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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



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# Thick disk: formation scenarios

**Table 1** Models of Intermediate Population II Formation

| Model                                                                                                             | Thin disk disjoint? | Halo disjoint? | Key age features                                  | Key abundance features              | Key kinematic features                              |
|-------------------------------------------------------------------------------------------------------------------|---------------------|----------------|---------------------------------------------------|-------------------------------------|-----------------------------------------------------|
| <u>Pre-thin disk (“top down”) models</u>                                                                          |                     |                |                                                   |                                     |                                                     |
| 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                             |                                     |                                                     |
| <u>Post-thin disk (“bottom up”) models</u>                                                                        |                     |                |                                                   |                                     |                                                     |
| 5. Secular kinematic diffusion of thin disk stars (Norris 1987)                                                   | No                  | Yes            | Wide range of ages. Gradient, overlaps thin disk. | Gradient, [Fe/H] ≤ 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 $\sigma_z$ 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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***Rix & Bovy 2013, Astron. Astrophys. Rev. 21, 61***

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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?**

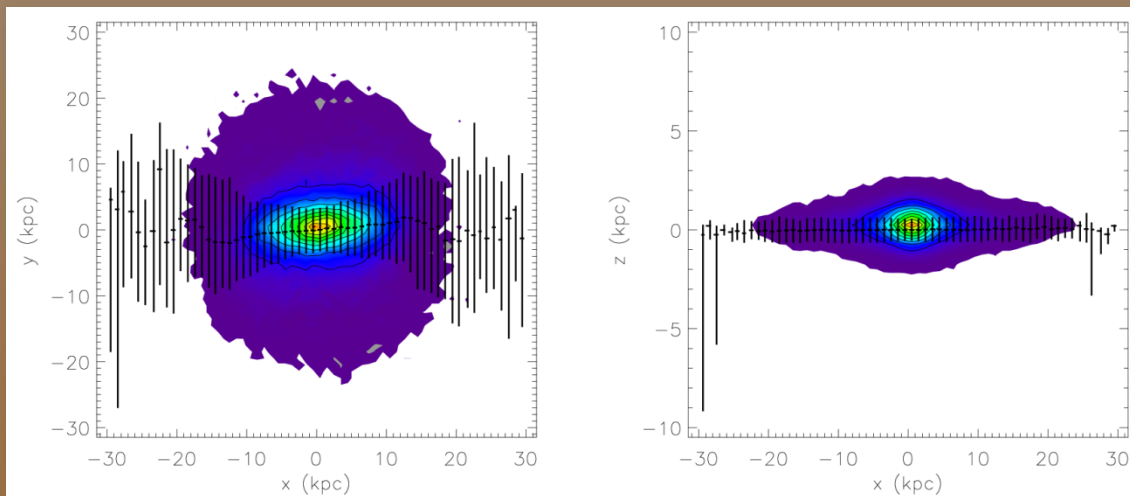


# N-body simulations



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      | $\epsilon$ | $M_{DM}$           |
|------|-----------|-----------|-----------|-----------|--------|------------|--------------------|
| Halo | $10^{12}$ | 258       | 7.40      | 336       | $10^7$ | 0.11       | $1.07 \times 10^5$ |

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.  $\epsilon$ : 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                | $\epsilon$ | $Q$ |
|-------|---------------------|-------------------|-------|-------|------------------|------------|-----|
| 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.  $\epsilon$ : softening length in kpc.  $Q$ : Toomre parameter.

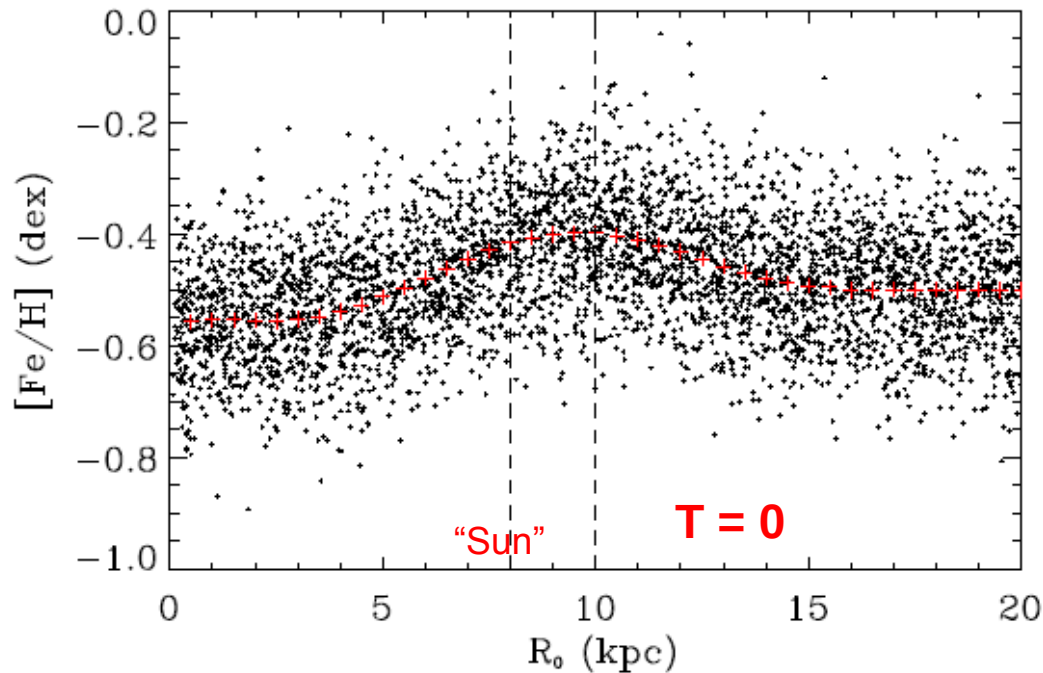
**Table 3.** Properties of the bulge (Hernquist profile)

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

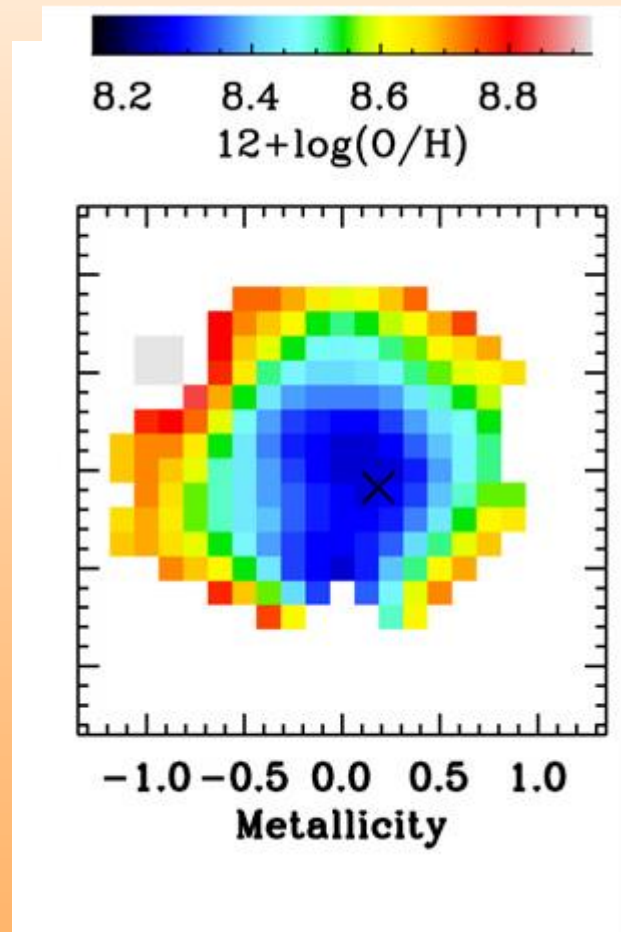
Notes.  $M_*$ : mass in  $M_{\odot}$ . N: number of particles.  $\epsilon$ : softening length in kpc.  $a$ : Hernquist scale radius in kpc.  $M_b$ : mass of the particle in  $M_{\odot}$ .



## Radial metallicity gradient



**Initial condition.** Each particle in the initial configuration is tagged with a  $[\text{Fe}/\text{H}]$  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  $z \sim 3$ .

(Cresci et al. 2010)



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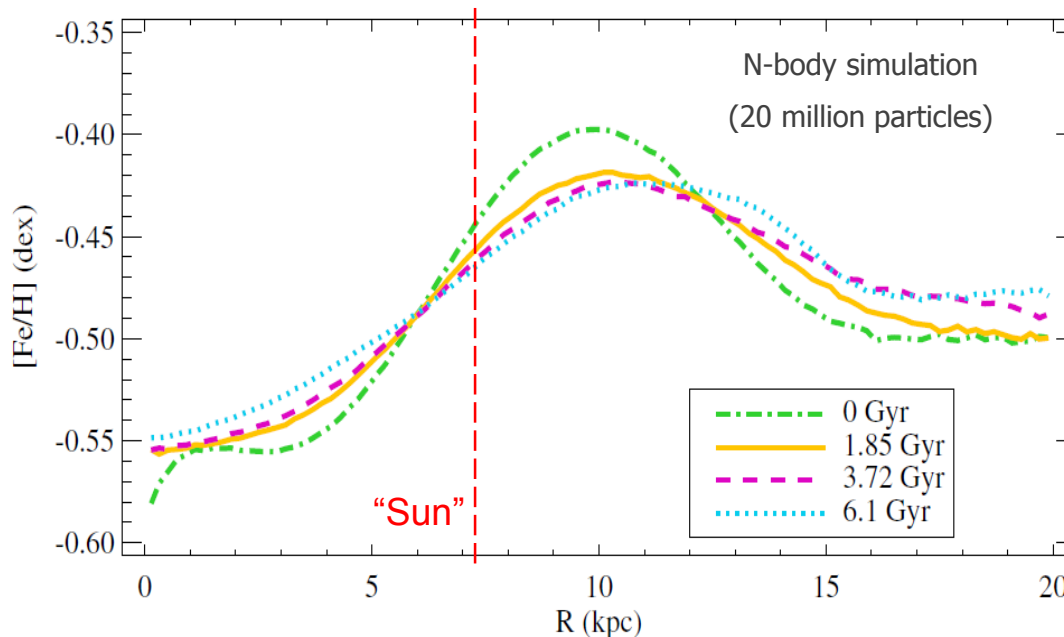
# Thick disk:

# 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

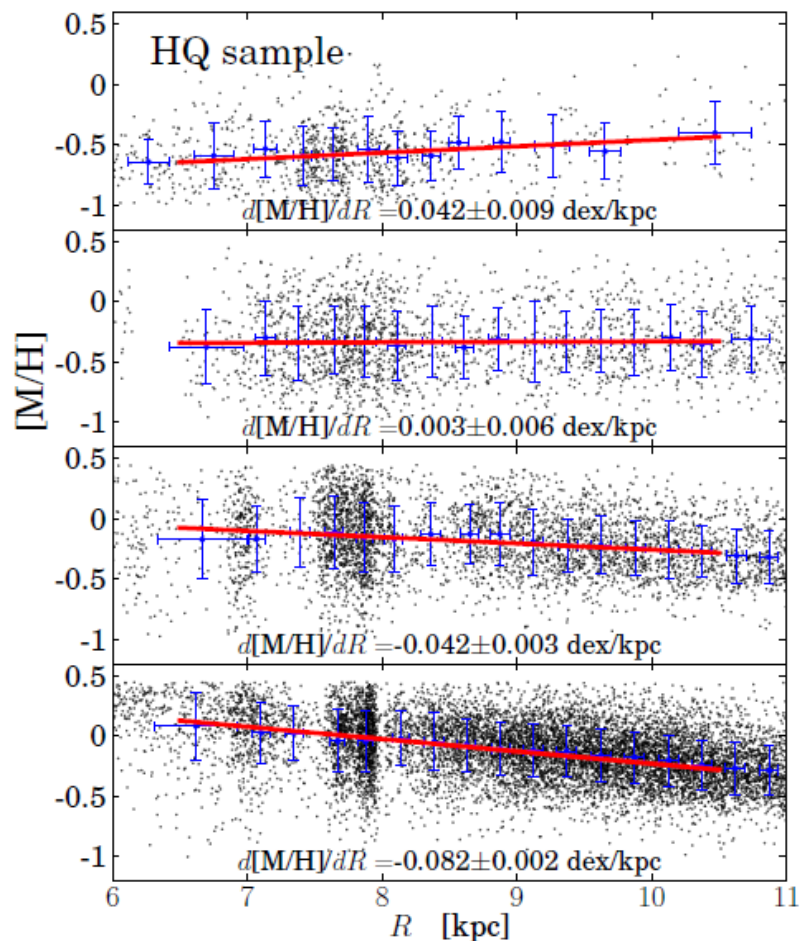


Evolution of the median radial chemical distribution of a simulated *barred* Milky Way-like galactic disk.

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

# Radial metallicity gradient

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

## Observations 1: APOGEE

$1.5 \text{ kpc} < |z| < 3 \text{ kpc}$

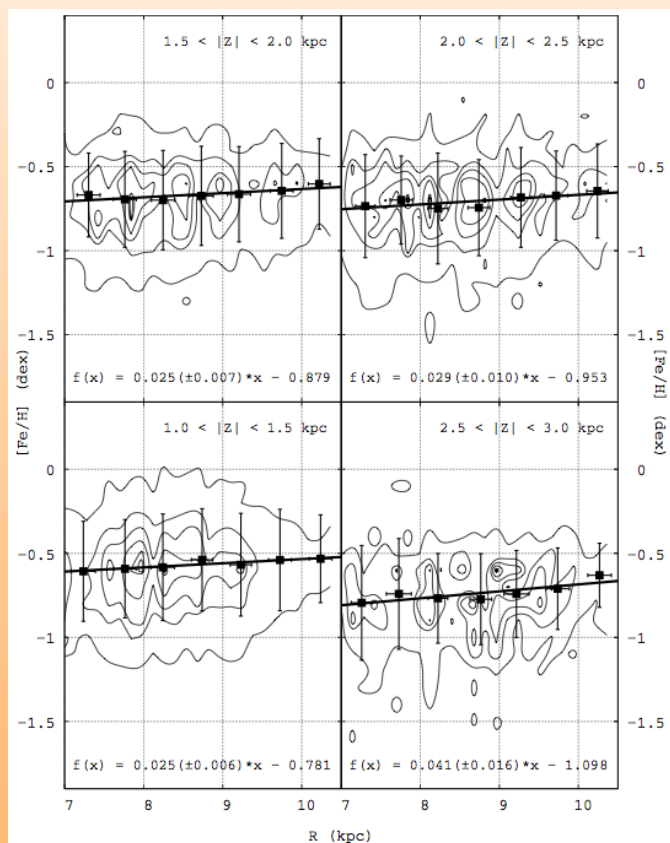
$0.8 \text{ kpc} < |z| < 1.5 \text{ kpc}$

$0.4 \text{ kpc} < |z| < 0.8 \text{ kpc}$

$0.0 \text{ kpc} < |z| < 0.8 \text{ kpc}$



## Observations 2:



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

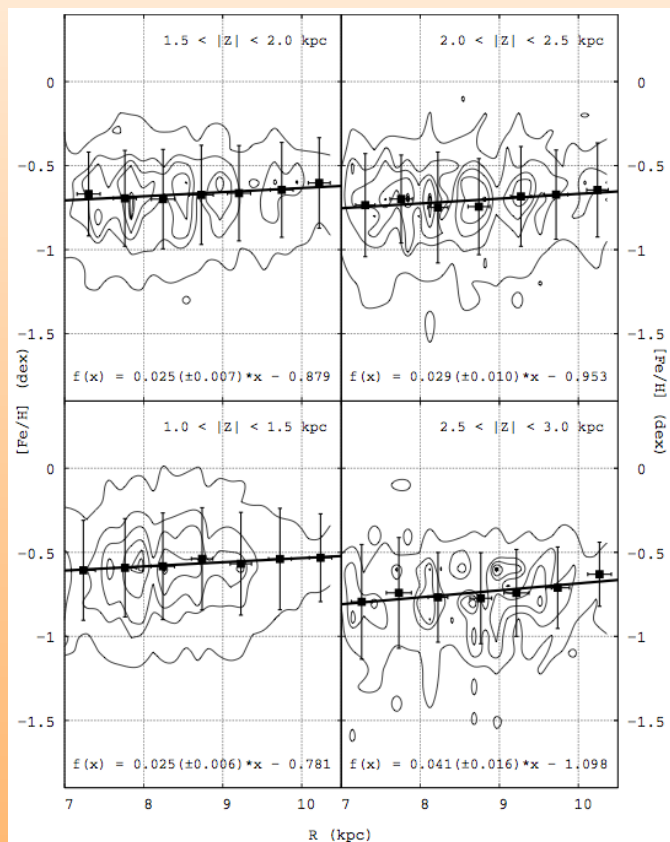
# Radial metallicity gradient

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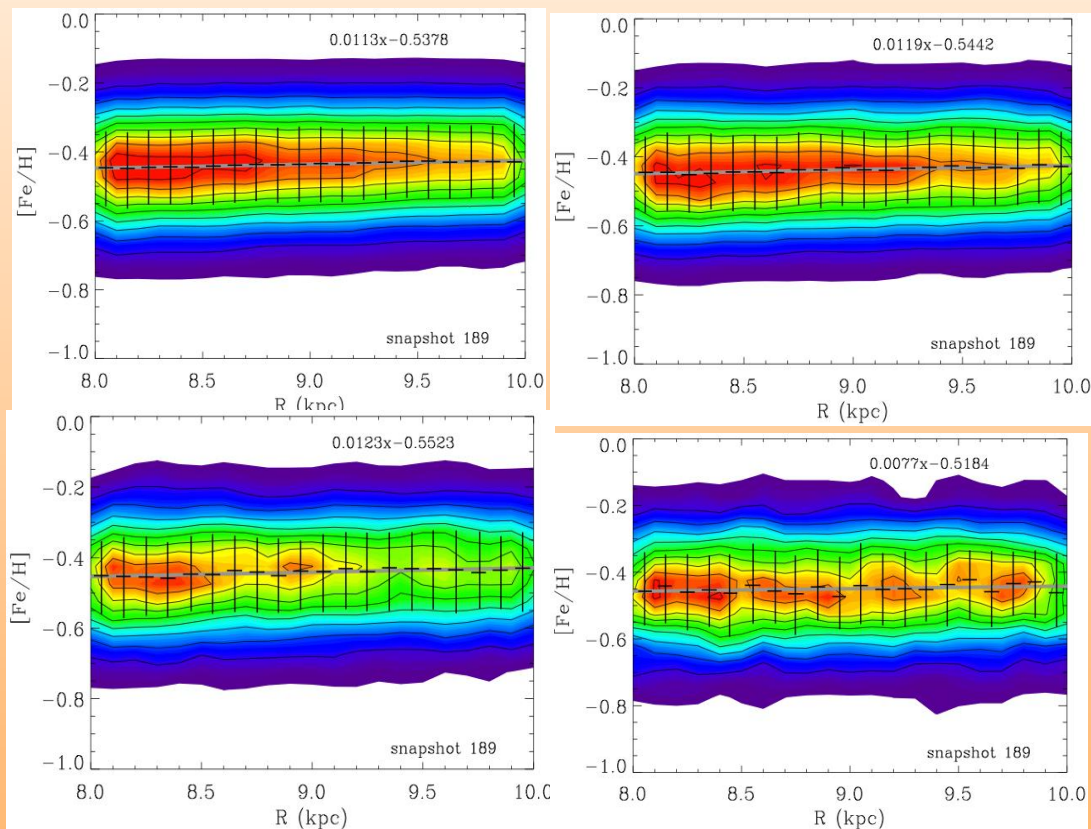


## Observations 2:

## vs. Simulations



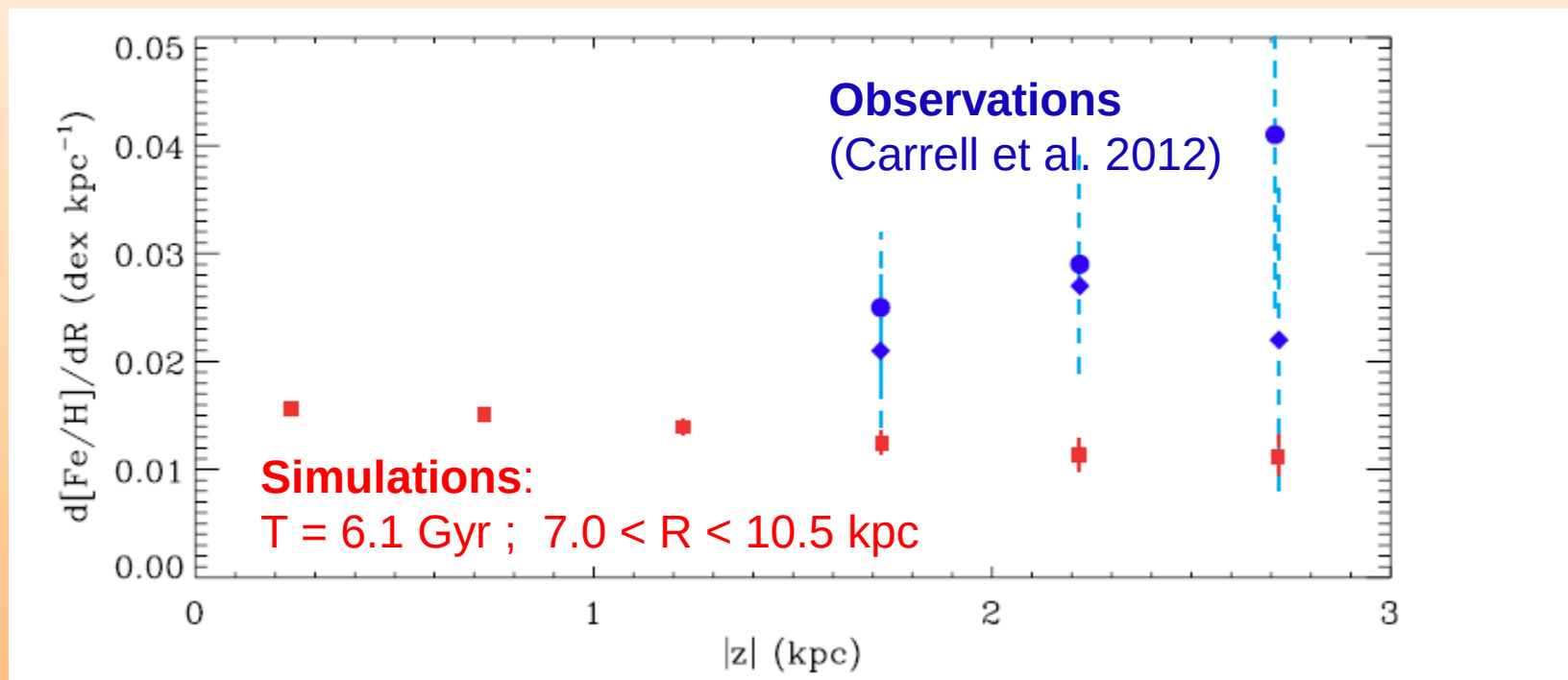
(Carrell et al. 2012, ApJ, 144, 185)



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

# Radial metallicity gradient

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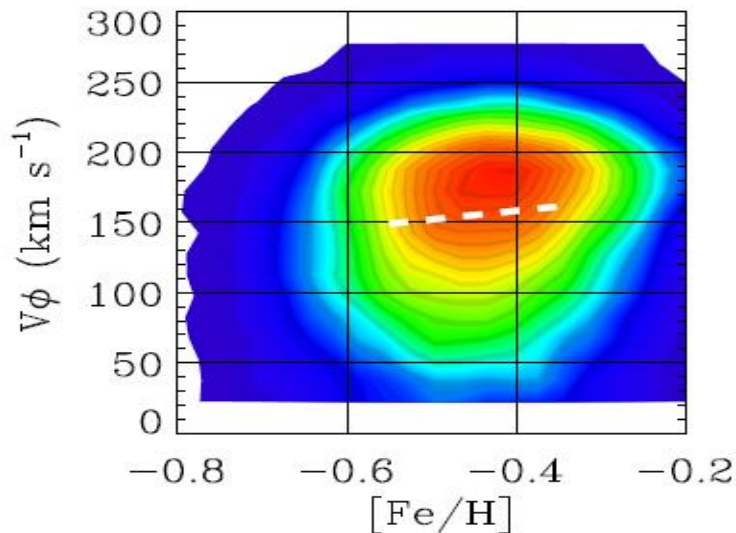


(Curir et al. 2014, ApJ, 784, L24)



# Rotation - metallicity correlation

## Simulations

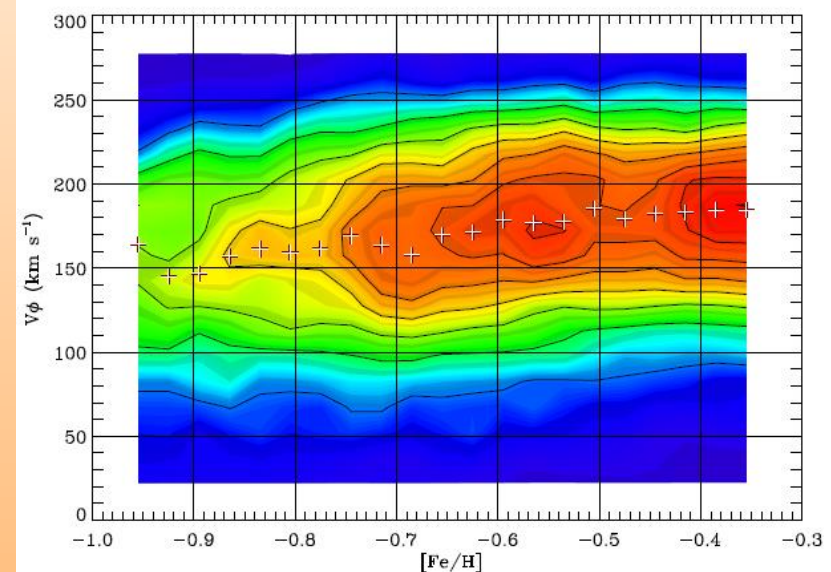


**100 km/s/dex**

$1.5 \text{ kpc} < |z| < 2.0 \text{ kpc}$  ( $T=5 \text{ Gyr}$ )

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

## Observations



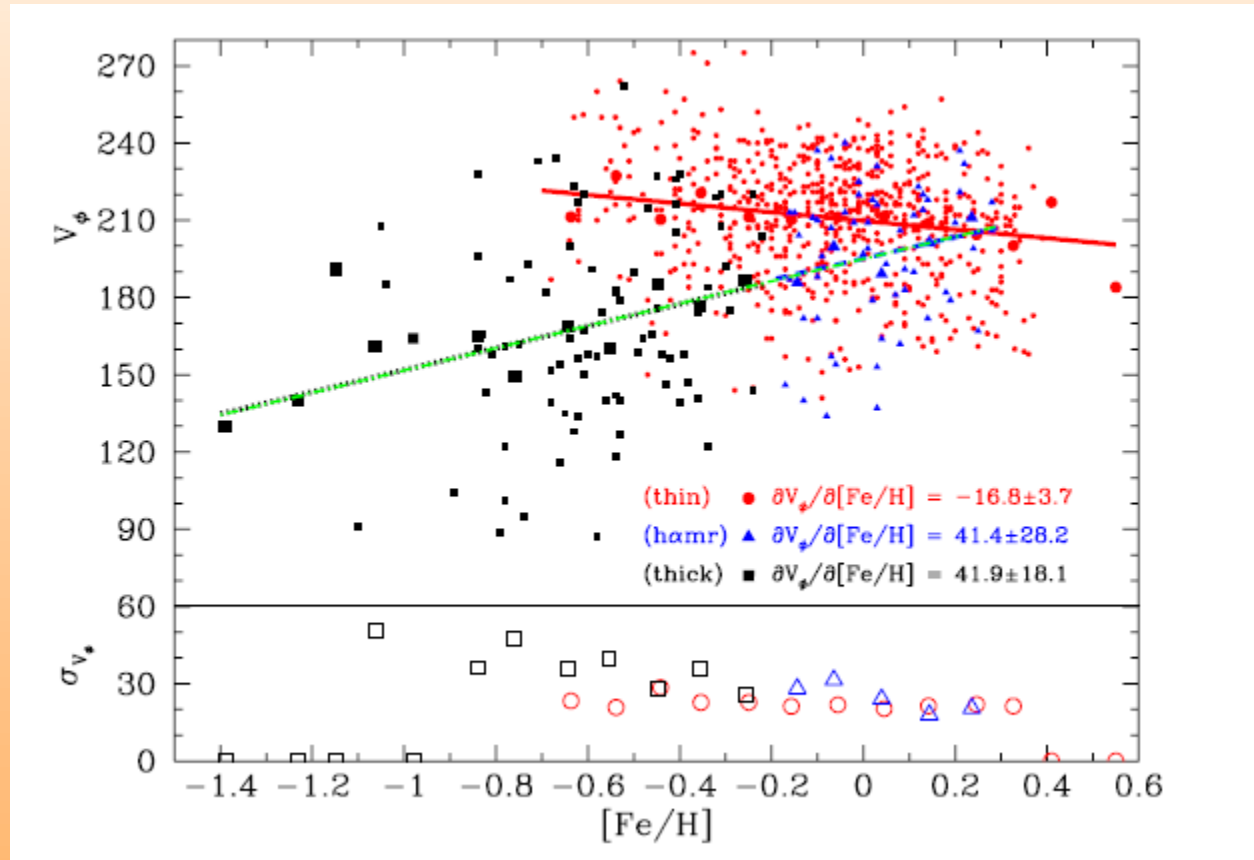
**40-50 km/s/dex**

$1.5 \text{ kpc} < |z| < 3.0 \text{ kpc}$

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



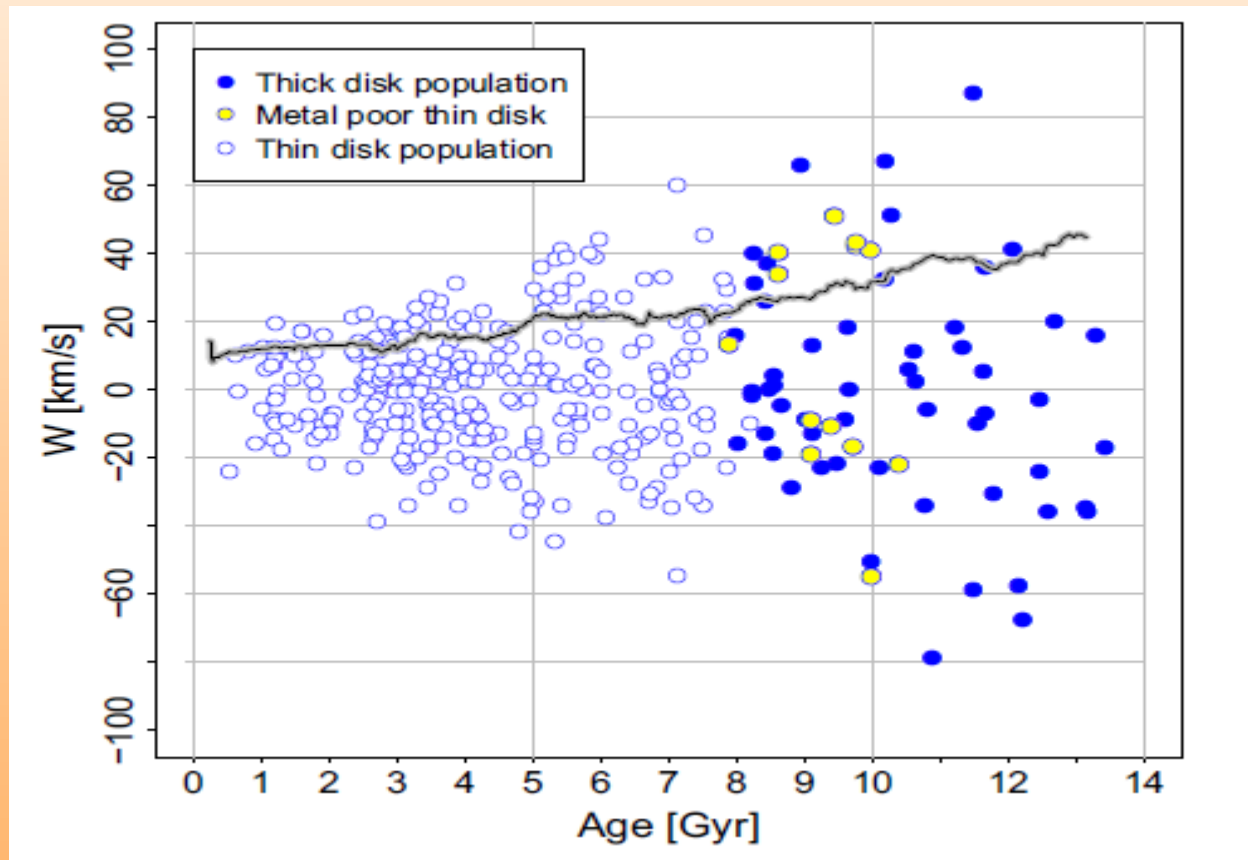
# Rotation - metallicity correlation



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



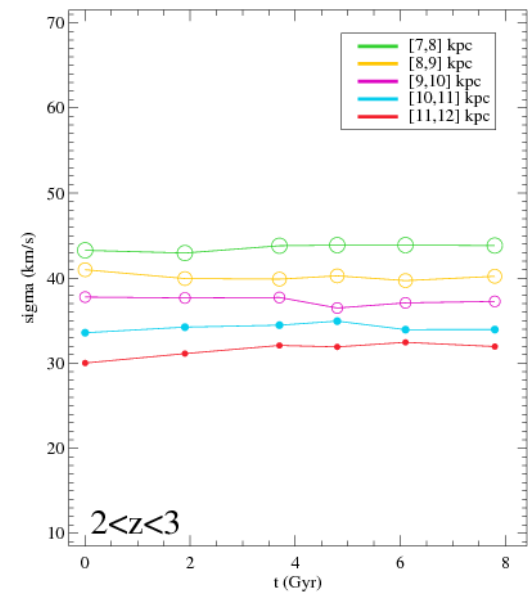
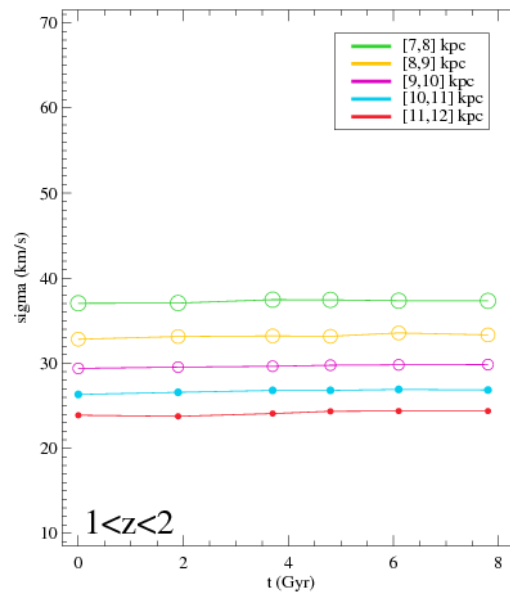
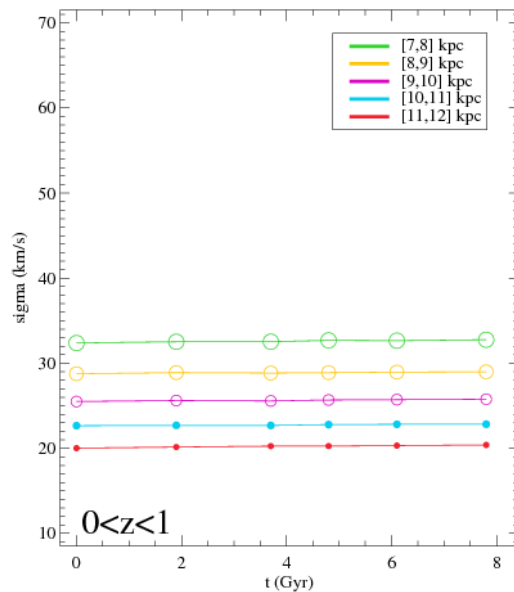
# Vertical velocity distribution



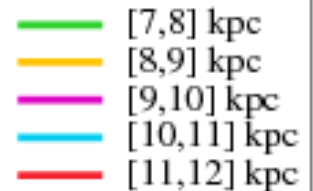
(Haywood et al. 2013, A&A, 560, A109)



# Vertical velocity distribution

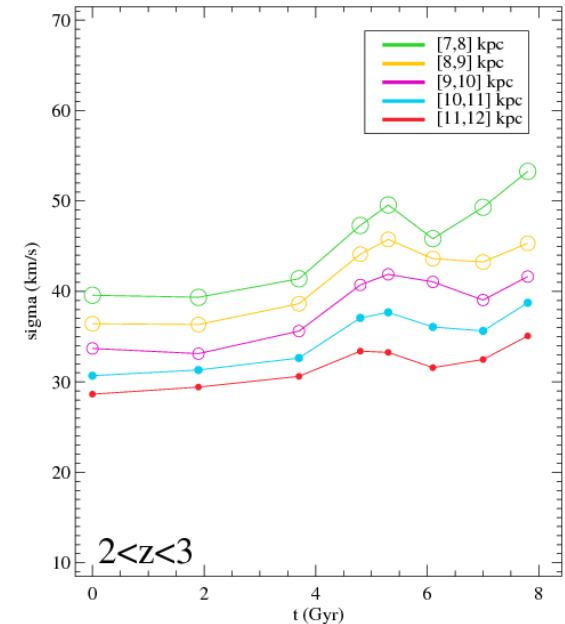
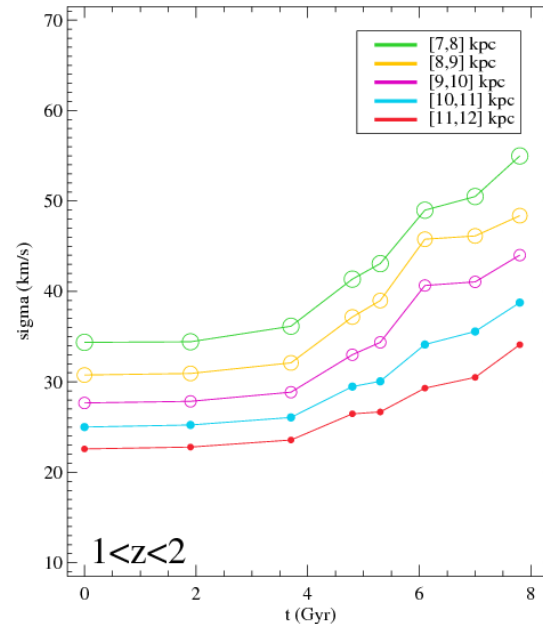
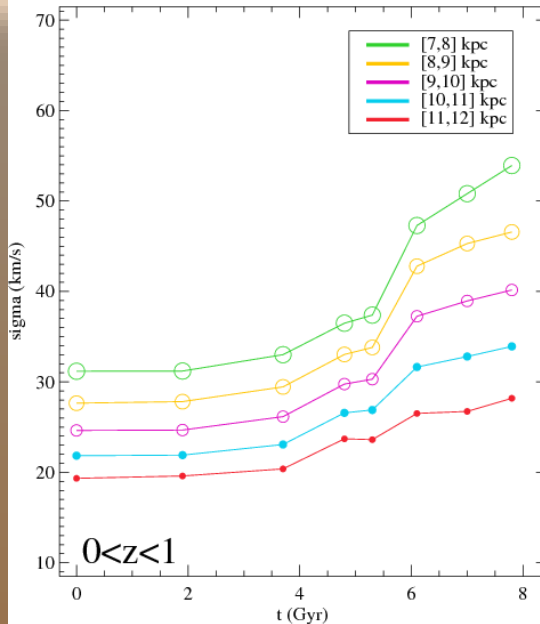


N-body simulation: **Unbarred disk**

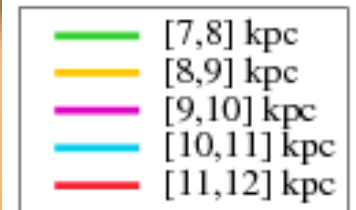




# Vertical velocity distribution



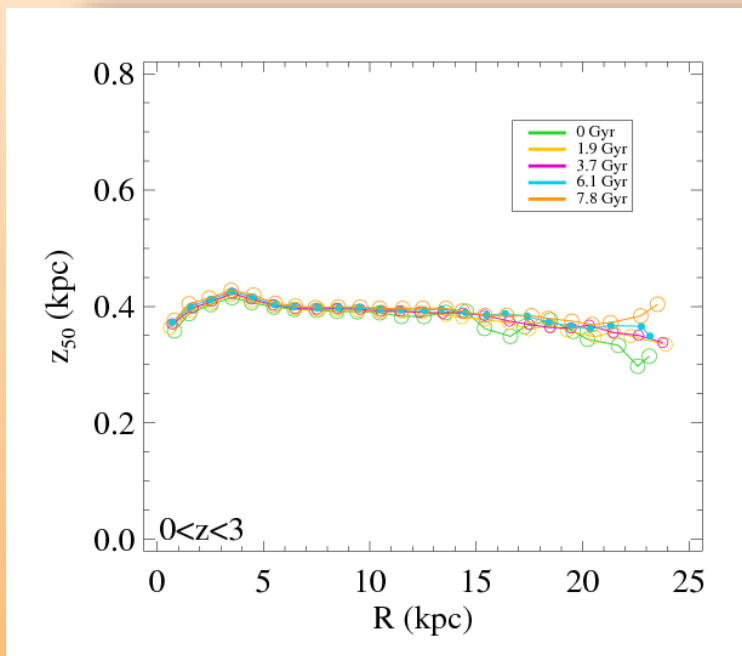
N-body simulation: **Barred disk**



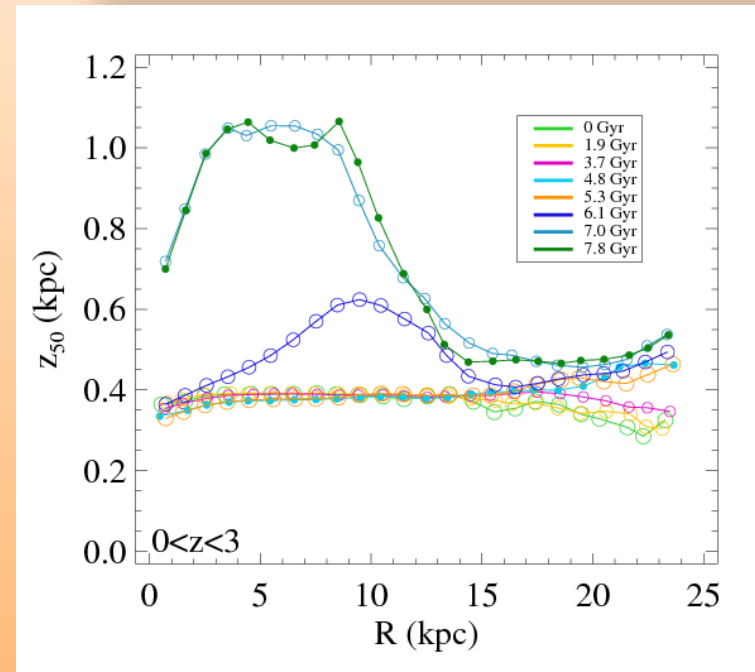


# Vertical spatial distribution

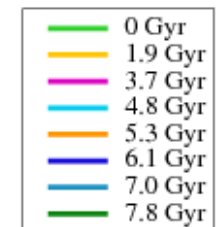
## Unbarred disk



## Barred disk



(Spagna et al. 2015, in preparation )





# Conclusions

- A  $V\phi$  vs.  $[\text{Fe}/\text{H}]$  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  $[\text{Fe}/\text{H}]$  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,  $\sigma_{V_z}$ , and the **thickness**,  $h_z$ , of the whole inner disk.