The Stellar Local Velocity Distribution and its Implications for Dark Matter

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Based on
Herzog-Arbeitman, Lisanti, Madau, Necib PRL 120(2018) no.4, 041102
Herzog-Arbeitman, Lisanti, Necib, JCAP 1804 no. 4, 052
Direct Detection

X

SM

SM

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

\[ R \propto \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} \, dv \]

\( v_{\text{min}} \) depends on the experimental threshold, and the dark matter mass.

Goodman & Witten (1985)
Lewin & Smith (1996)
Direct Detection

The detection rate depends on the incoming velocity of Dark Matter.

Aprile et al. (2018)
Direct Detection

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Assumes the standard Maxwell Boltzmann velocity distribution.

Aprile et al. (2018)
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We have always assumed a Maxwell-Boltzmann distribution. It relies on the system being:
1. Isotropic
2. In equilibrium

Goodman & Witten (1985)
Lewin & Smith (1996)
How to get the velocity distribution of Dark Matter?

Start with the Stars!
From Simulations:
Accreted Stars trace the velocity of their Dark Matter counterparts.

From Gaia DR1/DR2:
We get the local velocity distribution of accreted stars.

Therefore:
We empirically obtain the Dark Matter velocity distribution.

Herzog-Arbeitman, Lisanti, Madau, Necib (2018)
Herzog-Arbeitman, Lisanti, Necib (2018)
The only thing we get out of the simulation, is the correlation between Dark Matter and the stars; all distributions found are empirical!
Feedback in Realistic Environments (FIRE)

Hopkins et al. (2014) MNRAS 445,581
Hopkins et al. (2017) arXiv:1702.06148

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

Stars
Dark Matter

Dwarf Galaxy

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Merging Stages

Stars
Dark Matter

Dwarf Galaxy

Stream

Ivezic et al. (2000)
Yanny et al. (2000)

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Merging Stages

Stars
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Dwarf Galaxy

Stream

Debris Flow

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Helmi & White (1999)
Lisanti & Spergel (2012)
Kuhlen et al. (2012)
Lisanti et al. (2015)
Old Relaxed Mergers

Strong correlation between the Dark Matter and the stars accreted from 21 old satellites at $z > 3$.

Necib, Lisanti, Garrison Kimmel et al. (2018)
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*Necib*, Lisanti, Garrison Kimmel et al. (2018)

Strong correlation between the Dark Matter and the stars accreted from a satellite at redshift 0.9, with mass $8.2 \times 10^{10}$ Msun, and average metallicity $\sim 0.97$, contributing 18% of local accreted stellar mass, and 3.5% of local accreted Dark Matter.

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Necib, Lisanti, Garrison Kimmel et al. (2018)
Strong correlation between the Dark Matter and the stars accreted from a satellite at redshift 0.9, with mass $8.2 \times 10^{10}$ Msun, and average metallicity $\sim -0.97$, contributing 18% of local accreted stellar mass, and 3.5% of local accreted Dark Matter.

Necib, Lisanti, Garrison-Kimmel et al. (2018)
So, What Does our Milky Way Look Like?

What we learned:
Accreted stars trace their dark matter counterparts.
A merging event shows a lobe-structure in the radial direction.
Launched December 2013

Goal: Positional measurement of 1 billion stars (1% of the Milky Way), radial velocity for the brightest 150 million.

Second data release was in April: proper motions of 1 billion stars, and radial velocities of 6 million stars!

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Gaia Enceladus/Sausage


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Belokurov et al. (2018)
Deason et al. (2018)
Myeong et al. (2018)
Helmi et al. (2018)
Lancaster et al. (2018)
With Gaia, a merging event in the solar neighborhood was found, and is referred to as the Gaia Sausage, or Gaia Enceladus.

Mass ~ $10^{8-9}$ Msun.
Infall Time $z$ ~ 1-3.
Average Metallicity ~ -1.4
New Structure!

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Mass $\sim 10^{8-9}$ Msun.  
Infall Time $z \sim 1-3$.  
Average Metallicity $\sim -1.4$

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Disk, Halo, and Substructure

Metal-Rich, Younger Population

Azimuthal Rotation

Necib, Lisanti, Belokurov (2018)
Disk, Halo, and Substructure

$\nu_\phi$ [km/s]  
$[\text{Fe/H}]$ [dex]  

Isotropic  
Older Population  

Necib, Lisanti, Belokurov (2018)
Disk, Halo, and Substructure

Necib, Lisanti, Belokurov (2018)

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-400  -200  0  200  400  -3  -2  -1  0

$v_\phi$ [km/s]  [Fe/H] [dex]
Disk, Halo, and Substructure

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)
Not that "Sub" of a Structure

Caveat: We only modeled $|z| > 2.5$ kpc.

High non-disk fraction!

No spatial dependence has been found in the region studied.
Implications for Direct Detection

What we learned:
There is a dominant structure of debris flow in the solar neighborhood.
Accreted stars should trace their dark matter counterparts from mergers.
BUT! Mergers do not contribute the same amounts of Dark Matter and Stars!
Subhalos do not contribute the same amounts of Dark Matter and Stars.

One needs a new relation from which we can extrapolate the amount of Dark Matter in a merger.

Gallazzi et al. 2005
Kirby et al. 2013
Garrison-Kimmel et al. 2017a
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Dark Subhalos
Smooth Accretion
Debris Flow 1
Stream 1
Stream 2
Old Mergers!
Younger Mergers!
We reconstruct the dark matter distribution component by component!
New Velocity Distribution!

\[ f_{\text{total}}(v) = c_{\text{halo}} f_{\text{halo}}(v) + c_{\text{subs}} f_{\text{subs}}(v) \]

\[ c_{\text{subs}} = 0.42 \pm 0.26 \]

Rescaling from the Metallicity-Mass/Light Ratio derived.

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Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)
New Velocity Distribution!

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\[
\begin{align*}
    c_{\text{subs}} &= 0.42^{+0.26}_{-0.22} \\
\end{align*}
\]

Similarly to simulations, we build the different components of the velocity distribution.

Are there any components missing?

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)
New Velocity Distribution!

\[ f_{\text{total}}(v) = c_{\text{halo}} f_{\text{halo}}(v) + c_{\text{subs}} f_{\text{subs}}(v) \]

This only holds for subhalos that have stars in them! Smooth accretion, and dark subhalos cannot be tracked this way.

\[ c_{\text{subs}} = 0.42^{+0.26}_{-0.22} \]

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)
New Velocity Distribution!

\[ f_{\text{total}}(v) = c_{\text{halo}} f_{\text{halo}}(v) + c_{\text{subs}} f_{\text{subs}}(v) \]

This fraction is taken with respect to the luminous satellite fraction, not the total Dark Matter fraction!
New Velocity Distribution!

Can be found in a github repository near you
https://linoush.github.io/DM_Velocity_Distribution/


Final distribution different from the assumed Maxwell Boltzmann distribution

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)
Implications for Direct Detection

Largest changes are at low dark matter masses.

This is schematic, where we used hard thresholds and did not incorporate efficiencies.
Implications for Direct Detection

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Effects on different operators need investigation!

Largest changes are at low dark matter masses.
Implications for Direct Detection

Anisotropy of the system leads to modulation effects.

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Implications for Direct Detection

Anisotropy of the system leads to modulation effects.
Conclusions

Stars trace the velocity of the Dark Matter.
This is only true for merging satellites that have stars in them. Diffuse/Smooth Dark Matter and dark subhalos cannot be traced this way!

We can use stars to empirically measure the velocity distribution of Dark Matter accreted from luminous satellites.

We live in a huge debris flow that affects our direct detection limits.
Conclusions

**More to do:**

1. Generalizing to more mergers (Sequoia?)
2. Modeling down to the Solar position.
3. Estimating the fraction of Dark Matter from non-luminous sources and their velocities.
4. Better understanding the correlation between the dark matter and the stars in the case of a stream.
5. Expanding to self-interacting dark matter.
Bonus
Unresolved component

Host Halo m12i, All Dark Matter Components

\[ v_r \text{ [km/s]} \]

\[ \sqrt{v_r^2 + v_\phi^2} \text{ [km/s]} \]

\[ |\vec{v}| \text{ [km/s]} \]
Direct Detection Rate

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

\[ R \propto \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} \, dv \]

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Goodman & Witten (1985)
Lewin & Smith (1996)
Implications for Direct Detection

\[ g(\nu_{\text{min}}) = \int_{\nu_{\text{min}}}^{\infty} \frac{f(\nu)}{\nu} d\nu \]

\( \nu_{\text{min}} \) depends only on the dark matter mass and the experimental threshold.