Radial migration and the evolution of the MW disk

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I: arXiv: 1412.0585

II: AA accepted

1D semi-analytical model

with parametrized infall in a DM halo,

SFR from H2, detailed chemical evolution (H to Ni)

and radial motions of gas and stars

Probabilistic treatment of radial migration (*Sellwood and Binney 2002)*

a star born at radius r' at time t' may be found at time t (i.e. after time $\tau = t - t'$) in radius r with a probability $P(r, r', \tau)$ given

$$P(r, r', \tau) = (2\pi\sigma_\tau^2)^{-1/2} \exp\left[-\frac{(r - r')^2}{2\sigma_\tau^2}\right]$$

$$\sigma_{\tau,r} = (\sigma_b^2 + \sigma_c^2)^{1/2}$$

Blurring (epicycles)

$$\langle \sigma_b^2 \rangle = \frac{\langle \sigma_v(r)^2 \rangle}{\kappa_r^2}$$

Epicyclic frequency

$$\kappa_r = \sqrt{2}\, \frac{V_C(r)}{r}$$

Radial velocity dispersion

$$\sigma_v(r, T) = 40\, \mathrm{e}^{-(\mathrm{r}-\mathrm{R}_\odot)/8\ \mathrm{kpc}}\ \mathrm{km/s}$$

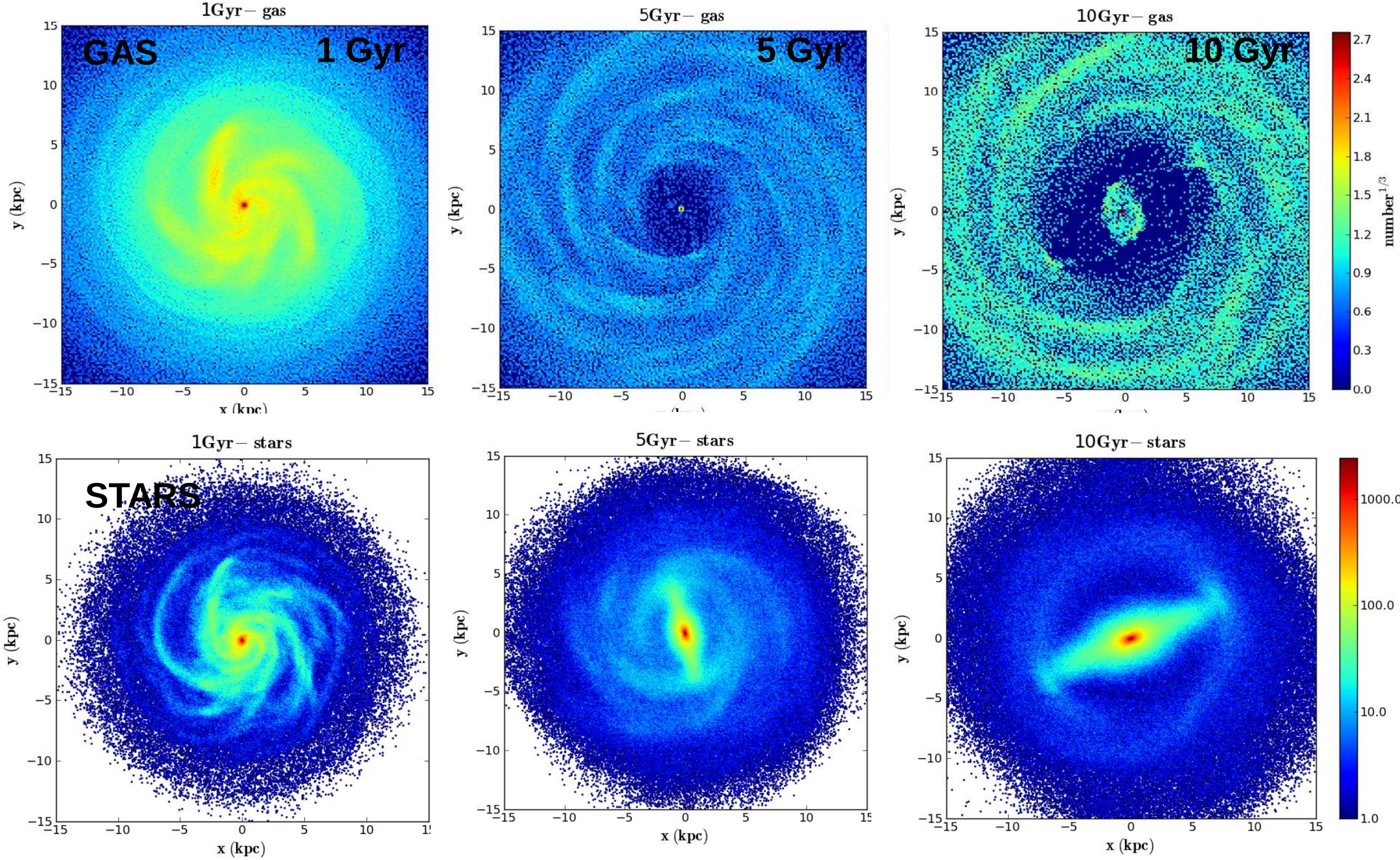
Churning (radial migration)

$$\sigma_C = \alpha(r)\tau^N + \beta(r)$$

Coefficients $\alpha(r,t)$ and $\beta(r,t)$ extracted from the numerical simulation of KPA2013 *at t=2.5 Gyr (bar similar in size to the one of the Milky Way)*

N-body+SPH simulations of a disk galaxy (*Kubryk, NP, Athanassoula MNRAS 2013)*

DM halo + baryonic disk + SFR + chemistry (1 «metal» + IRA), no infall



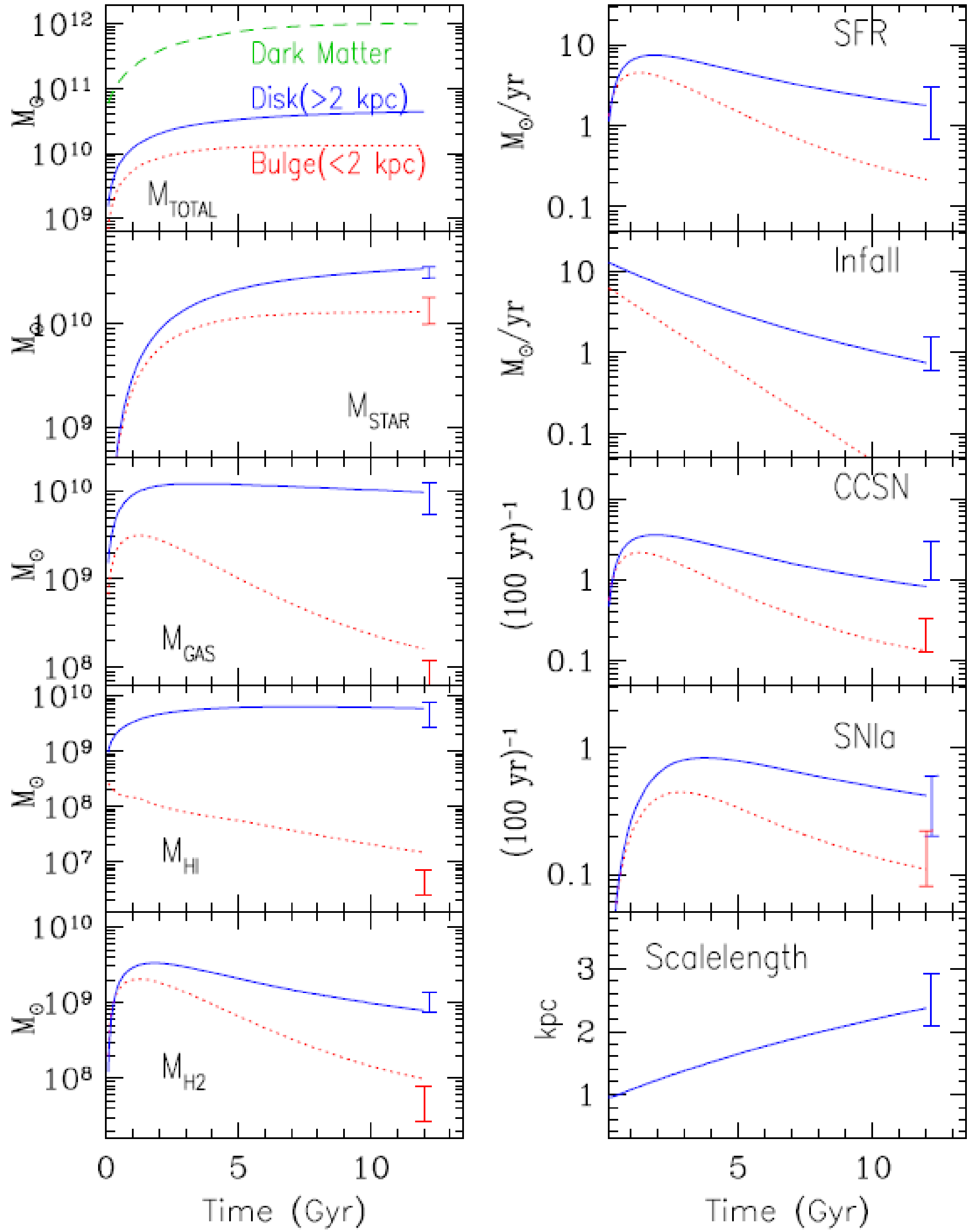
« Early type galaxy » with a strong bar, formed after the first 1.4 Gyr

Evolution of global quantities for Milky Way

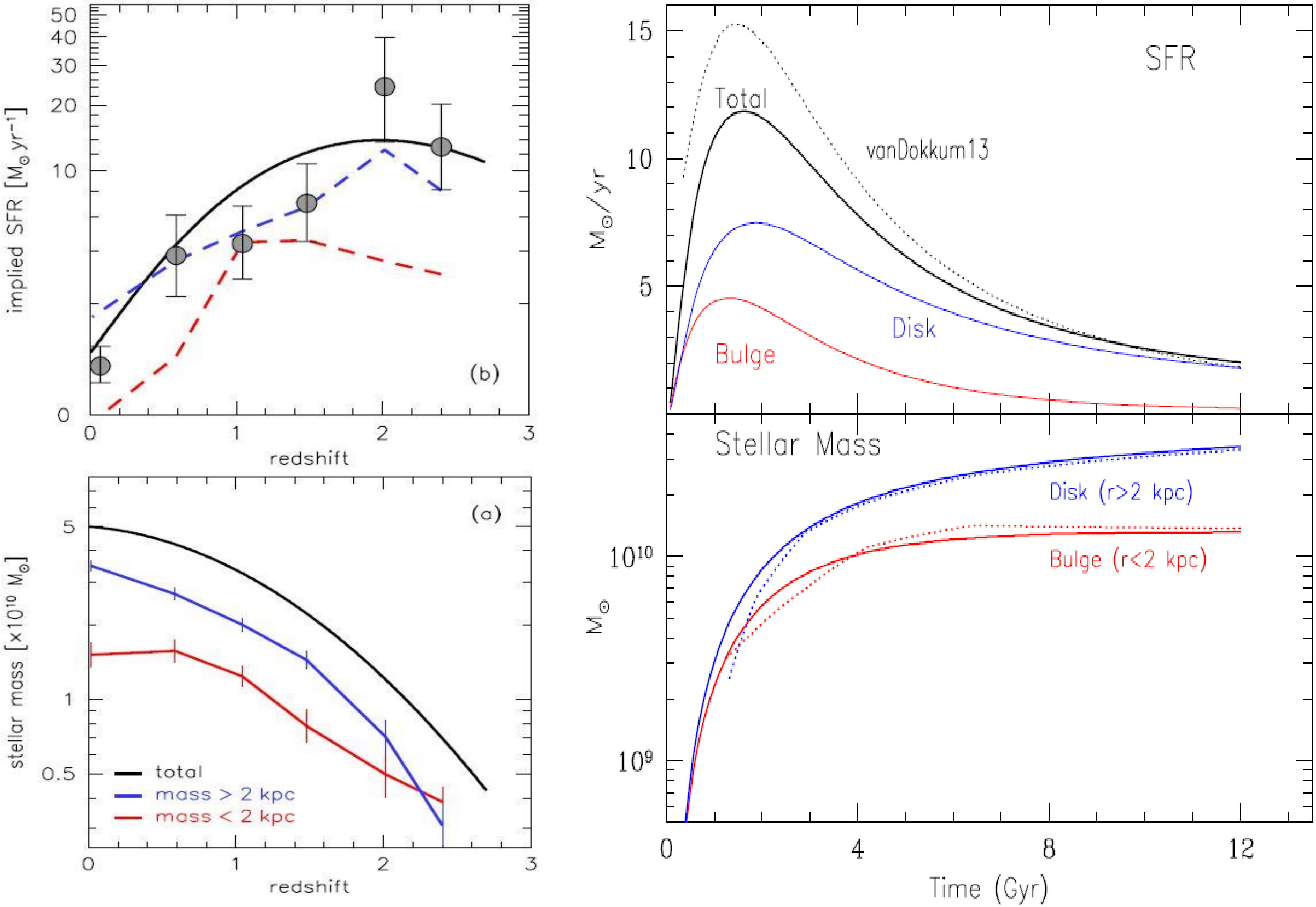
Bulge (<2 kpc)

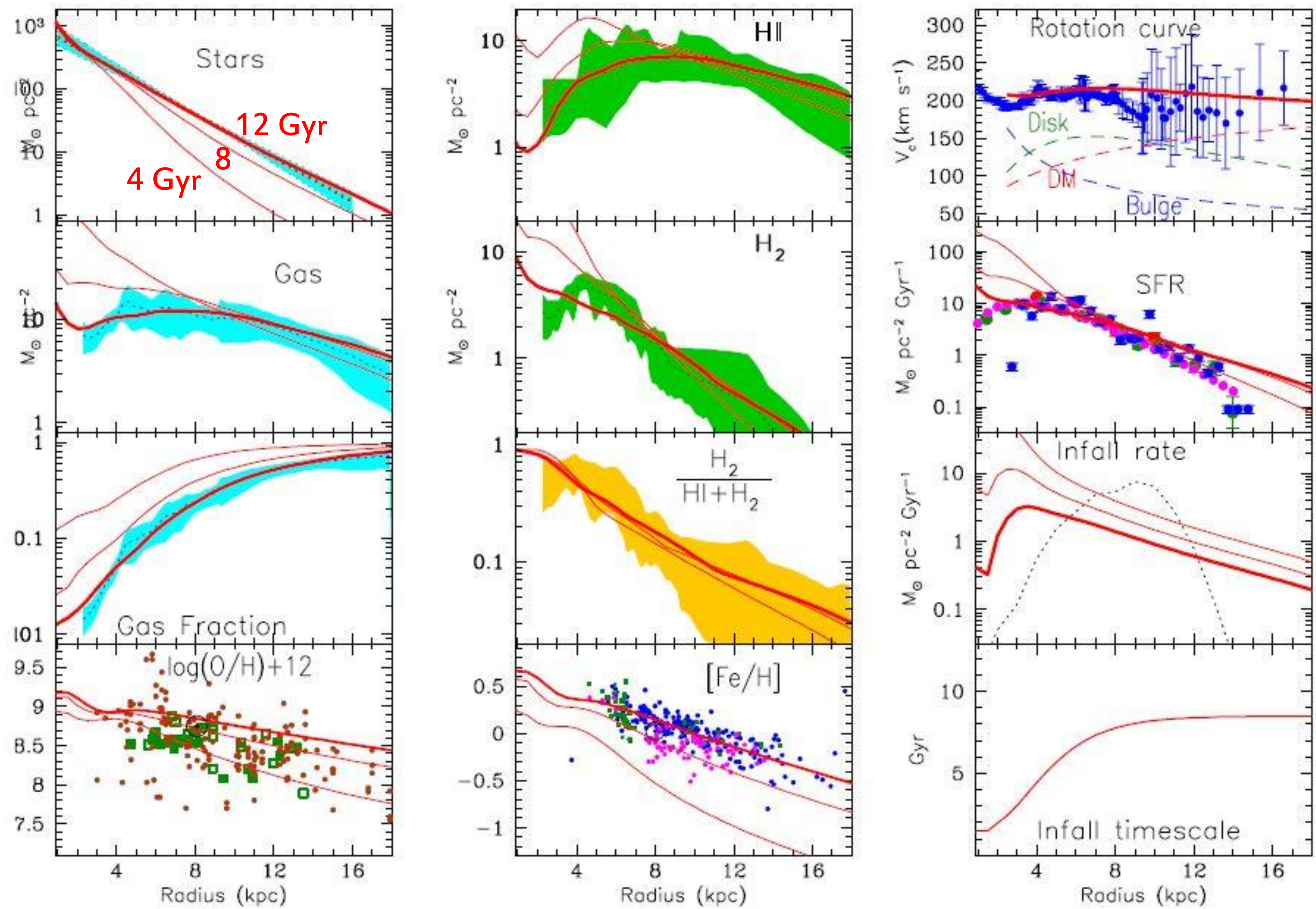
and

Disk (>2 kpc)

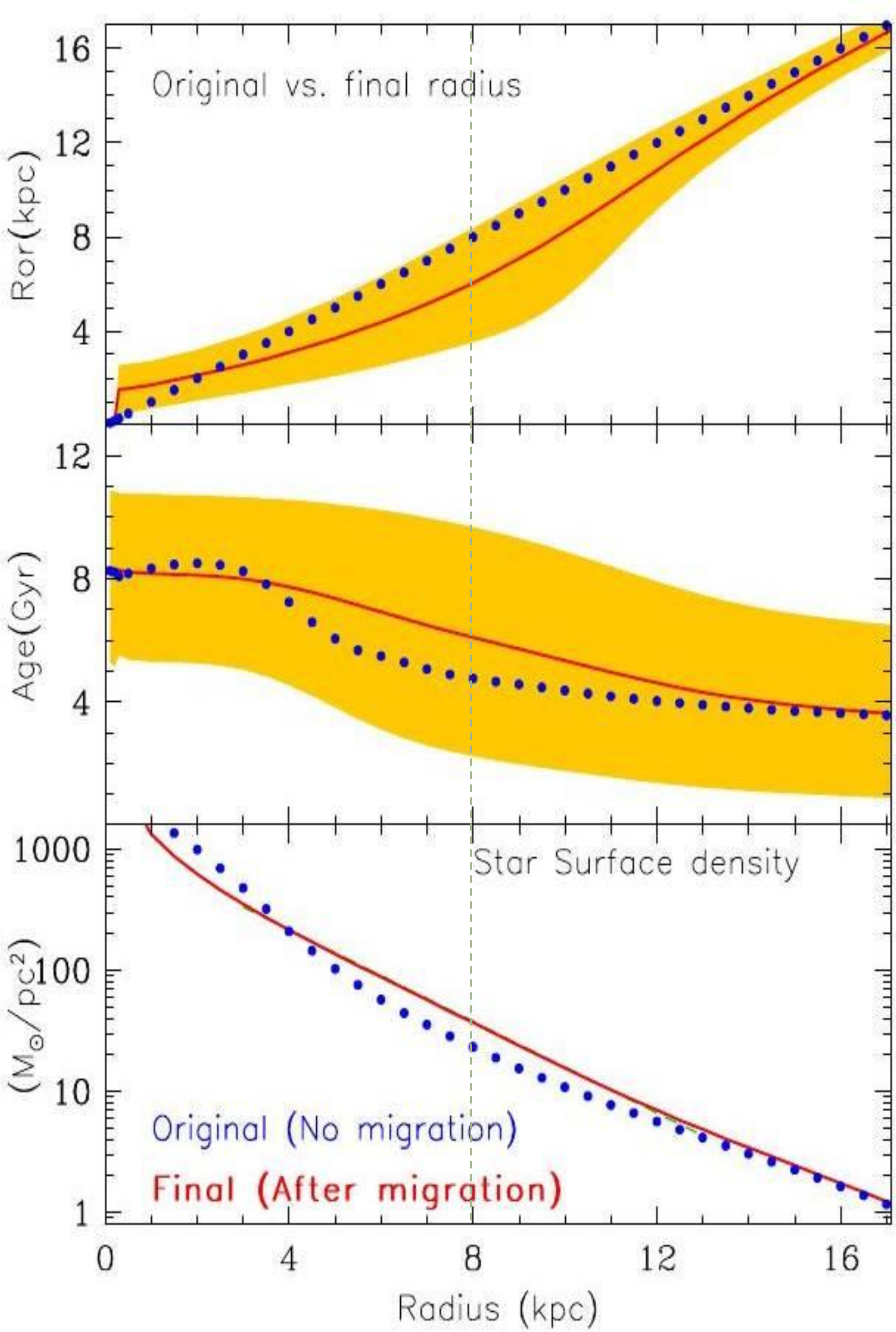


Comparison to average (« stacked ») evolution of *van Dokkum et al. (2013)* with 3D-HST and CANDELS data up to z~2.5



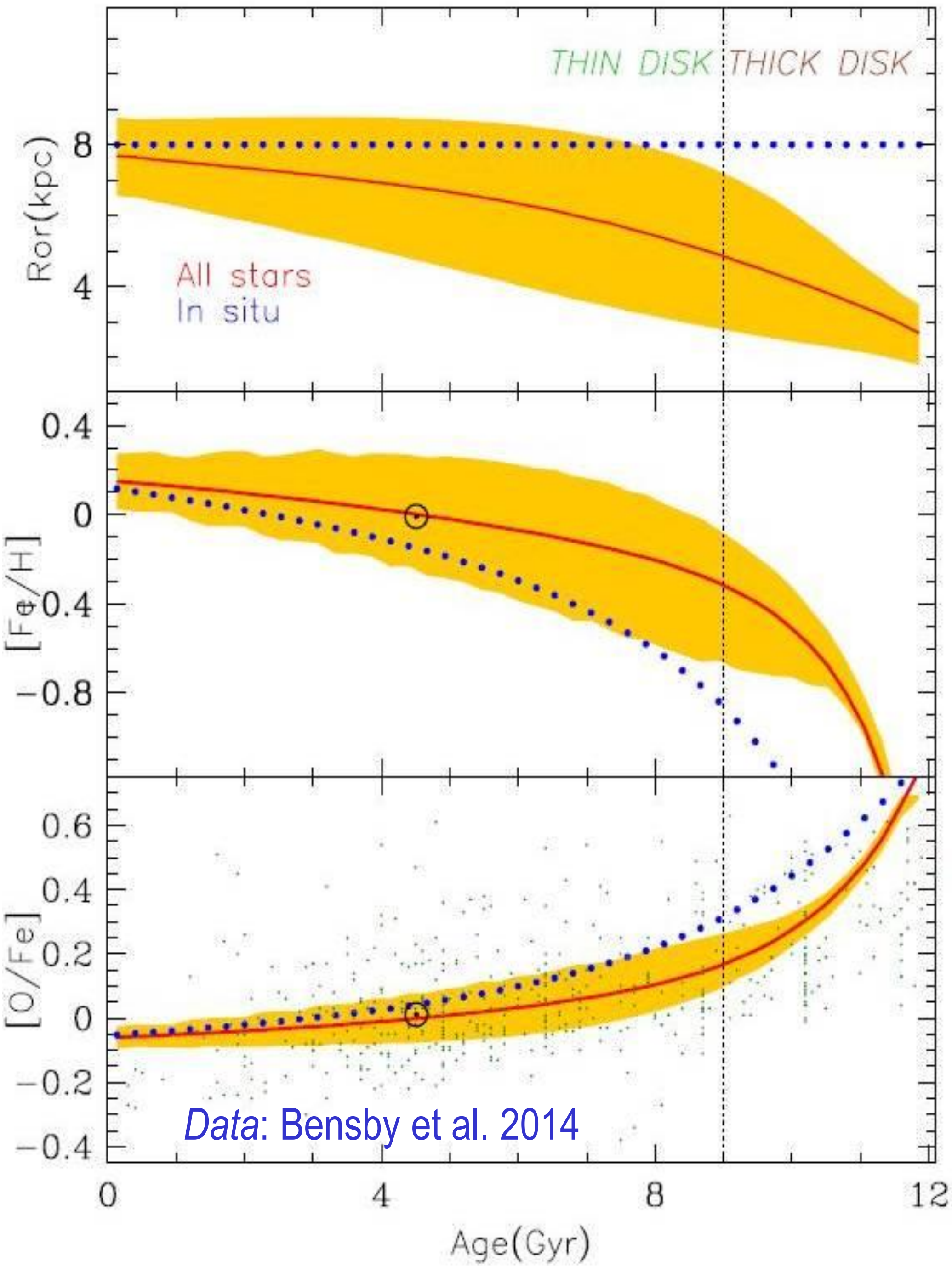


Stars
12 Gyr
8
4 Gyr
Gas
Gas Fraction
log(O/H)+12
HI
H2
H2 / HI+H2
[Fe/H]
Rotation curve
Disk
DM
Bulge
SFR
Infall rate
Infall timescale
Radius (kpc)



**Radial migration
affects a large fraction
of the disk,
up to 12 kpc**

**In the solar neighborhood
it brings stars
mostly from inner regions,,
(on average, from 1.5 kpc inwards)
mostly older than
the locally formed ones
(by 1.5 Gyr)**

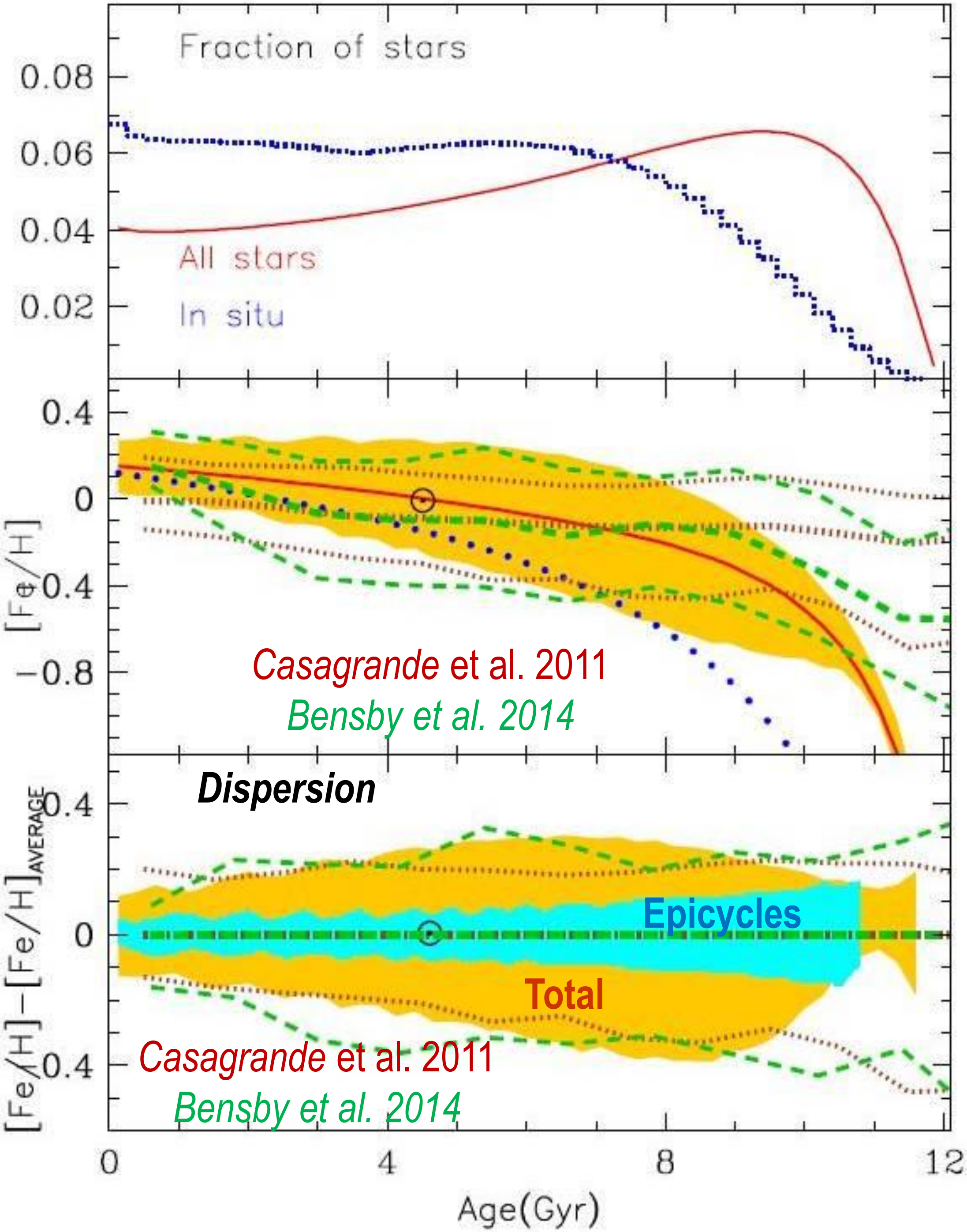


Solar neighborhood

1. Older stars come from inner regions

2. The local age-metallicity relation flattens ; dispersion in Fe/H increases with age except for the oldest stars (thick disk)

3. Very little dispersion in O/Fe (best « chronometer » ?



Solar Neighborhood

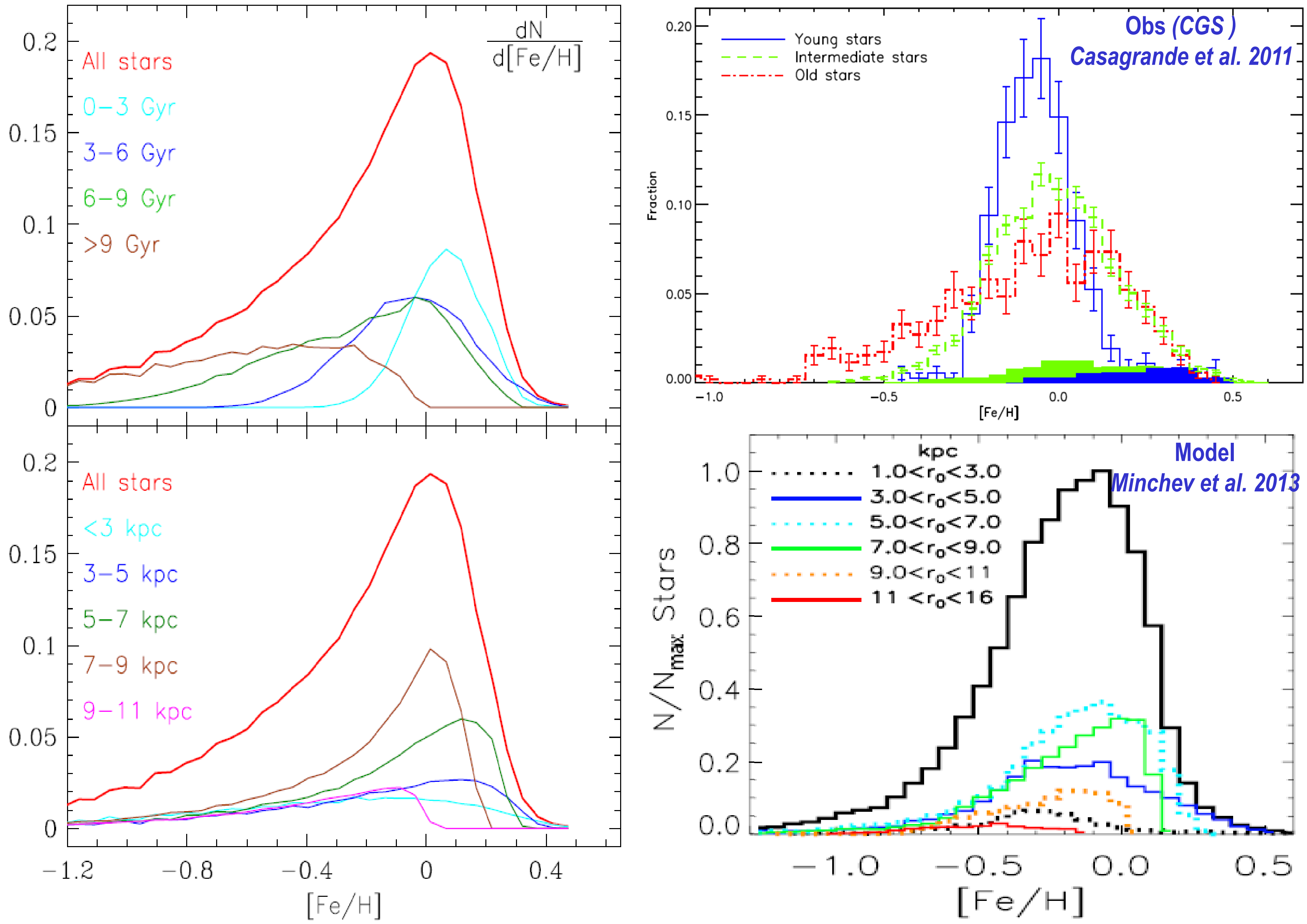
Radial Migration

1. Modifies the apparent local SFR

2. Creates dispersion in the age-metallicity relation…

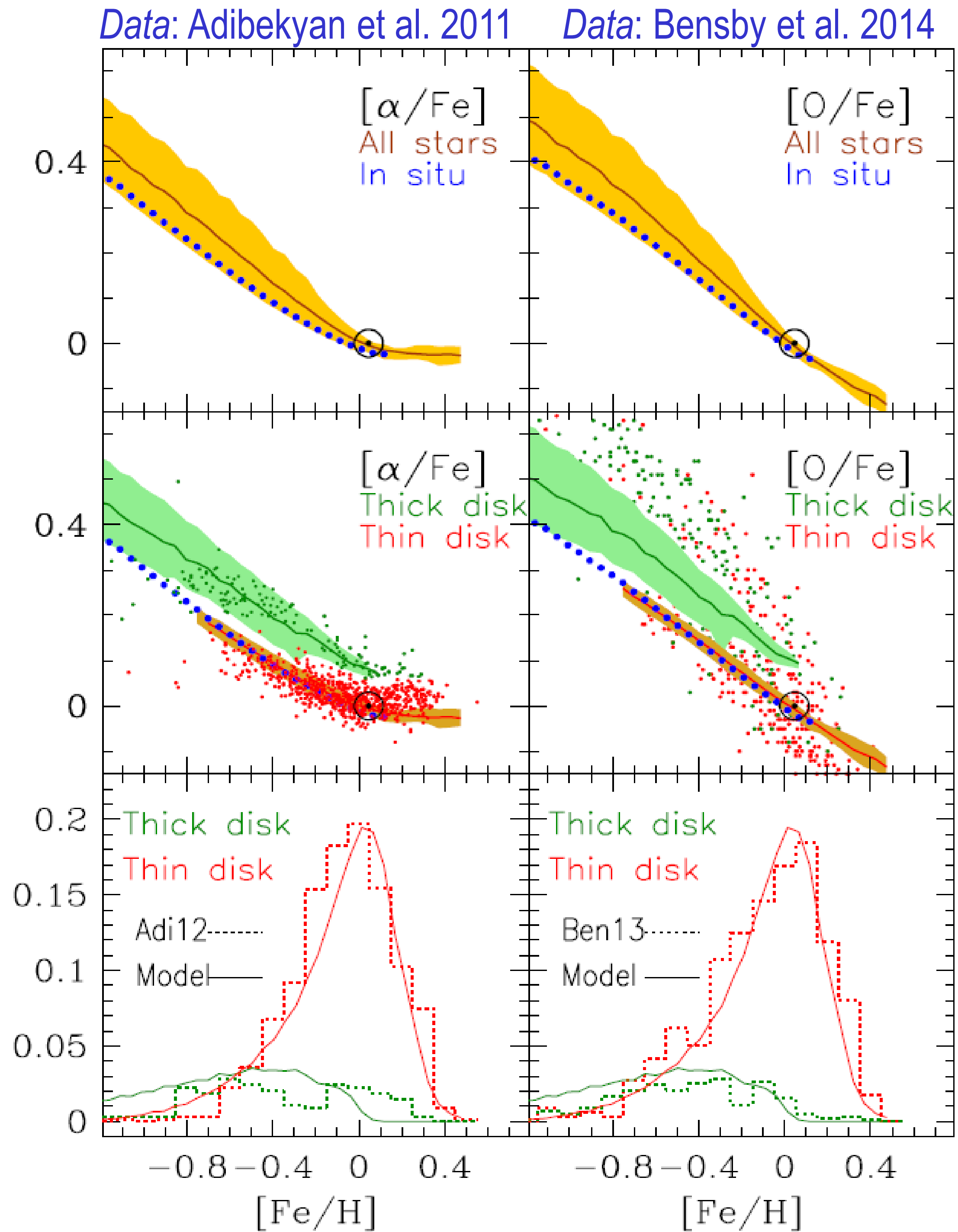
3. … much more than the epicyclic motion

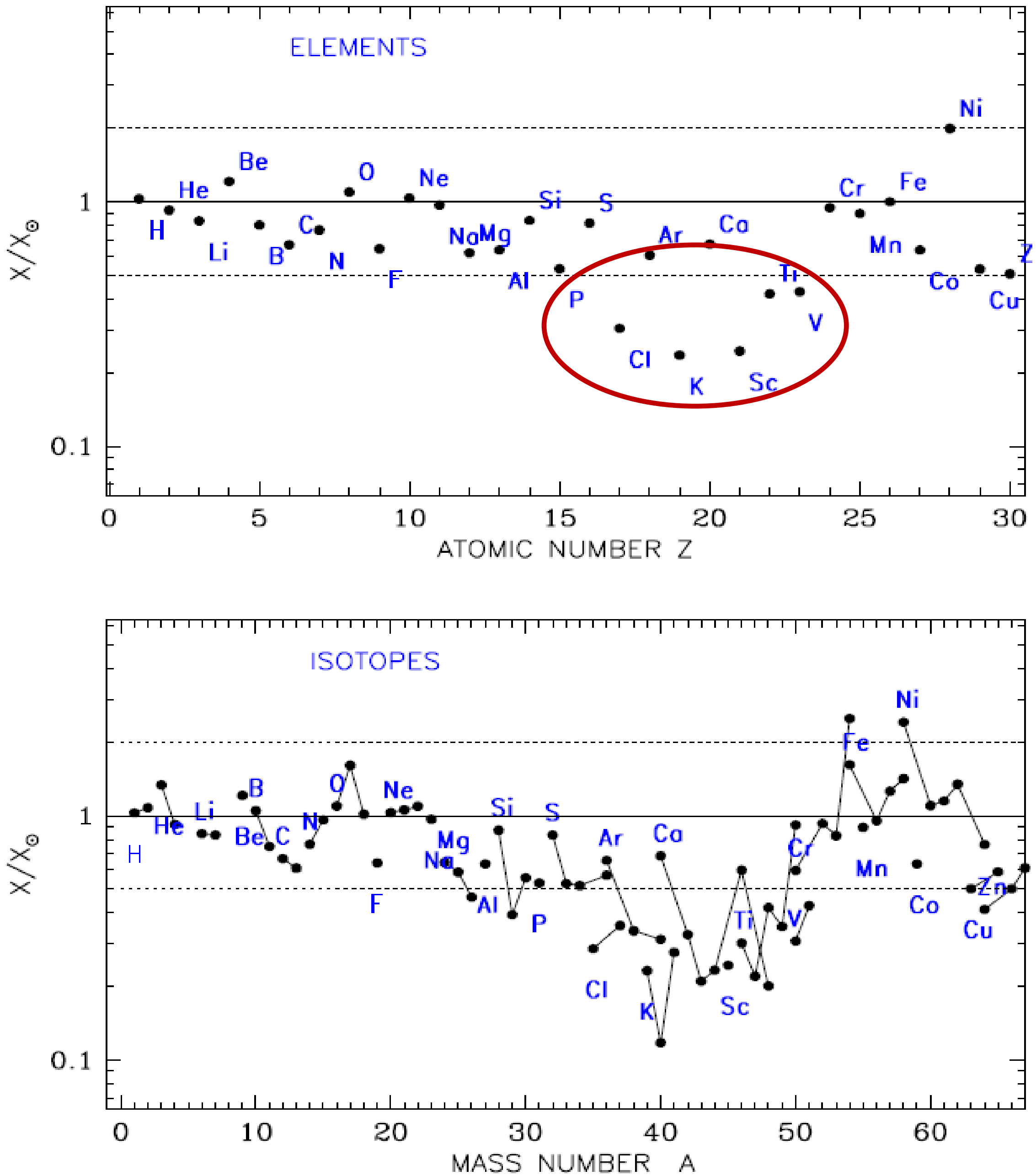
Solar Neighborhood : stars with different ages and from different regions *at all metallicities*



Assuming that
the thick disk is
the old disk (>9 Gyr)

we recover the
[a/Fe] vs Fe/H behaviour
and the
metallicity distributions
of both
the thick and thin disks





The yields

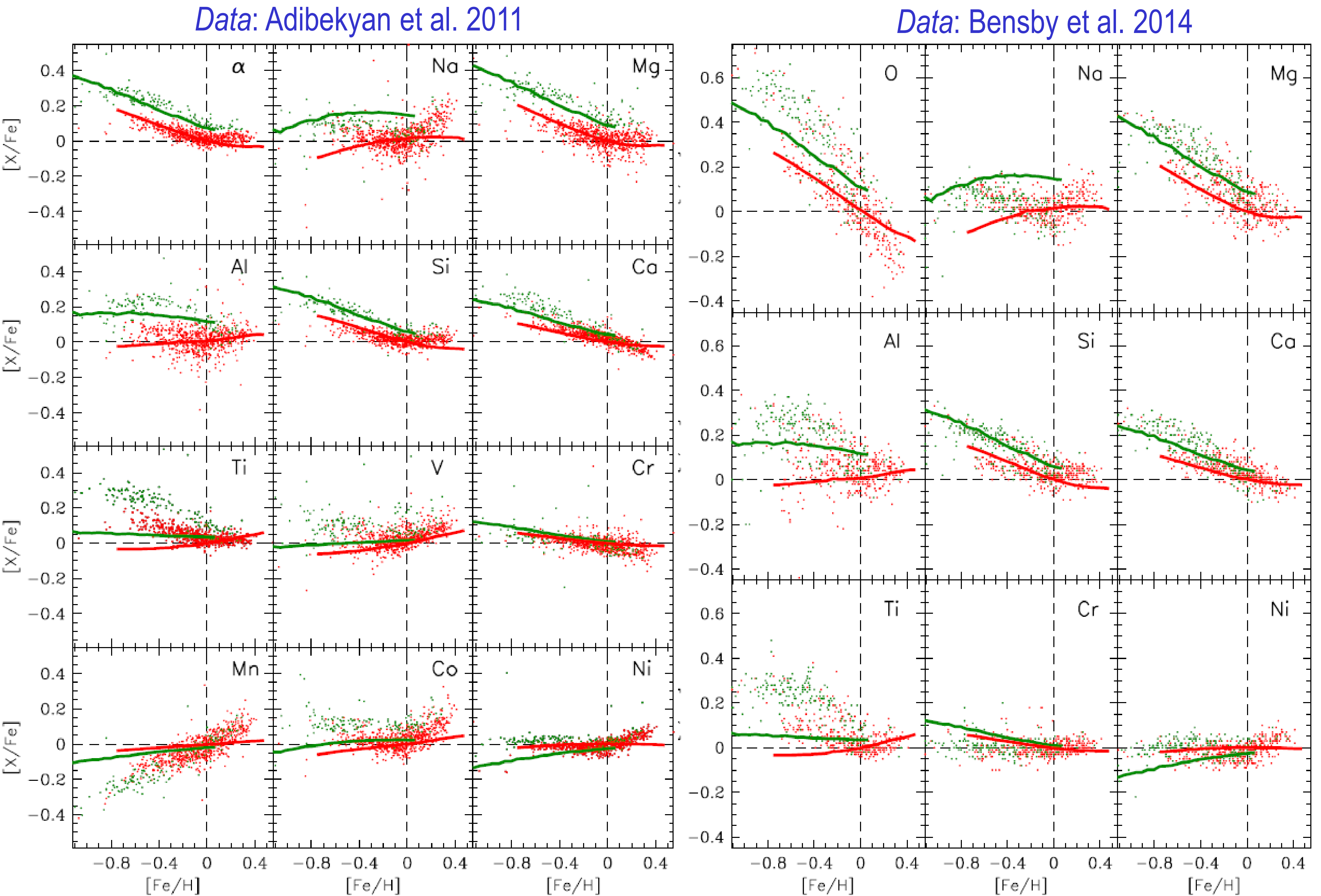
of Nomoto et al. 2013

have some problems

in the region

P to V

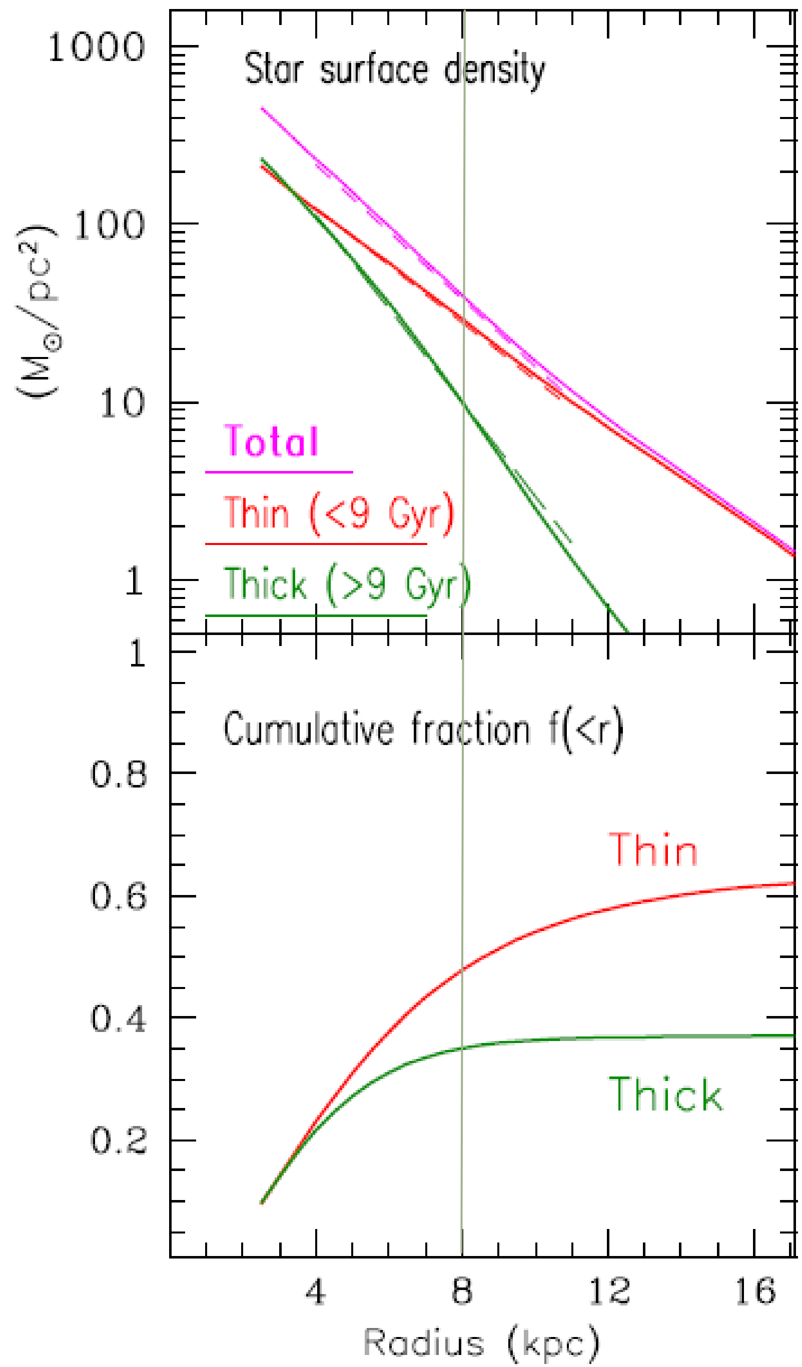
Evolution of thin (<9 Gyr) and thick (>9 Gyr) disks
with yields NORMALISED to solar for AVERAGE LOCAL (8 kpc) STAR 4.5 Gyr old



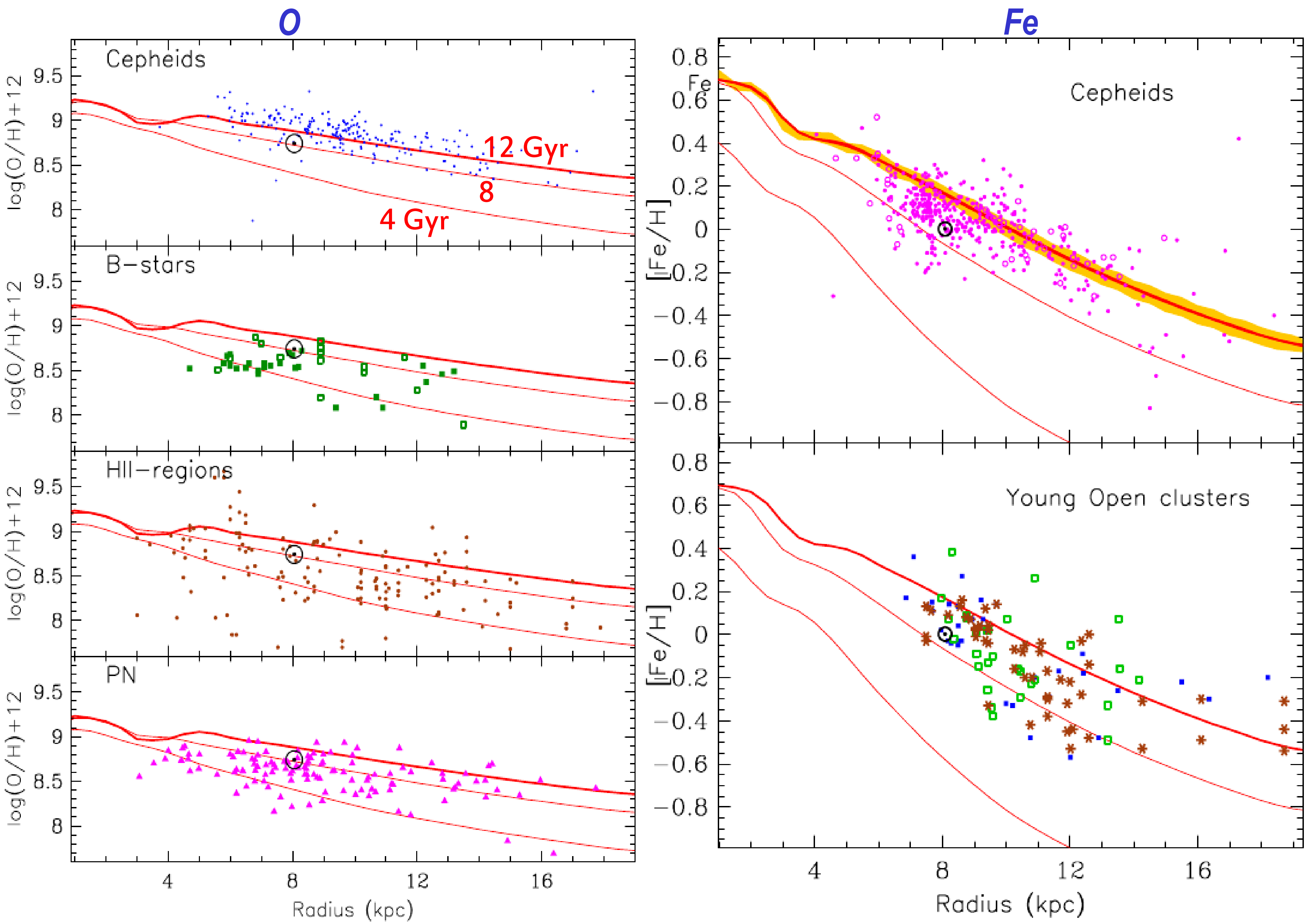
Assuming that
the thick disk is
the old disk (>9 Gyr)

we recover the
[a/Fe] vs Fe/H behaviour
and the
metallicity distributions
of both
the thick and thin disks

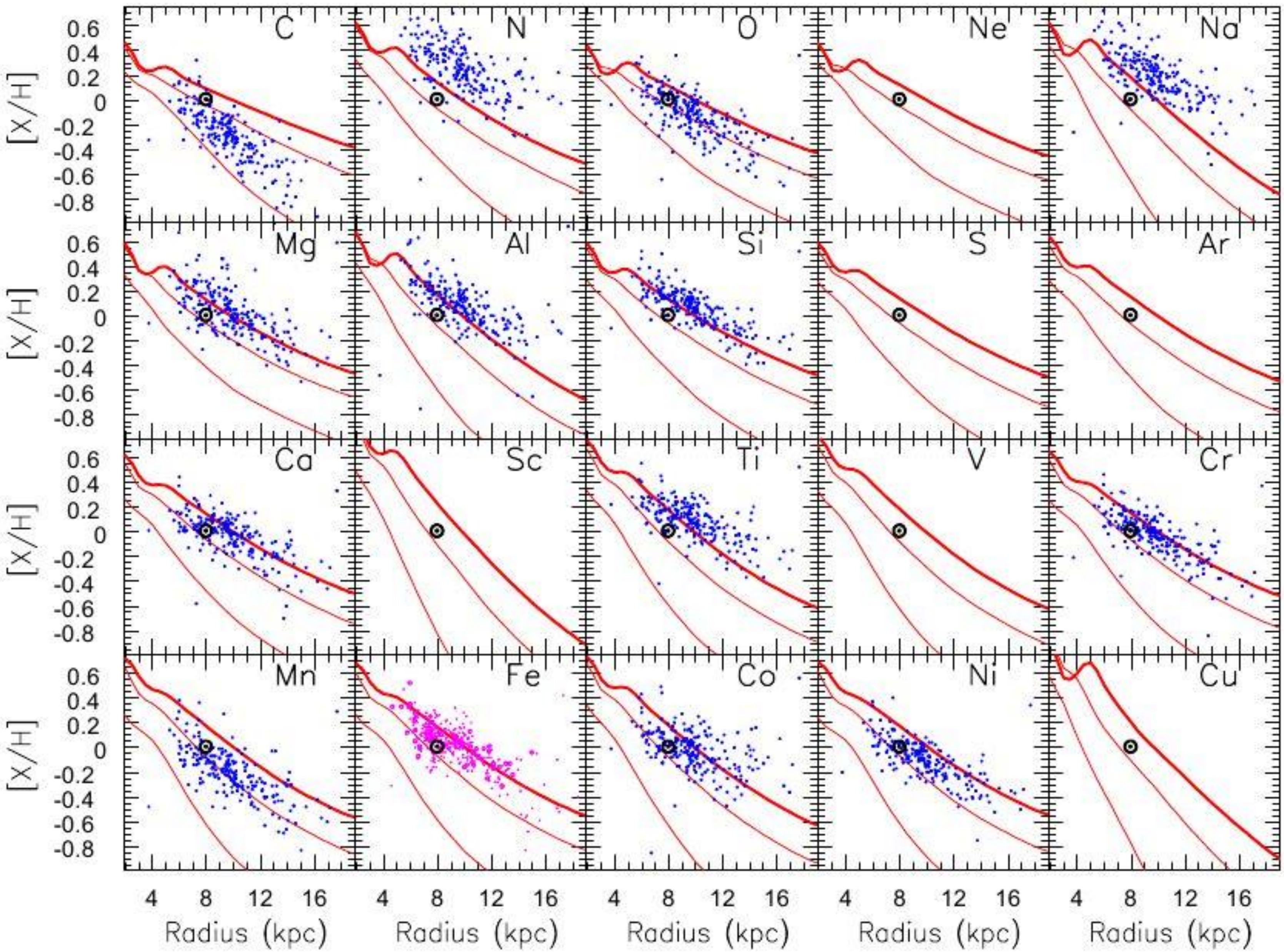
and we reproduce
the local surface densities
of both disks
and the short scalelength
of the thick disk (~2 kpc)
which accounts for ~1/3
of the total disk mass

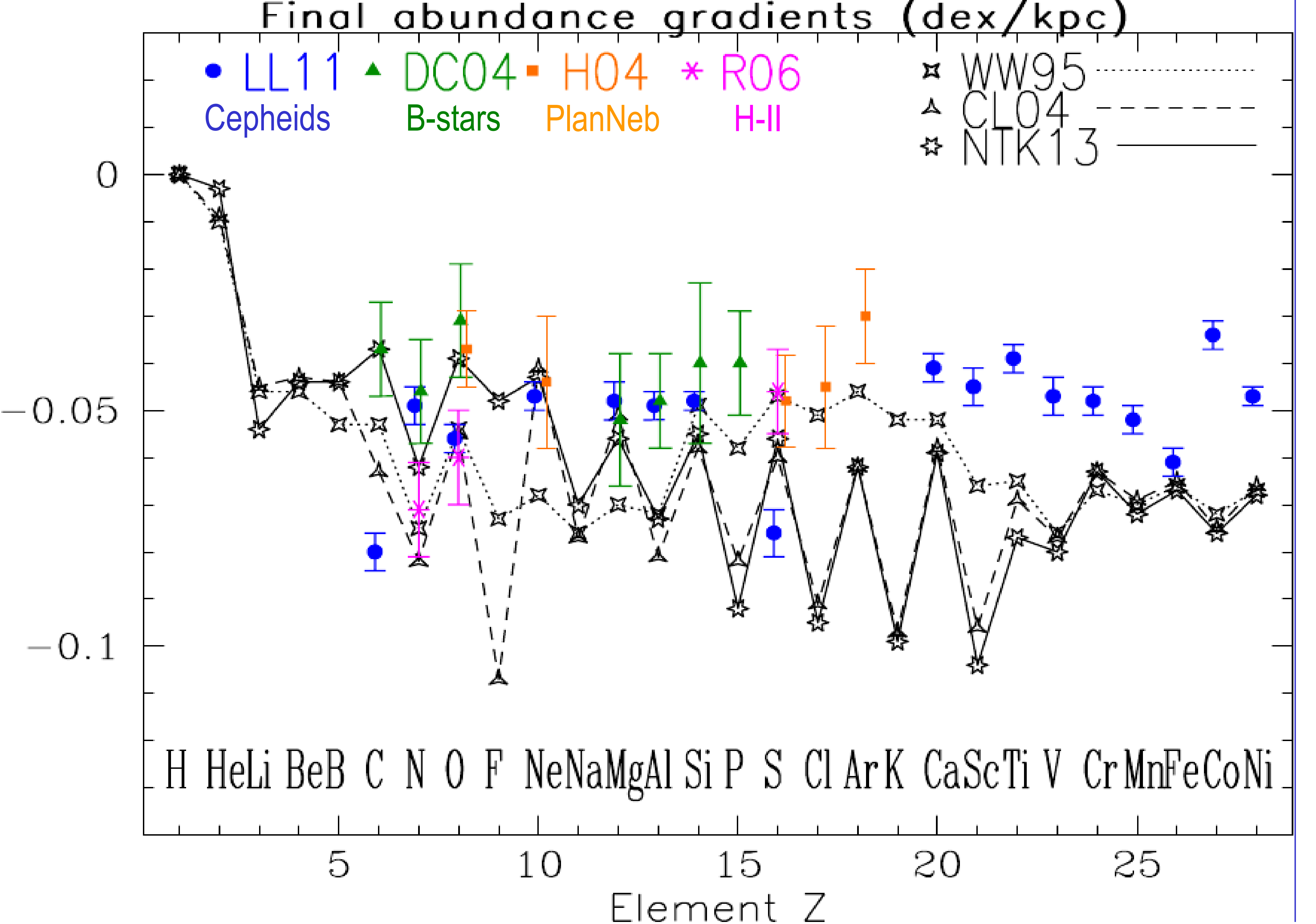


Abundance profiles

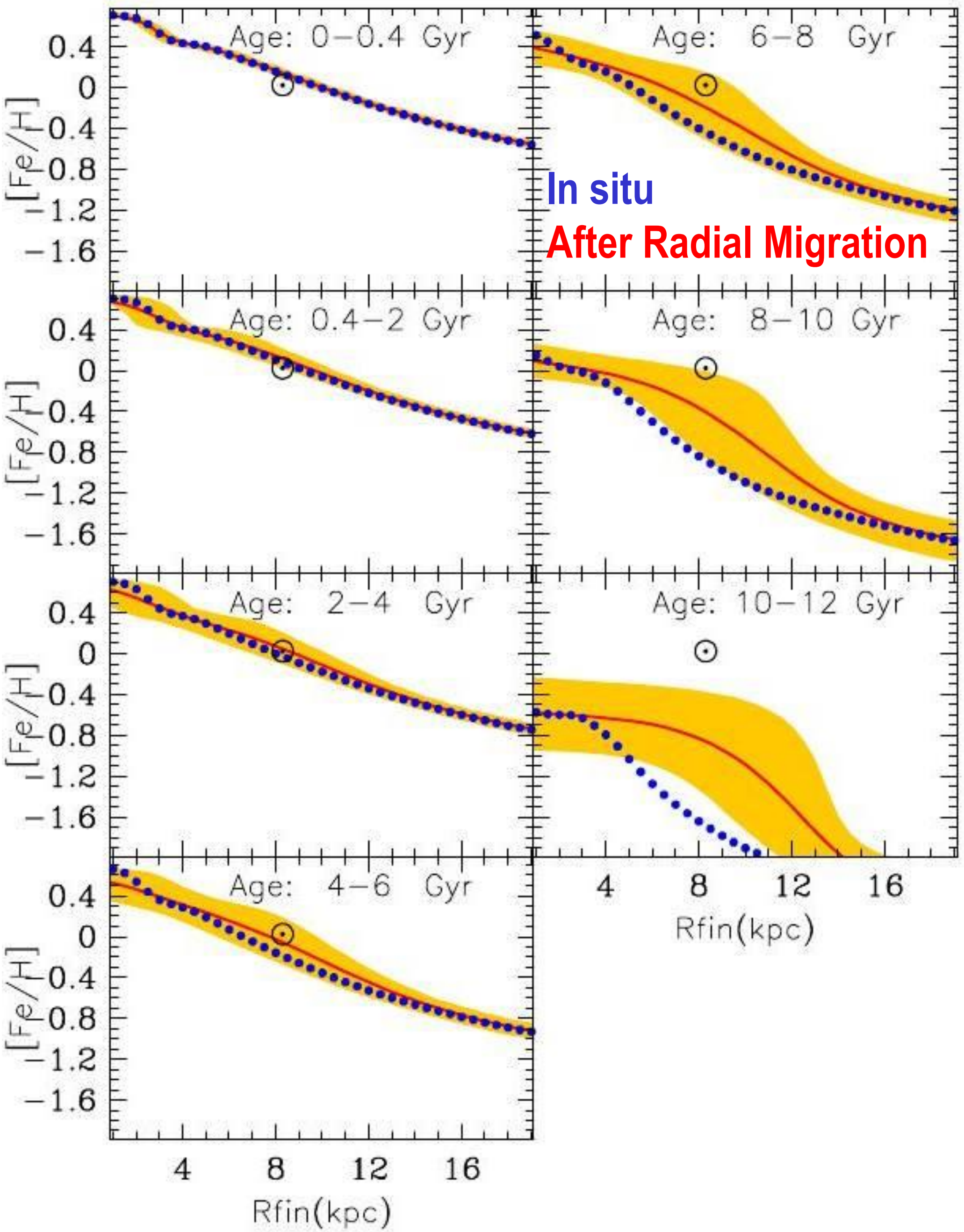


Abundance profiles in Cepheids





An odd-even effect on gradients ? Not seen in observations…



Radial migration flattens the past stellar profiles
(Roskar et al. 2008)

bringing old and metal poor stars in the outer disk

Impact of gas and star migration on chemical observables of the disk

LOCALLY:

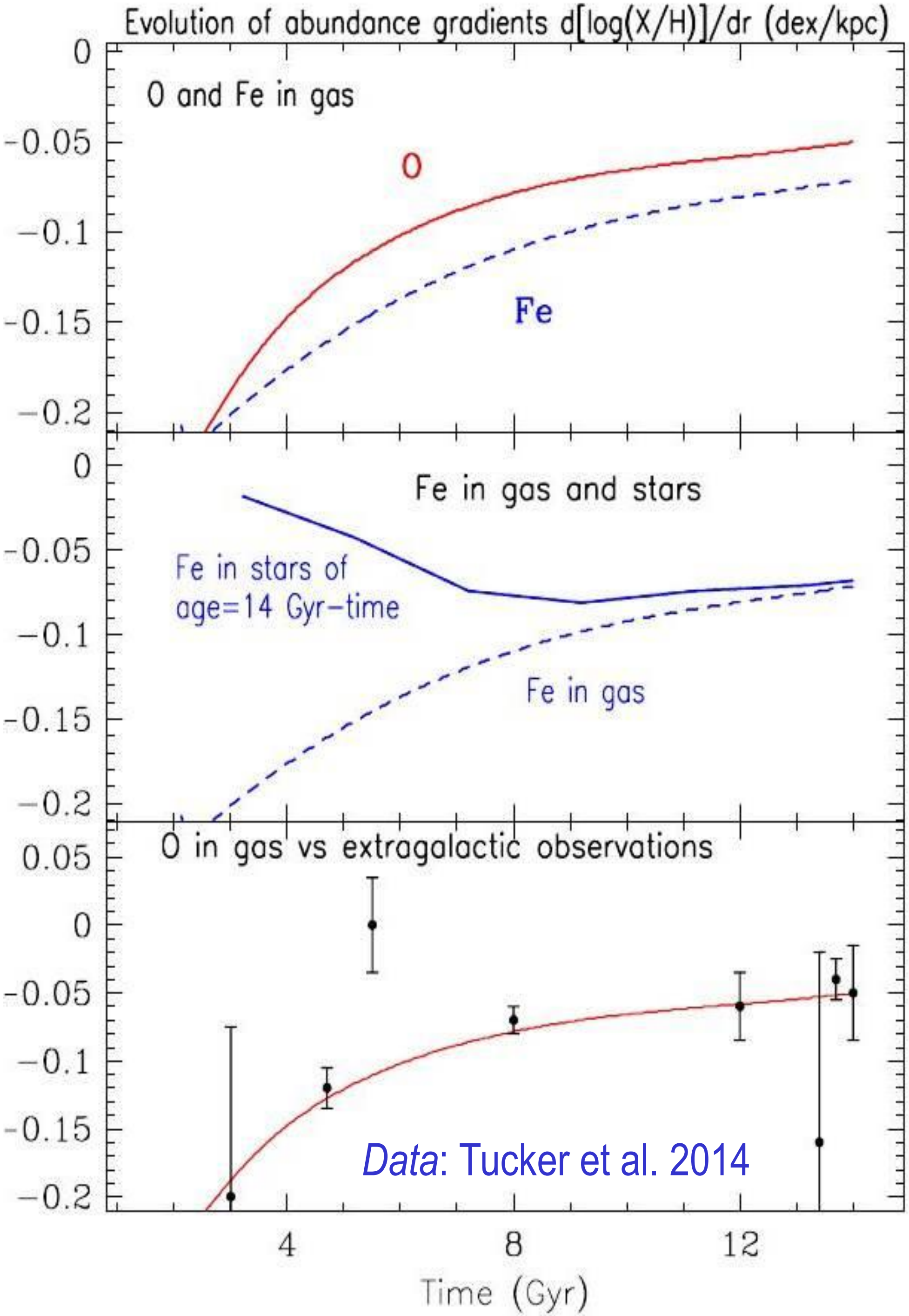
- **Increases dispersion in age-metallicity relation (*observations require more than epicyclic motions)***
- **Broadens metallicity distribution**
- **Modifies apparent SF histories(*more in outer disk than in inner disk*)**
- **- Creates a « two-branch » behaviour of O/Fe vs Fe/H**

GALAXYWIDE:

- **Flattens abundance profiles of X/H**
- **Modifies profiles of X/Y with X and Y produced by different sources: *short-lived (0) vs long-lived (Fe or s-elements)***
- **Erases past radial abundance profiles of stars**
- ***May* produce a *thick disk* (*Schoenrich -Binney 2009, Loebman et al. 2010, Minchev et al. 2013*)**

BUT these observables are ALSO affected to various extents by other factors e.g. *infall* [dm/dt(R,t) and Z(R,t)], *galactic fountains/outflows, mergers*, etc.

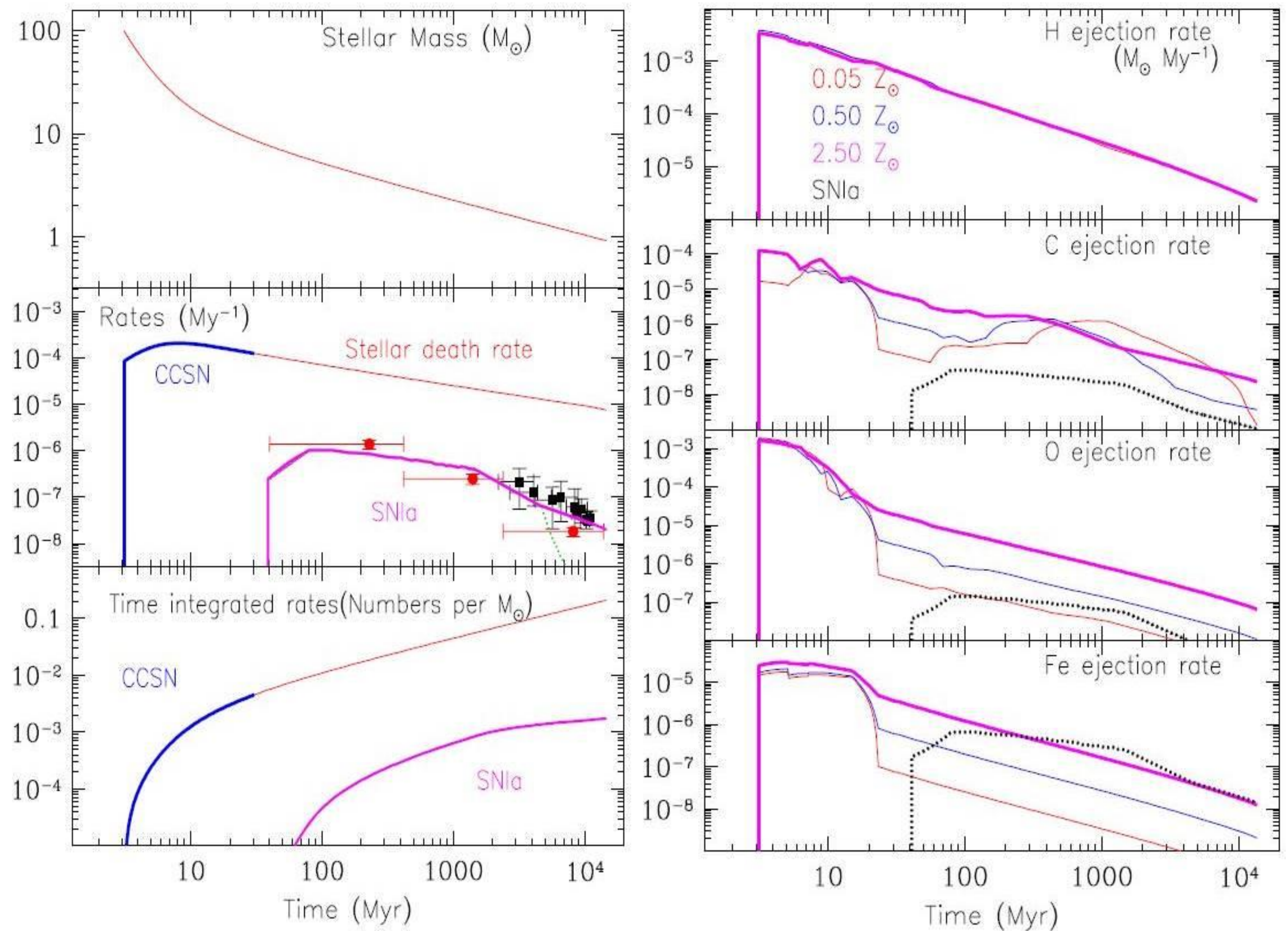
It will not be easy to disentangle those effects…



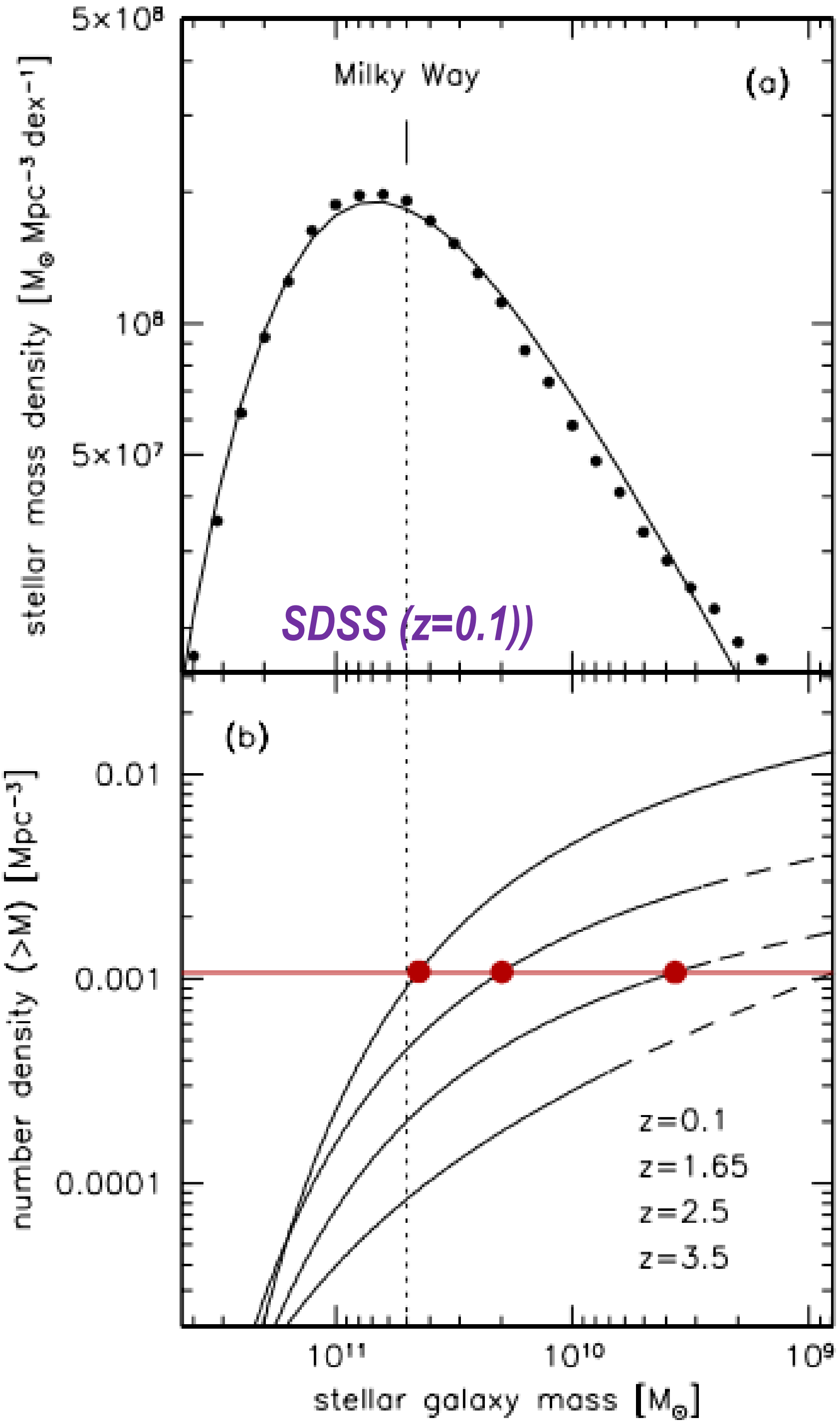
1. Because the SNIa/CCSN ratio increases in the inner disk, the Fe profile is steeper than the O one

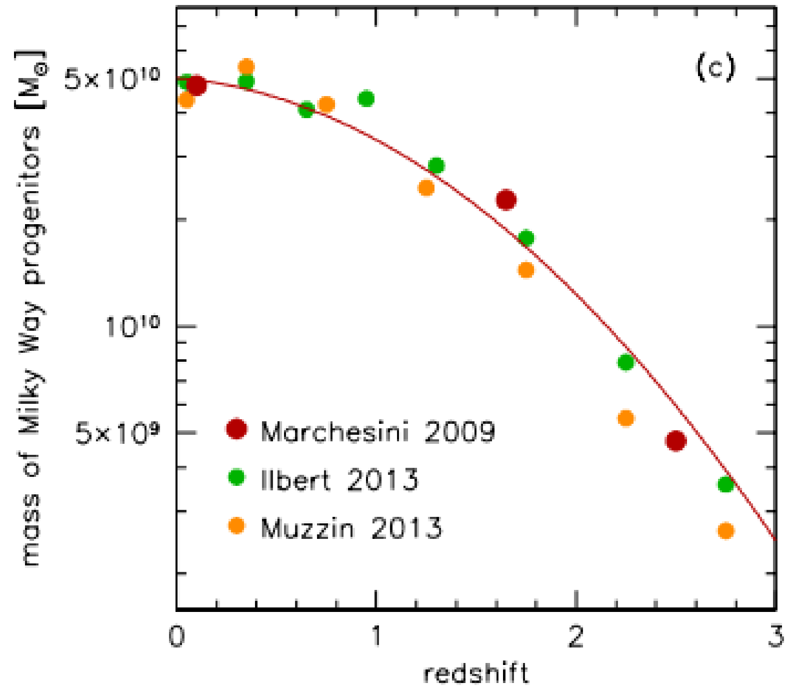
2. Because of radial migration, the past stellar Fe profile (as observed today locally) Is much flatter than what we may observe in the gas of high redshift systems

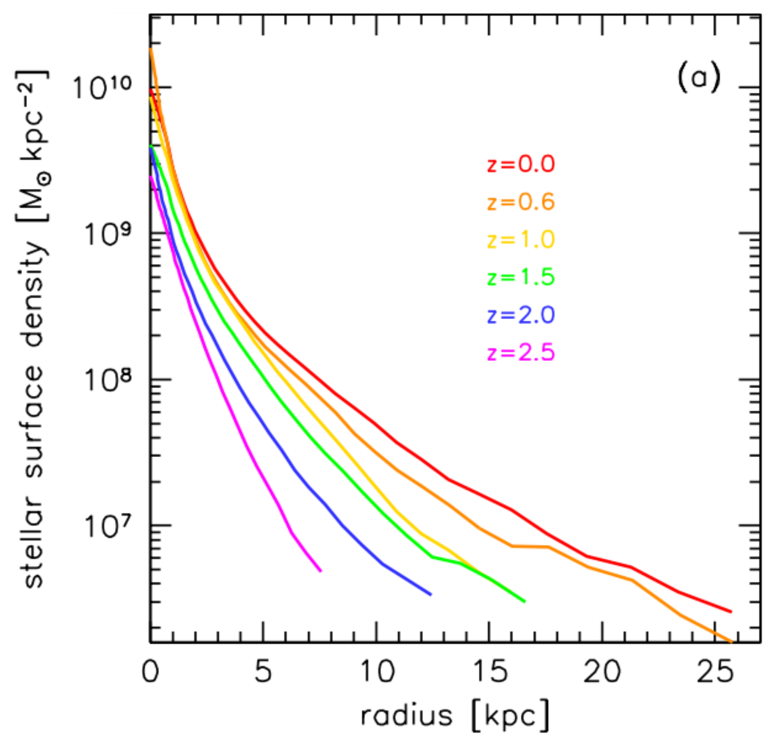
3. The evolution of the O profile in the gas of the MW corresponds to observations of high redshift lensed galaxies

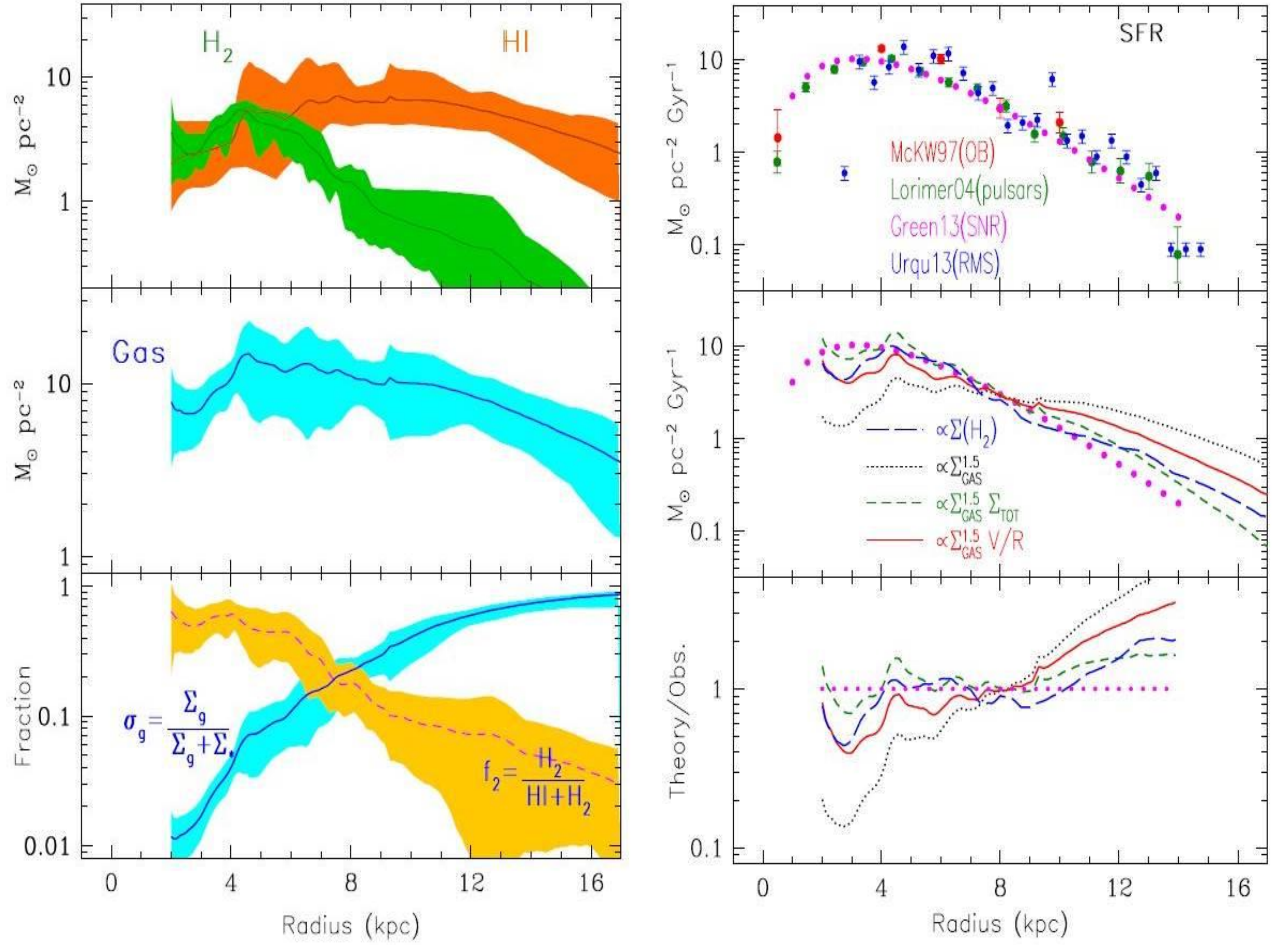


Stellar Mass ($M_\odot$)
Rates (My^{-1})
Stellar death rate
CCSN
SNIa
Time integrated rates(Numbers per $M_\odot$)
CCSN
SNIa
Time (Myr)
H ejection rate
($M_\odot$ My^{-1})
0.05 $Z_\odot$
0.50 $Z_\odot$
2.50 $Z_\odot$
SNIa
C ejection rate
O ejection rate
Fe ejection rate
Time (Myr)


Milky Way
(a)
stellar mass density [M⊙ Mpc⁻³ dex⁻¹]
5×10⁸
10⁸
5×10⁷
SDSS (z=0.1))
(b)
number density (>M) [Mpc⁻³]
0.01
0.001
0.0001
z=0.1
z=1.65
z=2.5
z=3.5
10¹¹
10¹⁰
10⁹
stellar galaxy mass [M⊙]

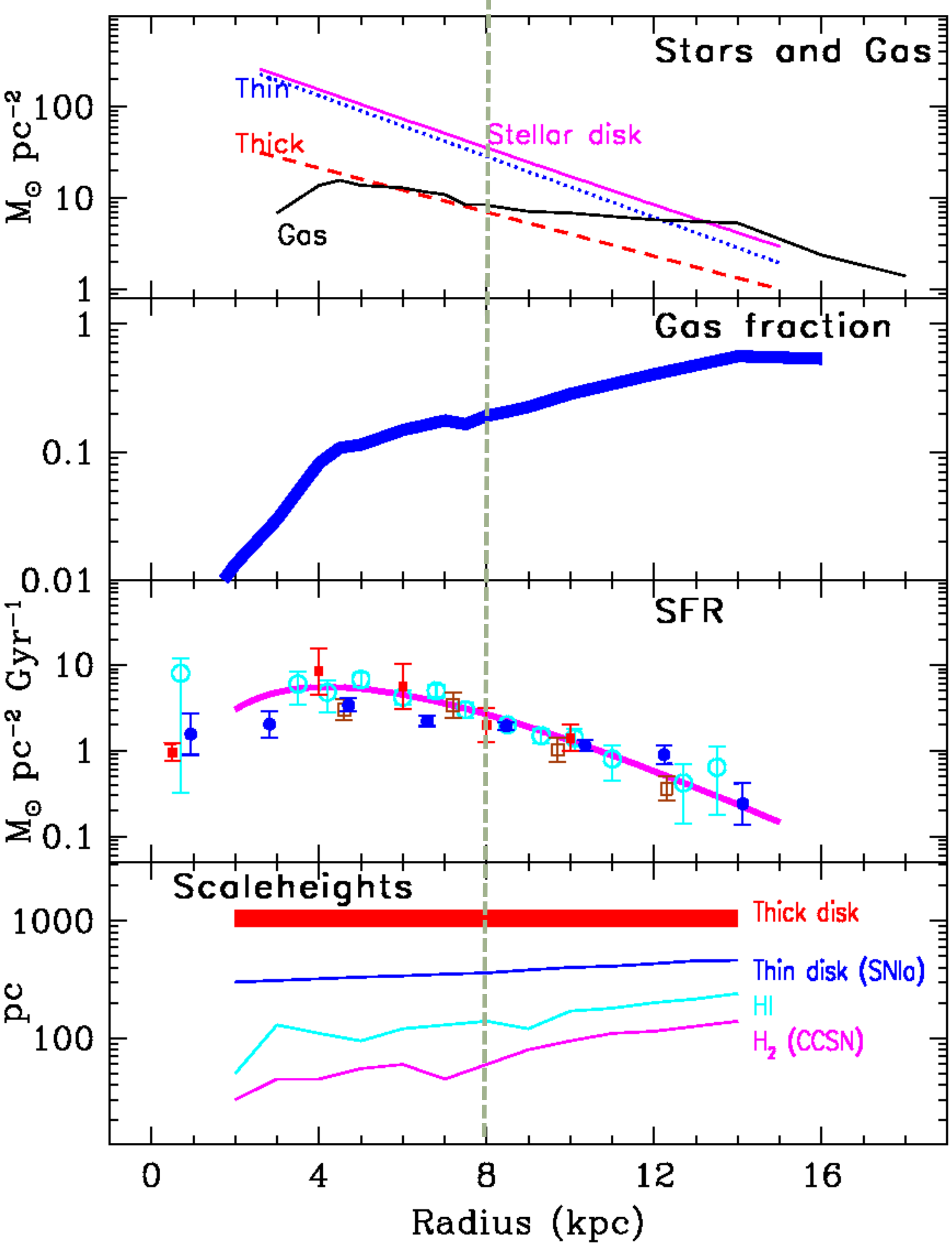

(c)
mass of Milky Way progenitors [M⊙]
5×10¹⁰
10¹⁰
5×10⁹
Marchesini 2009
Ilbert 2013
Muzzin 2013
0
1
2
3
redshift


(a)
stellar surface density [M⊙ kpc⁻²]
10¹⁰
10⁹
10⁸
10⁷
z=0.0
z=0.6
z=1.0
z=1.5
z=2.0
z=2.5
0
5
10
15
20
25
radius [kpc]



H$_2$
HI
Gas
$\sigma_g = \frac{\Sigma_g}{\Sigma_g + \Sigma_*}$
$f_2 = \frac{H_2}{HI + H_2}$
$M_\odot$ pc^{-2}
Fraction
Radius (kpc)
SFR
McKW97(OB)
Lorimer04(pulsars)
Green13(SNR)
Urqu13(RMS)
$M_\odot$ pc^{-2} Gyr^{-1}
$\propto \Sigma(H_2)$
$\propto \Sigma_{GAS}^{1.5}$
$\propto \Sigma_{GAS}^{1.5}\ \Sigma_{TOT}$
$\propto \Sigma_{GAS}^{1.5}\ V/R$
Theory/Obs.

The Milky Way disk: (2) Star and SFR profiles



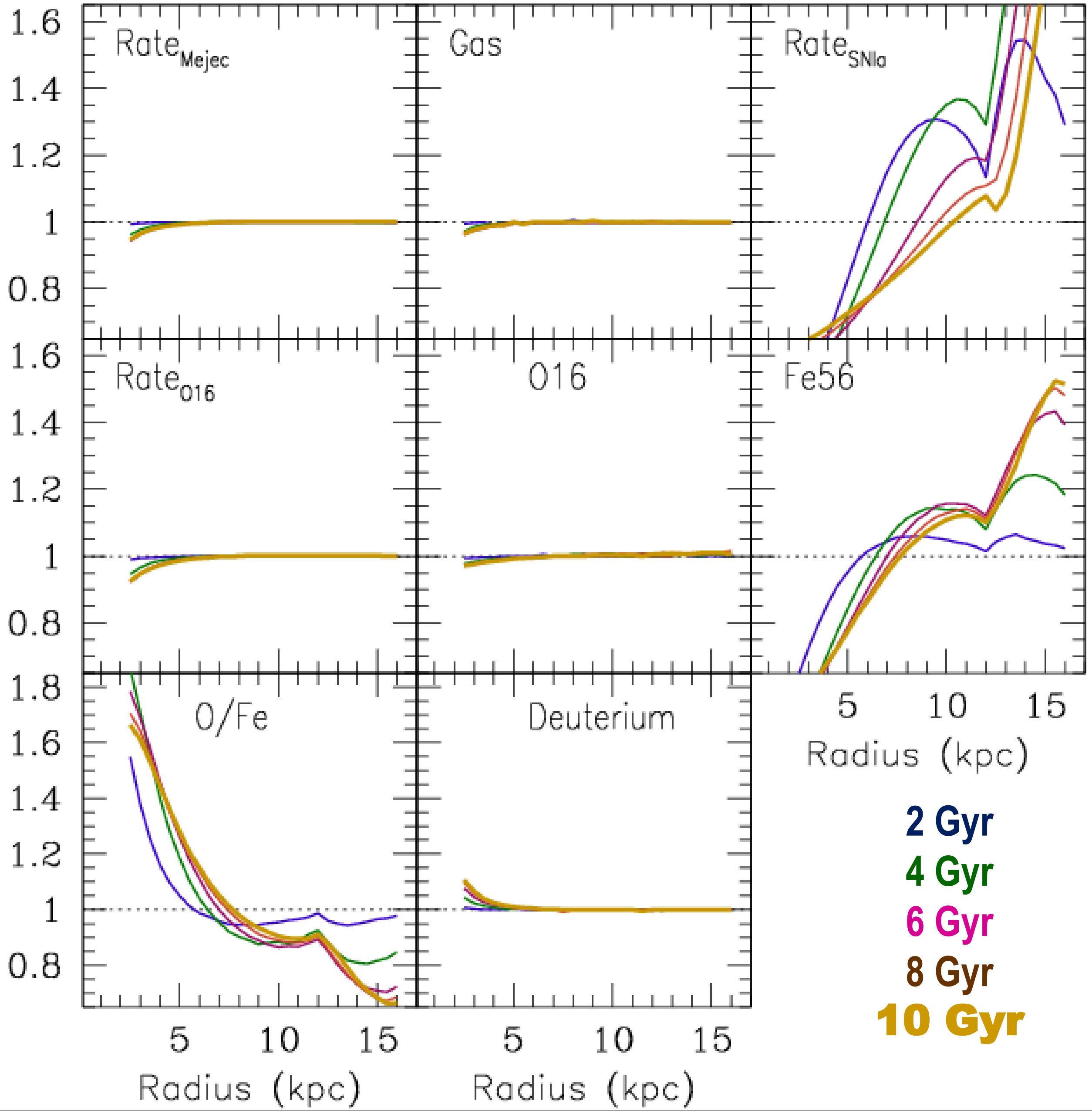
Exponential stellar profile
$\Sigma(R) = \Sigma_0 \exp(-R/S_R)$
with $S_R \sim 2.5$ kpc

Gas Mass ~ 10^{10} $M_\odot$

Star Mass ~ 4 10^{10} $M_\odot$

Inner disk more “processed” than outer disk (gas fraction profile)

$\frac{\text{Migration}}{\text{No migration}}$ **with IRA**

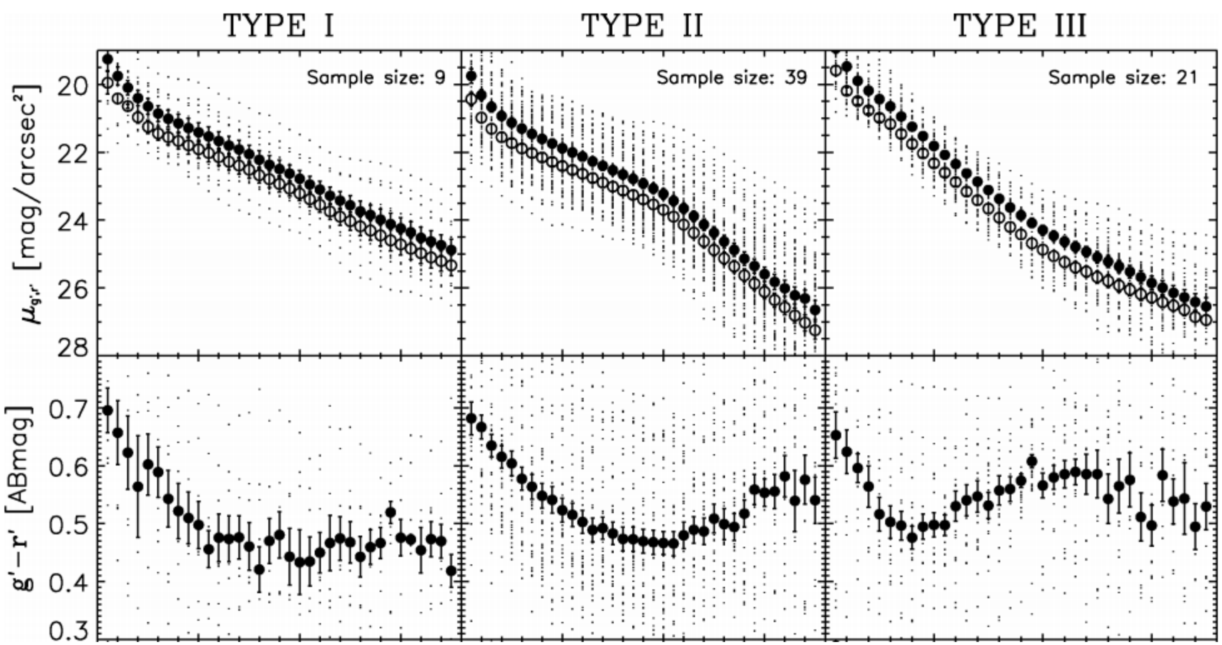


Migration may alter significantly the results of chemical evolution

Directly, **moving outwards long-lived Nucleosynthesis sources, e.g. SNIa**

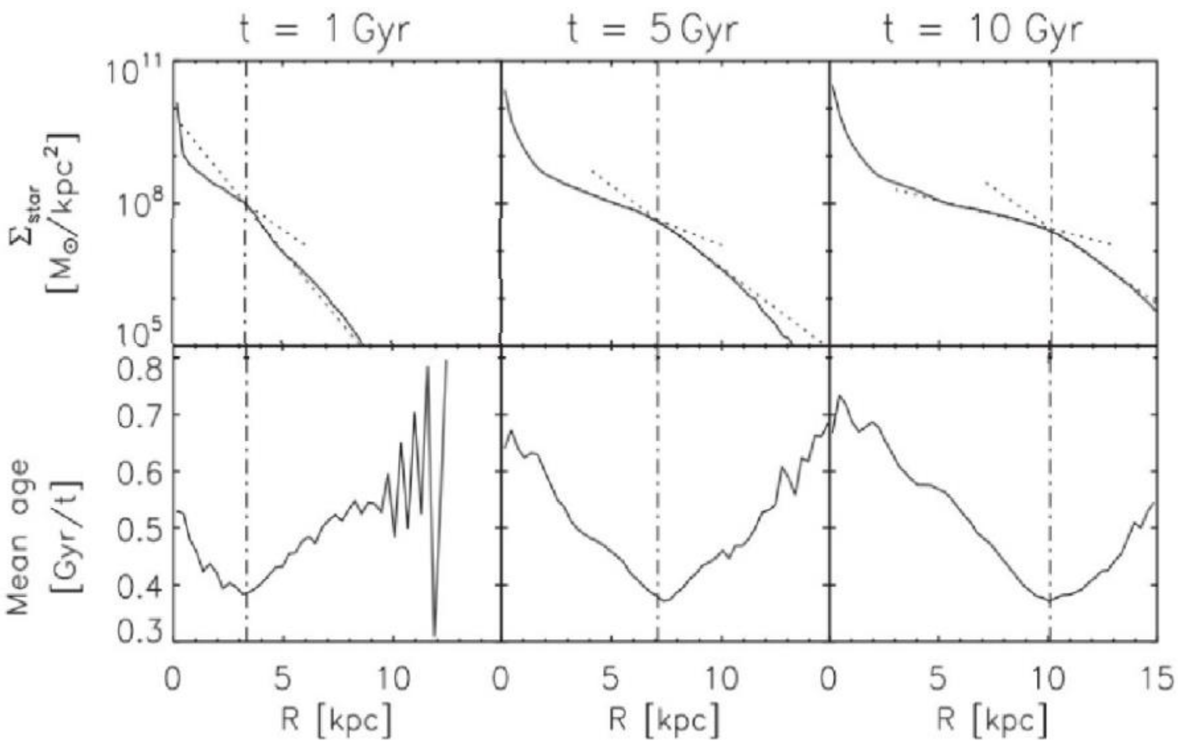
Fe increases in outer disk and decreases in inner disk

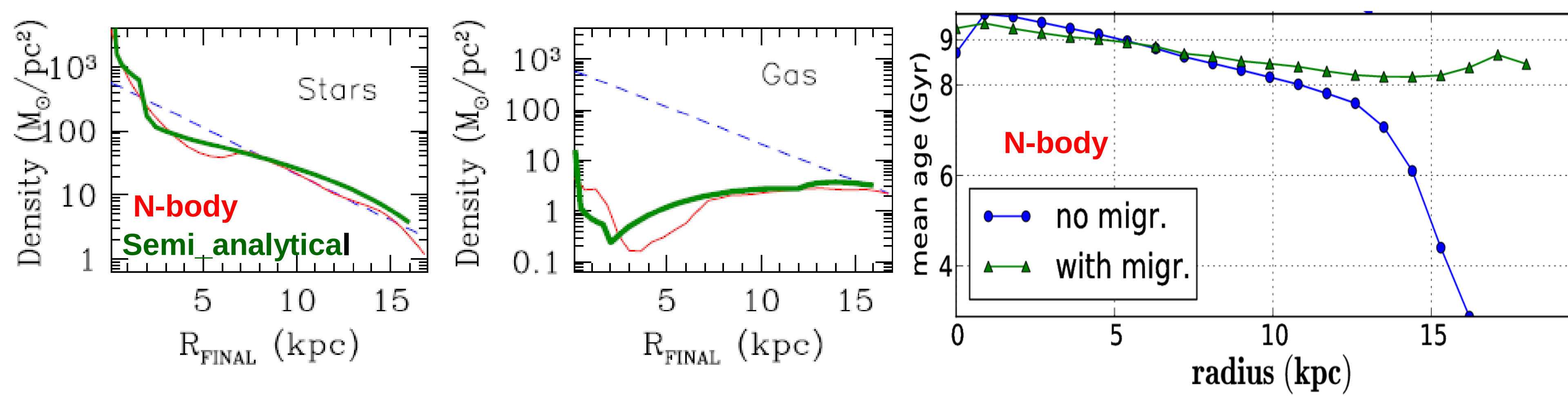
O/Fe profile steepens

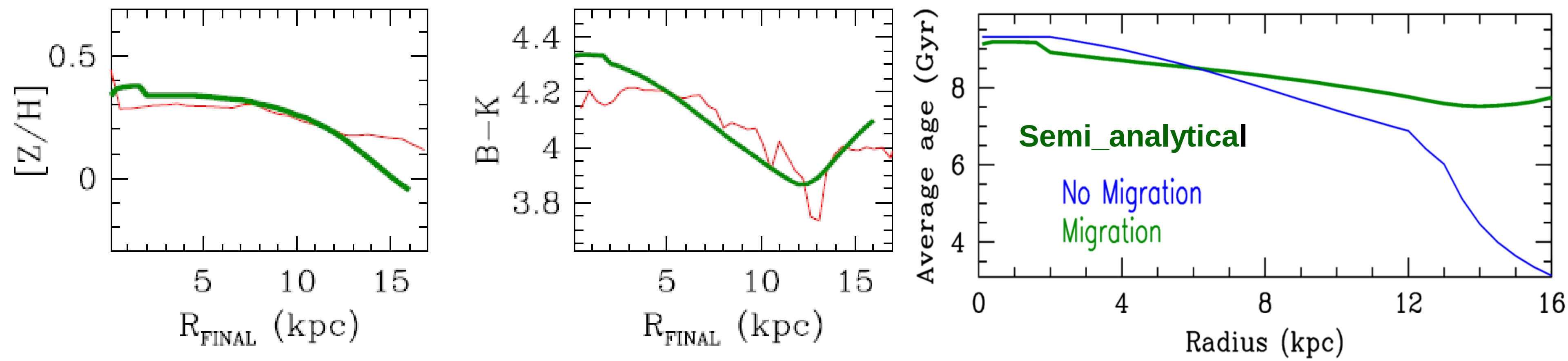


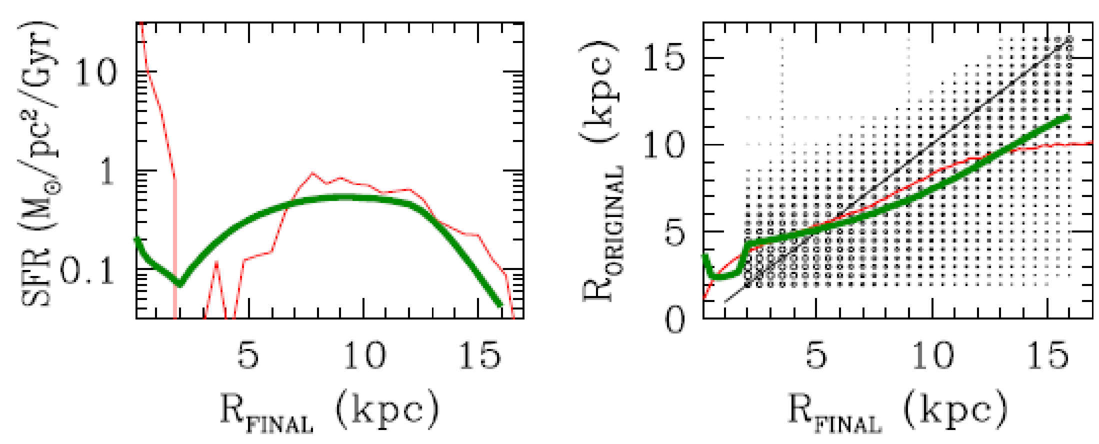
Observations:
Redenning
in disk outskirts
(Bakos et al. 2008)

Models:
old (=red) stars from inner disk found in the outer disk through radial migration
(Roskar et al. 2008)



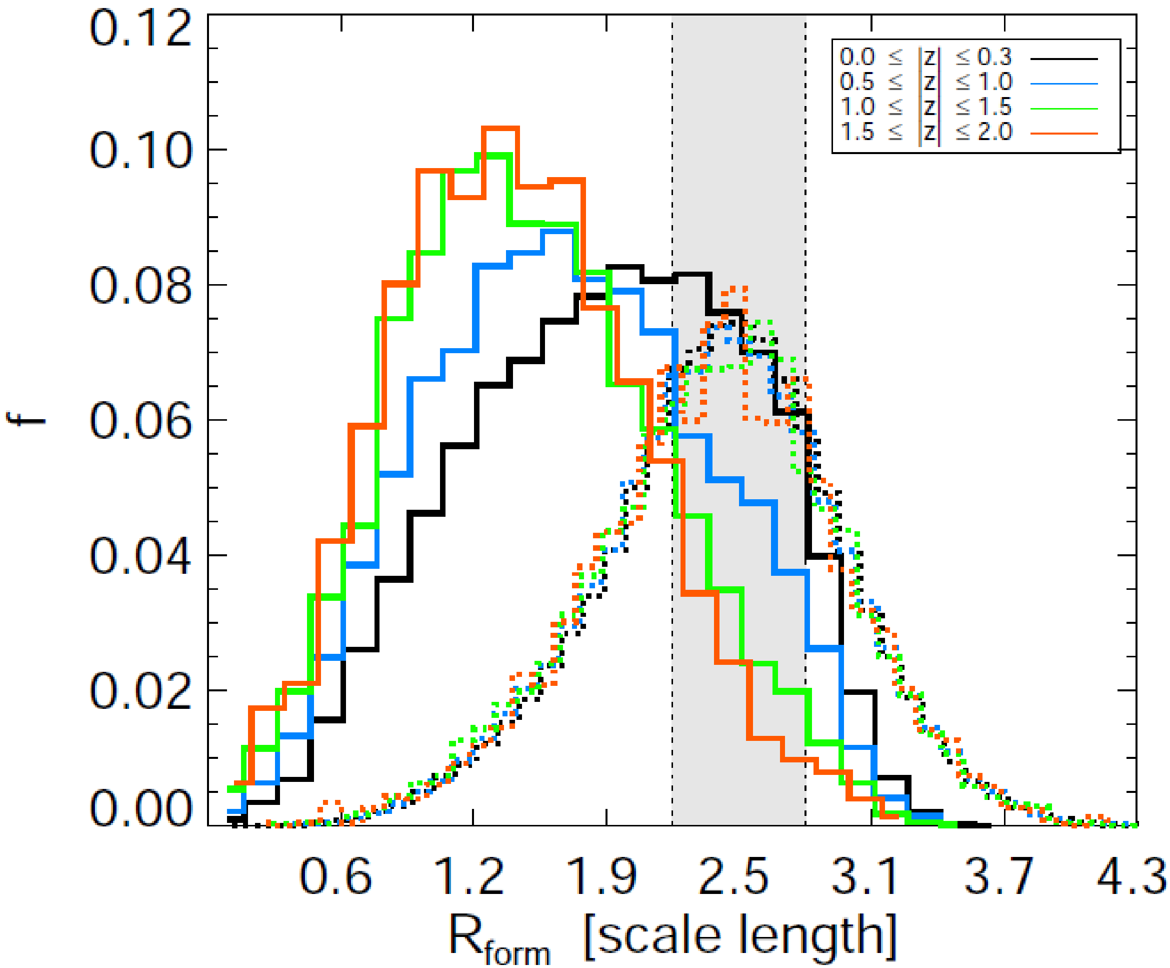


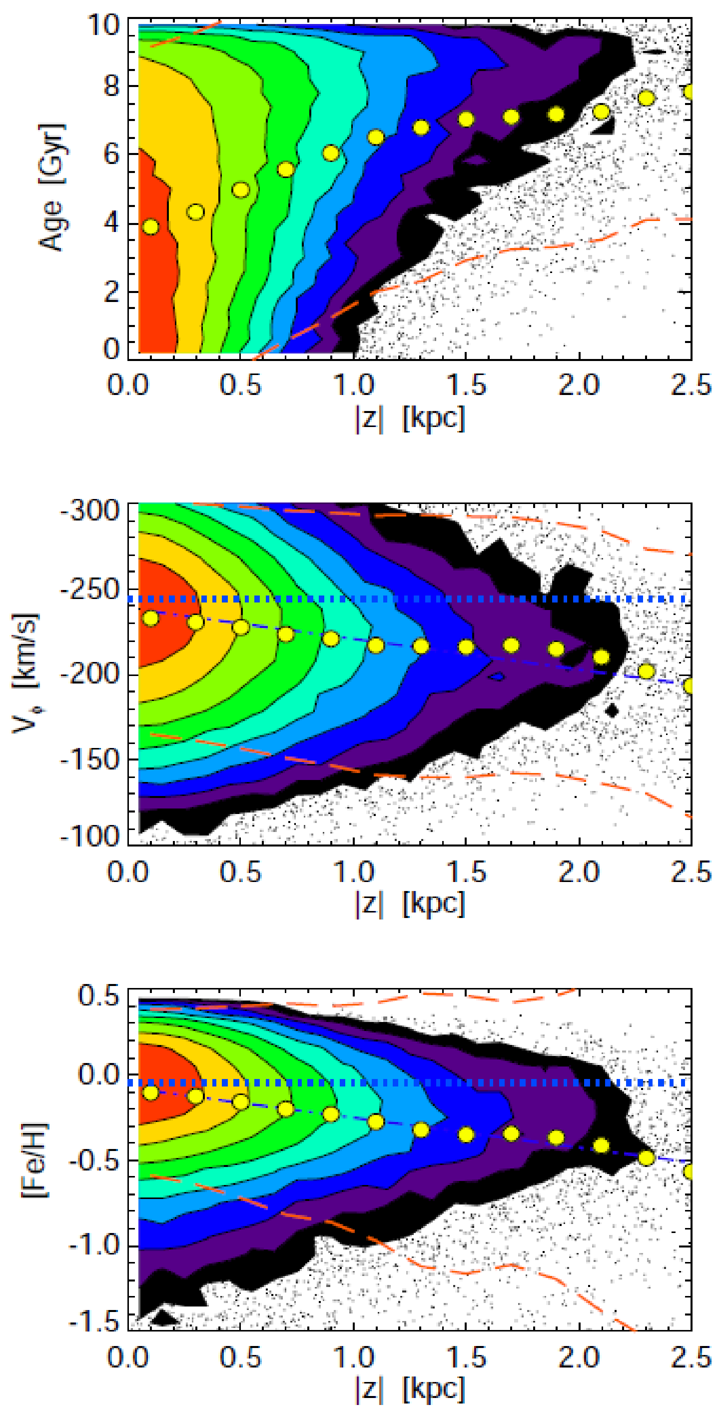




Semi-analytical models, augmented with a probabilistic description of radial migration, can reproduce satisfactorily the results of N-body+SPH models

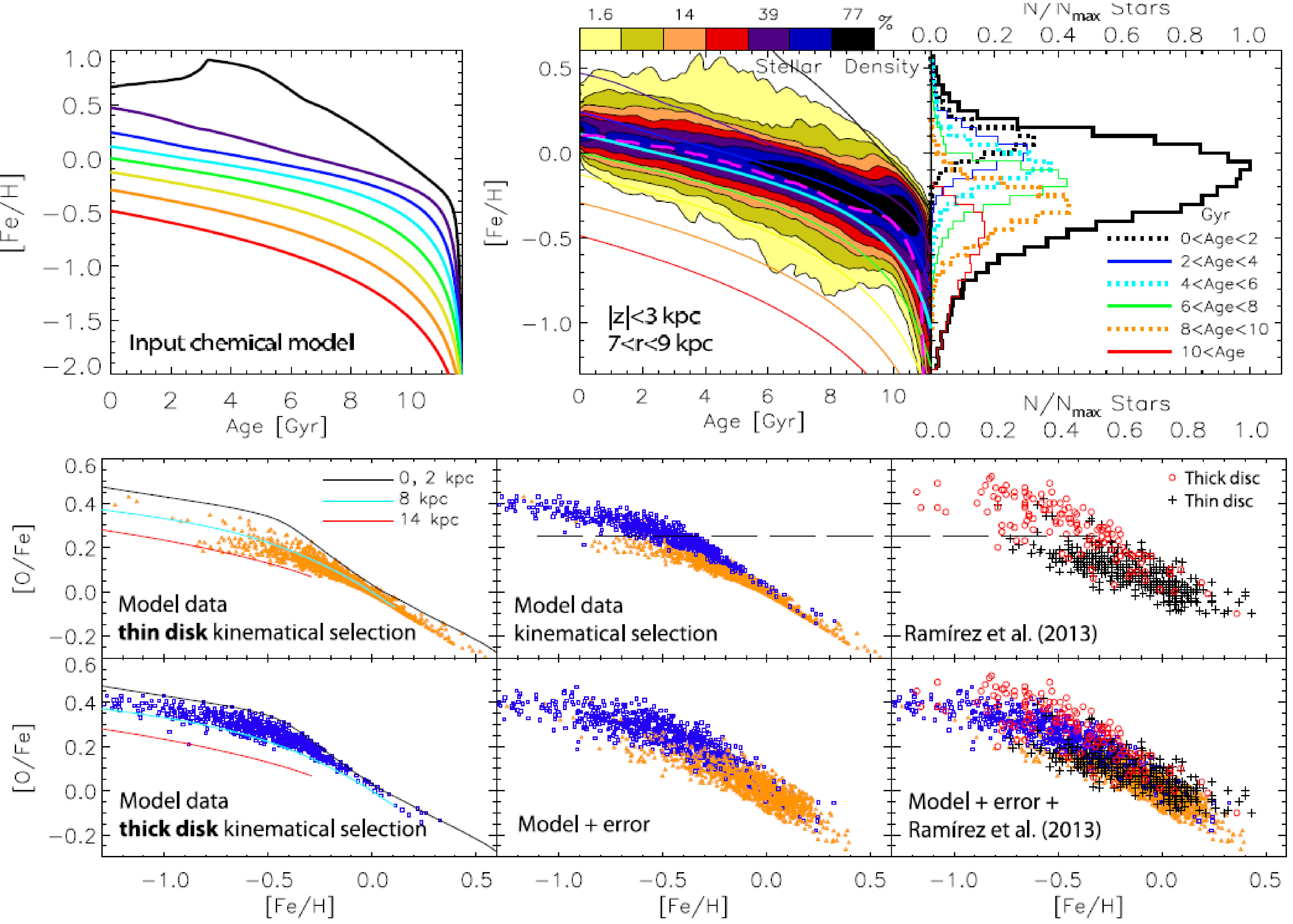
N-body + SPH simulations of a disk galaxy (*Loebman et al. 2010*)
formation of a thick disk





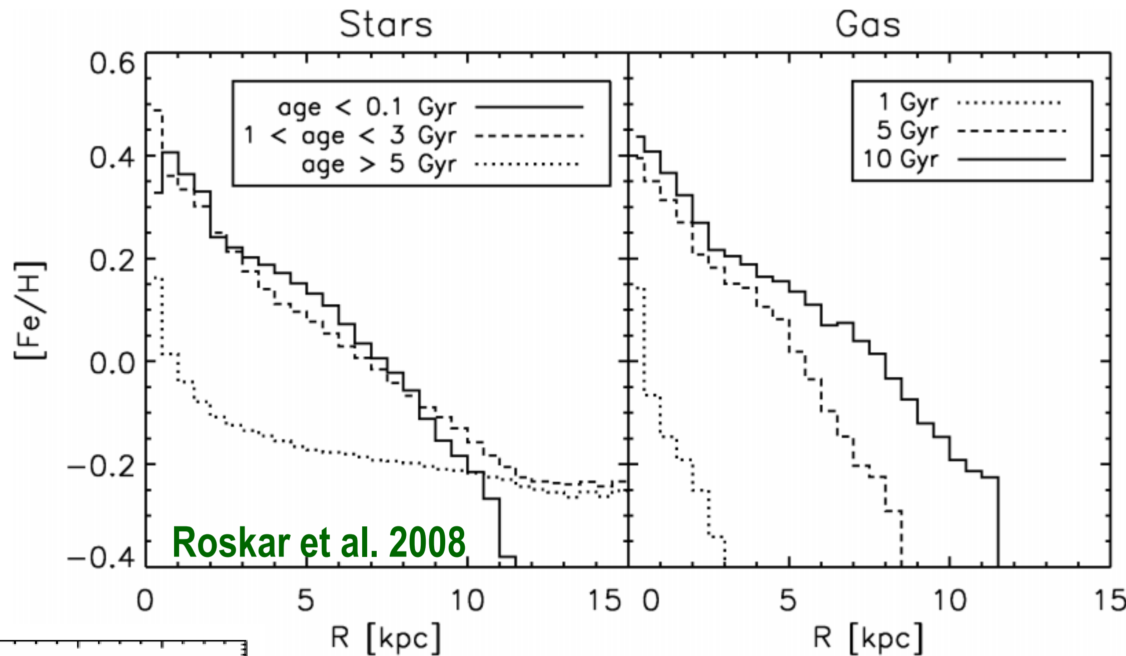
Local stars away from the plane are formed in the inner disk with large velocity dispersion; migrating outwards, they are found in smaller gravitational potential and, for the same velocity dispersion, they acquire larger scaleheight.

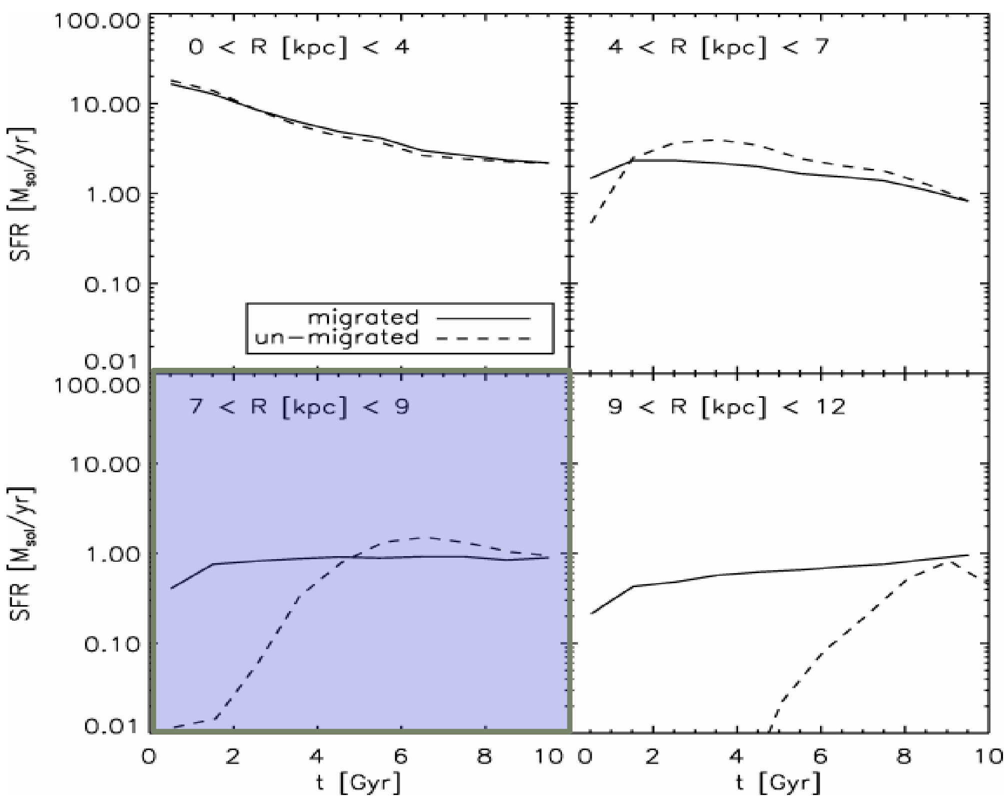
mpact of radial migration on local disk (*Minchev et al. 2013, semi-analytical+N-body*)



Radial migration flattens the abundance profile of old stars *(Friedli et al. 1994)*

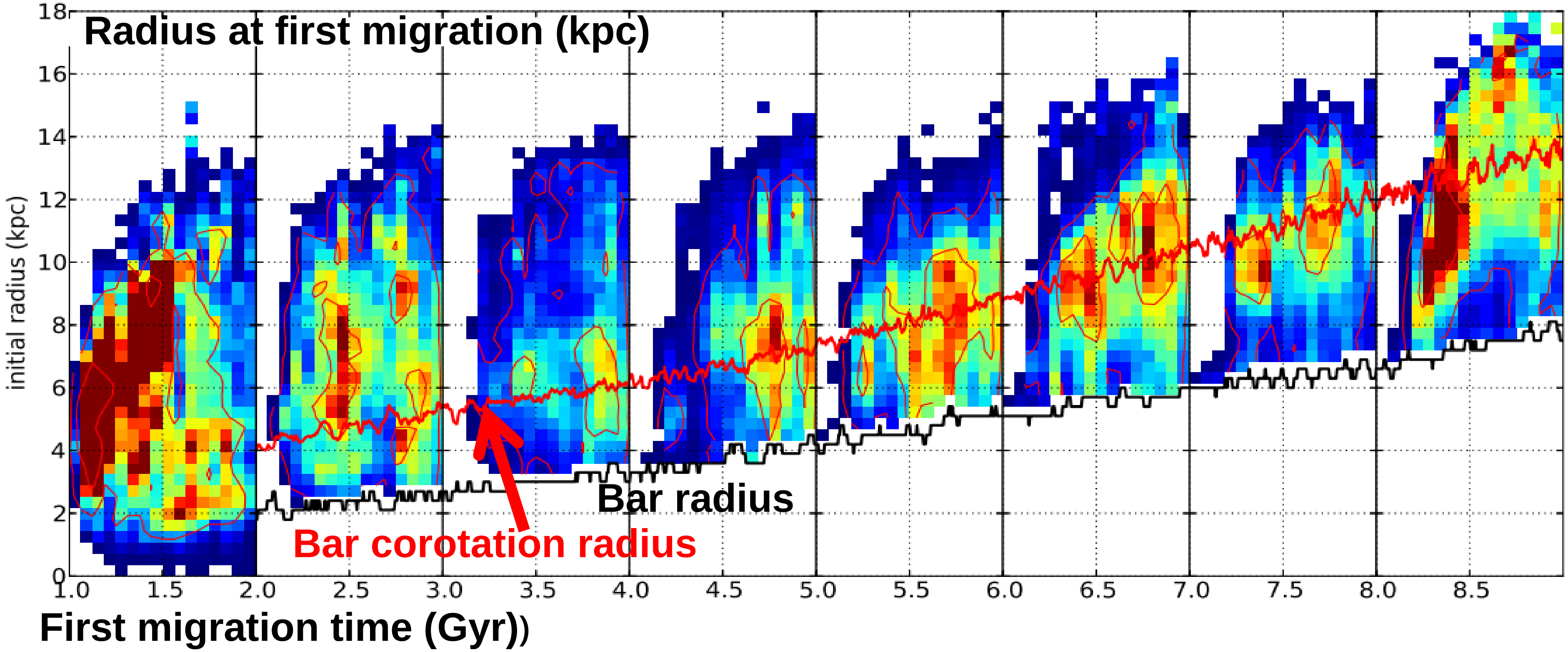
…making it IMPOSSIBLE to derive the true evolution of radial profiles of stellar abundances as function of stellar age



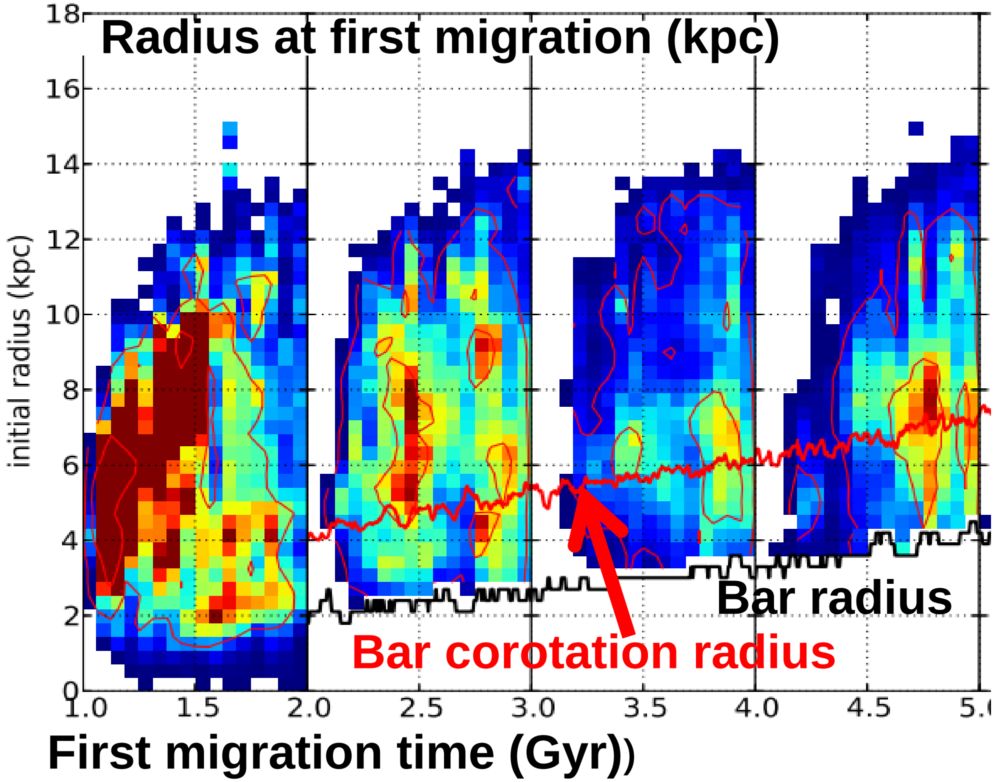


Radial migration flattens the SFR history in the outer disk *(Roskar et al. 2008)* as it could be derived from observations of old stars

Hard to uncover the true history of the local SFR from observations

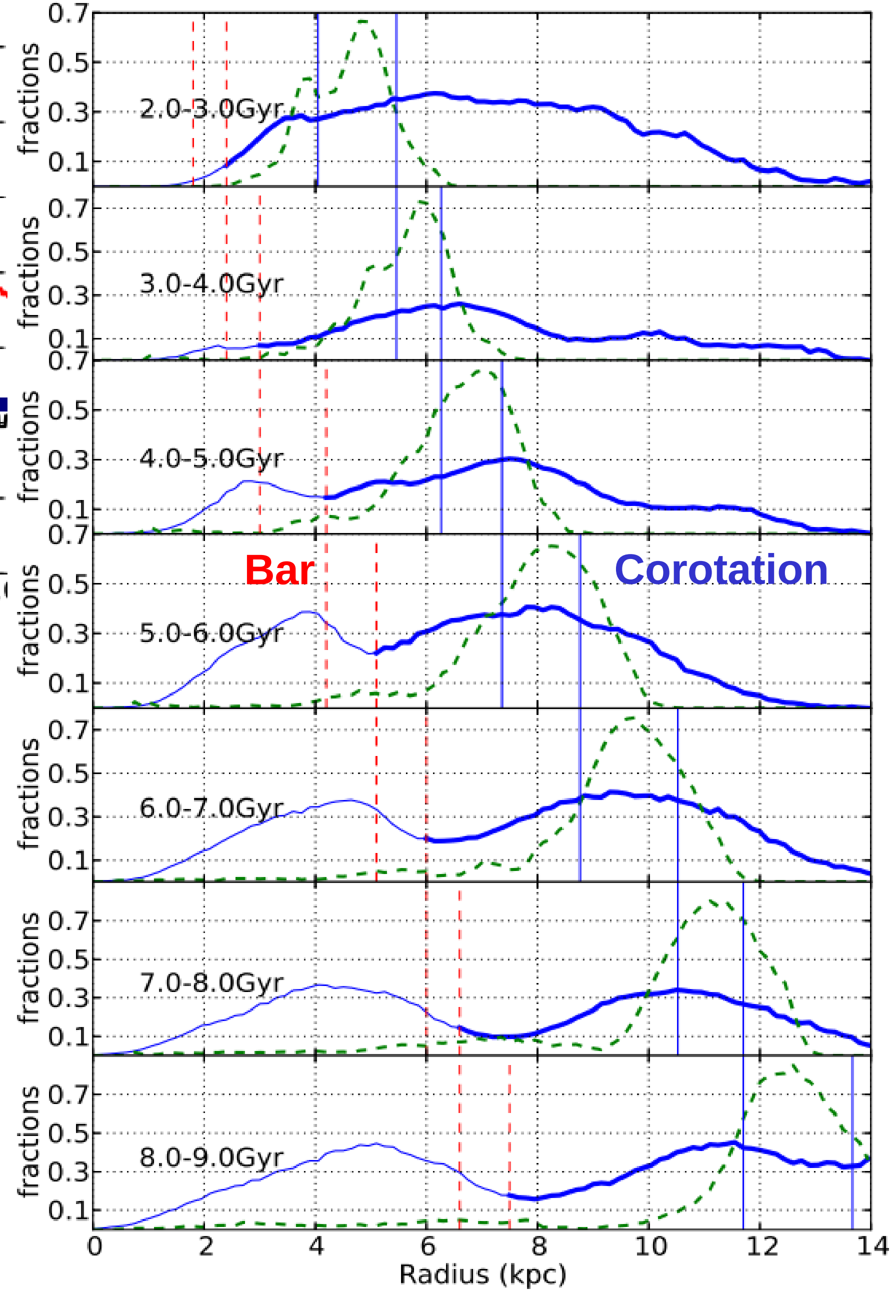


Most migrating particles start doing so when at *corotation with the bar*



Fraction of migrating particles

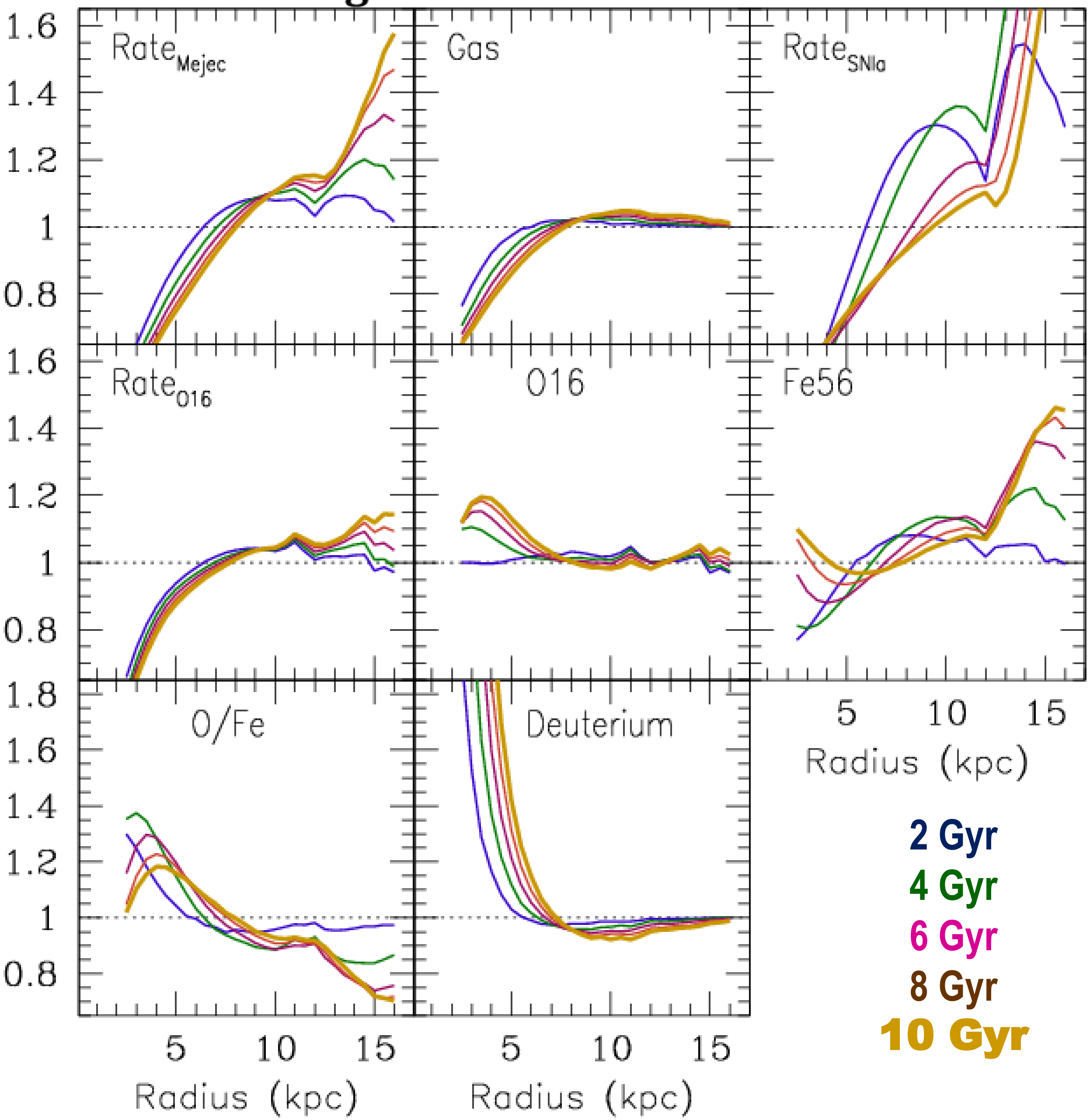
Fraction of migrating particles at corotation



Most migrating particles start doing so when at *corotation with the bar*

This concerns ~2/3 of the migrating particles

Migration / No migration **No IRA**



Migration may alter significantly the results of chemical evolution

Directly, moving outwards long-lived Nucleosynthesis sources, e.g. SNIa

Fe increases in outer disk and decreases in inner disk

O/Fe profile steepens

Indirectly, removing from inner disk low-mass stars which dilute with their H-rich ejecta locally produced metals

O and D increase in inner disk

O/Fe profile steepens *LESS* than with IRA

Bars (and asymmetries in the gravitational potential in general)

affect chemical evolution by:

1) Moving around a « passive agent » of chemical evolution : the gas

2) Moving around a tracer of chemical evolution :

low-mass long lived stars (~1 $M_\odot$ ~10 Gyr)

3) Moving around another « passive agent » of chemical evolution :

Low mass long lived stars (several Gyr) which dilute metallicity

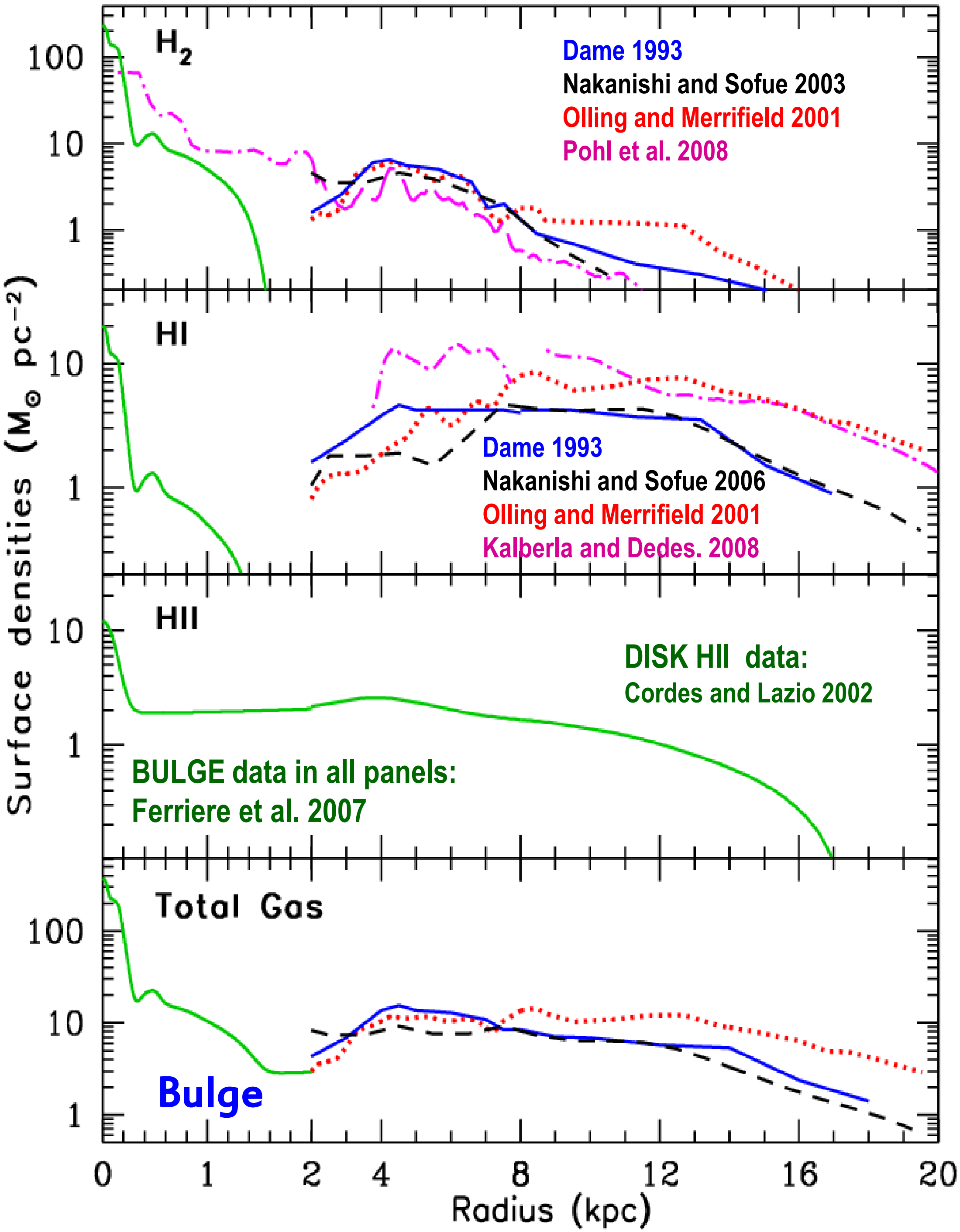
by ejecting lately metal poor gas *(impact on D)*

4) Moving around some active agents of chemical evolution :

long lived nucleosynthesis sources

SNIa: Fe-peak elements

2-1.3 $M_\odot$ stars (1-3 Gyr): s-process elements



The Milky Way disk:

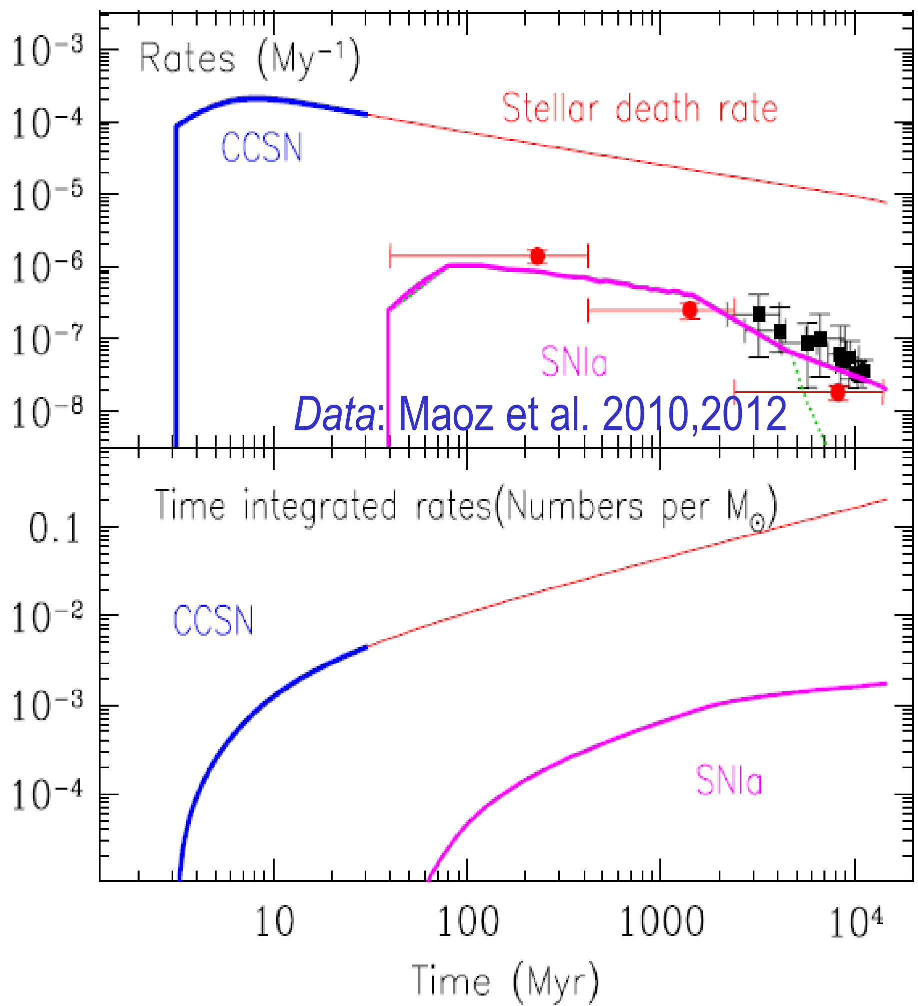
Gas profiles:

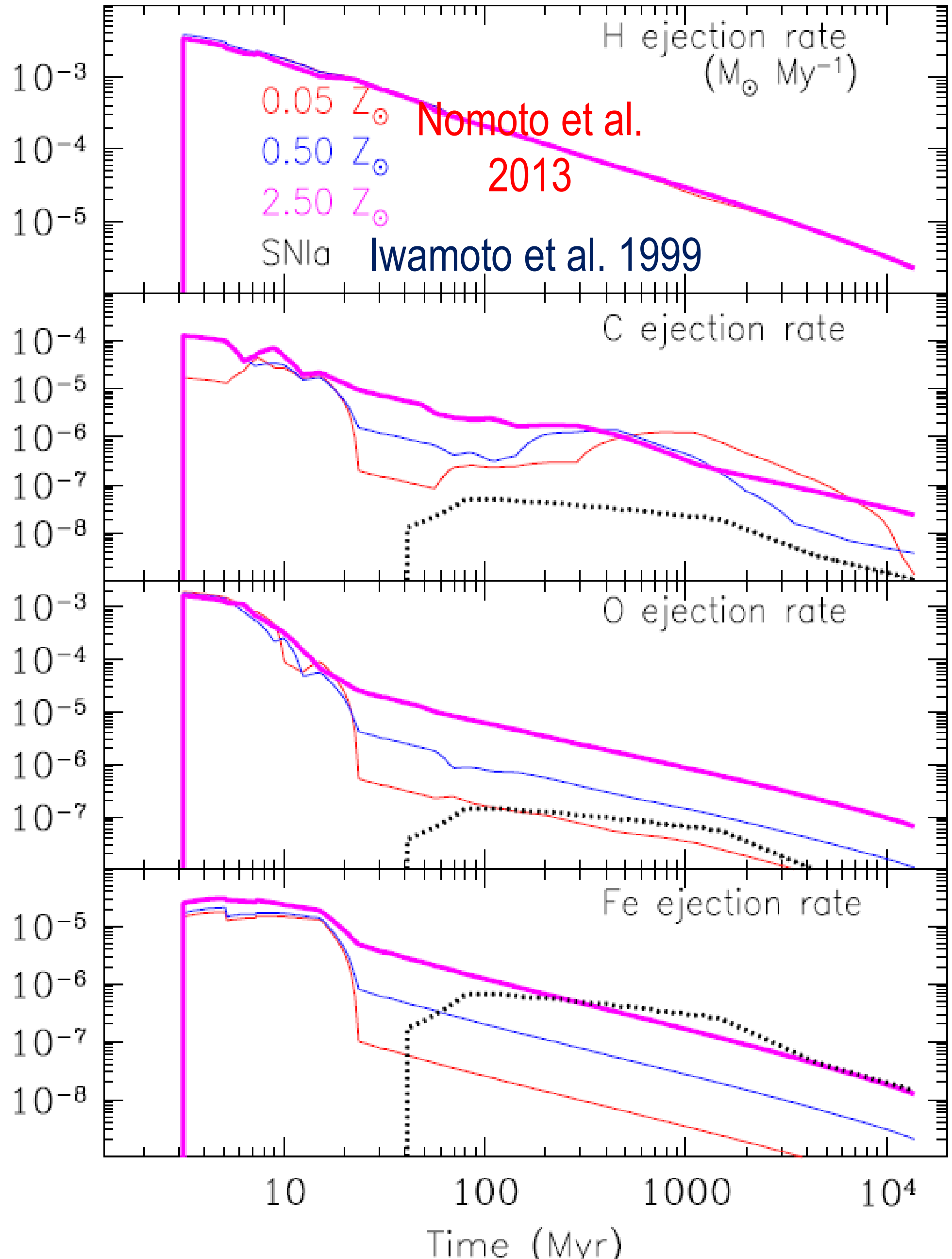
relatively flat, except for molecular gas in inner disk

Basic ingredient of chemical evolution in N-body models, or in semi-analytical ones with radial migration : *Single Stellar Populations*

Mass ejection rates (death rates X Yields) for 1 M⊙ of stars formed

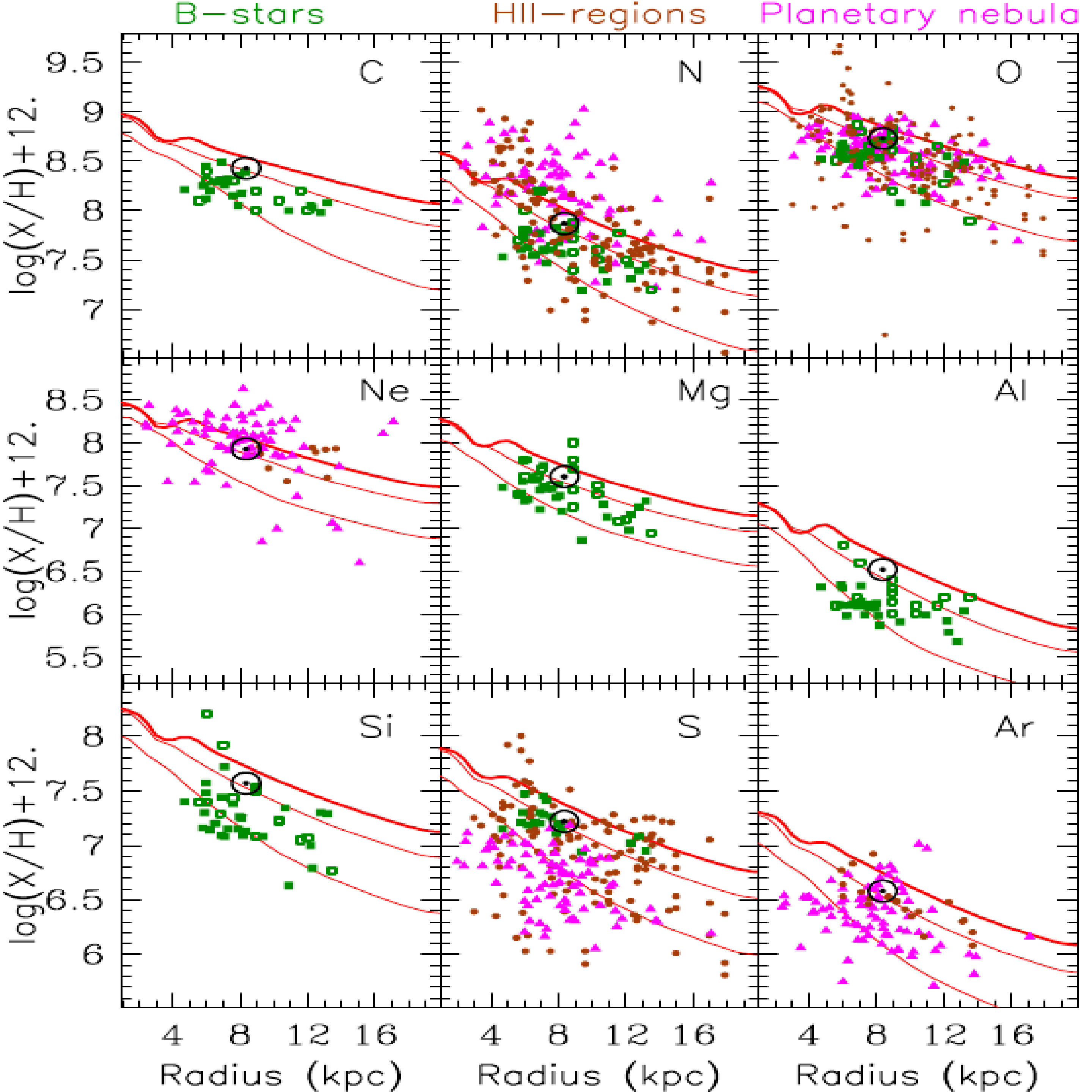
Death rates for 1 M⊙ of stars formed





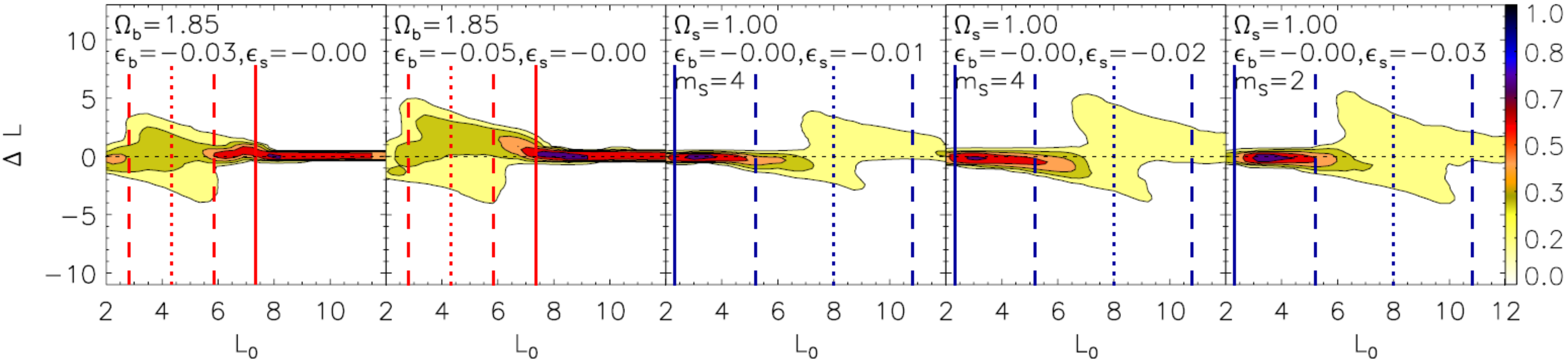
Radial inflows induced by the bar flatten the abundance profiles in the 3-5 kpc region

They also fuel star formation which creates increased metallicity in the inner bulge

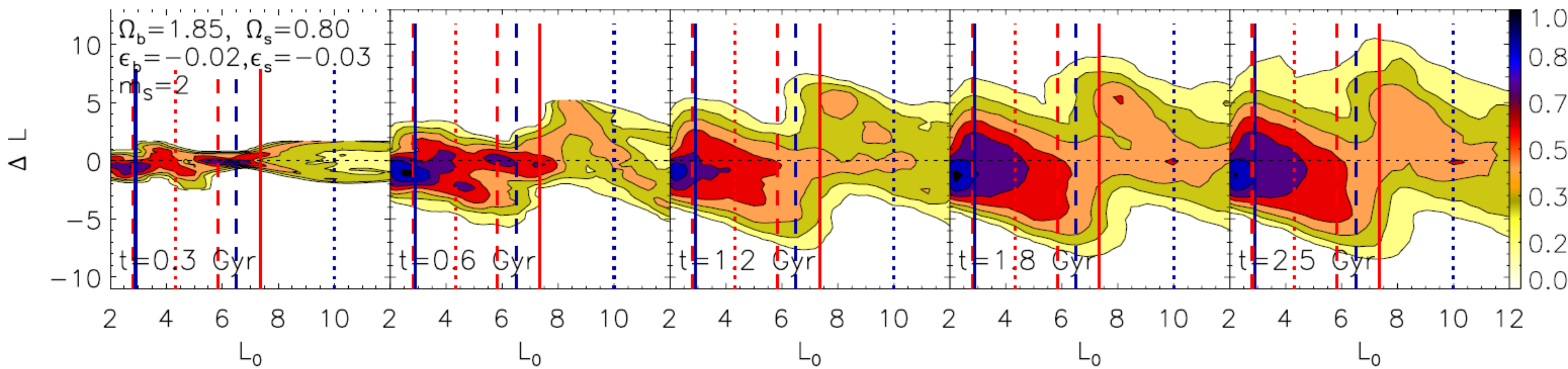


A NEW MECHANISM FOR RADIAL MIGRATION IN GALACTIC DISKS: SPIRAL–BAR RESONANCE OVERLAP

I. Minchev and B. Famaey 2010

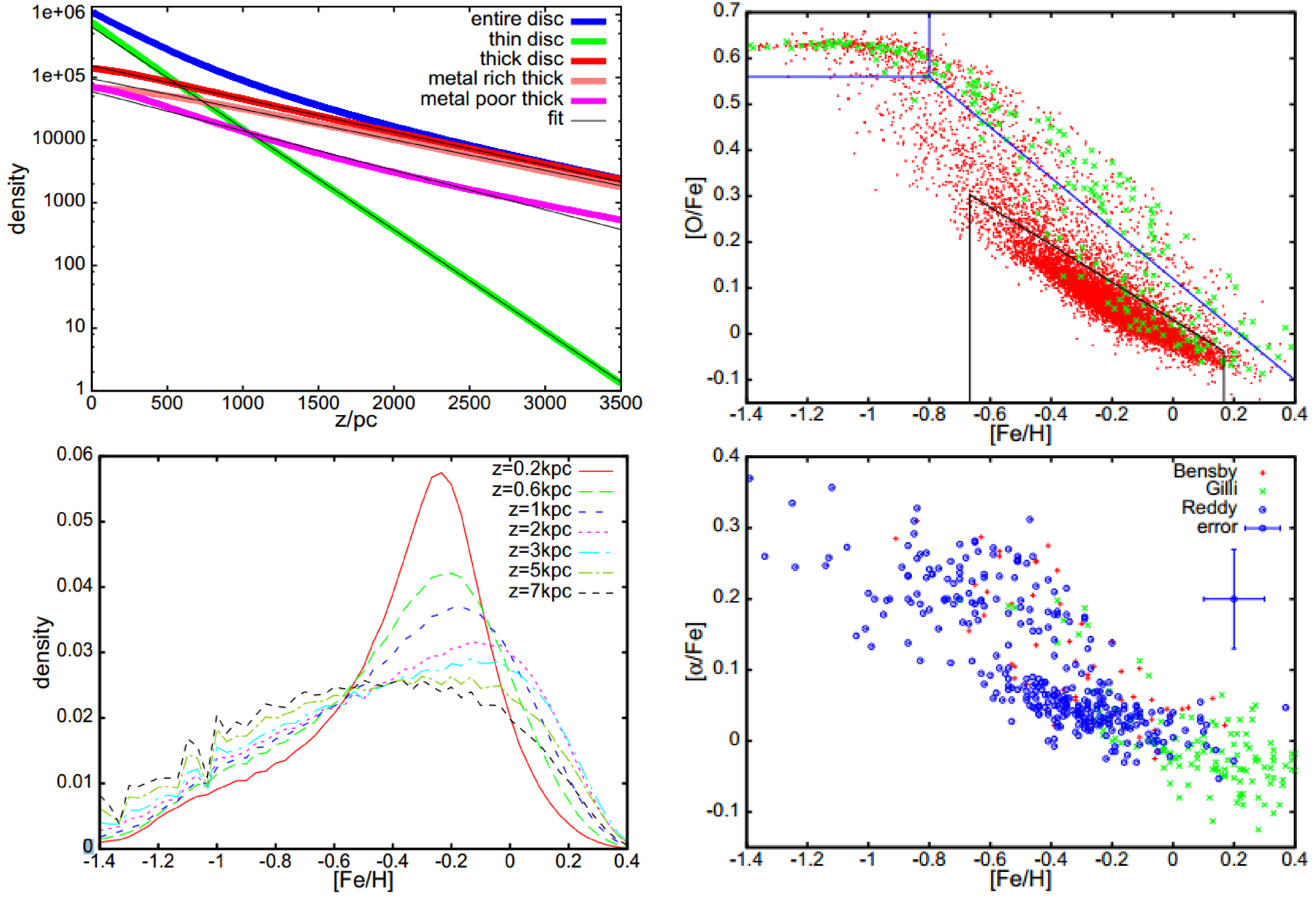


Only bar or spiral pattern

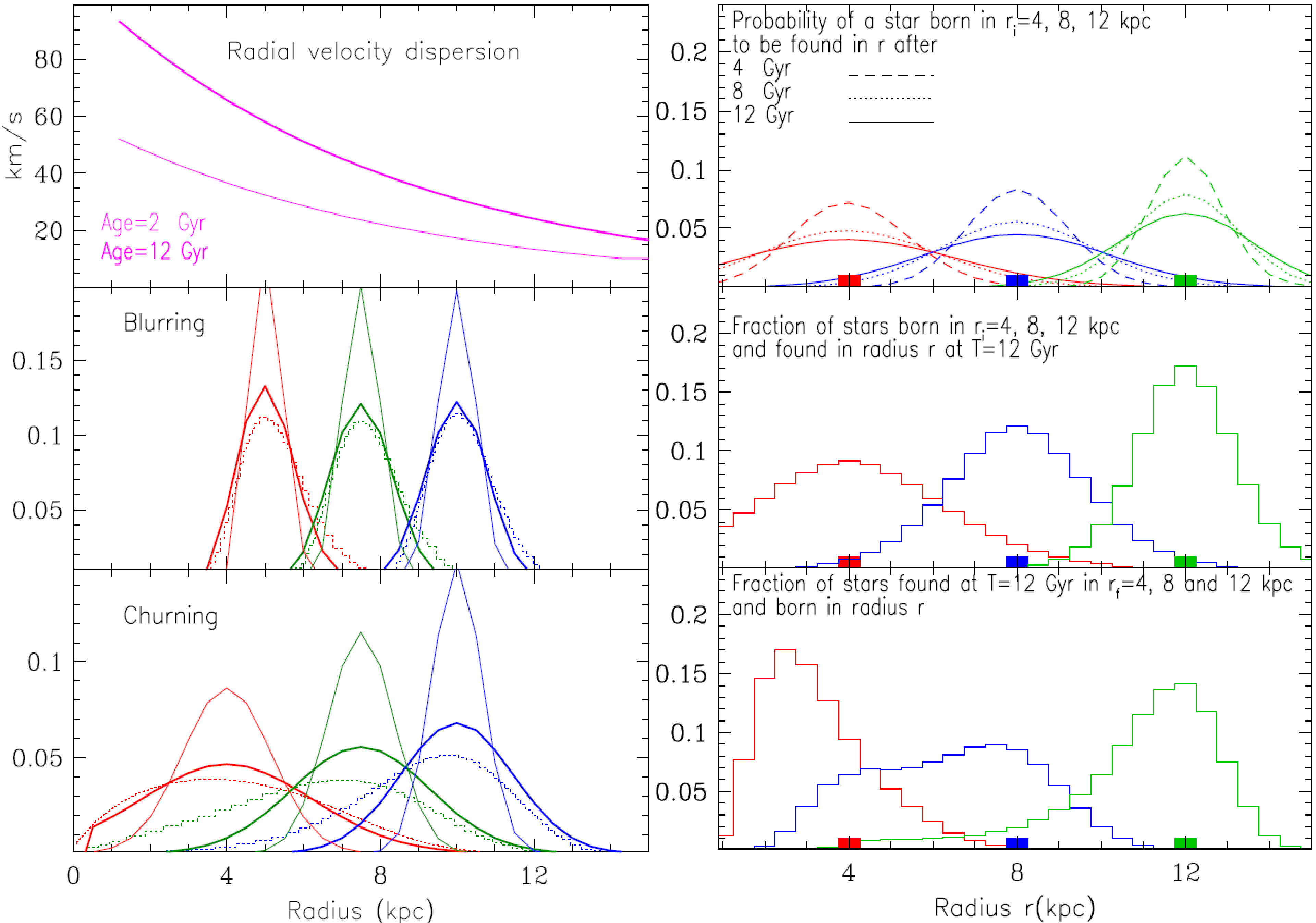


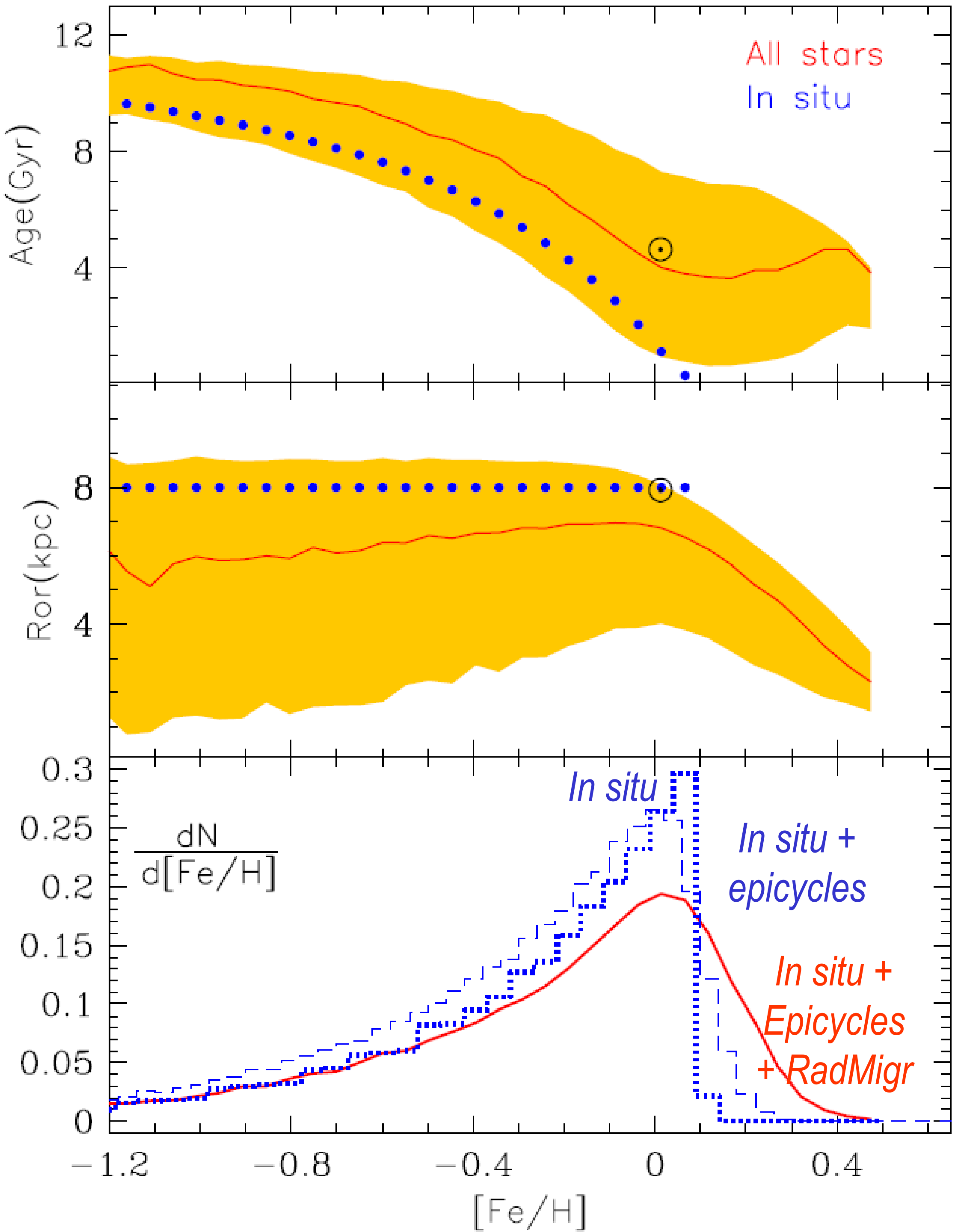
Both bar and spiral pattern

Radial migration and formation of thick disk *(Schoenrich and Binney 2009, semi_analytical)*



Probabilistic treatment of radial migration: transfert coefficients





Solar Neighborhood

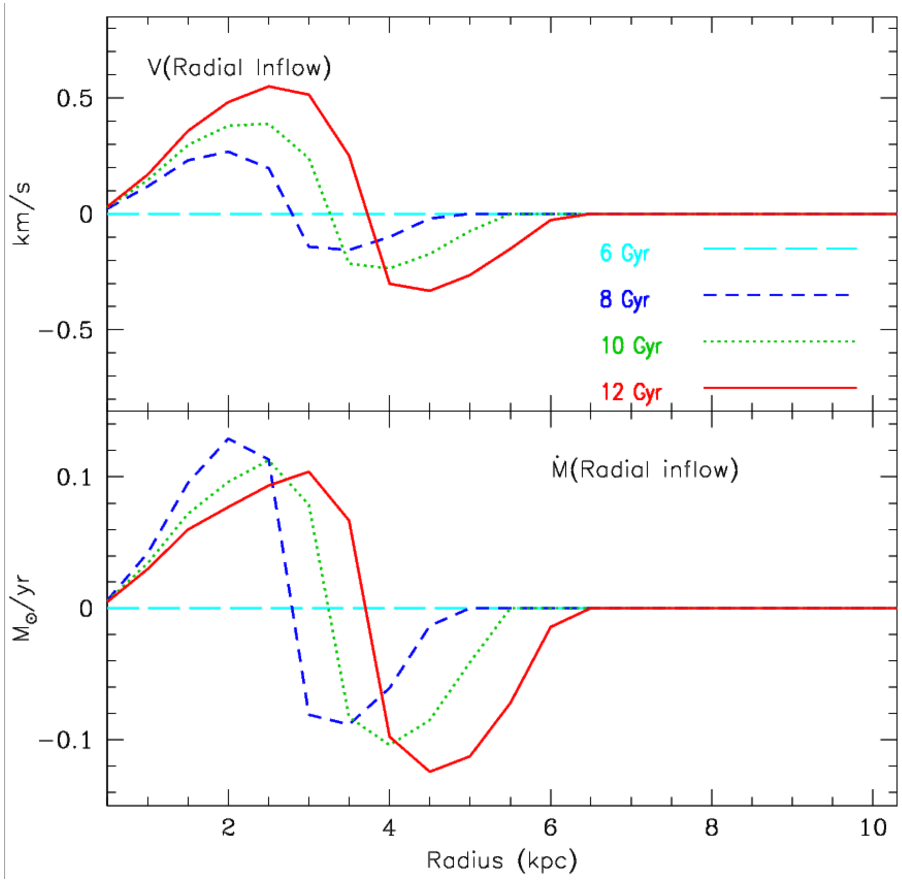
Radial Migration

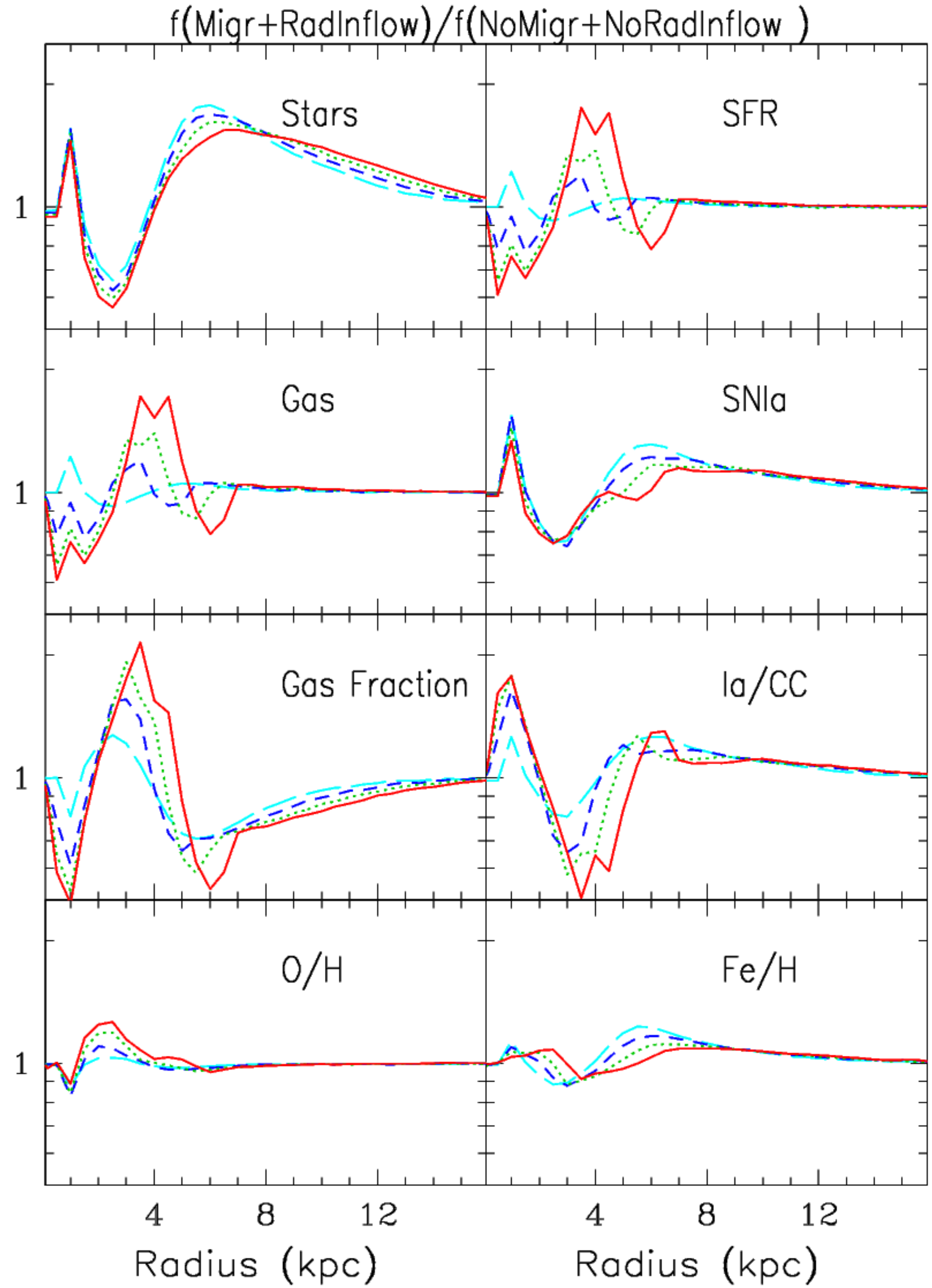
1. Increases the average stellar age by ~1 Gyr

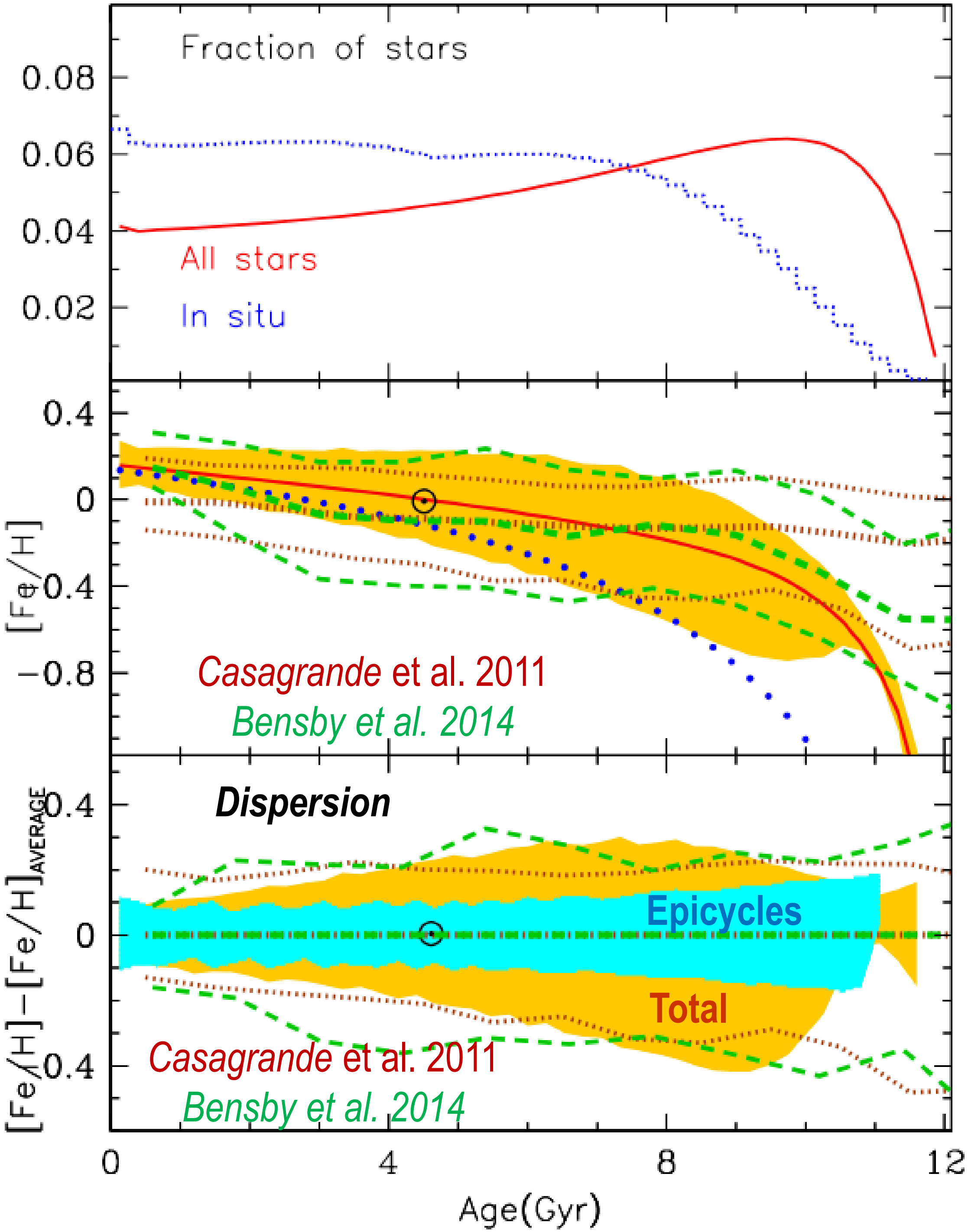
2. … and brings locally stars from ~1. kpc inwards (on average)

3. The most metal-rich local stars come from several kpc inwards and are ~4 Gyr old

Impact of radial migration and radial flows on the results







Solar Neighborhood

Radial Migration

1. Modifies the apparent local SFR

2. Creates dispersion in the age-metallicity relation…

3. … much more than the epicyclic motion