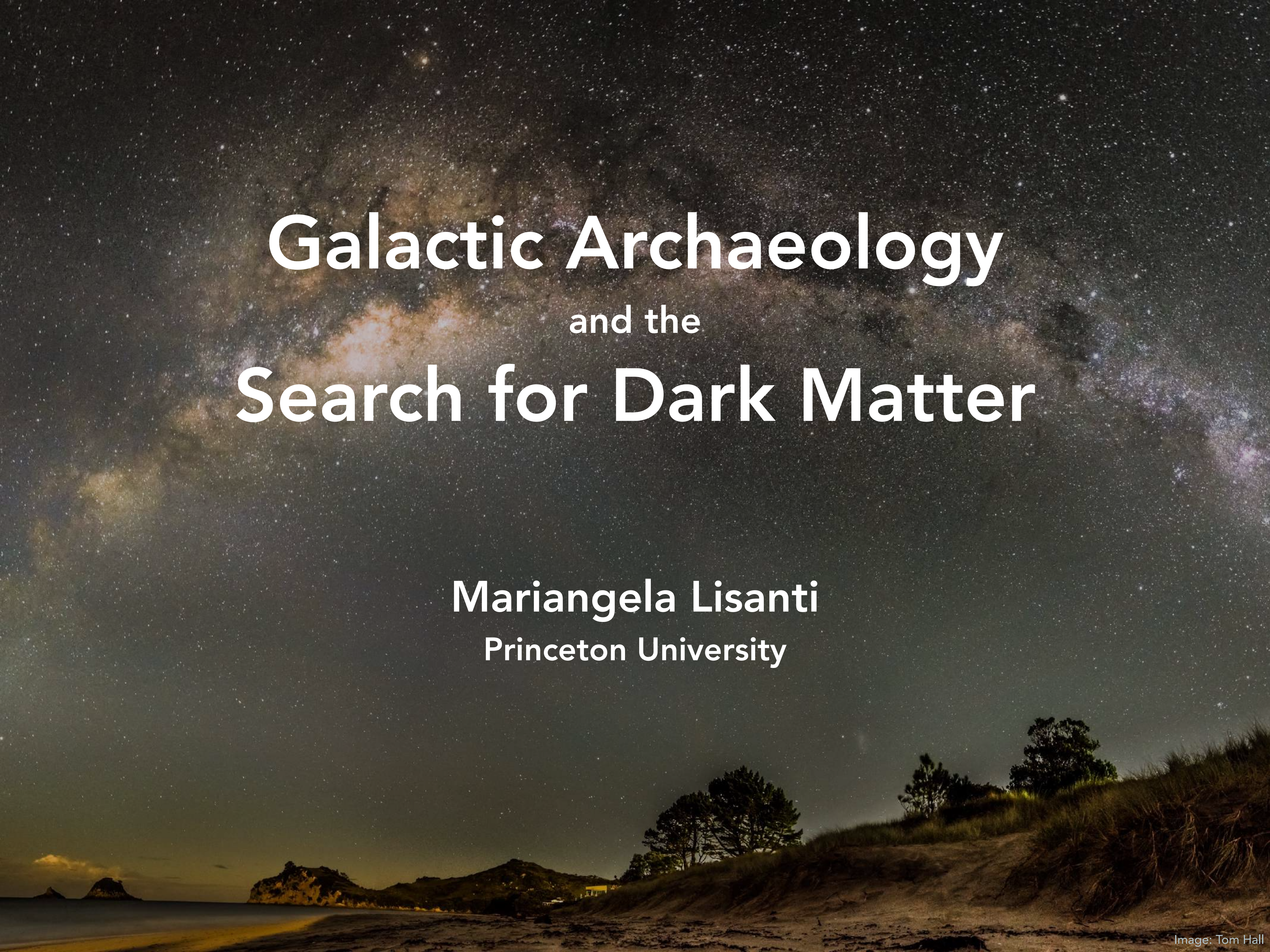


# Galactic Archaeology
## and the
# Search for Dark Matter

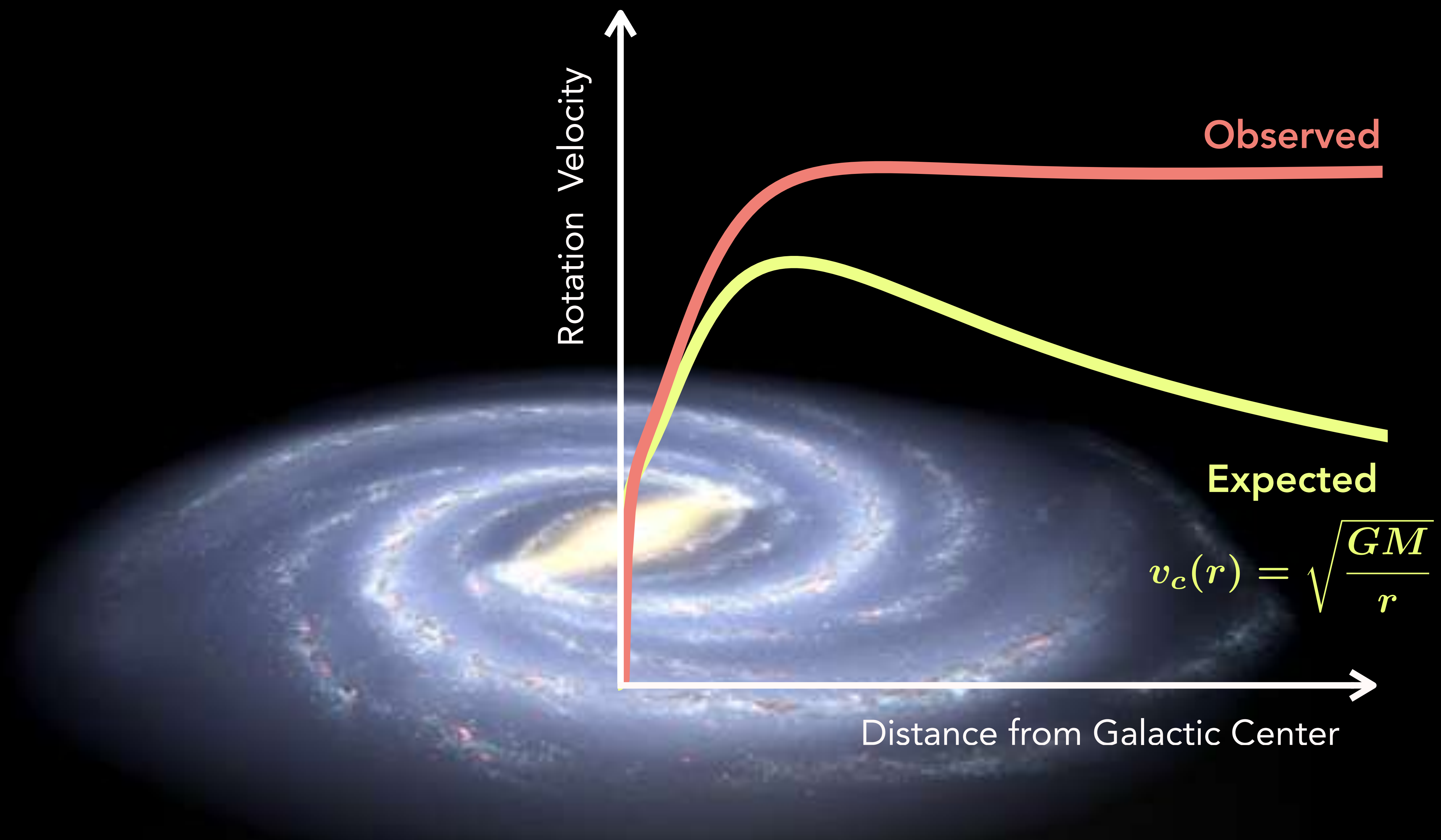
Mariangela Lisanti
Princeton University

Image: Tom Hall

# Galactic Rotation

Image: NASA

# Galactic Rotation




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

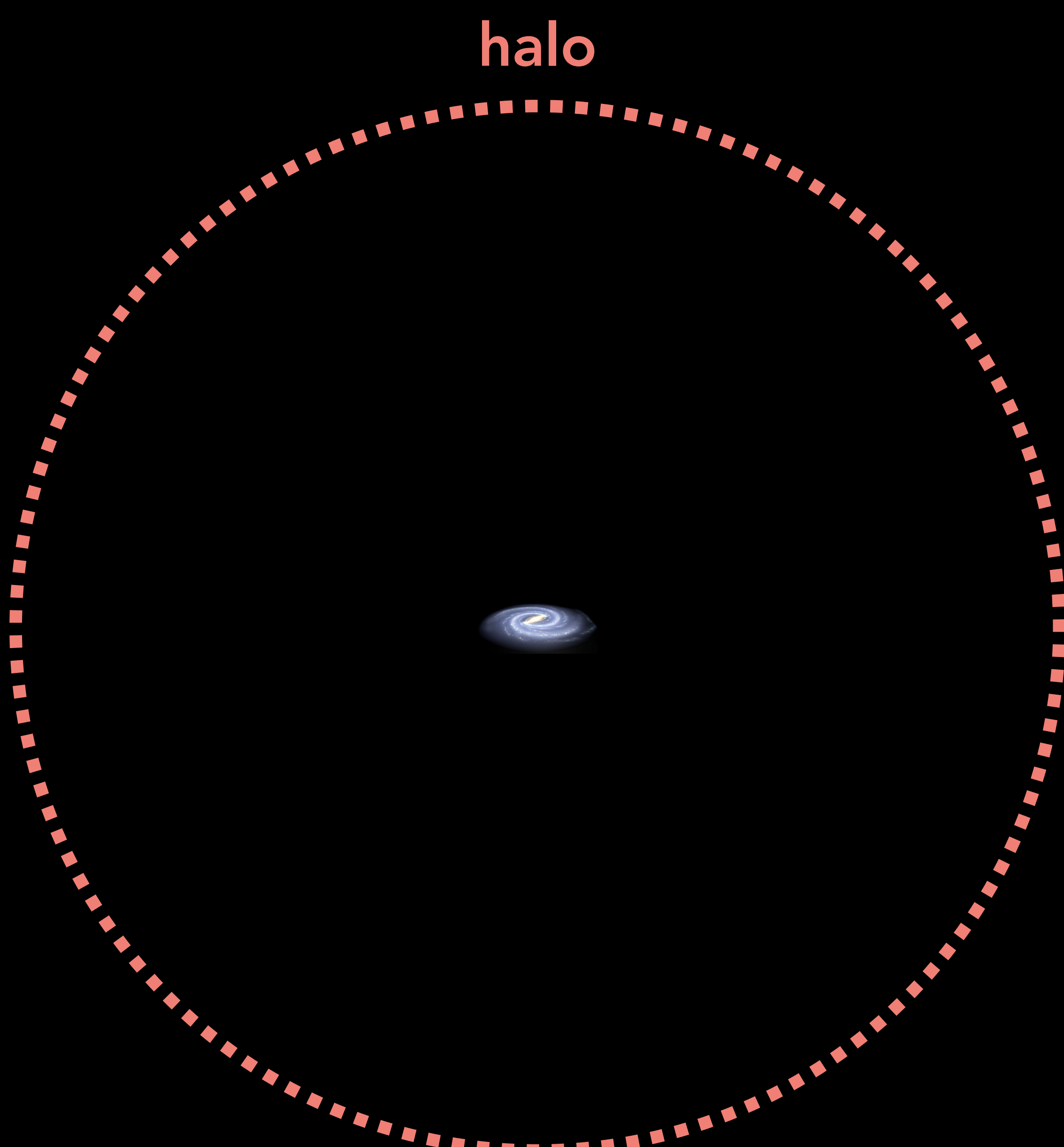
# Modify Gravity

Can visible matter source accelerations larger than Newton predicted?

Reproducing flat rotation curves over-predicts the vertical velocity of stars; highly constrained by current surveys

ML, Moschella, Outmezguine, and Slone, PRD (2019)

# Add Some (Dark) Matter




Dark matter forms a halo, not a thin disk, because it is non-dissipative

A flat rotation curve implies that the enclosed mass scales as

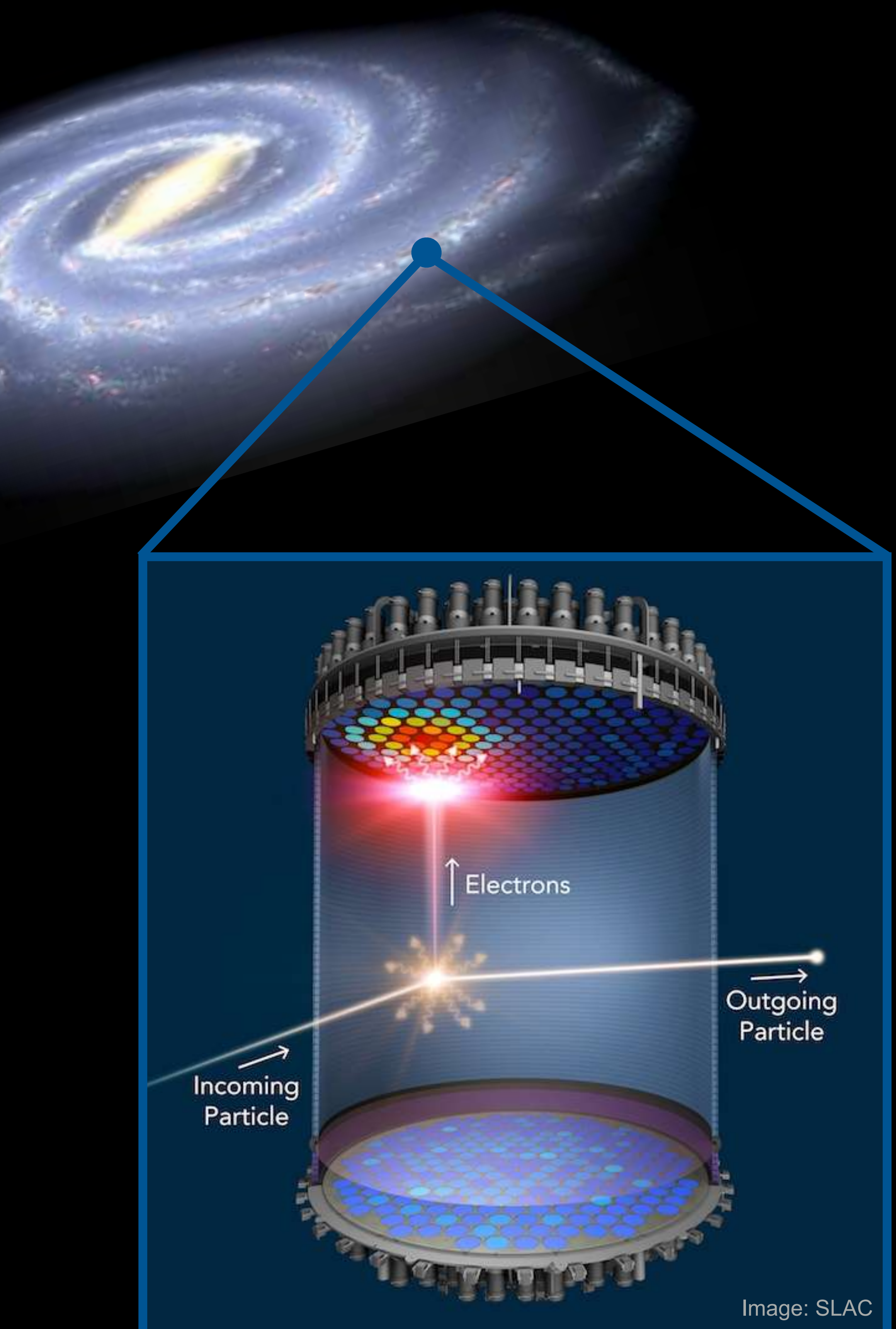
$$M(r) \sim r$$

**relevant scales**

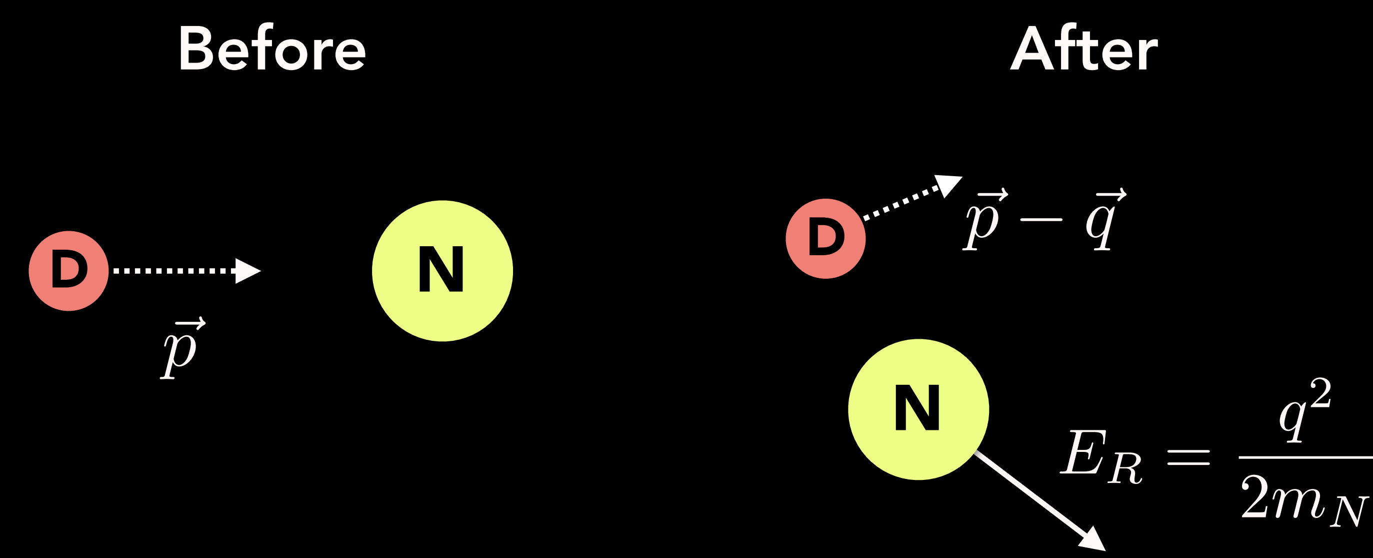
$$M_{\rm halo} \sim 10^{12}\ \mathrm{M}_\odot \qquad R_{\rm halo} \sim 100\ \mathrm{kpc}$$

$$\langle v \rangle \sim \sqrt{\frac{G M_{\rm halo}}{R_{\rm halo}}} \sim 200\ \mathrm{km/s}$$

# 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

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

# 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**

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

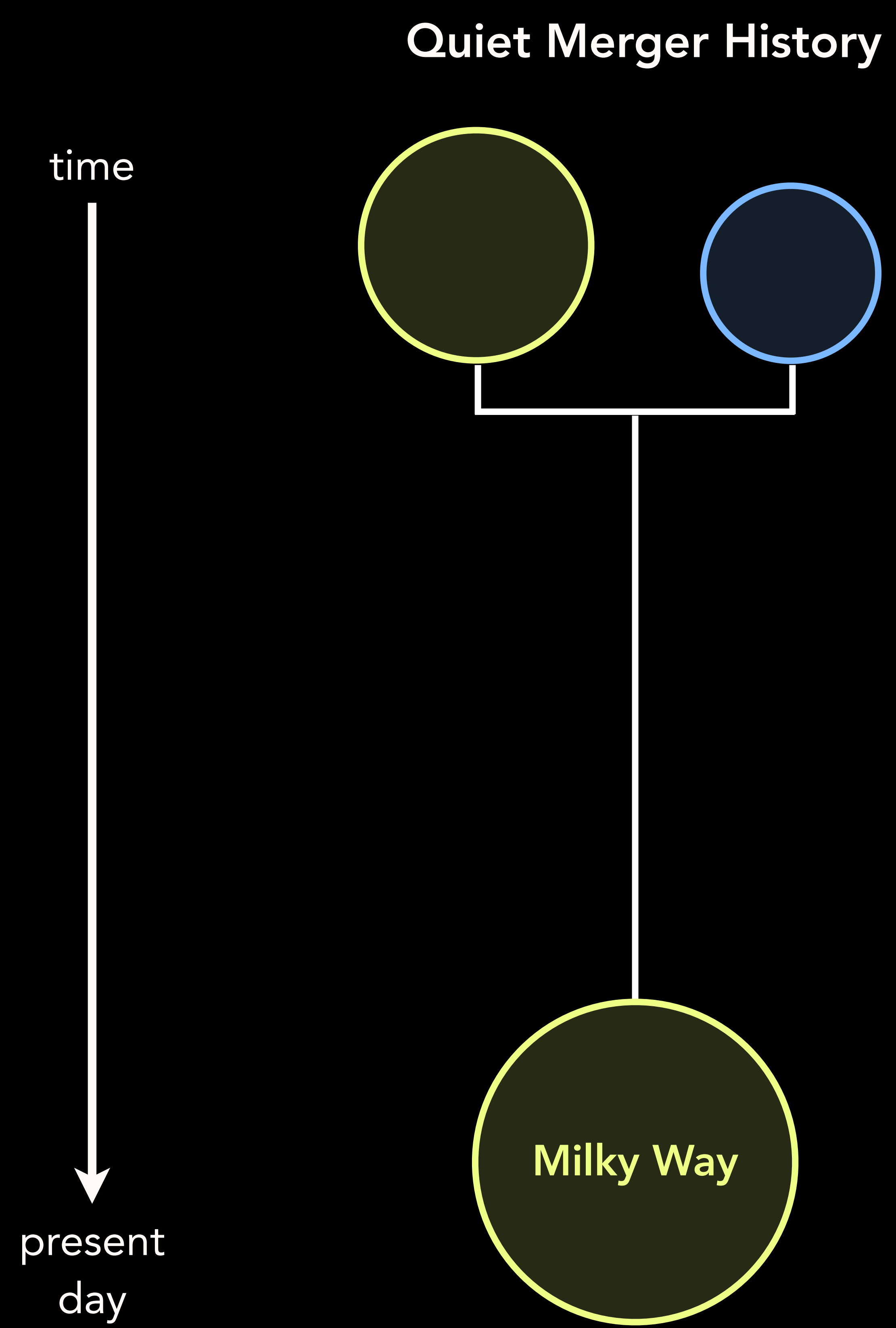
←

**Maxwell-Boltzmann**

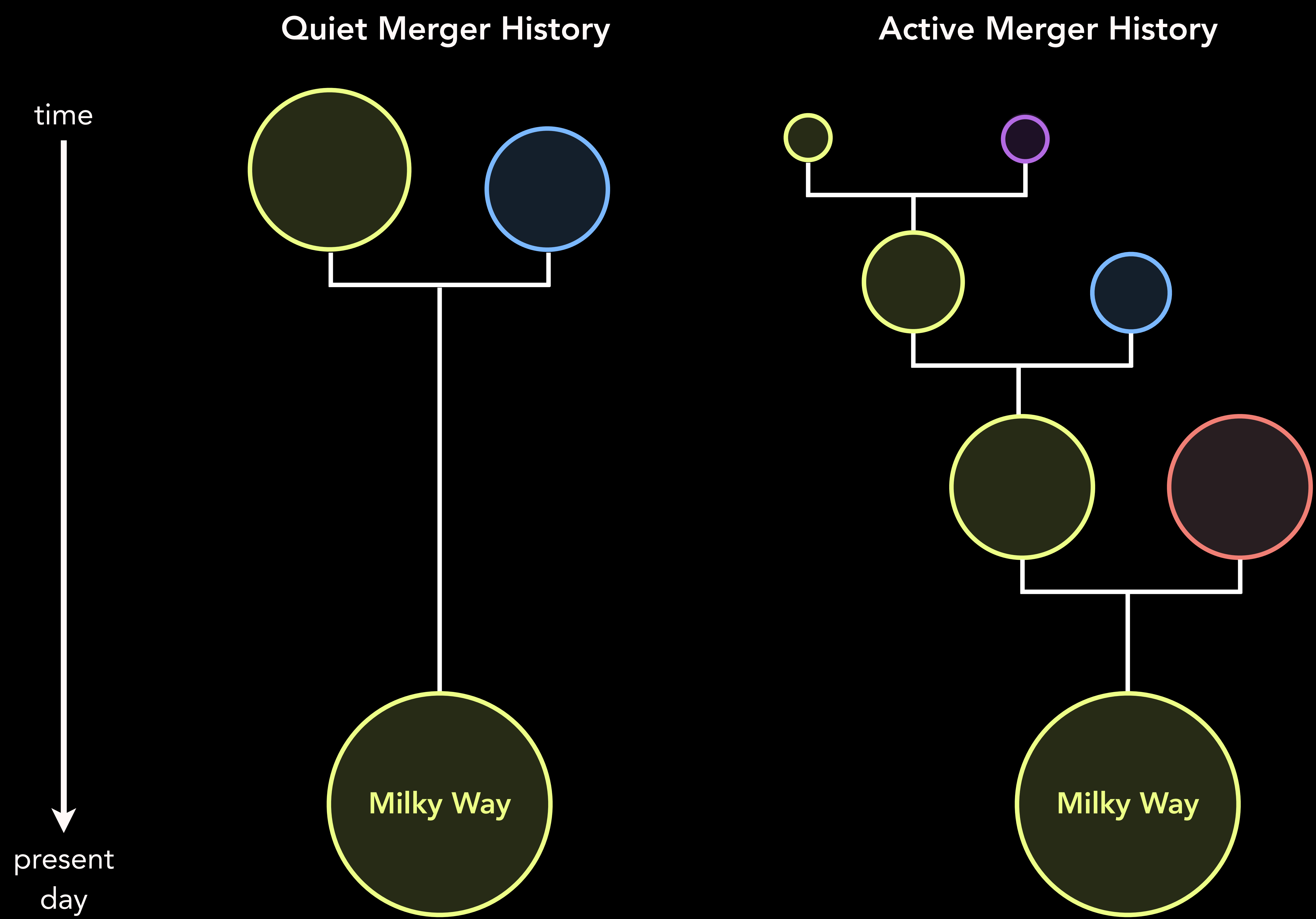
$$f(v) \sim e^{-v^2/2\sigma^2}$$

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



# The Local Milky Way's Family Tree



Galactic Cannibalism & Dark Matter

Unveiling the Milky Way’s Past with *Gaia*

# Simulated Galaxy Formation

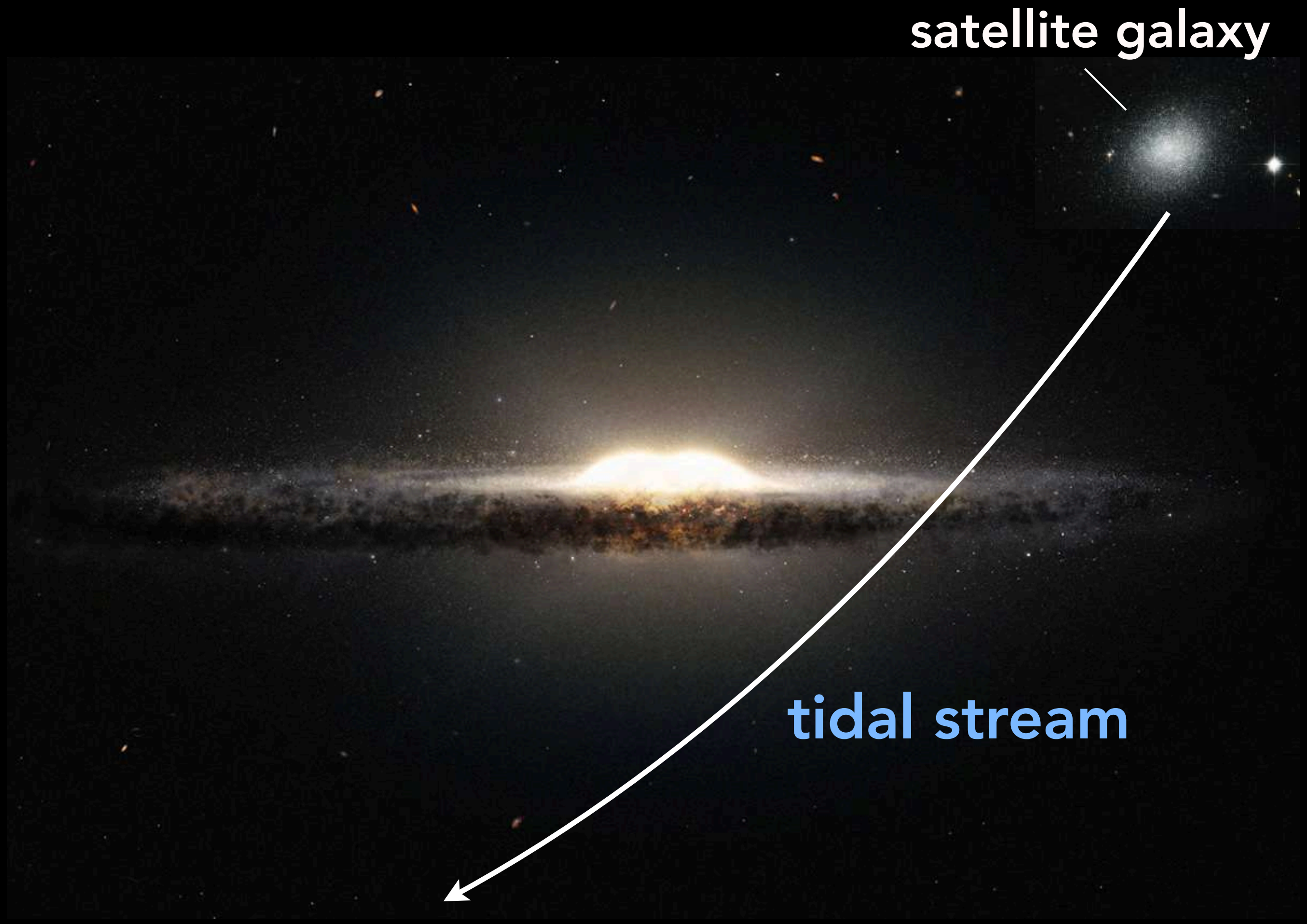
Stellar Structure Evolution in the FIRE Simulation

Hopkins et al. (2015)


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

# Recent Mergers

Tidal forces strip dark matter and stars from a satellite galaxy as it falls into the Milky Way



# The Sagittarius Stream

Stellar stream has been observed for the Sagittarius merger

Ibata et al (1994); Ivezic et al (2000); Yanny et al (2000)

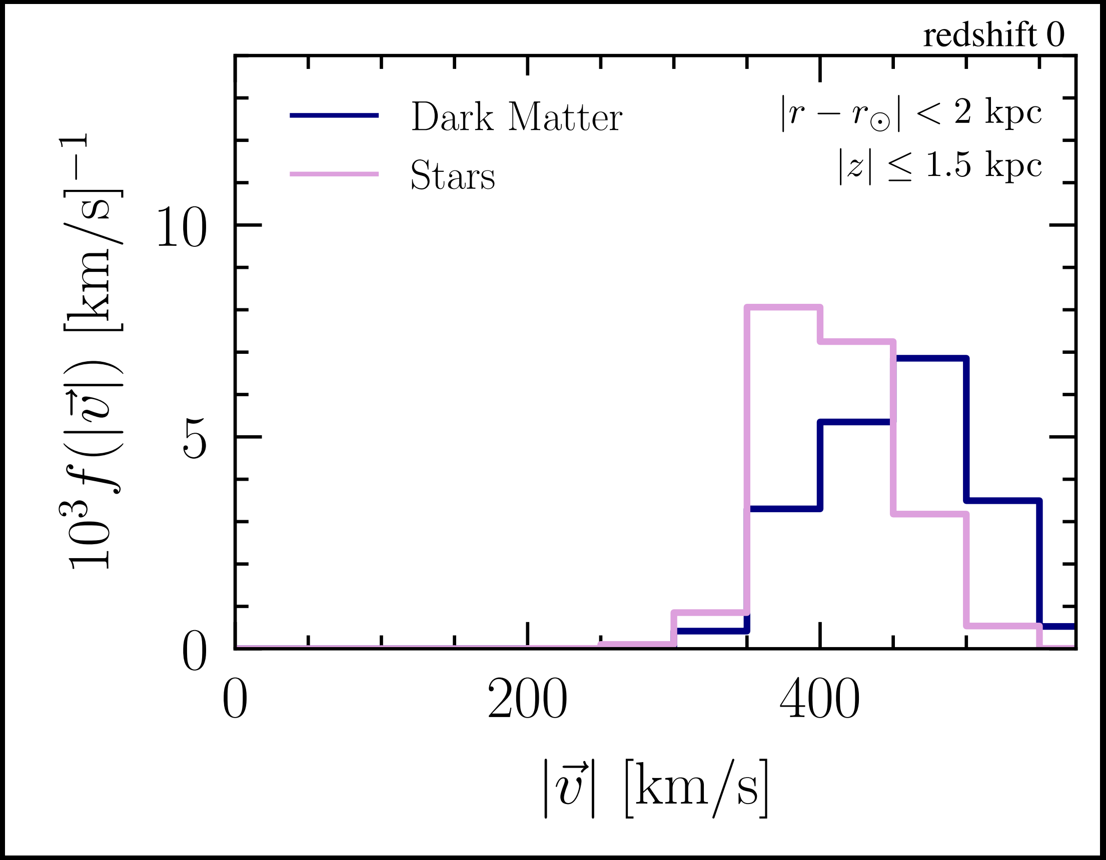

David R. Law
UCLA

(dark matter not shown)

# Streams in FIRE Simulation

Streams are spatially very narrow and have coherent velocities

Example of a Recent Merger in FIRE Galaxy




FIRE m12f Galaxy (CDM)

Both dark matter and stars form a stream

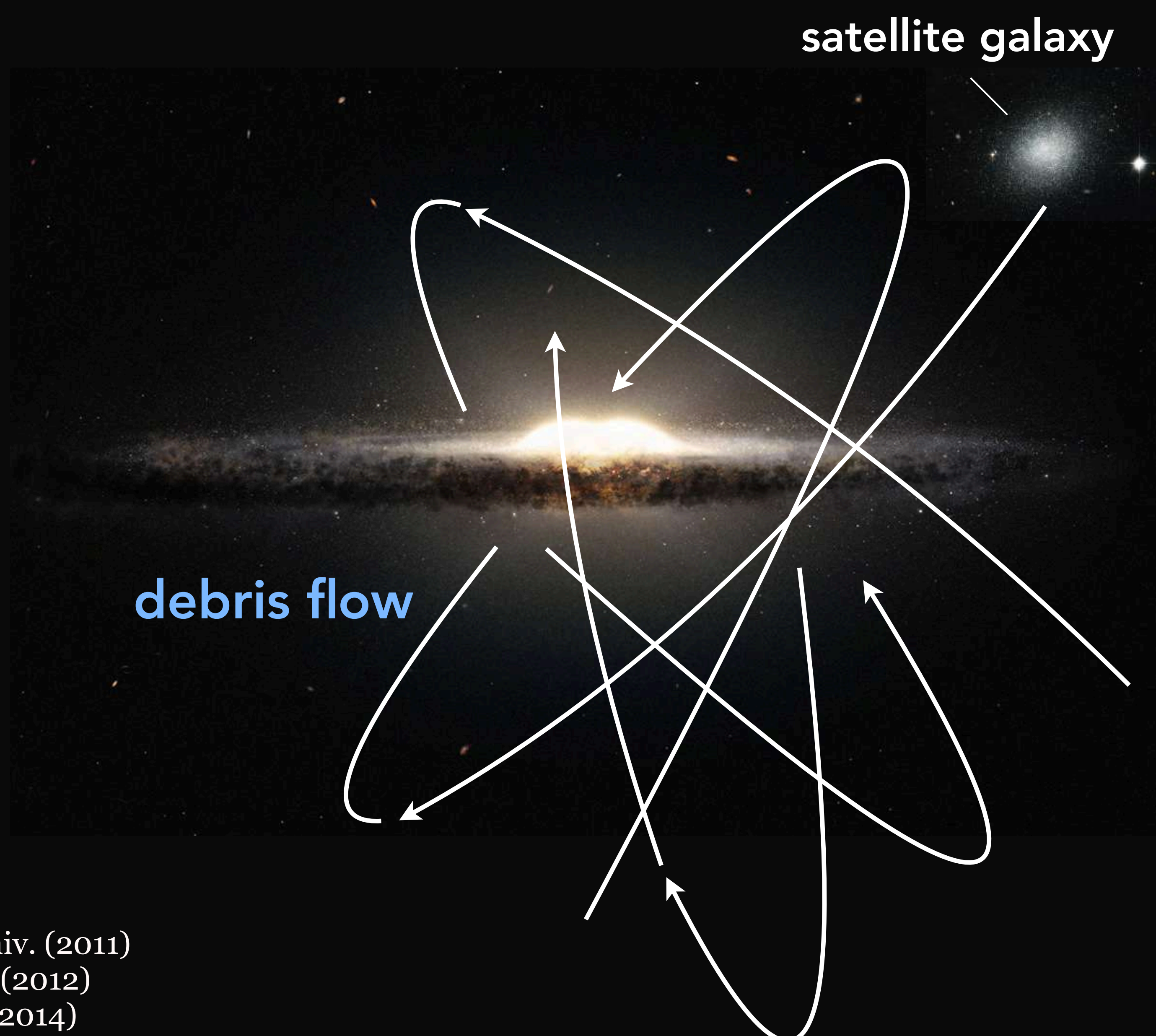
Close, but not perfect, speed correspondence

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

# Not-So-Recent Mergers

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

Velocity features remain

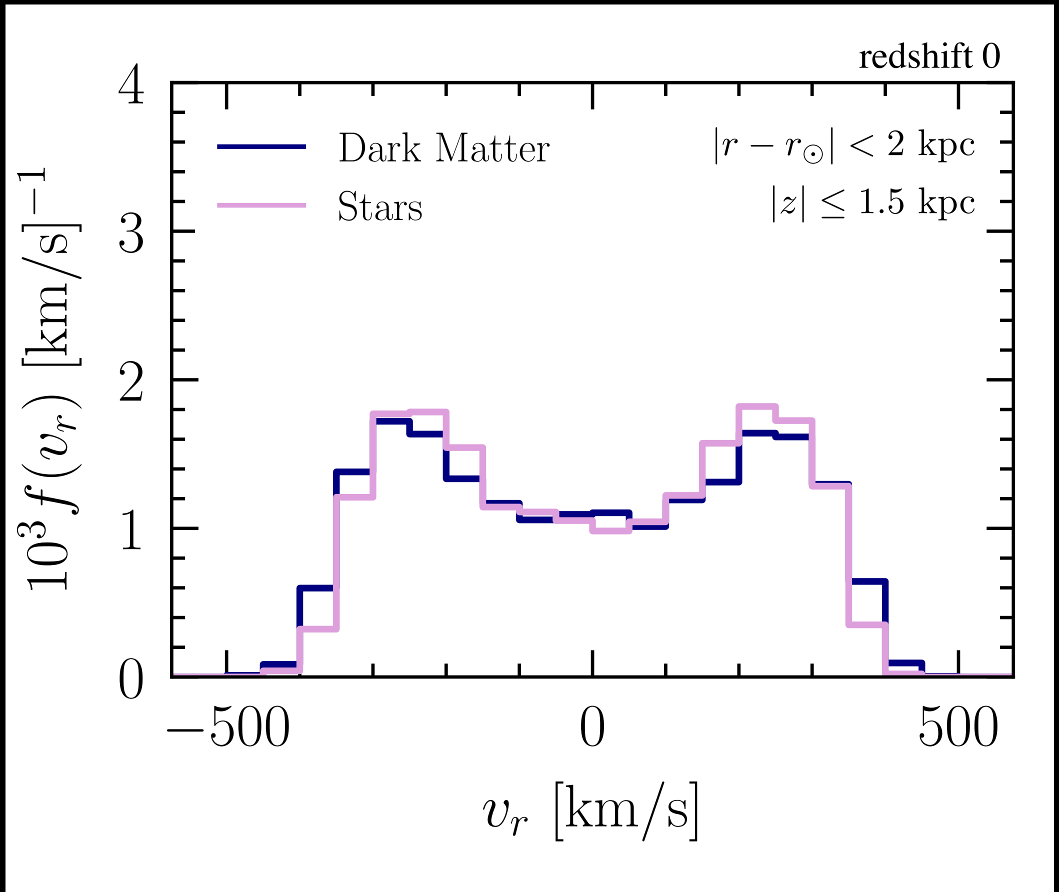



ML and Spergel, Phys. Dark Univ. (2011)
Kuhlen, ML, and Spergel, PRD (2012)
ML, Spergel, and Madau, ApJ (2014)

# Debris Flow in FIRE Simulation

Dark matter and stars spatially spread out, but retain distinctive kinematics

Example of a Not-so-recent Merger in FIRE Galaxy




FIRE m12i Galaxy (CDM)

Bimodal velocity distribution due to radial orbit of merging galaxy

Dark matter and stars share similar velocity distributions

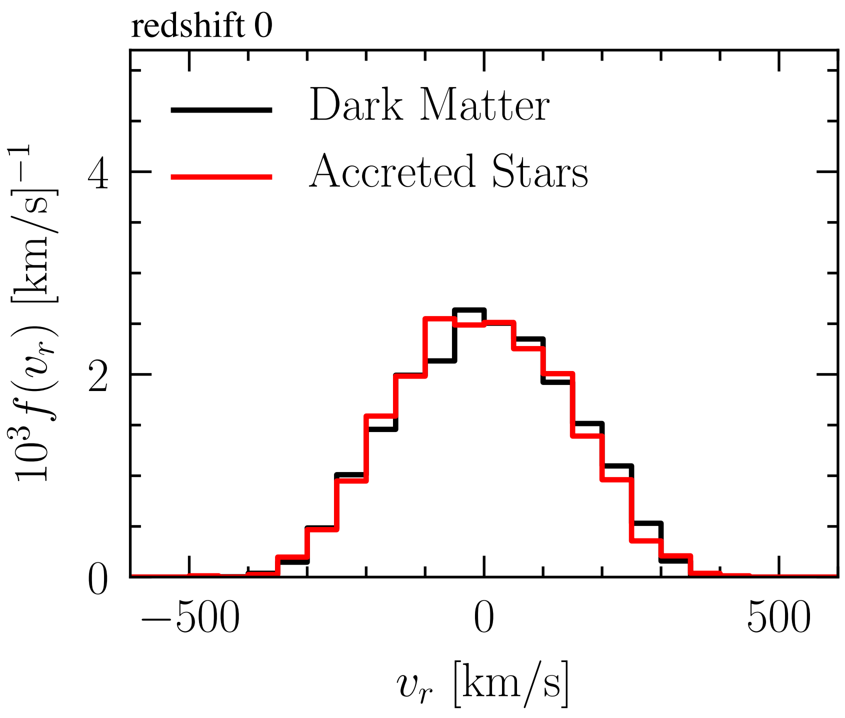
Necib, ML, Garisson-Kimmel, et al., ApJ (2018)

# Oldest Mergers

Oldest stars and dark matter in the Milky Way should have similar kinematics today

They should also have time to equilibrate by today

Oldest Mergers in FIRE Galaxy




FIRE m12i Galaxy (CDM)

Herzog-Arbeitman, ML, Madau, and Necib, PRL (2018); Herzog-Arbeitman, ML, and Necib, JCAP (2018);
Necib, ML, Garisson-Kimmel, et al., ApJ (2019)

# Oldest Mergers

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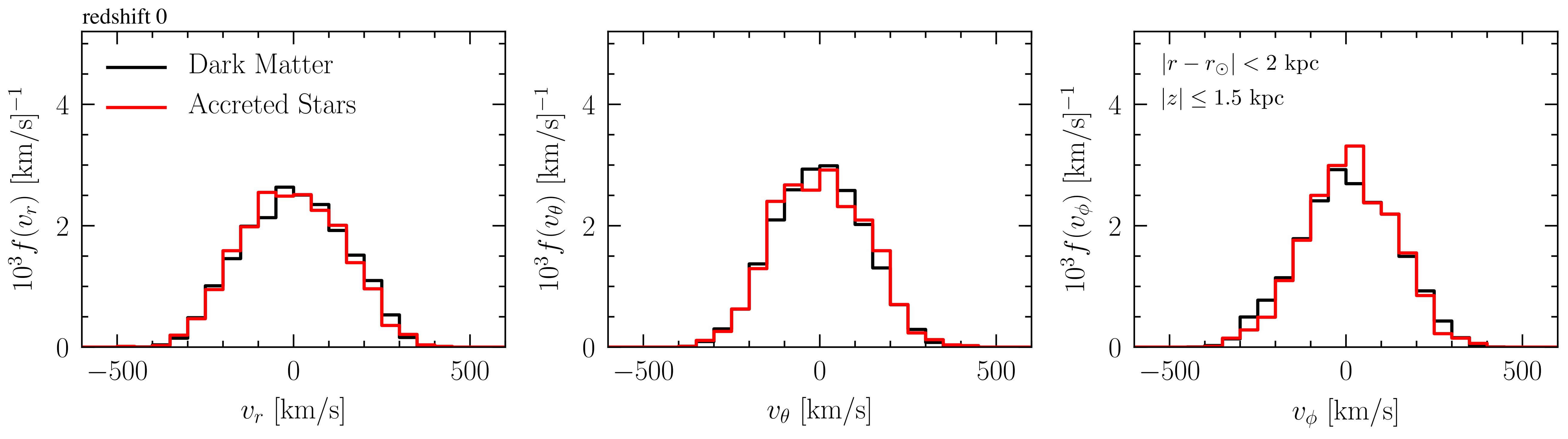
Oldest Mergers in FIRE Galaxy




FIRE m12i Galaxy (CDM)

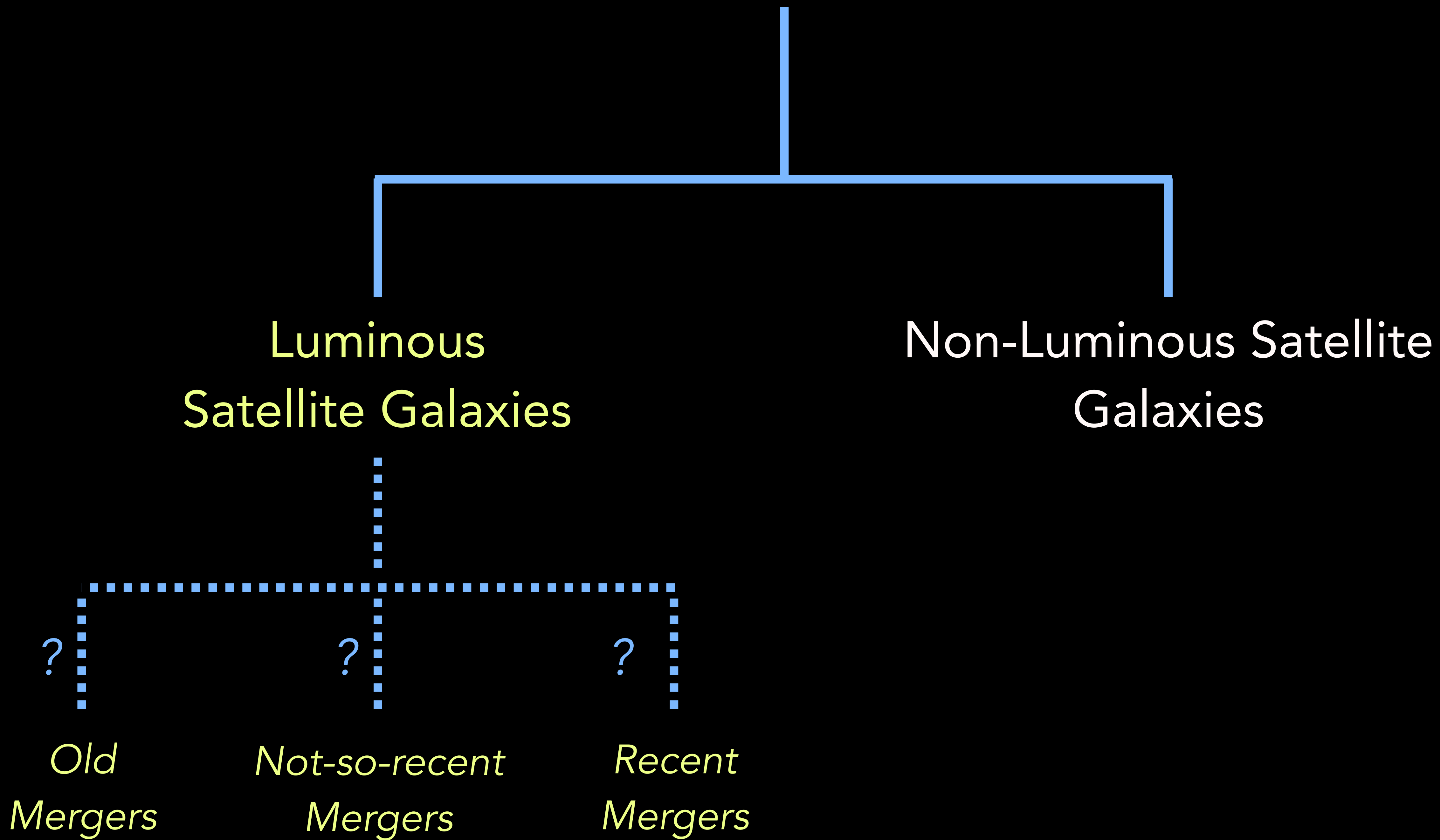
Herzog-Arbeitman, ML, Madau, and Necib, PRL (2018); Herzog-Arbeitman, ML, and Necib, JCAP (2018);
Necib, ML, Garisson-Kimmel, et al., ApJ (2019)

# Local Dark Matter

Luminous
Satellite Galaxies

Non-Luminous Satellite
Galaxies

# Local Dark Matter



Galactic Cannibalism & Dark Matter

Unveiling the Milky Way's Past with *Gaia*

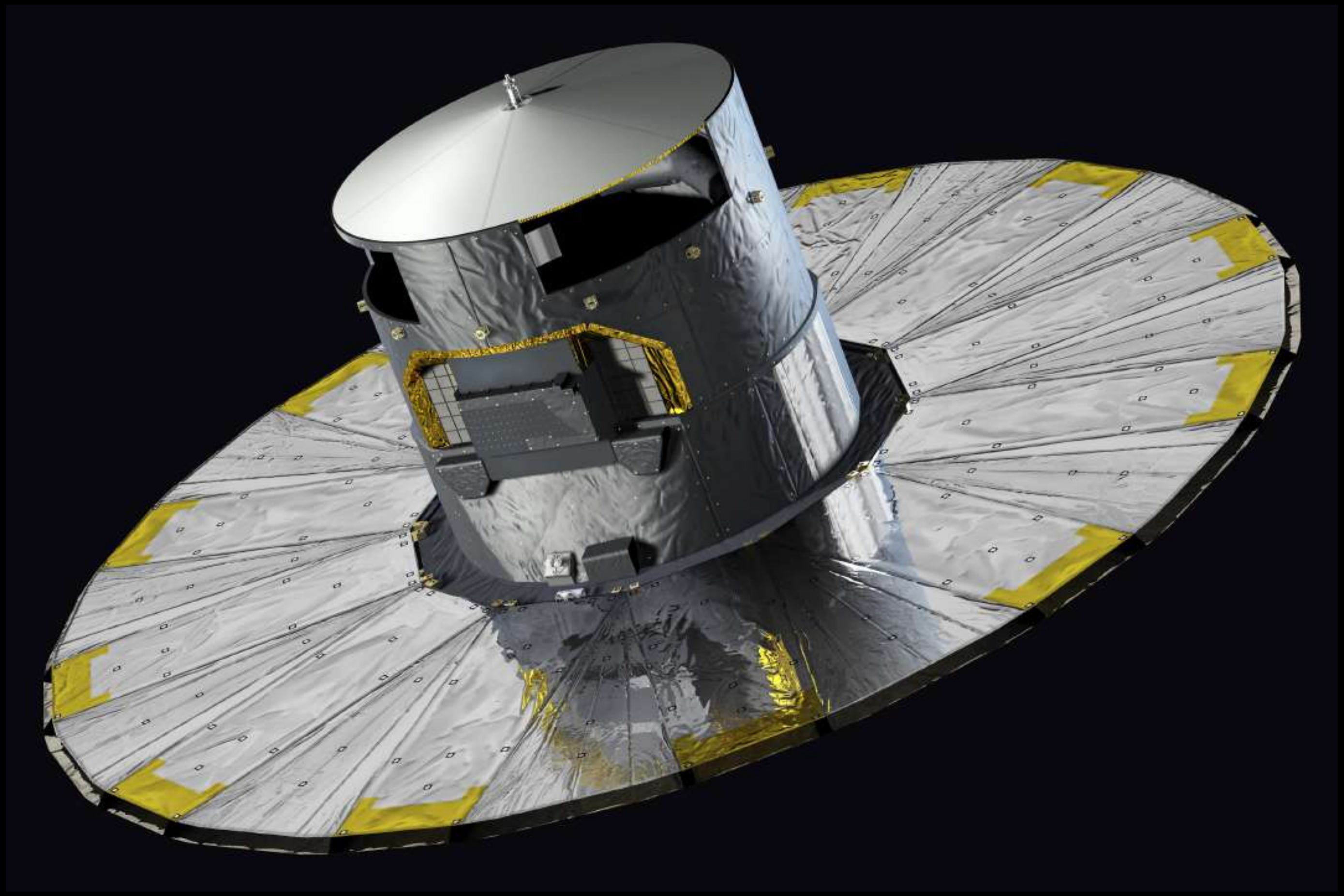
# The *Gaia* Mission

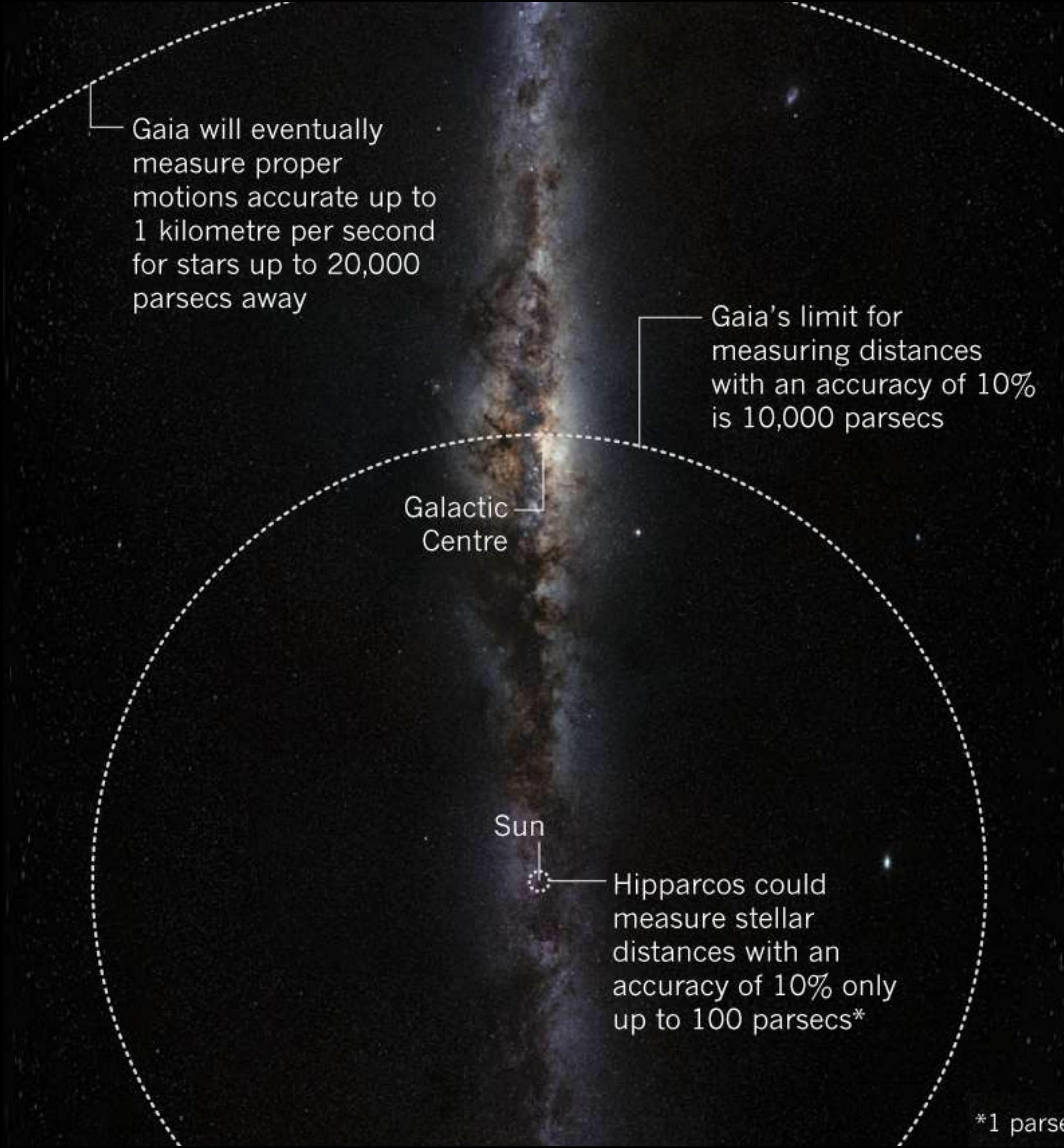
*Gaia* Collaboration (2018)

*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





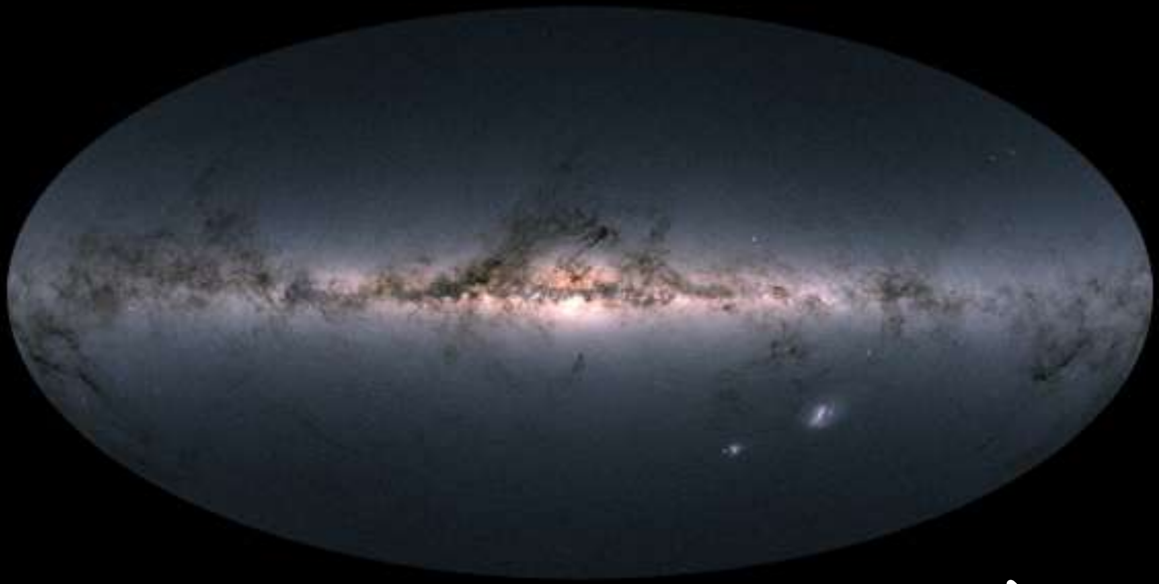



*1 parsec = 3.26 light years

# Galactic Archaeology

Fossil Shape
Fossil Environment
Radioactive Dating

# Galactic Archaeology

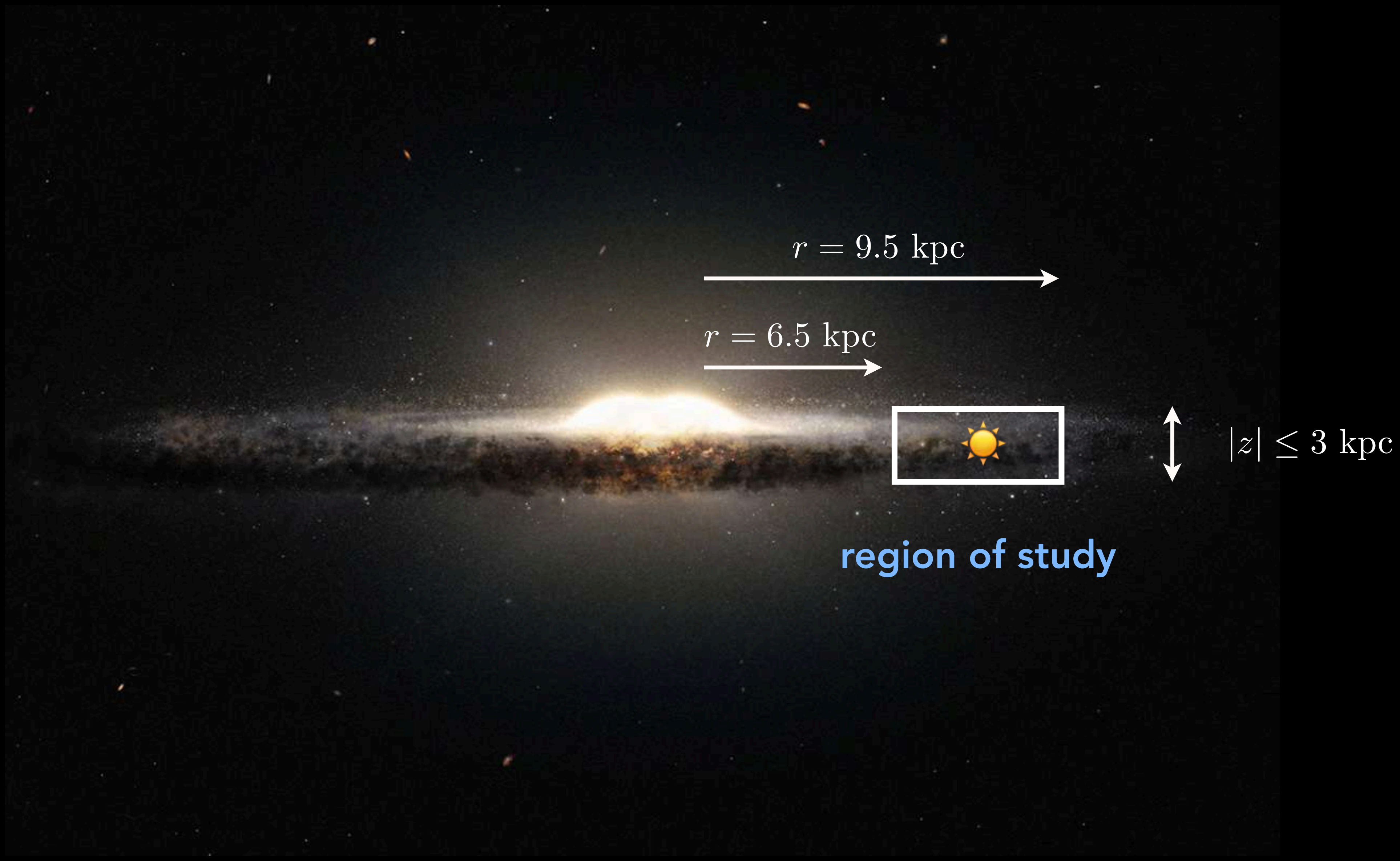


Fossil Shape
Fossil Environment
Radioactive Dating

Stellar position
Stellar velocity
Chemical abundance

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

# Spatial Region of Analysis

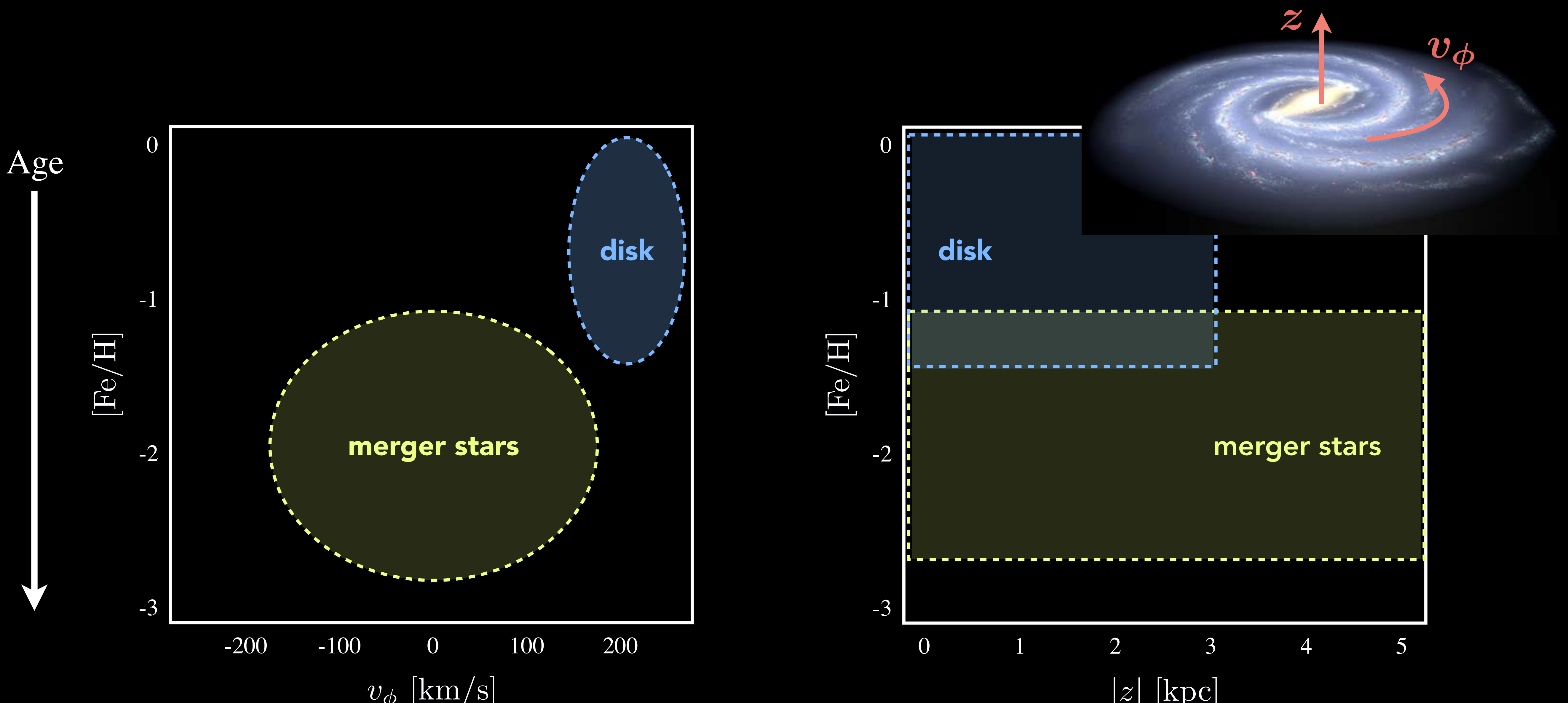



Only ~1% of stars in this region originate from galaxy mergers

# "Traditional" Search Strategies

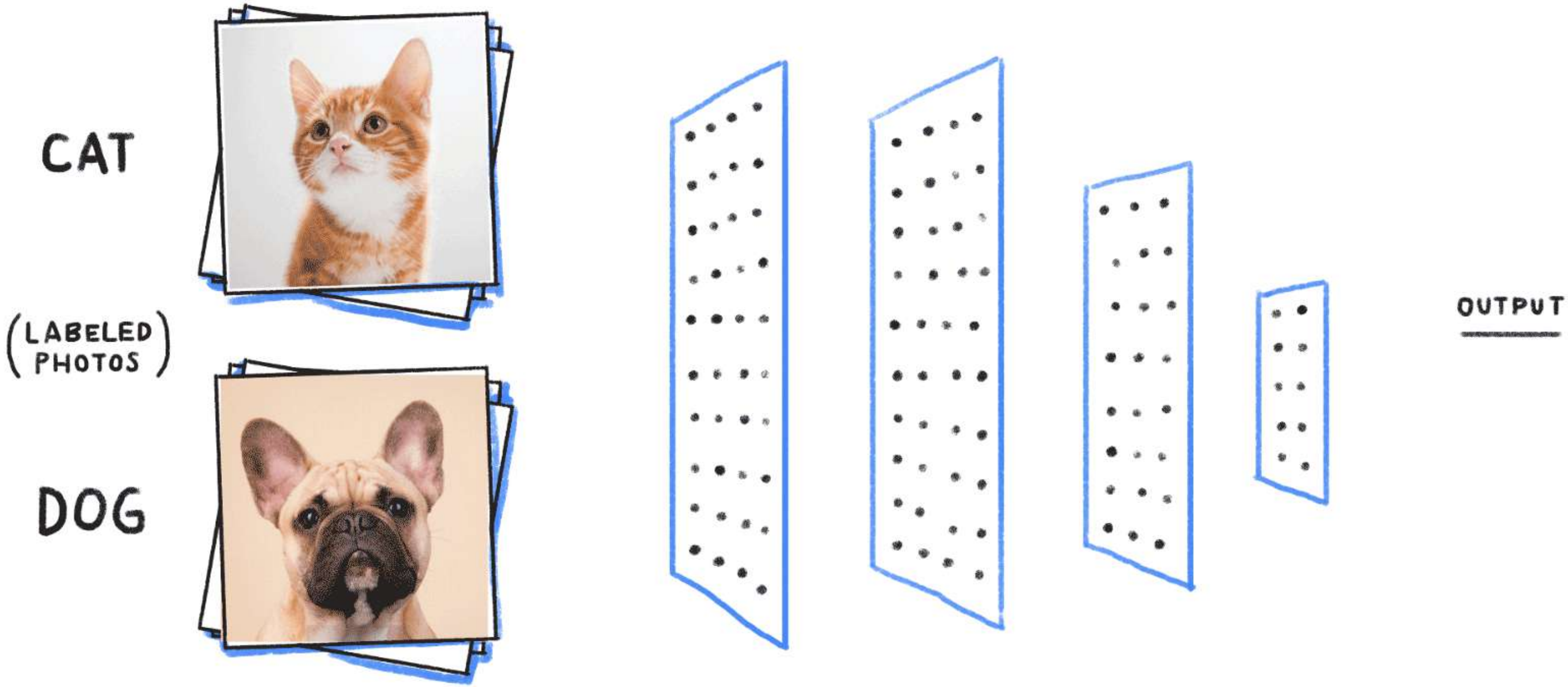
Stars from mergers have distinctive velocities and chemical abundances

Place hard cuts on these quantities to separate from disk stars



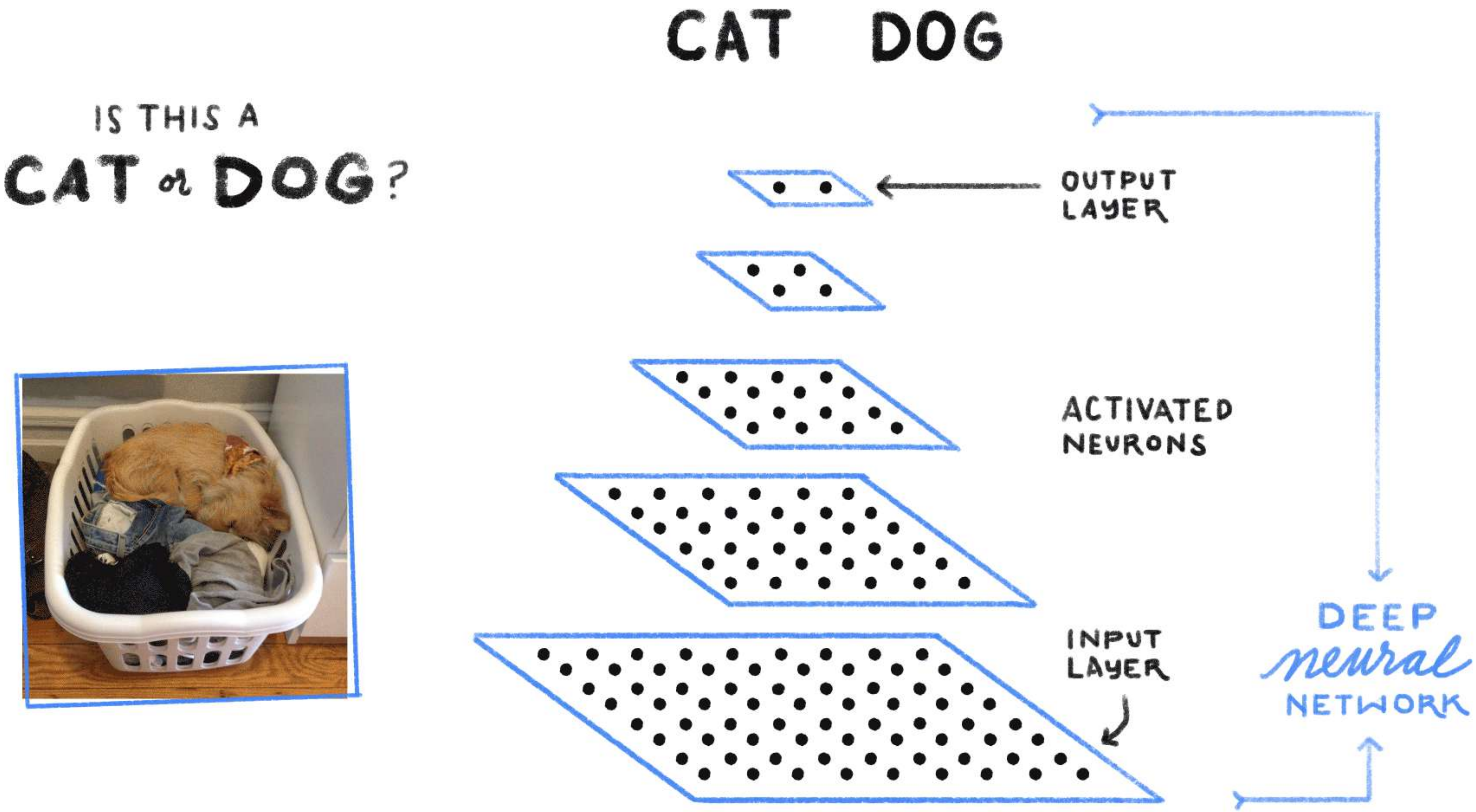

Johnston et al. (1996), Helmi & White (1999), Bullock et al. (2001), Harding et al. (2001)

# Neural Networks




https://becominghuman.ai/building-an-image-classifier-using-deep-learning-in-python-totally-from-a-beginners-perspective-be8dbaf22dd8

# Neural Networks

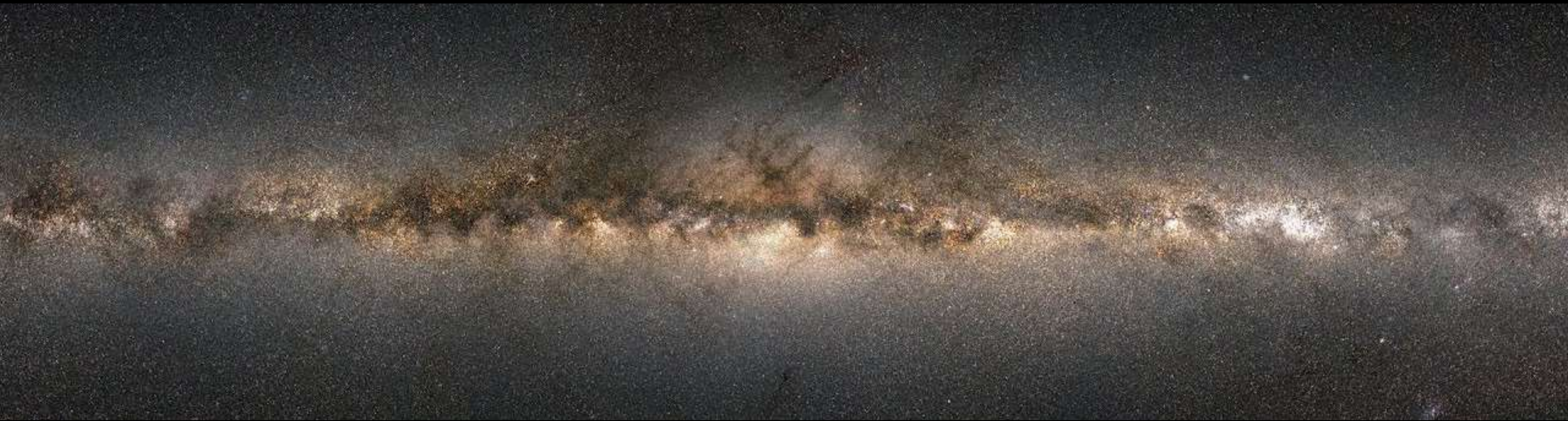



https://becominghuman.ai/building-an-image-classifier-using-deep-learning-in-python-totally-from-a-beginners-perspective-be8dbaf22dd8

# Ananke Mock Galaxy (Training Set)

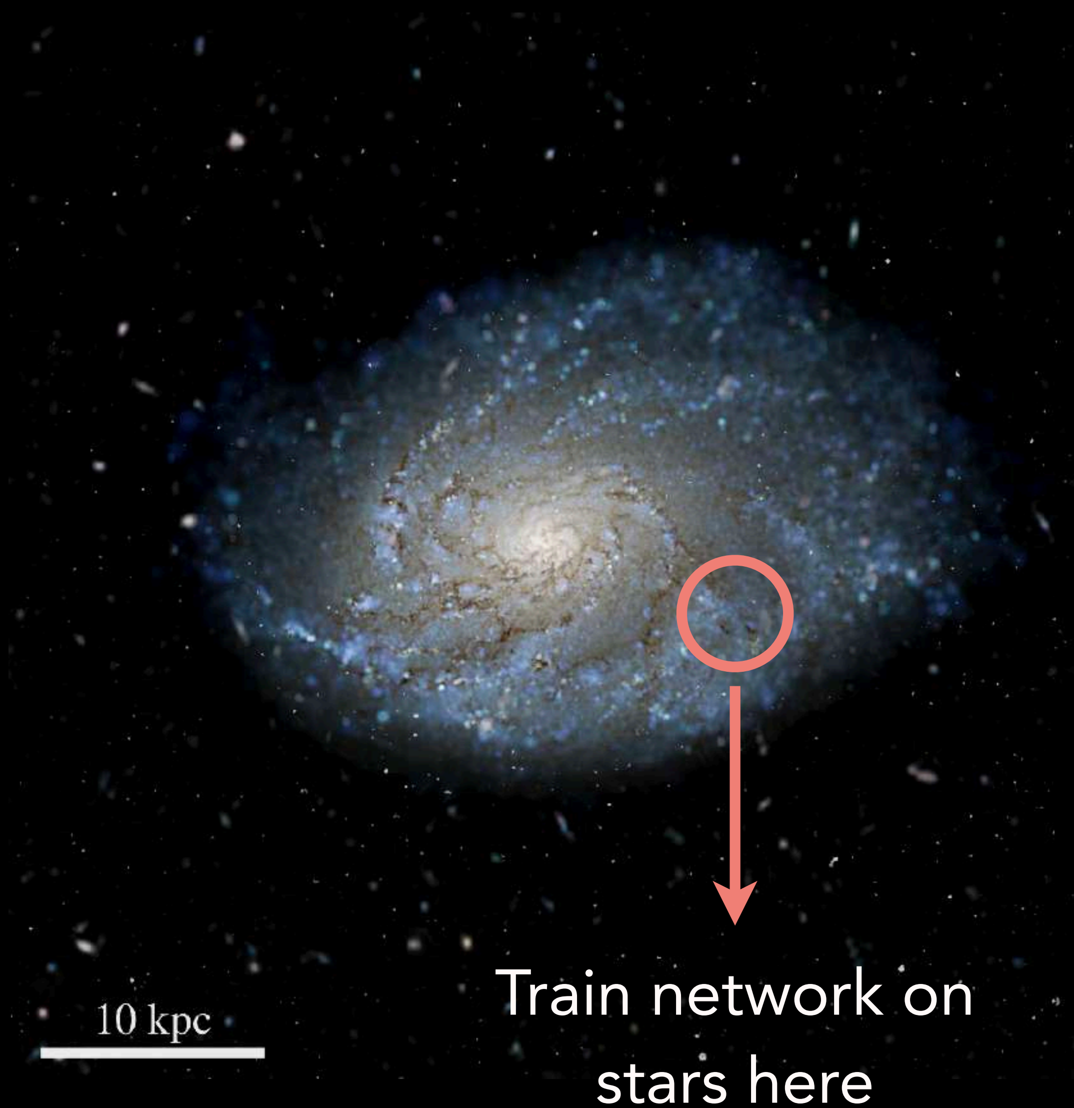
Sanderson *et al.* [1806.10564]

# *Gaia* Data



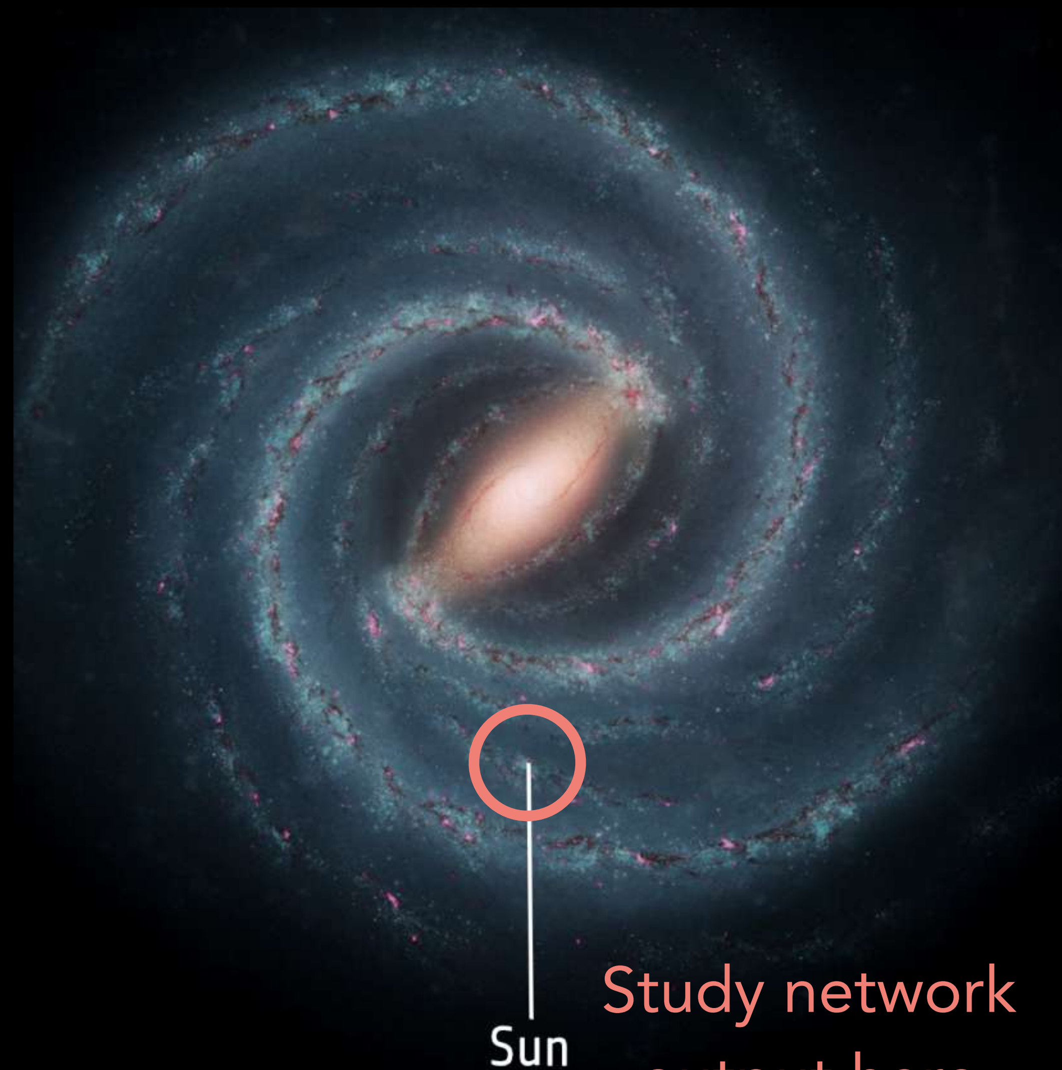
# Training the Network

Simulated Ananke Galaxy




Transfer training

Real Milky Way Data




Extensive testing performed on simulated Milky Way-like galaxies to characterize potential biases of the methodology

B. Ostdiek, L. Necib, T. Cohen, M. Freytsis, ML, et al. Astron. Astrophys. (2020)

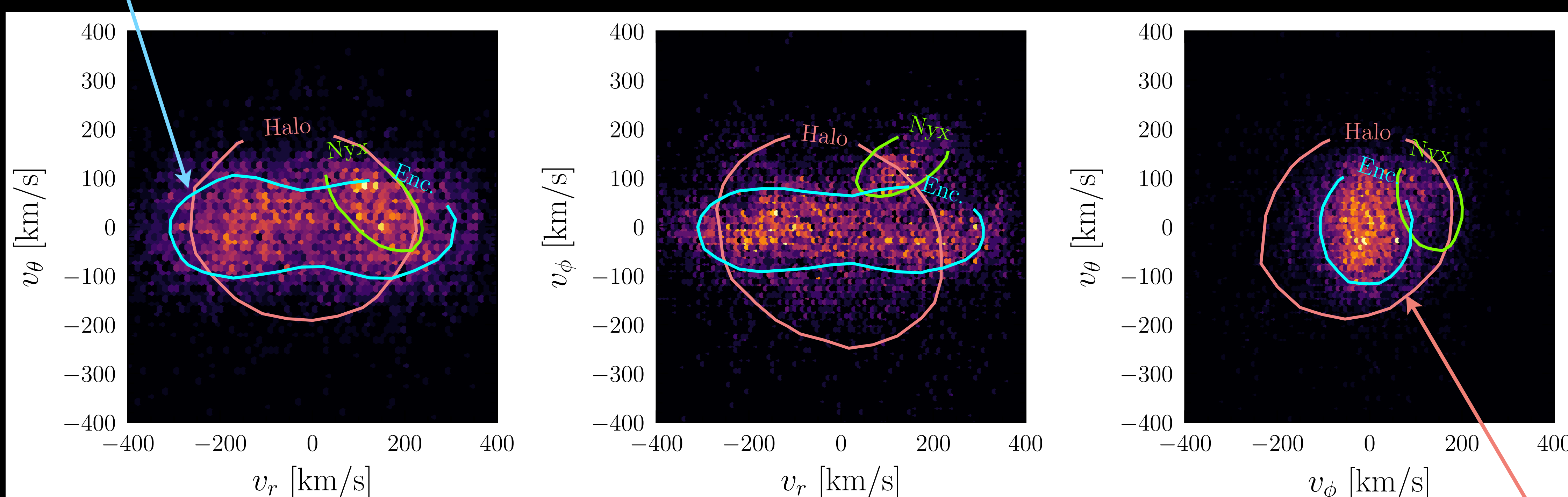
# *Gaia* Accreted Star Catalog

New catalog provides unprecedented look at substructure in disk plane

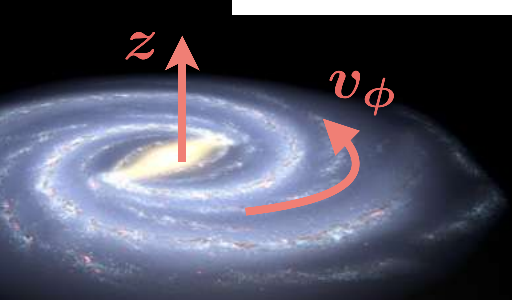
Recover well-studied substructures, as well as a vast new stellar stream

not-so-recent merger

**Gaia stars labeled as accreted with high confidence**




oldest mergers

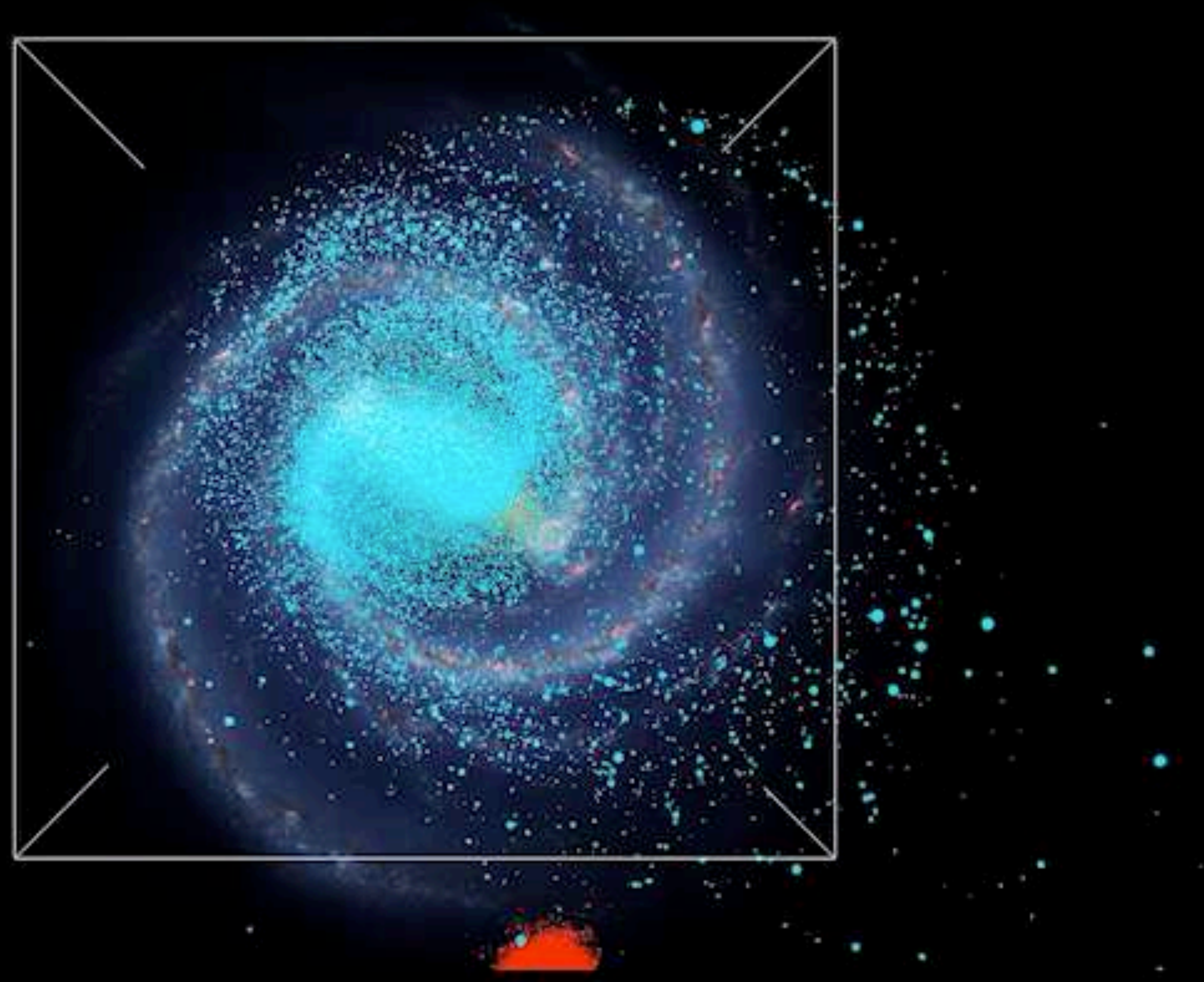



L. Necib, B. Ostdiek, ML, T. Cohen, et al. ApJ (2020); Nat. Astron. (2020)

# *Gaia* Enceladus

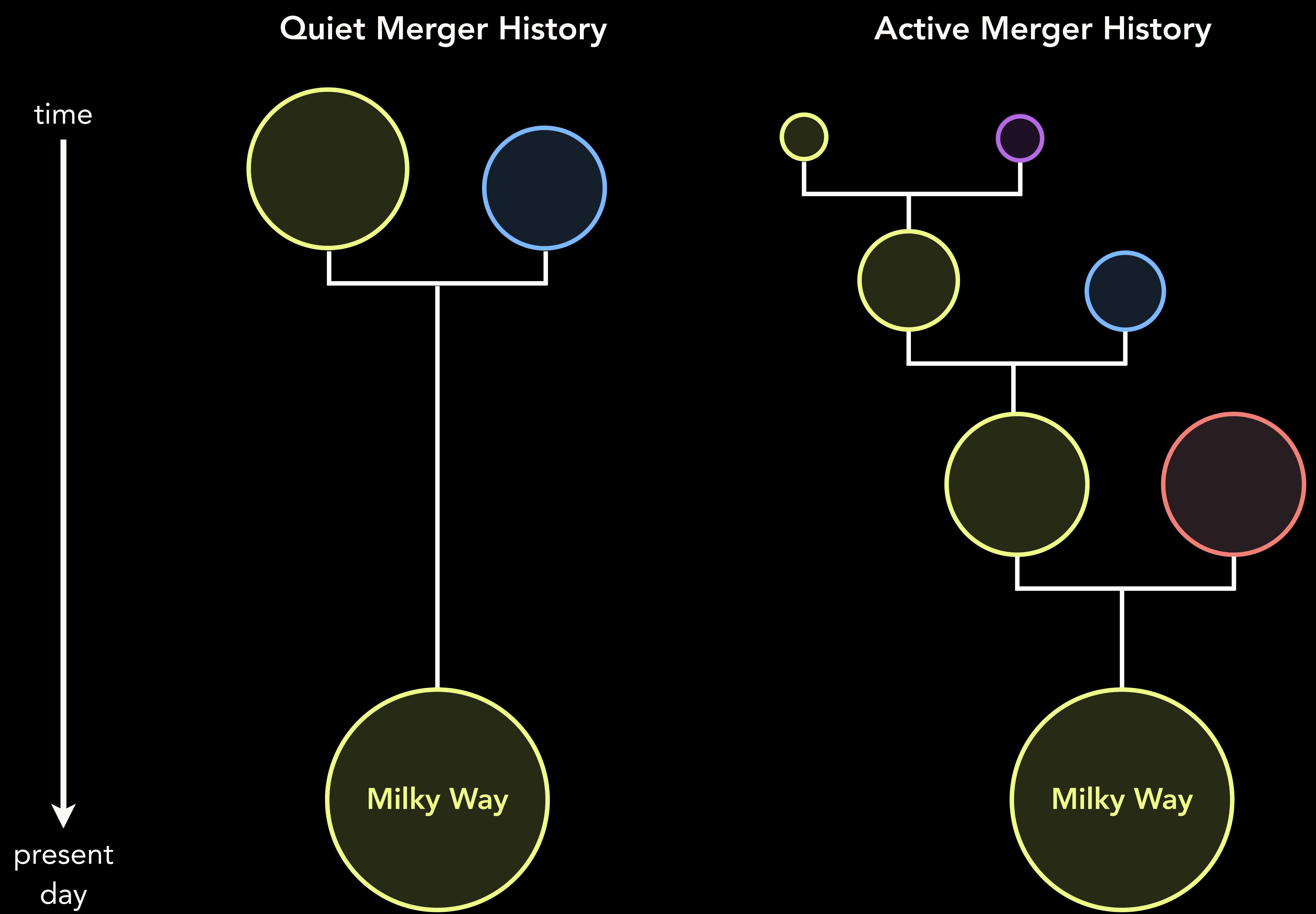
Single merger dragged in the majority of the local accreted stars

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



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

# The Local Milky Way’s Family Tree



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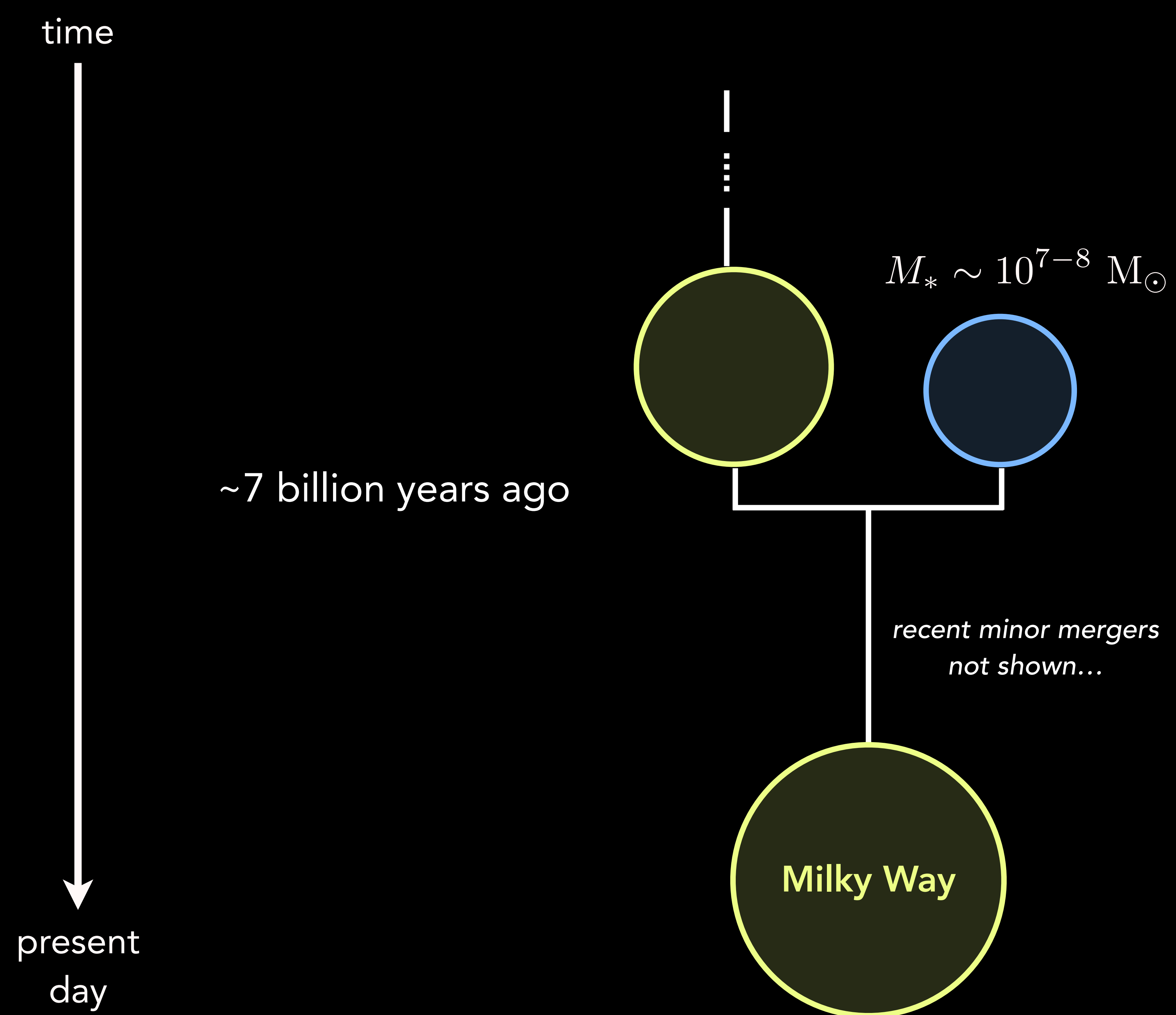
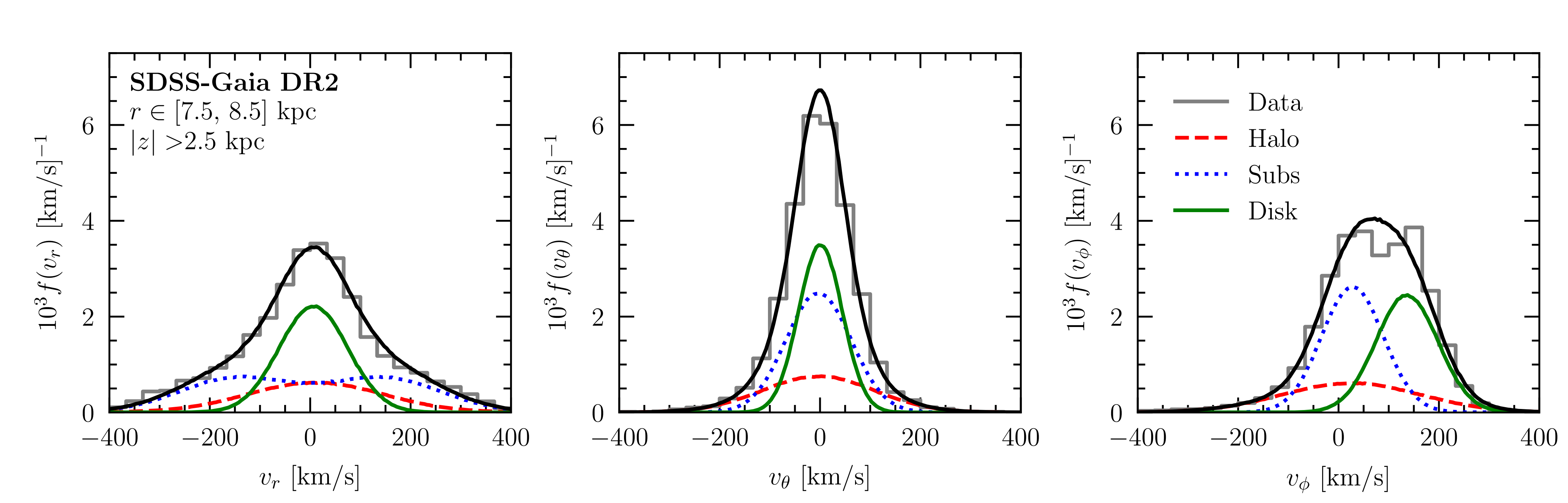


# *Gaia* Enceladus

Dark matter would also be accreted from Enceladus merger

Based on time of accretion, this dark matter likely in debris flow, and so its velocities should track that of Enceladus stars

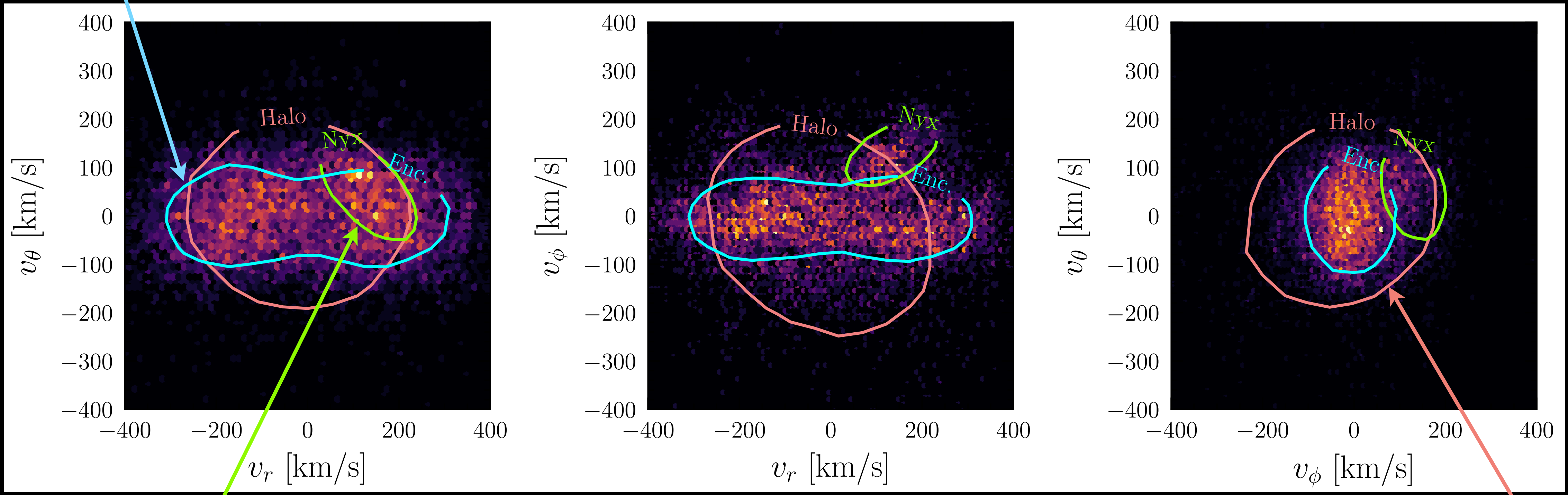



Necib, ML, and Belokurov, ApJ (2019)

# *Gaia* Accreted Star Catalog

not-so-recent merger

**Gaia stars labeled as accreted with high confidence**




recent merger?

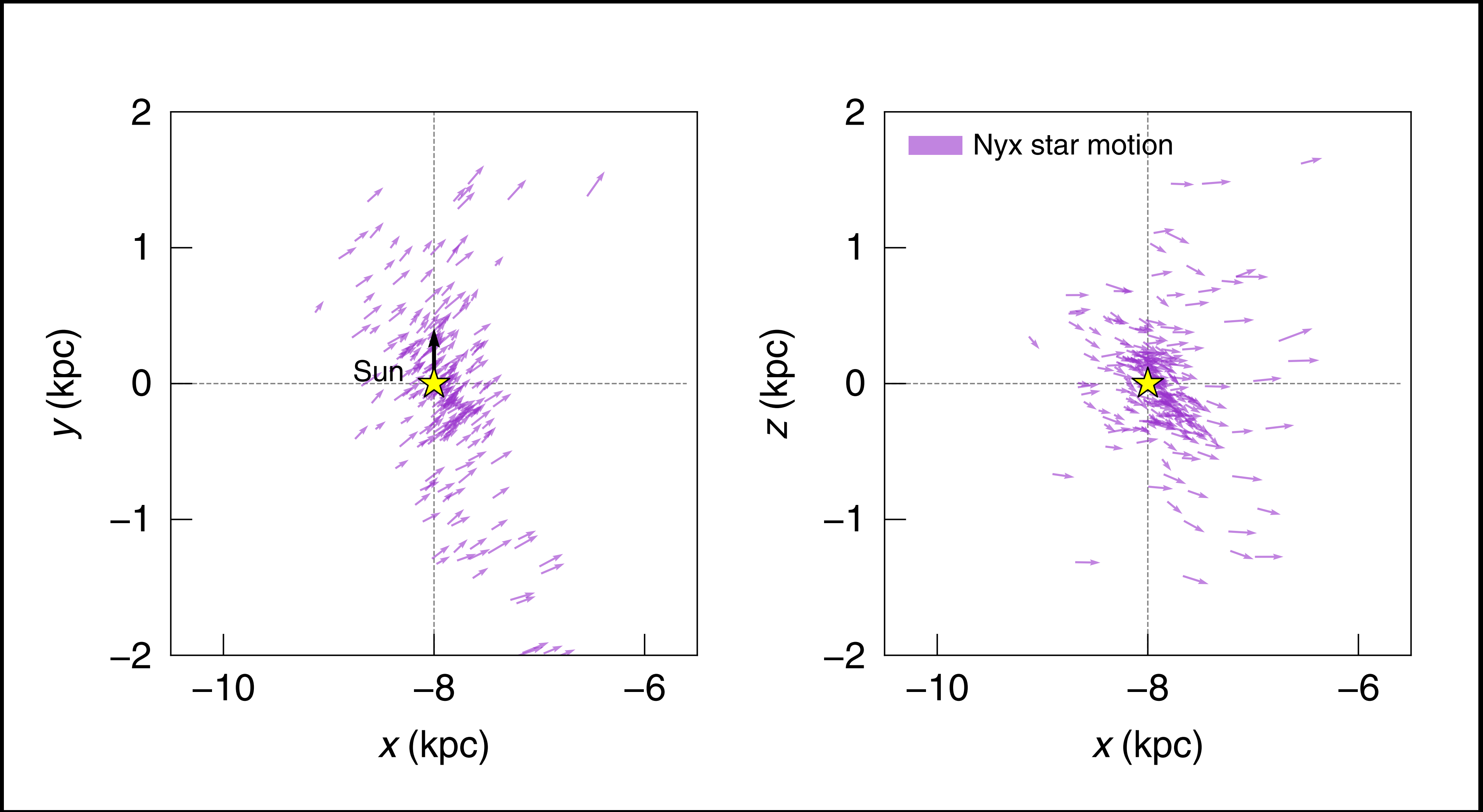
oldest mergers

L. Necib, B. Ostdiek, ML, T. Cohen, et al. ApJ (2020); Nat. Astron. (2020)

# The Nyx Stream

~200 stars with coherent velocities passing near the Sun

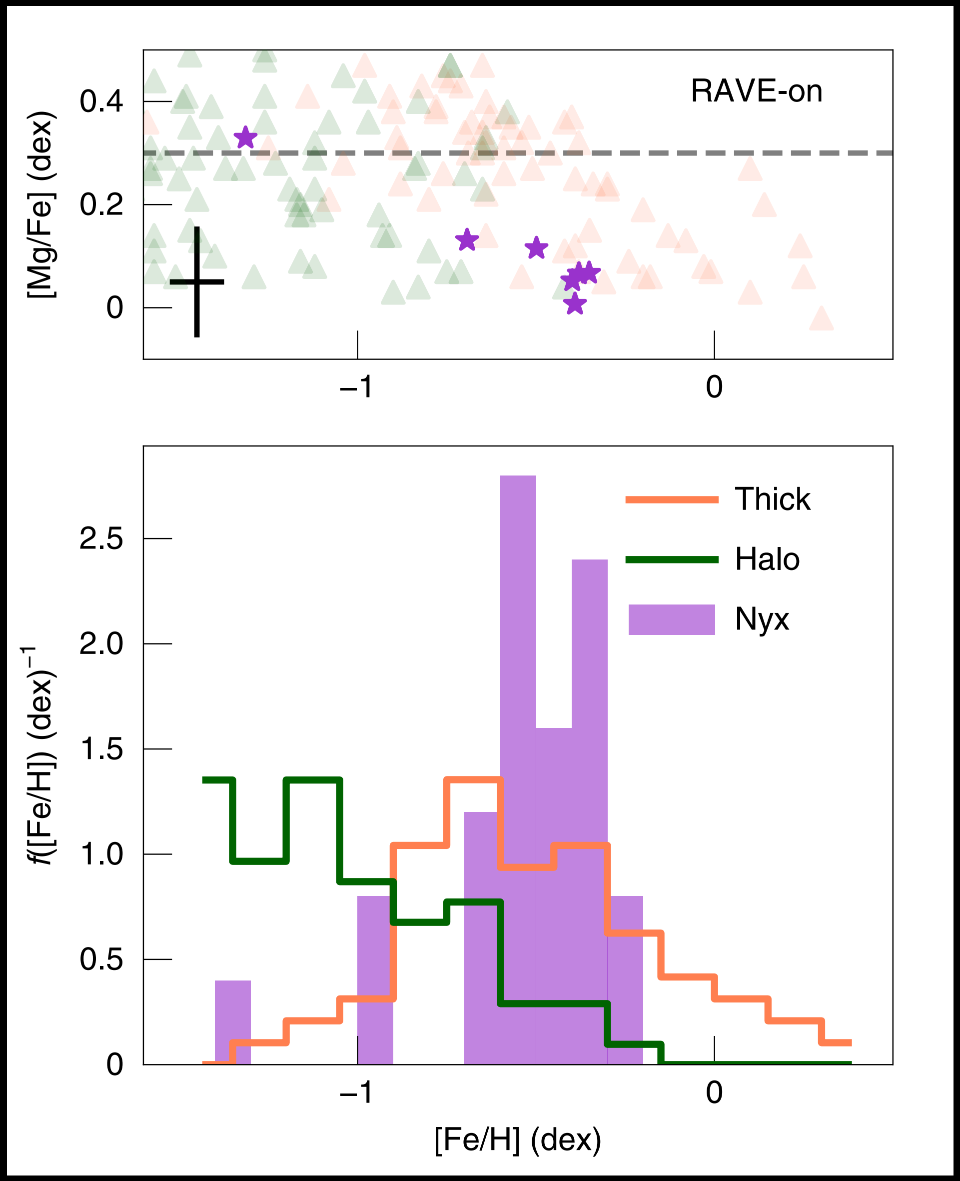
Nyx stars rotate more slowly than disk stars and are on more eccentric orbits




L. Necib, B. Ostdiek, ML, T. Cohen, et al. ApJ (2020); Nat. Astron. (2020)

# Origin of the Nyx Stream

Nyx stars are relatively metal-rich with ages ~6-10 Gyr




L. Necib, B. Ostdiek, ML, T. Cohen, et al. Nat. Astron. (2020)

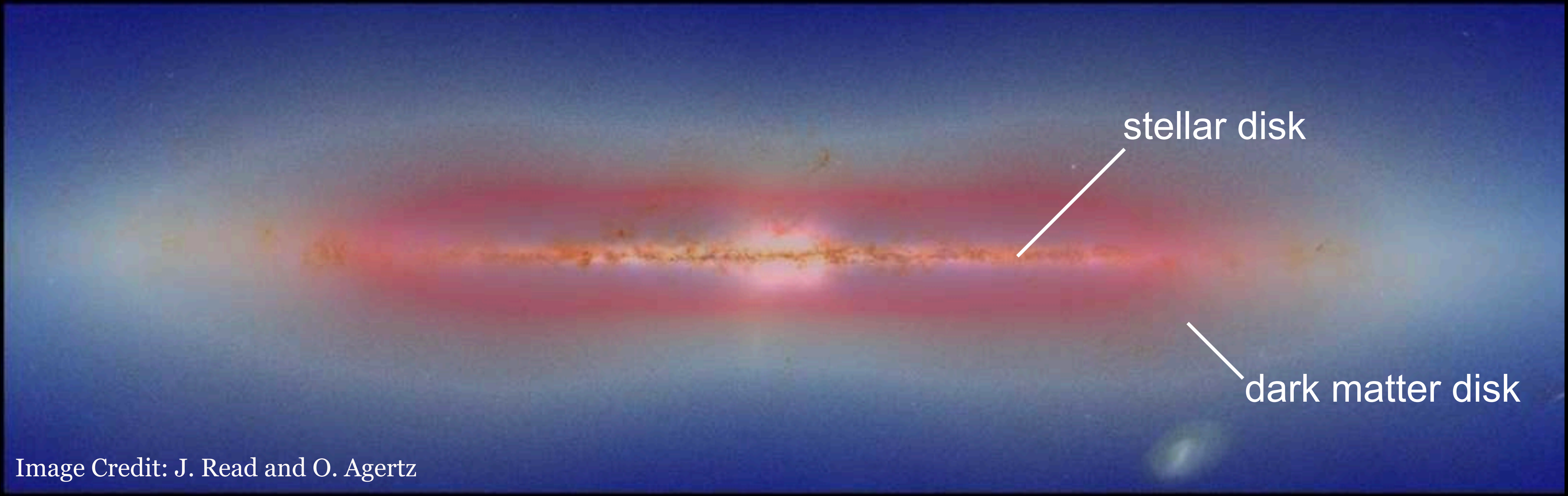
Kinematics of Nyx suggest it is the remnant of a galaxy merger

Further spectroscopic studies needed to confirm that Nyx is distinct from the disk

# Dark Matter Disk

Co-rotating dark matter disks predicted to be a natural consequence of prograde mergers

Read et al. (2008, 2009); Purcell et al. (2009); Ling et al. (2010); Pillepich et al. (2014)

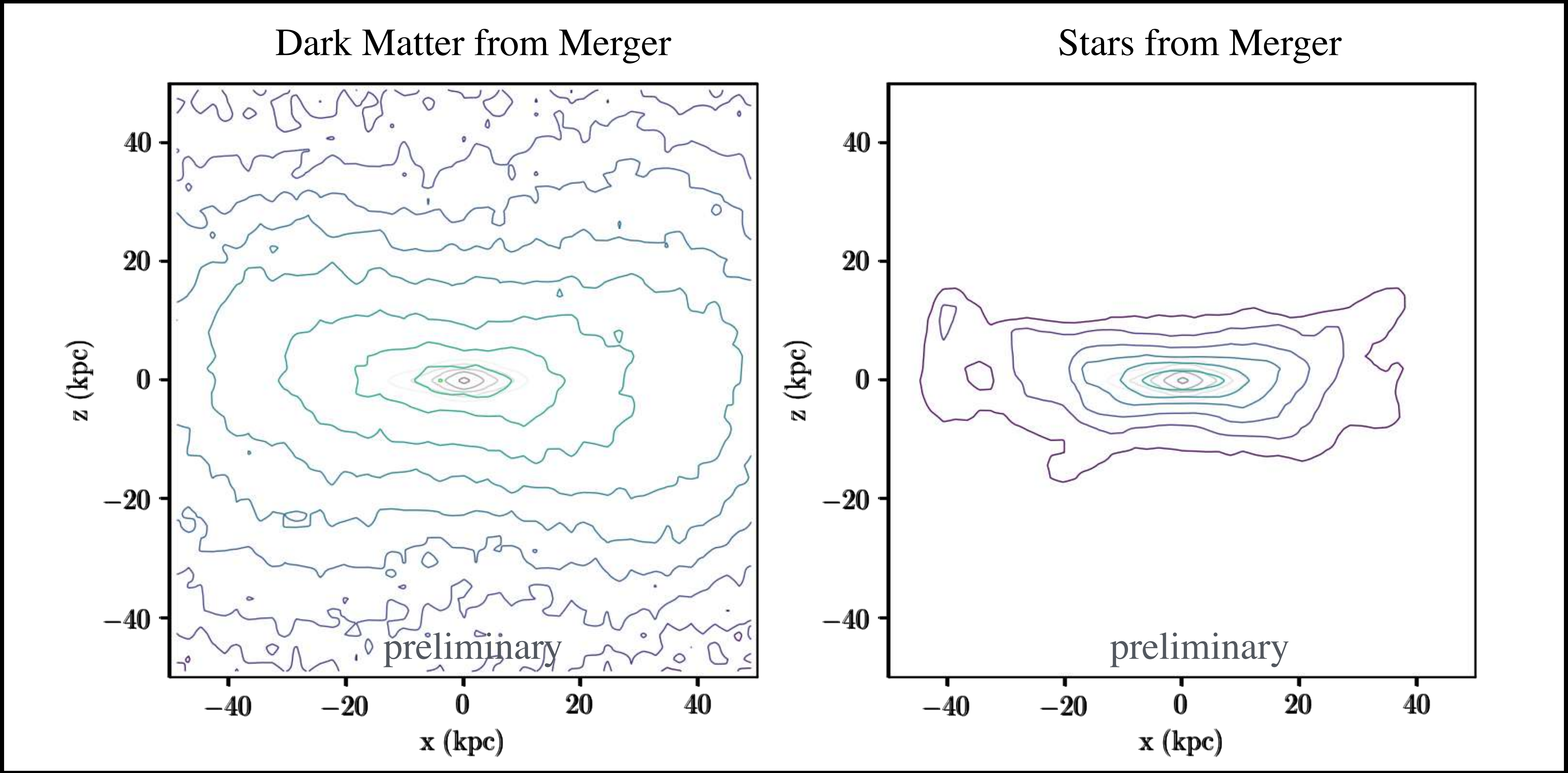



If Nyx originated from a disrupted galaxy, it may have significant implications for dark matter distribution

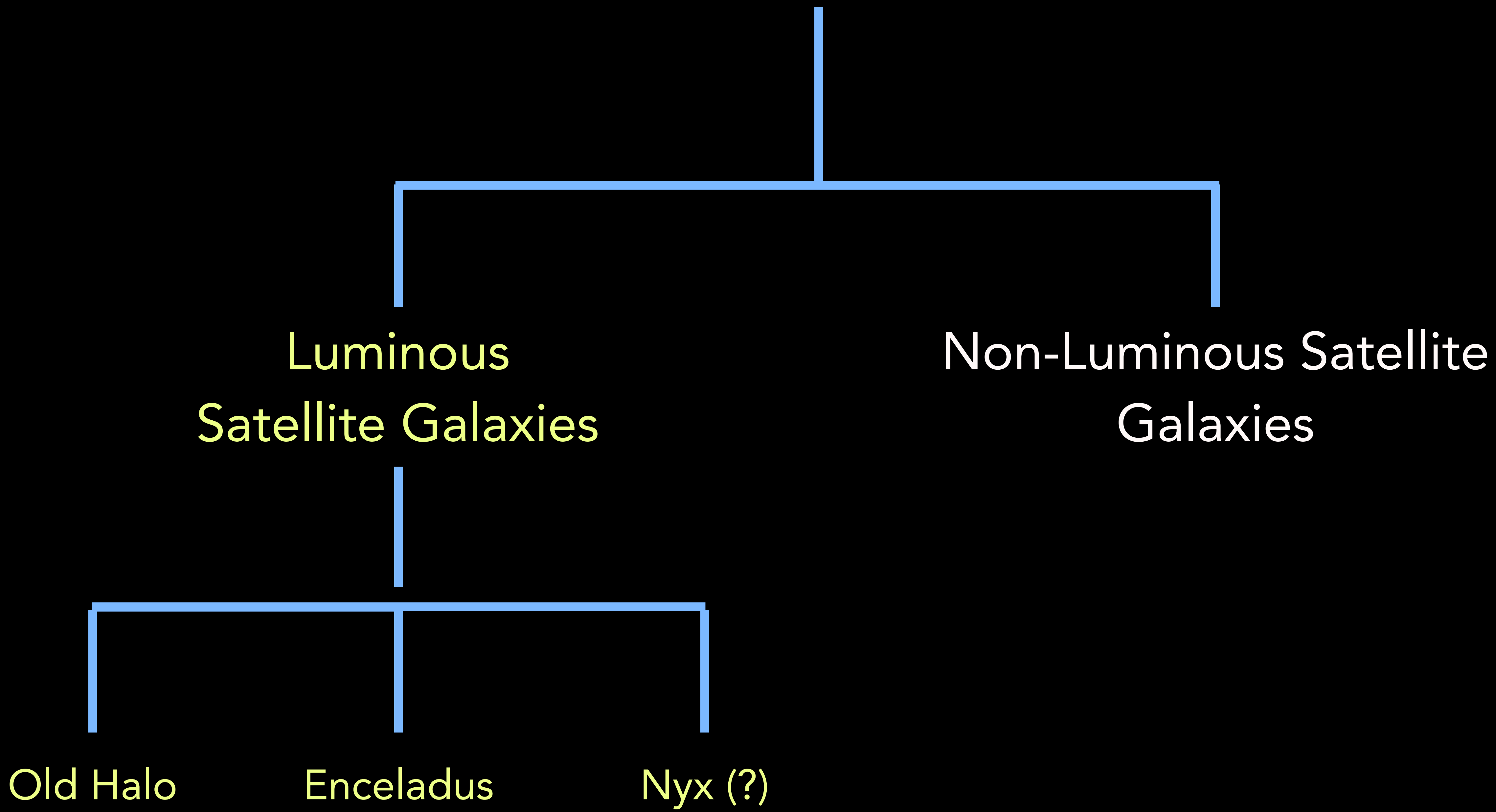
# Dark Matter Disks

Dedicated simulation studies underway to determine expected dark matter distribution from Nyx-like merger

work in progress with B. Dodge, O. Slone, L. Necib, B. Ostdiek, T. Cohen



# Local Dark Matter



# Follow-Up Studies of Nyx

Spectroscopic studies of Nyx stream underway

M. Truong, A. Ji, L. Necib, et al. (in progress)

Analyze larger fraction of *Gaia* data to find more candidate stream members

Dropulic, Ostdiek, Chang, Liu, Cohen, and ML [2103.14039]

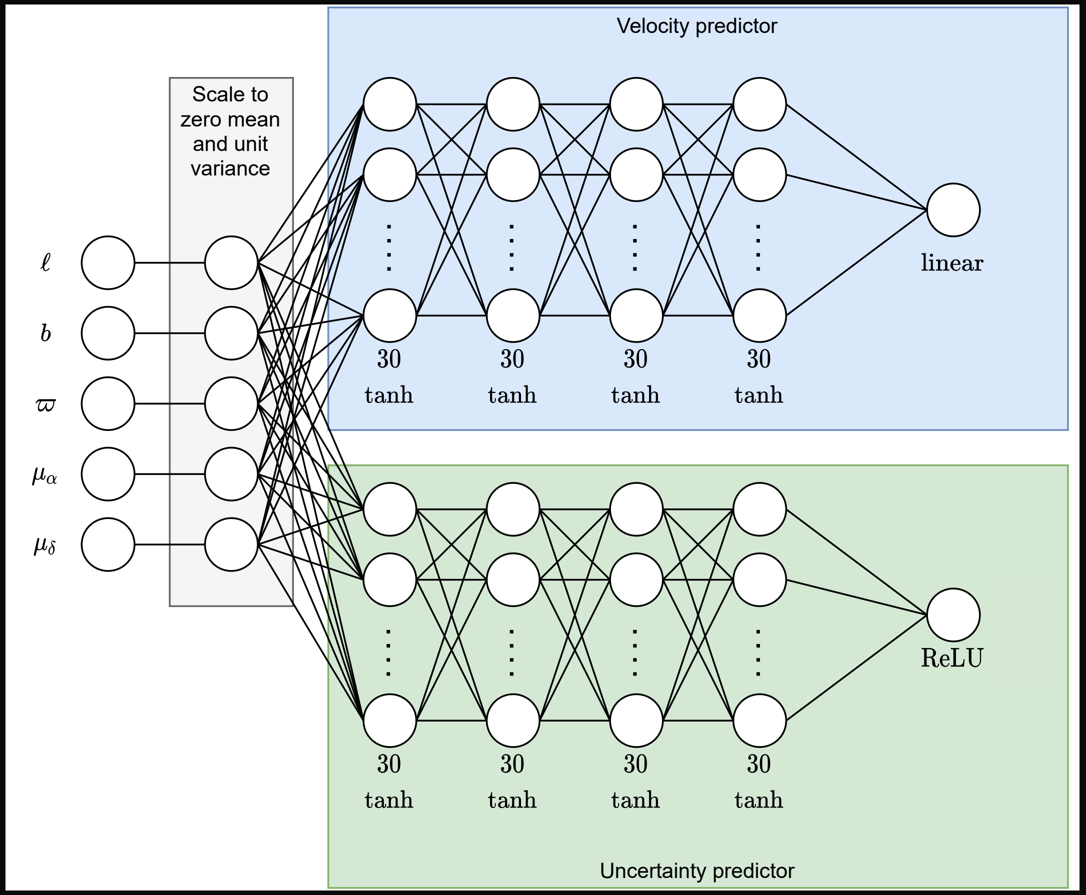
# Machine Learning Radial Velocities

Currently, less than 1% of *Gaia* stars have complete phase-space information

Can a machine accurately fill in phase space for remaining stars?

**Network Inputs**

5D astrometric coordinates




Dropulic, Ostdiek, Chang, Liu, Cohen, and ML [2103.14039]

**Network Outputs**

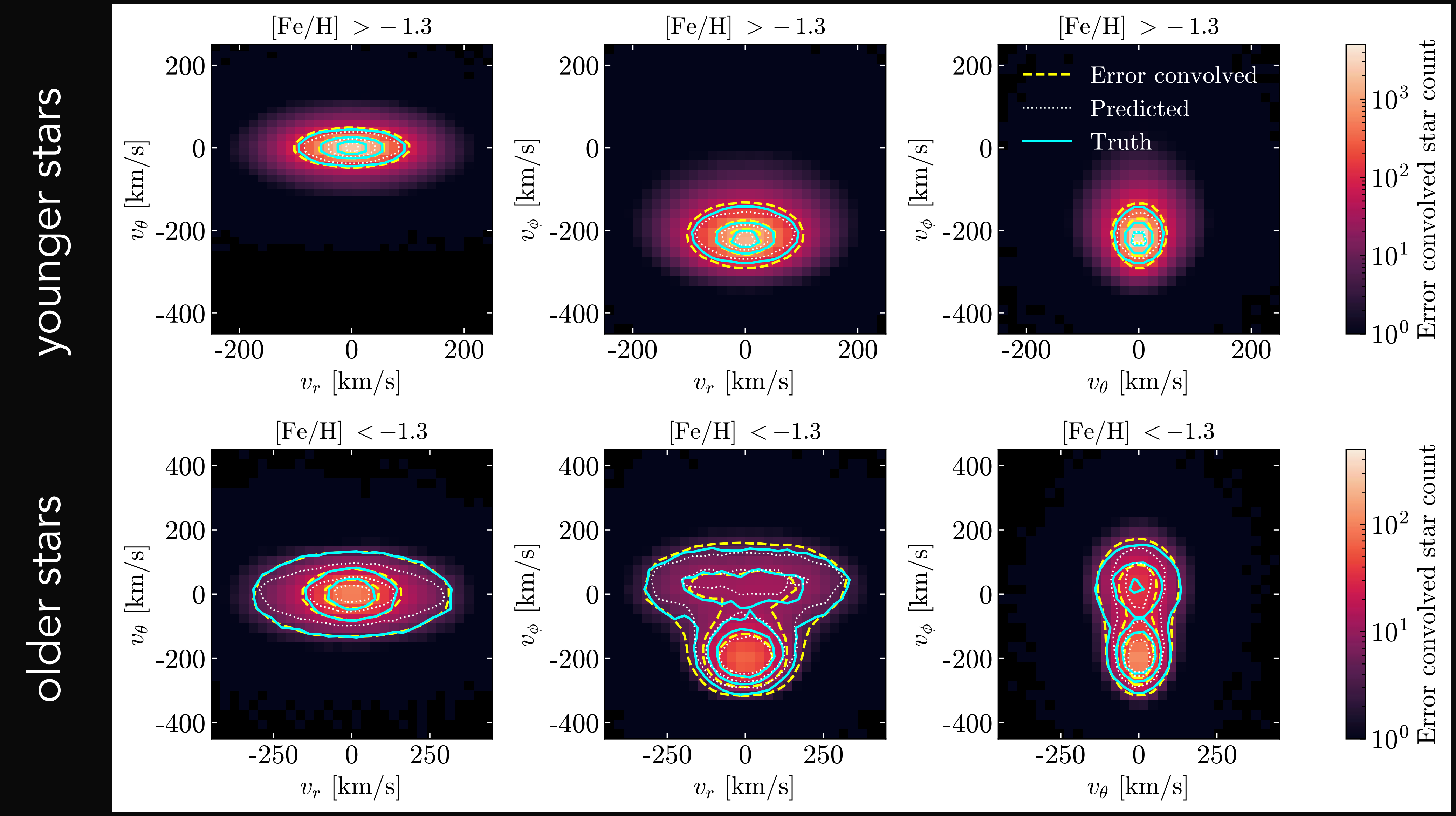
line-of-sight velocity

uncertainty on line-of-sight velocity prediction

supported by the Schmidt DataX Fund

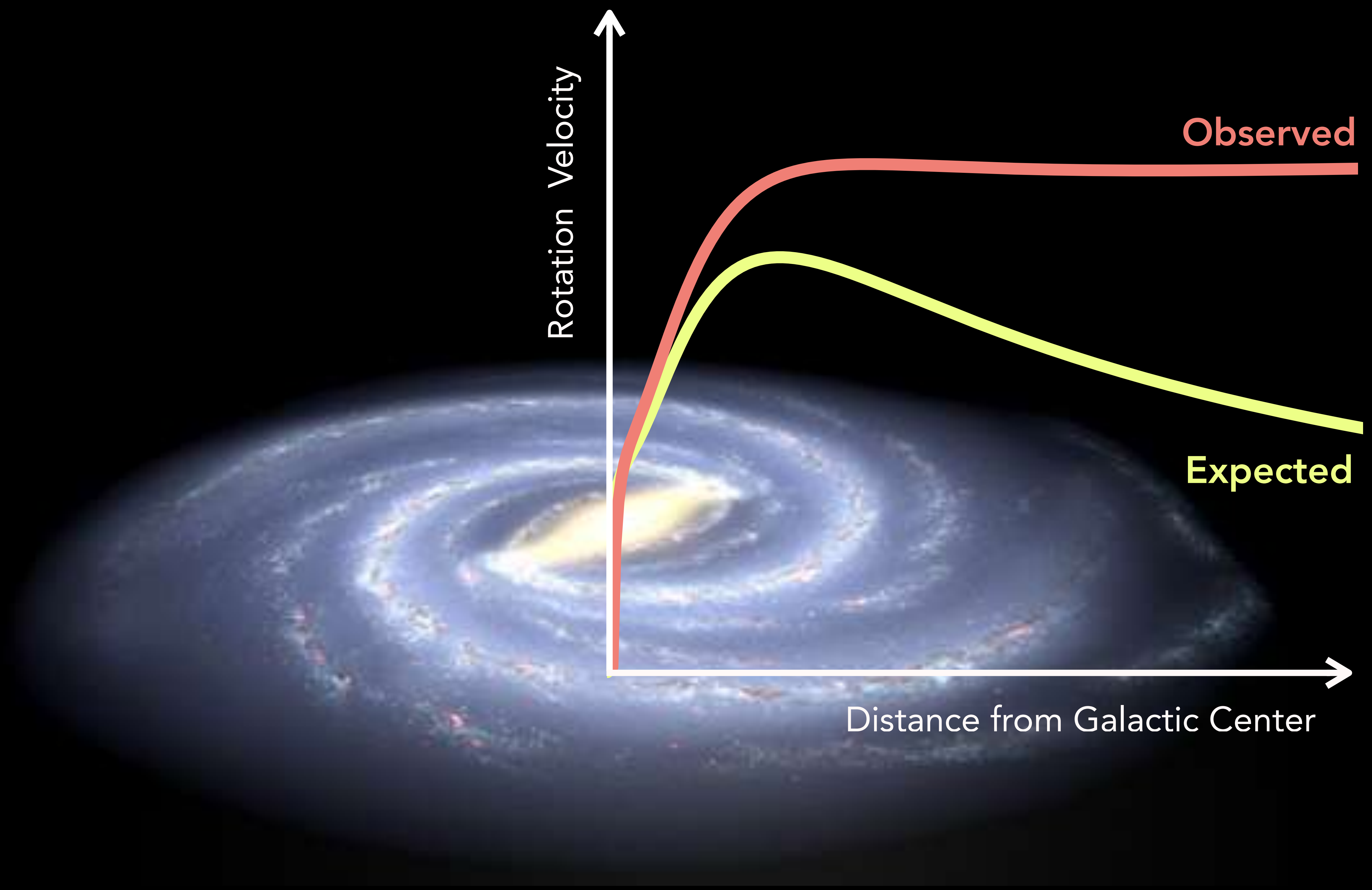
# Tests on Mock *Gaia* Data

Network is trained on subset of mock catalog with complete 6D information, then applied to remainder of mock catalog




Dropulic, Ostdiek, Chang, Liu, Cohen, and ML [2103.14039]

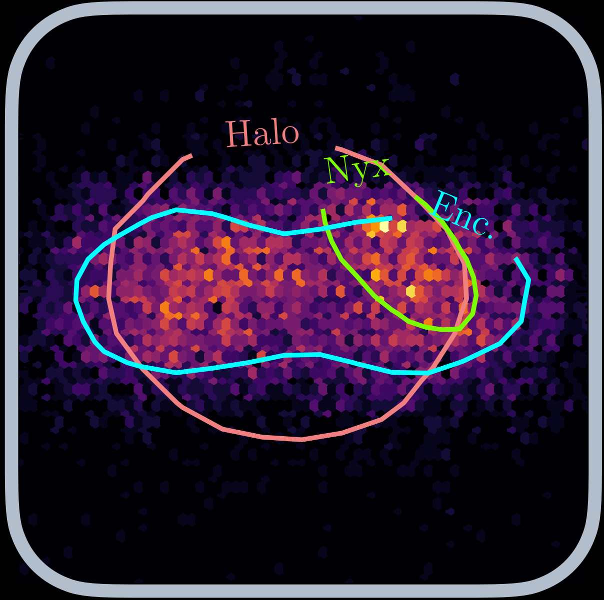
# The Dark Matter Halo v2.0

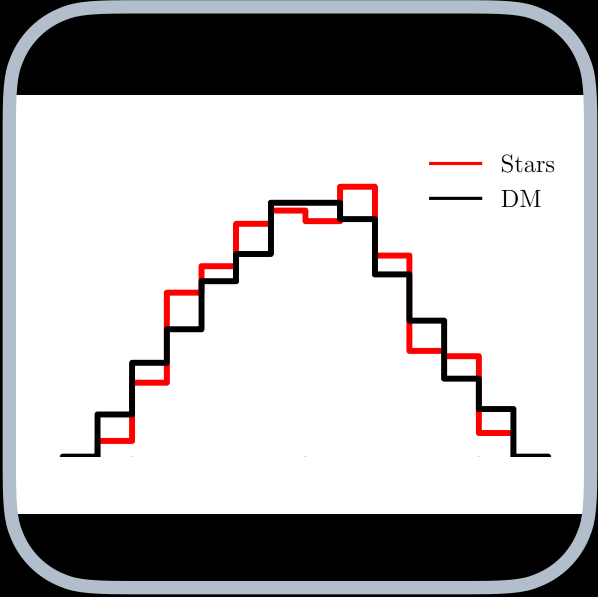


# The Dark Matter Halo v2.0

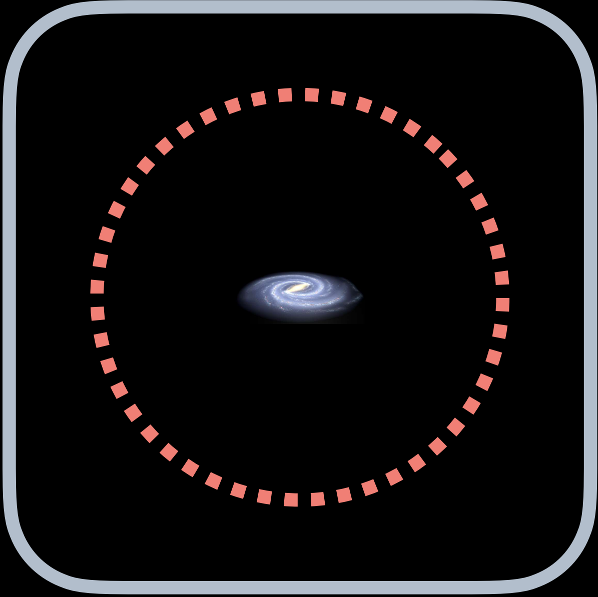
**Galaxy Mergers**

**Stellar Substructure**




**Dark matter-stellar correspondence**



**Empirical Halo Model**