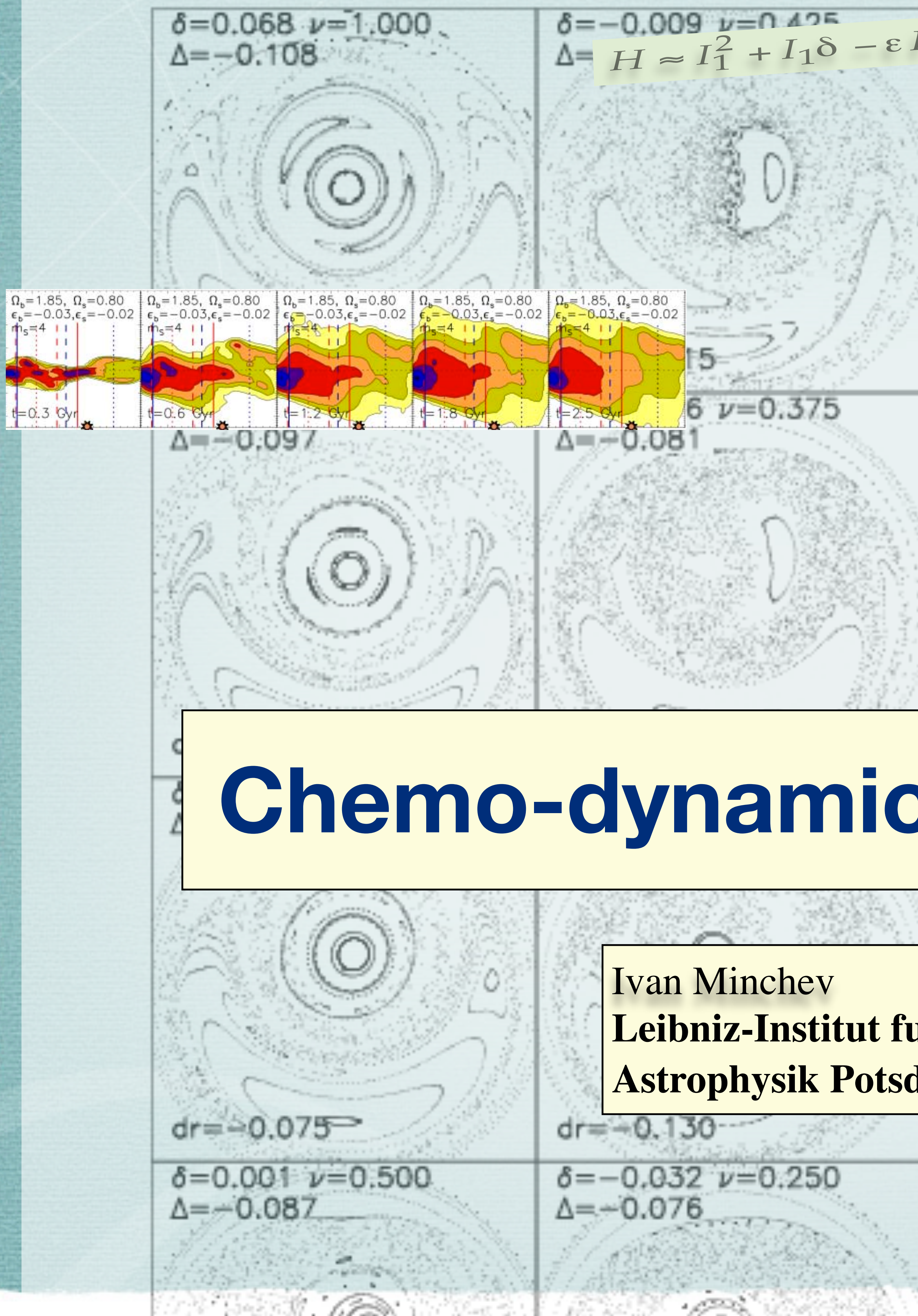
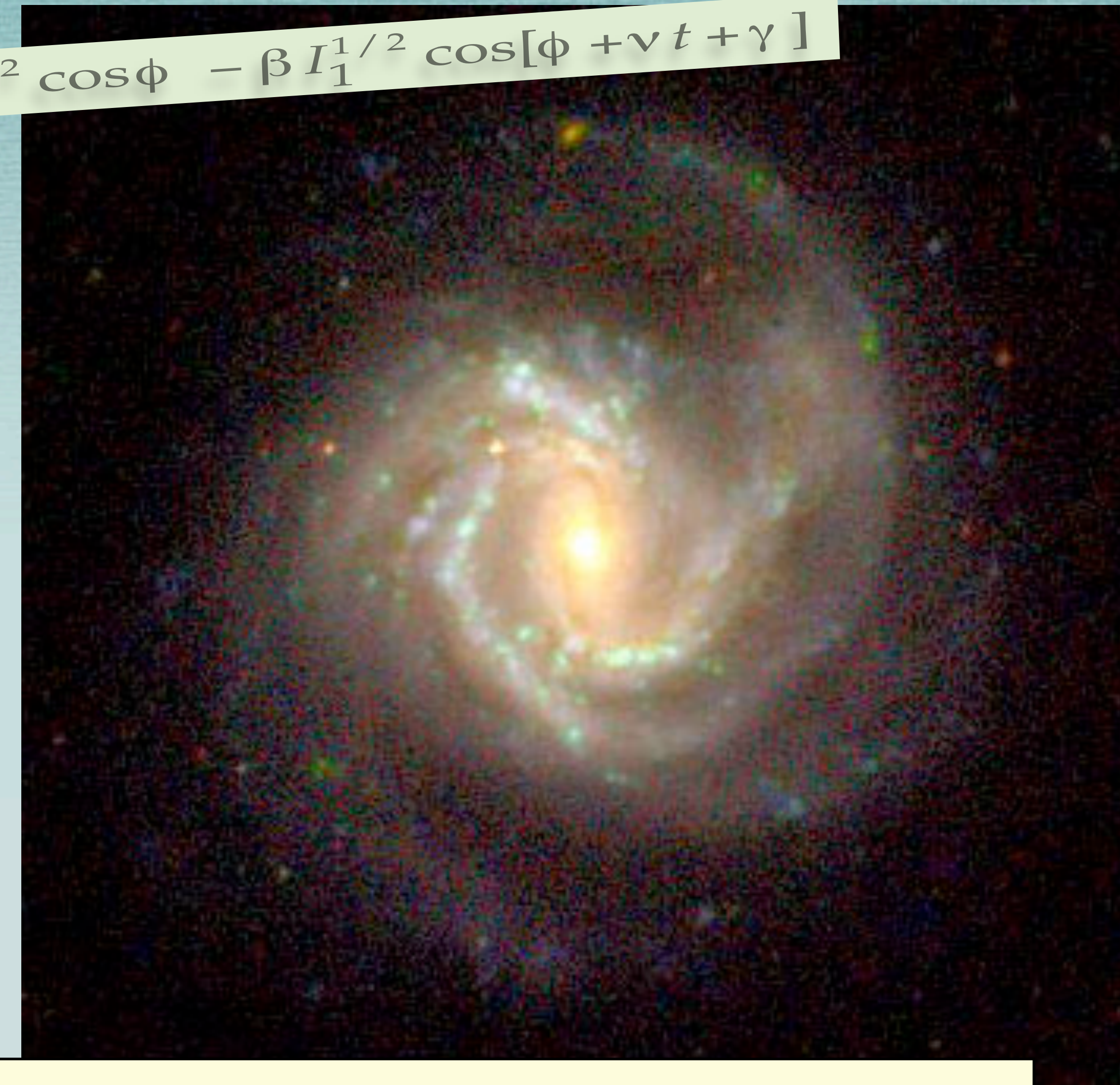


$$H \approx I_1^2 + I_1\delta - \varepsilon I_1^{1/2}\cos\phi \; - \beta I_1^{1/2}\cos[\phi + \nu t + \gamma]$$



Chemo-dynamical disk modeling

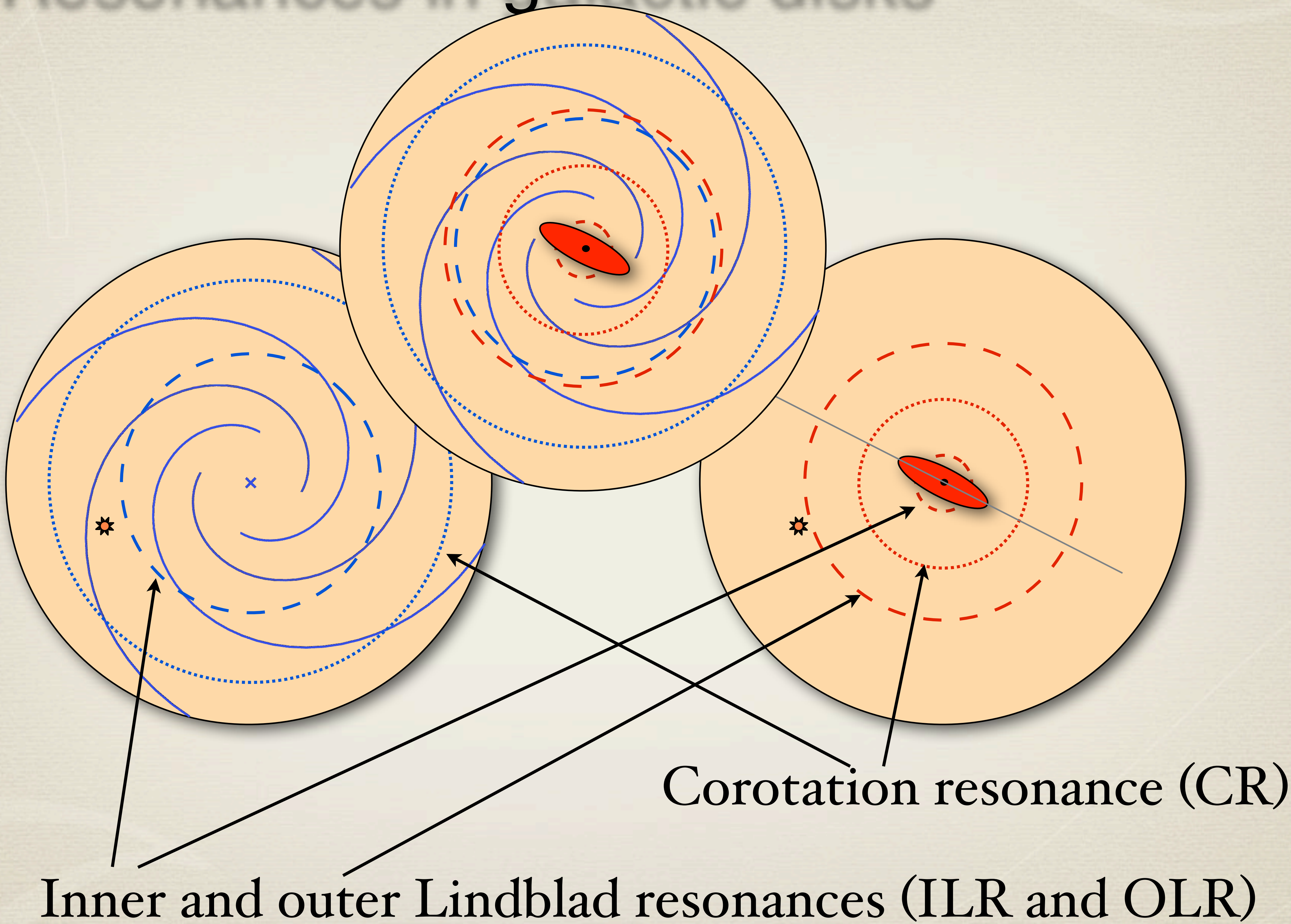
Ivan Minchev
Leibniz-Institut fur
Astrophysik Potsdam (AIP)

AIP
Leibniz-Institut für
Astrophysik Potsdam

Talk outline

- Effect of disk asymmetries on disk dynamics.
- Radial migration in galactic disks.
- Chemo-dynamical disk modeling.
- Chemo-kinematic observational constraints.

Resonances in galactic disks

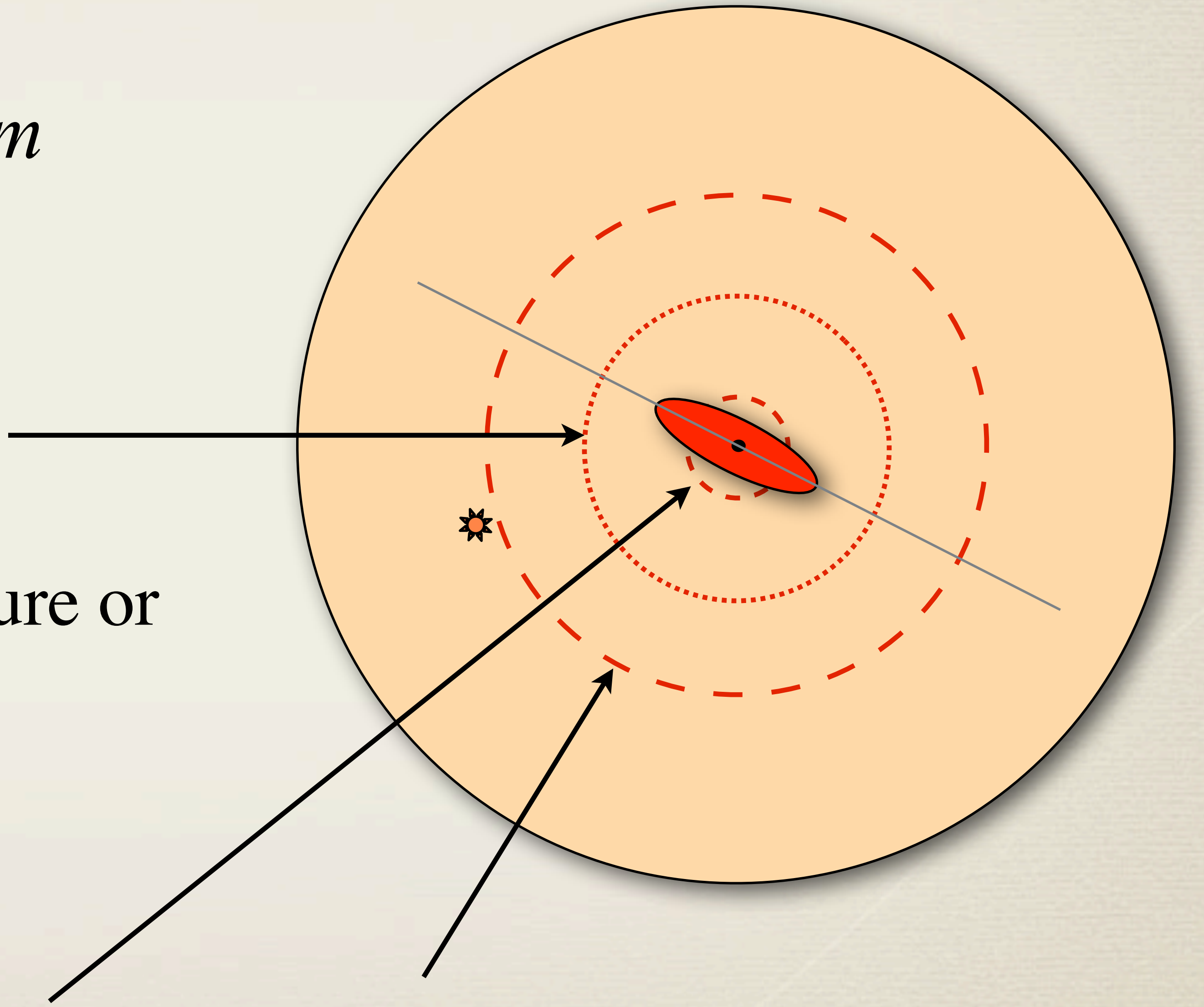


Resonances in galactic disks

- 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.

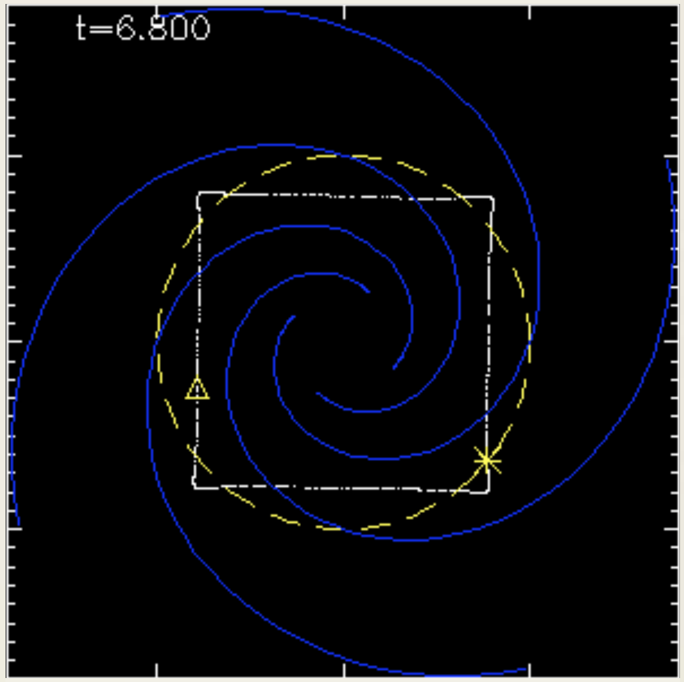


Inner and Outer Lindblad resonances

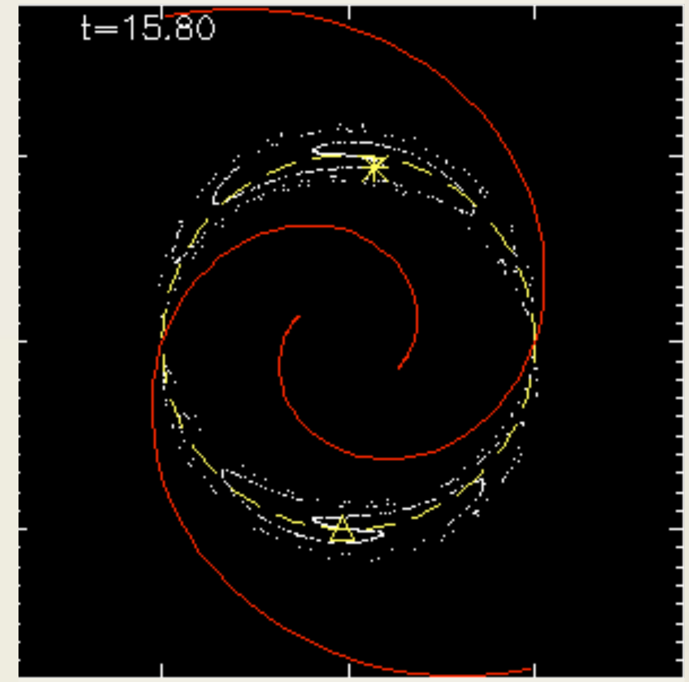
Stellar orbits near resonances

Single spiral wave

Near OLR

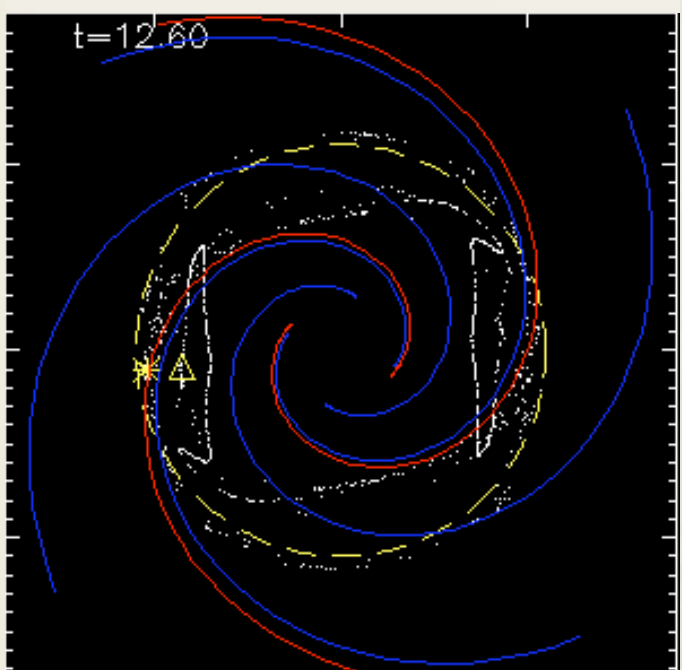


Near Corotation (CR)

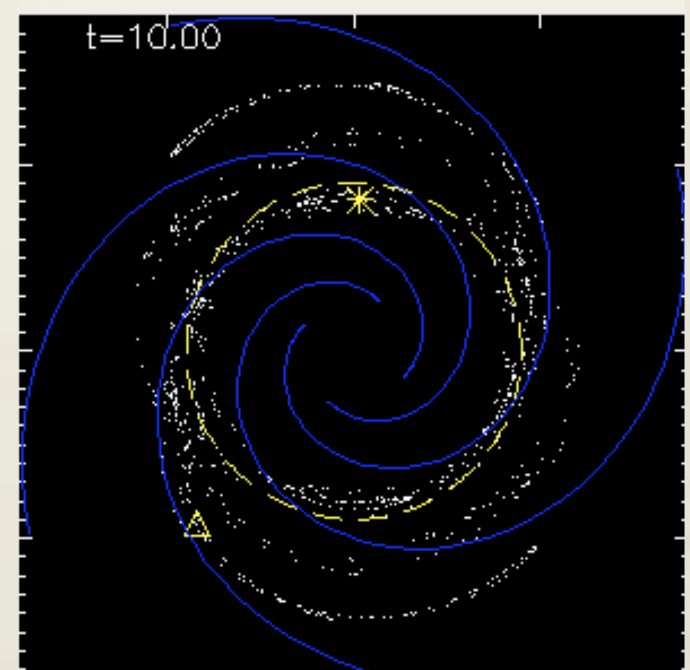


2 spiral waves

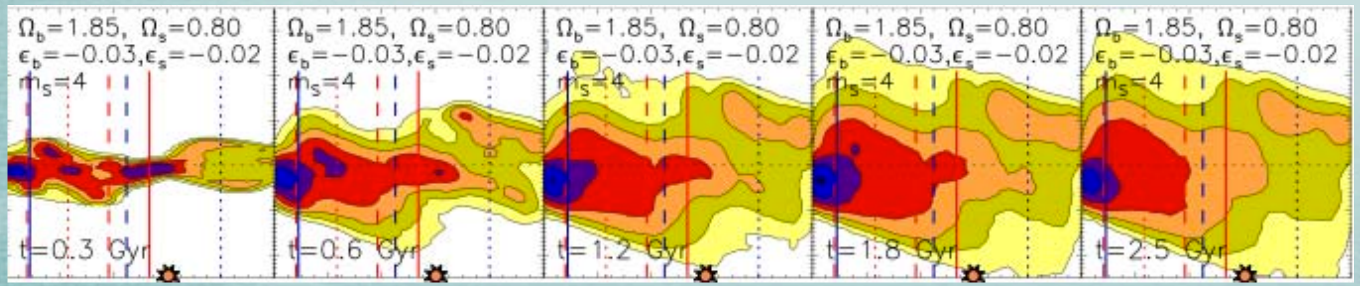
Outside OLR+CR

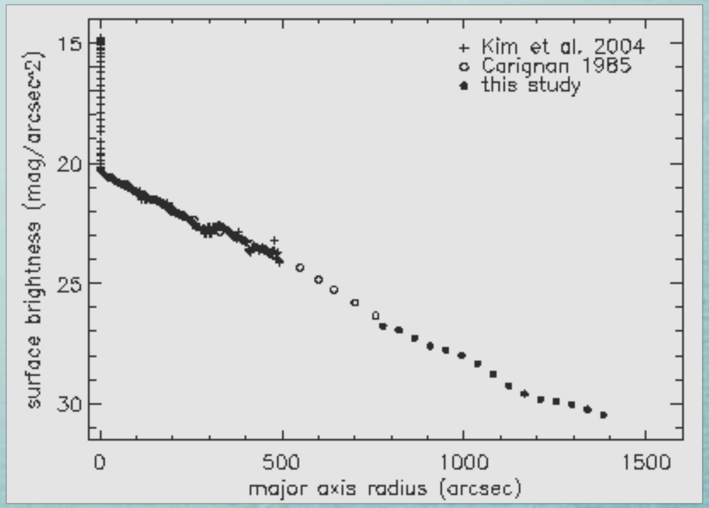


Inside OLR+CR

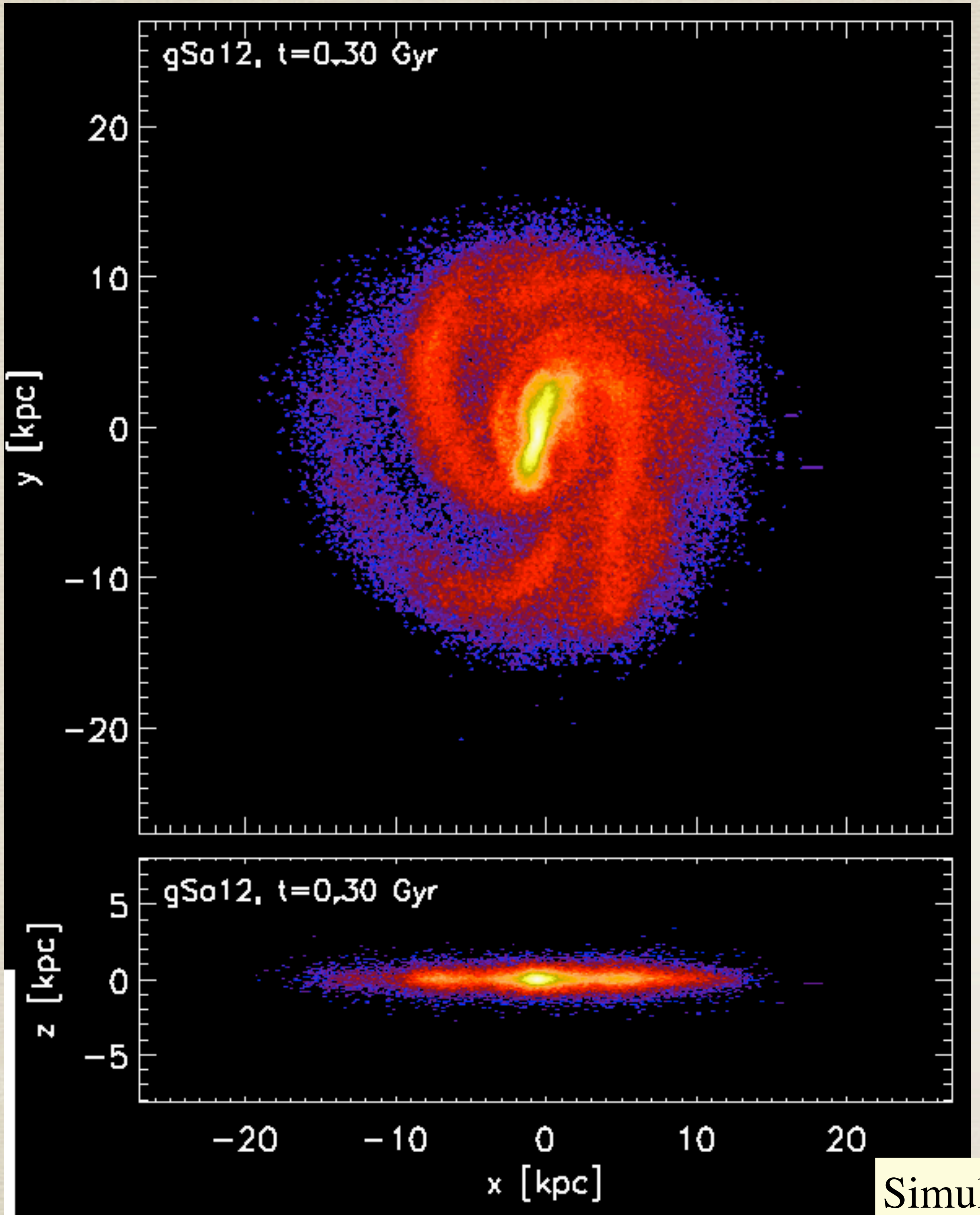


Radial migration





N-body Tree-SPH



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

Formation of a pseudobulge

Simulations by P. Di Matteo

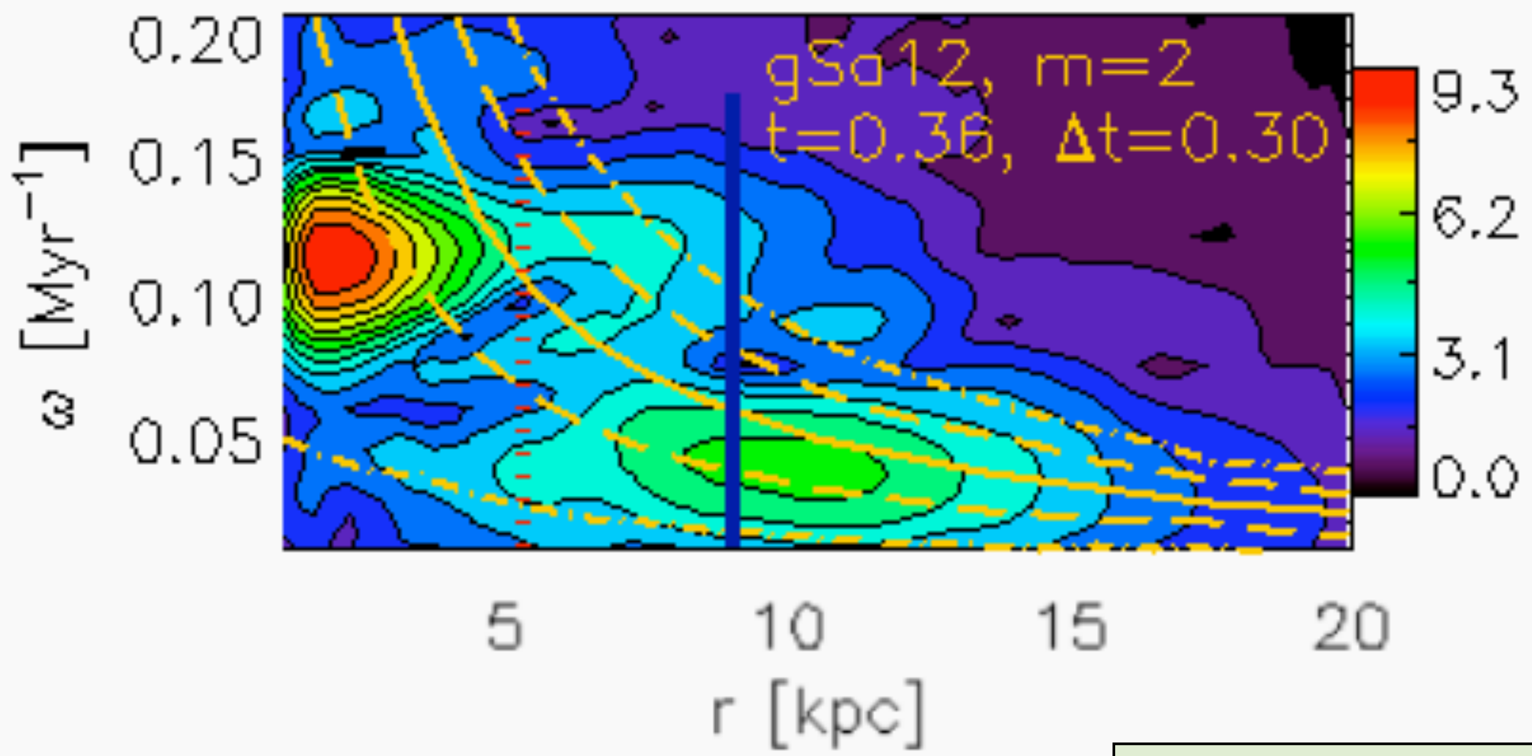
Power spectrograms reveal multiple patterns

Overlap of bar and spiral creates transient stellar mass clumps!

Existence of **multiple patterns** in disks long known in simulations:
Tagger et al. (1987)
Signet et al. (1988)
Quillen et al. (2011)
Minchev et al. (2012a)

and in observations:
Elemegreen et al. (1992)
Rix & Rieke (1993)
Meidt et al. (2009)

Sa model

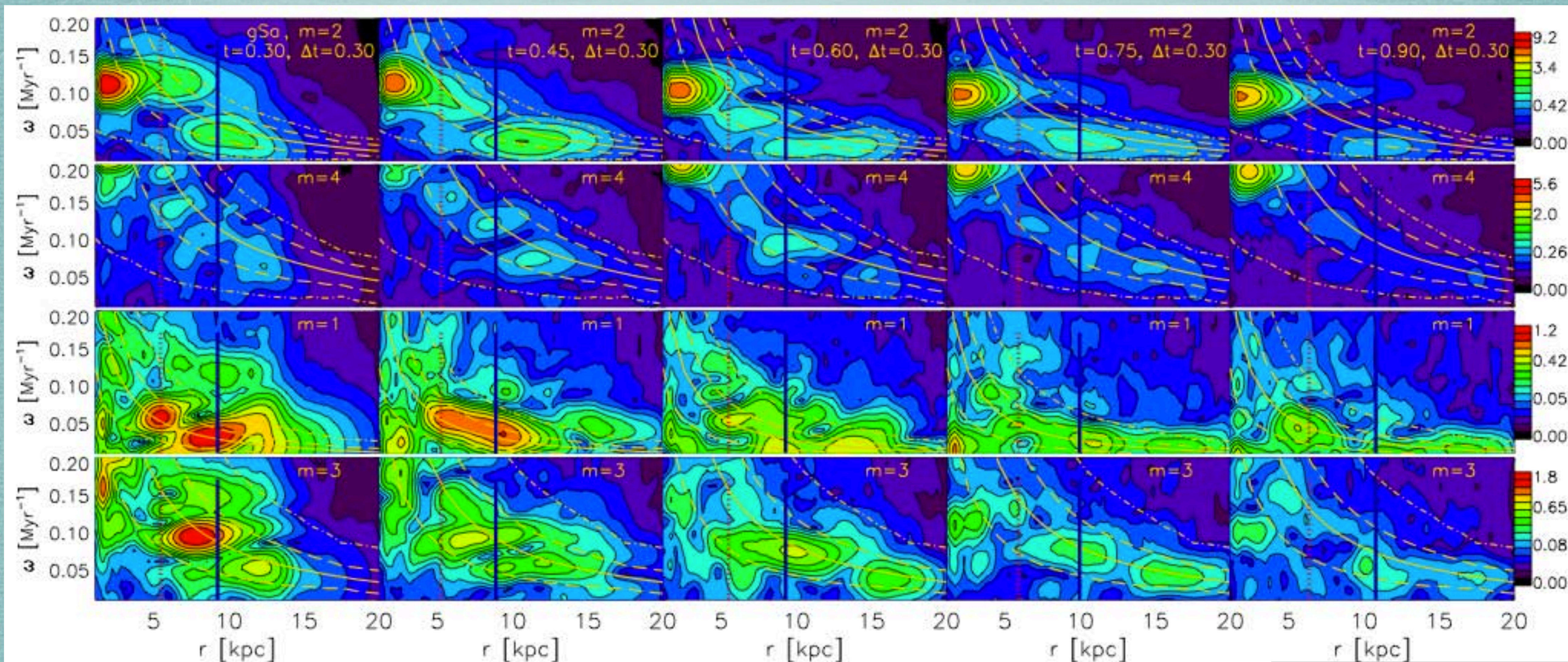


Minchev et al. (2012a)

Interaction between the bar and the spiral when reconnecting

Power spectrograms reveal multiple patterns

Time



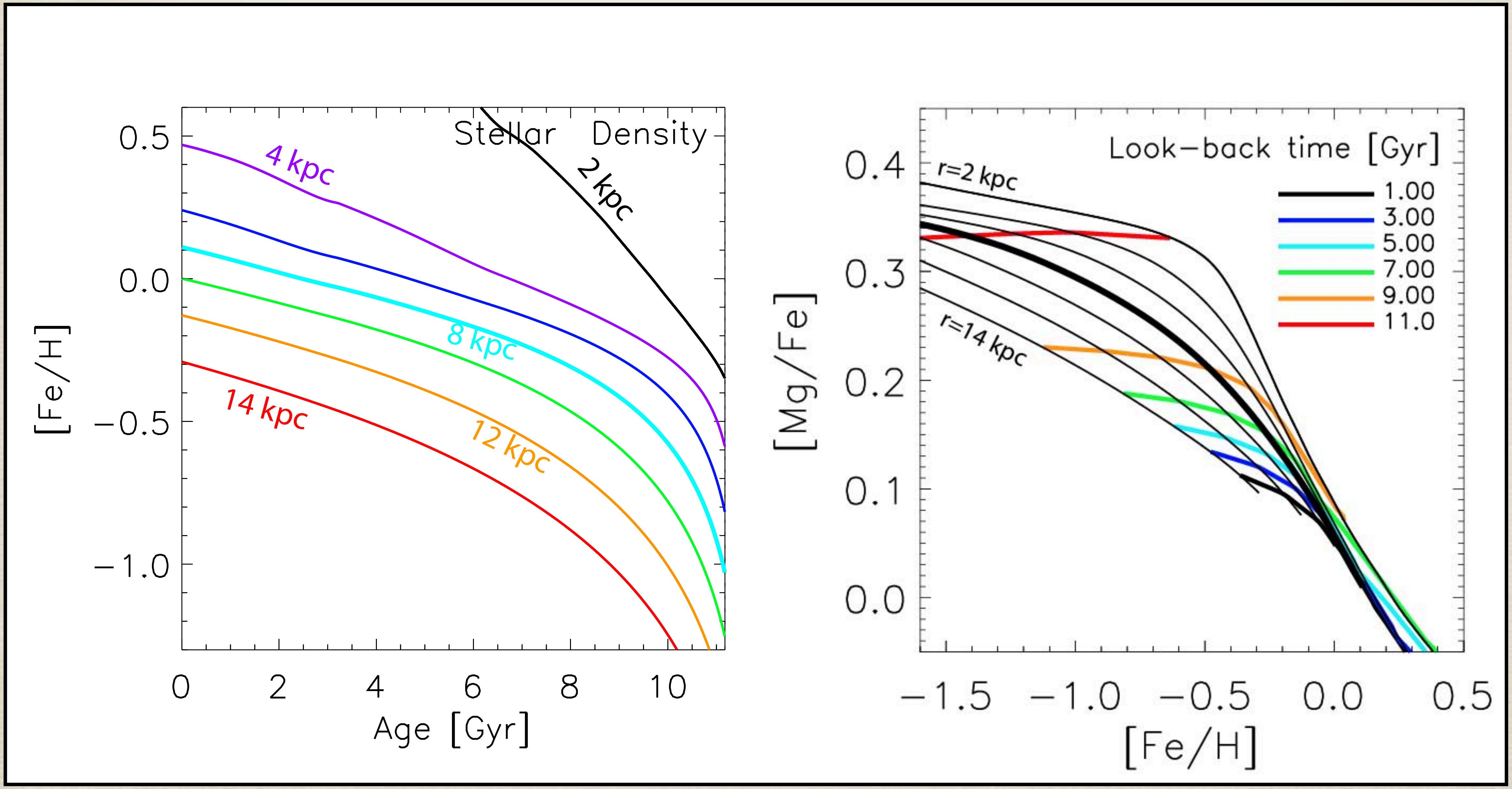
Minchev et al. (2012a)

Quasi-steady spiral patterns of multiplicity 1-4

Chemo-dynamical evolution modeling of the Milky Way

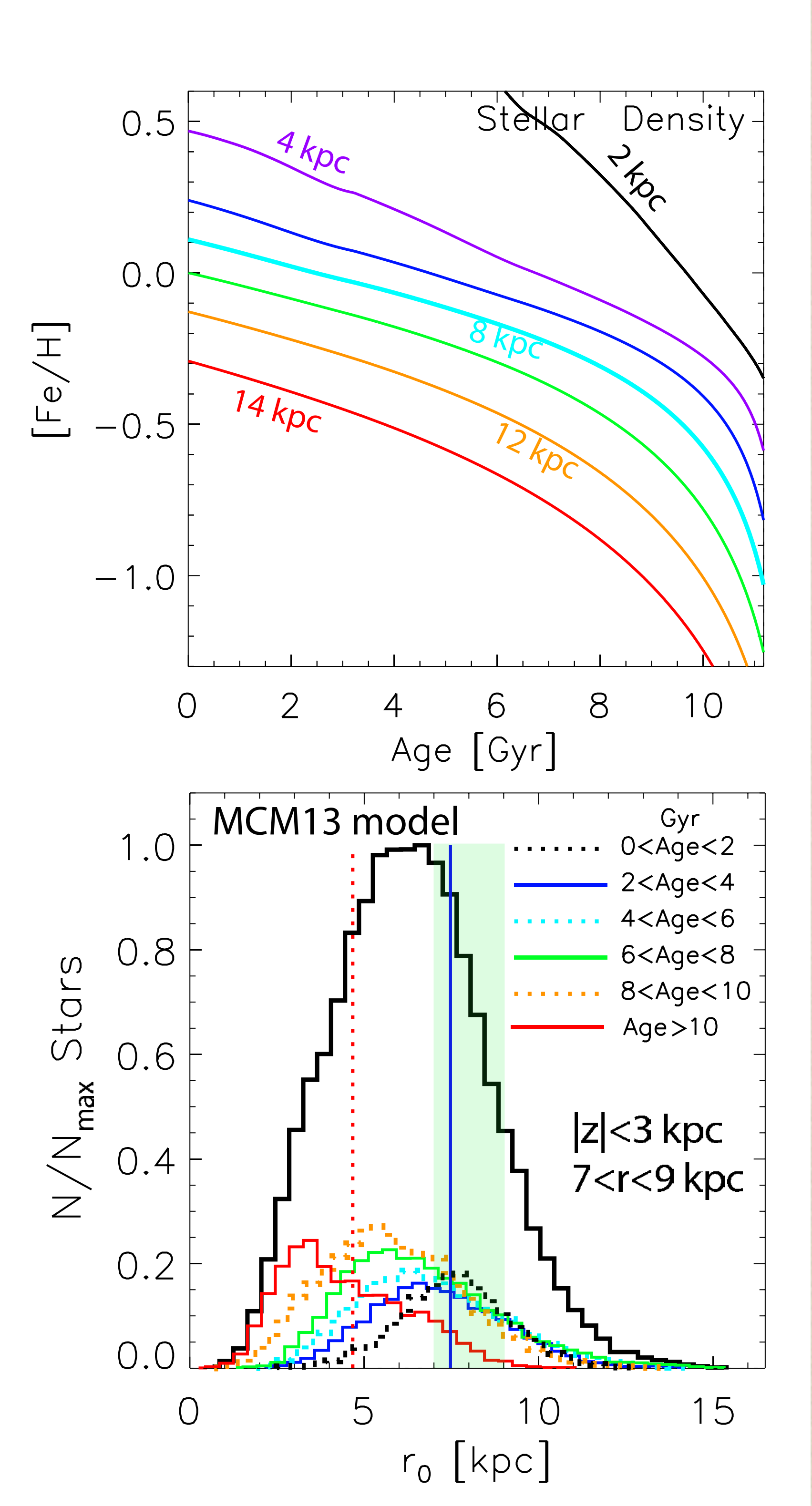
Classical chemical evolution modeling

- Classical chemical evolution models (Matteucci & Francois 1989; Prantzos & Aubert 1995; Chiappini et al. 1997, 2001).
- Stars assumed to die close to their birth places.



Classical chemical evolution modeling hampered by radial migration

- Stars move away from their birth places (Sellwood and Binney 2002).



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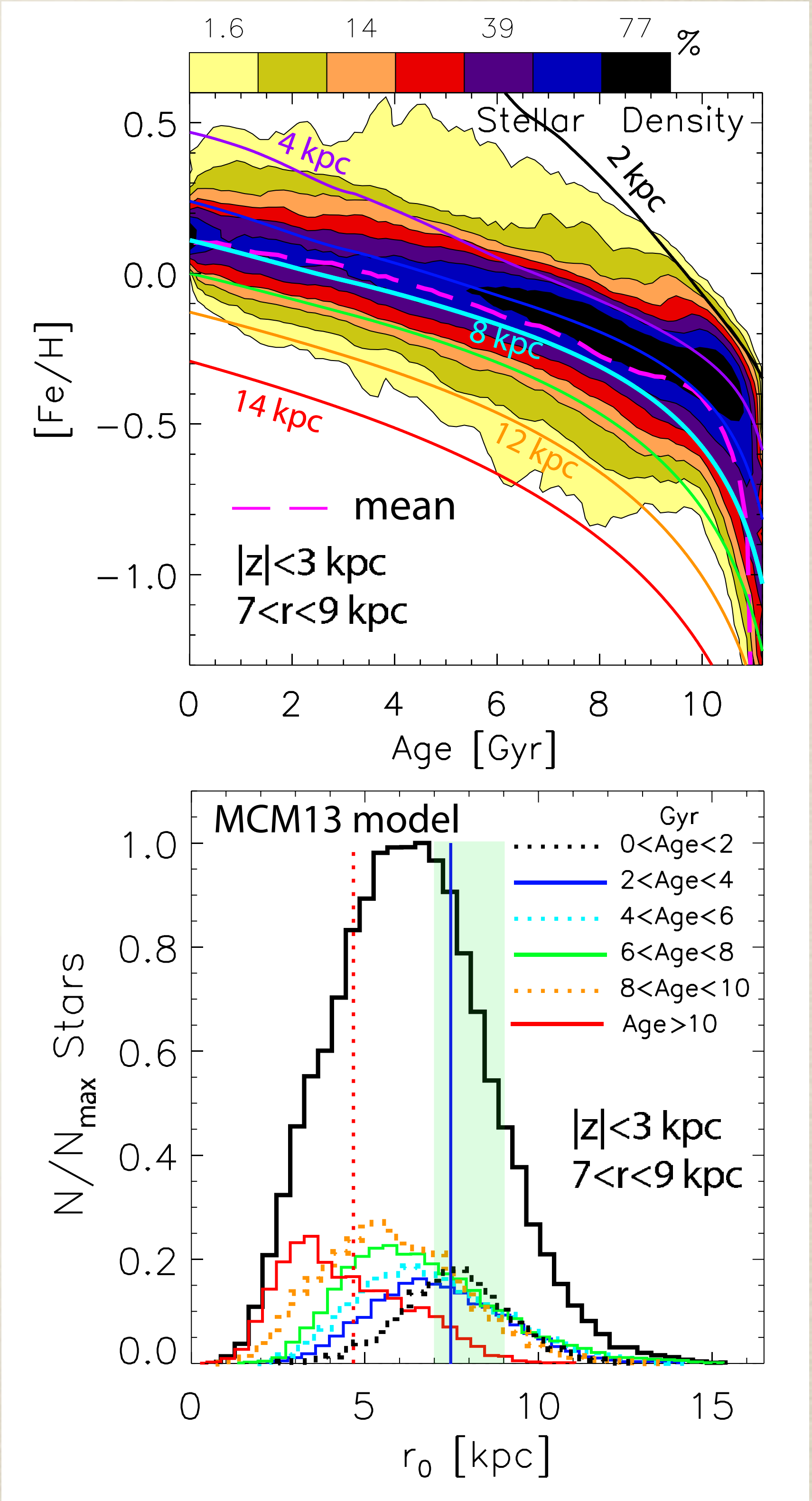
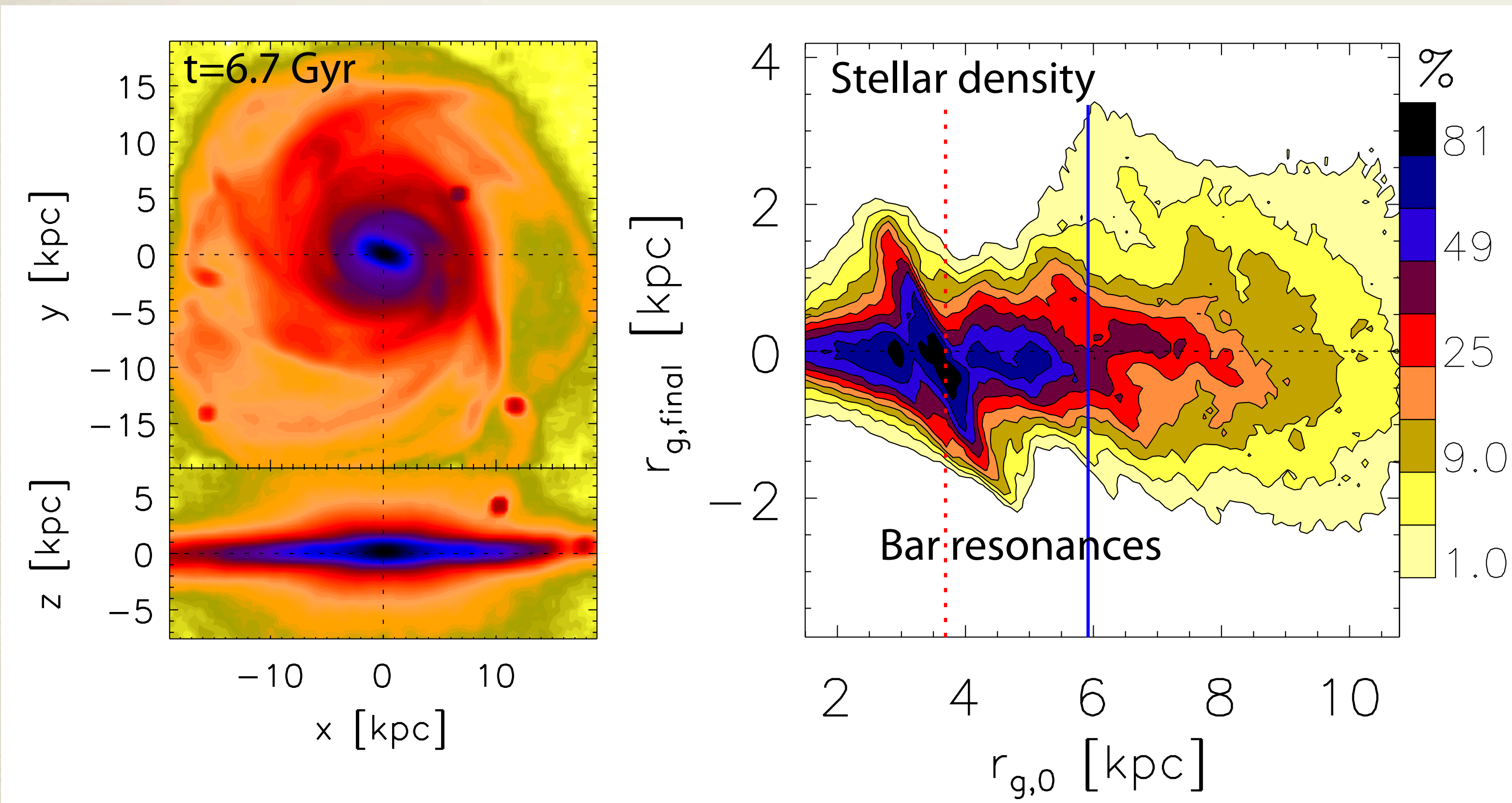
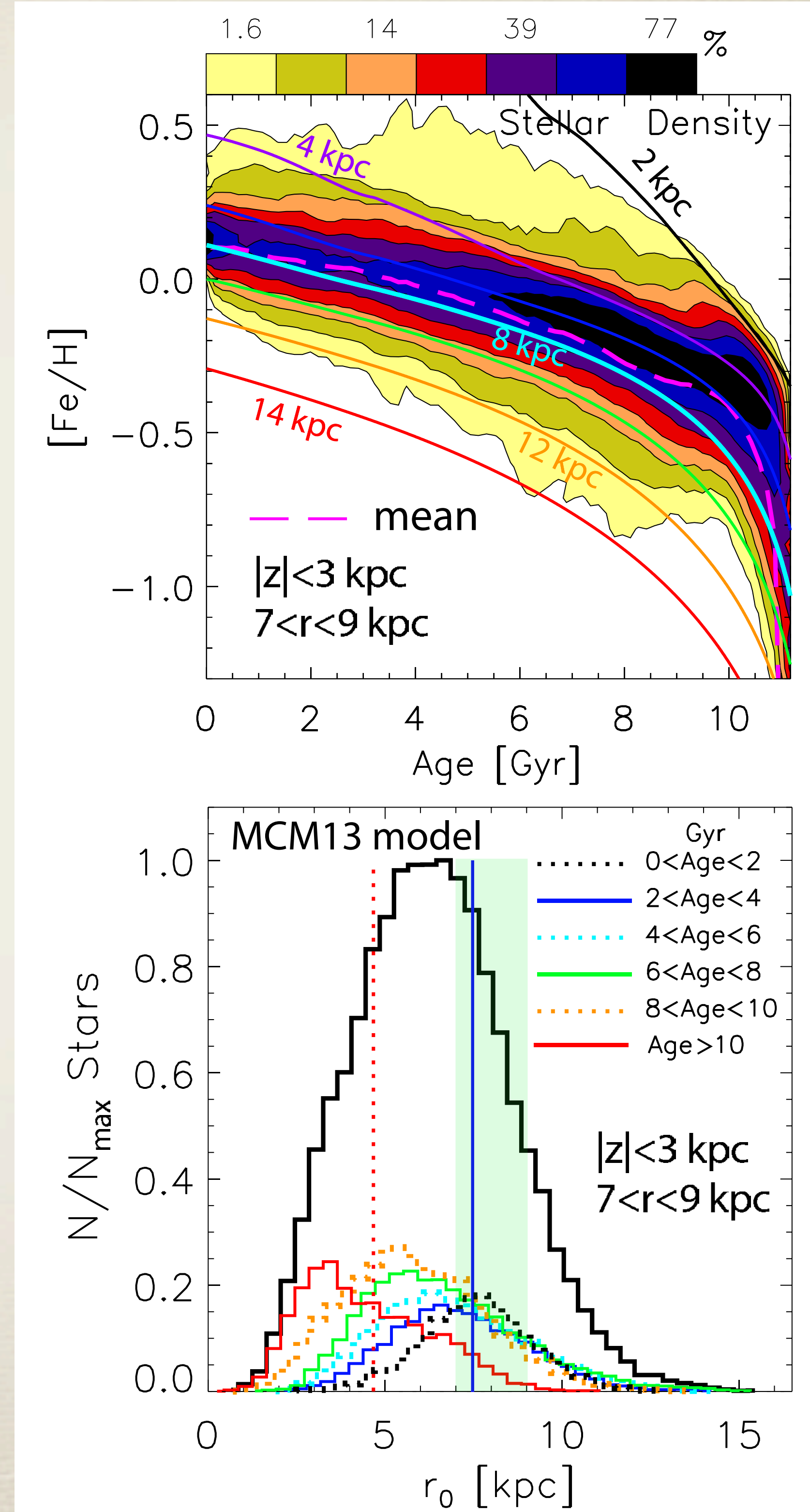


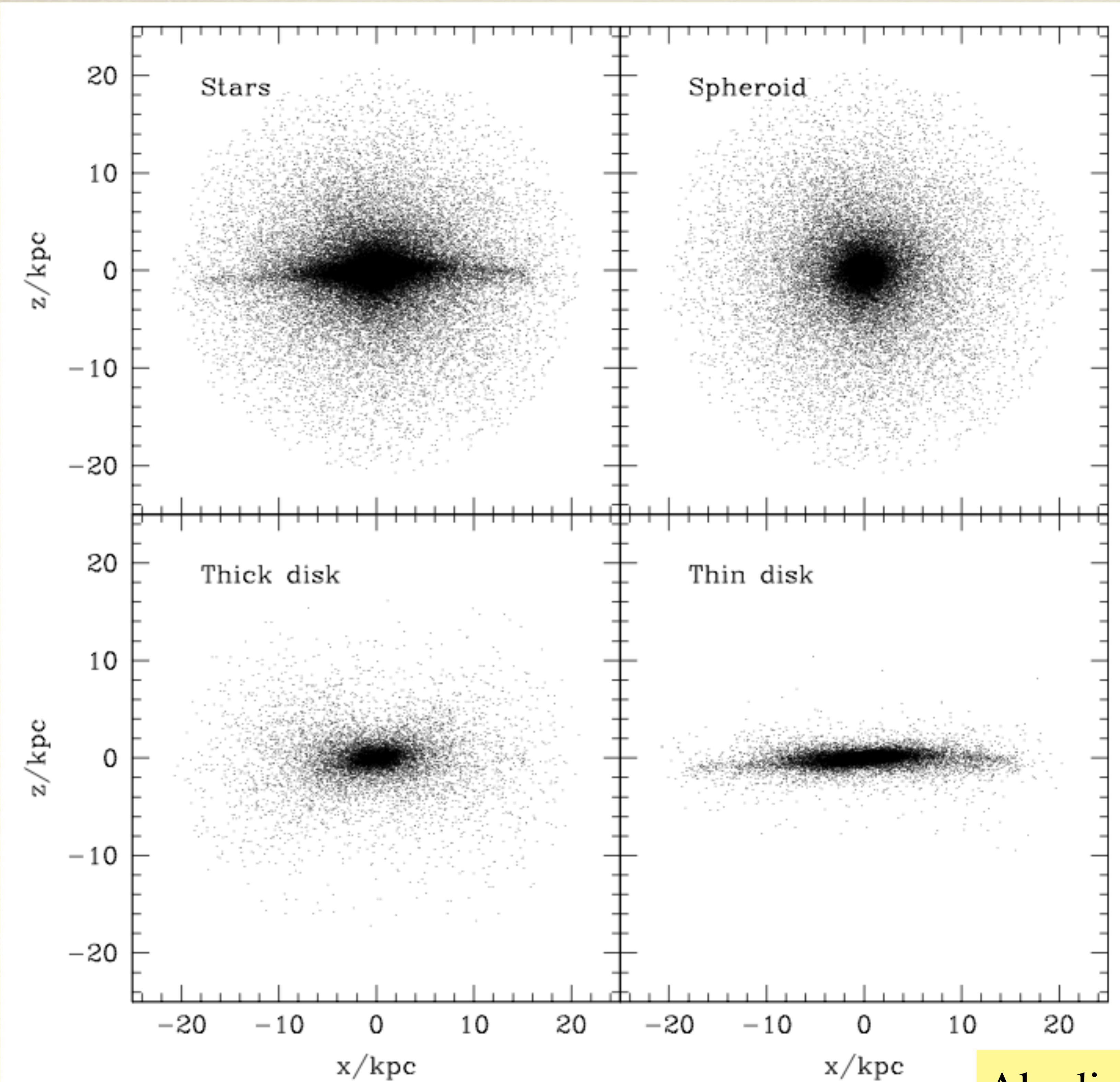
Classical chemical evolution modeling
hampered by radial migration

- Stars move away from their birth places (Sellwood and Binney 2002).
- We need to recover the migration efficiency as a function of Galactic radius and time.





Disk formation in cosmological simulations

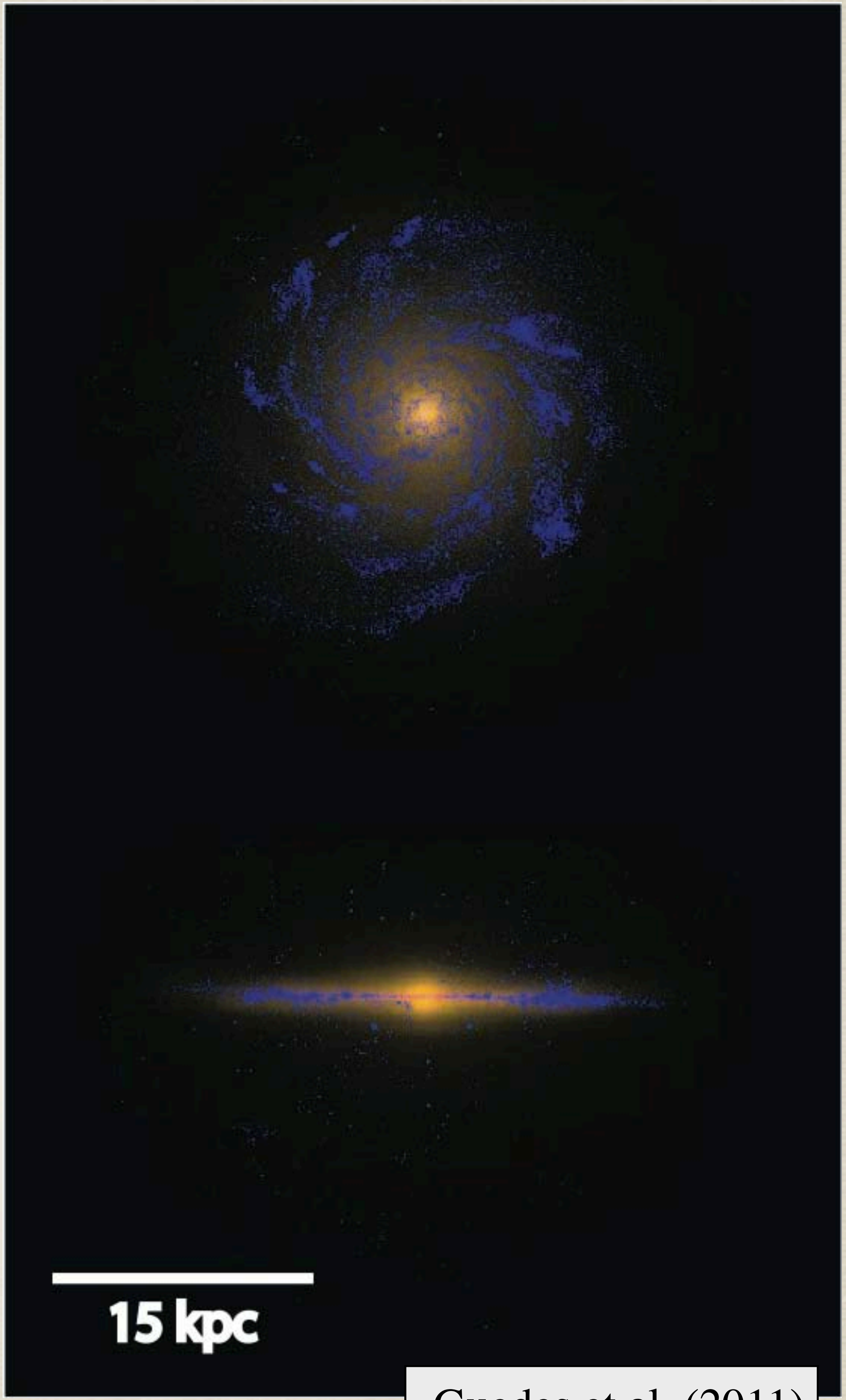


- Traditionally a challenge (e.g., Navarro and Benz 1991; Abadi et al., 2003):
- Extreme angular momentum loss during mergers.
- Overly-concentrated mass distributions and massive bulges.

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



Guedes et al. (2011)

Recent improvements in chemical enrichment

- Simulations including chemical treatment – Raiteri et al. (1996), Mosconi et al. (2001), Lia et al. (2002), Kawata and Gibson (2003), Kobayashi (2004), Scannapieco et al. (2005), Martínez-Serrano et al. (2008), Oppenheimer and Davé (2008), Wiersma et al. (2009), Few et al. (2012)

- Encouraging results recently – global observed trends reproduced:

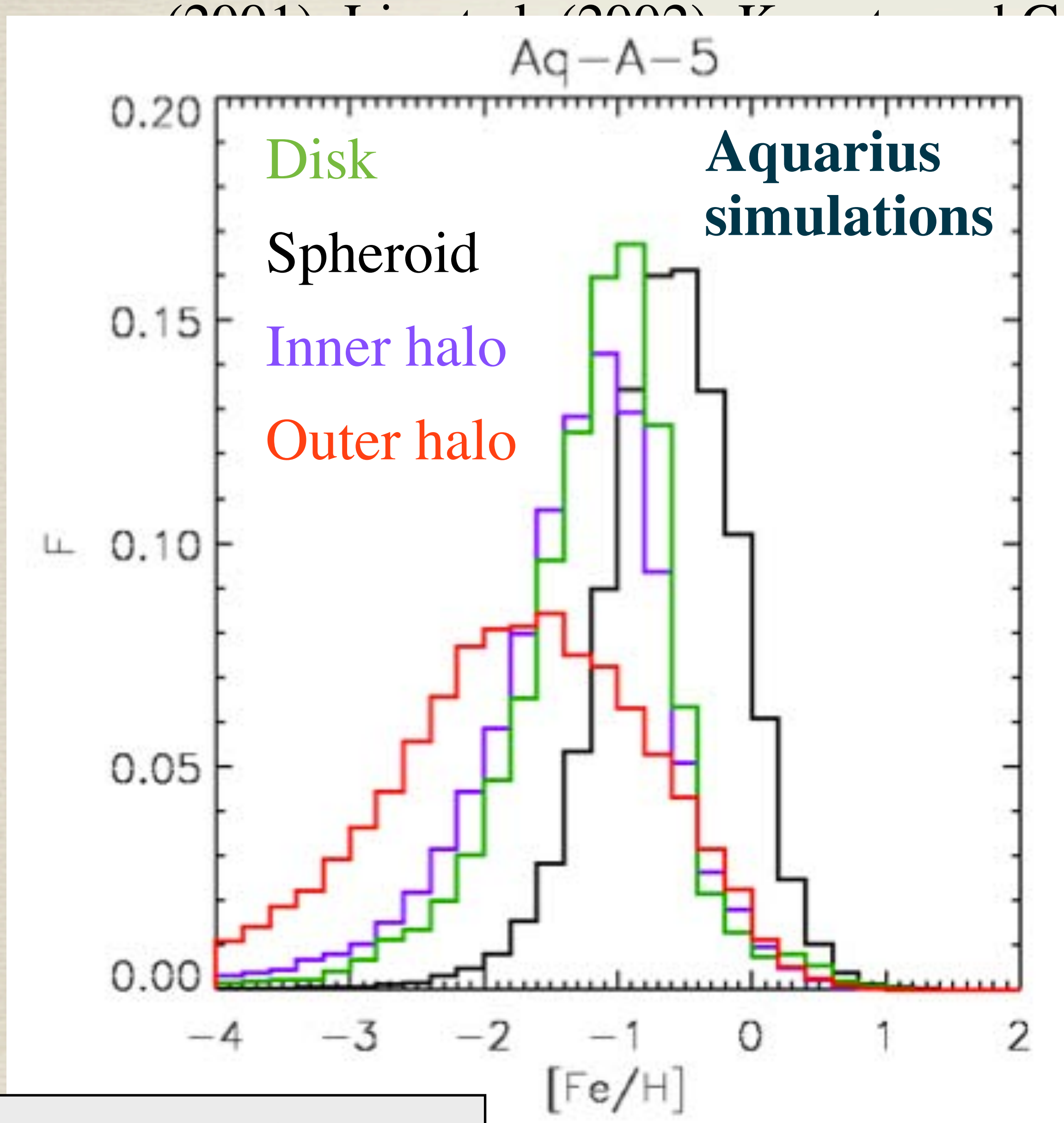
    - The mass-metallicity relation (e.g., Kobayashi et al. 2007)

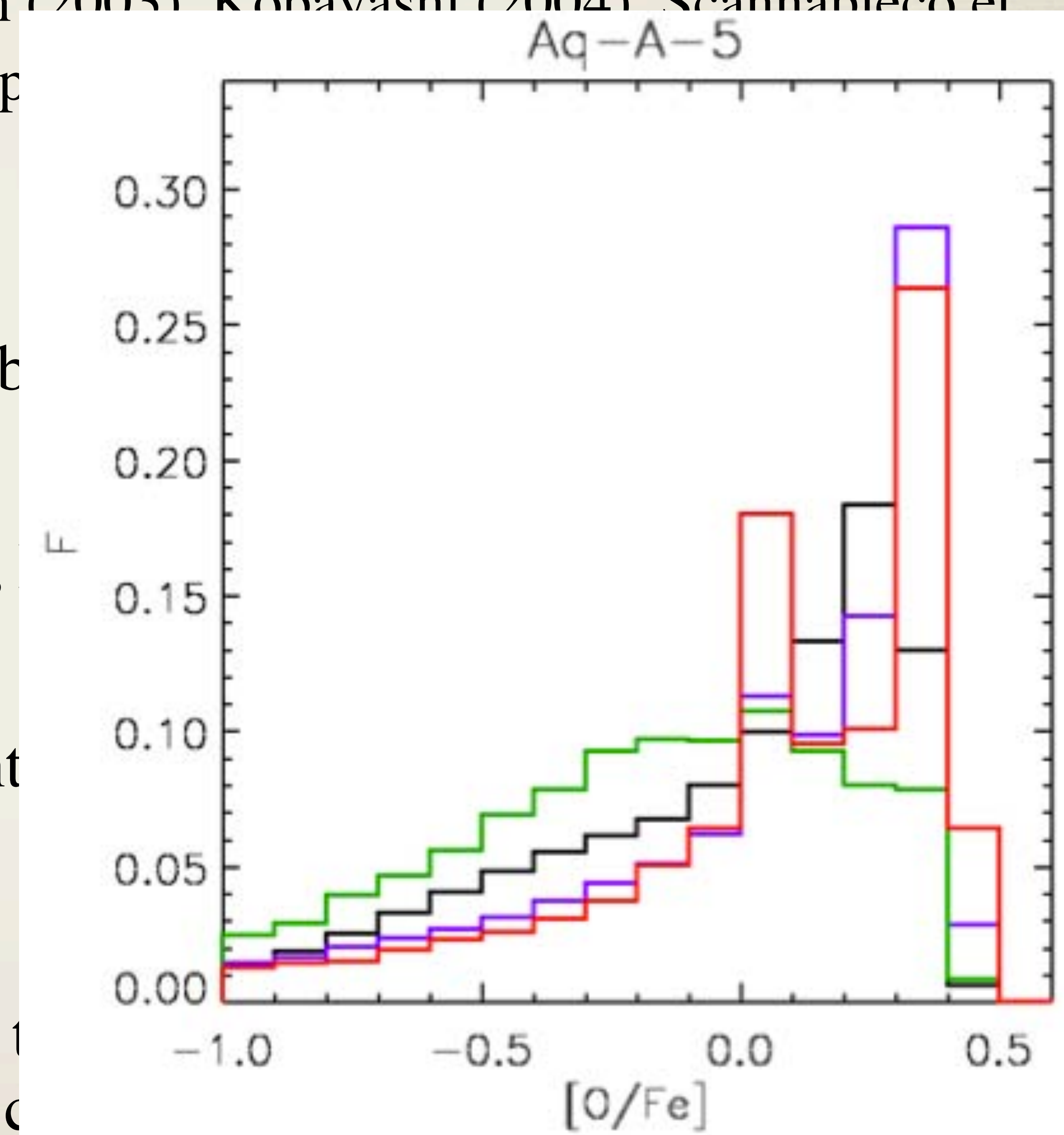
    - Metallicity trends between different galactic components (e.g., Tissera et al. 2012)

- However, still a challenge to reproduce the properties of the Milky Way, e.g., the typical metallicities of the different components – Tissera et al. (2012).

Recent improvements in chemical enrichment

- Simulations including chemical treatment – Raiteri et al. (1996), Mosconi et al.





Tissera et al. (2012)

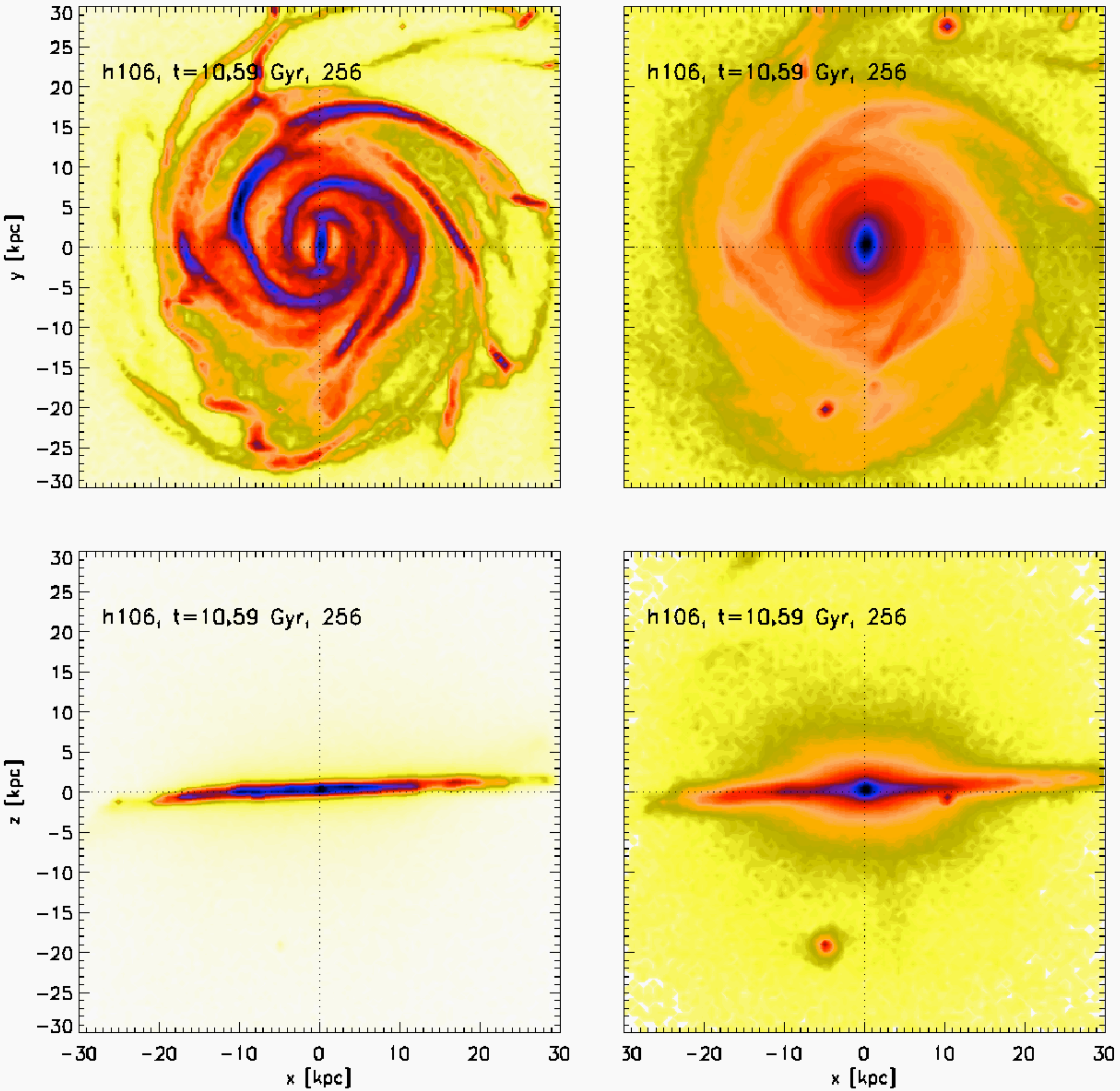
Seek an alternative approach to circumvent problems with fully self-consistent simulations

- Radial migration must be considered in the disk’s chemical evolution (Sellwood and Binney 2002, Schonrich and Binnery 2009a,b).

Use present day Milky Way disk morphology and kinematics as constraints

Ingredients

- 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 several observational constraints in the Milky Way.



Simulation in cosmological context

Martig et al. (2009, 2012)

Stars born hot at high redshift:

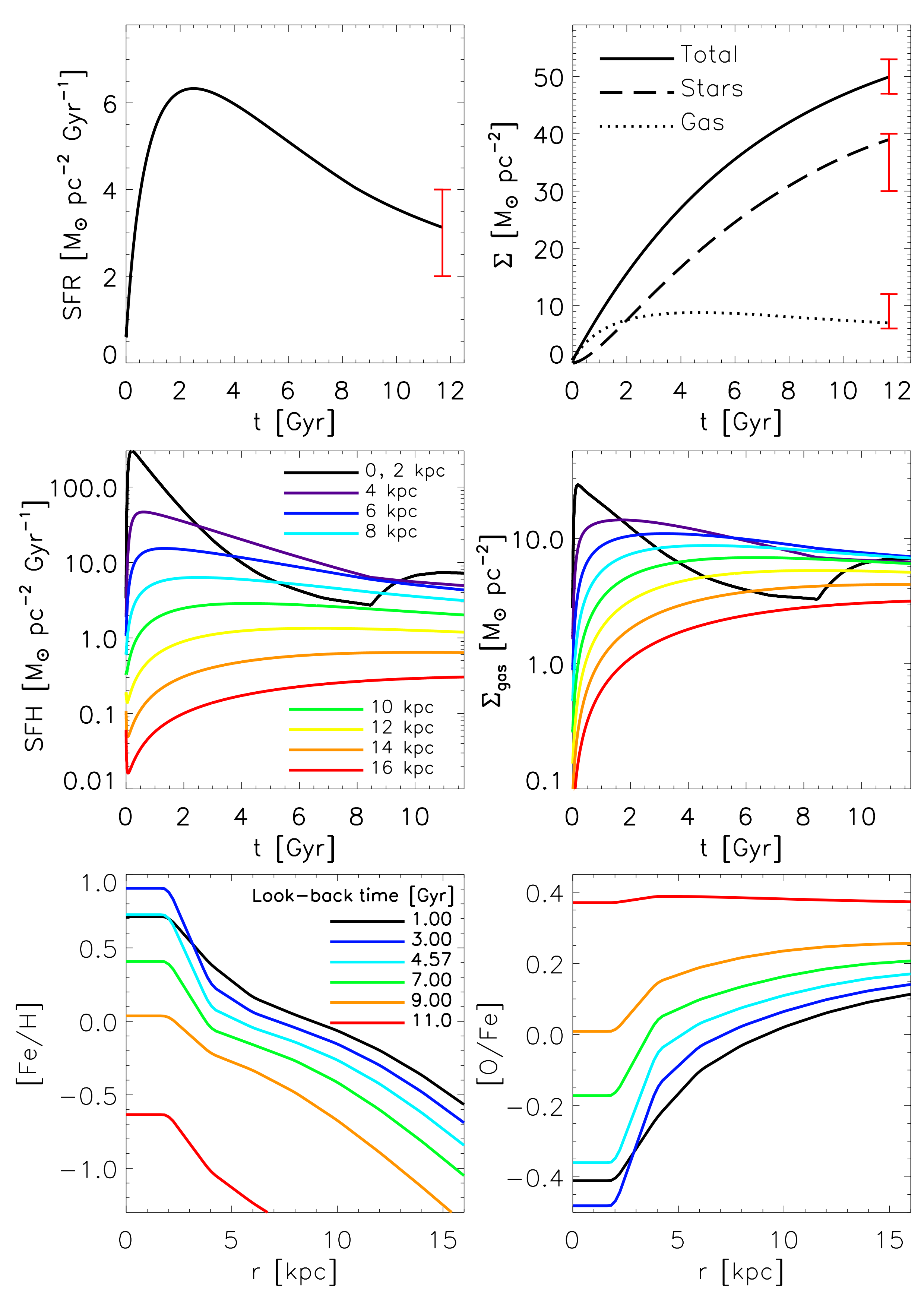
Similar to

Brook et al. (2012),

Stinson et al. (2013),

Bird et al. (2013)

Chemical model



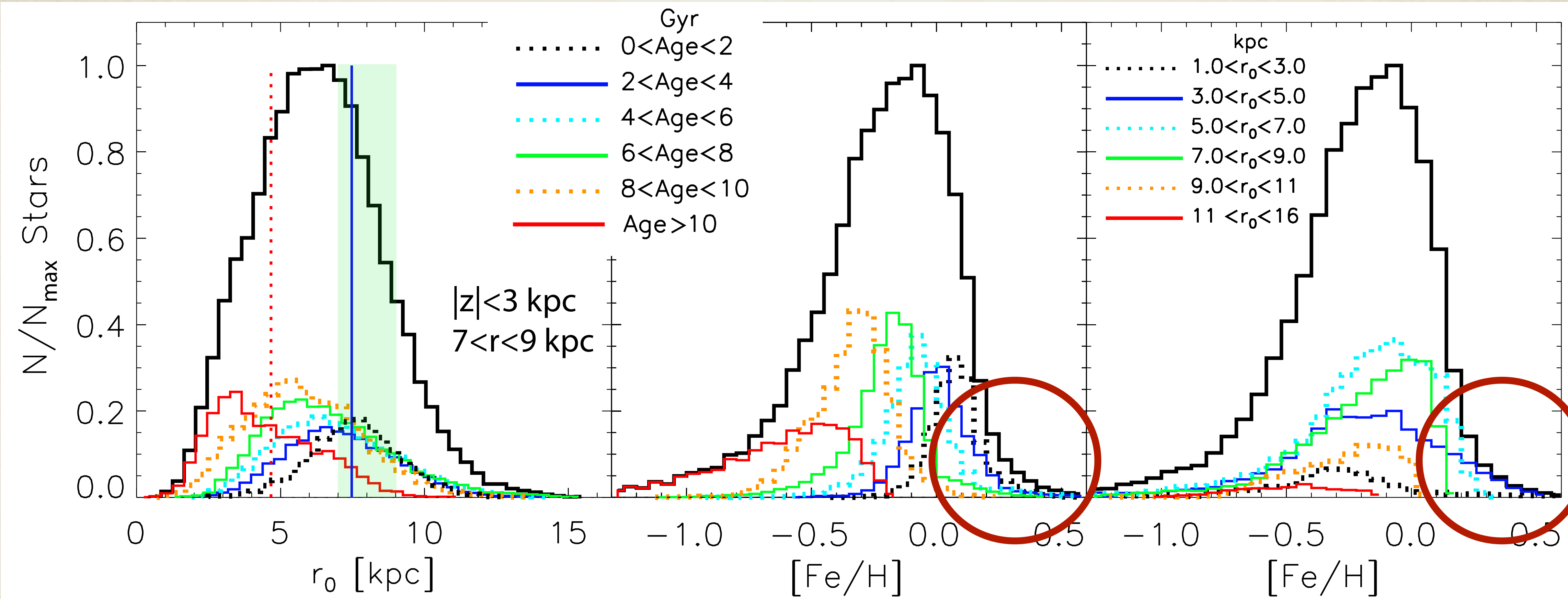
Similar to Chiappini (2009)

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

- Only thin disk chemistry used!

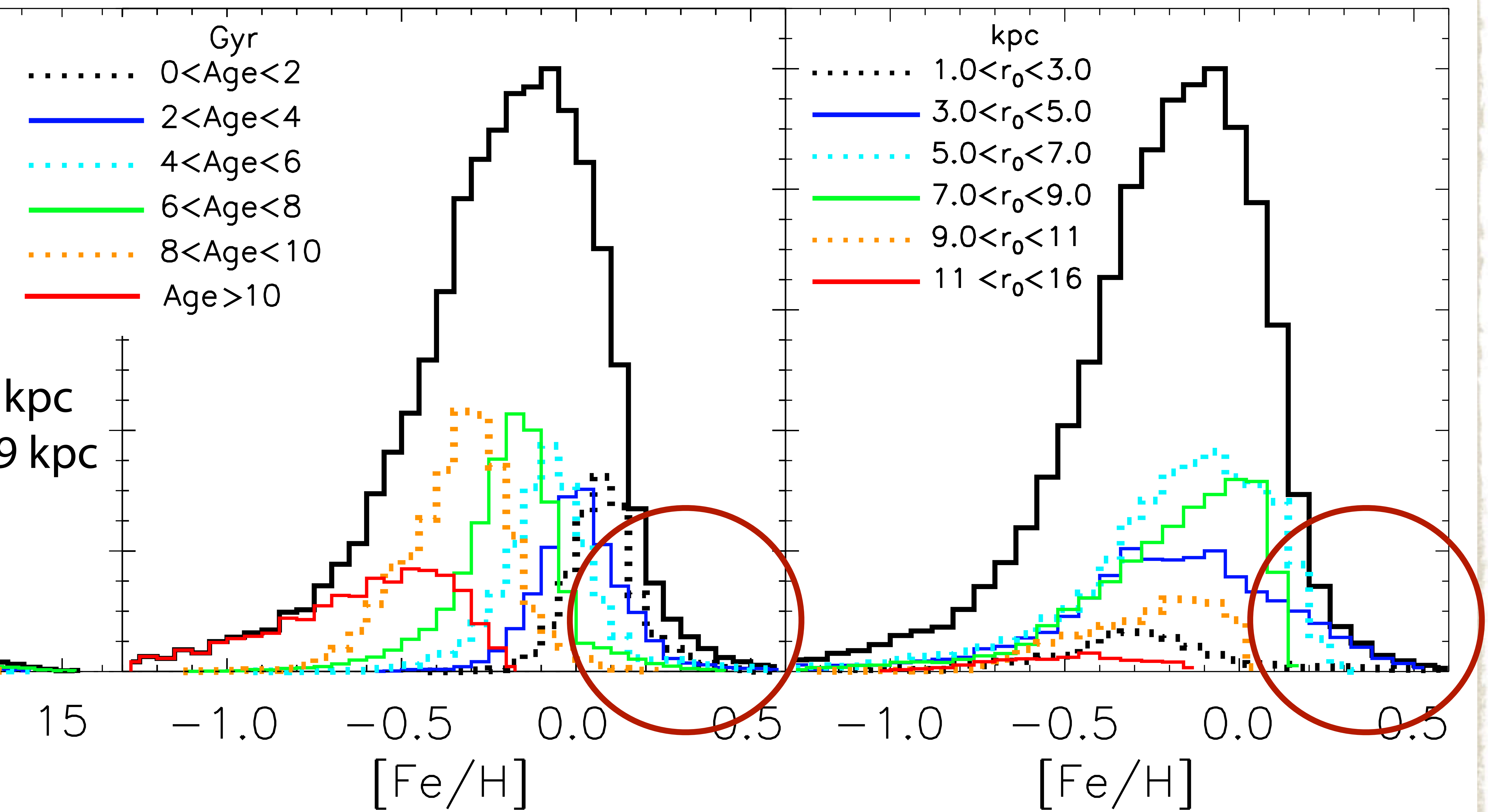
Origin and metallicity distributions of local stars



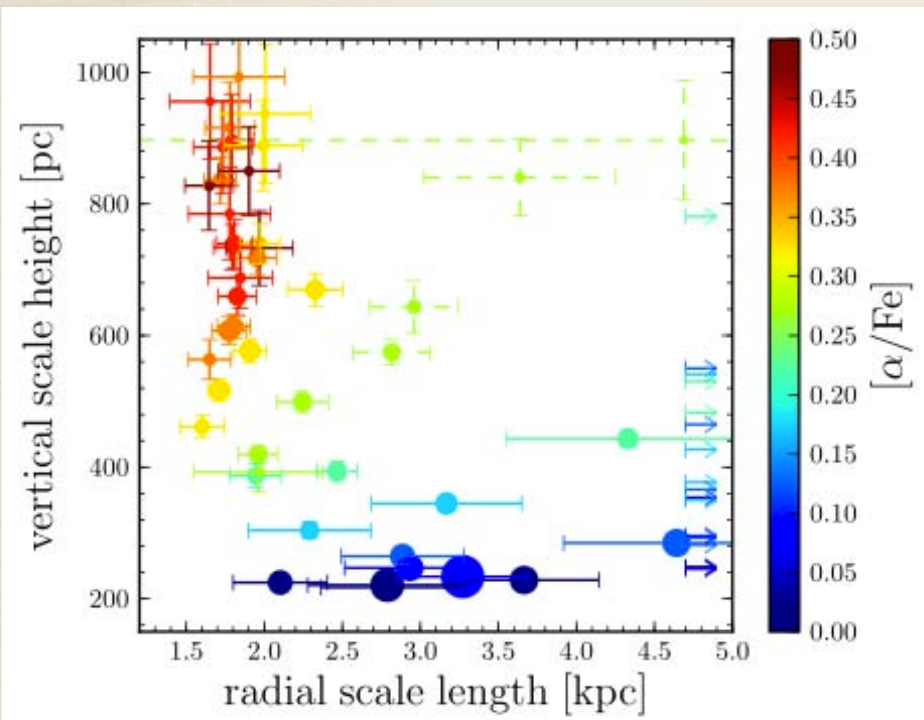
Minchev, Chiappini & Martig (2013)

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

Origin and metallicity distributions of local stars

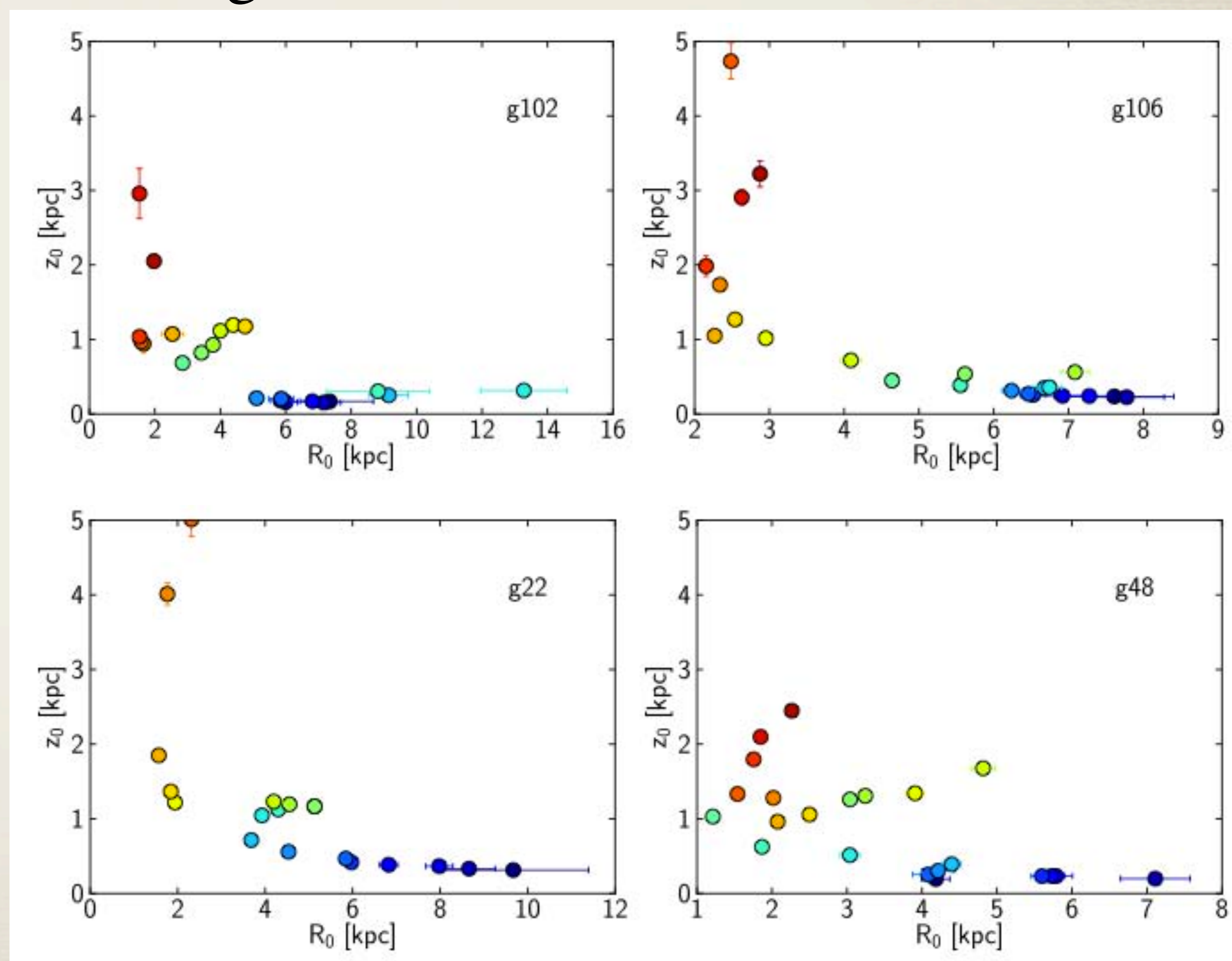


Increase of disk scale-length with age:
A legacy of inside-out formation



Bovy et al. (2012a)

Simulations with strong merger activity at high redshift

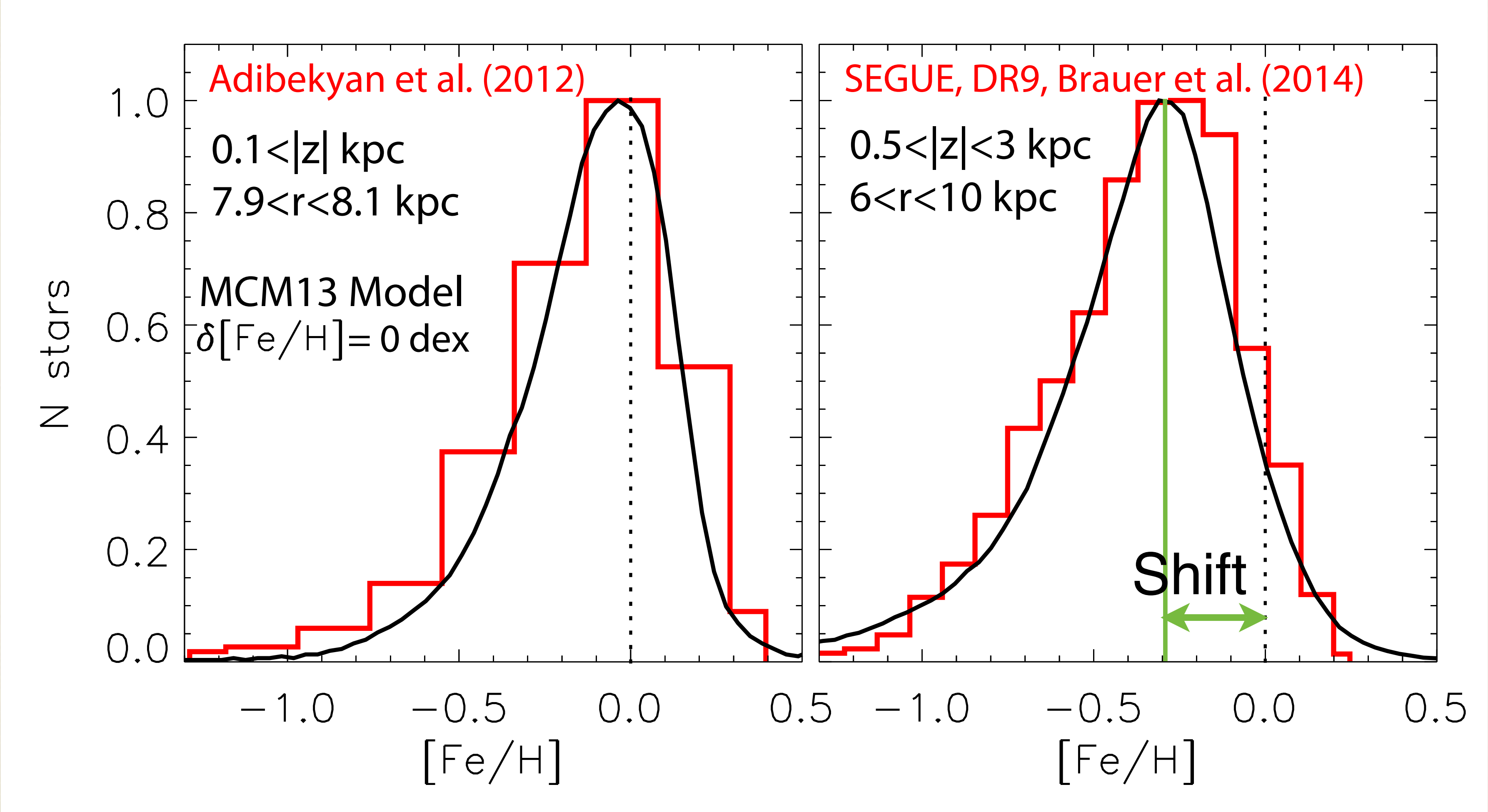


Martig et al. (2014a)

- Radial migration cannot compete with inside-out formation.

The metallicity distribution

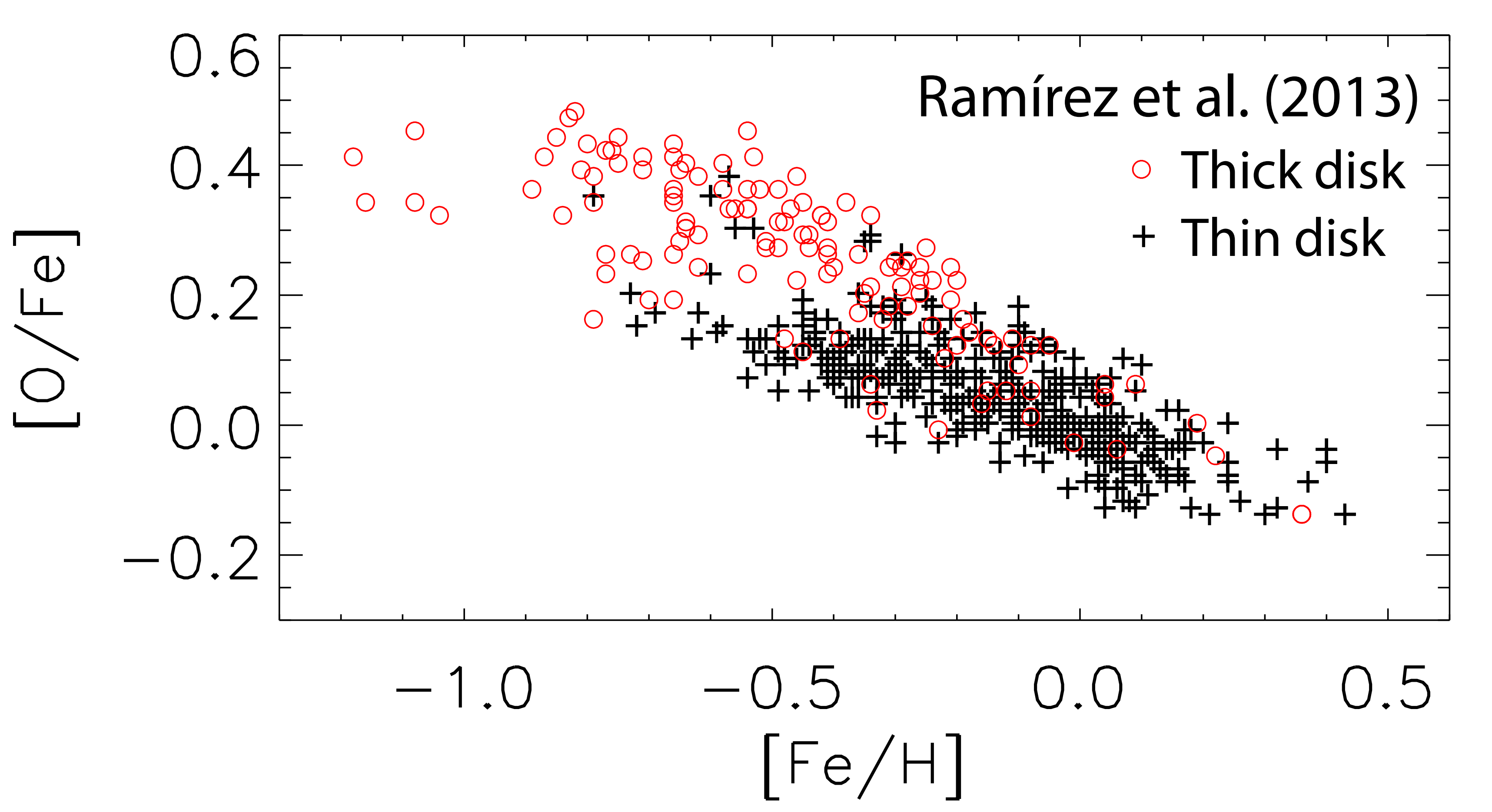
|z| < 40 pc　　|z| > 500 pc



For both model and observations the MDF peak shifts to lower [Fe/H] with distance from the disk plane

The [Fe/H]-[O/Fe] relation

Kinematical selection of thin- and thick-disk populations



The [Fe/H]-[O/Fe] relation

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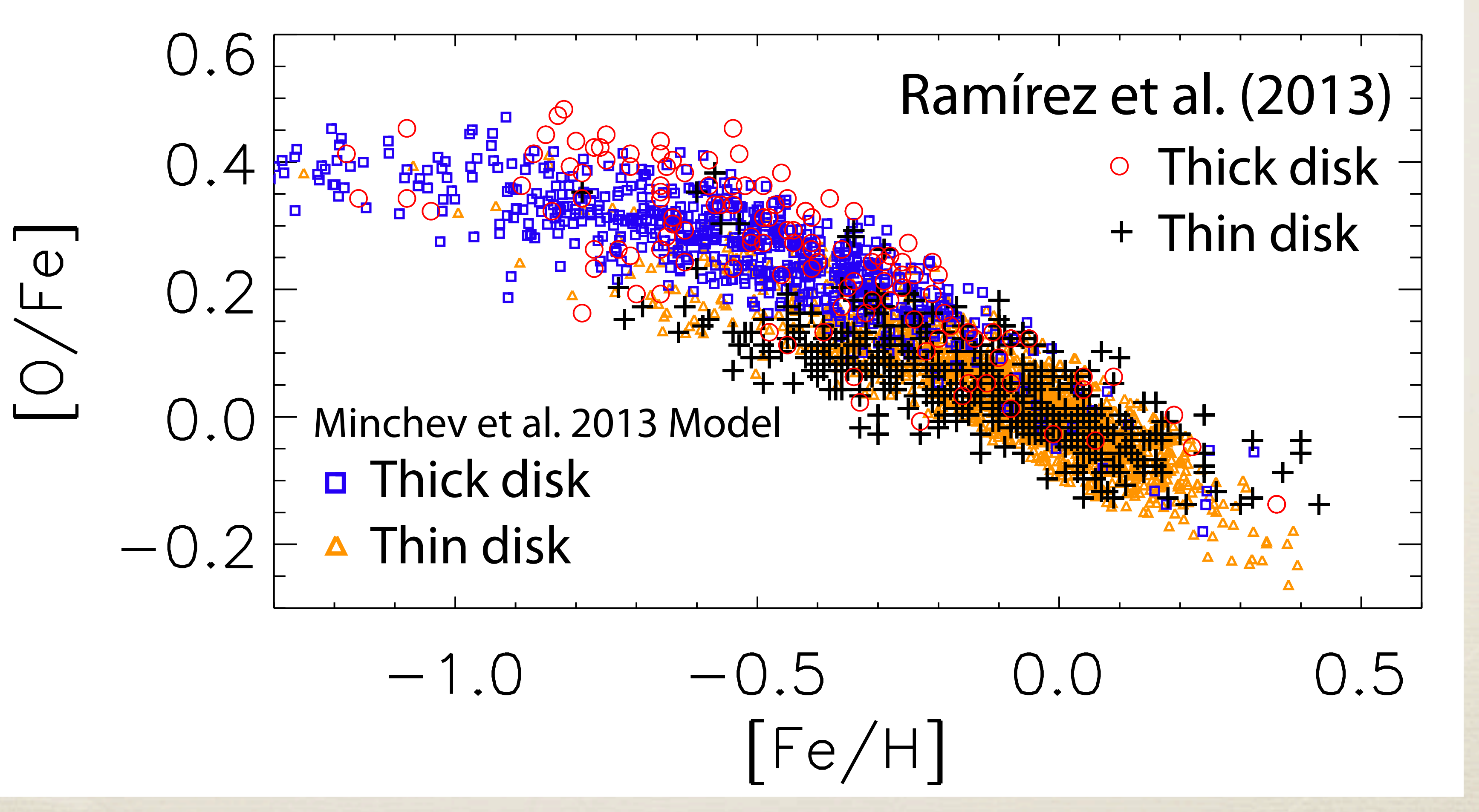
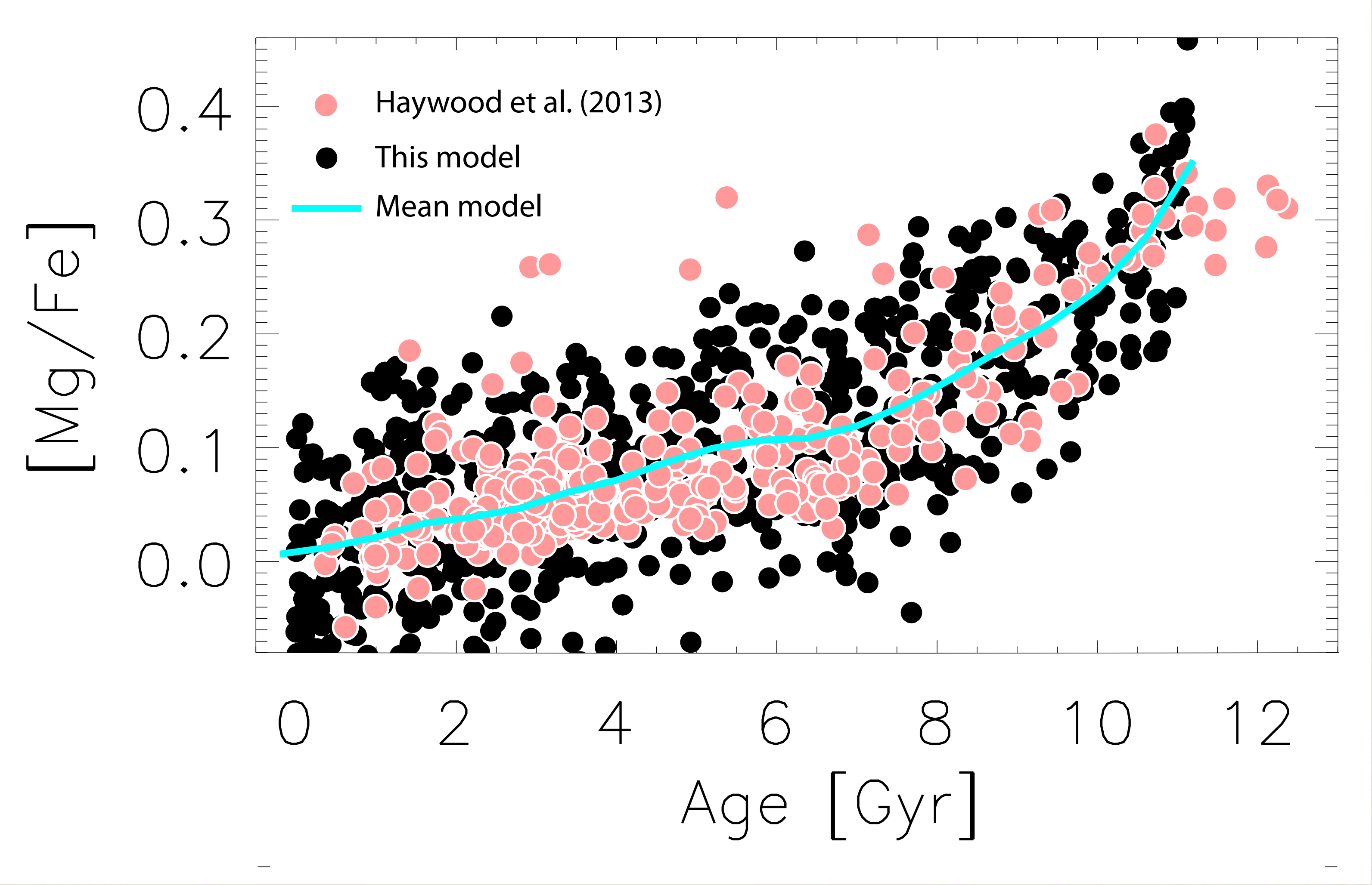
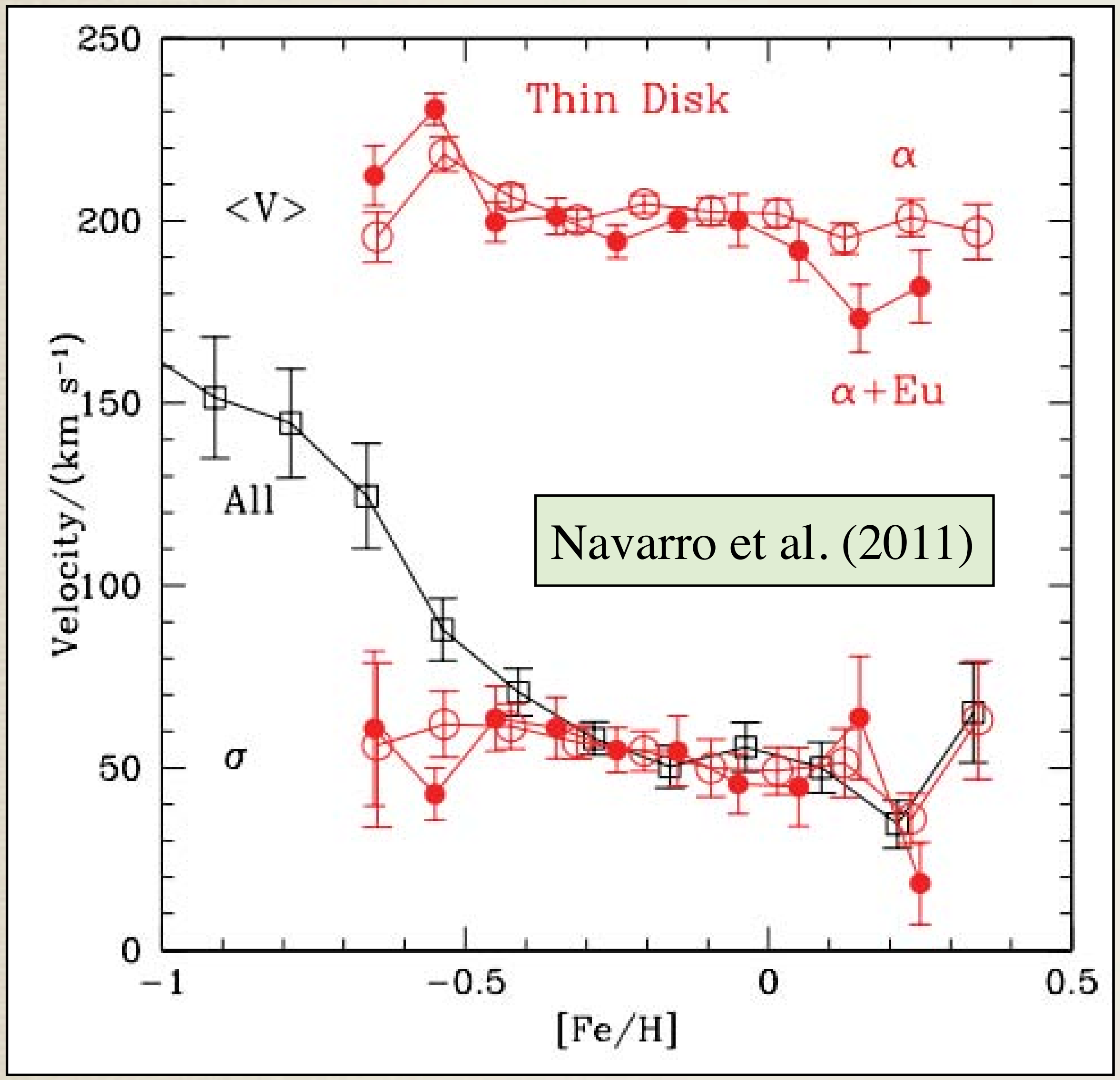
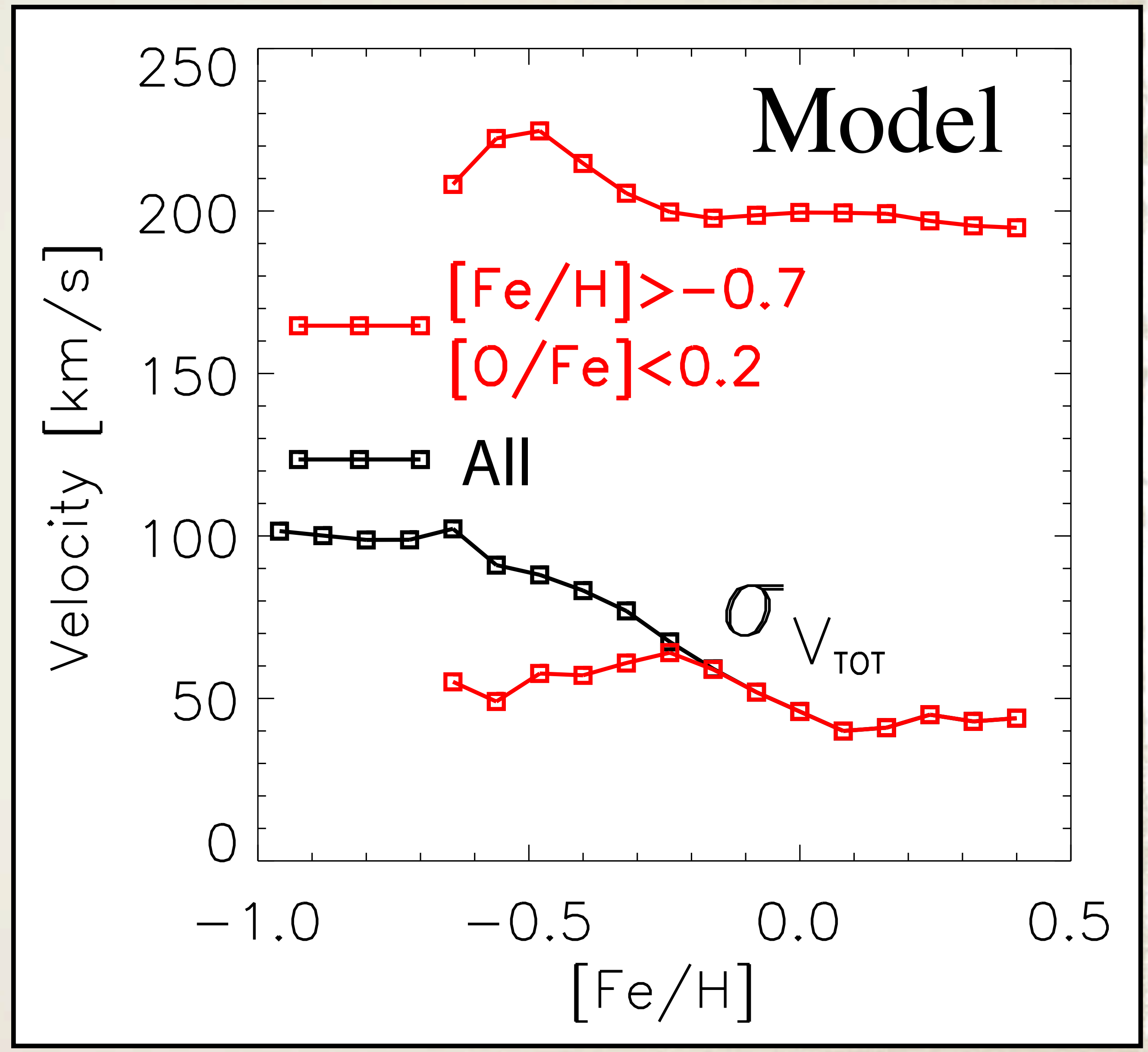


The age-[α/Fe] relation



The Rotational velocity - Metallicity relation

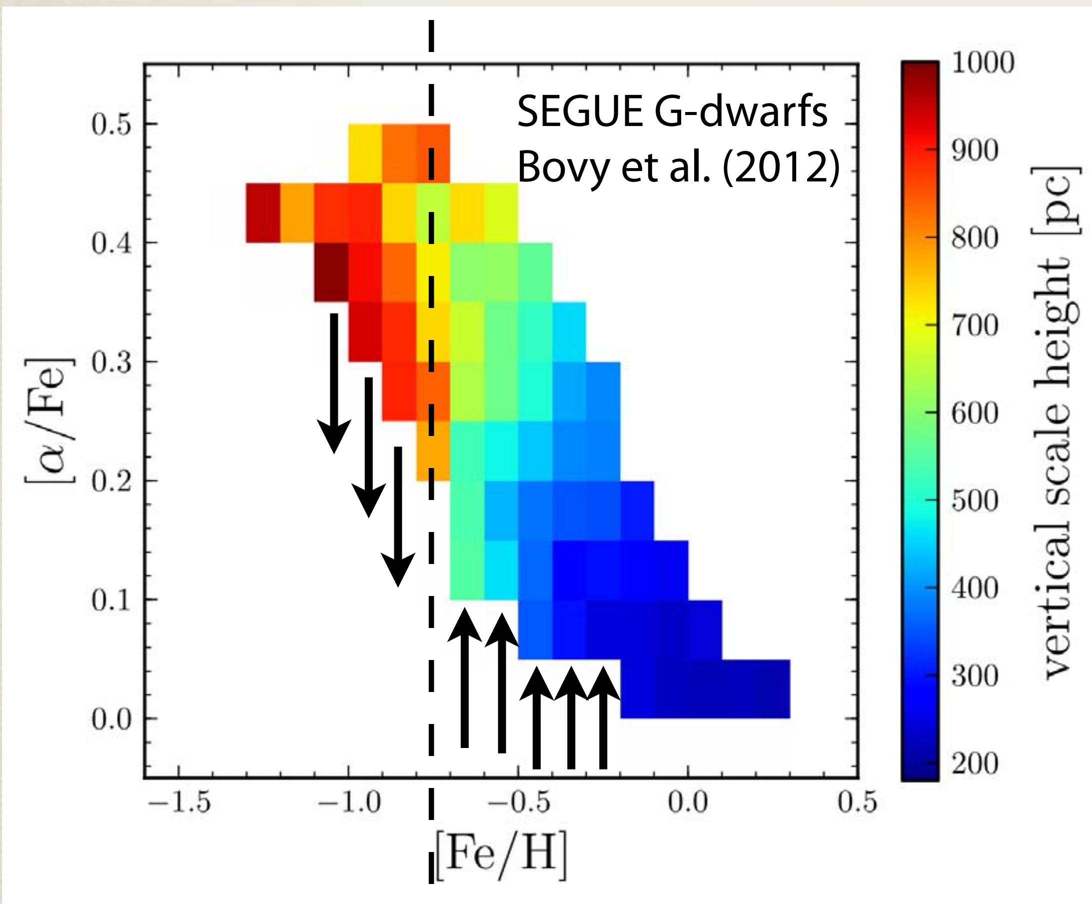




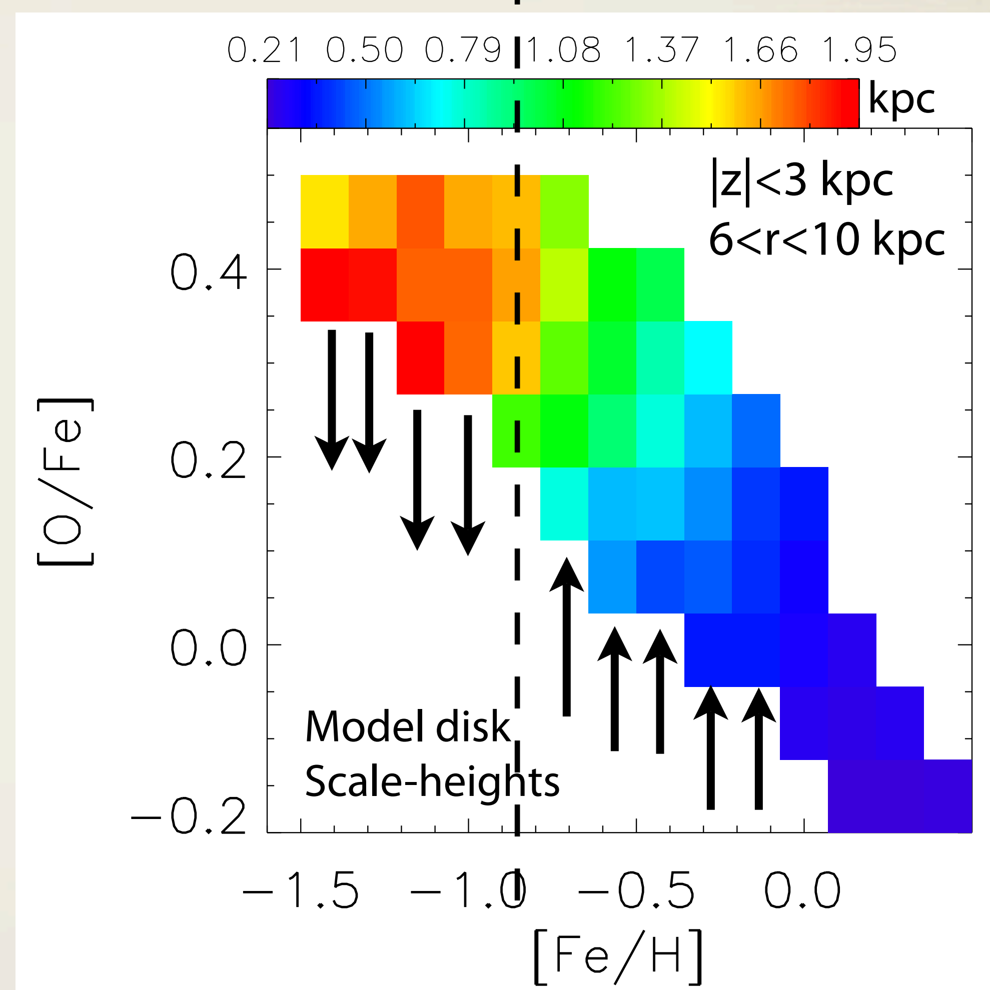
Significant migration in model, yet flat relation for thin disk.

Scale-height distribution of mono-abundance subpopulations

Bovy et al. (2012), SEGUE data

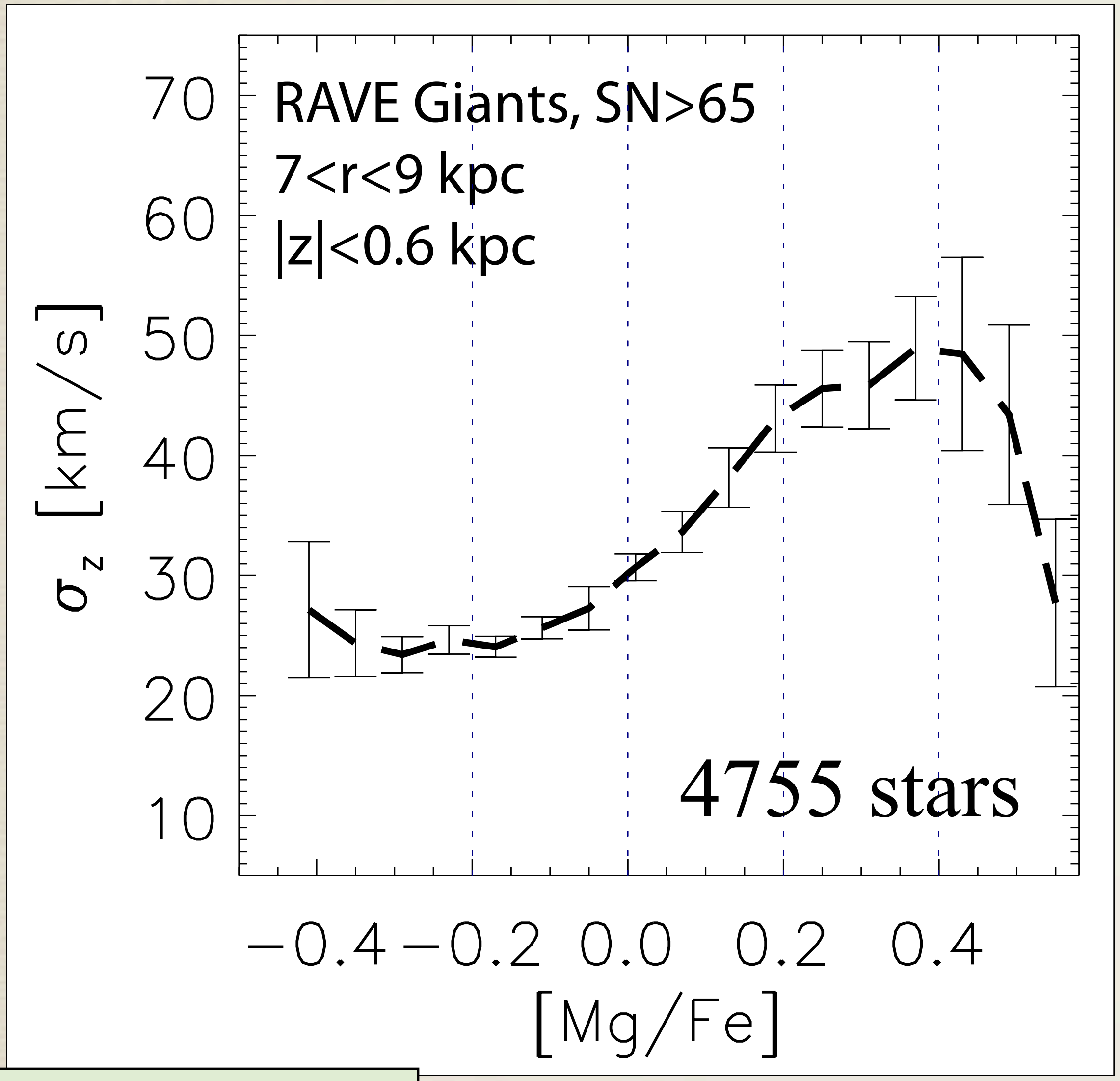


Model data



A new chemo-kinematic relation can recover the disk merger history

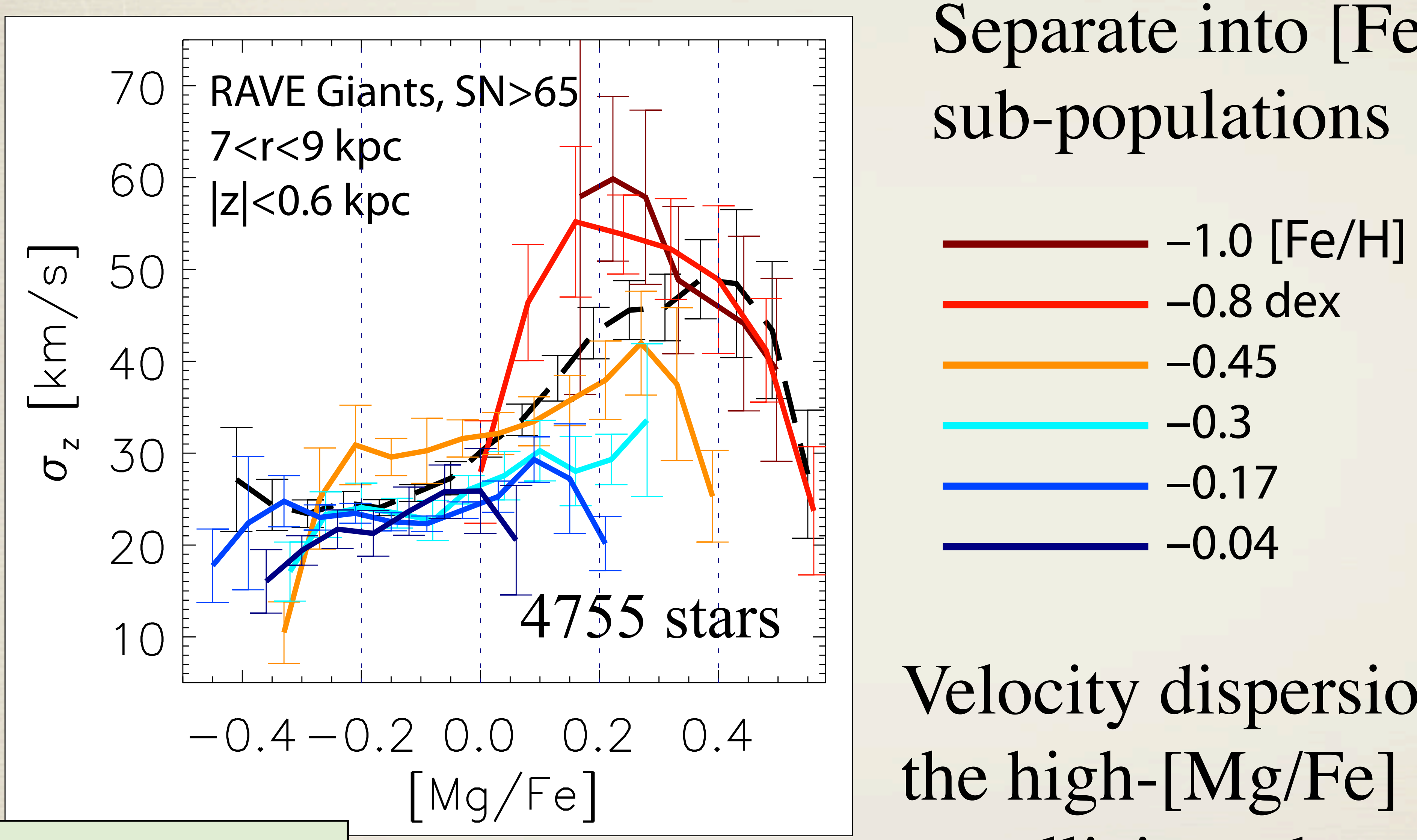
Vertical velocity dispersion as a fn of [Mg/Fe] in RAVE



Minchev + RAVE (2014)

Velocity dispersion drops at [Mg/Fe] > 0.4 dex

Vertical velocity dispersion as a fn of [Mg/Fe] in RAVE

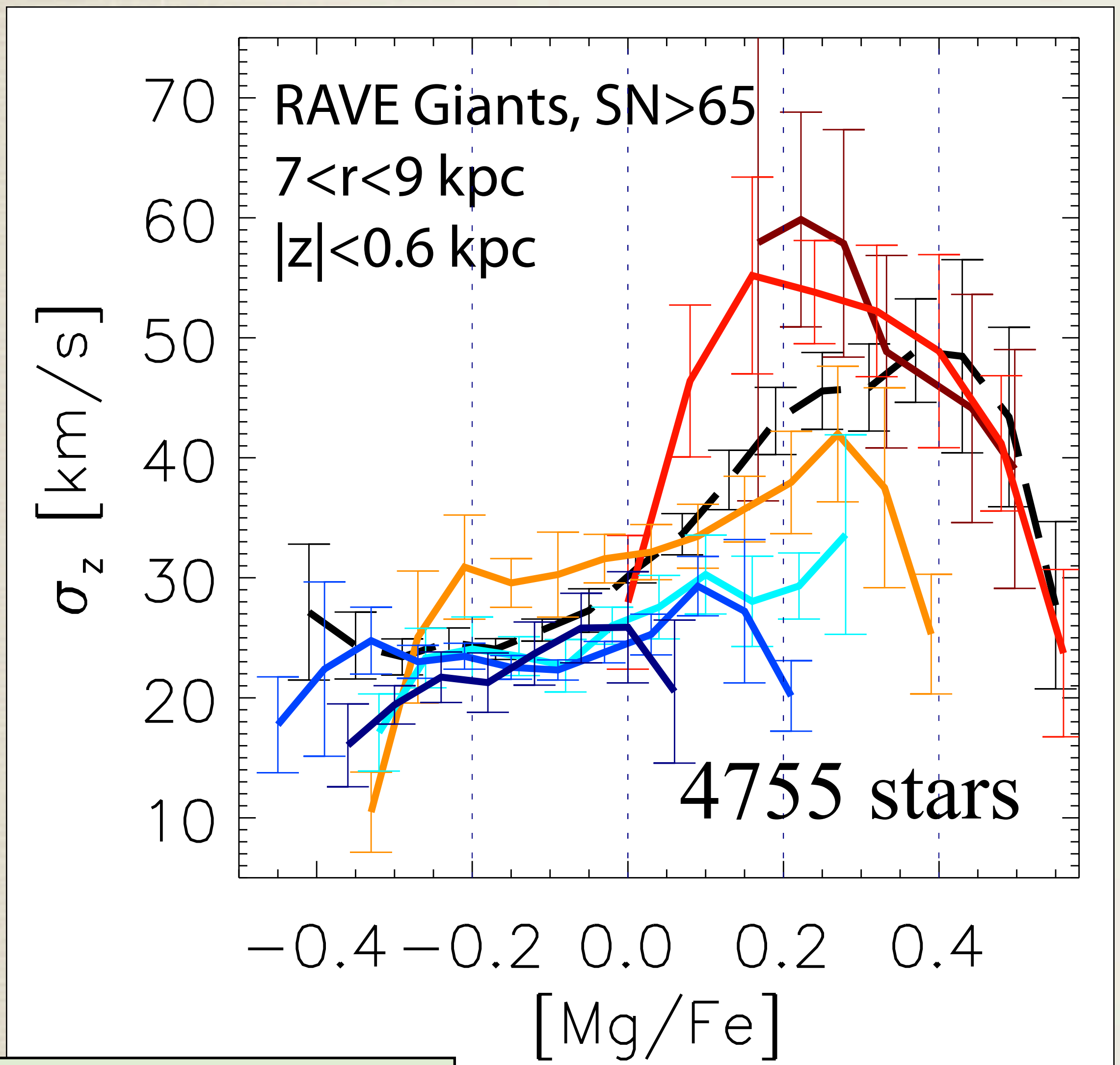


Minchev + RAVE (2014)

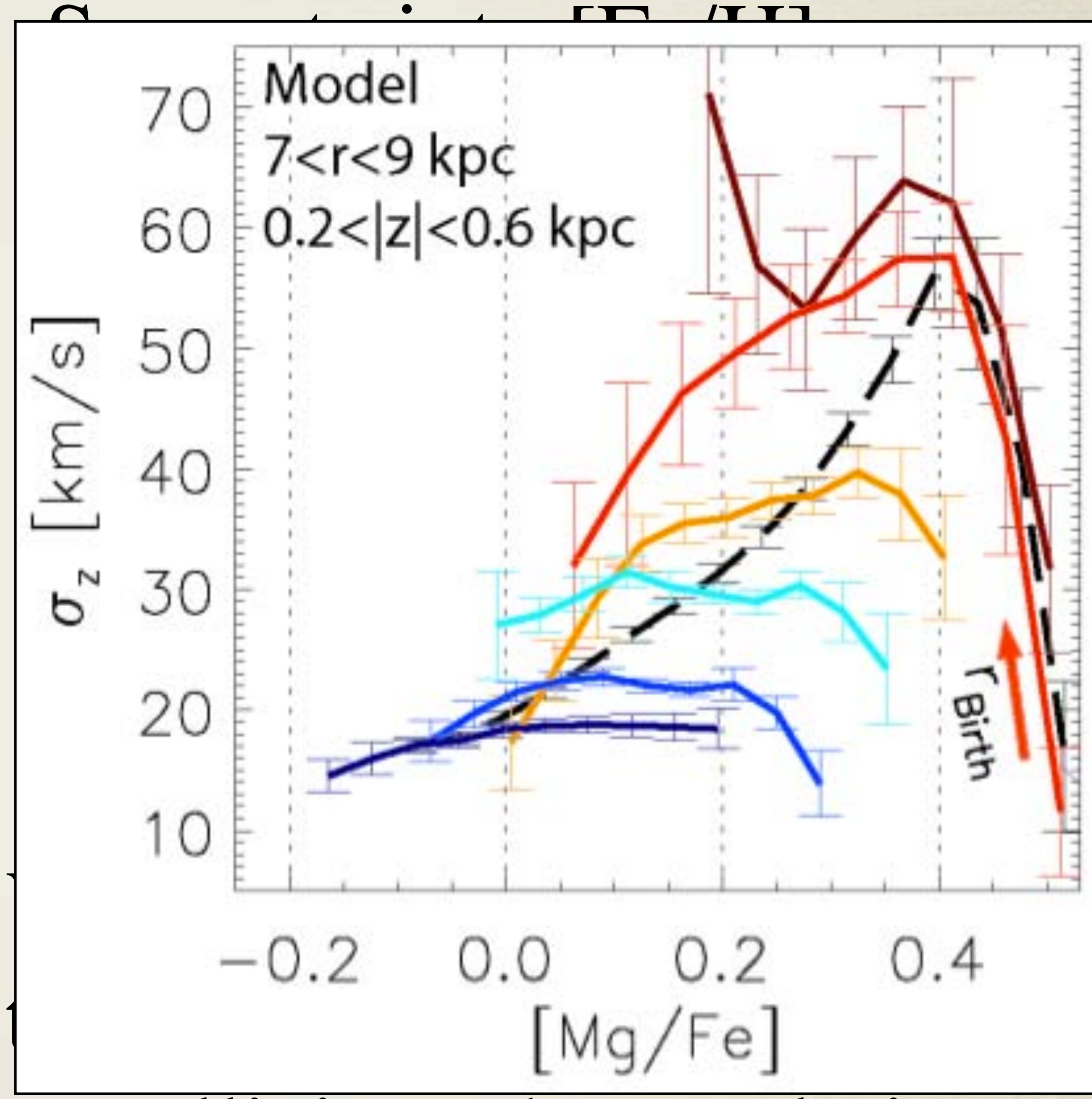
Separate into [Fe/H] sub-populations

Velocity dispersion drops at the high-[Mg/Fe] end for each metallicity sub-population

Vertical velocity dispersion as a fn of [Mg/Fe] in RAVE

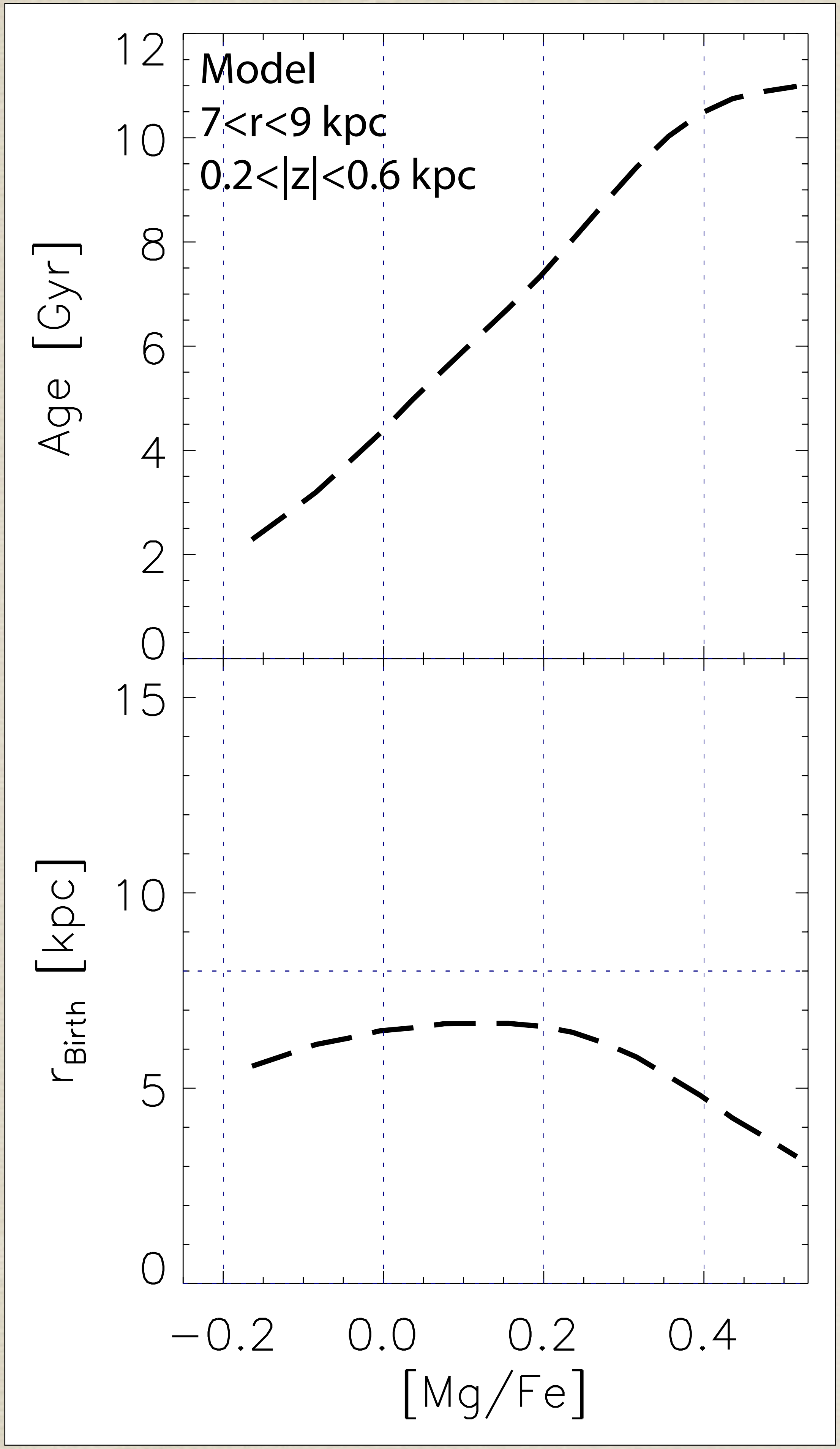


Minchev + RAVE (2014)



metallicity sub-population

Origin of stars currently in the solar neighborhood



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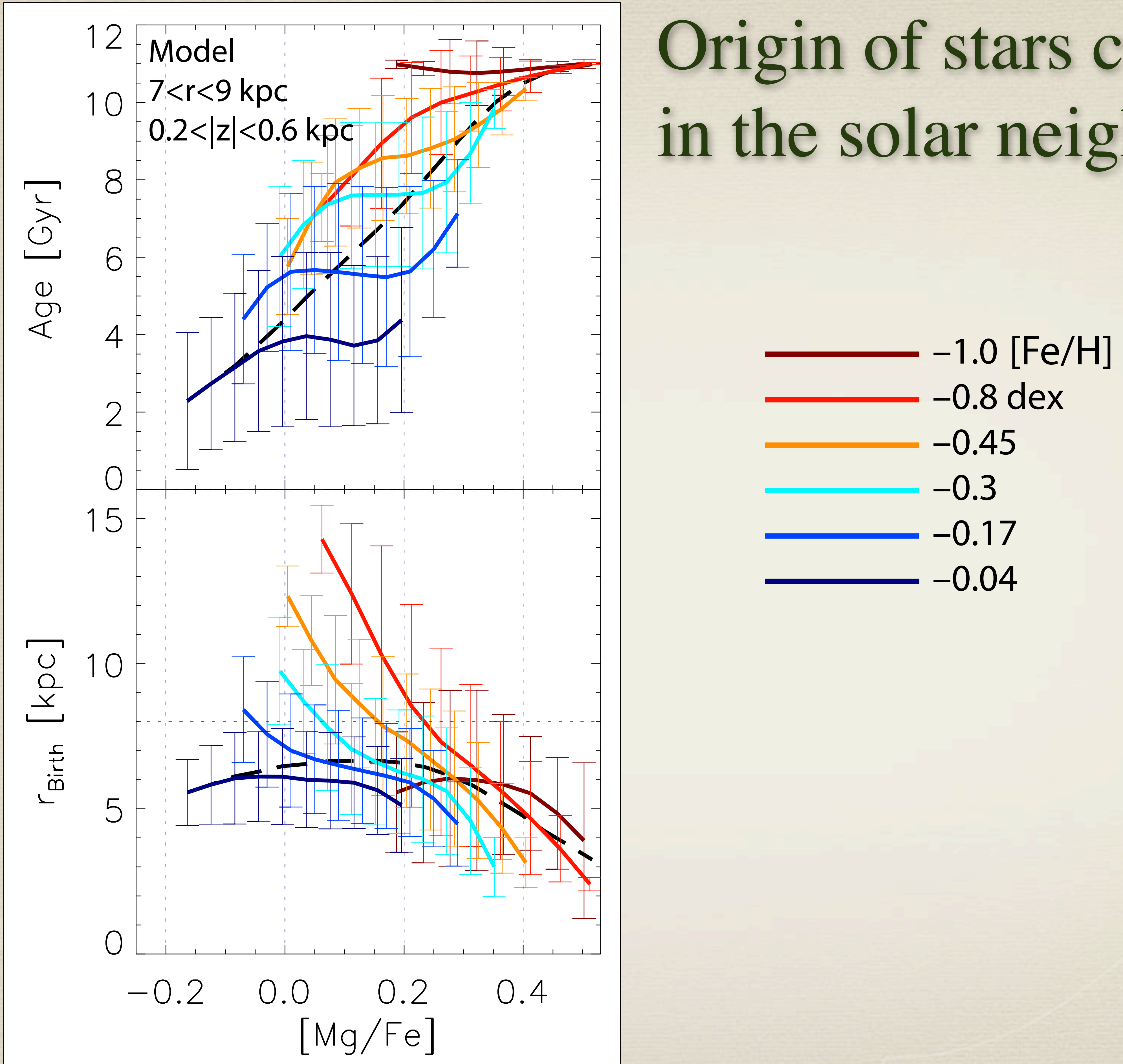

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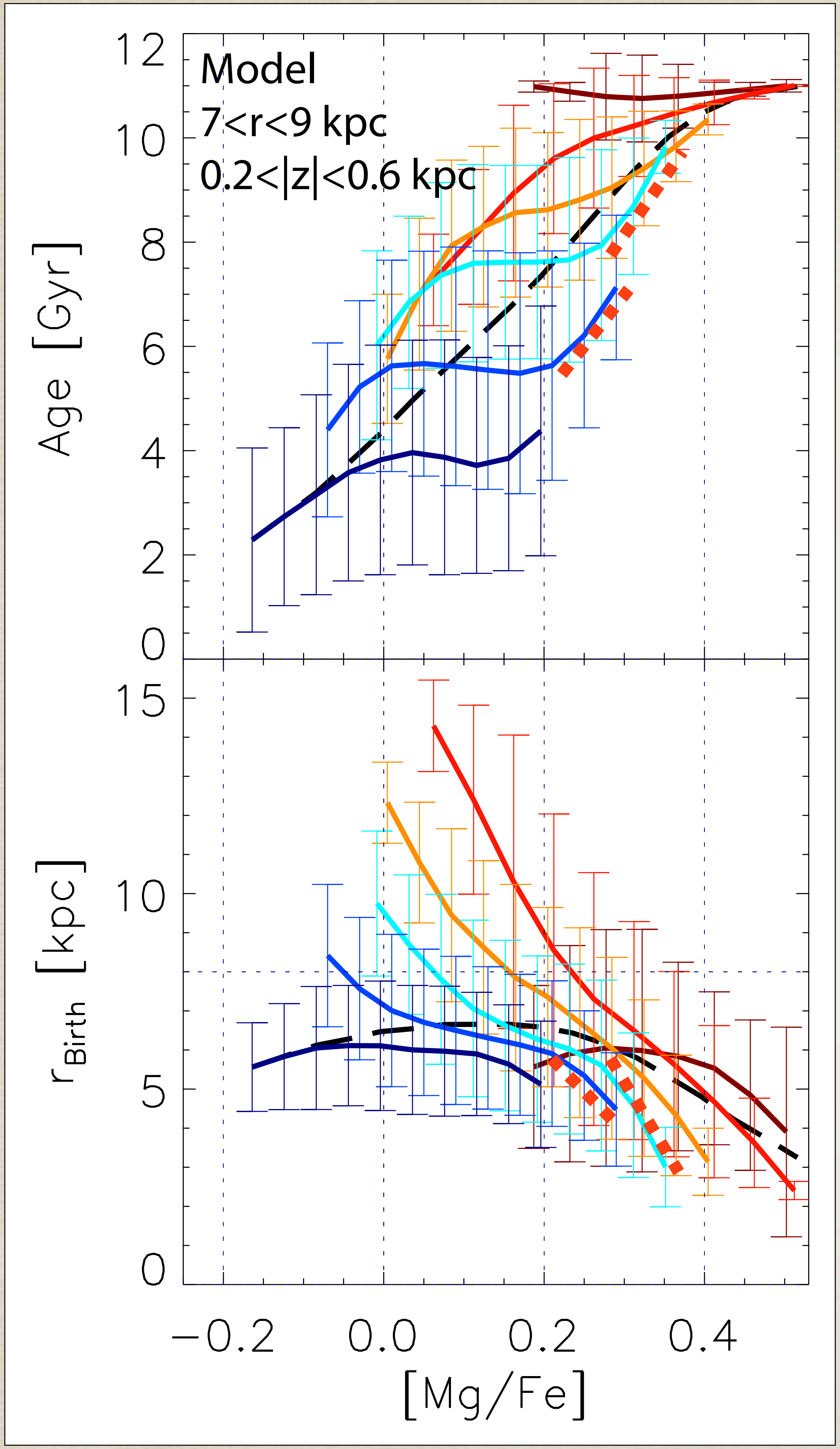
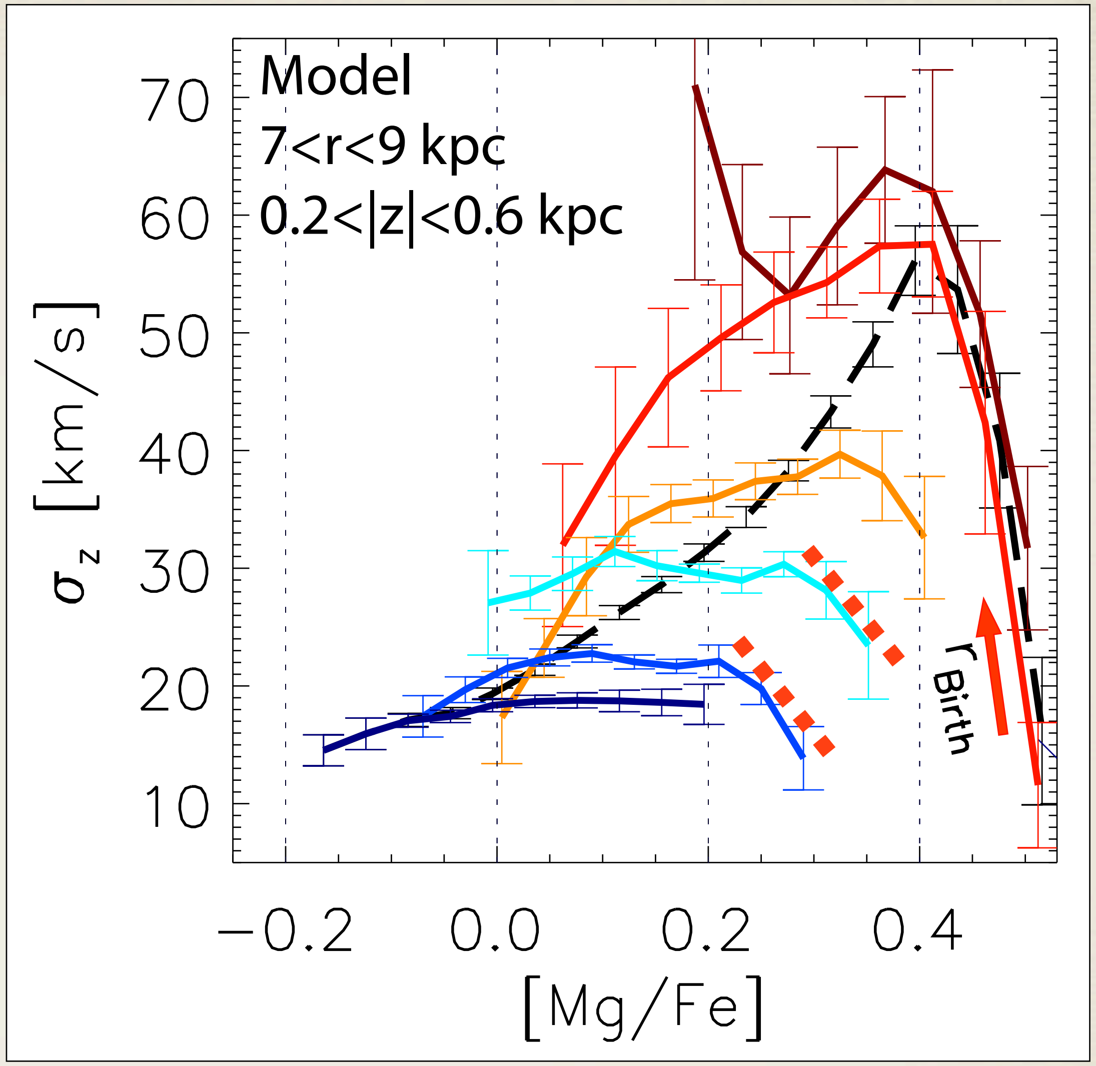
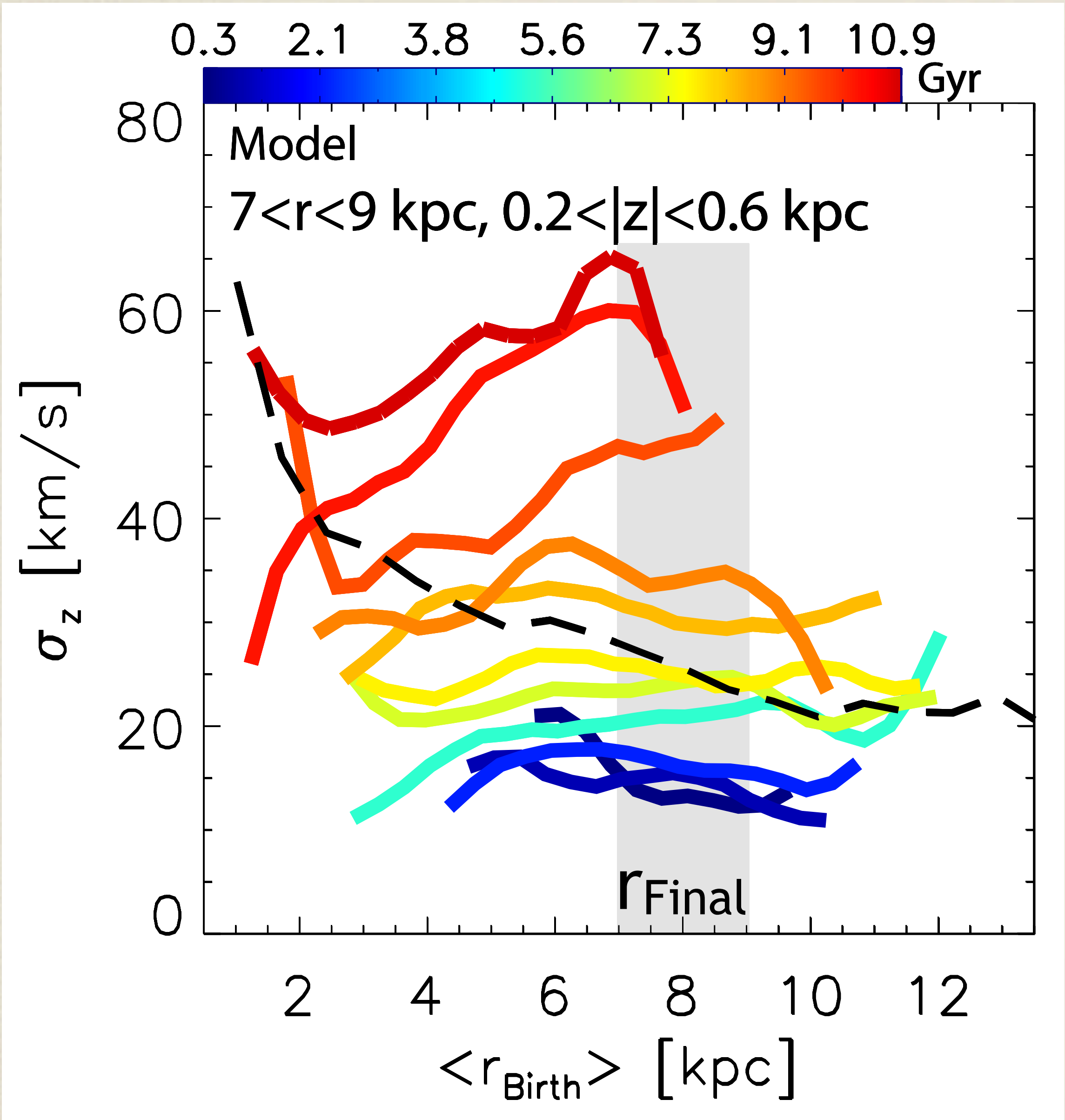




For a given metallicity bin, stars coming from the inner disc are kinematically colder and older.

Cool old stars arrive from inner disk during mergers

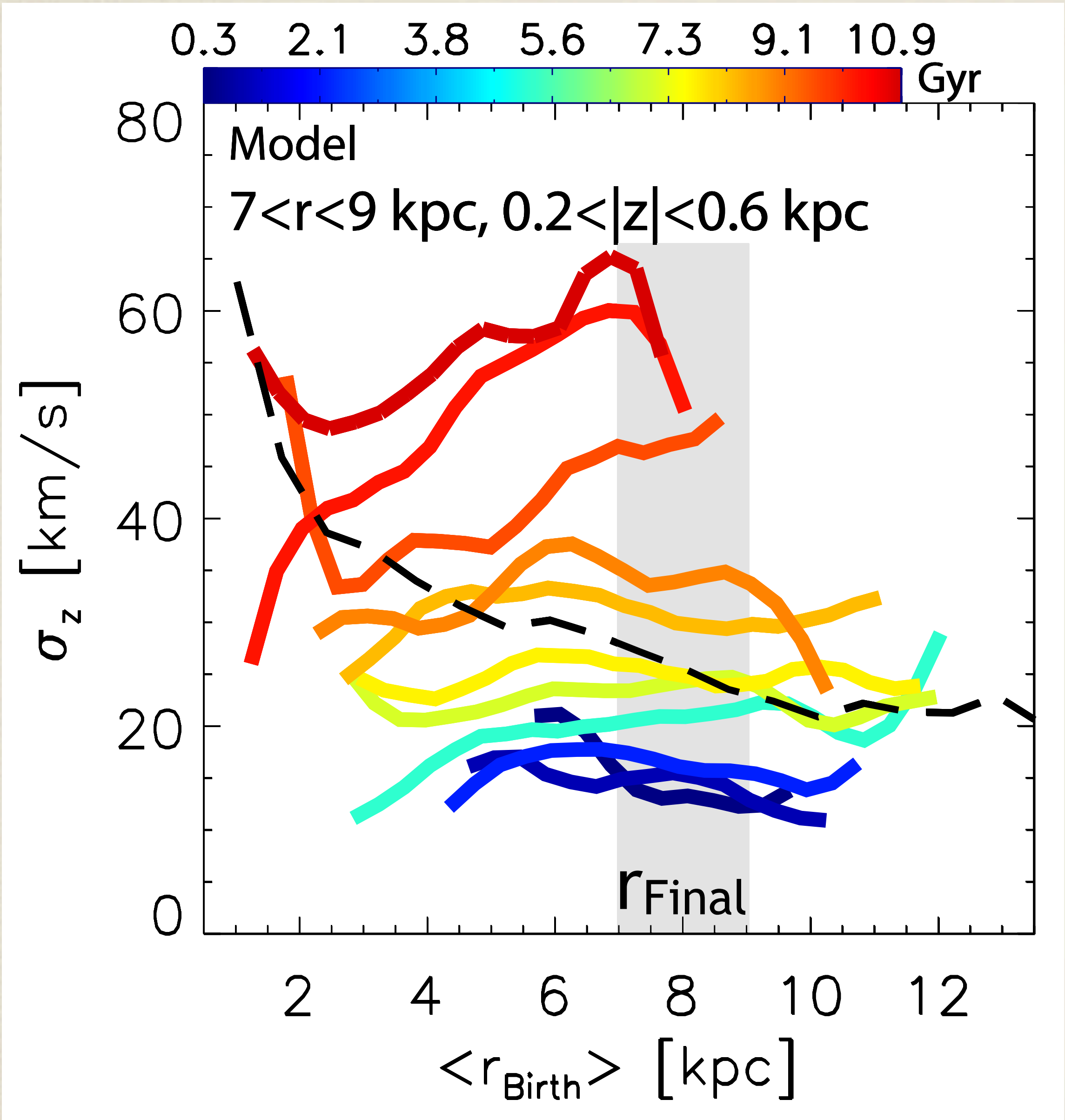


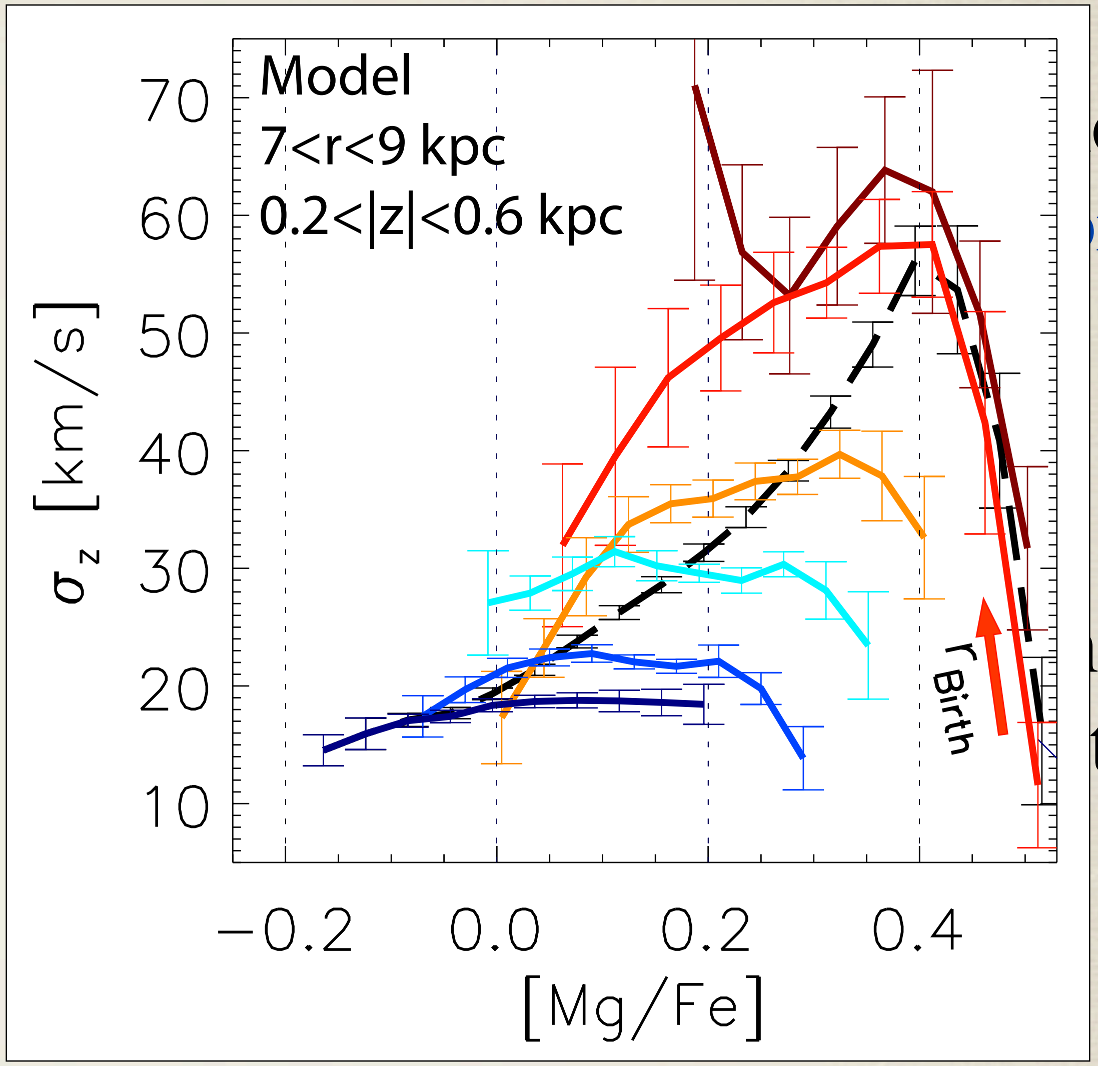
Old stars coming from the inner disk are cooler than locally born stars by up to 30 km/s.

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.

Cool old stars arrive from inner disk during mergers





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

Summary

- Great improvements in chemo-dynamics in cosmological simulations, however, still hard to apply to Milky Way.
- Important for disk models to match the Milky Way morphology today.
- Our chemo-dynamical model explains everything.
  - Great care taken in defining properly the "solar neighborhood".
  - More than 30 elements available for doing Galactic Archeology (e.g., GALAH, APOGEE, 4MOST, Gaia).
- Decline in velocity dispersion found in RAVE and SEGUE at [α/Fe] ≈ 0.4 dex. Can be related to perturbations from satellite-disk interactions over the Galaxy lifetime.
- Extragalactic Archaeology will be made possible with the E-ELT!

Summary

- Great improvements in chemo-dynamics in cosmological simulations, however, still hard to apply to Milky Way.
- Important for disk models to match the Milky Way morphology today.
- Our chemo-dynamical model ~~explains everything~~ consistent with a wide range of observational constraints.
    - Great care taken in defining properly the "solar neighborhood".
    - More than 30 elements available for doing Galactic Archeology (e.g., GALAH, APOGEE, 4MOST, Gaia).
- Decline in velocity dispersion found in RAVE and SEGUE at [α/Fe] $\approx$ 0.4 dex. Can be related to perturbations from satellite-disk interactions over the Galaxy lifetime.
- Extragalactic Archaeology will be made possible with the E-ELT!