# Dark Matter in Disequilibrium

Mariangela Lisanti
Princeton University

Image: Tom Hall

# The Dark Matter Halo

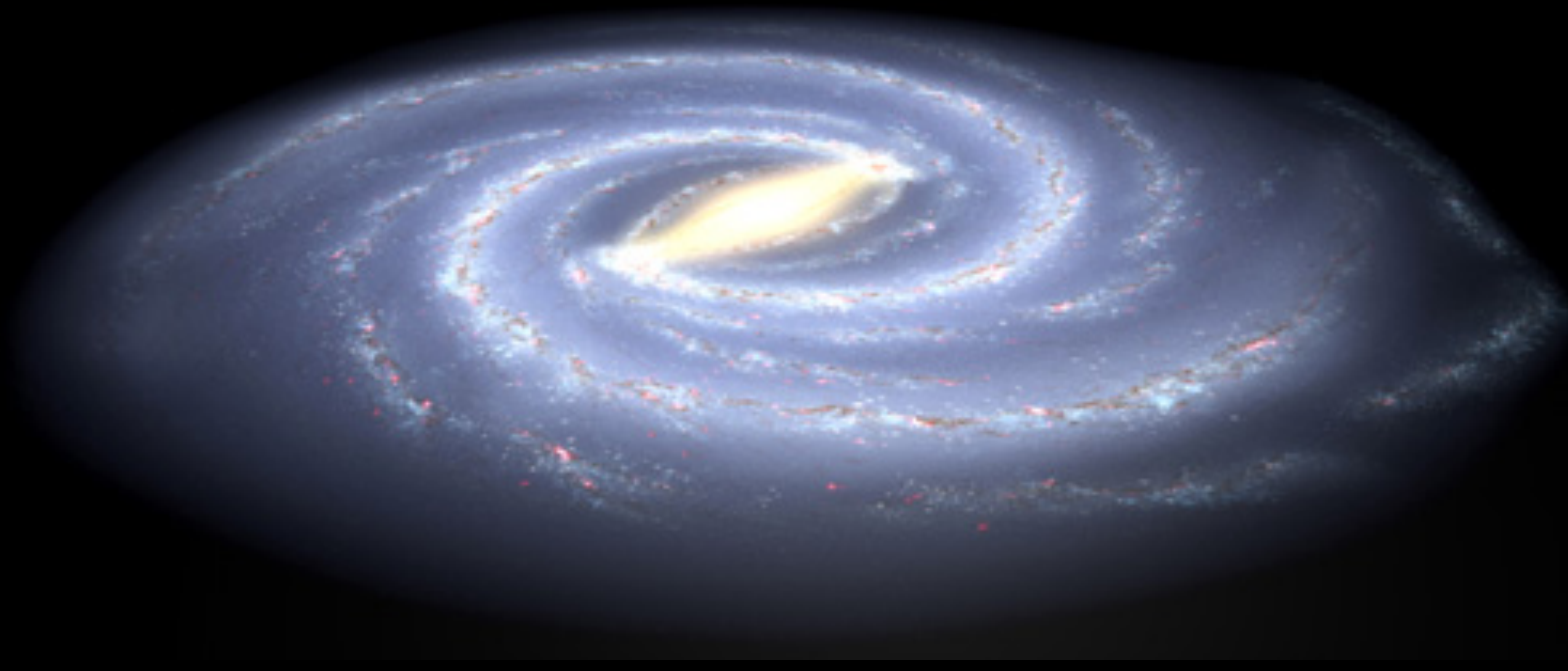

Image: NASA

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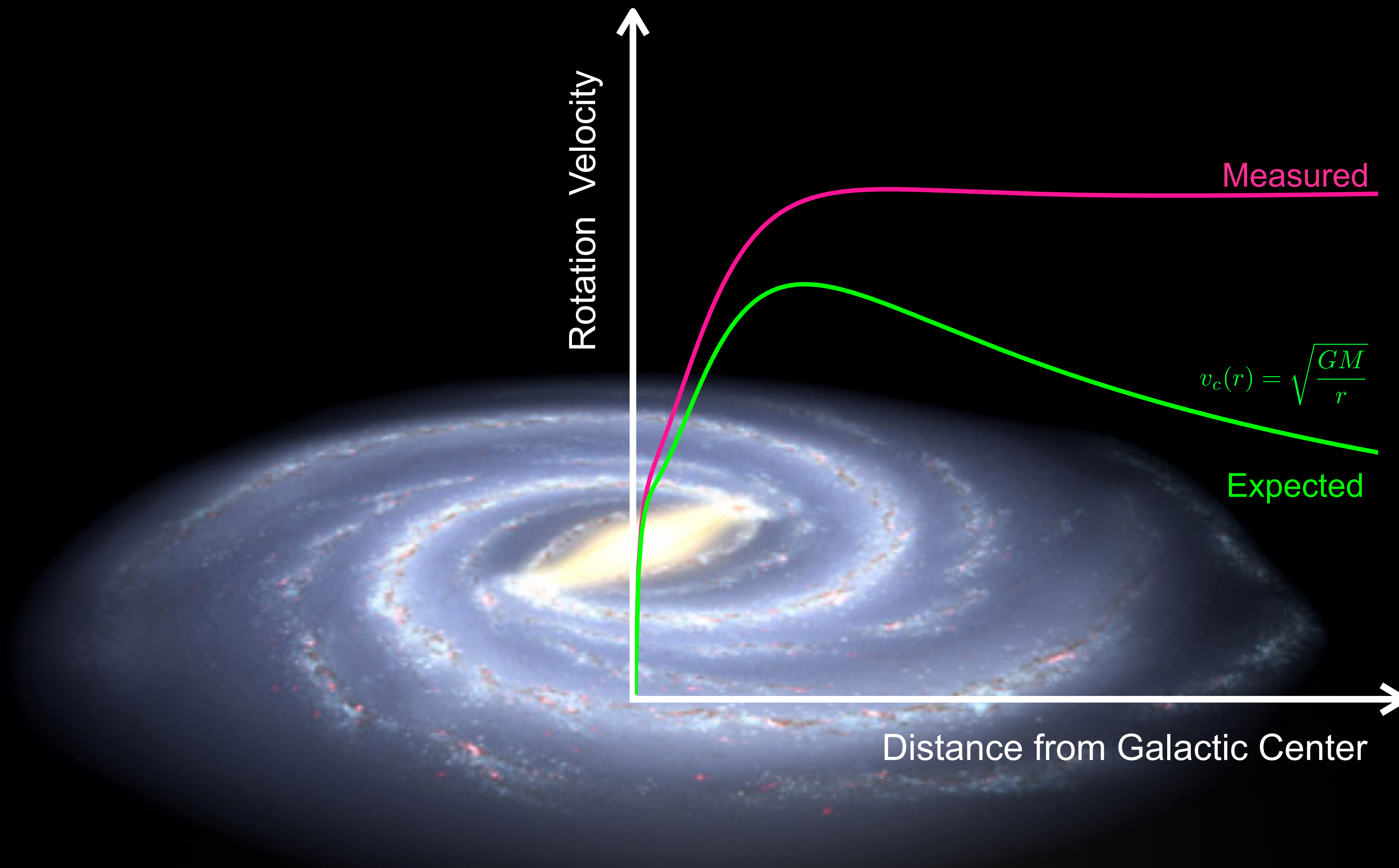
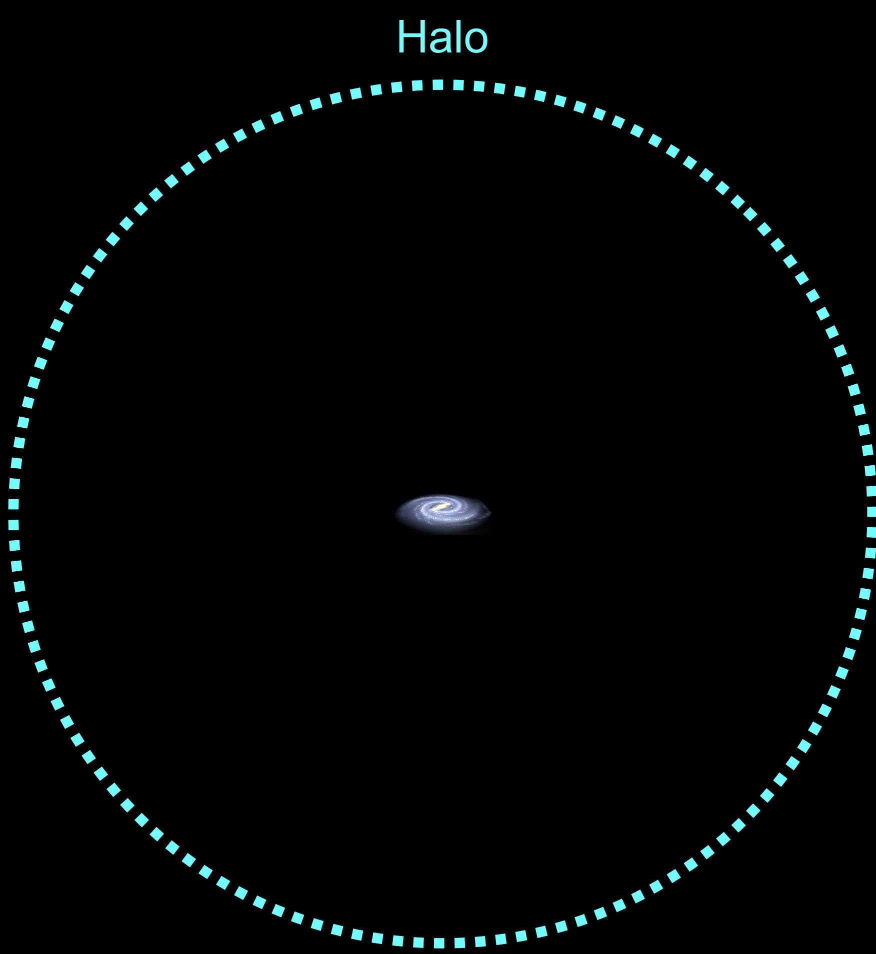



Rubin and Ford (1970); Roberts and Whitehurst (1975); Rubin, Thonnard and Ford (1980); Bosma (1981)

# The Dark Matter Halo




A flat rotation curve implies that the enclosed mass scales as

$$M(r) \propto r$$

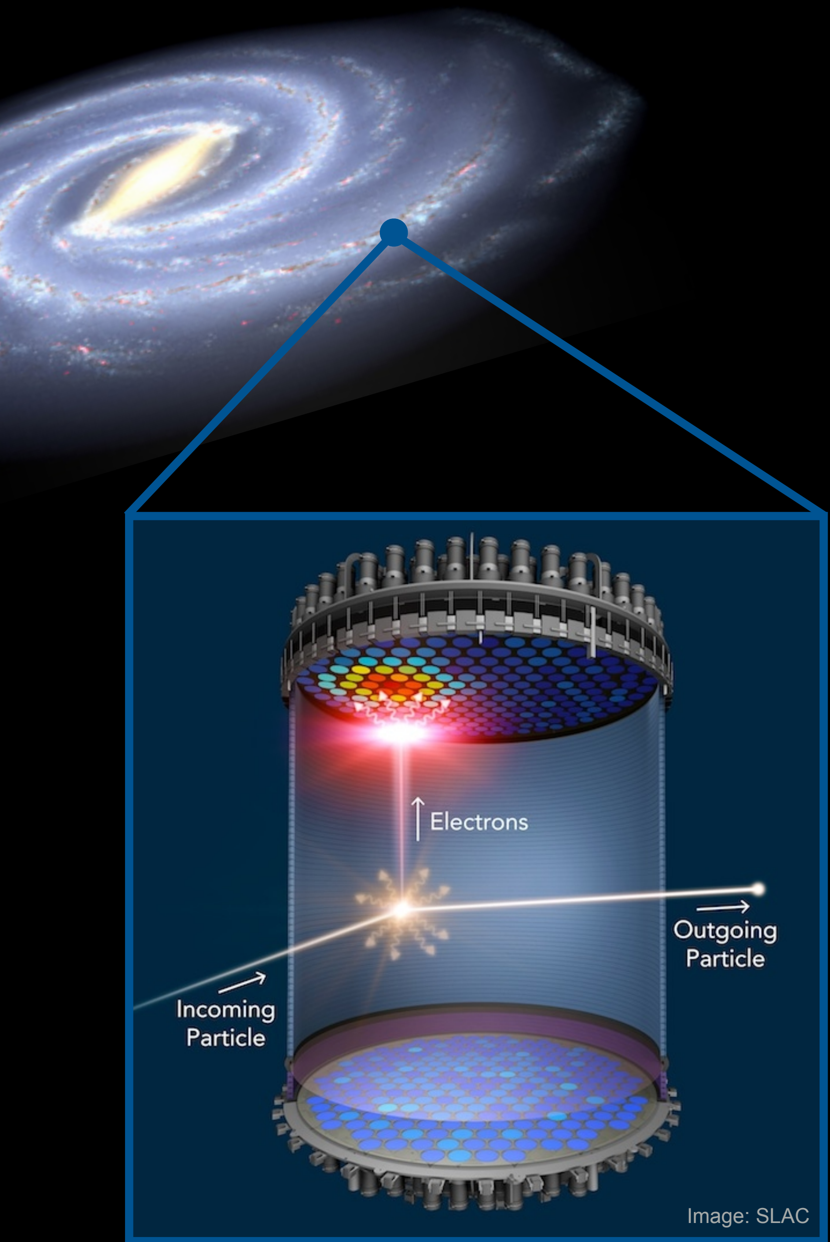
Dark matter forms a halo as it interacts weakly and is non-dissipative

relevant scales

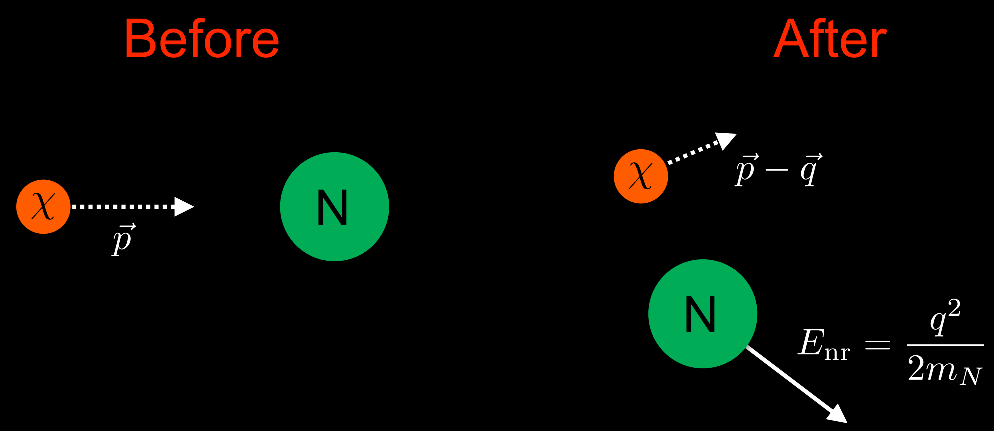
$$M_{\rm halo} \sim 10^{12}\,{\rm M}_\odot \qquad R_{\rm halo} \sim 100\,{\rm kpc}$$

$$\langle v \rangle \sim \sqrt{\frac{GM_{\rm halo}}{R_{\rm halo}}} \sim 200\,{\rm km/s}$$

# Dark Matter Direct Detection




Dark matter can scatter off a nucleus in a detector to yield an observable nuclear recoil




Scattering rate depends on the local dark matter number density and velocity distribution

$$\mathrm{Rate} = n_\chi \, \langle \sigma \, v_\chi \rangle$$

# The Dark Matter Halo v1.0

Treat the dark matter as a collision-less fluid with phase space distribution

$$f(\mathbf{x}, \mathbf{p}, t)$$

**conservation of fluid mass**

$$\frac{\partial f}{\partial t} + \dot{\mathbf{x}} \frac{\partial f}{\partial \mathbf{x}} + \dot{\mathbf{p}} \frac{\partial f}{\partial \mathbf{p}} = 0$$

→

**additional assumptions**

steady state
isotropic velocities
flat rotation curve

↓

**isothermal density**

$$n_\chi \sim r^{-2}$$

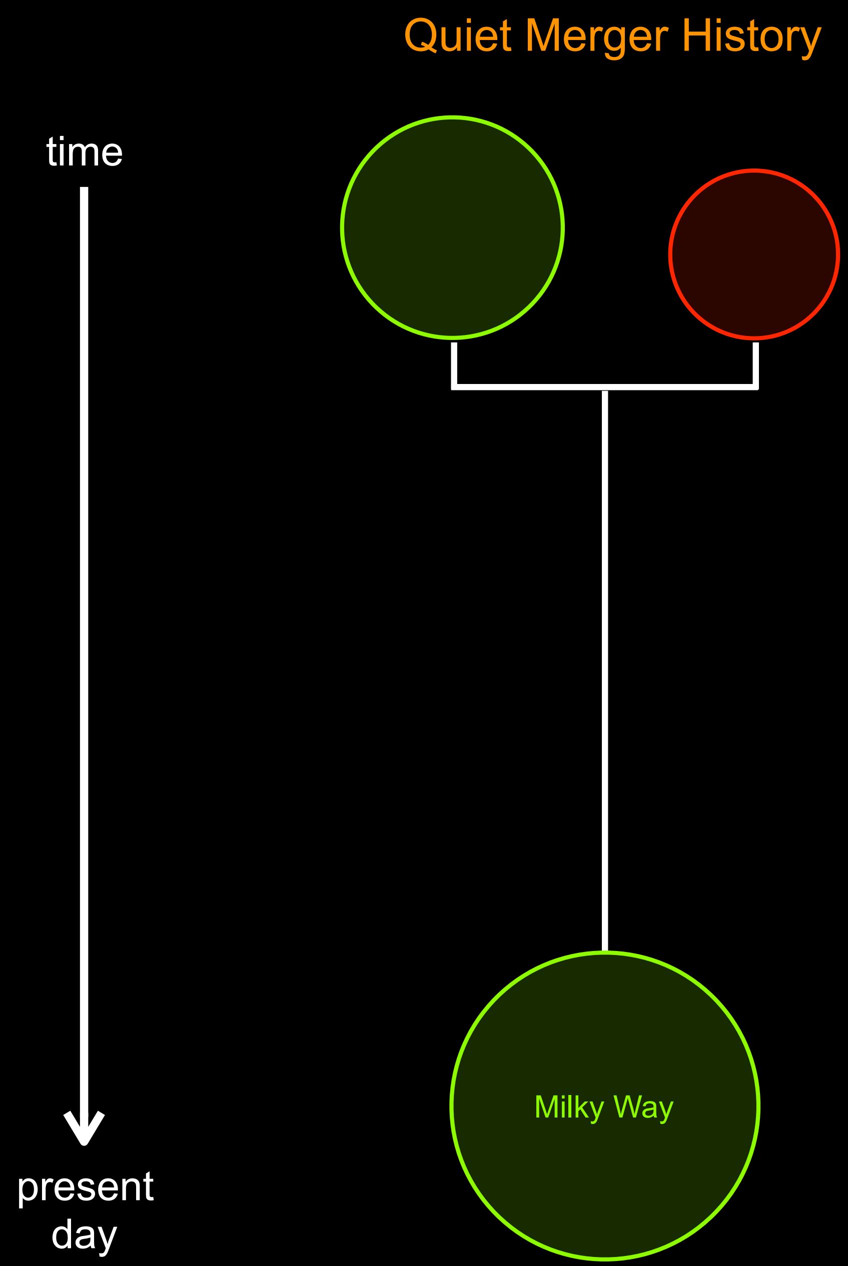
←

**Maxwell-Boltzmann**

$$f(v_\chi) \sim e^{-v_\chi^2/2\sigma^2}$$

Ostriker, Peebles, and Yahil (1974); Bahcall and Soneira (1980); Caldwell and Ostriker (1981); Drukier, Freese, and Spergel (1986)

# The Local Milky Way's Family Tree



# Simulated Galaxy Formation

Stellar Structure Evolution in the FIRE Simulation

Hopkins et al. (2015)


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

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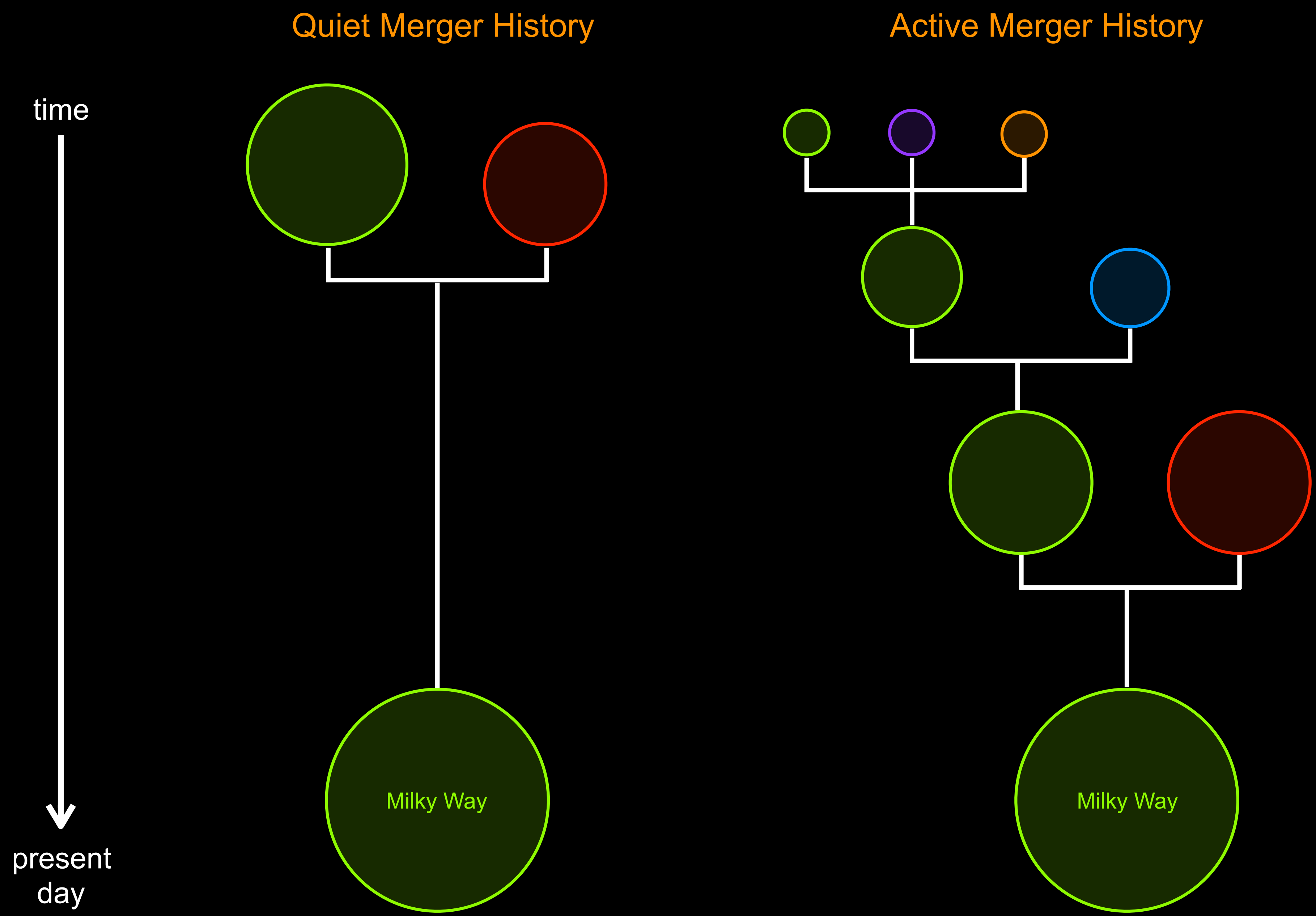
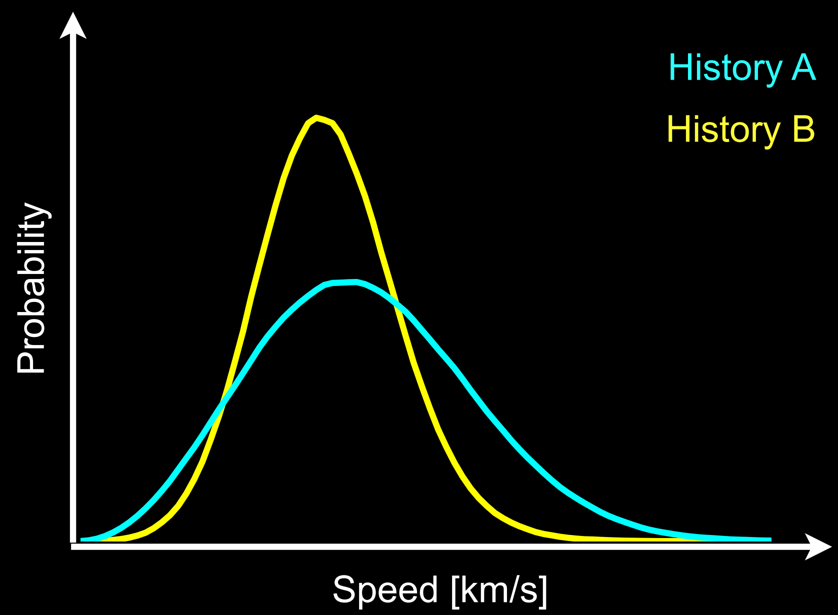


# Dark Matter Direct Detection

The Milky Way's merger history shapes the local dark matter distribution



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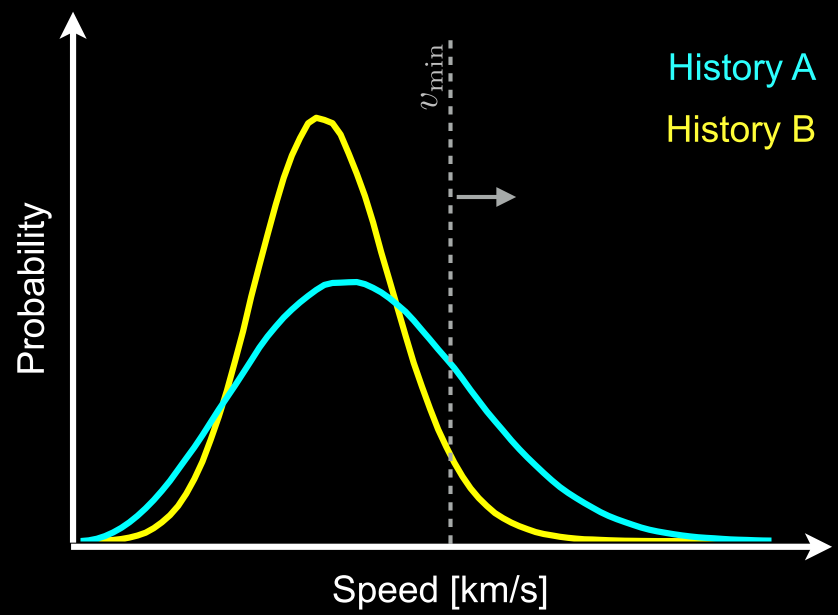
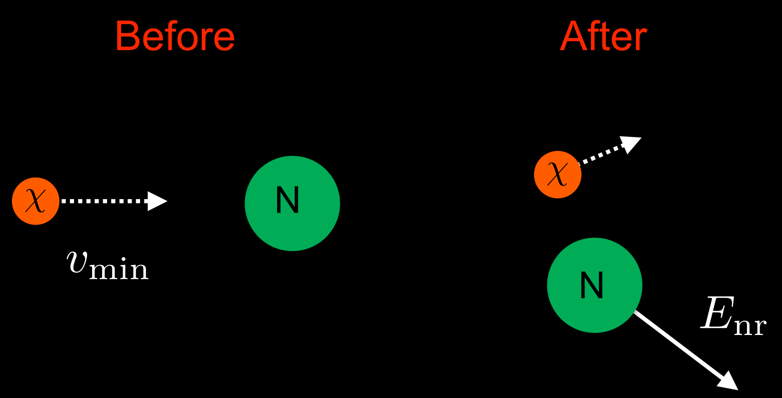



Minimum dark matter speed required to give nucleus sufficient kick

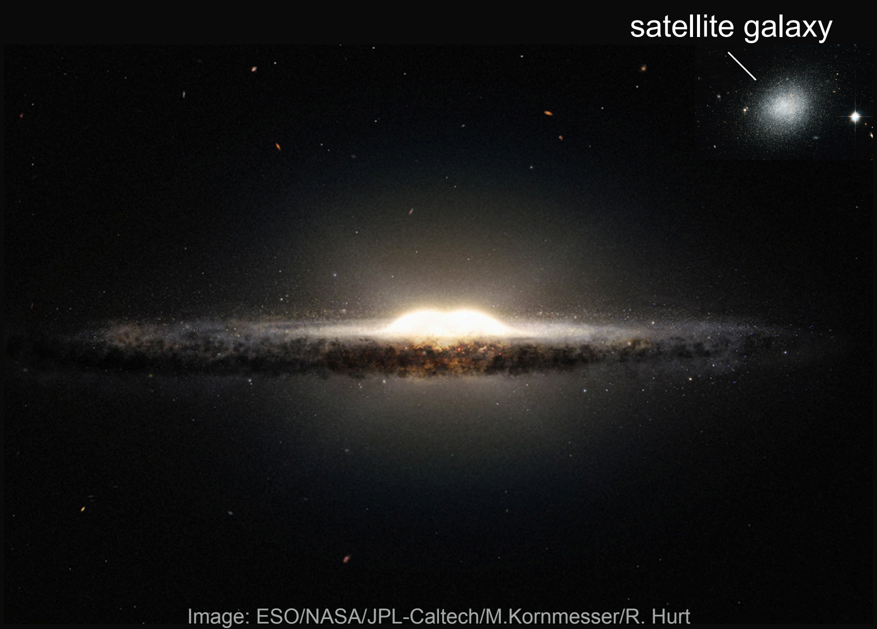



History A could lead to higher scattering rates in experiments

How is the local dark matter distribution built up?

# Galactic Cannibalism

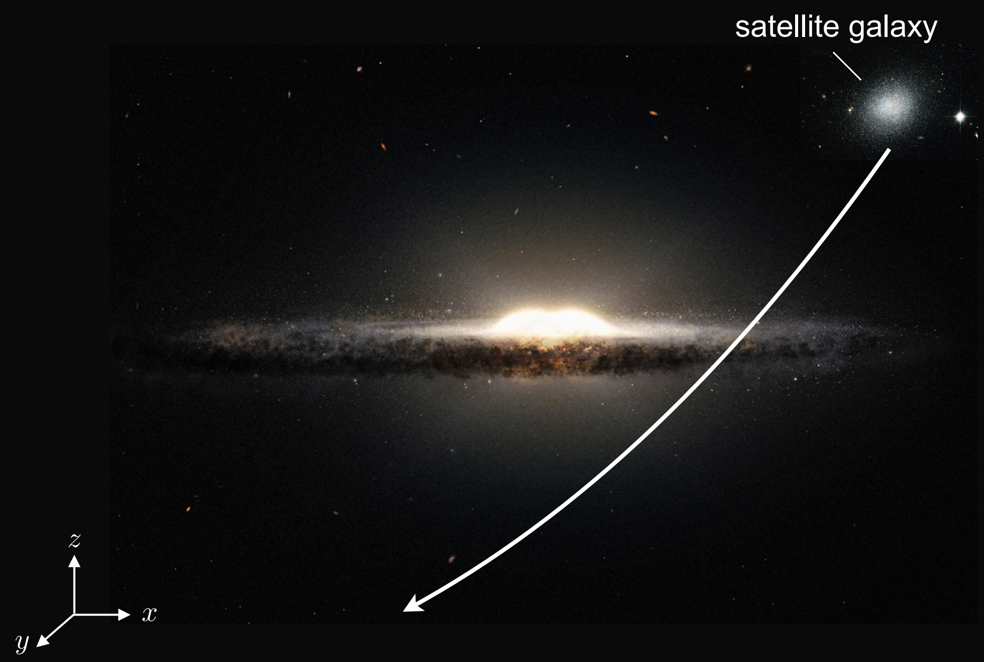
Strong tidal forces strip dark matter off an infalling satellite galaxy

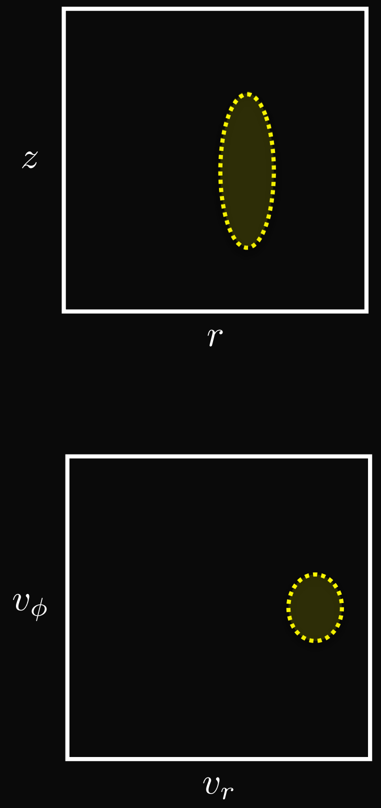


# Galactic Cannibalism

Soon after infall, tidal debris is clustered in position and velocity

e.g., tidal stream



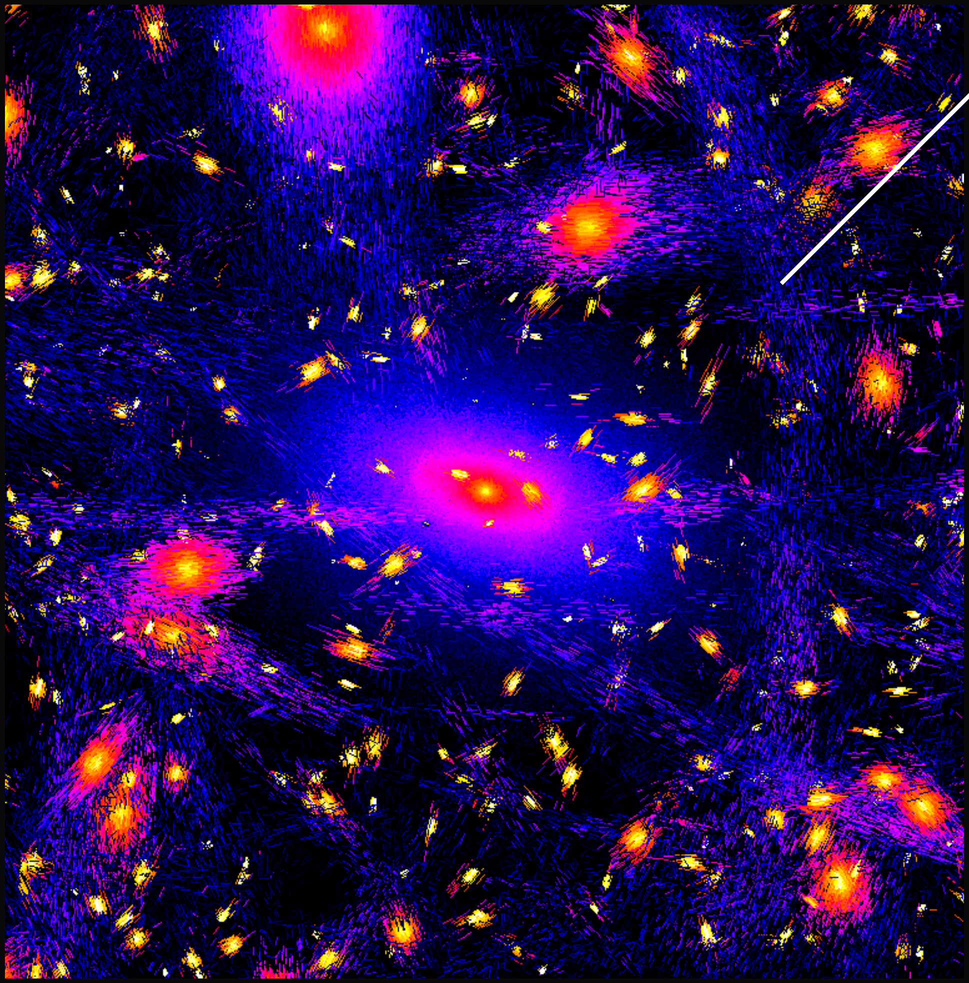




Zemp et al. (2009); Vogelsberger et al. (2009); Diemand et al. (2008)

# Galactic Cannibalism

Via Lactea N-body Simulation

(Dark Matter Only)

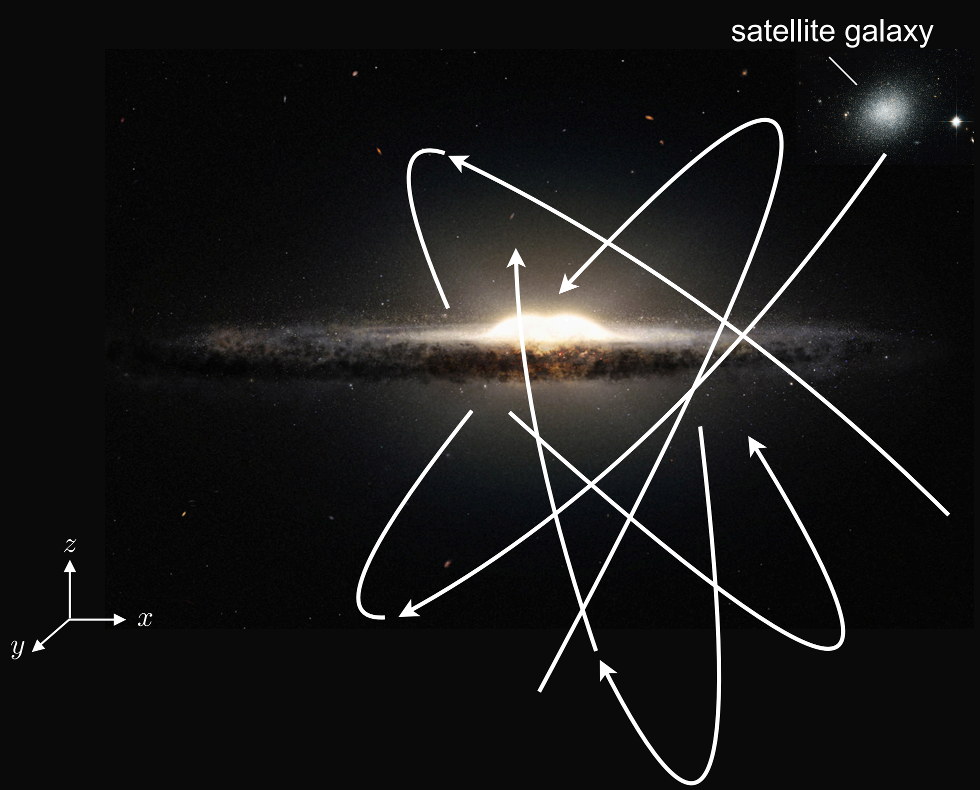


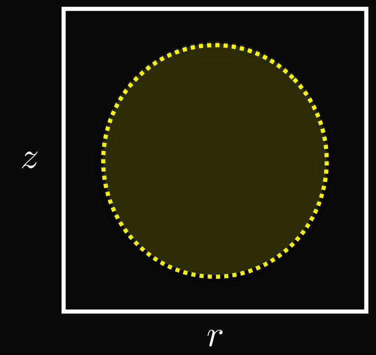

Diemand et al. (2008)

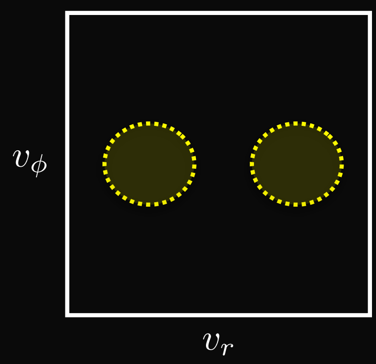
# Galactic Cannibalism

Velocity substructure can survive after many orbital wraps

e.g., debris flow




**ML** and Spergel, Phys. Dark Univ. [1105.4166]; Kuhlen, **ML**, and Spergel, PRD [1202.0007]; **ML**, Spergel, and Madau, ApJ [1410.2243]

# Galactic Cannibalism

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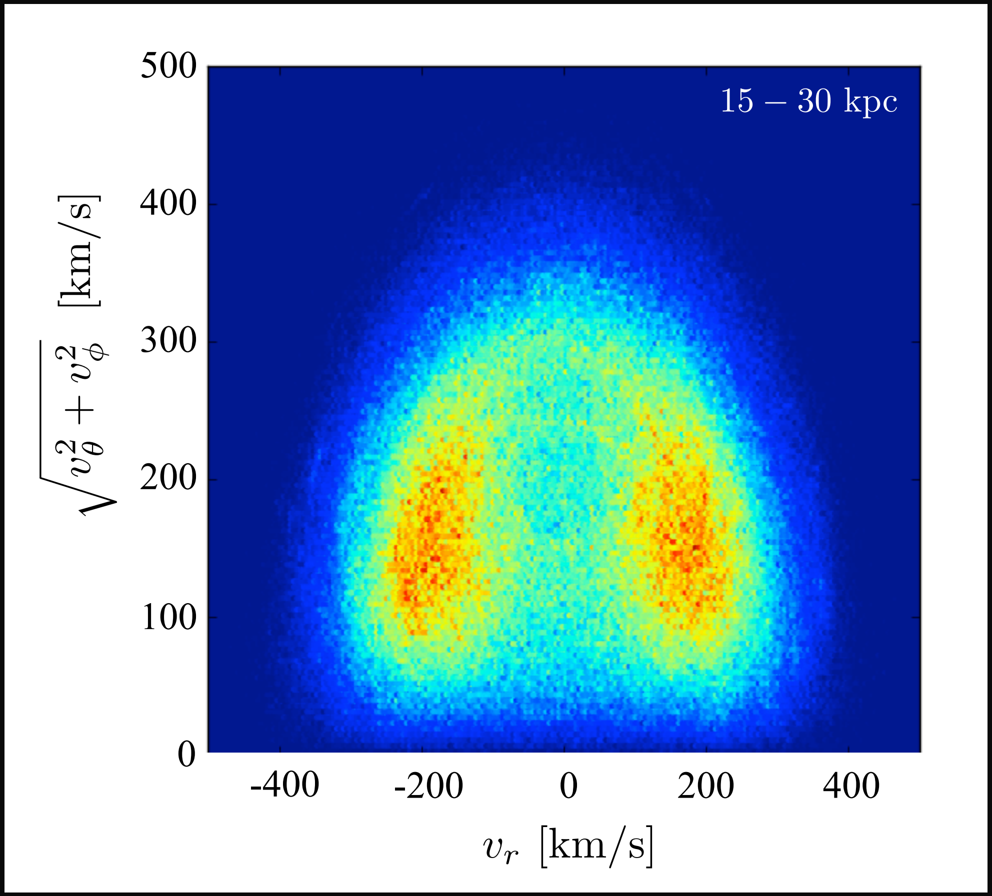
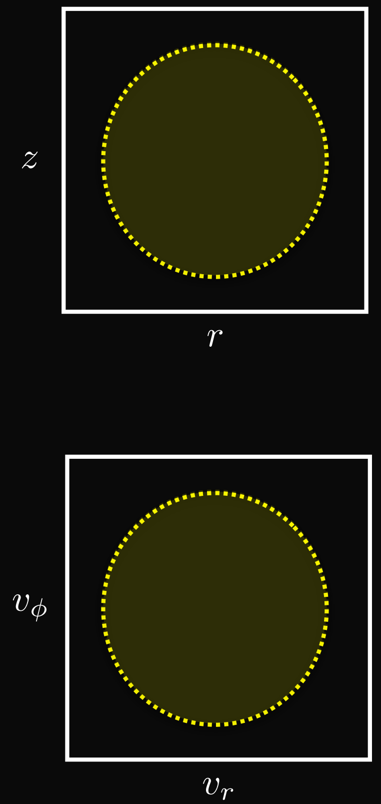



**ML** and Spergel, Phys. Dark Univ. [1105.4166]

# Galactic Cannibalism

Long after infall, tidal debris becomes fully phase mixed

e.g., virialized halo

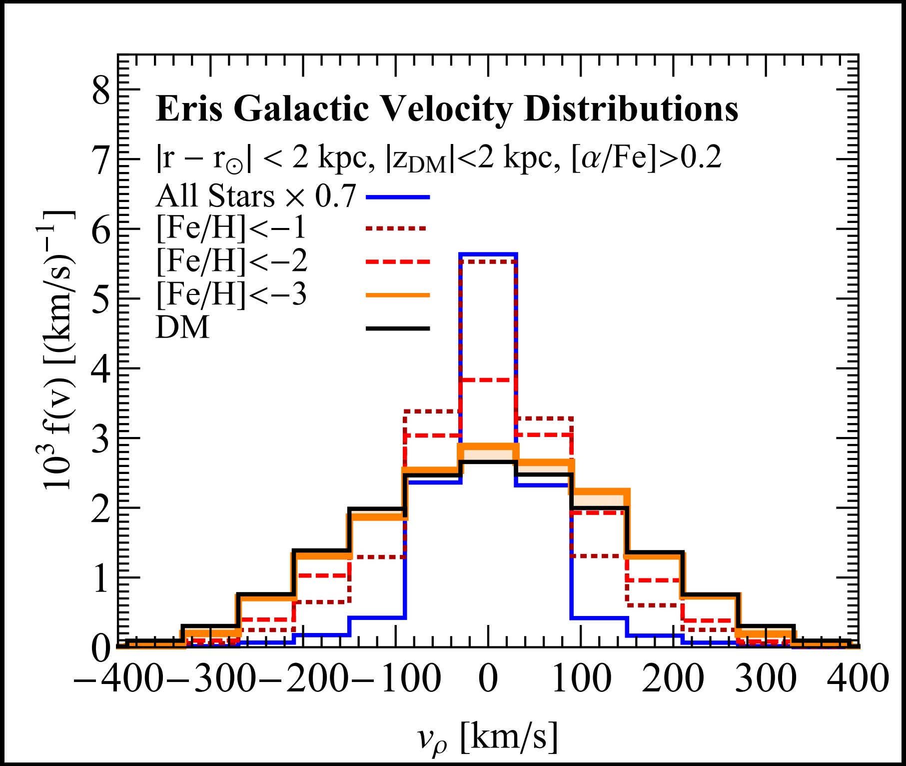
Stars are also stripped from merging satellites

↓

Visible tracers for the underlying dark matter

# Stellar Tracers for Dark Matter

Simulations demonstrate that stars and dark matter from old mergers follow similar trajectories in a Galaxy




Herzog-Arbeitman, **ML**, Madau,and Necib, PRL [1704.04499]; Herzog-Arbeitman, **ML**, and Necib, JCAP [1708.03635]

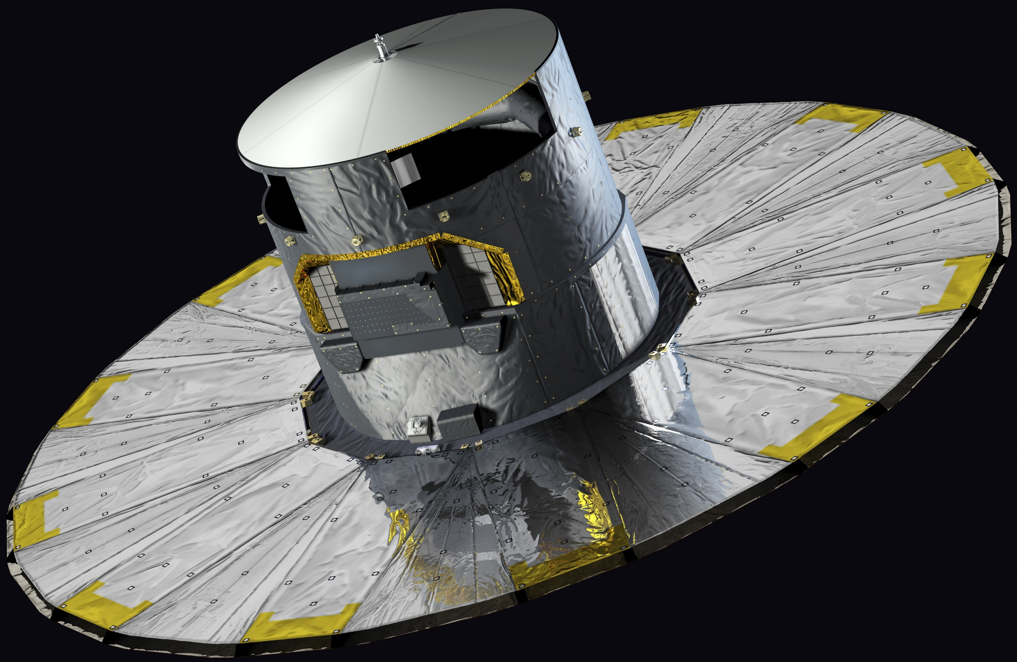
# The *Gaia* Mission

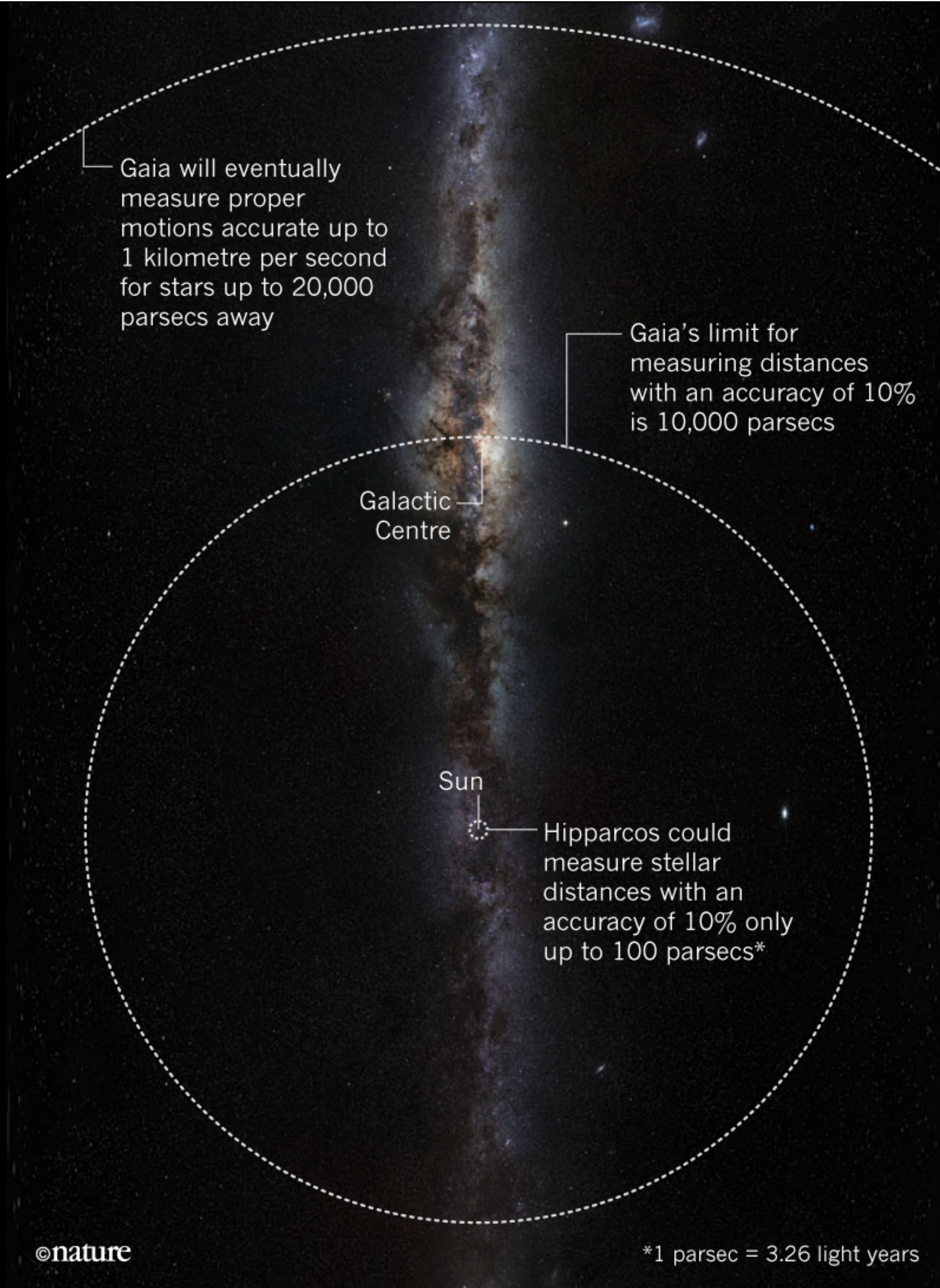
Gaia Collaboration [1804.09365]

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

Launched December 2013; second data release April 2018

Provides measurements for over a billion stars, ~1% of the Milky Way's stars

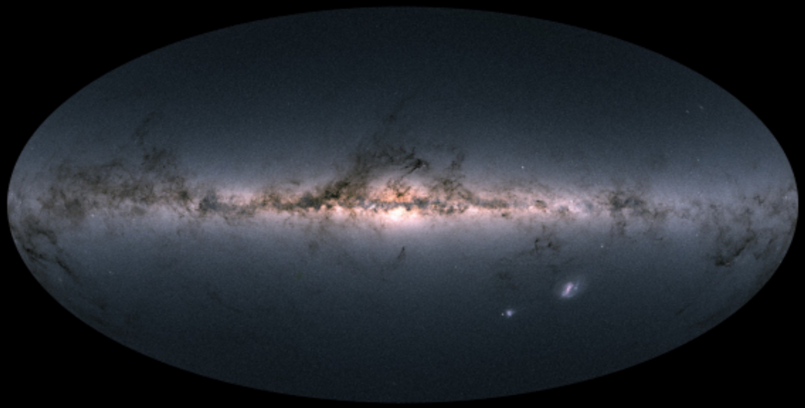



Gaia will eventually measure proper motions accurate up to 1 kilometre per second for stars up to 20,000 parsecs away
Gaia's limit for measuring distances with an accuracy of 10% is 10,000 parsecs
Galactic Centre
Sun
Hipparcos could measure stellar distances with an accuracy of 10% only up to 100 parsecs*
©nature
*1 parsec = 3.26 light years

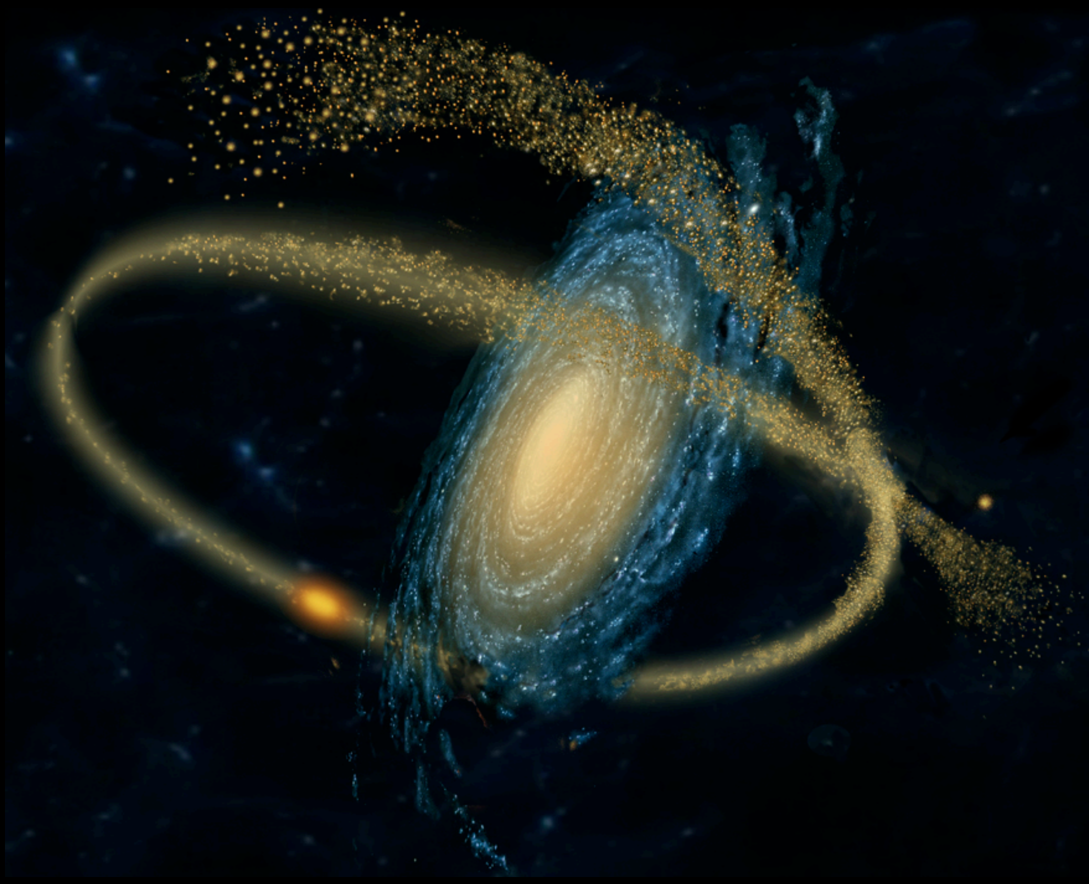
# Milky Way Archaeology

Geometry, Environment,
Radioactive Dating, …

# Milky Way Archaeology



Stellar Chemical Abundance,
Phase-space Distribution, …



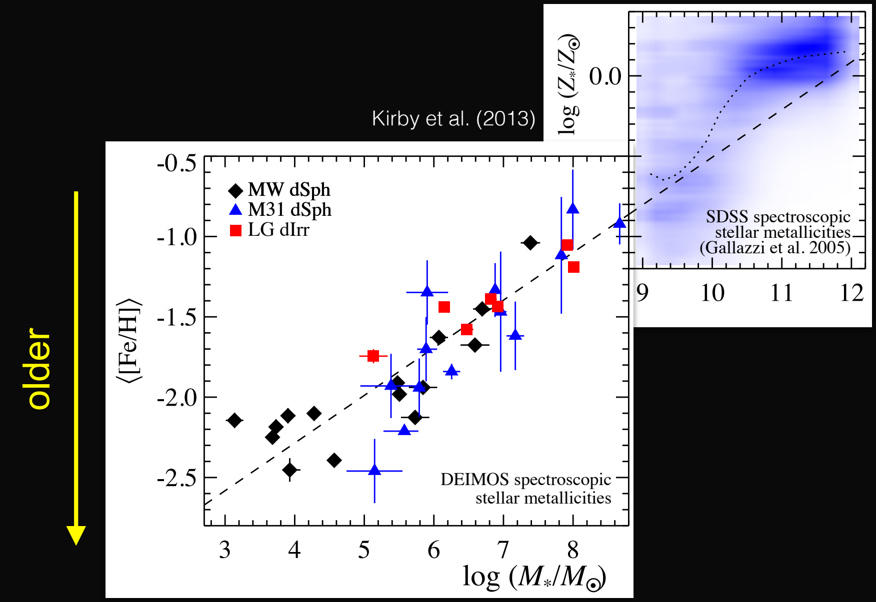
Images: ESA/Gaia/DPAC (left), John Lomberg (right)

# Metallicity

The average stellar metallicity of a satellite galaxy is correlated with its stellar mass

Link stars with similar chemical abundance to a parent satellite

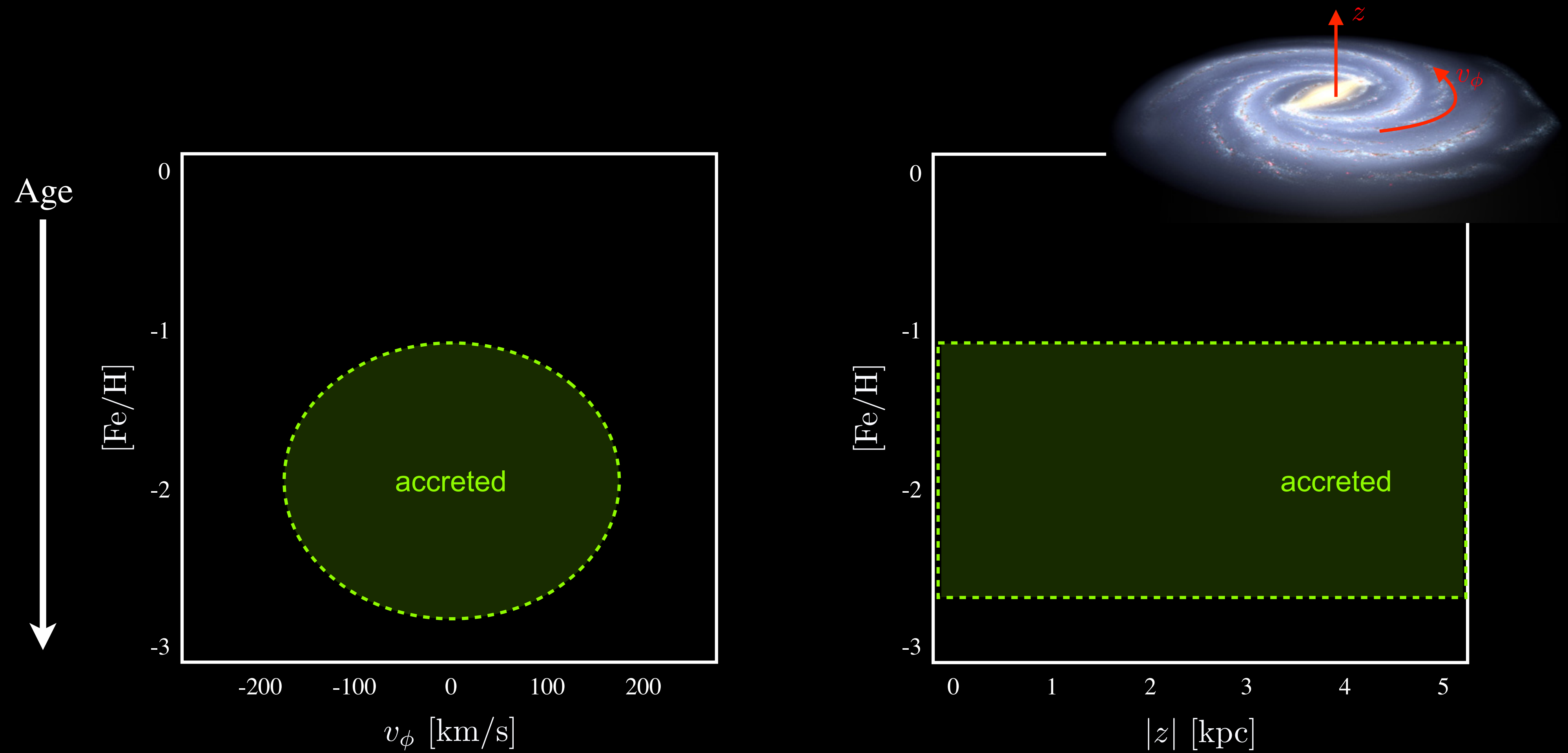

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right) - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\odot}$$



# Accreted Stars

Accreted stars are typically older than those born in the Milky Way disk

Their velocity and spatial distributions also differ from disk stars




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

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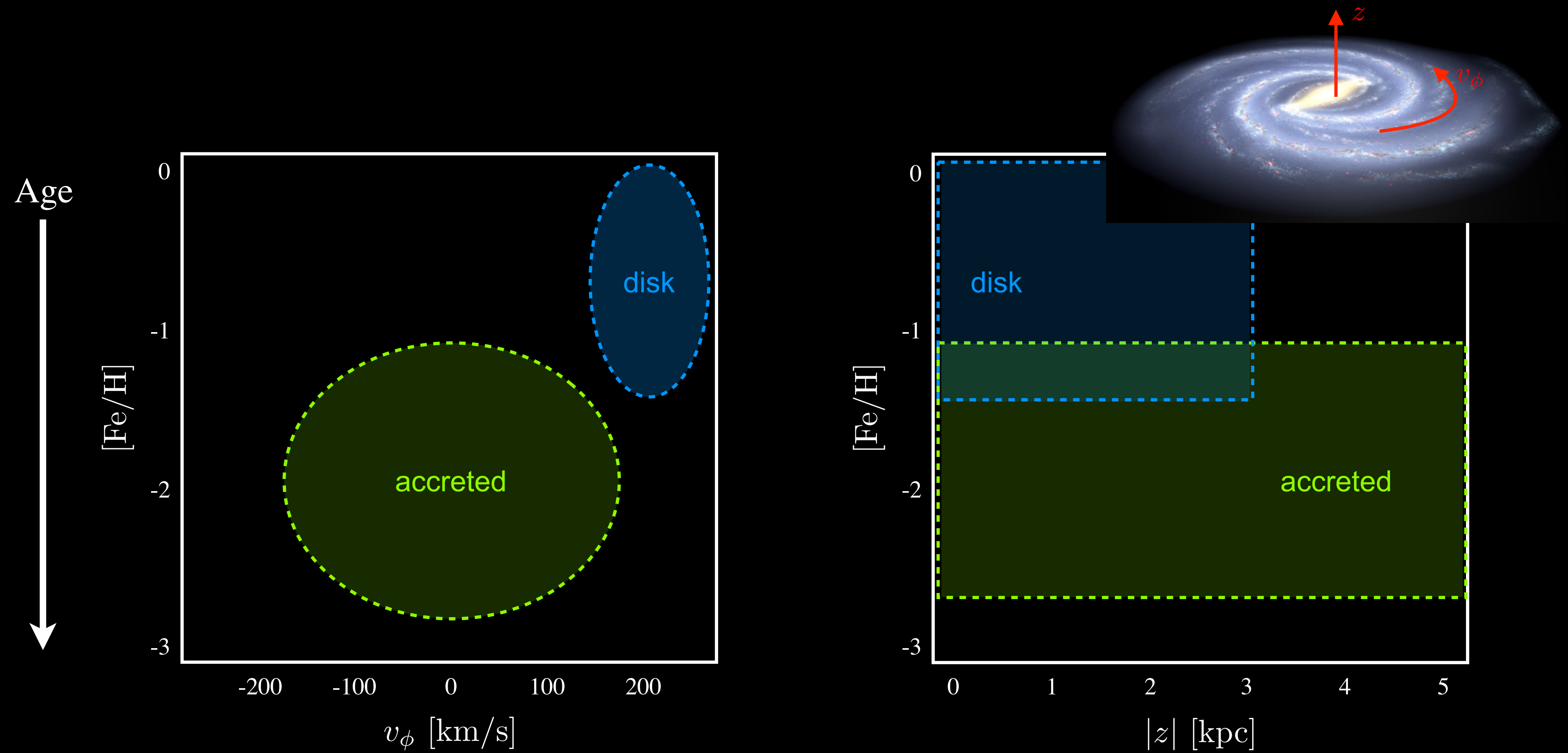


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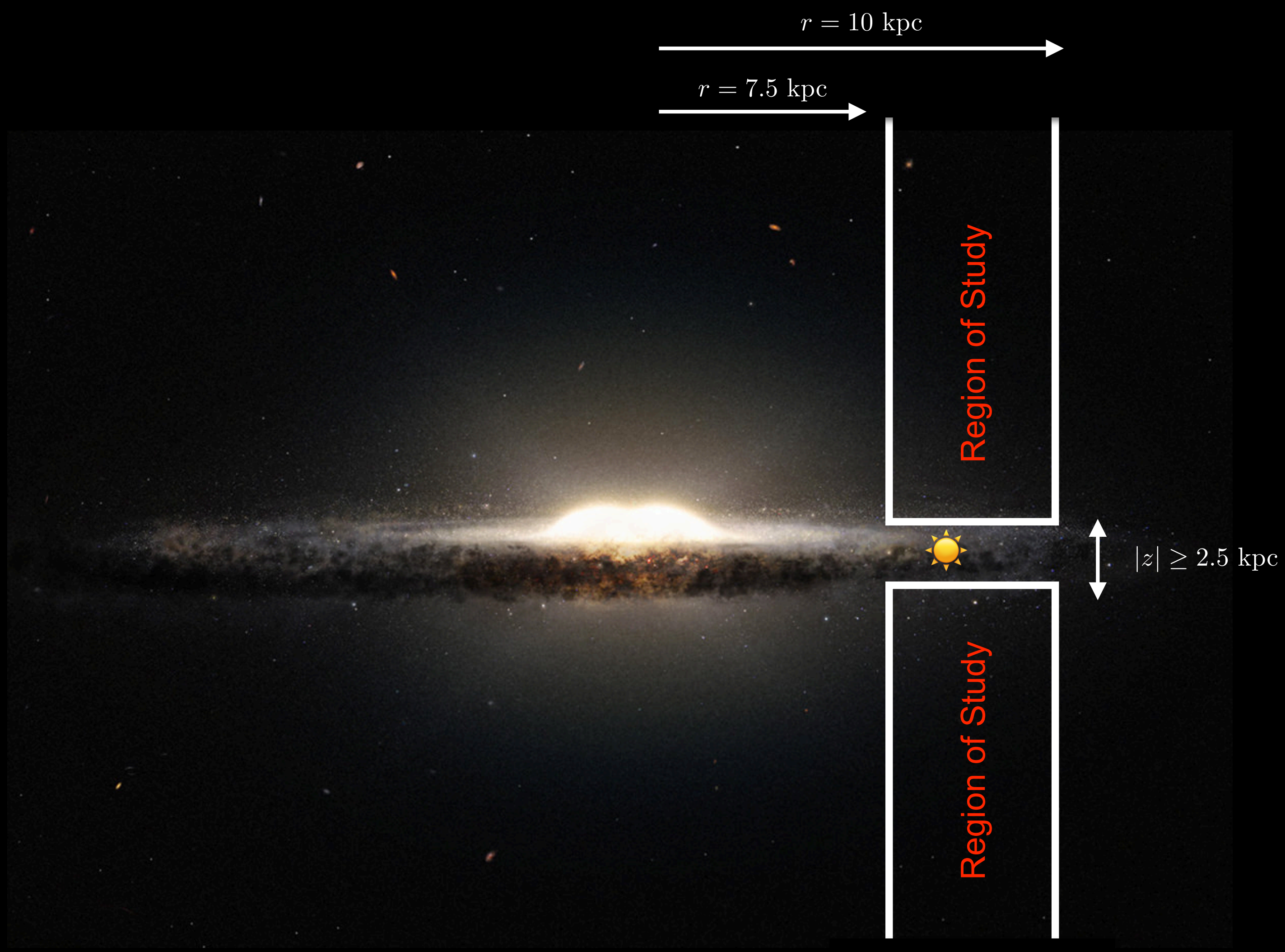
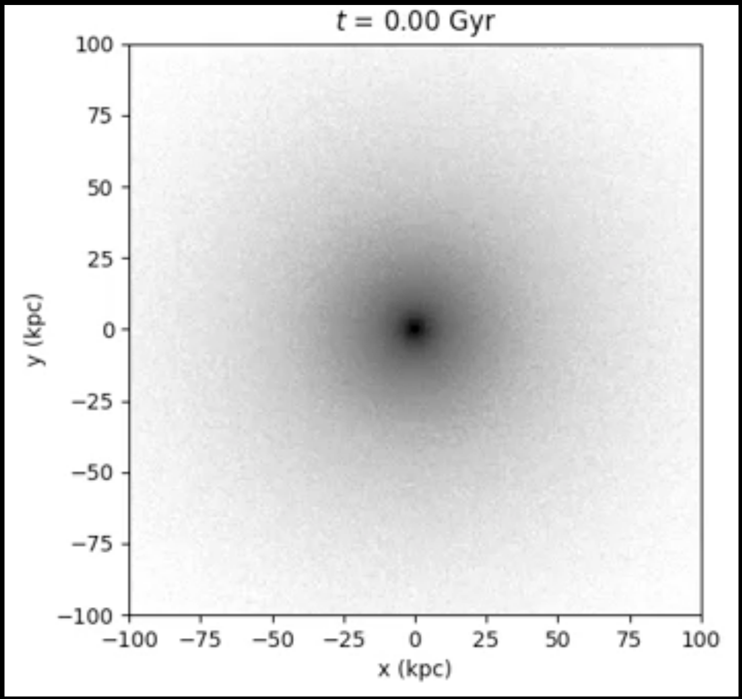
# The Local Neighborhood



# The *Gaia* Sausage

Accreted stellar population is dominated by the debris of a single large merger

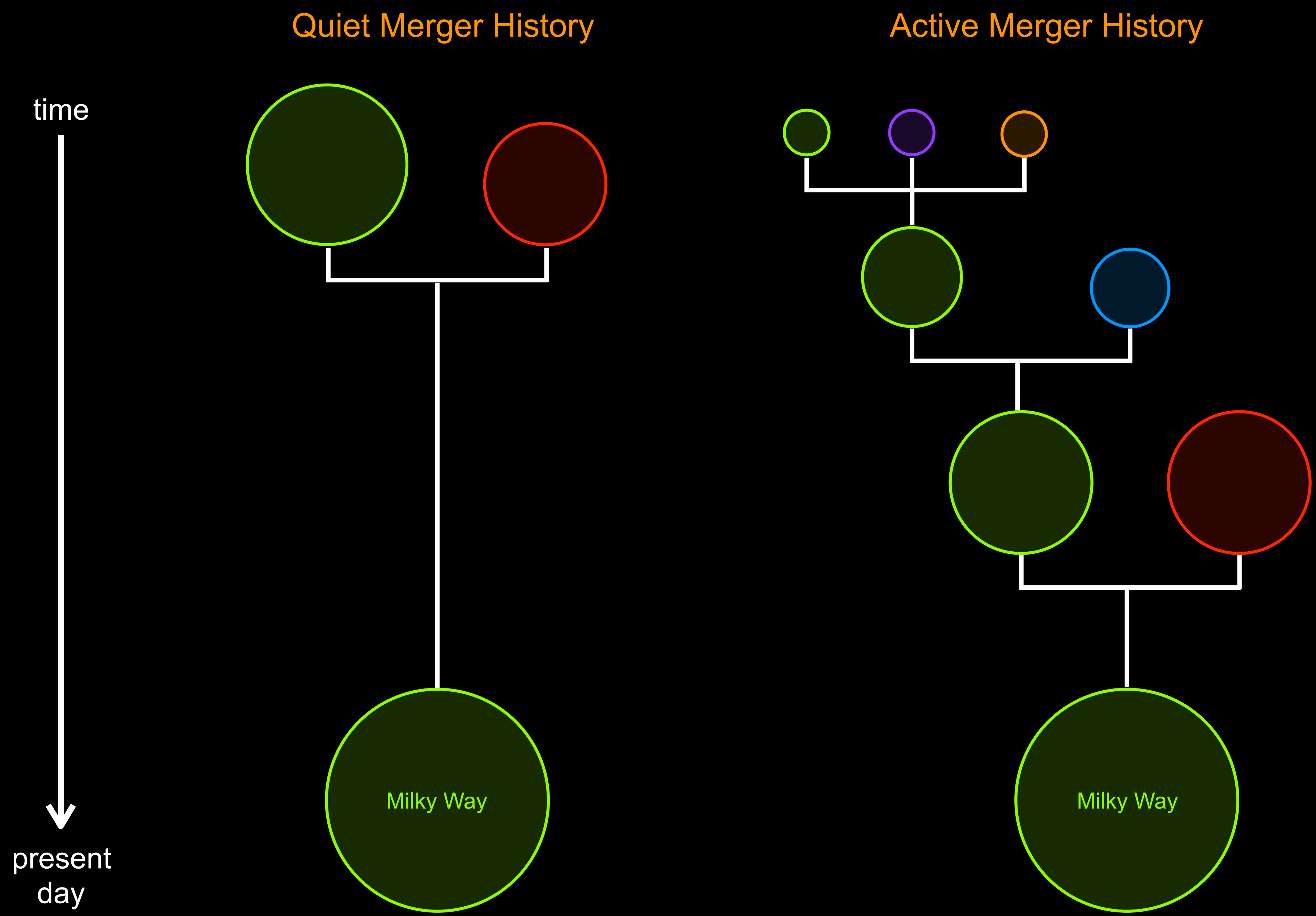
Gray: Milky Way stars     Red: Accreted stars




Video: Denis Erkal

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

# The Local Milky Way's Family Tree



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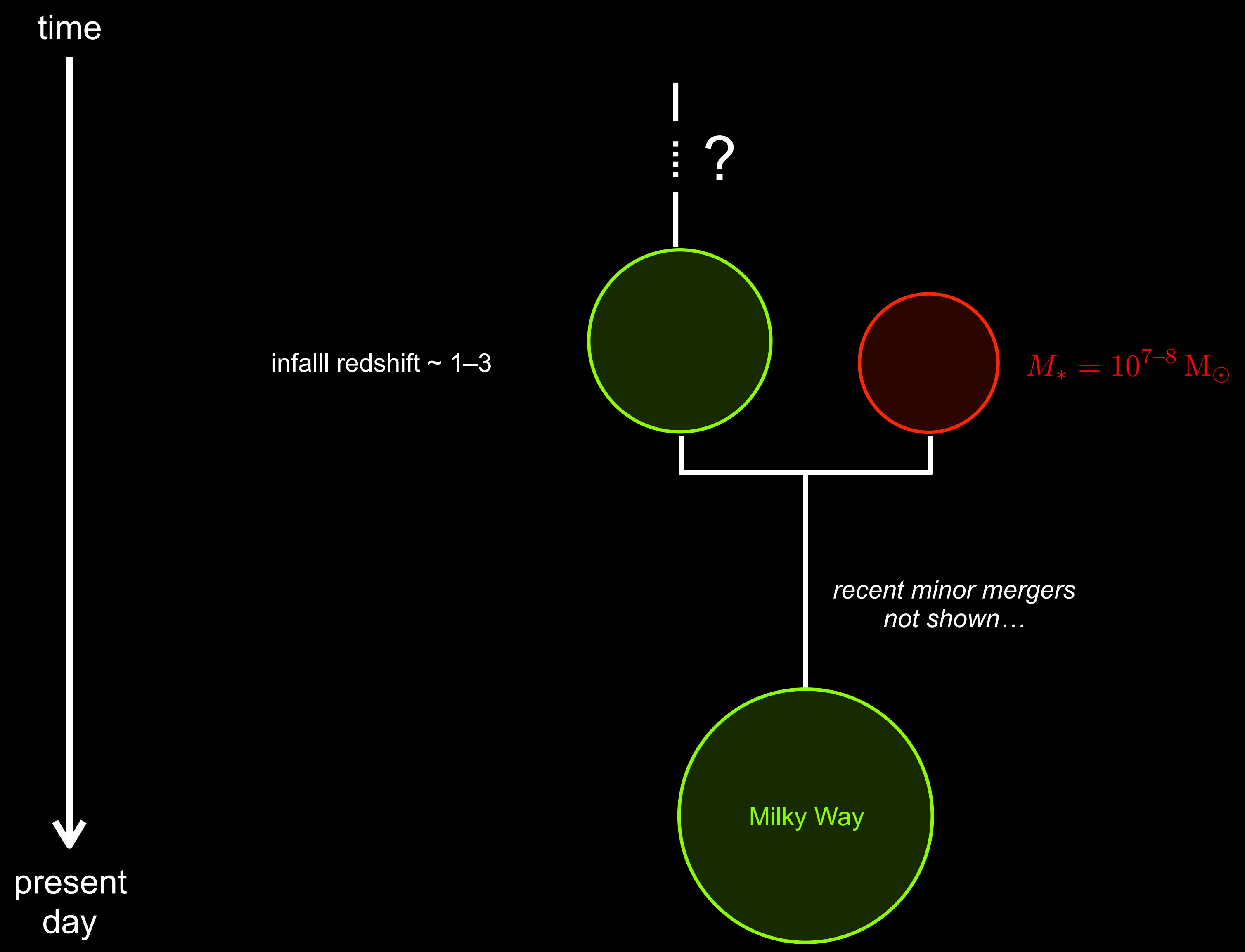

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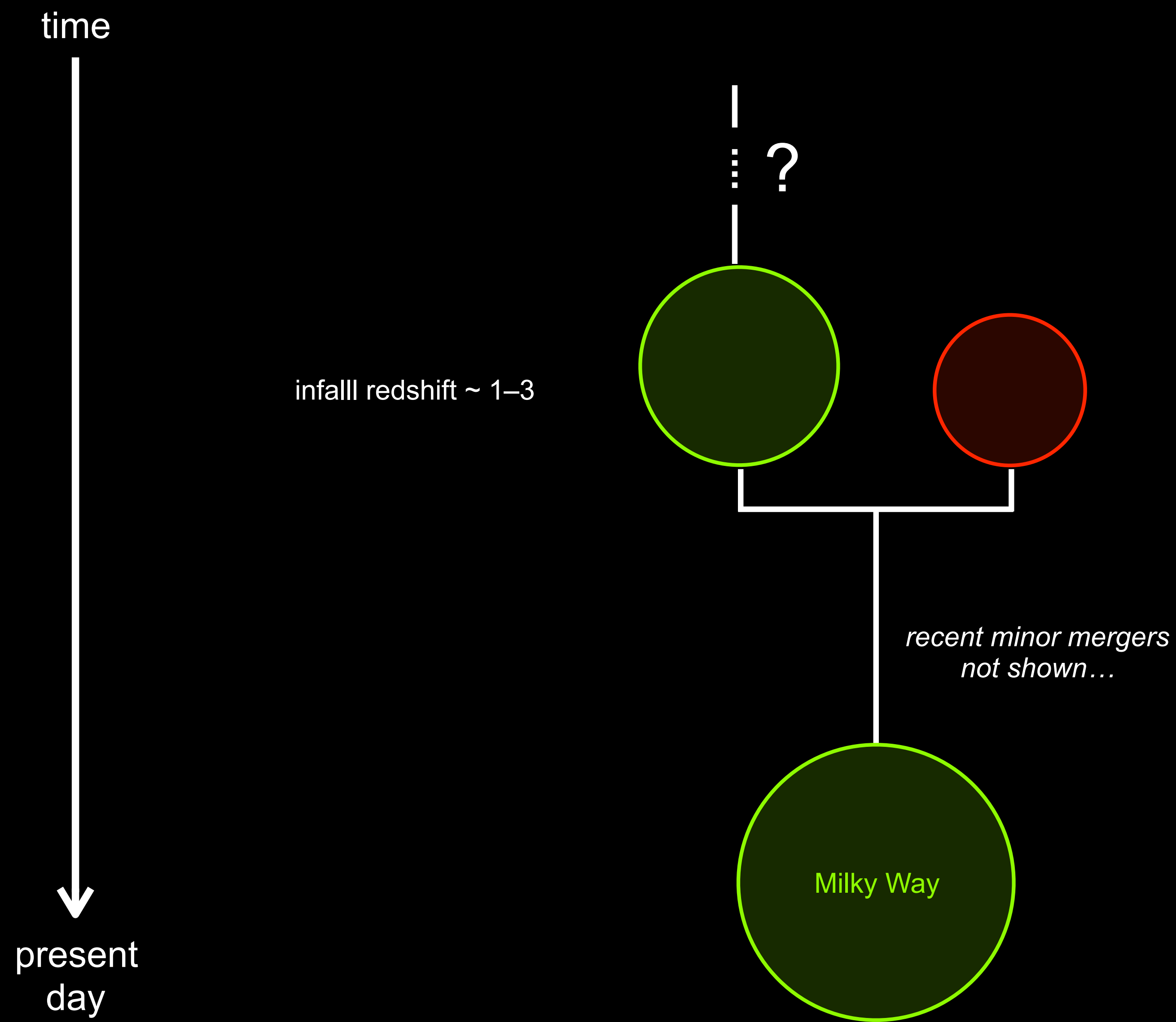



# Dark Matter, All Mixed Up

Necib, **ML**, and Belokurov [1807.02519]

Revisit assumptions about the dark matter distribution in light of new results from *Gaia*

Need to separate the following stellar populations:

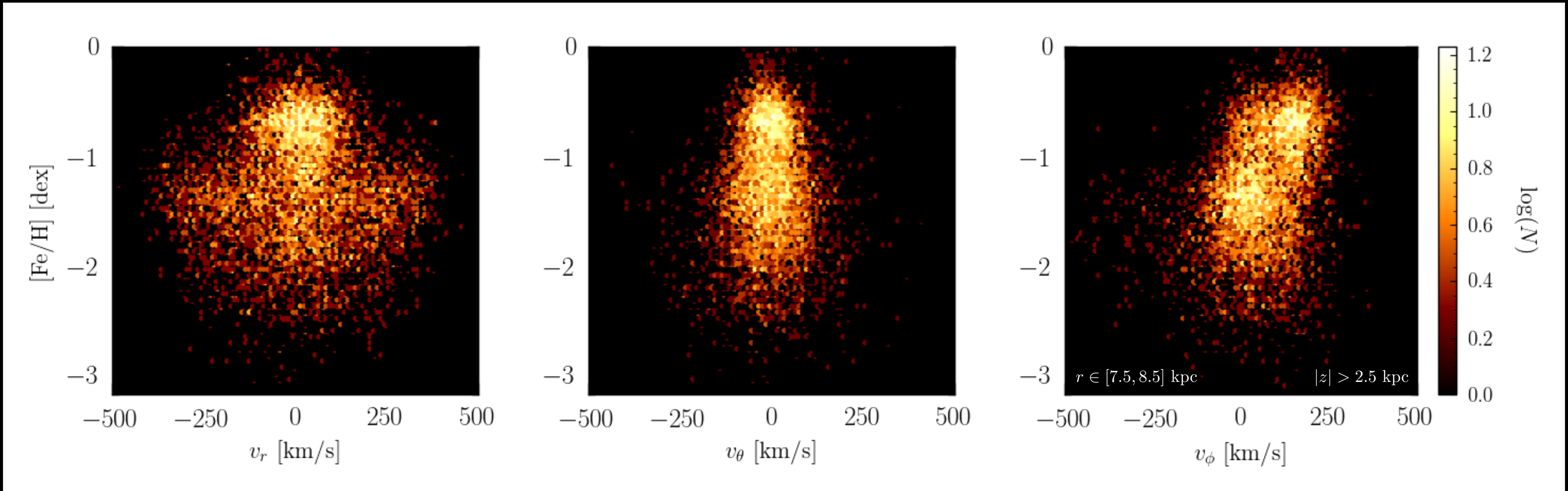
Disk stars

*unrelated to dark matter*

Accreted stars

*trace dark matter halo & substructure*

SDSS-*Gaia* DR2 cross-match



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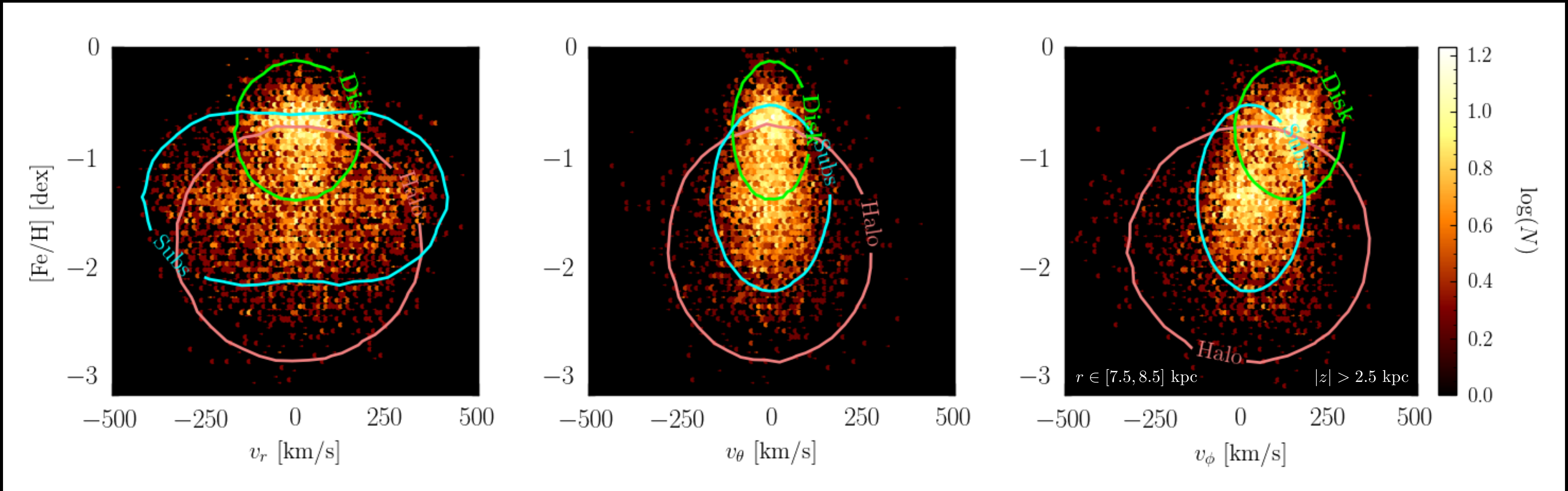
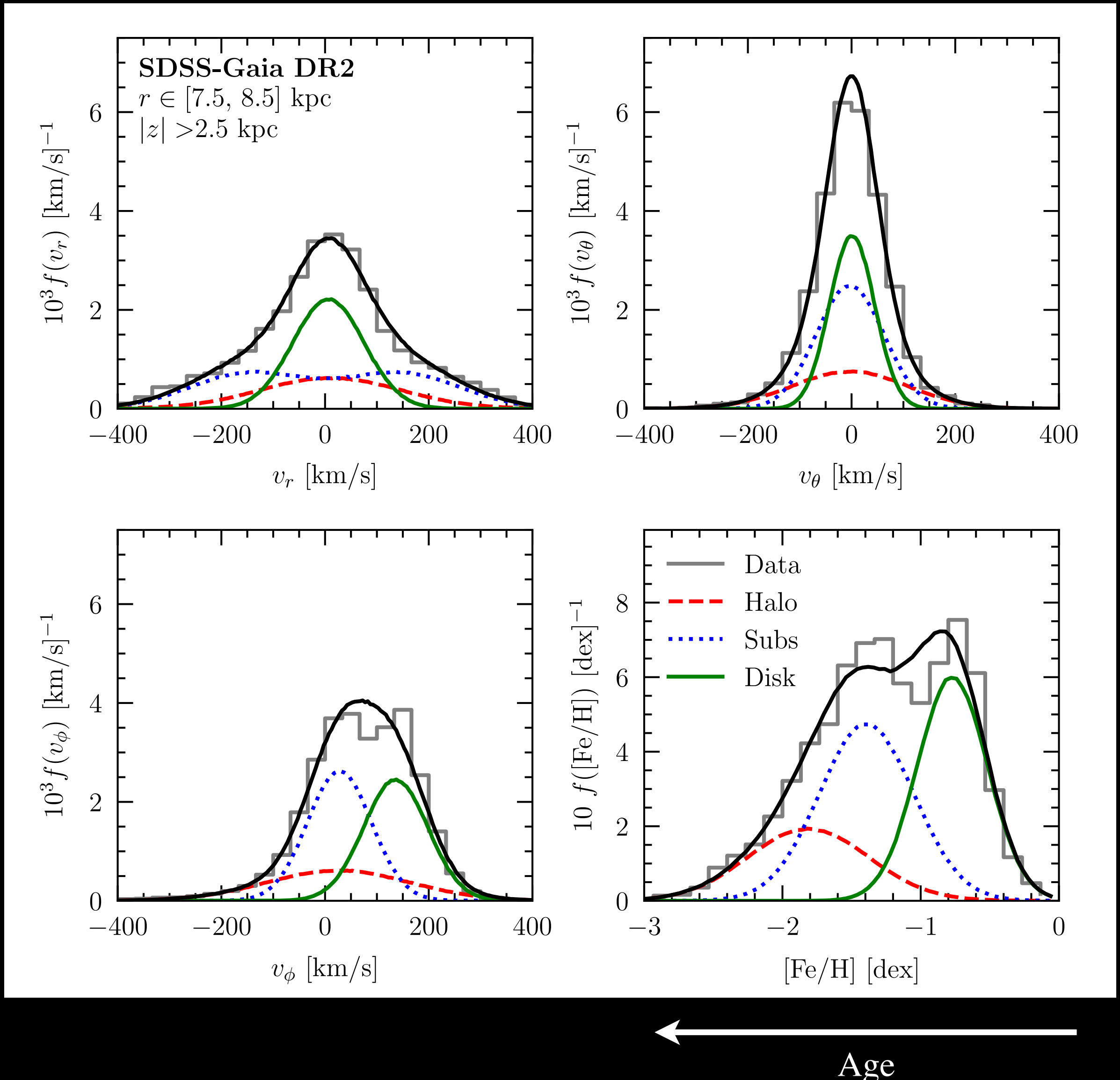


# A Story of Three Populations

Necib, **ML**, and Belokurov [1807.02519]



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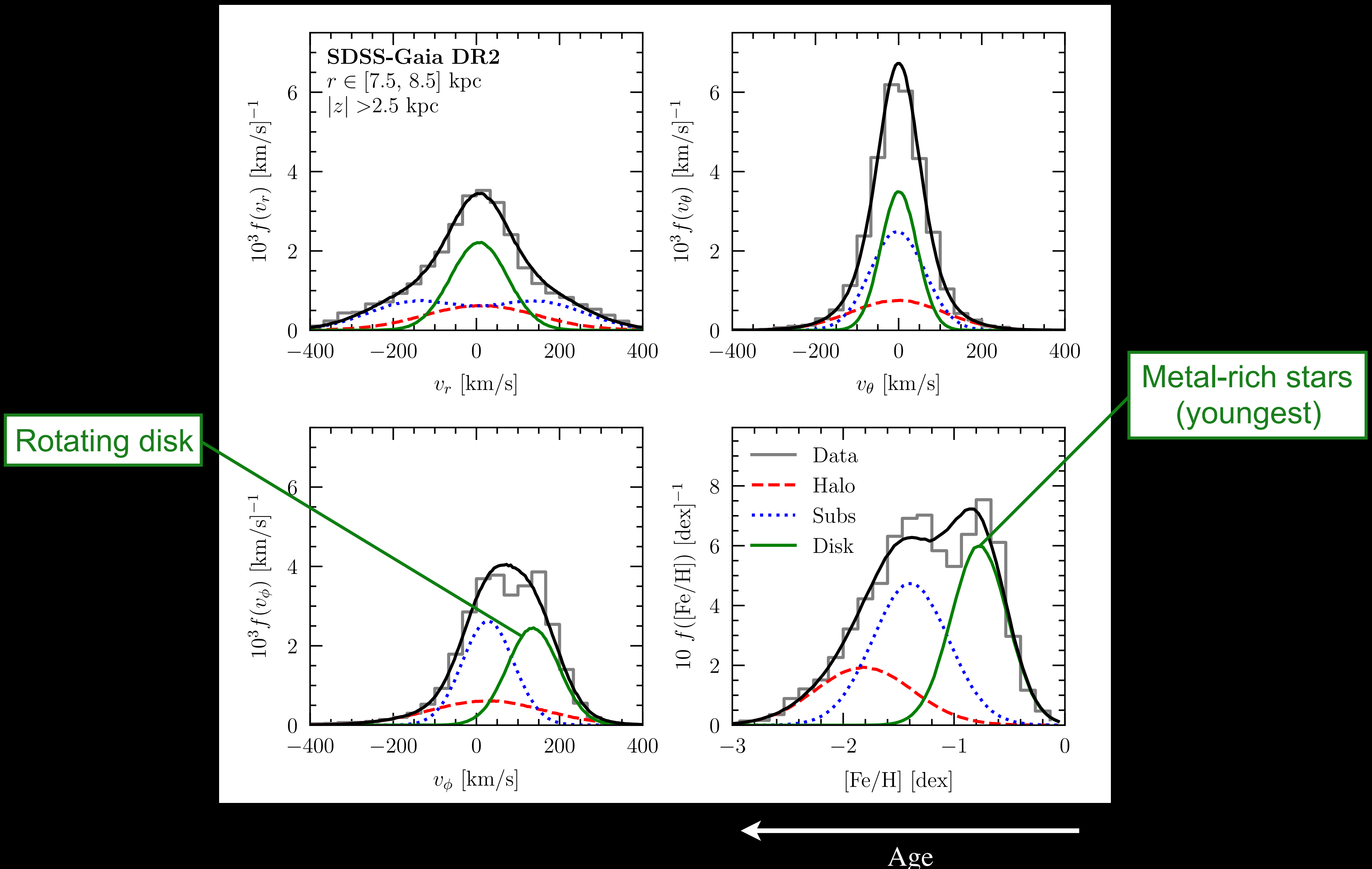

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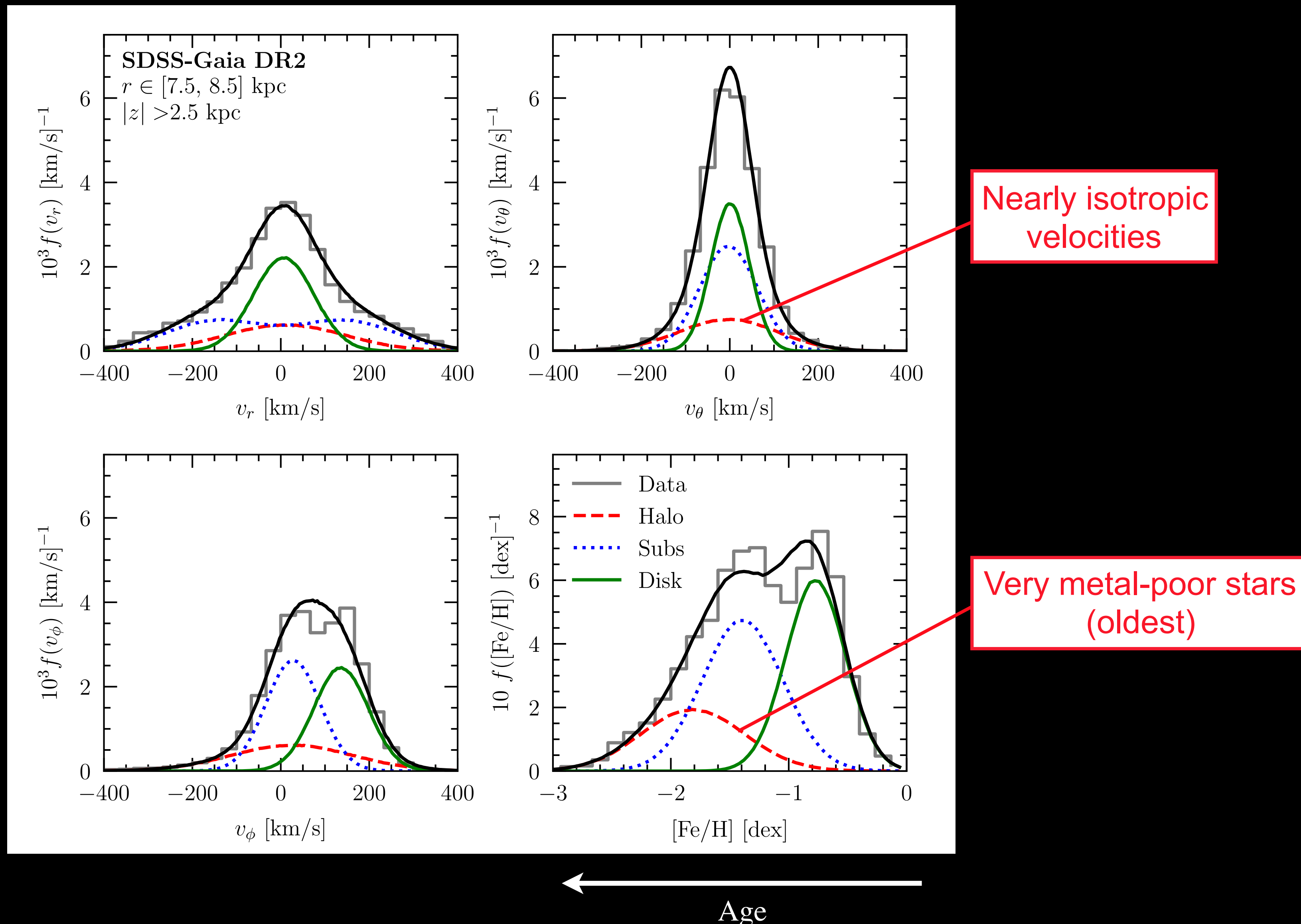

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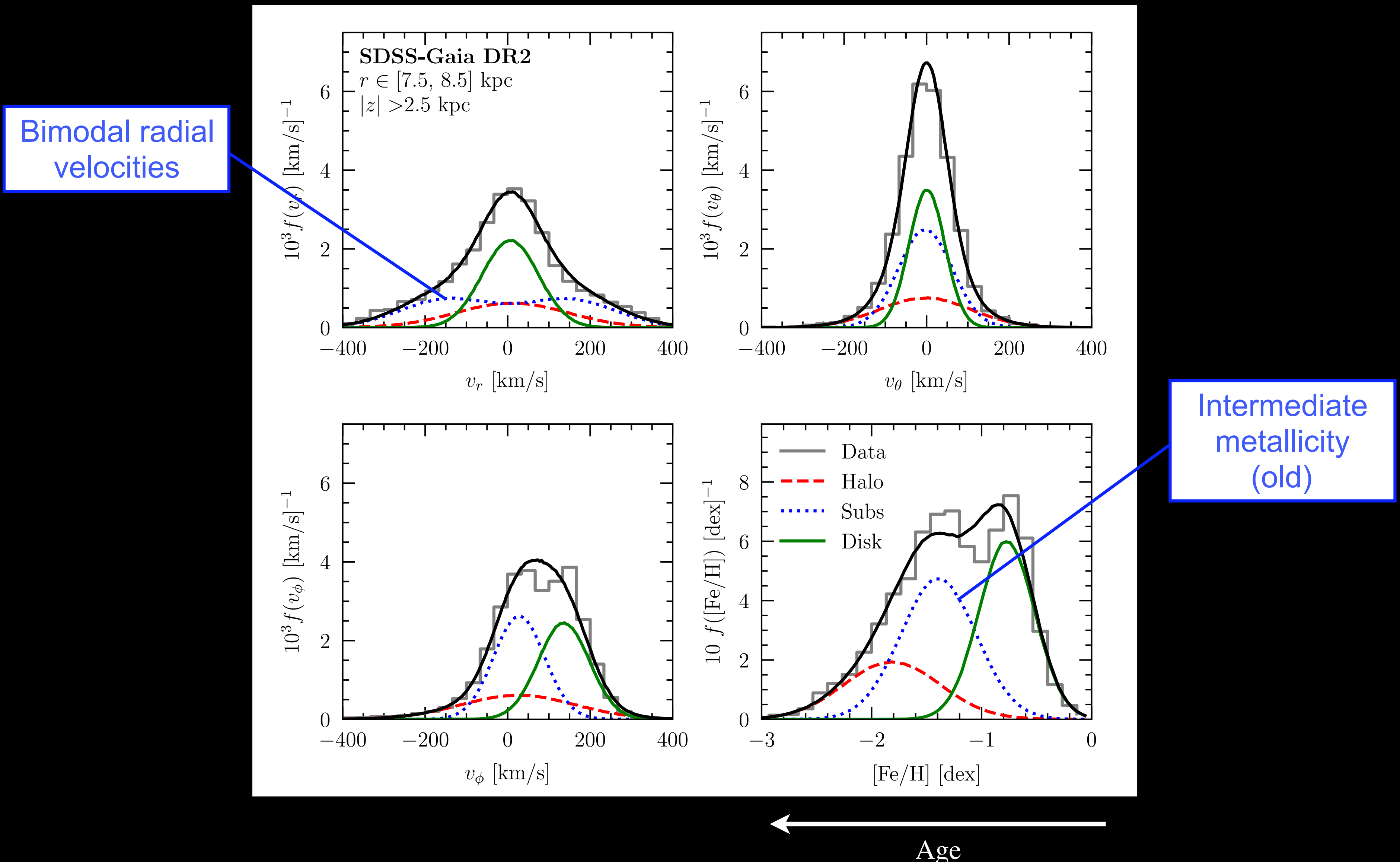
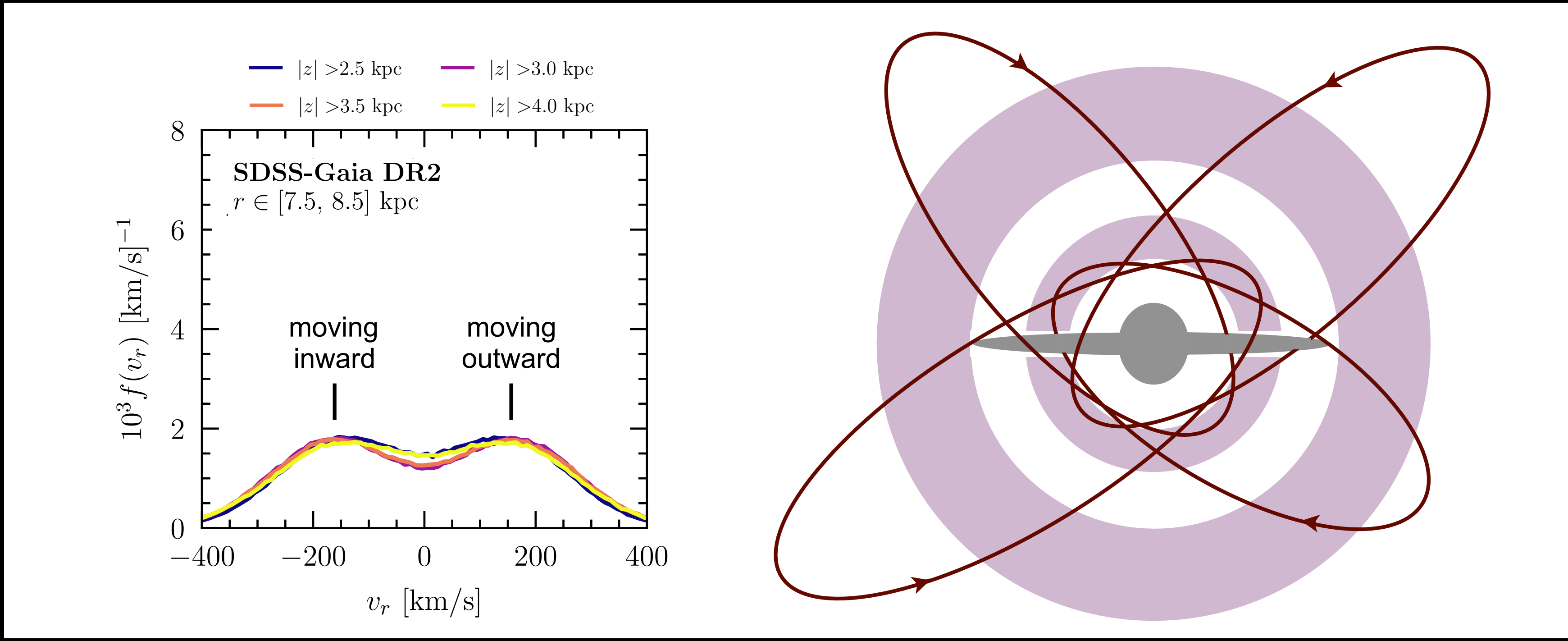


# Radial Velocity Distribution

Necib, **ML**, and Belokurov [1807.02519]

Radial lobes correspond to debris stripped from satellite as it moves towards/away from the Galactic Center

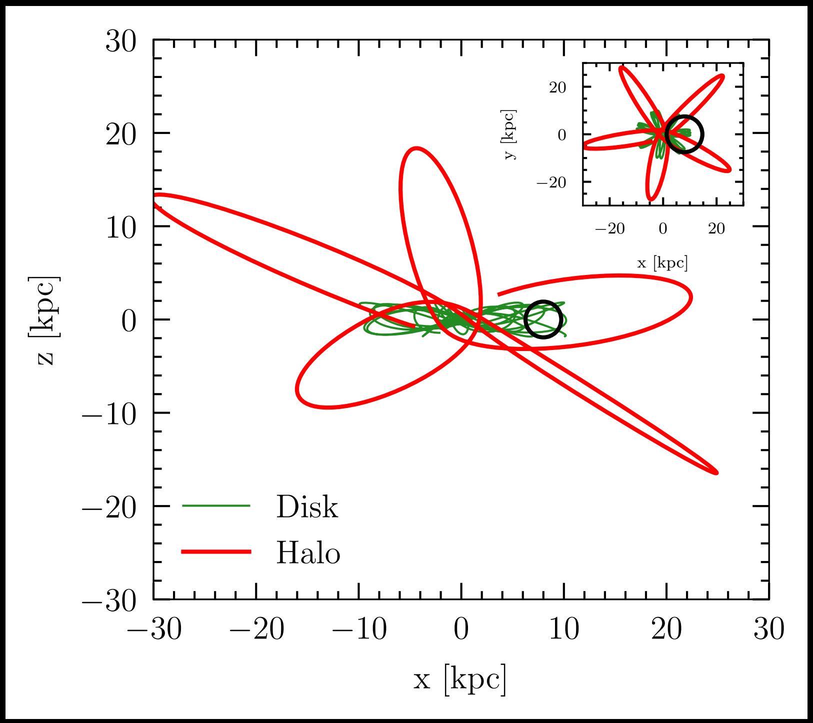
Halo and substructure exhibit no spatial features within region studied

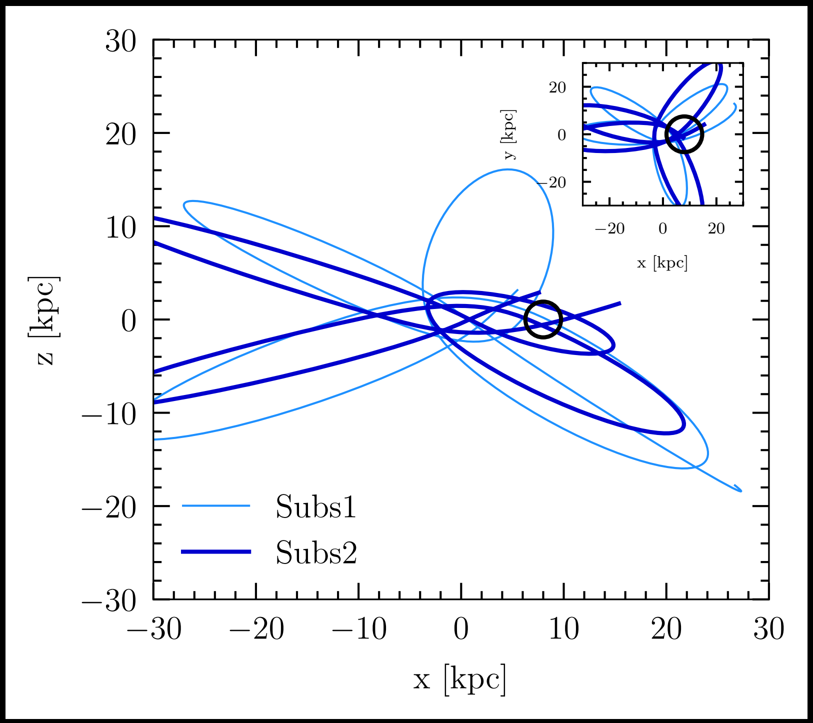


# Example Stellar Orbits

Necib, **ML**, and Belokurov [1807.02519]

Orbits of the disk, halo, and substructure stars look quite different

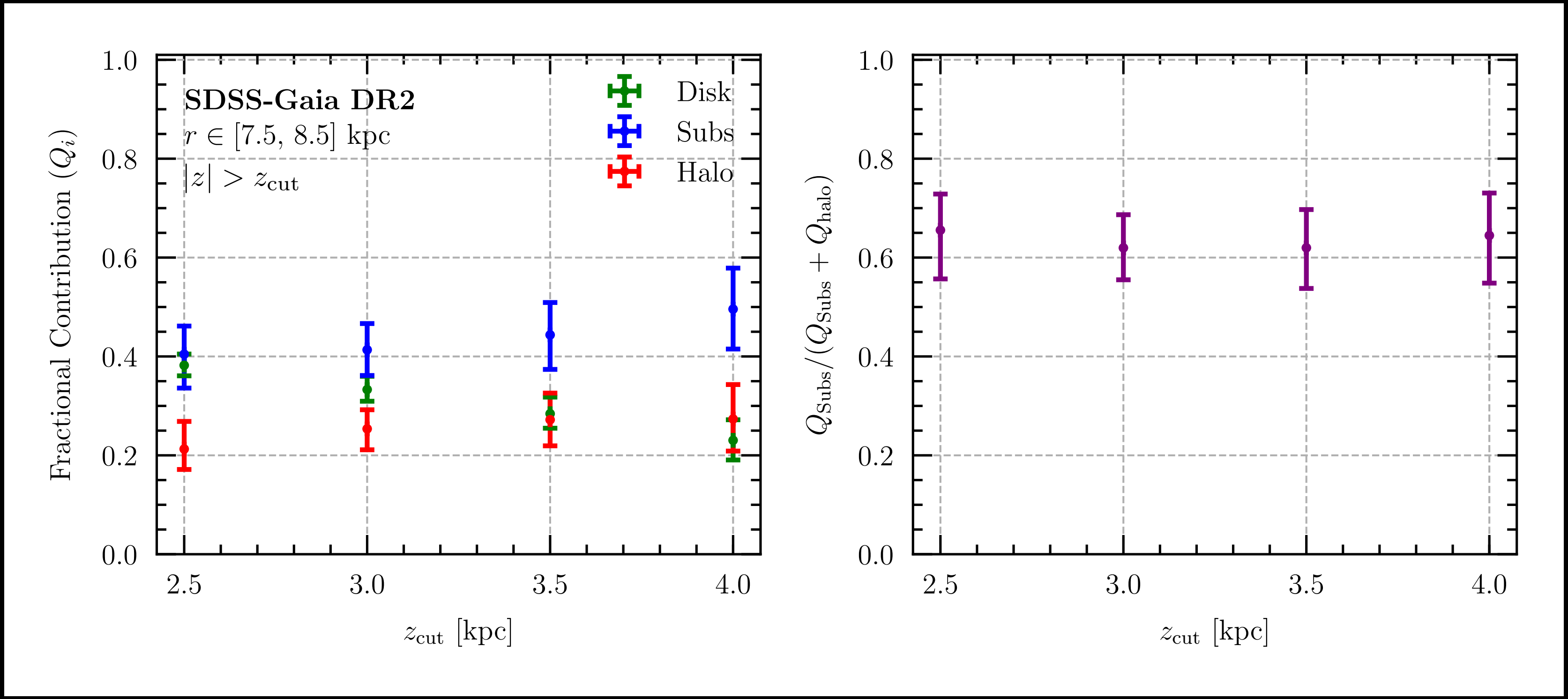


# Not that 'Sub' of a Structure

Necib, **ML**, and Belokurov [1807.02519]

Substructure comprises approximately ~60% of the accreted stellar population

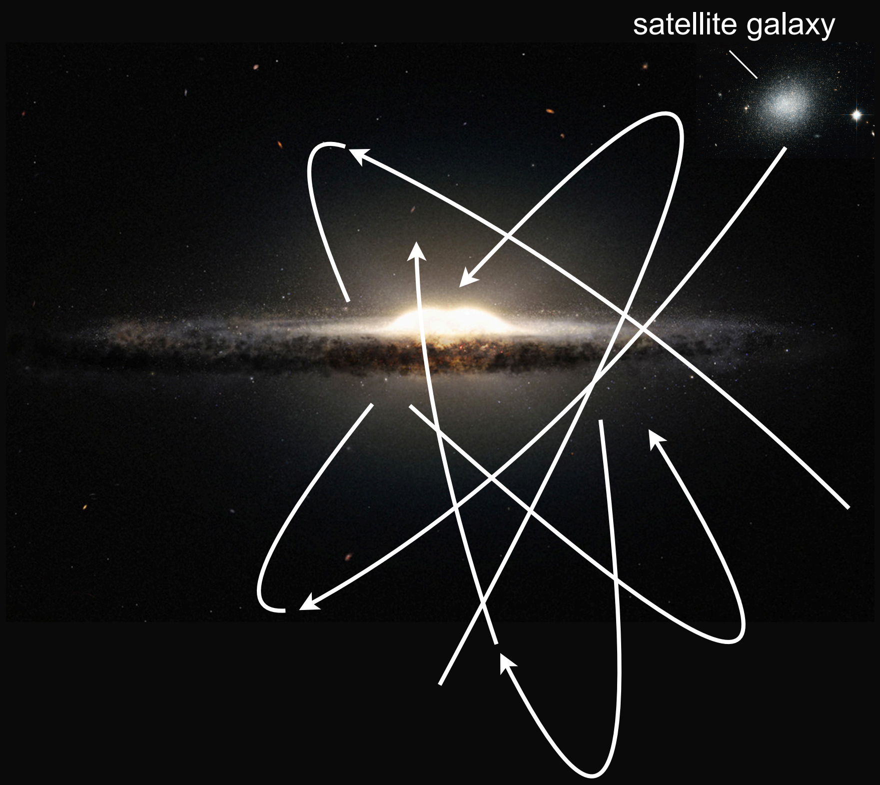


# Dark Matter Implications

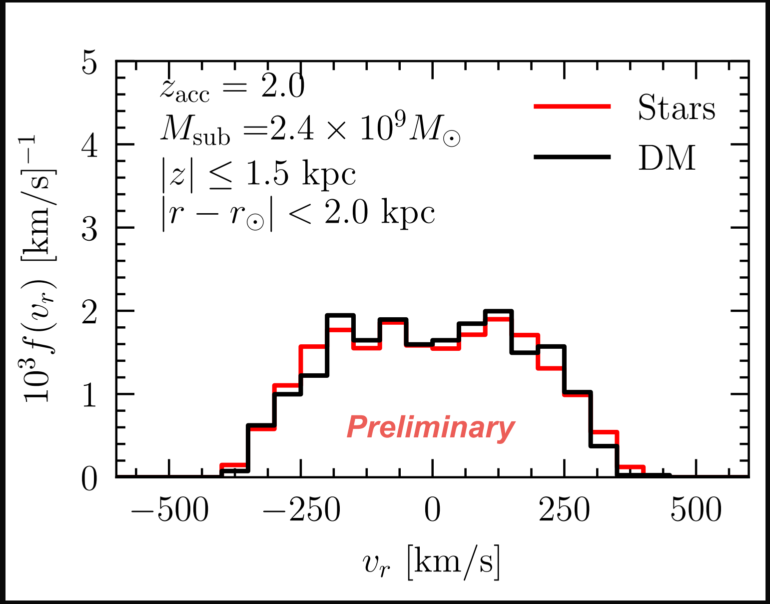
# The Old Debris Flow

Stellar debris from older mergers tracks the dark matter very well

Okay to infer dark matter distribution from observed stellar debris flow




FIRE Simulation (m12i)



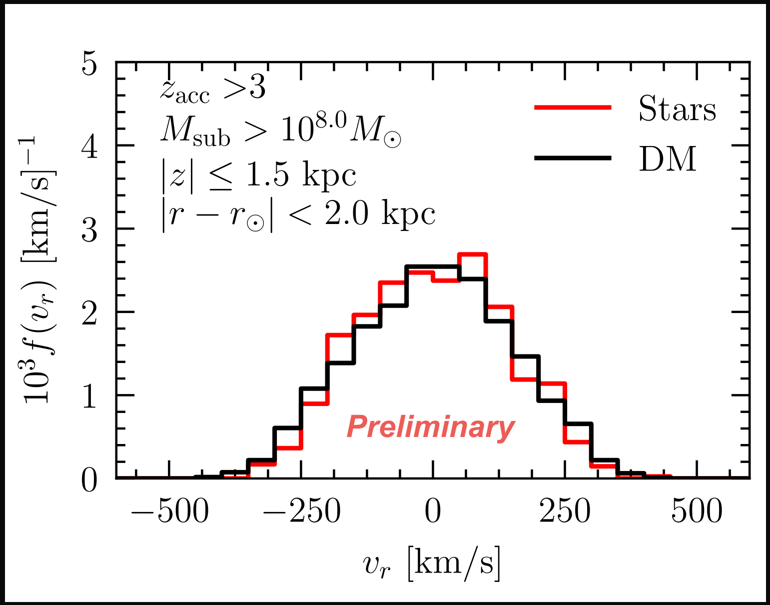

Necib, **ML**, Garisson-Kimmel, et al. (2018) in prep.

# The Very Old Halo

The stellar halo traces the virialized dark matter halo
…rather miraculous given that this sums over *all* the early accretion events

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

FIRE Simulation (m12i)

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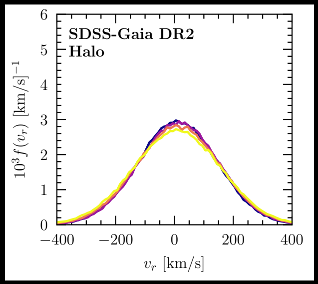
# Putting it All Together

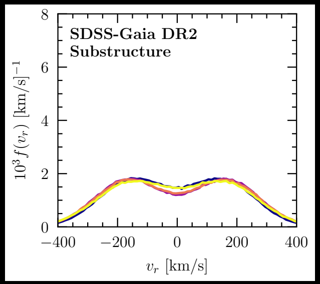
Local Accreted Stars = 0.4 · 

Halo




+ 0.6 ·

Debris Flow



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Halo

Debris Flow

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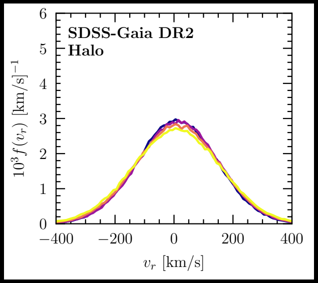
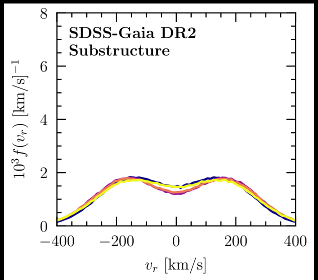
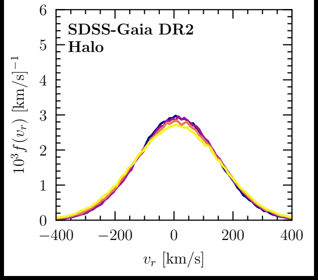



\+ 0.6 ·

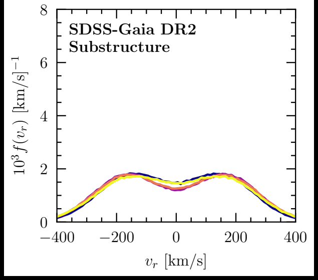



Dark Matter-Stellar Correlation

Local Dark Matter = 0.4 $f_h$ ·




\+ 0.6 $f_s$ ·

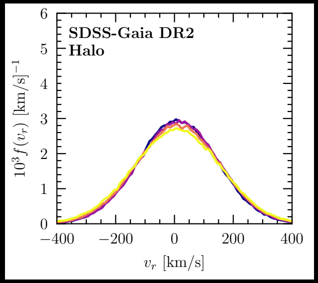



$f_{h,s}$ are order-1 factors that account for different mass-to-light ratios of satellites

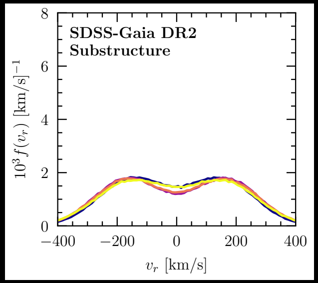
# Putting it All Together

**Halo** | **Debris Flow**

Local Accreted Stars = 0.4 ·




\+ 0.6 ·

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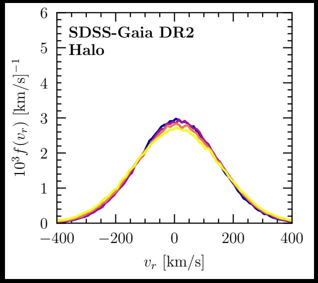
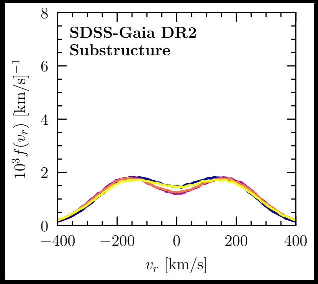



\+ $0.6\, f_s$ ·



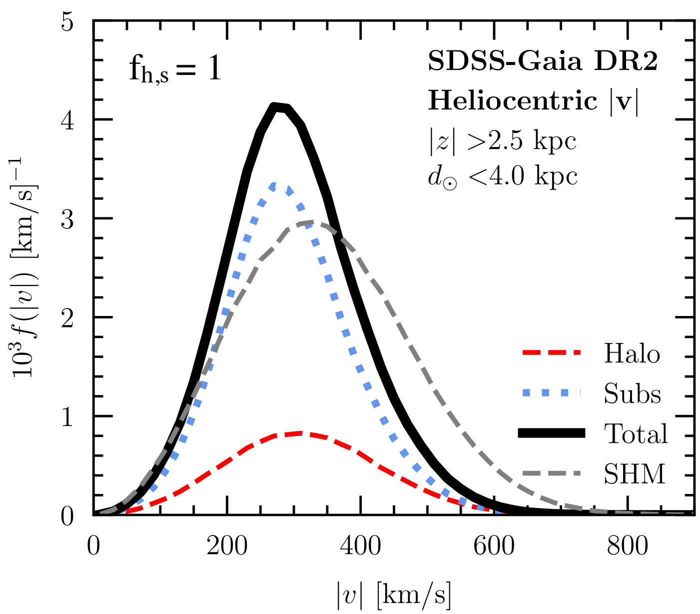

(+ dark subhalo contribution?)

$f_{h,s}$ are order-1 factors that account for different mass-to-light ratios of satellites

# Direct Detection Implications

Necib, **ML**, and Belokurov [1807.02519]

Non-trivial fraction of the local dark matter distribution is in substructure, potentially reducing sensitive to low-mass dark matter



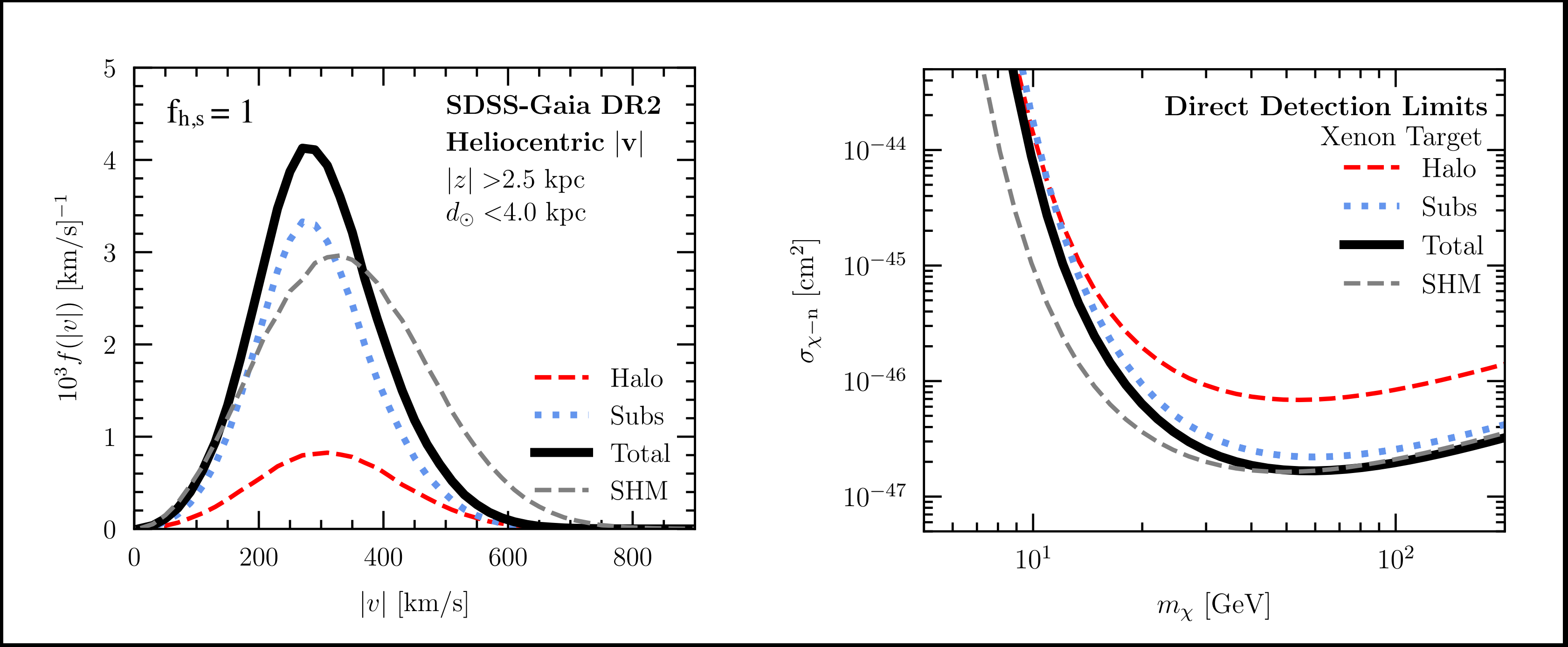

Interpolated distributions can be found at

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

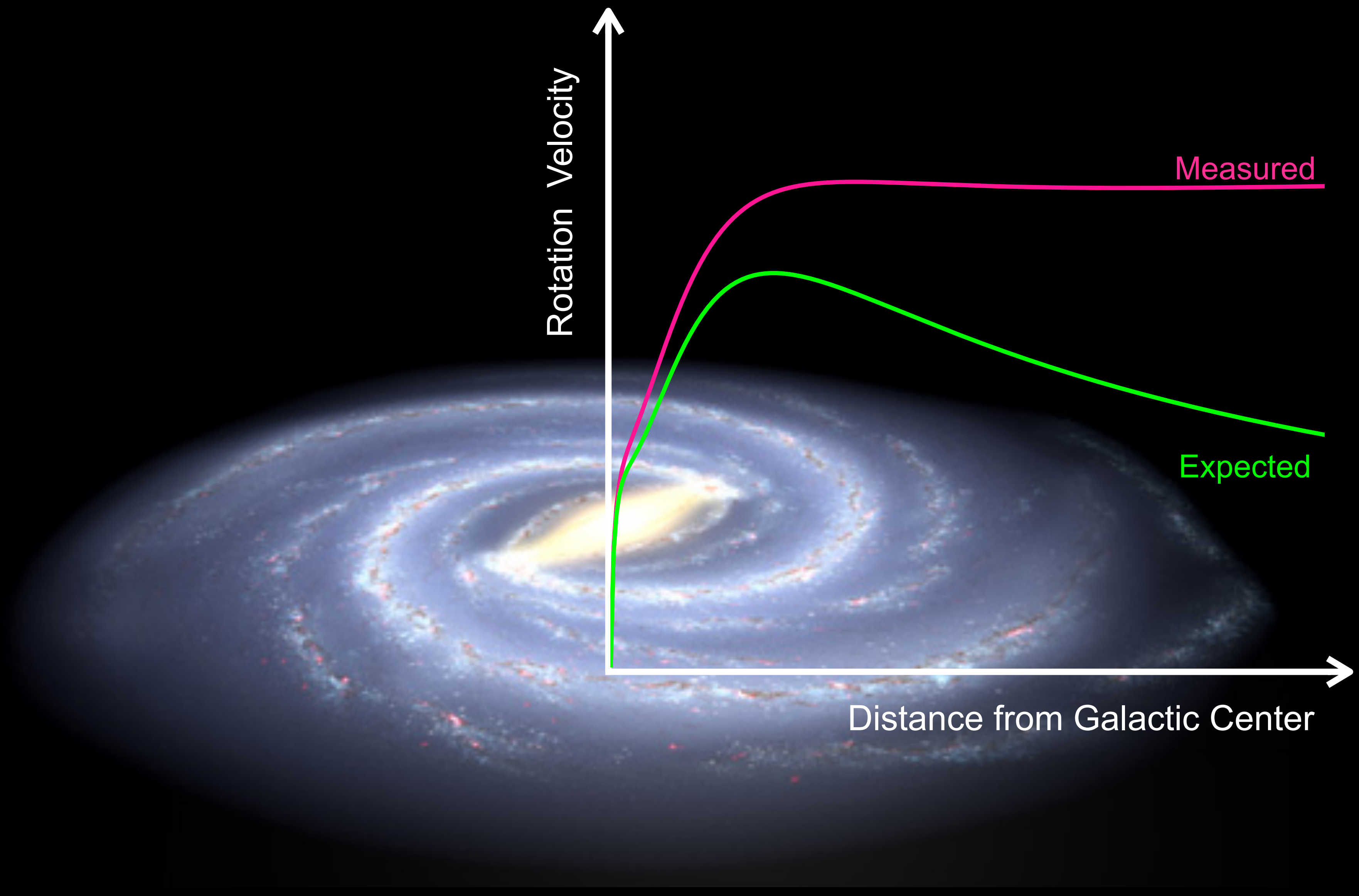
# Direct Detection Implications

Necib, **ML**, and Belokurov [1807.02519]

Non-trivial fraction of the local dark matter distribution is in substructure, potentially reducing sensitive to low-mass dark matter



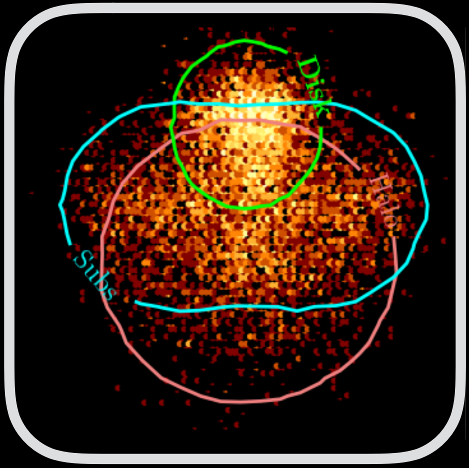
# The Dark Matter Halo v2.0

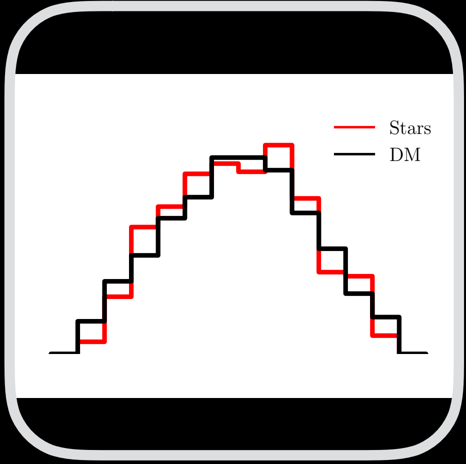


# The Dark Matter Halo v2.0

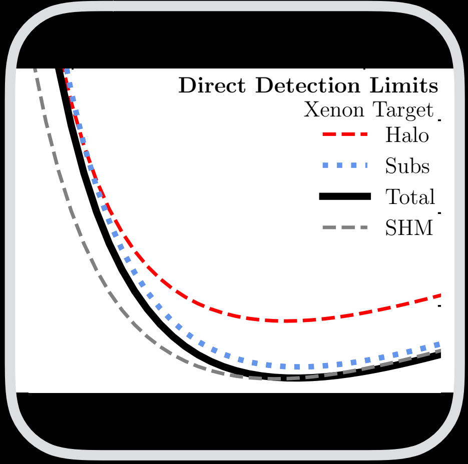
Closest relative discovered

Lots of stellar substructure



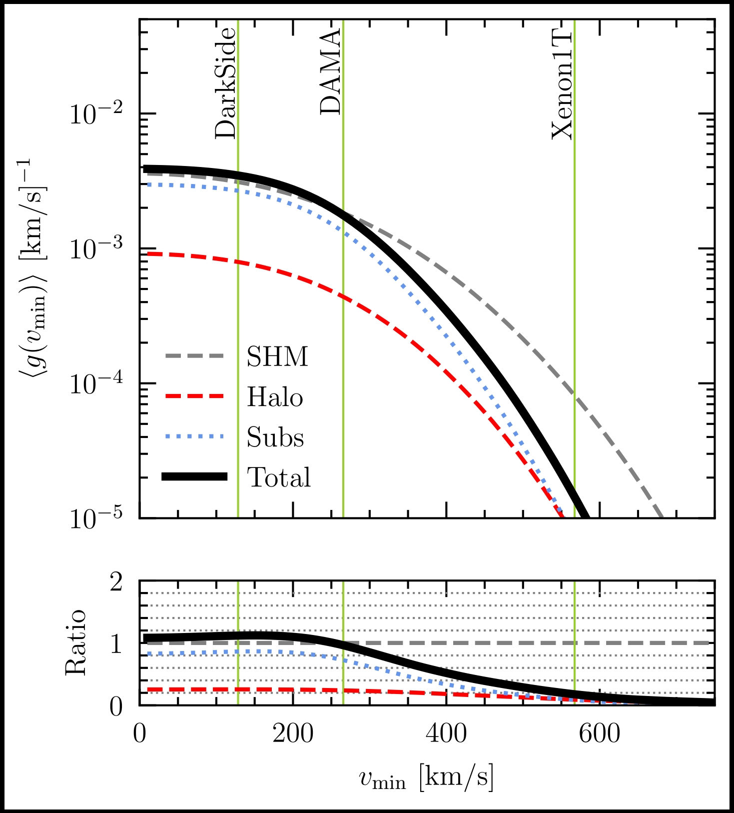

Infer local dark matter distribution

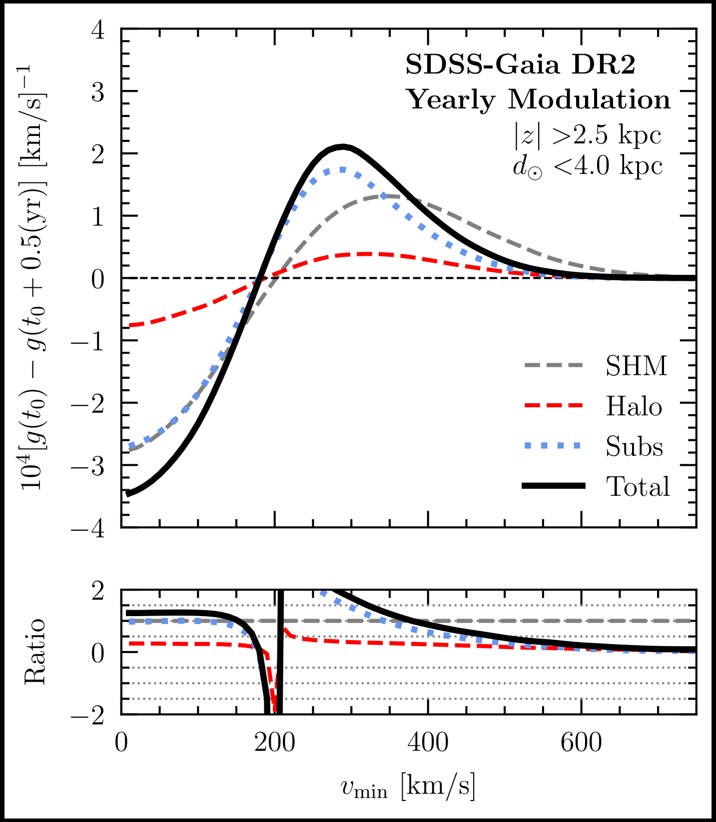



Challenge the Standard Halo Model

Backup Slides

# Direct Detection Implications



# The Likelihood

**Disk/Halo**

$$p_d\left(O_i \,|\, \theta\right) = \mathcal{N}\left(\mathbf{v}_i \,|\, \boldsymbol{\mu}^d, \boldsymbol{\Sigma}_i^d\right) \mathcal{N}\left([\mathrm{Fe/H}]_i \,|\, \mu^d_{[\mathrm{Fe/H}]}, \sigma^d_{[\mathrm{Fe/H}],i}\right)$$

**Substructure**

$$p_s\left(O_i \,|\, \theta\right) = \frac{1}{2}\left[\mathcal{N}\left(\mathbf{v}_i | \boldsymbol{\mu}^{\tilde{s}}, \boldsymbol{\Sigma}_i^s\right) + \mathcal{N}\left(\mathbf{v}_i | \boldsymbol{\mu}^s, \boldsymbol{\Sigma}_i^s\right)\right] \times \mathcal{N}\left([\mathrm{Fe/H}]_i \,|\, \mu^s_{[\mathrm{Fe/H}]}, \sigma^s_{[\mathrm{Fe/H}],i}\right)$$

**Total**

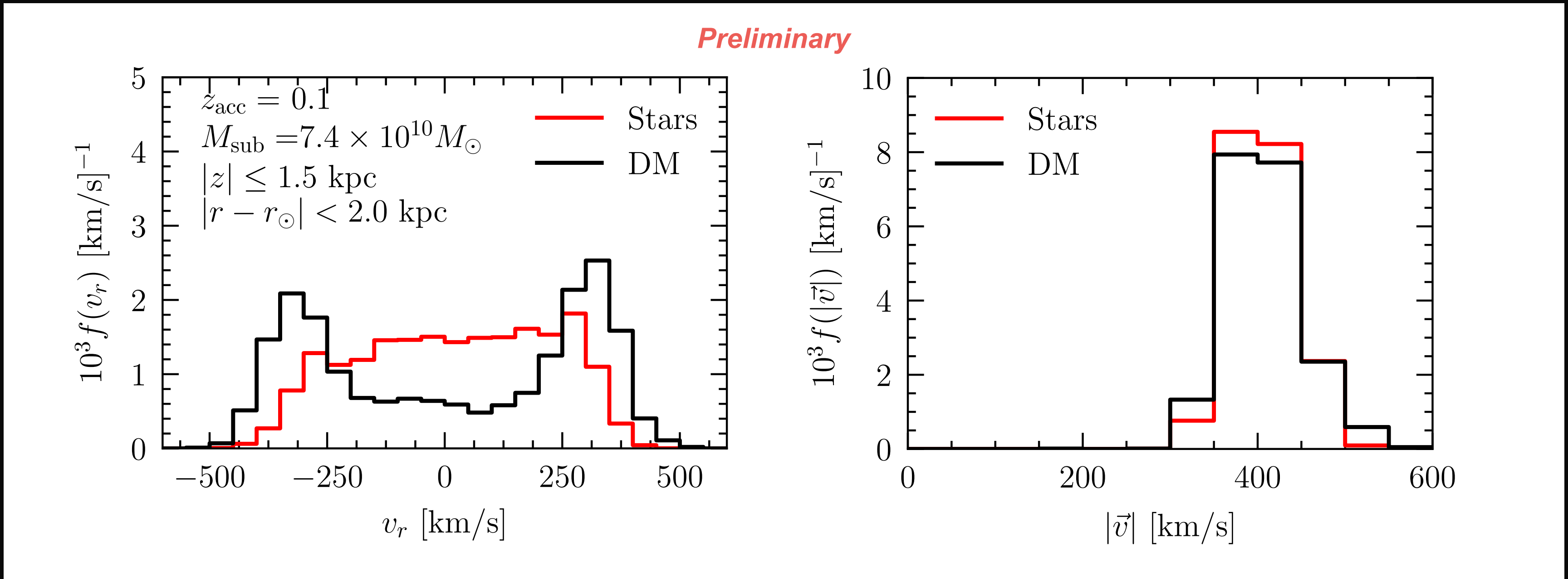
$$p\left(\{O_i\} \,|\, \theta\right) = \prod_{i=1}^{N} \sum_{j=d,h,s} Q_j \, p_j\left(O_i \,|\, \theta\right)$$

# The Young Tidal Stream

Dark matter and stars from recent accretion events may not be well-correlated

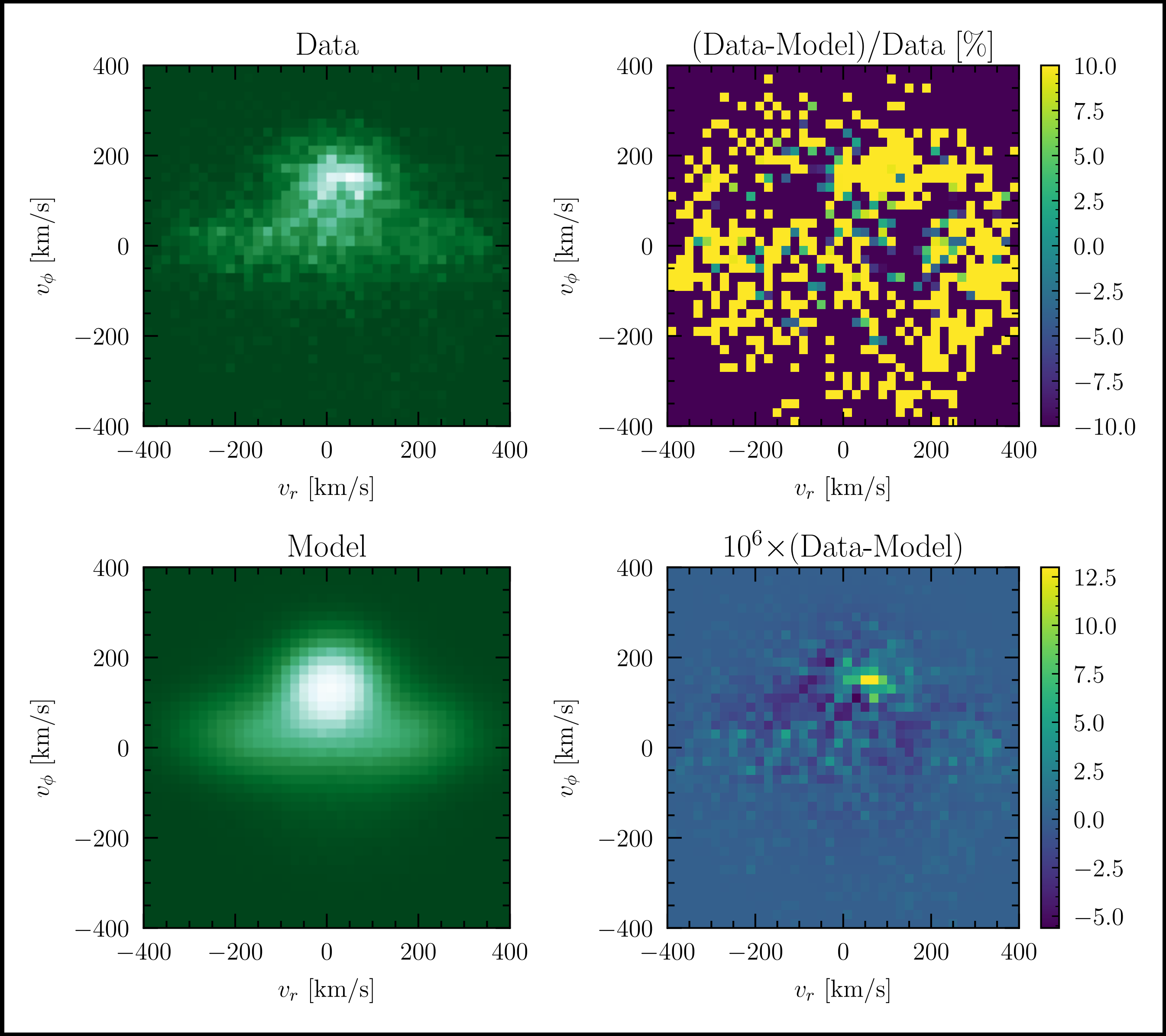
Care must be taken when inferring properties of dark matter streams from stellar observations

FIRE Simulation (m12f)

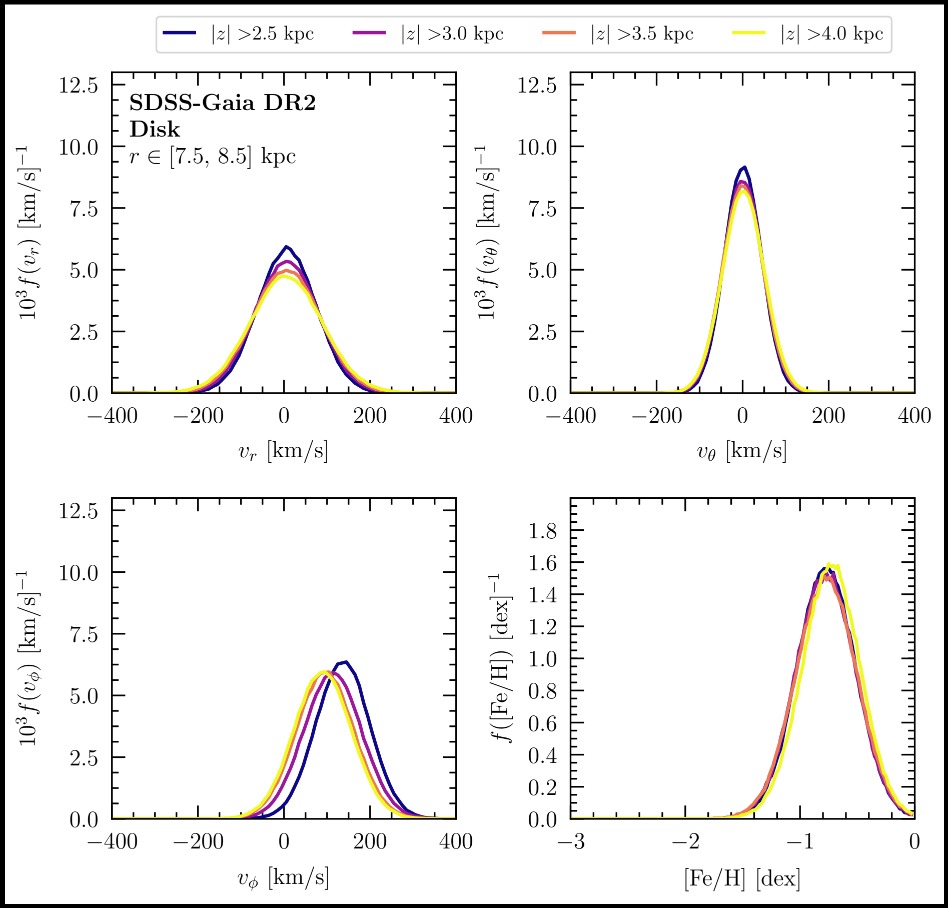


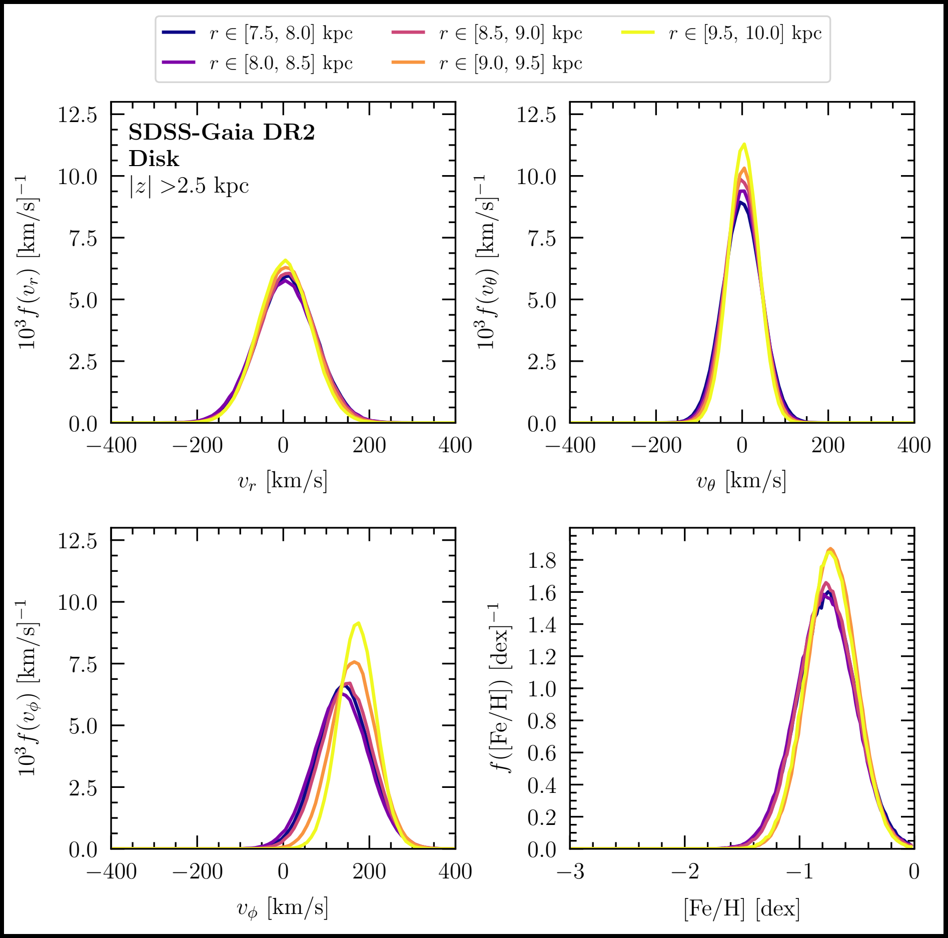

Necib, ML, Garisson-Kimmel, et al. (2018) in prep.

# Model Residuals

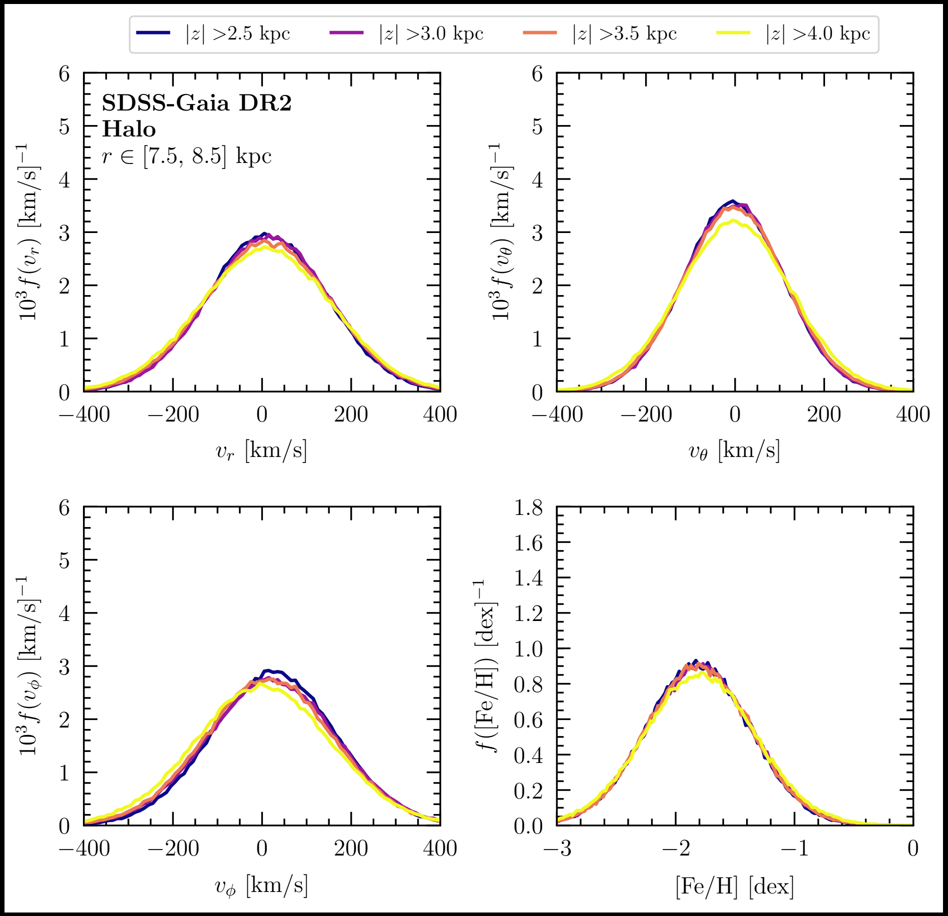


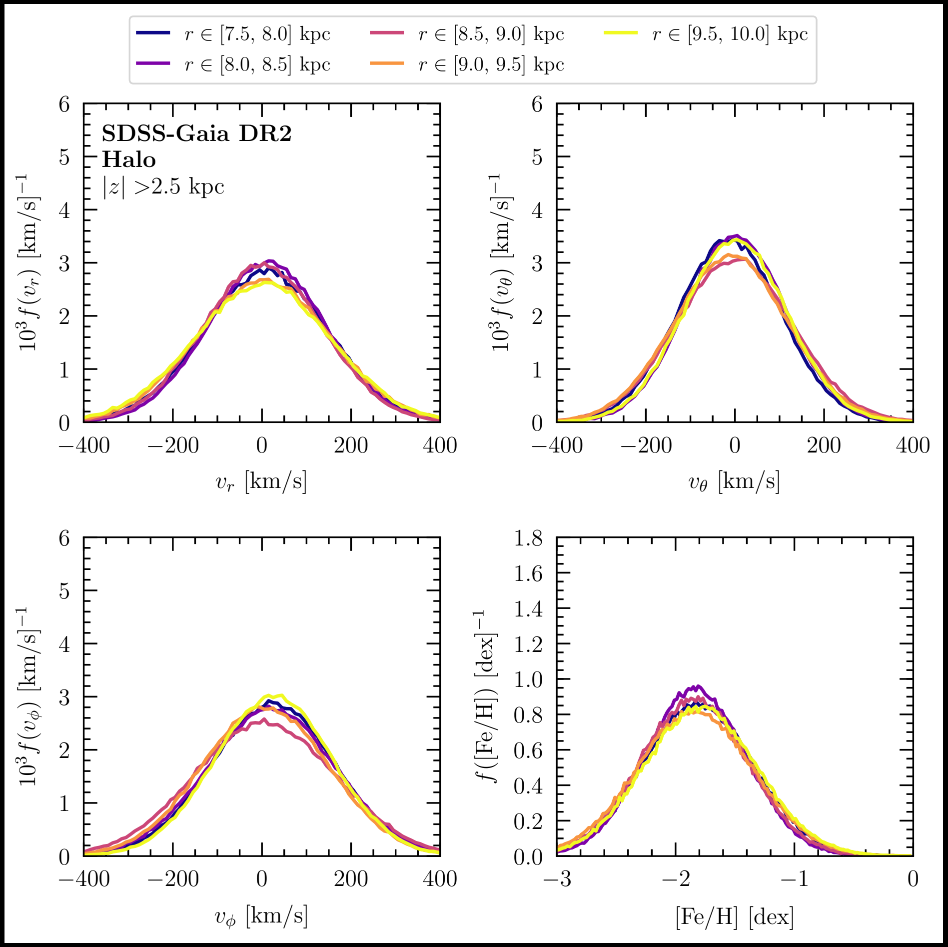
# The Disk Population



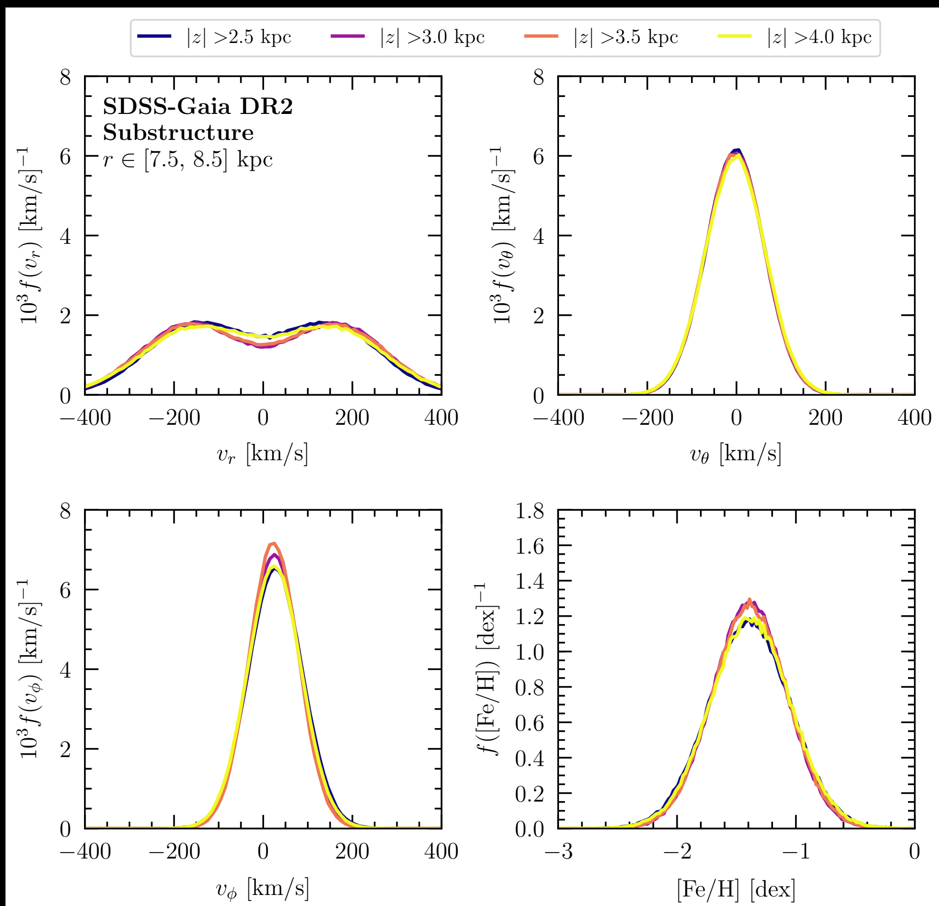



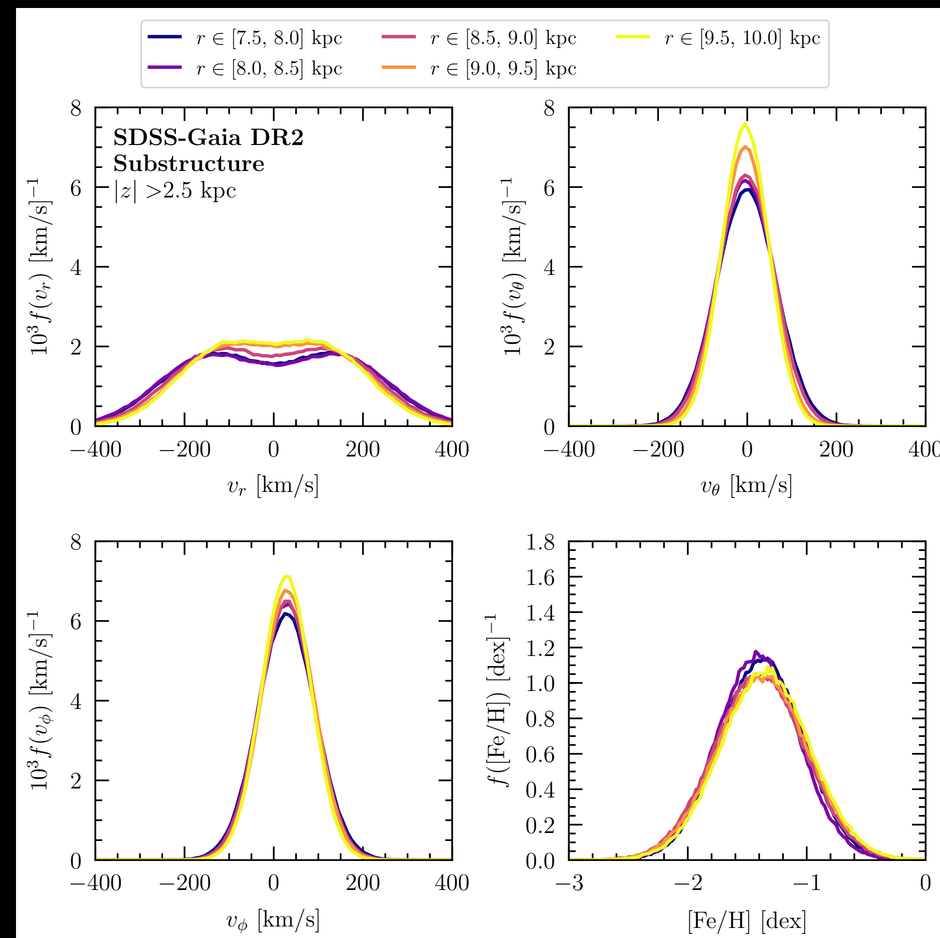
# The Halo Population



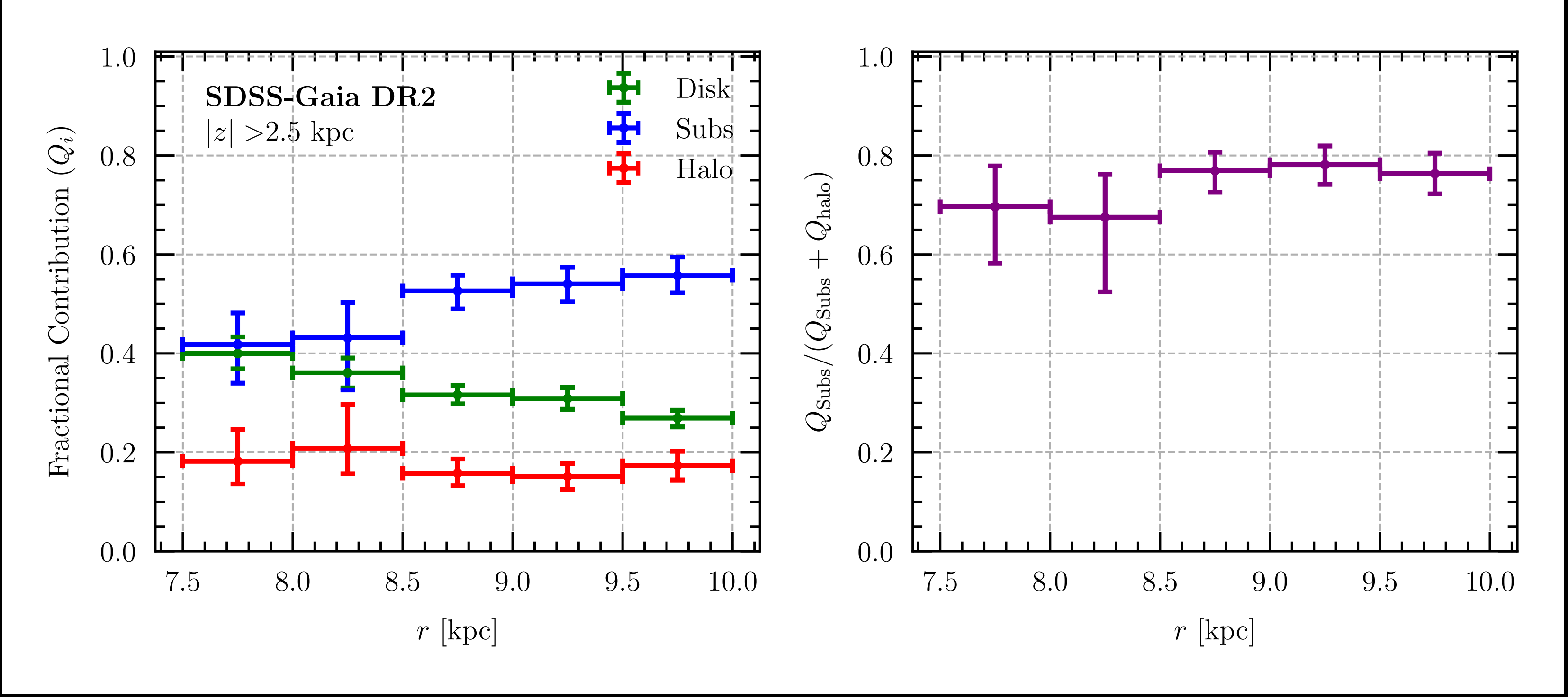



# The Substructure Population



# Fractional Contribution



# Chemical Abundance

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 $\alpha$-elements
Act on longer timescales

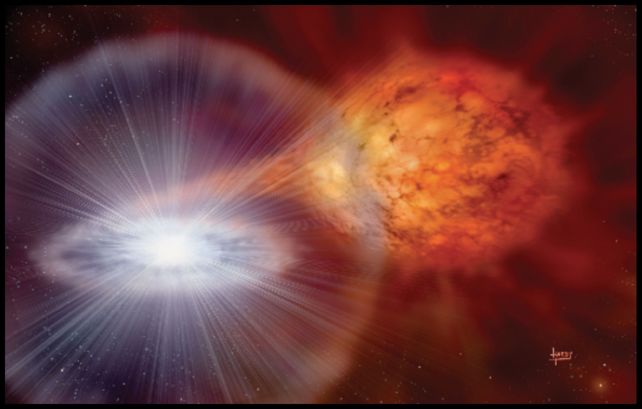


Image: D. Hardy (astroart.org)

## Core-collapse Supernova

Large amounts of $\alpha$-elements relative to Fe
Act on shorter timescales

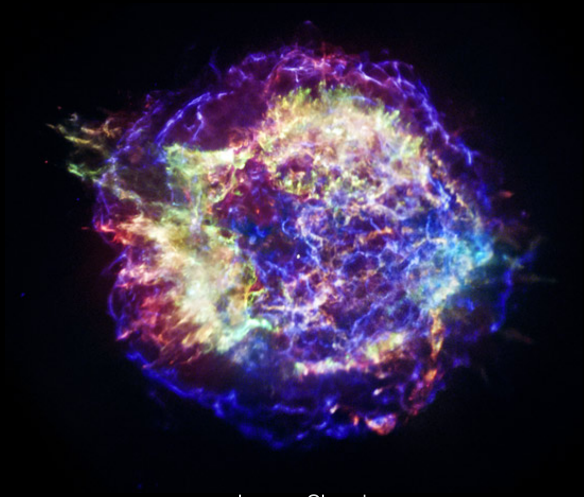


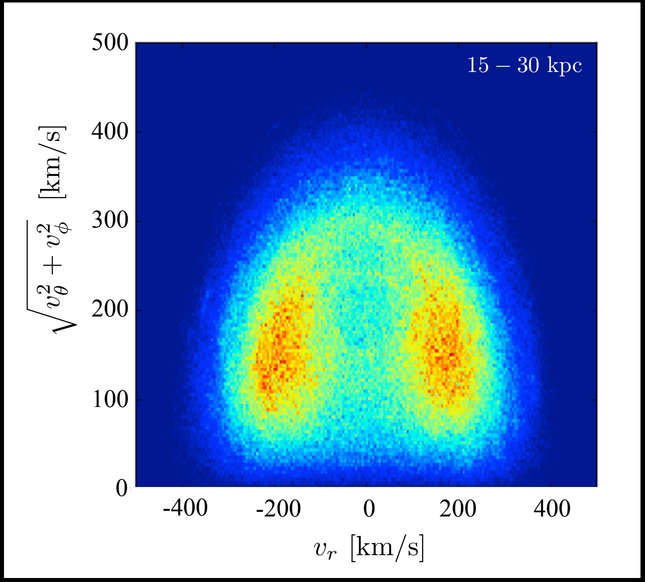
Image: Chandra

# Debris Flow in Via Lactea

Radial-velocity substructure had already been observed in Via Lactea, a dark matter-only *N*-body simulation

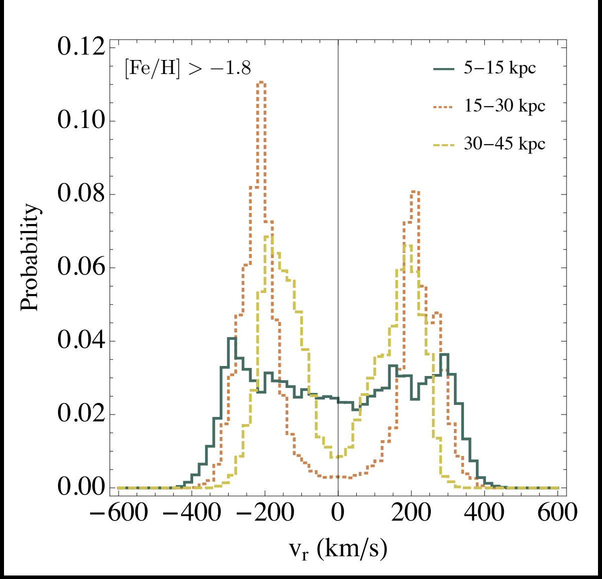
'Painting' stars onto the dark matter particles in the simulation showed that the substructure was also present in the simulated stellar halo

Dark Matter Debris




ML and Spergel, Phys. Dark Univ. [1105.4166]
Kuhlen, ML, and Spergel, PRD [1202.0007]

Stellar Debris




ML, Spergel, and Madau, ApJ [1410.2243]