ON THE IMPACT OF RADIAL MIGRATION ON THE CHEMICAL EVOLUTION OF THE MILKY WAY

0. Elementary introduction to galactic chemical evolution

1. The simple picture of disk evolution:
   independent ring evolution, successes and failures

2. The dynamical picture: stars (and gas) moving around

3. A new model for the MW disk

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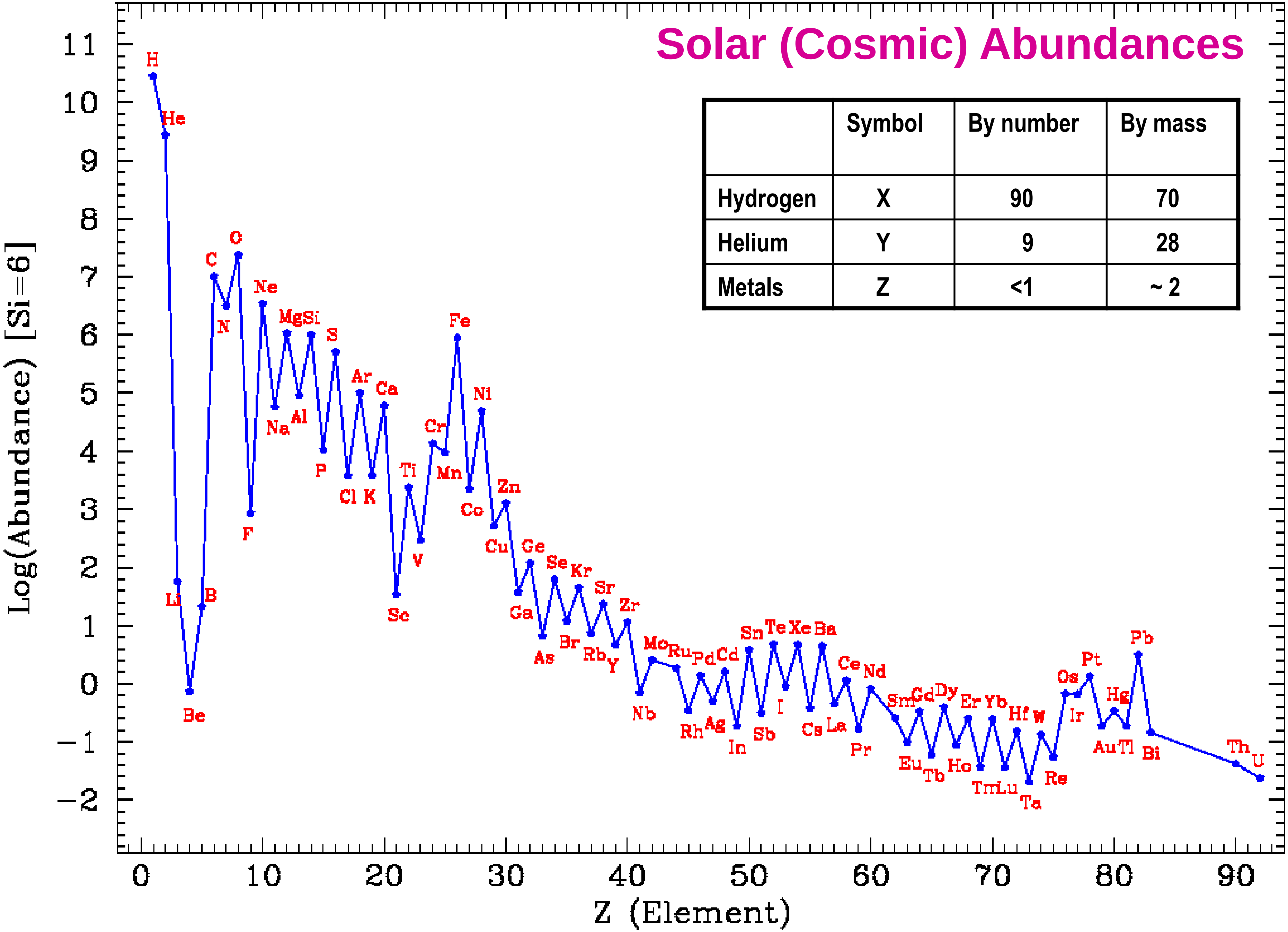
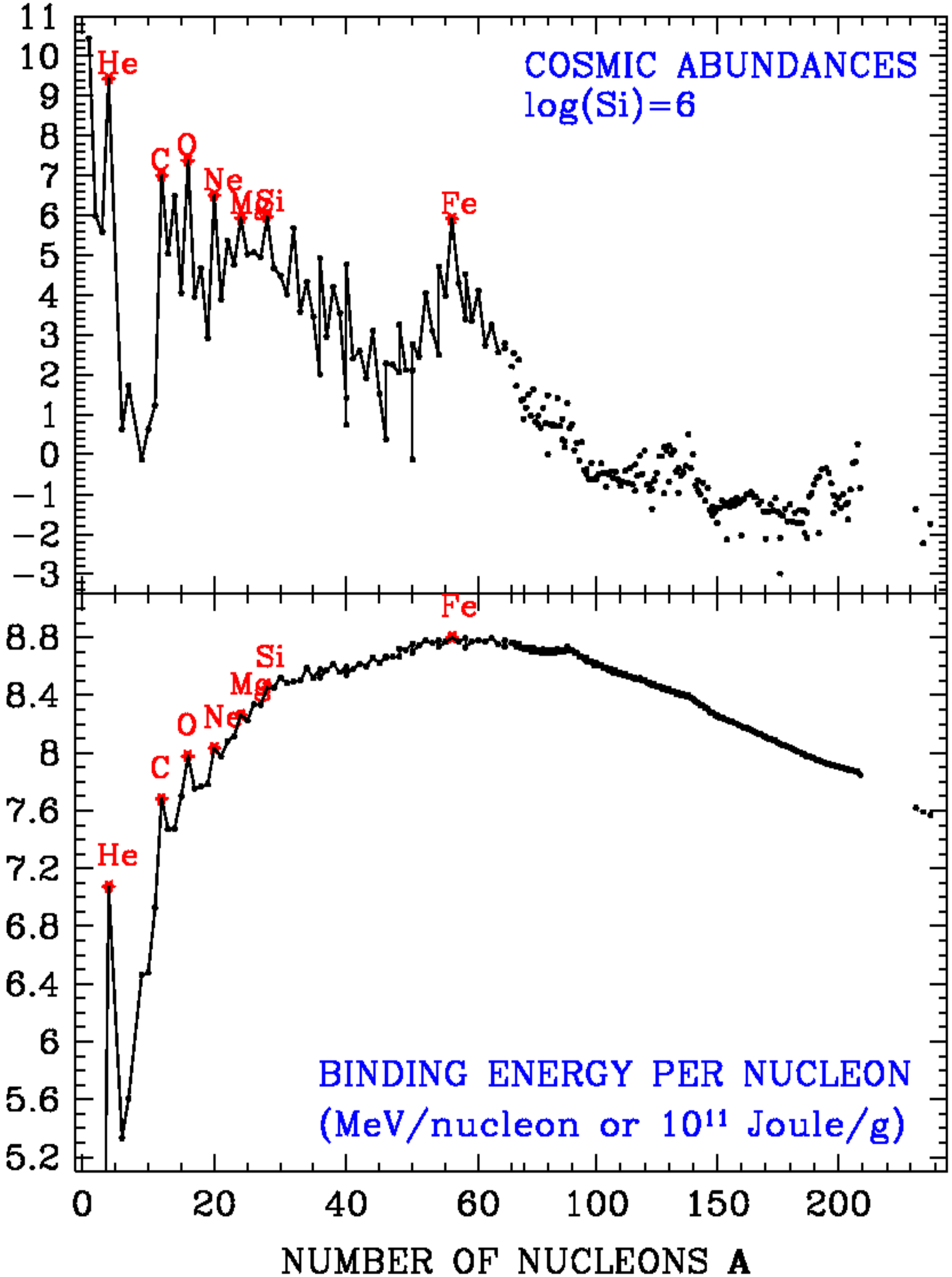
Solar (Cosmic) Abundances



	Symbol	By number	By mass
Hydrogen	X	90	70
Helium	Y	9	28
Metals	Z	<1	~ 2



Cosmic abundances

of nuclides are **locally** correlated with **nuclear stability**

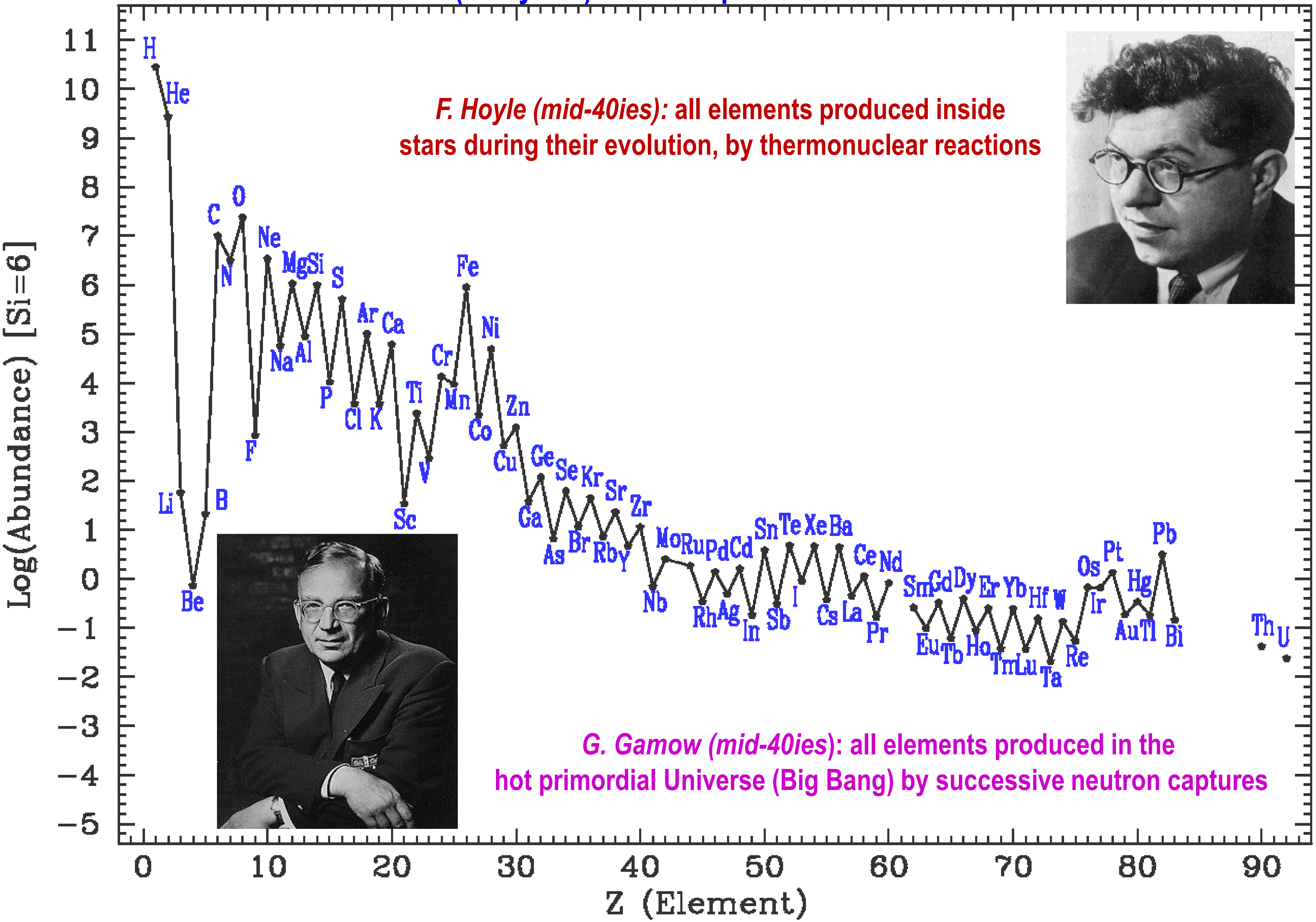
(alpha-nuclei, Fe peak nuclei, nuclei with "magic" nucleon numbers, nuclei with even nucleon number are more abundant than their neighbors)

alpha-nuclei : mass number = multiple of 4 (C-12, O-16, Ne-20, Mg-24, Si-28, S-32, Ar-36, Ca-40)

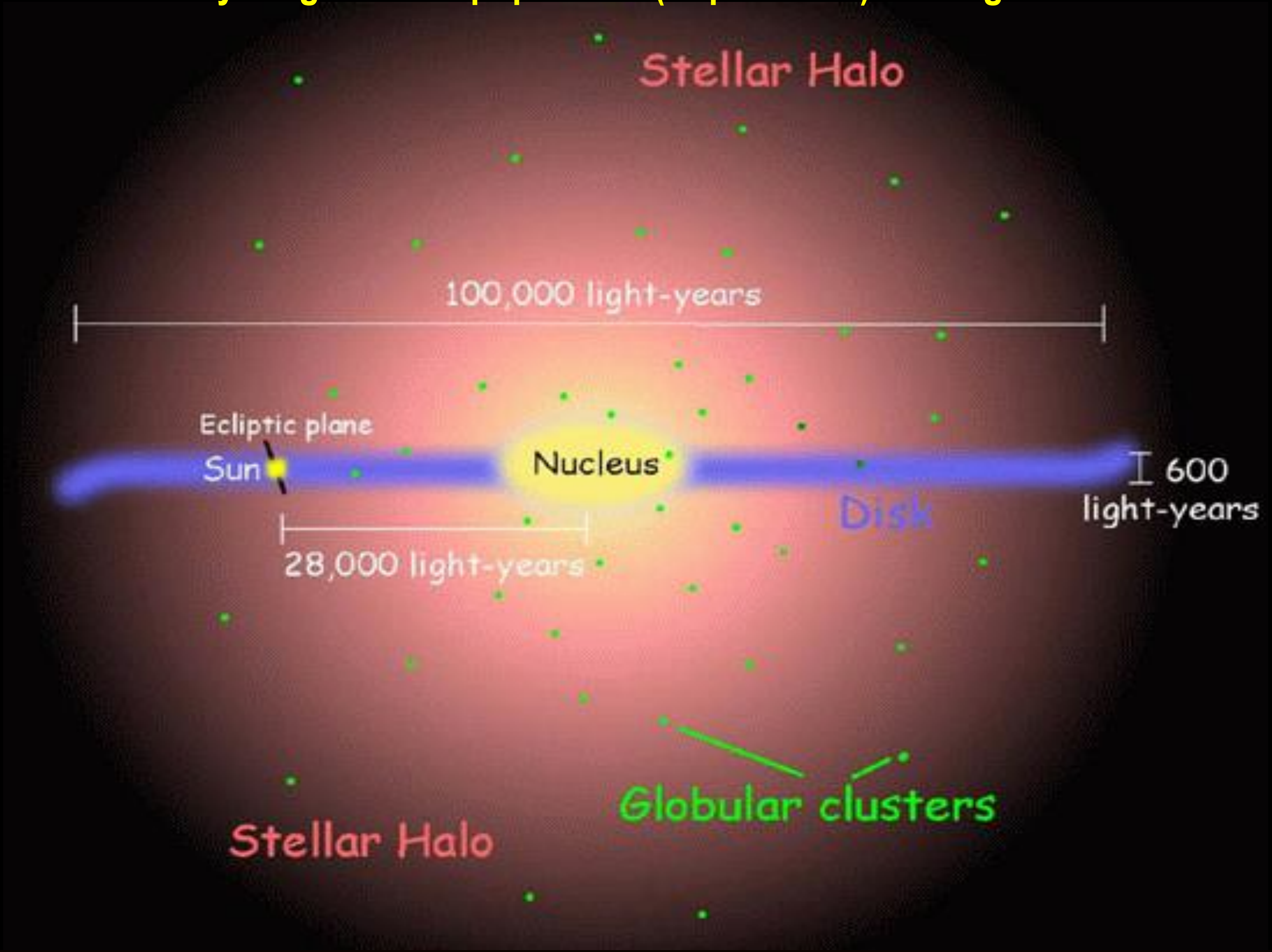
Nuclear processes have shaped the **cosmic abundances** of the chemical elements

Solar (= Cosmic) abundances : related to nuclear properties (nuclear binding energies)

➔ a hot (many MK) site is required : which one ?



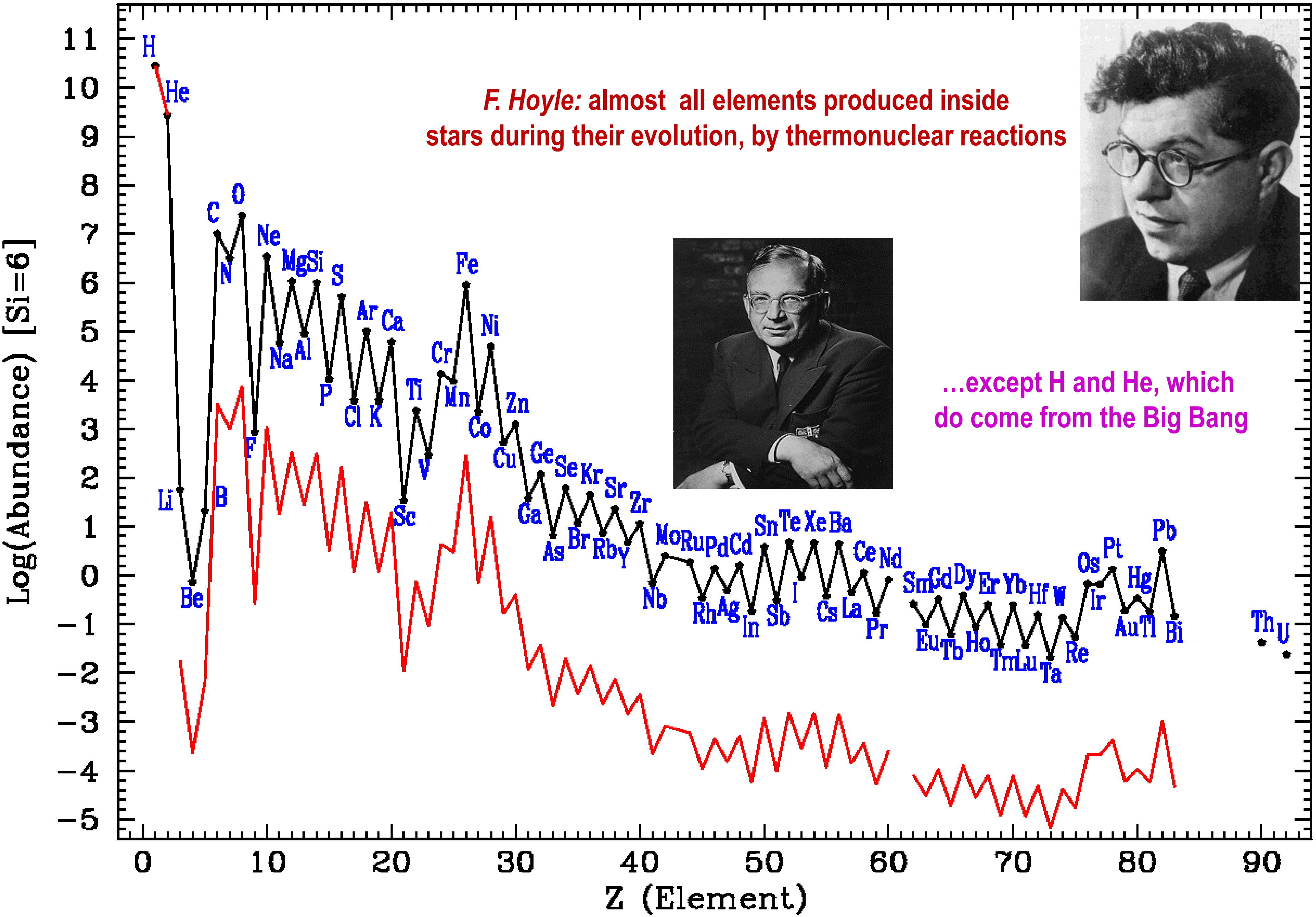
Old stars of galactic halo (Population II) contain less heavy elements (metals) than the younger stellar population (Population I) of the galactic disk



The chemical composition of the Milky Way was substantially different in the past

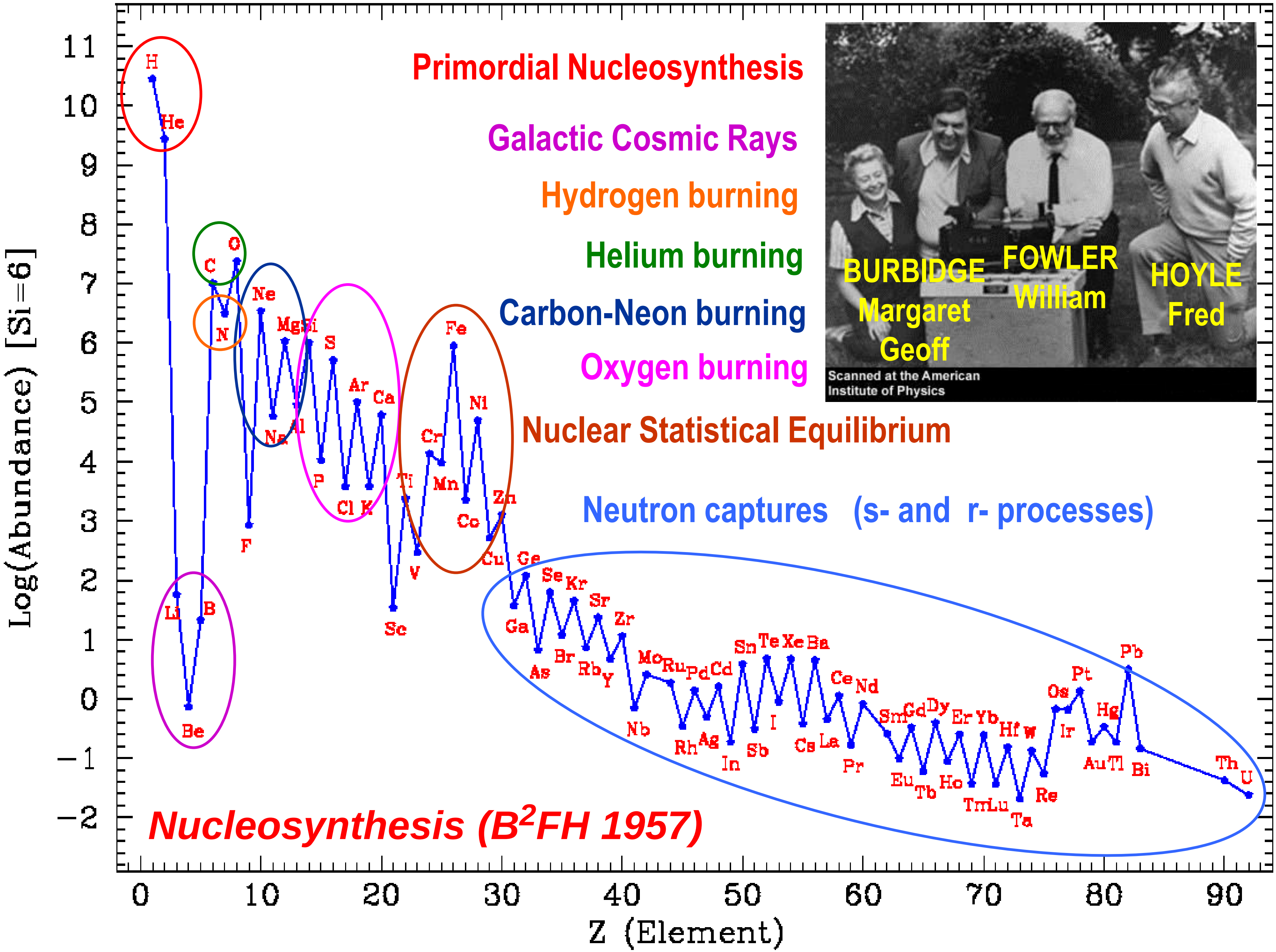
Early 50ies: **metal (heavier than He) abundances are not always the same ;**

Galactic halo stars have low metallicities



F. Hoyle: **almost all elements produced inside stars during their evolution, by thermonuclear reactions**

…except H and He, which do come from the Big Bang


Primordial Nucleosynthesis
Galactic Cosmic Rays
Hydrogen burning
Helium burning
Carbon-Neon burning
Oxygen burning
Nuclear Statistical Equilibrium
Neutron captures (s- and r- processes)
BURBIDGE Margaret Geoff
FOWLER William
HOYLE Fred
Scanned at the American Institute of Physics
Nucleosynthesis (B²FH 1957)
Log(Abundance) [Si=6]
Z (Element)
H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Ru Rh Pd Ag Cd In Sn Sb Te I Xe Cs Ba La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Th U
0 10 20 30 40 50 60 70 80 90
−2 −1 0 1 2 3 4 5 6 7 8 9 10 11

Galactic Chemical Evolution (GCE) Basics

Main ingredients of Galactic Chemical Evolution models

Stellar properties

(function of mass M and metallicity Z)

- **Lifetimes**
- **Yields (quantities of elements ejected)**
- **Masses of residues (WD, NS, BH)**

From theory of

Stellar evolution and nucleosynthesis

Collective Stellar Properties

- **Star Formation Rate (SFR)**
- **Initial Mass Function (IMF)**

Observations
Phenomenological recipes +
Theoretical arguments

Gas Flows

- **Infall**
- **Outflow**
- **Radial inflow (in disks)**

Observationally and theoretically motivated

Our understanding / modelling of galactic astrophysics (galaxy evolution) is far behind the corresponding ones in stellar astrophysics

	Star	Galaxy
Driver of evolution	Nuclear reaction rates *NRR = f(T,ρ,X)* *Well known*	Star Formation Rate *SFR = f(Gas……..)* *Poorly known*

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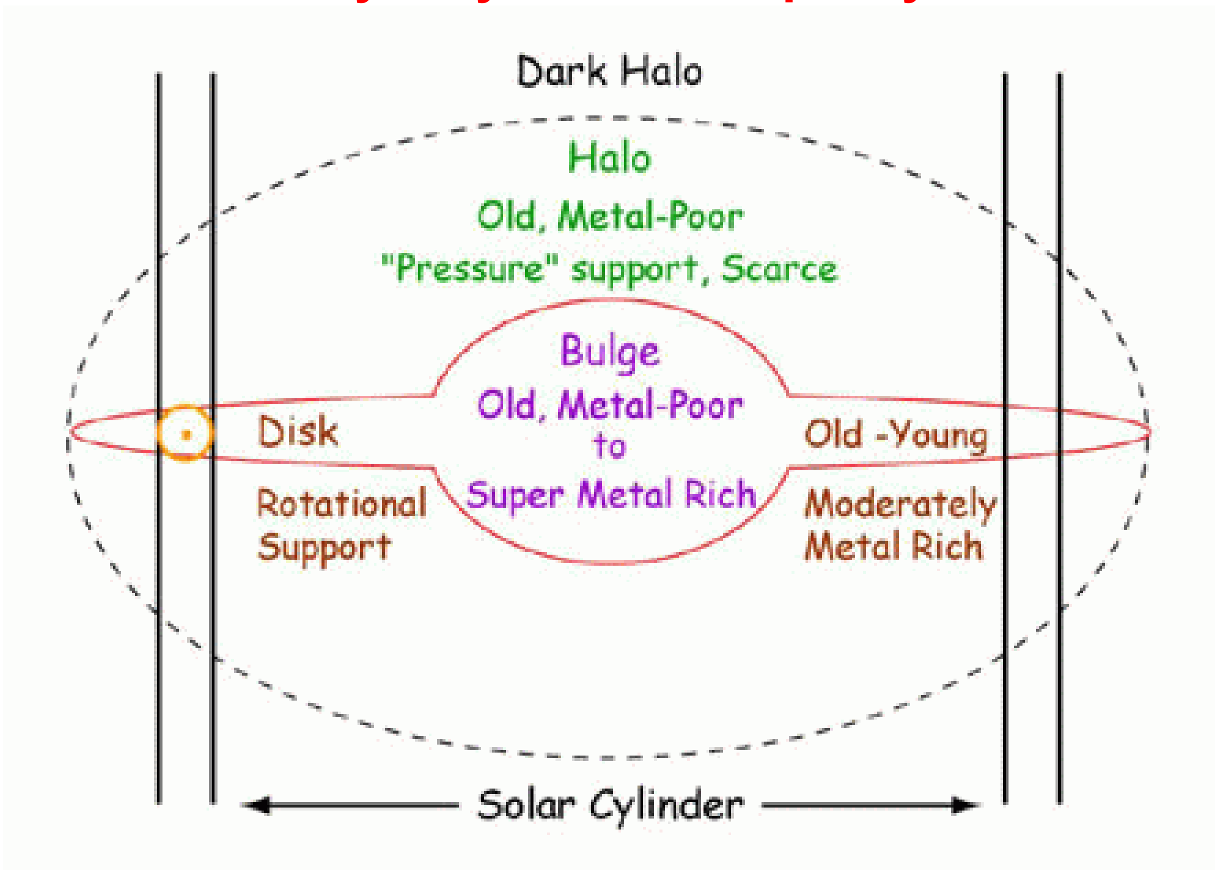
The Milky Way : not a simple system



Local disk (8 kpc from GC): Composition of nearby young stars and gas is ~ solar
(*But: older stars are more metal poor, by a factor up to ten*)

Inner Galactic disk: metal rich young stars and gas (up to 3 times solar)

Outer Galactic disk: metal poor young stars and gas (down to 1/3 solar)

Galactic halo: very metal poor old stars (from 1/10 down to 1/10000 solar)
But: relative abundances between metals always about the same

Solar Neighborhood Constraints:

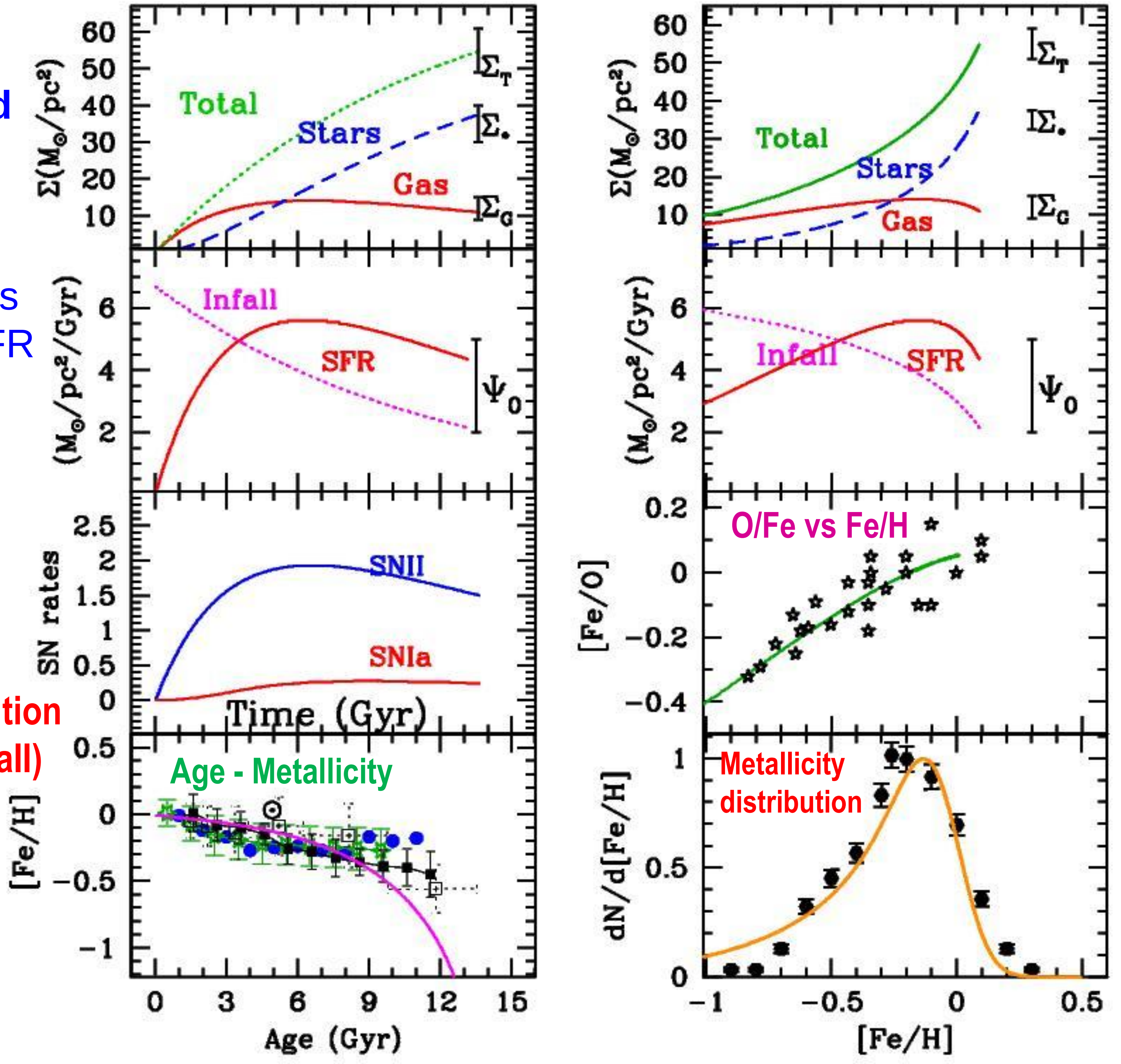
Local column densities of gas, stars, SFR

as well as

Age – Metallicity (uncertain)

Metallicity distribution (requires slow infall)

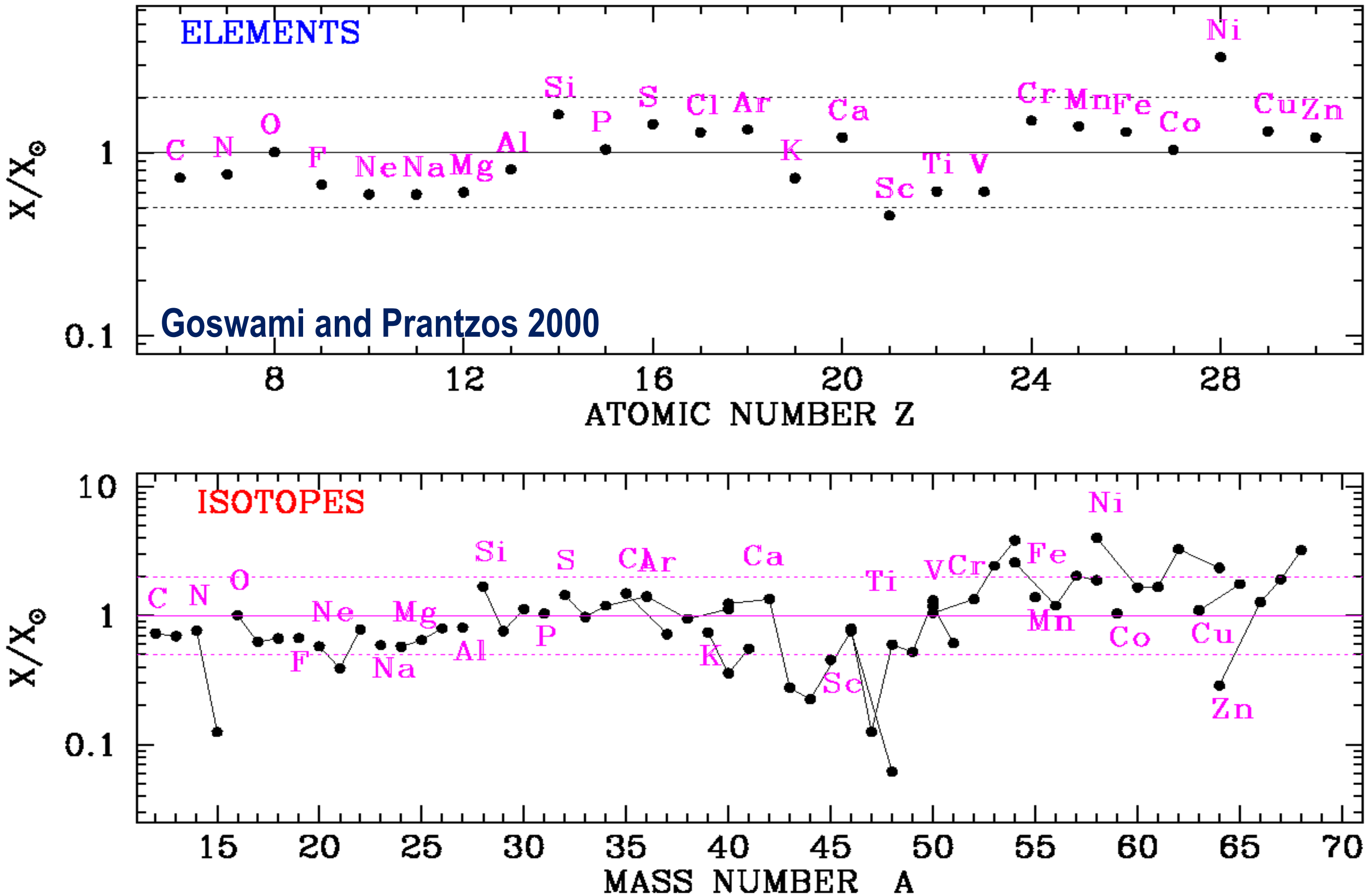
O/Fe vs Fe/H (requires SNIa for late Fe)



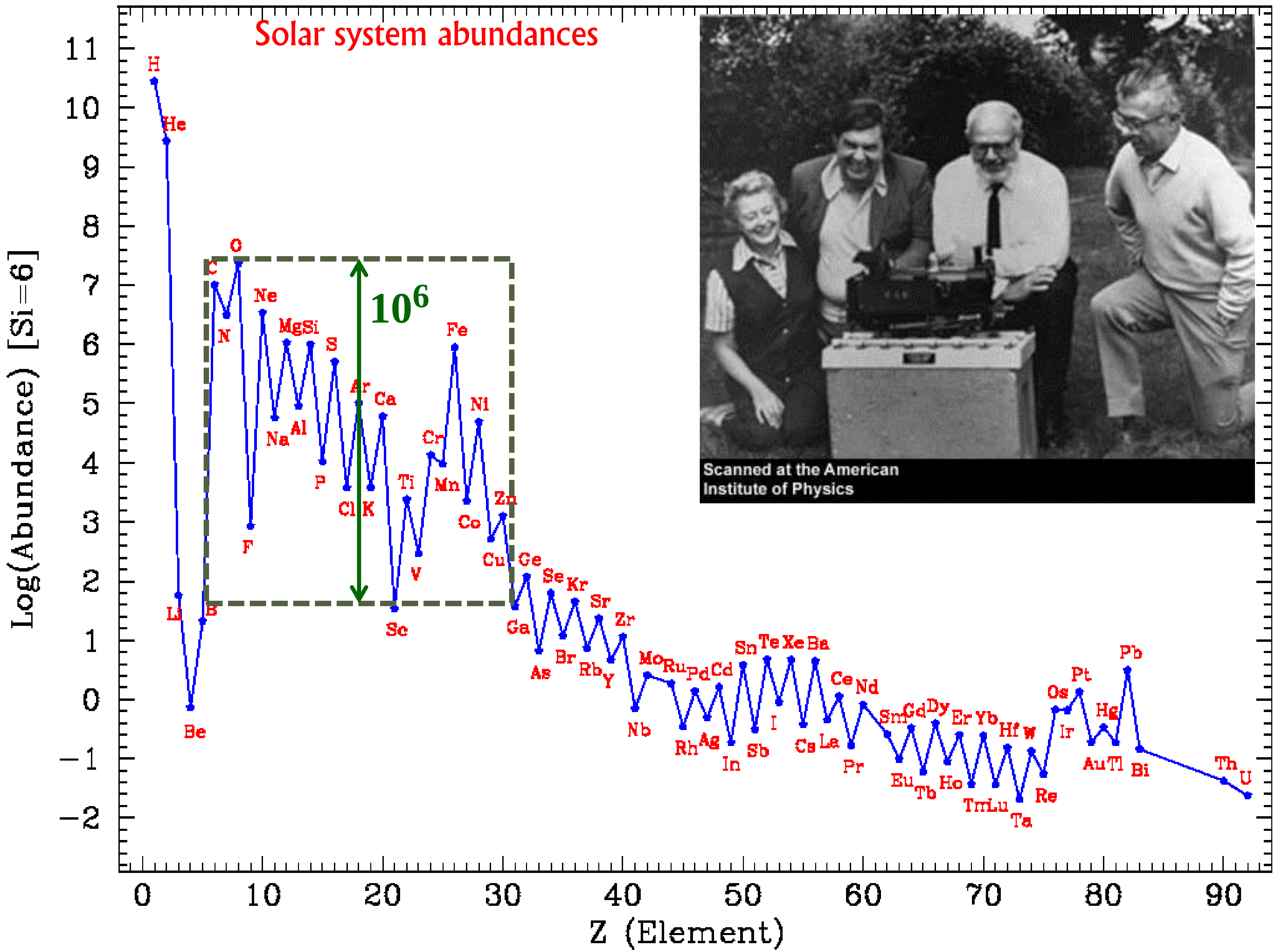
The Solar Neighborhood

Abundances at Solar system formation

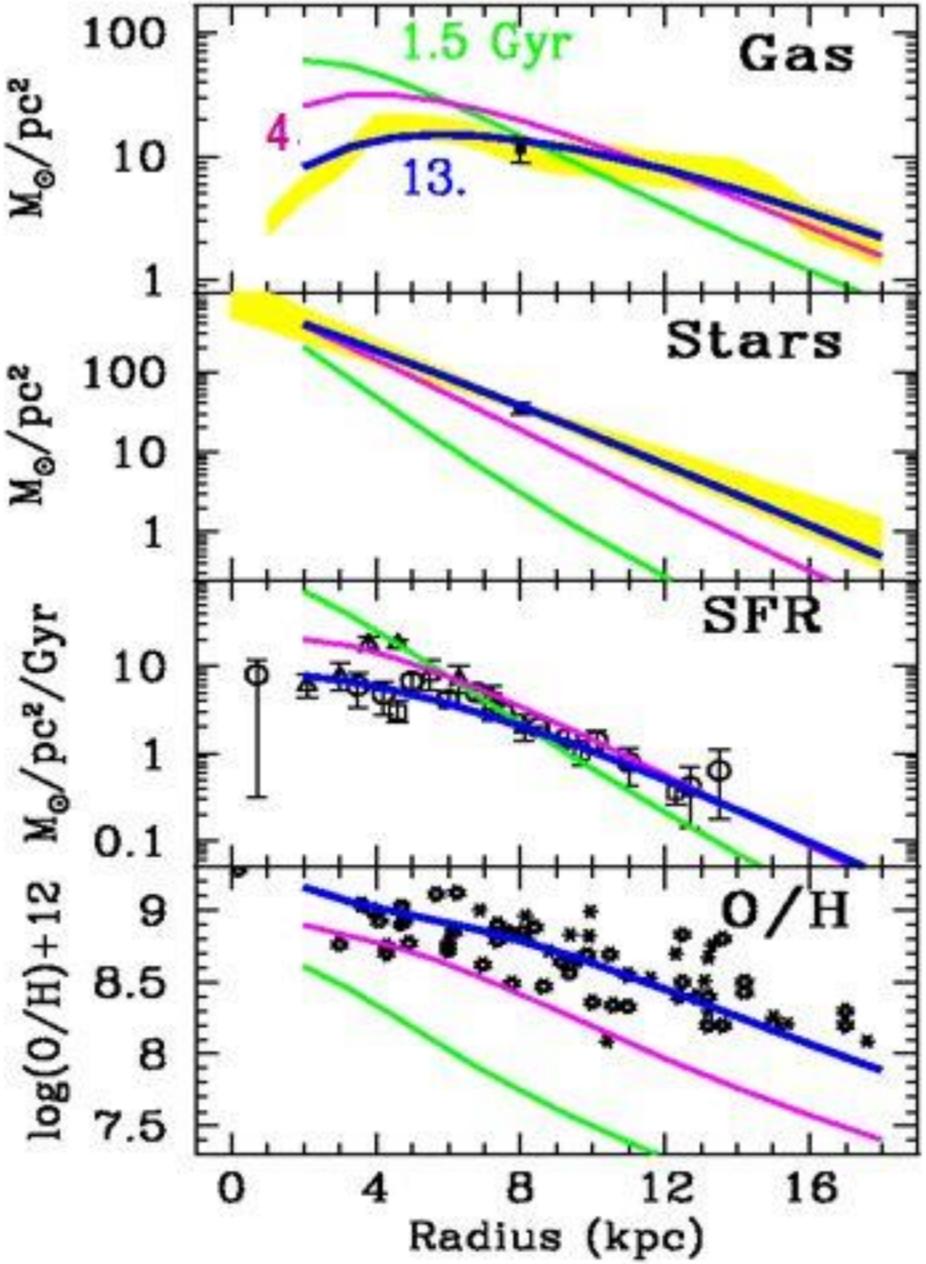
(Massive stars: *Woosley+Weaver 1995*;
Intermediate mass stars: *van den Hoek+Gronewegen 1997*; SNIa: *Iwamoto et al. 2000*)



A triumph for stellar nucleosynthesis and chemical evolution !


Solar system abundances
10^6
Scanned at the American
Institute of Physics
Log(Abundance) [Si=6]
Z (Element)
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

The Milky Way disk

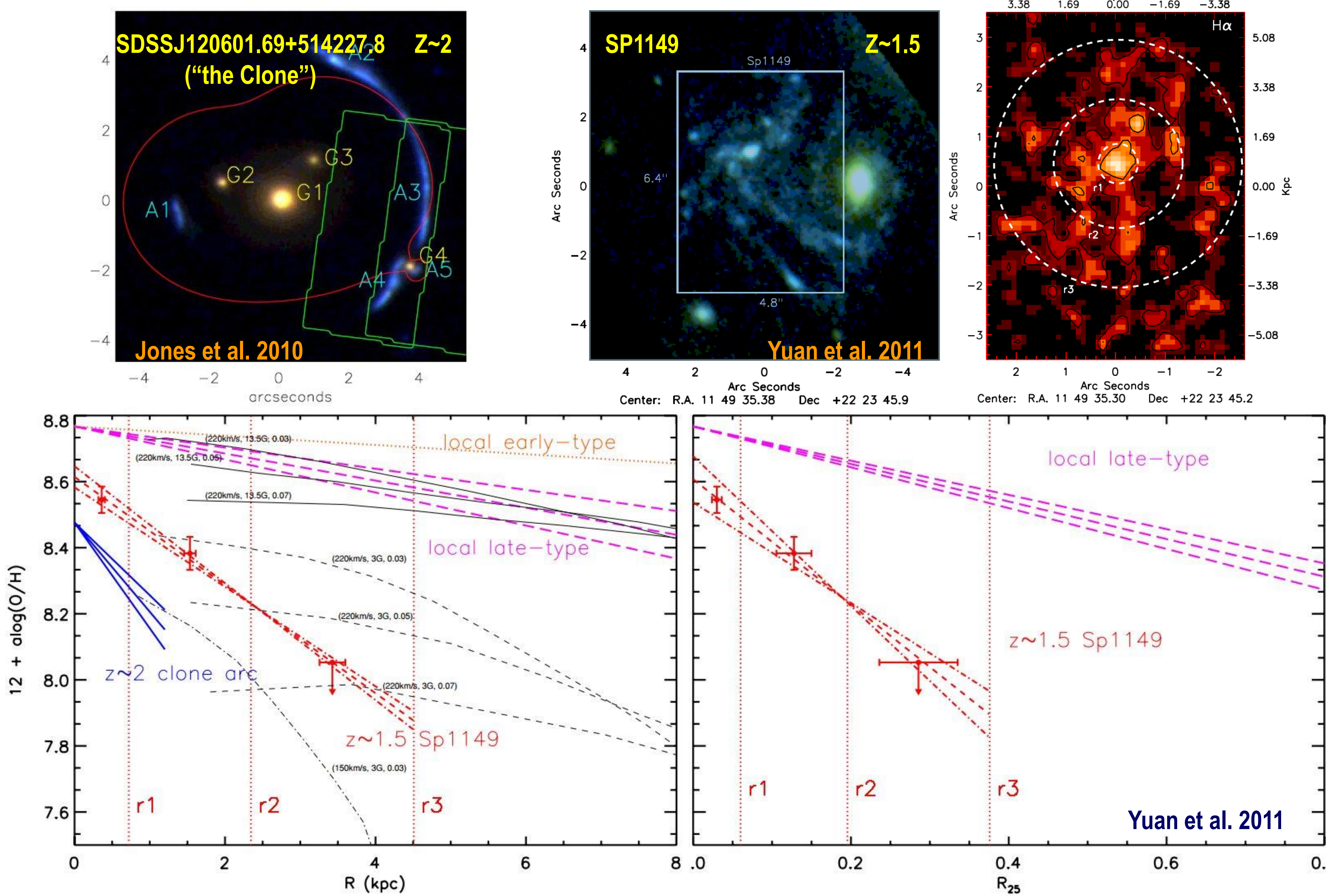


In general: only present-day profiles of gas, stars, SFR, metallicity, and luminosities available, not any past profiles

Inside-Out formation by infall and radially varying SFR efficiency required to reproduce observed SFR, gas and colour profiles (Scalelengths: $R_B \cong 4$ kpc, $R_K \cong 2.6$ kpc) in "independent-ring" models (*Boissier and Prantzos 1999*)

Models predict that abundance profiles where steeper in the past (because of "*inside-out*" formation)

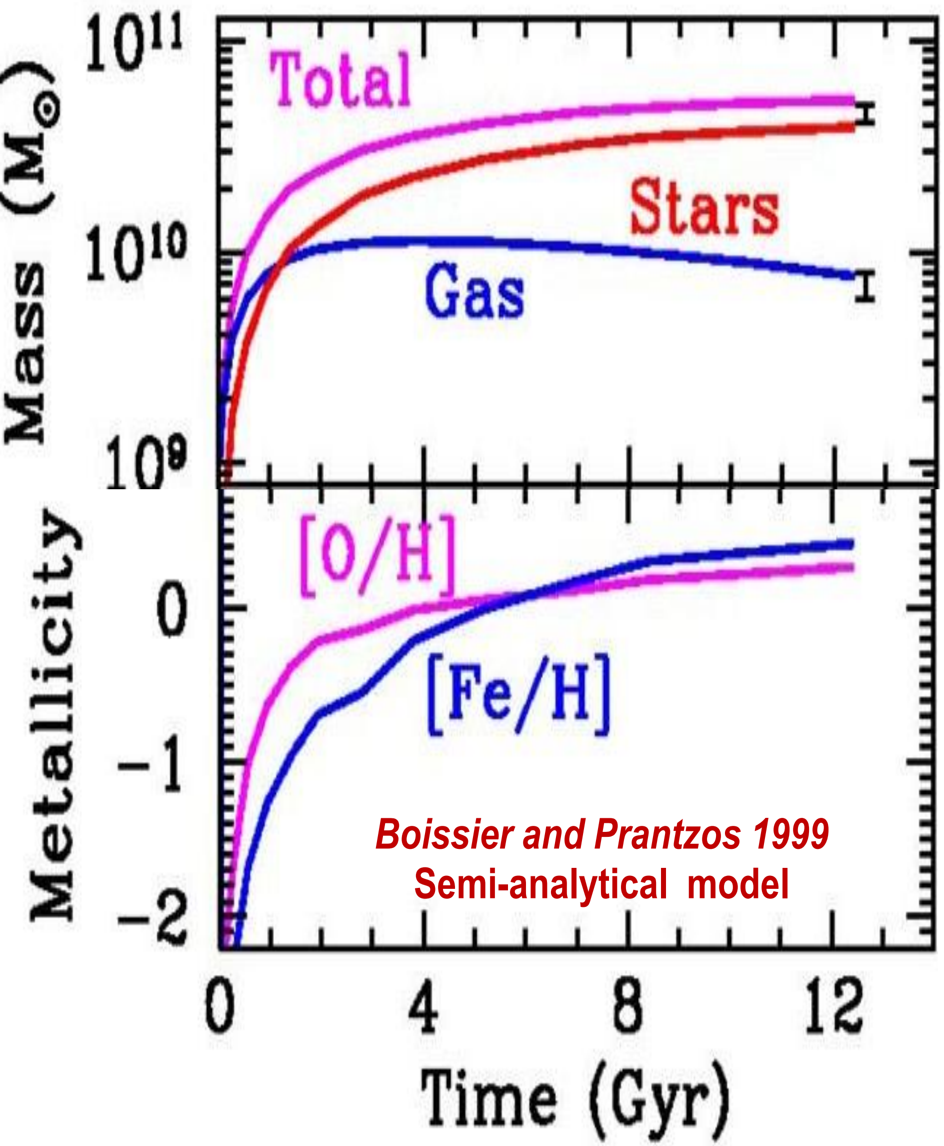
Observation of abundance profiles at high redshift in lensed galaxies

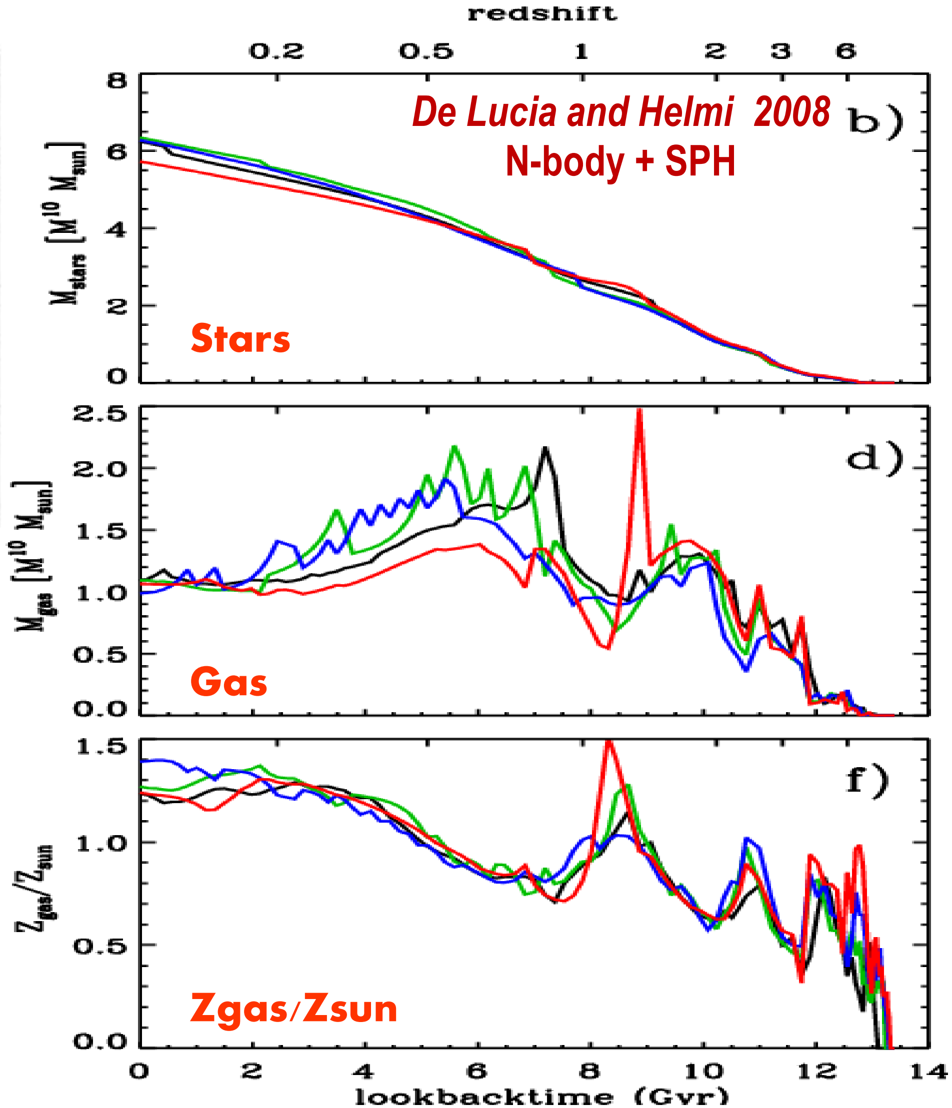


The abundance profiles appear to be much steeper than typical profiles of local disks…

HISTORY OF MILKY WAY DISK IN THE PAST 12 GYR

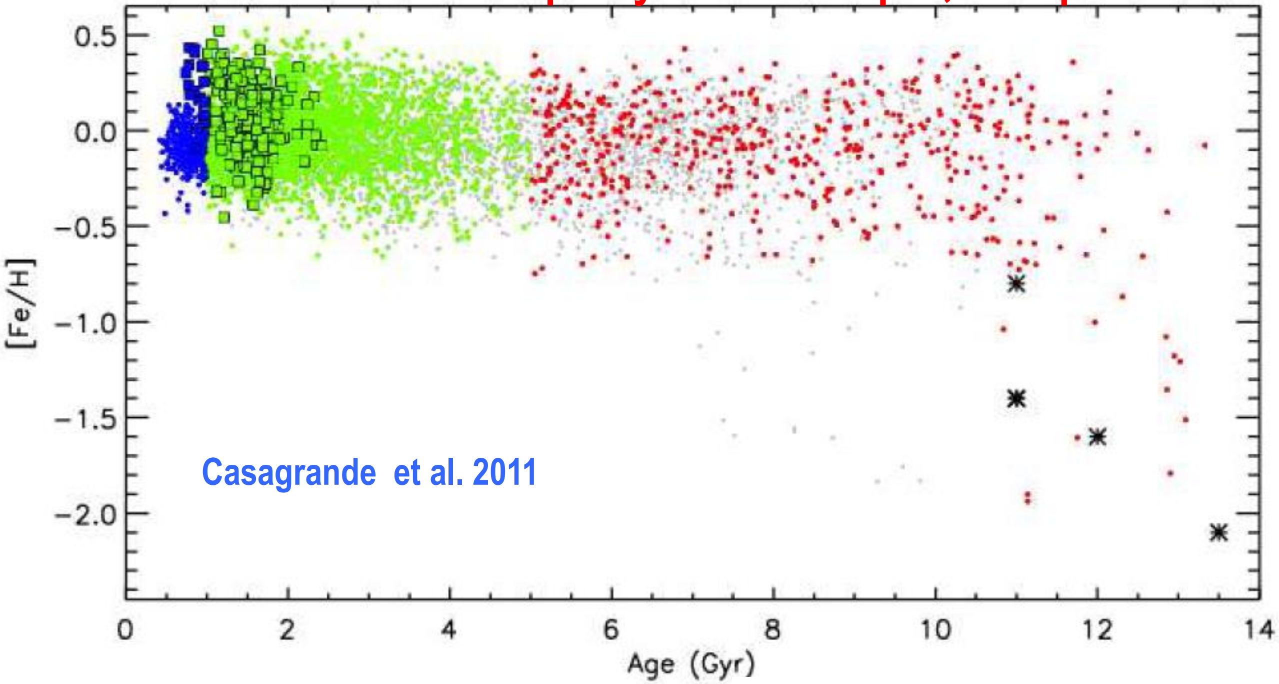
M_{STARS} increased by 3-4 ; M_{GAS} remained ~constant ; Z_{GAS} increased by 2-3





Simple models constitute a good approximation of more complex (realistic?)ones

Inadequacy of the simple, independent-ring models



GCS Survey of
Solar neighborhood
(*Nordstrom et al. 2004*,
Holmberg et al. 2009)

-Little metallicity evolution in the past 10 Gyr

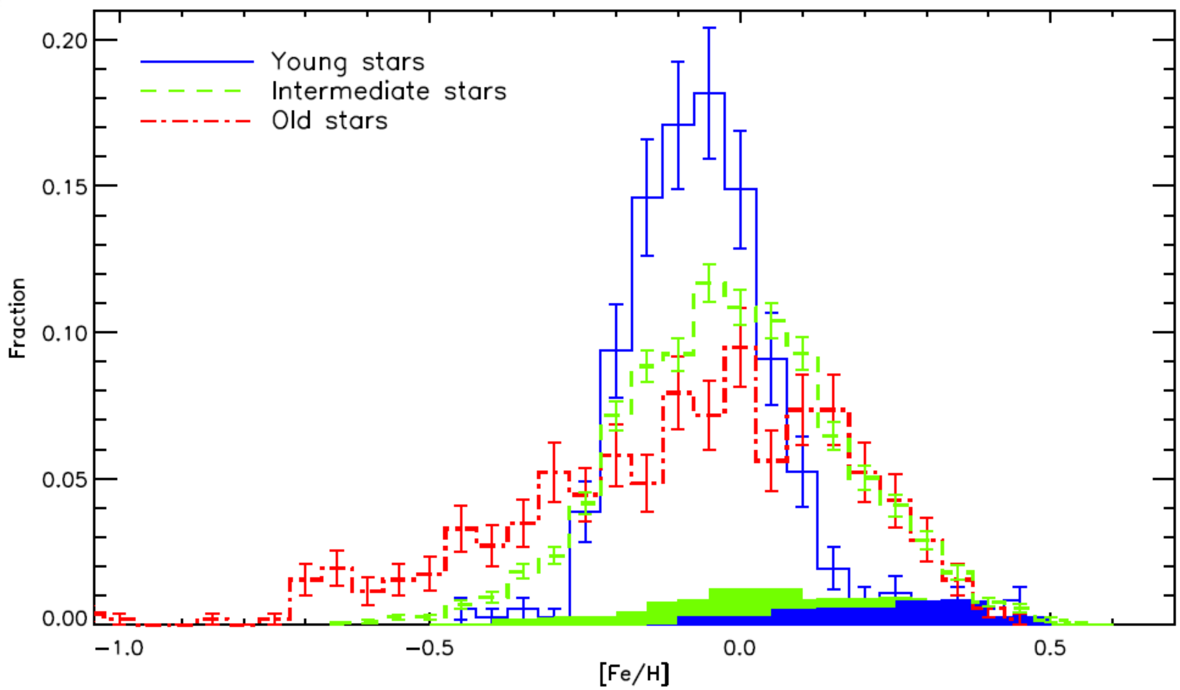
- Large scatter in Fe/H at all ages

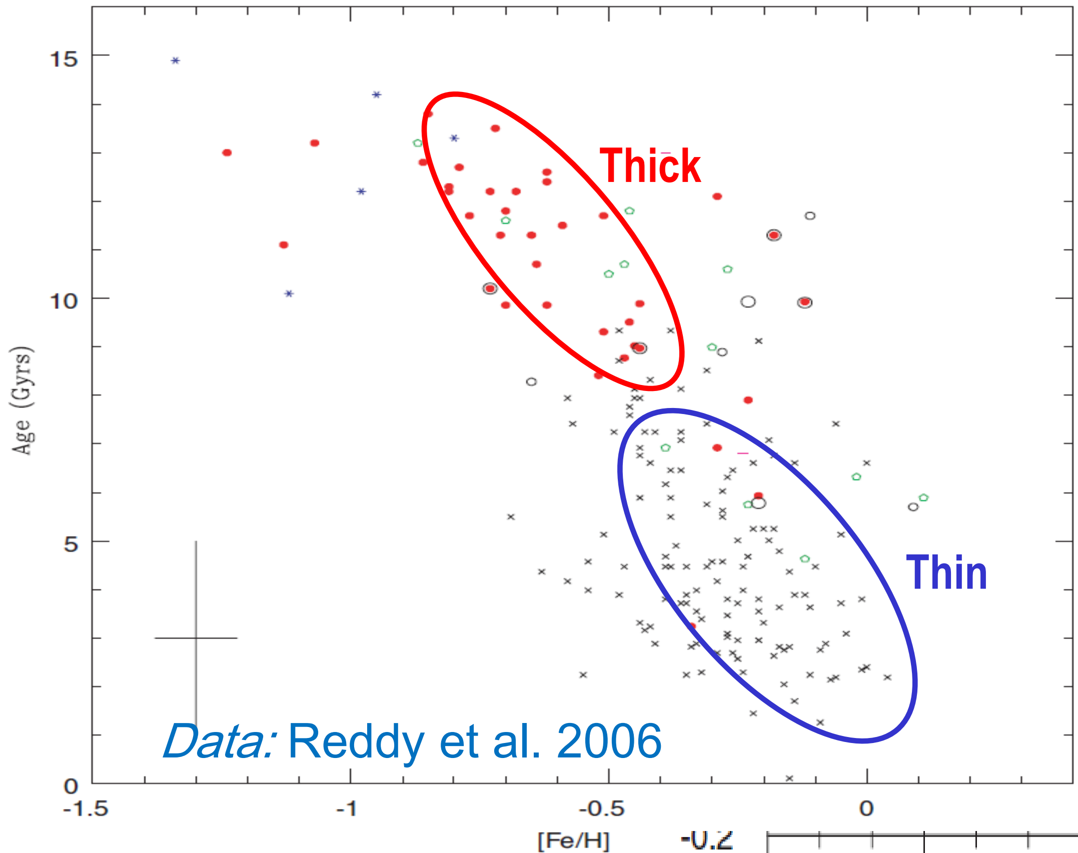
(also *Edvardsssson et al. 1993*)

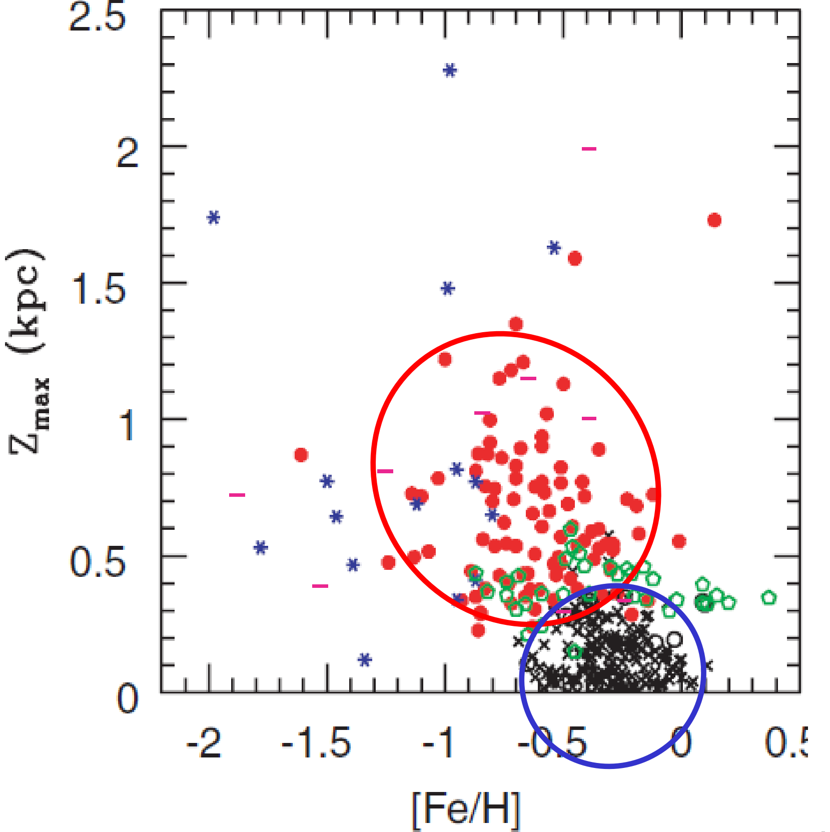
Old stars of **both *high*** and ***low*** metallicities

Inadequacy of the simple (independent ring) model

(*Edvardsson et al. 1993*, *Haywood 2006*)

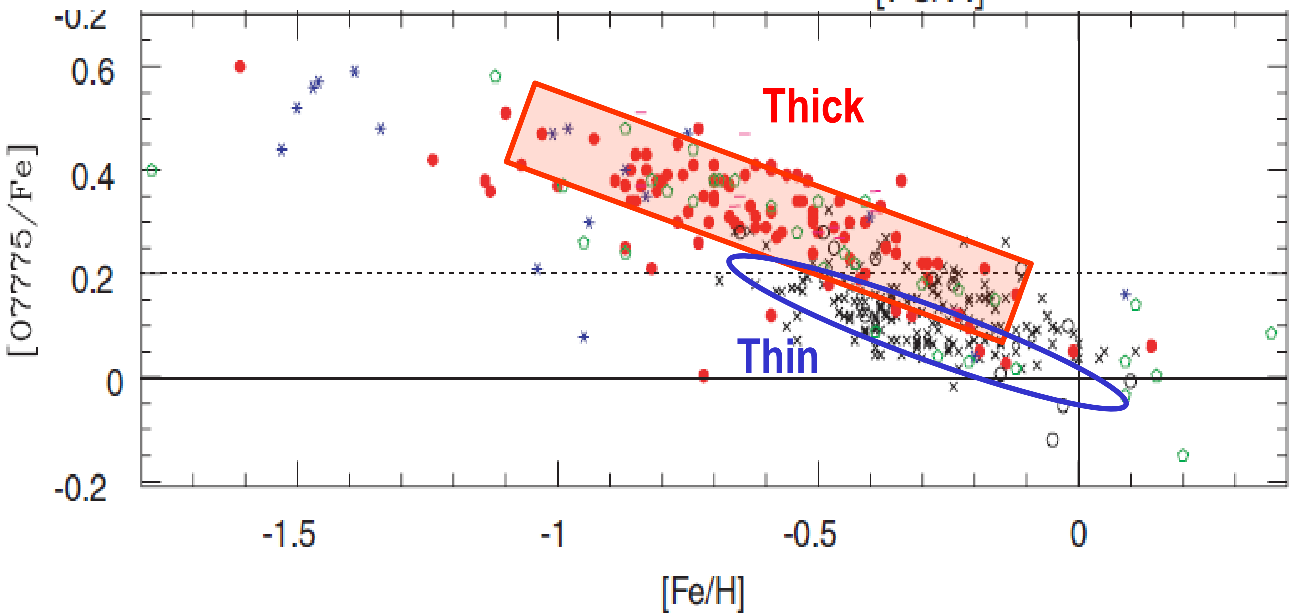






The issue of the thick disk

Old (>9 Gyr) stars,
away from the plane
having **higher O/Fe ratio**
than thin disk stars
of the same metallicity



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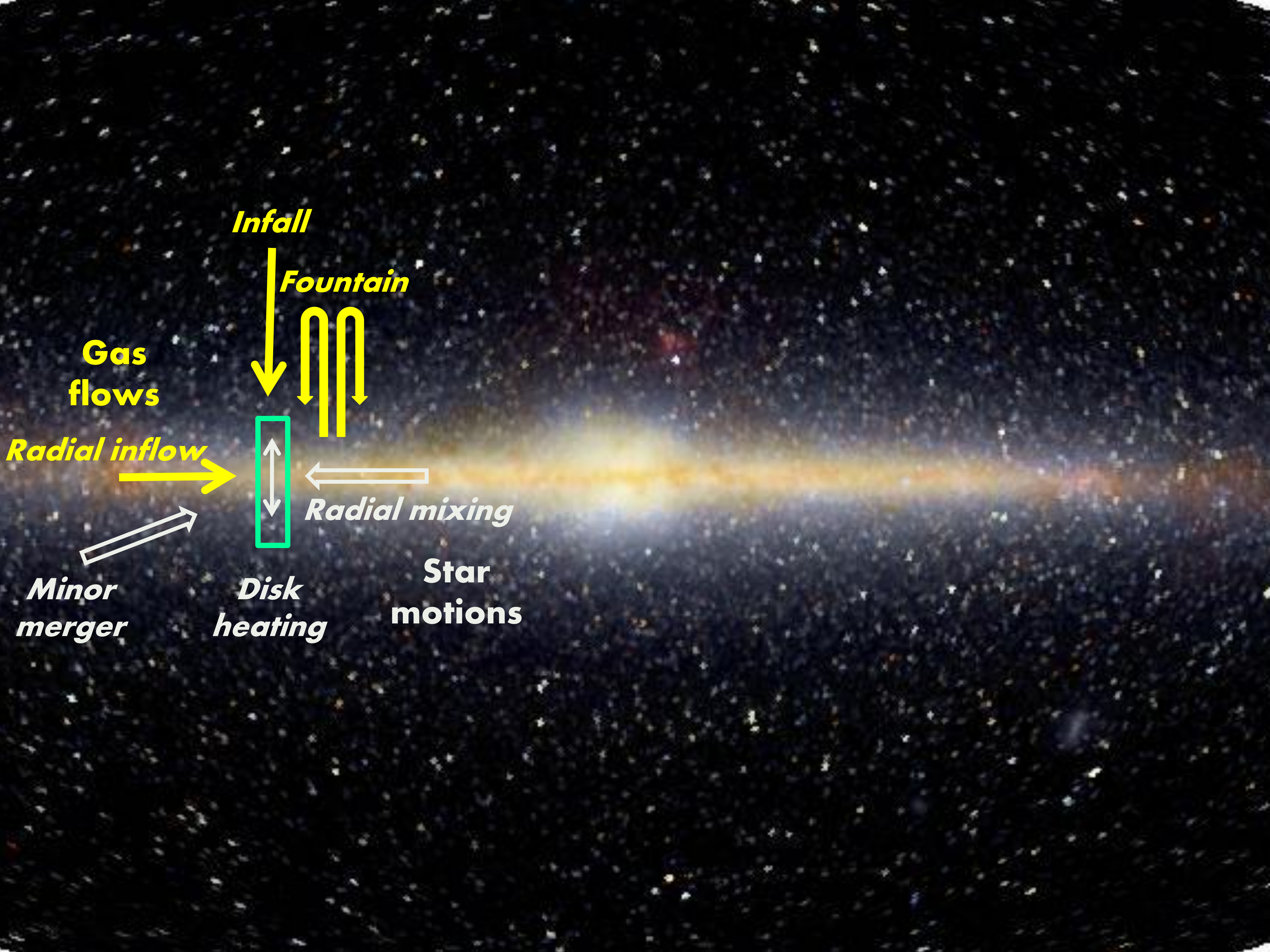
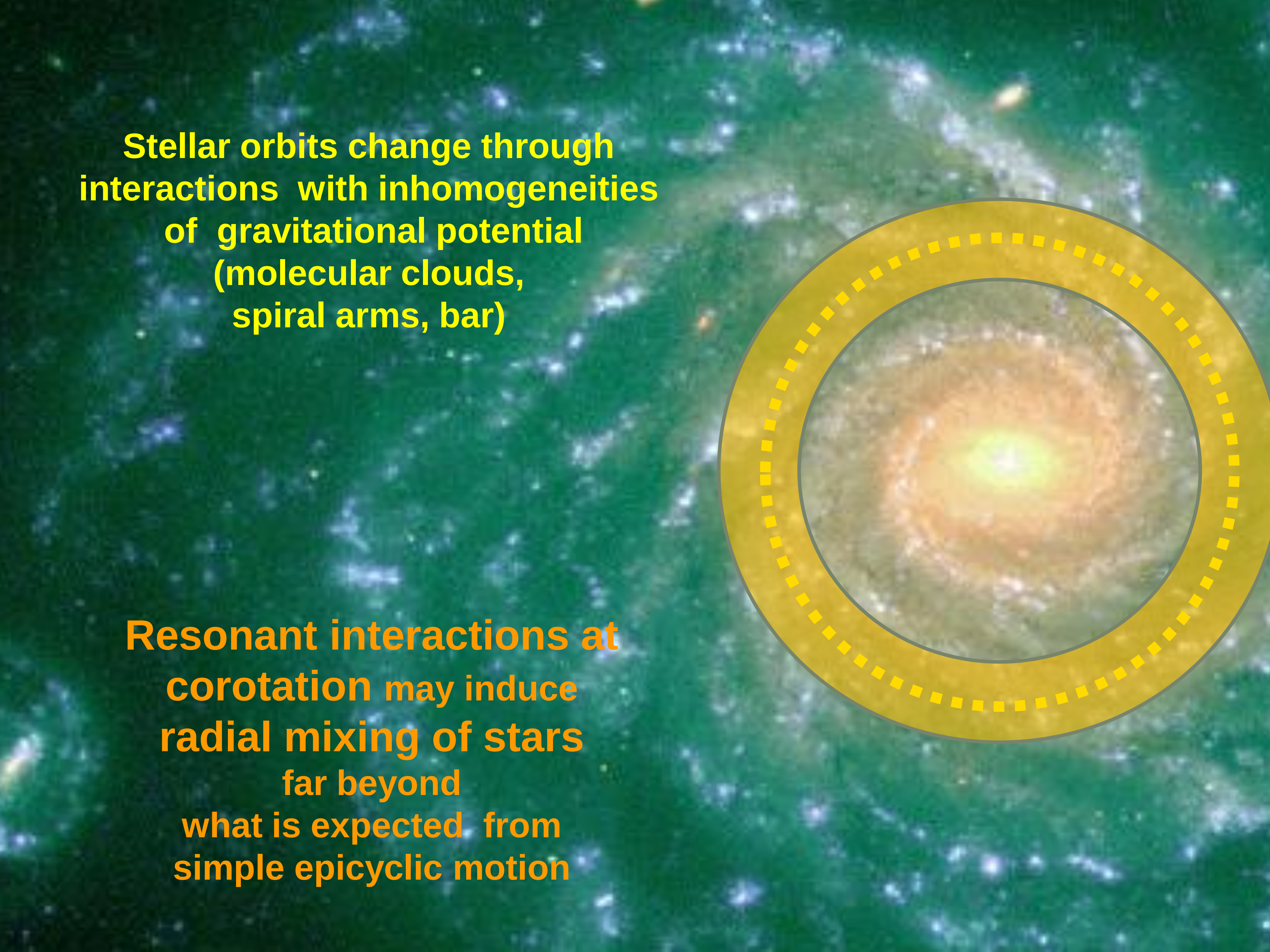
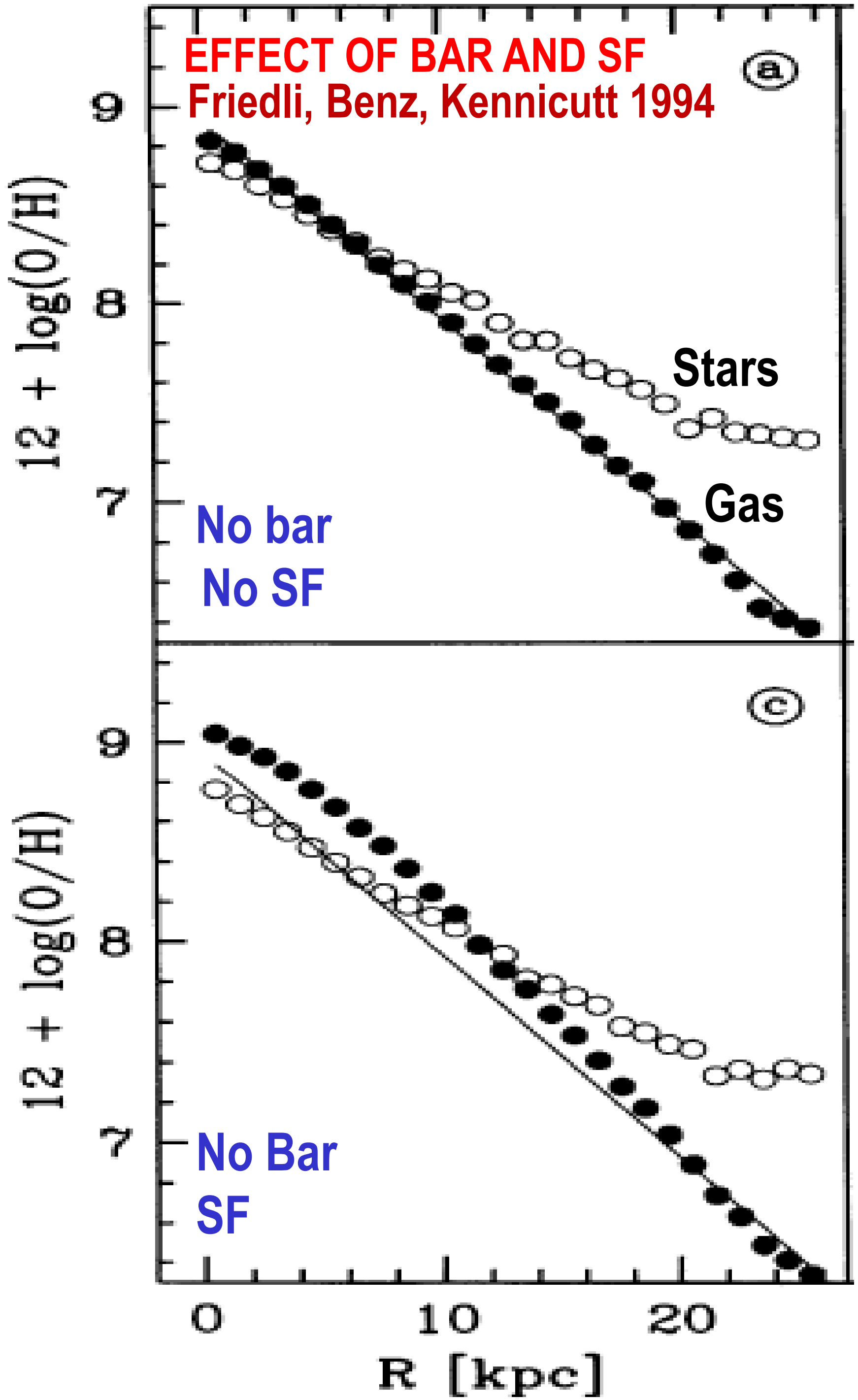
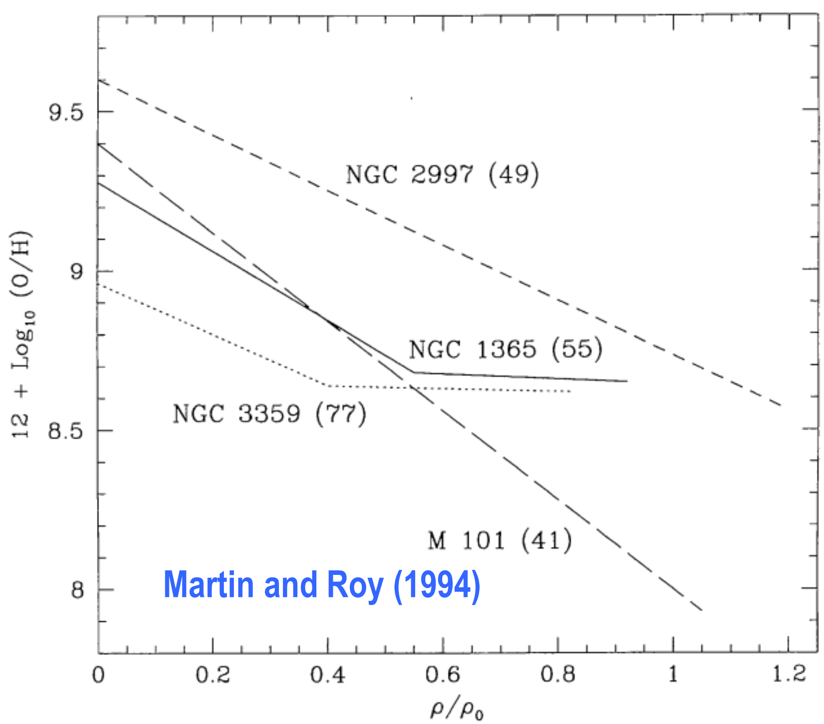
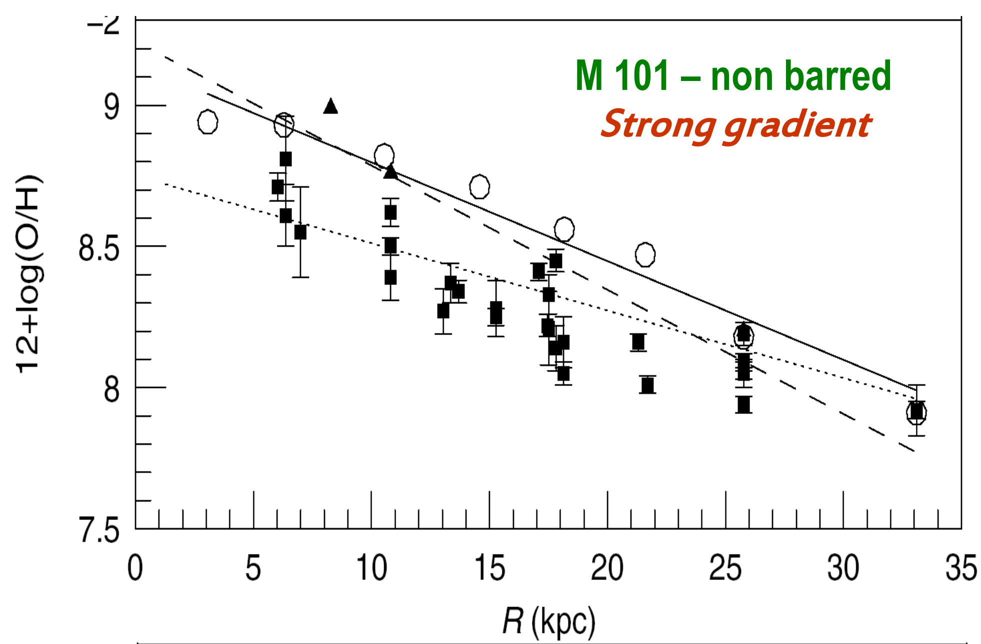
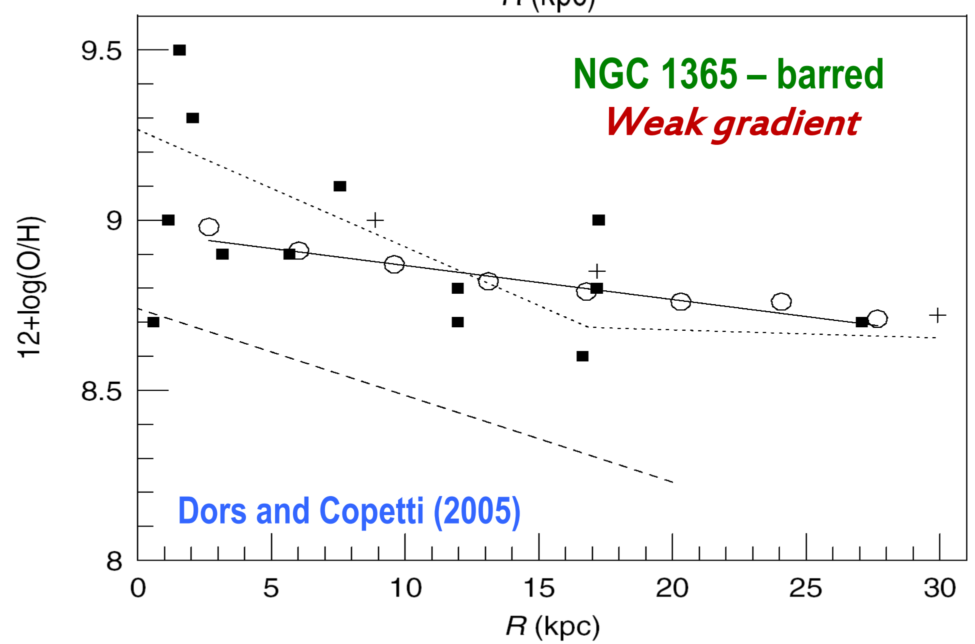

Infall
Fountain
Gas
flows
Radial inflow
Radial mixing
Star
motions
Minor
merger
Disk
heating


Stellar orbits change through
interactions with inhomogeneities
of gravitational potential
(molecular clouds,
spiral arms, bar)
Resonant interactions at
corotation may induce
radial mixing of stars
far beyond
what is expected from
simple epicyclic motion


EFFECT OF BAR AND SF
Friedli, Benz, Kennicutt 1994
(a)
Stars
Gas
No bar
No SF
(c)
No Bar
SF
12 + log(O/H)
9
8
7
0
10
20
R [kpc]



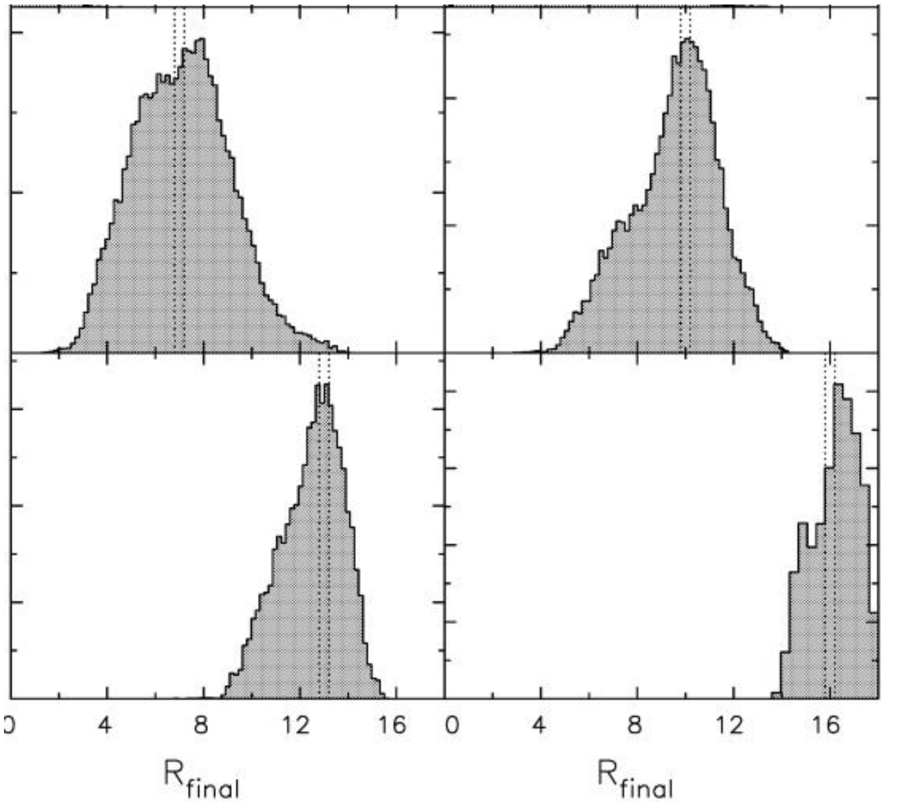




The value of the abundance gradient is crucial regarding the action of a **galactic bar**

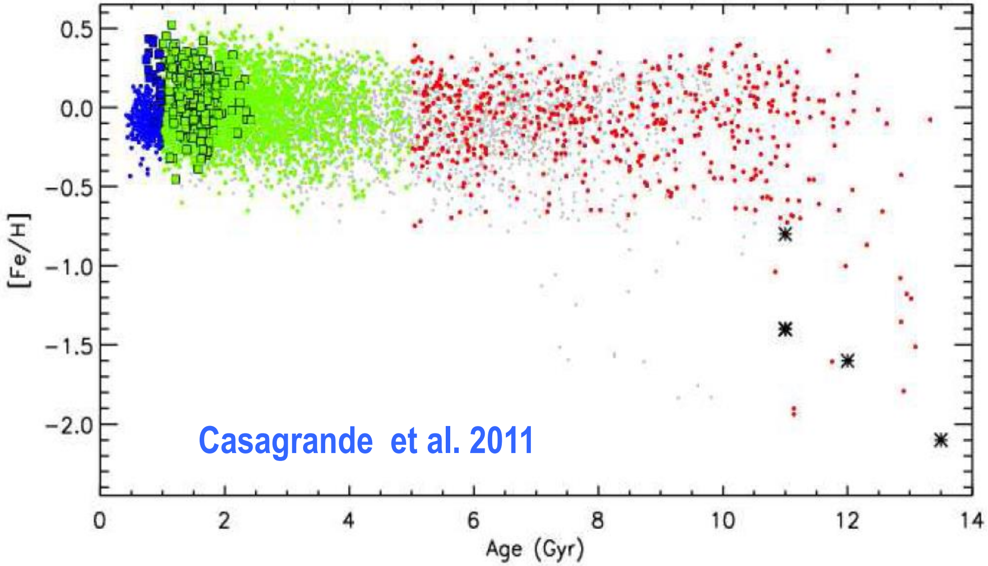
A bar drives (metal-poor) gas from the corotation region inwards, and this **radial inflow** tends to **reduce abundance gradients**

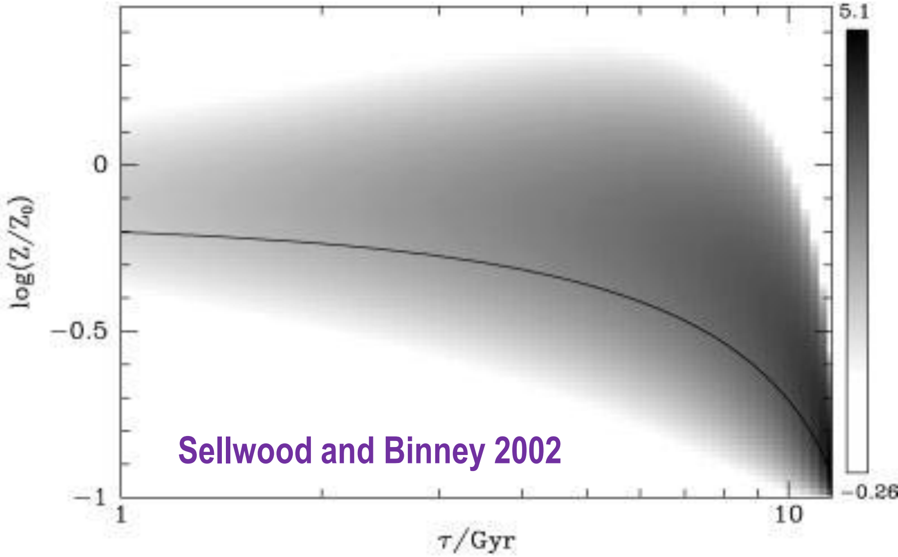
EFFECT OF TRANSIENT SPIRALS
(Sellwood and Binney 2002)



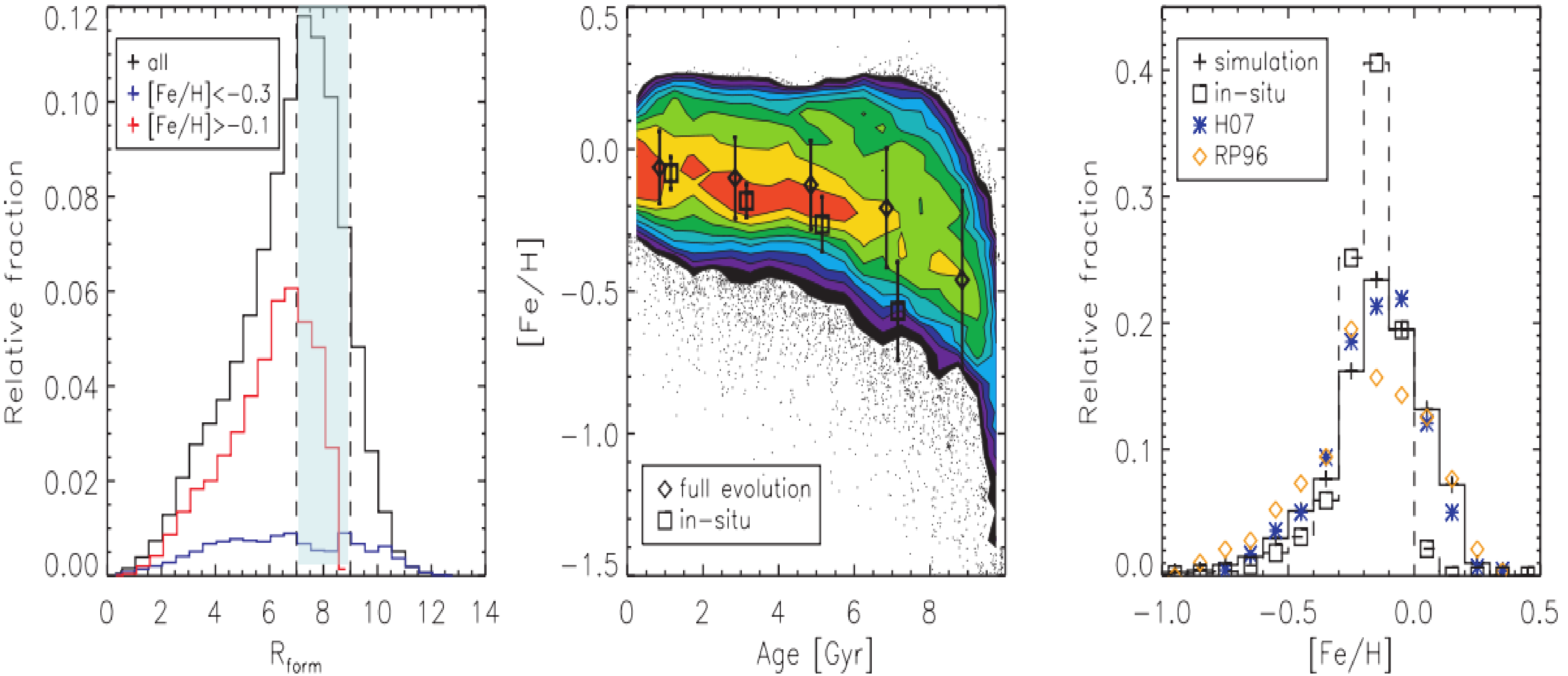
Stars just inside corotation swap places with those just outside it;
Radial migration (churning)
without heating radially the disk

It can « naturally » explain *(assuming* a disk metallicity gradient) the observed *dispersion* in local age-metallicity relation





Impact of radial migration on local disk (*Roskar et al. 2008, N-body+SPH*)



Fraction of stars now present In Solar neighborhood, but born in other places of the disk
Only 50% born in situ !

This impacts the Age-metallicity relation
Making it flatter and more dispersed

And the local Metallicity distribution
Making it broader

What if the Sun has migrated from the inner (higher than local metallicity) MW disk ?

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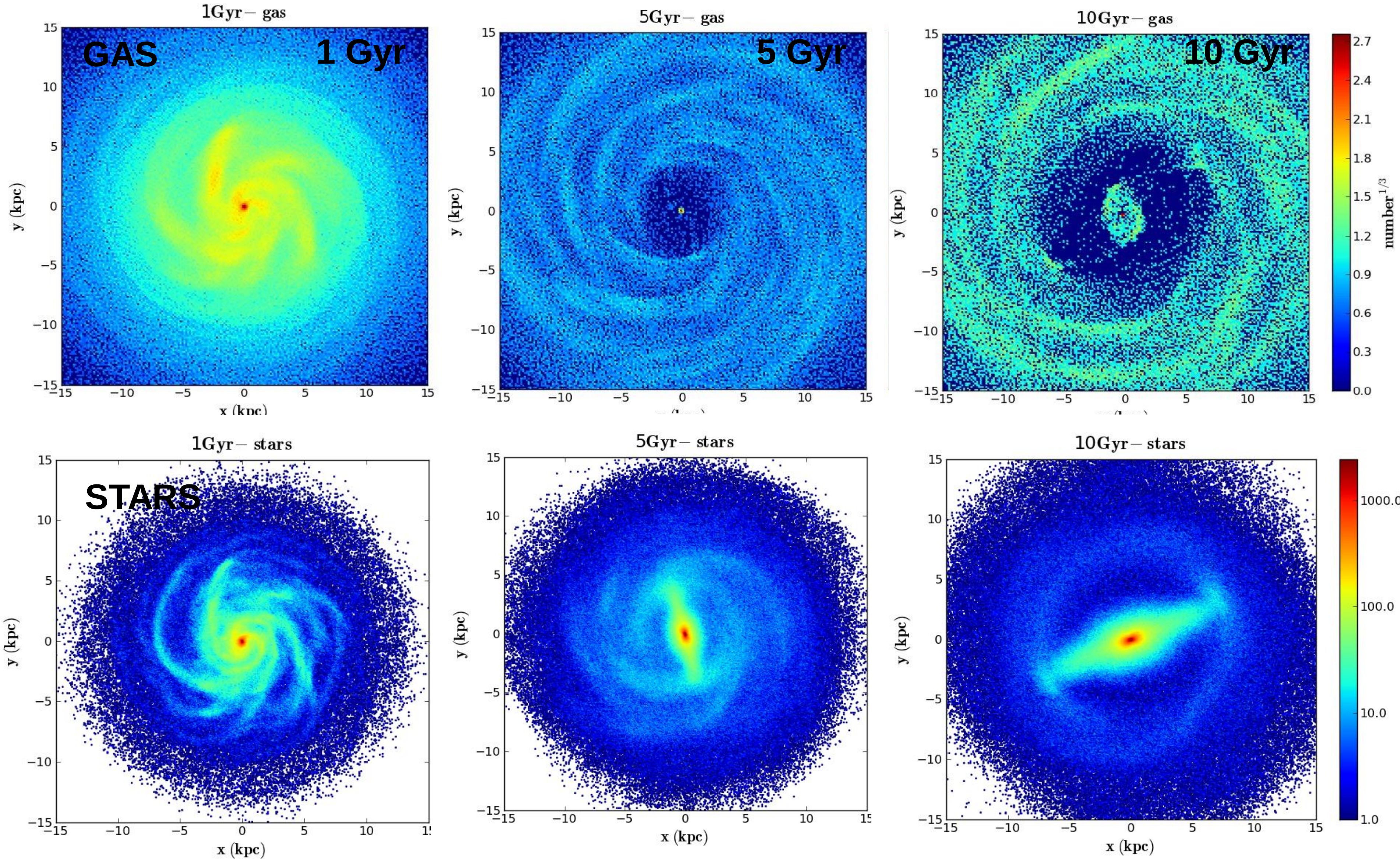
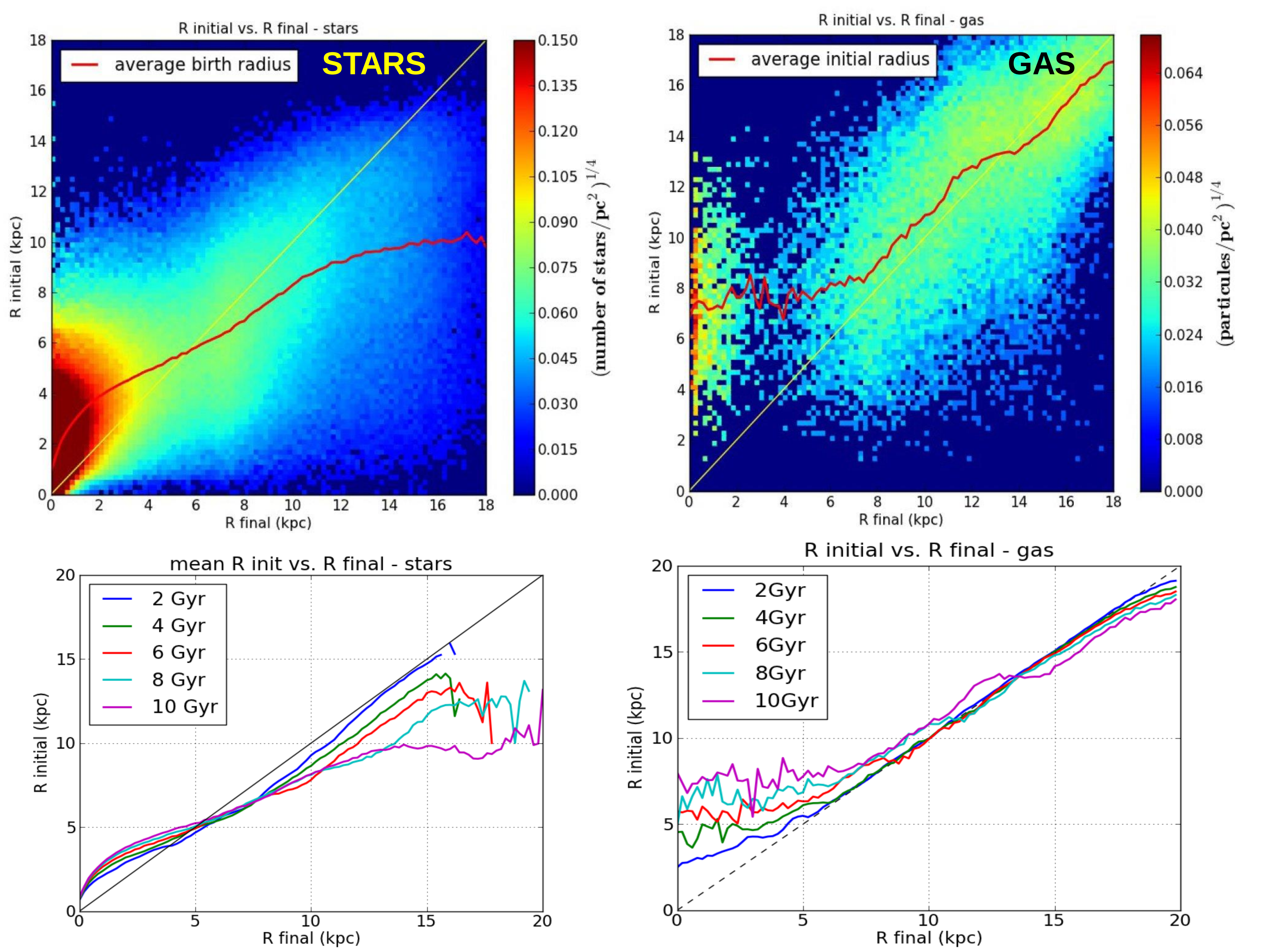
N-body+SPH simulations of a disk galaxy ***(Kubryk, NP, Athanassoula MNRAS 2013)***

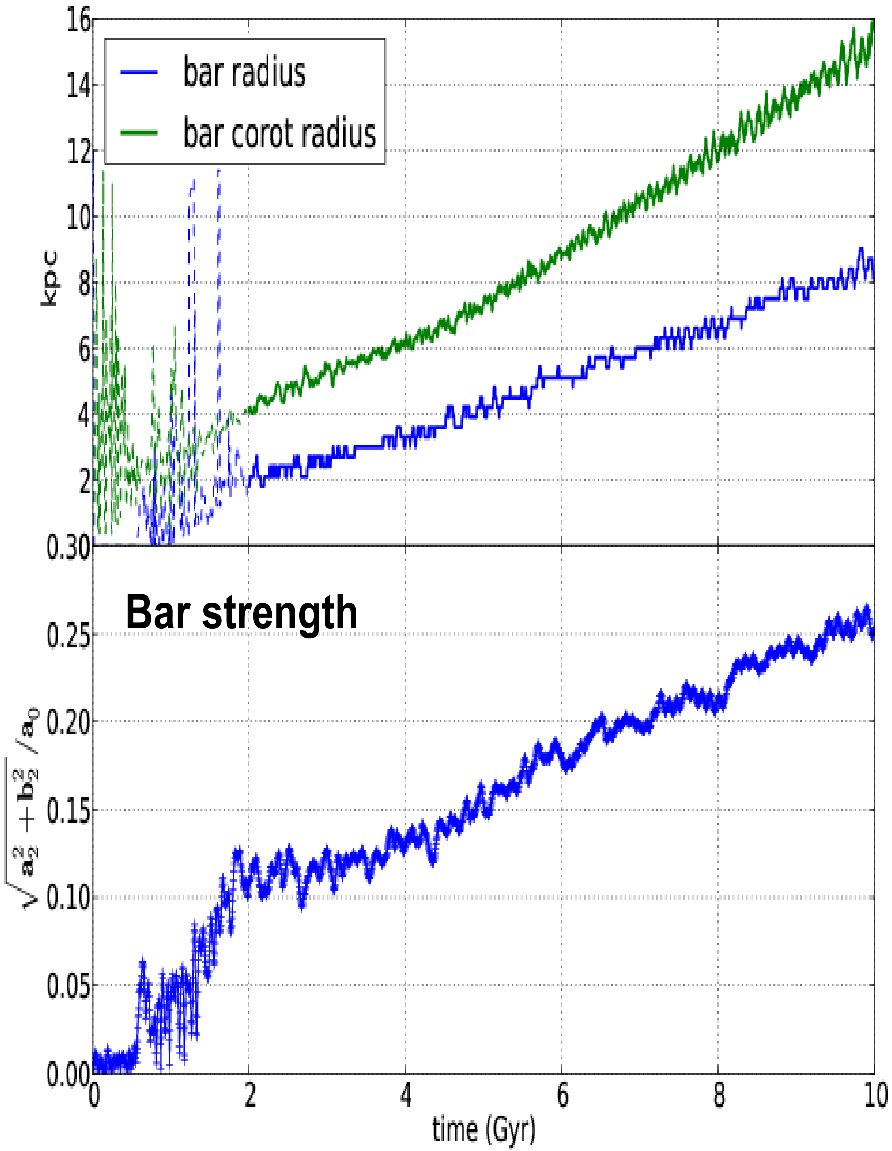
DM halo + baryonic disk + SFR + chemistry (1 «metal» + IRA), no infall



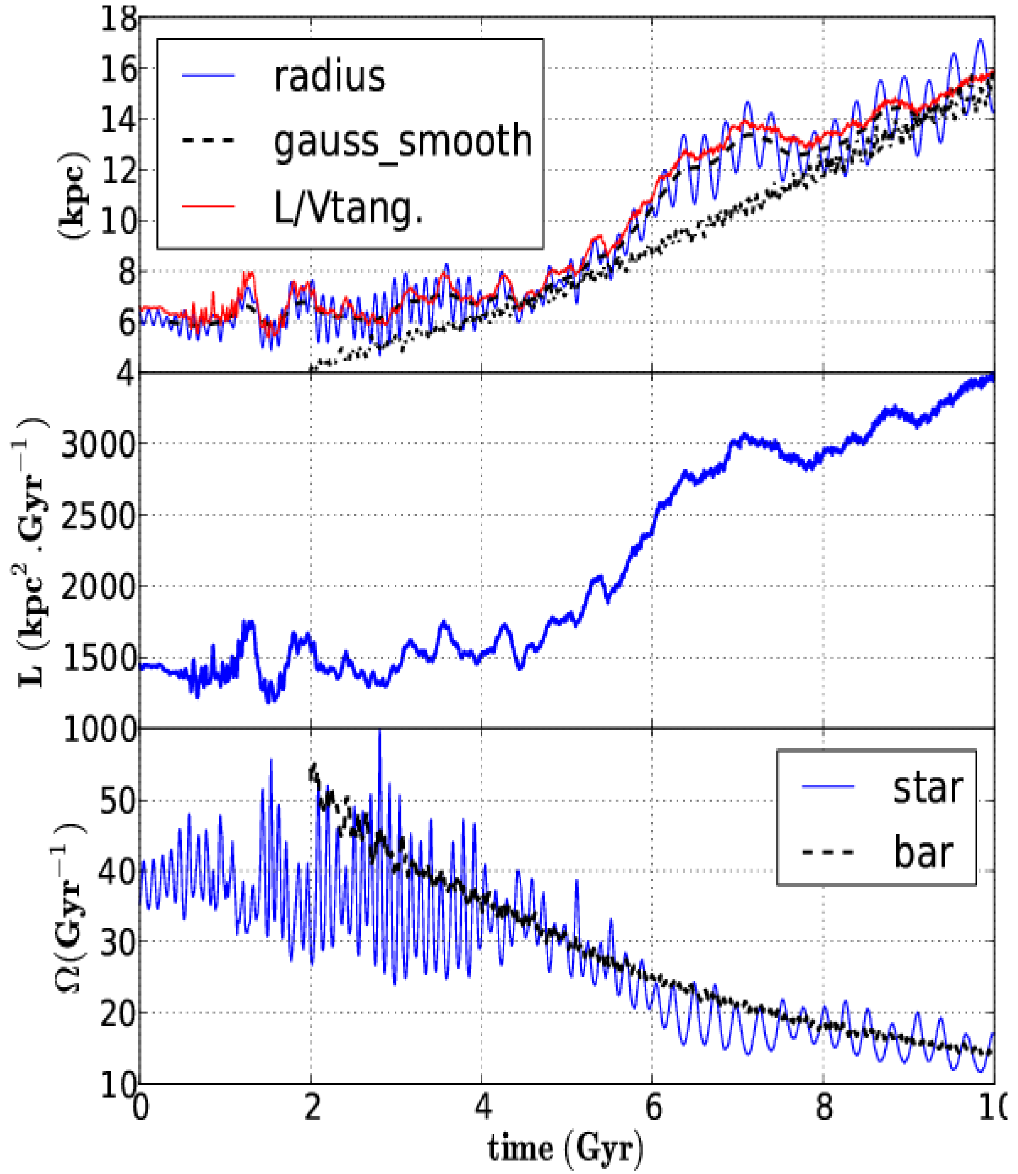
« Early type galaxy » with a strong bar, formed after the first 2 Gyr

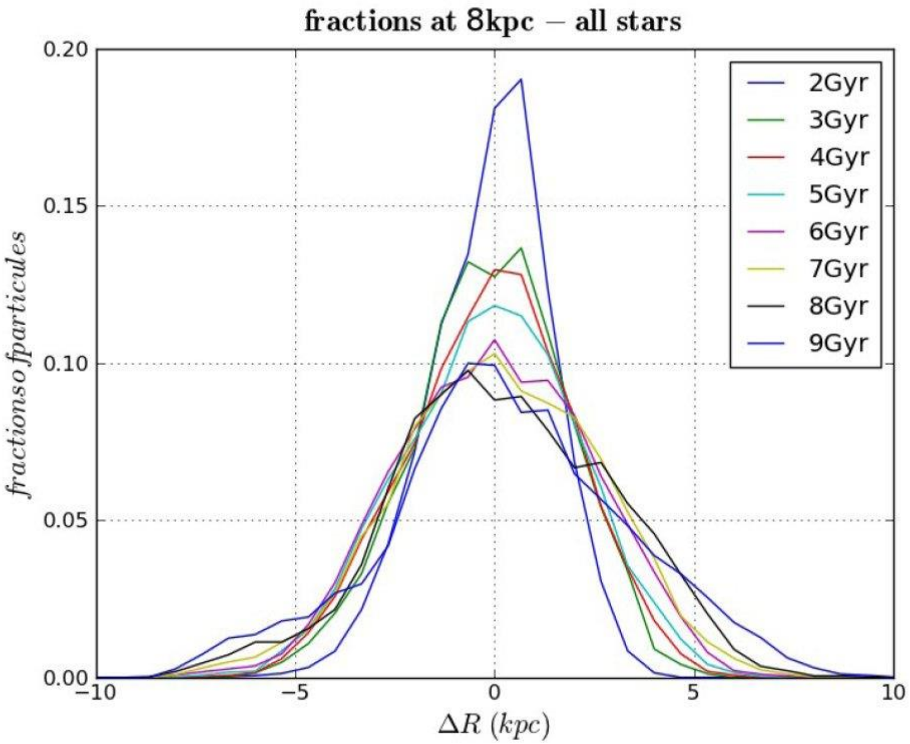

R initial vs. R final - stars
average birth radius
STARS
R initial (kpc)
R final (kpc)
(number of stars/pc^2)$^{1/4}$
R initial vs. R final - gas
average initial radius
GAS
R initial (kpc)
R final (kpc)
(particules/pc^2)$^{1/4}$
mean R init vs. R final - stars
2 Gyr
4 Gyr
6 Gyr
8 Gyr
10 Gyr
R initial (kpc)
R final (kpc)
R initial vs. R final - gas
2Gyr
4Gyr
6Gyr
8Gyr
10Gyr
R initial (kpc)
R final (kpc)

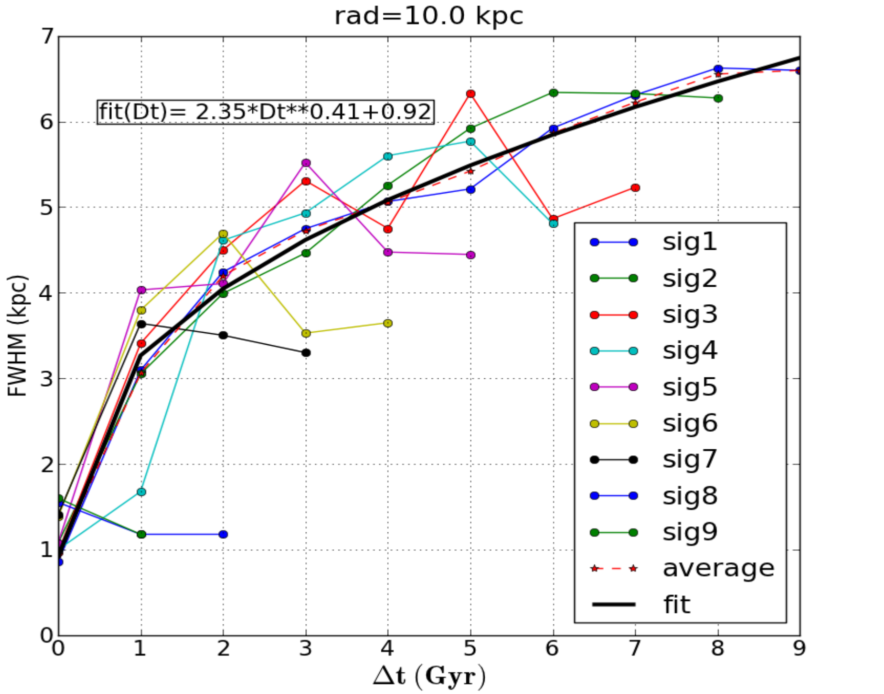
Bar radius and strength



Churning (true radial migration, *changing L*)

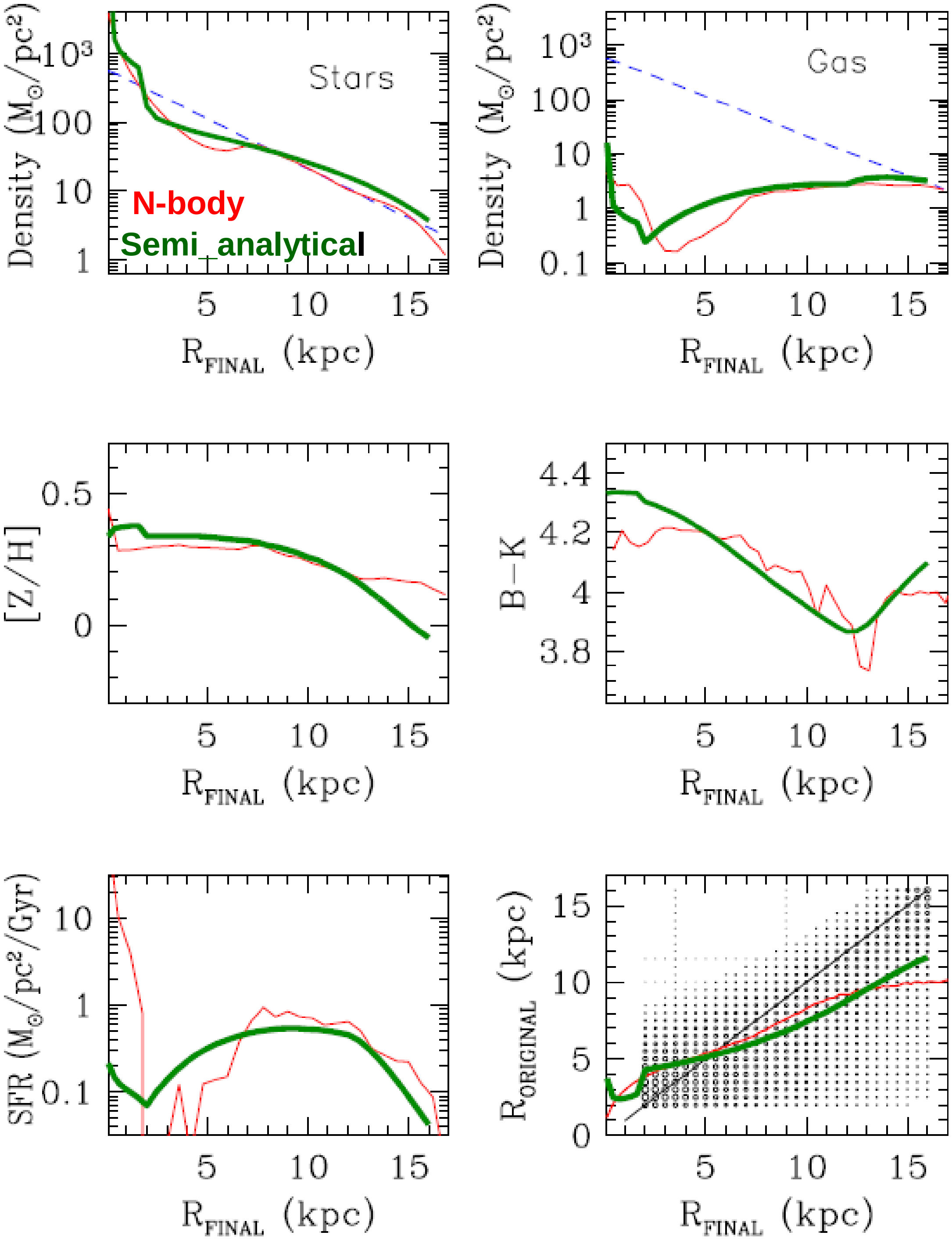






Modelling radial migration as a diffusion process with coefficients depending on time and radius (*see also Brunetti et al. 2011*)

$$\sigma(R0,t) = a(R0)\, t^{N} + b(R0)$$



Semi-analytical models,

augmented with

a probabilistic description

of radial migration,

can reproduce

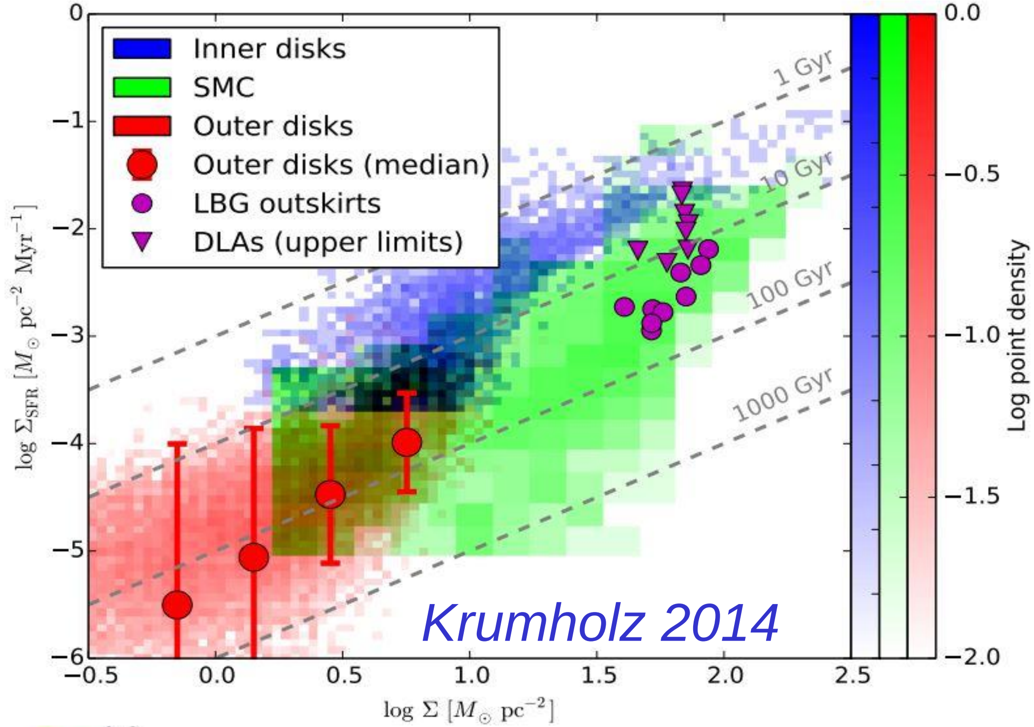
Satisfactorily

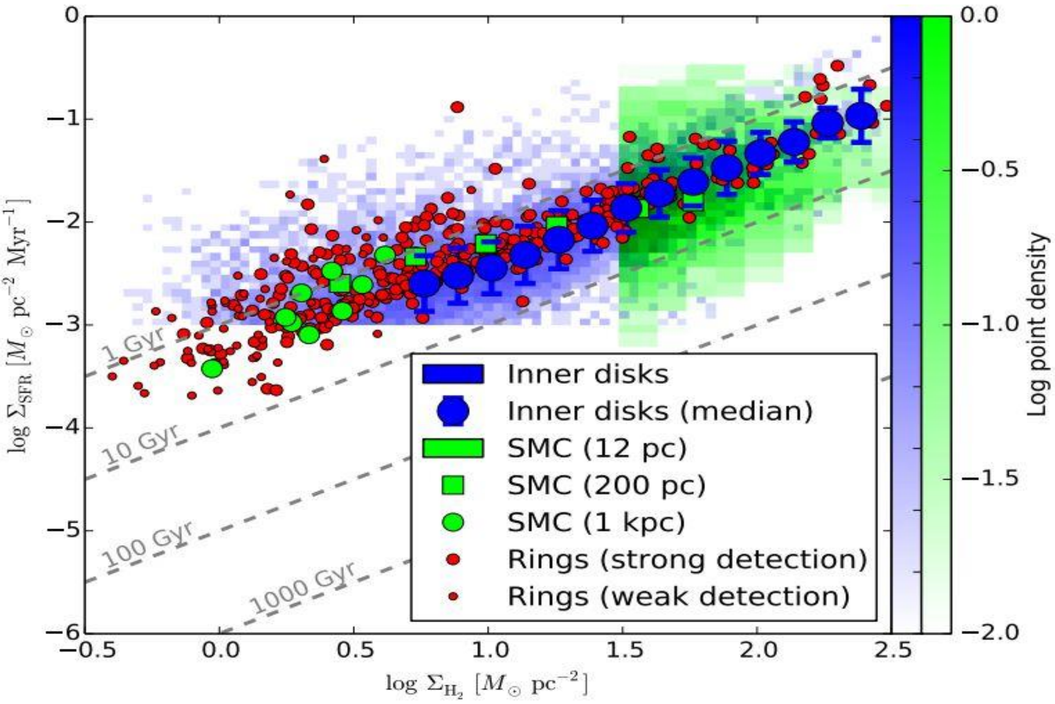
the results of

N-body+SPH models

WHICH PRESCRIPTION FOR STAR FORMATION ?

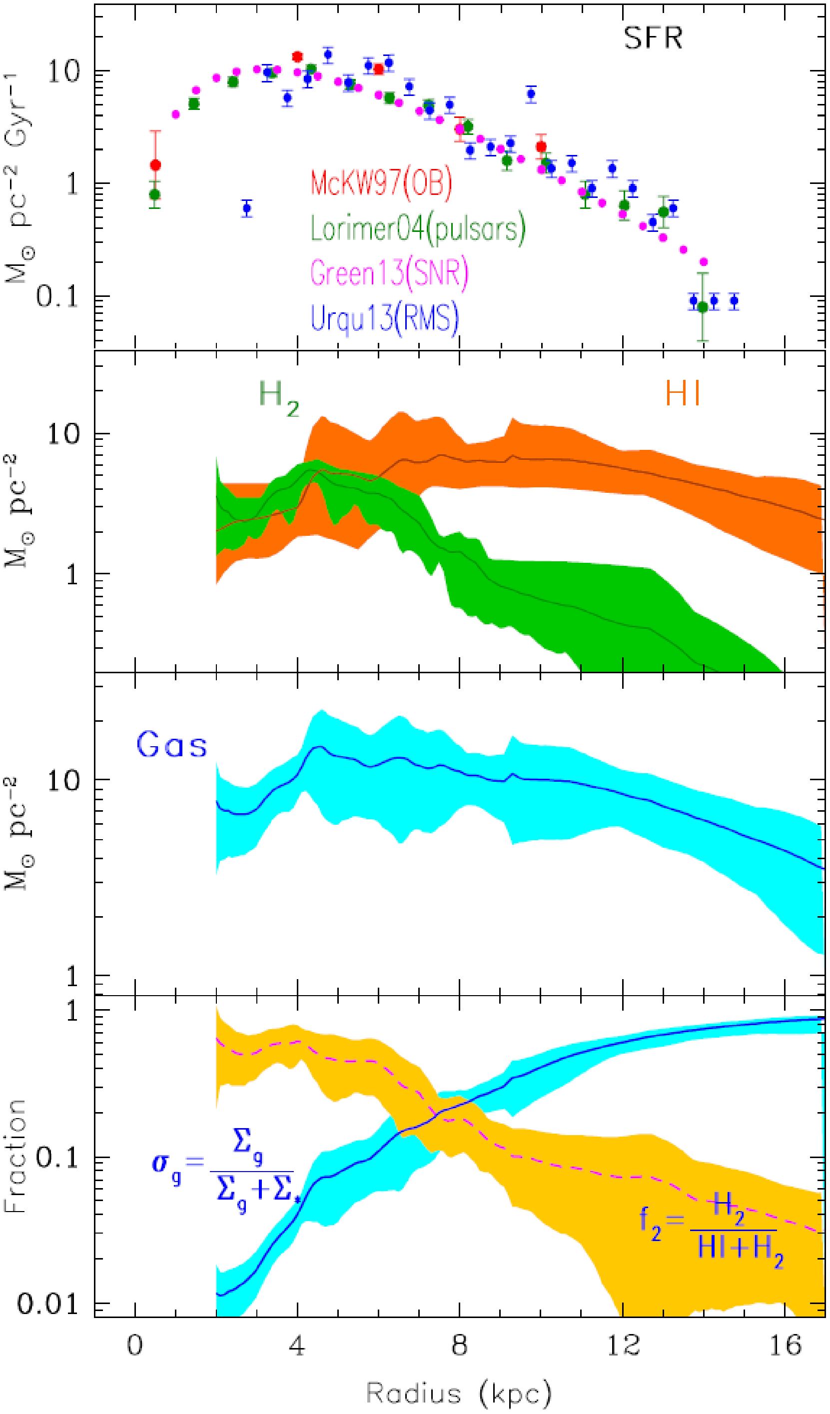
SFR vs Gas (HI+H2)





SFR vs Molecular Gas

In the MW also, the SFR follows better the molecular gas



$$SFR \propto H_2 \propto f_2 \Sigma_{GAS}$$

$$f_2 = \frac{H2}{HI+H2}$$

$$f_2 = \frac{R_{mol}}{R_{mol}+1}$$

$$R_{mol} = \frac{H_2}{HI}$$

Blitz and Rossolowski 2006 :

$$R_{mol} = \left[\frac{P_{ext}/k}{(4.3 \pm 0.6x10^4} \right]^{0.92 \pm 0.10}$$

$$\frac{P_{ext}}{k} = 272\,\mathrm{cm}^{-3}\mathrm{K} \left(\frac{\Sigma_G}{10\,M_\odot/\mathrm{pc}^2} \right) \left(\frac{\Sigma_*}{10\,M_\odot/\mathrm{pc}^2} \right)^{0.5} \left(\frac{v_G}{\mathrm{km/s}} \right) \left(\frac{h_*}{\mathrm{pc}} \right)$$

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)

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

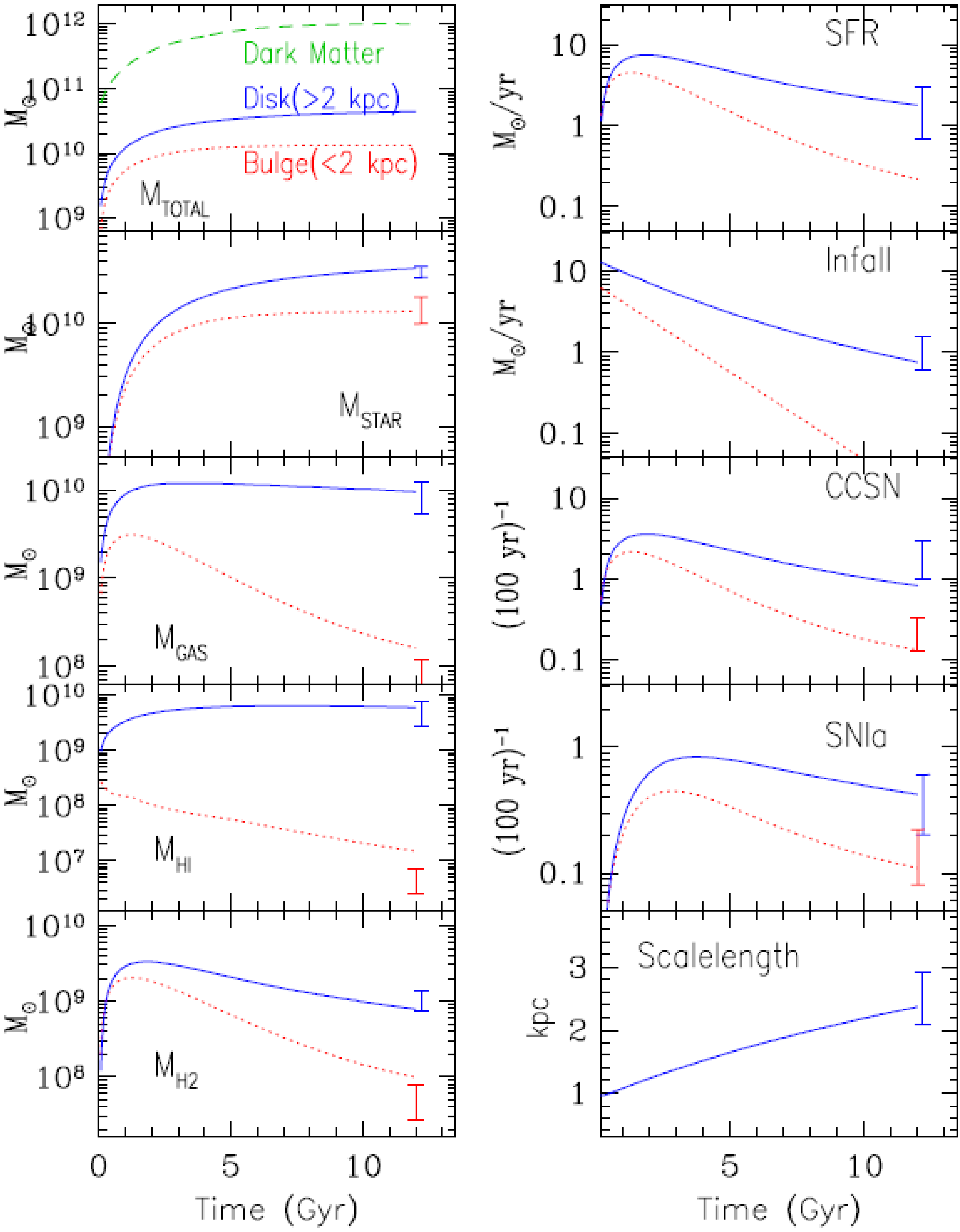
Coefficients α(r,t) and β (r,t) extracted from the numerical simulation of KPA2013
at t=2.5 Gyr
(bar similar in size to the one of the Milky Way)

Evolution of global quantities for Milky Way

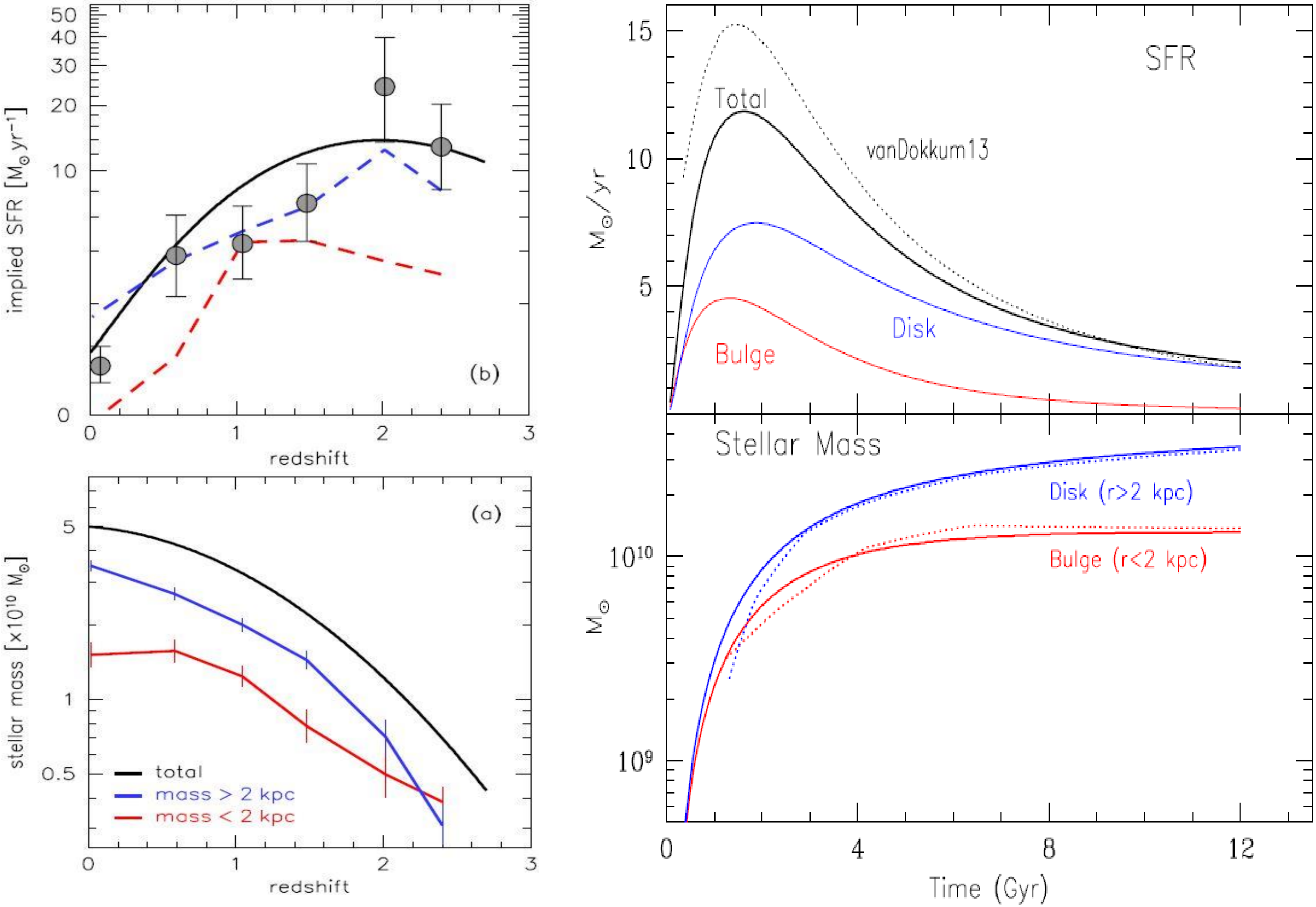
Bulge (<2 kpc)

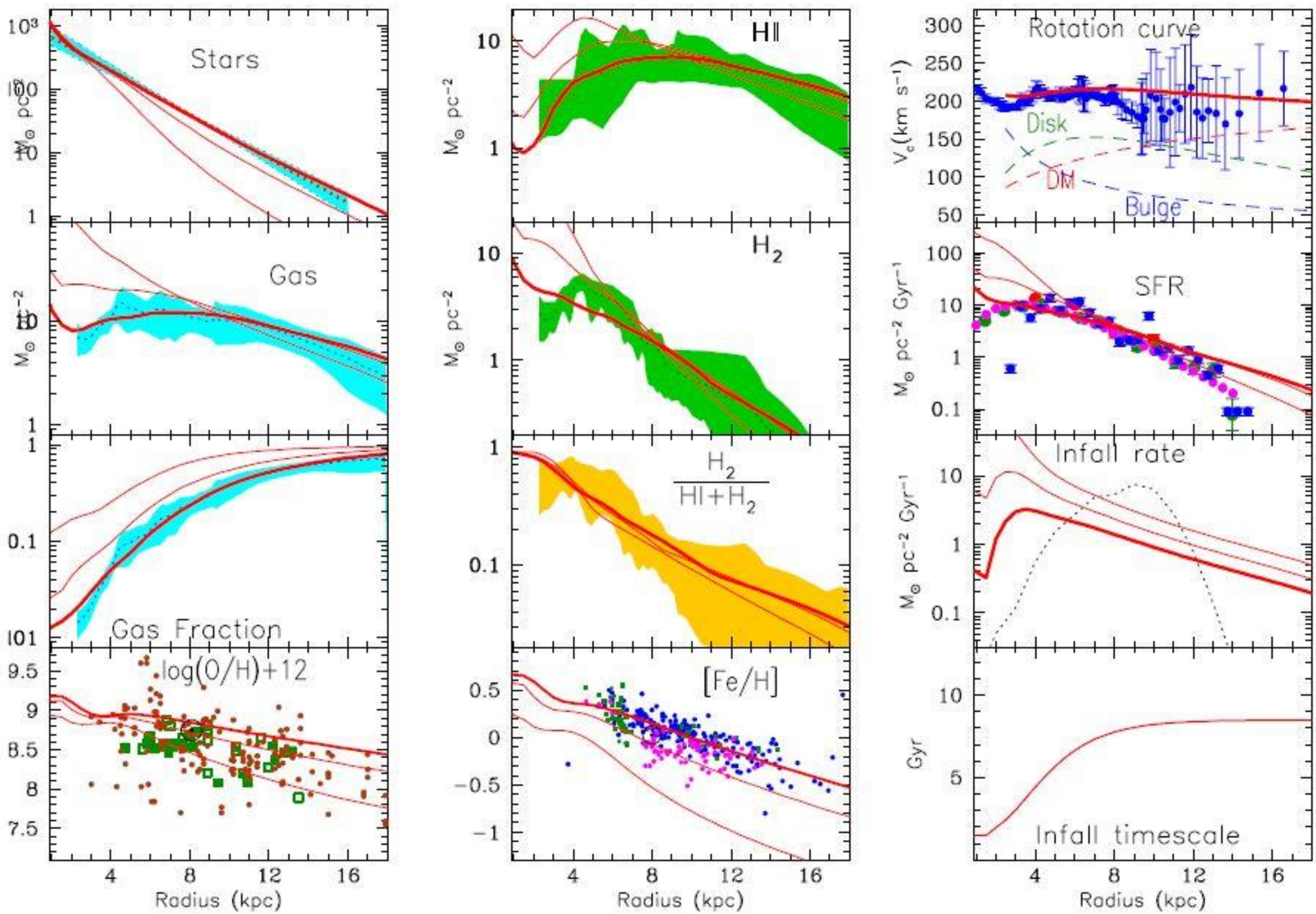
and

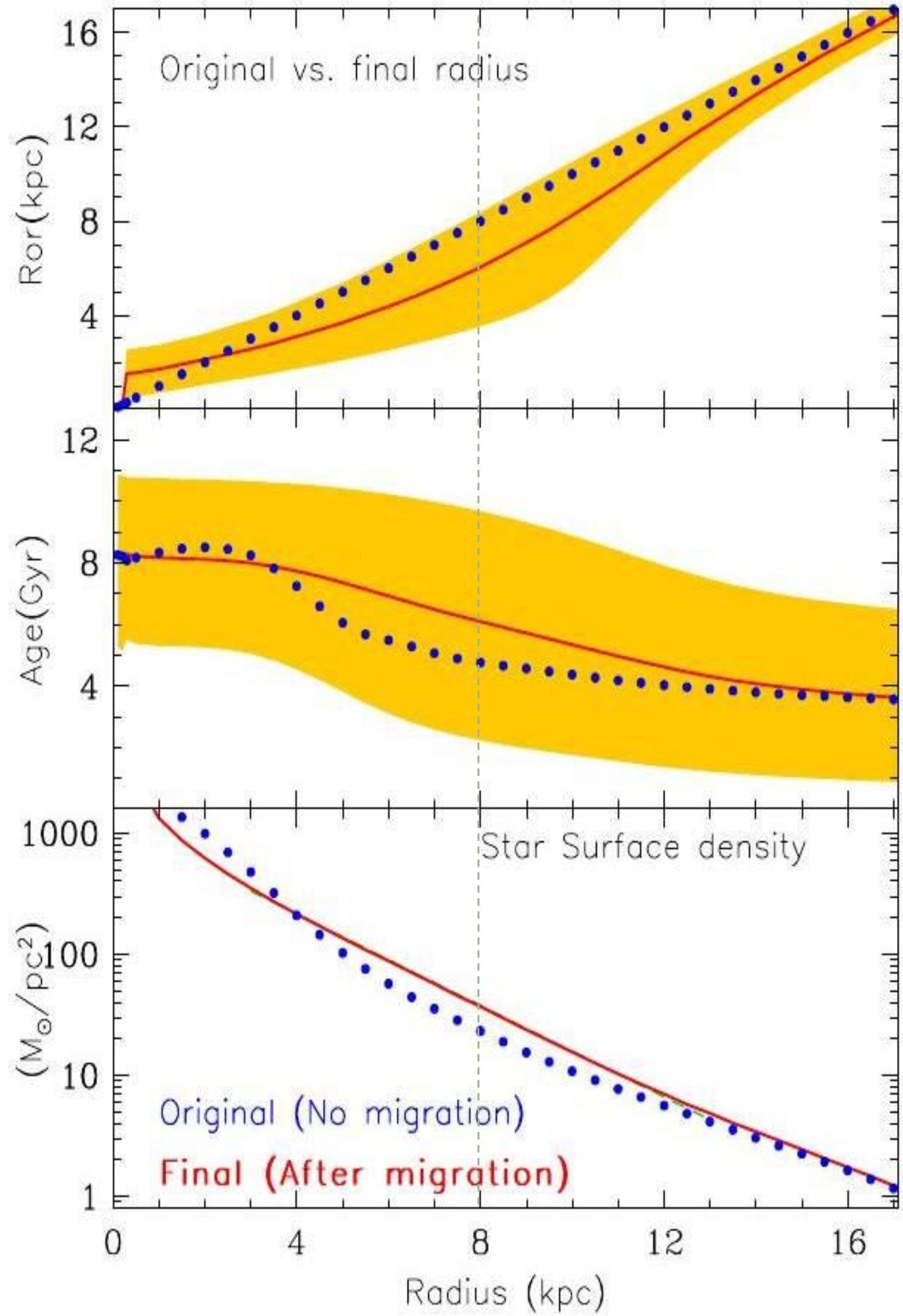
Disk (>2 kpc)



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

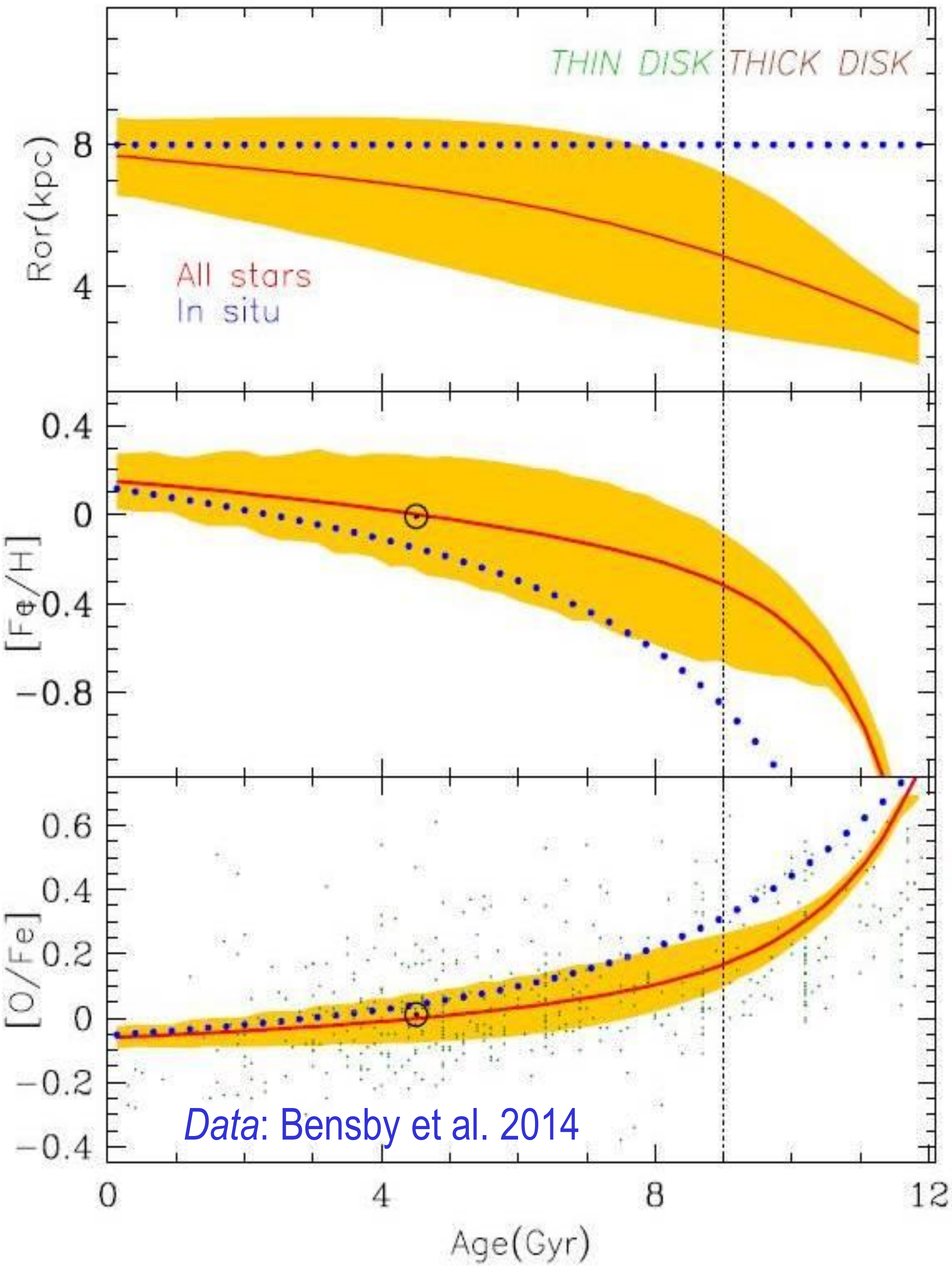



Stars
Gas
Gas Fraction
log(O/H)+12
HII
H2
H2 / HI+H2
[Fe/H]
Rotation curve
Disk
DM
Bulge
SFR
Infall rate
Infall timescale
M⊙ pc−2
M⊙ pc−2 Gyr−1
Vc(km s−1)
Gyr
Radius (kpc)



Radial migration affects a large fraction of the disk

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

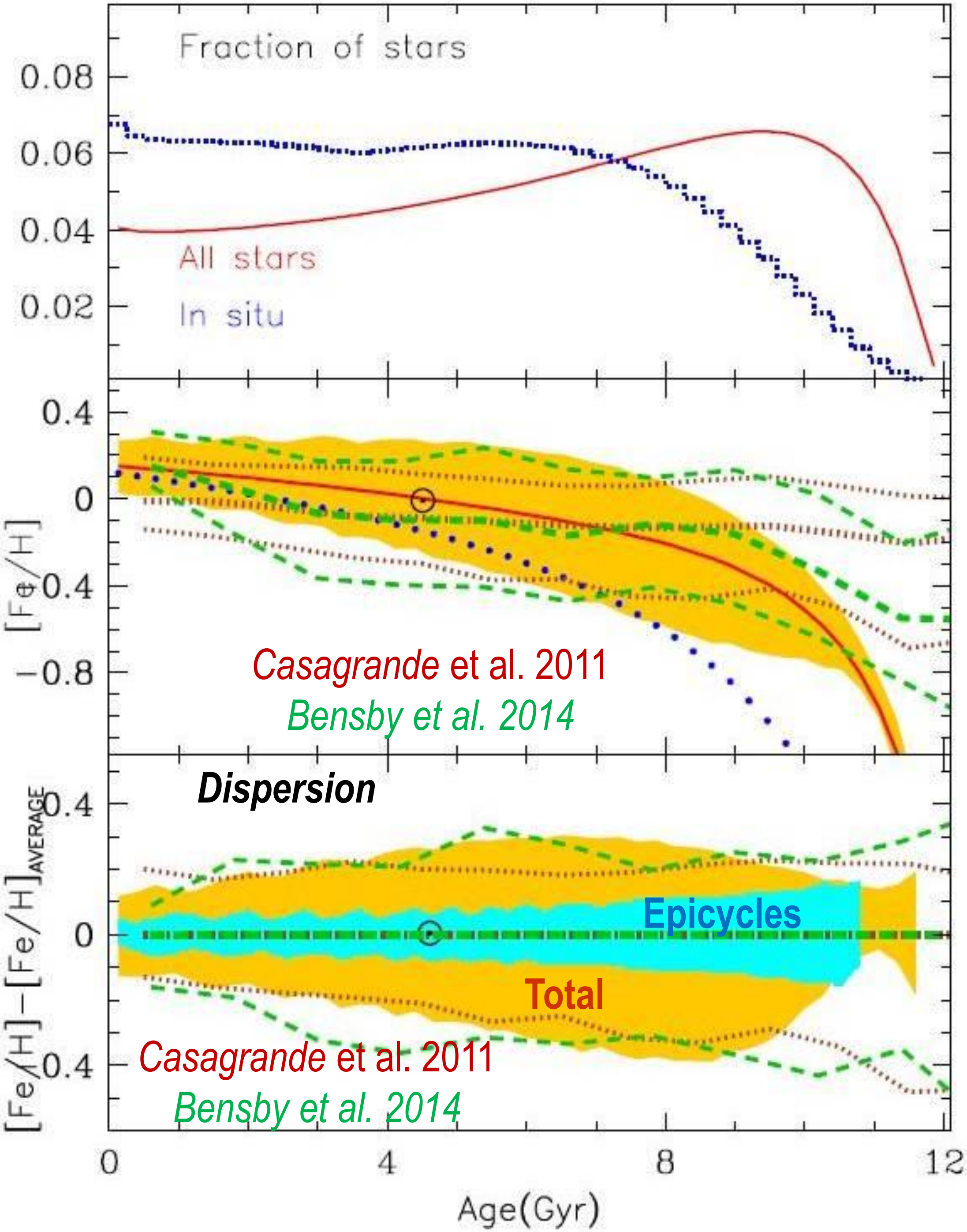


Solar neighborhood

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

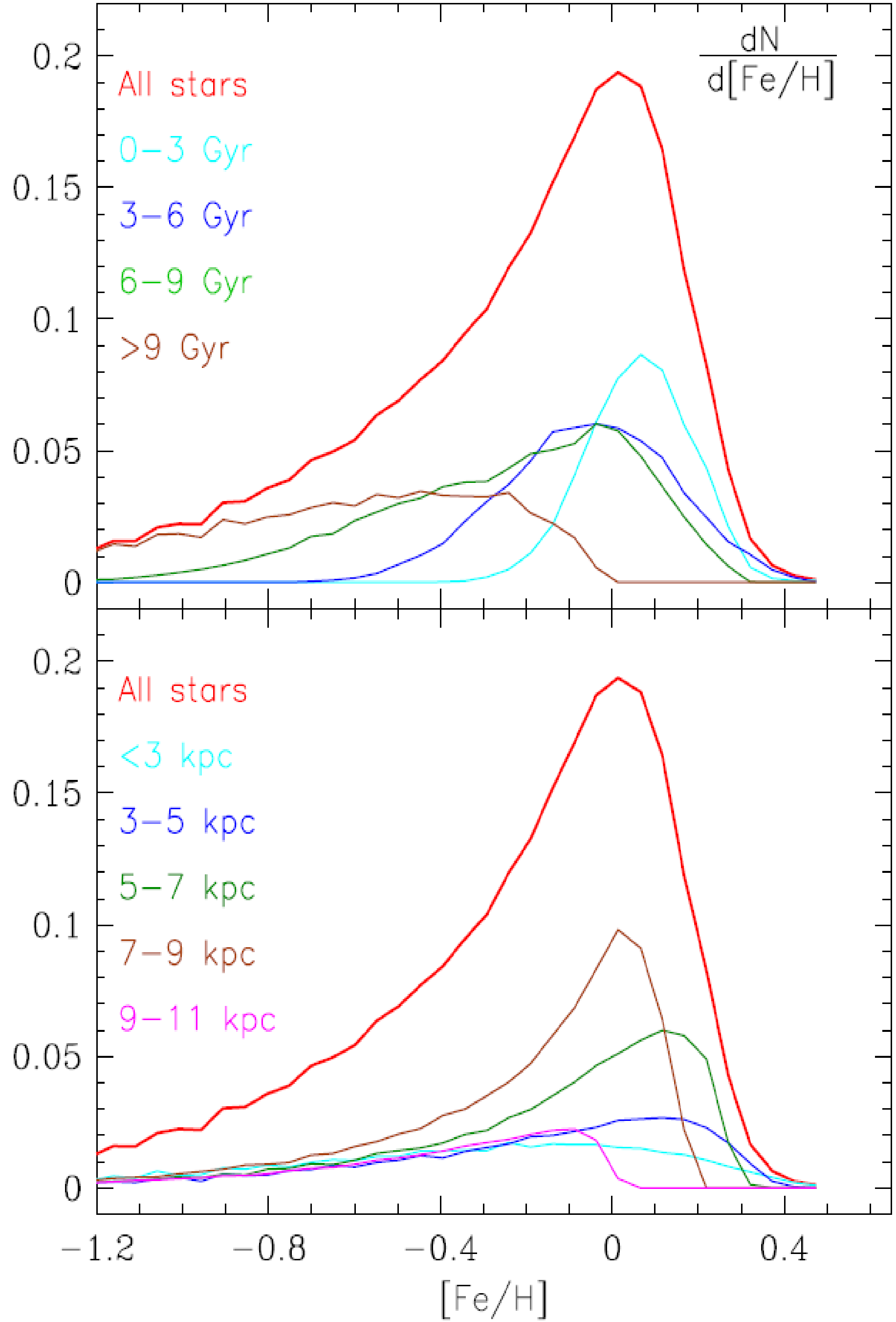
Radial Migration

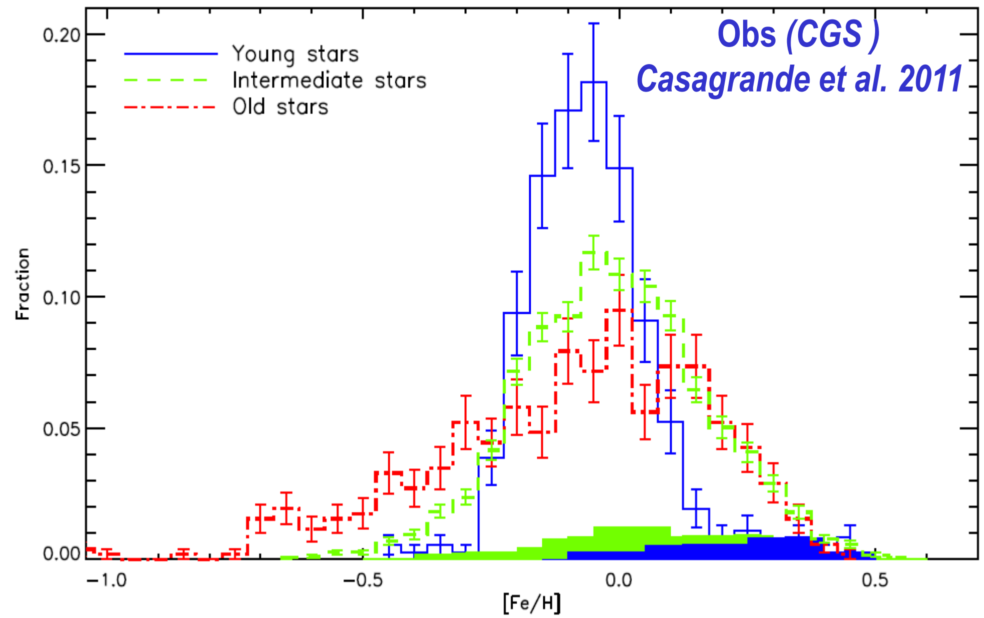
1. Modifies the apparent local SFR

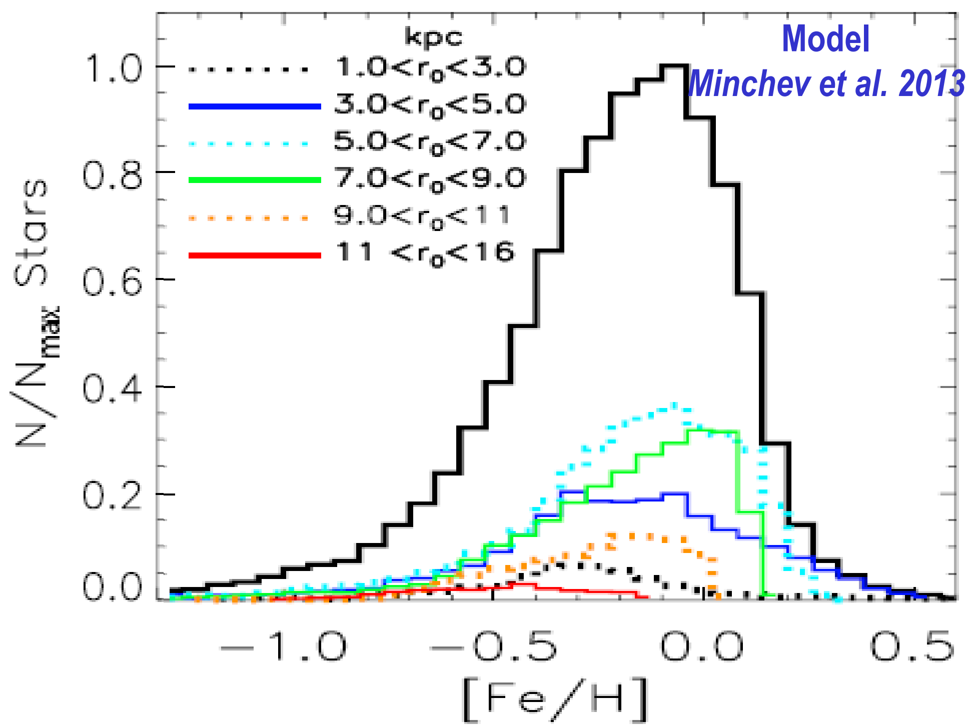
2. Creates dispersion in the age-metallicity relation…

3. … much more than the epicyclic motion

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

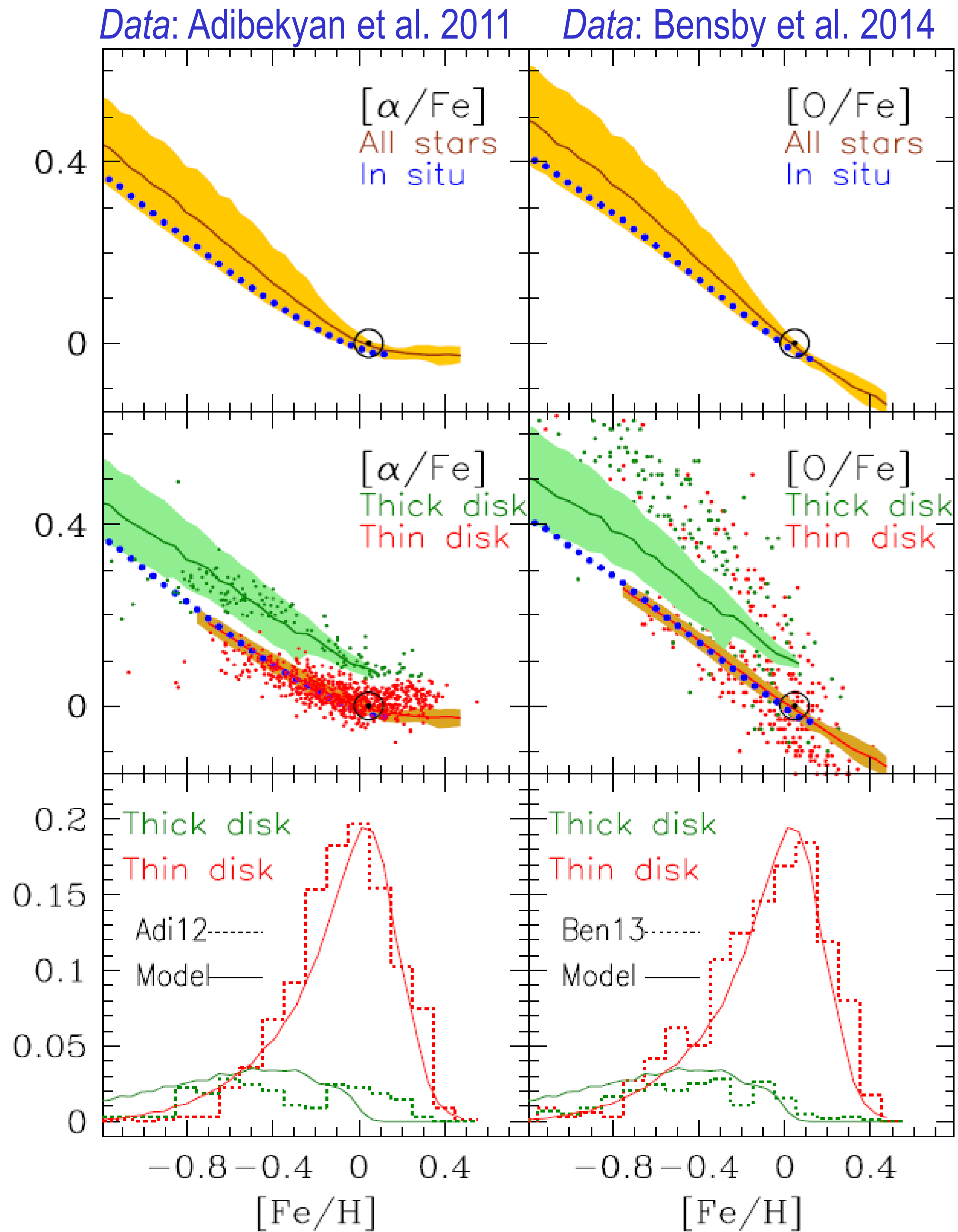


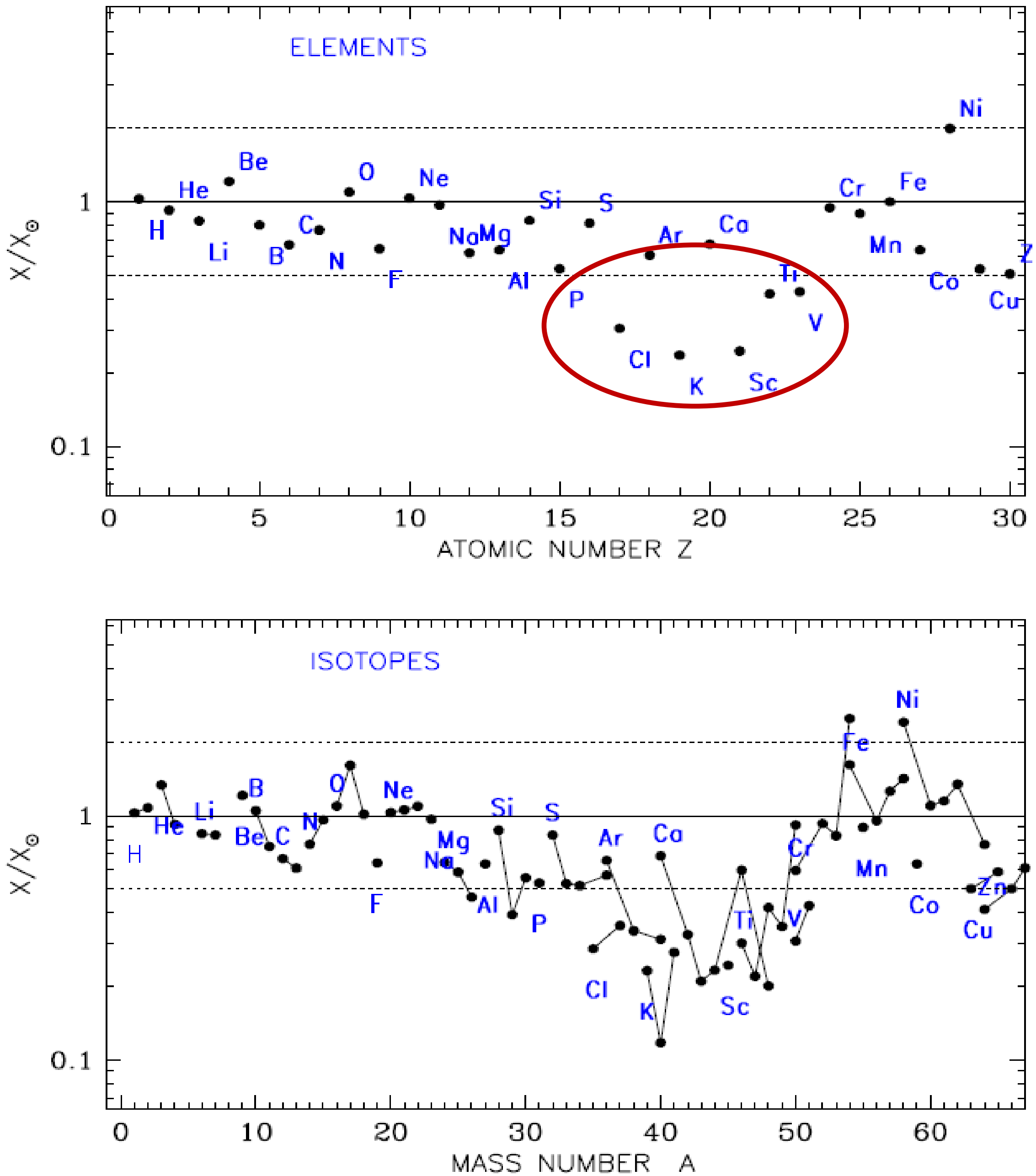




Assuming that
the thick disk is
the old disk (>9 Gyr)

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

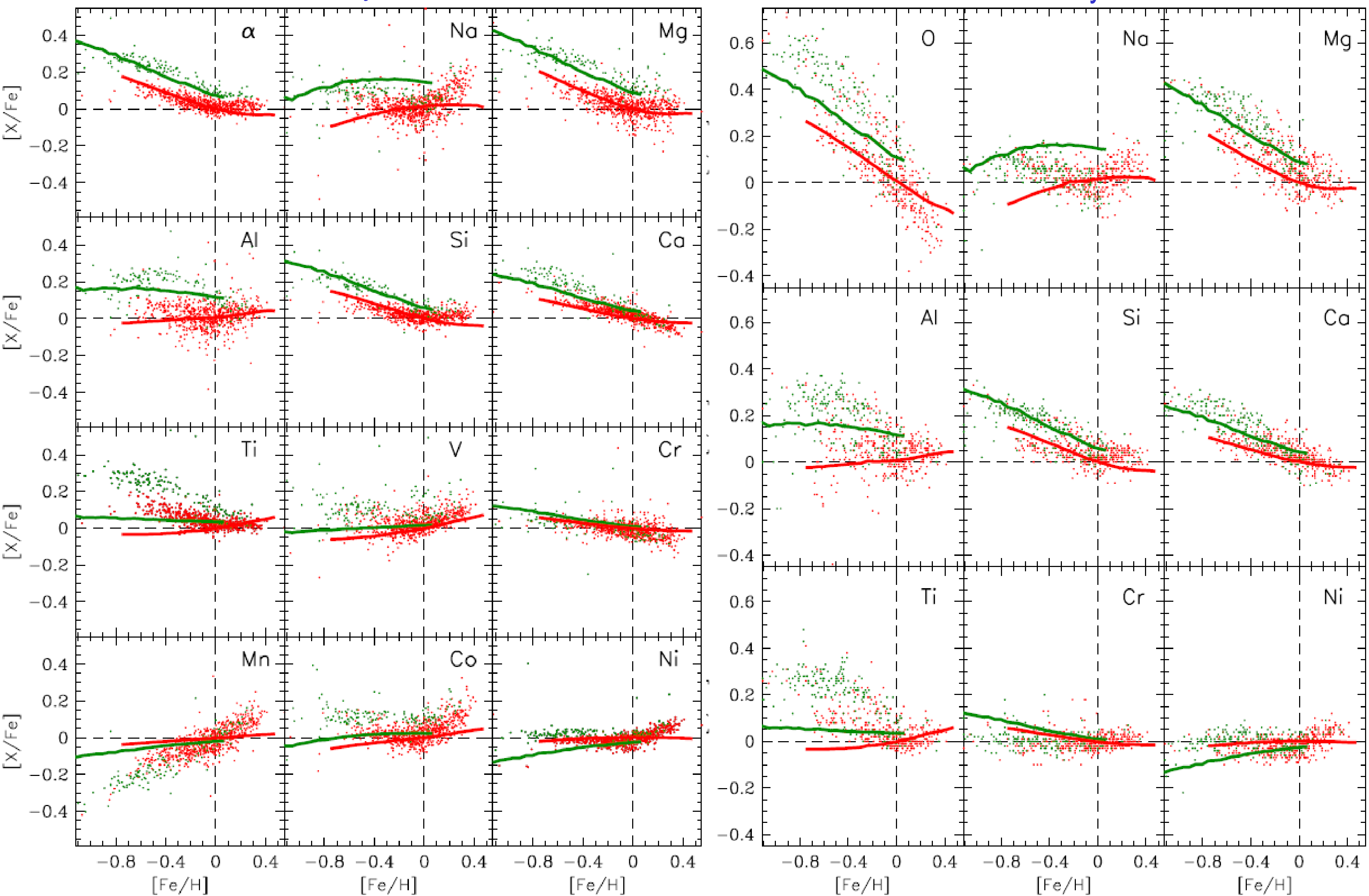
in the region

P to V

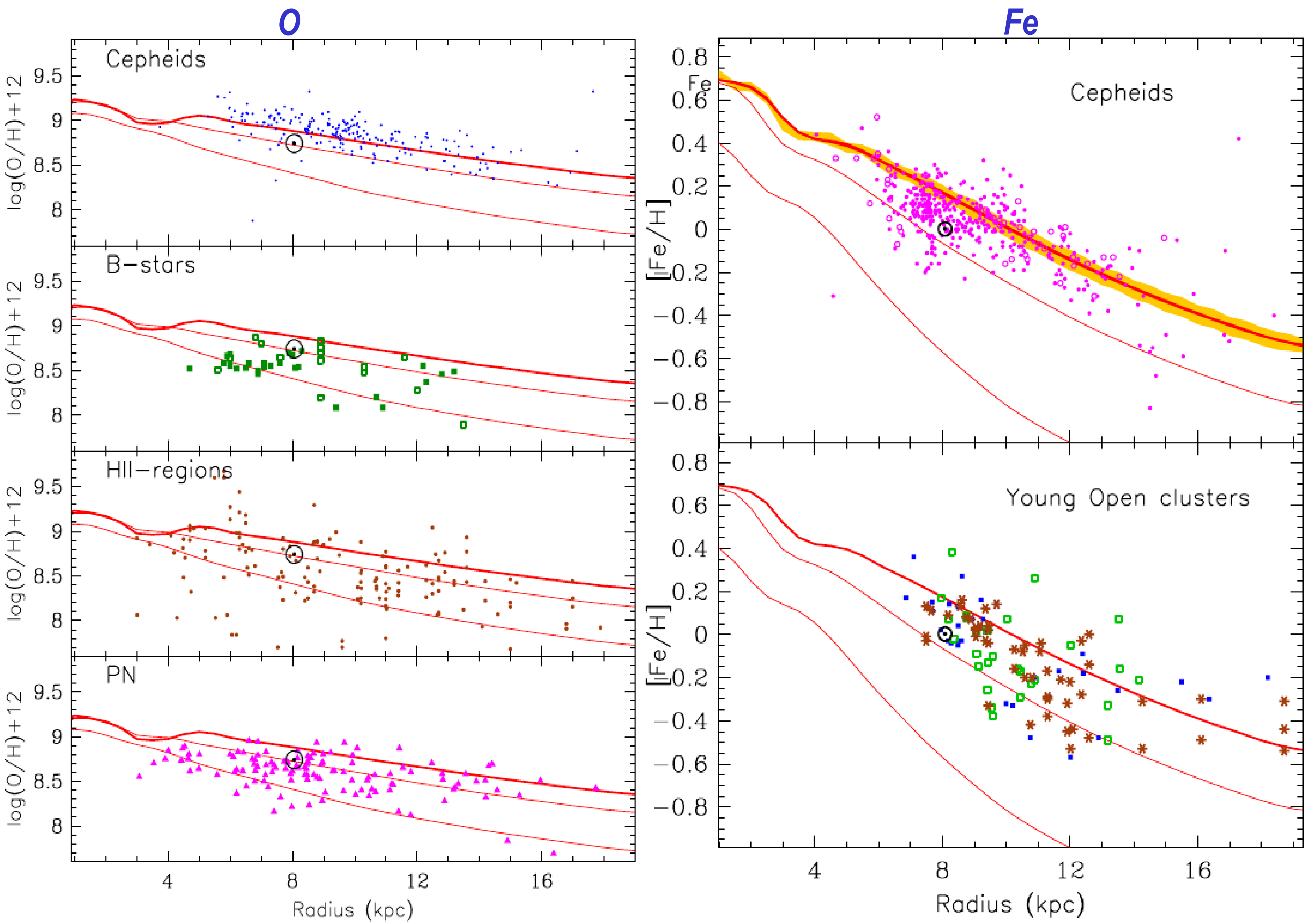
Evolution of thin (<9 Gyr) and thick (>9 Gyr) disks
with yields NORMALISED to solar for AVERAGE LOCAL (8 kpc) STAR 4.5 Gyr old

Data: Adibekyan et al. 2011

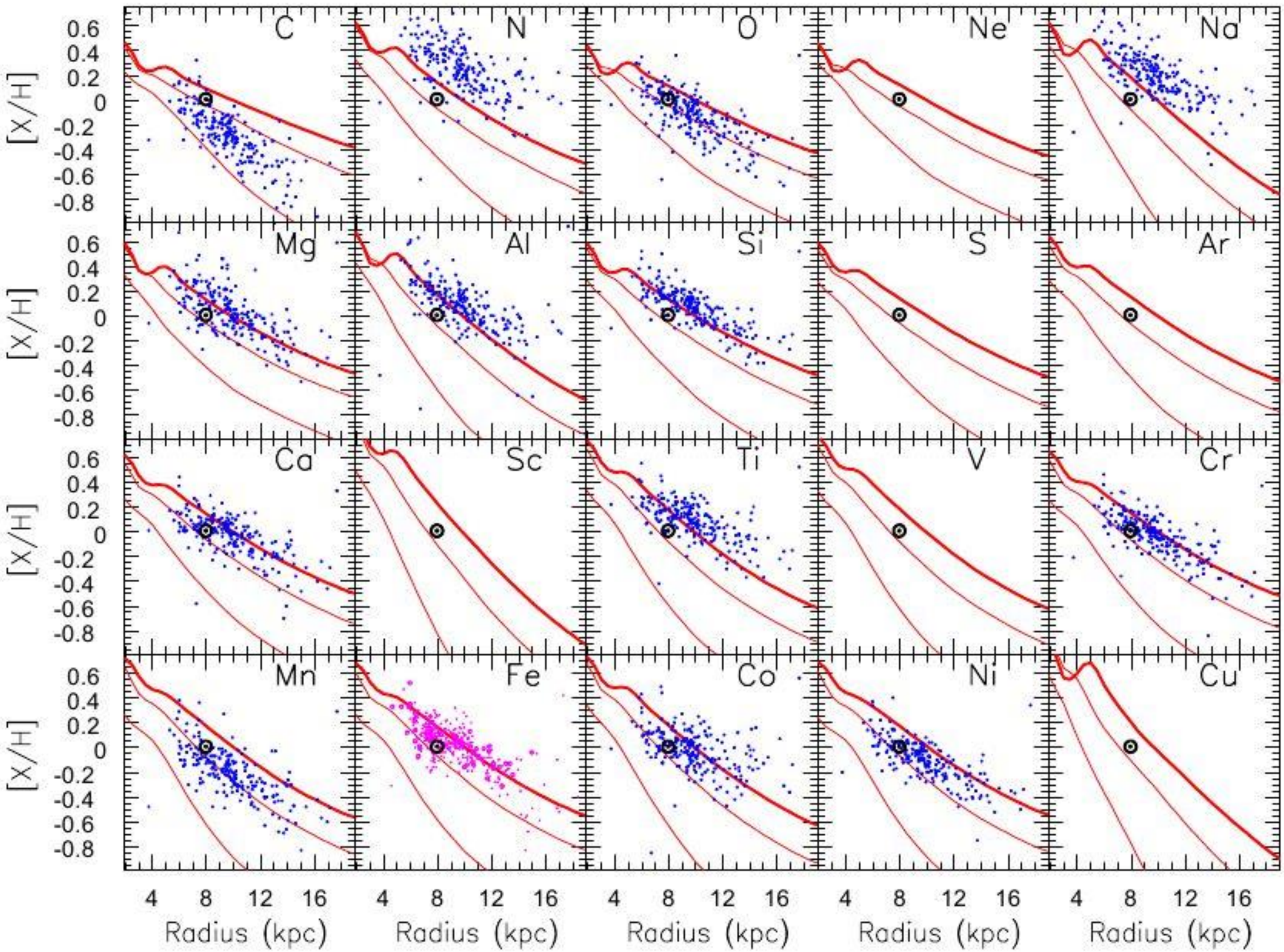
Data: Bensby et al. 2014

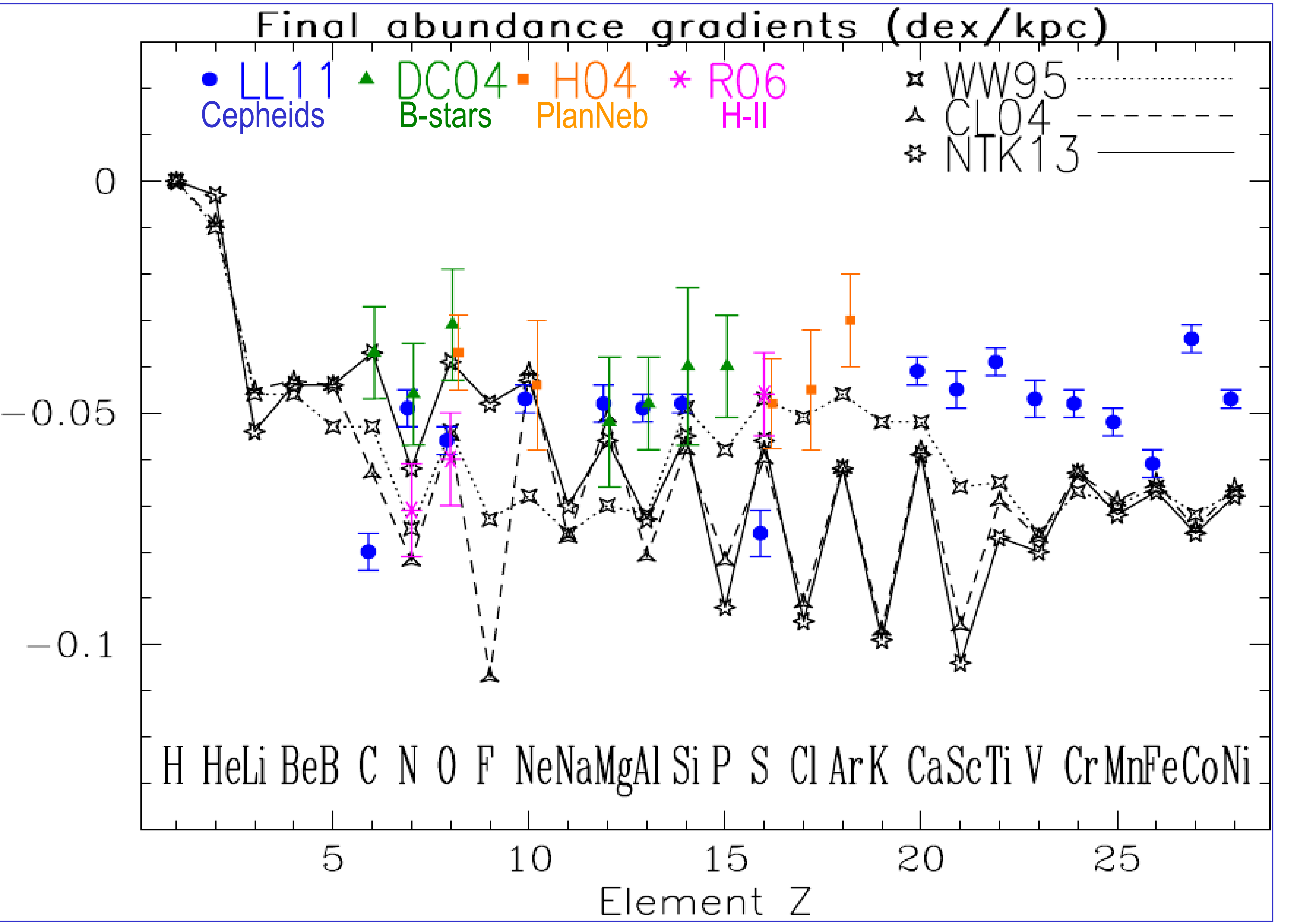


Abundance profiles

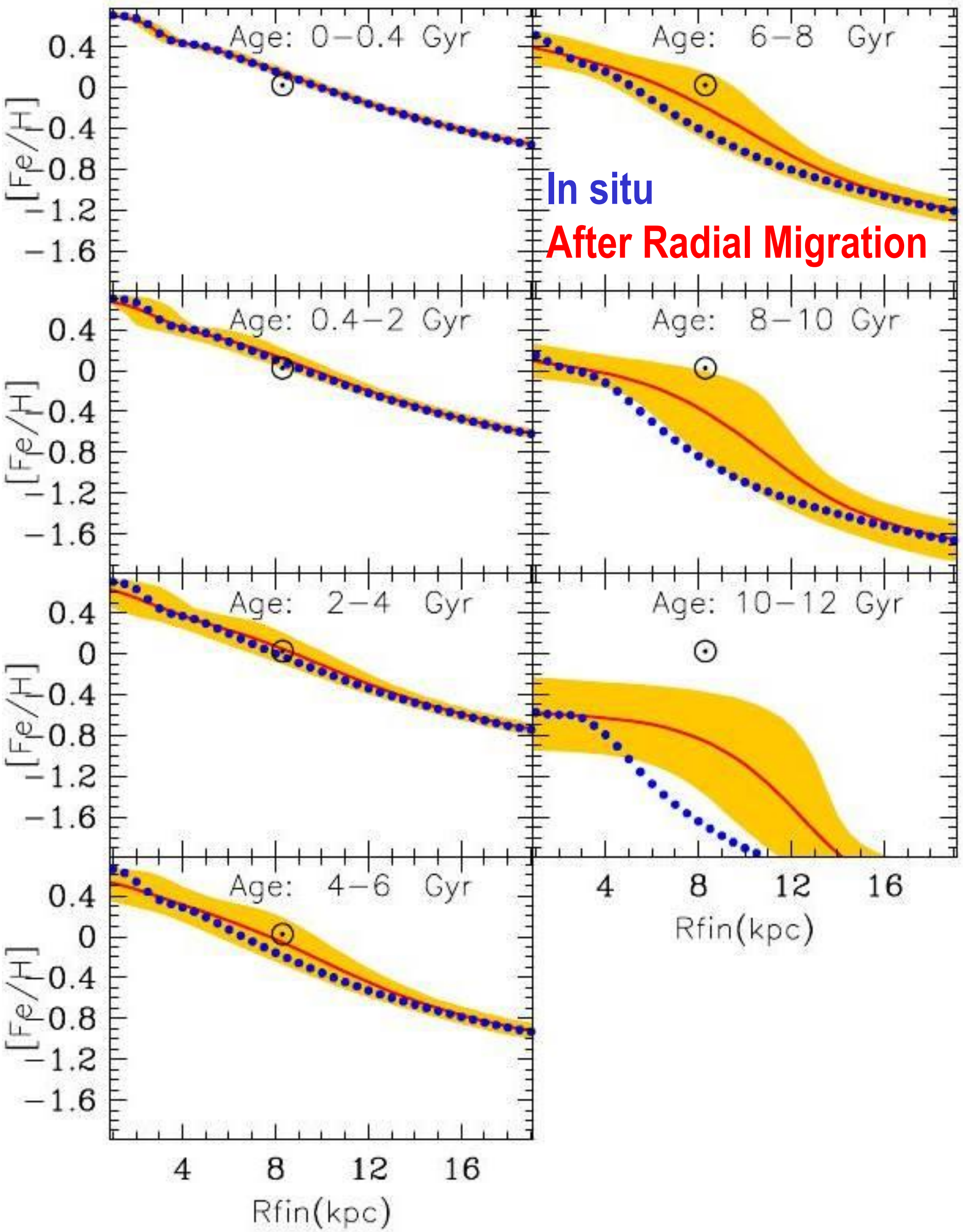


Abundance profiles in Cepheids





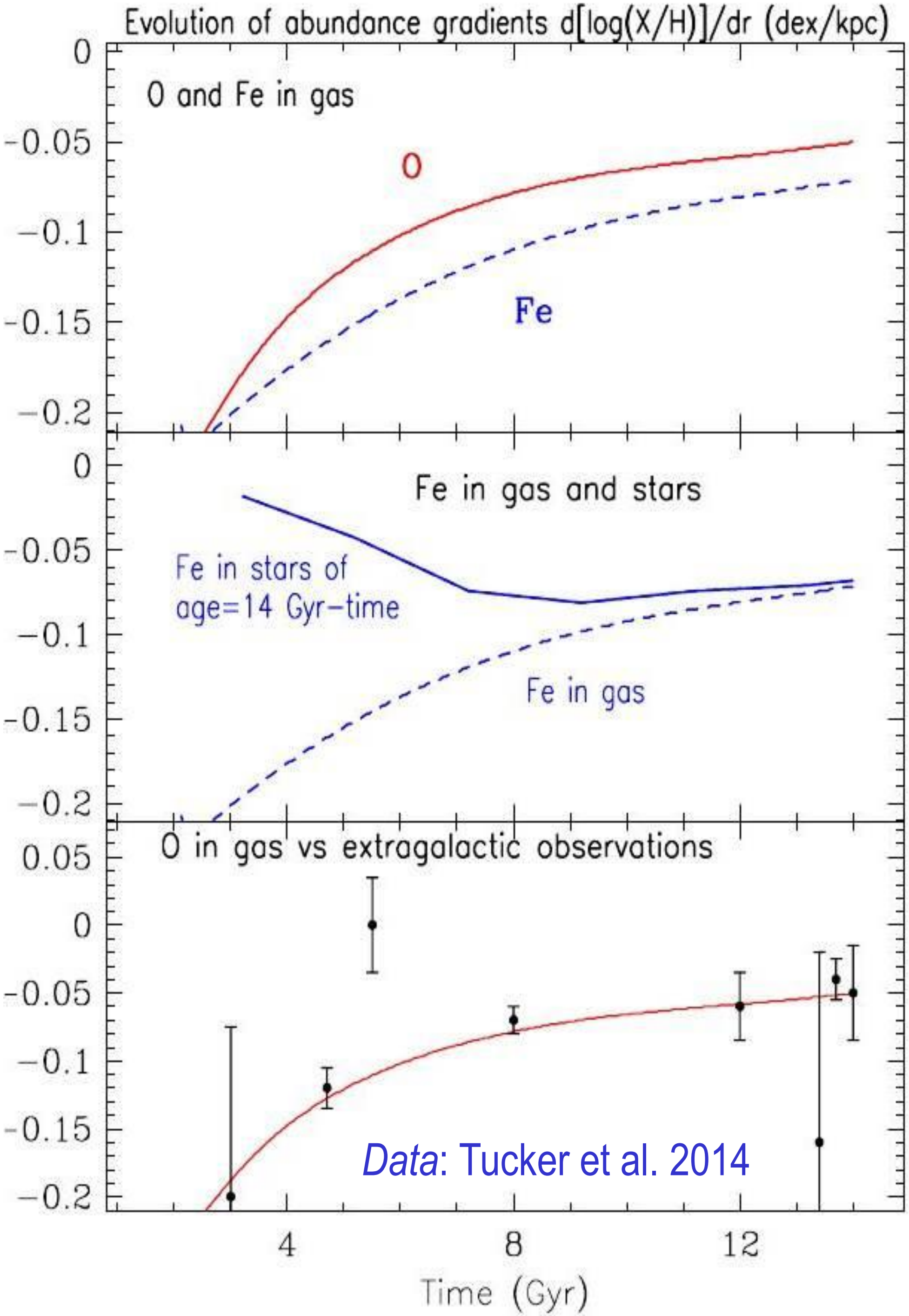
Final abundance gradients (dex/kpc)
LL11
Cepheids
DC04
B-stars
H04
PlanNeb
R06
H-II
WW95
CL04
NTK13
0
−0.05
−0.1
H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni
5
10
15
20
25
Element Z



Radial migration flattens the past stellar profiles

(Roskar et al. 2008)

bringing old and metal poor stars in the outer disk



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

SUMMARY

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

LOCALLY:

- Increases dispersion in age-metallicity relation
- Broadens metallicity distribution
- Modifies apparent SF histories(*more in outer disk than in inner disk*)

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 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

even after systematic observations (e.g. *GAIA* for the MW)