Machine Learning the 6th Dimension: Stellar Radial Velocities from 5D Phase-Space Correlations

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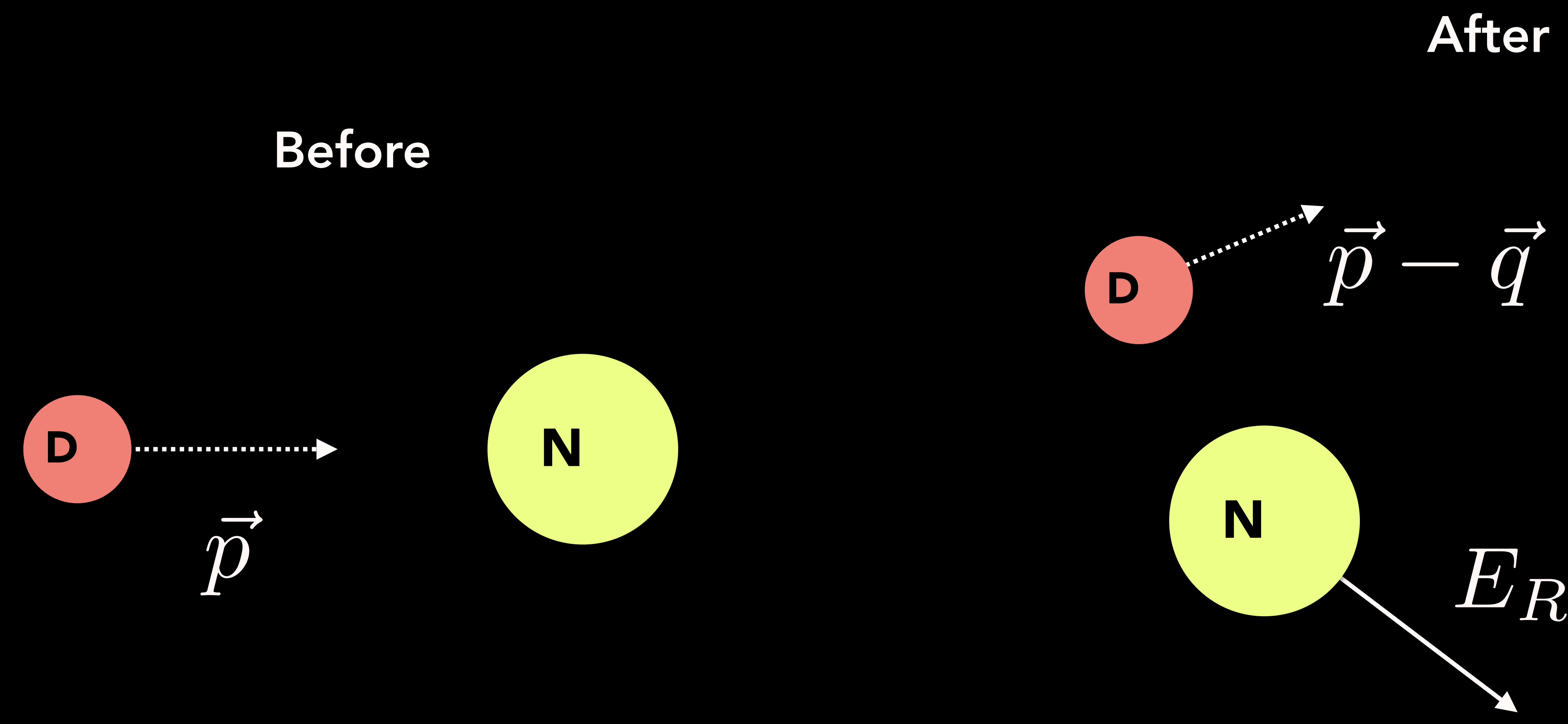
Direct Detection

& Dark Matter Velocity Distribution $f(v)$



$$E_R = \frac{q^2}{2m_N}$$

$$q \sim m_\chi v_{DM}$$

$$R = n\sigma \langle v_{DM} \rangle / m_N$$

Event rate

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} v f(v) \frac{d\sigma}{dE_R} d^3 v$$

Recoil energy of nucleus

DM velocity distribution —> needs to be determined astrophysically

$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2} \langle | M_{NR} |^2 \rangle$$

Depends on properties of DM particle and mediator of interaction

Dark Matter Velocity Distribution $f(v)$
& The Standard Halo Model

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

$$f(x, p, t)$$

Assumes DM is fully virialized!

conservation of fluid mass

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

→

additional assumptions

steady state
isotropic velocities
flat rotation curve

↓

isothermal density

$$n \sim r^{-2}$$

←

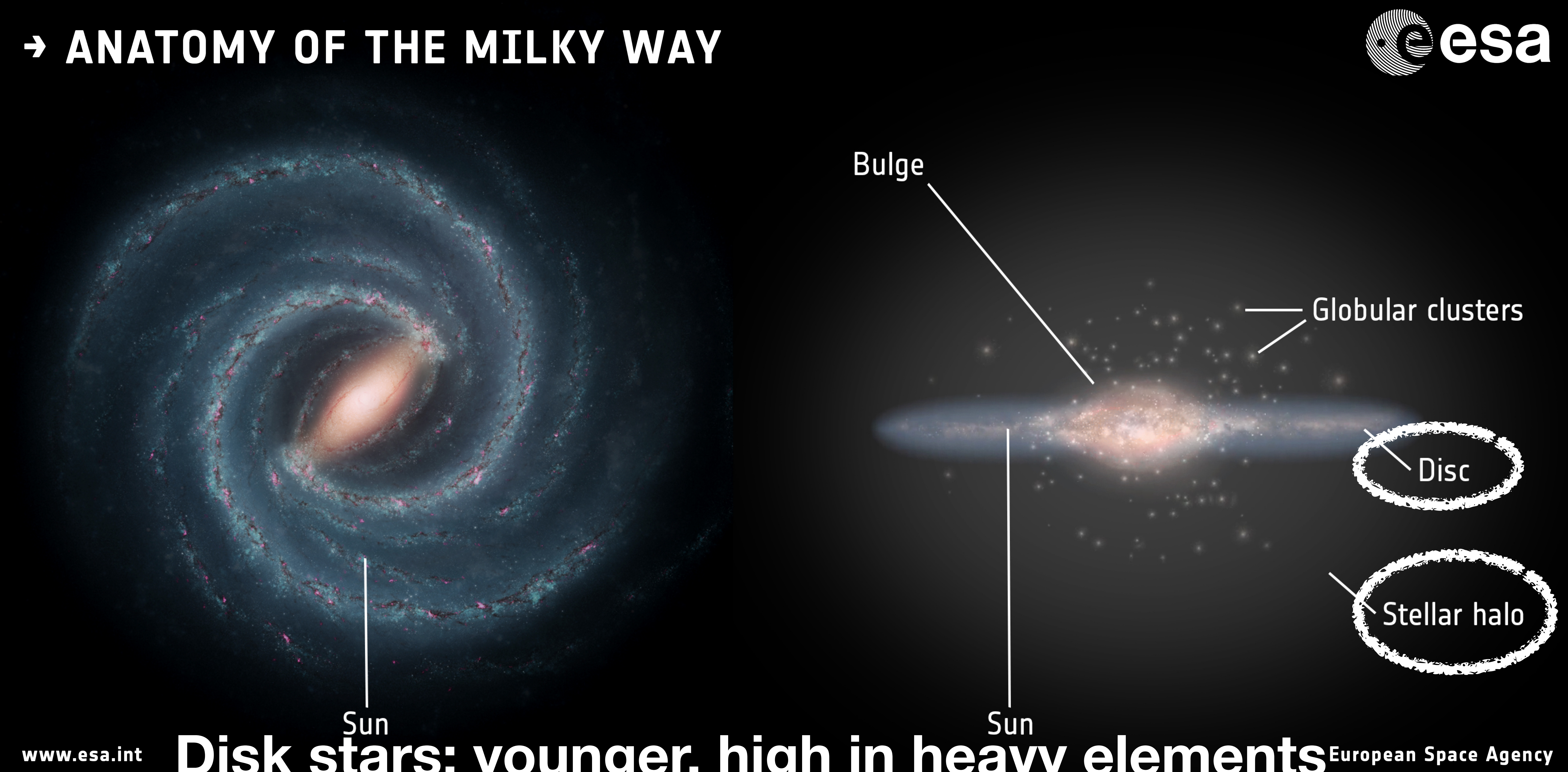
Maxwell-Boltzmann

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

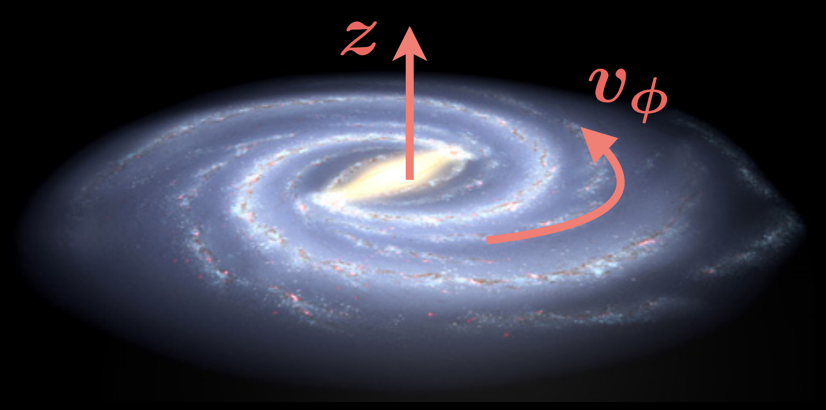
Can there be substructure?

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

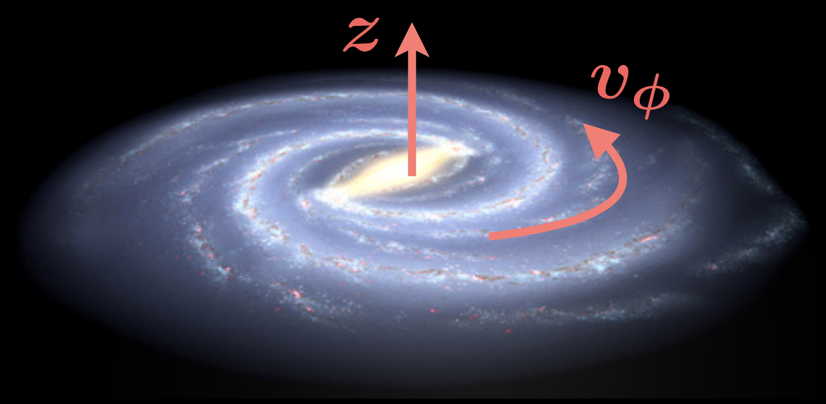
Quick Guide to Stars in the Galaxy



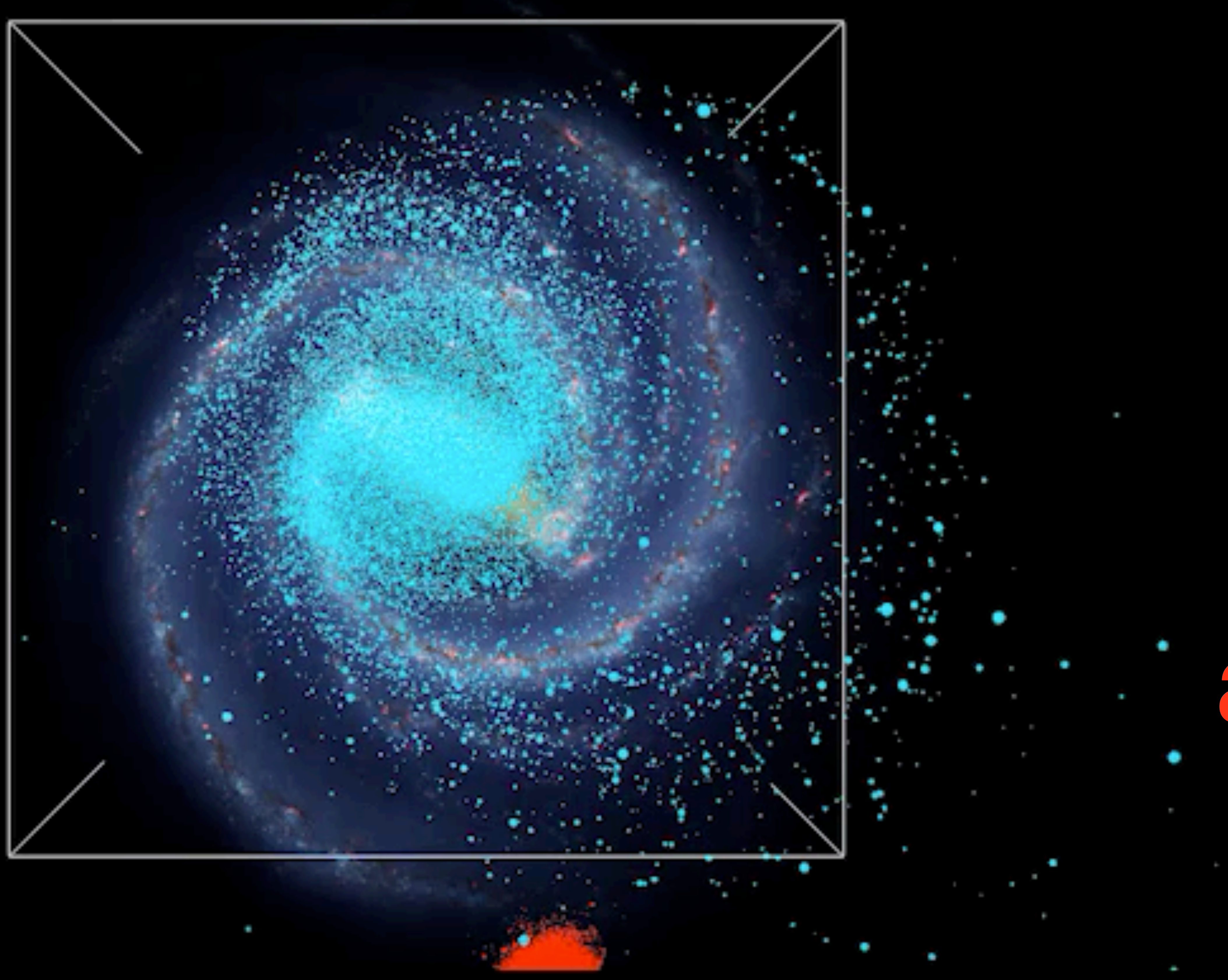
Disk stars: younger, high in heavy elements
Halo stars: older, low in heavy elements, primarily from accreted satellite mergers



Merger History of the Milky Way



- Single merger dragged in the majority of the local accreted stars



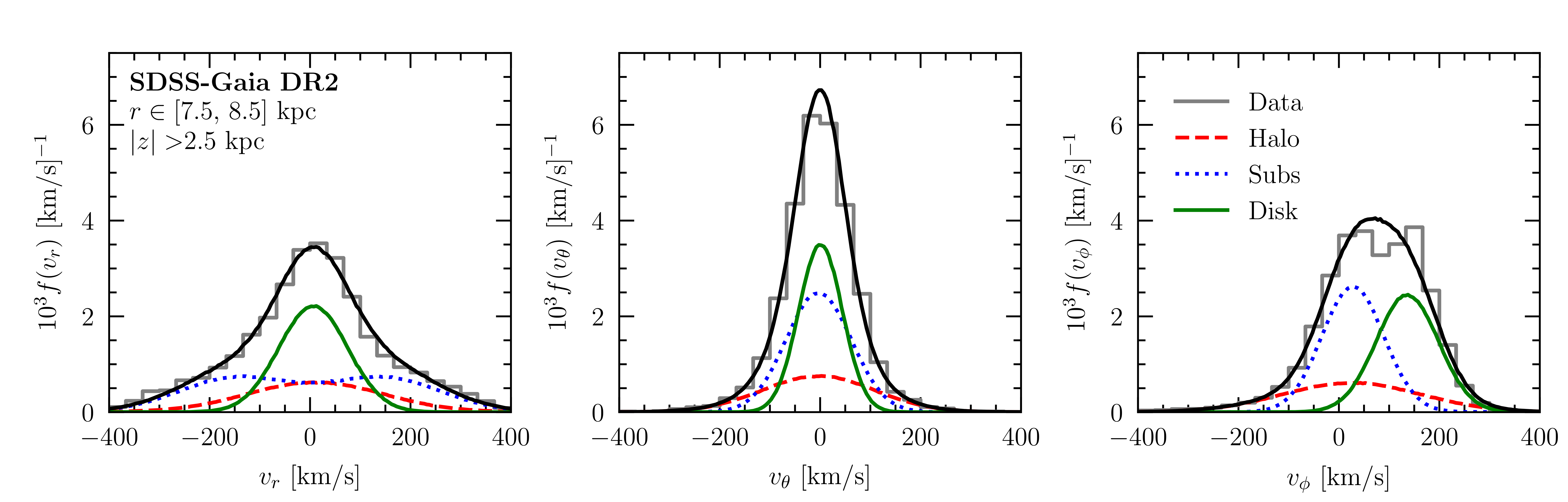
How does Gaia-Enceladus affect $f(v)$?

Belokurov et al. (2018); Helmi et al. (2018)

Video Credit: H. Koppelman, A. Villalobos, A. Helmi

Effect of Gaia-Enceladus on $f(v)$

- DM velocities should track that of Gaia-Enceladus (subs) stars
- ~ 40% of local DM is in Gaia-Enceladus
- We want to study the properties of these stars (but first we need to find more of them)!

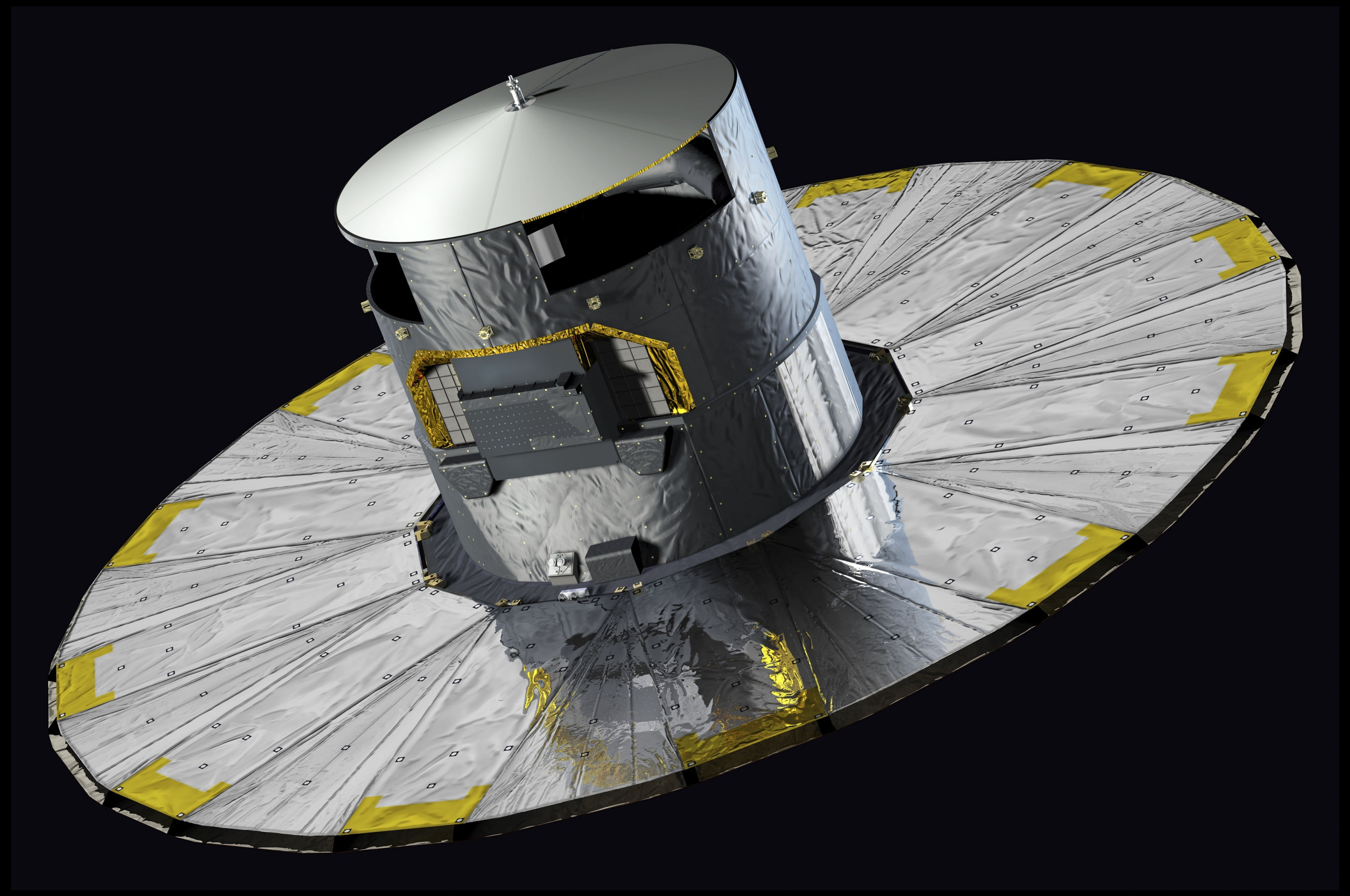


L. Necib, M. Lisanti, and V. Belokurov, ApJ (2019)

The Gaia Mission

Gaia Collaboration (2018)

- Astrometric survey, goal to observe positions and velocities of ~1 billion Milky Way stars
- But, only a small number of these (~7 million) have full velocity information
- → Machine learning! (on a mock Gaia catalog)
- Neural network can predict accurate velocity distributions

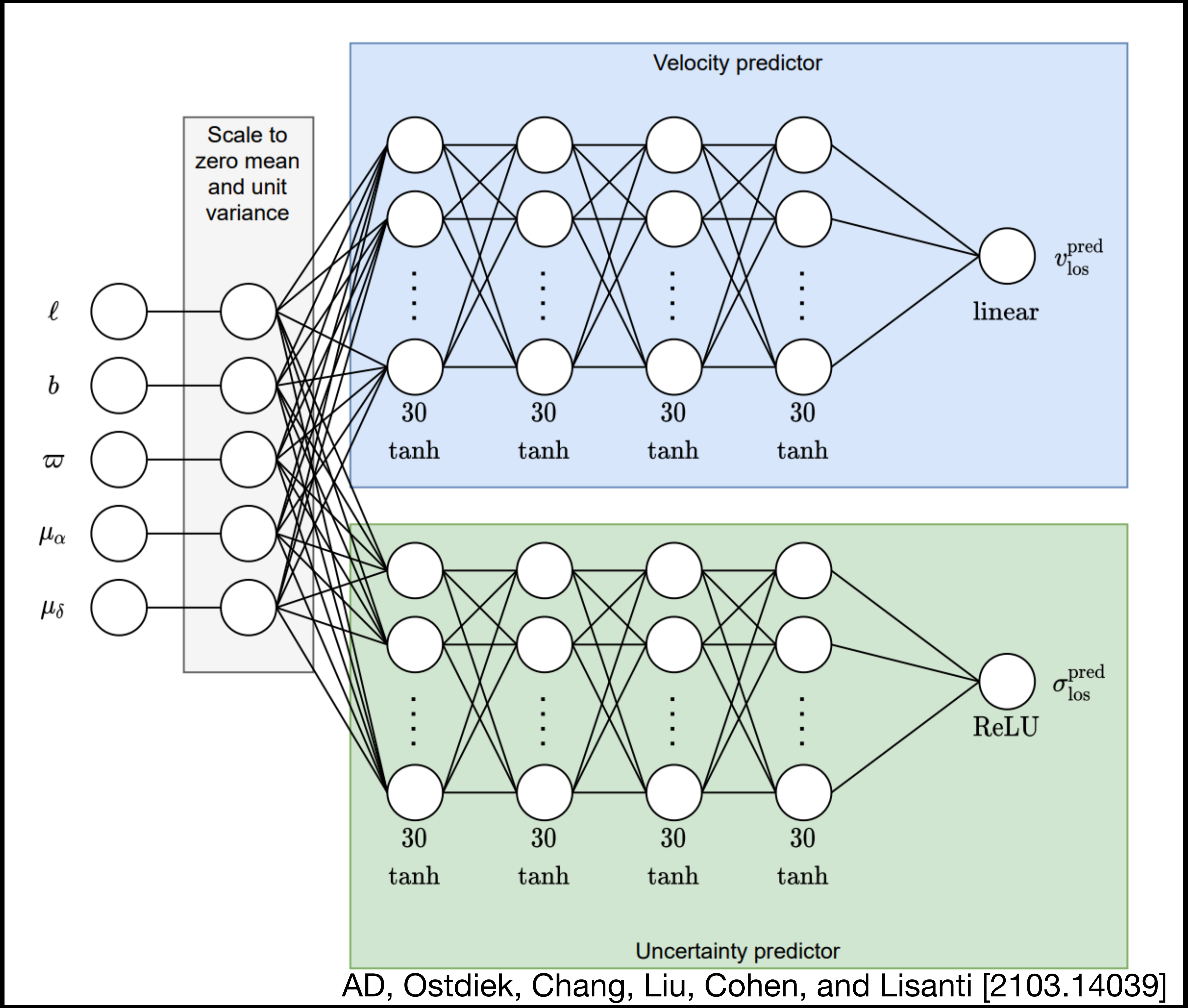


Machine Learning the 6th Dimension

6th dimension = velocity along the line-of-sight

Network Inputs

5D astrometric coordinates



Network Outputs

line-of-sight velocity

uncertainty on line-of-sight velocity prediction

$$\mathscr{L} = \sum_{i=1}^{N} \frac{w_i}{N} \left[\frac{\left(v_{los,i} - v_{los,i}^{pred}\right)^2}{\left(\sqrt{2}\sigma_{los,i}^{pred}\right)^2} - log\left(\frac{1}{\sqrt{2\pi}\,\sigma_{los,i}^{pred}}\right) \right]$$

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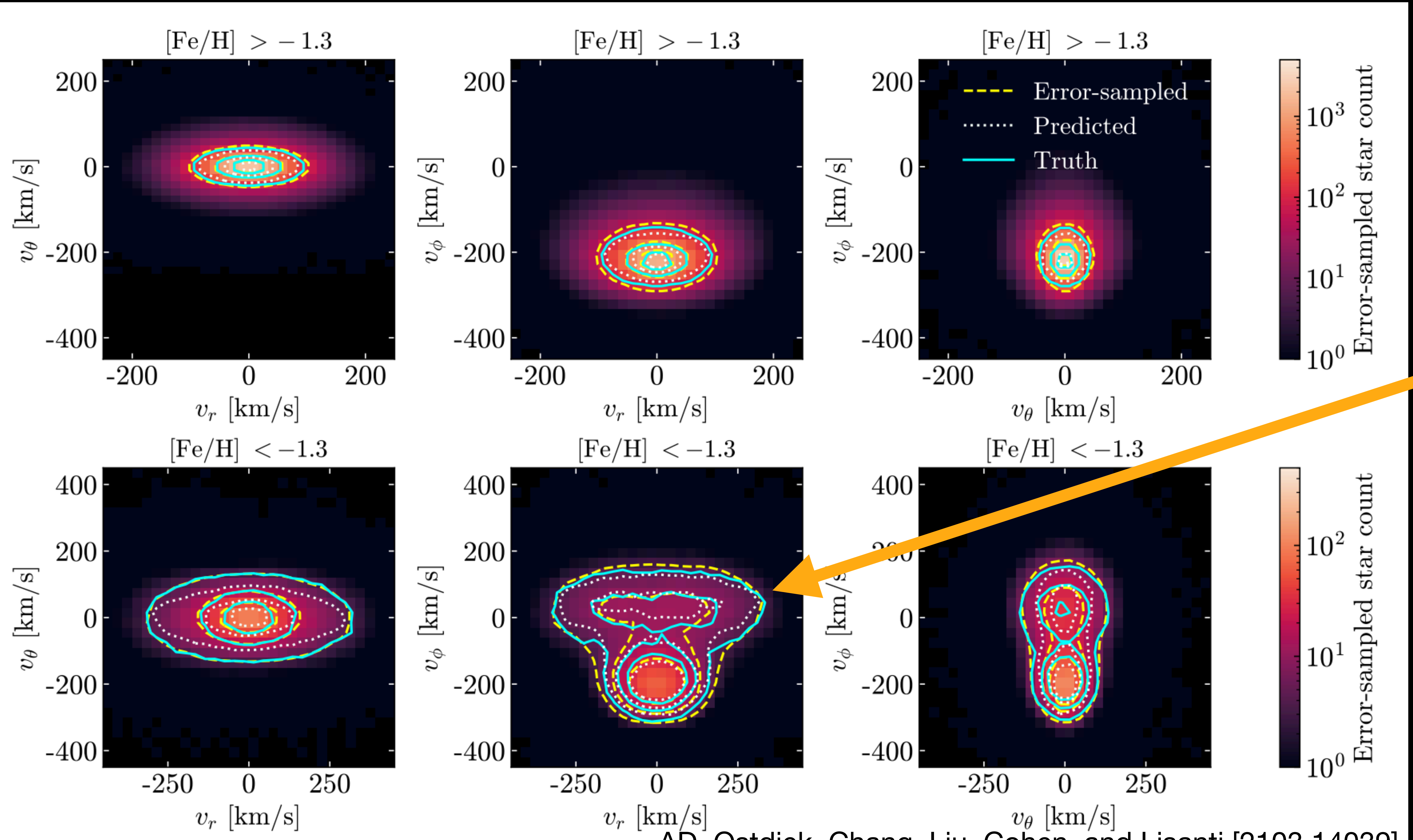
Results on Mock Gaia Data

- Network is trained on subset of mock catalog with full 6D information (+ Enceladus-like stars) and tested on the rest of the catalog

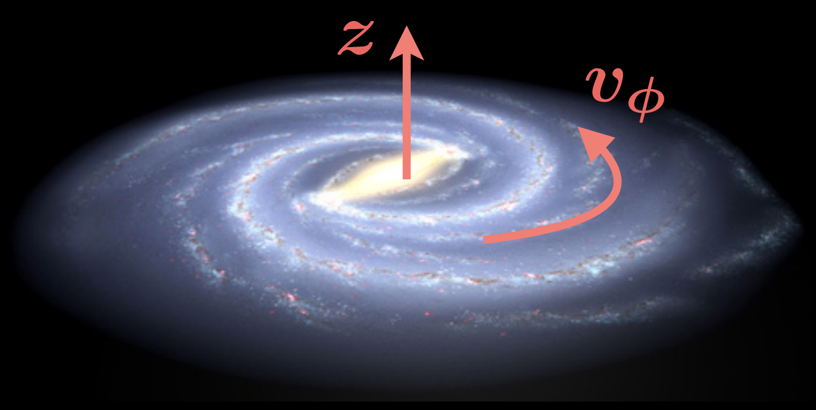
younger stars

older stars



AD, Ostdiek, Chang, Liu, Cohen, and Lisanti [2103.14039]

We can already see Enceladus in the extended radial velocity distribution (that the network can correctly identify)!



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Current and Future Work

Apply the network to real Gaia data

↓

Identify more Enceladus stars

↓

Dark matter - stellar correspondence

↓

Improve empirical halo model

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Backup

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Chemical Abundance

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

- Low metallicity of the halo: majority of gas was expelled from the halo before significant supernova-induced enrichment could occur.
    - 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
- This gas may have formed much of the Galaxy's bulge.

Thermonuclear Supernova

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

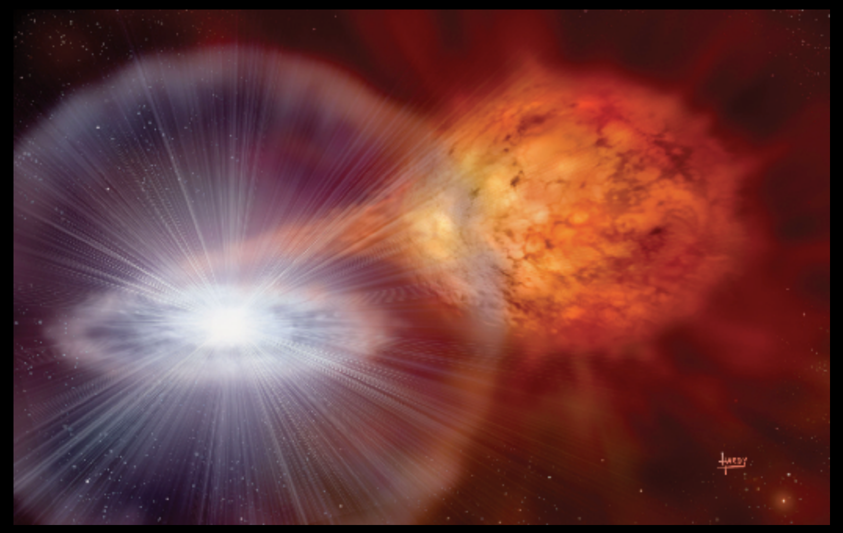


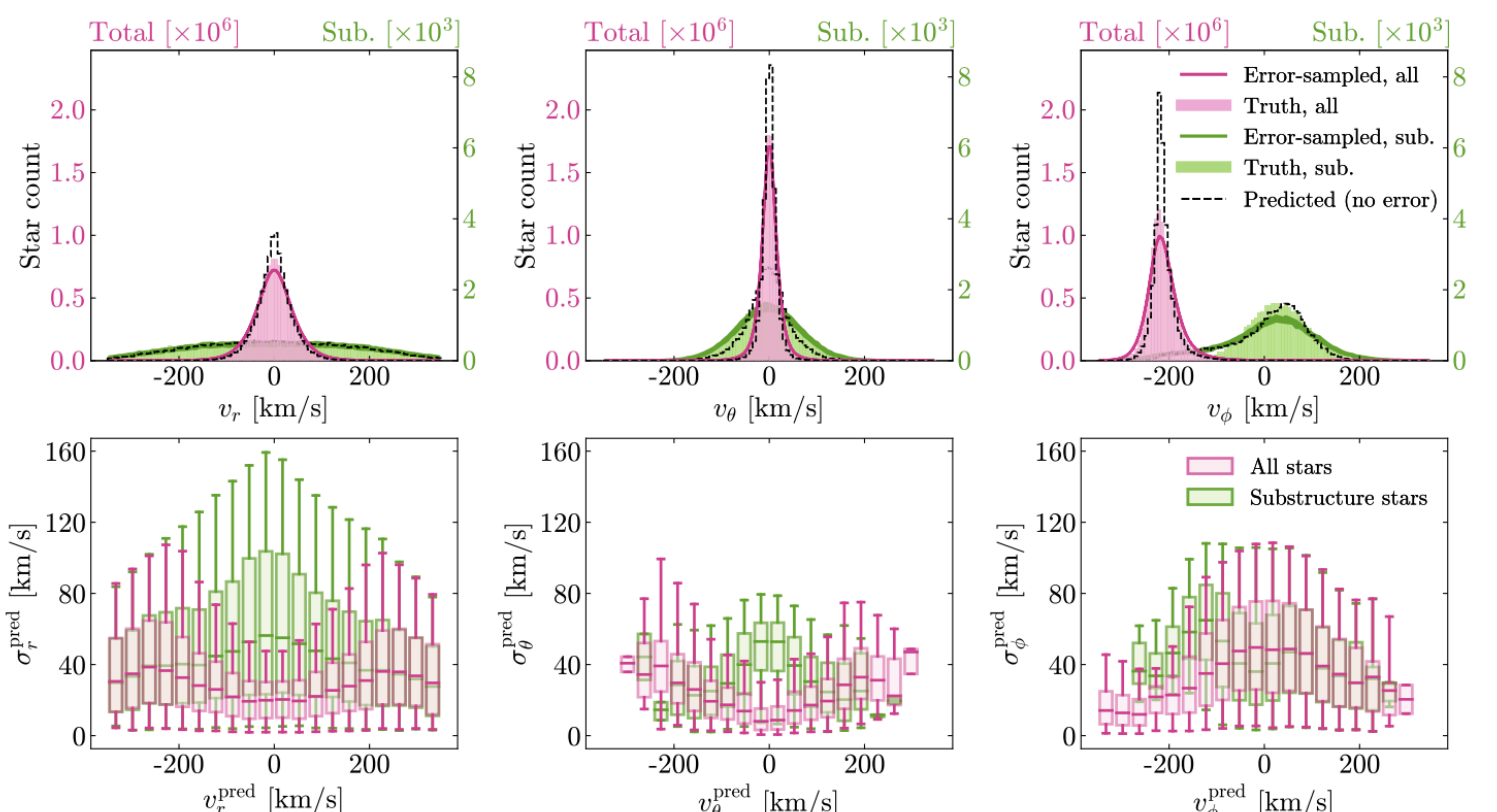
Image: D. Hardy (astroart.org)

Core-collapse Supernova

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

Image: Chandra

How well can we identify Gaia-Enceladus?



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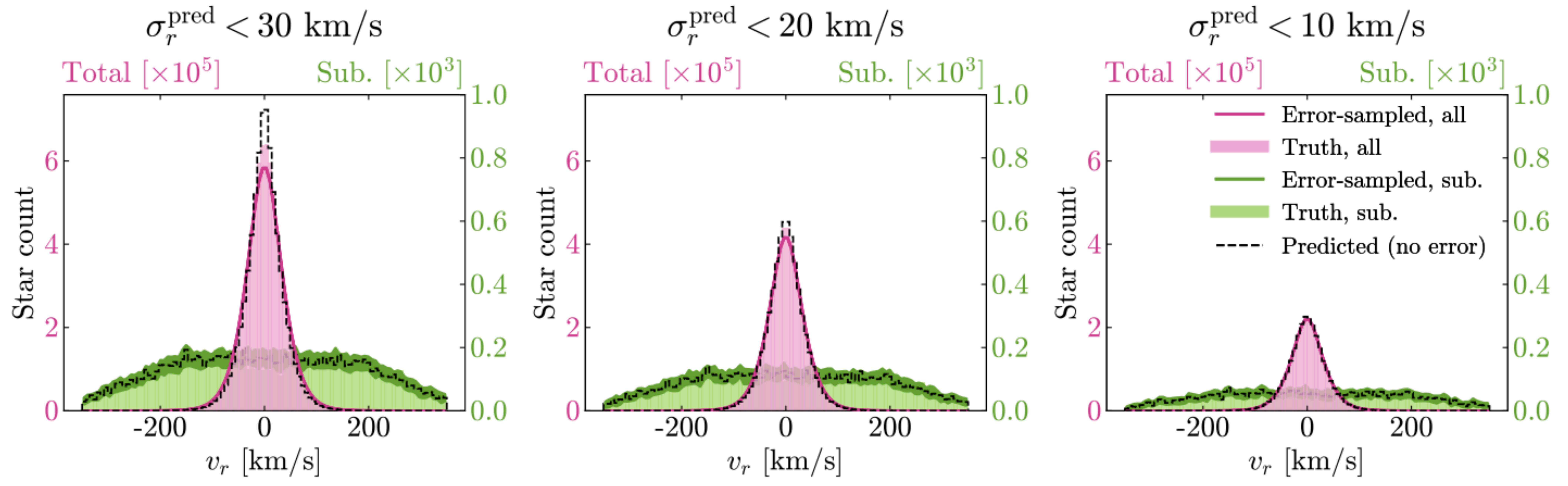

Figure A2. The lines depicted in this figure are the same as those in Fig. 1. However, this figure specifically focuses on the Galactocentric radial velocity v_r, to show that the distribution is unbiased as more restrictive cuts on σ_r^{pred} are made.

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