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On the connection between the galactic disk and the galactic bar

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Outline

1. formation scenarios
2. N-body simulations
3. Chemo-kinematic signatures
4. Conclusions

Thick disk:

formation scenarios

Majewski 1993, Ann. Rev A&A, 31, 575

Table 1 Models of Intermediate Population II Formation

Model	Thin disk disjoint?	Halo disjoint?	Key age features	Key abundance features	Key kinematic features
Pre-thin disk ("top down") models					
1. First phases of partial pressure support as gas begins dissipational collapse (Sandage 1990a)	No	No	No age gap with halo	Gradient	Gradient
2. Rapid ELS collapse, gap in star formation, then pressure-supported collapse (Larson 1976; Gilmore 1984)	No	Yes	Age gap with halo	Gradient	Gradient
3. Rapid increase in dissipation due to line radiation cooling (Wyse & Gilmore 1988; Burkert et al 1992)	No	Yes	Small range of age	[Fe/H] > -1, little/no gradient	Gradient
4. Formation disconnected from halo, "disk first" (Jones & Wyse 1983, Norris & Ryan 1991)		Yes	Can overlap with halo		
Post-thin disk ("bottom up") models					
5. Secular kinematic diffusion of thin disk stars (Norris 1987)	No	Yes	Wide range of ages. Gradient, overlaps thin disk.	Gradient, [Fe/H] $\leq$ old disk	Gradient
6. Violent thin disk heating by satellite accretion (Carney et al 1989; Hernquist & Quinn 1989, Quinn et al 1992)	Yes	Yes	Older than oldest thin disk star	Expansion of disk gradient at event	Modest asymmetric drift, radial σ_z gradient
7. Accretion of thick disk material directly, e.g. debris of accreted satellite	Yes	?	Lots of possibilities	Probably no gradient	?
8. Halo response to disk potential (van der Kruit & Searle 1981a,b; Gilmore & Reid 1983)	Yes	No	As old as halo	Halo metallicity properties	Halo (large) asymmetric drift

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Top down

Bottom-up

Rix & Bovy 2013, Astron. Astrophys. Rev. 21, 61

What processes might determine galaxy disk structure?

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In particular, what processes set the exponential radial and vertical profiles seen in the stellar distributions of galaxy disks?

Were all or most stars born from a well-settled gas disk near the disk plane and acquired their vertical motions subsequently?

Or was some fraction of disk stars formed from very turbulent gas early on (e.g., Bournaud et al. 2009; Ceverino et al. 2012), forming a primordial thick disk?

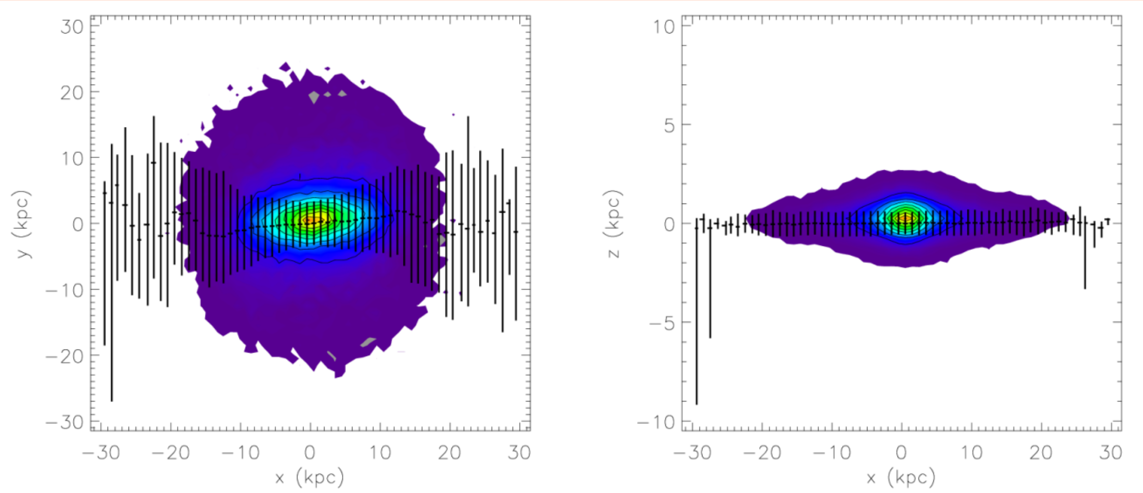
N-body simulations

N-body simulations

Two cases of a Milky Way-like galaxies:

a. **BARRED DISK GALAXY**, produced by instability of a stellar disk (Tab. 2) within a DM halo (Tab. 1)

b. **UNBARRED DISK GALAXY**, including an additional massive central bulge (Tab. 3)



Barred galaxy: density distribution of the disk particles after a dynamical evolution of **T= 6 Gyr**

(*Curir* et al. 2012, A&A, 545, A133)

Table 1. Halos properties (Navarro, Frenk and White profile)

DM	M_{vir}	R_{vir}	C_{vir}	R_{max}	N	ϵ	M_{DM}
Halo	10^{12}	258	7.40	336	10^7	0.11	1.07×10^5

Notes. M_{vir}: Halo's virial mass in $M_{\odot}$; R_{vir}: virial radius in kpc. C_{vir}: NFW concentration parameter. R_{max}: maximum radius. N: total number of Halo particles. ϵ: softening length in kpc. M_{DM}: mass of DM particle in $M_{\odot}$.

Table 2. Properties of the disk

Stars	M_*	M_{star}	h_d	z_d	N	ϵ	Q
Disk	$5.6 \cdot 10^{10}$	$7.47 \cdot 10^3$	3.5	0.7	$7.5 \cdot 10^6$	0.044	2

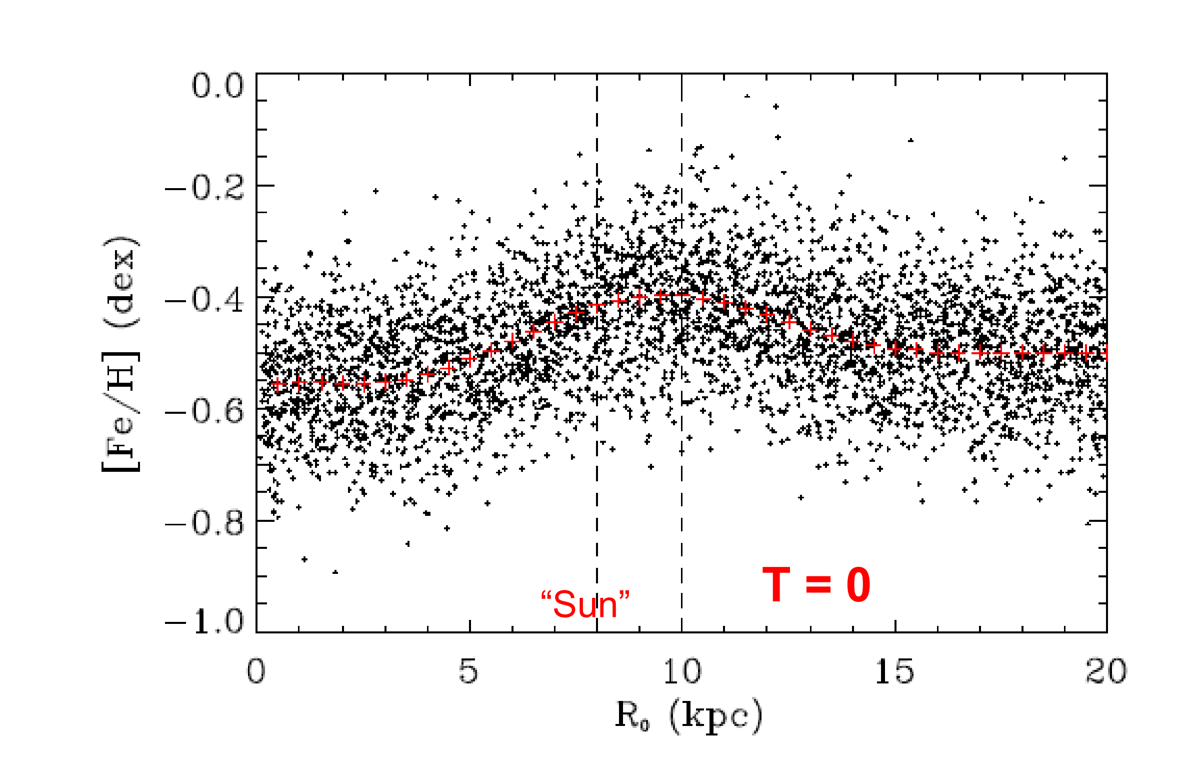
Notes. M_*: disk mass in $M_{\odot}$. M_{star}: mass of the disk particle in $M_{\odot}$. h_d: disk scale length in kpc. z_d: initial disk thickness. N: number of particles. ϵ: softening length in kpc. Q: Toomre parameter.

Table 3. Properties of the bulge (Hernquist profile)

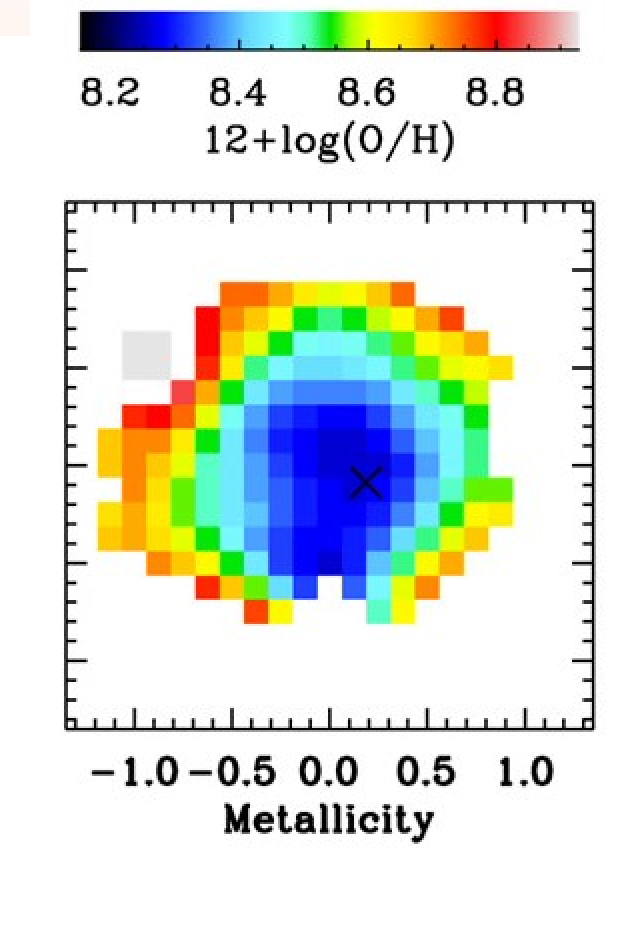
Stars	M_*	N	ϵ	a	M_b
Bulge	$1.85 \cdot 10^{10}$	$2.5 \cdot 10^6$	0.044	1.12	$7.39 \cdot 10^3$

Notes. M_*:mass in $M_{\odot}$. N: number of particles. ϵ: softening length in kpc. a: Hernquist scale radius in kpc. M_b: mass of the particle in $M_{\odot}$.

Radial metallicity gradient



Initial condition. Each particle in the initial configuration is tagged with a [Fe/H] label according to the initial radial chemical model S2IT from *Spitoni & Matteucci* (2011).



Radial metallicity gradient

AMAZE/LSD data shows examples of "inverted" positive metallicity gradients among face-on undisturbed disk galaxies at **z ~3**.

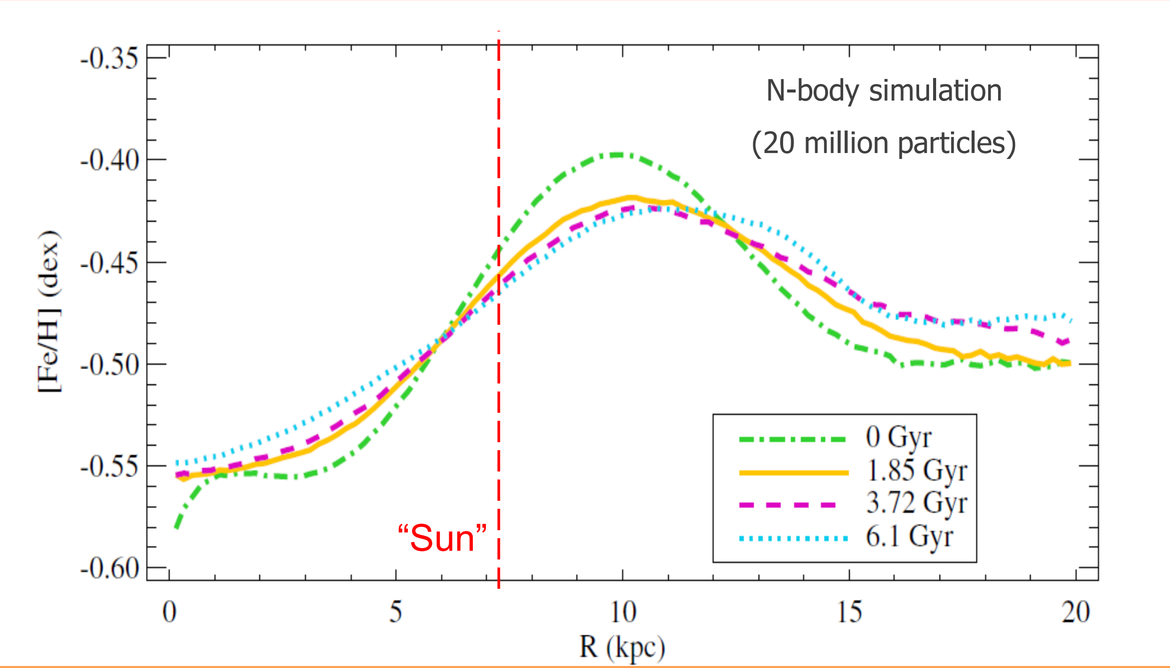
(*Cresci et al.* 2010)

Thick disk:

Chemo-kinematic signatures

Radial metallicity gradient

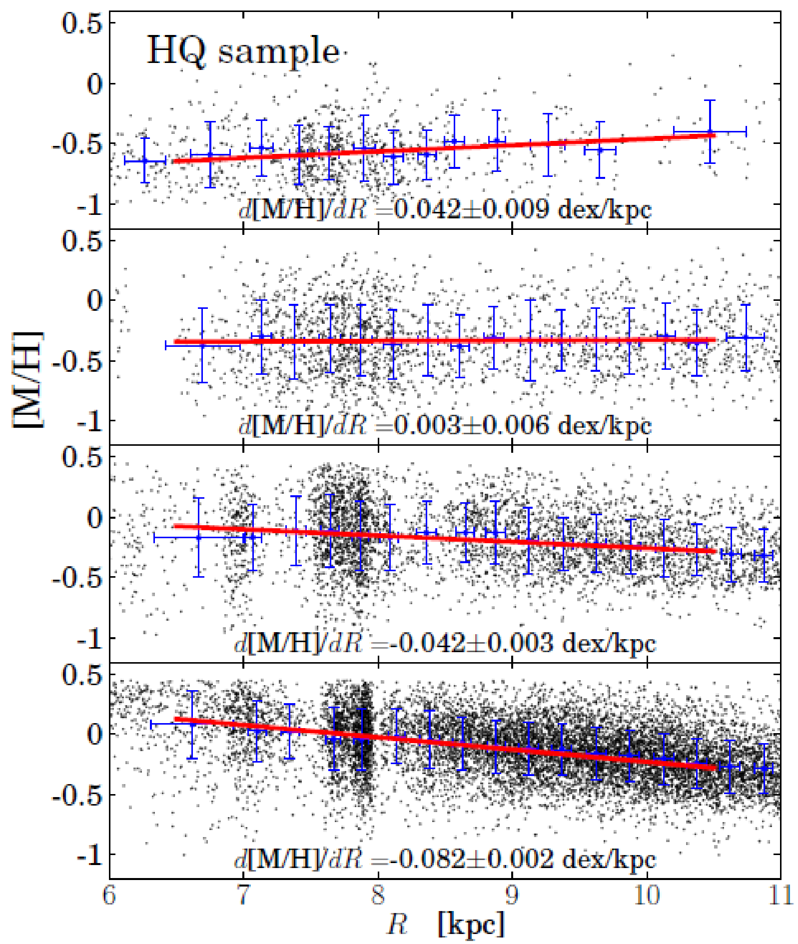
The secular disk evolution does ***not*** seem significantly the disk chemical profiles in *both* the **barred/unbarred** disks examined



Evolution of the median radial chemical distribution of a simulated *barred* Milky Way-like galactic disk.

(Figure from *Curir* et al. 2014, ApJ, 784, L24).

Radial metallicity gradient



Anders et al. 2014, A&A, 564, A115

Observations 1: APOGEE

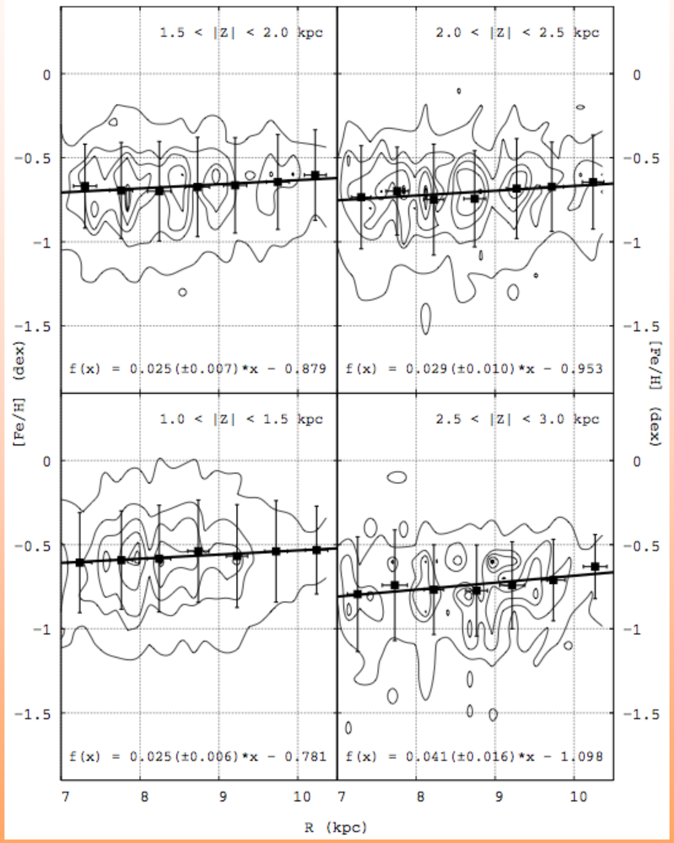
1.5 kpc < |z| < 3 kpc

0.8 kpc < |z| < 1.5 kpc

0.4 kpc < |z| < 0.8 kpc

0.0 kpc < |z| < 0.8 kpc

Observations 2:



(*Carrell* et al. 2012, ApJ, 144, 185)

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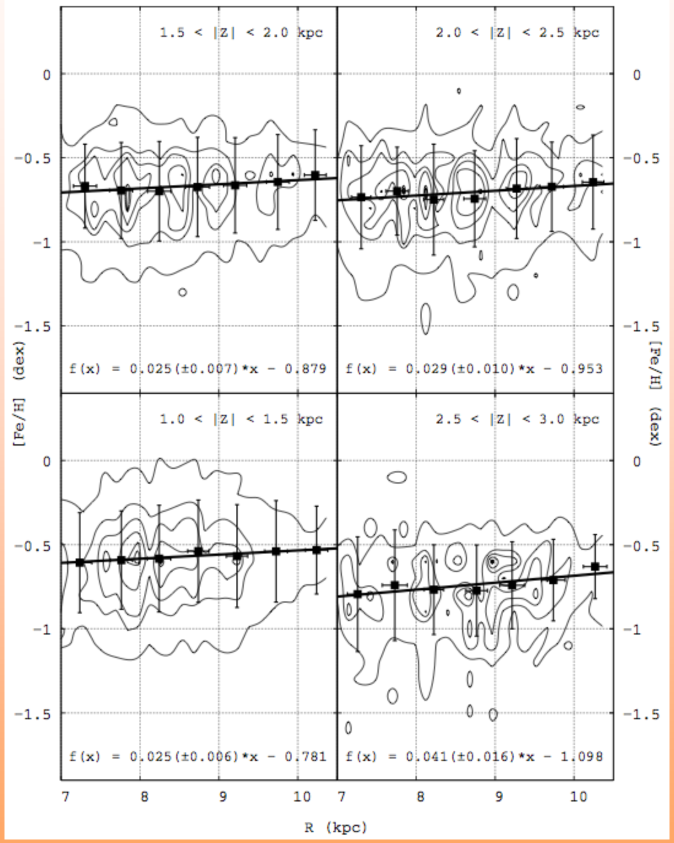

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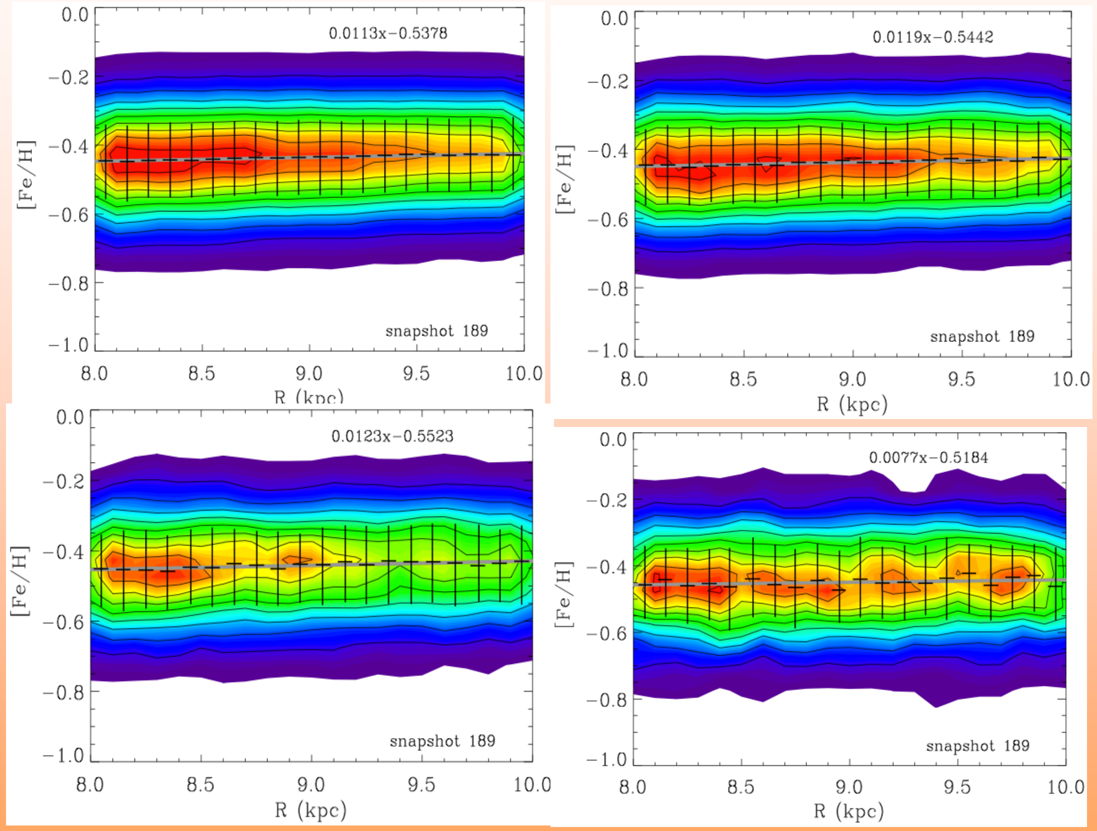
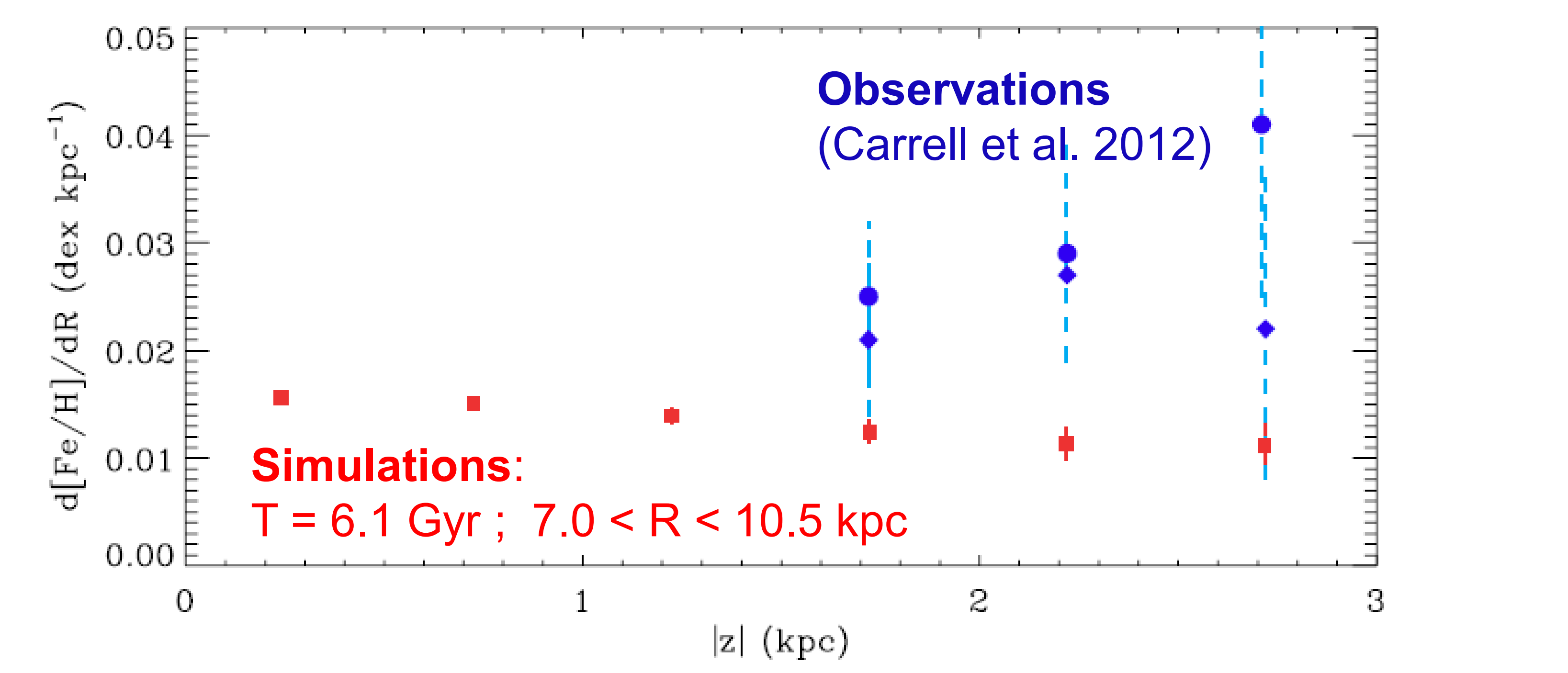
vs. Simulations



(*Curir* et al. 2014, ApJ, 784, L24)

Radial metallicity gradient



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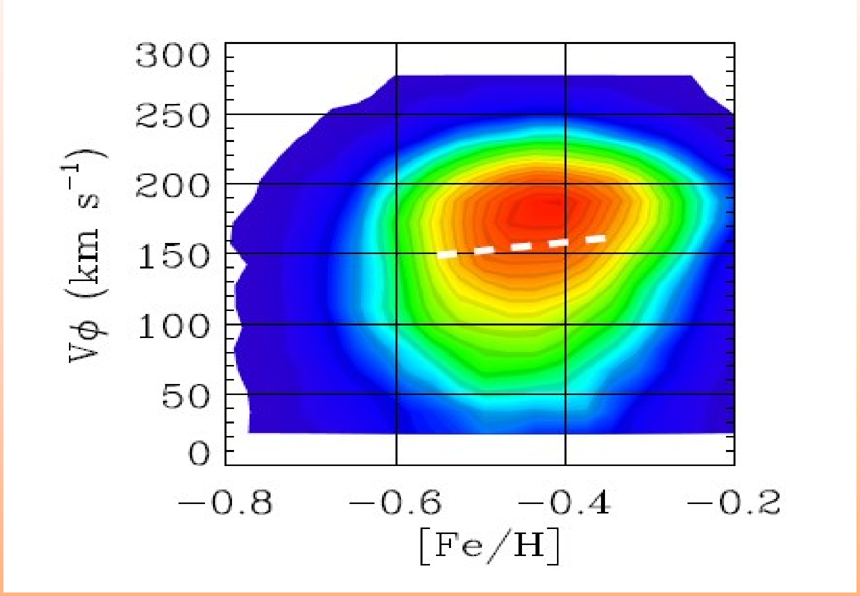
Rotation - metallicity correlation

Simulations

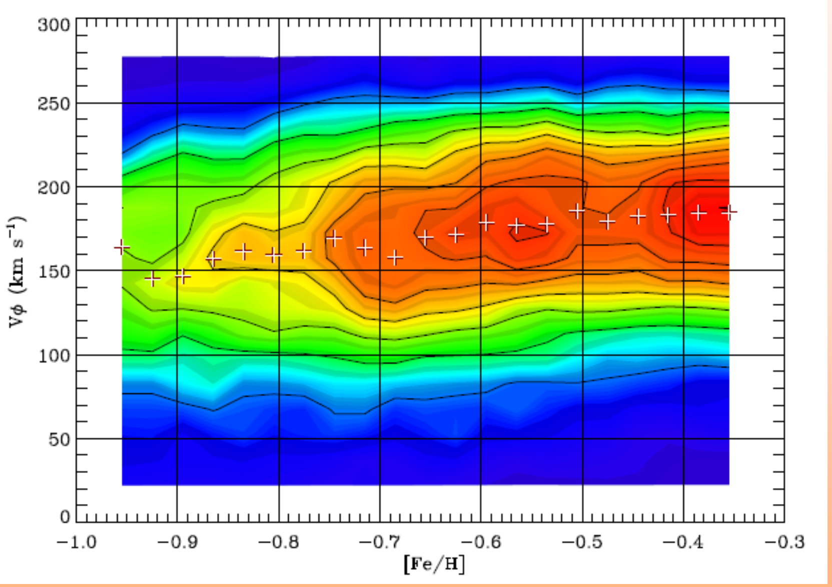


100 km/s/dex

1.5 kpc < |z| < 2.0 kpc (T=5 Gyr)

(*Curir* et al. 2012, A&A, 545, A133)

Observations

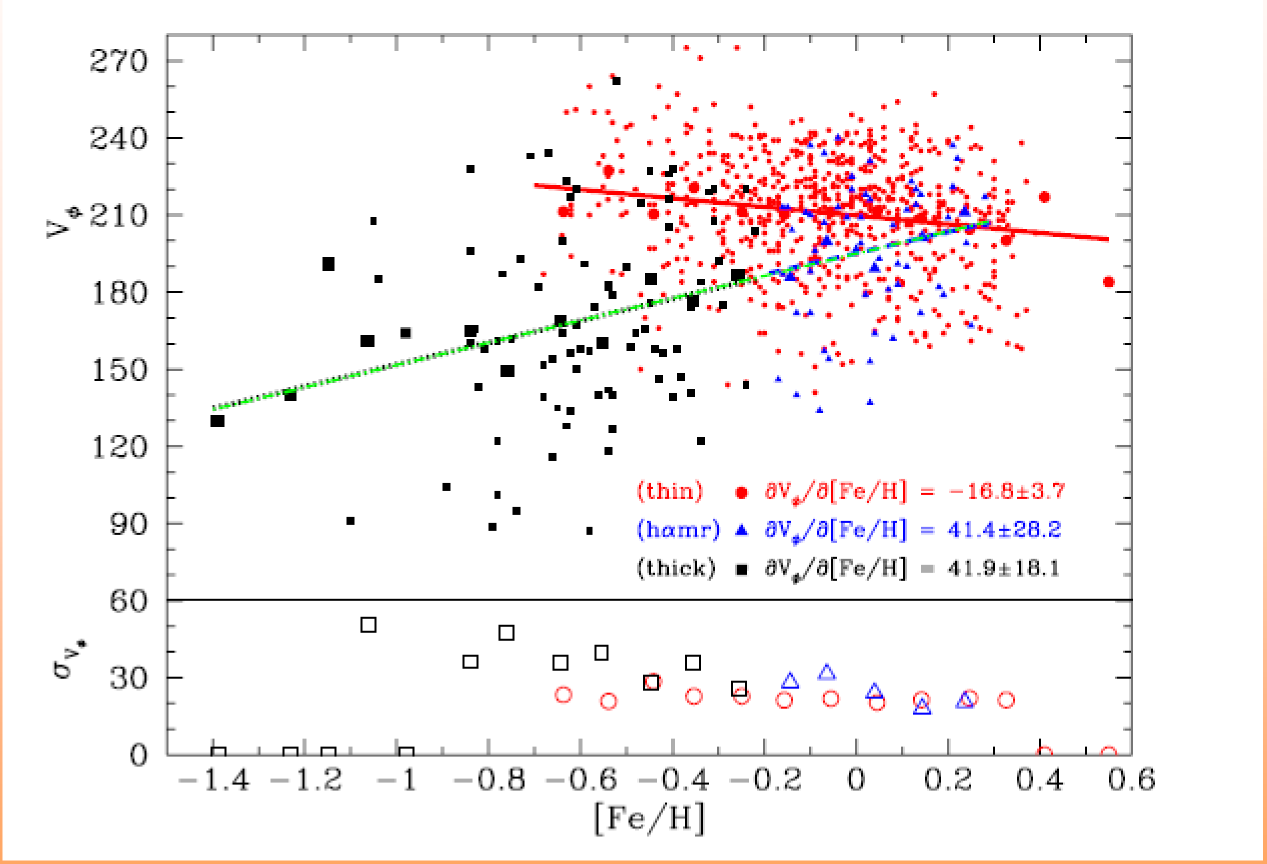


40-50 km/s/dex

1.5 kpc < |z| < 3.0 kpc

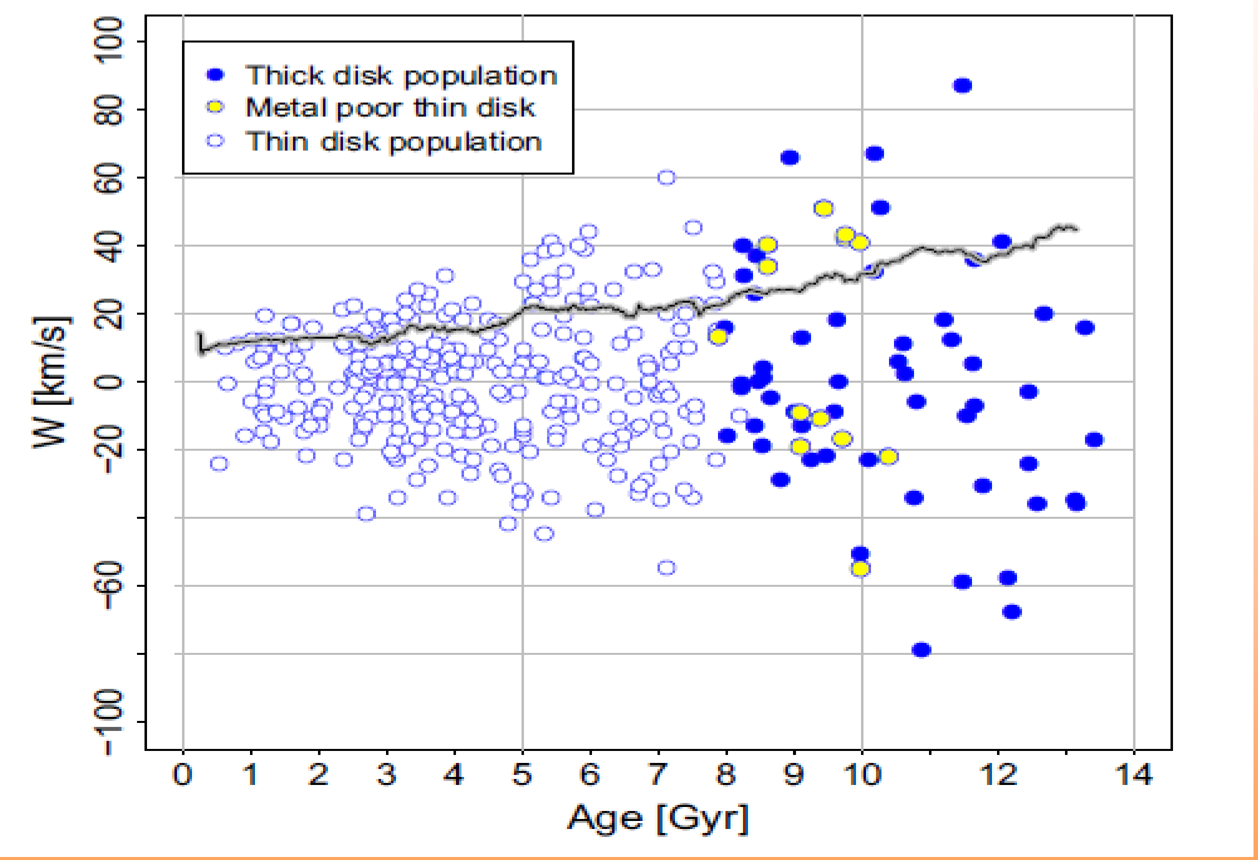
(*Spagna* et al. 2010, A&A, 510, L4)

Rotation - metallicity correlation



(*Adibekian* et al. 2013, A&A, 554, A44)

Vertical velocity distribution



(*Haywood* et al. 2013, A&A, 560, A109

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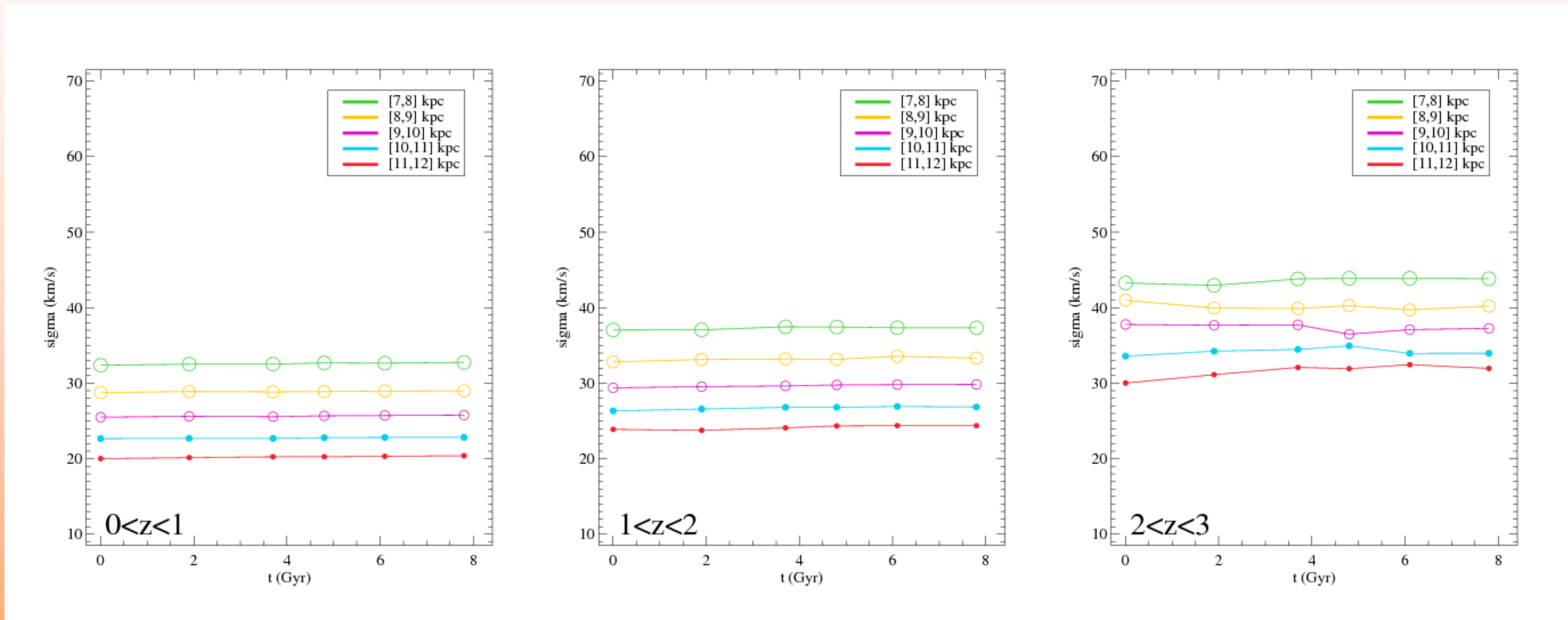
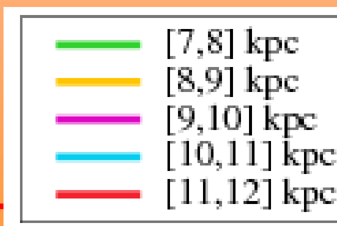


N-body simulation: **Unbarred disk**



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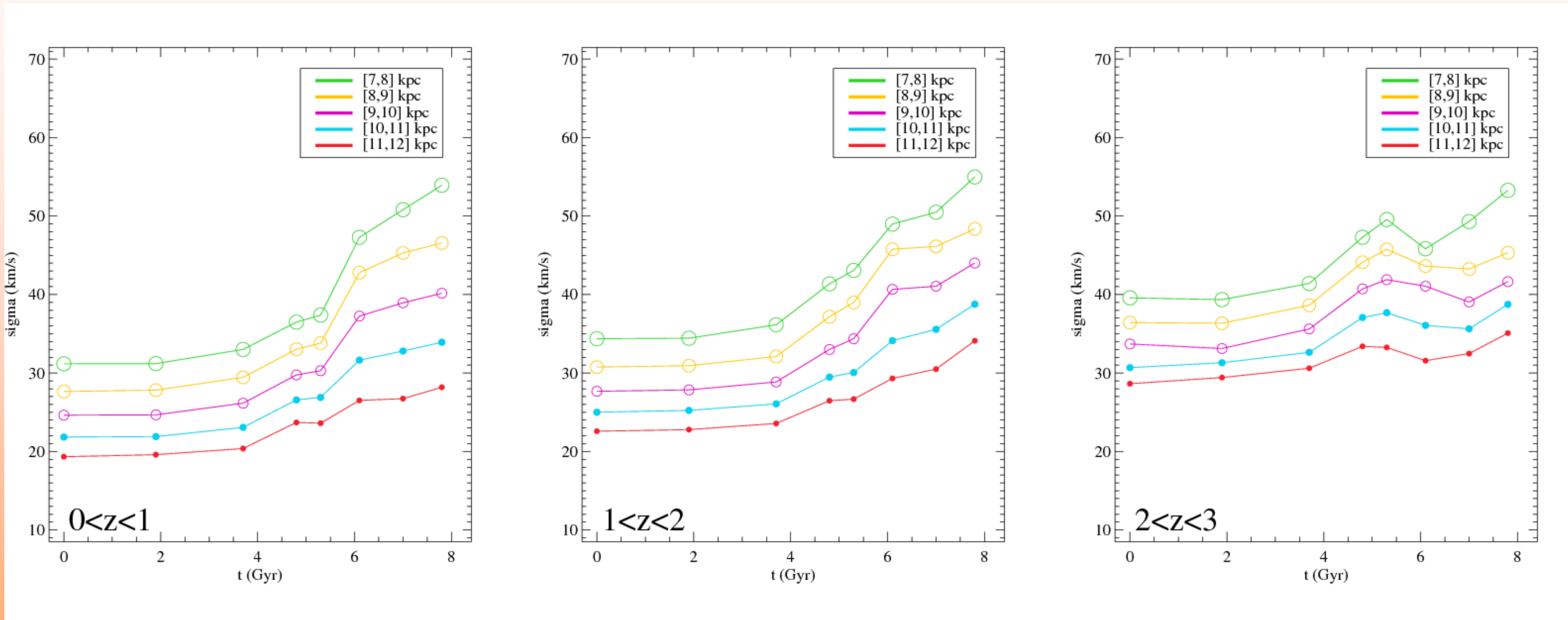
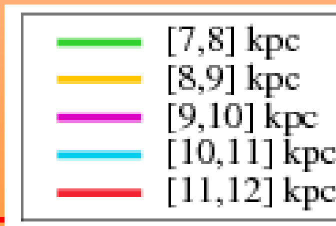
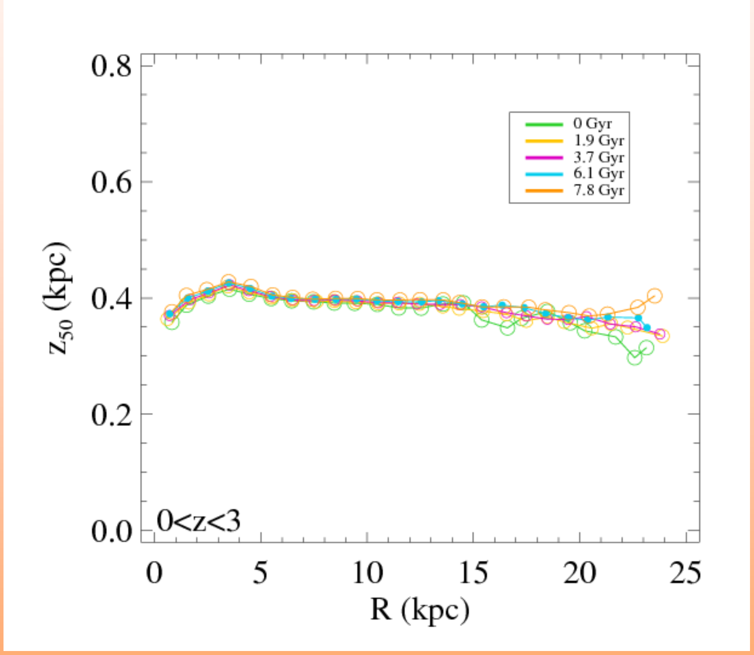


N-body simulation: **Barred disk**

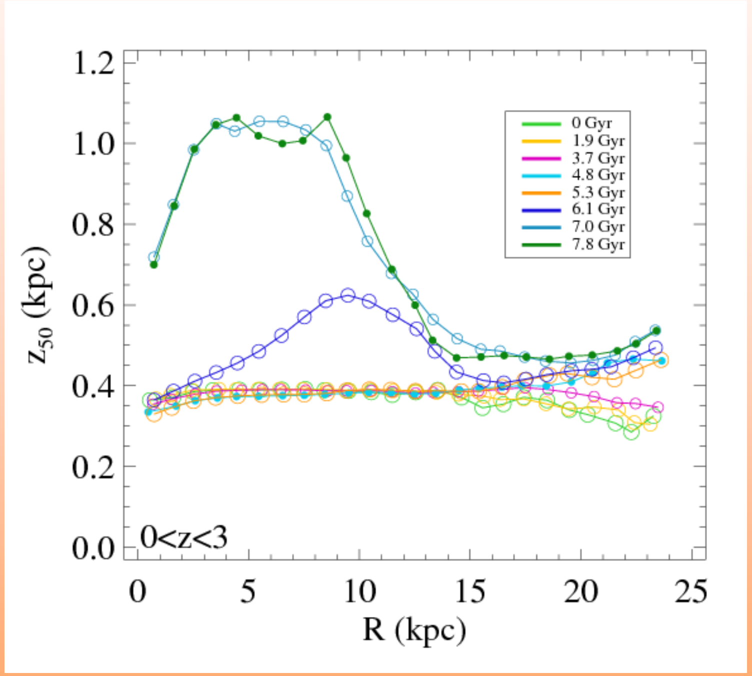


Vertical spatial distribution

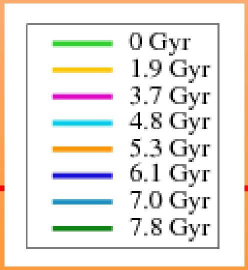
Unbarred disk



Barred disk



(*Spagna* et al. 2015, in preparation)



Conclusions

- A **$V\phi$ vs. [Fe/H] correlation** (*Spagna et al* 2010) can be produced in a Milky Way –like disk, if we assume an initial radial chemical gradient as suggested by *Spitoni and Matteucci* (2011) in their chemical evolution model for an early disk

- The **[Fe/H] vs. R gradient** recently observed in the MW thick disk (eg. *Carrell et al.* 2012) can also be reproduced by such a model

- The secular disk evolution does ***not*** affect significantly the disk chemical profiles in *both* the **barred/unbarred** disks examined

- We found that the presence of a strong **bar** can increase significantly the vertical velocity dispersion, σ_{Vz}, and the **thickness**, h_z, of the whole inner disk.