Impact of simulation results for dark matter searches

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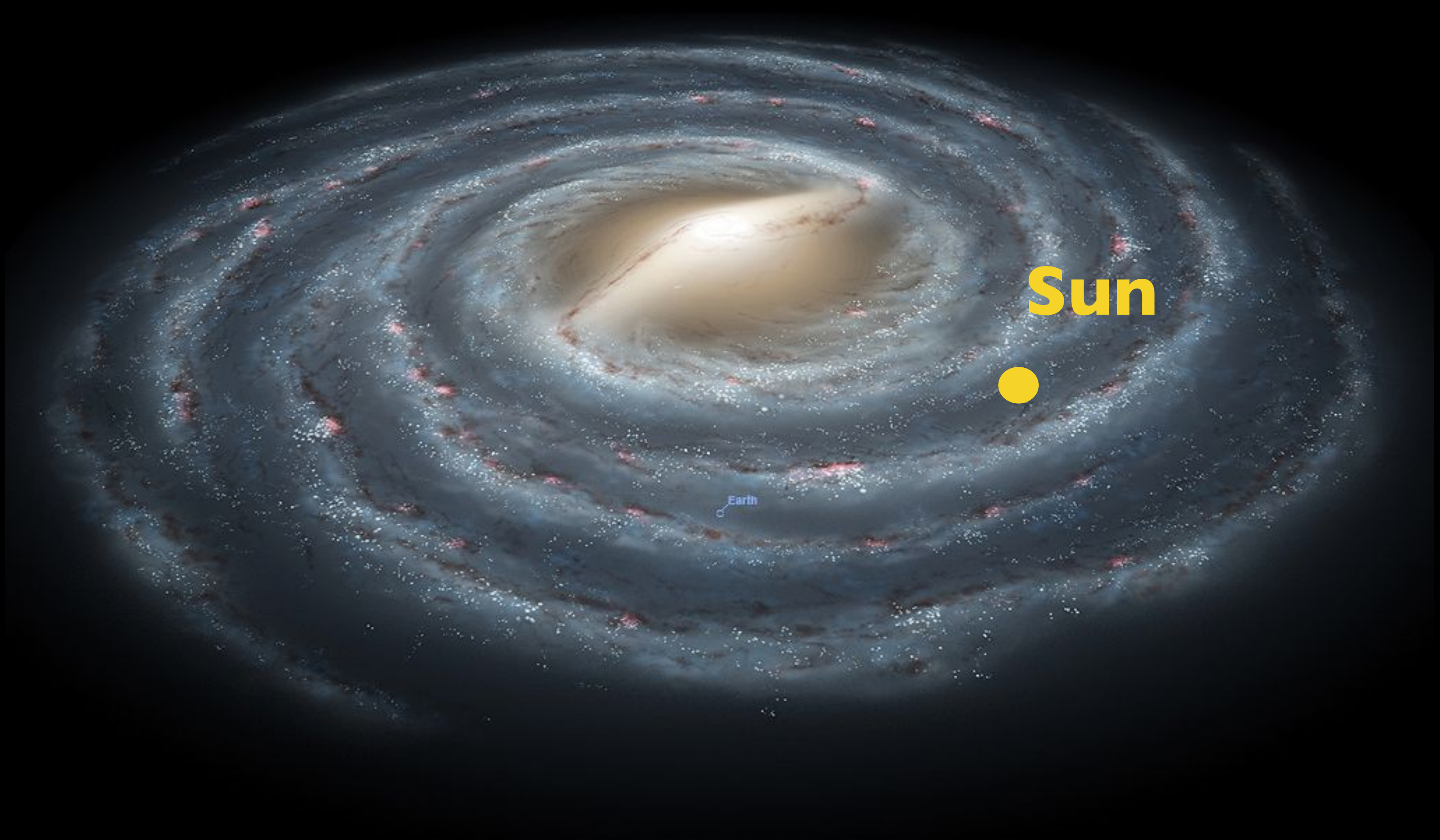
IP3

Dark Matter distribution

Signals in direct and indirect dark matter (DM) searches strongly depend on the DM distribution in our Galaxy.



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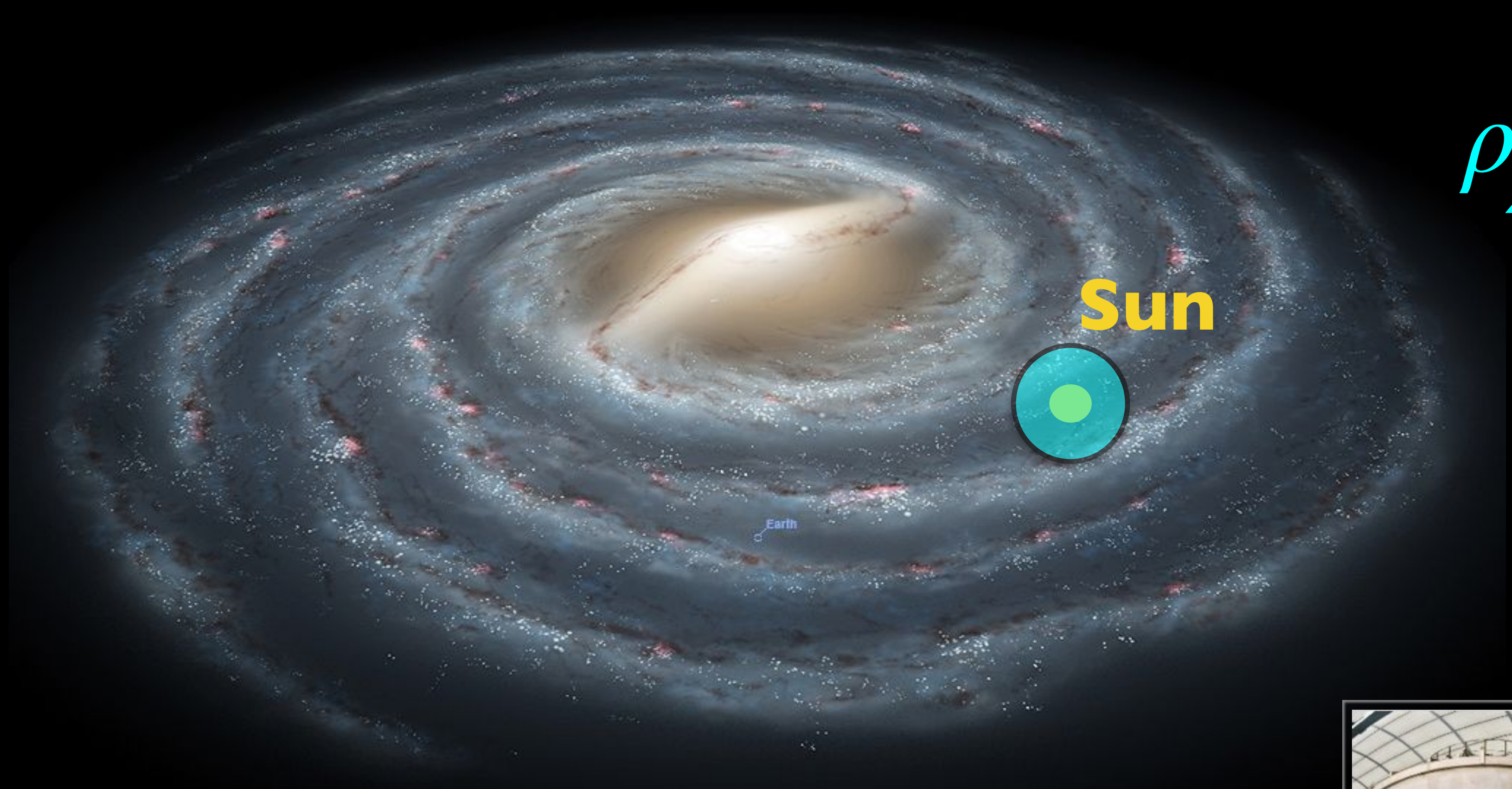
Direct Detection

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



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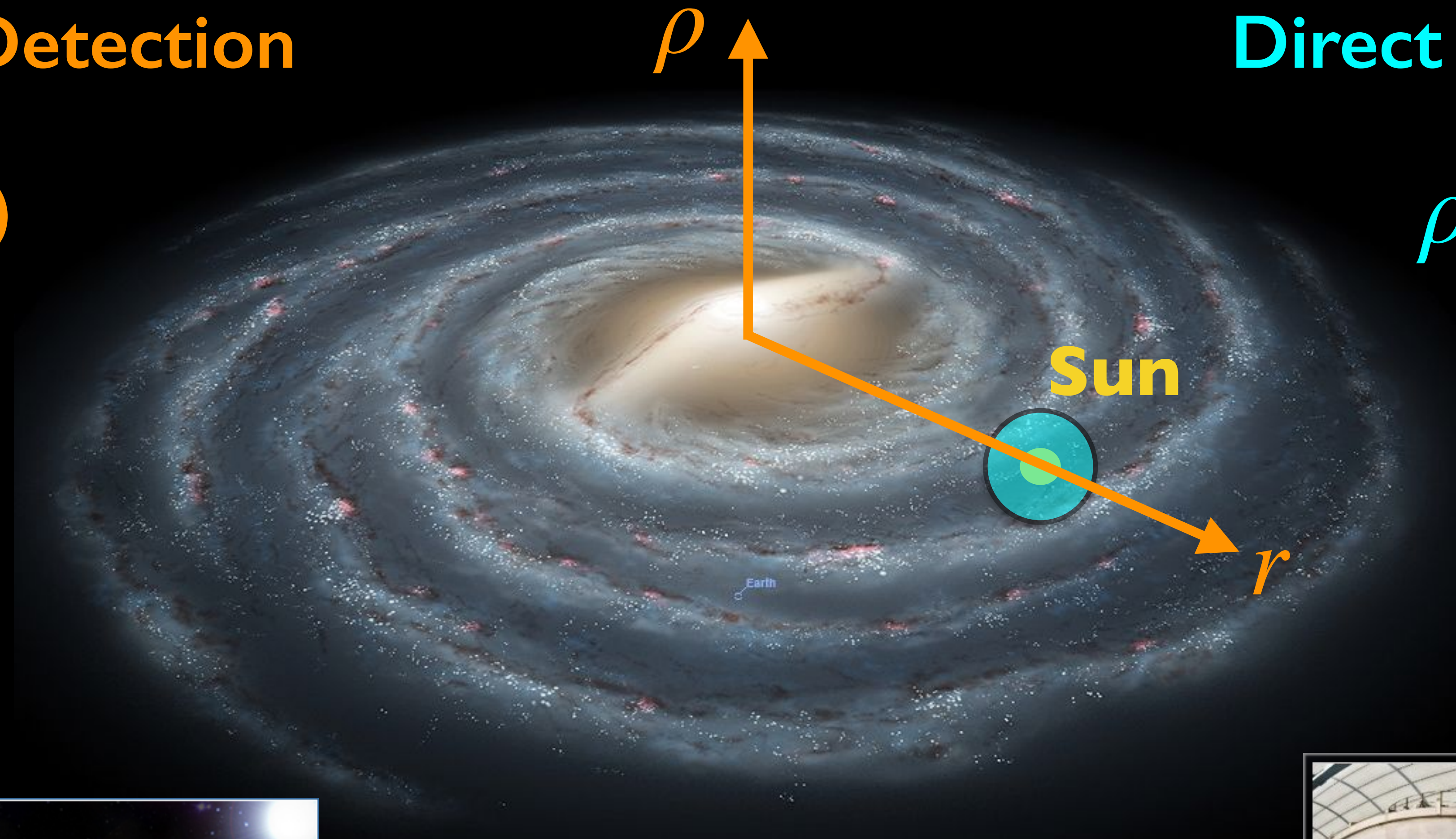
Indirect Detection

$\rho(r)$



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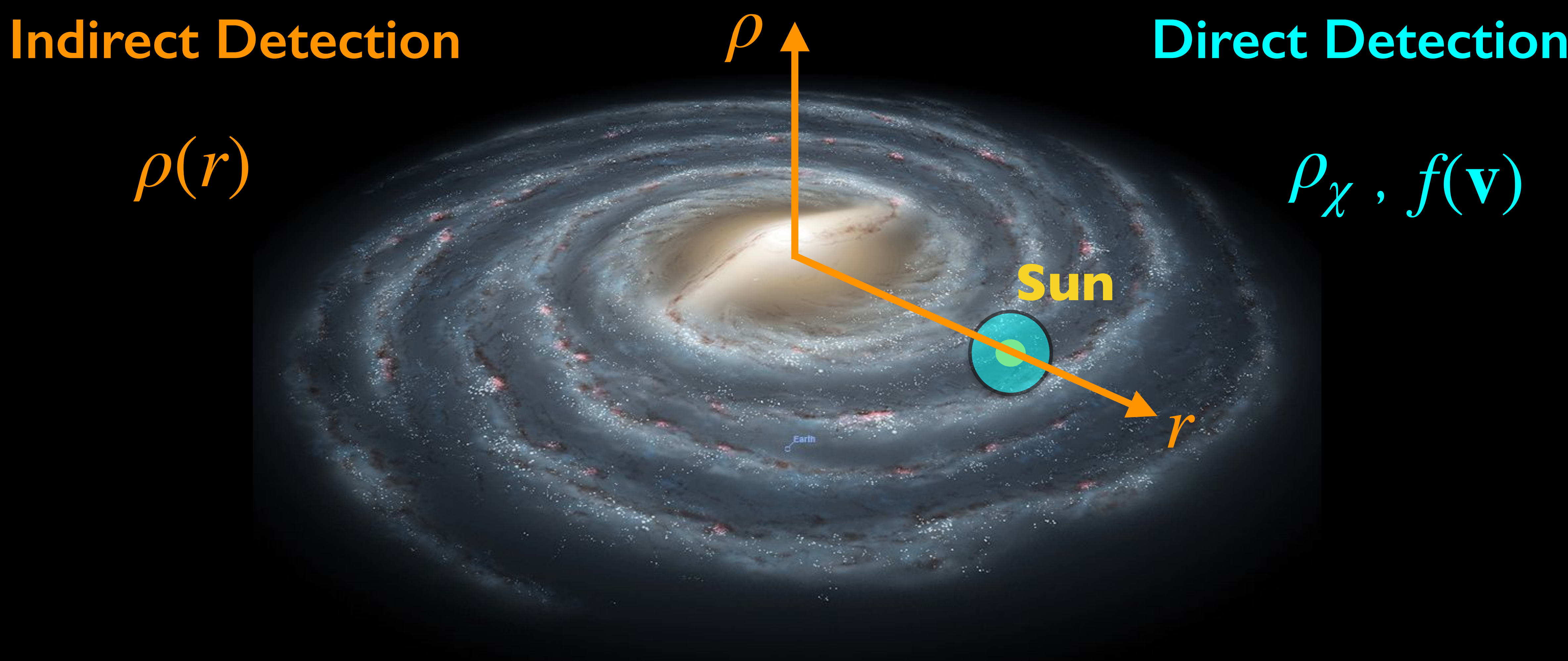

- Extract the DM distribution from high resolution cosmological simulations to make accurate predictions for DM searches.

Prospects for direct DM searches

Astrophysical inputs

astrophysics

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

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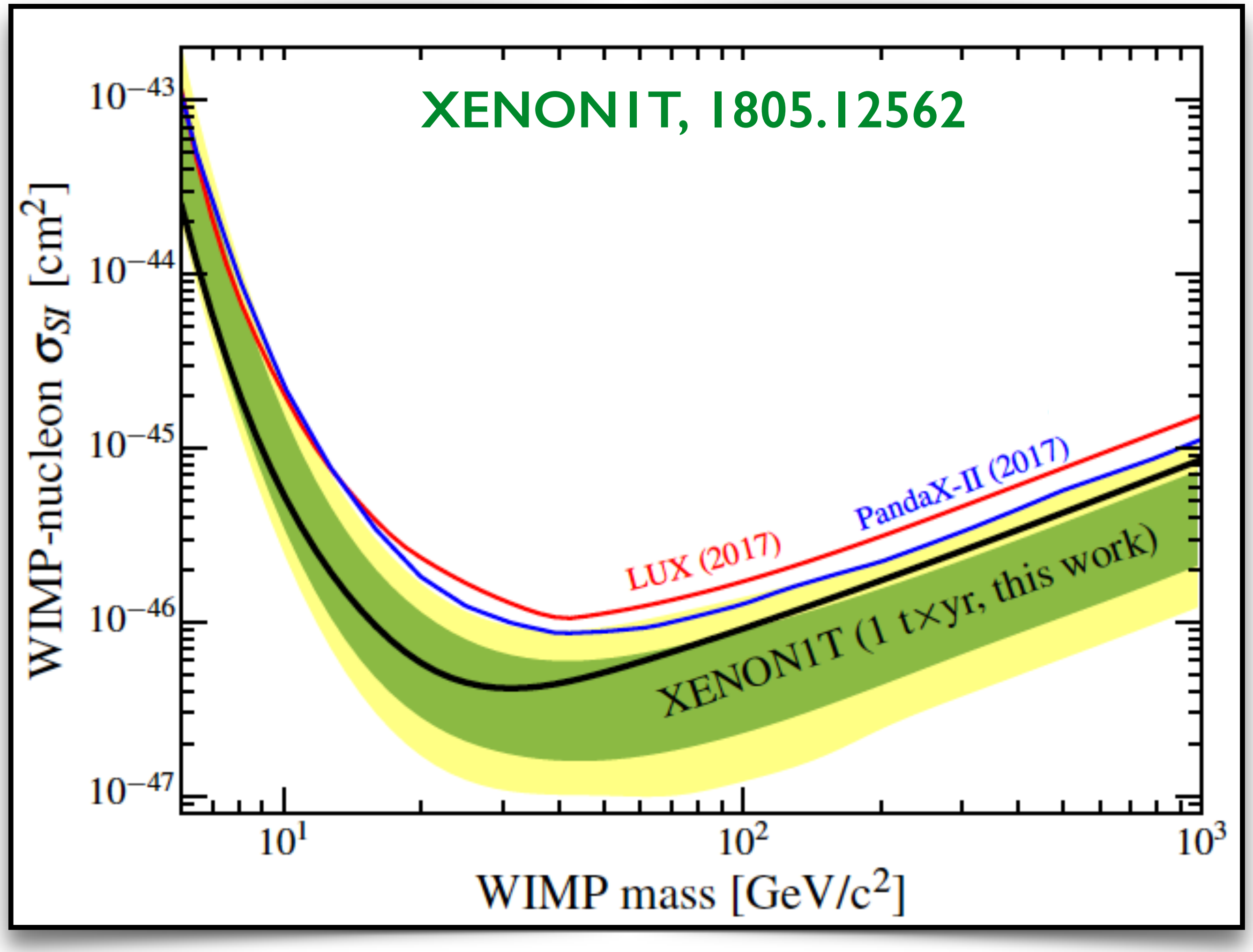
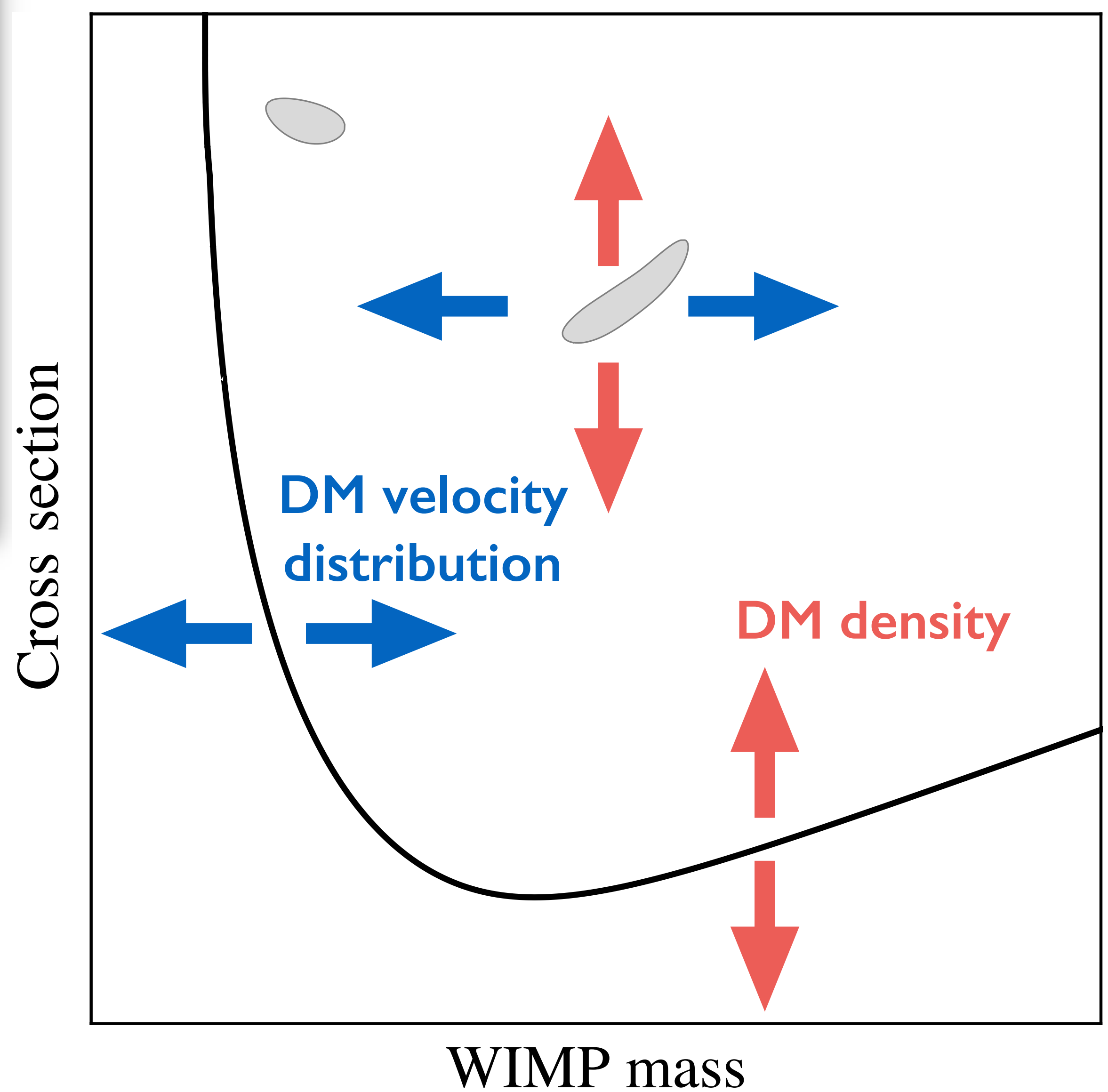
- **Standard Halo model (SHM):** isothermal sphere with an isotropic Maxwell-Boltzmann velocity distribution with a ***peak speed*** equal to the ***local circular speed*** (~220 km/s).

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

Astrophysical inputs



Assumption: **SHM**



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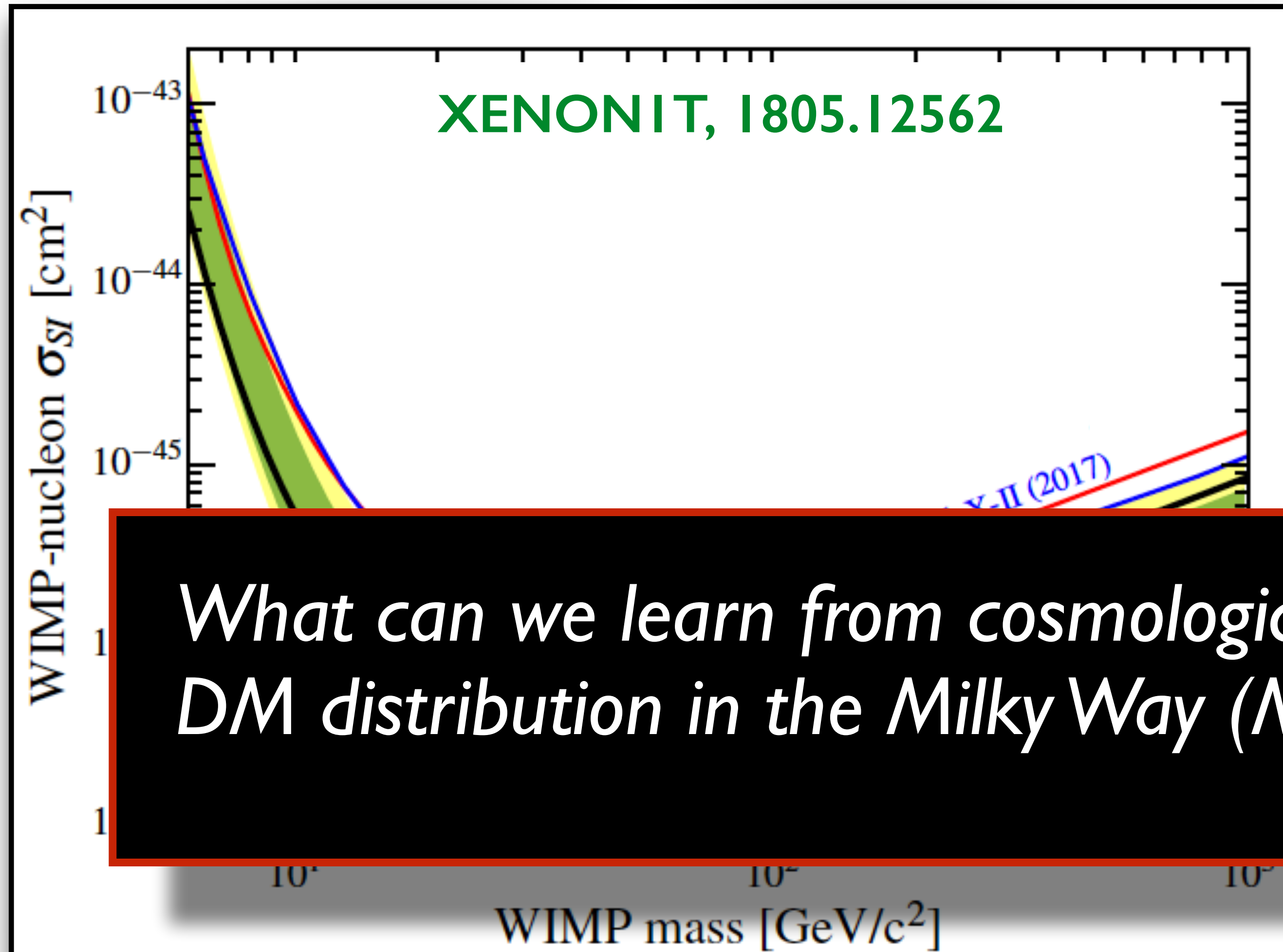

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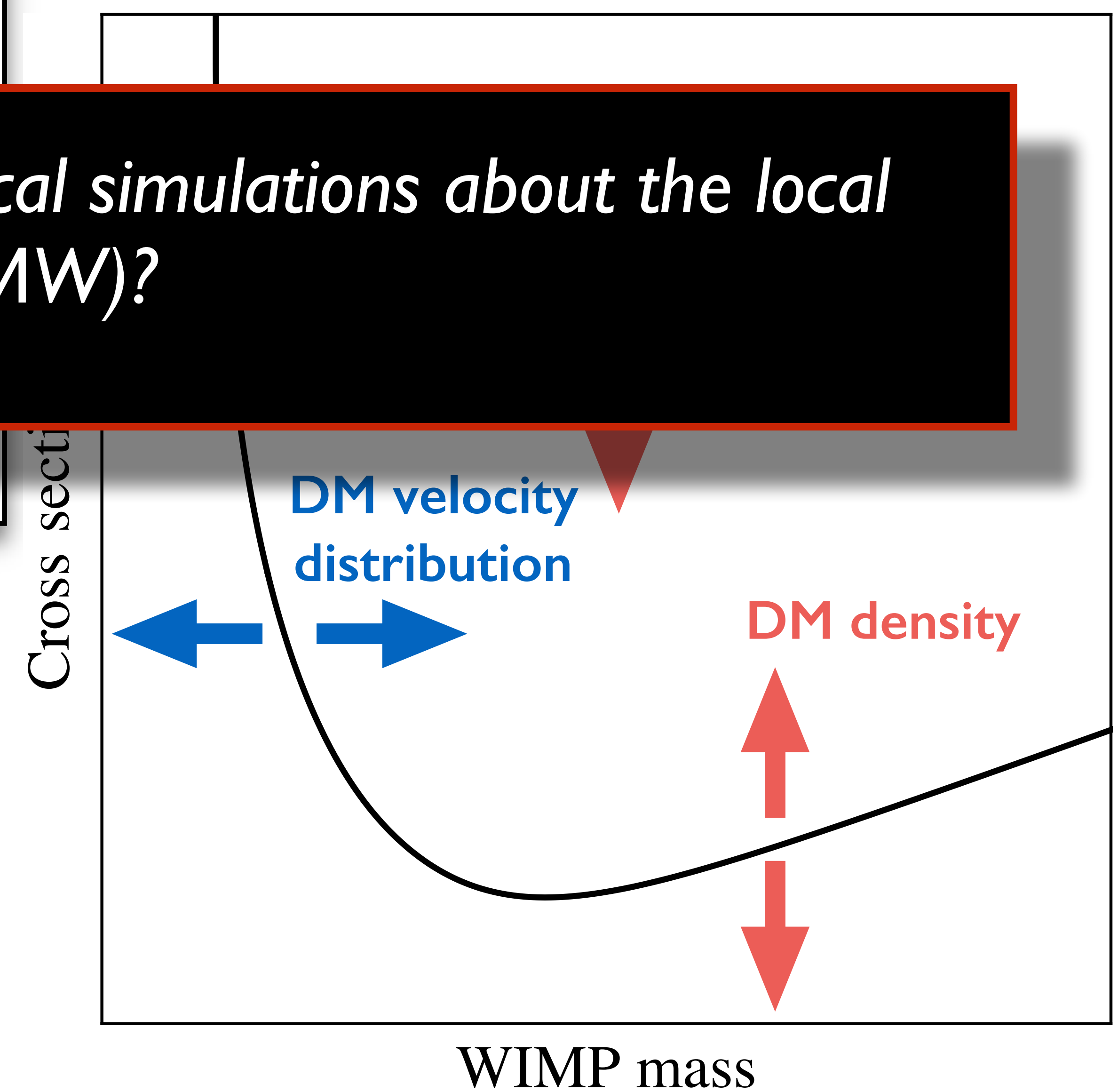
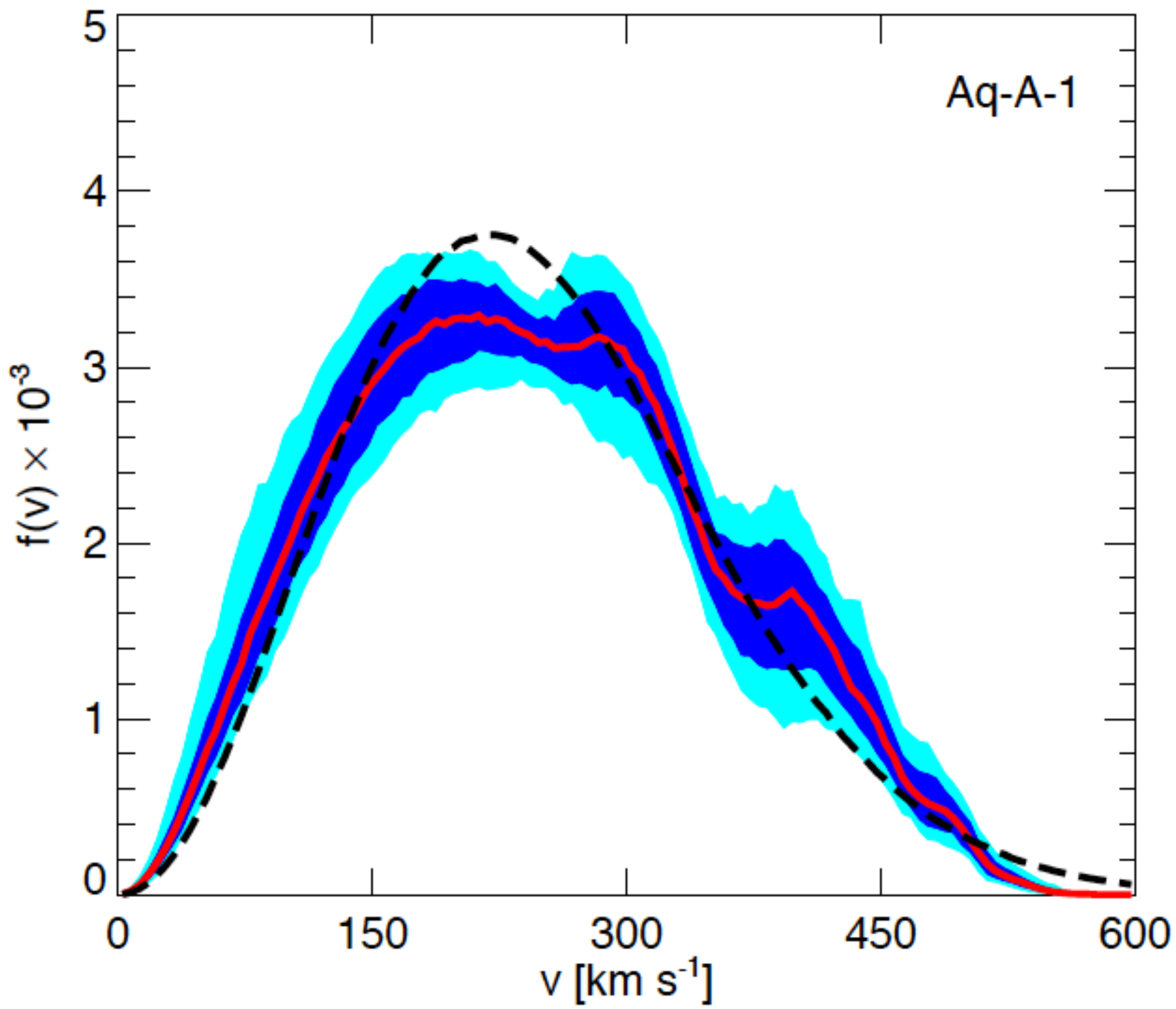


What can we learn from cosmological simulations about the local DM distribution in the Milky Way (MW)?

Dark Matter only simulations

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



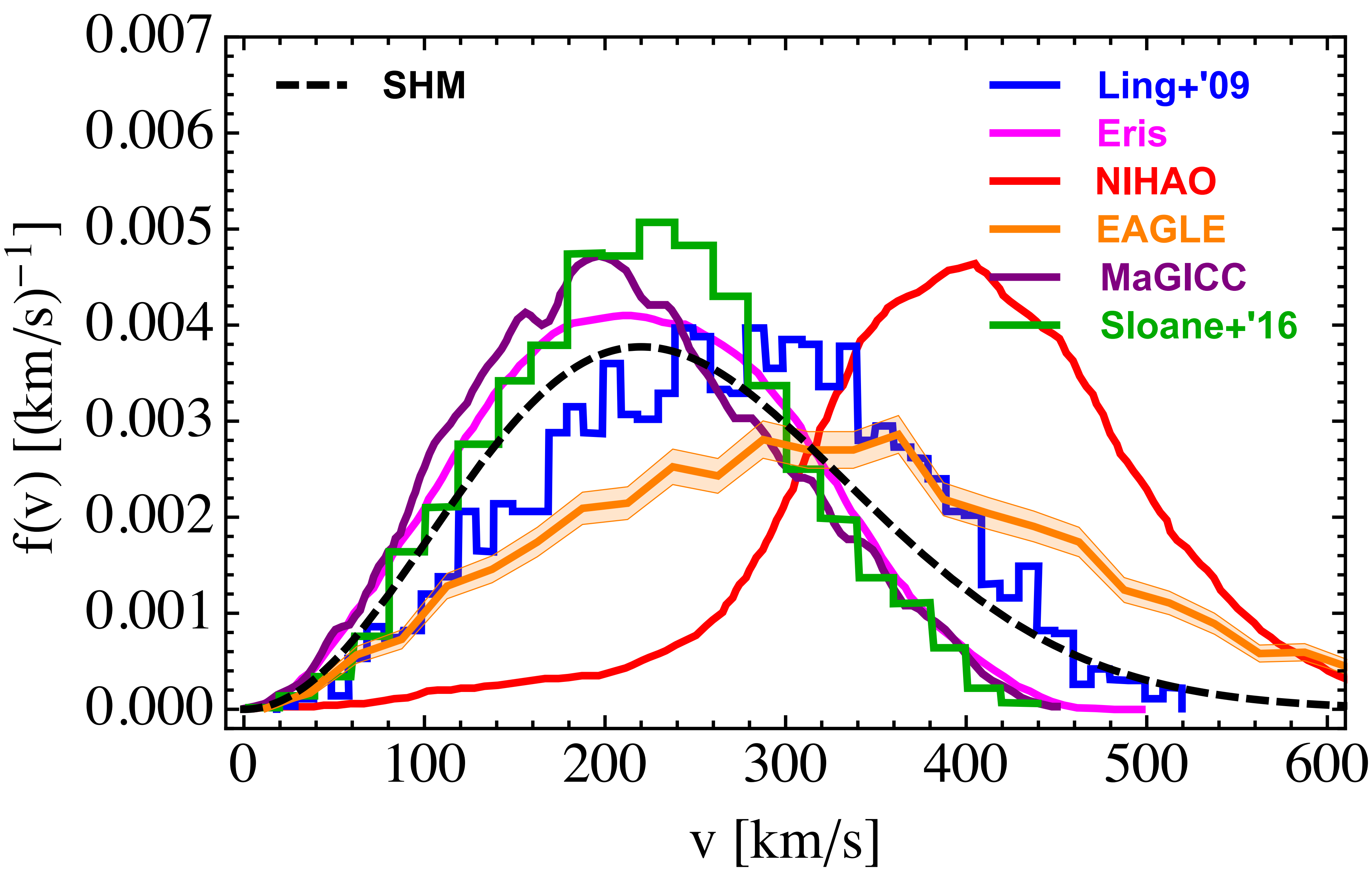
$$f(|\mathbf{v}|) = v^2 \int d\Omega_{\mathbf{v}} f(\mathbf{v})$$

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*, *particle mass*.



Bozorgnia & Bertone, 1705.05853

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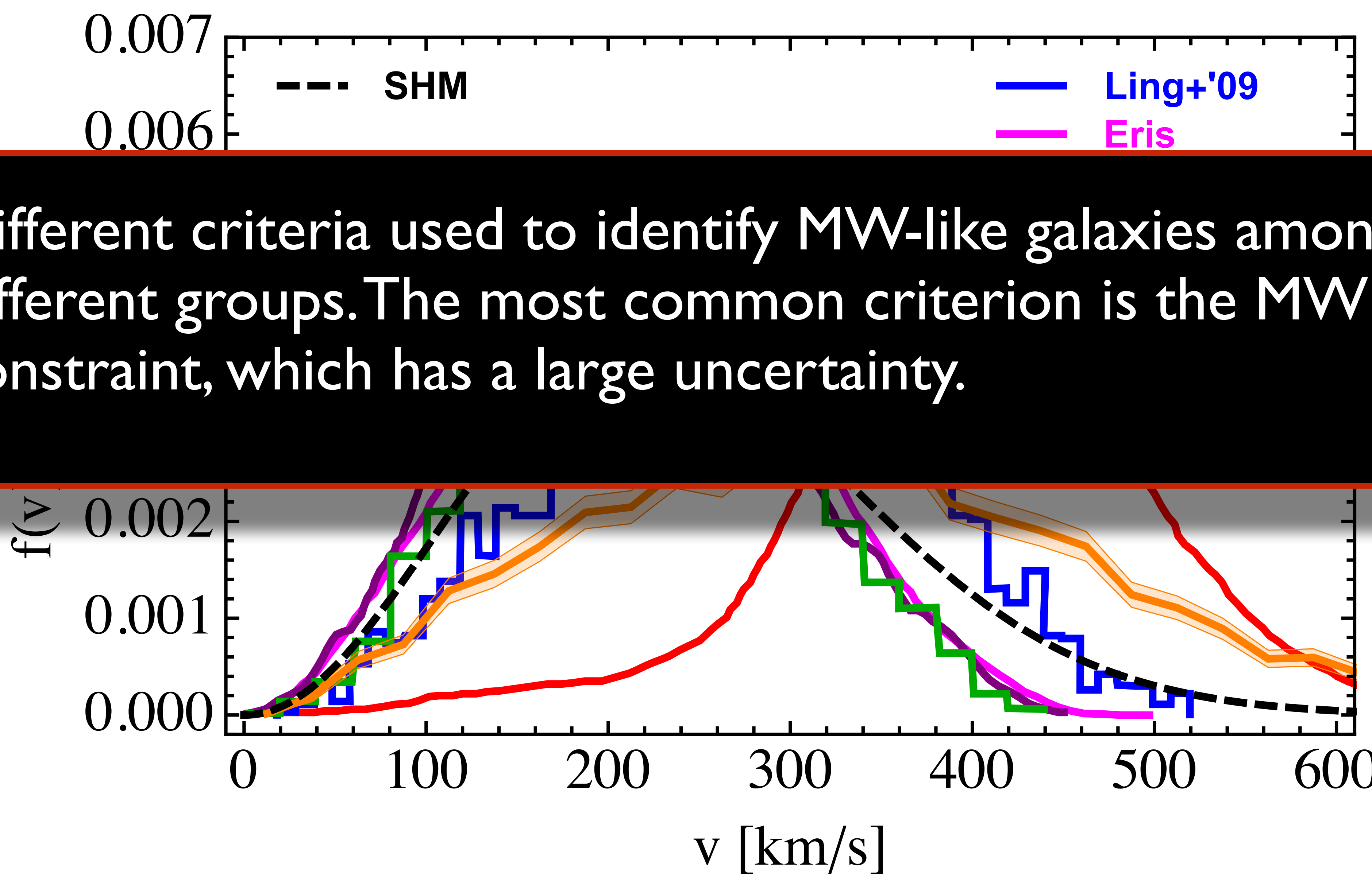
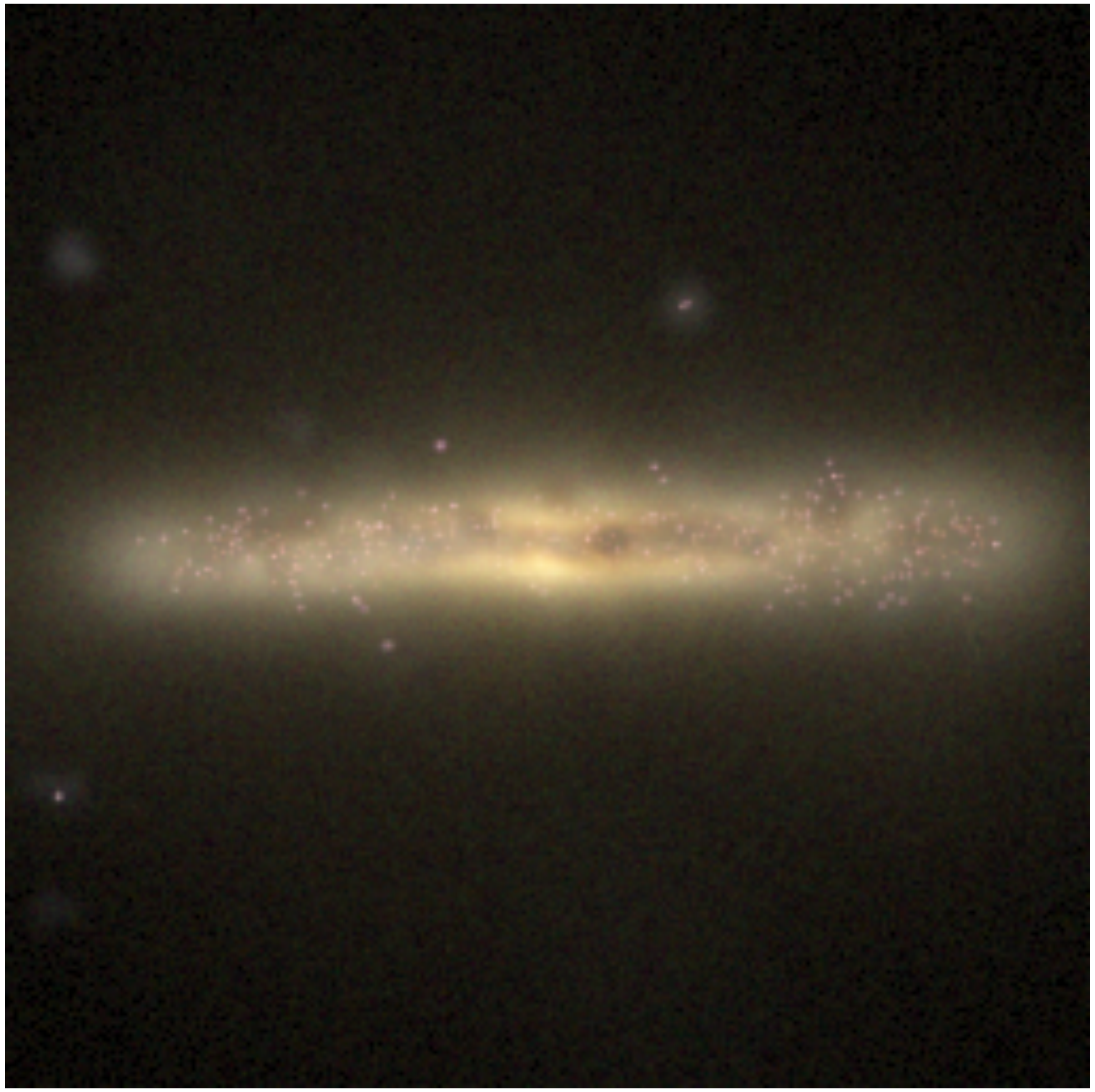


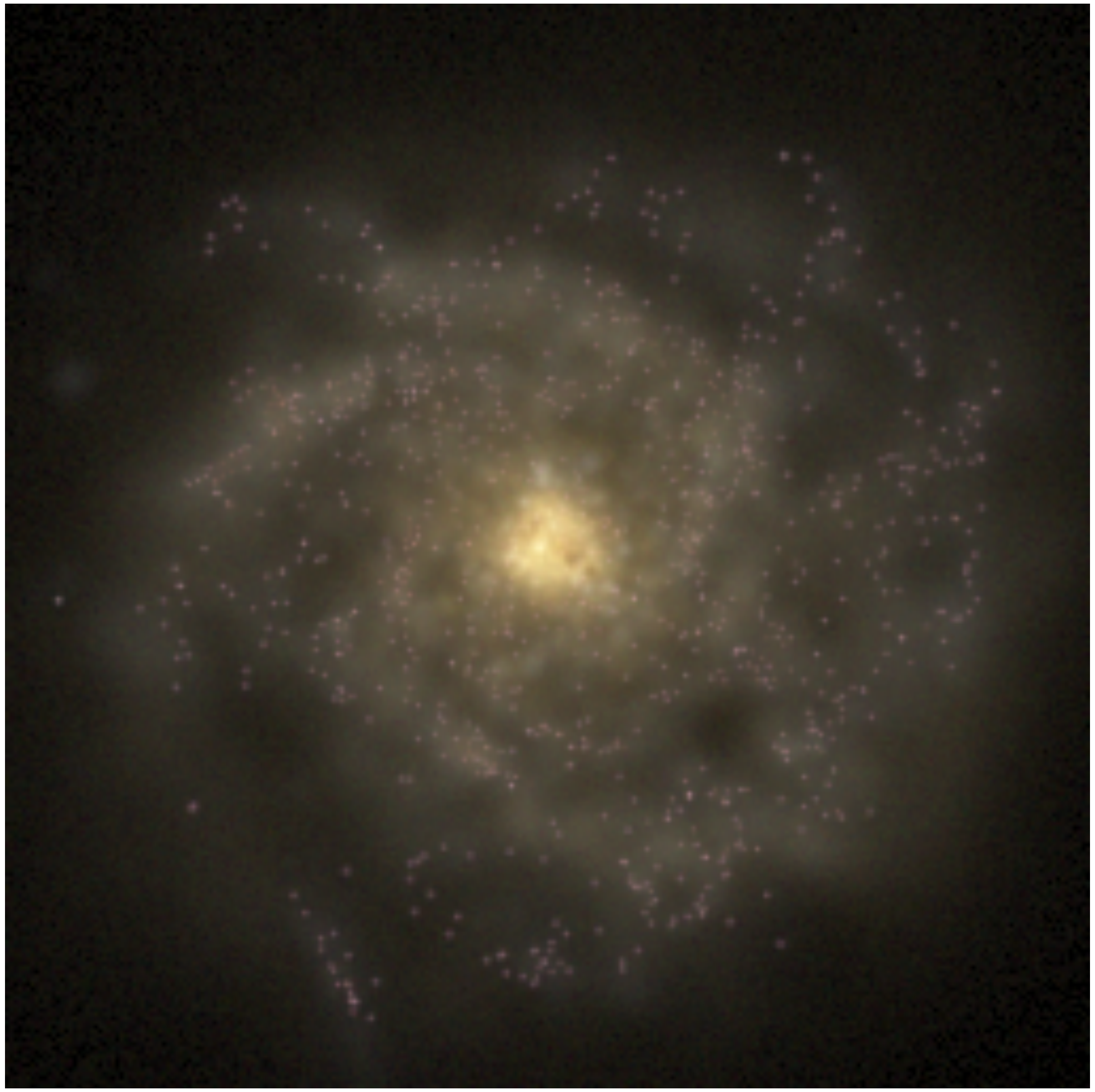
Different criteria used to identify MW-like galaxies among different groups. The most common criterion is the MW mass constraint, which has a large uncertainty.

Bozorgnia & Bertone, 1705.05853

EAGLE and APOSTLE

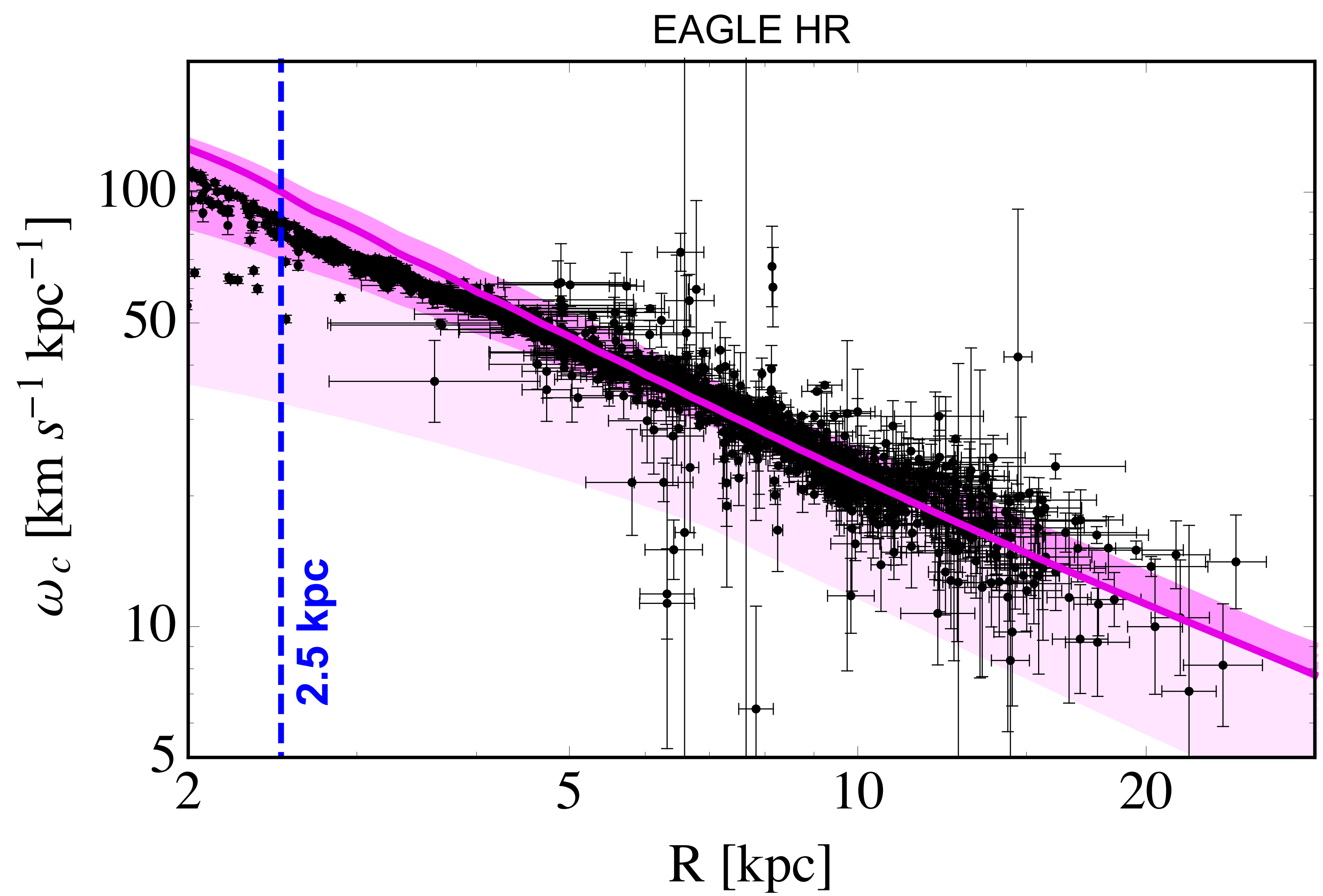
- We use the **EAGLE** and **APOSTLE** hydrodynamic simulations. *Calibrated to reproduce the observed distribution of stellar masses and sizes of low-redshift galaxies.*





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.**

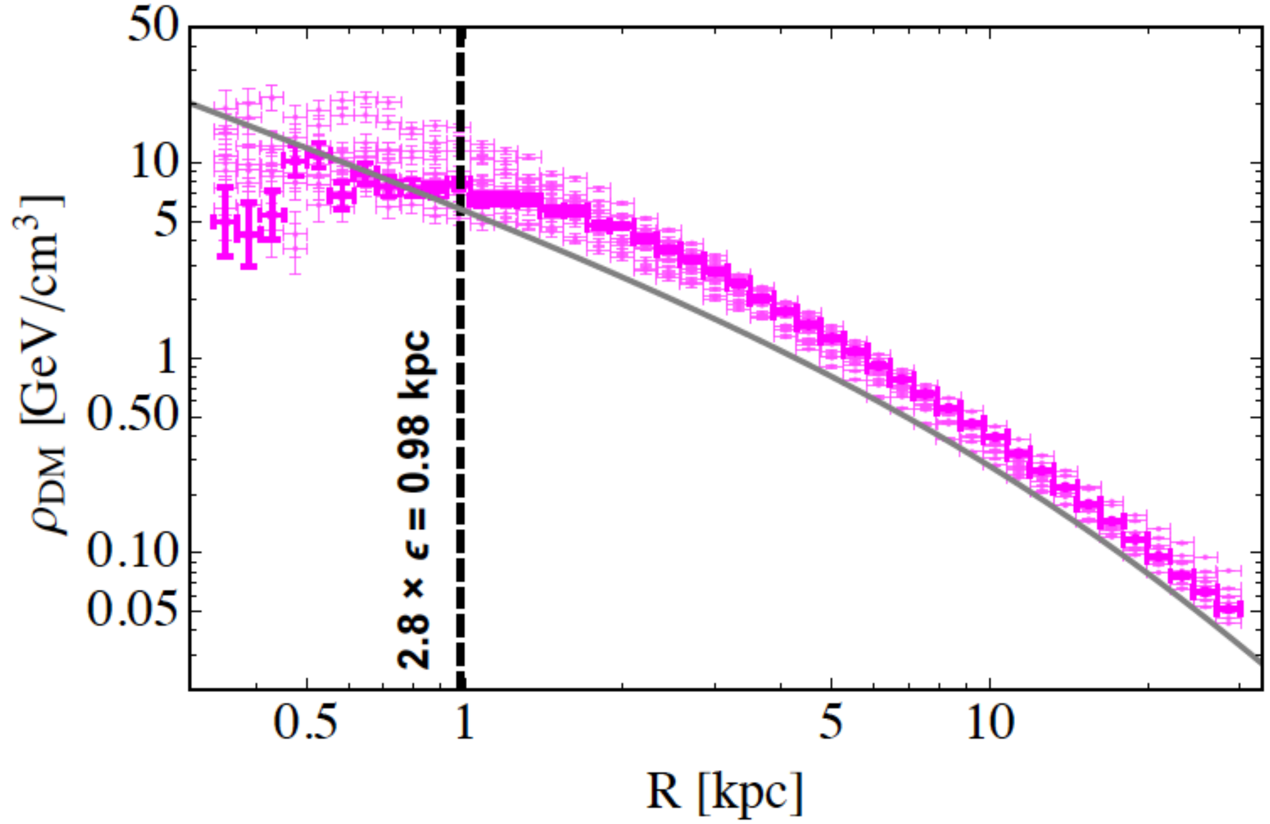


14 MW analogues

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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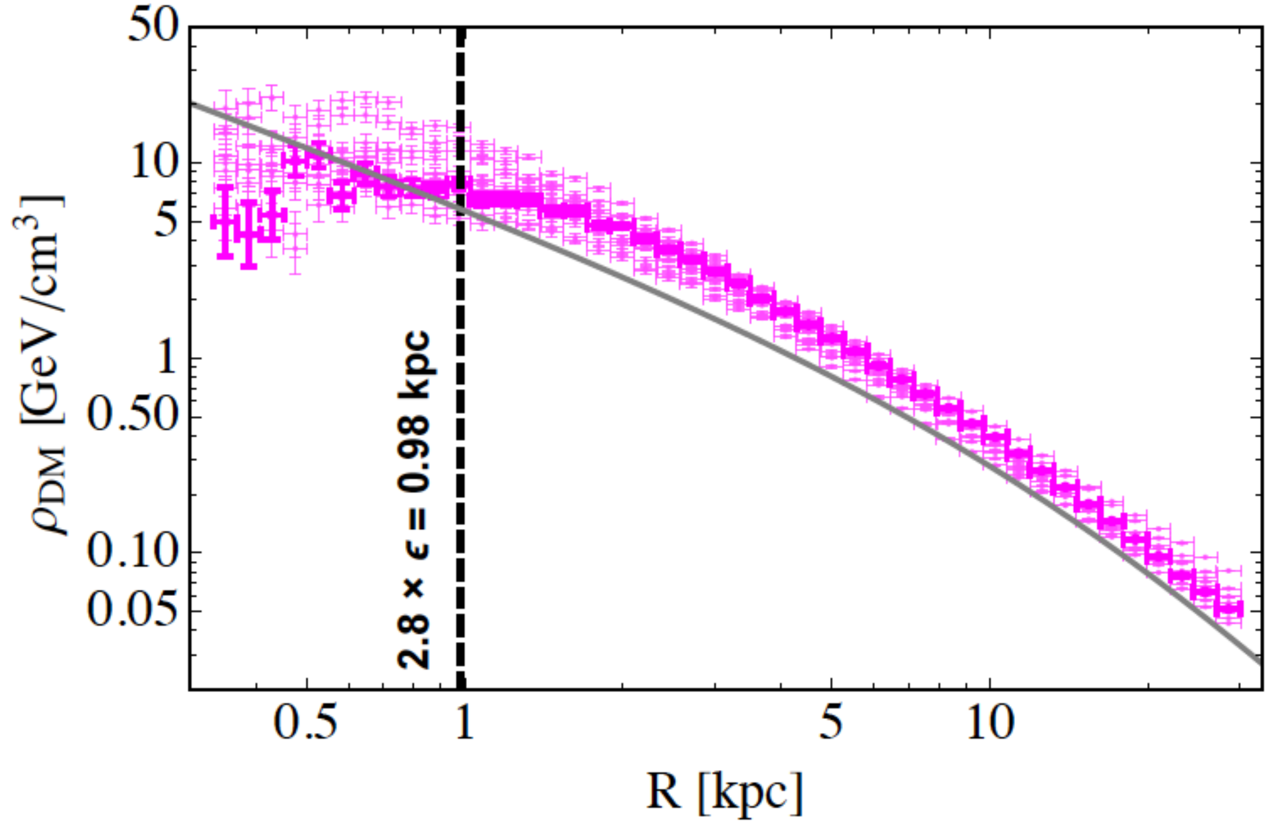
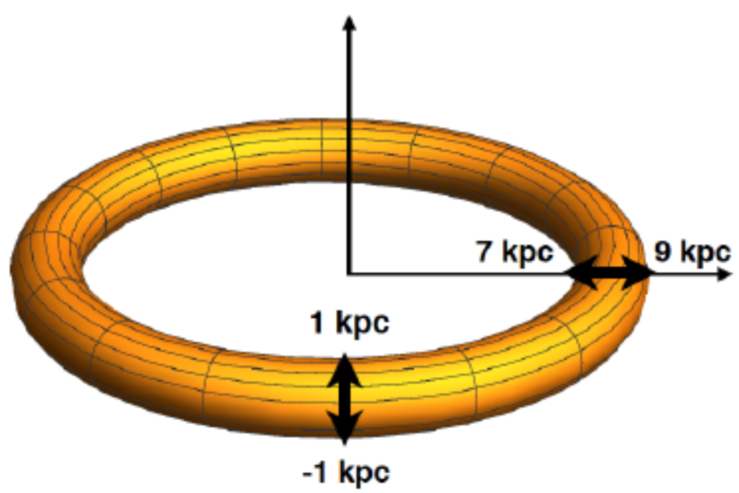


- To find the DM density at the position of the Sun, consider a torus aligned with the stellar disc.

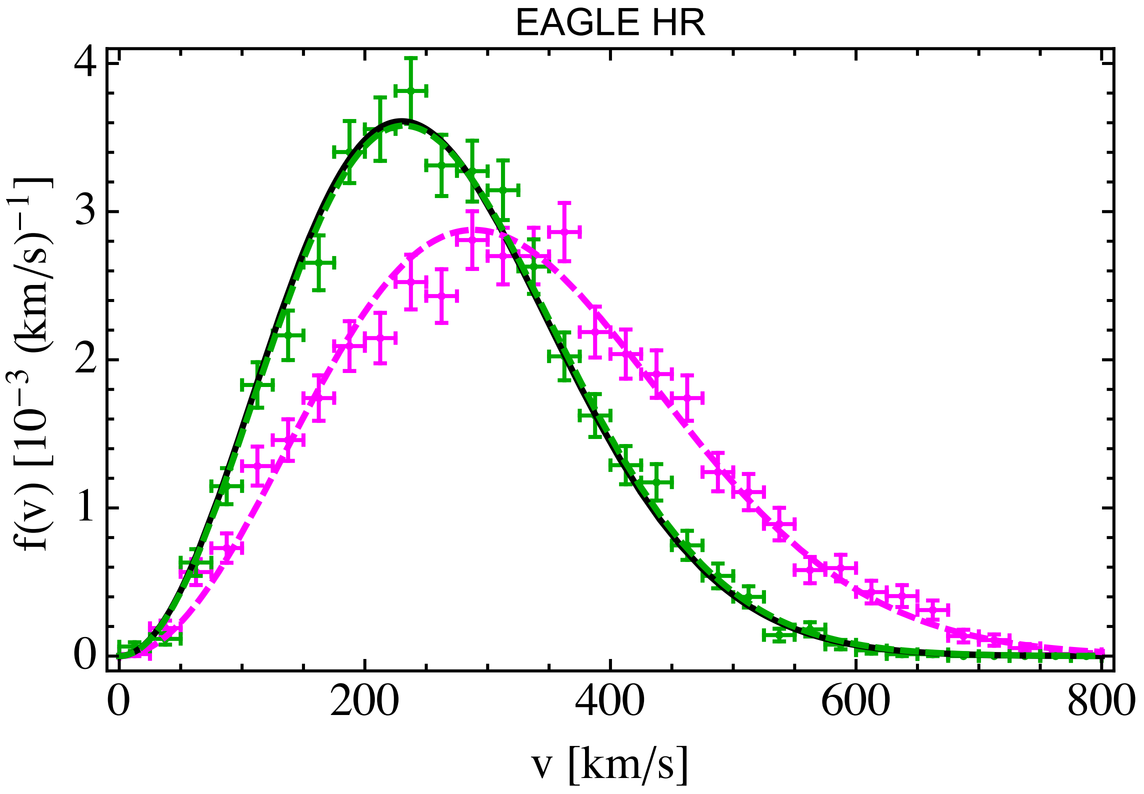


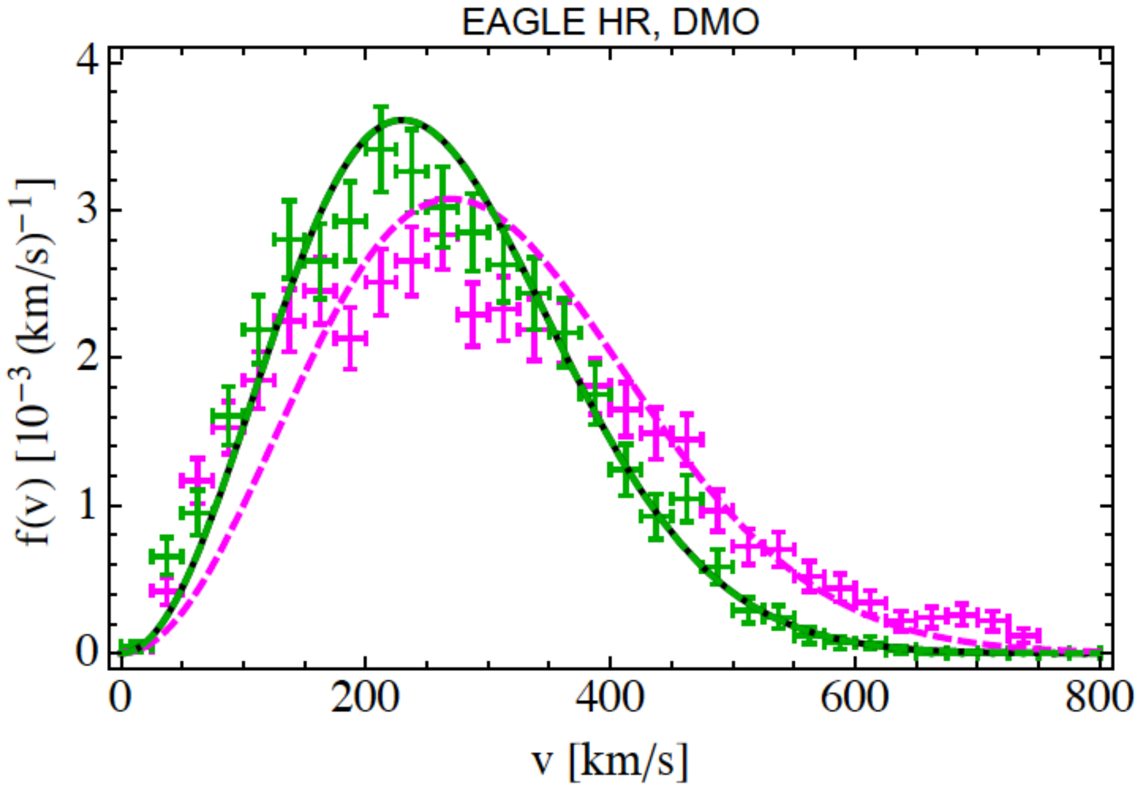
$$\boxed{\rho_\chi = 0.41 - 0.73\ \mathrm{GeV/cm^3}}$$

Local speed distributions

In the galactic rest frame:

DMO simulations





Bozorgnia et al., 1601.04707

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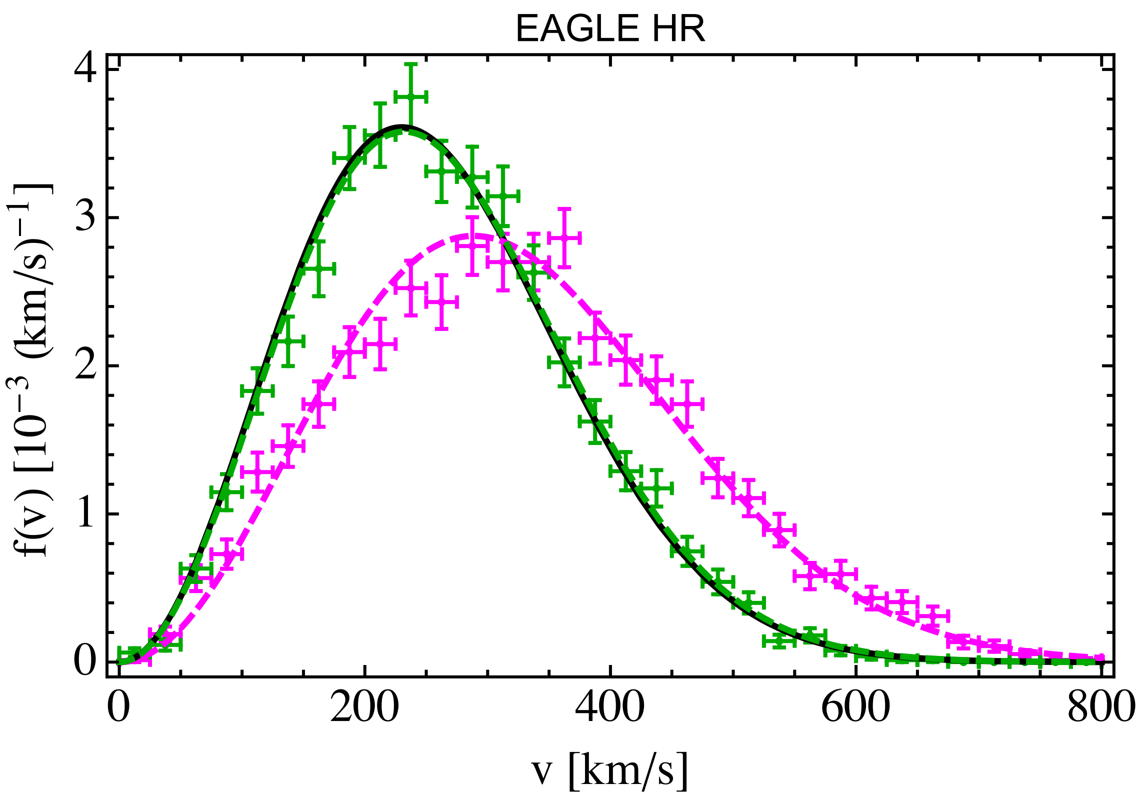
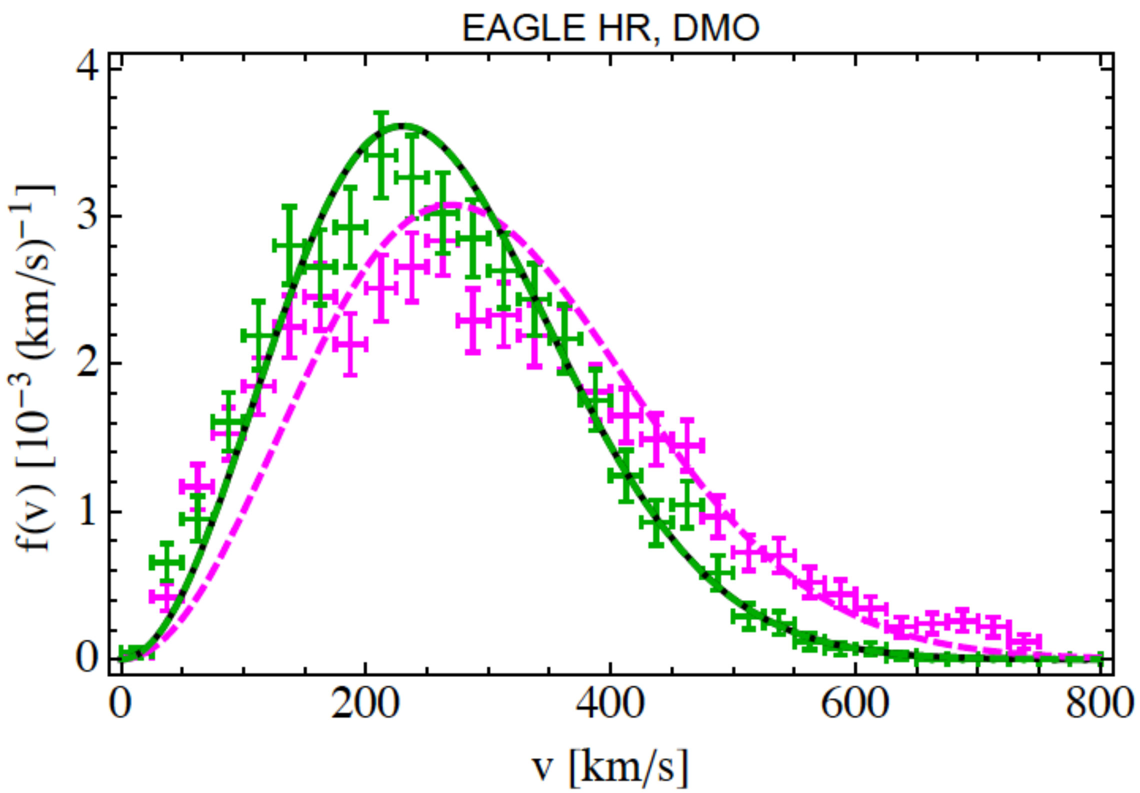




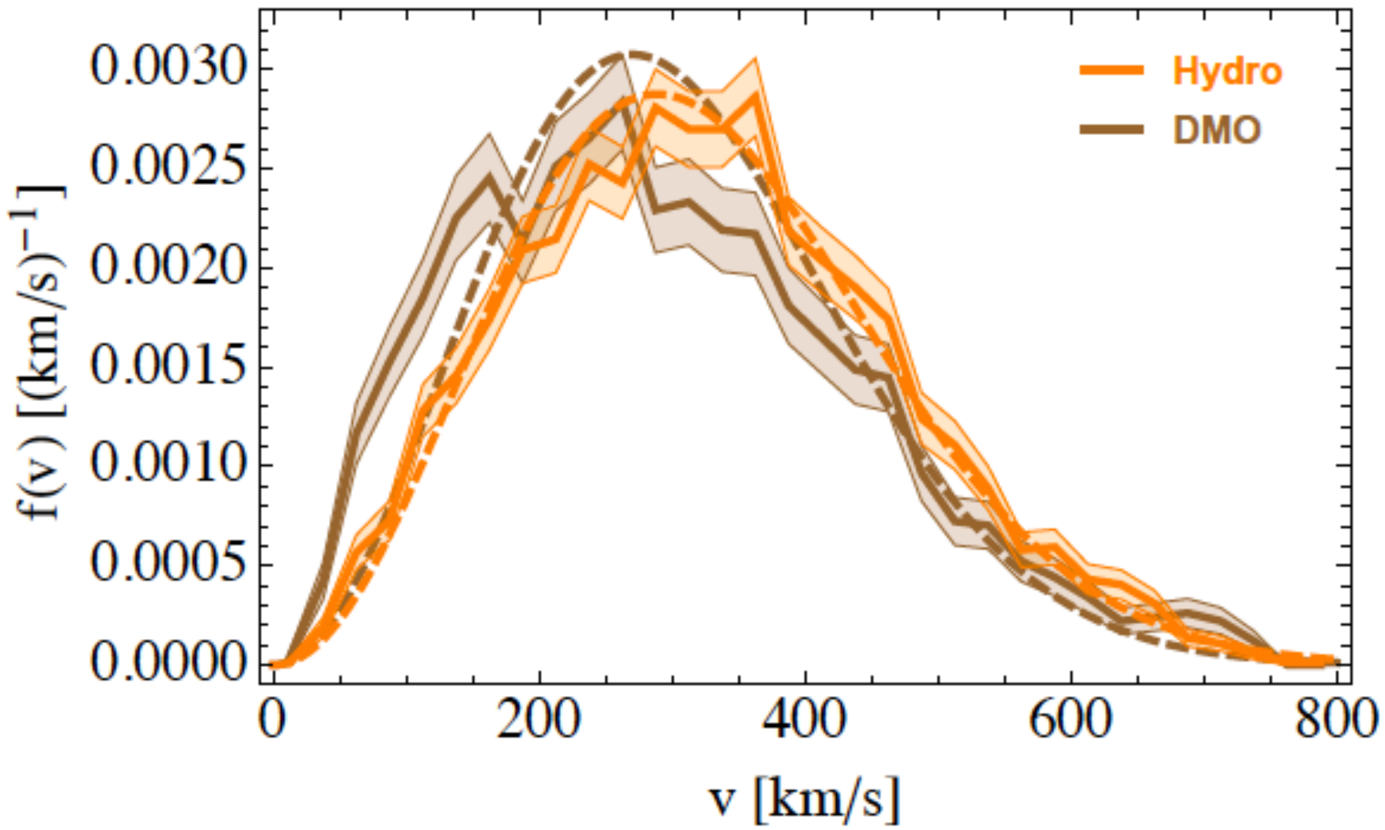
Bozorgnia et al., 1601.04707

- 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: $\boxed{v_{peak} = 223 - 289 \text{ km/s}}$

Local speed distributions

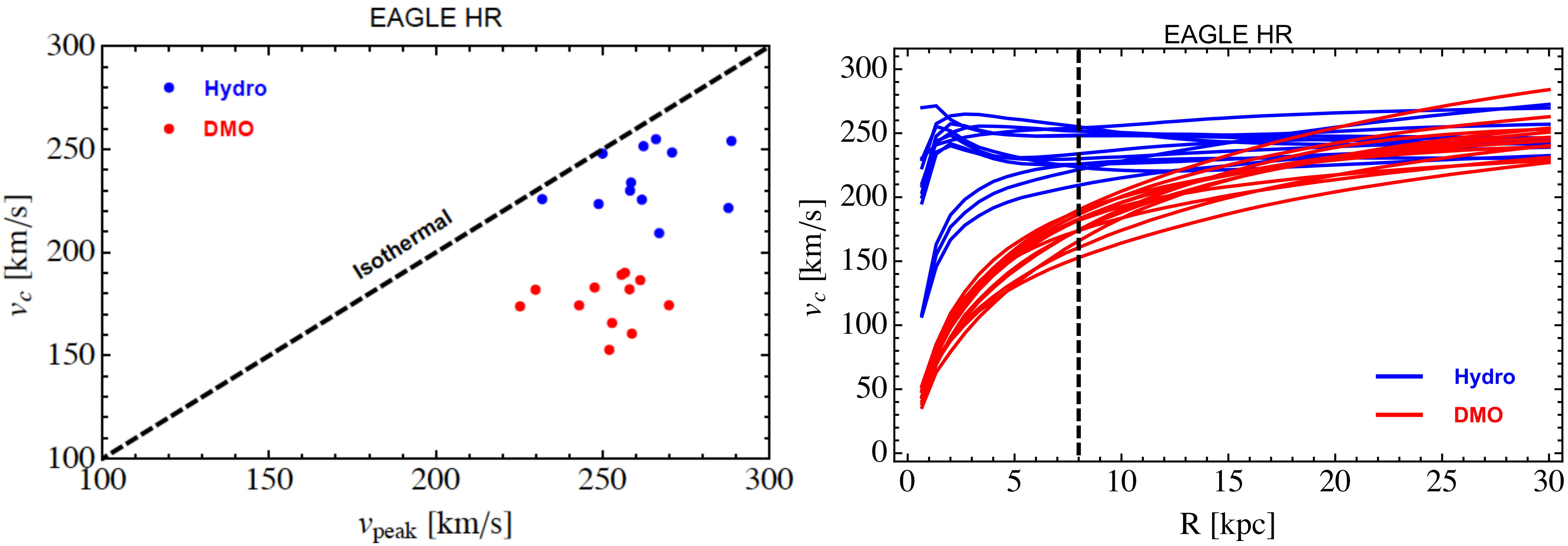
Common trends in different hydrodynamical simulations:

- 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

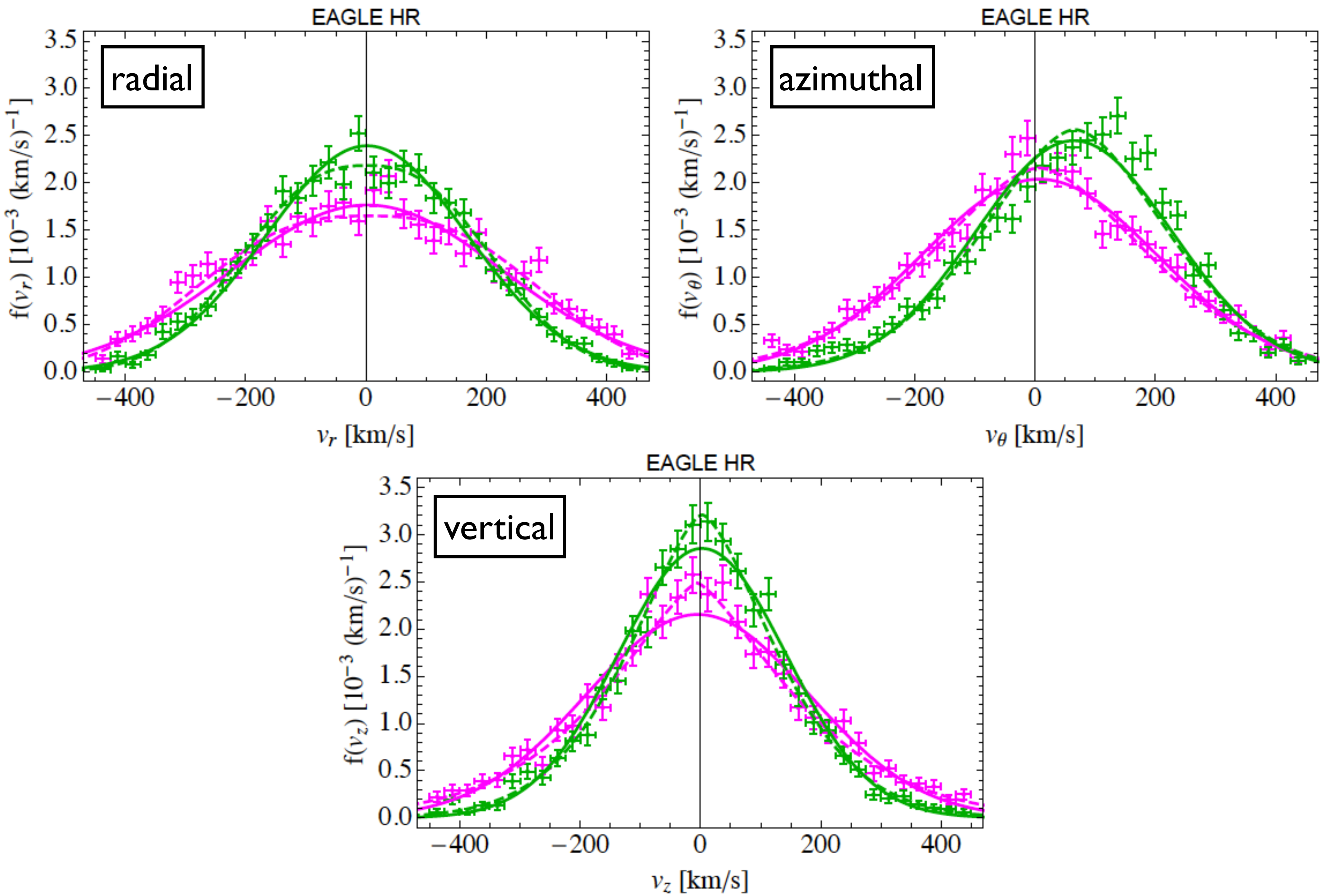
Departure from isothermal



Bozorgnia & Bertone, 1705.05853

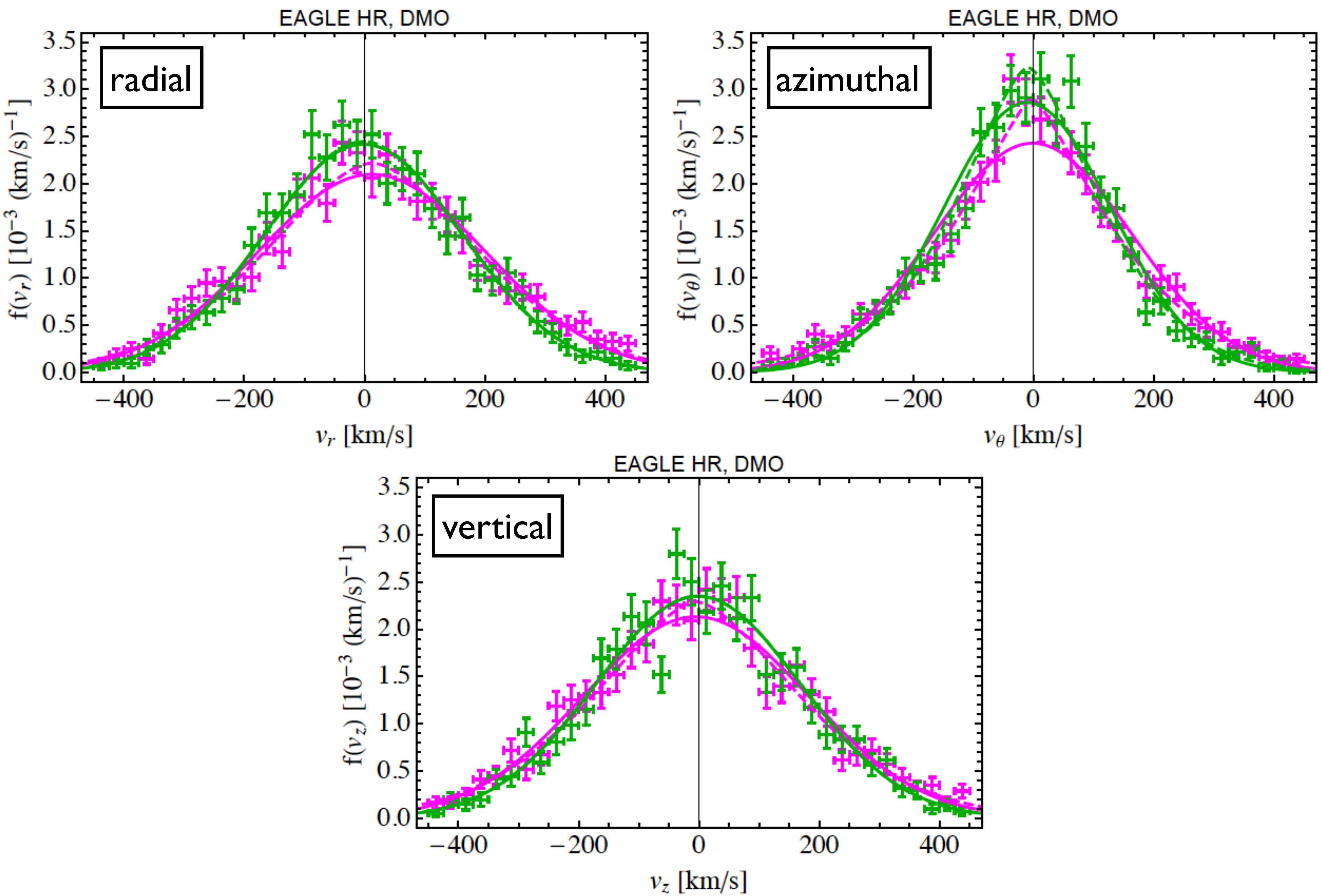
- At the Solar circle, haloes in the hydrodynamical simulation are closer to isothermal than their DMO counterparts.

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.
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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

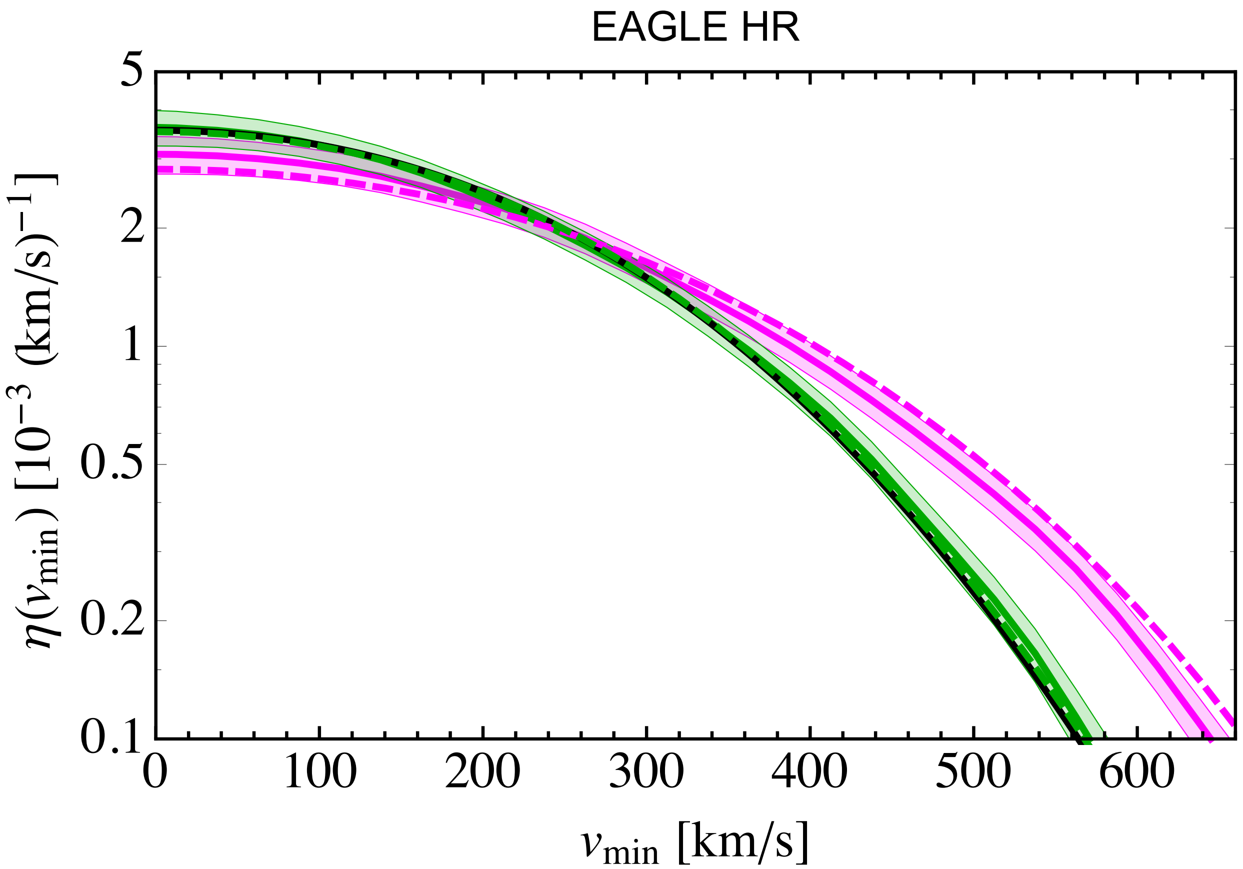
The halo integral

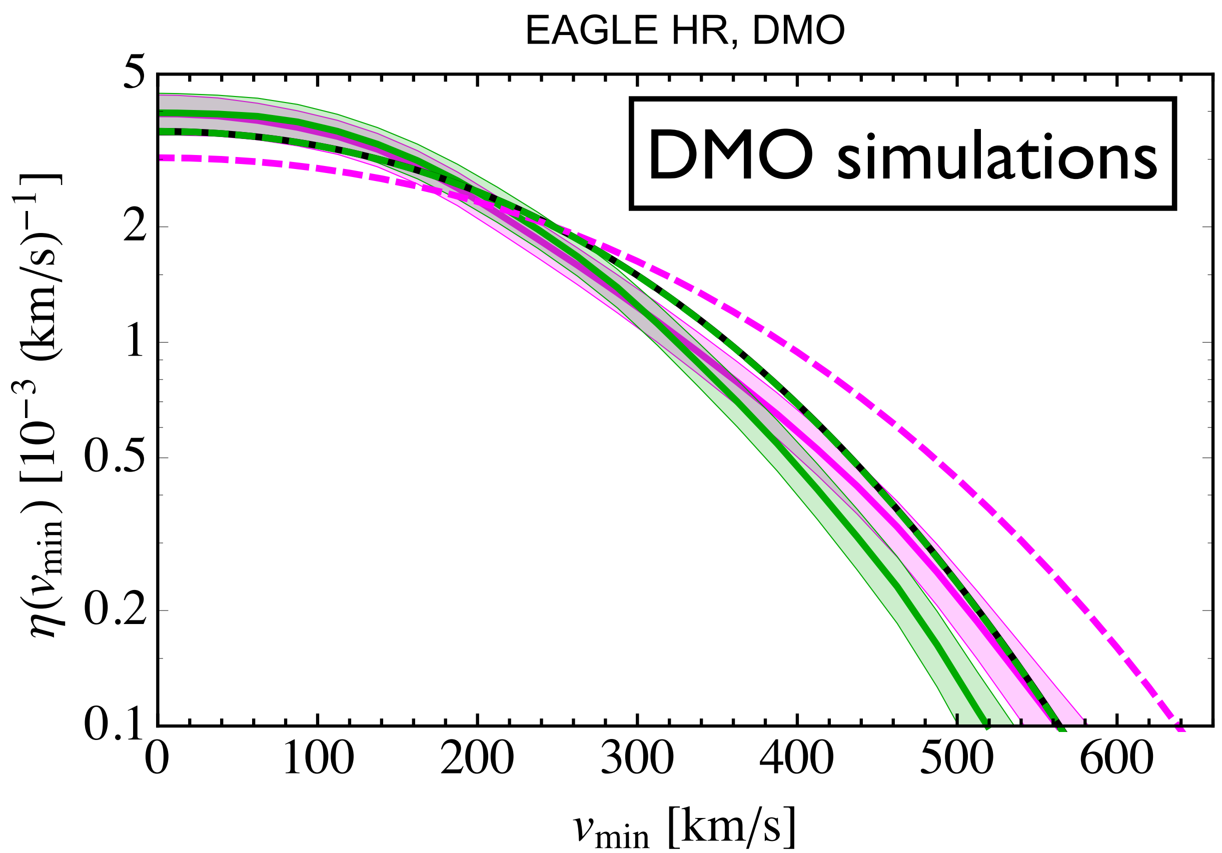
- For standard spin-independent and spin-dependent interactions:

$$\frac{dR}{dE_R} = \underbrace{\frac{\sigma_0 F^2(E_R)}{2 m_\chi \mu_{\chi N}^2}}_{\text{particle physics}} \overbrace{\rho_\chi \eta(v_{\rm min}, t)}^{\text{astrophysics}}$$

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

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

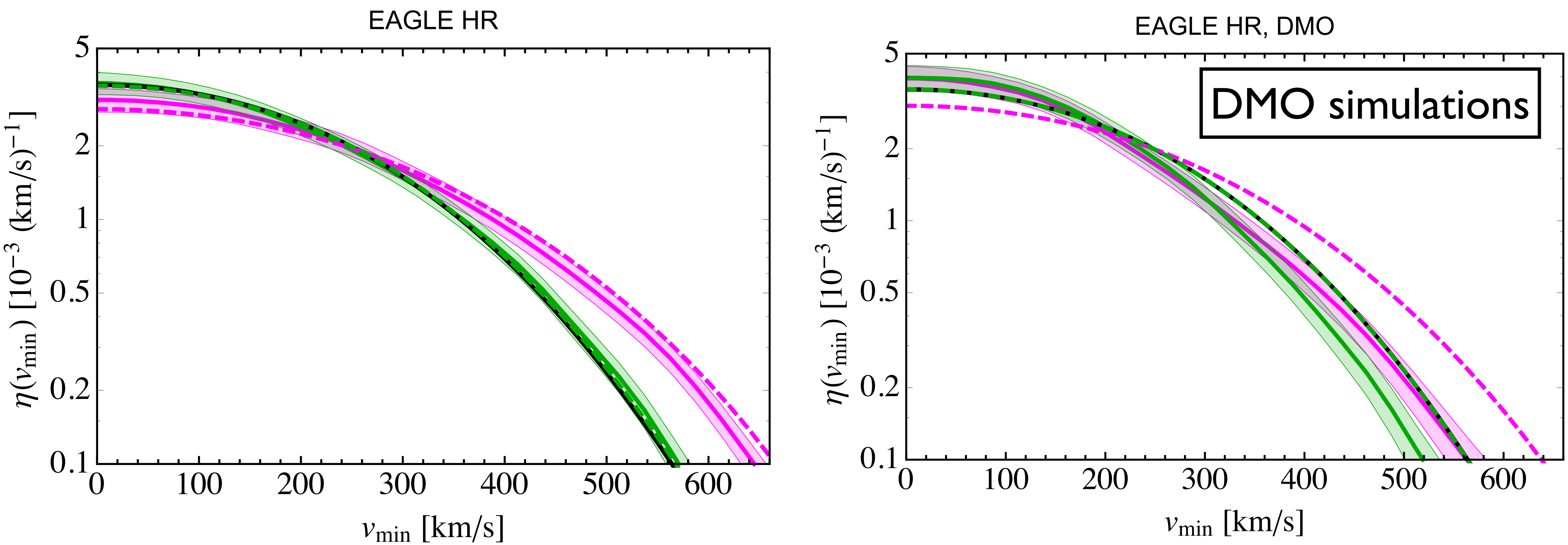




Bozorgnia et al., 1601.04707

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

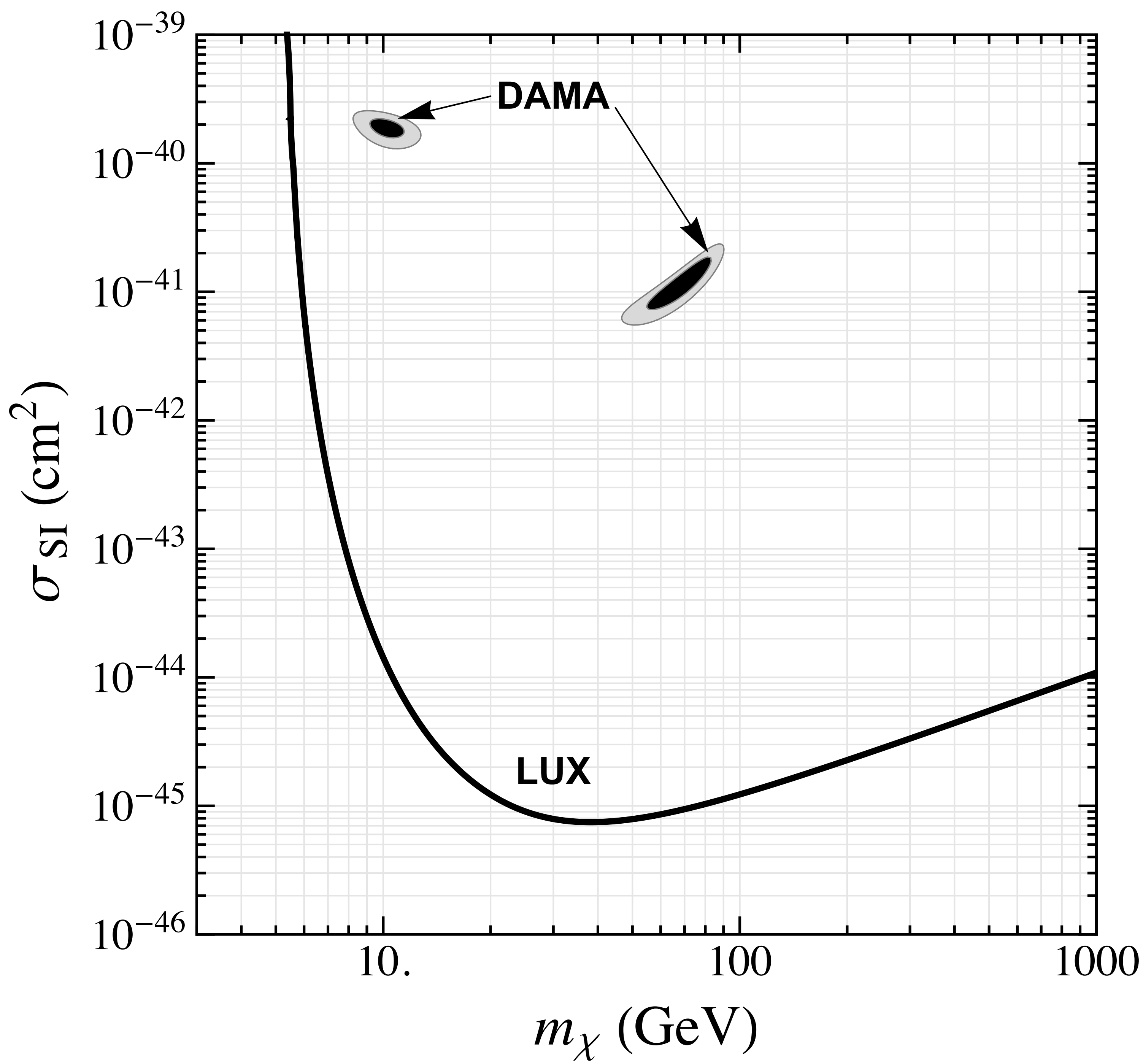
Common trend in different hydrodynamical simulations:

- 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

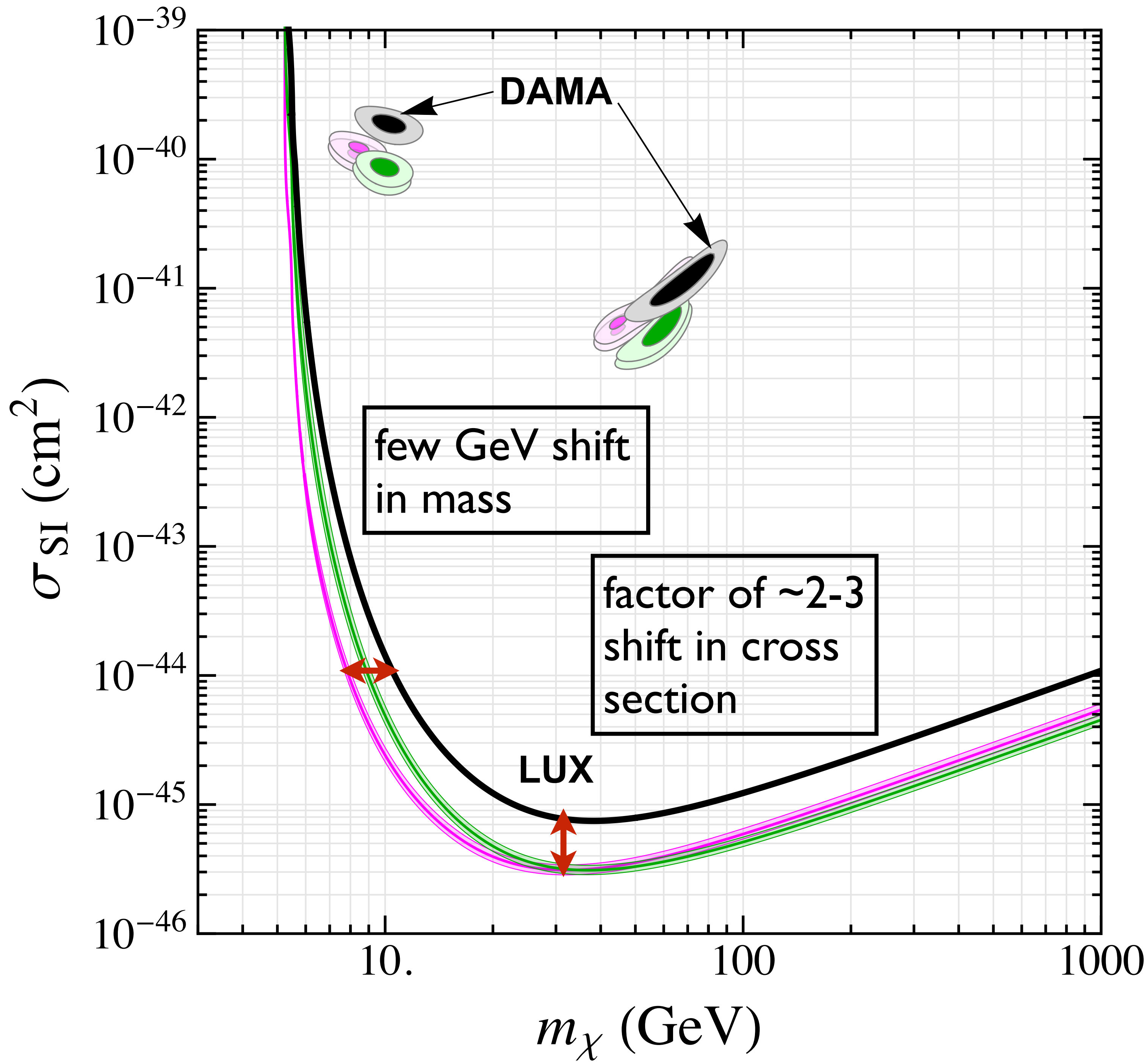
Implications for direct detection

- Assuming the **Standard Halo Model**:



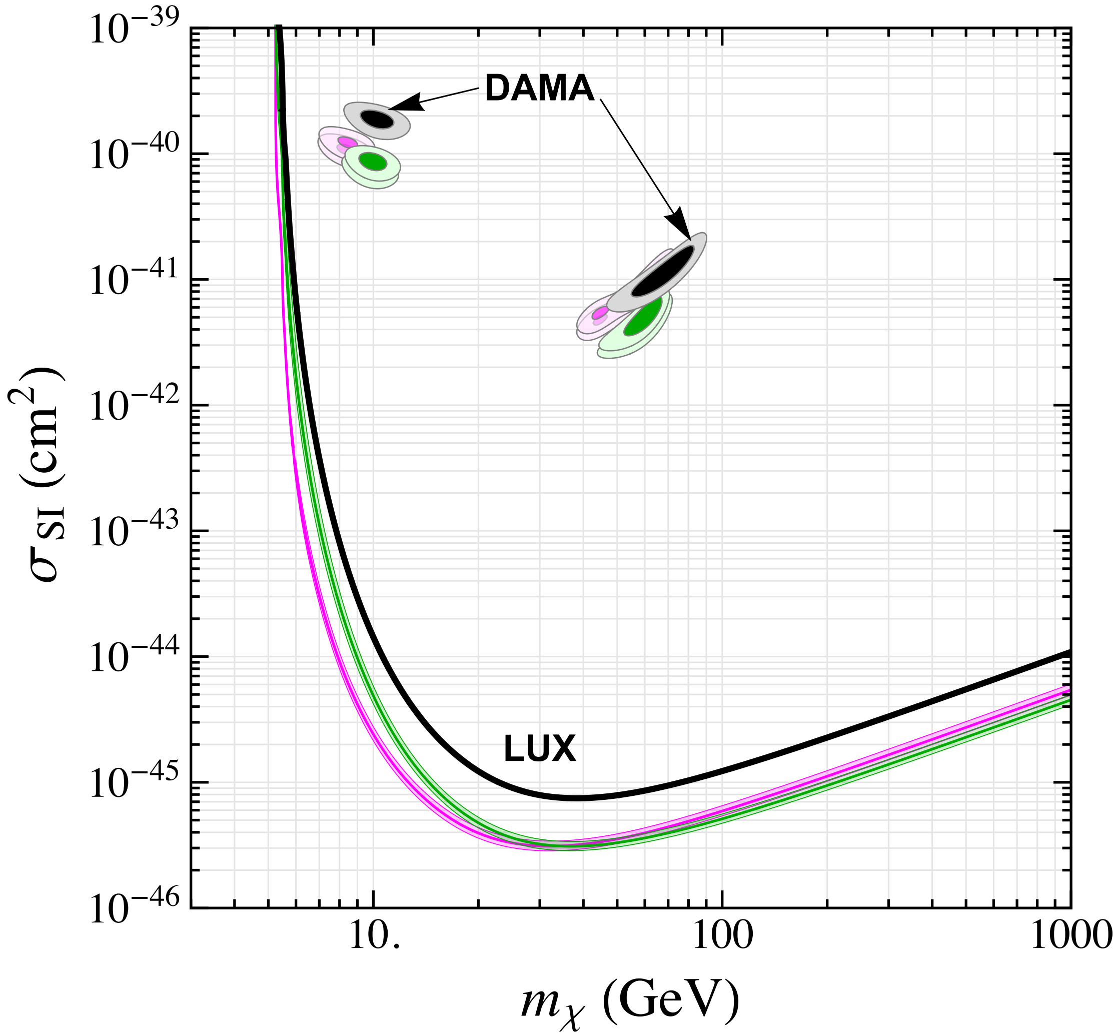
Implications for direct detection

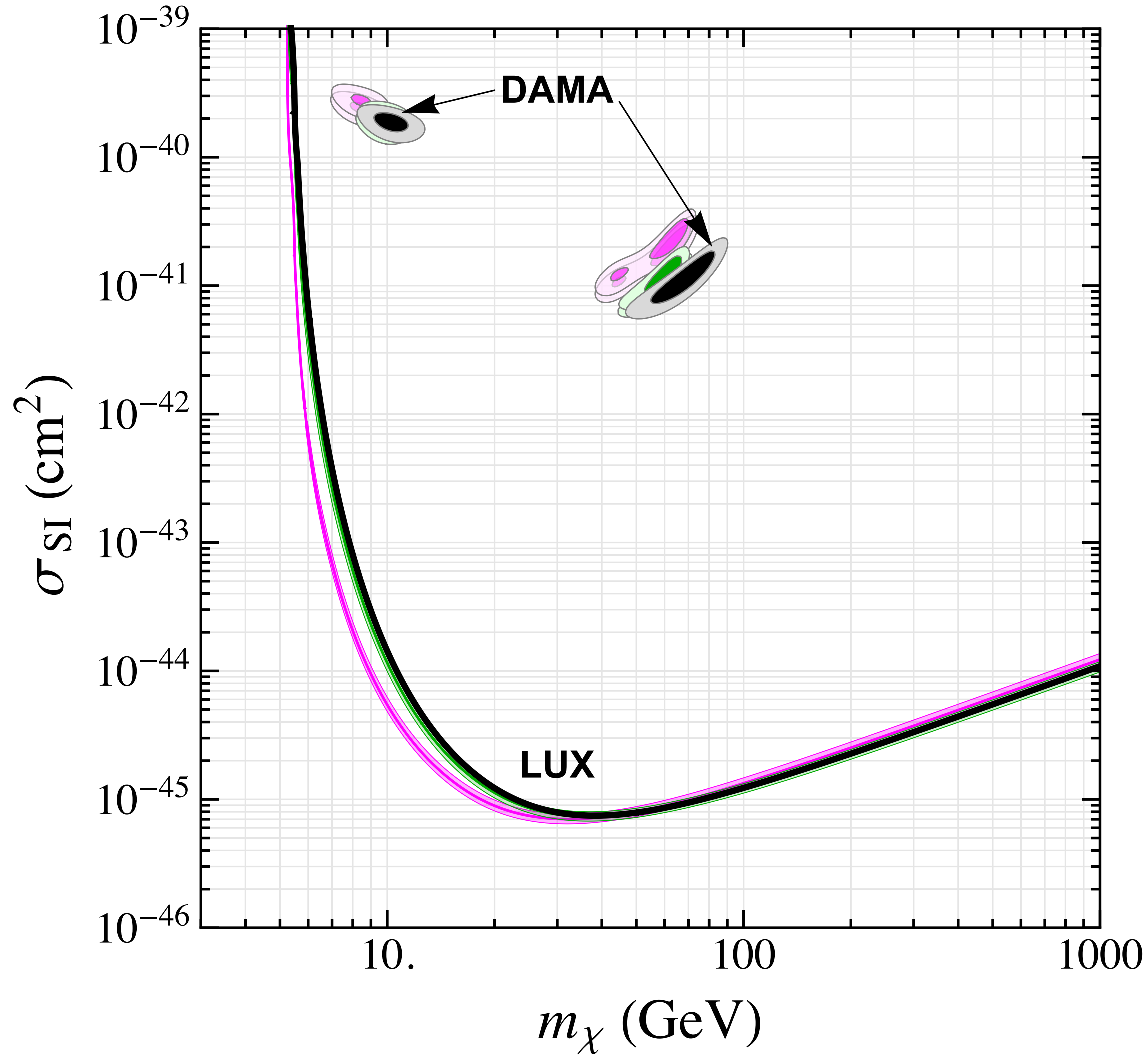
- Compare with simulated Milky Way-like haloes:



Implications for direct detection

Fix local ρ_χ=0.3 GeV cm^{-3}



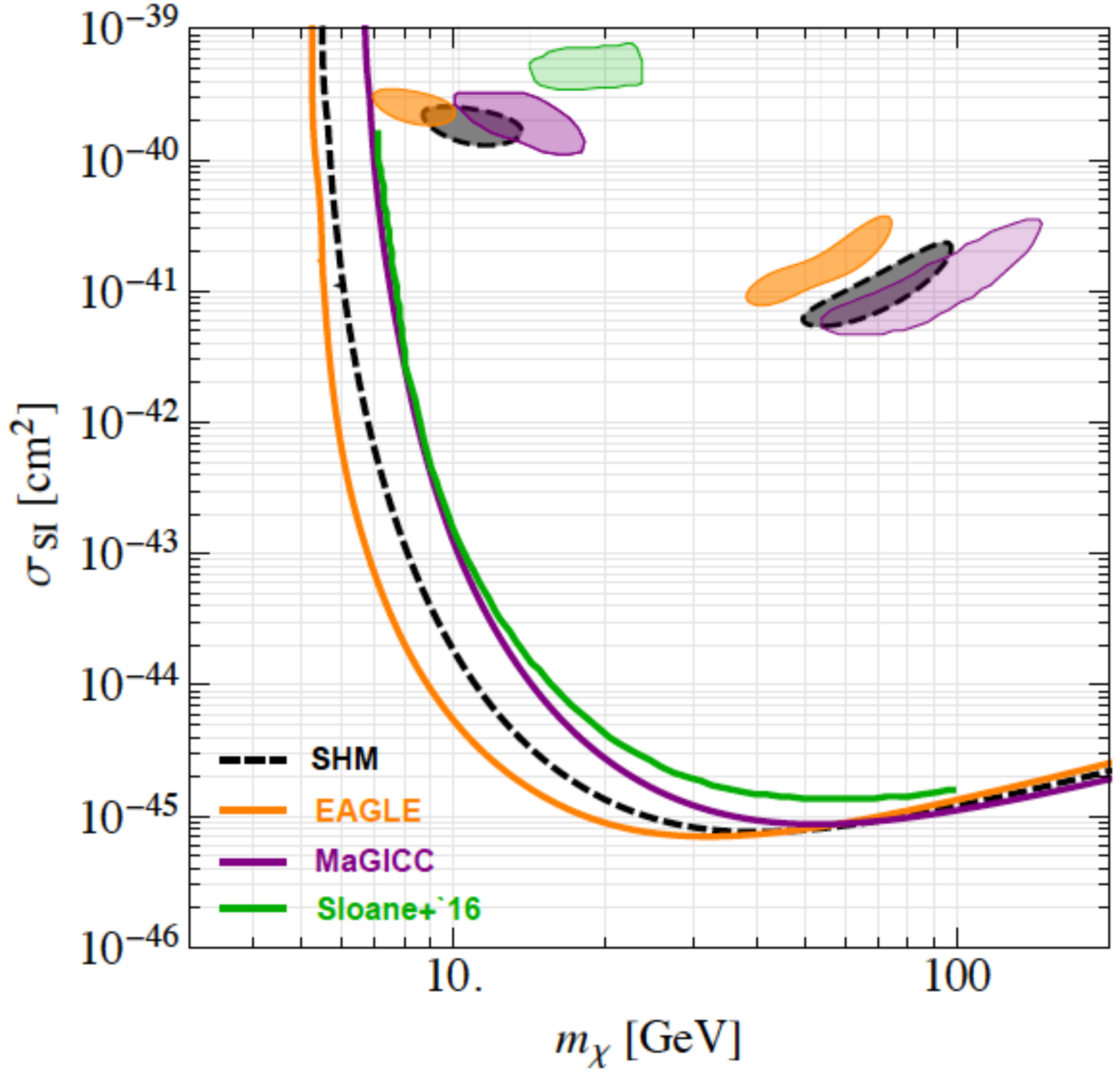


- Difference in the local DM density ➡ overall difference with the SHM.
- Variation in the peak of the DM speed distribution ➡ shift in the low mass region.

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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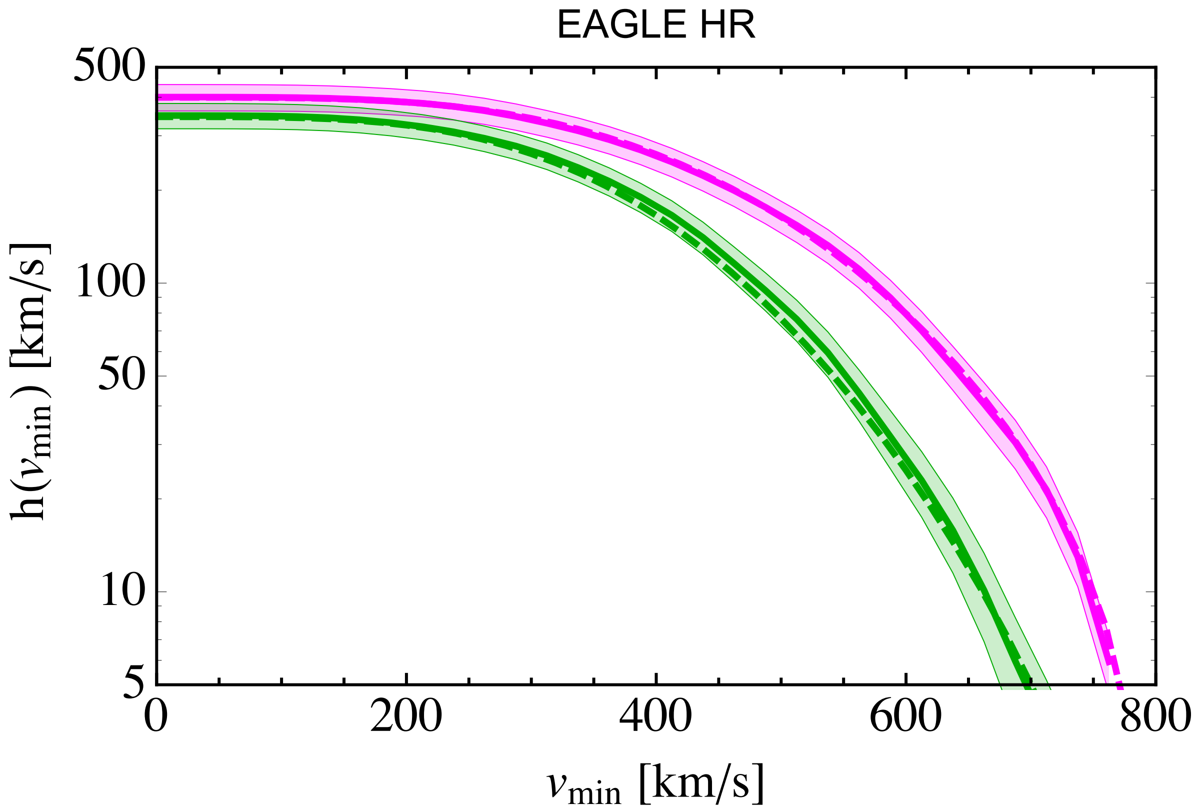

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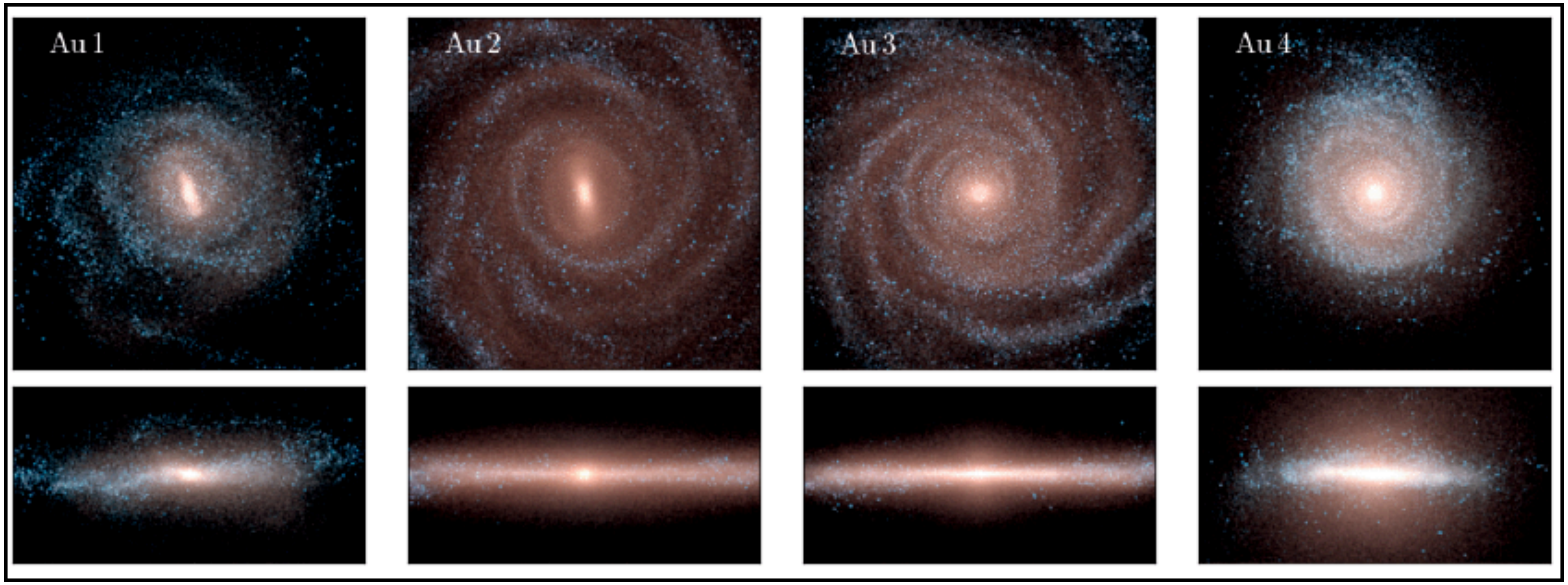
- Best fit Maxwellian $h(v_{\rm min})$ falls within the 1σ uncertainty band of the $h(v_{\rm min})$ of the simulated haloes.

Future perspective

New high resolution simulations available:

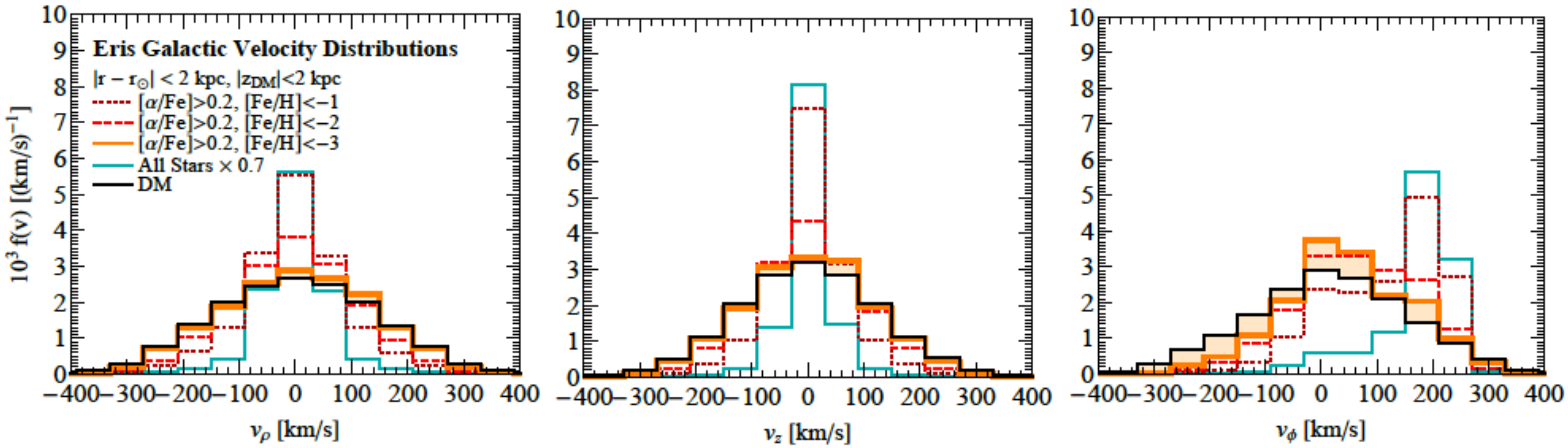
Auriga simulations: 30 hydrodynamic simulations of MW size haloes



- Search for correlations between the local DM and stellar velocity distributions.

Future perspective

Are the DM and stellar velocity distributions correlated?



Herzog-Arbeitman, Lisanti, Madau, Necib, 1704.04499

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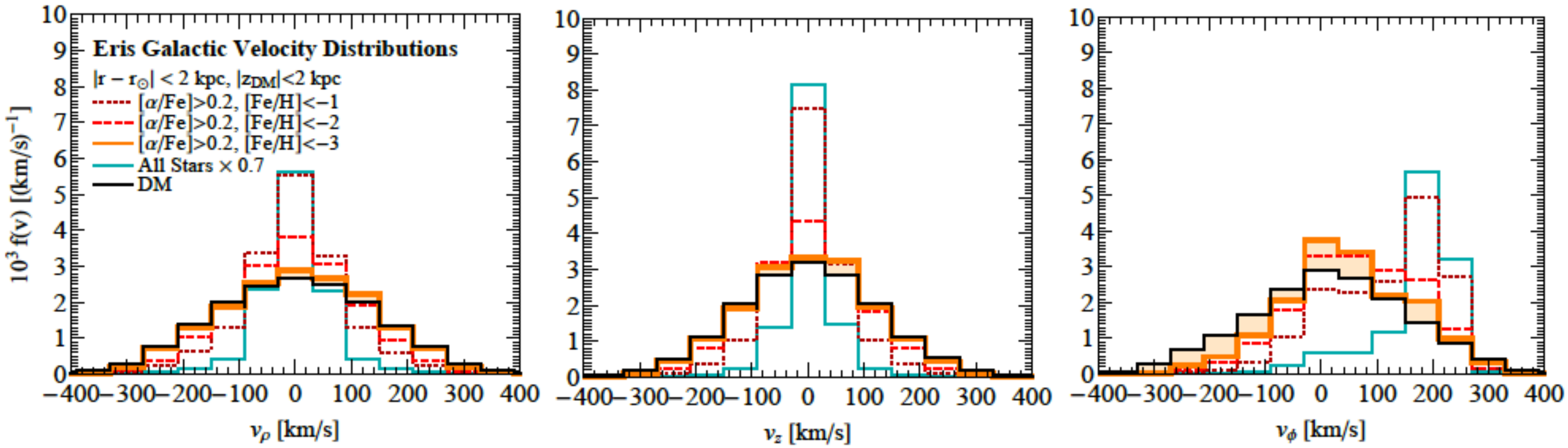
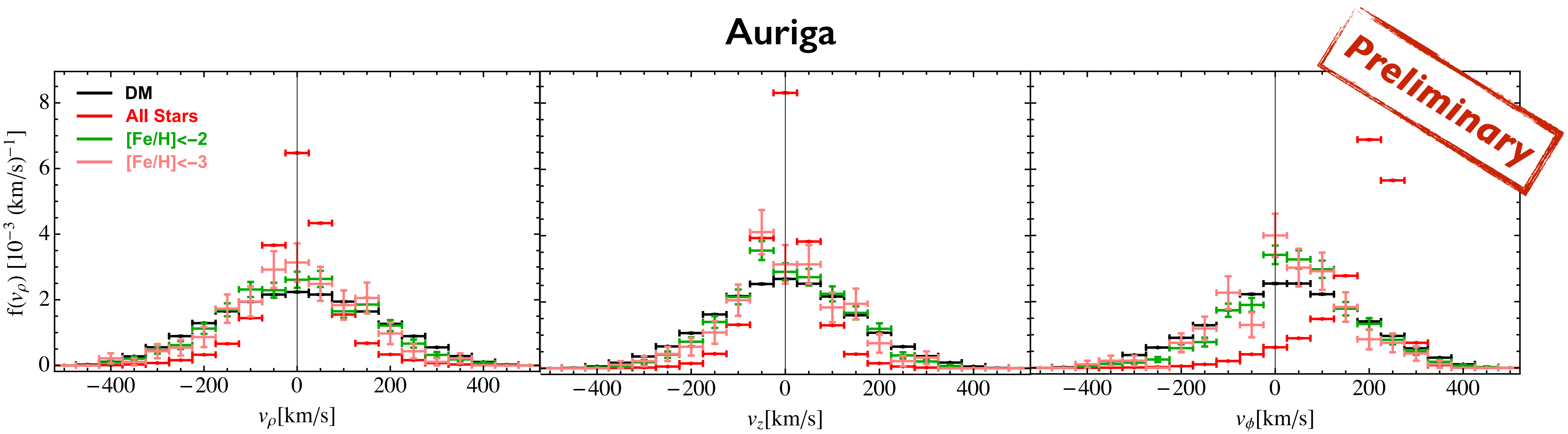


Herzog-Arbeitman, Lisanti, Madau, Necib, 1704.04499

Auriga



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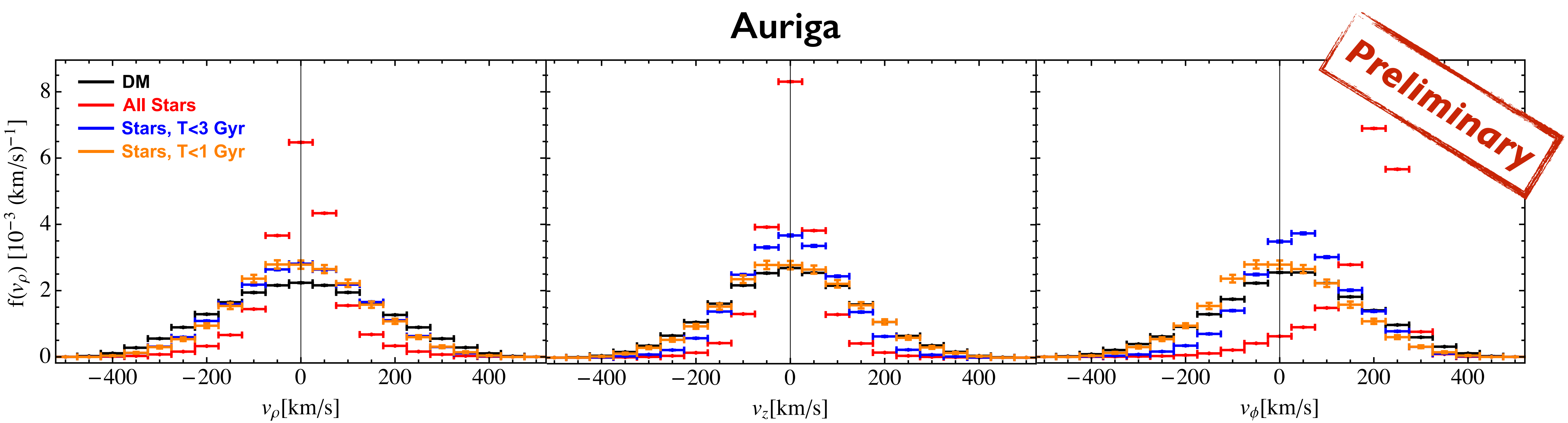
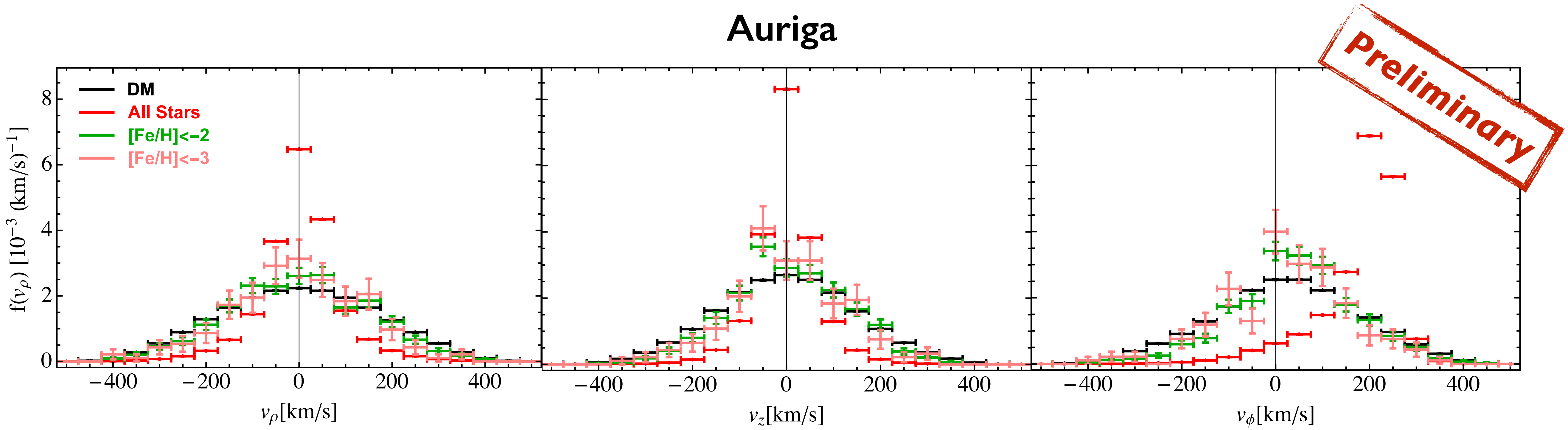




Prospects for indirect DM searches

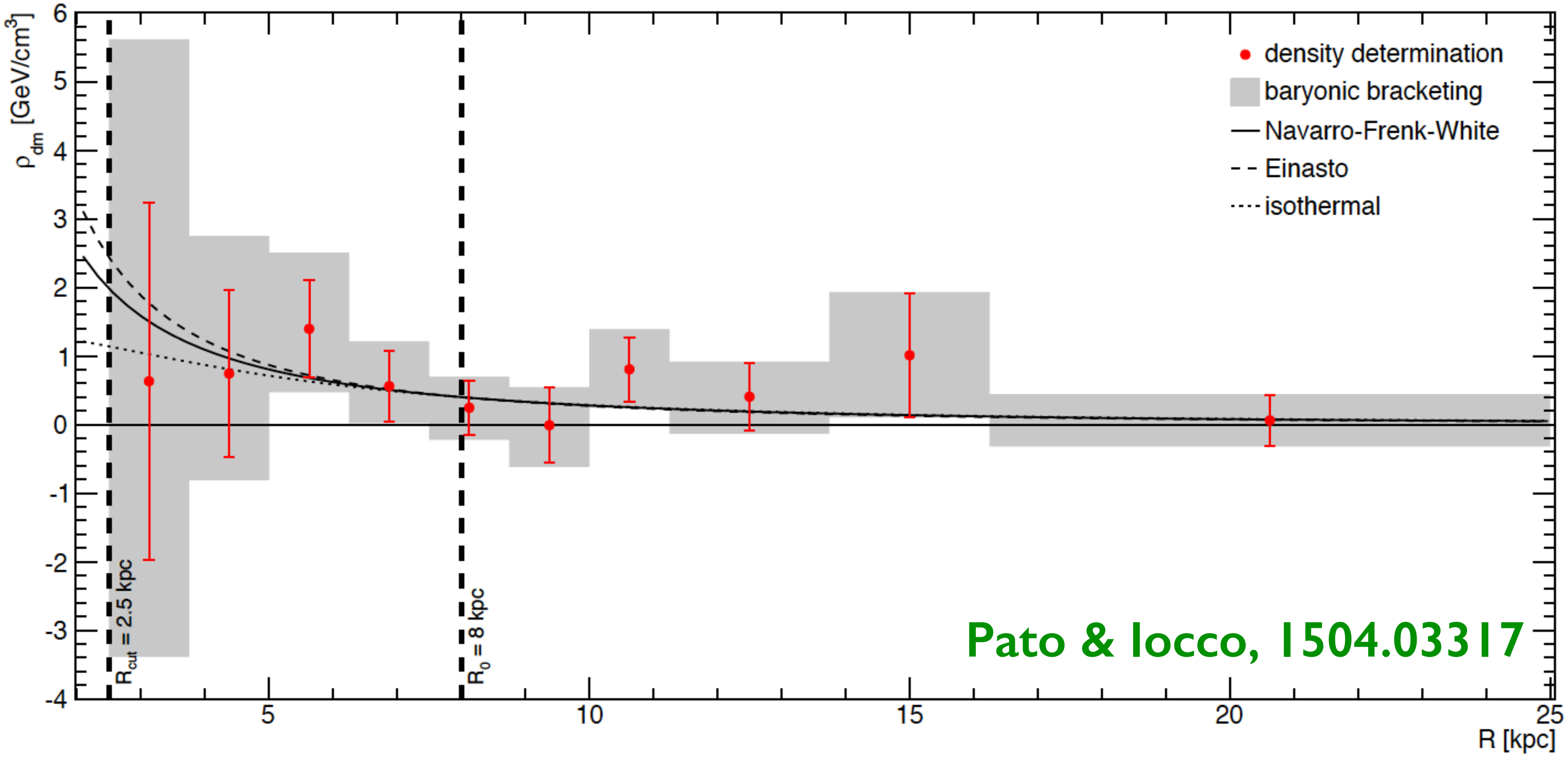
Indirect DM searches

- Expected gamma-ray flux from DM annihilation:

astrophysics

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

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



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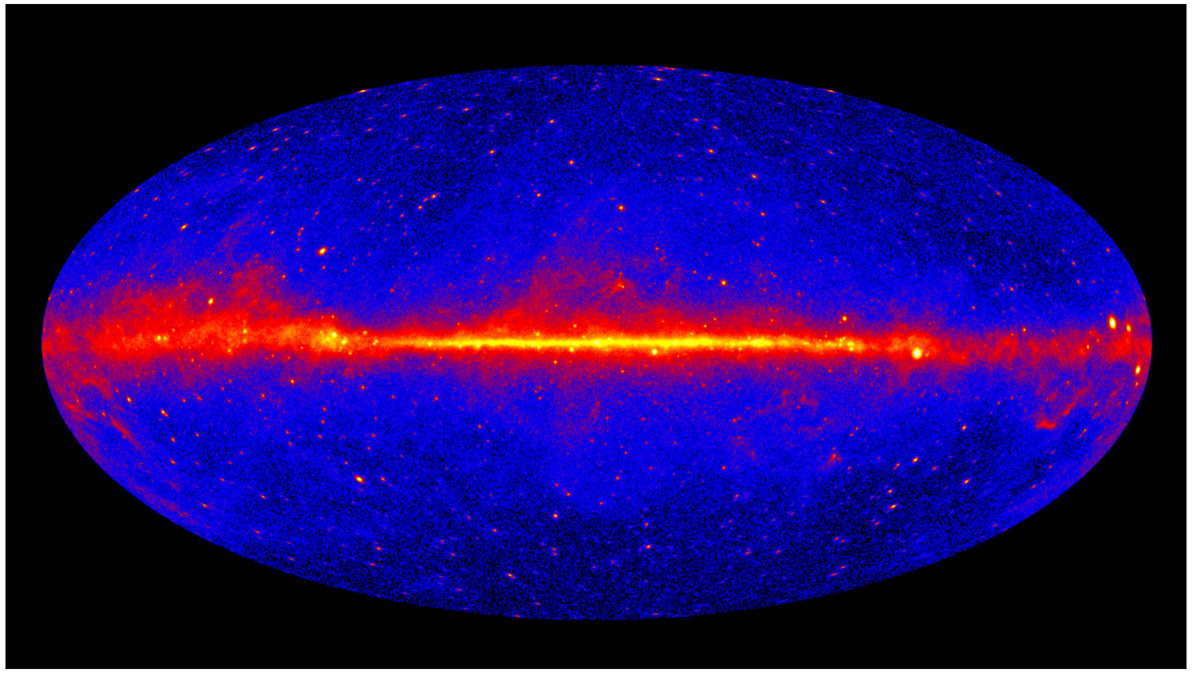
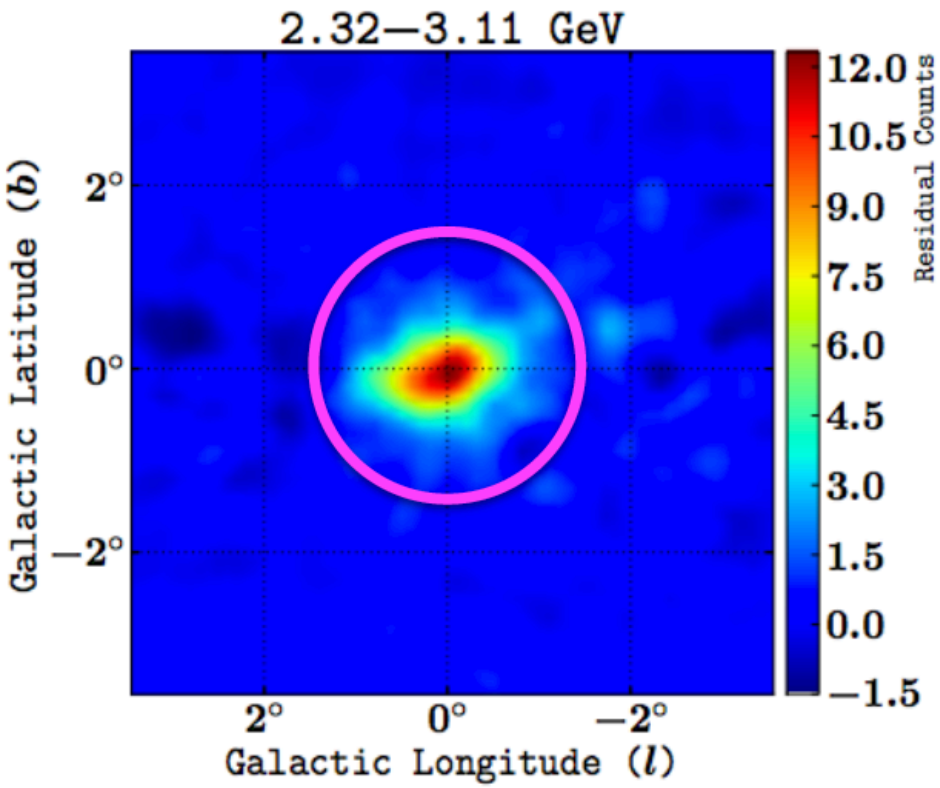
Use cosmological simulations:

- 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 photons from cosmic rays, stellar source population in the Galactic bulge, …*

Galactic centre GeV excess

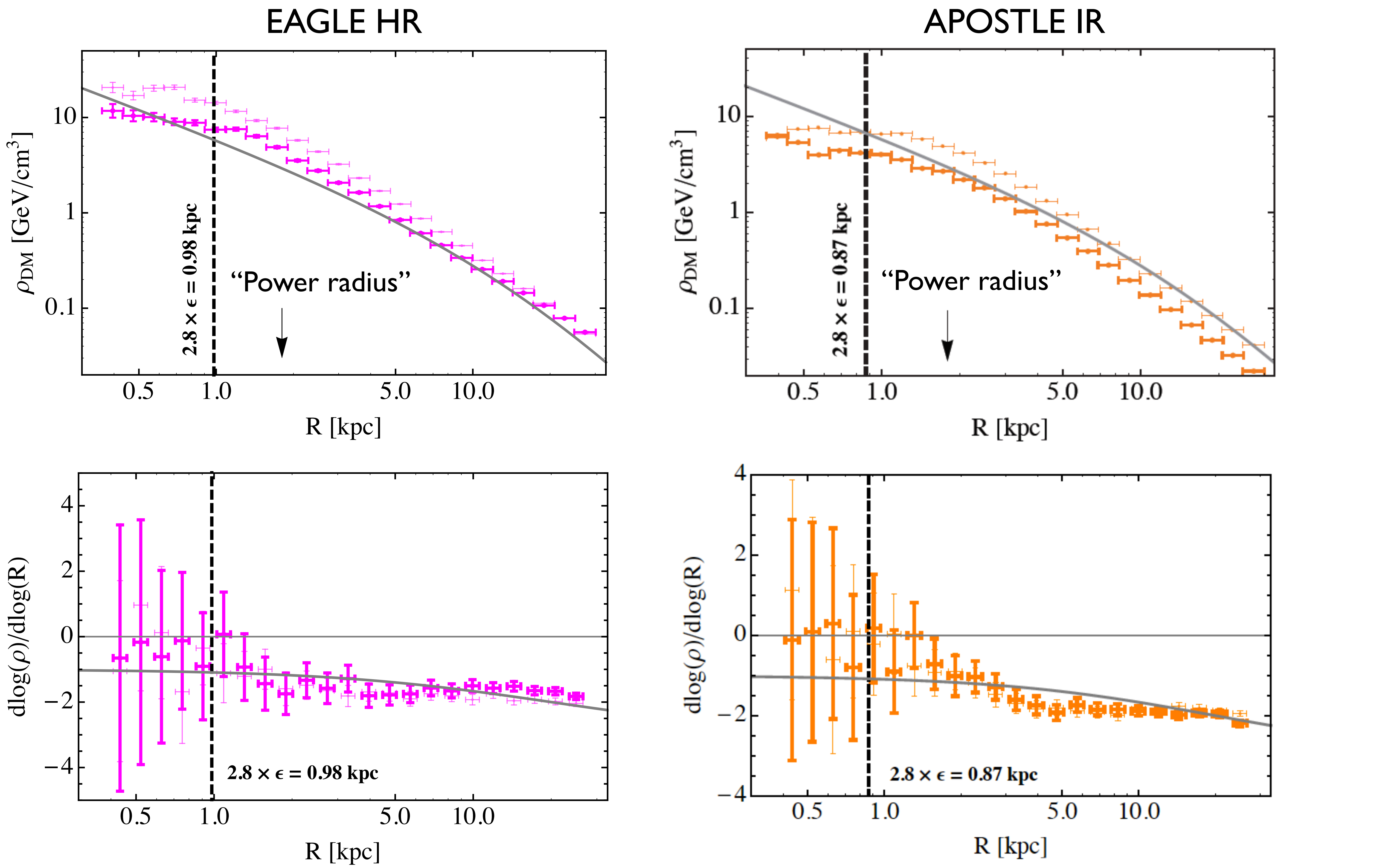
- Test the DM density profile predicted by hydrodynamical simulations against the GeV excess data.

- Additional selection criterion of MW-like galaxies: substantial stellar disk component.

4 MW analogues:

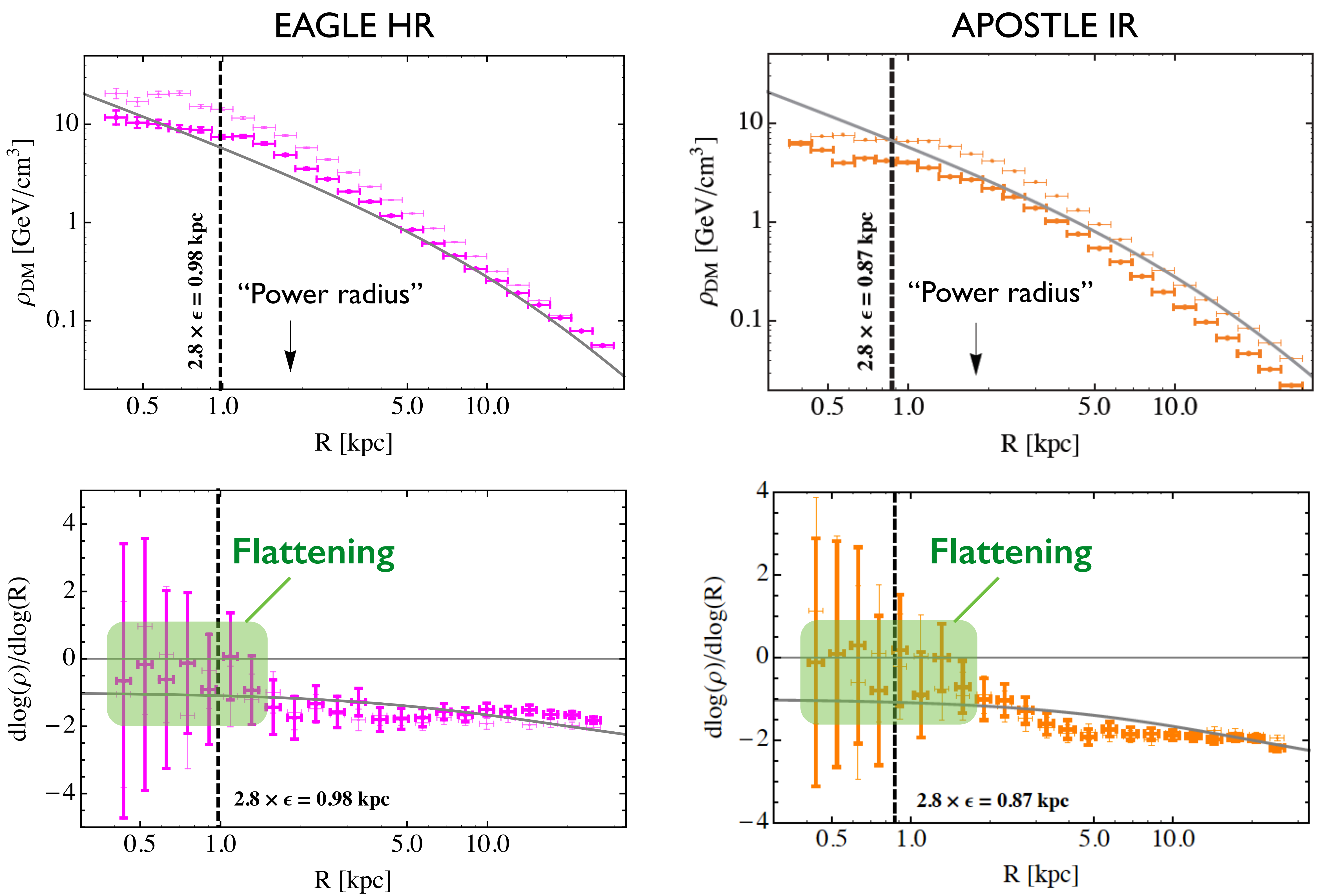
2 EAGLE + 2 APOSTLE

DM density profiles



Calore, Bozorgnia et al., 1509.02164

DM density profiles



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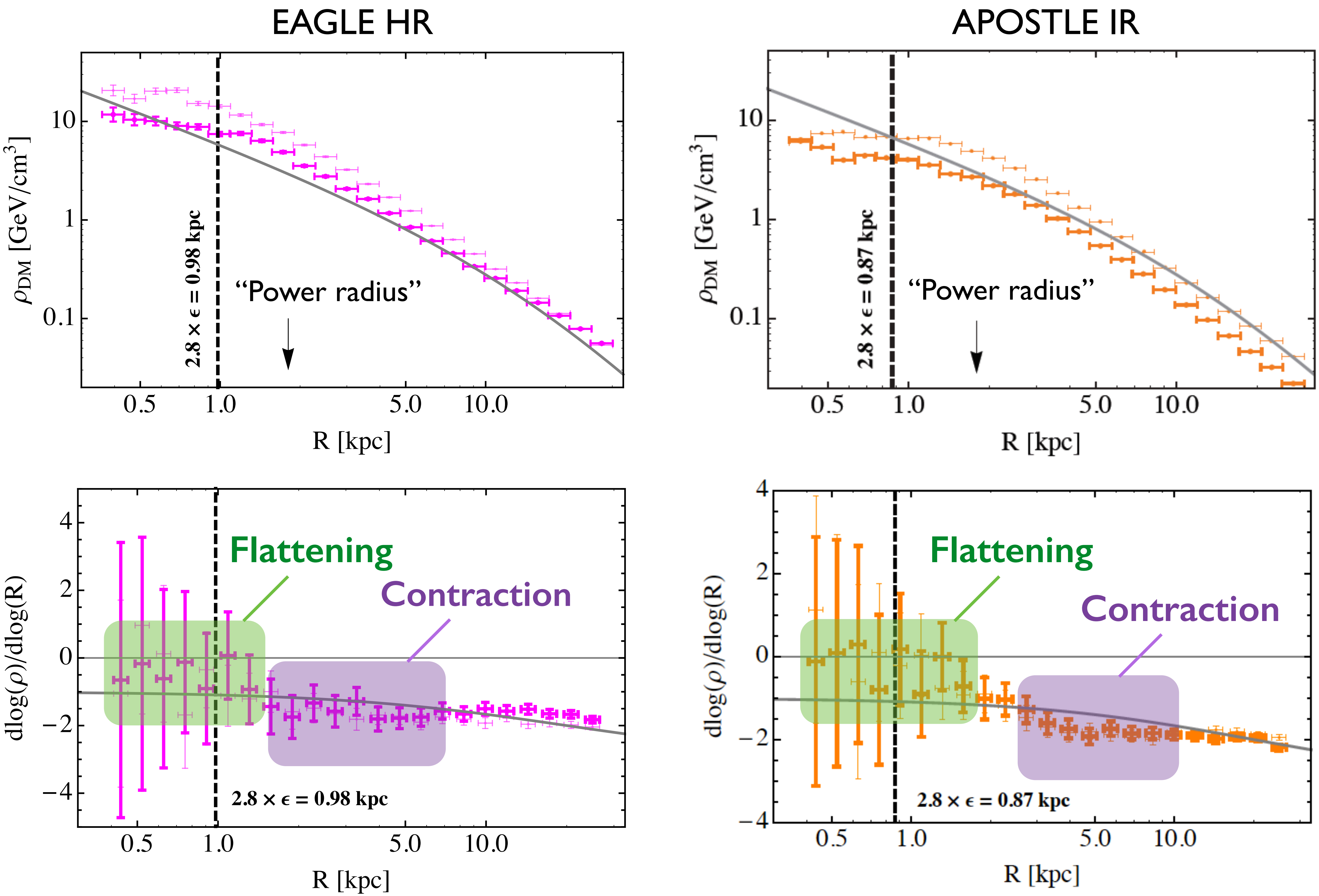


Calore, Bozorgnia et al., 1509.02164

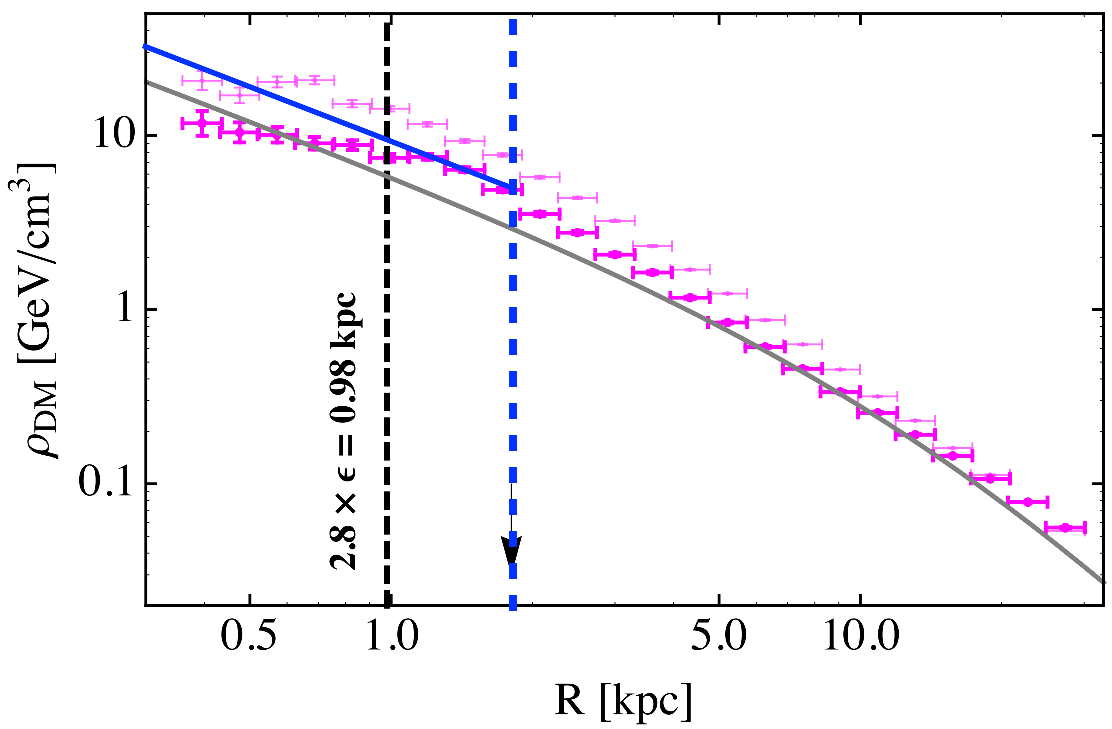
DM density profiles

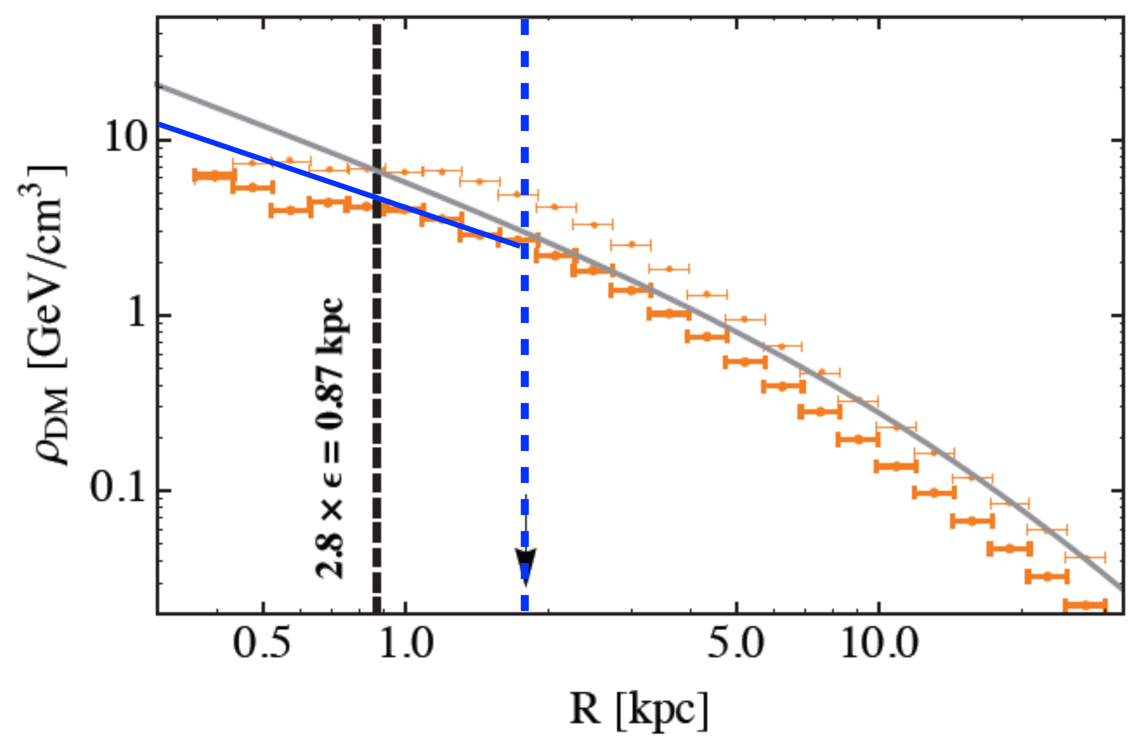
- GeV excess data analyzed in the region:

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

radial scale: 0.3 - 3 kpc

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



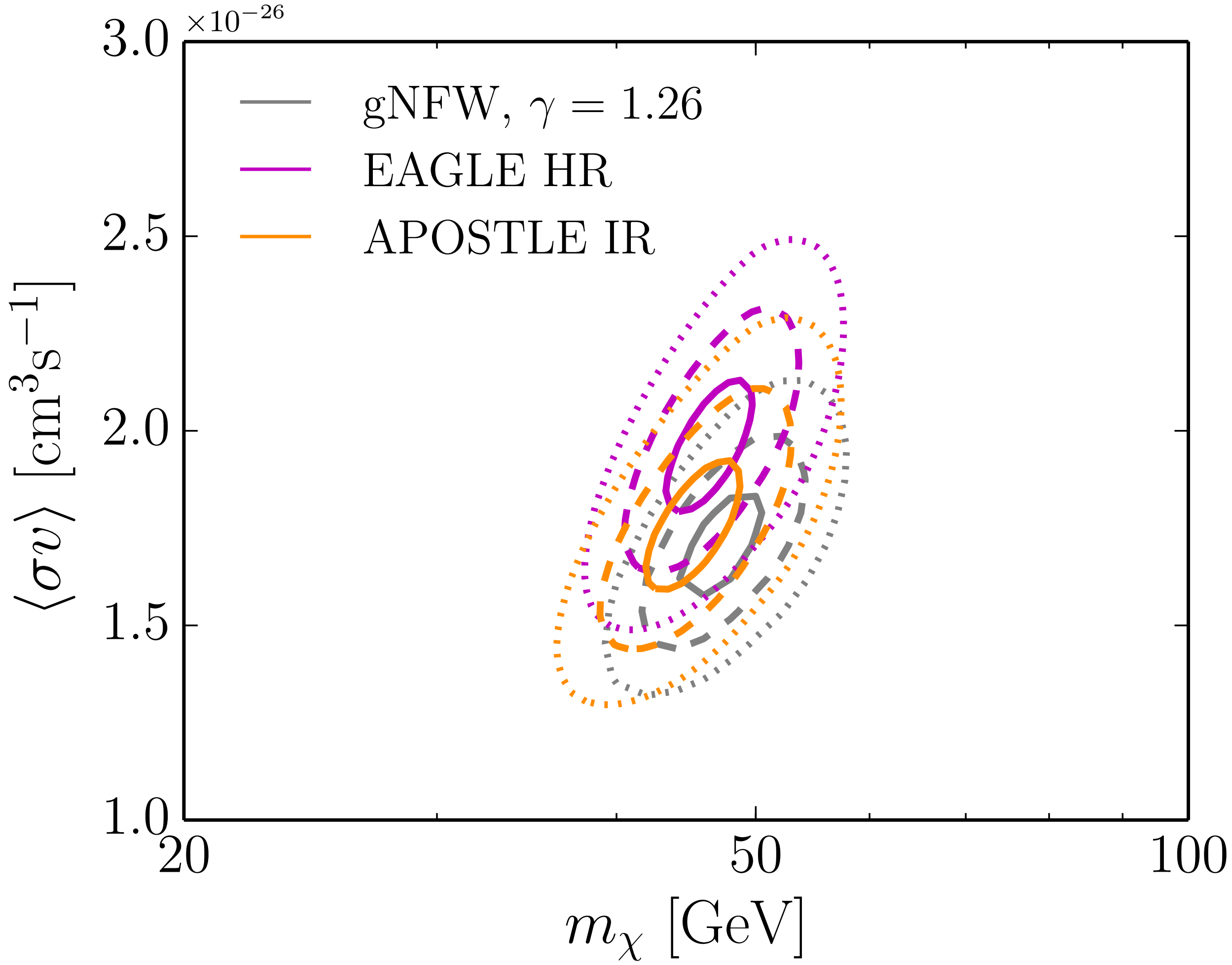


EAGLE HR (2 haloes): $0.94 < \gamma_{\rm max} < 0.98$ at $R_{\rm P03} = 1.8$ kpc

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

Fitting the GeV excess

- Assuming 100% annihilation into b-quarks:



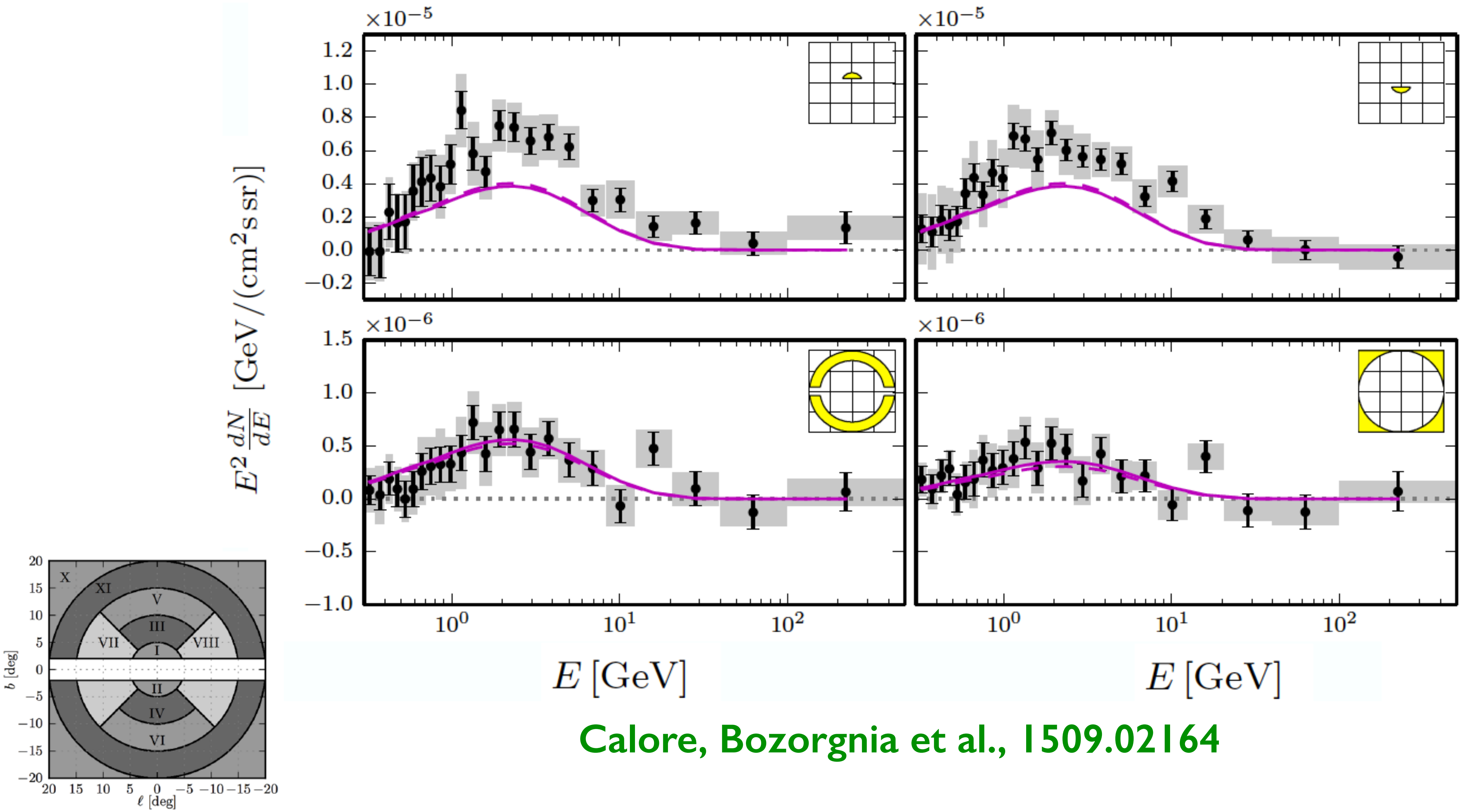
- Similar constraints on DM mass and annihilation cross section, but significantly worse fit.

(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

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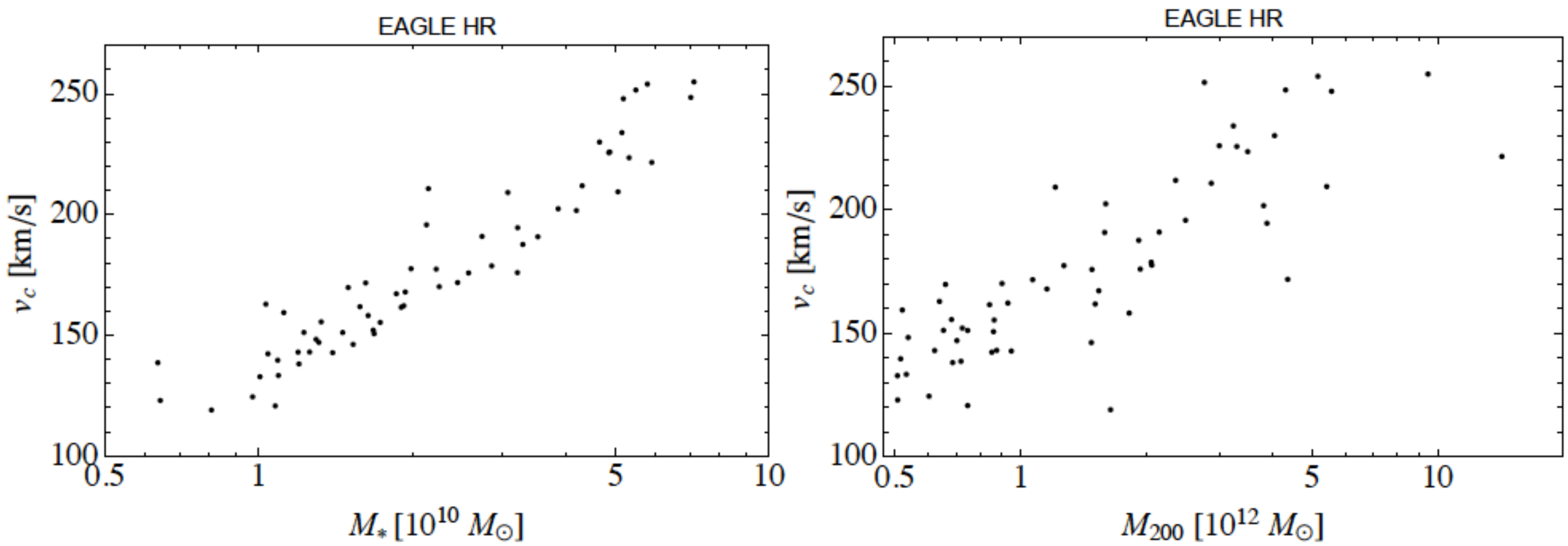
- Maxwellian works for the analysis of direct detection data. → ***Can substantially reduce astrophysical uncertainties by a better selection of MW-like galaxies in simulations.***
- DM density profiles of MW-like galaxies fail to reproduce the GeV excess.

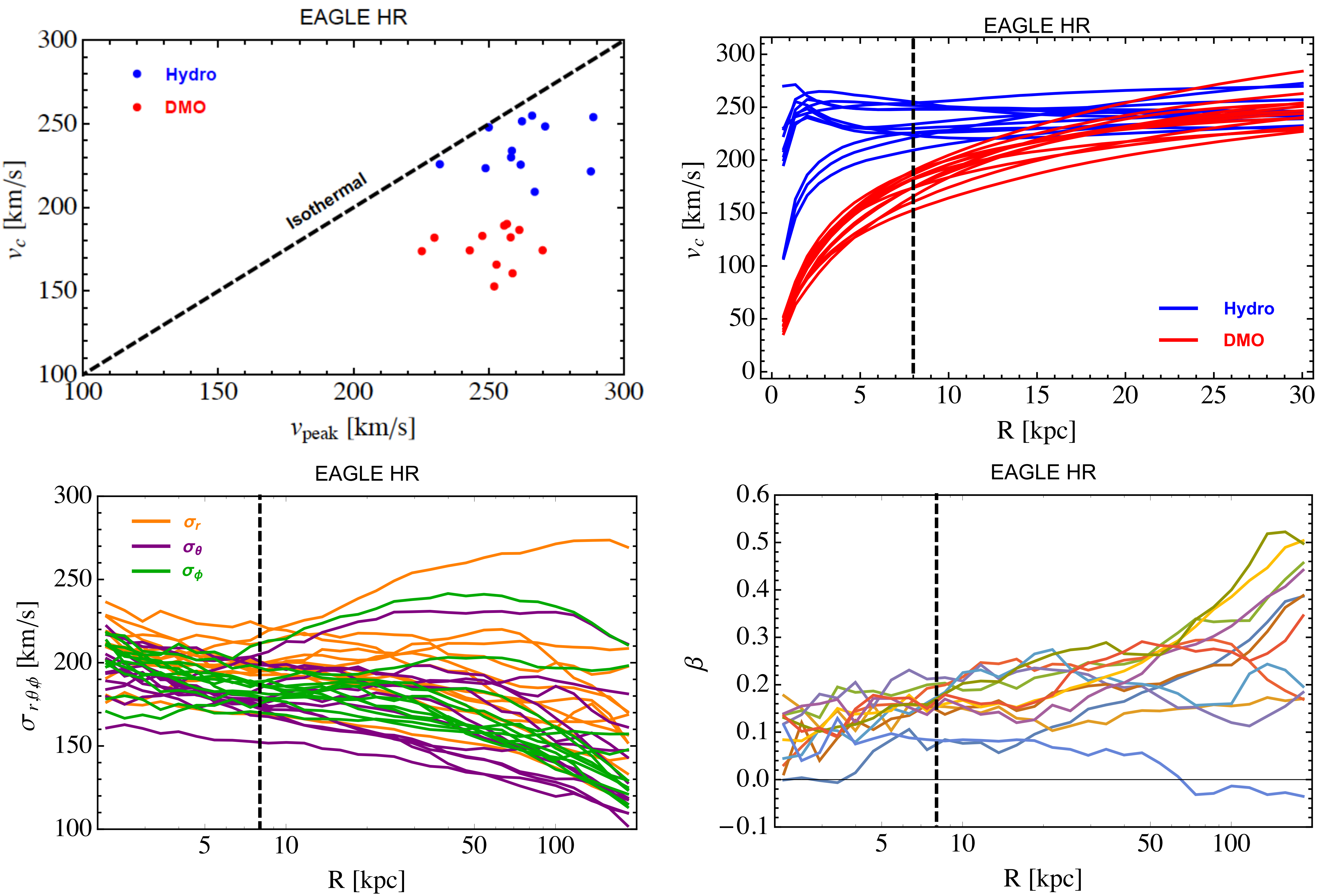
Backup Slides

Selection criteria for MW analogues



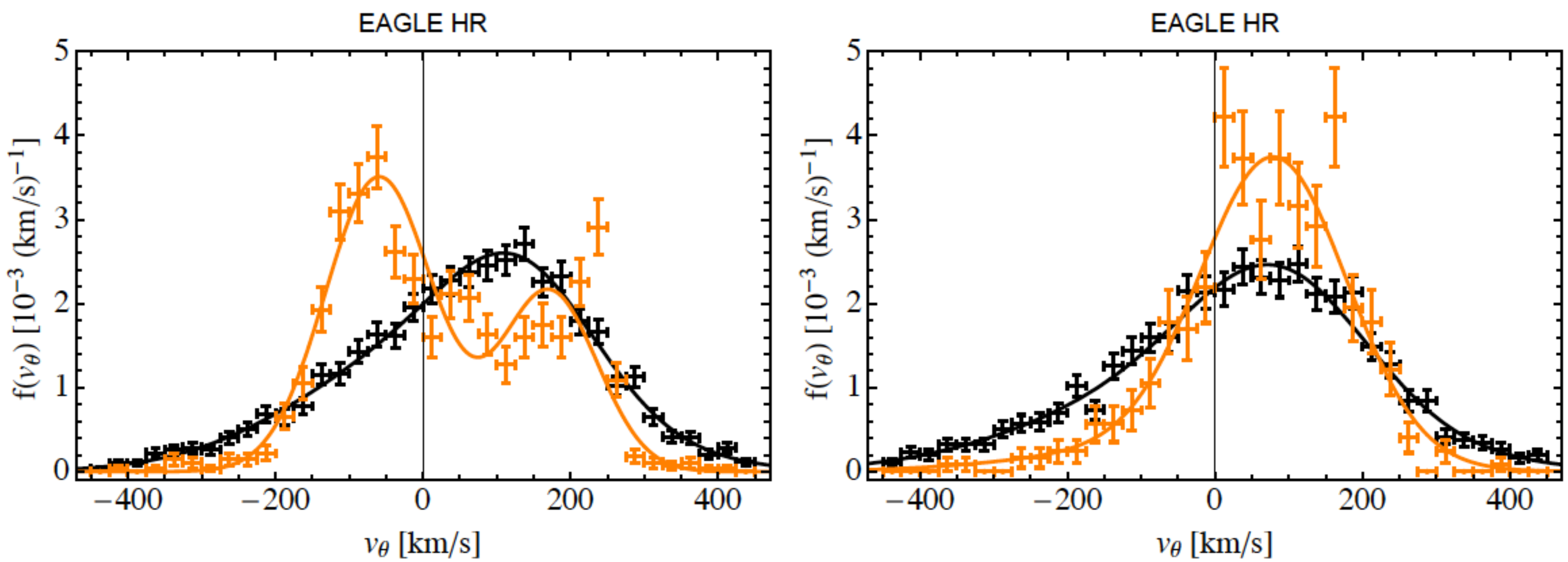
- $M_\star$ strongly correlated with v_c at 8 kpc, while the correlation of M_{200} with v_c is weaker.
- $M_\star(R < 8\ \mathrm{kpc}) = (0.5 - 0.9)M_\star$.
- $M_{\mathrm{tot}}(R < 8\ \mathrm{kpc}) = (0.01 - 0.1)M_{200}$.
- Over the small halo mass range probed, little correlation between $M_{\mathrm{DM}}(R < 8\ \mathrm{kpc})$ and M_{200}.

Departure from isothermal



Searching for dark disks

DM and stellar velocity distributions:



- Fit with a double Gaussian. Difference in the mean speed of second Gaussian between DM and stars is 35 km/s in the left, and 7 km/s in the right panel.
- Fraction of second Gaussian is 32% in the left panel and 43% in the right panel.

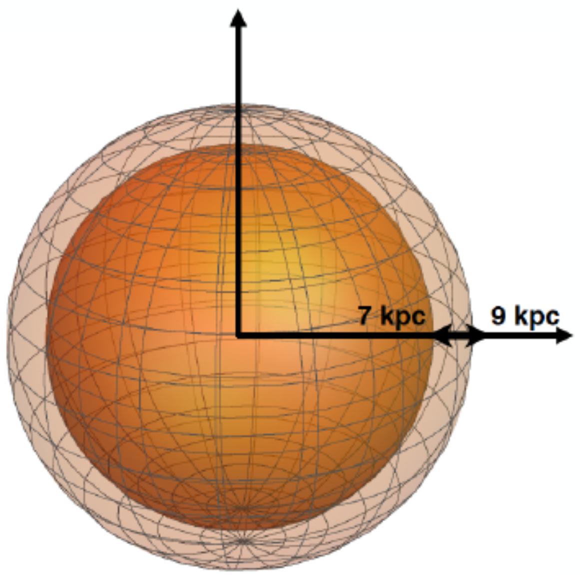
Searching for dark disks

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

- Compare the the average ρ_{DM} in the torus with the value in a spherical shell at $7 < R < 9$ kpc.

  $\rho_{\mathrm{DM}}^{\mathrm{torus}}$ is larger than $\rho_{\mathrm{DM}}^{\mathrm{shell}}$ by:

  2 – 27% for 10 haloes,
  greater than 10% for 5 haloes, and
  greater than 20% for only two haloes.



- The increase in the DM density in the disc 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, we calculate the inertia tensor of DM particles within 5 and 8 kpc.
  $\Rightarrow$ ellipsoid with three axes of length $a \geq b \geq c$.

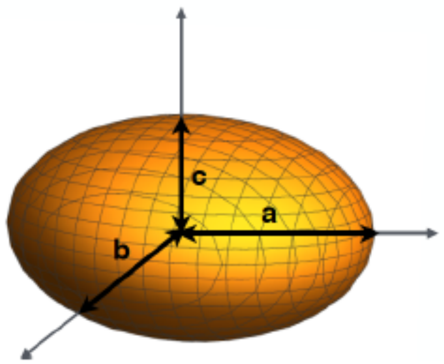
- Calculate the sphericity: $s = c/a$.
  - $s = 1$: perfect sphere. $s < 1$: increasing deviation from sphericity.
  - At 5 kpc, $s = [0.85, 0.95]$. At 8 kpc, s lower by less than 10%.
  - Due to dissipational baryonic processes, DM sphericity systematically higher in the hydrodynamic simulations compared to DMO haloes in which $s = [0.75, 0.85]$.

Halo shapes

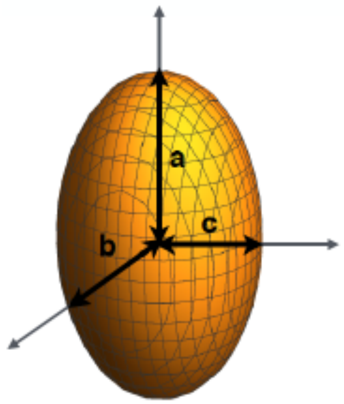
- Describe a deviation from sphericity by the triaxiality parameter:

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

- 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, since inner haloes are very close to spherical, 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

Parameters of the simulations

Auriga simulations

Resolution level	$\frac{m_{\mathrm{DM}}}{[\mathrm{M}_\odot]}$	$\frac{m_{\mathrm{b}}}{[\mathrm{M}_\odot]}$	$\frac{\epsilon}{[\mathrm{pc}]}$
4	3×10^5	5×10^4	369
5	2×10^6	4×10^5	738
3	4×10^4	6×10^3	184

Morphology of simulated haloes

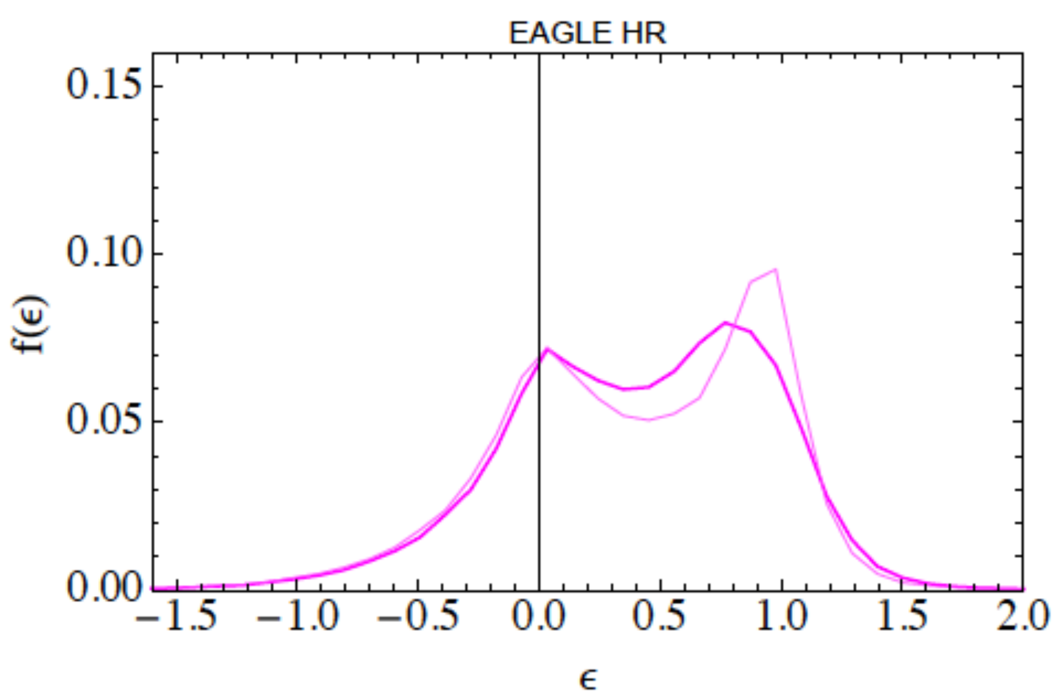
- Select simulated galaxies whose stellar kinematics show a disc component, rather than ellipticals or undergoing mergers.
- Characterize the morphology of each simulated galaxy by looking for evidence of coherent rotation.
- Use the distribution of angular momentum vectors of individual particles relative to the net angular momentum of the galaxy to discriminate between discs (coherent rotation) and spheroids (no coherent rotation).
- Derive the distribution of the stellar orbital circularity parameter,

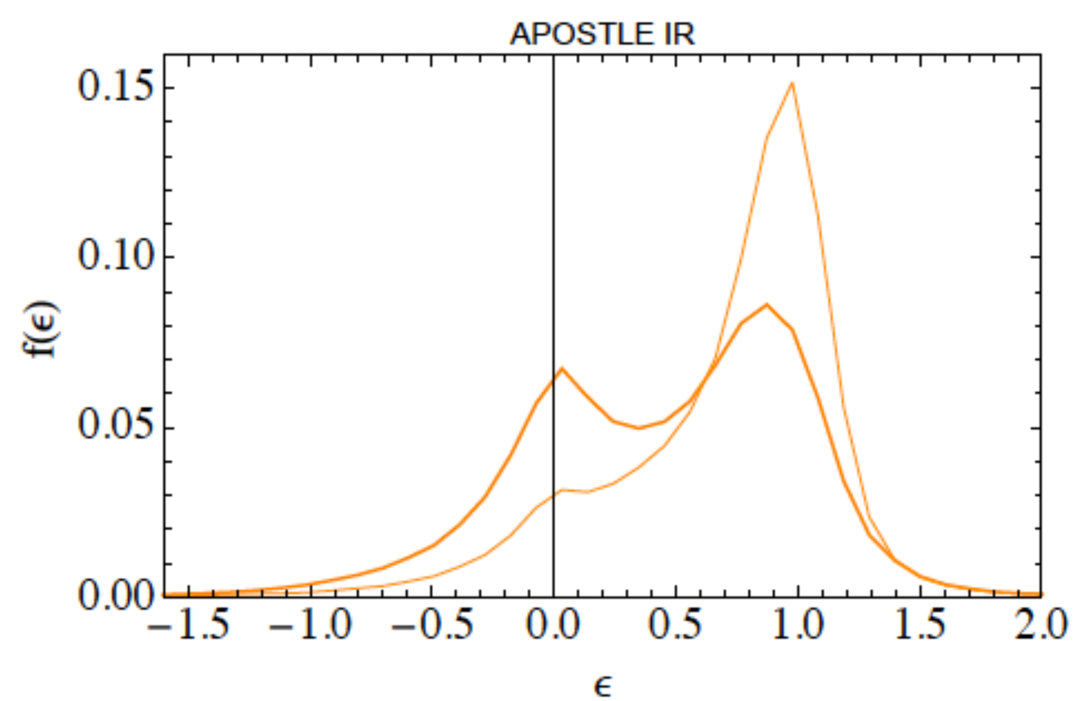
$$\epsilon(r) = \frac{j_z}{j_c(r)}$$

A distribution peaked at $\epsilon = 1 \Rightarrow$ disc
An almost symmetric distribution around $\epsilon = 0 \Rightarrow$ spheroidal system

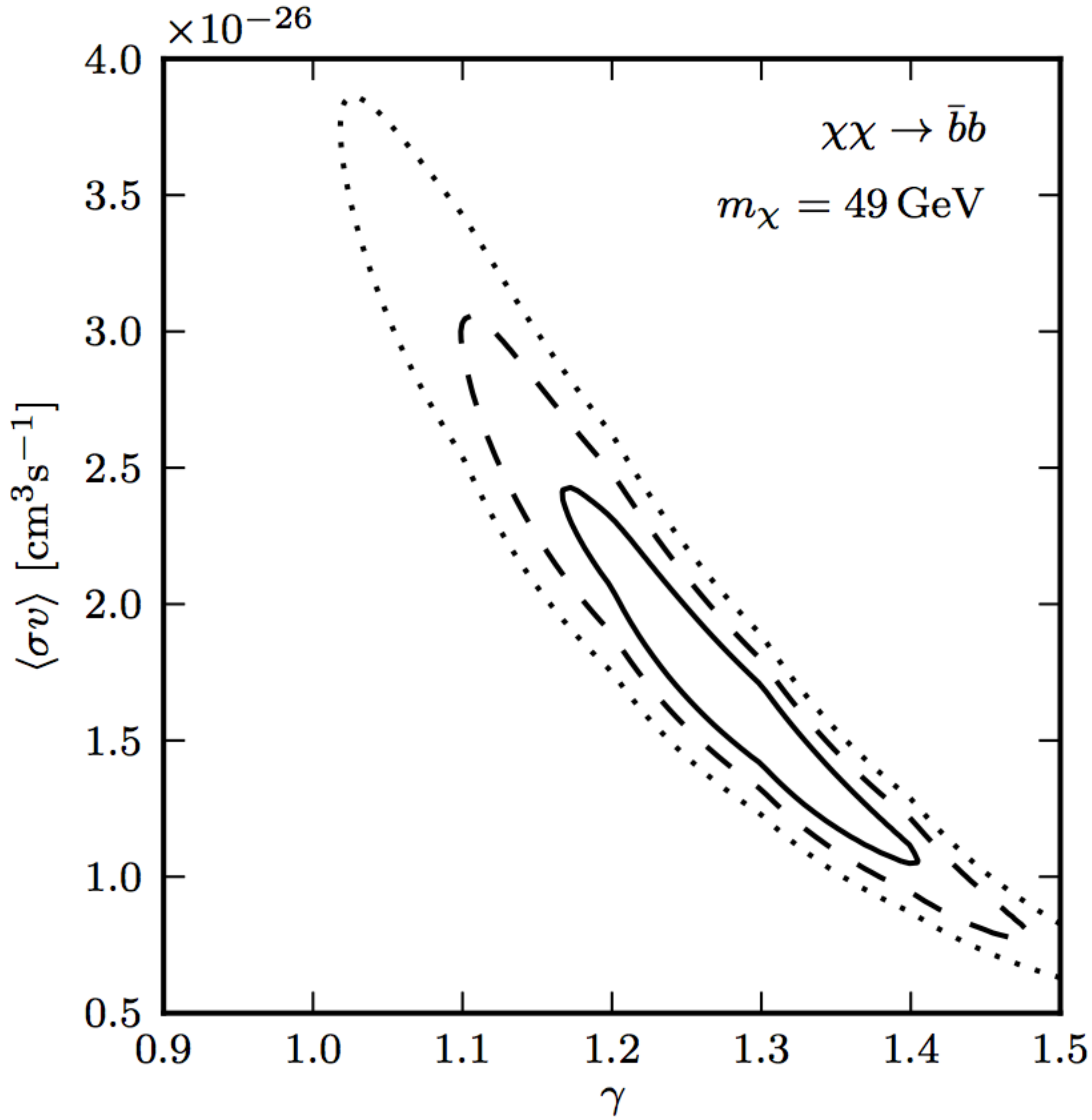
Morphology of simulated haloes

- We retain a galaxy if the stellar fraction in the range $\epsilon > 0.45$ is larger than 50%.
- With this criterion we can identify galaxies that have a dominant disc, and remove galaxies that show an almost symmetric distribution around $\epsilon = 0$.





GeV excess spatial profile

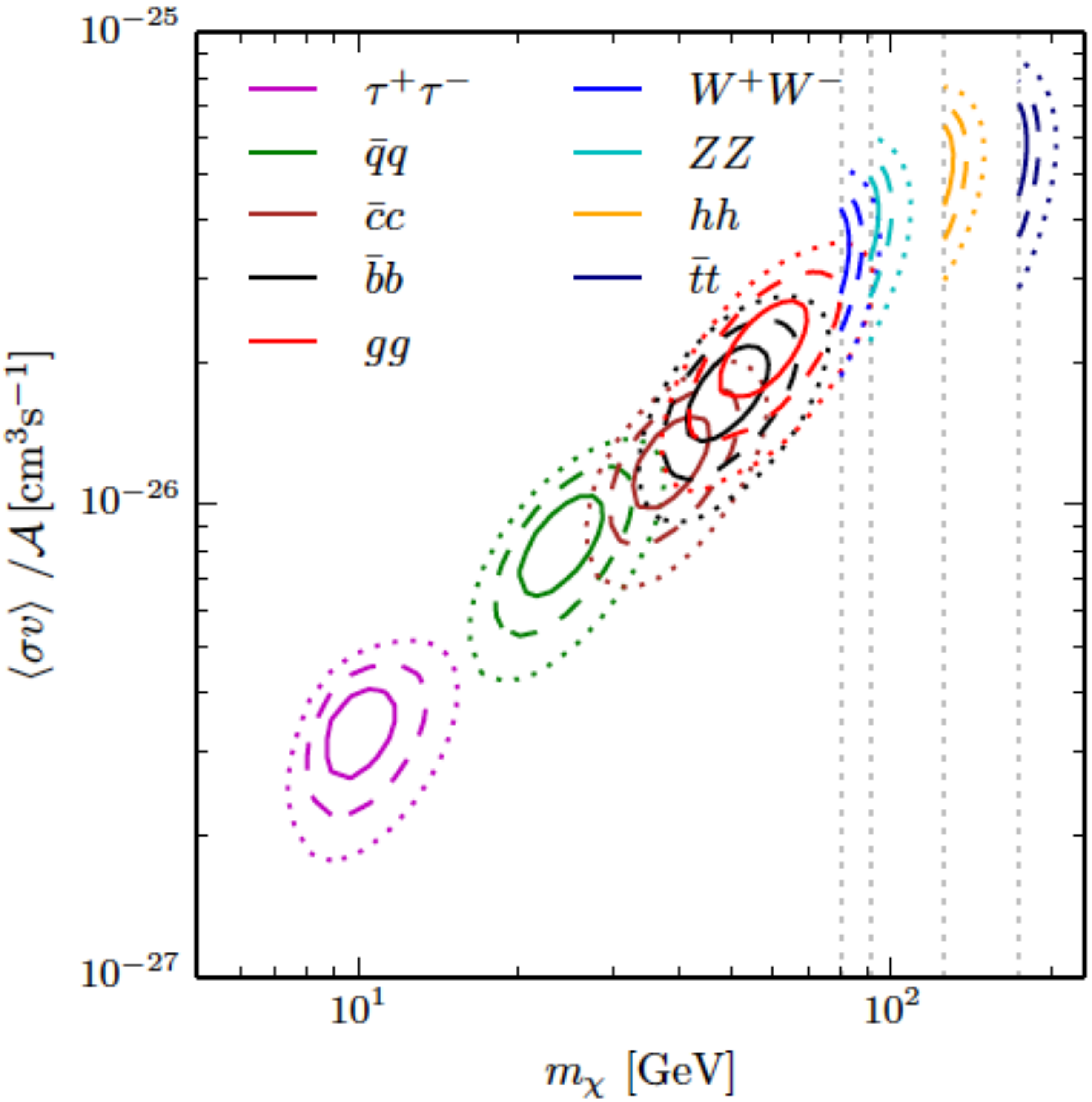


Calore et al., 1409.0042

Generalized NFW:

$$\rho(r) = \rho_s \frac{r_s^3}{r^\gamma (r + r_s)^{3-\gamma}}$$

GeV excess DM interpretation



Channel	$\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm^3\ s^{-1}})$	m_χ (GeV)	$\chi^2_{\min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
$[\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	$0.0036]_{\cancel{\mathrm{ICS}}}$

Calore et al., 1411.4647