Simulating the Evolving Milky Way: From Disk to Halo

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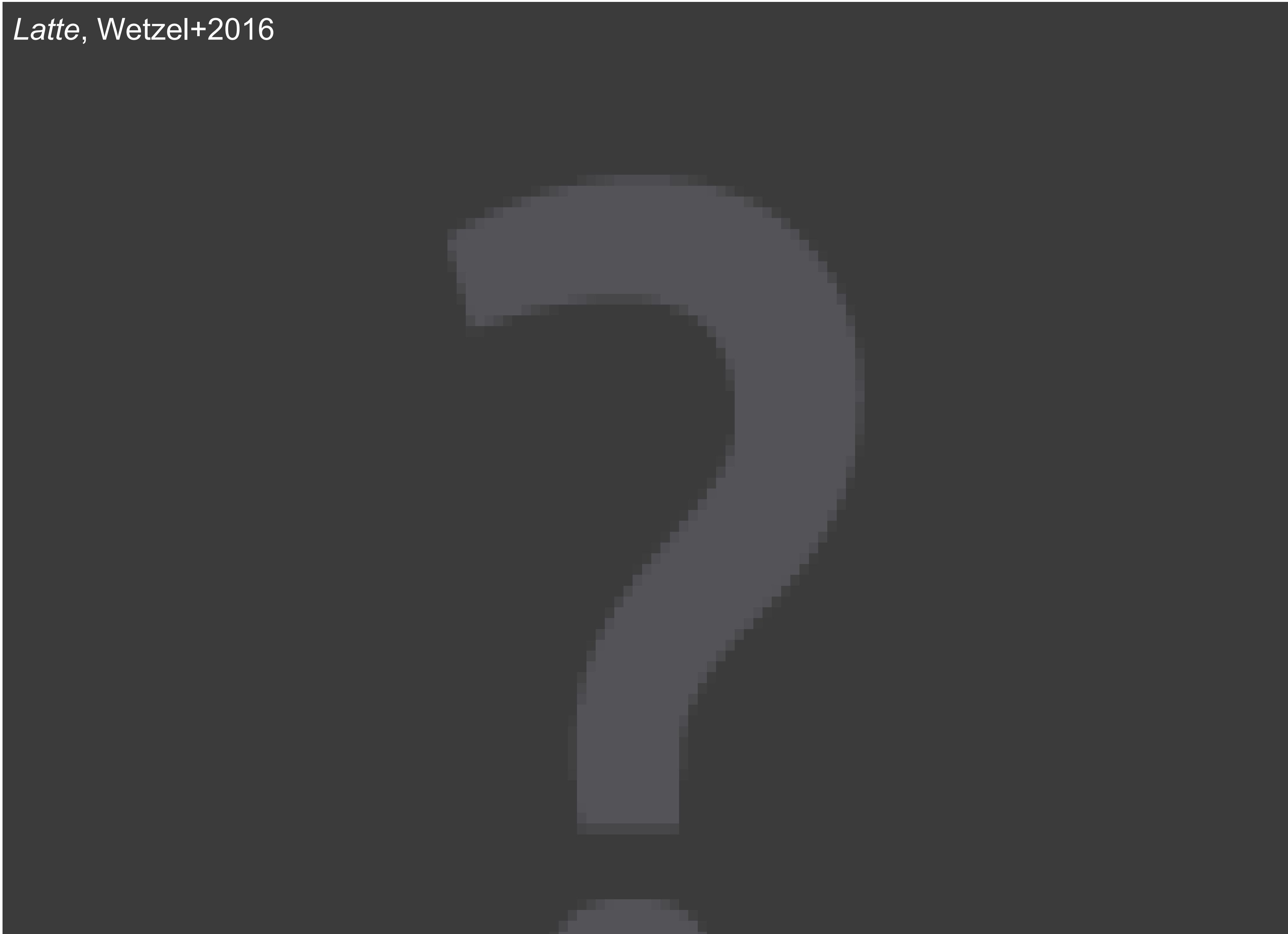
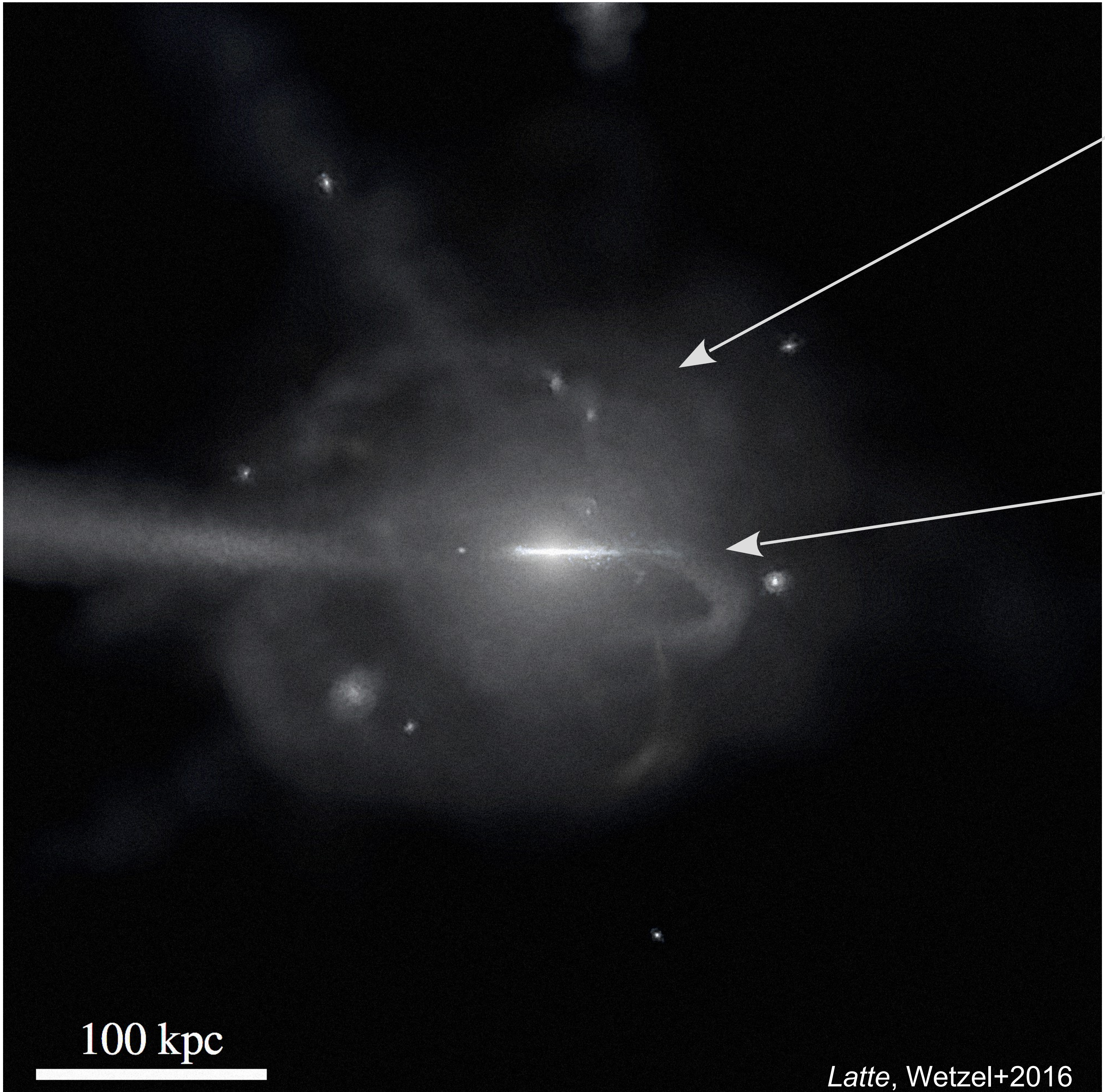
Galactic archeology: what can we learn about MW's past from stars?

Galactic simulations: stars across time & differing perspective



OUTLINE: 1) Stellar Disk & 2) Stellar Halo



2) Stellar Halo

a) Predictions
Orbits in ΛCDM

b) Future Obs
Gaia DR2

1) Stellar Disk

a) Theory
Radial Migration

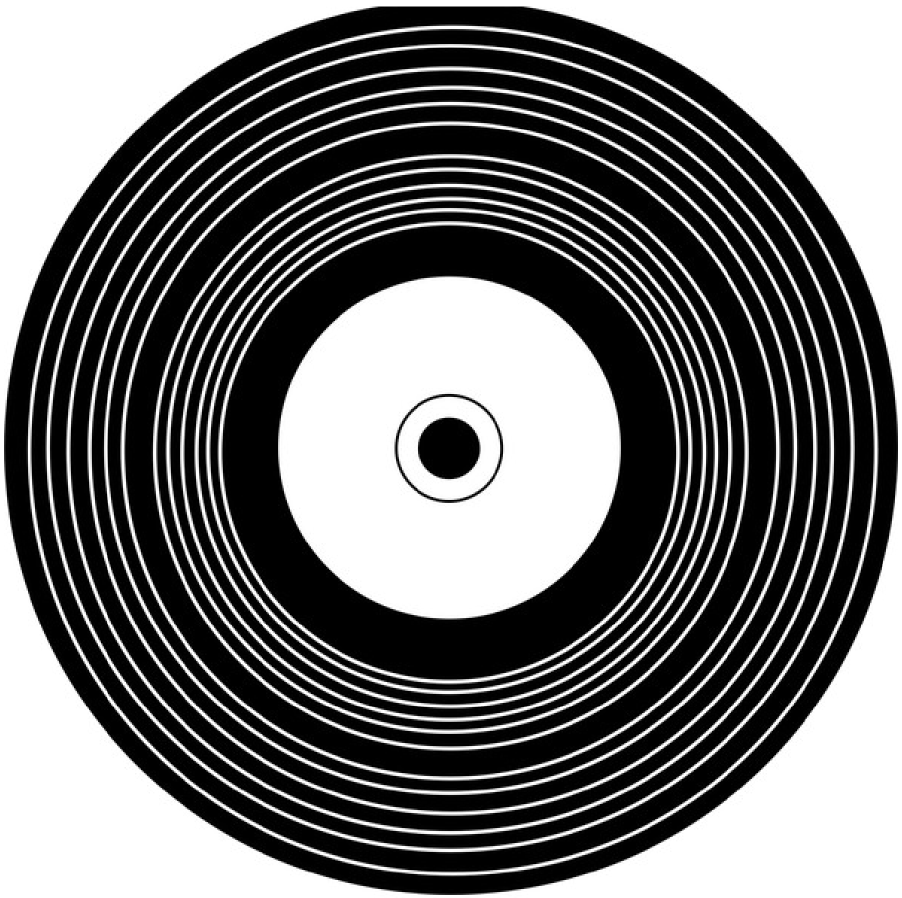
b) Observations
APOGEE

Disk Galaxies

- Disk galaxies are ubiquitous
  Majority of blue galaxies and up to ~85% of red galaxies
  (e.g. ATLAS3D, Emsellem+2011)
- Found at a range of stellar mass
  $10^{7}\sim10^{11.5}$ M_{sun}
- Majority contain bars
  50–75% in the near IR *(Knapen 1999; Eskridge et al. 2000)*
- Majority of massive blue galaxies likely contain both
  bars and spiral structure
- Generally thought to form inside-out *(e.g. Fall & Efstathiou 1980)*
  Recently being reconsidered...

Star Formation & Heating/Movement

Stars in disk galaxies are traditionally thought to stay close to their guiding center of formation;



Range of ways to heat stars to make orbits more eccentric

1) interaction bar structure
2) bouncing off molecular cloud
3) feedback from star formation
4) satellite accretion
5) dark matter sub halo heating

only one mechanism that changes the guiding center with-out significantly kinematically heating stars: radial migration.

Radial Migration

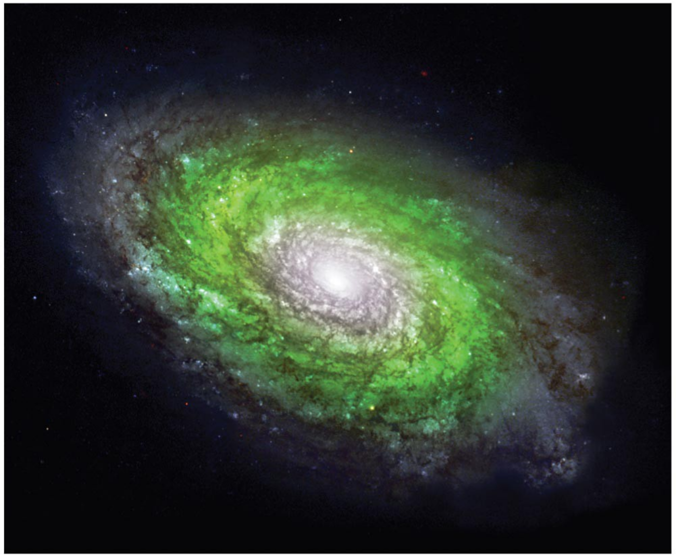
Transient spirals can rearrange orbital angular momentum without causing kinematic heating.

Sellwood & Binney 2002

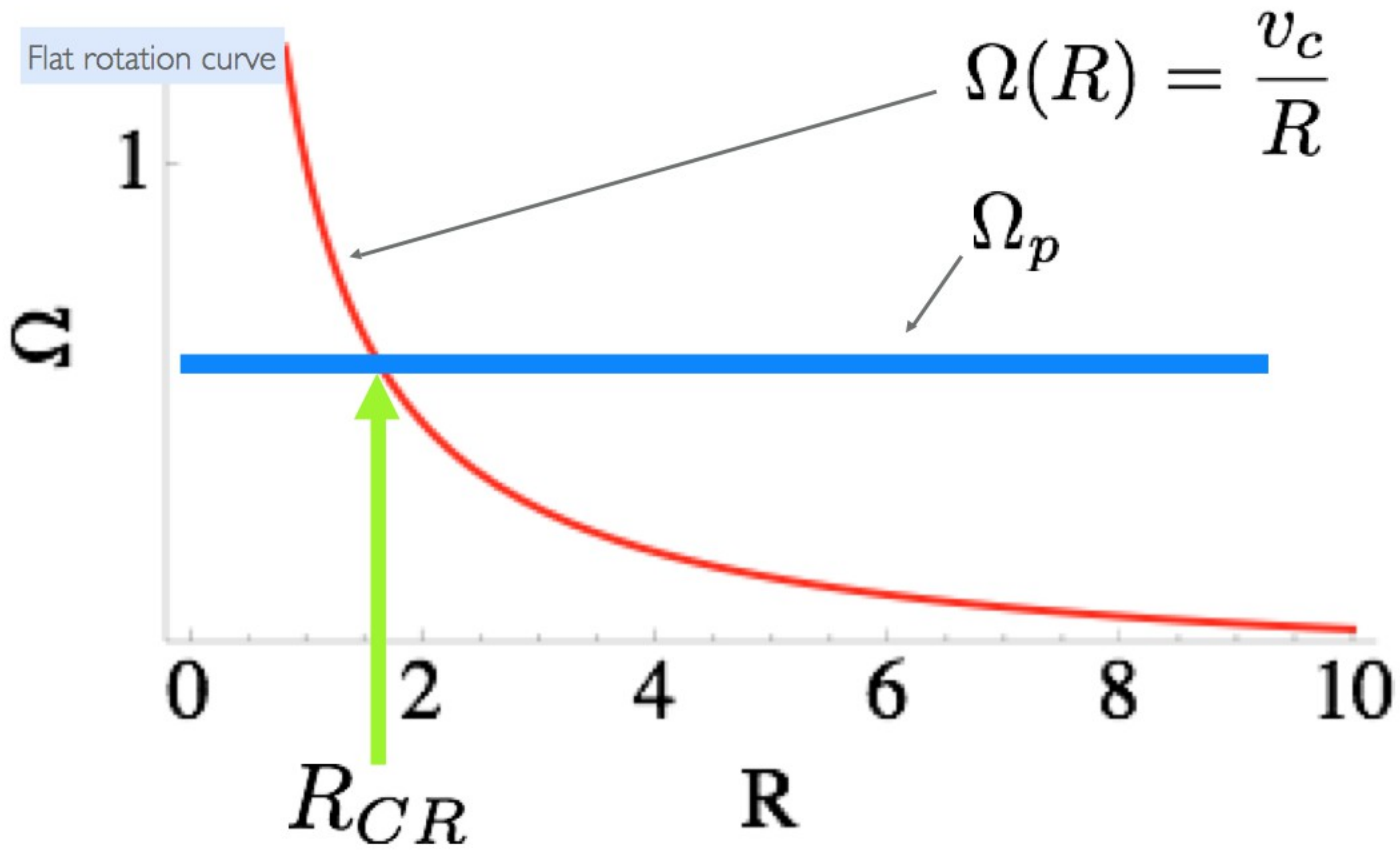
Questions for galaxy evolution:

- (How) does it affect disk structure? Thick disk? Outer disk?
- Can it smooth rotation curve? Change surface density profile?
- Role in vertical and radial metallicity profiles?

- Has radial migration significantly impacted the Milky Way?
- Could the Sun have radially migrated?
- Modify "galactic habitable zone?"

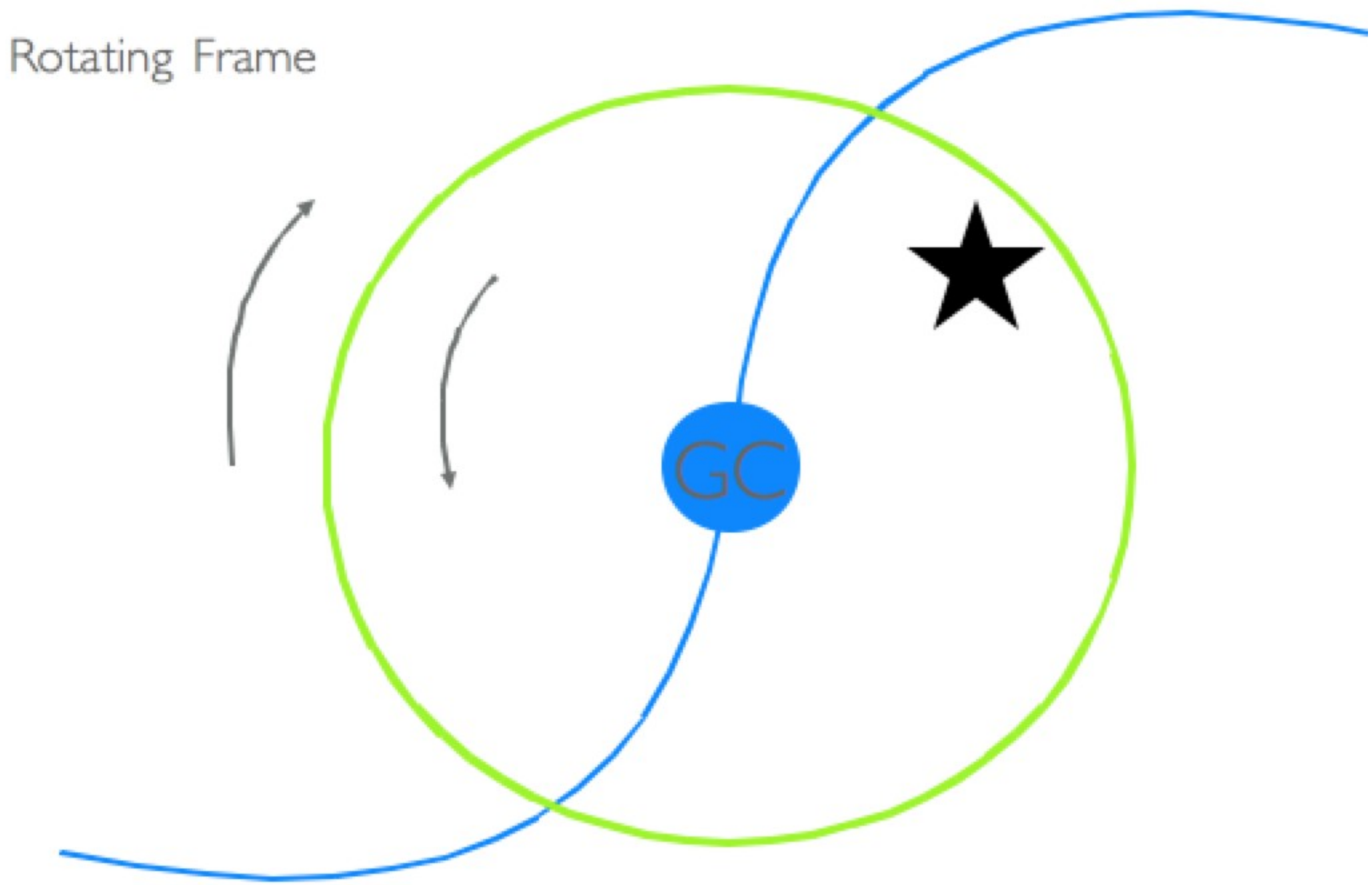


Reconsider where life could form?



corotation - where the circular orbital frequency of the disk equals the spiral pattern speed

Physics of Radial Migration



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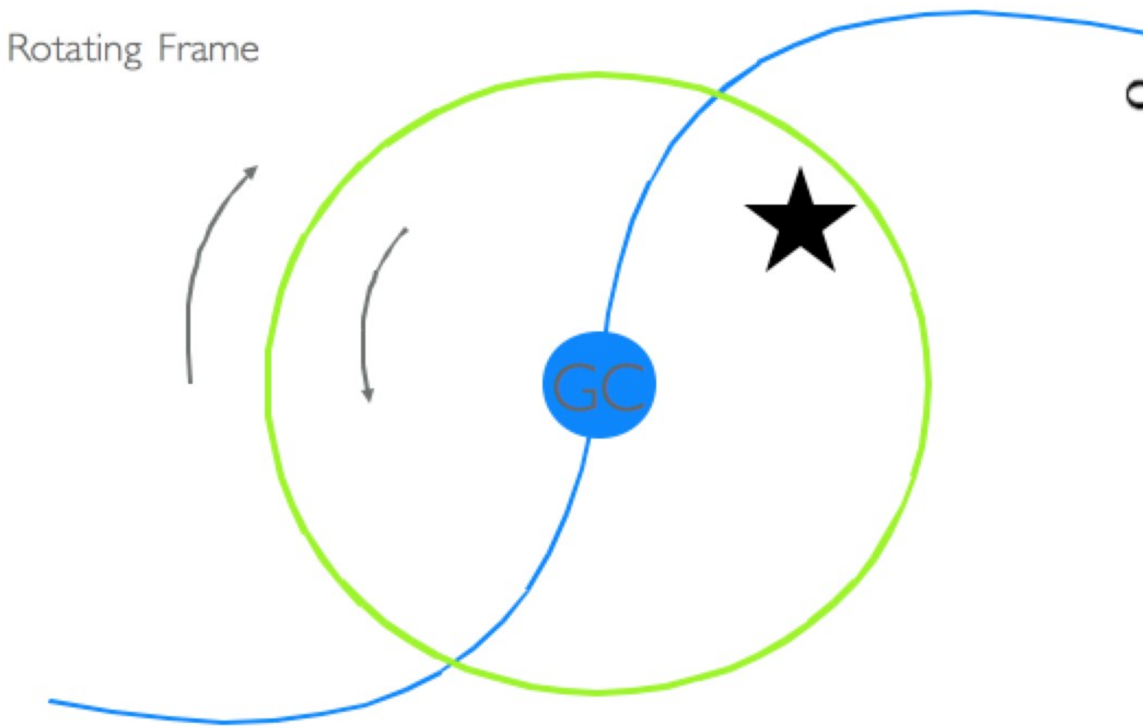
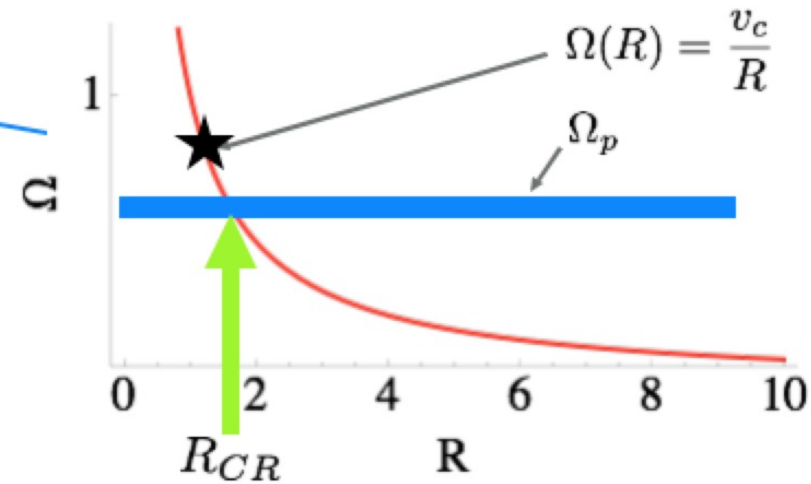


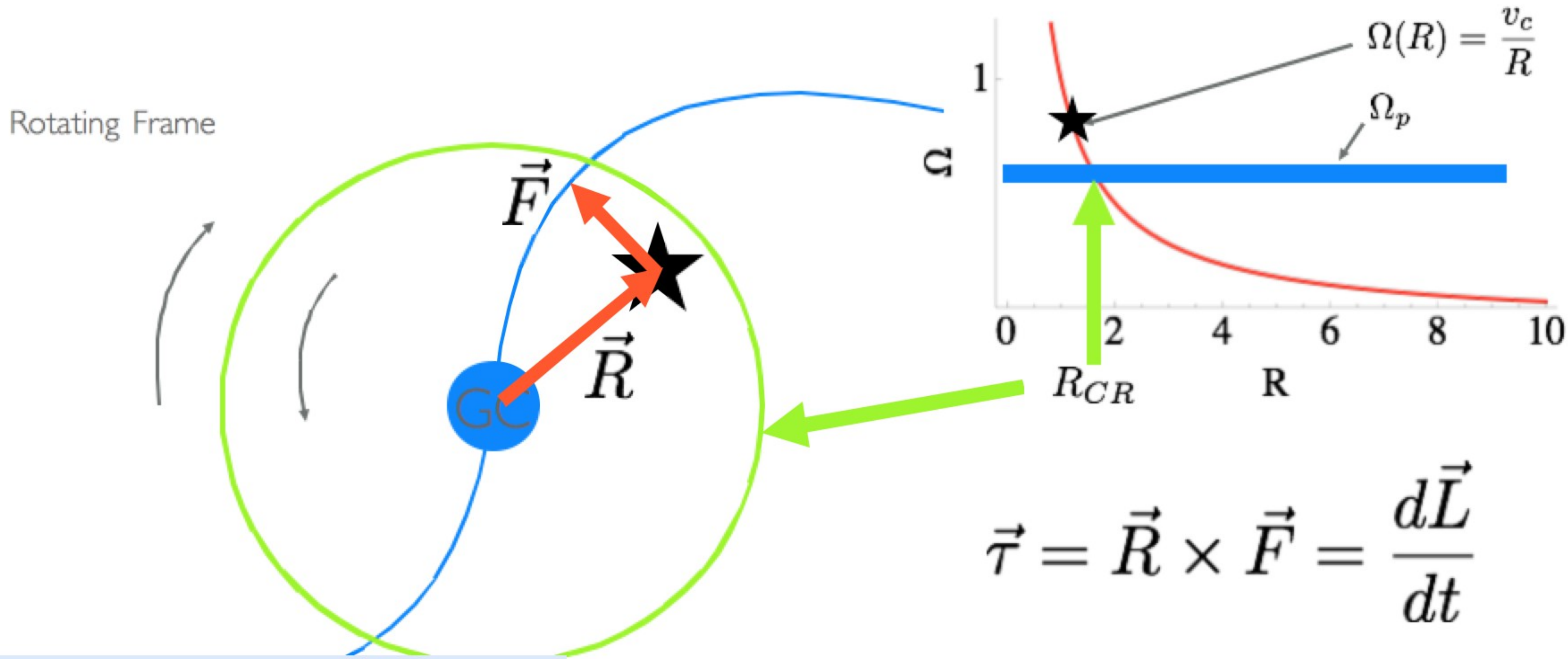


$$\vec{\tau} = \vec{R} \times \vec{F} = \frac{d\vec{L}}{dt}$$

$$\vec{L} = \vec{R} \times \vec{v}$$

corotation - where the circular orbital frequency of the disk equals the spiral pattern speed

Physics of Radial Migration



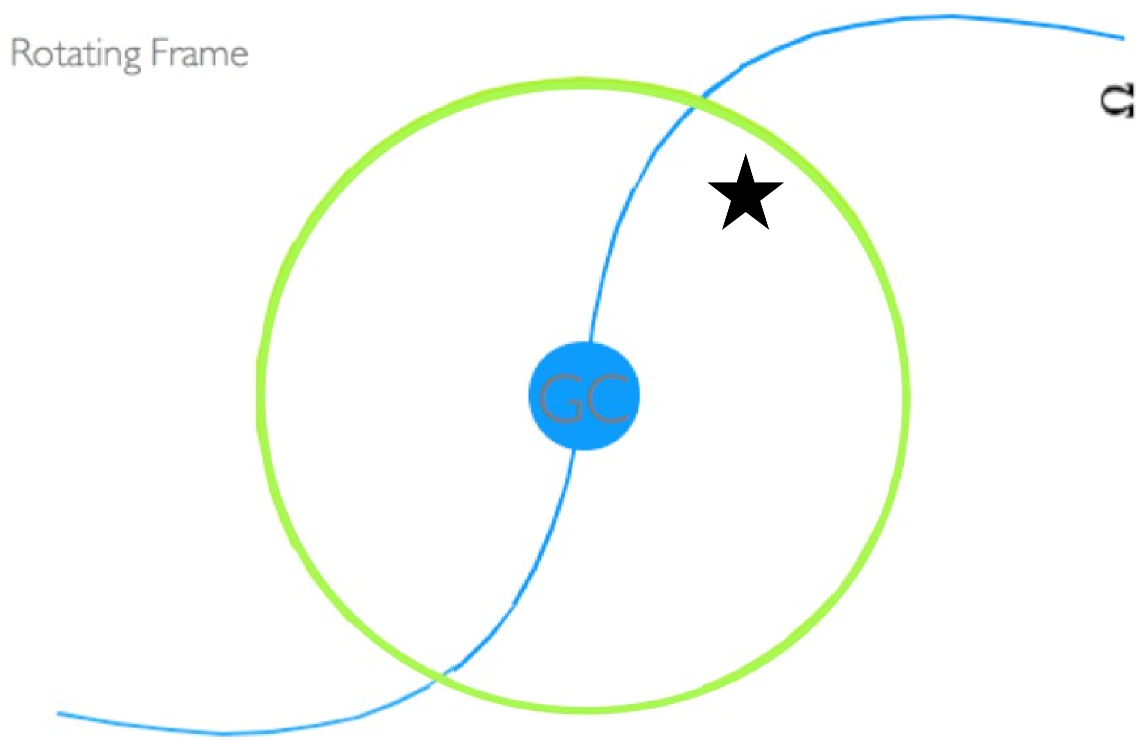
Increase orbital angular momentum implies an increase mean orbital radius

$$\vec{\tau} = \vec{R} \times \vec{F} = \frac{d\vec{L}}{dt}$$

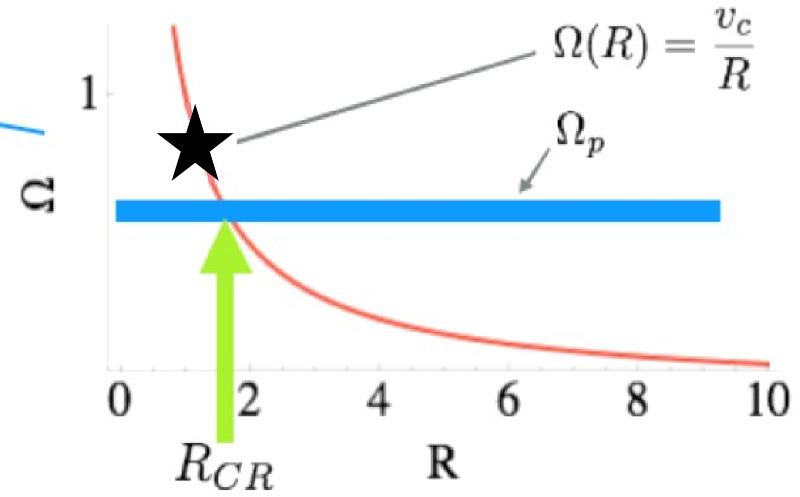
$$\vec{L} = \vec{R} \times \vec{v}$$

corotation - where the circular orbital frequency of the disk equals the spiral pattern speed

Physics of Radial Migration



Orbital frequency slower than spiral pattern speed => drifts behind



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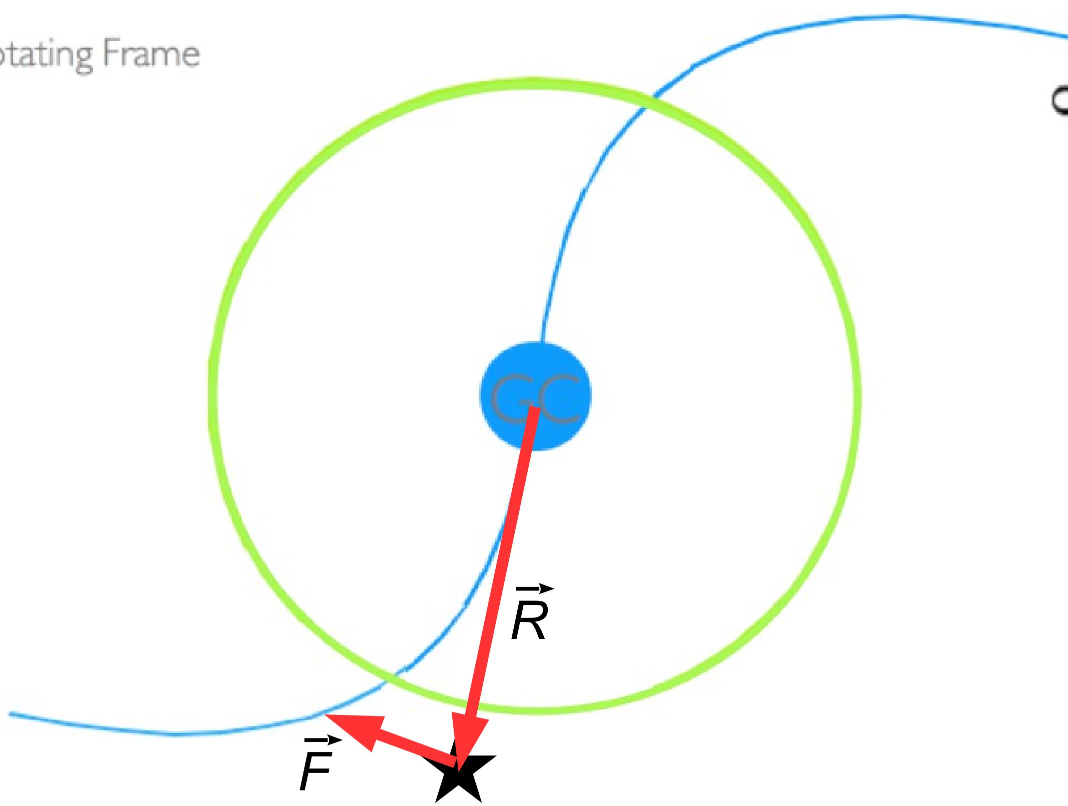
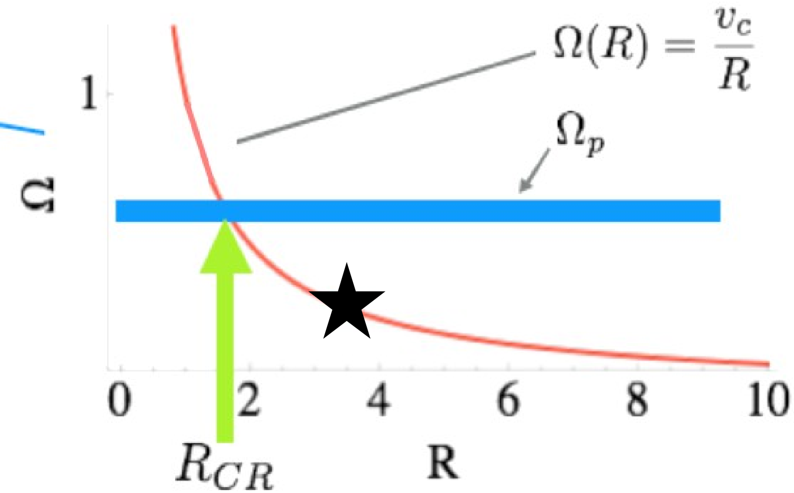
corotation - where the circular orbital frequency of the disk equals the spiral pattern speed

Physics of Radial Migration





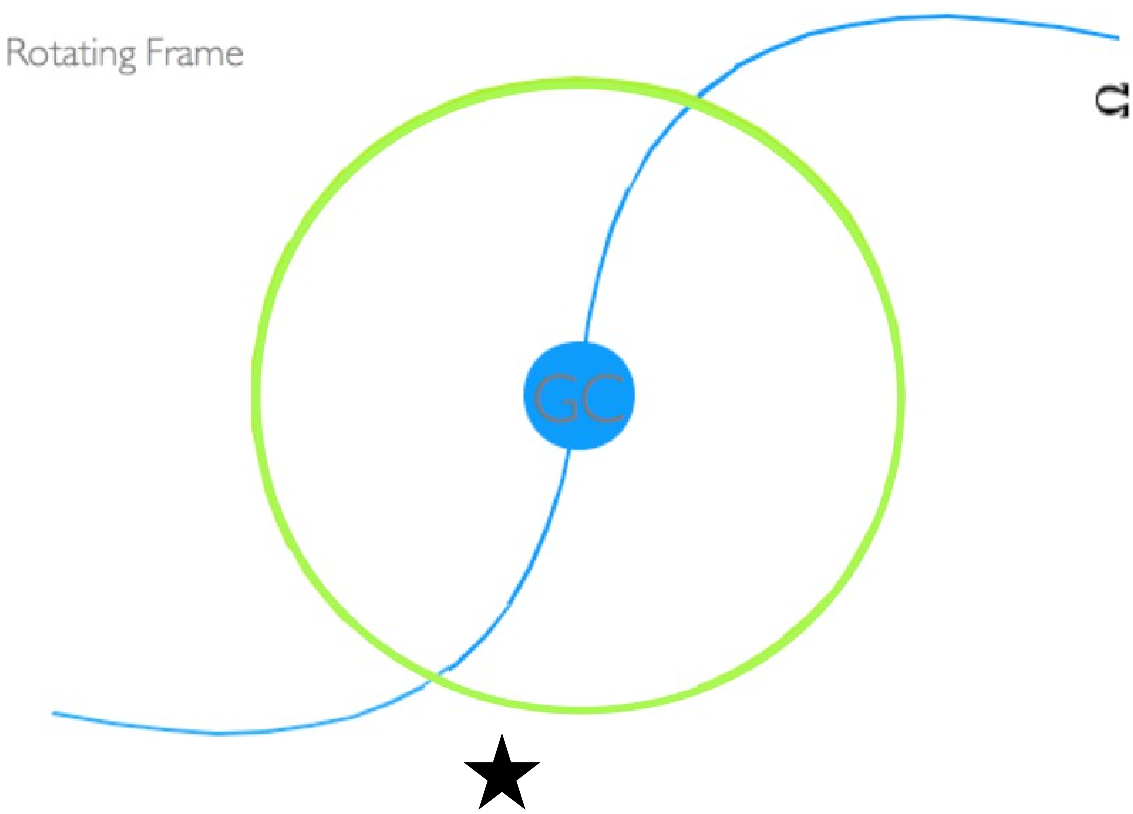
$$\vec{\tau} = \vec{R} \times \vec{F} = \frac{d\vec{L}}{dt}$$

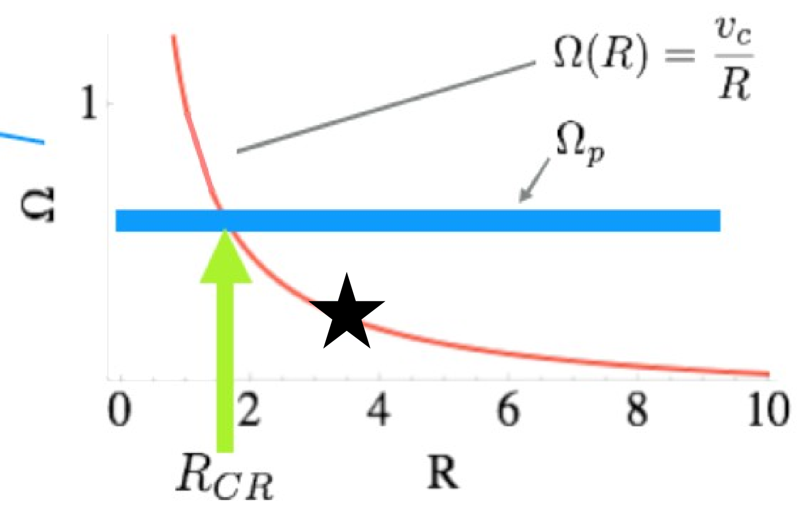
$$\vec{L} = \vec{R} \times \vec{v}$$

Decrease in orbital angular momentum implies decrease in mean orbital radius

corotation - where the circular orbital frequency of the disk equals the spiral pattern speed

Physics of Radial Migration





$$\vec{\tau} = \vec{R} \times \vec{F} = \frac{d\vec{L}}{dt}$$

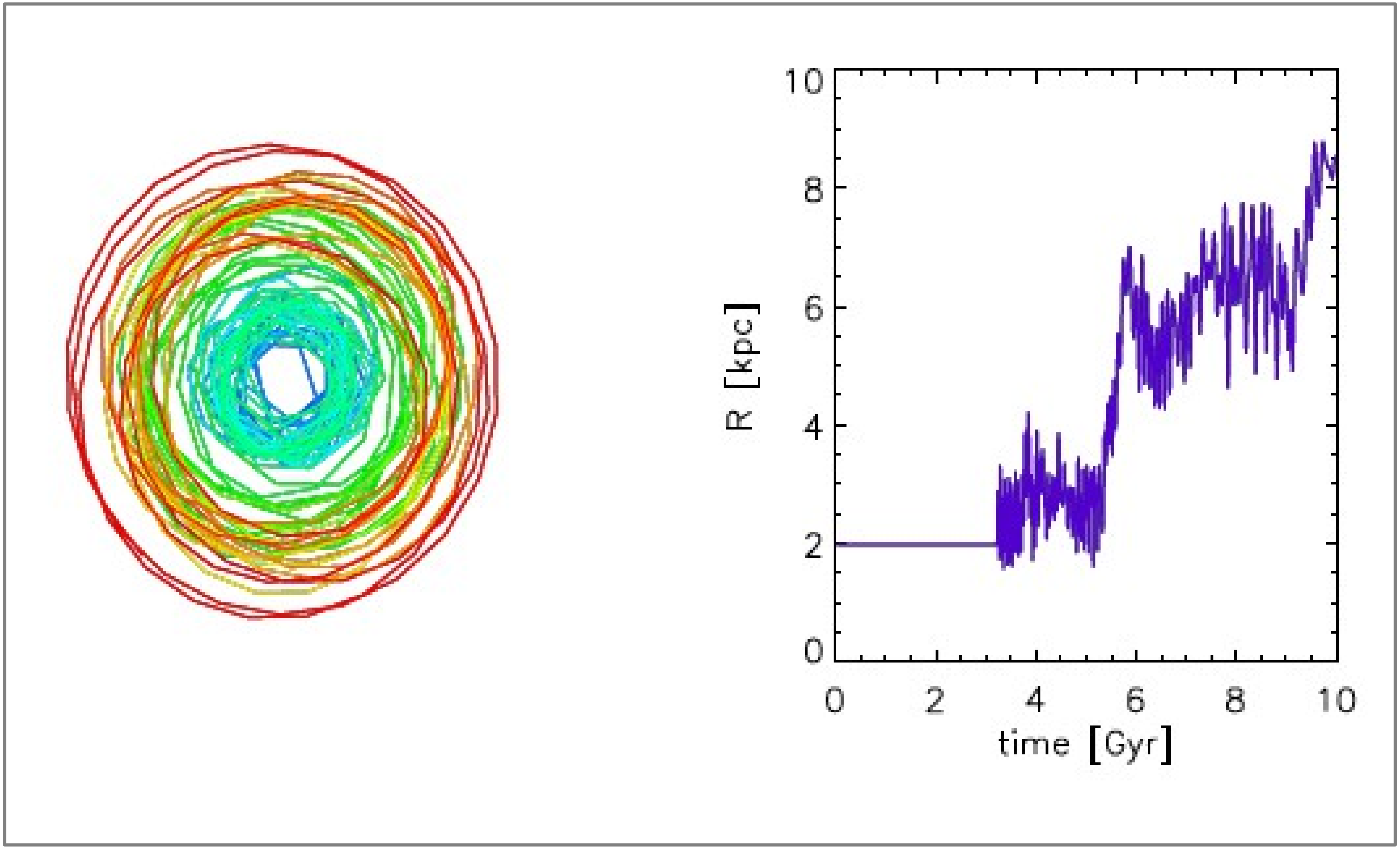
$$\vec{L} = \vec{R} \times \vec{v}$$

Orbital frequency faster than spiral pattern speed => drifts ahead

corotation - where the circular orbital frequency of the disk equals the spiral pattern speed

Movie courtesy of Rok Roškar

Simulation: large radial movement in short time & remains circular



Roškar et al. (2008)

Motivation

Radial Migration is a very cool dynamical effect
We'd like to know how much its influenced the MW

Problem

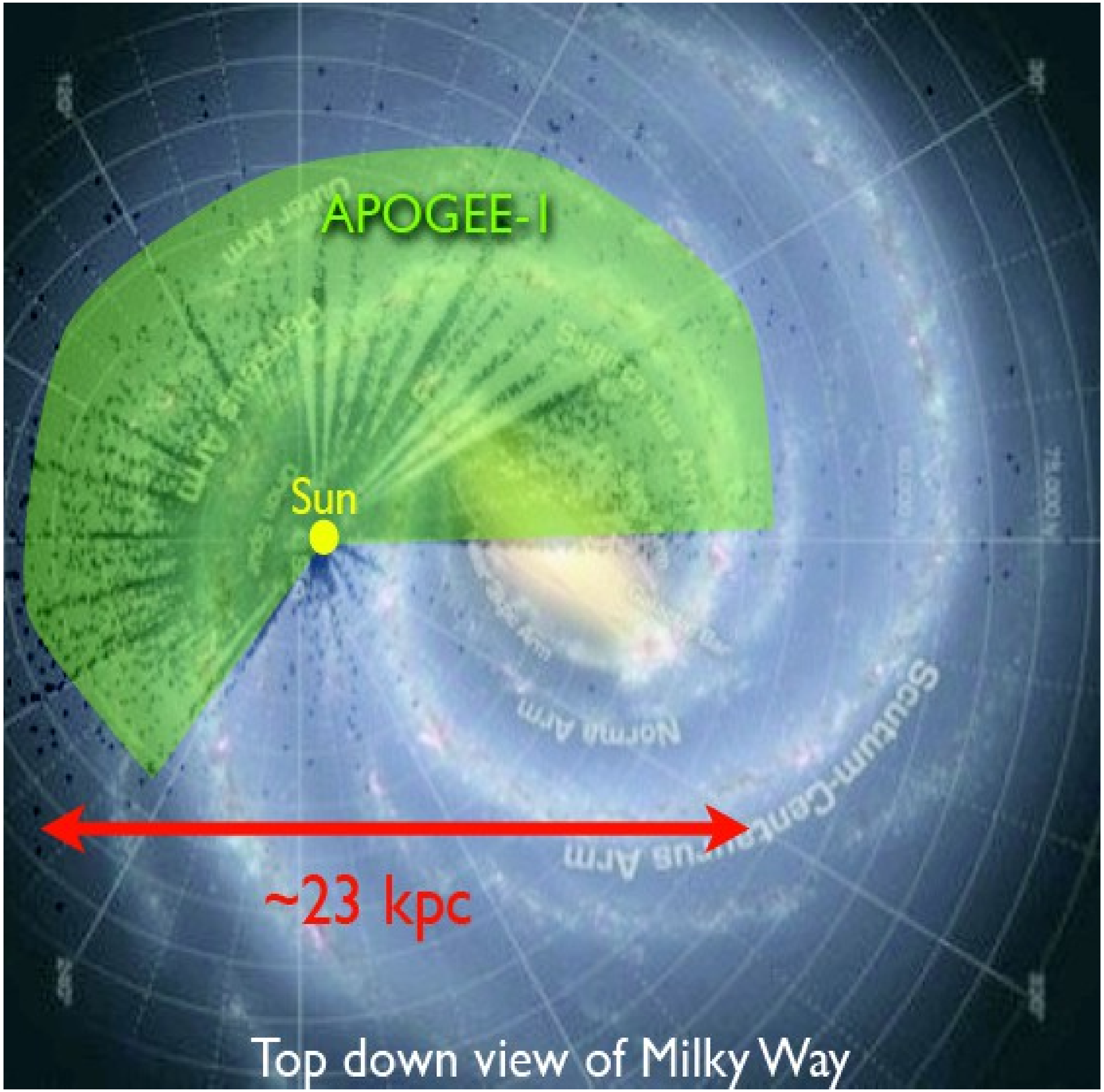
Present day kinematics (orbital eccentricity) doesn't give us an obvious way to find migrators

Solution

Look to other (immutable) quantities.

Chemistry
(APOGEE)

APOGEE – Largest ever coverage of the Galactic Disk

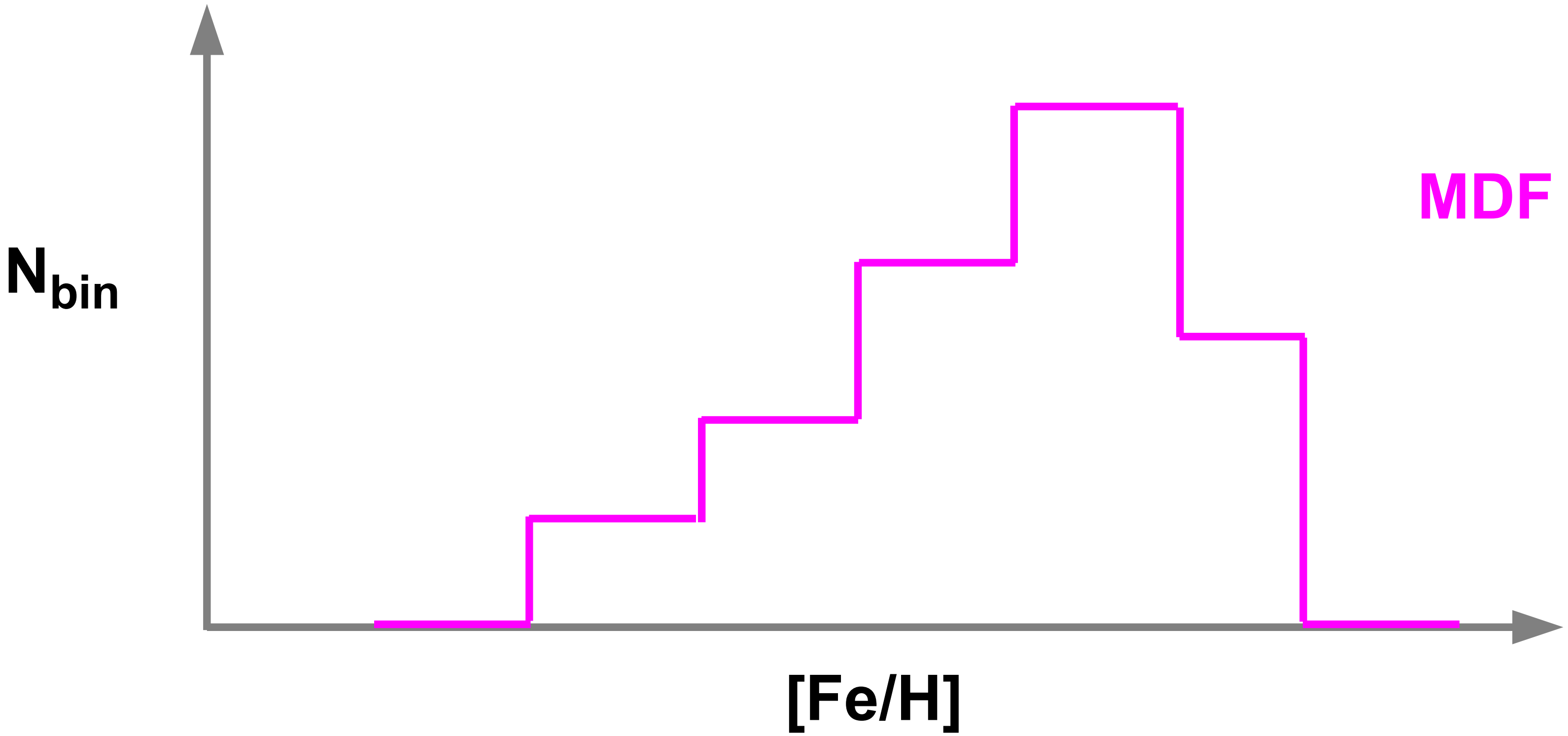


chemistry & kinematics: high-res, high-SN spectra ~150,000 giants

What can we learn about stars as a function of radius?

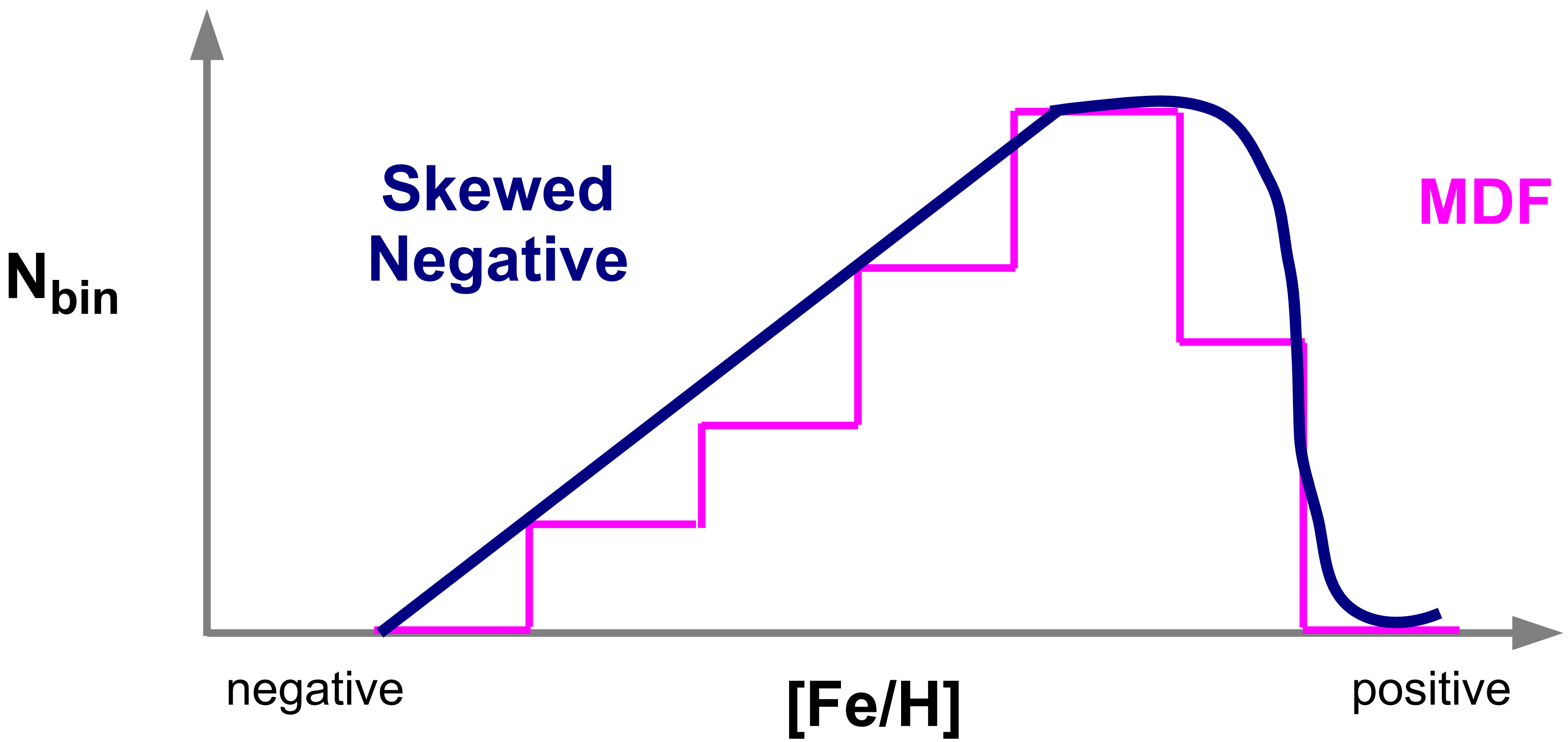
Consider MW's Metallicity Distribution Function (MDF)

Select N stars in a region of R & z



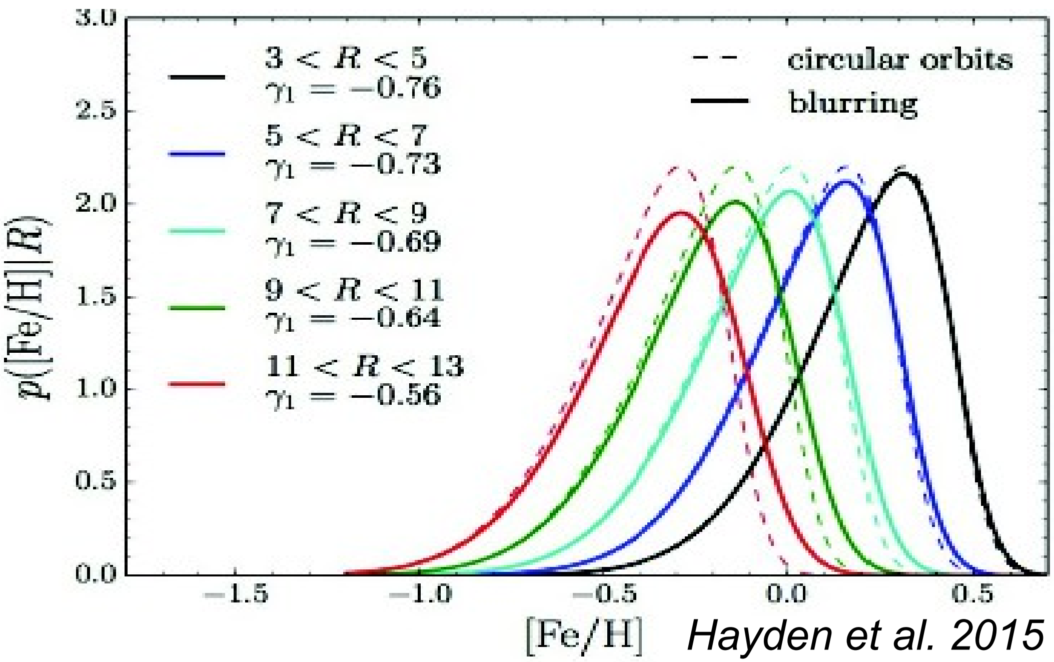
What is MDF skewness?

Look at the global shape of the distribution



What is the shape of MW MDFs if stars don't radially migrate?

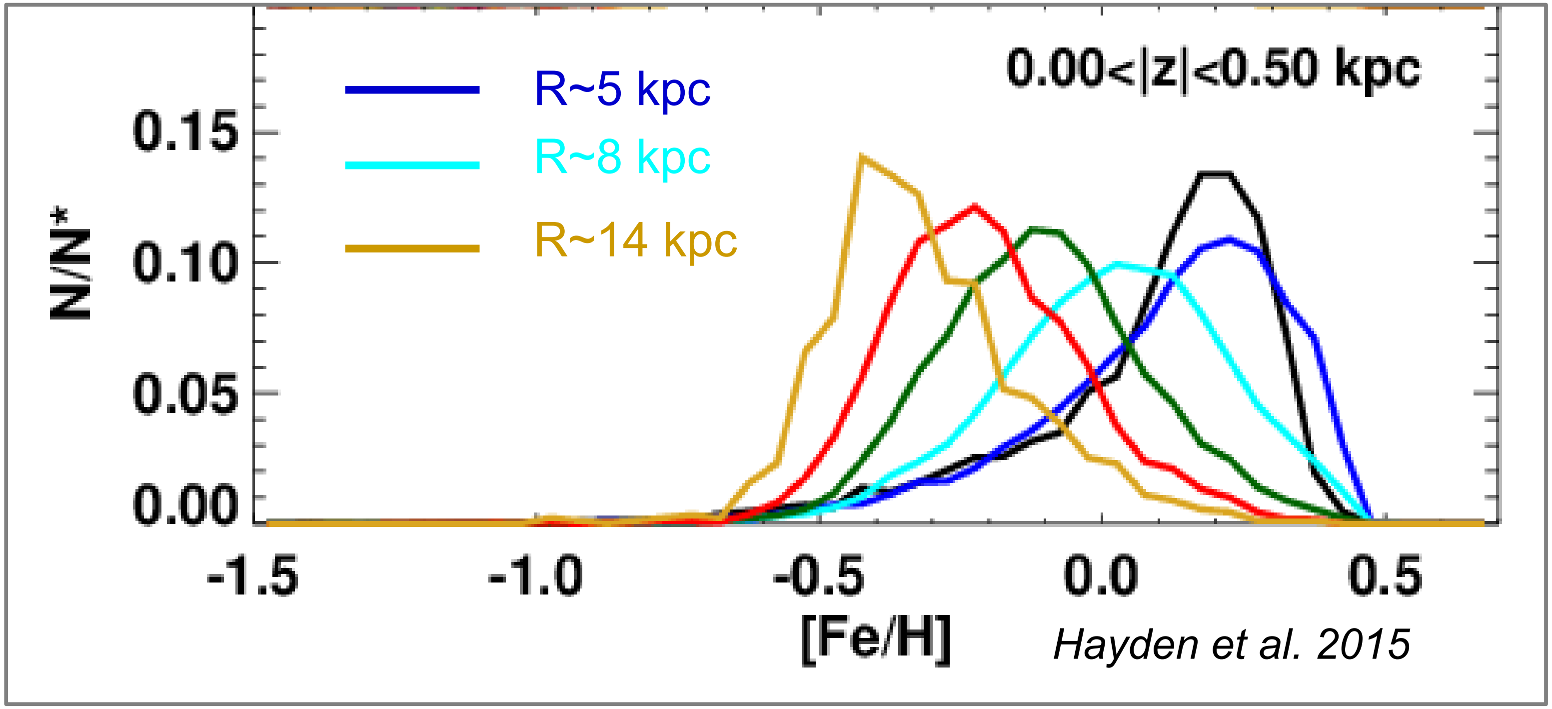
Simple models: constant MDF shape regardless of R & z



Hayden et al. 2015

blurring with 30 km/s velocity dispersion

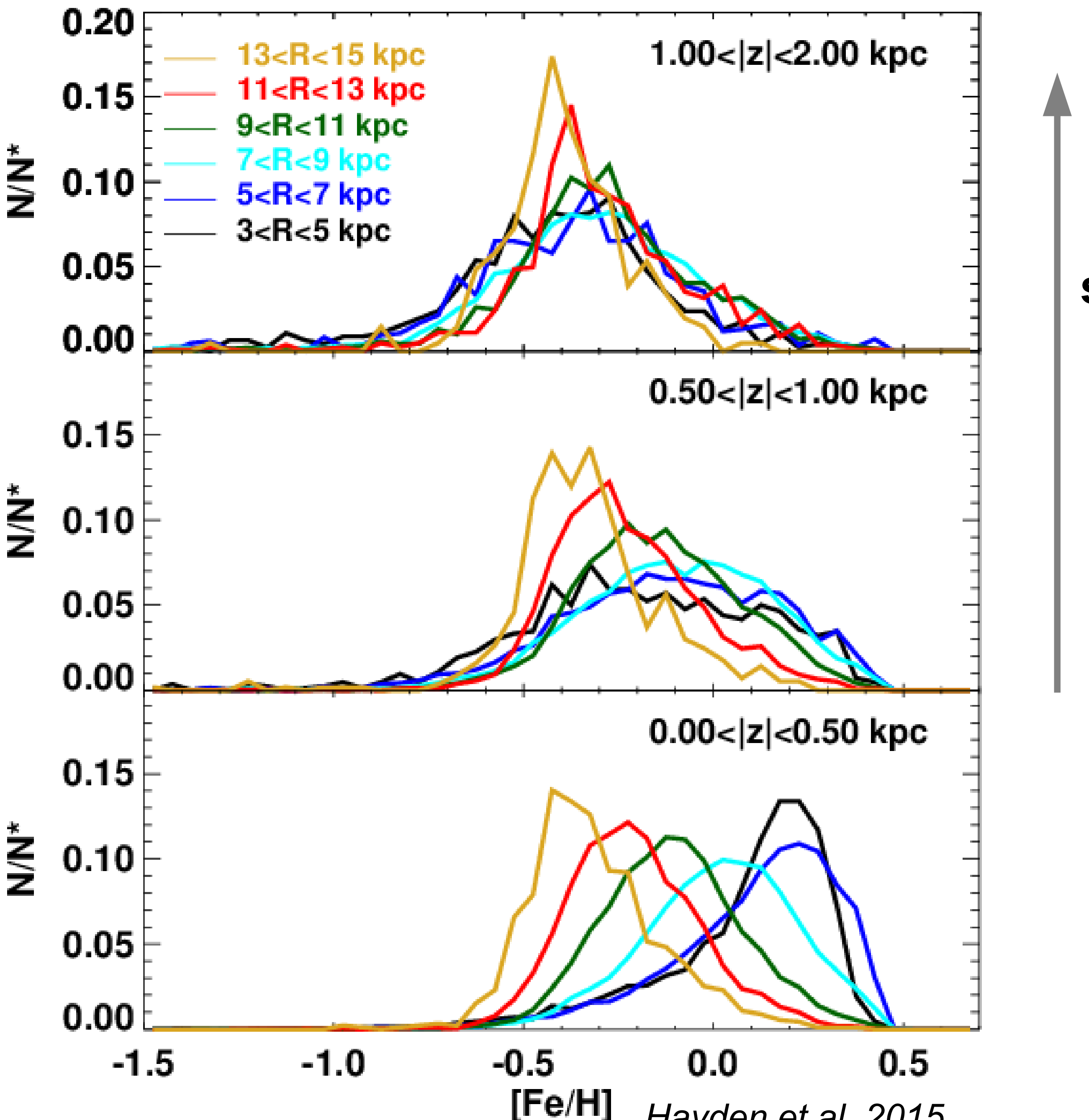
Surprising results in mid-plane



MDF skewness changes with radius

- Skew-negative in inner Galaxy
- Roughly Gaussian at Solar Cylinder
- Skew-positive in outer Galaxy

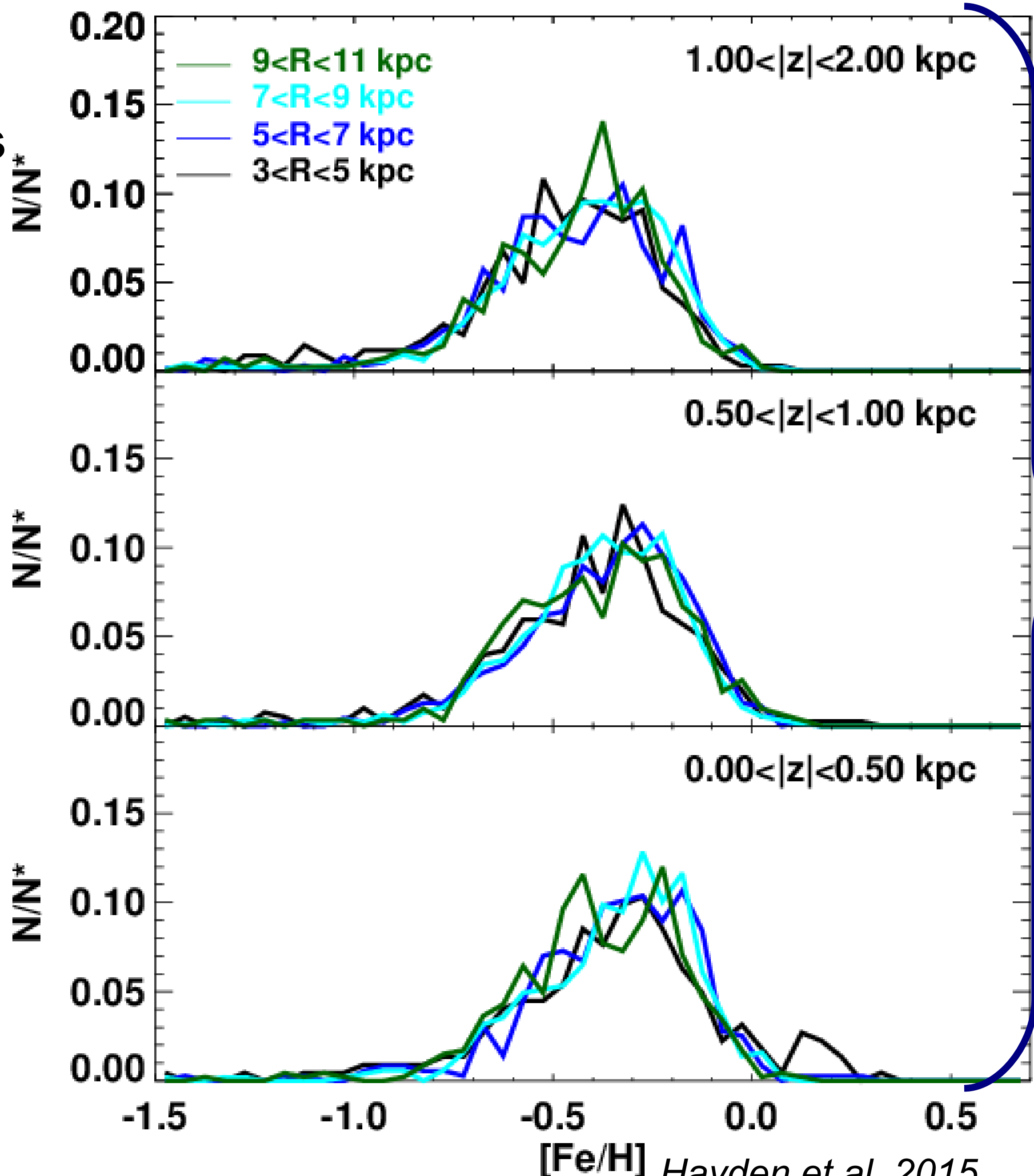
APOGEE: MDF skewness shift decreases out of mid-plane



Hayden et al. 2015

Increasingly similar shape out of midplane

high-[α/Fe] stars form at early epoch during vigorous star formation



Hayden et al. 2015

high-[α/Fe] MDF has similar shape everywhere!

unexpected! (well mixed ISM)

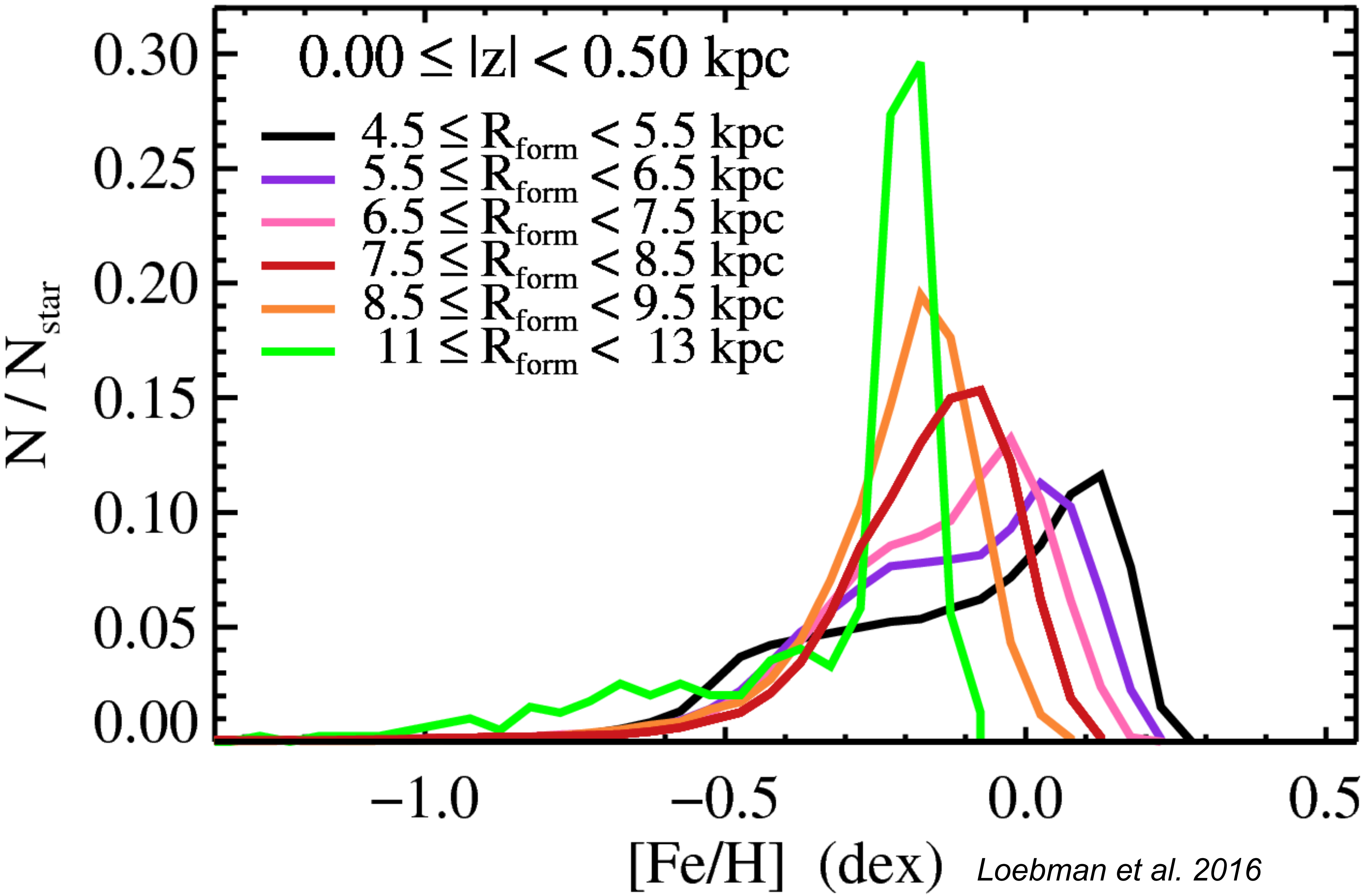
A successful theory of MW disk formation must:

- Shift the MDF skewness in the mid-plane with increased radius
- Decrease shift in the MDF skewness out of the mid-plane
- Create globally similar MDF for high-[α/Fe] population

Standard disk growth (inside-out, no radial mixing) does not work

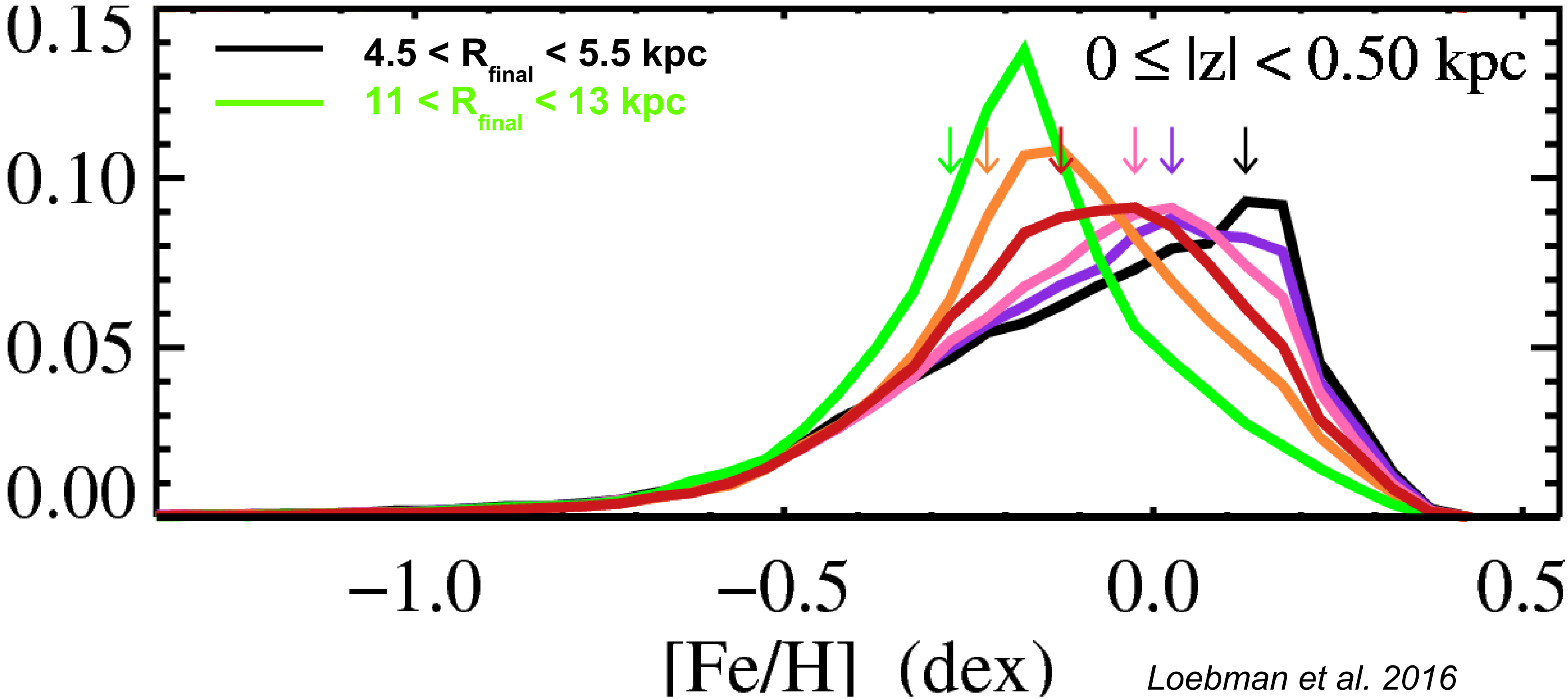
Courtesy of Rok Roškar *Gasoline (hydro+Nbody), cosmo-motivated*

All stars in the simulation are born on in negatively skewed MDF



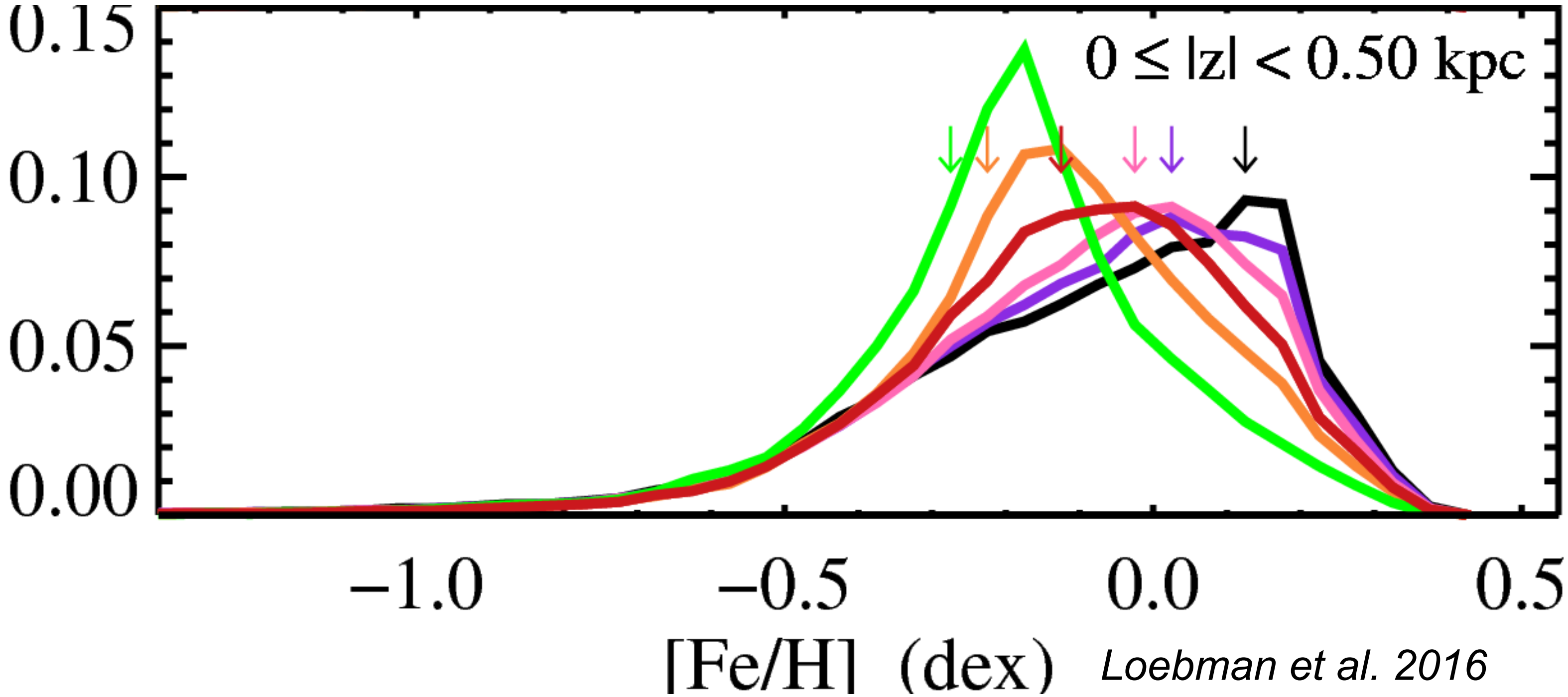
Loebman et al. 2016

End simulation, MDFs at large radius are positively skewed

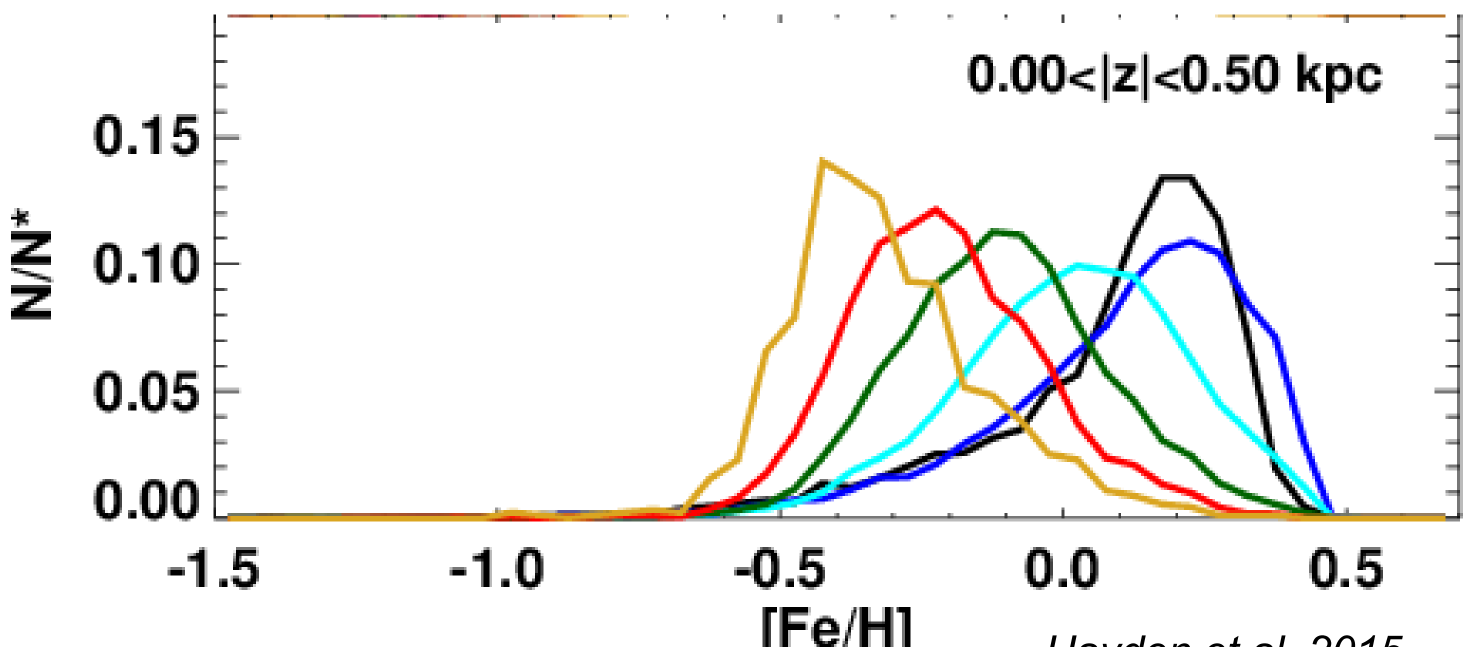


Loebman et al. 2016

Simulation & APOGEE MDFs qualitatively the same!

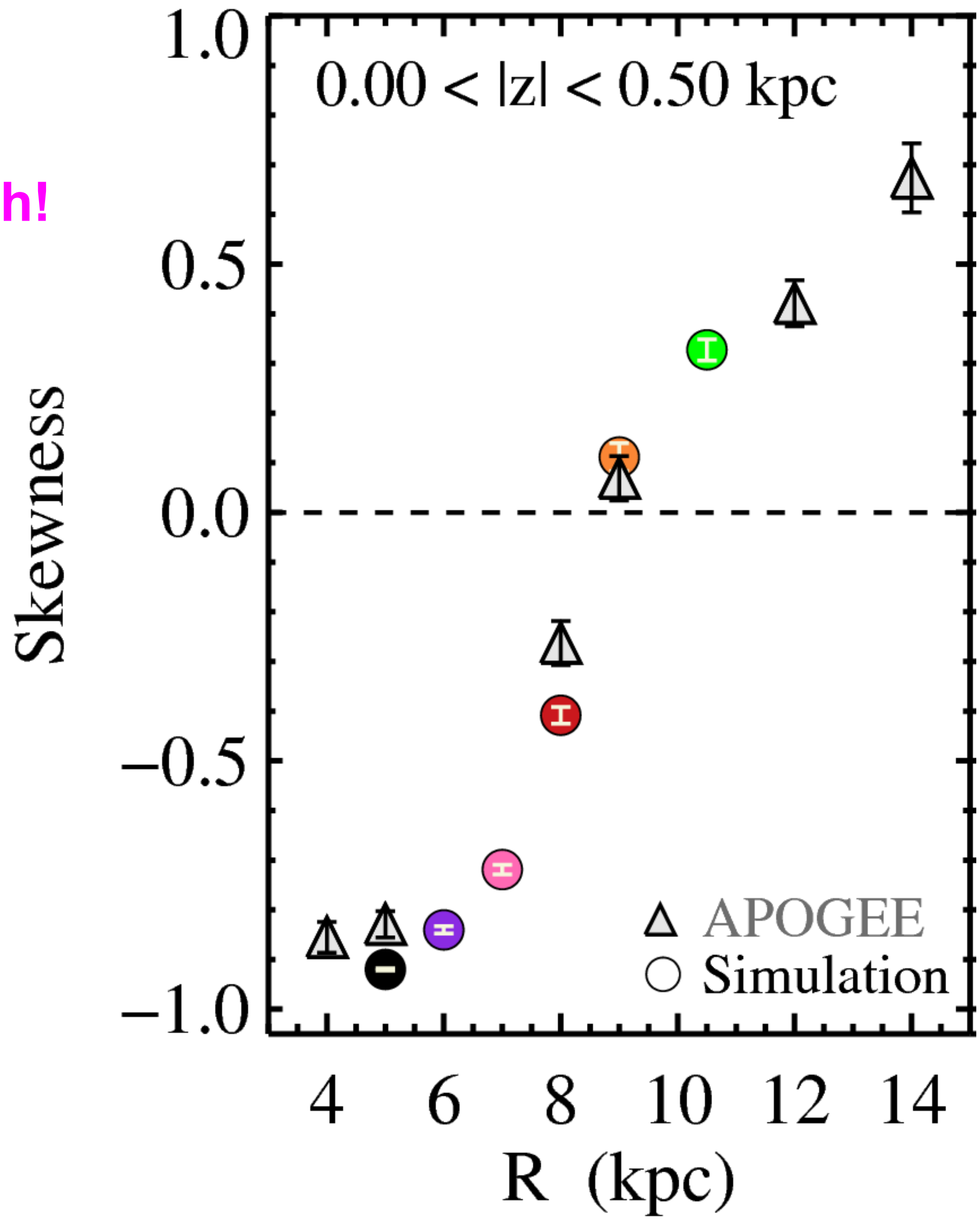


Loebman et al. 2016



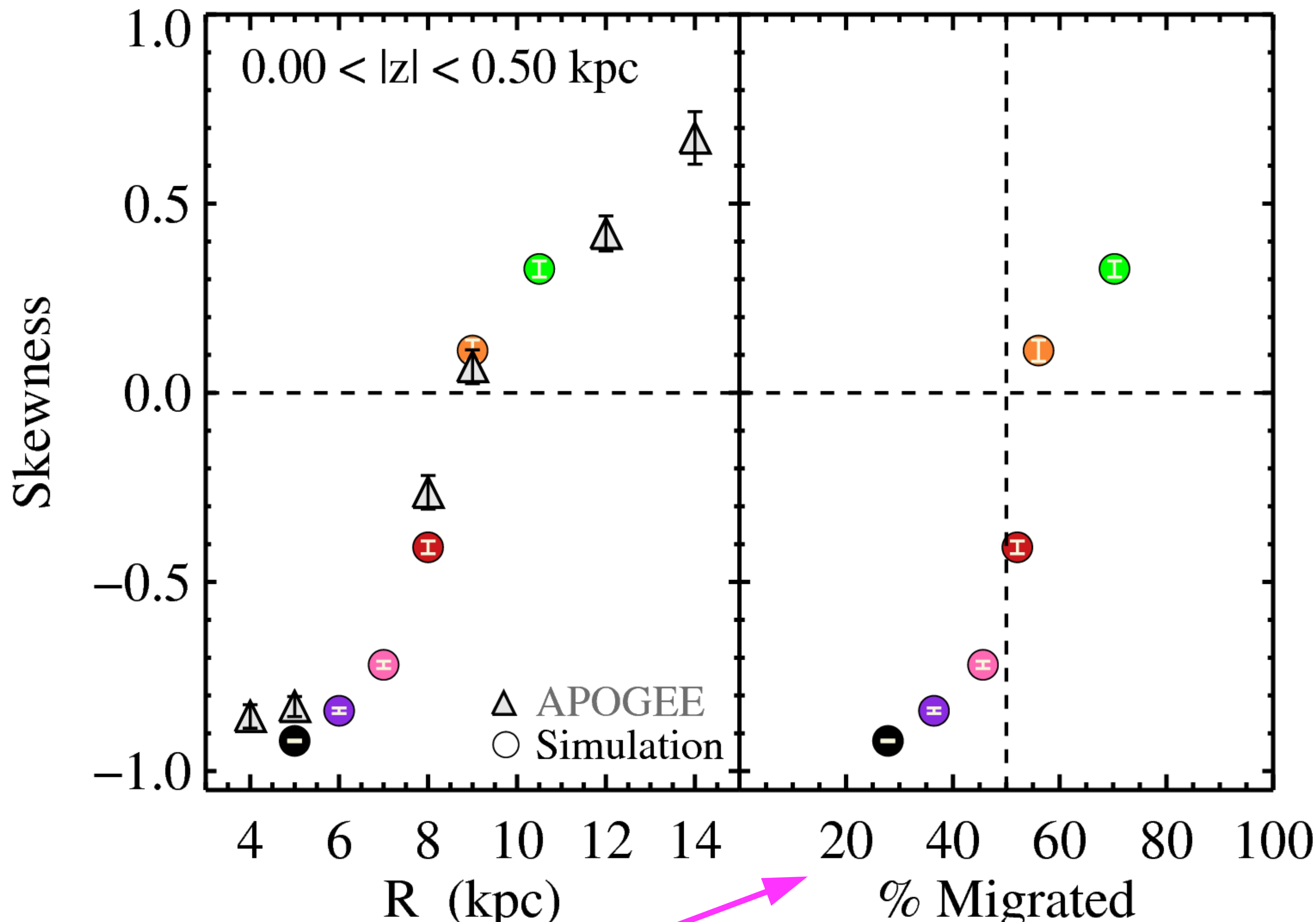
Hayden et al. 2015

No fine-tuning:
Skewness Parameters match!



Loebman et al. 2016

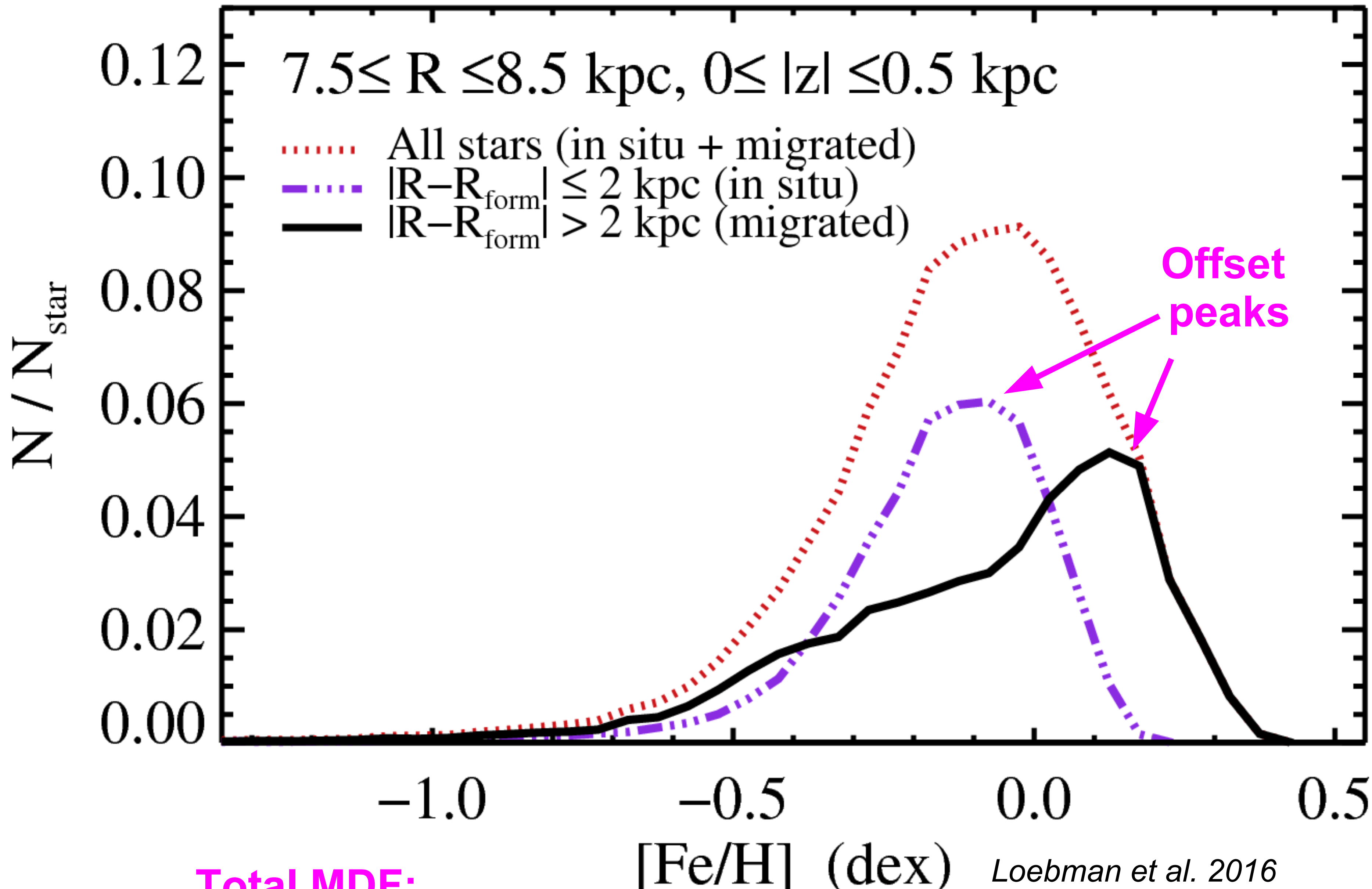
Mid-plane: skewness parameter connected to migrated fraction



The golden science result from this talk!

Loebman et al. 2016

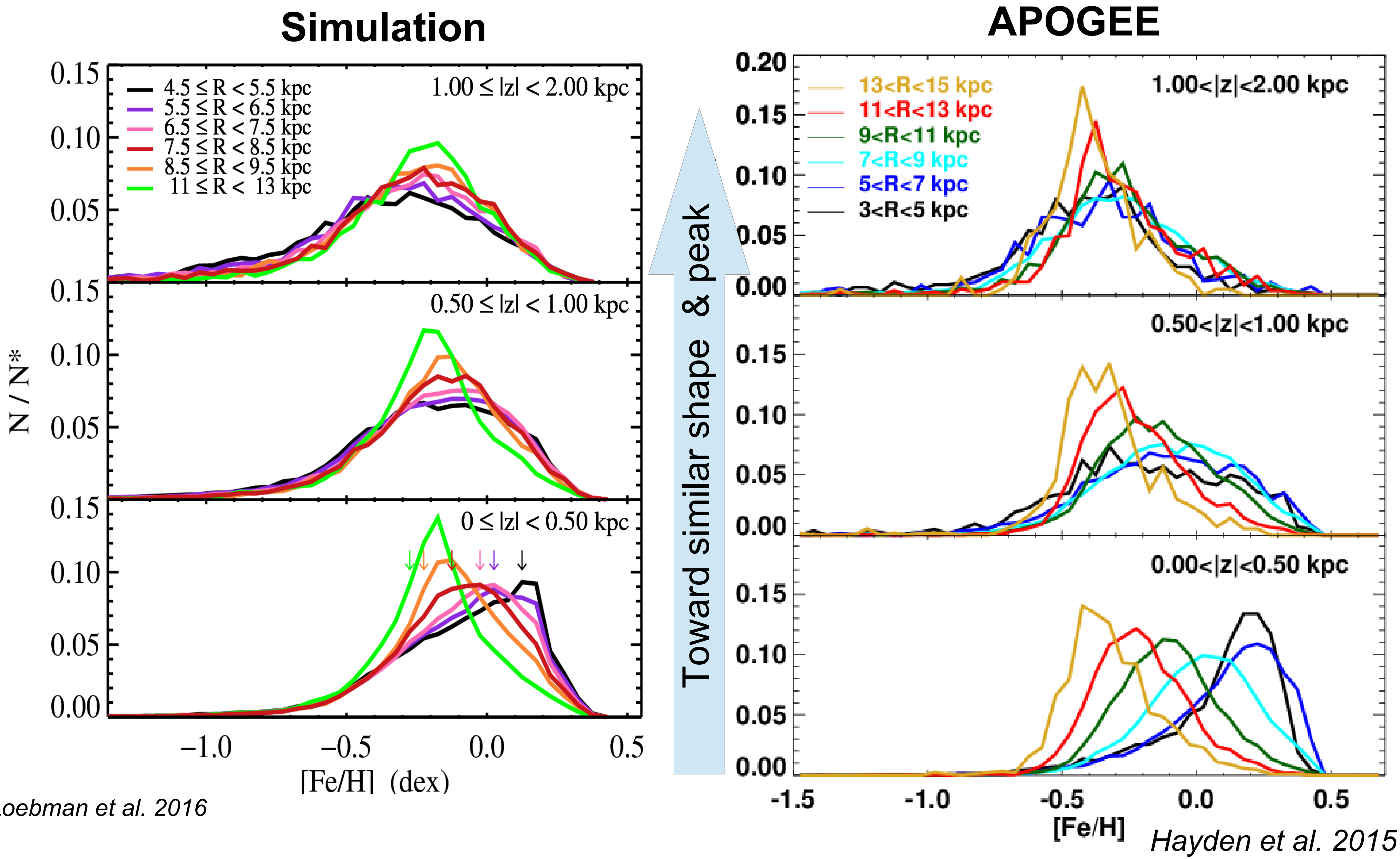
In situ & migrated MDF add up to make total MDF



Loebman et al. 2016

Total MDF:
Superposition of in situ & migrated

APOGEE & Simulation MDFs have same out-of-plane trend

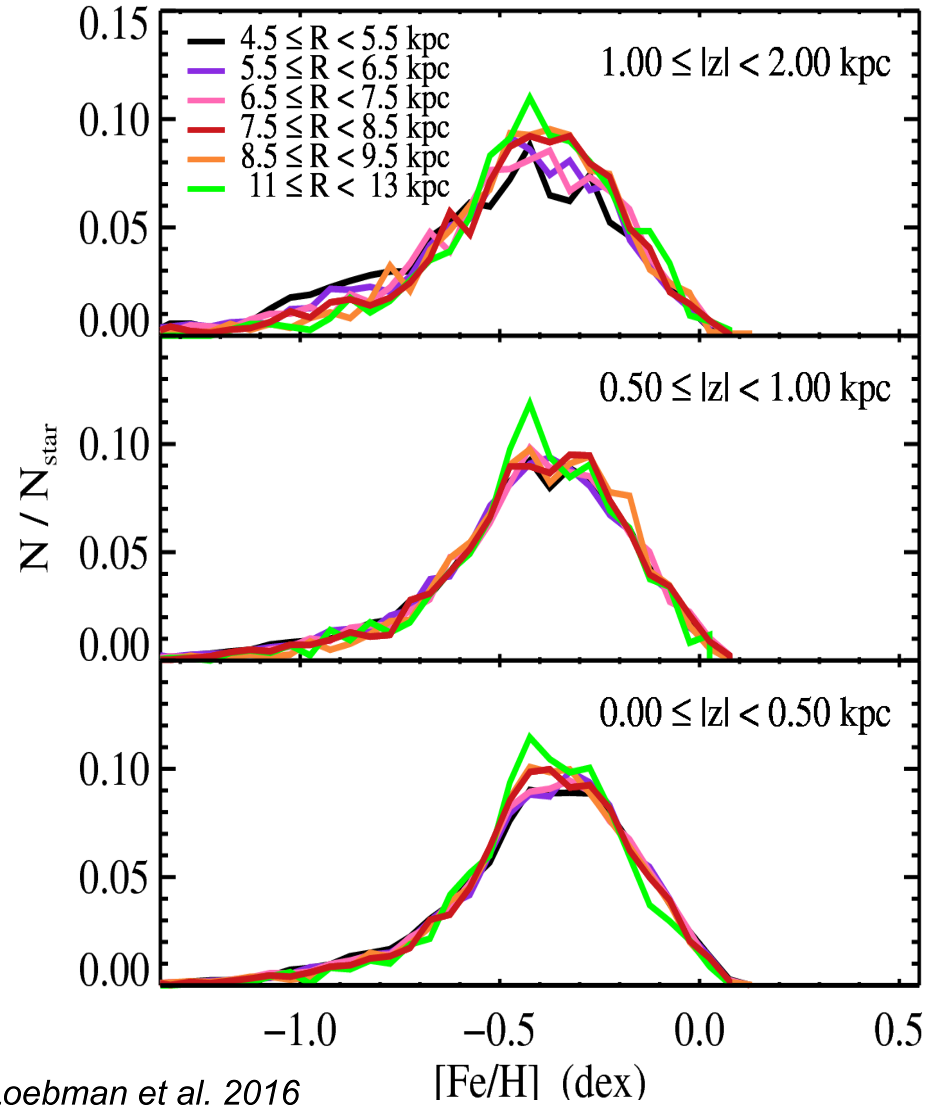


Loebman et al. 2016

Hayden et al. 2015

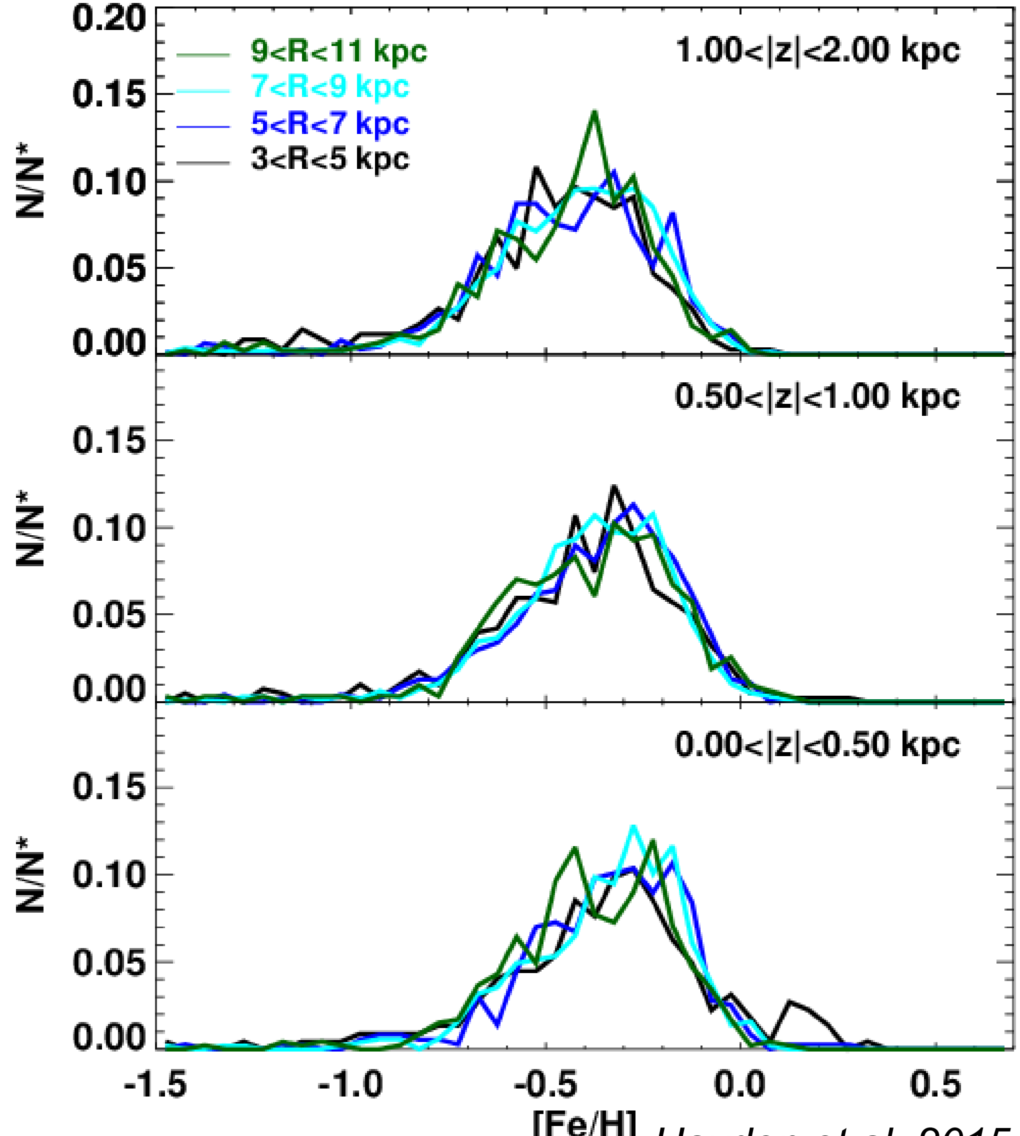
APOGEE & Simulation high-[α/Fe] MDFs match

Simulation



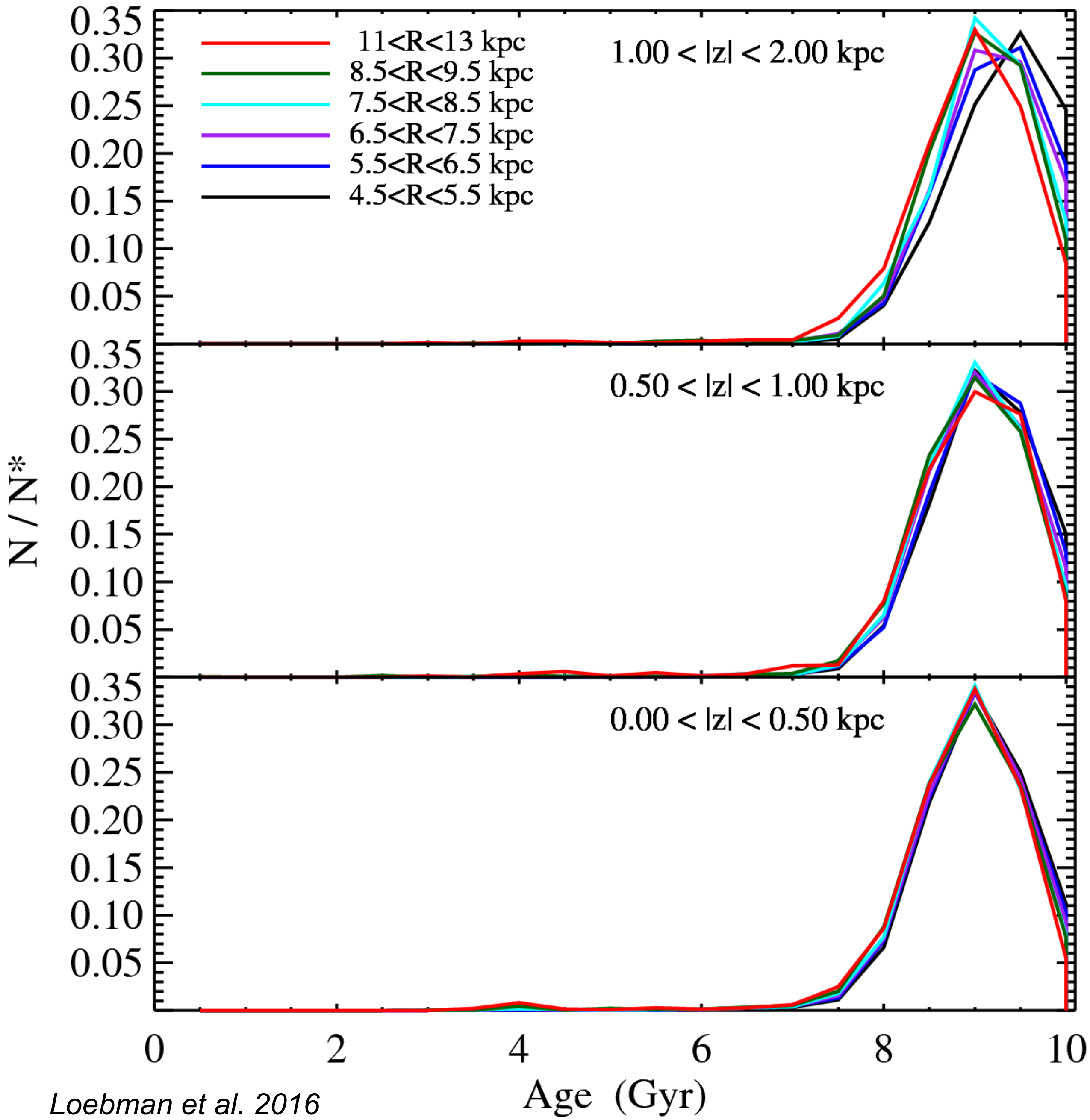
Loebman et al. 2016

APOGEE



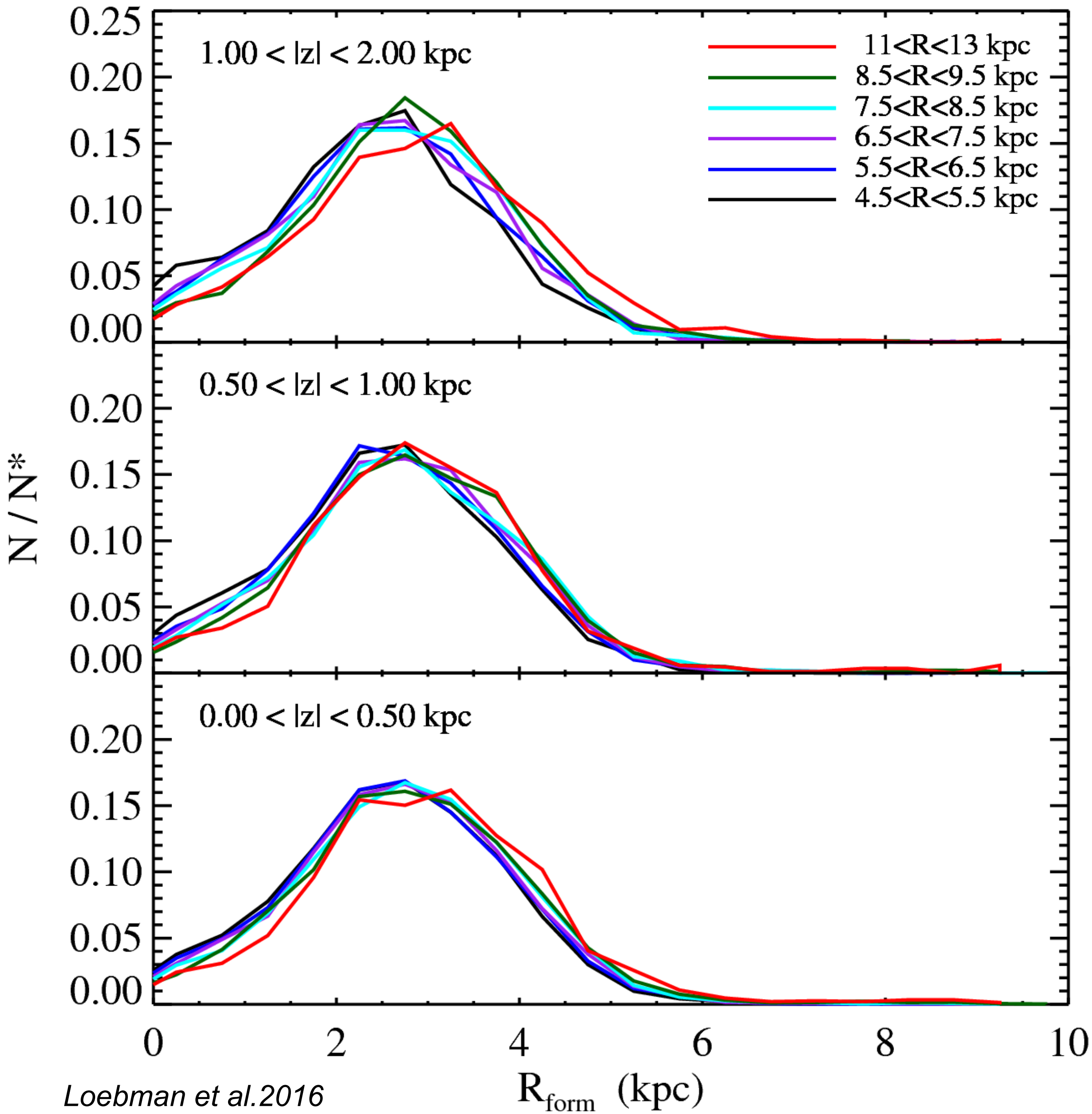
Hayden et al. 2015

Simulation high-[α/Fe] stars form at roughly same time



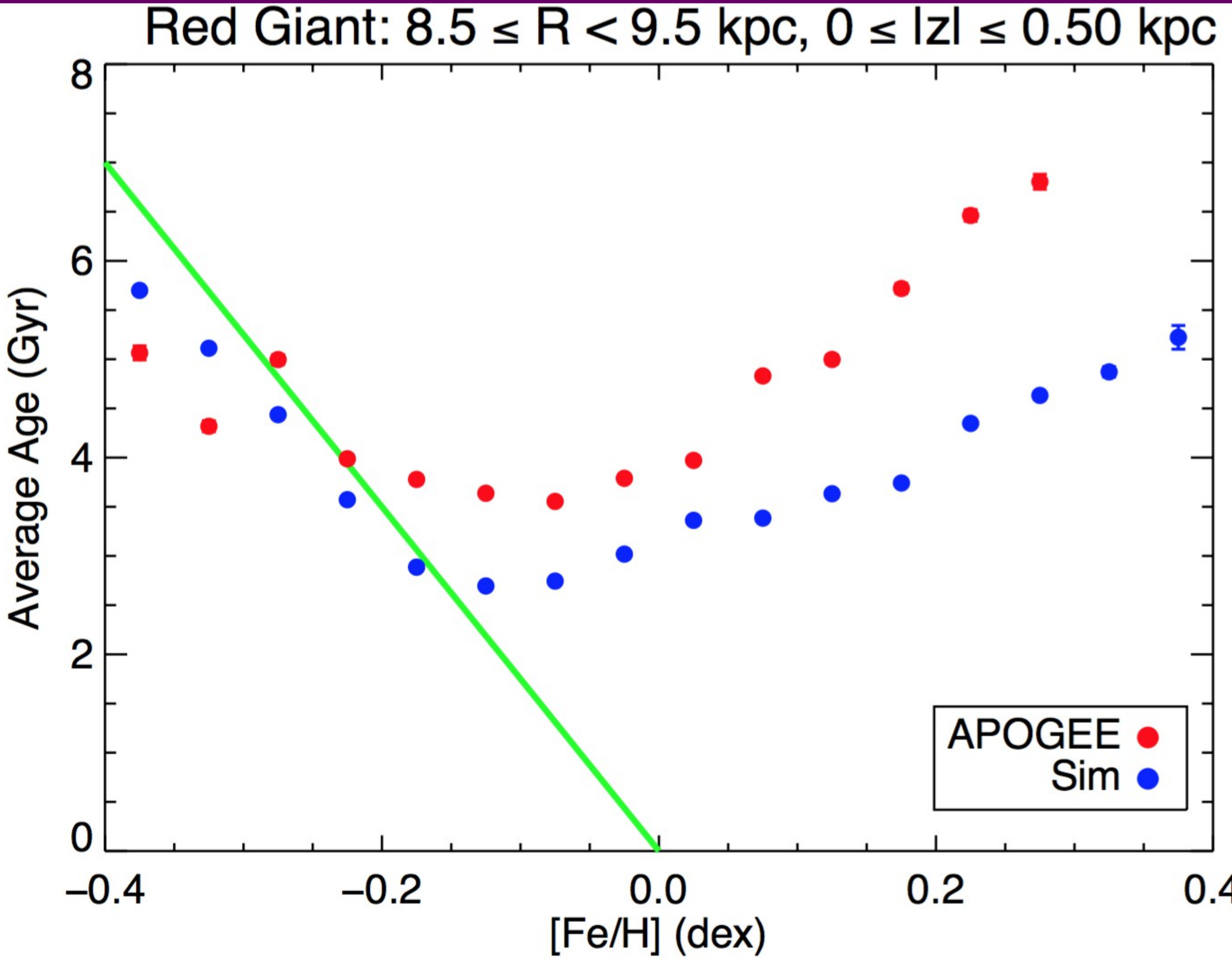
Loebman et al. 2016

Simulation high-[α/Fe] stars form at roughly same place



Loebman et al.2016

APOGEE high metallicity stars too old to have formed locally

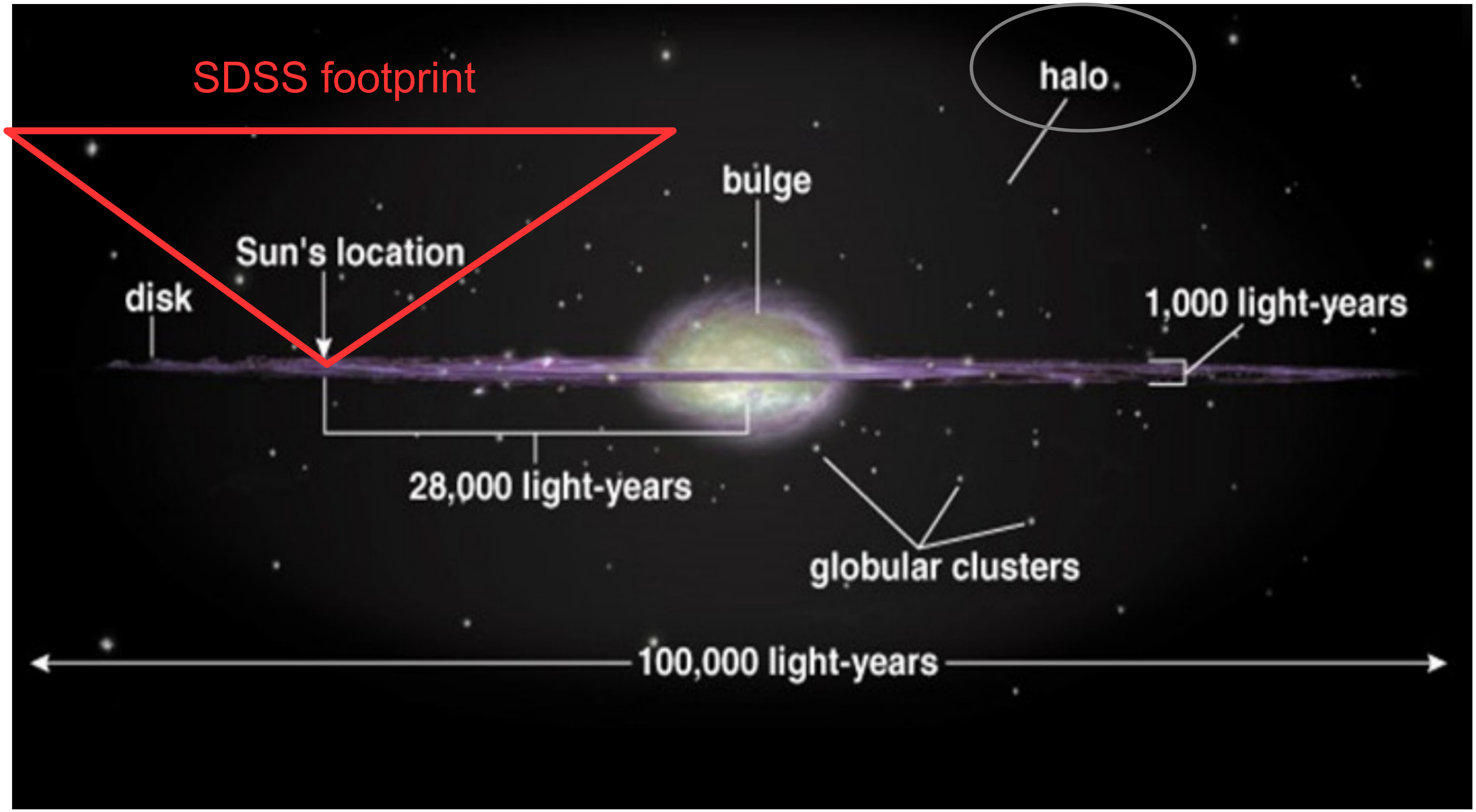


Disk Summary

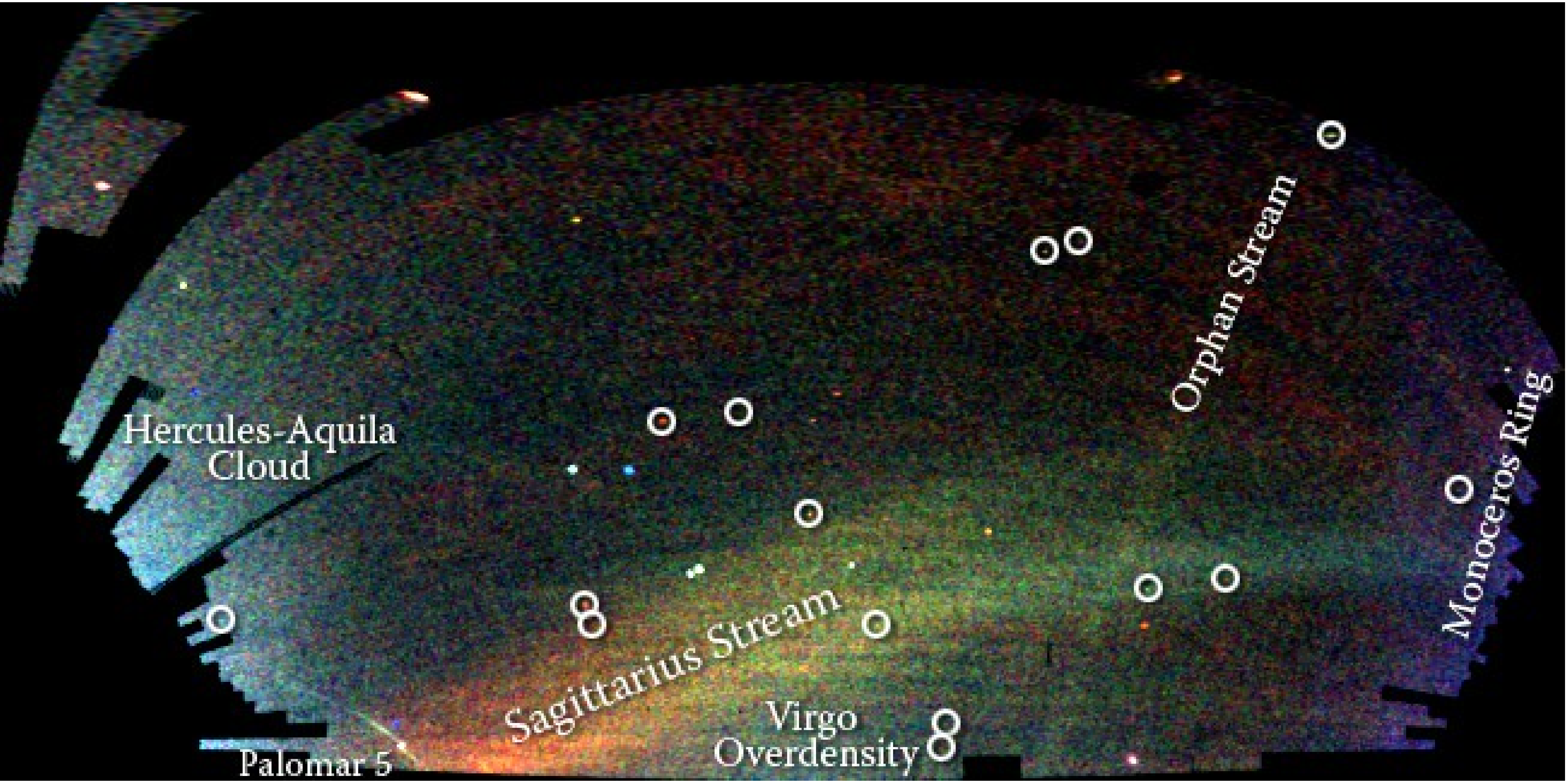
Radial Migration reproduces key APOGEE results:

- ✓ Shift the MDF skewness in the mid-plane with increased radius
  Increasing fraction of migrated stars at large radii
- ✓ Decrease shift in the MDF skewness out of the mid-plane
  Fewer and fewer in situ stars
- ✓ Create globally similar MDF for high-[α/Fe] population
  Stars formed in local reservoir & then migrated!
- ✓ The highest [Fe/H] stars are on average older than mid [Fe/H] stars
  These stars formed in the inner disk in the past and migrated

Part 2:
Stellar Halo

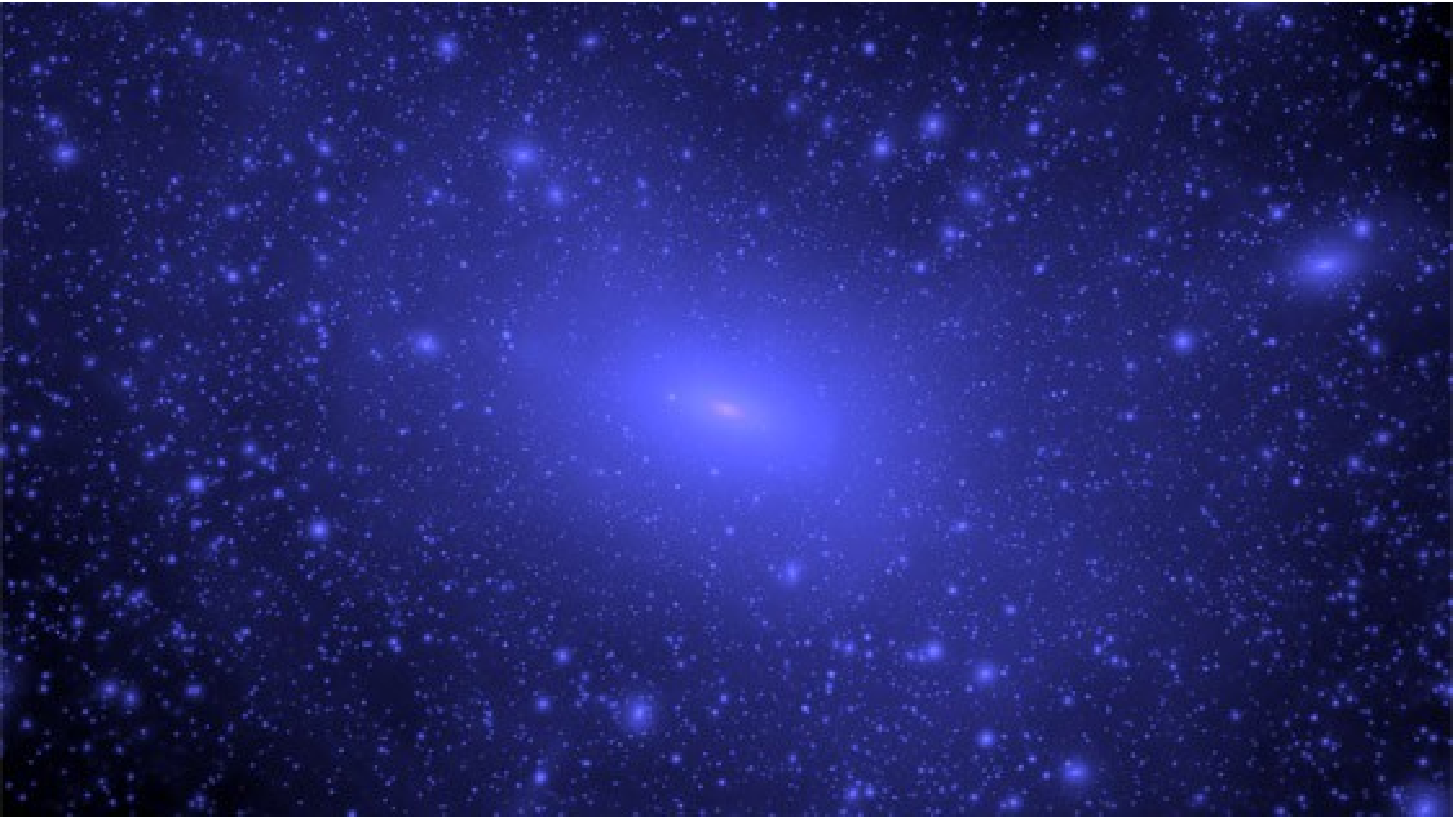


SDSS Milky Way Field of Streams



V. Belokurov and the Sloan Digital Sky Survey

Motion of stars in MW stellar halo to find DM mass, accretion history?



Jurg Diemand and the Via Lactea Project, http://www.ucolick.org/~diemand/vl/

β: statistical measure of how stars orbit in the stellar halo

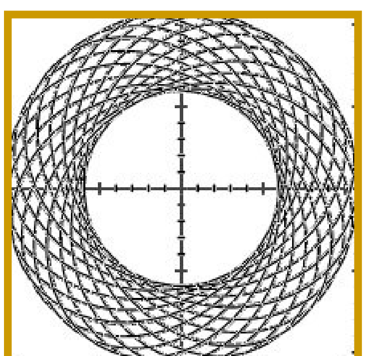
Measure:
x,y,z
V_r, V_ϕ, V_θ

Gaia

bin by r

$$\beta(r) = 1 - \frac{\sigma_\theta(r)^2 + \sigma_\phi(r)^2}{2\sigma_r(r)^2}$$

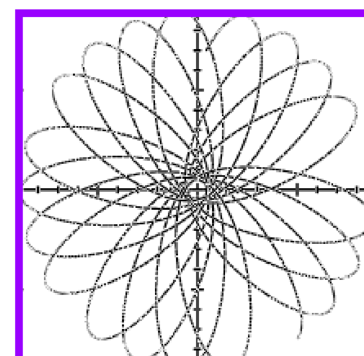
β < 0



orbits are tangentially biased

β = 0
orbits are isotropic

β > 0

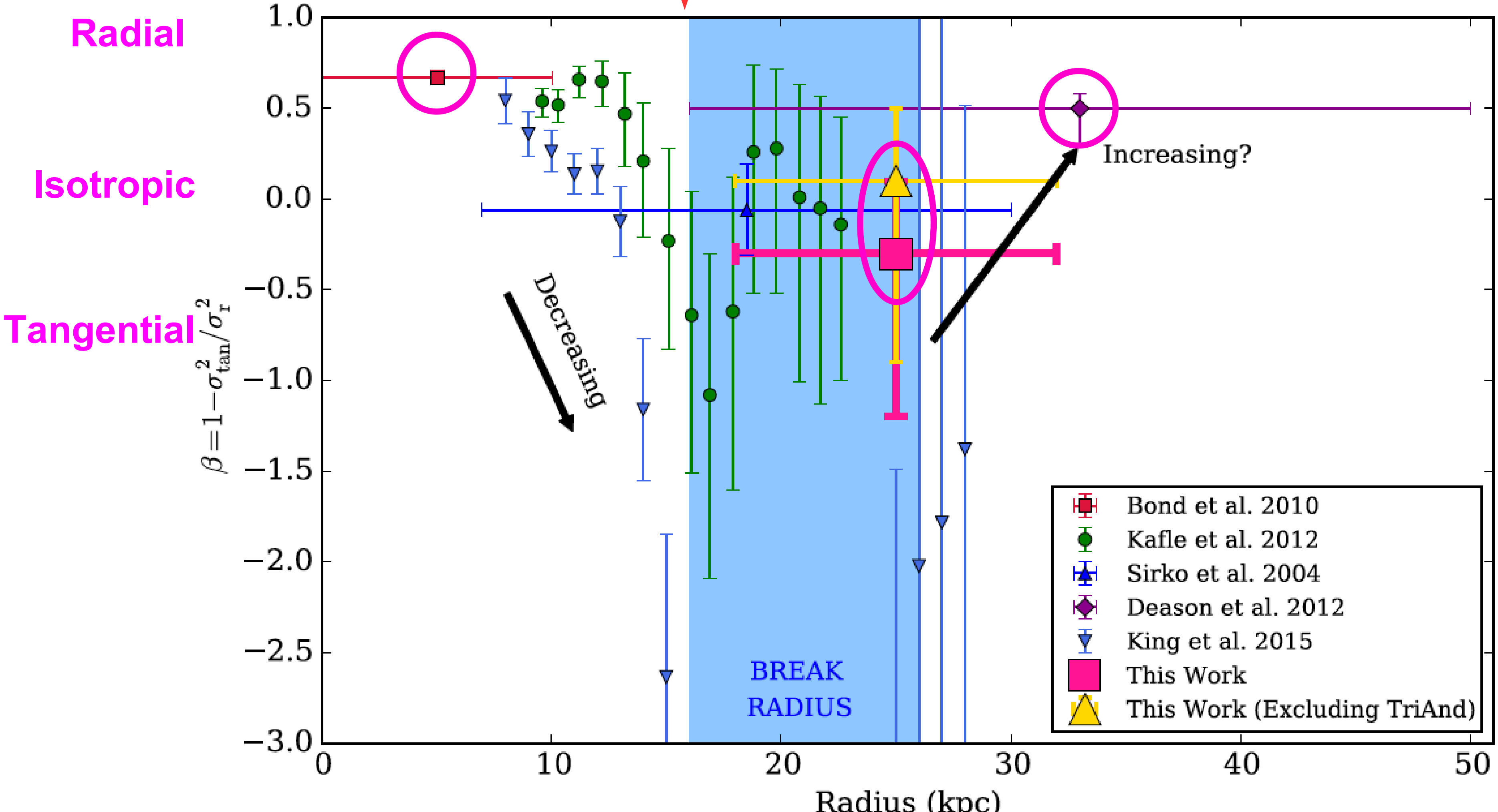


orbits are radially biased

β all over the place in the MW

Outside 16 kpc, 4D measurements likely biased tangentially
Hattori et al. 2017

The Astrophysical Journal, 820:18 (9pp), 2016 March 20 Cunningham et al.

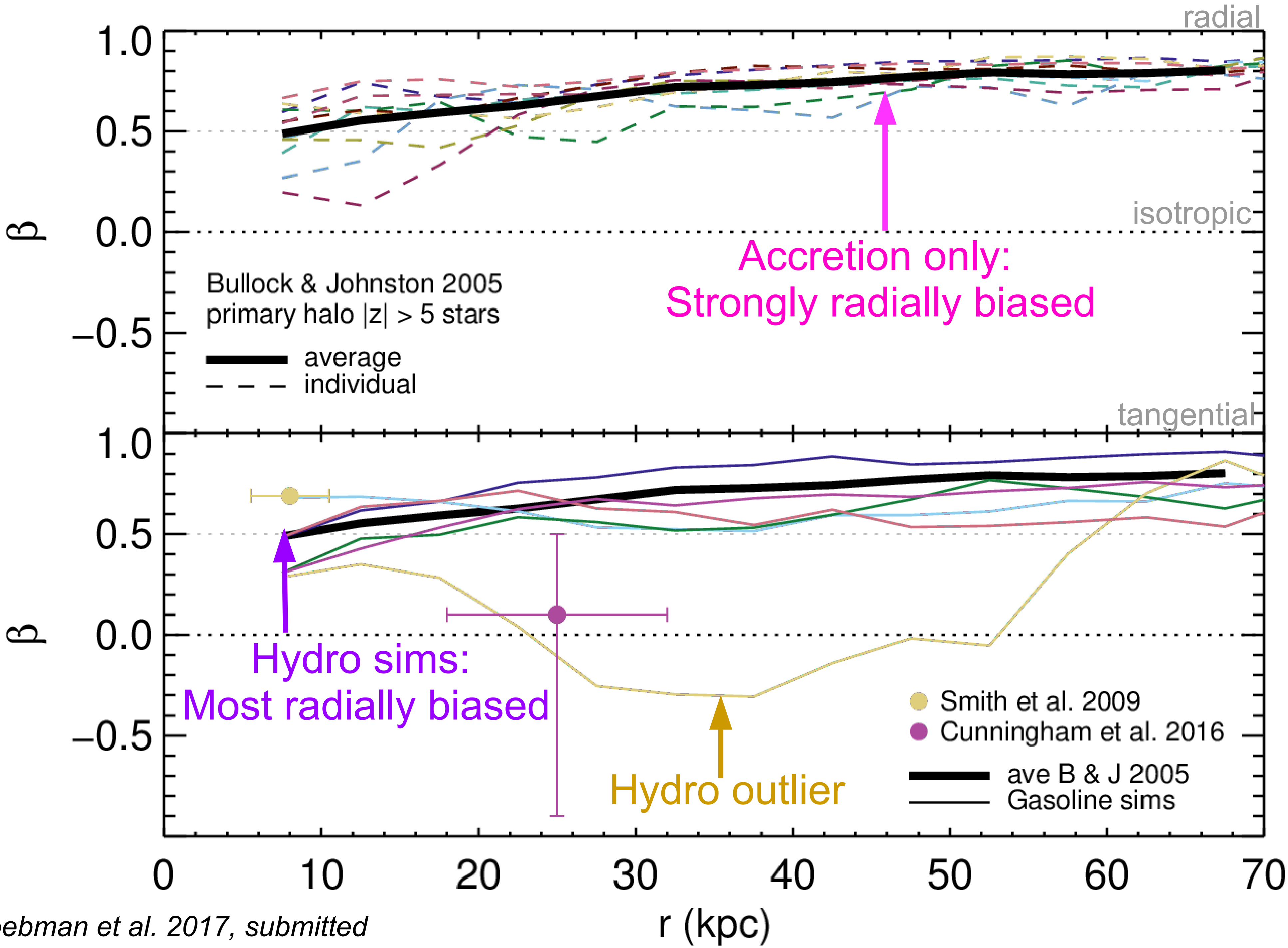


Cunningham et al. 2016

Simulations enable exploration of the build up of the stellar halo & β

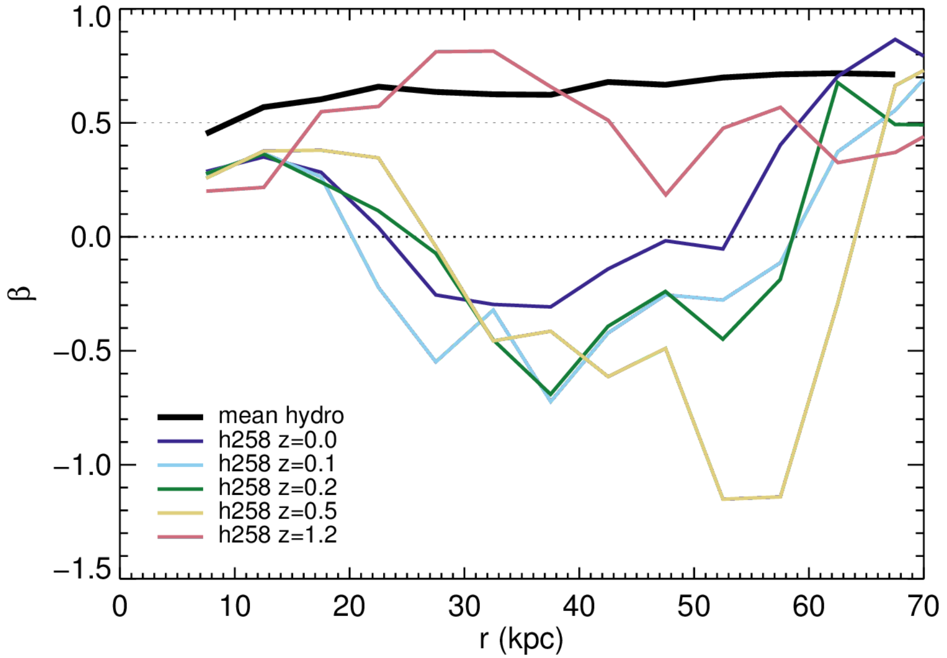
Bullock & Johnston 2005

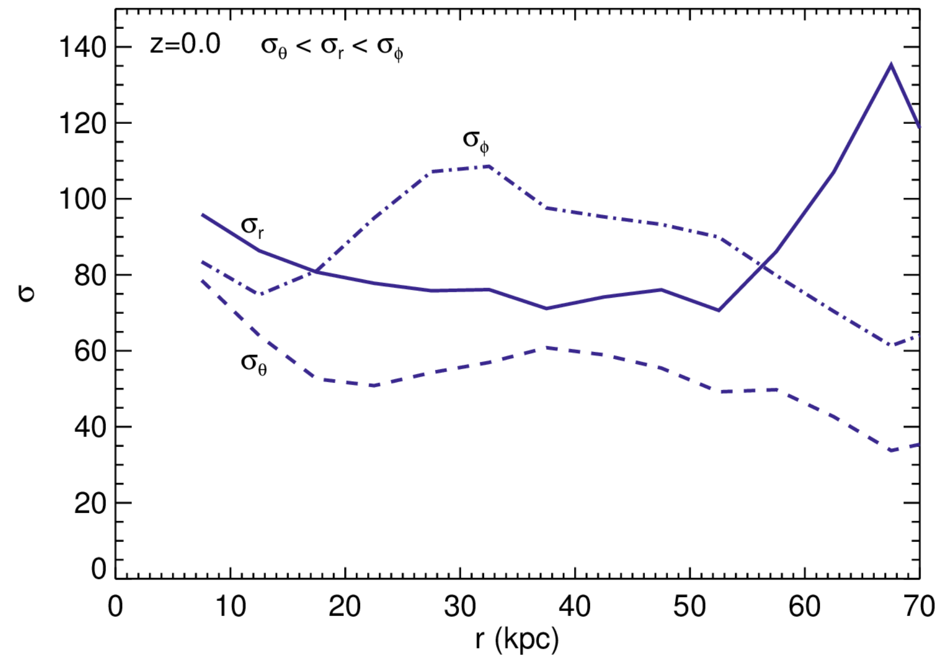
Simulations radially biased



Loebman et al. 2017, submitted

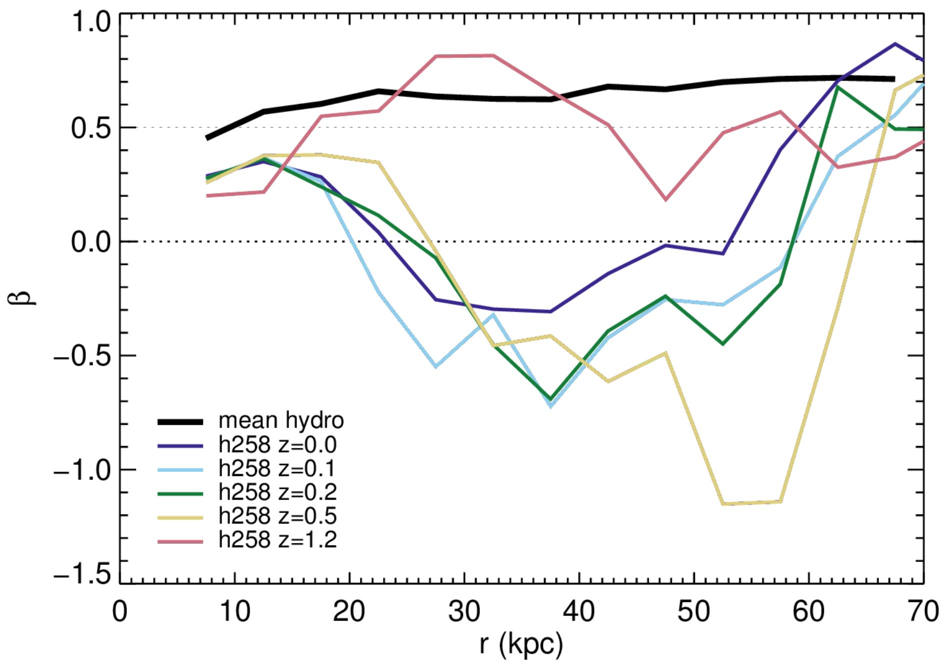
Merger boosts σ_Φ above σ_r – persists until present day

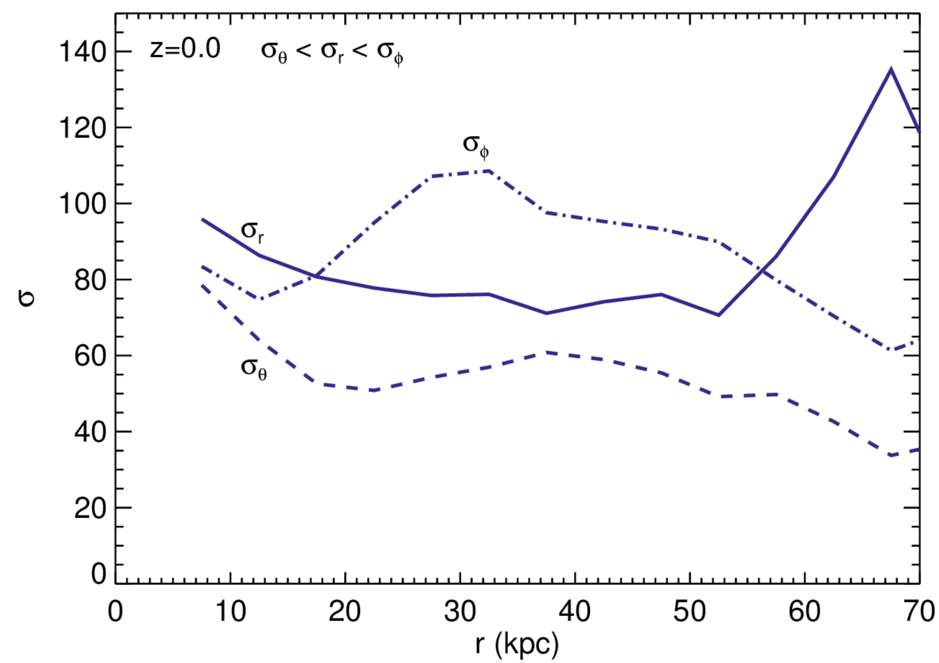




Loebman et al. 2017, submitted

Merger boosts σ_ϕ above σ_r – persists until present day





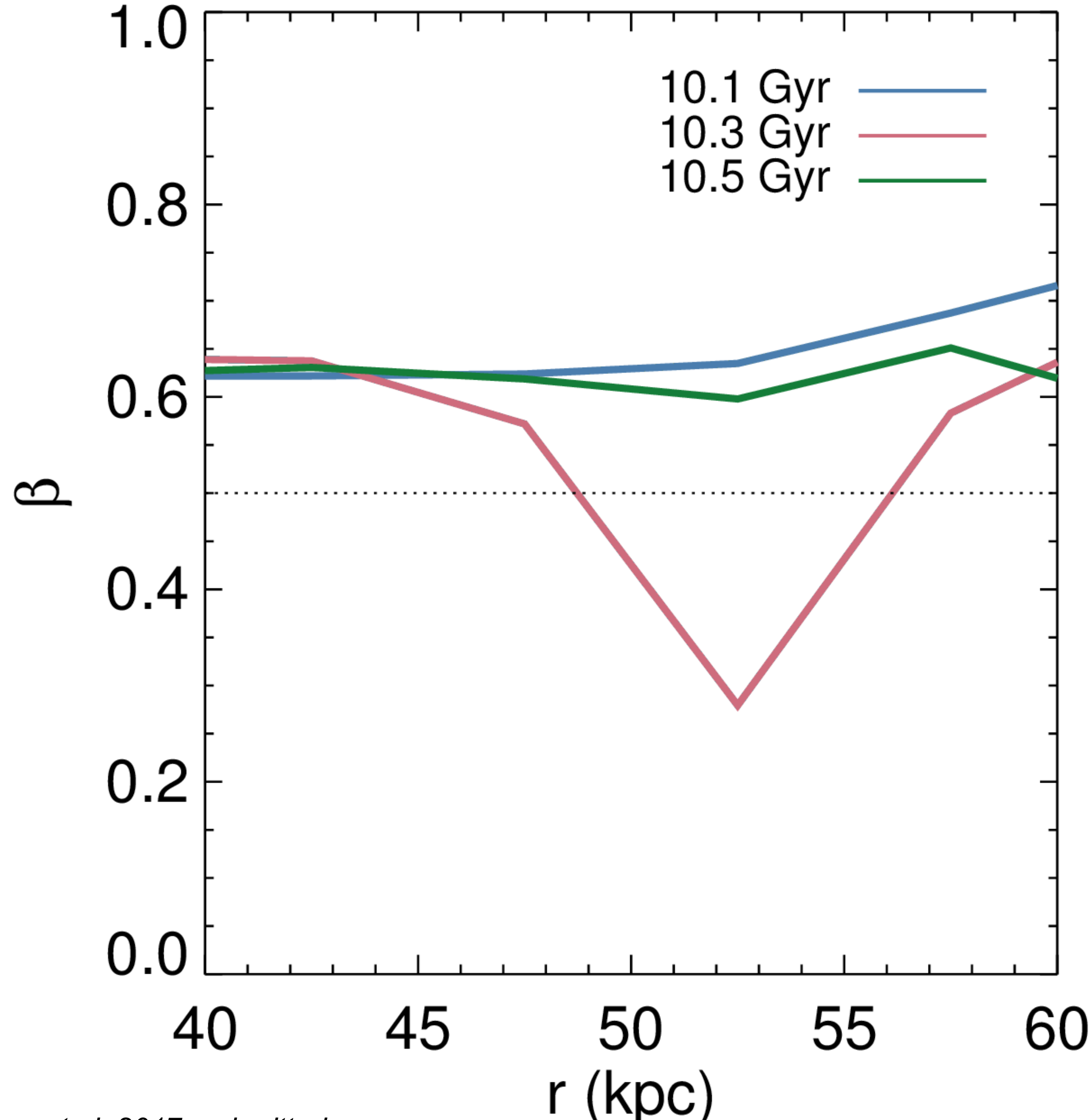
Loebman et al. 2017, submitted

Major merger z~1

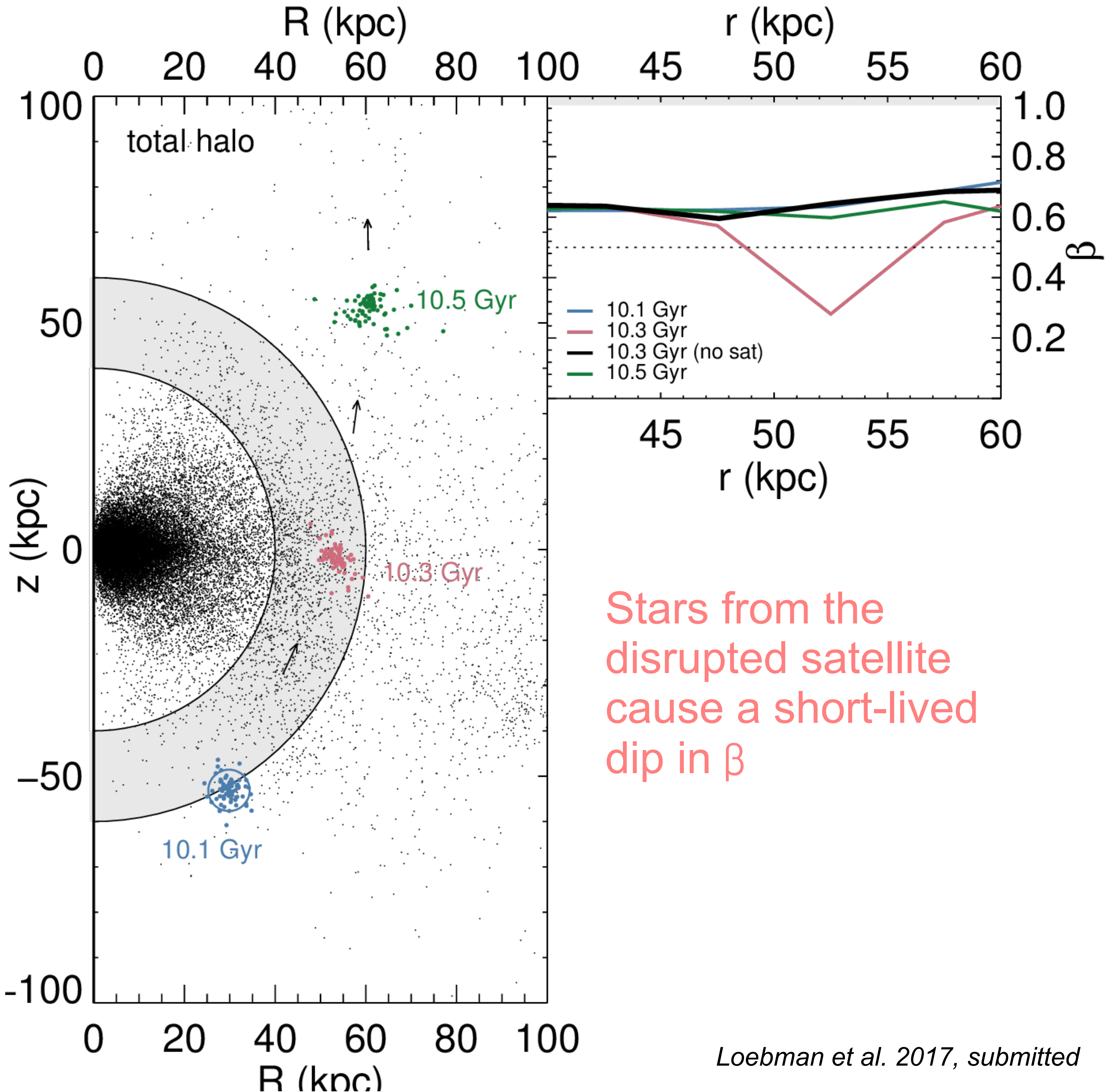
Movie of courtesy of A. Brooks

β Gaia accessible – exciting possibility for understanding past!

What causes short term β dips?



Loebman et al. 2017, submitted



Stars from the disrupted satellite cause a short-lived dip in β

Loebman et al. 2017, submitted

Halo Summary

Simulations make strong predictions for expected β:

- ΛCDM predicts strongly radial β

  Halo stars retain memory of their radial infall

- Tangential β over a wide range of radii could indicate major merger

  Proto-disks nearly aligned

- Tangential β over a small range of radii could indicate recent accretion

  Spectroscopic follow-up to confirm

Thank you!
Questions?