The local dark matter distribution from simulations

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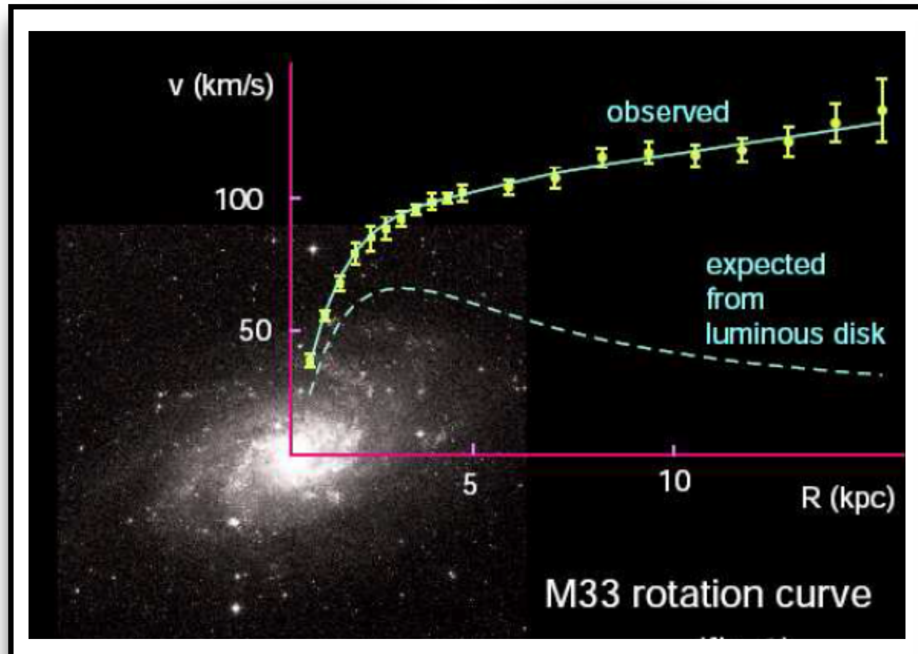
24 Oct 2018

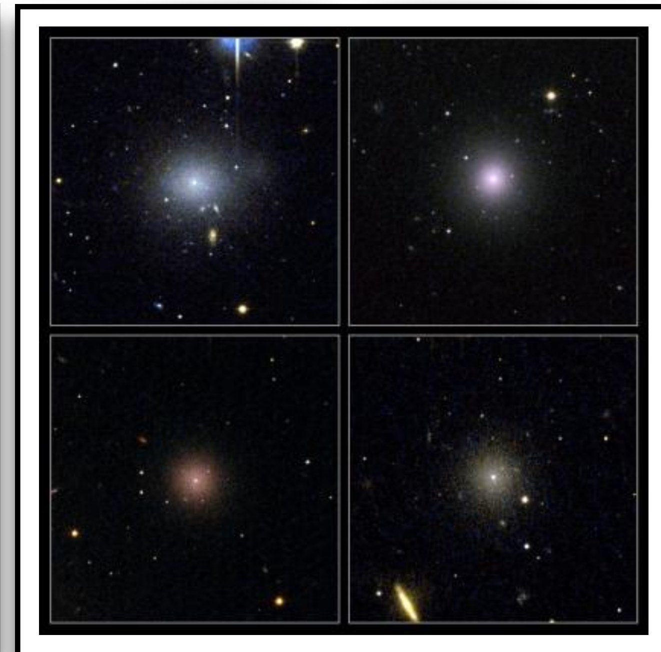
IP3

Evidence for Dark Matter

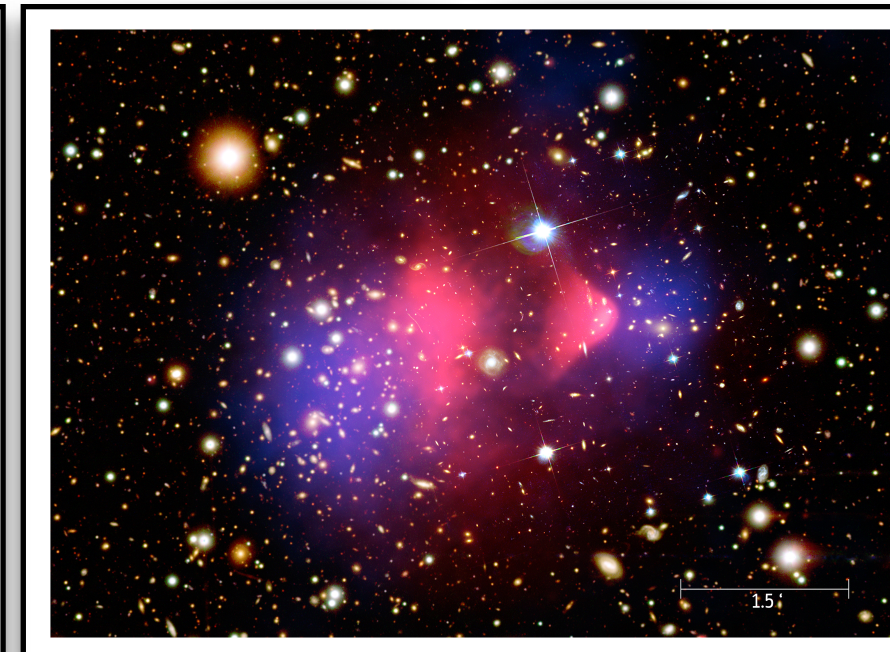
Galaxy rotation curves



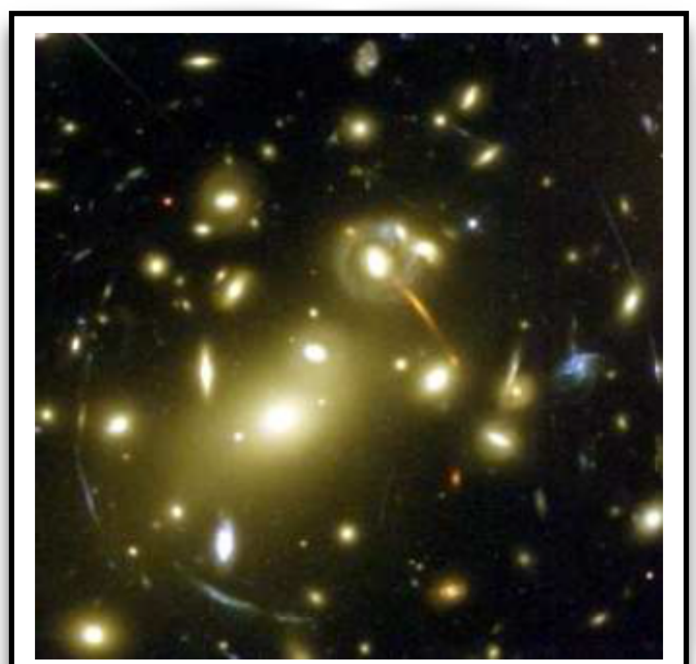
Dwarf galaxies



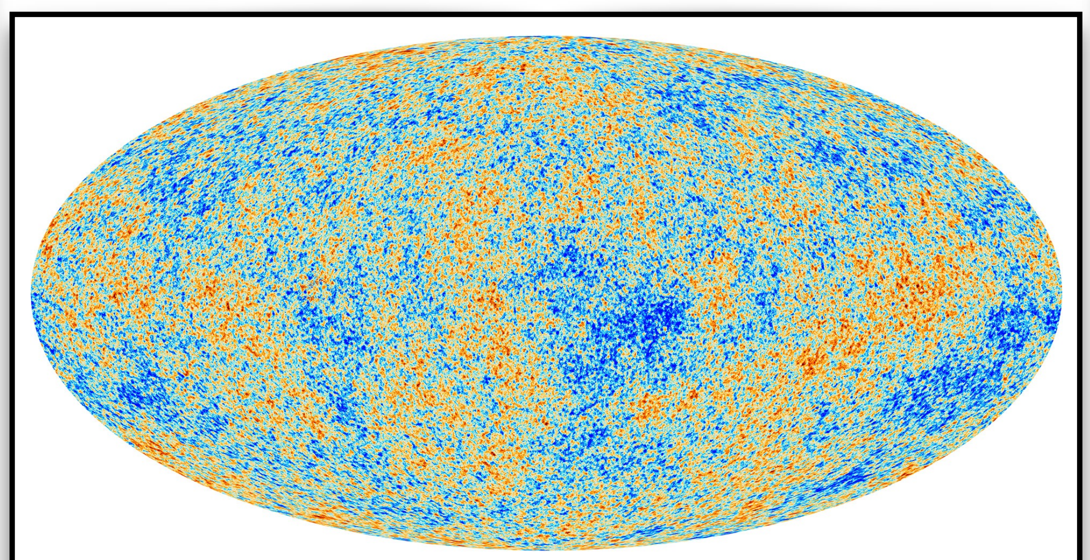
Galaxy clusters



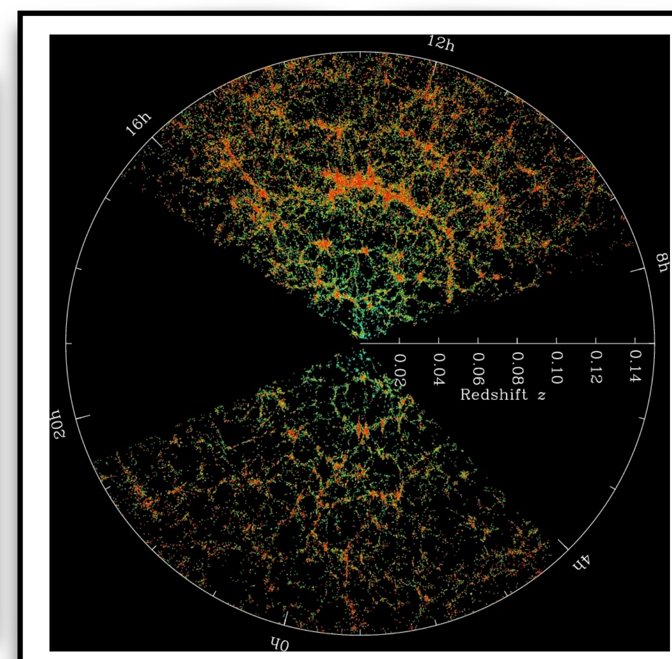
Gravitational lensing



Cosmic Microwave Background

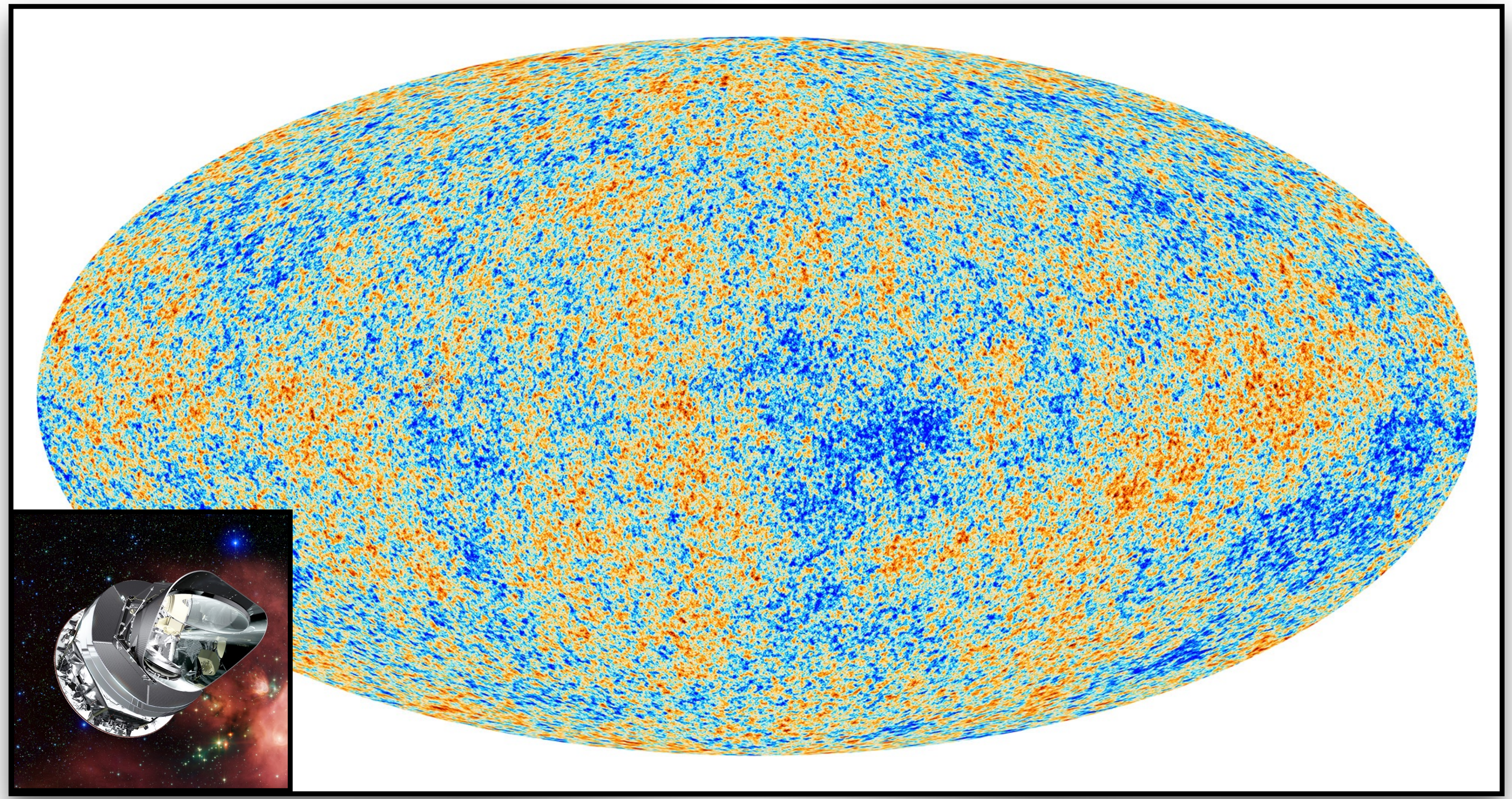


Large Scale Structure

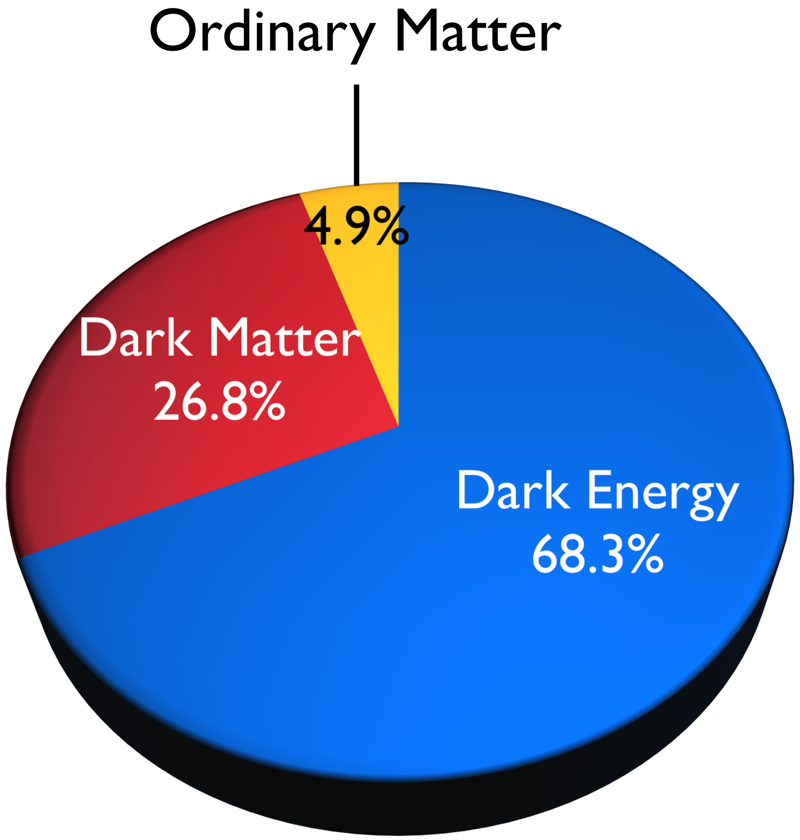


Cosmic Microwave Background

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



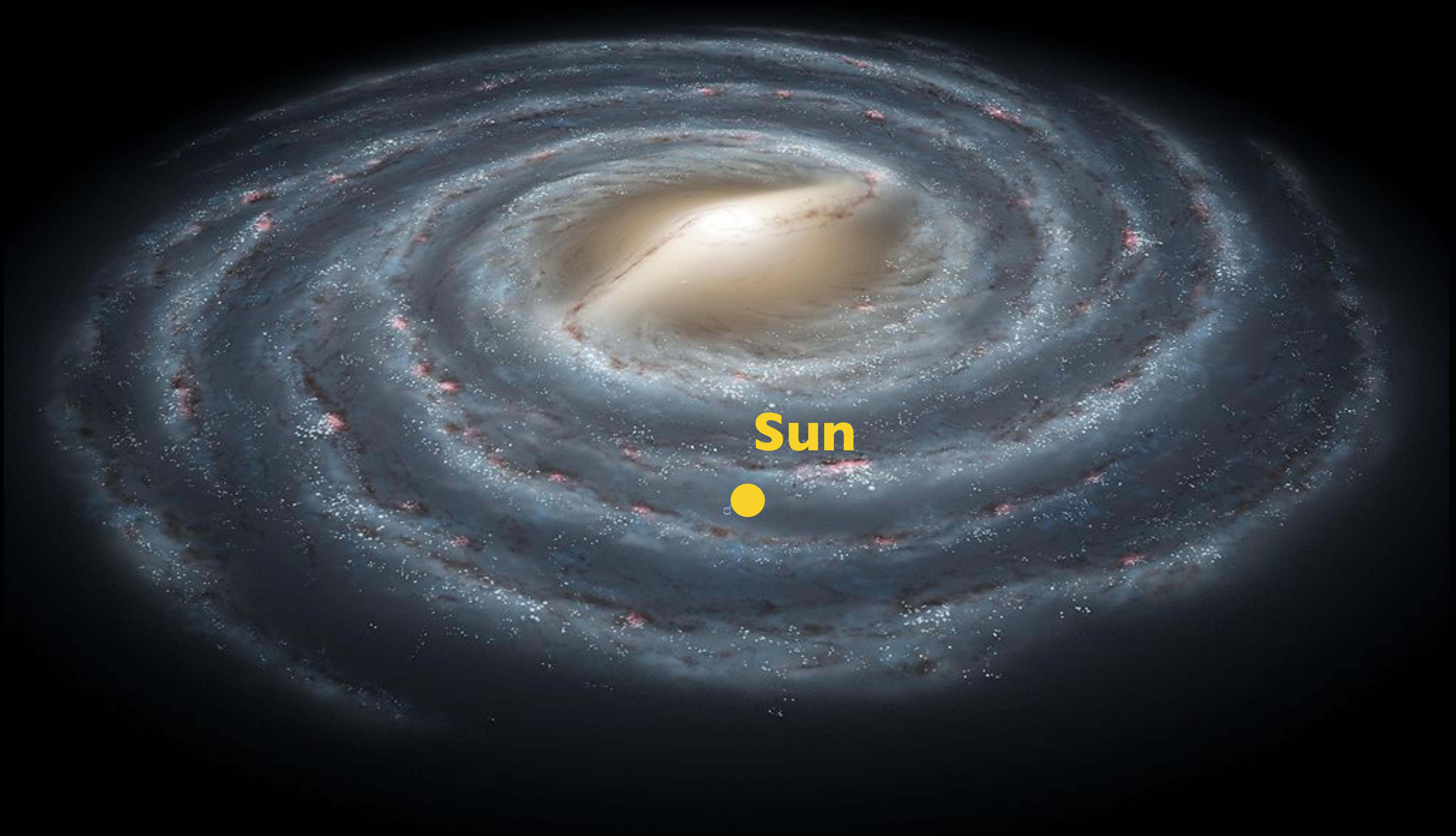
Planck 2015



Our simulated Universe

Local Dark Matter distribution

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



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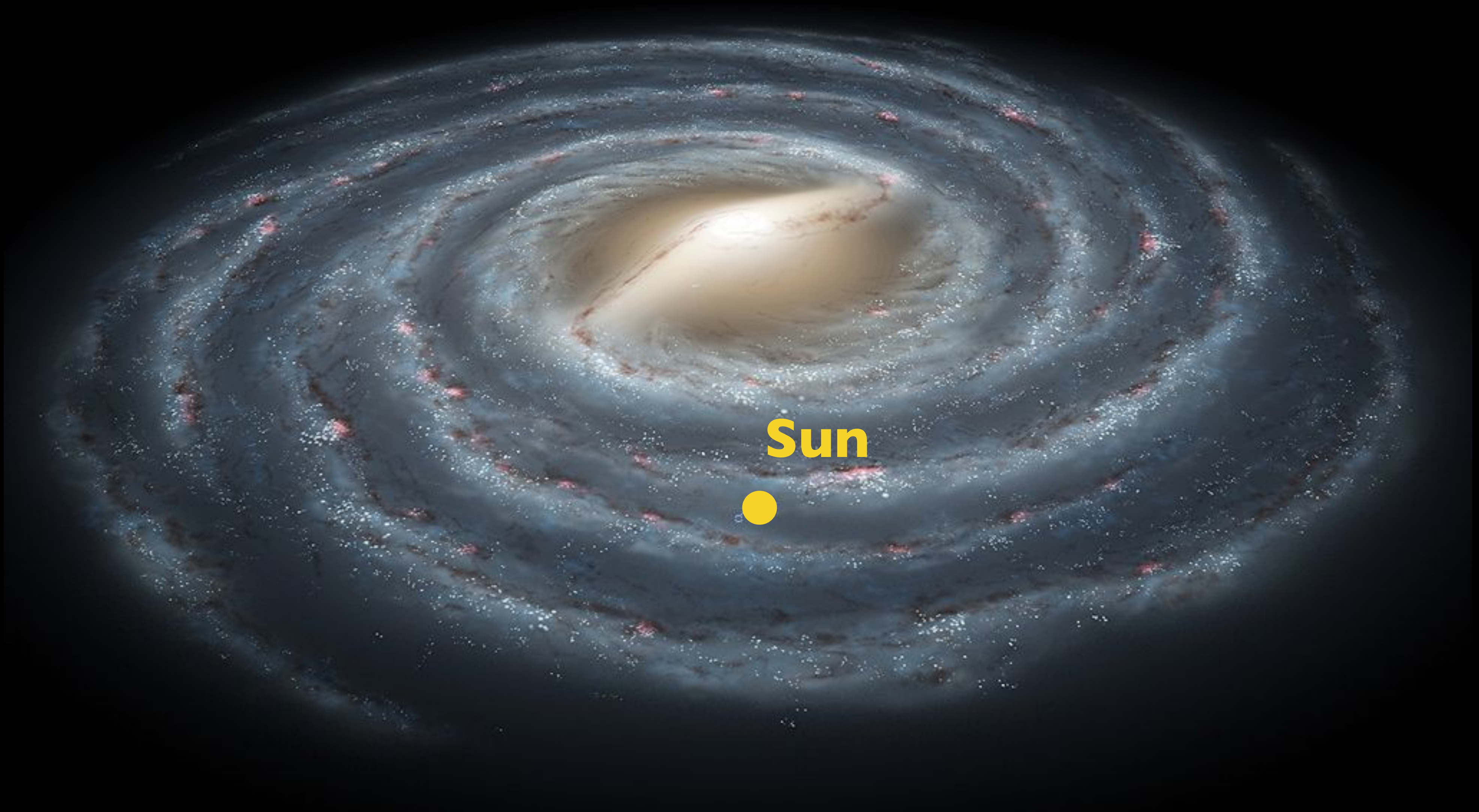
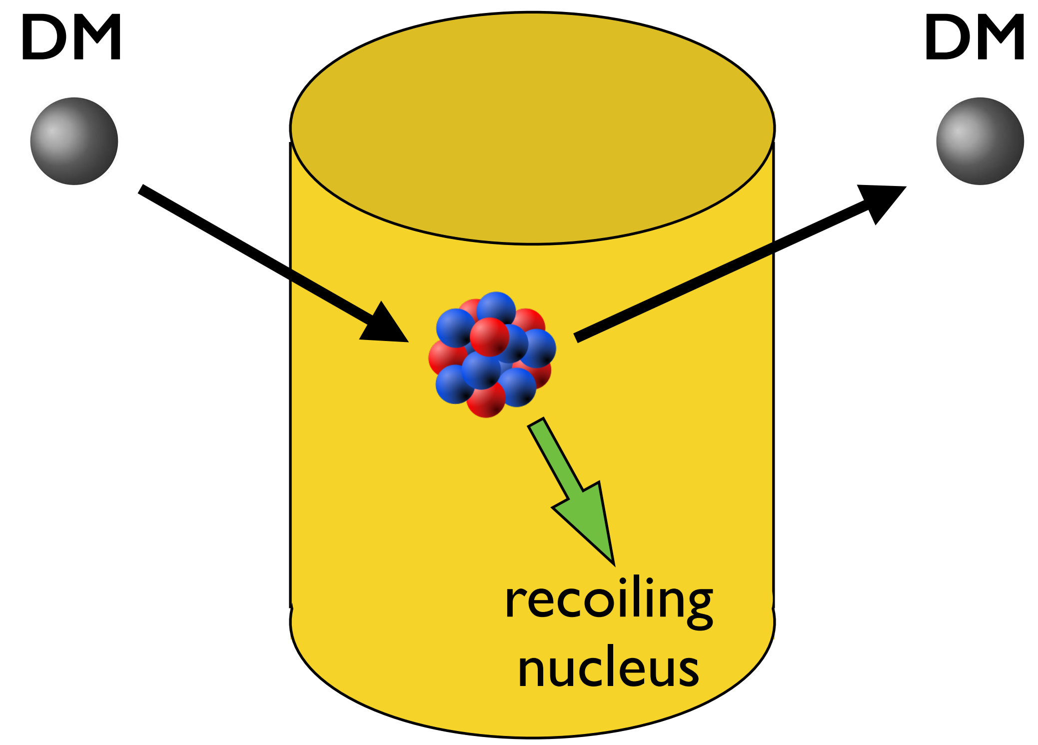


Uncertainties in the local DM distribution → ***large uncertainties in the interpretation of direct detection data.***

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):

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

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astrophysics

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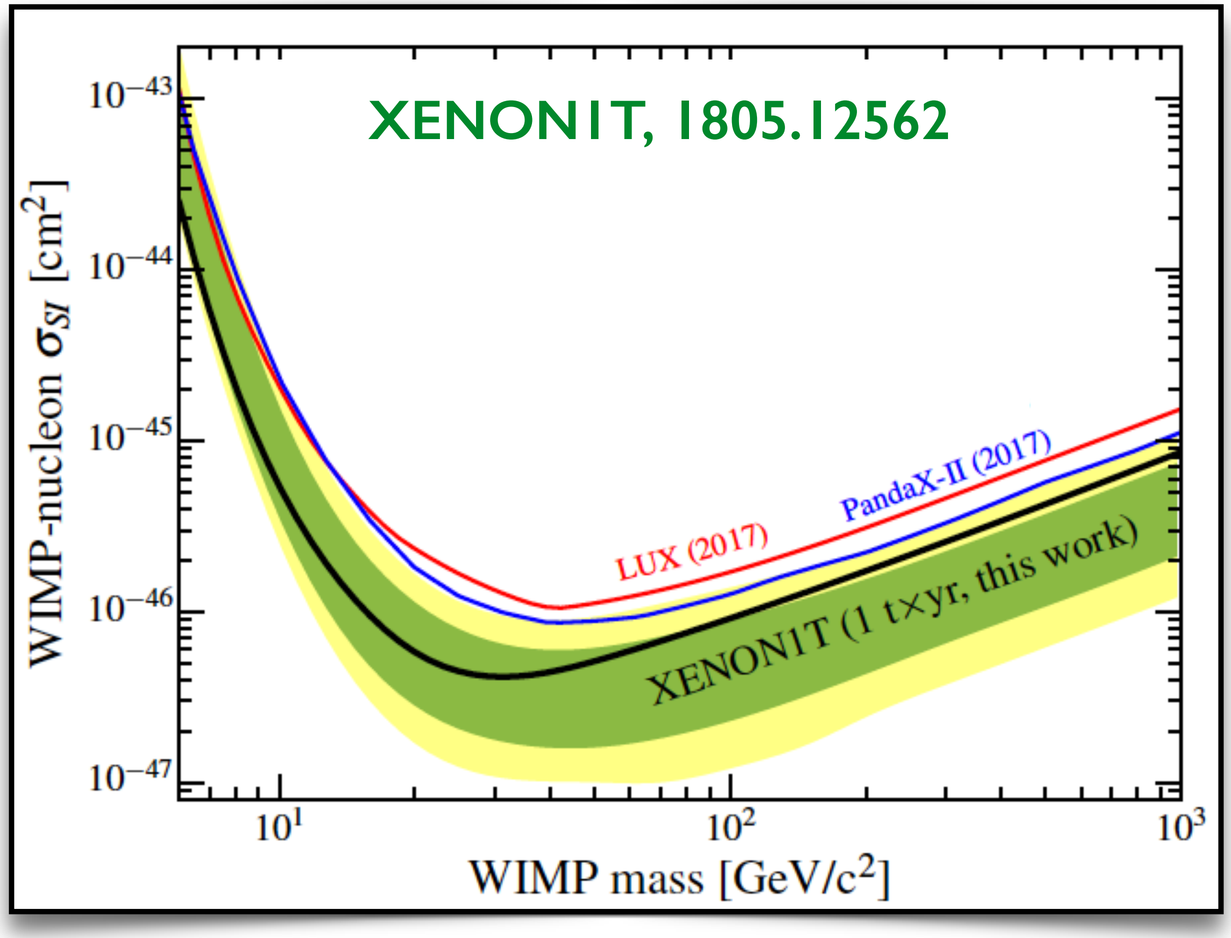
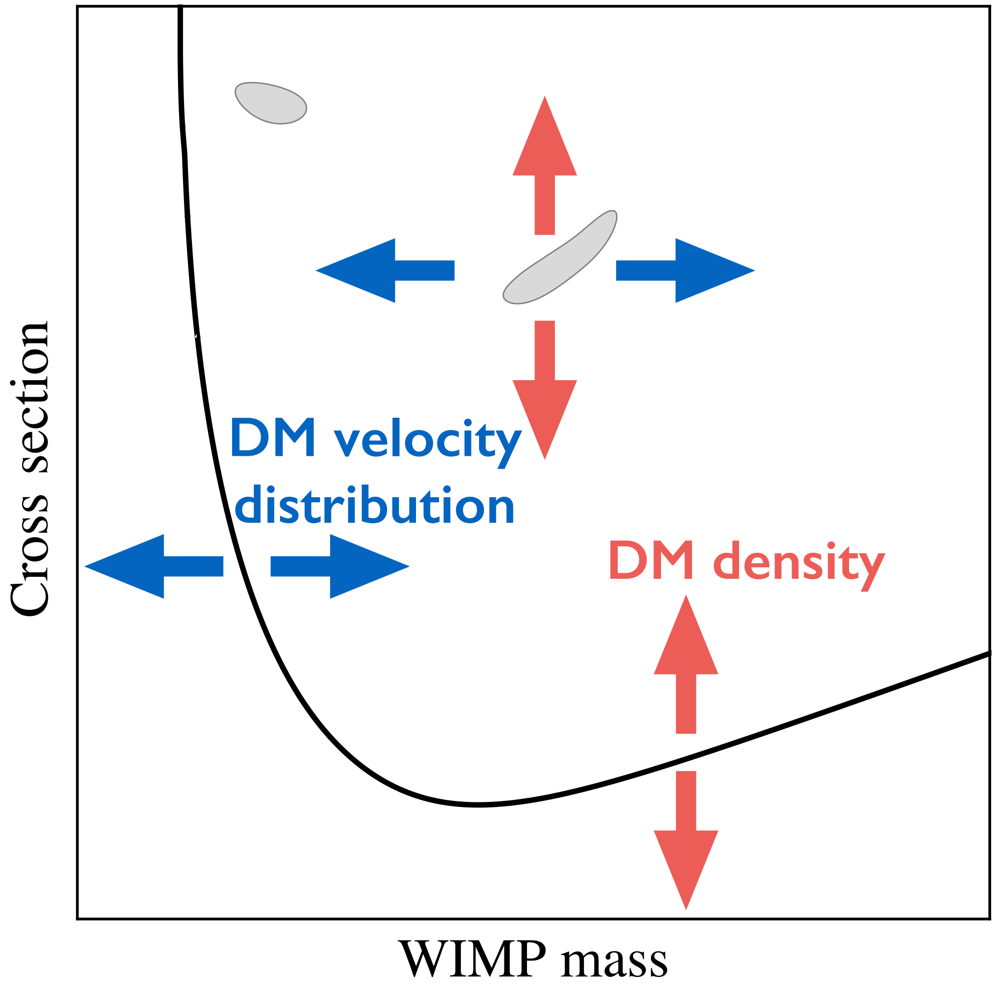
- **Astrophysical inputs:**
  - **local DM density:** *normalization in event rate.*
  - **local DM velocity distribution:** *enters the event rate through an integration.*

Astrophysical inputs





Assumption: **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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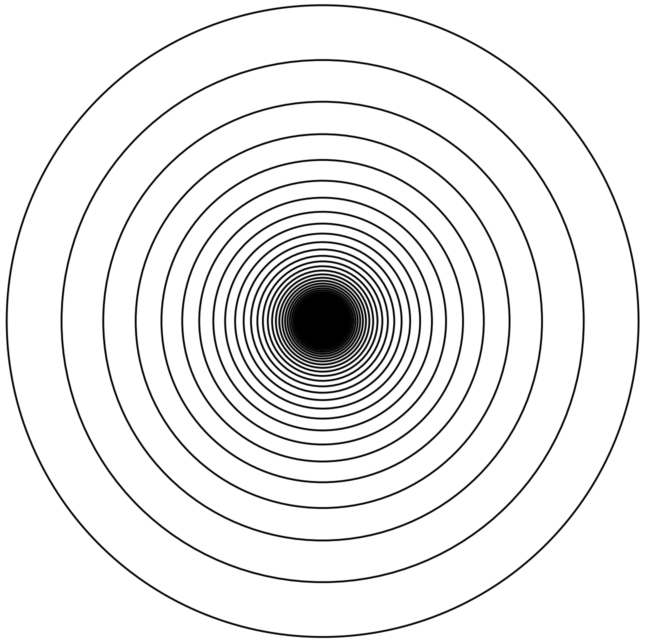
Drukier, Freese, Spergel, 1986

  - Hydrostatic equilibrium: collisionless 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

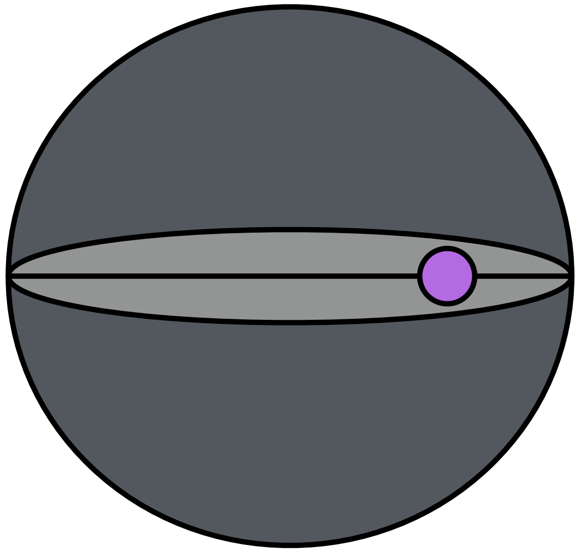


- Actual DM distribution may ***deviate substantially*** from the SHM.

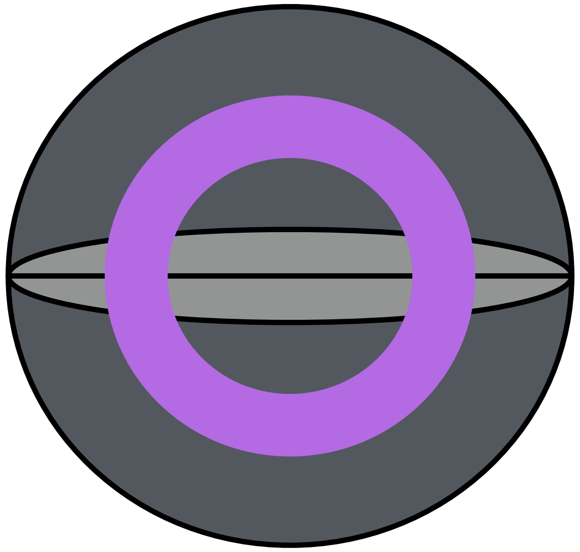
Local Dark Matter density

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.

Dark Matter 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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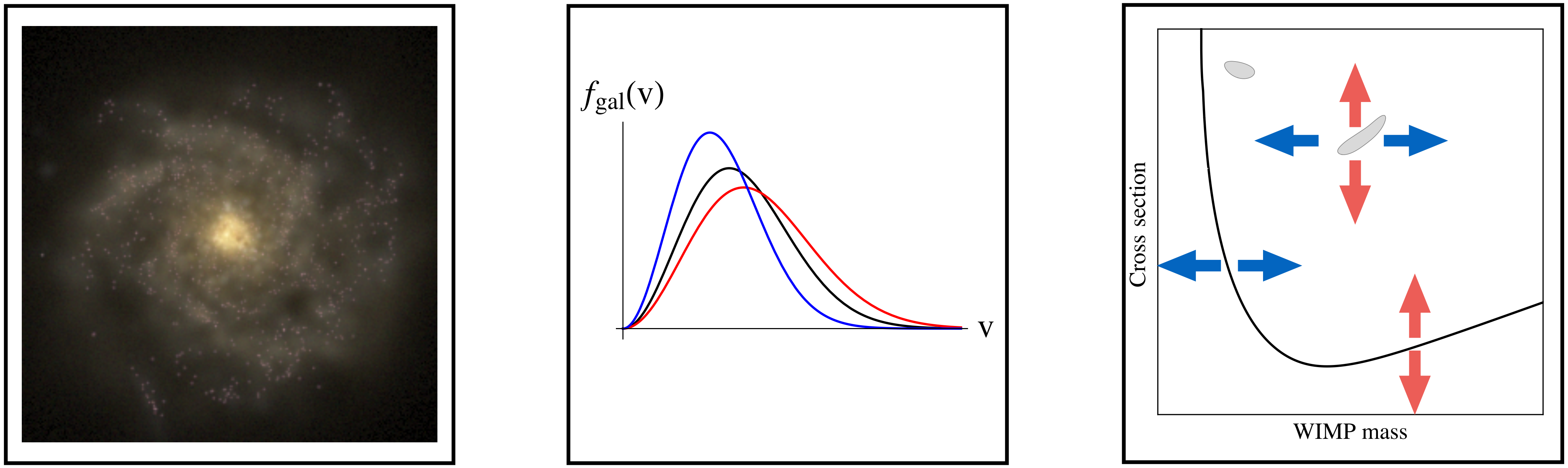
- *How can we obtain information from simulations and observations about the local DM velocity distribution?*

Dark Matter velocity distribution

- **From simulations:**



- **From observations and simulations:**

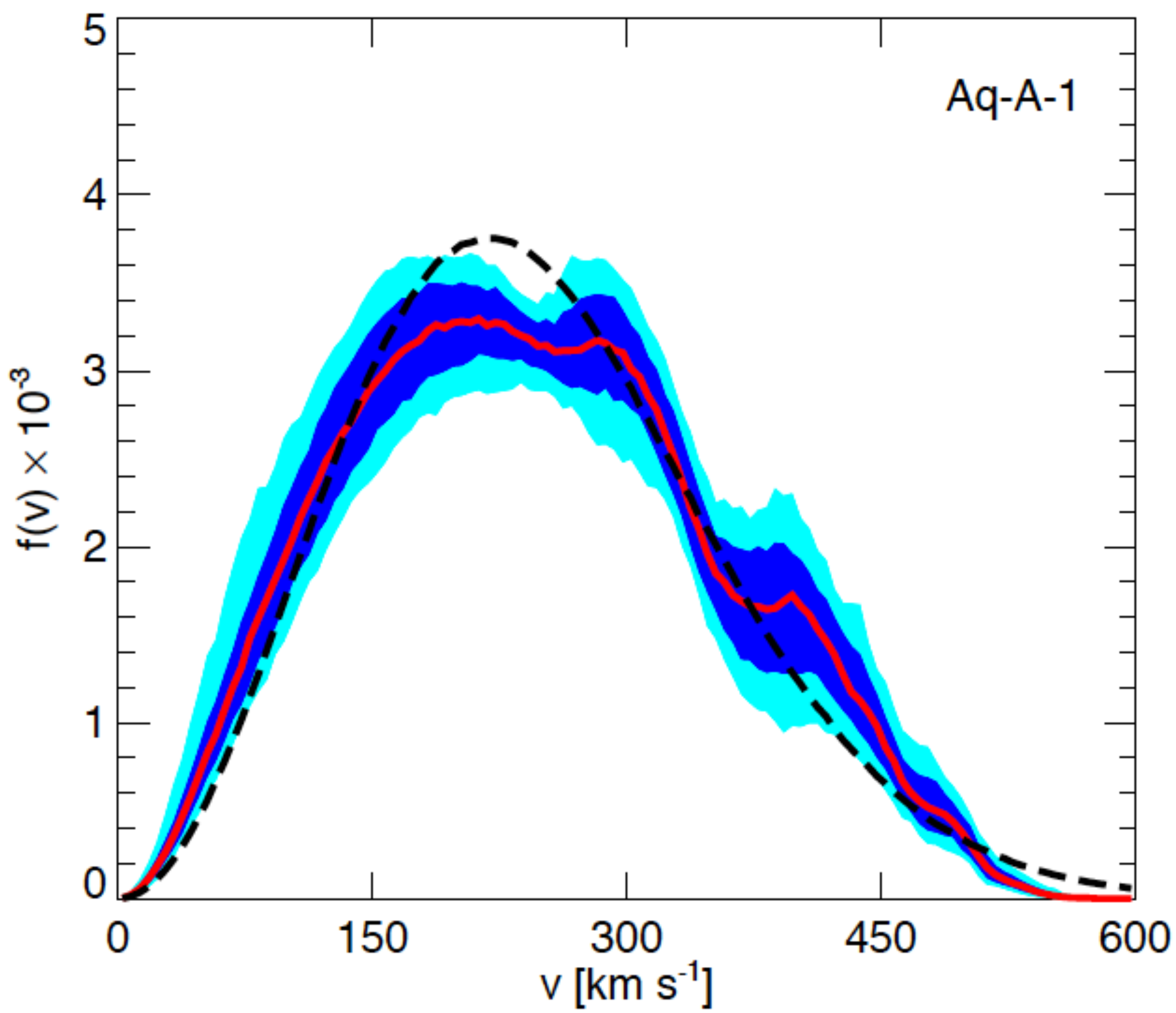
Find a population of stars which trace the DM velocity distribution in *multiple simulations*. ➔ Use *observations* of those stars to infer the DM velocity distribution.

Herzog-Arbeitman et al., 1704.04499, 1708.03635, Necib, Lisanti, Belokurov, 1807.02519

Dark Matter velocity distribution from simulations

Dark Matter only simulations

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



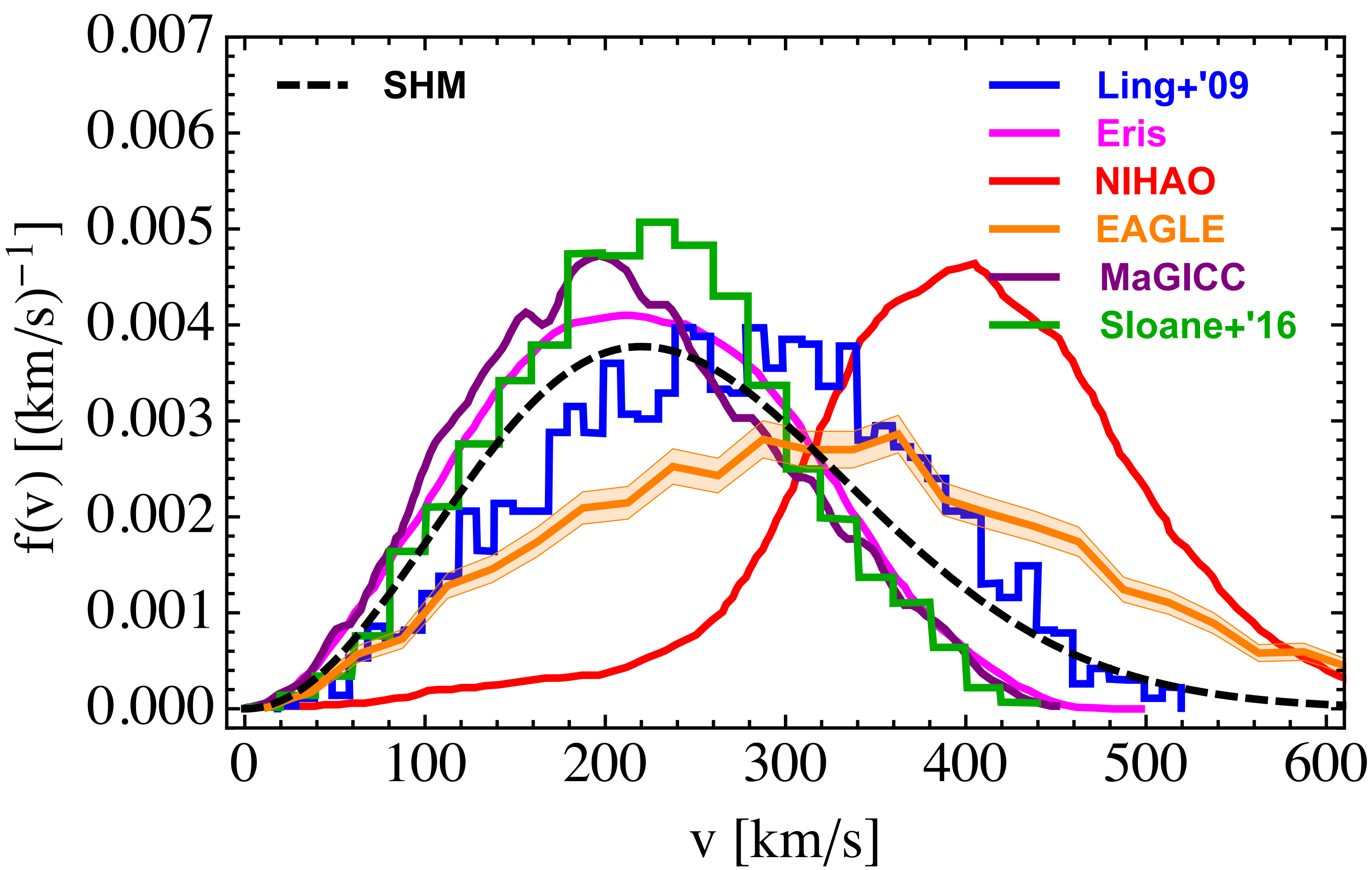
$$f(|\mathbf{v}|) = v^2 \int d\Omega_{\mathbf{v}} f(\mathbf{v})$$

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

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

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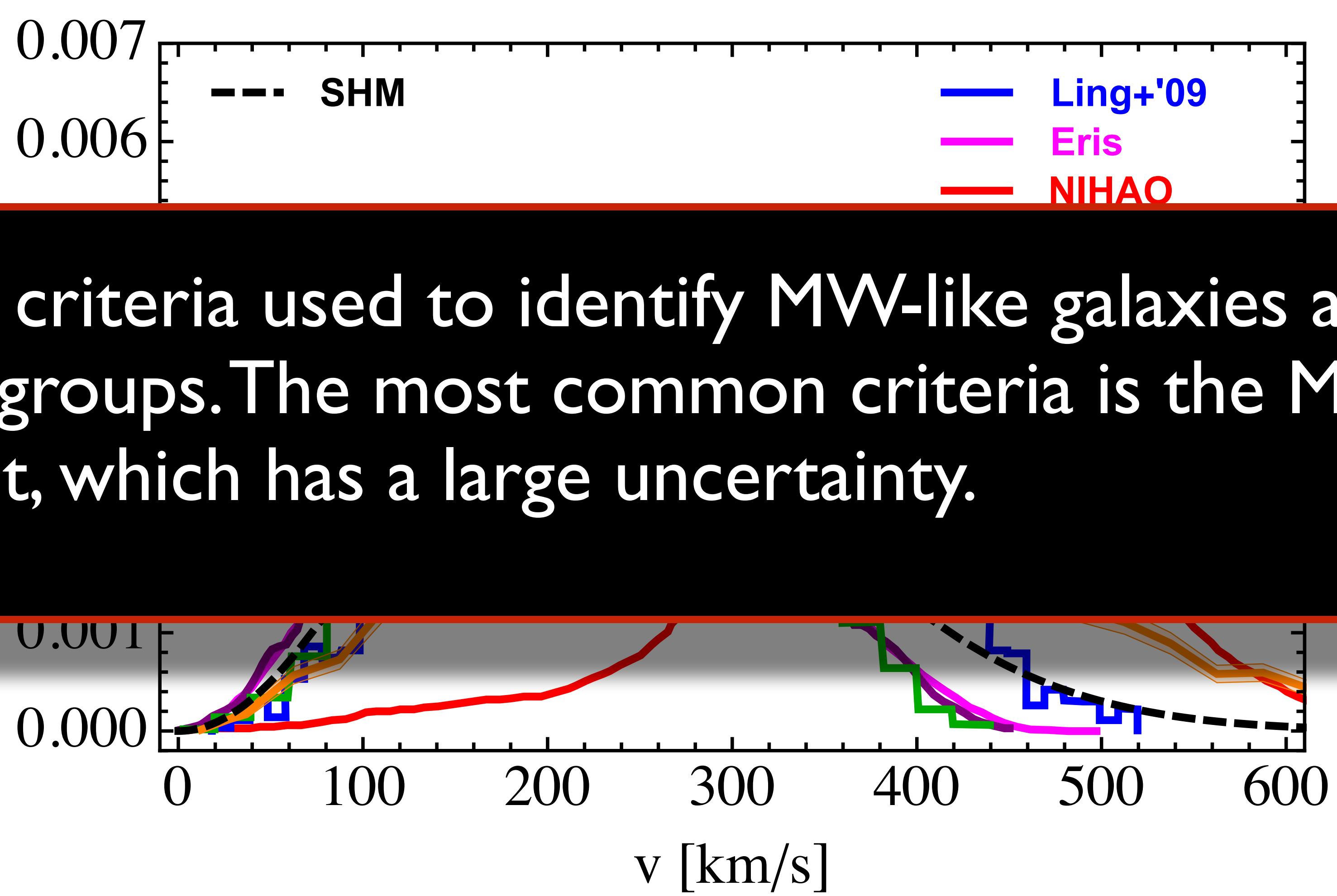

Different criteria used to identify MW-like galaxies among different groups. The most common criteria is the MW mass constraint, which has a large uncertainty.

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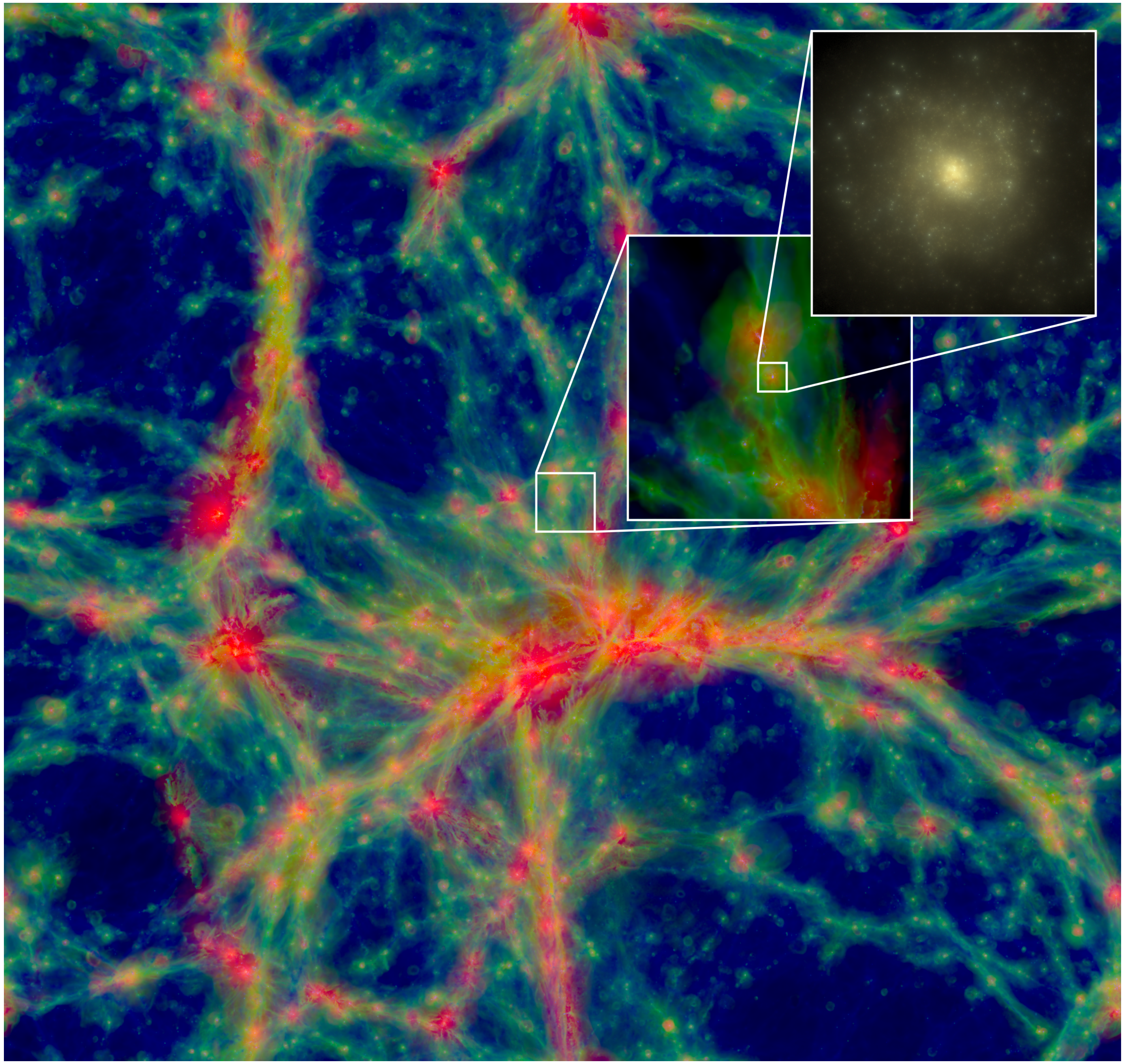
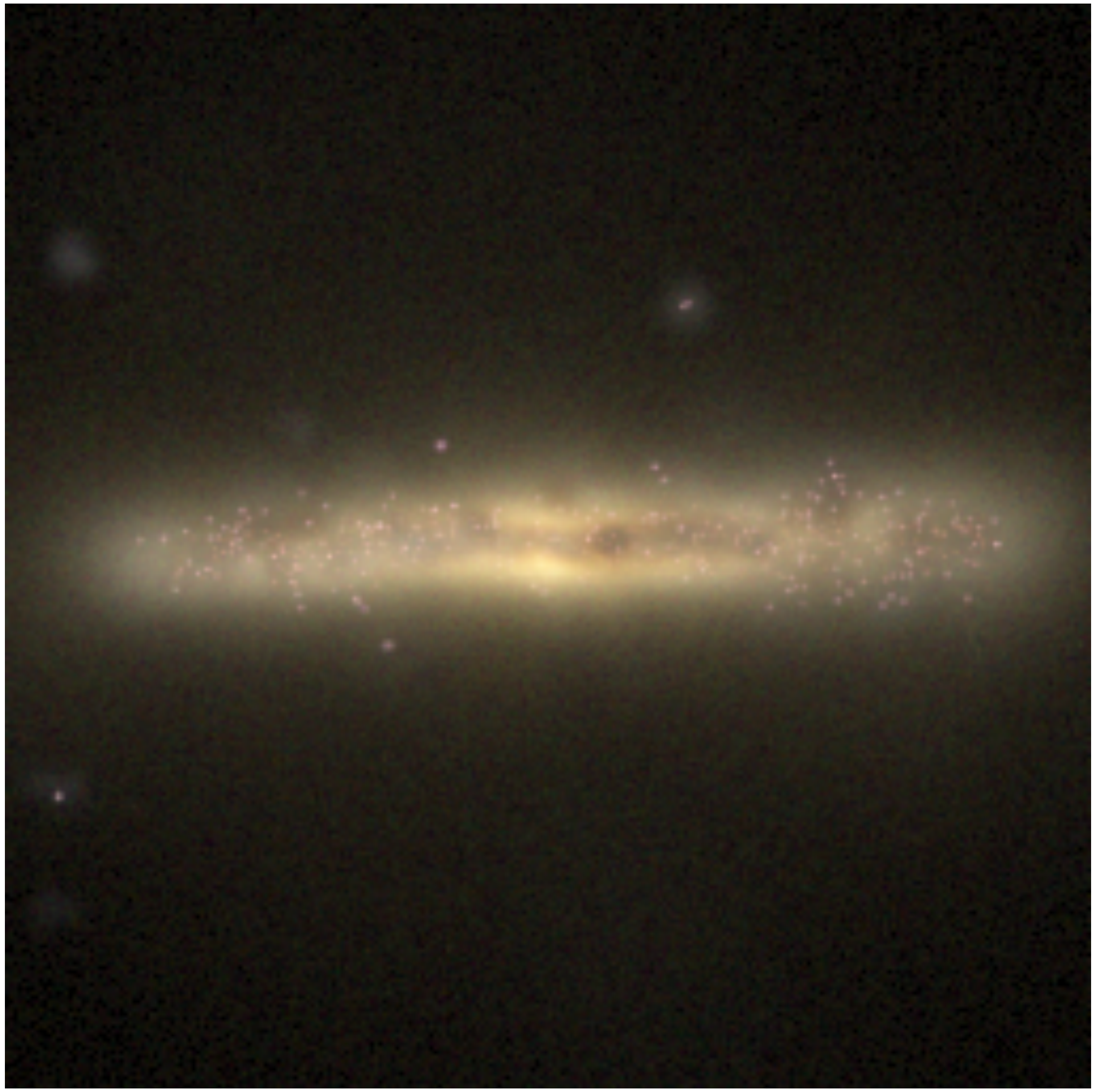
- **APOSTLE IR**: zoomed simulations of Local Group-analogue systems, comparable in resolution to **EAGLE HR**.
- *Calibrated to reproduce the observed distribution of stellar masses and sizes of low-redshift galaxies.*
- Companion Dark Matter only (DMO) simulations were run assuming all the matter content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

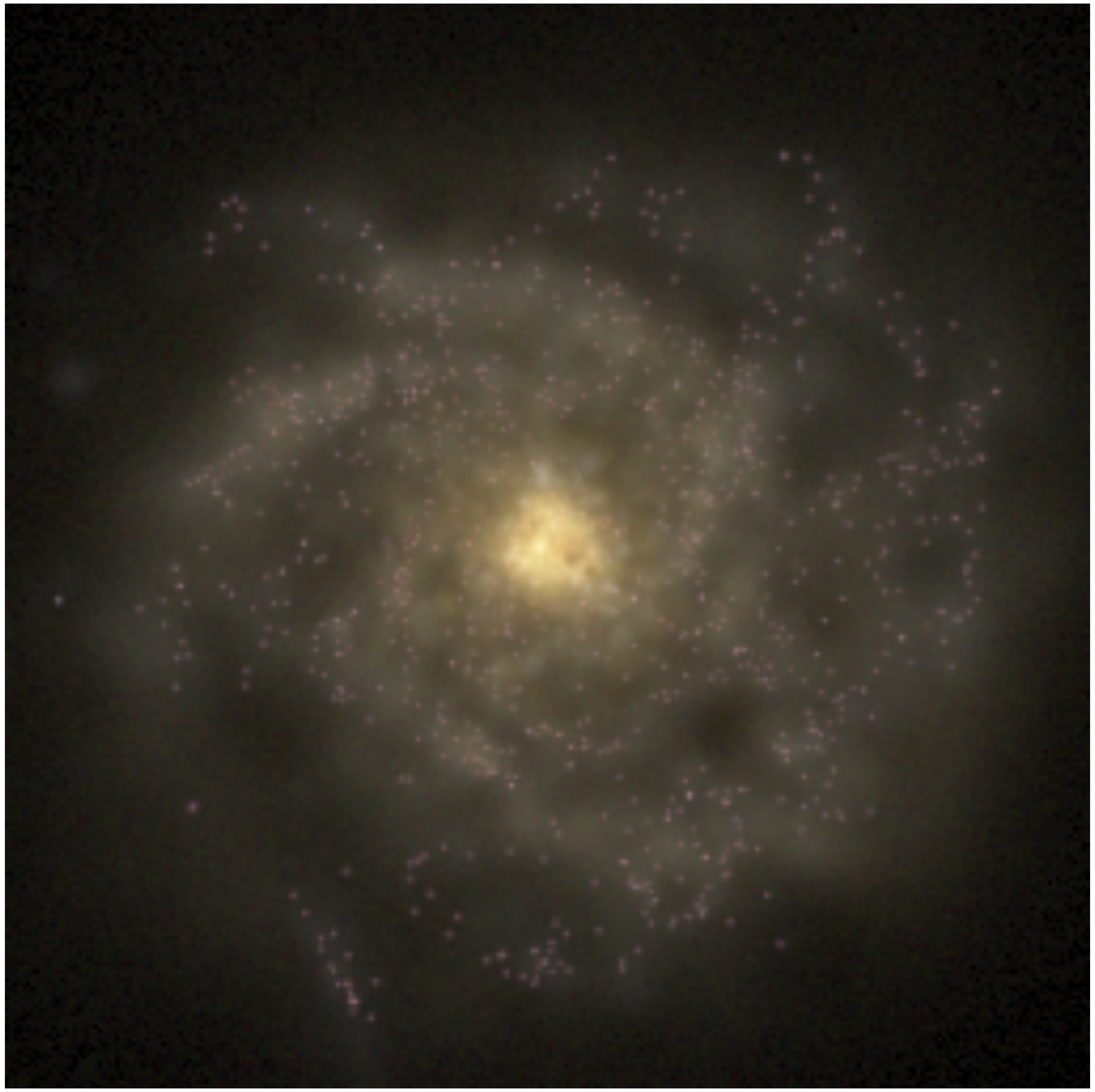
EAGLE Simulations



EAGLE Simulations, 1407.7040

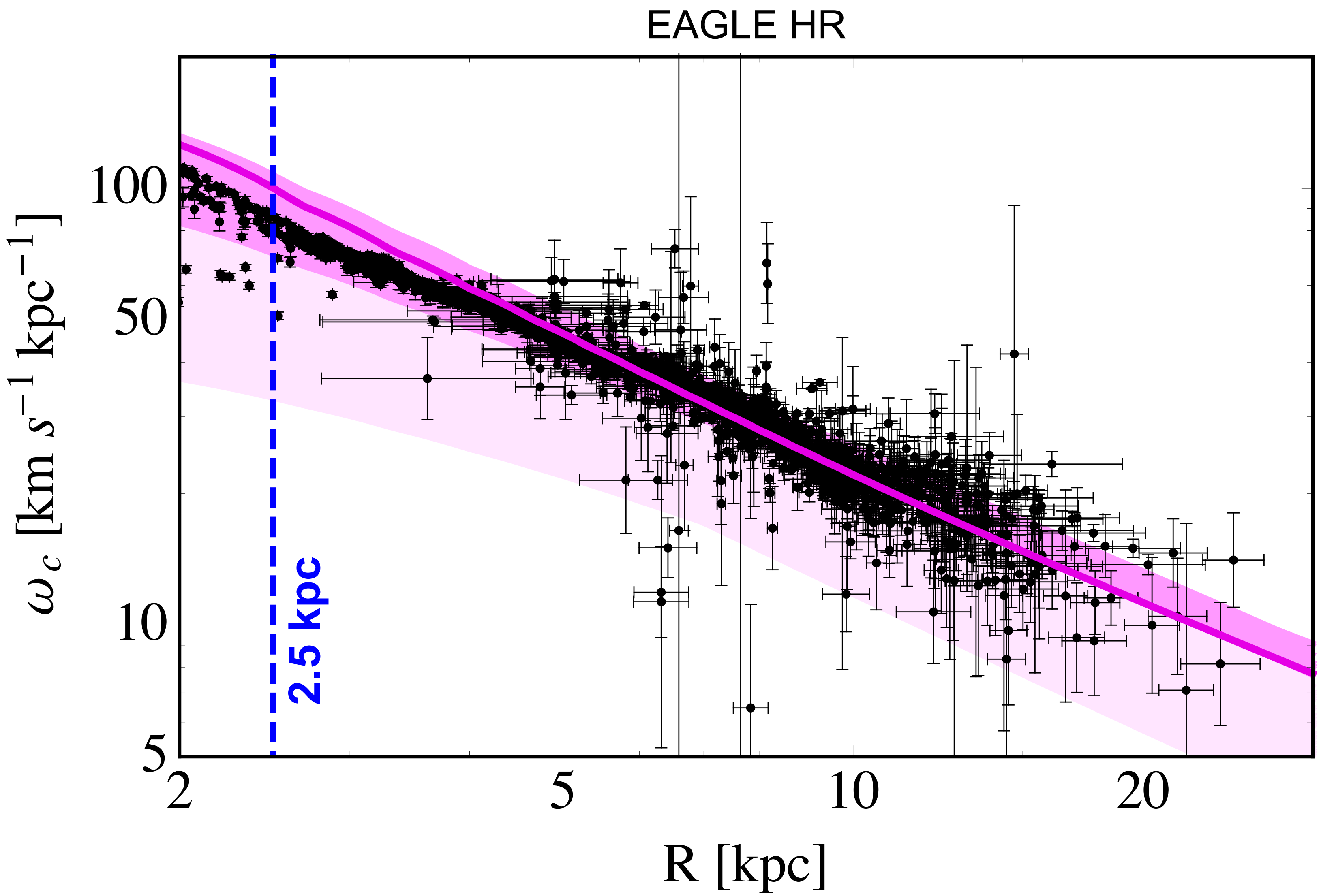
Milky Way analogues





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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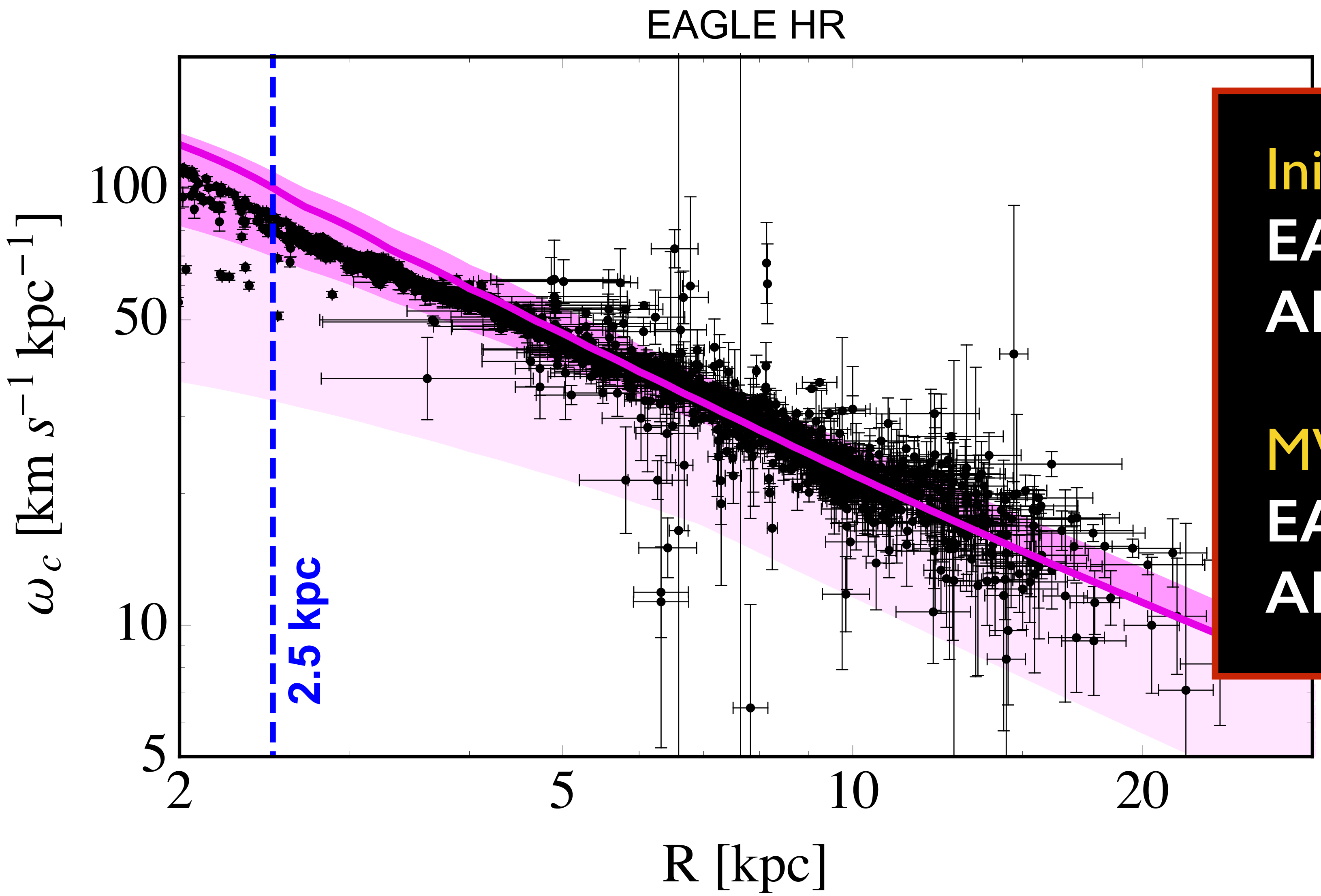


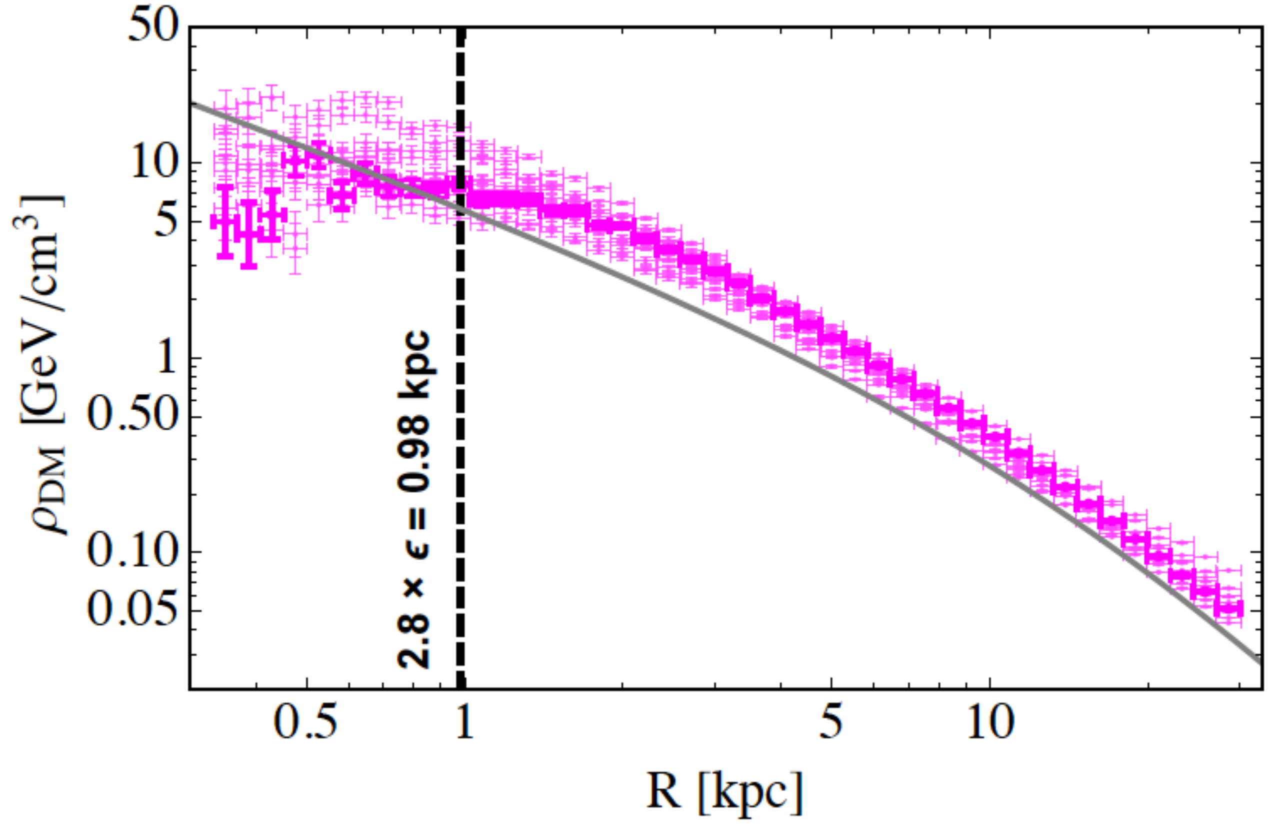
Initial haloes:
EAGLE: 61
APOSTLE: 24

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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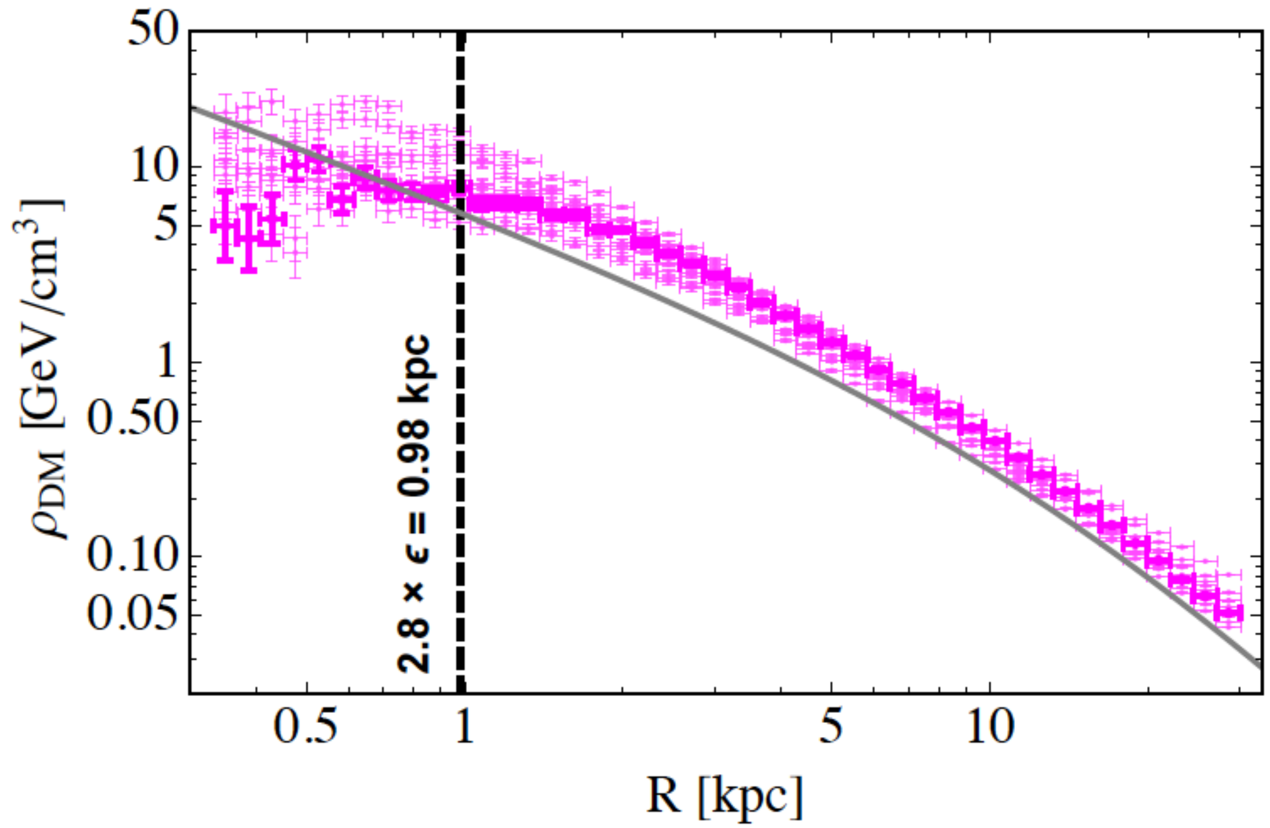
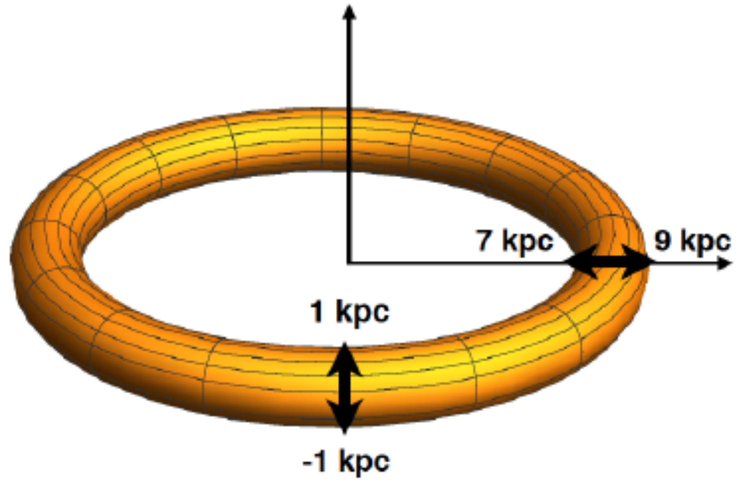


- To find the DM density at the position of the Sun, consider a torus aligned with the stellar disc.



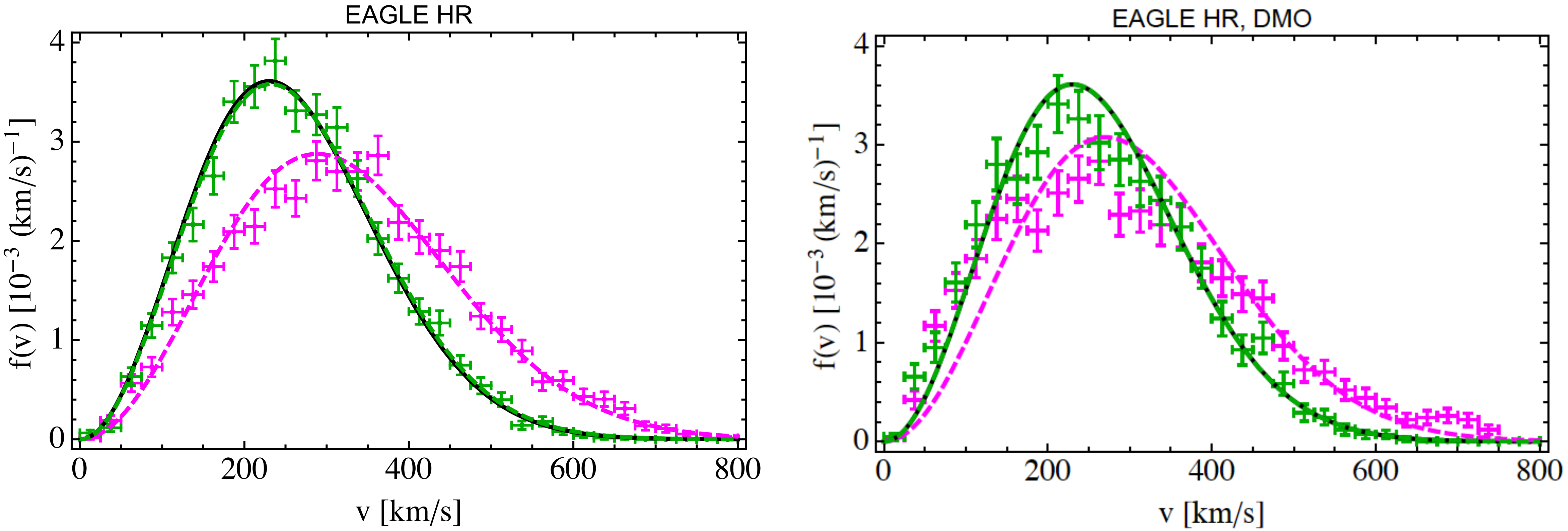
ρ_χ = 0.41 - 0.73 GeV/cm^3

Bozorgnia et al., 1601.04707

Local speed distributions

In the galactic rest frame:

DMO simulations



Bozorgnia et al., 1601.04707

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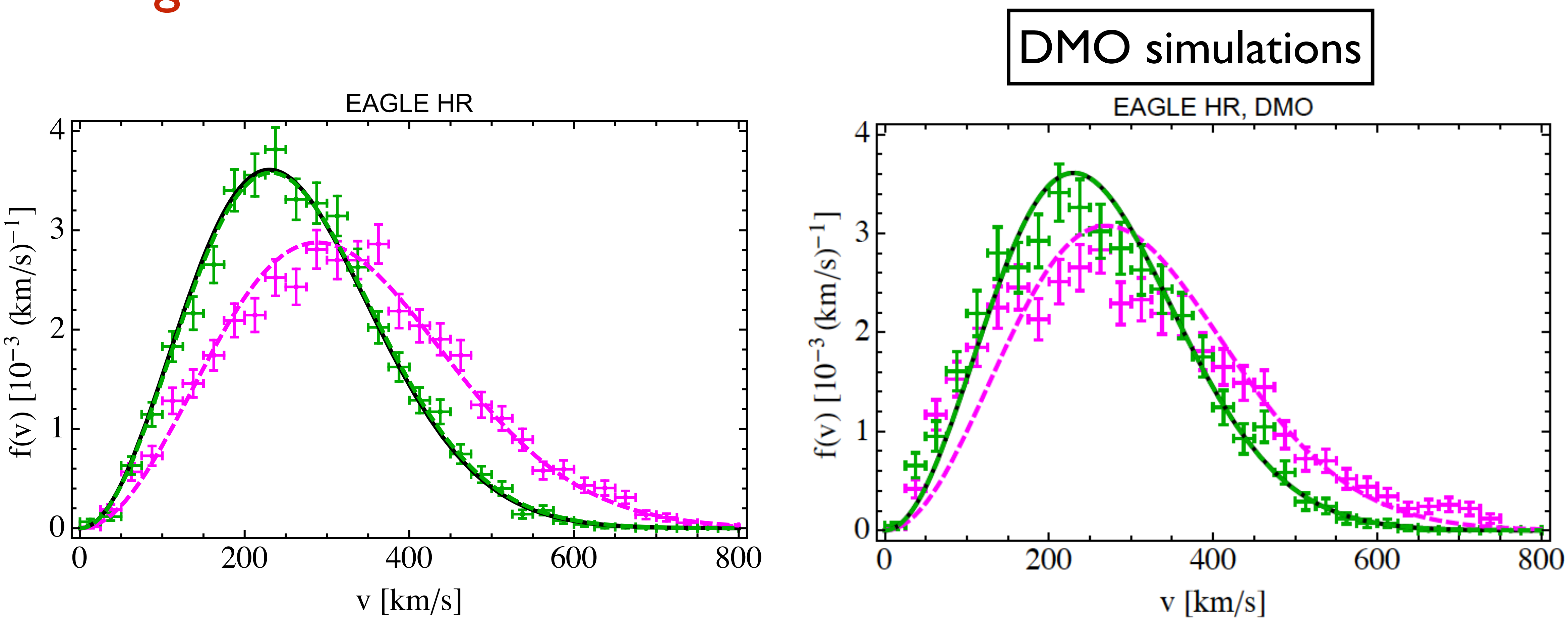


Bozorgnia et al., 1601.04707

- 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

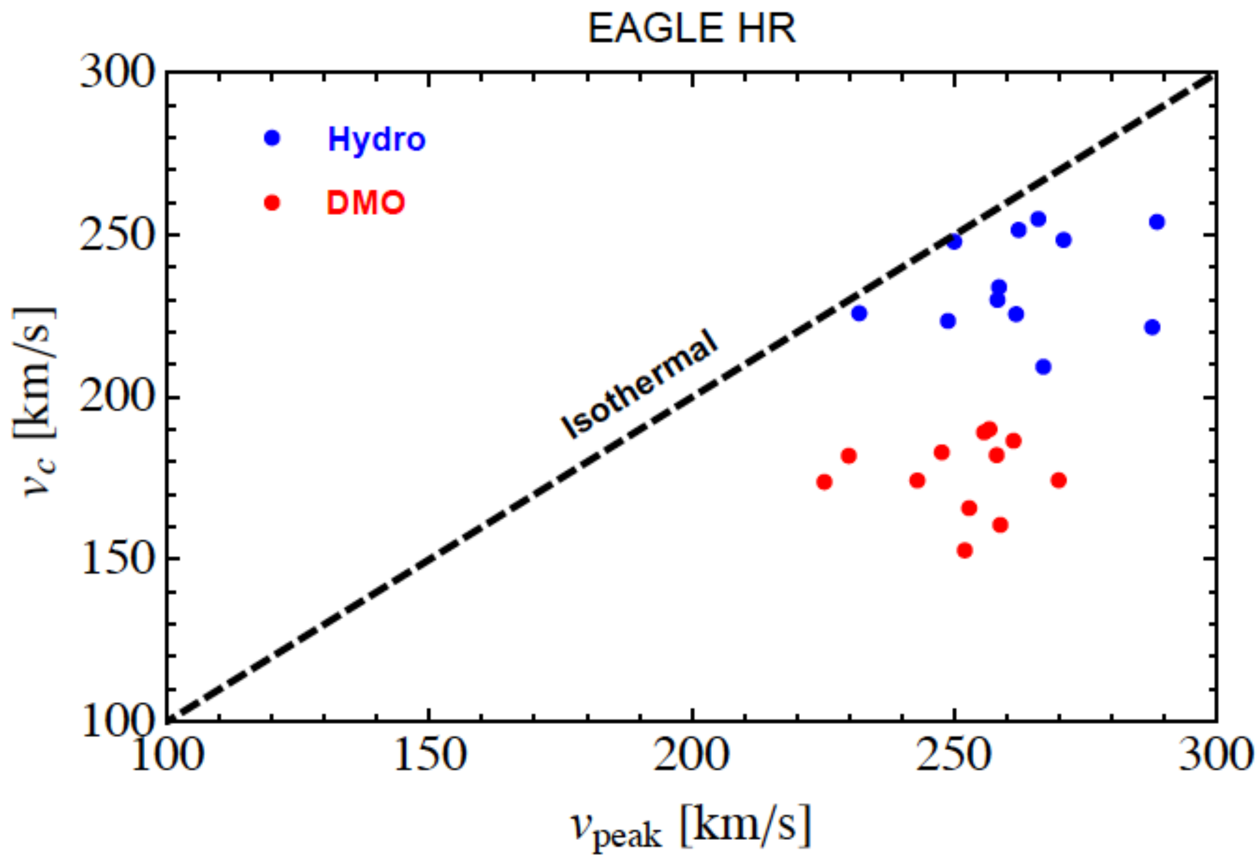
Local speed distributions

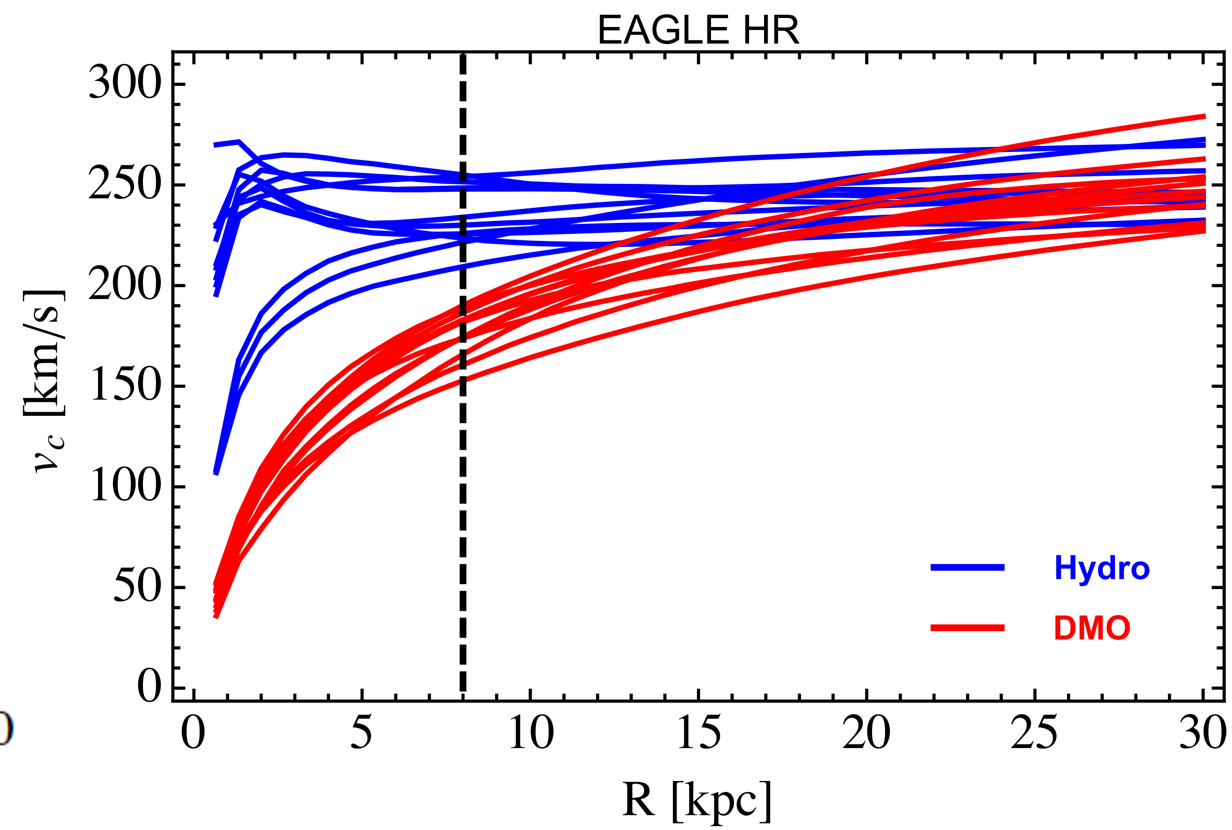
Common trends in different hydrodynamical simulations:

- 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

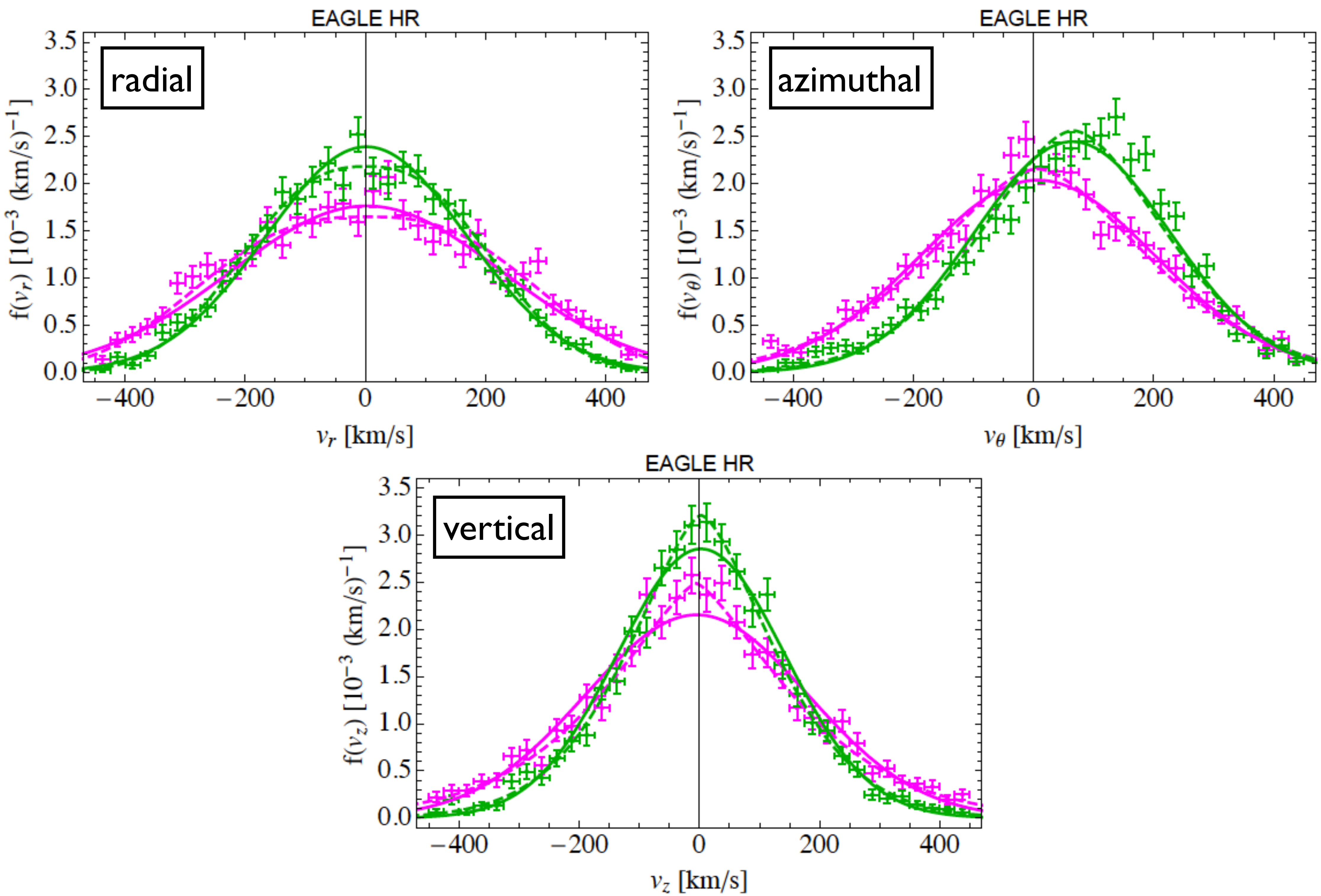




Bozorgnia & Bertone, 1705.05853

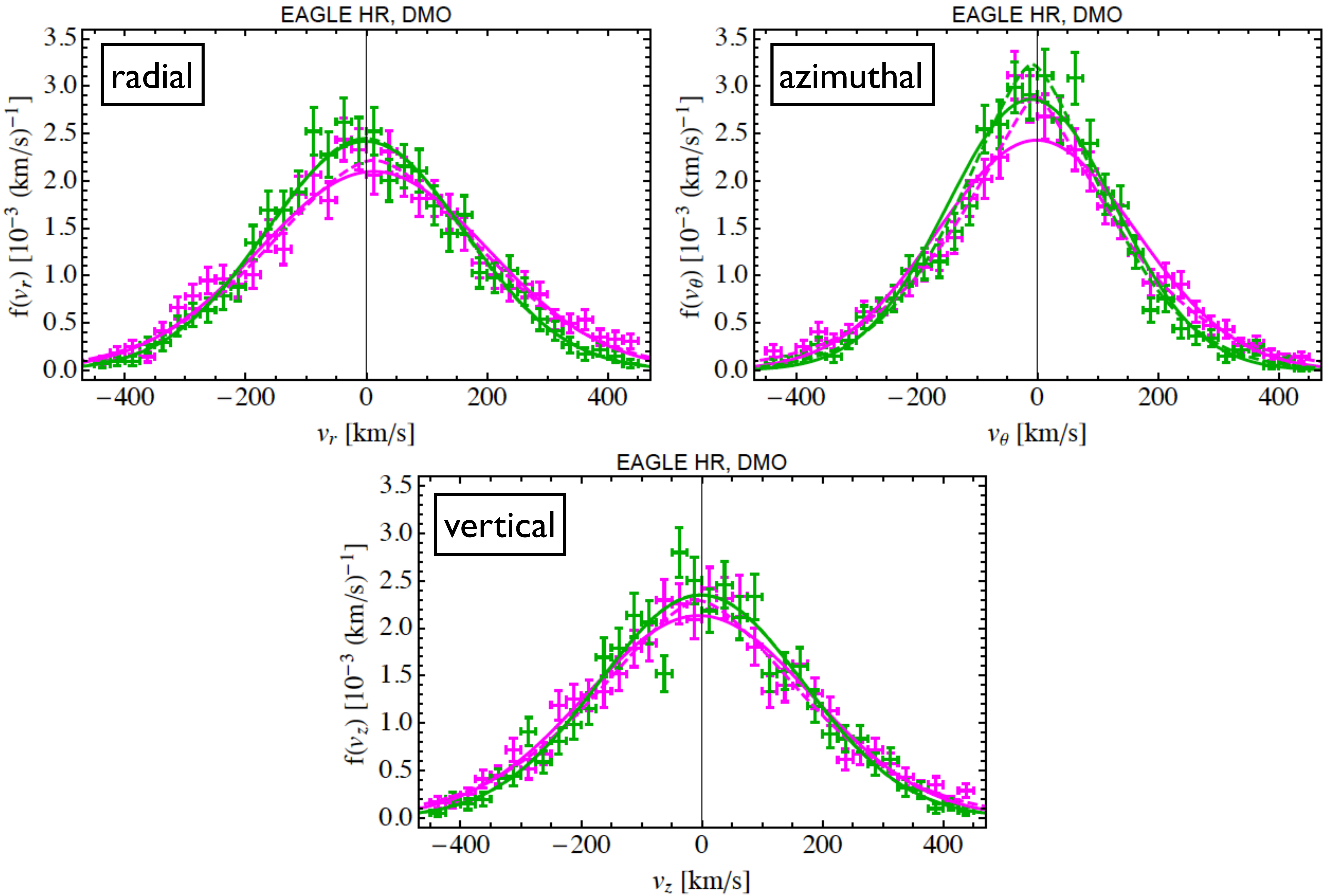
- At the Solar circle, haloes in the hydrodynamical simulation are closer to isothermal than their DMO counterparts.

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

Direct detection event rate

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

astrophysics

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

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

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

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astrophysics

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astrophysics

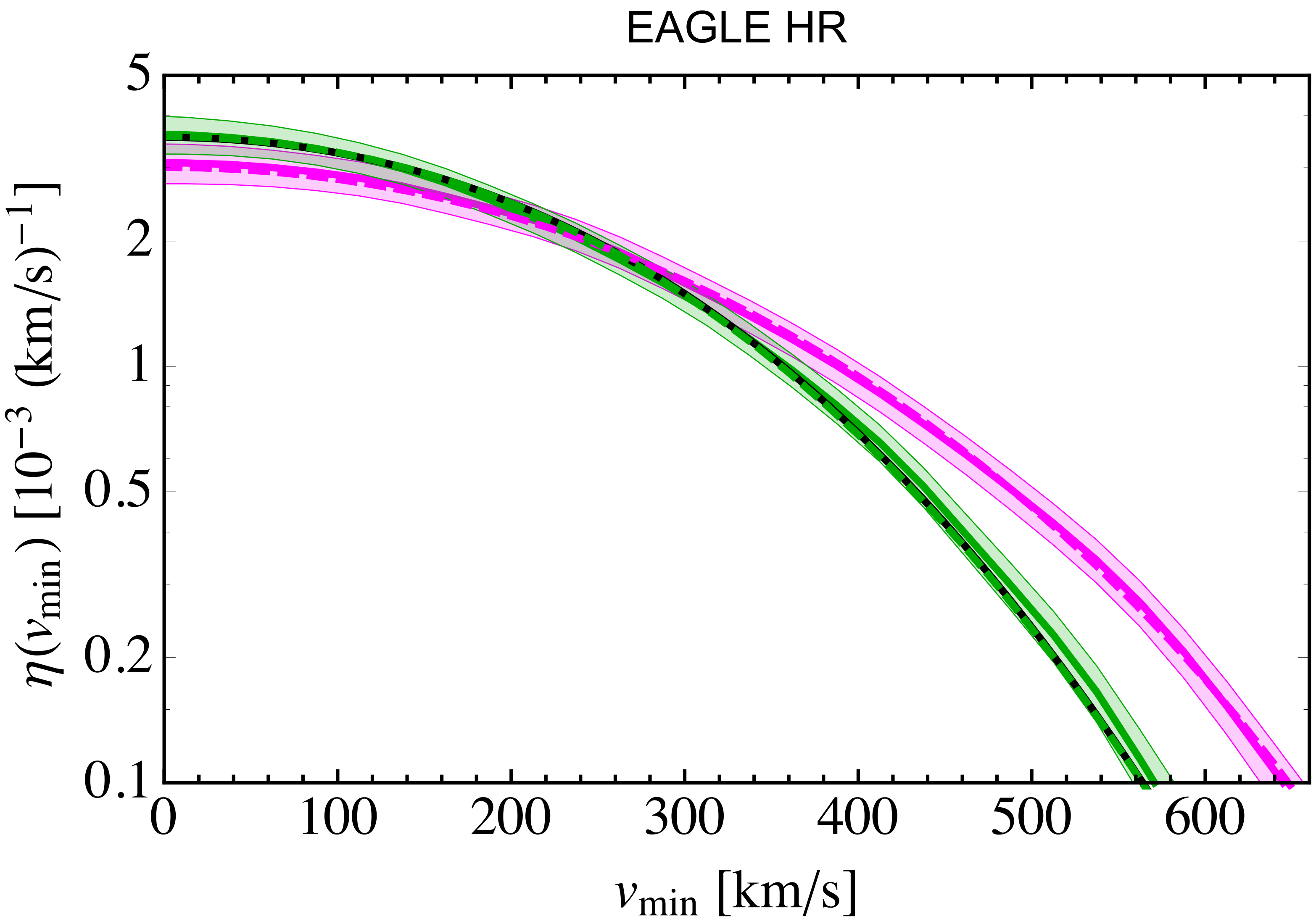
$$\frac{dR}{dE_R} = \frac{\sigma_0 F^2(E_R)}{2 m_\chi \mu_{\chi N}^2} \rho_\chi \eta(v_{\min}, t)$$

where

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

Halo integral

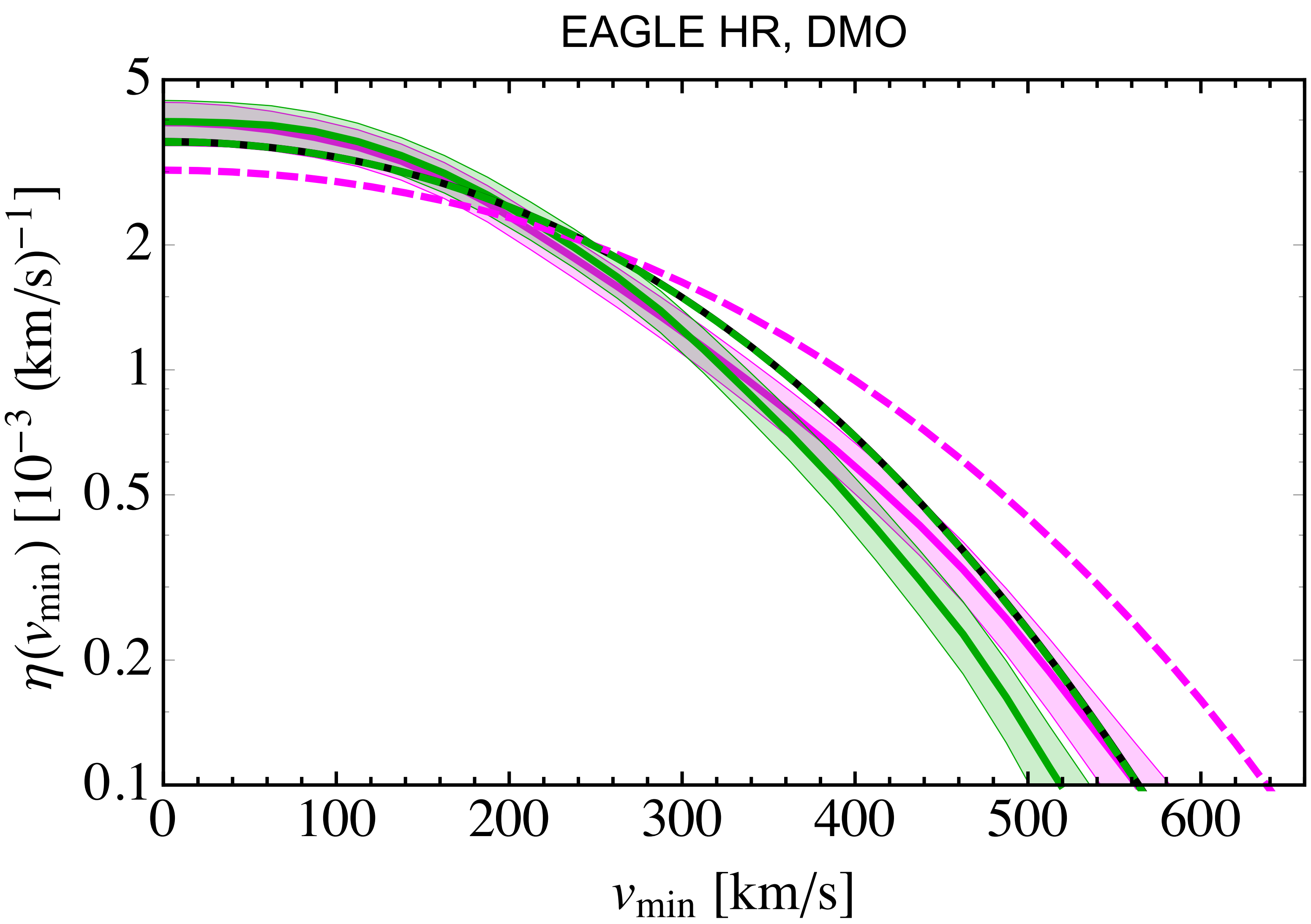
The halo integral



- 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 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

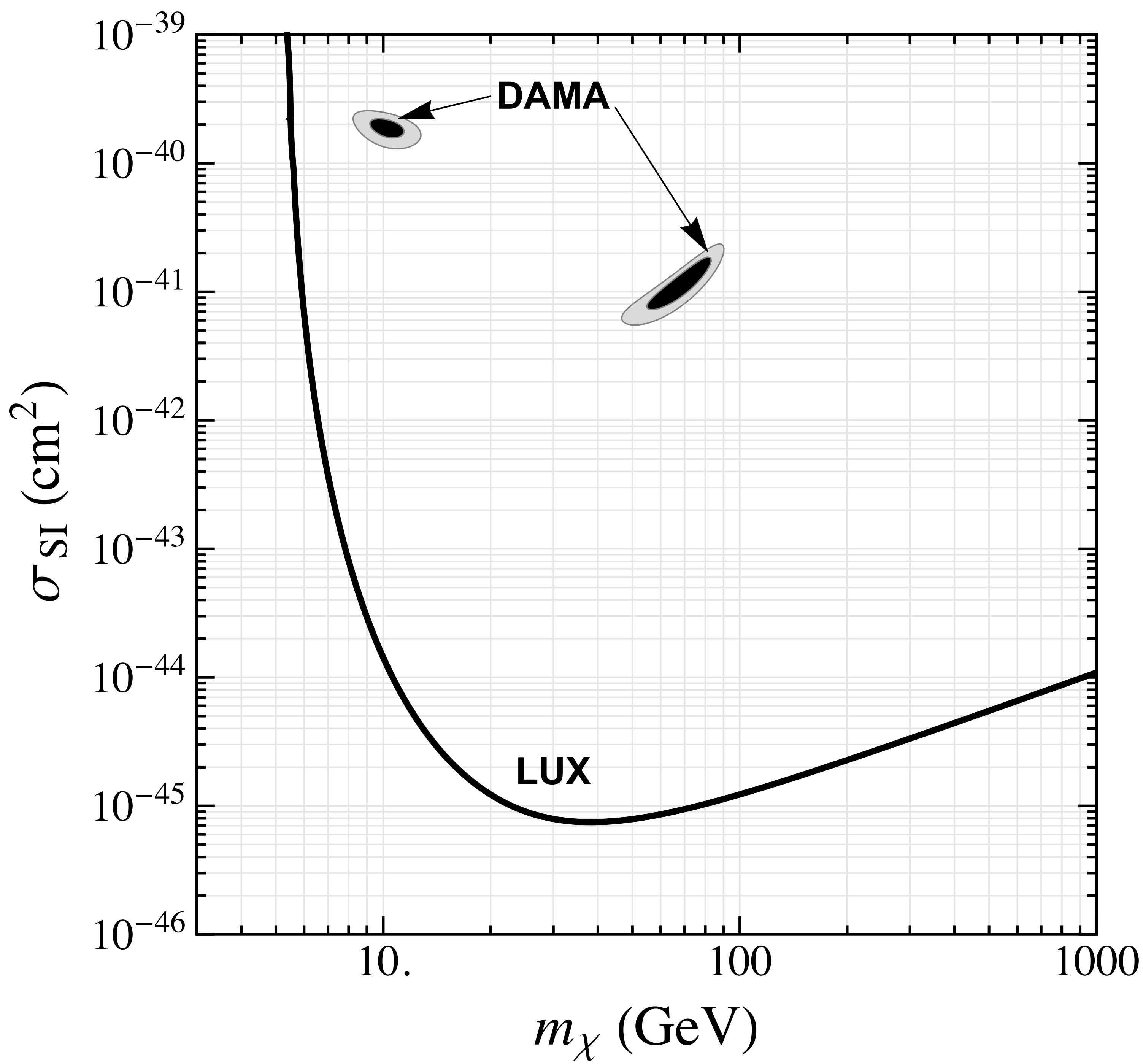
Common trend in different hydrodynamical simulations:

- 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

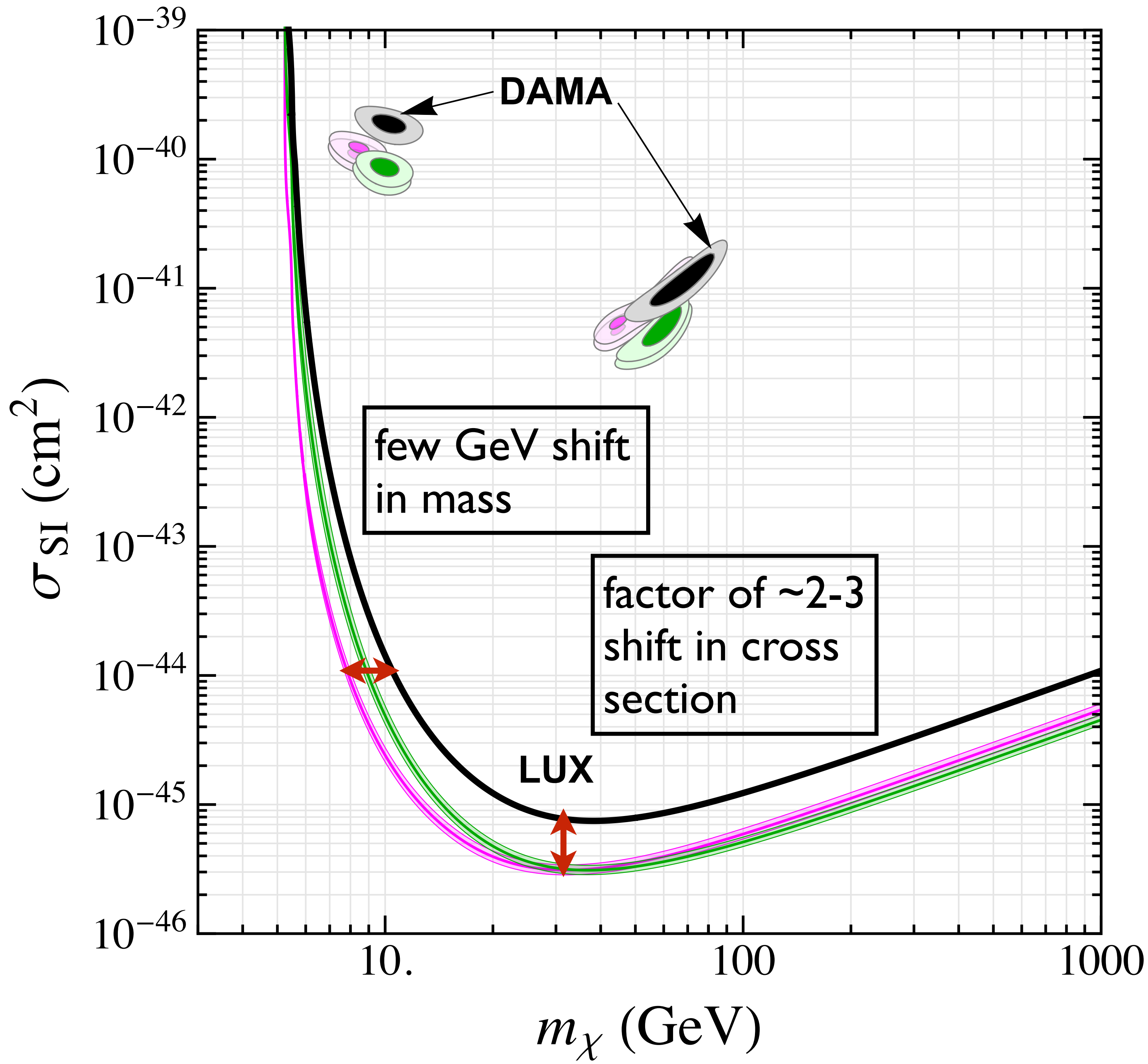
Implications for direct detection

- Assuming the **Standard Halo Model**:



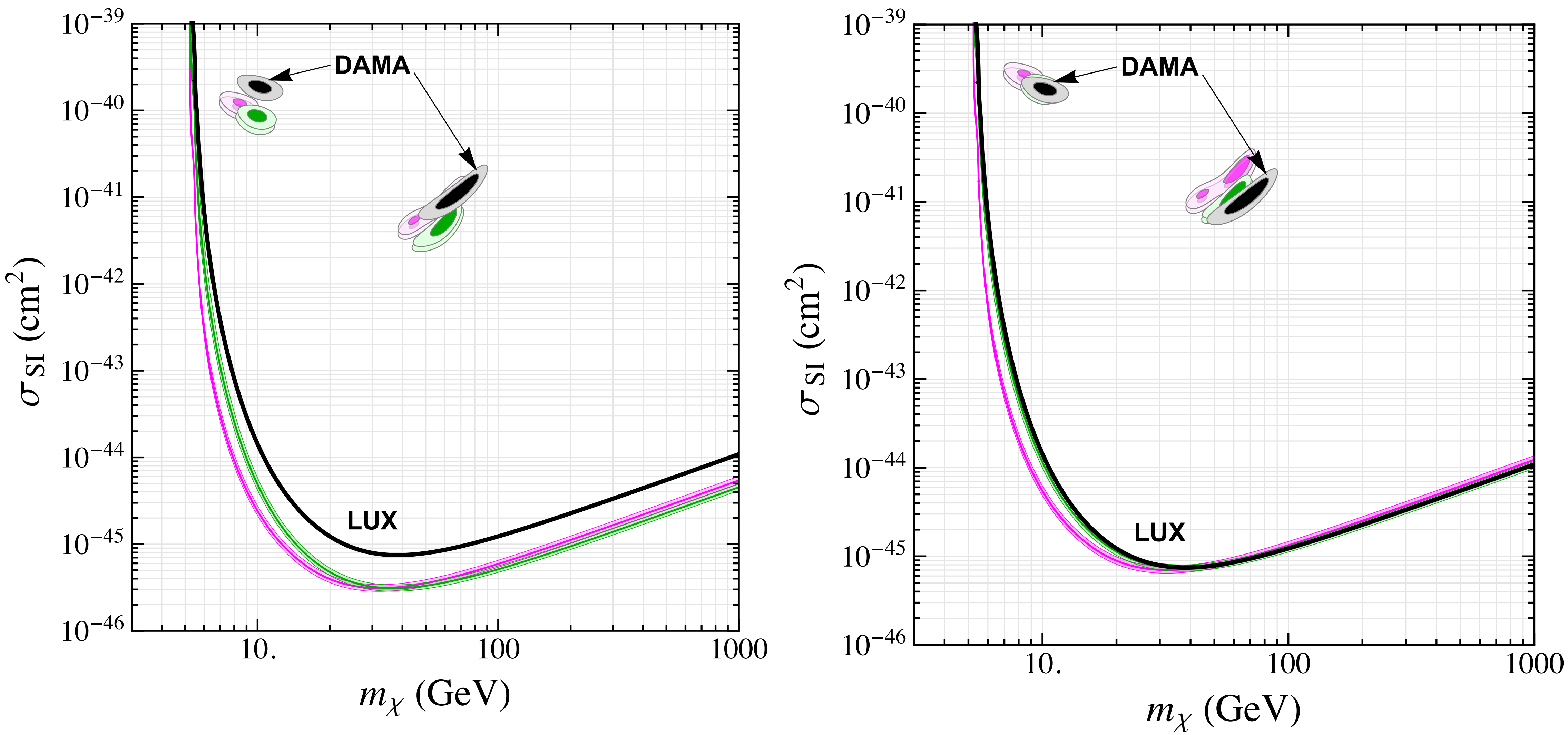
Implications for direct detection

- Compare with simulated Milky Way-like haloes:



Implications for direct detection

Fix local ρ_χ=0.3 GeV cm^{-3}

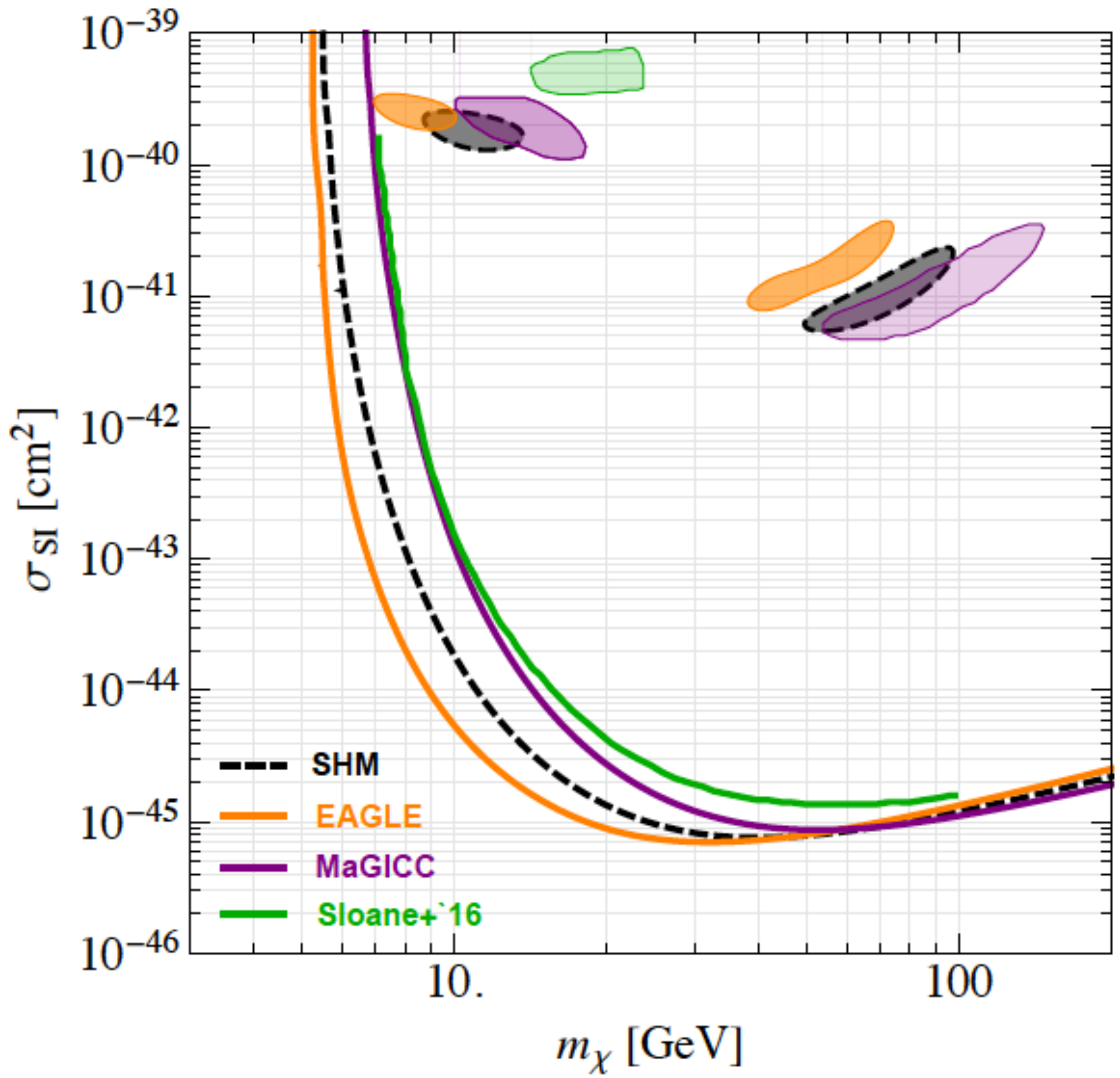


- Difference in the local DM density → overall difference with the SHM.
- Variation in the peak of the DM speed distribution → shift in the low mass region.

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

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

Non-standard interactions

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

Kahlhoefer & Wild, 1607.04418

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

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

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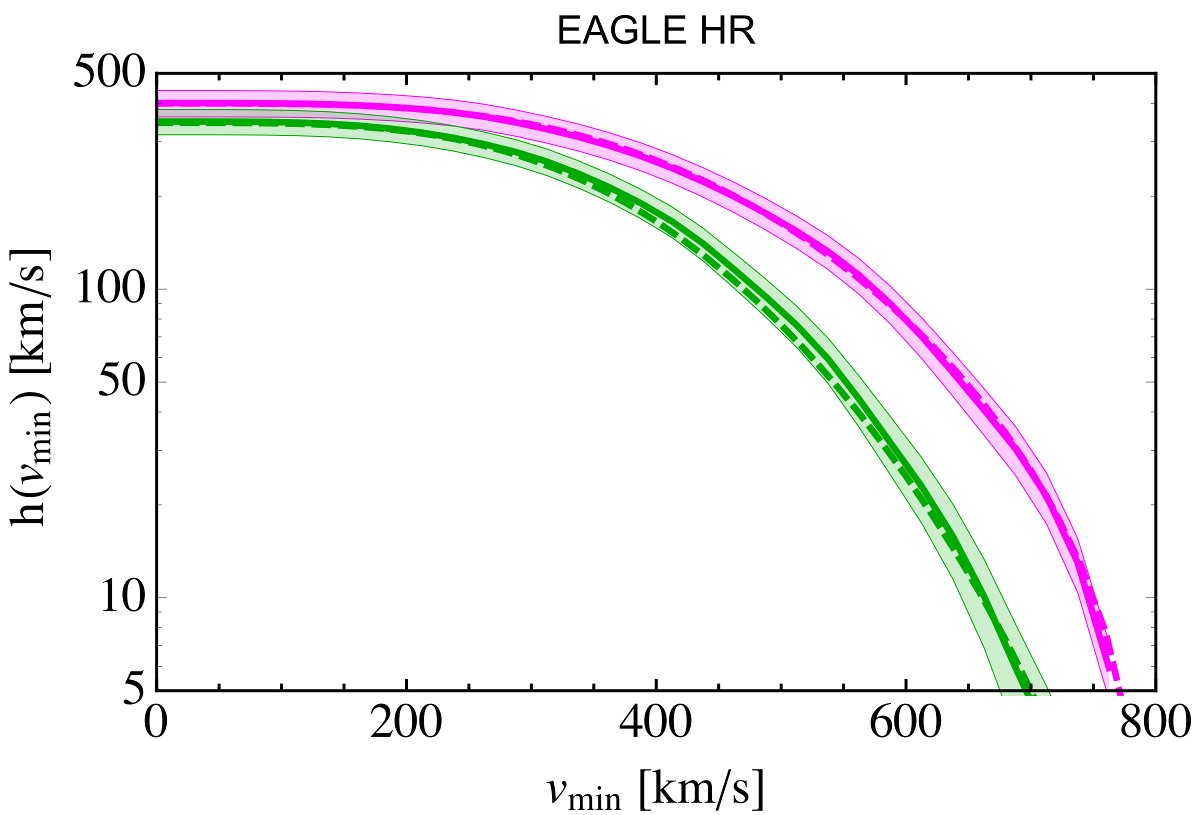


Bozorgnia & Bertone, 1705.05853

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

Dark Matter substructure

What we know from simulations:

- High resolution **DMO** simulations predict:
  - DM density at the Solar position very smooth. Chance of the Sun residing in a DM subhalo of any mass is 10^{-4}.
    Vogelsberger et al., 0812.0362
  - DM streams at the Solar position are unlikely to be important. Vogelsberger & White, 1002.3162

- **What happens when baryons are included?**

  Substructure abundance reduced. Sawala et al., 1609.01718
  Garrison-Kimmel et al., 1701.03792

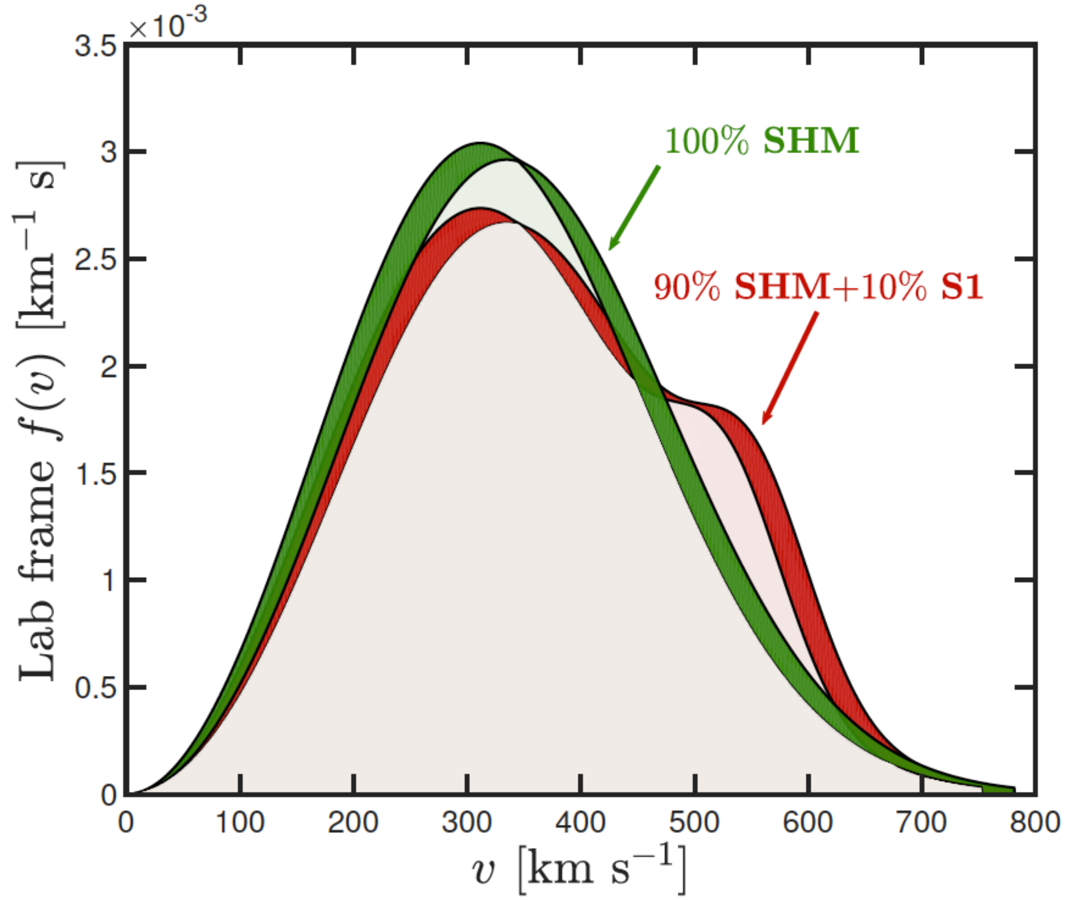
  Need higher resolution hydro simulations to probe Solar position.

Dark Matter substructure

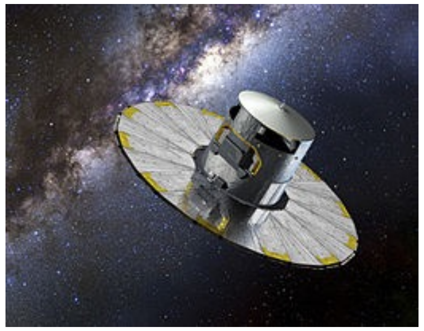
Input from Gaia and other surveys:

- *DM subhalos:* search for the interaction of *DM subhalos* and *stellar streams.* Subhalo flybys can cause measurable perturbations in the streams. **N. Banik, G. Bertone, J. Bovy and N. Bozorgnia, 1804.04384**

- *DM streams:* consider the DM counterparts of observed stellar streams.



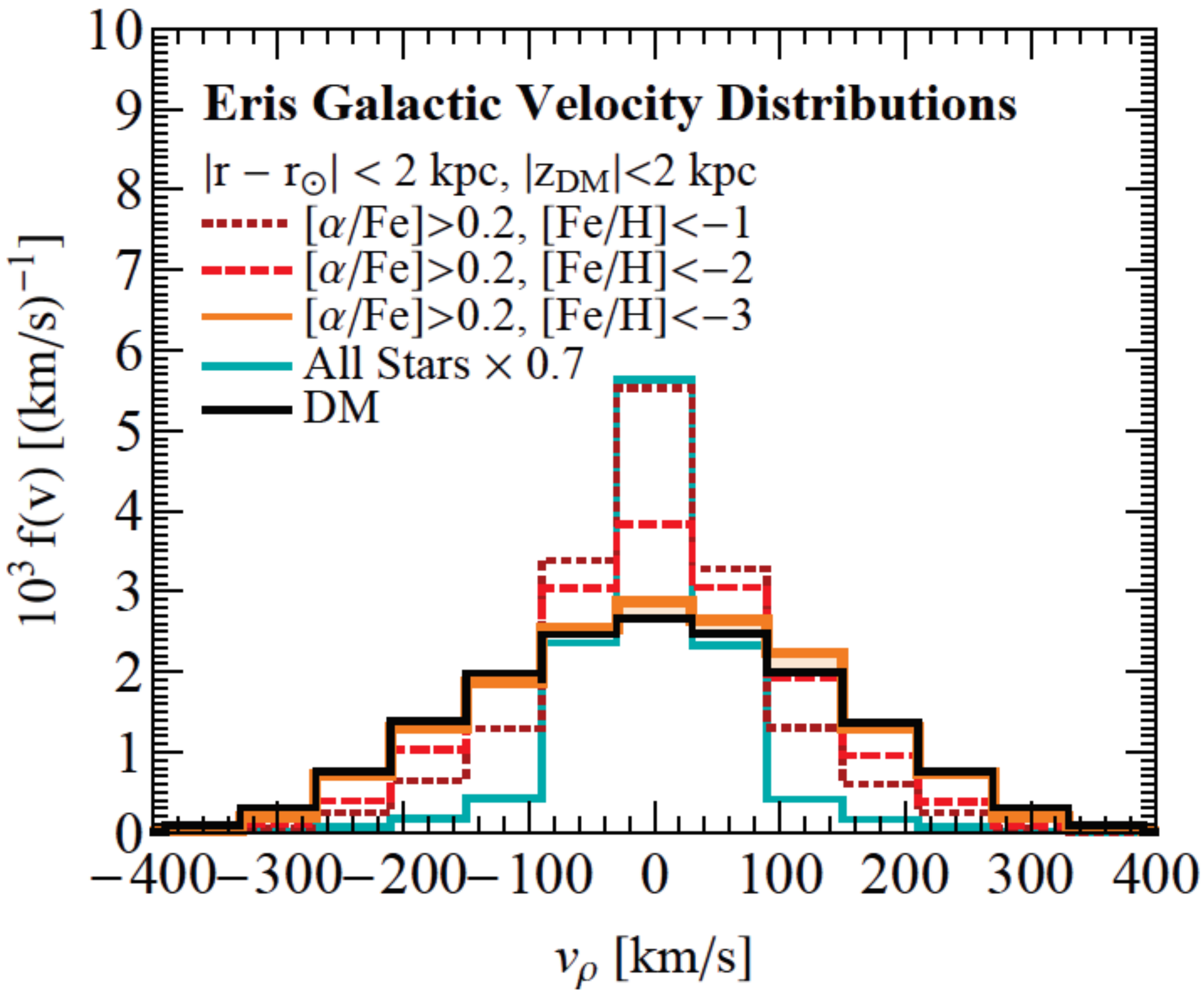
O'Hare et al., 1807.09004



Dark Matter velocity distribution from simulations & observations

DM and stellar distributions

- Older and metal-poor stars may have a common origin with the DM in the Milky Way due to similar merger history. → *Correlations between the DM and stellar velocity distributions.*



$[Fe/H] = -1$ means 1/10 of the Sun's iron fraction

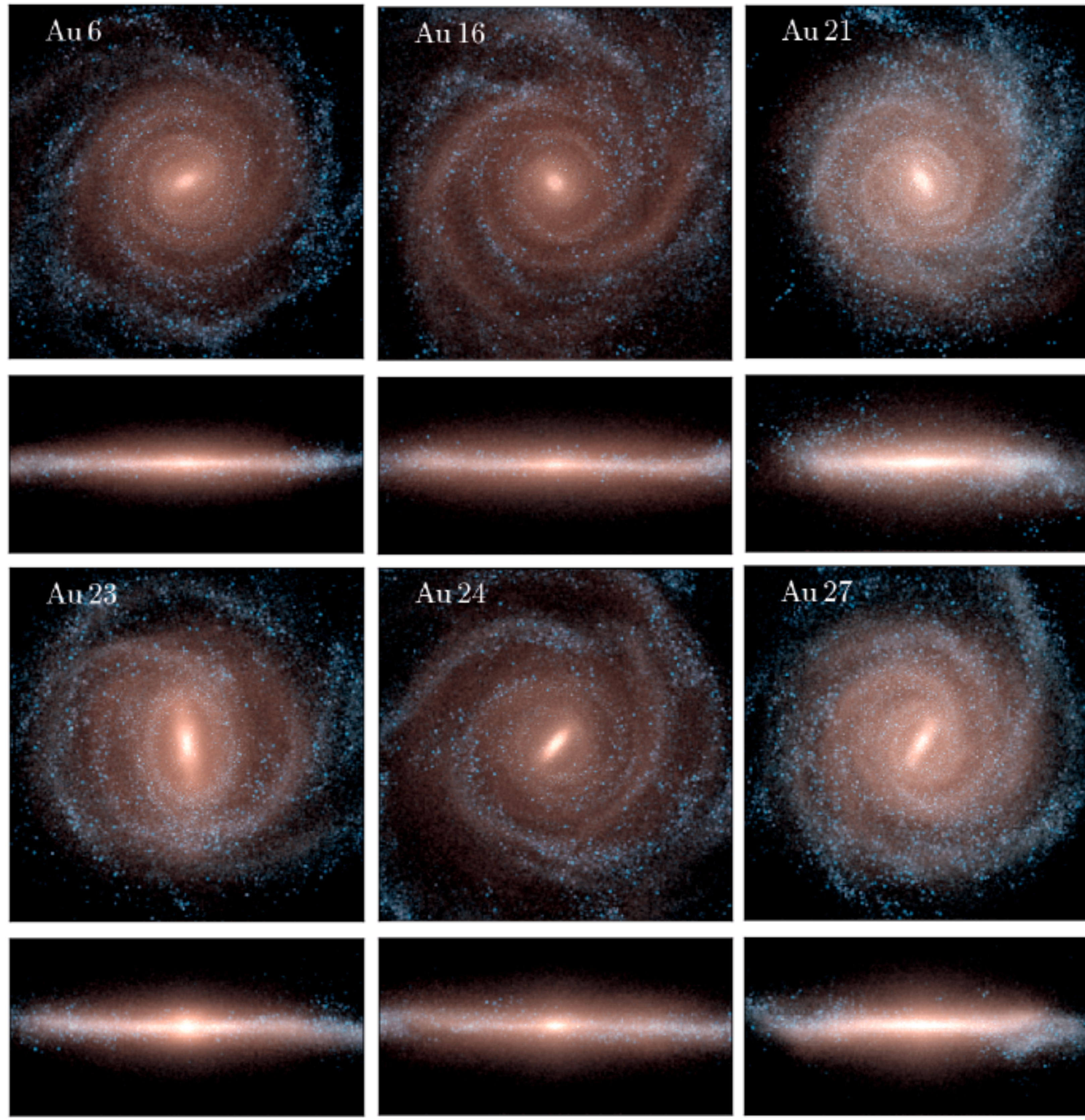
Herzog-Arbeitman, Lisanti, Madau, Necib, 1704.04499

Auriga simulations

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

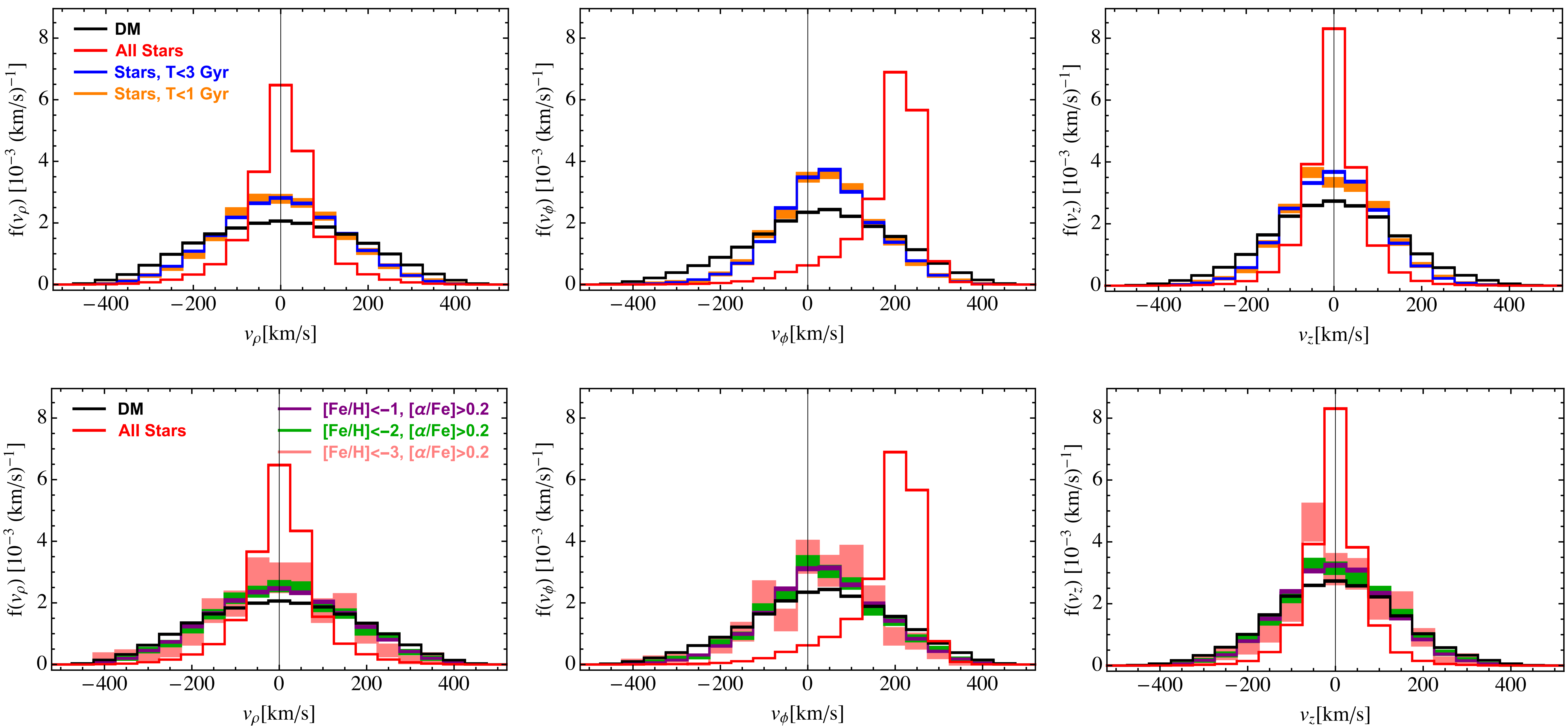
- Six halos at the highest resolution:

m_{DM} [$M_\odot$]	m_b [$M_\odot$]	ϵ [pc]
4×10^4	6×10^3	184



Correlations in Auriga

Au 6

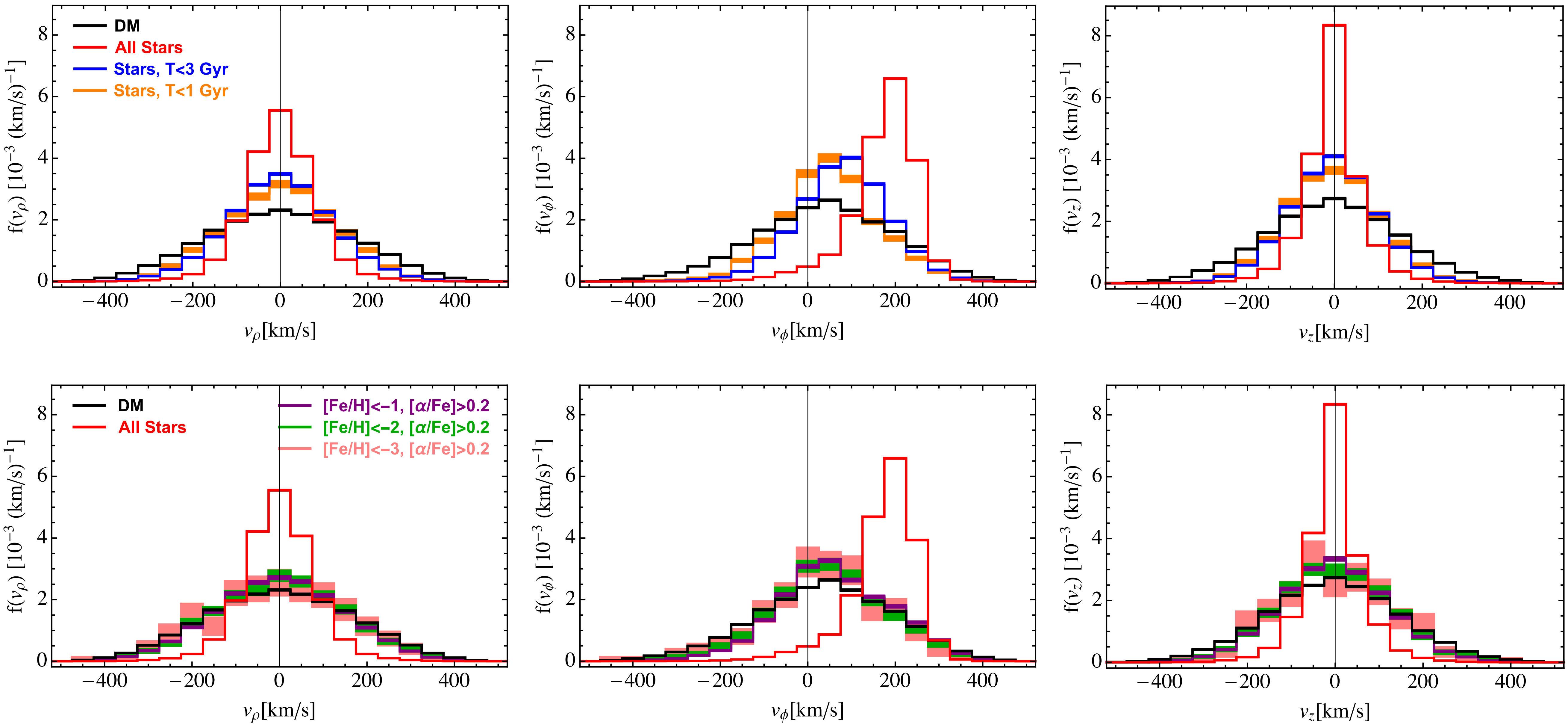


v_ρ	v_ϕ	v_z
$p=2.5 \times 10^{-4}$	$p=2.1 \times 10^{-7}$	$p=8.9 \times 10^{-5}$
$p=2.8 \times 10^{-2}$	$p=3.7 \times 10^{-3}$	$p=7.6 \times 10^{-3}$

Bozorgnia, Cerdeño, Fattahi, Frenk, *in preparation*

Correlations in Auriga

Au 16



$p=4.9\times10^{-3}$
$p=7.8\times10^{-1}$

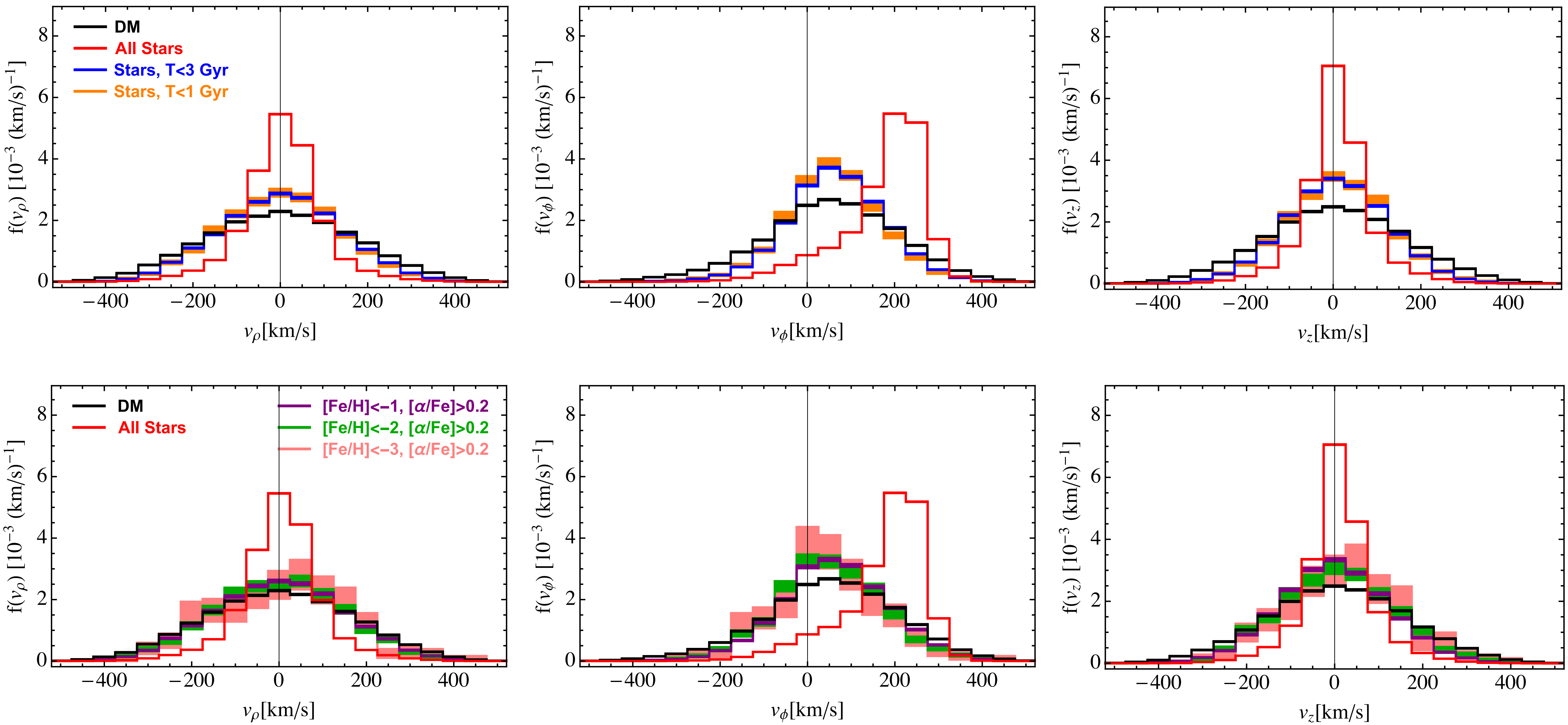
$p=2.0\times10^{-8}$
$p=2.1\times10^{-1}$

$p=3.3\times10^{-4}$
$p=3.4\times10^{-1}$

Bozorgnia, Cerdeño, Fattahi, Frenk, *in preparation*

Correlations in Auriga

Au 21

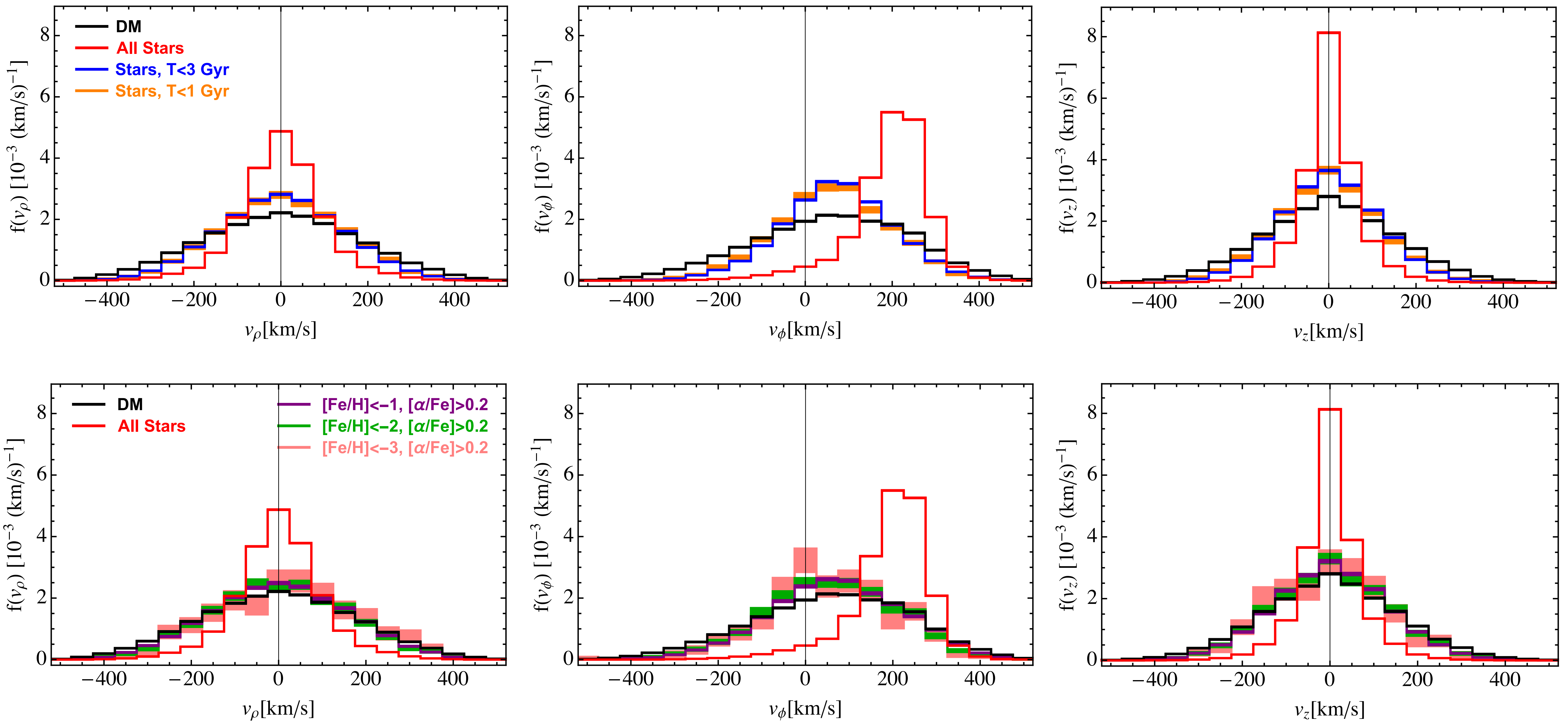


$p=7.7\times10^{-4}$ $p=3.4\times10^{-1}$	$p=4.1\times10^{-8}$ $p=3.6\times10^{-2}$	$p=7.0\times10^{-5}$ $p=4.4\times10^{-2}$

Bozorgnia, Cerdeño, Fattahi, Frenk, *in preparation*

Correlations in Auriga

Au 23

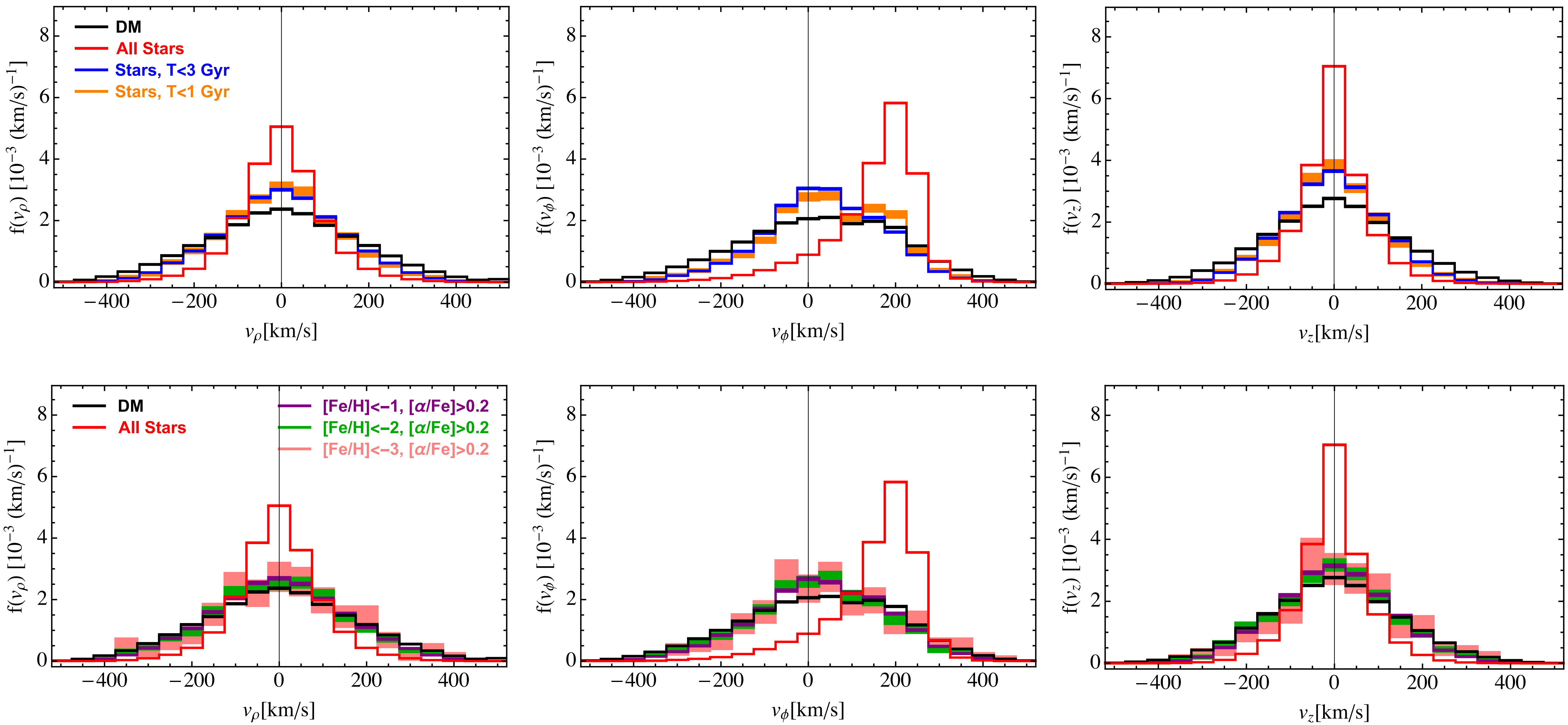


$p=2.1\times10^{-4}$	$p=5.3\times10^{-9}$	$p=4.9\times10^{-5}$
$p=3.5\times10^{-2}$	$p=7.9\times10^{-4}$	$p=4.2\times10^{-2}$

Bozorgnia, Cerdeño, Fattahi, Frenk, *in preparation*

Correlations in Auriga

Au 24



$p=2.4\times10^{-3}$
$p=2.8\times10^{-1}$

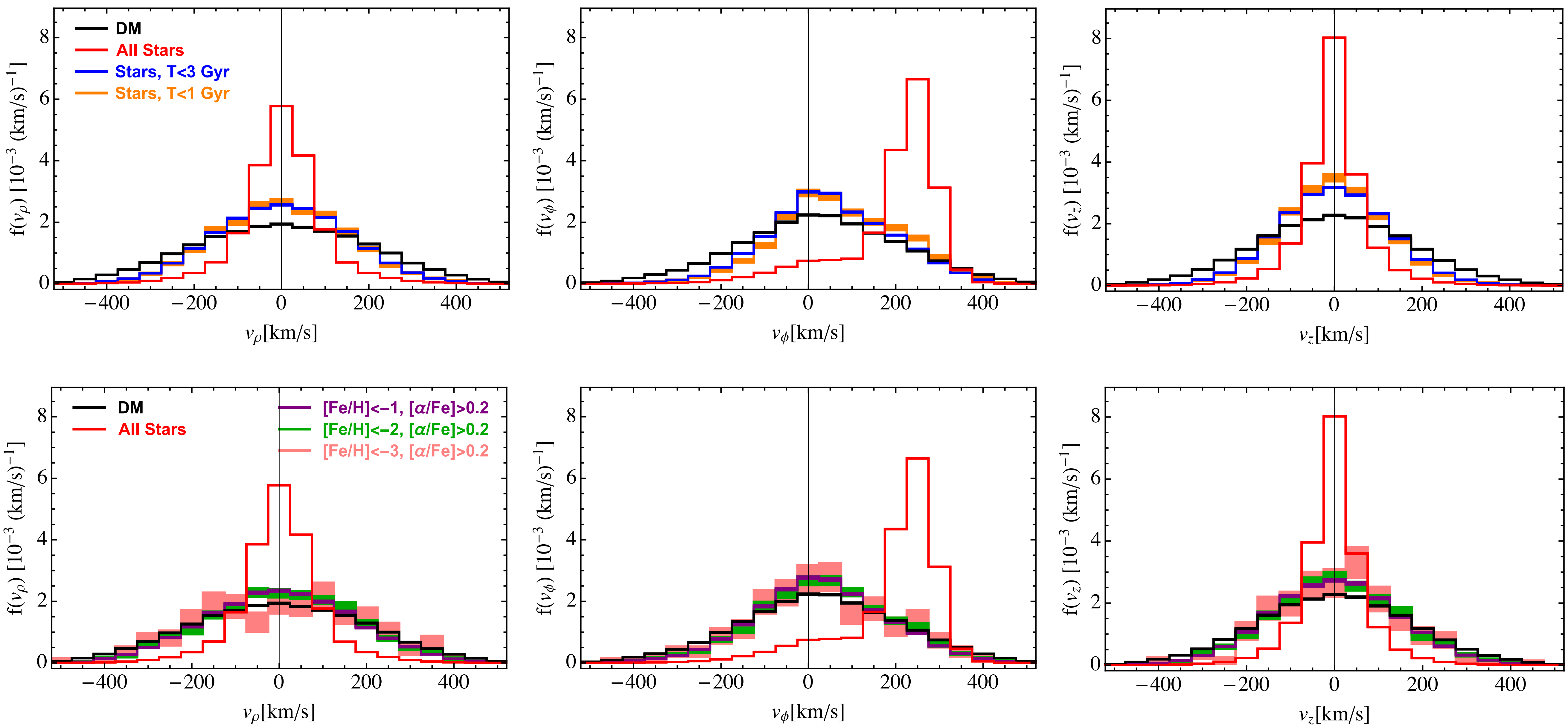
$p=1.7\times10^{-6}$
$p=6.6\times10^{-2}$

$p=6.6\times10^{-3}$
$p=8.7\times10^{-2}$

Bozorgnia, Cerdeño, Fattahi, Frenk, *in preparation*

Correlations in Auriga

Au 27

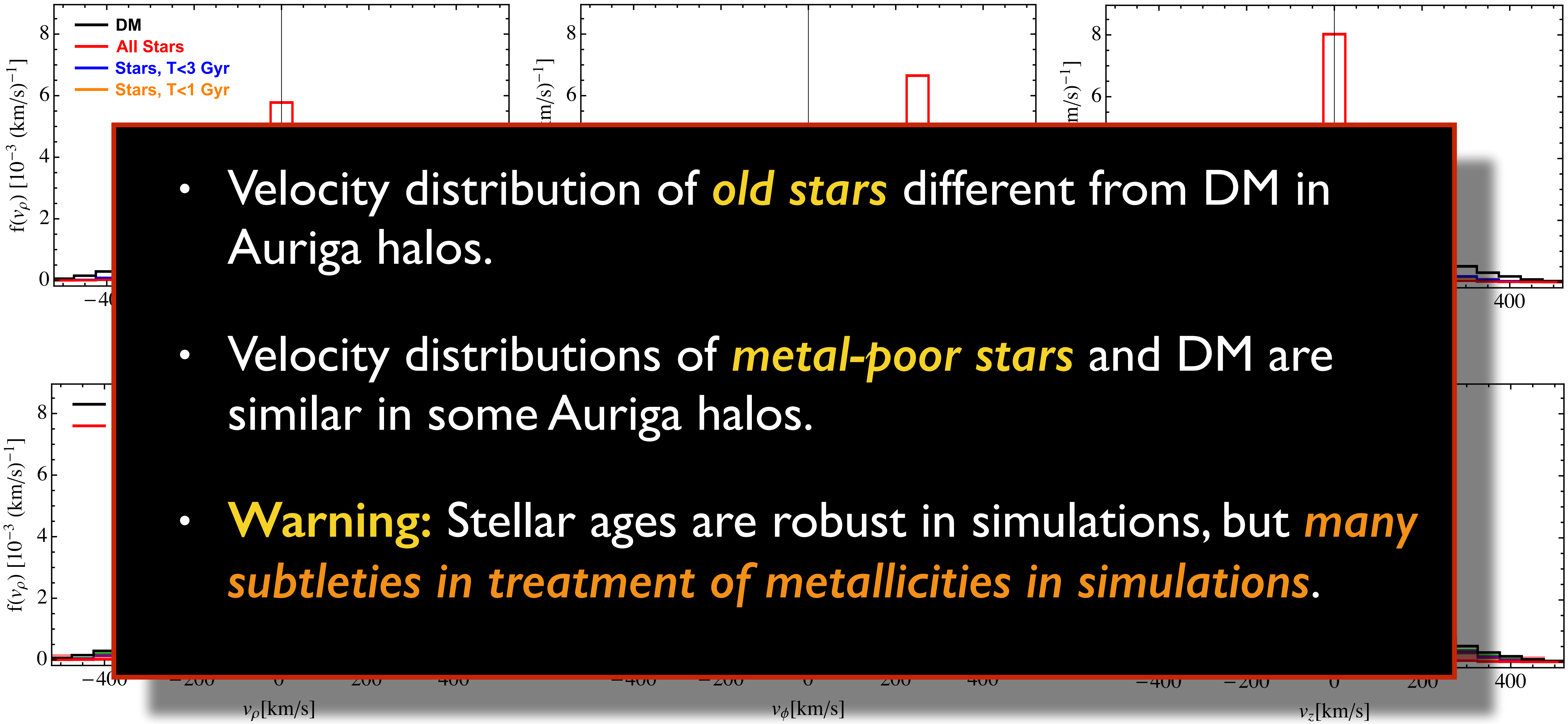


v_ρ	v_ϕ	v_z
$p=5.2\times10^{-7}$	$p=1.8\times10^{-9}$	$p=5.2\times10^{-7}$
$p=8.4\times10^{-1}$	$p=3.5\times10^{-1}$	$p=4.9\times10^{-2}$

Bozorgnia, Cerdeño, Fattahi, Frenk, *in preparation*

Correlations in Auriga

Au 27



- Velocity distribution of ***old stars*** different from DM in Auriga halos.
- Velocity distributions of ***metal-poor stars*** and DM are similar in some Auriga halos.
- **Warning:** Stellar ages are robust in simulations, but ***many subtleties in treatment of metallicities in simulations***.

v_ρ	v_ϕ	v_z
$p=5.2\times10^{-7}$	**$p=1.8\times10^{-9}$**	**$p=5.2\times10^{-7}$**
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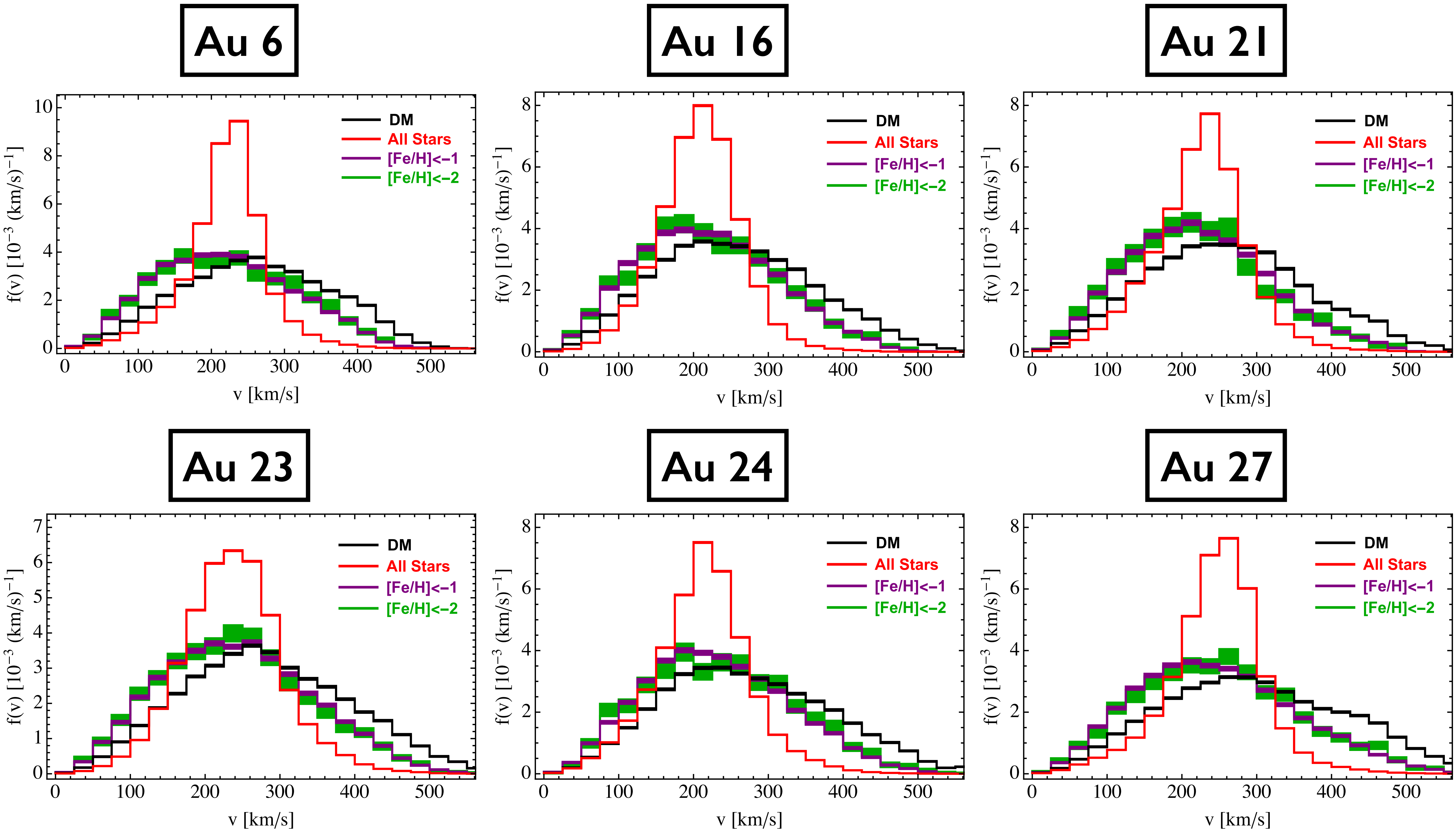
Bozorgnia, Cerdeño, Fattahi, Frenk, *in preparation*

Speed distributions

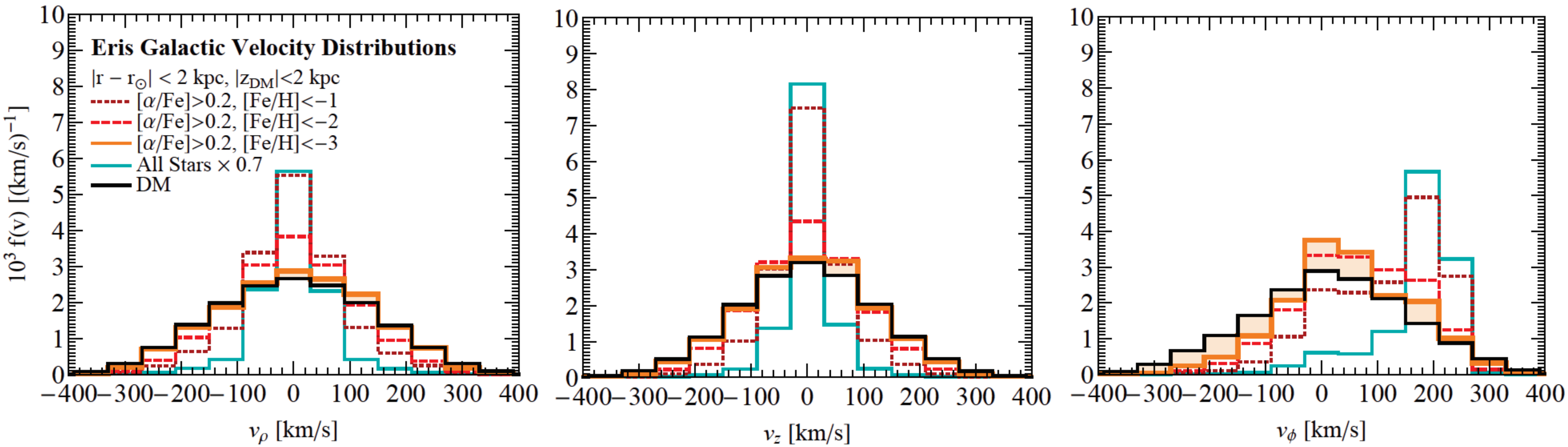


Summary

- The local DM distribution is an important input in the direct detection event rate.
- **From Simulations:** need to Identify simulated MW-like galaxies by taking into account observational constraints on the MW.
  - **Local DM density** agrees with local and global estimates.
  - **Maxwellian velocity distribution** works well.
- **From Observations & Simulations:** need to identify a population of stars tracing the DM in multiple simulations.
  - **Auriga**: velocity distribution of old stars different from DM. Difficult to draw strong conclusions just based on metallicities.

Backup Slides

Correlations in Eris



Herzog-Arbeitman, Lisanti, Madau, Necib, 1704.04499

$$[X/Y] = \log_{10}(N_X/N_Y) - \log_{10}(N_X/N_Y)_\odot$$

$m_{\rm DM}$ [$M_\odot$]	m_g [$M_\odot$]	ϵ [pc]
9.8×10^4	2×10^4	120

Correlations in Eris

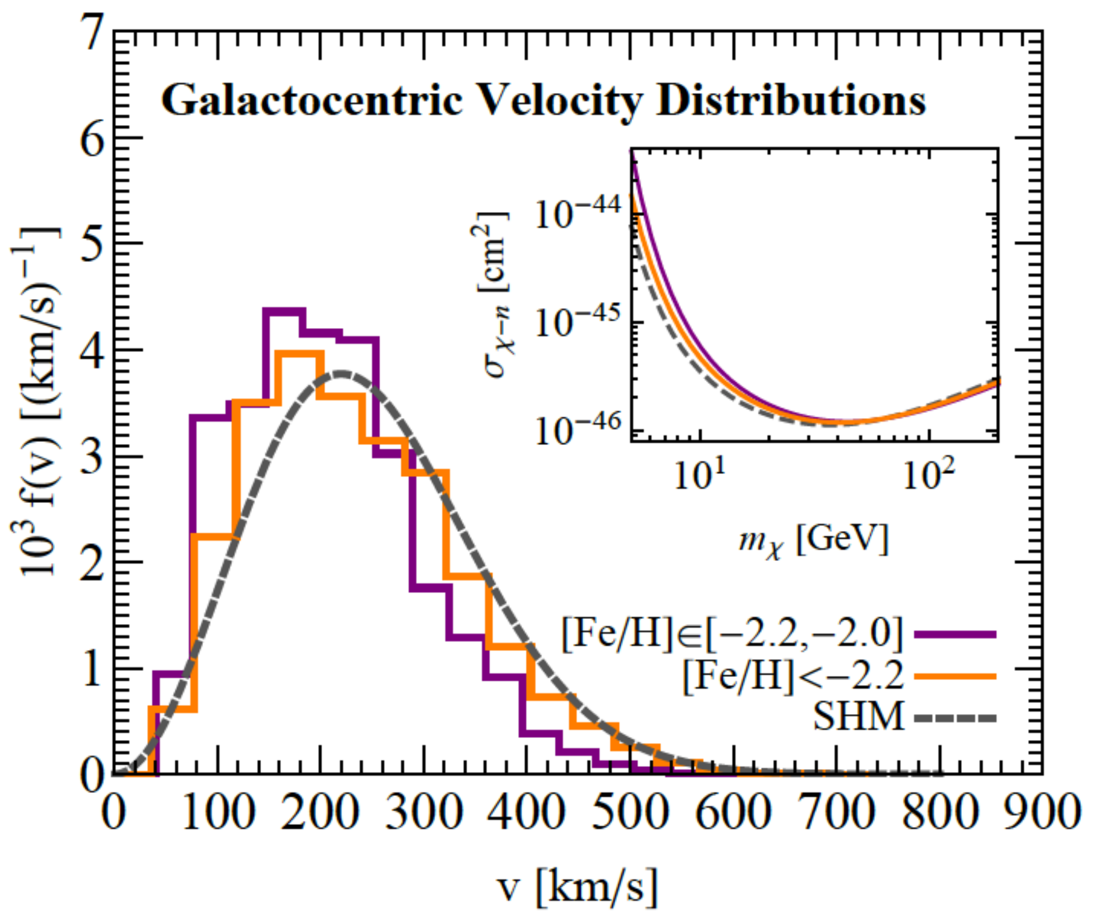
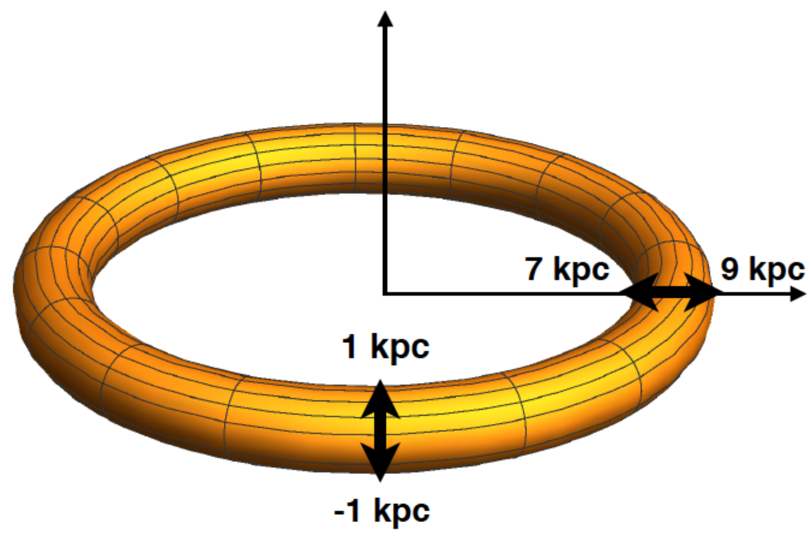


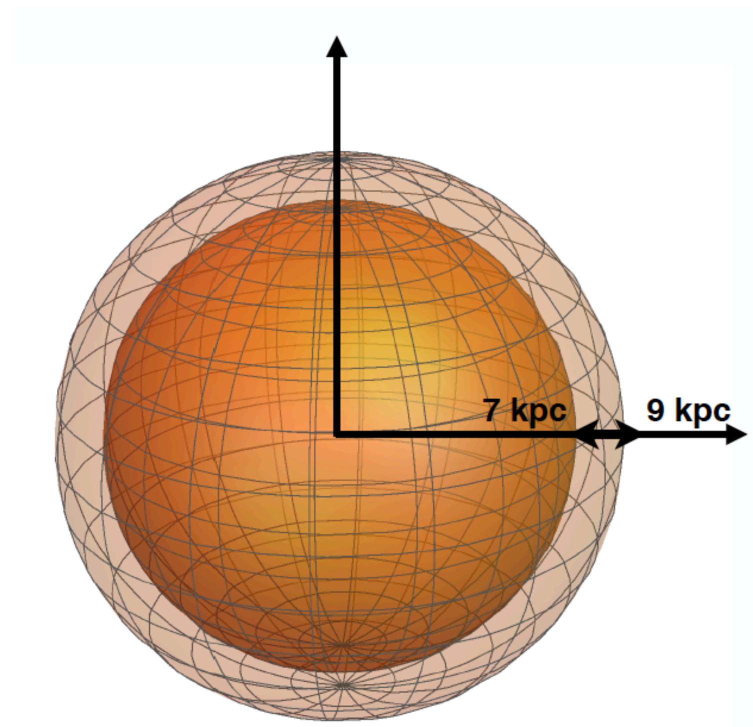
FIG. 3: Galactocentric speed distributions for SDSS stars within 4 kpc of the Sun and Galactocentric distances of $7 < r < 10$ kpc, based on results from [54]. The distributions are shown for [Fe/H] $\in [-2.2, -2]$ (solid purple) and [Fe/H] < -2.2 (solid orange). For comparison, we show the Standard Halo Model (dashed gray) with $v_c = 220$ km/s. Not captured by this figure is the fact that the stellar distributions are not isotropic, as is typically assumed for the Standard Halo Model. The inset shows the expected background-free 95% C.L. limit on the DM spin-independent scattering cross section, assuming the exposure and energy threshold of the LUX experiment [55] for the SDSS and SHM velocity distributions.

Herzog-Arbeitman, Lisanti, Madau, Necib, 1704.04499

Local Dark Matter density

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





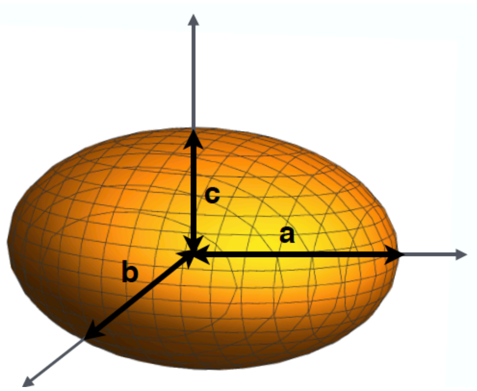
- ρ_{torus} larger than ρ_{shell} by 2 – 27% for 10 haloes.
- The increase in the DM density in the disk could be due to the DM halo contraction as a result of dissipational baryonic processes.

Halo shapes

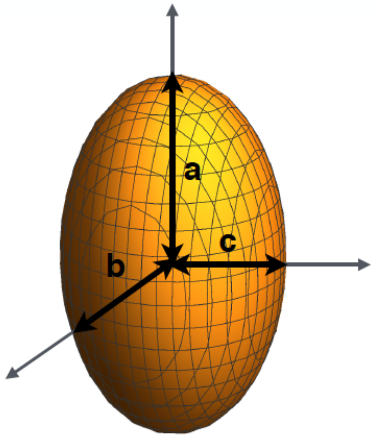
- Describe a deviation from a sphere by the triaxiality parameter:

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

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



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

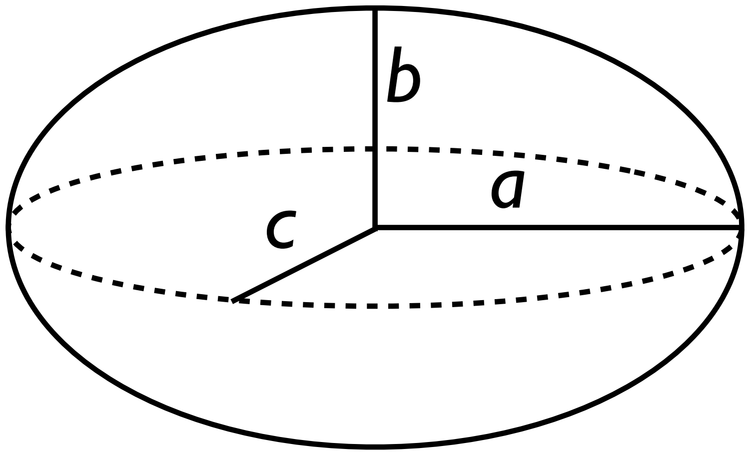


- In the hydro case, inner haloes very close to spherical and deviation towards either oblate or prolate is small. DMO counterparts have a preference for *prolate inner haloes*.

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.

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