

Dark Matter in Disequilibrium, and Implications for Direct Detection

Lina Necib, Caltech

Based on

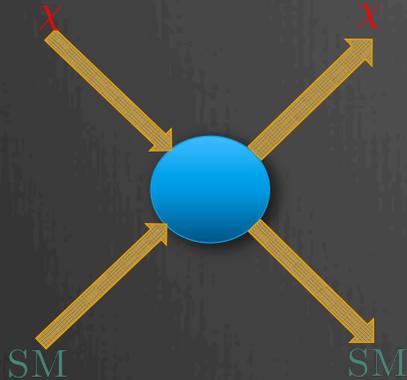
Necib, Lisanti, Belokurov, arXiv:1807.02519

Necib, Lisanti, Garisson Kimmel, Sanderson, Wetzel, Hopkins, arXiv:1808.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.

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

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.

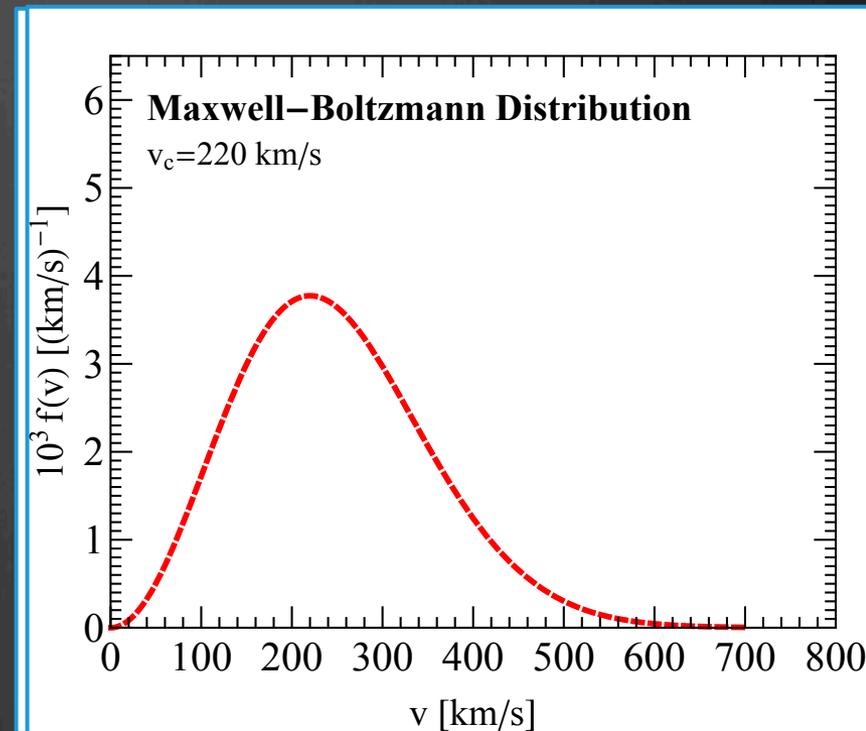
Experimental Parameters:
Form factors, mass of the nucleus (also experimental mass/exposure should be added)

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

Maxwell-Boltzmann Distribution

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

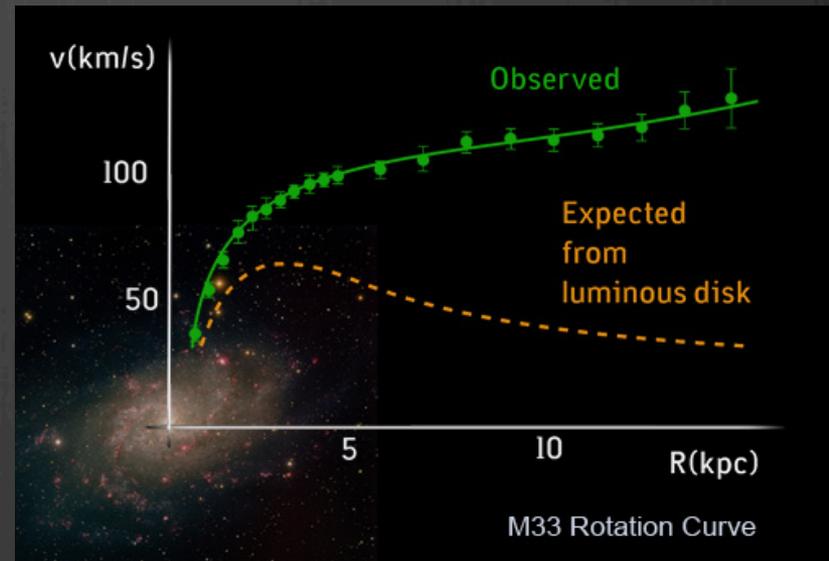
This is the standard velocity distribution, used as a reference for direct detection limits.



Drukier et al. (1986)
Freese et al. (1988)

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

$$\left\{ \begin{array}{l} v_c(r) = \sqrt{2}\sigma \\ \rho(r) = \frac{\sigma^2}{2\pi G r^2} \\ M(r) = \frac{2\sigma^2 r}{G} \end{array} \right.$$

Maxwell-Boltzmann Distribution: Origins

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Poisson

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

Maxwell-Boltzmann Distribution

Standard Halo Model

$$\left\{ \begin{array}{l} v_c(r) = \sqrt{2}\sigma \\ \rho(r) = \frac{\sigma^2}{2\pi G r^2} \\ M(r) = \frac{2\sigma^2 r}{G} \end{array} \right.$$

Poisson (1813)

J Jeans (1915)

Binney & Tremaine (2008)

Maxwell-Boltzmann Distribution: Origins

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Poisson

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

Maxwell-Boltzmann Distribution

Standard Halo Model

We assumed Equilibrium and Isotropy!

$$v_c(r) = \sqrt{2}\sigma$$
$$M(r) = \frac{2\pi G r^2 \sigma^2}{G}$$

Poisson (1813)

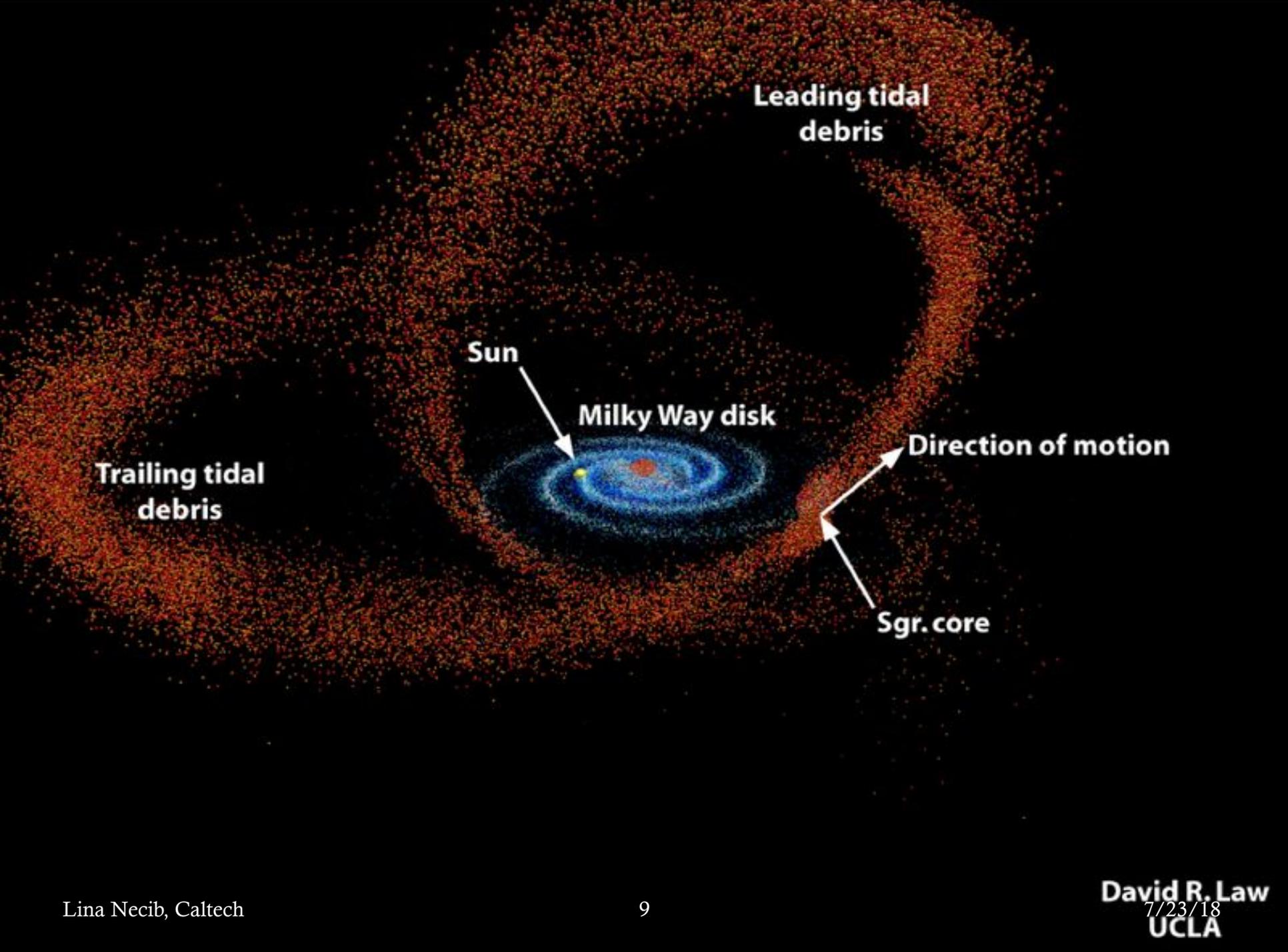
Jeans (1915)

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

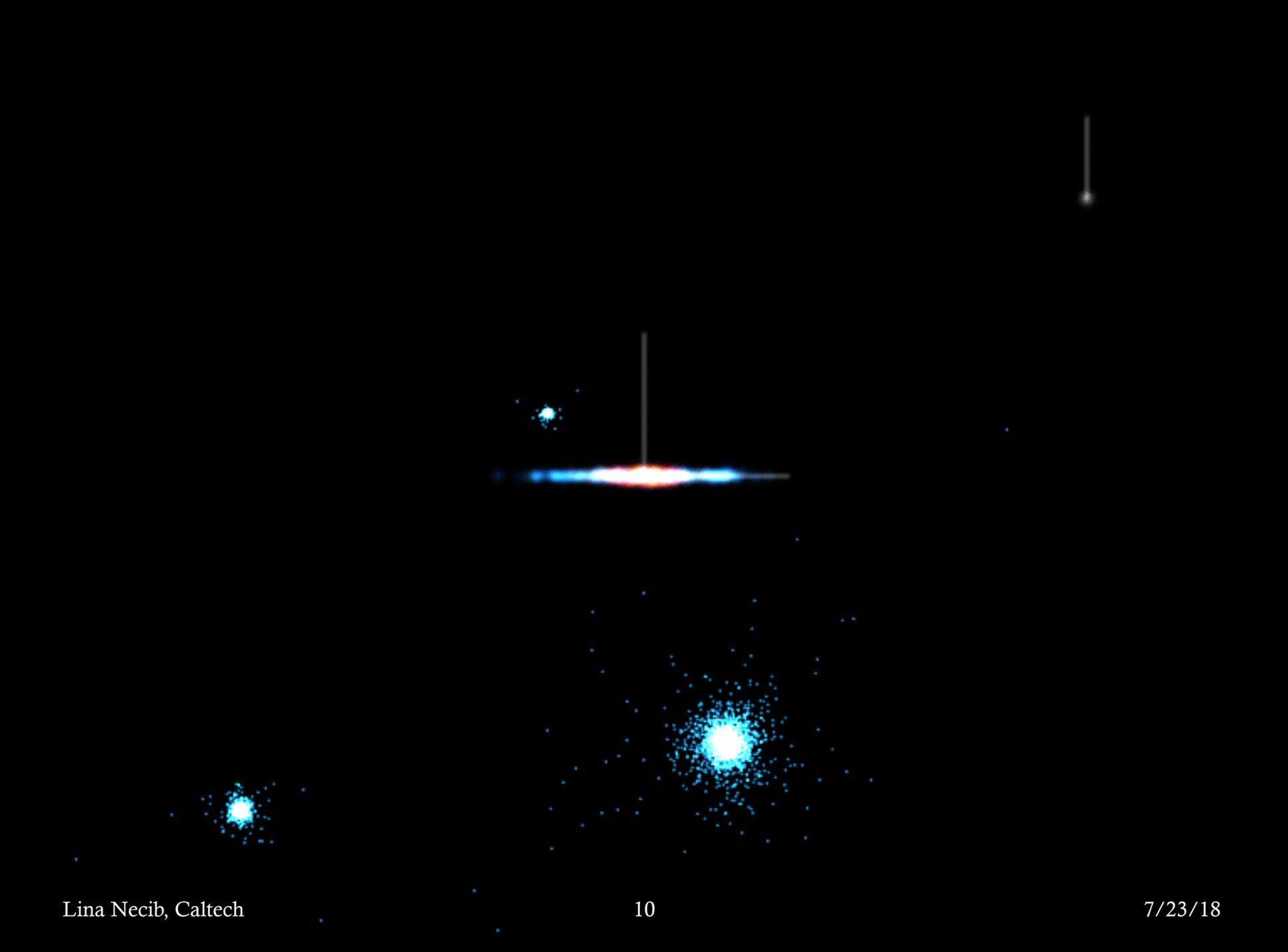
Sun

Milky Way disk

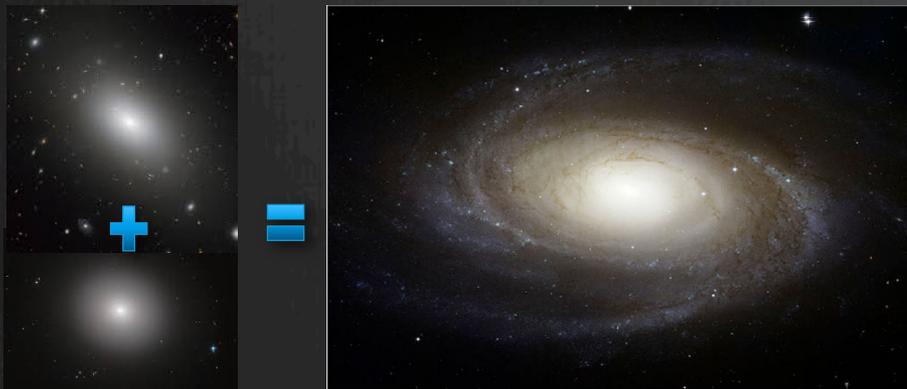
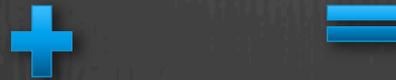
Direction of motion

Trailing tidal debris

Sgr. core



Galaxies Form Hierarchically!



White & Rees (1978)

Feedback in Realistic Environments (FIRE)

$z=9.9$

10 kpc



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

Lina Necib, Caltech

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

From
Simulations:

Accreted
Stars trace
the velocity
of their Dark
Matter
counterparts.

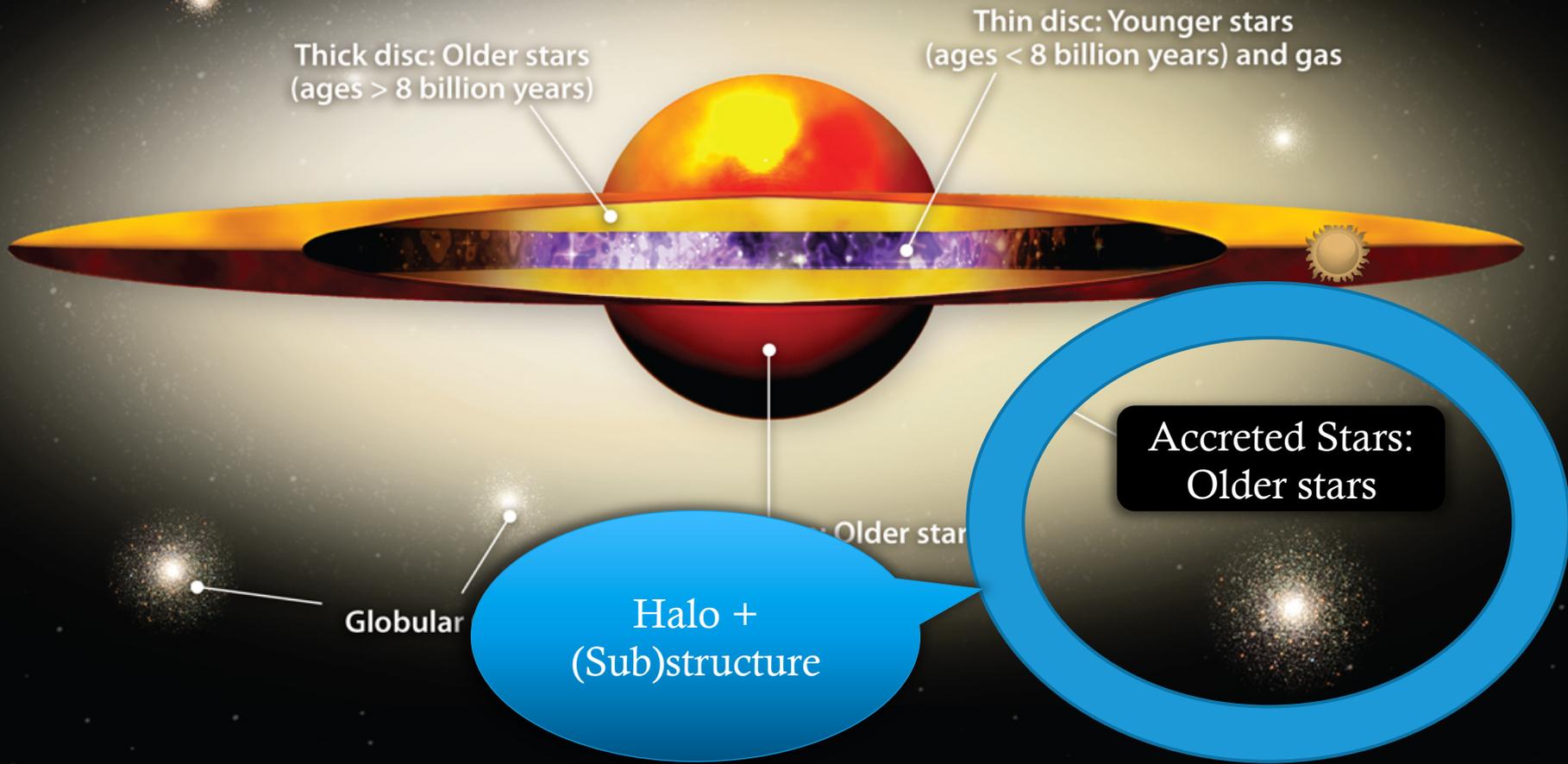
From Gaia
DR1/DR2:

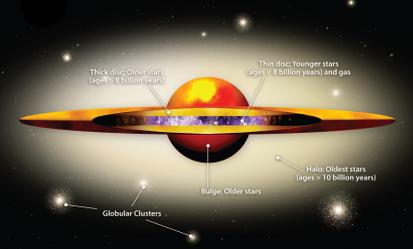
We get the
local velocity
distribution
of accreted
stars.

Therefore:

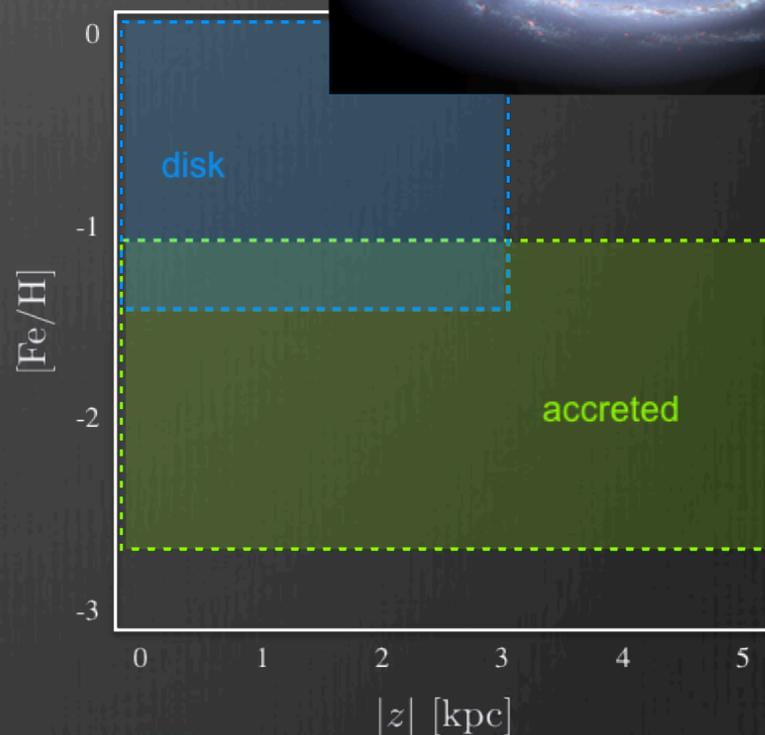
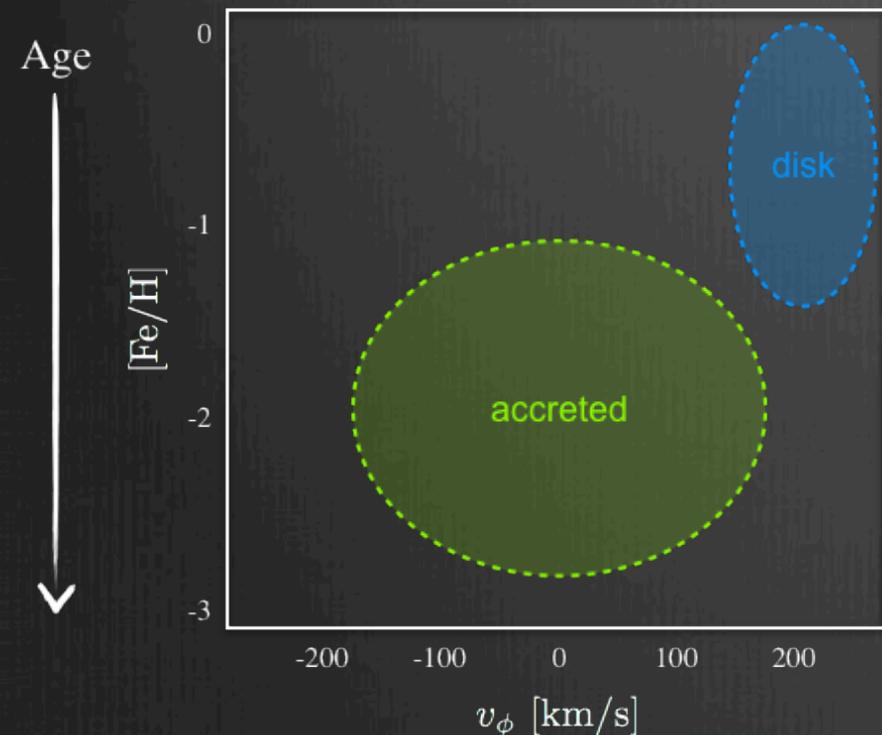
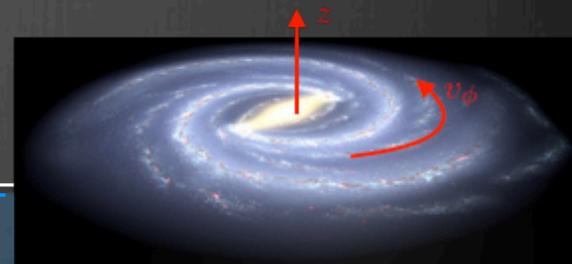
We
empirically
obtain the
Dark Matter
velocity
distribution.

Herzog-Arbeitman, Lisanti, Madau, [Necib](#) (2018)
Herzog-Arbeitman, Lisanti, [Necib](#), (2018)





Chemodynamics



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

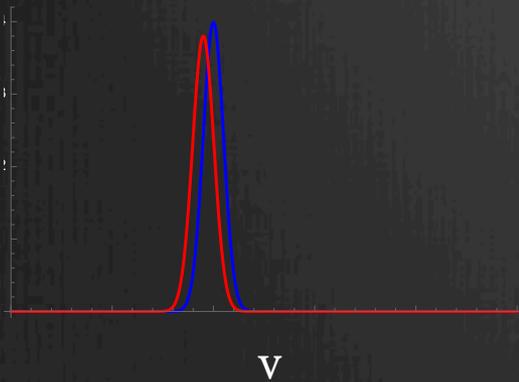
Galaxies form hierarchically.

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

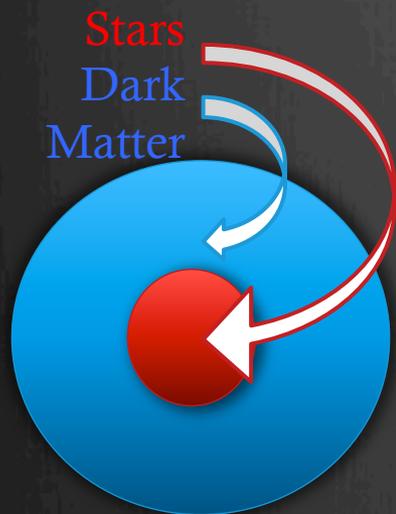
Merging Stages



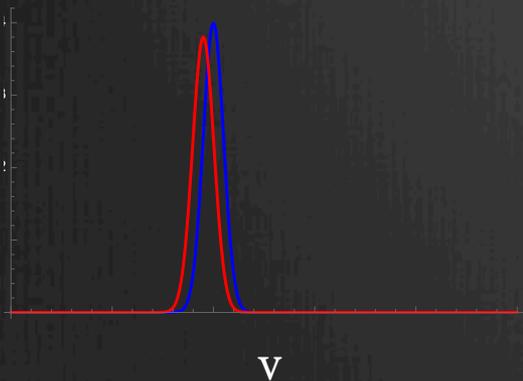
Dwarf Galaxy



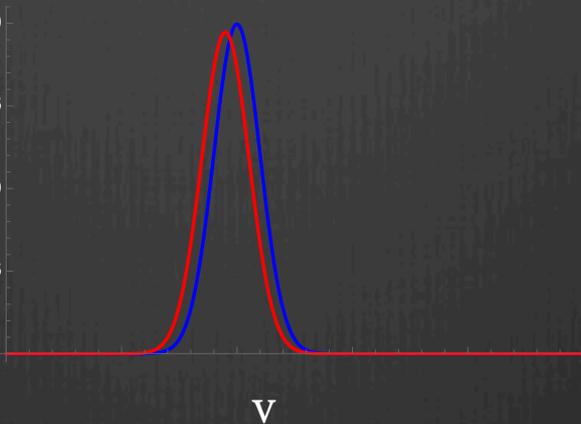
Merging Stages



Dwarf Galaxy



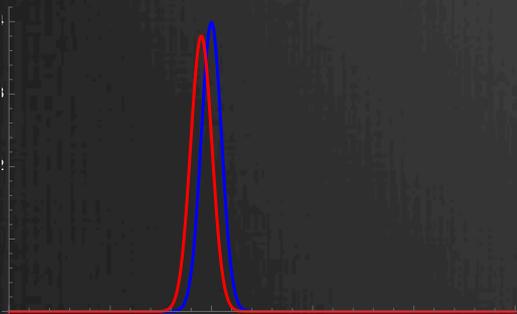
Stream



Merging Stages

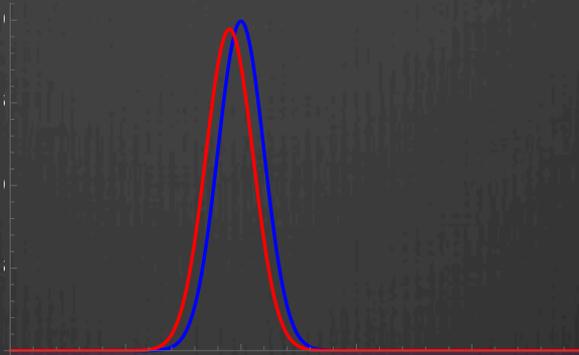


Dwarf Galaxy



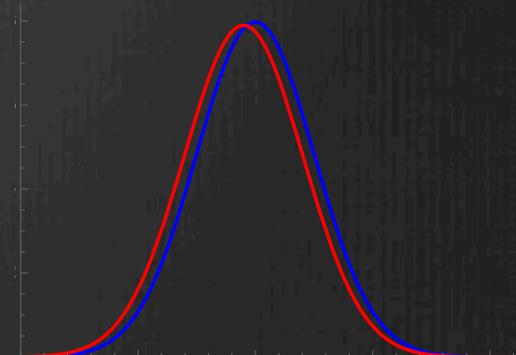
v

Stream



v

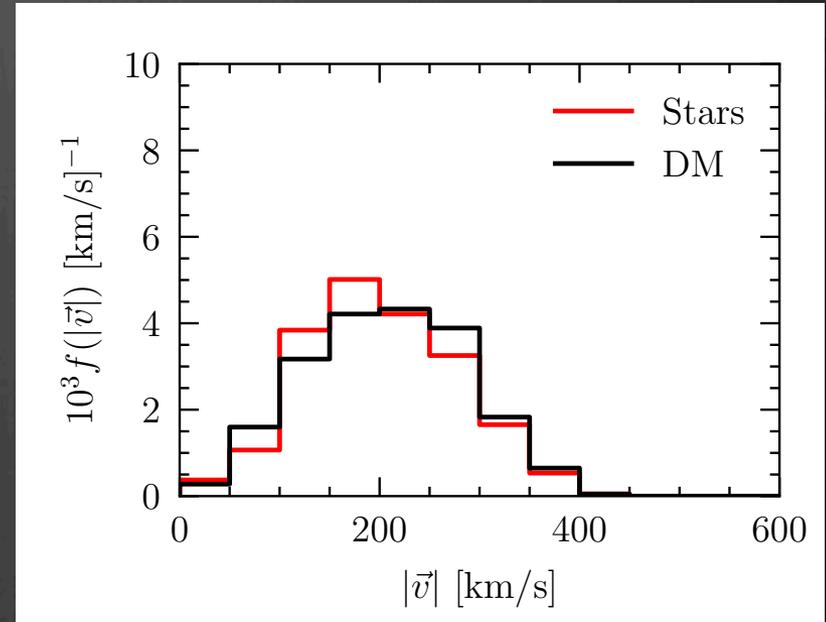
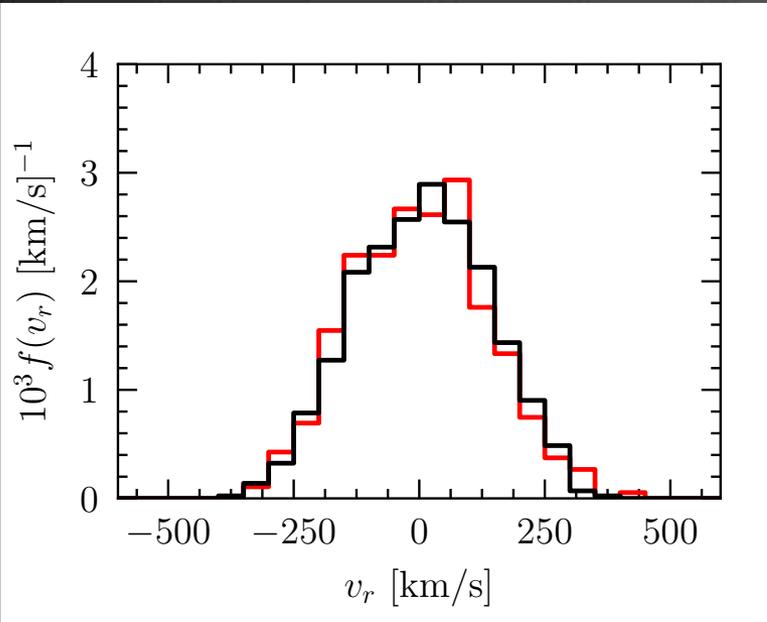
Debris Flow



v

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

Old Virialized Merger

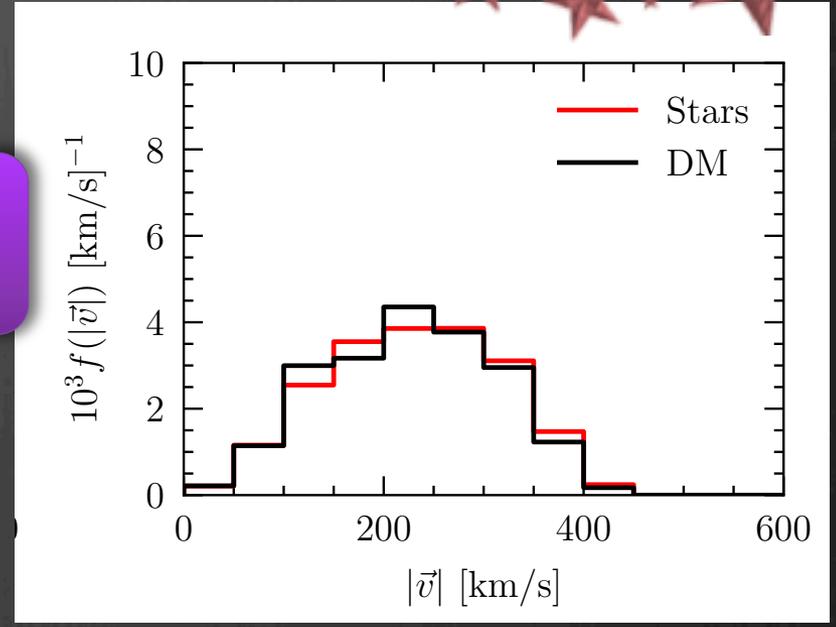
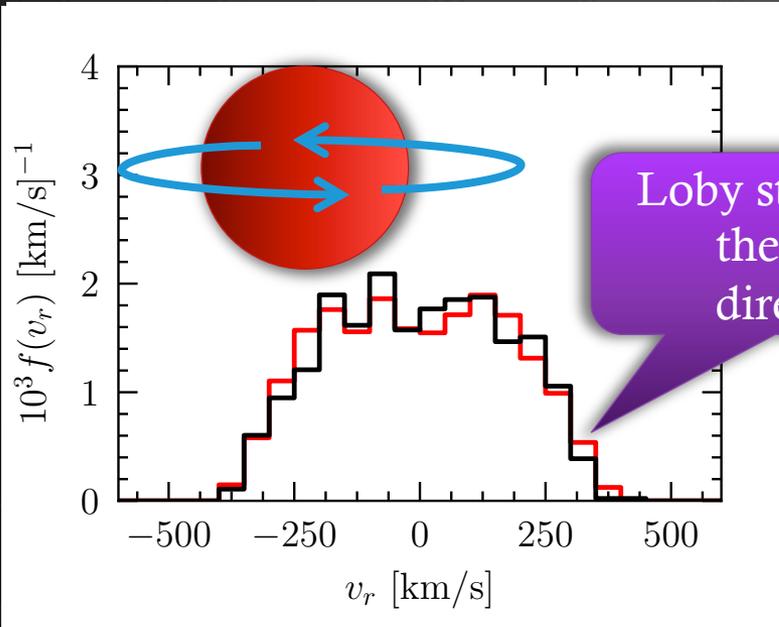


Strong correlation between the Dark Matter and the stars accreted from an old satellite at redshift 4, with mass $2 \times 10^{10} M_{\text{sun}}$, and average metallicity ~ -2.0 , contributing 3% of the local stellar mass.

[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 2, with mass $2 \times 10^9 M_{\text{sun}}$, and average metallicity ~ -1.6 , contributing 32% of local stellar mass.

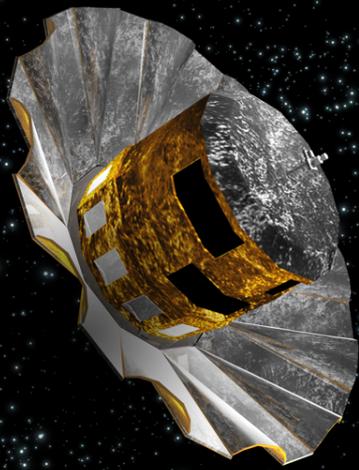
Necib, Lisanti, Garisson Kimmel et al. (2018), in prep.

So, What Does our Milky Way Look Like?

What we learned:

Accreted stars trace their dark matter counterparts.

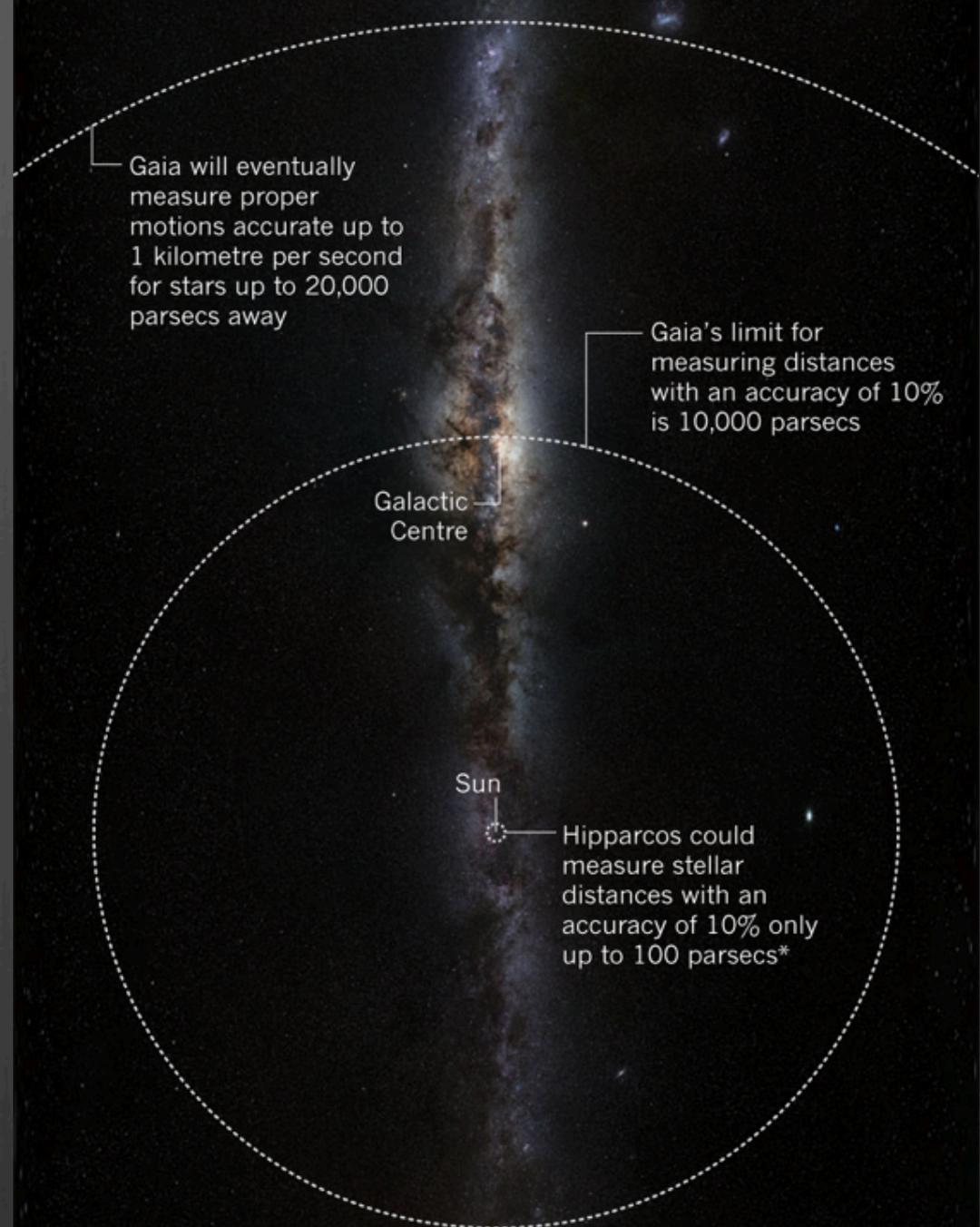
A merging event shows a lobe-structure in the radial direction.



Gaia

- ☉ 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, we found a merging event in the solar neighborhood referred to as the Gaia Sausage, or Gaia Enckeidus.

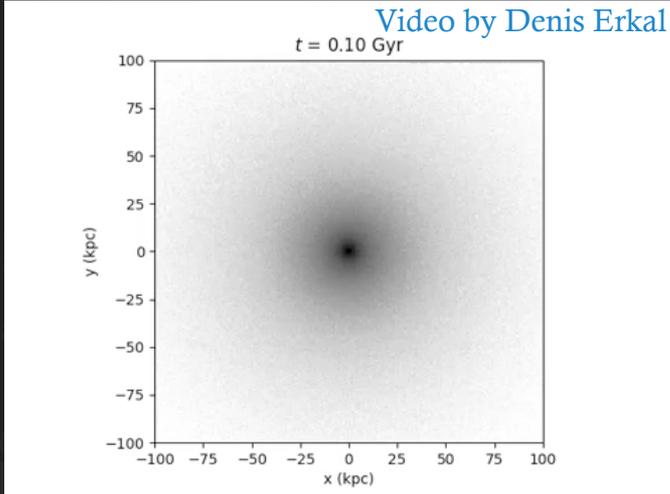
Mass $\sim 10^{8-9} M_{\text{sun}}$.
Infall Time $z \sim 1-3$.
Average Metallicity ~ -1.4



Belokurov et al. (2018)
Deason et al. (2018)
Myeong et al. (2018)
Helmi et al. (2018)
Lancaster et al. (2018)
7/23/18

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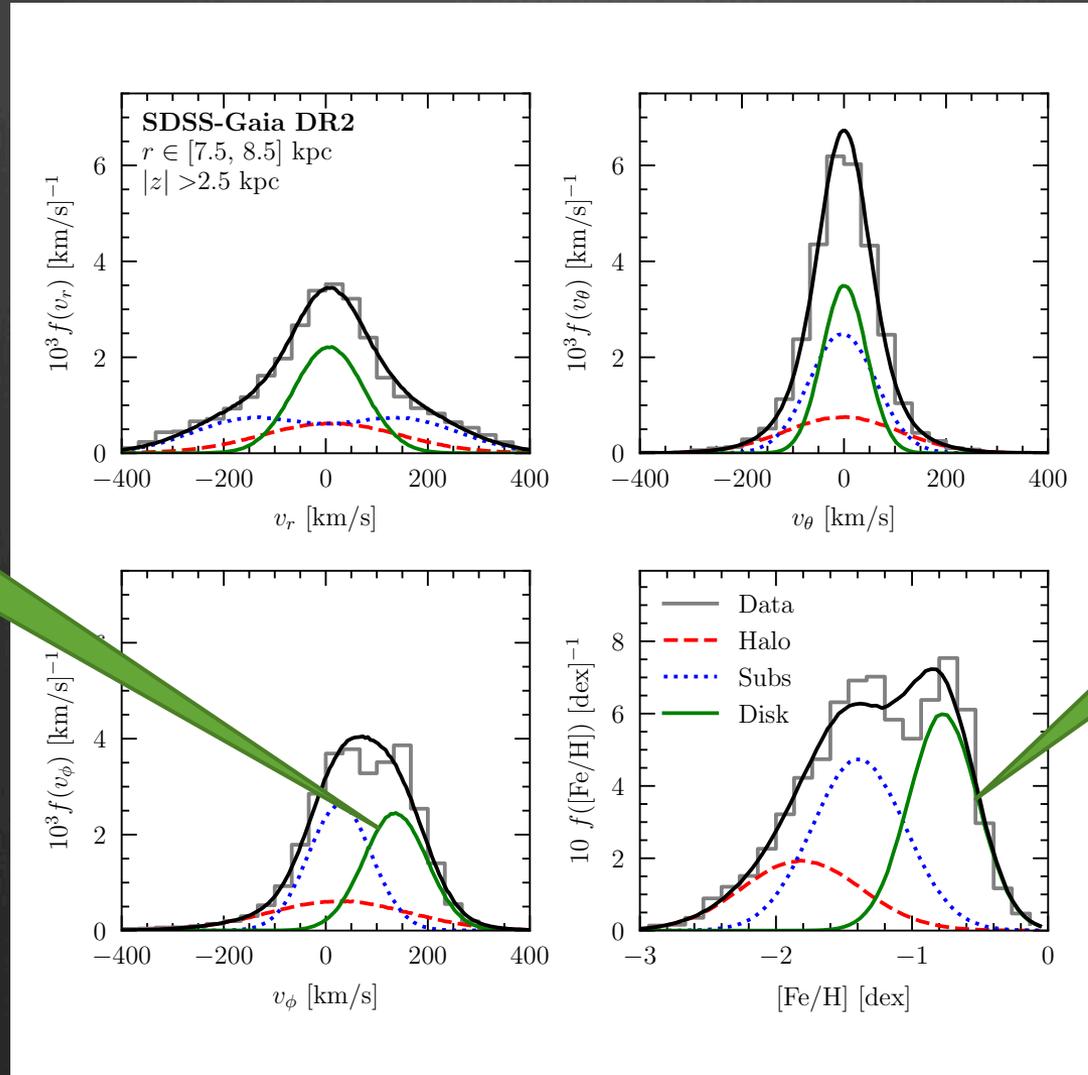
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Belokurov et al. (2018)
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7/23/18

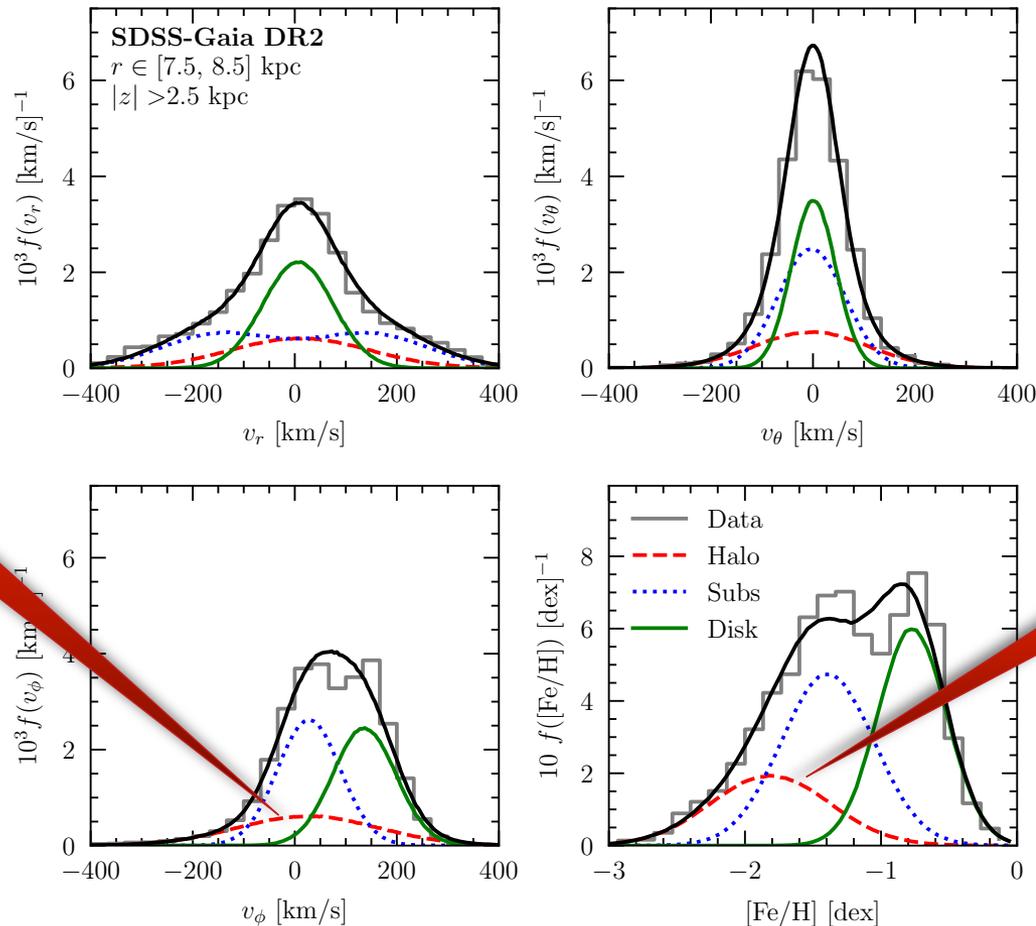
Disk, Halo, and Substructure



Azimuthal
Rotation

Metal-Rich,
Younger
Population

Disk, Halo, and Substructure



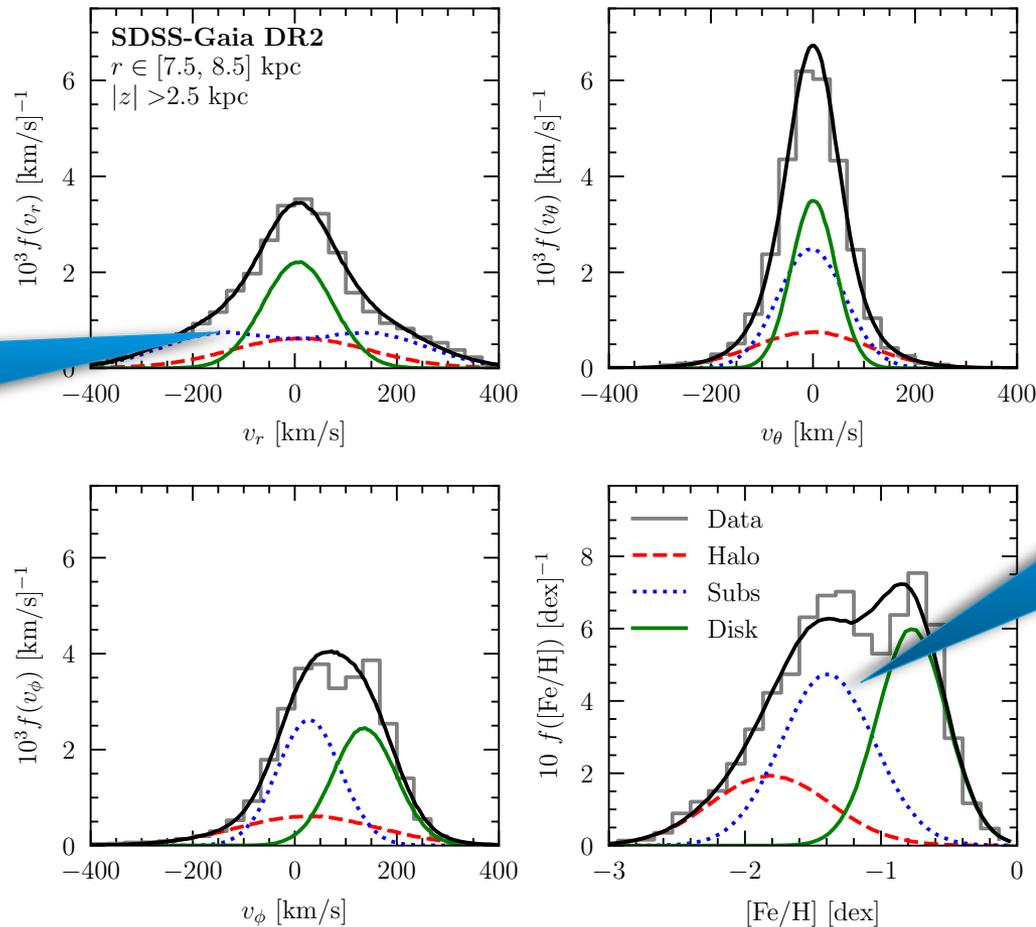
Isotropic

Older Population

Necib, Lisanti,
Belokurov (2018)

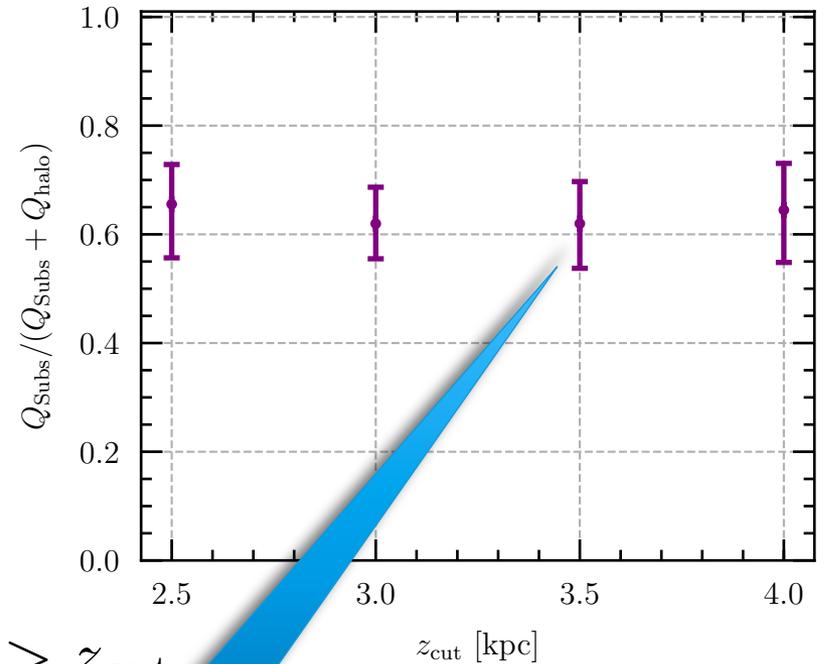
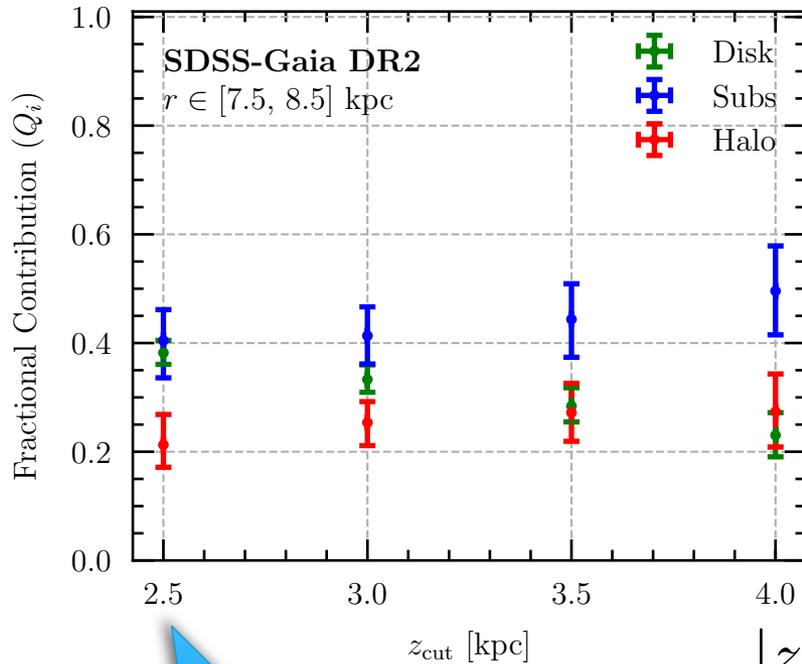
Disk, Halo, and Substructure

Loby
Structure



Older than
the Disk,
Younger than
the Halo

Not that ‘‘Sub’’ of a Structure



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

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

High non-disk fraction!

No spatial dependence has been found in the region studied.

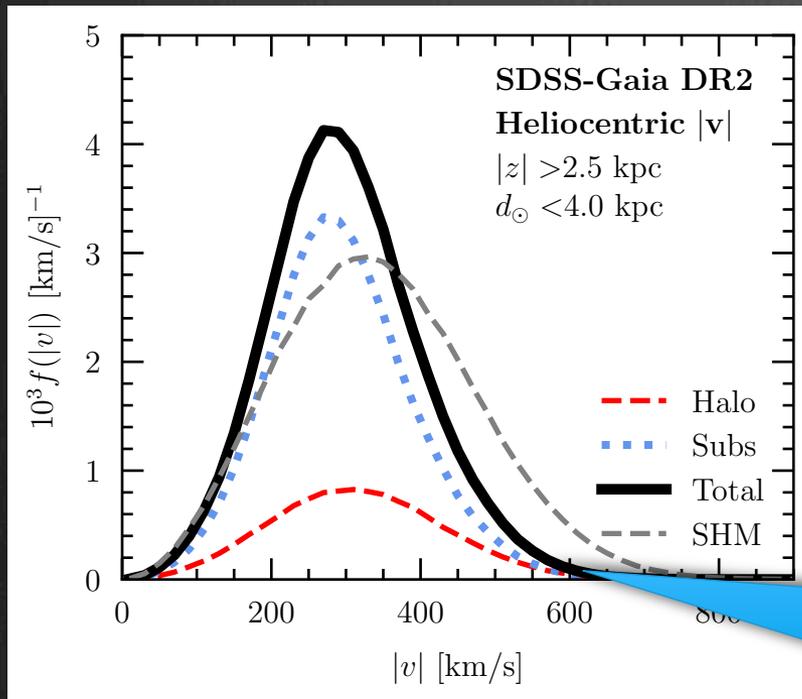
Implications for Direct Detection

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.

New Velocity Distribution!



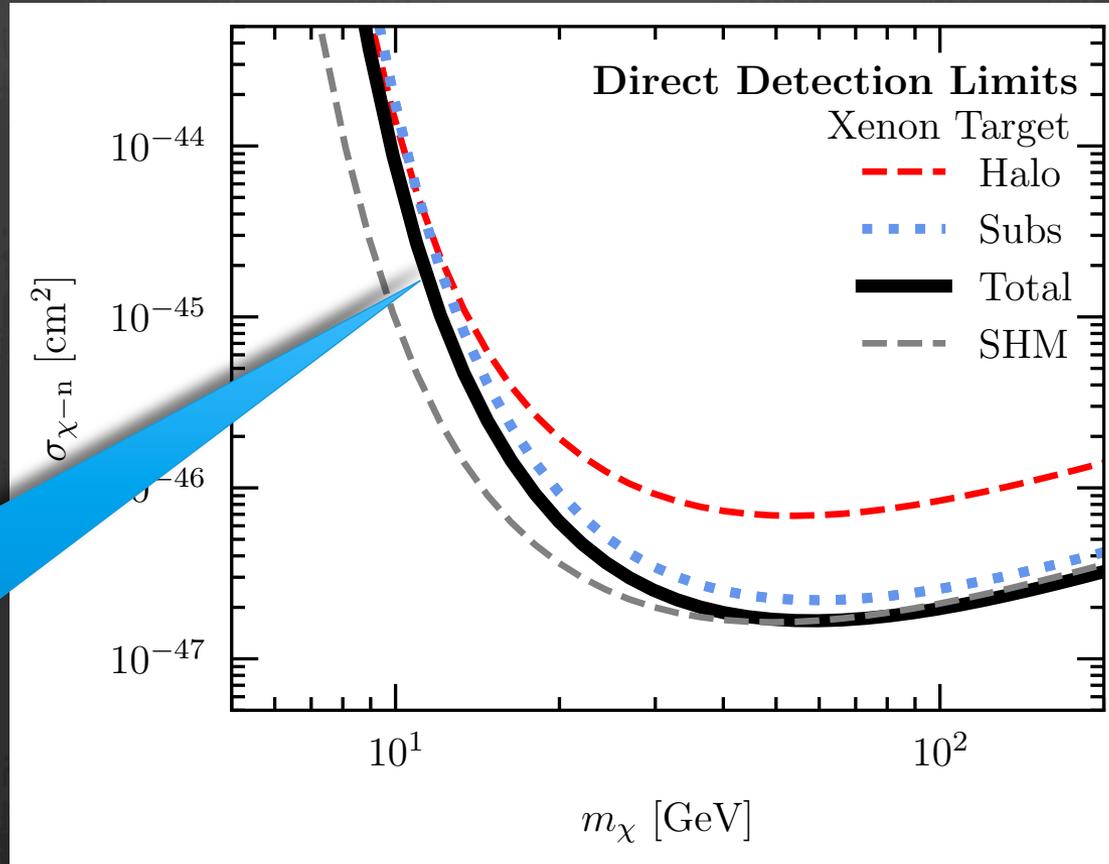
Can be found in a github repository near you

https://linoush.github.io/DM_Velocity_Distribution/

Link in paper arXiv:1807.02519.

Final distribution dominated by the substructure, and very different from the assumed Maxwell Boltzmann distribution

Implications for Direct Detection

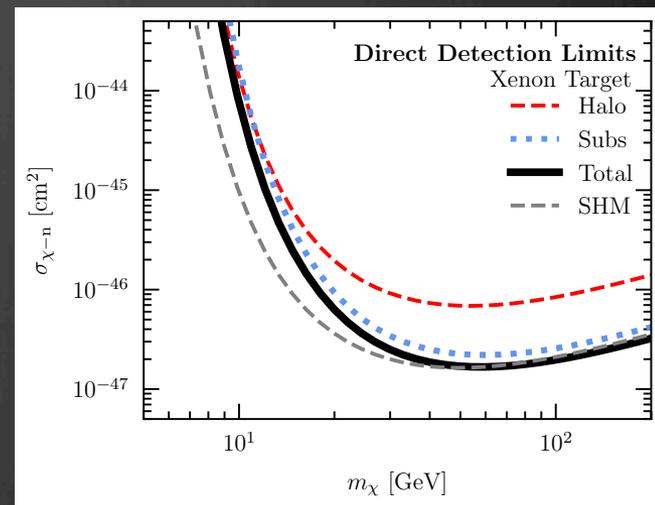


Drastic changes at low dark matter masses

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

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.

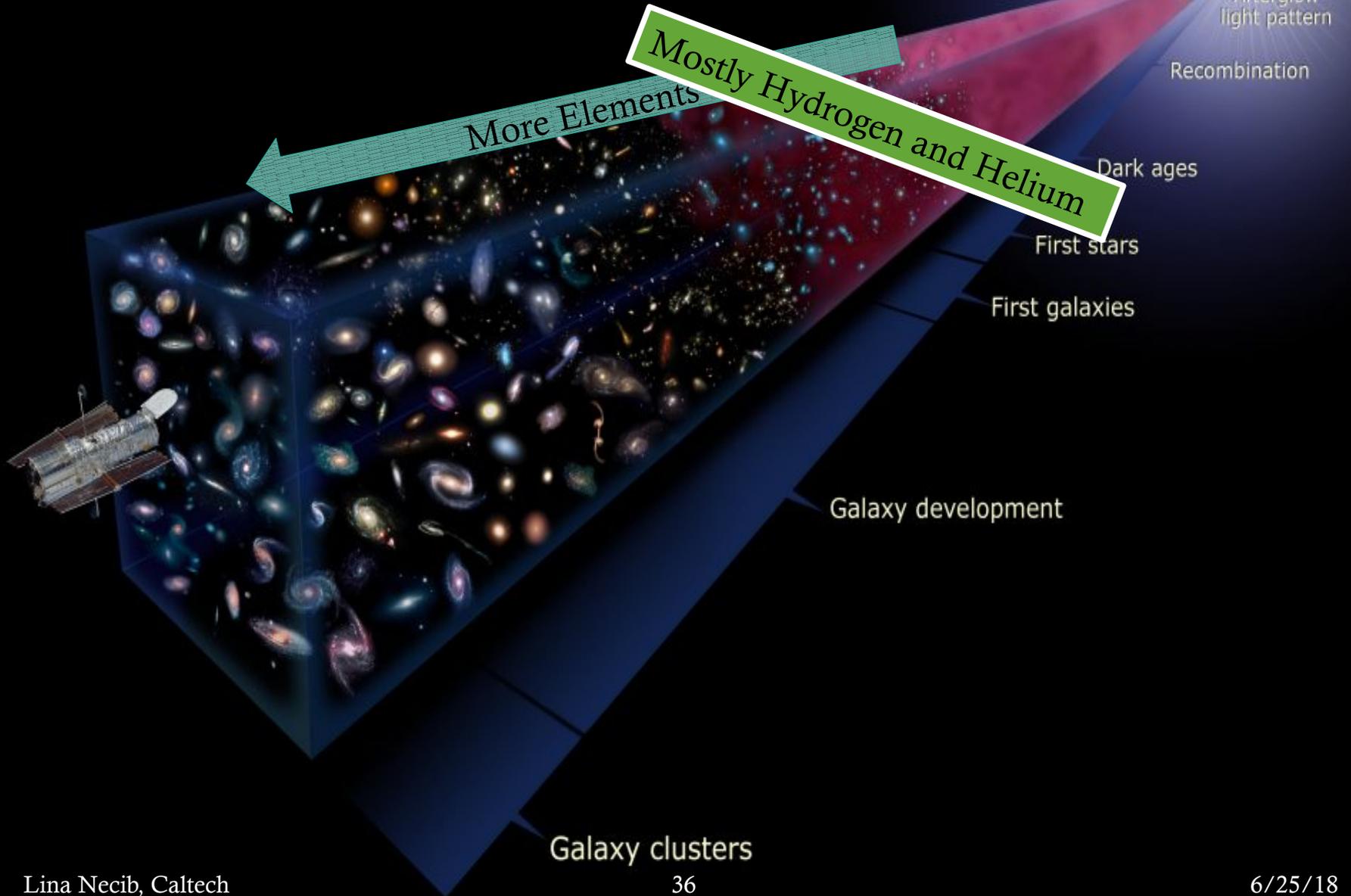


Bonus Slides

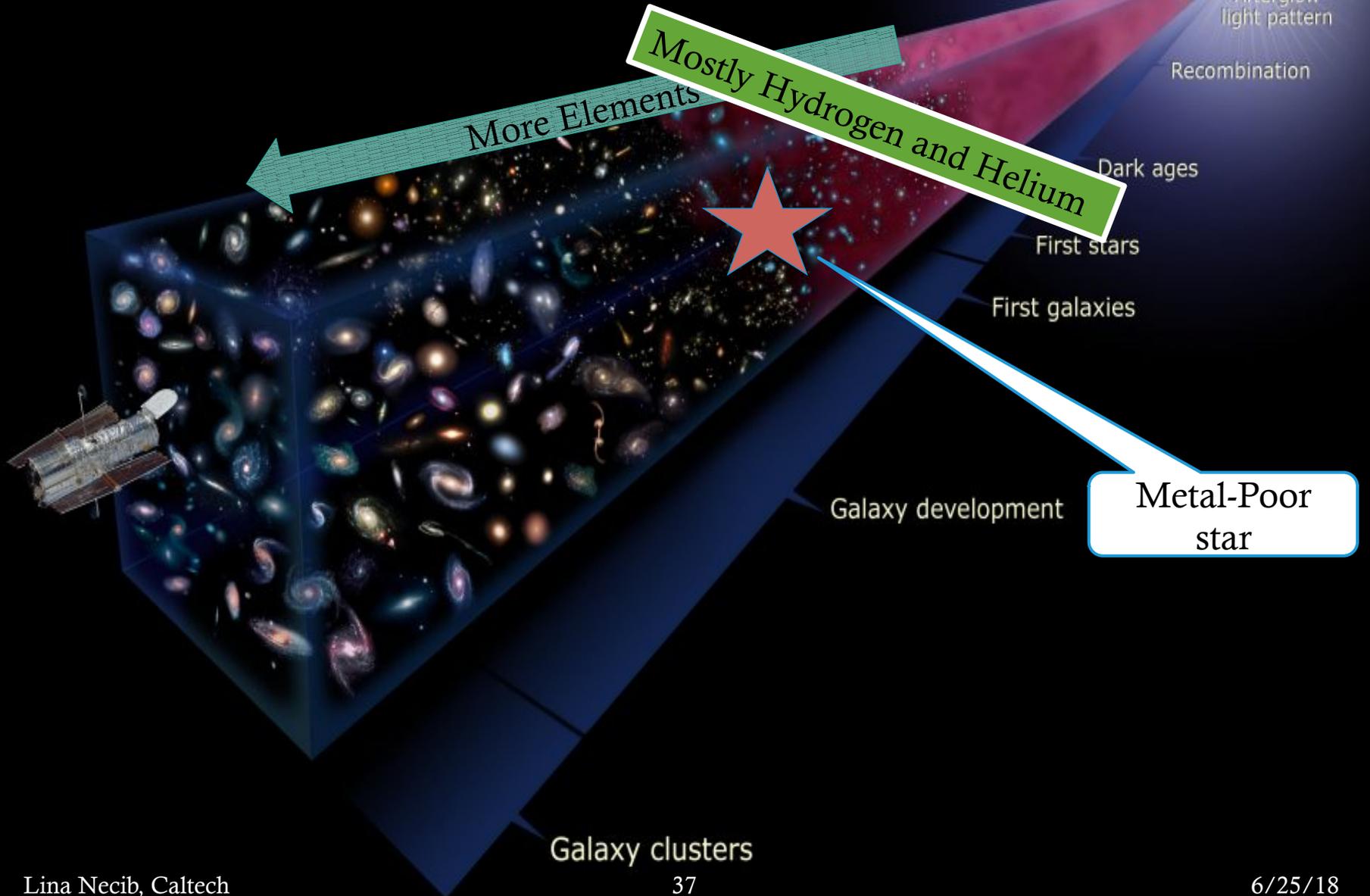


Quick Disclaimer:
Everything beyond
helium is a metal!

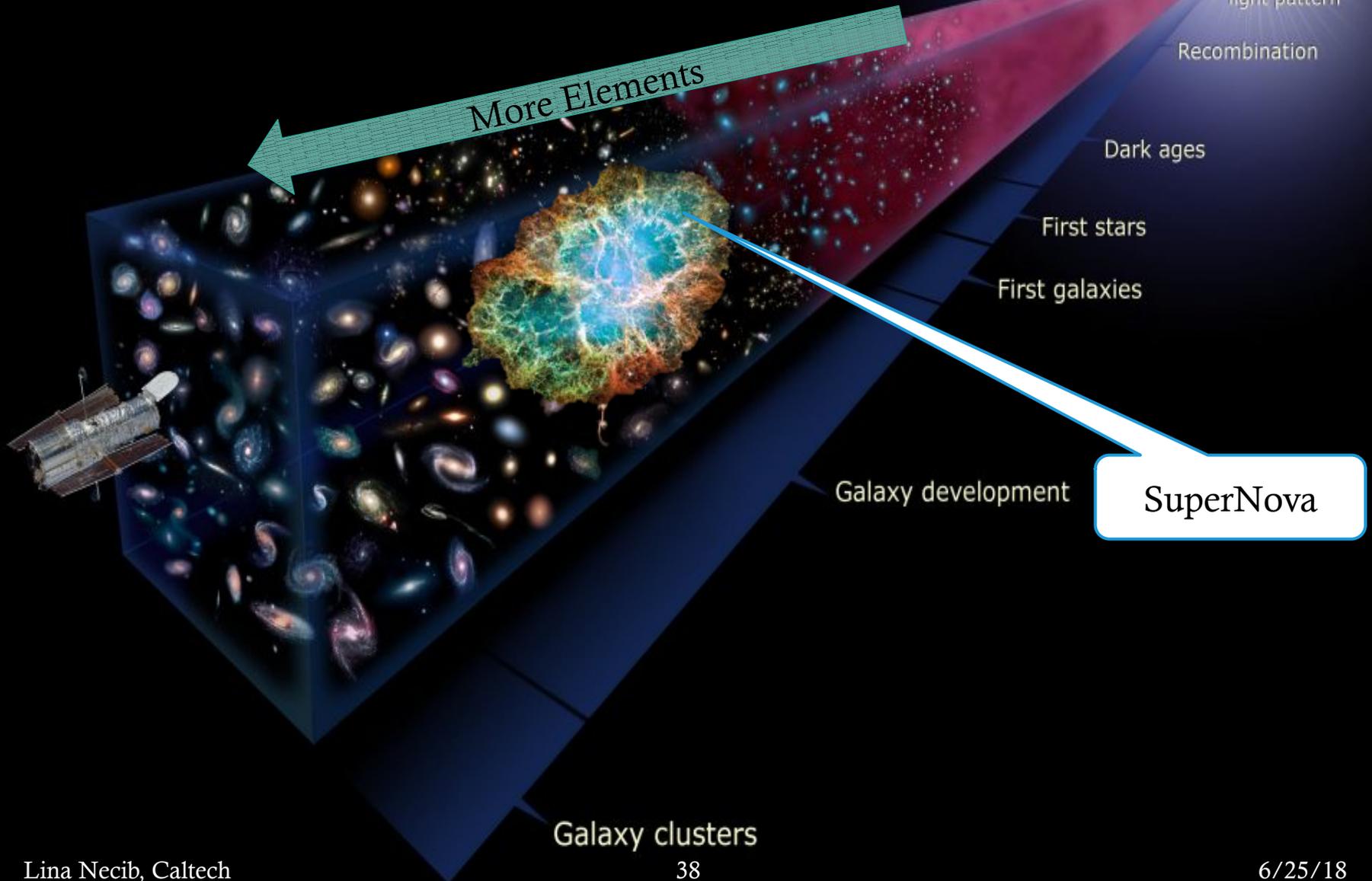
EVOLUTION OF GALAXIES



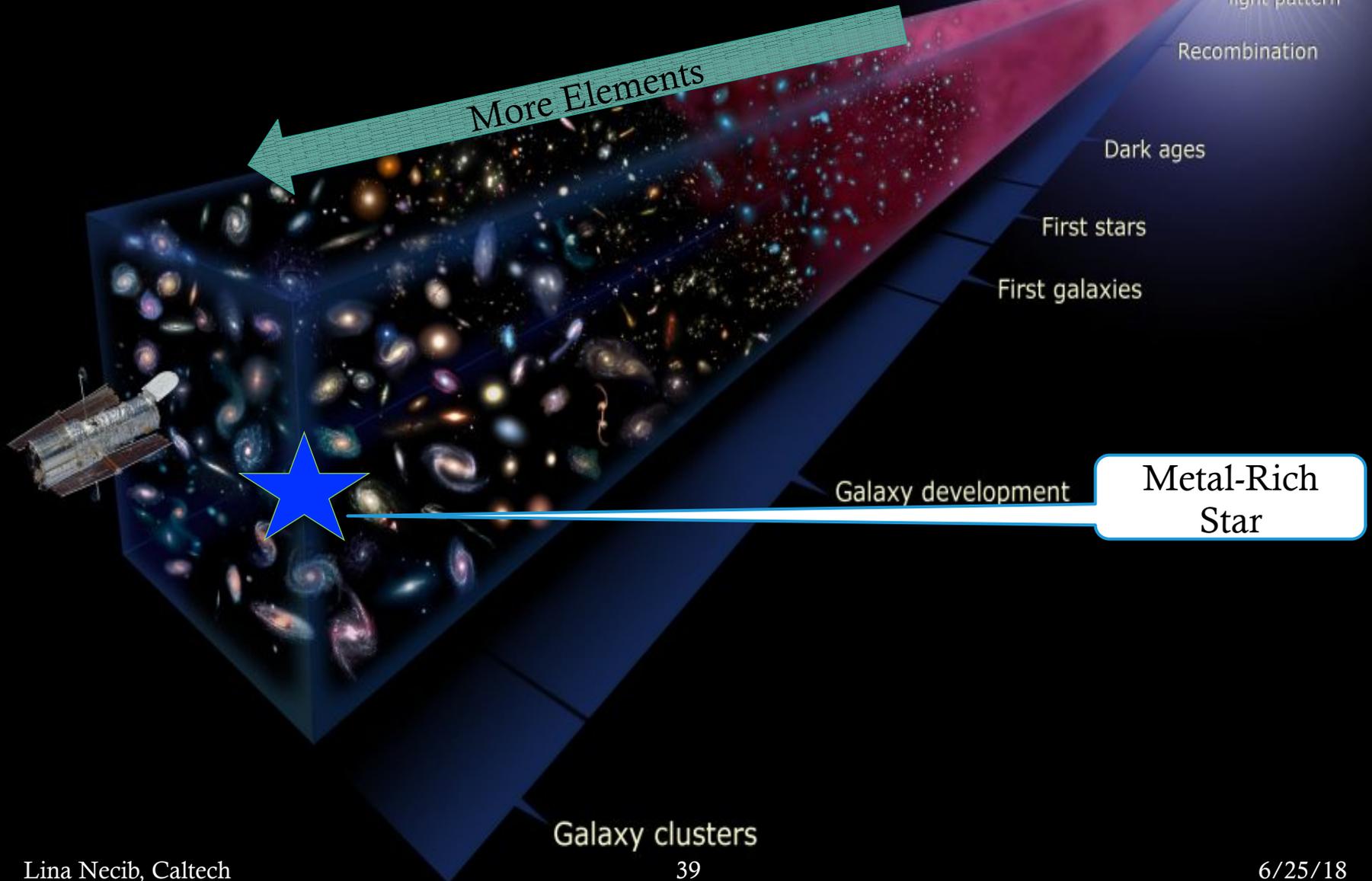
EVOLUTION OF GALAXIES



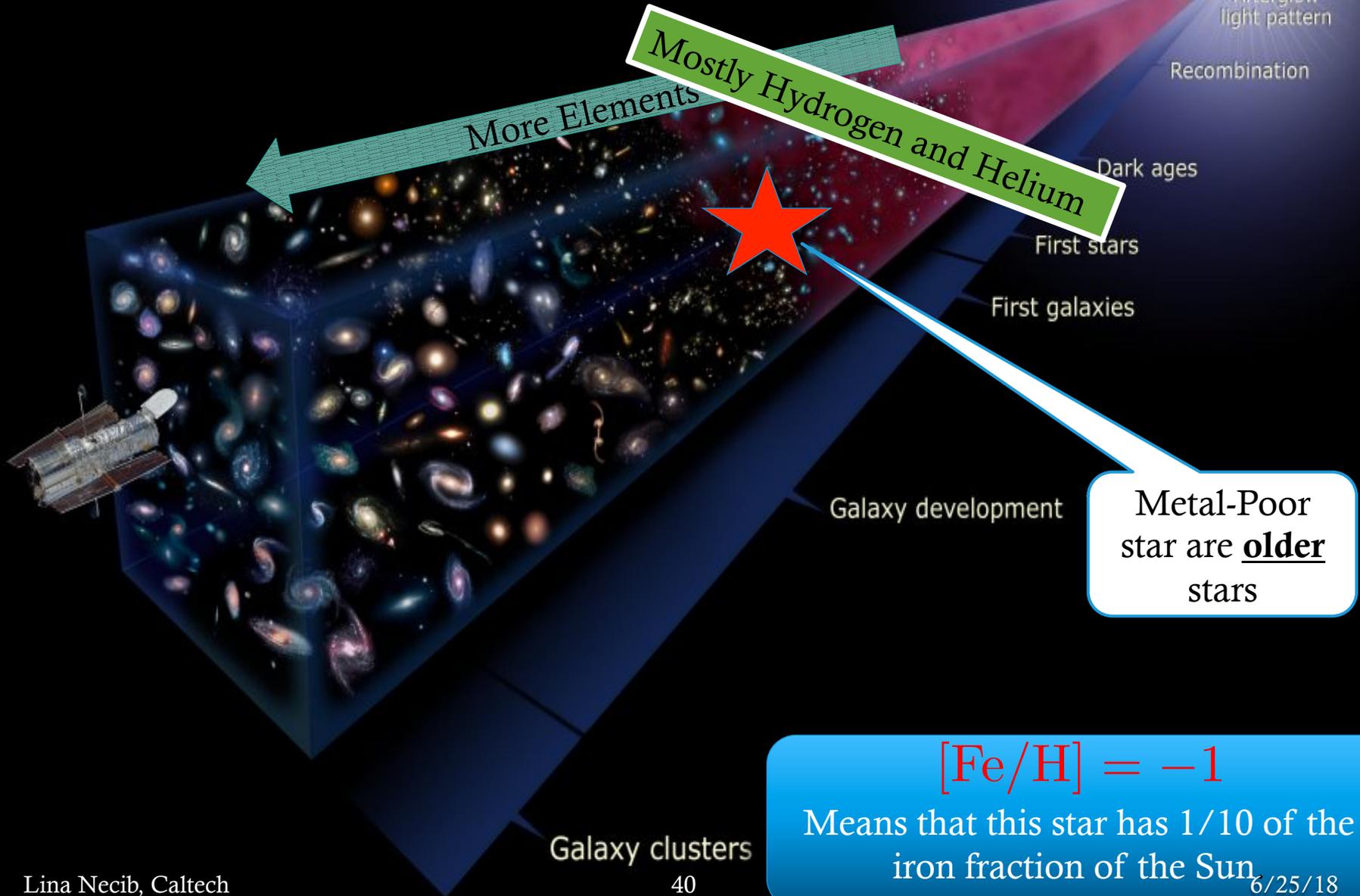
EVOLUTION OF GALAXIES

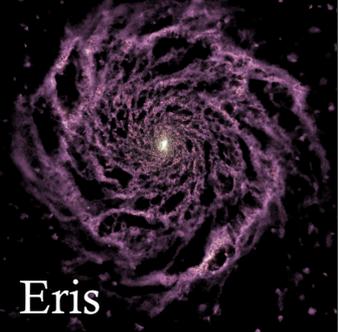


EVOLUTION OF GALAXIES

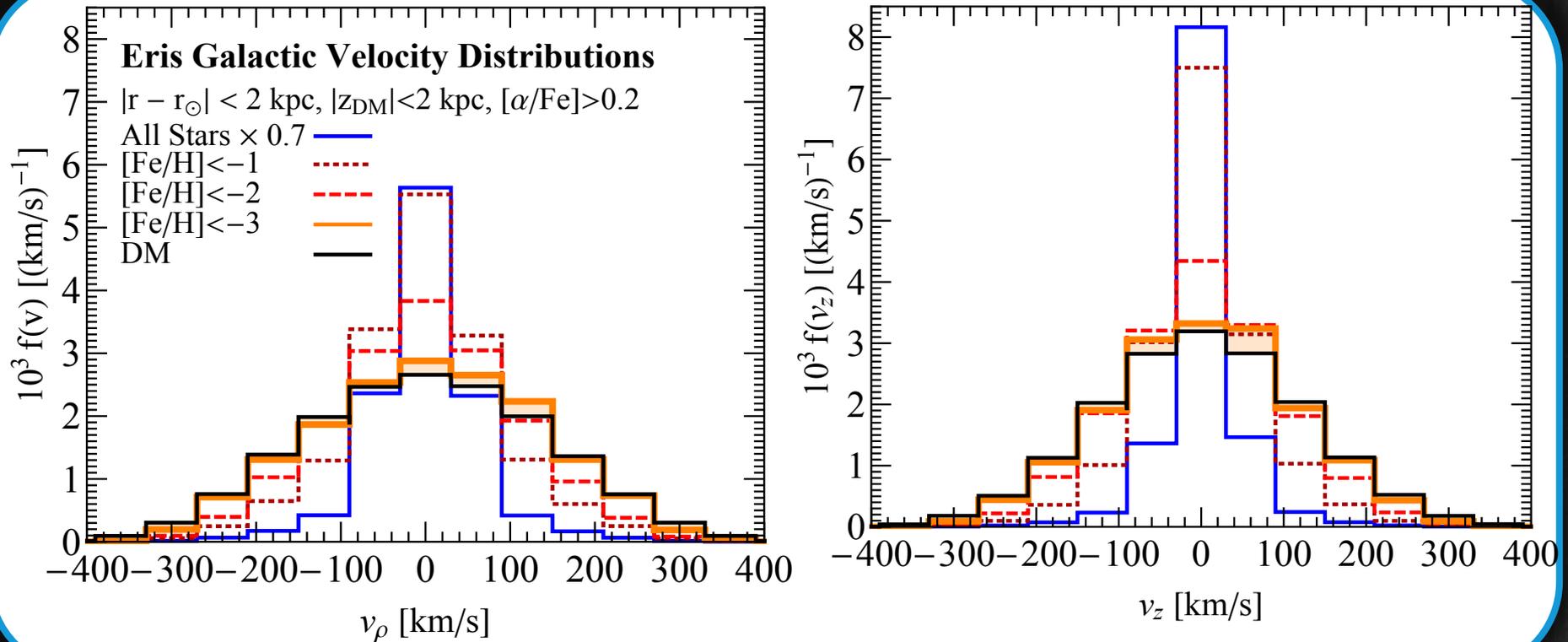


EVOLUTION OF GALAXIES





Stellar and Dark Matter Distributions



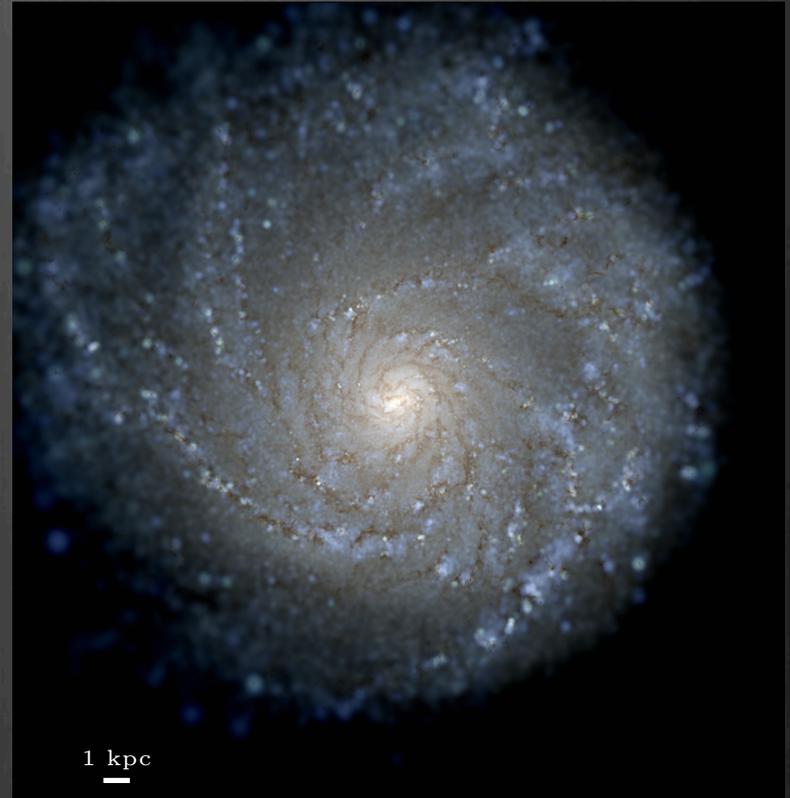
Herzog-Arbeitman, Lisanti, Madau, [Necib](#) PRL 120(2018) no.4, 041102

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:

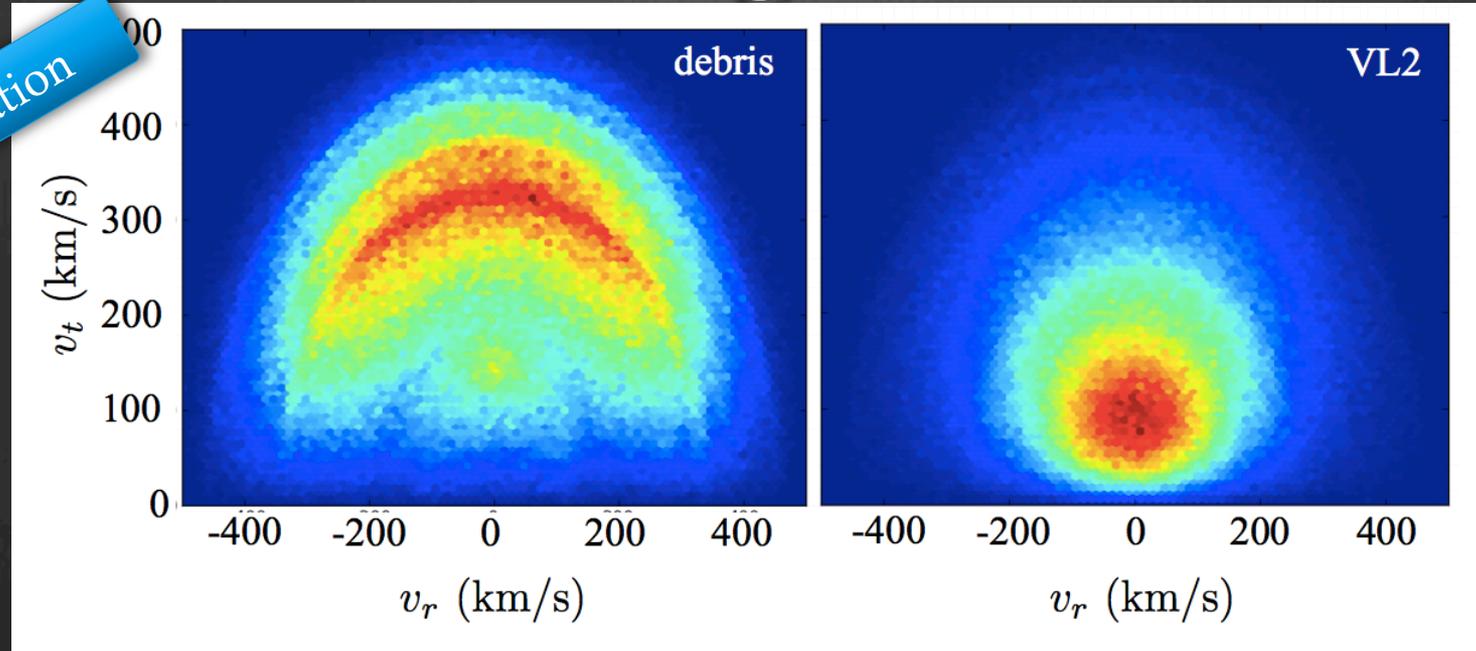
- Total mass: $(1.2-1.6) 10^{12} \text{ Msun}$.
- Particle mass: 7000 Msun .
- Dark Matter softening length: 30 pc .



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

Understanding Substructure

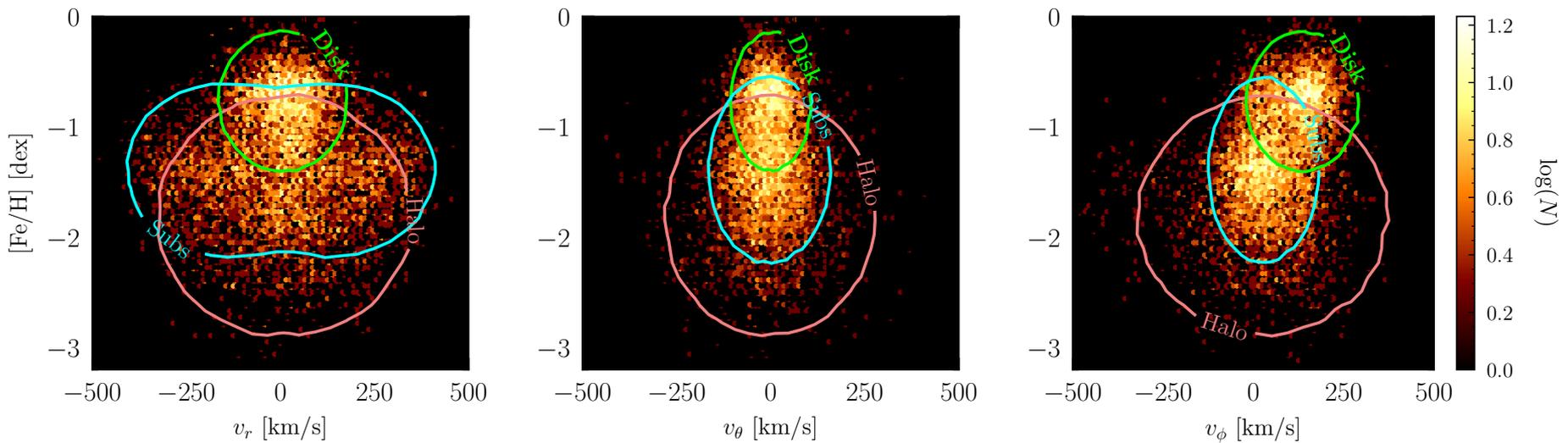
Simulation

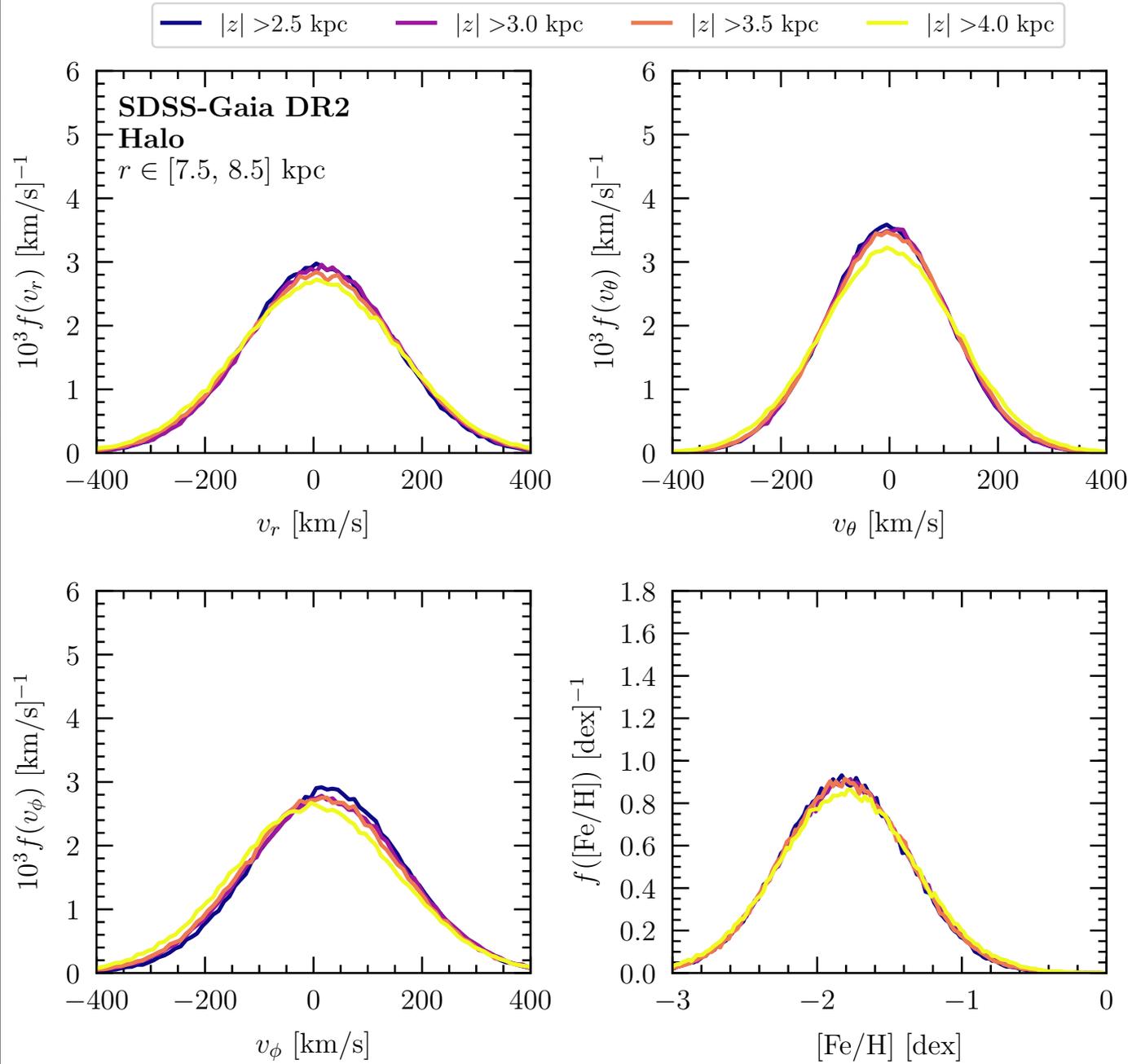


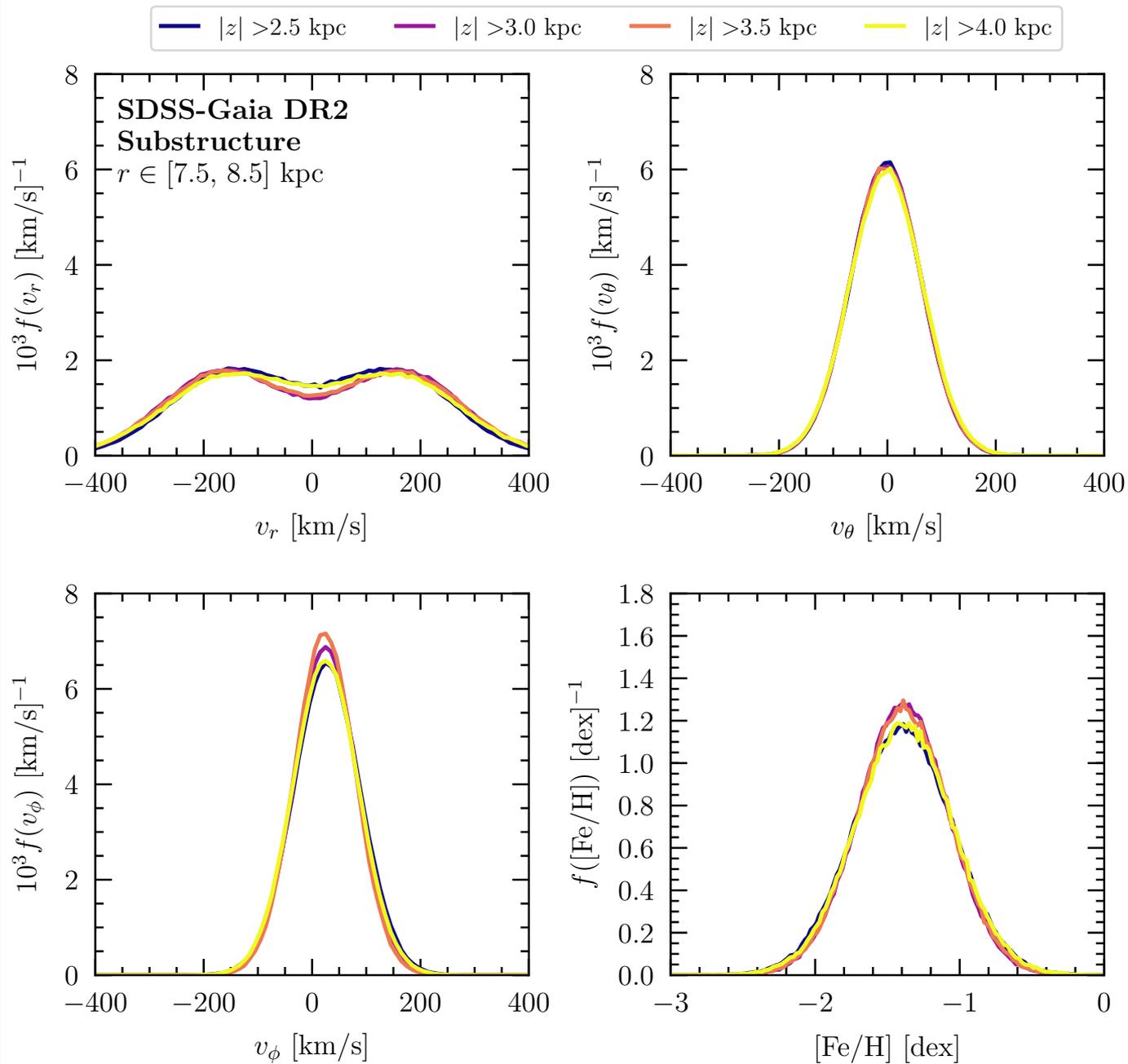
This is debris flow: unlike streams, these stars and dark matter have lost all spatial features but maintain coherence in velocity space.

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

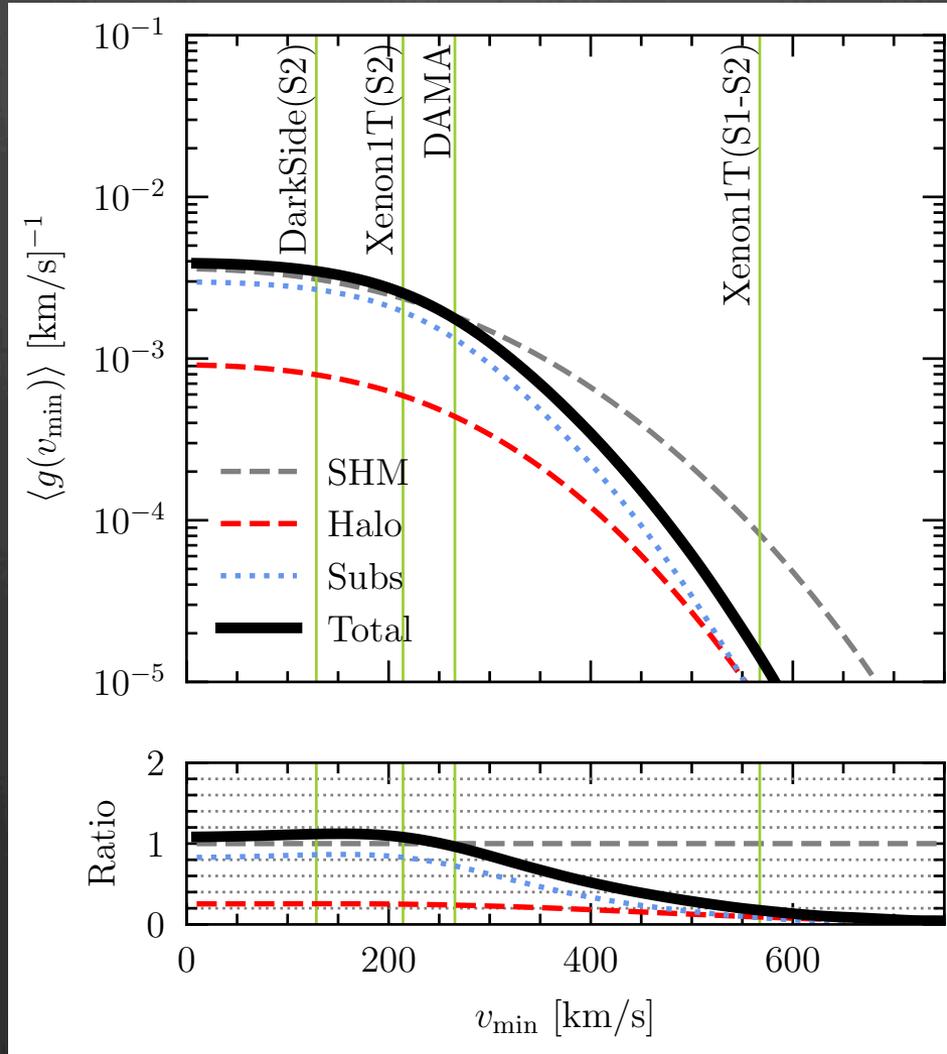
Disk, Halo, Substructure







Direct Detection



We use **Markov Chain Monte Carlo** to find the best fit parameters for the halo, disk, and substructure.



Substructure



Disk



Stellar Halo

1 Dimensional
Gaussian for
the metallicity
Distribution

Substructure

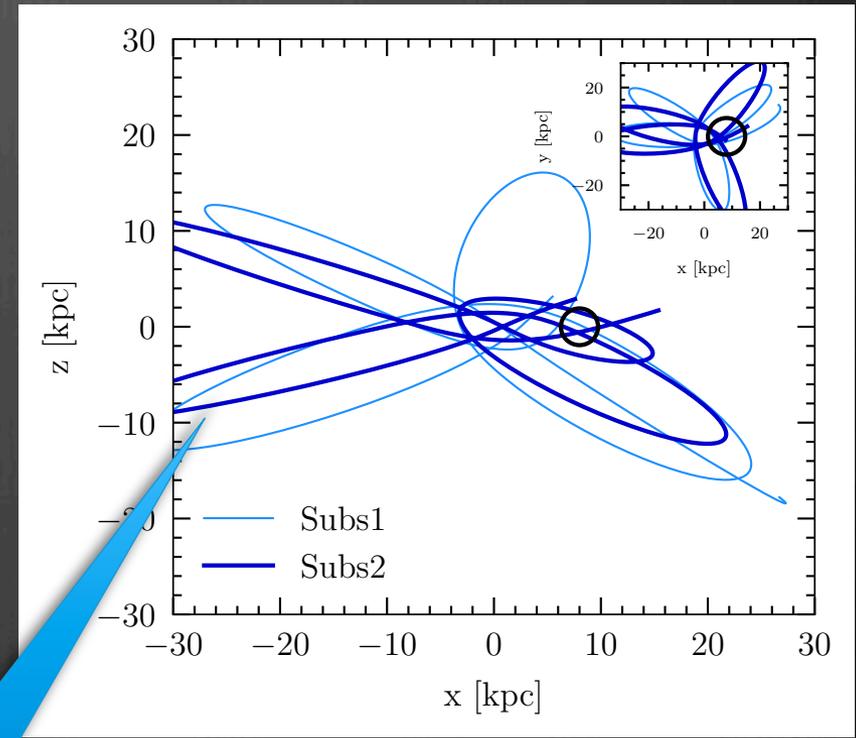
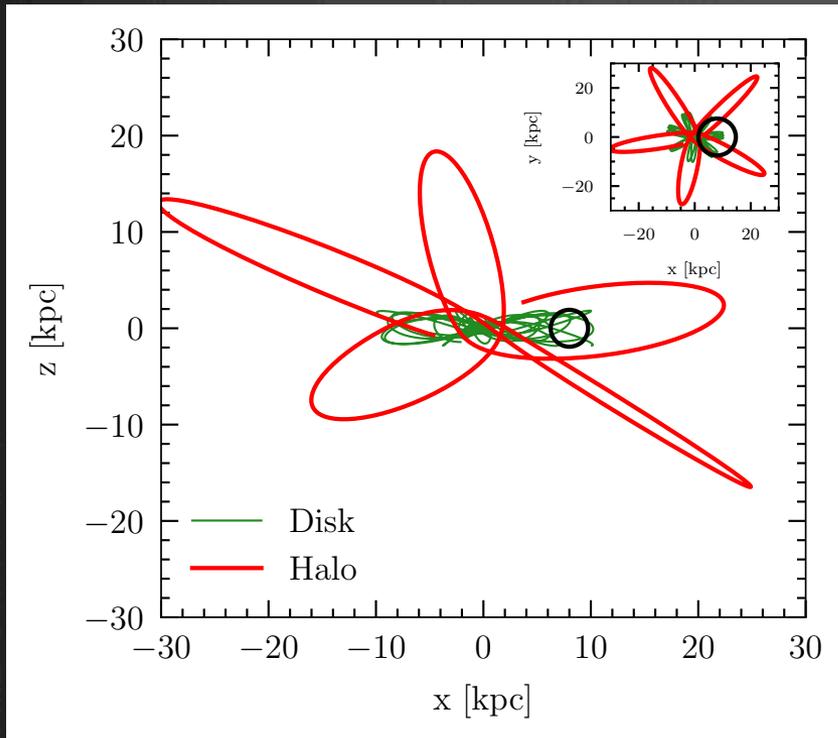
3 Dimensional
Gaussian for
velocity in
spherical
coordinates

Disk

35
parameter
fit!

Stellar Halo

Disk, Halo, and Substructure



This is Debris Flow!

Example of stars from the Substructure, also referred to as Gaia Sausage, or Gaia Enckeleadus.

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

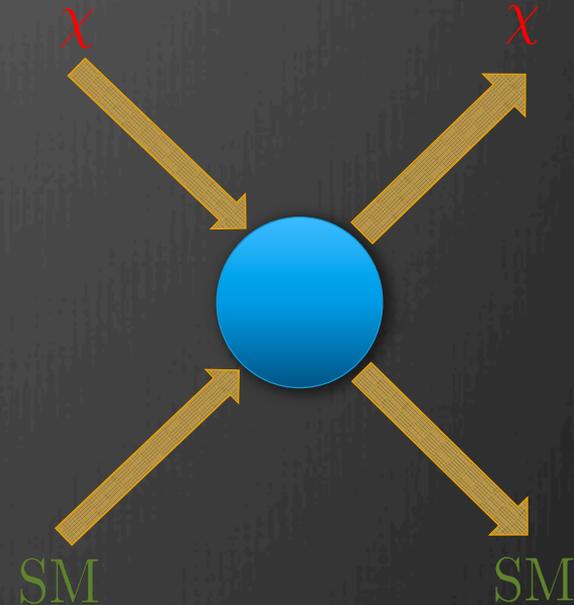
Direct Detection Rate

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

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

Focus of today's talk

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



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

Drukier et al. (1986)