Gaia anisotropic structure & direct detection

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York University *(from Jan 2020)*

Based on arXiv:1910.07536

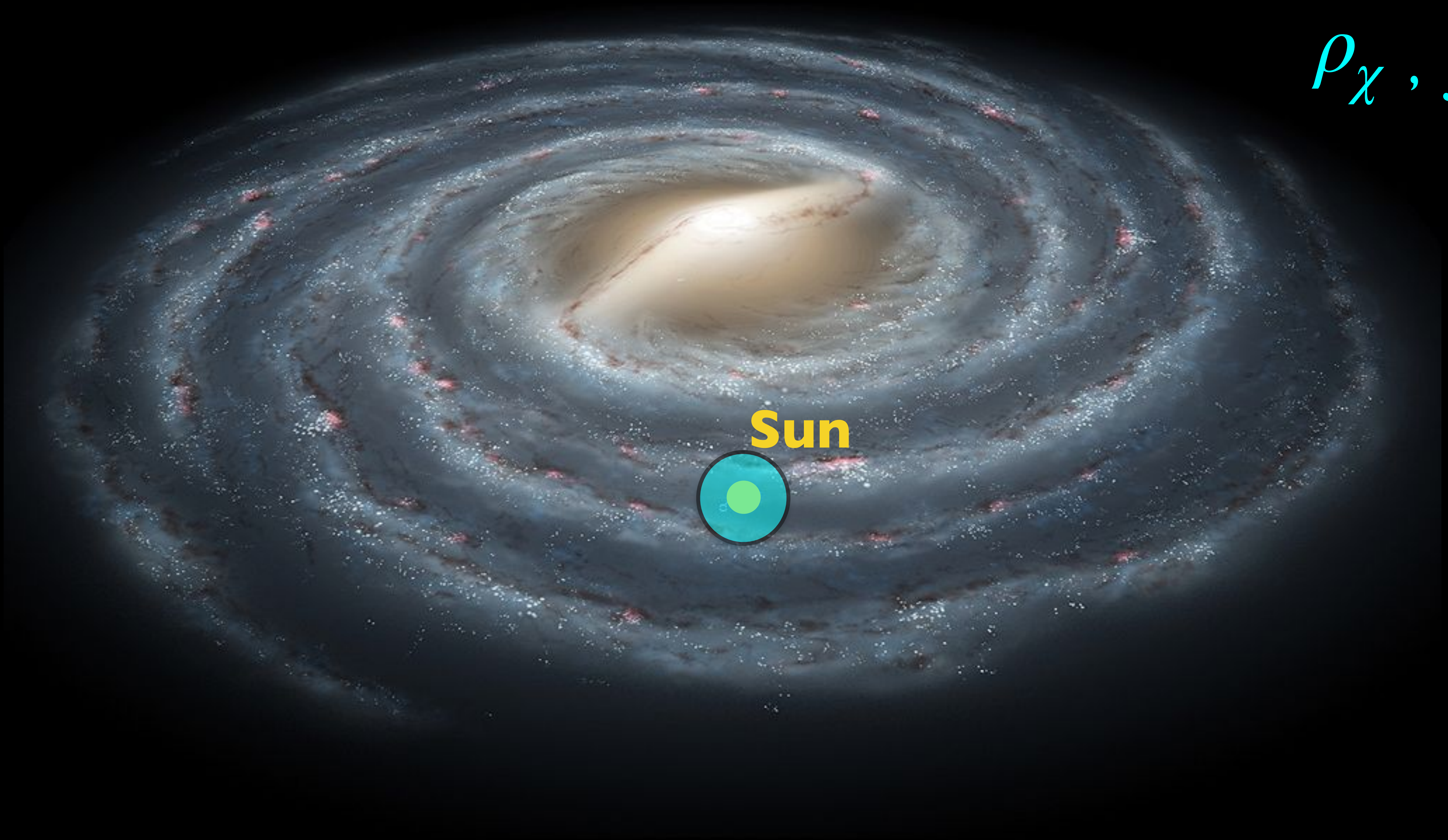
Durham University

IP3

Local dark matter halo

What are the properties of the dark matter (DM) component of the
Gaia Radially Anisotropic Stellar Population (GRASP)?

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



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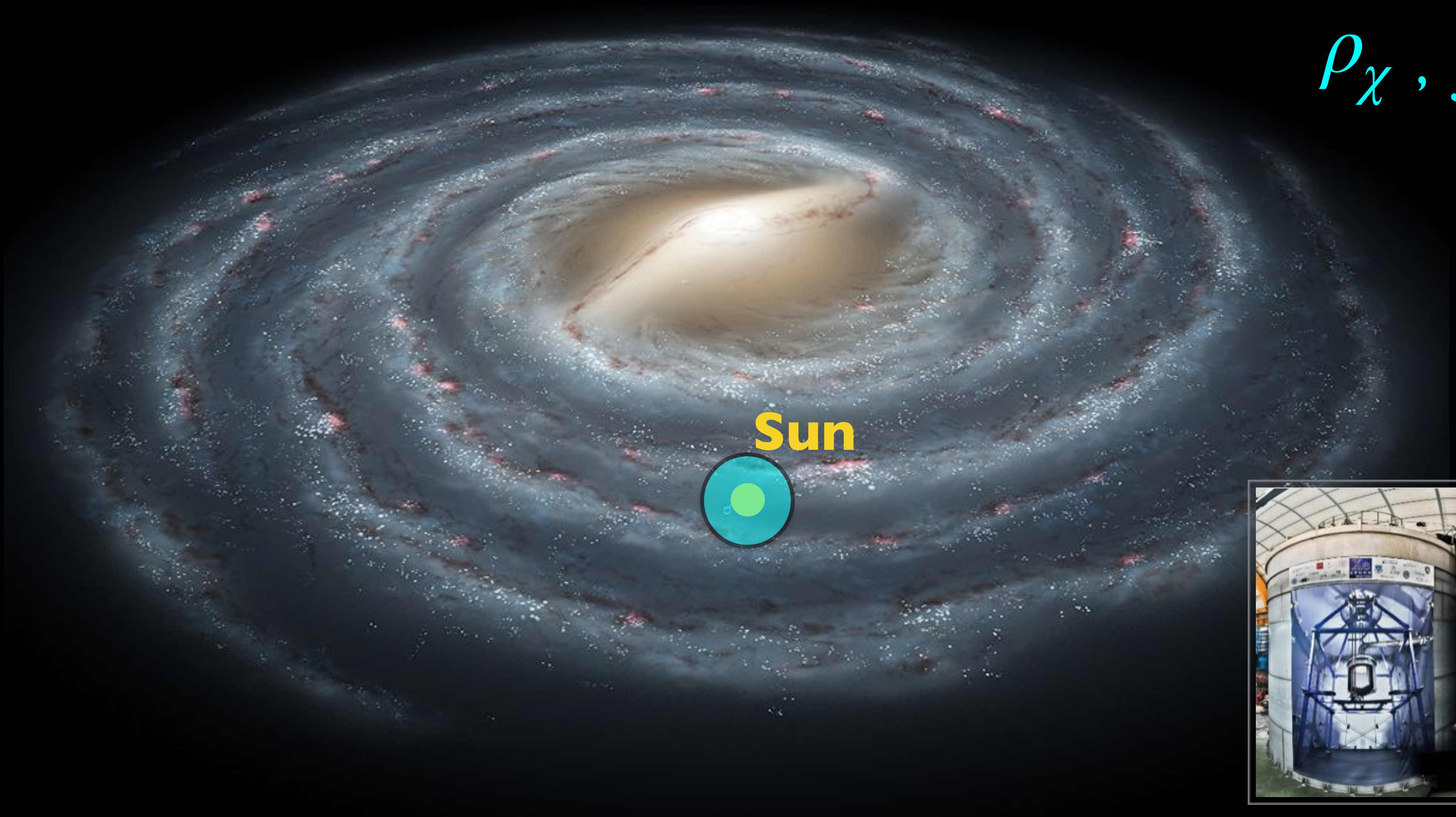
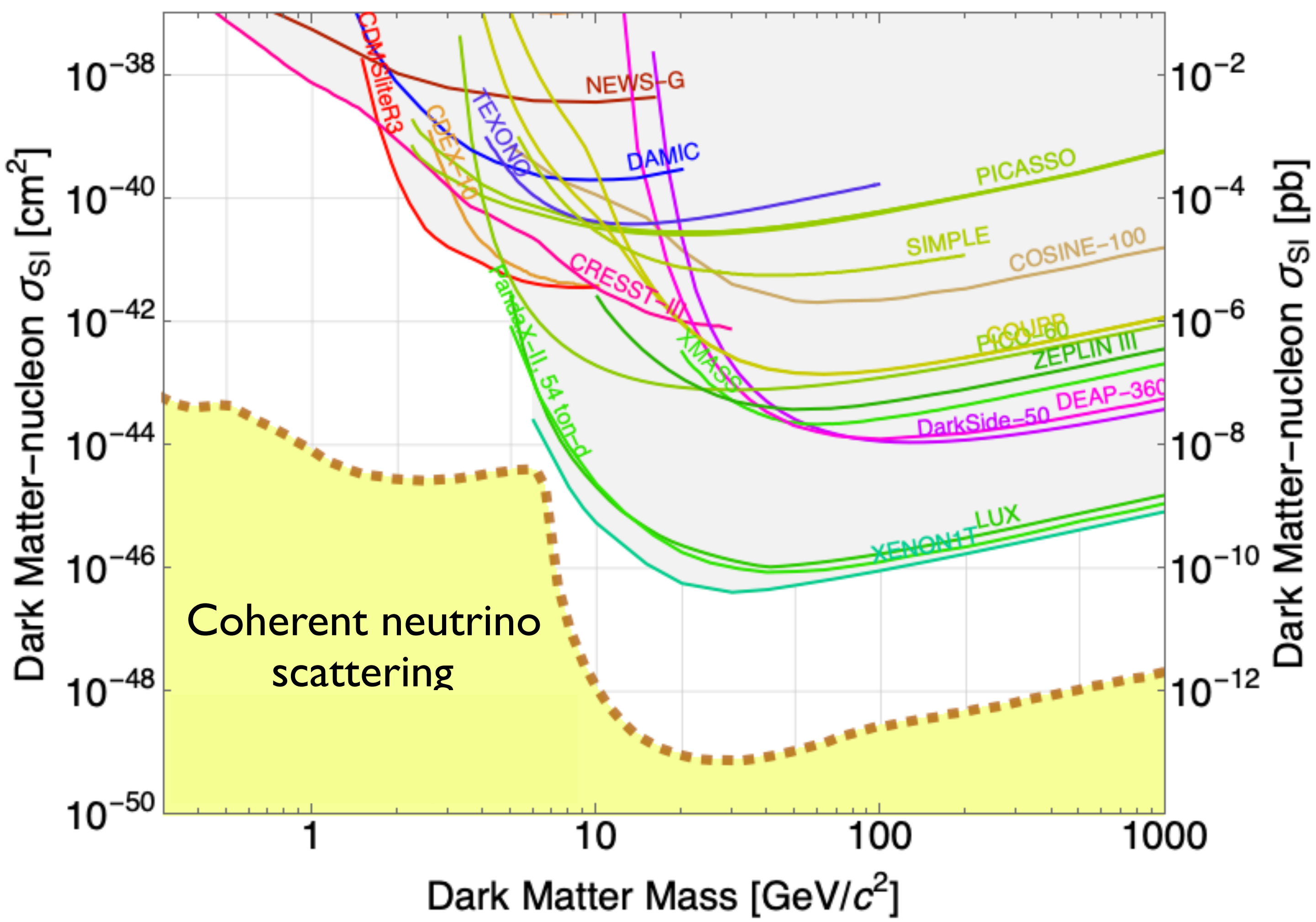


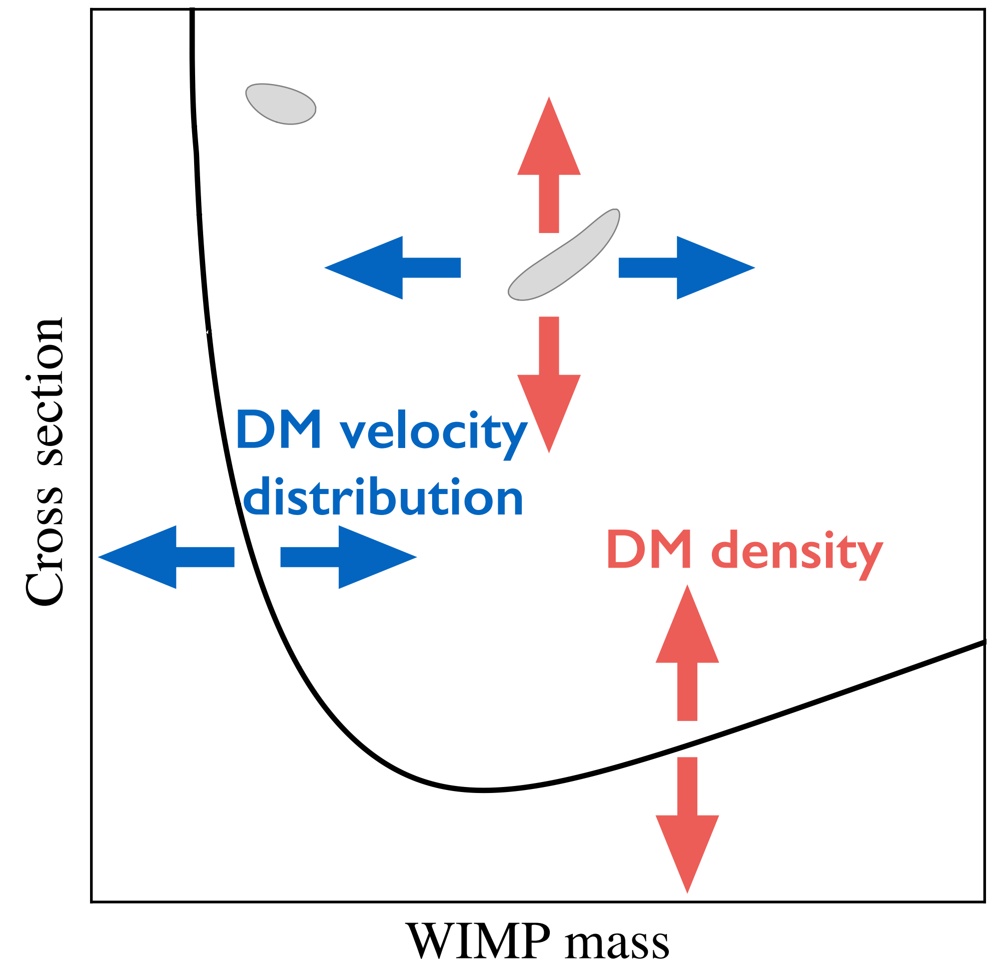
How does it change the interpretation of direct detection results?

Astrophysical uncertainties

astrophysics

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

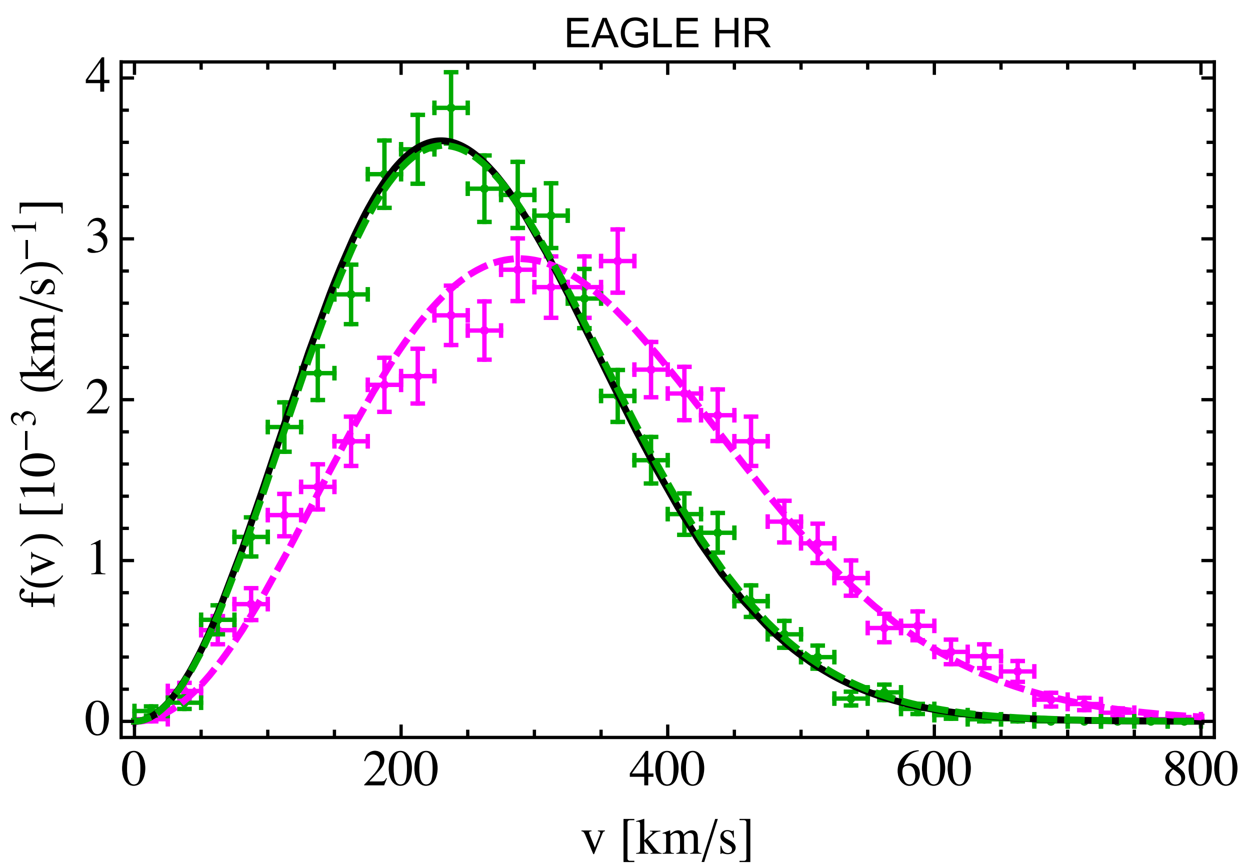




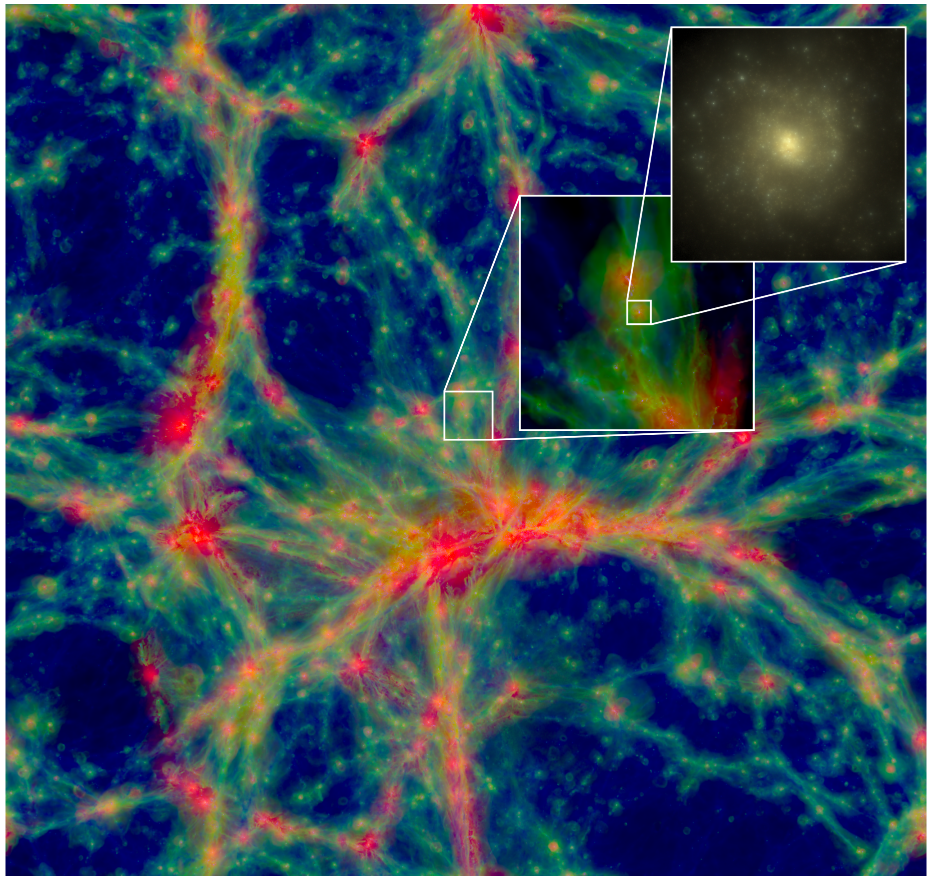
Assumption: **Standard Halo Model (SHM)**

Local dark matter distribution

- **From hydrodynamic simulations:**



Bozorgnia et al., 1601.04707
Bozorgnia & Bertone, 1705.05853

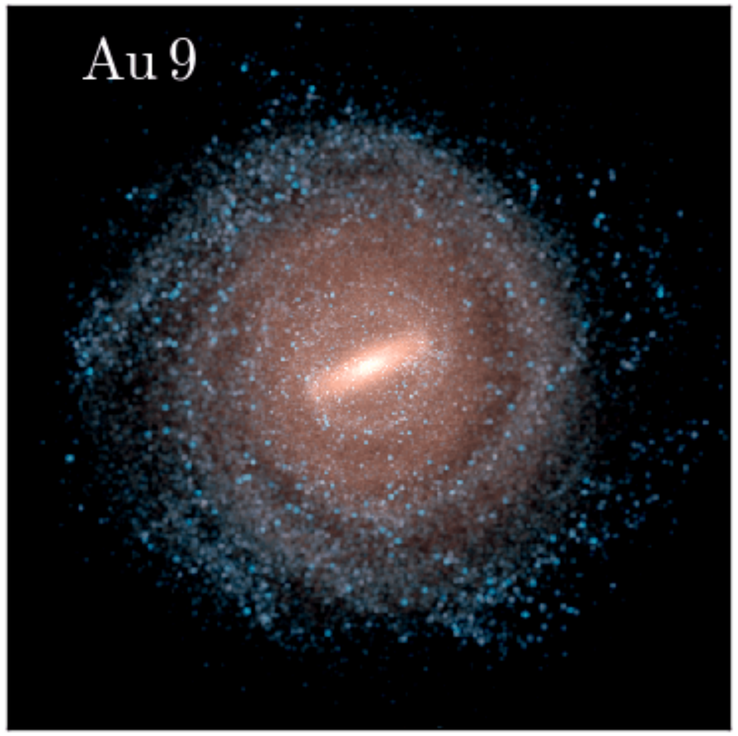


EAGLE Simulations, 1407.7040

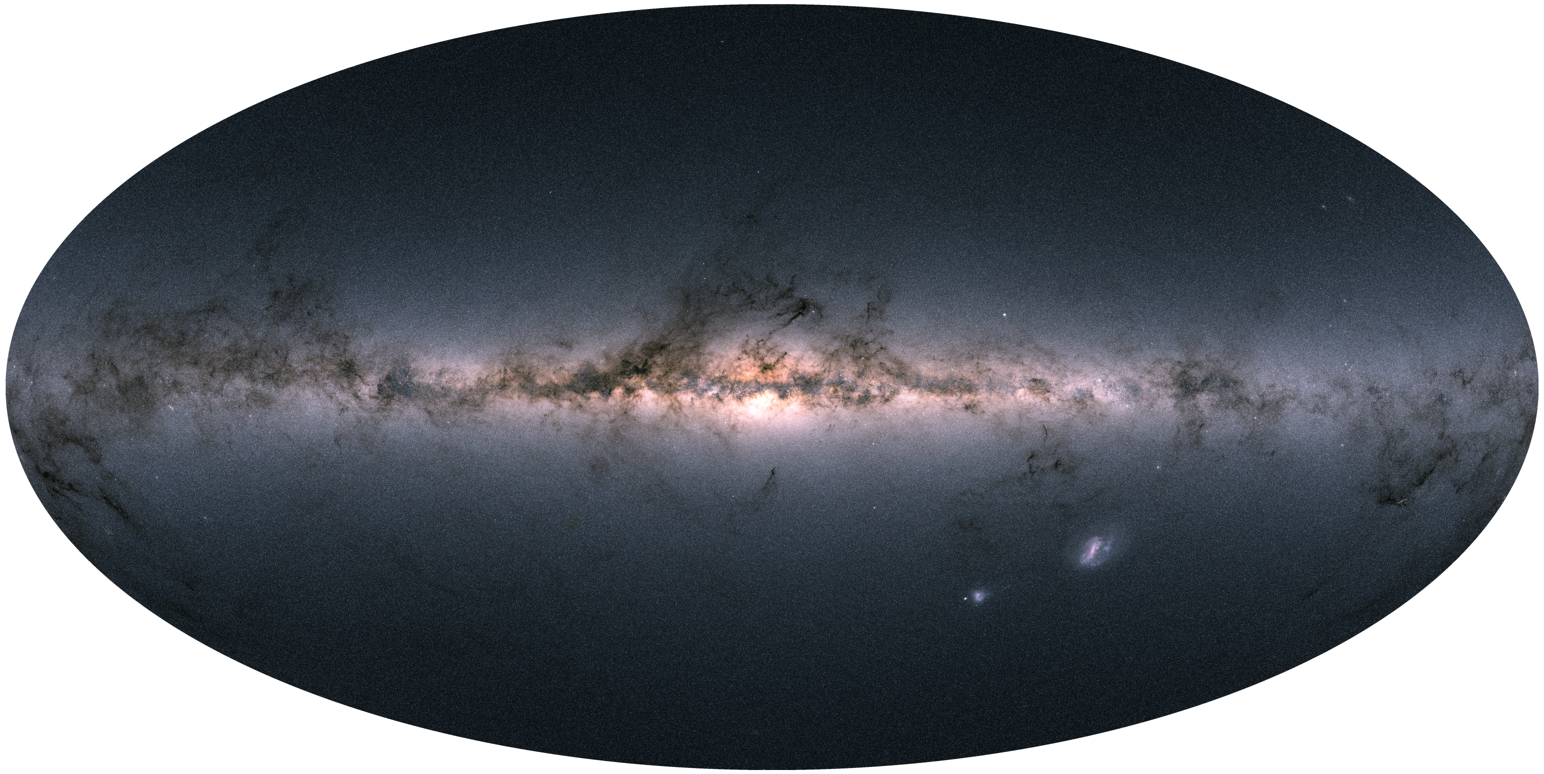
- Baryons appear to make the local DM speed distribution *more Maxwellian*. Best fit peak speed: $v_{peak} = 223 - 289$ km/s

Local dark matter distribution

- **From hydrodynamic simulations & observations:**



Auriga Simulations



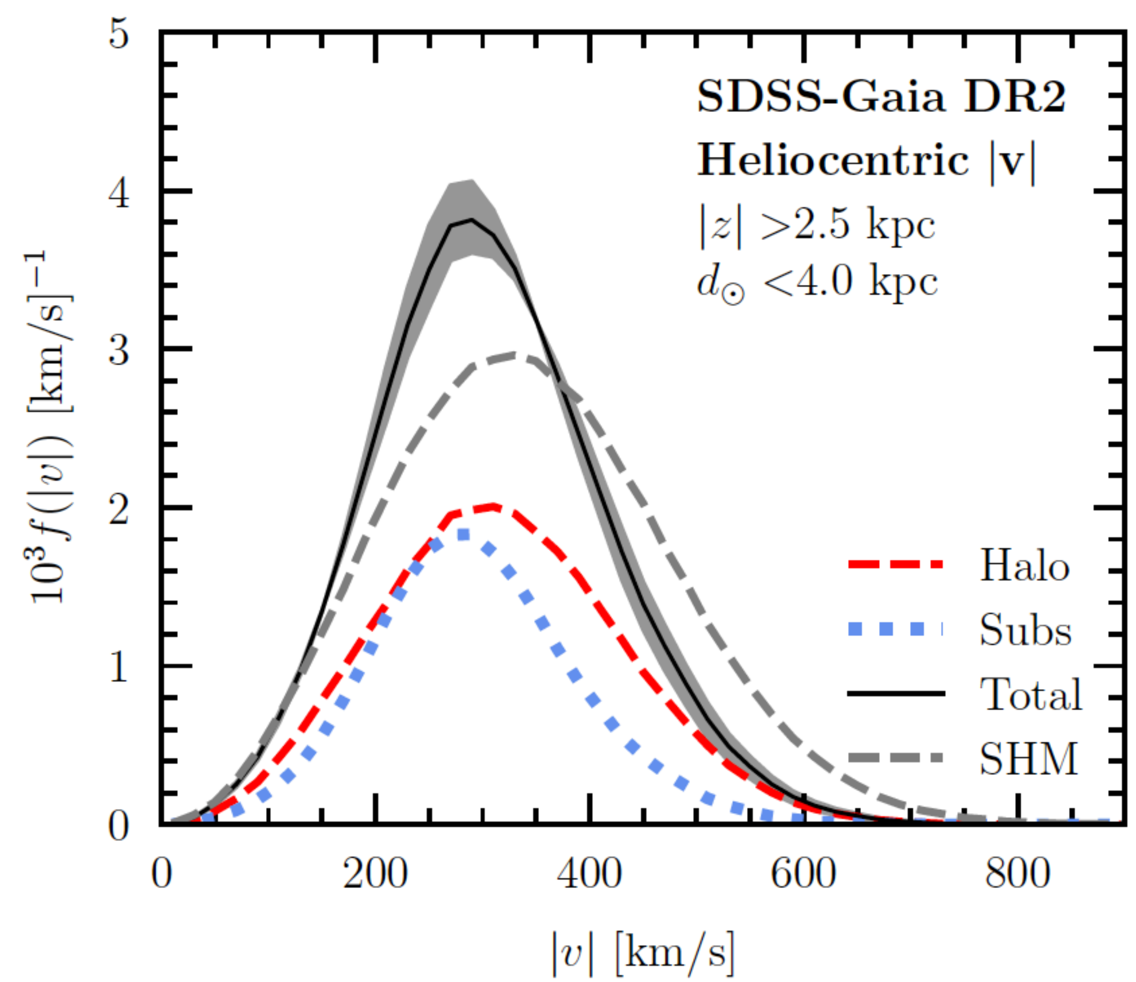
Gaia's DR2 sky map. *Credit: ESA/Gaia/DPAC*

- Extract the DM component of specific ***observed*** stellar structures from ***simulations***. An important example is the DM component of the **GRASP** *(i.e. DM originating from the GRASP progenitor)*.

DM component of GRASP

- Two recent studies modeling the DM distribution of the GRASP:

- **FIRE simulations:** old metal-poor stars trace the DM accreted from *oldest luminous mergers* and intermediate metallicity stars trace the DM accreted from *younger mergers*. → Use the stellar distributions from SDSS-Gaia DR2 to model the DM velocity distribution.



Necib et al. 1807.02519, 1810.12301

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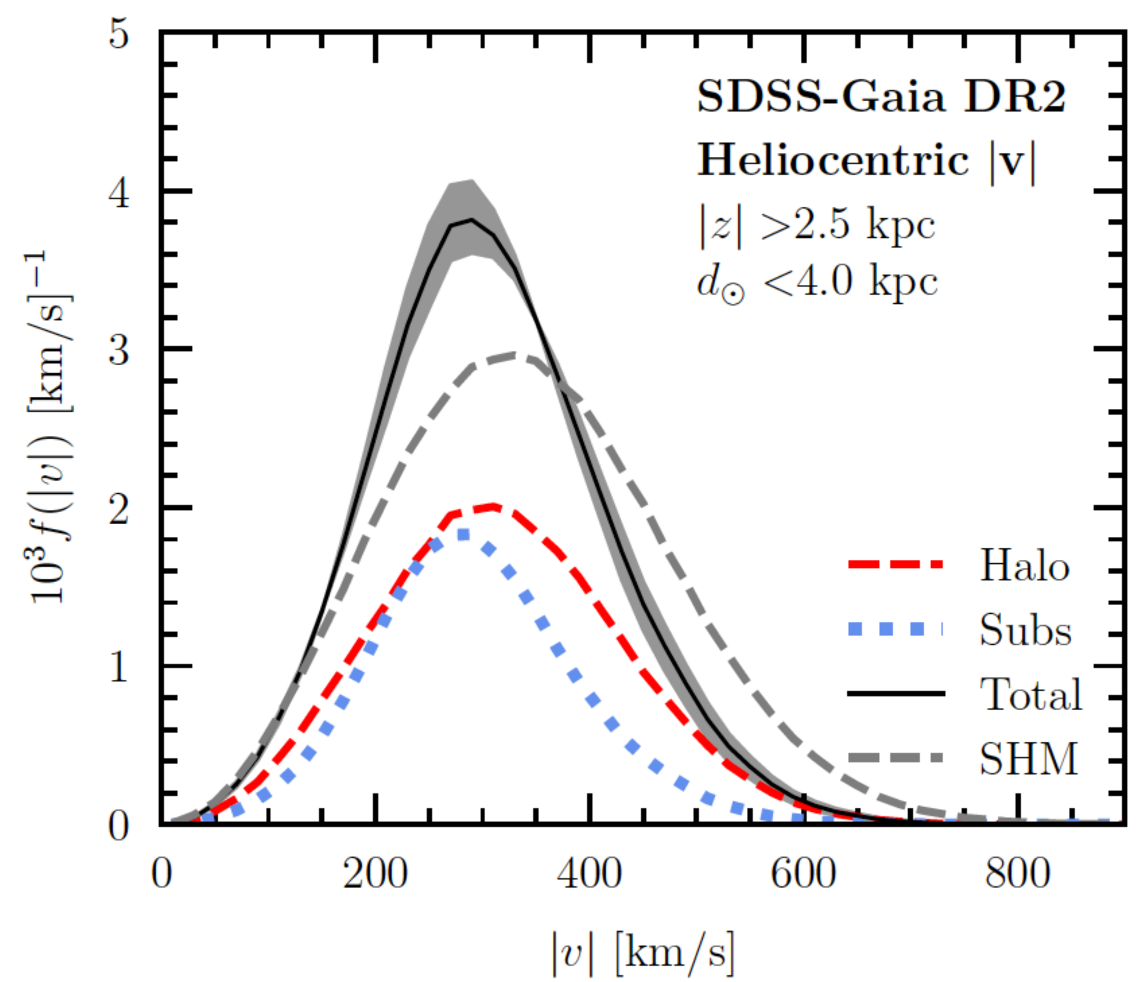


Necib et al. 1807.02519, 1810.12301

- However, non-negligible part of the local DM halo originates from smooth accretion and dark substructures.

DM component of GRASP

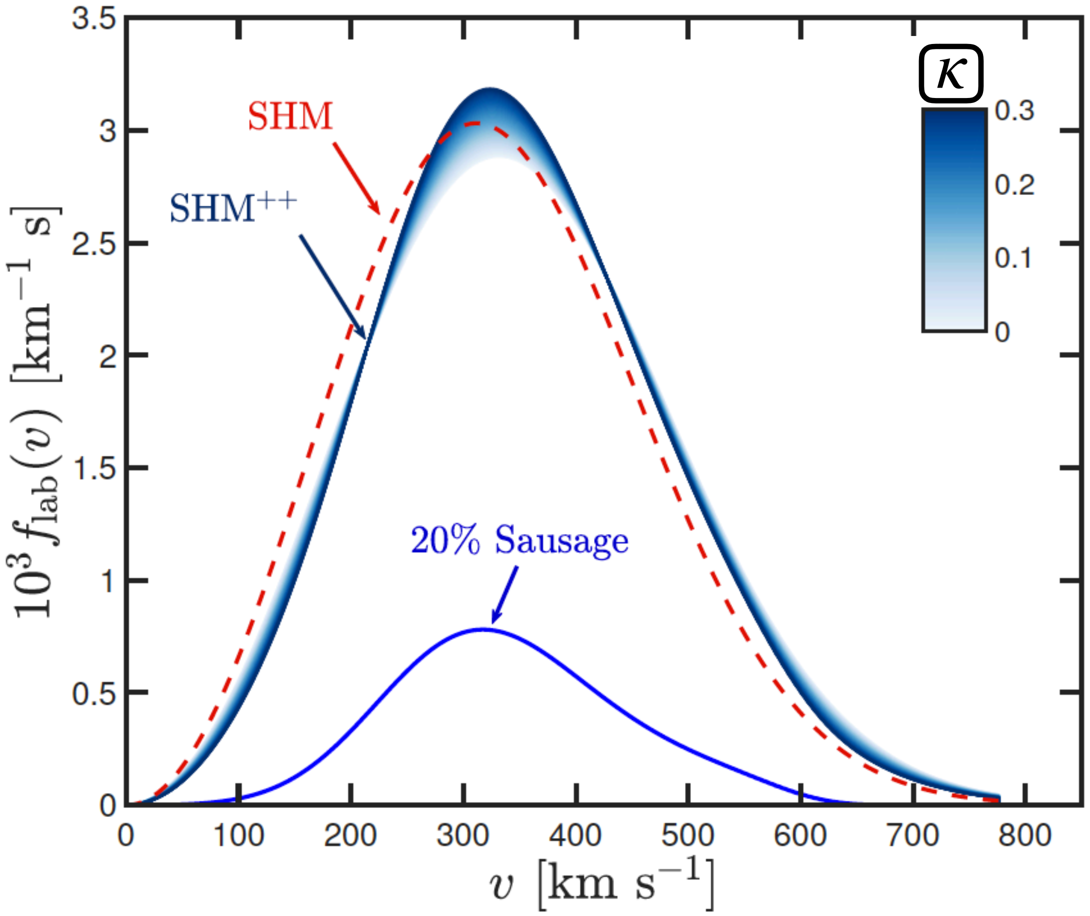
- Two recent studies modeling the DM distribution of the GRASP:

- **Modeling the DM velocity distribution:**

$$f(\mathbf{v}) = (1-\kappa)\underbrace{f_{\rm R}(\mathbf{v})}_{\text{Maxwellian}} + \kappa \underbrace{f_{\rm S}(\mathbf{v})}_{\text{Anisotropic}}$$

$$f_{\rm S}(\mathbf{v}) \propto \exp\left(-\frac{v_r^2}{2\sigma_r^2} - \frac{v_\theta^2}{2\sigma_\theta^2} - \frac{v_\phi^2}{2\sigma_\phi^2}\right)$$

$$\boxed{\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}}$$



Evans, O'Hare, McCabe 1810.11468

SHM++: $\boxed{\beta = 0.9 \pm 0.05\ ,\ \kappa = 0.2 \pm 0.1}$

Wyn's Talk

Auriga simulations

- 30 halos at the standard resolution:

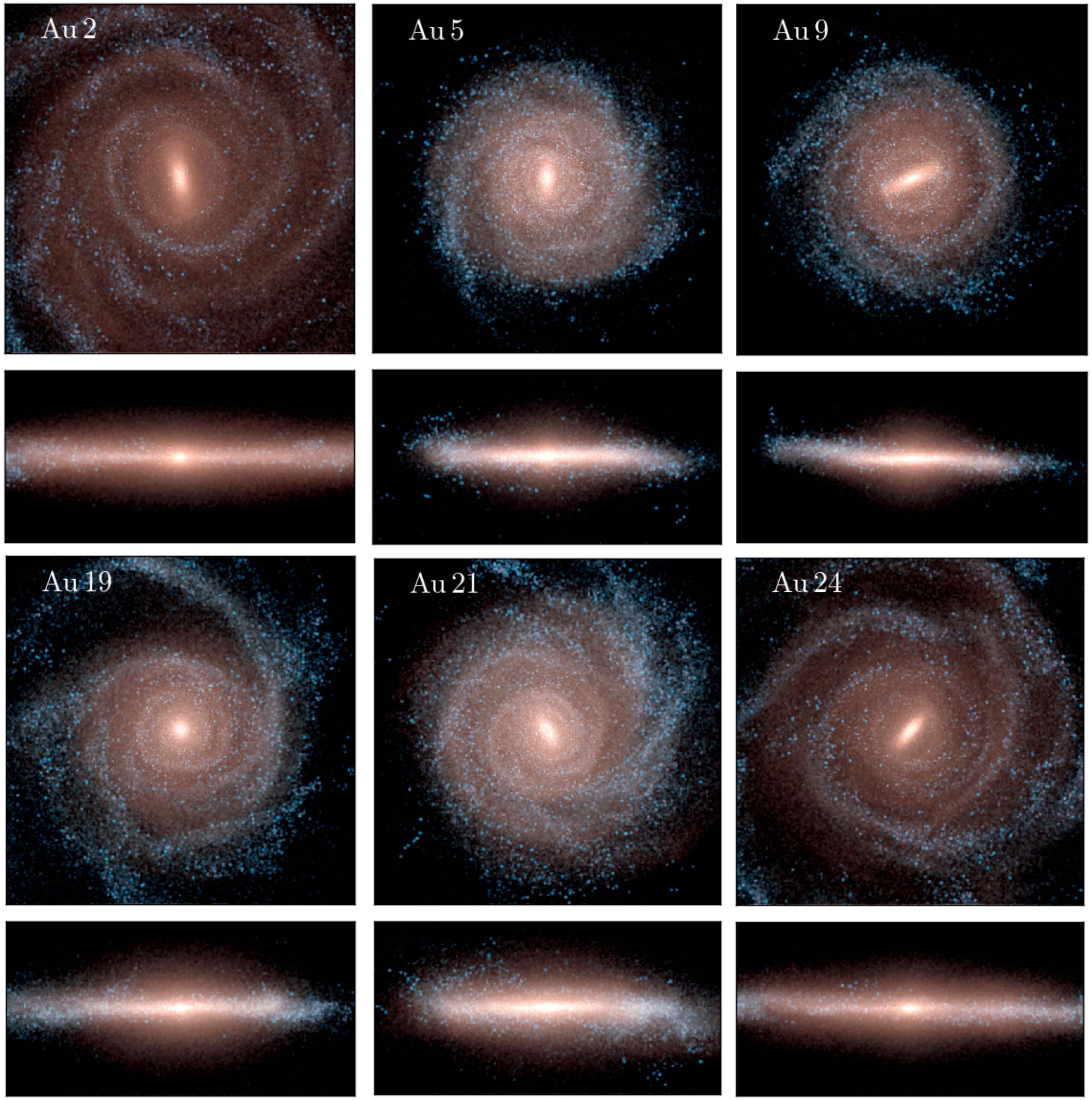
$m_{\rm DM}$ [$M_\odot$]	$m_{\rm b}$ [$M_\odot$]	ϵ [pc]
3×10^5	5×10^4	369

- All halos have their dark matter only (DMO) counterparts.

- **10 Auriga halos have the GRASP.**

Fattahi et al., 1810.07779

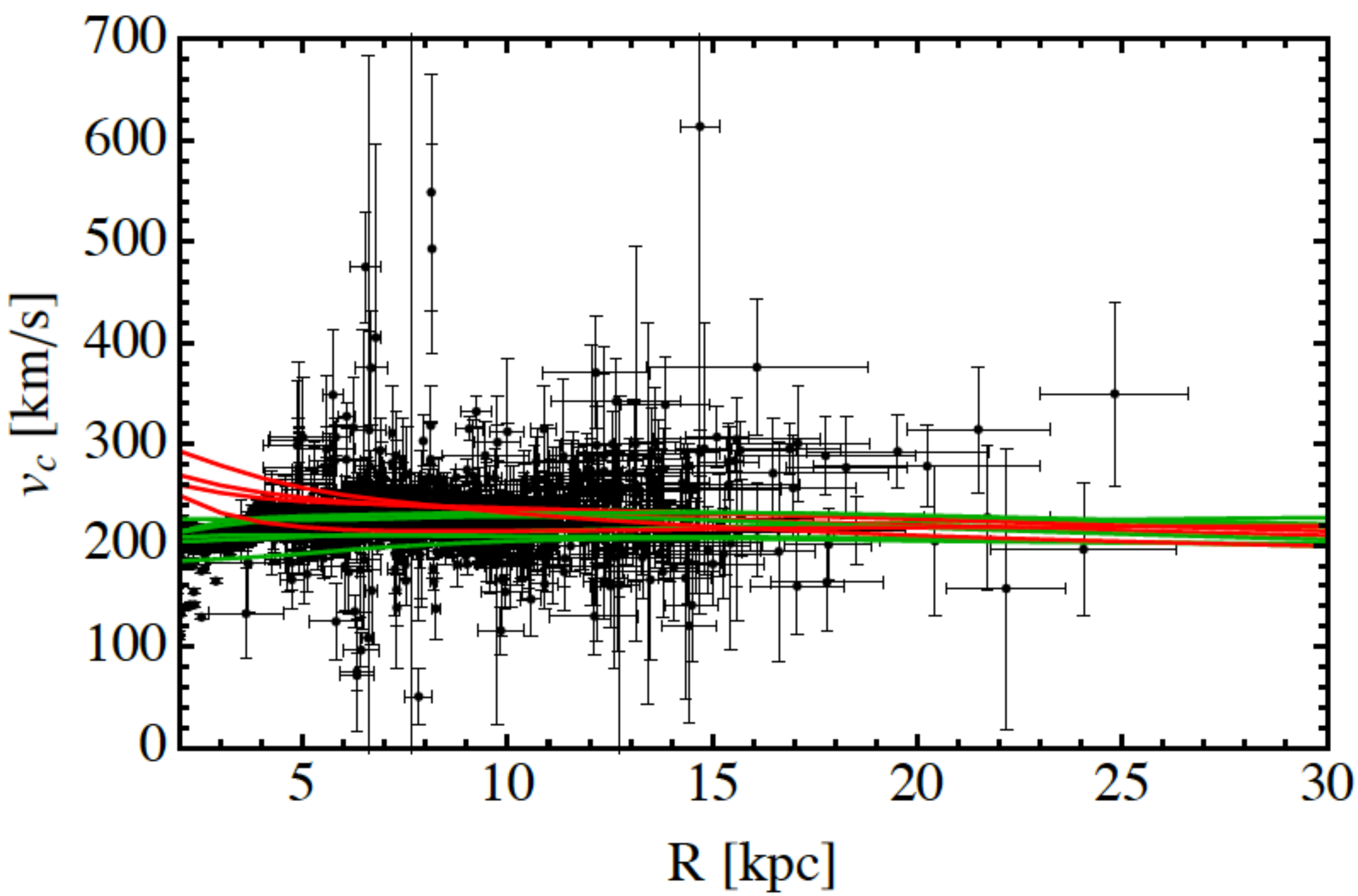
Azi's Talk



Milky Way-like Auriga halos

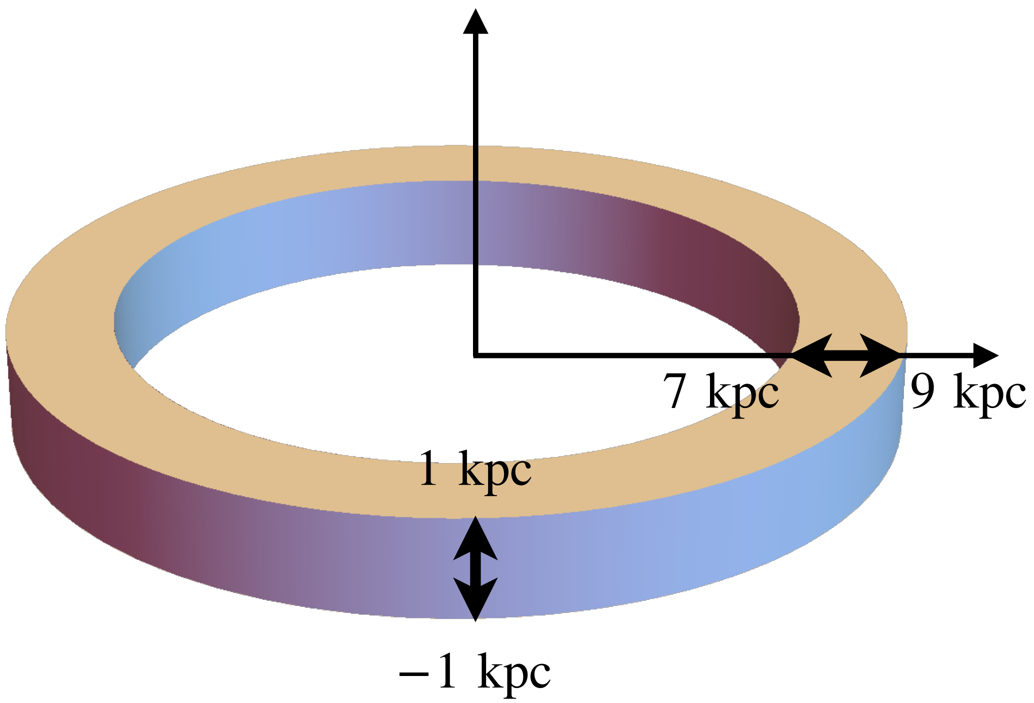
- Identify Milky Way analogues by requiring that **total stellar mass** and **rotation curves** fit observations **[Iocco, Pato, Bertone, 1502.03821]**.

- **10 Milky Way-like Auriga halos, 4 of which have the GRASP.**



Properties of DM in GRASP

- Consider the DM particles in a torus around the Solar circle.



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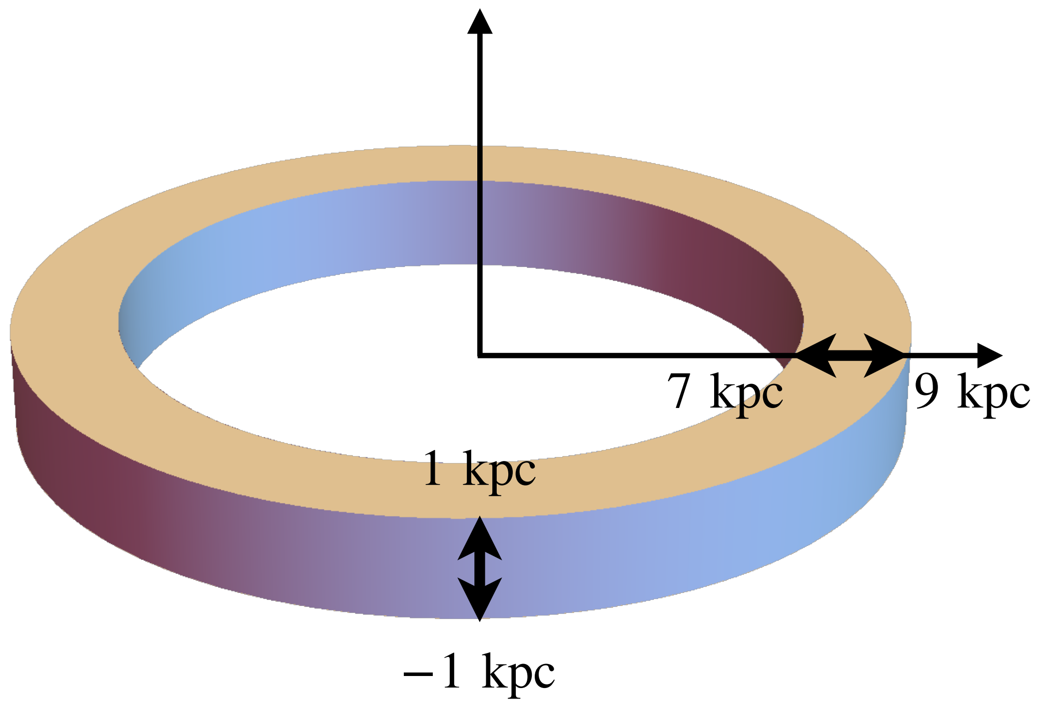


- For Auriga **Milky Way-like** halos:
  - Fraction of DM particles belonging to the GRASP in the torus:

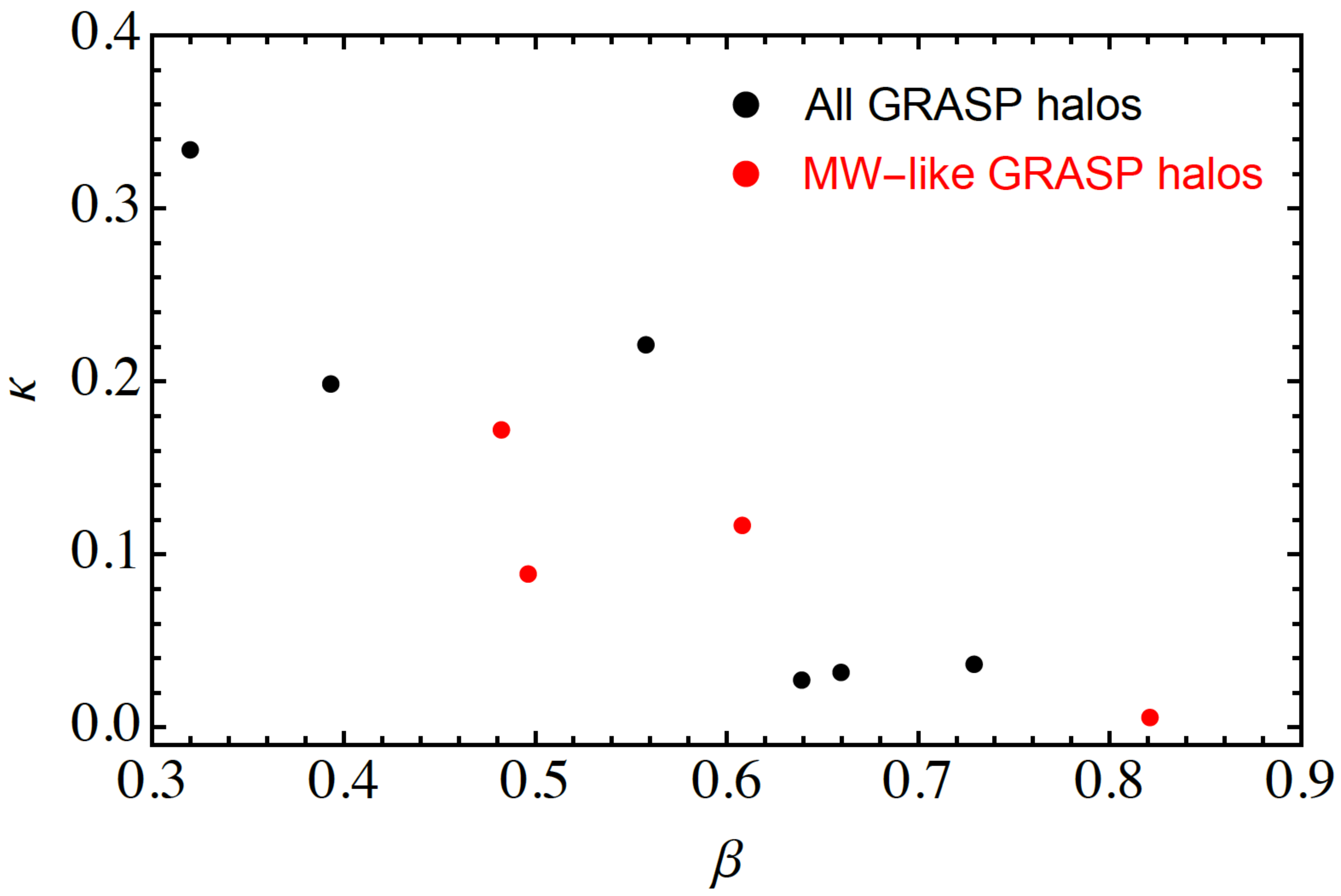
$$\boxed{\kappa = [0.006 - 0.17]}$$

  - Anisotropy parameter of DM particles in the GRASP:

$$\boxed{\beta = [0.48 - 0.82]}$$

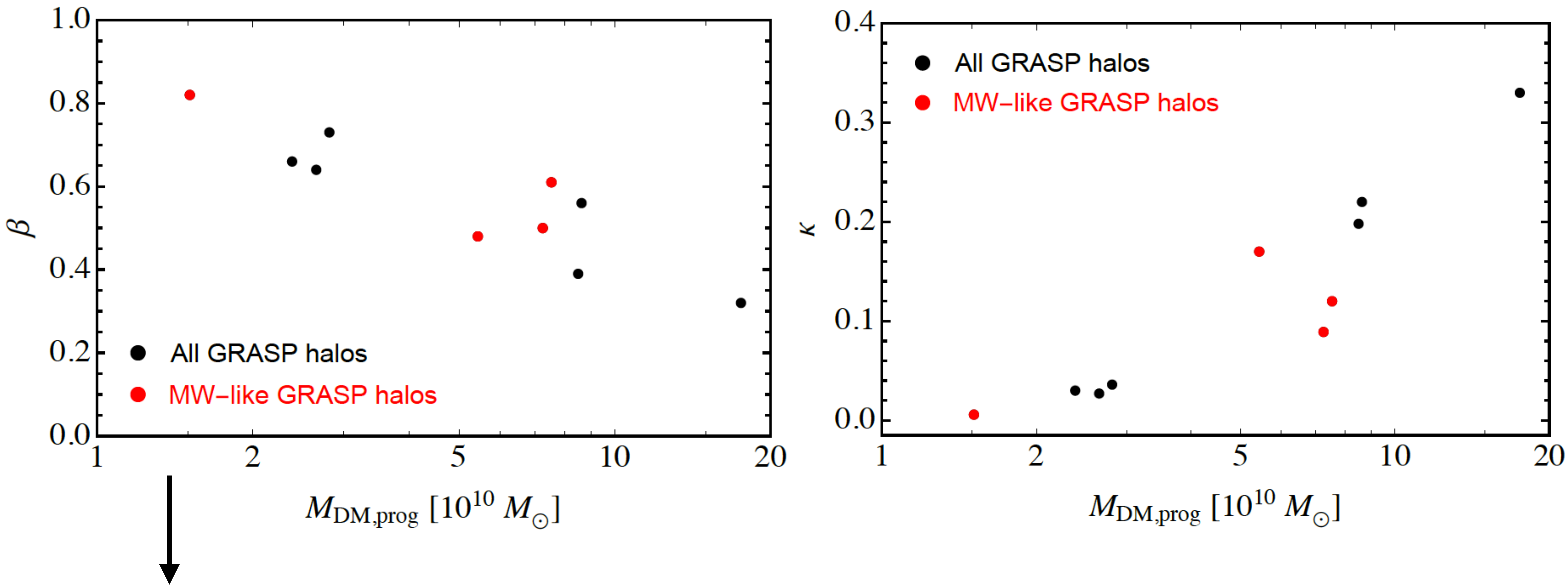
Properties of DM in GRASP

- Consider the DM particles in a torus around the Solar circle.



Properties of DM in GRASP

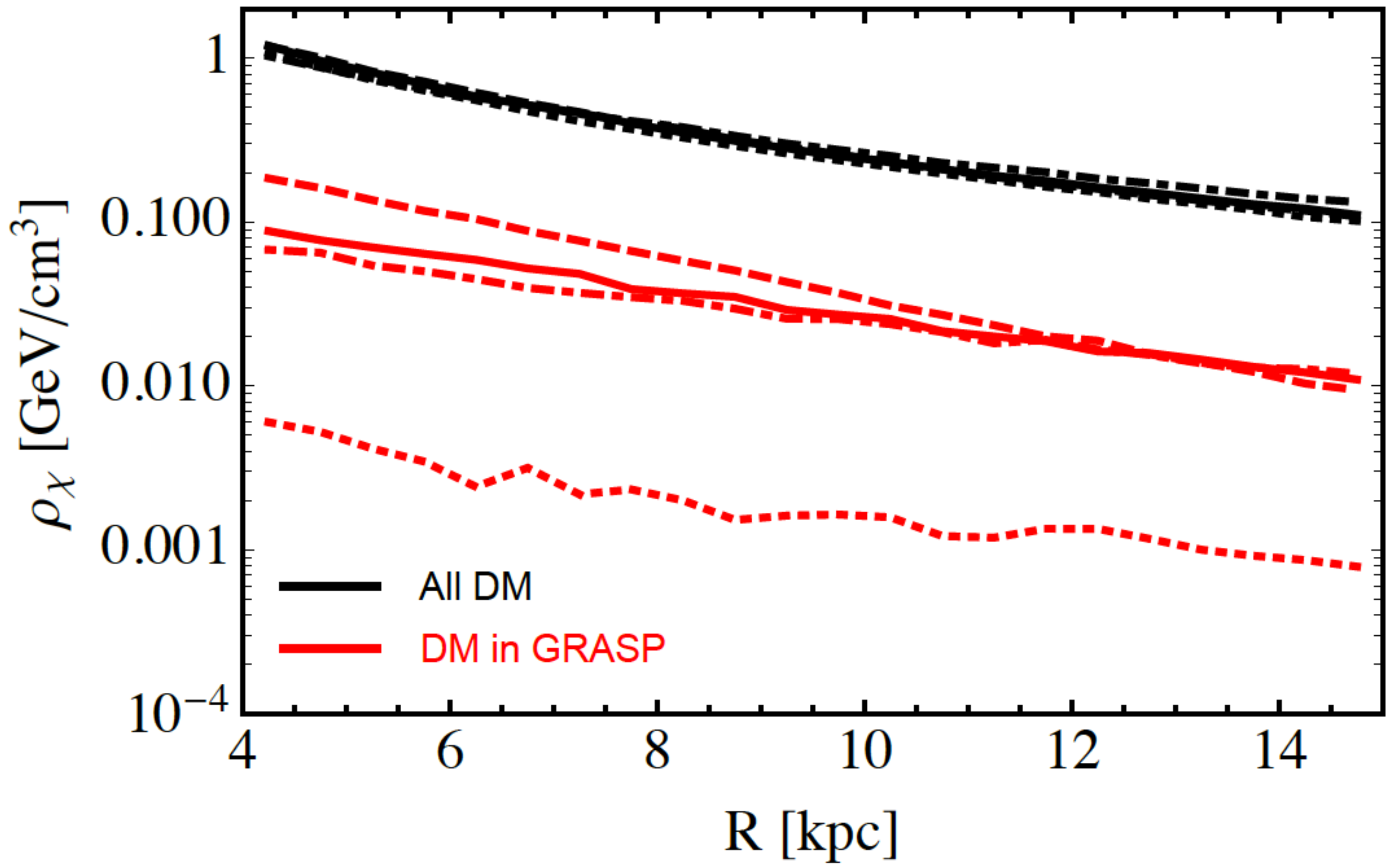
- The DM masses of the GRASP progenitors at infall are correlated with the ***anisotropy*** and ***fraction*** of the DM particles belonging to the GRASP in the torus.



- *Anti-correlation due to an interplay between tidal stripping, dynamical friction, and dependence of orbital parameters on subhalo mass at infall.*

Dark matter density profiles

- Spherically averaged DM density profiles for the four Auriga Milky Way-like halos with the GRASP.



Dark matter density profiles

- Slope of the density profiles in the Solar neighborhood, $6 \leq R \leq 10$ kpc

Halo Name	DM in GRASP	DM not in GRASP	All DM
Au5	1.76 ± 0.068	1.94 ± 0.023	1.92 ± 0.022
Au9	2.30 ± 0.055	1.89 ± 0.024	1.95 ± 0.022
Au22	1.35 ± 0.303	1.89 ± 0.023	1.89 ± 0.023
Au24	1.29 ± 0.075	1.69 ± 0.023	1.66 ± 0.022

Slopes computed by fitting a power law, $\rho_\chi(R) \propto R^{-a}$, to the density profiles of ***DM in the GRASP, DM not in the GRASP,*** *and* ***all DM***.

Local dark matter density

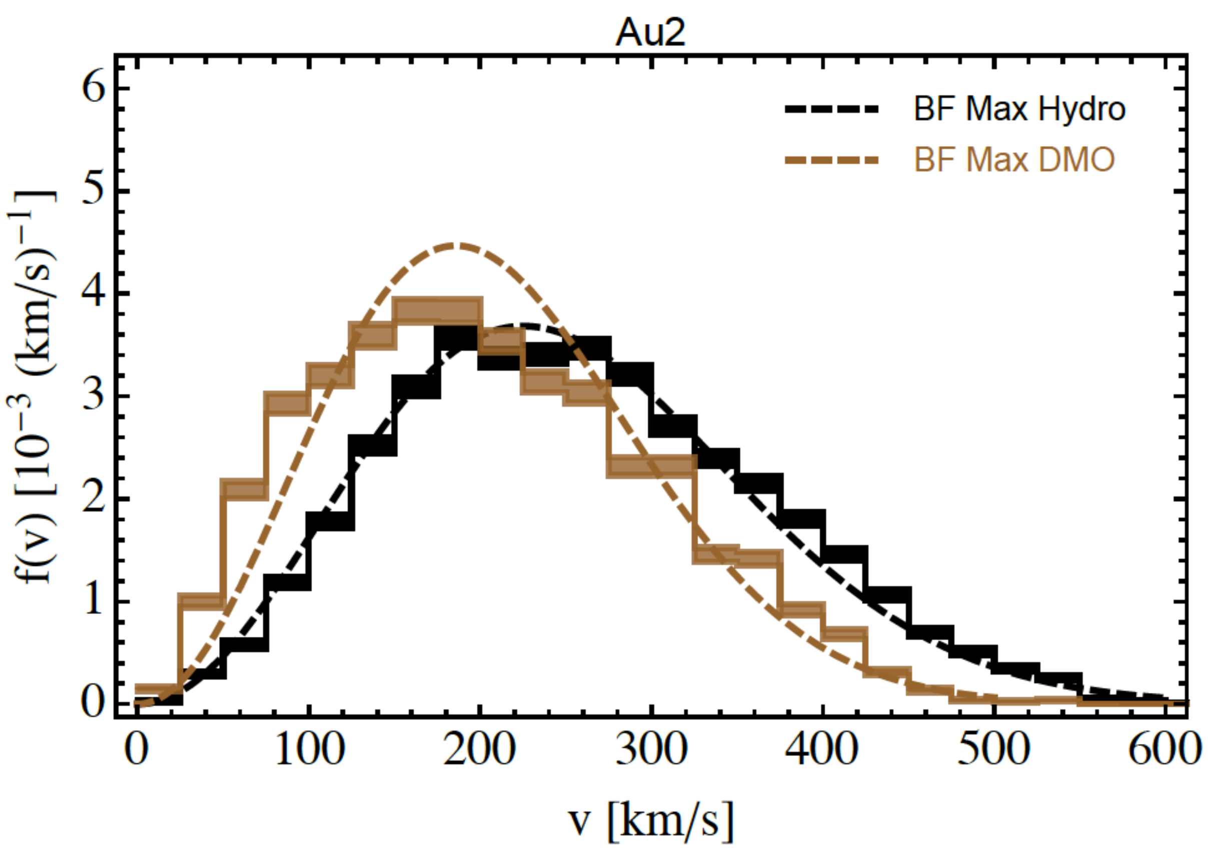
- Average DM density in the torus for Milky Way-like halos:

Halo Name	ρ_χ^{loc} [GeV/cm^3]
Au2	0.479
Au4	0.398
Au5 ($\star$)	0.444
Au7	0.386
Au9 ($\star$)	0.449
Au12	0.427
Au19	0.437
Au21	0.444
Au22 ($\star$)	0.370
Au24 ($\star$)	0.483

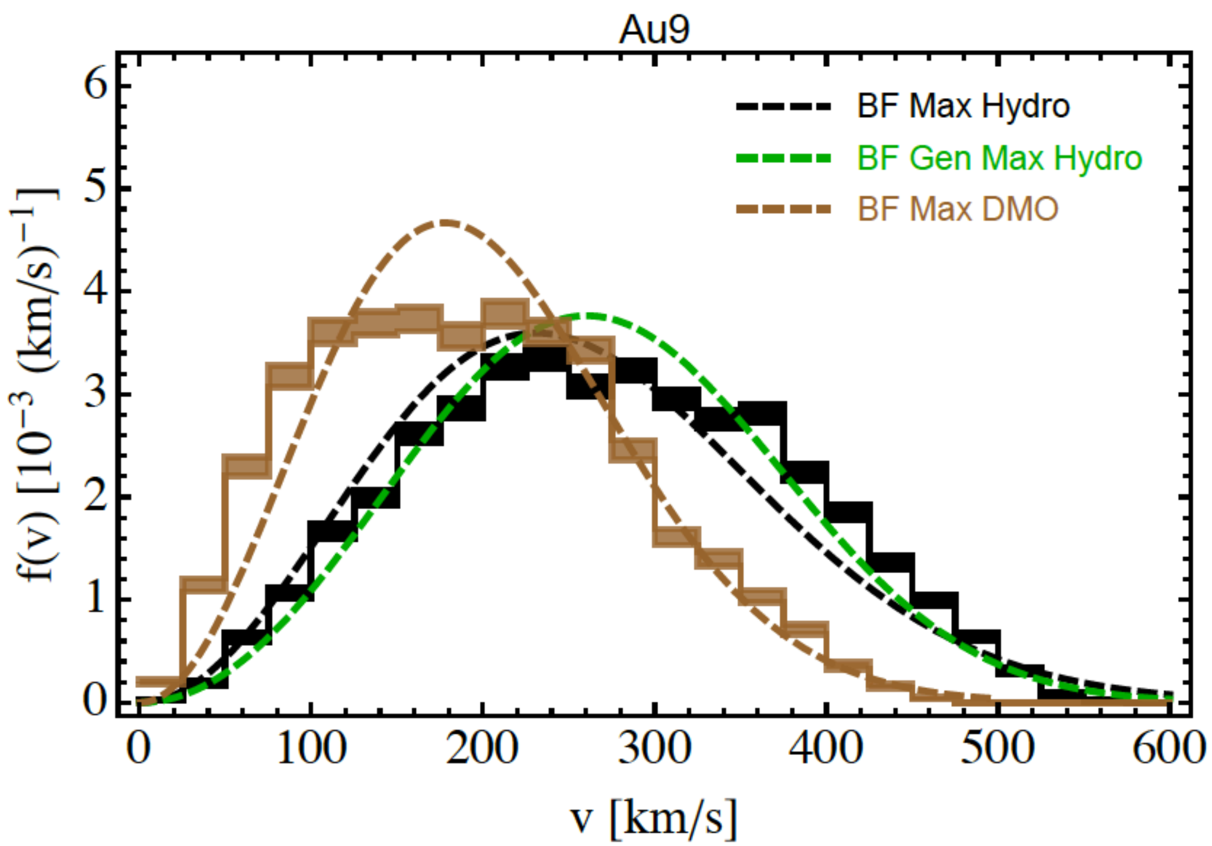
- No significant difference between the values of the local DM density for halos with and without the GRASP.

Local DM speed distributions

Halo without GRASP



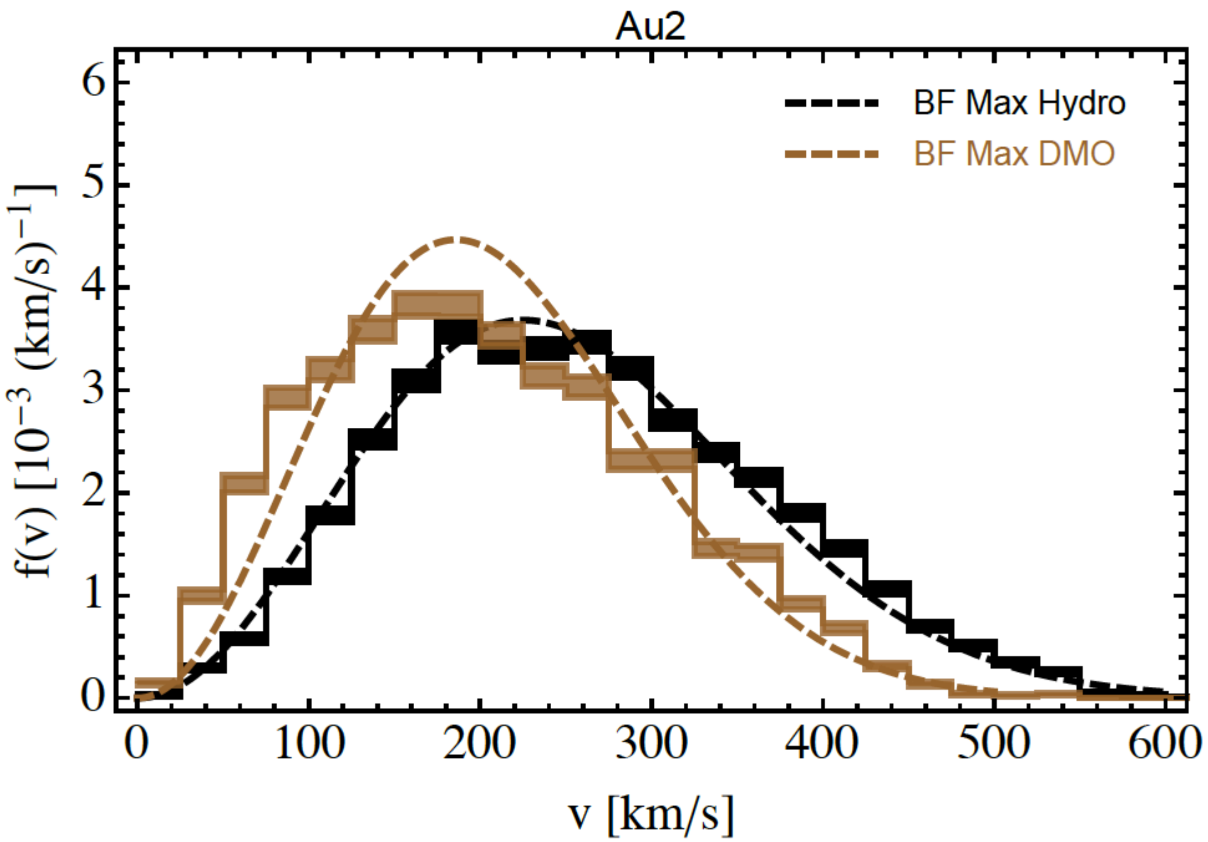
Halo with GRASP

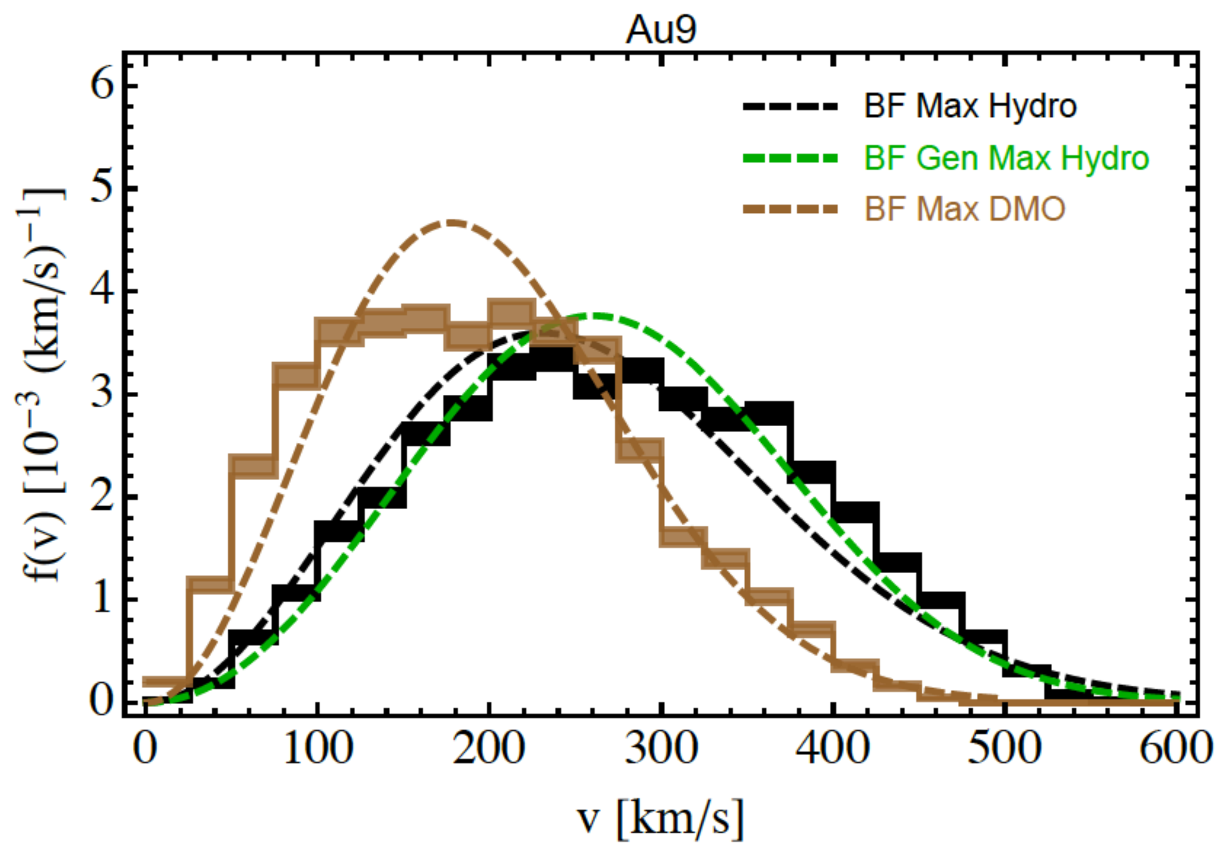


Local DM speed distributions

Halo without GRASP

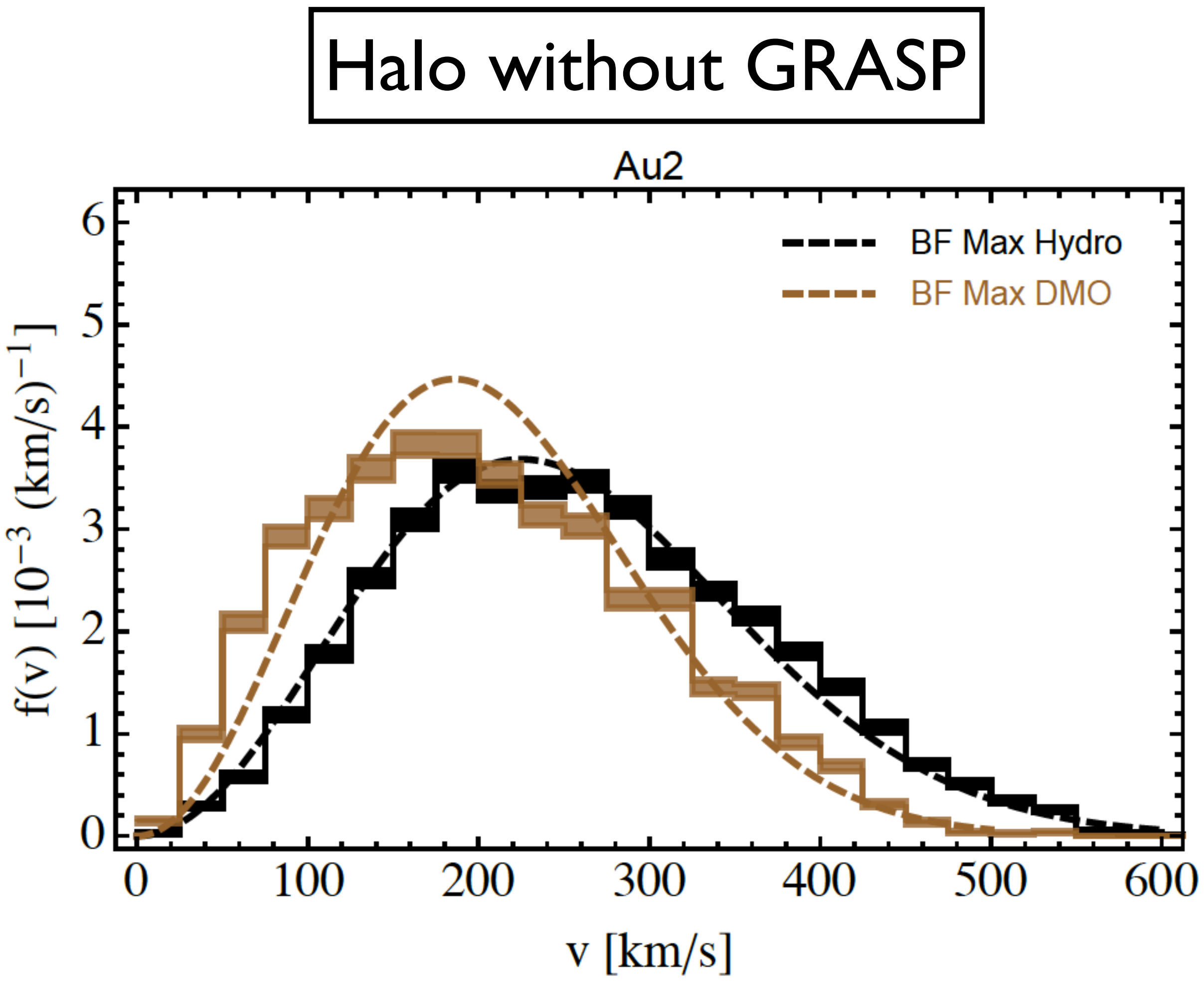
Halo with GRASP

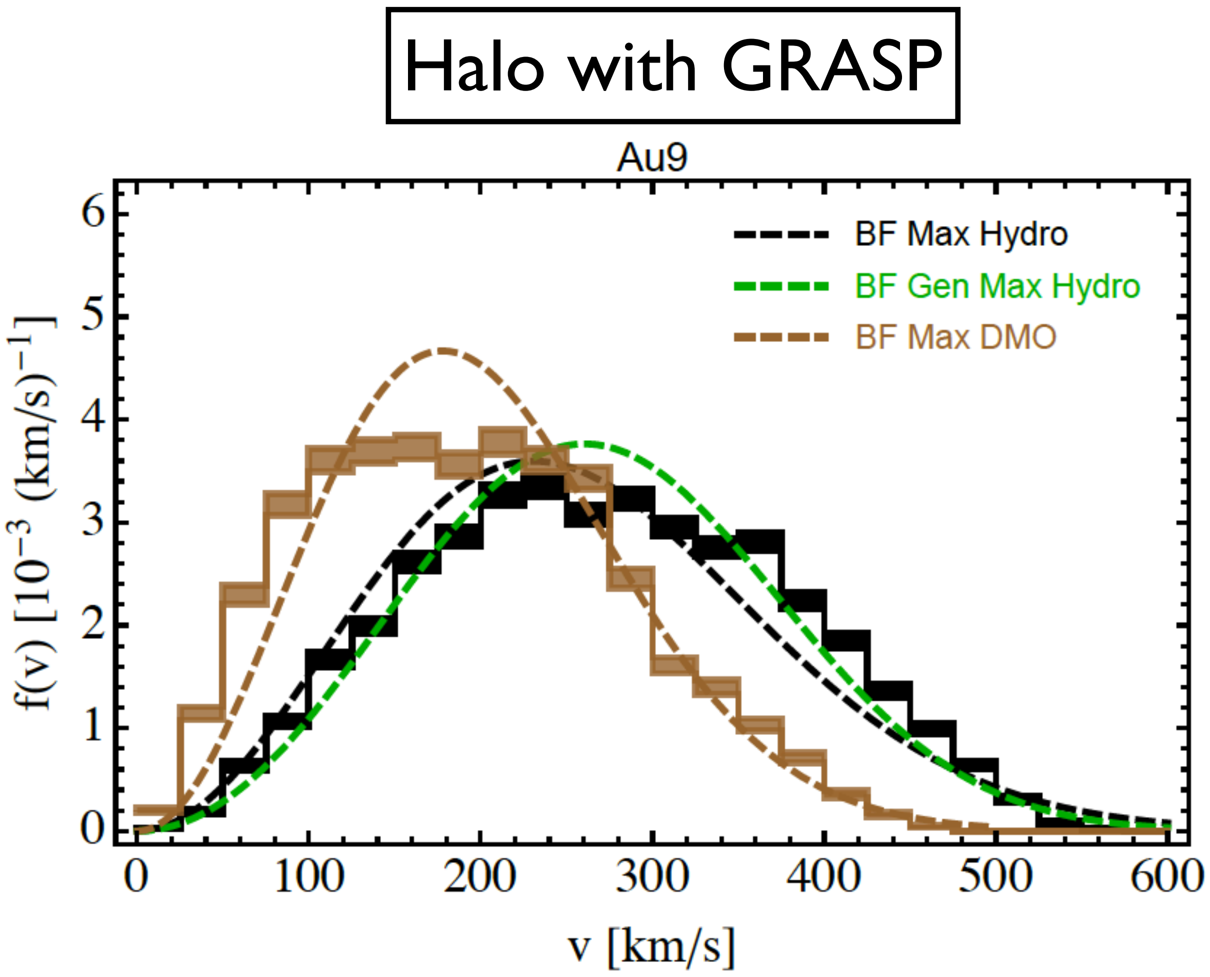




- Baryons deepen the gravitational potential in the inner halo, shifting the peak of the DM speed distribution to *higher speeds.*

Local DM speed distributions

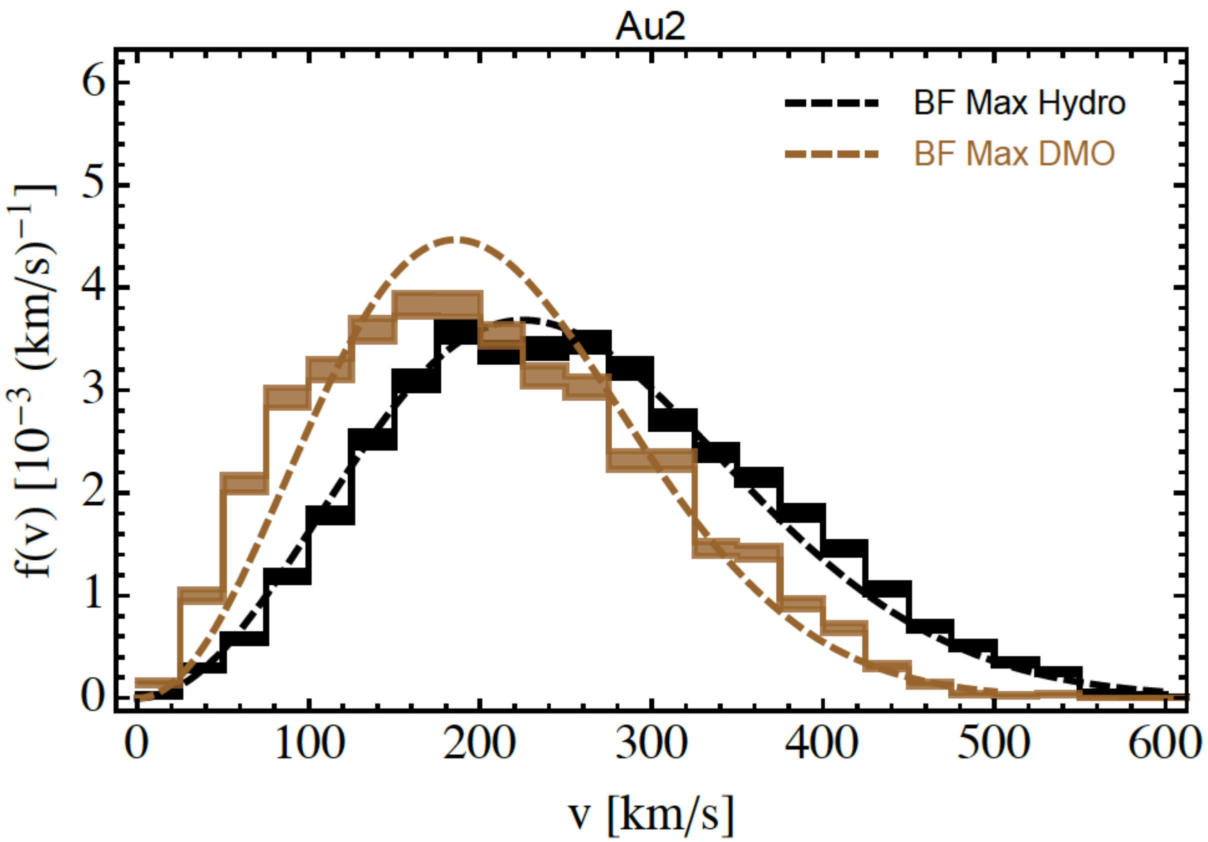




- Baryons deepen the gravitational potential in the inner halo, shifting the peak of the DM speed distribution to *higher speeds.*
- The combination of a **Maxwellian** and an **anisotropic** velocity distribution does not does not fit well.

Local DM speed distributions

Halo without GRASP



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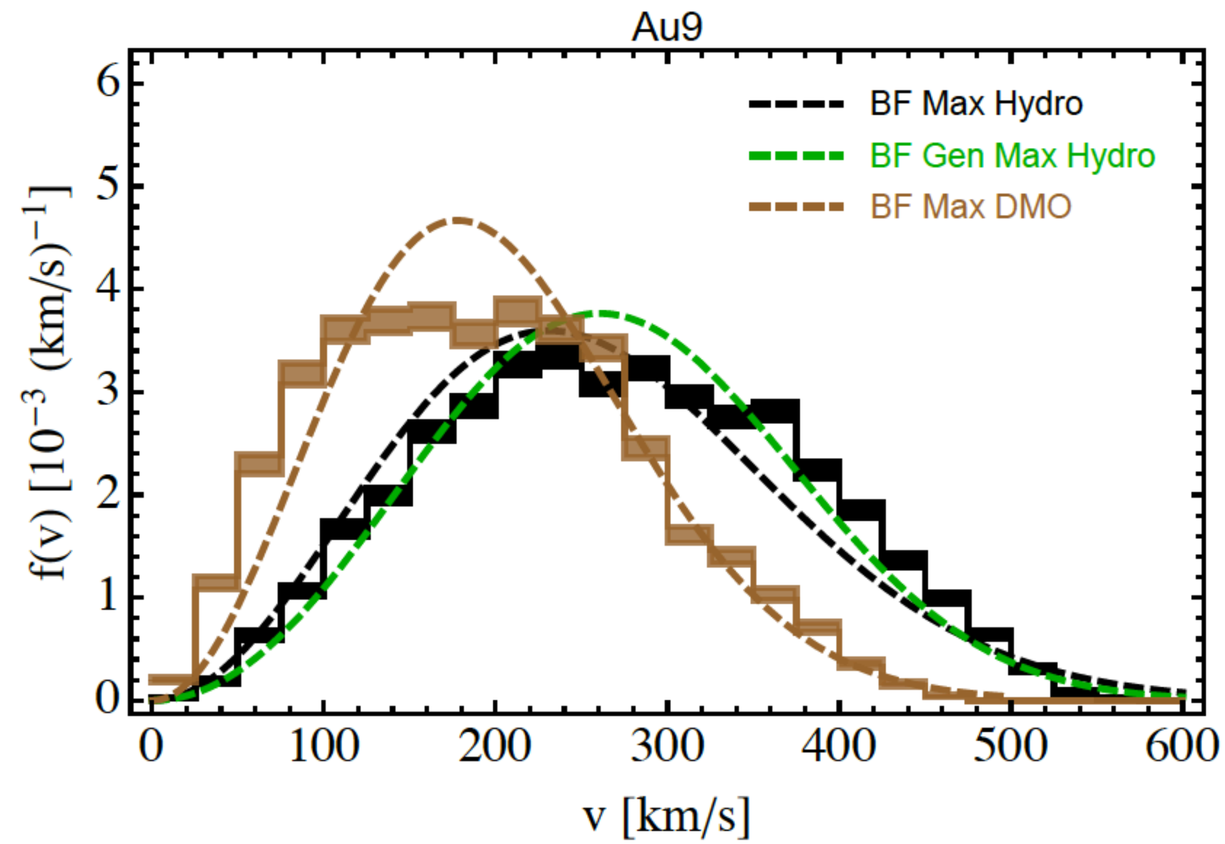


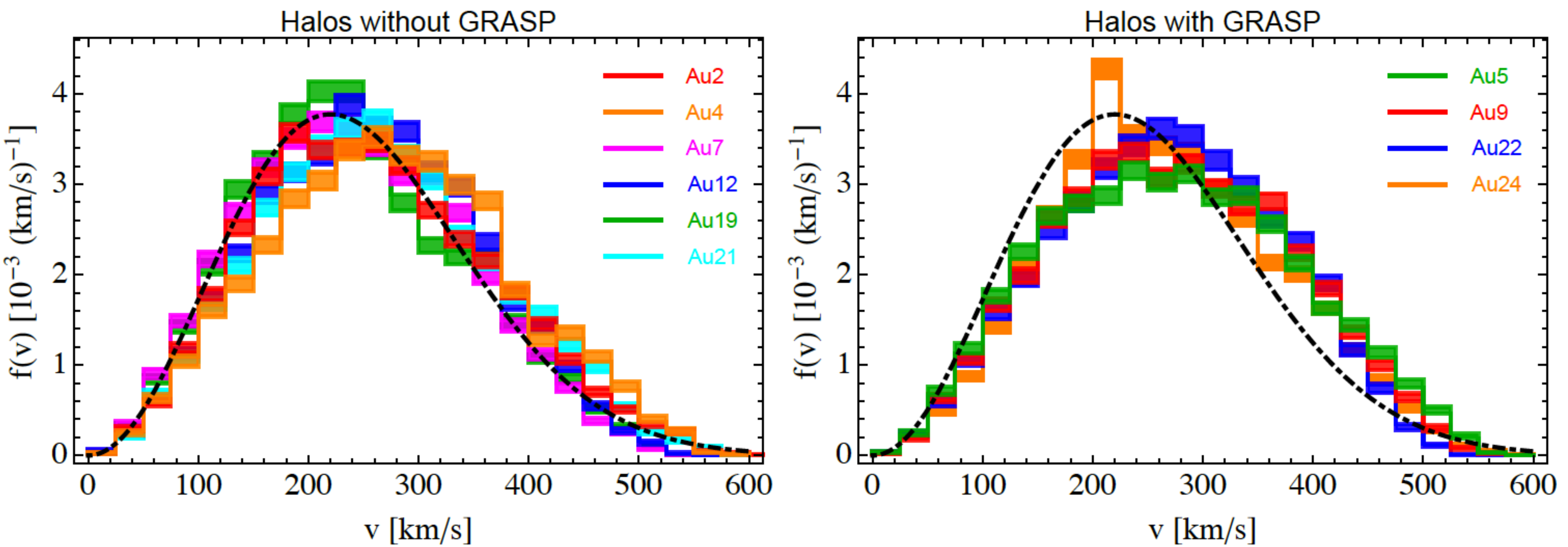
- The ***generalized Maxwellian*** distribution fits better than the standard Maxwellian.

$$\boxed{f(v) \propto v^2 \exp[-(v/v_0)^{2\alpha}]}$$

v_0 [km s^{-1}]	α
296	**1.42**
292	**1.37**
319	**1.77**
280	**1.32**

Local DM speed distributions

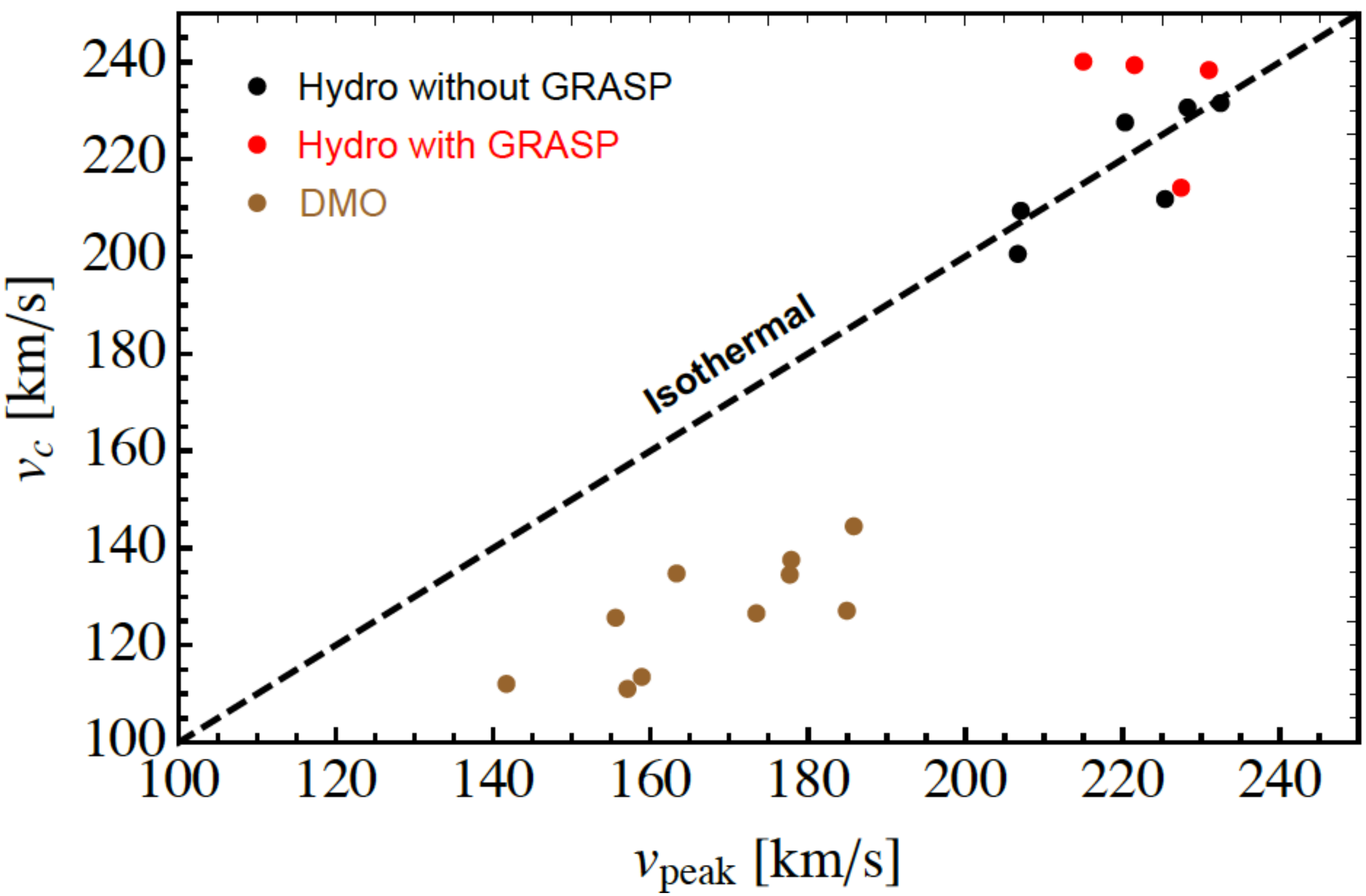
Comparison with the SHM Maxwellian:



- Speed distribution of halos with GRASP are shifted to higher speeds compared to the SHM.
- Larger halo-to-halo variation for halos without the GRASP, due to their larger numbers.

Departure from isothermal

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

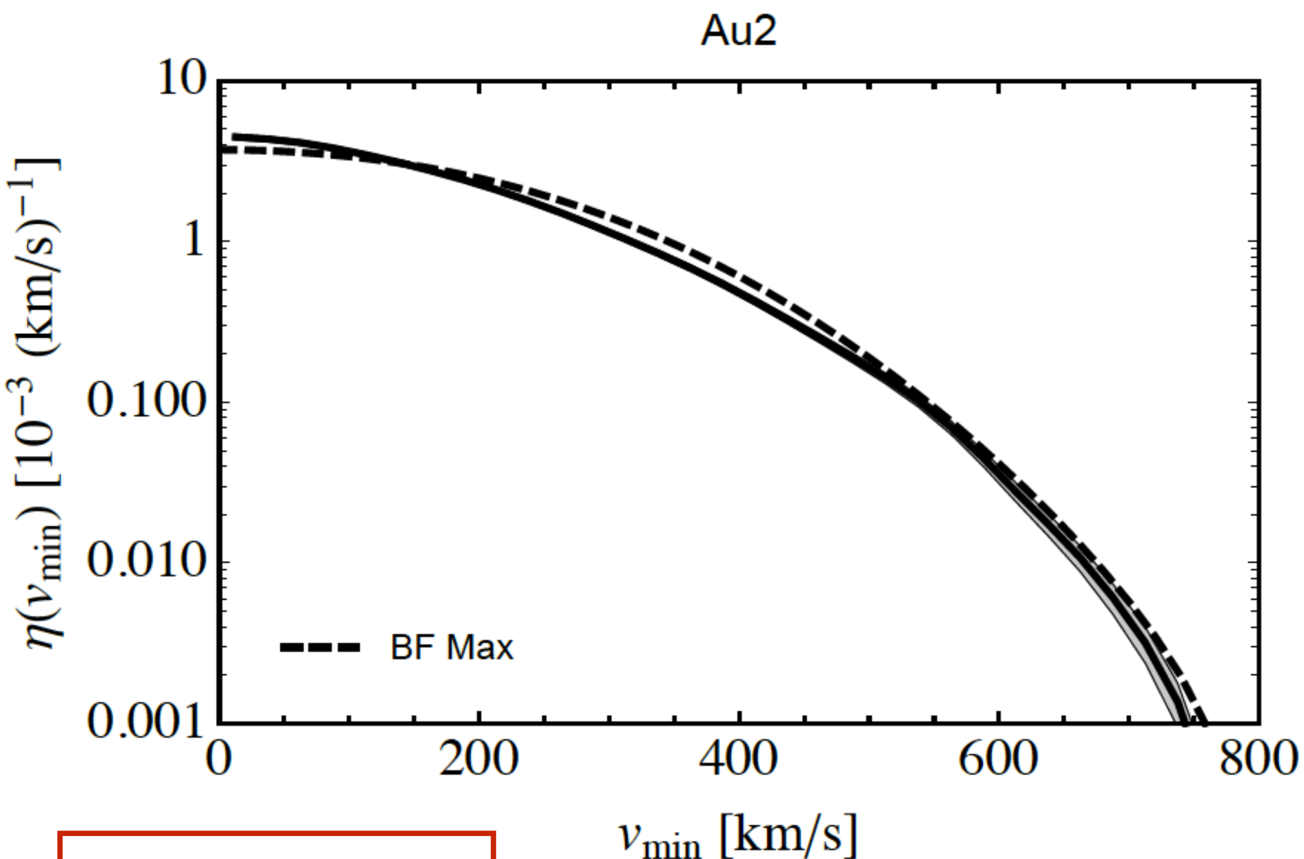


The halo integral

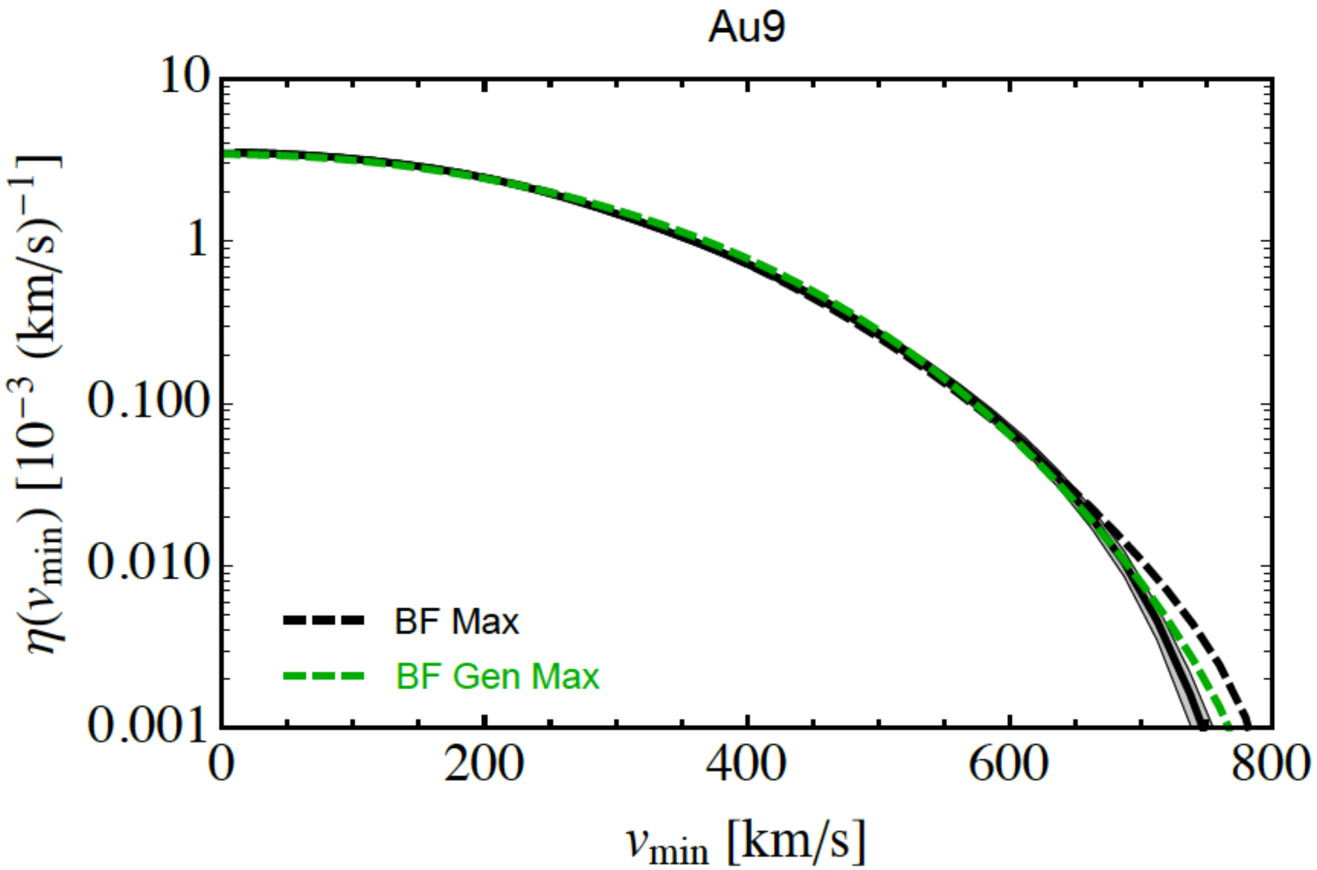
- For standard spin-independent and spin-dependent interactions:

$$\frac{dR}{dE_R} \propto \eta(v_{\min}, t) \equiv \int_{v>v_{\min}} d^3v \, \frac{\tilde{f}_{\det}(\mathbf{v}, t)}{v}$$

Halo without GRASP



Halo with GRASP

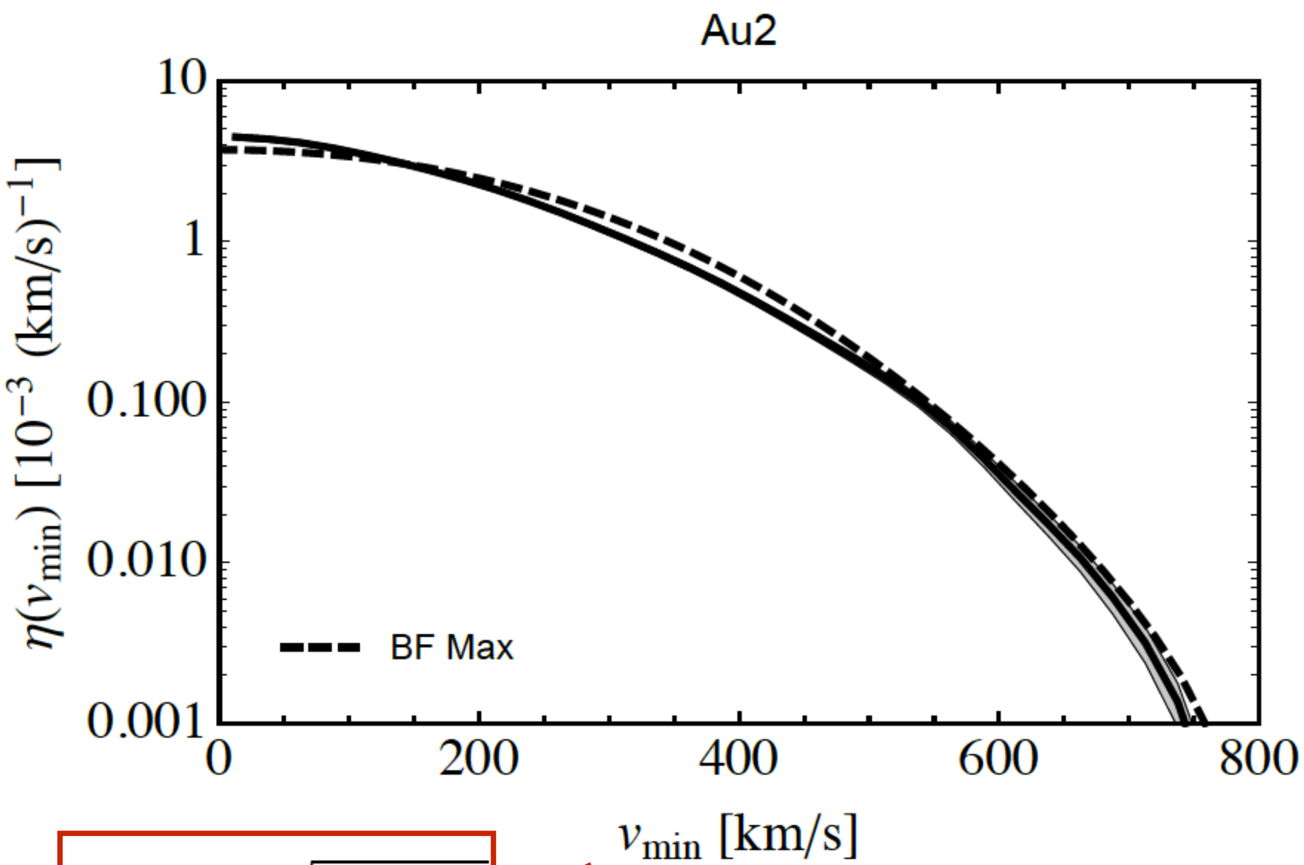


$$\boxed{v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_{\chi T}^2}}}$$

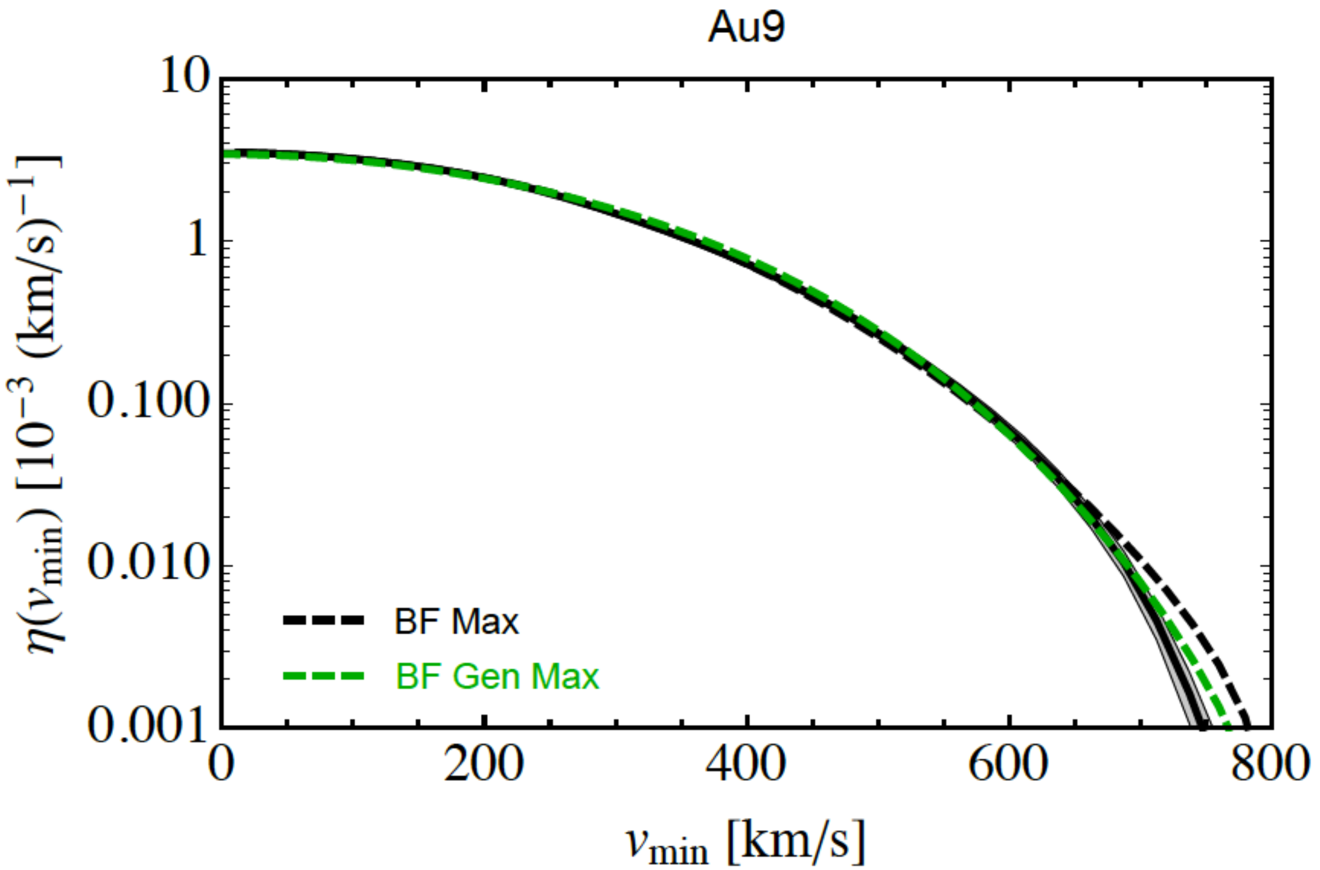
The halo integral

- Halo integrals of a *generalized Maxwellian* velocity distribution agree well with the halo integrals of the simulated Milky Way-like halos with the GRASP.

Halo without GRASP



Halo with GRASP



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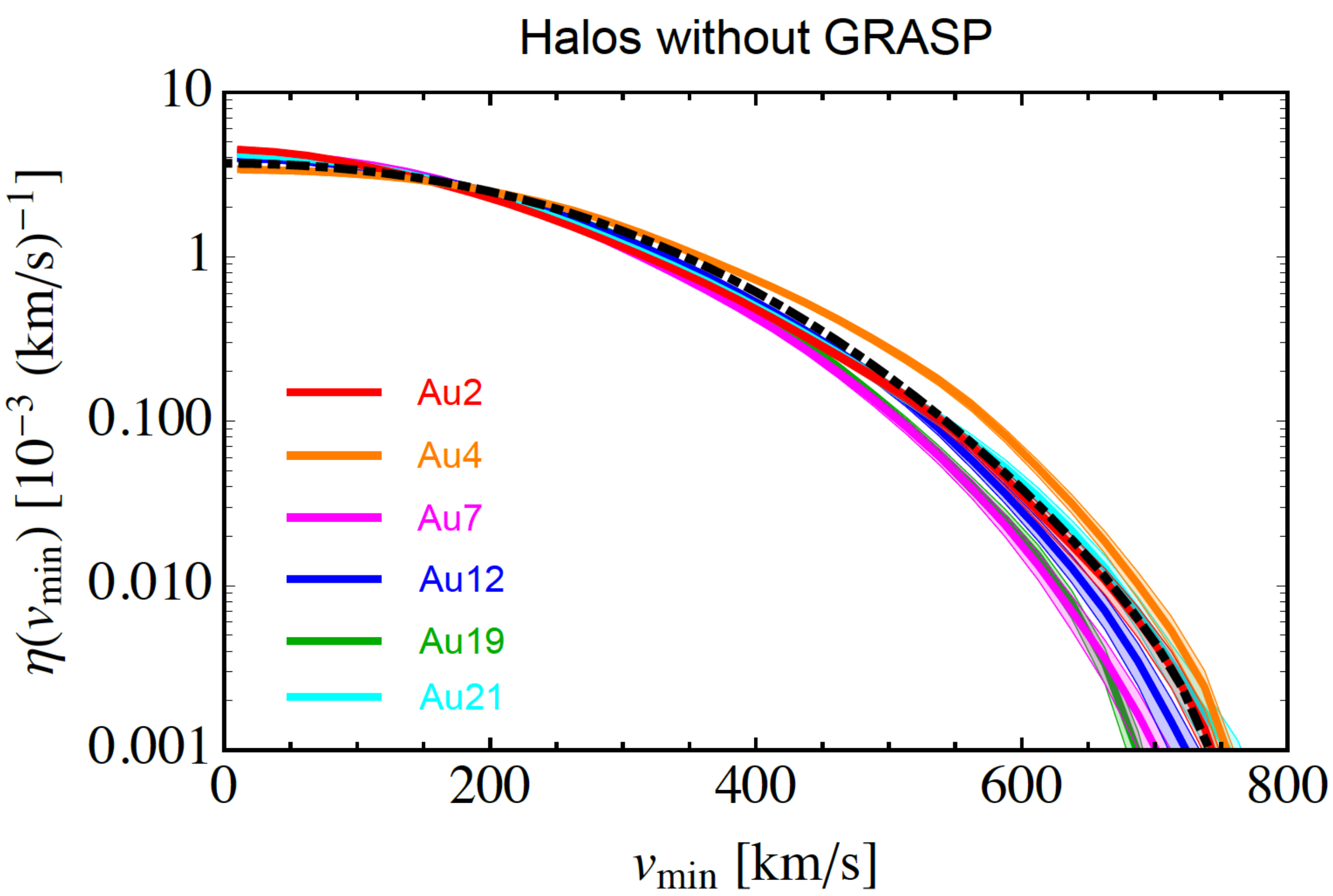
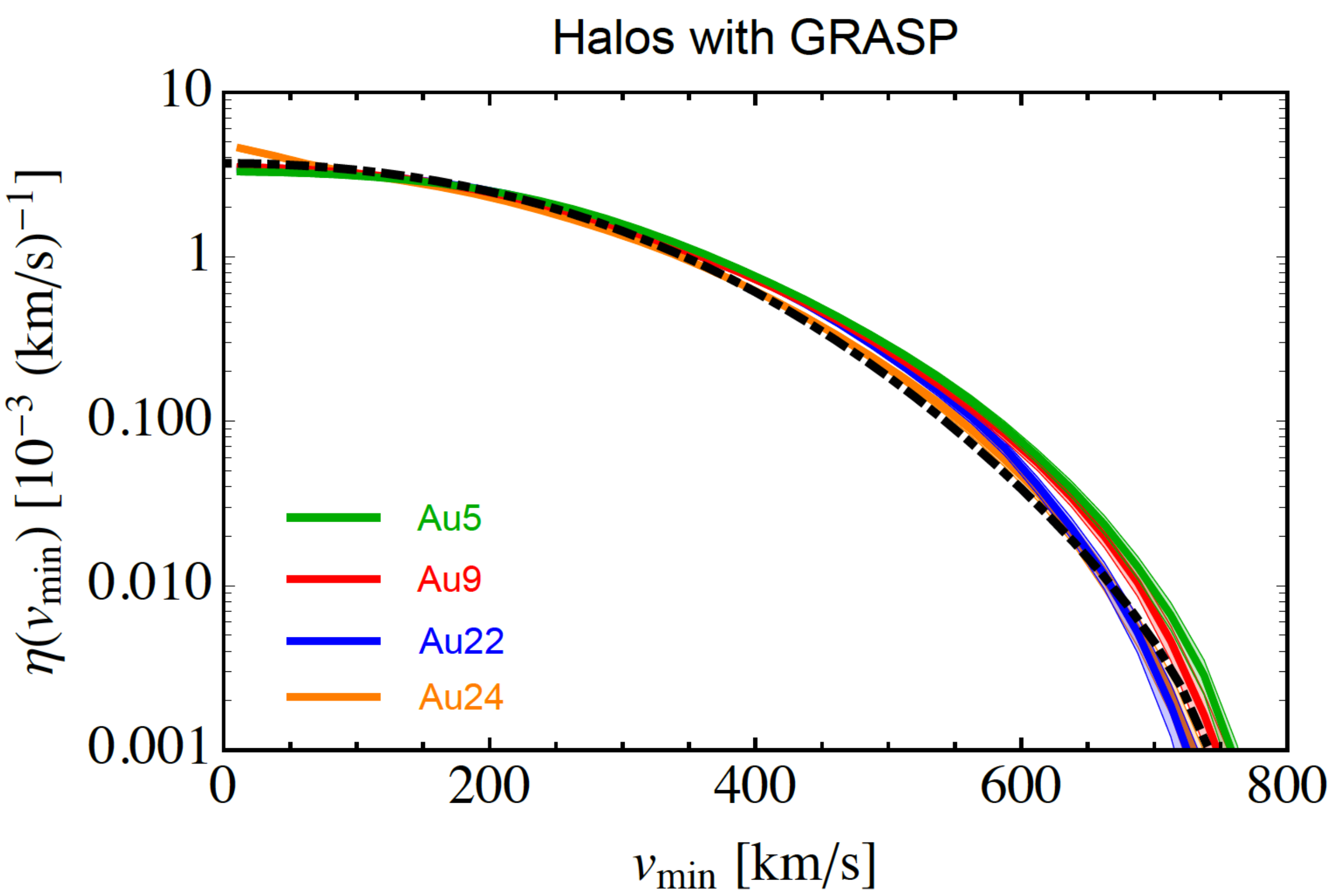
The halo integral

Comparison with the SHM Maxwellian:





- Halo integral of halos with GRASP mostly show an excess in their tails, compared to the SHM.
- Larger variation in the tails of the halo integrals of halos without GRASP, since they are more numerous.

Direct detection exclusion limits

- Simulate the signals in 2 idealized direct detection experiments: **Germanium** & **Xenon**.

- **Germanium based detector:**

  - **Low threshold design:** [40–300] eV, 1.6 x 10^4 kg days

  - **Low background design:** discriminate electronic & nuclear recoils, [3–30] keV, 2.04 x 10^4 kg days

Exposures achievable by SuperCDMS after 5 years of operation during 2020-2024.

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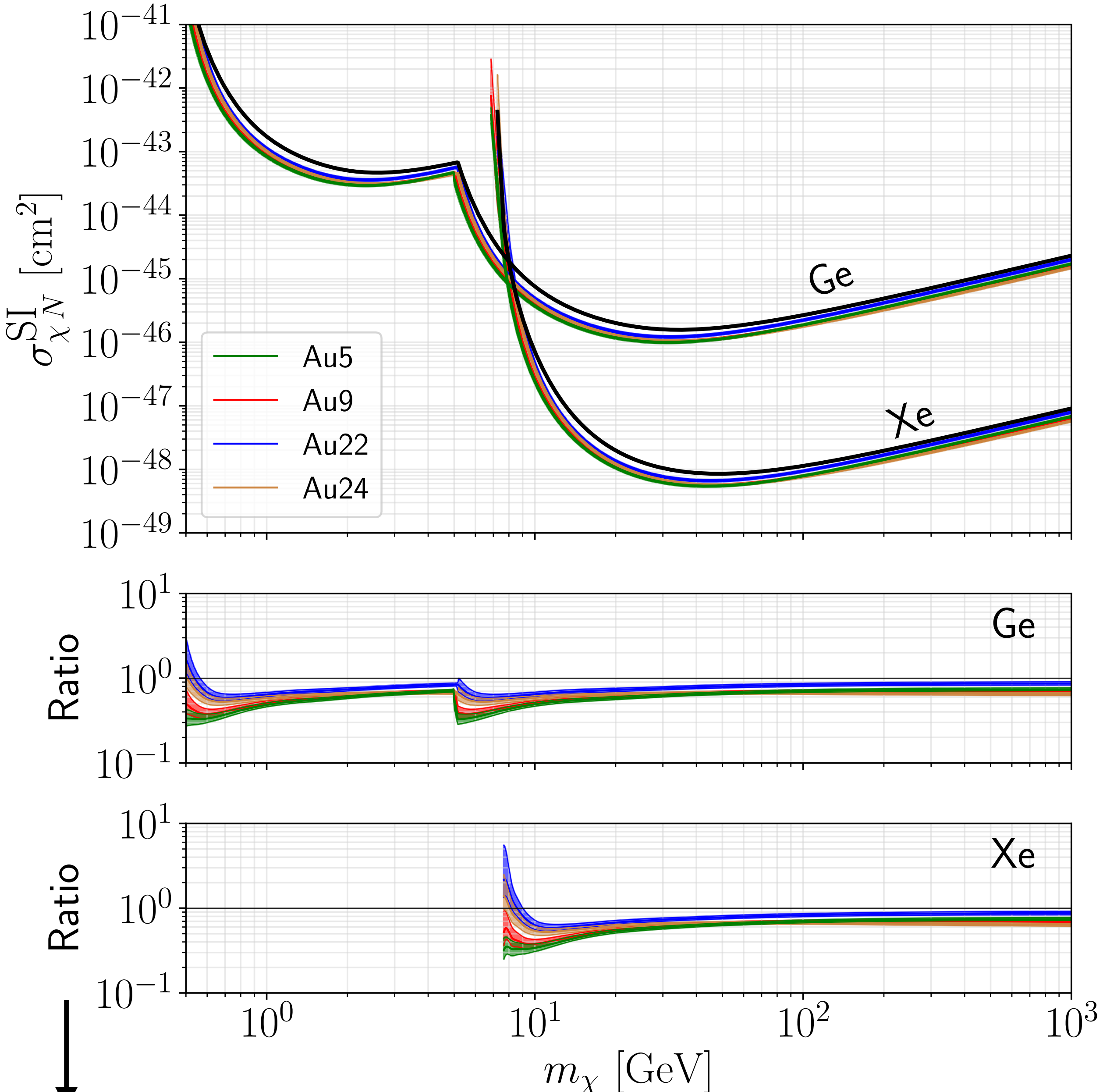
Exposures achievable by SuperCDMS after 5 years of operation during 2020-2024.

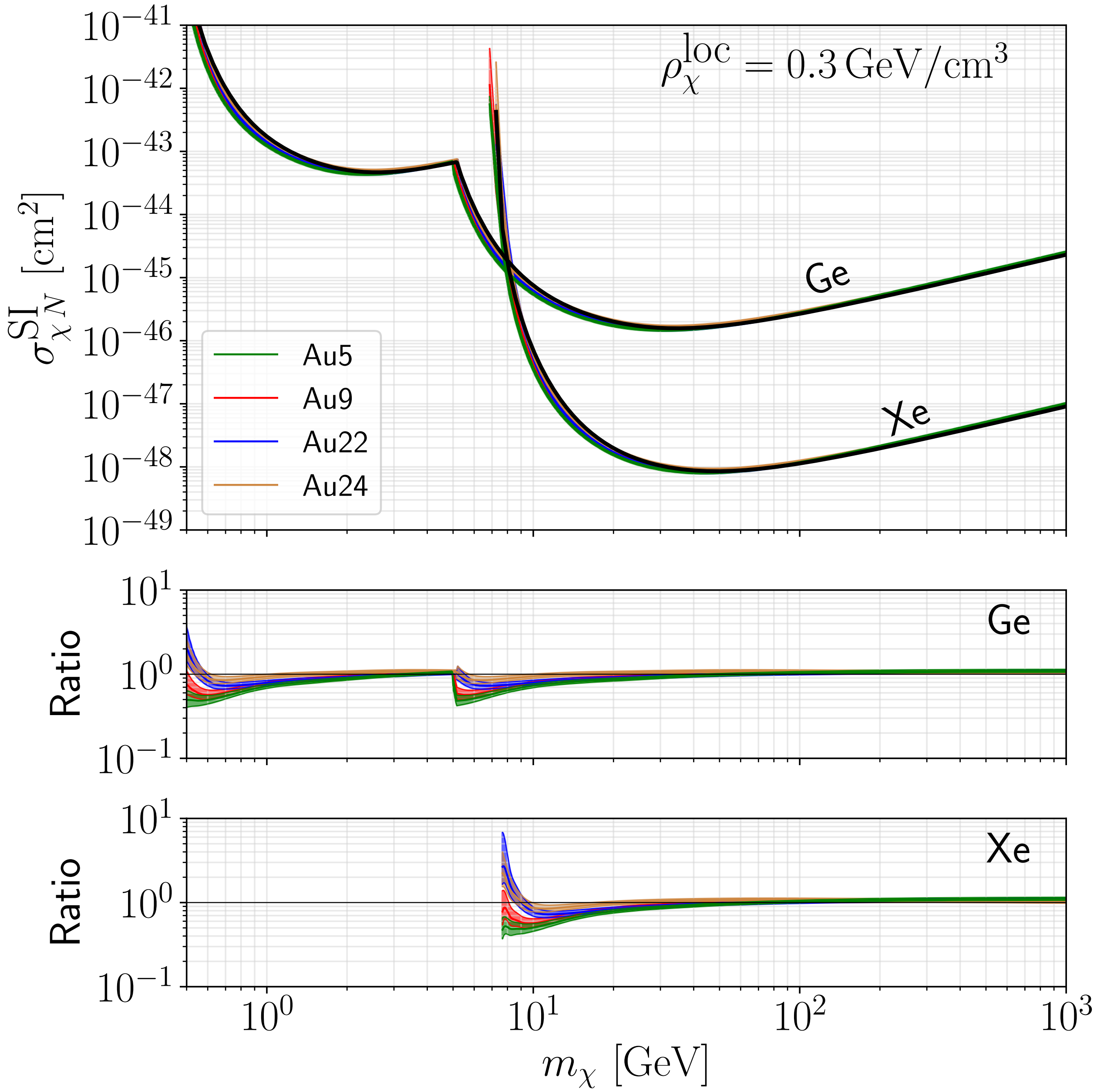
- **Xenon based detector:** [5–50] keV, 5.6 x 10^6 kg days

Exposure achievable by LZ which will operate during 2020-2025.

Direct detection exclusion limits

Halos with GRASP

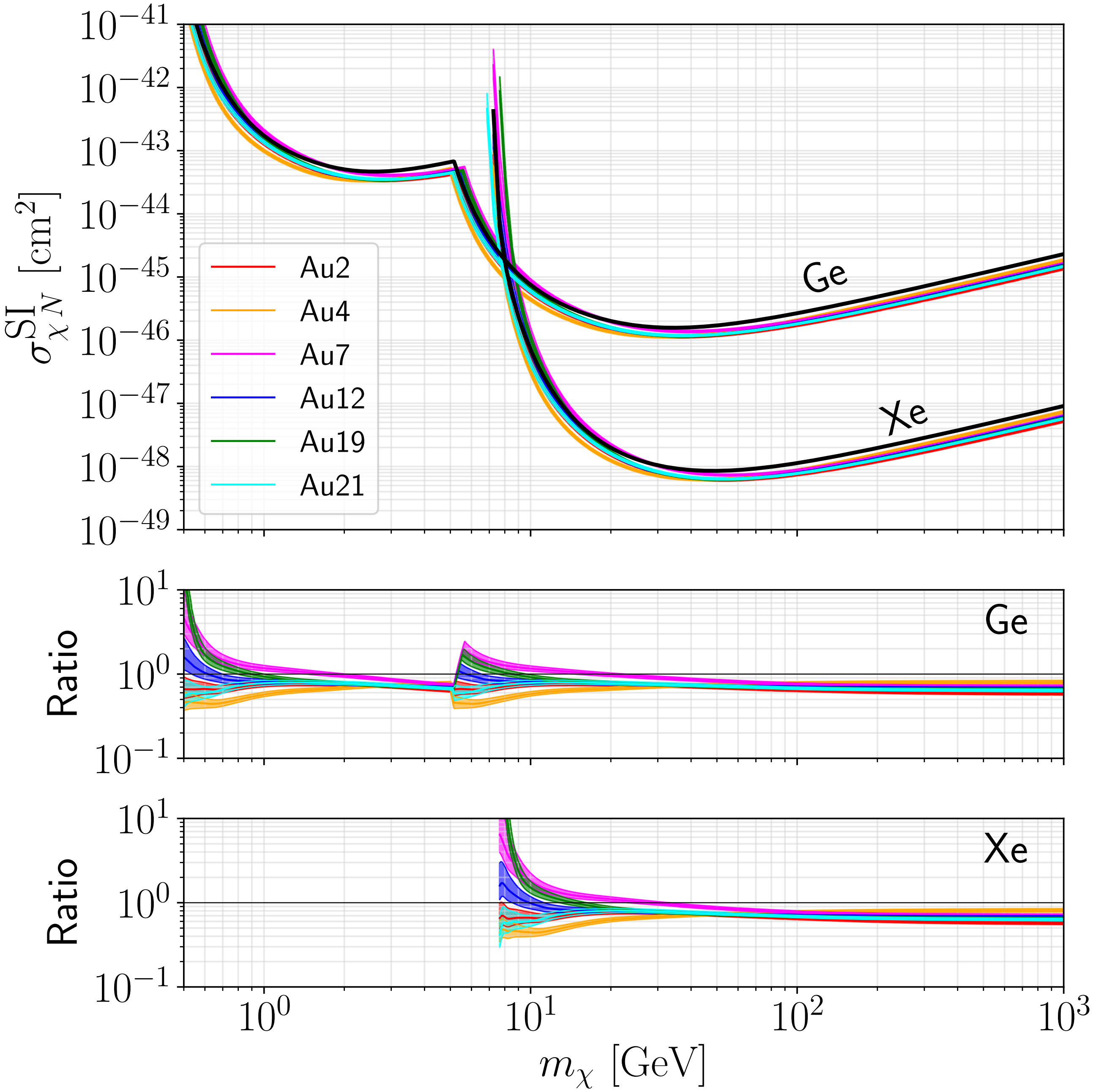


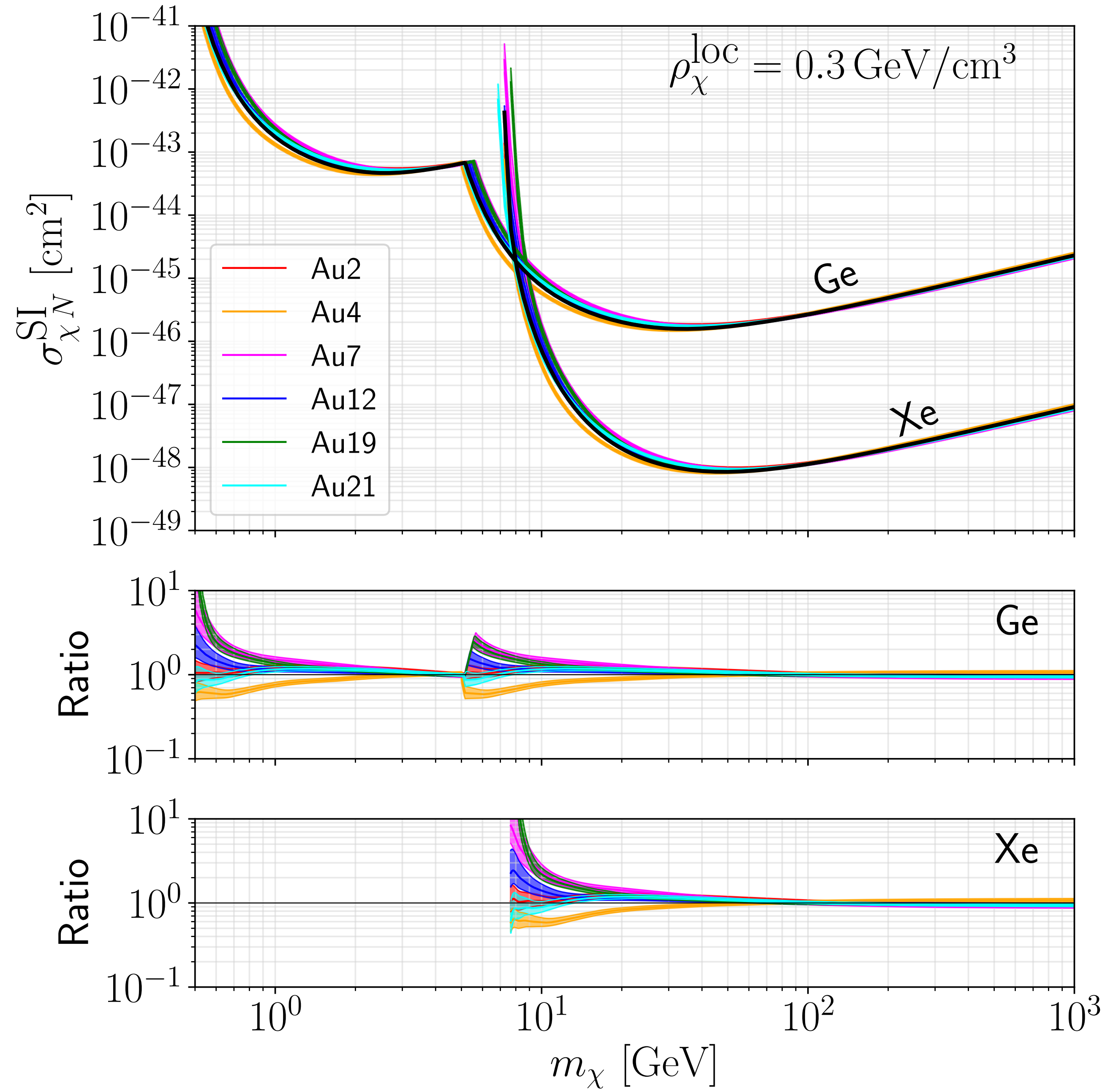


$$\text{Ratio} = \frac{\sigma^{SI}_{90\%,\text{Auriga}}(m_\chi)}{\sigma^{SI}_{90\%,\text{SHM}}(m_\chi)}$$

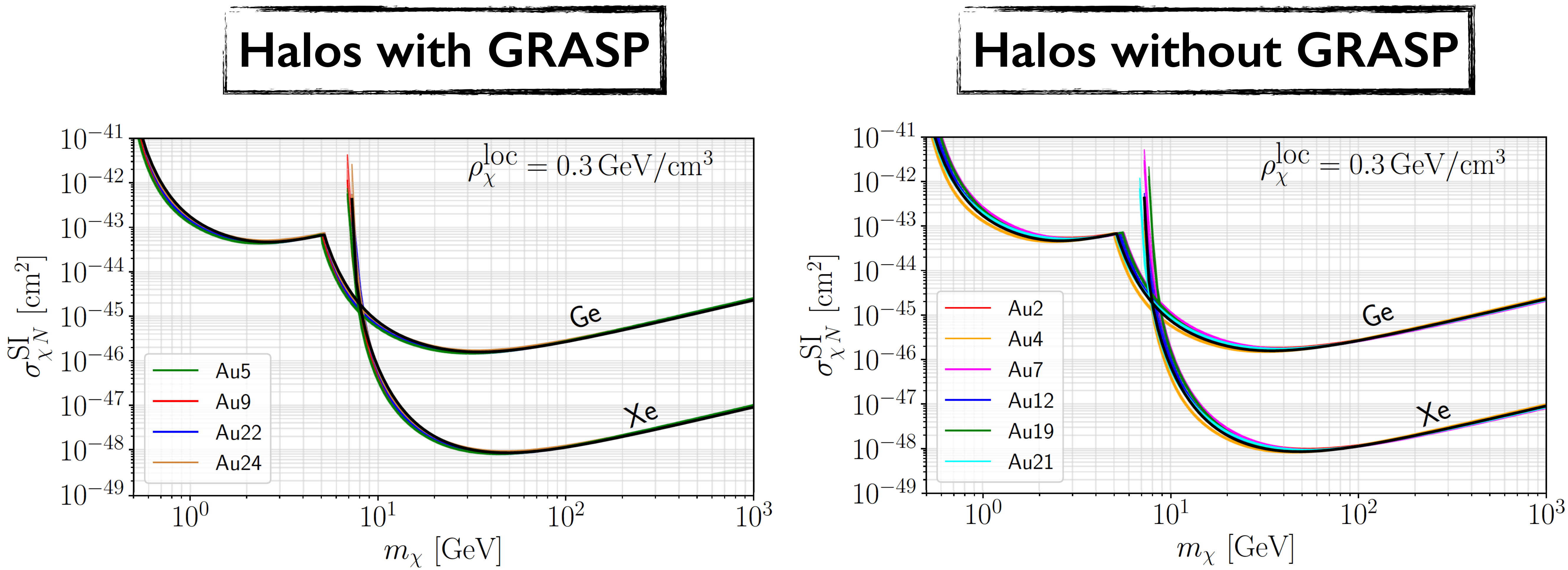
Direct detection exclusion limits

Halos without GRASP





Direct detection exclusion limits



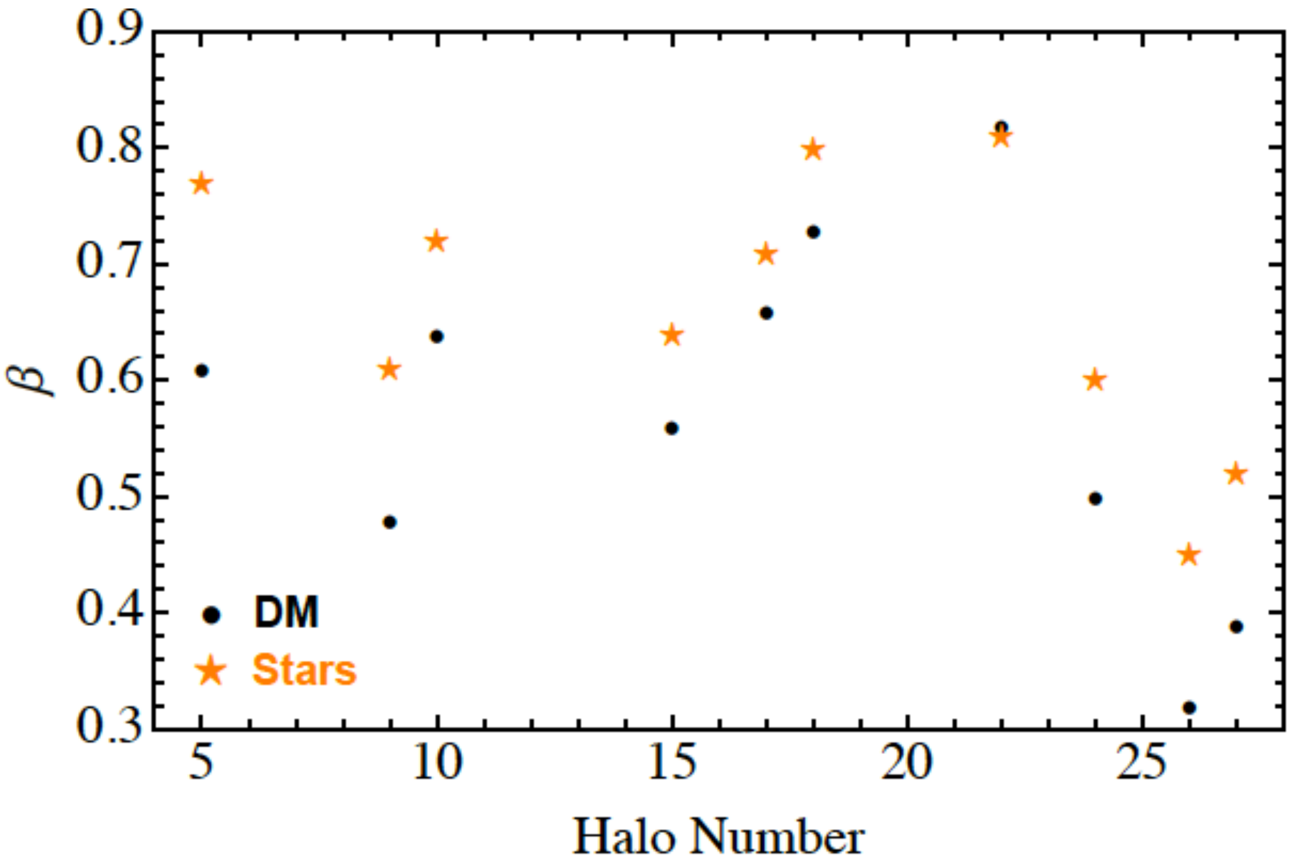
- Larger halo-to-halo variation for halos without the GRASP, since they are more numerous.
- Mild shift of the exclusion limits for halos with the GRASP towards smaller DM masses compared to the SHM.

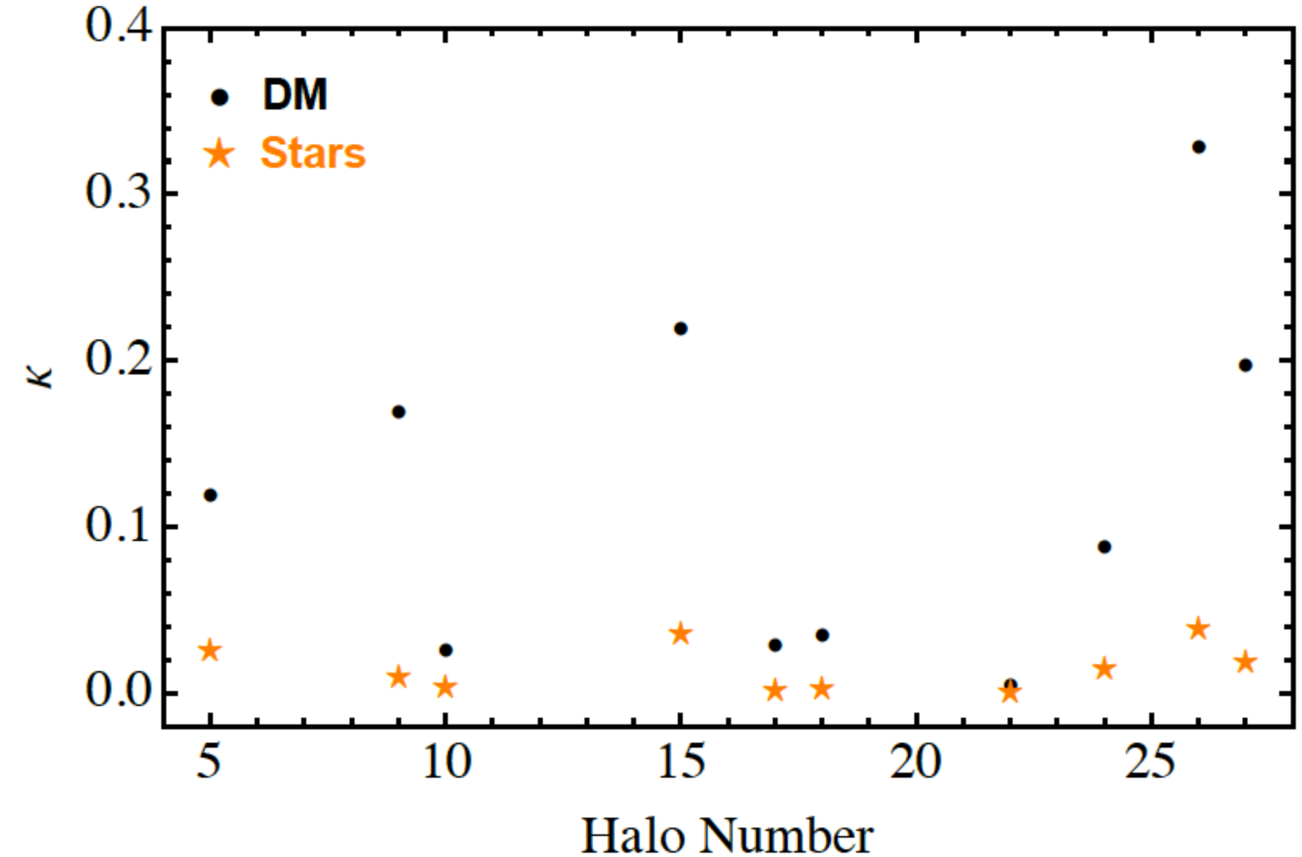
Summary

- Investigated the implications of the DM component of the **Gaia Radially Anisotropic Stellar Population (GRASP)** in Auriga Milky Way-like halos.
- Fraction of DM particles belonging to the GRASP in the Solar circle is **[0.6% - 17%]**, and the anisotropy is $\beta = [0.48 - 0.82]$.
- The local DM speed distributions of the halos with GRASP are shifted to ***higher speeds*** compared to SHM.
- Best fit ***generalized Maxwellian distribution*** works well for halos with the GRASP.
- For light DM, the exclusion limits for halos with the GRASP are mildly shifted towards smaller DM masses compared to the SHM.

Backup Slides

DM and stars in GRASP



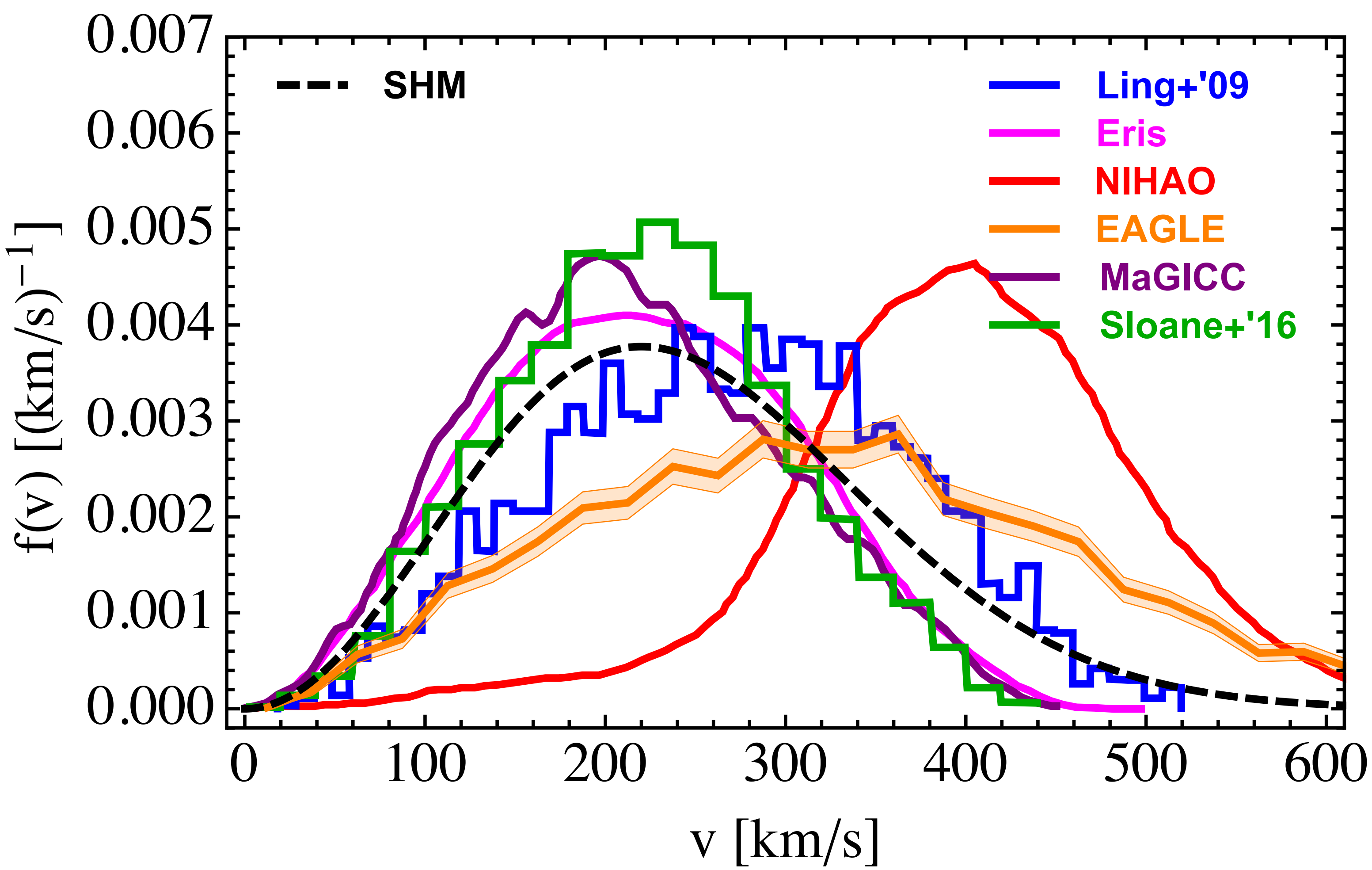


Best fit peak speeds

	Maxwellian		Generalized Maxwellian		
Halo Name	v_0 [km/s]	χ^2_{red}	v_0 [km/s]	α	χ^2_{red}
Au2	225.39	11.63	248.18	1.12	8.45
Au4	232.45	30.38	292.58	1.36	13.49
Au5 ($\star$)	221.51	65.19	296.44	1.42	37.00
Au7	207.06	27.19	250.16	1.26	15.19
Au9 ($\star$)	230.96	34.96	292.05	1.37	18.37
Au12	220.31	30.24	281.28	1.41	7.98
Au19	206.67	23.94	235.27	1.17	18.16
Au21	228.24	16.73	267.79	1.22	7.86
Au22 ($\star$)	215.00	83.17	319.39	1.77	19.61
Au24 ($\star$)	227.43	31.29	280.07	1.32	10.24
Au30	197.81	5.09	204.01	1.04	5.18

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.

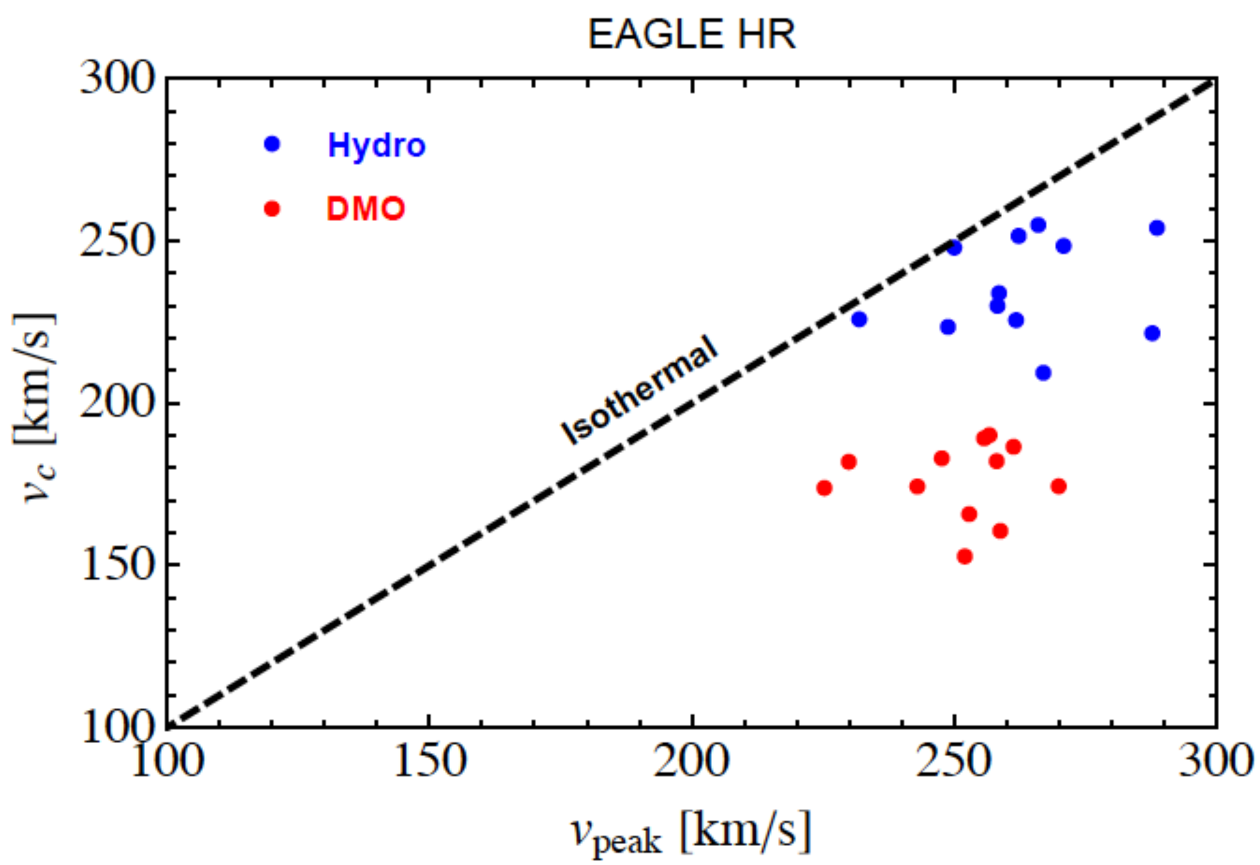
Hydrodynamical simulations

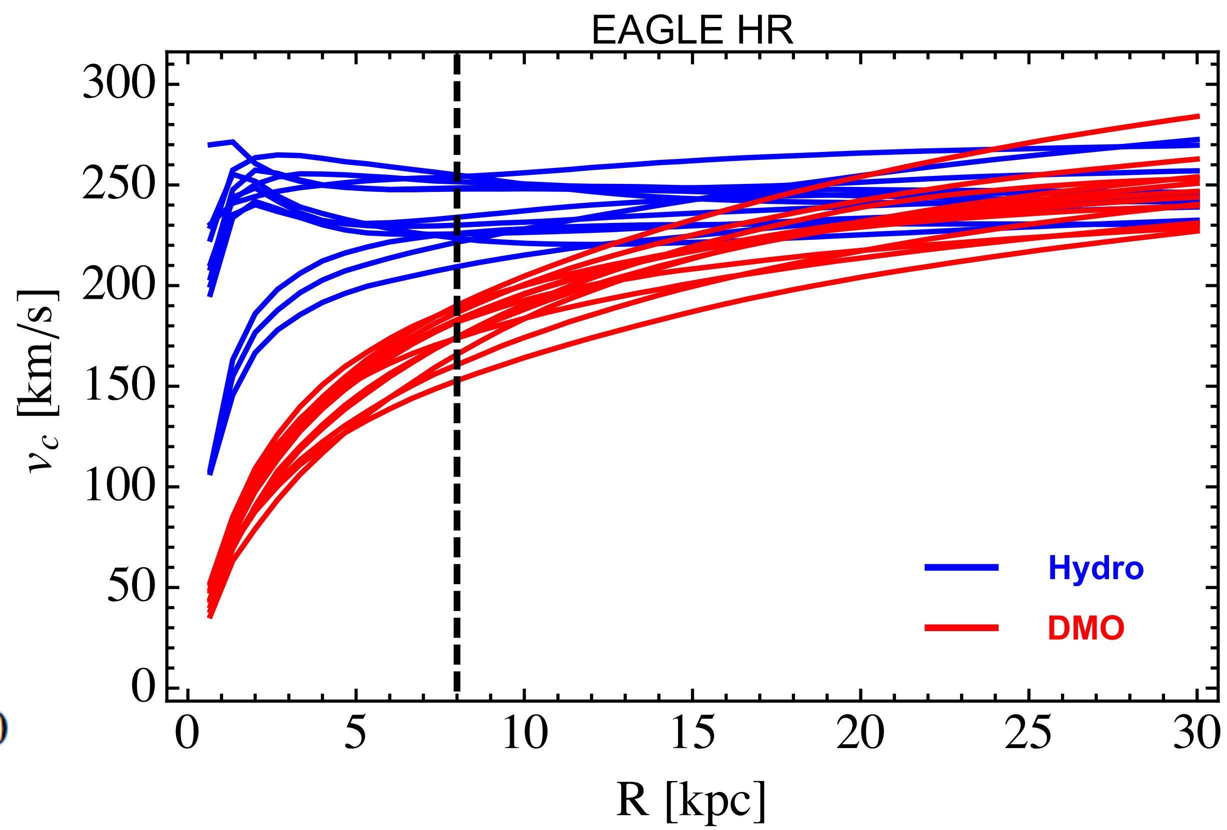
- We use the **EAGLE** and **APOSTLE** hydrodynamic simulations.

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**.
- *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.

Departure from isothermal

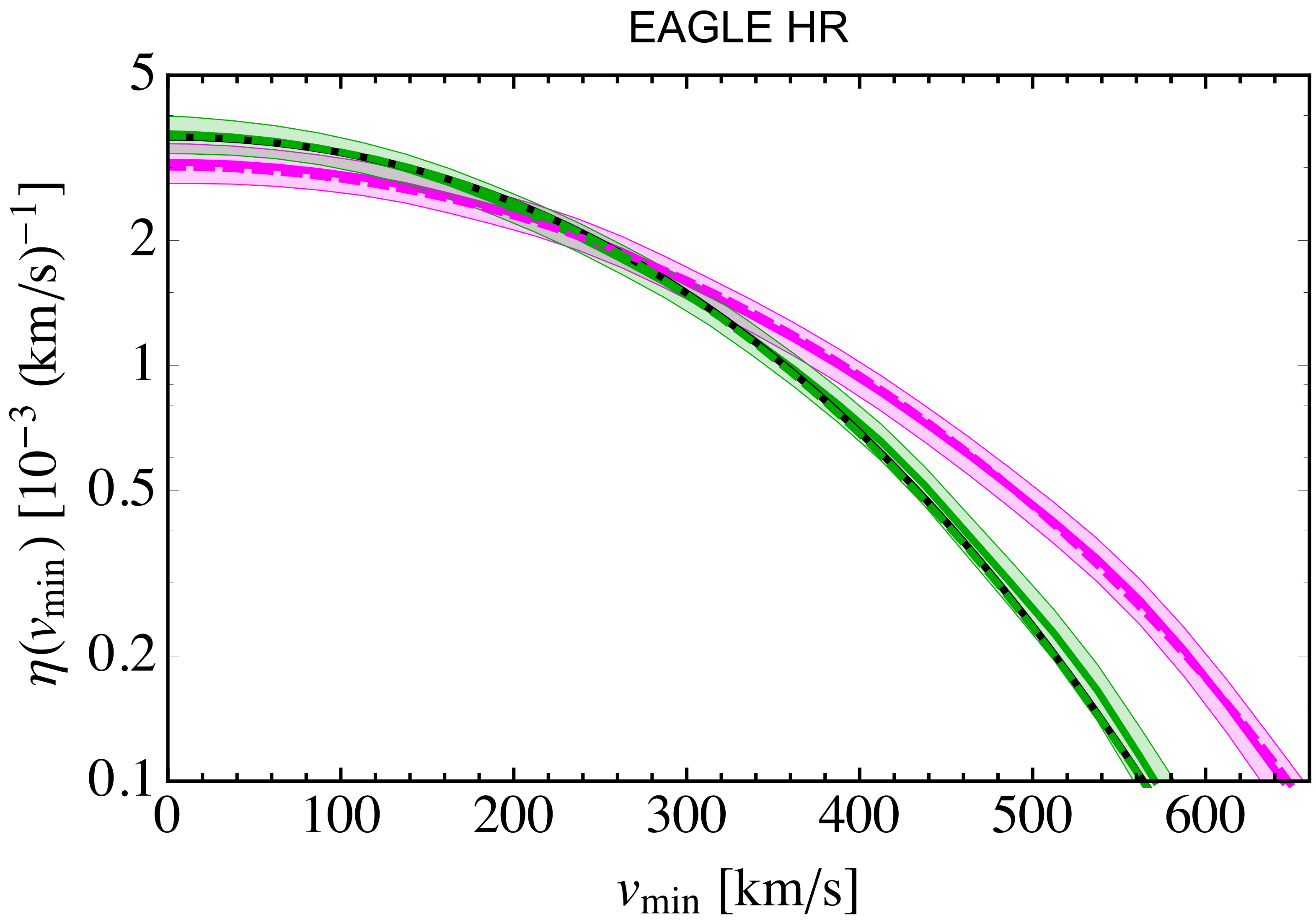




Bozorgnia & Bertone, 1705.05853

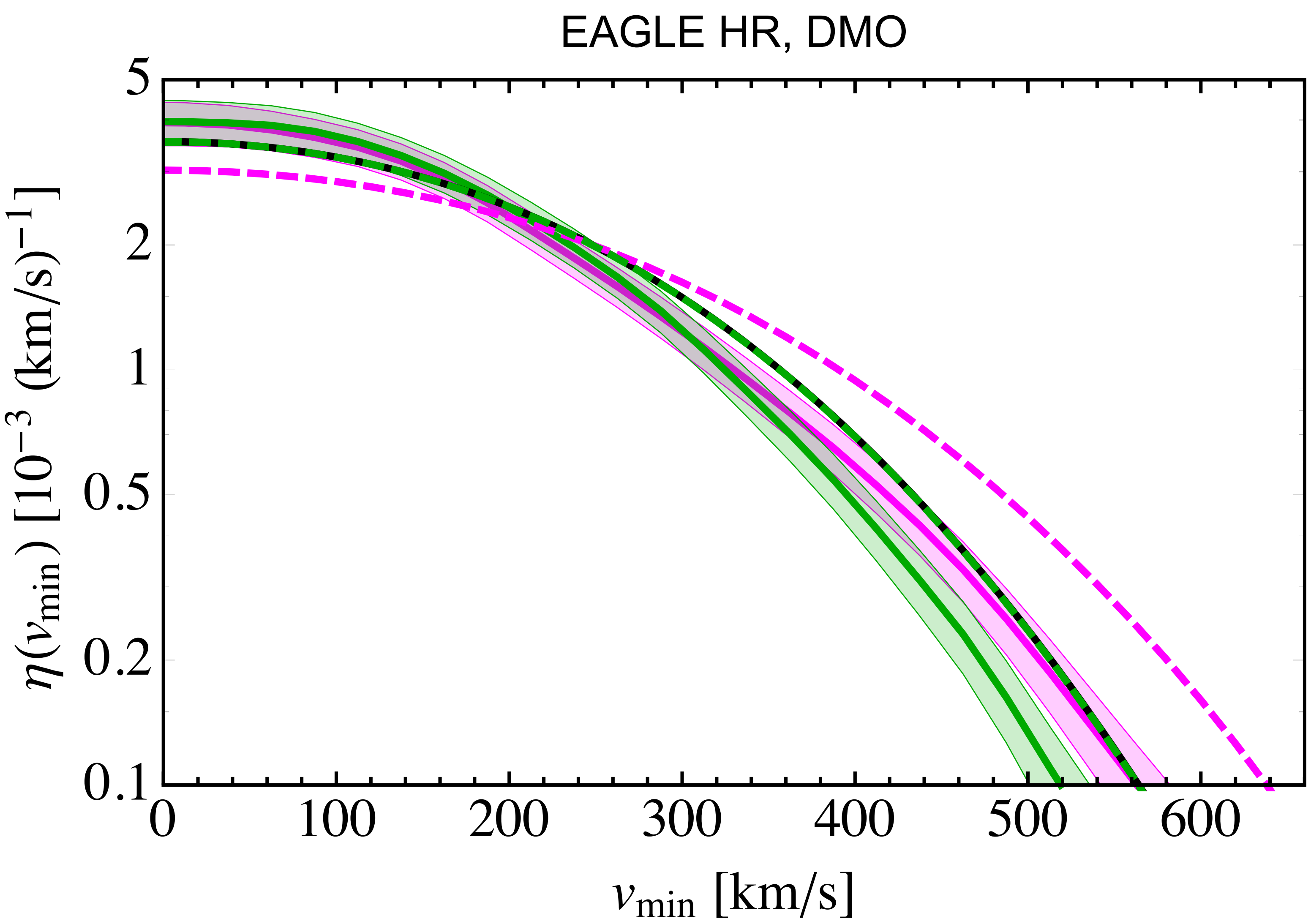
- At the Solar circle, halos in the hydrodynamical simulation are closer to isothermal than their DMO counterparts.

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

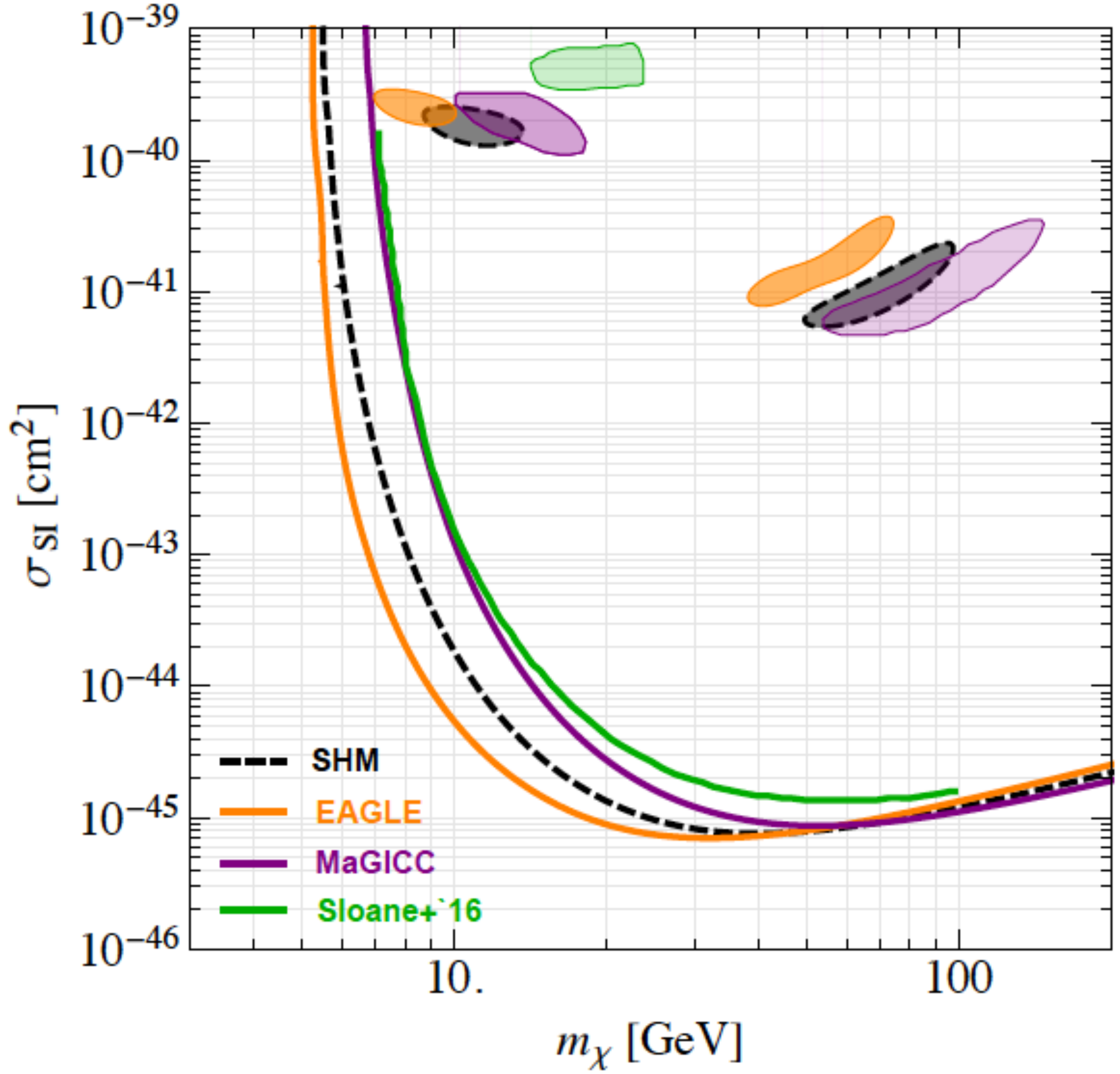


- Baryons affect the velocity distribution strongly at the Solar position, resulting in a shift of the tails of the halo integrals to higher velocities with respect to DMO.

Implications for direct detection

Comparison to other hydrodynamical simulations:

Fix local ρ_χ=0.3 GeV cm^{-3}



Bozorgnia & Bertone, 1705.05853

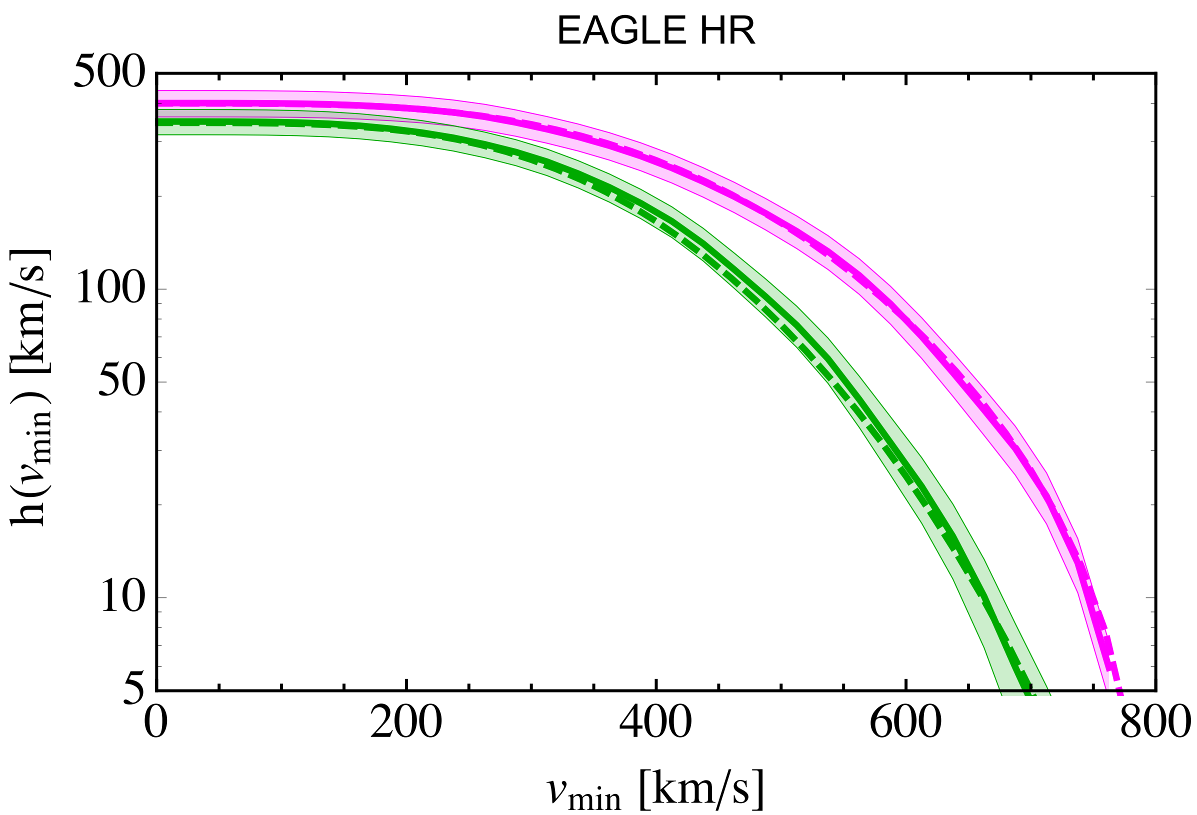
Non-standard interactions

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

Kahlhoefer & Wild, 1607.04418

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

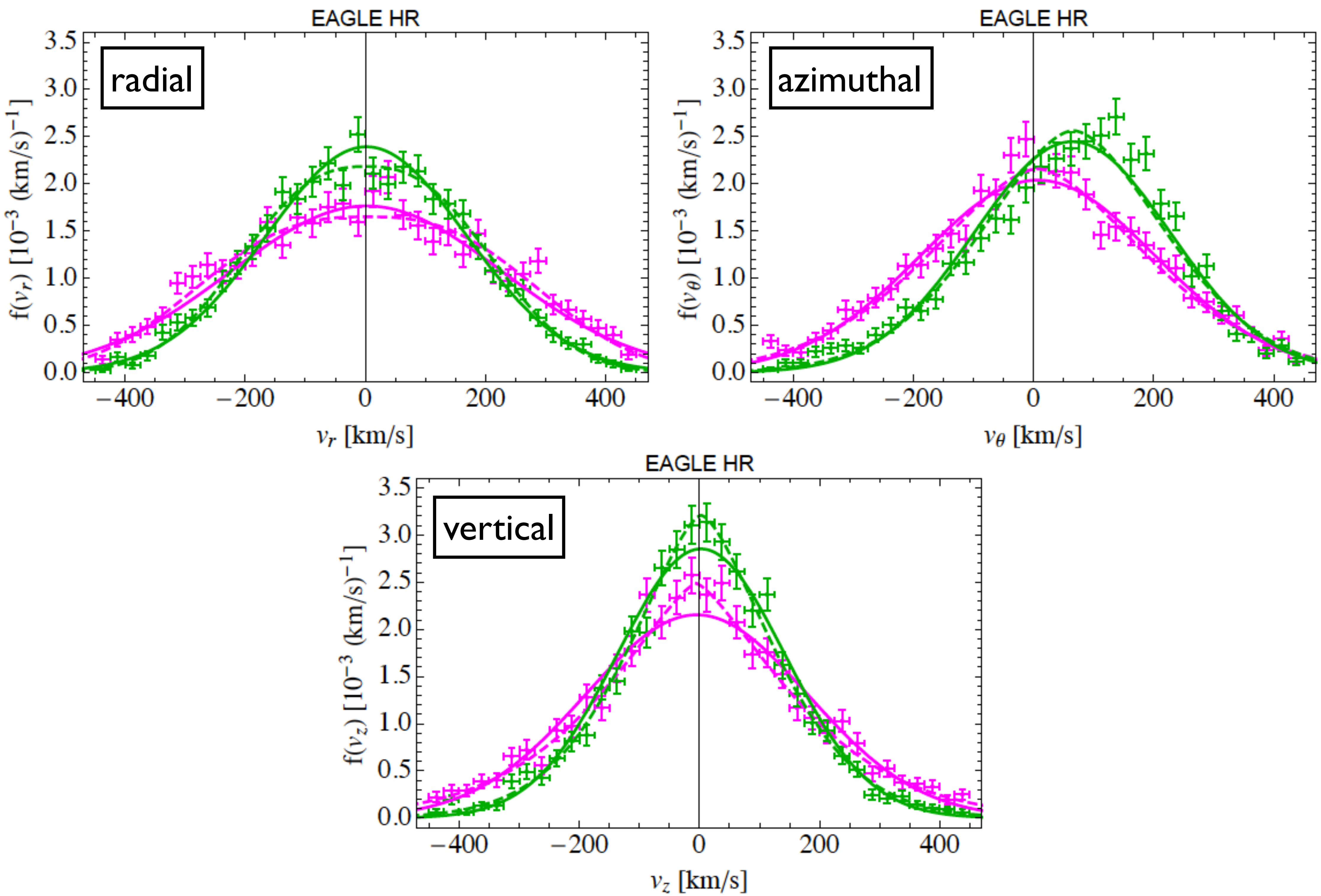
$$\eta(v_{\rm min}, t) \qquad\qquad h(v_{\rm min}, t) = \int_{v>v_{\rm min}} d^3v \; v \; f_{\rm det}(\mathbf{v}, t)$$



Bozorgnia & Bertone, 1705.05853

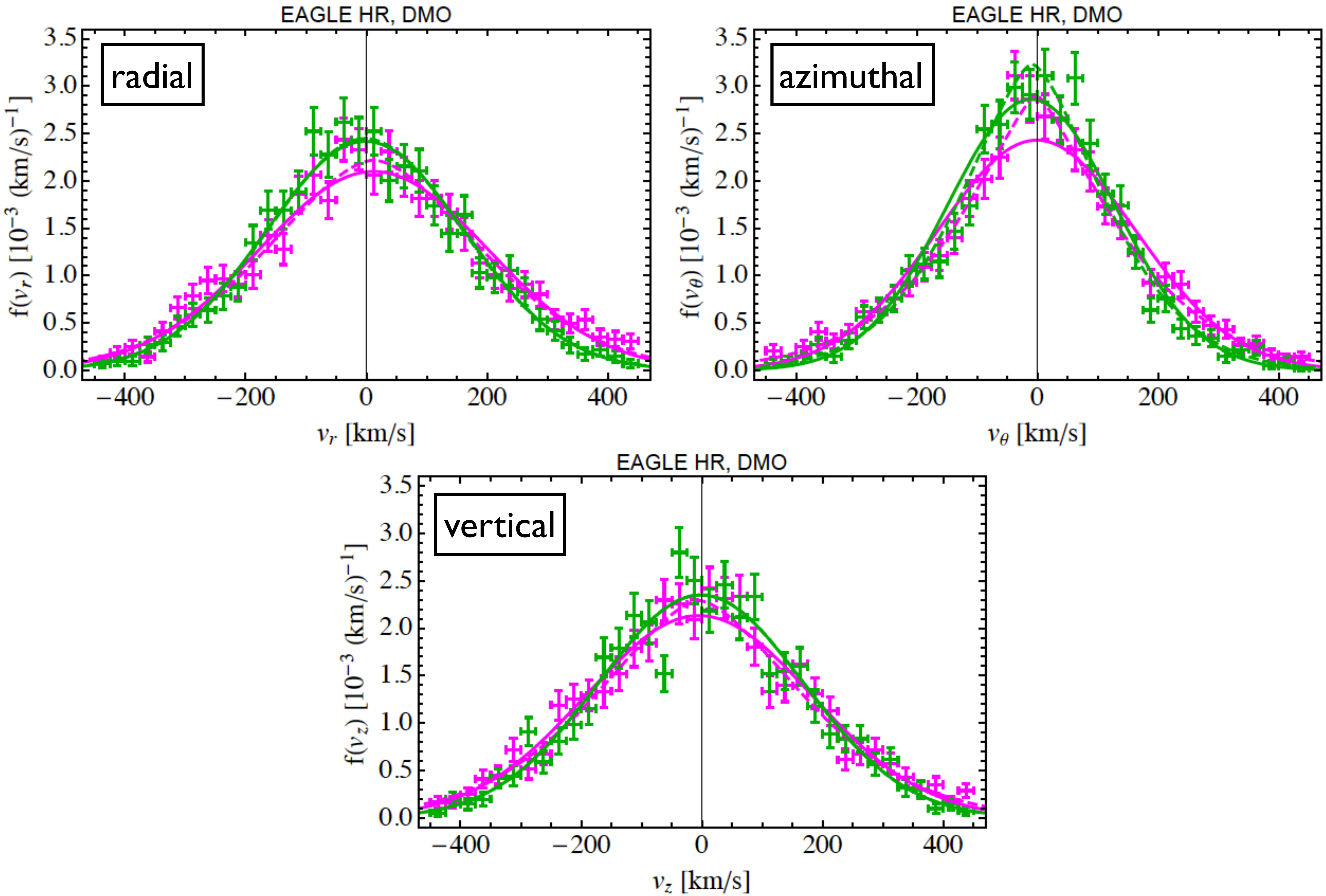
- Best fit Maxwellian $h(v_{\rm min})$ falls within the 1σ uncertainty band of the $h(v_{\rm min})$ of the simulated haloes.

Components of the velocity distribution



Bozorgnia et al., 1601.04707

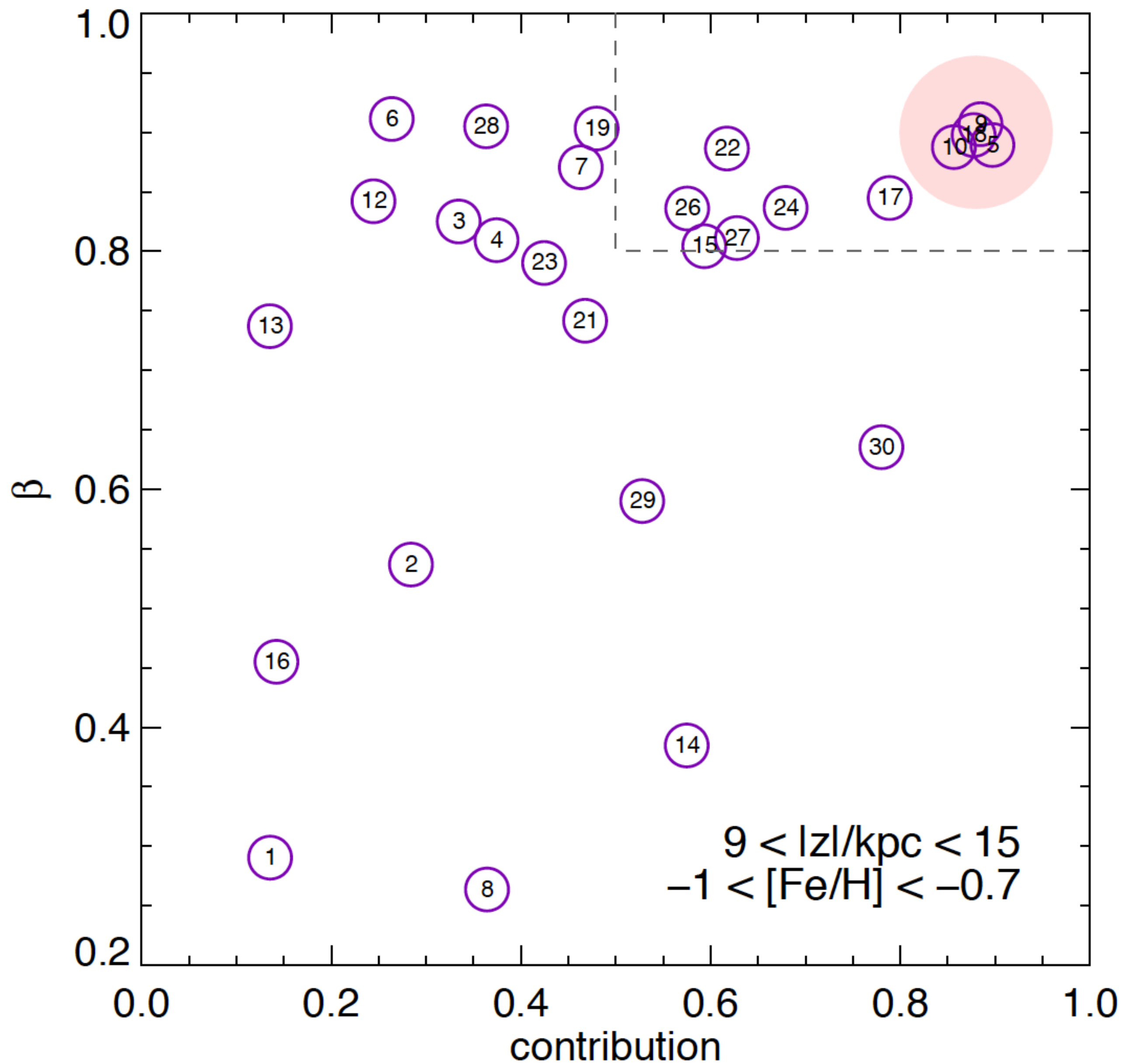
Comparison with DMO



Bozorgnia et al., 1601.04707

Halos with GRASP in Auriga

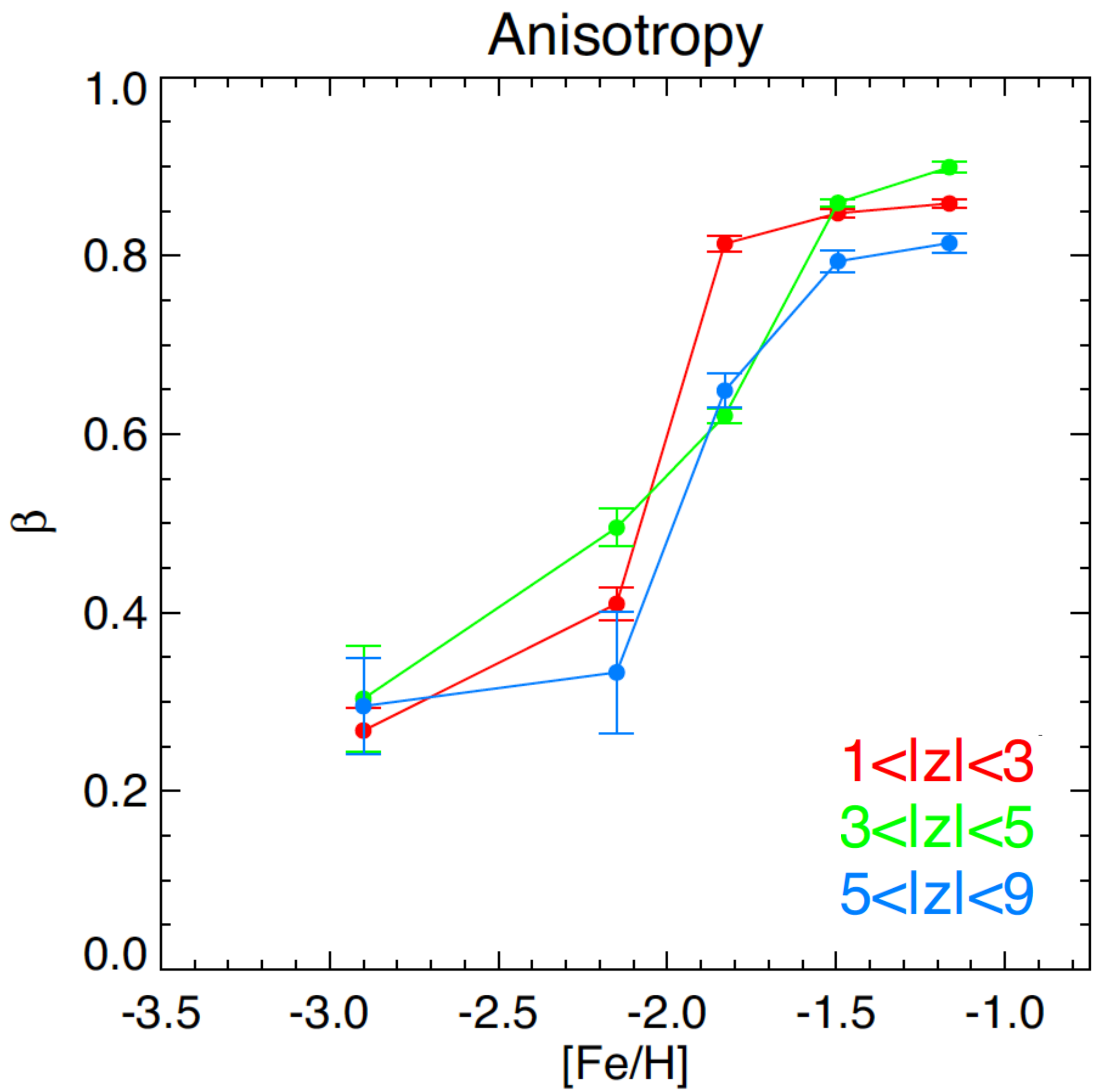
- 10 halos in Auriga show a GRASP ($\beta_{\rm stars} > 0.8$, contribution to the stellar halos $> 50\,\%$).



Fattahi et al., 1810.07779

Local stellar halo

SDSS-Gaia
(1-10 kpc from Sun)



Belokurov et al., 1802.03414