



Clustering Stellar Structures and Connections to Dark Matter

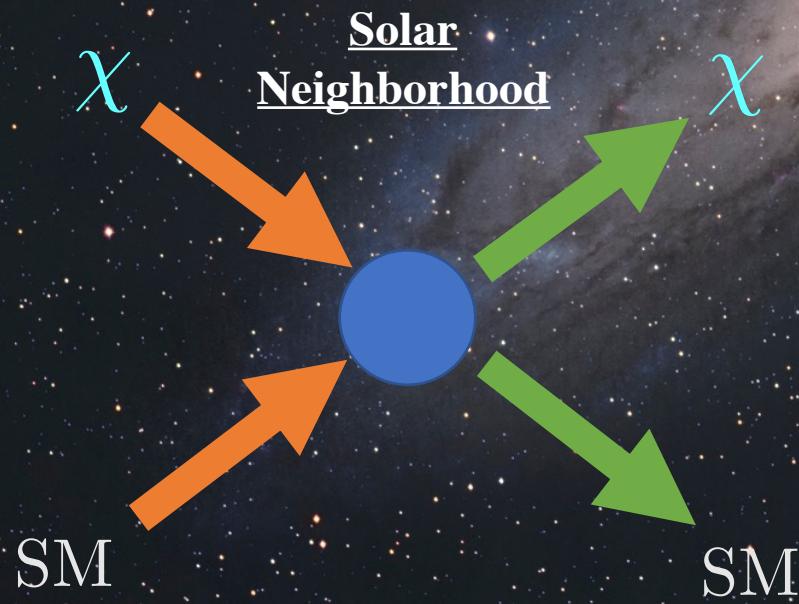
Lina Necib

MIT

Direct Detection

Direct detection depends on astrophysical parameters:

- Dark matter density
- Dark Matter velocity

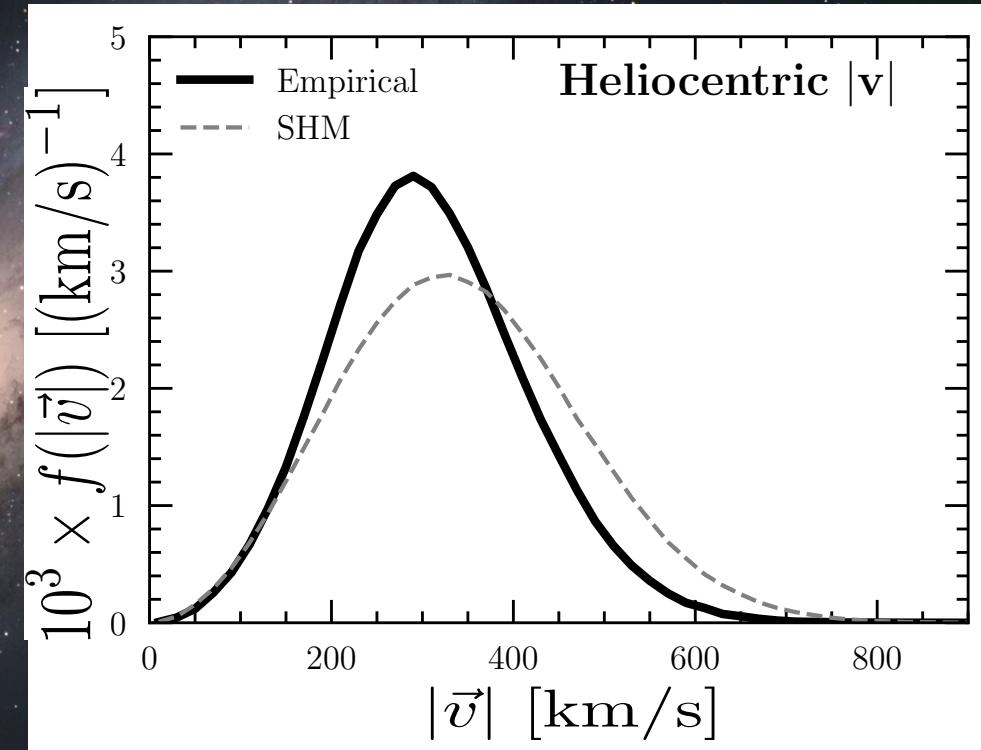
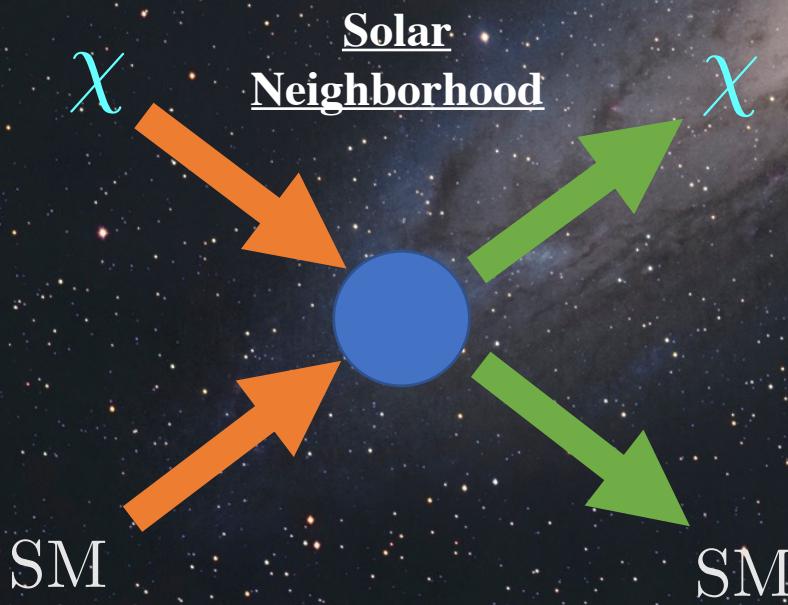


Goodman & Witten (1985)
Freese et al. (1988)
<https://www.ge.com/reports/5-coolest-things-earth-week-29-6/andromeda-galaxy/>

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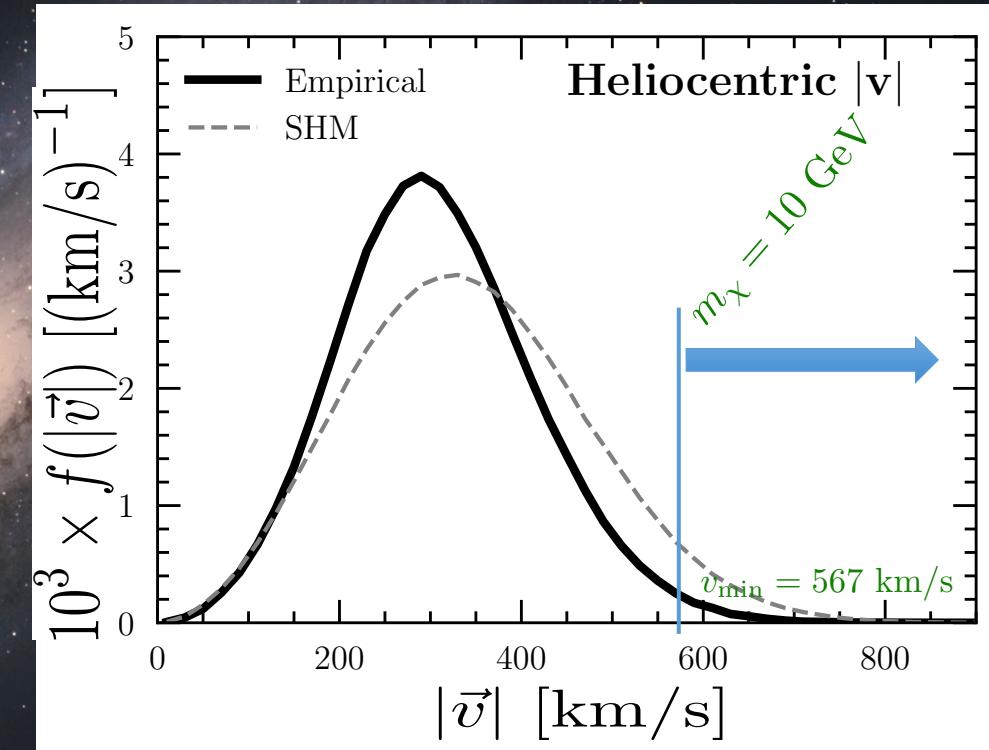
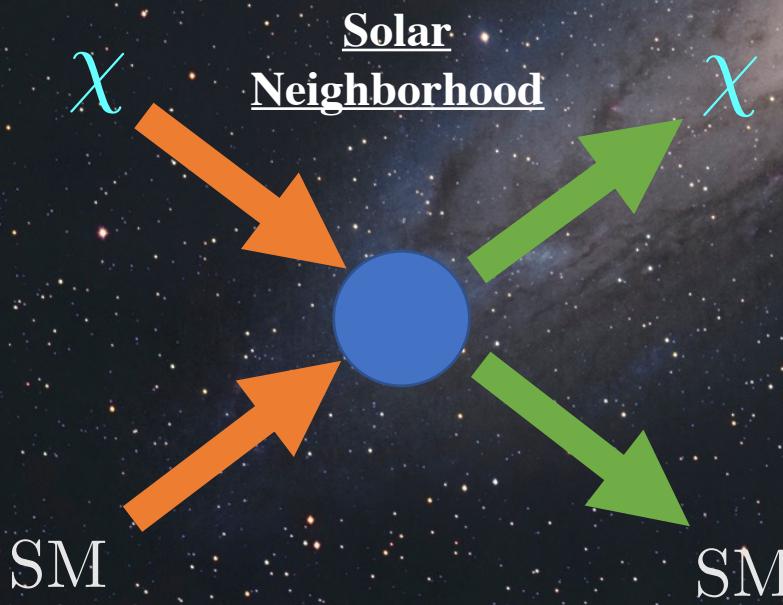


$$\text{Rate} \propto \rho_{DM} \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$
$$v_{\min} = v_{\min}(E_{\text{thresh}}, m_{\chi})$$

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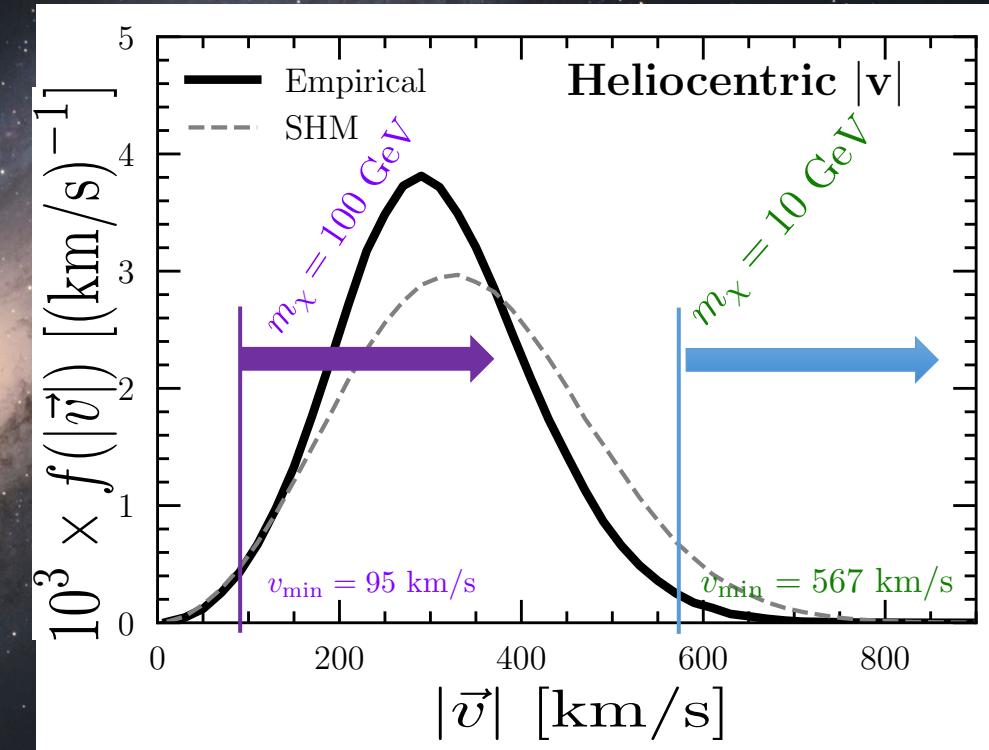
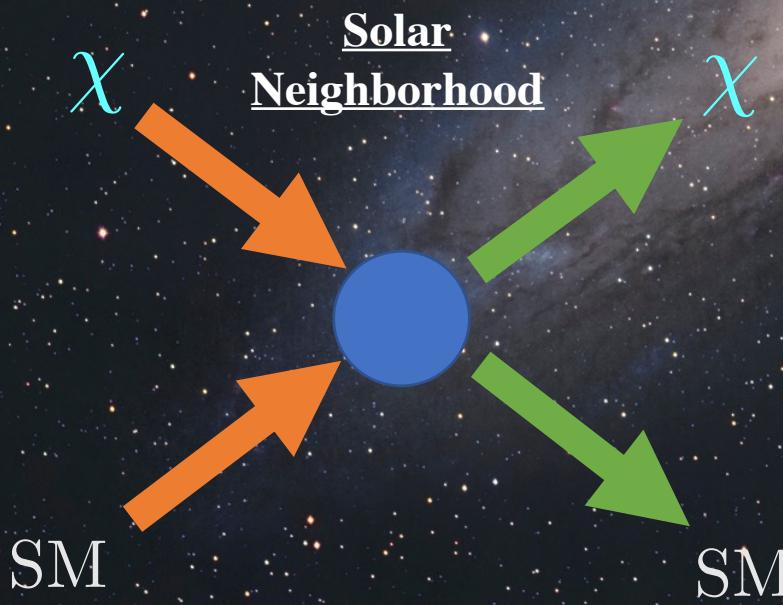


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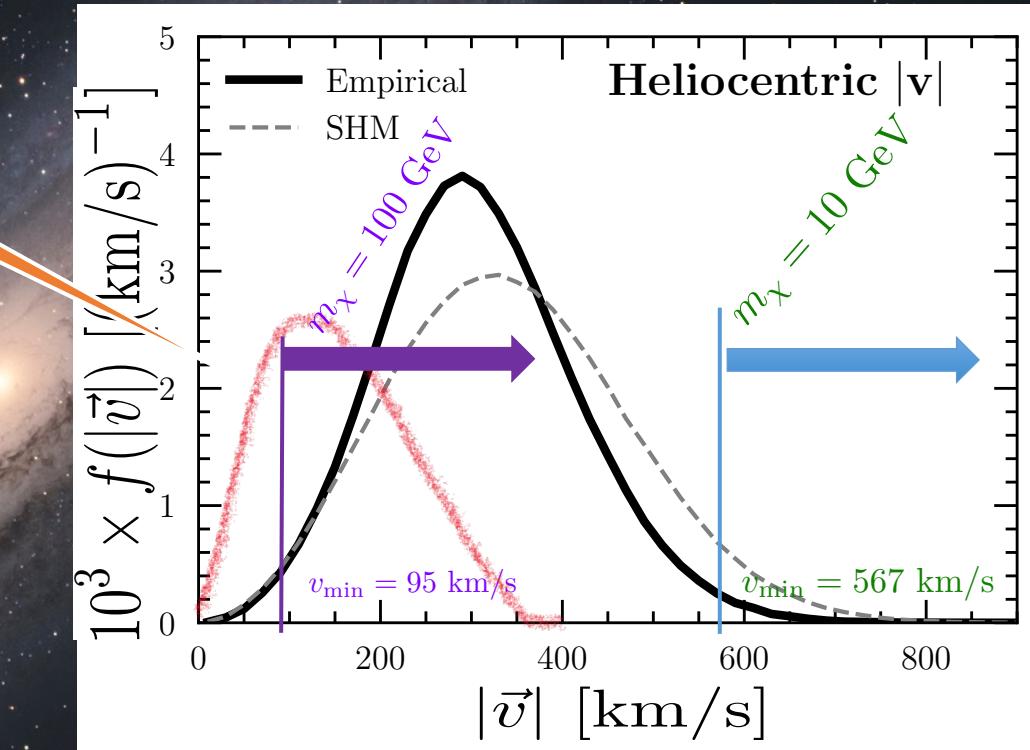
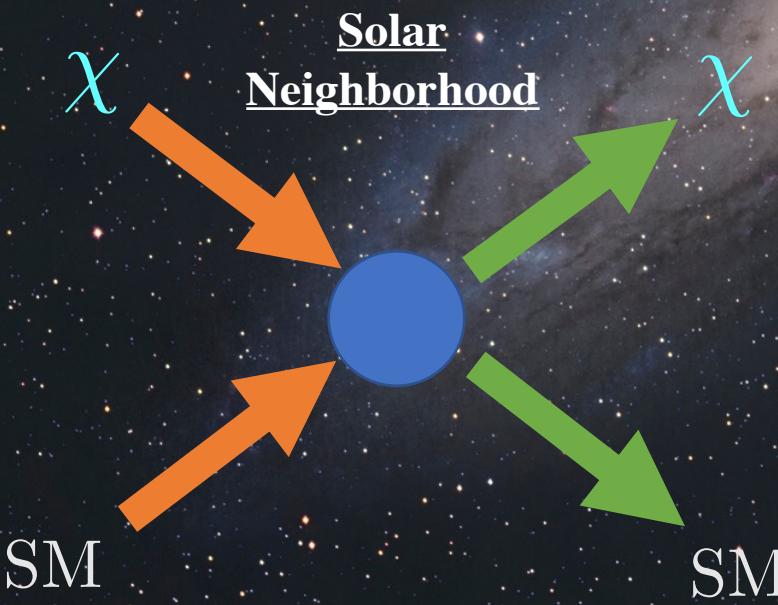


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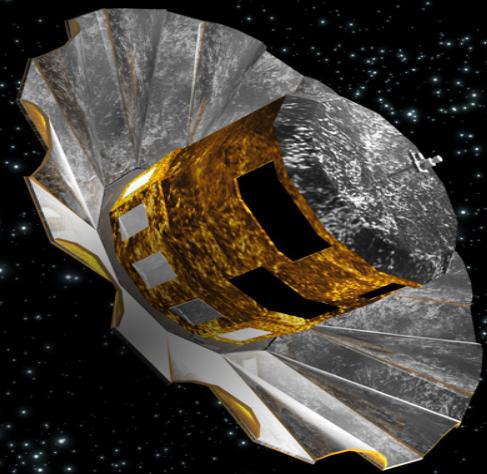


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We Need to Understand Dark
Matter Substructure

Gaia

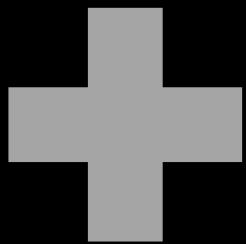
- Launched December 2013
- Goal: Positional and kinematic measurement of 1 billion stars (1% of the Milky Way)
- DR2: 7 million radial velocities
- DR3: 33 million radial velocities



esa



Correlation
between the
Stellar and
Dark Matter
Velocity
Distributions

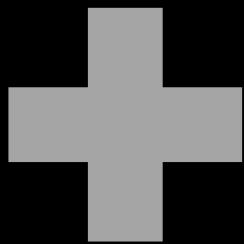


Identification
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Structure



Building the
Velocity
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Identification
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Building the
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Simulated Milky-Way like halo

Starks Matter

Host Halo

Subhalo

Dark
Subhalo

100 kpc

Lina Necib, MIT

Necib, Lisanti, Garrison-Kimmel et al. (2018)

$z=9.9$

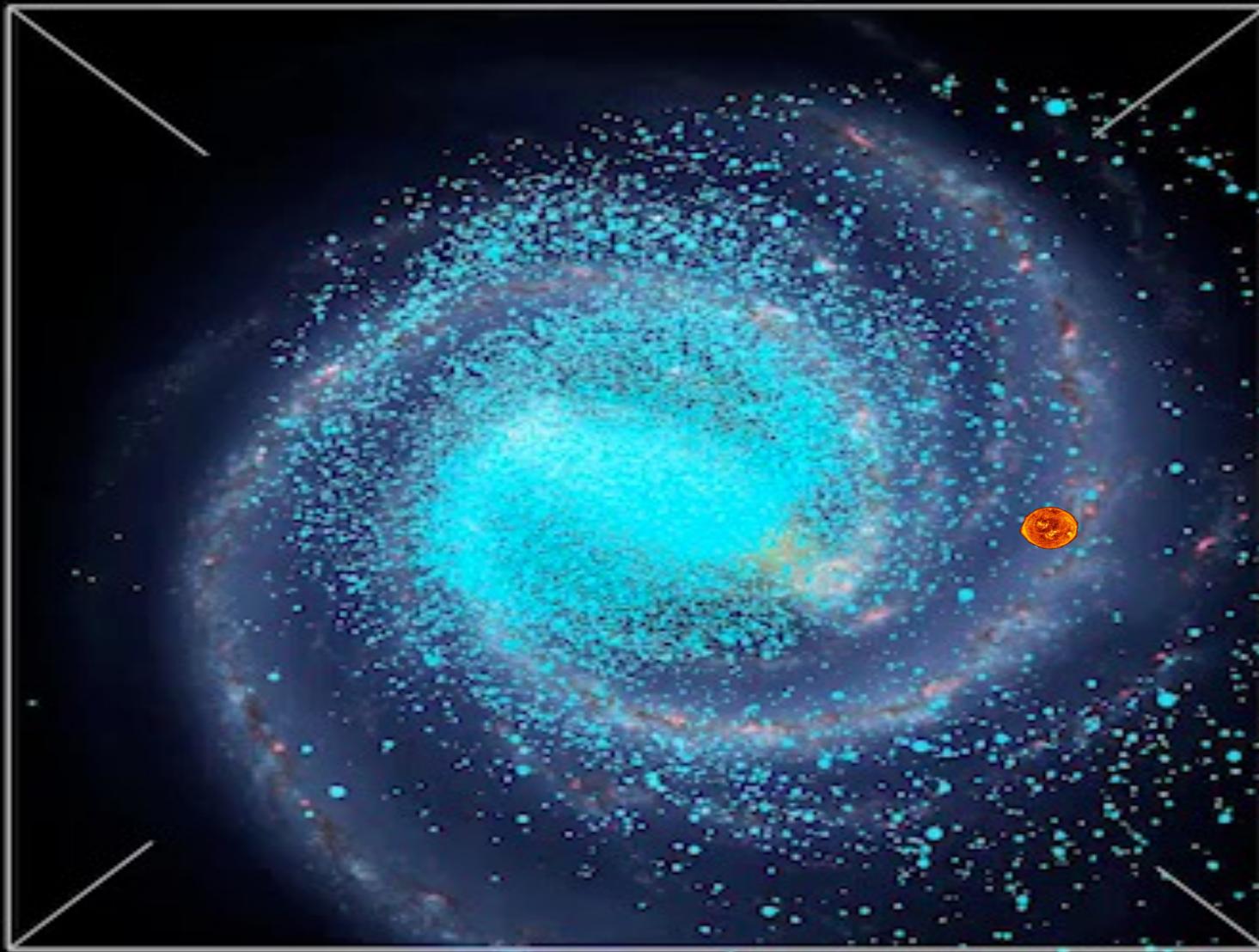
FIRE simulations

Lina Necib, MIT

10 kpc

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

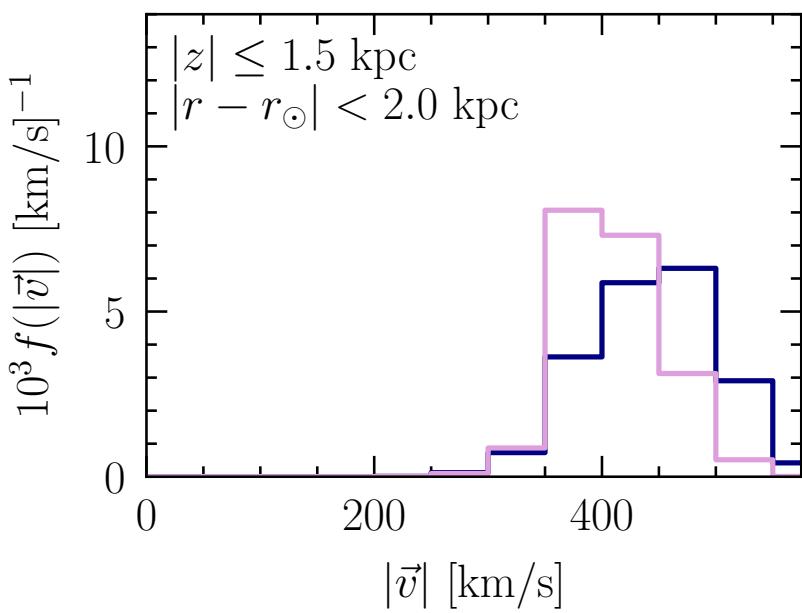
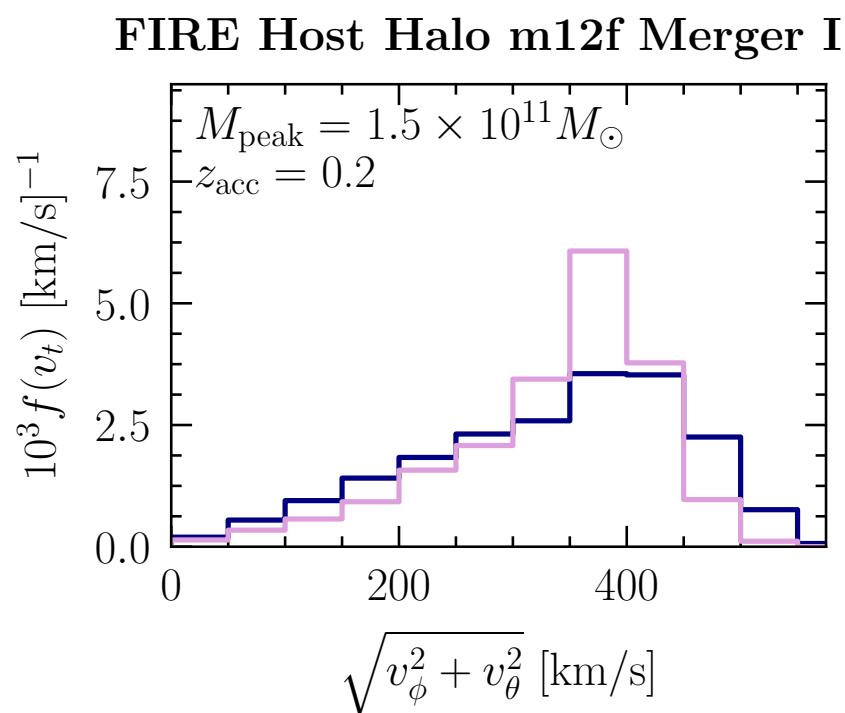
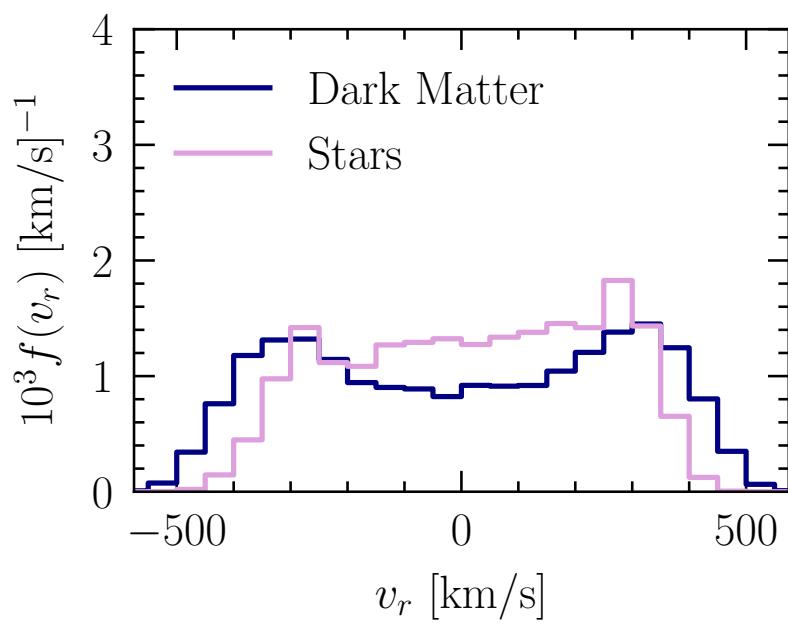
Gaia Sausage Enceladus



Credit: H.H. Koppelman, A. Villanlobos, A. Helmi

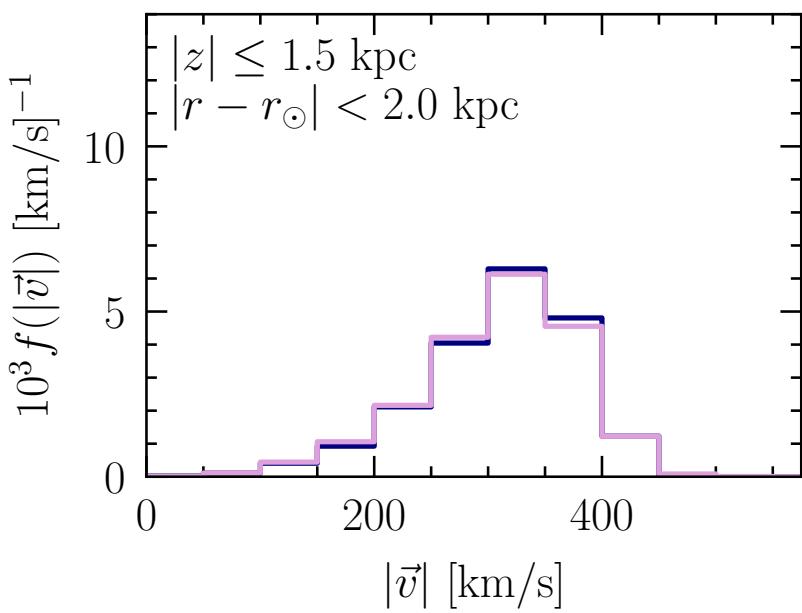
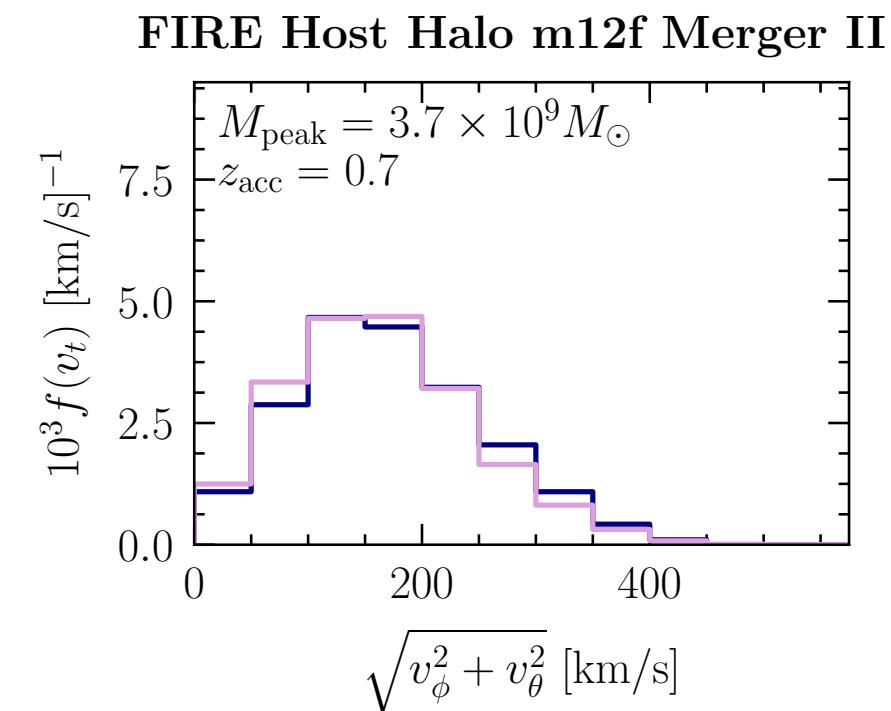
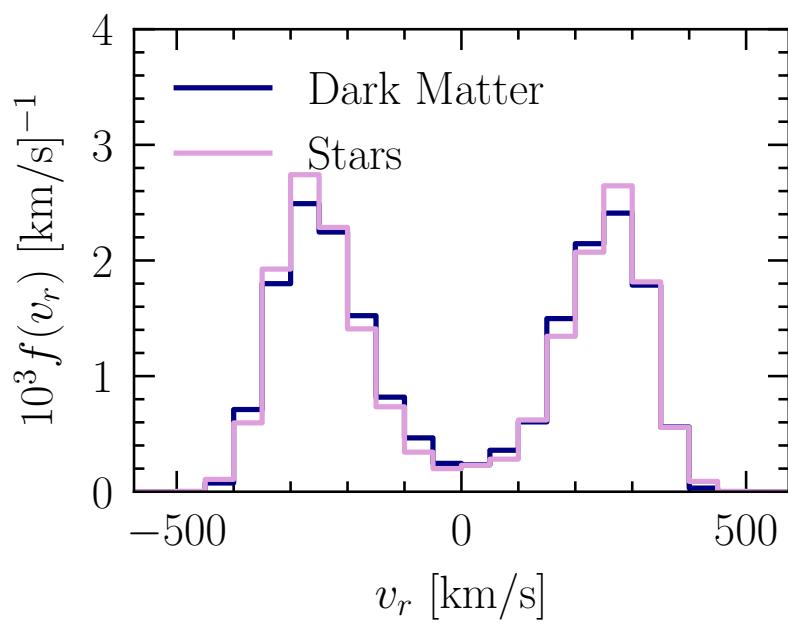


Correlating the velocity distributions of Dark Matter and stars merger by merger.



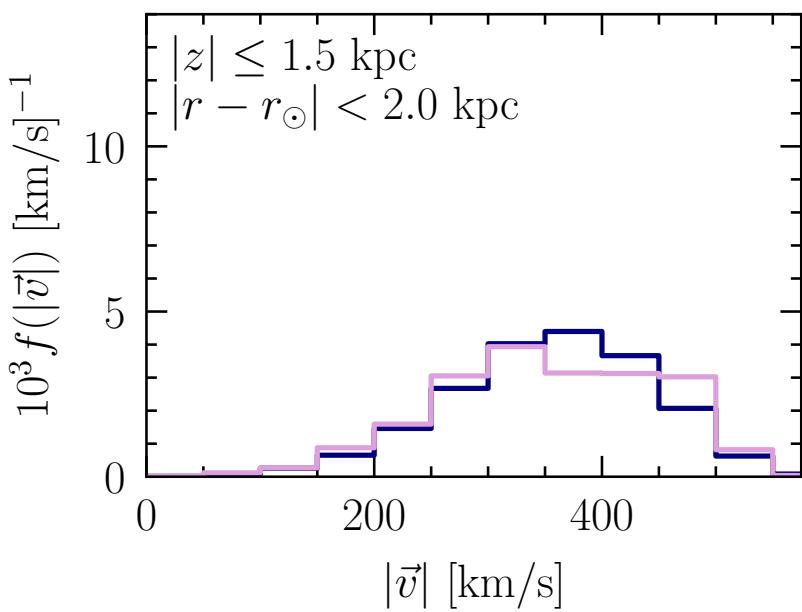
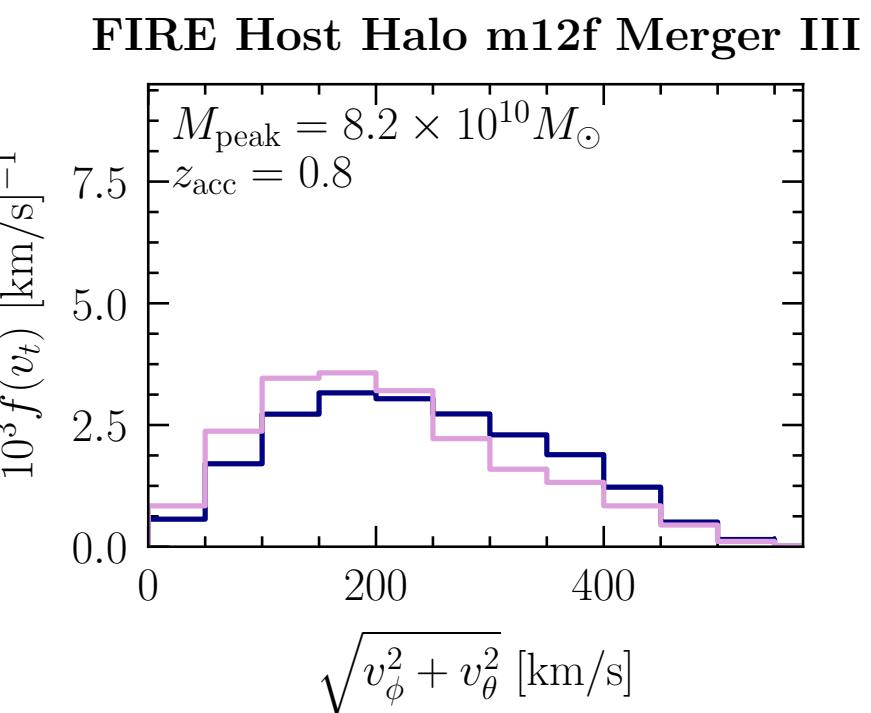
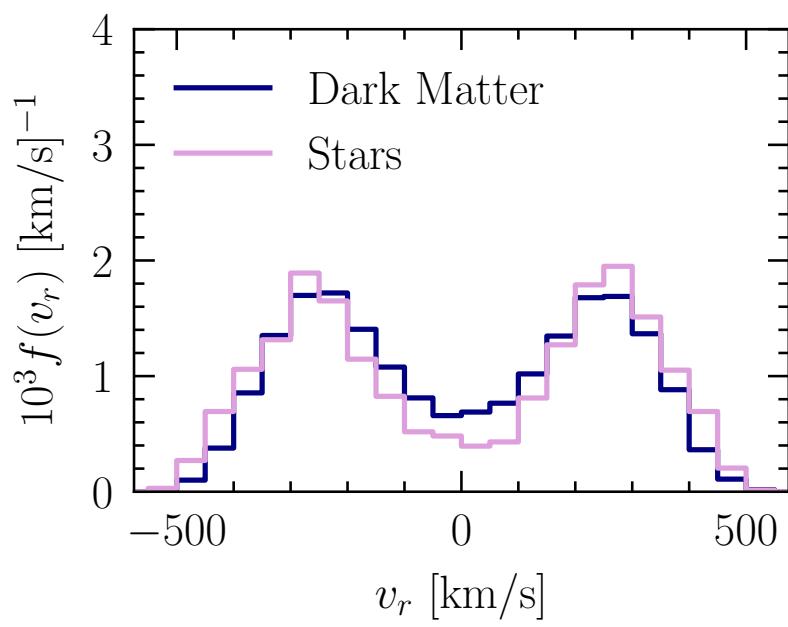


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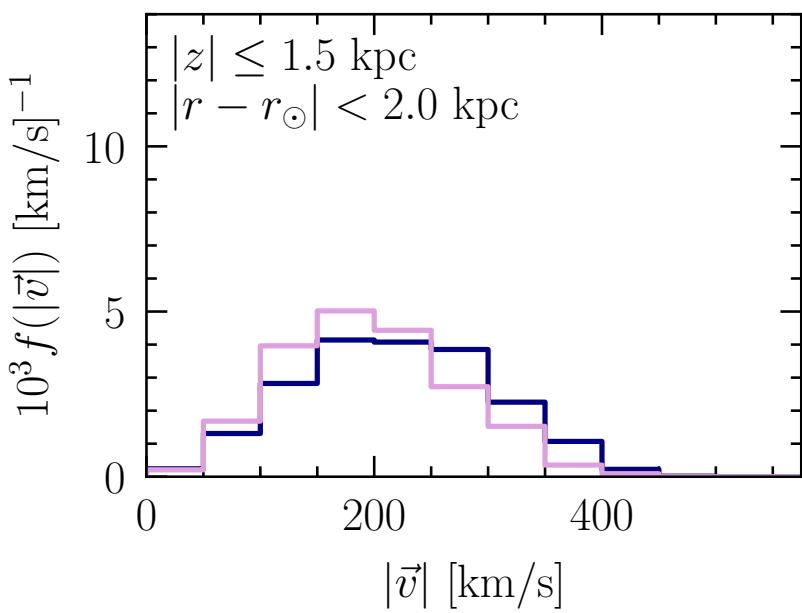
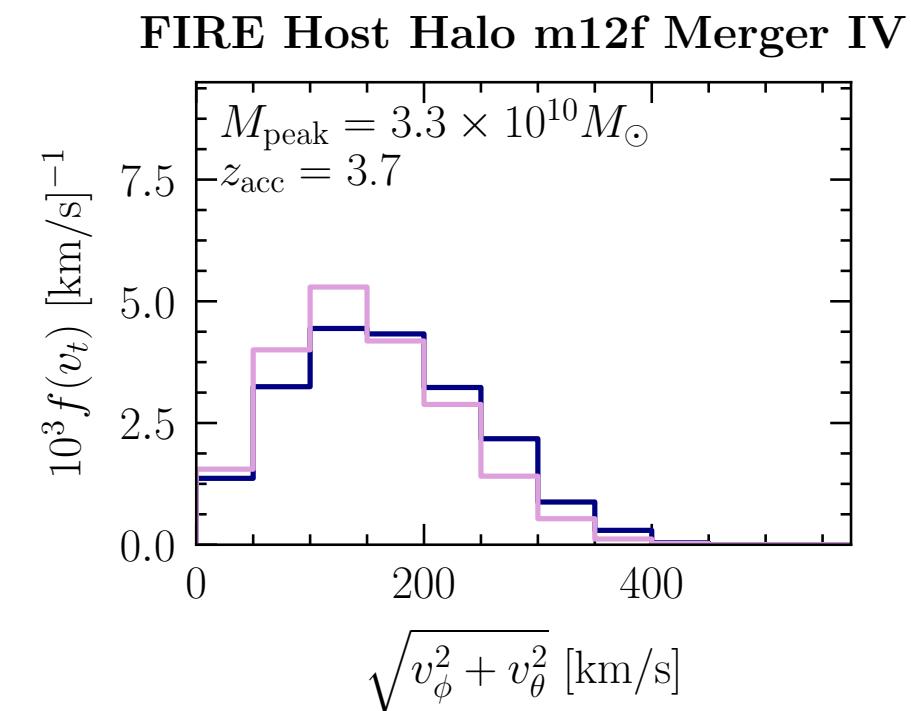
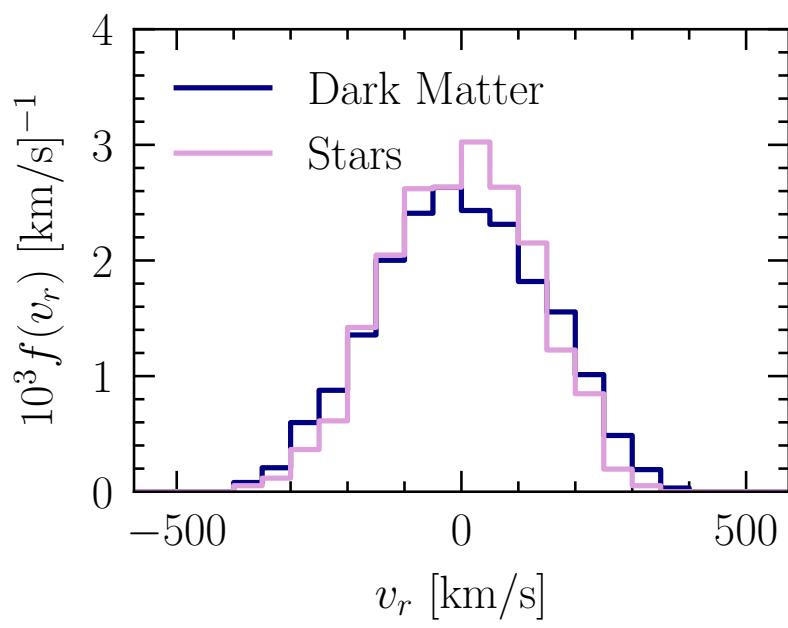


Correlating the velocity distributions of Dark Matter and stars merger by merger.





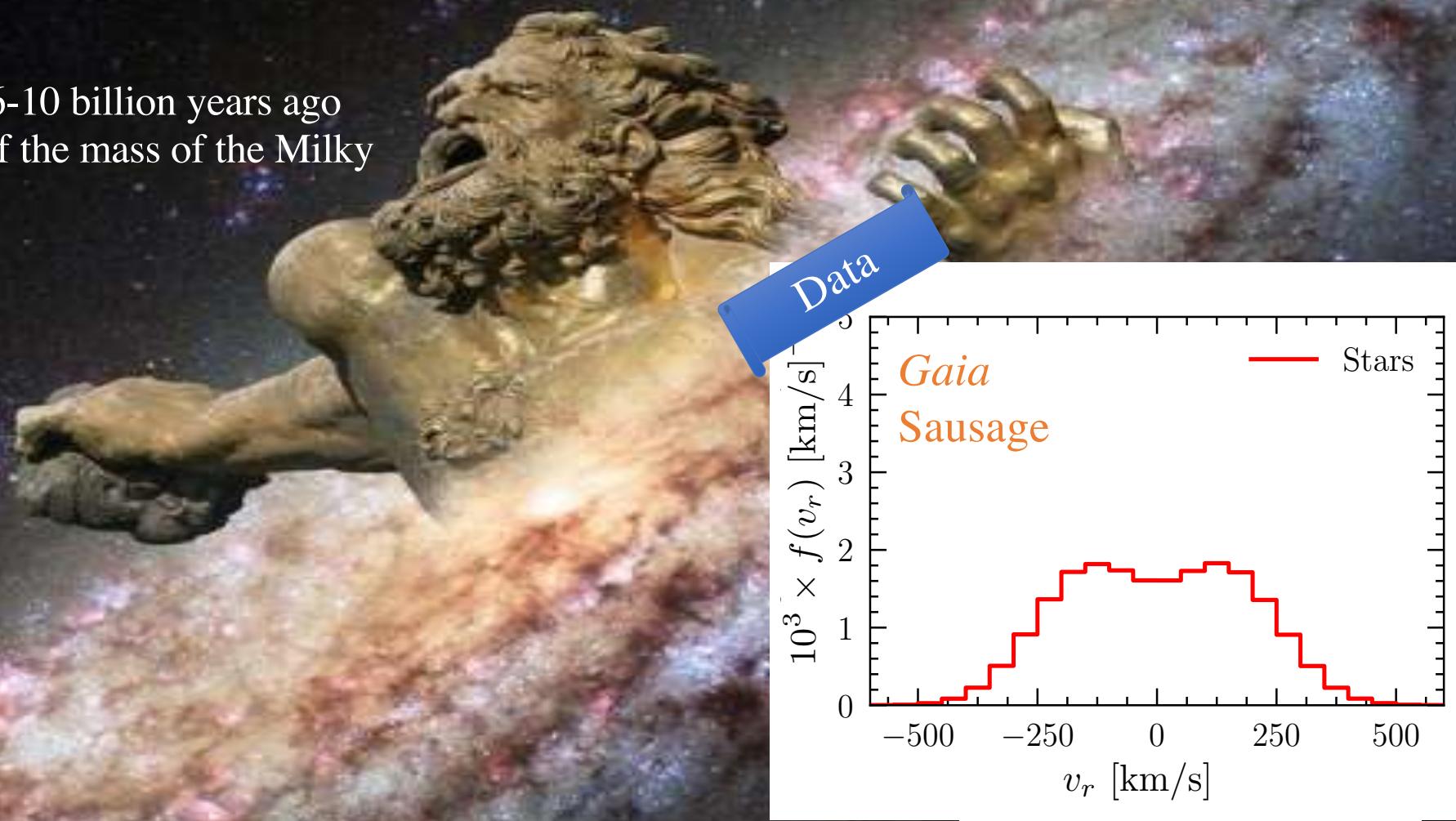
Correlating the velocity distributions of Dark Matter and stars merger by merger.



Gaia Sausage Enceladus

Accretion time: 6-10 billion years ago

Mass: 1%-10% of the mass of the Milky Way



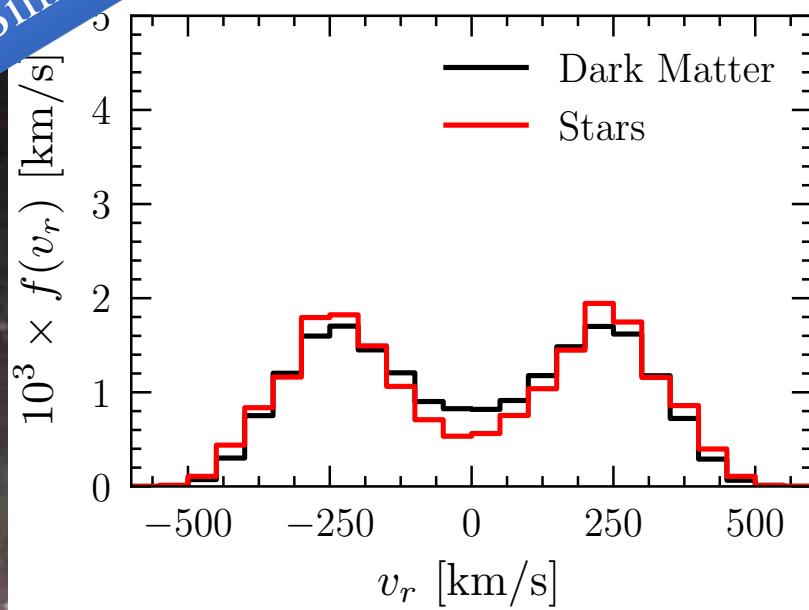
Necib, Lisanti, Belokurov (2019)

Gaia Sausage Enceladus

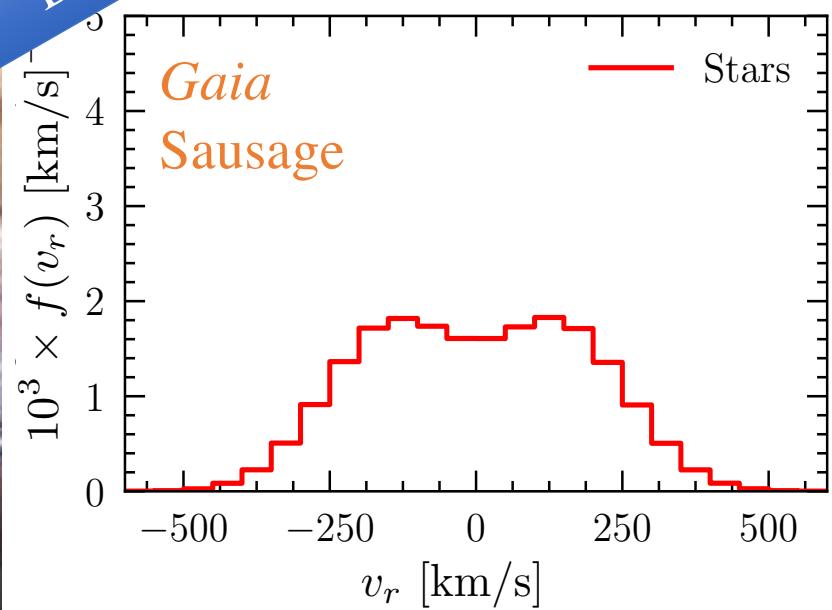
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Simulation



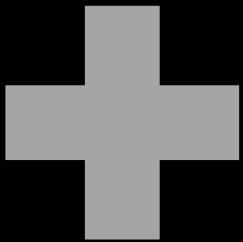
Data



Necib, Lisanti, Belokurov (2019)

Necib, Lisanti, Garrison-Kimmel et al. (2018)

Correlation
between the
Stellar and
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Velocity
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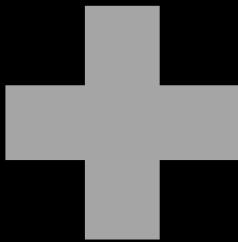


Identification
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Building the
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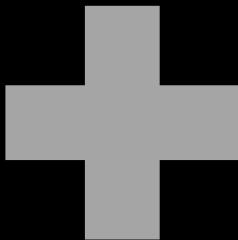
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Building the
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- Build an accreted star catalog
- Model the stellar distributions
- Cluster in action and velocity spaces for kinematic structures

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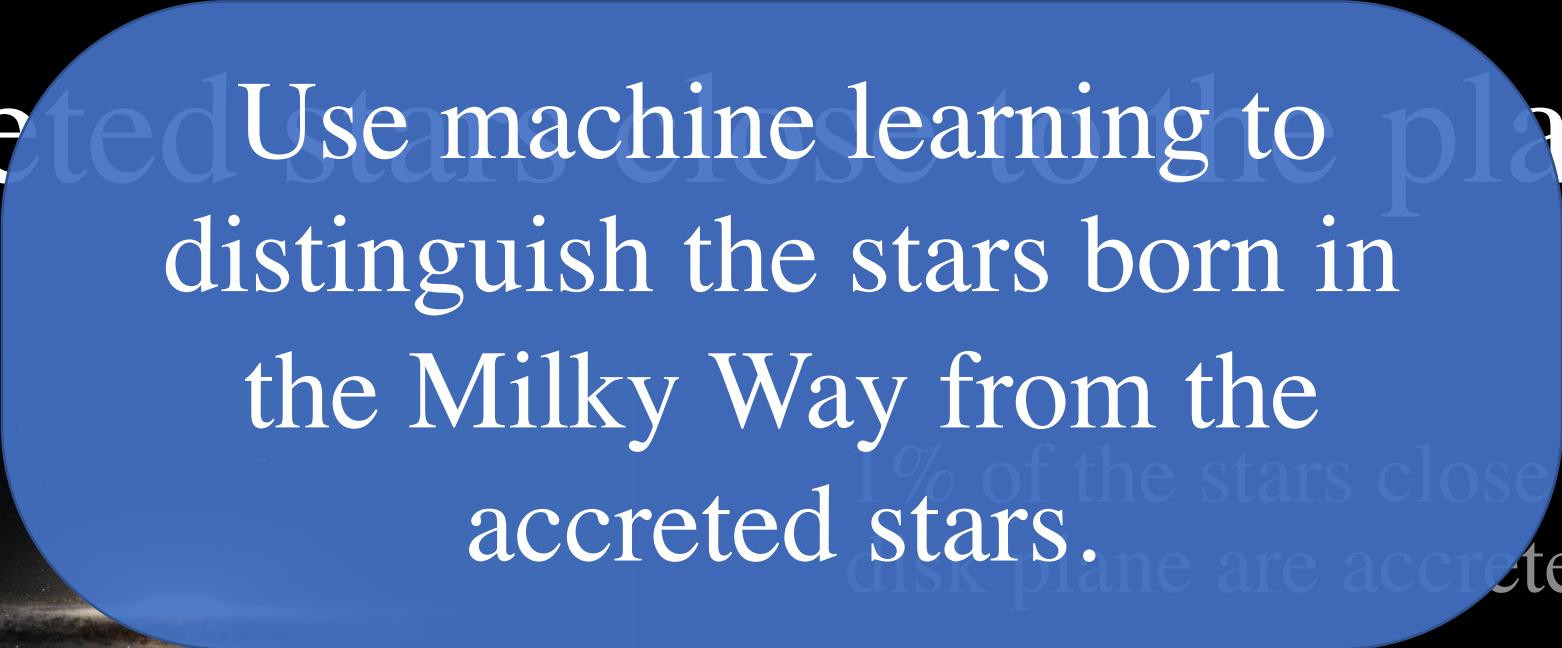
- Build an accreted star catalog
- Model the stellar distributions

Accreted stars close to the plane?



1% of the stars close to the disk plane are accreted

- Build an accreted star catalog
- Model the stellar distributions



Accreted stars close to the plane?
Use machine learning to distinguish the stars born in the Milky Way from the accreted stars.

1% of the stars close to the disk plane are accreted

Ananke

Gaia

Sanderson et al. (2019)

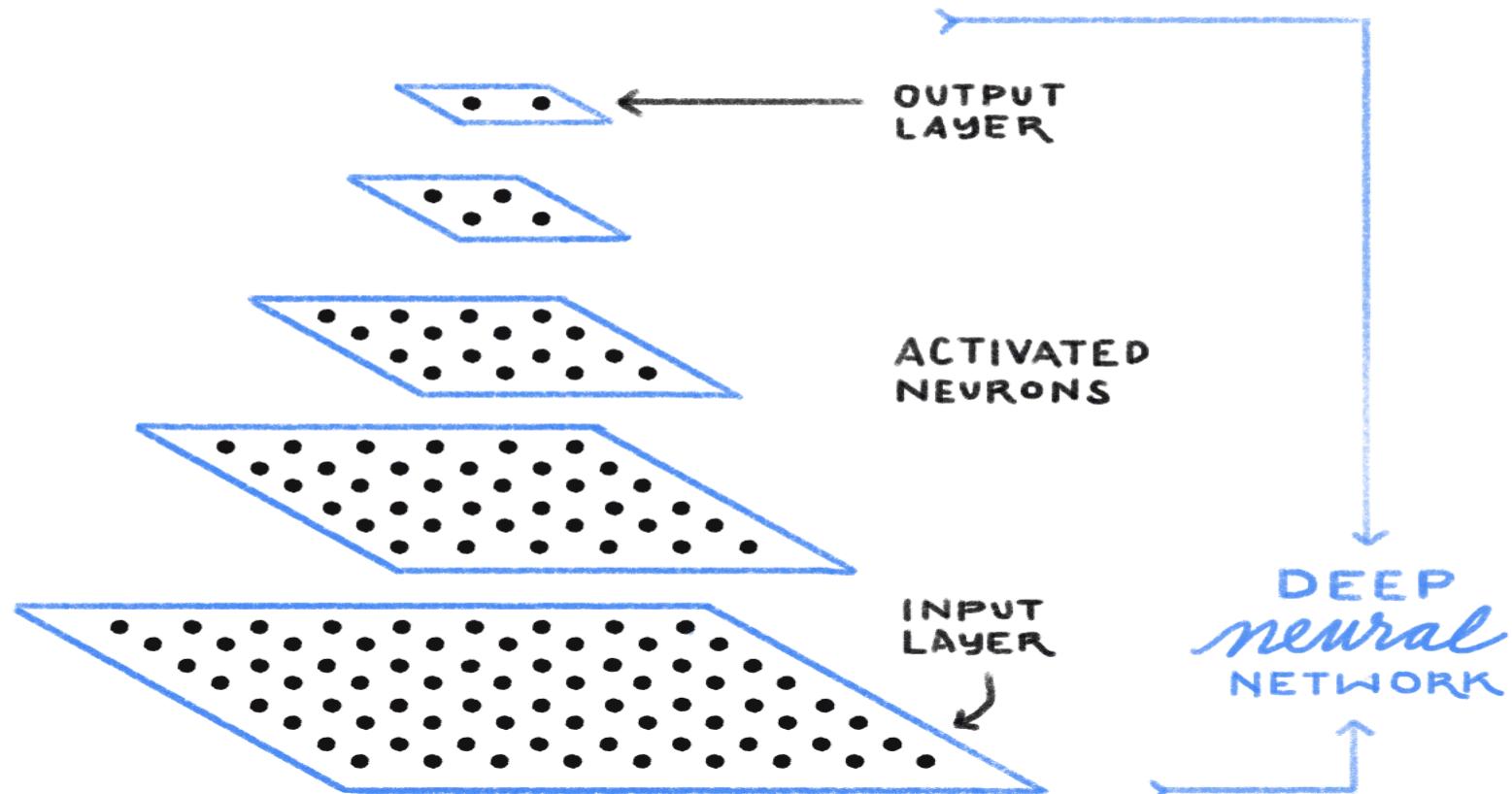
1. Train on simulation.
2. Label *Gaia* stars.

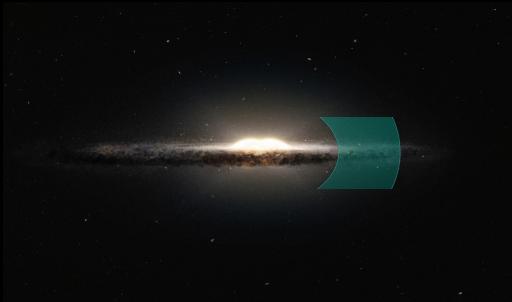
IS THIS
Accreted or
not?



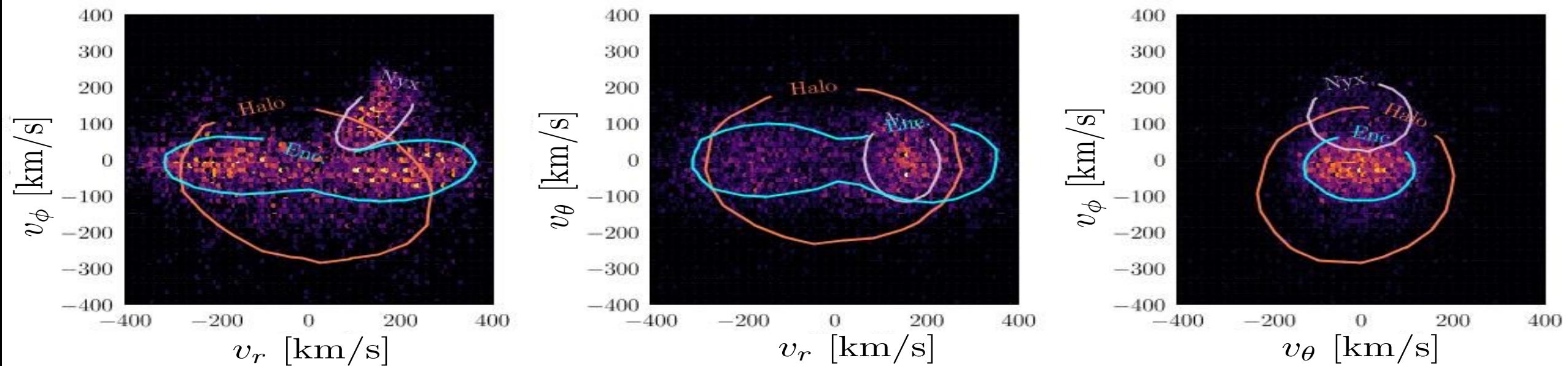
Accreted

Not Accreted

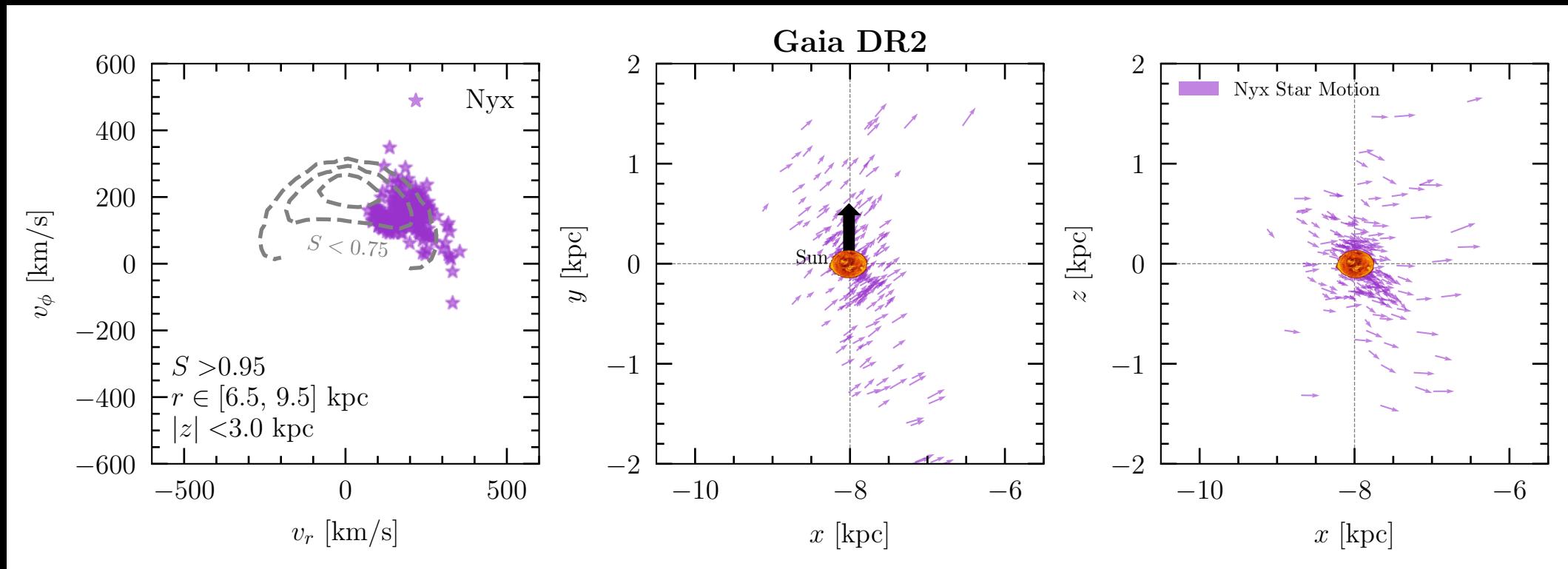


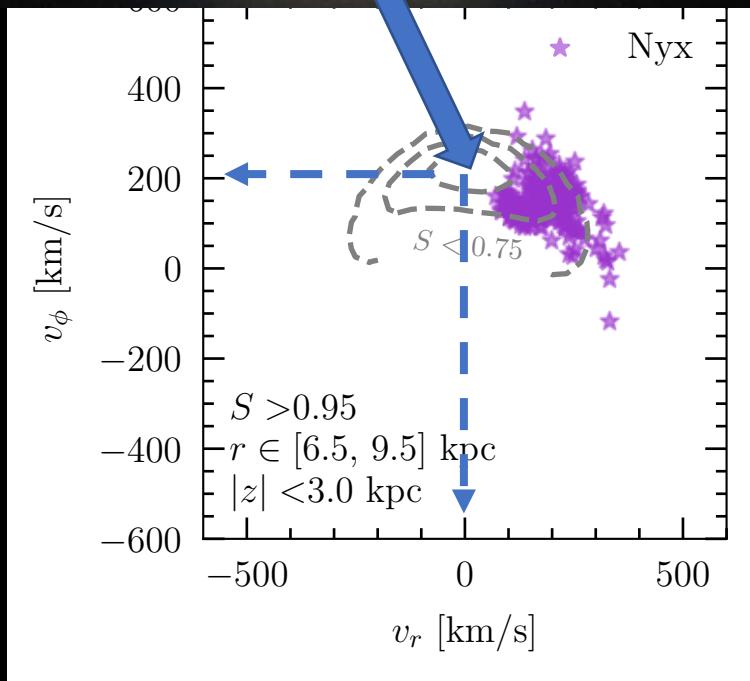


Structures close to the Disk



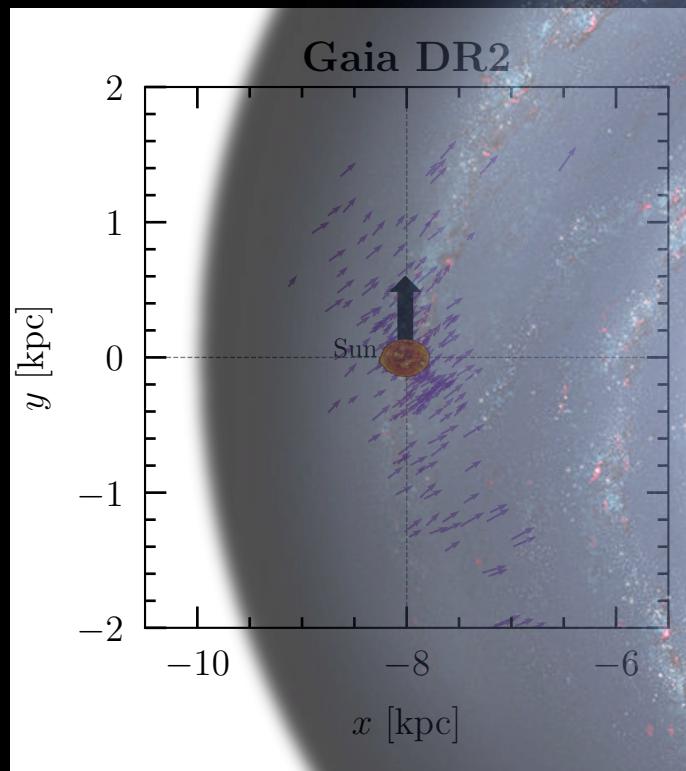
Nyx





Nyx

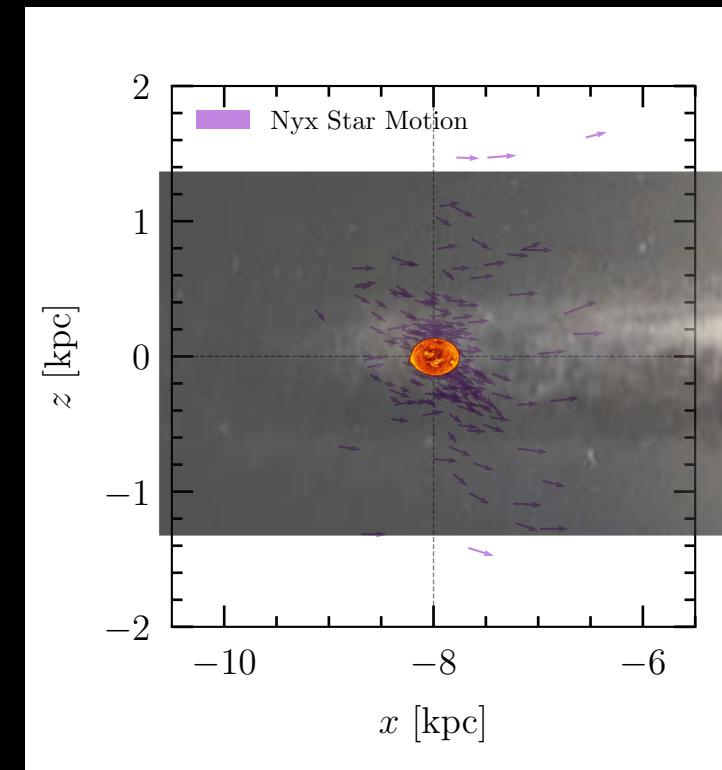
Nyx



Lina Necib, MIT

Necib, Ostdiek, et al. (2019a)

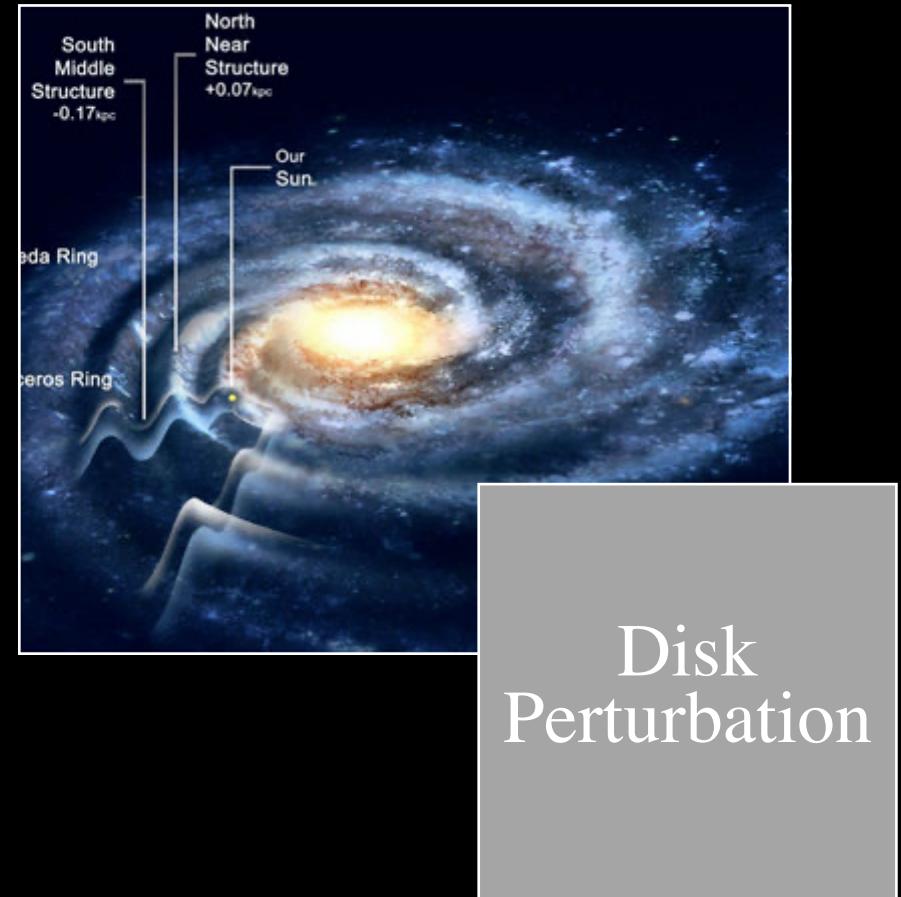
Nyx



Nyx



Or



Simulation Analog

$z=0.12$



10 kpc

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

Simulation Analog

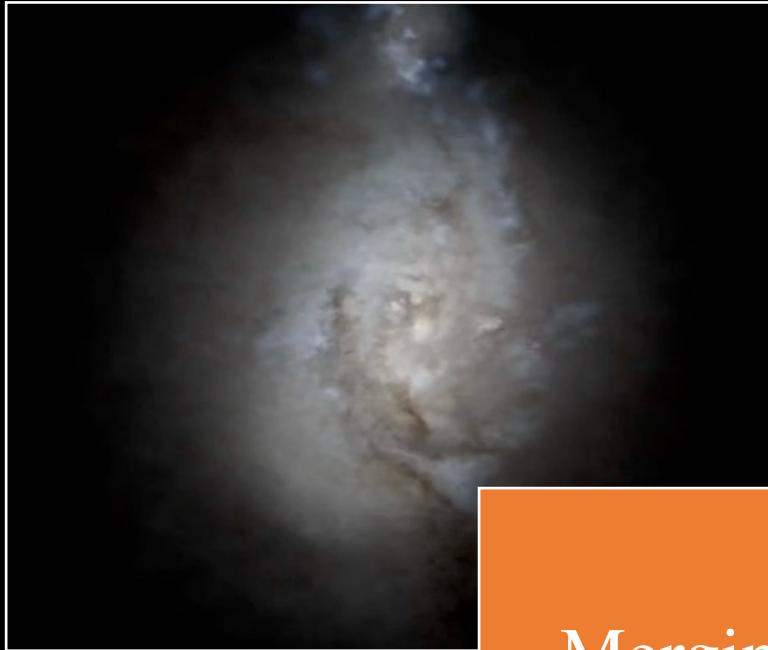
$z=0.12$

Such mergers are important as
they might have an associated
accreted dark disk!

10 kpc

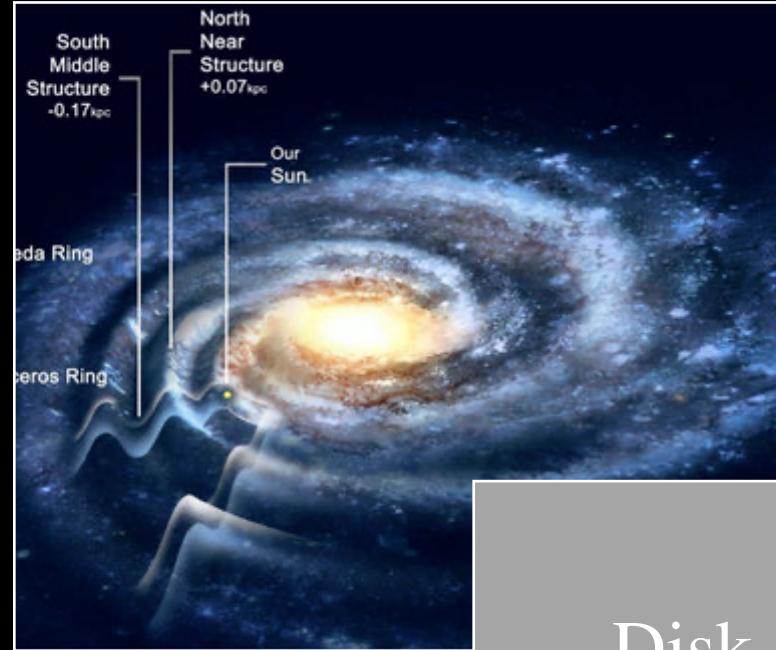
Nyx

Or



Merging
Galaxy

Observe Nyx stars at Magellan
and Keck II to obtain high
resolution chemical abundances.



Disk
Perturbation

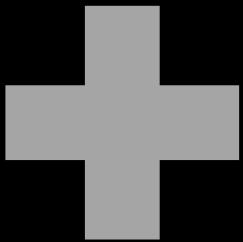
Nyx

Currently, we are finding that Nyx is chemically consistent with the thick disk. However, it could have been caused by a merger that perturbed the disk.

Observe Nyx stars at Magellan and Keck II to obtain high resolution chemical abundances.

Disk
Perturbation

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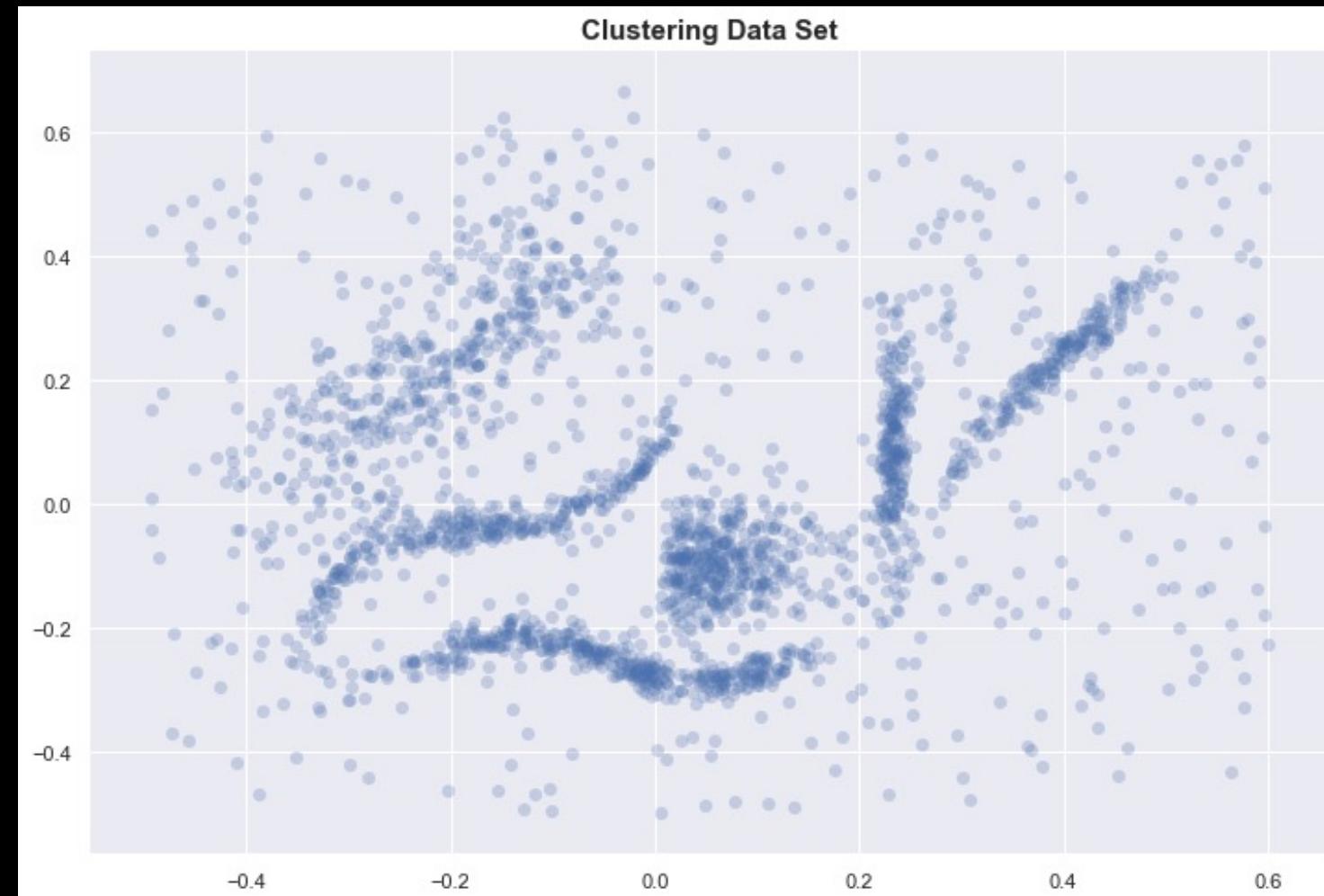
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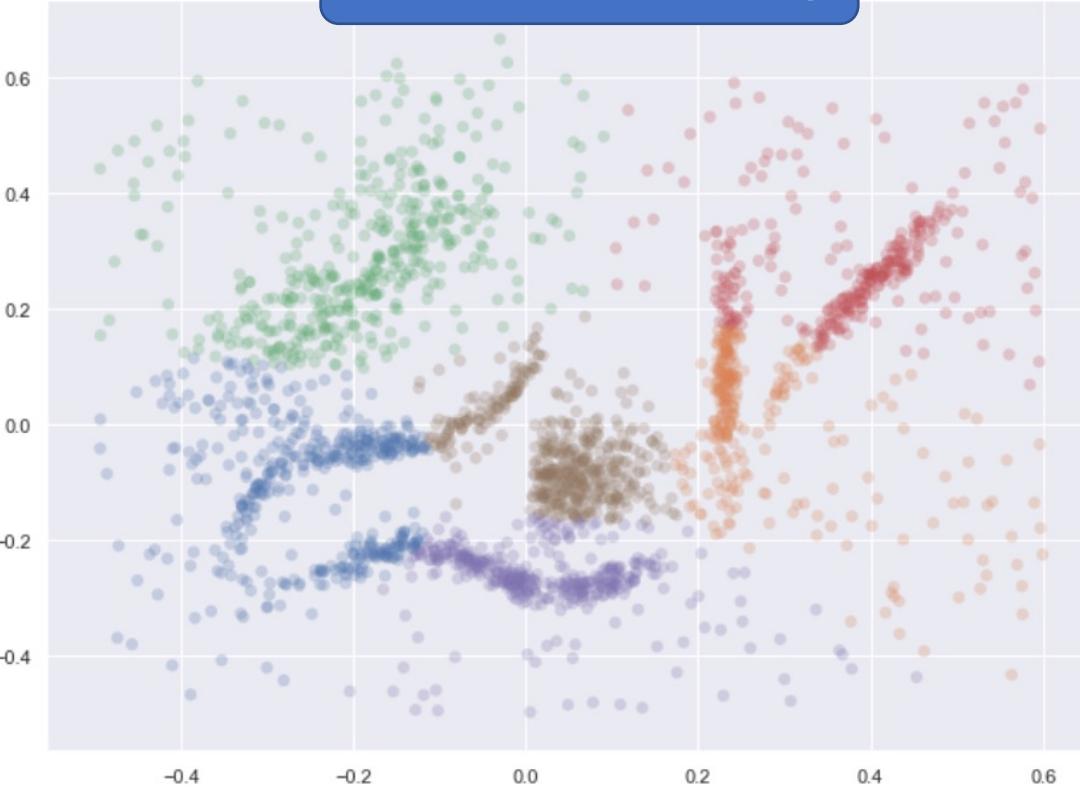
Alternatively, we can use clustering



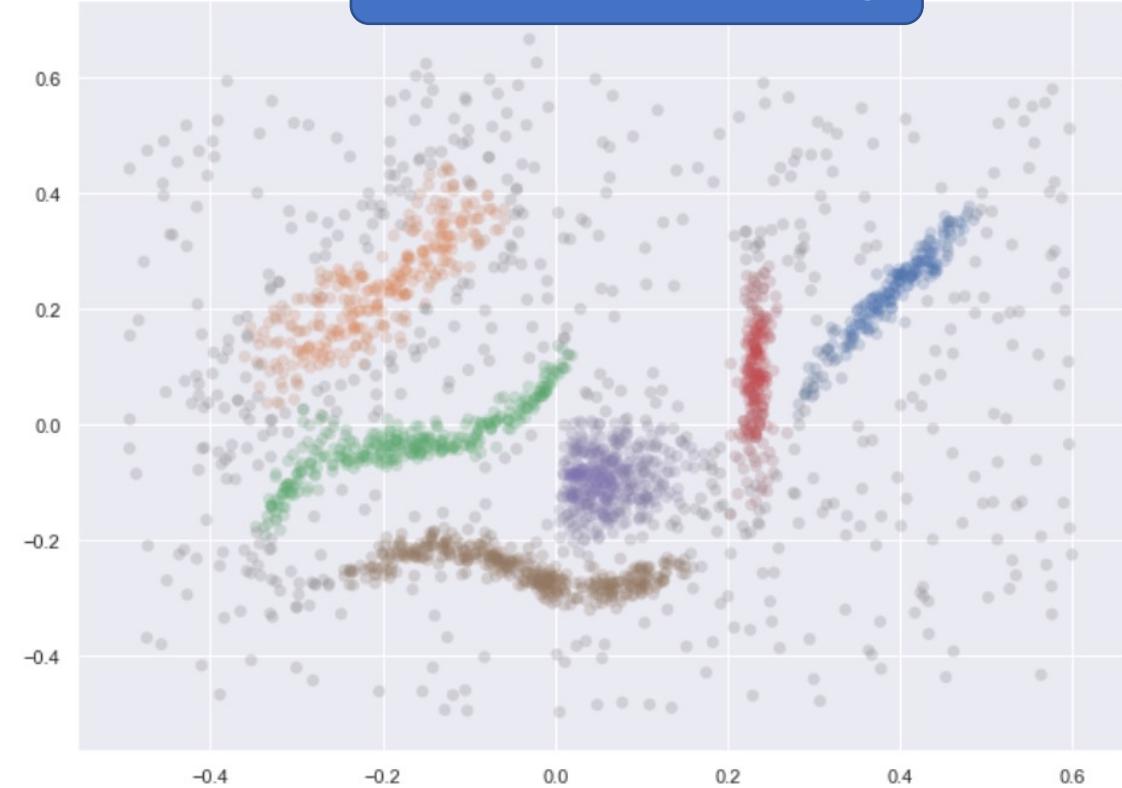
- Cluster in action and velocity spaces for kinematic structures

Alternatively, we can use clustering

K-Means Clustering

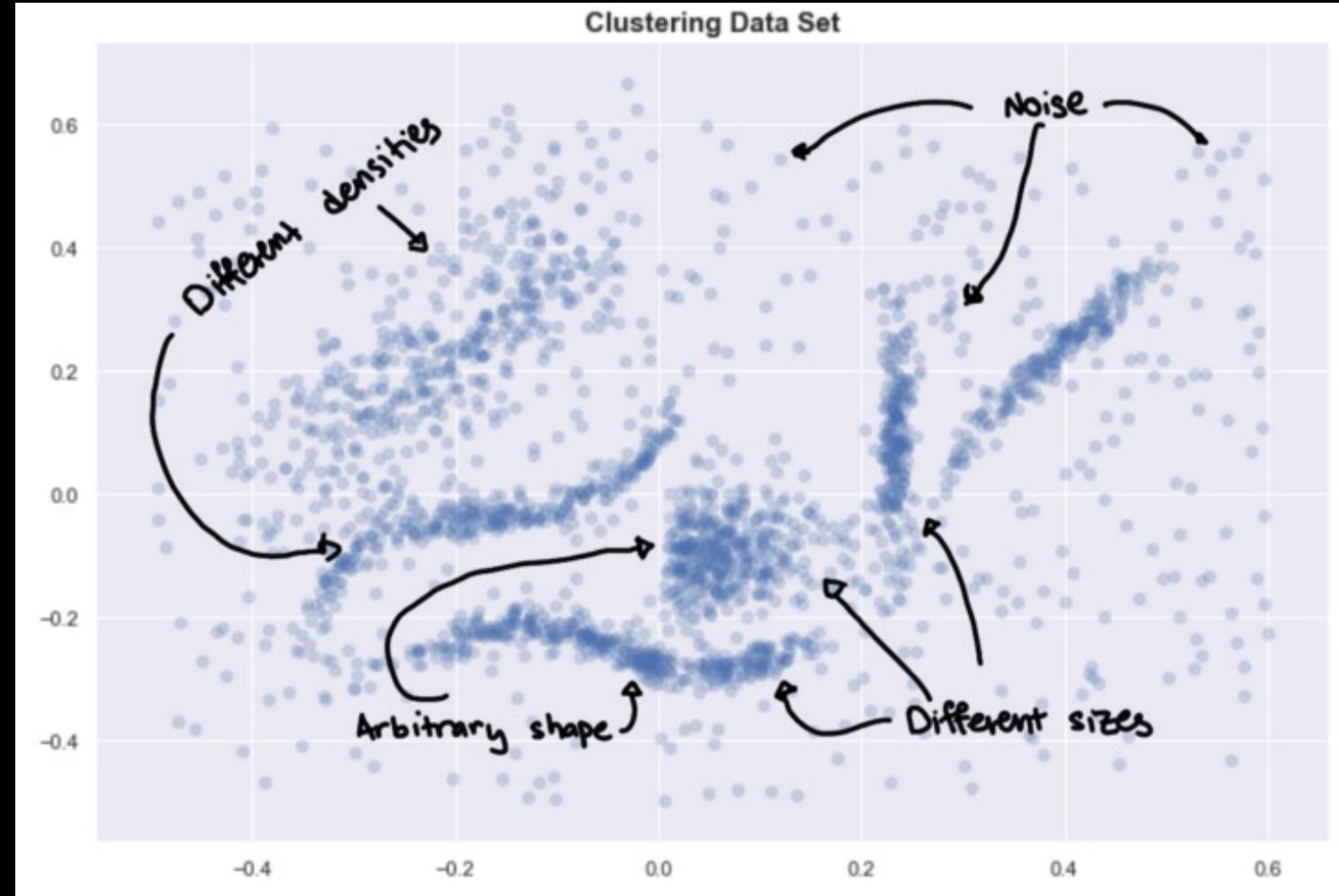


HDBScan Clustering



- Cluster in action and velocity spaces for kinematic structures

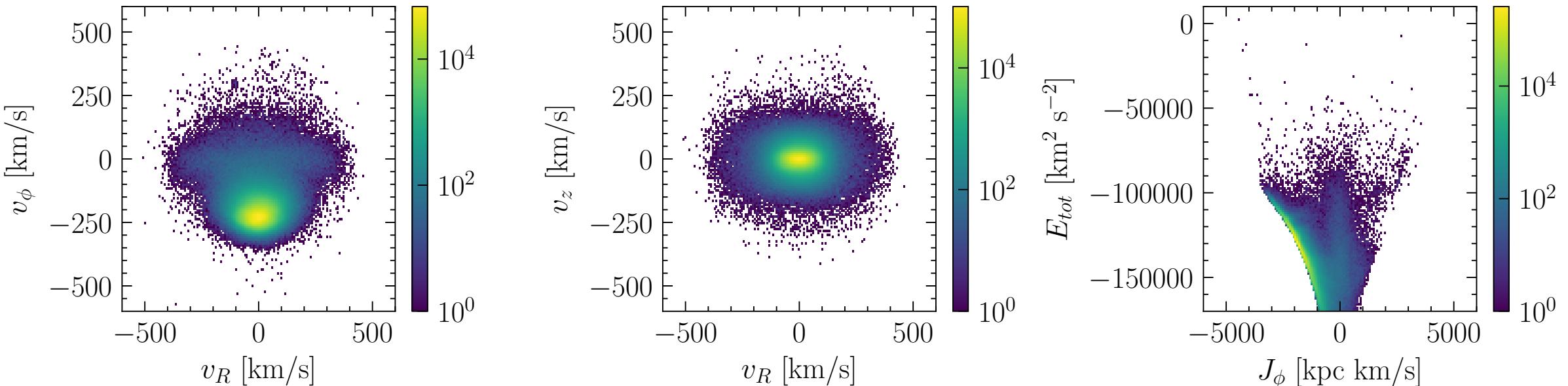
Alternatively, we can use clustering



We apply clustering on Gaia dataset



Xiaowei Ou

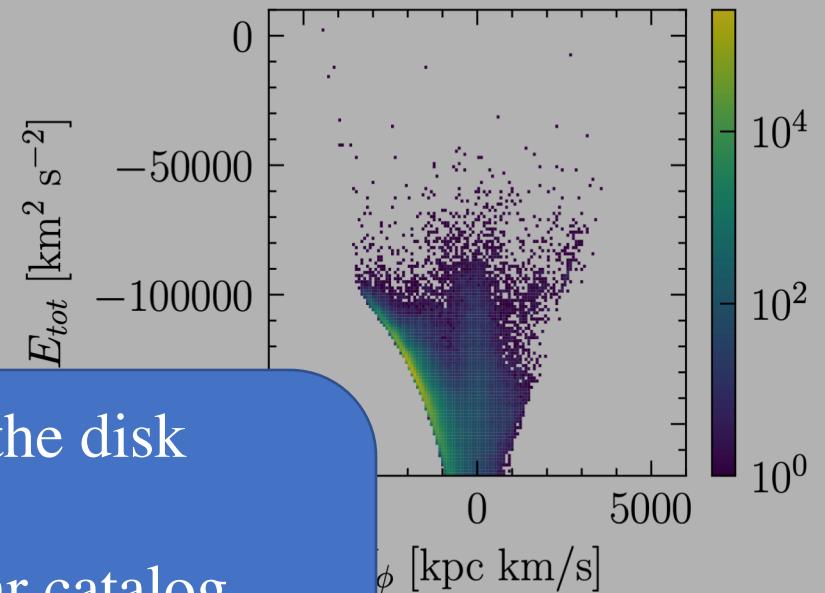
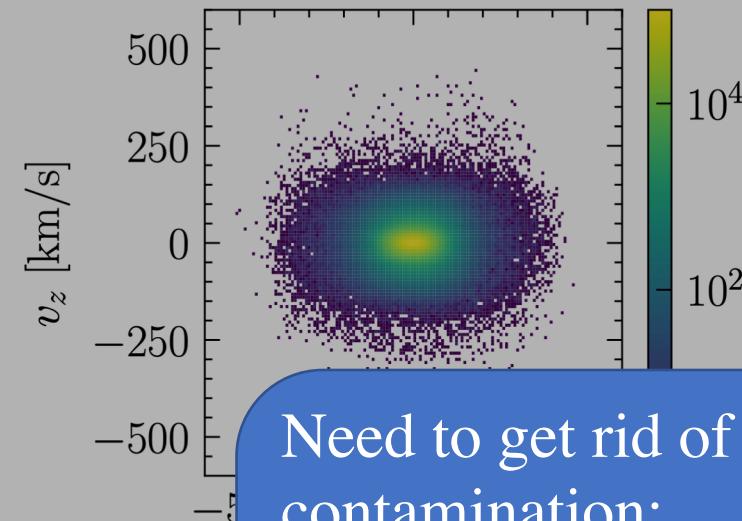
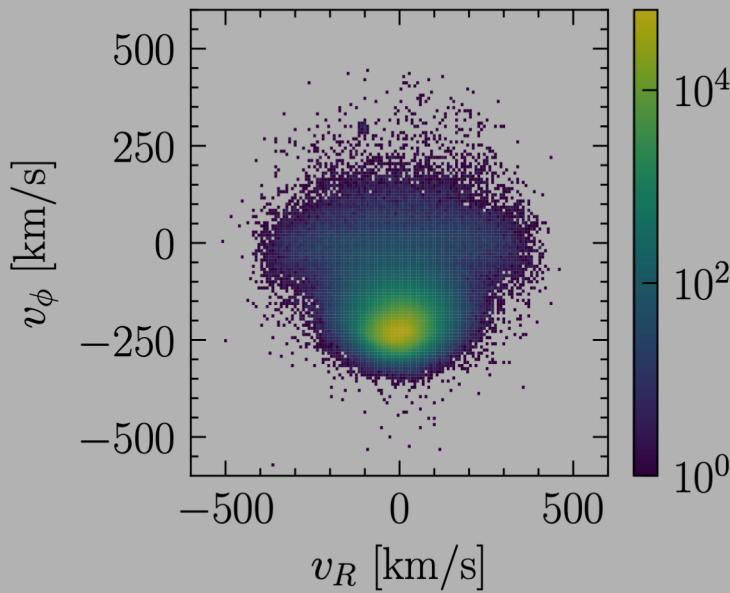


- Gaia eDR3 proper motions
- Gaia DR2 radial velocities
- Quality cuts

We apply clustering on Gaia dataset



Xiaowei Ou



Need to get rid of the disk contamination:

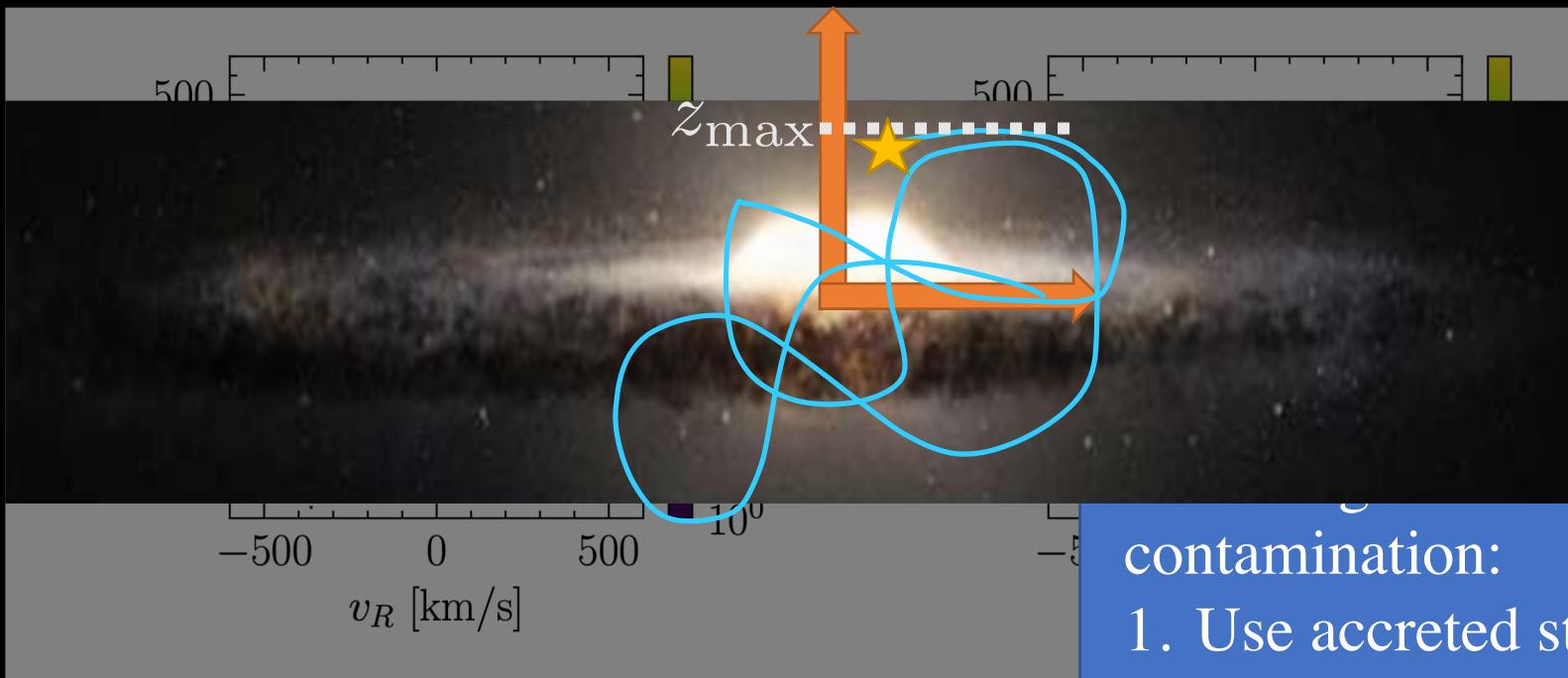
1. Use accreted star catalog.
2. Toomre plot cut.
3. Metallicity cut.
4. zmax cut.

- Gaia eDR3 proper motions
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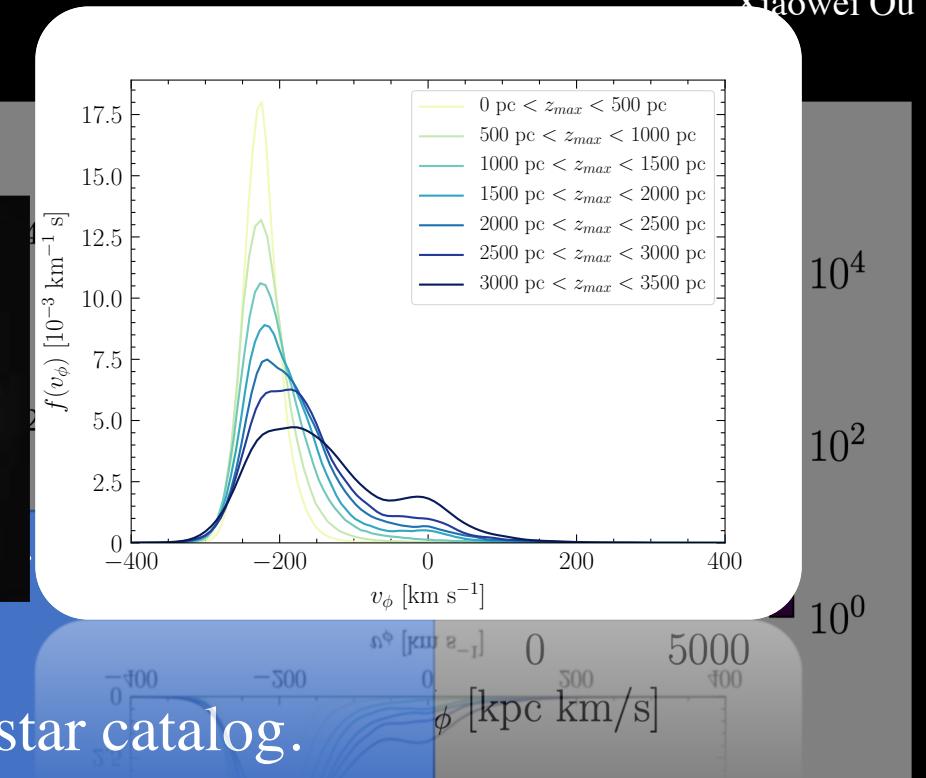
Xiaowei Ou



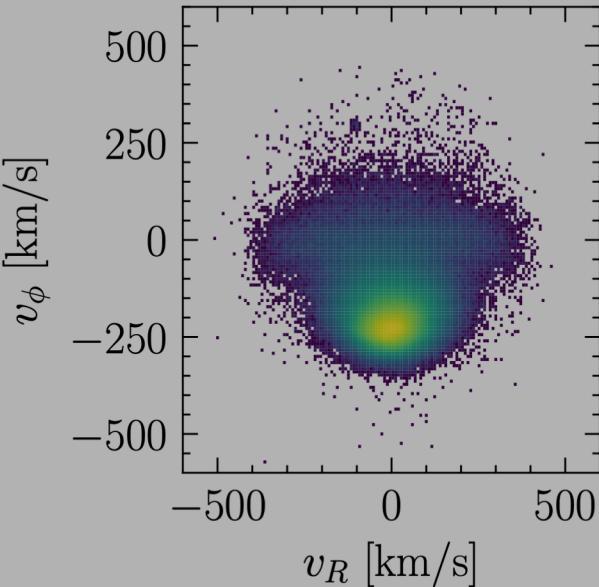
- Gaia eDR3 proper motions
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contamination:

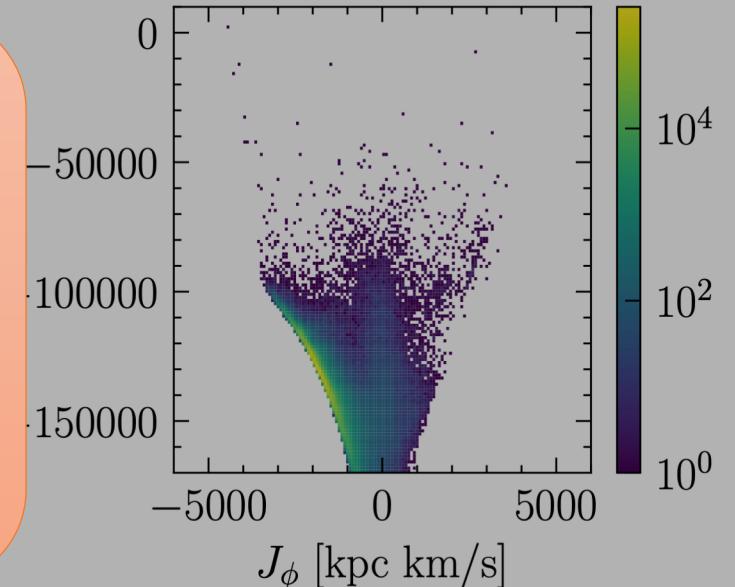
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4. **zmax cut.**



We apply clustering on Gaia dataset

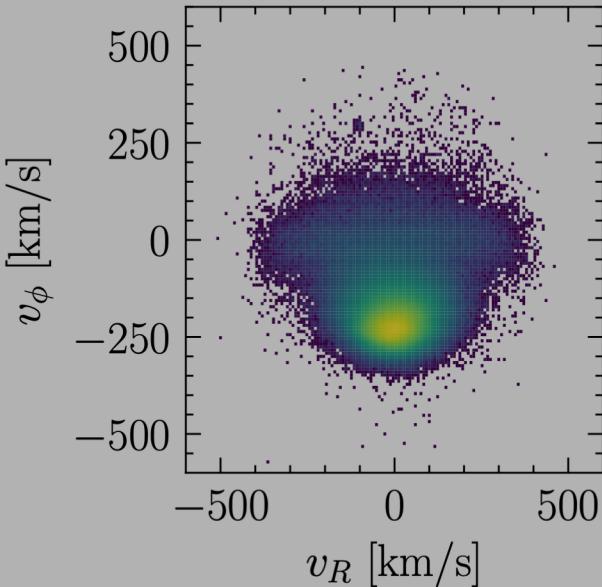


Main Requirement:
Stable clusters



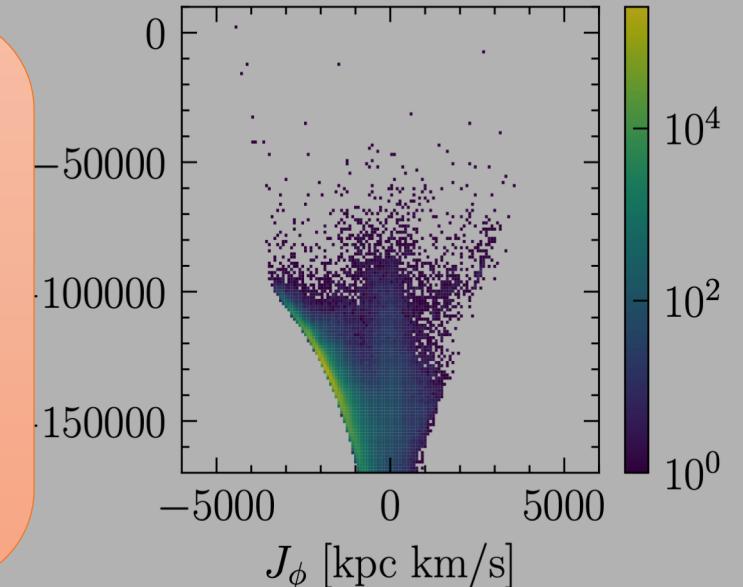
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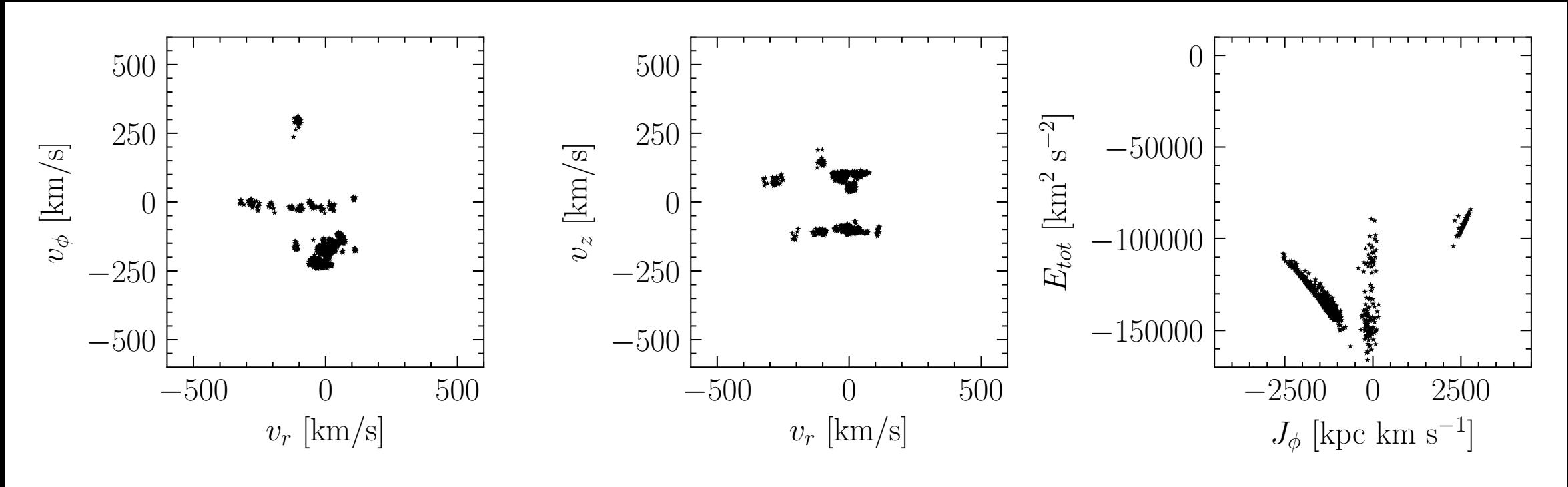
Main Requirement:
Stable clusters

Reclustering over different
realizations show that few
clusters are indeed stable



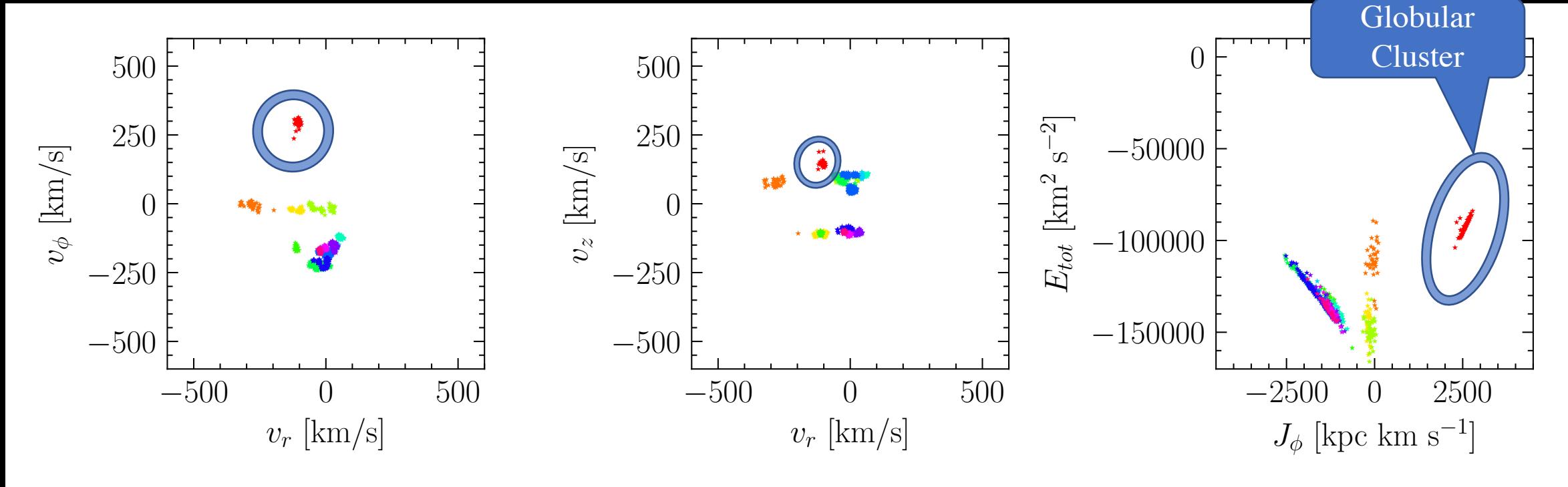
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Stability of Clusters

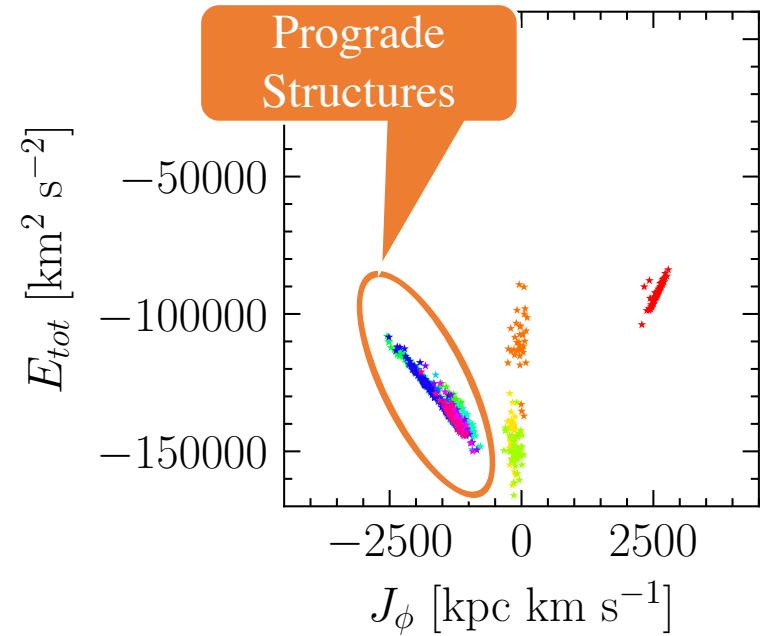
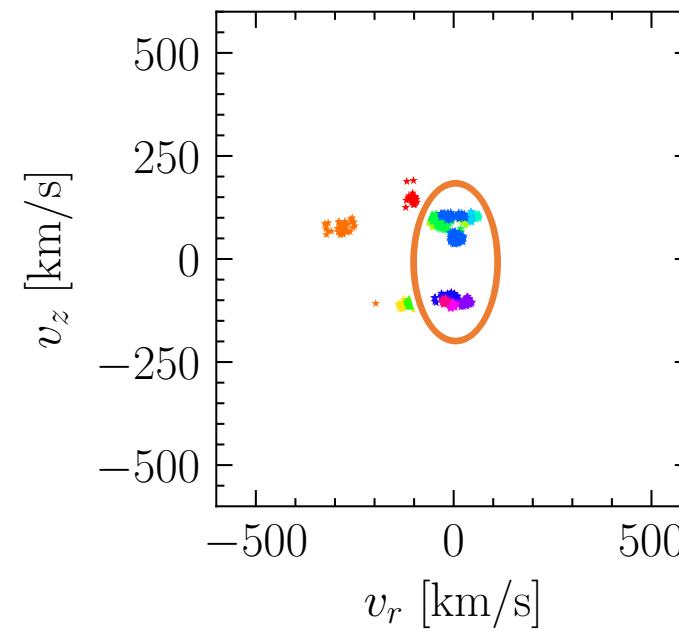
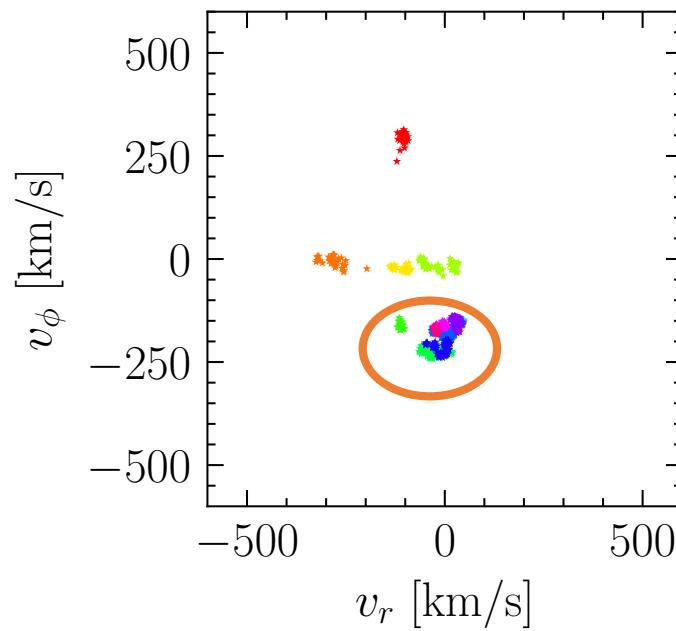


- Prioritized stable clusters.
- Looked at the stars that got clustered at least 40 times through 100 realizations. Dropped the stars always associated as noise.
- These structures are stable, although possibly incomplete.

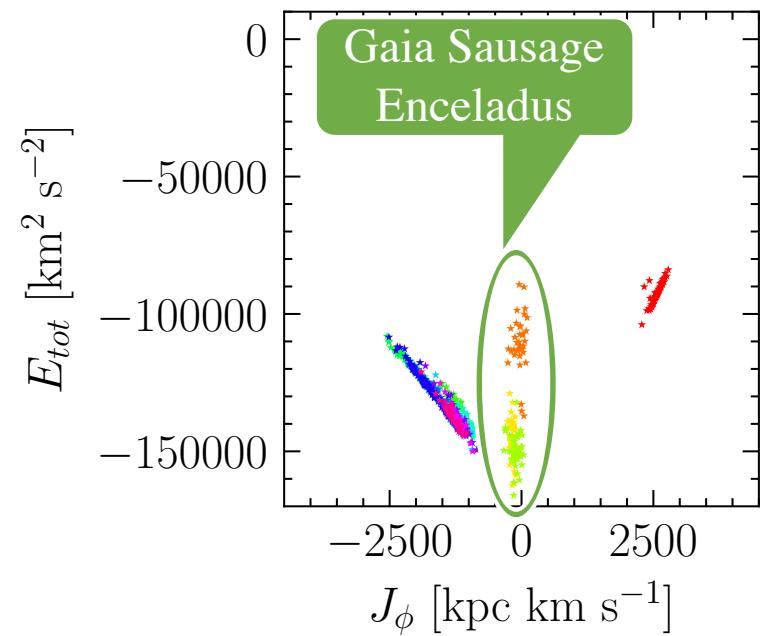
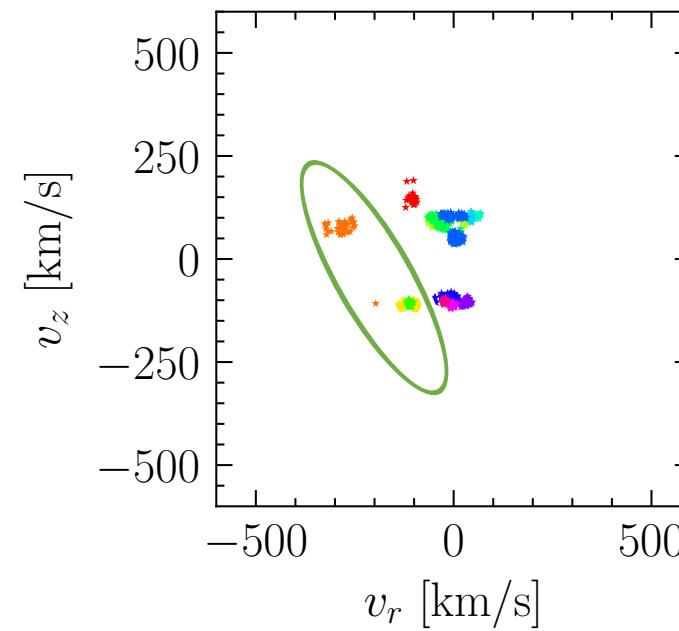
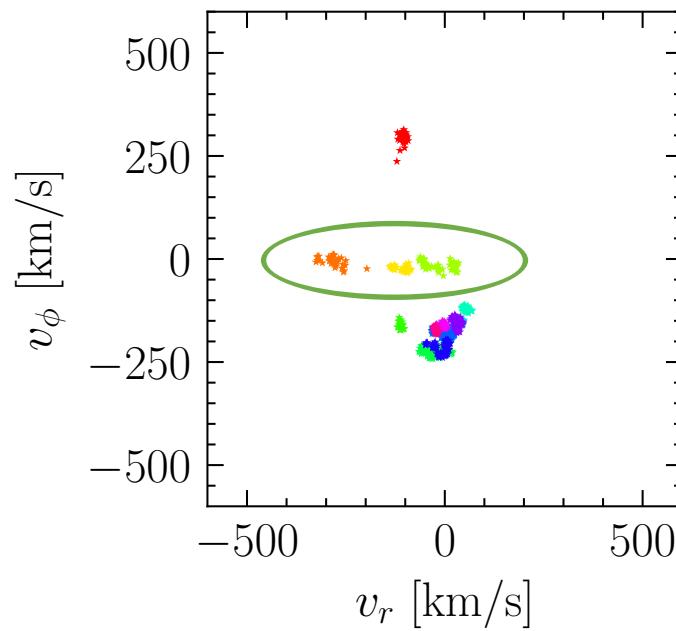
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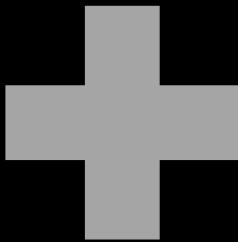
Stability of Clusters



Stability of Clusters



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Stellar and
Dark Matter
Velocity
Distributions



Identification
of Stellar
Structure



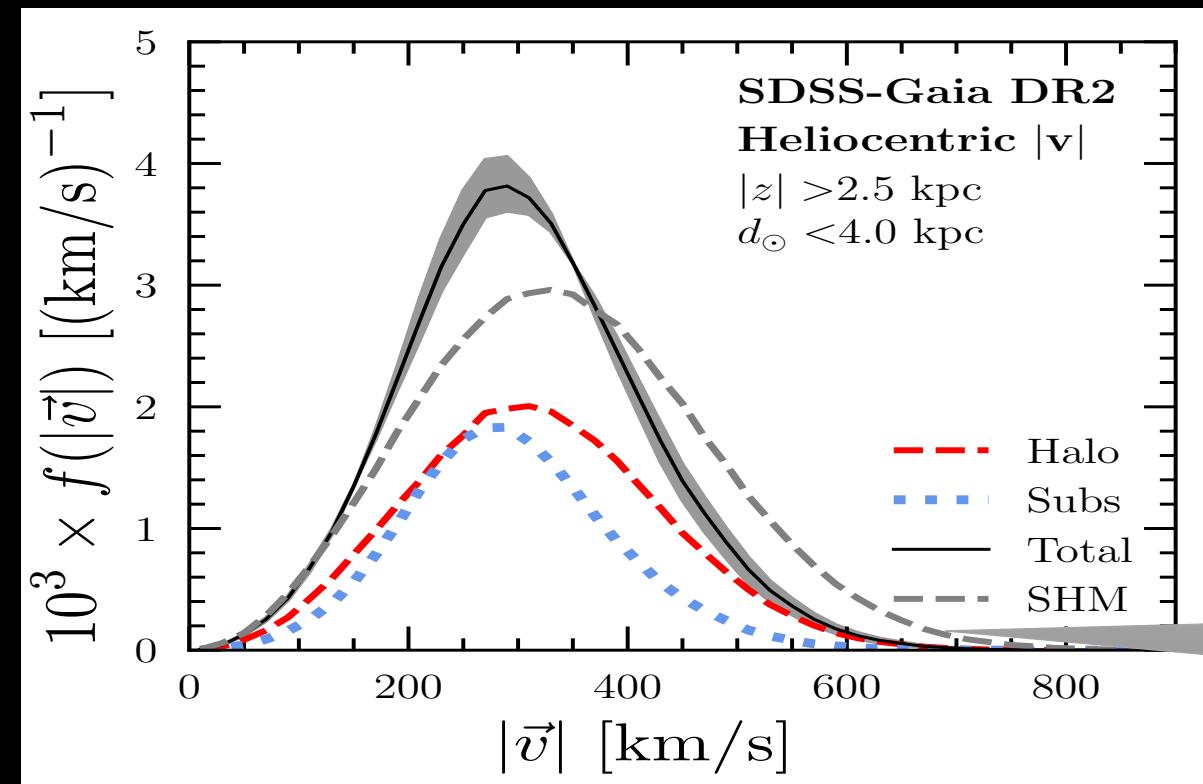
Building the
Velocity
Distribution
of Dark
Matter

- Build an accreted star catalog
- Model the stellar distributions

- Cluster in action and velocity spaces for kinematic structures

New Dark Matter Velocity Distribution

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



- Fraction Dark Matter \neq Fraction Stars.
- Use Mass-Metallicity relation to estimate fractions.

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

Final distribution different from
the assumed Maxwell
Boltzmann distribution

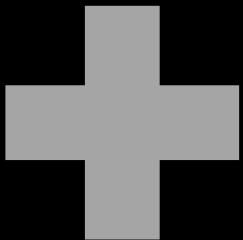
Kirby et al. (2013)

Garrison-Kimmel et al. (2015)

Necib, Lisanti, Belokurov (2018)

Necib, Lisanti, Garrison-Kimmel et al. (2018)

Correlation
between the
Stellar and
Dark Matter
Velocity
Distributions



Identification
of Stellar
Structure

- Build an accreted star catalog
- Model the stellar distributions



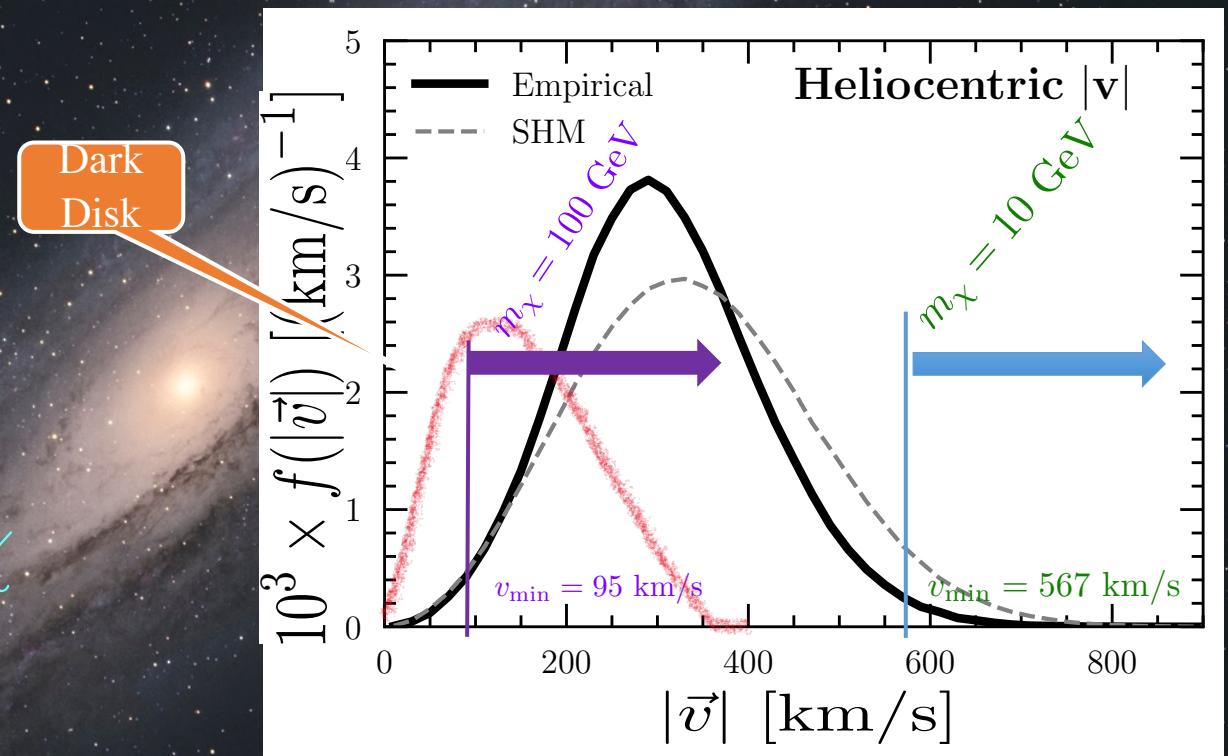
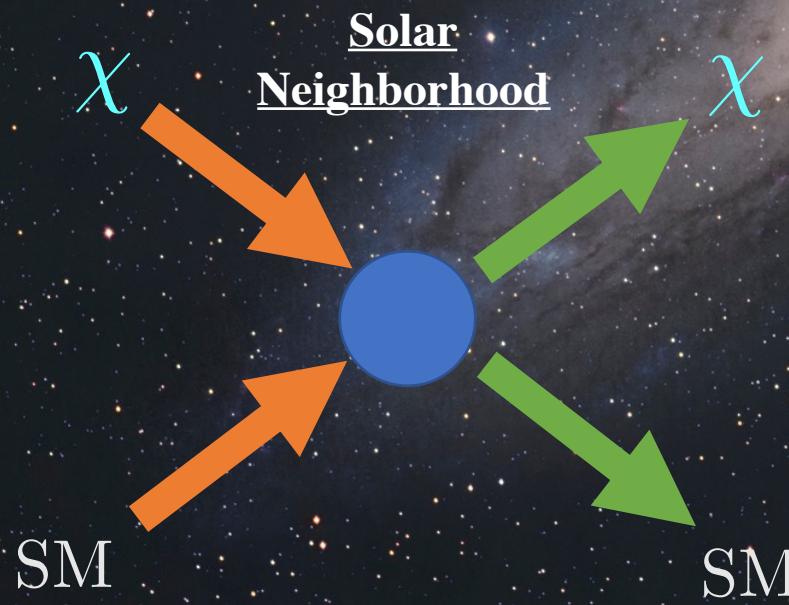
Building the
Velocity
Distribution
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Will address the smallest
structures.
Missing: Dark Subhalos

Direct Detection

End result:

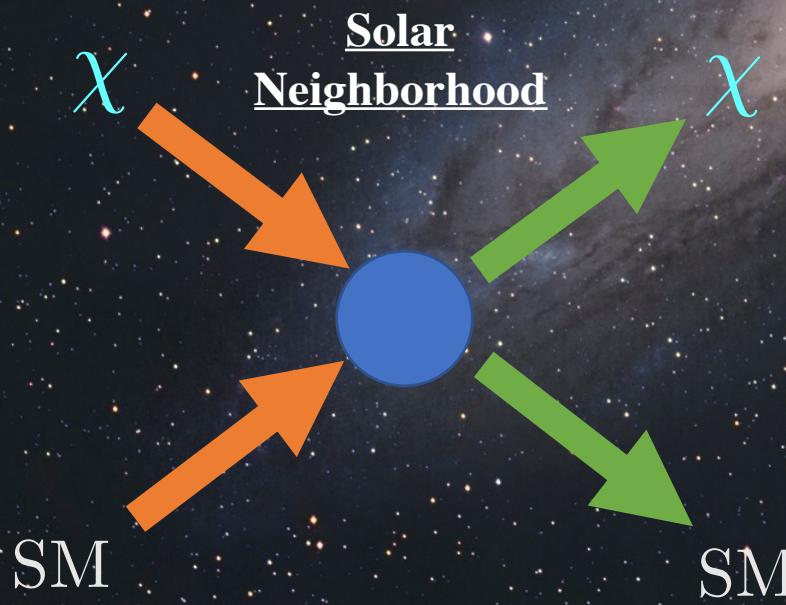
Build an accurate velocity distribution of Dark Matter that includes all structures.



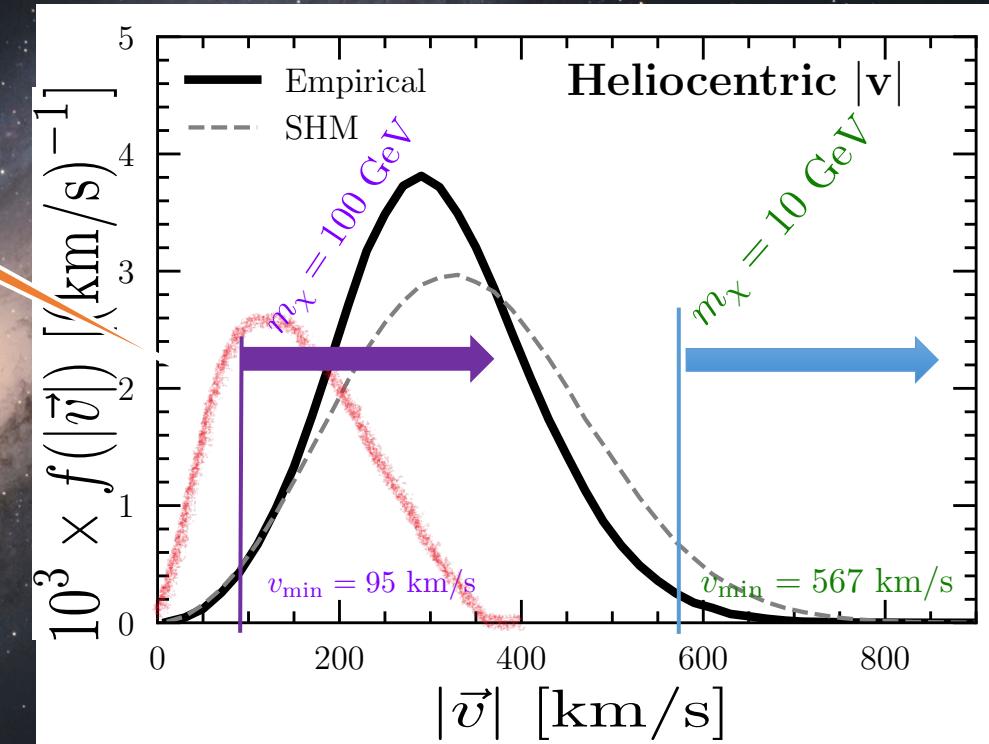
$$\text{Rate} \propto \rho_{DM} \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$
$$v_{\min} = v_{\min}(E_{\text{thresh}}, m_\chi)$$

Direct Detection

We finally have the resources
in observations and
simulations to address the
elephant in the room in Dark
Matter detection:
Astrophysics!



Dark Disk



$$\text{Rate} \propto \rho_{DM} \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$
$$v_{\min} = v_{\min}(E_{\text{thresh}}, m_\chi)$$