The Stellar Local Velocity Distribution and its Implications for Dark Matter

Lina Necib, Caltech

Based on

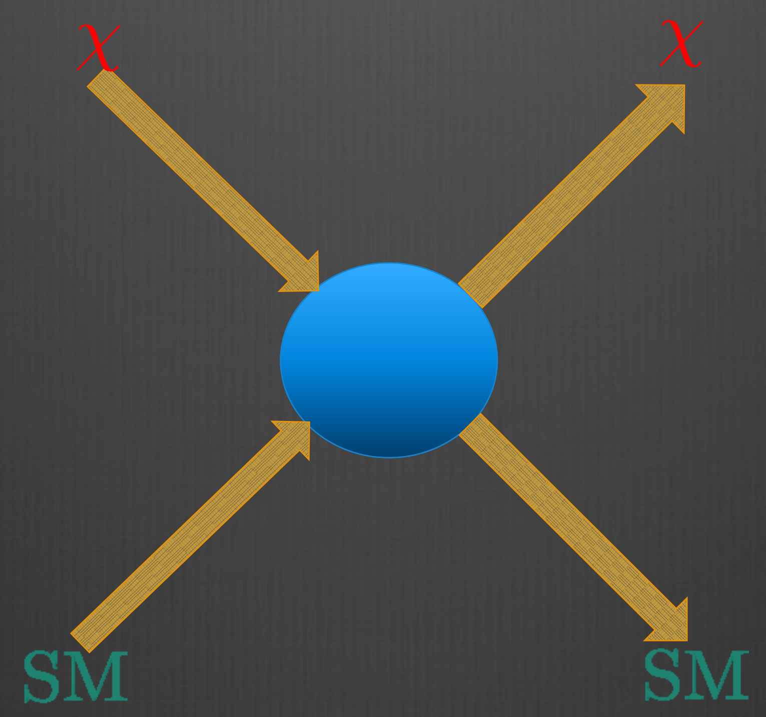
Necib, Lisanti, Garrison-Kimmel, Wetzel, Sanderson, Hopkins, Faucher-Giguère, Kereš arXiv:1810.12301

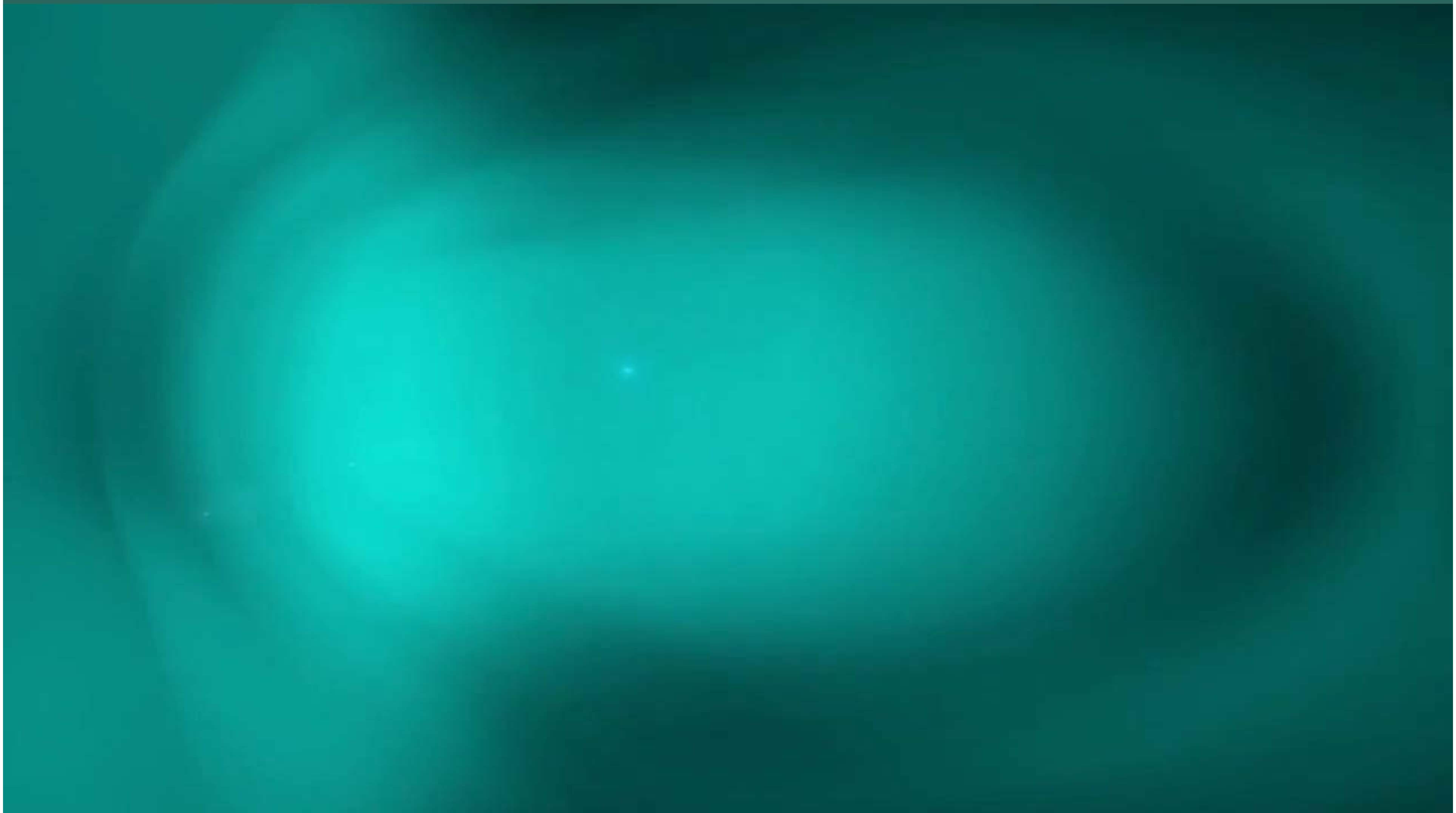
Necib, Lisanti, Belokurov, ApJ. 874 np.3, 22

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

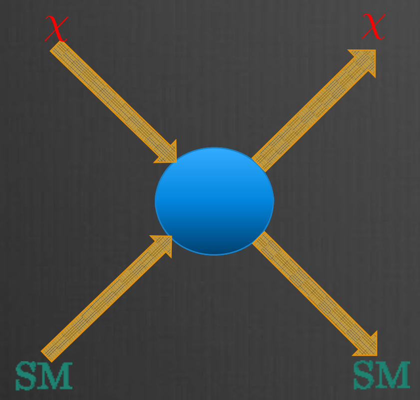
Herzog-Arbeitman, Lisanti, Necib, JCAP 1804 no. 4, 052

Direct Detection





Direct Detection Rate



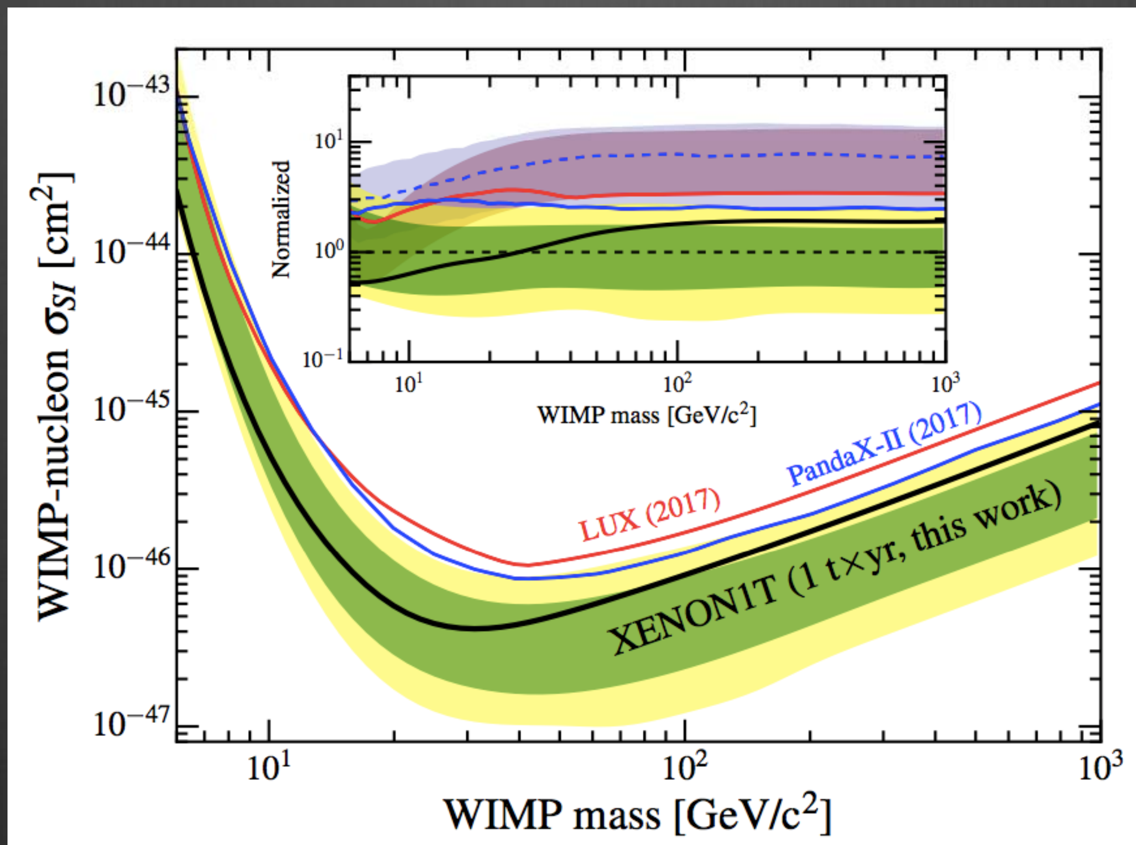
The Dark Matter velocity distribution is part of the computation of the expected direct detection rate.

$$R \propto \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$

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

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

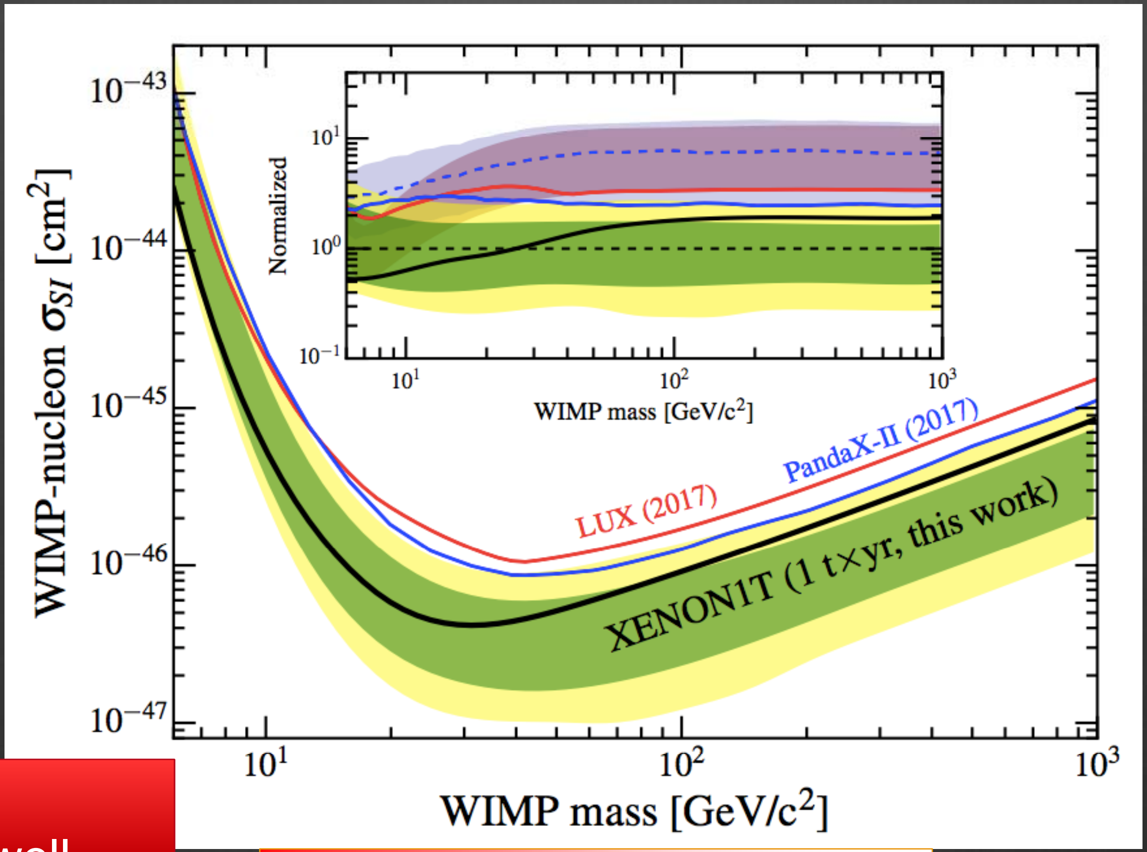
Direct Detection



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

Aprile et al. (2018)

Direct Detection



Assumes the standard Maxwell Boltzmann velocity distribution.

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

Aprile et al. (2018)

Direct Detection Rate

We have always assumed a Maxwell-Boltzmann distribution. It relies on the system being:

1. Isotropic
2. In equilibrium

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

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

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

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

How to get the velocity distribution of Dark Matter?

<u>Start with the Stars!</u>

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:

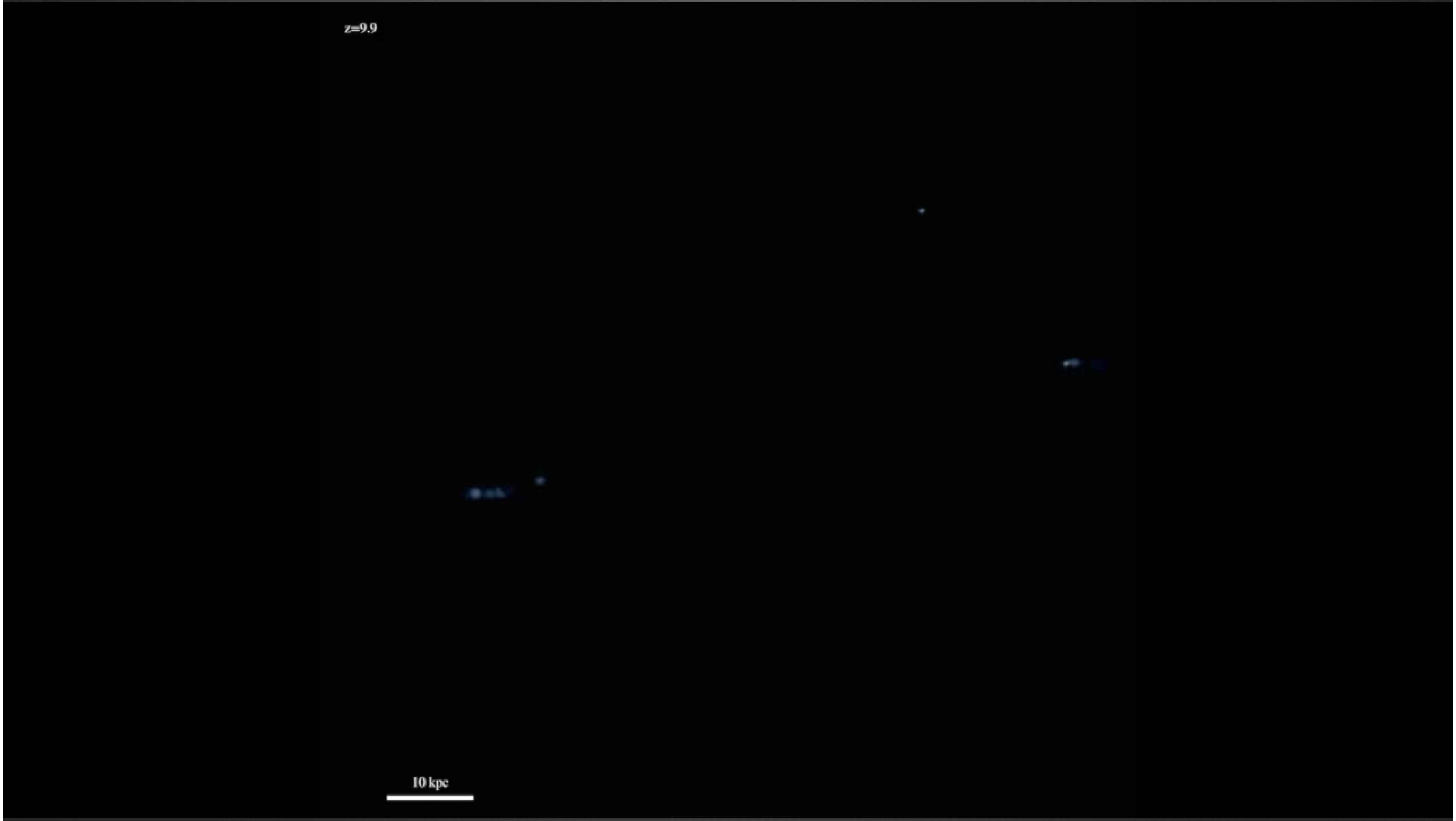
We empirically obtain the Dark Matter velocity distribution.

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!

Herzog-Arbeitman, Lisanti, Madau, **Necib** (2018)
Herzog-Arbeitman, Lisanti, **Necib** (2018)

Feedback in Realistic Environments (FIRE)

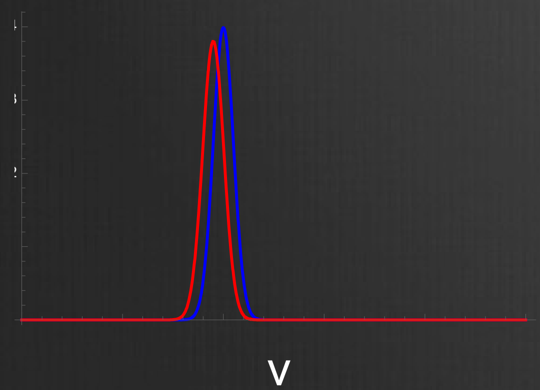


Hopkins et al. (2014) MNRAS 445,581
Wetzel et al. (2016) ApJL, 827, L23
Hopkins et al. (2017) arXiv:1702.06148

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

Merging Stages

Dwarf Galaxy



Merging Stages

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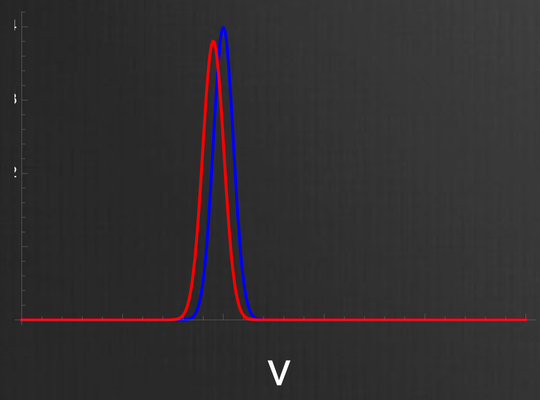
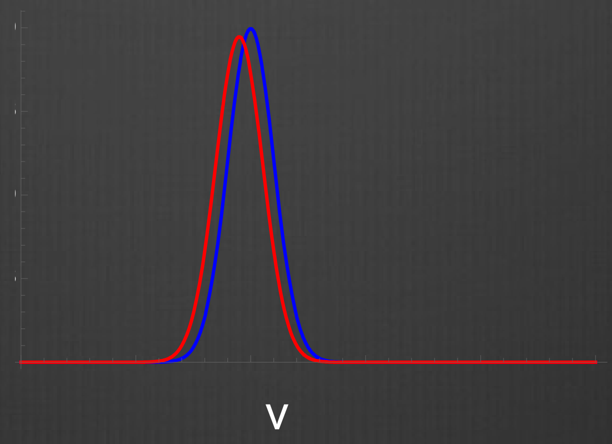
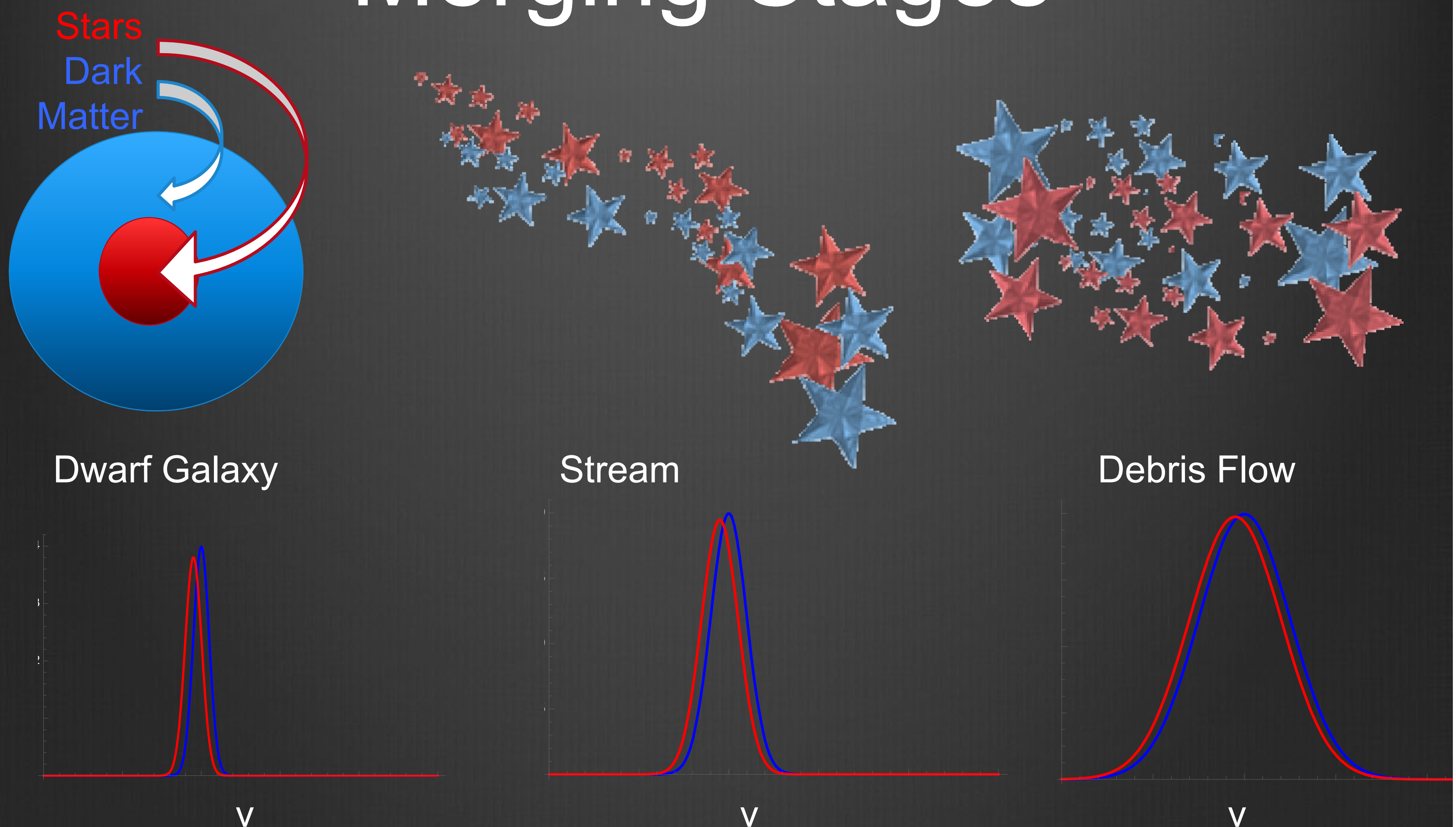


Stream



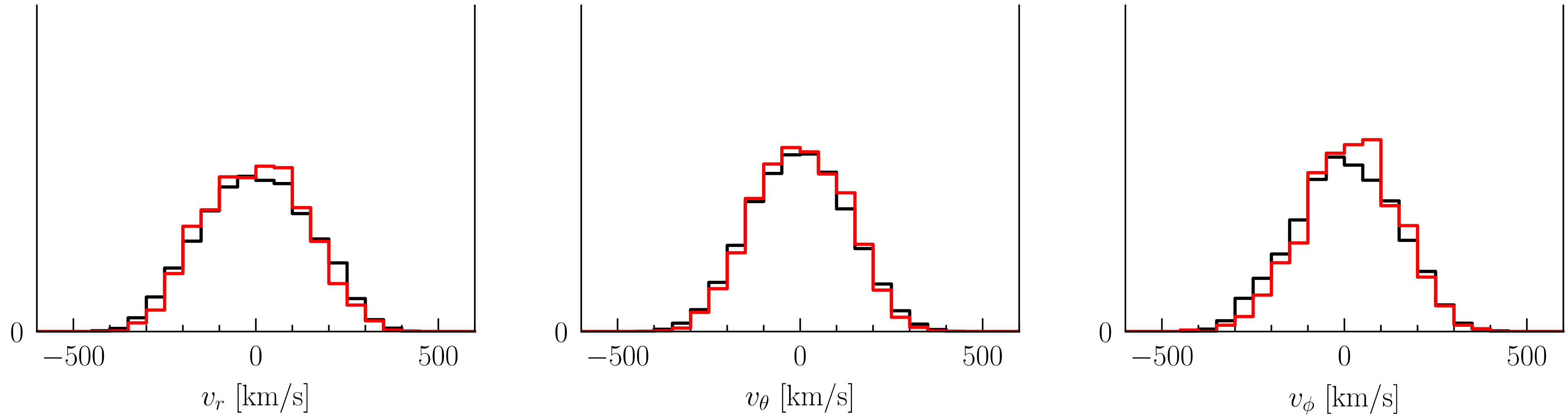
Ivezic et al. (2000)
Yanny et al. (2000)

Merging Stages



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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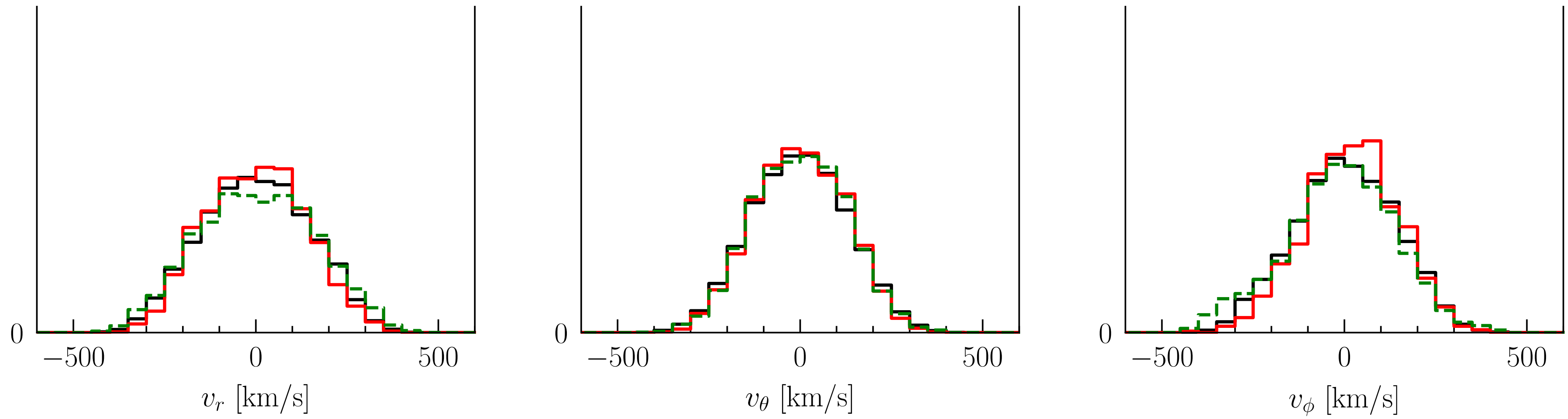

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Necib, Lisanti, Garrison Kimmel et al. (2018)
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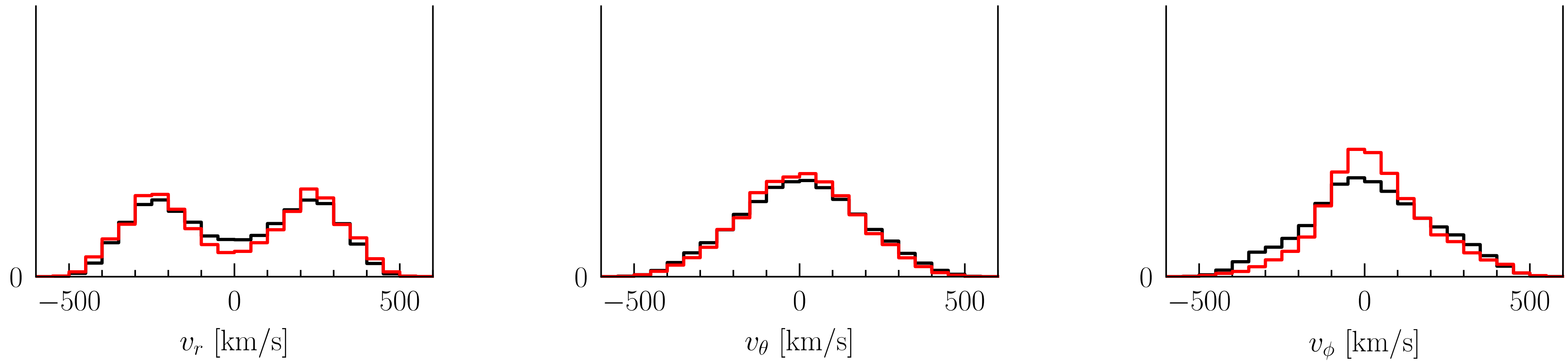
Debris Flow



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

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

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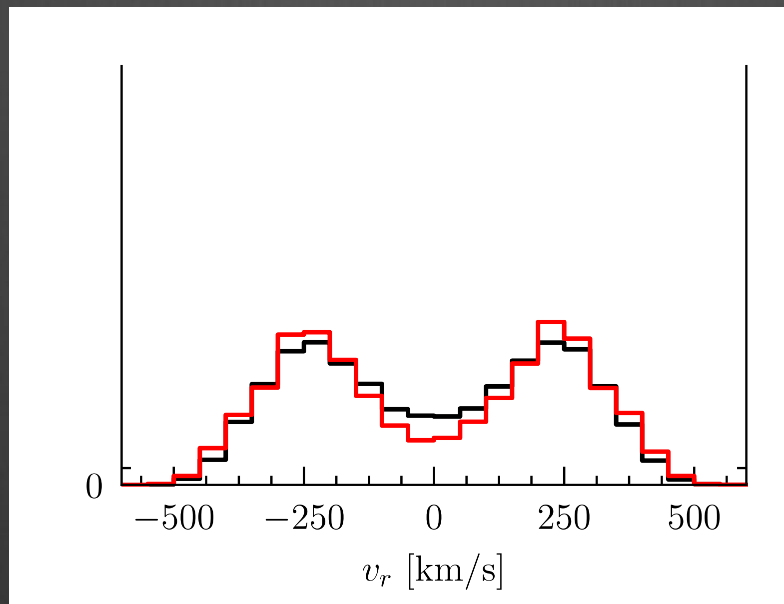

y structure in
he radial
direction!

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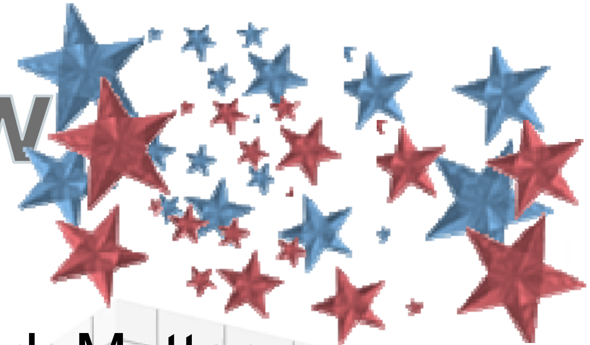

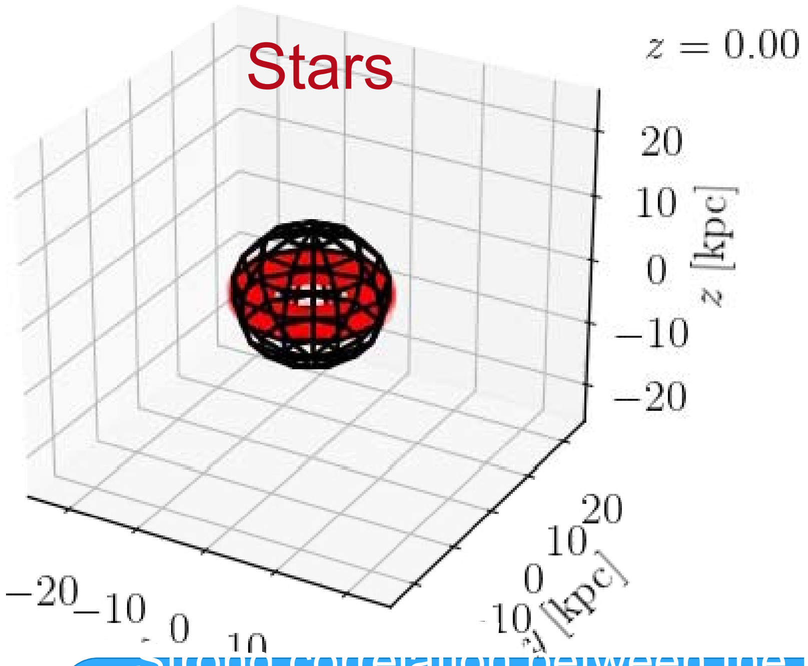

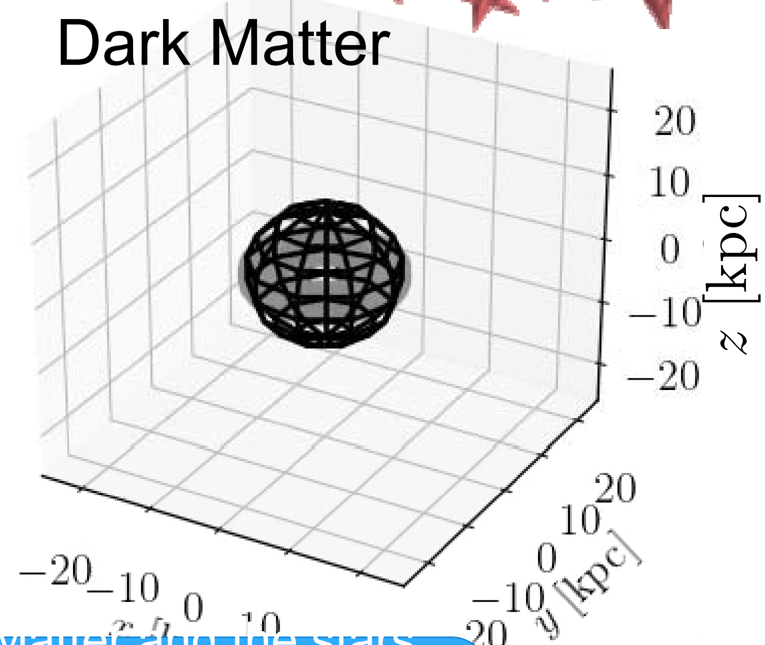

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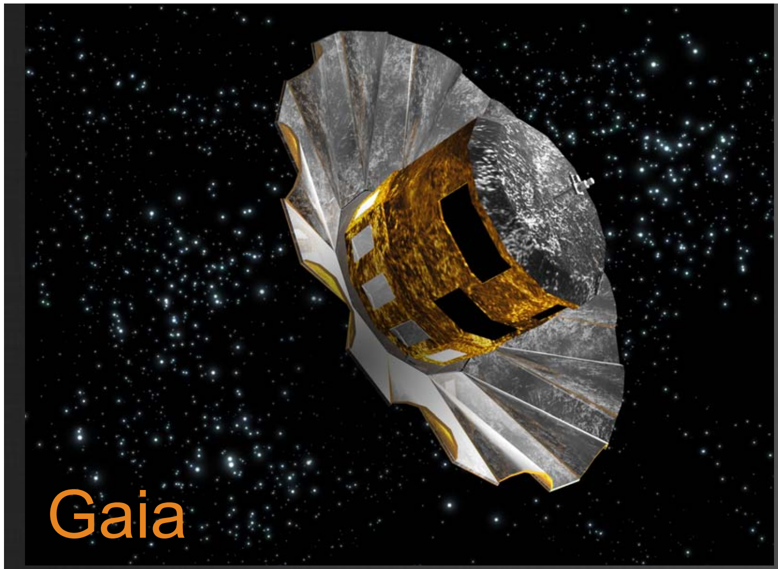
Necib, Lisanti, Garrison-Kimmel et al. (2018)

So, What Does our Milky Way Look Like?

<u>What we learned:</u>

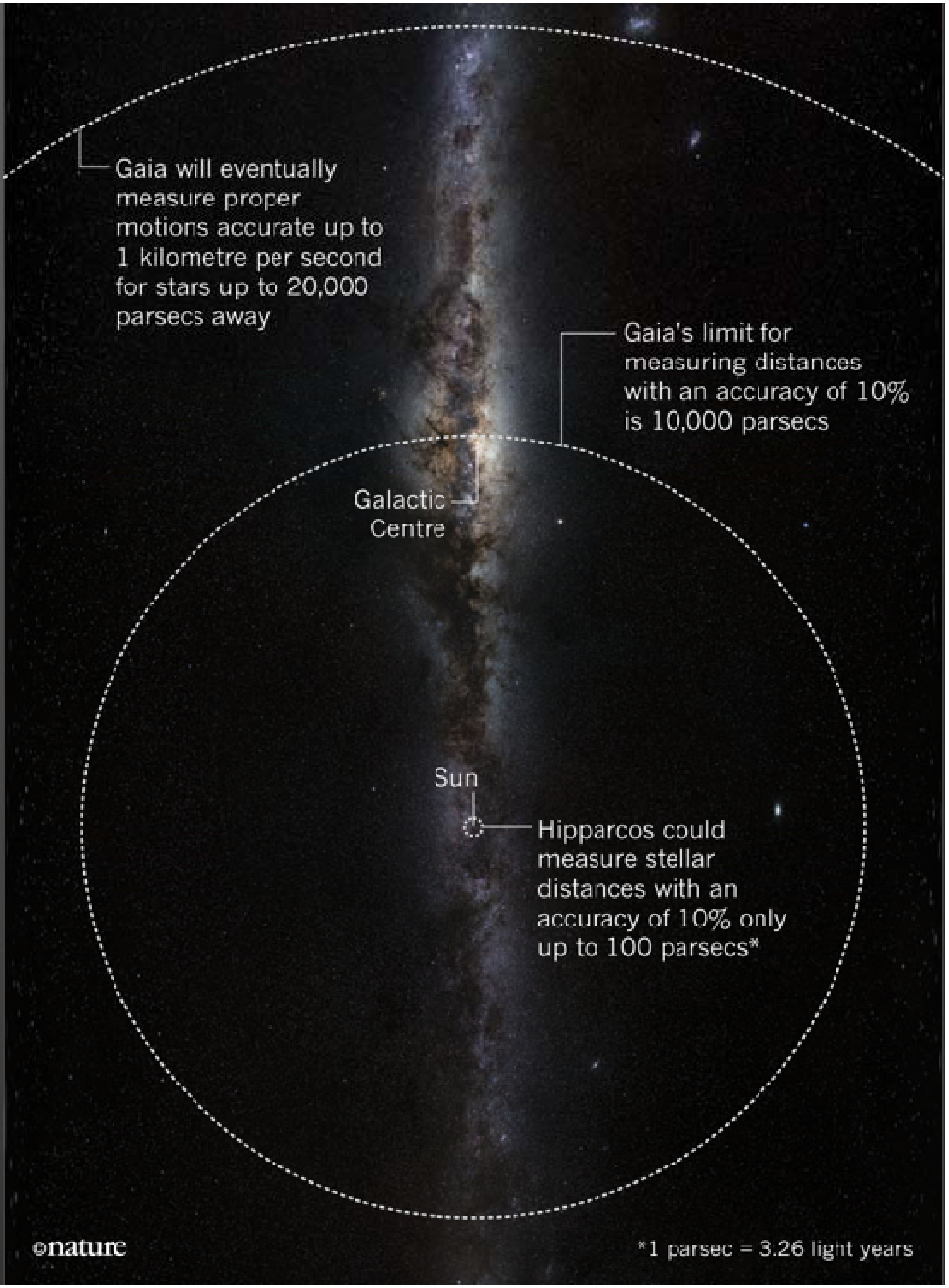
Accreted stars trace their dark matter counterparts.

A merging event shows a loby-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!

Lina Necib, Caltech



Gaia Enceladus/Sausage

https://phys.org/news/2018-10-astronomers-giant-early-days-milky.html

Belokurov et al. (2018)
Deason et al. (2018)
Myeong et al. (2018)
Helmi et al. (2018)
Lancaster et al. (2018)

New Structure!

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

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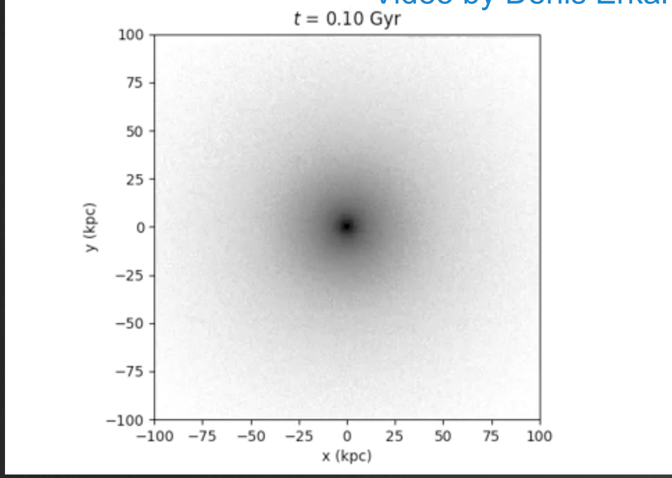
Video by Denis Erkal



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Belokurov et al. (2018)
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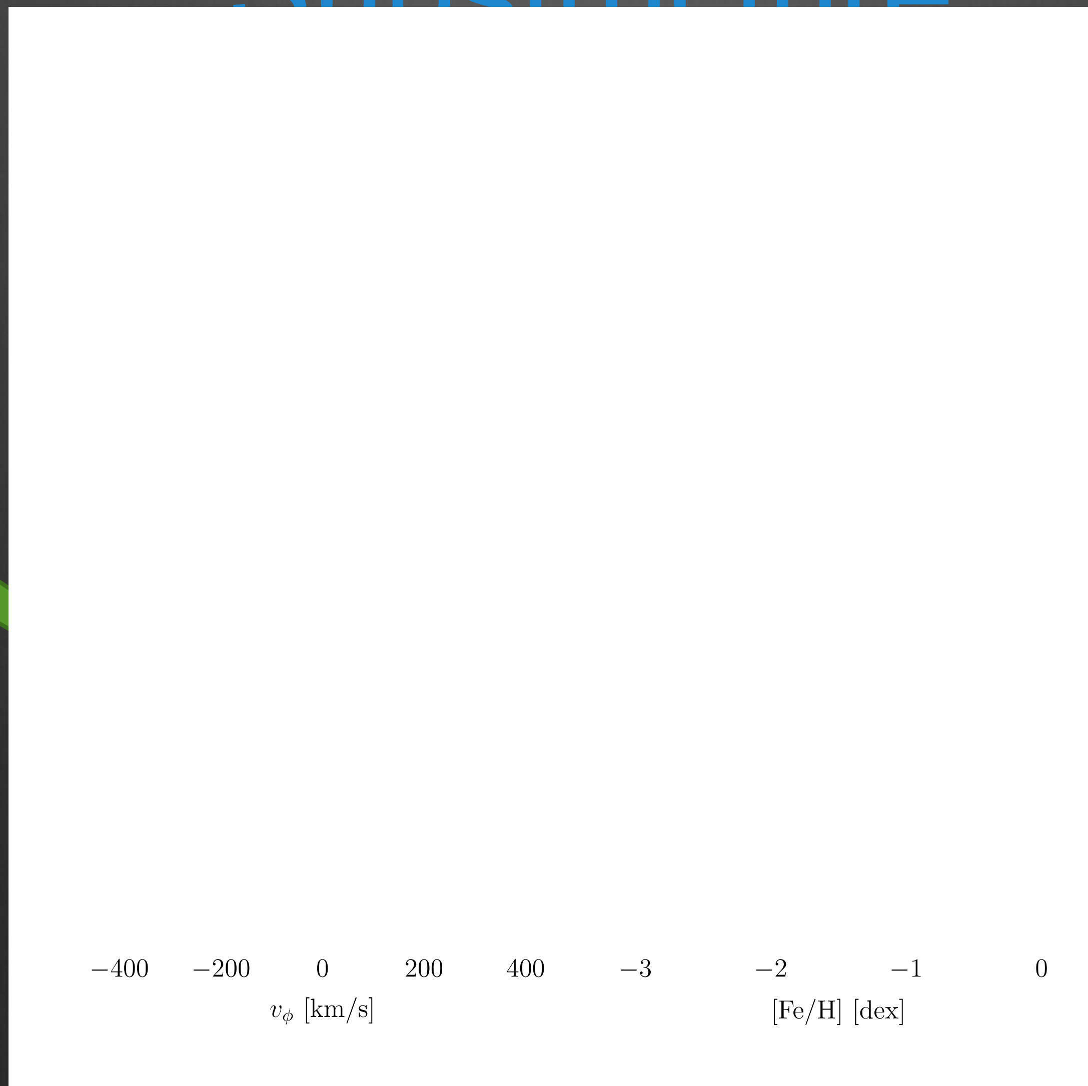
Lancaster et al. (2018)

Disk, Halo, and Substructure

Azimuthal Rotation

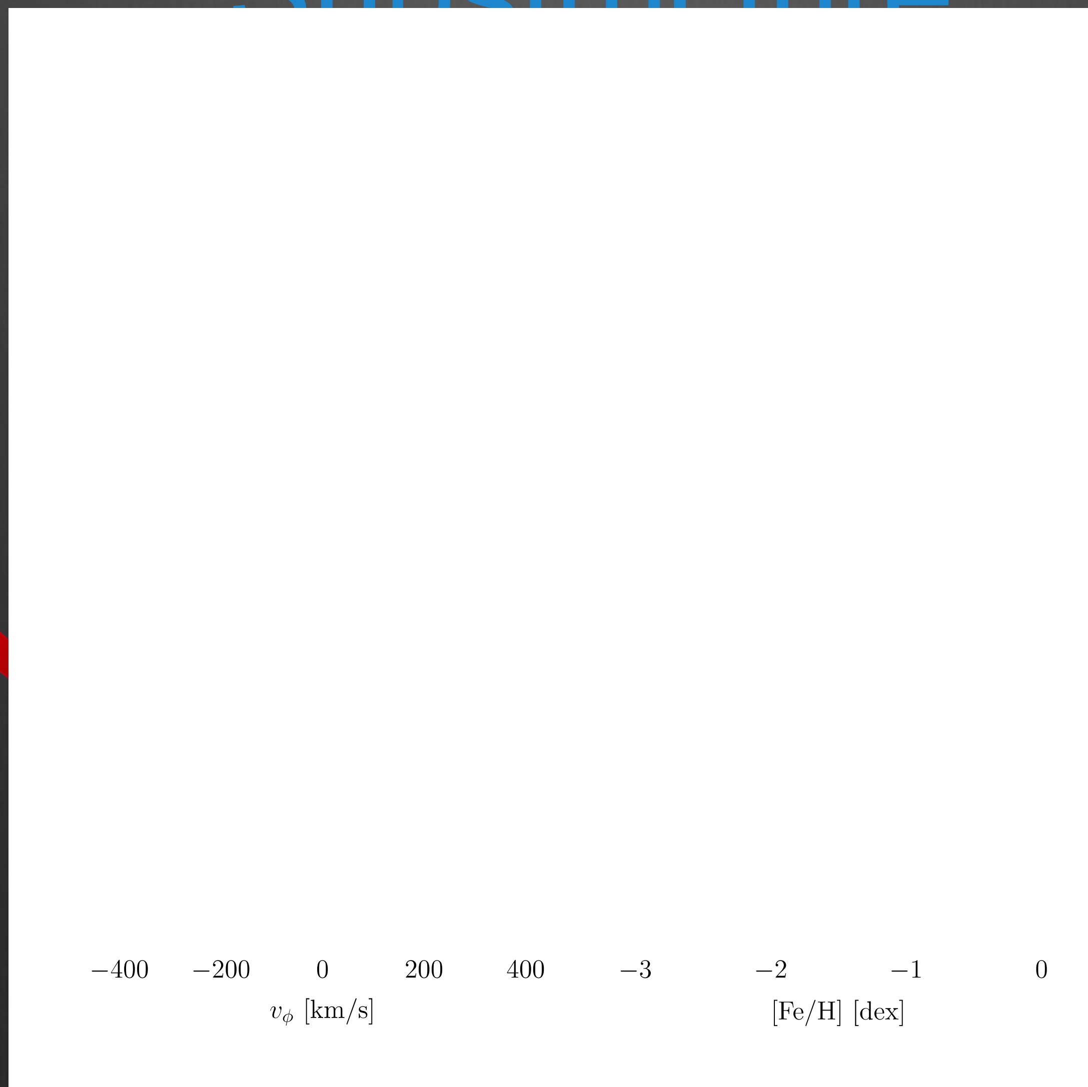


Metal-Rich, Younger Population

Necib, Lisanti, Belokurov (2018)

Disk, Halo, and Substructure

Isotropic

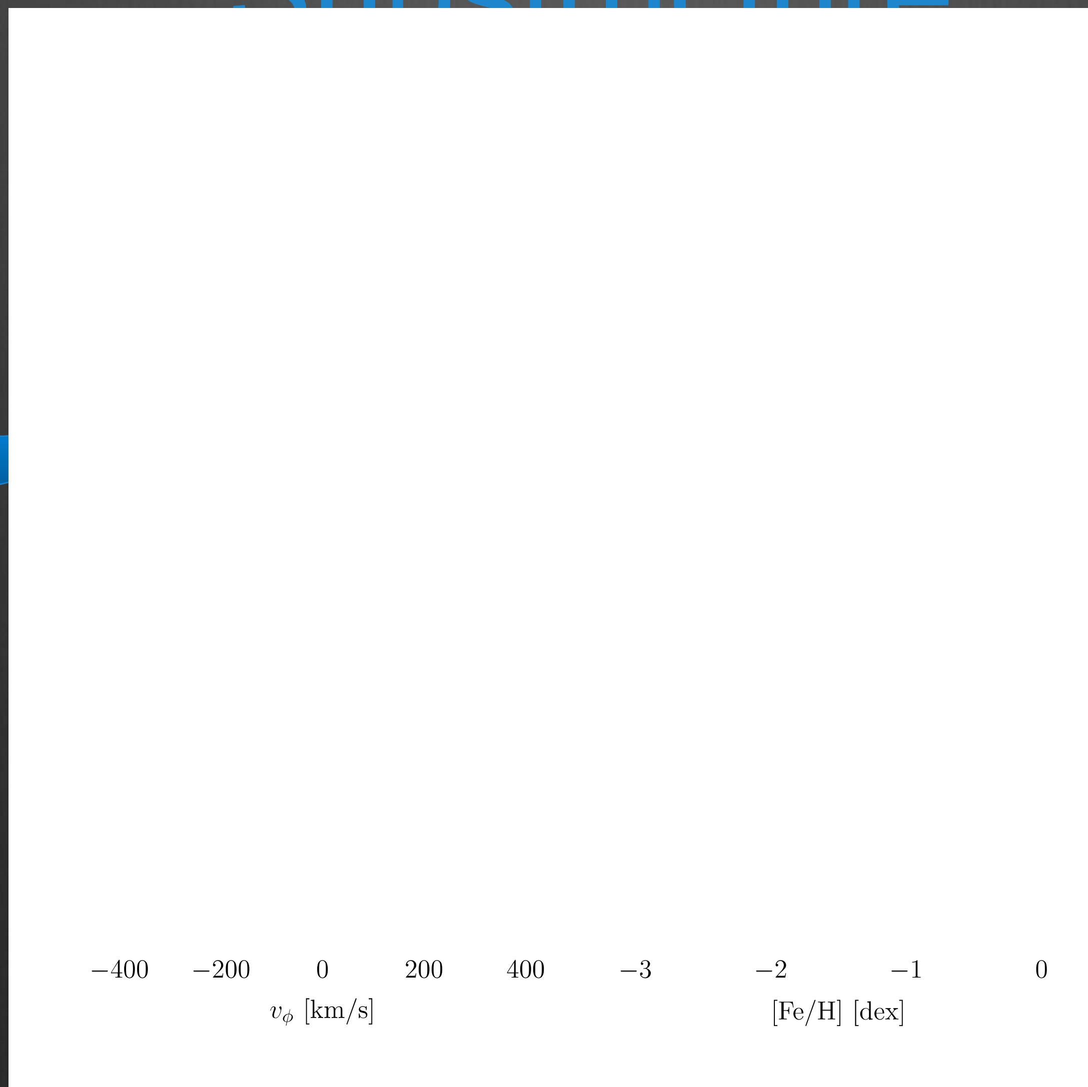


Older Population

Necib, Lisanti, Belokurov (2018)

Disk, Halo, and Substructure

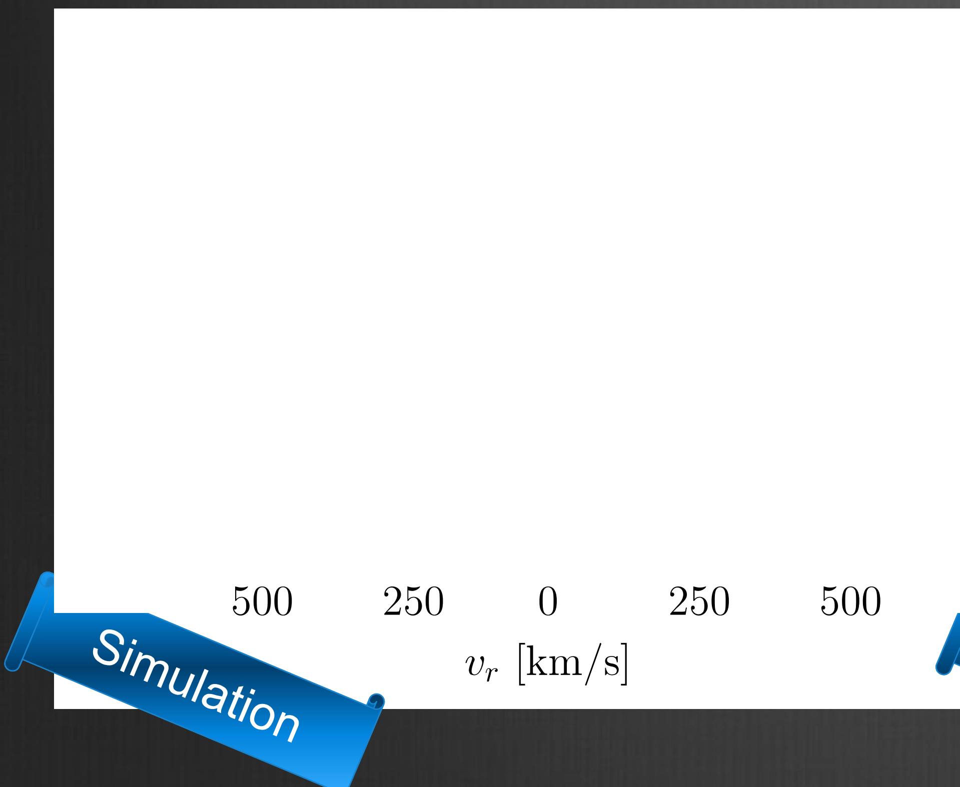
Loby Structure

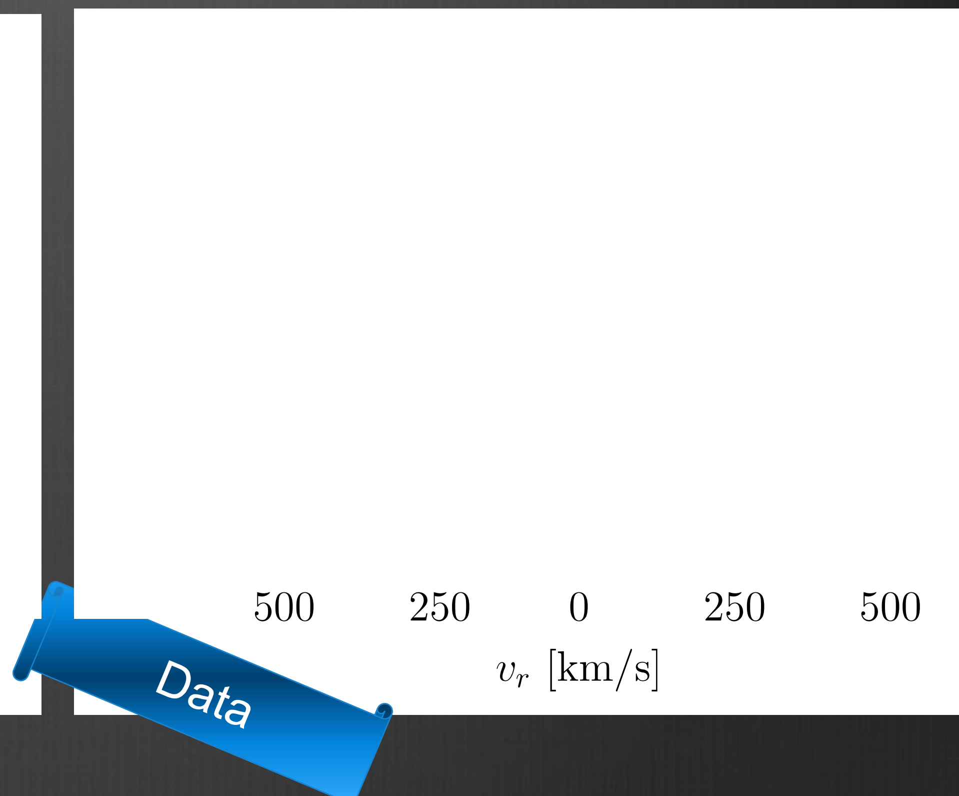


Older than the Disk, Younger than the Halo

Necib, Lisanti, Belokurov (2018)

Disk, Halo, and Substructure





Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)

Not that ``Sub" of a Structure

$z_{\rm cut}$ [kpc]

$|z| > z_{\rm cut}$

$z_{\rm cut}$ [kpc]

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

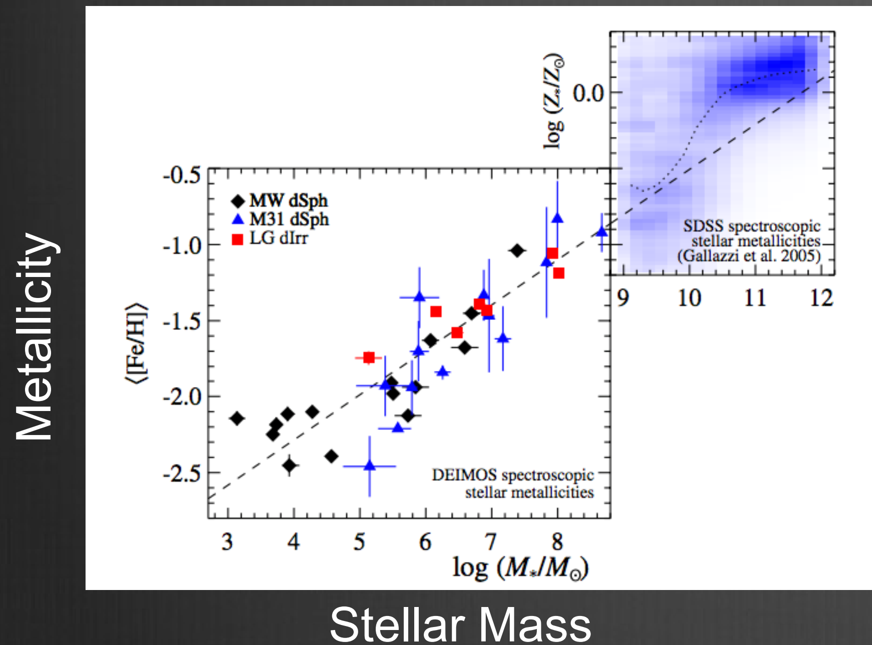
<u>What we learned:</u>

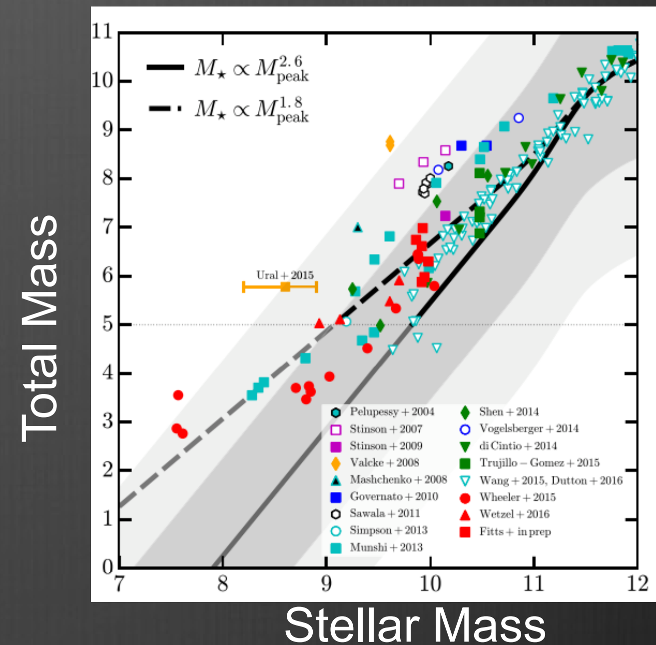
There is a dominant structure of debris flow in the solar neighborhood.

Accreted stars should trace their dark matter counterparts from mergers.

BUT! Mergers do not contribute the same amounts of Dark Matter and Stars!

Rescaling Dark/Light Contributions

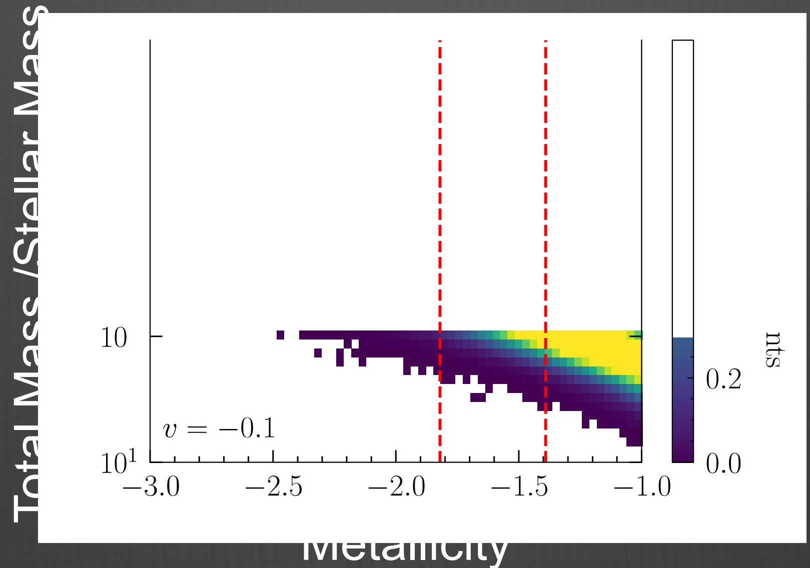




- Subhalos do not contribute the same amounts of Dark Matter and Stars.
- One needs a new relation from which we can extrapolate the amount of Dark Matter in a merger.

Gallazzi et al. 2005
Kirby et al. 2013
Garrison-Kimmel et al. 2017a
Necib, Lisanti, Garrison-Kimmel et al (2018)

Rescaling Dark/Light Contributions



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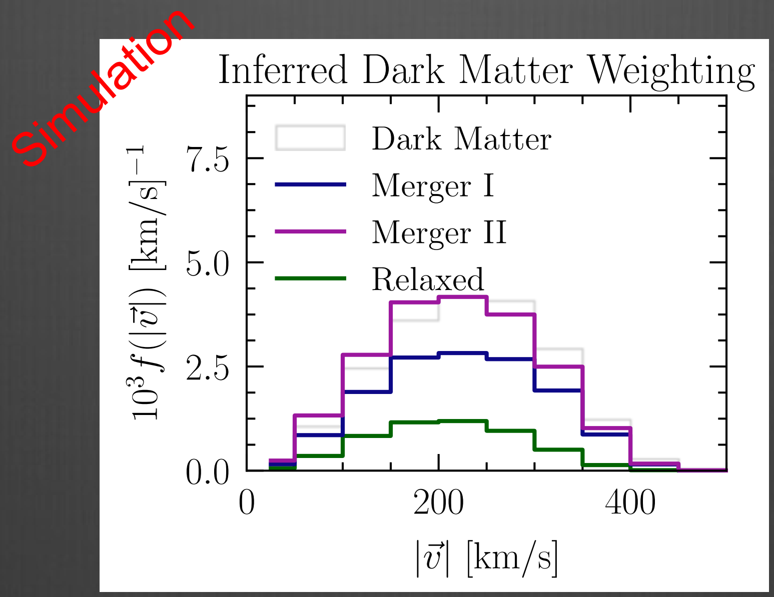

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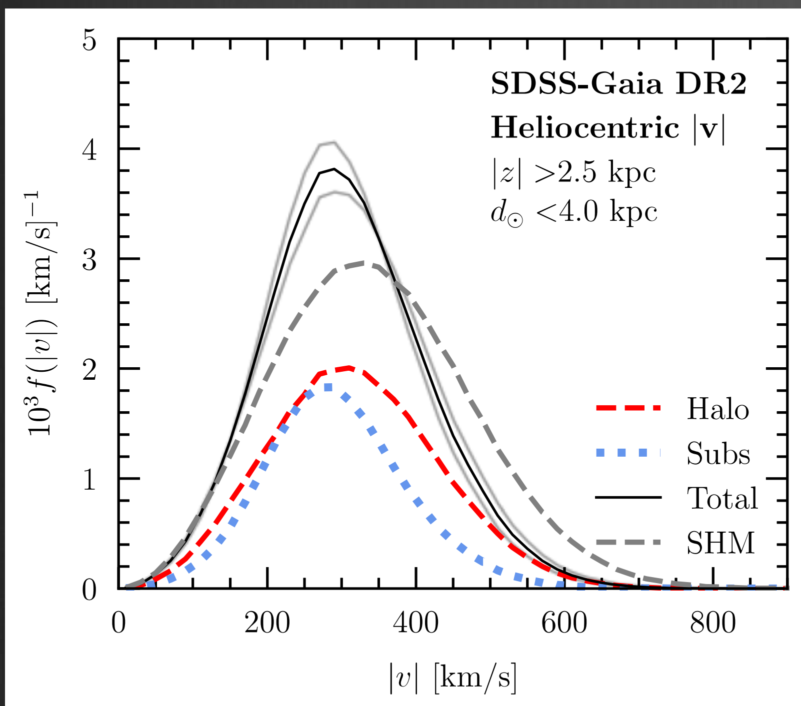
Necib, Lisanti, Garrison-Kimmel et al (2018)


Smooth Accretion
Dark Subhalos
Stream 2
Debris Flow 1
Stream 1
Old Mergers!
Younger Mergers !

We reconstruct the dark matter distribution component by component!

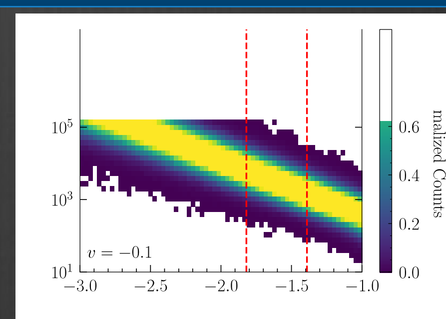
New Velocity Distribution!

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



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

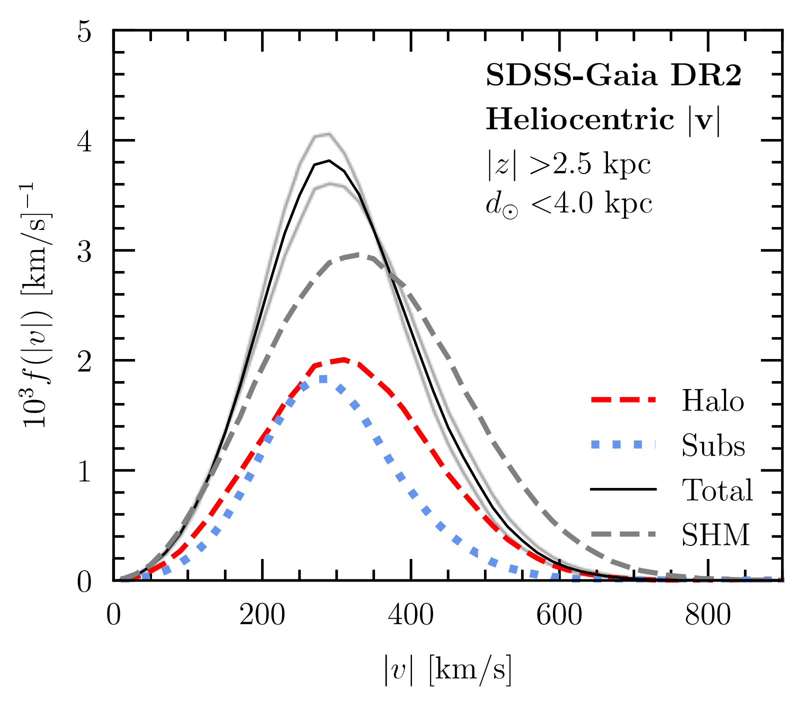
Rescaling from the Metallicity-Mass/Light Ratio derived.



Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)

New Velocity Distribution!

$$f_{\rm total}(v) = c_{\rm halo} f_{\rm halo}(v) + c_{\rm subs} f_{\rm subs}(v)$$



$$c_{\rm subs} = 0.42^{+0.26}_{-0.22}$$

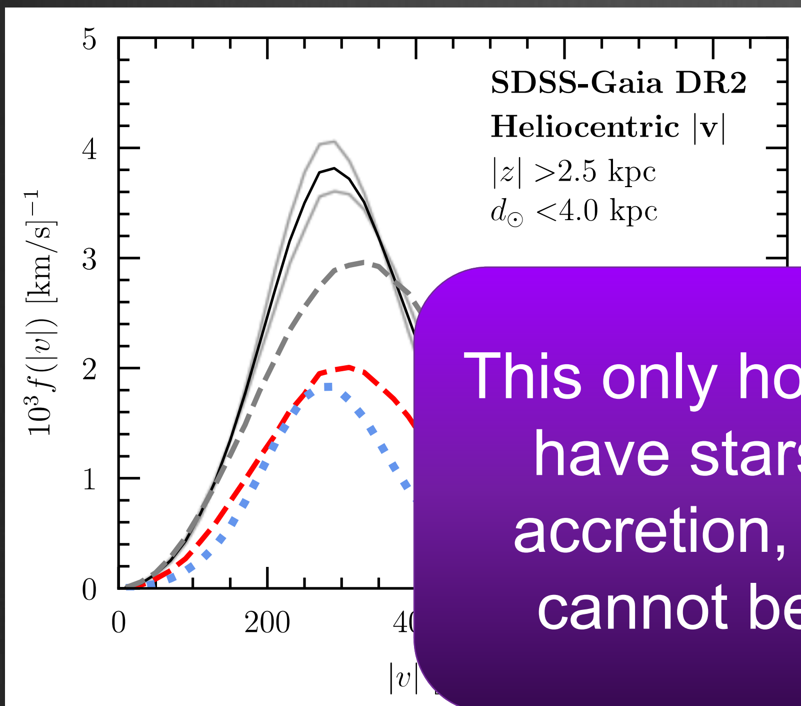
Similarly to simulations, we build the different components of the velocity distribution.

Are there any components missing?

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)

New Velocity Distribution!

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



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

ns, we build the
s of the velocity

onents missing?

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

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)

New Velocity Distribution!

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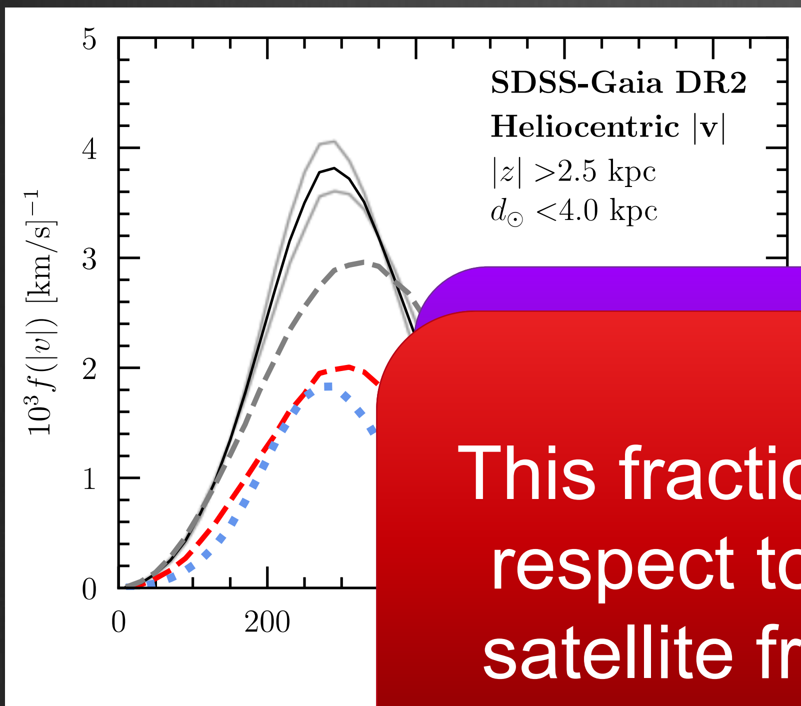


$$c_{\mathrm{subs}} = 0.42^{+0.26}_{-0.22}$$

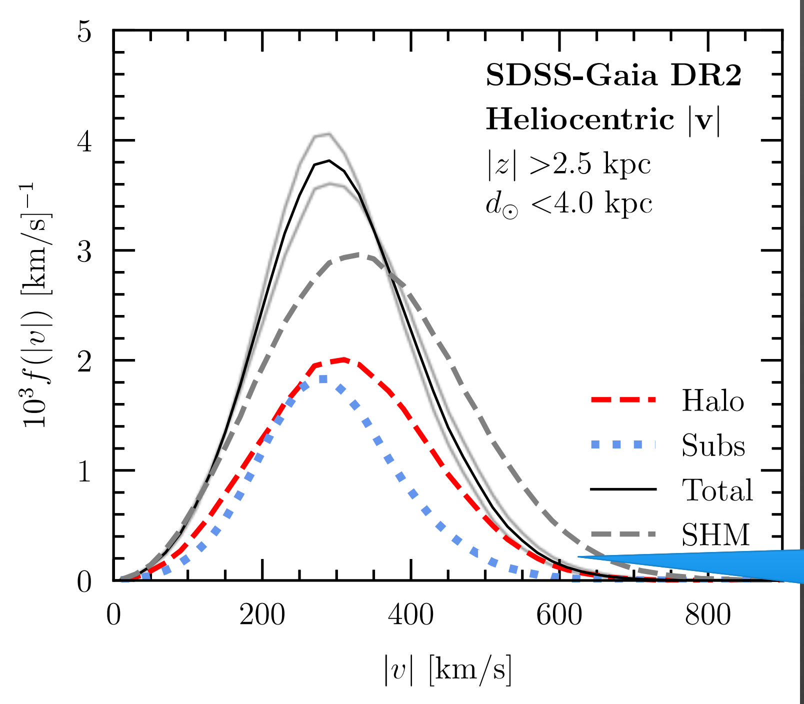
This fraction is taken with respect to the luminous satellite fraction, not the total Dark Matter fraction!

ns, we build the
s of the velocity

onents missing?

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)

New Velocity Distribution!



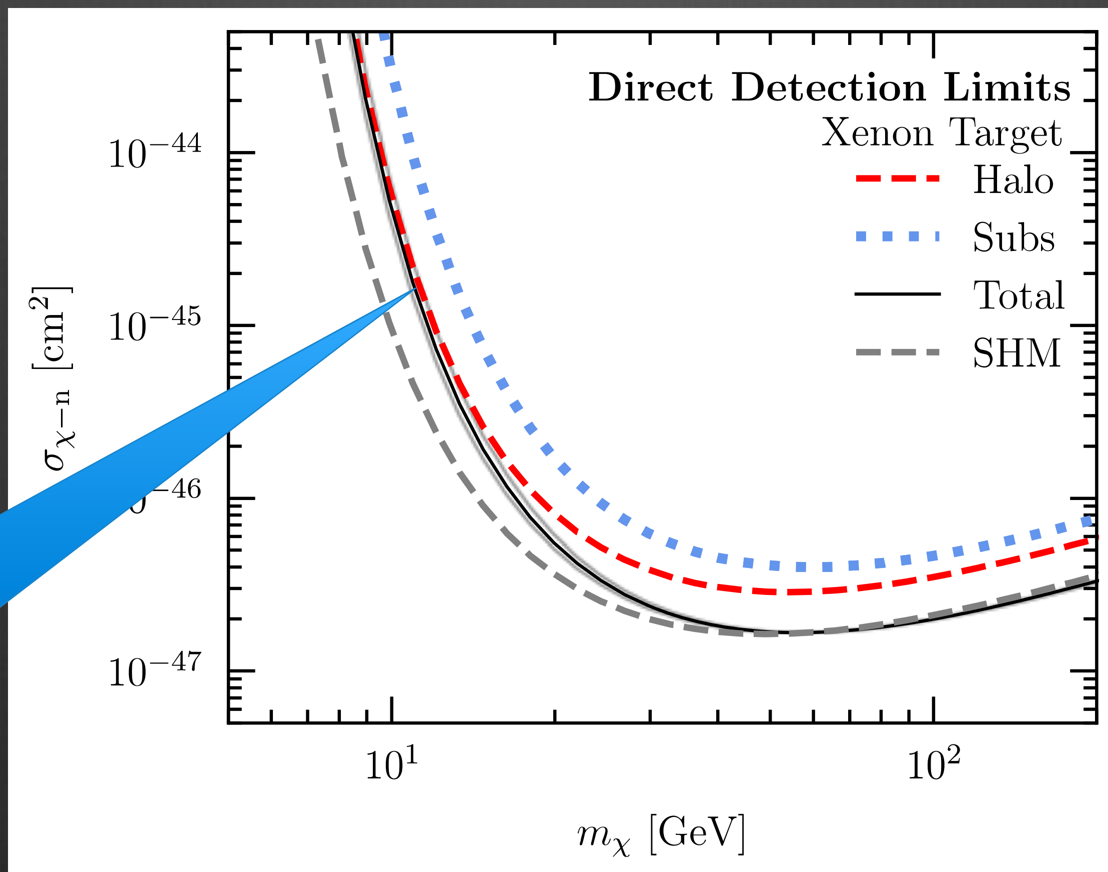
Can be found in a github repository near you
https://linoush.github.io/DM_Velocity_Distribution/

Link in paper arXiv:1807.02519.

Final distribution different from the assumed Maxwell Boltzmann distribution

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrison-Kimmel et al. (2018)

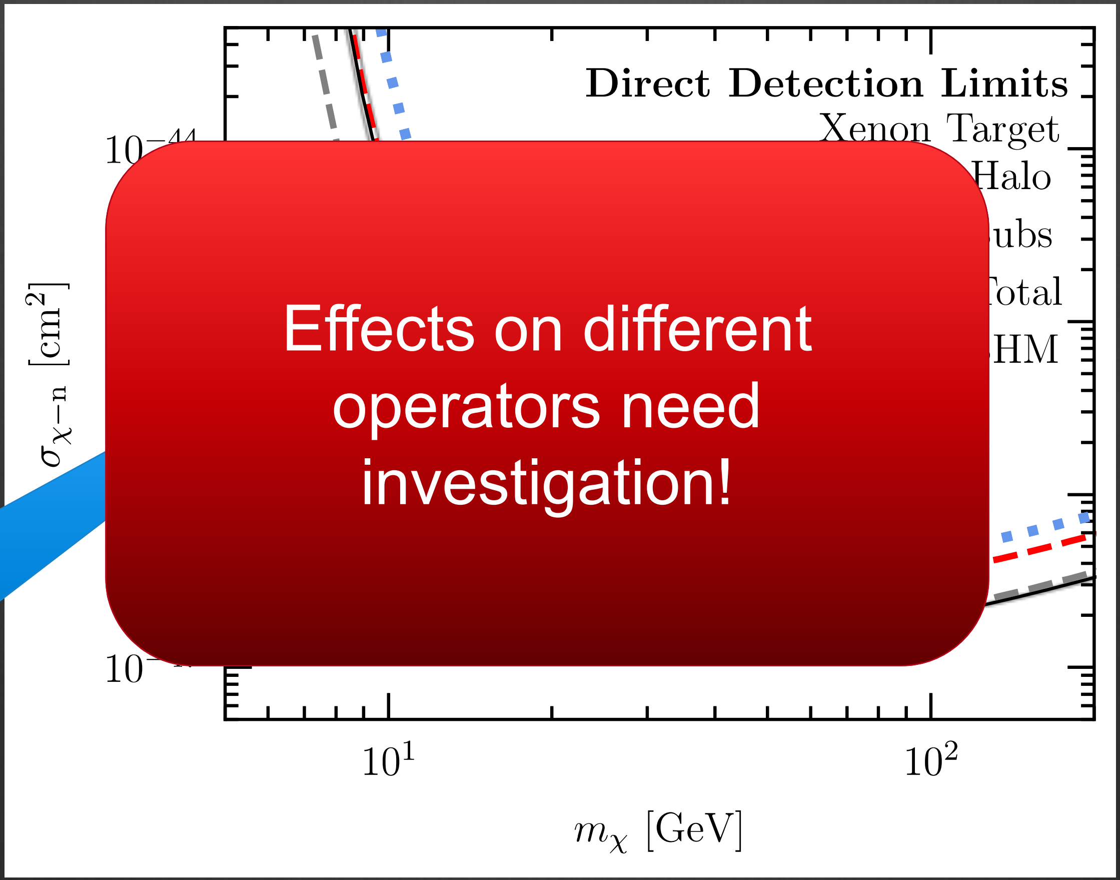
Implications for Direct Detection



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

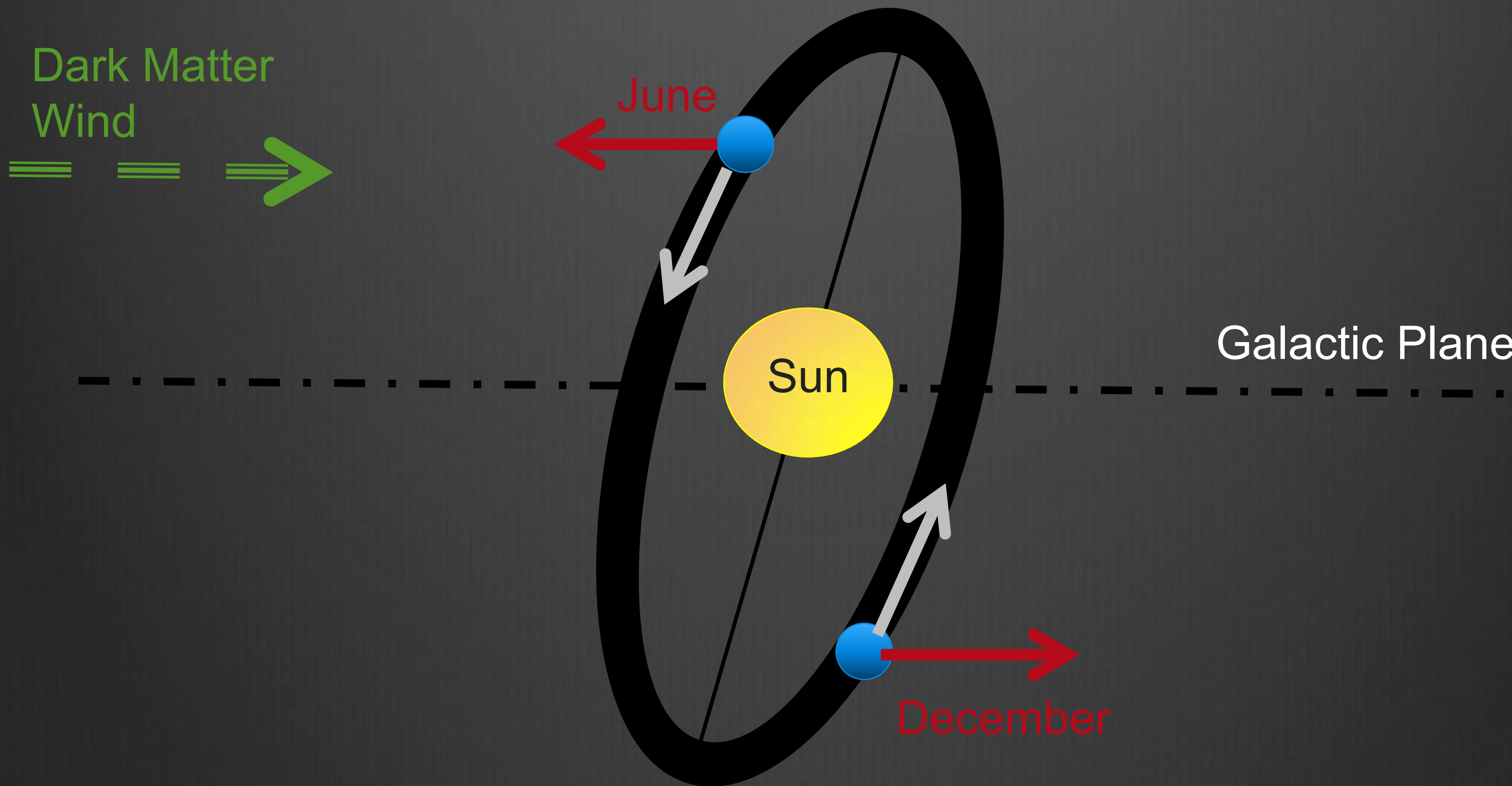


Effects on different operators need investigation!

Largest changes are at low dark matter masses

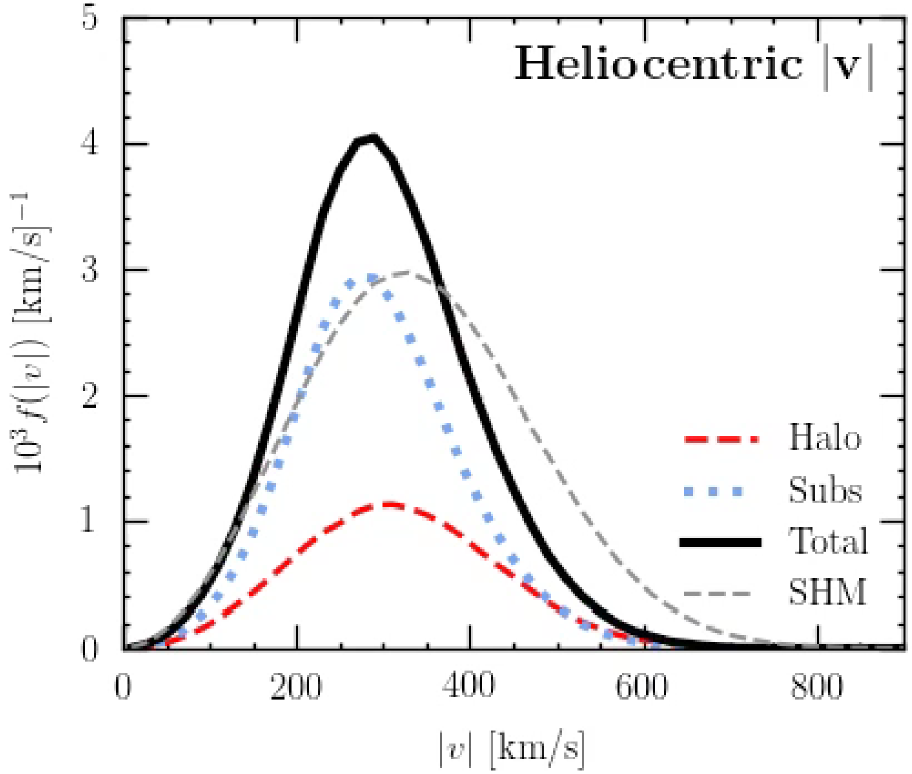
This is schematic, where we used hard thresholds and did not incorporate efficiencies.

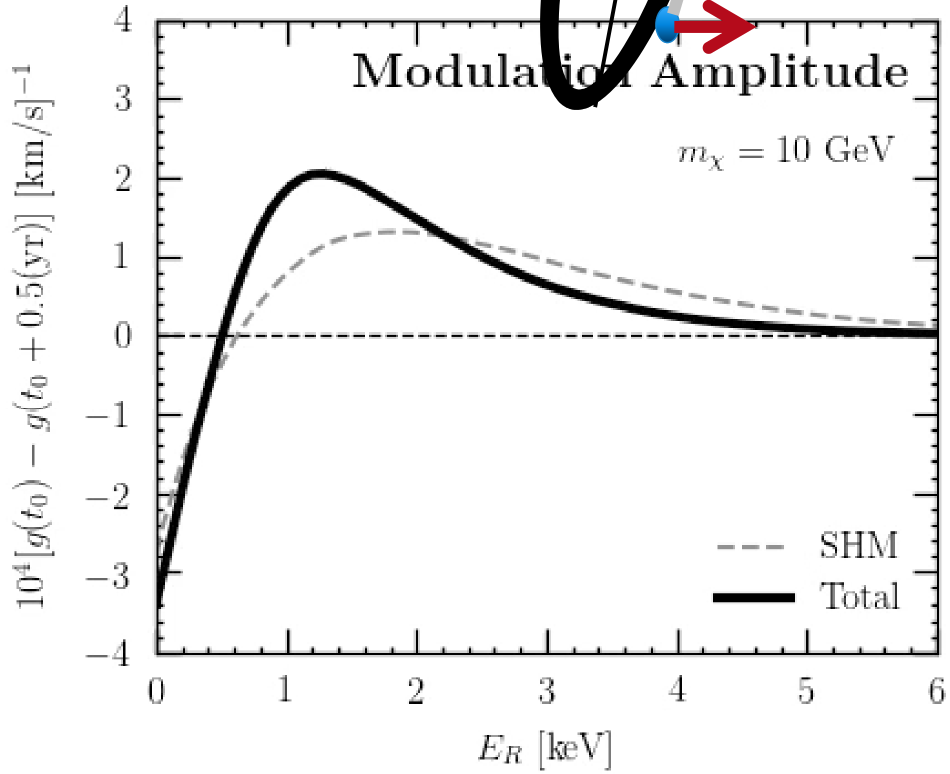
Implications for Direct Detection

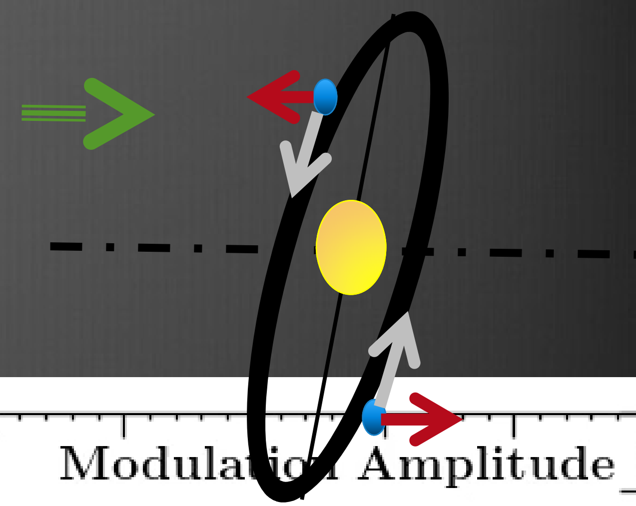


Anisotropy of the system leads to modulation effects.

Implications for Direct Detection



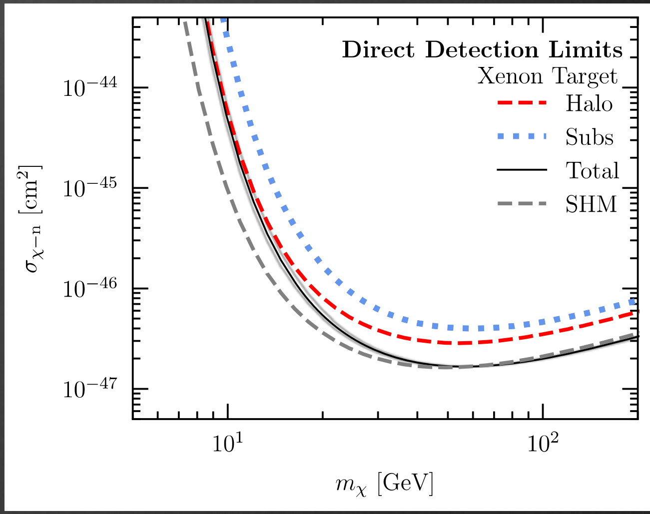




Anisotropy of the system leads to modulation effects.

Conclusions

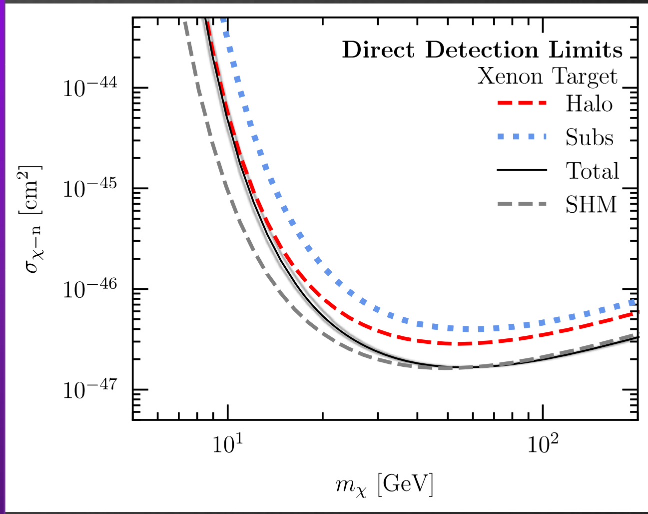
- Stars trace the velocity of the Dark Matter.
  - This is only true for merging satellites that have stars in them. Diffuse/Smooth Dark Matter and dark subhalos cannot be traced this way!
- We can use stars to empirically measure the velocity distribution of Dark Matter accreted from luminous satellites.
- We live in a huge debris flow that affects our direct detection limits.



Conclusions

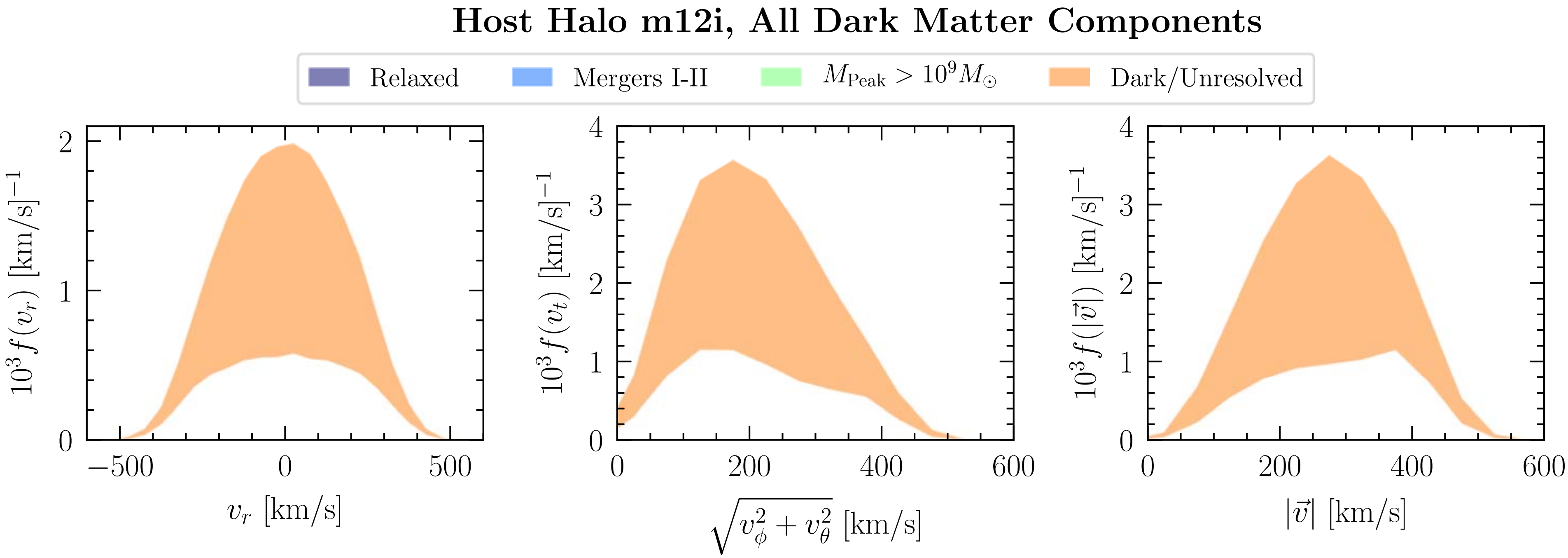
More to do:

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.

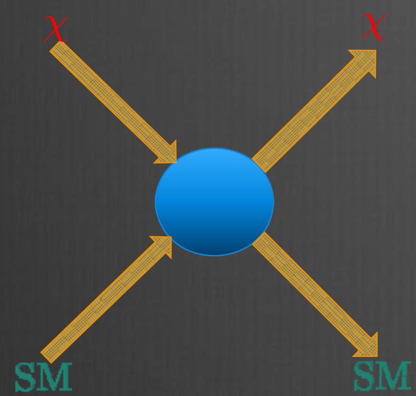


Bonus

Unresolved component



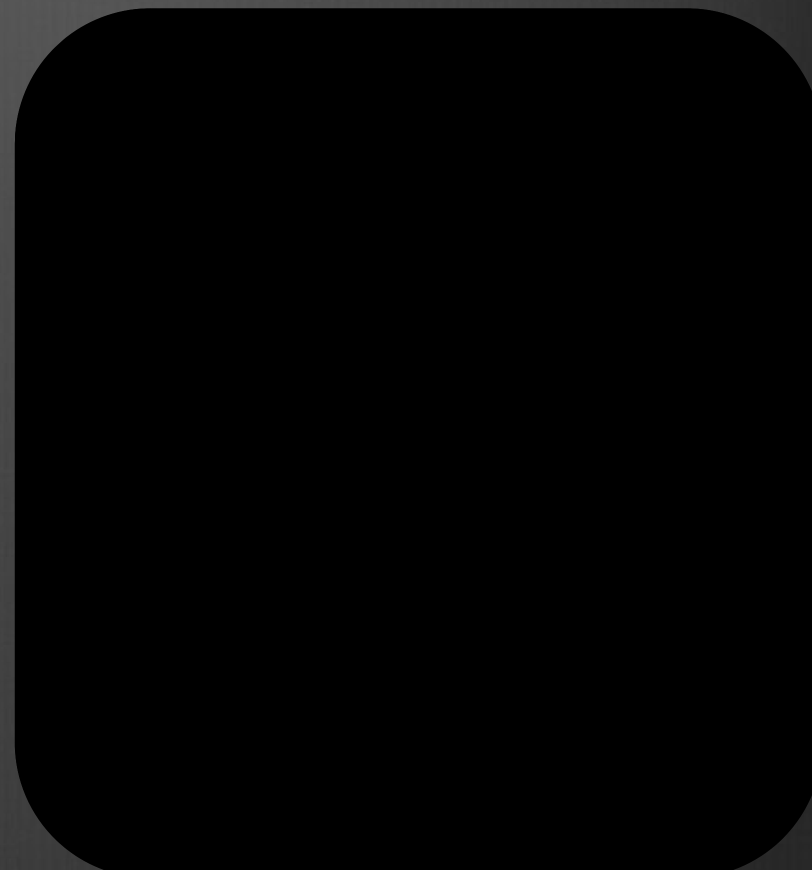
Direct Detection Rate



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

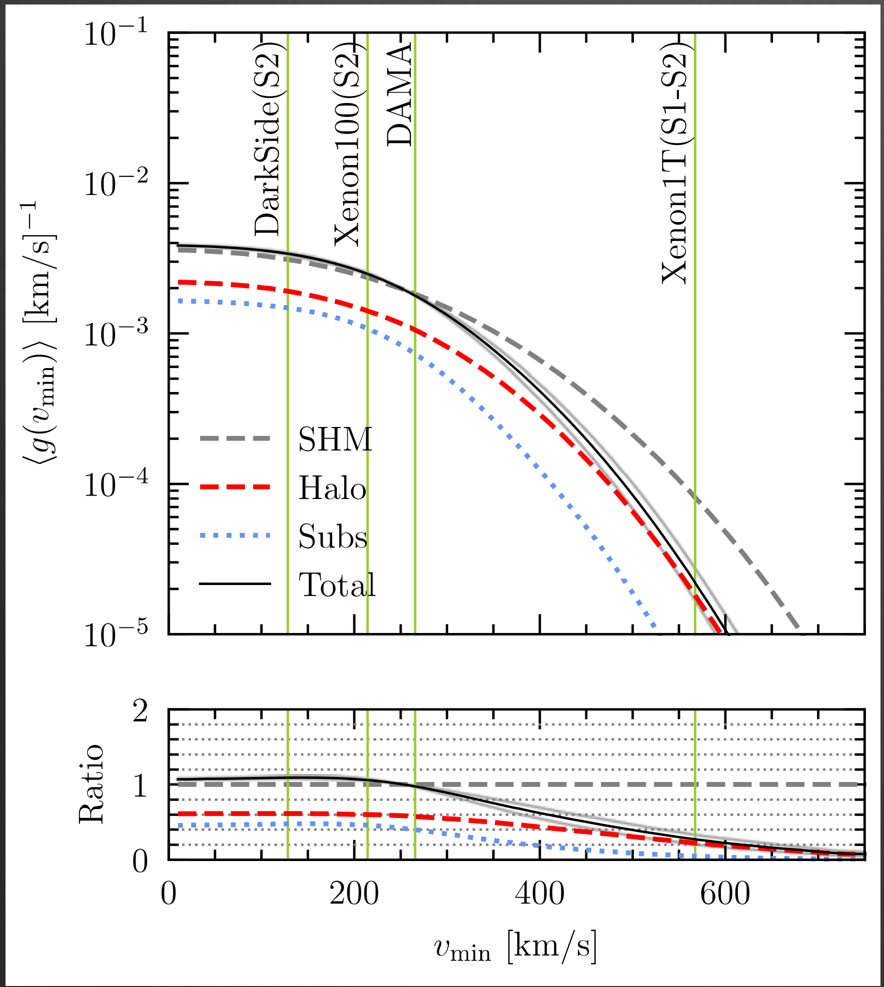
$$R \propto \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v} dv$$

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



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

Implications for Direct Detection



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

v_{min} depends only on the dark matter mass and the experimental threshold.