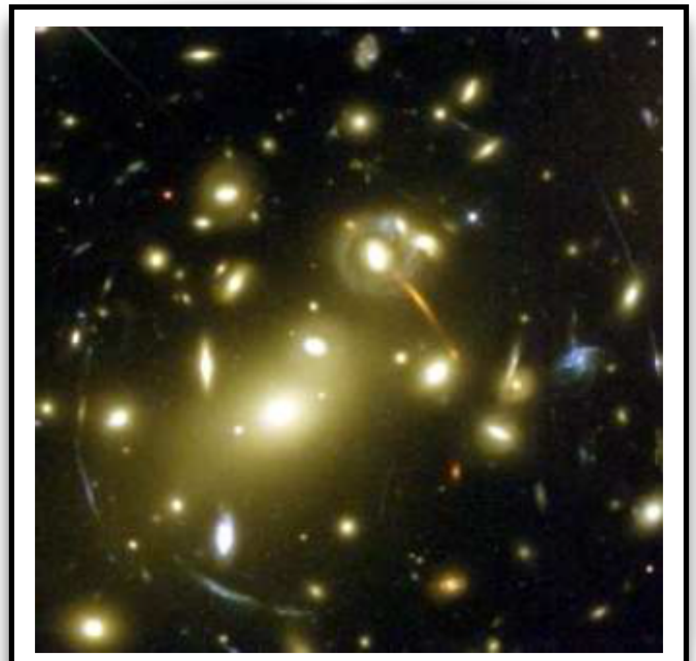
Dwarf galaxies



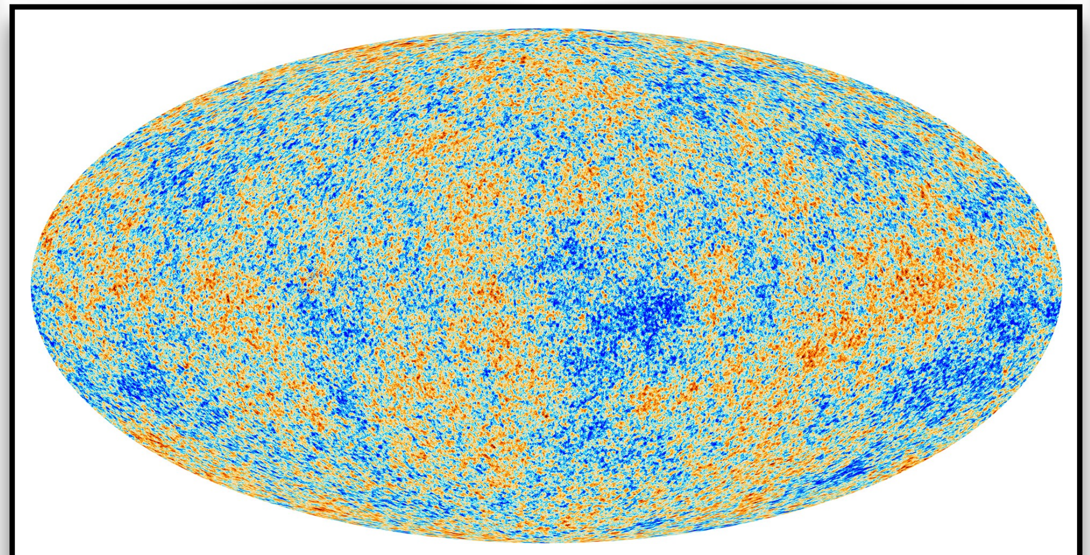
Galaxy clusters



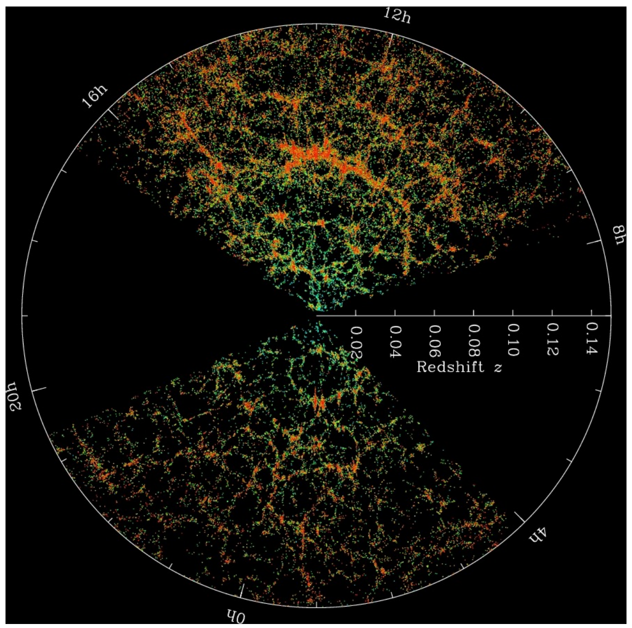
Gravitational lensing



Cosmic Microwave Background

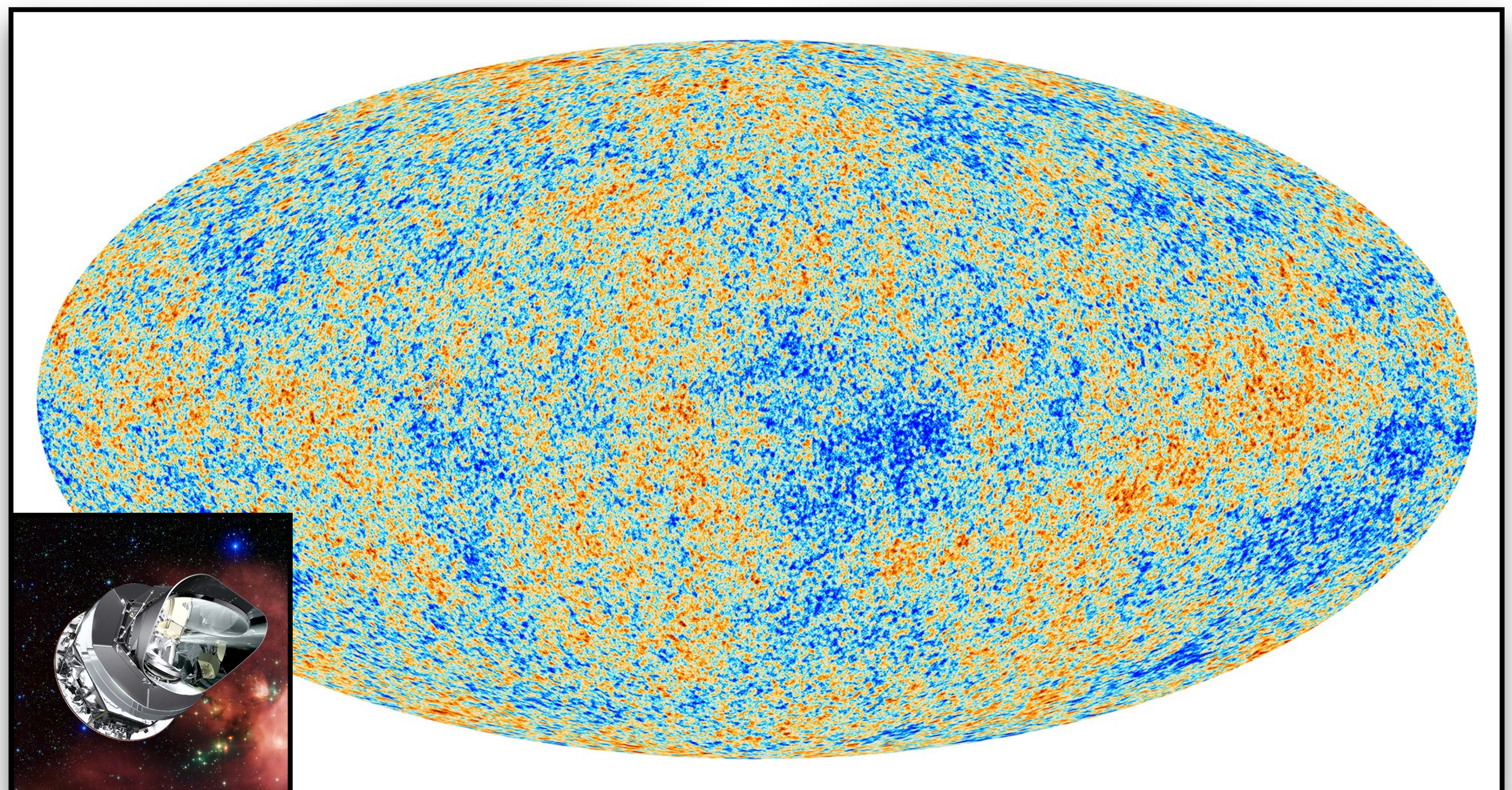


Large Scale Structure

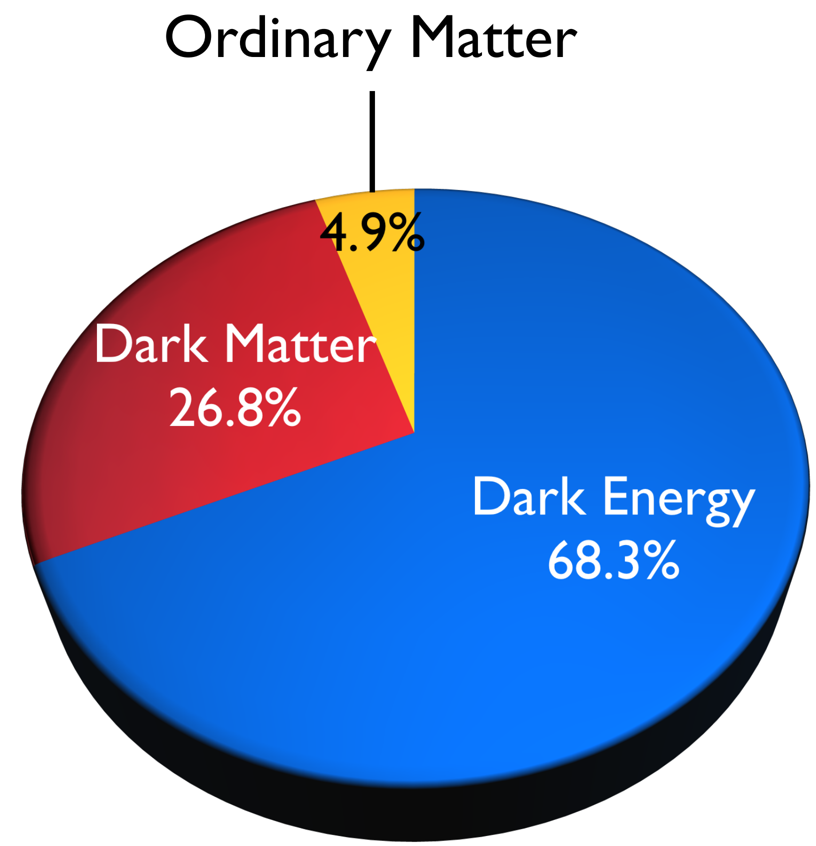


Cosmic Microwave Background

Measurements of temperature fluctuations in the CMB provide a precise determination of the Dark Matter (DM) density in the Universe.



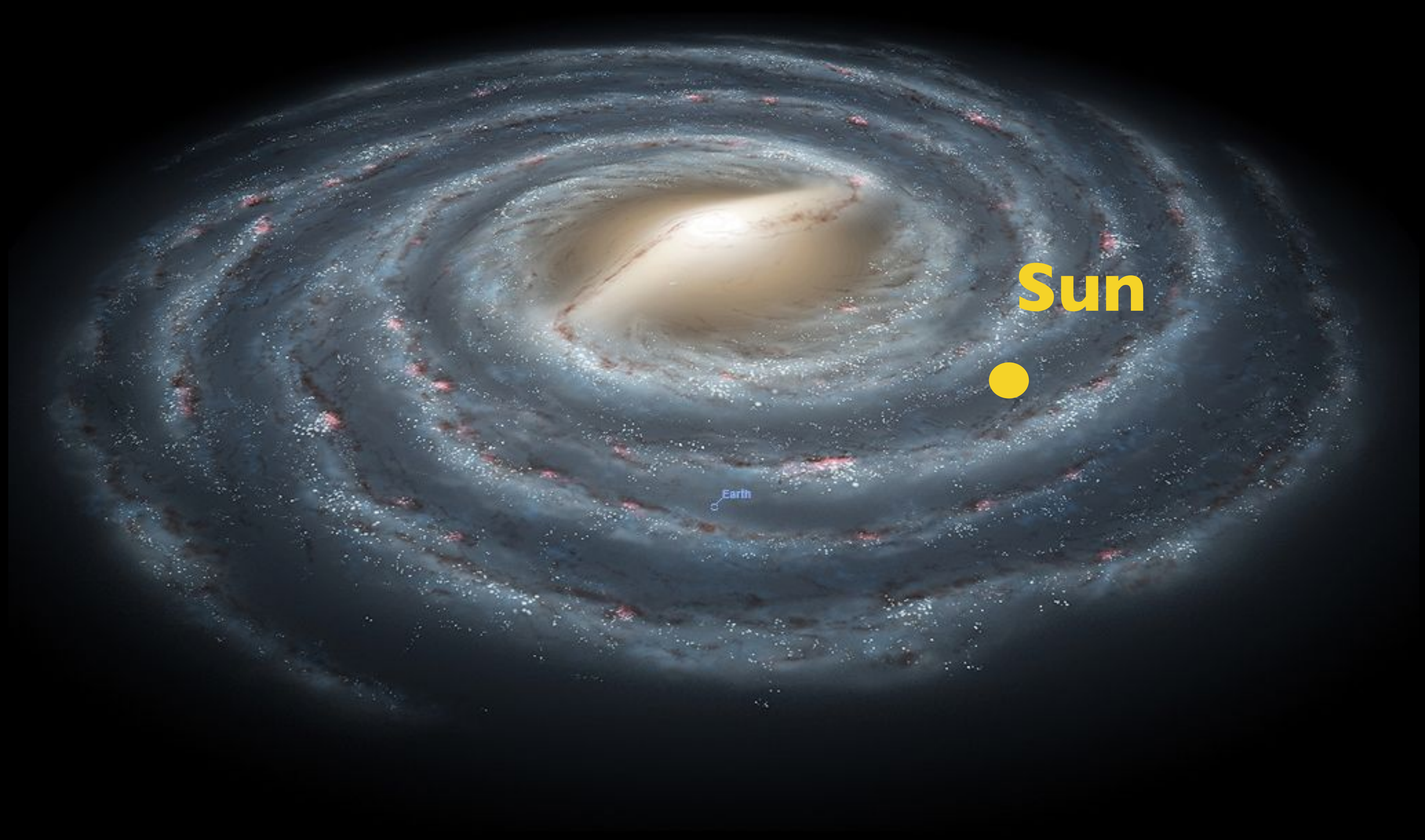
Planck 2015



Our simulated Universe

Dark Matter distribution

Signals in direct and indirect DM searches strongly depend on the DM distribution in the Milky Way (MW).



Dark Matter distribution

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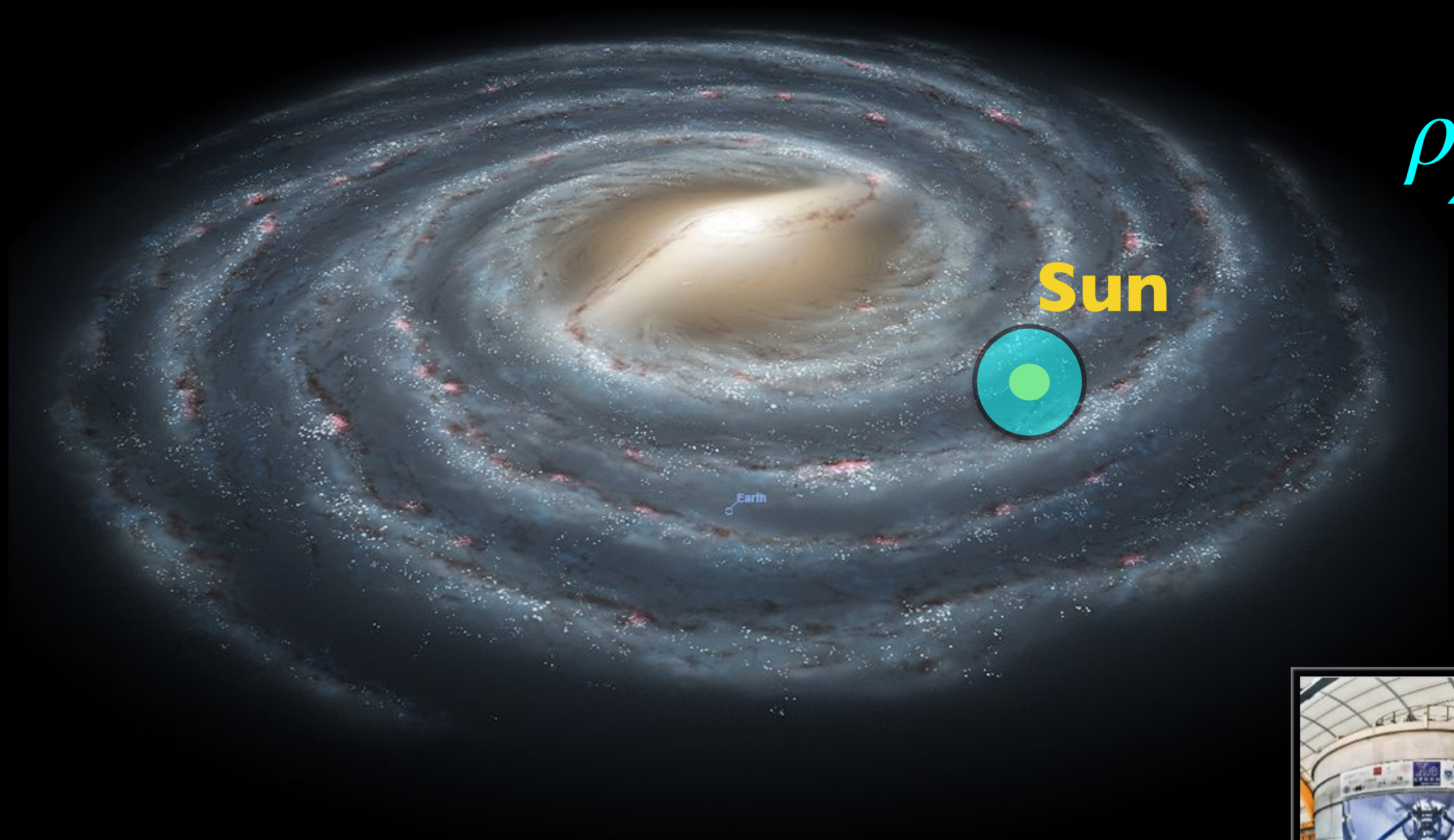
Direct Detection

$$\rho_\chi \ , \ f(\mathbf{v})$$



Dark Matter distribution

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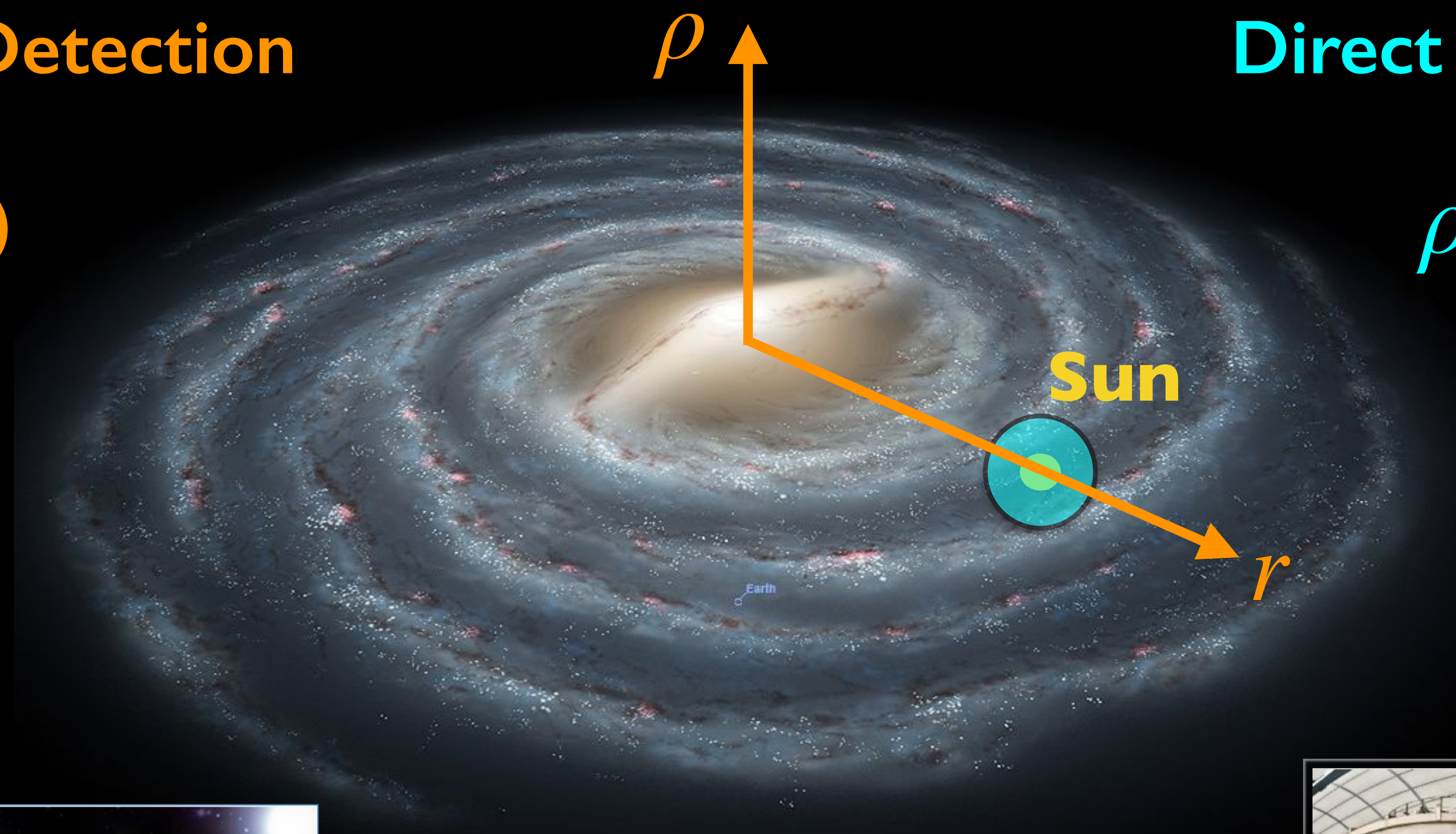
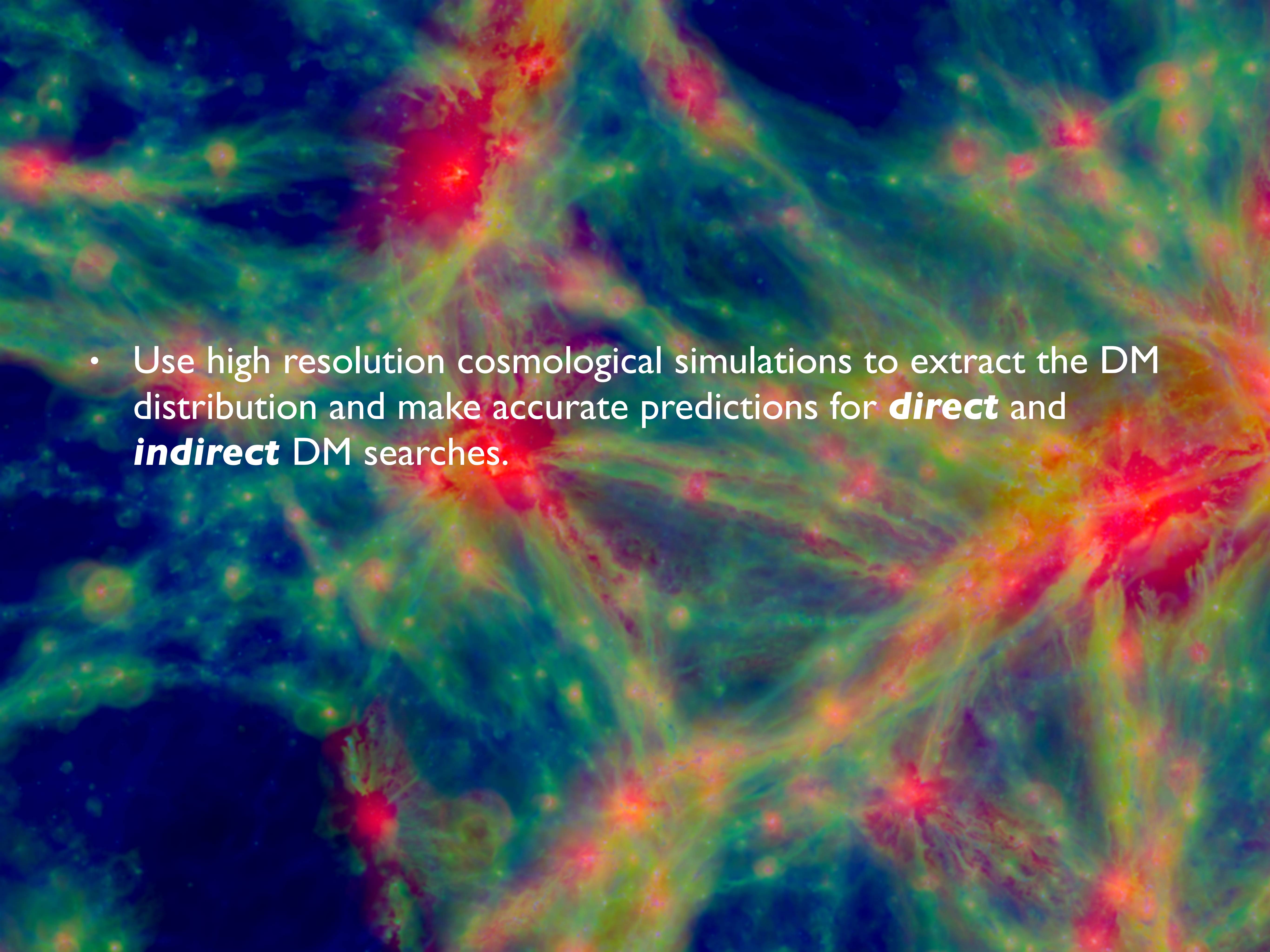
Indirect Detection

$\rho(r)$



Direct Detection

$\rho_\chi \; , \; f(\mathbf{v})$

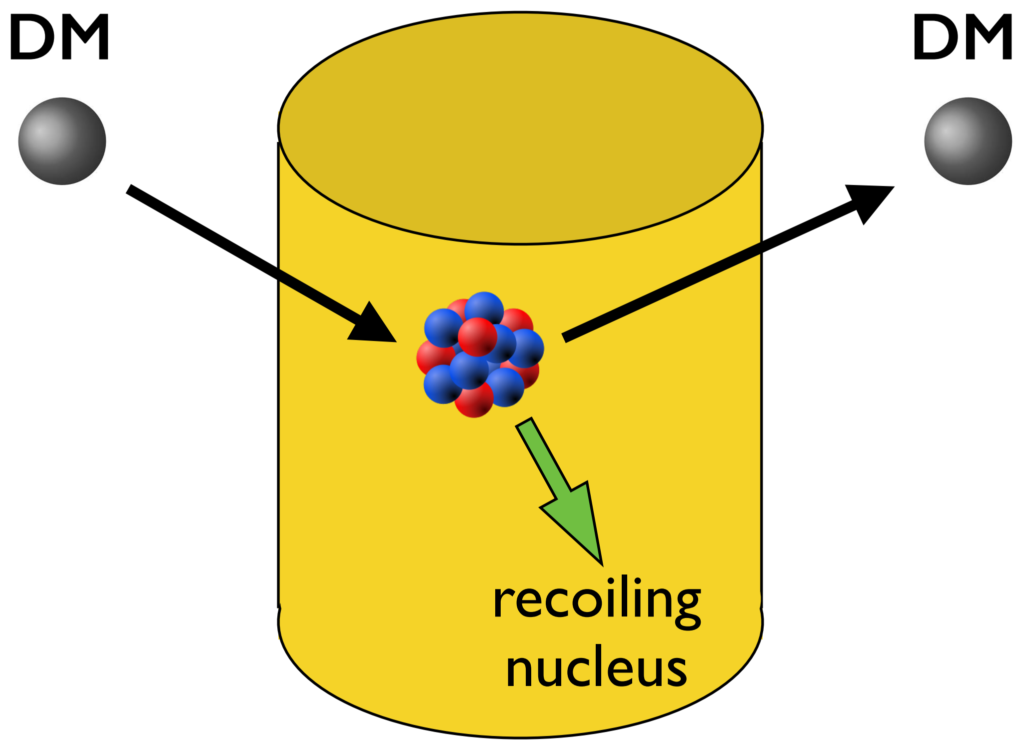


- Use high resolution cosmological simulations to extract the DM distribution and make accurate predictions for ***direct*** and ***indirect*** DM searches.

Prospects for direct DM searches

Dark Matter direct detection

- Search for DM by measuring the recoil energy of a nucleus in an underground detector after collision with a DM particle.



- Elastic recoil energy:

$$E_R = \frac{2\mu_{\chi N}^2 v^2}{m_N} \cos^2\theta$$

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

$$v_{\rm min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Direct detection event rate

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

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

Direct detection event rate

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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 event rate

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astrophysics

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

$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{m_N}{2\mu_{\chi N}^2 v^2} \sigma_0 \, F^2(E_R)$$

Direct detection event rate

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astrophysics

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astrophysics

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

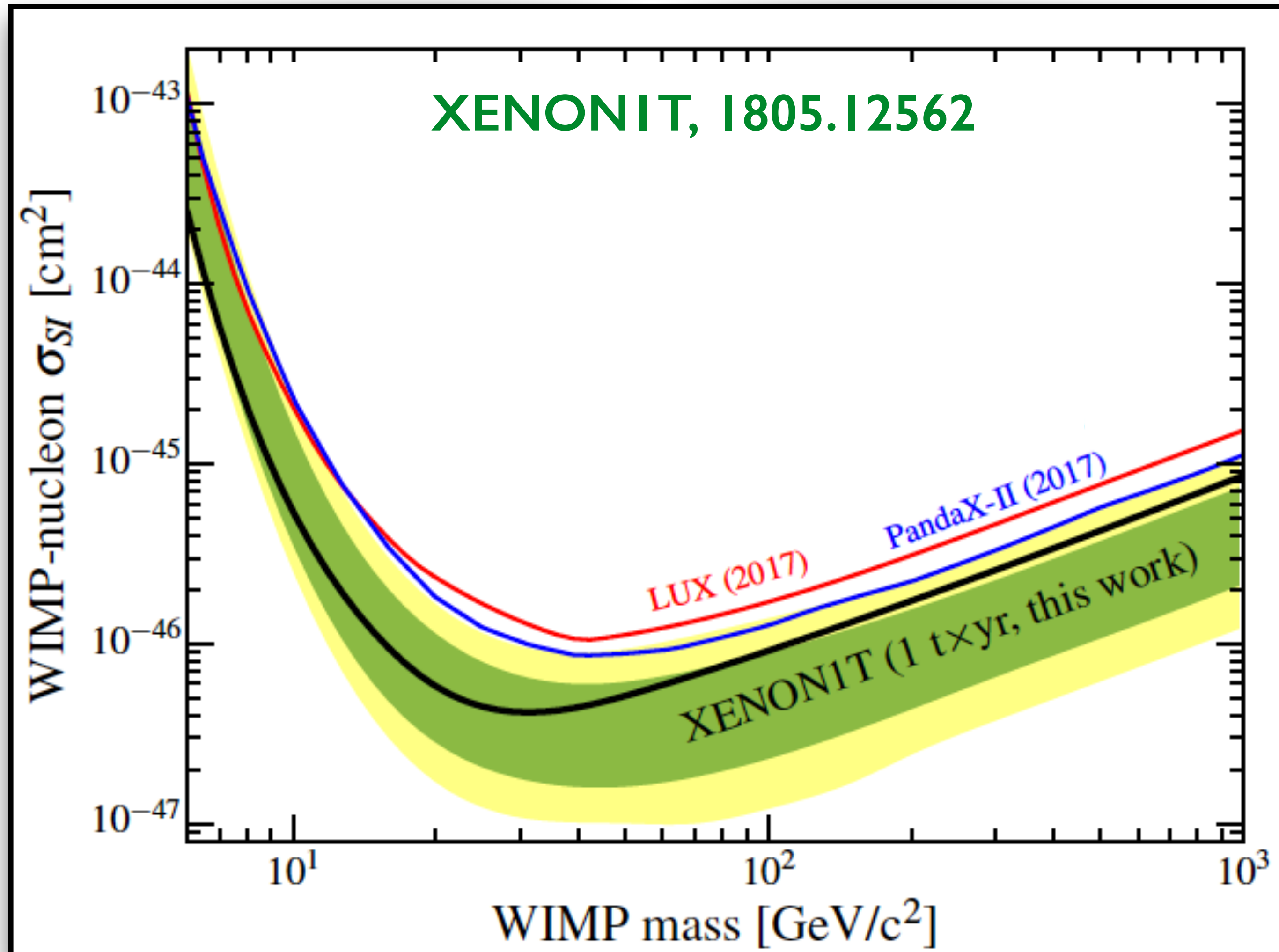
particle physics

where

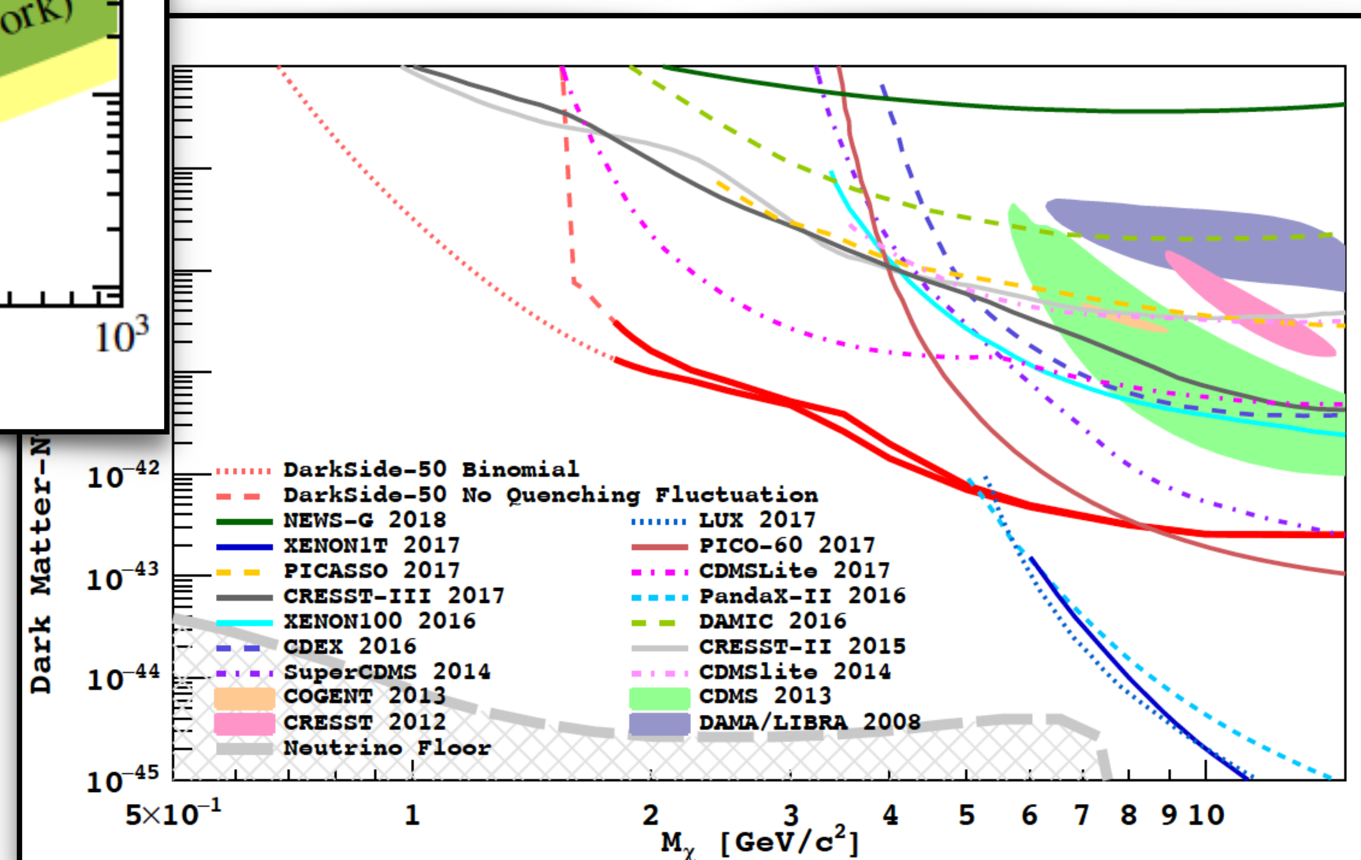
$$\eta(v_{\rm min}, t) \equiv \int_{v>v_{\rm min}} d^3v \, \frac{f_{\rm det}(\mathbf{v}, \mathbf{t})}{v}$$

Halo integral

Direct detection results



DarkSide-50, 1802.06994



- Assumption in these kinds of plots: **Standard Halo Model (SHM)**

Standard Halo Model

- The simplest model for the DM distribution in our Galaxy is the ***Standard Halo model***: isothermal sphere with an isotropic Maxwell-Boltzmann velocity distribution.

Drukier, Freese, Spergel, 1986

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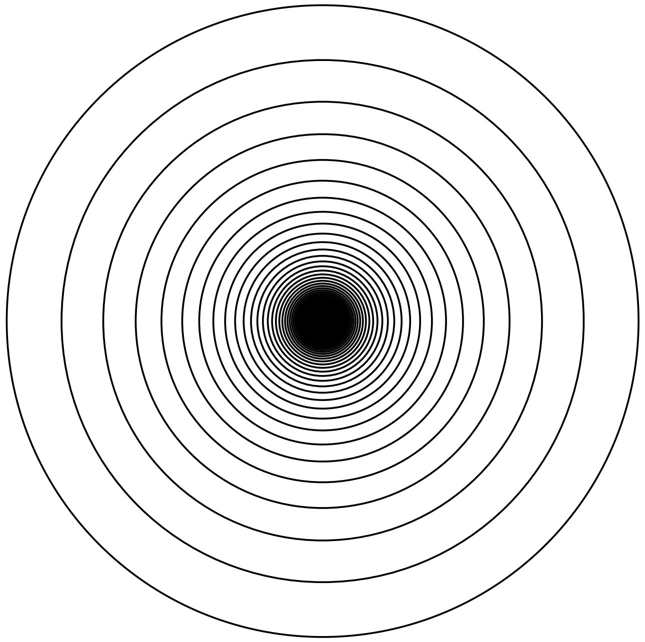
Drukier, Freese, Spergel, 1986

  - Hydrostatic equilibrium: pressure balances gravitational potential
  - Density profile: $\rho(r) \propto r^{-2}$
  - Local DM density: 0.3 GeV/cm^3
  - Typical DM speed: 220 km/s

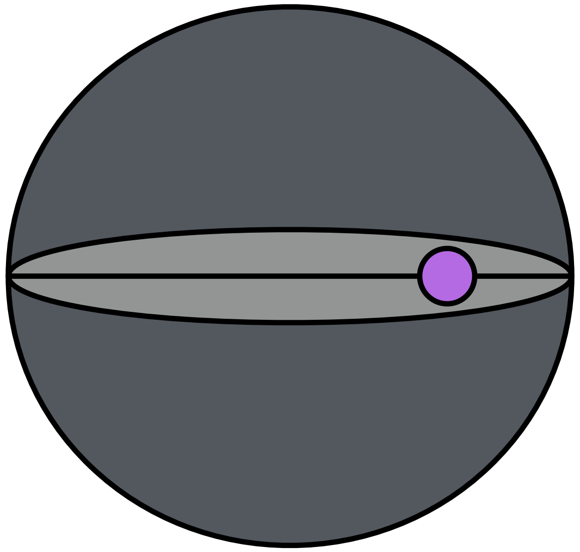


- Actual DM distribution may ***deviate substantially*** from the SHM.

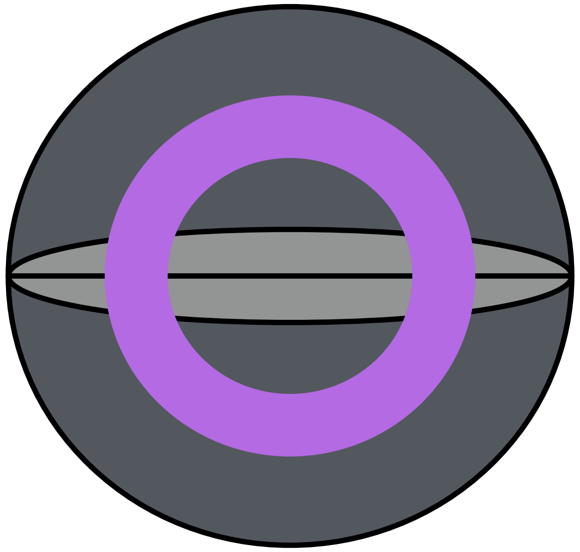
Local Dark Matter density

From observations:

- **Local estimates:** use kinematical data from a nearby population of stars.
  - Robust measurements, but need to account for the local contribution of baryons which has significant uncertainties. → *large error bars*



- **Global estimates:** based on mass modeling of the MW, and fits to kinematical data across the Galaxy.
  - Good precision (~10%), but estimates are strongly model dependent. → *systematic uncertainties*



Local Dark Matter density

How well we know it:

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

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- Some recent local estimates:

$$\rho_\chi = 0.46^{+0.07}_{-0.09}\ \mathrm{GeV/cm^3}$$ **Sivertsson et al., 1708.07836,** *with SDSS*

$$\rho_\chi = 0.69 \pm 0.08\ \mathrm{GeV/cm^3}$$ **Hagen & Helmi, 1802.09291,** *with TGAS & Rave*

$$\rho_\chi = 0.874 \pm 0.380\ \mathrm{GeV/cm^3}$$ **Buch, Leung, Fan, 1808.05603,** *with Gaia DR2*

- Estimates affected by systematic uncertainties.

Local DM velocity distribution

- The velocity distribution depends on the halo model.
- In the **SHM**, a truncated Maxwellian velocity distribution is assumed:

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

with $v_c = 220 \text{ km/s}$ and $v_{\rm esc} = 550 \text{ km/s}$.

$\sigma_v = \sqrt{3/2}\, v_c$ independent of radius.

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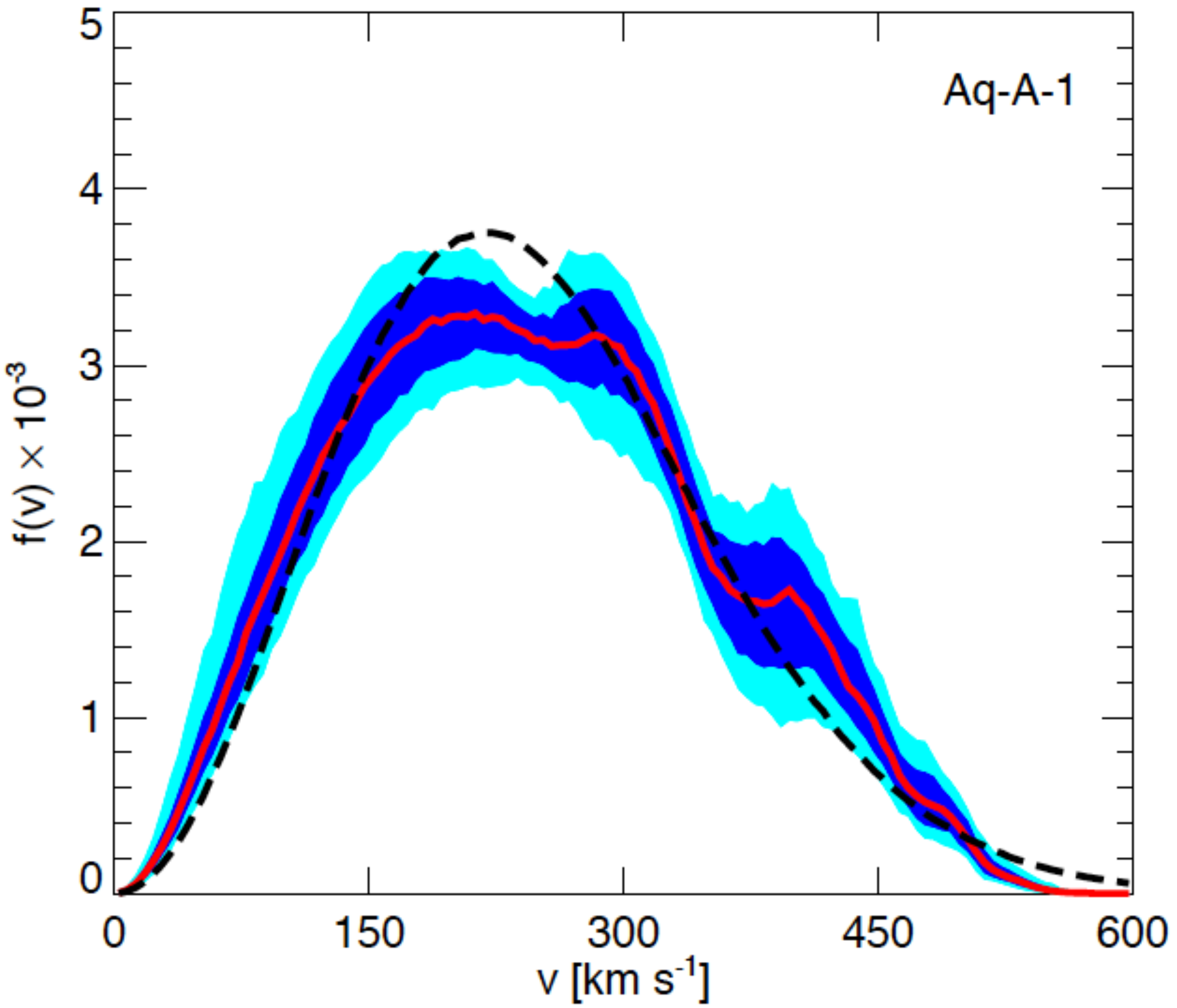
- What can we learn from numerical simulations of galaxy formation about the local DM velocity distribution?

Dark Matter only simulations

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



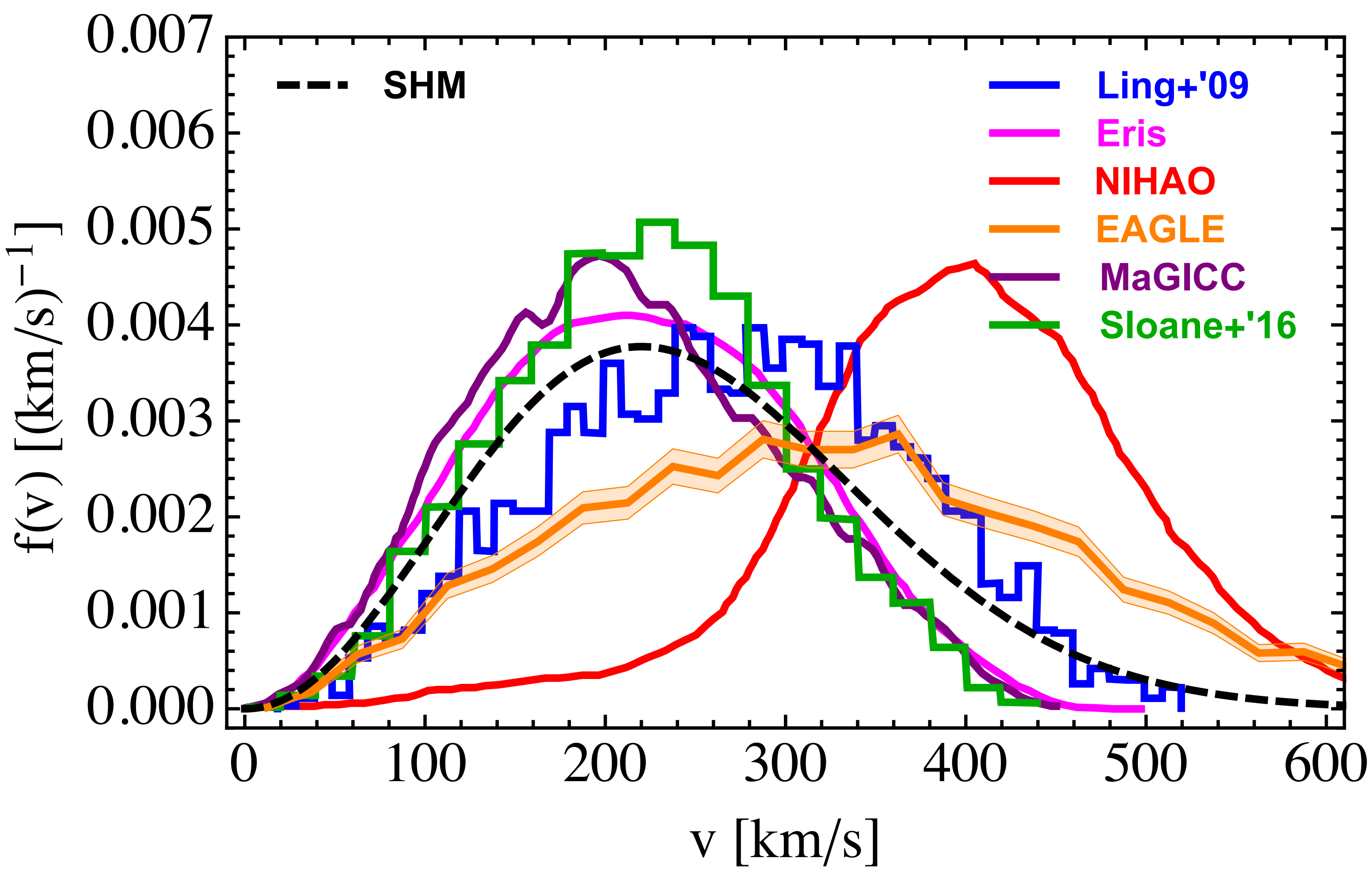
$$f(|\mathbf{v}|) = v^2 \int d\Omega_{\mathbf{v}} f(\mathbf{v})$$

Vogelsberger et al., 0812.0362

- *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, 1705.05853

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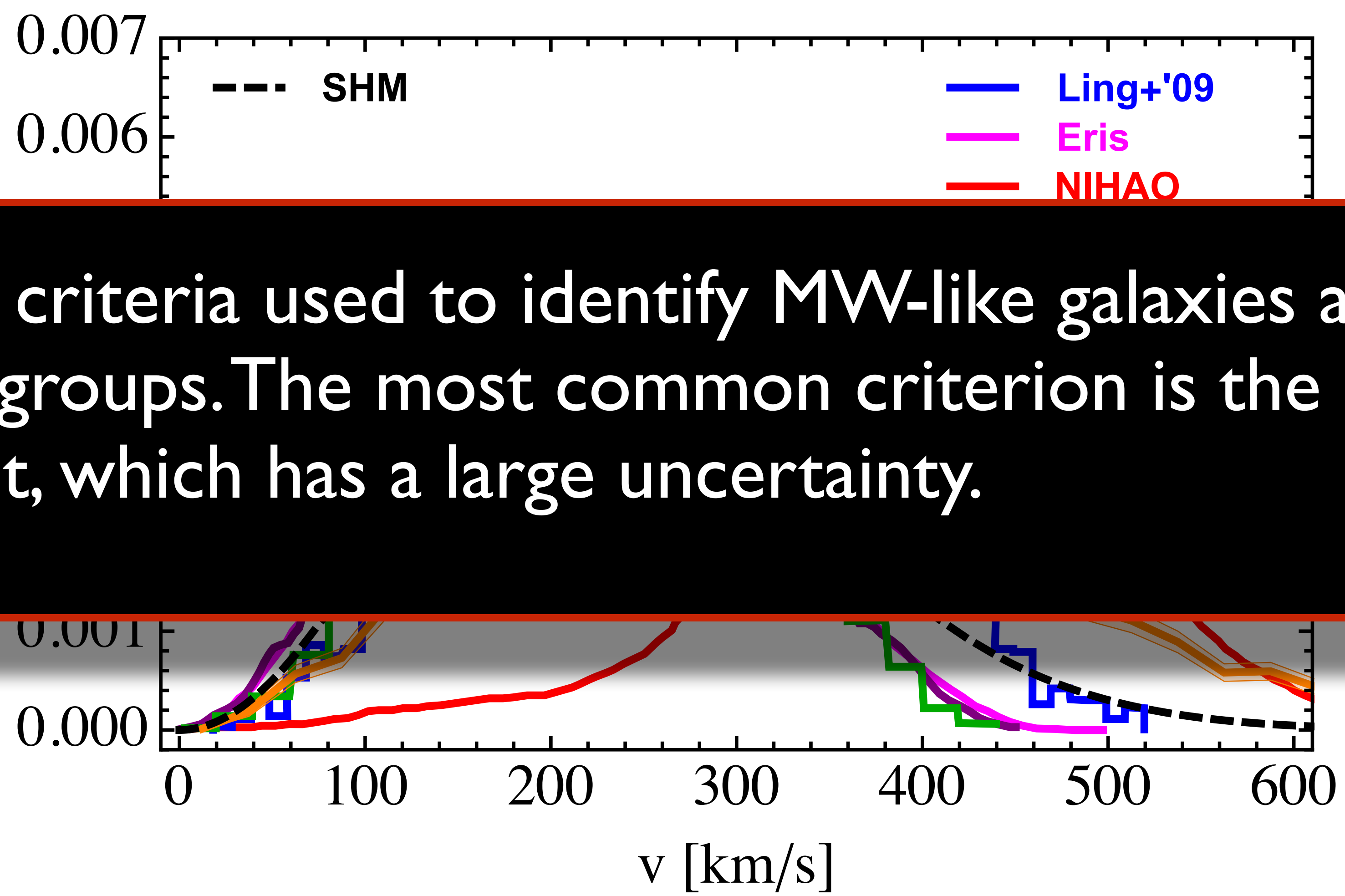

Different criteria used to identify MW-like galaxies among different groups. The most common criterion is the MW mass constraint, which has a large uncertainty.

Bozorgnia & Bertone, 1705.05853

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

Hydrodynamical simulations

- To make precise quantitative predictions:
  - Model baryonic processes in a way that the main galaxy population properties are broadly reproduced.
  - Identify MW-like galaxies by taking into account *observational constraints on the MW*.

Hydrodynamical simulations

- We use the **EAGLE** and **APOSTLE** hydrodynamic simulations.

Name	L (Mpc)	N	m_g (M_{sun})	m_{DM} (M_{sun})
EAGLE HR	25	8.5×10^8	2.26×10^5	1.21×10^6
APOSTLE IR	—	—	1.3×10^5	5.9×10^5

- **APOSTLE IR**: zoomed simulations of Local Group-analogue systems, comparable in resolution to **EAGLE HR**.

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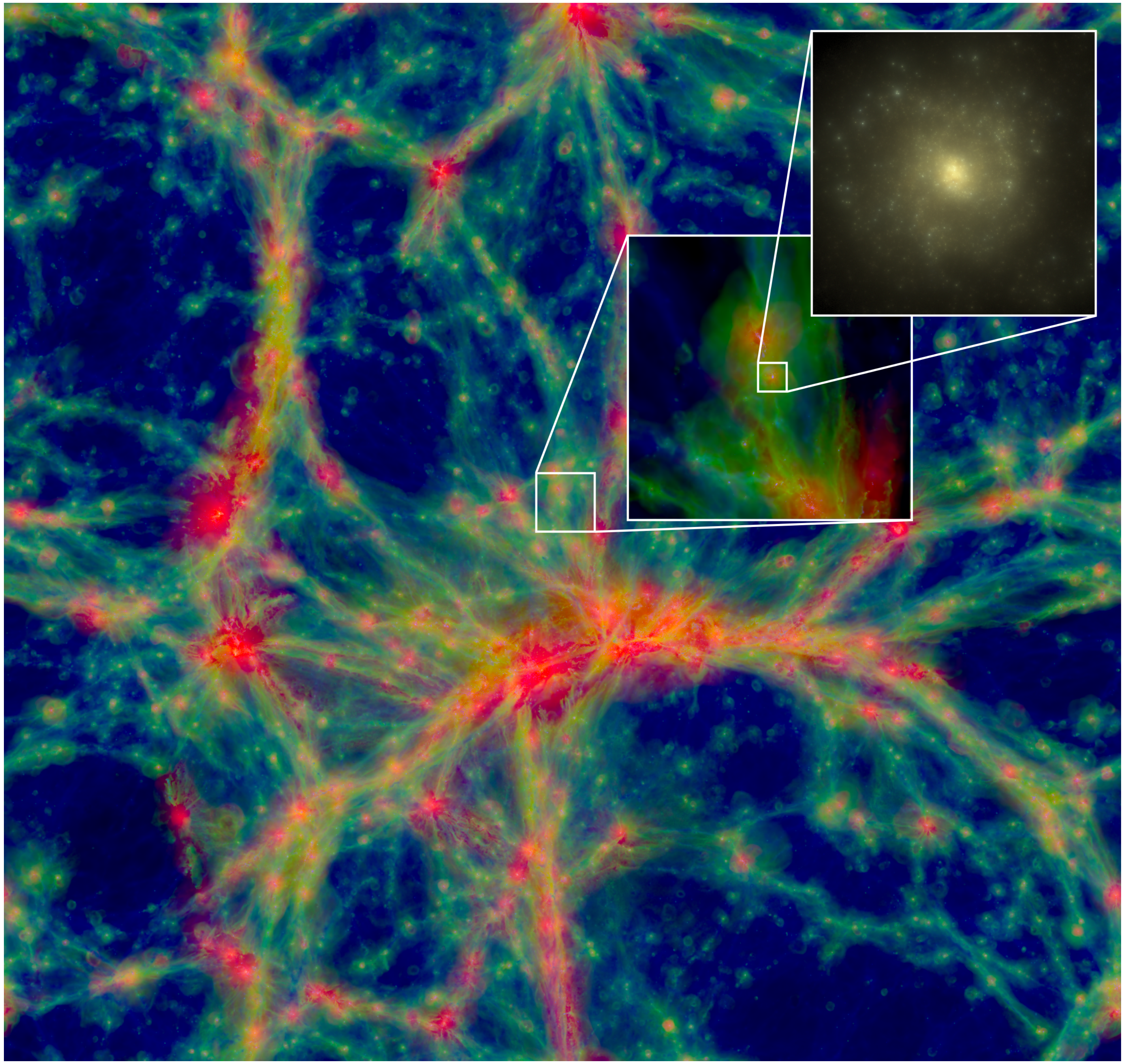
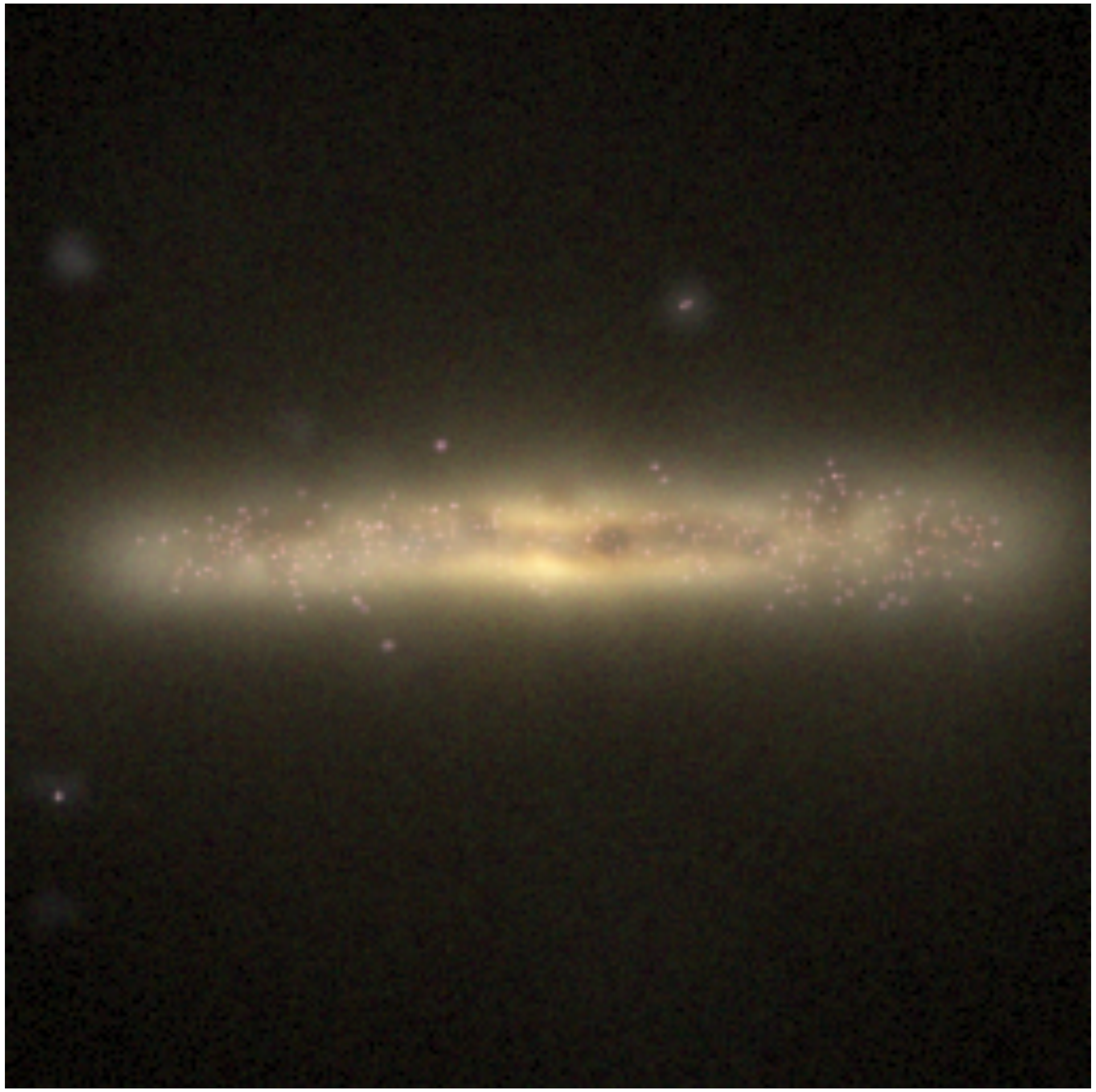
- **APOSTLE IR**: zoomed simulations of Local Group-analogue systems, comparable in resolution to **EAGLE HR**.
- *Calibrated to reproduce the observed distribution of stellar masses and sizes of low-redshift galaxies.*
- Companion Dark Matter only (DMO) simulations were run assuming all the matter content is collisionless.

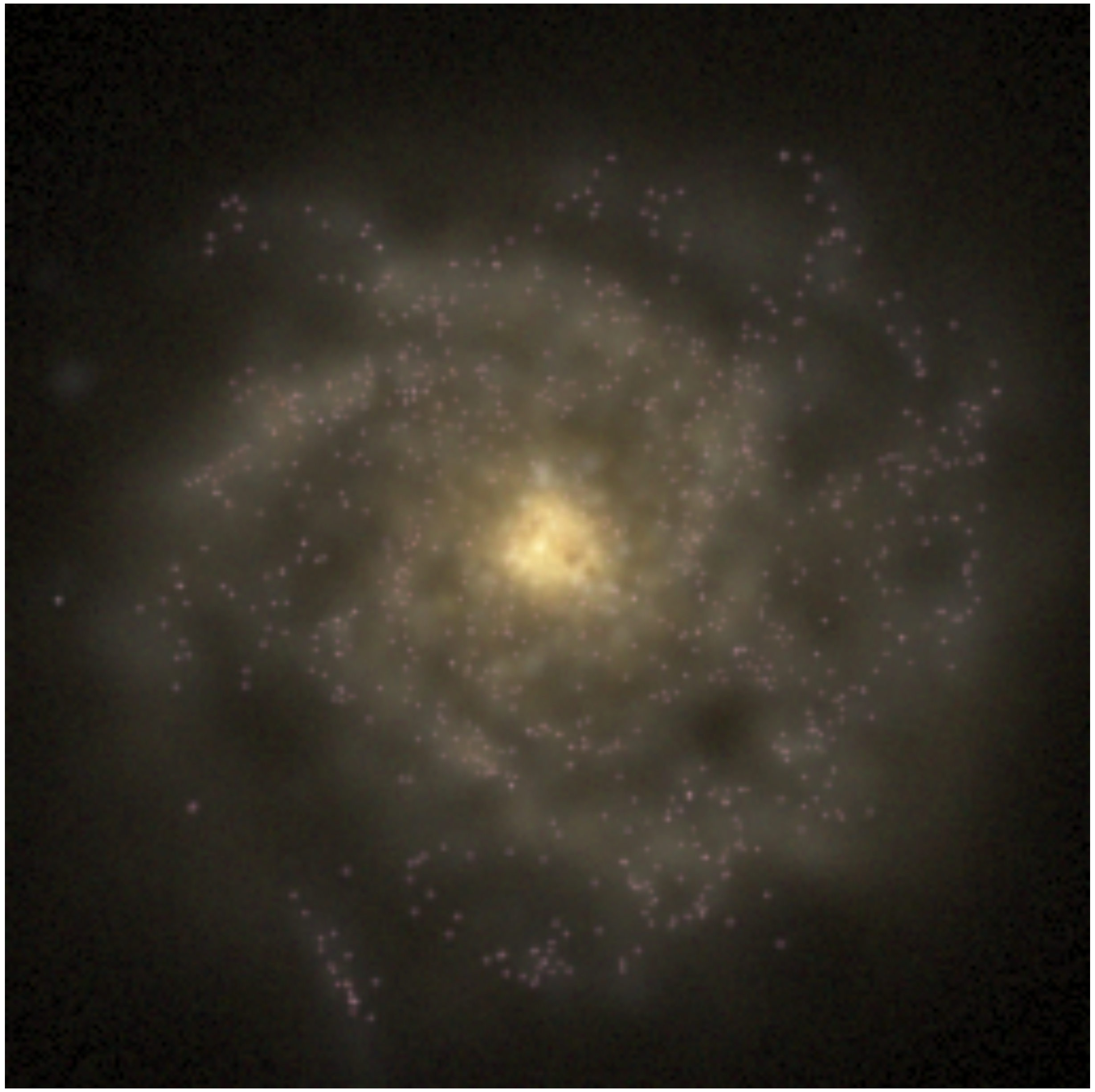
EAGLE Simulations



EAGLE Simulations, 1407.7040

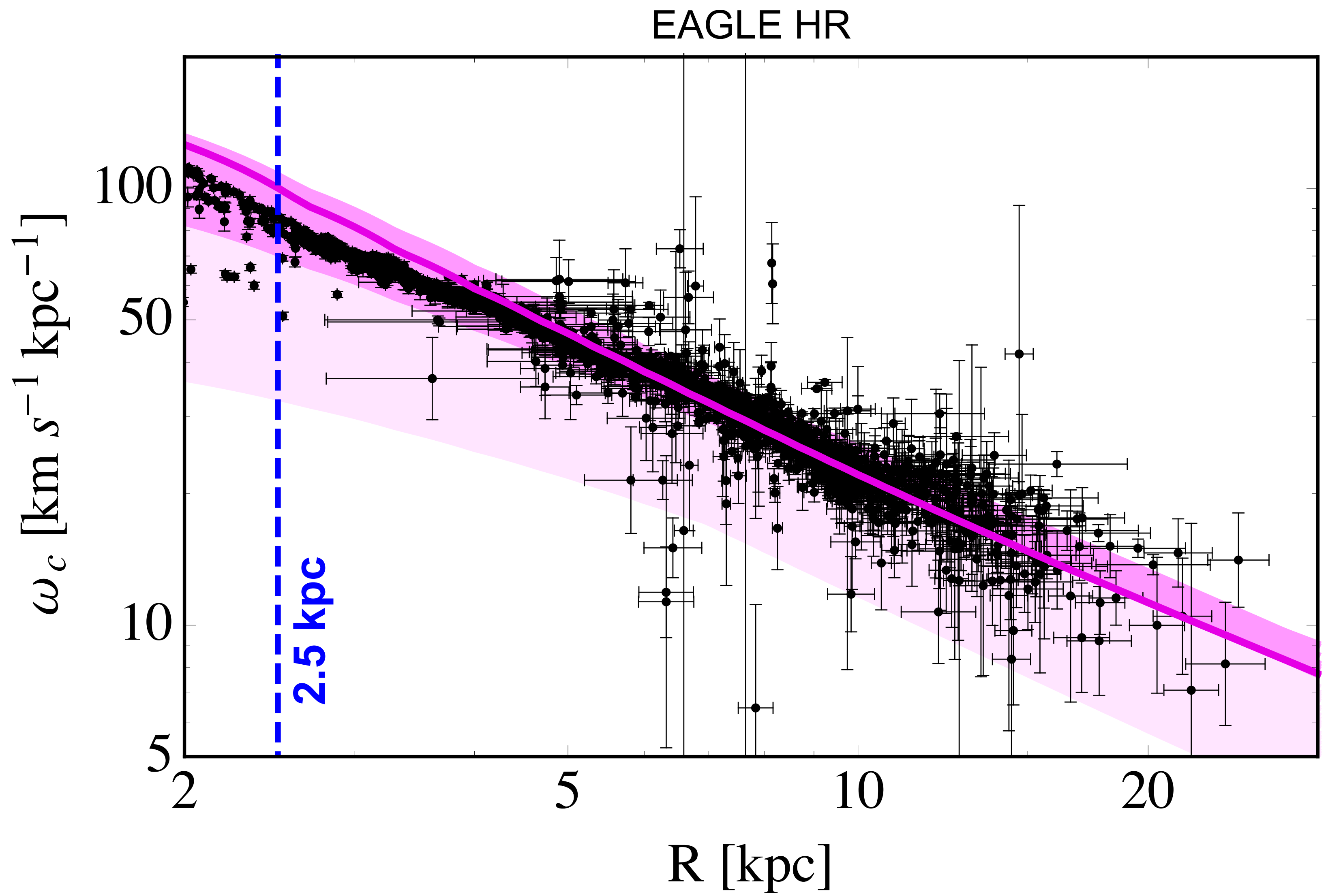
Milky Way analogues





Identifying Milky Way analogues

- Identify MW-like galaxies by taking into account observational constraints on the MW, in addition to the mass constraint: **rotation curves [Iocco, Pato, Bertone, 1502.03821], total stellar mass.**



Bozorgnia et al., 1601.04707
Calore, Bozorgnia et al., 1509.02164

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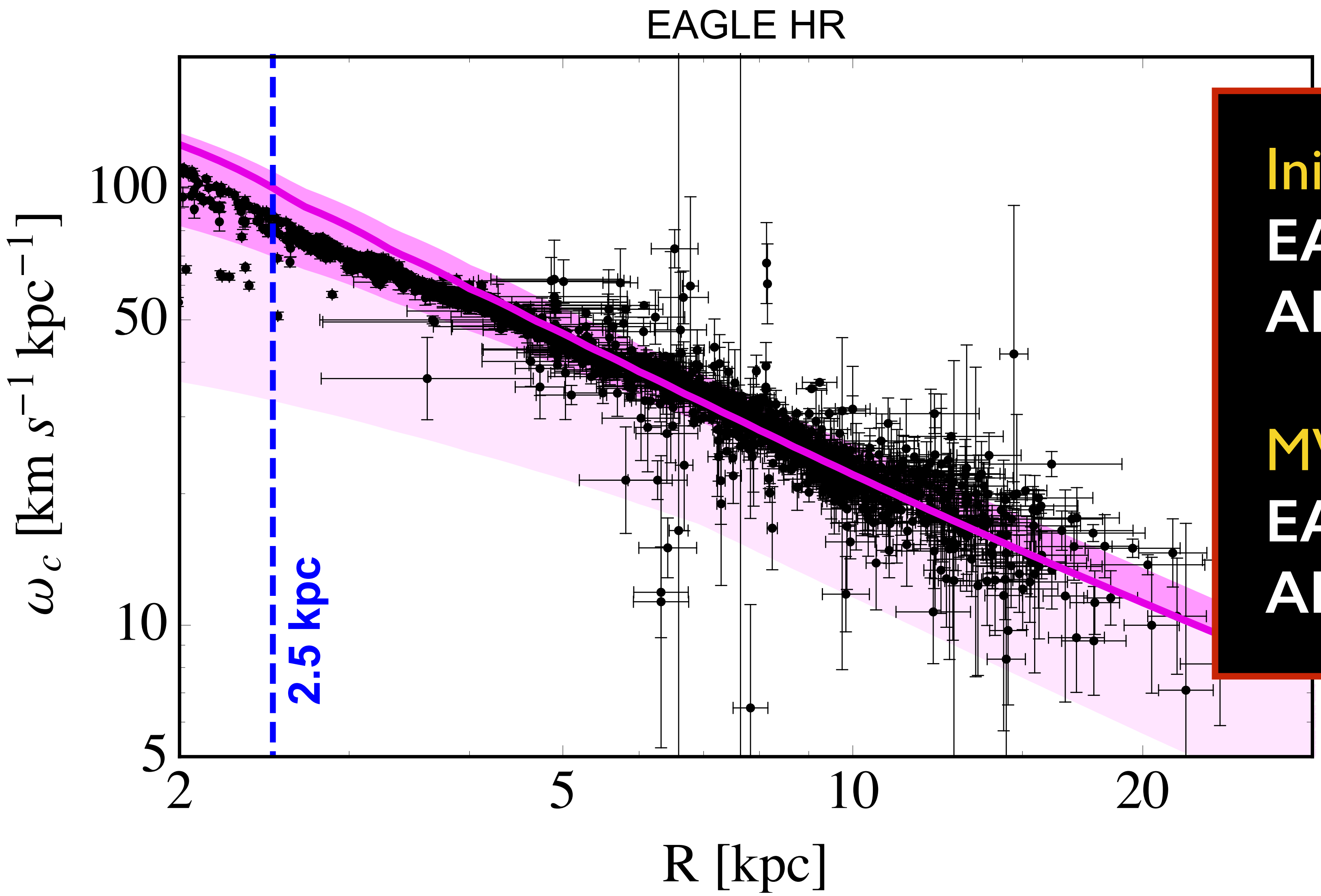


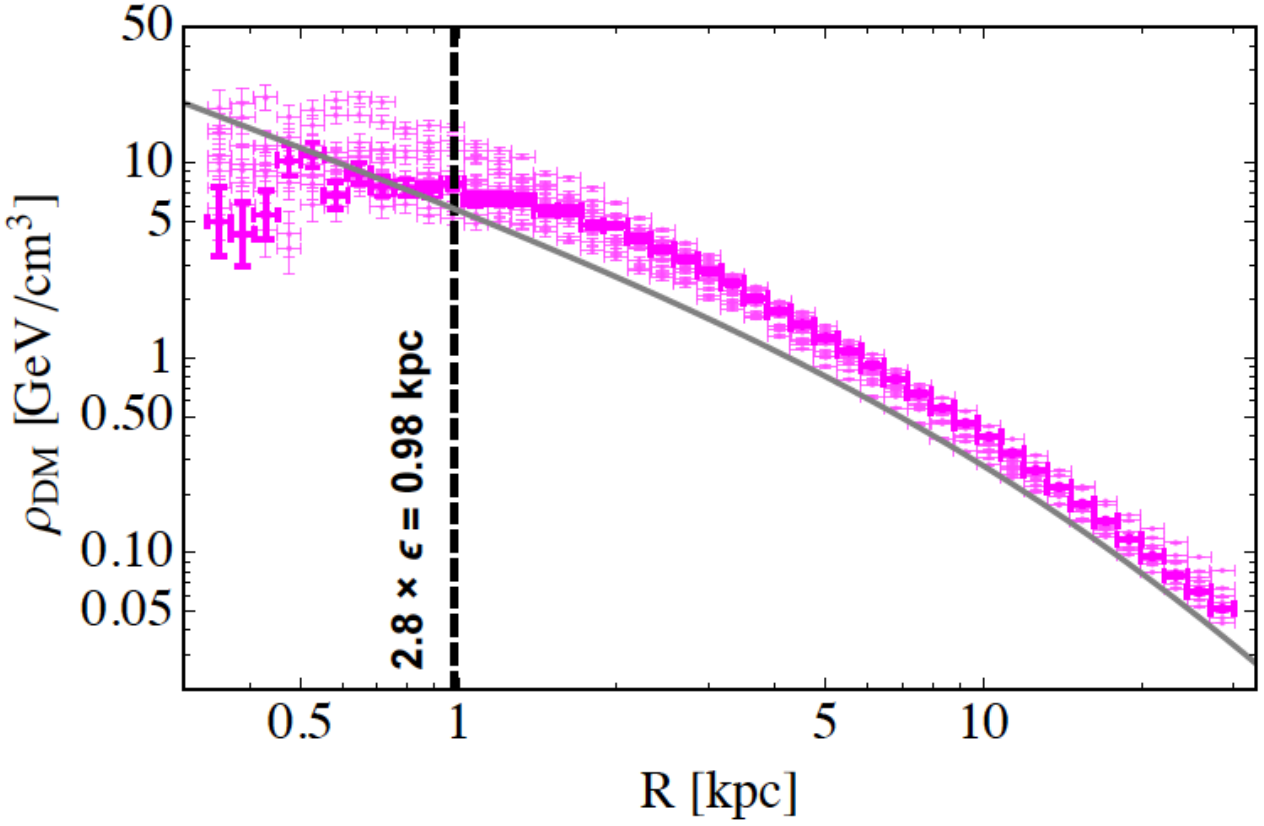
Initial haloes:
EAGLE: 61
APOSTLE: 24

MW analogues:
EAGLE: 12
APOSTLE: 2

Bozorgnia et al., 1601.04707
Calore, Bozorgnia et al., 1509.02164

Dark Matter density profiles

- Spherically averaged DM density profiles of the MW analogues:



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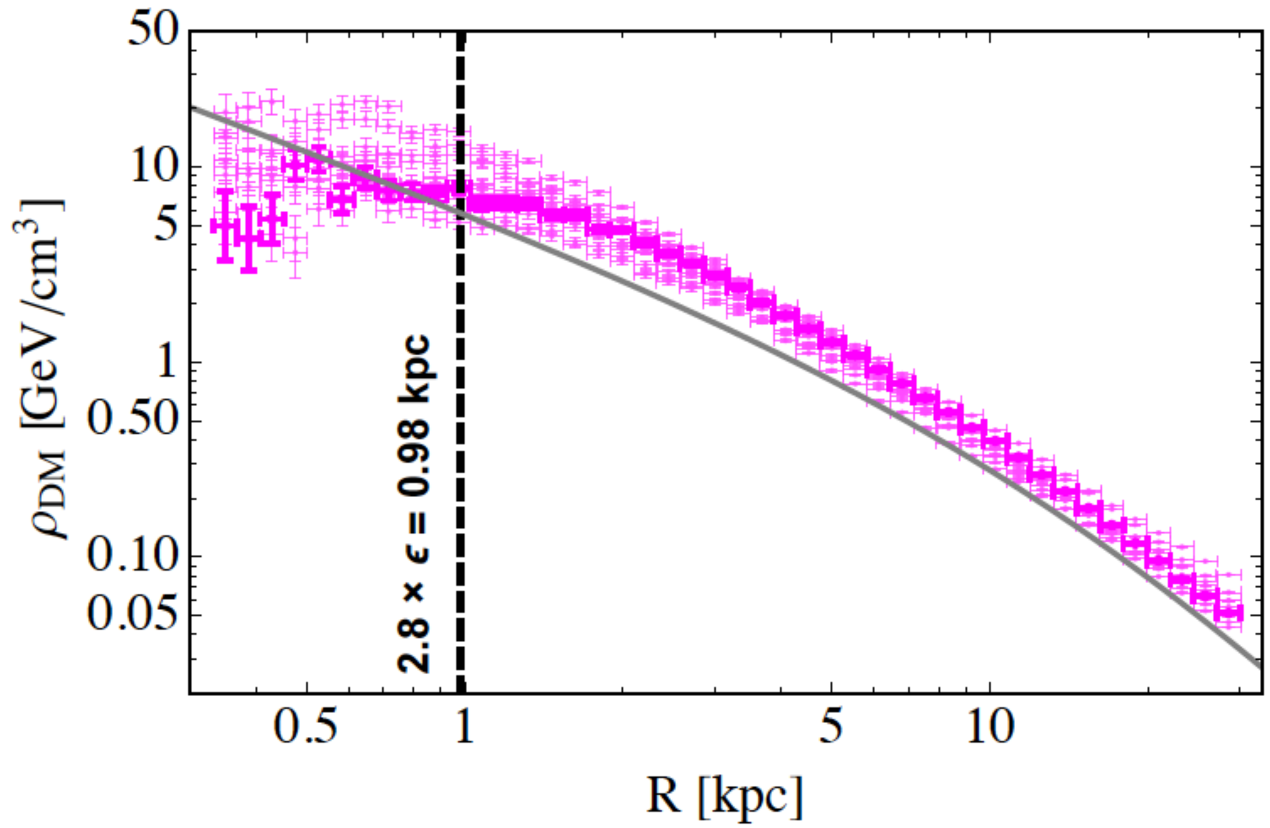
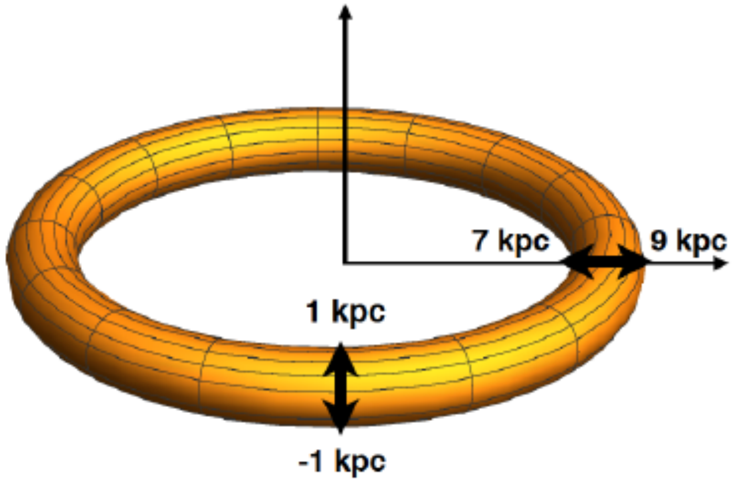


- To find the DM density at the position of the Sun, consider a torus aligned with the stellar disc.

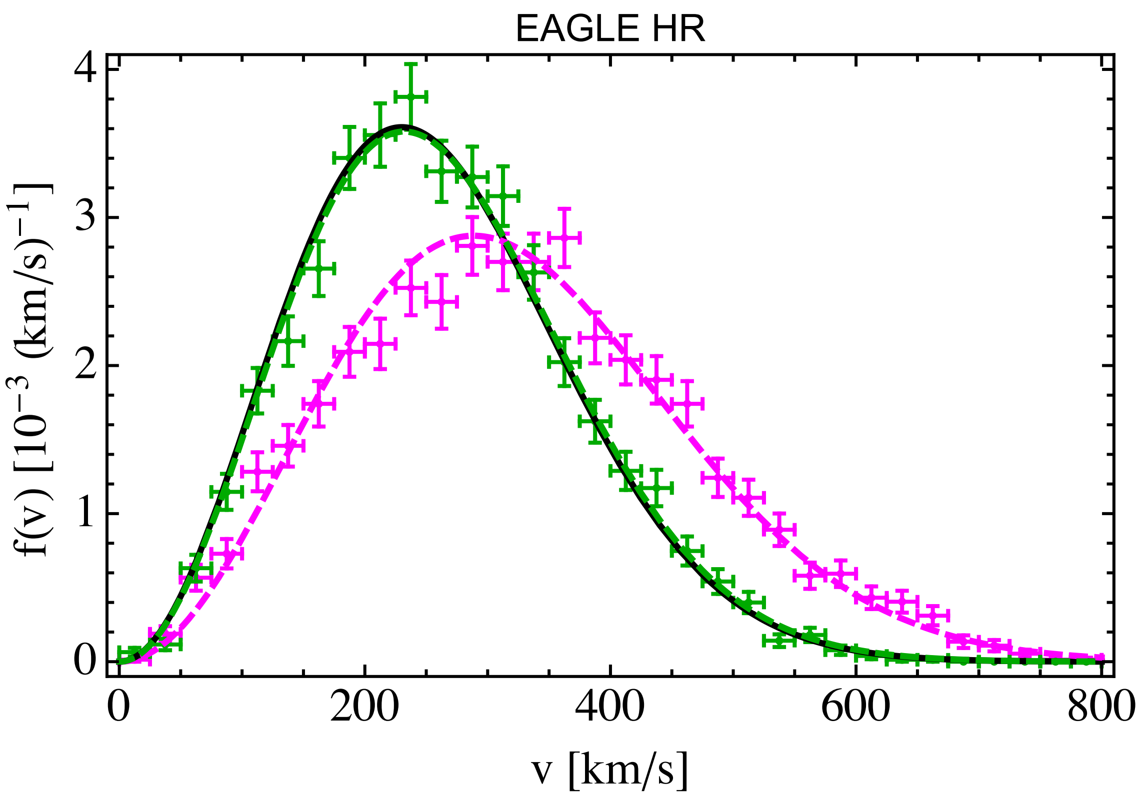


$\rho_\chi = 0.41 - 0.73$ GeV/cm^3

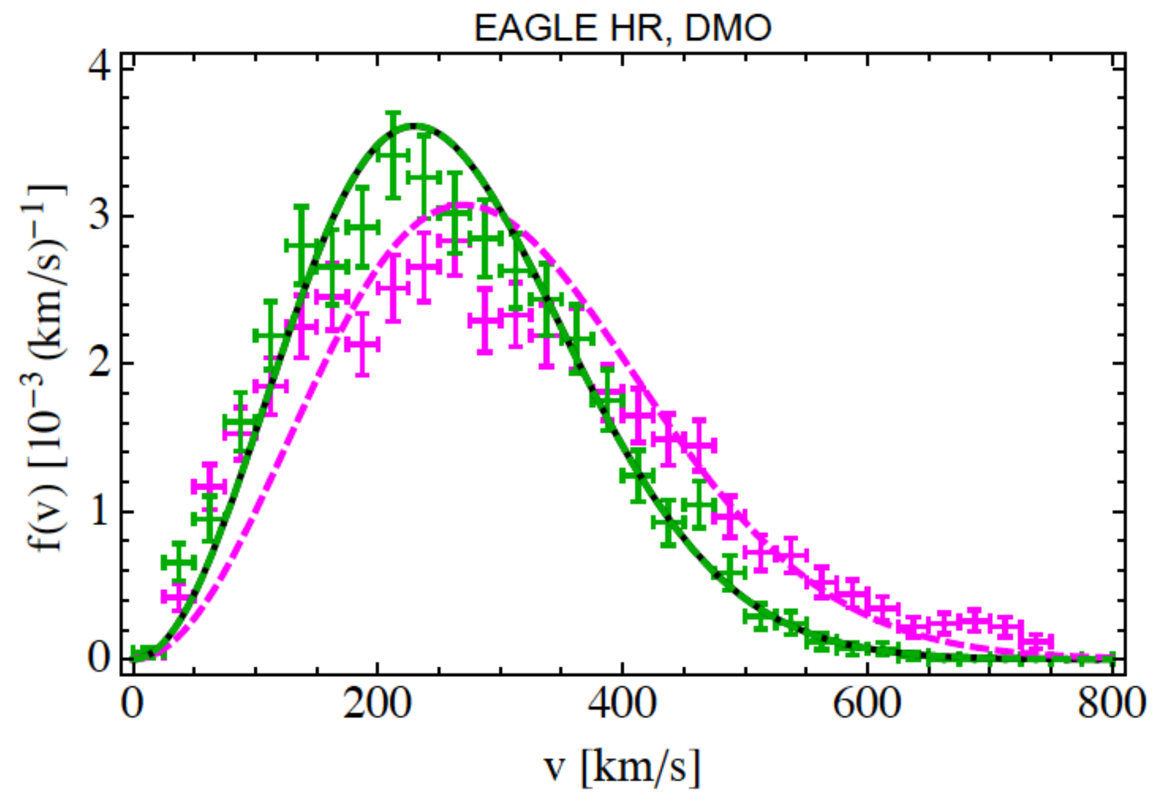
Bozorgnia et al., 1601.04707

Local speed distributions

In the galactic rest frame:



DMO simulations



Bozorgnia et al., 1601.04707

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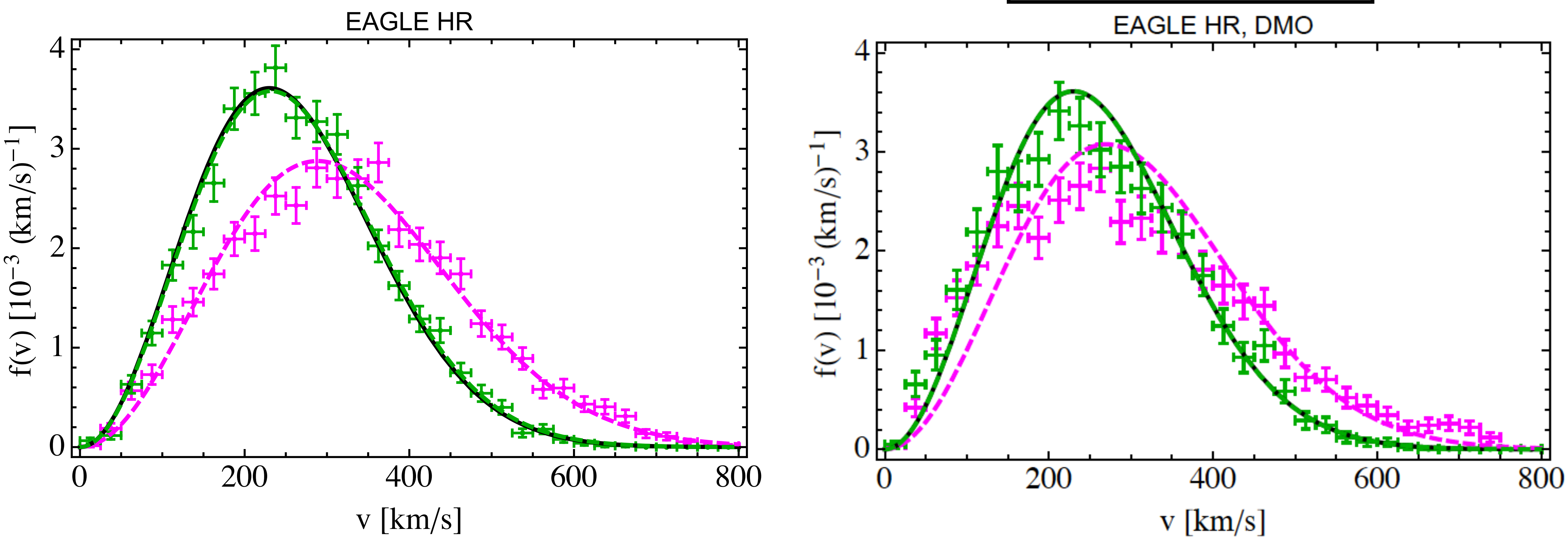


Bozorgnia et al., 1601.04707

- Maxwellian distribution with a free peak provides a better fit to haloes in the hydrodynamical simulations compared to their DMO counterparts.
- Best fit peak speed: v_{peak} = 223 - 289 km/s

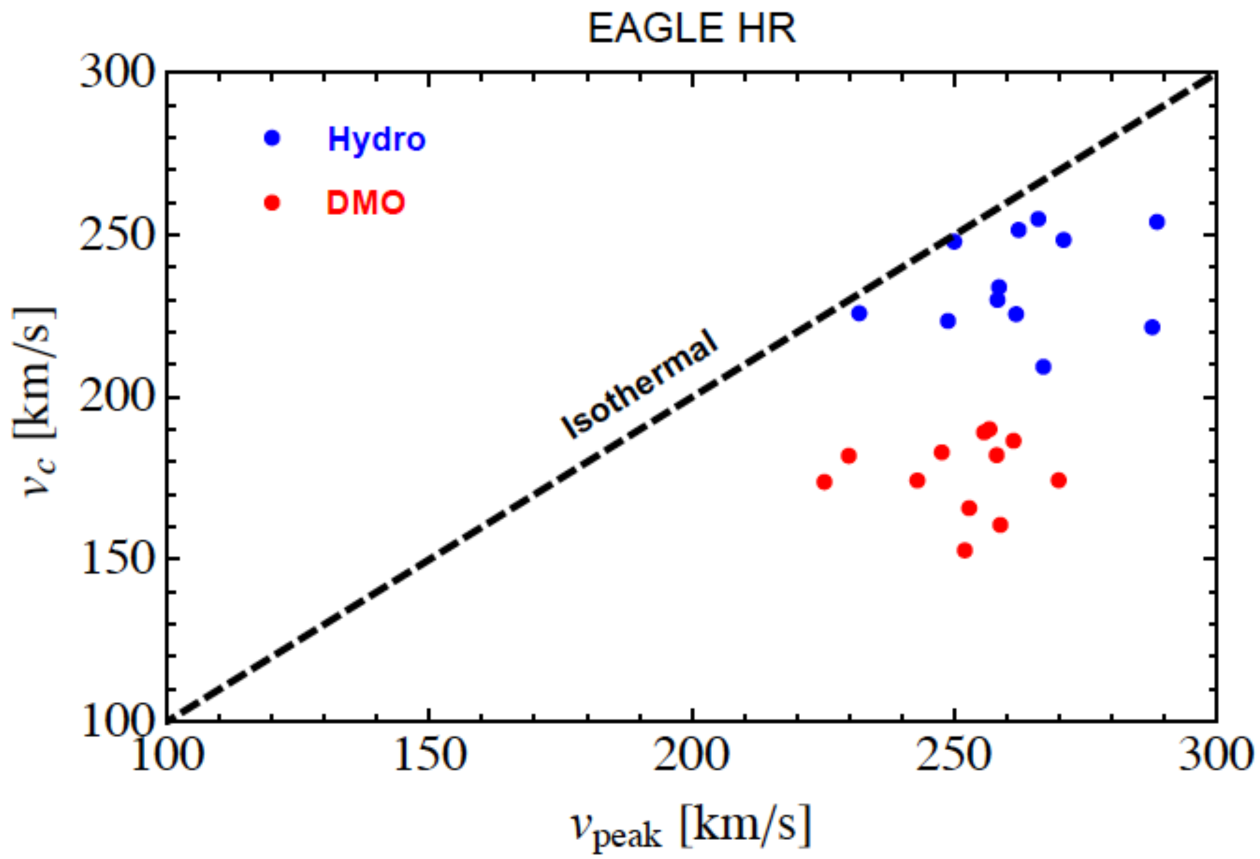
Local speed distributions

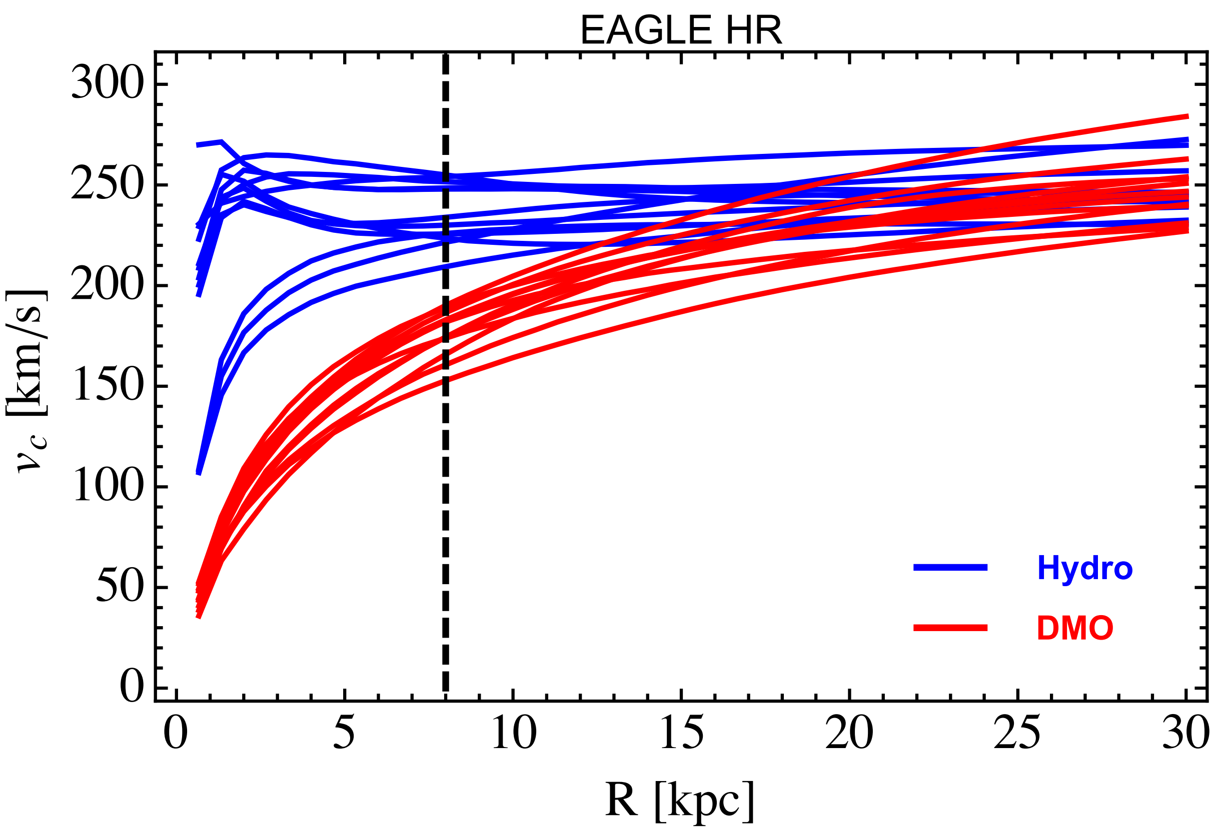
Common trends in different hydrodynamical simulations:

- 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 & Bertone, 1705.05853

Departure from isothermal

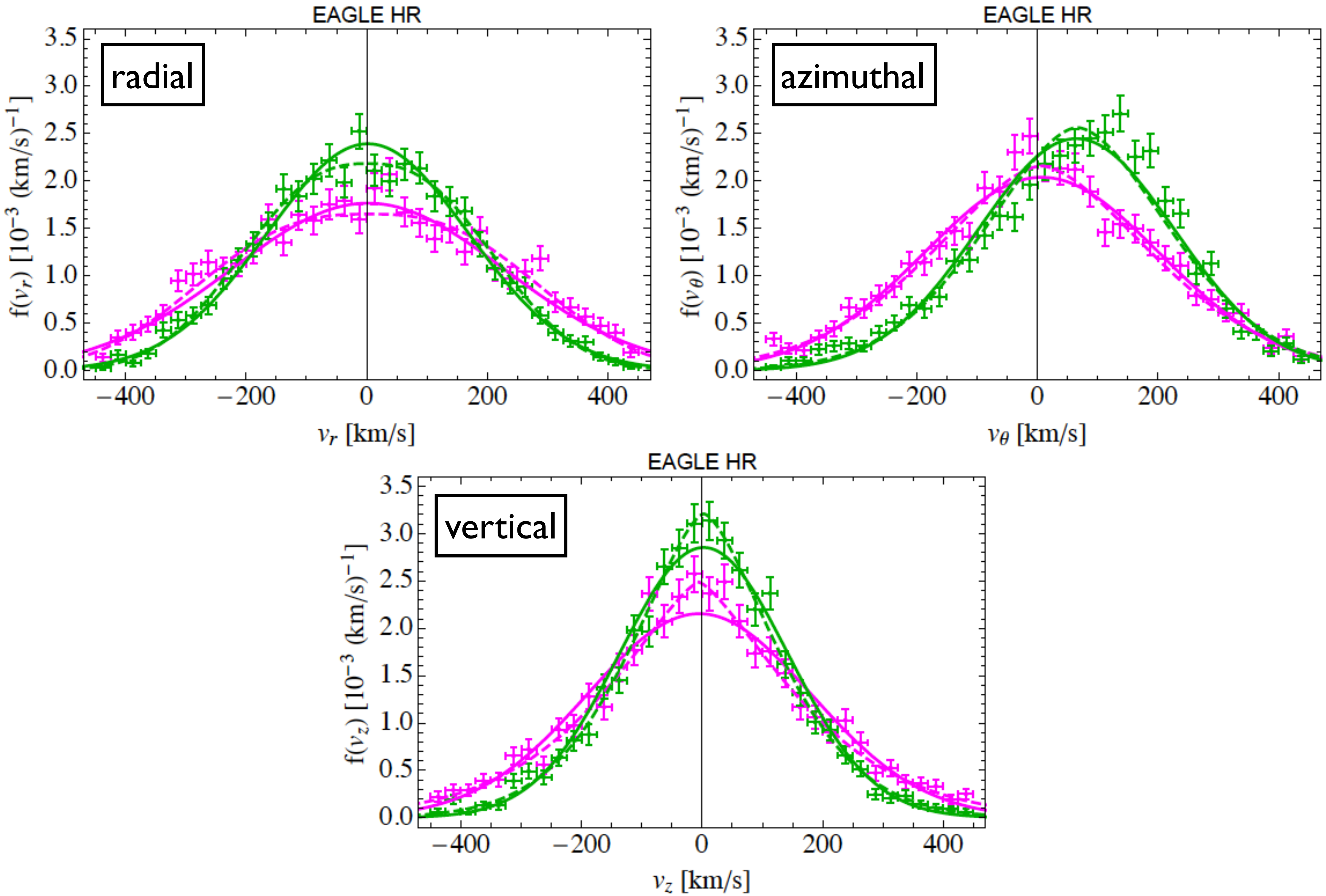




Bozorgnia & Bertone, 1705.05853

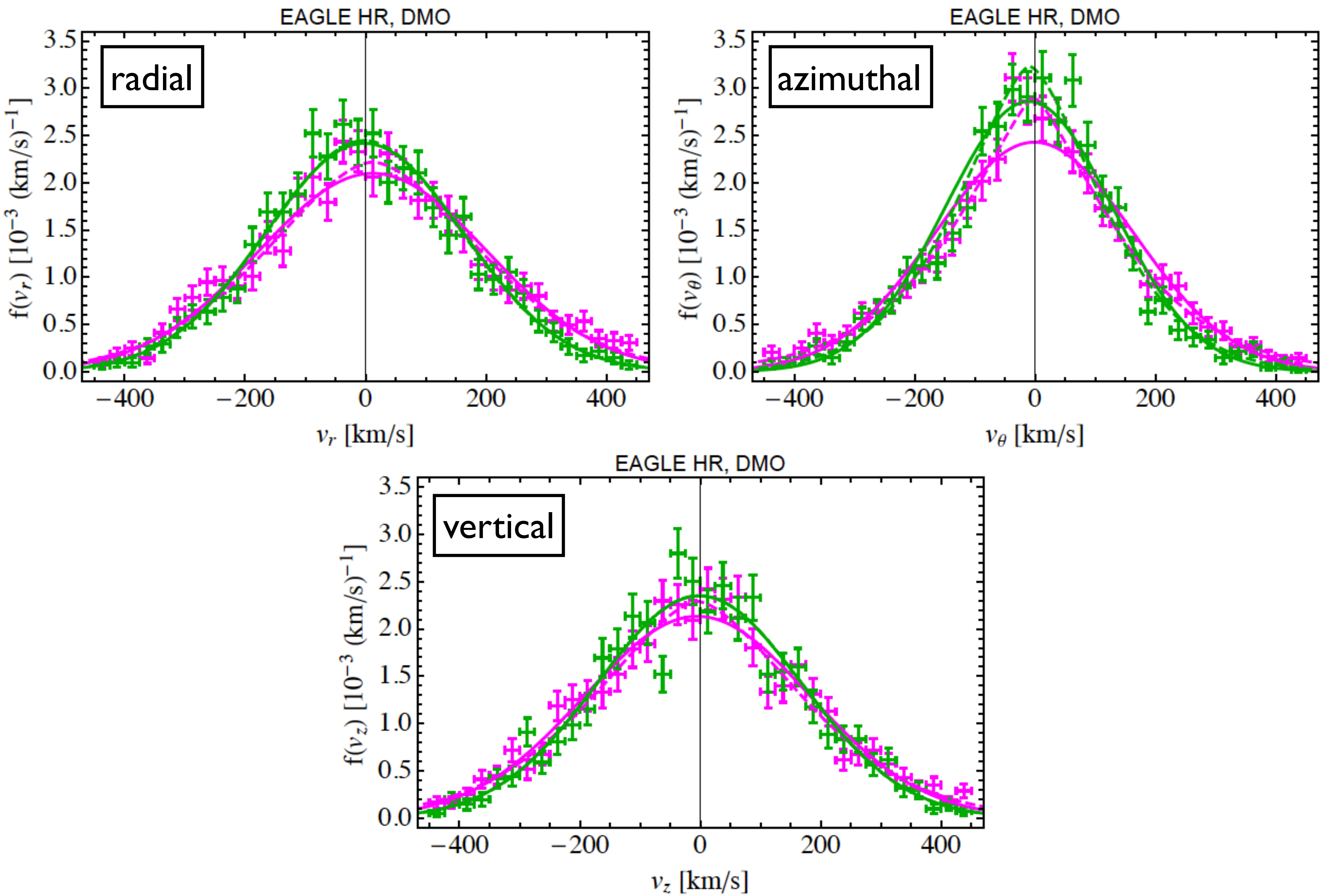
- At the Solar circle, haloes in the hydrodynamical simulation are closer to isothermal than their DMO counterparts.

Components of the velocity distribution



Bozorgnia et al., 1601.04707

Comparison with DMO



Bozorgnia et al., 1601.04707

How common are dark disks?

- Clear velocity anisotropy at the Solar circle.
- Two haloes have a rotating DM component in the disc with mean velocity comparable (within 50 km/s) to that of the stars.

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- Hint for the existence of a co-rotating dark disk in 2 out of 14 MW-like haloes. → **Dark disks are relatively rare in our halo sample.**

Bozorgnia et al., 1601.04707
Schaller et al., 1605.02770

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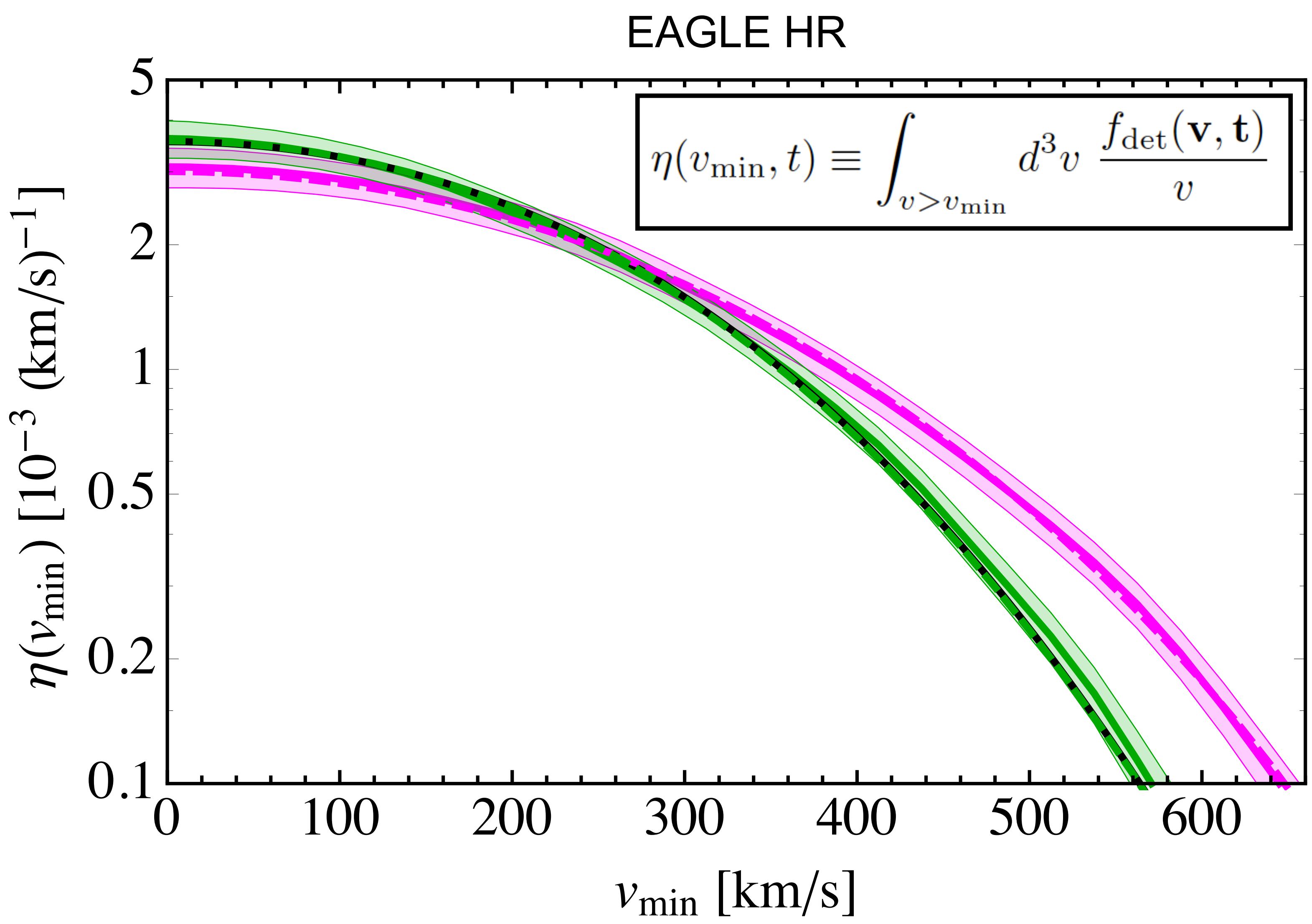
Bozorgnia et al., 1601.04707
Schaller et al., 1605.02770

- *Sizable dark disks also rare in other hydro simulations:*
  - They only appear in simulations where a large satellite merged with the MW in the recent past, which is robustly excluded from MW kinematical data.

Bozorgnia & Bertone, 1705.05853

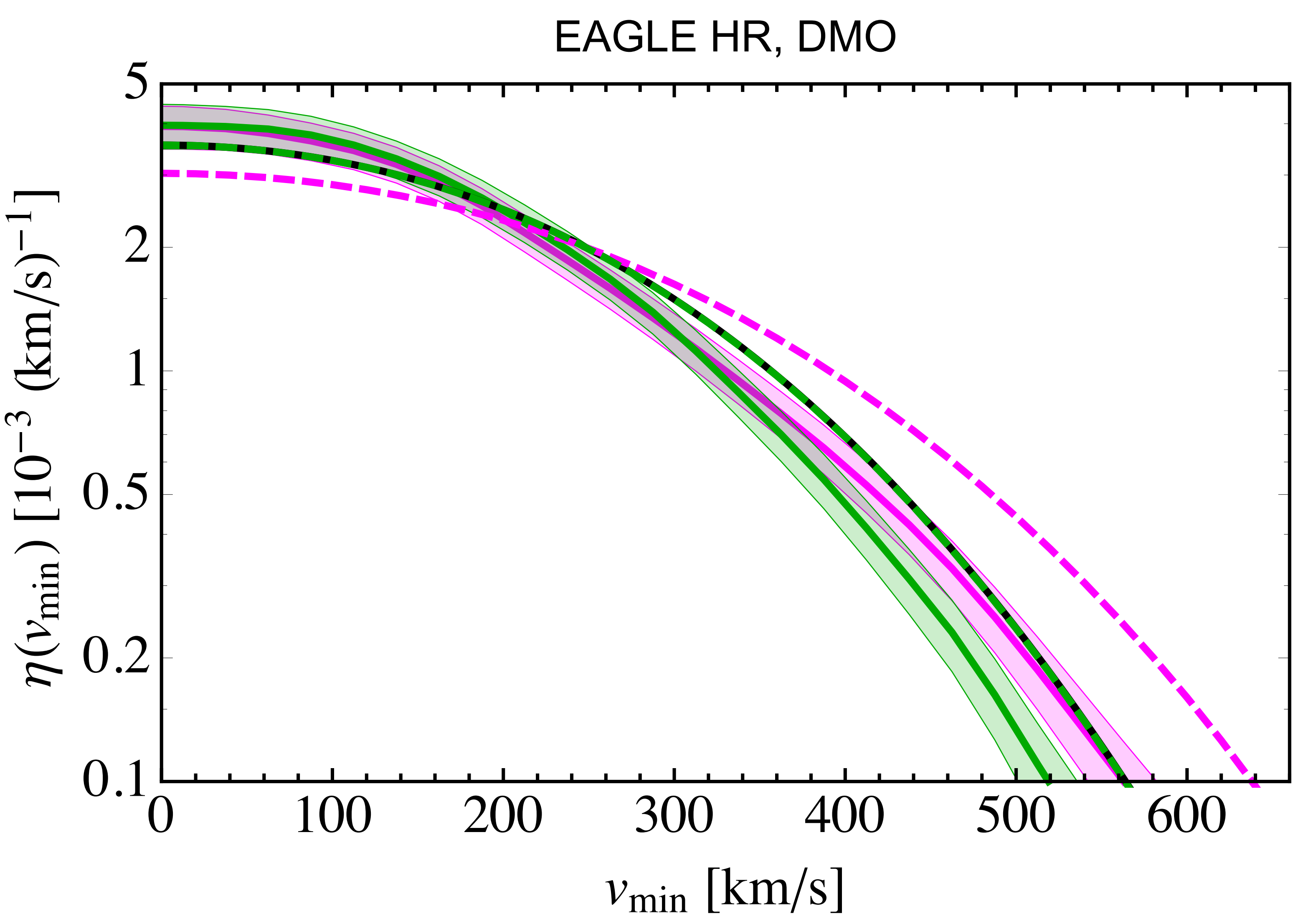
The halo integral



- 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 haloes.

Bozorgnia et al., 1601.04707

The halo integral



- Baryons affect the velocity distribution strongly at the Solar position, resulting in a shift of the tails of the halo integrals to higher velocities with respect to DMO.

Bozorgnia et al., 1601.04707

The halo integral

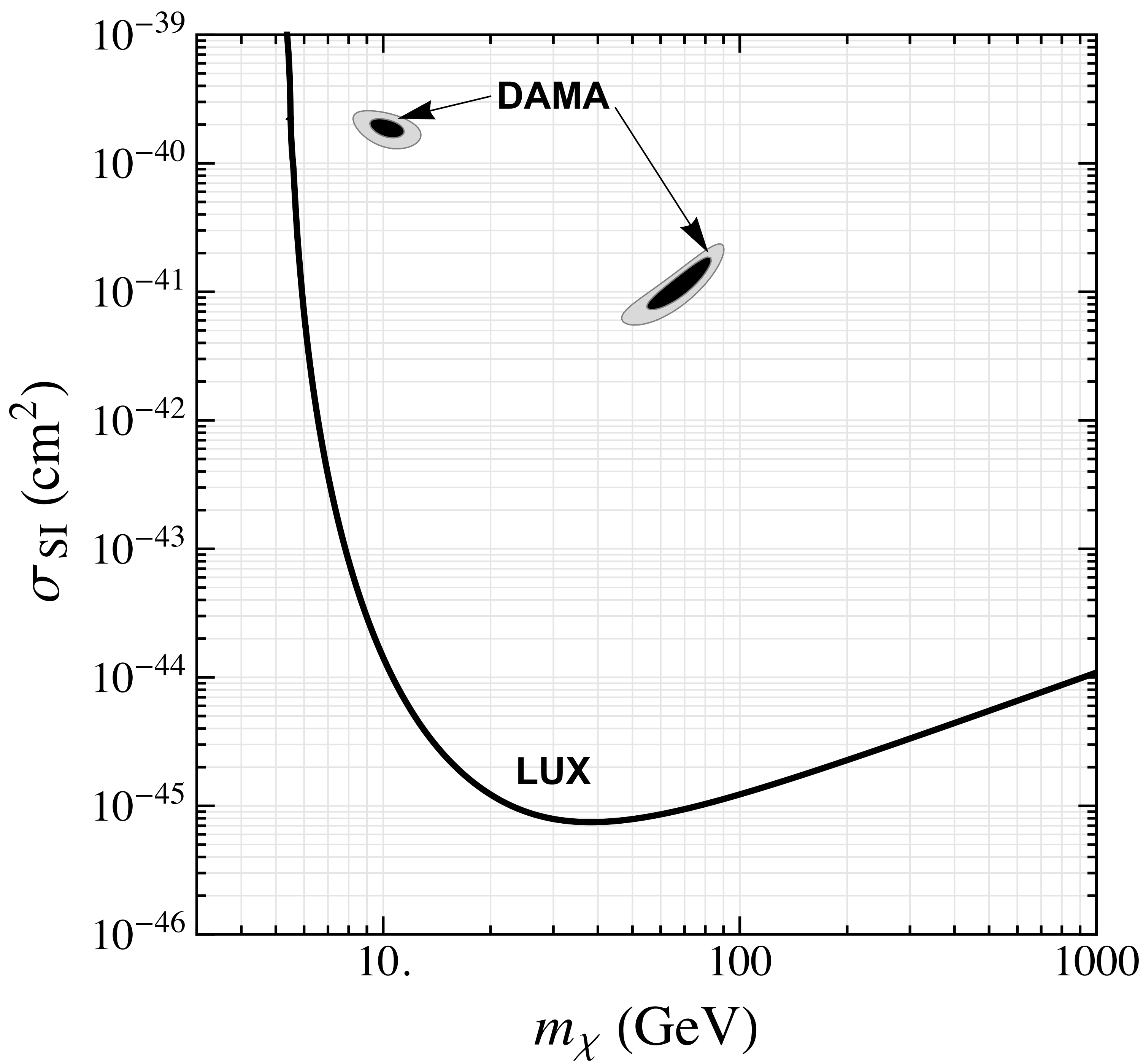
Common trend in different hydrodynamical simulations:

- 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 haloes.

Bozorgnia et al., 1601.04707 (EAGLE & APOSTLE)
Kelso et al., 1601.04725 (MaGICC)
Sloane et al., 1601.05402
Bozorgnia & Bertone, 1705.05853

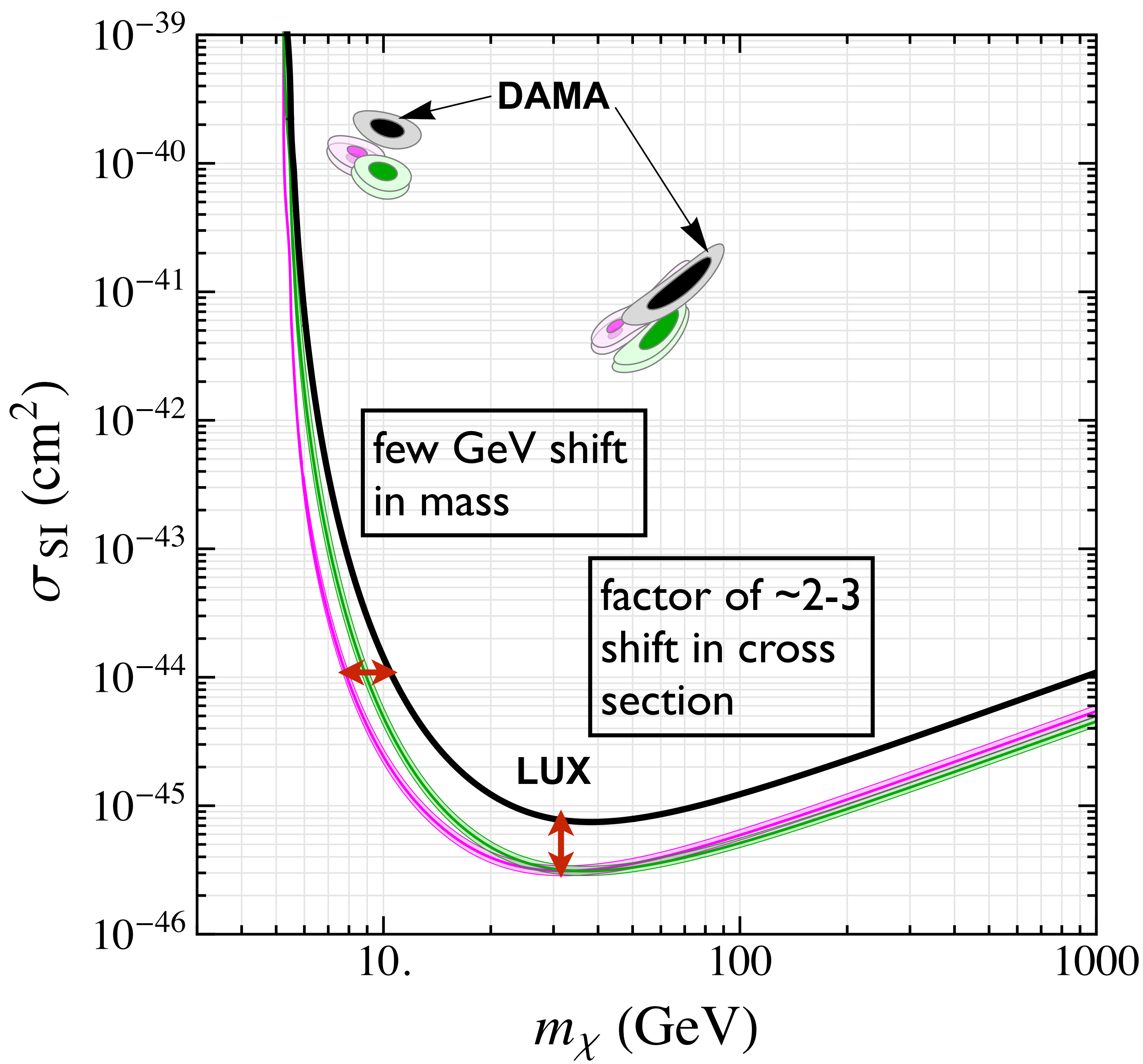
Implications for direct detection

- Assuming the **Standard Halo Model**:



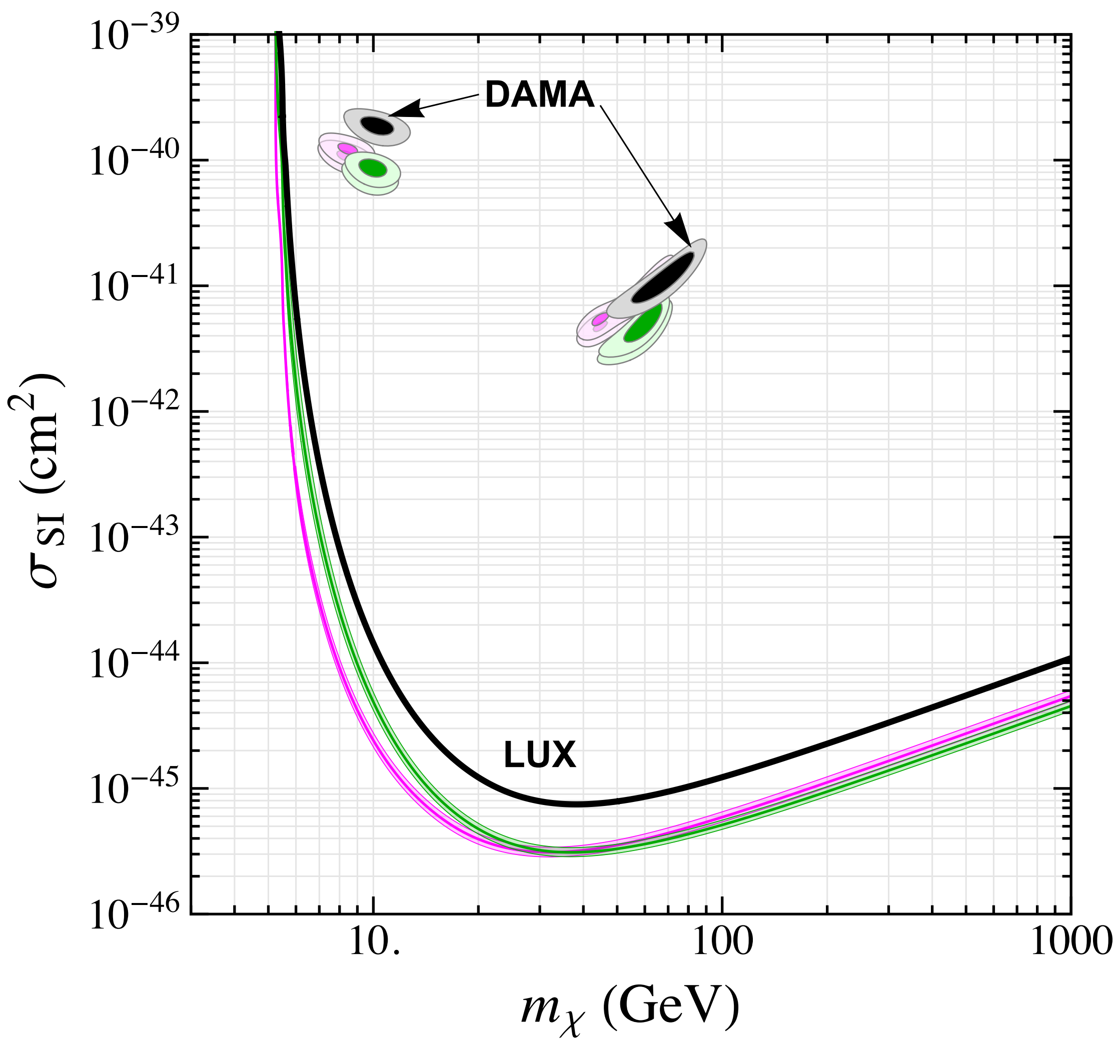
Implications for direct detection

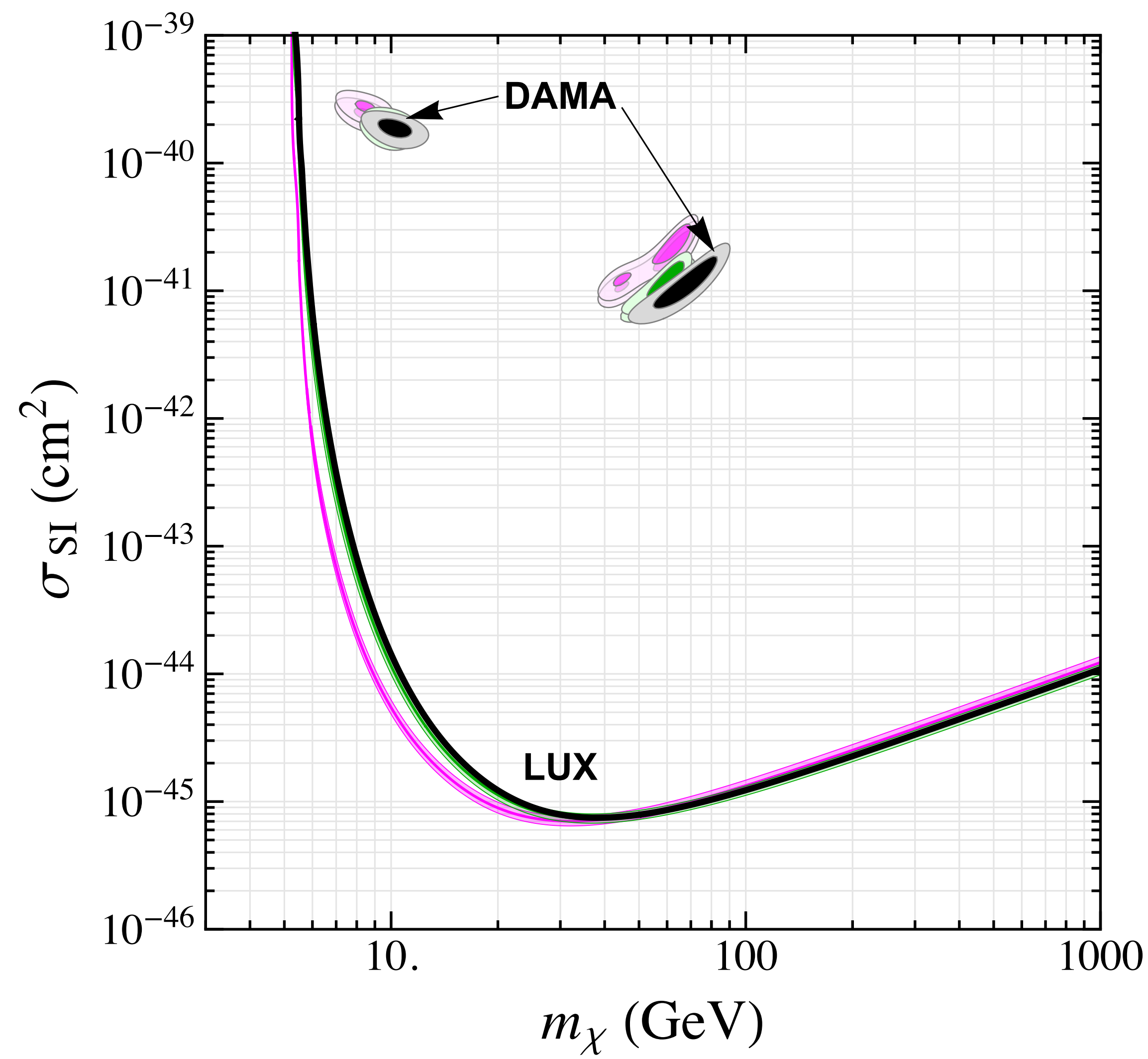
- Compare with simulated Milky Way-like haloes:



Implications for direct detection

Fix local ρ_χ=0.3 GeV cm^{-3}



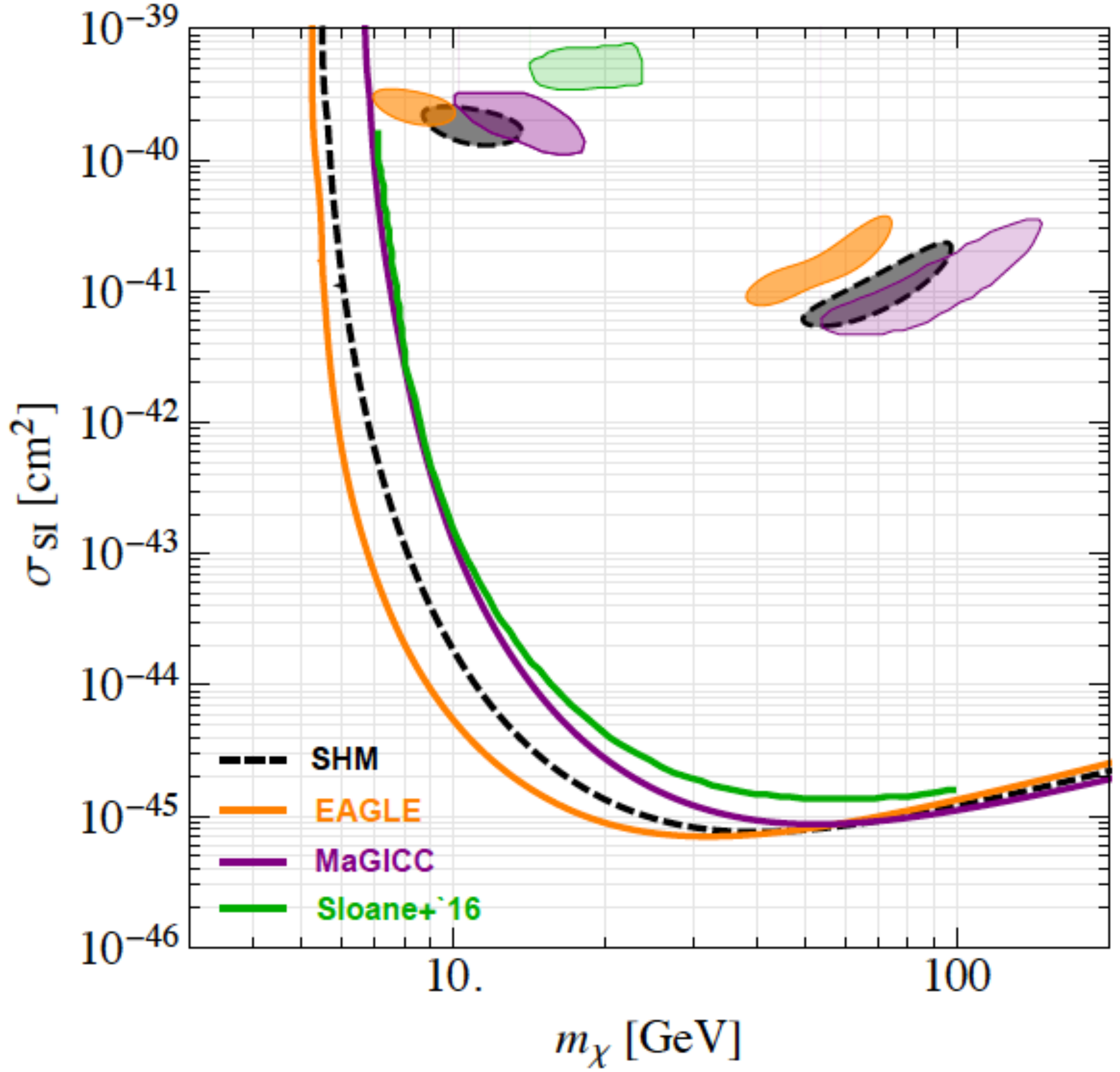


- Difference in the local DM density → overall difference with the SHM.
- Variation in the peak of the DM speed distribution → shift in the low mass region.

Implications for direct detection

Comparison to other hydrodynamical simulations:

Fix local ρ_χ=0.3 GeV cm^{-3}



Bozorgnia & Bertone, 1705.05853

Non-standard interactions

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

Kahlhoefer & Wild, 1607.04418

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

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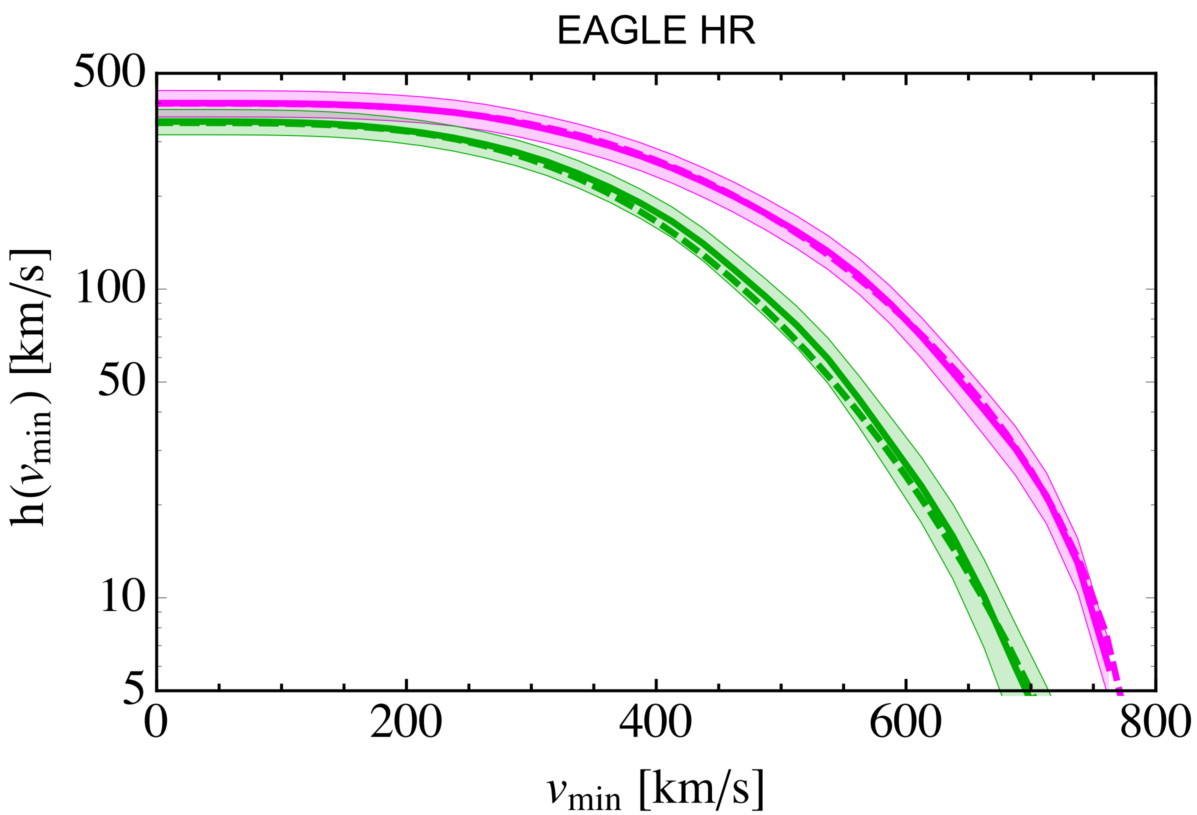


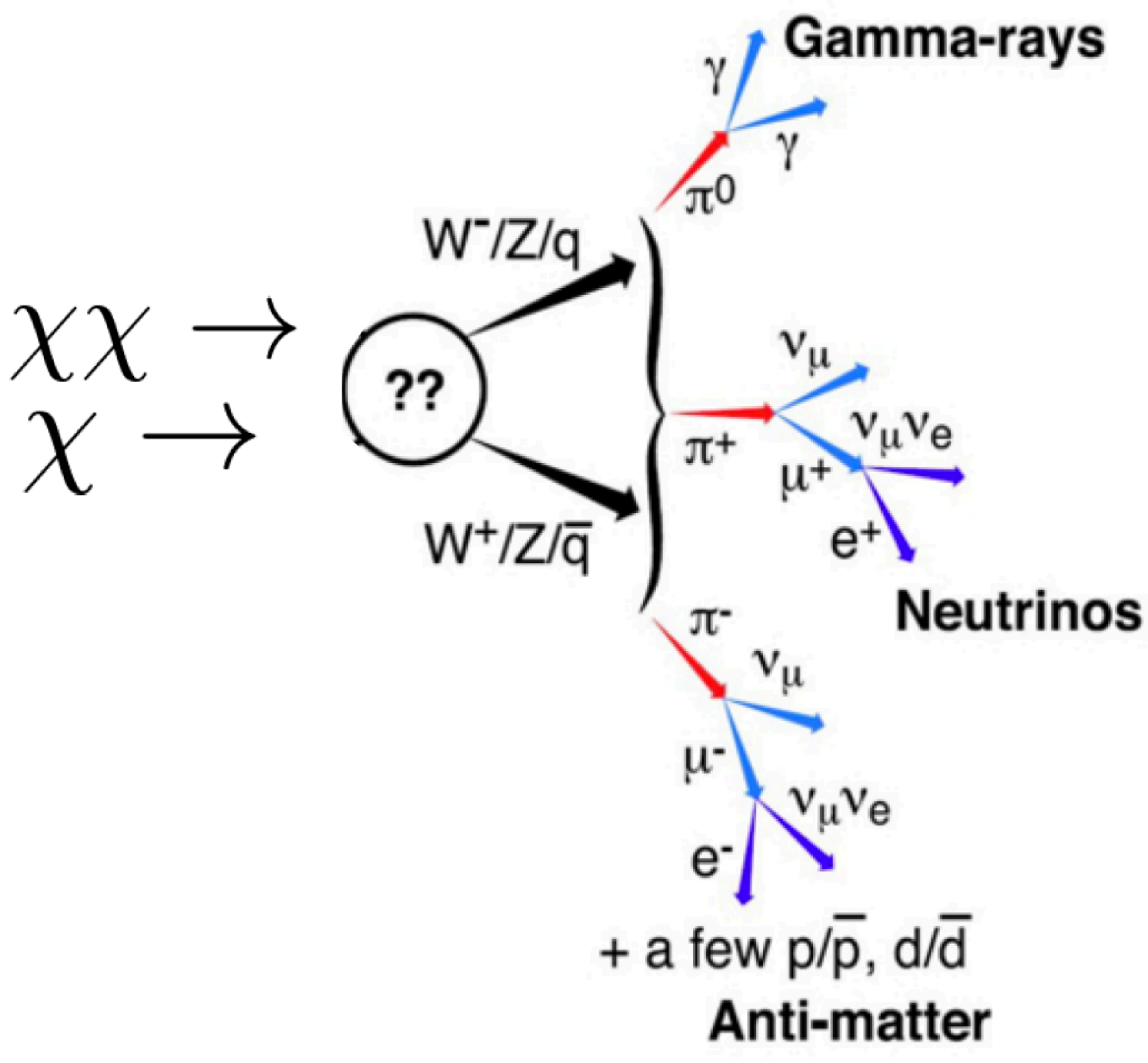
Bozorgnia & Bertone, 1705.05853

- Best fit Maxwellian $h(v_{\min})$ falls within the 1σ uncertainty band of the $h(v_{\min})$ of the simulated haloes.

Prospects for indirect DM searches

Dark Matter indirect detection

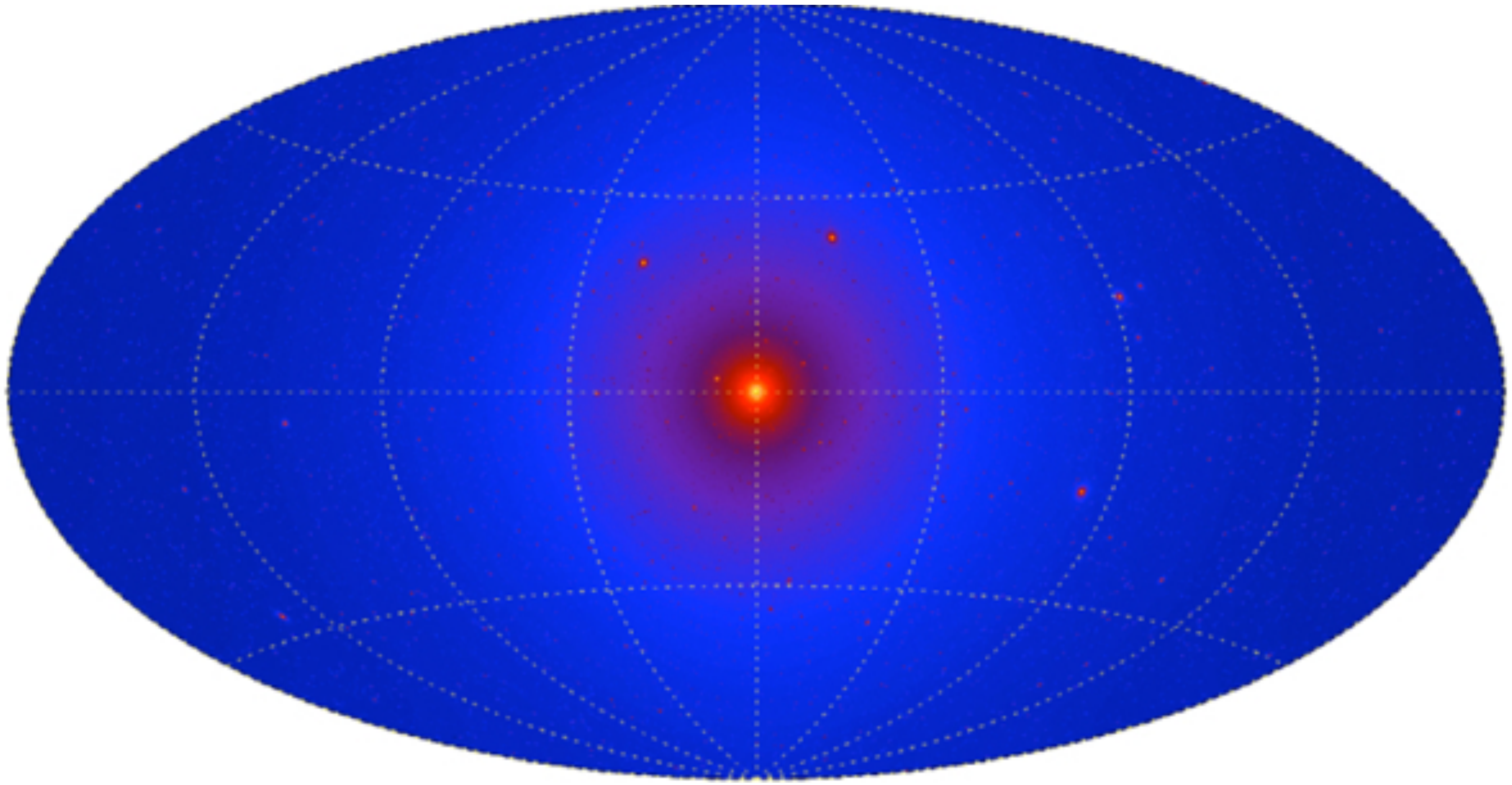
- Search for Standard Model particles produced by the annihilation or decay of DM.



Dark Matter indirect detection

- Expected gamma-ray flux from DM annihilation:

$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma v \rangle}{8\pi\, m_\chi^2} \frac{dN_\gamma}{dE} \int_{\text{l.o.s.}} ds\ \rho^2(r(s,\psi))$$



Pieri et al, 0908.0195

Dark Matter indirect detection

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astrophysics

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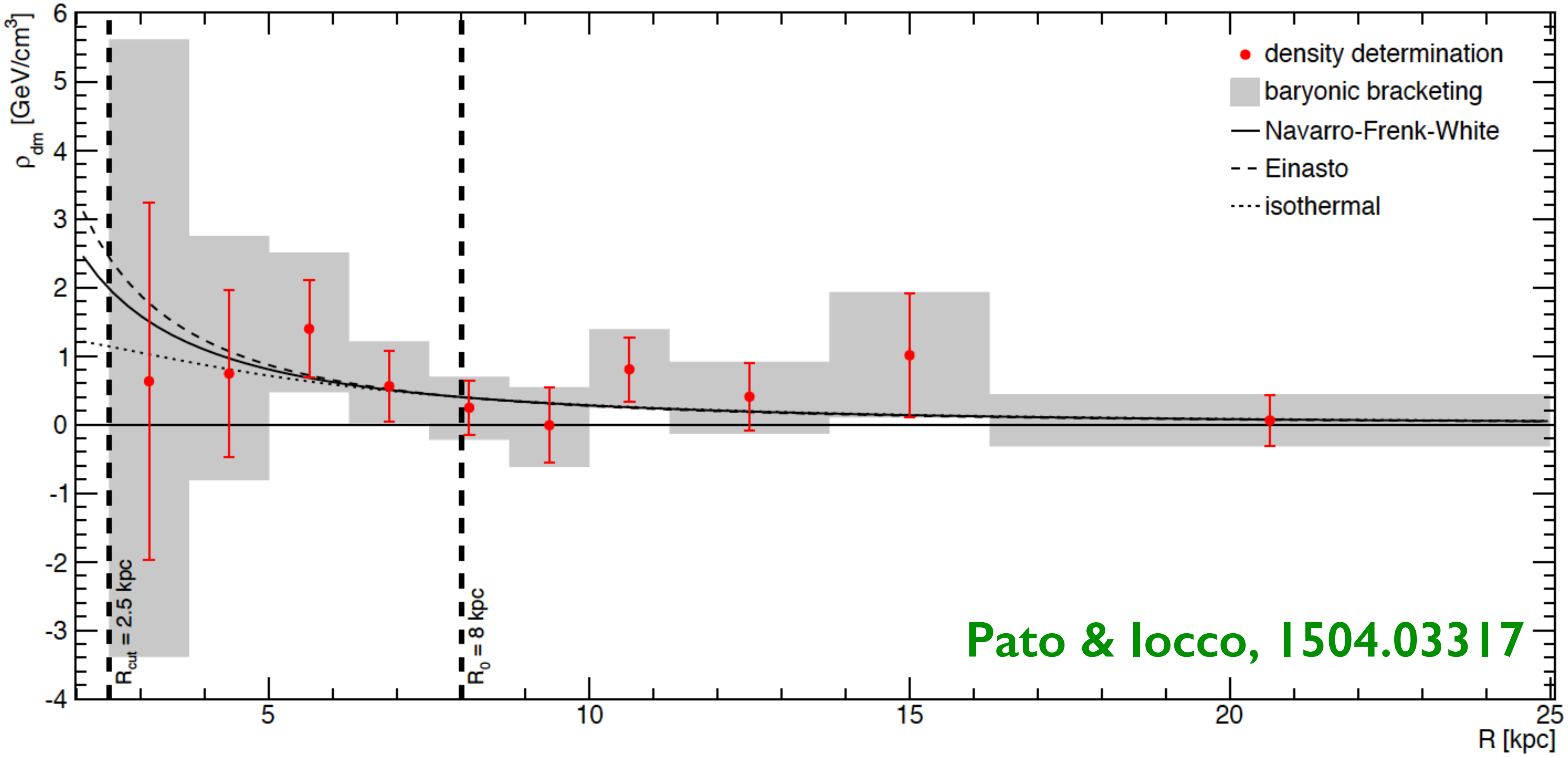
- Large uncertainties in the DM density profile in the inner few kpc.



Pato & Iocco, 1504.03317

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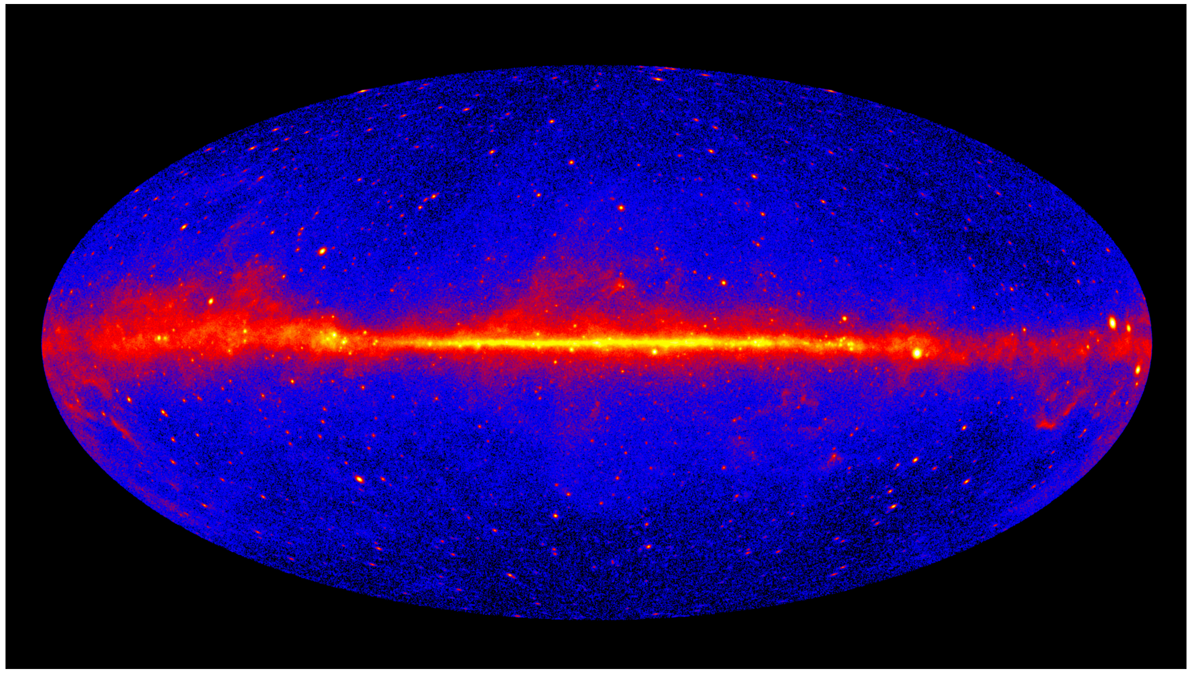
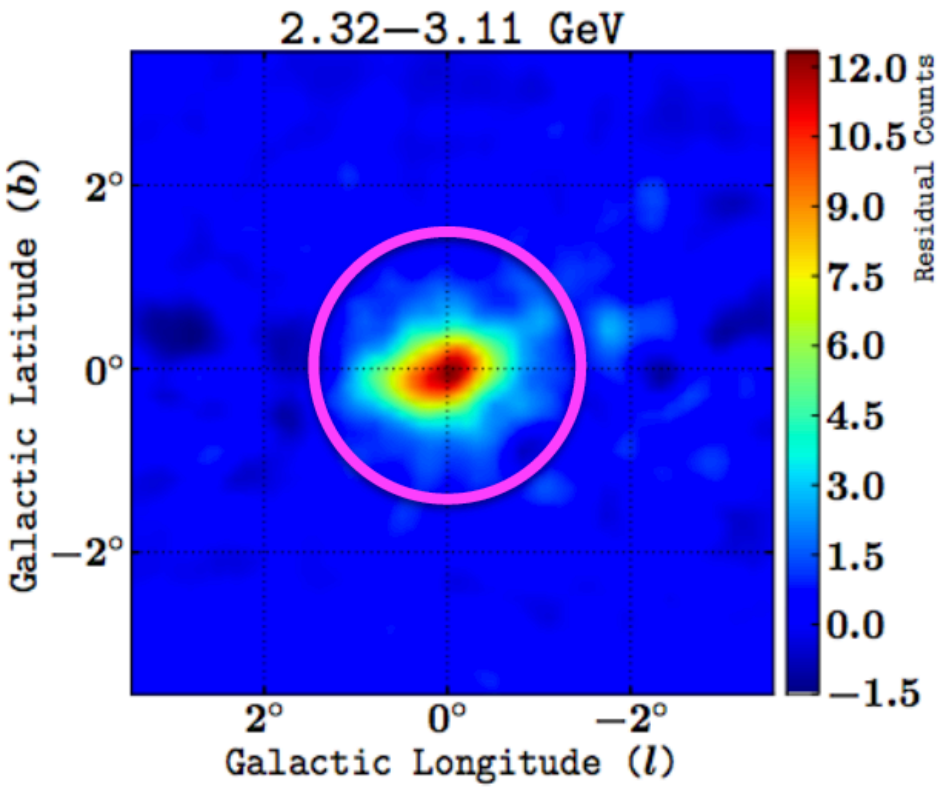
Use cosmological simulations:

- DMO simulations predict NFW profile: $r^{-\gamma}$, where $\gamma \approx 1$ in the inner few kpc.
- What is the DM density profile for MW-like galaxies in hydrodynamical simulations?

Galactic centre GeV excess

- Unexplained excess of gamma rays in Fermi-LAT data from the centre of our Galaxy, above the known astrophysical background. Hooper & Goodenough '09, Vitale & Morselli '09, ….





Macias & Gordon, 1312.6671

- **DM interpretation:**

  Best fit value for the inner slope: $\gamma = 1.26 \pm 0.15$

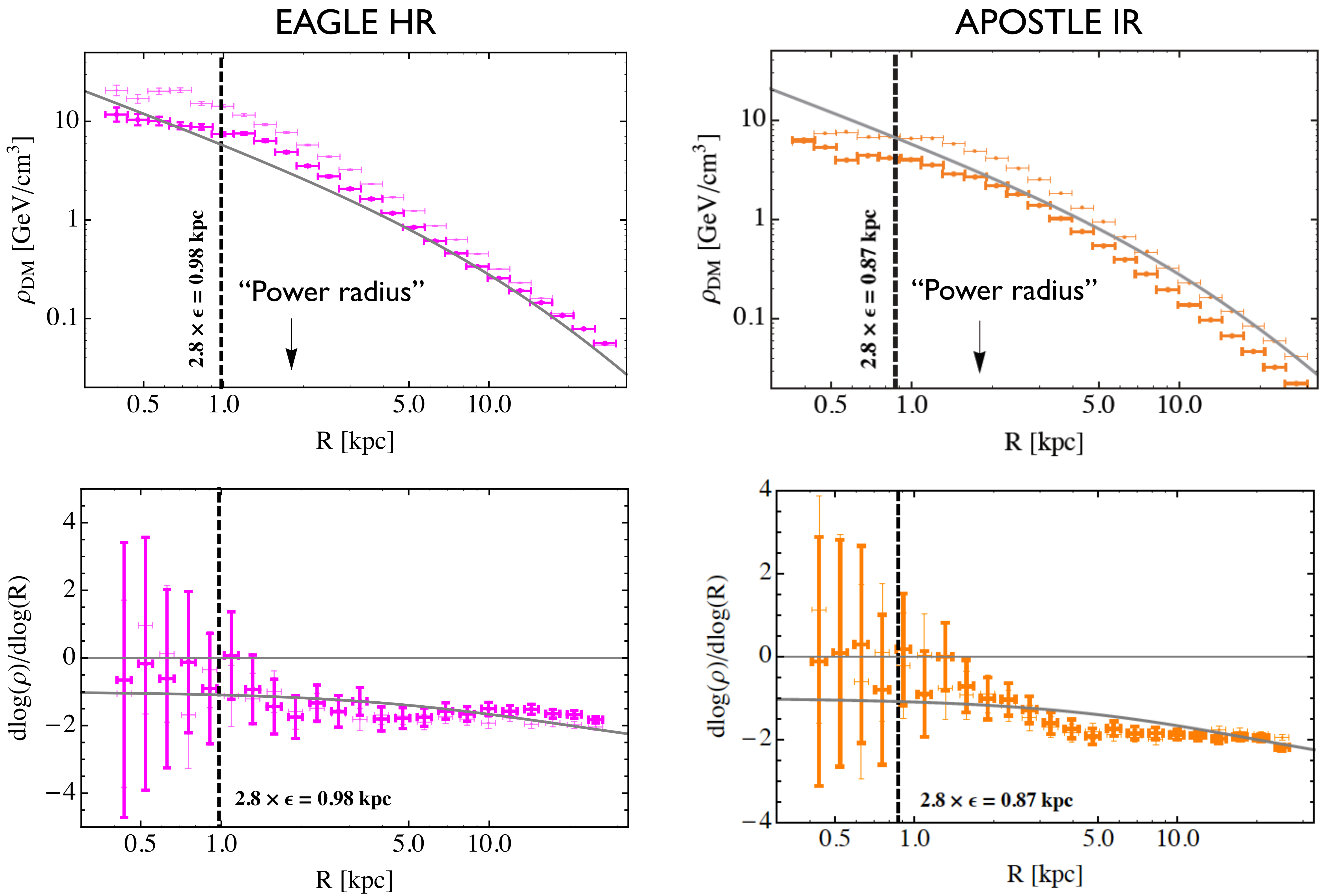
- **Other interpretations:** *unresolved millisecond pulsars, diffuse emission from electrons/positrons, stellar source population in the Galactic bulge, …*

GeV excess DM interpretation

- Test the DM density profile predicted by hydrodynamical simulations against the GeV excess data.
- Additional selection criterion of MW-like galaxies: substantial stellar disk component.

4 MW analogues:
2 EAGLE + 2 APOSTLE

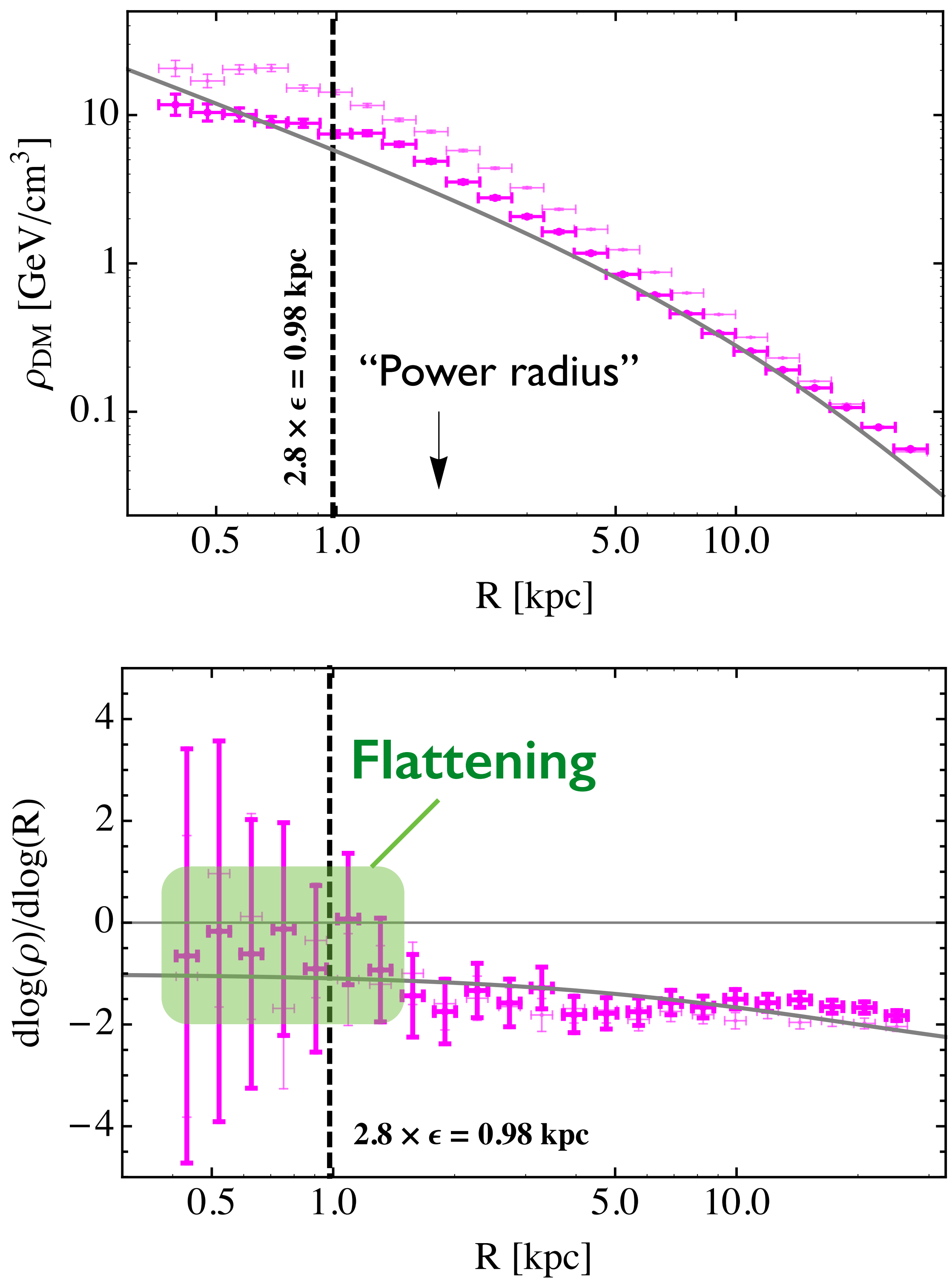
Dark Matter density profiles



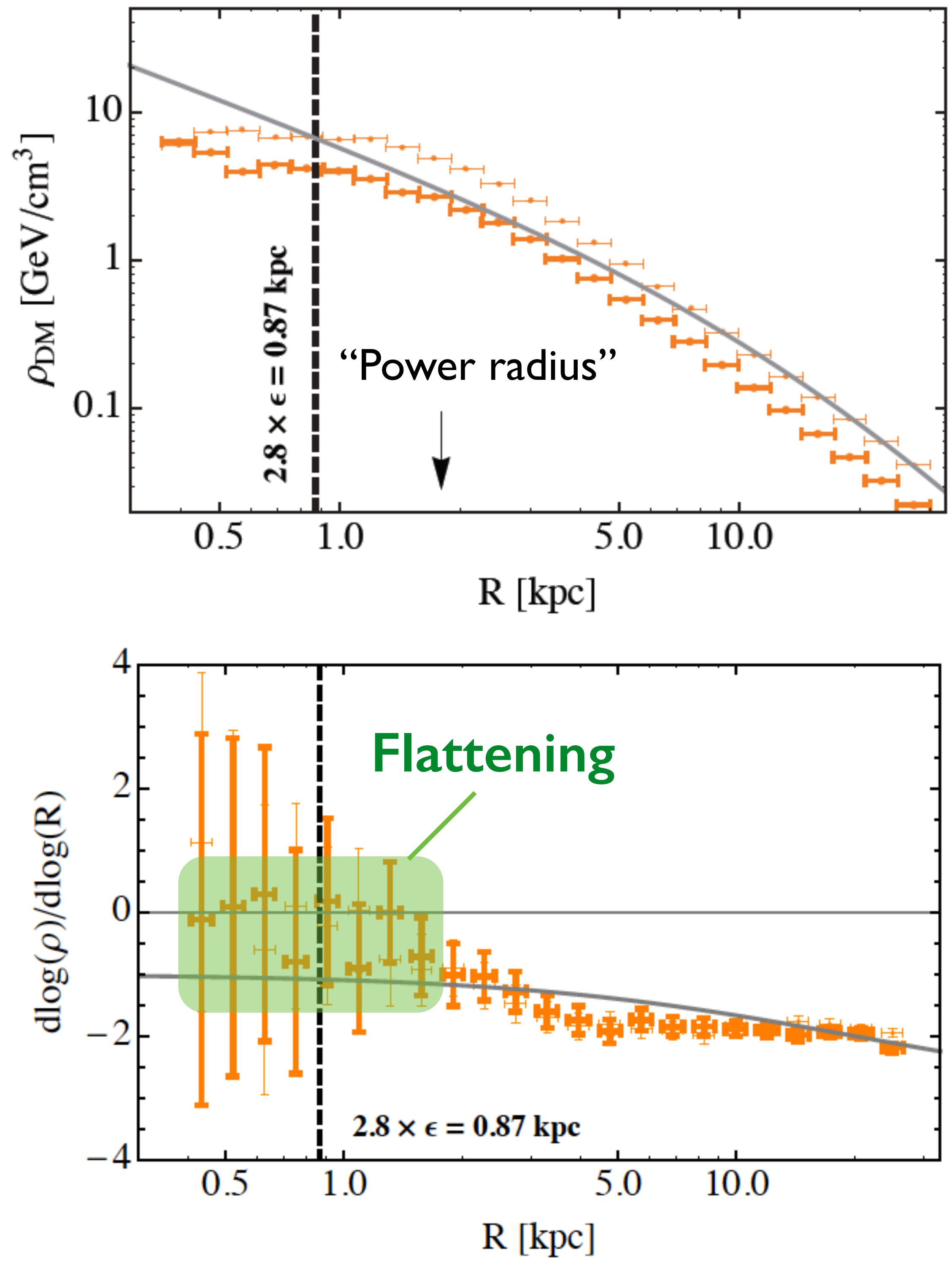
Calore, Bozorgnia et al., 1509.02164

Dark Matter density profiles

EAGLE HR

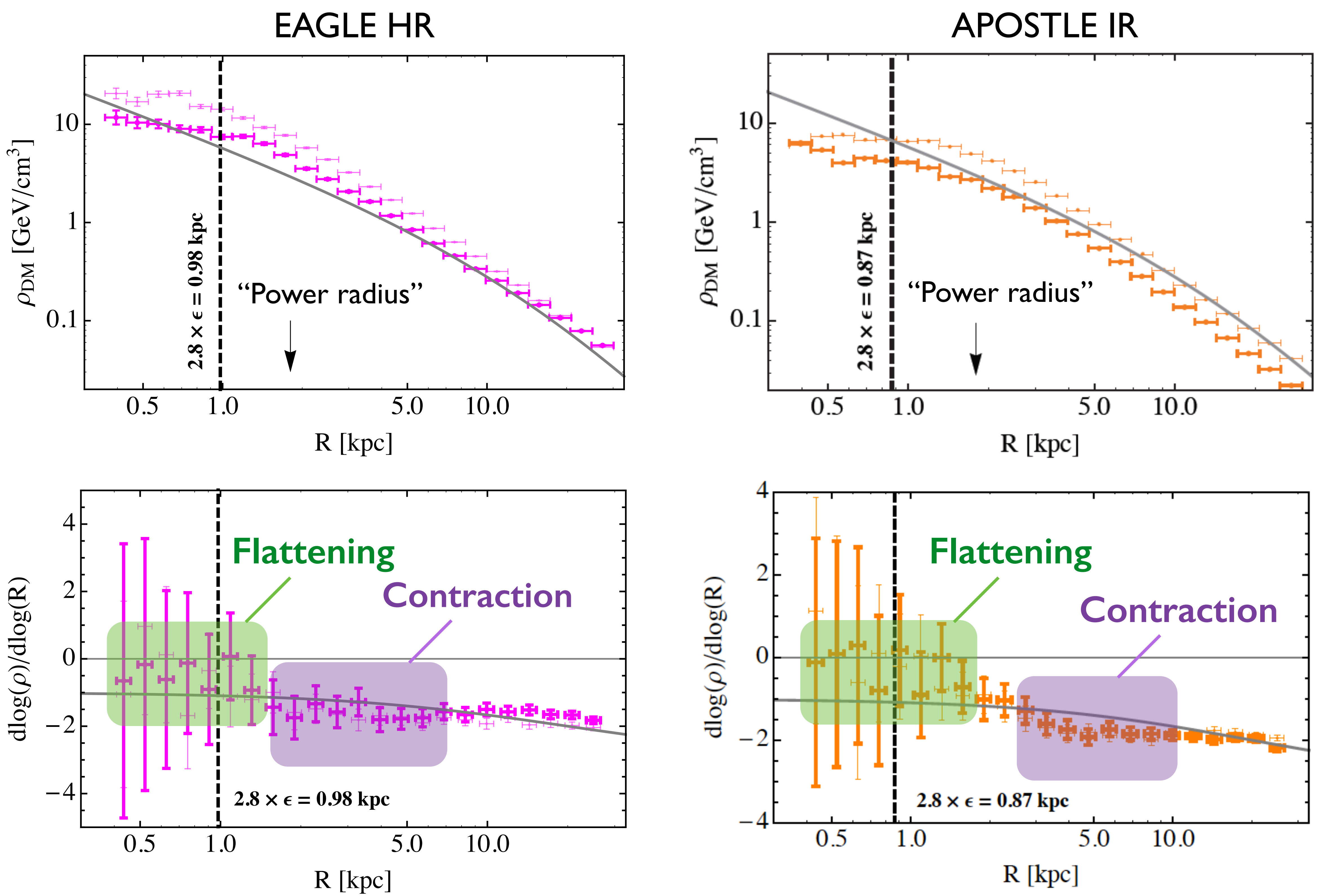


APOSTLE IR



Calore, Bozorgnia et al., 1509.02164

Dark Matter density profiles



Calore, Bozorgnia et al., 1509.02164

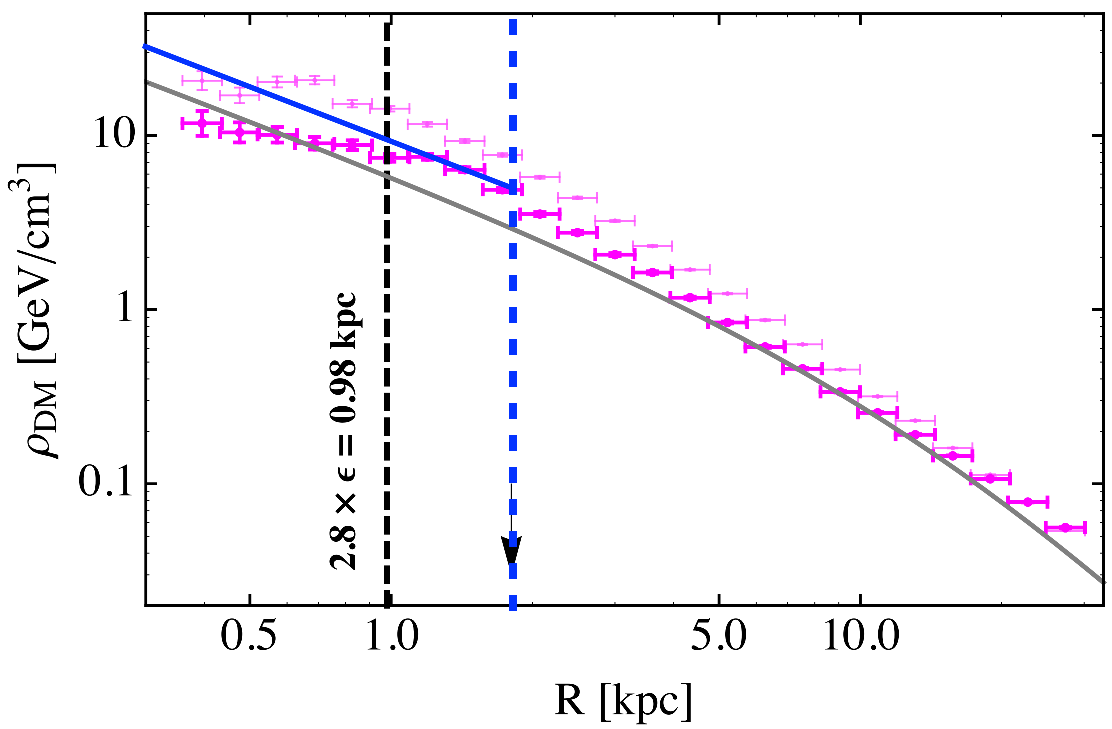
Dark Matter density profiles

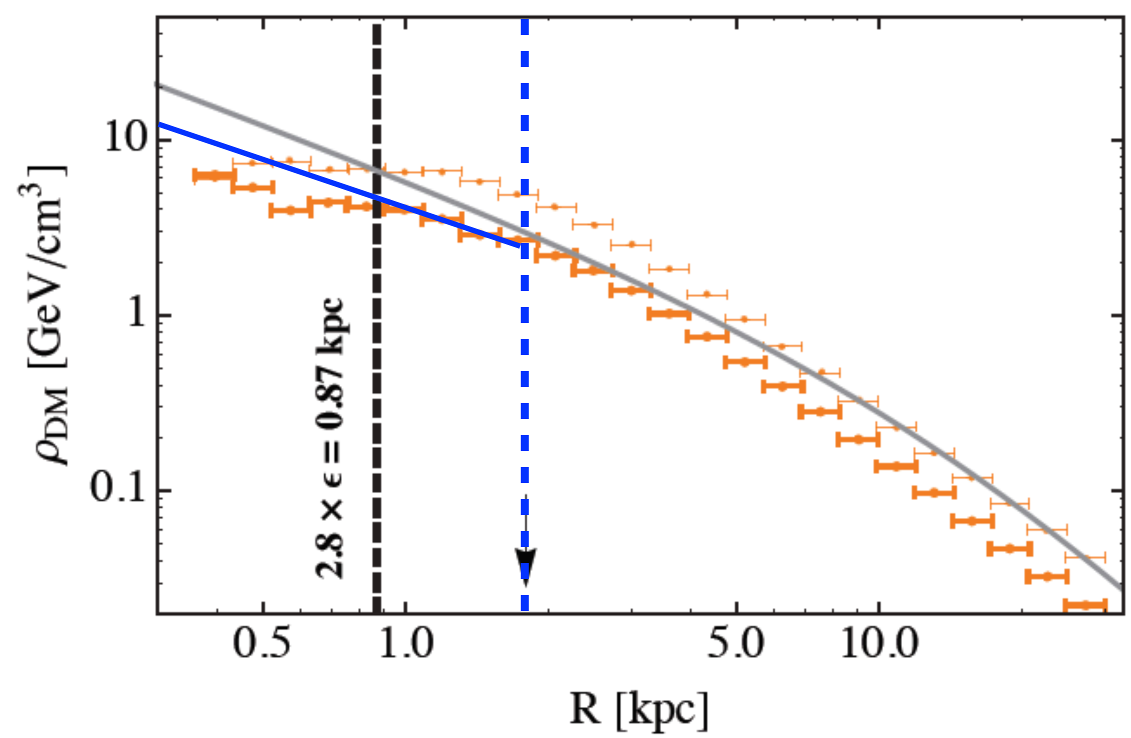
- GeV excess data analyzed in the region:

$$2^\circ \leq |b| \leq 20^\circ \;\&\; |l| \leq 20^\circ$$

radial scale: 0.3 - 3 kpc

- **A very conservative approach:** power-law extrapolation with maximal asymptotic slope at the Power radius.



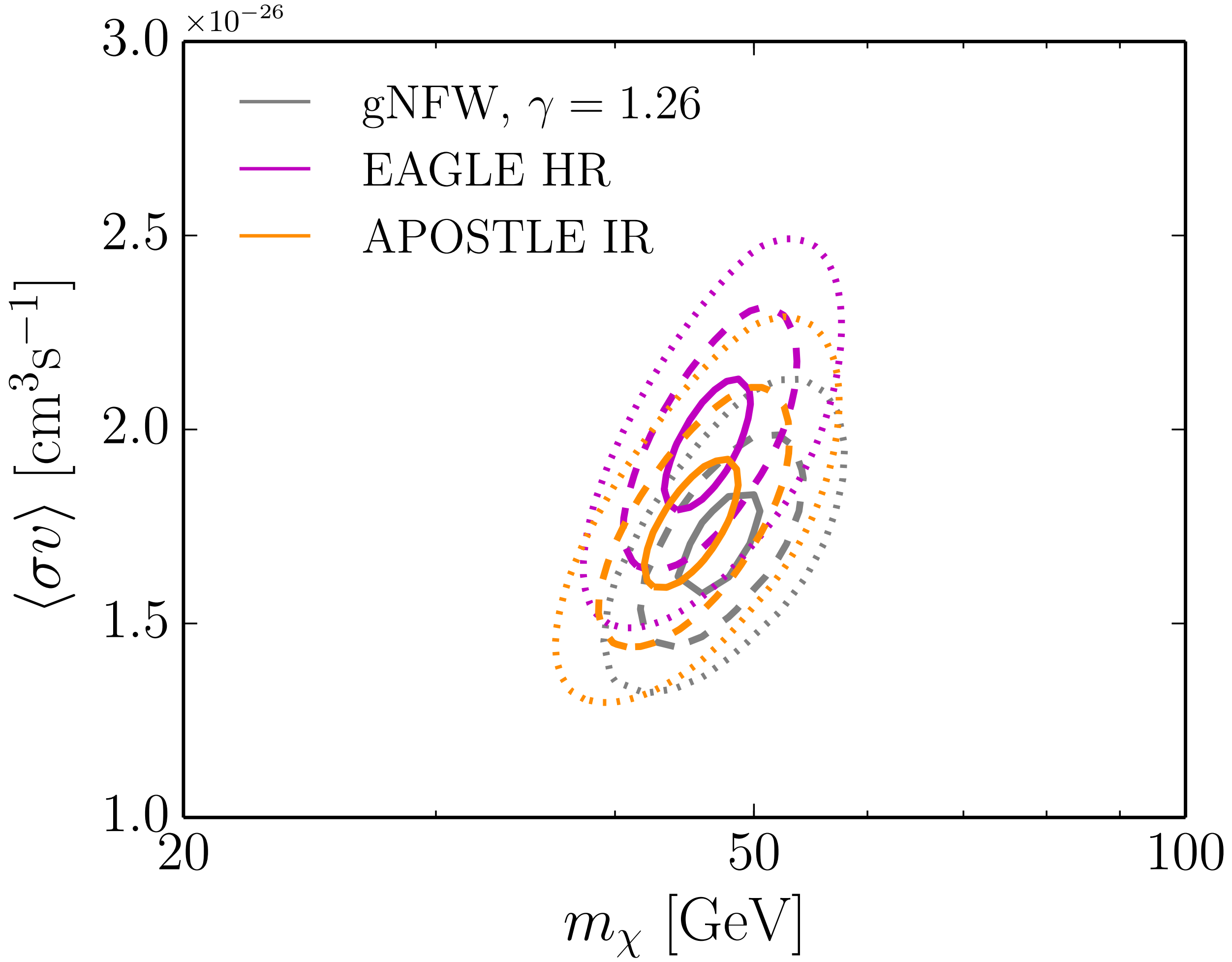


EAGLE HR (2 haloes): $0.94 < \gamma_{\max} < 0.98$ at $R_{\rm P03} = 1.8$ kpc

APOSTLE IR (2 haloes): $0.50 < \gamma_{\max} < 0.62$ at $R_{\rm P03} = 1.8$ kpc

Fitting the GeV excess

- Assuming 100% annihilation into b-quarks:



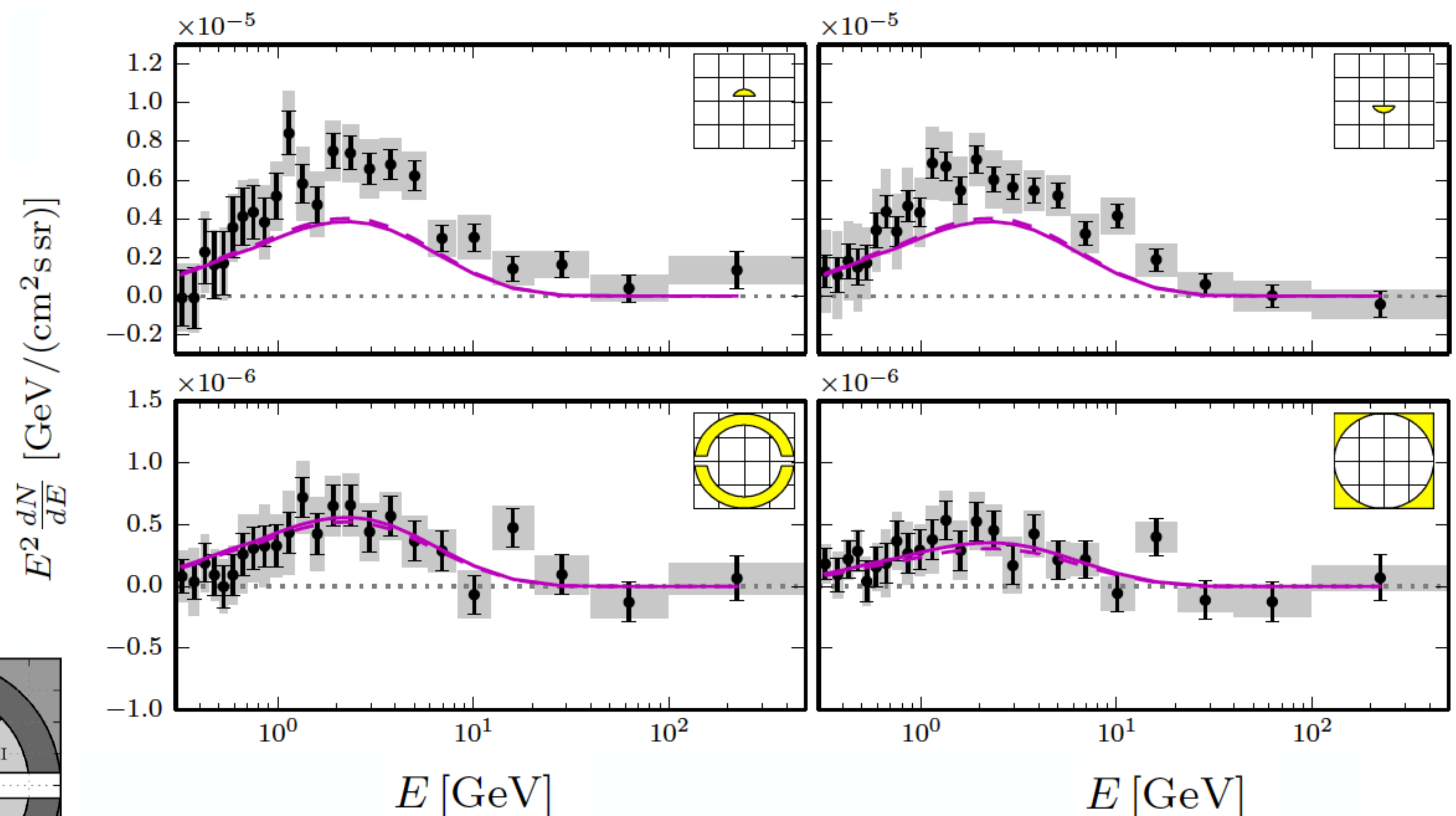
- Similar constraints on DM mass and annihilation cross section, but significantly worse fit.

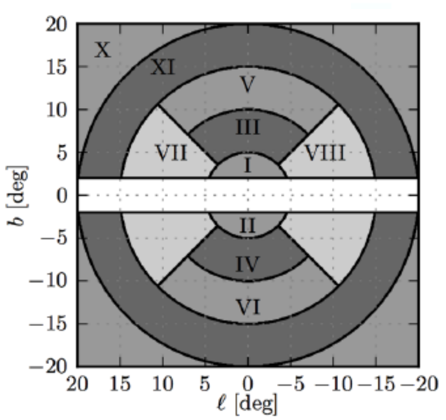
(238 dof)

Profile	$\langle \sigma v \rangle [\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}]$	m_χ [GeV]	χ^2	p-value
gNFW (γ=1.26)	1.71 ± 0.11	47.32 ± 1.07	223.9	0.73
EAGLE HR	1.96 ± 0.14	46.37 ± 1.37	246.3	0.34
APOSTLE IR	1.76 ± 0.16	45.36 ± 2.96	283.9	0.02

Fitting the GeV excess

- Even under our very conservative assumption, DM density profiles of our MW-like galaxies do not reproduce the correct morphology of the GeV excess in the inner most regions.





Calore, Bozorgnia et al., 1509.02164

Summary

- To make ***precise quantitative predictions*** for the DM distribution from simulations → Identify MW analogues by taking into account ***observational constraints on the MW***.

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  - **Local DM density** agrees with local and global estimates.
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  - **Halo integrals** of MW analogues match well those obtained from *best fit Maxwellian velocity distributions*.

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    - **DM density profiles** show flattening in the inner few kpc and contraction up to 10 kpc.

    - **Halo integrals** of MW analogues match well those obtained from ***best fit Maxwellian velocity distributions***.

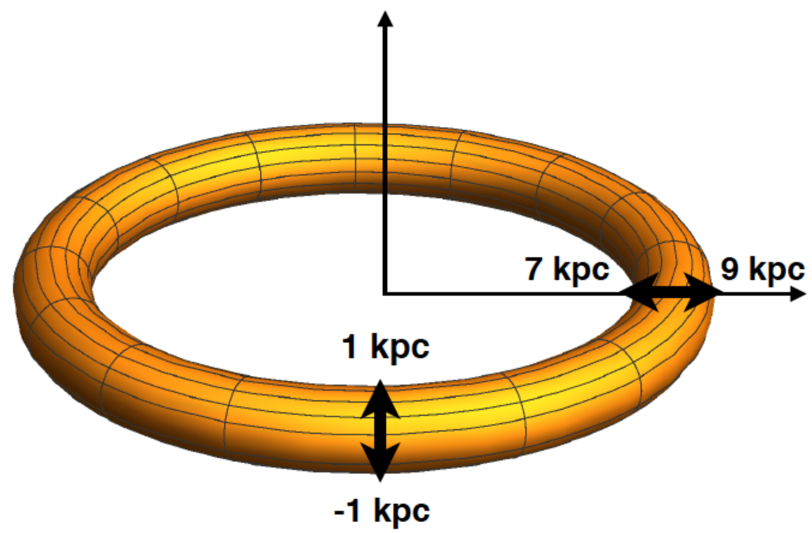
- Maxwellian works for the analysis of direct detection data. → ***Can substantially reduce astrophysical uncertainties by a better selection of MW-like galaxies in simulations.***

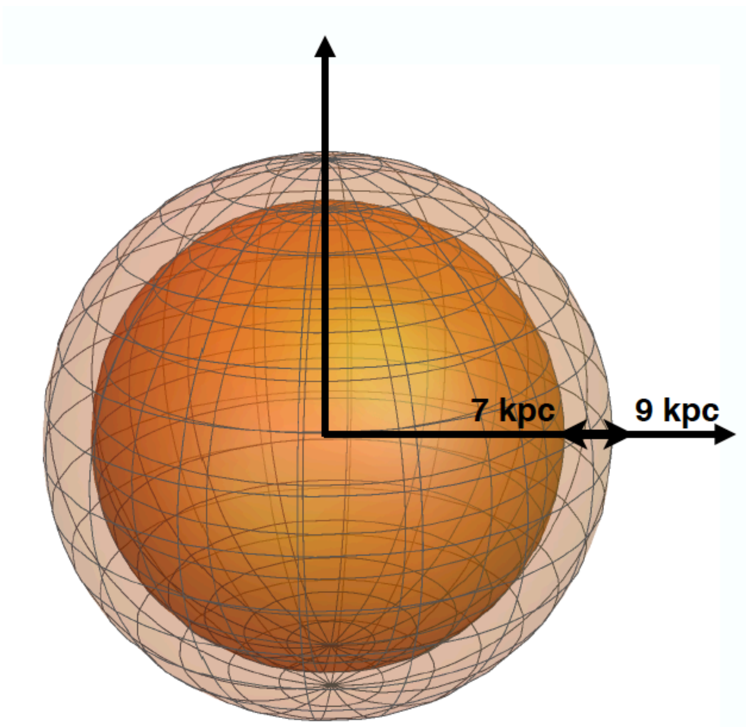
- DM density profiles of MW-like galaxies fail to reproduce the GeV excess.

Backup Slides

Local Dark Matter density

Is there an enhancement of the local DM density in the Galactic disk compared to the halo?



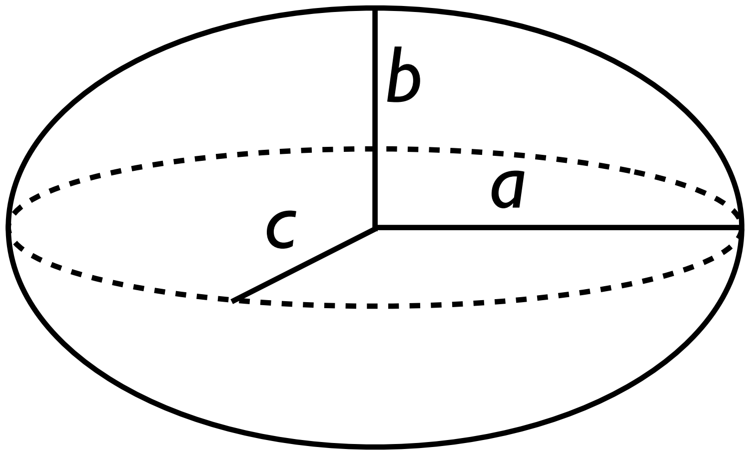


- ρ_{torus} larger than ρ_{shell} by 2 – 27% for 10 haloes.
- The increase in the DM density in the disk could be due to the DM halo contraction as a result of dissipational baryonic processes.

Halo shapes

- To study the shape of the inner (R < 8 kpc) DM haloes, calculate the inertia tensor of DM particles within 5 and 8 kpc.
  → ellipsoid with three axes of length:

  $a \geq b \geq c$



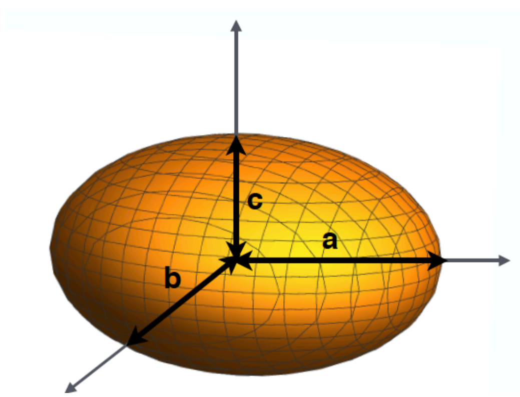
- **Sphericity**: $s = c/a$ $(s = 1$: perfect sphere)
  - Hydro haloes: at 5 kpc, $s = [0.85, 0.95]$. At 8 kpc, s lower by less than 10%.
  - DMO haloes: $s = [0.75, 0.85]$
- Due to dissipational baryonic processes, DM sphericity systematically higher in the hyrdo compared to DMO haloes.

Halo shapes

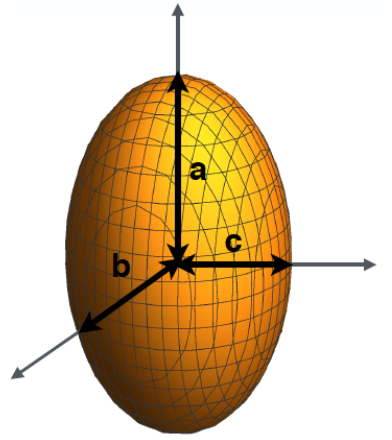
- Describe a deviation from a sphere by the triaxiality parameter:

$$T = \frac{a^2 - b^2}{a^2 - c^2}$$

- Oblate systems: $a \approx b \gg c \rightarrow T \approx 0$



- Prolate systems: $a \gg b \approx c \rightarrow T \approx 1$



- In the hydro case, inner haloes very close to spherical and deviation towards either oblate or prolate is small. DMO counterparts have a preference for *prolate inner haloes*.

Parameters of the simulations

Simulation	code	$N_{\rm DM}$	$m_{\rm g}$ [$M_\odot$]	$m_{\rm DM}$ [$M_\odot$]	ϵ [pc]
Ling *et al.*	RAMSES	2662	–	7.46×10^5	200
Eris	GASOLINE	81213	2×10^4	9.80×10^4	124
NIHAO	EFS-GASOLINE2	–	3.16×10^5	1.74×10^6	931
EAGLE (HR)	P-GADGET (ANARCHY)	1821–3201	2.26×10^5	1.21×10^6	350
APOSTLE (IR)	P-GADGET (ANARCHY)	2160, 3024	1.3×10^5	5.9×10^5	308
MaGICC	GASOLINE	4849, 6541	2.2×10^5	1.11×10^6	310
Sloane *et al.*	GASLOINE	5847–7460	2.7×10^4	1.5×10^5	174

Properties of the selected MW analogues

Simulation	Count	$M_{\rm star}$ [$\times 10^{10} M_\odot$]	$M_{\rm halo}$ [$\times 10^{12} M_\odot$]	ρ_χ [GeV/cm^3]	$v_{\rm peak}$ [km/s]
Ling *et al.*	1	~ 8	0.63	0.37–0.39	239
Eris	1	3.9	0.78	0.42	239
NIHAO	5	15.9	~ 1	0.42	192–363
EAGLE (HR)	12	4.65–7.12	2.76–14.26	0.42–0.73	232–289
APOSTLE (IR)	2	4.48, 4.88	1.64–2.15	0.41–0.54	223–234
MaGICC	2	2.4–8.3	0.584, 1.5	0.346, 0.493	187, 273
Sloane *et al.*	4	2.24–4.56	0.68–0.91	0.3–0.4	185–204