Dark Matter in Disequilibrium: The Velocity Distribution

Lina Necib, Caltech

Based on
Herzog-Arbeitman, Lisanti, Madau, Necib PRL 120(2018) no.4, 041102
Herzog-Arbeitman, Lisanti, Necib, JCAP 1804 no. 4, 052
Necib, Lisanti, Belokurov, arXiv:180X.XXXXX
Empirically Determined Velocity Distribution of Dark Matter

Heliocentric Distribution of $|v|$

Eris Galactic Velocity Distributions
$|r - r_\odot| < 2 \text{kpc}, |z_{DM}|<2 \text{kpc}, [\alpha/Fe]>0.2$

All Stars $\times 0.7$

- $[\text{Fe/H}]<-1$
- $[\text{Fe/H}]<-2$
- $[\text{Fe/H}]<-3$
- DM

$10^3 f(v) \text{ [km/s]^{-1}}$

$\nu_\rho \text{ [km/s]}$

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Empirically Determined Velocity Distribution of Dark Matter

SDSS-Gaia DR2

Heliocentric $|v|$

$|z| > 1.0 \text{ kpc}$

$d_\odot < 2.0 \text{ kpc}$

Necib, Lisanti, Belokurov, 2018
Find Dark Matter Tracers!

Strategy

How to empirically measure the velocity distribution of Dark Matter!
From Simulations:
Metal-Poor Stars trace the velocity of Dark Matter.

From Gaia DR1/DR2:
We get the local velocity distribution of Metal-Poor Stars.

Therefore:
We empirically obtain the Dark Matter velocity distribution.
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: $(1.2-1.6) \times 10^{12}$ Msun.
- Particle mass: 7000 Msun.
- Dark Matter softening length: 30pc.

Hopkins et al. (2014) MNRAS 445,581
Hopkins et al. (2017) arXiv:1702.06148
When we cut at low [Fe/H], we are primarily selecting stars that are born in dwarf galaxies.
Quiet Merger History

Tracking particles from the same merger back to redshift zero!

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Telescopes

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

- Sloan Digital Sky Survey: 2.5 meter telescope at the Apache Point Observatory.
- Gathered spectra of more than 1 million objects.
- SDSS: Radial Velocity + Chemical information
Telescopes

Combining these catalogs leads to 6D coordinates of stars
New Analysis:
Using Gaia DR2 + SDSS
We use Markov Chain Monte Carlo to find the best fit parameters for the halo, disk, and substructure.
Substructure

1 Dimensional Gaussian for the metallicity Distribution

3 Dimensional Gaussian for velocity in spherical coordinates

Disk

35 parameter fit!

Stellar Halo
Best Fit Velocity/Metallicity

[Graphs showing velocity and metallicity distributions for different components: Halo, Disk, Subs]
Best Fit Velocity/Metallicity

Data!

SDSS-Gaia DR2

$r \in [7.5, 8.5] \text{ kpc}$

$|z| > 1.0 \text{ kpc}$
This is debris flow: unlike streams, these stars and dark matter have lost all spatial features but maintain coherence in velocity space.

Lisanti & Spergel (2011)
Kuhlen, Lisanti & Spergel (2012)
Understanding Substructure

SDSS-Gaia DR2
$r \in [7.5, 8.5] \text{ kpc}$

Disk
Subs
Halo

Fractional Contribution ($Q_i$)

Large fraction!
Understanding Substructure

Data!

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Understanding Substructure

Eccentric orbits at small angles from the disk
Local Velocity Distribution

**Drum Roll**
Posterior Distribution of $|v|$ 

Galactic Distribution of $|v|$ 
$|z| > 1.5 \text{ kpc}$ 

$10^3 f(|v|) \text{ [km/s]}^{-1}$ 

- $[\text{Fe/H}] < -1.5$ 
- $[\text{Fe/H}] < -1.8$ 
- --- SHM 

Old distribution from Gaia DR1. 
High metallicity cut, no fit for substructure!
Posterior Distribution of $|v|$

SDSS-Gaia DR2
Heliocentric $|v|$

$|z| > 1.0 \text{ kpc}$
$d_{\odot} < 2.0 \text{ kpc}$

New distribution from Gaia DR2. Uncovered substructure dominating the distribution!

The Maxwell Boltzmann distribution we are taught at school!
The DM velocity distribution is part of the computation of the expected direct detection rate.

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

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

\(v_{\text{min}}\) depends on the experimental threshold, and the dark matter mass.
These limits are too strong!

Assumes the standard Maxwell Boltzmann velocity distribution.
The Velocity Distribution of Dark Matter is FAR from Equilibrium!

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We need to stop assuming that the Milky Way is in equilibrium!
The Velocity Distribution of Dark Matter is FAR from Equilibrium!

- Finalizing the study of mergers in the FIRE simulations
- Studying more complex dynamics of Milky Way-like galaxies.
- Looking for a tracer for Self-Interacting Dark Matter.
- Currently running a simulation for Warm Dark Matter.
- Stay tuned for more to come!
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Exciting times ahead!

Thank you!