Reconsidering the Milky Way's Thick Disk:
What We Can Learn from Observations & Simulations

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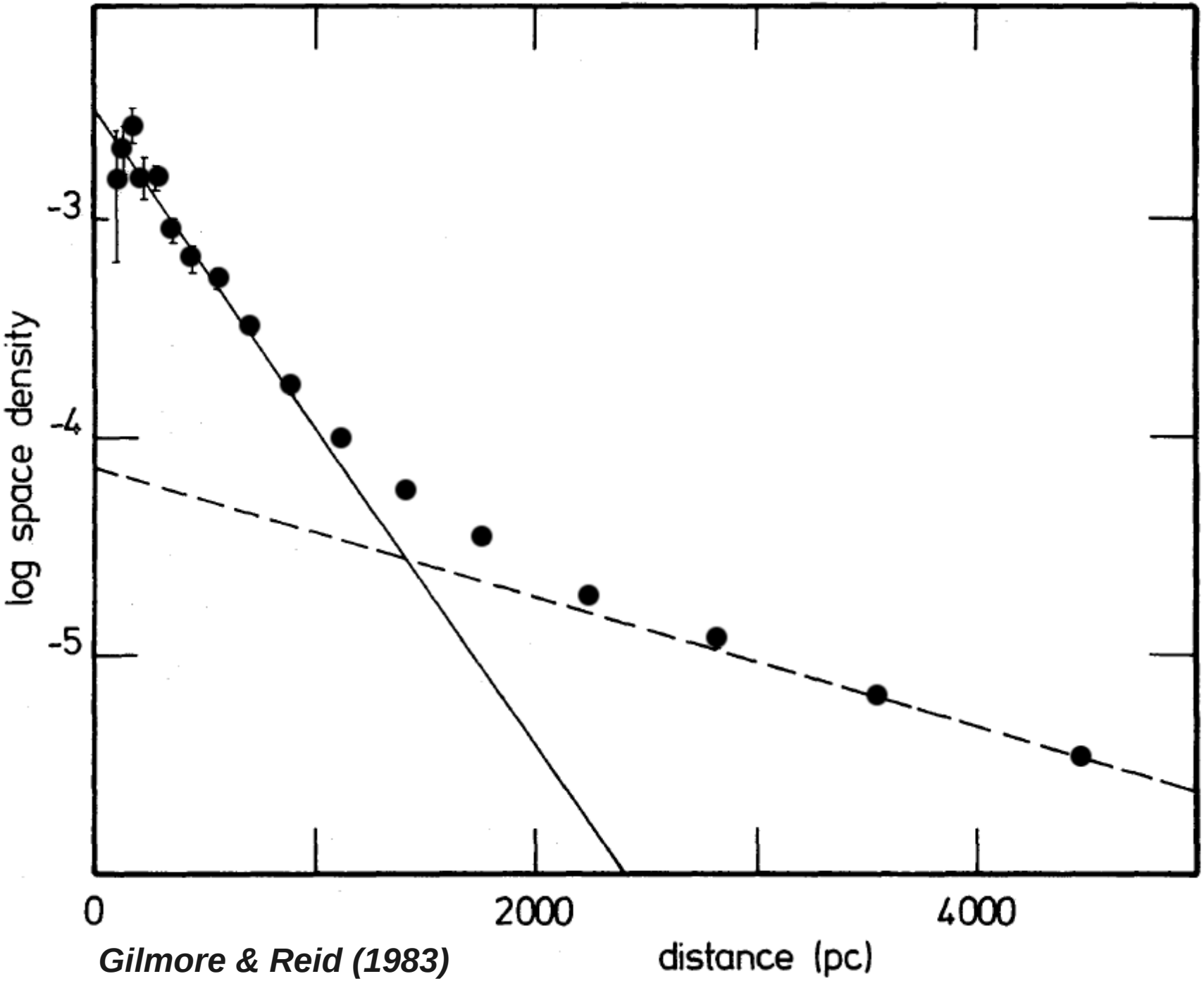
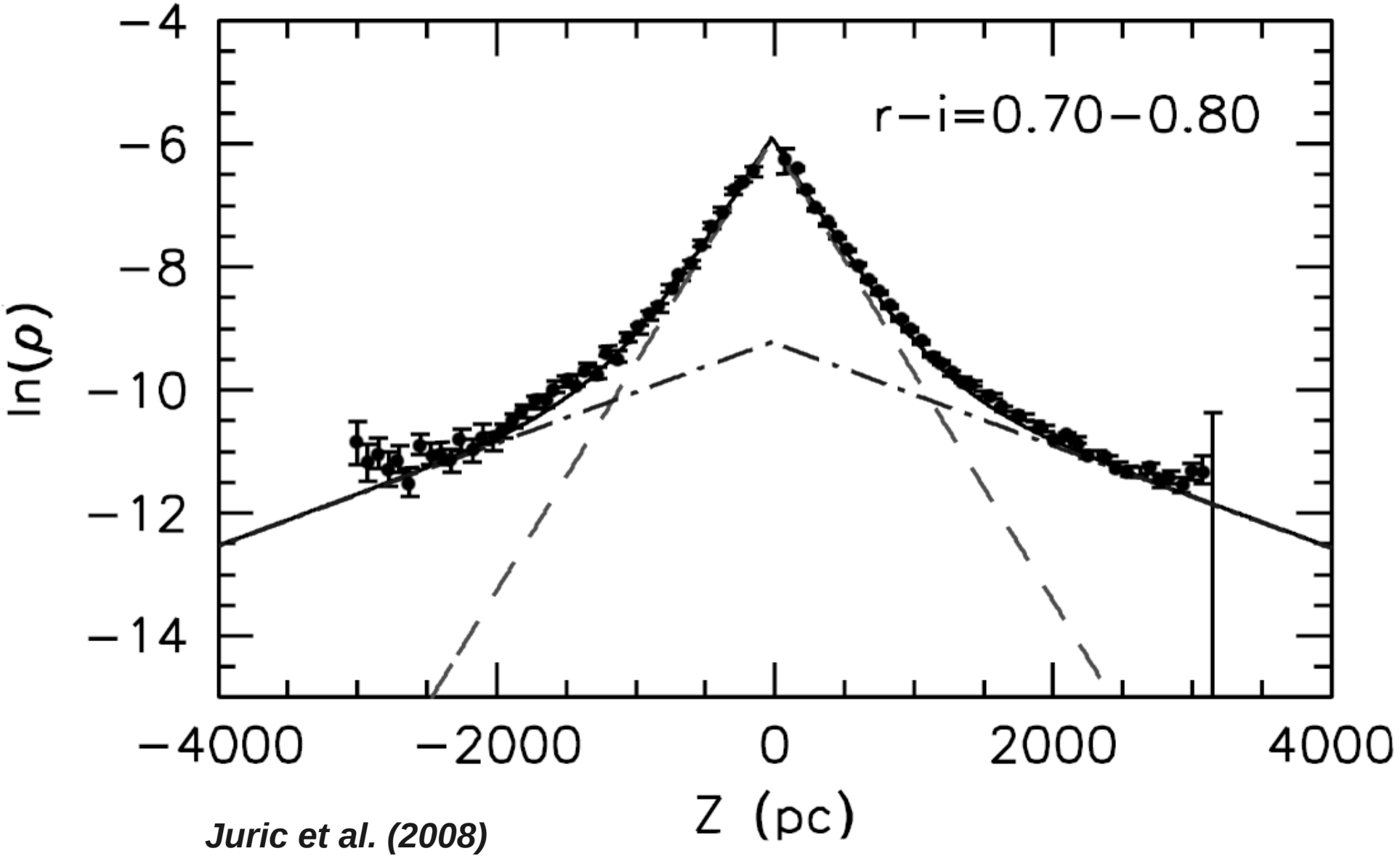
& James Wadsley

Outline

- Background
- Observational Properties (SDSS)
- Theories of Formation
- Radial Migration Simulations (*Roškar et al.*)
- [α/Fe] (SEGUE)
- Predictions & Future Observations (APOGEE)
- Conclusions & Future Work

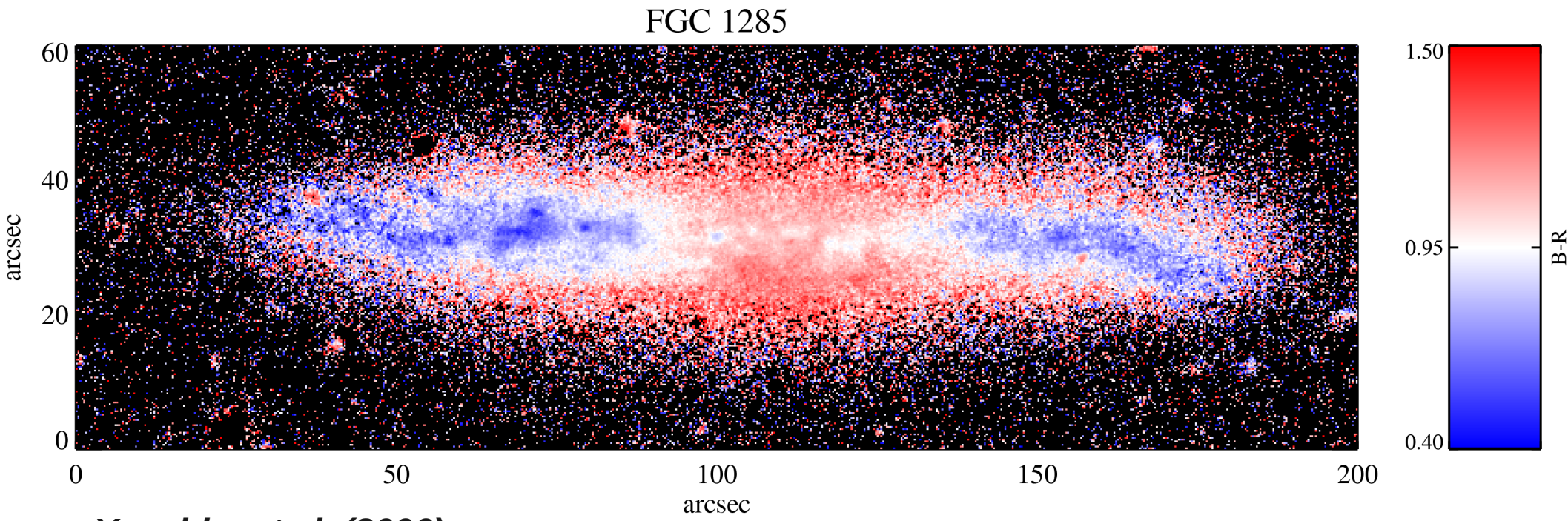


Gilmore & Reid (1983)



Juric et al. (2008)

What sort of distribution should we expect?



Yoachim et al. (2006)

Thick Disks

- Ubiquitous Feature in Spiral Galaxies
- Fossil Record of Violent Past?
- Passively Evolving via Secular Processes?

Internal vs External

Early vs Ongoing

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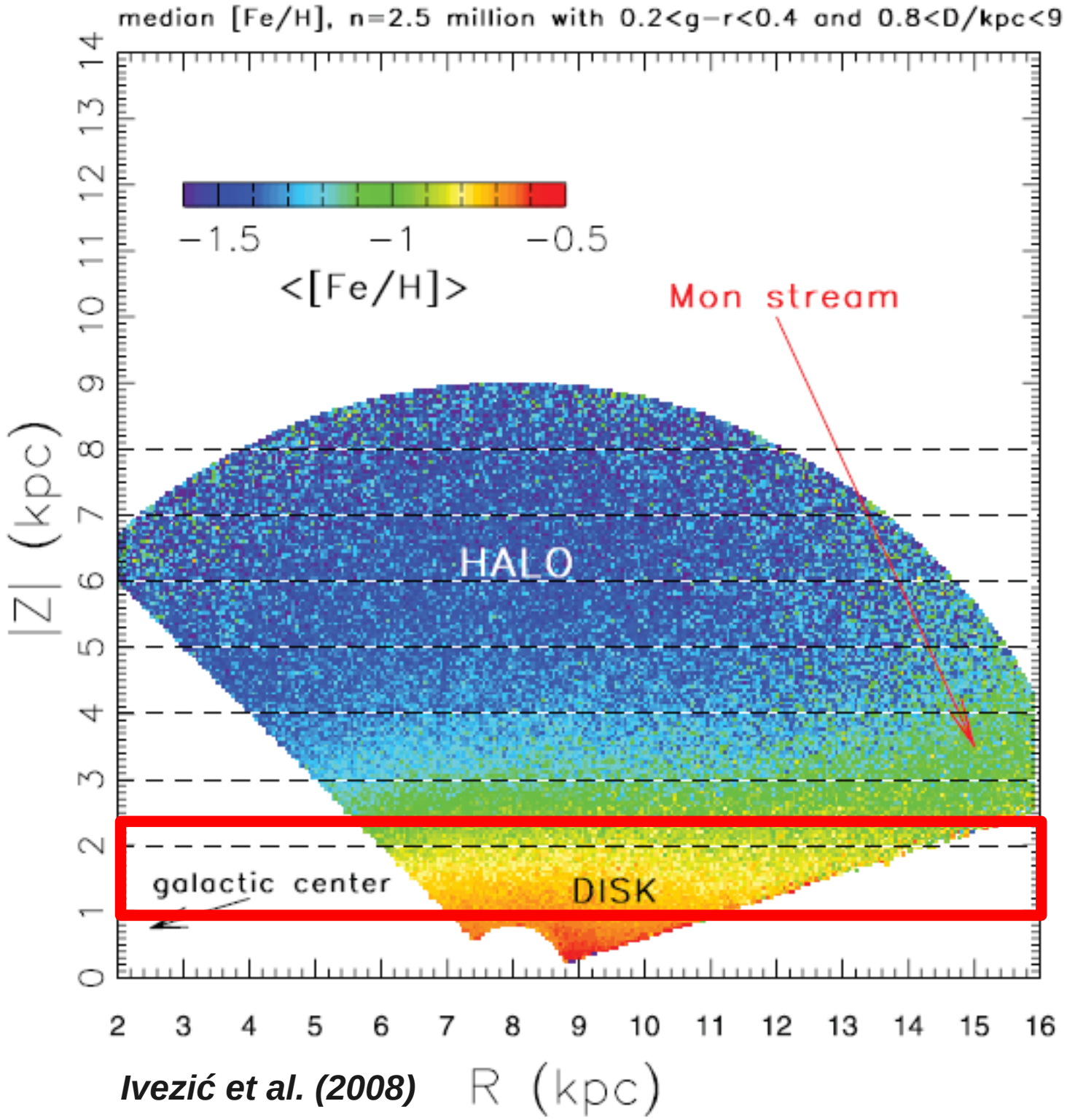
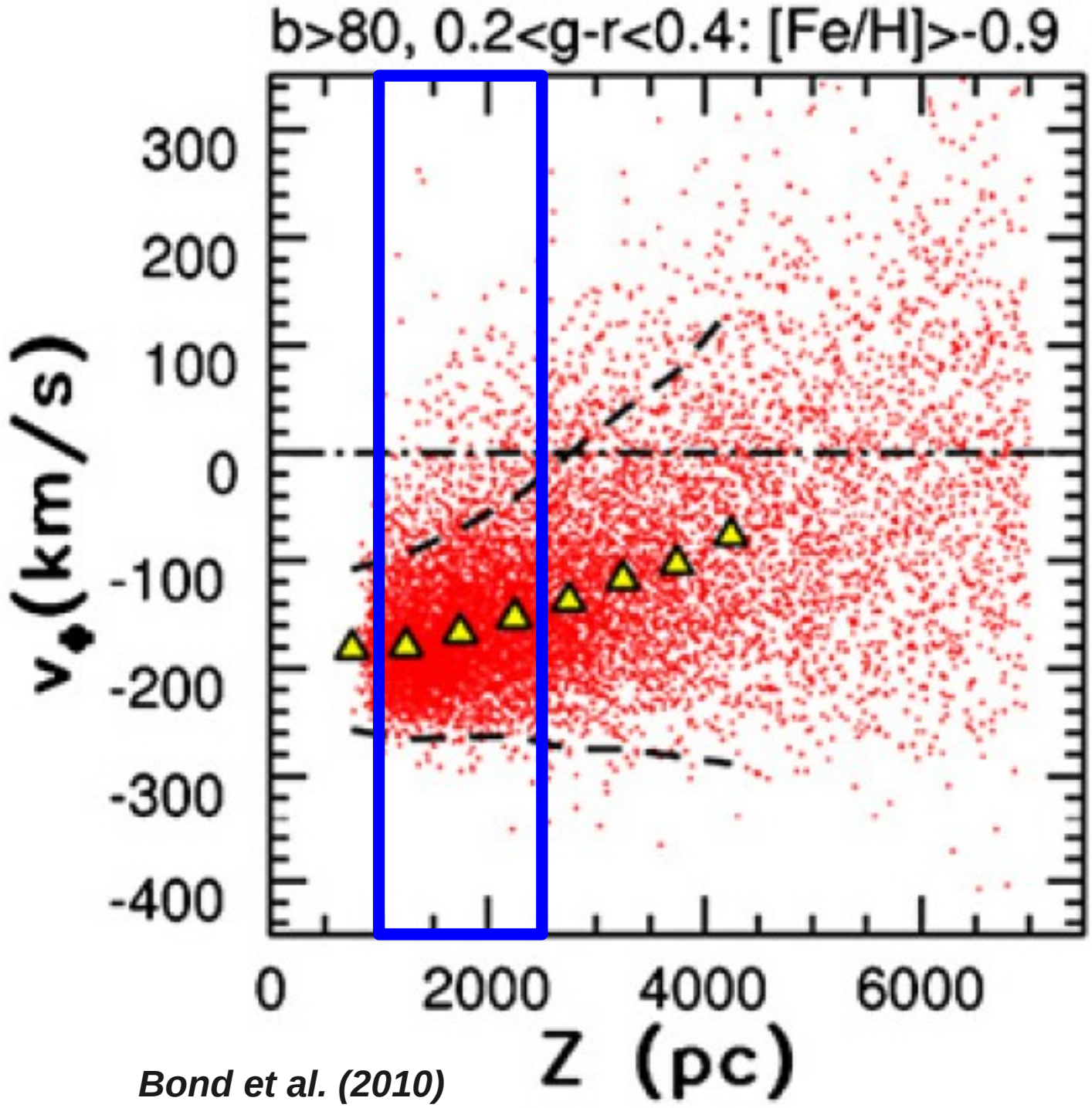


Ivezić et al. (2008)



Bond et al. (2010)

	THIN	THICK
Scale Height	270 pc	1200 pc
<[Fe/H]>	-0.2 dex	-0.7 dex (1.5 kpc)
$\langle V_\Phi \rangle$	-220 km/s	-175 km/s (1.5 kpc)

Should we consider these properties together or separately?

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4 Theories of Thick Disk Formation

1. Violent Relaxation *(Jones & Wyse 1983)*

   thin disk rapid heating

2. Direct Accretion *(Statler 1988)*

   satellite stars

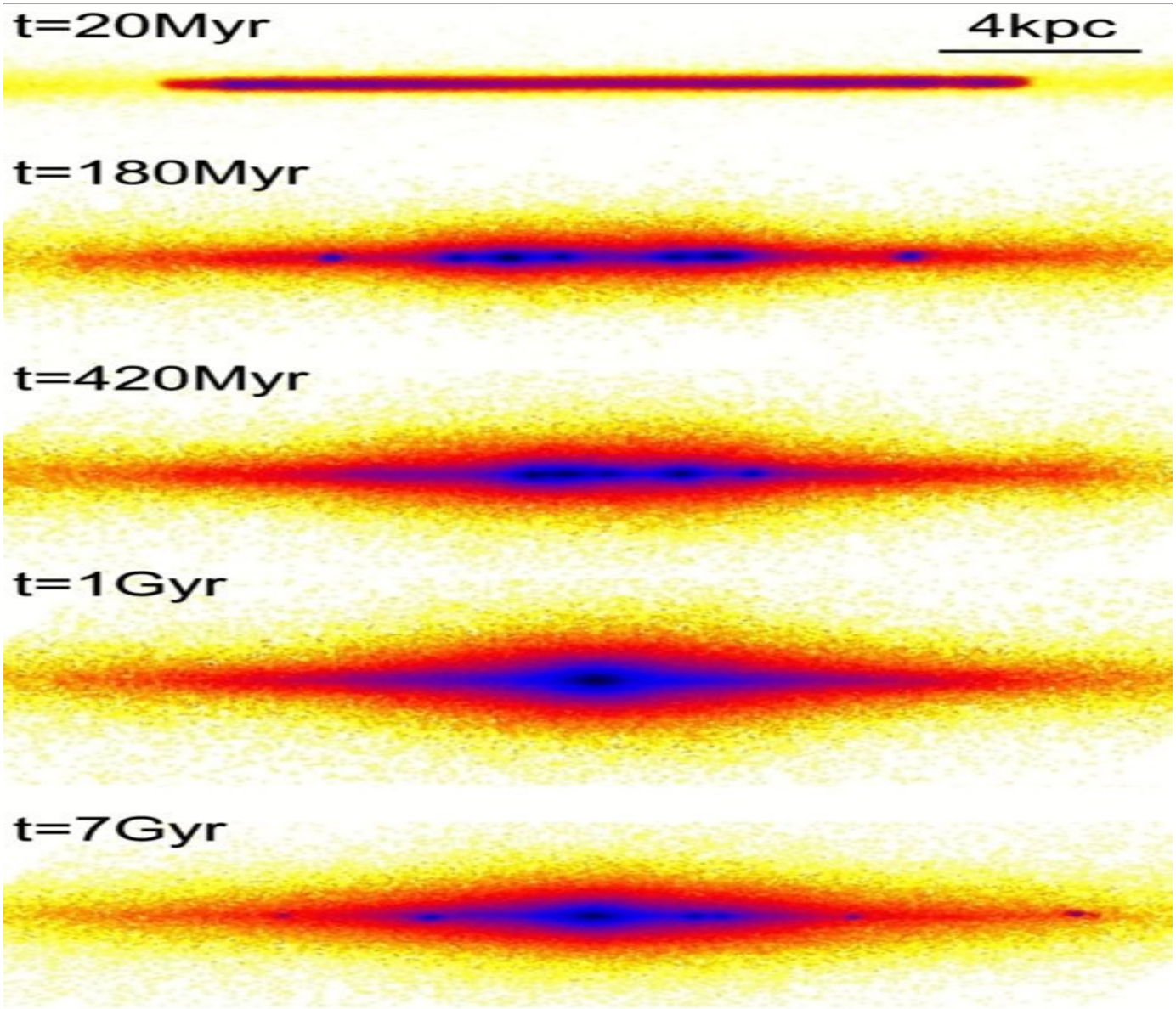
3. Heating by Substructure *(Quinn 1993)*

   thin disk heated by dark matter halos

4. Radial Migration *(Sellwood & Binney 2002)*

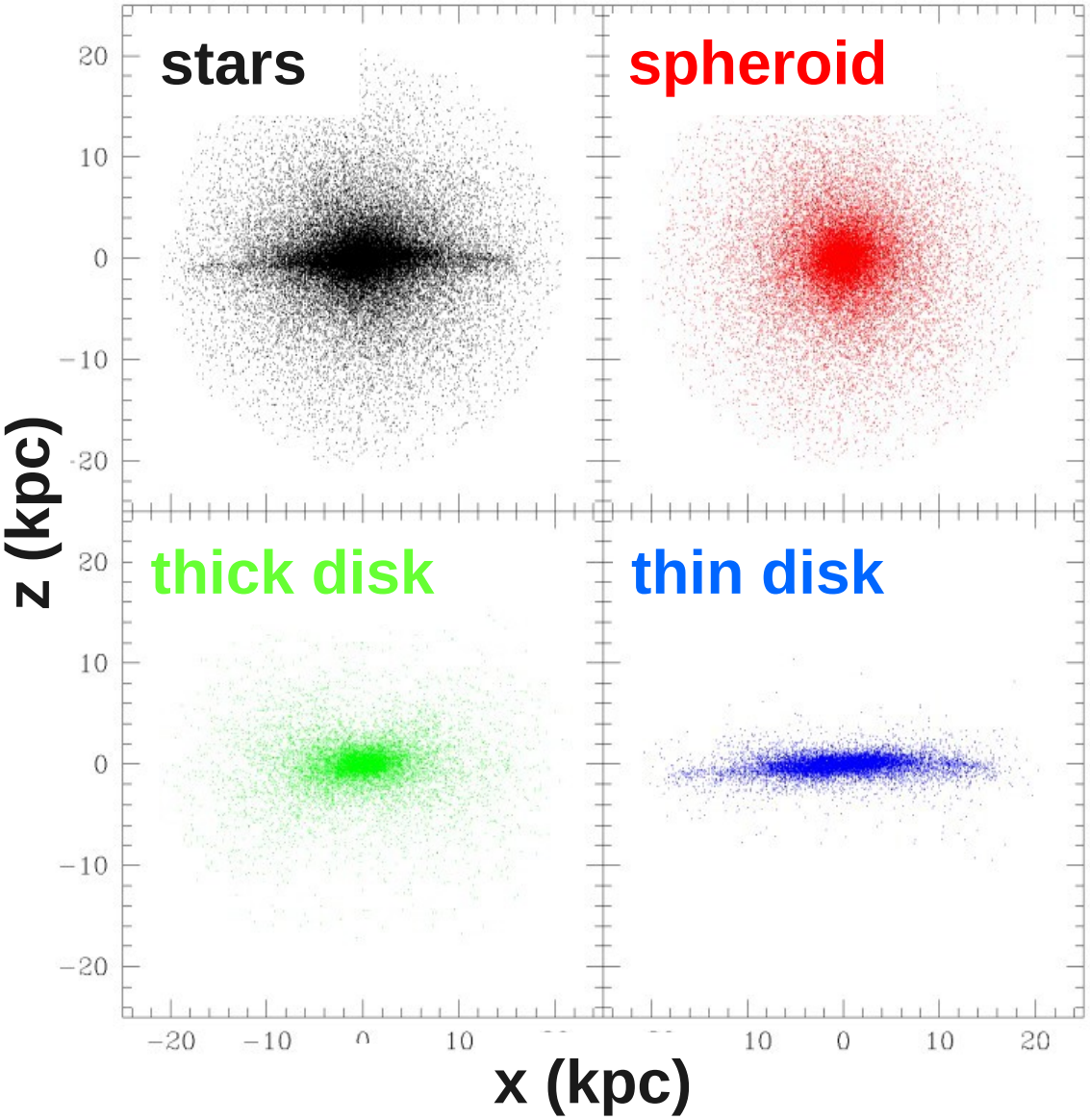
   thin disk redistribution by spiral structure

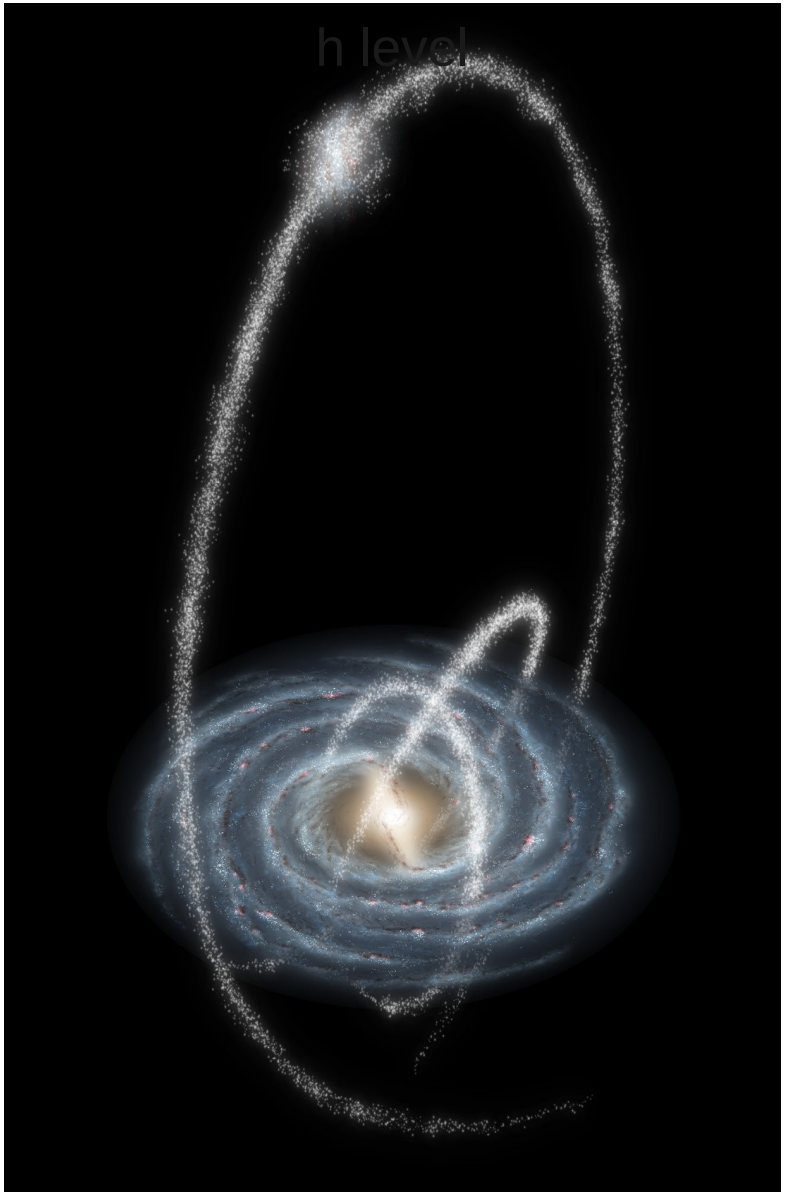
Violent Relaxation



Theory: *Jones & Wyse 1983*
Models: *Brook et al. 2004,* ***Bournaud et al. 2009***

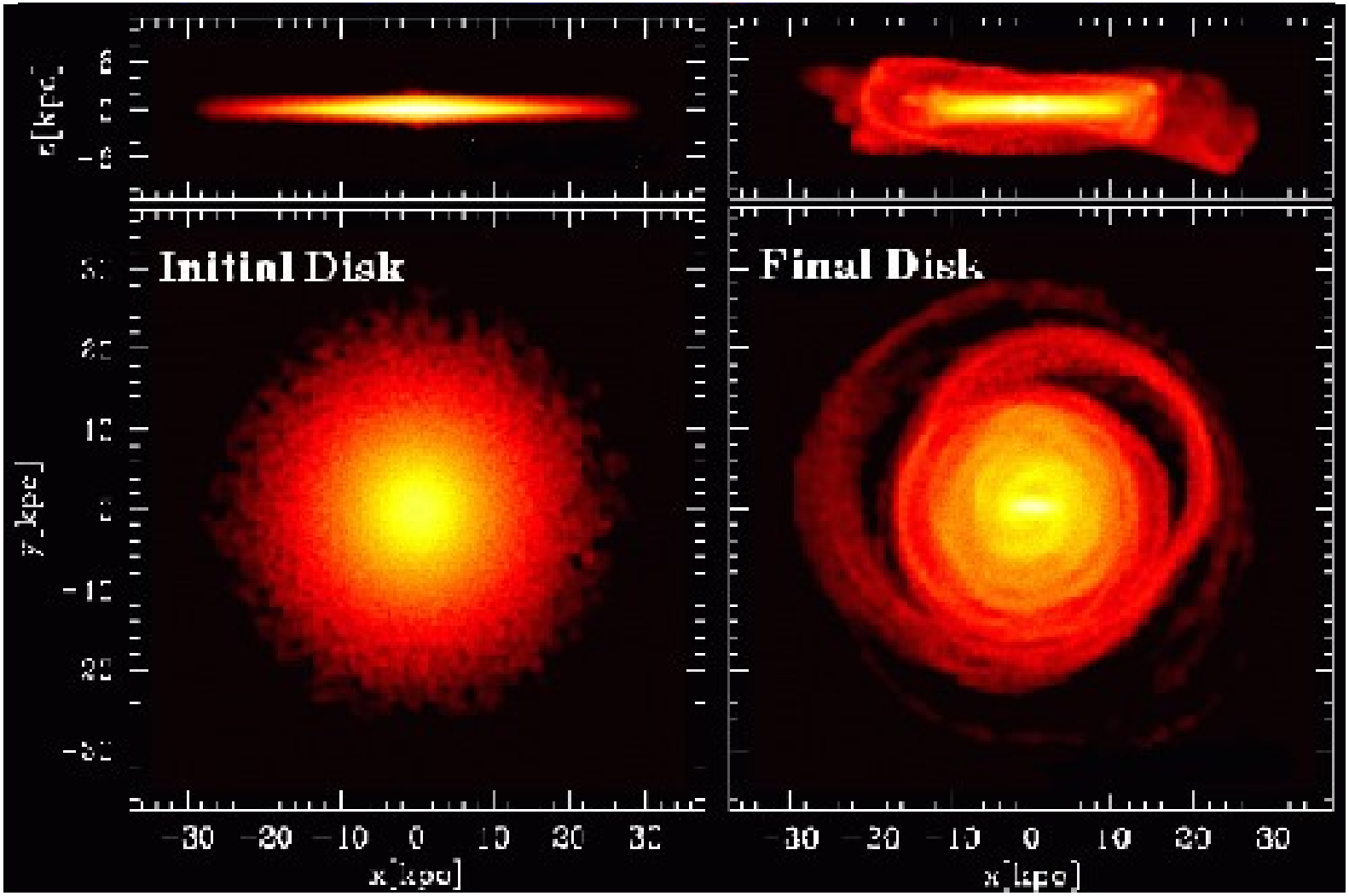
Direct Accretion of Satellites





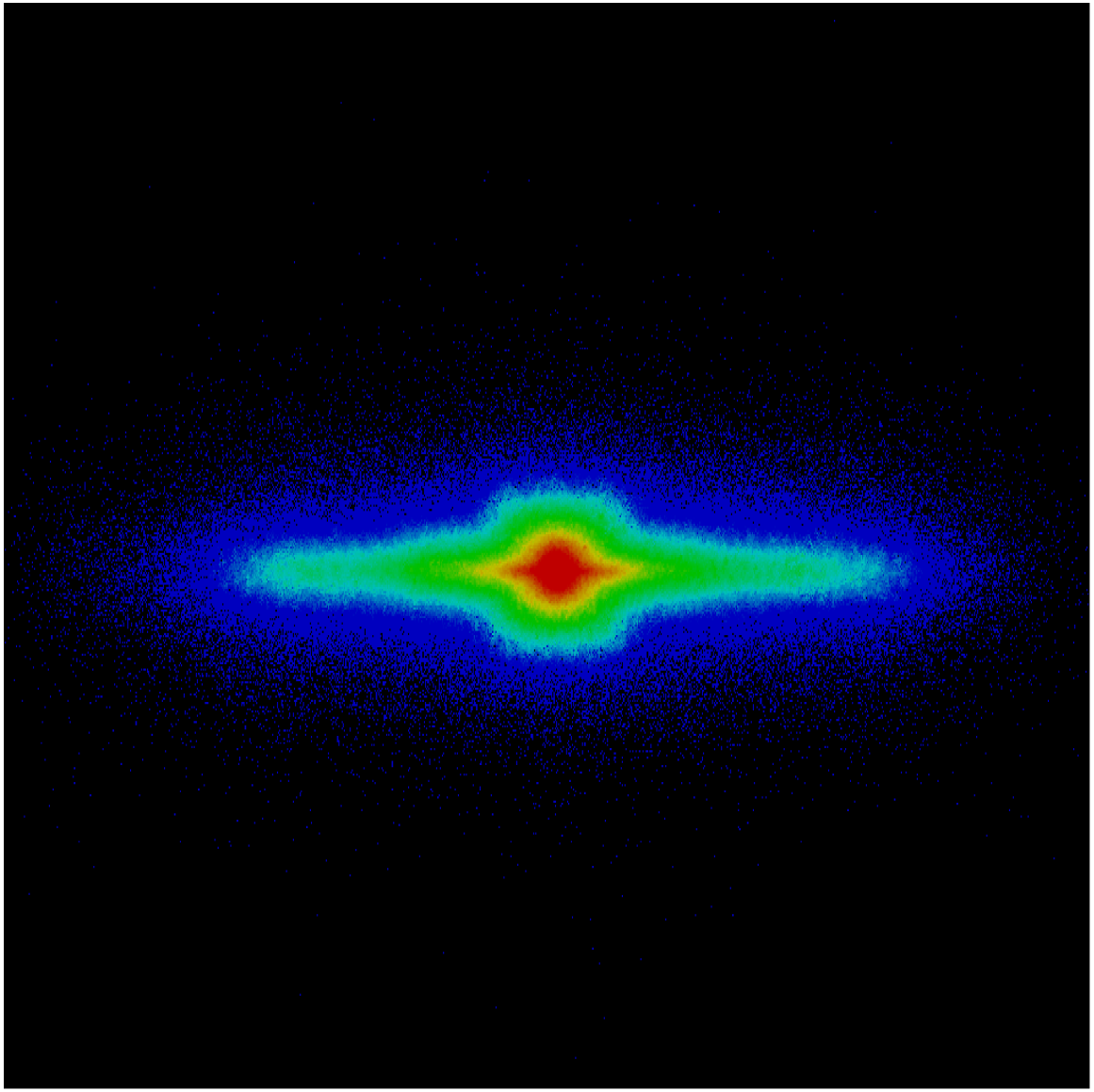
Theory: *Statler 1988*
Model: ***Abadi et al. 2003***

Heating by Substructure



Theory: *Quinn (1993)*
Models: ***Kazantzidis et al. (2008)***, *Villalobos & Helmi (2008)*,
and *Villalobos et al. (2010), Bird (2011)*

Radial Migration

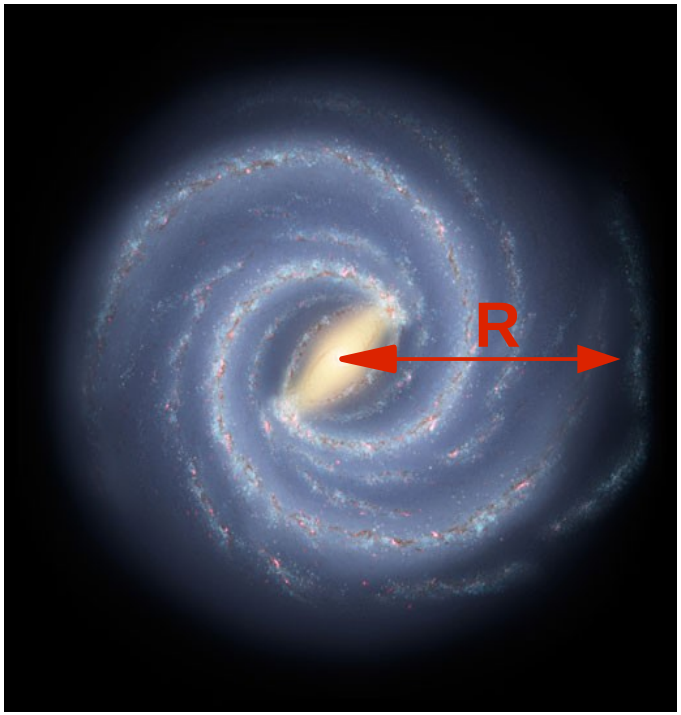


Theory: *Sellwood & Binney (2002)*
Models: ***Roškar et al. (2008)***, *Schönrich (2009), and Bird (2011)*

4 Theories of Thick Disk Formation

1. Violent Relaxation: Early, Internal
2. Direct Accretion: Ongoing*, External
3. Heating by Substructure: Ongoing*, External
4. Radial Migration: Ongoing, Internal

Radial Migration



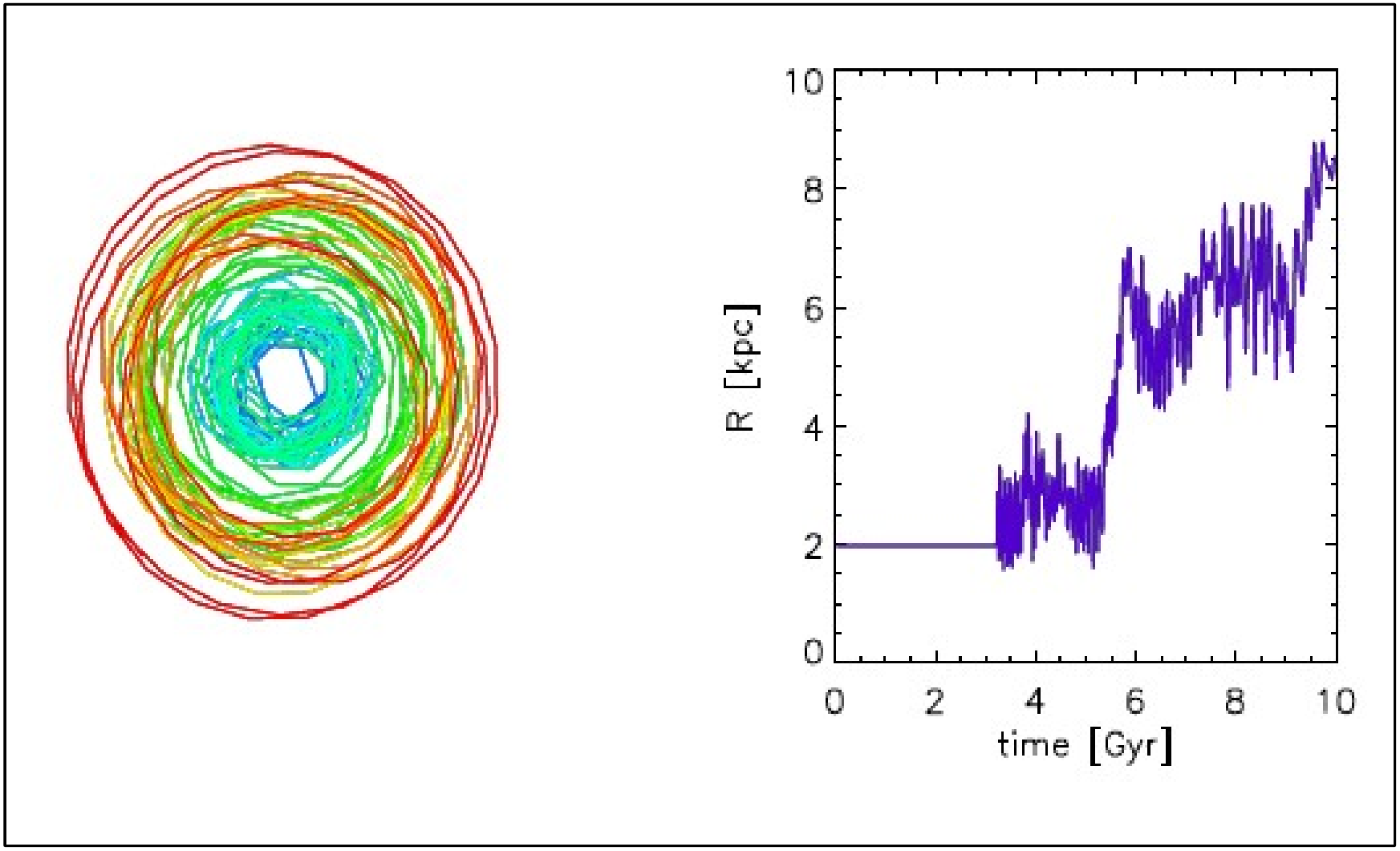
Caused by transient spiral arms

- < 200,000 yr timescales
- inward/outward
- maintains ellipticity

Not scattering

- ~~molecular clouds~~
- ~~bar structure~~
- ~~“heating”~~

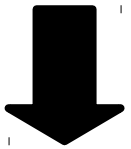
Roškar et al. (2008)



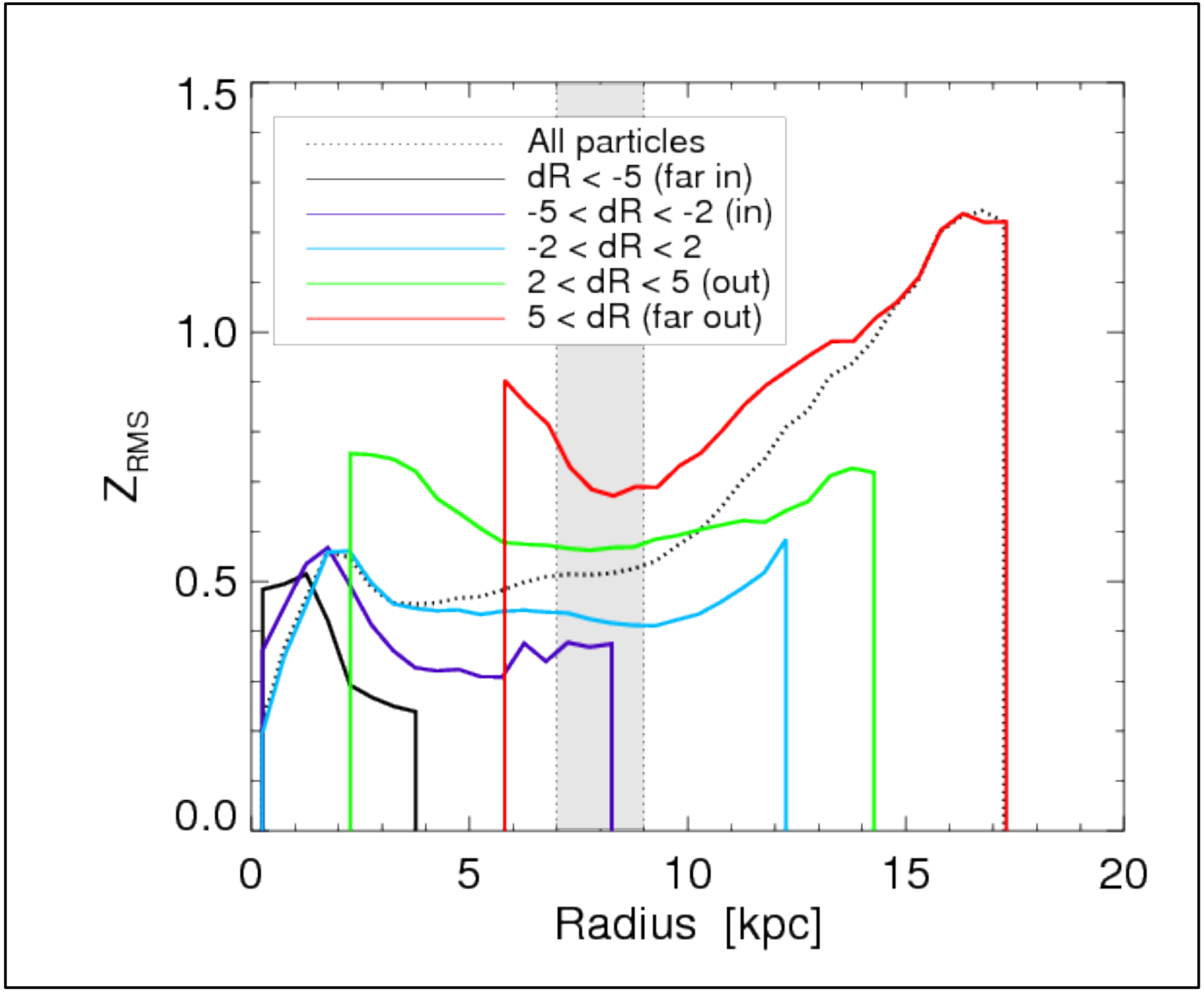
Roškar et al. (2008)

Radial Migration: Thick Disk

- Resonant Interaction works best on stars on Circular Orbits
- Migrated stars conserve J_z & J_R-action
  Maintain Circularity of Orbit
- Migrated Stars experience a Change in Angular Momentum
- Stars moved to larger radii feel less restoring force



Greater/longer excursions in the z direction


All particles
dR < -5 (far in)
-5 < dR < -2 (in)
-2 < dR < 2
2 < dR < 5 (out)
5 < dR (far out)
1.5
1.0
0.5
0.0
Z_{RMS}
0
5
10
15
20
Radius [kpc]

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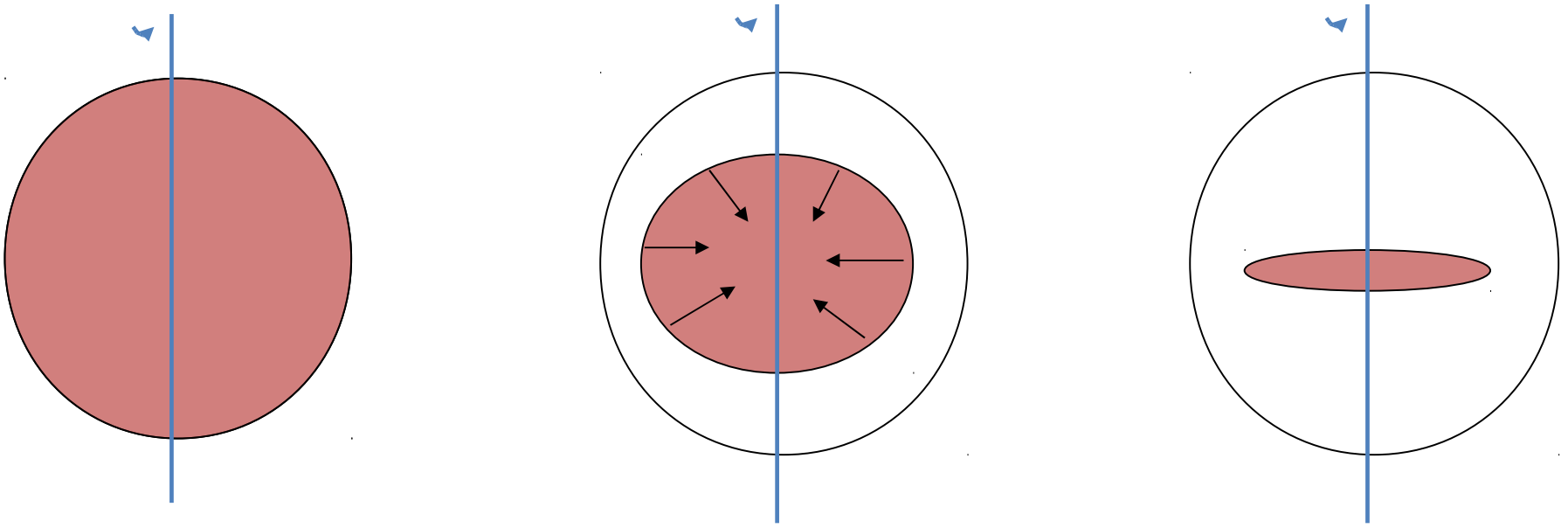
Roškar et al. Simulations

Studying Disk Formation
with N-body + SPH Simulations
<u>after</u>
the Last Major Merger

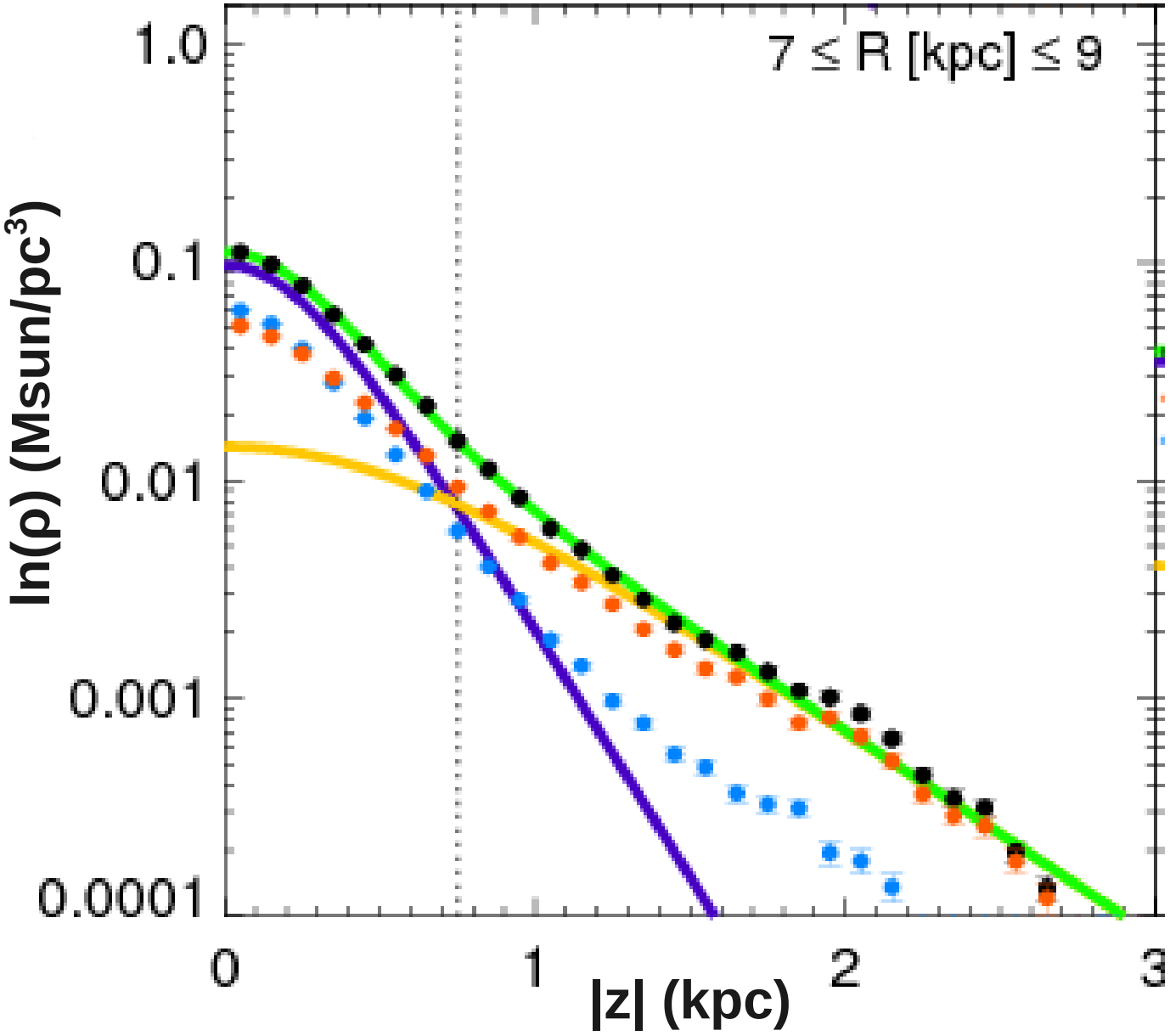


Roškar et al. (2008)

Roškar et al. Simulations

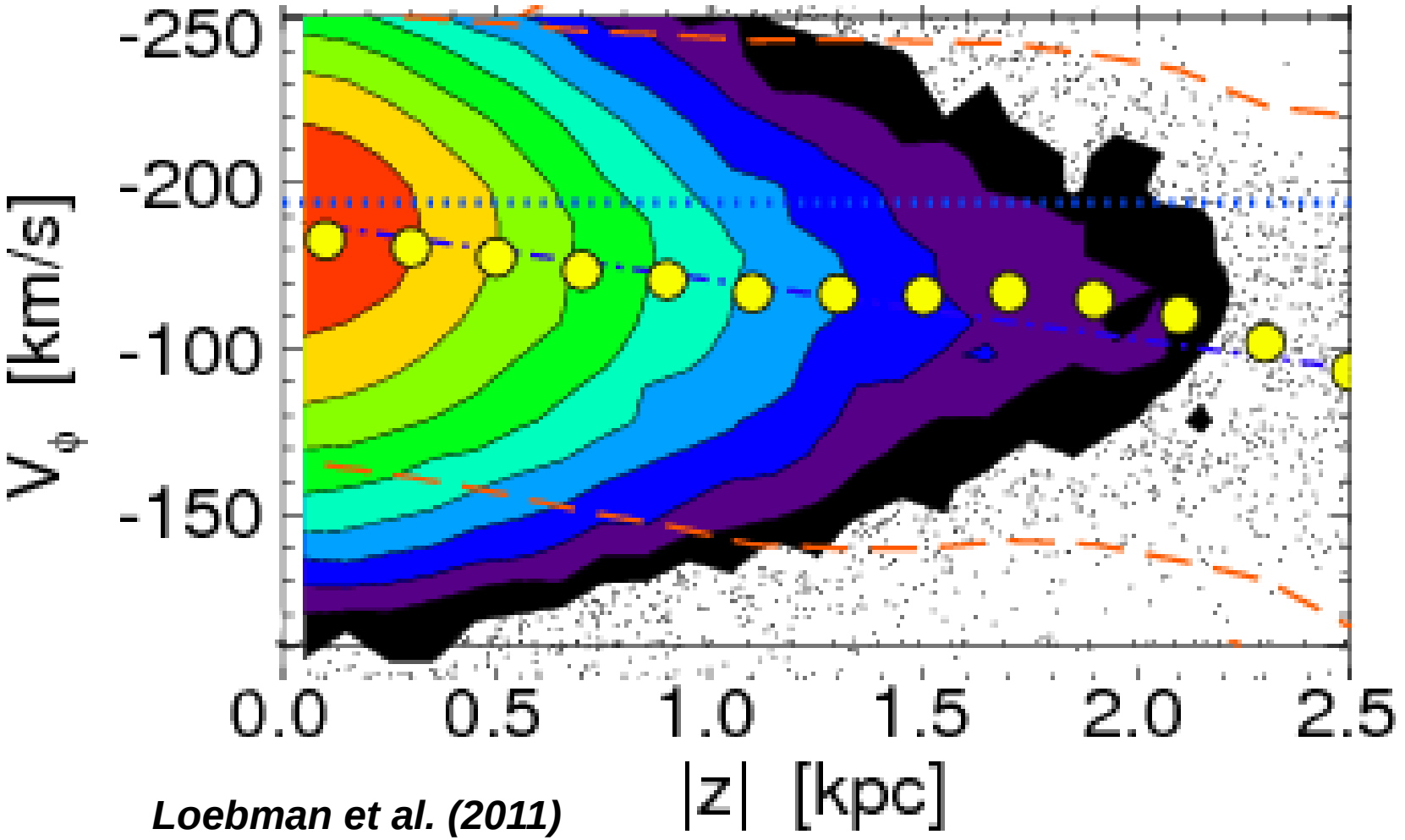
CON	PRO
·No Mergers ·No Substructure ·No Stellar Halo Forms ·No Pre-Enrichment ·Gas Infall Non-cosmological	·Very High Resolution (50 pc) ·~3 Million Particles Total ·Each star ~few x 10^4 Msol ·Gas infall physically motivated ·Cooling gas injects dynamically cool stars into the system ·Stellar Formation/Feedback Comparable to Observations ·Fully Self-Consistent ·Complete Modeling of Dynamics

N-body Simulations with Resolution Sufficient Enough to Detect Radial Migration!

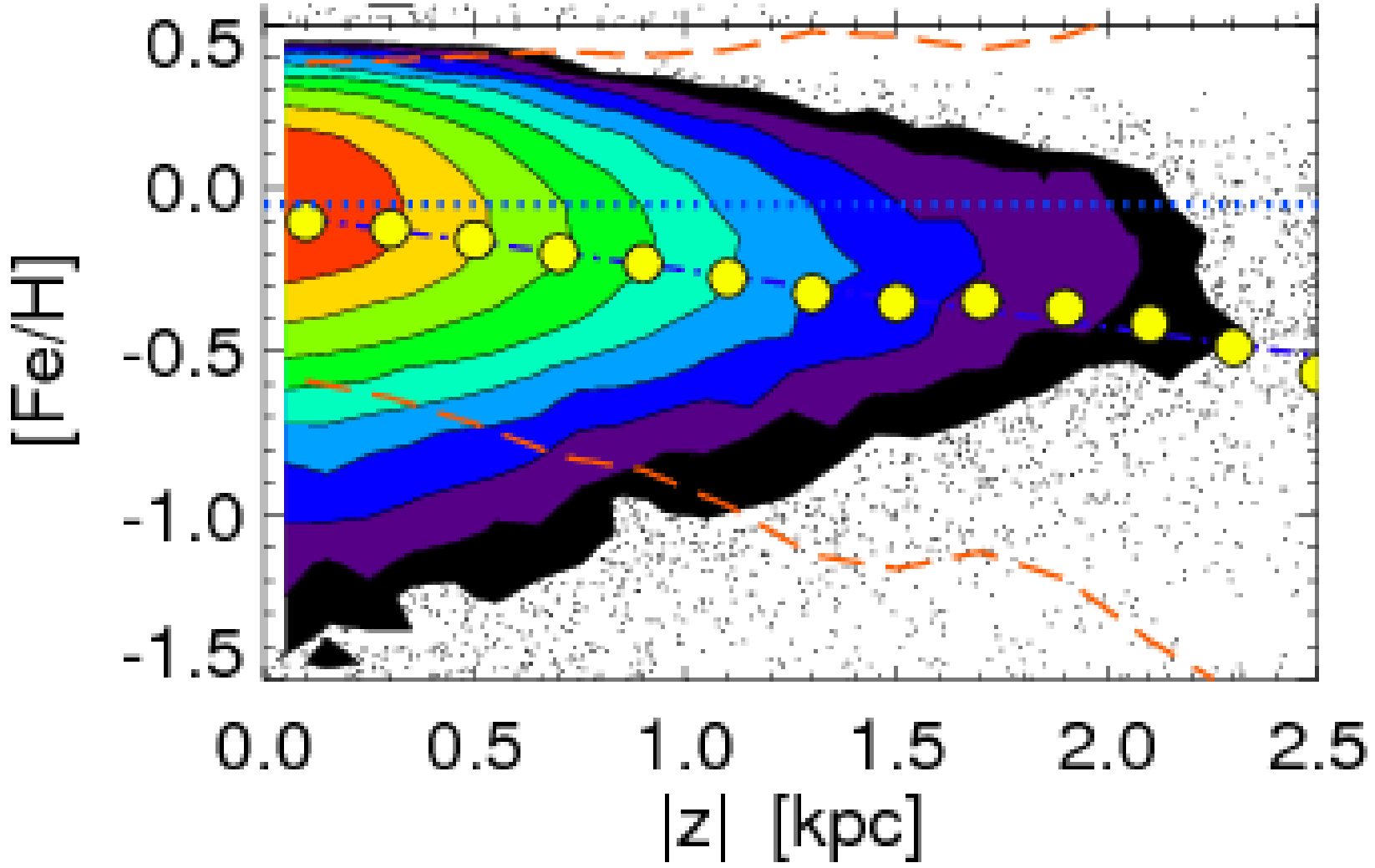


Loebman et al. (2011)

R [kpc]	N1 [$M_\odot/pc^3$]	h1 [pc]	N2 [$M_\odot/pc^3$]	h2 [pc]
2 – 4	0.638	239	1.000	266
4 – 6	0.237	316	0.044	763
7 – 9	0.098	381	0.014	913
9 – 12	0.035	444	0.004	1197



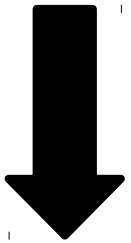
Loebman et al. (2011)



Loebman et al. (2011)

Roškar et al. Simulations: Chemistry

- ***Raiteri et al. (1996)* Oxygen Abundances**
- **SNII Mostly Produce Oxygen (*Hoffman et al. 1999*)**



Oxygen Proxy for α-elements

- **SNIa Iron Abundance derived from binary model (*Greggio & Renzini, 1983*)**
- **Metal Diffusion derived from subgrid model of eddy turbulence (*Smagorinsky 1963*)**

- **Qualitative not Quantitative Comparisons**

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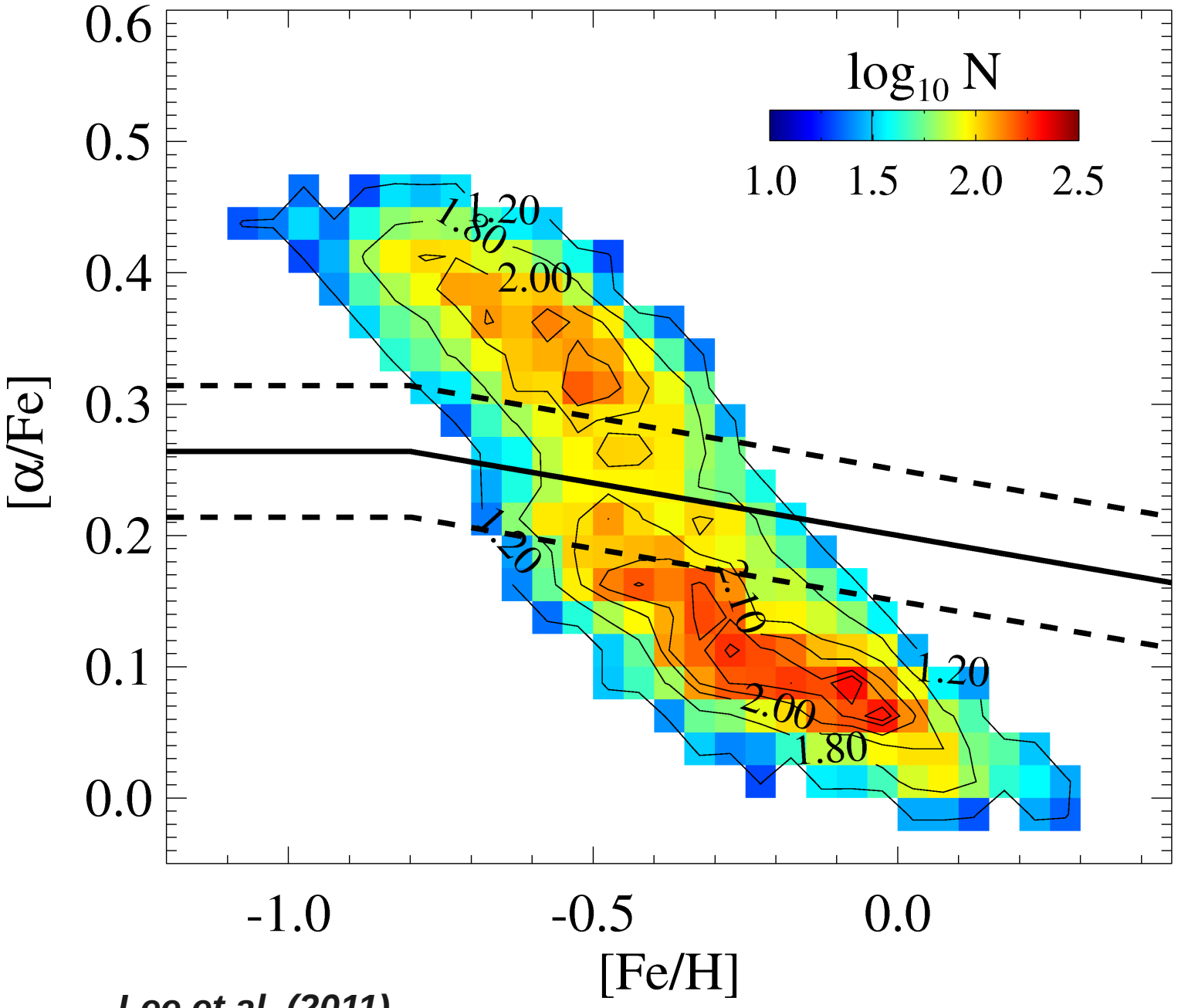
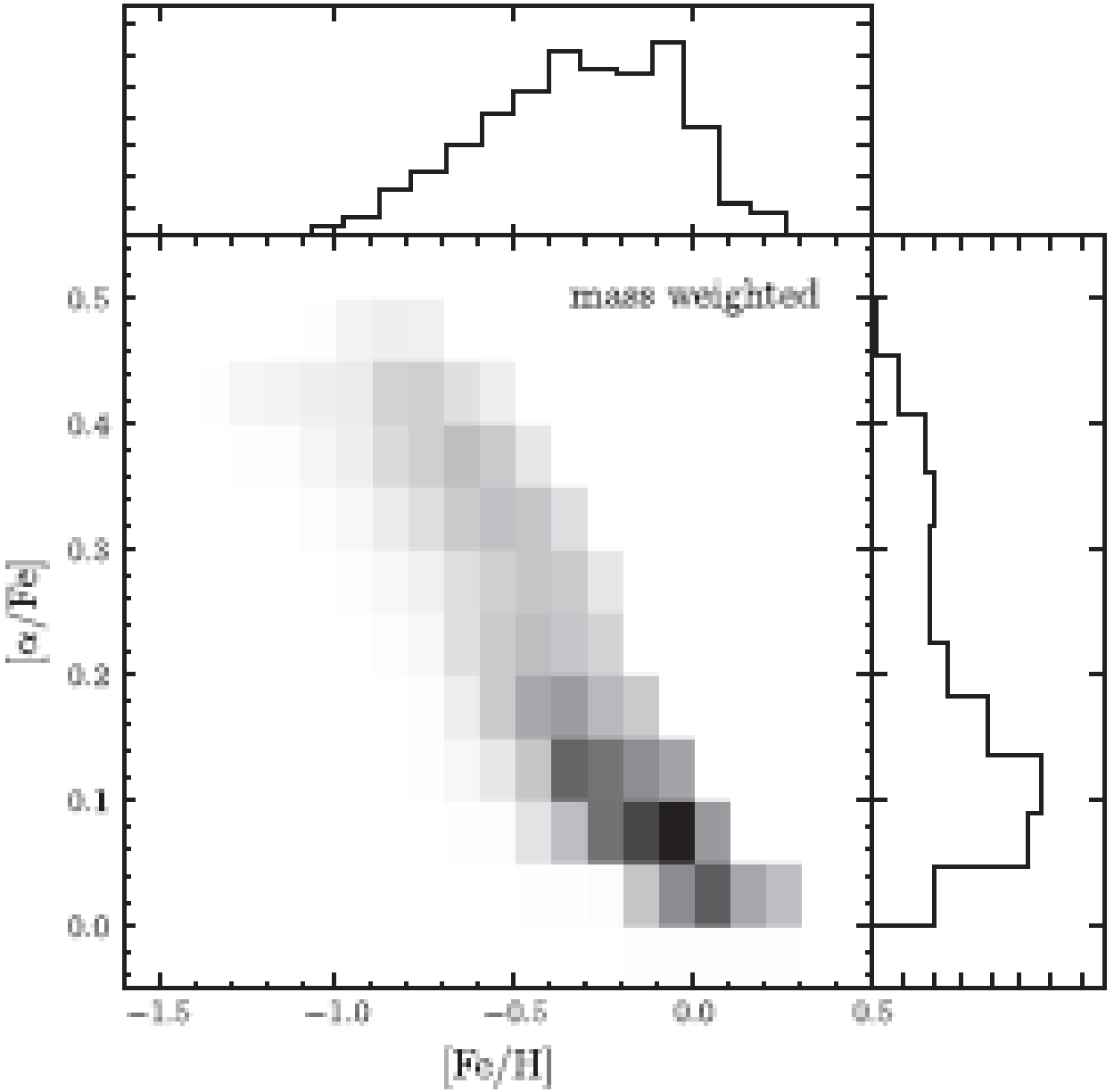
Assign membership based on?

- If distinct populations, position alone not sufficient
- Kinematics & Position influenced by non-formation driven mechanisms
- Chemistry immutable!

Is [α/Fe] better to consider than [Fe/H]?



Lee et al. (2011)



Bovy et al. (2012)

	THIN	THICK
Scale Height	270 pc	1200 pc
<[Fe/H]>	-0.2 dex	-0.7 dex (1.5 kpc)
$\langle V_\Phi \rangle$	-220 km/s	-175 km/s (1.5 kpc)
<[α/Fe]>	0.05 dex	0.3 dex

What Does High [α/Fe] Mean?

- Early vigorous star formation
- How could this have happened?
  - Accretion of satellites (dSph)
  - Rapid insitu formation
  - Inside-out growth & radial migration

In solar cylinder [α/Fe] constrains but doesn't eliminate formation theories

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Predictions of Radial Migration

- Imprint on density distributions

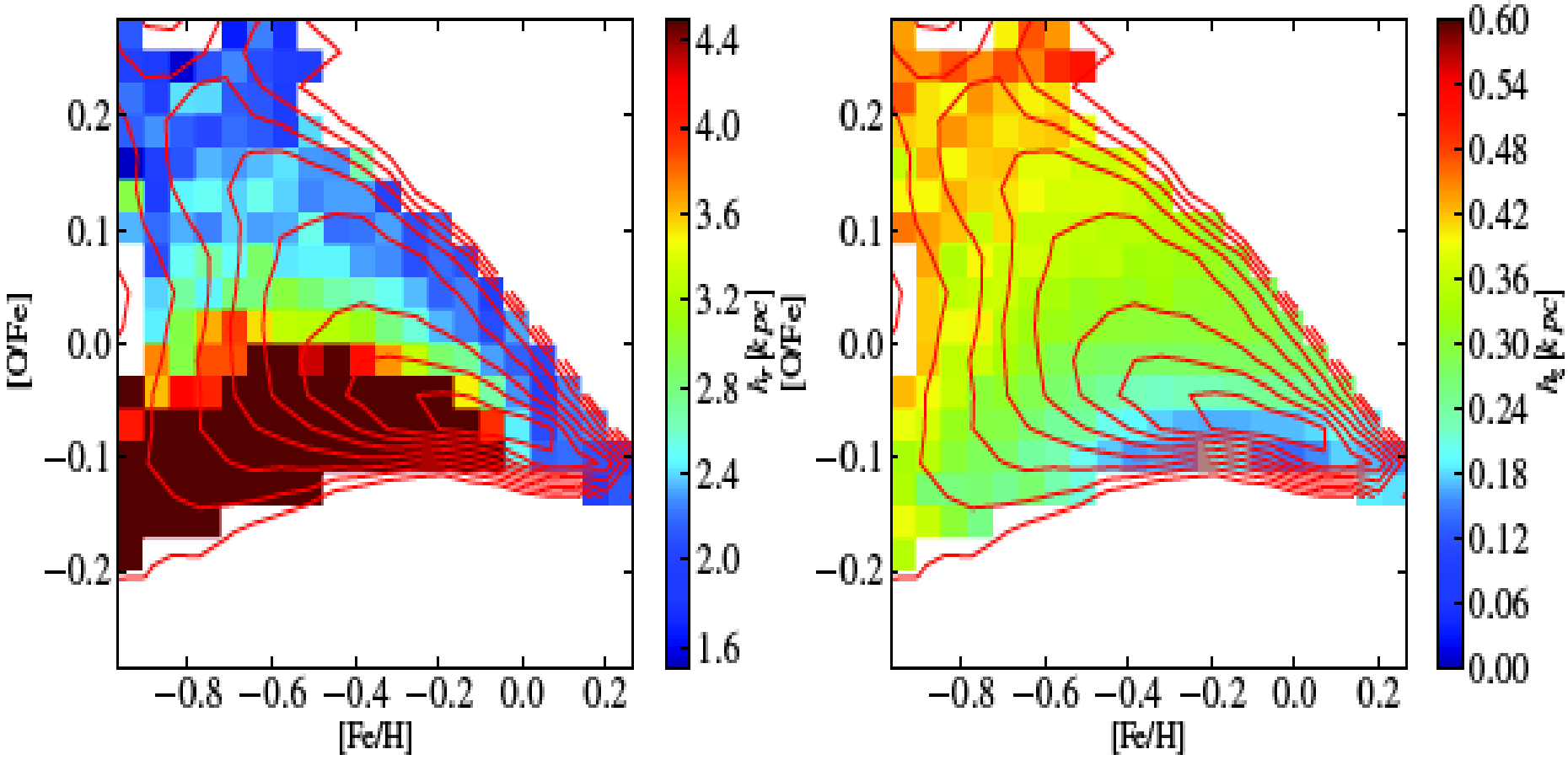
  varying scale height as a function of radius

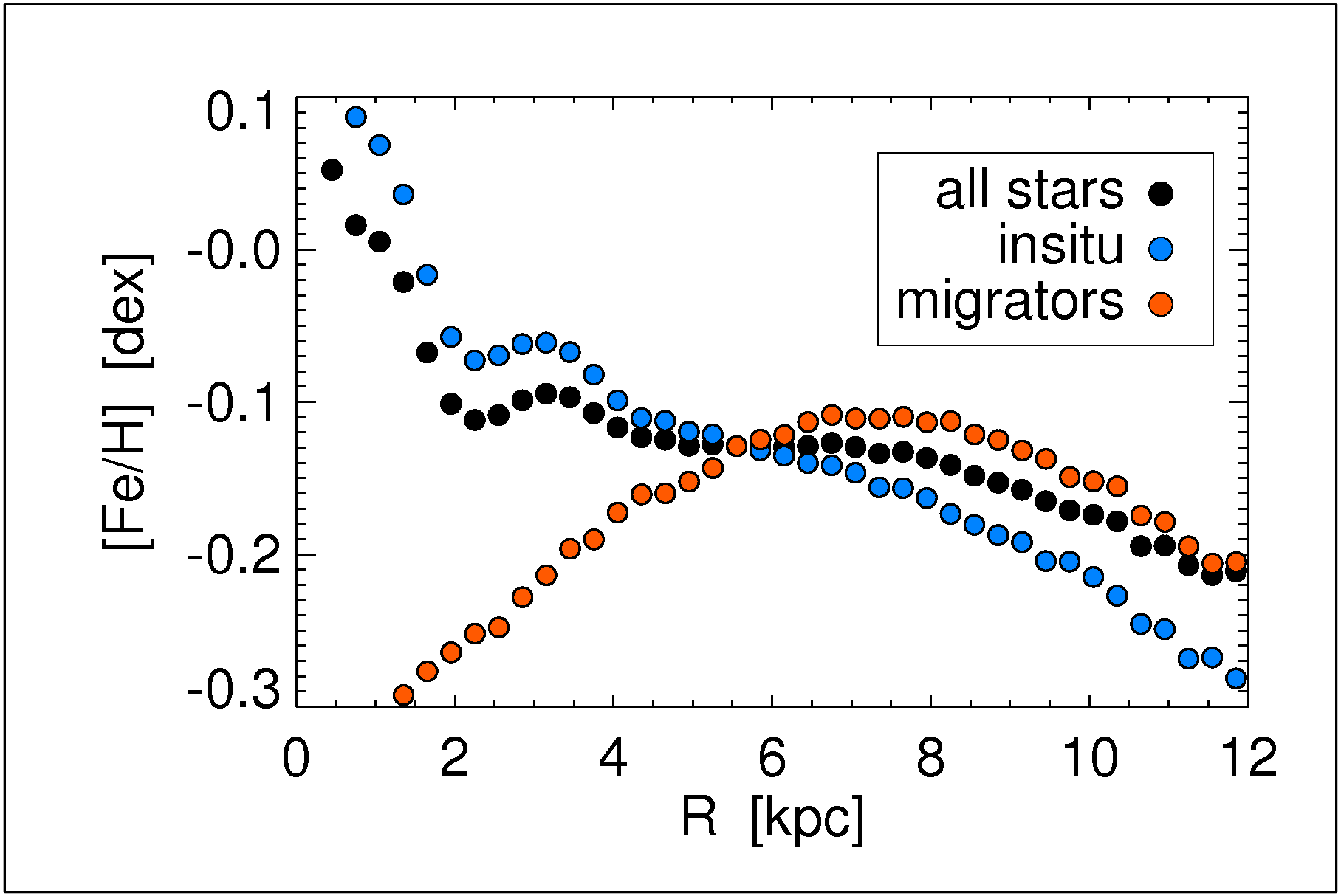
- Imprint on chemistry

  flattening of [Fe/H] vs R gradient

  [α/Fe] similar to interior of disk

Need to Consider Radial Distributions!


[O/Fe]
0.2
0.1
0.0
−0.1
−0.2
−0.8 −0.6 −0.4 −0.2 0.0 0.2
[Fe/H]
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
h_r [kpc]
[O/Fe]
0.2
0.1
0.0
−0.1
−0.2
−0.8 −0.6 −0.4 −0.2 0.0 0.2
[Fe/H]
0.60
0.54
0.48
0.42
0.36
0.30
0.24
0.18
0.12
0.06
0.00
h_z [kpc]


0.1
-0.0
-0.1
-0.2
-0.3
[Fe/H] [dex]
0
2
4
6
8
10
12
R [kpc]
all stars
insitu
migrators

APOGEE

- Density Distribution (~100,000 stars)

  Uniform sample of a single stellar population (red giants)

- Positions (wide range of R)

  spectroscopic parallax (distance) + l,b

- Chemistry (15 species)

  R = 24,000 (order of magnitude greater than SEGUE)

- Velocities

  radial velocities + proper motions (hipparcos, tycho, GAIA)

- Ages

  Kepler astroseismology

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Conclusions & Future Work

- Thick Disk Formation Mechanism Still Unknown
- [α/Fe] Provides New Constraints
- Solar Cylinder Data Not Enough
- APOGEE Data Will Provide Chemistry & Radial Information in next 3-5 Years
- In meantime, Cosmological Simulations Needed to Parameterize Relative Importance of Each Formation Mechansim