Dark Matter in Disequilibrium, and Implications for Direct Detection

Lina Necib, Caltech

Based on

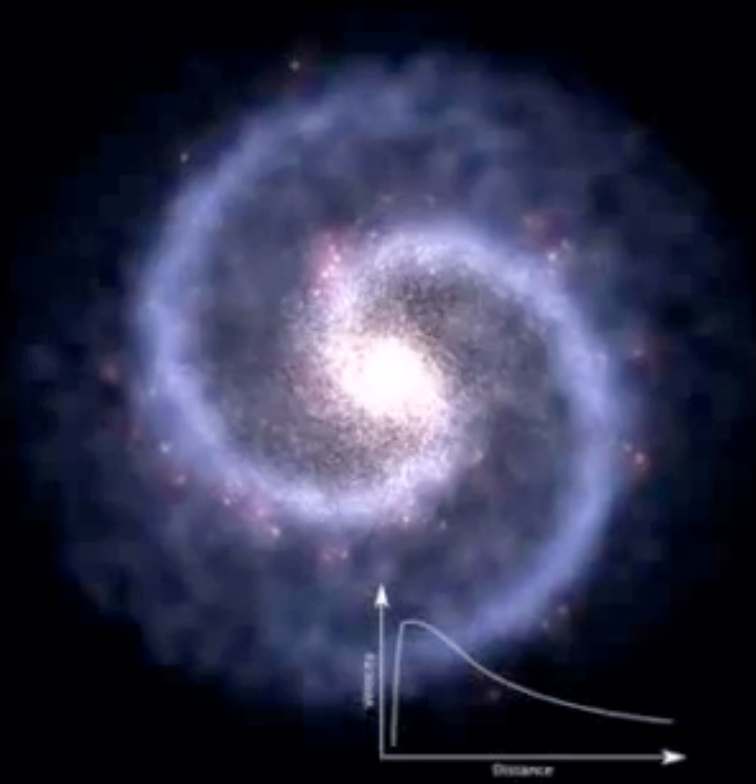
Necib, Lisanti, Garisson-Kimmel, Wetzel, Sanderson, Hopkins, Faucher-Giguère, Kereš arXiv:1810.12301

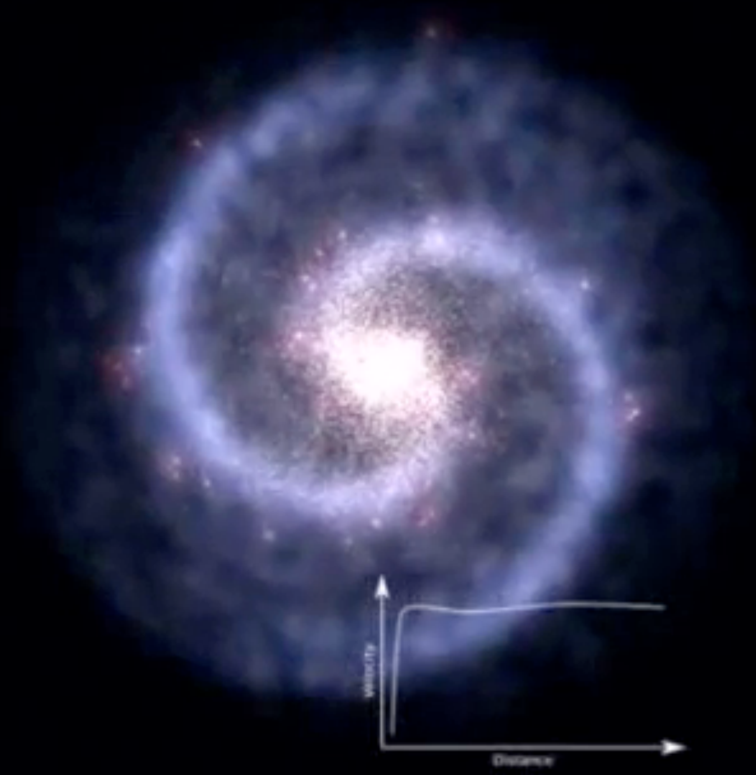
Necib, Lisanti, Belokurov, arXiv:1807.02519

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

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

Dark Matter Exists!



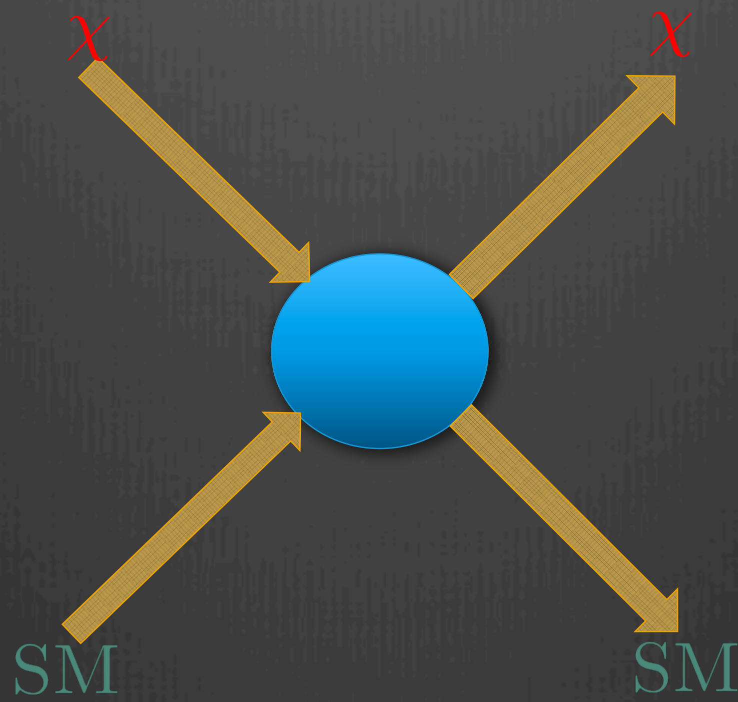


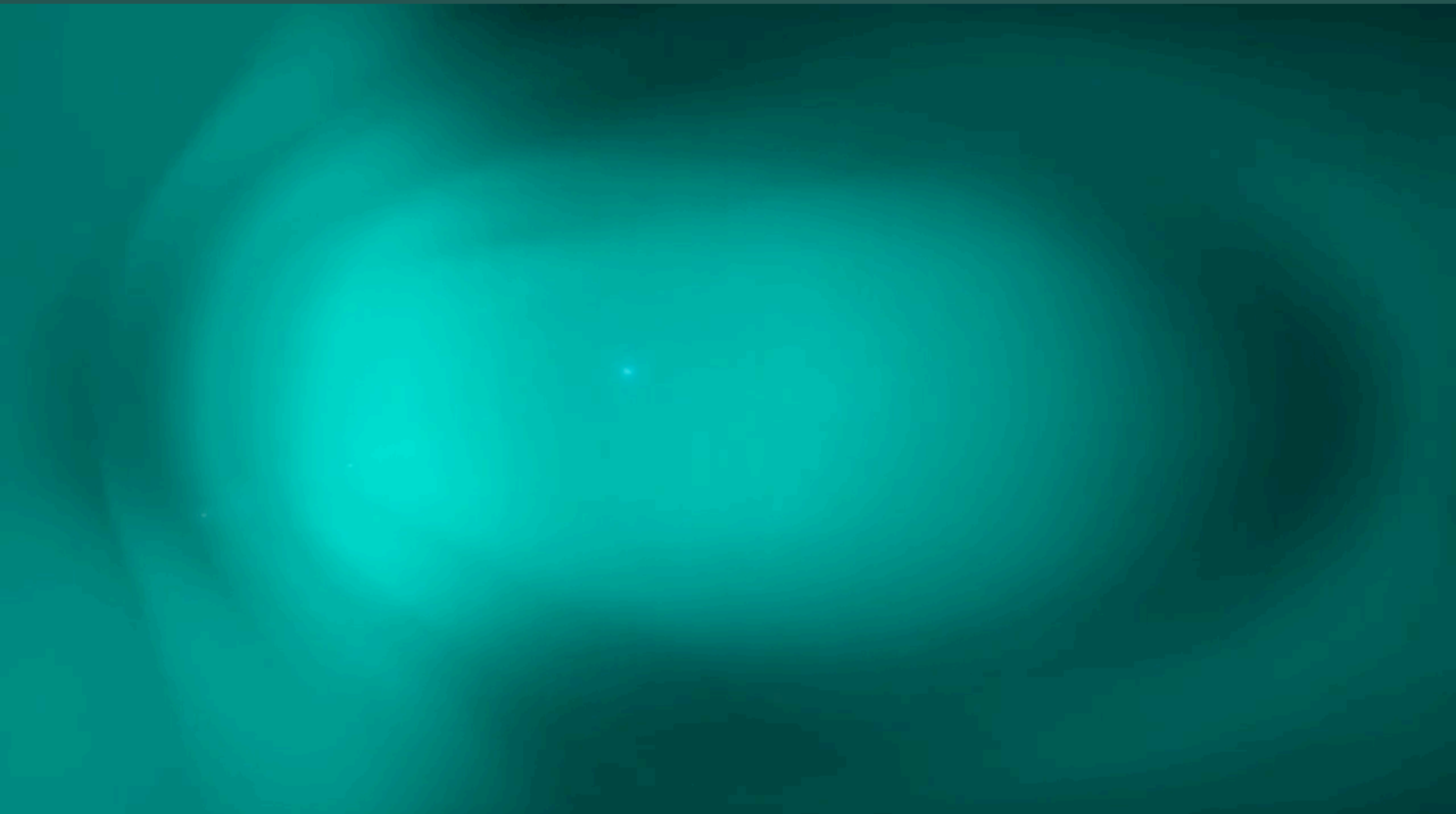
Focus of today's talk!

What is the Dark Matter Velocity Distribution?

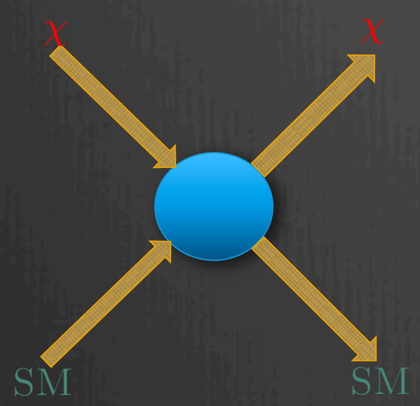
But before that, let me tell you why you should care!

Direct Detection





Direct Detection Rate



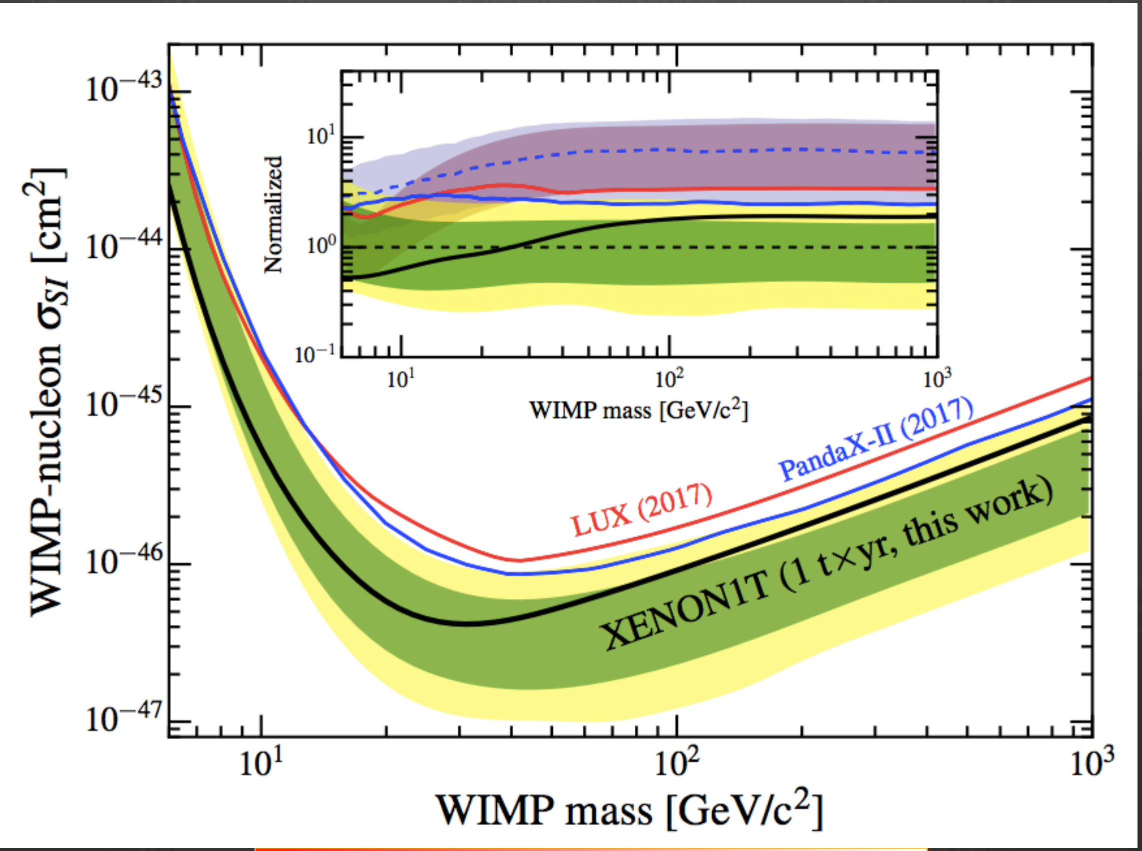
The Dark Matter velocity distribution is part of the computation of the expected direct detection rate.

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

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

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

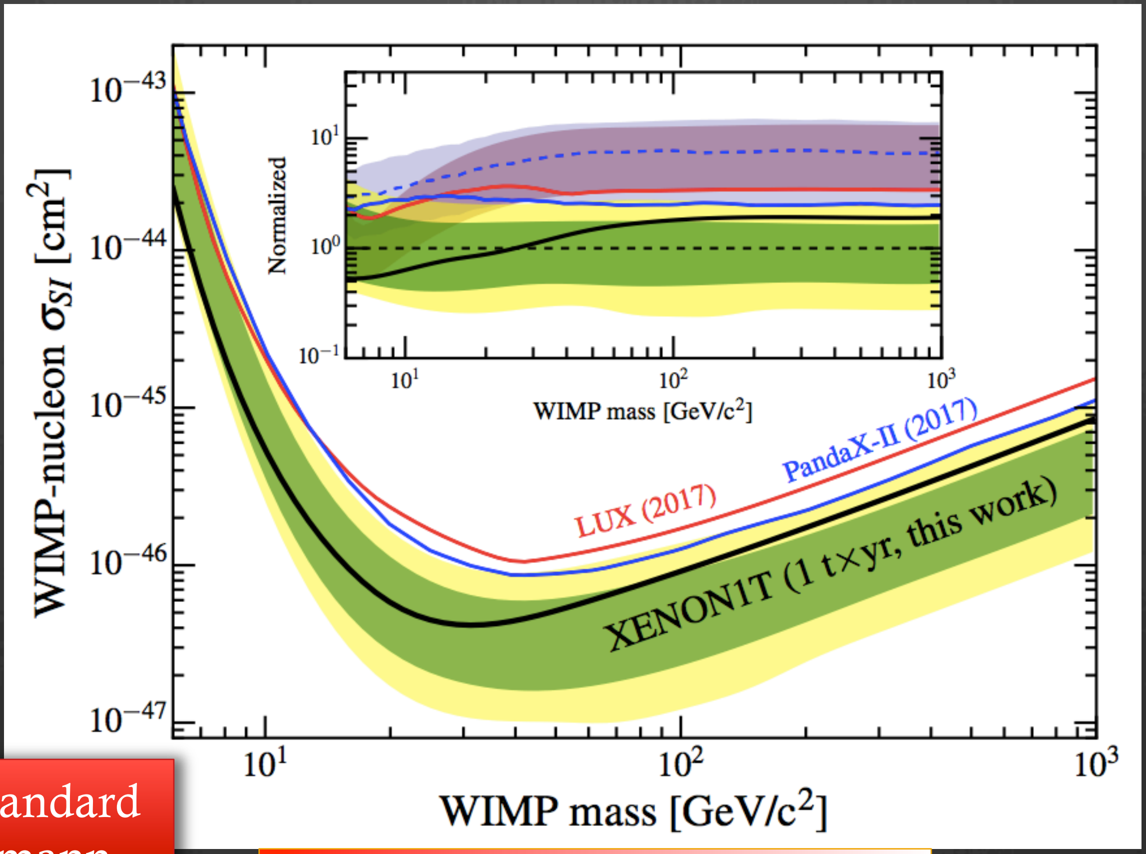
Direct Detection



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

Aprile et al. (2018)

Direct Detection



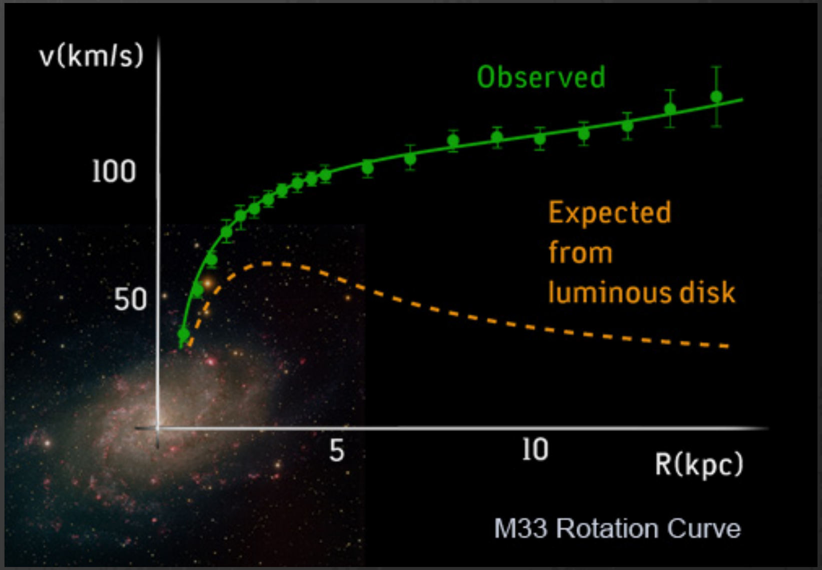
Assumes the standard Maxwell Boltzmann velocity distribution.

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

Aprile et al. (2018)

Maxwell-Boltzmann Distribution: Origins

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



Rubin & Ford (1970)

Maxwell-Boltzmann Distribution: Origins

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

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)

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Poisson

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

Maxwell-Boltzmann Distribution

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

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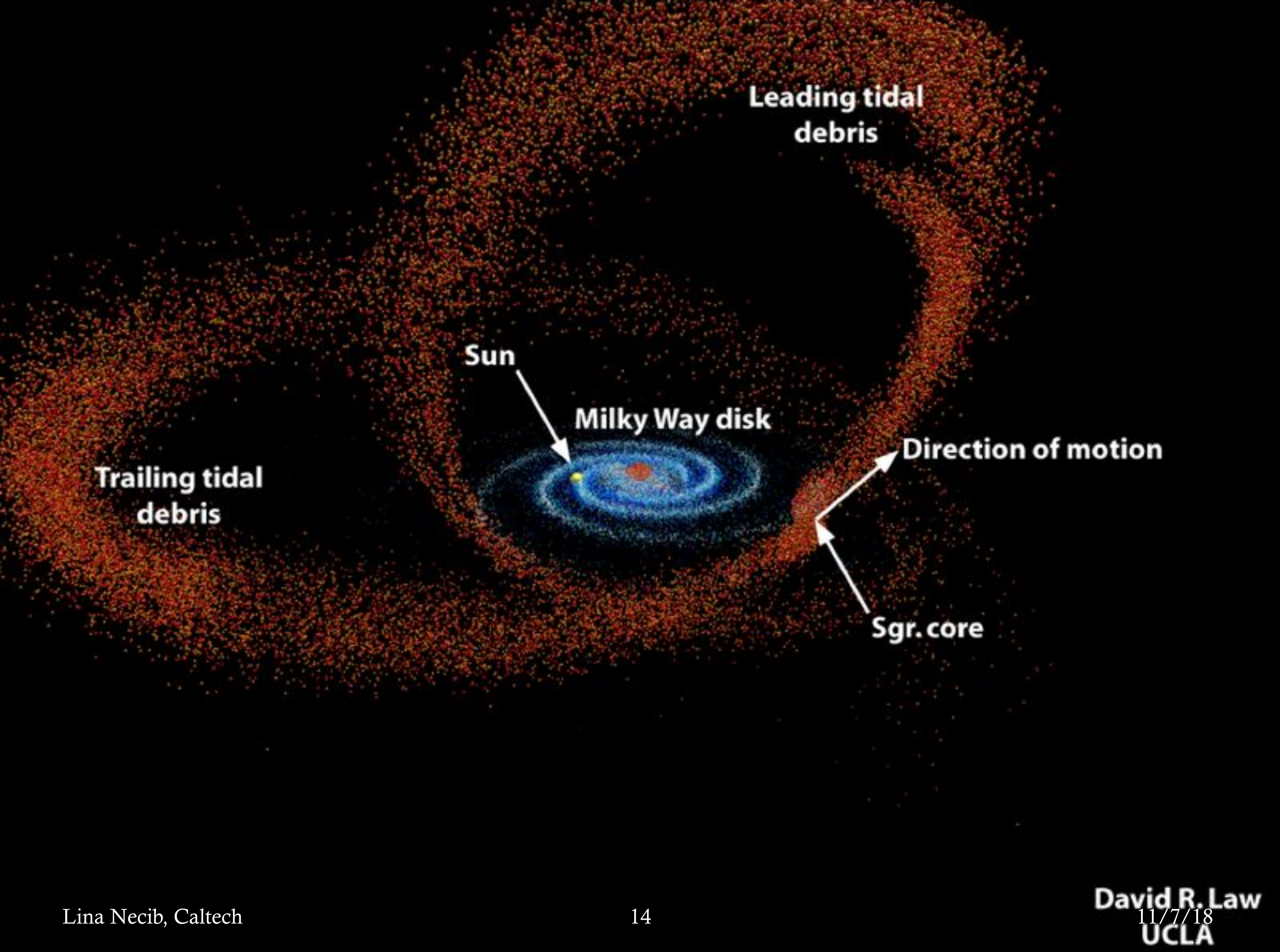
We assumed Equilibrium and Isotropy!

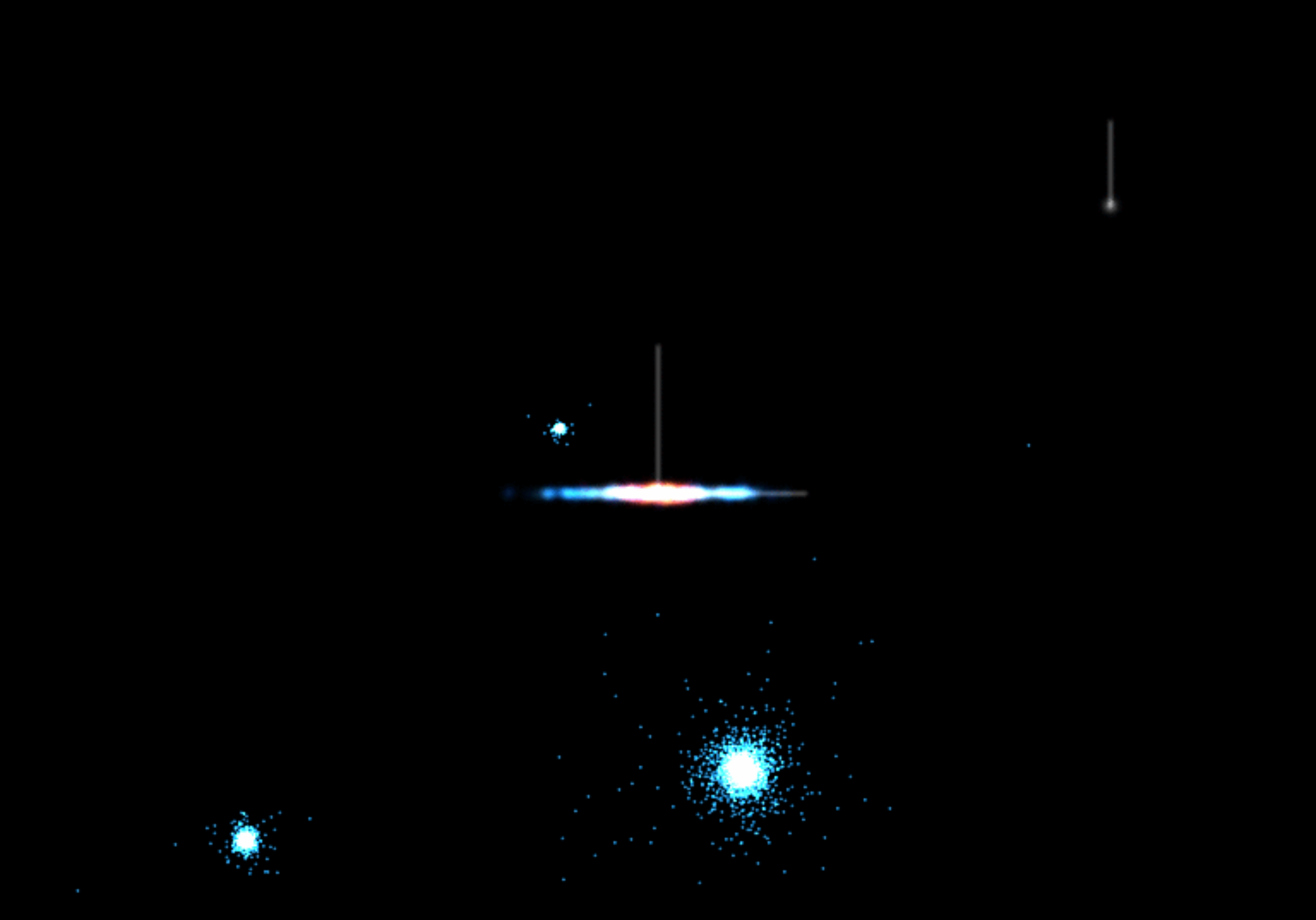
Poisson (1813)
Jeans (1915)
Binney & Tremaine (2008)

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.


Leading tidal debris
Sun
Milky Way disk
Direction of motion
Trailing tidal debris
Sgr. core
David R. Law
UCLA



Understanding the Velocity Distribution

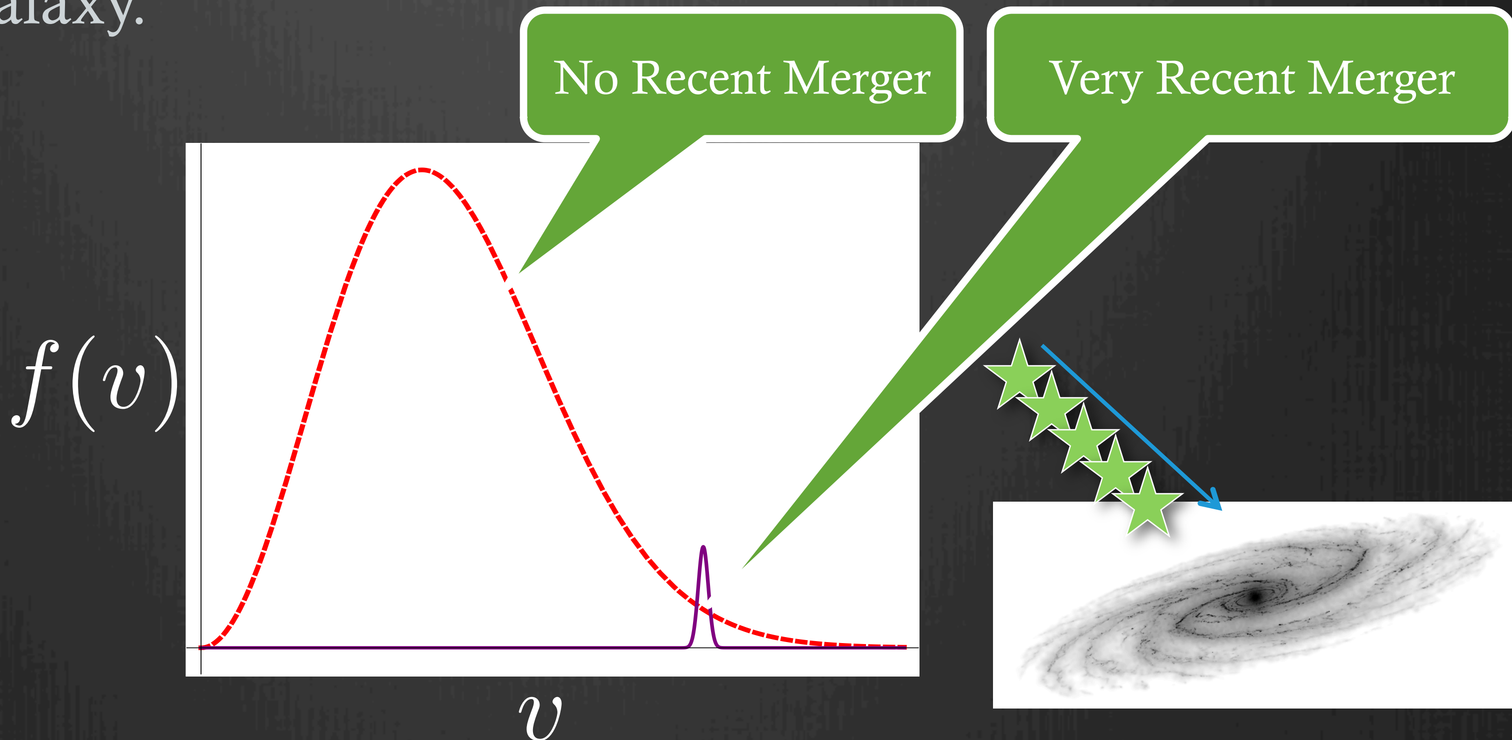
- Velocity distribution of dark matter tells us the story of our galaxy.

No Recent Merger

Very Recent Merger

Understanding the Velocity Distribution

- Velocity distribution of dark matter tells us the story of our galaxy.



Galaxies Form Hierarchically!





White & Rees (1978)

How to get the velocity distribution of Dark Matter?

What we learned:

Our Galaxy is not in equilibrium, and is not isotropic

From Simulations:

Accreted Stars trace the velocity of their Dark Matter counterparts.

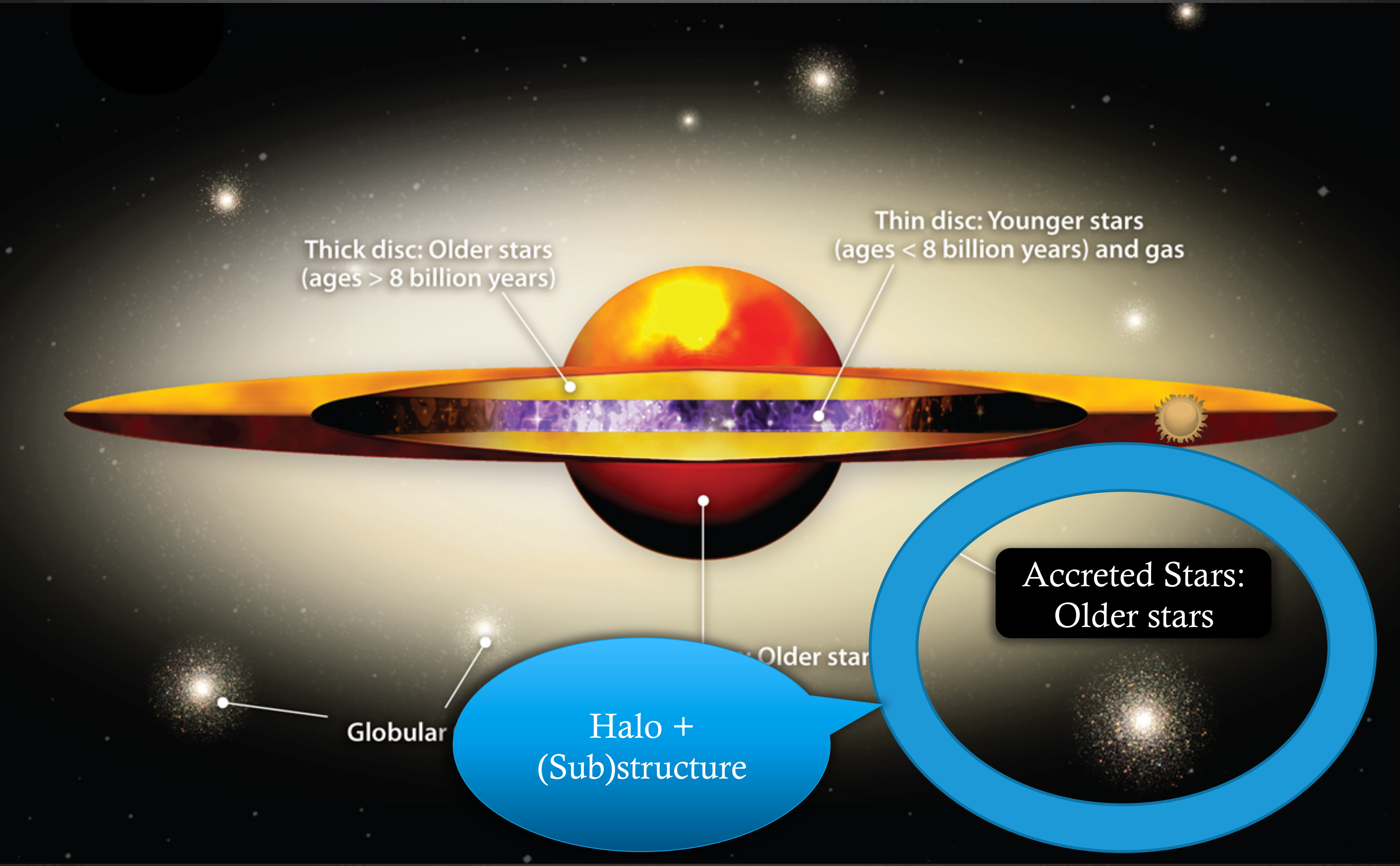
From Gaia DR1/DR2:

We get the local velocity distribution of accreted stars.

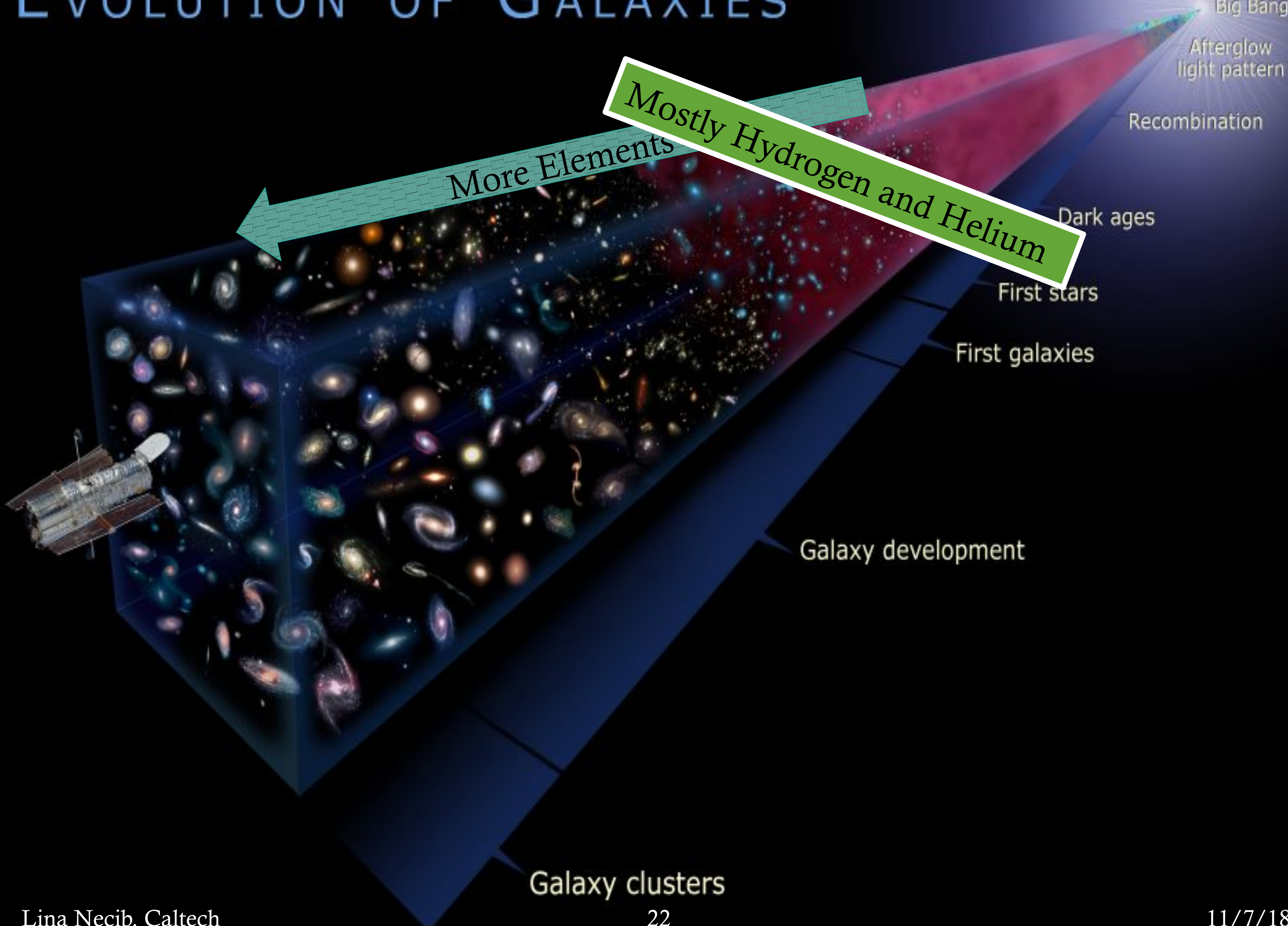
Therefore:

We empirically obtain the Dark Matter velocity distribution.

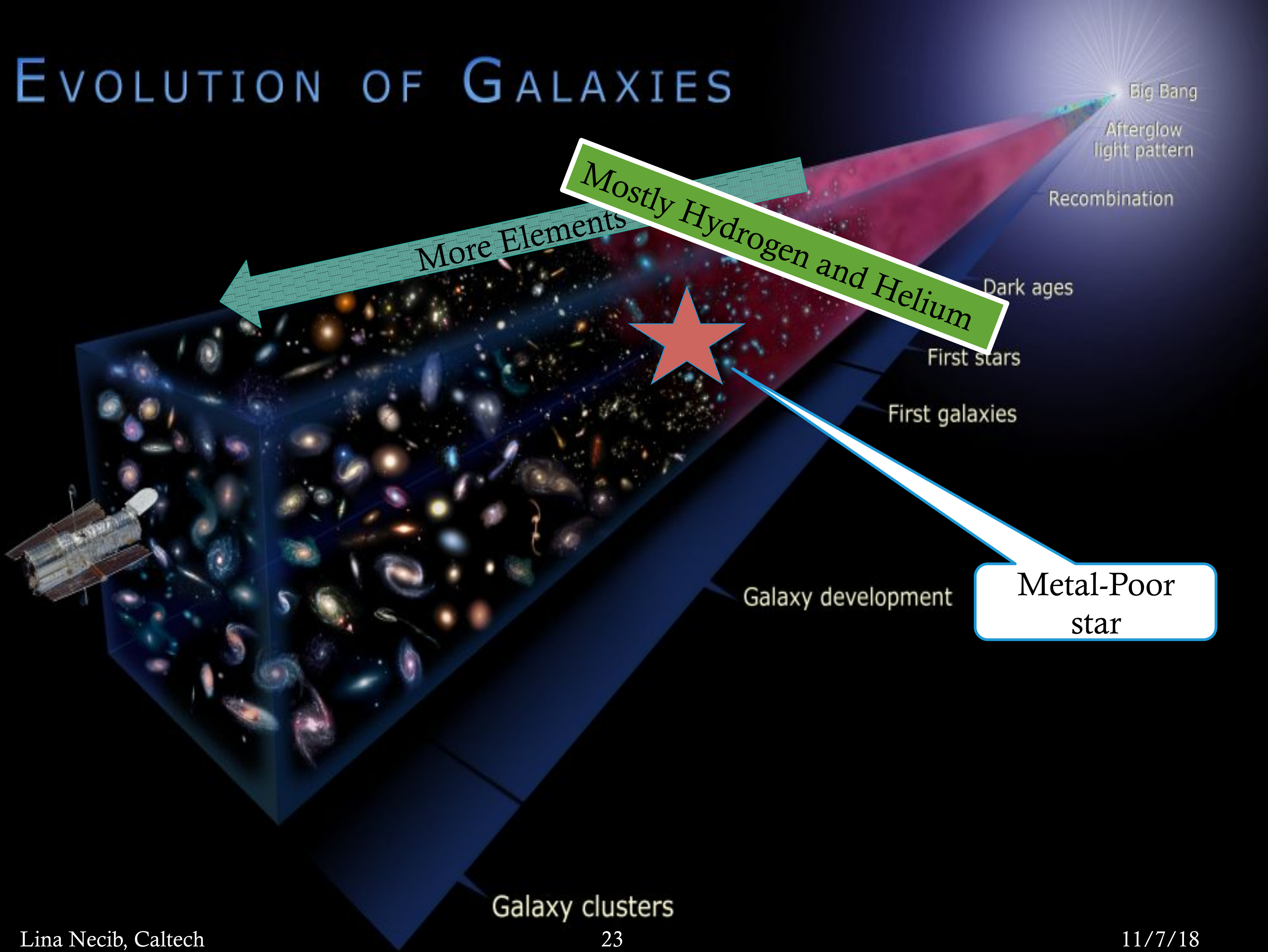
Herzog-Arbeitman, Lisanti, Madau, **Necib** (2018)
Herzog-Arbeitman, Lisanti, **Necib**, (2018)

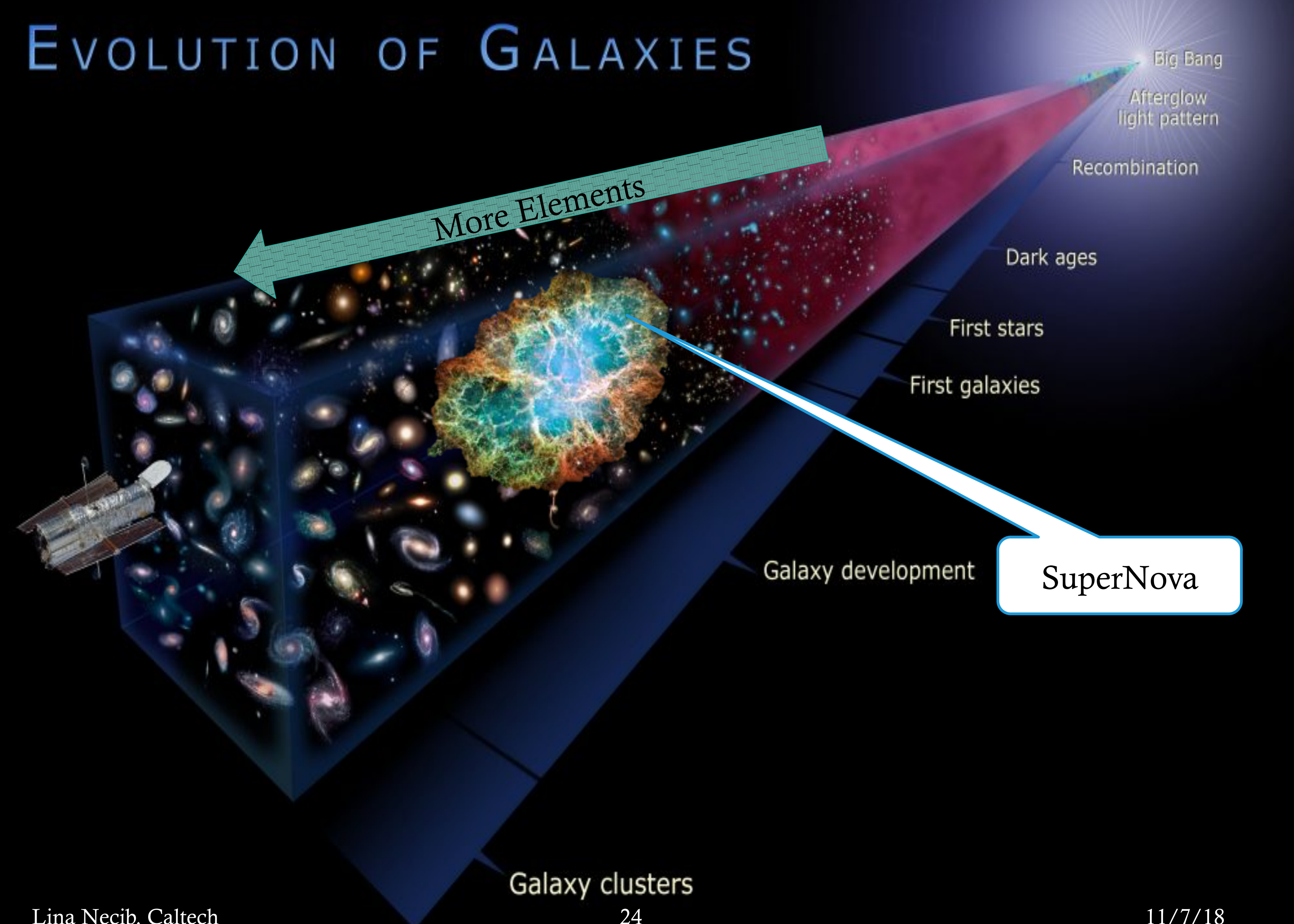

Thin disc: Younger stars
(ages < 8 billion years) and gas
Thick disc: Older stars
(ages > 8 billion years)
Accreted Stars:
Older stars
Older star
Globular
Halo +
(Sub)structure

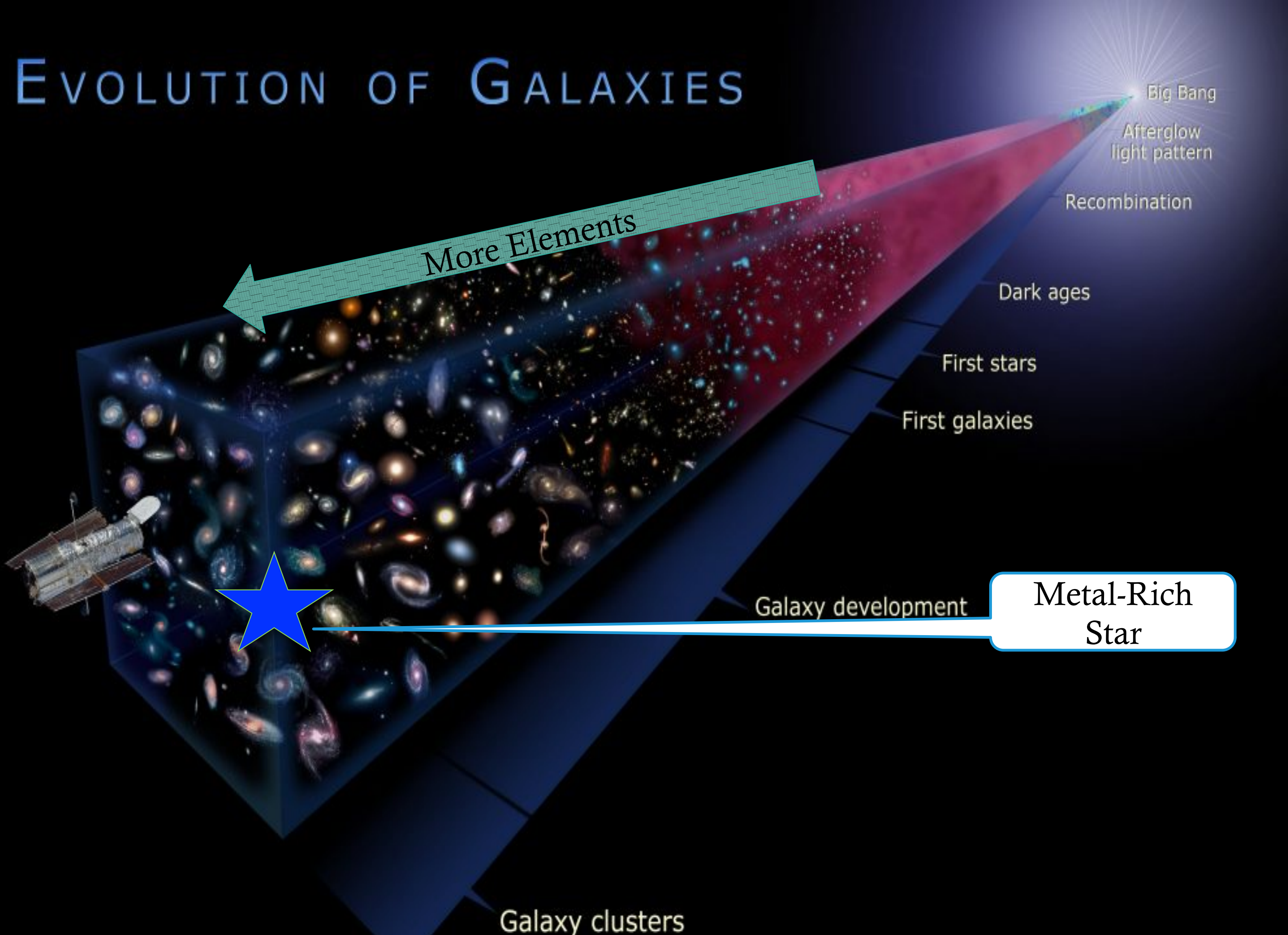
Evolution of Galaxies

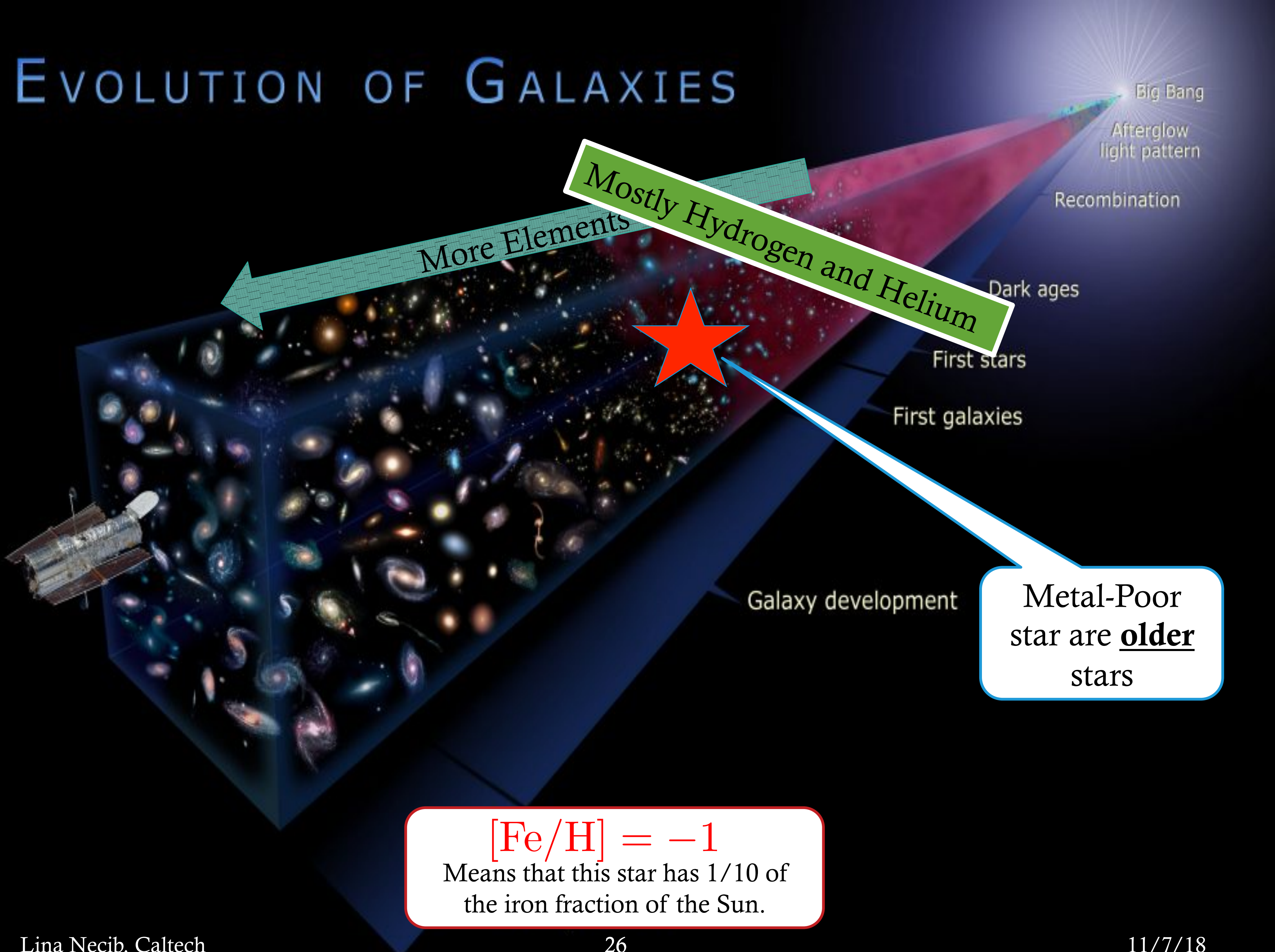


Evolution of Galaxies



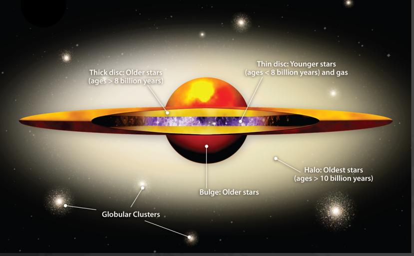

Evolution of Galaxies
Big Bang
Afterglow light pattern
Recombination
More Elements
Dark ages
First stars
First galaxies
Galaxy development
SuperNova
Galaxy clusters


EVOLUTION OF GALAXIES
Big Bang
Afterglow light pattern
Recombination
More Elements
Dark ages
First stars
First galaxies
Galaxy development
Metal-Rich Star
Galaxy clusters

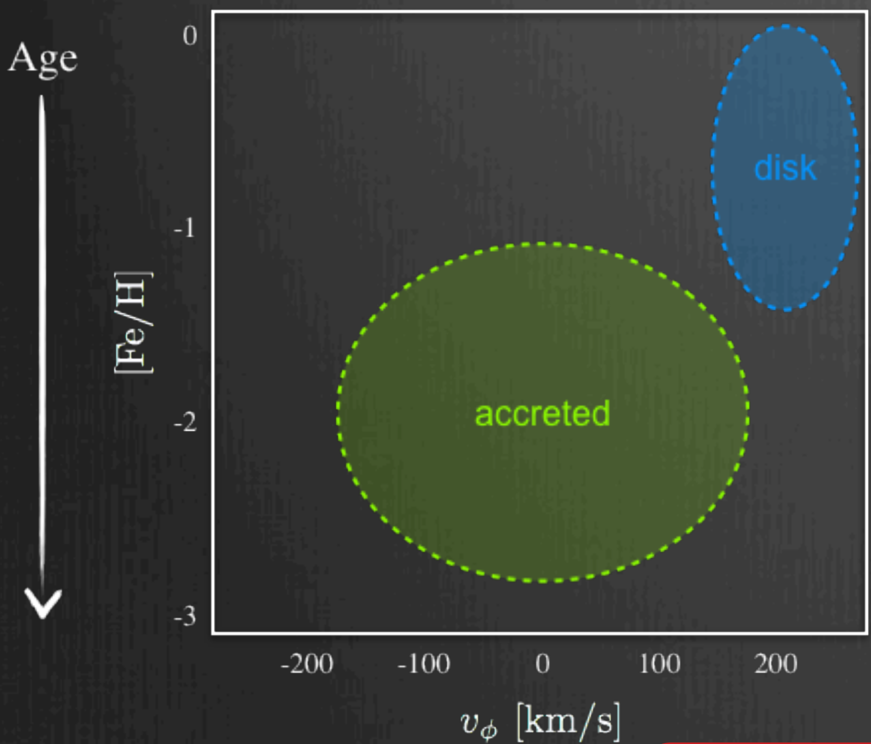


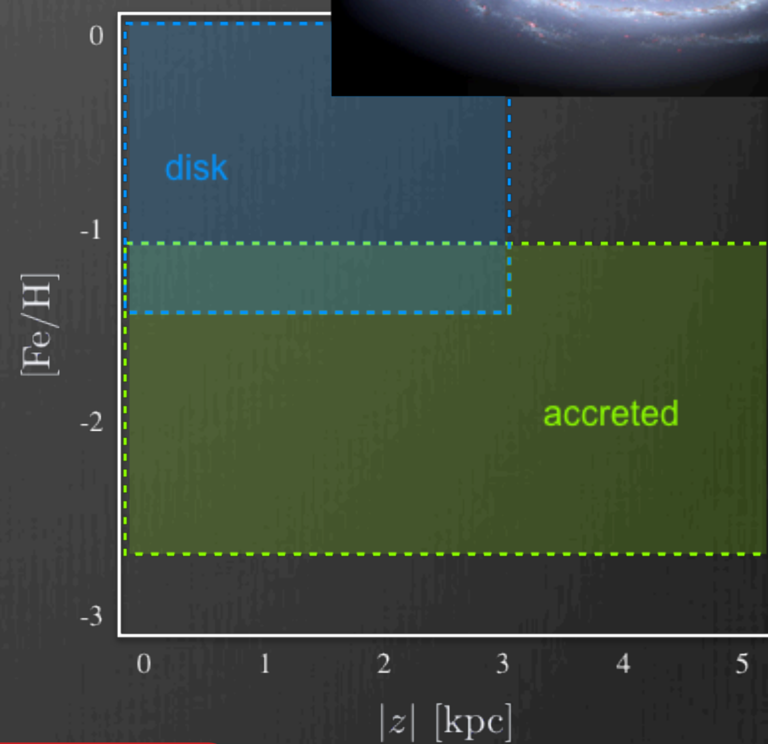
$[\mathrm{Fe/H}] = -1$

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



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?

What we learned:

Galaxies form hierarchically.

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

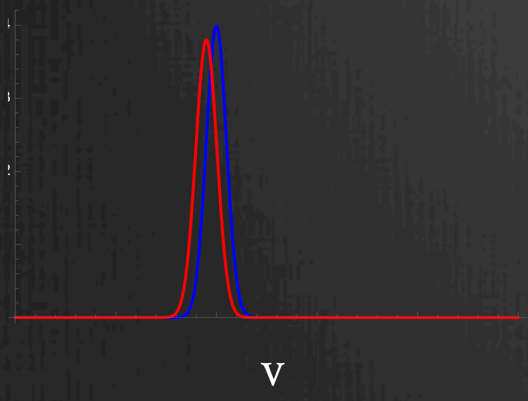
Feedback in Realistic Environments (FIRE)

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



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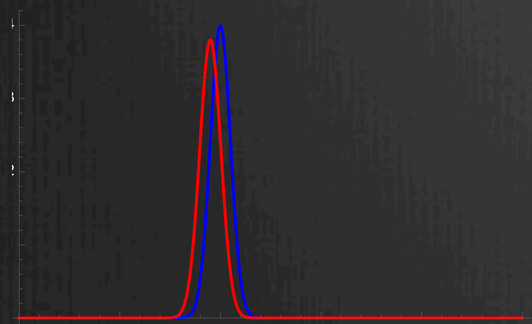
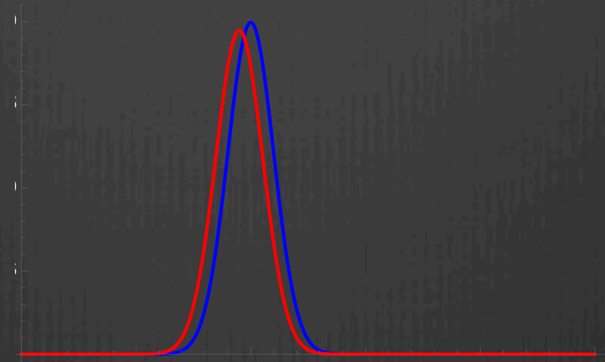


v

Stream

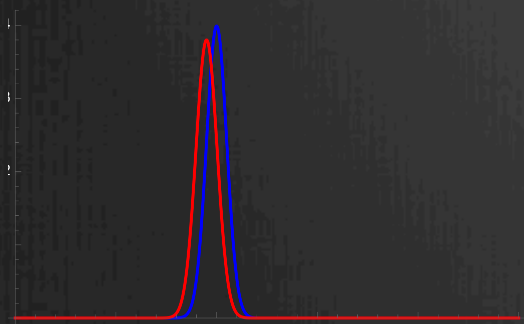


v

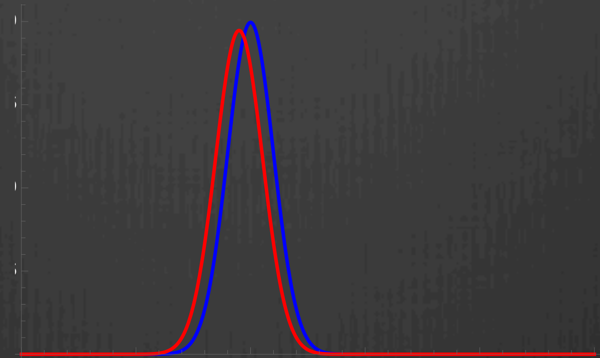
Ivezic et al. (2000)
Yanny et al. (2000)

Merging Stages

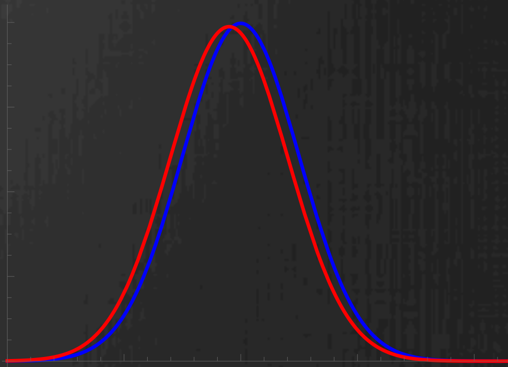
Dwarf Galaxy



Stream

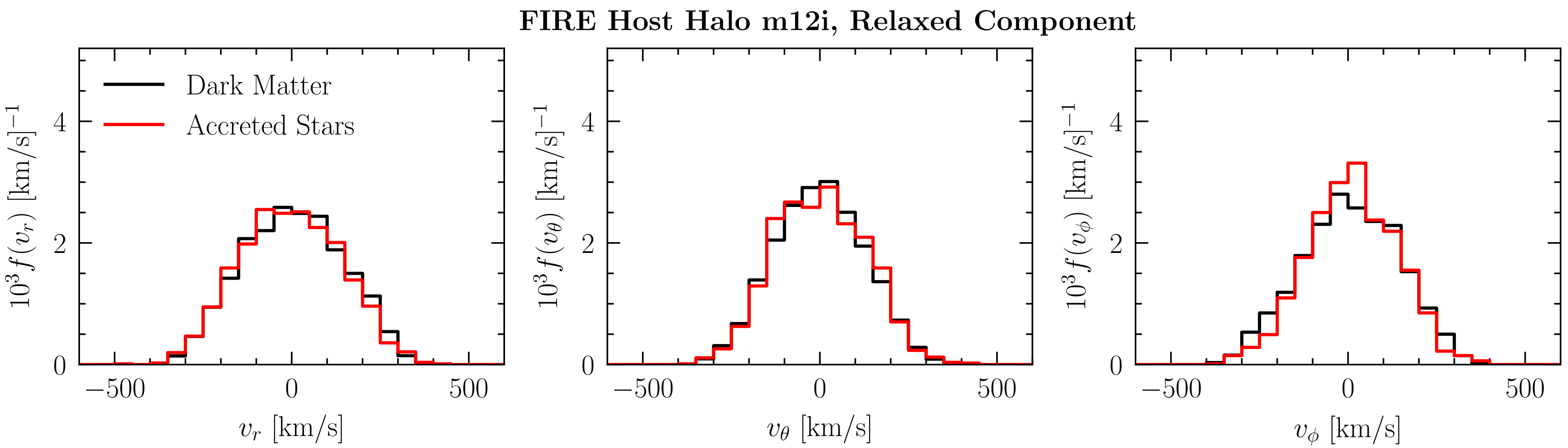


Debris Flow



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, Garisson Kimmel et al. (2018)

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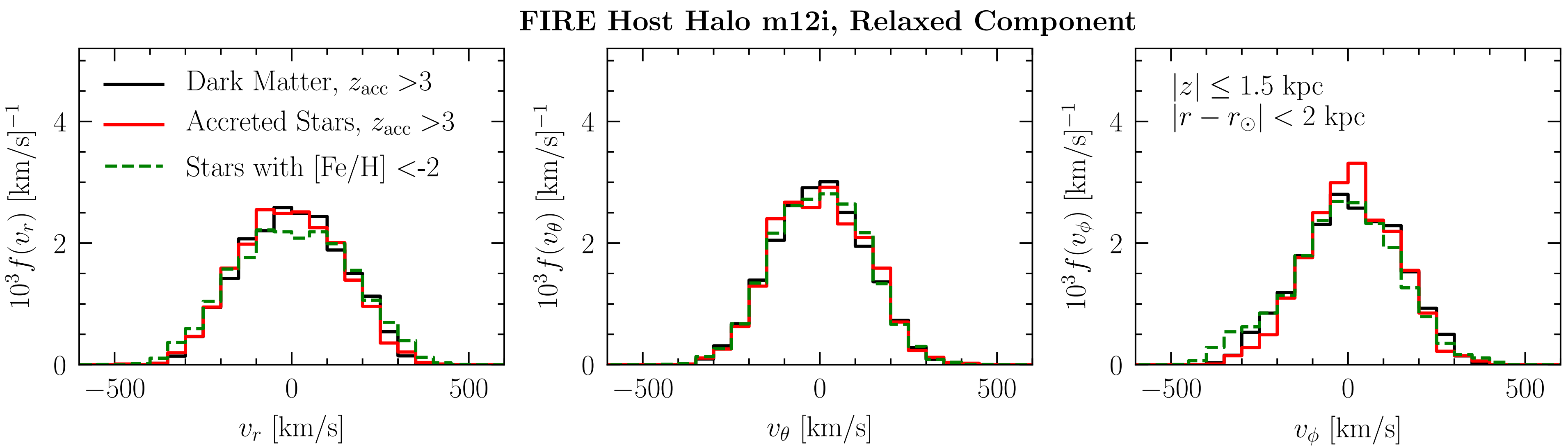

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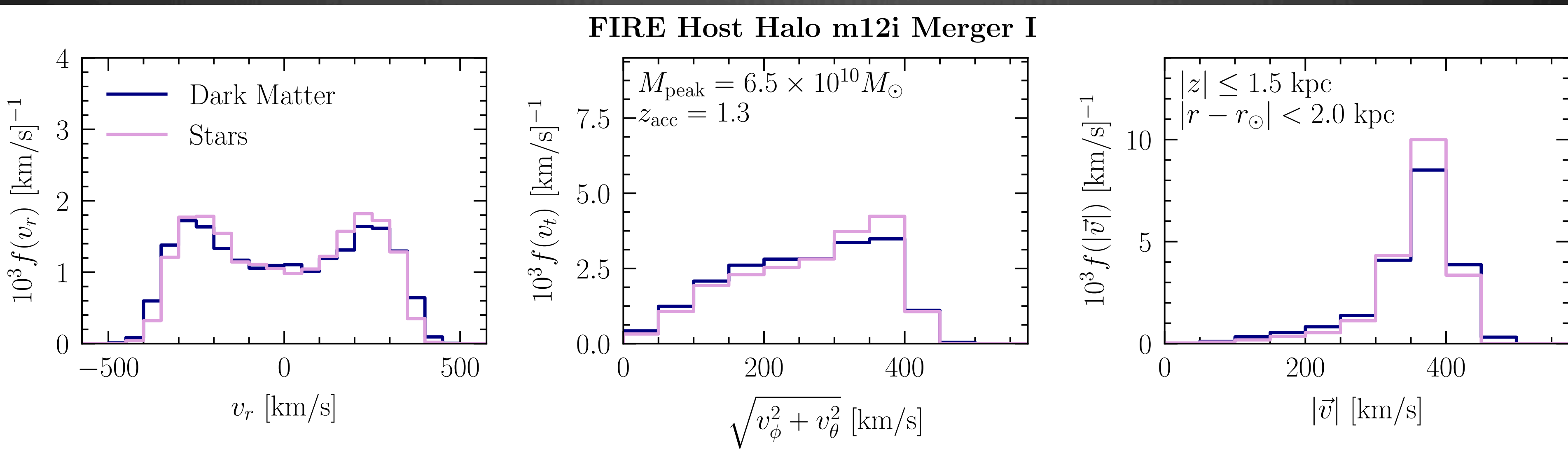
Herzog-Arbeitman, Lisanti, Madau, **Necib** (2018)

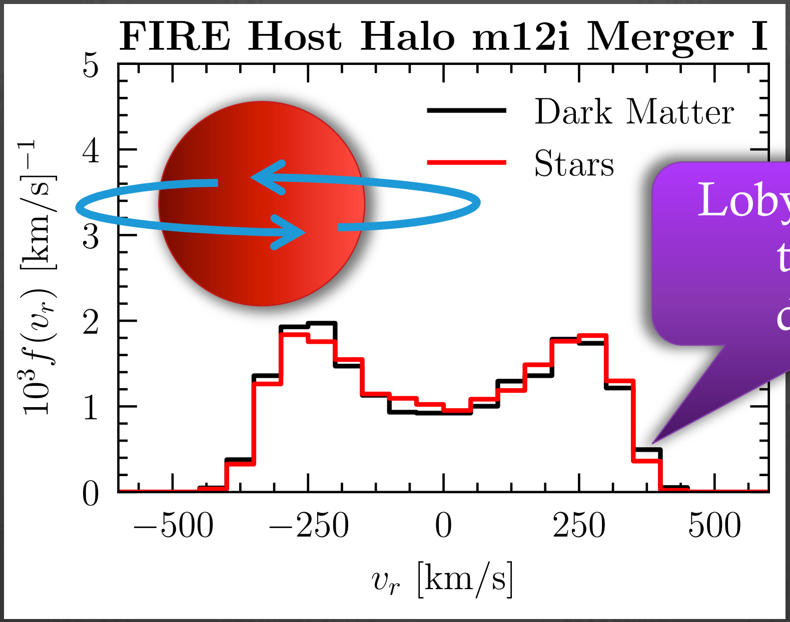
Debris Flow



Strong correlation between the Dark Matter and the stars accreted from a satellite at redshift 1.5, with mass 6.7x10^{10} Msun, and average metallicity ~-1.5, contributing 34% of local accreted stellar mass, and 24% of local accreted Dark Matter.

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

Debris Flow



Loby structure in the radial direction!

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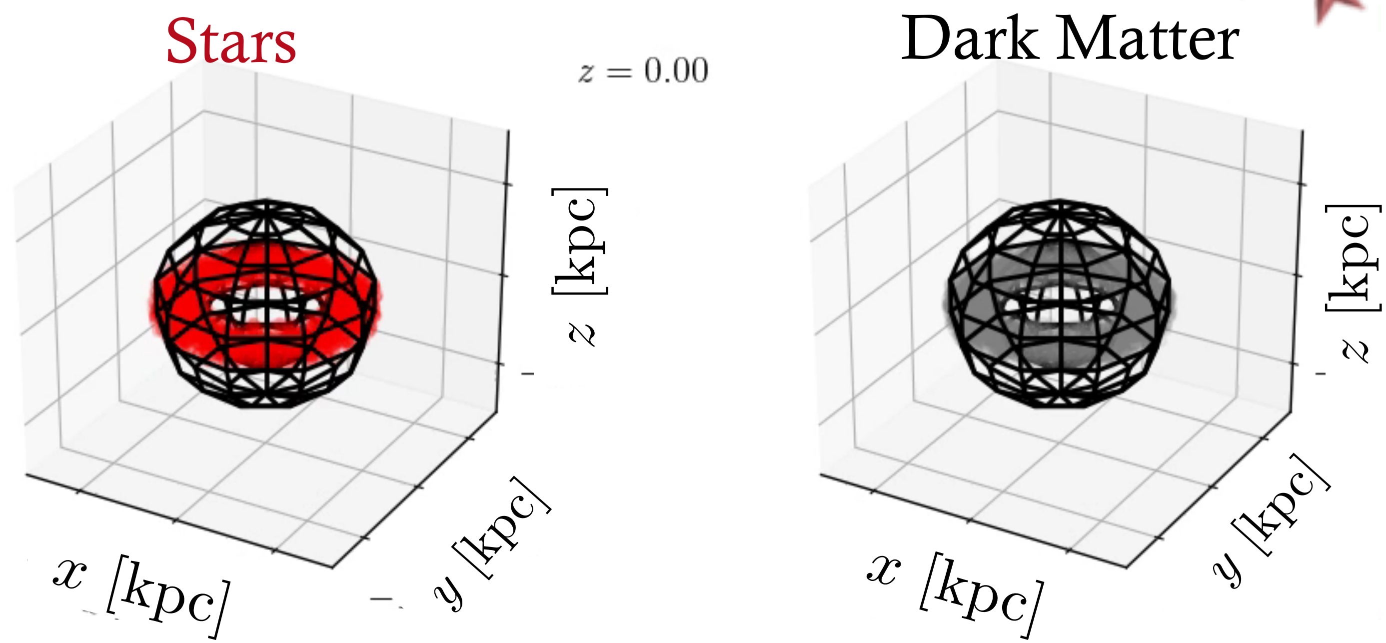

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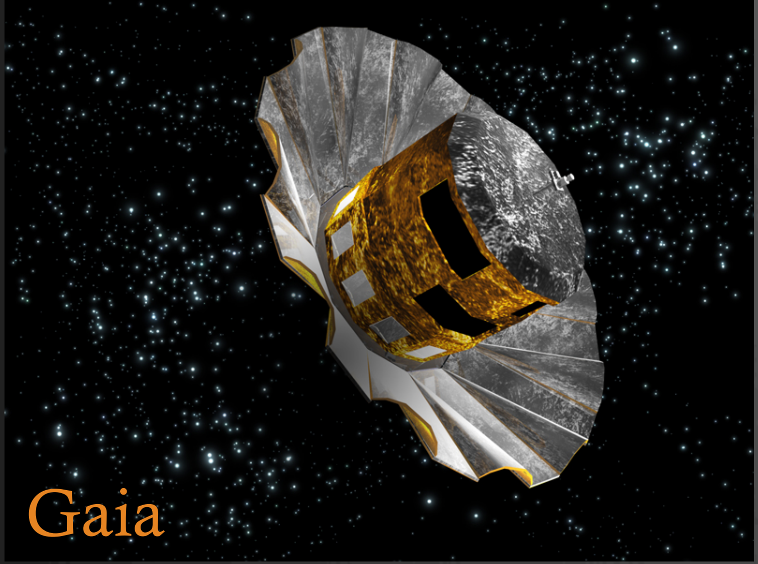
Necib, Lisanti, Garisson Kimmel et al. (2018)

So, What Does our Milky Way Look Like?

What we learned:

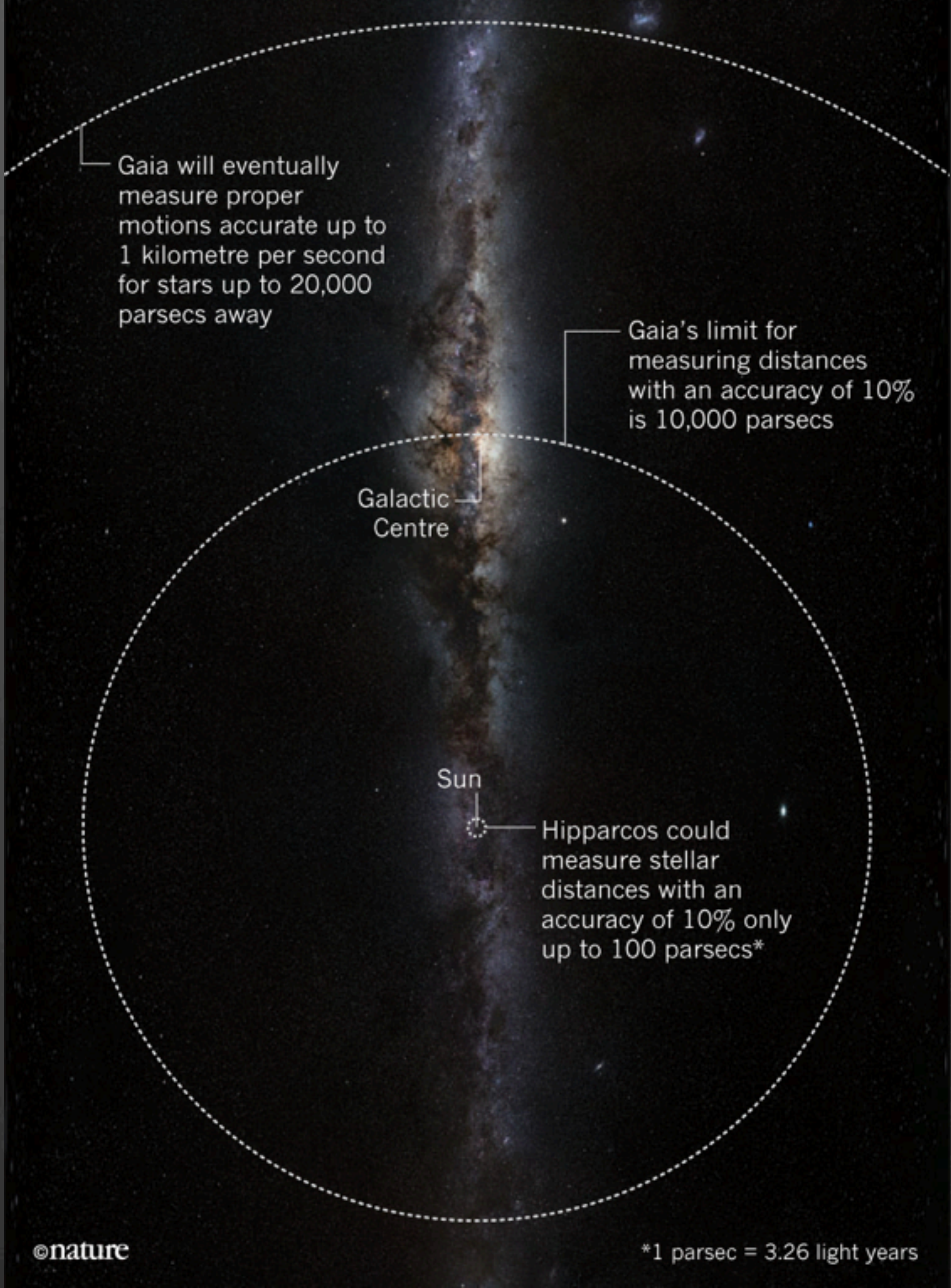
Accreted stars trace their dark matter counterparts.

A merging event shows a 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 Enceleadus

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

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

New Structure!

With Gaia, a merging event in the solar neighborhood was 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)
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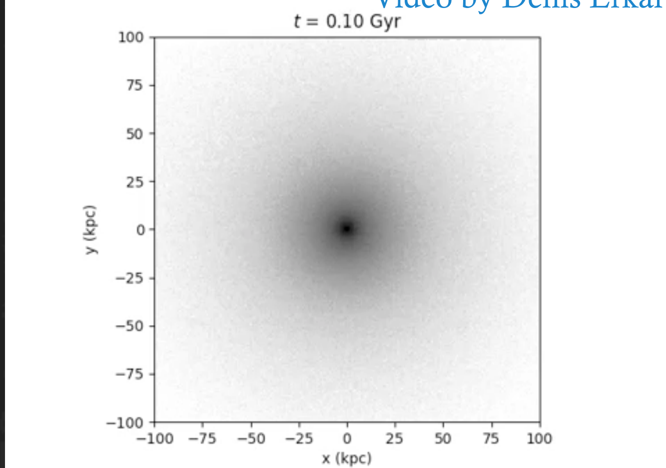
Video by Denis Erkal



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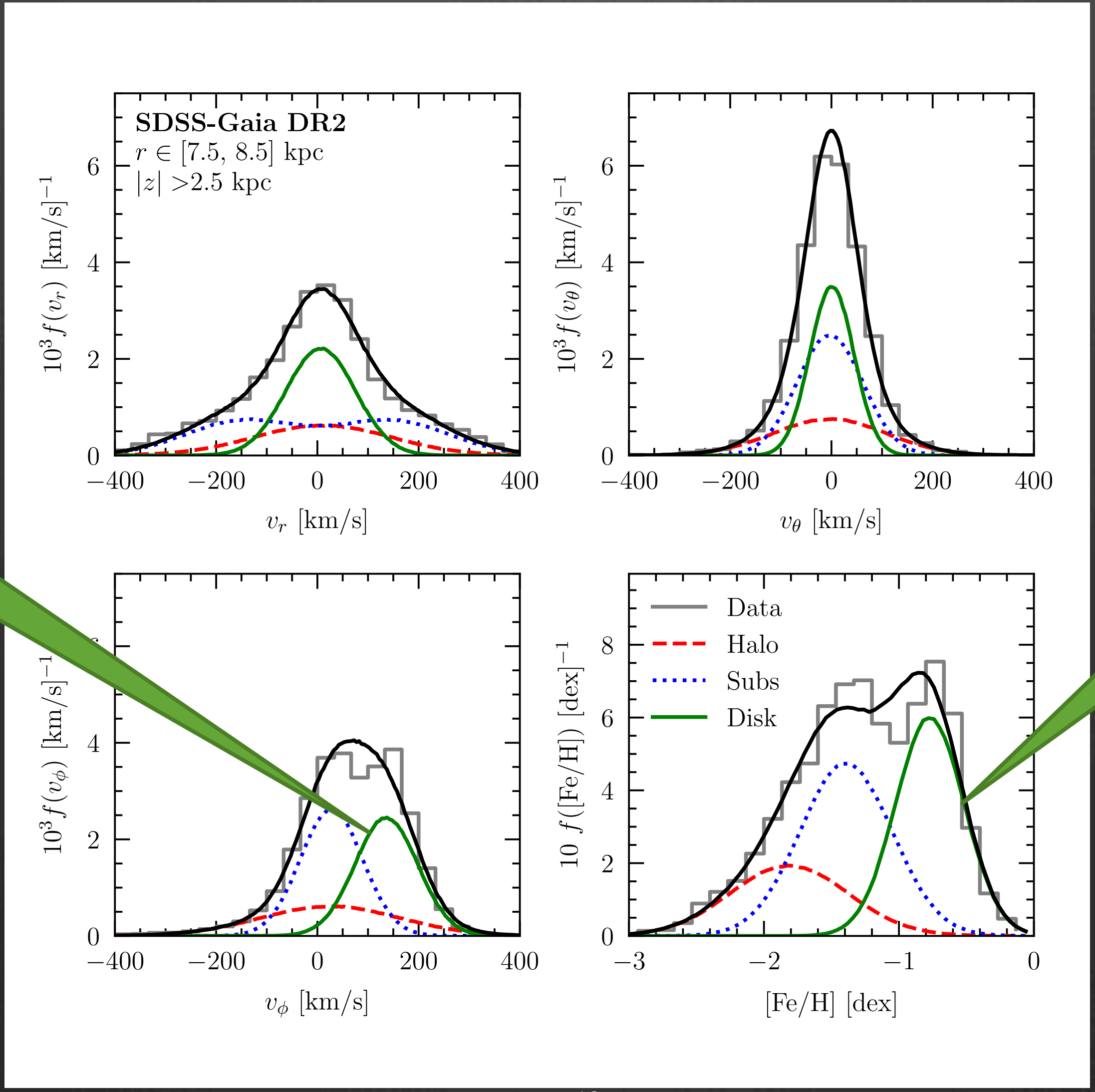
Disk, Halo, and Substructure

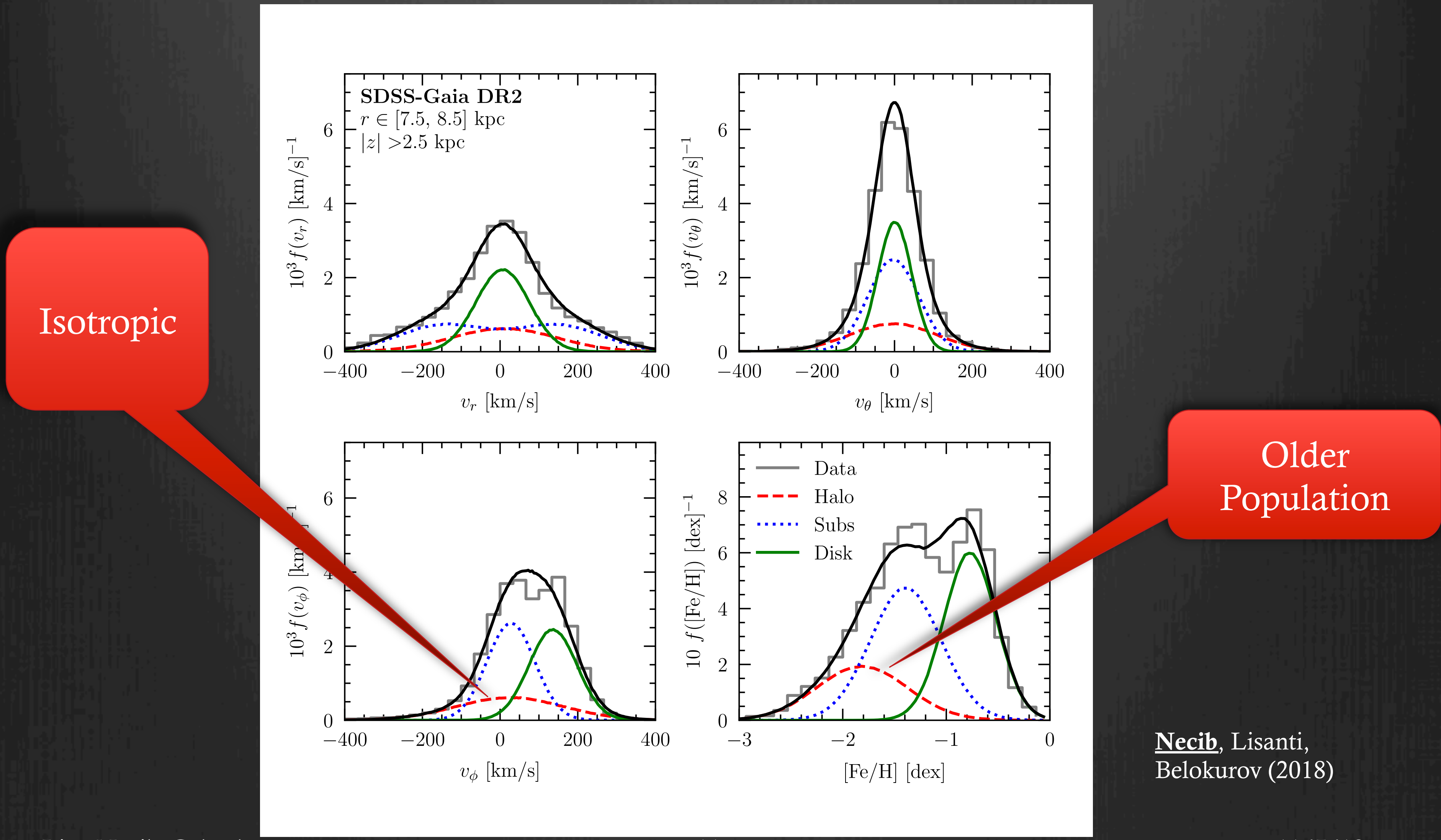


Azimuthal Rotation

Metal-Rich, Younger Population

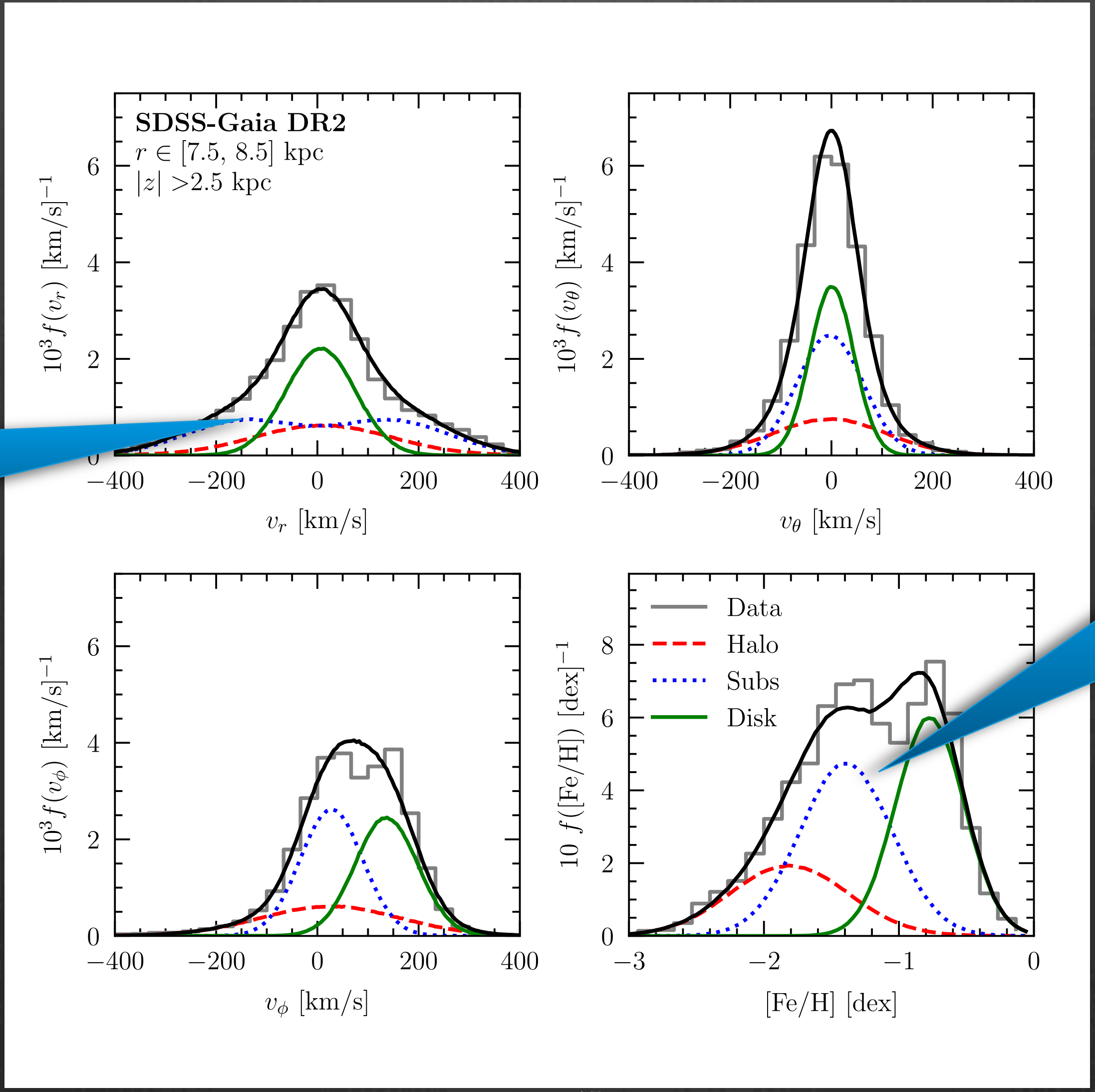
Necib, Lisanti, Belokurov (2018)

Disk, Halo, and Substructure



Necib, Lisanti, Belokurov (2018)

Disk, Halo, and Substructure

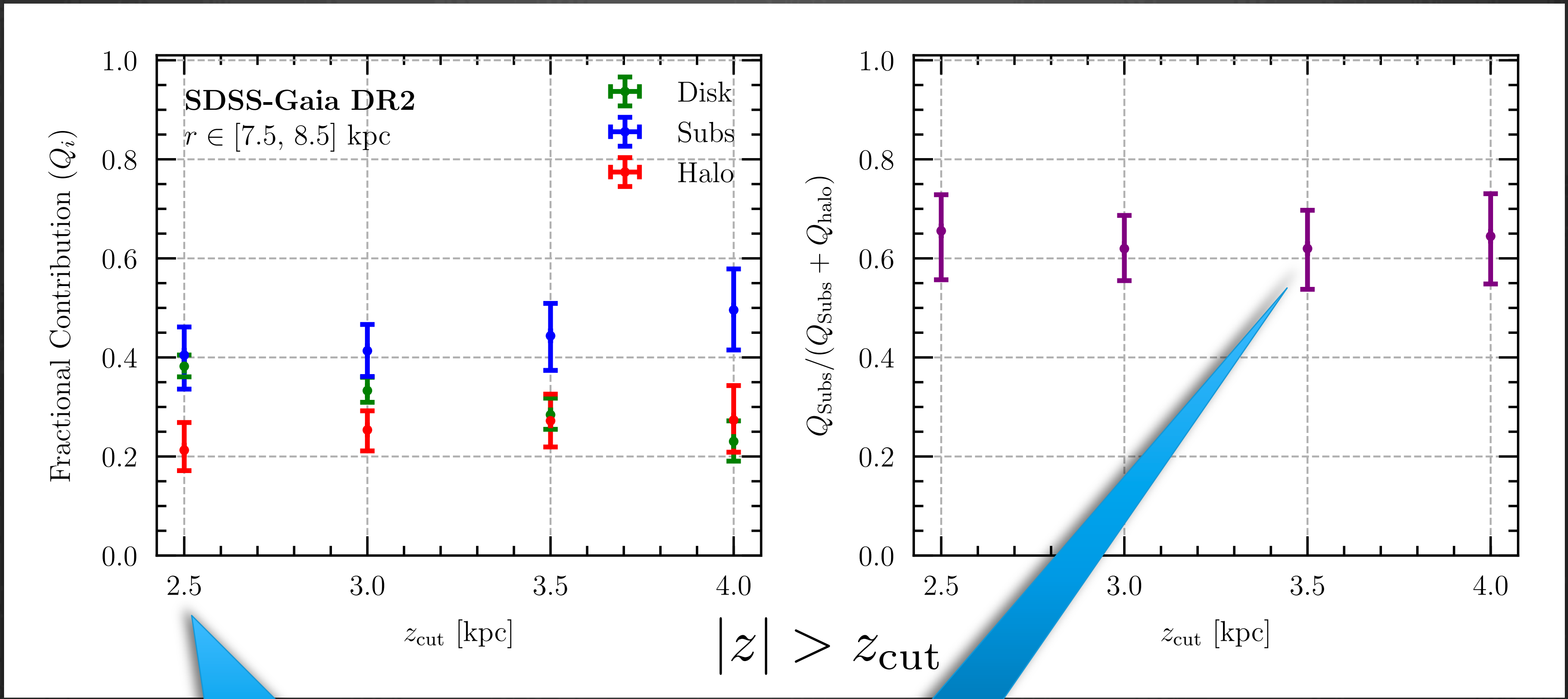


Loby Structure

Older than the Disk, Younger than the Halo

Necib, Lisanti, Belokurov (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.

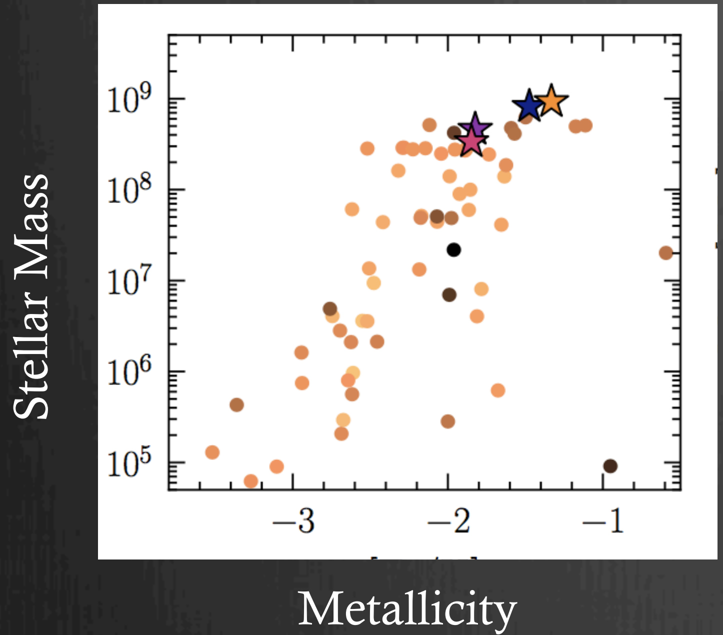
Implications for Direct Detection

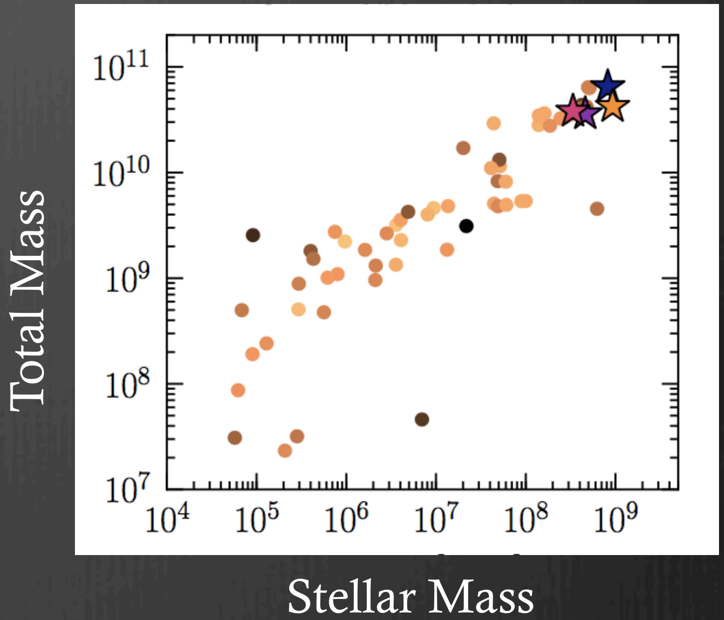
What we learned:

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

Accreted stars should trace their dark matter counterparts from mergers.

One last thing

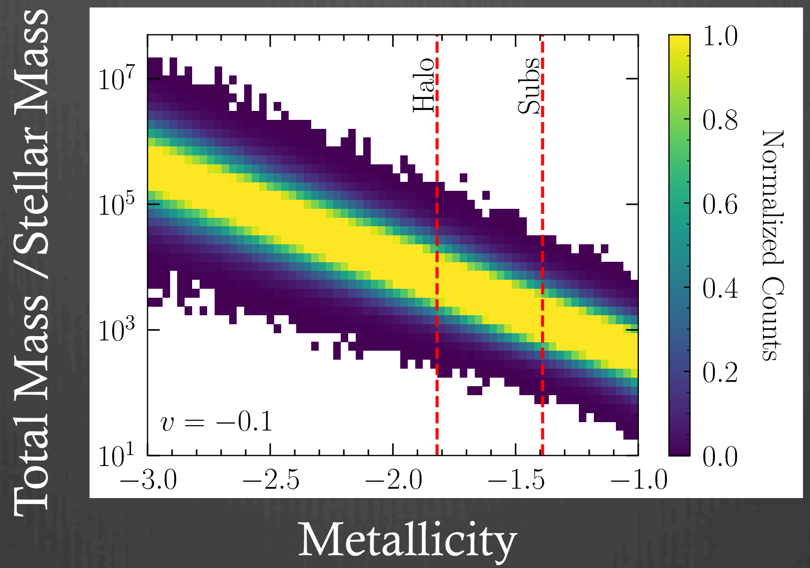




- Subhalos do not contribute the same amounts of Dark Matter and Stars.
- One needs a new relation from which we can extrapolate the amount of Dark Matter in a merger.

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

One last thing



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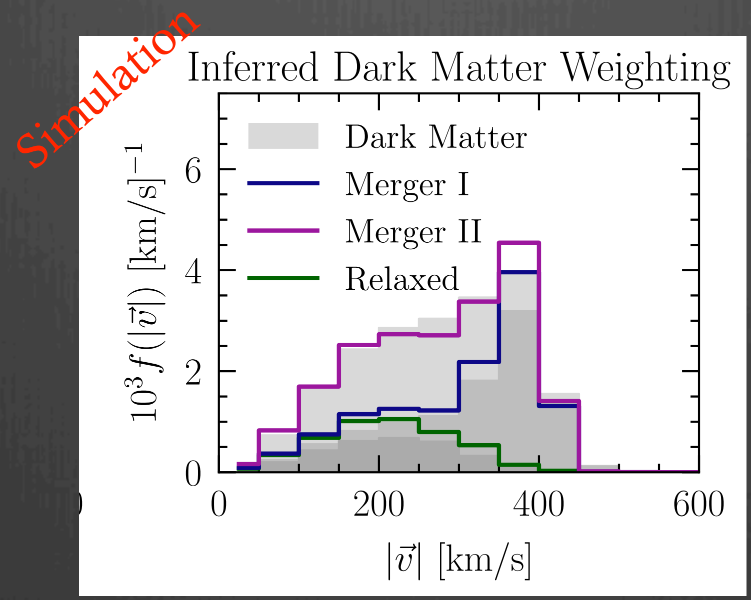

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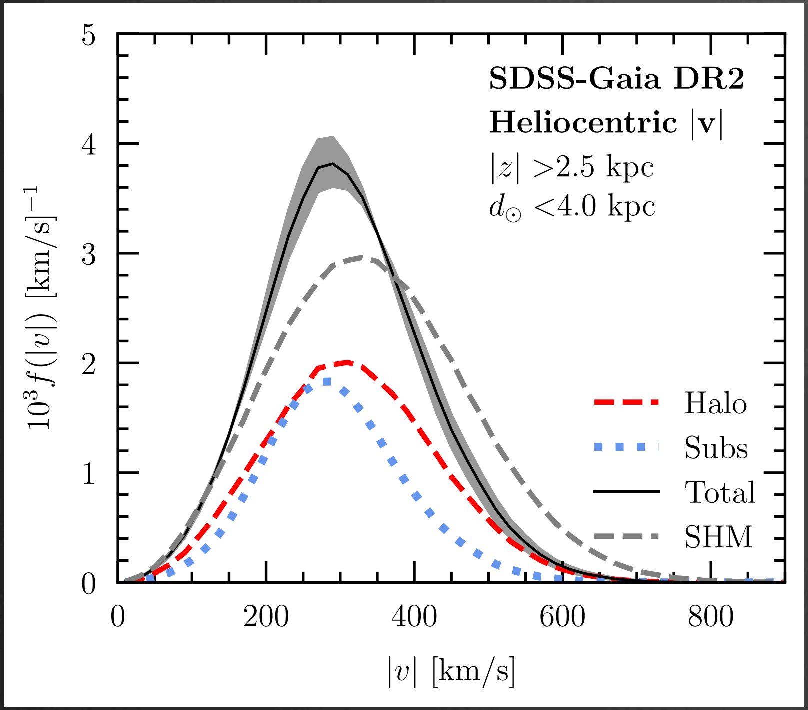
Necib, Lisanti, Garrisson-Kimmel et al (2018)

New Velocity Distribution!

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

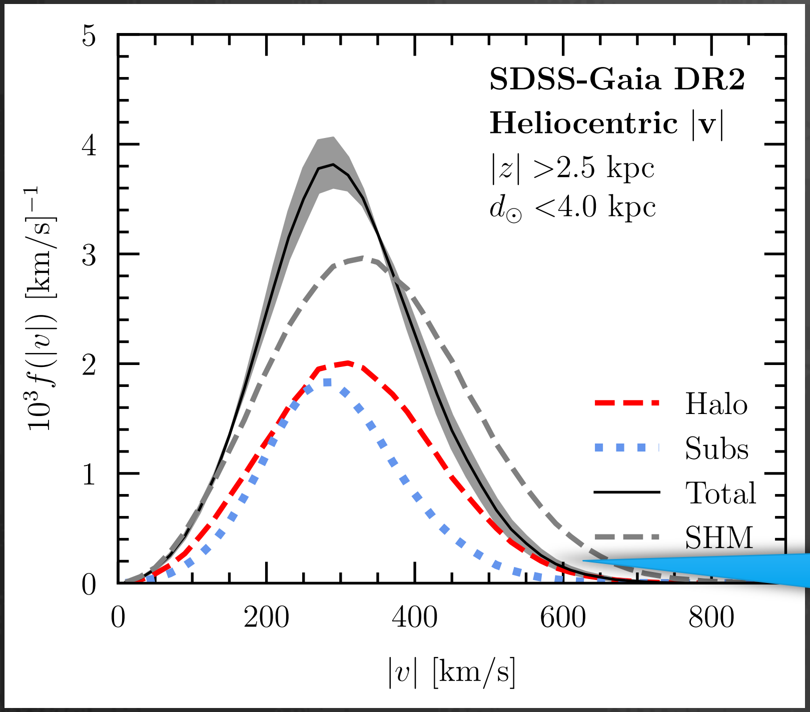


$$c_{\text{subs}} = 0.42^{+0.26}_{-0.22}$$

Similarly to simulations, we build the different components of the velocity distribution.
Are there any components missing?

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrisson-Kimmel et al (2018)

New Velocity Distribution!



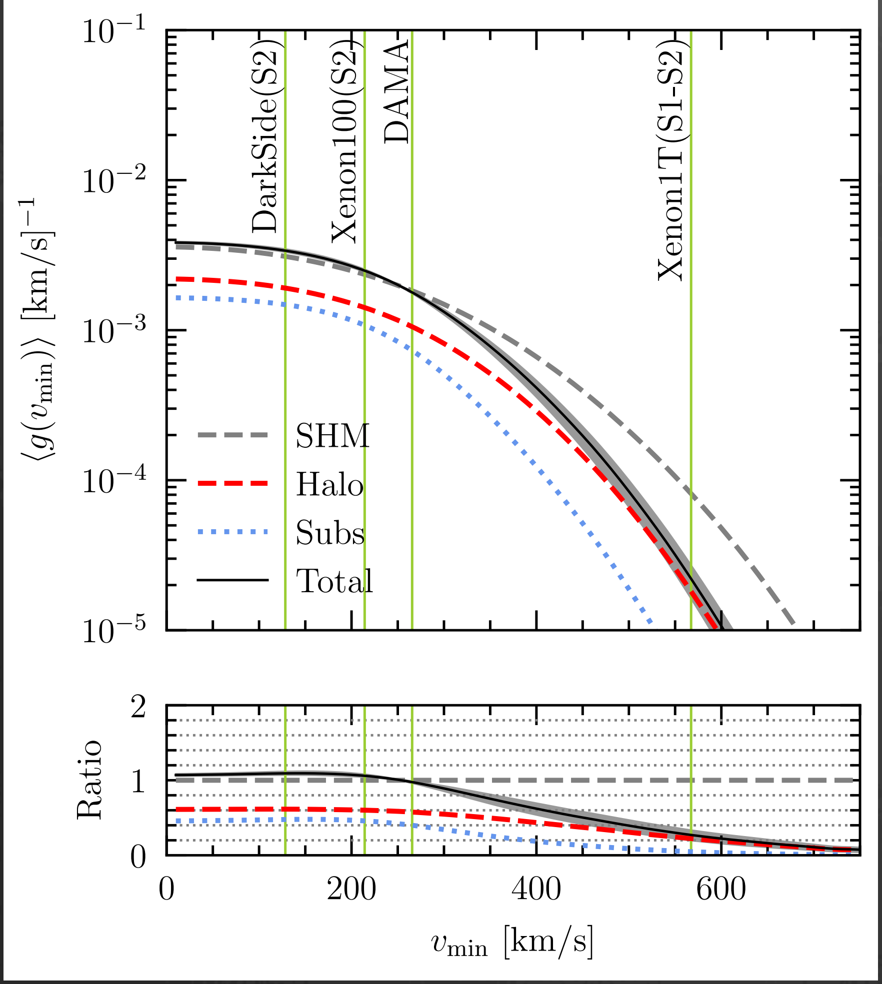
Can be found in a github repository near you
https://linoush.github.io/DM_Velocity_Distribution/

Link in paper arXiv:1807.02519.

Final distribution different from the assumed Maxwell Boltzmann distribution

Necib, Lisanti, Belokurov (2018)
Necib, Lisanti, Garrisson-Kimmel et al (2018)

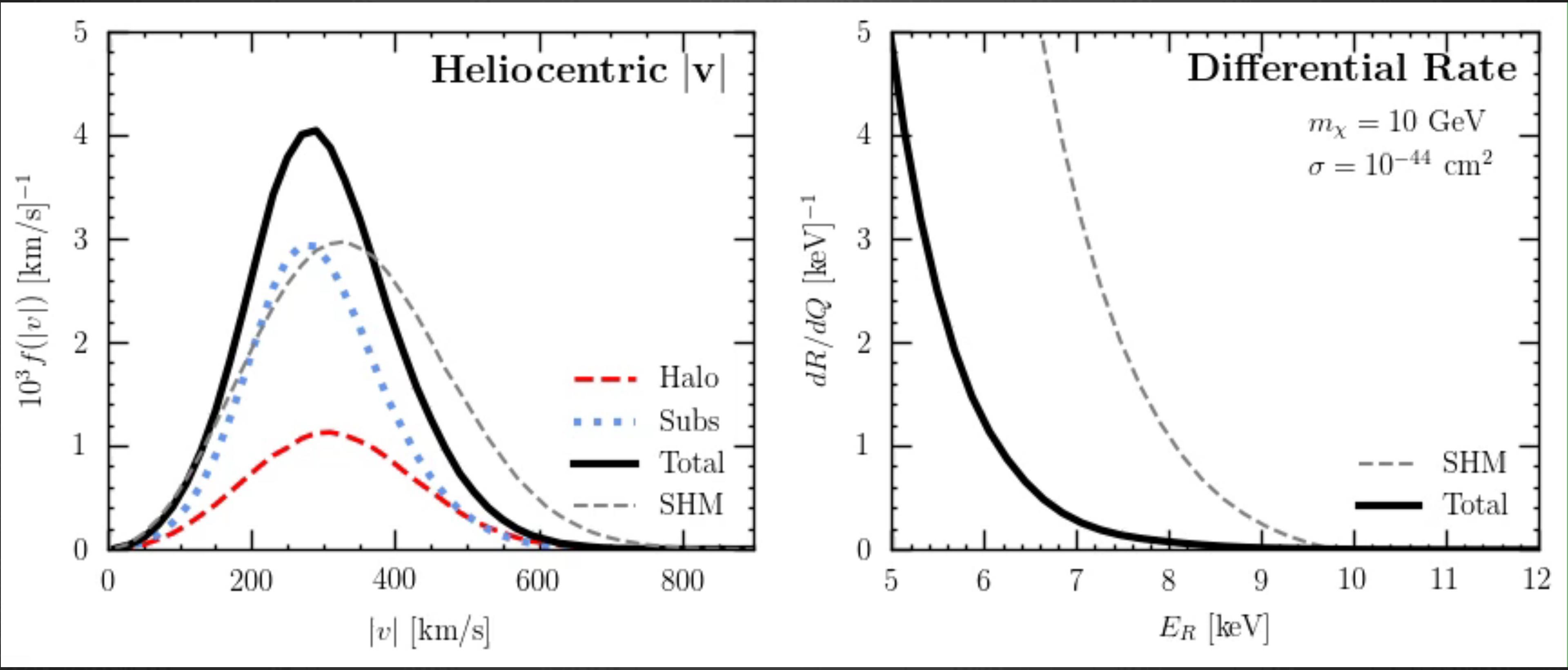
Implications for Direct Detection



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

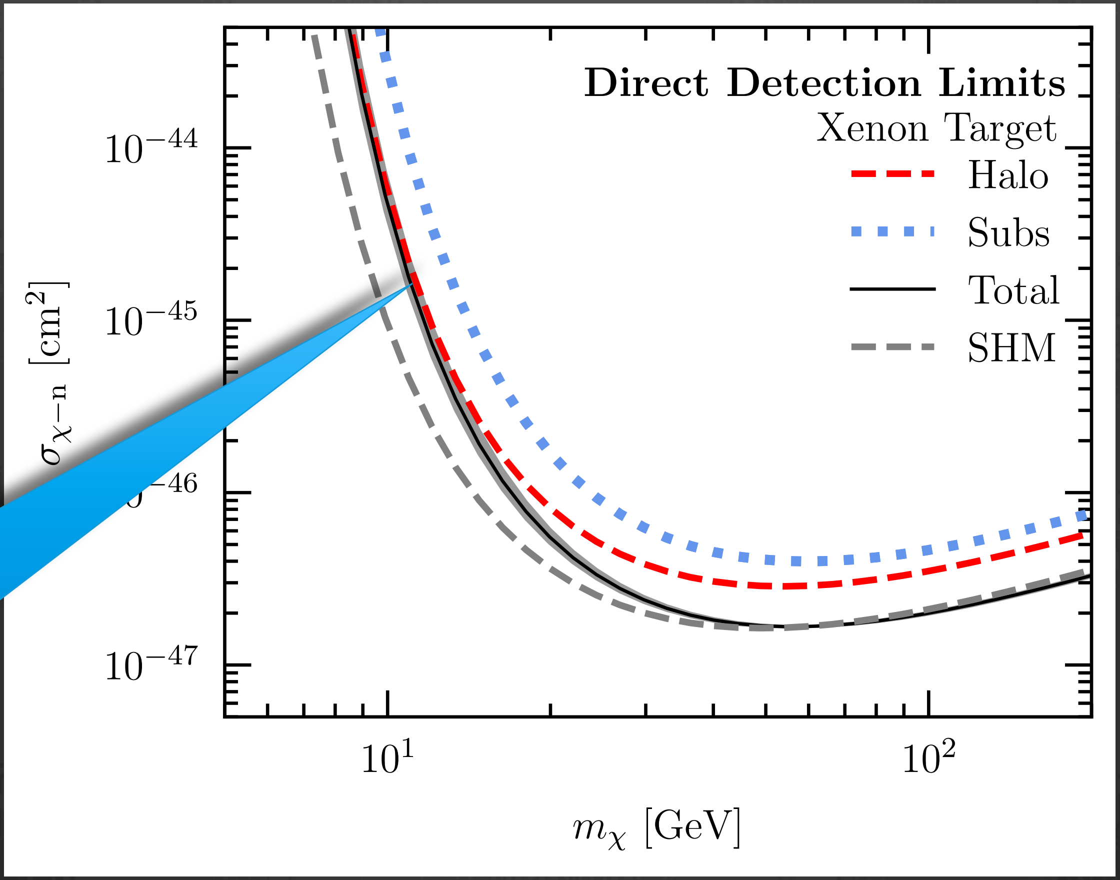
v_{min} depends only on the dark matter mass and the experimental threshold.

Differential Rate



Spanning the possible ratios of the substructure contribution relative to the halo.

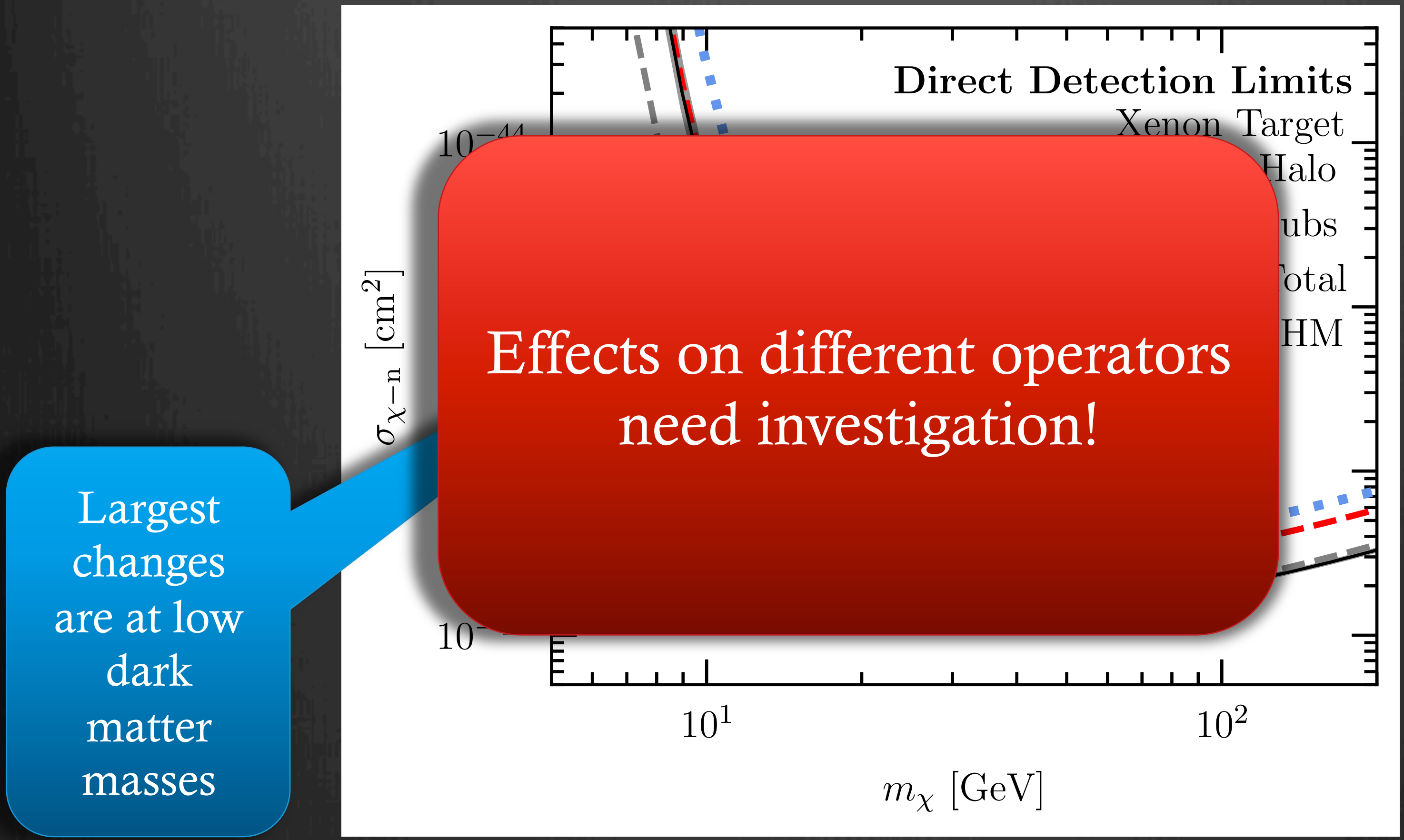
Implications for Direct Detection



Largest changes are at low dark matter masses

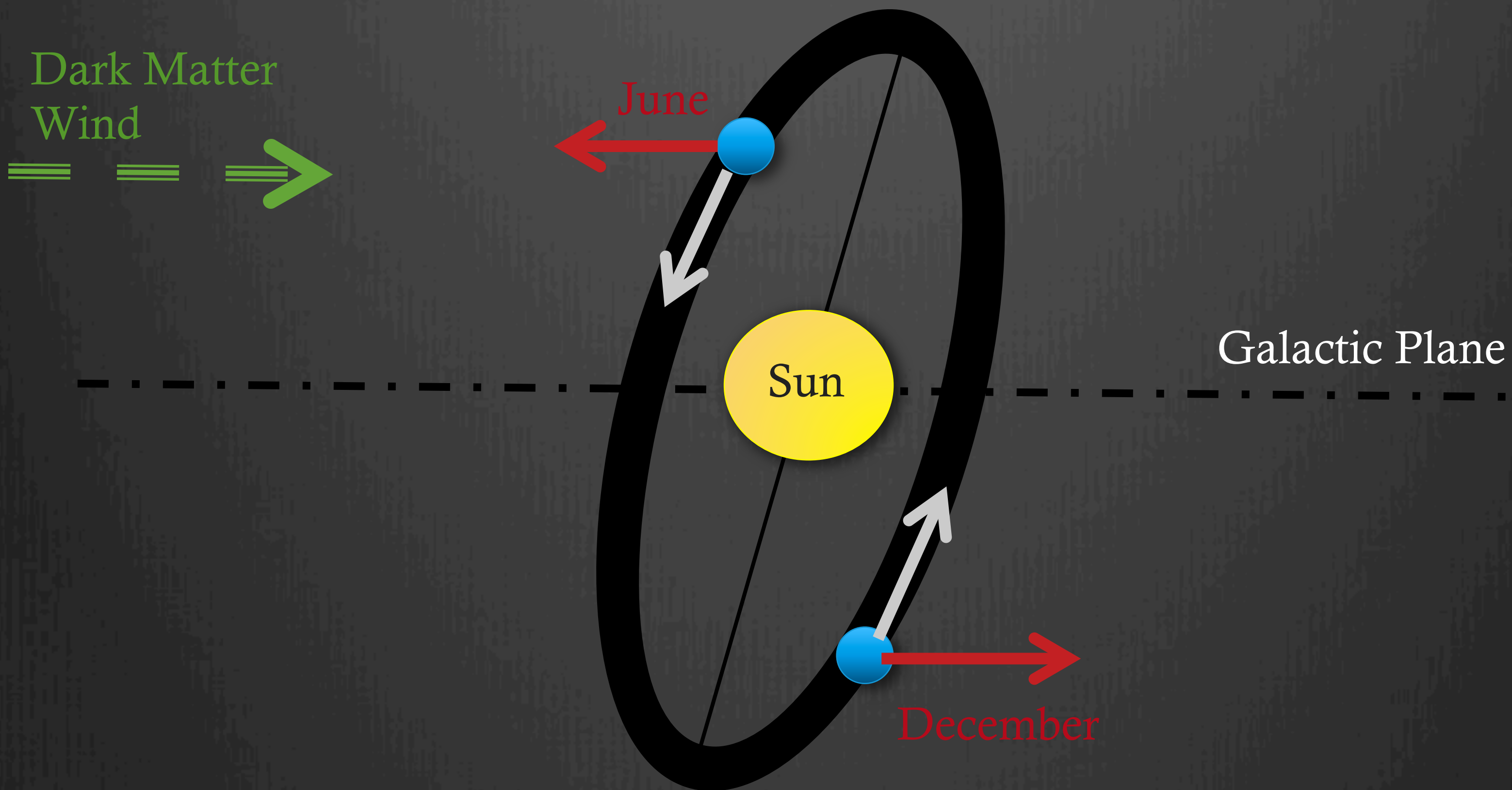
This is schematic, where we used hard thresholds and did not incorporate efficiencies.

Implications for Direct Detection



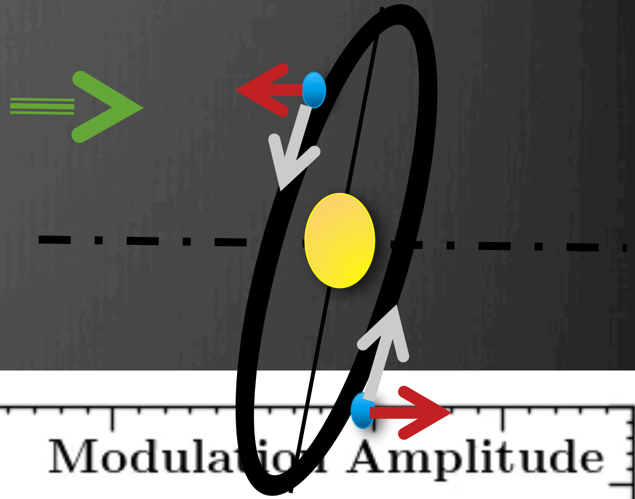
This is schematic, where we used hard thresholds and did not incorporate efficiencies.

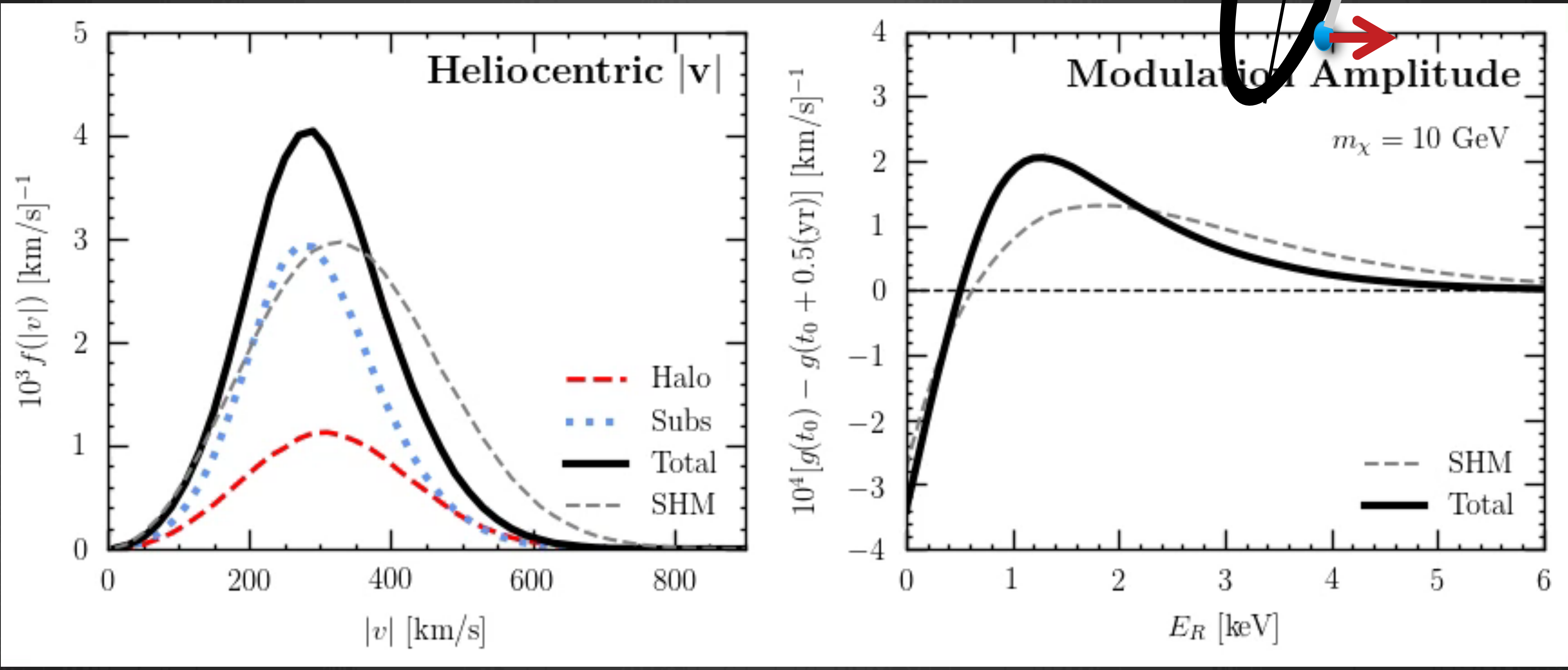
Implications for Direct Detection



Anisotropy of the system leads to modulation effects.

Implications for Direct Detection

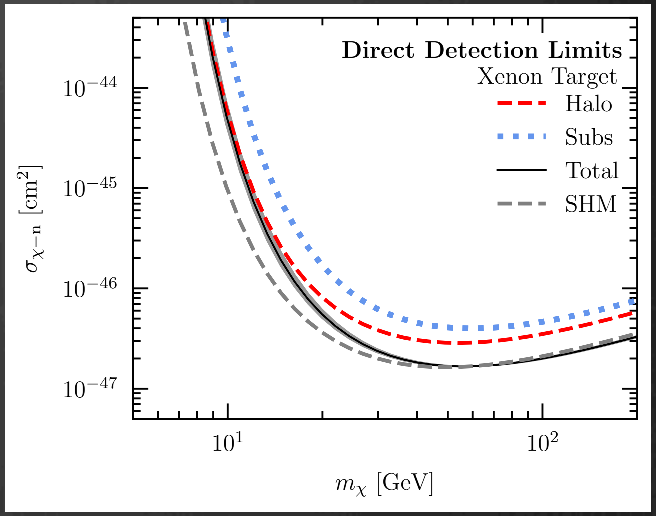




Anisotropy of the system leads to modulation effects.

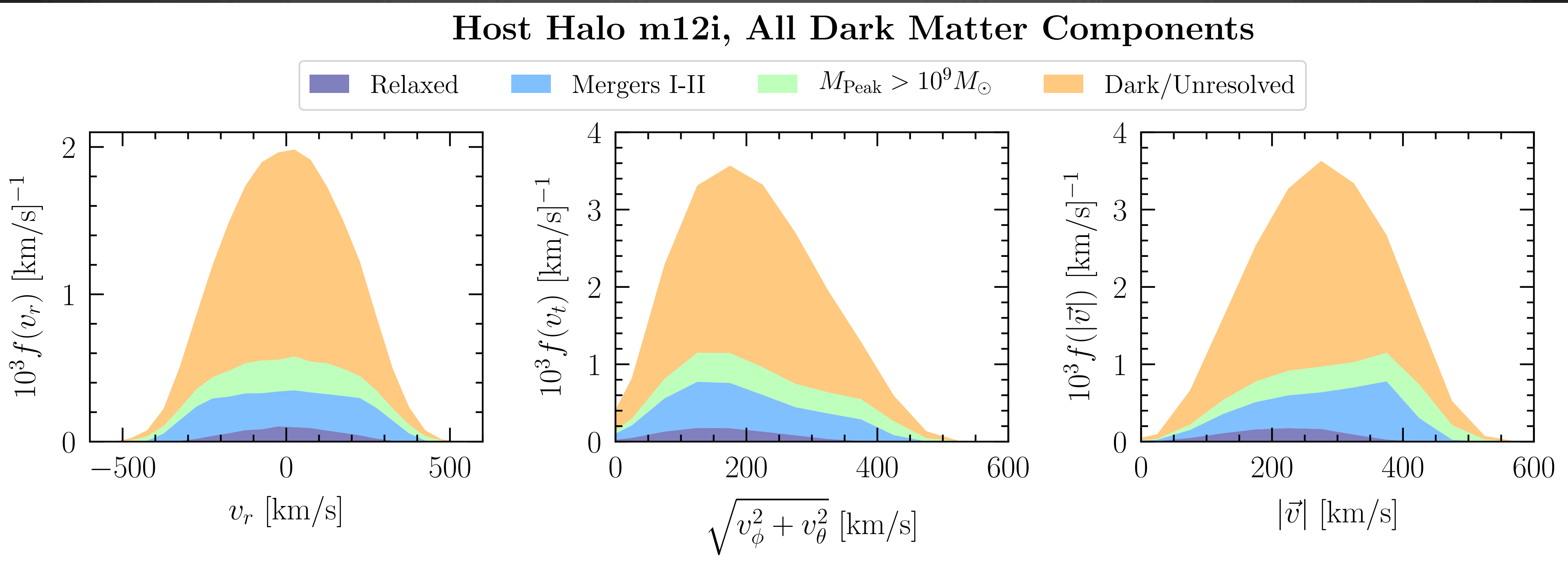
Conclusions

- Stars trace the velocity of the Dark Matter.
  - This is only true for merging satellites that have stars in them. Diffuse 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.

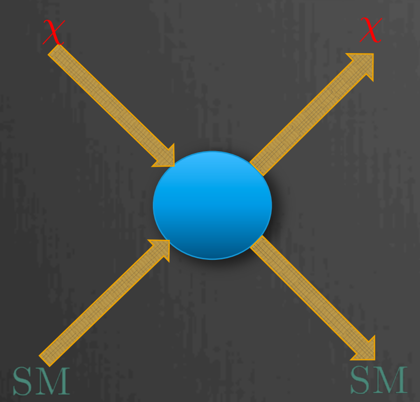


Bonus

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.

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)