Empirical Determination of the Dark Matter Velocity Distribution

Lina Necib, Caltech

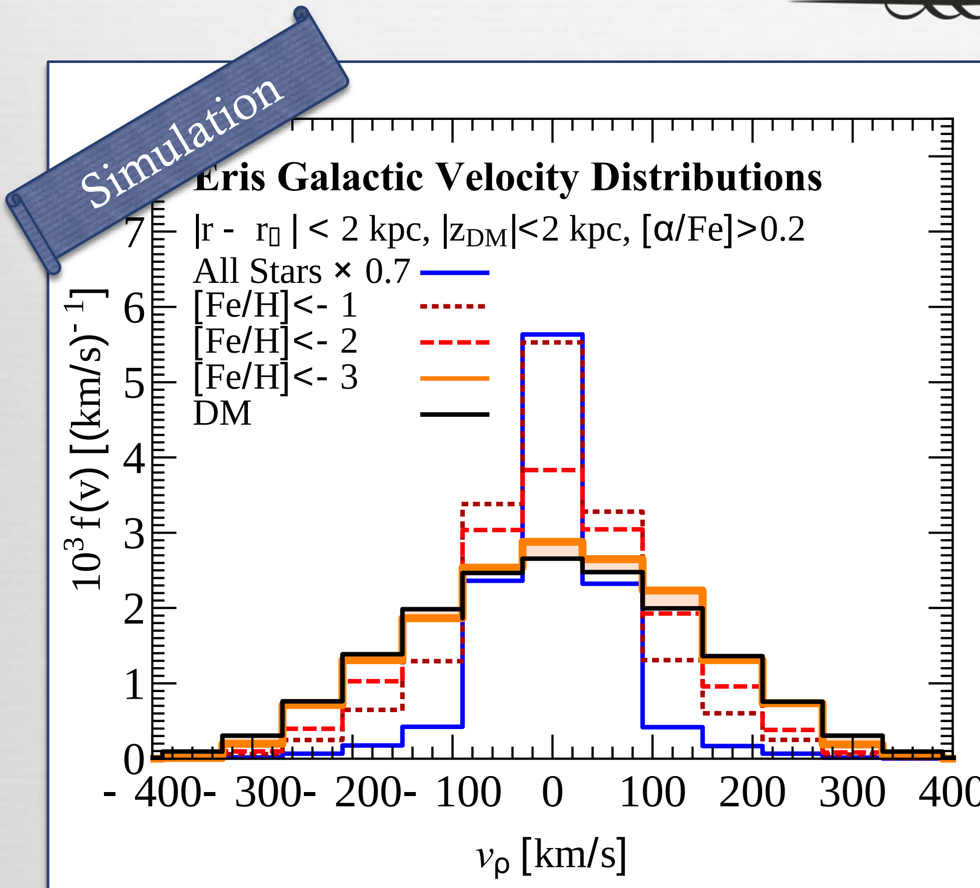
Based on

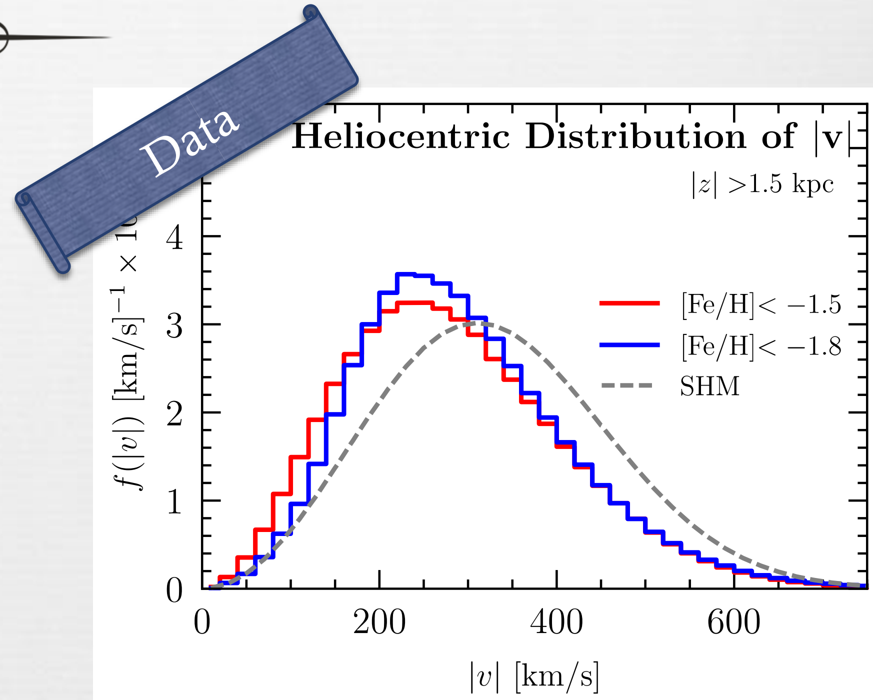
Herzog-Arbeitman, Lisanti, Madau, Necib PRL 120(2018) no.4, 041102

Herzog-Arbeitman, Lisanti, Necib, arXiv:1708.03635

Necib, Lisanti, Garisson-Kimmel, Sanderson, Fitts, Boylan-Kolchin, Wetzel, Hopkins, arXiv:180X.XXXXX

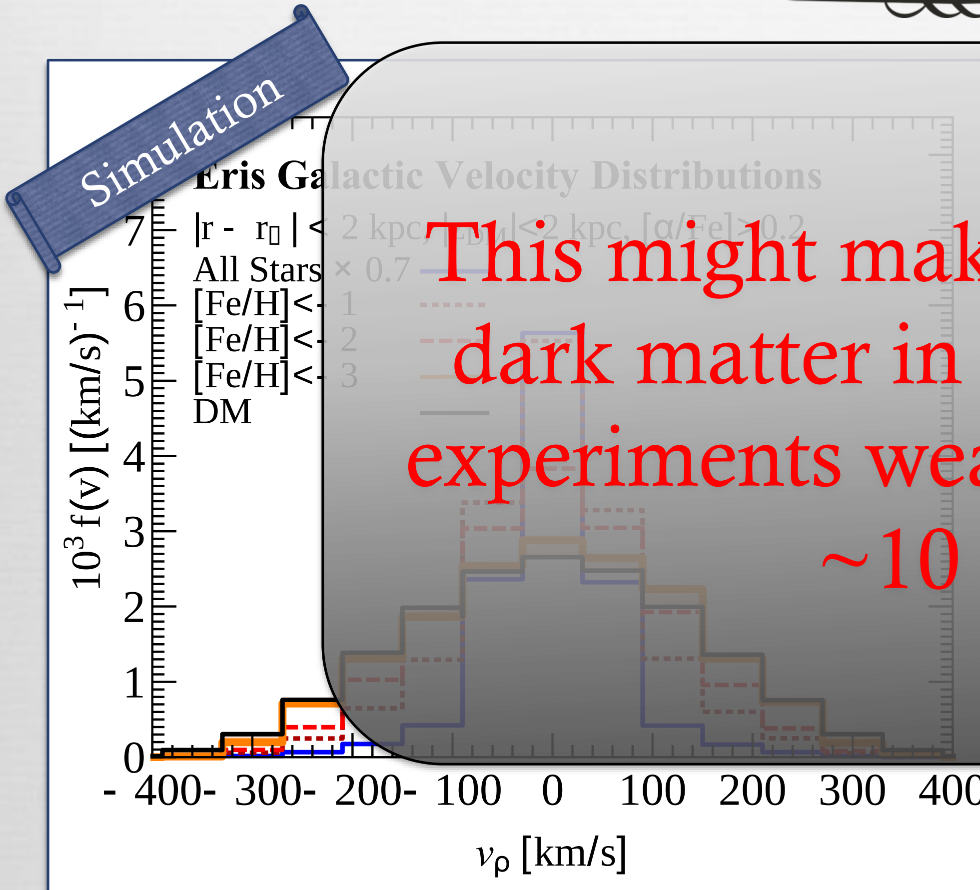
Empirically Determined Velocity Distribution of Dark Matter



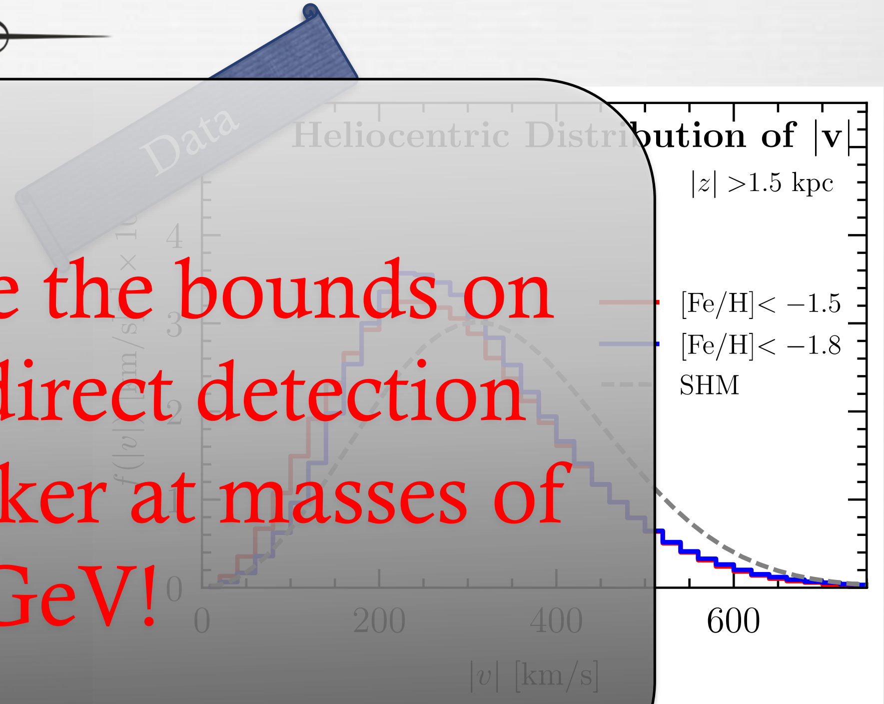


Herzog-Arbeitman, Lisanti, Madau, **Necib** PRL 120(2018) no.4, 041102
Herzog-Arbeitman, Lisanti, **Necib**, arXiv:1708.03635

Empirically Determined Velocity Distribution of Dark Matter



This might make the bounds on dark matter in direct detection experiments weaker at masses of ~10 GeV!



Herzog-Arbeitman, Lisanti, Madau, **Necib** PRL 120(2018) no.4, 041102

Herzog-Arbeitman, Lisanti, **Necib**, arXiv:1708.03635

From Simulations:

Metal-Poor Stars trace the velocity of Dark Matter.

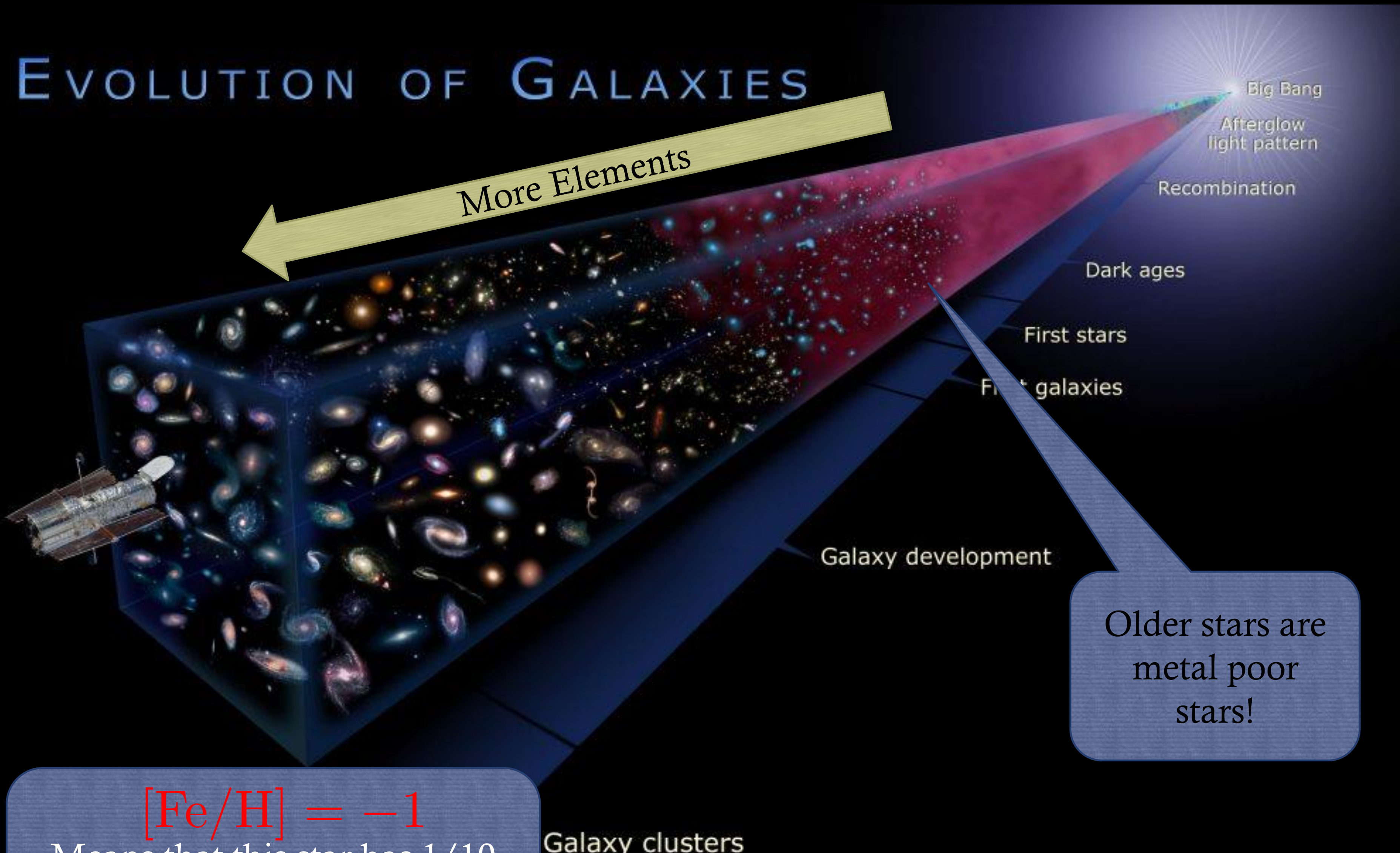
From Gaia DR1:

We get the local velocity distribution of Metal-Poor Stars.

Therefore:

We empirically obtain the Dark Matter velocity distribution.

Focus of today's talk is to understand this correlation by looking at more simulations!



More Elements

Older stars are metal poor stars!

$$[\mathrm{Fe/H}] = -1$$

Means that this star has 1/10 of the iron fraction of the Sun.

Video by Shea Garisson-Kimmel,
http://www.tapir.caltech.edu/~sheagk/firemovies.html

FIRE: Feedback In Realistic Environments

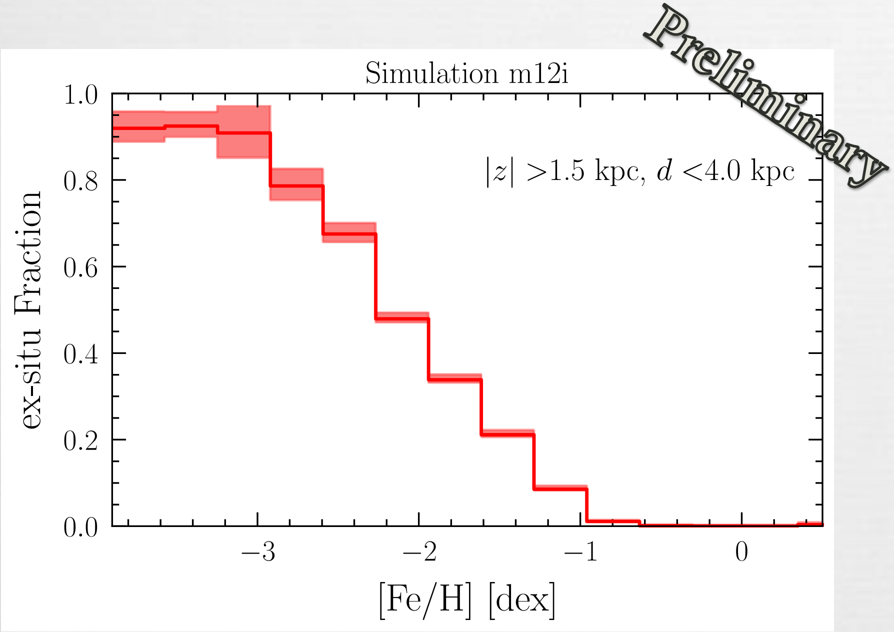
A suite of high resolution simulations, with different merger histories, and particle physics dynamics.

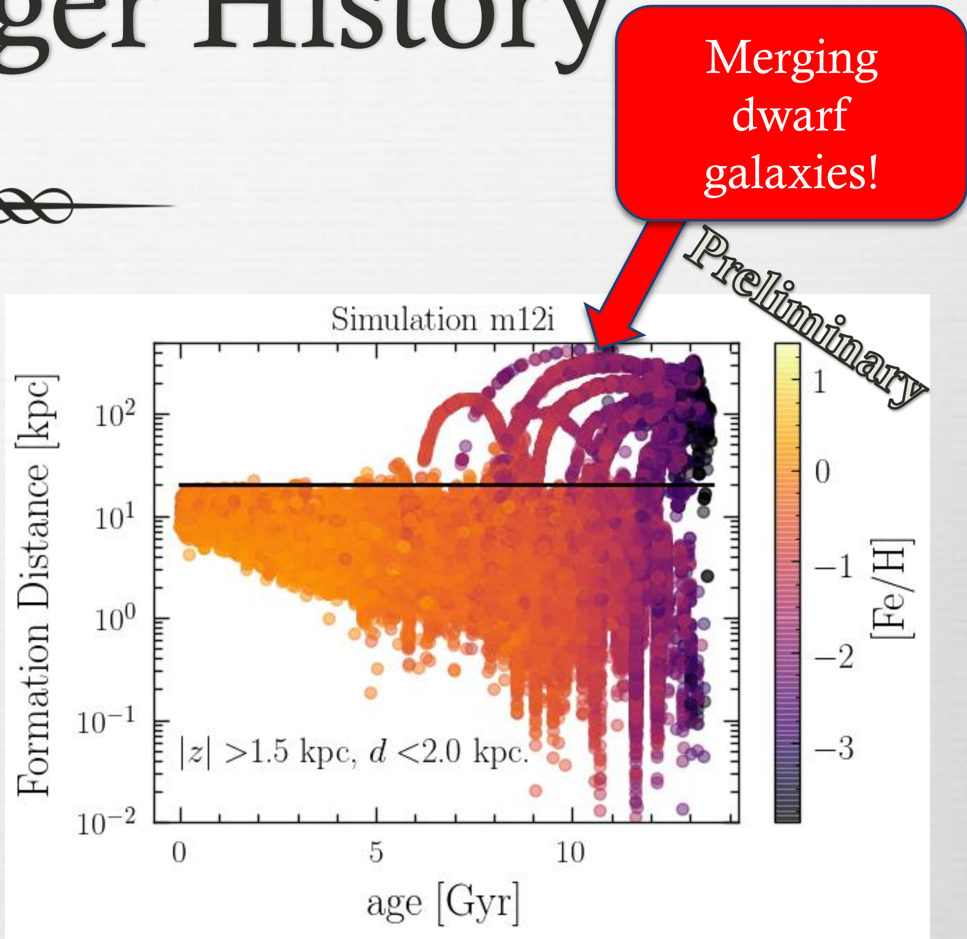
Focus on Milky Way like simulations:

- Total mass: (1.2-1.6) 10^{12} Msun.
- Particle mass: 7000 Msun.
- Dark Matter softening length: 30pc.

Hopkins et al. (2014) MNRAS 445,581
Wetzel et al. (2016) ApJL, 827, L23
Hopkins et al. (2017) arXiv:1702.06148

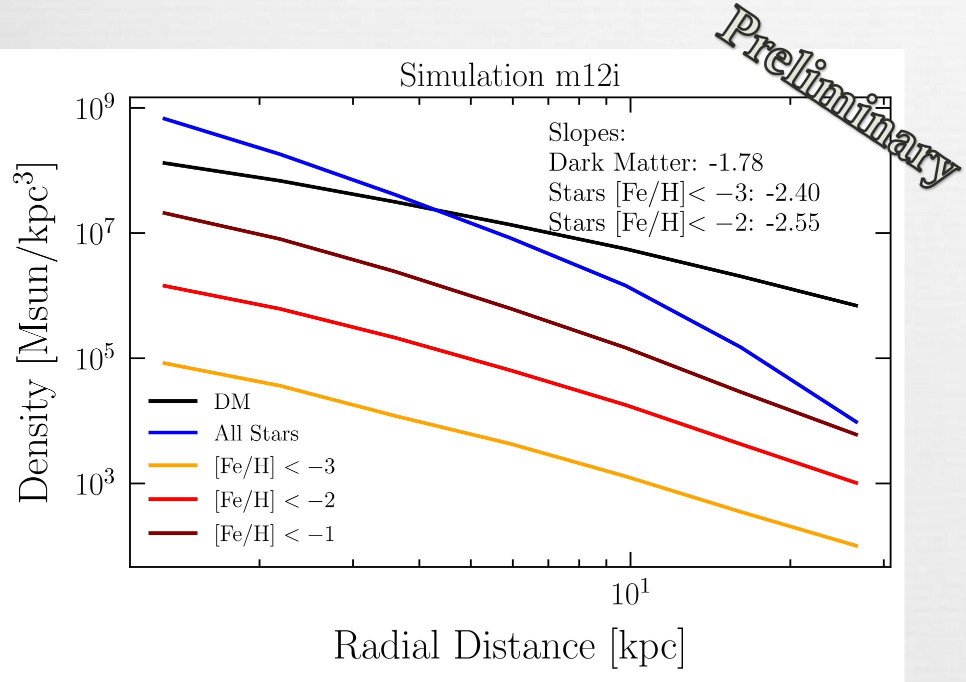
Quiet Merger History

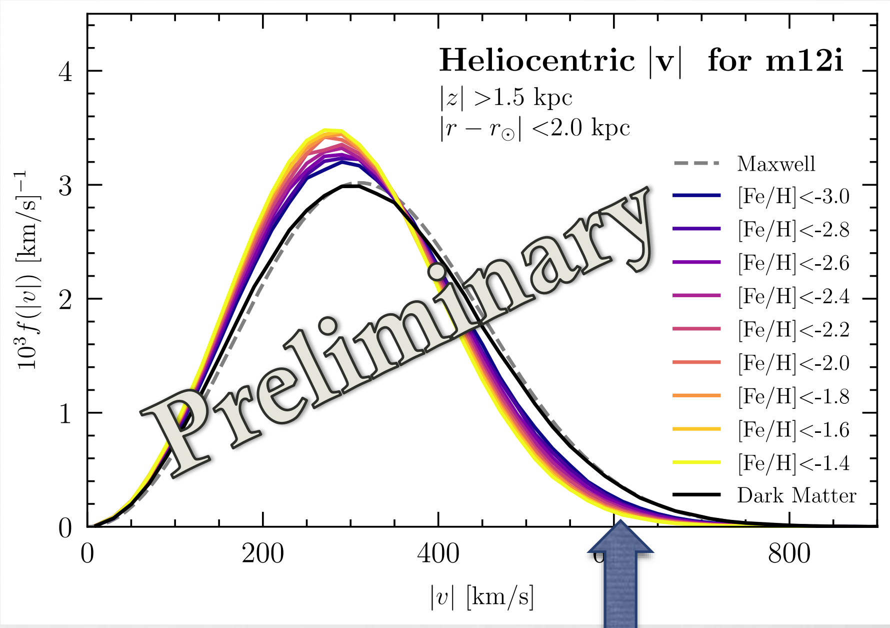




When we cut at low [Fe/H], we are primarily selecting stars that are born in dwarf galaxies.

Quiet Merger History





Increased convergence with harder cuts at [Fe/H].

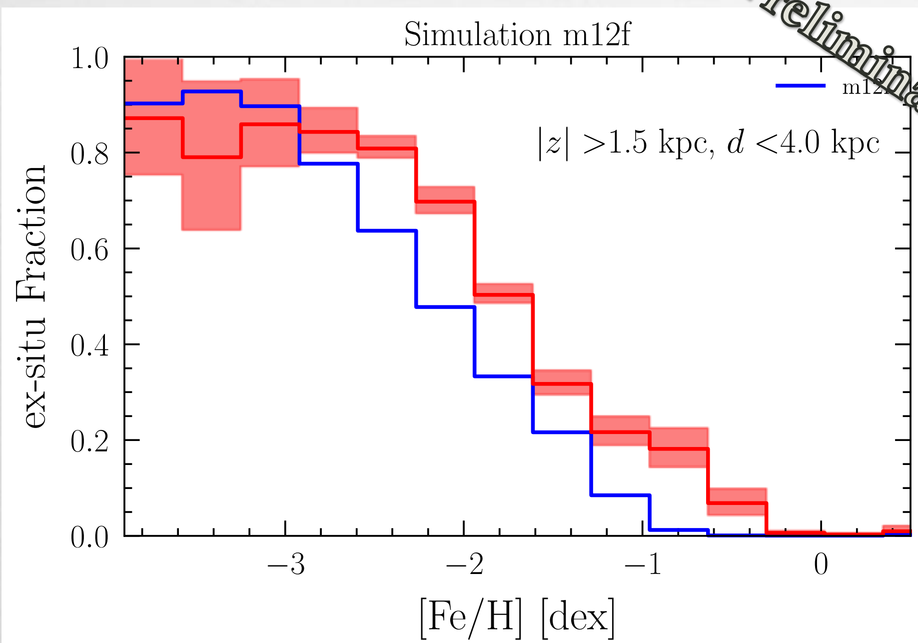
Currently working on understanding the discrepancy at the tail.

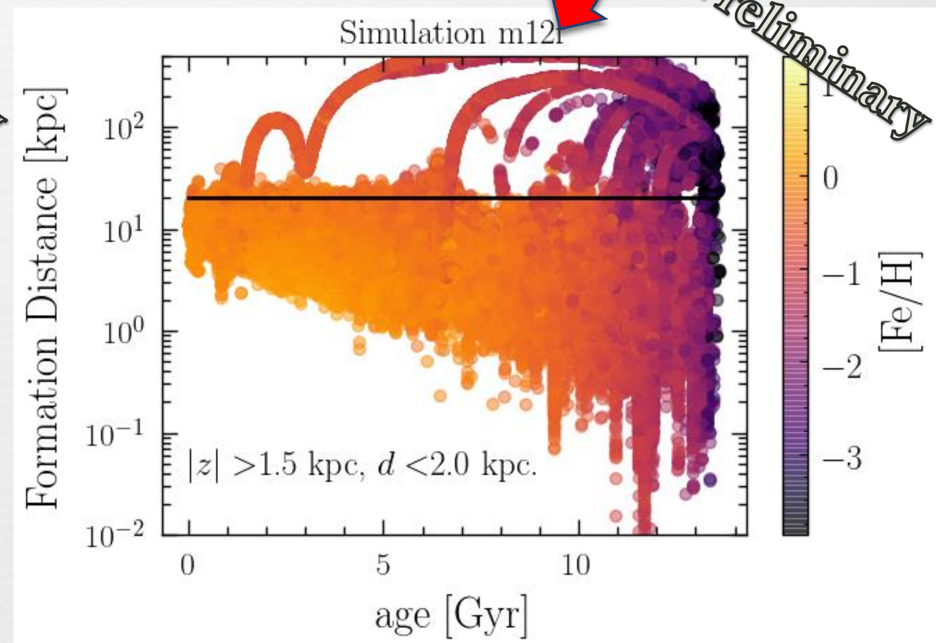
More Active Merger History?

Video by Shea Garisson-Kimmel,
http://www.tapir.caltech.edu/~sheagk/firemovies.html

Active Merger History

Merging dwarf galaxies!

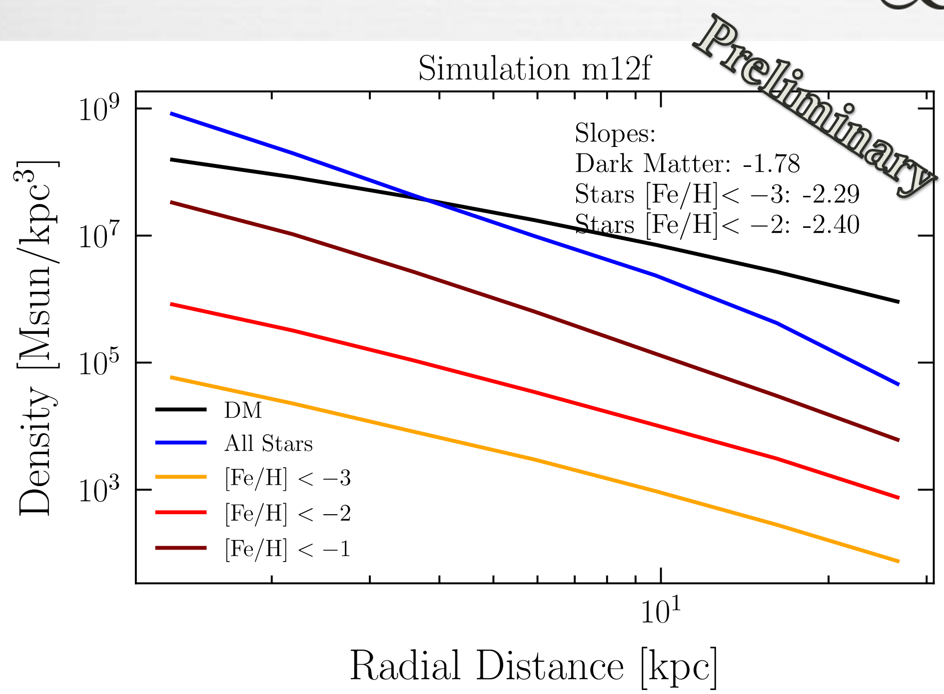


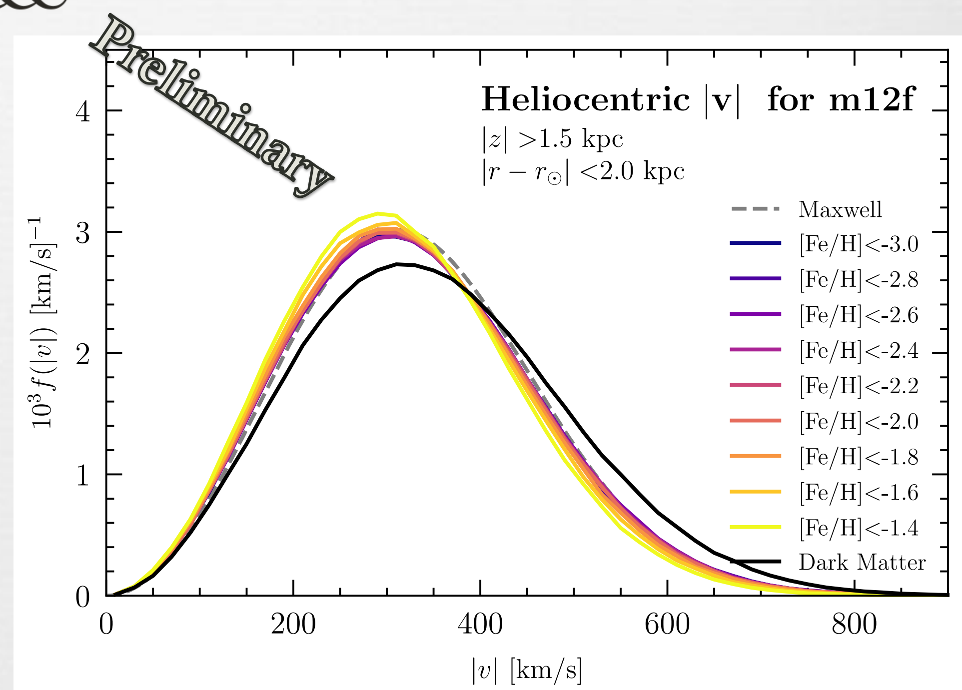


We can still get a high ex-situ fraction with a higher [Fe/H] cut than the previous simulation.

The late merger brought in a younger population of stars!

Active Merger History





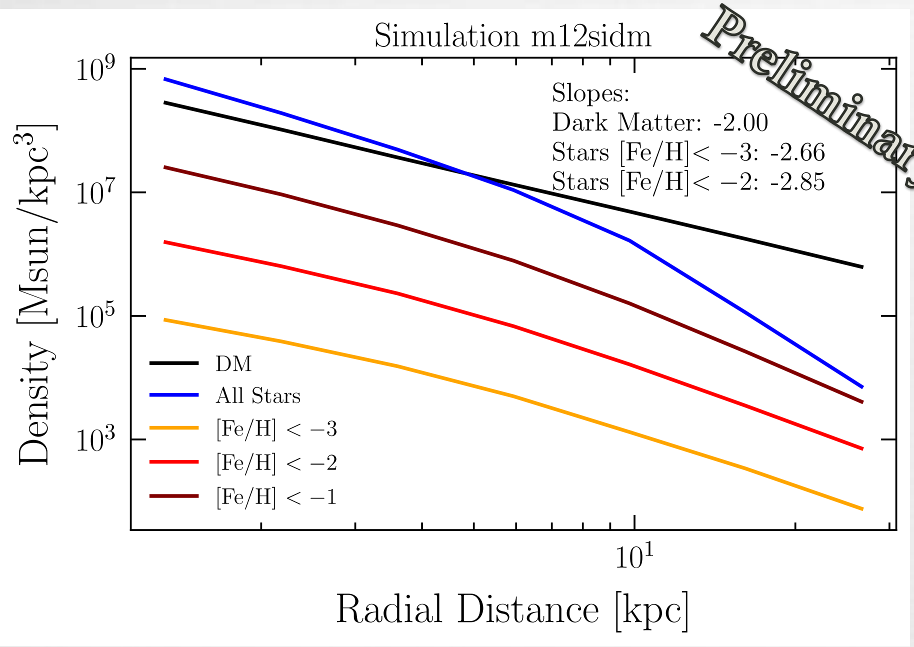
Not seeing an increased convergence at lower metallicities.
Merger brought in younger stars.

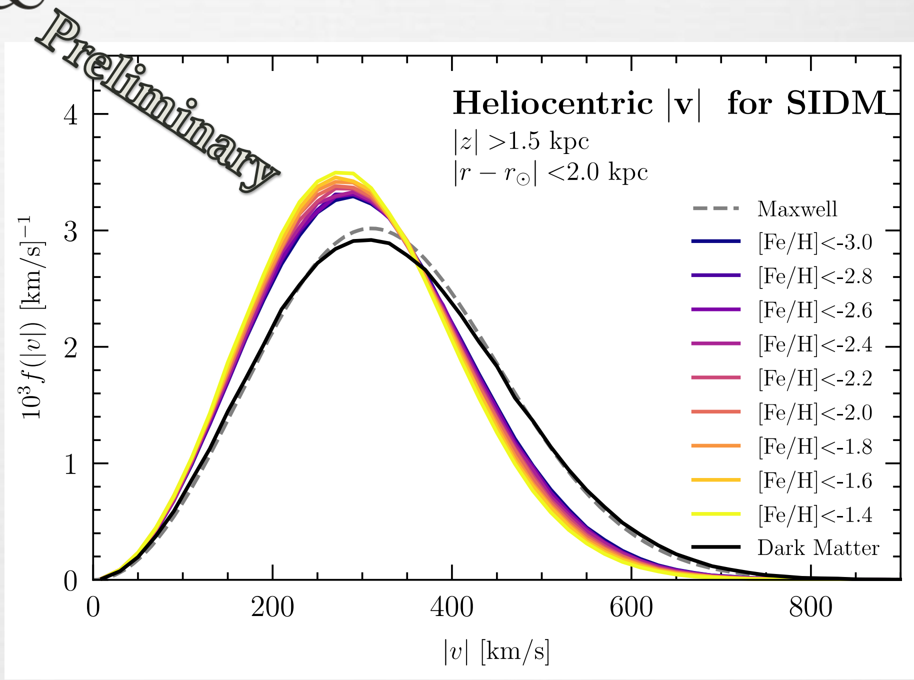
Self-Interacting Dark Matter

$$\sigma = 1\ \mathrm{cm}^2/\mathrm{g}$$

Rocha et al. (2013) MNRAS 430, 81
Robles et al. (2017) MNRAS 472, 2945

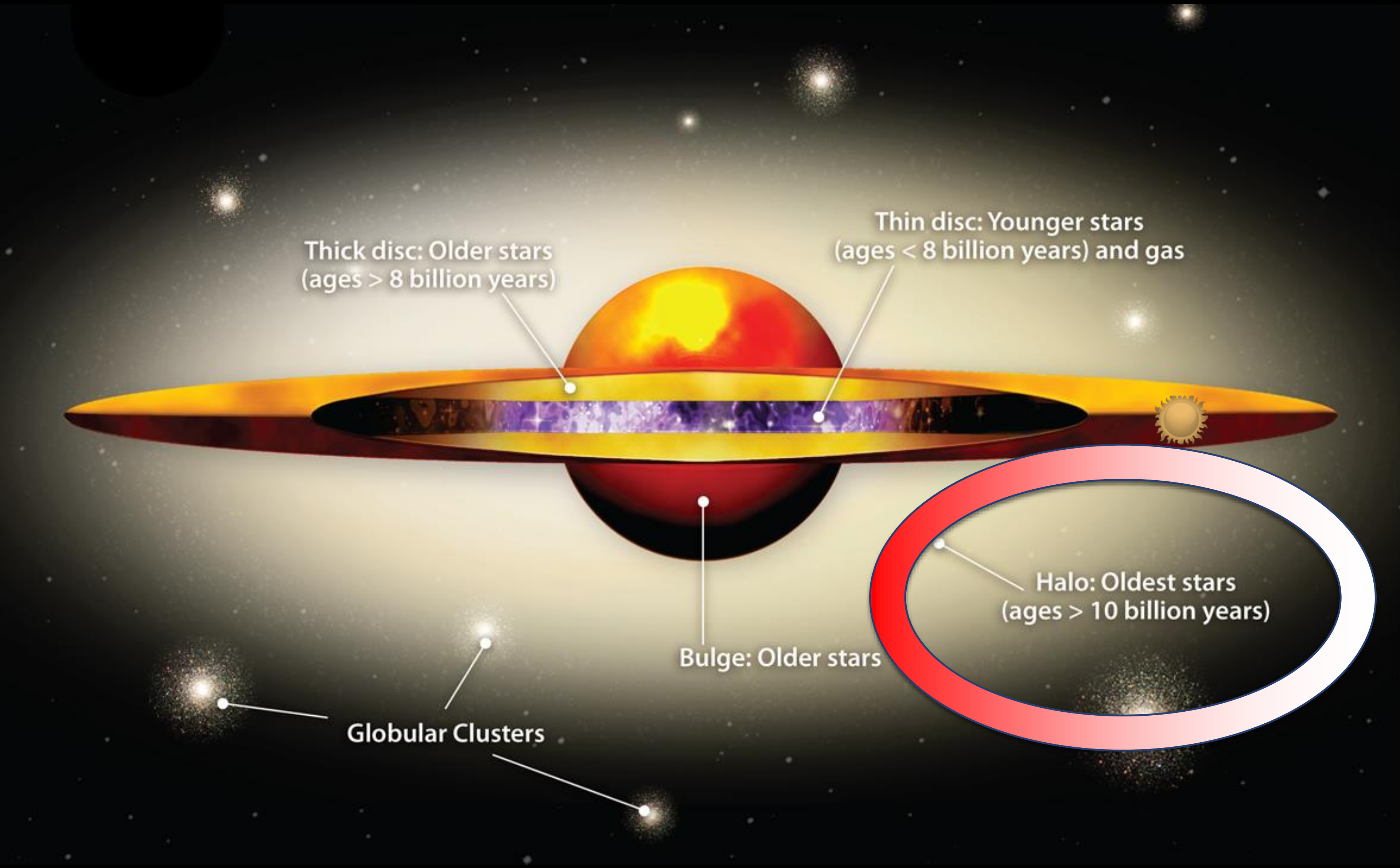
Self-Interacting Dark Matter

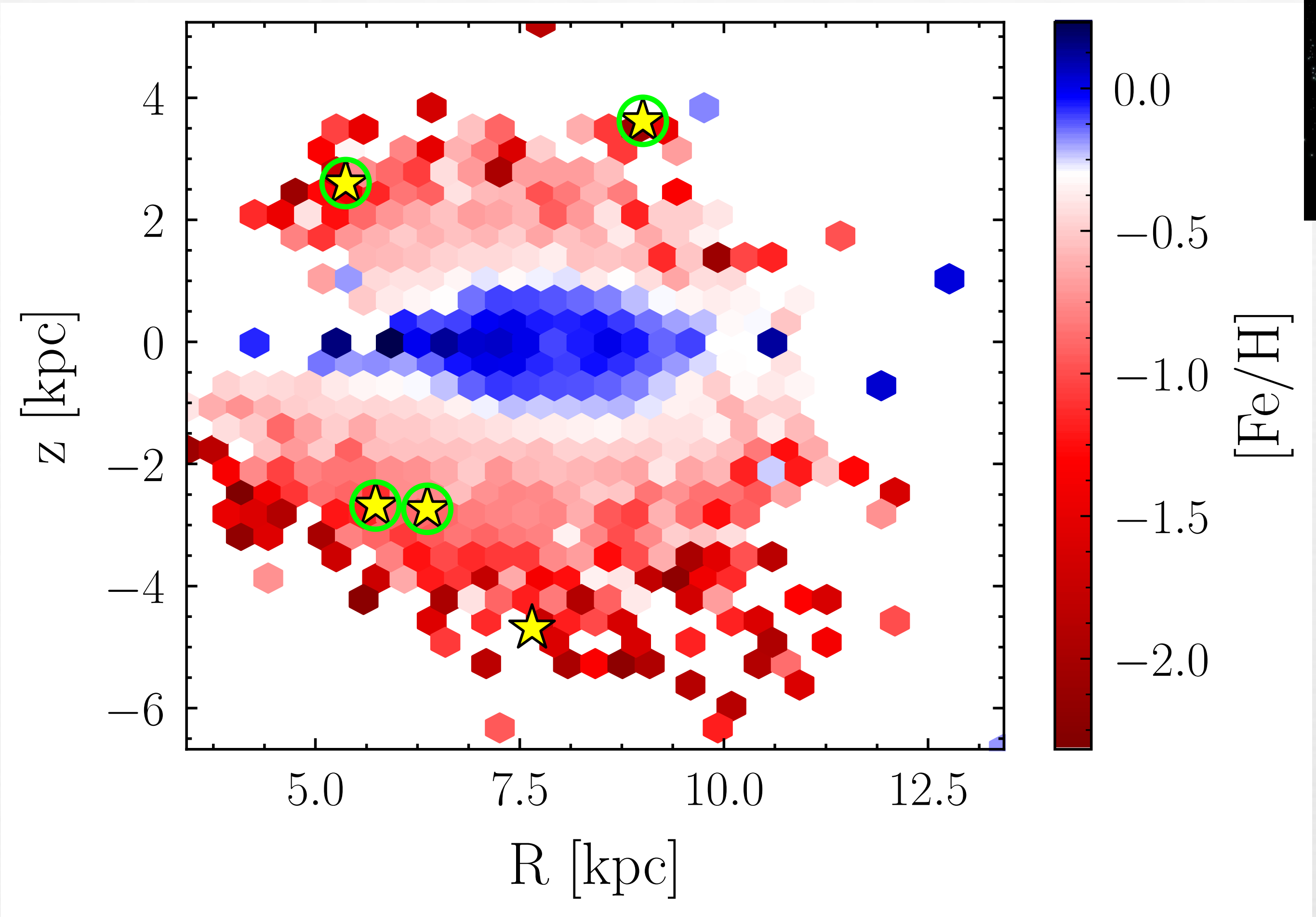




Dark Matter and Stars do not behave similarly in this case: Dark Matter is not collisionless anymore.
Working on identifying a new observable for the self-interacting Dark Matter case.

Where do we find these Metal Poor Stars?


Thin disc: Younger stars
(ages < 8 billion years) and gas
Thick disc: Older stars
(ages > 8 billion years)
Halo: Oldest stars
(ages > 10 billion years)
Bulge: Older stars
Globular Clusters



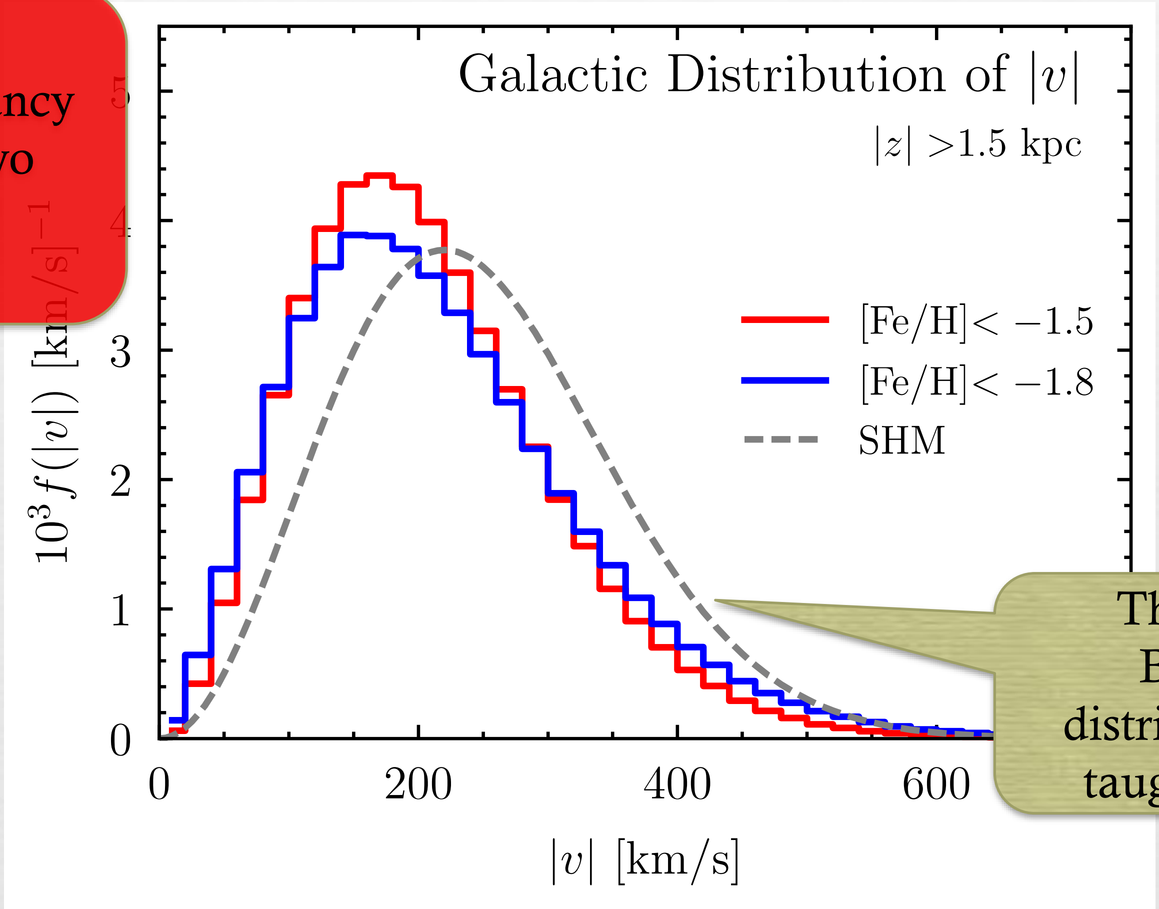
Gaia DR1: Lindergren et al. (2016)
RAVE heliocentric velocities: Kunder et al. (2017)
TGAS (Tycho-Gaia) proper motions: Michalik et al.(2015)
RAVE-on chemical properties: Casey et al. (2016)
Distances: McMillan et al. (2017)

Local Velocity Distribution

Drum Roll

Posterior Distribution of |v|

6-sigma discrepancy between the two distributions!



The Maxwell Boltzmann distribution we are taught at school!

The discrepancy is largely due to anisotropy of the distributions.

Direct Detection Rate

The DM velocity distribution is part of the computation of the expected direct detection rate.

$$\frac{dR}{dQ} \propto \frac{\sigma_0 \rho_0}{m_\chi m_r^2} F^2(Q) g(v_{\min})$$

Astrophysical Parameters:
Dark matter density, velocity.

Particle Physics Parameters:
Scattering cross section, mass of the dark matter.

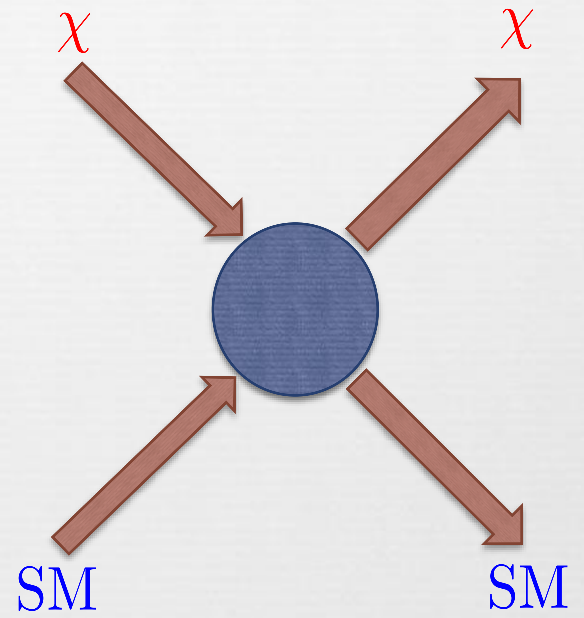
Experimental Parameters:
Form factors, mass of the nucleus (also experimental mass/exposure should be added)

Direct Detection Rate

The DM velocity distribution is part of the computation of the expected direct detection rate.

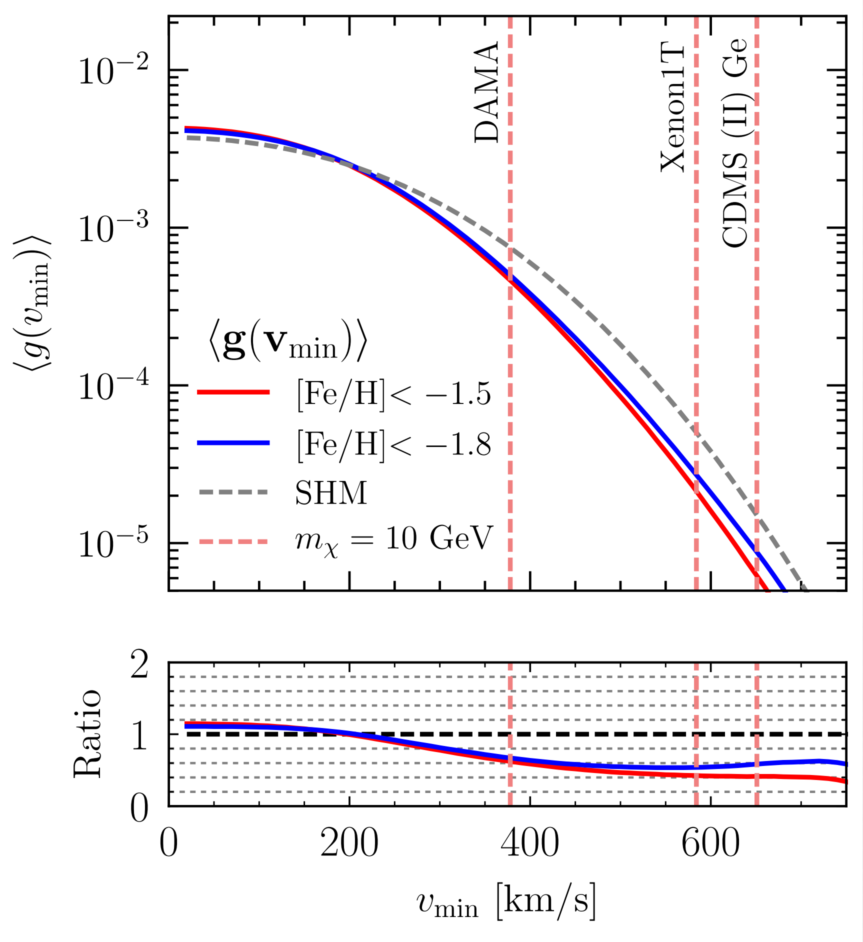
$$\frac{dR}{dQ} \propto \frac{\sigma_0 \rho_0}{m_\chi m_r^2} F^2(Q) g(v_{\rm min})$$

$$g(v_{\rm min}) = \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v} dv$$



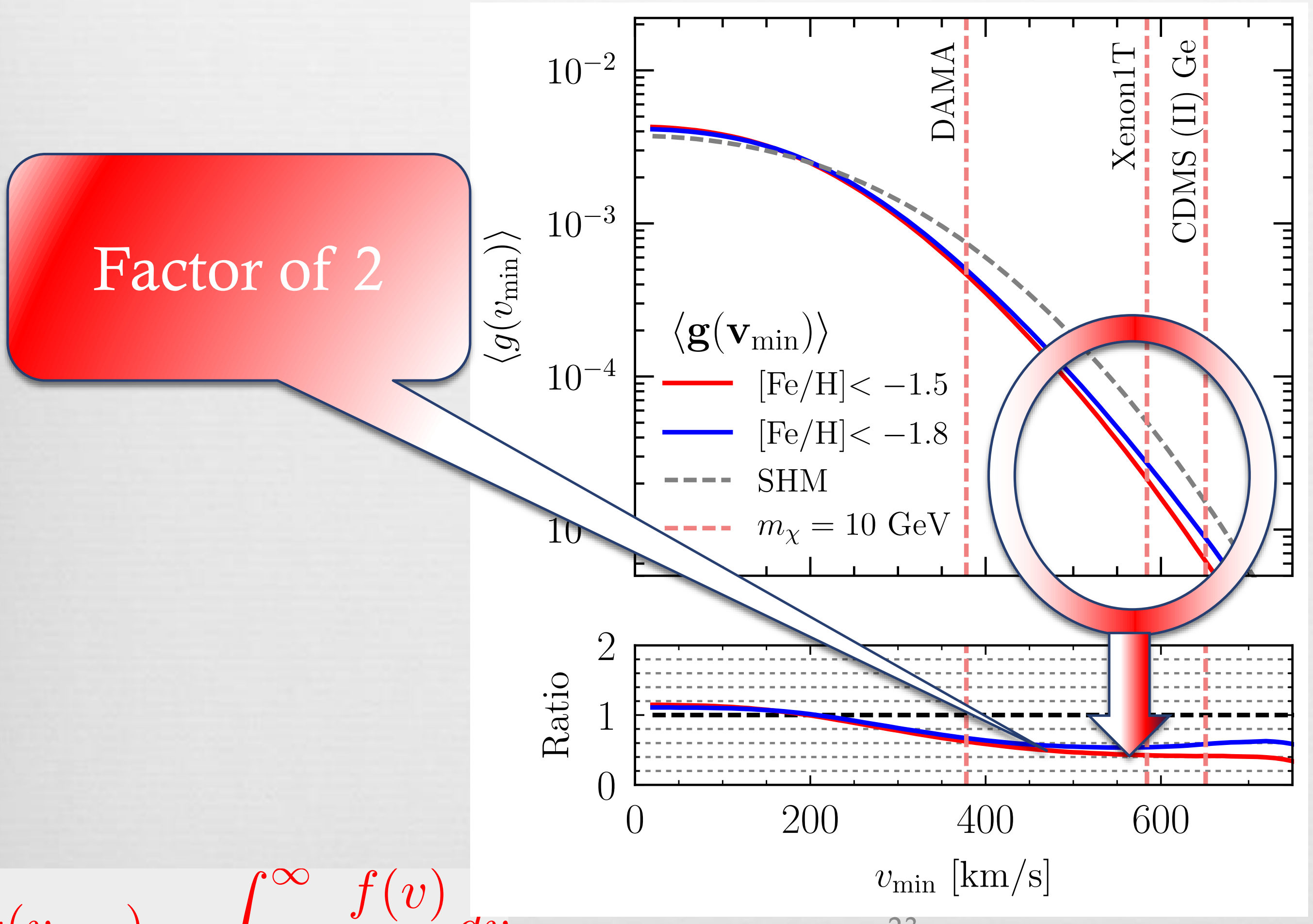
$v_{\rm min}$ depends on the experimental threshold, and the dark matter mass.

In terms of Direct Detection Experiments



$$g(v_{\rm min}) = \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v} dv$$

In terms of Direct Detection Experiments



We expect similar effects on direct detection with electron scattering experiments.

$$g(v_{\min}) = \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$

First Empirical Velocity Distribution of Dark Matter

- Currently studying Gaia dataset crossed with the 9th release of the Sloan Digital Sky Survey (SDSS).
- Also studying more complex dynamics of Milky Way-like galaxies.
- Looking for a better observable for Self-Interacting Dark Matter.
- Currently running a simulation for Warm Dark Matter.
- Gearing up for Gaia DR2 in April.
- Stay tuned for more to come!

Thank you!

Understanding the Velocity Distribution

- The simplest potential to produce a constant rotation curve is that of an isothermal sphere.

Jeans & Poisson

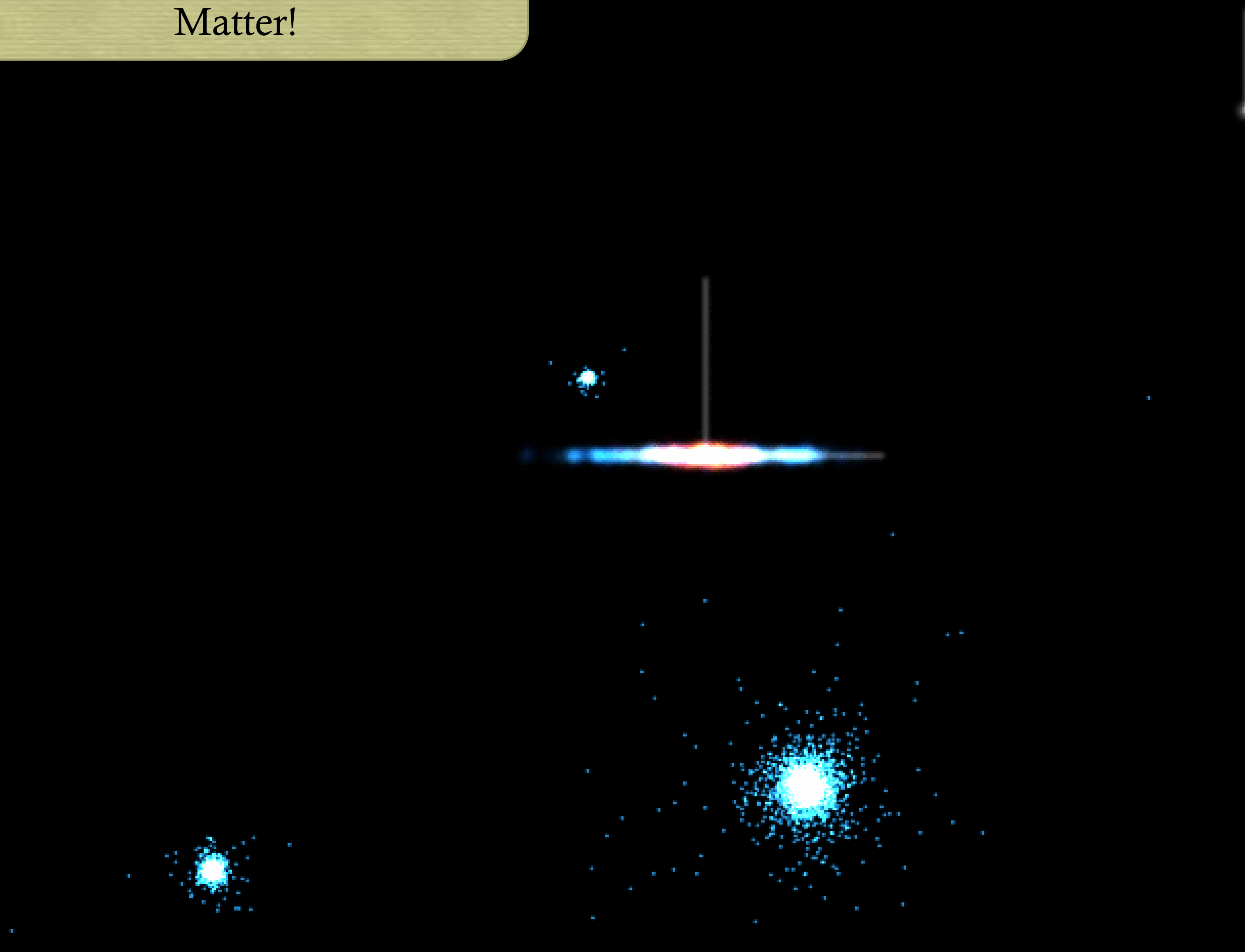
$$f(v) \propto v^2 \exp\left(-\frac{v^2}{2\sigma^2}\right)$$

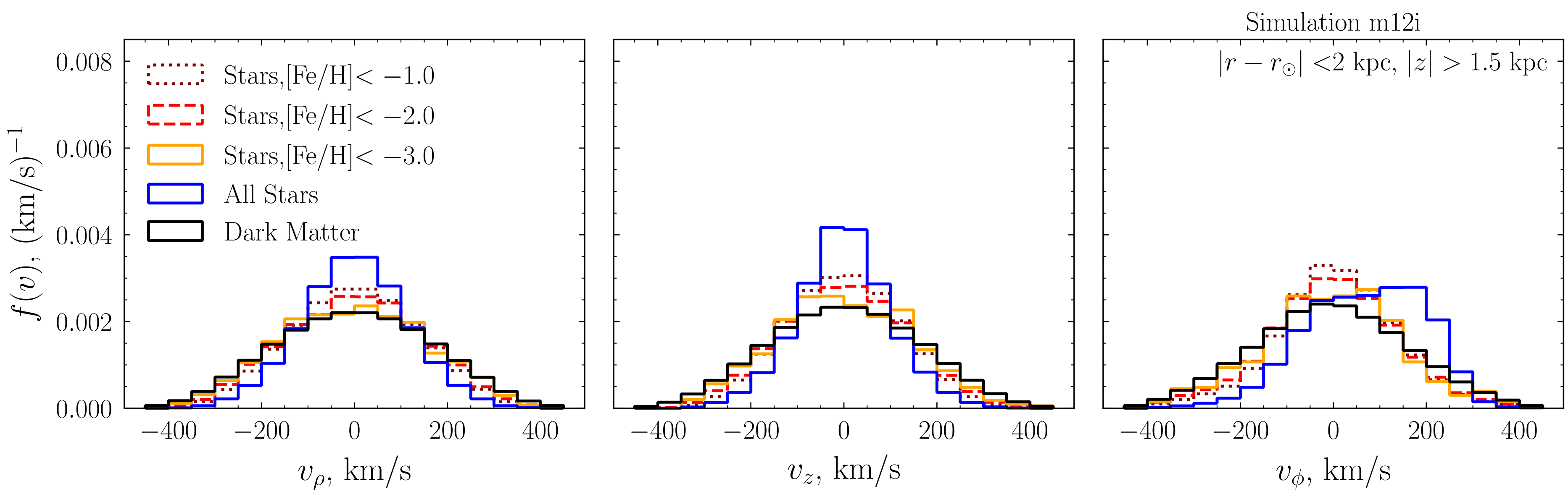
Maxwell-Boltzmann Distribution

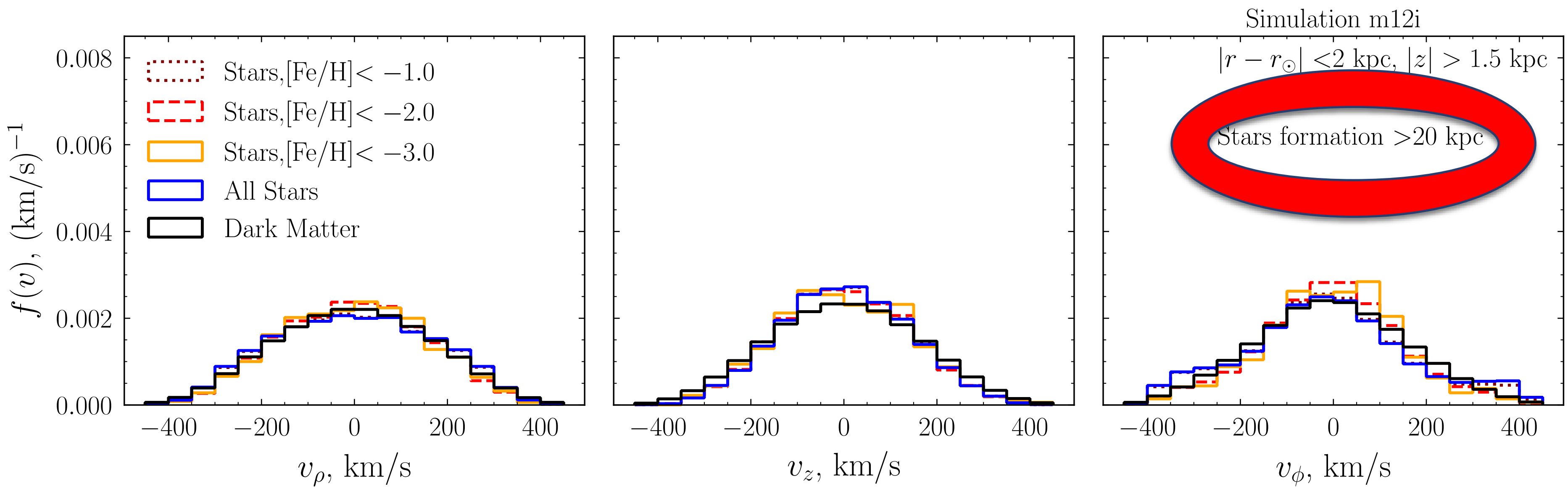
Standard Halo Model

$$\begin{cases} v_c(r) = \sqrt{2}\sigma \\ \rho(r) = \dfrac{\sigma^2}{2\pi G r^2} \\ M(r) = \dfrac{2\sigma^2 r}{G} \end{cases}$$

These old stars merged with our Milky Way along with the Dark Matter!

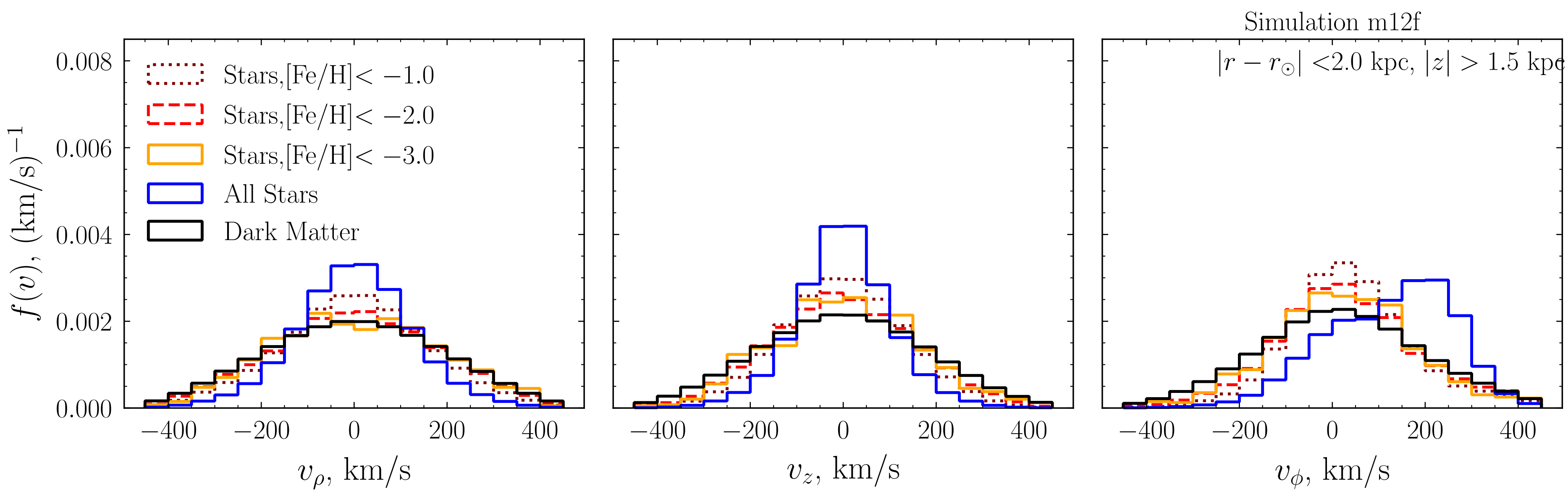



Simulation m12i
$|r - r_\odot| < 2$ kpc, $|z| > 1.5$ kpc
Stars,[Fe/H]< −1.0
Stars,[Fe/H]< −2.0
Stars,[Fe/H]< −3.0
All Stars
Dark Matter
$f(v)$, $(\mathrm{km/s})^{-1}$
0.008
0.006
0.004
0.002
0.000
−400
−200
0
200
400
v_ρ, km/s
v_z, km/s
v_ϕ, km/s

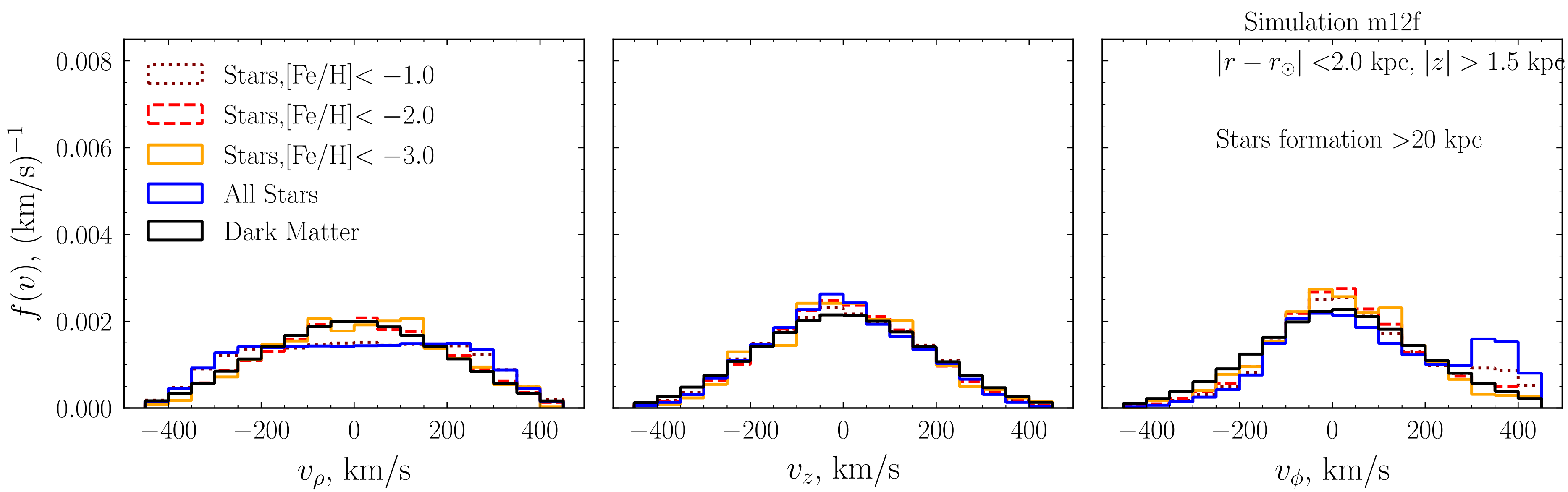


This confirms the assumption that accreted stars behave more similarly as dark matter.

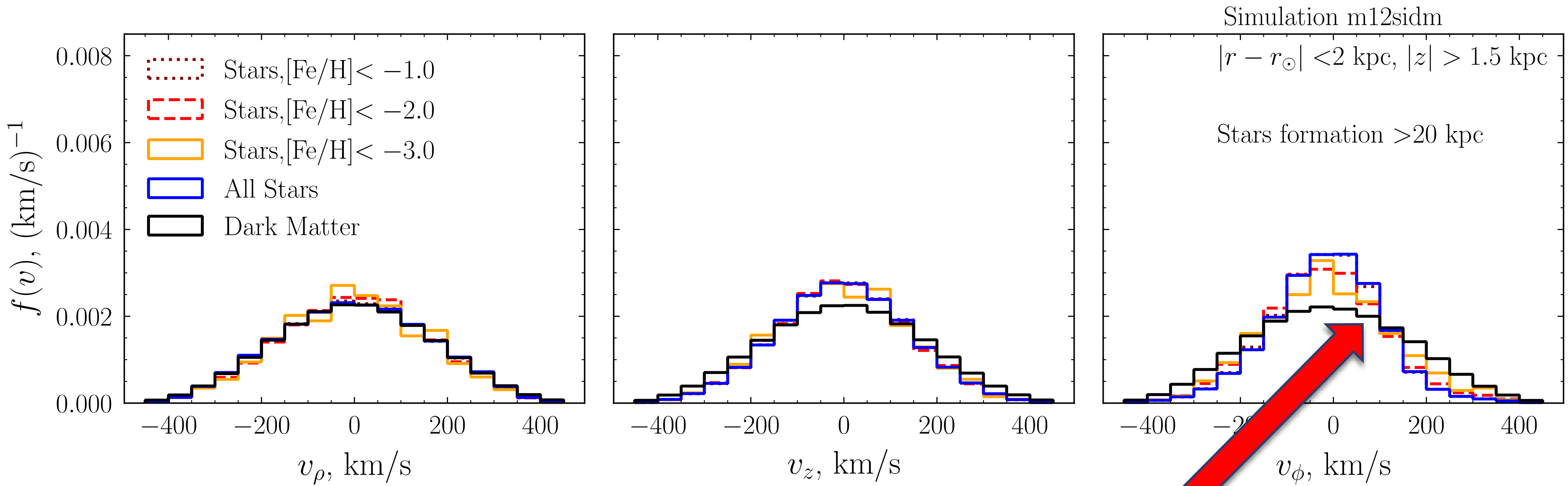
Not the greatest fit…



Things do improve when we only select the accreted stars.

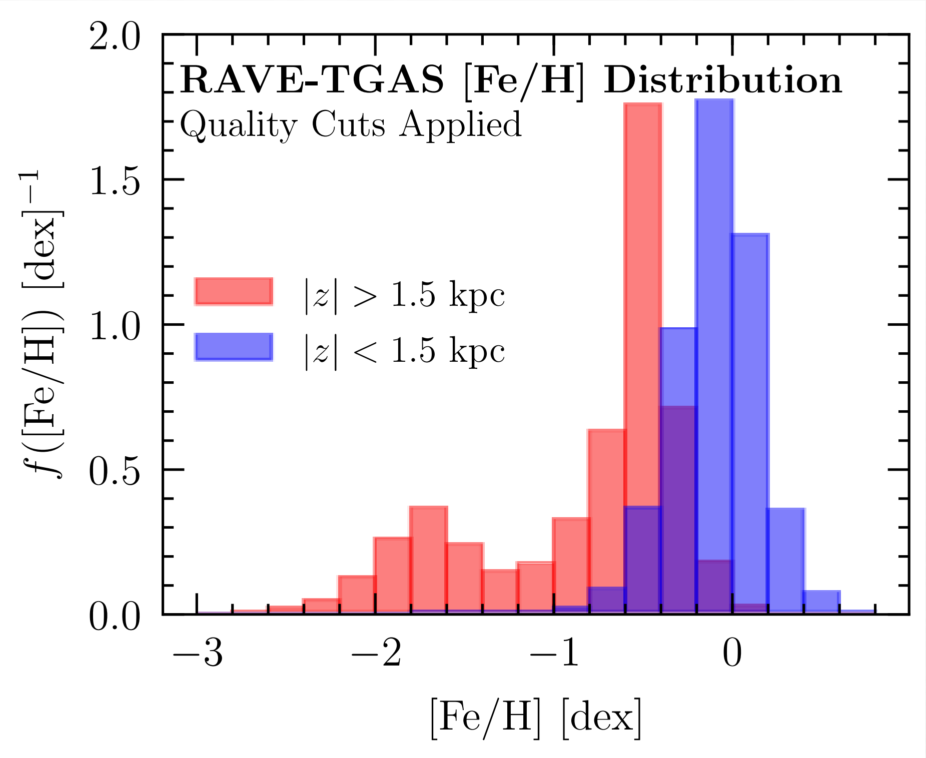


$\sigma = 1\ \mathrm{cm^2/g}$

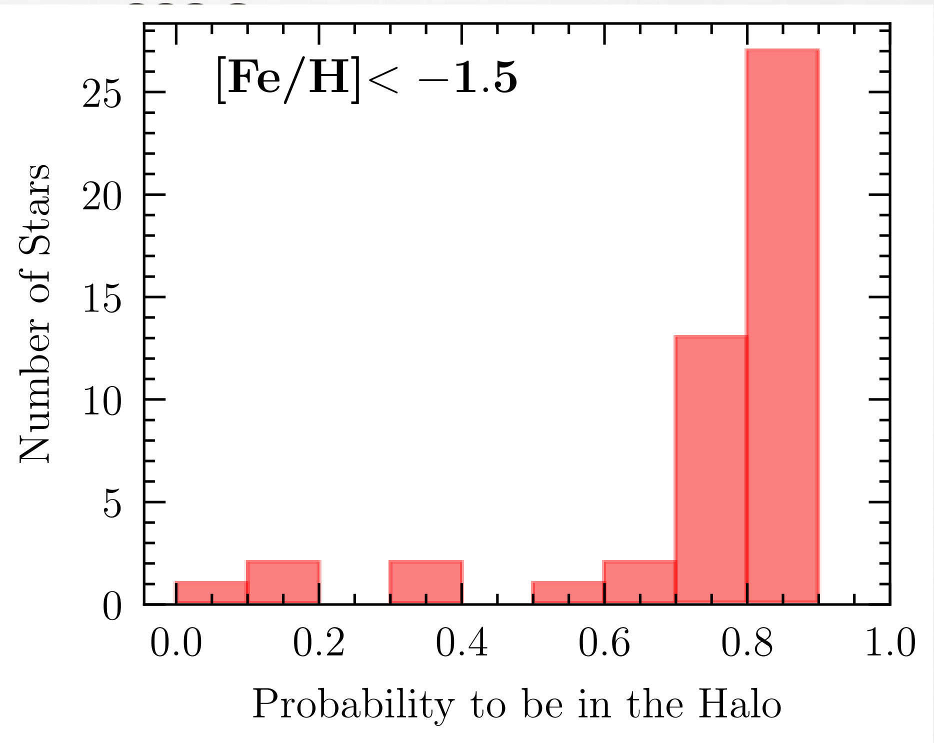


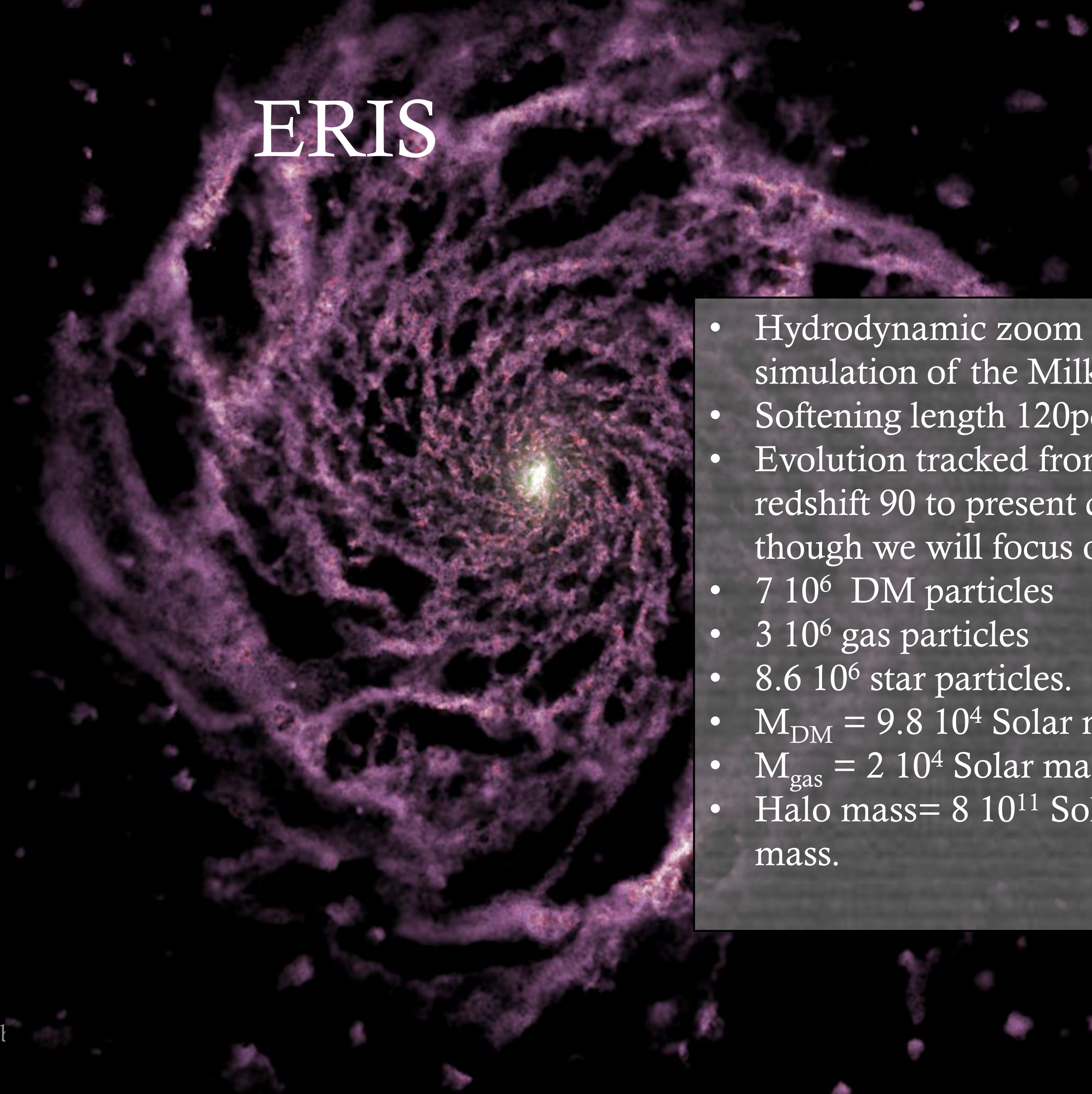
As expected, the fit is not as good for SIDM.

Need to find a better way to constrain kinematics of SIDM!



RAVE-TGAS [Fe/H] Distribution
Quality Cuts Applied
|z| > 1.5 kpc
|z| < 1.5 kpc
2.0
1.5
1.0
0.5
0.0
−3
−2
−1
0
[Fe/H] [dex]
f([Fe/H]) [dex]⁻¹

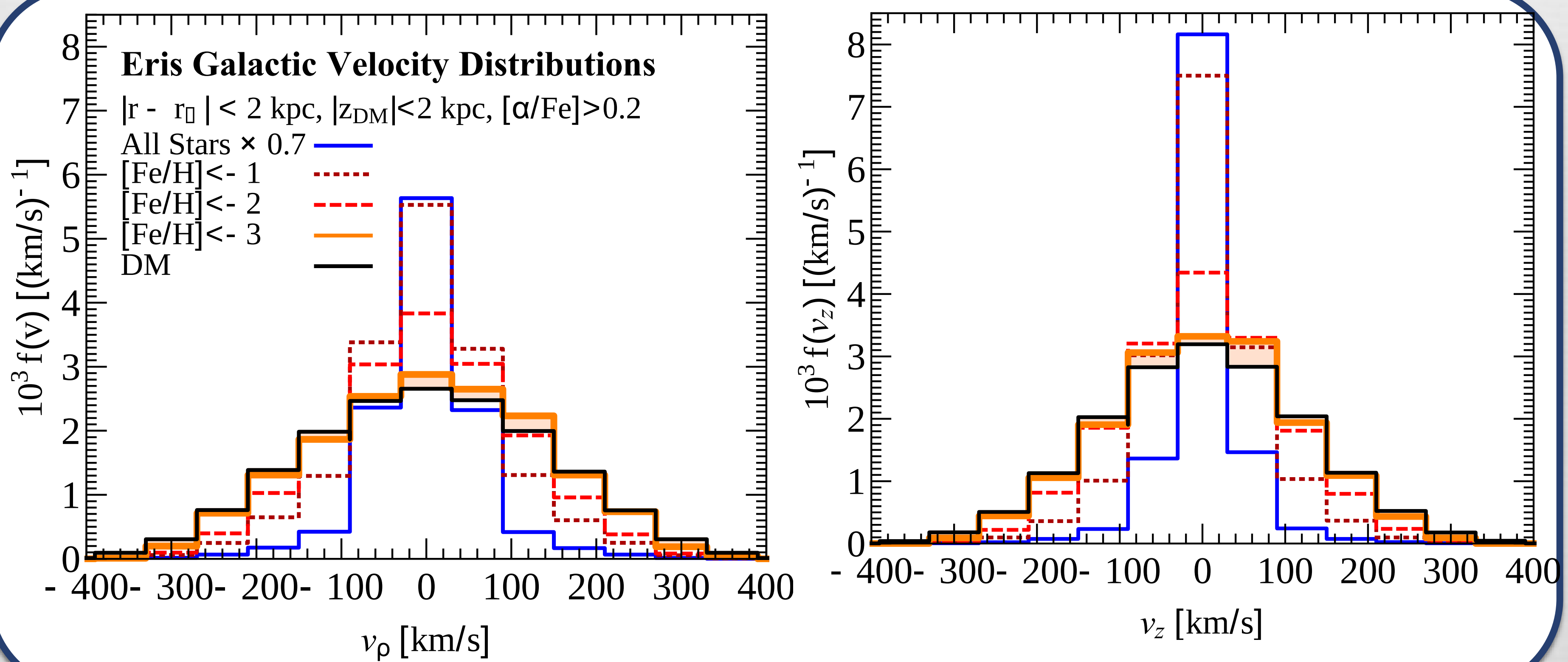

[Fe/H]< −1.5
Number of Stars
0
5
10
15
20
25
0.0
0.2
0.4
0.6
0.8
1.0
Probability to be in the Halo



ERIS

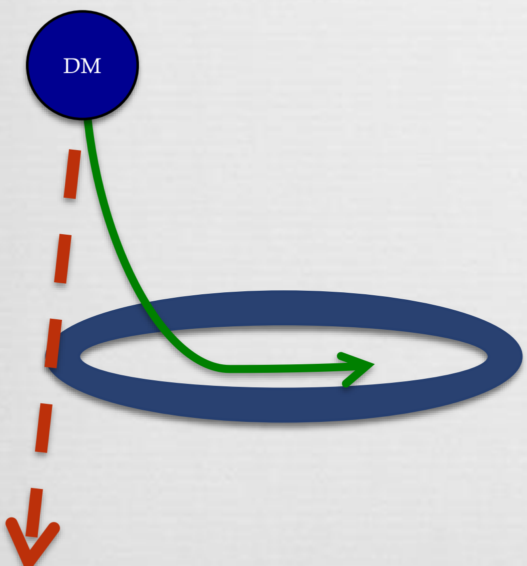
- Hydrodynamic zoom in simulation of the Milky way.
- Softening length 120pc.
- Evolution tracked from redshift 90 to present day, though we will focus on z=0.
- $7\ 10^6$ DM particles
- $3\ 10^6$ gas particles
- $8.6\ 10^6$ star particles.
- $M_{DM} = 9.8\ 10^4$ Solar mass
- $M_{gas} = 2\ 10^4$ Solar mass
- Halo mass= $8\ 10^{11}$ Solar mass.

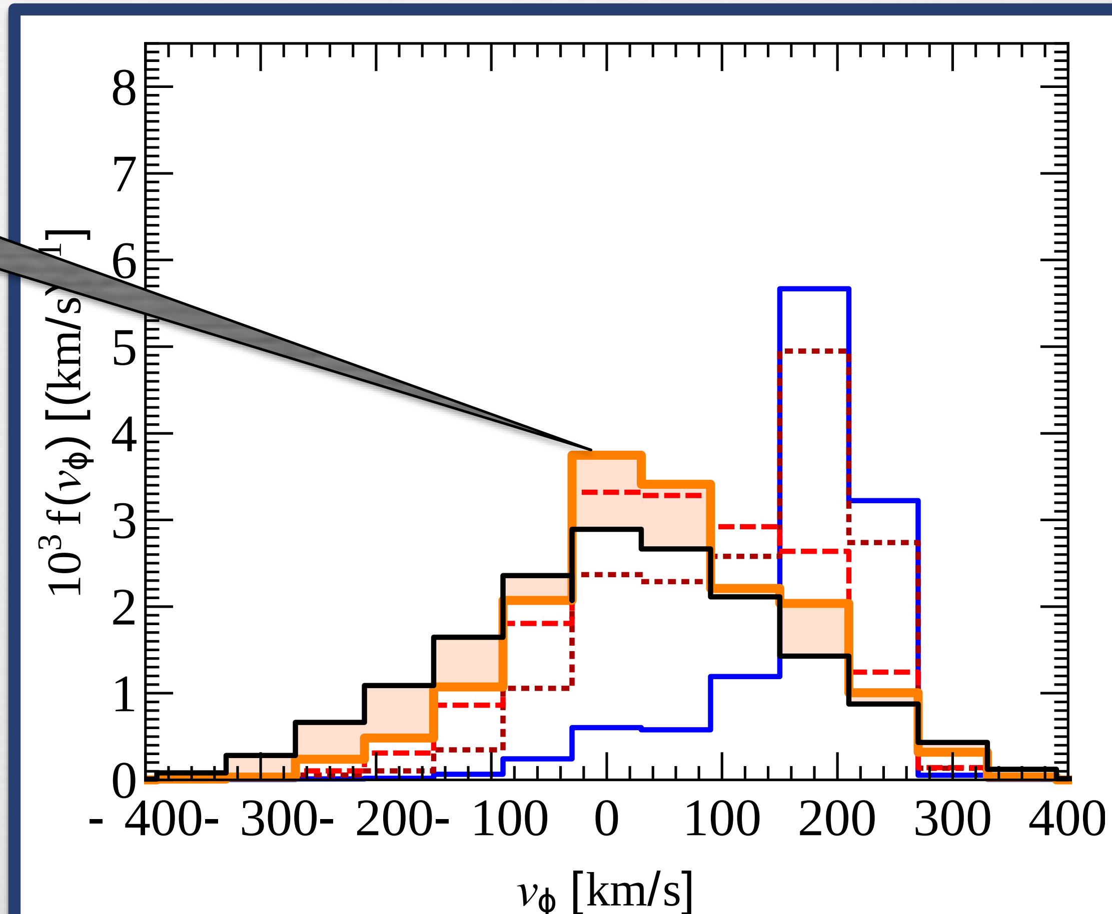
Stellar and Dark Matter Distributions



Stellar and Dark Matter Distributions

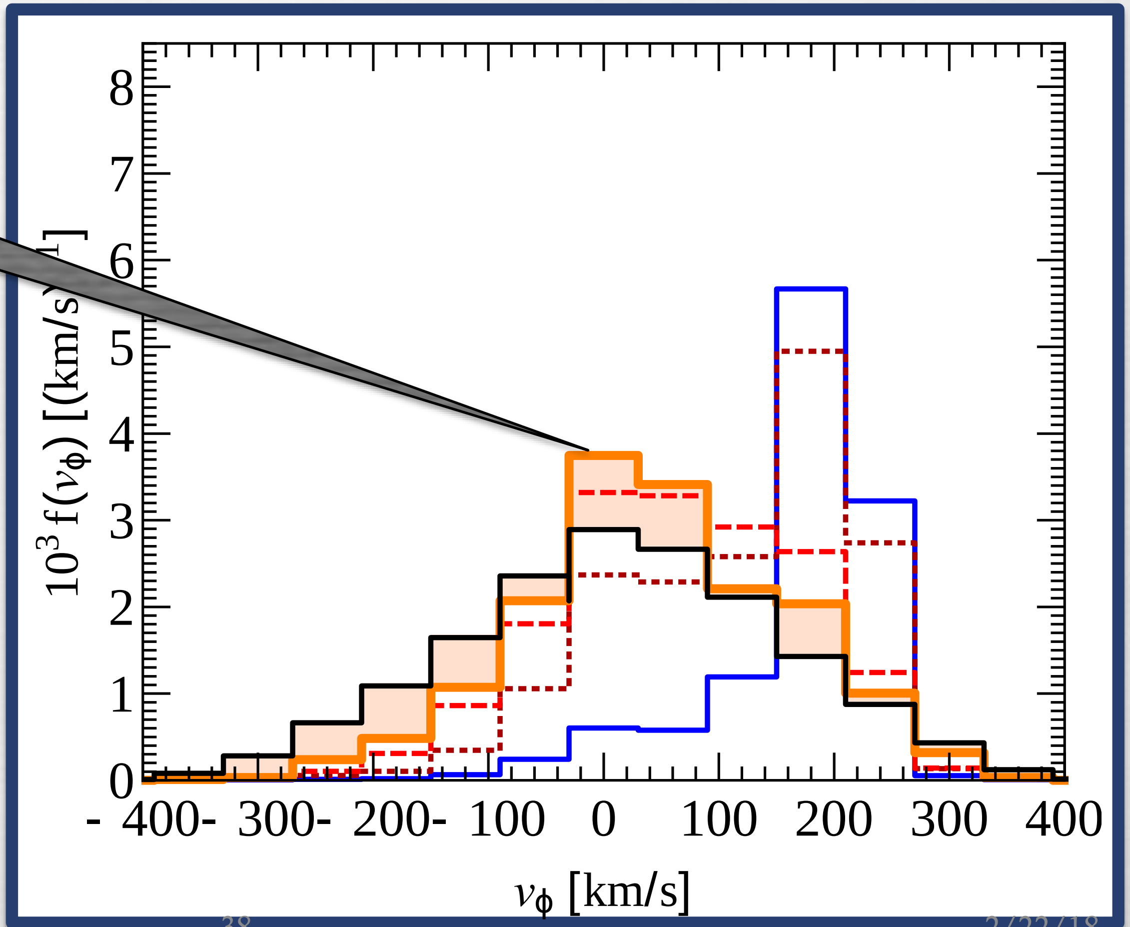
Prograde rotation found in Eris





Stellar and Dark Matter Distributions

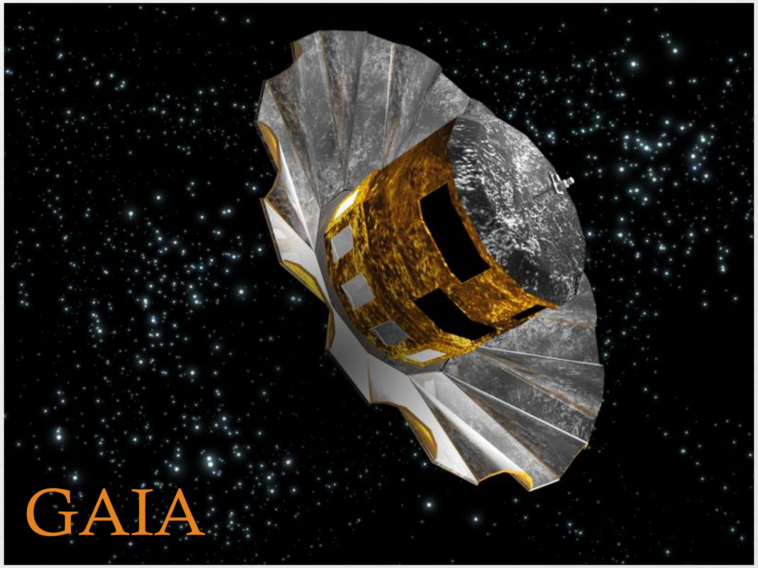
Prograde rotation found in Eris



There is no evidence for significant prograde rotation for metal poor stars in data.

Telescopes

- Launched December 2013
- Goal: Positional measurement of 1 billion stars, radial velocity for the brightest 150 million



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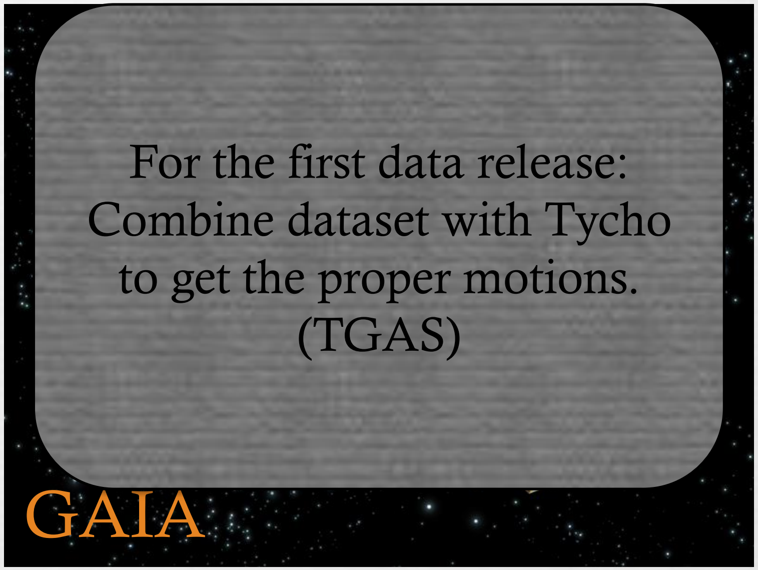
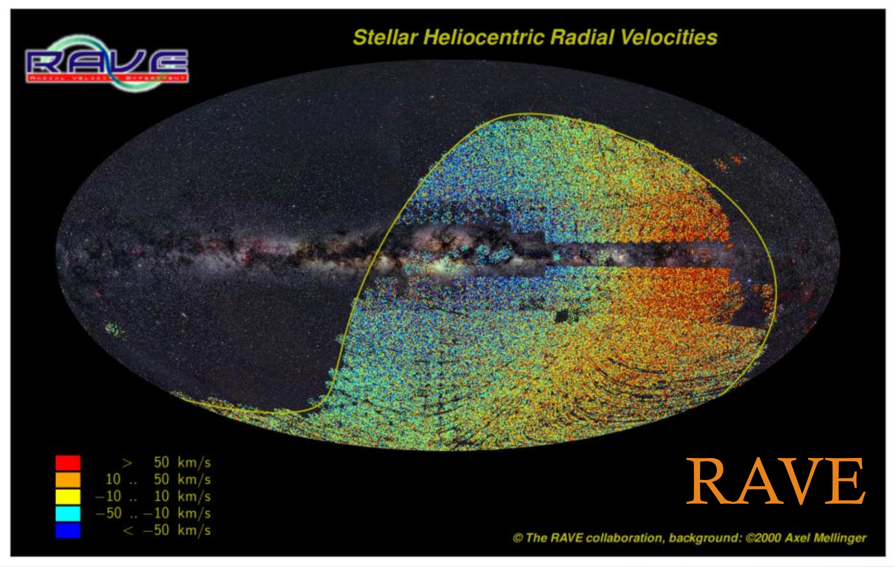


For the first data release: Combine dataset with Tycho to get the proper motions. (TGAS)

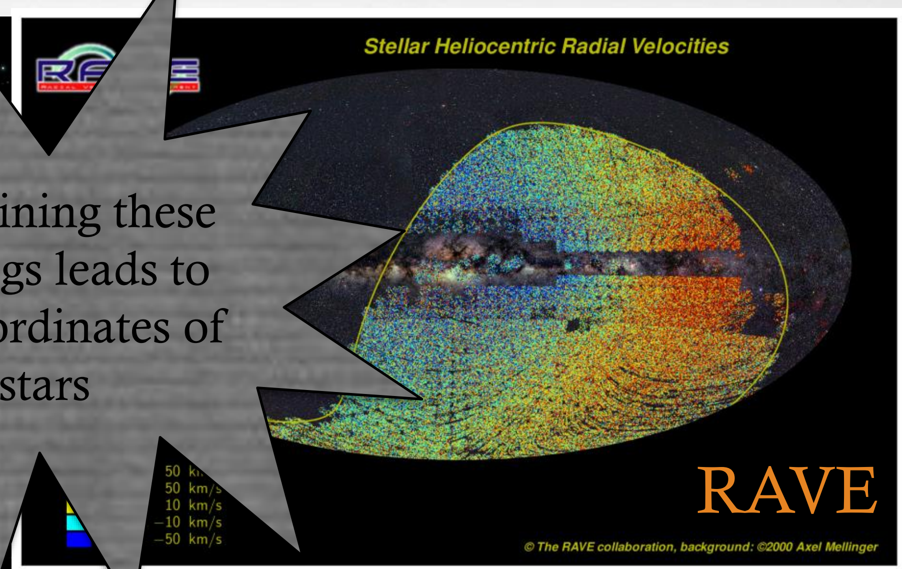
Telescopes

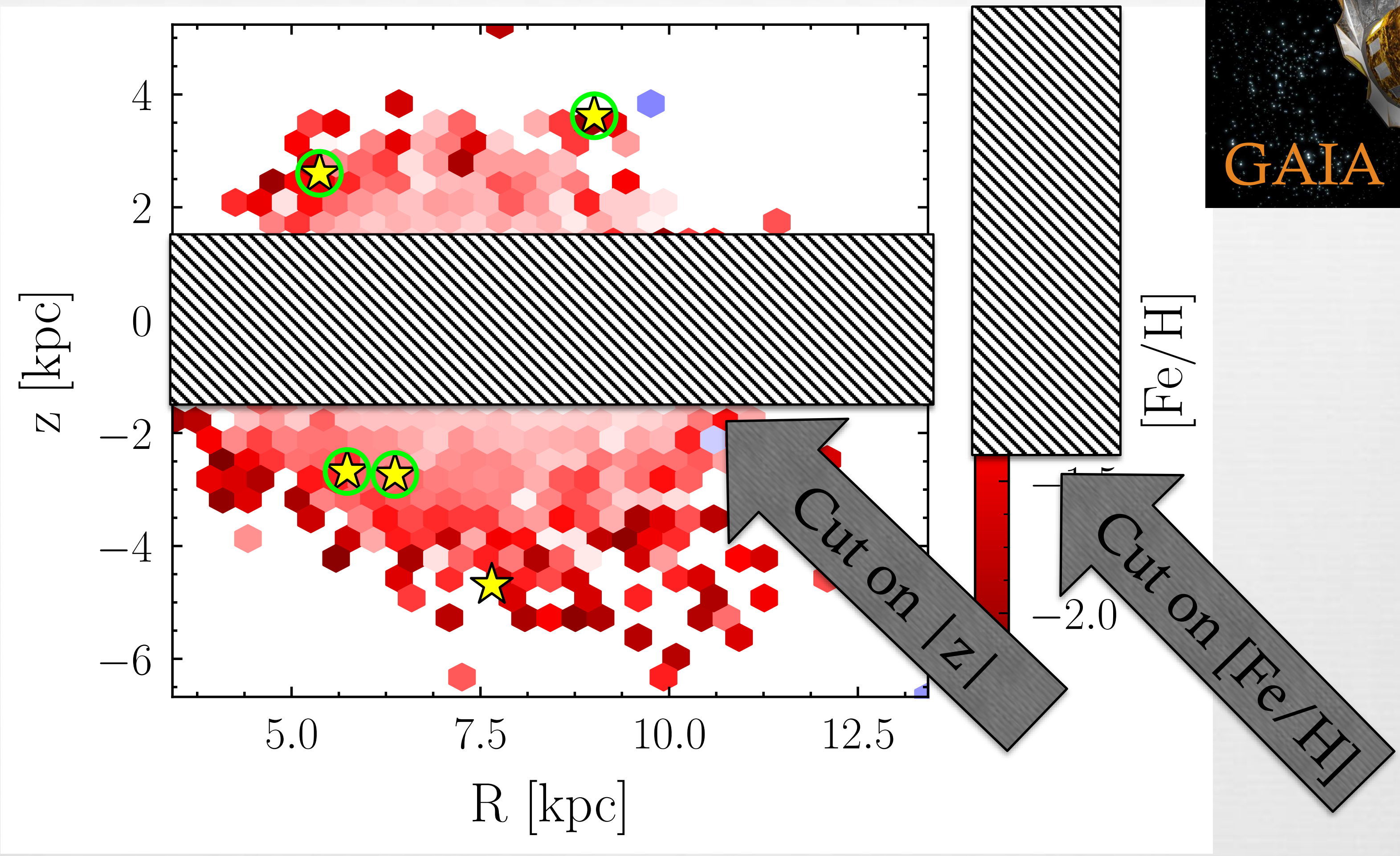
- RAdial Velocity Experiment: 400K stars, 200K overlap with Tycho-Gaia catalog (2003-2013)
- RAVE: Radial Velocity+ Chemical information



Telescopes

Combining these catalogs leads to 6D coordinates of stars





Gaia DR1: Lindergren et al. (2016)
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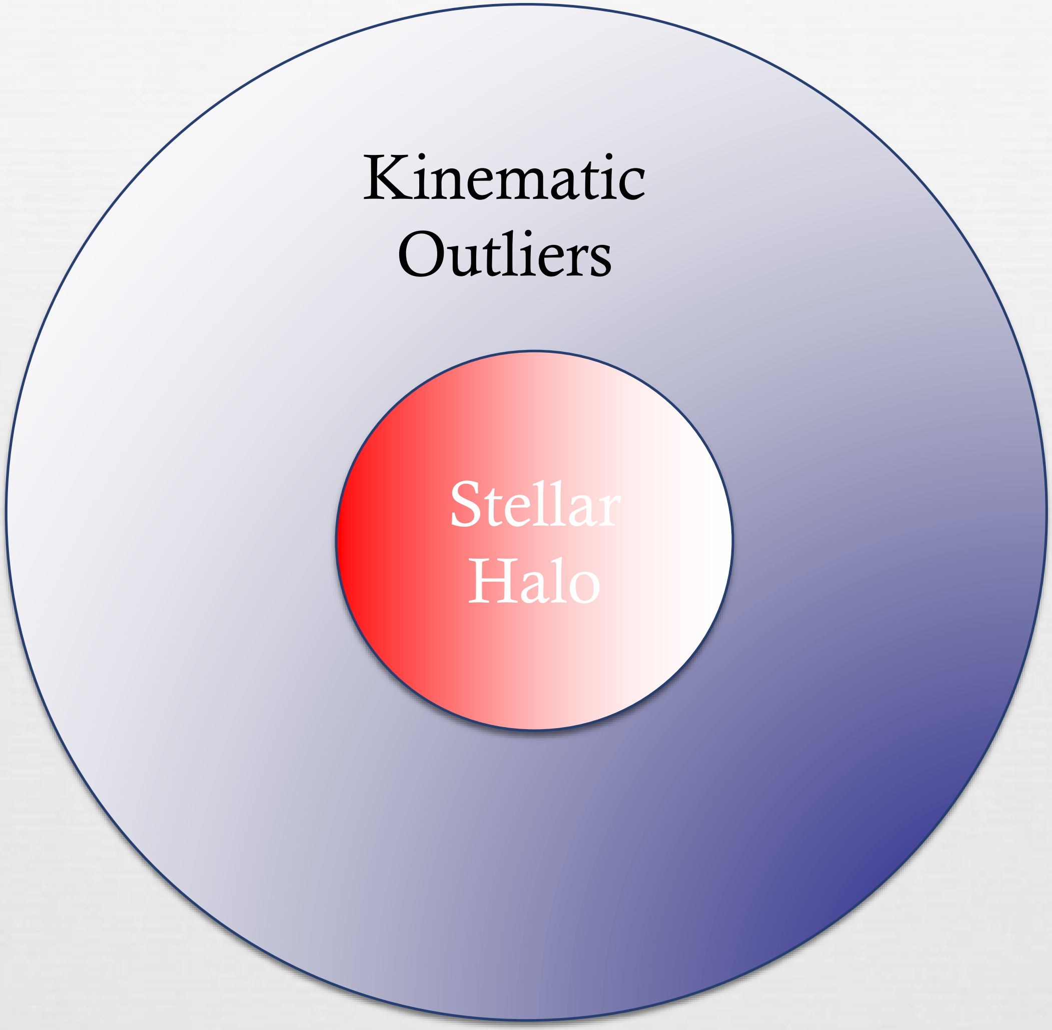
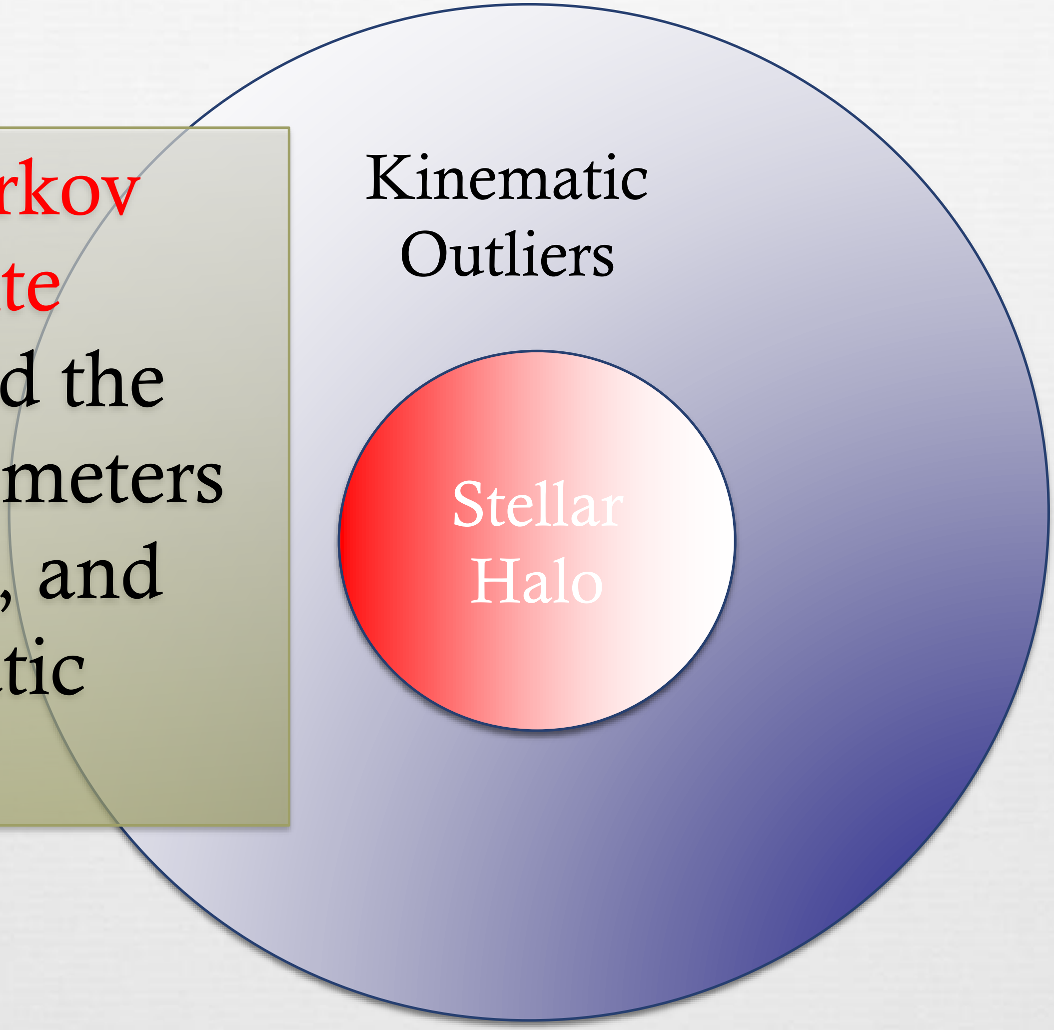
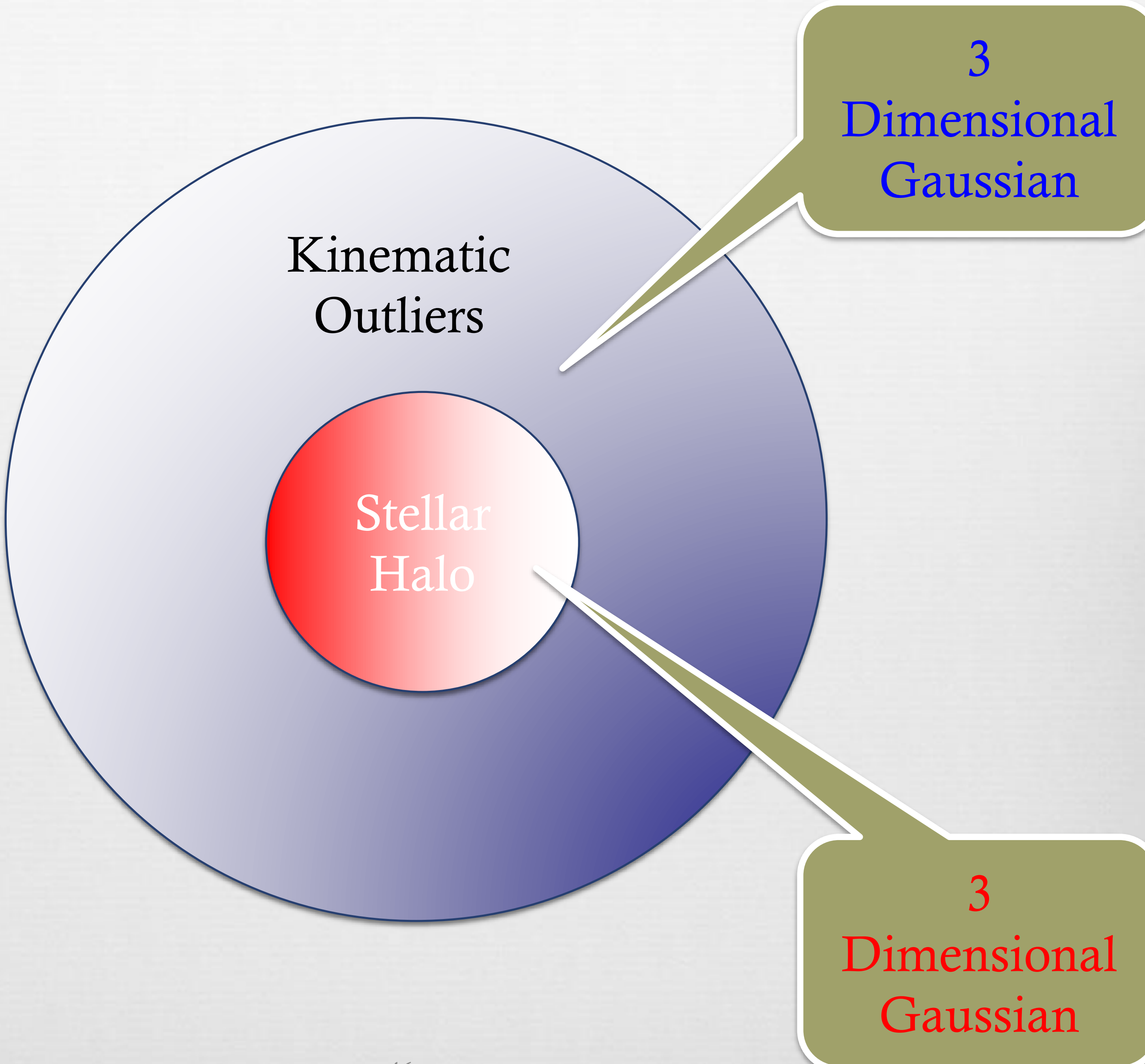
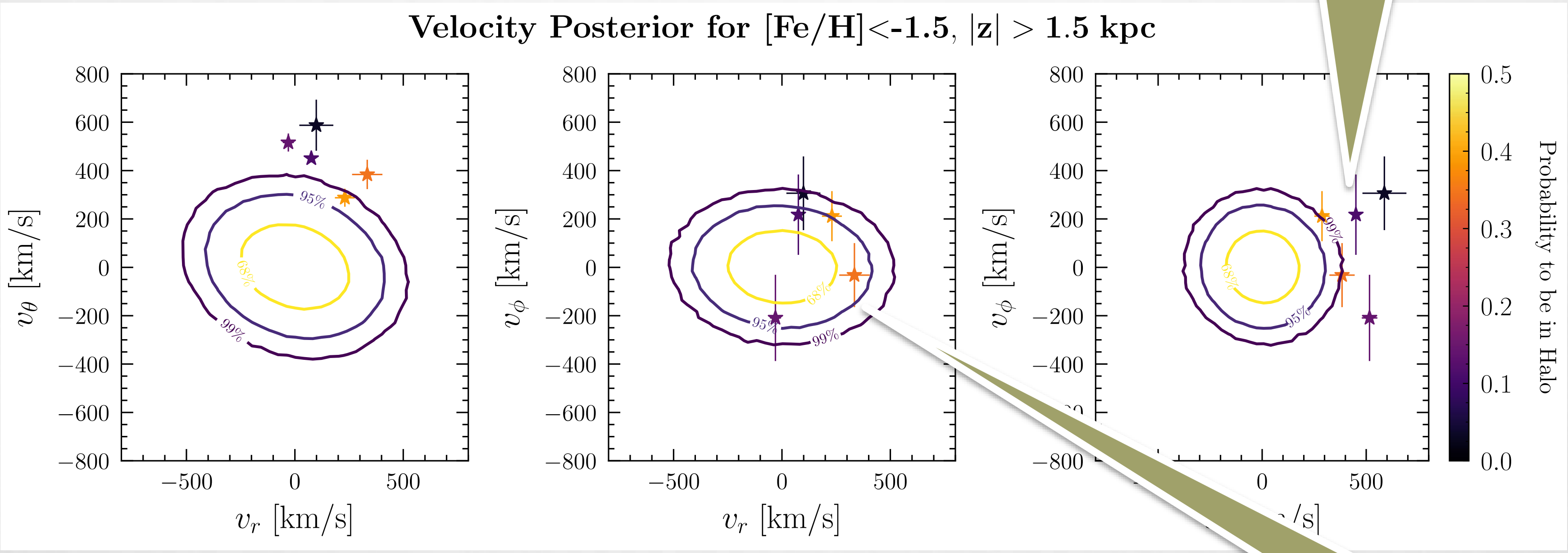

Kinematic
Outliers
Stellar
Halo

We use Markov Chain Monte Carlo to find the best fit parameters for the halo, and any kinematic outliers.




Kinematic Outliers
Stellar Halo
3 Dimensional Gaussian
3 Dimensional Gaussian

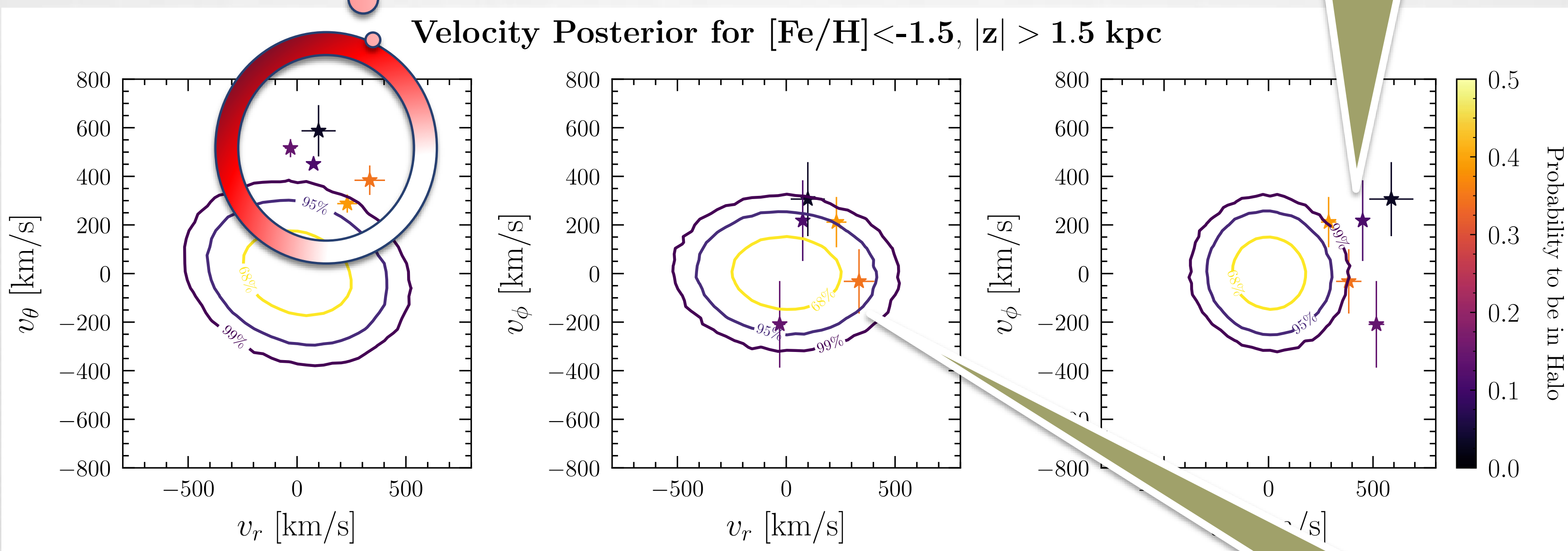
Kinematic Outliers


Velocity Posterior for [Fe/H]<-1.5, |z| > 1.5 kpc
800
600
400
200
0
−200
−400
−600
−800
−500
0
500
v_θ [km/s]
v_r [km/s]
v_ϕ [km/s]
95%
99%
68%
0.5
0.4
0.3
0.2
0.1
0.0
Probability to be in Halo

Best Fit Halo

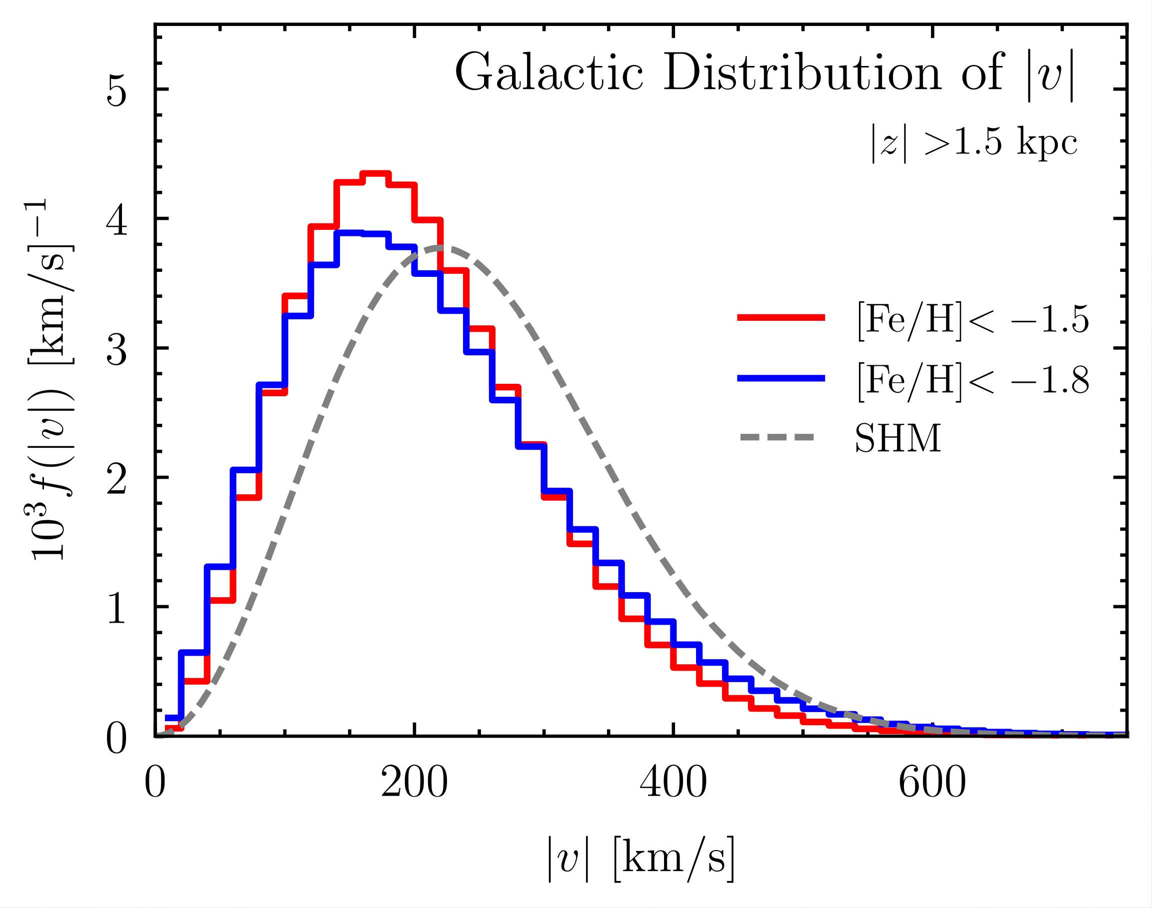
Hints of dark matter substructure?

Kinematic Outliers

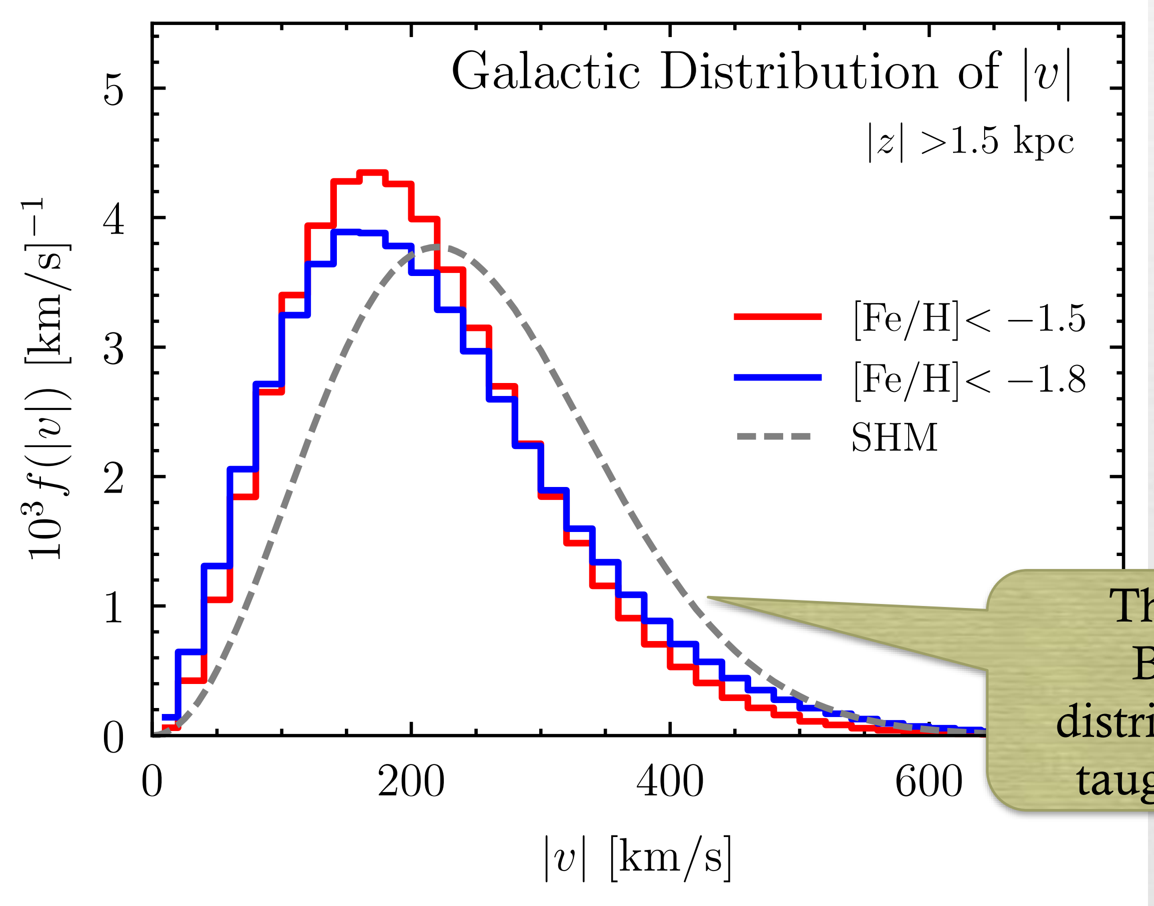


Best Fit Halo

Posterior Distribution of |v|



Posterior Distribution of |v|



The Maxwell Boltzmann distribution we are taught at school!