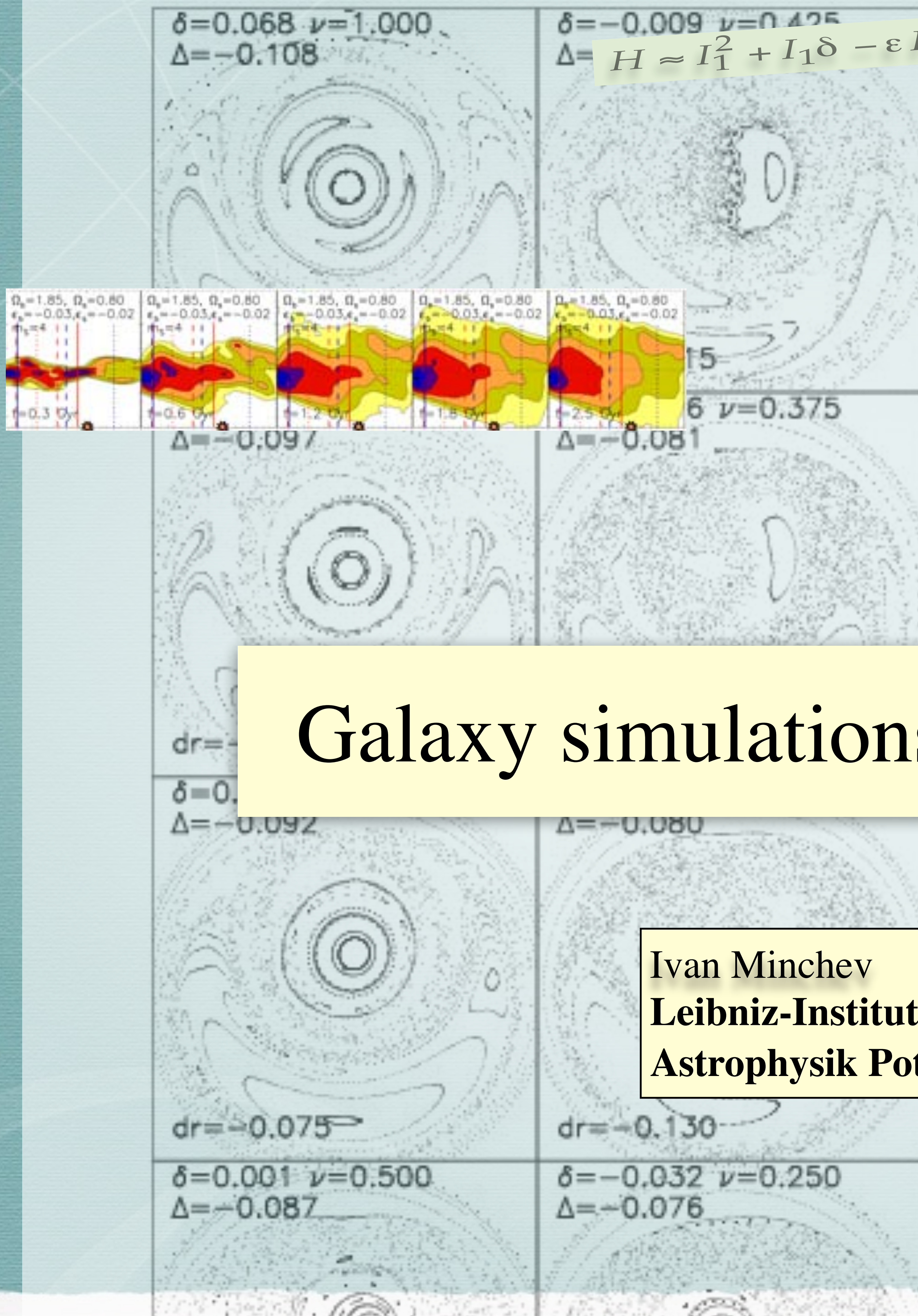


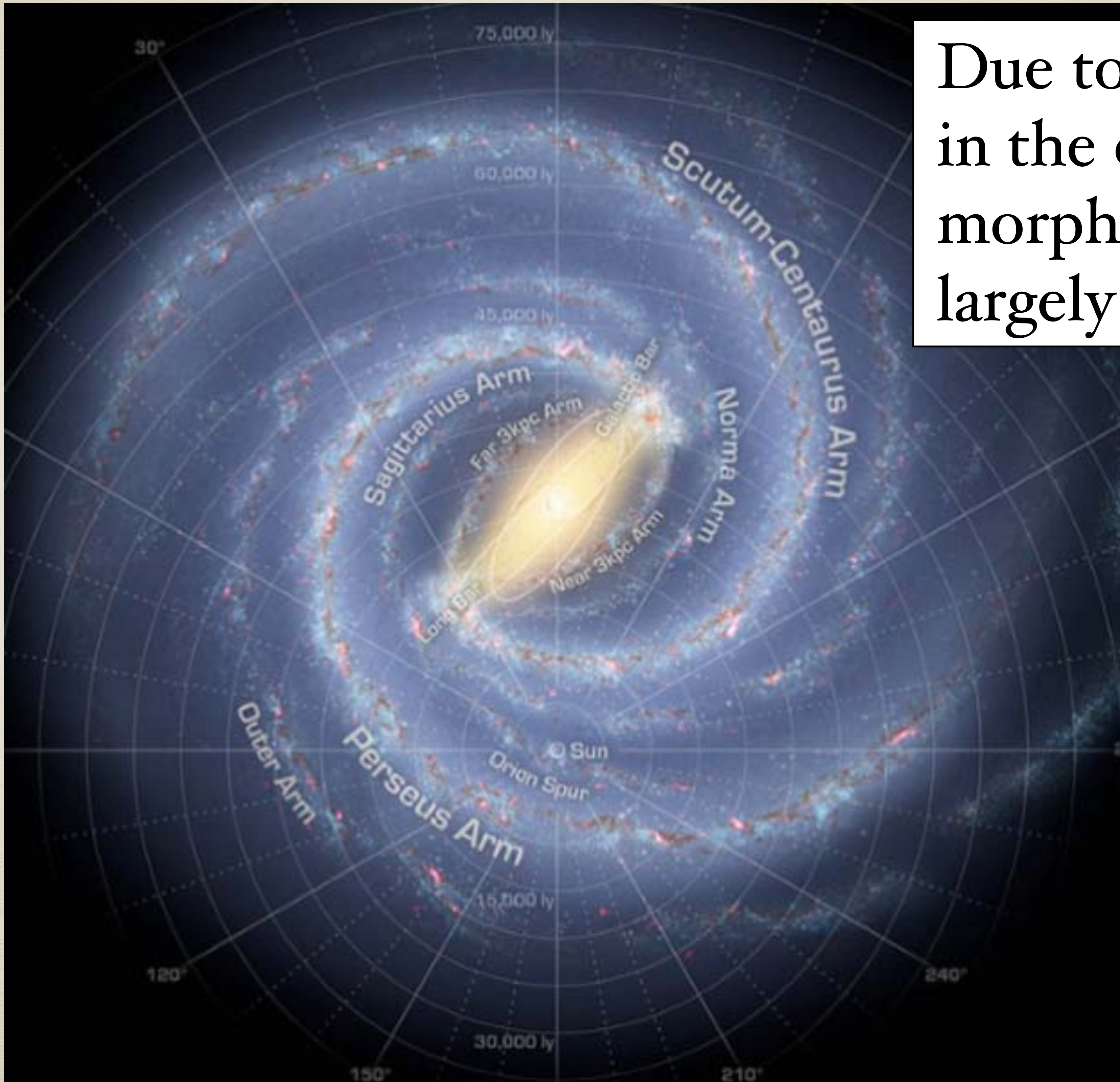
$$H \approx I_1^2 + I_1\delta - \varepsilon I_1^{1/2}\cos\phi \; - \beta I_1^{1/2}\cos[\phi + \nu t + \gamma]$$

Galaxy simulations in the Gaia era

Ivan Minchev
Leibniz-Institut fur Astrophysik Potsdam (AIP)

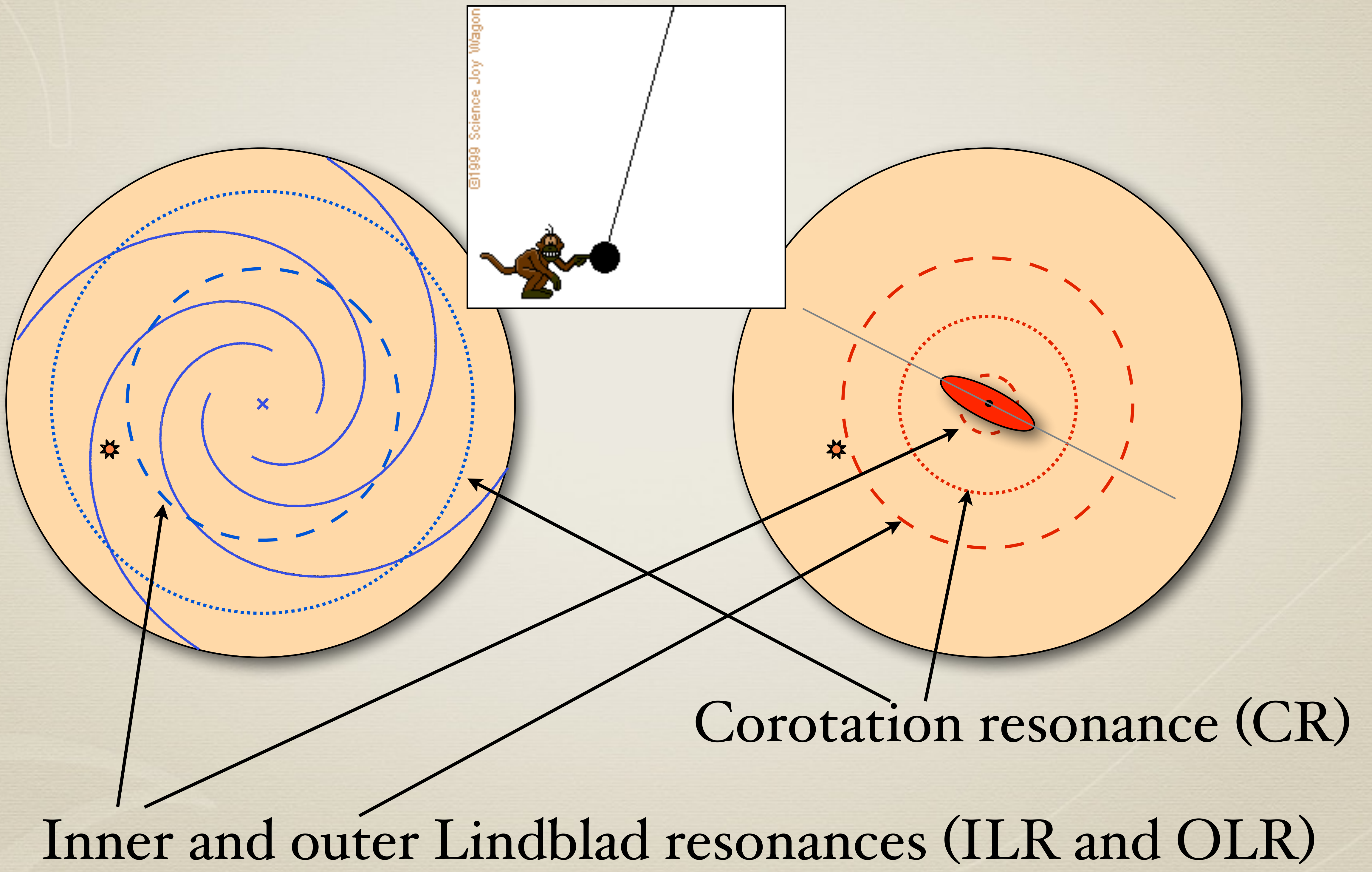
Leibniz-Institut für Astrophysik Potsdam
AIP

What we think our Galaxy looks like



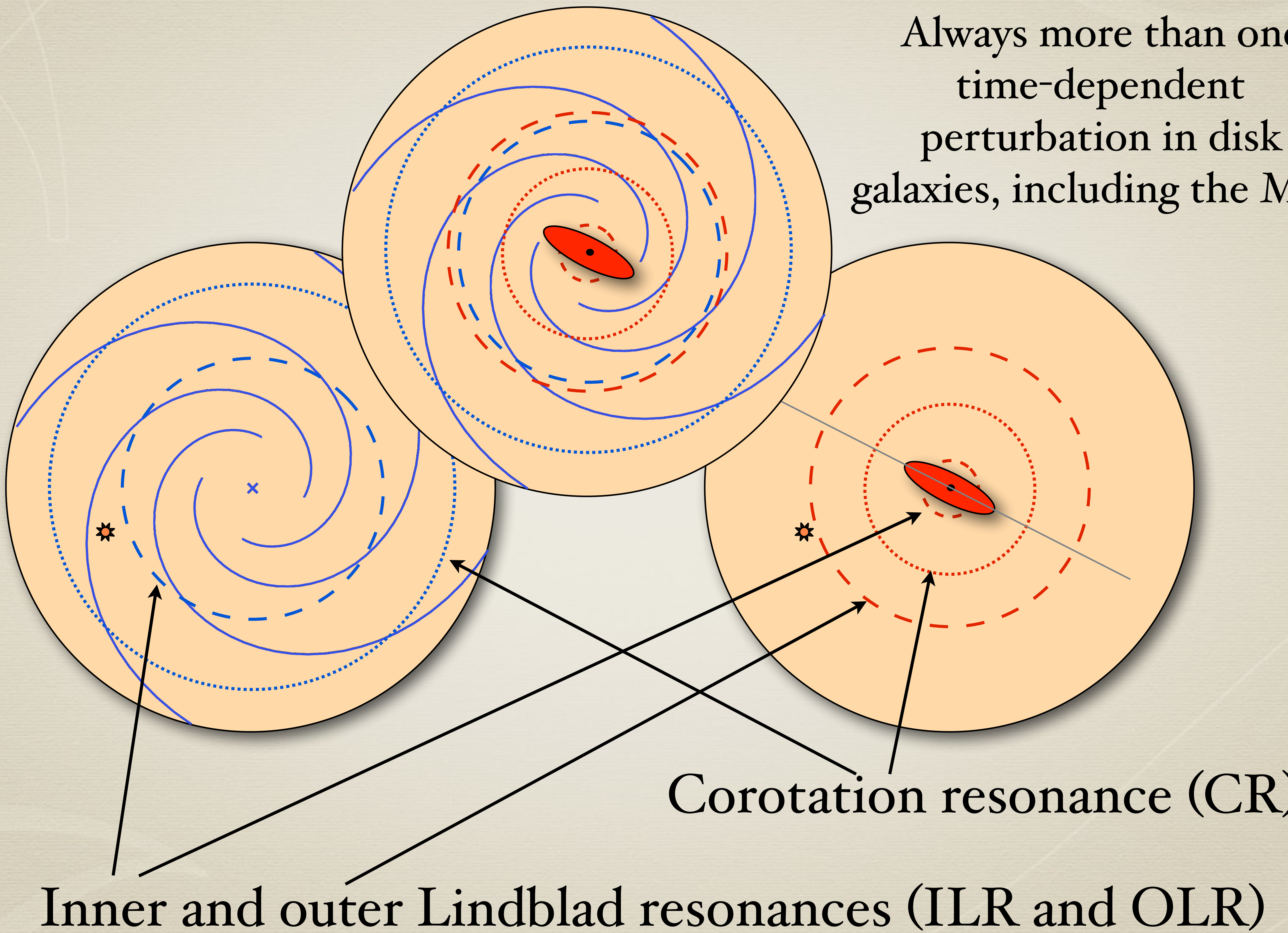
Due to our position in the disk, its morphology is still largely unknown

Resonances in galactic disks



Resonances in galactic disks

Always more than one time-dependent perturbation in disk galaxies, including the MW

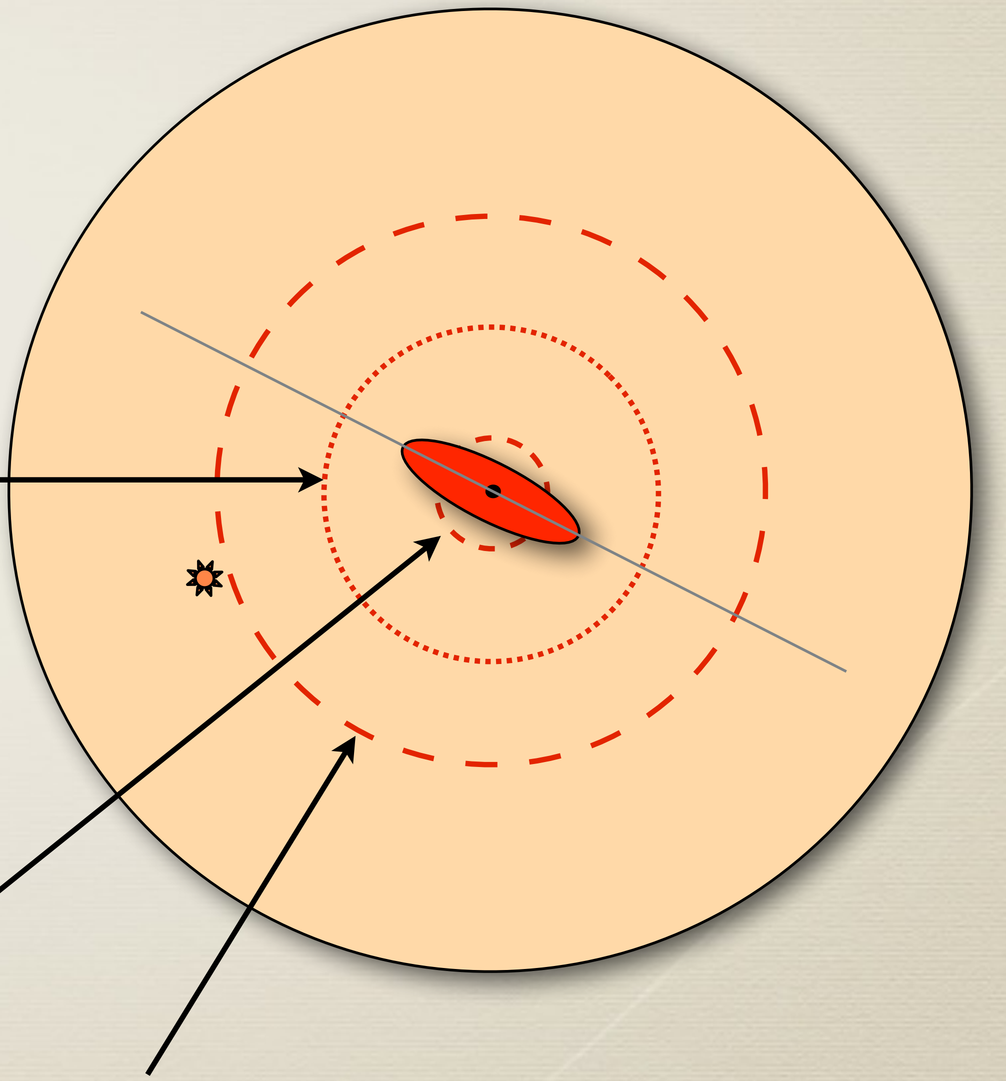


Resonances in galactic disks

- For a flat rotation curve Lindblad resonances are given by

$$\Omega_s = \Omega_0 \pm \kappa / m$$

- Corotation is at $\Omega_s = \Omega_0$
- For a 2-armed spiral structure or a bar m=2.
- For a 4-armed spiral m=4.



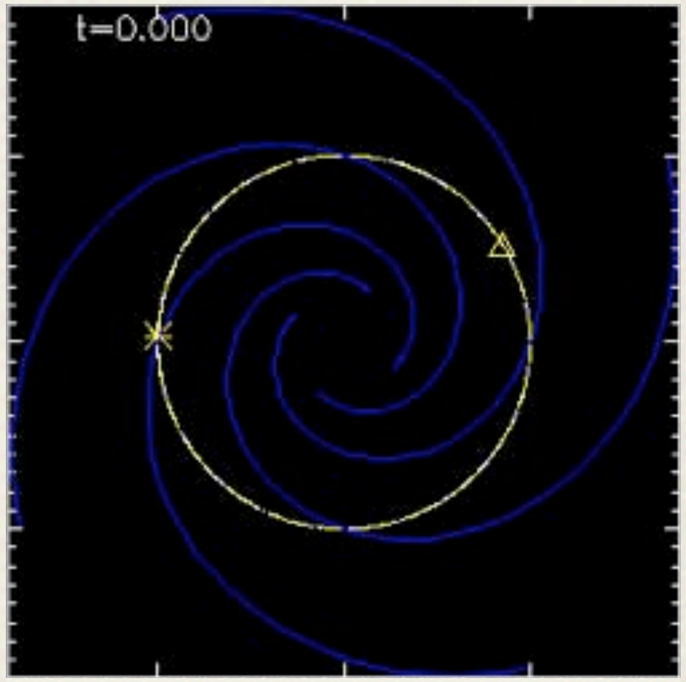
Inner and Outer Lindblad resonances

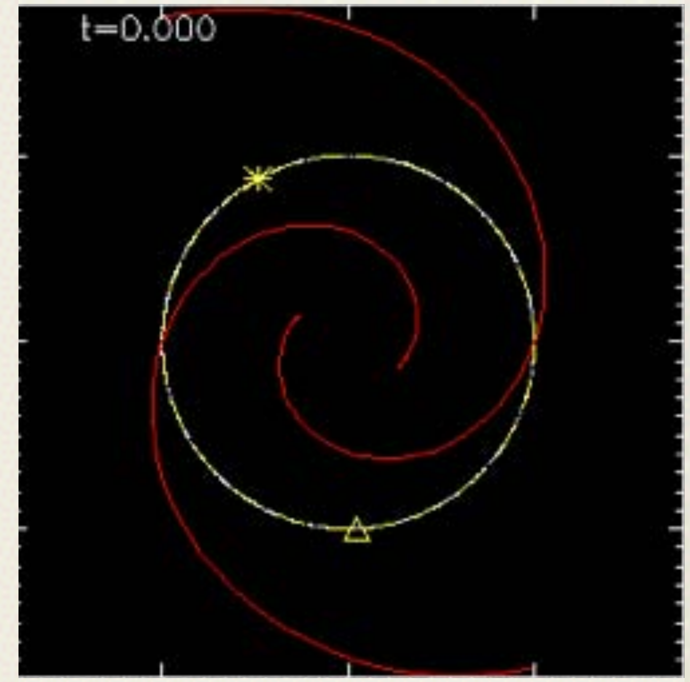
Stellar orbits near resonances

Near OLR

Near Corotation (CR)

Single spiral wave

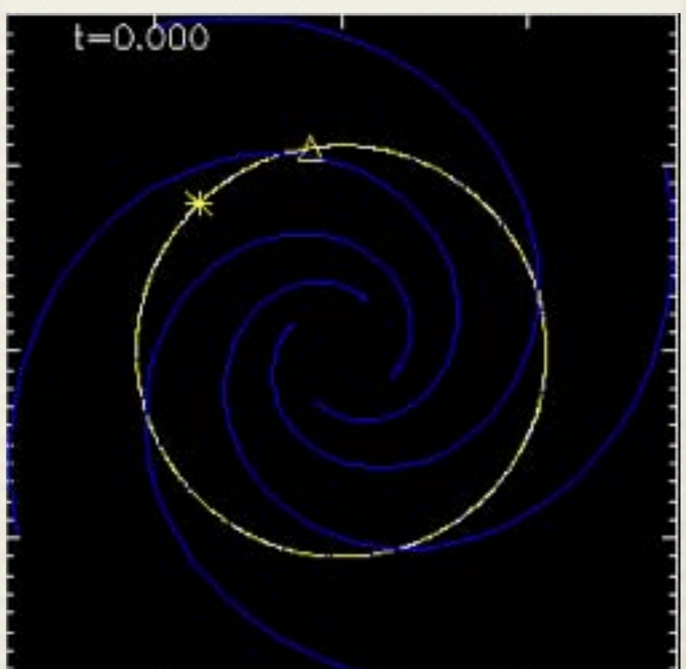


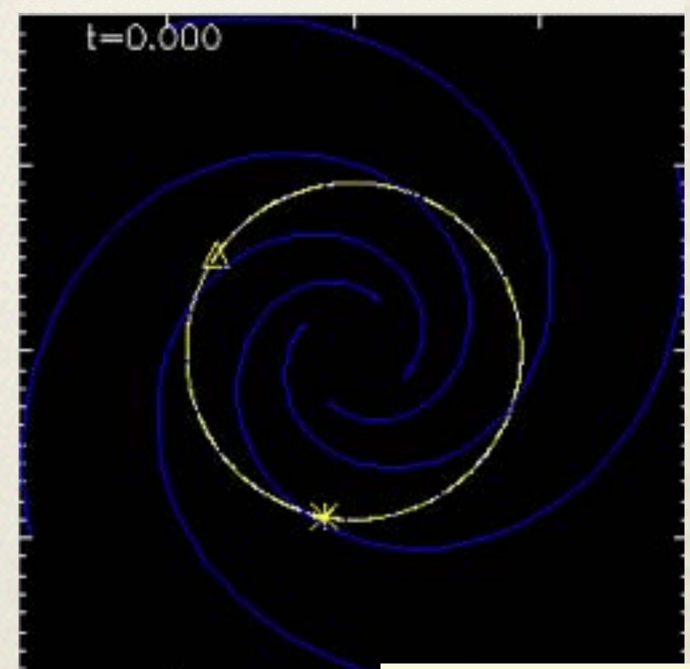


Outside OLR+CR

Inside OLR+CR

2 spiral waves



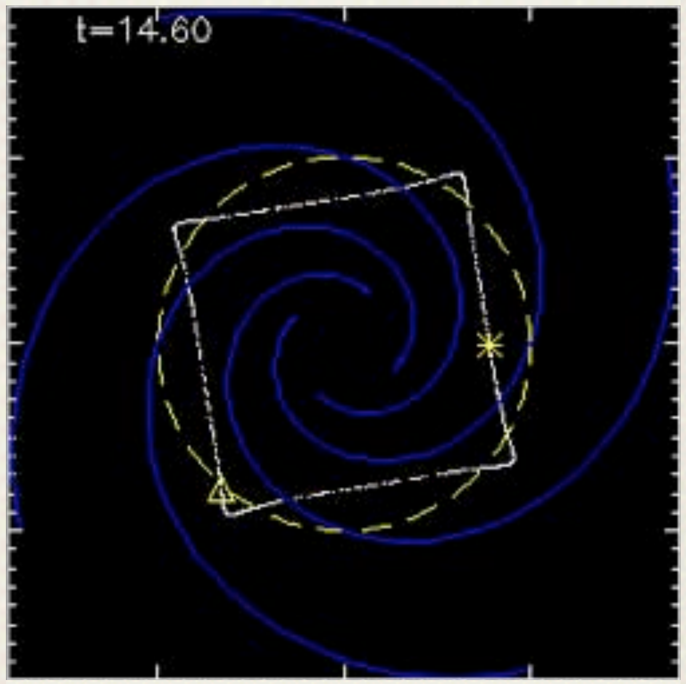


Minchev & Quillen (2007)

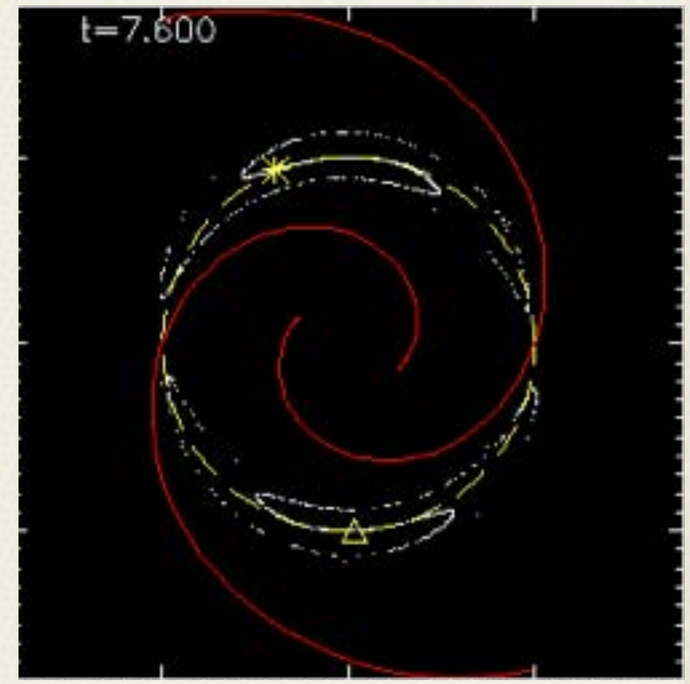
Stellar orbits near resonances

Single spiral wave

Near OLR

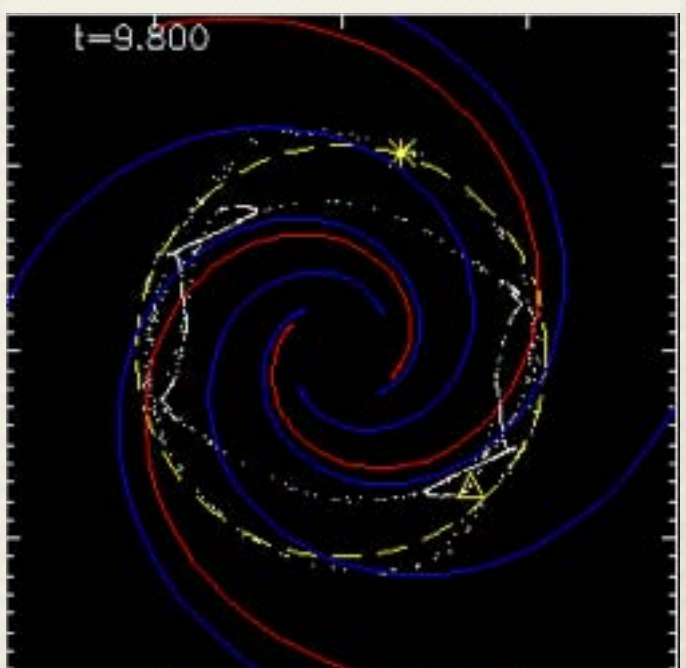


Near Corotation (CR)

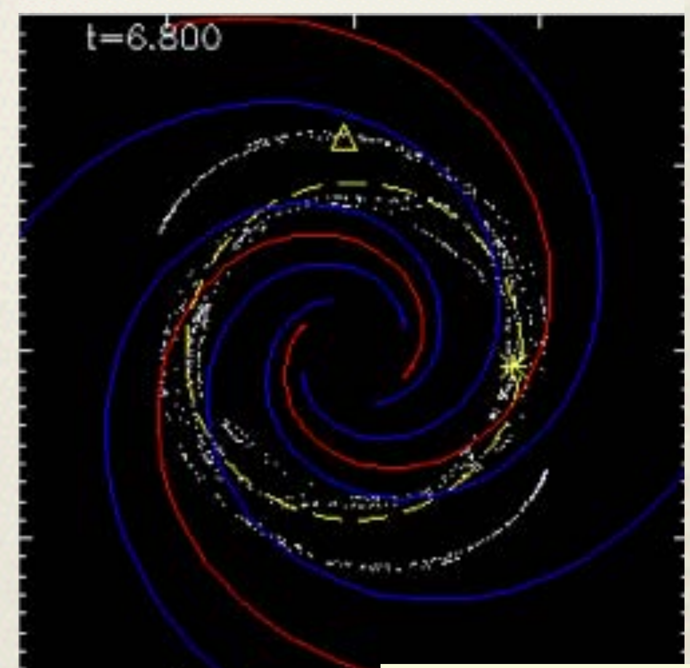


2 spiral waves

Outside OLR+CR



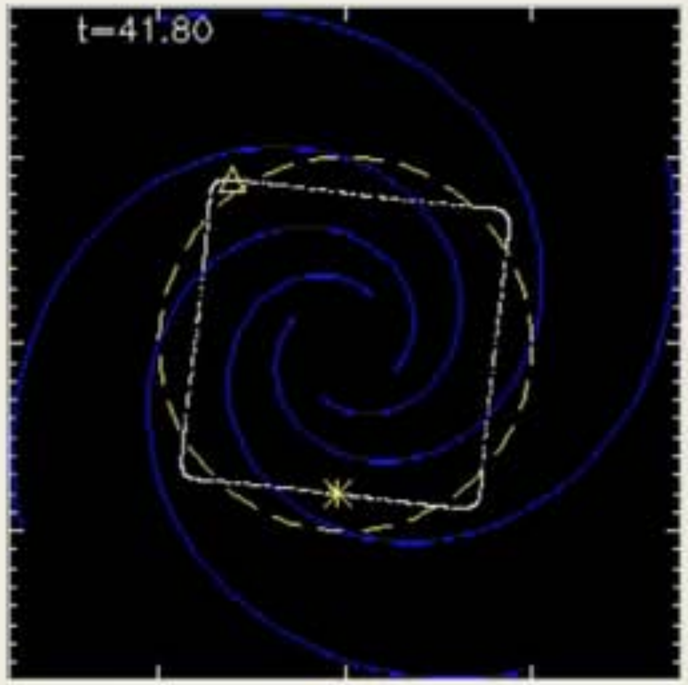
Inside OLR+CR



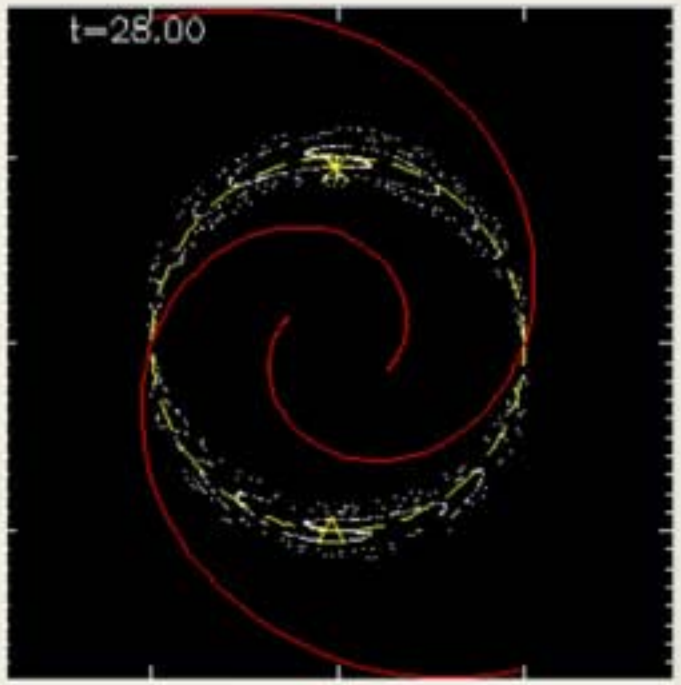
Minchev & Quillen (2007)

Stellar orbits near resonances

Near OLR

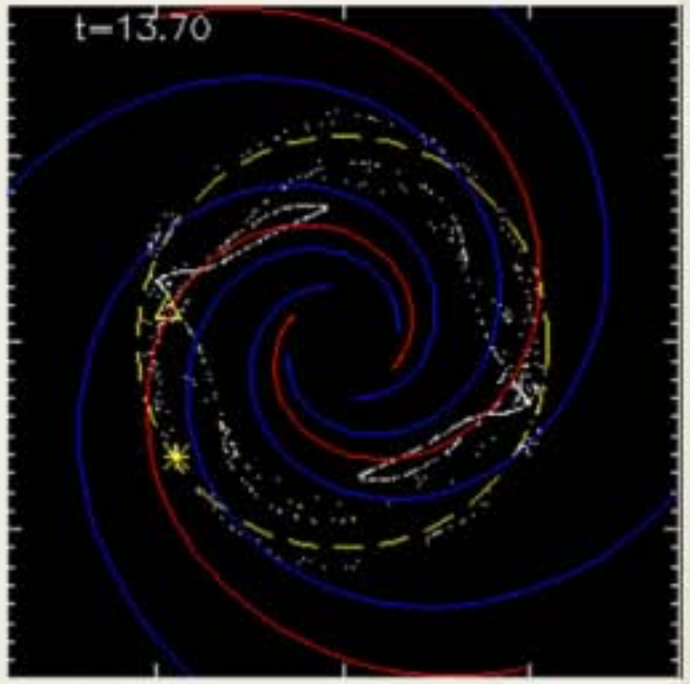


Near Corotation (CR)

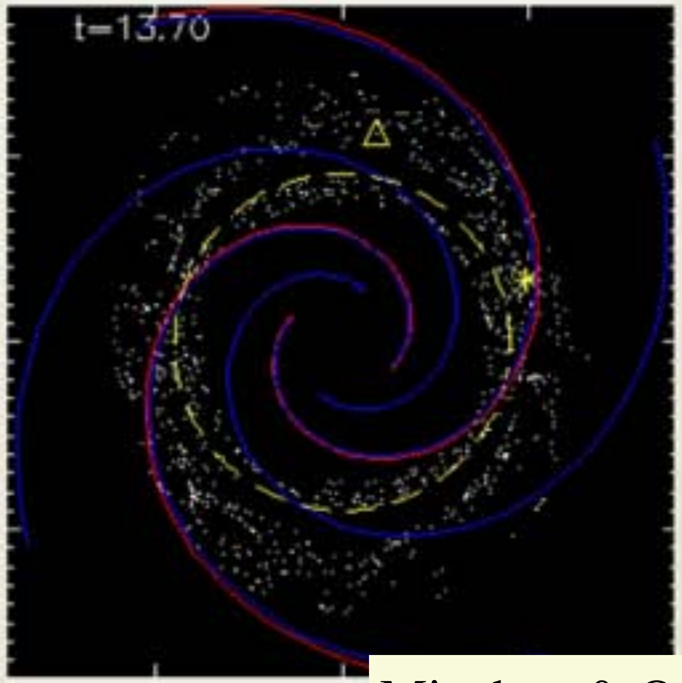


Single spiral wave

Outside OLR+CR



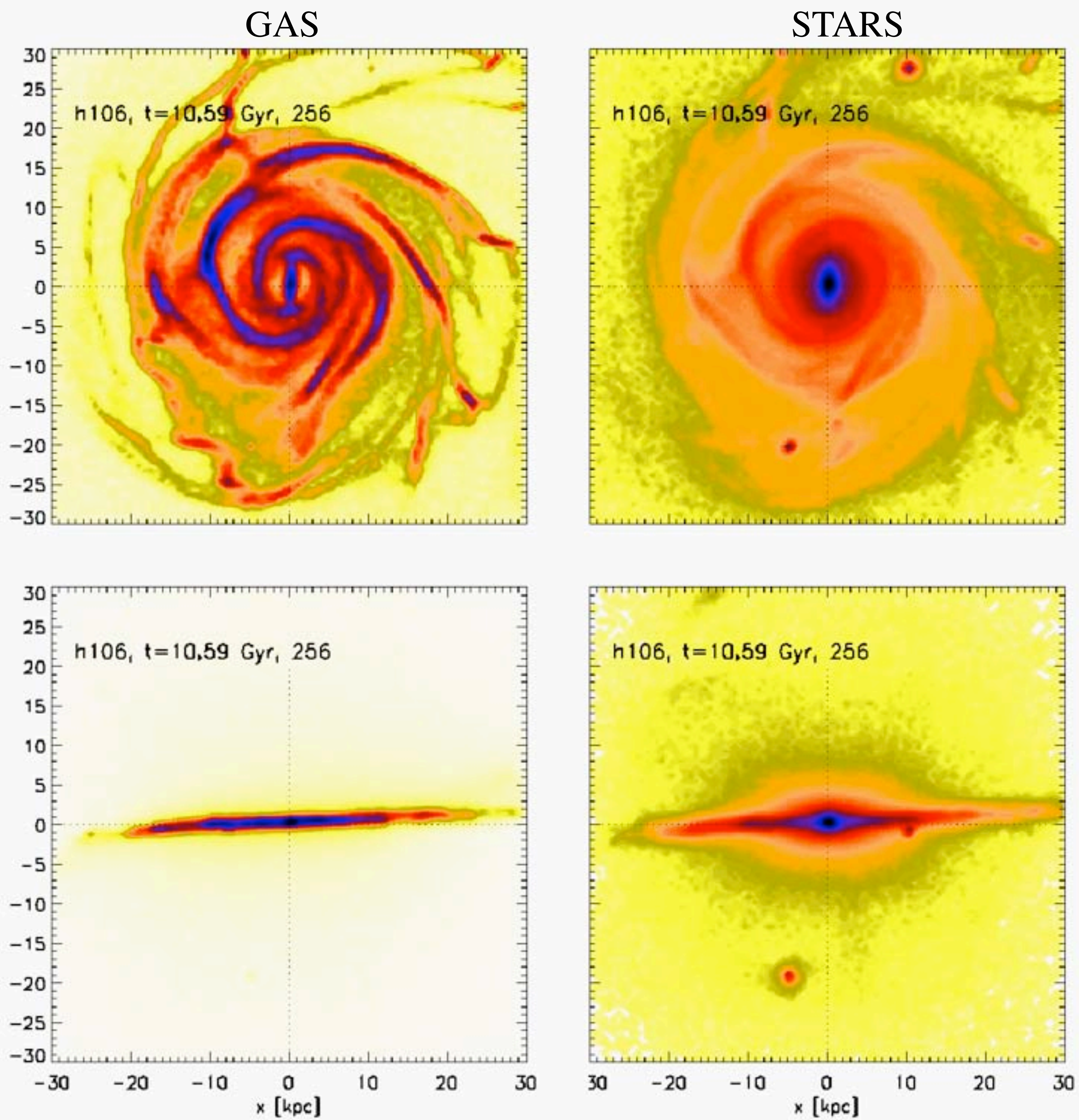
Inside OLR+CR



2 spiral waves

Much more complex dynamics when 2 perturbations with different pattern speeds

Minchev & Quillen (2007)



Simulation in cosmological context
Martig et al. (2009, 2012)

Dynamics yet more complex from a range of perturbers acting at the same time!

The disk is perturbed by the **central bar, spirals**, and **infalling satellites**.

The need for numerical simulations

- The complex dynamics of stars in the Galaxy **demands the use of N-body simulations**. This allows to take into account the perturbative **effect of spiral arms, central bar**, and **minor mergers** resulting from infalling satellites.
- **Questions we would like to answer:**
  - Spiral structure parameters?
  - Bar parameters?
  - Bulge structure?
  - Disk structure as a fn of radius and distance from plane?

describing current disk state

  - How did the Milky Way thick disk form?
  - How/when did the bulge/bar form?
  - How much radial mixing happened in the disk (fn of time and radius)?
  - Inside-out disk formation?

requires a disk formation model

A. Helmi will tell us about halo next

Some examples of outstanding problems

- Pattern speed and length of the Galactic bar and nature of the Hercules stream.

Fast bar, about 3 kpc long (Dehnen 2000, Fux et al. 2001, Minchev et al. 2007, 2010, Antoja et al. 2008, Monari et al. 2017)

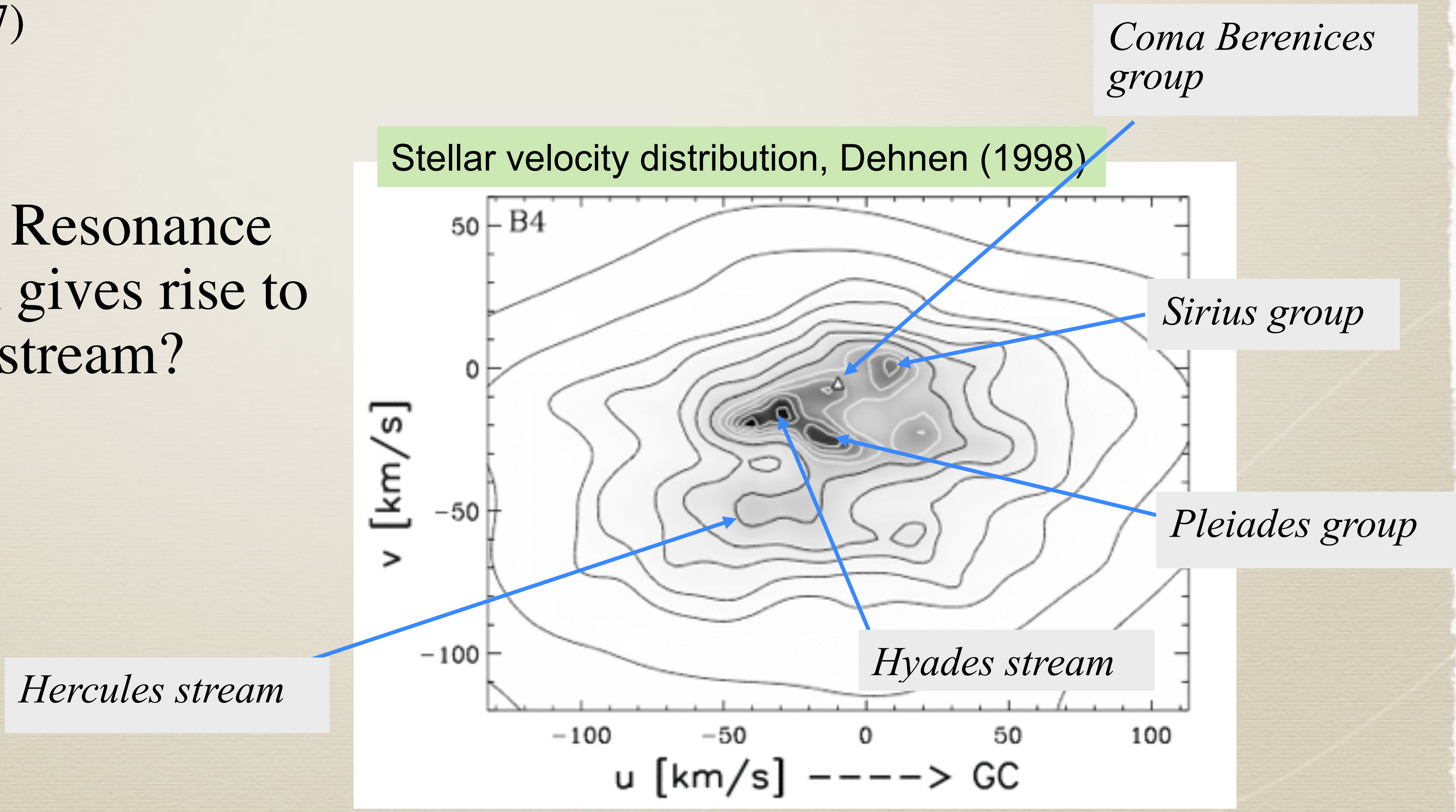
or

Slow bar, about 5 kpc long (Wegg et al. 2015, Pérez-Villegas 2017)

Outer Lindblad Resonance or Corotation gives rise to the Hercules stream?

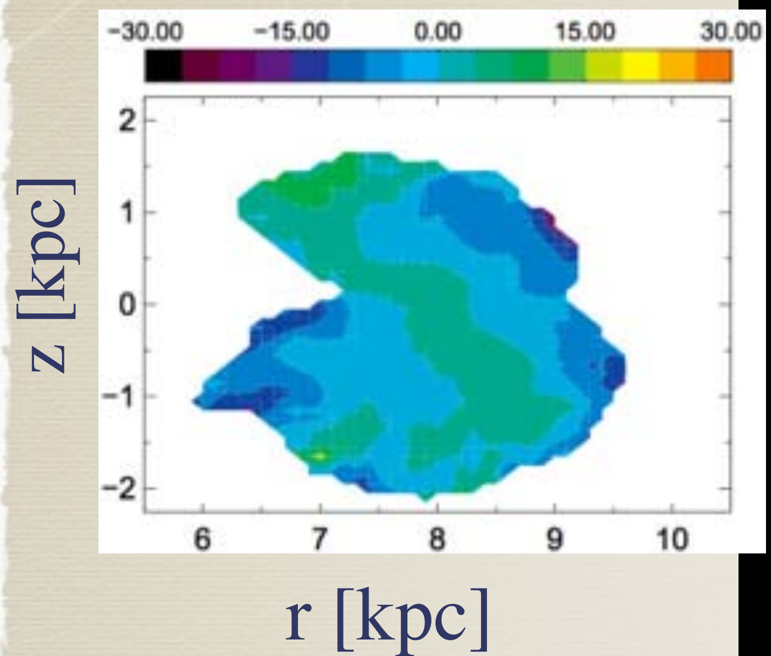
Neither?

Stellar velocity distribution, Dehnen (1998)



Some examples of outstanding problems

- What is the nature of the vertical wave patterns seen in the Milky Way disk?

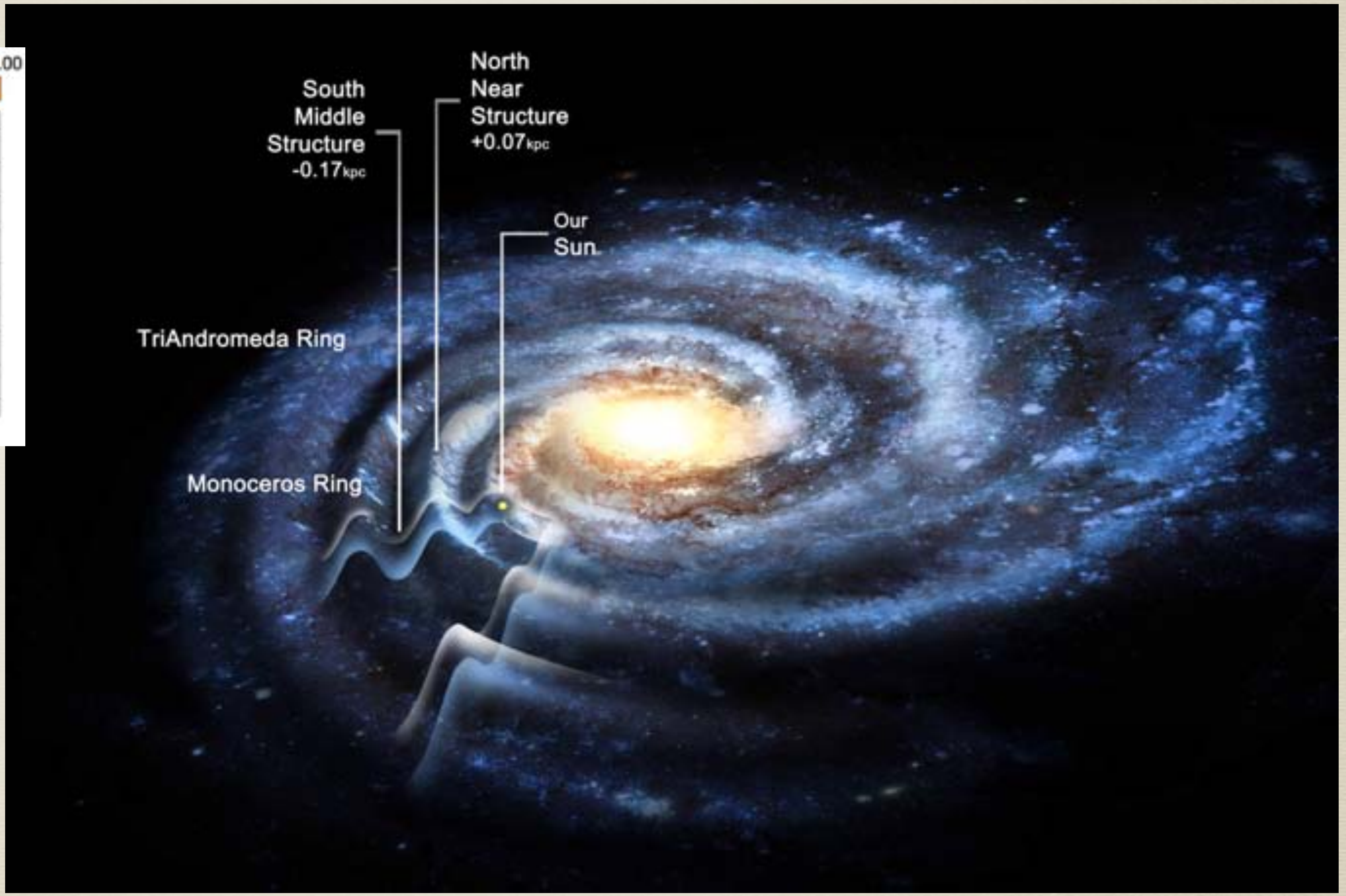


Willams + RAVE (2013)

First reported from SEGUE G-dwarfs by Widrow et al. (2012)

Also seen in LAMOST data

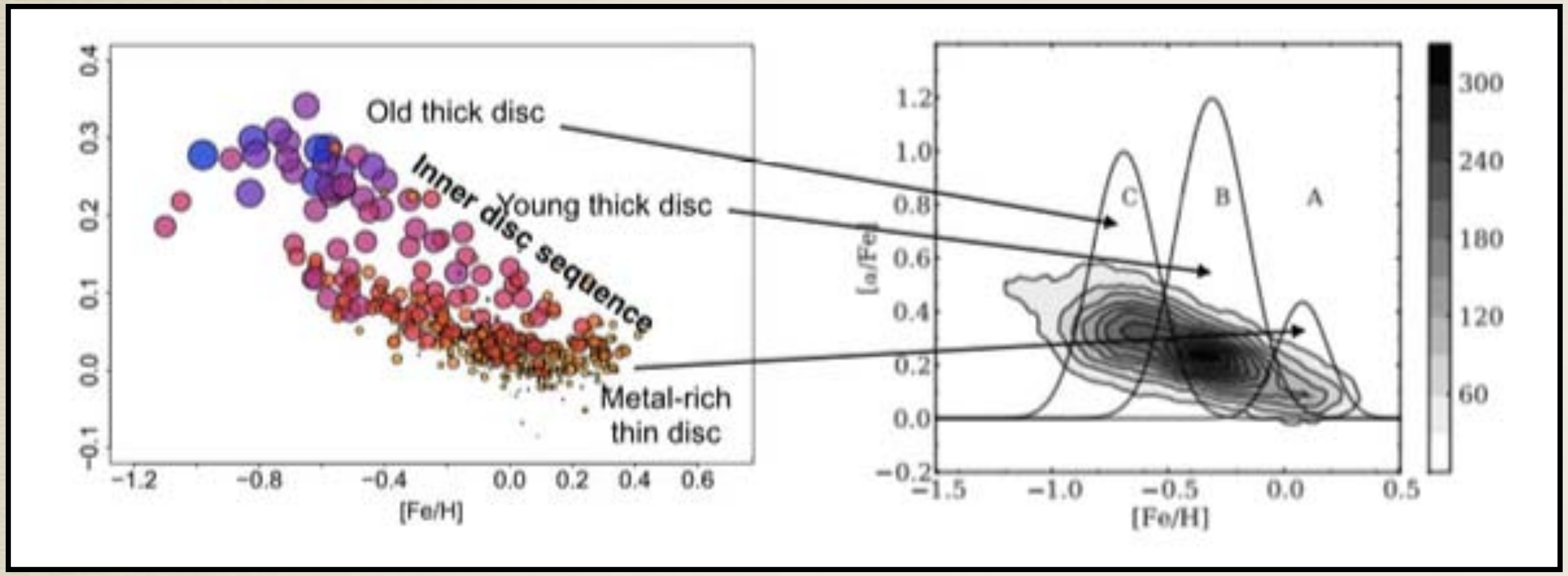
(Carlin et al. 2013)



- Are the local vertical disk asymmetries and Monoceros Ring part of the same global structure?
- Caused by bar/spirals or Sgr dwarf?

Some examples of outstanding problems

- **Bulge formation:** Inward stellar migration gives rise to different stellar populations in the bulge?



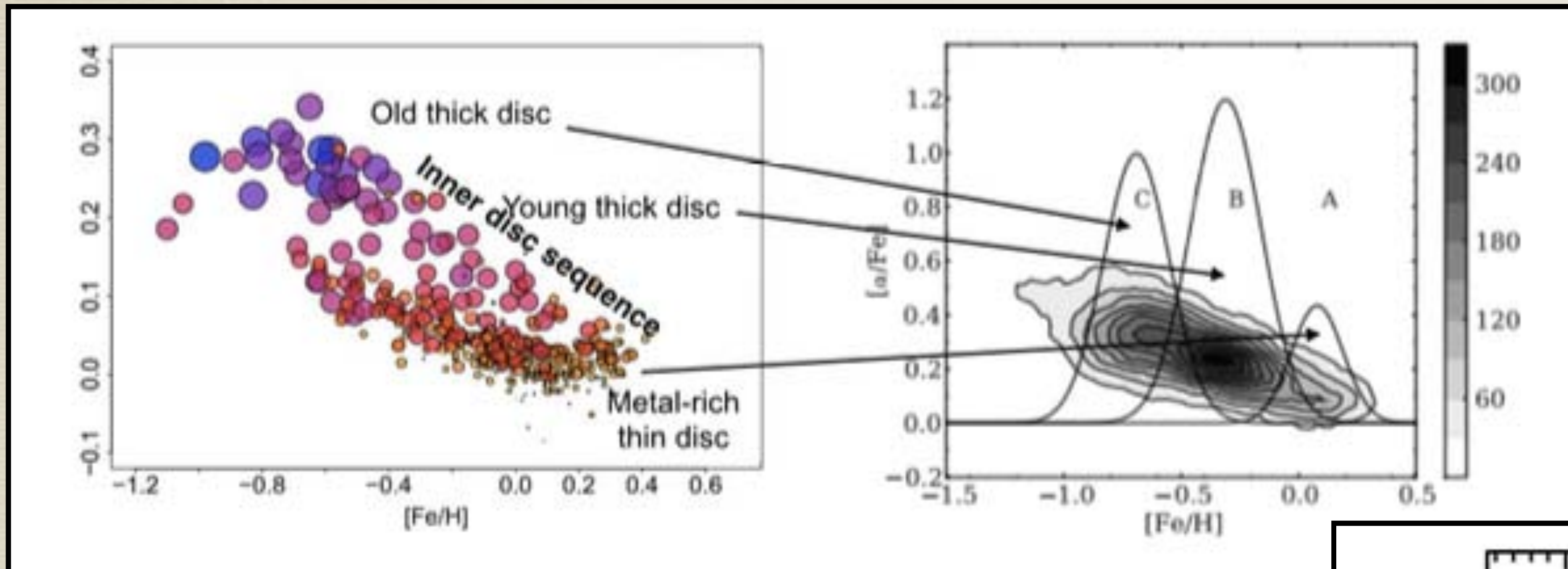
Di Matteo (2016)

Local HARPS Adibekyan sample Haywood et al. (2013)

ARGOS bulge data Ness et al. (2014)

Some examples of outstanding problems

- **Bulge formation:** Inward stellar migration gives rise to different stellar populations in the bulge?



Di Matteo (2016)

Local HARPS Adibekyan

sample Haywood et al. (2013)

ARGOS bulge da

Ness et al. (2014)

or

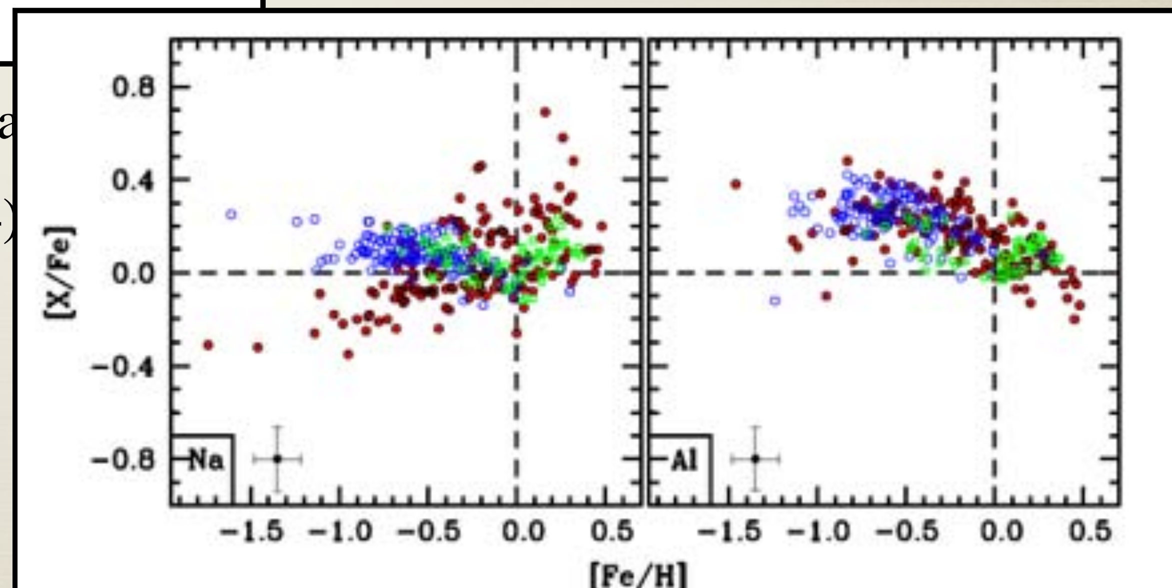


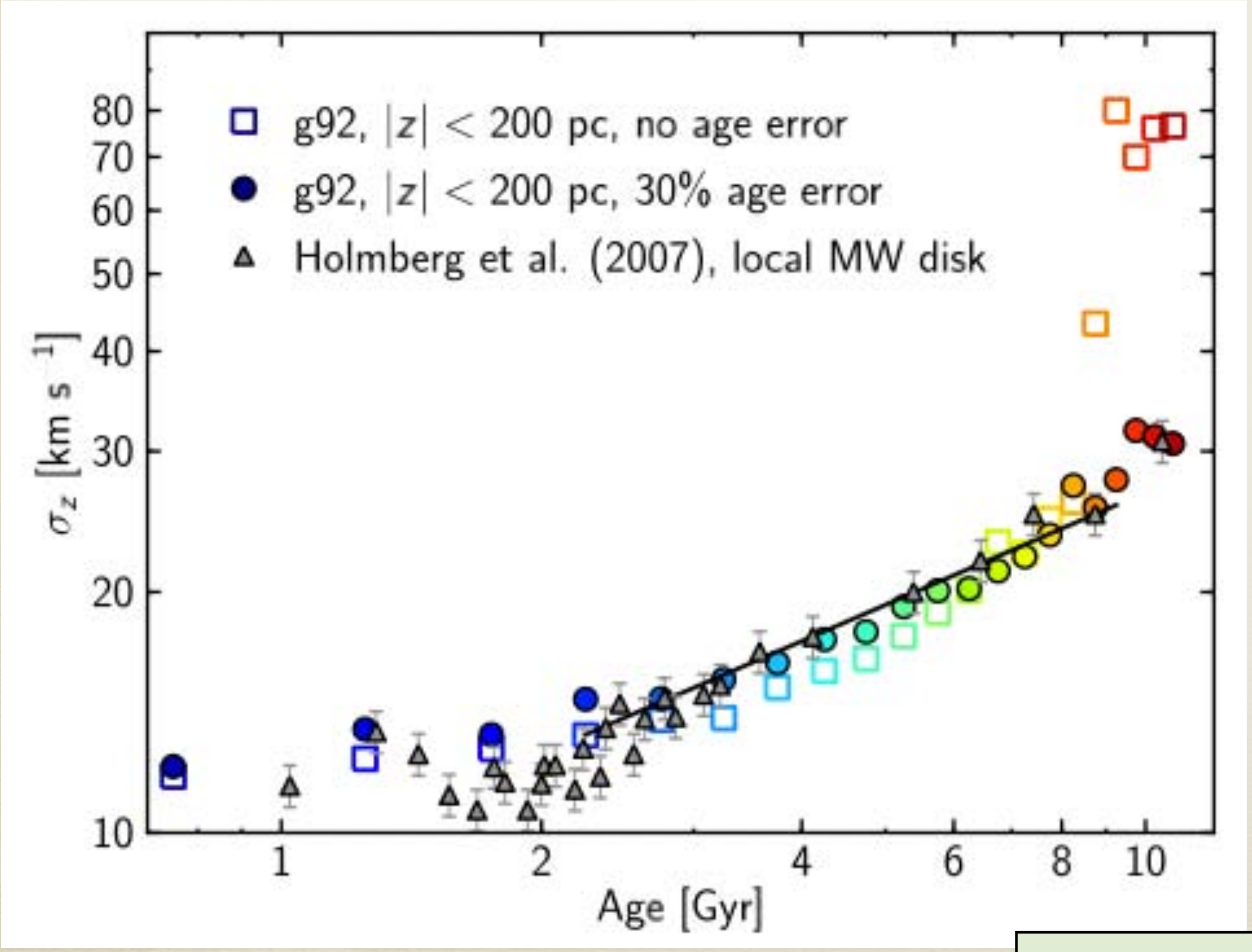
Figure 16. Plot of [Na/Fe] and [Al/Fe] ratios as a function of [Fe/H] for the bulge stars measured here (filled red circles), thick disk stars (open blue circles), and thin disk stars (open green boxes). The literature data are from the sources referenced in Figure 14.

Johnson et al. (2014)

- Bulge chemistry distinct from that of the thick disk?

Some examples of outstanding problems

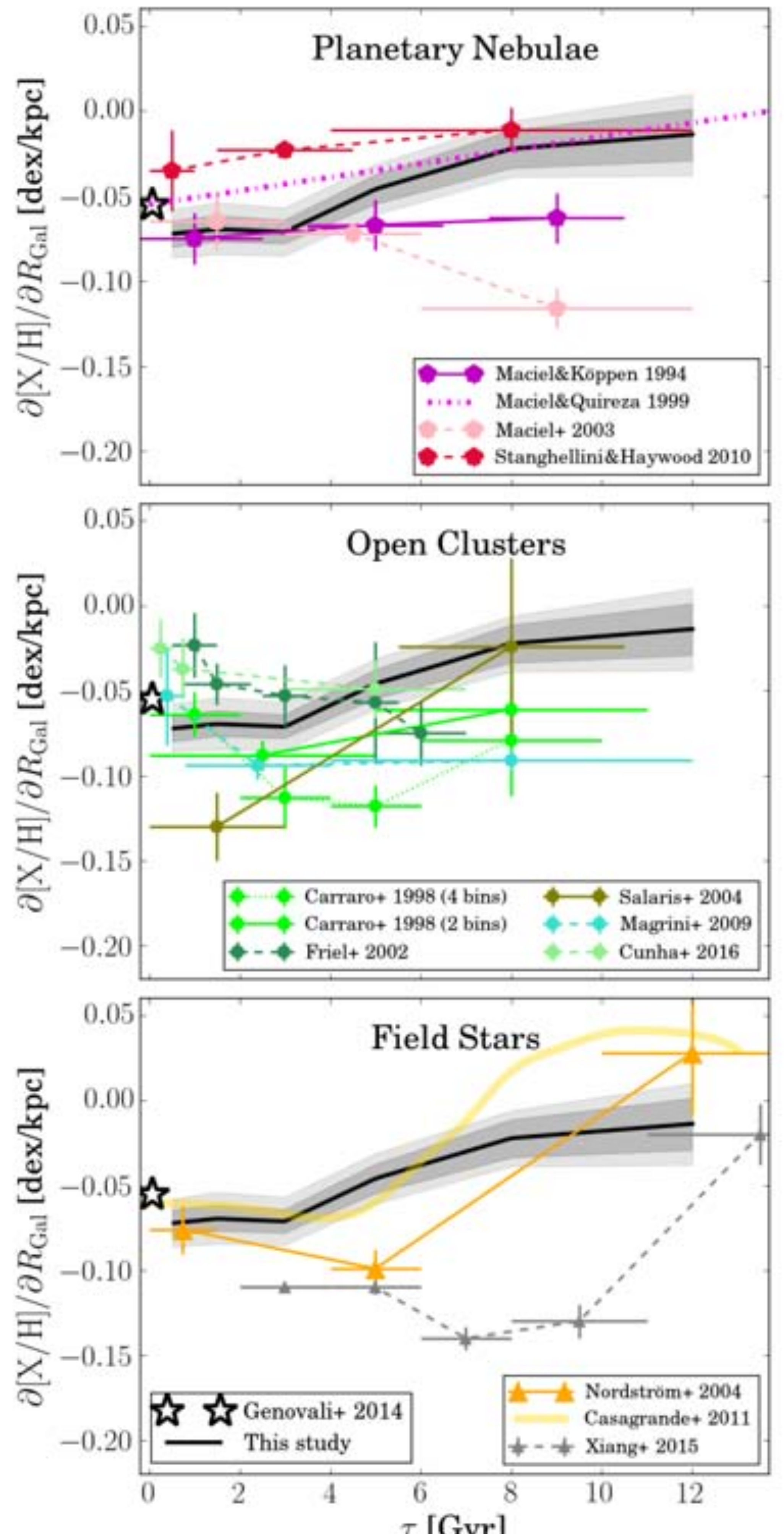
- **The age-velocity relation**: Increase of stellar velocity dispersion with age as a power law or a step at 8-10 Gyr from last massive merger?



Step at 10 Gyr due to strong mergers.

Erased when 30% age errors convolved into simulated data.

Martig, Minchev and Flynn (2014b)

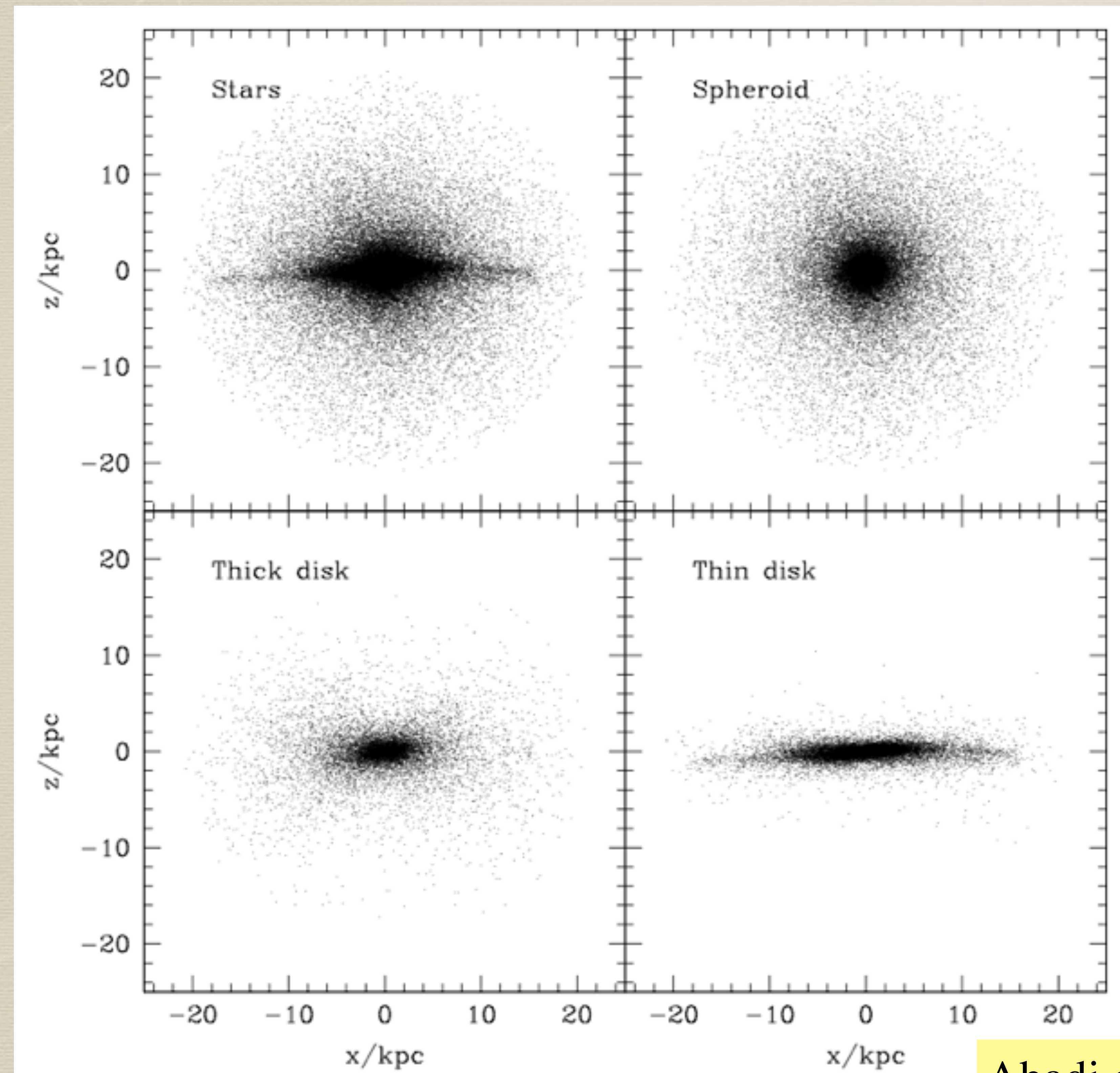


The time evolution of the radial metallicity gradient

- Using APOGEE abundances + CoRoT asteroseismic ages (CoRoTGEE sample)
- Mean gradient mostly constant over the past 5 Gyr
- Scatter caused by radial migration

Anders et al. (2016b)

Disk formation in cosmological simulations



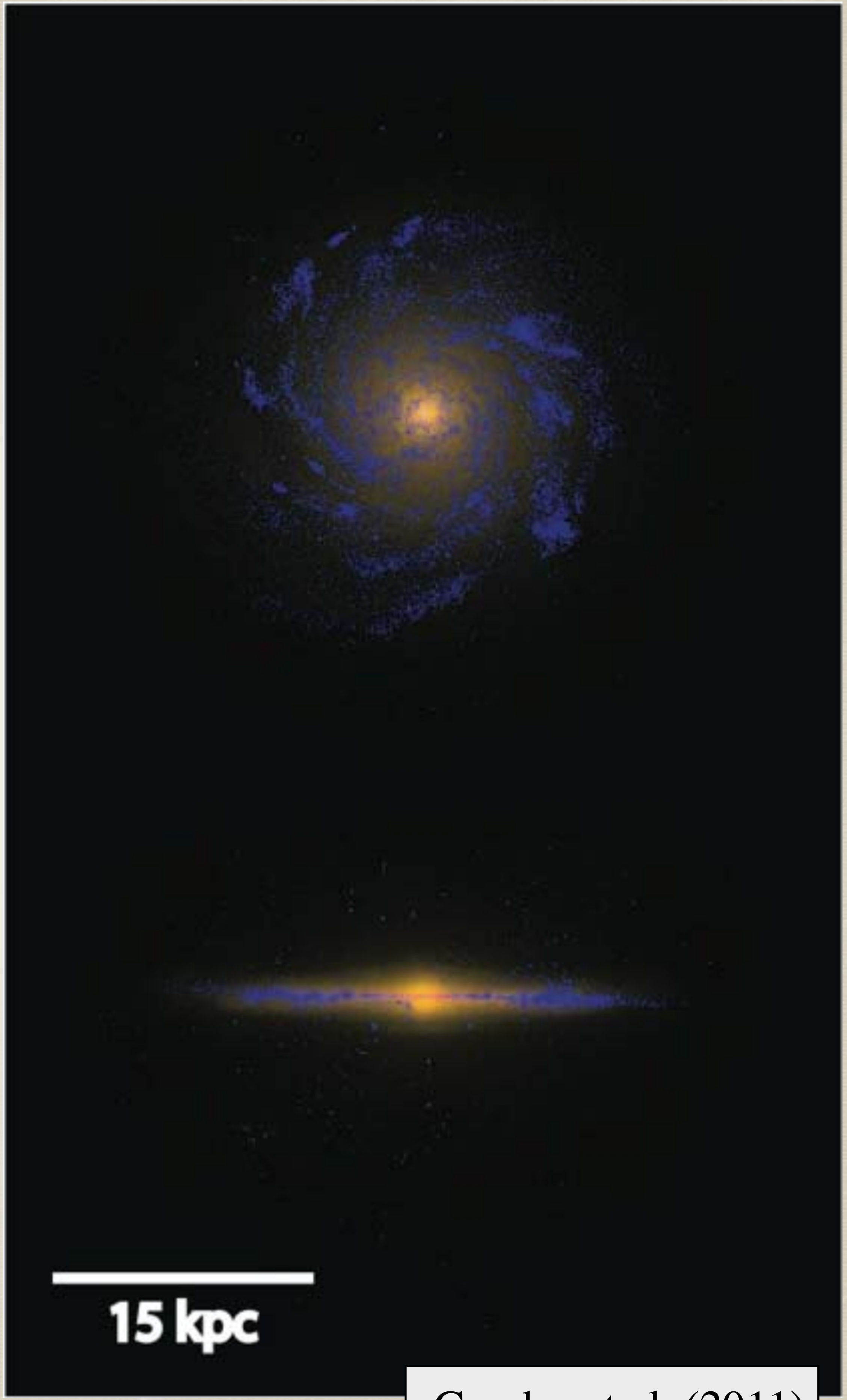
- Traditionally a challenge (e.g., Navarro and Benz 1991; Abadi et al. 2003):
- Extreme angular momentum loss during mergers.
- Overly-concentrated mass distributions and massive bulges.

Abadi et al. (2003)

Recent improvements

- Increase in resolution and better modeling of star formation and feedback produce MW-mass galaxies with reduced bulge fractions (e.g., Agertz et al. 2011; Guedes et al. 2011; Martig et al. 2012).

- However, no chemical treatment!



ERIS simulation

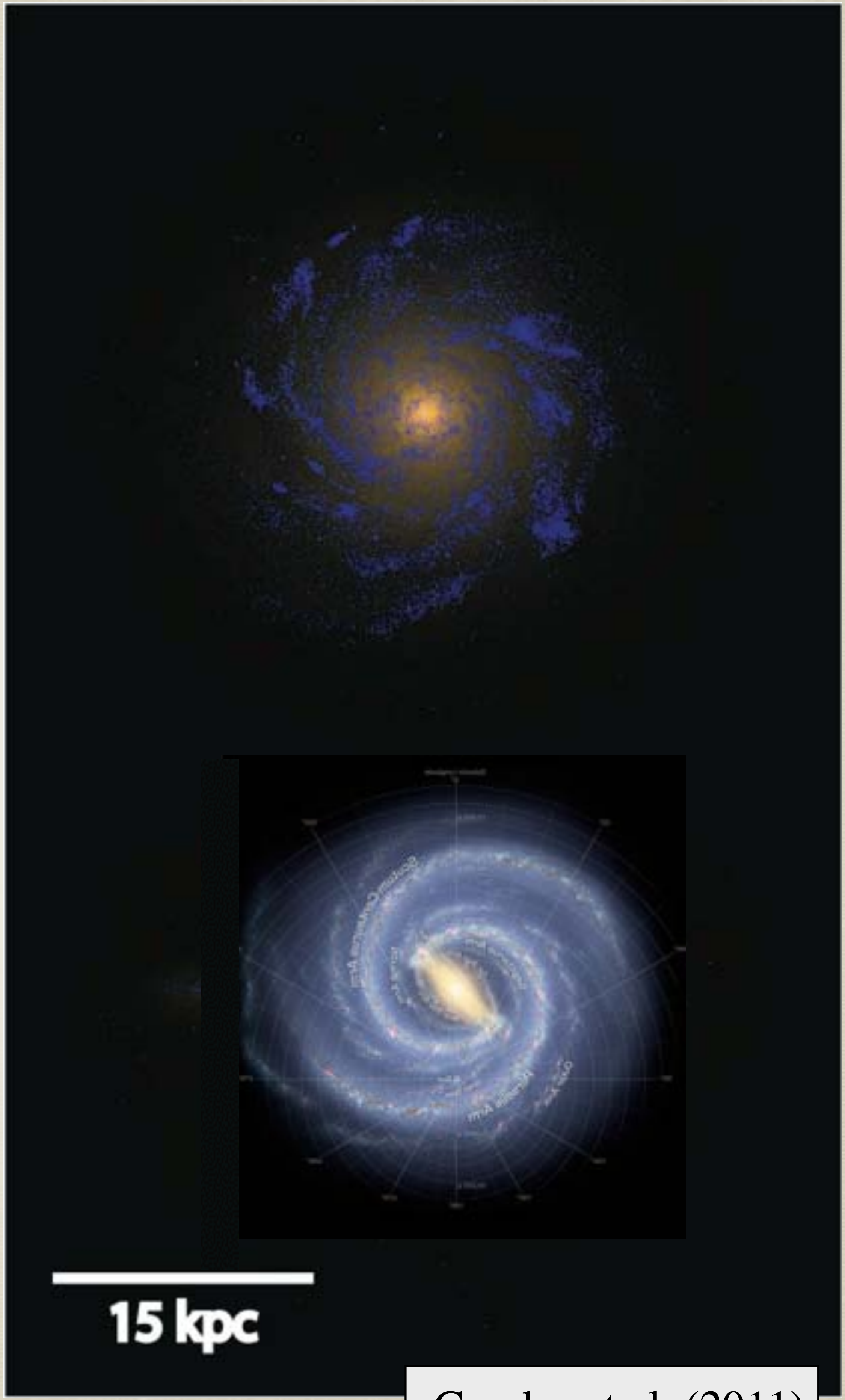
Guedes et al. (2011)

Recent improvements

- Increase in resolution and better modeling of star formation and feedback produce MW-mass galaxies with reduced bulge fractions (e.g., Agertz et al. 2011; Guedes et al. 2011; Martig et al. 2012).

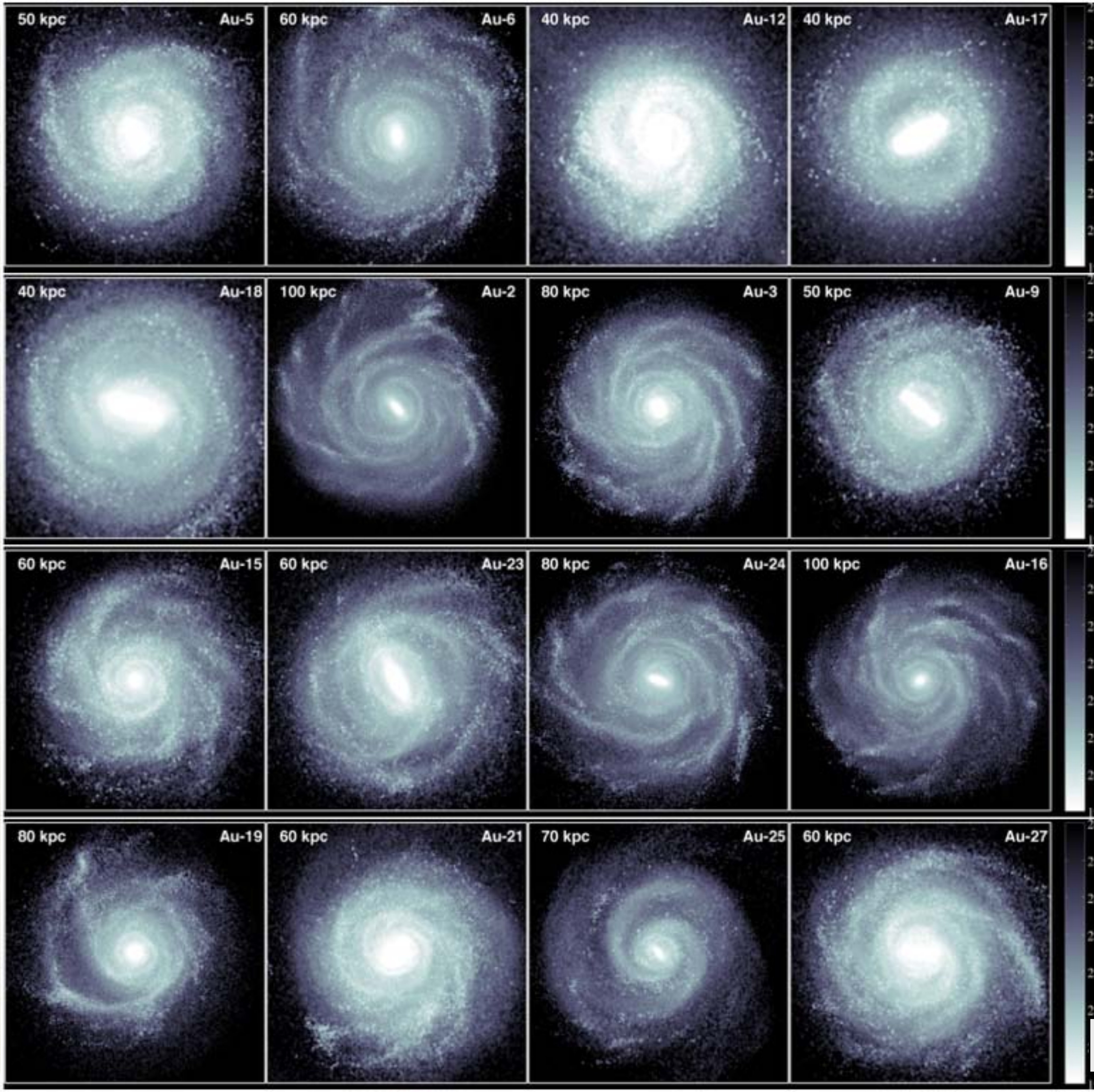
- However, no chemical treatment!

- Milky Way disk morphology not easily reproducible in fully cosmological simulations.



ERIS simulation

Guedes et al. (2011)



Auriga simulations

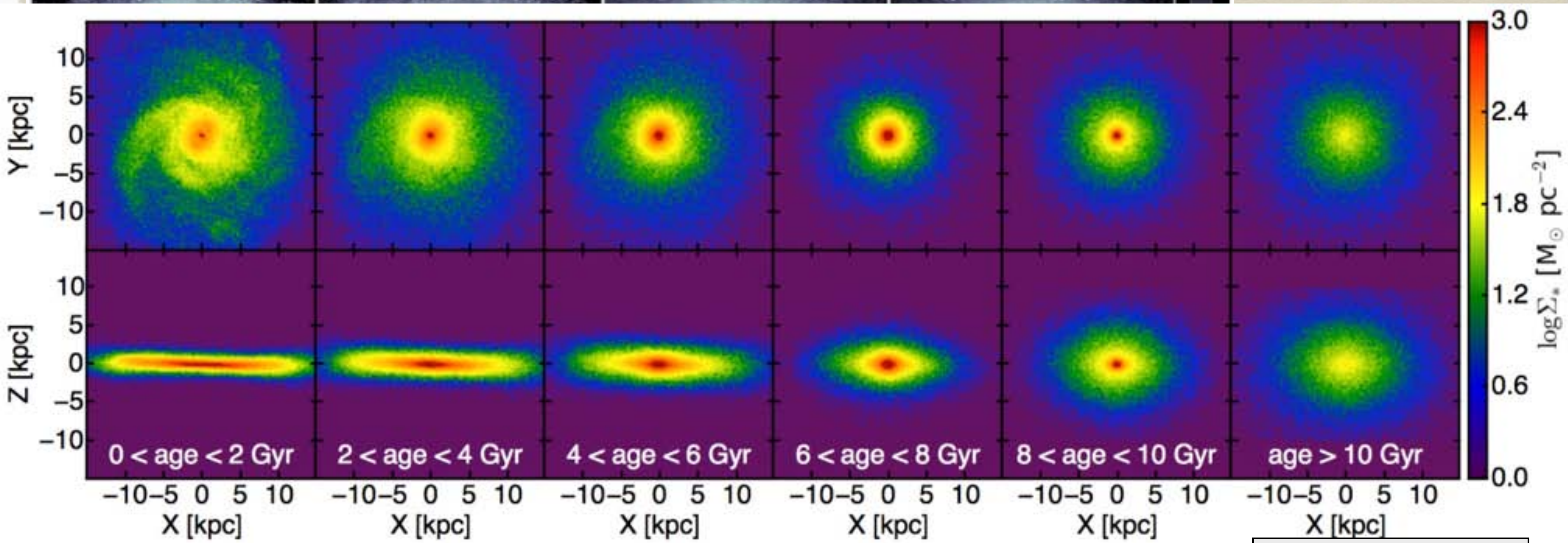
AREPO code

(Springel 2010, Vogelsberger et al. 2013, Marinacci et al. 2014)

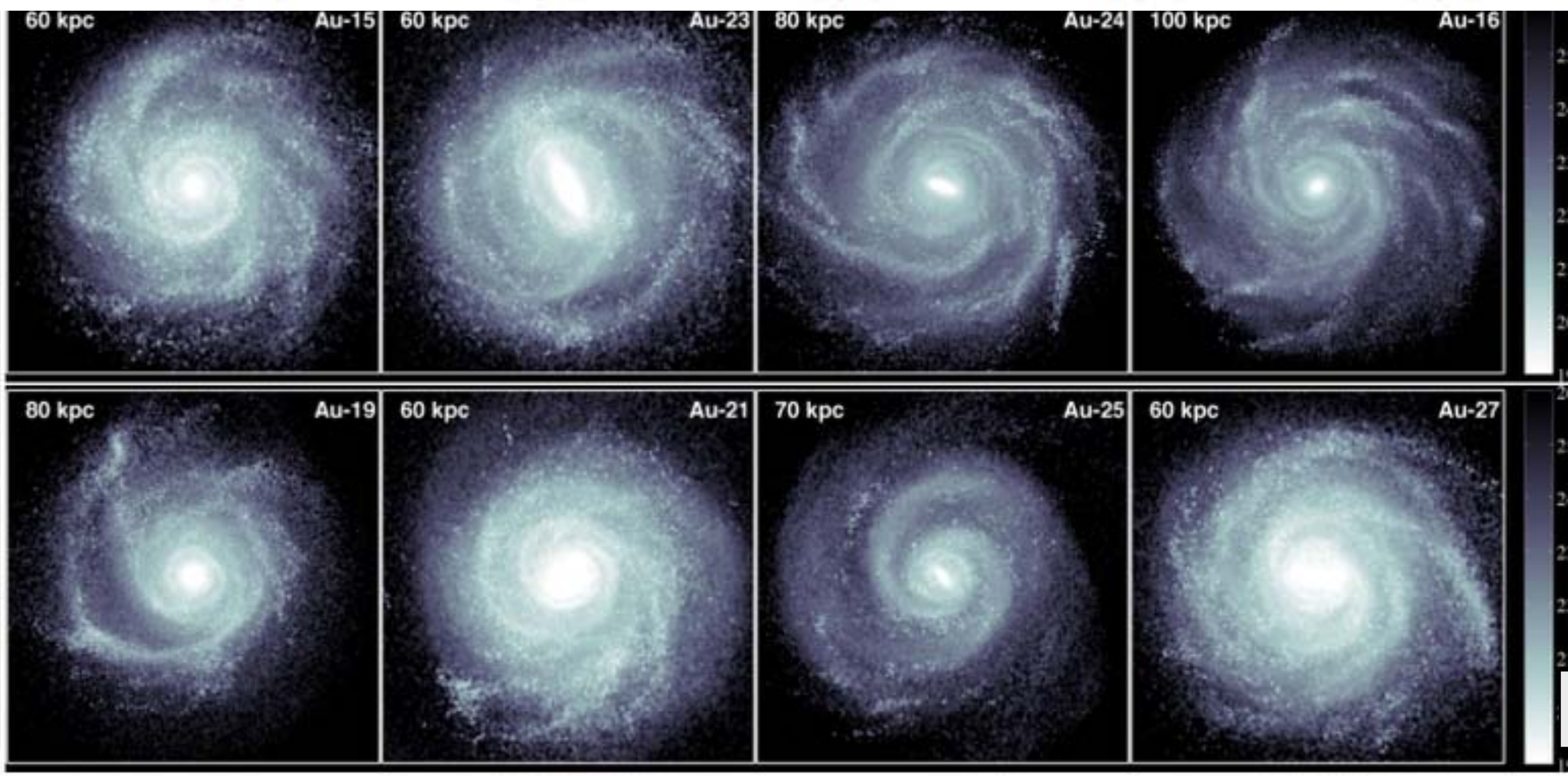
~10e4 M* resolution.

369 pc spatial res.

Gómez et al. (2016)



Ma et al. (2016)

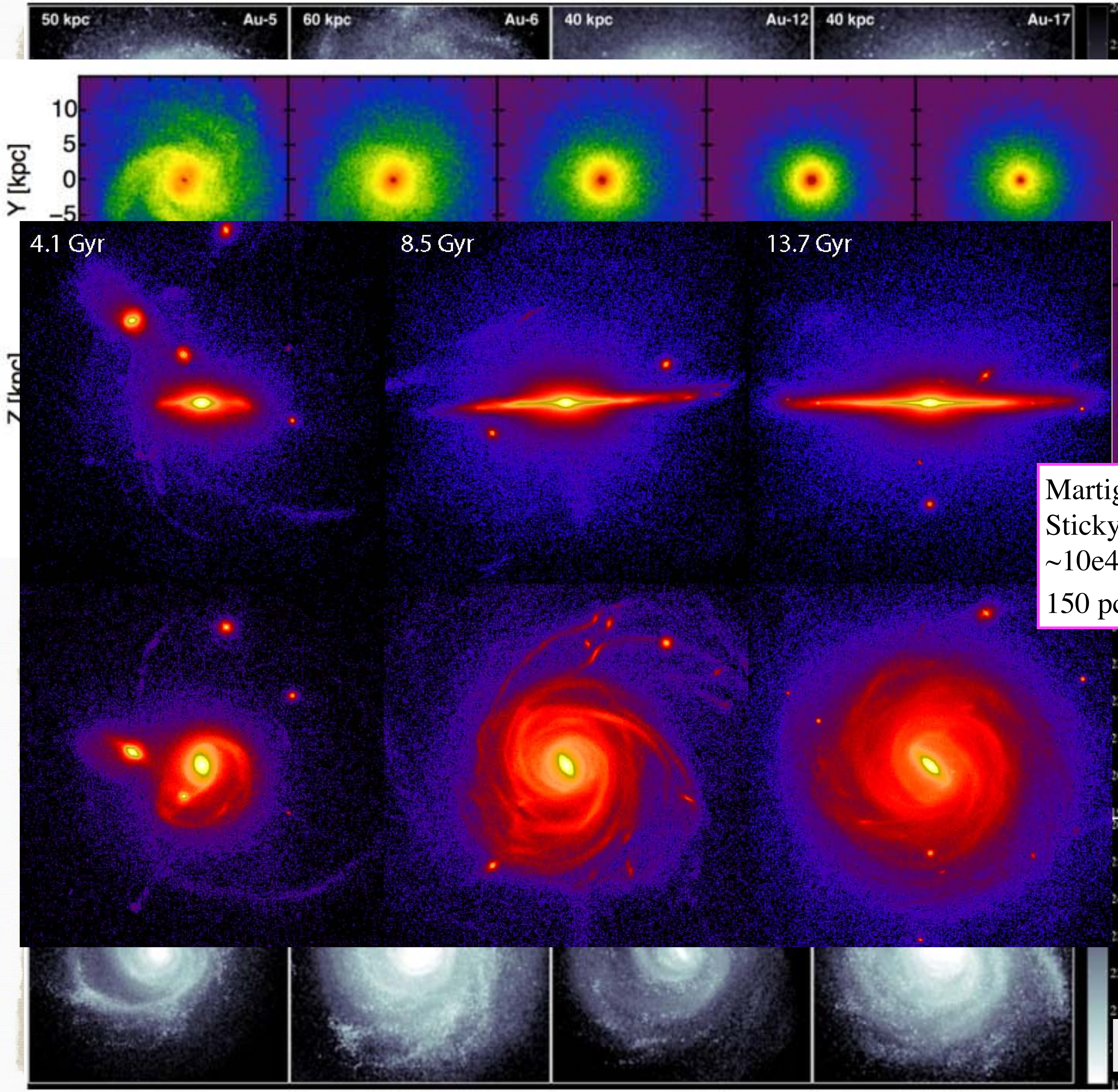


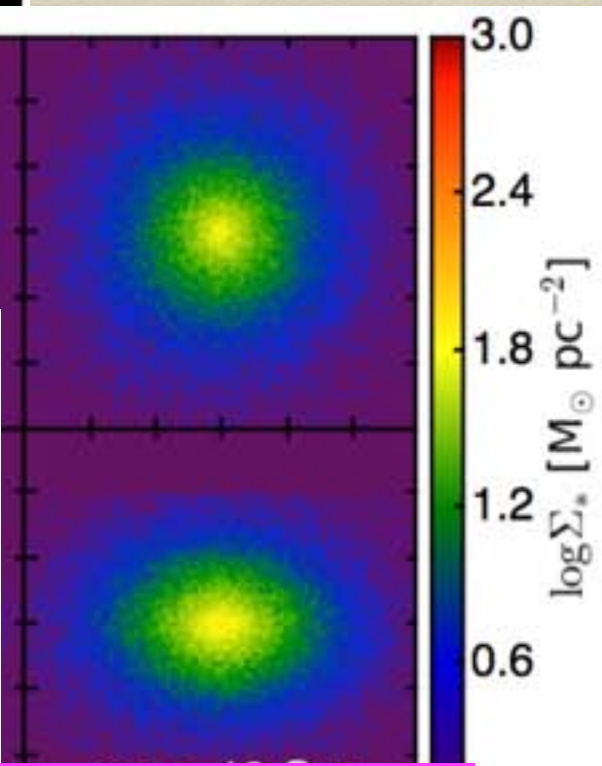
FIRE project simulation
(GIZMO code, Hopkins 2014)

~10e4 M* resolution.

50 pc spatial res.

Gómez et al. (2016)





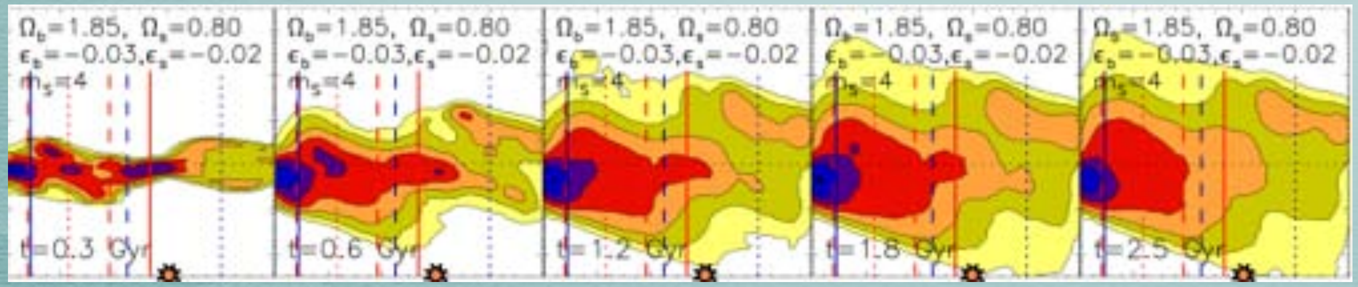
Martig et al. (2012)
Sticky particles
~10e4 M* resolution.
150 pc spatial res.

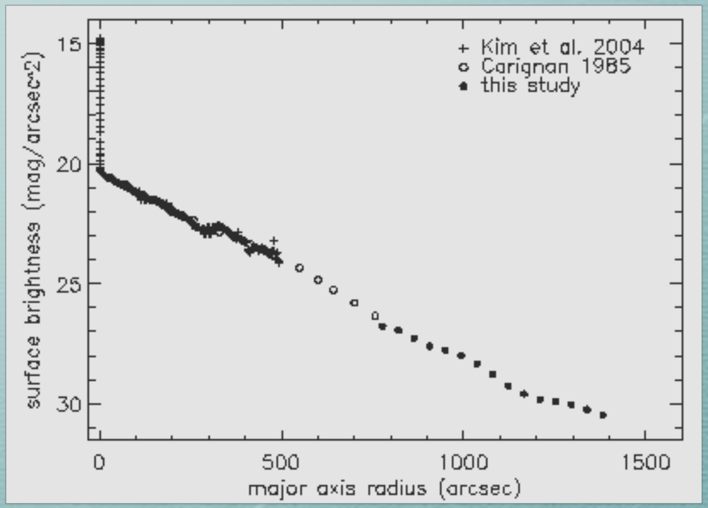
FIRE project simulation
(GIZMO code, Hopkins 2014)
~10e4 M* resolution.
50 pc spatial res.

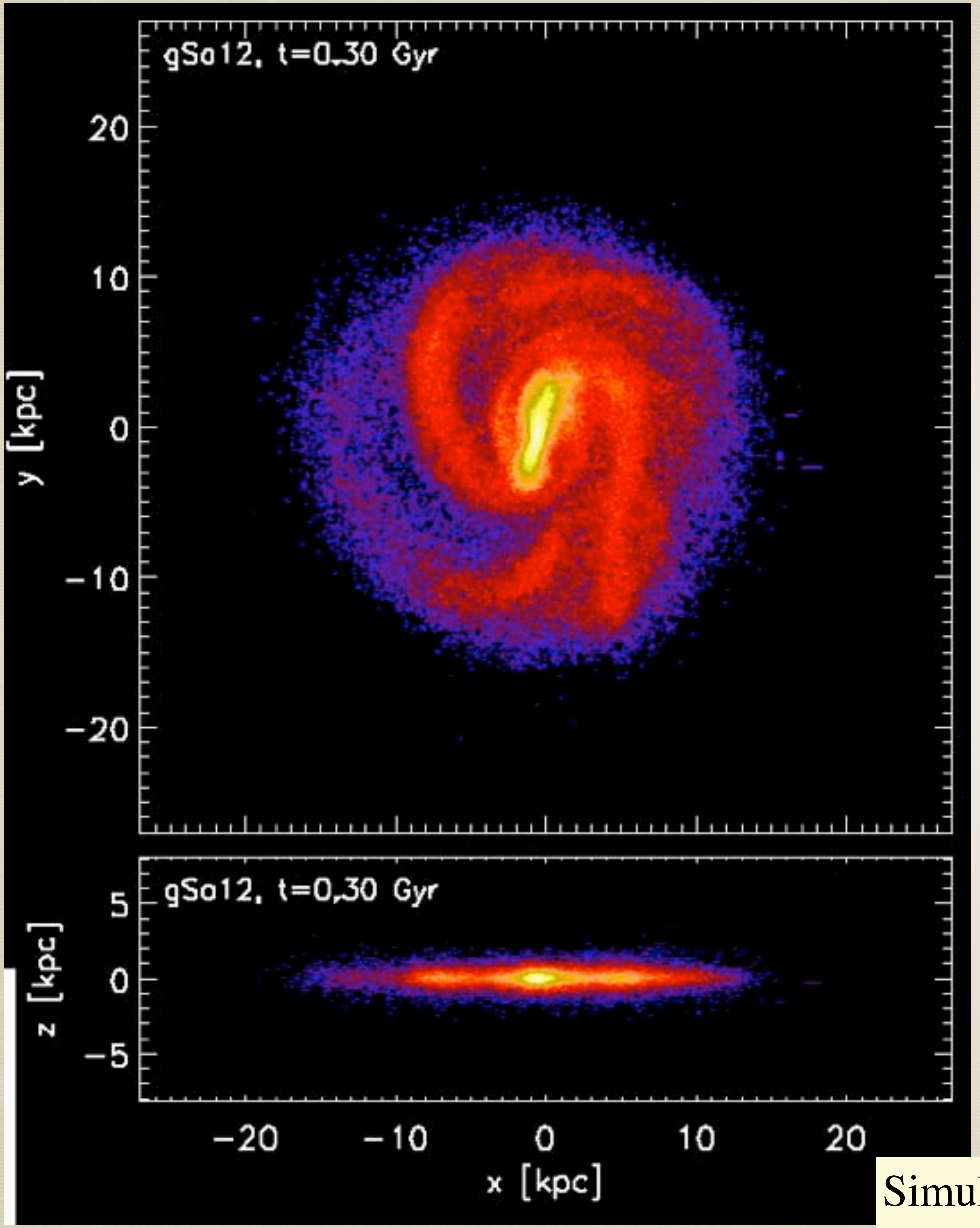
Gómez et al. (2016)

Stellar radial migration

- Formally introduced by Sellwood and Binney (2002)
- A number of works on the topic since:
  - Roskar et al. (2008), Schoenrich and Binney 92009) - from transient spirals
  - Quillen et al. (2009), Bird et al. (2013) - from orbiting satellites
  - Minchev and Famaey (2010) - from multiple long-lived patterns
  - Grand et al. (2012) - corotating spirals







N-body Tree-SPH

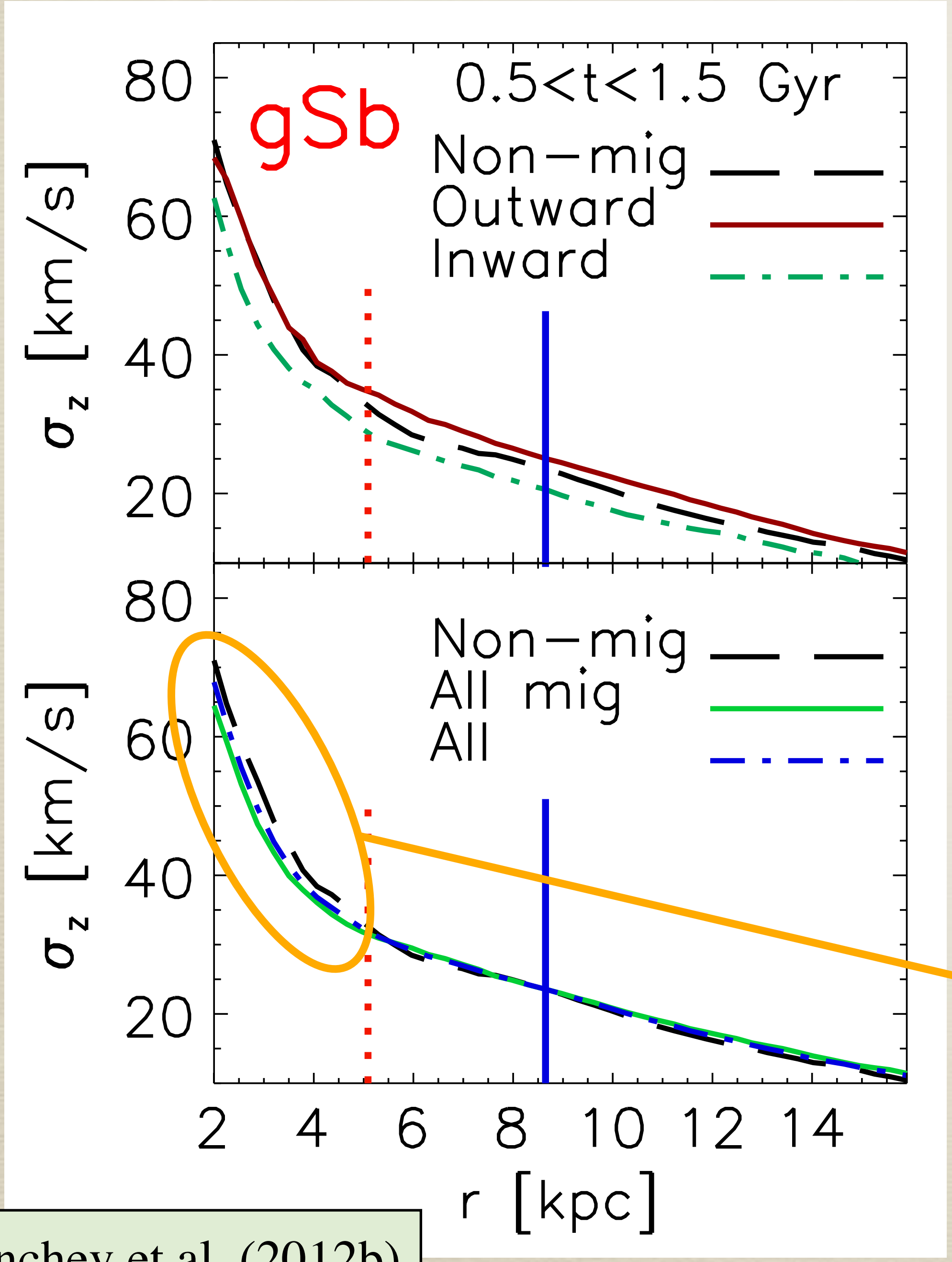
Disk expands due to strong angular momentum transport outwards (Minchev et al. 2012a).

Disk thickens from bar/ spirals. Not from radial migration (see Minchev et al. (2012b)!

Simulation by P. Di Matteo

Migrators' contribution to the disk velocity dispersion in the absence of mergers

Vertical velocity dispersion

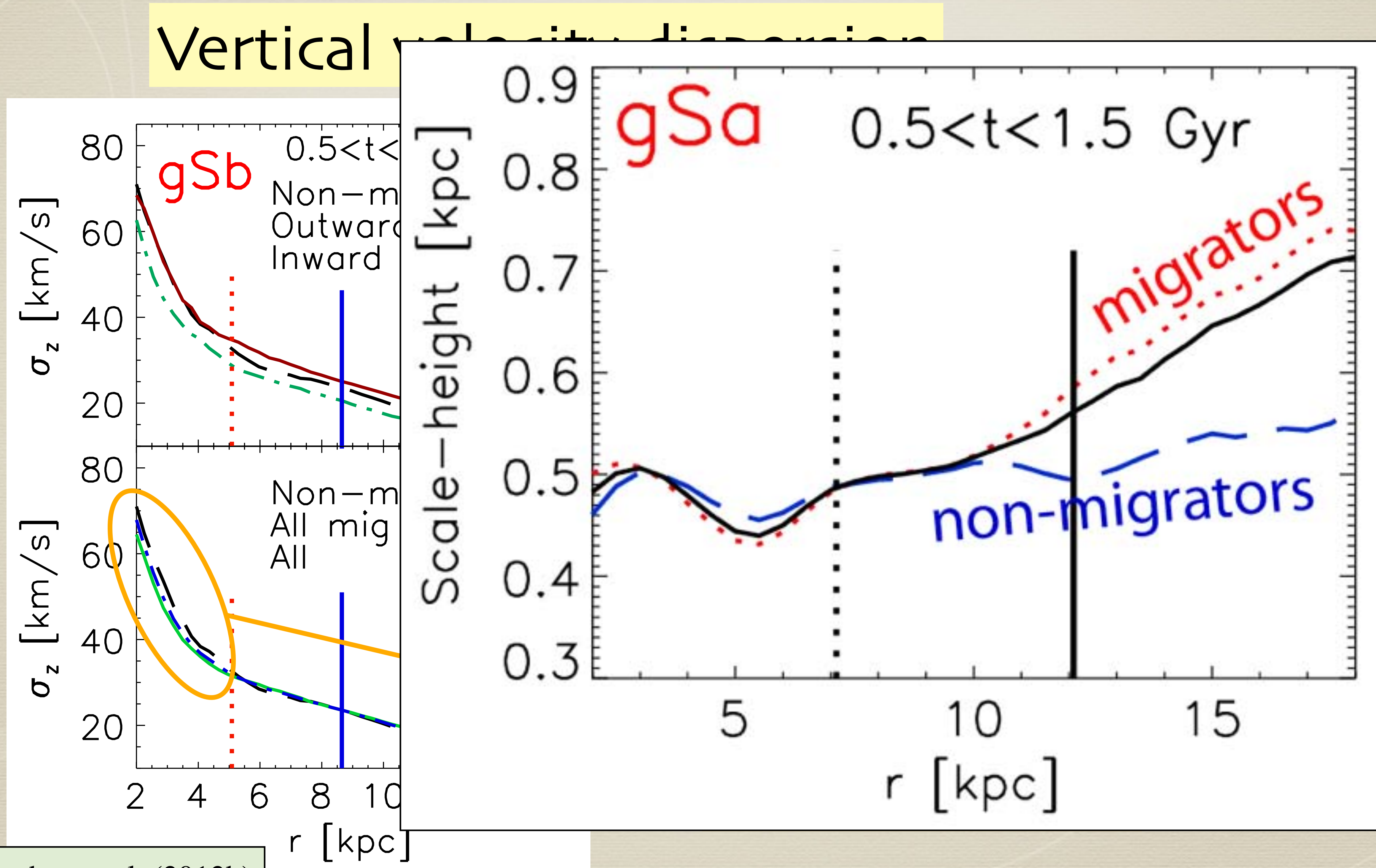


Minchev et al. (2012b)

- Some increase in velocity dispersion from outward migrators.
- Some decrease in velocity dispersion resulting from inward migrators.
- Negligible overall effect to disk thickening.
- In agreement with Vera-Ciro et al. (2013, 2014), Martig et al. (2014), Grand et al. (2016), Aumer et al. (2016)

Vertical disk cooling!

Migrators' contribution to the disk velocity dispersion in the absence of mergers



Minchev et al. (2012b)

Conservation of vertical action

Vertical and radial actions conserved if:

- Vertical motion decouples from the radial motion
- Stars migrate (change guiding radii) slower than vertical and epicyclic oscillations.

Then $J_z = E_z/\nu = Const.$

Vertical energy — Vertical epicyclic frequency

From Gauss' law and Poisson's equation $\nu \sim \sqrt{2\pi G\Sigma}$,

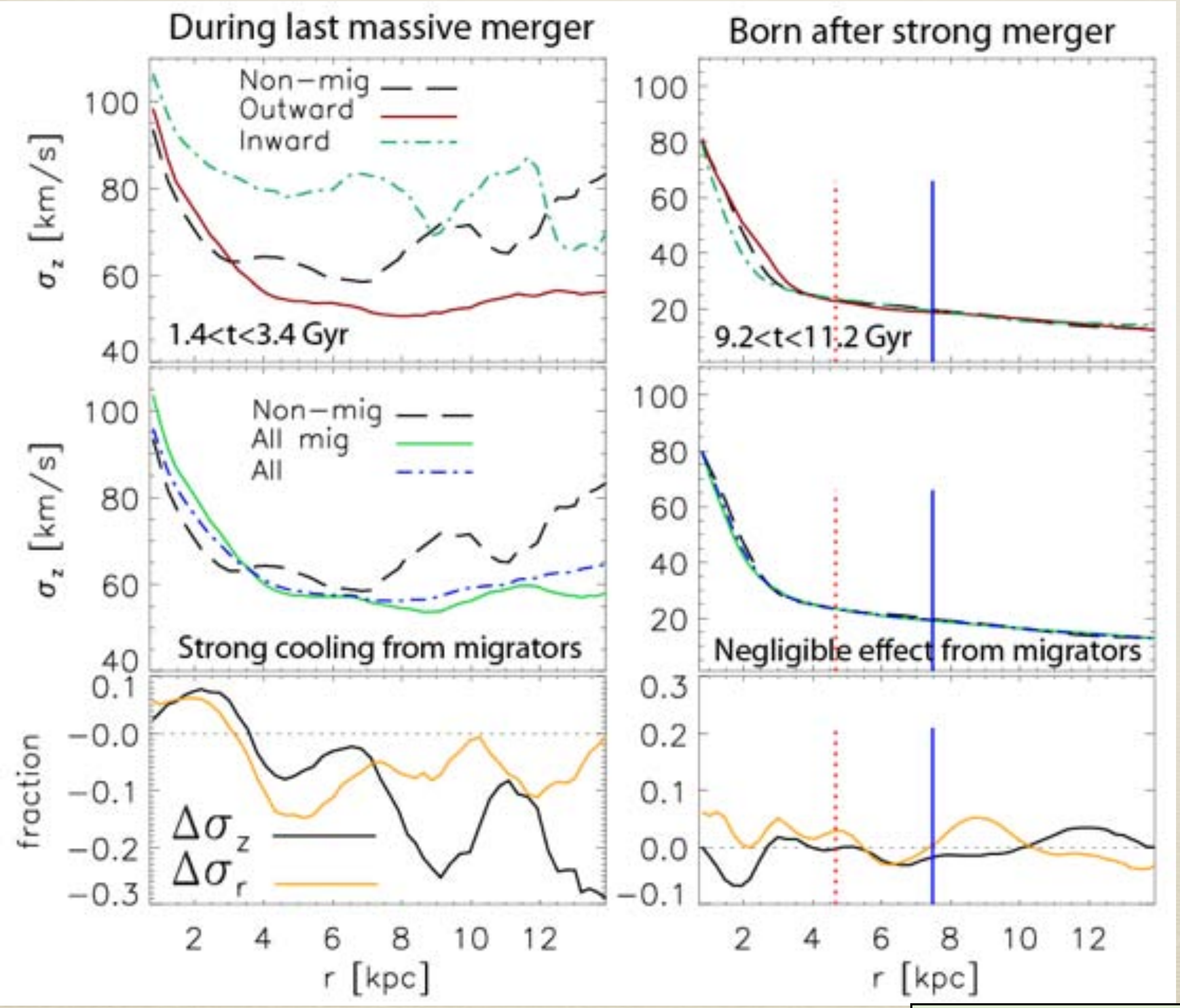
$\Sigma \sim \exp(-r/r_d)$ ⟶ $\nu(r) \sim \exp(-r/2r_d)$

Therefore, to preserve vertical action $\langle E_z \rangle \sim \sigma_z^2 \sim \exp(-r/r_d)$

Migration cools the disk during mergers

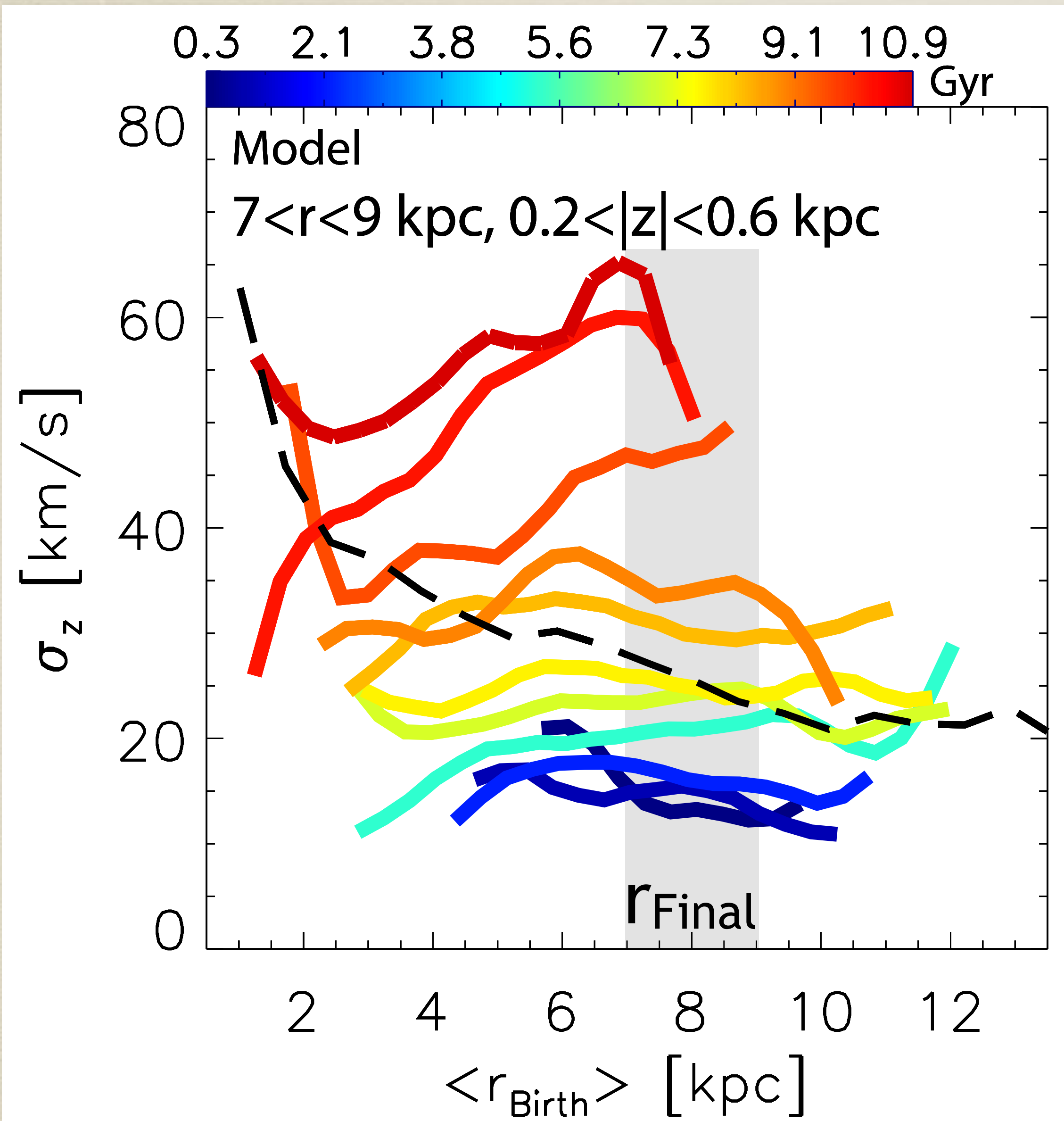
Migration works against disk flaring

No effect on the vertical velocity dispersion.



Minchev, Chiappini and Martig (2014)

Radial migration cools outer disk



Minchev + RAVE (2014)

When a realistic disk growth in the cosmological context considered, migration cools outer disk.

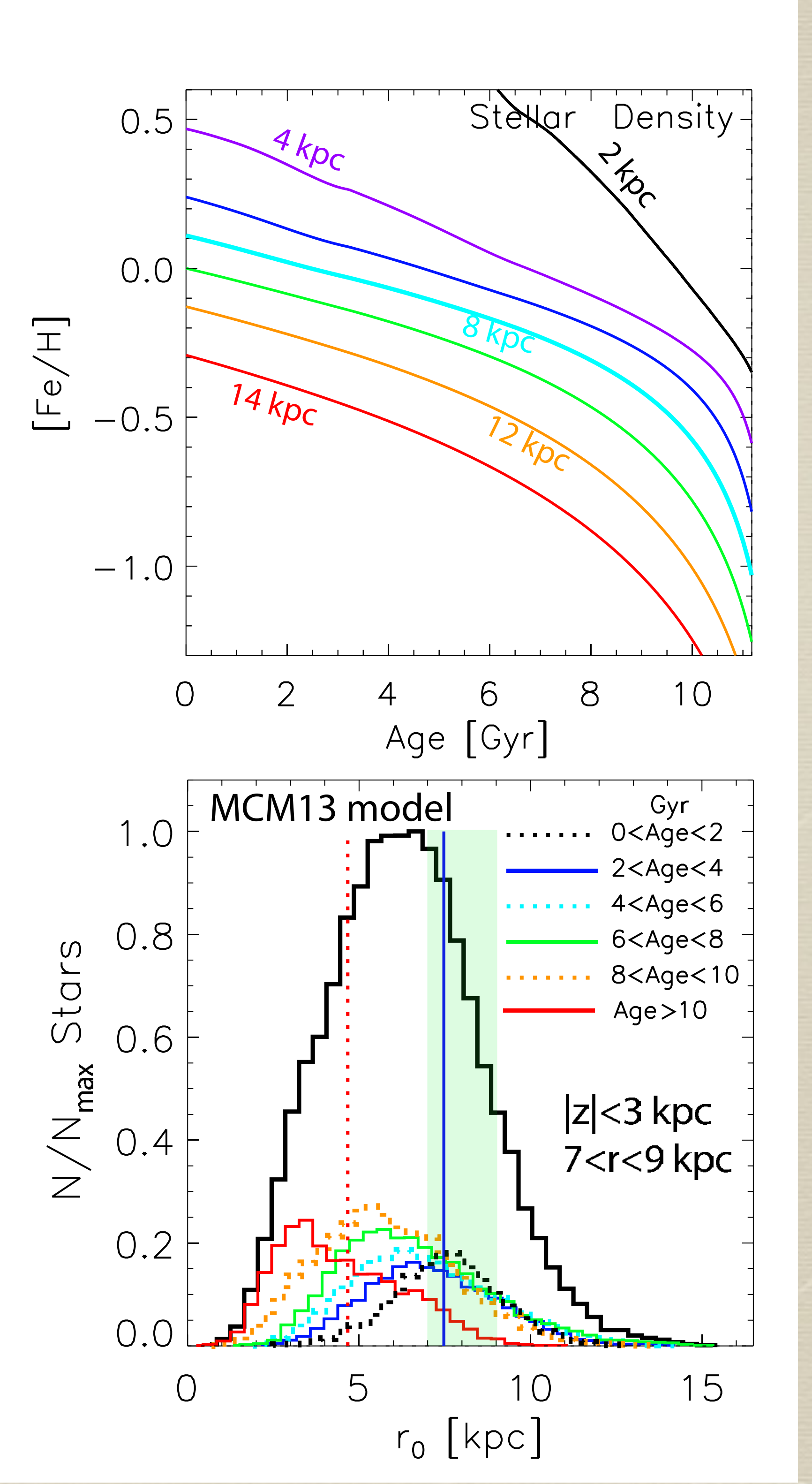
Old stars coming from the inner disk are cooler than locally born stars by up to 30 km/s.

Slope becomes negative for the last several Gyr (no significant mergers).

Explains inversion of vel. dispersion - [Mg/Fe] relation in RAVE and SEGUE G-dwarf data.

Classical chemical evolution modeling hampered by radial migration

- Stars move away from their birth places (e.g., Sellwood and Binney 2002, Roskar et al. 2008, Schoenrich and Binney 2009).



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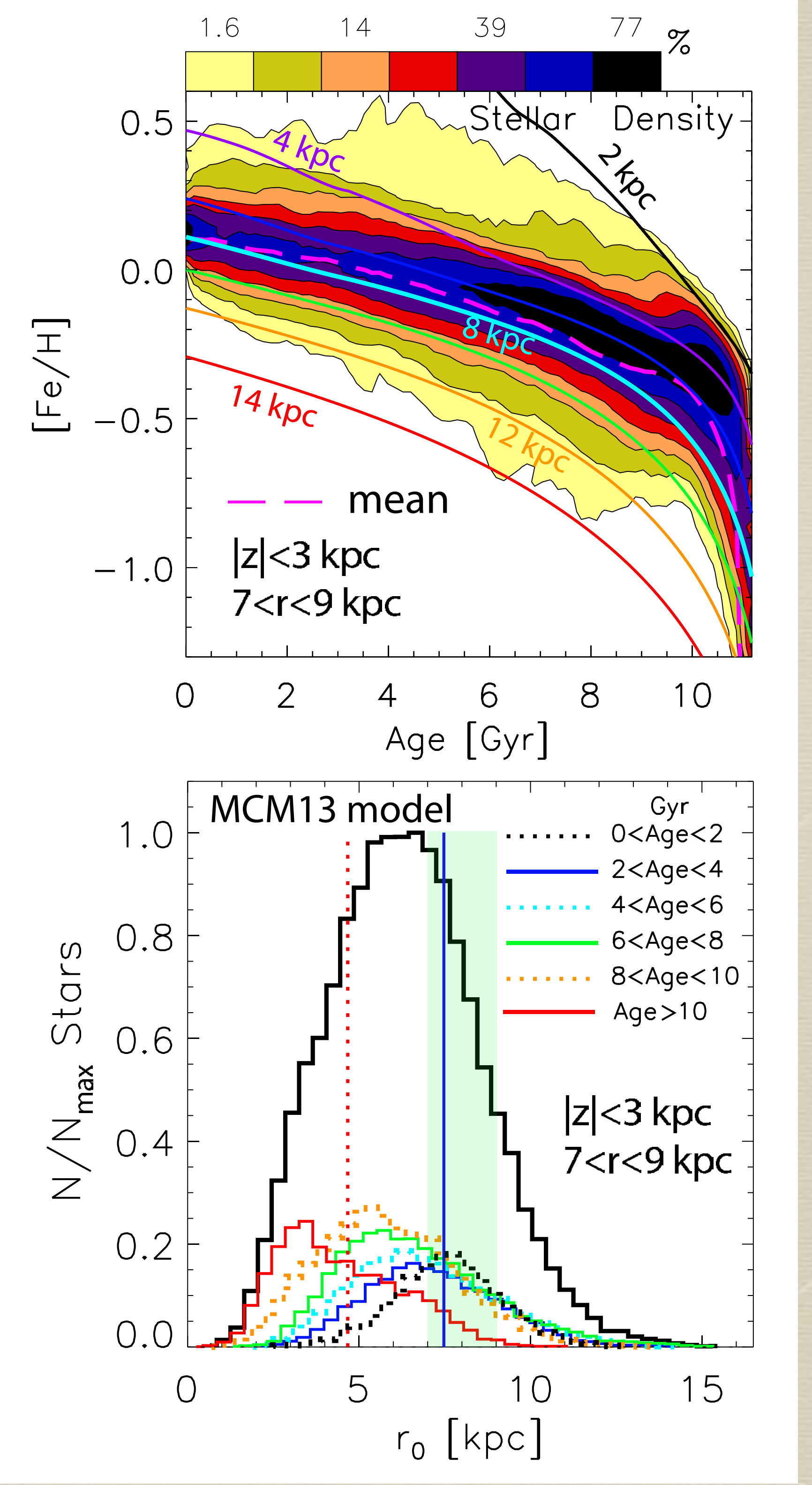
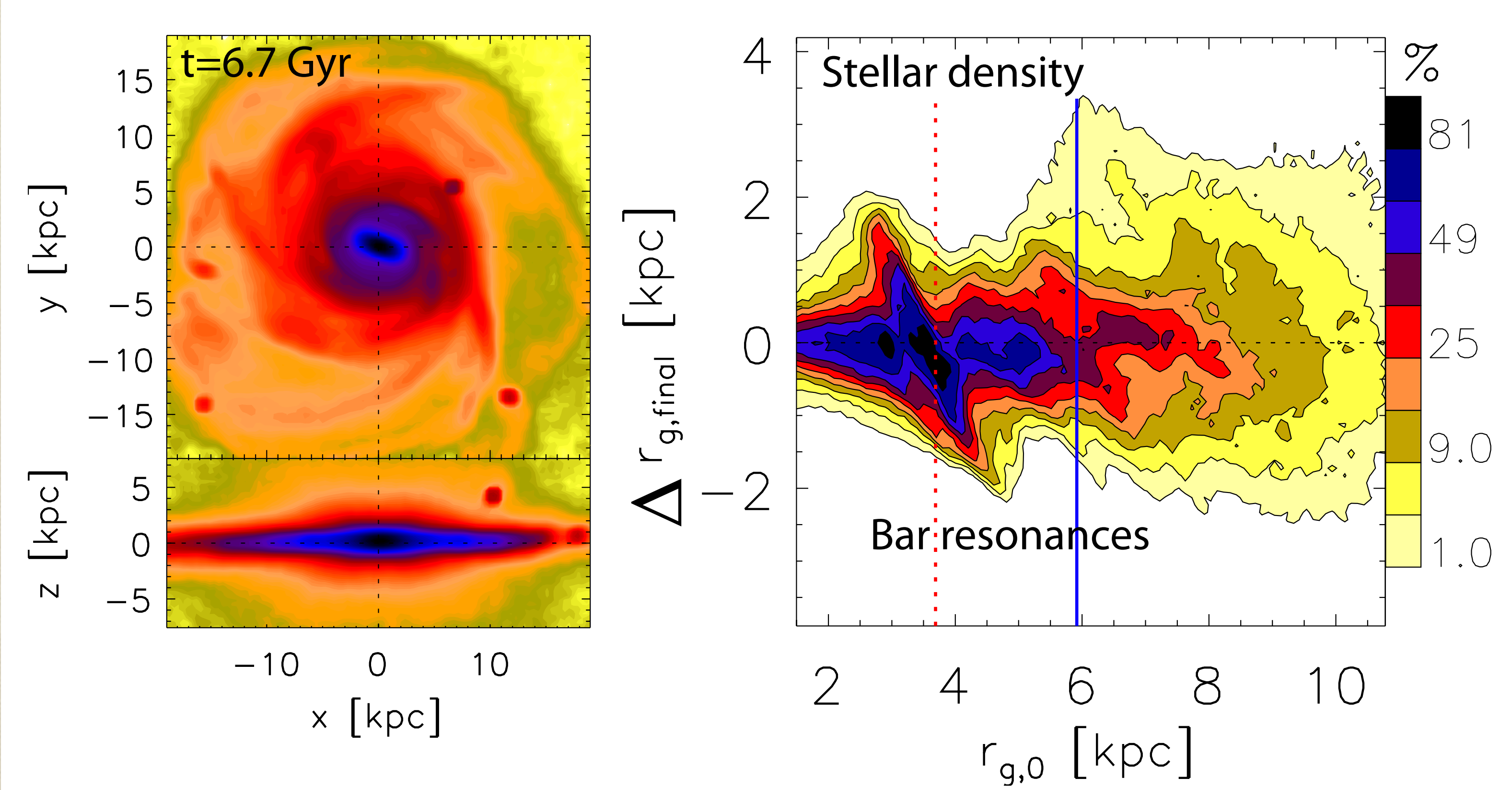
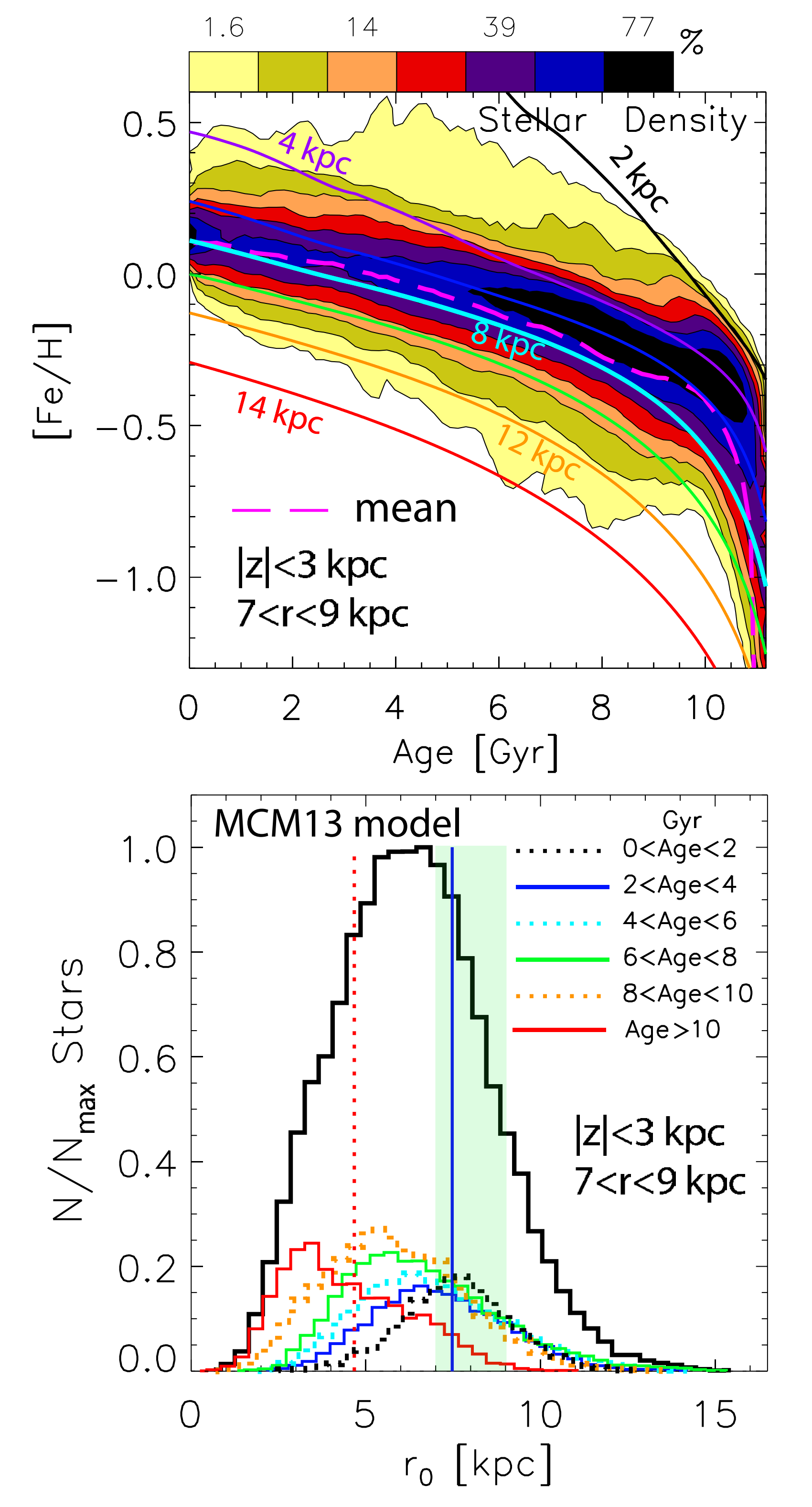


Classical chemical evolution modeling hampered by radial migration

- Stars move away from their birth places (e.g., Sellwood and Binney 2002, Roskar et al. 2008, Schoenrich and Binney 2009).
- We need to recover the migration efficiency as a function of Galactic radius and time.

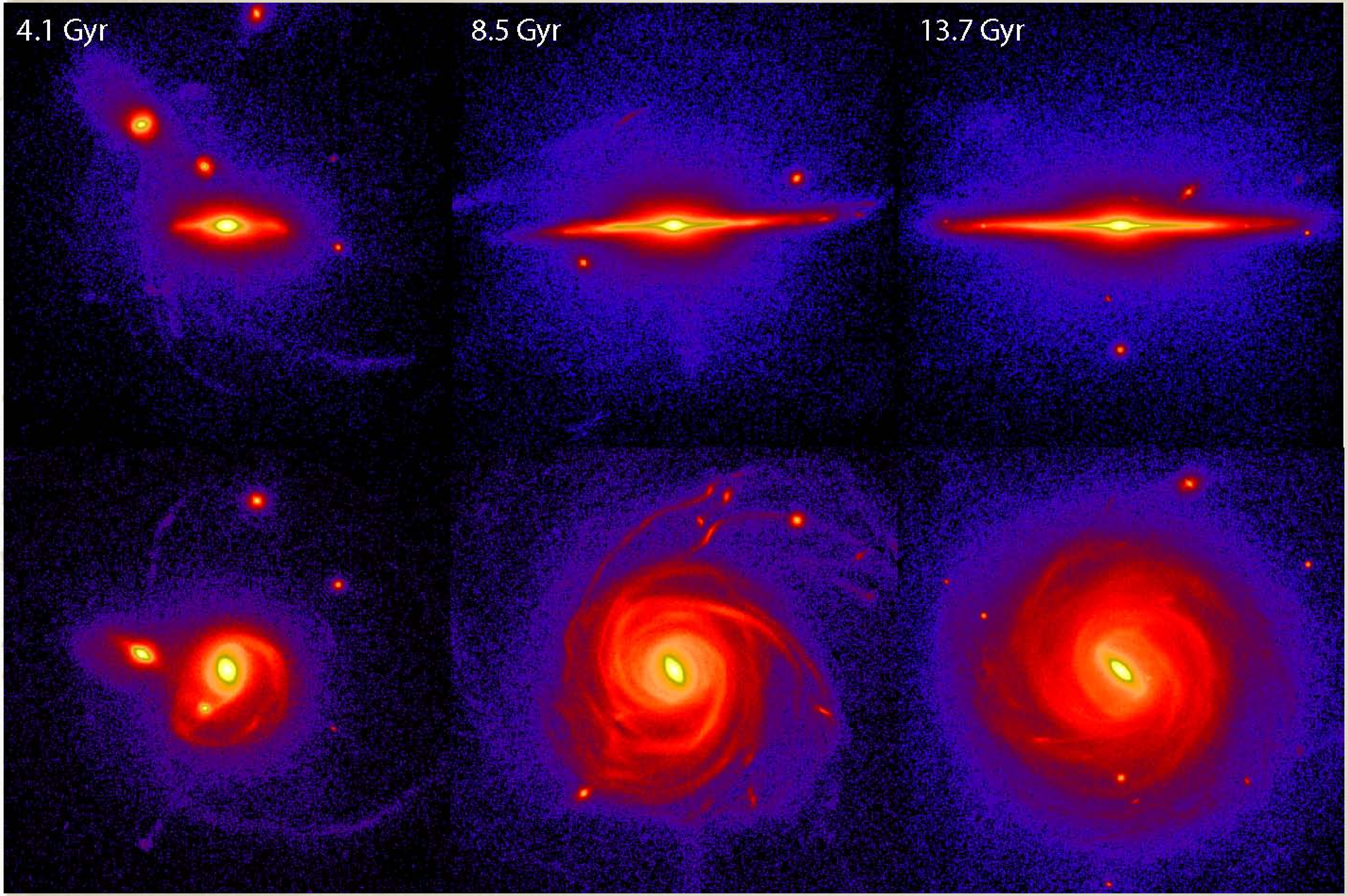




A hybrid chemo-dynamical evolution model for the Milky Way

- A high-resolution simulation of a disk assembly in the cosmological context:
  - Gas infall form filaments and gas-rich mergers
  - Merger activity decreasing toward redshift zero
- Disk properties at redshift zero consistent with the dynamics and morphology of the Milky Way:
  - The presence of a Milky Way-size bar
  - A small bulge
  - Bar's Outer Lindblad Resonance at ~2.5 disk scale-lengths
- A detailed chemical evolution model:
  - Matching a number of observational constraints in the Milky Way, similar to Matteucci and Francois (1989), Prantzos & Aubert (1995), Chiappini et al. (1997).

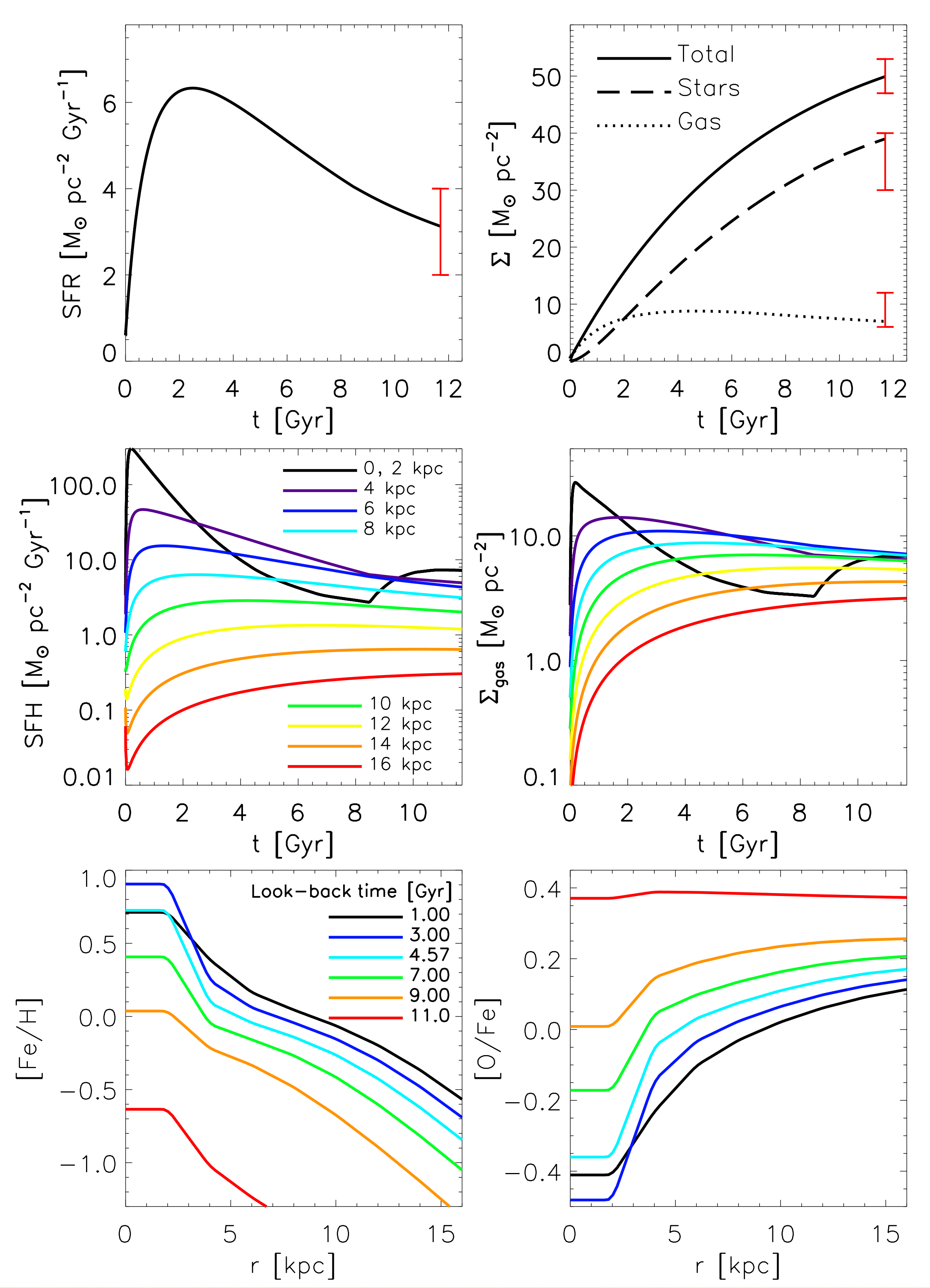
Galactic disk assembly in the cosmological context



Simulation in cosmological context
Martig et al. (2009, 2012)

Used for our chemo-dynamical model (Minchev, Chiappini & Martig 2013, 2014)

Stars born hot at high redshift:
Similar to
Brook et al. (2012),
Stinson et al. (2013),
Bird et al. (2013)



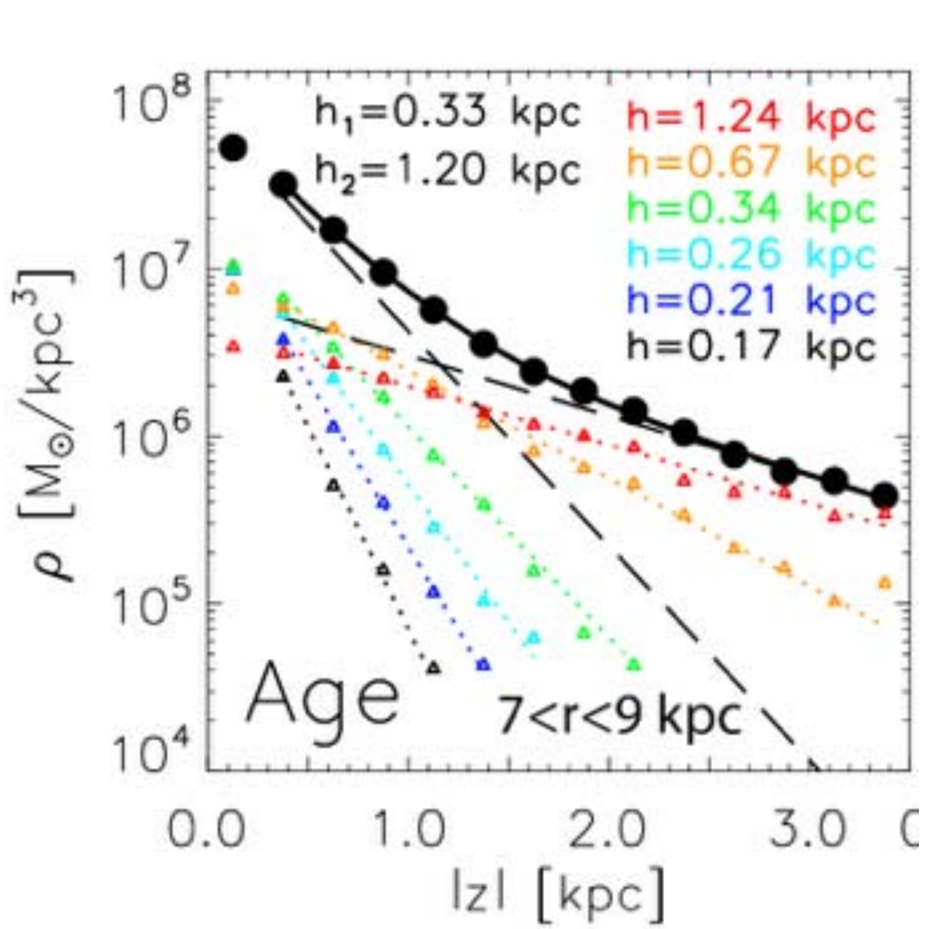
Similar to Chiappini (2009)

A classical chemical model coupled with the simulation

Constrained by:

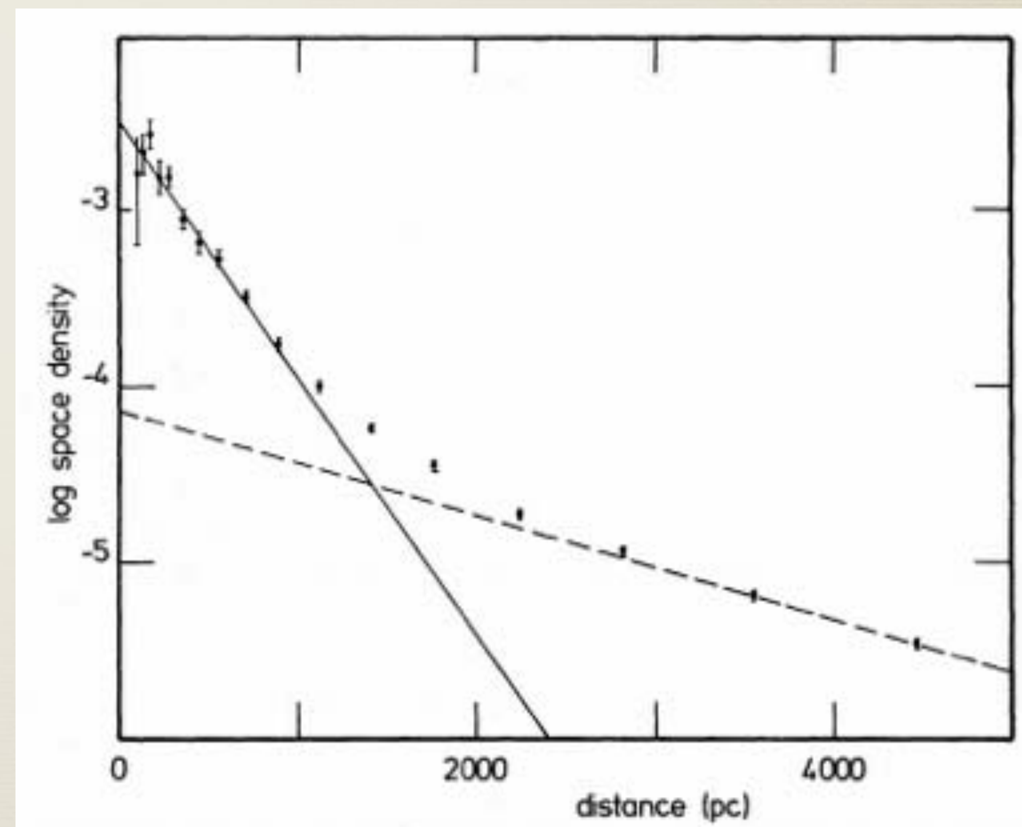
- The solar and present day abundances of more than 30 elements
- The present SFR
- The current stellar, gas and total mass densities at the solar vicinity
- The present day supernovae rates of type II and Ia
- The metallicity distribution of G-dwarf stars

Thin-thick disk decomposition near Sun

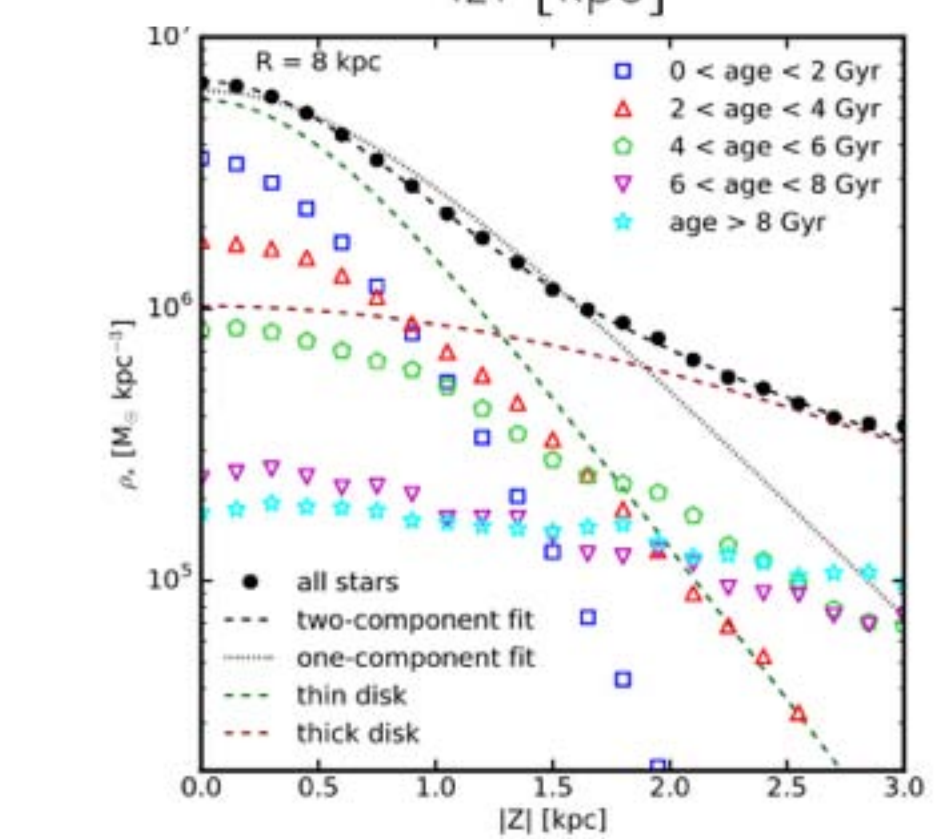


Minchev, Chiappini and Martig (2013)

Sticky particles
simulation by Martig et al.



Gilmore and Ried (1983)

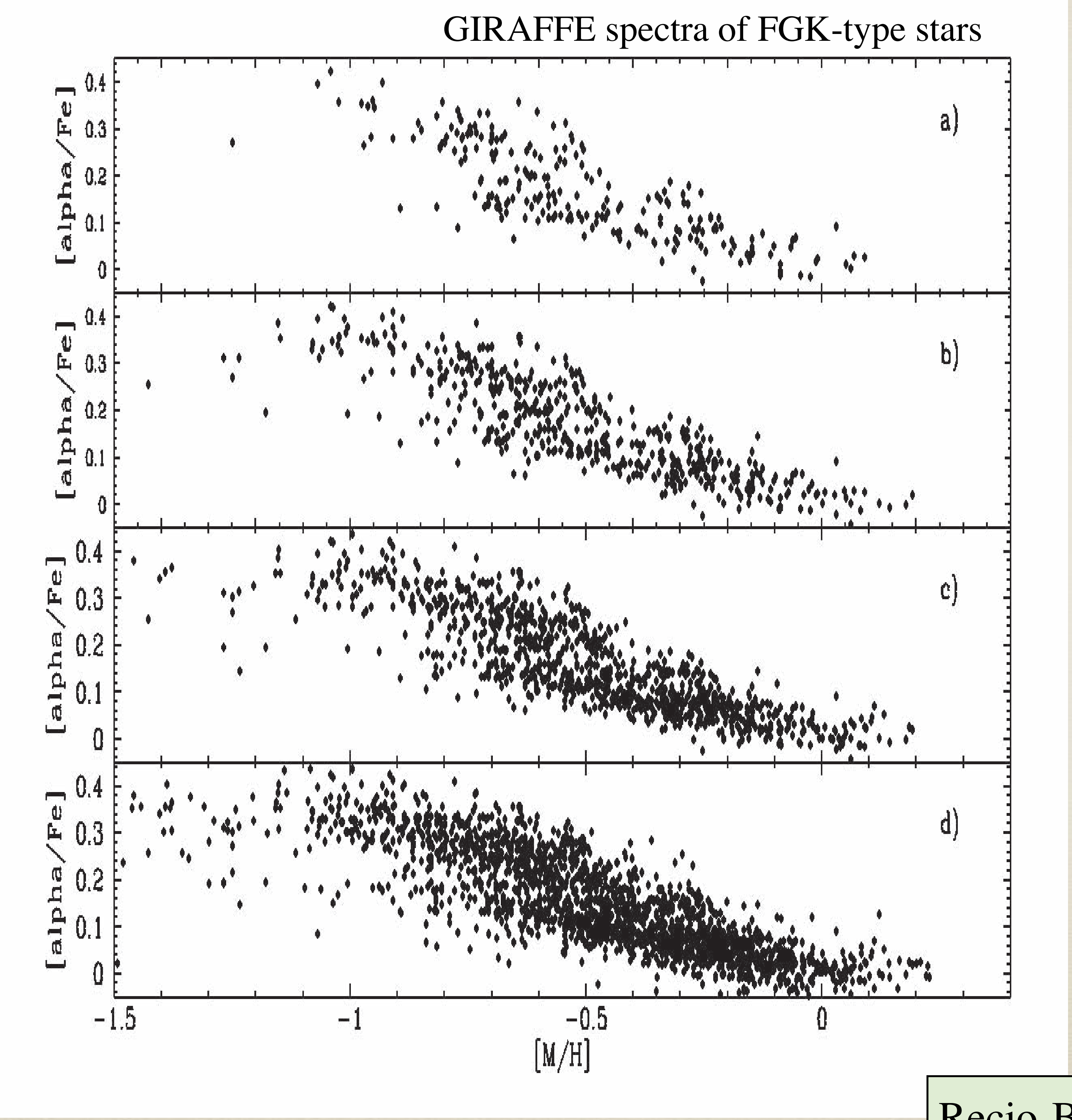


Ma et al. (2016)
Simulation from the FIRE project
(GIZMO code)

The [Fe/H]-[α/Fe] relation

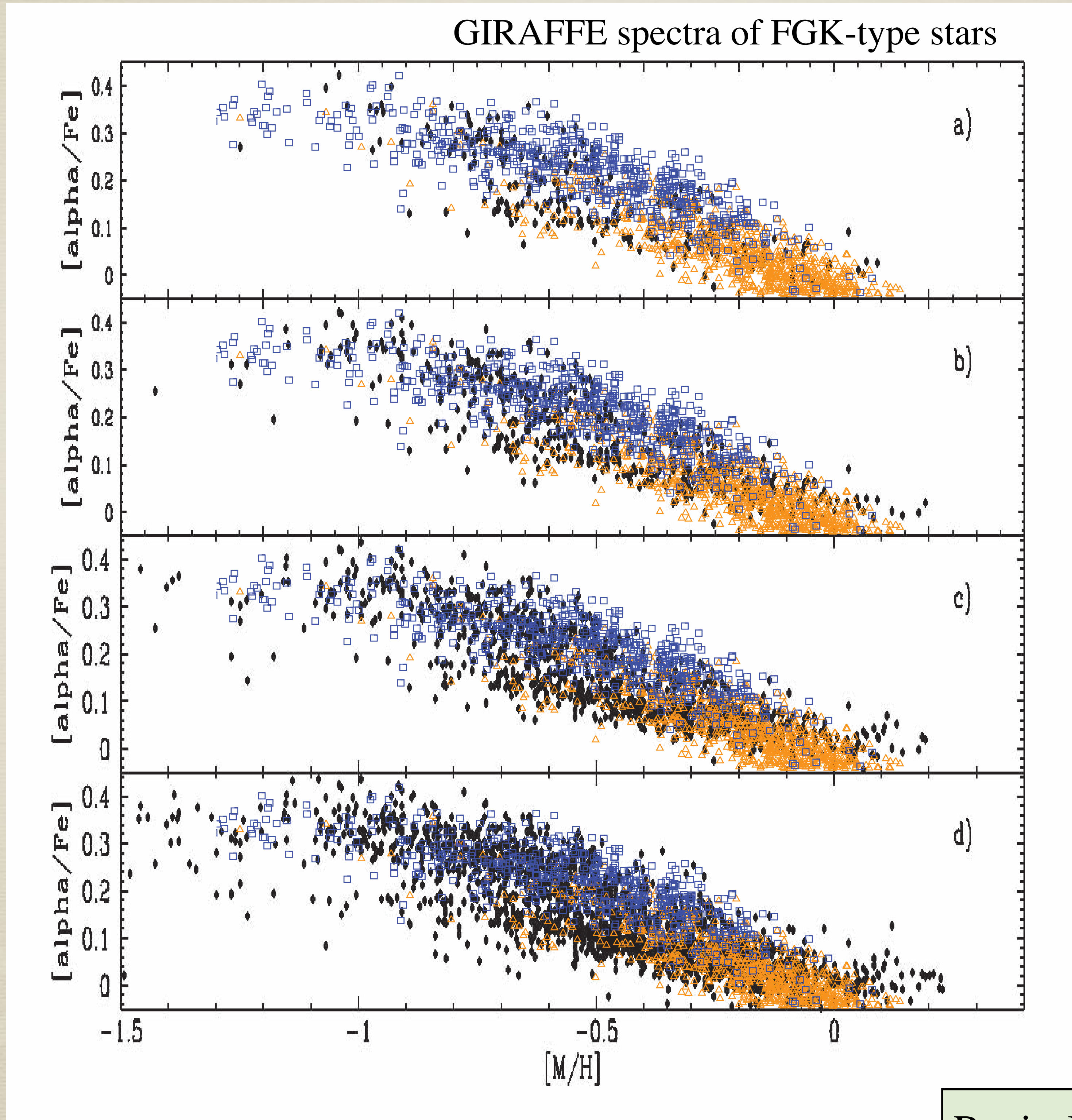
Gaia-ESO data

<---------- Uncertainties



Recio-Blanco et al. (2014)

The [Fe/H]-[α/Fe] relation

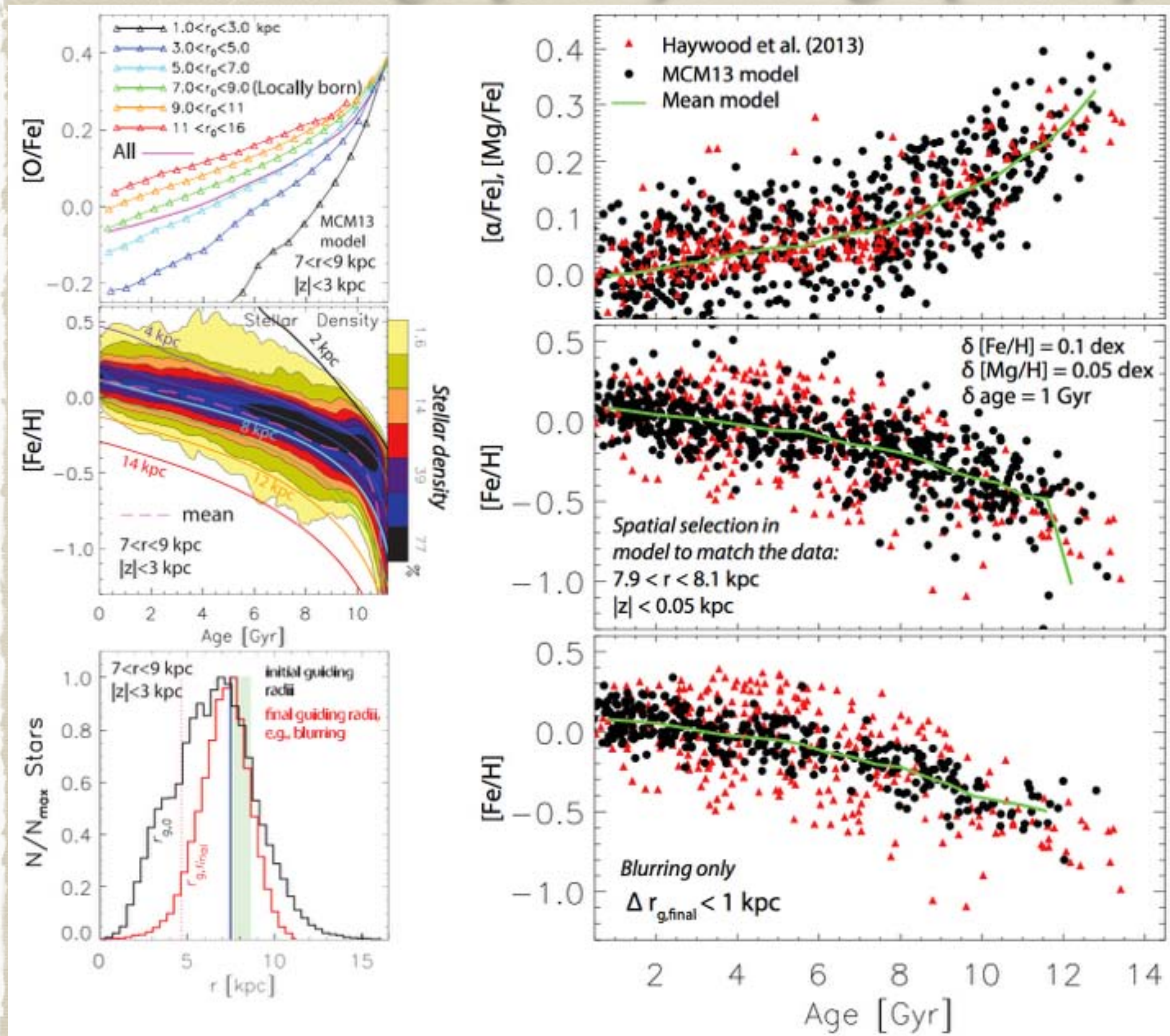


Gaia-ESO data

<------- Uncertainties

Recio-Blanco et al. (2014)

The age-[α/Fe] and age-[Fe/H] relations



Comparison to the Adibekyan (HARPS) + Haywood (ages) sample

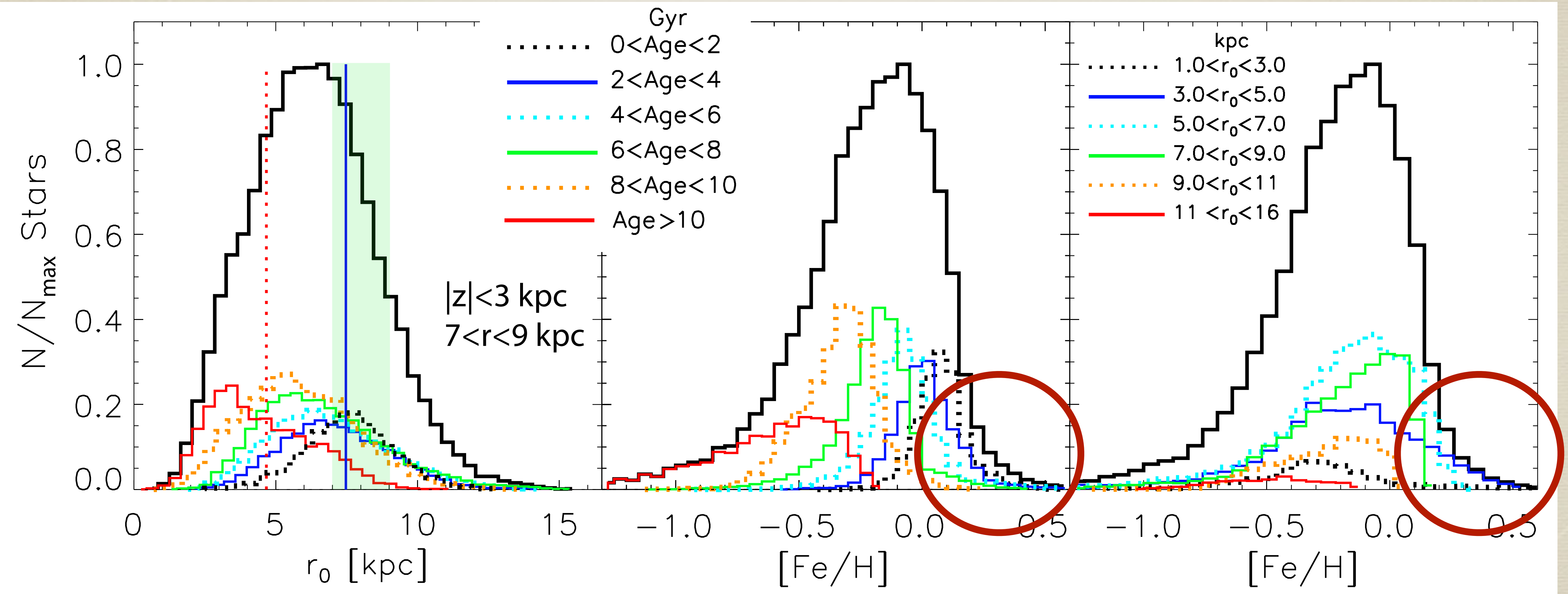
Artificial errors added similar to the observations. Yet, scatter in model AMR less than in data

Hot orbits only (blurring) insufficient to explain AMR

see also poster by J. Wojno

Minchev et al. (2016)

Origin and metallicity distribution of local stars

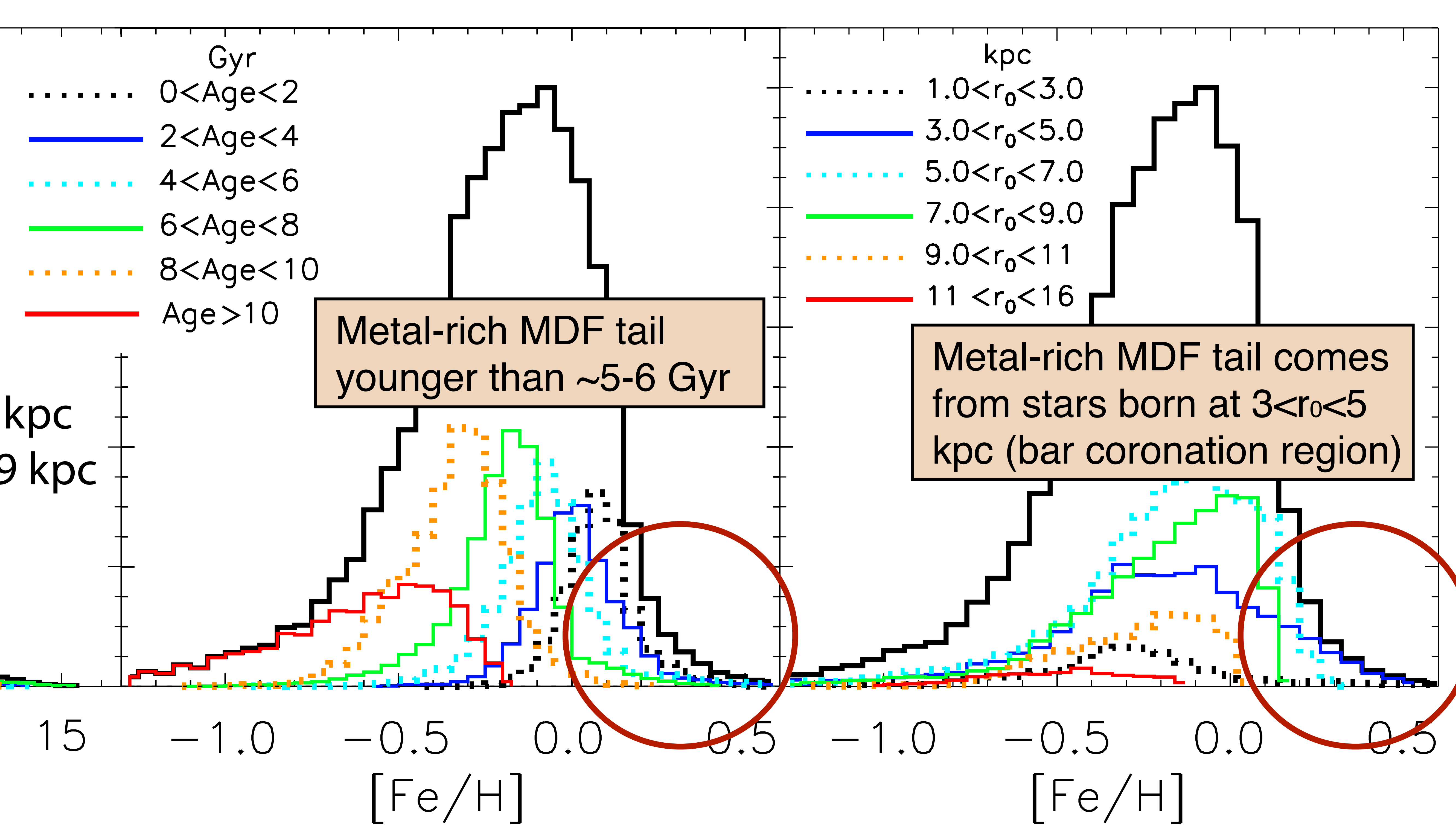


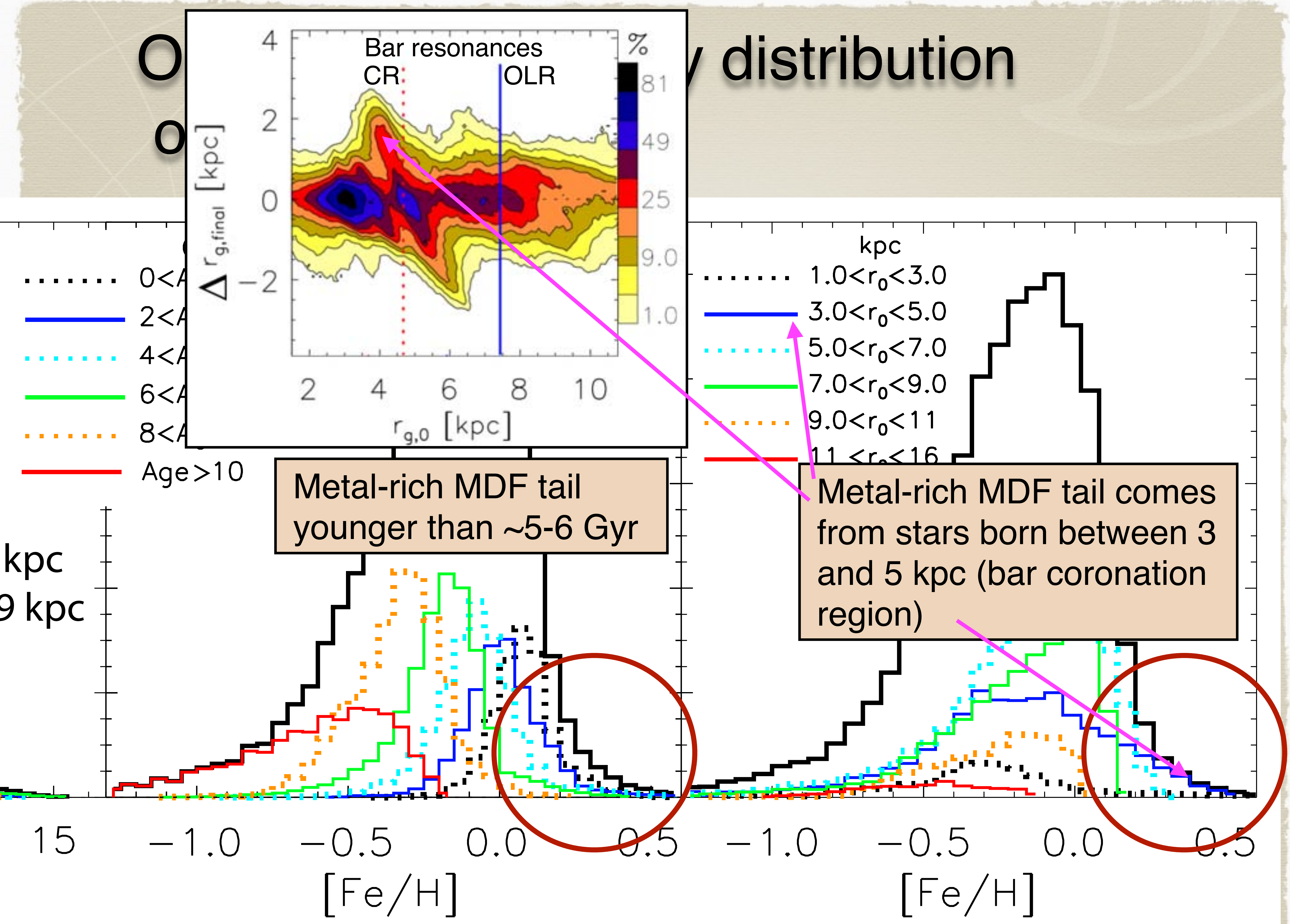
Minchev, Chiappini & Martig (2013)

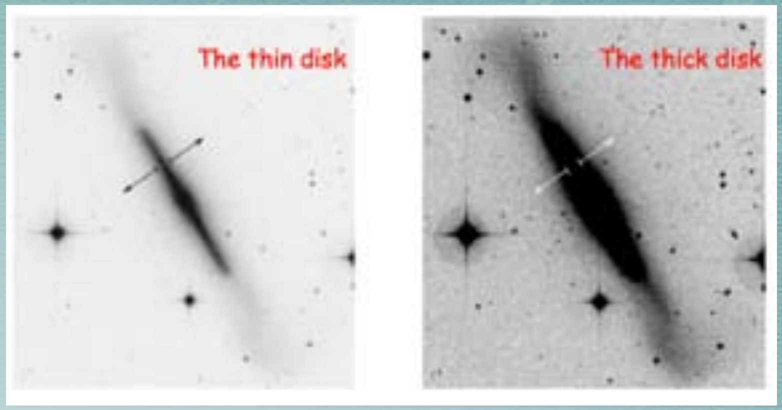
Older populations arrive from progressively smaller galactic radii due to their longer exposure to migration.

Kordopatis will tell us more about the MDF

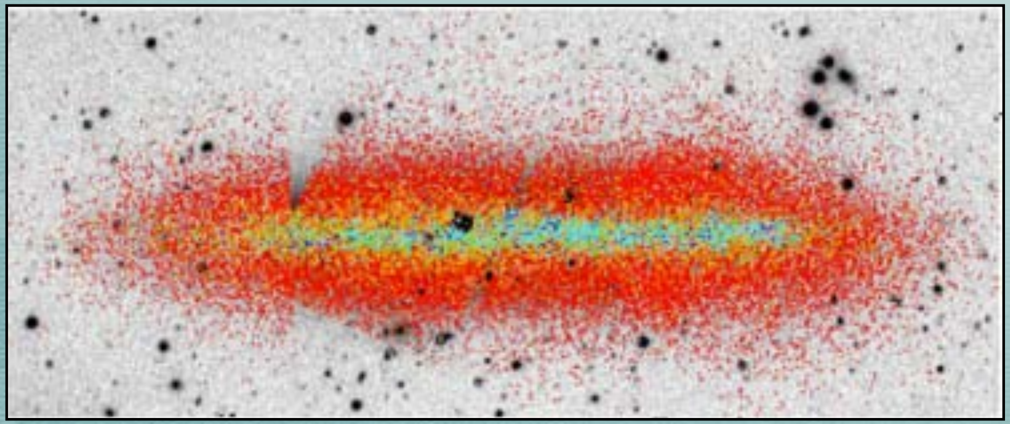
Origin and metallicity distribution of local stars



O
y distribution
o
Bar resonances
CR
OLR
%
81
49
25
9.0
1.0
$\Delta r_{g,final}$ [kpc]
$r_{g,0}$ [kpc]
4
2
0
−2
2
4
6
8
10
0<A
2<A
4<A
6<A
8<A
Age>10
kpc
9 kpc
kpc
$1.0<r_0<3.0$
$3.0<r_0<5.0$
$5.0<r_0<7.0$
$7.0<r_0<9.0$
$9.0<r_0<11$
$11<r_0<16$
Metal-rich MDF tail younger than ~5-6 Gyr
Metal-rich MDF tail comes from stars born between 3 and 5 kpc (bar coronation region)
15
−1.0
−0.5
0.0
0.5
[Fe/H]
−1.0
−0.5
0.0
0.5
[Fe/H]

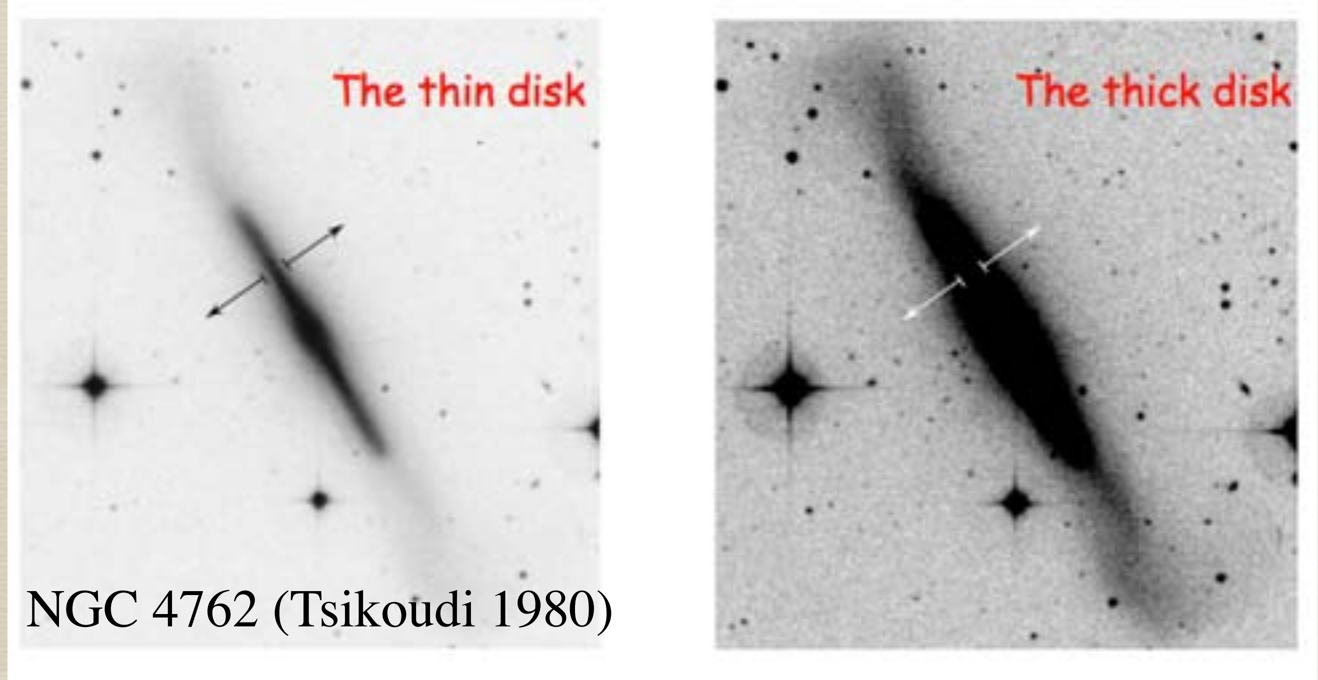


On the formation of galactic thick disks

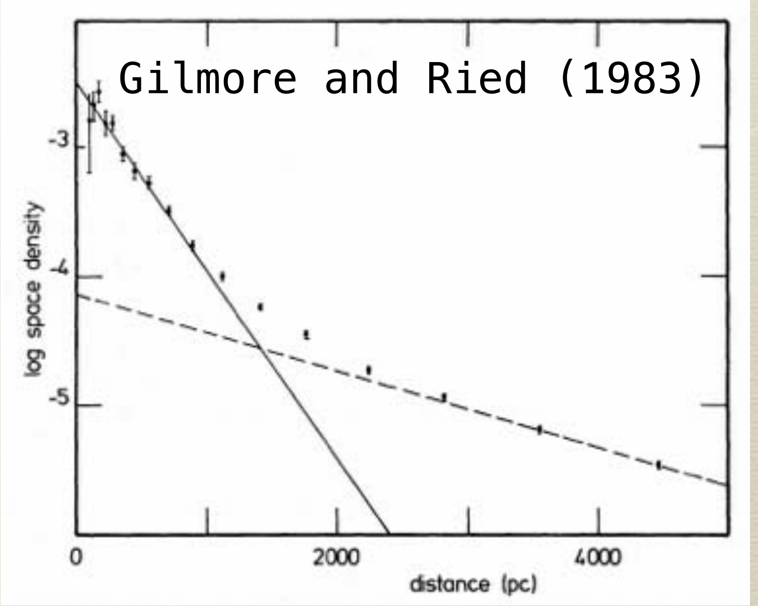


Thick disks formation mechanisms

- Turbulent gas-rich clouds at high redshift (e.g., Bournaud et al. 2009) - seen at high redshift
- Gas-rich mergers (Brook et al. 2004, 2005) - seen in most/all cosmological simulations
- Accretion of satellites (Meza et al. 2005, Abadi et al. 2003) - possibly ruled out at this point for the Milky Way
- Perturbations by merging satellites on an initially thin disk (Quinn et al. 2004, Villalobos and Helmi 2008, Di Matteo et al. 2011)
- Some combination of the above (see next)

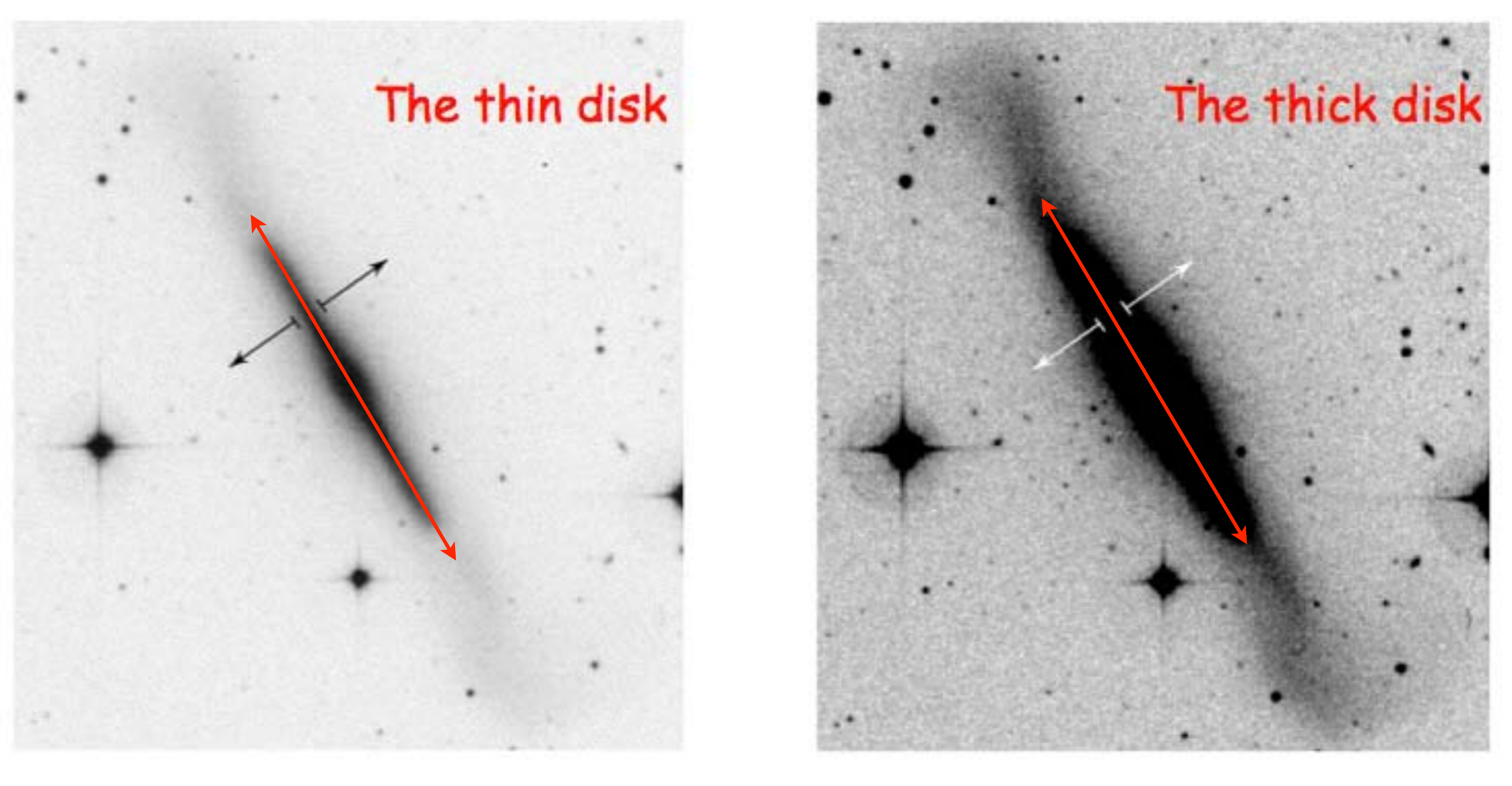


NGC 4762 (Tsikoudi 1980)



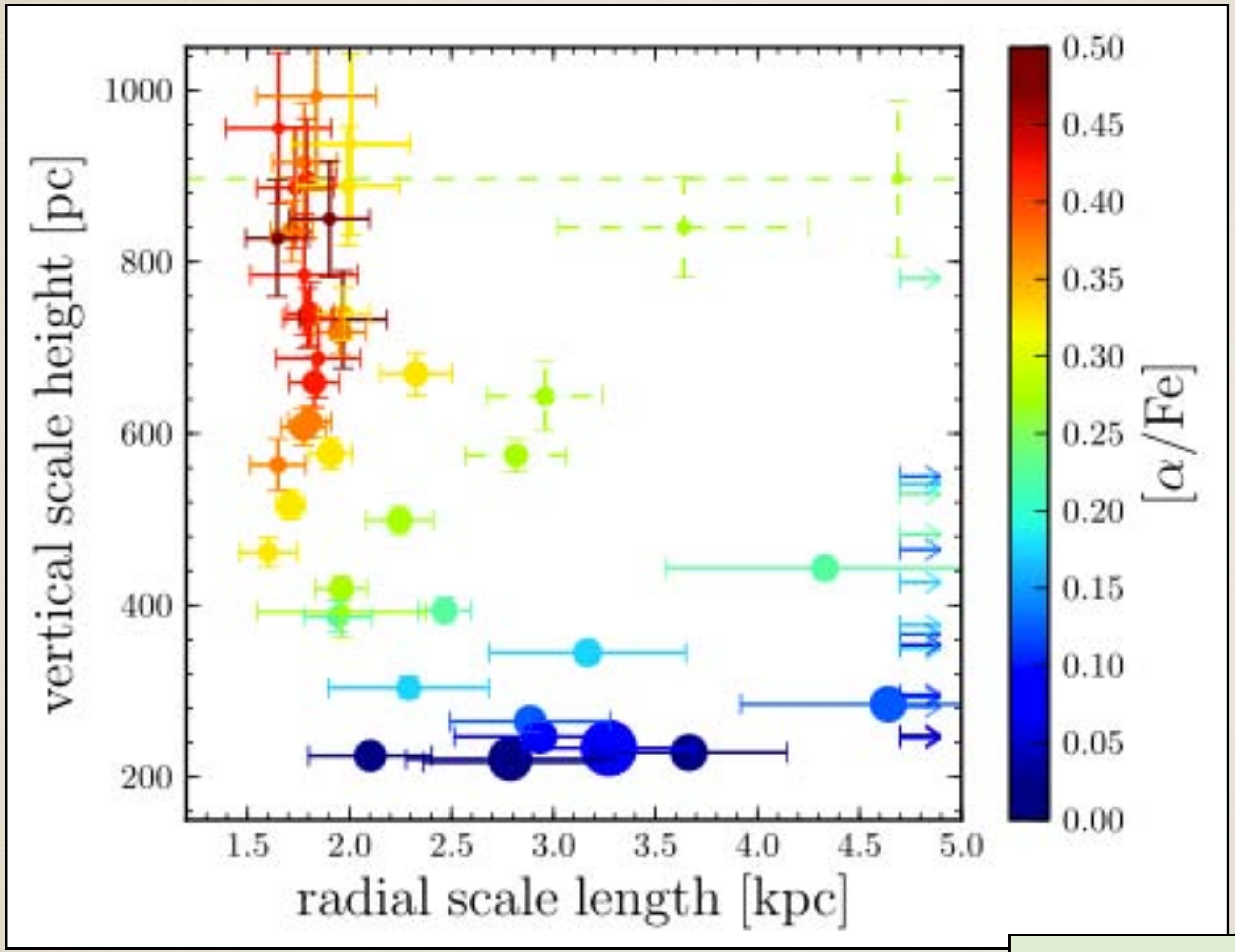
Thick disks are **extended**
(when morphologically defined)

NGC 4762 (Tsikoudi 1980)



Also argued by Yoachim and Dalcanton (2006); Pohlen et al. (2007); Comerón et al. (2012)

Chemically/Age defined Milky Way thick disk **centrally concentrated** (e.g., not extended)

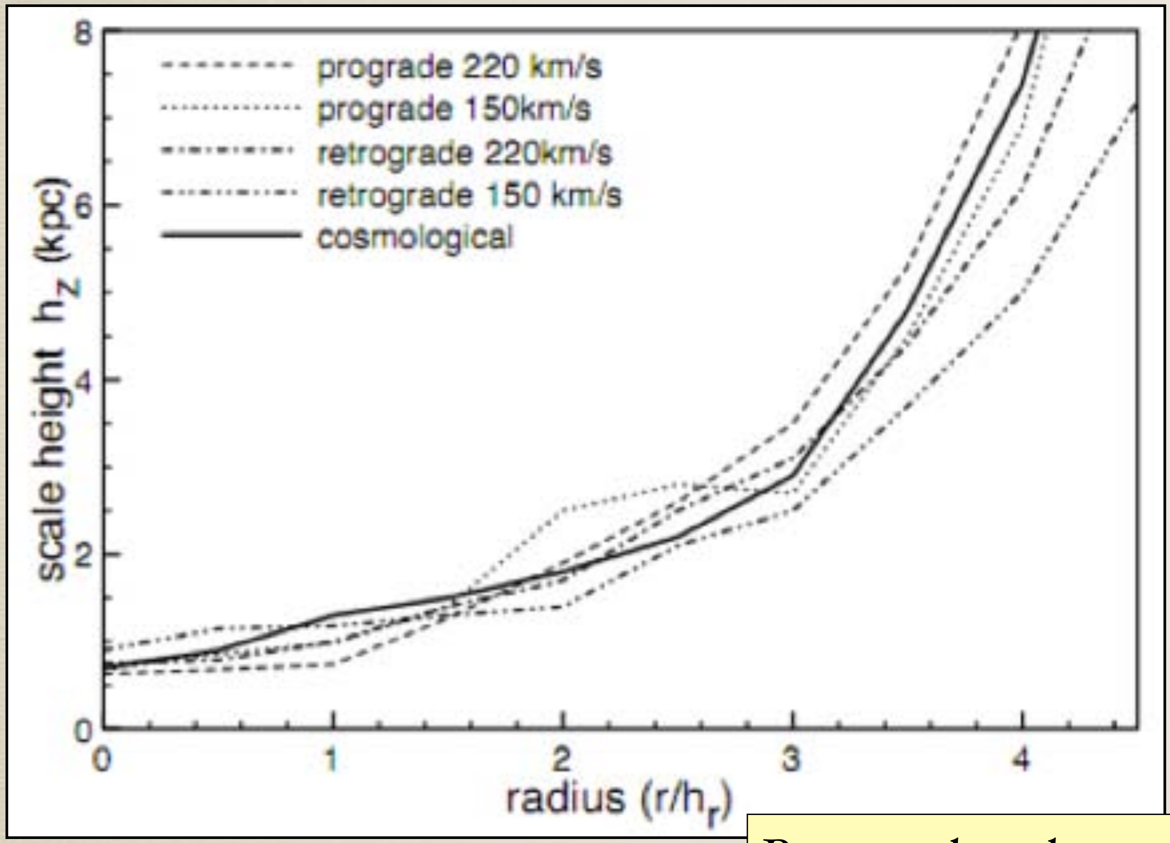


Bovy et al. (2012)

Found also in Bensby et al. (2011) data and SEGUE data (Cheng et al. 2012)

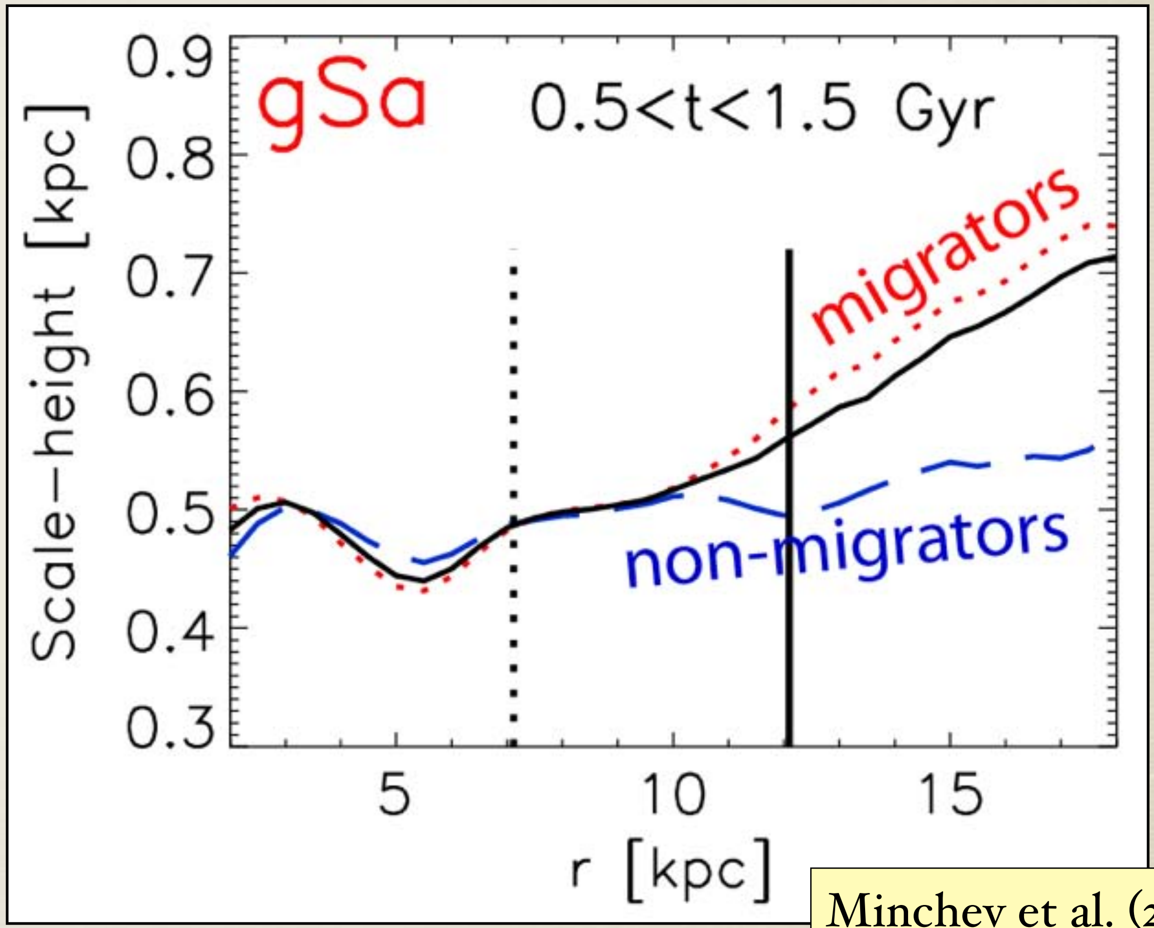
Simulated disks **always flare** (for a single stellar population)

Mergers flare disks



Bournaud et al. 2009

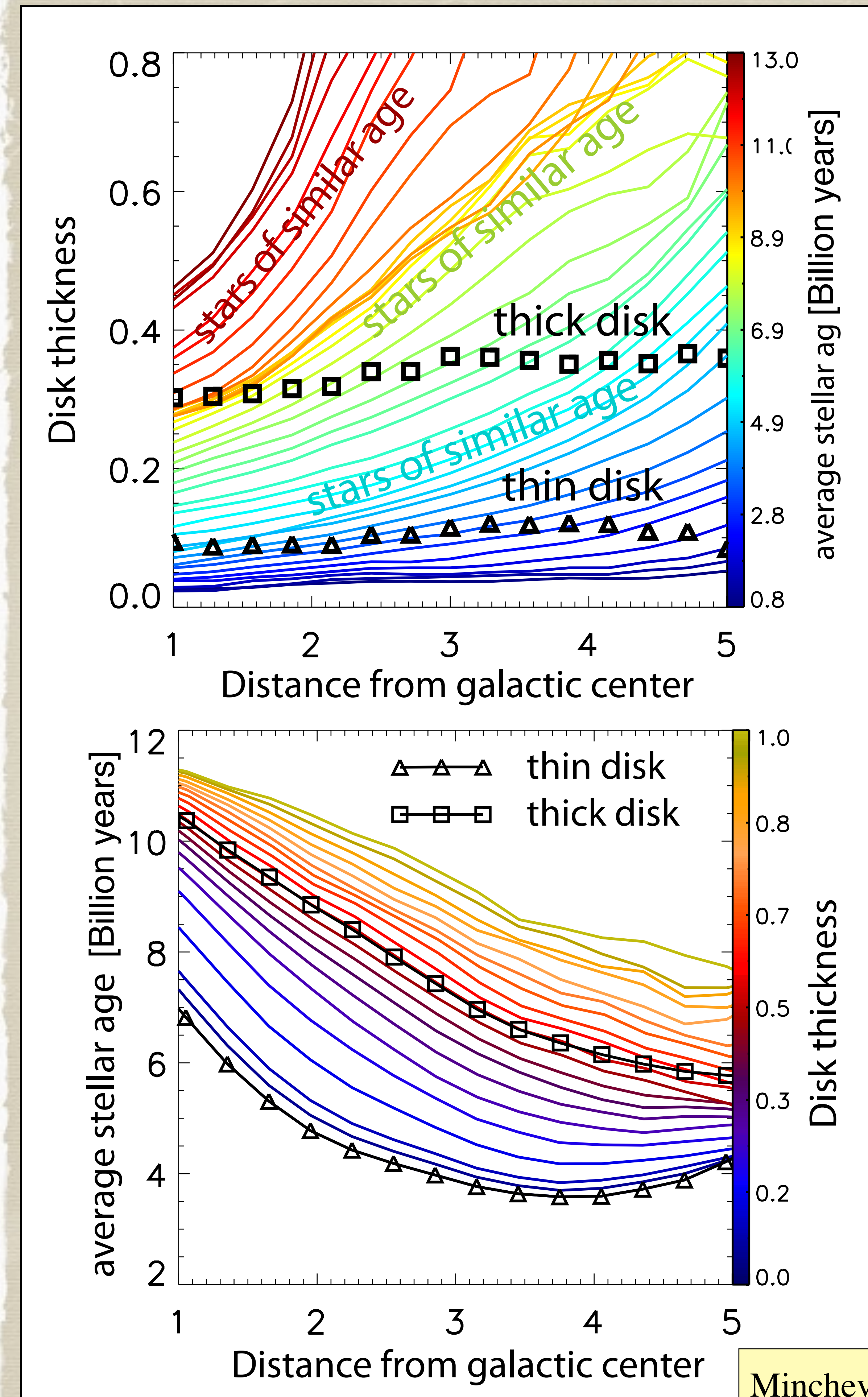
Migration flares disks



Minchev et al. (2012)

But observed edge-on disks do not flare (de Grijs 1998; Comerón et al. 2011)

Disk flaring in inside-out galaxy formation



Minchev et al. (2015)

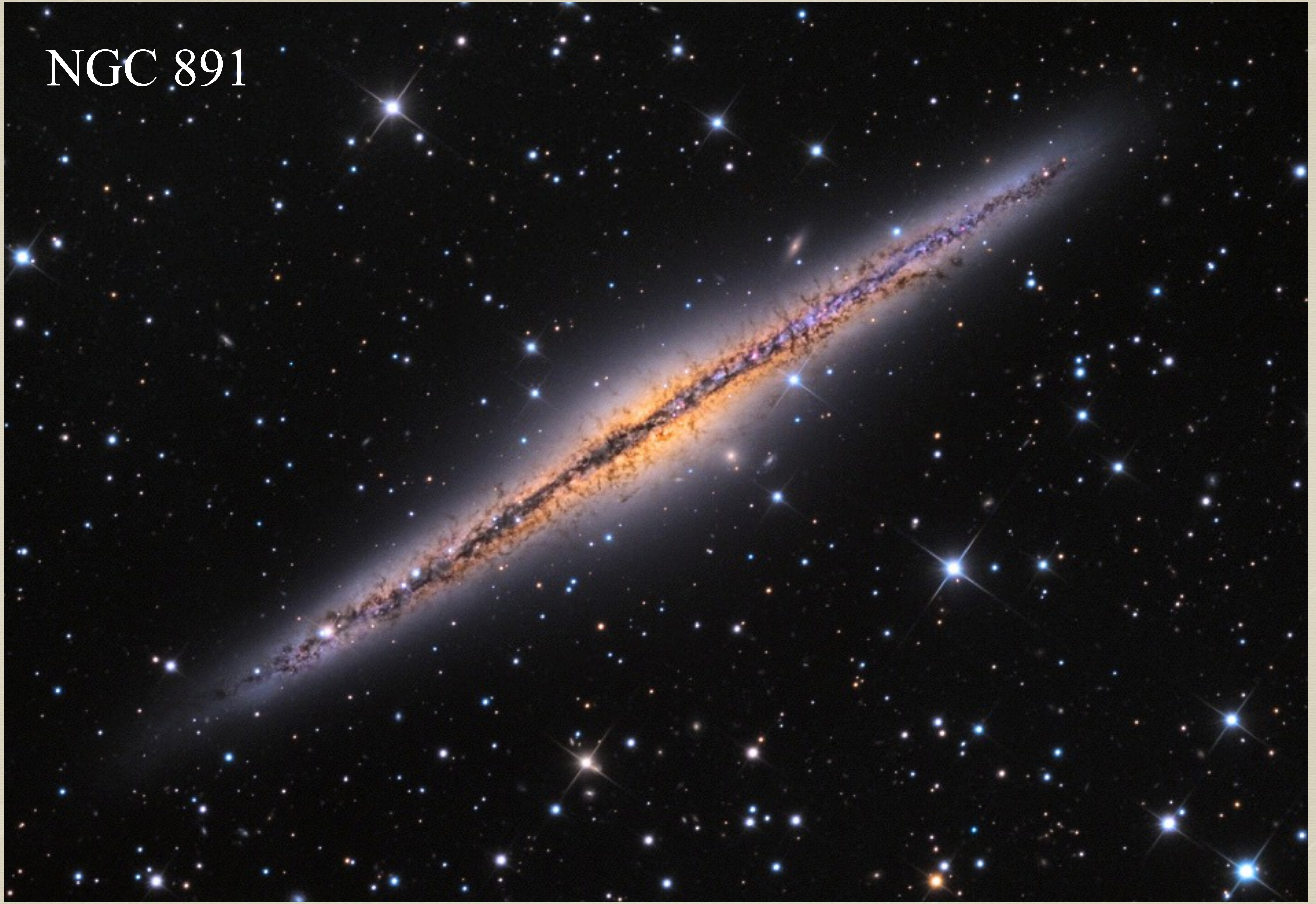
Seen in 2 simulation suites: by Martig and by Aumer/Scannapieco

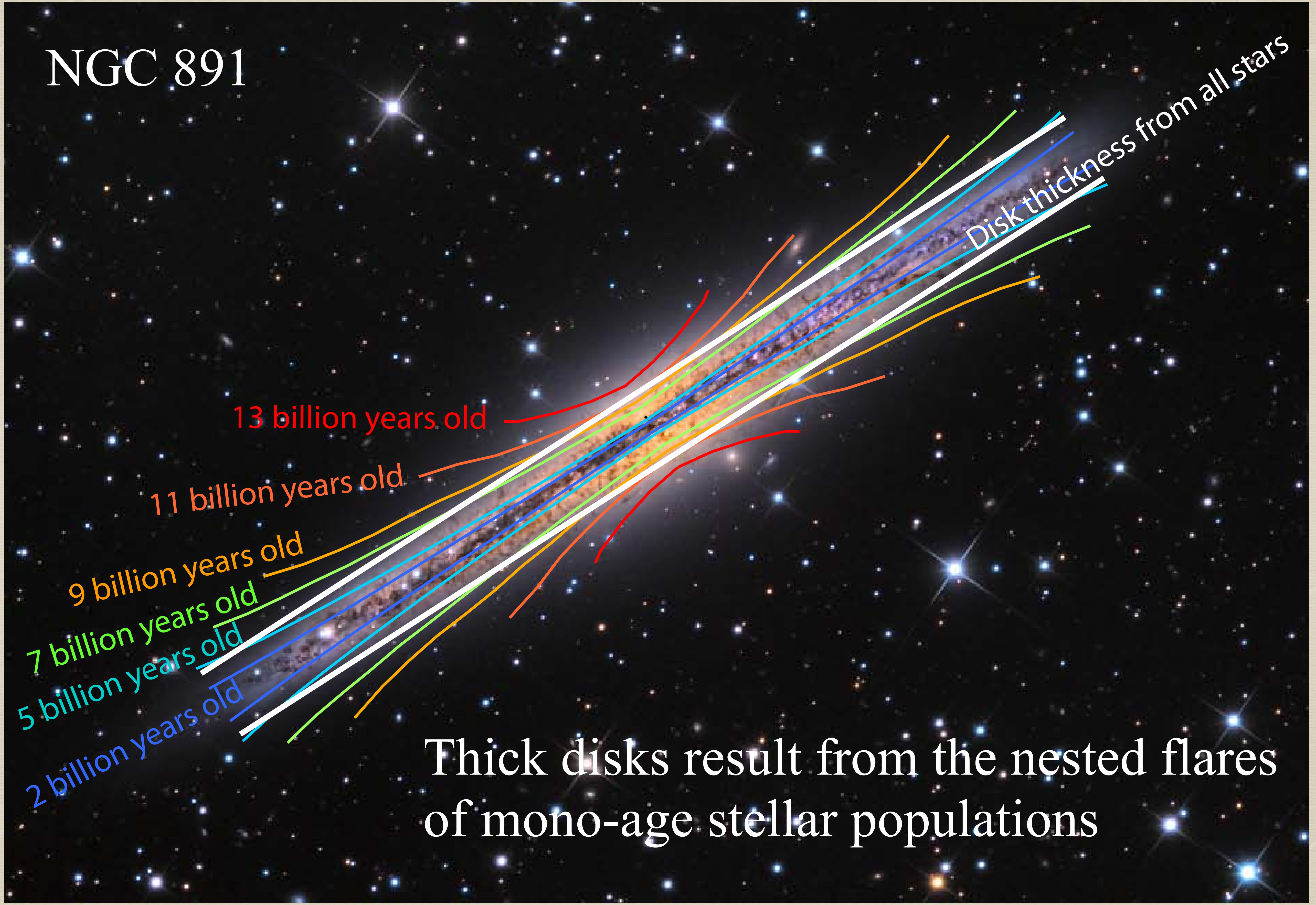
Flaring also reported in FIRE (Ma et al. 2016) and Auriga simulations (Grand et al. 2016)

See also poster by A. Spagna

Age gradient in thick disk predicted

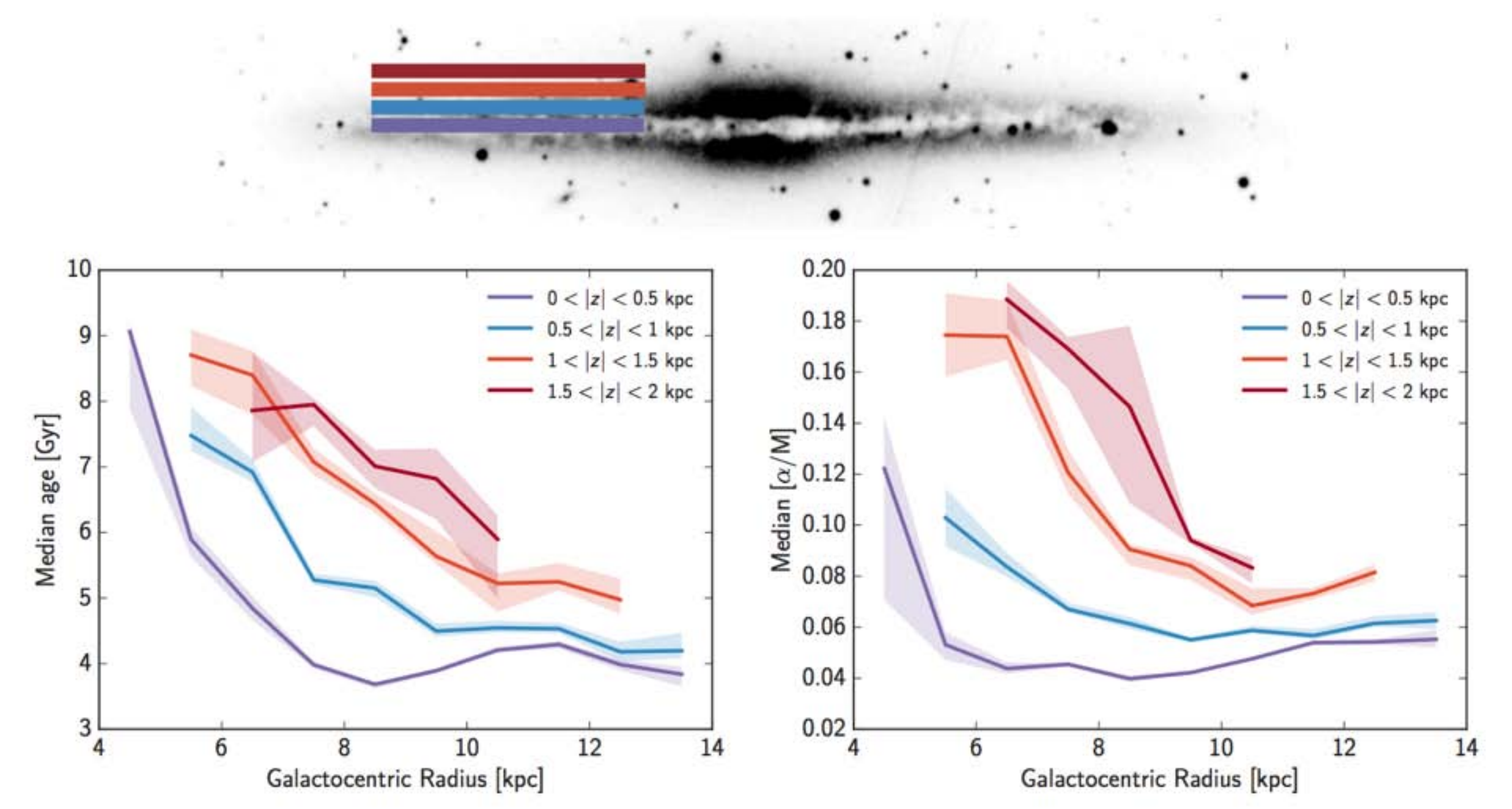
Chemical thick disk ≠ Morphological thick disk


NGC 891


NGC 891
Disk thickness from all stars
13 billion years old
11 billion years old
9 billion years old
7 billion years old
5 billion years old
2 billion years old
Thick disks result from the nested flares of mono-age stellar populations

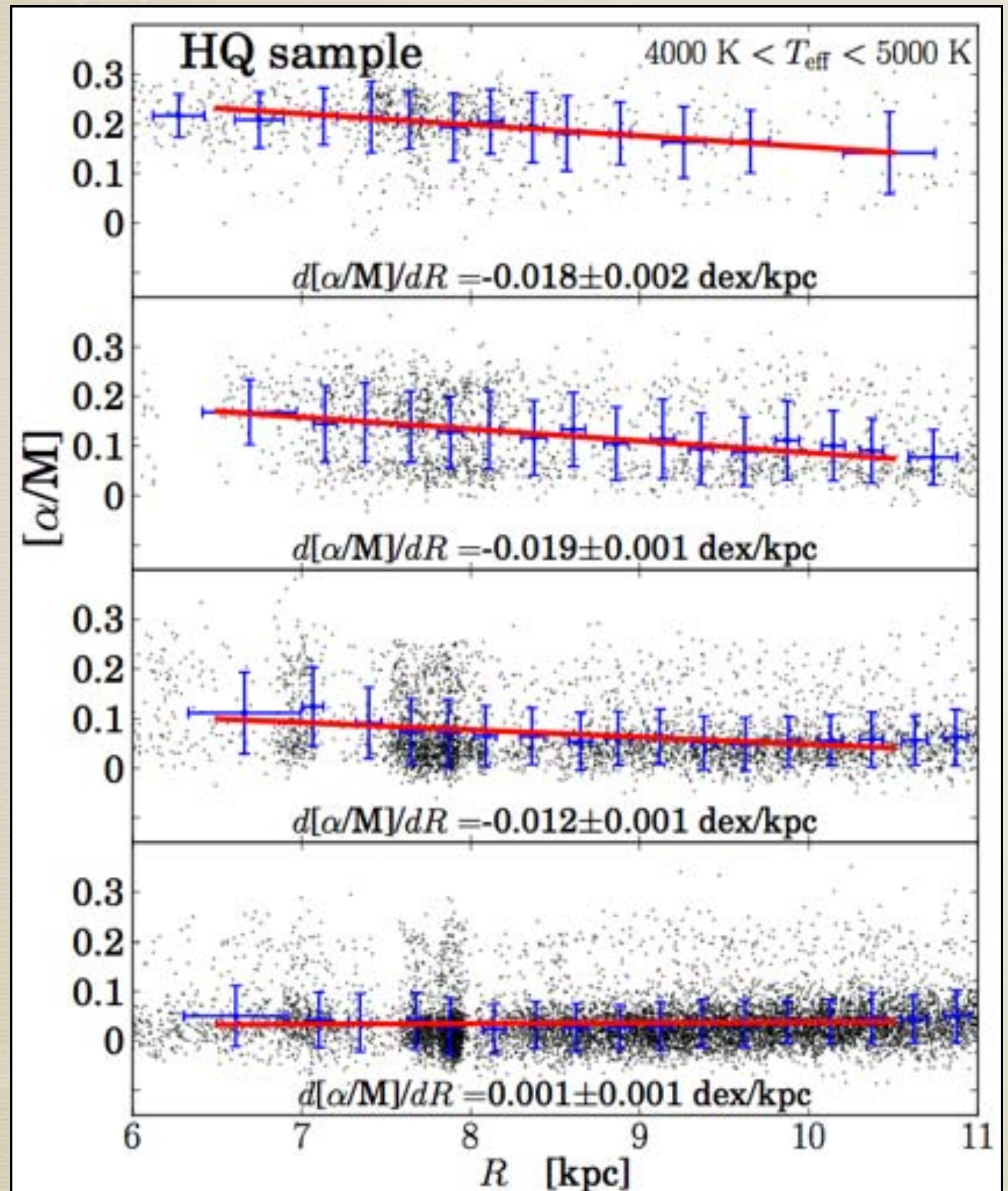
Negative age and [α/Fe] gradients at high |z| in APOGEE

Consistent with flaring of mono-age populations



Martig, Minchev et al. (2016)

Consistent with: Inversion in [α/Fe] gradient away from disk plane



APOGEE data

1.5 < |z| < 3.0 kpc

0.8 < |z| < 1.5 kpc

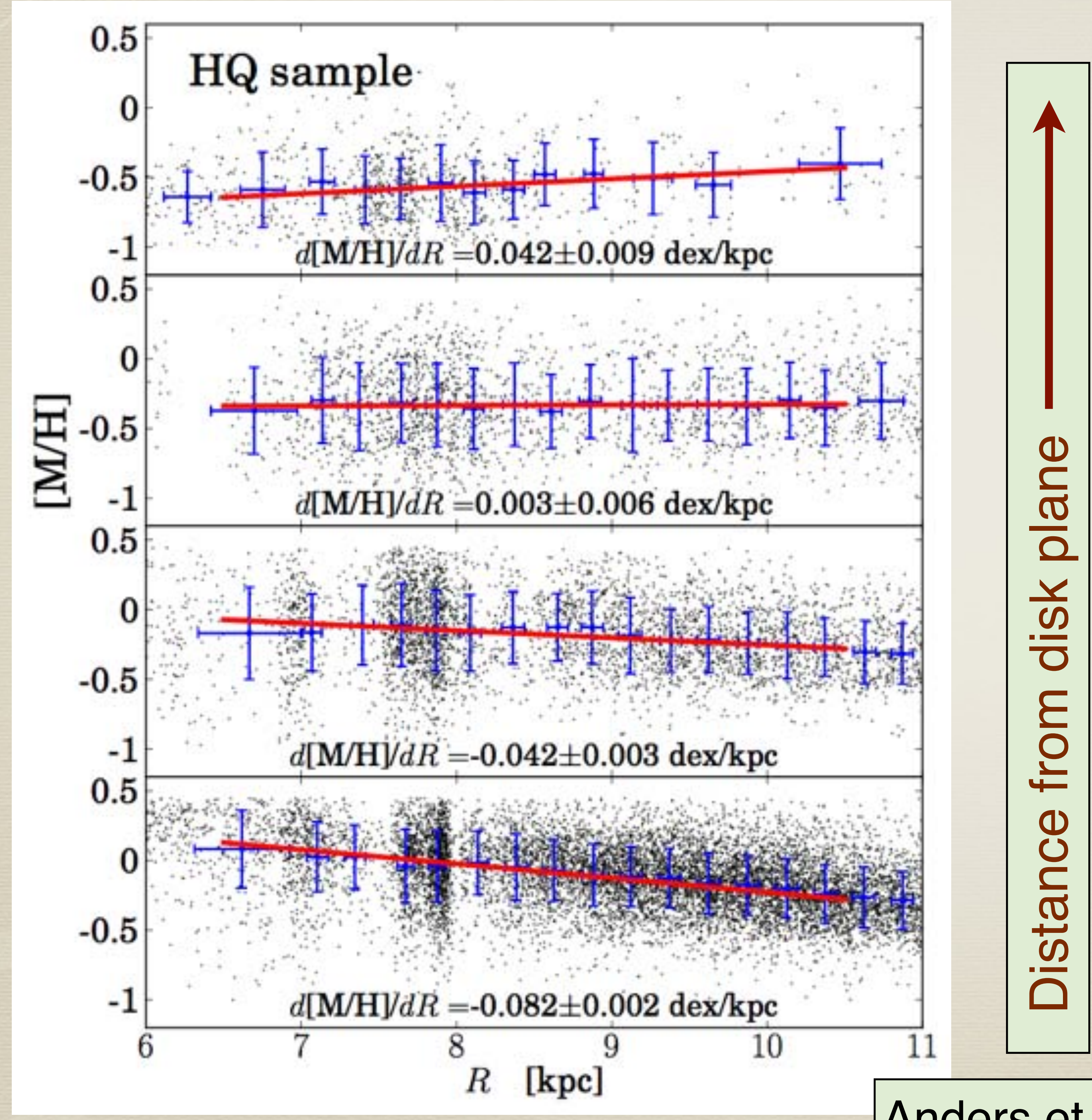
0.4 < |z| < 0.8 kpc

0.0 < |z| < 0.4 kpc

Distance from disk plane

Anders et al. (2014)

Consistent with: Inversion in [M/Fe] gradient away from disk plane



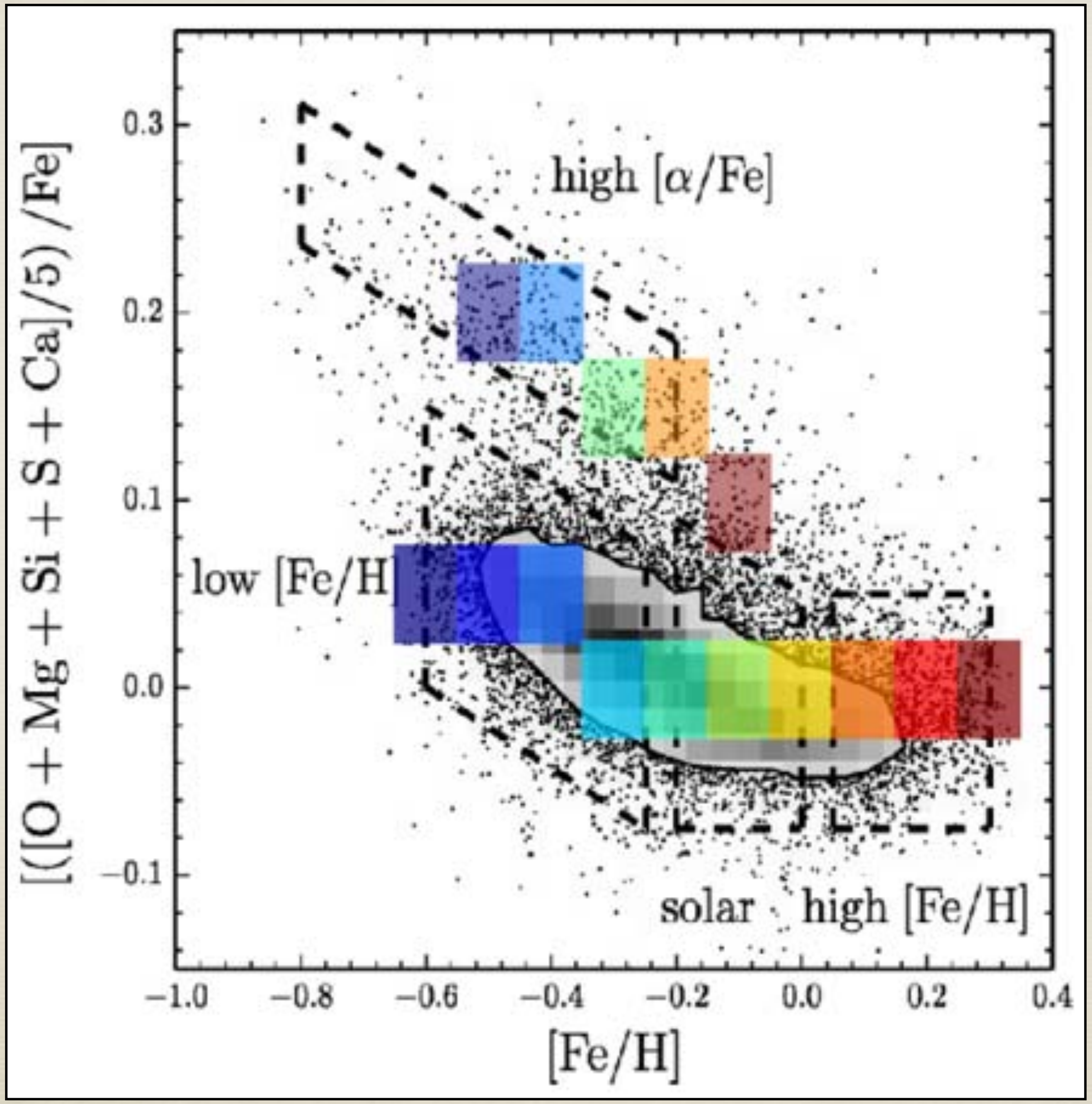
APOGEE data

Also seen in RAVE (Boeche + RAVE. 2014)

and in SEGUE (Cheng et al. 2012)

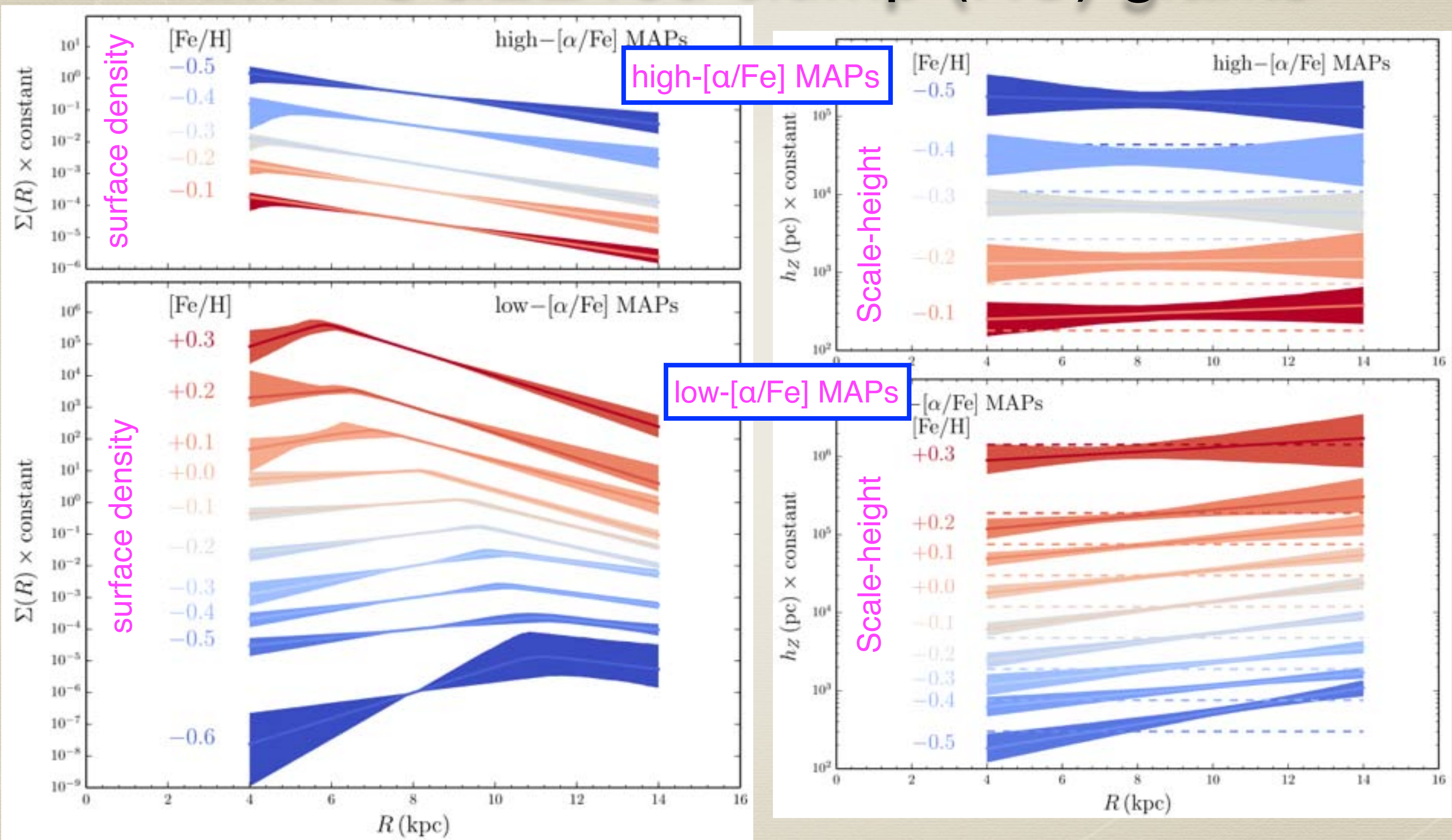
Anders et al. (2014)

Mono-abundance populations (MAPs) in APOGEE red clump (RC) giants



Bovy et al. (2016)

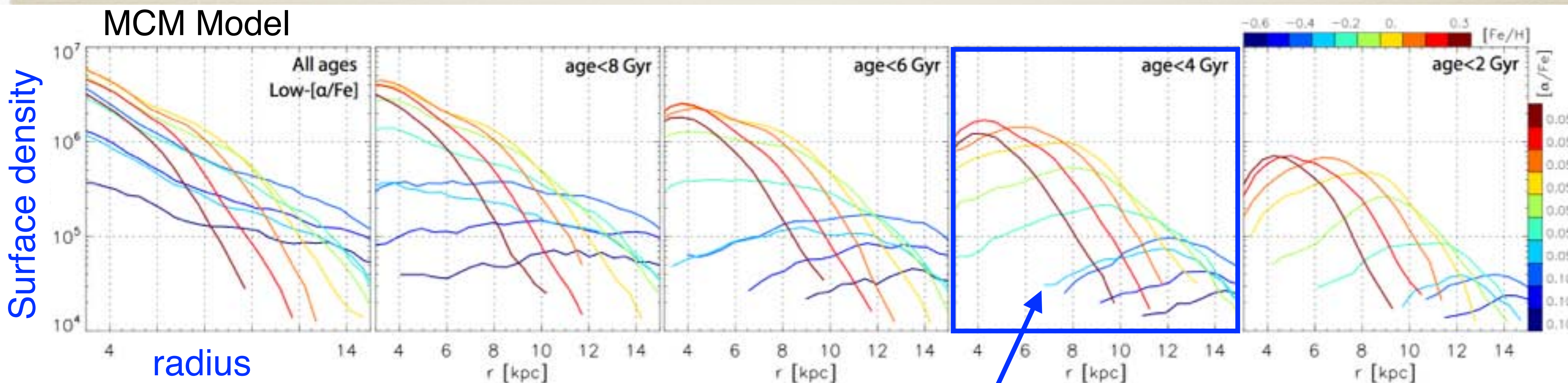
Mono-abundance populations (MAPs) in APOGEE red clump (RC) giants

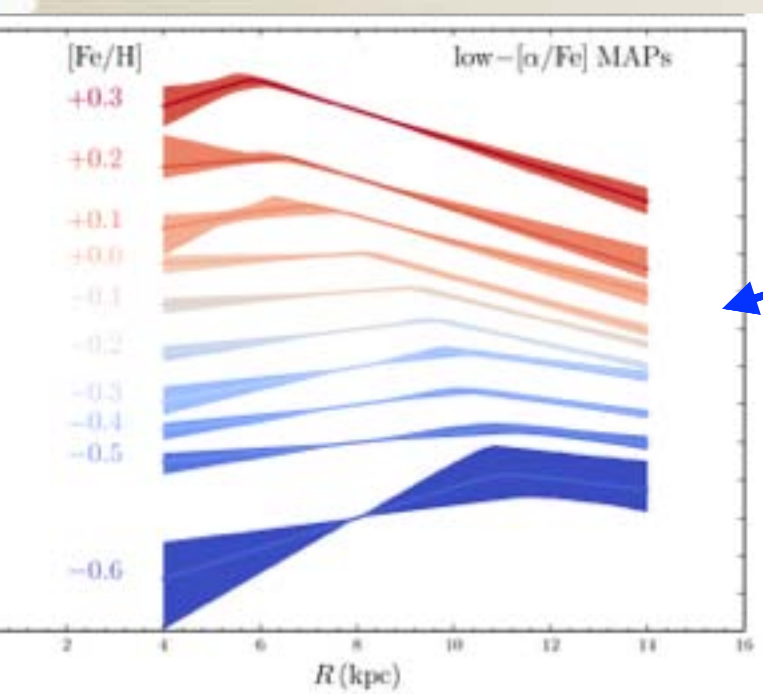


Bovy et al. (2016)

Variation in the shape of MAPs surface density with age

age decreases

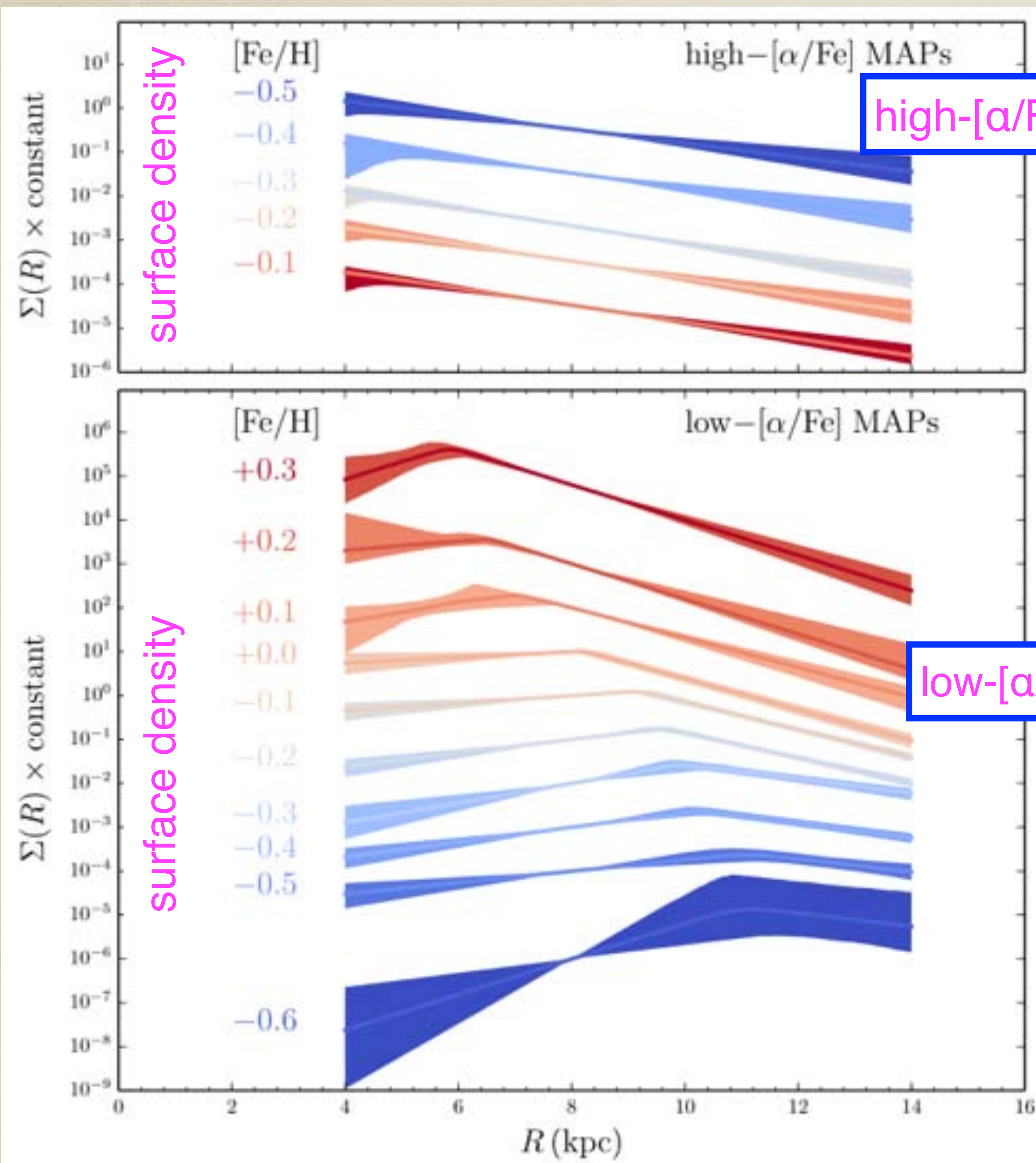




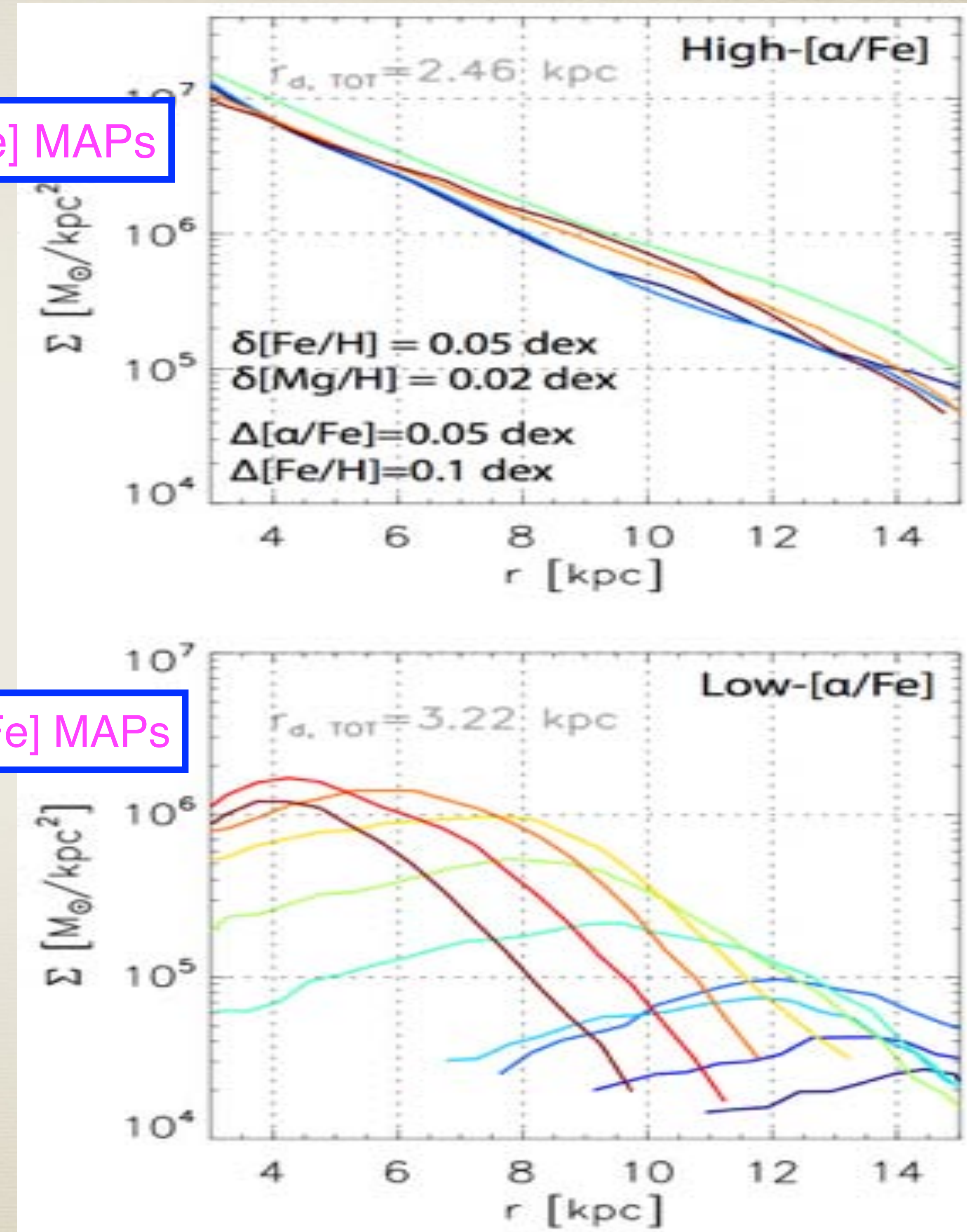
Red-clump sample peaks at age = 2-4 Gyr

MAPs probably not mono-age!

Matching APOGEE density profiles



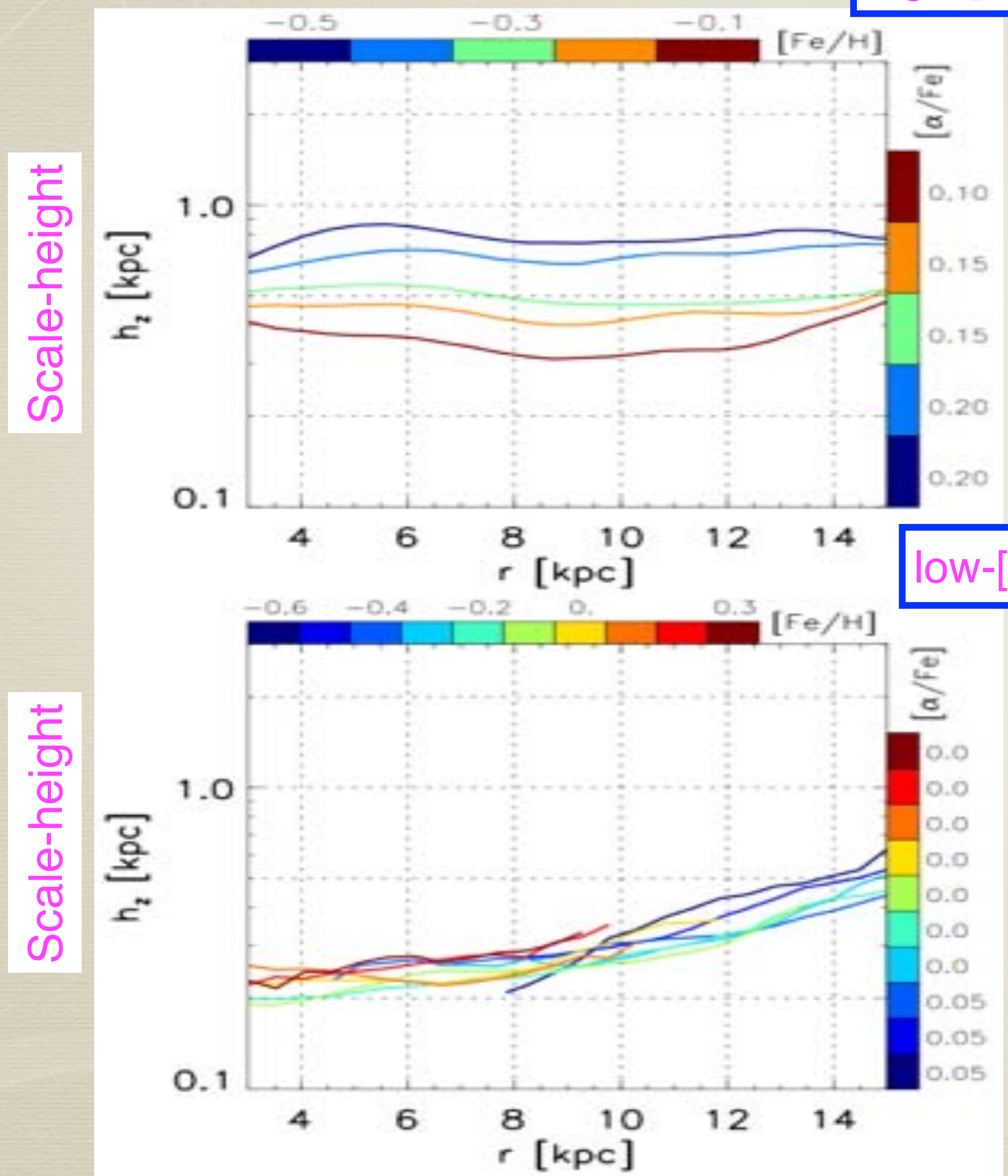
Bovy et al. (2016)



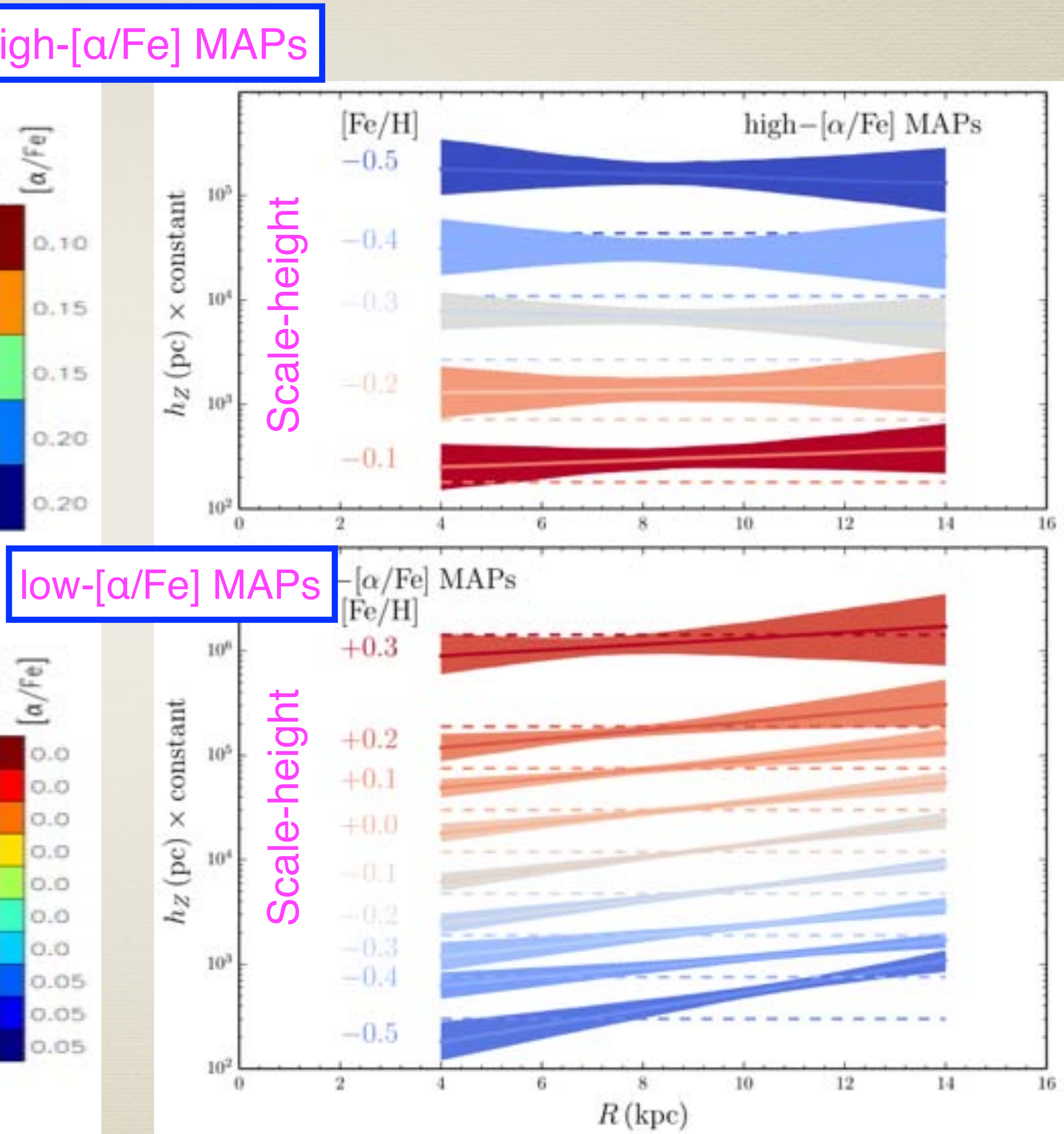
Minchev et al. (2016), model

Matching APOGEE disk thickness variation with radius

Flaring lost in model high-[α/Fe] MAPs,
although present for all mono-ages!!



Minchev et al. (2016), model

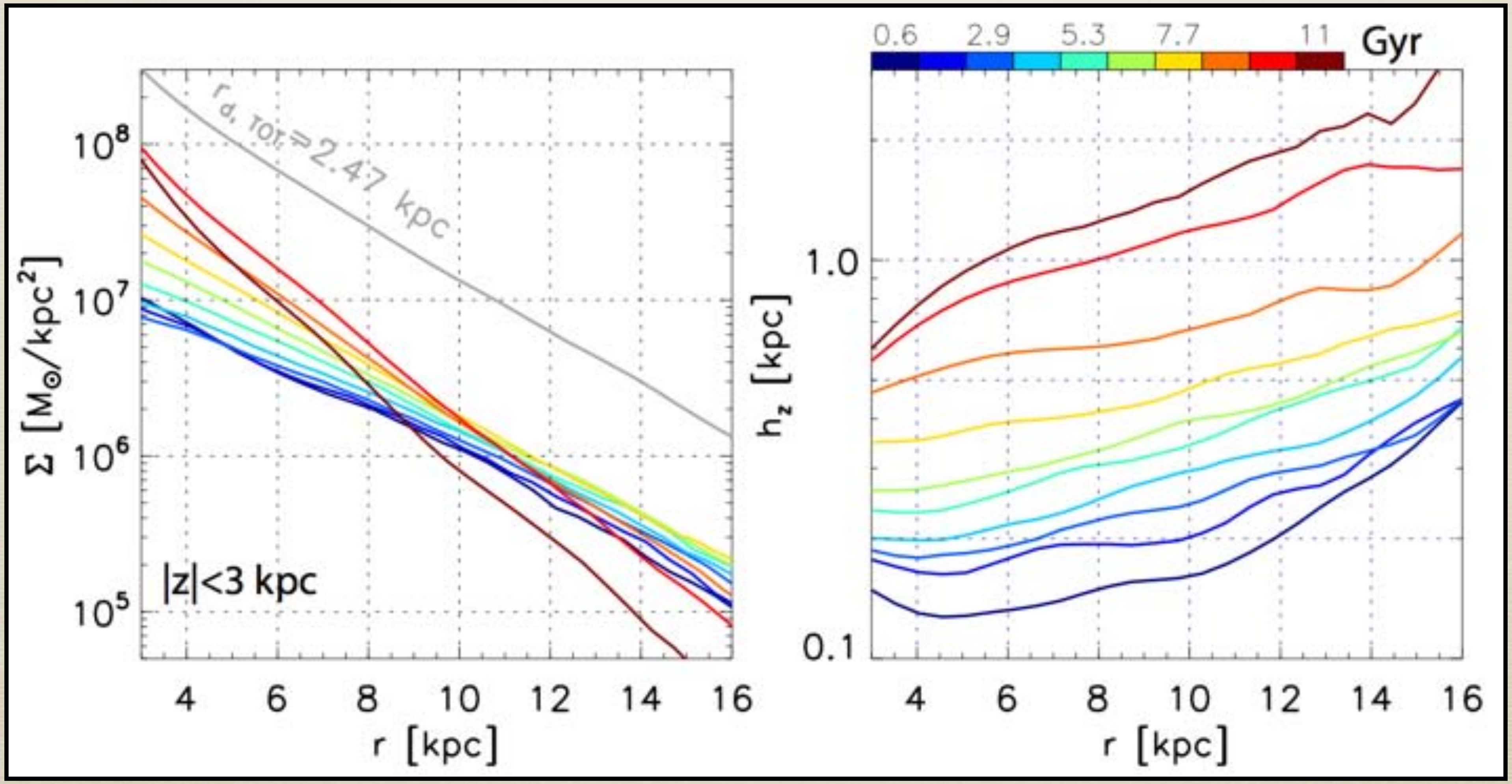


Bovy et al. (2016)

Disk structure in our model at the final simulation time

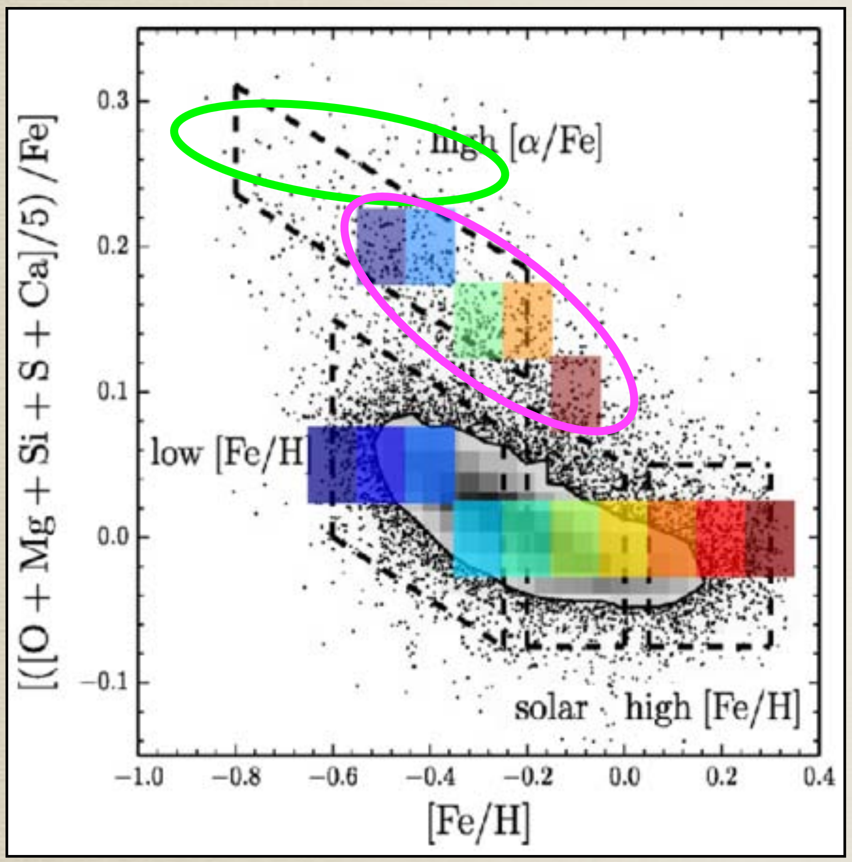
- Older populations more centrally concentrated as expected for the Milky Way
- Flaring present for all mono-age populations

Note that flaring is always present in mono-ages, although lost in model MAPs (previous slide)

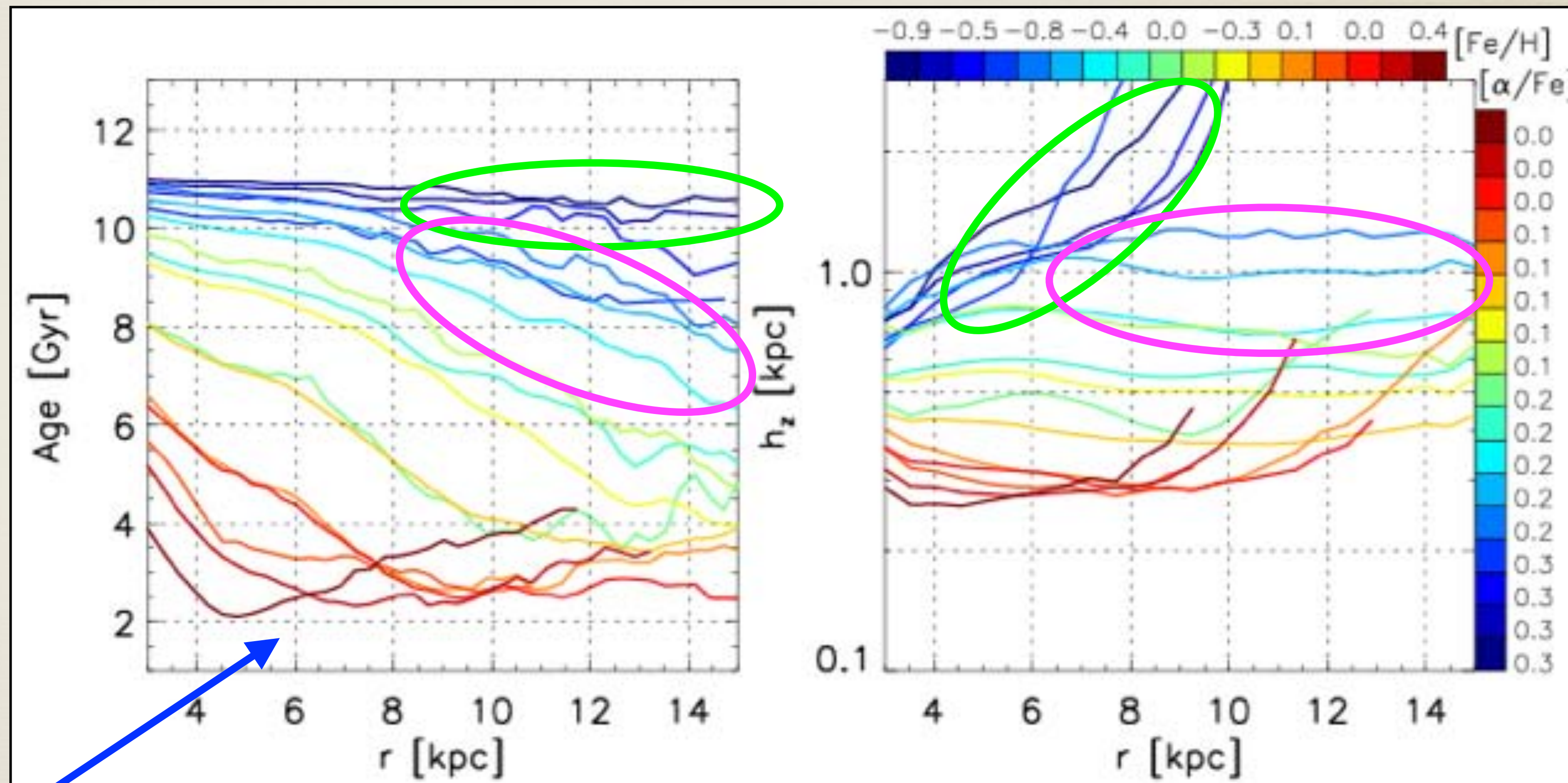


Why is flaring lost in model when MAPs considered?

- Note that APOGEE RC MAPs limited to [α/Fe]<0.2 and [Fe/H]<0.5 dex
- Negative age gradient of high-[α/Fe] MAPs causes the lack of flaring



Bovy et al. (2016)

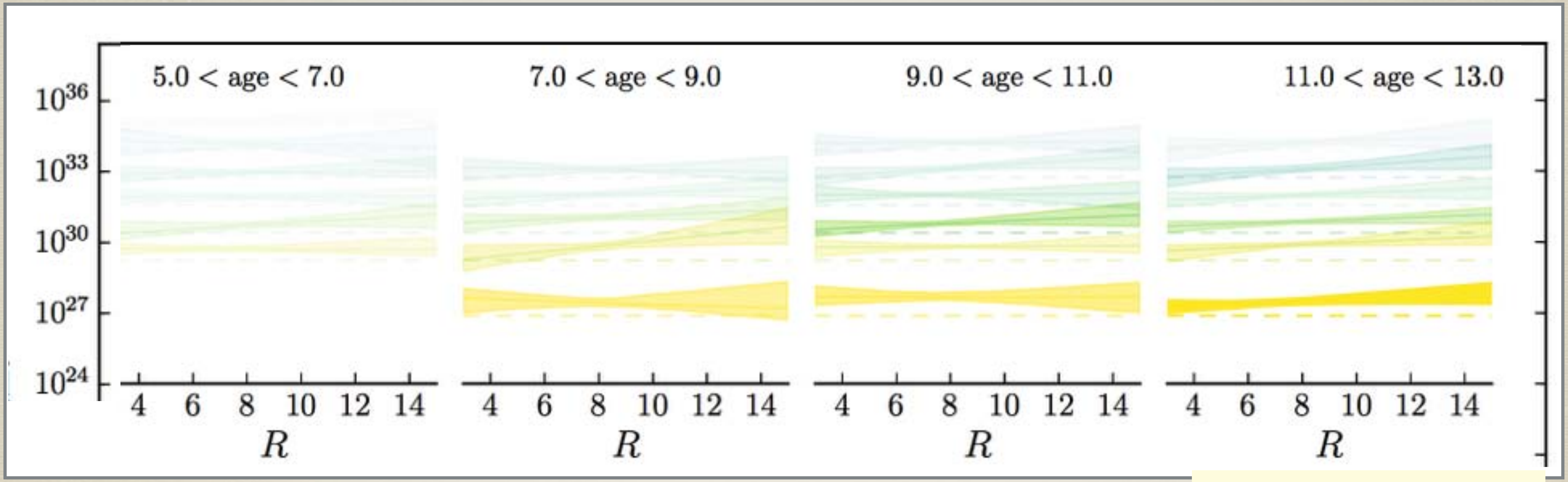


Minchev et al. (2016), MCM model

- Due to a mixture of ages, flaring in low-[α/Fe] MAPs not easily interpreted.
- We predict flaring in the highest [α/Fe] MAPs - larger sample needed (APOGEE-2?).

APOGEE mono-age populations show flaring in old stars!

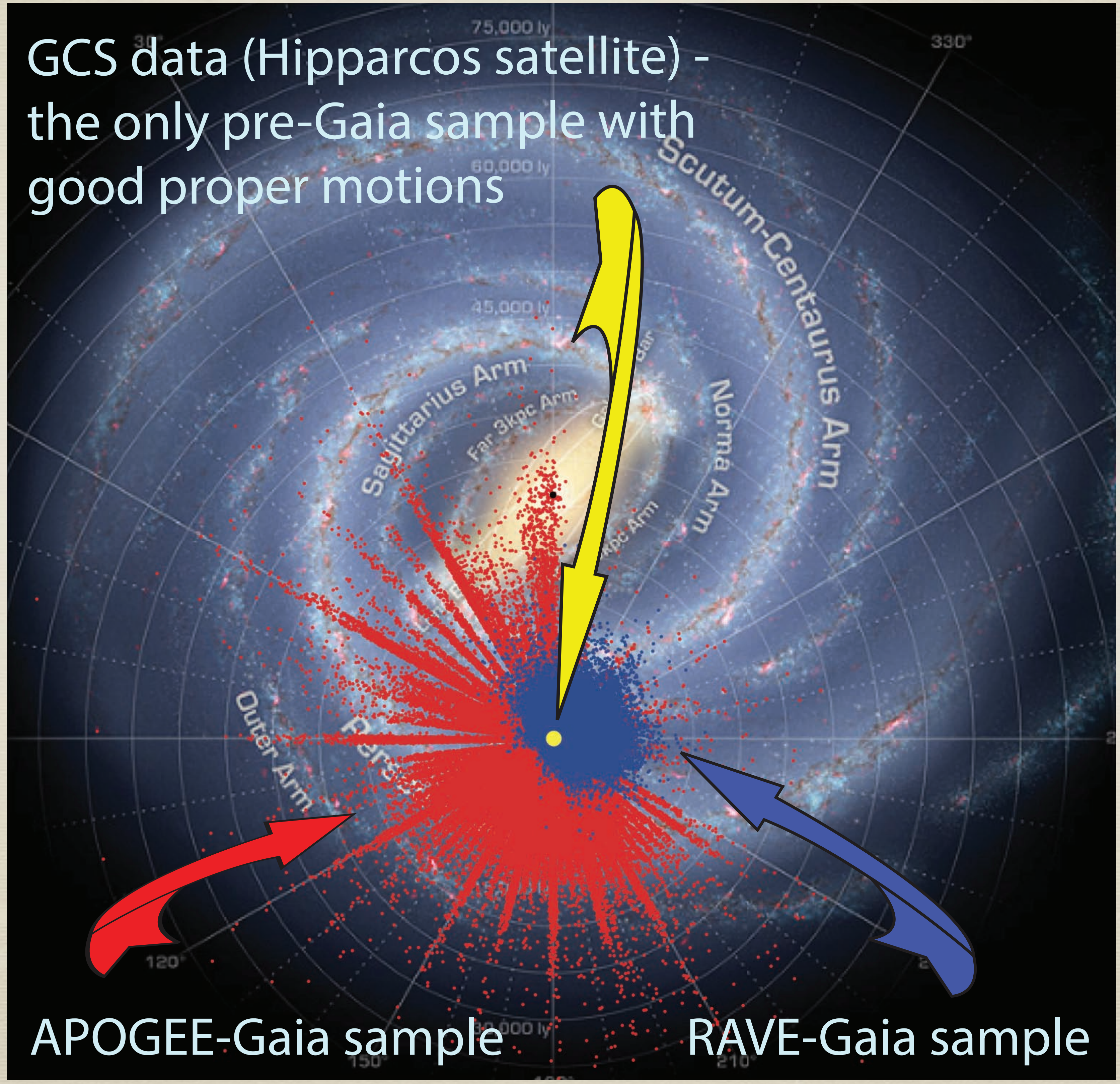
When APOGEE RC data are binned by age, **flaring does appear**



Mackereth, Bovy et al., submitted

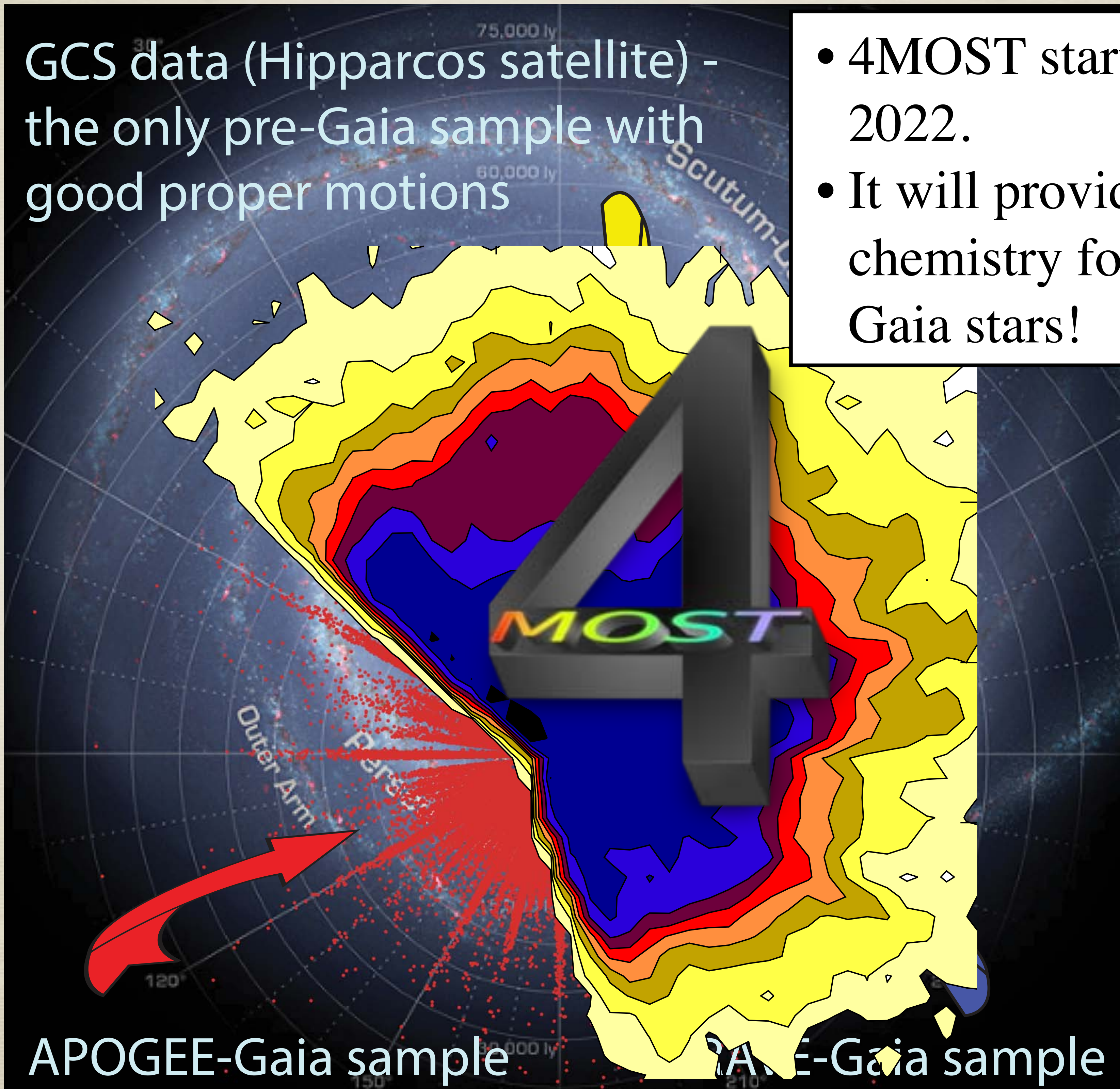
APOGEE ages based on C/N ratio, calibrated by asteroseismology from Martig et al. (2015)

Gaia+APOGEE and Gaia+RAVE samples
(at the end of Gaia mission)



Gaia+APOGEE and Gaia+RAVE samples

(at the end of Gaia mission)



- 4MOST starts operation in 2022.
- It will provide RVs and chemistry for 10-15 Million Gaia stars!

Summary of the effects of radial migration

- **Radial migration can**:
  - Flare disks during quiescent times
  - Suppress disk flaring during mergers
  - Introduce scatter in the AMR
  - Explain the high metallicity tail

- **Radial migration cannot**:
  - Explain the thick disks
  - Create a gap in the [α/Fe]-[Fe/H] relation
  - Compete with inside out formation
  - Cannot be avoided - gotta deal with it!

Conclusions

- In order to interpret the unprecedented Gaia + follow-up surveys data, **simulation in cosmological context are needed**!
- Improvements in simulations needed with respect to resolution and chemical treatment.
- **Radial migration unavoidable!** Have to deal with it.
- **Thick disk composed of the nested flares of mono-age populations**
  - disk flaring unavoidable!
  - total mass does not flare if inside-out formation
  - results in inversion of the metallicity, [α/Fe], and age gradients with increasing distance from the disk midplane.
- Mono-abundance populations (MAPs) **most likely not mono-age**.
- **Age information is crucial for understanding the Milky Way disk structure and evolution -** great expectations from Kepler, PLATO and TESS in the near future!