Chemodynamical Evolution of the Milky Way like Galaxies in N-body simulations

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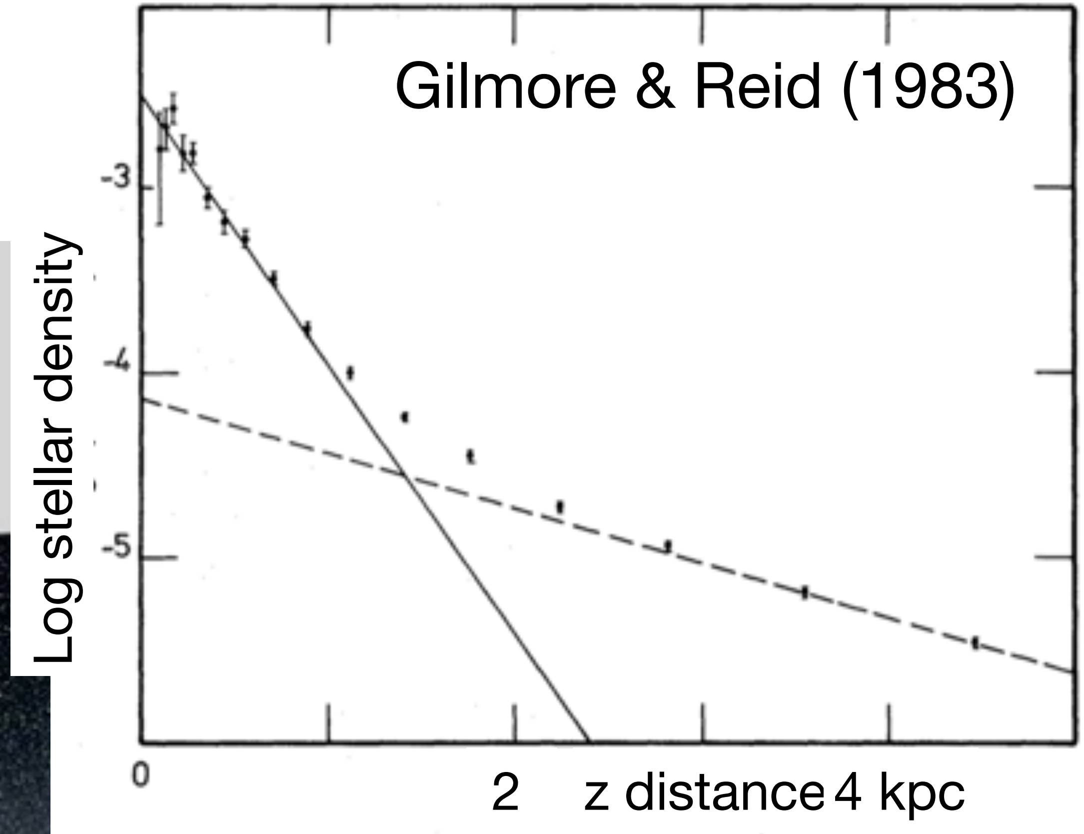
My very biased Big Questions to answer with Gaia and MOS

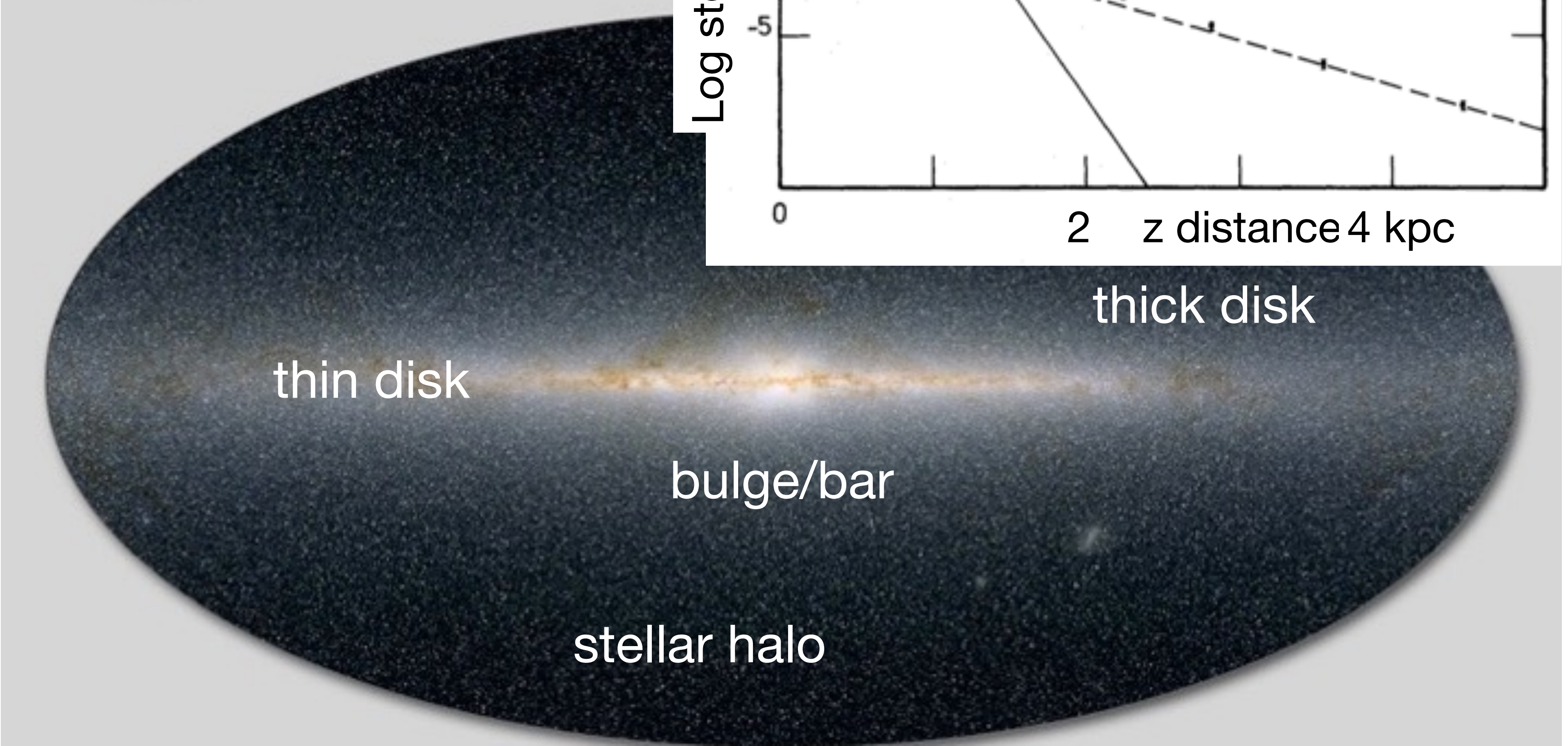
Main topic today!

- How Brook et al. (2004) thick disk scenario fit to the formation of the Milky Way disks?

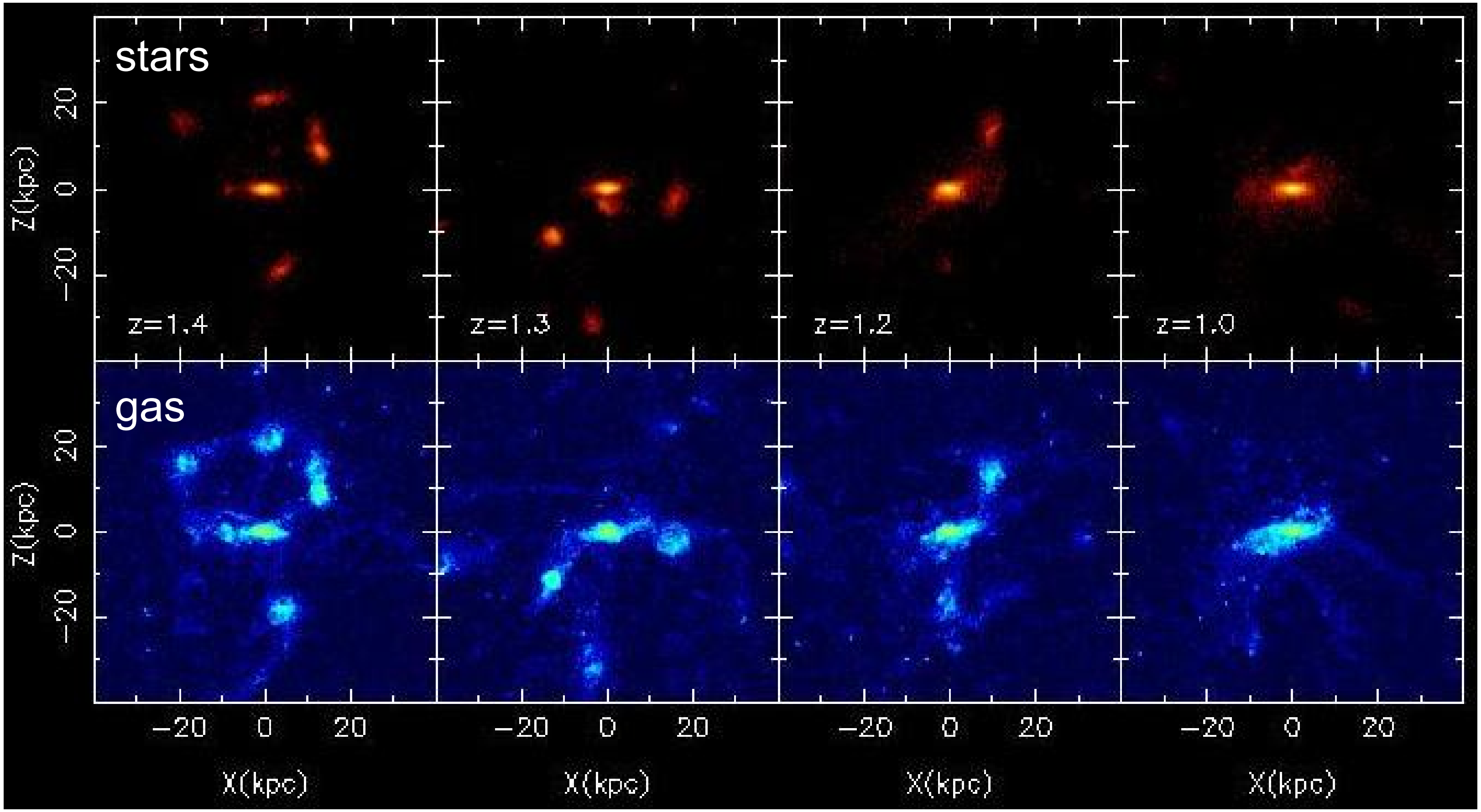
- Spiral arms in the Milky Way are transient/co-rotating like the N-body simulated disk?
  (5 series of papers of **Grand**, Kawata, Cropper, 2012-2015
  Comparison with APOGEE DR10 and VLBI data: Kawata et al. 2014, MNRAS, 443, 2757
  Gaia prediction: **Hunt,** Kawata et al. arXiv:1501.01969, Kawata et al. arXiv:1502.03570)

Thick disk


Gilmore & Reid (1983)
Log stellar density
-3
-4
-5
0
2
z distance
4 kpc

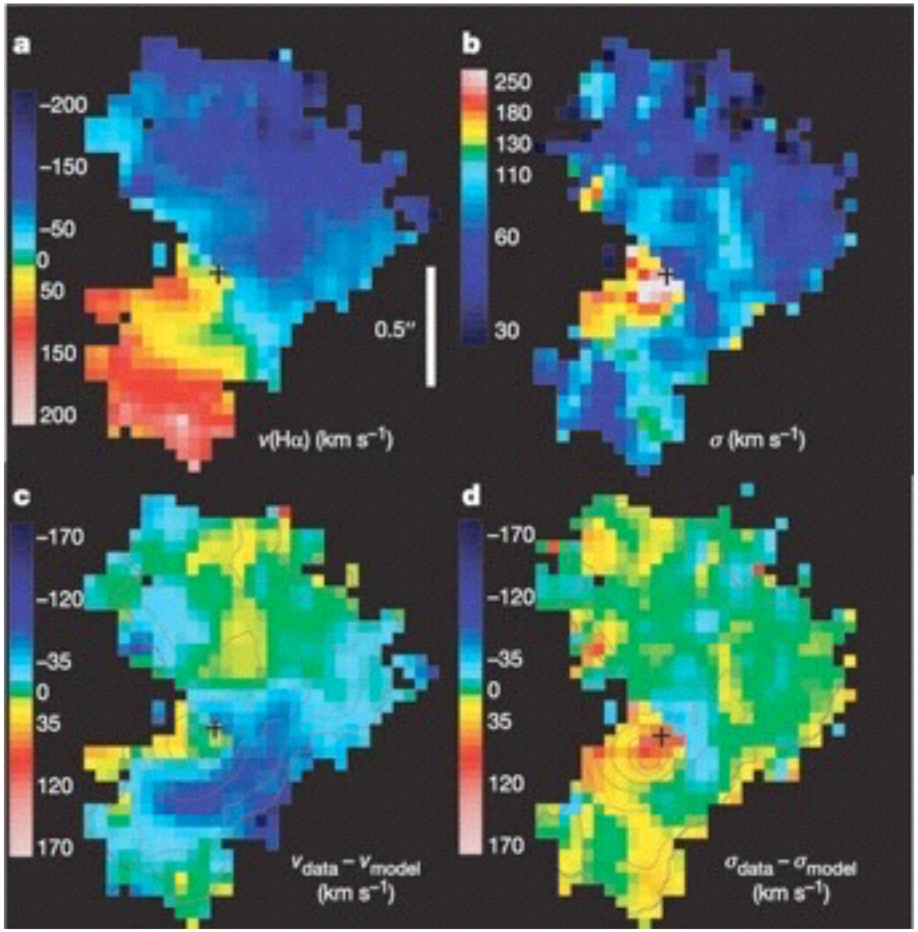

thick disk
thin disk
bulge/bar
stellar halo

In-situ high-z thick disk formation in CDM Universe
(Brook, Kawata, Gibson, Freeman 2004)

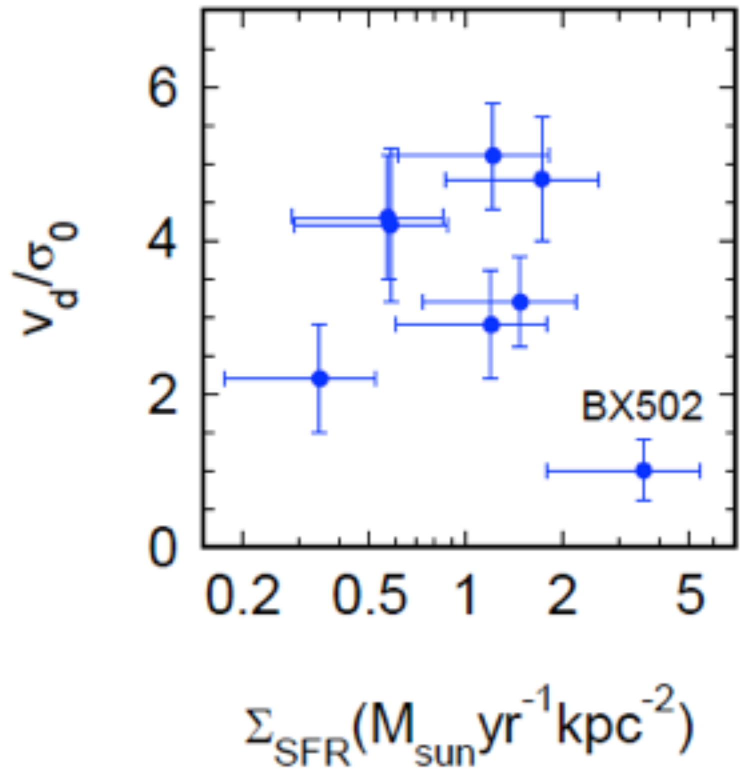


thick disk←kinematically hot gas disk
during multiple gas rich mergers of building blocks at z>1
before the formation of the thin disk.

high-z (z>1) disc are kinematically hot.

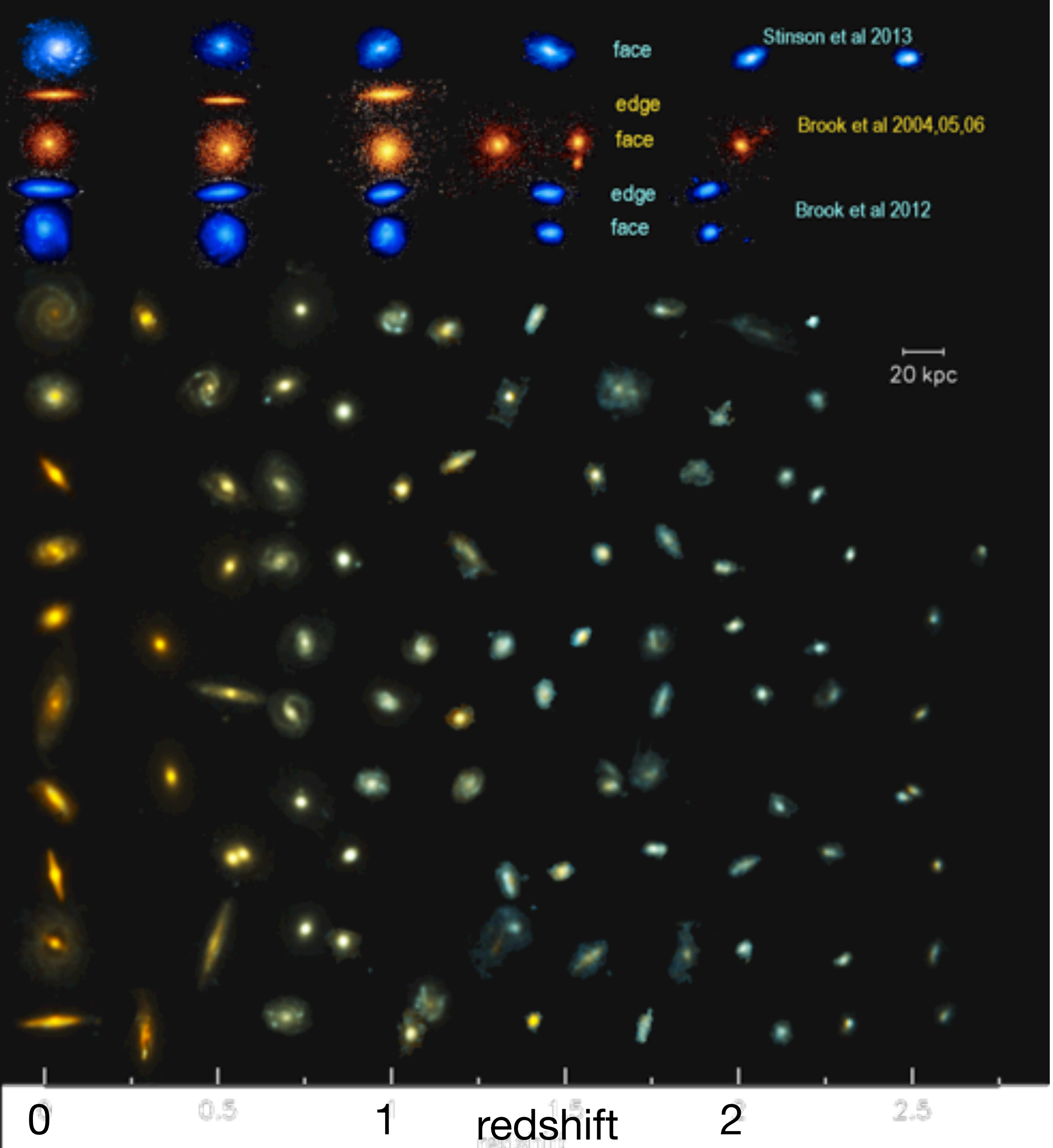


SINS survey with SINFONI/VLT
Genzel et al. (06), Förster-Schreiber et al. (09)



Genzel et al. (08)

local discs v/σ~10-20
(e.g. Dib et al. 06)



Stinson et al. (2013)

Brook et al. (2004,5,6)

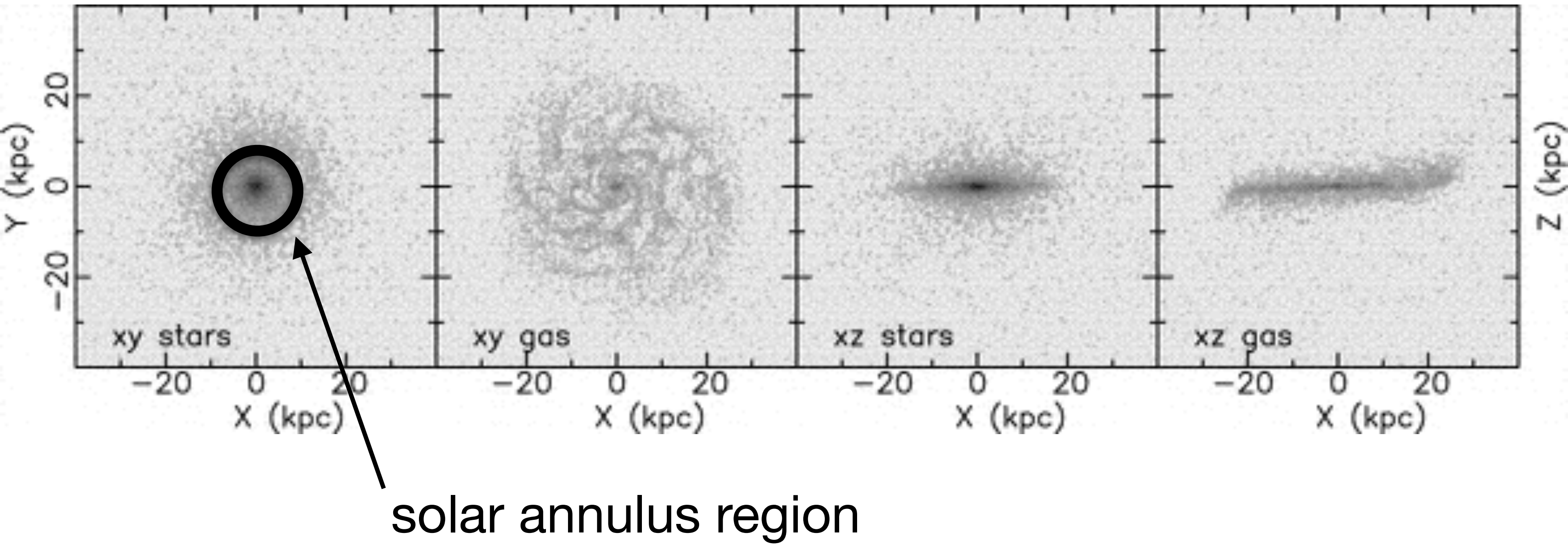
Brook et al. (2013)

Smaller and thicker at high z (Brook et al. 2006)

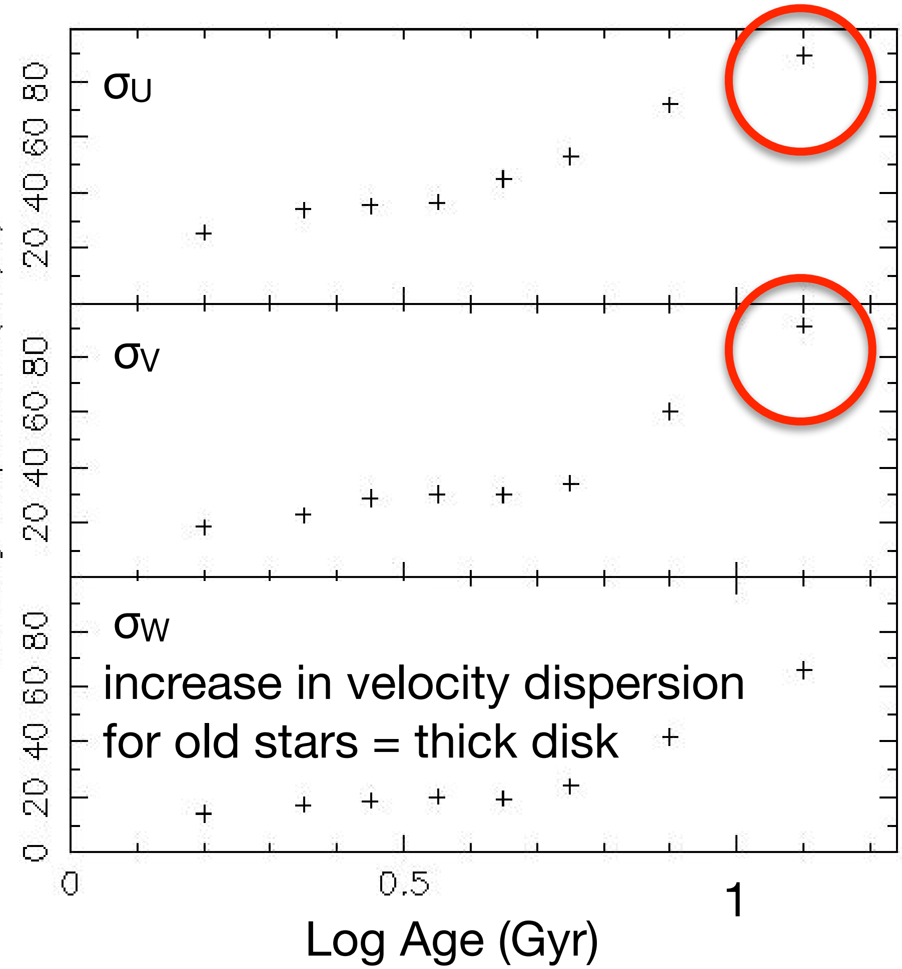
Observations:
van Dokkum et al. (2013)
Milky Way progenitors

Not far from our sims in 10 years ago!

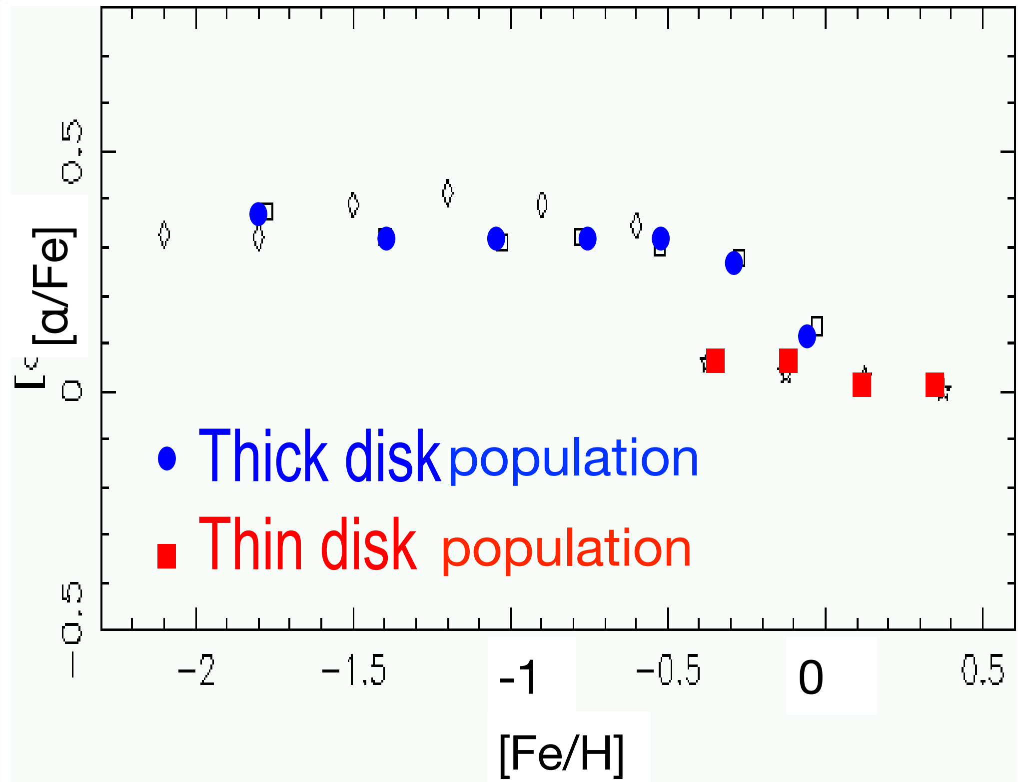
In-situ high-z thick disk formation
(Brook, Kawata, Gibson, Freeman 2004)
snapshot at z=0



Properties of solar-neighbour stars in the Brook et al. simulations (2004-6)

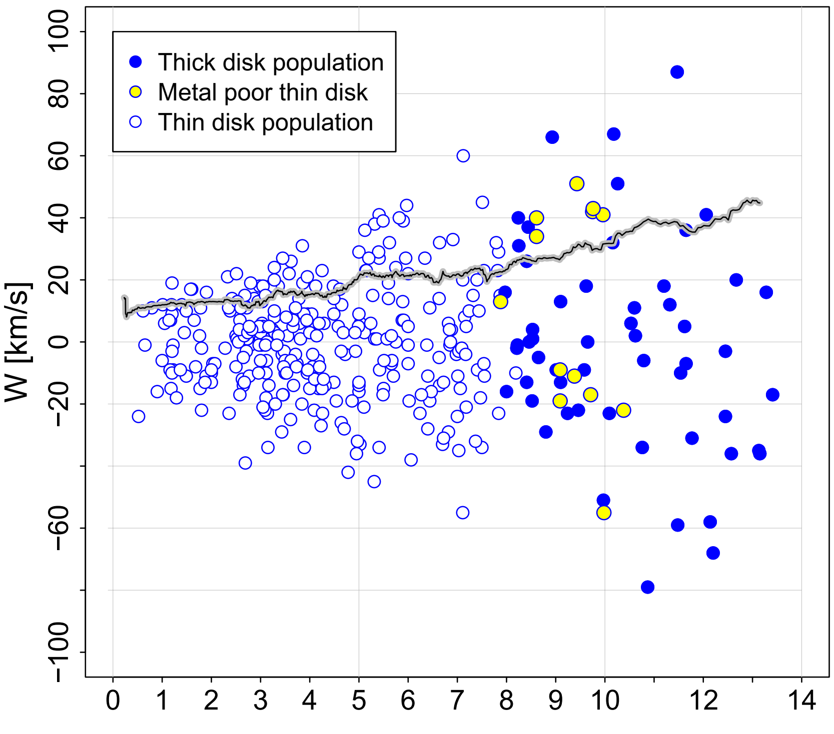


Brook et al. (2004)

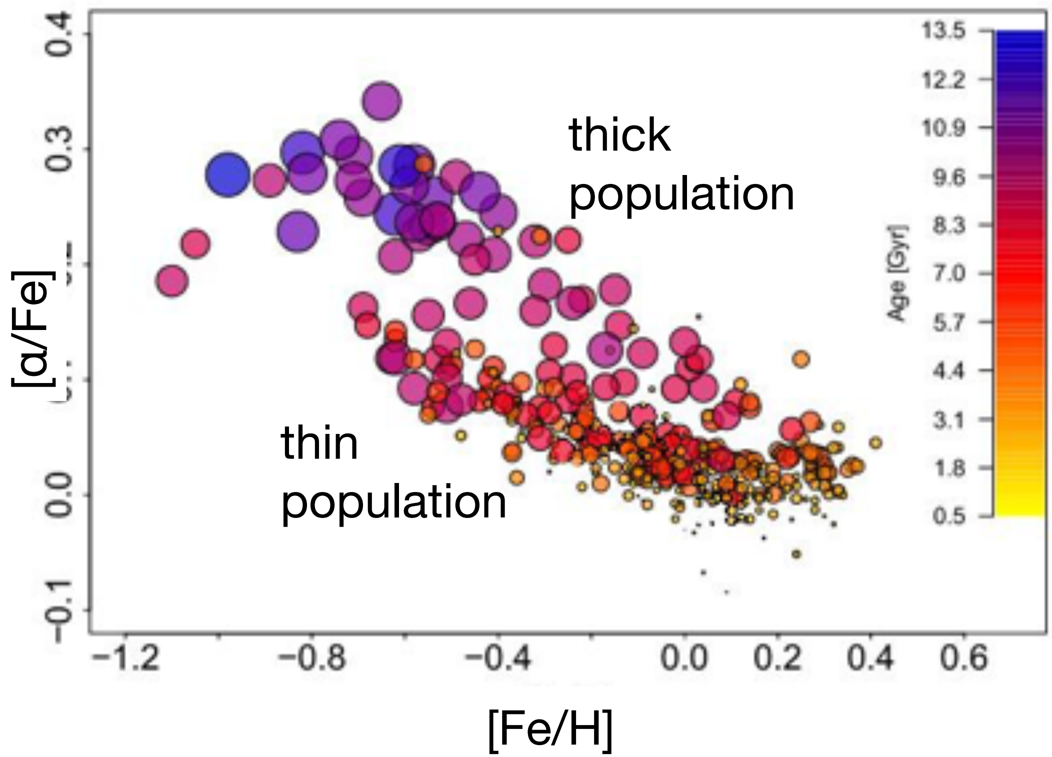


Brook et al. (2005)

Properties of solar-neighbour stars in observation (e.g. Haywood et al. 2013) consistent with Brook et al. (2004) scenario!



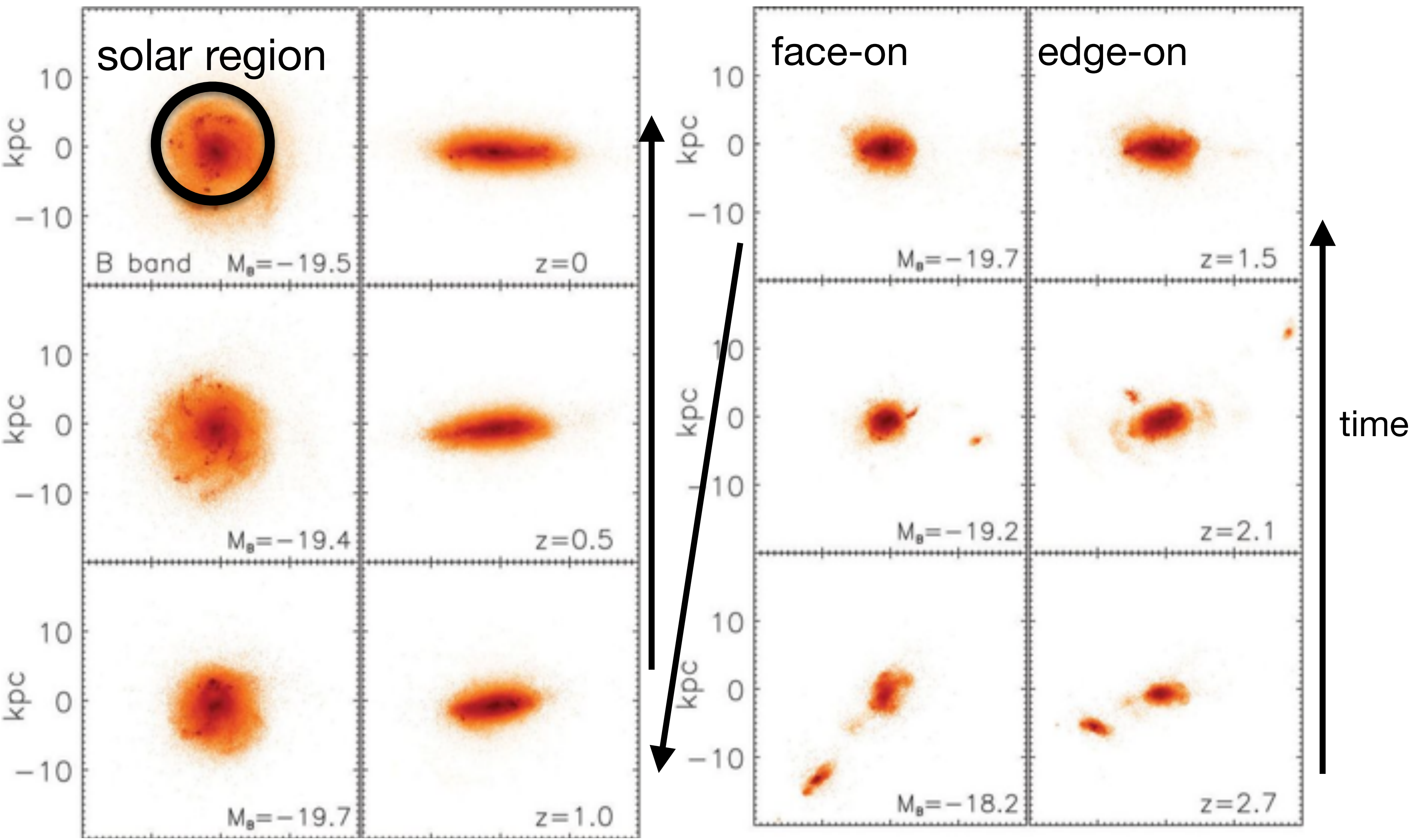
increase in velocity dispersion for old stars = thick disk



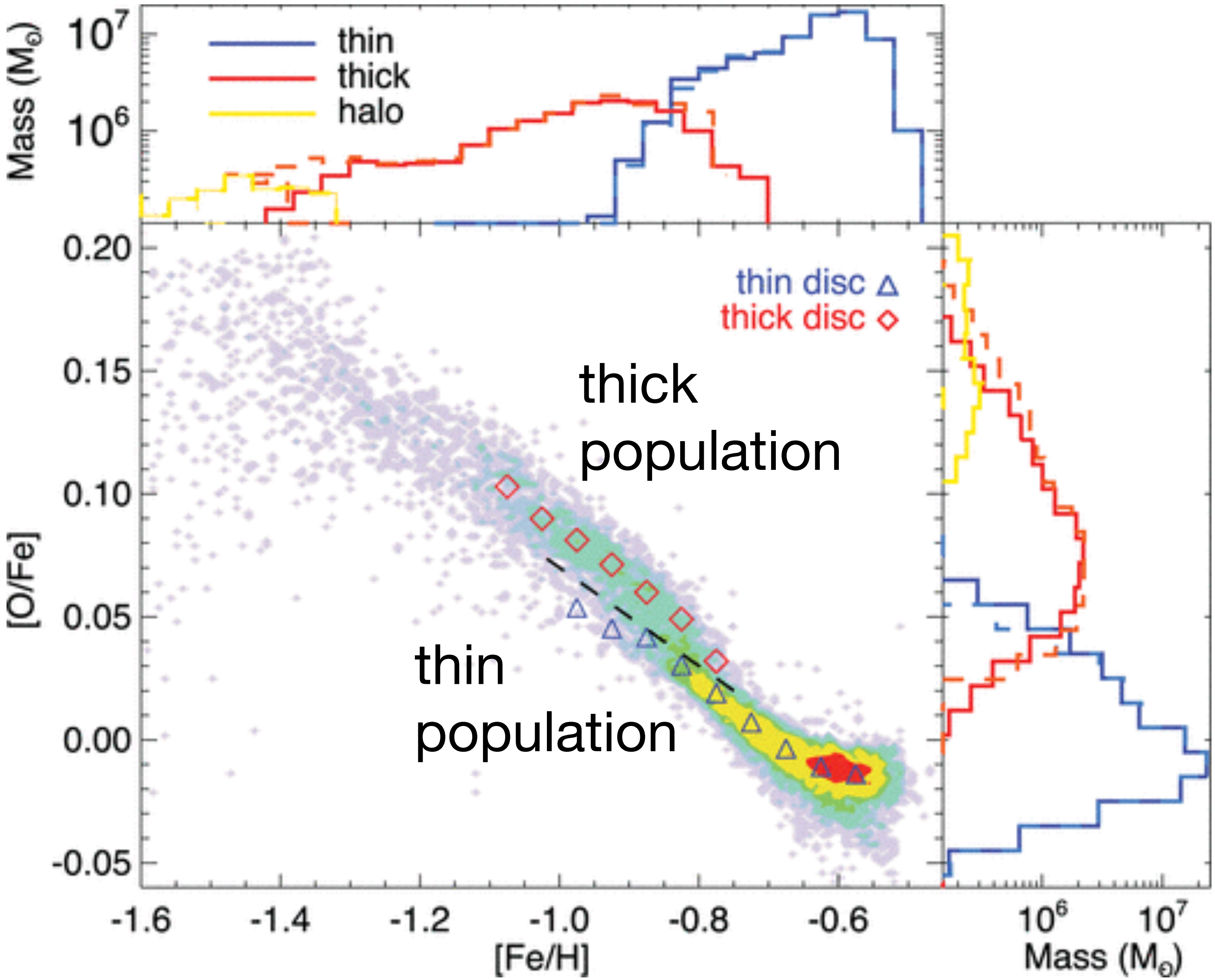
see also Adibekyan et al. (2012), Bensby et al. (2014), Recio-Blanco et al. (2014), Anders et al. (2014)

Brook, Stinson, Gibson, Kawata et al. (2012)
in-situ high-z thick disk + radial migration

followed by Stinson et al. (2013), Bird et al. (2013), Minchev et al. (2014)

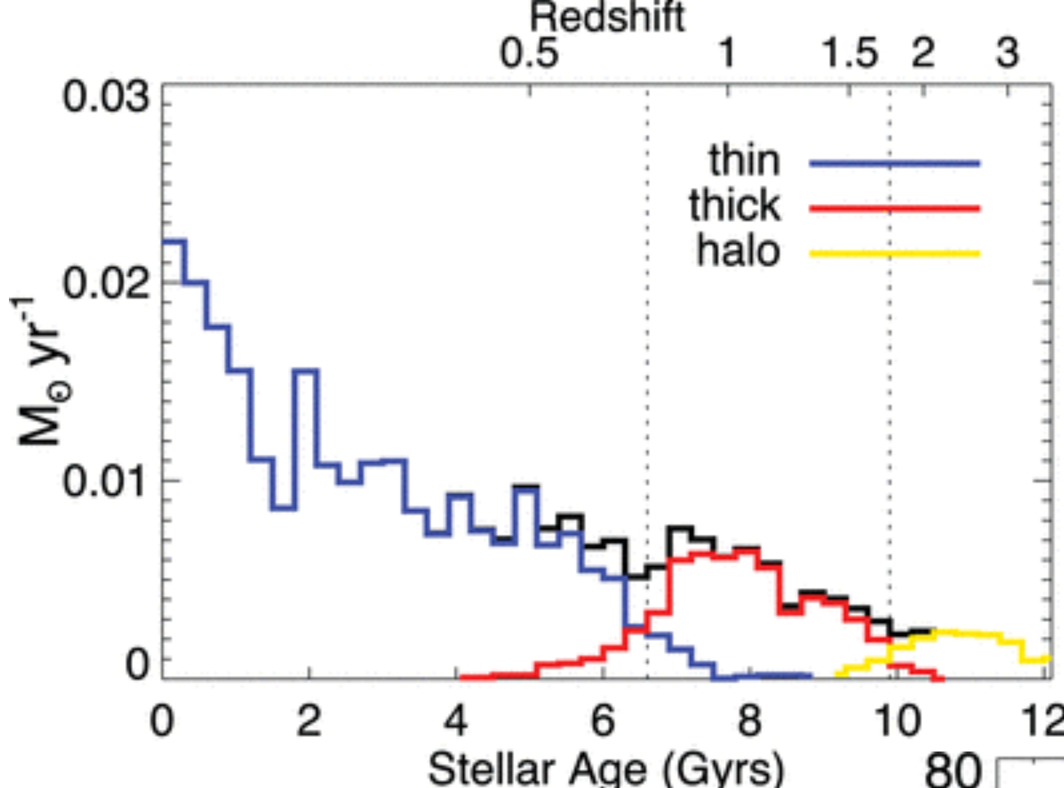


Chemically defining thick and thin populations for solar annulus stars

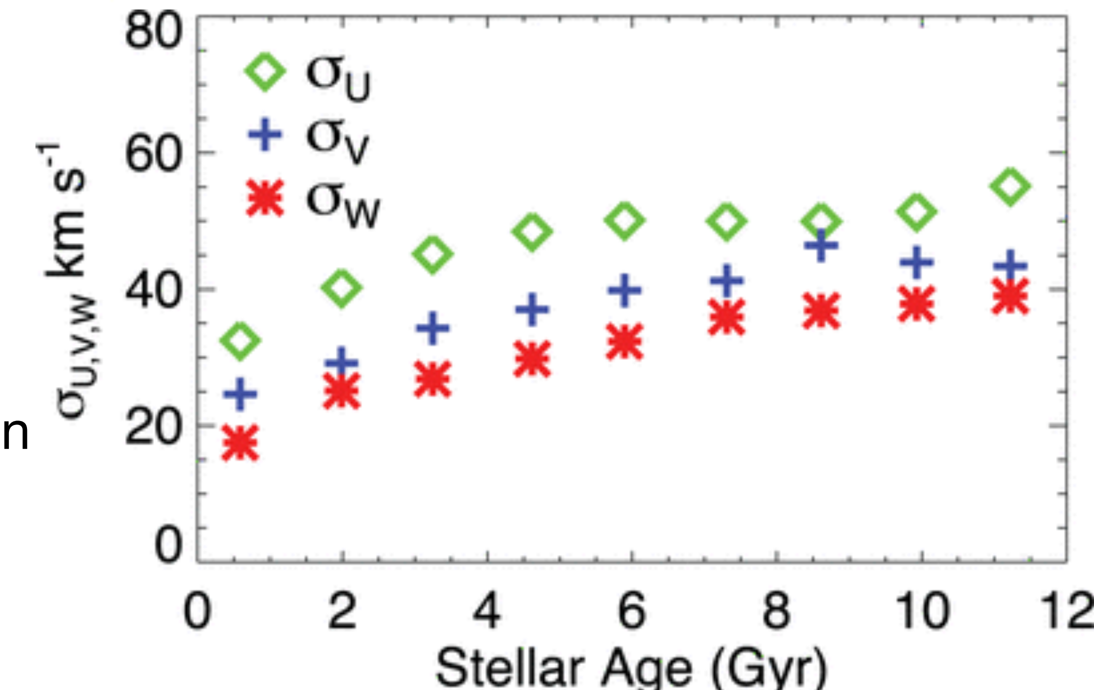


small simulated galaxy
[Fe/H] should scale up for the Milky Way

Brook et al. (2012)



Old thick populations

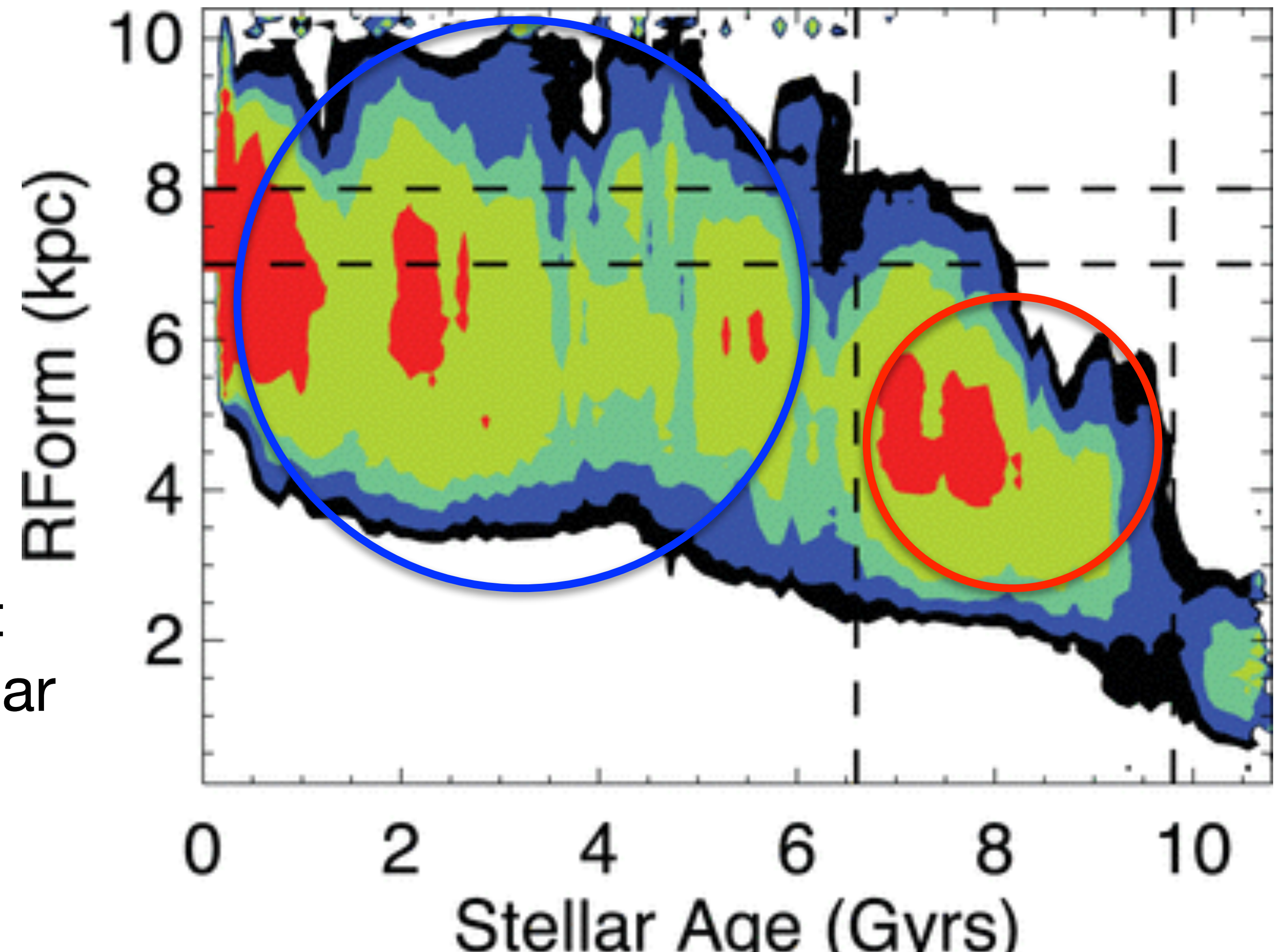


Old thick populations
higher velocity dispersion

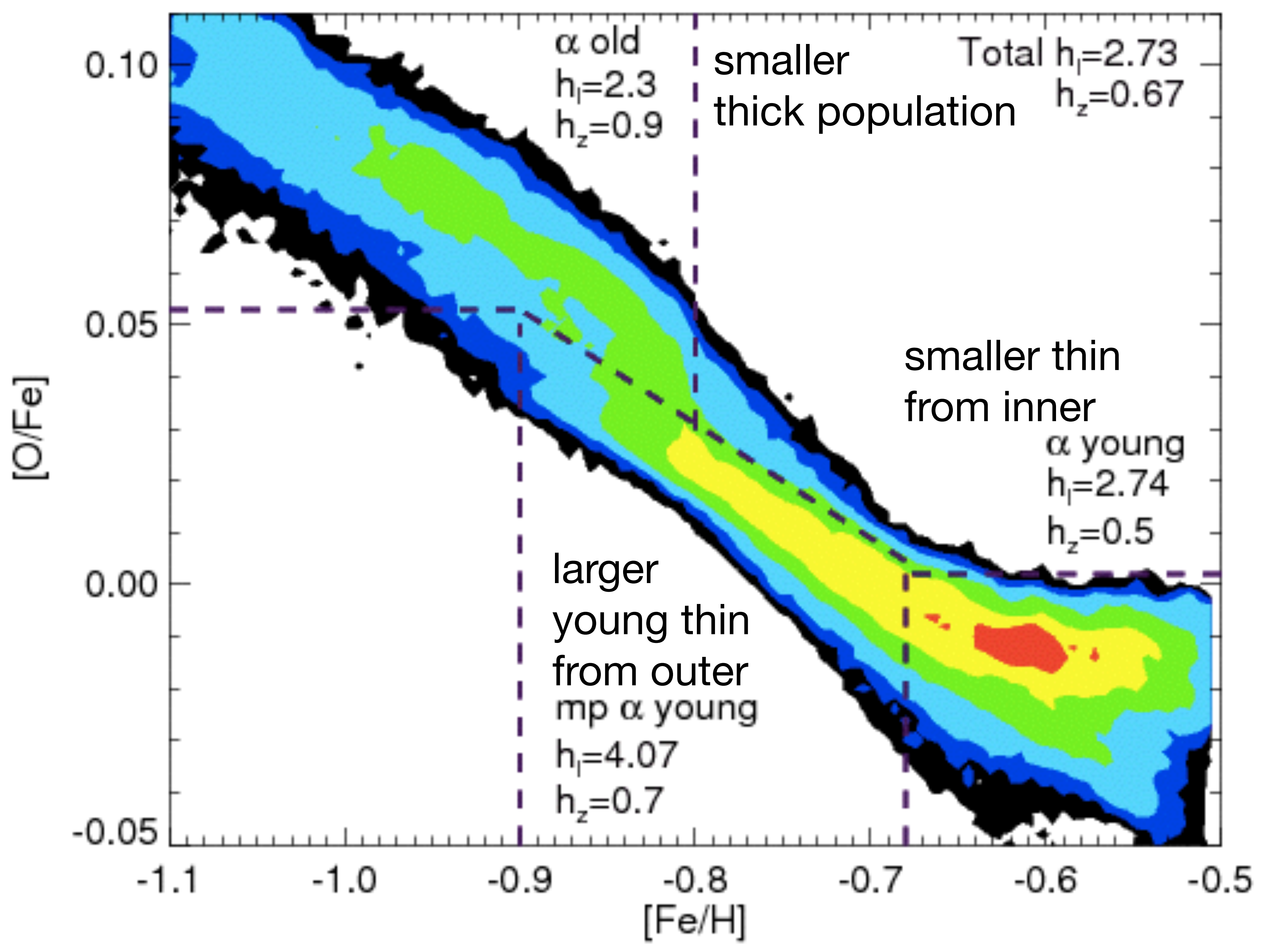
Brook et al. (2012)

Disk scale length of thick population
was 1.7 kpc at z=1, but 2.3 kpc at z=0
radial migration!

stars at
R~Rsolar
at z=0.

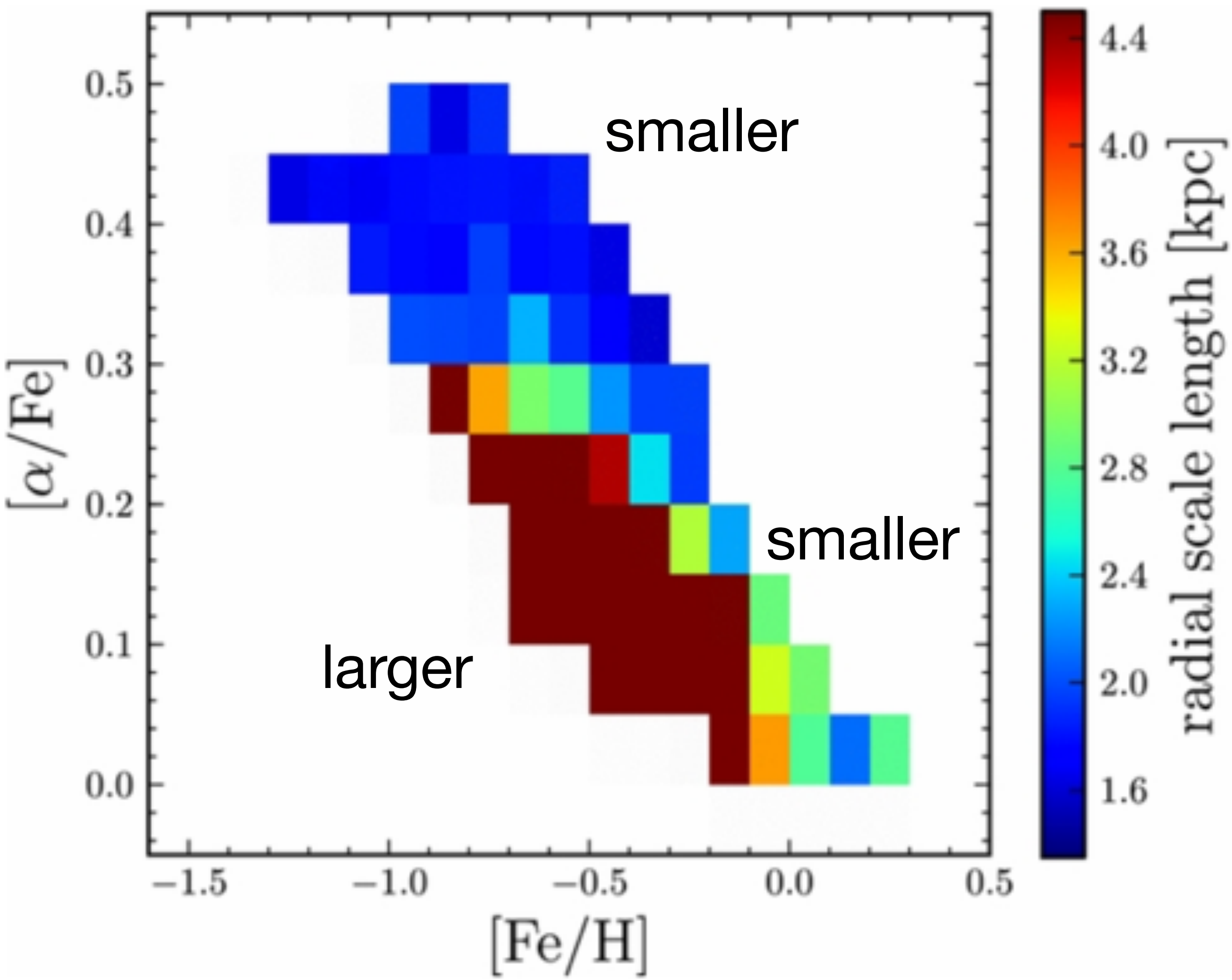


Old thick disk radially migrated from inner region.
Younger stars come from a large range of radii.



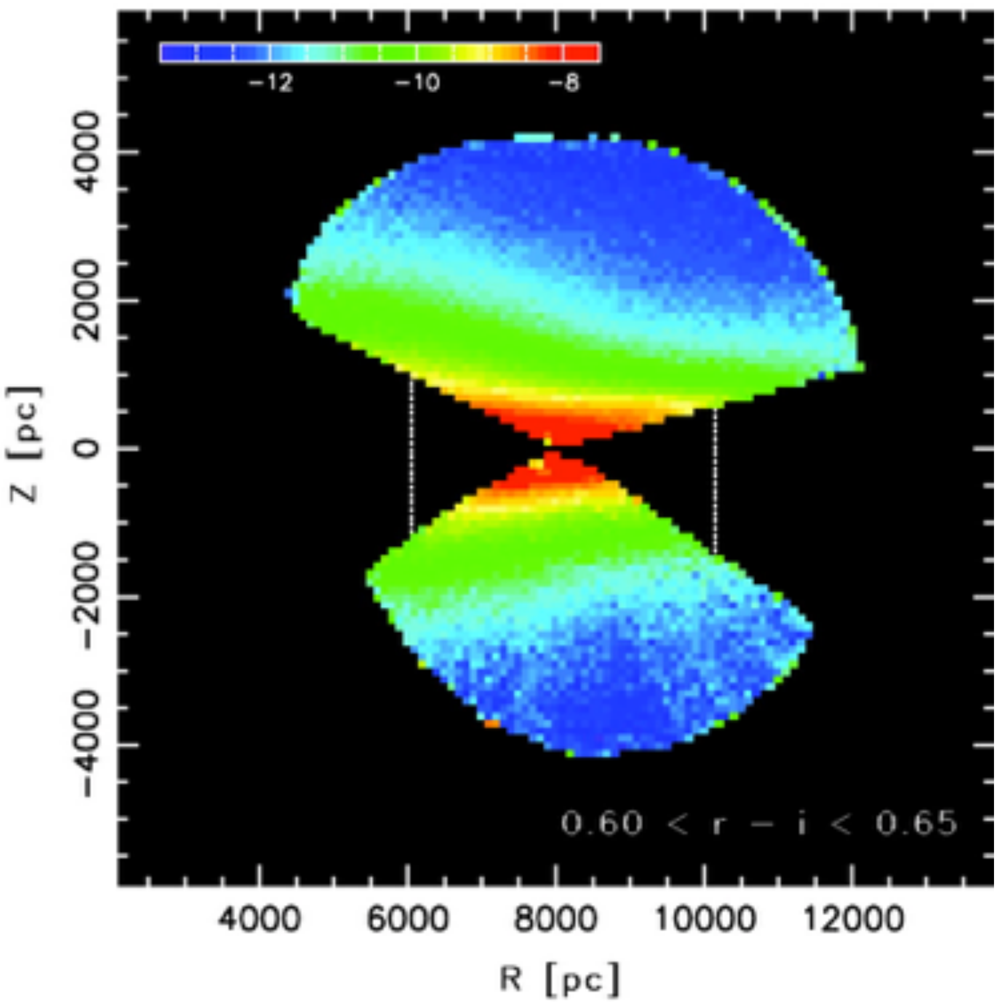
α old
h_l=2.3
h_z=0.9
smaller
thick population
Total h_l=2.73
h_z=0.67
smaller thin
from inner
α young
h_l=2.74
h_z=0.5
larger
young thin
from outer
mp α young
h_l=4.07
h_z=0.7
[O/Fe]
[Fe/H]
0.10
0.05
0.00
-0.05
-1.1
-1.0
-0.9
-0.8
-0.7
-0.6
-0.5

e.g. Bovy et al. (2012): SDSS SEGUE



Smaller thick disk population than thin disk

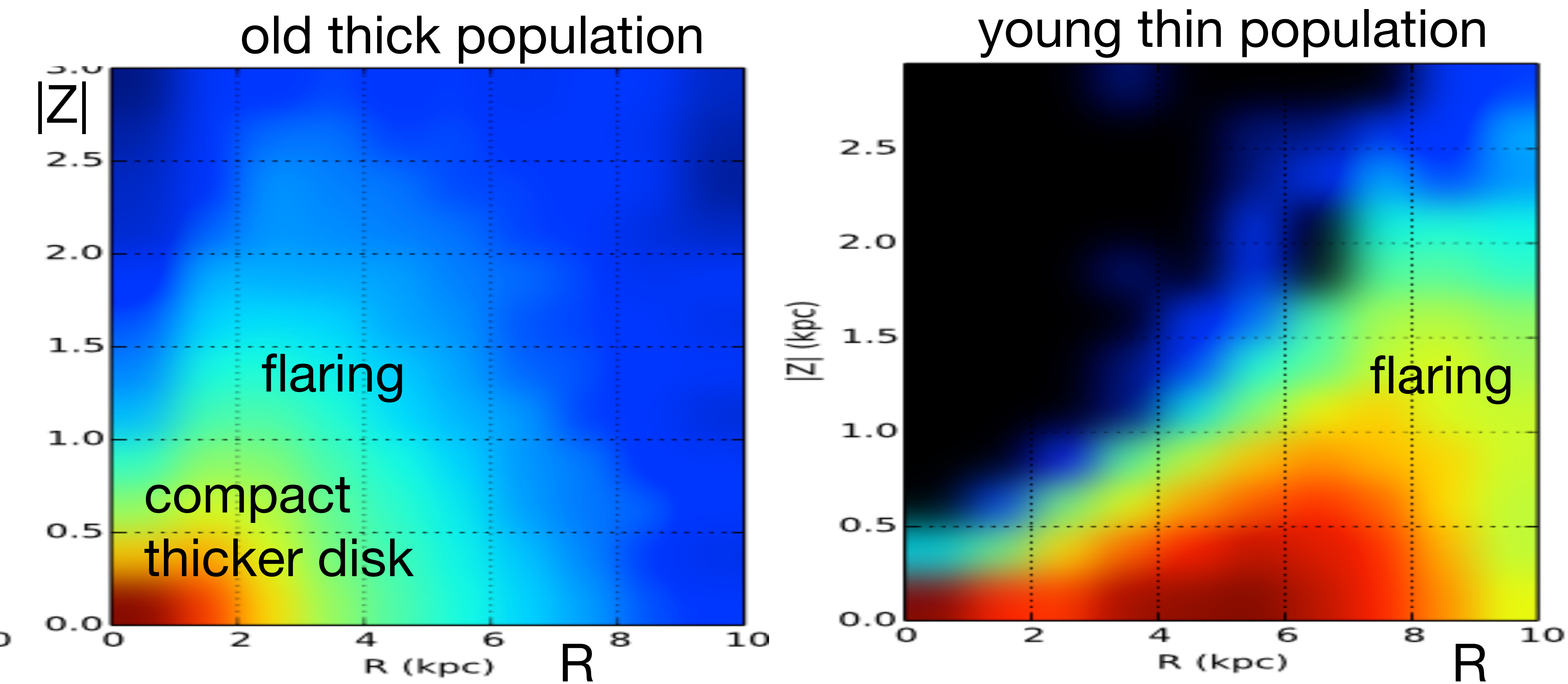
“Geometric” thick disk bigger than thin disk?
(Juric et al. 2008, SDSS Milky Way Tomography)



	Scale Length	Scale hight
thick	3.6 kpc	0.9 kpc
thin	2.6 kpc	0.3 kpc

Focus on geometric structure of all the population.
Not considering chemical properties.

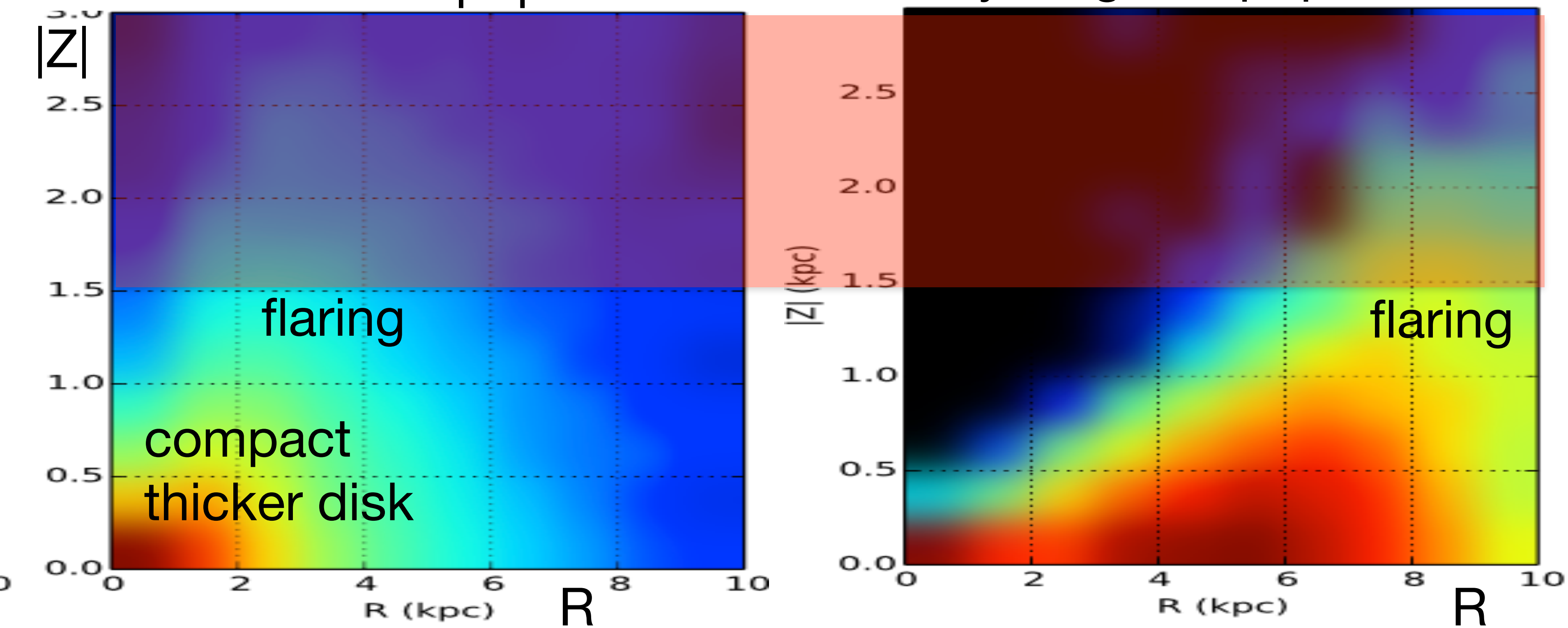
Flaring small thick + thin populations at the outer radius
= large geometric thick disk



Numerical simulation in Rahimi, Carrell, Kawata (2014) explained **positive d[Fe/H]/dR** and **negative d[α/Fe]/dR** at high |z|
(see also Bensby et al. 2011)

Flaring small thick + thin populations at the outer radius
= large geometric thick disk

old thick population young thin population



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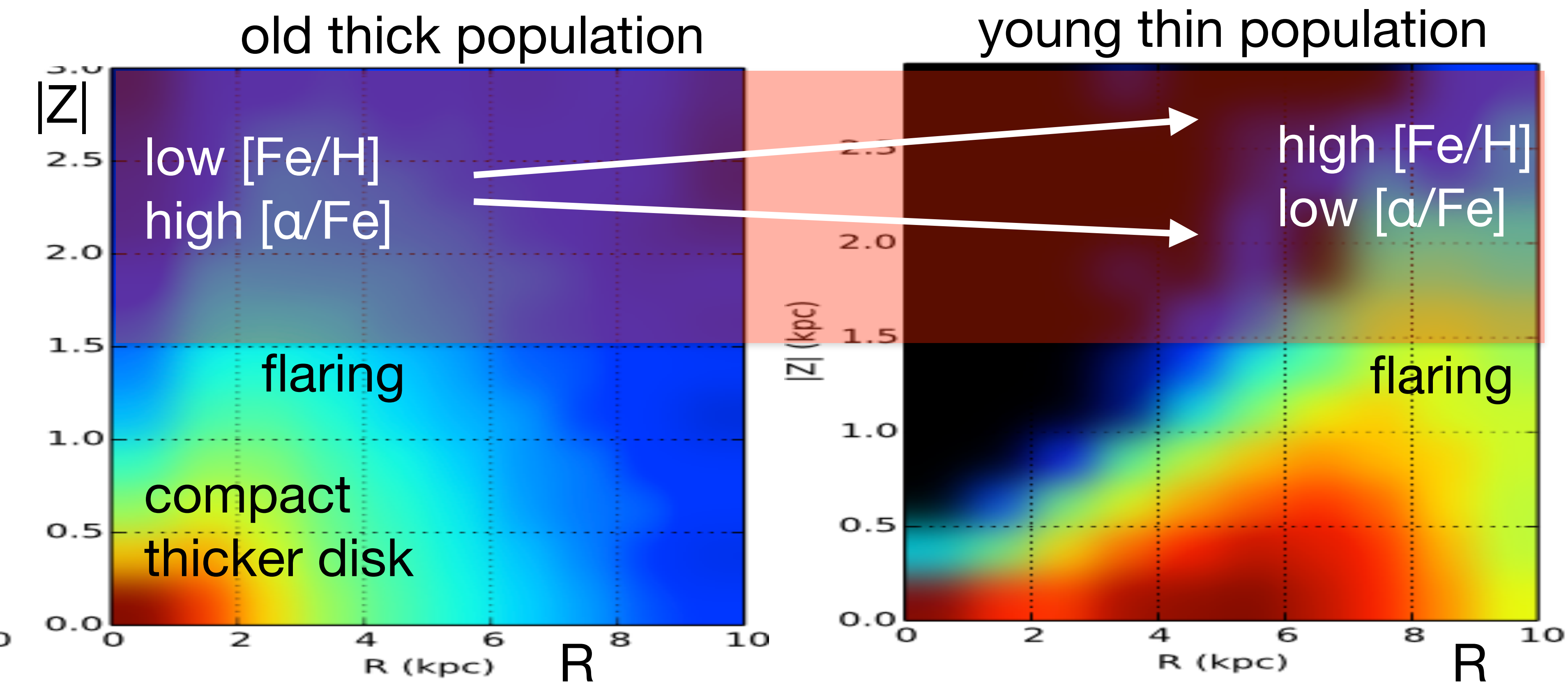

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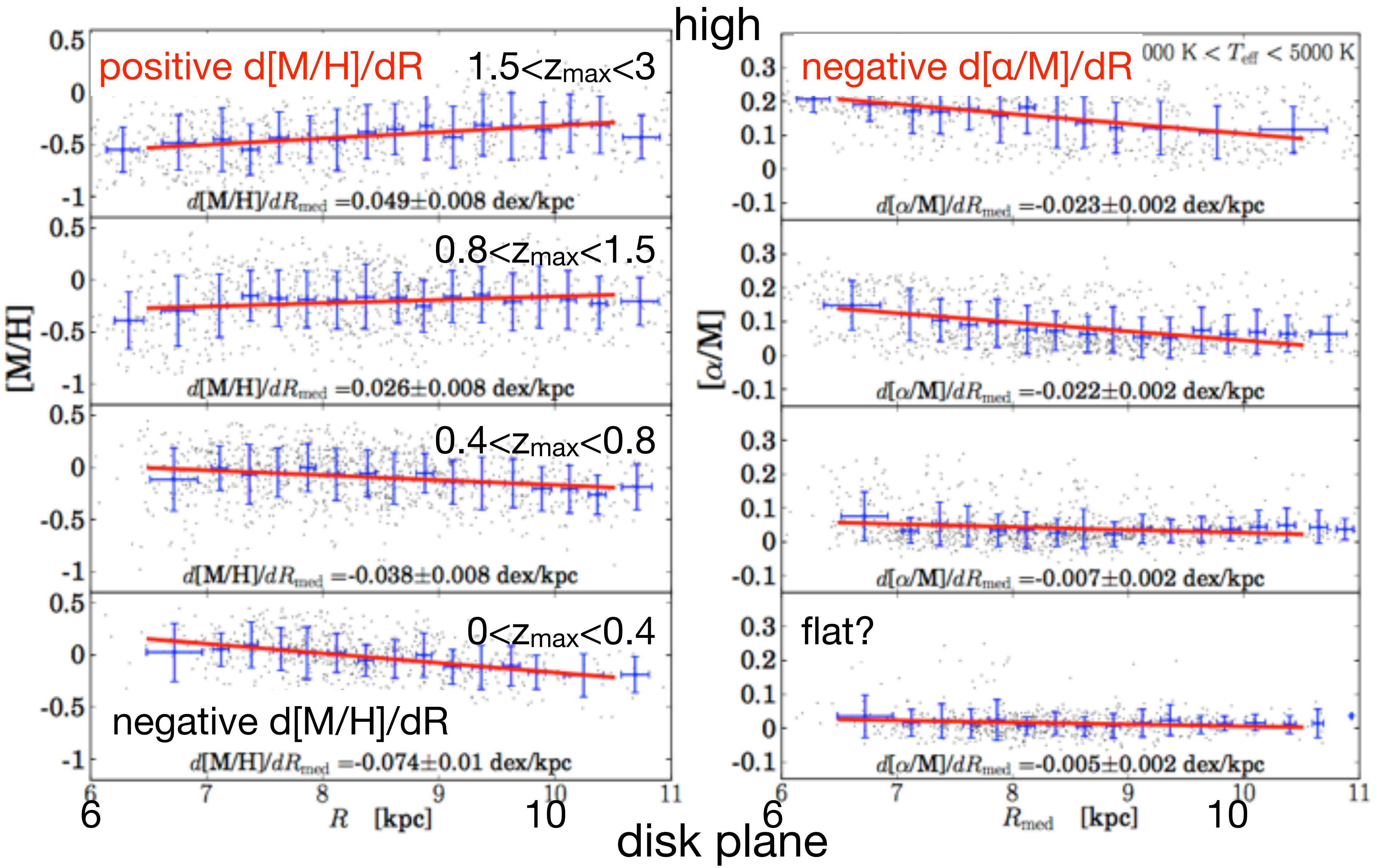
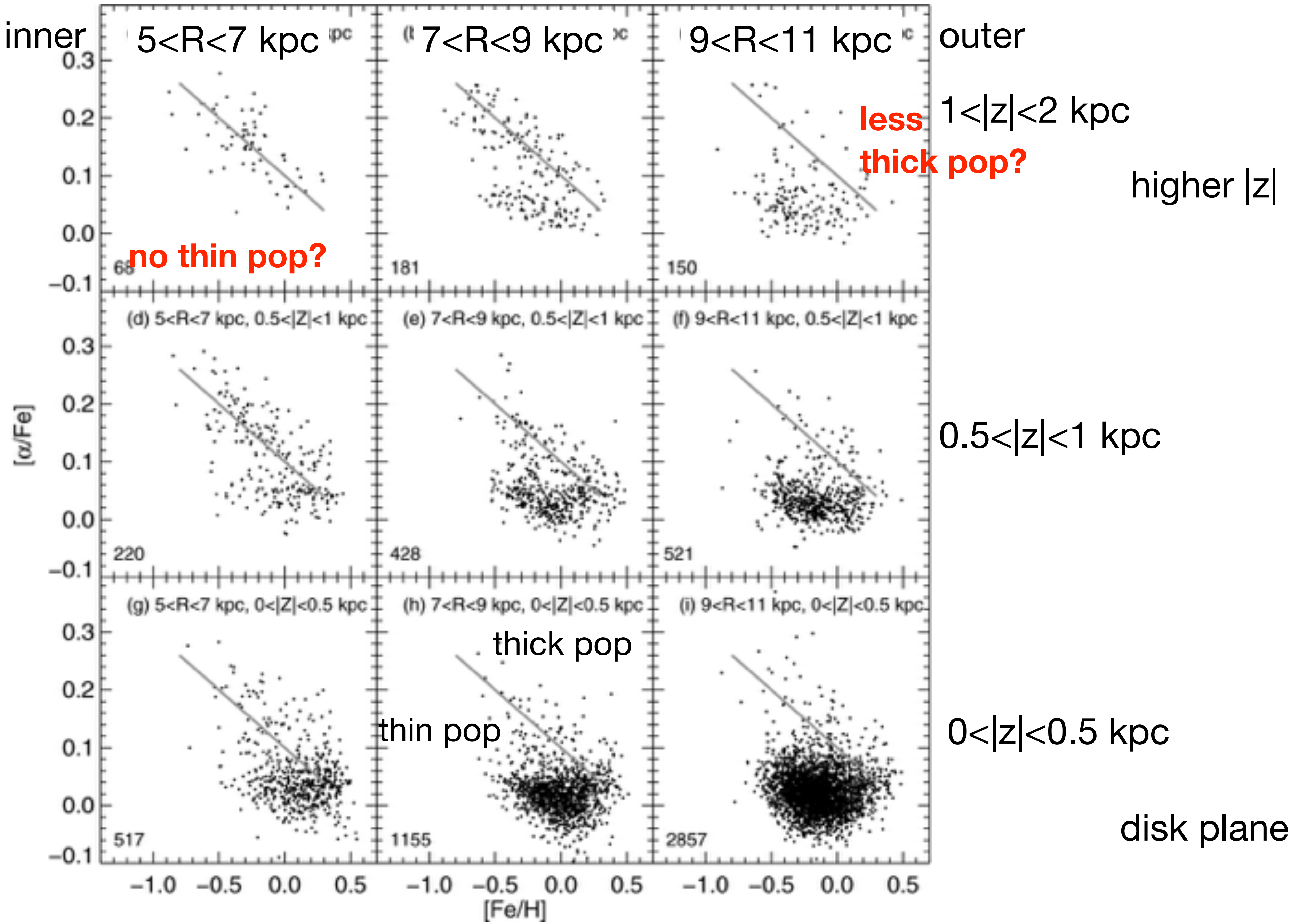
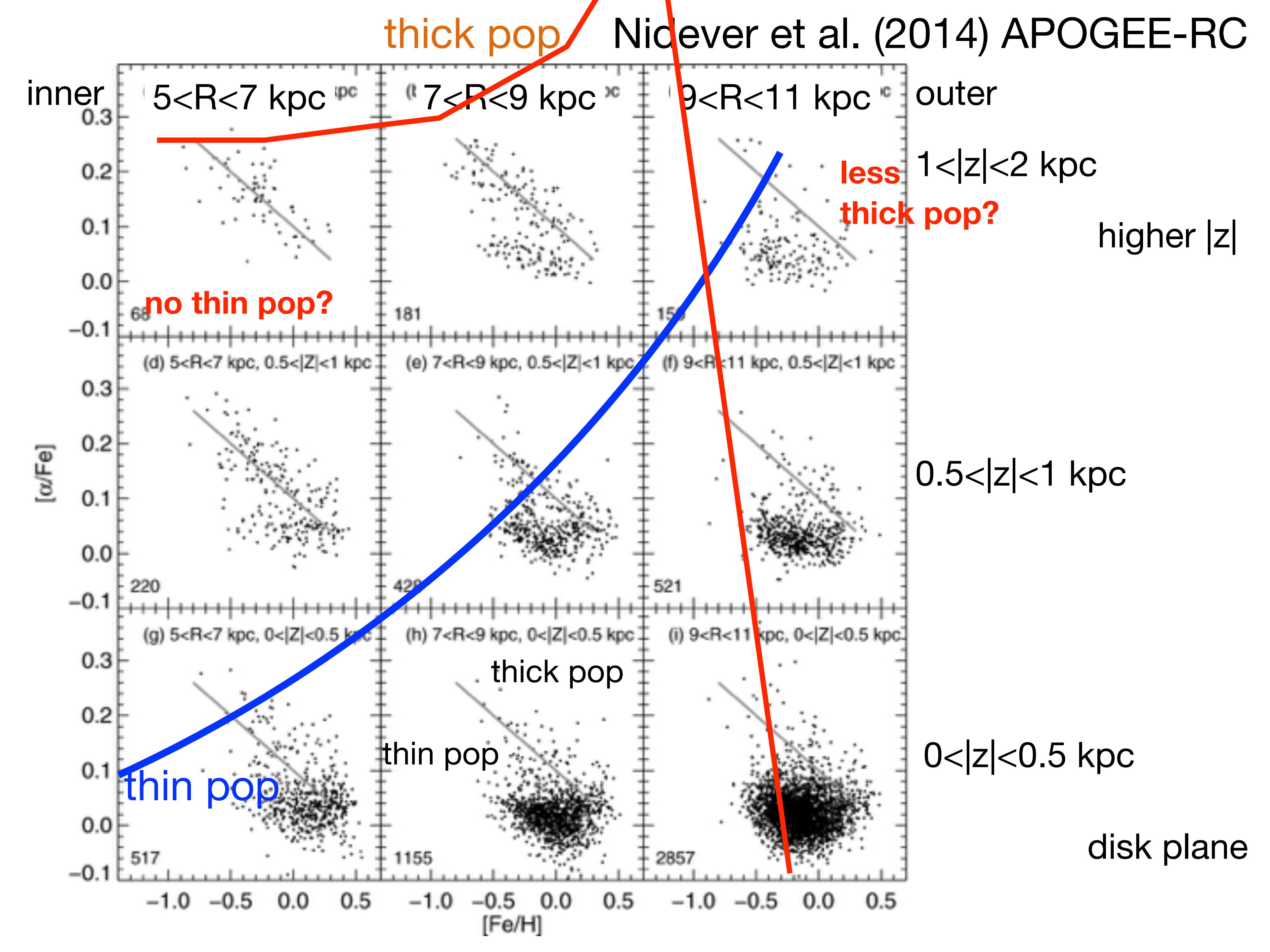
(see also Bensby et al. 2011)

e.g. Anders et al. (2014): APOGEE



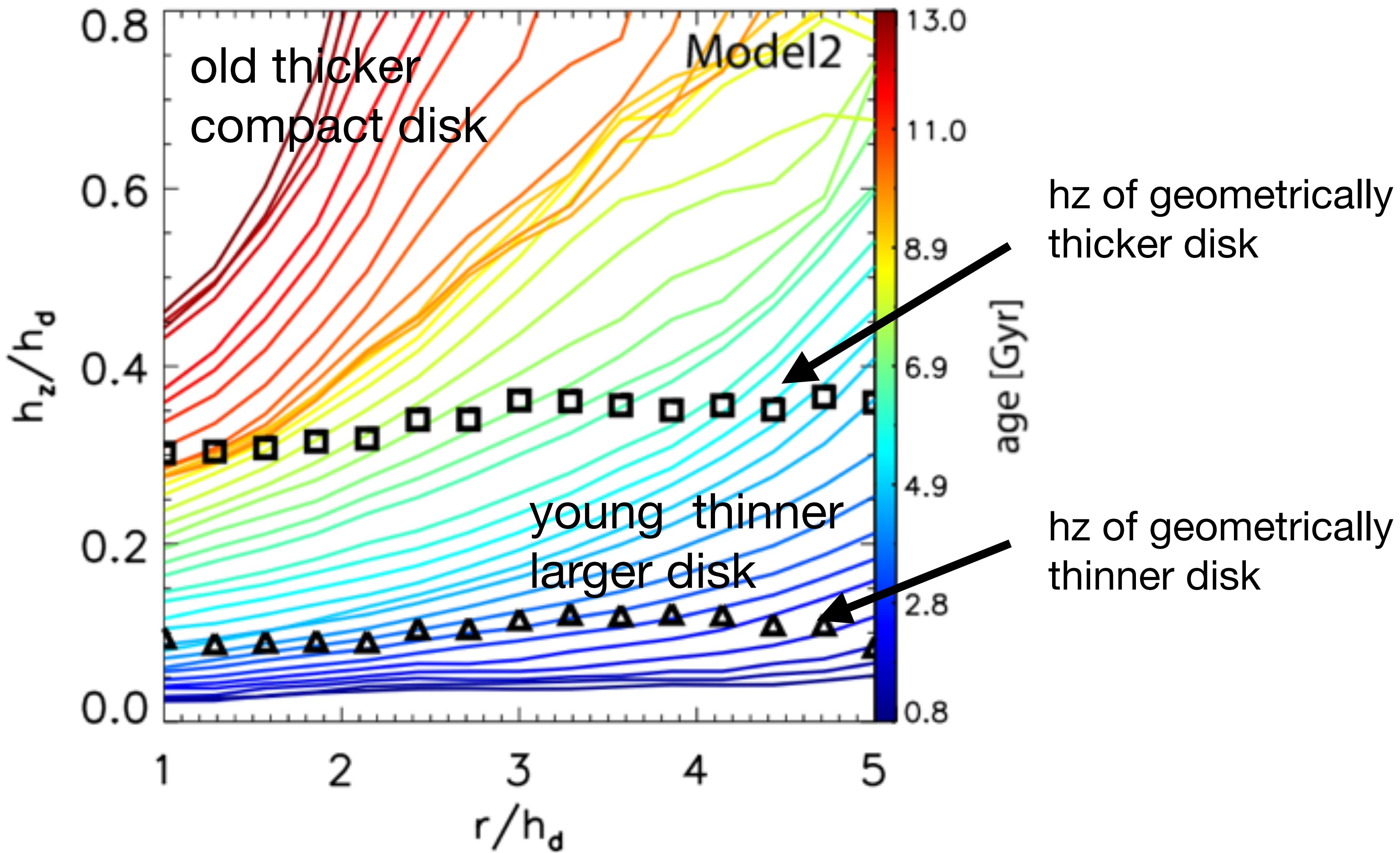
Nidever et al. (2014) APOGEE-RC





thick pop
Nidever et al. (2014) APOGEE-RC
inner
5<R<7 kpc
7<R<9 kpc
9<R<11 kpc
outer
1<|z|<2 kpc
less
thick pop?
higher |z|
no thin pop?
181
0.5<|z|<1 kpc
(d) 5<R<7 kpc, 0.5<|Z|<1 kpc
(e) 7<R<9 kpc, 0.5<|Z|<1 kpc
220
521
(g) 5<R<7 kpc, 0<|Z|<0.5 kpc
(h) 7<R<9 kpc, 0<|Z|<0.5 kpc
(i) 9<R<11 kpc, 0<|Z|<0.5 kpc
thick pop
thin pop
thin pop
0<|z|<0.5 kpc
517
1155
2857
disk plane
[α/Fe]
[Fe/H]

Minchev et al. (arXiv:1502.06606): simulations
inside-out disk formation: nested flaring mono-age disks
older disk is thicker and more compact




Flaring could be important?
NGC 3628

Summary

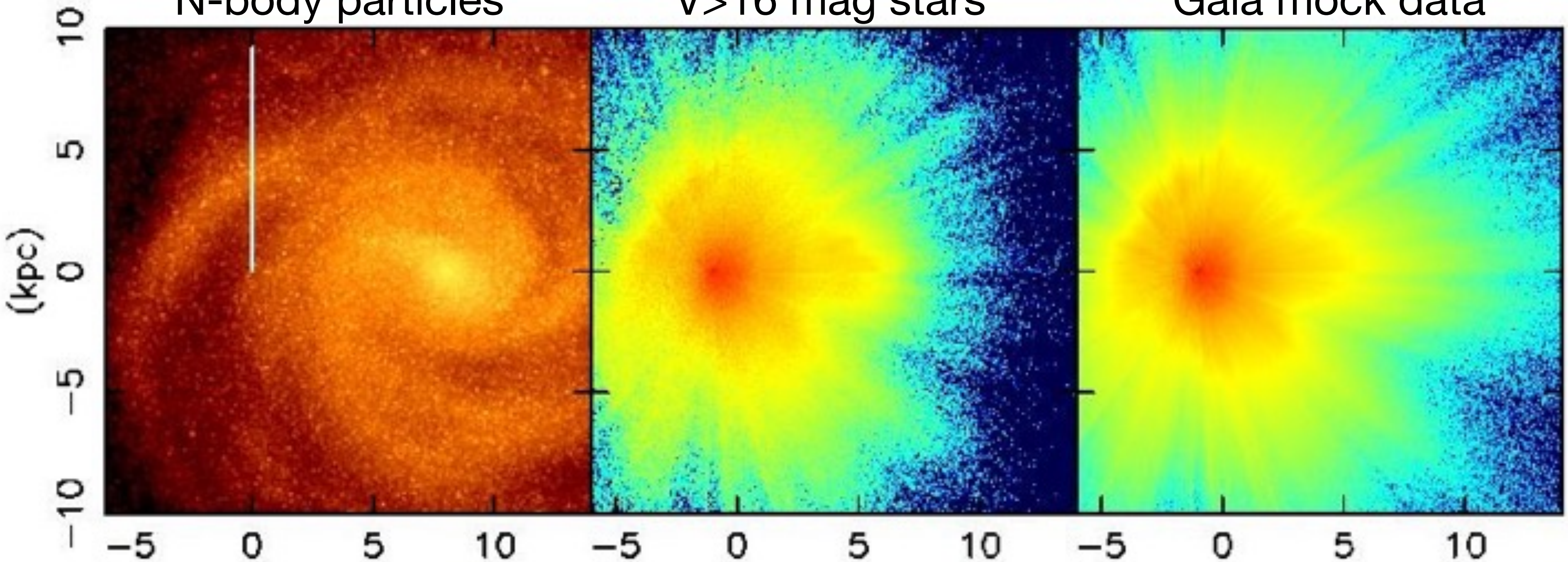
- **Please remember Brook et al. (2004)!**
- Inside-out thick-to-thin disk formation:
  smaller thicker older population
- Radial migration helps the initially compact thick population to be observed at solar neighbourhood
- Flaring thiner disk at outer radius → a large geometric thick disk and positive Z and negative [α/Fe] gradient at high |z|
- geometric structures (exp law or not?) of chemically decomposed (mono-abundance) disk populations
  → constraints on the disk formation scenario

MOS+Gaia!

SNAPDORAGONS

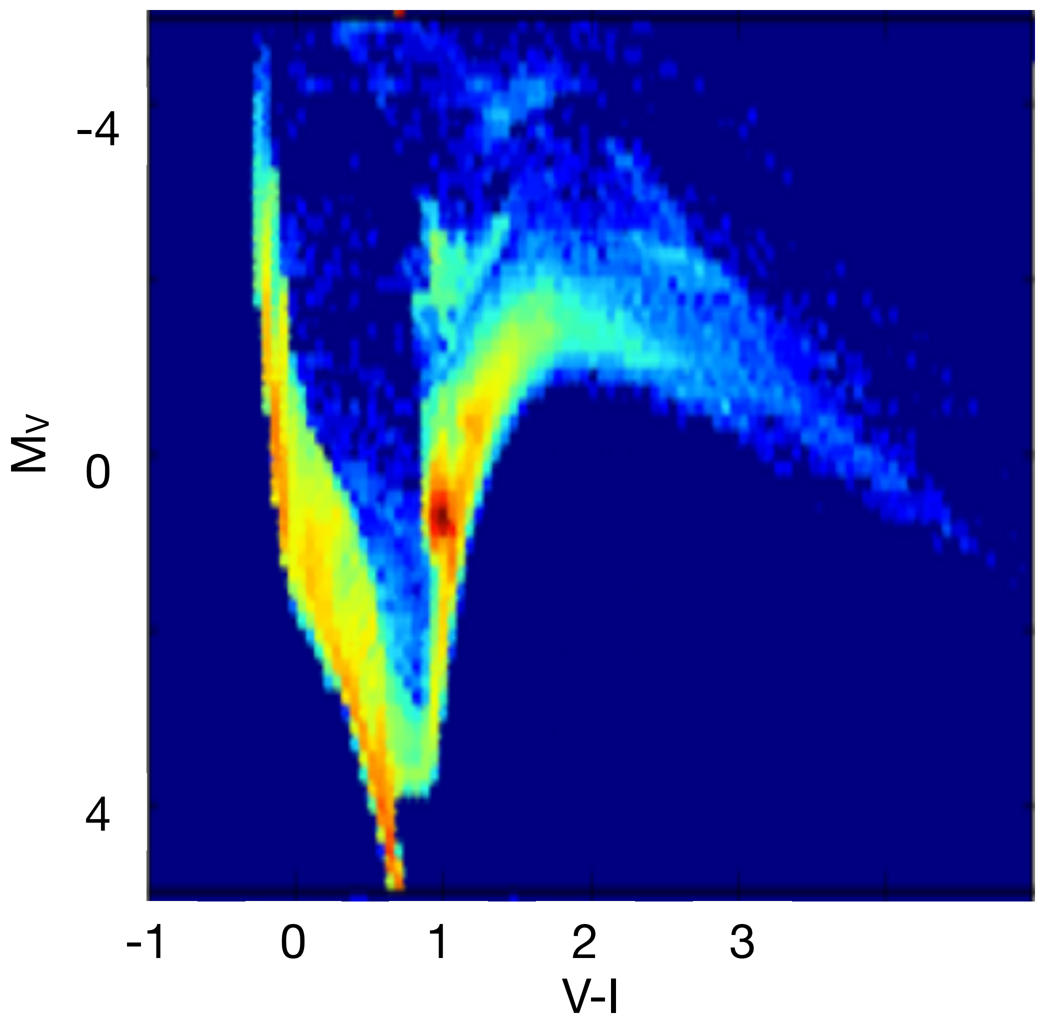
(Stellar Numbers And Parameters Determined Routinely And Generated Observing N -body Systems)

Generating “stars” from star particles + 3D extinction (borrowing the data from Galaxia, Sharma et al. 2011) add Gaia post-launch errors (Romero-Gómez et al.)→ mock Gaia data.



(Hunt, Kawata et al. arXiv:1501.01969)

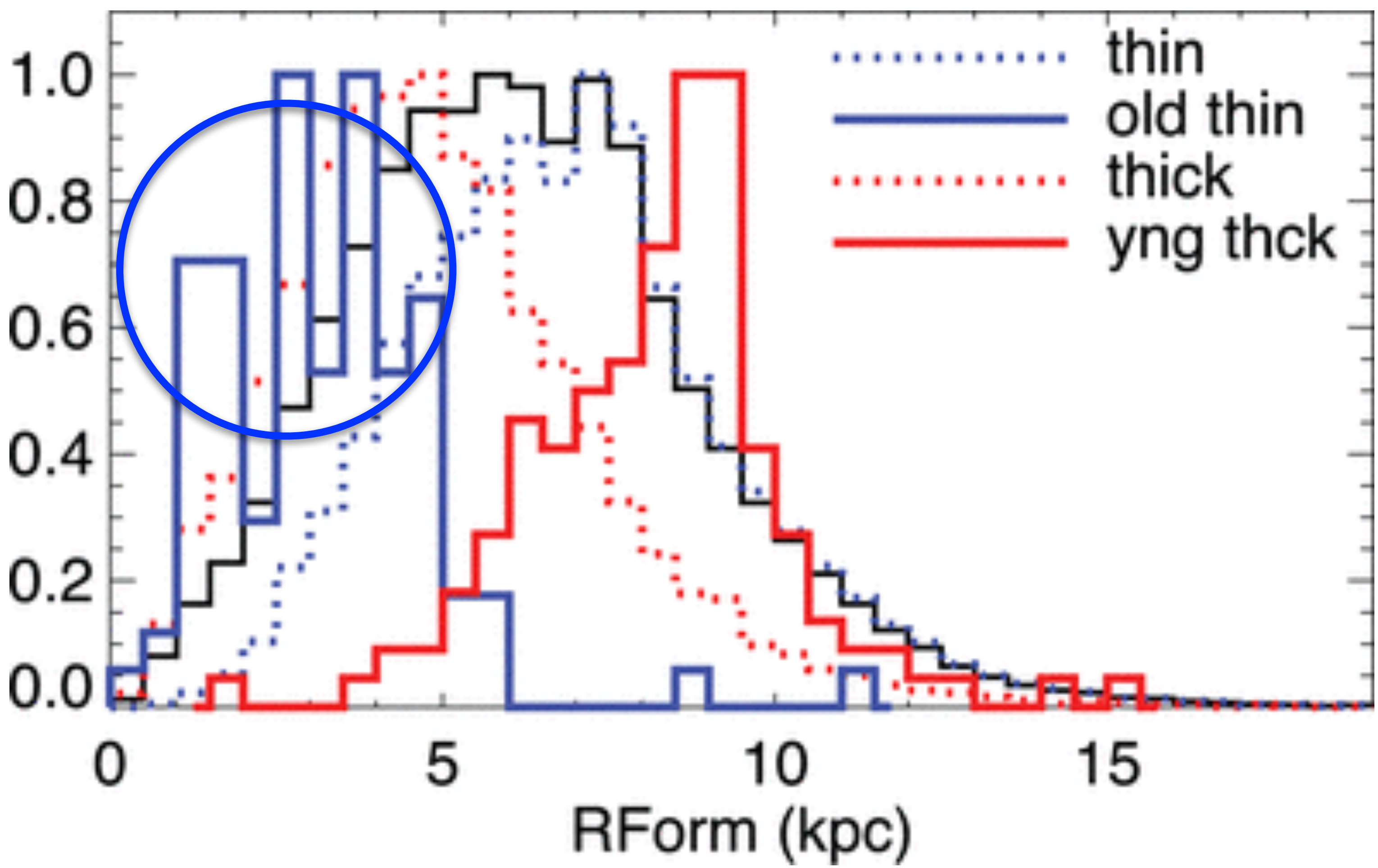
SNAPDORAGONS
(Hunt, Kawata et al. arXiv:1501.01969)
N-body simulation → mock Gaia catalogue

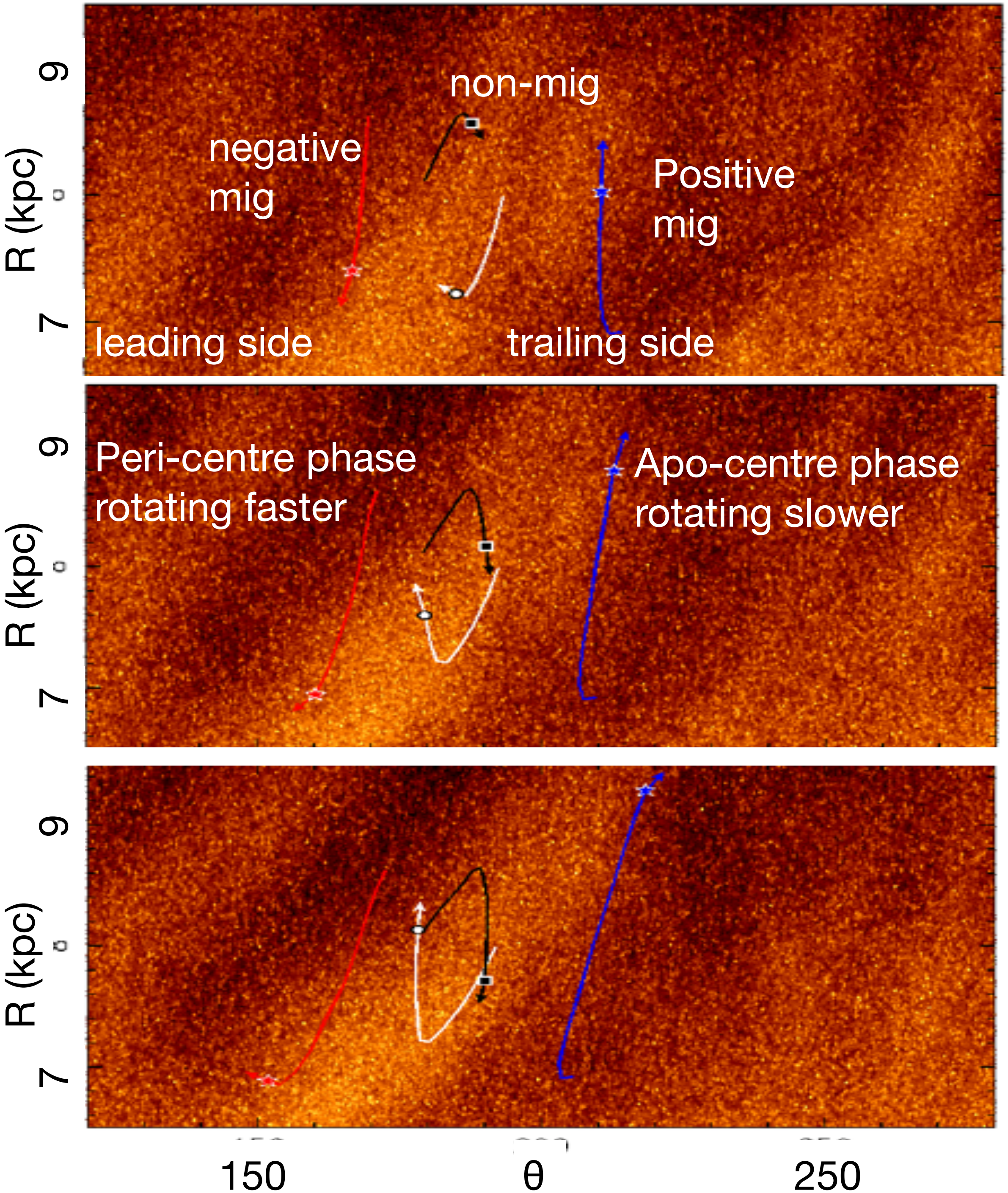


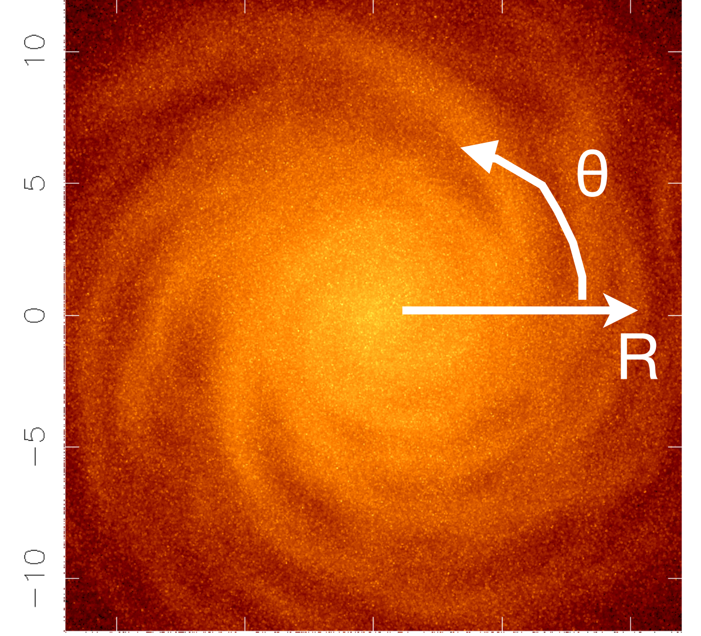
(l,b)=(90,0) deg sample

No smoothing is applied: clear connection particle ↔ stars.

old thin population came from inner region
inside-out thin disk formation:
thin population starts forming in the inner region
when thick population is forming in the outer region.



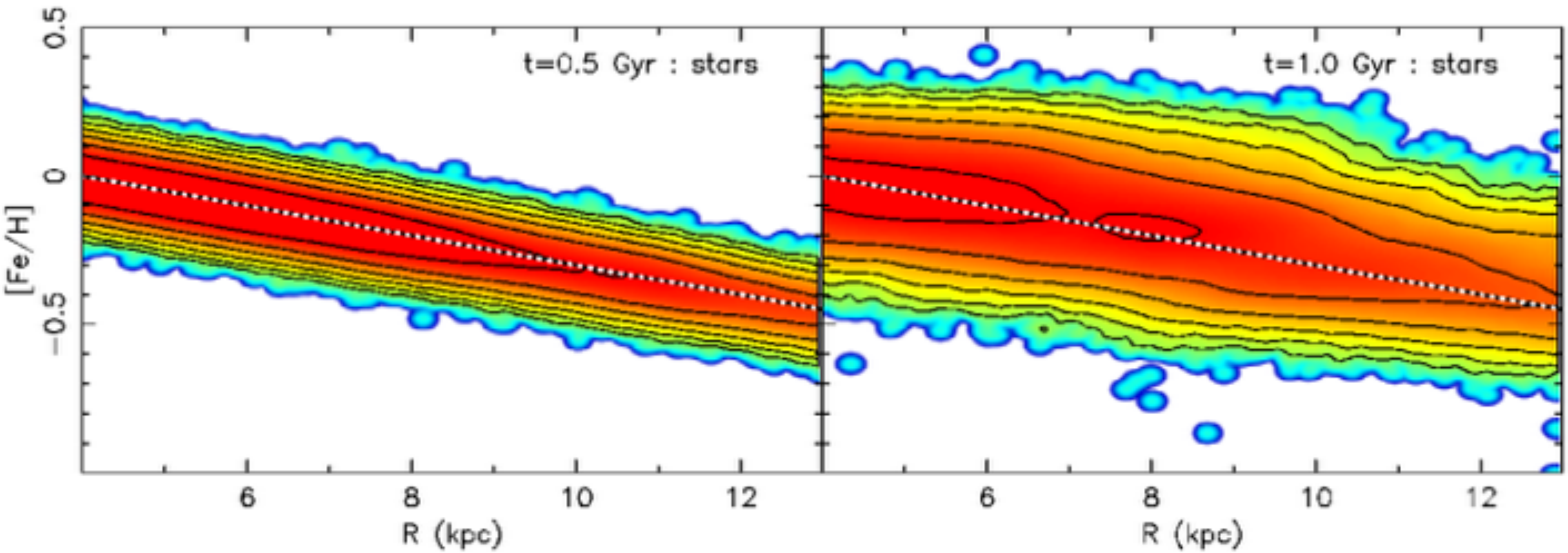




Positive (negative) migrators have Vrot < Vcirc (Vrot>Vcirc), stay behind (on the front of) the spiral arm, and keep gaining (losing) Ang.Mom. till the arm disappears.

Non-migrators orbit the spiral arm, continuously moving from one side to the other, and no net-Ang.Mom. change.

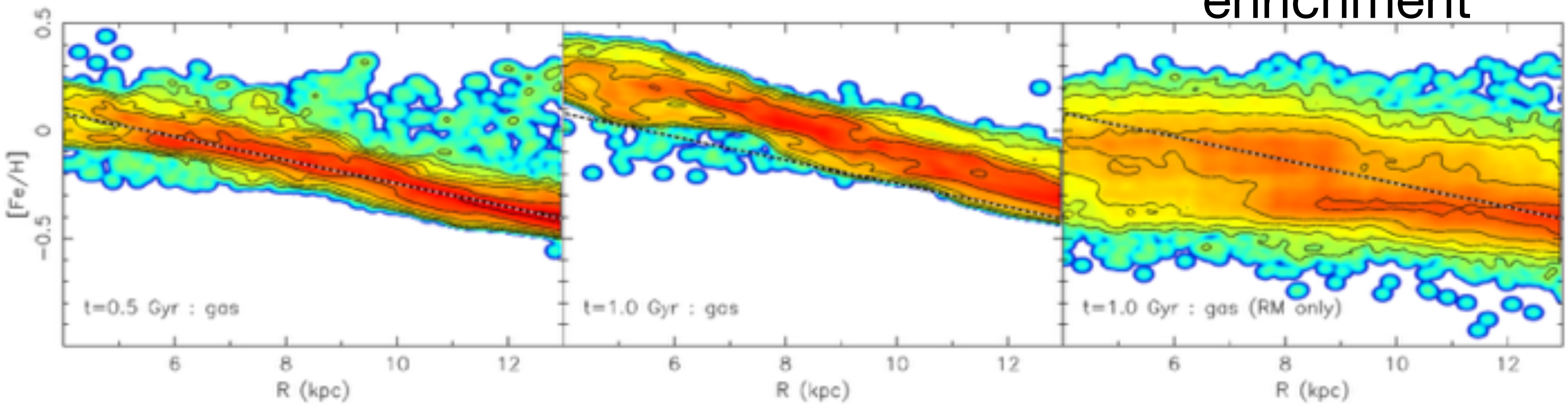
stellar metallicity gradient evolution



Grand, Kawata, Cropper (2014)

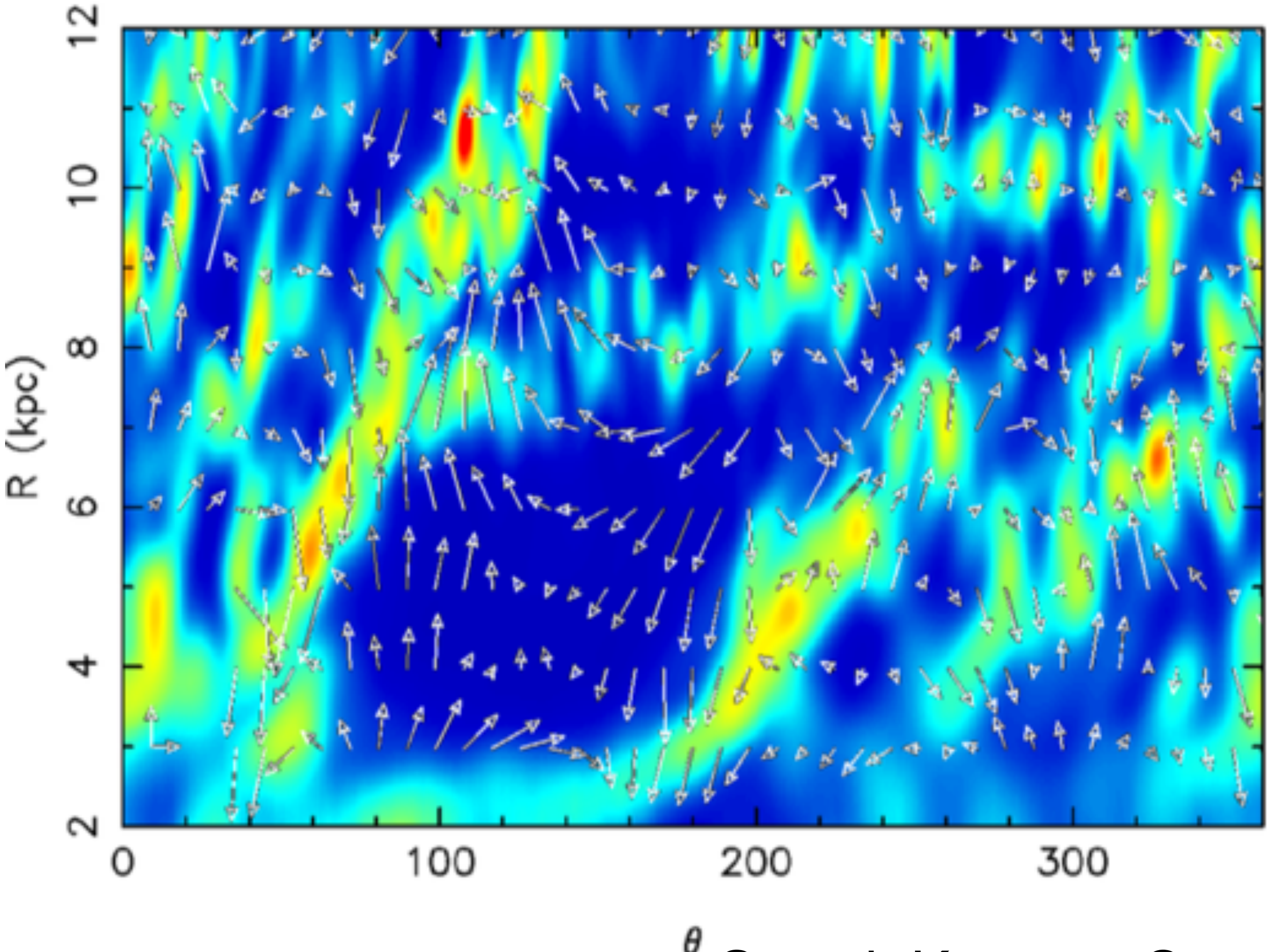
gas metallicity gradient evolution

Ignore
metal mixing
enrichment



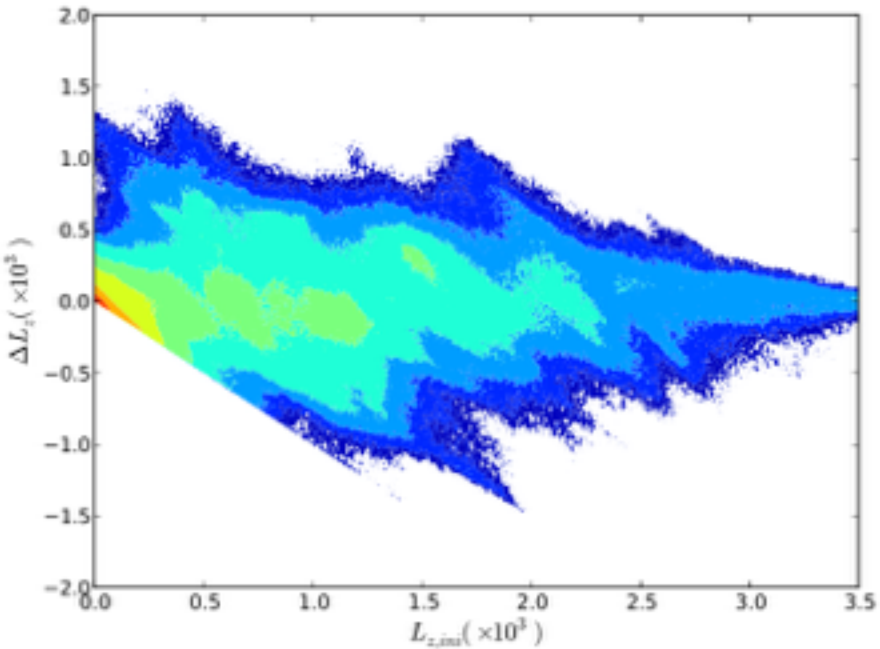
Grand, Kawata, Cropper (2014)

Gas motion

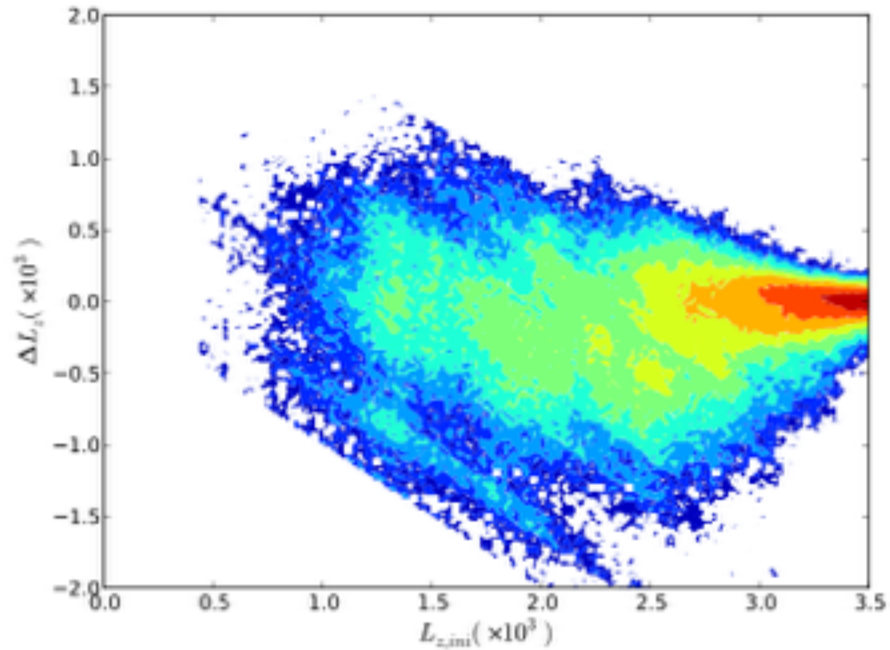


Grand, Kawata, Cropper (2014)

Stars



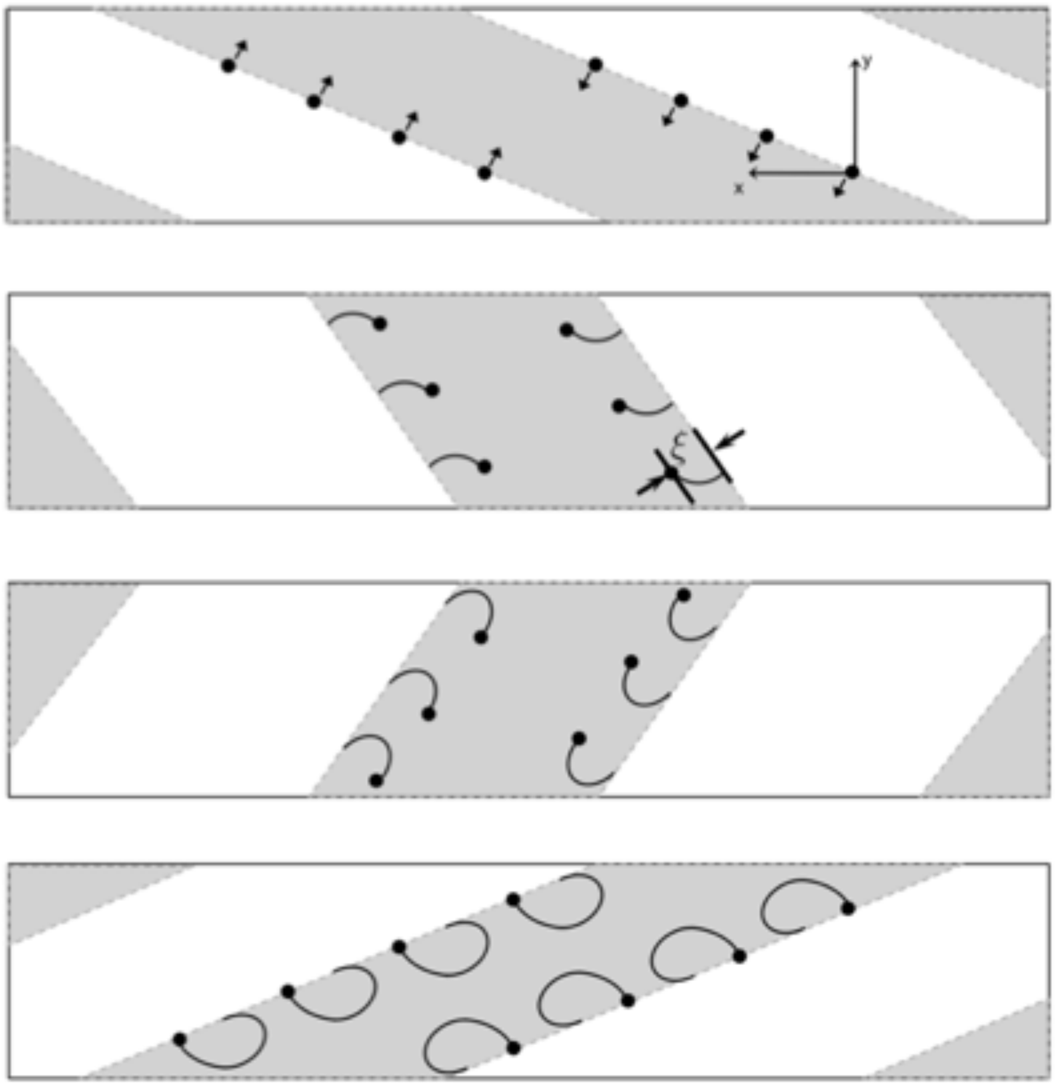
Gas



Grand, Kawata, Cropper (2014)

Swing Amplification

(Julian & Toomre 1966, Toomre 1981)



N-body spiral arm seems to form by similar mechanism to Swing Amplification. However, non-linear features, such as extreme migrators, are not described by linear perturbation theory.

Stellar motion

(example of different simulated galaxy)
trailing side going outward, and leading side going inward
private communication with Ivan Minchev (Beijing 2010)