Dark Matter Properties from GAIA

Lina Necib, Caltech

Based on

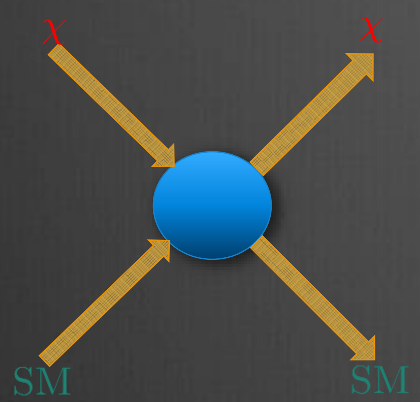
Necib, Lisanti, Belokurov, arXiv:1807.02519

Necib, Lisanti, Garisson-Kimmel, Wetzel, Sanderson, Hopkins,Faucher-Giguère, Kereš arXiv:1810.XXXXX

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

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

Direct Detection Rate



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

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

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

Direct detection depends on:

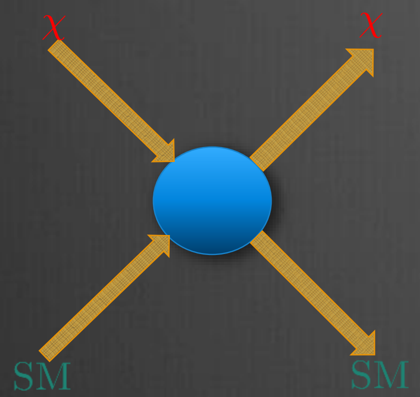
Astrophysical Parameters:
Dark matter density, velocity.

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)

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

Direct Detection Rate



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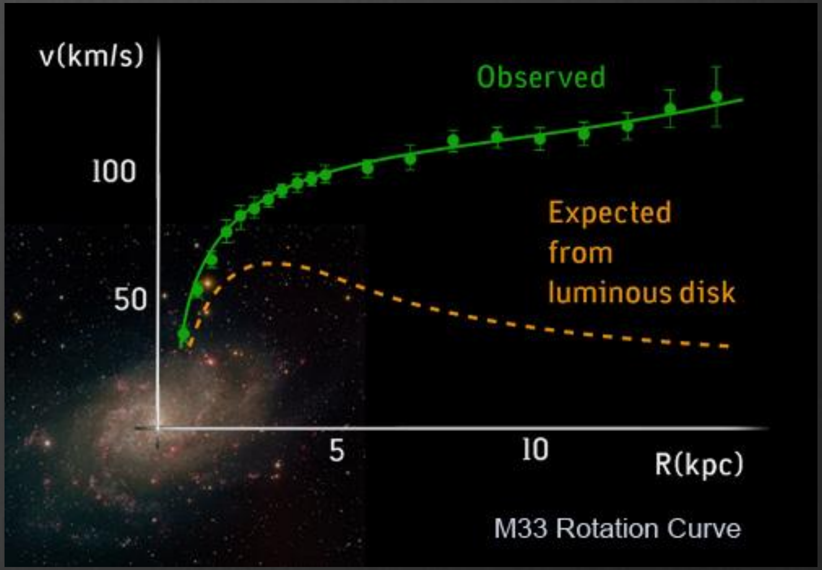
The Standard Halo Model

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



Rubin & Ford (1970)

The Standard Halo Model

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σ : velocity dispersion

Standard Halo Model

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

Jeans (1915)
Binney & Tremaine (2008)

Local Velocity Distribution

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

Poisson

Standard Halo Model

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

Maxwell-Boltzmann Distribution

Poisson (1813)
Jeans (1915)
Binney & Tremaine (2008)

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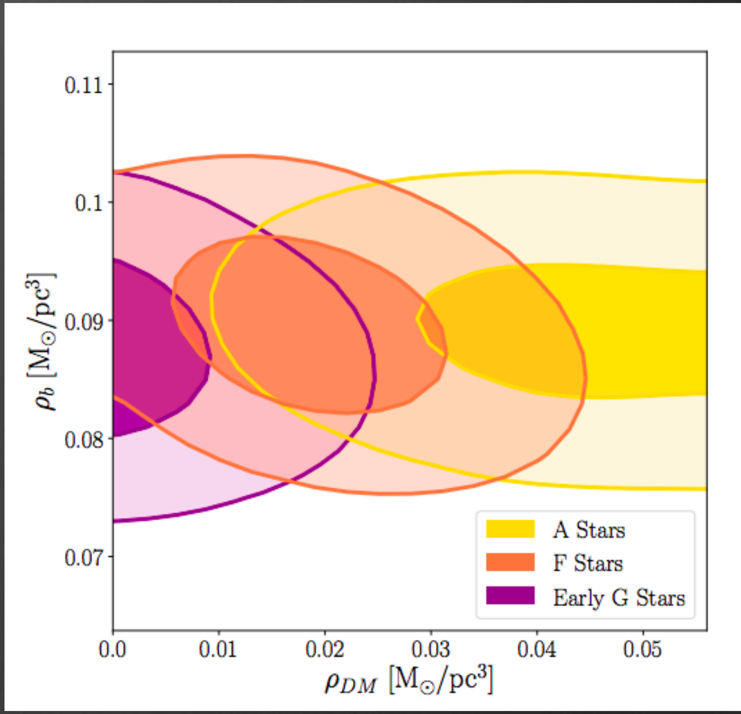
We assumed Equilibrium and Isotropy!

Poisson (1813)
Jeans (1915)
Binney & Tremaine (2008)

Local Density

The velocity of the local stars can be used to determine the local density of dark matter, by modeling the Jeans equation, and assuming that the system is in equilibrium.

$$\nabla^2 \Phi = 4\pi G(\rho_{\mathrm{DM}} + \rho_{\mathrm{b}})$$

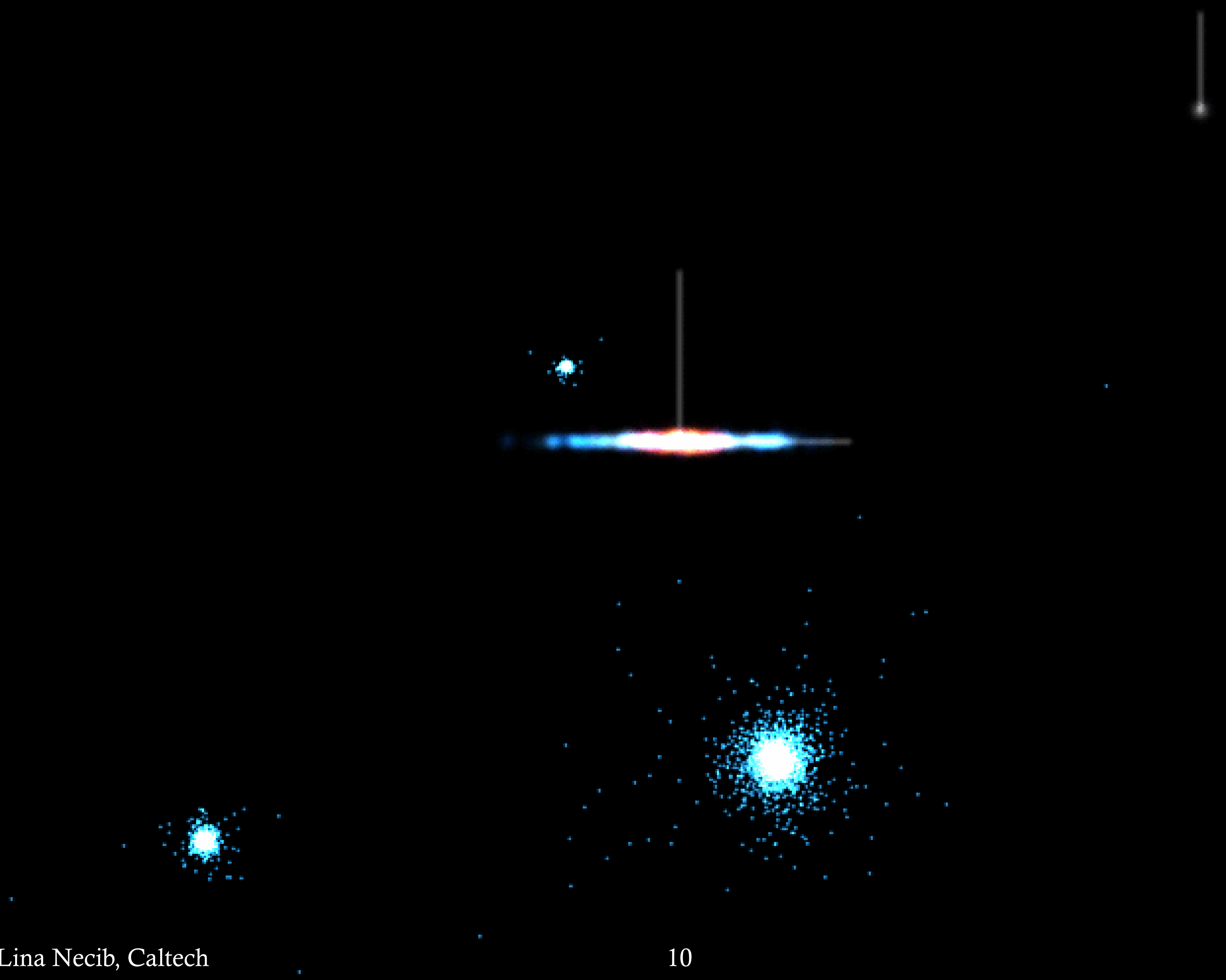


Kapteyn (1922)
Oort (1932)
Read (2014) for review
Shutz et al. (2017)
Buch et al. (2018)

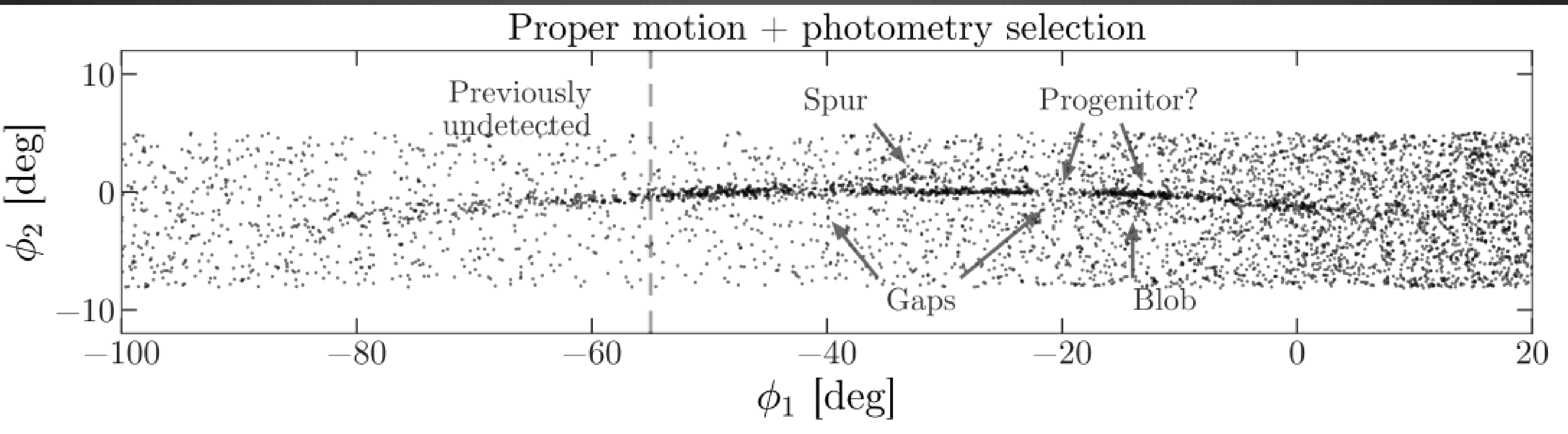
But is our Galaxy in Equilibrium and Isotropic?

What we learned:

For direct detection, we use the Maxwell Boltzmann velocity distribution which assumes equilibrium and isotropy.



Gaia: Stream Finder!



- Gaps in streams can constrain dark matter subhalo masses, and therefore models of warm dark matter!
- Streams are also used to constrain the potential of the Milky Way.

Grillmair & Dionatos (2006b)
Koposov et al. (2010)
Price-Whelan & Bonaca (2018)
Bonaca et al. (in prep)

Building the Dark Matter Velocity Distribution

What we learned:

Galaxies form hierarchically.

Merging galaxies bring in both dark matter and stars.

From Simulations:

Accreted Stars trace the velocity of their Dark Matter counterparts.

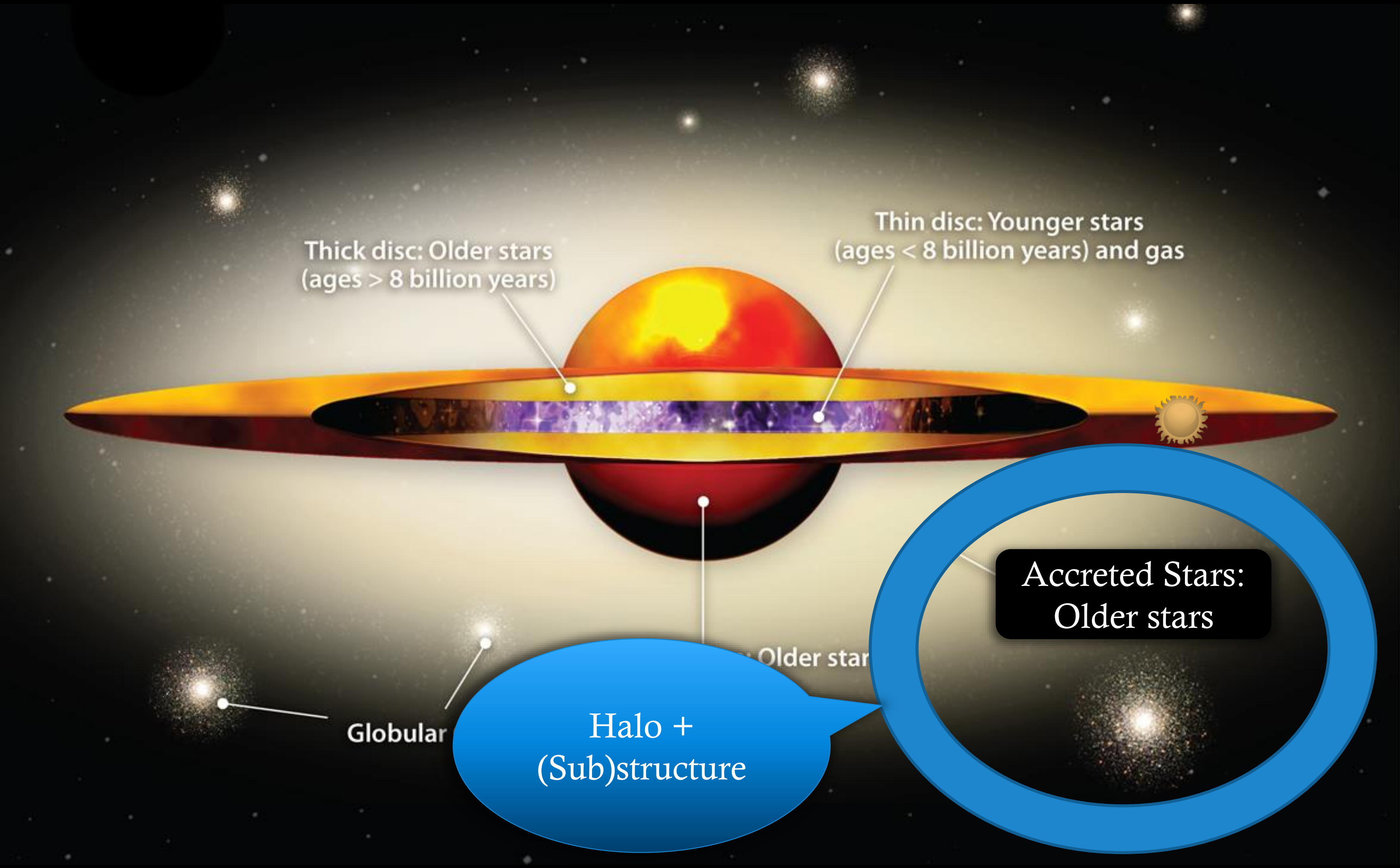
From Gaia DR1/DR2:

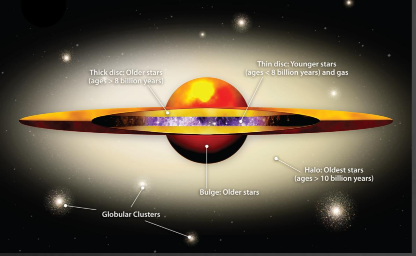
We get the local velocity distribution of accreted stars.

Therefore:

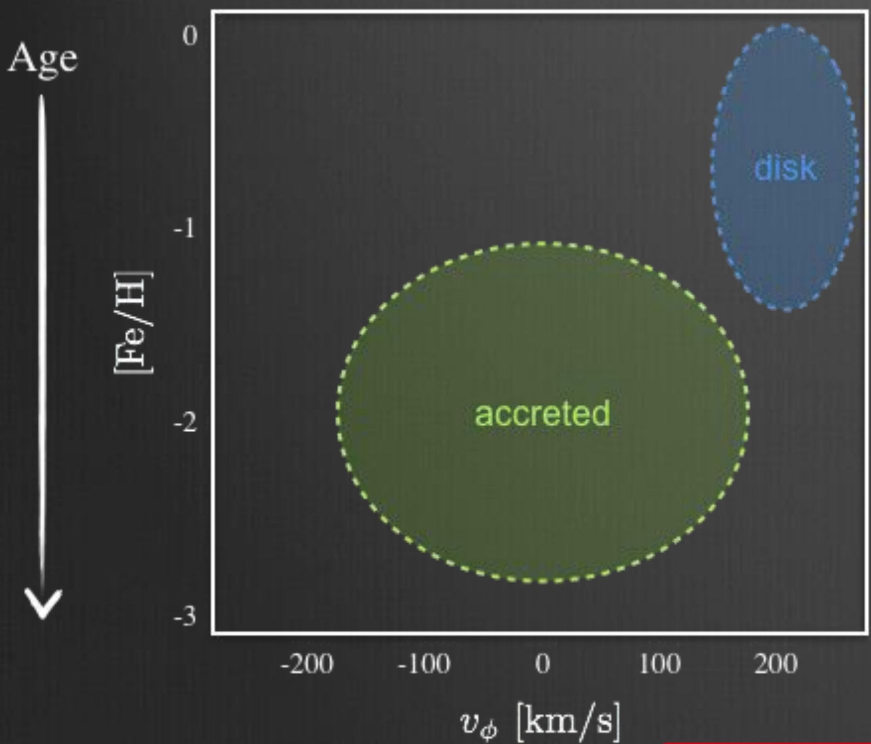
We empirically obtain the Dark Matter velocity distribution.

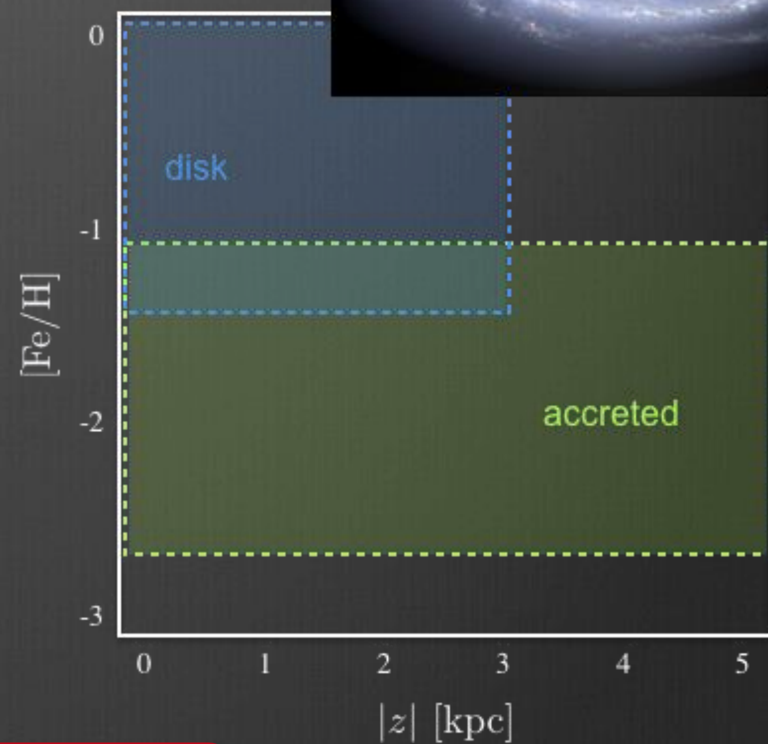
Herzog-Arbeitman, Lisanti, Madau, **Necib** (2018)
Herzog-Arbeitman, Lisanti, **Necib**, (2018)


Thick disc: Older stars
(ages > 8 billion years)
Thin disc: Younger stars
(ages < 8 billion years) and gas
Accreted Stars:
Older stars
Older star
Globular
Halo +
(Sub)structure



Chemodynamics





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

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

Ivezic et al. (2008)

What Do We Learn From Simulations?

<u>What we learned:</u>

Galaxies form hierarchically.

Stars in galaxies are either accreted or born in the disk, and we can use chemodynamics to break them up.

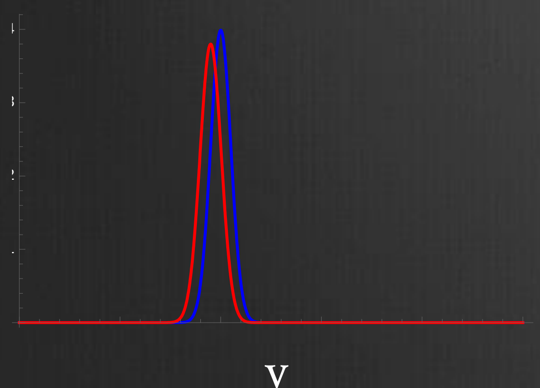
Feedback in Realistic Environments (FIRE)

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

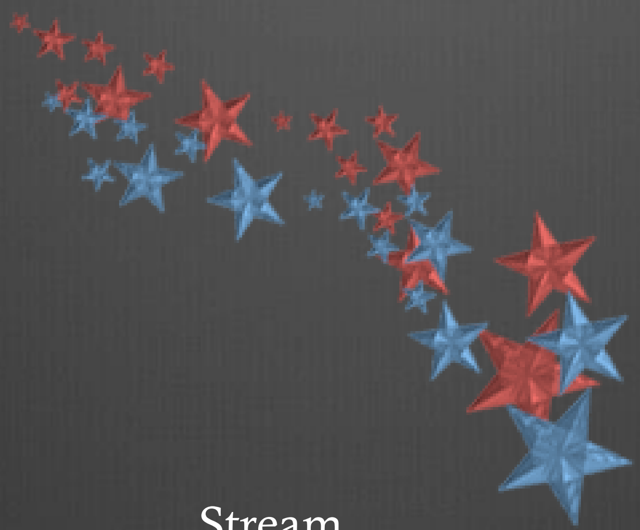
Video by Shea Garisson-Kimmel,
http://www.tapir.caltech.edu/~sheagk/firemovies.html

Merging Stages

Dwarf Galaxy

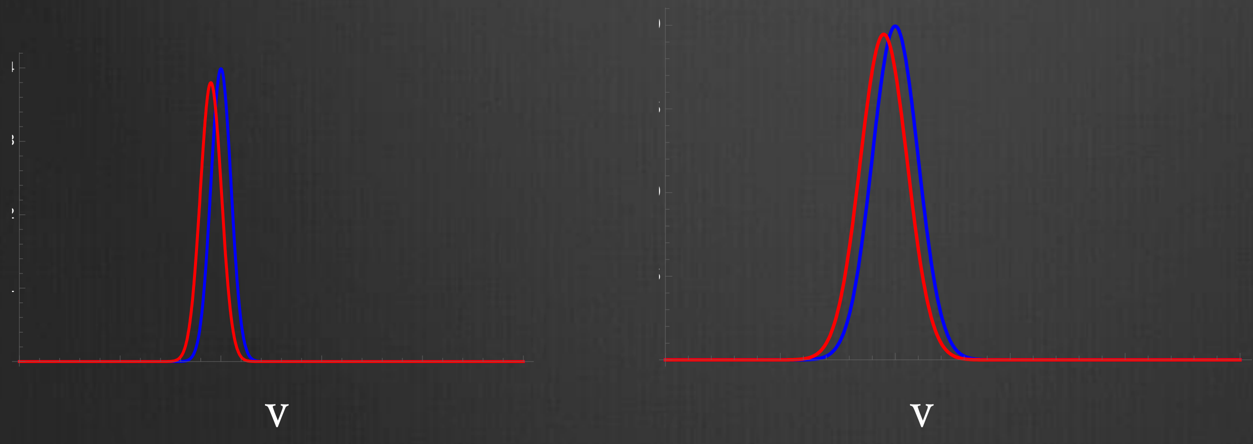


Merging Stages



Dwarf Galaxy

Stream



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

Merging Stages

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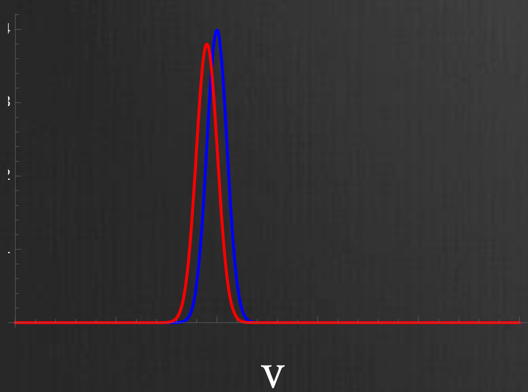
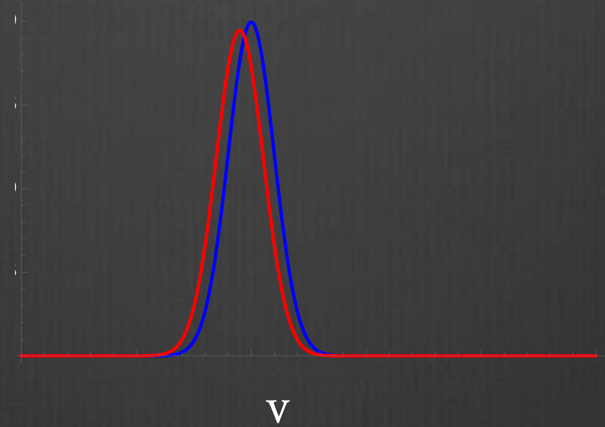
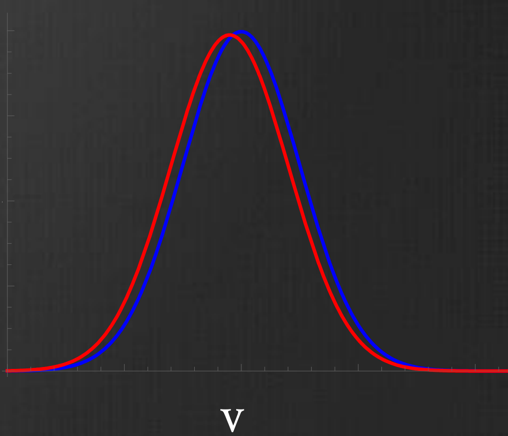


Stream

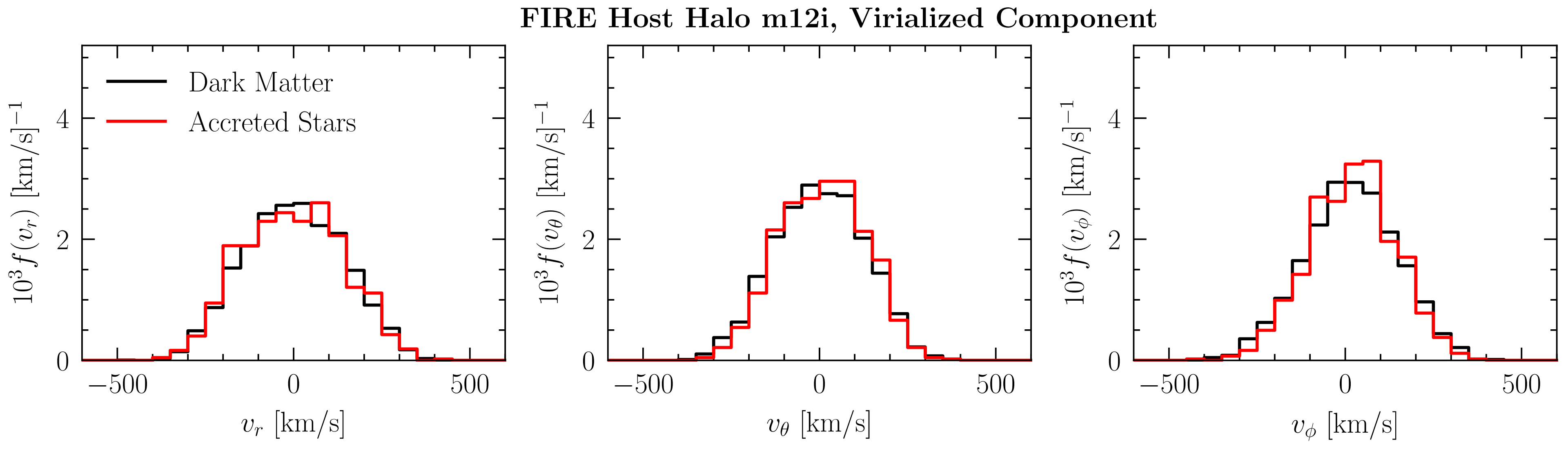


Debris Flow



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

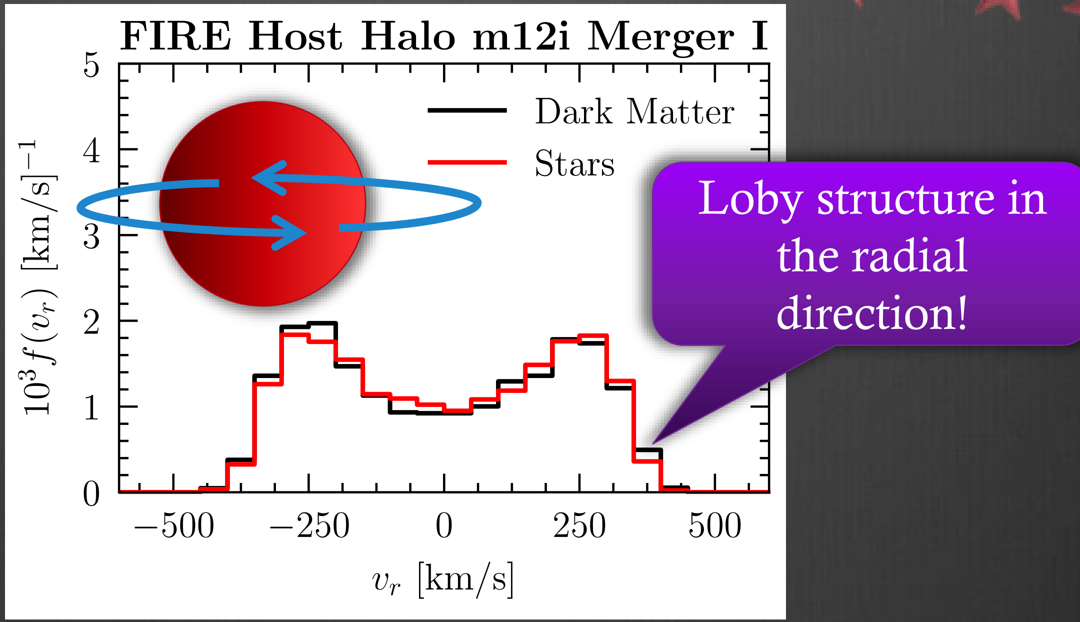
Old Virialized Mergers



Strong correlation between the Dark Matter and the stars accreted from 23 old satellites at z > 3.

Necib, Lisanti, Garisson Kimmel et al. (2018), in prep.

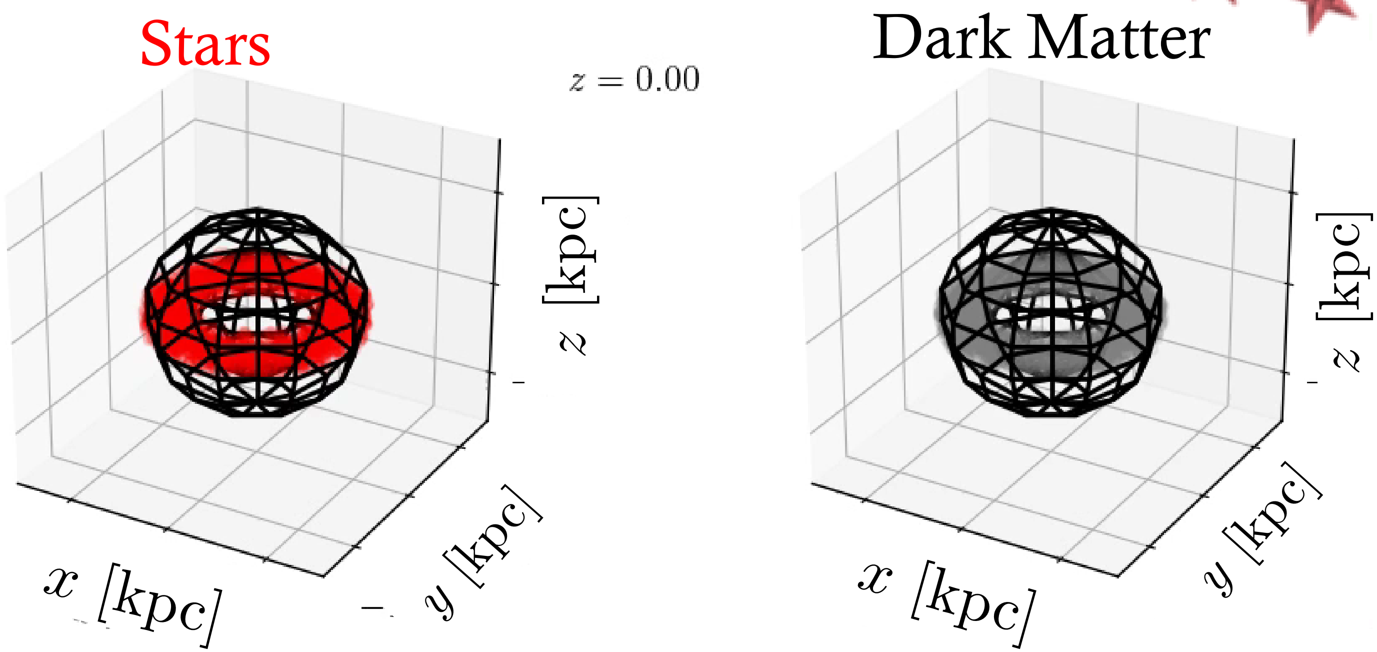
Debris Flow



Strong correlation between the Dark Matter and the stars accreted from a satellite at redshift 1.5, with mass 6.7×10^{10} Msun, and average metallicity ~-1.5, contributing 37% of local stellar mass.

Necib, Lisanti, Garisson Kimmel et al. (2018), in prep.

Debris Flow



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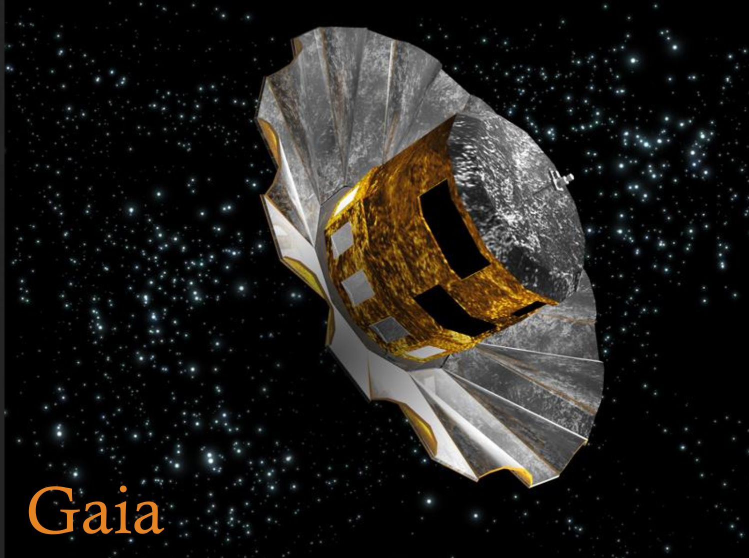
So, What Does our Milky Way Look Like?

What we learned:

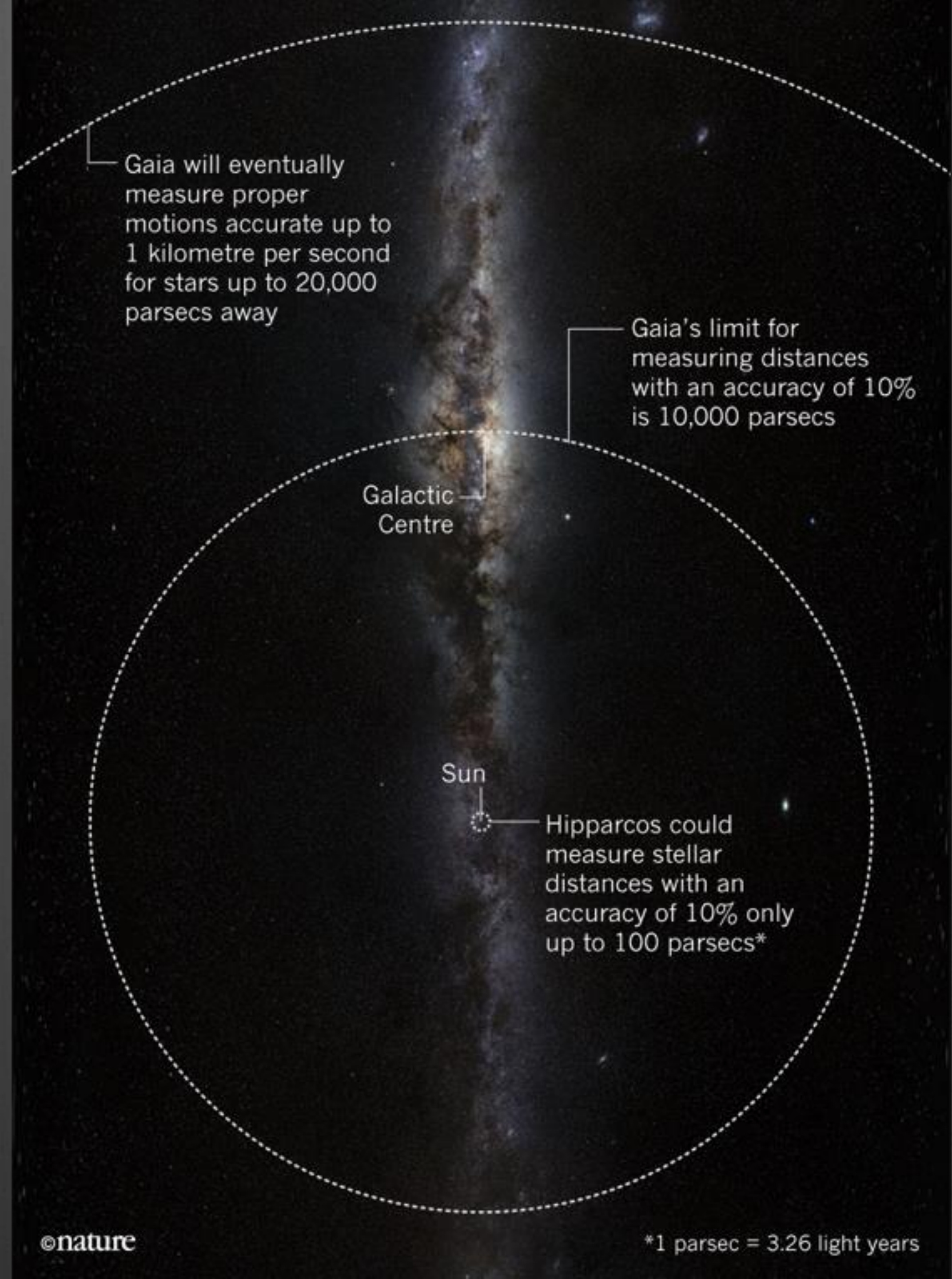
Accreted stars trace their dark matter counterparts.

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



New Structure!

With Gaia, a new merging event in the solar neighborhood has been found, and is referred to as the Gaia Sausage, or Gaia Enceleadus.

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

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

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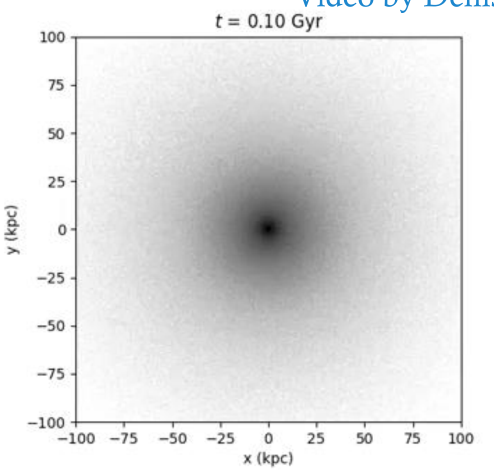
Video by Denis Erkal



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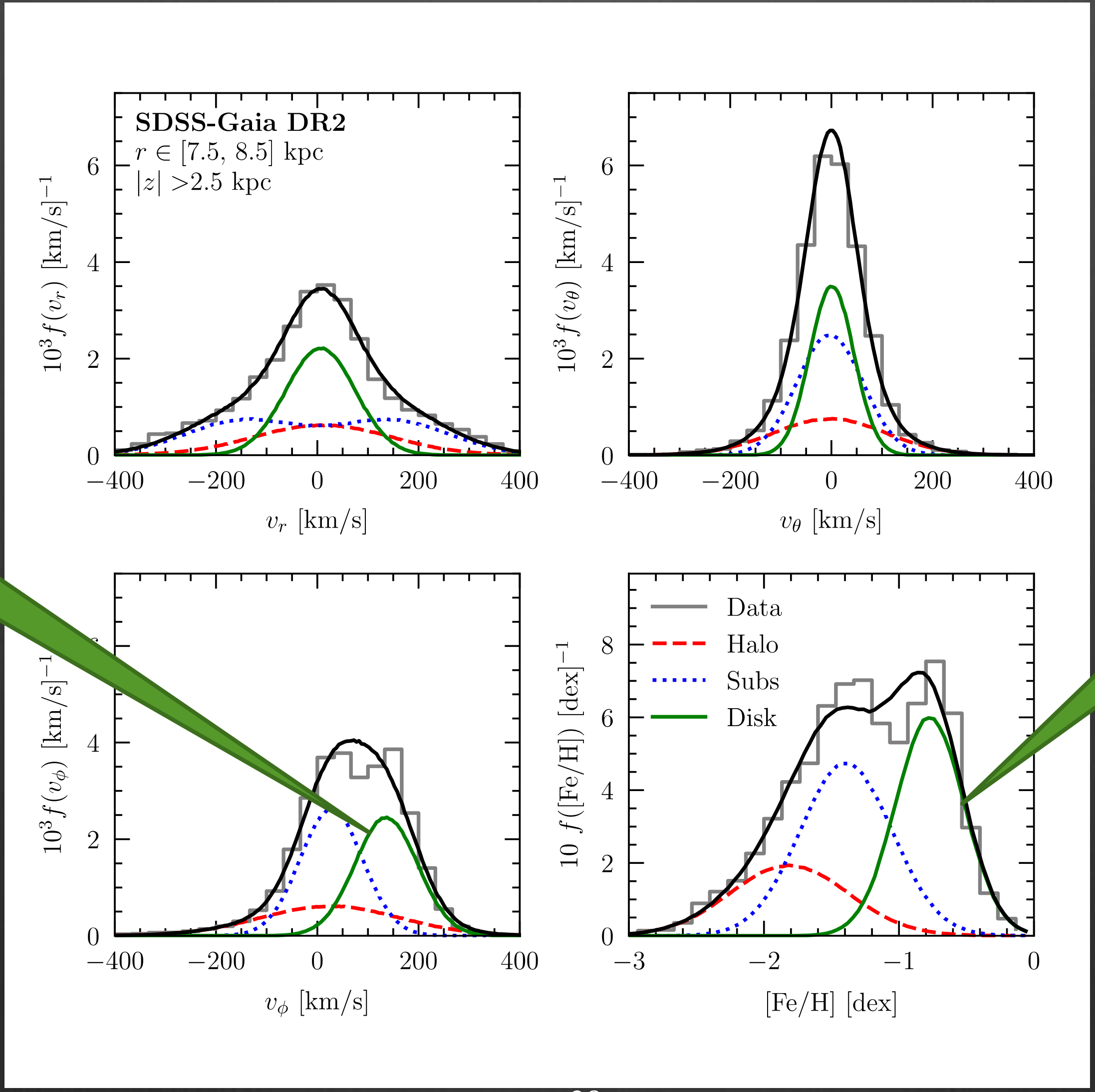
Disk, Halo, and Substructure

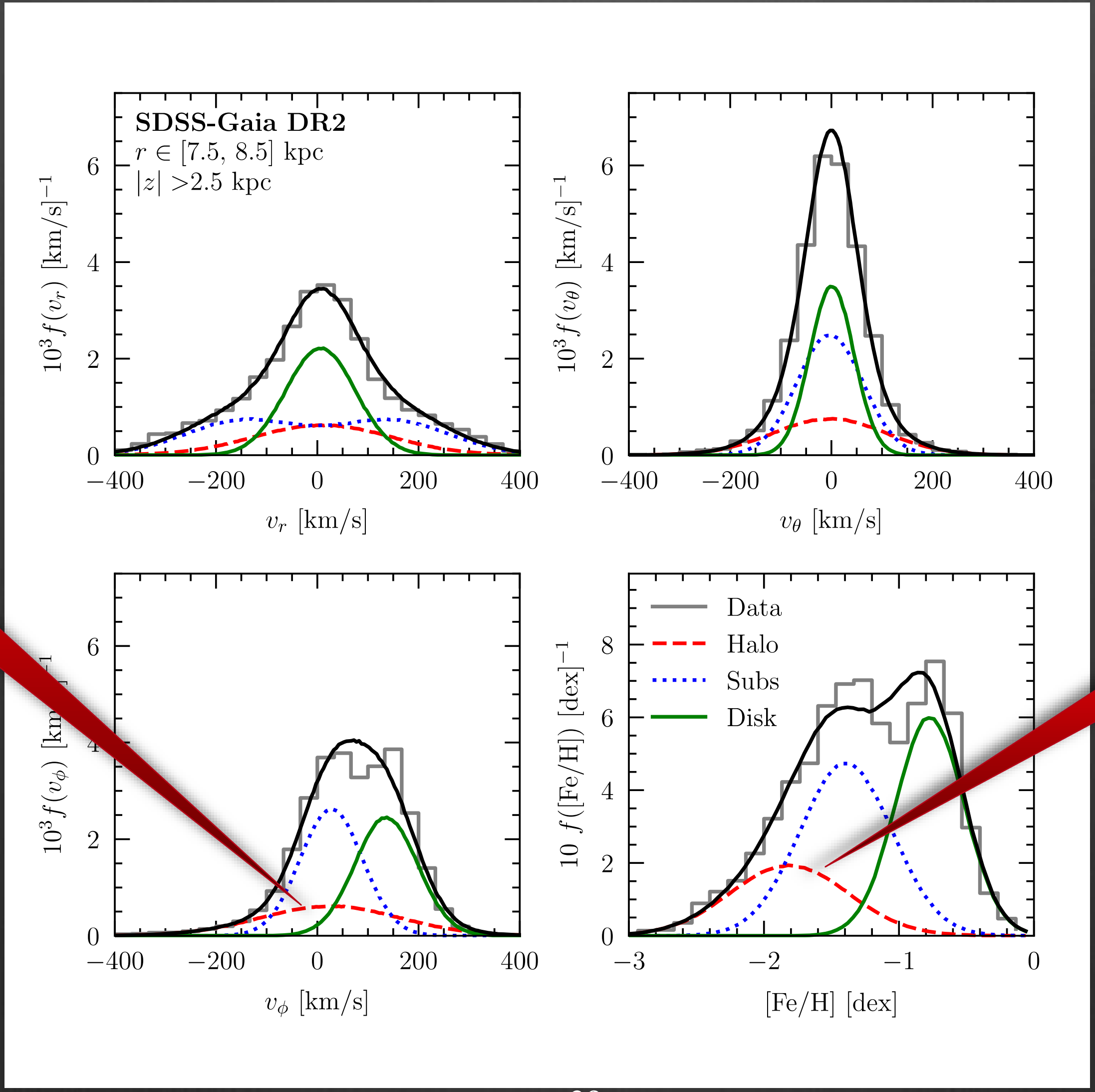


Azimuthal Rotation

Metal-Rich, Younger Population

Necib, Lisanti, Belokurov (2018)

Disk, Halo, and Substructure

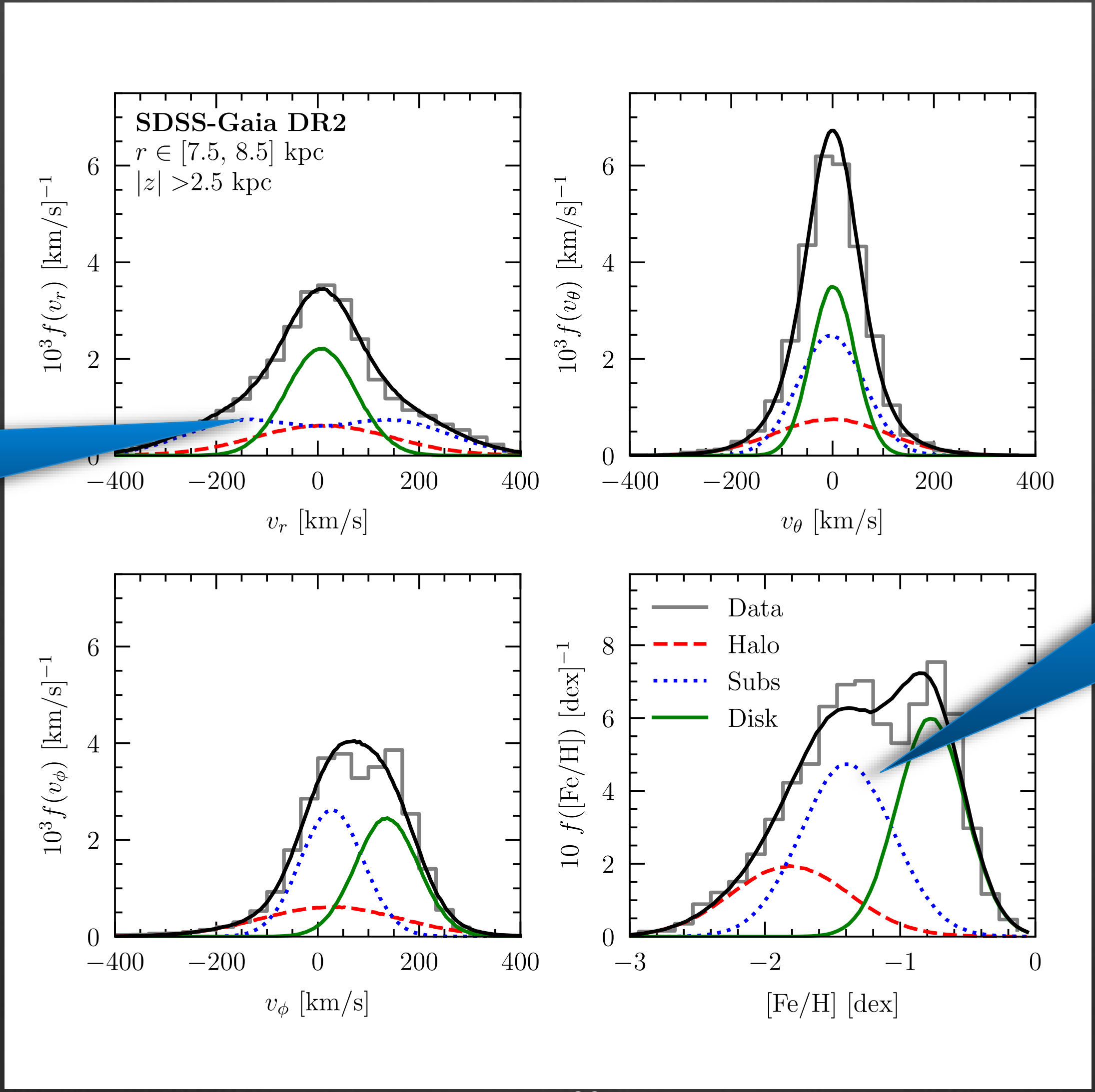


Isotropic

Older Population

Necib, Lisanti, Belokurov (2018)

Disk, Halo, and Substructure



Loby Structure

Older than the Disk, Younger than the Halo

Necib, Lisanti, Belokurov (2018)

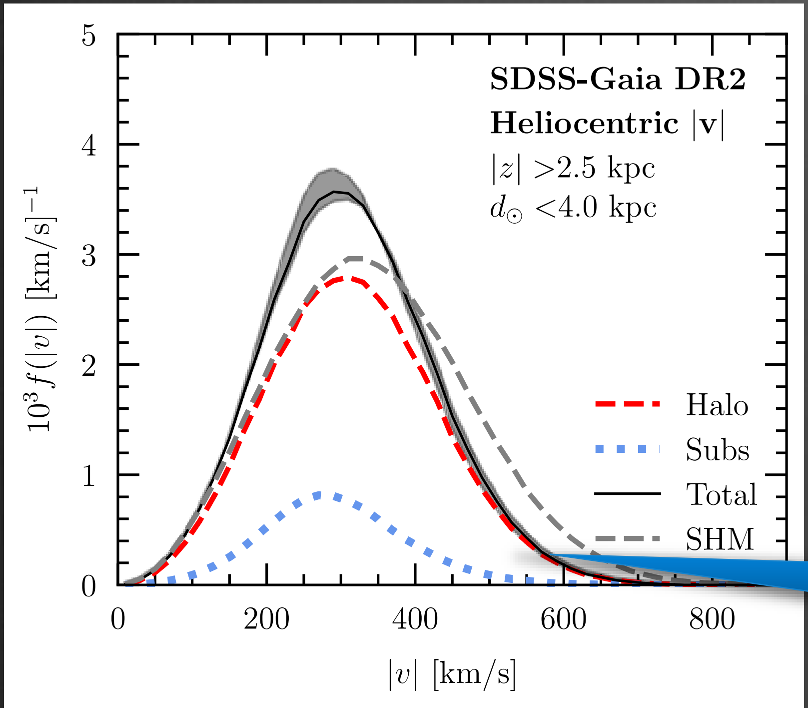
Implications for Direct Detection

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.

New Velocity Distribution!



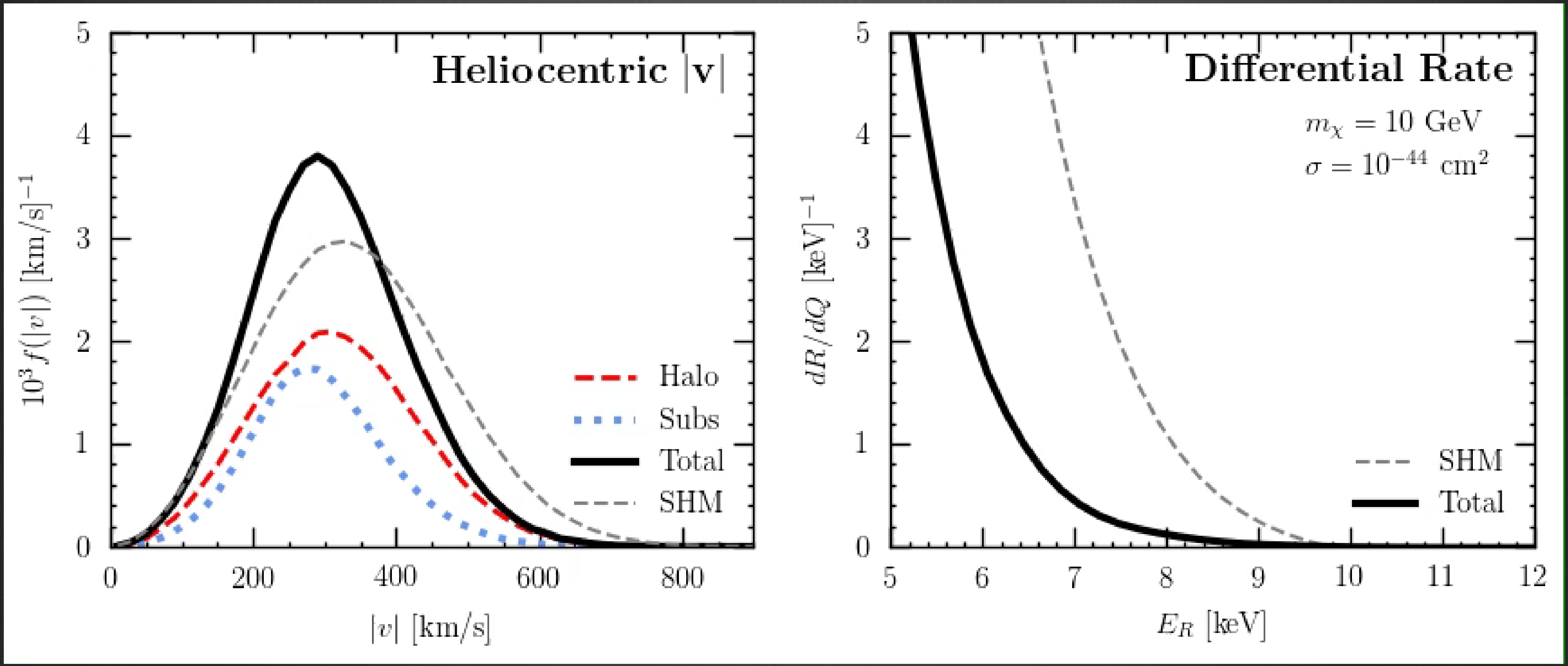
Can be found in a github repository near you
https://linoush.github.io/DM_Velocity_Distribution/

Link in paper arXiv:1807.02519.

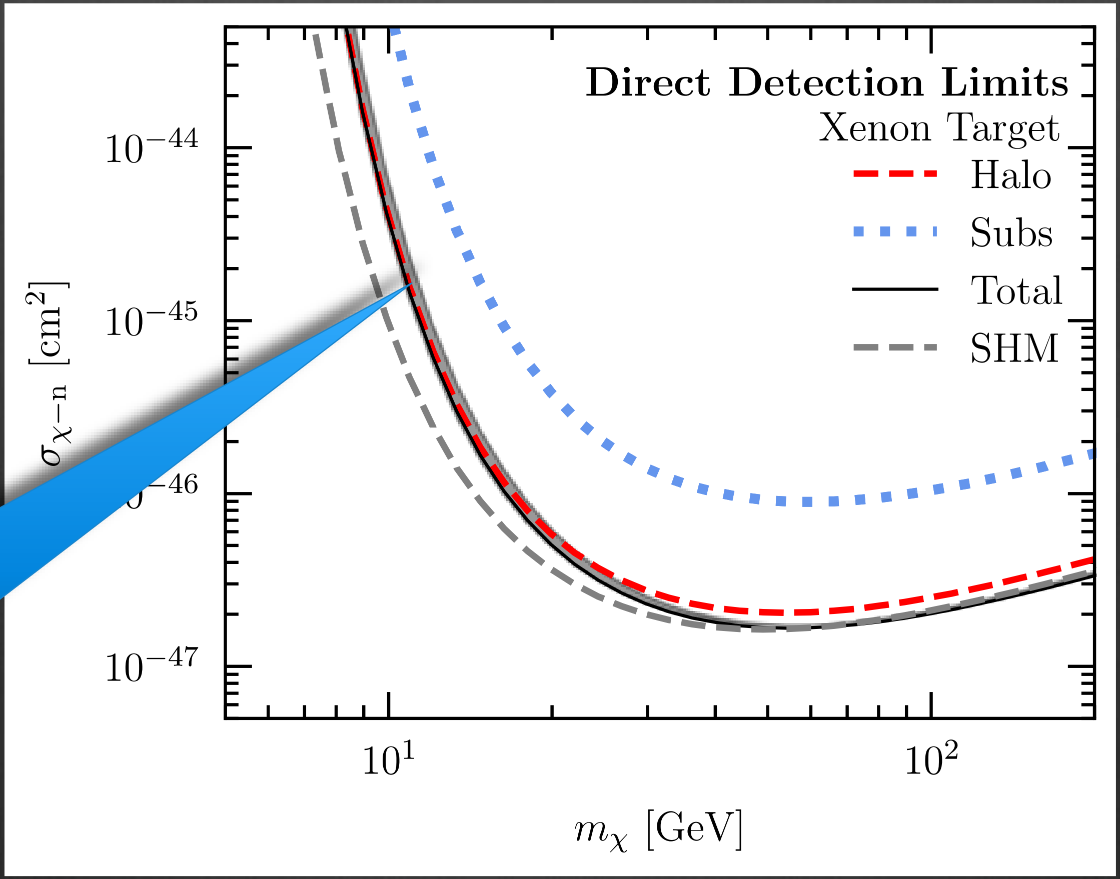
Final distribution different from the assumed Maxwell Boltzmann distribution

- 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. (See Necib, Lisanti, Garrison-Kimmel et al. (in prep))

Differential Rate



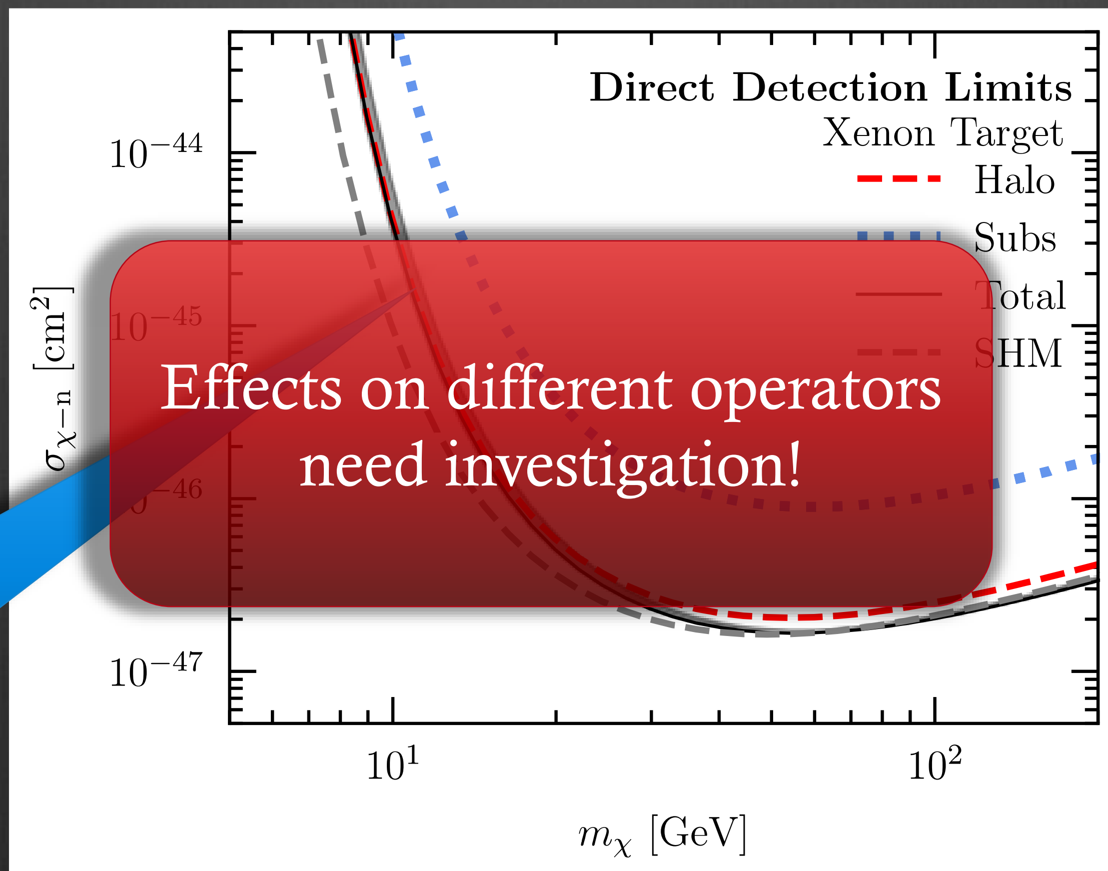
Implications for Direct Detection



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!

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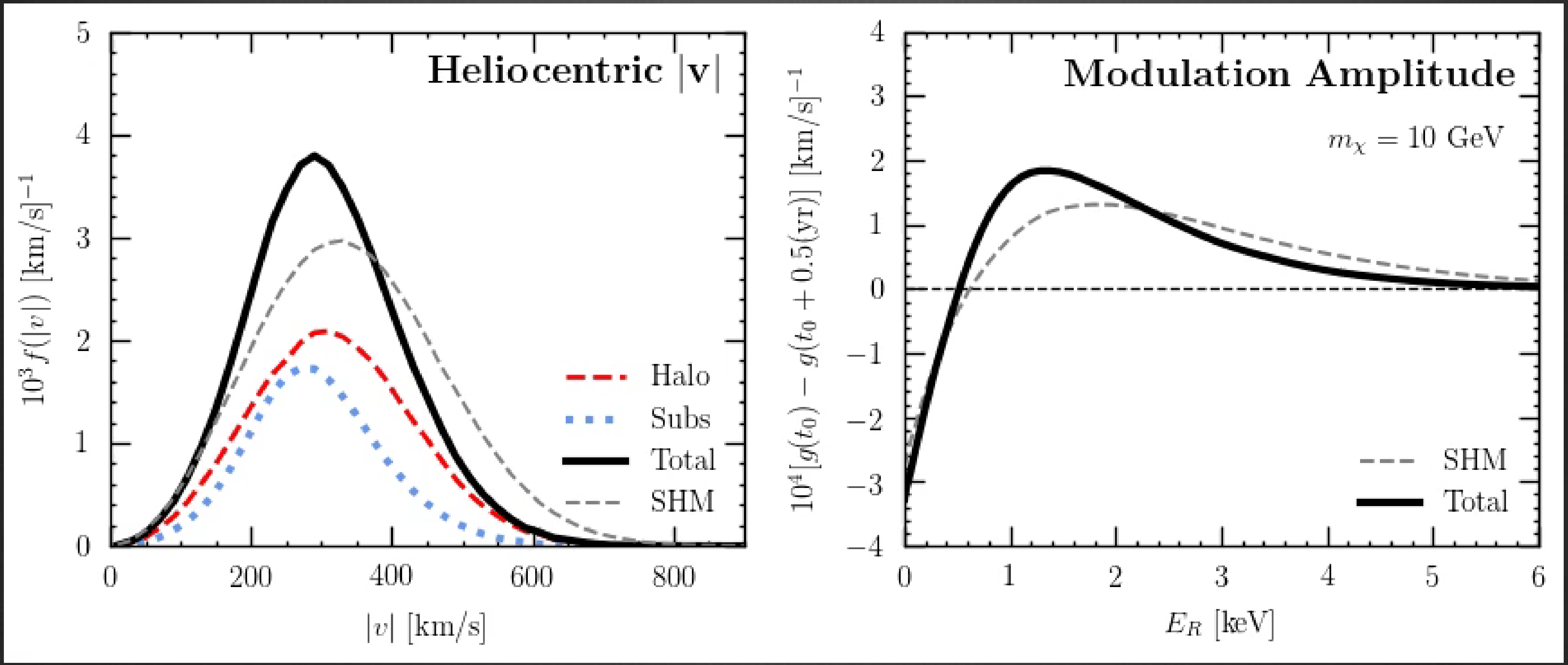
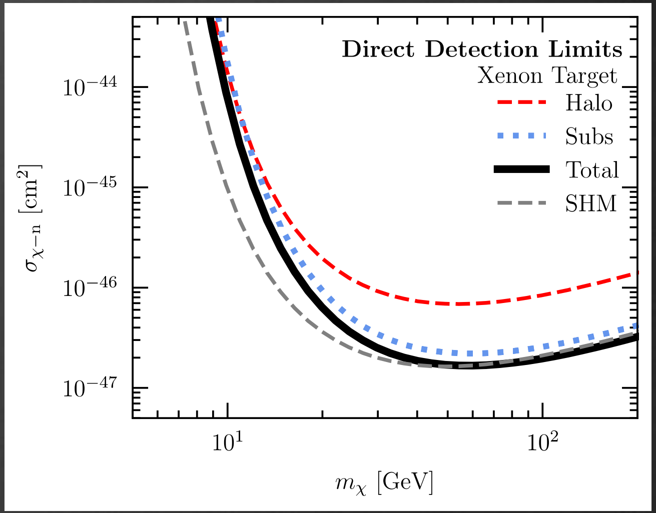
Implications for Direct Detection



Anisotropy of the system leads to modulation effects.

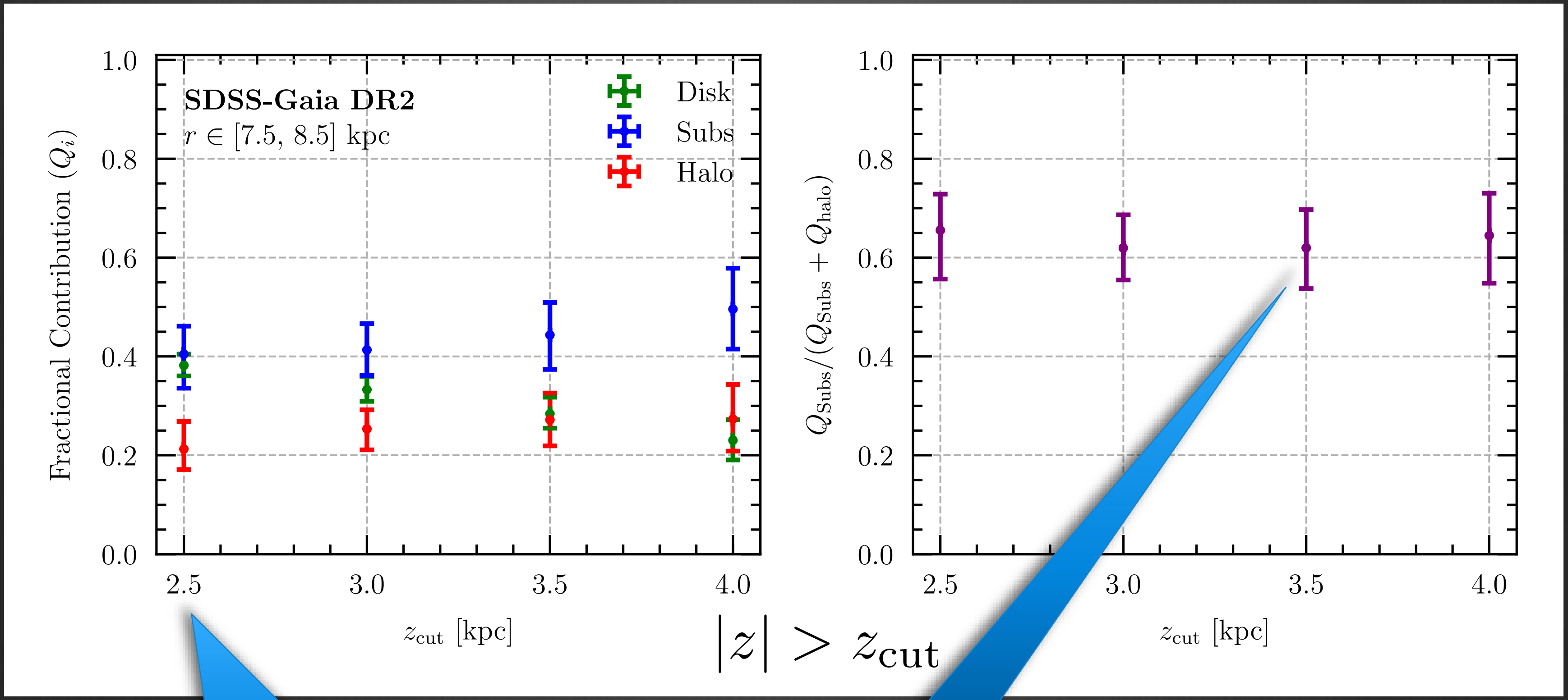
Conclusions

- Stars trace:
  - The Milky Way potential, constraining the local density of dark matter.
  - The velocity of the dark matter.
- We can use stars to empirically measure the phase space distribution of Dark Matter .
- We live in a huge debris flow that affects our direct detection limits.
- Tracing gaps in streams can constraint dark matter models.
- So much can be done with Gaia!



Bonus Slides

Not that ``Sub” of a Structure



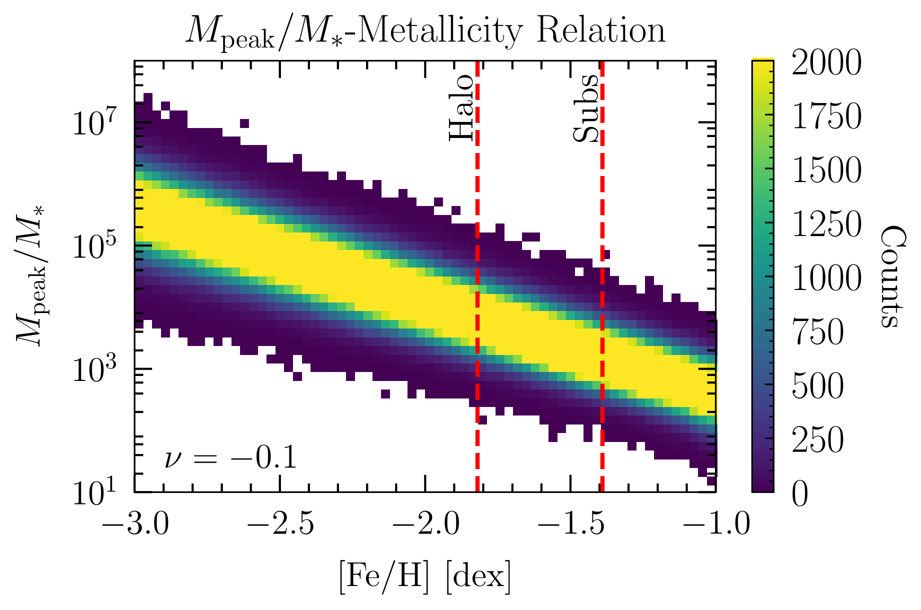
Caveat: We only modeled |z|>2.5 kpc.

High non-disk fraction!

No spatial dependence has been found in the region studied.

One last thing

- 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.



Necib, Lisanti, Garrisson-Kimmel et al (in prep)

Implications for Direct Detection