Title: Discovering the Goddess of the Night with Machine Learning

Speakers: Miriangela Lisanti

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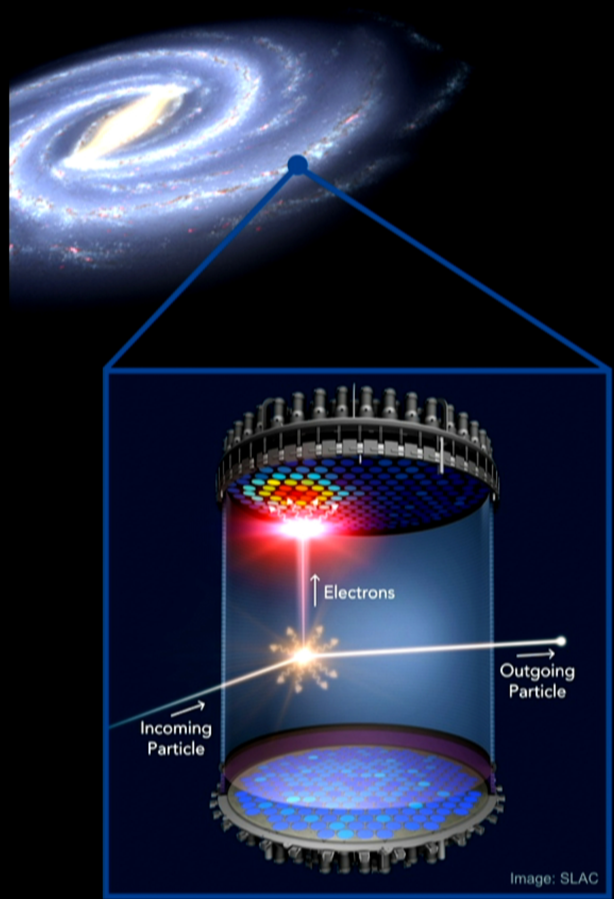
Abstract: The Gaia mission is in the process of mapping nearly 1% of the Milky Wayâ€™s stars. This data set is unprecedented and provides a unique view into the formation history of our Galaxy and its associated dark matter halo. My talk will focus primarily on recent work using deep learning methods to classify Gaia stars that were born inside the Milky Way, versus those that were accreted from satellite mergers. Using these techniques, we discovered a vast stellar stream, called Nyx (after the Goddess of the Night), in the Solar vicinity that co-rotates with the Galactic disk. If Nyx is the remnant of a disrupted dwarf galaxy, it may provide the first evidence for an accreted stellar disk and a dark matter disk.

Discovering the Goddess of the Night with Machine Learning

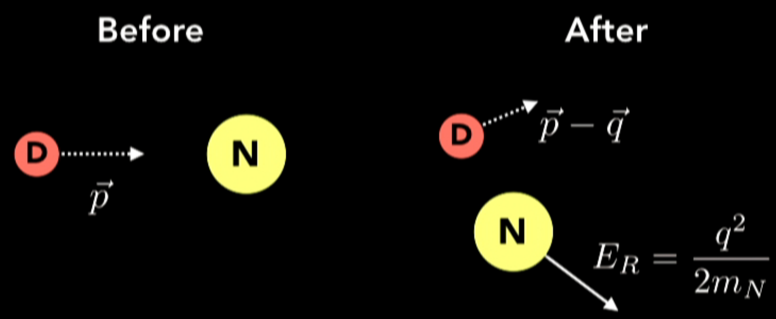
Mariangela Lisanti
Princeton University

"Nyx," Gregoire A. Meyer

Local Dark Matter Map



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



Need a phase-space map of the halo to accurately predict scattering rate

$$\text{Rate} = n\,\langle \sigma\, v \rangle$$

The Dark Matter Halo v1.0

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

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

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

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

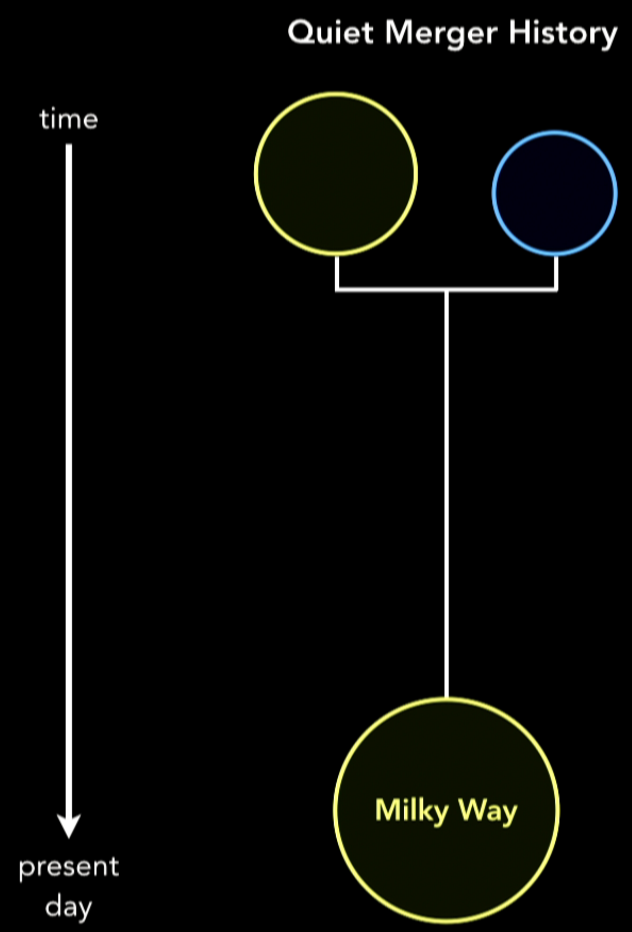
←

Maxwell-Boltzmann

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

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



Galactic Cannibalism & Dark Matter

Unveiling the Milky Way's Past with *Gaia*

Putting Machine Learning to Use

Simulated Galaxy Formation

Stellar Structure Evolution in the FIRE Simulation

Hopkins et al. (2015)

Simulated Galaxy Formation

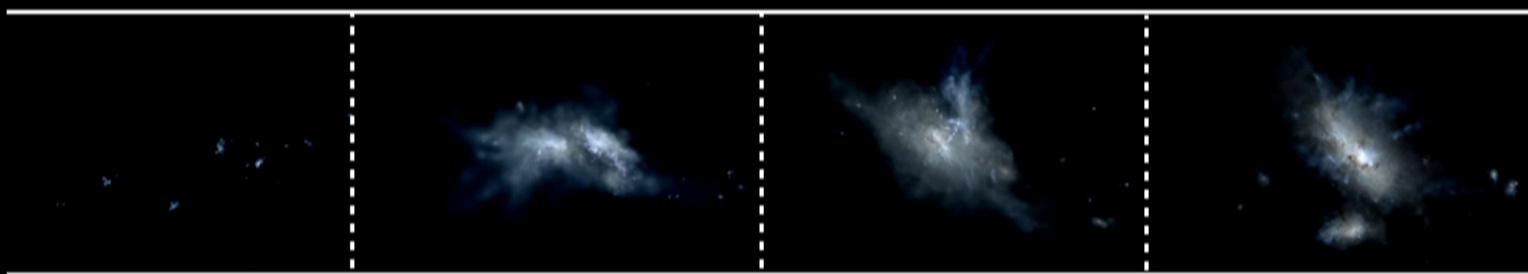
Stellar Structure Evolution in the FIRE Simulation

Hopkins et al. (2015)

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

The Very Old Halo

As proto-Milky Way forms, its potential varies significantly with time



This redistributes energy of dark matter and stars from early mergers, mixing them in phase space

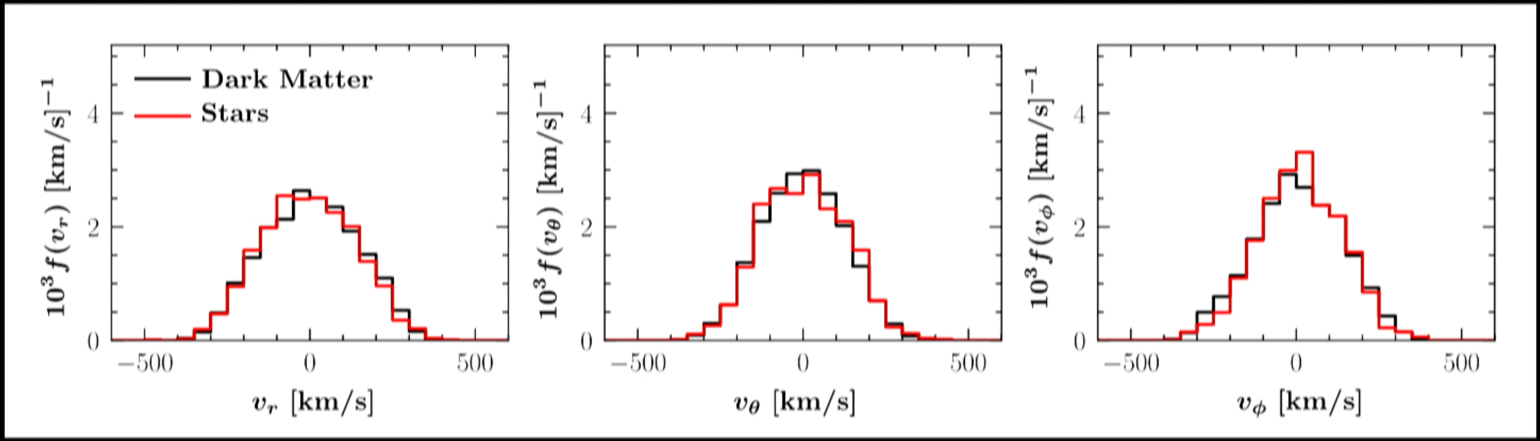
$$\frac{dE}{dt} = \frac{\partial \Phi}{\partial t}$$

The Very Old Halo

Oldest stars and dark matter in a galaxy share similar kinematics today

Herzog-Arbeitman, ML, Madau, and Necib, PRL (2018)
Herzog-Arbeitman, ML, and Necib, JCAP (2018)

Present-day velocities of stars and dark matter from oldest mergers in FIRE galaxy

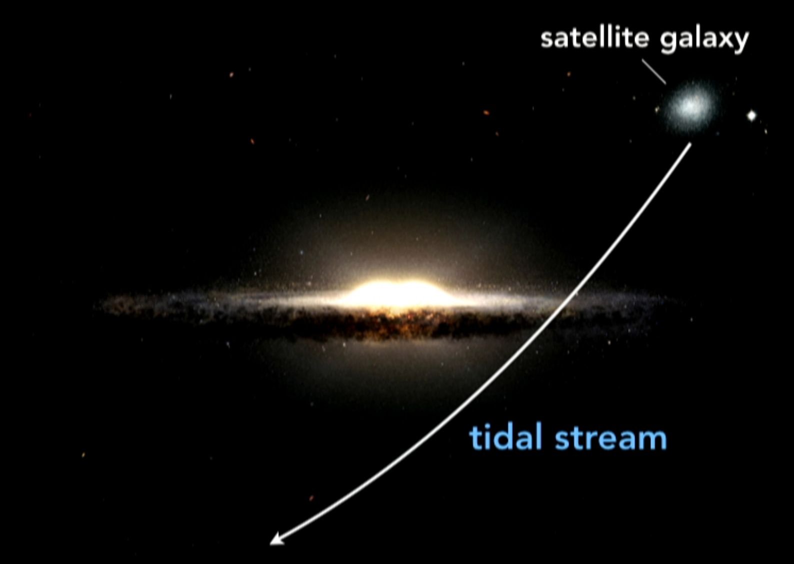


Necib, ML, Garisson-Kimmel, et al. [1810.12301]

Younger Mergers

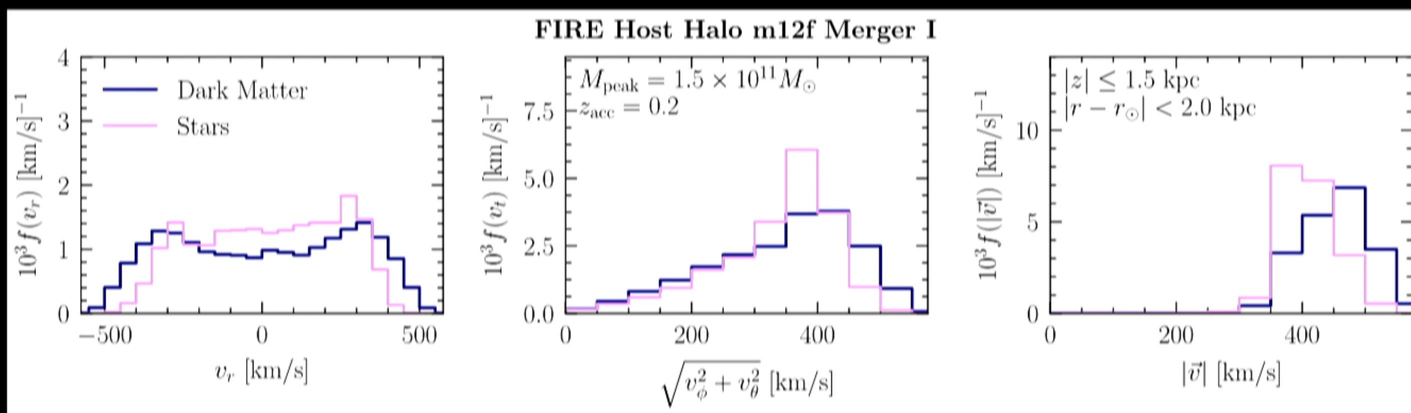
Once proto-galaxy in place, energy of tidal debris is conserved during merger

Streams of dark matter and stars created as a satellite falls in



Tidal Streams

Differences in spatial distributions lead to offsets in stellar and dark matter velocity distributions

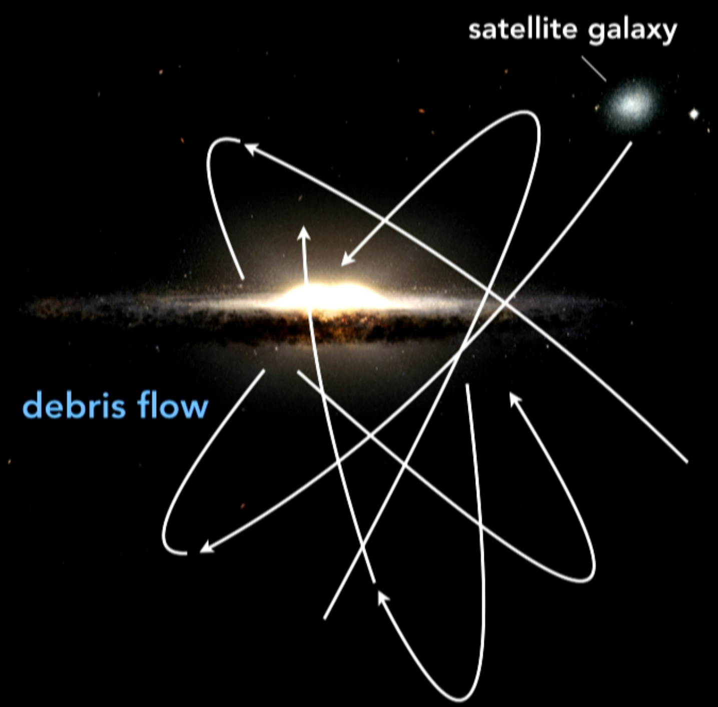


Necib, ML, Garrison-Kimmel, et al. [1810.12301]

Younger Mergers

After many orbits, the spatial coherence of tidal debris is lost

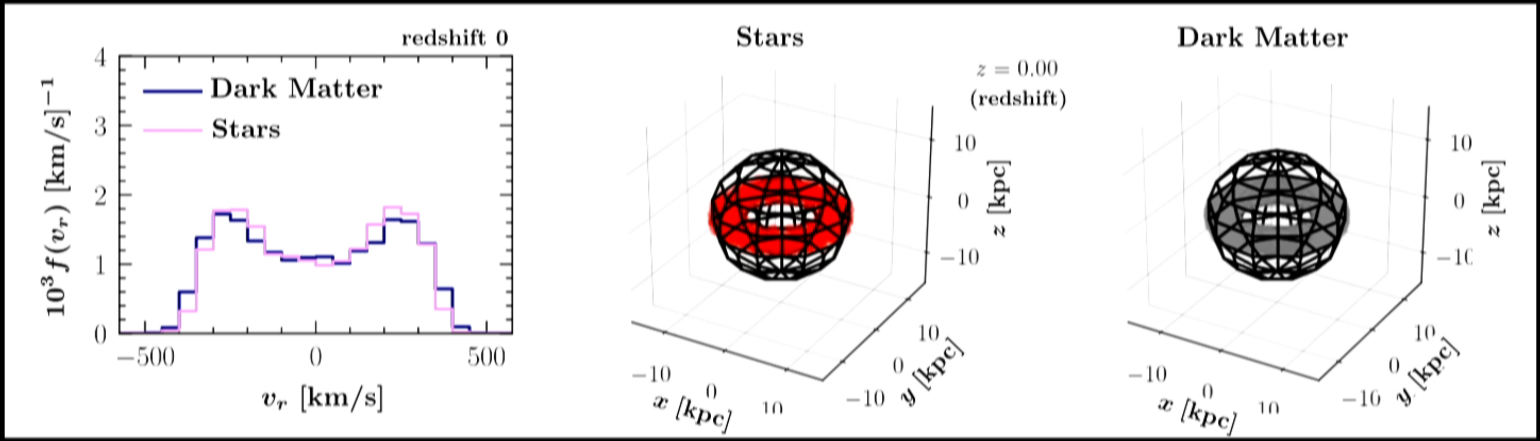
Velocity features remain



Debris Flow in Simulations

Kinematic features in stars trace underlying dark matter substructure

Present-day distributions of stars and dark matter from a recent merger in FIRE galaxy



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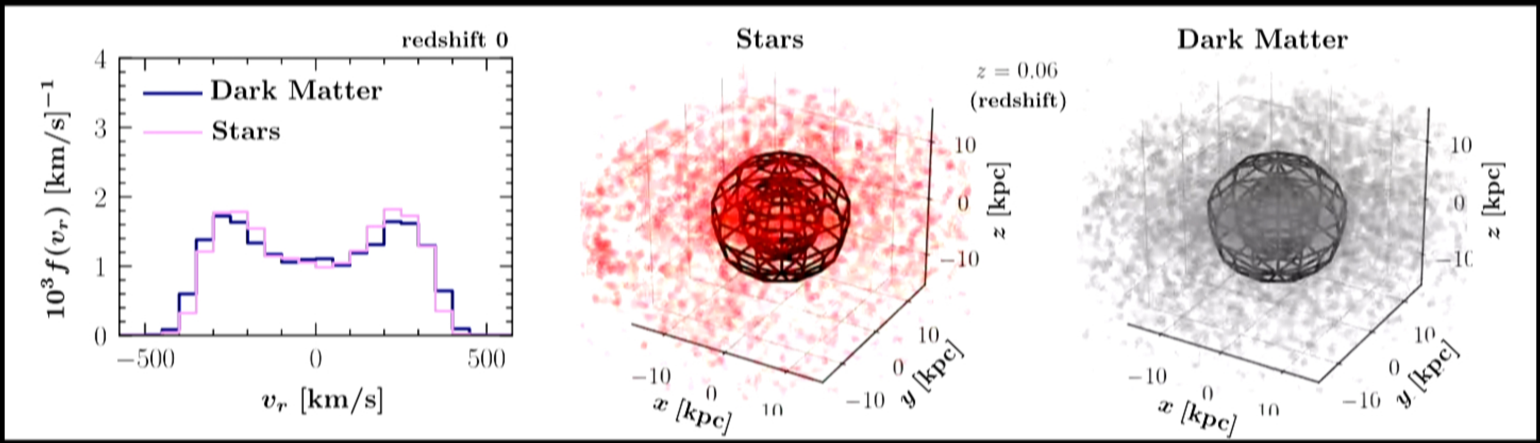

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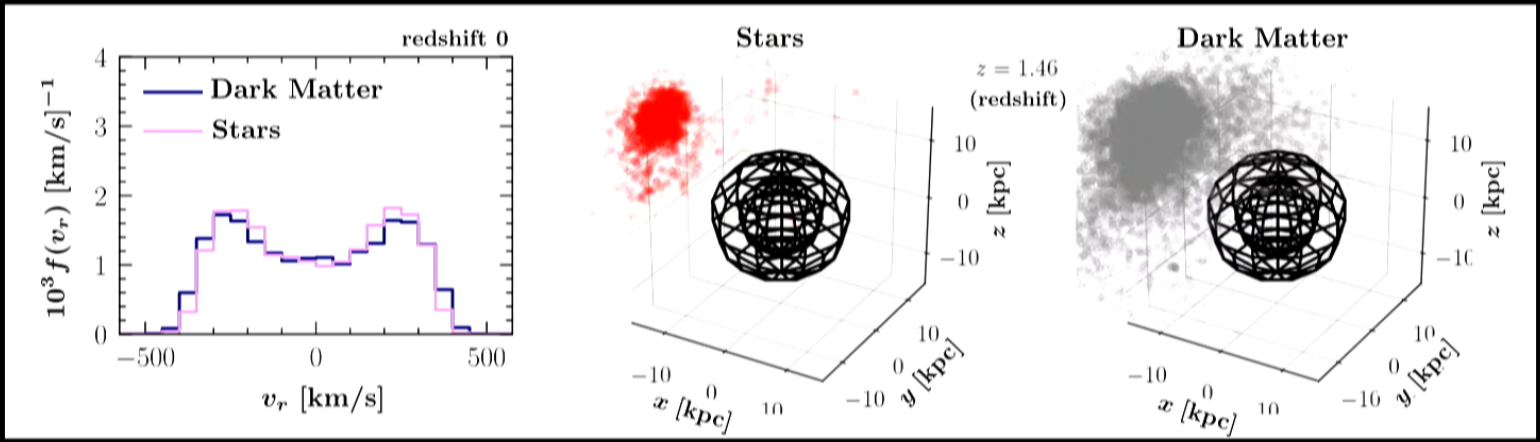


Necib, ML, Garisson-Kimmel, et al. [1810.12301]

Mergers that build up the Milky Way leave their imprint in a wealth of spatial and velocity structures

Use stars as visible tracers for the dark matter halo that was built up from luminous galaxies

NOTE: Stars do not trace any additional dark matter that may originate from non-luminous galaxies. Separate techniques are needed to map this component.

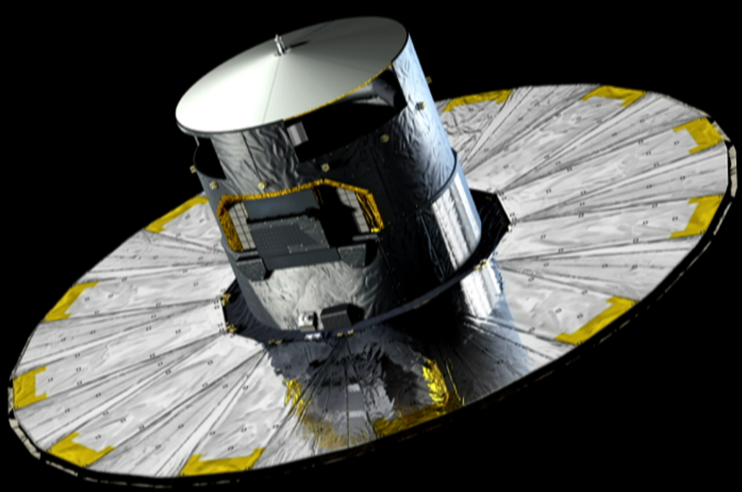
The *Gaia* Mission

Gaia Collaboration (2018)

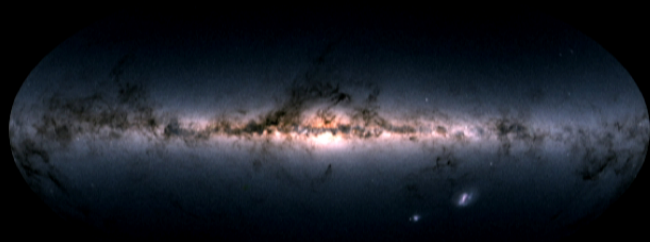
Gaia is the follow-up astrometric survey to the Hipparcos mission (1989-1993)

Launched December 2013; second data release April 2018

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



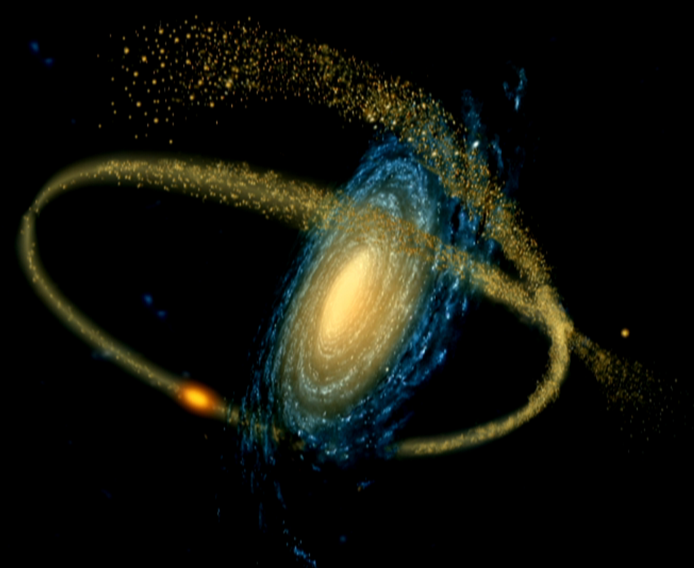
Milky Way Archaeology



Fossil Shape
Fossil Environment
Radioactive Dating

↓

Stellar position
Stellar velocity
Chemical abundance



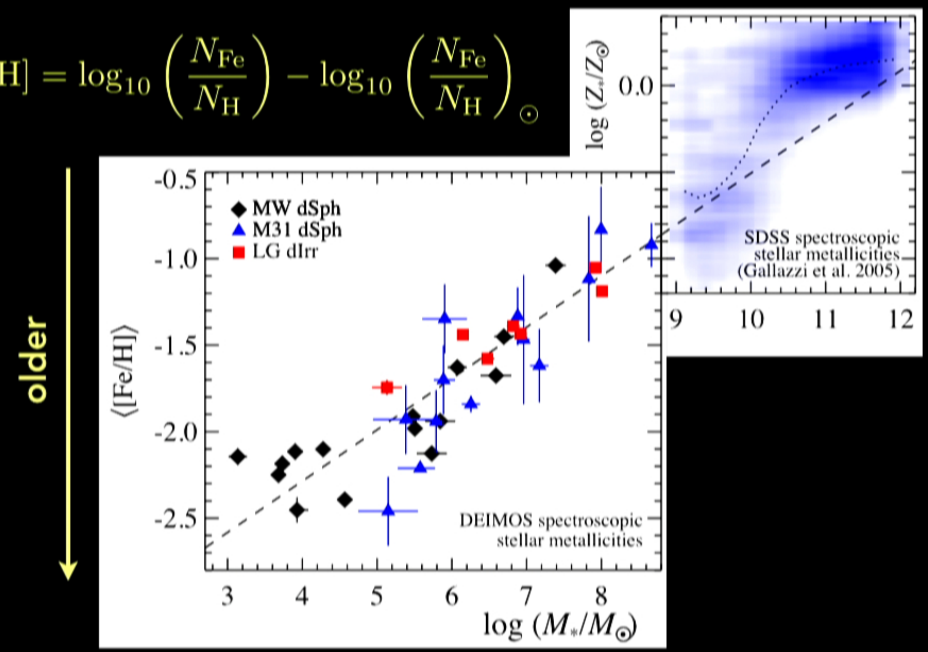
Images: ESA/Gaia/DPAC (left), John Lomberg (right)

Chemical Abundance

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

Stars with similar chemical abundance can be linked to a parent galaxy

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

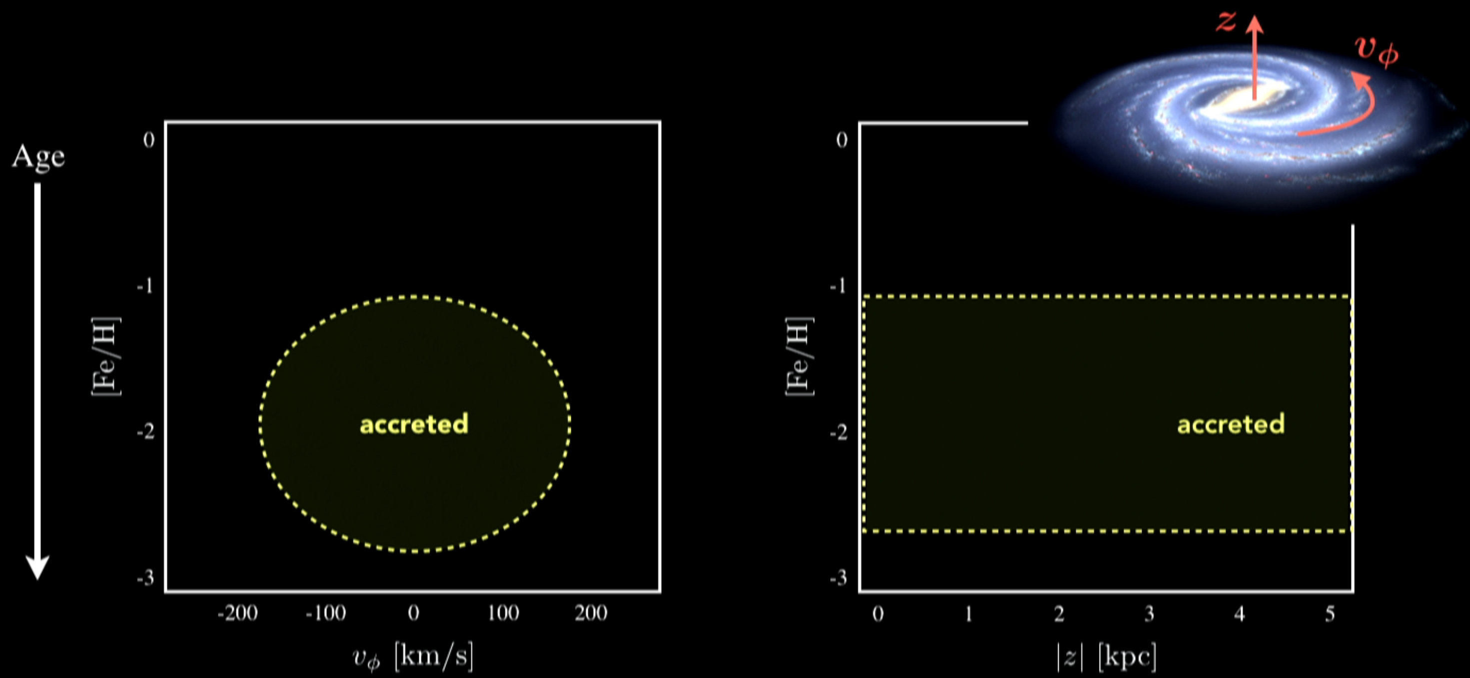


Kirby et al. (2013)

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

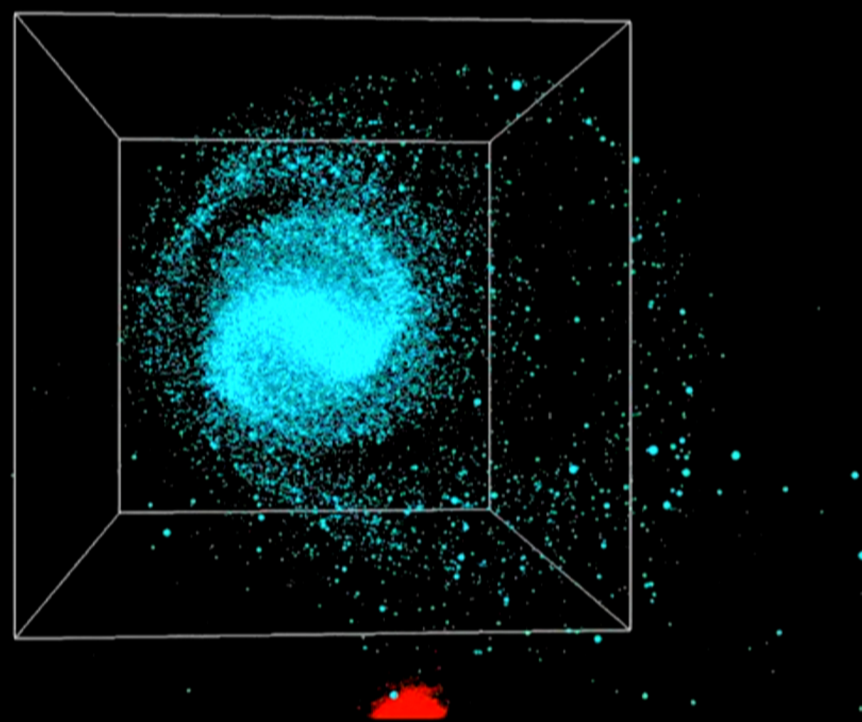


Johnston et al. (1996), Helmi & White (1999), Bullock et al. (2001), Harding et al. (2001)

Gaia Enceladus

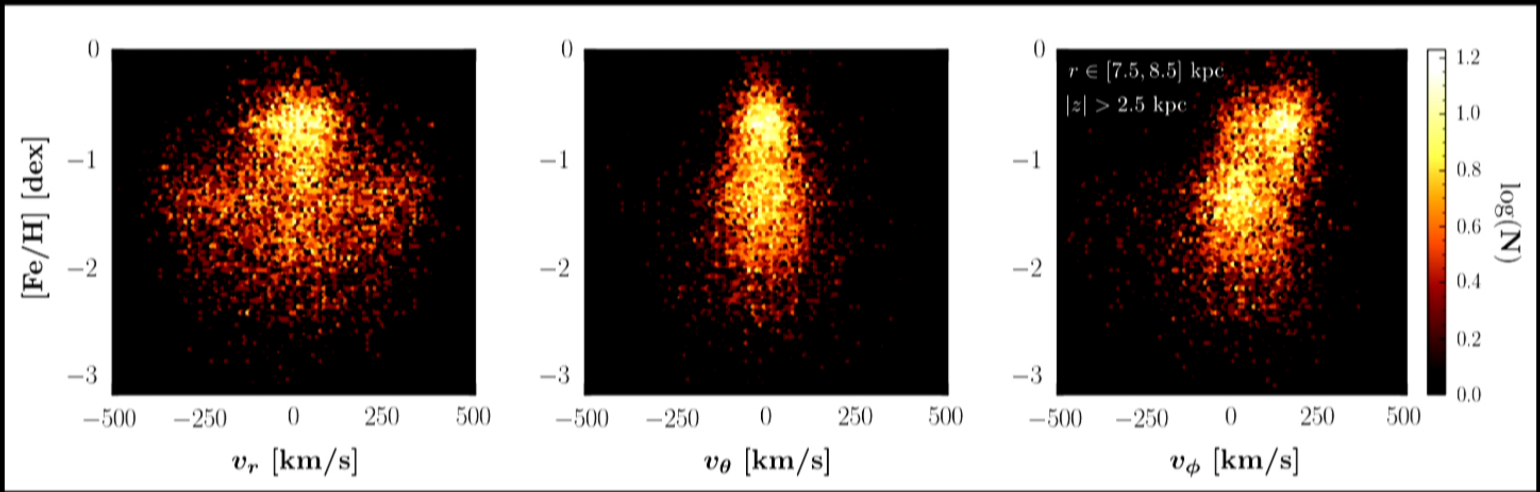
Single merger dragged in the majority of the local accreted stars

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



Video Credit: H. H. Koppelman, A. Villalobos, A. Helmi (University of Groningen)

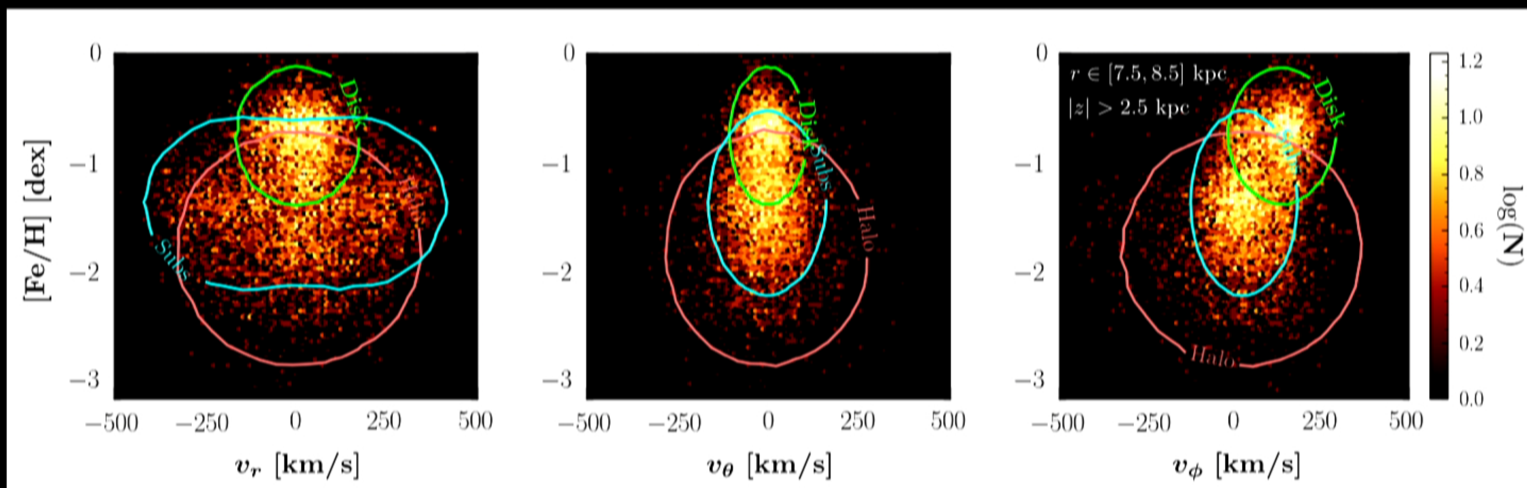
SDSS-*Gaia* Cross Match



Necib, ML, and Belokurov [1807.02519]

SDSS-*Gaia* Cross Match

HALO	SUBSTRUCTURE	DISK
very metal-poor stars	intermediate metallicity stars	metal-rich stars
↕	↕	
old dark matter halo	dark matter substructure	



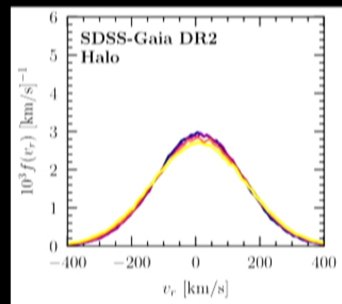
Necib, ML, and Belokurov [1807.02519]

The Local Neighborhood

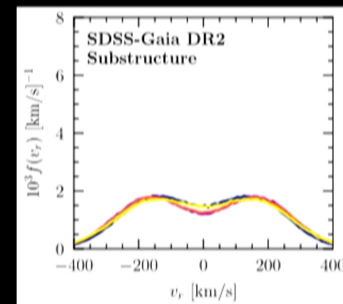
Necib, ML, and Belokurov [1807.02519]

Halo | **Enceladus**

Accreted Stars ~ 40%



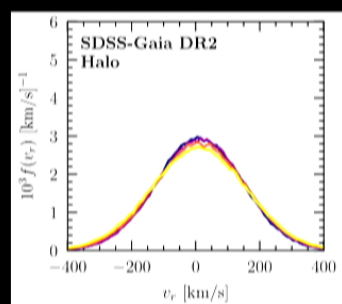
+ 60%



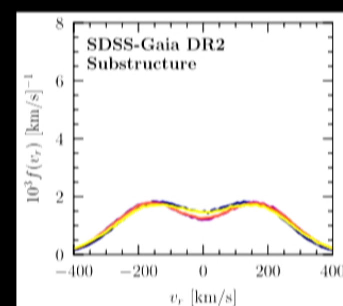
ML, Spergel, and Madau (2014)
Herzog-Arbeitman, ML, Madau, and Necib (2018)
Necib, ML, Garrison-Kimmel, et al. (2018)

Dark Matter-Stellar Correlation

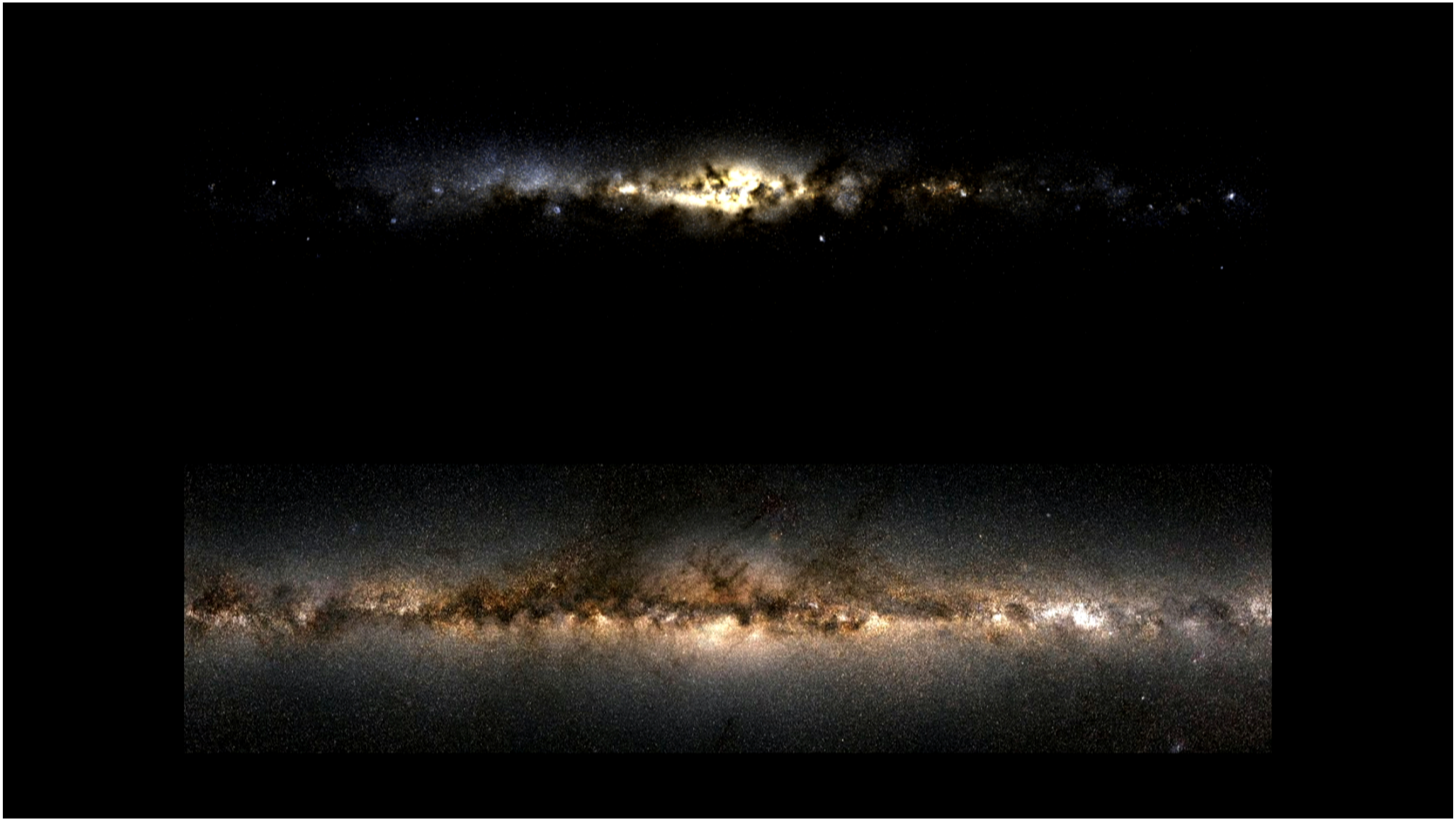
Dark Matter ~ 60%



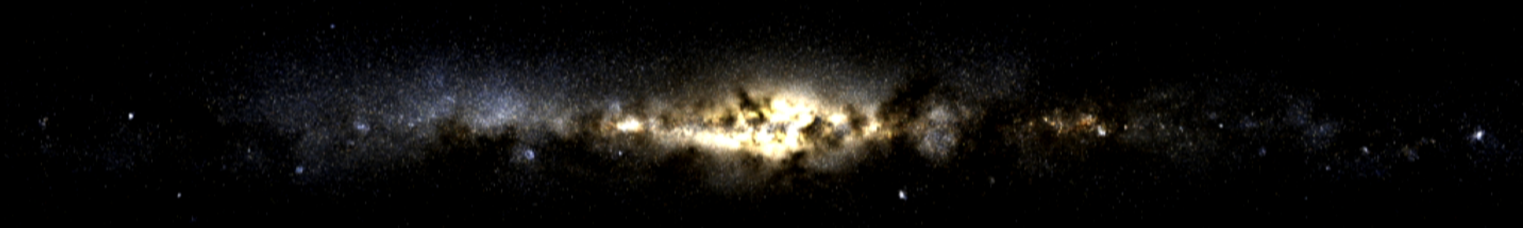
+ 40%



(Not including contribution from non-luminous galaxies)



Ananke

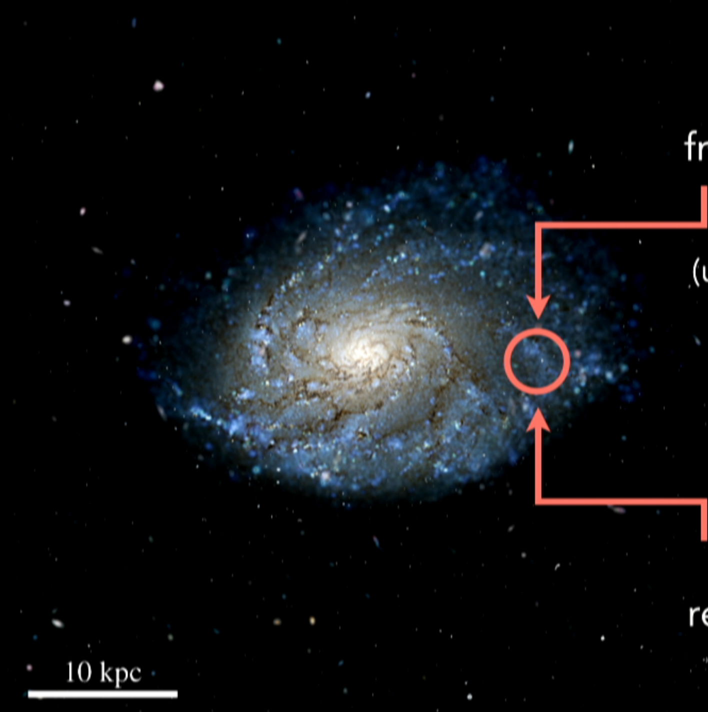


Sanderson *et al.* [1806.10564]

Gaia

Training the Network

FIRE m12i Galaxy



Train network on fraction of stars here

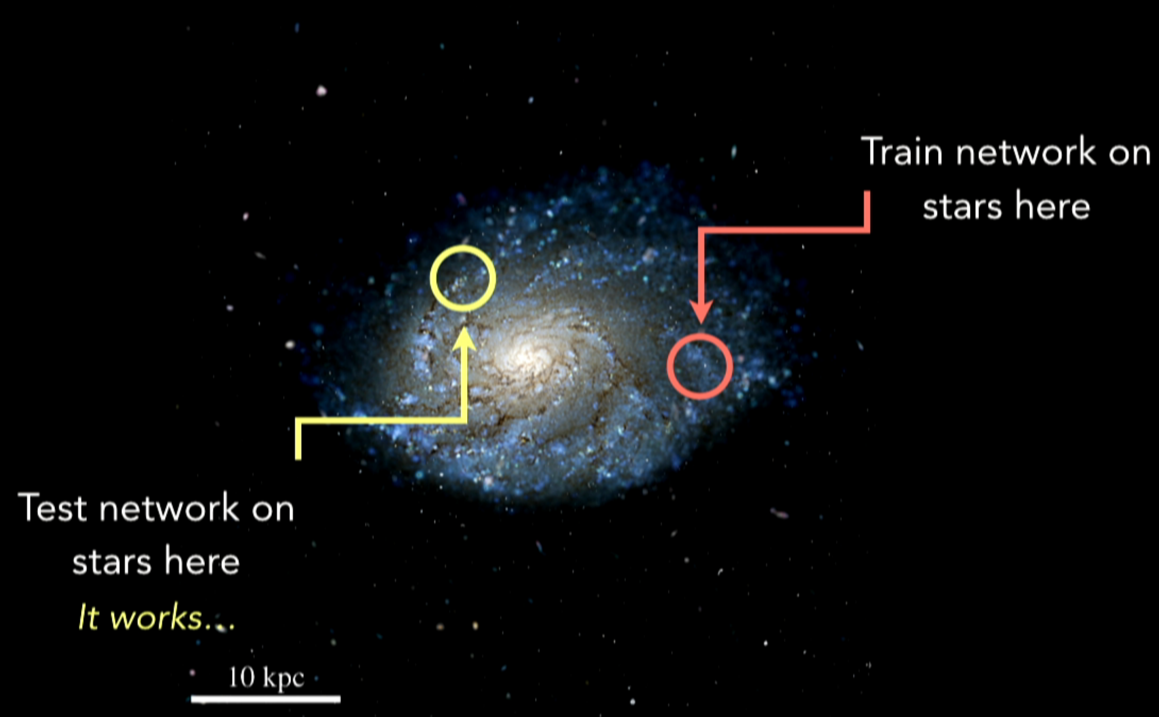
(using 5D kinematics as inputs)

Test network on remaining stars here

It works…

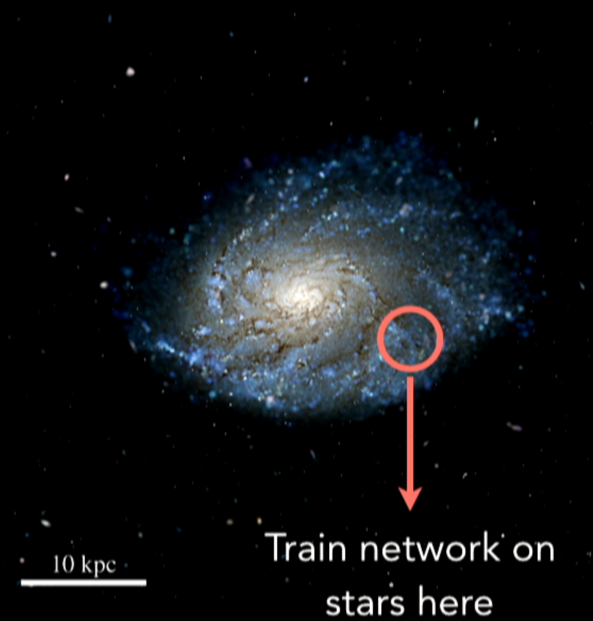
Training the Network

FIRE m12i Galaxy

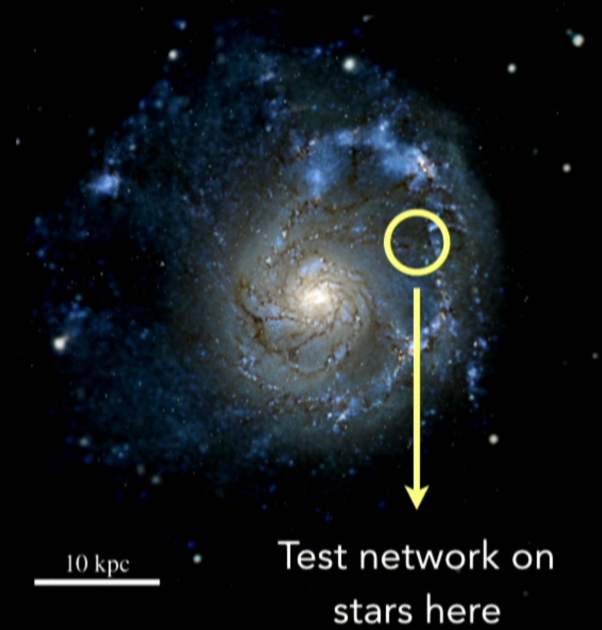


Training the Network

FIRE m12i Galaxy



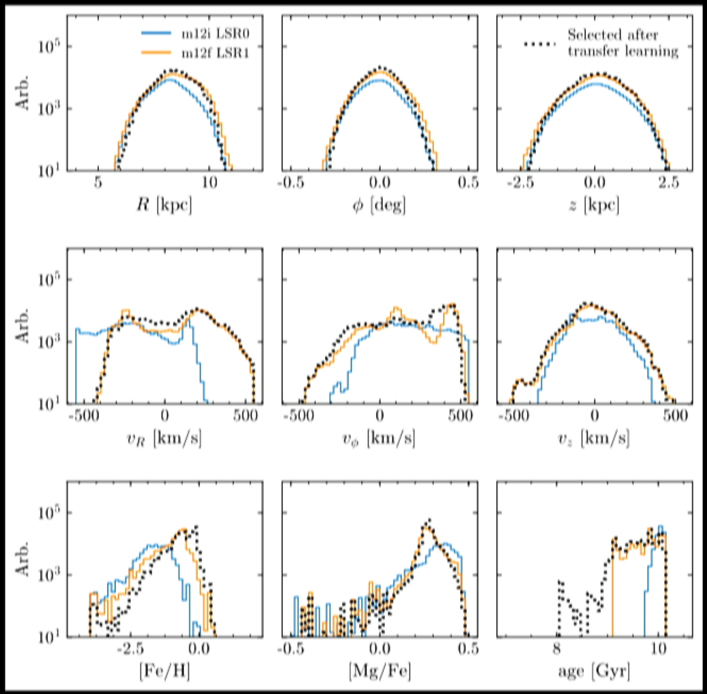
FIRE m12f Galaxy



Transfer training is important: Retrain last layer of network on new galaxy

Training the Network

Network successfully recovers distributions for new galaxy,
even when merger history is distinct from galaxy it was trained on



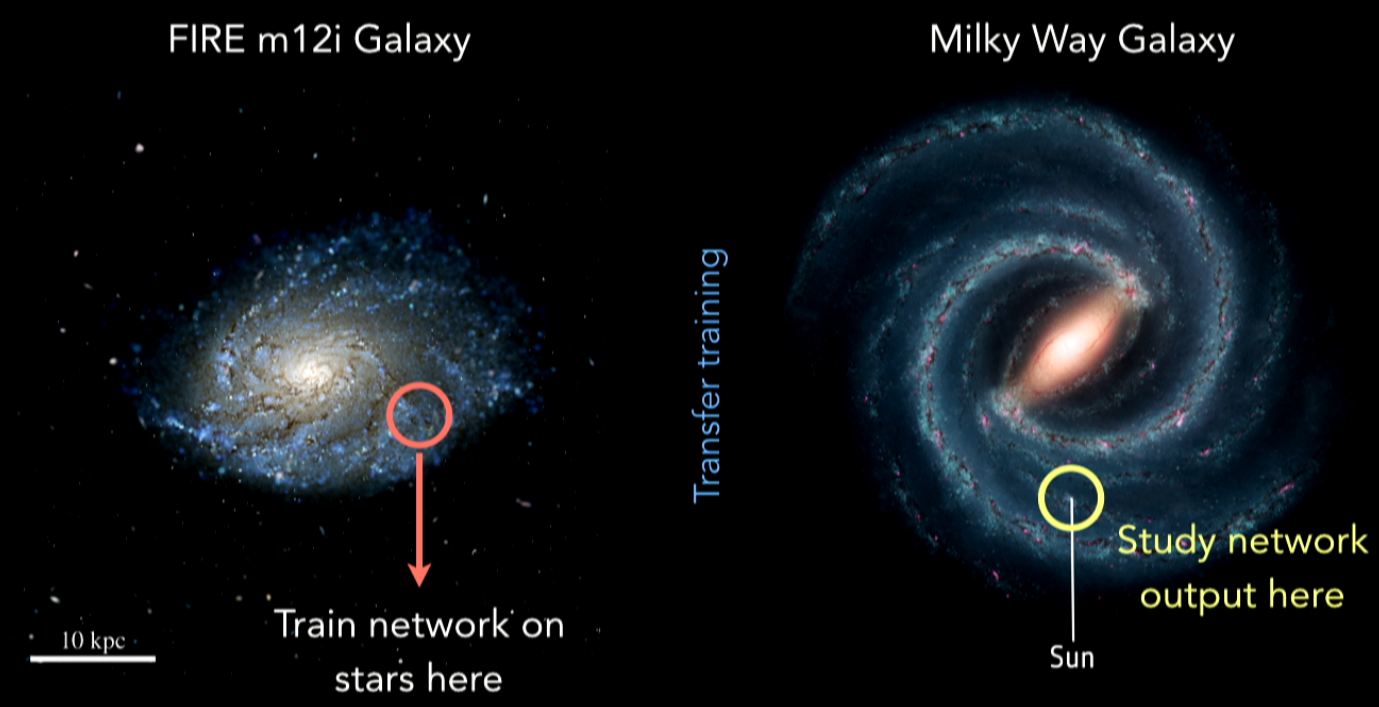
B. Ostdiek, L. Necib, T. Cohen, M. Freytsis, ML, et al. [1907.06652]

network trained on a galaxy with distributions shown in blue

network prediction for new galaxy shown in dotted black

truth distributions for new galaxy shown in orange

Training the Network



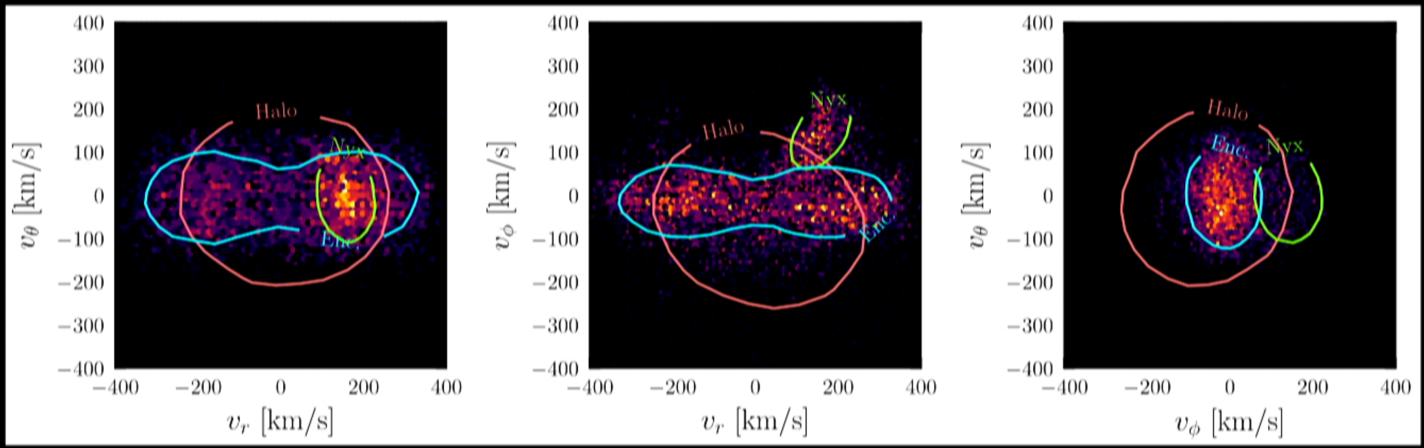
Gaia DR2 Accreted Star Catalog

We built the first catalog of accreted stars in *Gaia* DR2

B. Ostdiek, L. Necib, T. Cohen, M. Freytsis, ML, et al. [1907.06652]

With this catalog, we find evidence for Enceladus near the Solar position, as well as a vast new stellar stream

Gaia stars labeled as accreted with high confidence

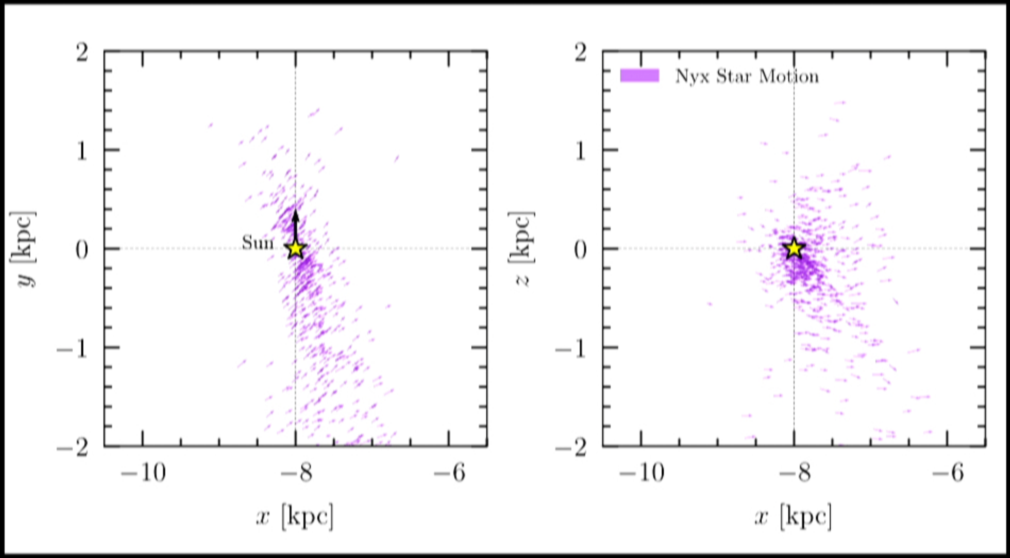


L. Necib, B. Ostdiek, ML, T. Cohen, et al. [1907.07190, 1907.07681]

The Nyx Stream

~500 stars with coherent velocities passing near the Sun

Nyx stars rotate more slowly than disk stars and are on more eccentric orbits



L. Necib, B. Ostdiek, ML, T. Cohen, et al. [1907.07190, 1907.07681]

The Nyx Stream

Nyx stream can be explained as the tidal debris of a massive dwarf galaxy disrupted in the Milky Way's disk

May also be due to perturbations of Milky Way disk stars from bar or spiral arms, but these explanations do not fit all pieces of evidence

Further spectroscopic observations of Nyx stars will be crucial for confirming its accreted origin

The Nyx Stream

Nyx stream can be explained as the tidal debris of a massive dwarf galaxy disrupted in the Milky Way's disk

↓

could be associated with a rotating disk of dark matter

Read et al. [0803.2714]; Read et al. [0902.0009]; Purcell et al. [0906.5348]

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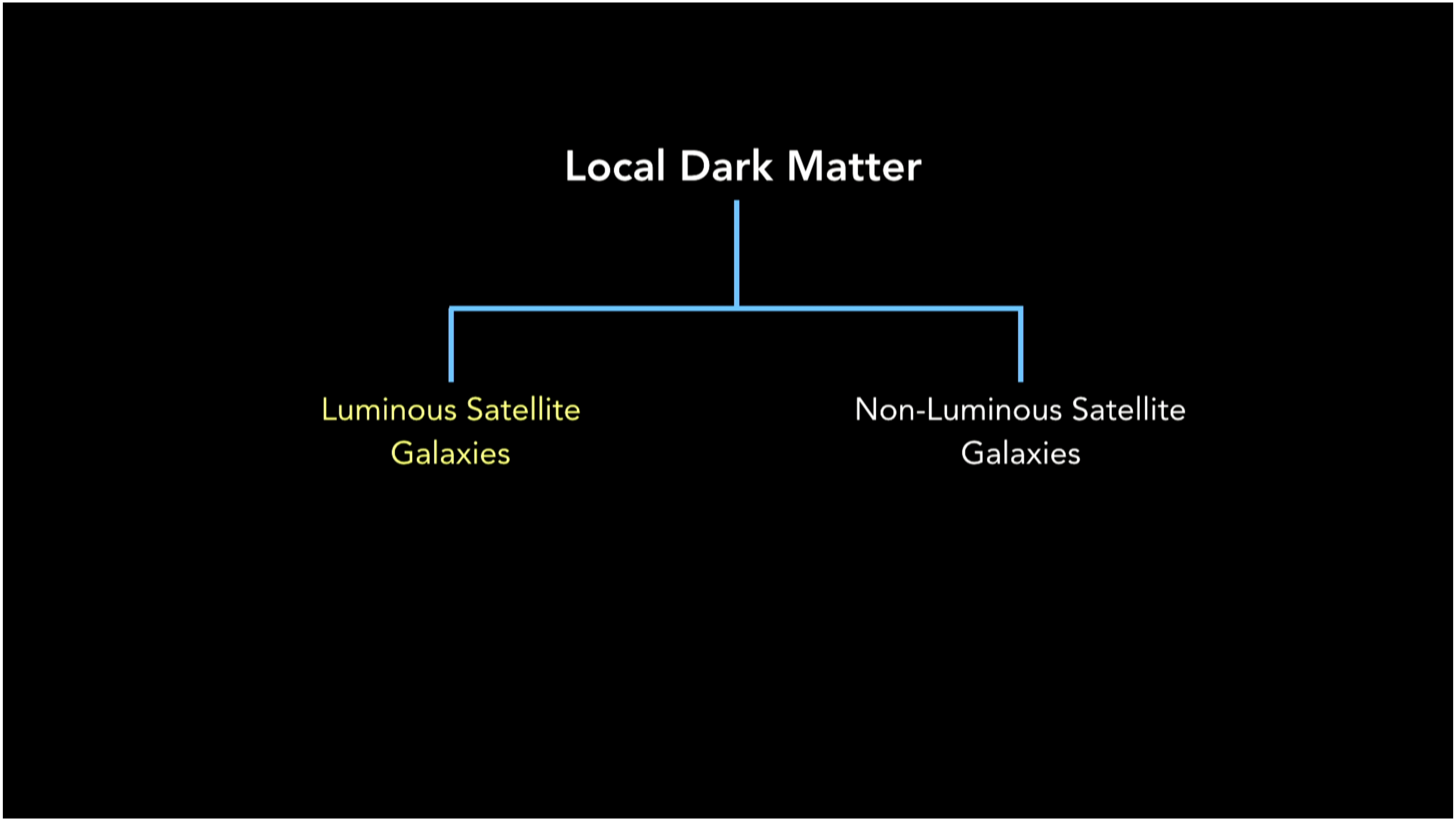
Local Dark Matter
Luminous Satellite Galaxies
Non-Luminous Satellite Galaxies