ON THE CHEMICAL EVOLUTION OF THE MILKY WAY

The Metallicity distribution of the halo
in the hierarchical merging paradigm

Halo abundance patterns and stellar yields

"Standard" chemical evolution of solar neighborhood
and Milky Way disk

Implications of radial mixing of stars for
local chemical properties and disk profiles

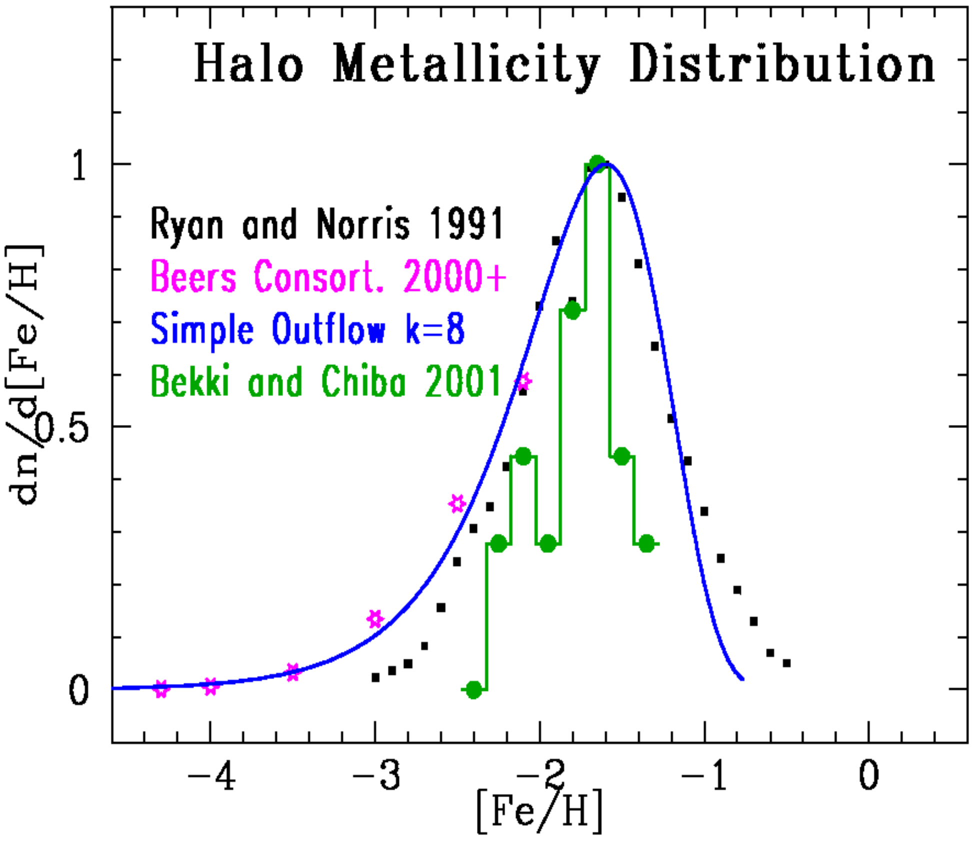
On the local *average* Age-Metallicity relation

The observed metallicity distribution (MD) of field halo stars is characterized by:

1) A peak at [Fe/H] = -1.6 implying a reduced effective yield $y_{EFF} \sim y_0/9$

most easily interpreted in a Simple model with Outflow rate = 8 SFR (*Hartwick 1975*)

What is the origin of such large Outflow ?

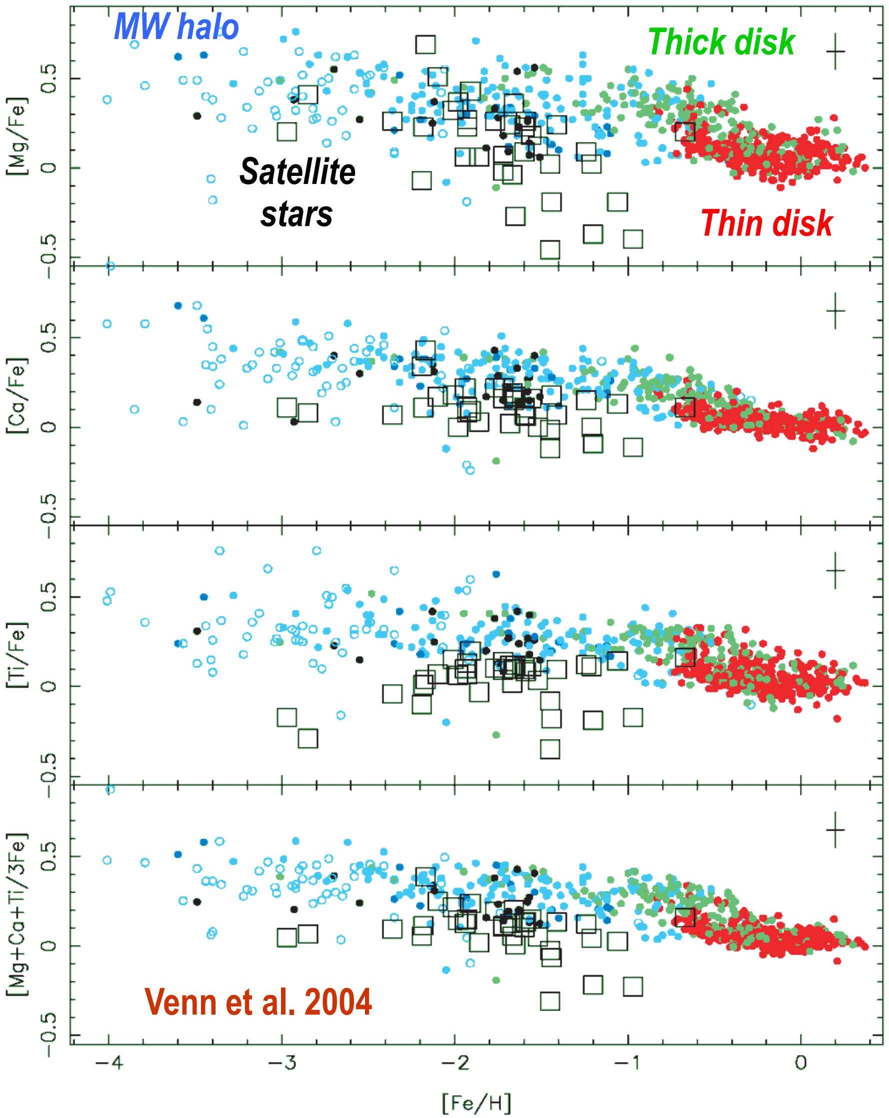


2) A very smooth shape;

is it compatible with the formation of the Halo from hierarchical merging plus tidal disruption of many small fragments ?

Early dynamical models of Halo formation in CDM scenario (*Bekki and Chiba 2001*) reproduce the peak of the observed Halo MD (reduced yield), but it is not clear why. However, the shape and smoothness of the observed MD are not reproduced.

Ingredients required to evaluate the halo MD as a sum of MDs of sub-haloes in the hierarchical merging paradigm :



1) Shape of sub-halo MD

2) Dependence of sub-halo MD on sub-halo mass

3) Baryon mass distribution of sub-haloes

Present day dwarf satellites of MW cannot be the building blocks of MW halo
(abundance ratios: Fe from SNIa)

The building blocks (sub-haloes) of MW halo must have evolved UNAFFECTED by SNIa ejecta
[short timescales (< 1 Gyr)]

(alternatively, SNIa ejecta preferentially lost from those systems)

The MDs of dSph satellites

of the MW

can be well described by the

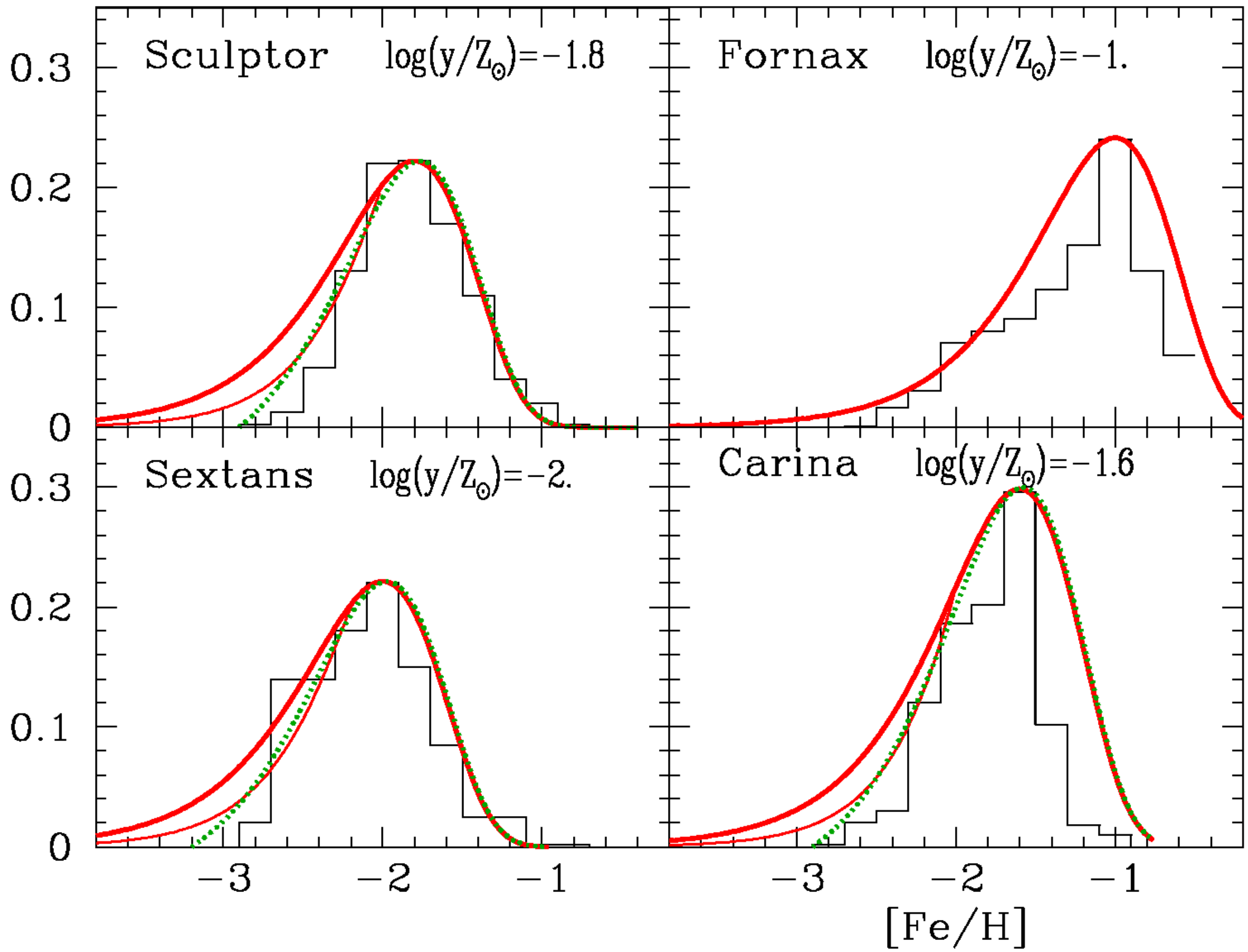
simple model with outflow

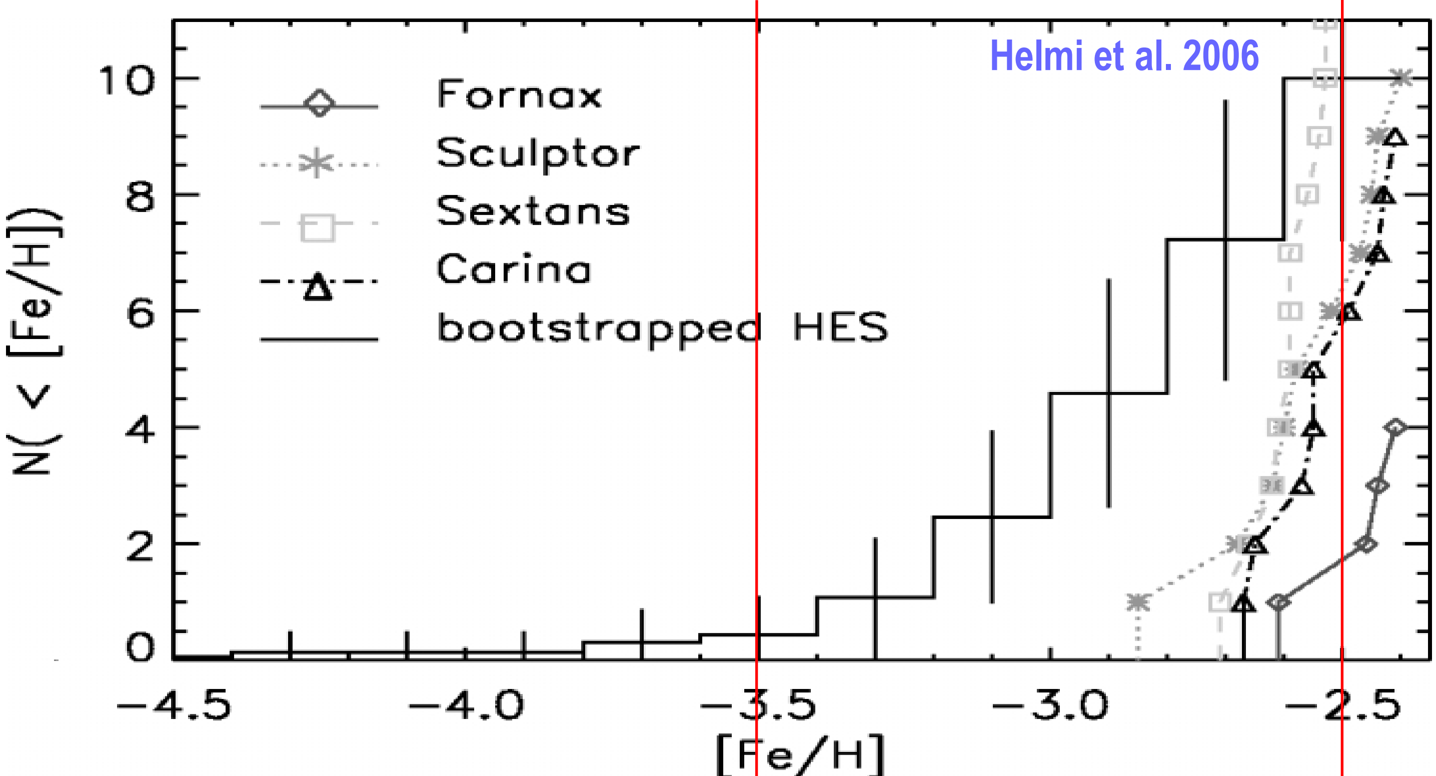
AND either

- pre-enrichment
(Helmi et al. 2006)

- early infall
(Prantzos 2007)

- both
(Salvadori et al. 2008)





Obs. of dSphs in 2006:

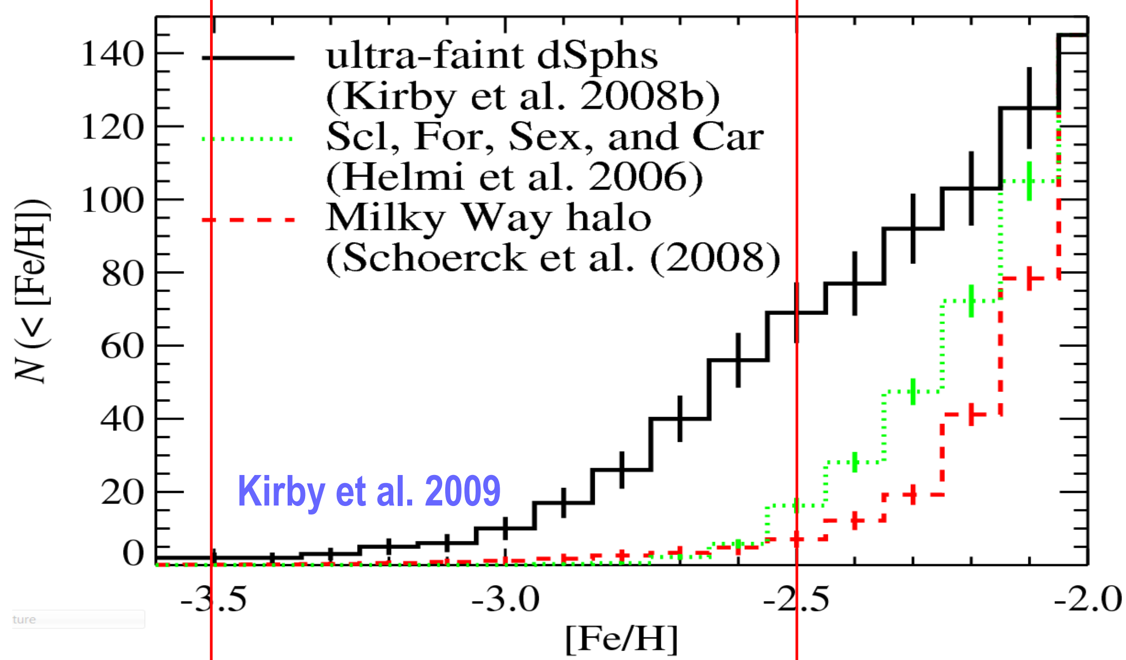
Not enough stars of low metallicity compared to Galactic halo

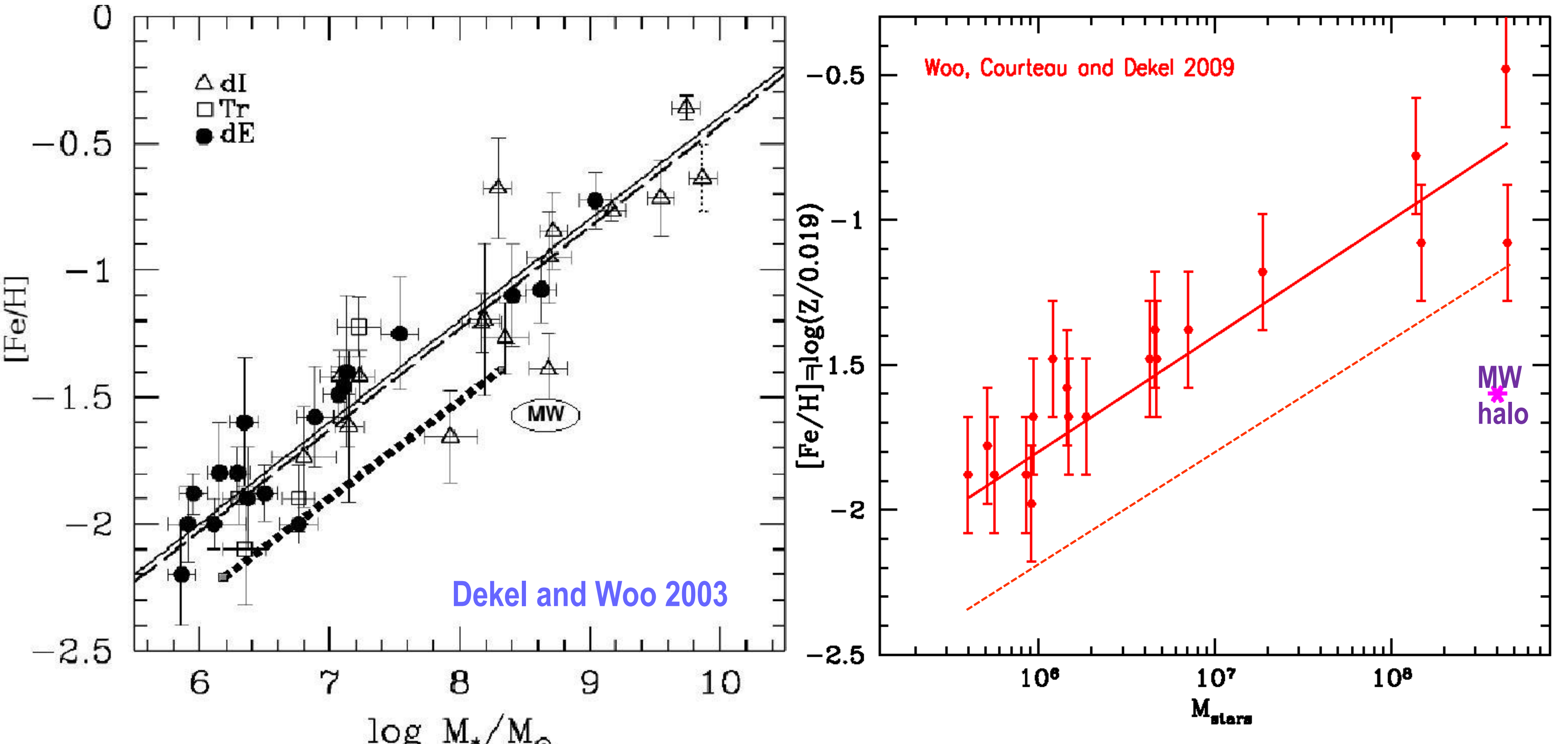
Implies that Galactic halo was NOT formed from such systems (BUT what about their progenitors ?)

Obs. of ultra-faint dSphs in 2009:

MORE stars of low metallicity compared to Galactic halo

Implies that Galactic halo MAY HAVE BEEN FORMED from such systems OR from their progenitors



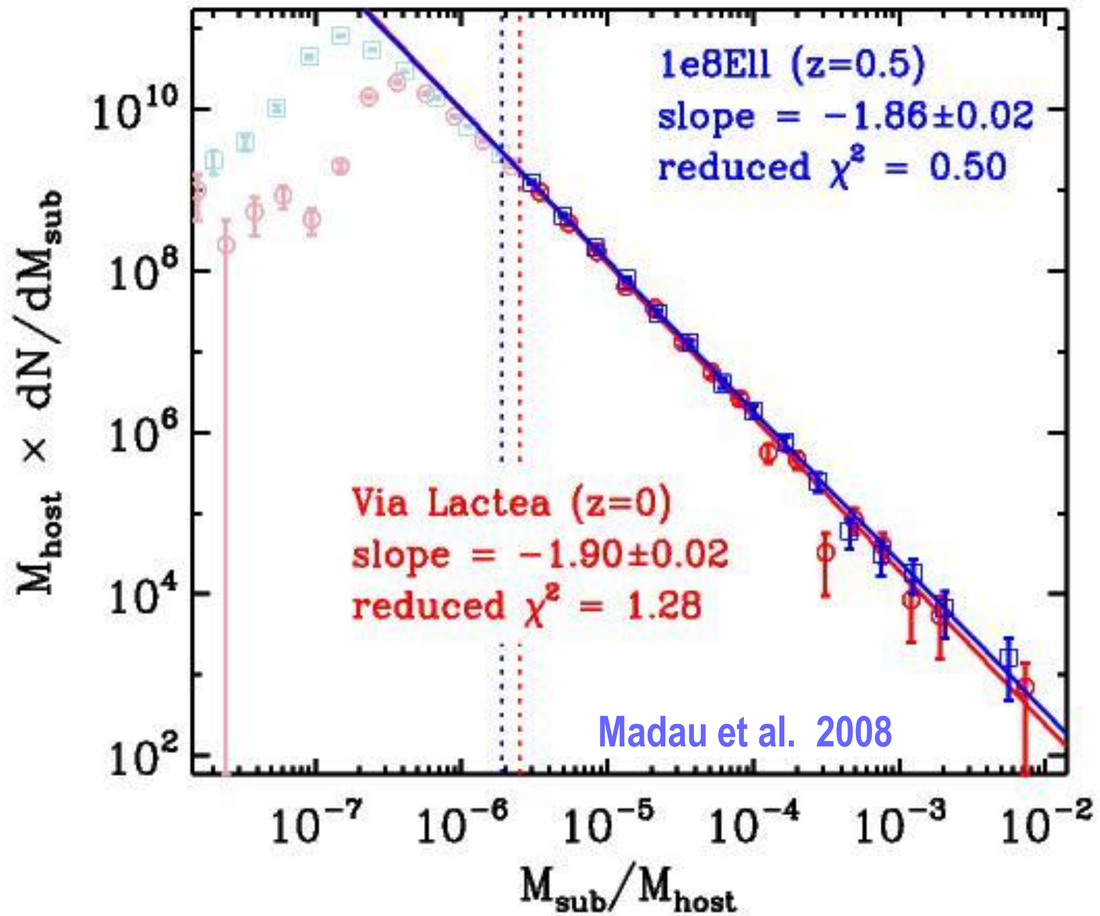


Local dwarf spheroidals today display a *Mass - (stellar) metallicity* relationship which may be explained by SN feedback, inducing stronger mass loss in less massive galaxies *(Dekel and Silk 1985, Dekel and Woo 2003)* and resulting in a *reduced effective yield*

$$y_{eff}(M) = \frac{y_0}{1+k(M)}$$

Assuming that *Outflow rate = k(M) * SFR*

N. B. The Milky Way halo (considered as a single entity) is found BELOW that relationship (steeper IMF, OR abnormally high mass loss for its mass, OR... ???)



Dark halo distribution function

Simulations find that for the dark matter sub-haloes

$$dN/dM \propto M^{-2}$$

(Diemand et al. 2006, Madau et al. 2008)

But lower mass sub-haloes are preferentially affected by outflow, and the baryonic mass distribution of sub-haloes will be flatter than the one of dark matter *(Prantzos 2008)*

$$\frac{dN}{dM_*} \propto M_*^{-1.2}$$

Normalization: Total halo mass

M_{*Halo} **= 4 10^{8} M$_{\odot}$** (*Bell et al. 2007*)

$$M_{*Halo} = \int_{M_1}^{M_2} \frac{dN}{dM_*} M_* dM_*$$

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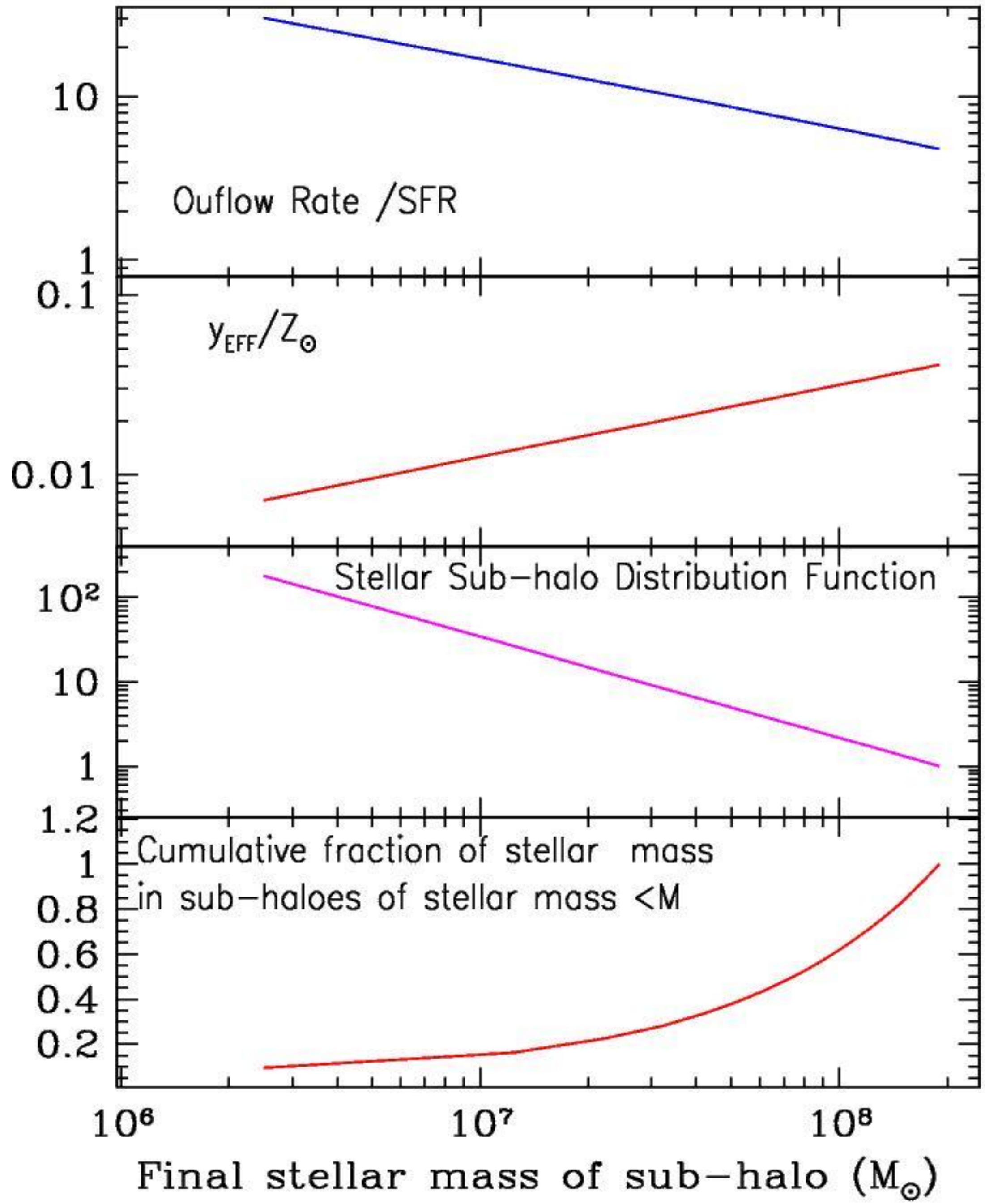
Properties of toy-model stellar subhaloes



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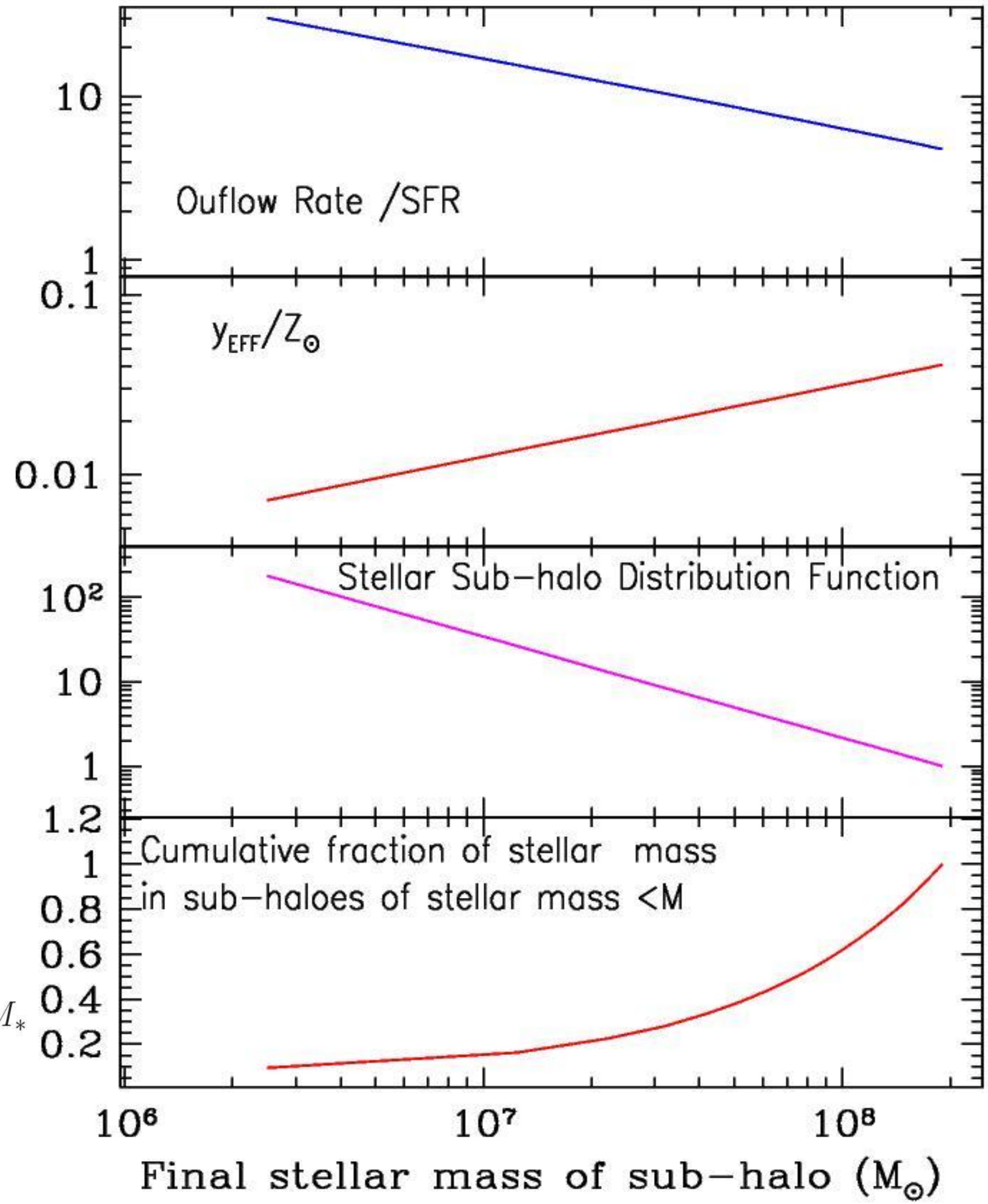
Metallicity distribution of halo = Sum of MDs of sub-haloes

$$\frac{d(n/n_1)}{d(logZ)} = \int_{M_1}^{M_2} \frac{d[n(M_*)/n_1(M_*)]}{d(logZ)} \frac{dN}{dM_*} M_* \, dM_*$$



The halo MD may result as the sum of the MDs of ~a few dozens of small galaxies (sub-haloes of $10^6 – 10^8$ $M_\odot$),

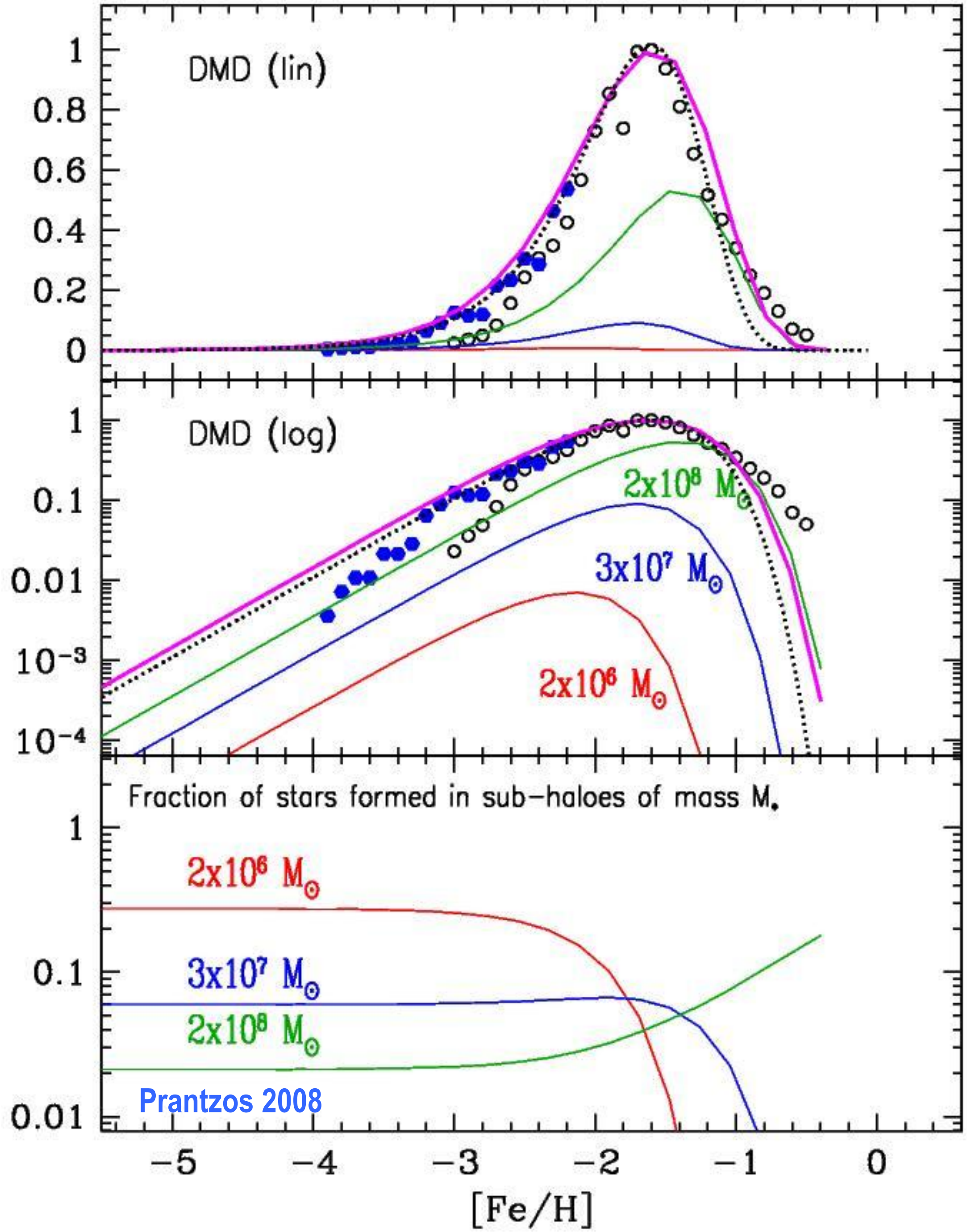
each one with an effective yield obtained from the observed *mass-metallicity relation* for local dwarf spheroidals

and with an appropriate number distribution

Most of the lowest metallicity stars of the halo ([Fe/H]<-2) have been formed in the numerous, smallest sub-haloes, while its high metallicity tail was formed in a COUPLE of relatively massive, sub-haloes NONE OF THEM REMAIN TODAY

Future extension of the MD to the lowest metallicities ([Fe/H] < -4) will allow to probe:

- The sub-halo distribution function
- The starting metallicity of sub-haloes

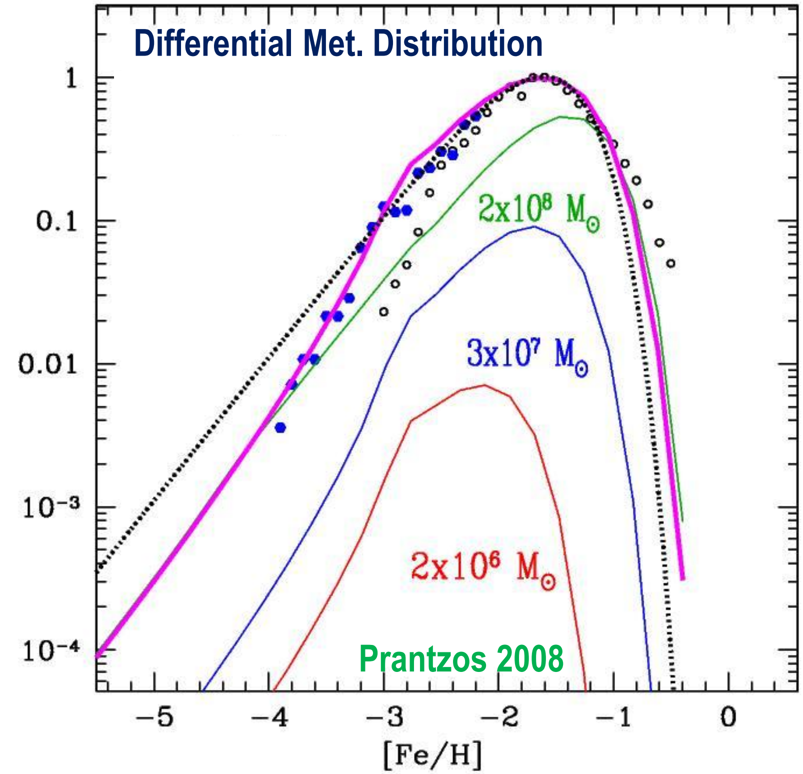


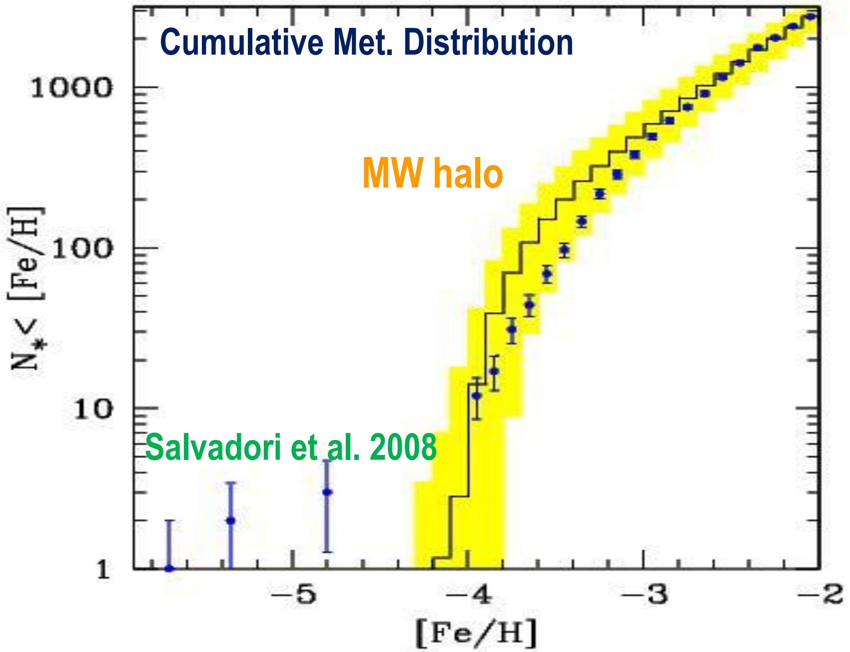
The low metallicity tail of the MW halo MD deviates from the simple outflow model and could be described by:

1) an early infall phase for all the sub-haloes and for their sum
(<100 Myr, *Prantzos 2003*, *2008*)

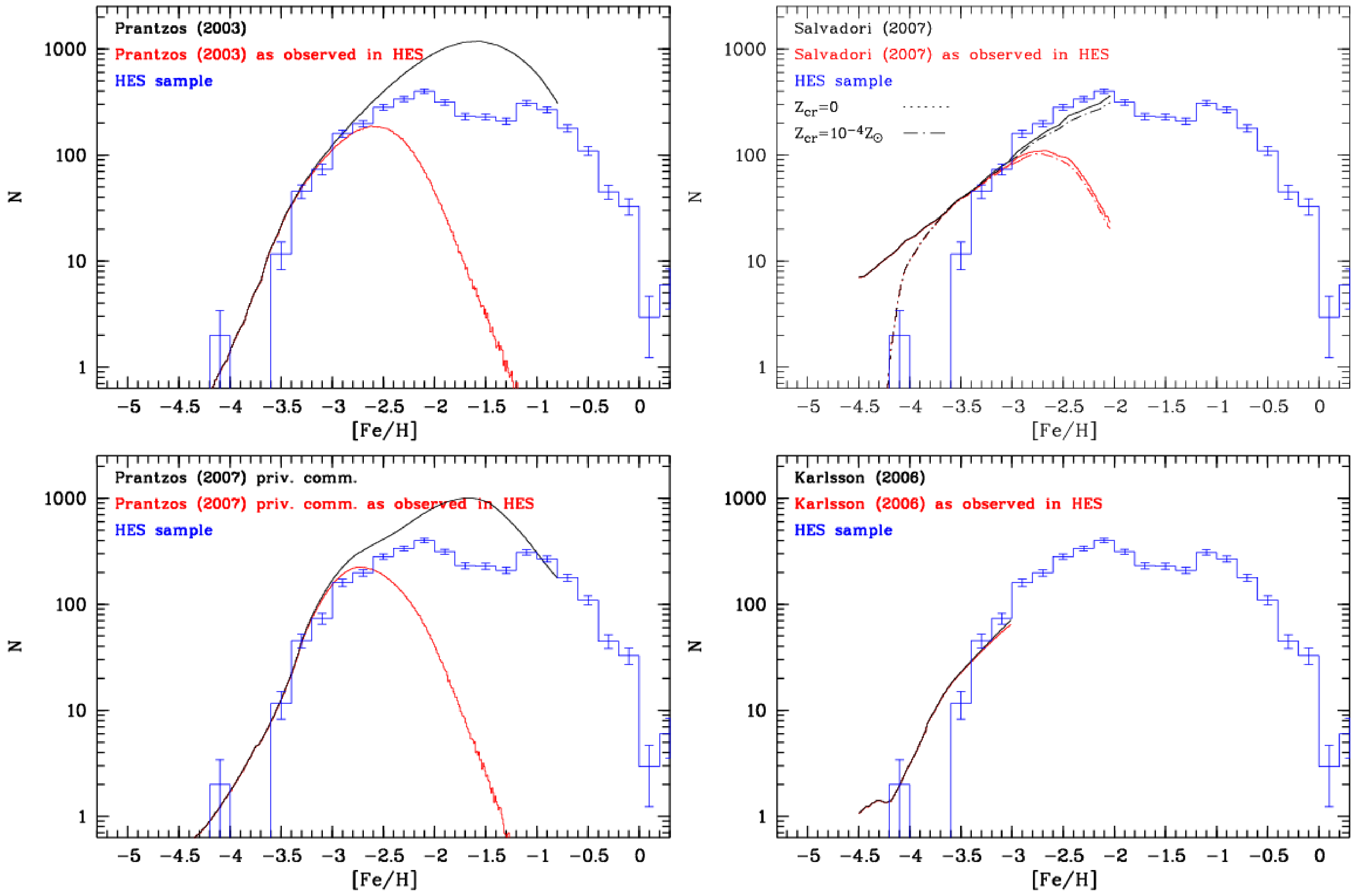
In that case, differences betweeen Z_{MIN} of halo ([Fe/H]~ -4) and luminous present-day dSphs ([Fe/H]~ -3) are due to more prolonged infall in the case of present-day luminous dSphs

2) A non-zero initial metallicity [Fe/H]~ -4 for the MW sub-haloes vs [Fe/H}~ -3 for the dSphs, due to late formation of the dSphs from a more enriched intragalactic medium
(Salvadori et al. 2007, 2008)



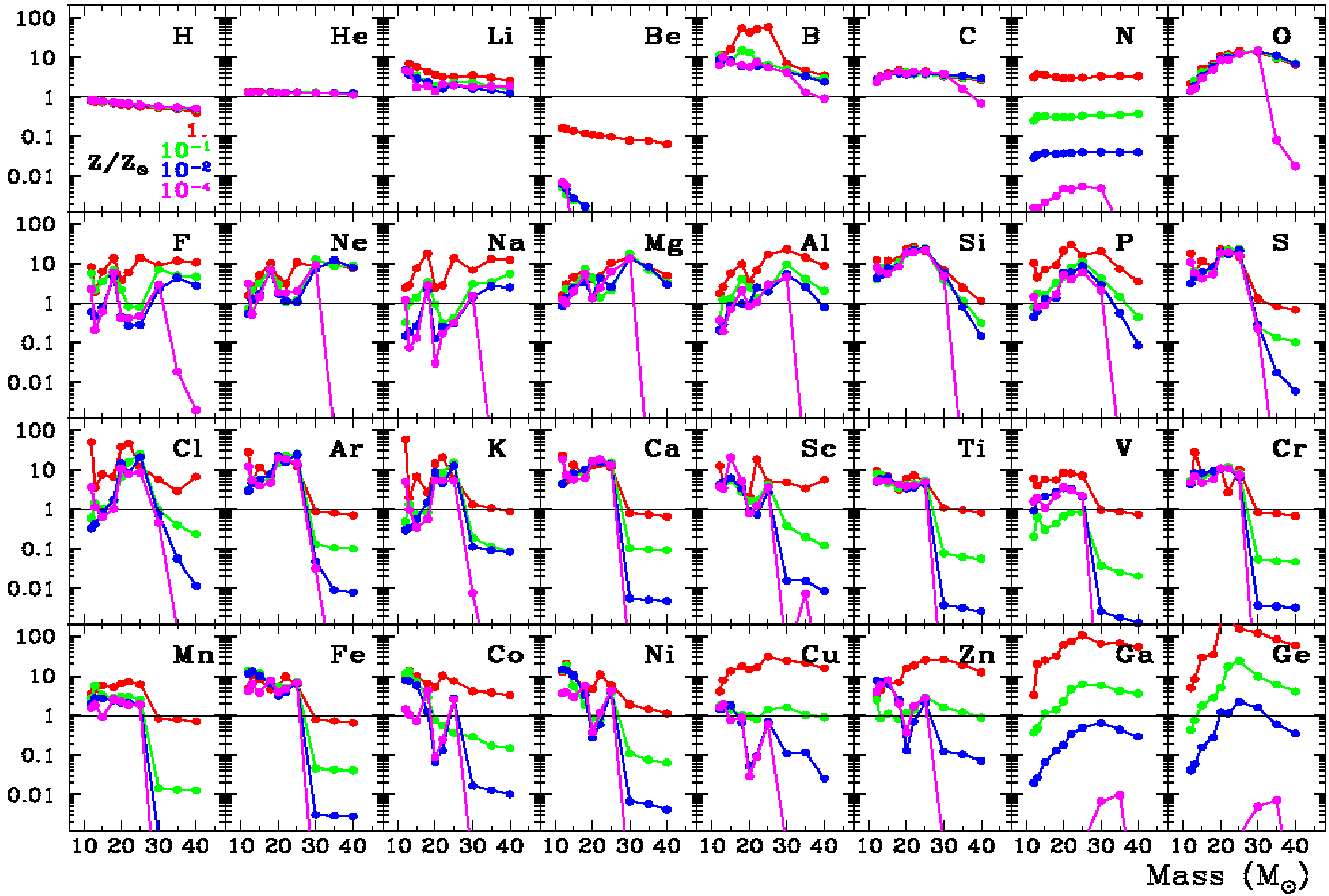


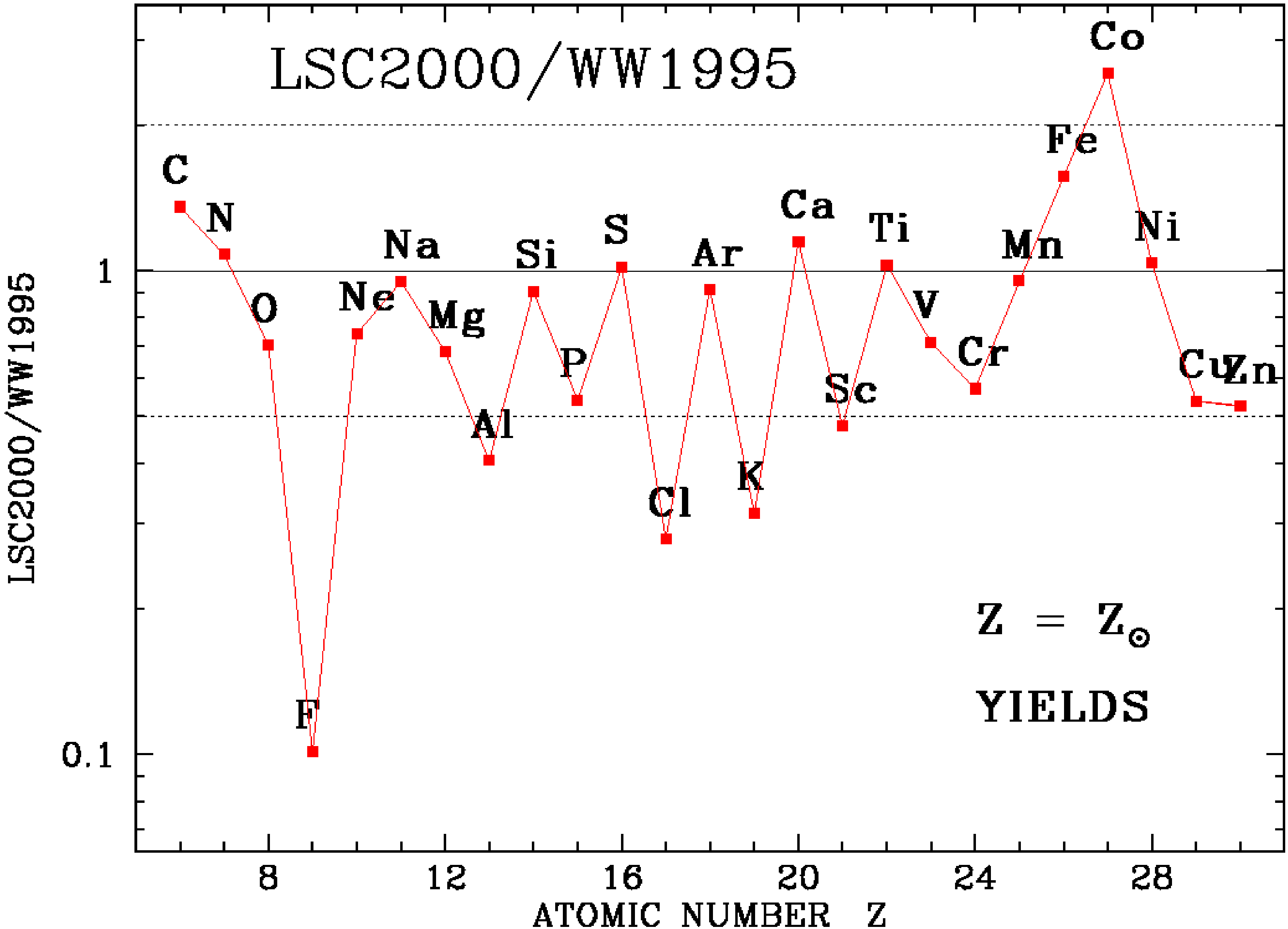
Hamburg/ESO survey (Schoerk et al. 2008)



STELLAR YIELDS

Woosley and Weaver 1995, Overproduction factors of elements in massive stars

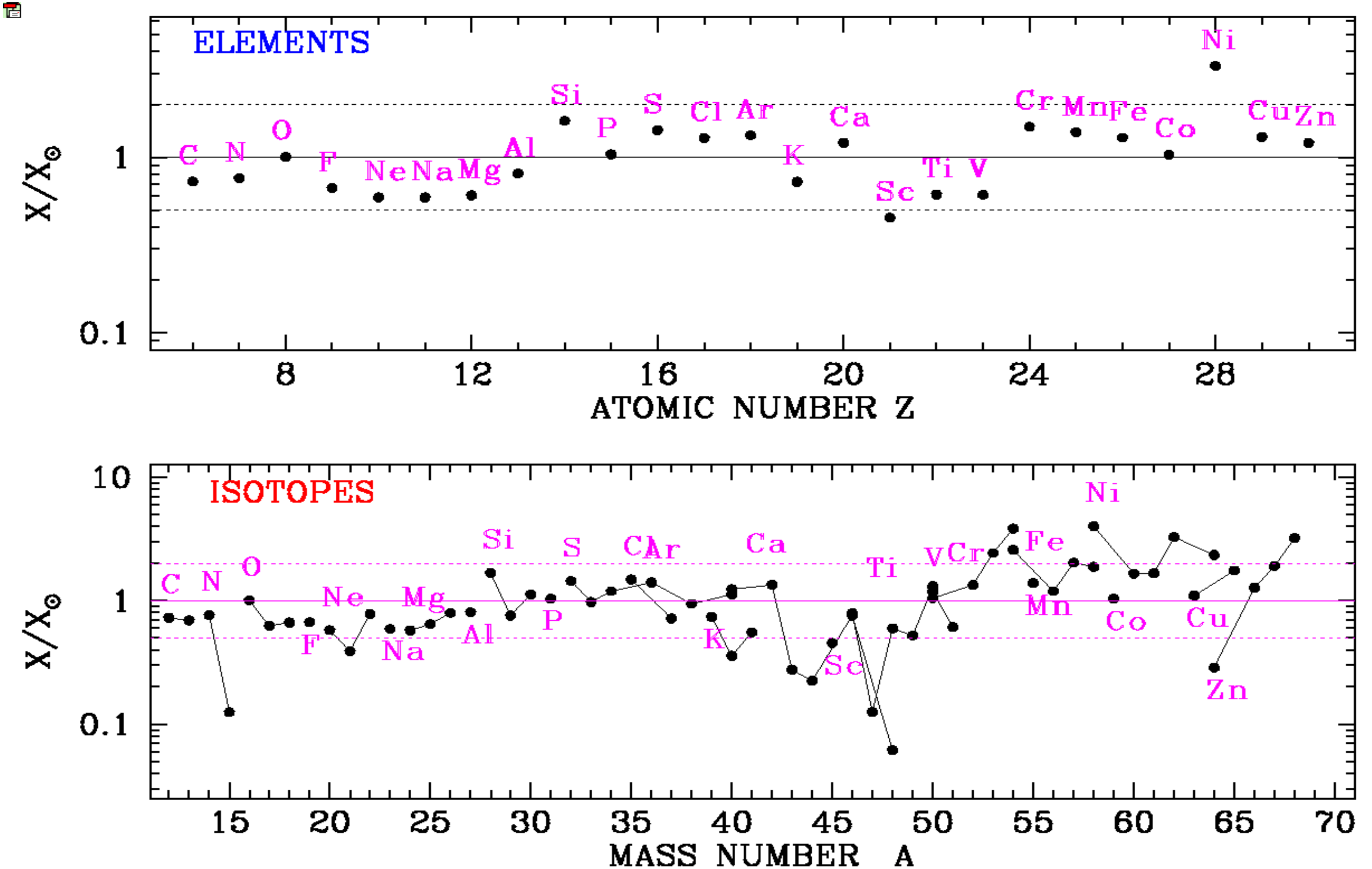


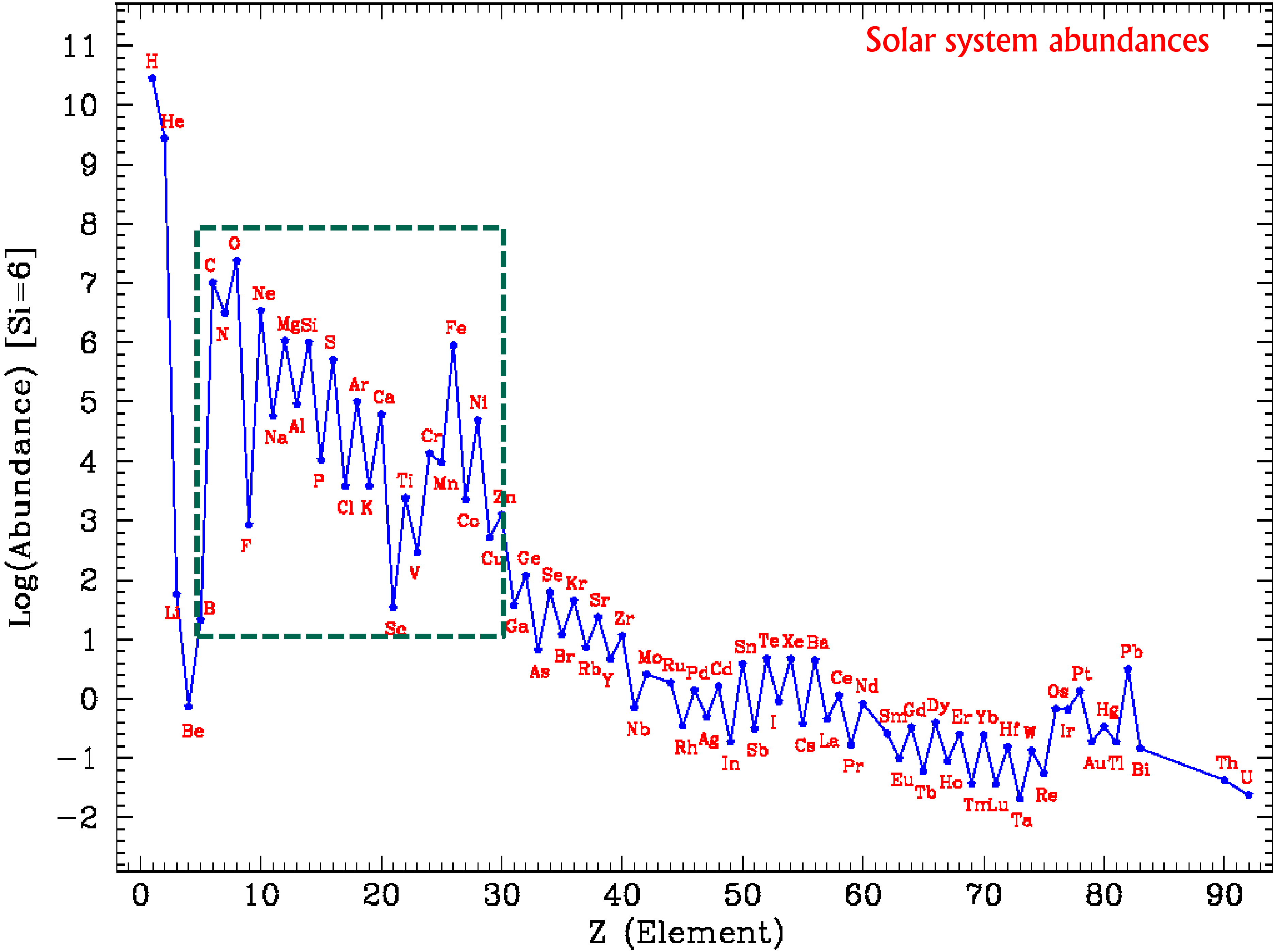


LSC2000/WW1995
Z = Z⊙
YIELDS
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
1
0.1
8
12
16
20
24
28
ATOMIC NUMBER Z
LSC2000/WW1995

ABUNDANCES AT SOLAR SYSTEM FORMATION

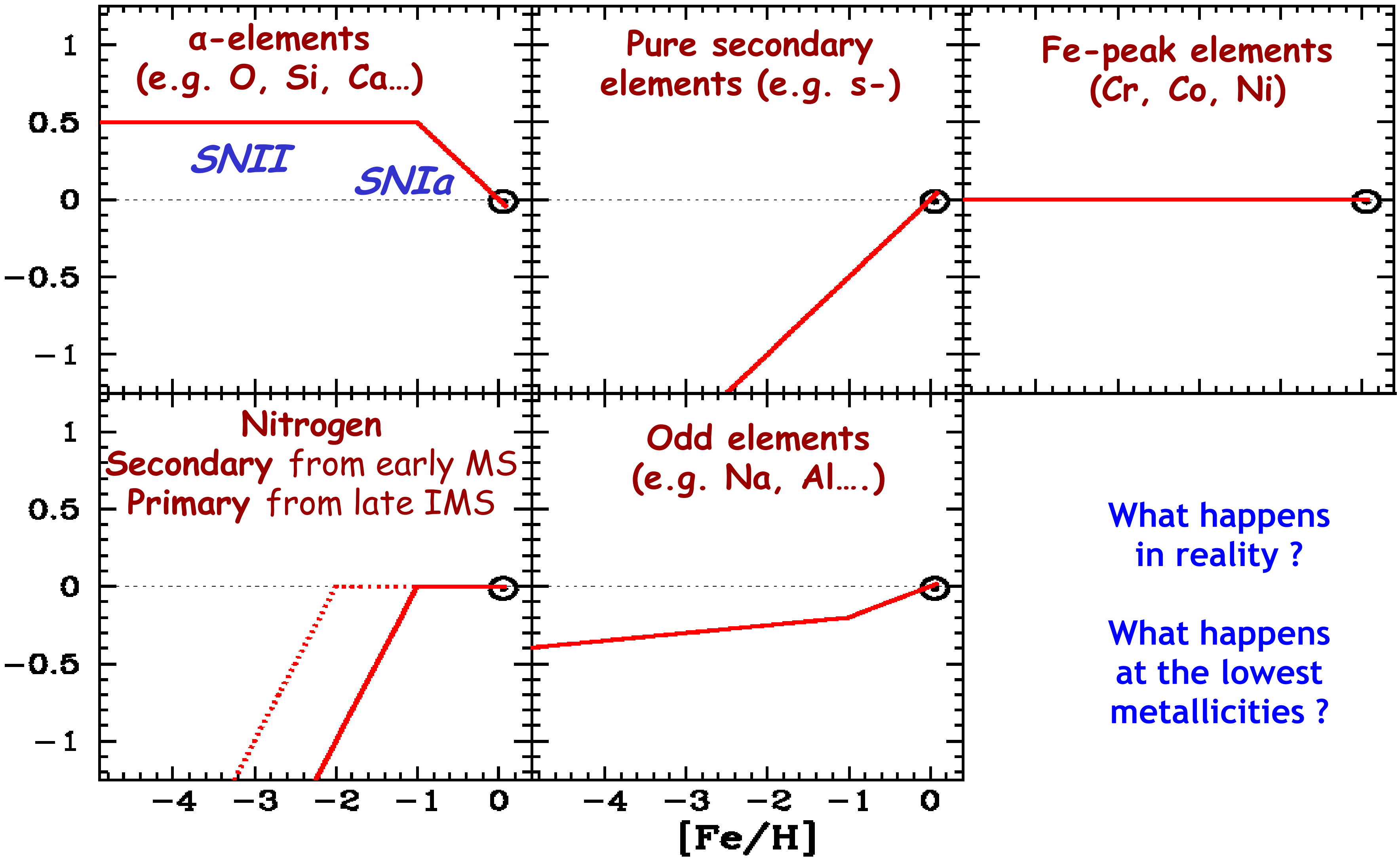
Massive stars: Woosley+Weaver 1995;
Intermediate mass stars: van den Hoek+Gronewegen 1997;
SNIa: Iwamoto et al. 2000





Solar system abundances
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

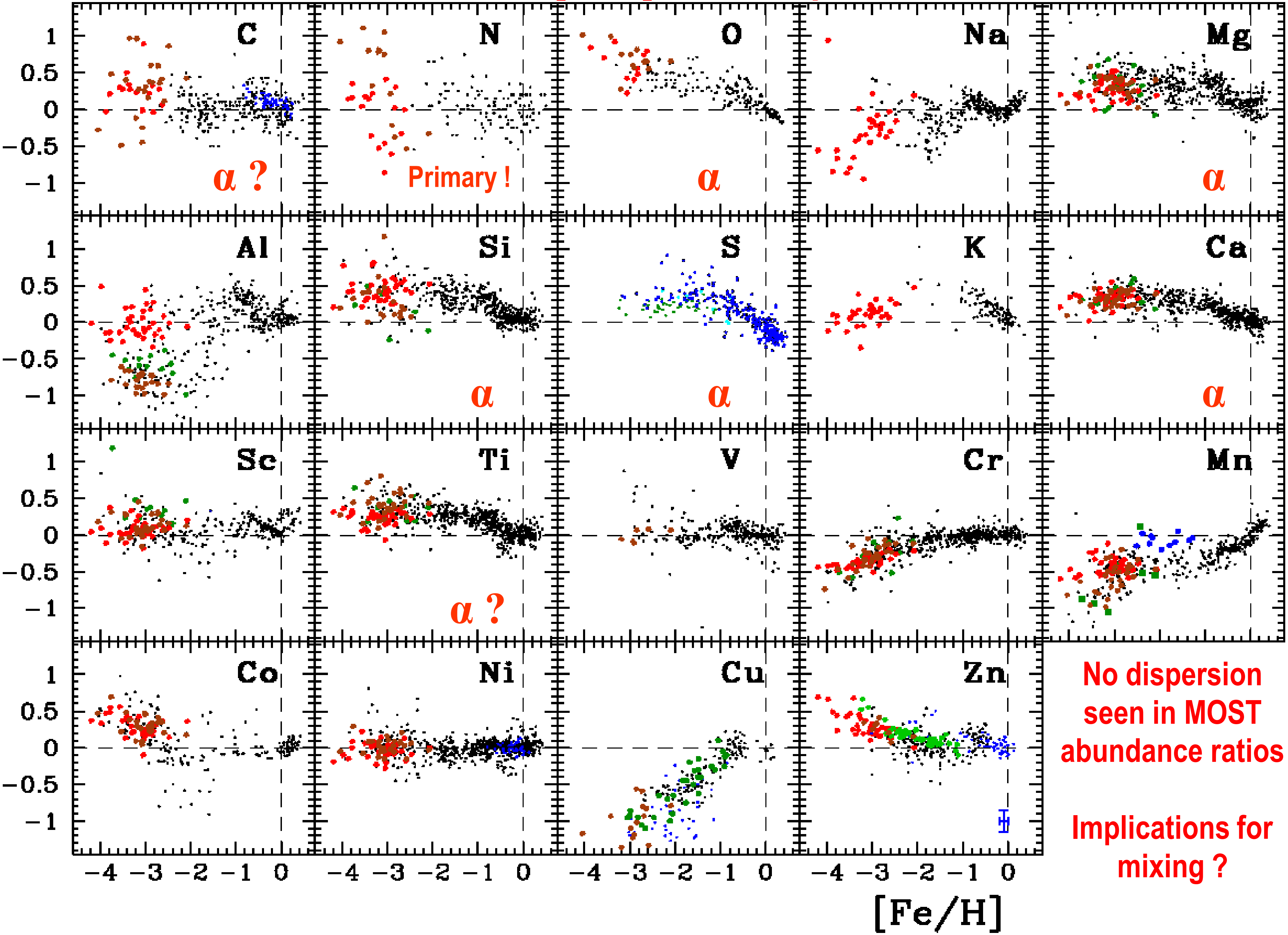
"Naive" expectation of the behavior of [X/Fe] vs [Fe/H] (circa mid-90ies)



What happens in reality ?

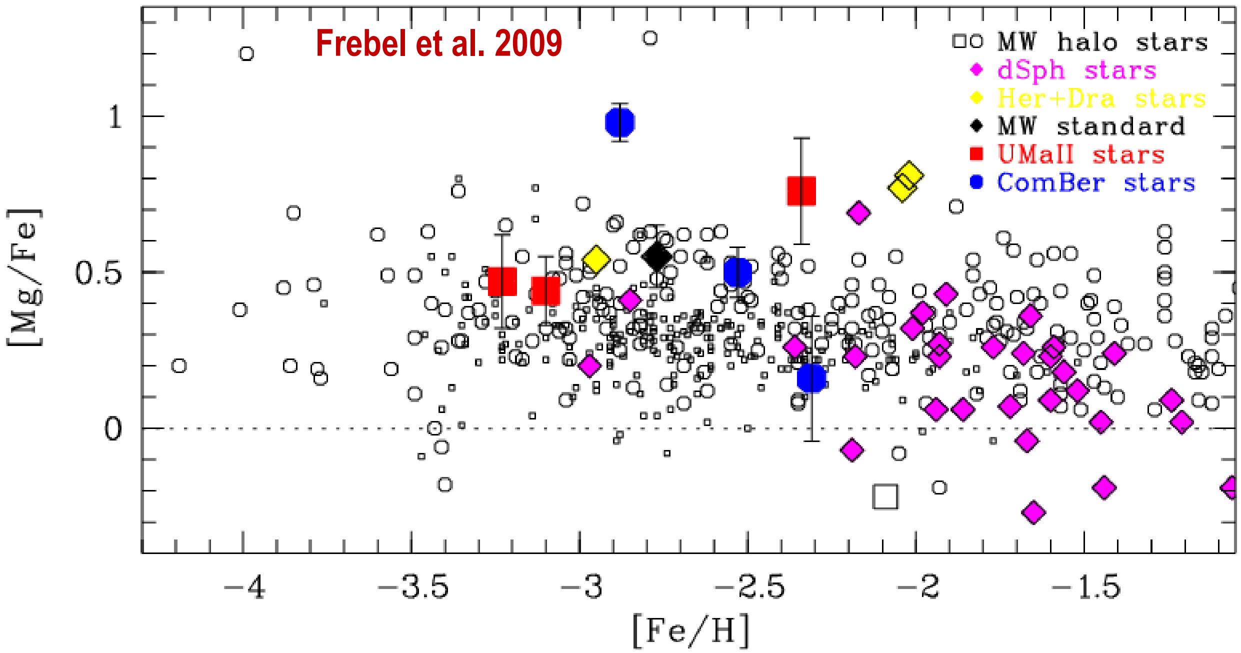
What happens at the lowest metallicities ?

Abundances [X/Fe] in metal poor stars



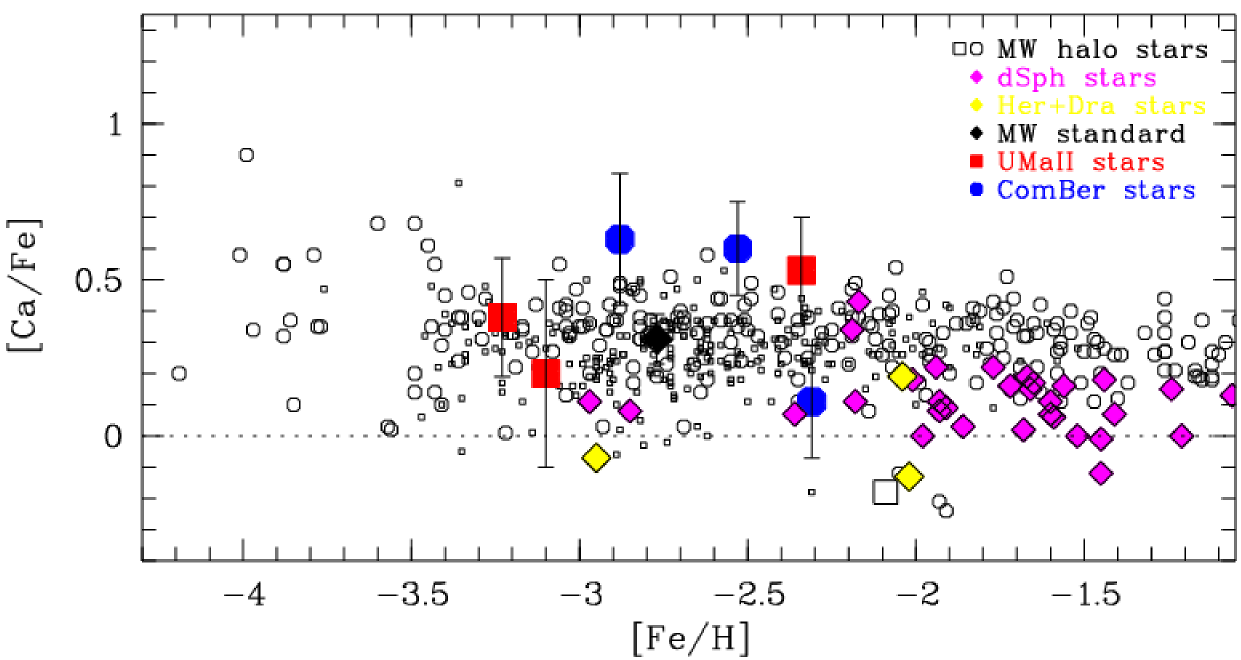
No dispersion seen in MOST abundance ratios

Implications for mixing ?



Local dSphs show BOTH
-*high* α/Fe at low metallicity
and
- *low* α/Fe at BOTH
high and low metallicities

Halo stars display ONLY
high α/Fe, up to [Fe/H]=-1

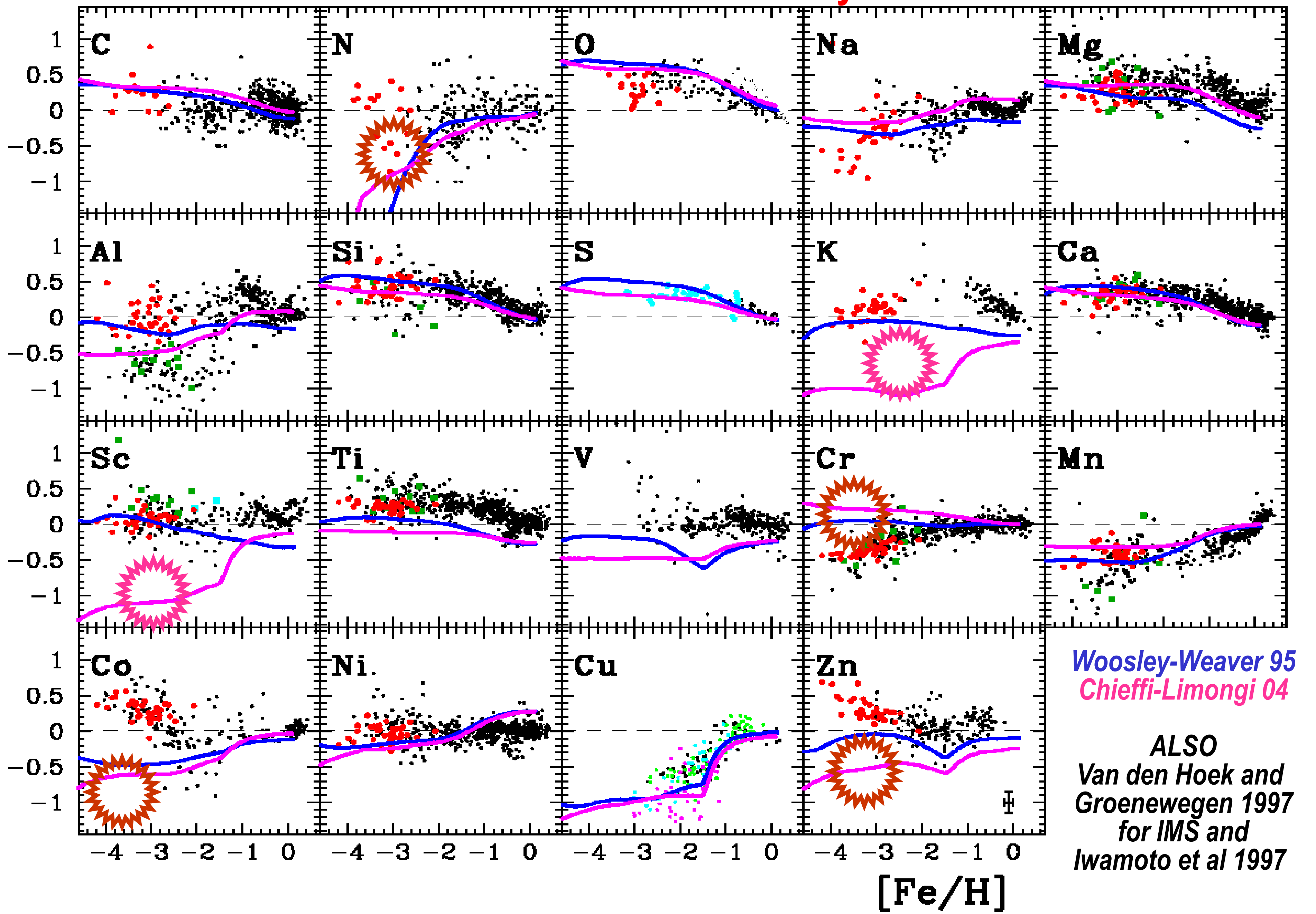


If halo is made by a **continuous** accretion/disruption of local dSphs, WHY ONLY low α/Fe stars accreted ?

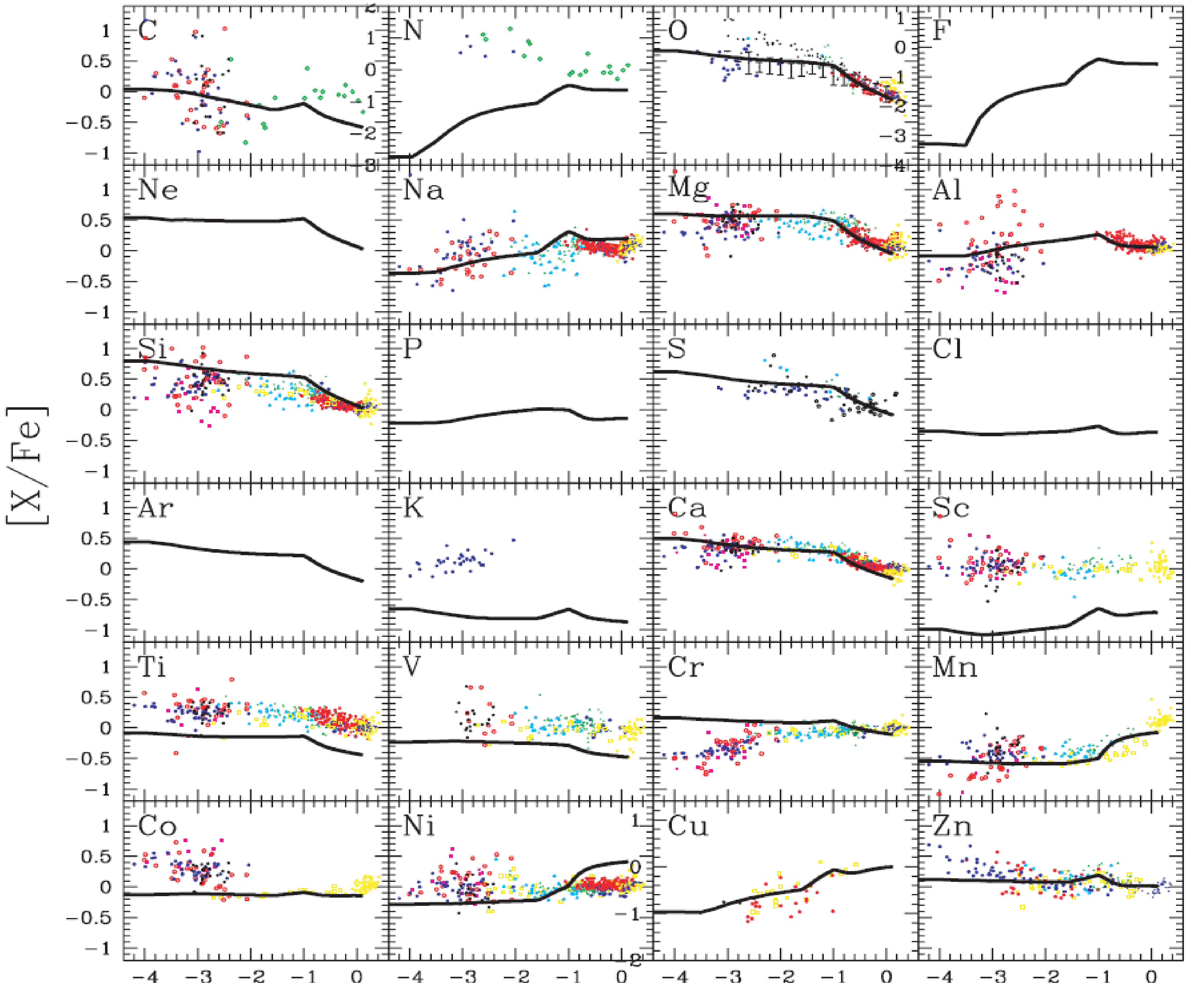
Only starts from the outskirts of dSphs ?
(Majewski, this morning)

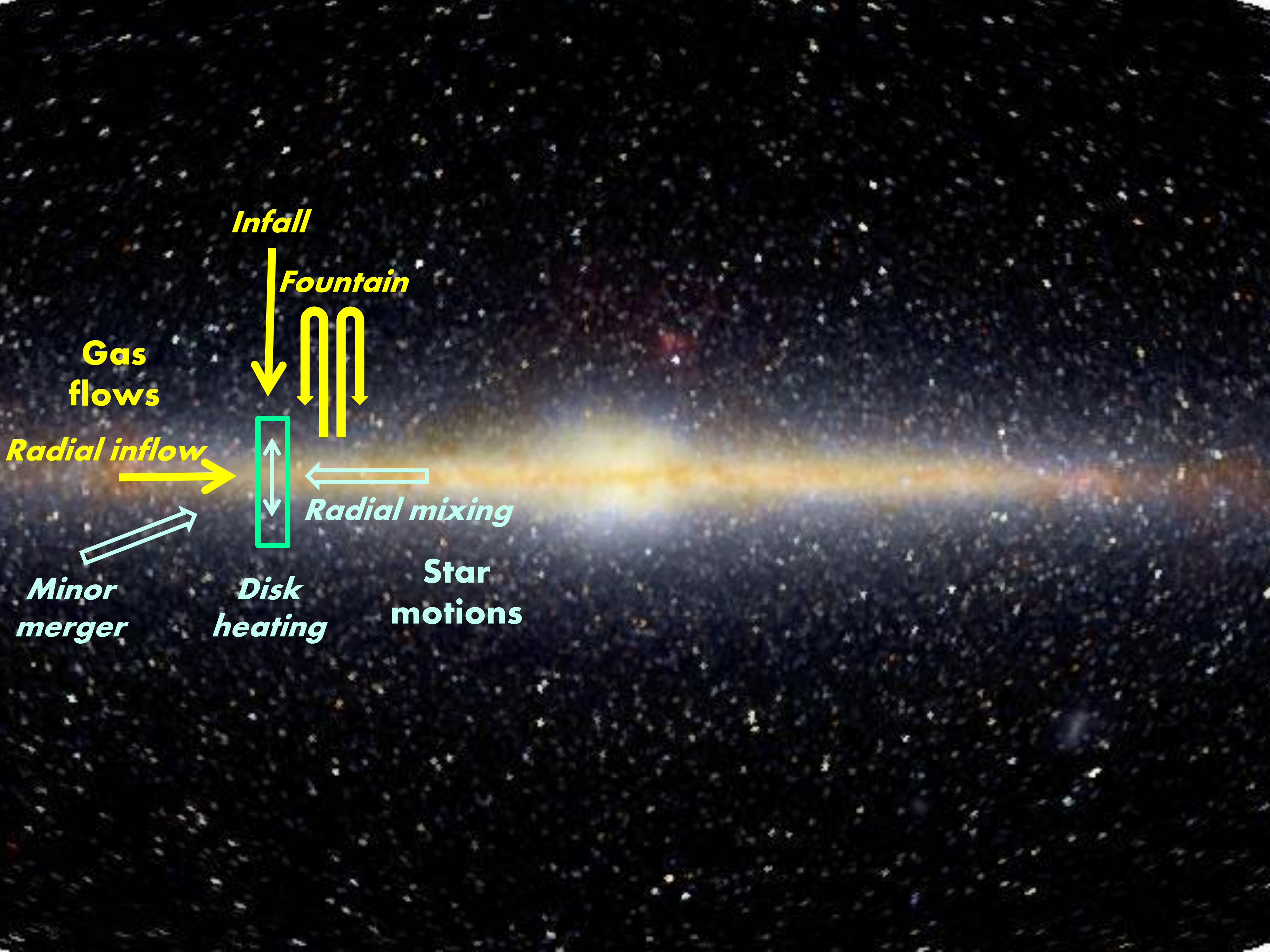
OK, but WHY all of them are >12 Gyr OLD ???

Chemical evolution from C to Zn : theory vs observations

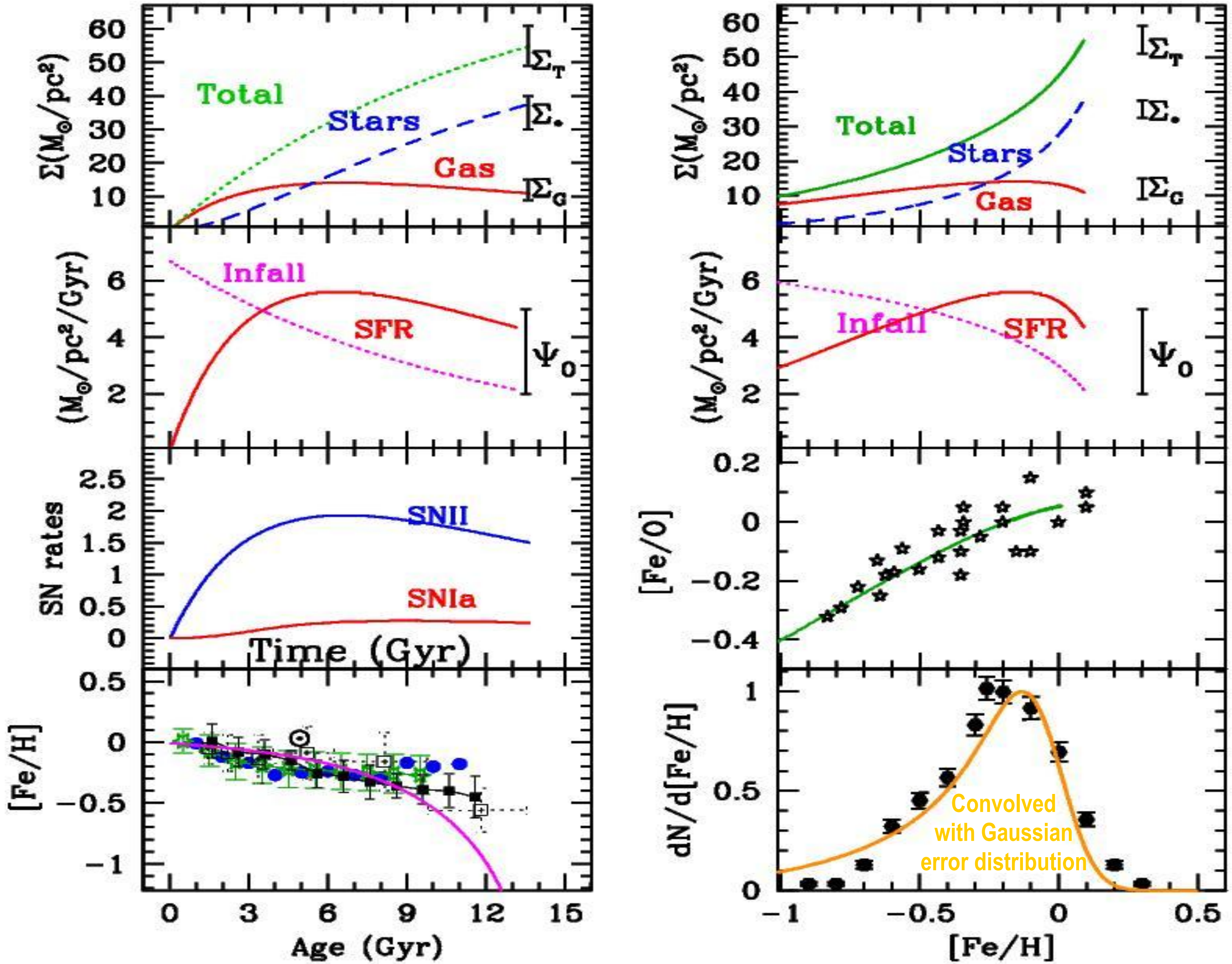


Kobayashi et al. 2007



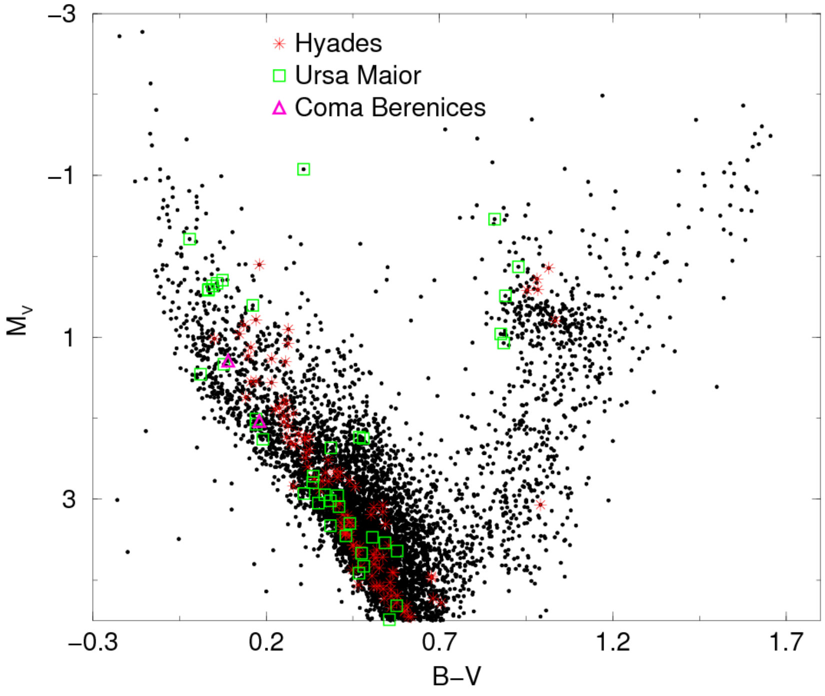

Infall
Fountain
Gas flows
Radial inflow
Radial mixing
Minor merger
Disk heating
Star motions

The Solar Neighborhood

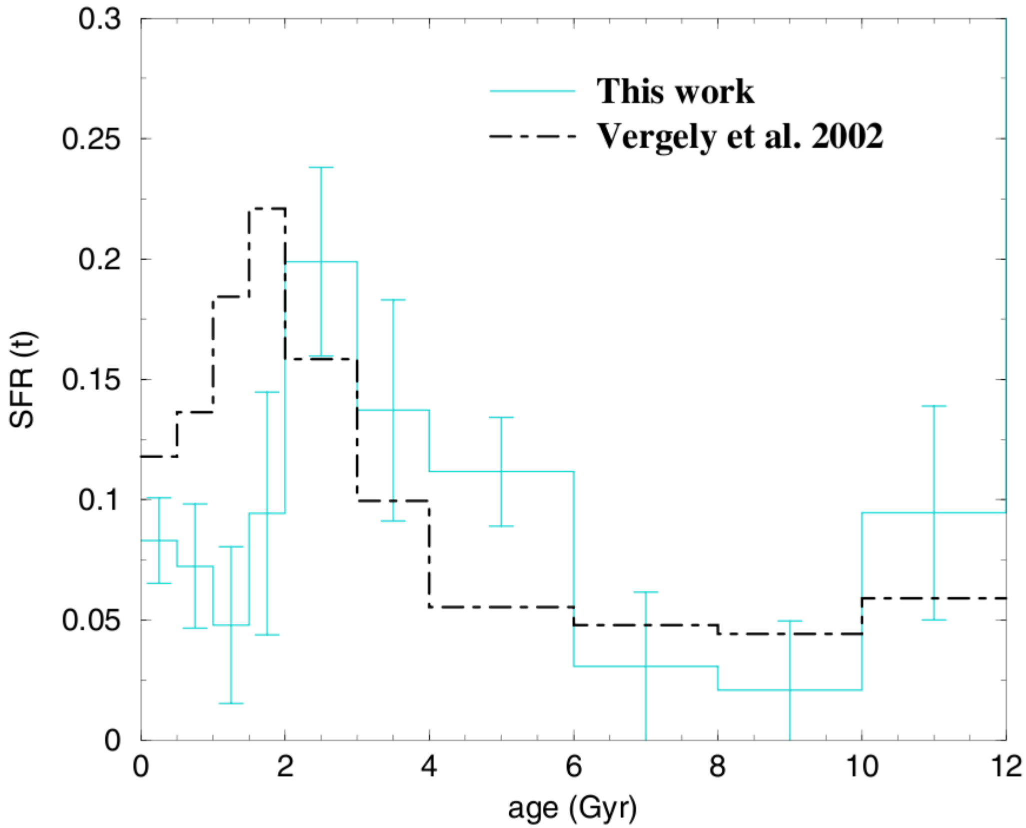


SLOW INFALL (τ = 7-8 Gyr) to fix G- (or M- or K-) dwarf problem *(metallicity distribution)*

and SNIa to account for [Fe/O] evolution



Deriving the local SFR history from the Colour-magnitude diagram (Cignoni et al. 2006)

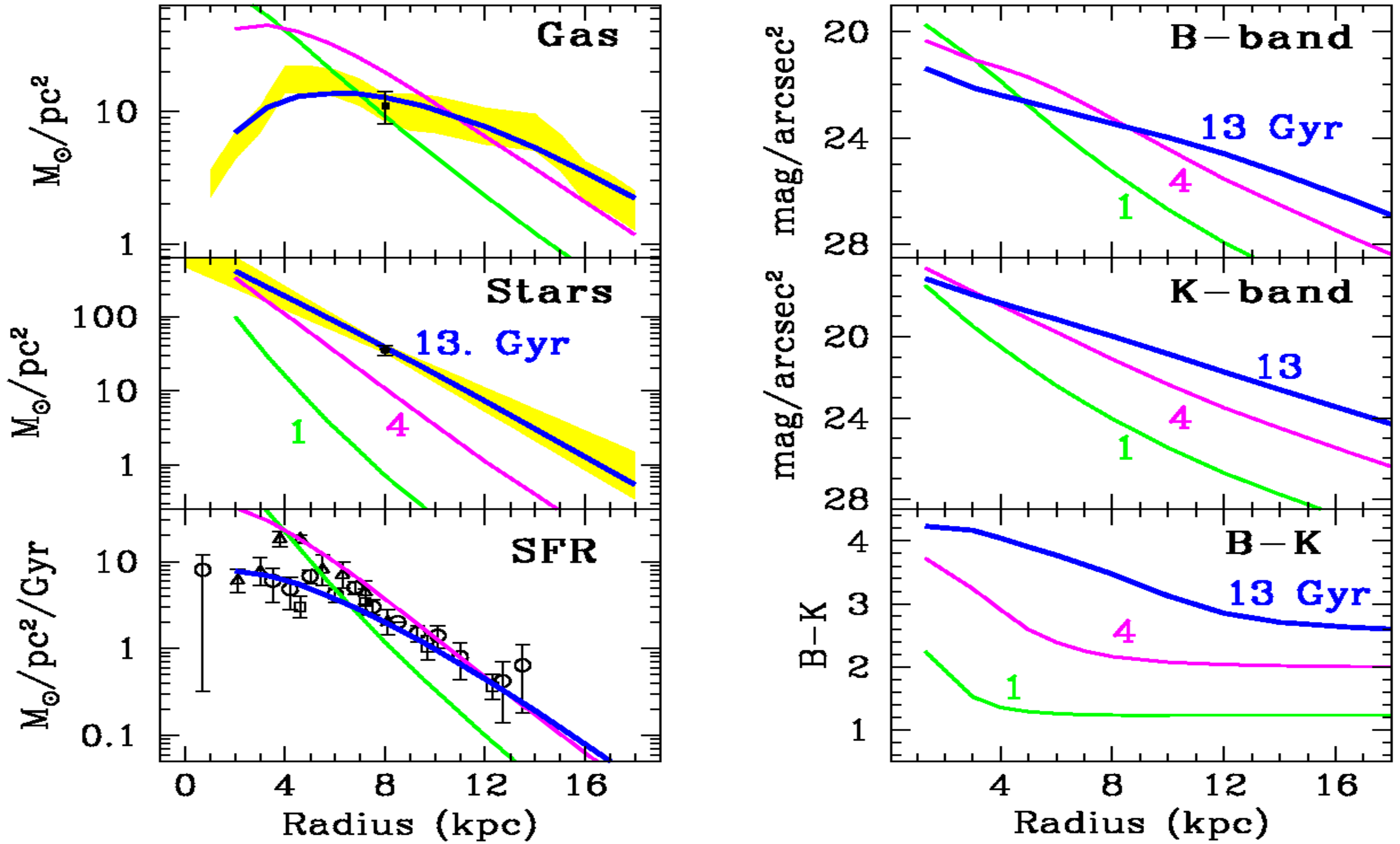


At present : many biases and limitations

BUT:

Things must improve with deeper and more accurate surveys (GAIA)

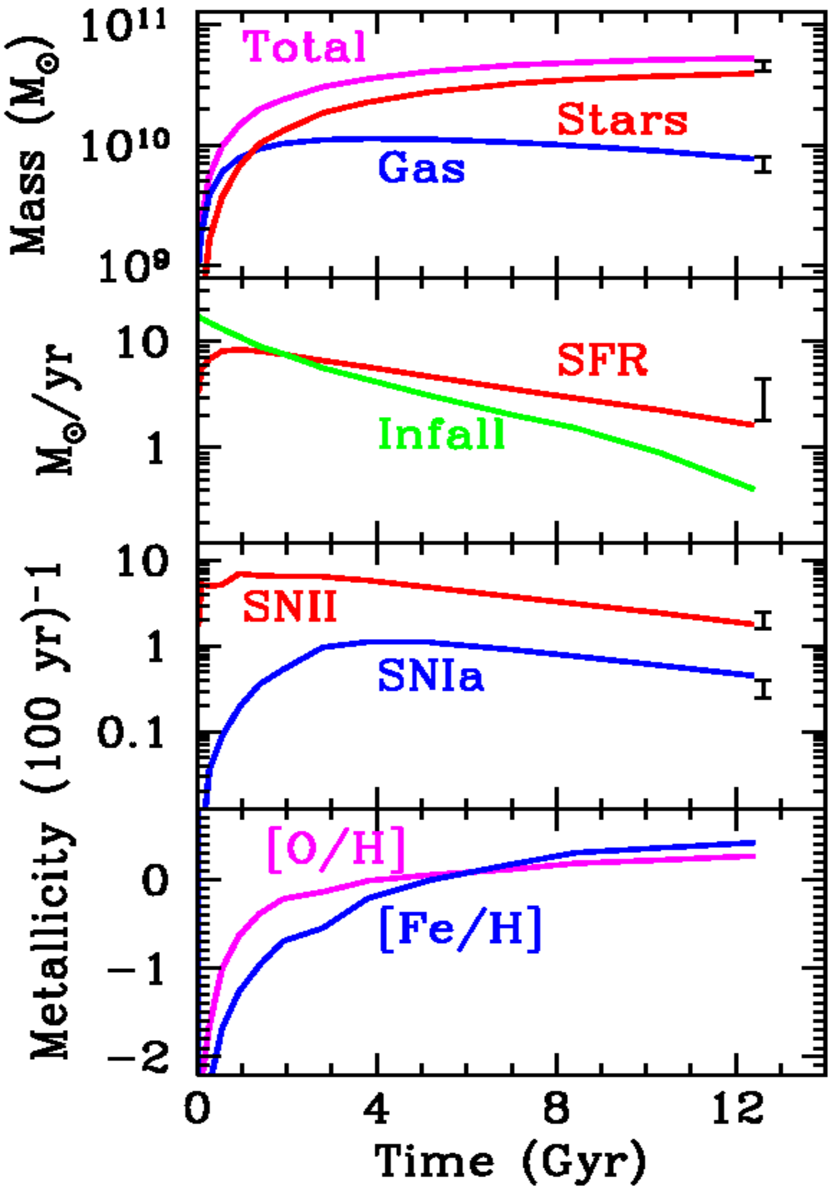
The Milky Way disk

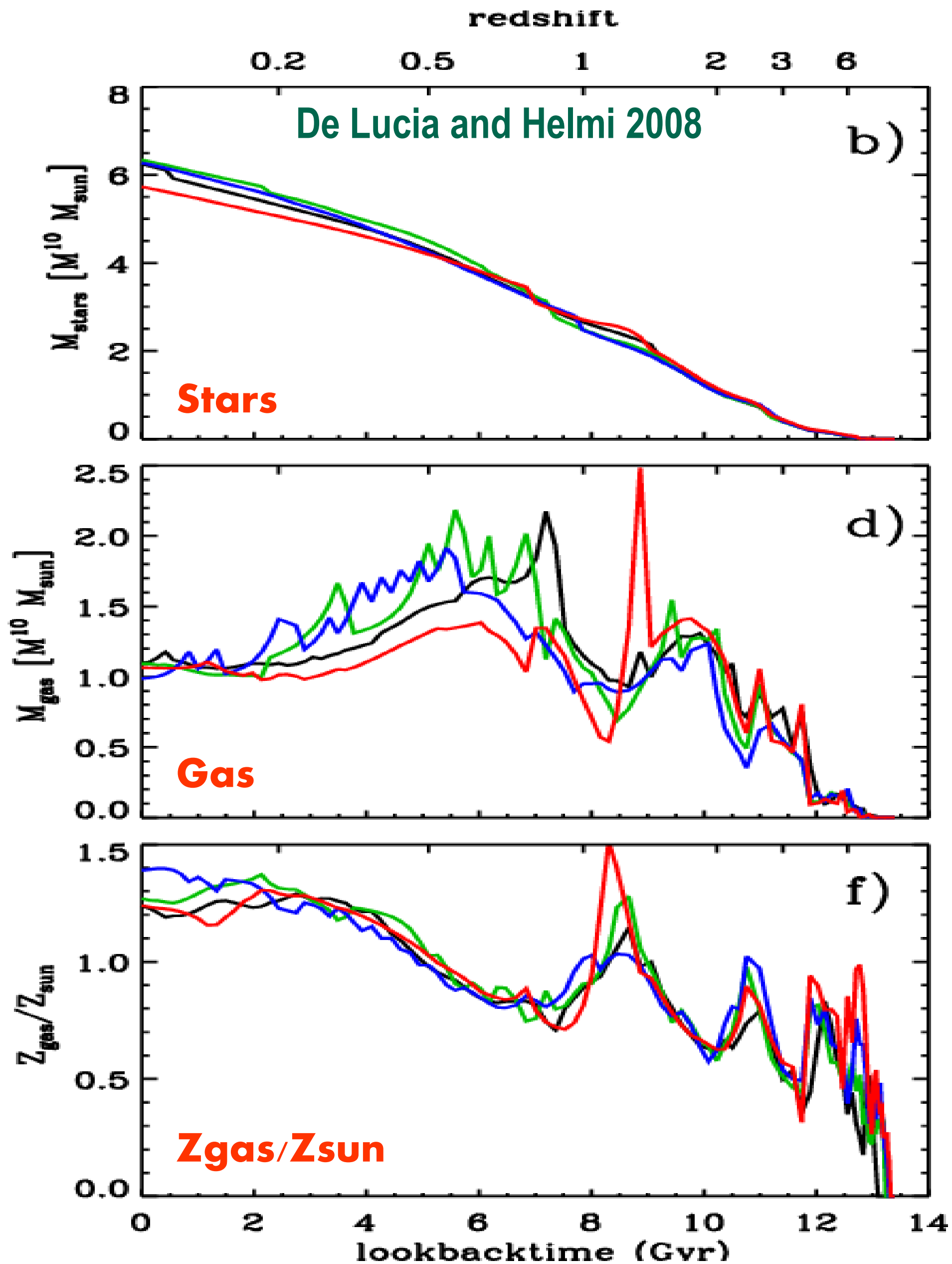


Inside-Out formation from infall and radially varying SFR efficiency required to reproduce observed SFR, gas and colour profiles (Scalelengths: $R_B \cong 4$ kpc, $R_K \cong 2.5$ kpc)

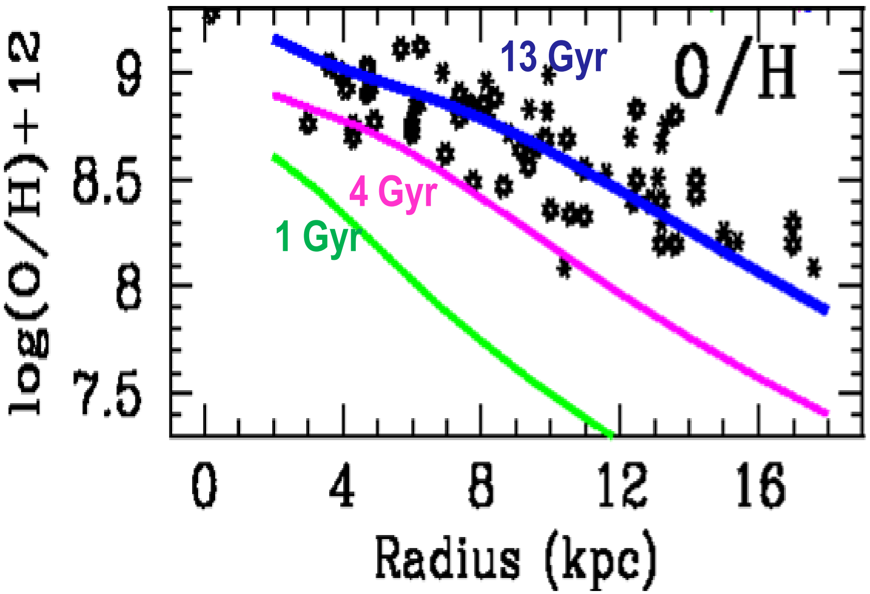
(*Boissier and Prantzos 1999*)

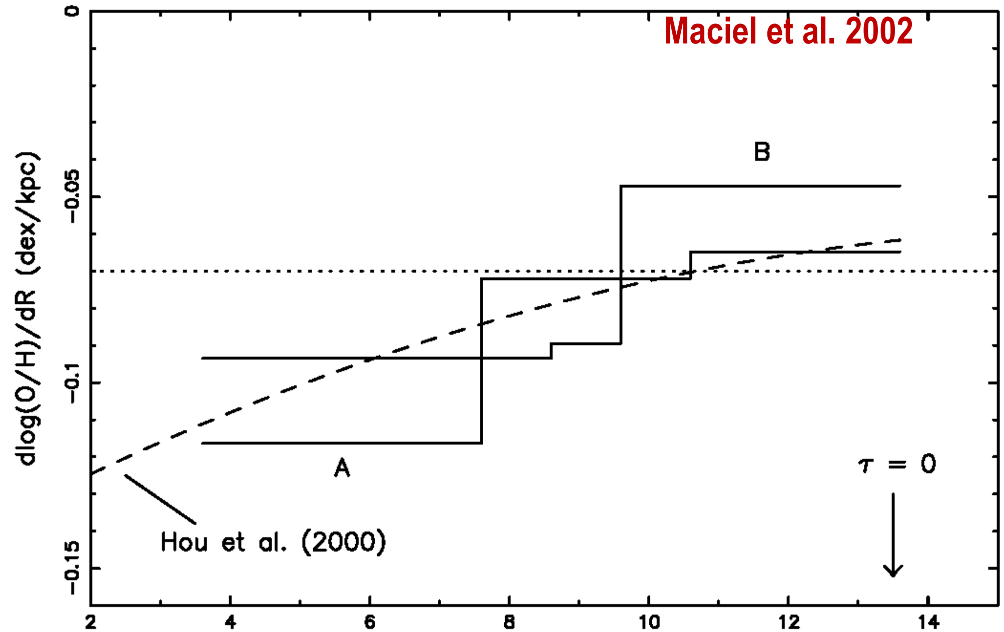
HISTORY OF MILKY WAY DISK





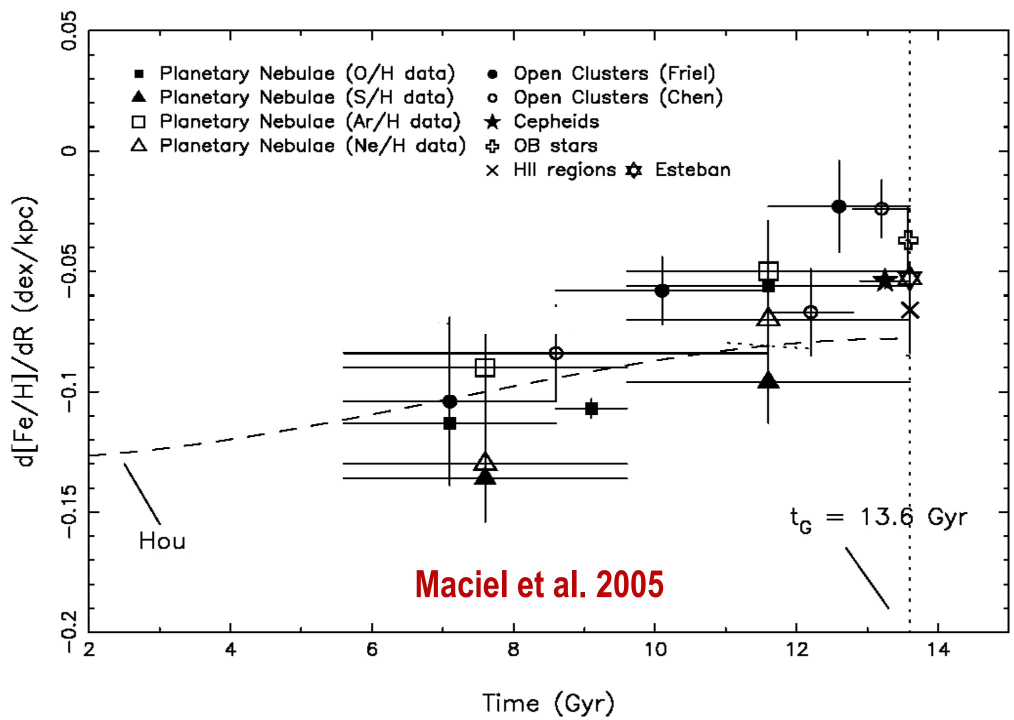
Abundance gradients generically produced, generally found to flatten with time
consequence of "inside-out" disk formation





"Observed" evolution of O gradient:
d[dlog(O/H)/dR]/dt ~ 0.004 dex/kpc/Gyr
In broad agreement with theory

But: large uncertainties in both abundance gradient (*abundances, distances*) and *age* determinations



The Milky Way disk

What is the value of the Galactic abundance gradient ?

Observations of OB stars

suggest a gradient of

dlog(O/H)/dR ~ -0.033 dex/kpc

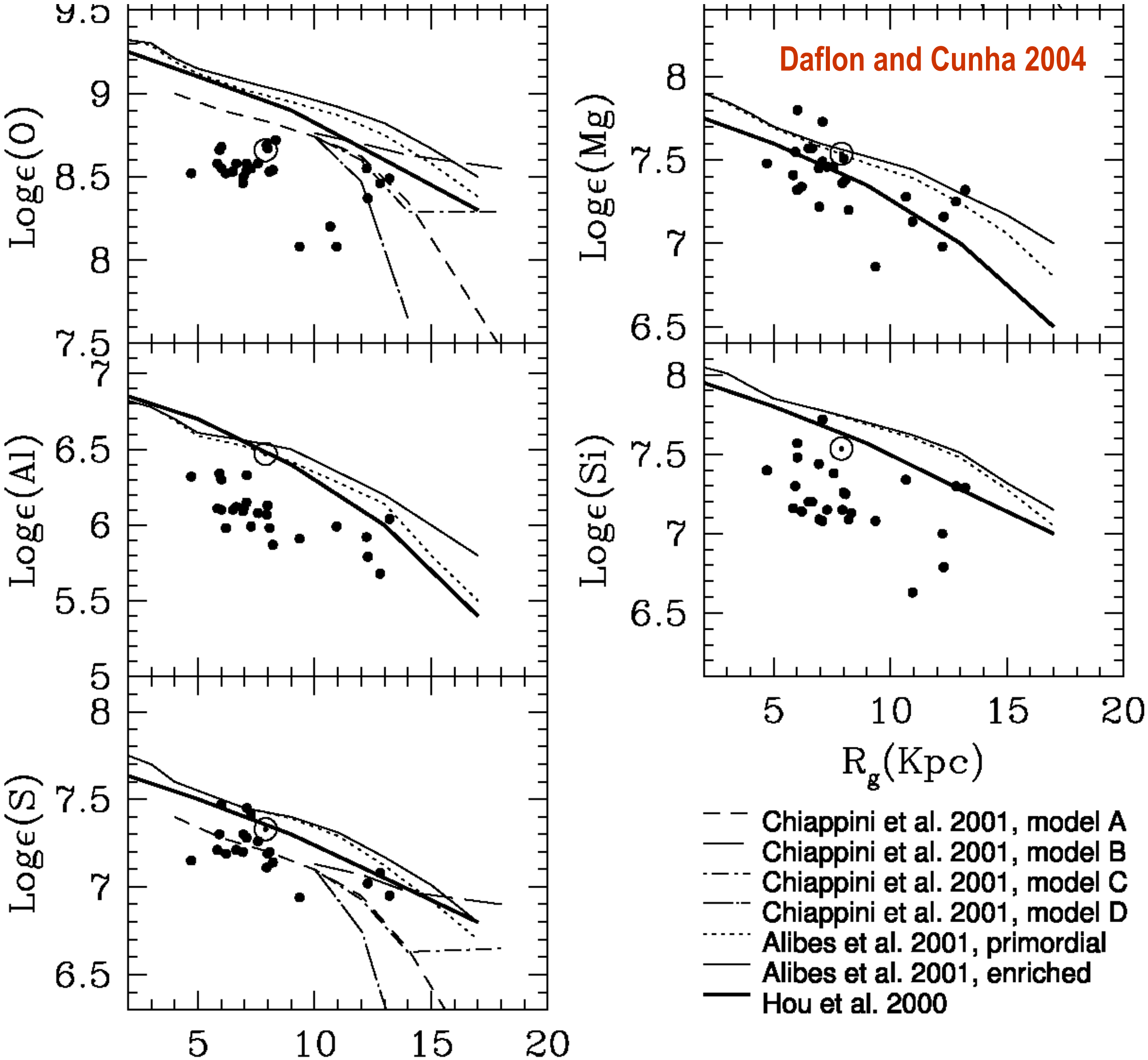
(about half the canonical value)

for oxygen,

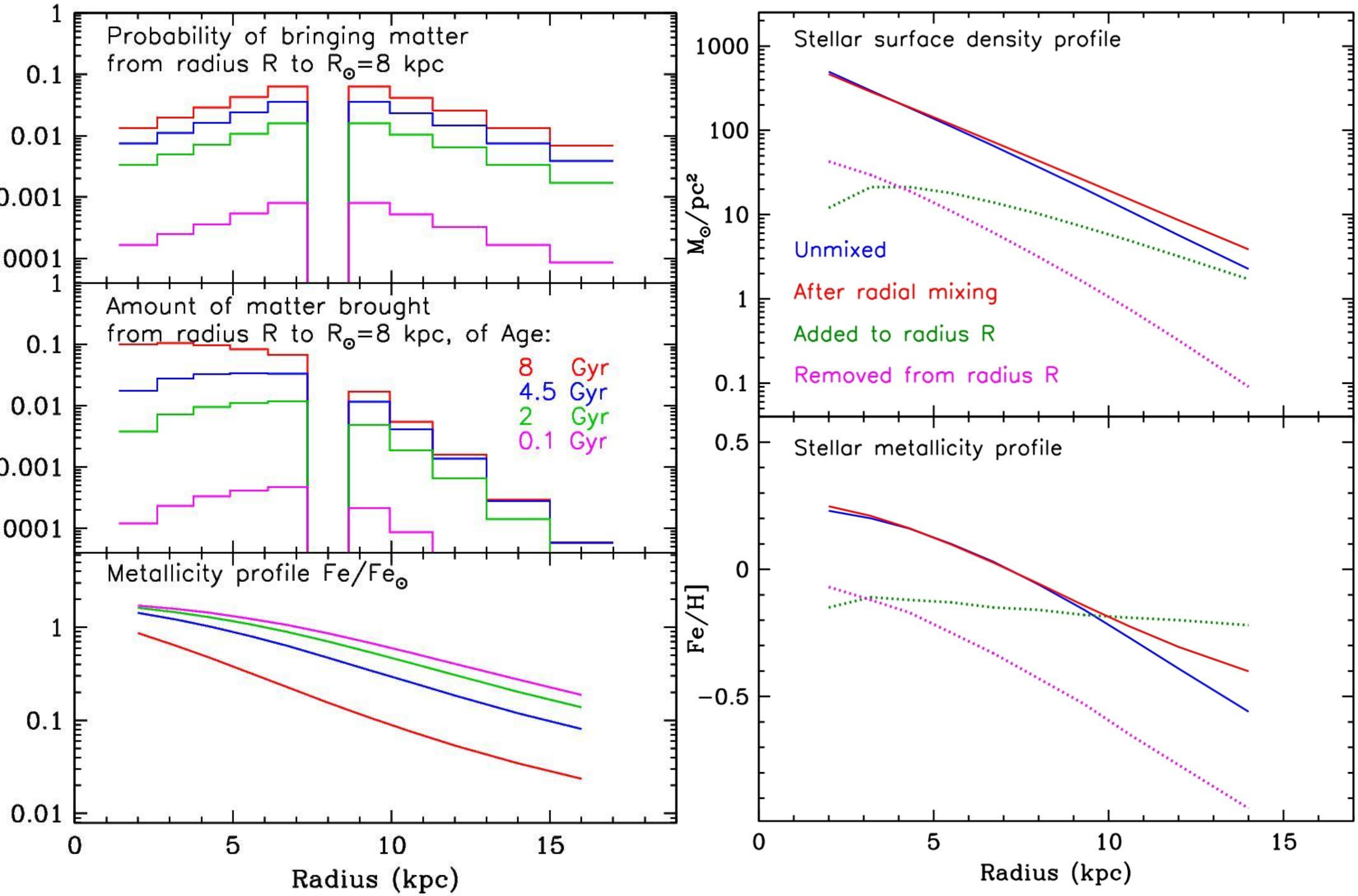
and slightly larger

for other elements

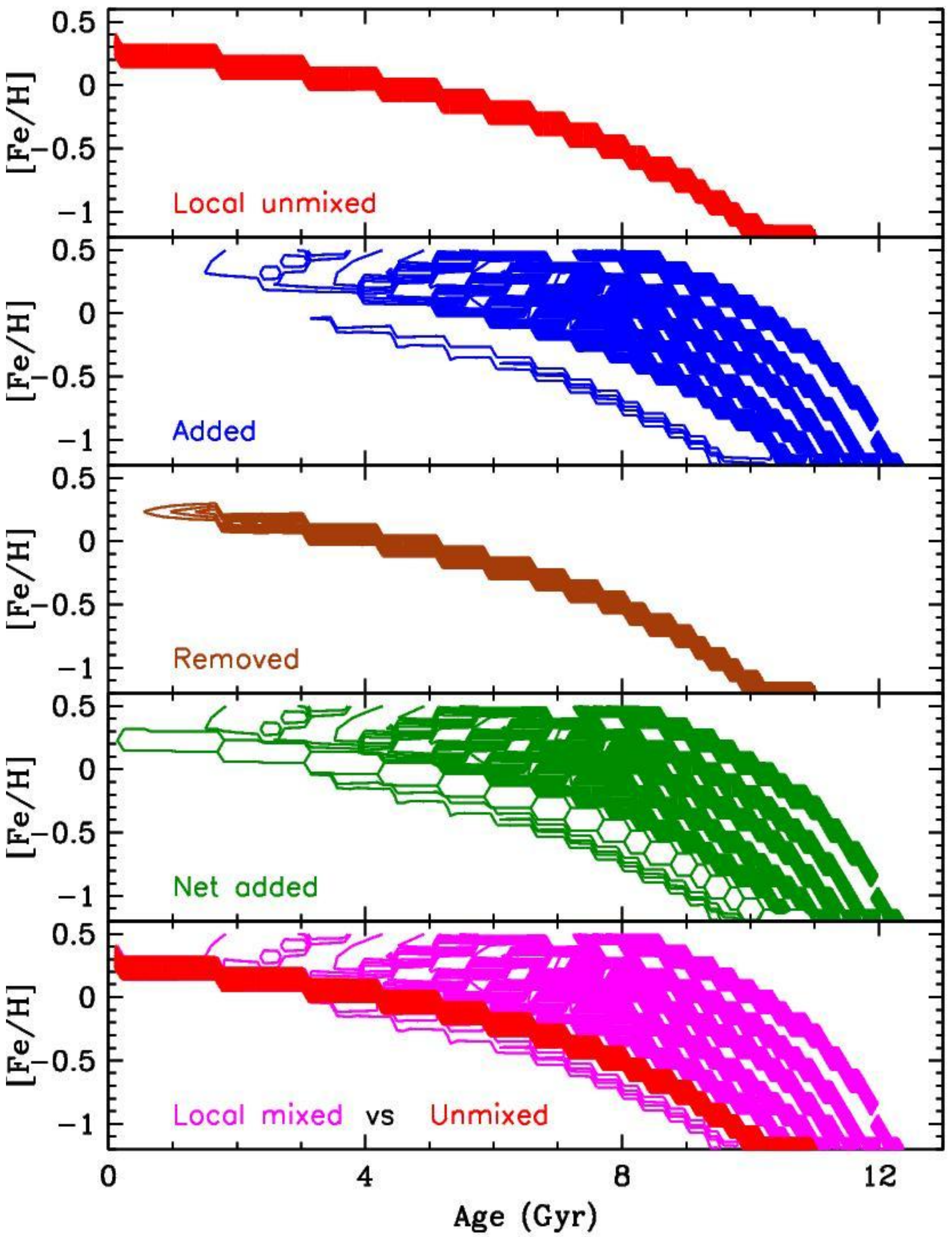
(Daflon and Cunha 2004)

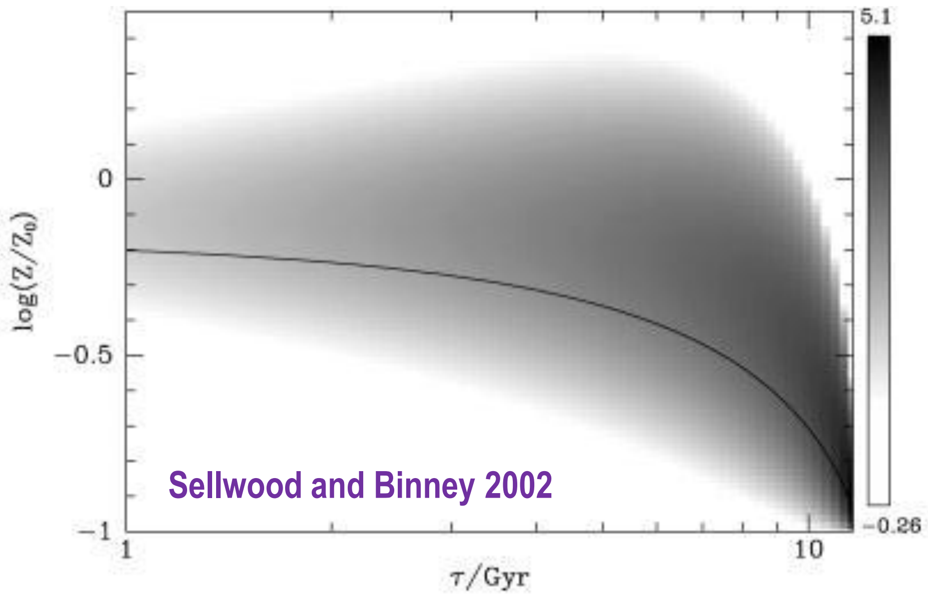


A toy model for radial mixing (a la *Sellwood and Binney 2002*)



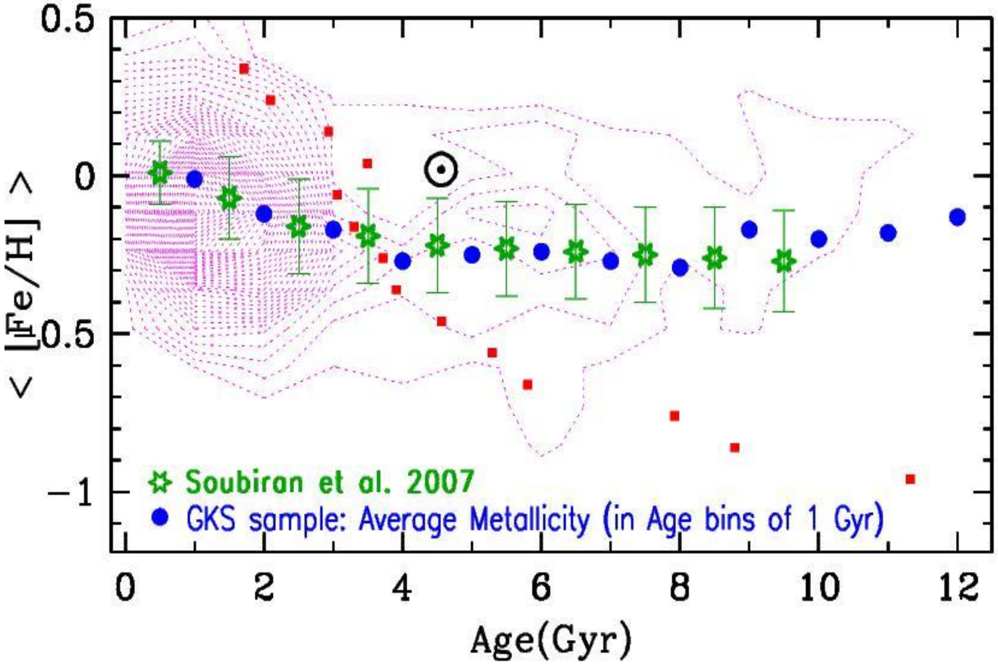
Effect of radial mixing on local age-metallicity relation



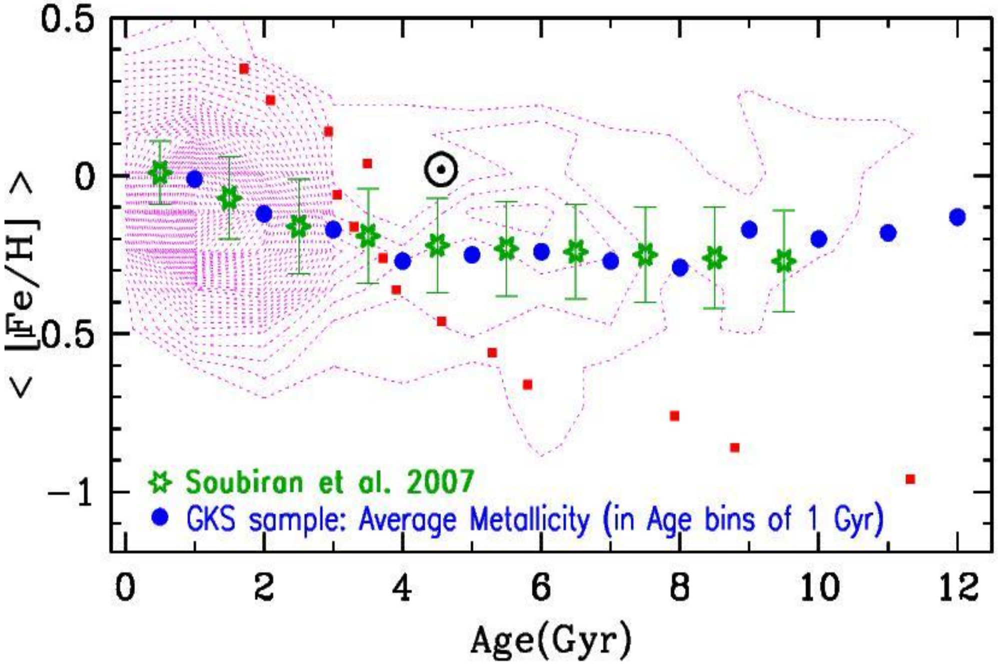


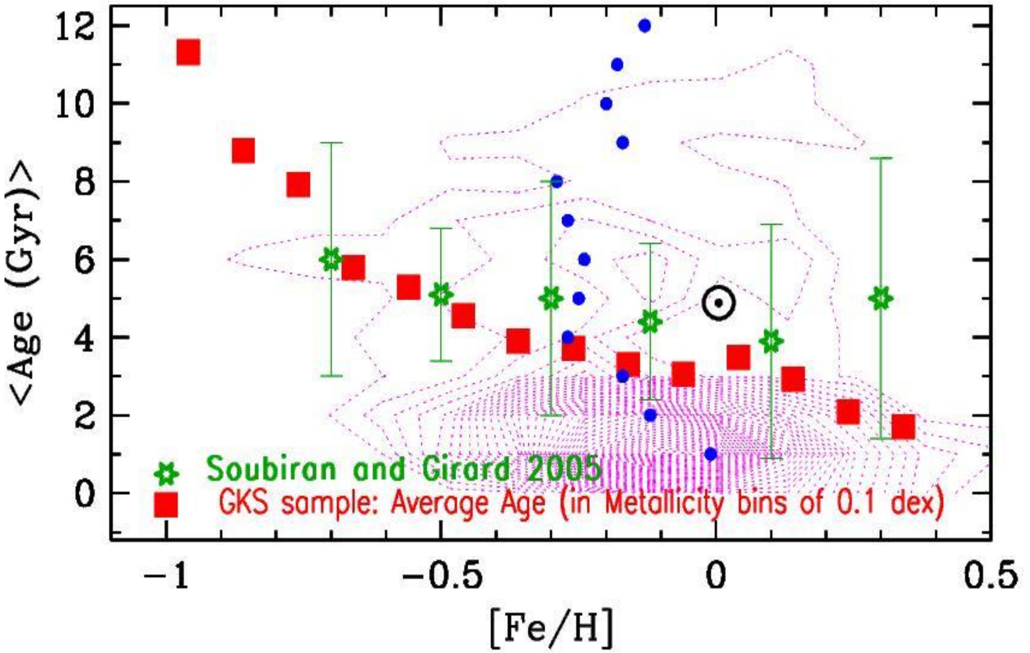
Radial mixing may induce dispersion into and slightly alter the average local age-metallicity relation

But *what is* the observed *average local age-metallicity relation ?*



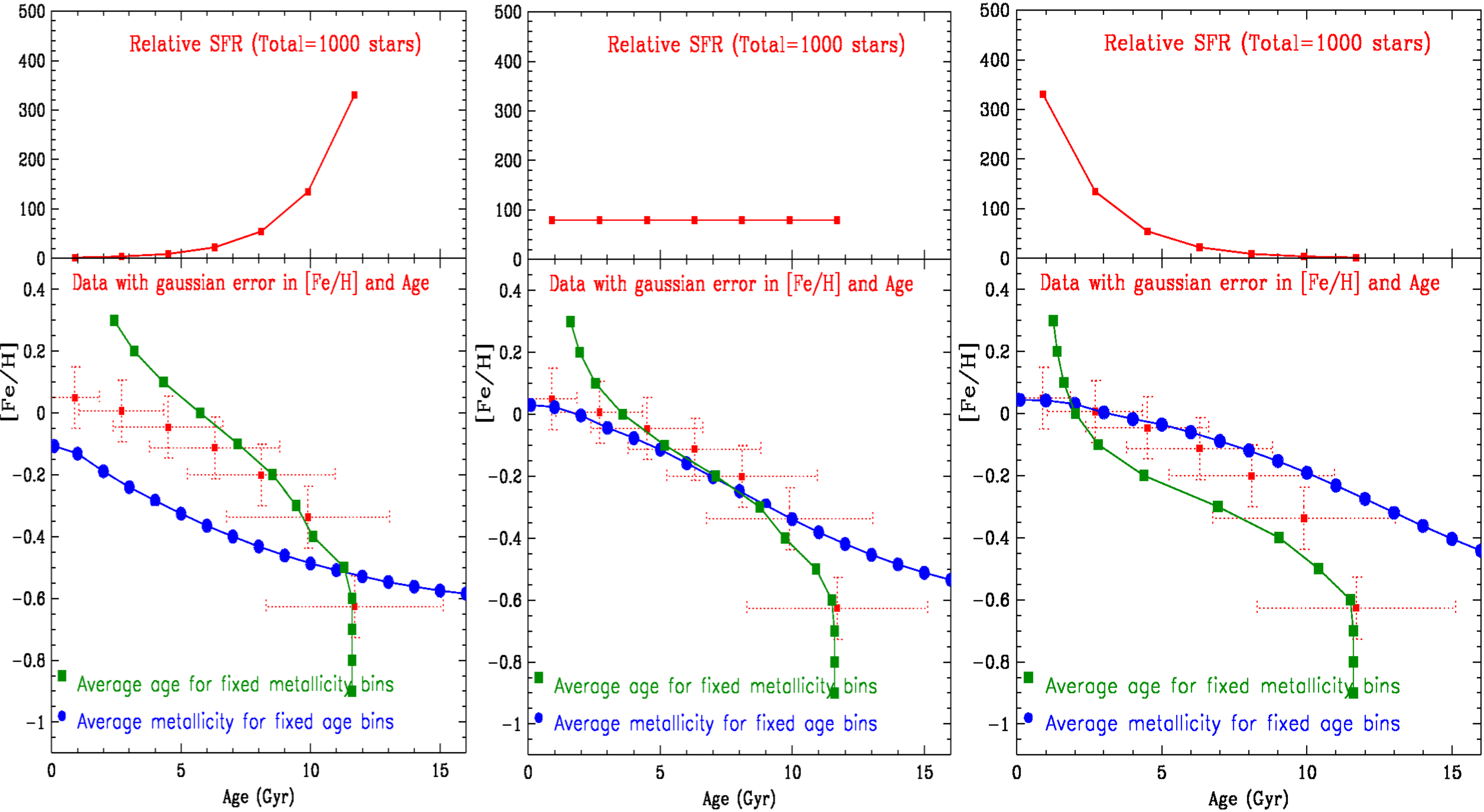
The answer depends on the question you ask





The answer depends on the question you ask

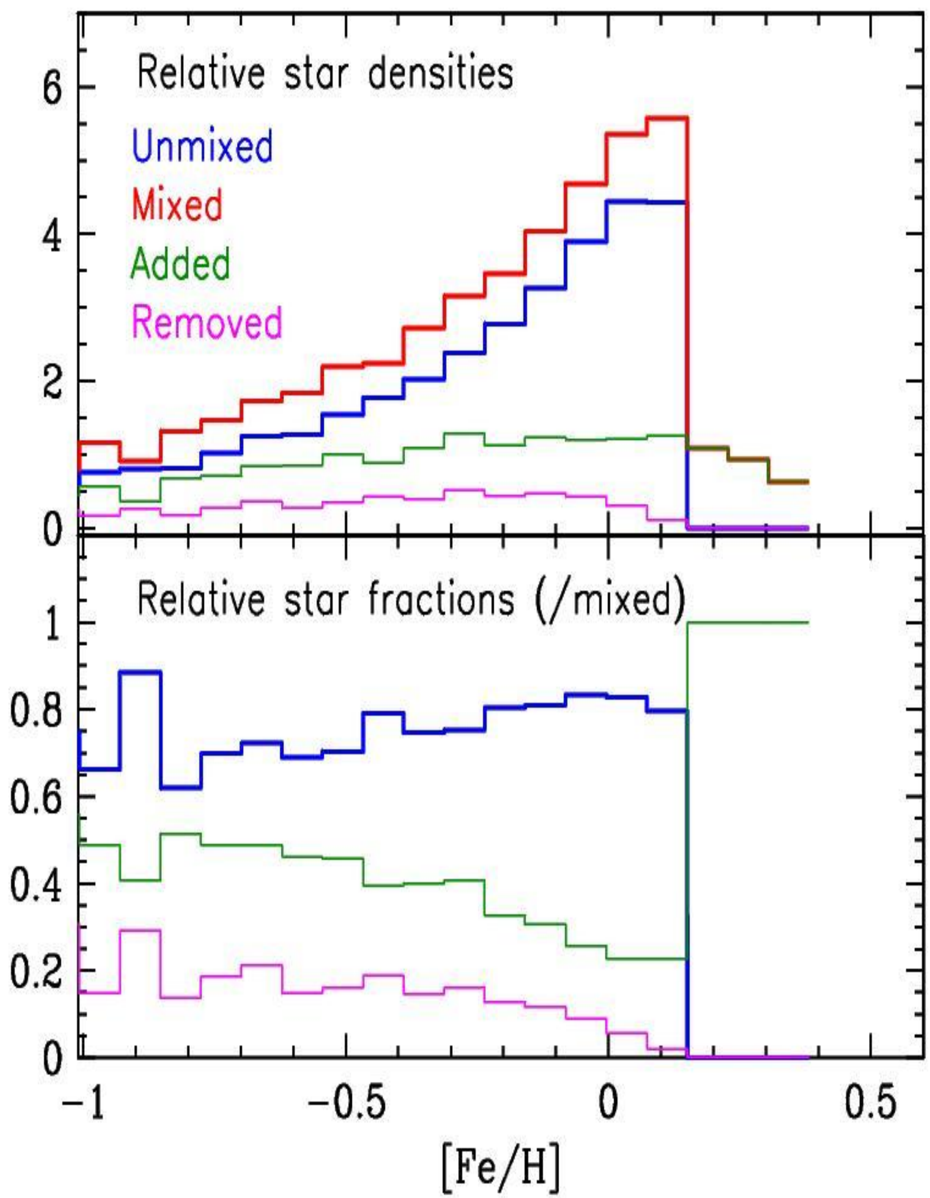
Average metallicity vs Age and Average age vs. metallicity from simulated input data



The average metallicity vs age relation is always flatter than the one in simulated input data

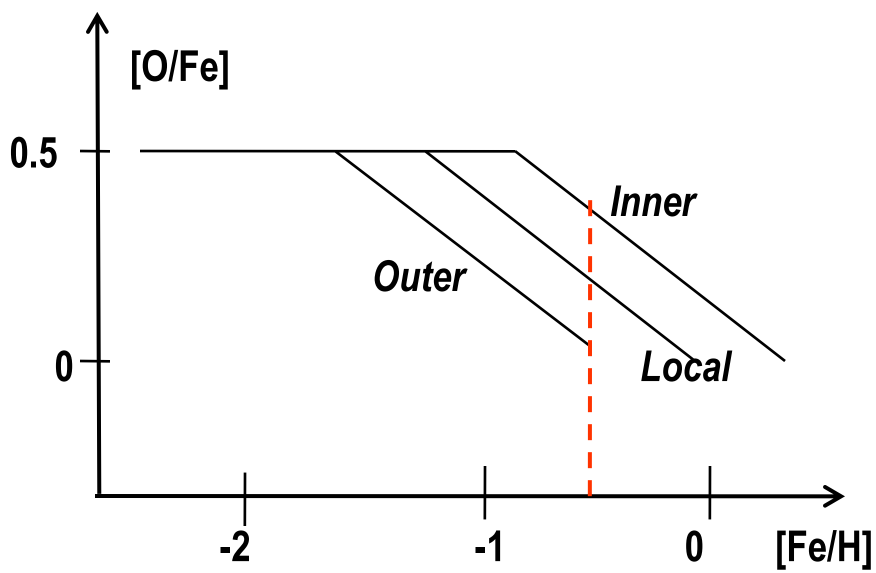
It is unfortunately meaningless to compare Age-Metallicity relation of simple one-zone models to average Age-Metallicity relation derived from surveys

Effect of radial mixing on the metallicity distribution



Radial mixing may bring
in the solar neighborhoud
stars of all metallicities,
Including a
HIGH METALLICITY TAIL
(not existing in the local simulation)
OF MOSTLY OLD STARS
coming from the inner disk
(e.g. *Haywood 2008*)

But this may induce dispersion in the
local [O/Fe] vs [Fe/H] relation
not seen in the data...

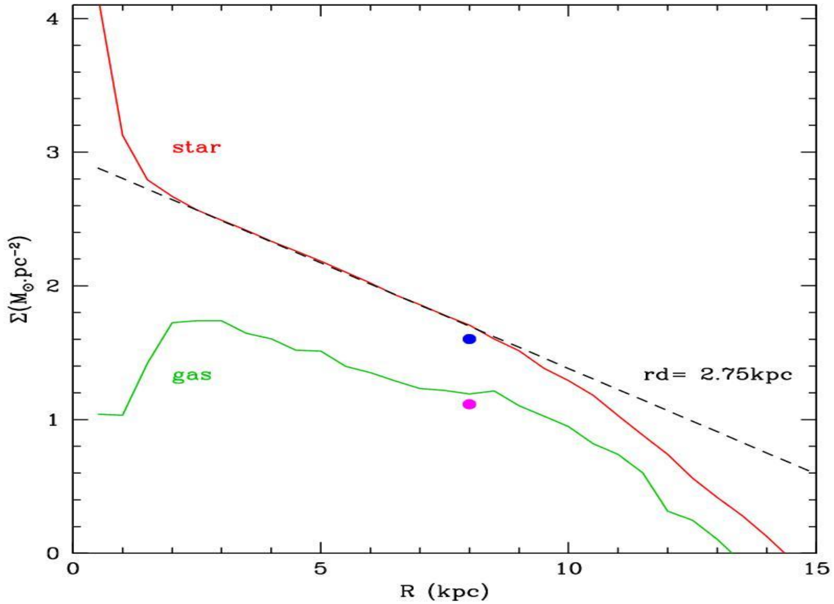


Induced Nested Galactic Bars
Inside Assembling Dark Matter Halos

Clayton Heller
Georgia Southern University

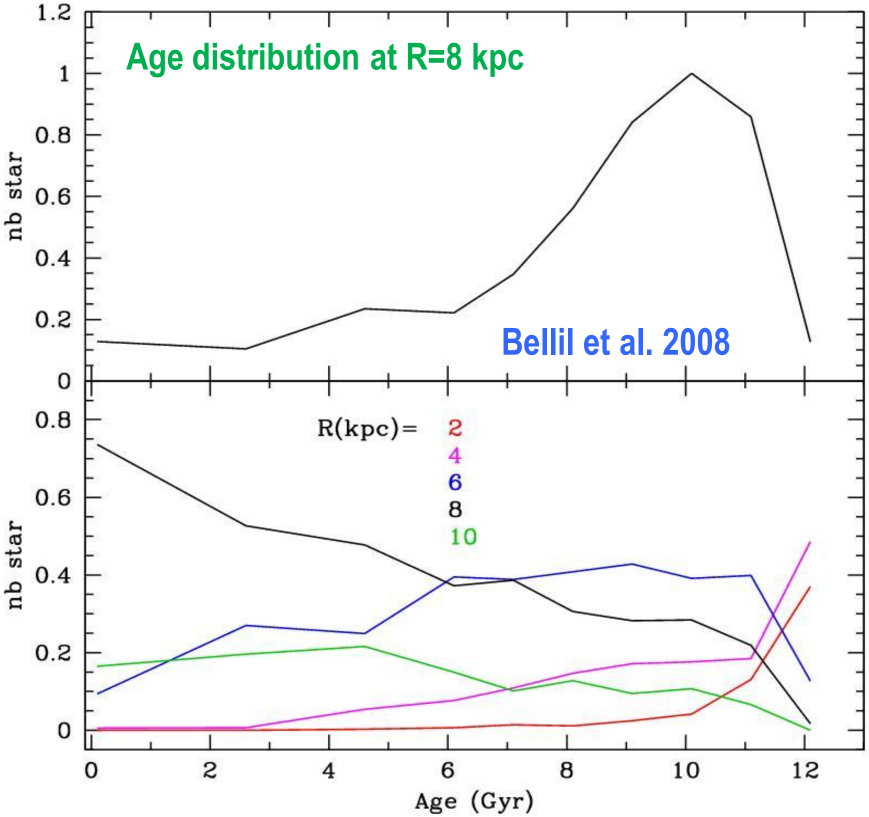
Isaac Shlosman
University of Kentucky

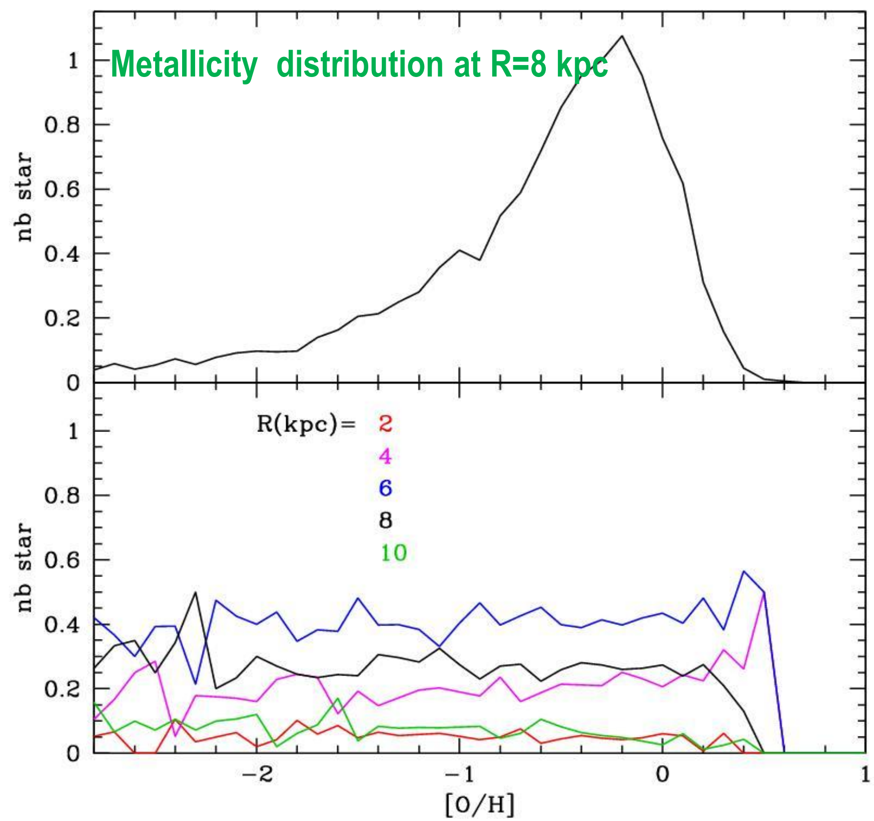
Lia Athanassoula
Observatoire de Marseille



Star and gas profiles not unlike the MW disk, BUT : early type galaxy

Substantial amount of radial mixing found





SUMMARY

Halo metallicity distribution compatible with hierarchical merging

assuming sub-halo properties (MD and $y_{Eff}(M)$) similar to those of dSphs (Outflow)

The metal-poorest halo ([Fe/H]<-2) stars were formed in the numerous low mass (<10^7 M$\odot$) satellites

and the metal-richest halo stars ([Fe/H]>-1.5)in a couple of massive(~10^8 M$\odot$) rapidly evolved, satellites

Early infall probably required in both MW sub-haloes and dSphs to explain their metal-poor MD;

Unclear whether a "floor" metallicity is seen in dSphs

Radial mixing may affect local observables
(dispersion in age-metallicity relation,
high-Z tail of old stars from inner disk)

But what is the true (if any) local age-metallicity relation?

but radial mixing may also have undesirable consequences on other observables
(scatter in O/Fe vs Fe/H)

It may also affect abundance profiles (flatter in outer disk)
and colour/age profiles (Rospar et al. 2008)

And what may be the effect of radial mixing on the exponential stellar profile ?