Dark Matter in the *Gaia* Era

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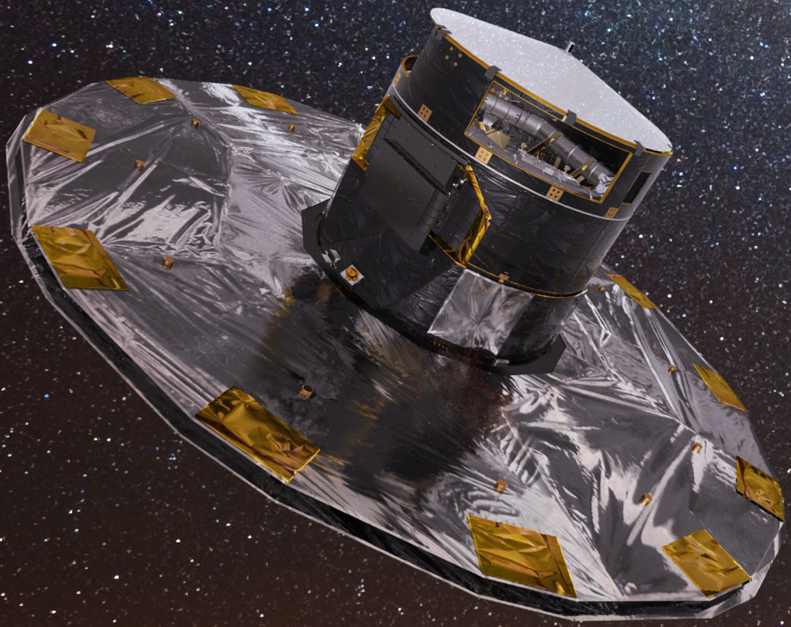
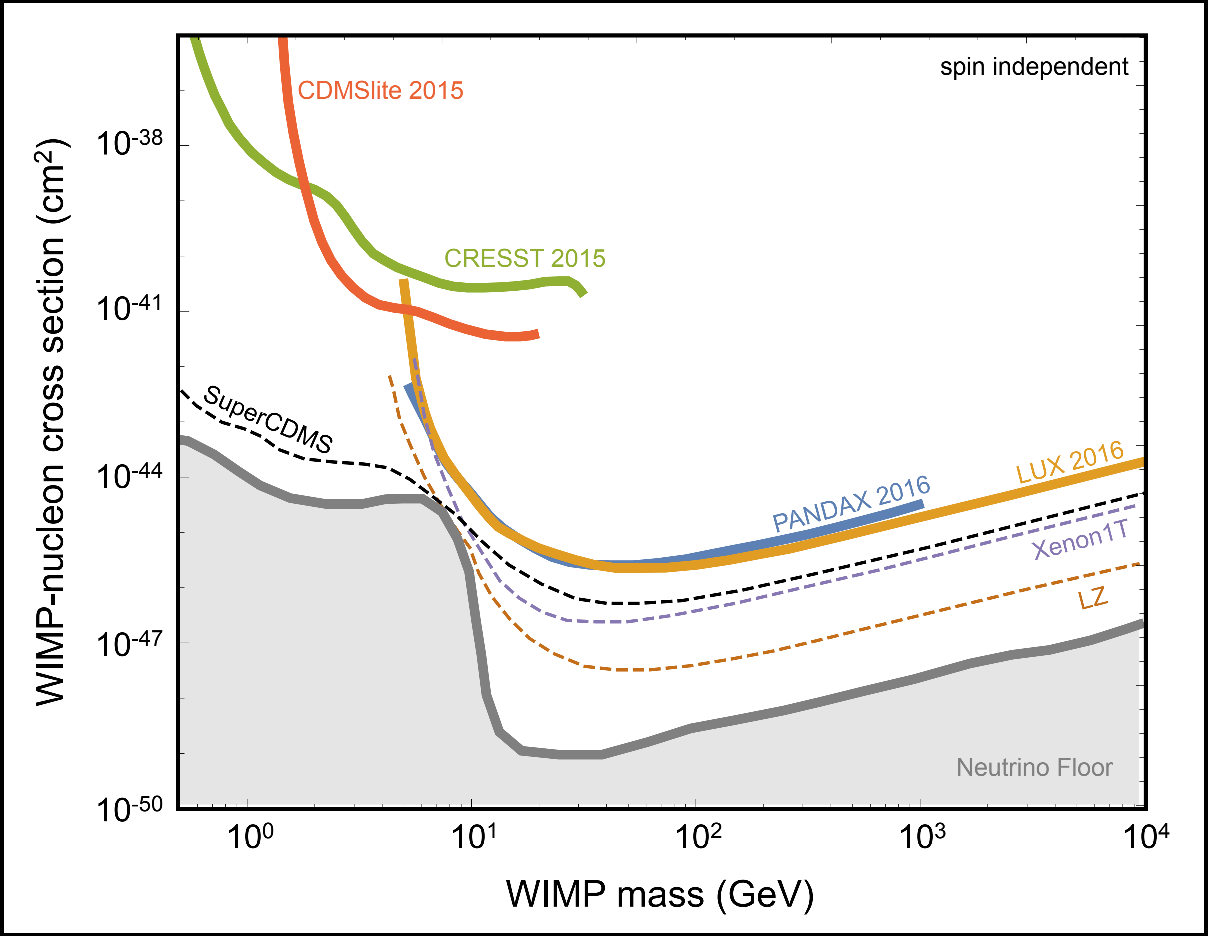
Princeton University



J. Herzog-Arbeitman, ML, P. Madau, and L. Necib [1704.04499]
J. Herzog-Arbeitman, ML, and L. Necib [in preparation]

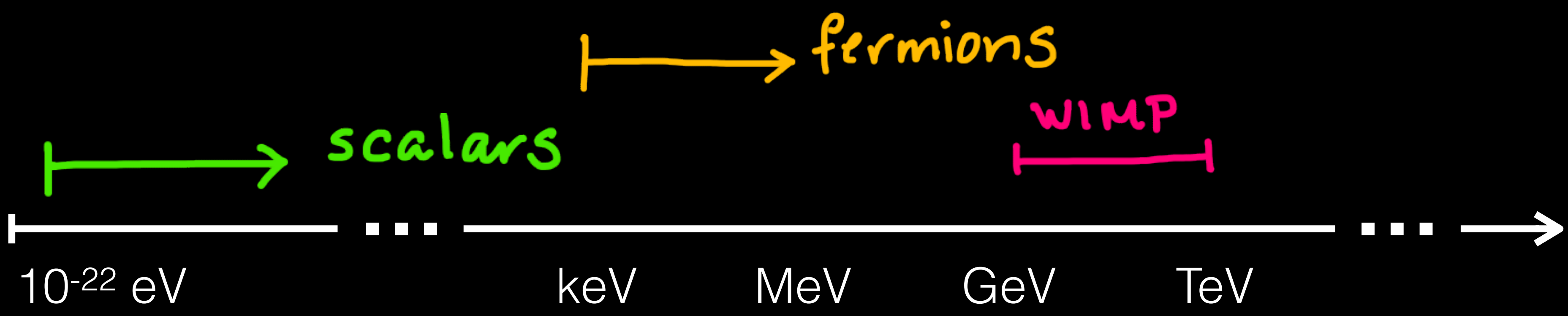
What's Going on at the Weak Scale?

Weak-scale dark matter has been the dominant paradigm in the last several decades



What’s Going on at the Weak Scale?

Constraints on WIMPs continue to tighten, motivating a search for new lampposts



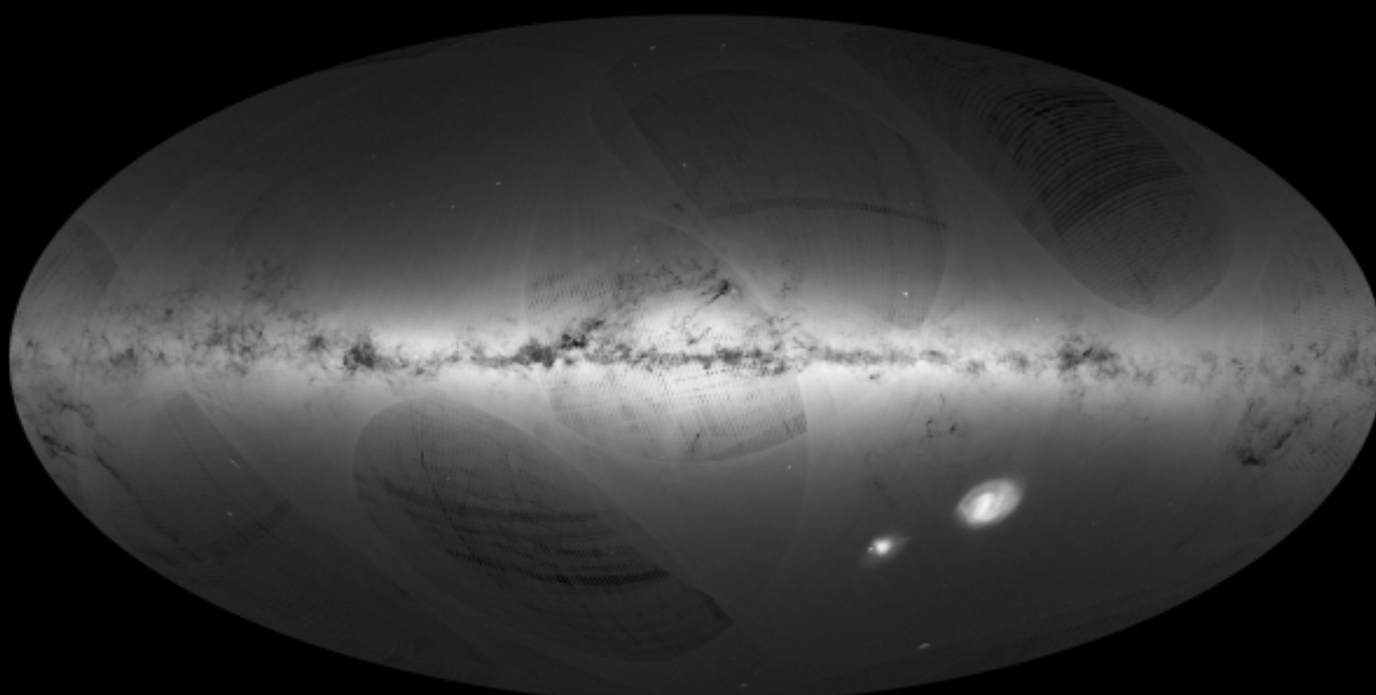
The broad range of possibilities before us prompts a reevaluation of experimental and observational strategies for dark matter

The *Gaia* Mission

Gaia is the follow-up astrometric survey to the Hipparcos mission (1989-1993)

Collects 30x more light than Hipparcos, allowing for 200x more accurate measurements of stellar positions and motions

Will provide measurements for over a billion stars—about 1% of the stellar population



Milky Way Formation History

Dark Matter Velocity Distribution

First Results from *Gaia* DR1

Stellar Halo

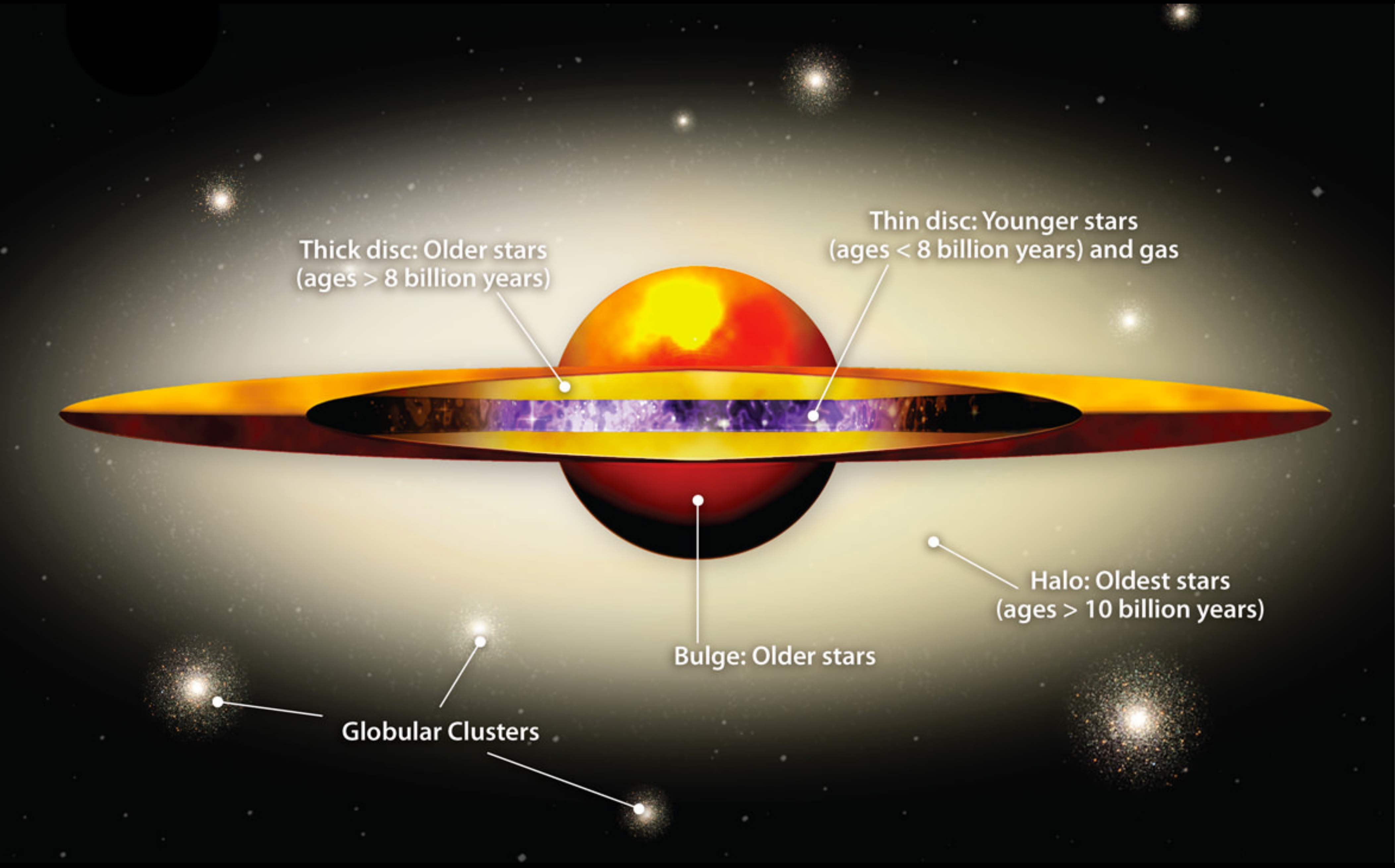
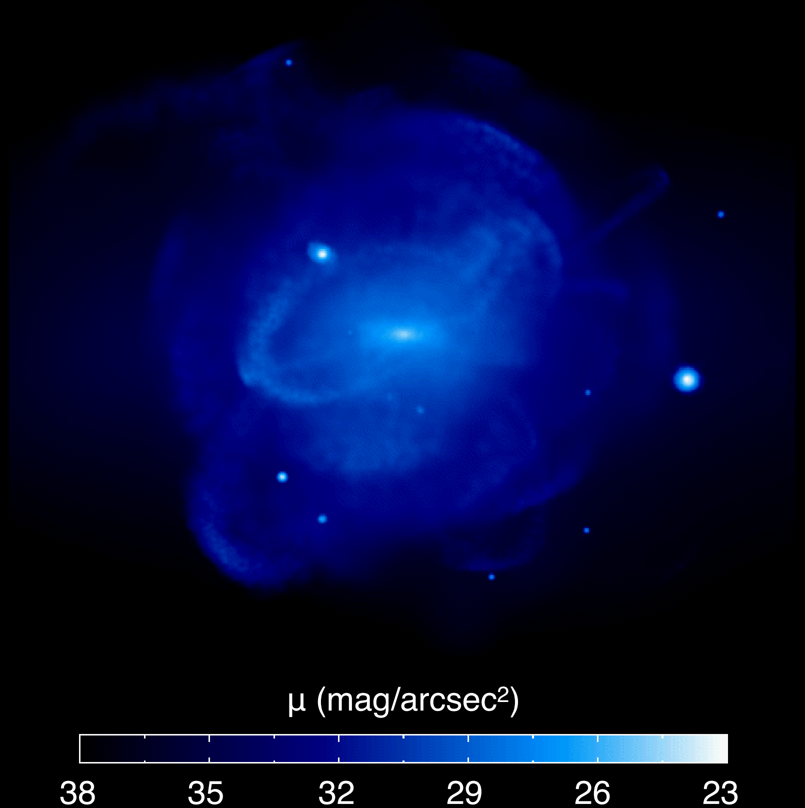


image credit: www.universetoday.com

Stellar Halo Formation

Stellar halo formed primarily from the tidal debris of disrupted satellite galaxies that merged with our Galaxy

Johnston et al. (1996), Helmi & White (1999), Bullock et al. (2001), Harding et al. (2001)



Helmi [0804.0019]
image credit: S. Sharma, K. Johnston, J. Bullock

$T \sim T_{infall}$

Tidal debris is coherent in position and velocity

$T > T_{infall}$

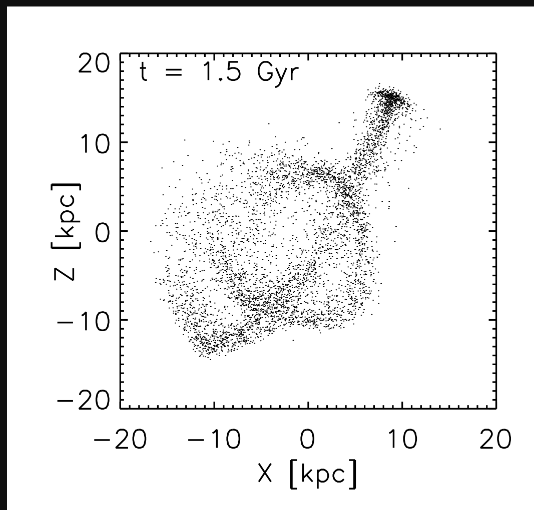
Spatially well-mixed, kinematic substructure
(phase-space density conservation)

$T \gg T_{infall}$

Equilibrium reached, no substructure

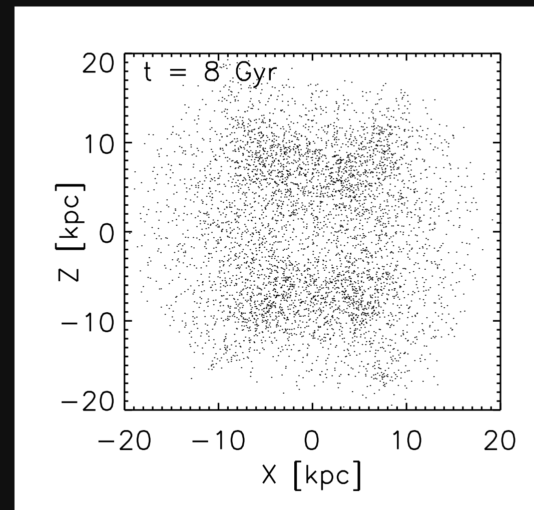
Stellar Halo Formation

Recent Merger



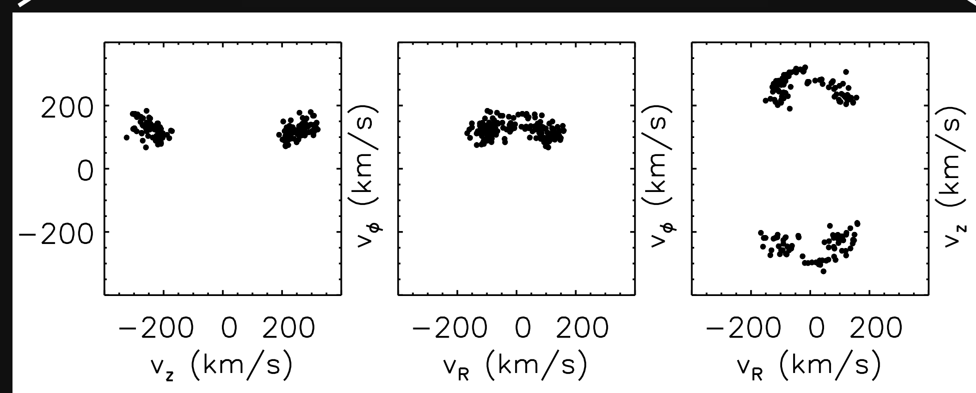
visible streams

Not-So-Recent Merger



spatially mixed

Kinematic substructure

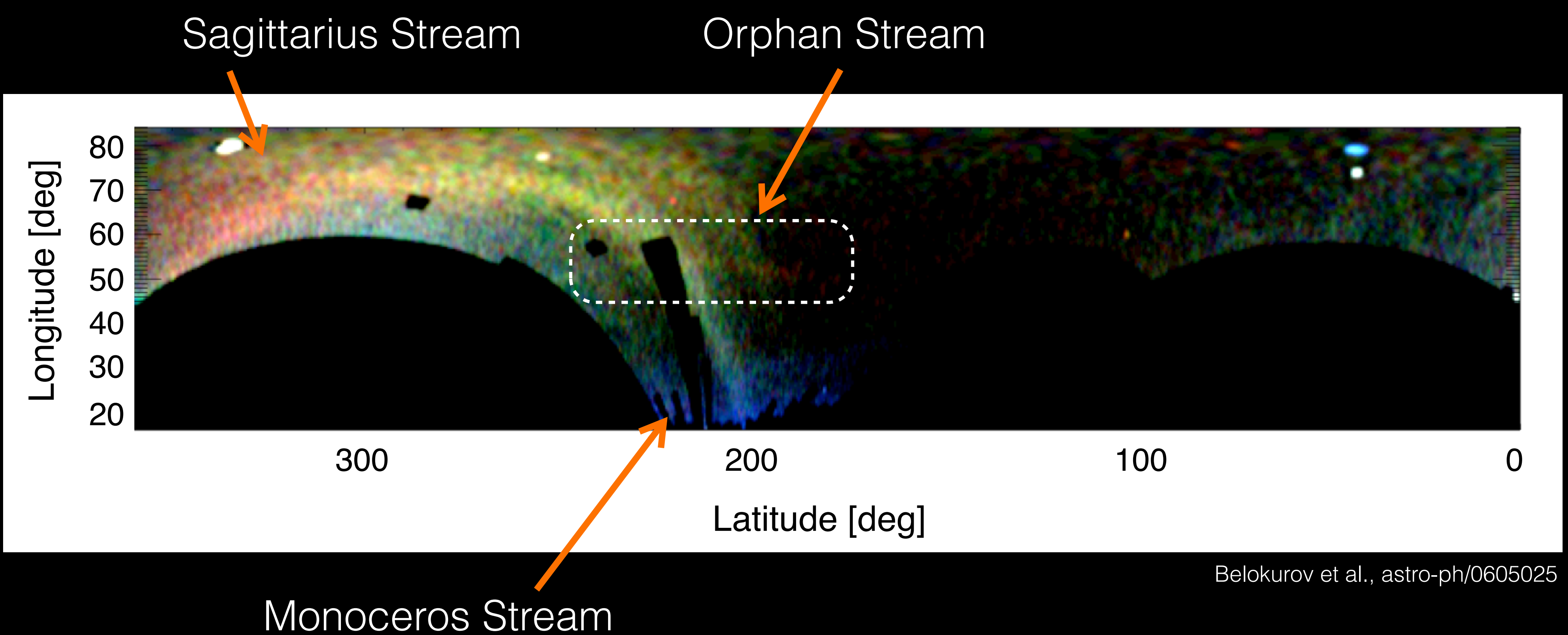


Helmi [0804.0019]

Field of Streams

Abundance of substructure observed in stellar surveys

Spatial overdensities indicate presence of stellar streams



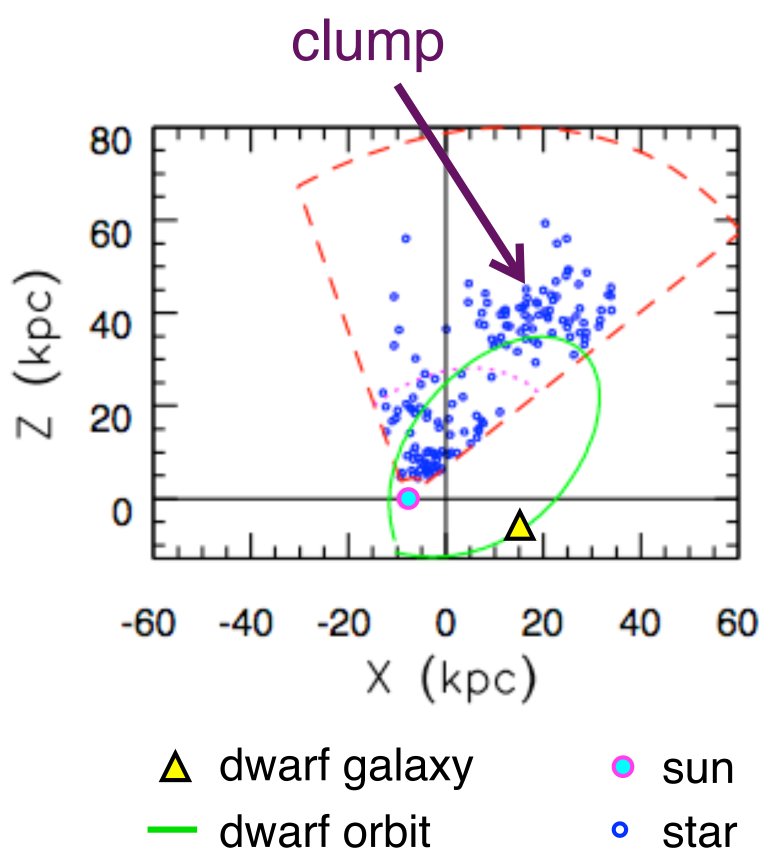
Belokurov et al., astro-ph/0605025

Sagittarius Stream

Evidence suggests that Sgr dwarf is in the process of being tidally disrupted

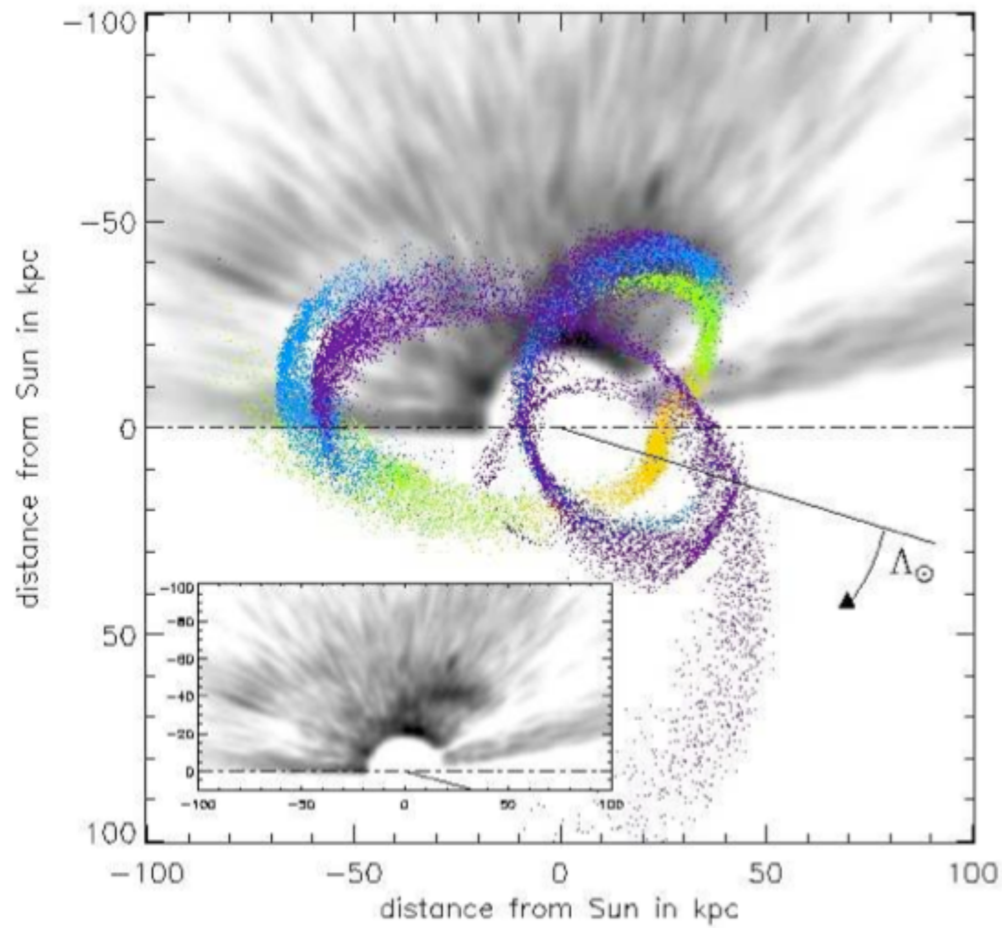
First Hints

SDSS Commissioning Run



Ibata et al. (1994), Ivezic et al. (2000), Yanny et al. (2000)

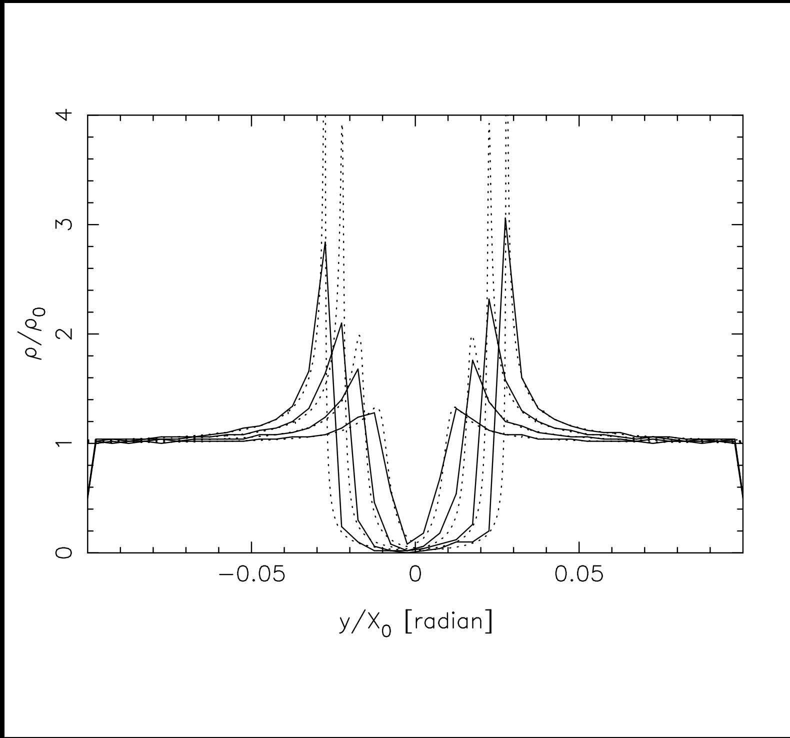
Complete Mapping



Ruhland et al. [1103.4610]

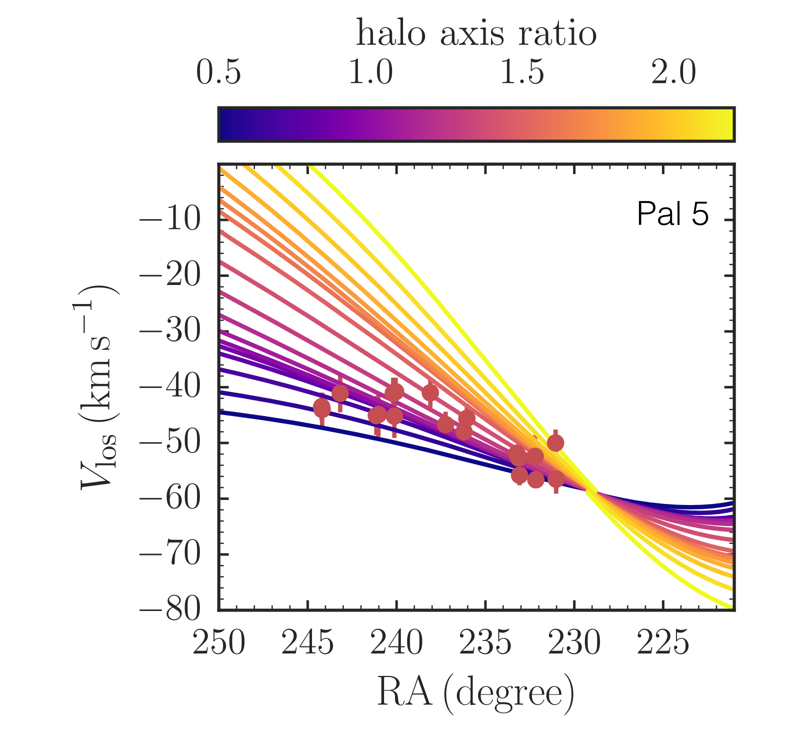
Stellar Streams & Dark Matter

Breaks in stellar streams may indicate the crossing of a dark matter subhalo



Carlberg [1307.1929]

Phase space density of streams is sensitive to gravitational potential; Pal 5 and GD-1 streams suggest spherical dark matter halo



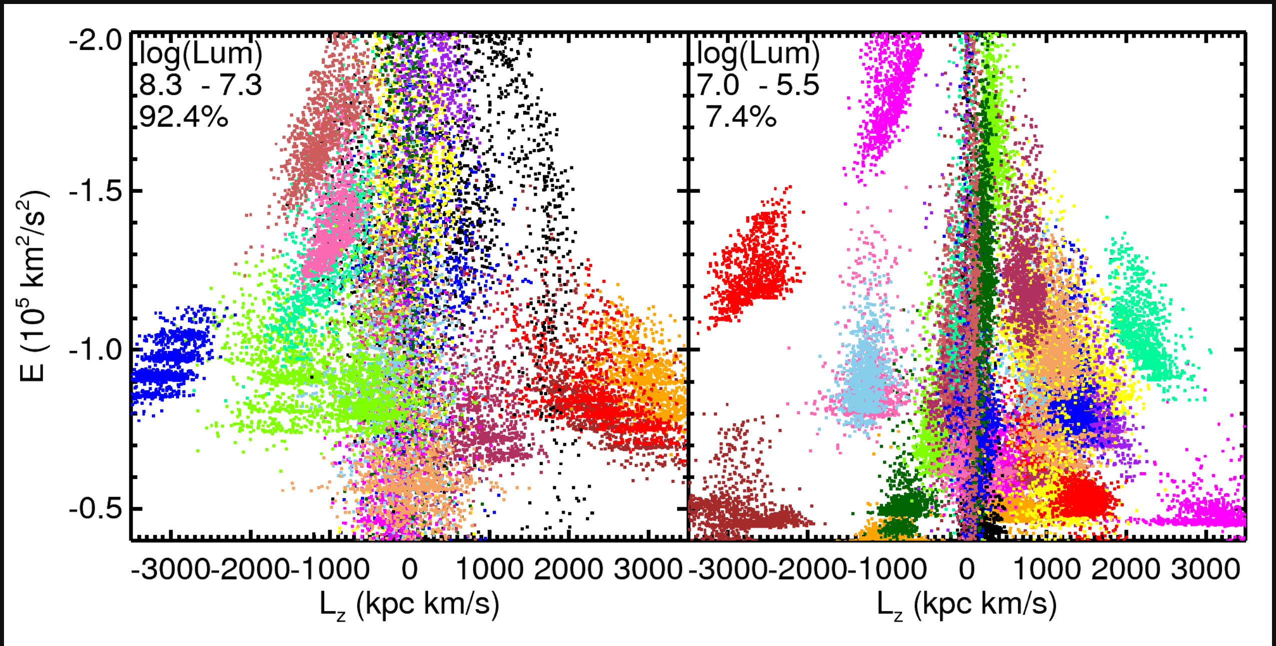
Bovy, *et al.* [1609.01298]

Outlook

Gaia will provide full phase-space coordinates for an unprecedented number of stars in the Milky Way

The goal is to reconstruct the Galaxy's merger history from mapping of tidal debris

each color represents debris from a different satellite ...



Sharma *et al.* [1101.3561]

Milky Way Formation History

Dark Matter Velocity Distribution

First Results from *Gaia* DR1

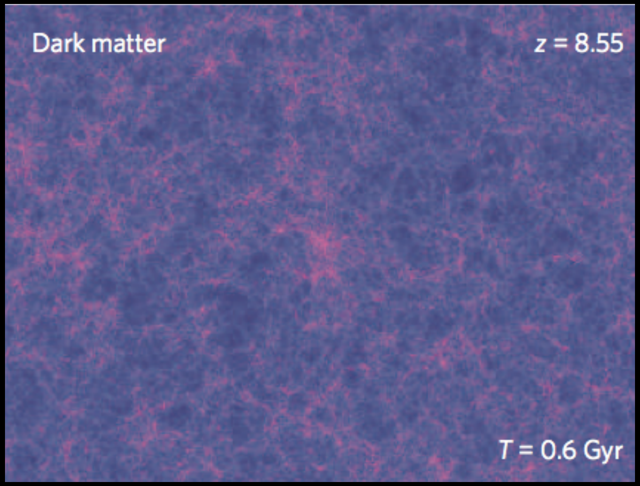
Dark Matter Structure Formation

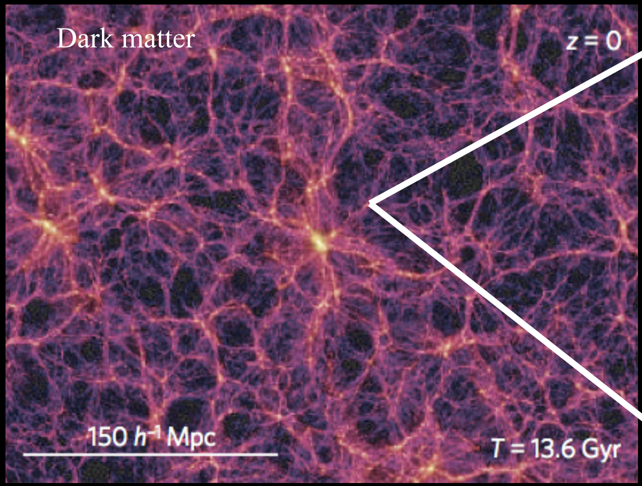
Dark matter halos merge hierarchically to form more massive systems

High resolution N-body simulations of Milky Way-like galaxies find wealth of spatial and kinematic substructure

Large-scale structure

Small-scale structure



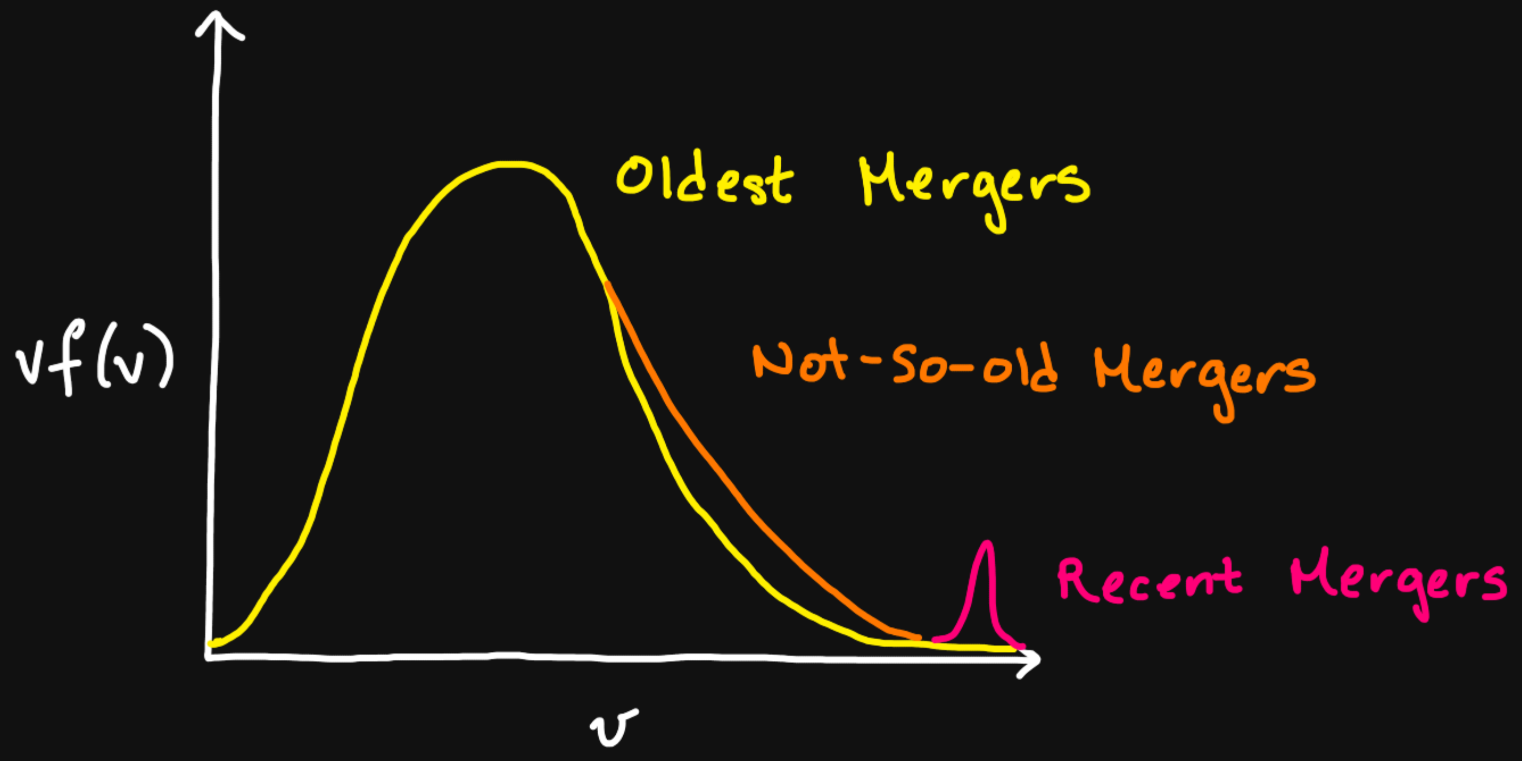


Millennium N-body Simulation

Via Lactea Simulation

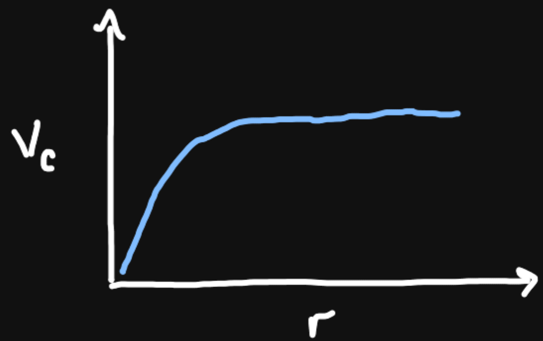
Fossil Record

Structure in dark matter velocity distribution is a fossil record of the merger history of the Milky Way



Oldest Mergers

Starting from the observation of flat rotation curves, we can derive self-consistent density and velocity distributions for the dark matter



$$V_c(r) = \sqrt{\frac{GM}{r}} \Rightarrow M(r) \propto r$$

Isothermal Density Distribution

$$\rho(r) \propto \frac{M(r)}{r^3} \sim \frac{1}{r^2}$$

$$\Longrightarrow$$

isotropic equilibrated halo

Maxwellian Velocity Distribution

$$f(v) \propto e^{-v^2/\sigma^2}$$

Recent Mergers

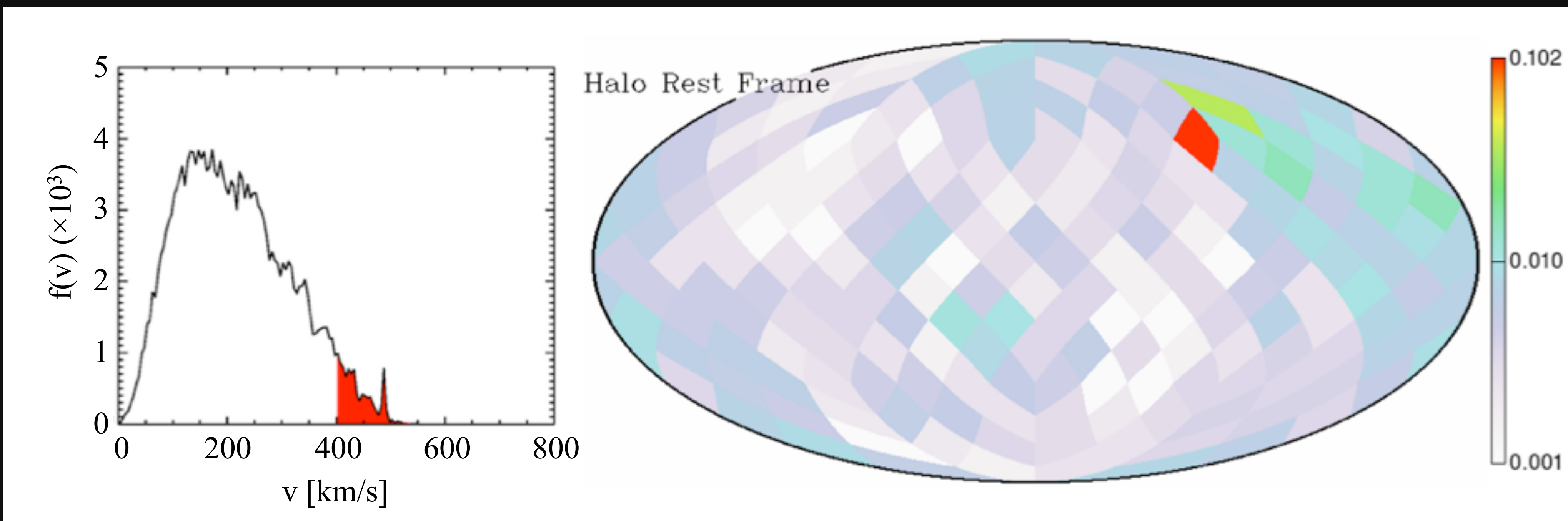
The most recent merger events leave behind dark matter streams that are localized in both position and velocity

Velocity Distribution

$f(\bar{v}) = \delta(\bar{v} - \bar{v}_{stream})$

Skymap

$\rho(\bar{r}) = \delta(\bar{r} - \bar{r}_{stream})$



Kuhlen *et al.* [0912.2358]

Direct Detection

Detection rates depend on local dark matter velocities

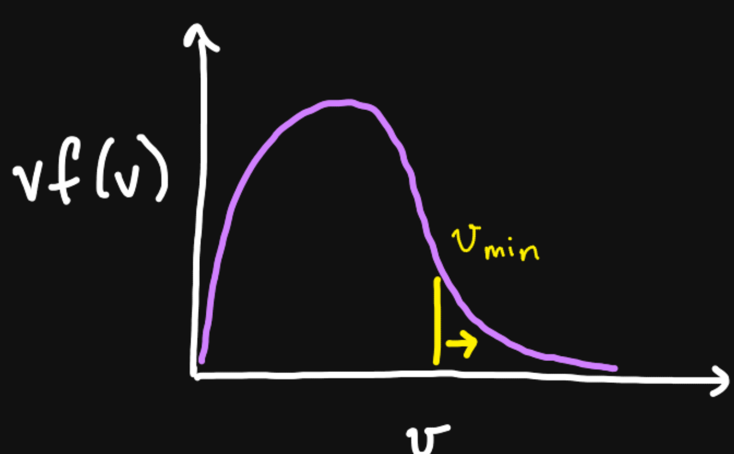
lab frame

$$\frac{dR}{dE_R} = n_{dm} \left\langle v \frac{d\sigma}{dE_R} \right\rangle \propto \int_{v_{min}}^{\infty} \frac{f(v)}{v} \, dv$$

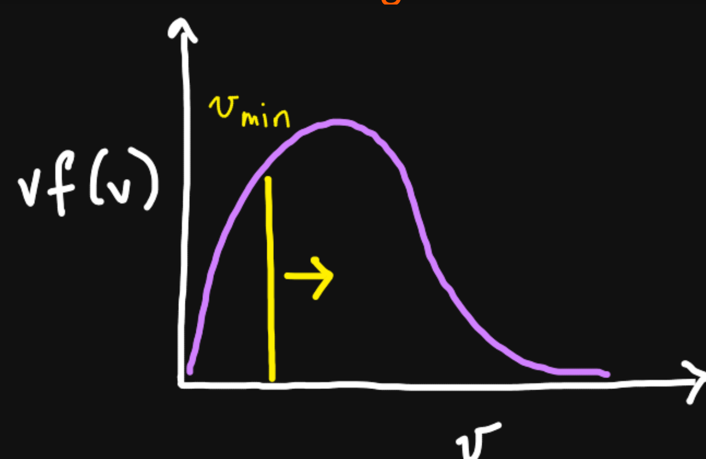
$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu^2}}$$

Lighter dark matter is more sensitive to high-velocity tail of dark matter distribution

Low Mass

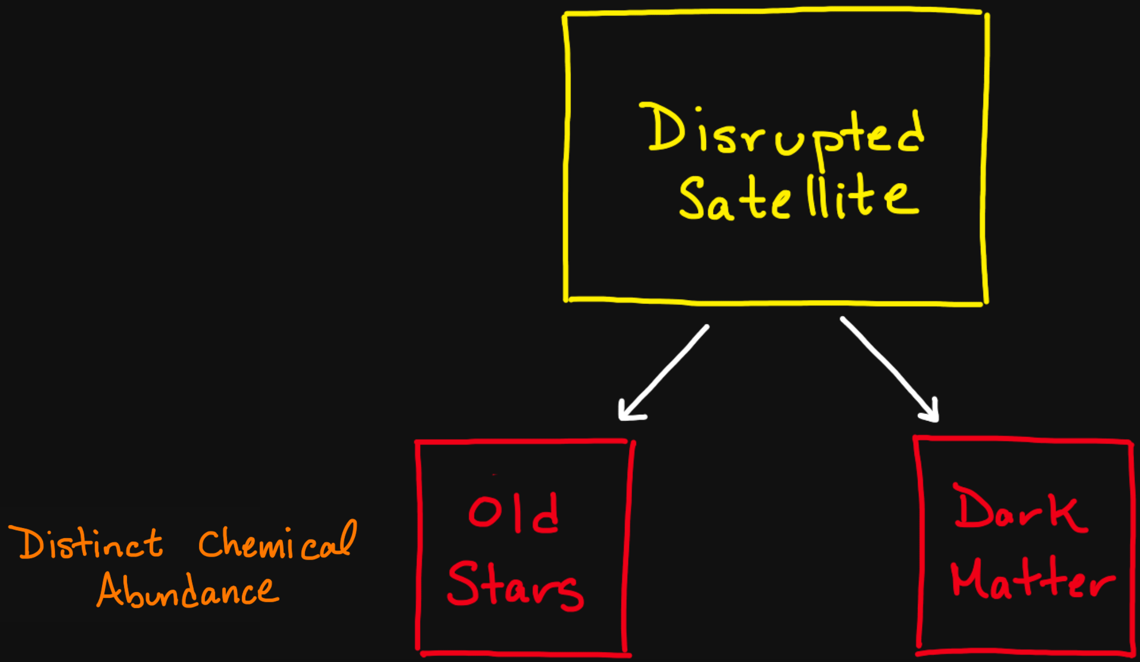


High Mass



Stellar Tracers

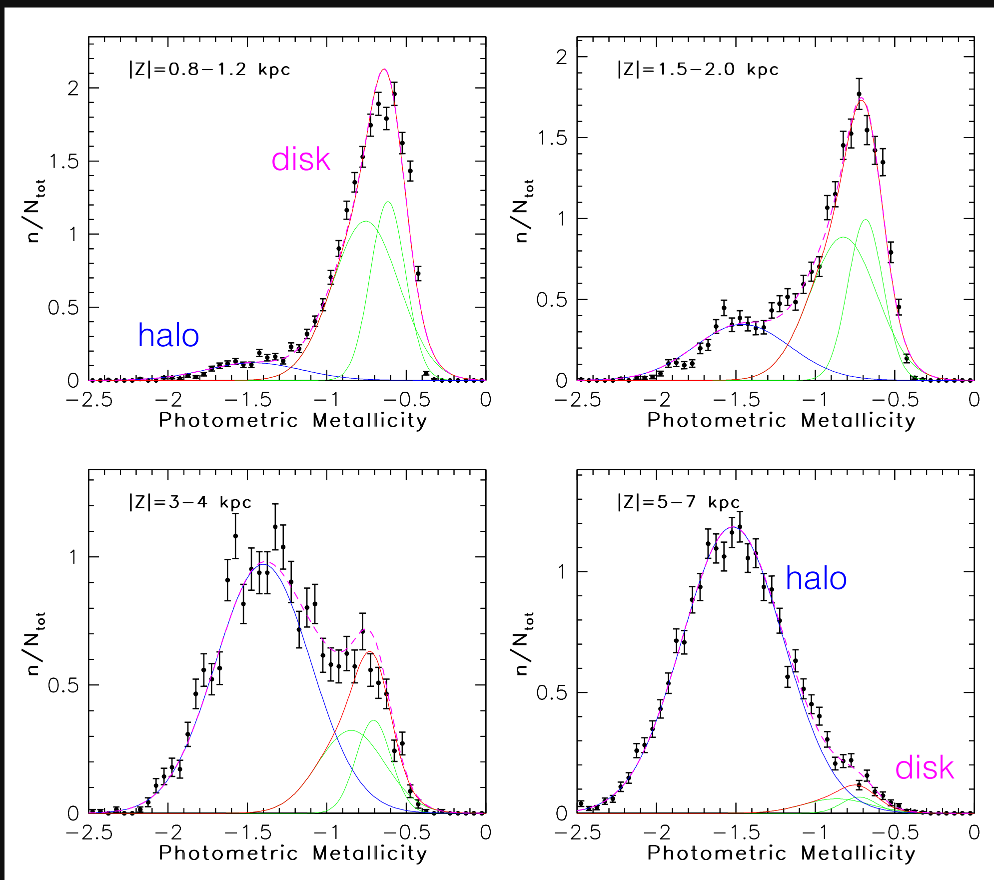
Can we use the primordial population of Milky Way stars as tracers for dark matter?



Older stars in the halo tend to be more metal-poor as compared to stars that were born in the Milky Way disk

Chemical Abundances

If the stellar halo is built out of disrupted galaxies, it will be metal-poor



Ivezic et al. [0804.3850]

[Fe/H]

Stellar abundance of element X relative to element Y is

$$\left[\frac{X}{Y}\right] = \log_{10}\left(\frac{N_x}{N_y}\right) - \log_{10}\left(\frac{N_x}{N_y}\right)_\odot$$

N_i = number density of element i

We will focus on Fe abundances and $\boldsymbol{\alpha}$-element enhancements

$$\left[\frac{Fe}{H}\right] \qquad \left[\frac{\alpha}{Fe}\right]$$

α = O, Ca, Mg, Si, Ti

Chemical Enrichment

Merging galaxies typically only experience a brief period of star formation

Their interstellar medium is dominated by explosions of core-collapse supernova, suppressing Fe abundances

Thermonuclear Supernova

Large amounts of Fe relative to α-elements
Act on longer timescales

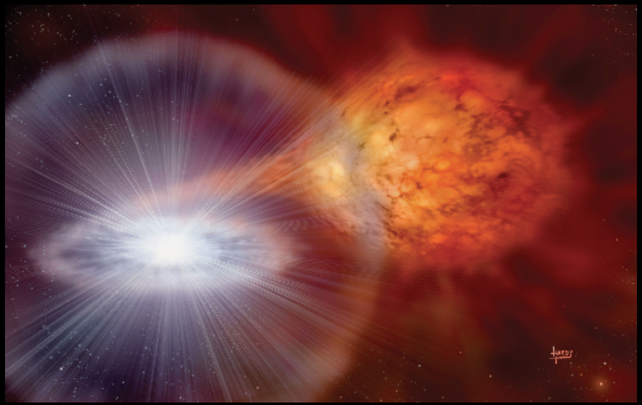


image credit: D. Hardy (astroart.org)

Core-collapse Supernova

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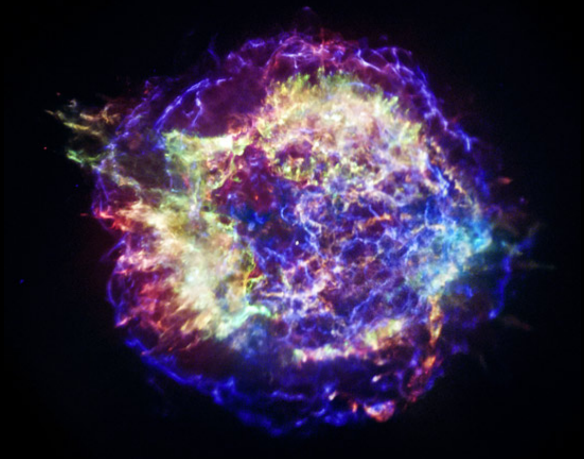


Chandra X-ray Observatory

Eris Simulation

Cosmological zoom-in simulation that models the dark matter, gas, and stars in a Milky Way-like galaxy

Properties of the Eris disk and halo are comparable to Milky Way values

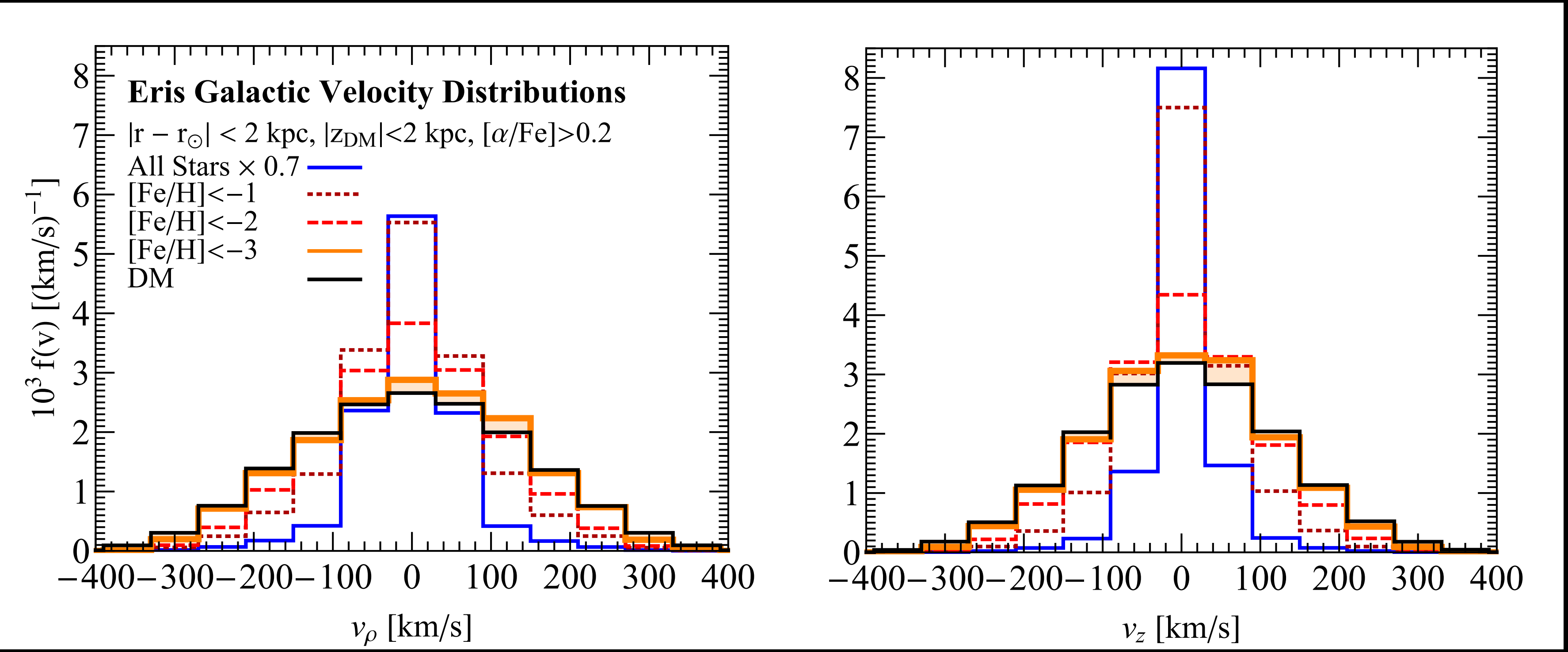
Metals are redistributed by stellar winds, as well as Type Ia and II SNe

Abundances of Fe and O are tracked by the simulation

Guedes et al. [1103.6030], Guedes et al. [1211.1713], Shen et al. [1407.3796], Pillepich et al. [1407.7855], Shen et al. [1612.02832]

Stellar Tracers

As increasingly more metal-poor stars are selected, velocity distribution of stars approaches that of the dark matter



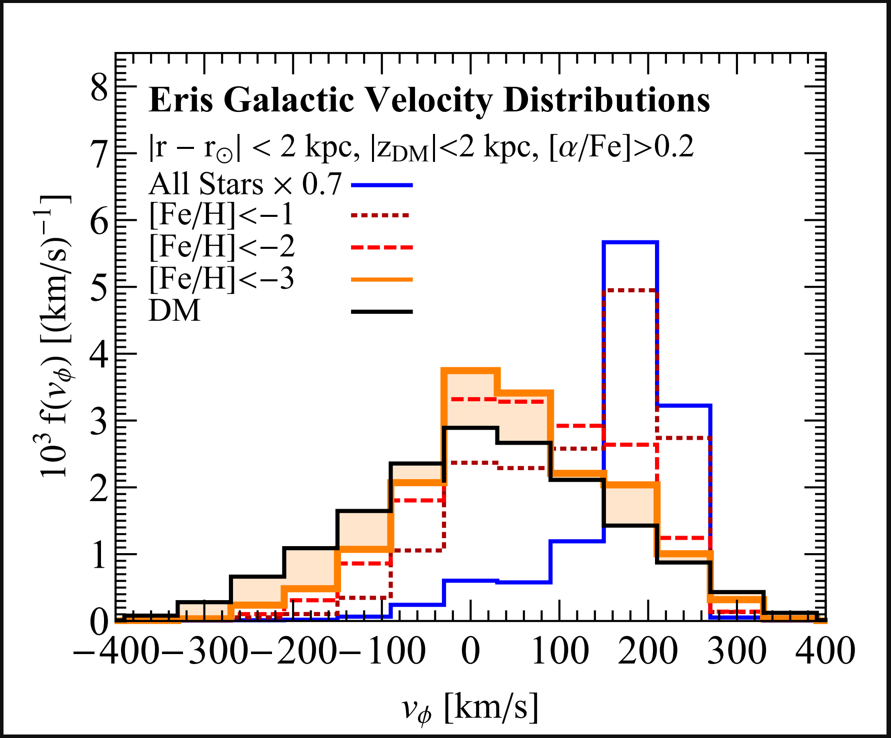
Herzog-Arbeitman, ML, Madau, and Necib [1704.04499]

Azimuthal Velocities

Subhalos on prograde orbits are preferentially disrupted due to dynamical friction

This leads to a co-rotating dark disk and prograde stellar halo in Eris

Pillepich et al. [1308.1703], Pillepich et al. [1407.7855]



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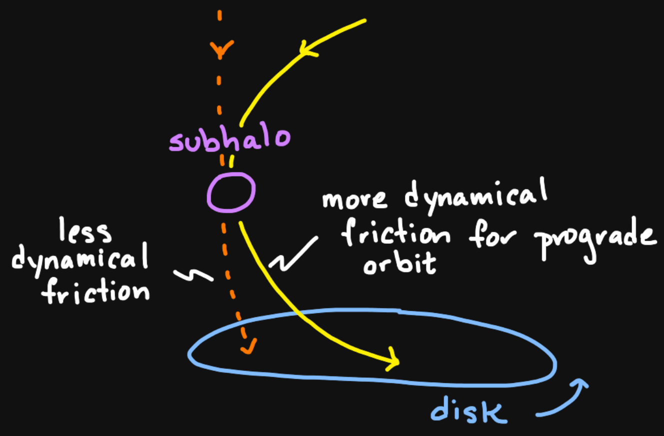


Unlike Eris, Milky Way stellar halo has only modest/vanishing prograde rotation—evidence against such mergers?

Lessons Learned

Dark matter and metal-poor stars in the Solar neighborhood share similar kinematics due to common origin

additional studies needed using other simulations to better understand effects of merger history

need to understand whether correspondence holds in generalizations of CDM

These results suggest that it is possible to determine dark matter velocities empirically

Empirical Distribution

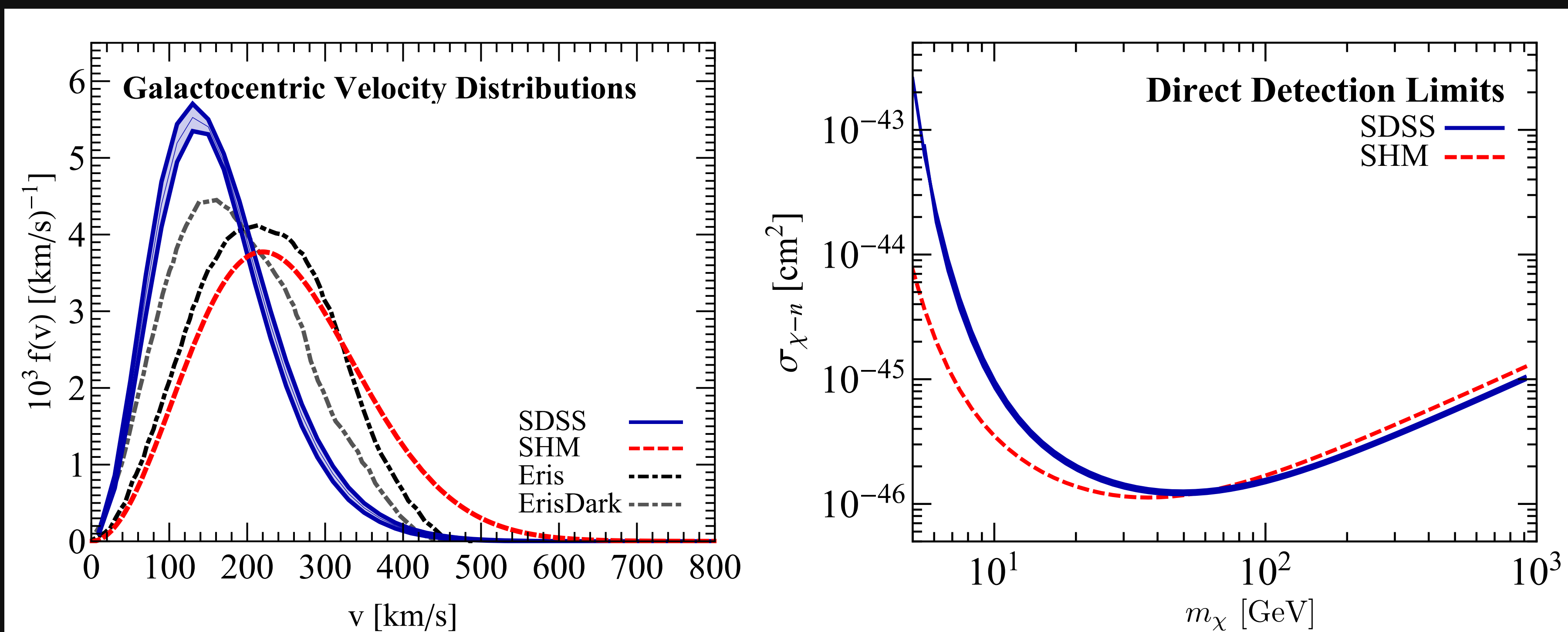
SDSS provides Galactic velocity distribution of candidate halo stars

Bond, *et al.* [0909.0013]

$\left[\frac{Fe}{H}\right] < -1.1$

$$f(\vec{v}) \propto \exp\left[-\frac{v_r^2}{2\sigma_r^2} - \frac{v_\theta^2}{2\sigma_\theta^2} - \frac{v_\phi^2}{2\sigma_\phi^2}\right] \qquad \{\sigma_r, \sigma_\theta, \sigma_\phi\} = \{141, 85, 75\}\ \text{km/s}$$

Differences with Standard Halo Model weaken bounds on dark matter below 10 GeV



Herzog-Arbeitman, ML, Madau, and Necib [1704.04499]

Milky Way Formation History

Dark Matter Velocity Distribution

First Results from *Gaia* DR1

Herzog-Arbeitman, ML, and Necib [in preparation]

Preliminary!

See also Helmi *et al.* [1611.00222] for initial studies of kinematic substructure in *Gaia* DR1 data

Maximizing DR1 Impact

Gaia DR1

Positions of billion stars from first 14 months of data

Distances, proper motions, and line-of-sight velocities will be provided in DR2 (2018)

Lindegren *et al.* [1609.04303]

TGAS Solution

Combine first-year *Gaia* data with *Tycho-2* catalog to obtain parallax and proper motions for ~2.5 million stars

Michelek, Lindegren, Hobbs [1412.8770]

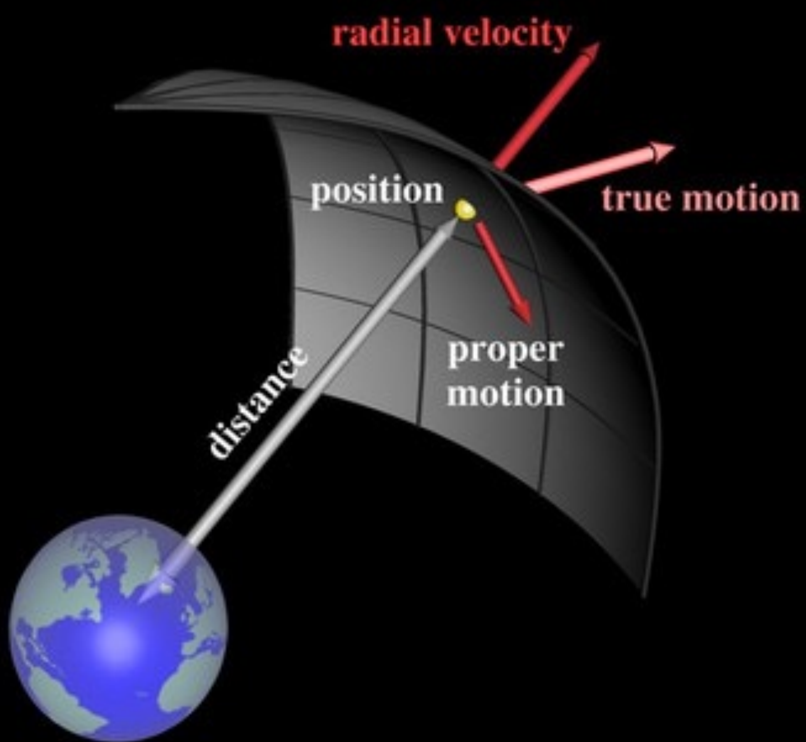
RAVE-TGAS Catalog

For ~200,000 stars that overlap between TGAS and RAVE, chemical abundances are known

Kunder *et al.* [1609.03210], Casey *et al.* [1609.02914]

Heliocentric Frame

Select RAVE-TGAS stars with |z| > 1.5 kpc and [Fe/H] < -1.5
(about 390 remain after selection cuts)



Local Velocities

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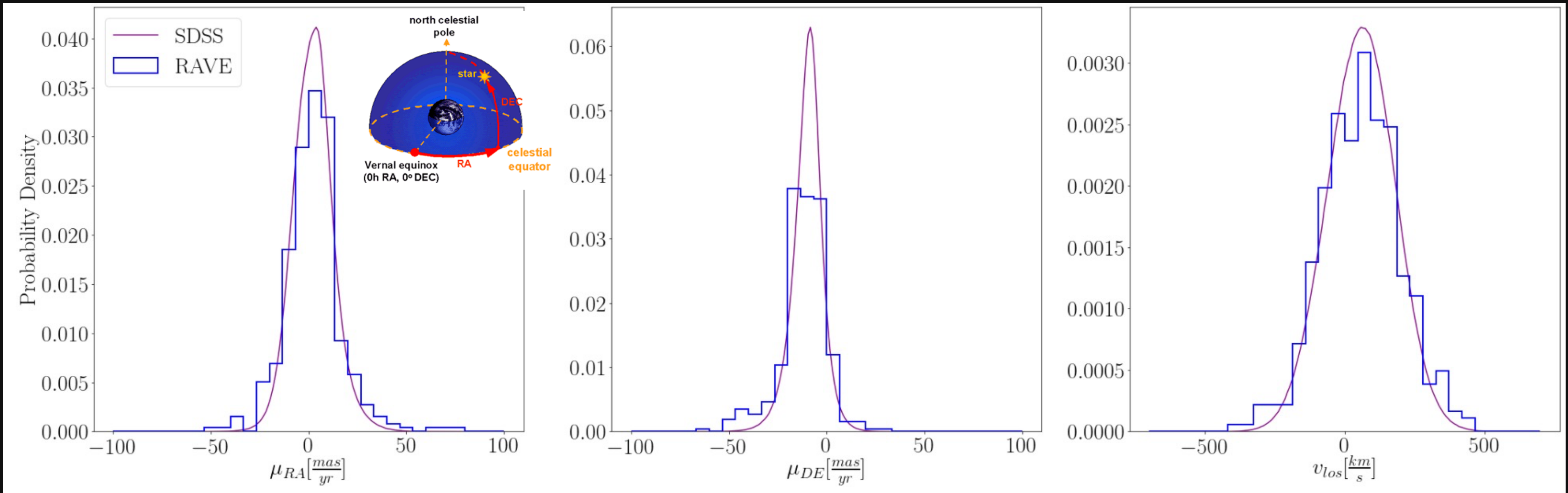
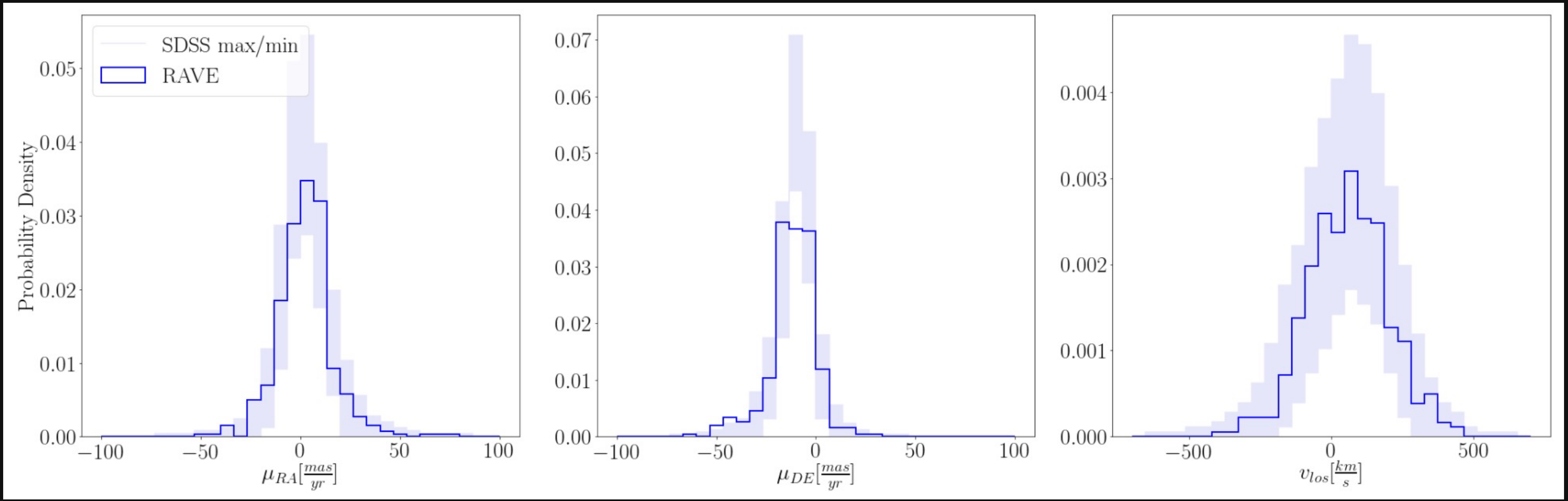


Preliminary!

Local Velocities

Select RAVE stars with |z| > 1.5 kpc and [Fe/H] < -1.5
(about 390 remain after selection cuts)

Compare with mock catalogs (390 stars each) drawn from the SDSS distribution



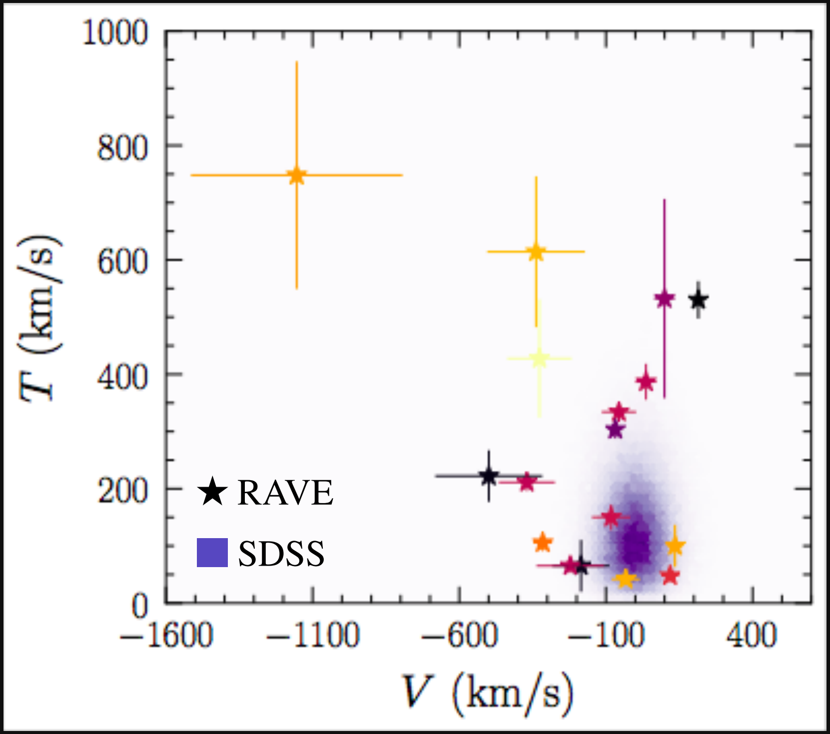
Preliminary!

Kinematic Outliers

Preliminary!

In 3D velocity space, we look for bins where the observed RAVE-TGAS count is 3σ higher than the SDSS expectation

Identify stars with peculiar kinematic behavior



Disclaimer: The analysis is still being refined and the list of peculiar stars has not been finalized yet

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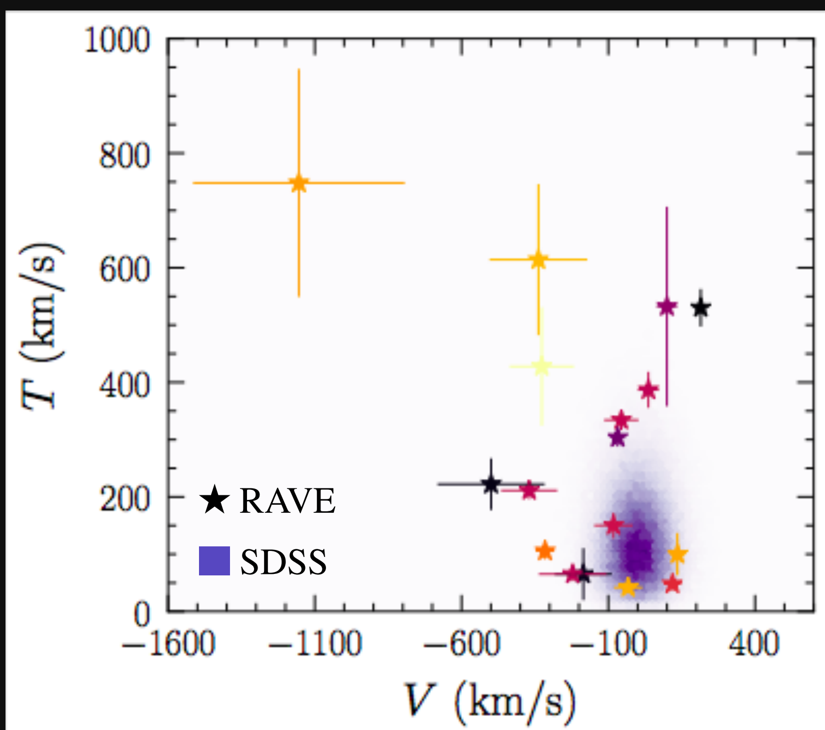

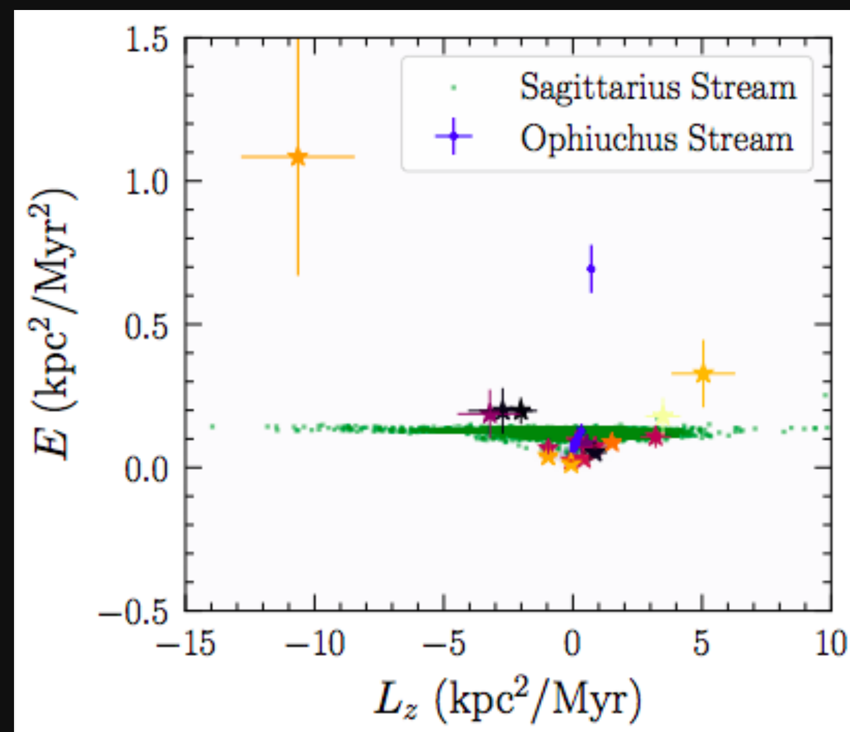

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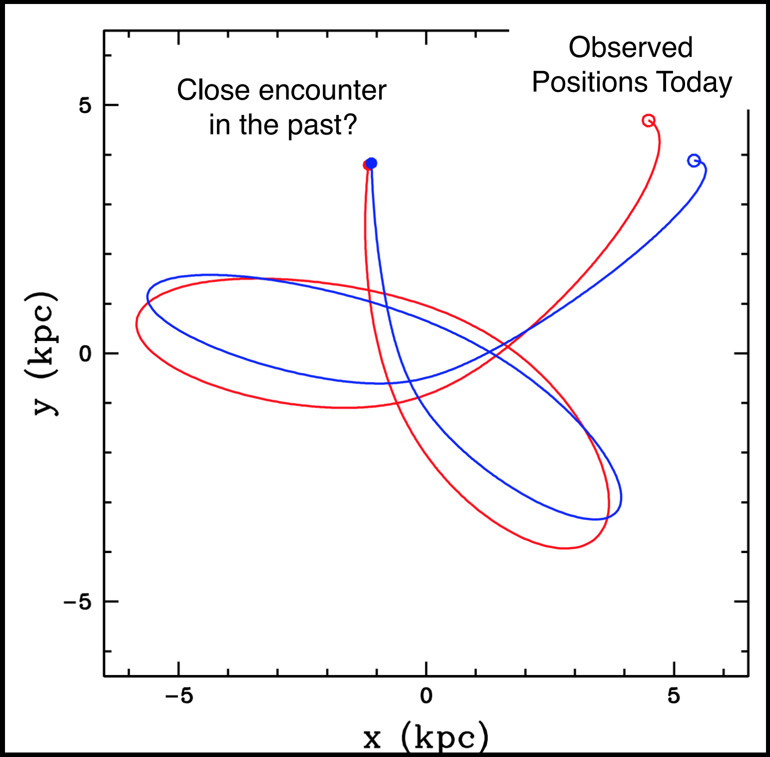
Origin of Peculiar Stars

Orbit analysis will allow us to determine if peculiar stars had a close encounter in the past with known satellites



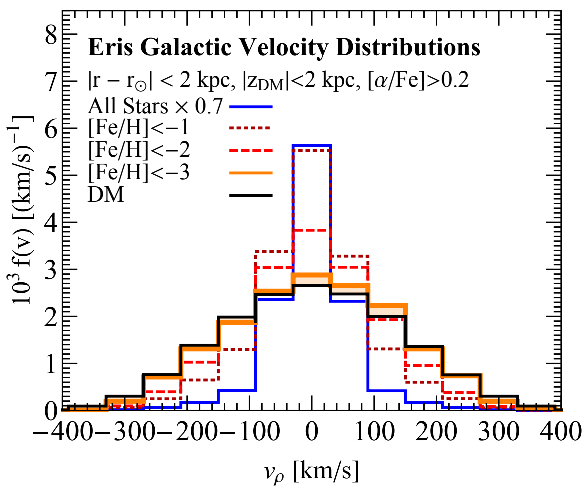
Fernandez-Trincado (2015)

Follow-up observations of peculiar stars will improve measurements of chemical abundances and search for additional counterparts

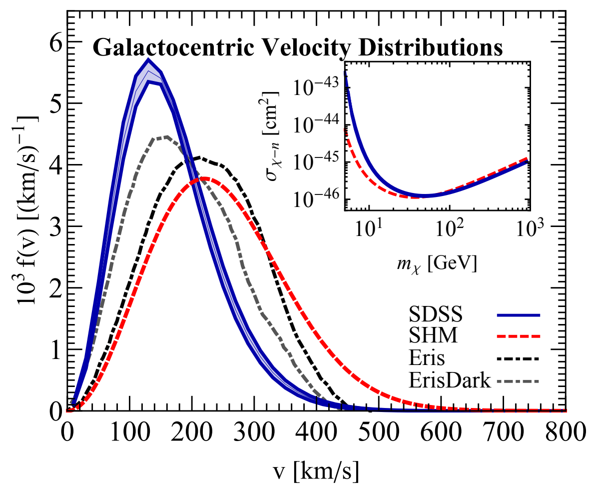
Conclusions

Gaia will provide an unprecedented view of the Milky Way's stellar halo, allowing us to reconstruct its formation history

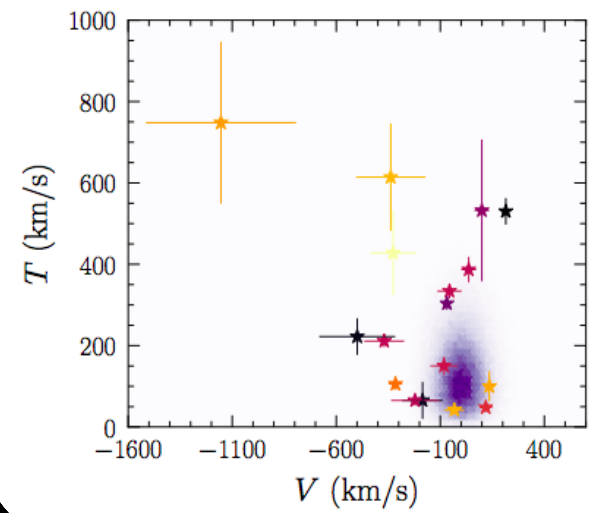
This will shed light on the dark matter potential and local distribution



Old metal-poor stars appear to be excellent tracers for the dark matter in the halo



Empirical velocity distributions can affect interpretations of direct detect experiments



Gaia DR1 may provide clues for local dark matter substructure