Topics in
Galactic Chemical Evolution

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1) Where have the *secondary* elements gone?

(N14, Be, s-elements,…)

2) Towards a more "realistic" framework for GCE

(The complex history of the Galactic halo ;

mixing up the Galactic disk of stars)

Primary vs Secondary elements

Primary: produced from initial
H and He inside the star

Yield: independent of initial metallicity (Z)
Examples: C, O, Fe...

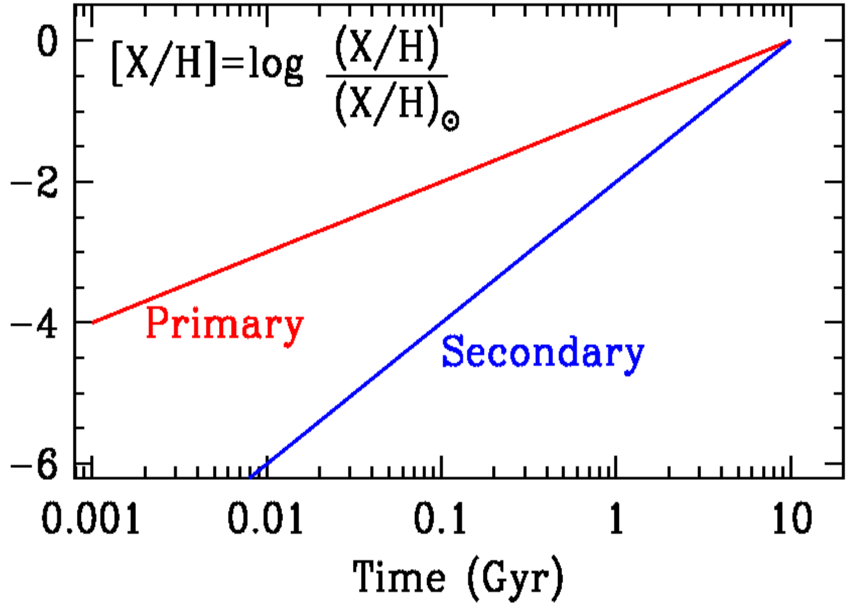
Secondary: produced from initial
metals (Z) inside the star

Yield: proportional to initial metallicity (Z)
Examples: N14, O17, s-nuclei...

Abundance(primary): $X_P \propto t \propto Z$

Abundance(secondary): $X_S \propto t^2 \propto Z^2$

Abundance X/H



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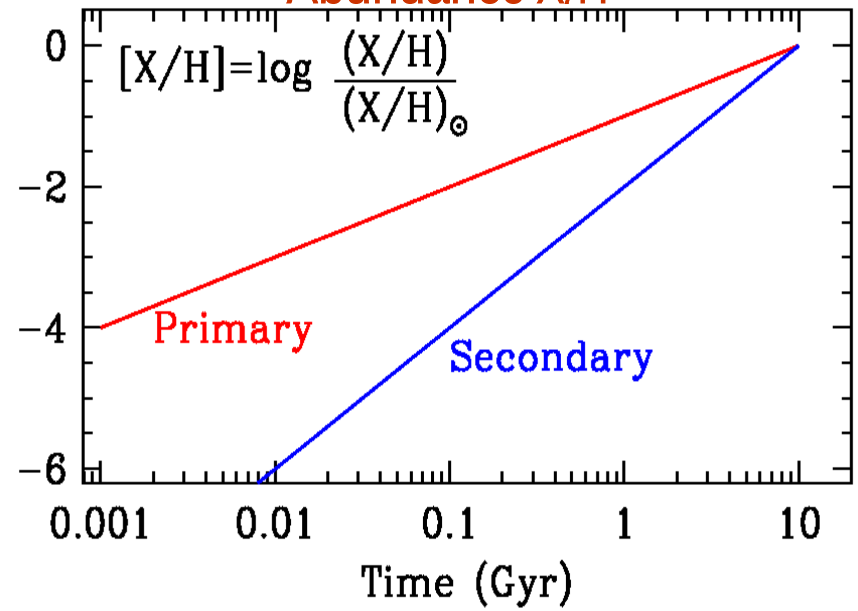
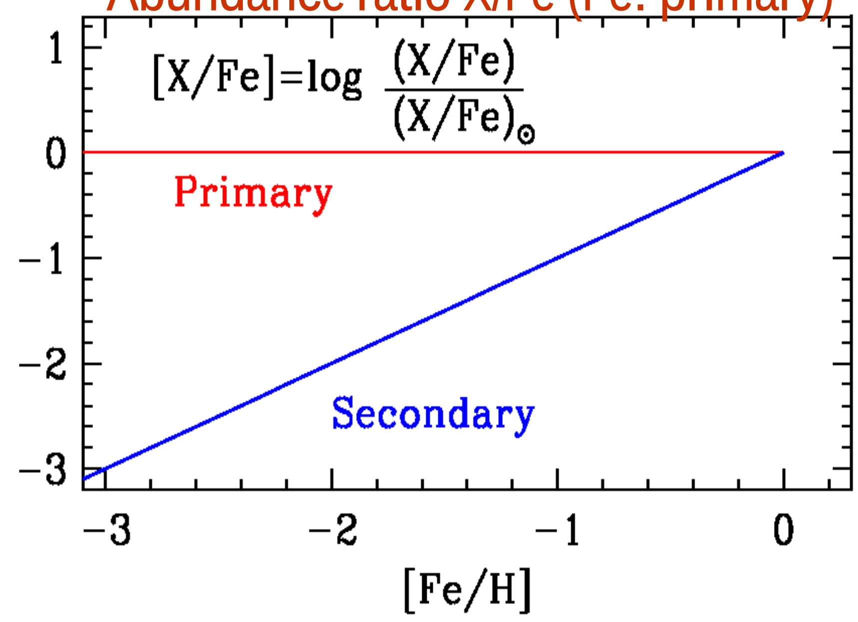
Abundance ratio

P/P : ~constant
S/P : $\propto X_P$

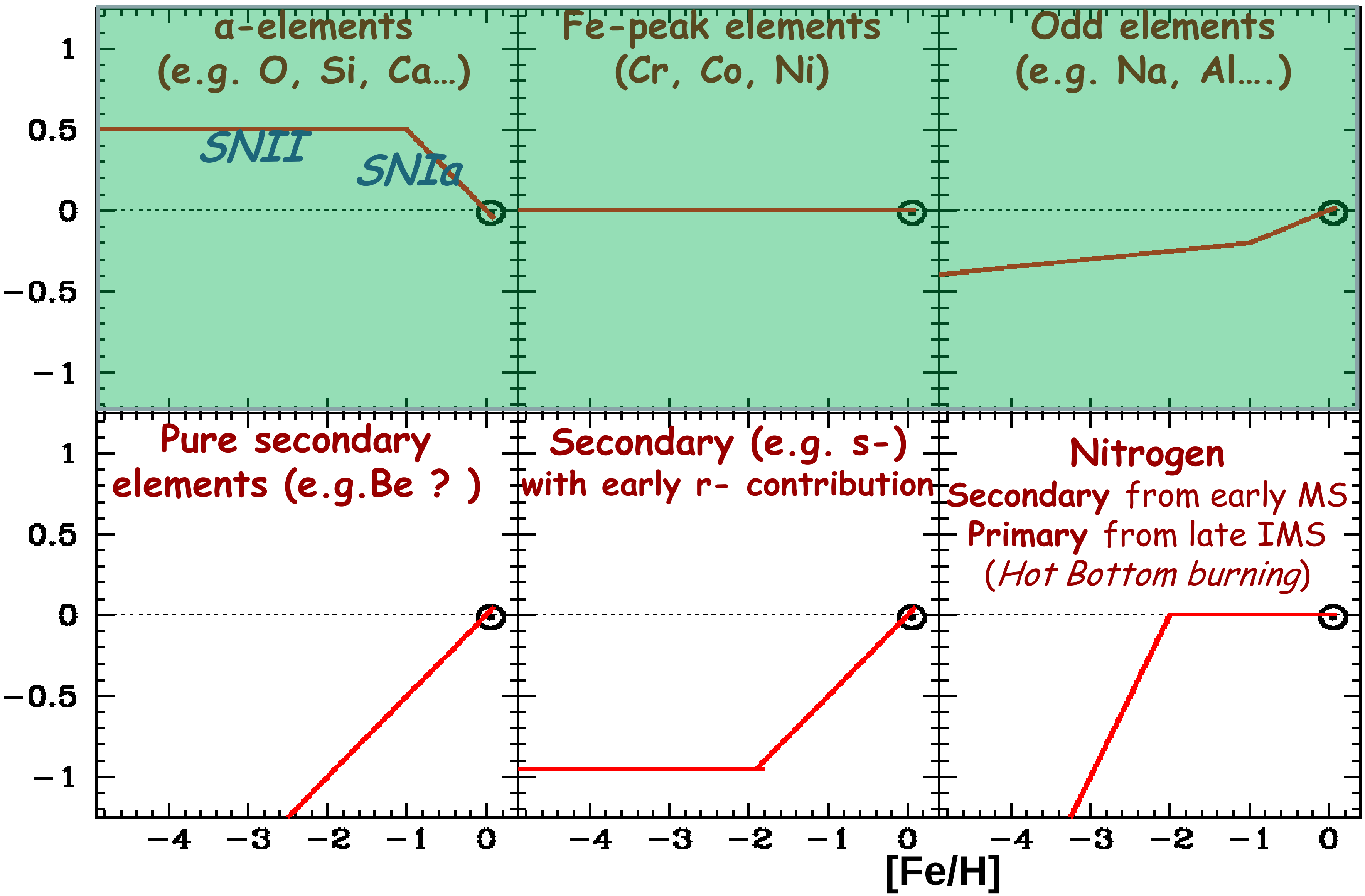
Abundance X/H

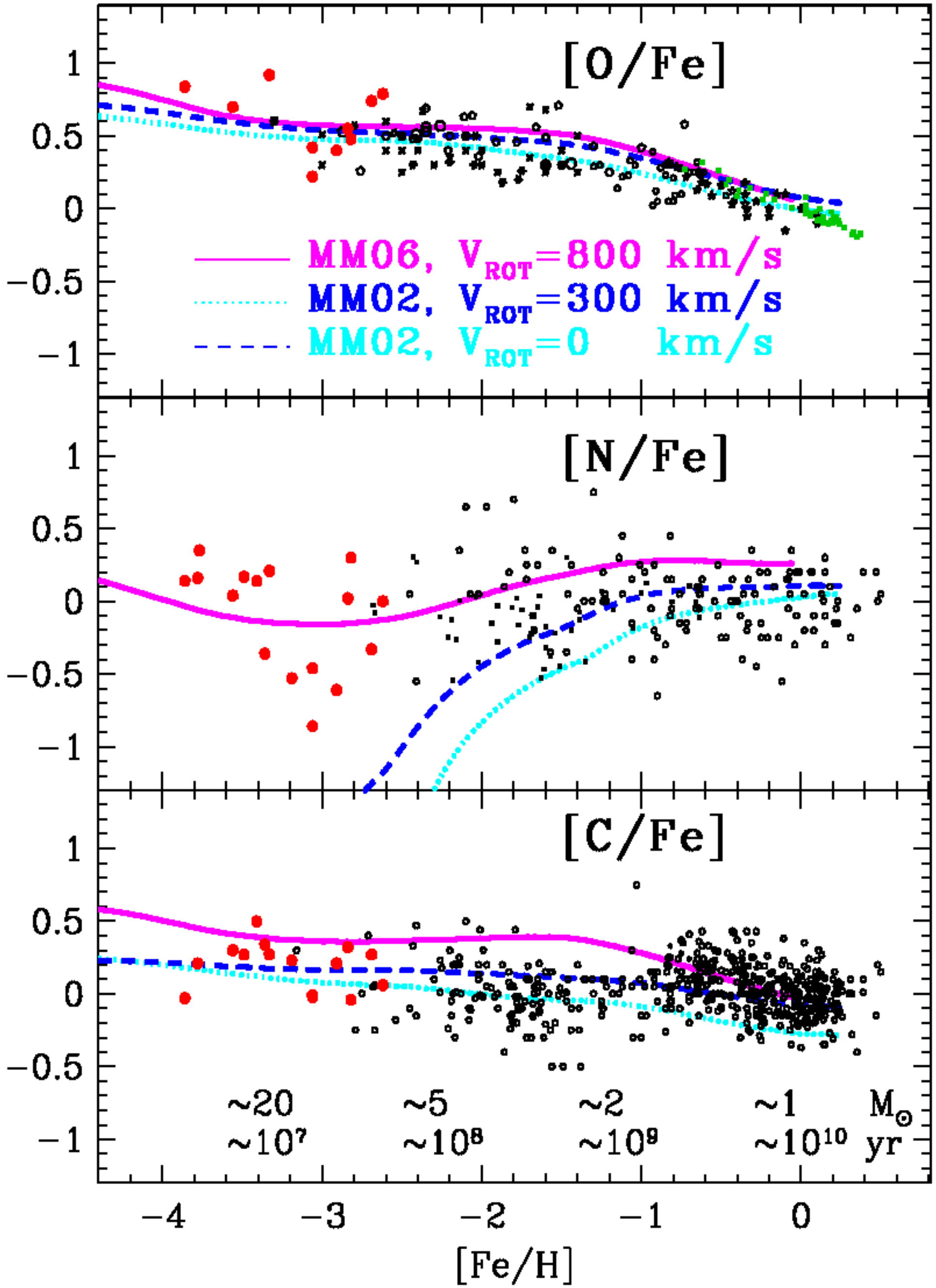


Abundance ratio X/Fe (Fe: primary)



“Naive” expectations of the behavior of [X/Fe] vs [Fe/H] (circa late-80’s)

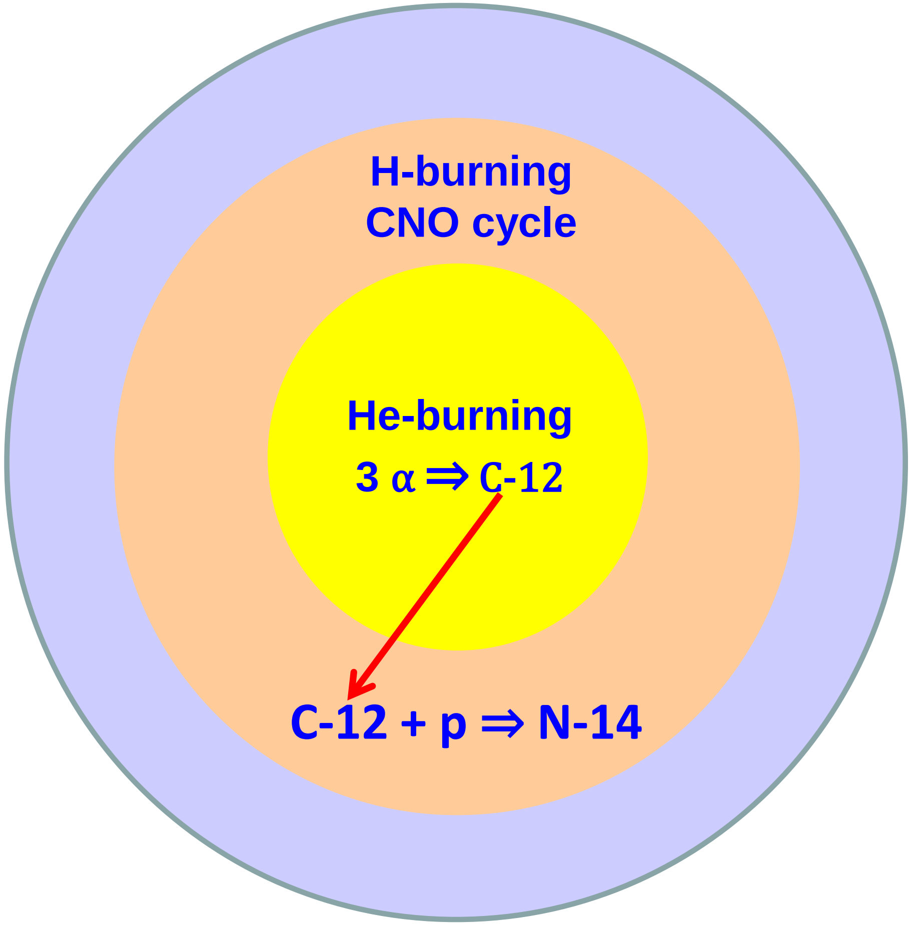




VLT data on non-mixed stars (Li present) suggest **primary N** down to the lowest metallicities (*Spite et al. 2004*)

Massive stars of Z~10^{-8} with **high rotation velocities** (800 km/s) can produce such primary N (Geneva models)

Chemical evolution : the quest for early primary nitrogen

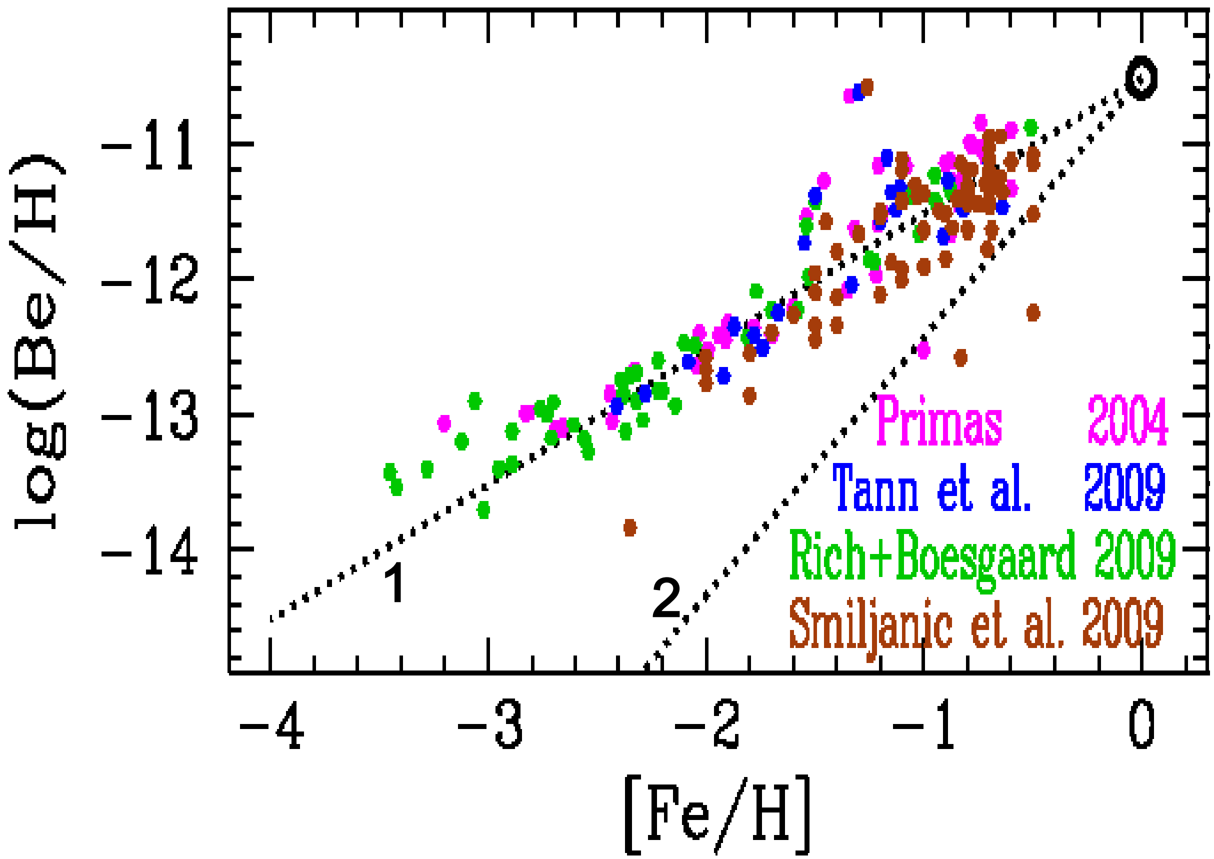


Non-rotating massive stars:
N-14 from INITIAL C-12
SECONDARY N-14

Rotating massive stars:
N-14 from C-12 PRODUCED
in the He-core through 3α
and subsequently mixed
to H-burning regions
by **rotationally induced mixing**
PRIMARY N-14
(*Meynet and Maeder 2004,*
Meynet et al. 2006)

Evolution of Be

Early 90ies: Be (and B) observations in low metallicity halo stars



Be abundance evolves exactly as Fe

(unexpected, since it is produced from CNO and it should behave as secondary)

p,a (GCR) + CNO (ISM) → Be_{SEC} BUT : p,a (ISM) + CNO (GCR) → $Be_{???}$

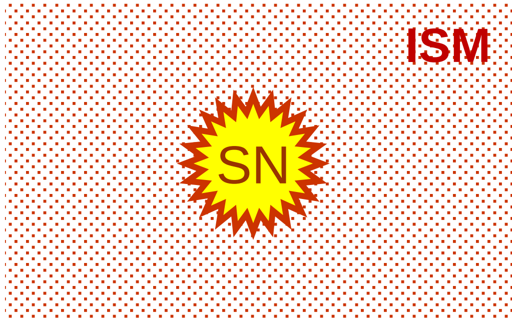
Is the composition of GCR time(metallicity) independent and why ?

Galactic Cosmic Rays : what is the composition of accelerated matter ?

1. Standard ISM accelerated by forward shock

X(GCR) = X(ISM)

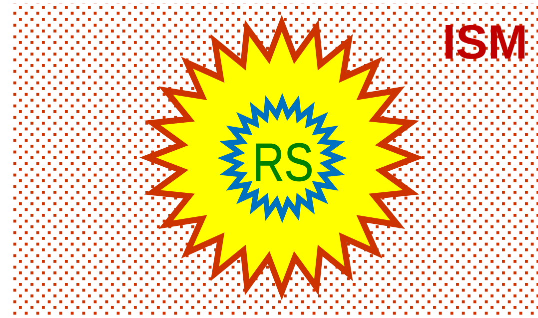
Secondary BeB



2. SN interior accelerated by reverse shock (RS)

X(GCR) = X(SN)

Primary BeB



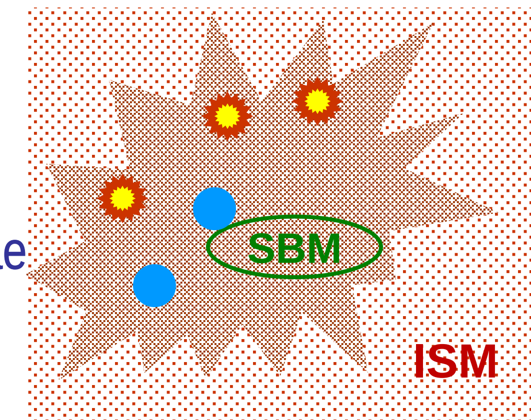
A) Energetically unfeasible (reverse shock too weak)

B) Absence of radioactive Ni59 (τ~10^5 yr) in observed GCR *(Wiedenbeck et al. 1998)* requires $\Delta t > 3\ 10^5$ yr between SN explosion and GCR acceleration

3) SuperBubble matter (SBM), always enriched to ~$Z_\odot$ from its own Supernovae (*Higdon et al. 1998)*

X(GCR) ~ X(SN)

Primary BeB



A) In Superbubbles, massive star winds continuously accelerate SBM, and do not allow Ni59 to decay

B) SN are observationally associated with HII regions, with widely different metallicities

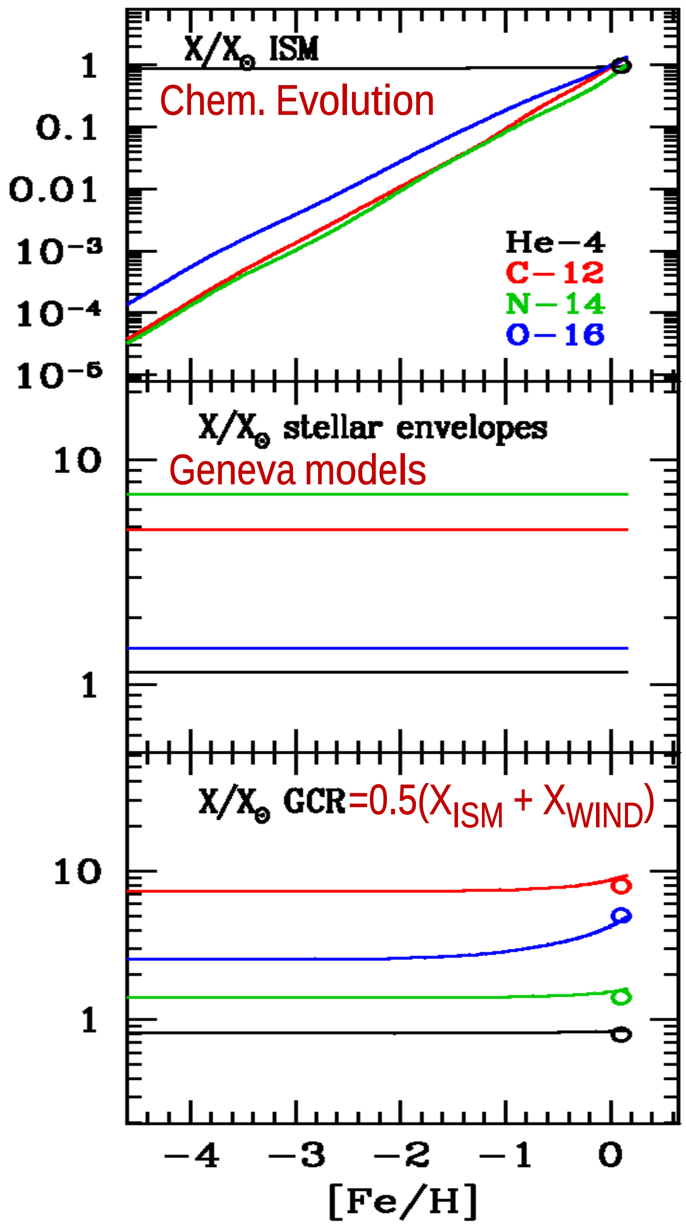
4. Massive star wind accelerated by forward shock

X_{CNO}(GCR) ~ X_{CNO}(Wind)

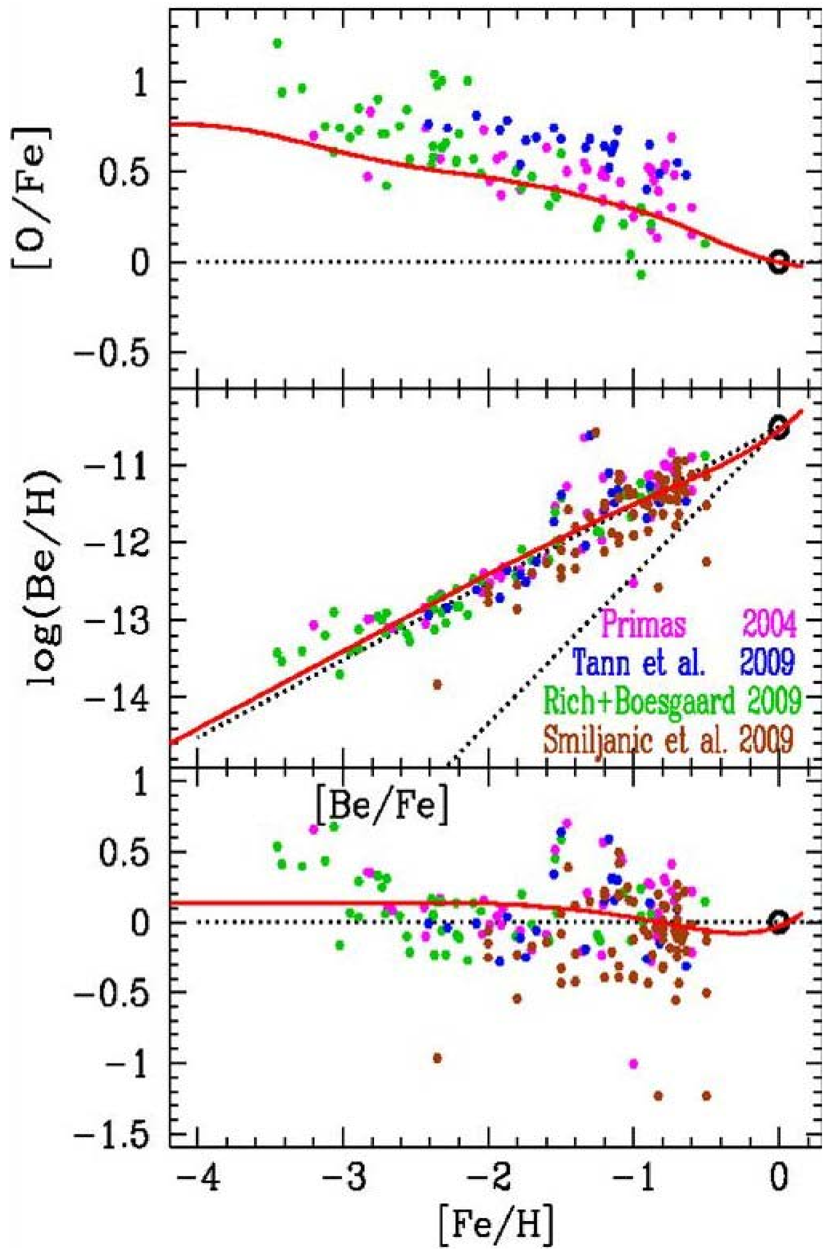
Primary BeB

BUT X_{Heavy}(GCR) ≠ X_{Heavy}(ISM)

Assumed composition of GCR :
$X_{GCR}(t) = 0.5\ (X_{WIND}(t) + X_{ISM}(t))$



With this, "physically motivated" GCR composition AND proper GCR/SN energetics, primary Be is naturally obtained



Evolution of s-elements

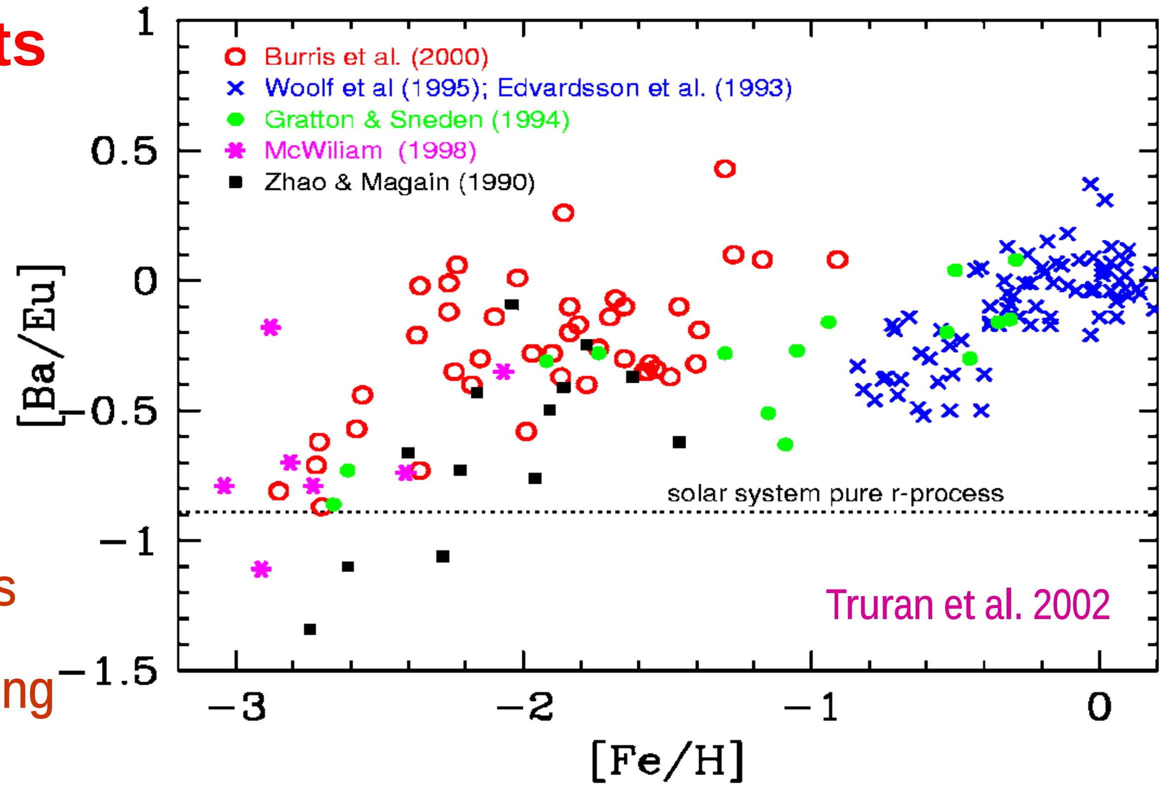
S-elements : secondary
(produced by n-captures
on pre-existing Fe seed nuclei)

As we go back in time (low Z),
the [s/Fe] ratio should decrease,

NOT only because of the
secondary nature of the s-process

but also because of the relatively long
lifetime of s-process sites
(AGB stars: a few 10^8 years)

And should finally hit a “floor”
due to the contribution of the
r-component
(which is PRIMARY
and produced by SHORT-LIVED
massive stars)
(Truran 1981)



At what metallicity – and *time* -
do intermediate mass stars
start contributing to the
abundances of s-elements?

Hints for source lifetimes / yields

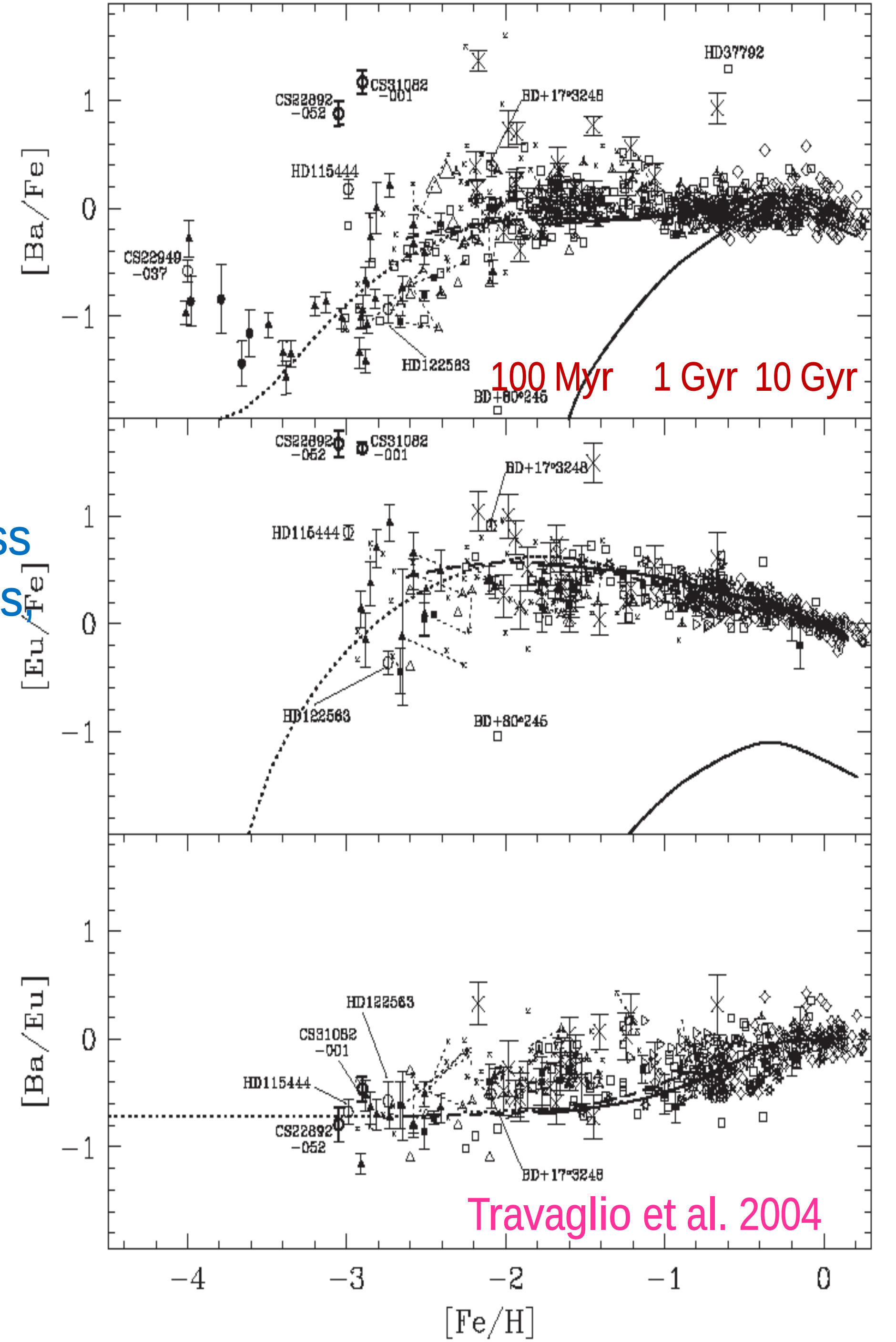
We do observe a late rise of Ba/Fe or Ba/Eu with metallicity
but it is not clear whether it is due to the long lifetimes of IMS
or to the secondary nature of s-process

Somewhat counterintuitively, the s-process efficiency may be higher at low metallicities, producing e.g. a lot of Pb-208 very early in GCE *(Clayton 1988)*

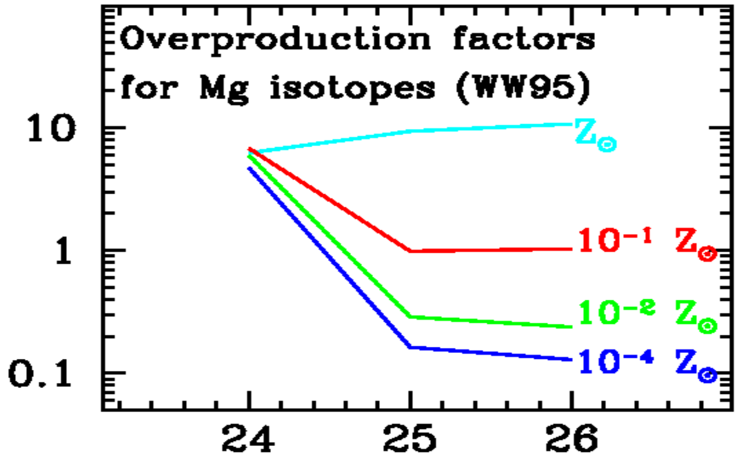
The efficiency of the s-process depends on the metallicity dependence of the "neutron economy trio"

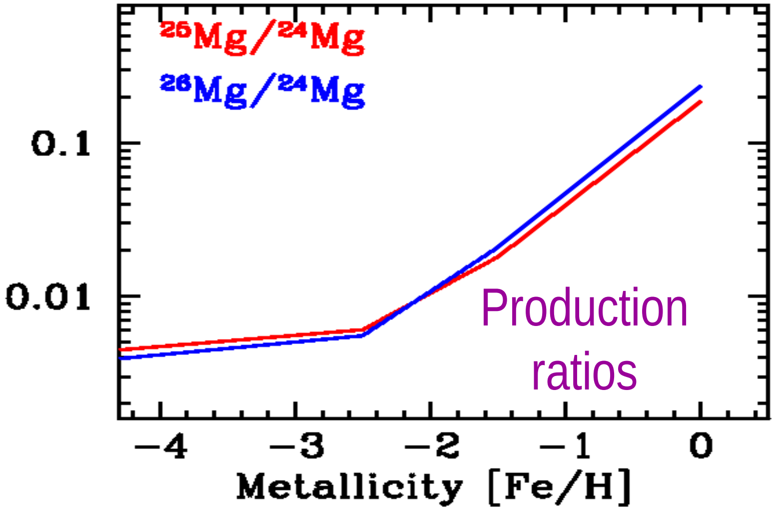
- seed nuclei (Fe-56)
- n-source nuclei (C-13 or Ne-22)
- n-poison nuclei (e.g. N-14)

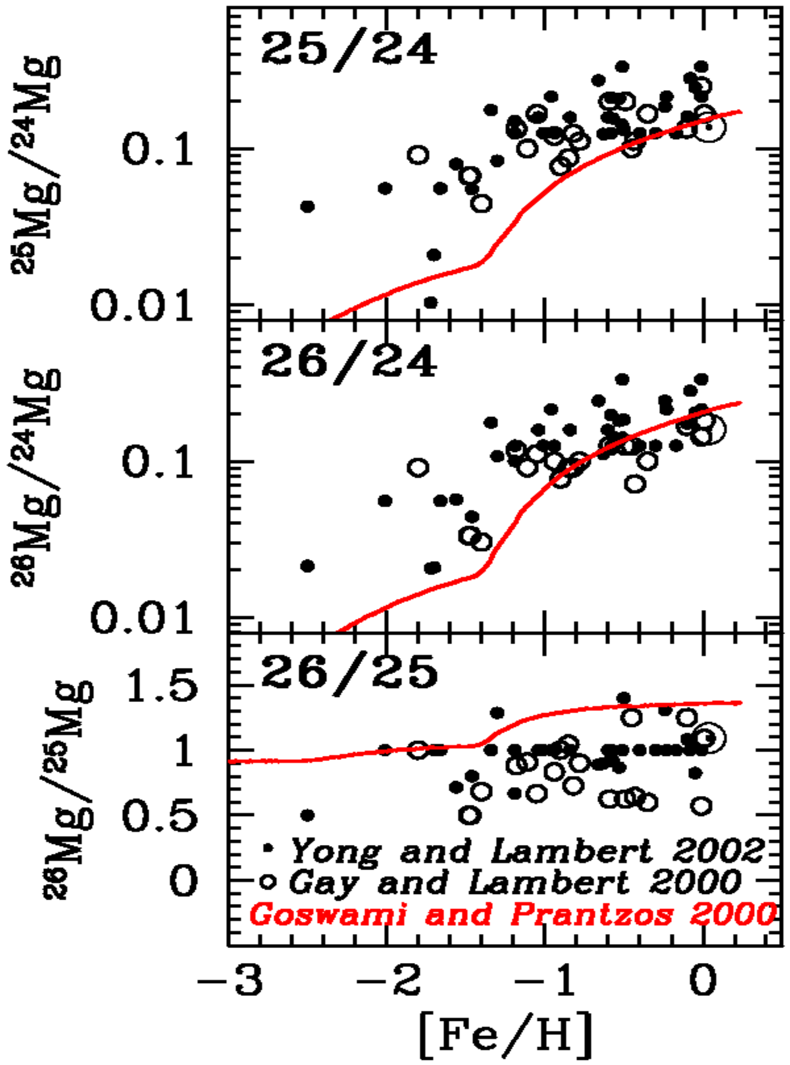
(Prantzos et al. 1990)



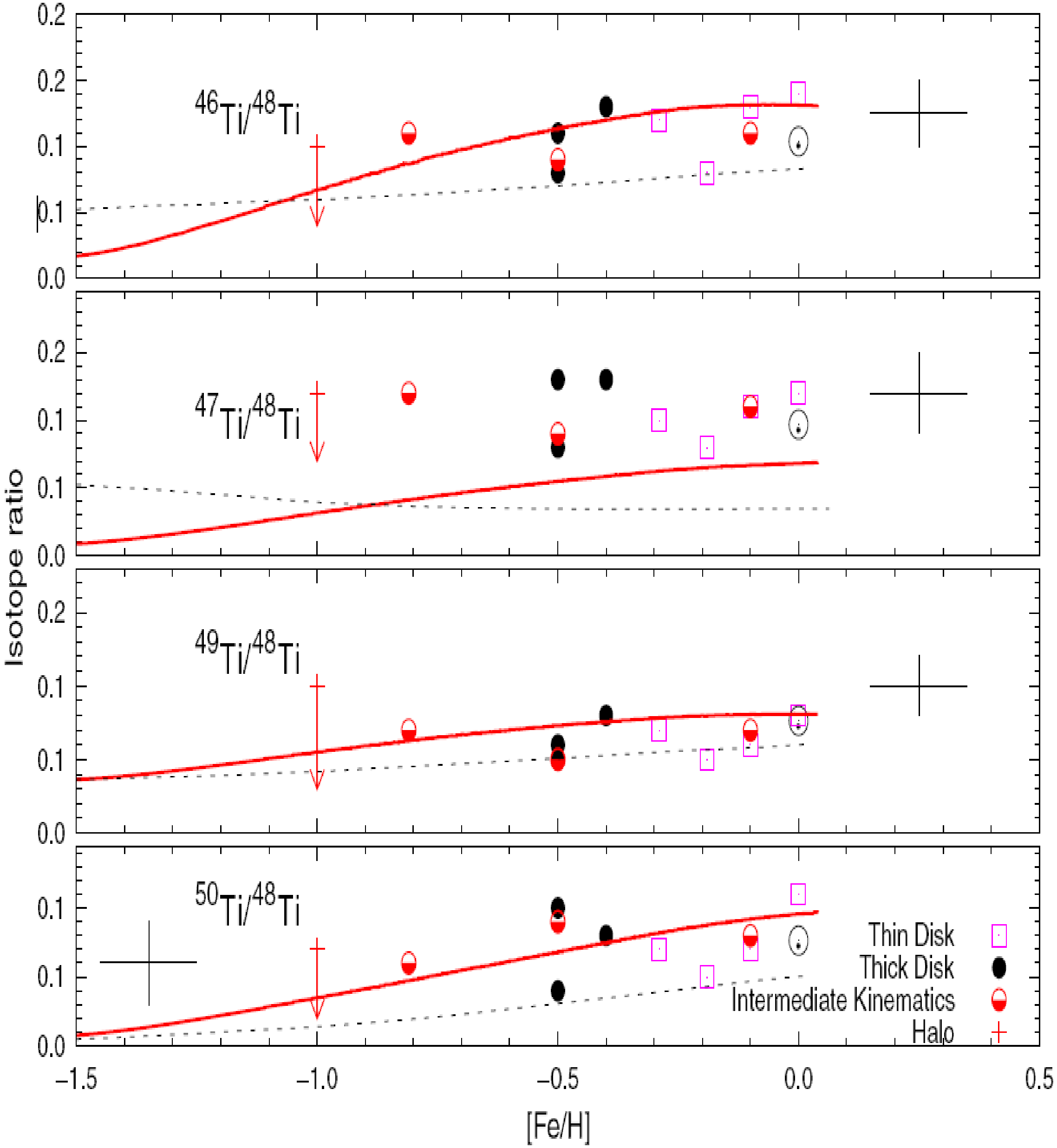
The Mg isotopic abundances







The Ti isotopic abundances



Data: Chavez and Lambert 2009

Model 1 : Prantzos 2008
(WW95 yields)

Model 2 : Kobayashi 2008
(Nomoto05 yields)

The formation of a Milky Way like galaxy

Galaxy formation simulations created at the

N-body shop

makers of quality galaxies

key: gas- green new stars- blue old stars- red

credits: Fabio Governato (University of Washington)
Chris Brook (University of Washington)
James Wadsely (McMaster University)

simulation run at the CINECA supercomputing center, (BO, Italy)

contact: fabio@astro.washington.edu

The MW Halo Metallicity Distribution (HMD)

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

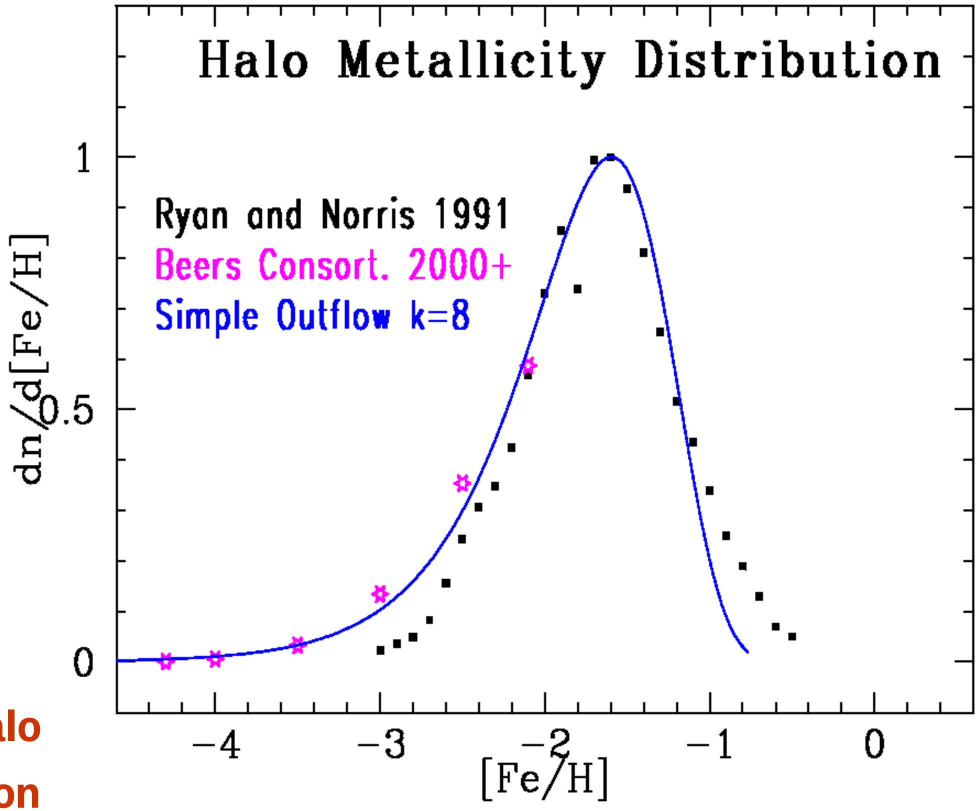
1) *A peak at [Fe/H] = -1.6* implying a **reduced effective yield**

$$p_{EFF} \sim p_0/9$$

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

2) *A very smooth shape;*

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



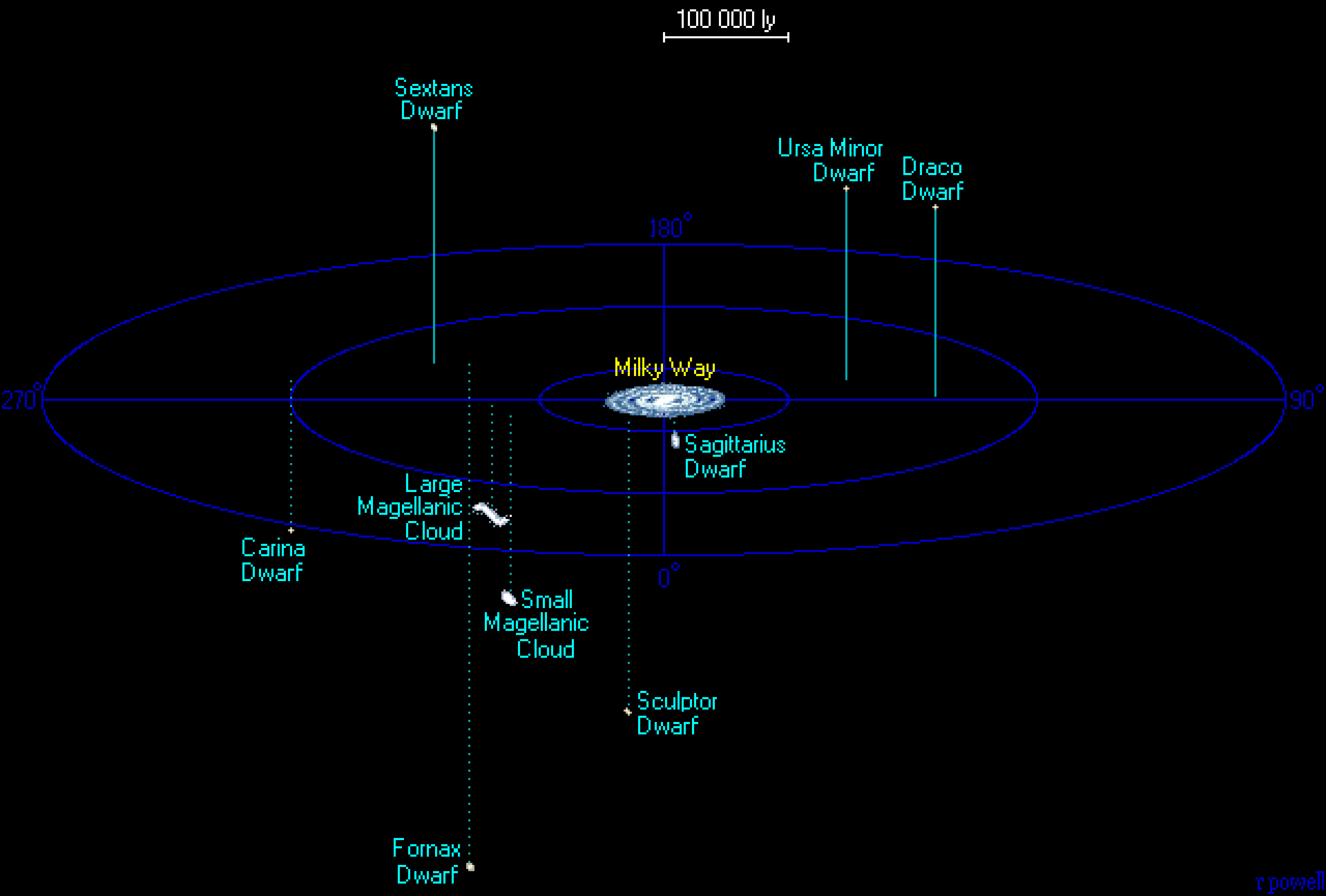
Ingredients required to evaluate the halo MD as a sum of MDs of sub-haloes in the hierarchical merging paradigm :

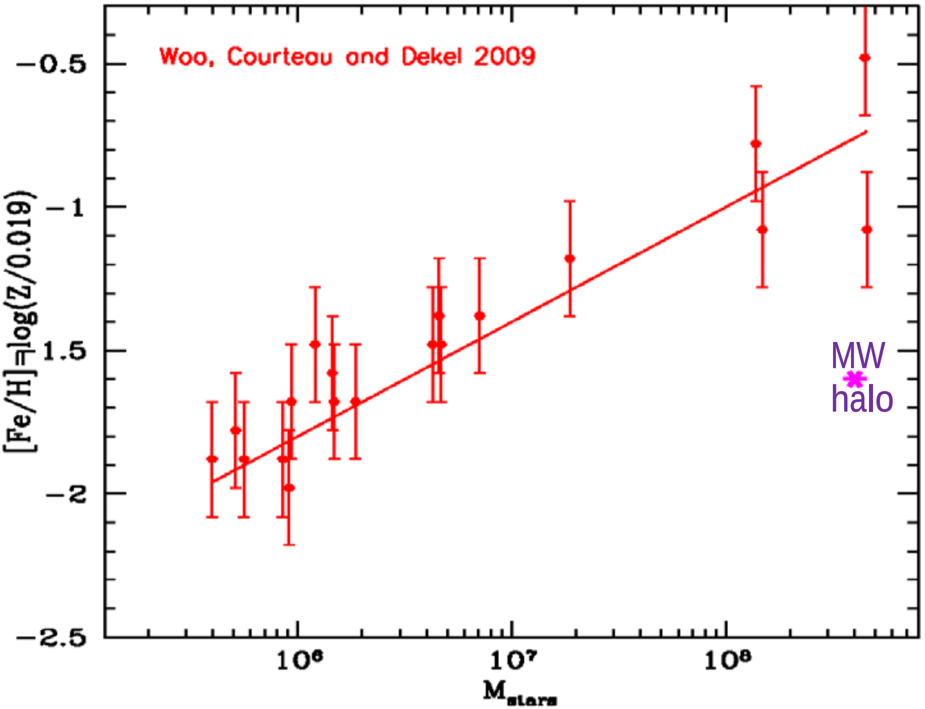
1) Shape of sub-halo MD

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

3) Baryon mass distribution of sub-haloes

For the former two ingredients, one may get inspiration by observations of nearby dwarf galaxies (satellites of Milky Way)


100 000 ly
Sextans Dwarf
Ursa Minor Dwarf
Draco Dwarf
180°
Milky Way
270°
90°
Sagittarius Dwarf
Large Magellanic Cloud
Carina Dwarf
0°
Small Magellanic Cloud
Sculptor Dwarf
Fornax Dwarf
r powell

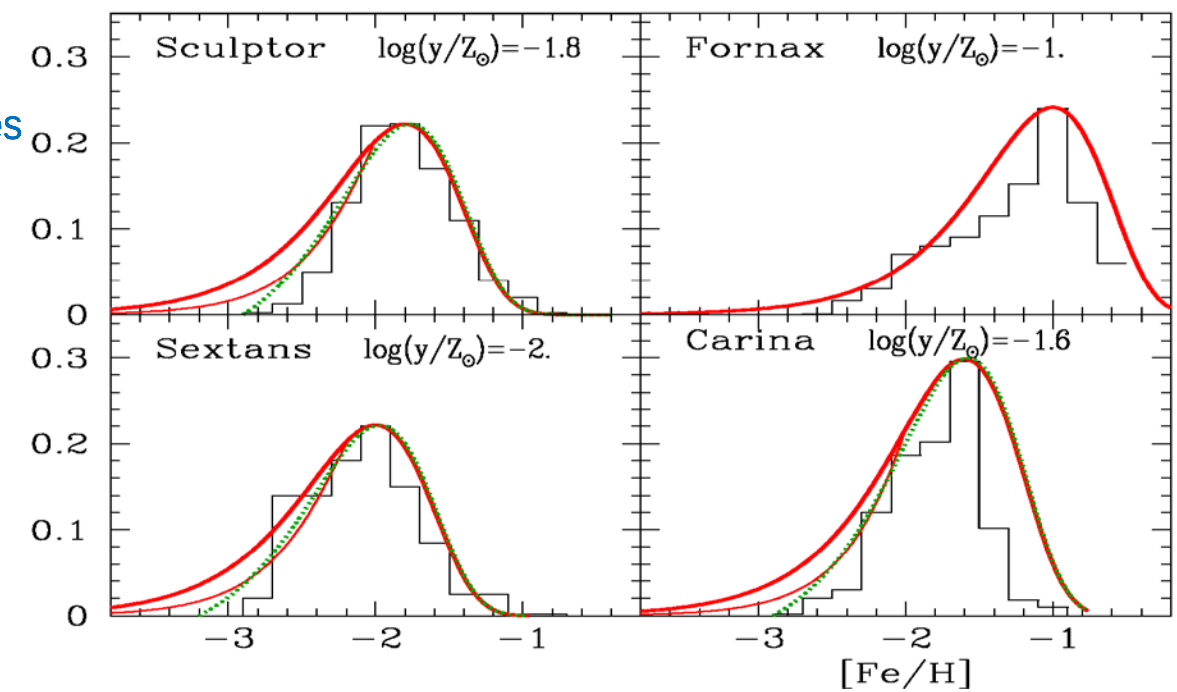


Mass - Metallicity relationship
of dwarf spheroidals

The MW halo lies far below that relation

Metallicity distributions of dwarf galaxies

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)*



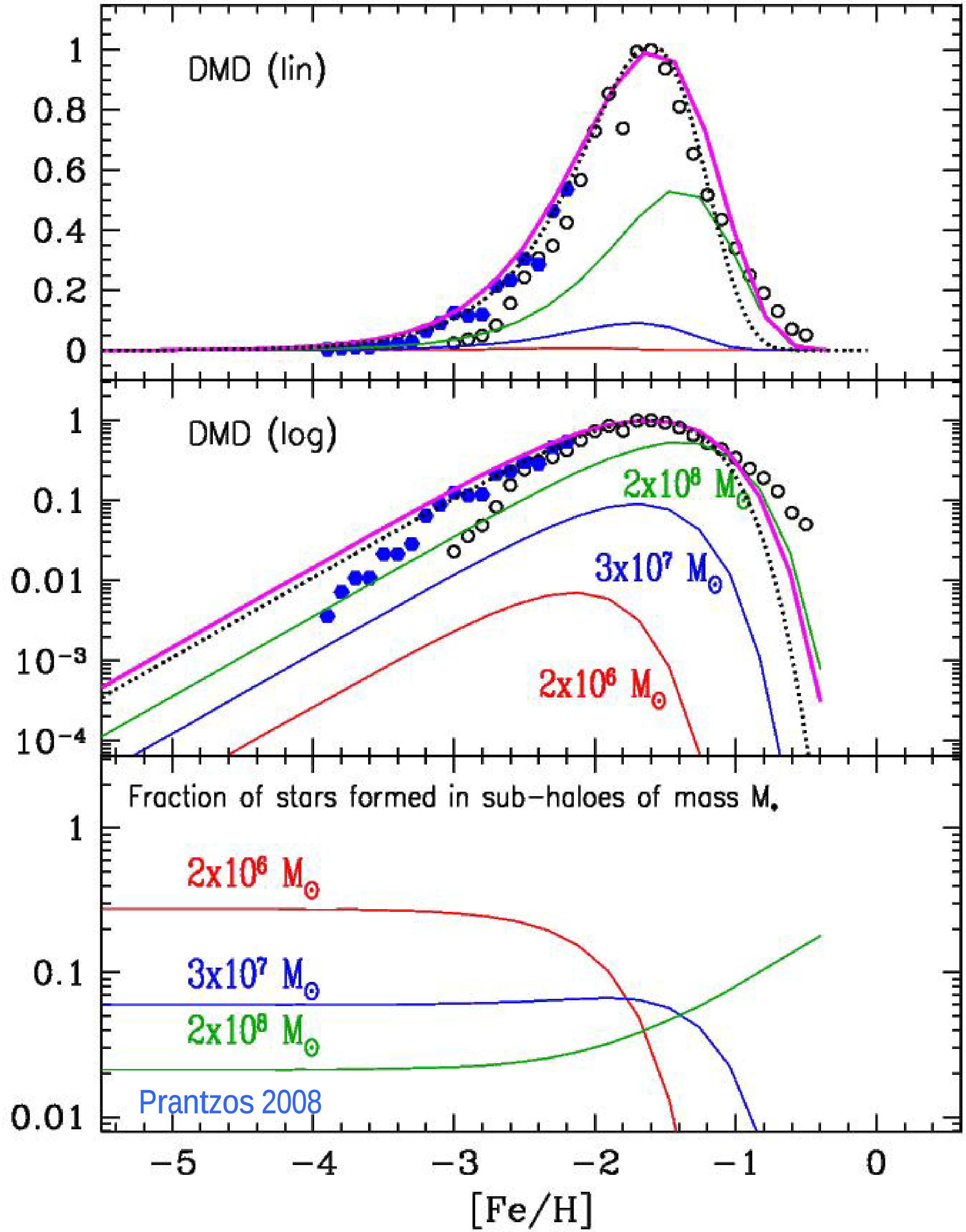
The halo MD may result as the sum of the MDs of ~a few dozens of small galaxies (sub-haloes of $10^6 - 10^8$ $M_\odot$),

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

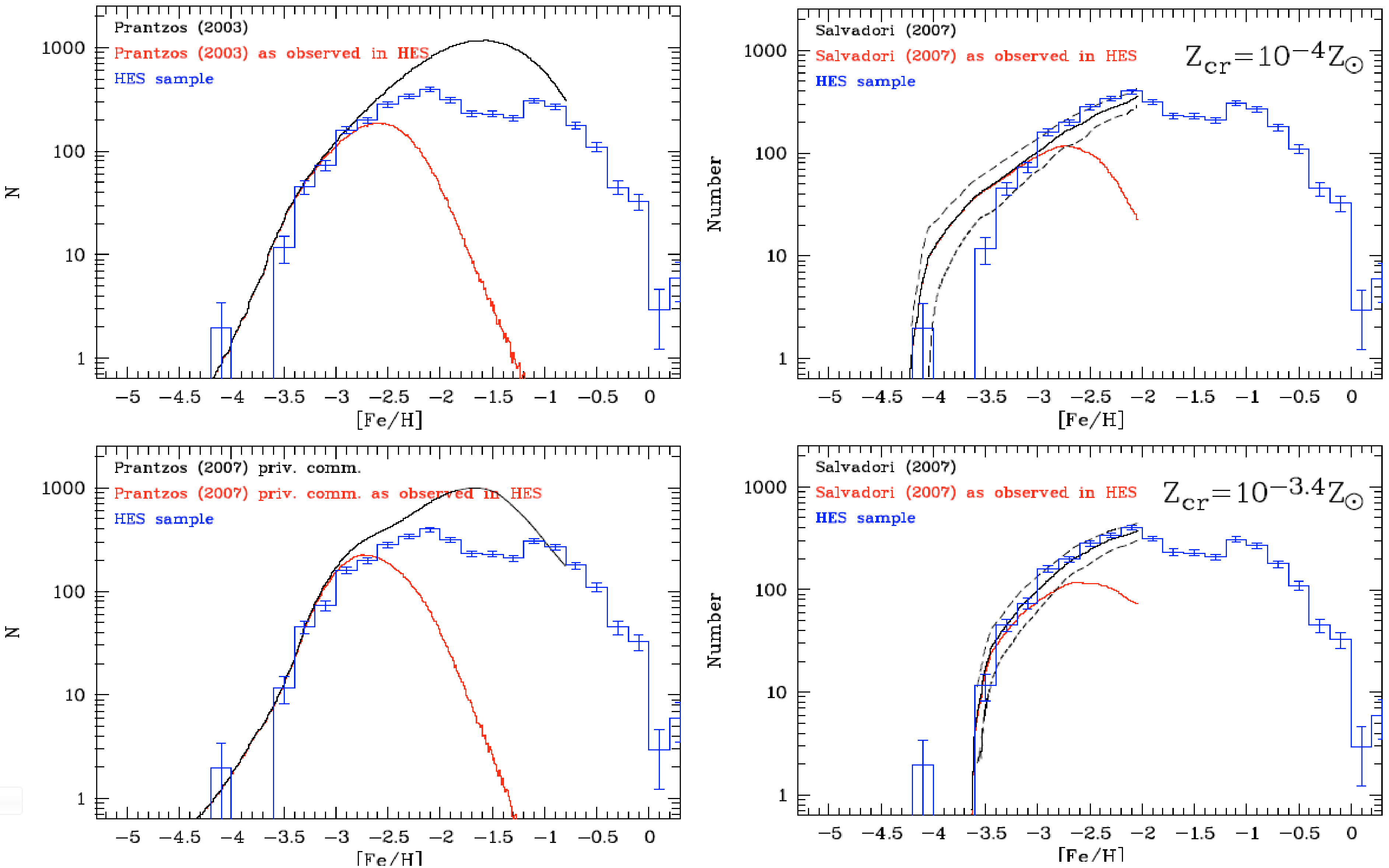
and with an appropriate number distribution

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 each sub-halo

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

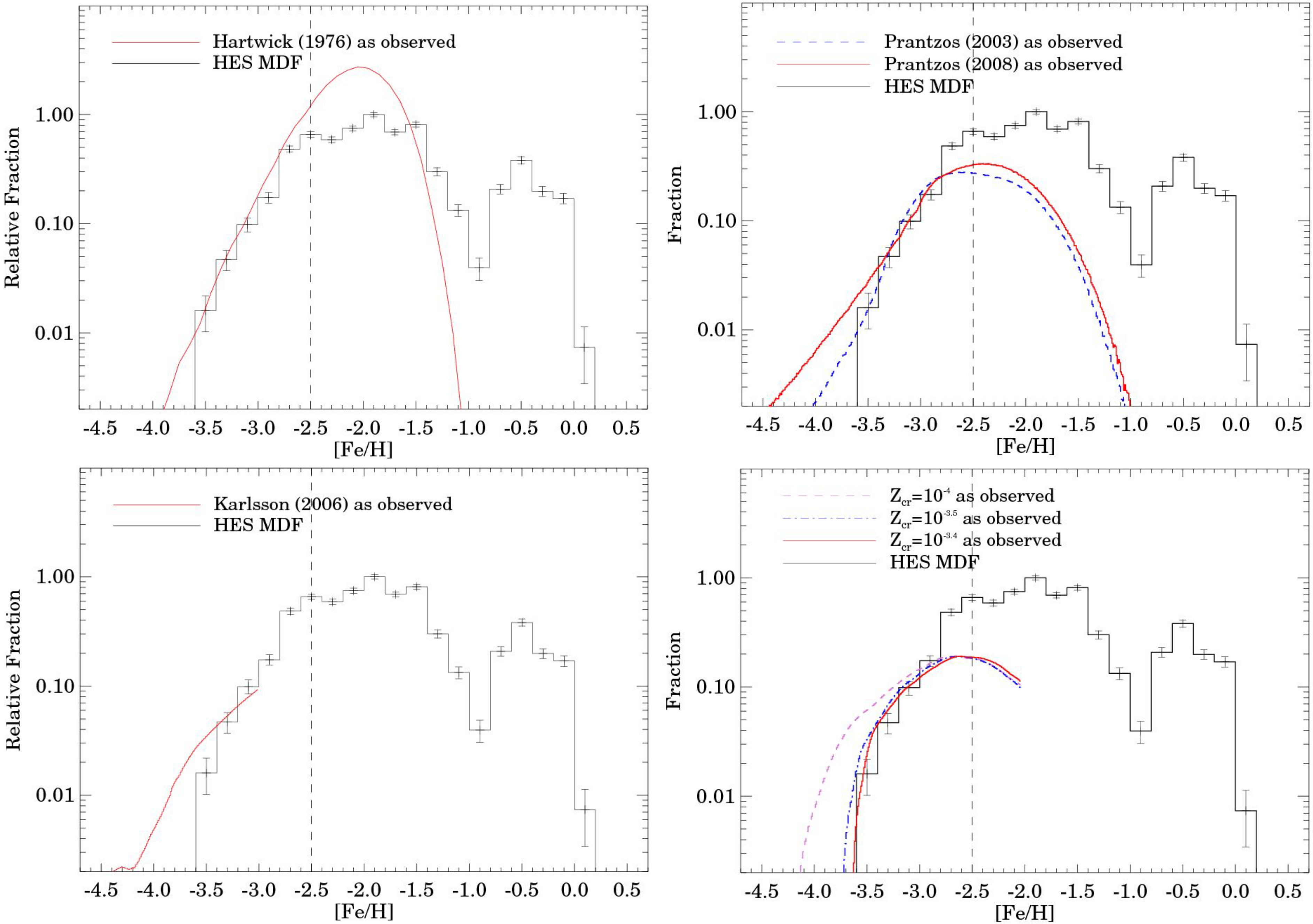


Comparison to Hamburg-ESO survey – 1600 stars (*Schoerck et al. 2009*)



Did the Galaxy halo start its evolution with [Fe/H]=-3.5 (metallicity of intergalactic medium at that time) ?

Comparison to Hamburg-ESO survey – 680 MSTO stars (*Li et al. 2010*)



Assuming the MW halo was indeed formed
from a few hundred sub-haloes,
each one of them evolving on a different timescale:

What are the implications for the evolution of abundance ratios ?

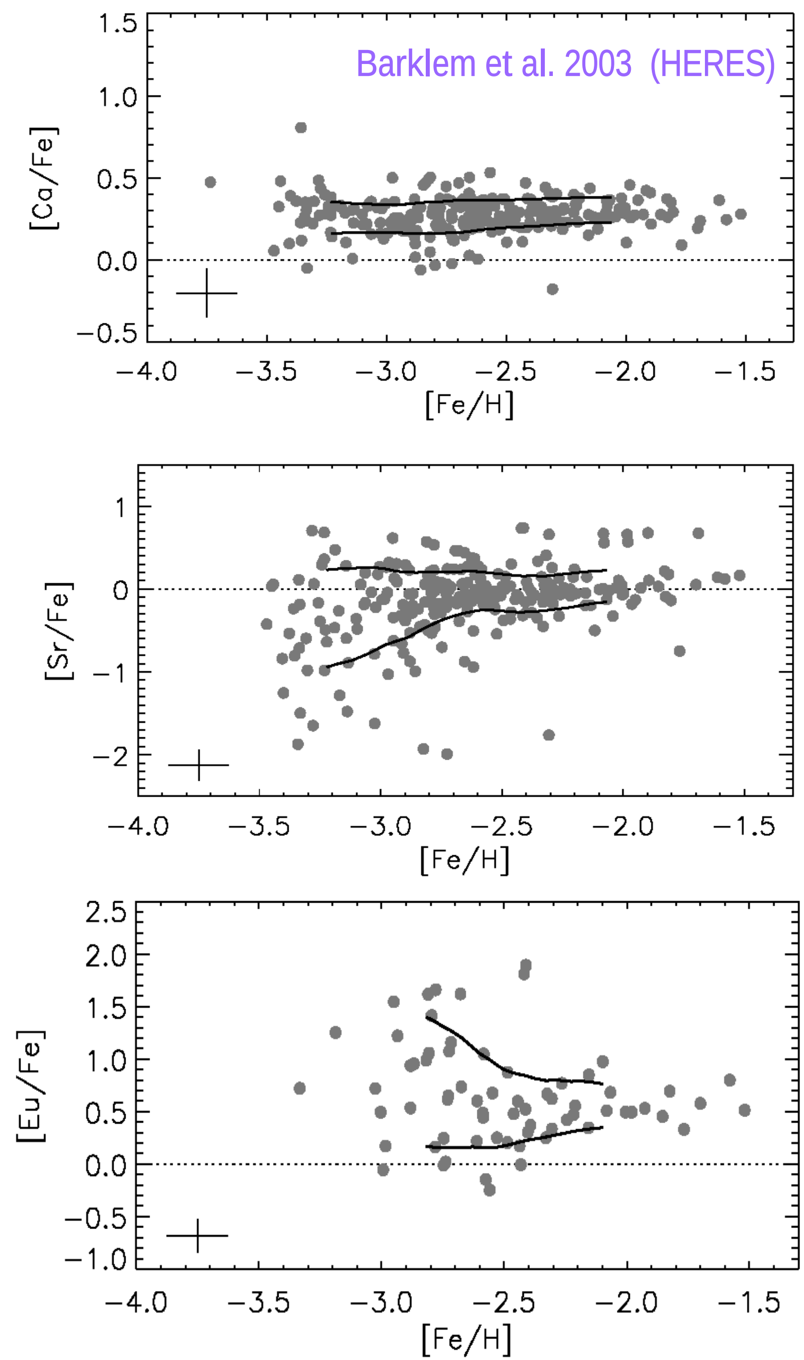
[Fe/H] is no more a "clock" :

the same value of [FeH] may be reached on
very different timescales in different sub-haloes
(depending on their star formation and outflow histories)

Elements produced in the same site
(e.g. **α**-elements and Fe, both in SNII)
will display a uniform abundance ratio
(no dispersion, at all [Fe/H]),
assuming efficient mixing with ISM

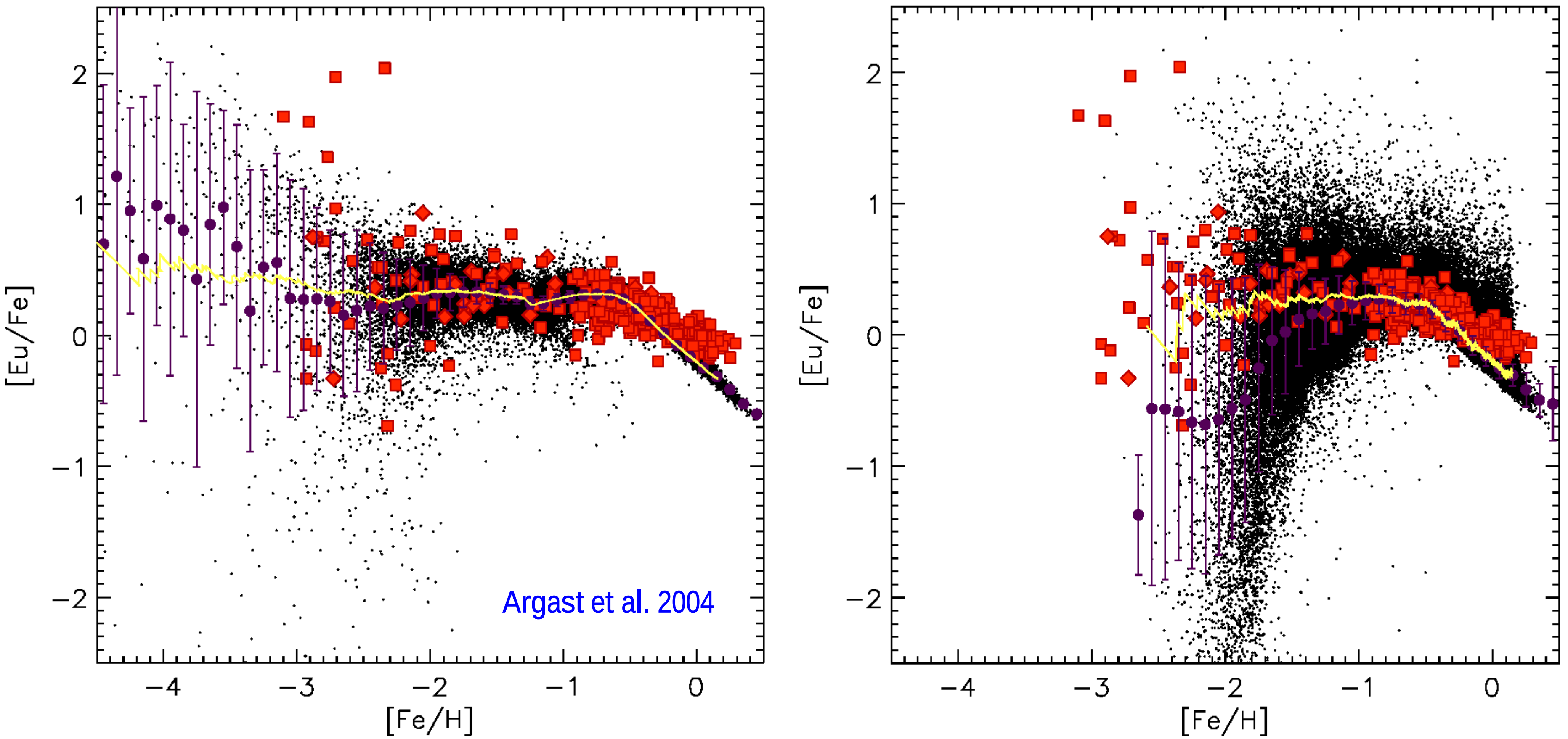
Elements produced in sites evolving on
different timescales, will display
dispersion in their abundance ratios,
even in case of efficient mixing

Could this explain the early dispersion in Eu/Fe ?
[assuming that r – elements are produced in both,
short (SNII) and long (NS mergers) timescales]



Sources of r-nuclei

Core collapse SN ("high" frequency, small yields) vs Neutron star mergers (low frequency, high yields)



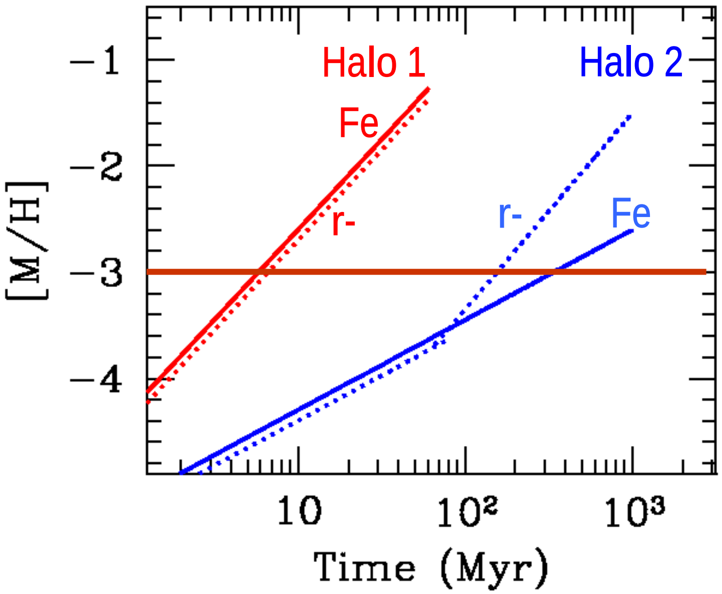
Within a given system (uniform evolution of average Fe/H),

NSM appear too late (at too high Fe/H) to be the main r- source

and produce too much dispersion in r/Fe *(Argast et al. 2004).*

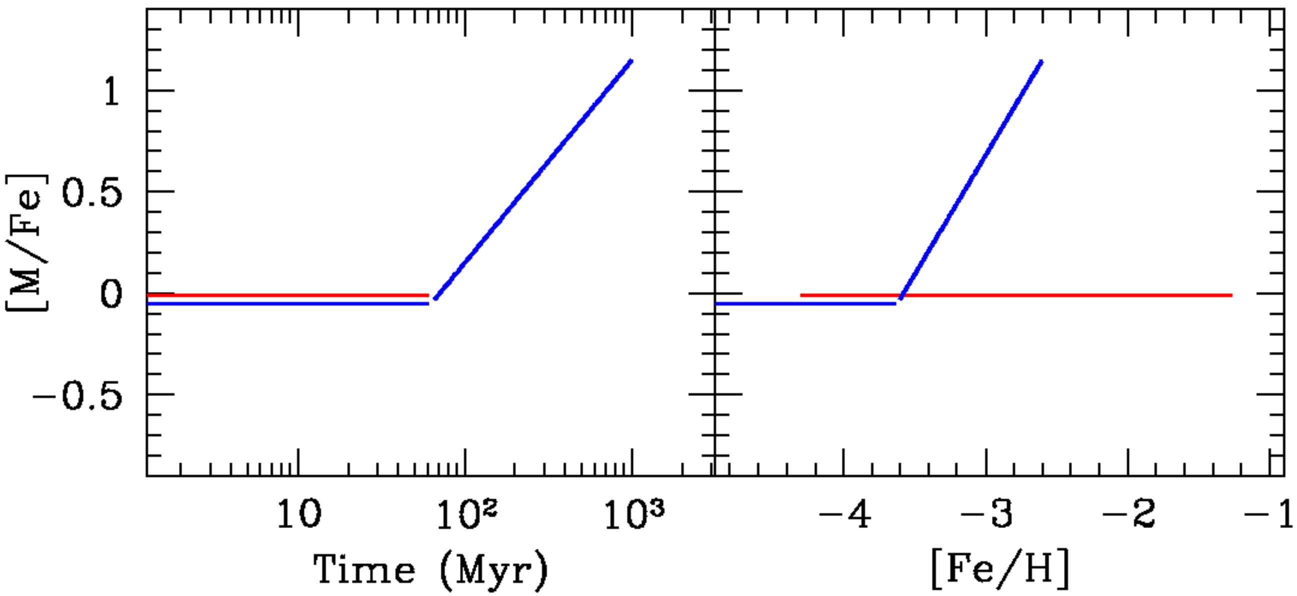
The former depends on assumed SF history, while the latter on assumed mixing scheme and yields

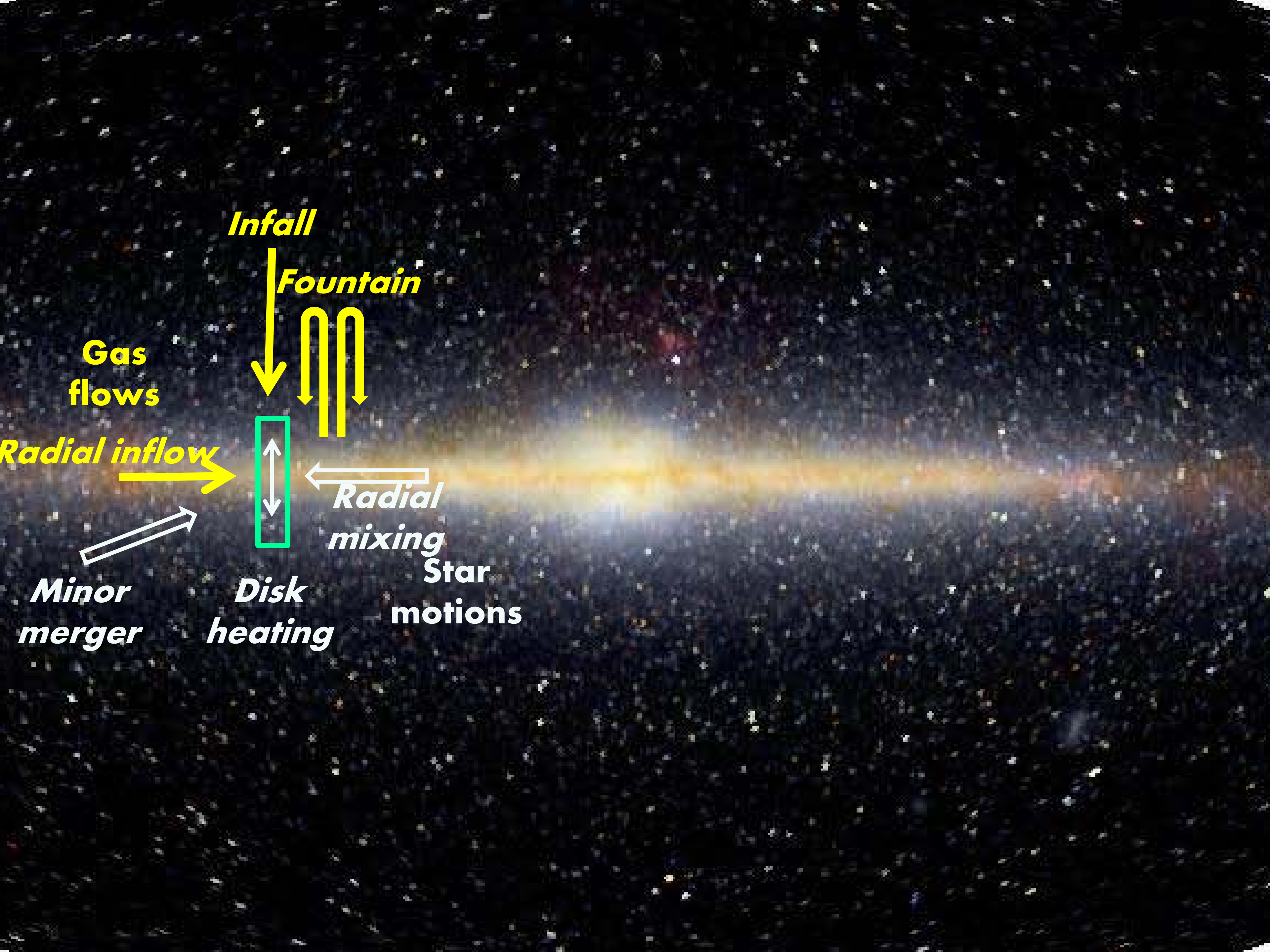
Cartoon for dispersion of r-elements



Halo 2 evolves slowly : a long lived source (NS mergers ?) has the time to inject e.g. Eu, and to increase the Eu/Fe ratio, even at very low [Fe/H] ~ -3

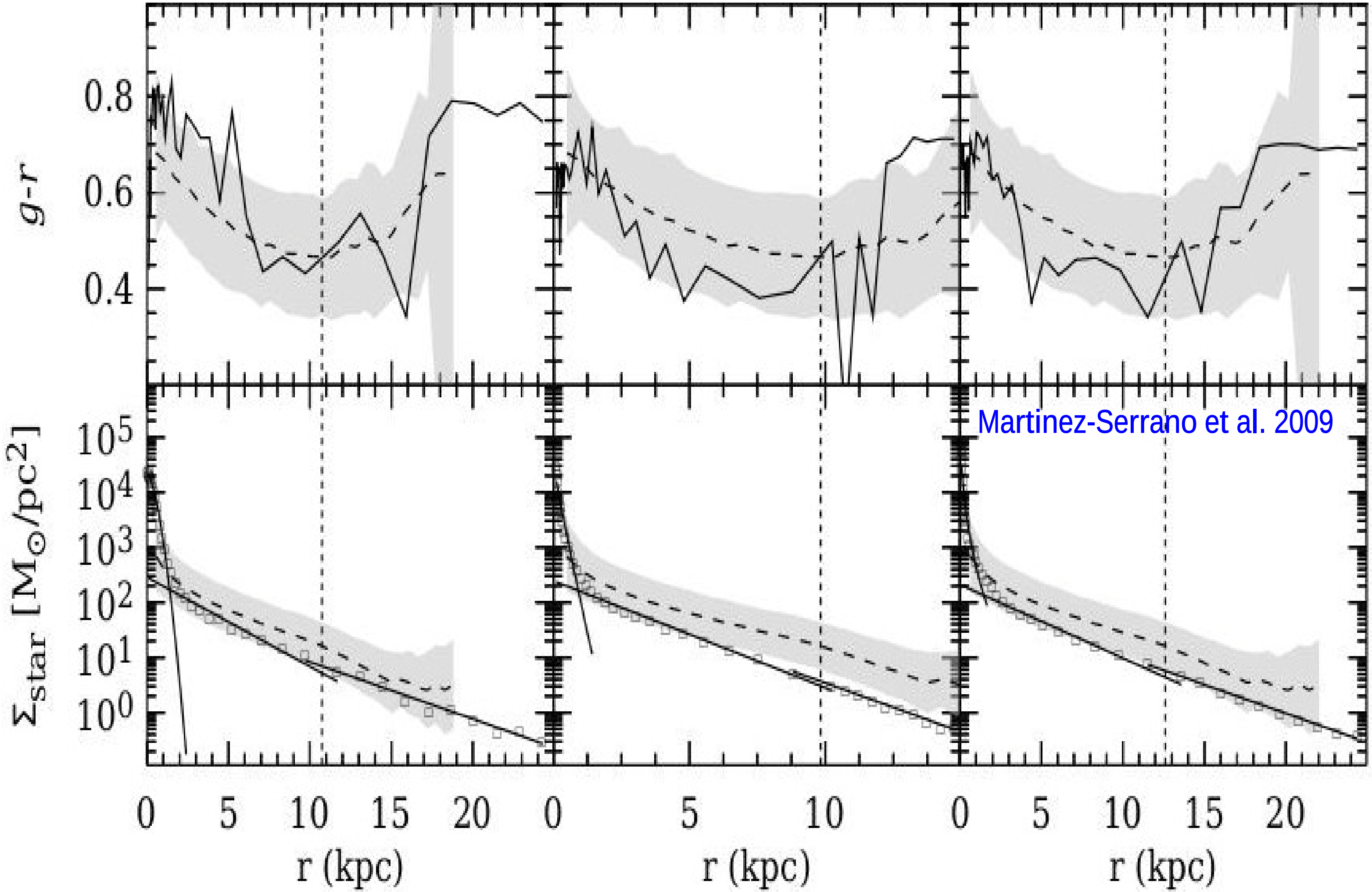
This is not the case for the rapidly evolving Halo 1



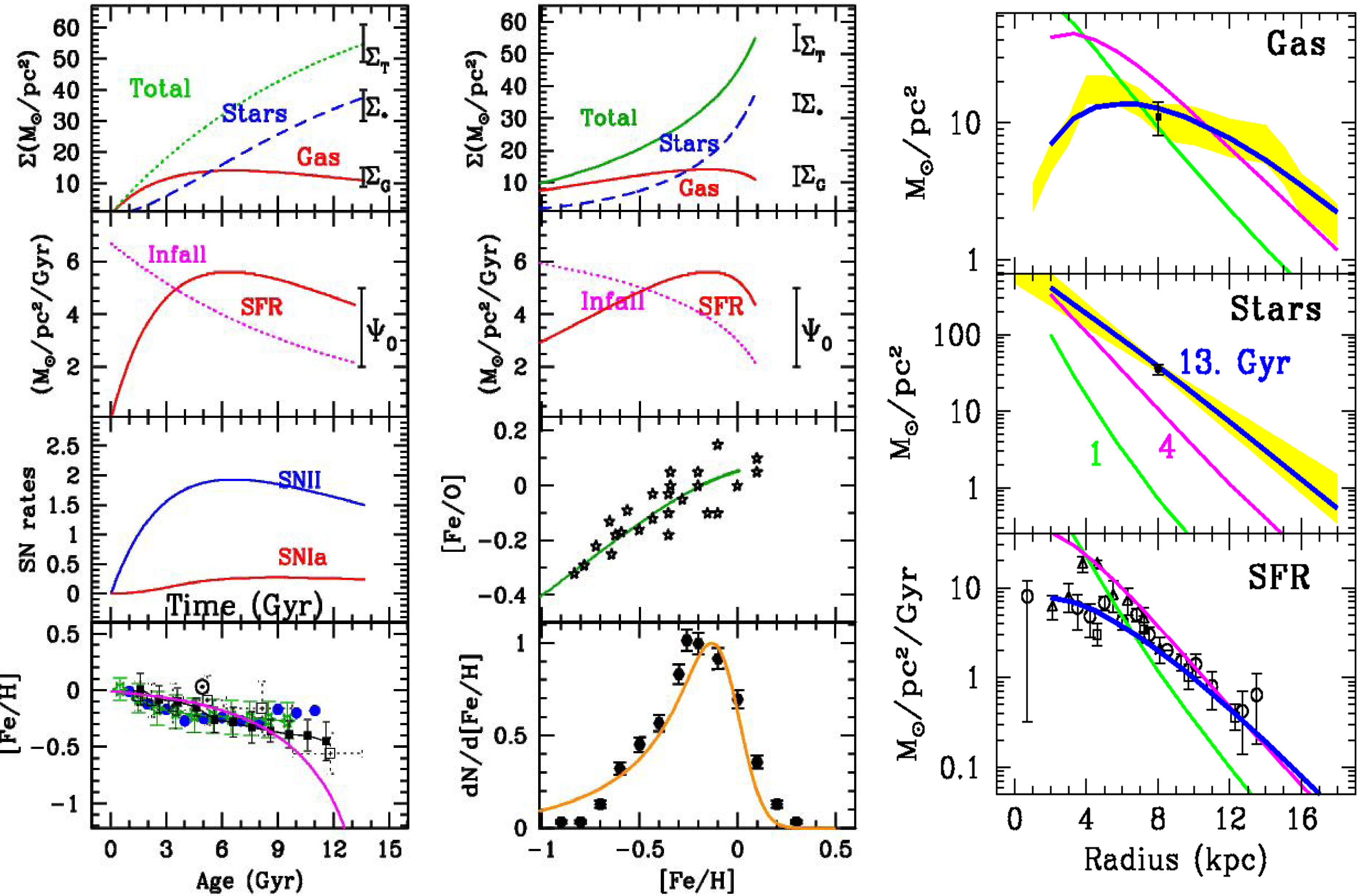

Infall
Fountain
Gas
flows
Radial inflow
Radial
mixing
Star
motions
Minor
merger
Disk
heating

Radial migration of stars produces naturally a U-shaped colour profile as observed in external spirals

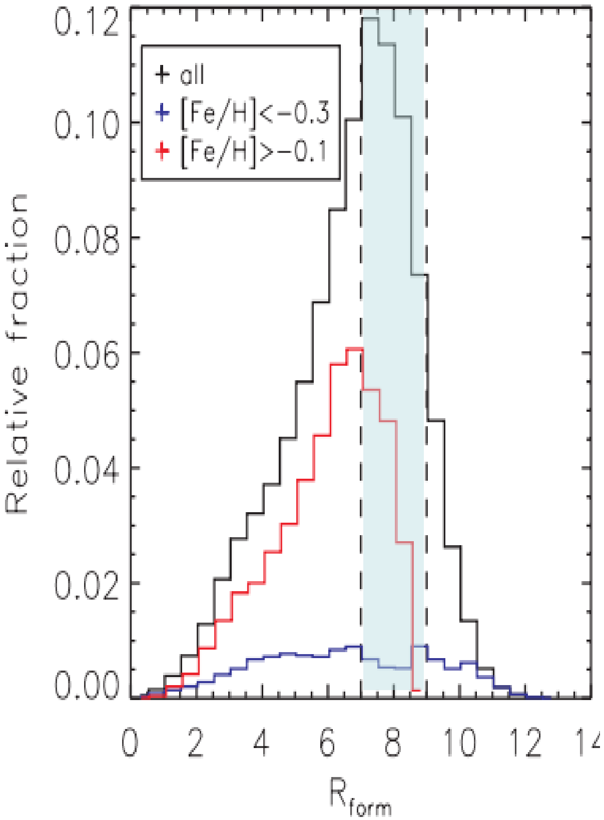
(*old/red stars formed early on in inner disk are found in outer disk and dominate its young star population, formed in situ*)



Evolution of solar neighborhood and MW disk (no radial migration)

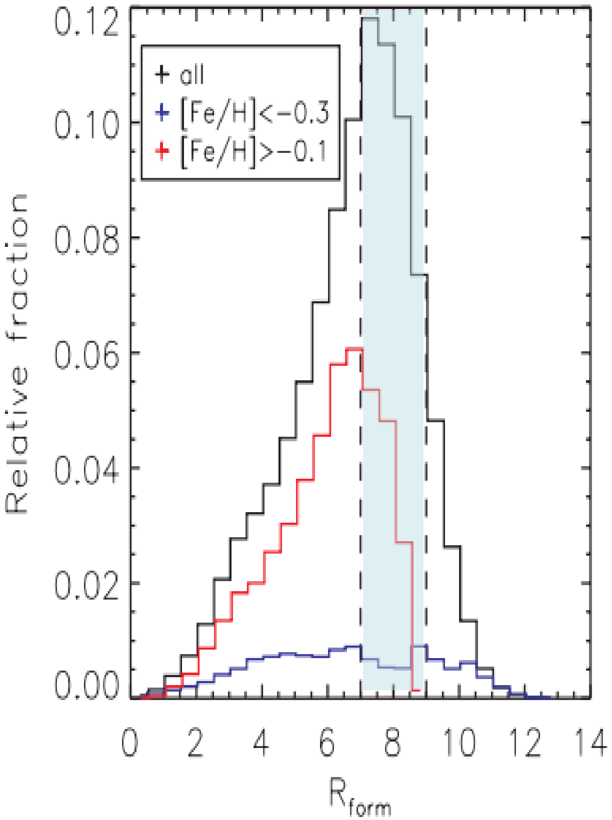


N-body + SPH simulations of a disk galaxy (Roskar et al. 2008)



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

N-body + SPH simulations of a disk galaxy (*Roskar et al. 2008)*



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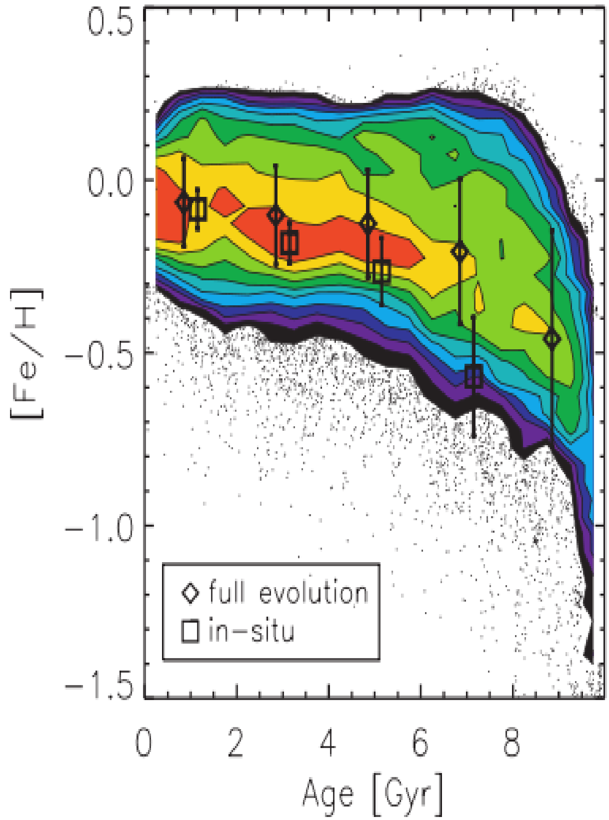

This impacts the
Age-metallicity relation
Making it flatter and
more dispersed

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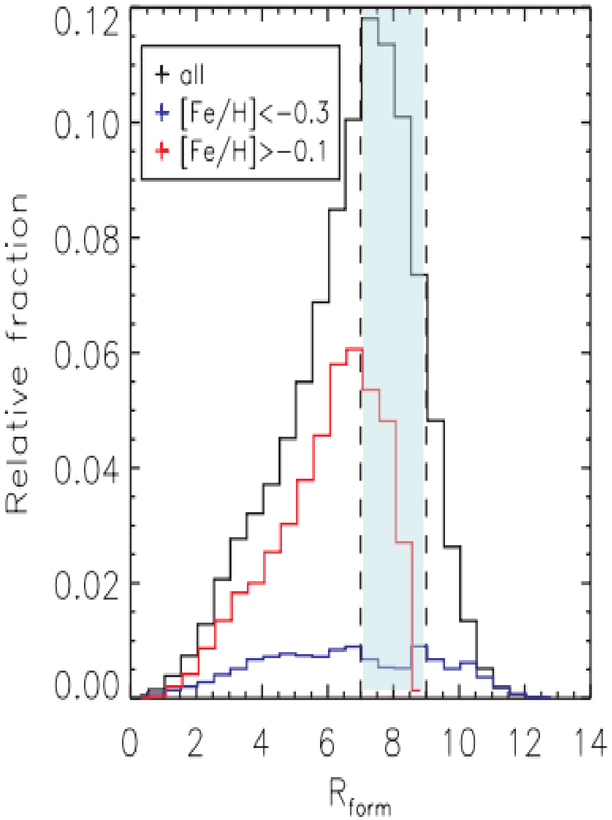

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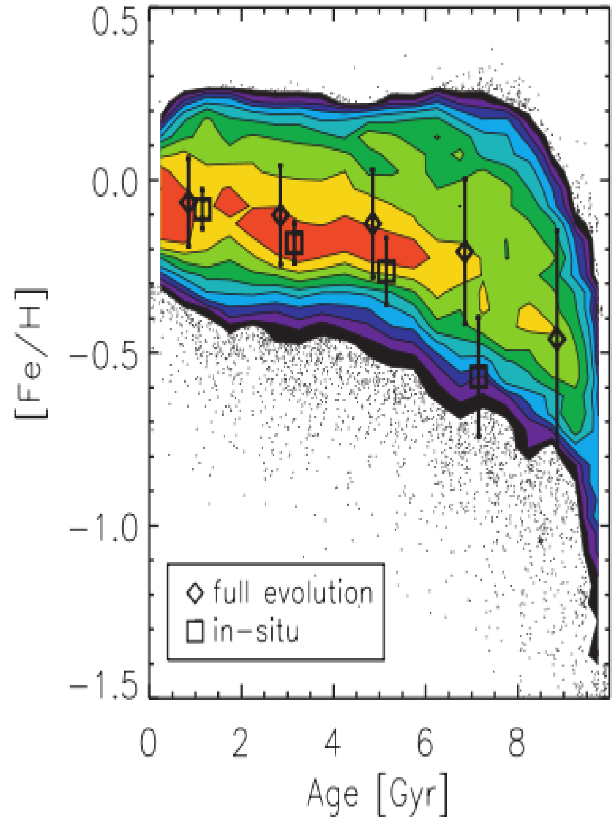

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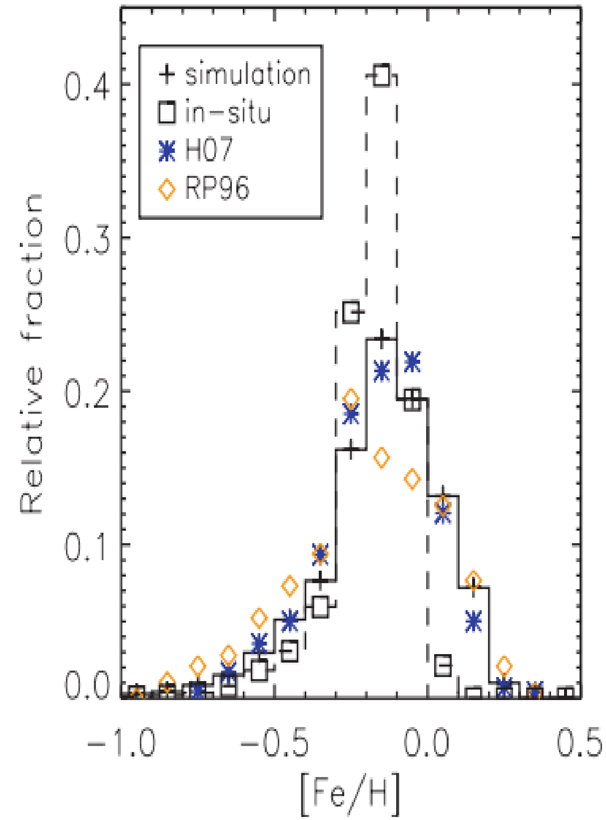
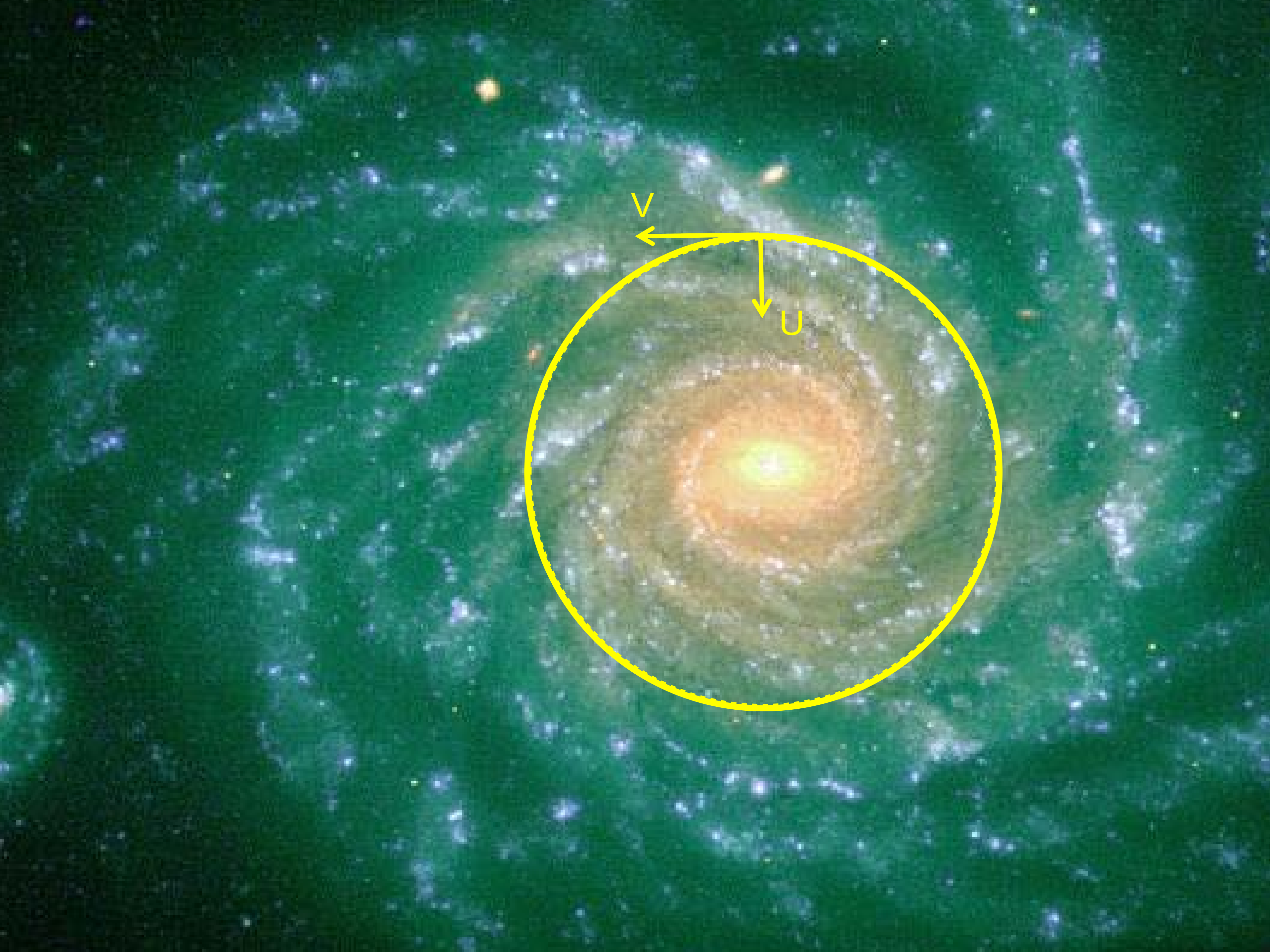


And the local
Metallicity distribution
Making it broader

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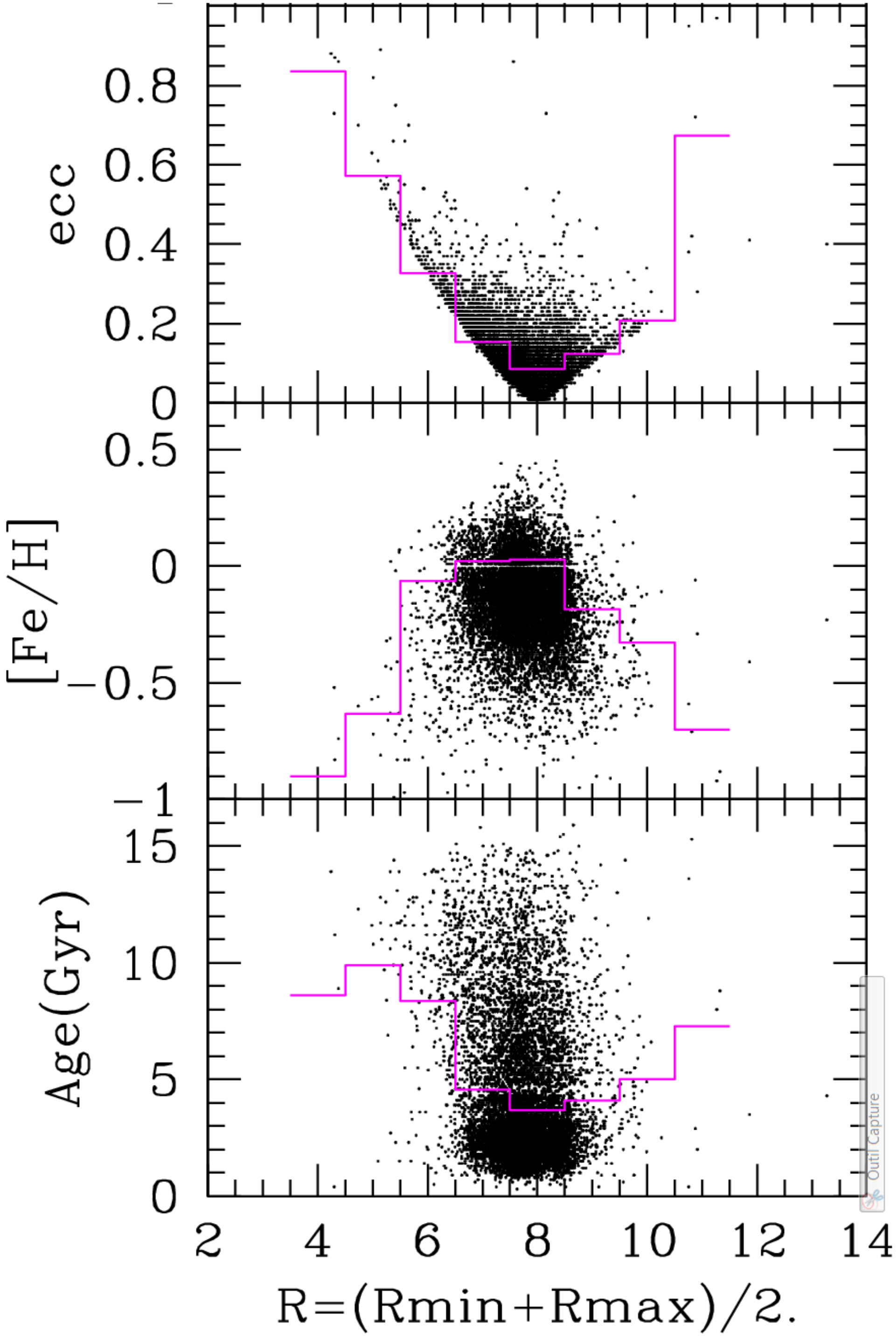
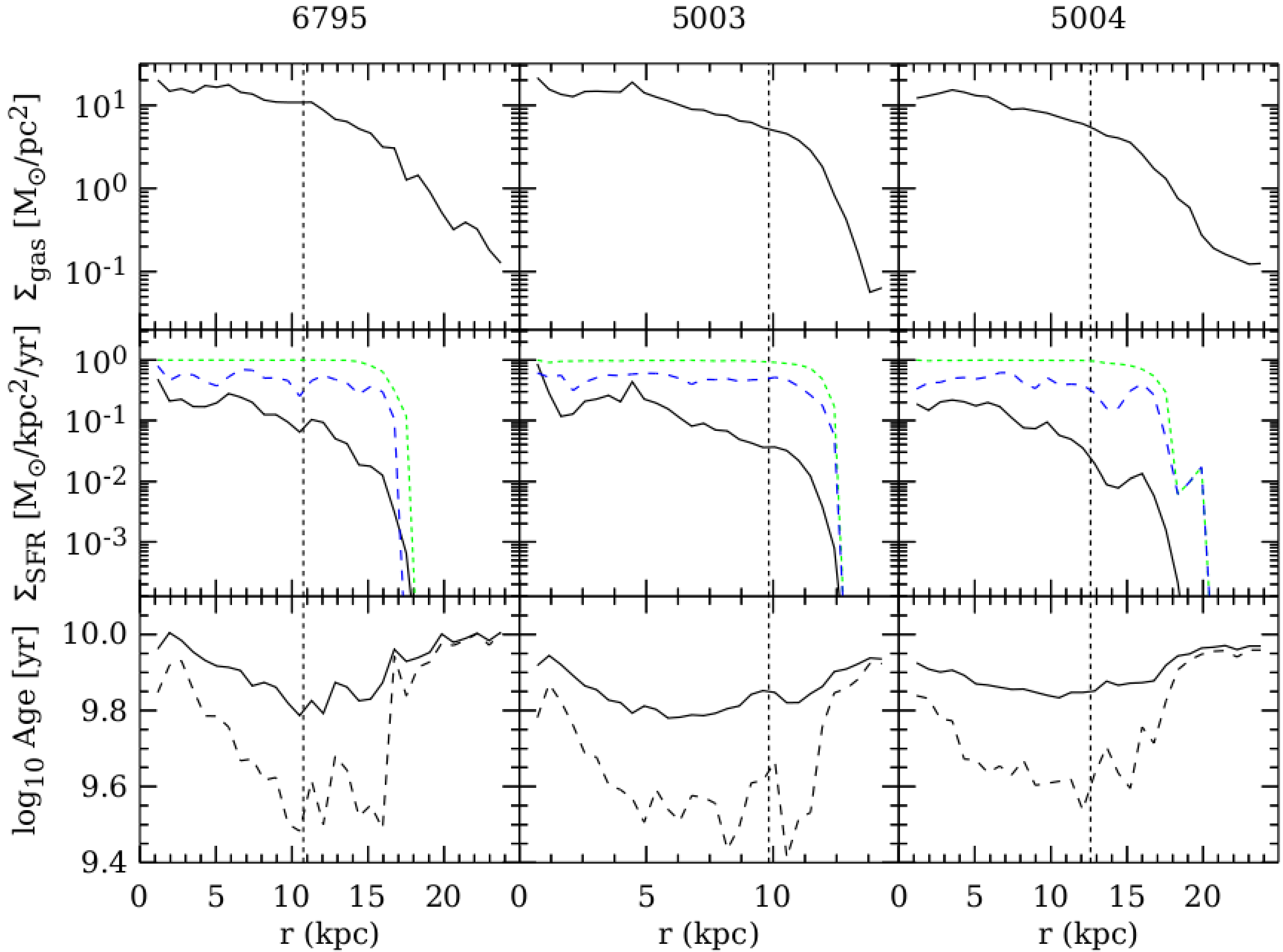
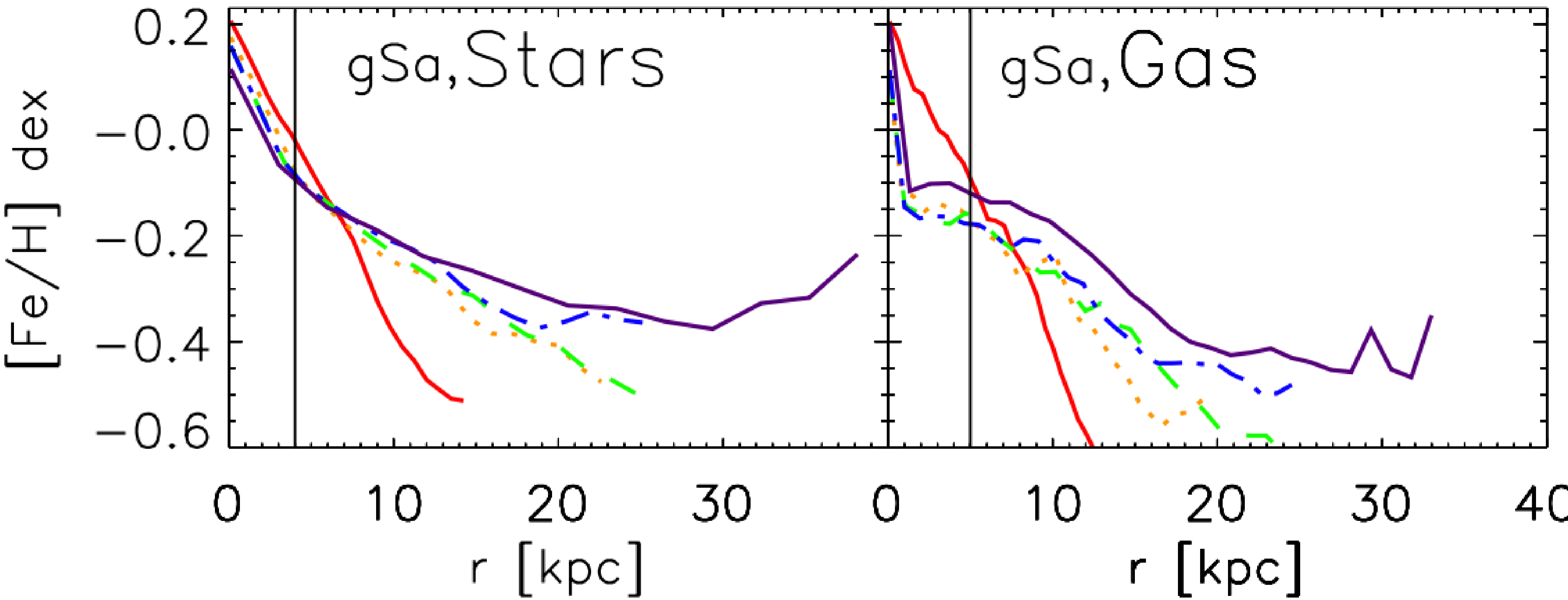


Analysis of kinematics, composition and age of stars in solar neighborhood (<200 pc) from GKS (*Holmberg et al. 2009*) shows that

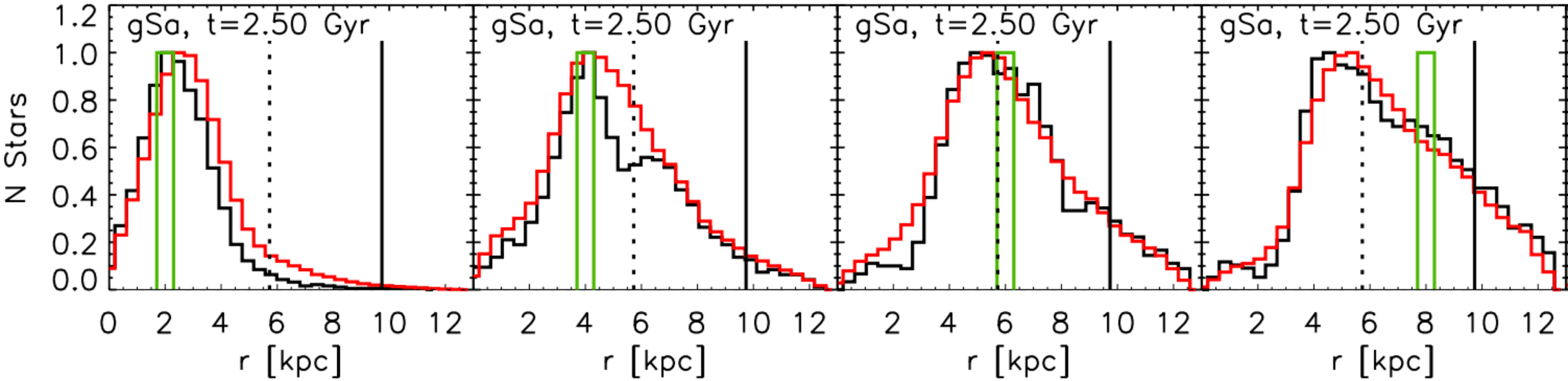
stars with **high eccentricities** (born either in the inner or the outer disk) have **lower metallicities** and **larger ages**, ON AVERAGE, than stars of low eccentricities (born locally)

Such stars are here either due to normal **epicyclic motion** or from **radial migration** ***(Sellwood and Binney 2002)***


6795
5003
5004
Σgas [M⊙/pc²]
ΣSFR [M⊙/kpc²/yr]
log10 Age [yr]
r (kpc)
r (kpc)
r (kpc)



gSa,Stars
gSa,Gas
[Fe/H] dex
0.2
−0.0
−0.2
−0.4
−0.6
0
10
20
30
40
r [kpc]
r [kpc]


gSa, t=2.50 Gyr
gSa, t=2.50 Gyr
gSa, t=2.50 Gyr
gSa, t=2.50 Gyr
N Stars
r [kpc]
r [kpc]
r [kpc]
r [kpc]

Energetics argument(*Ramaty et al. 1997)*

1) Producing one atom of Be by GCR

requires a certain amount of energy,

which depends on assumed GCR composition

2) CCSN produce Fe (~0.1 $M_\odot$) and

energy (~10^{50} ergs) for GCR acceleration

3) If the composition of GCR

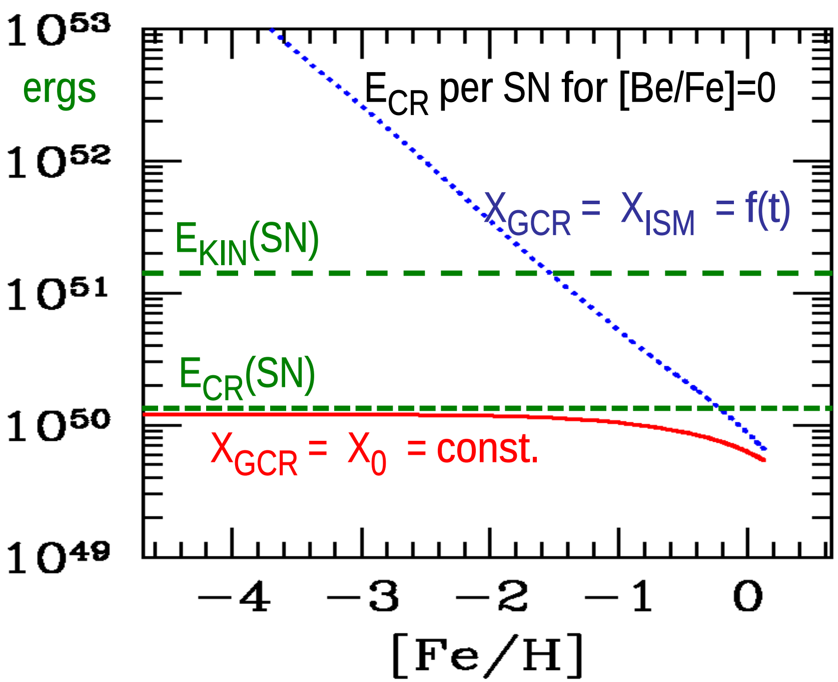
X(GCR,t) $\propto$ X(ISM,t) << $X_\odot$ at early times,

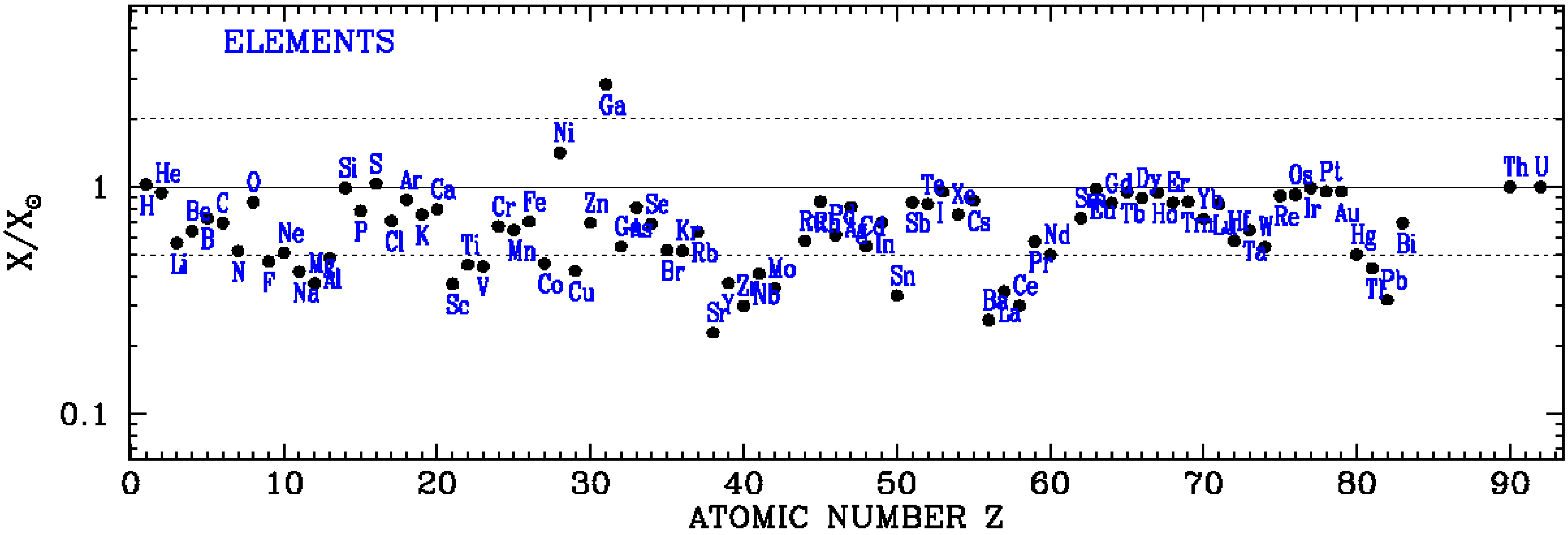
there is simply not enough energy in early GCR

accelerated by SN to maintain Be/Fe ~ const.

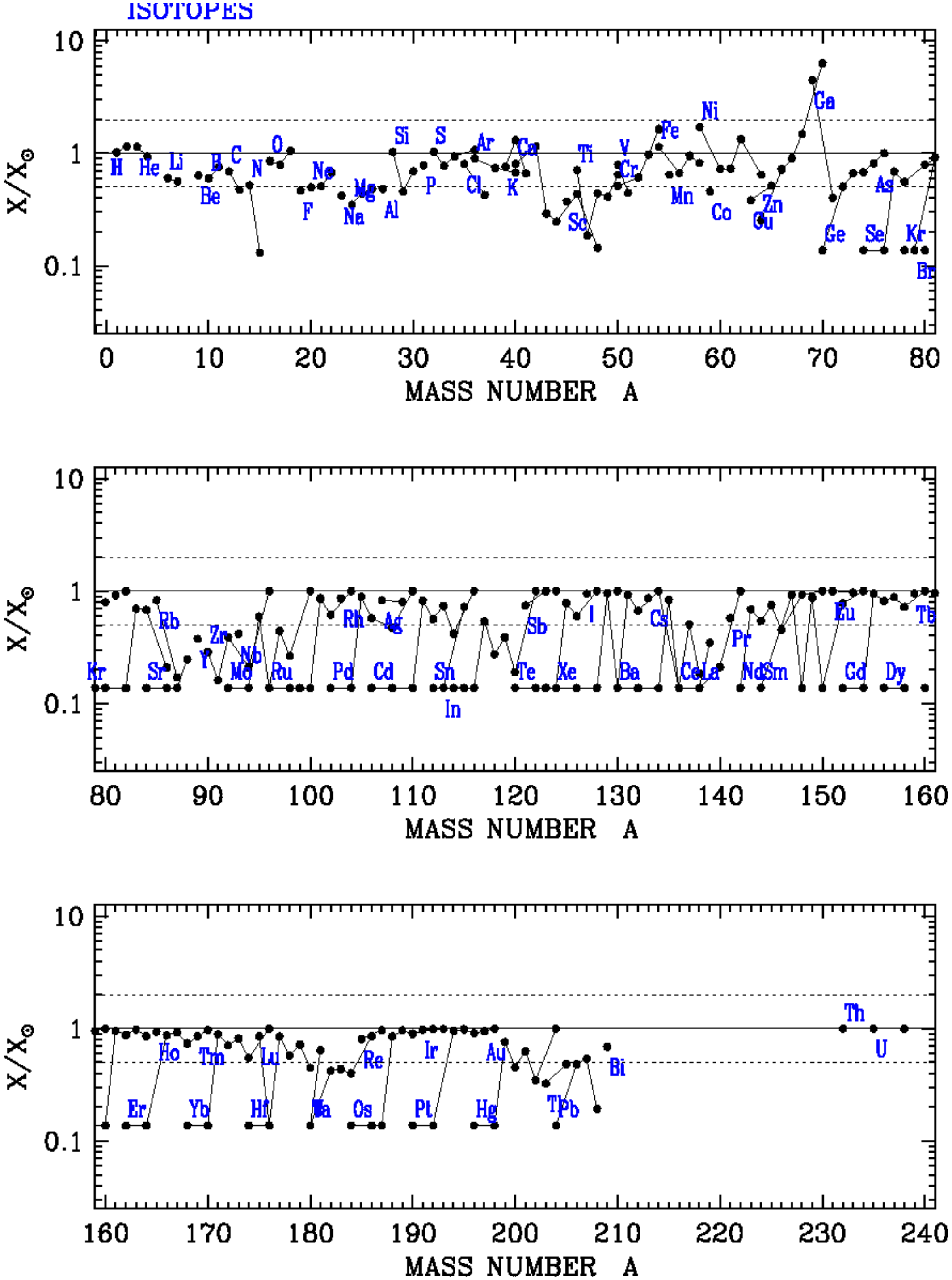
We need X_{CNO}(GCR,t) ~ X_{CNO} $\odot$ always

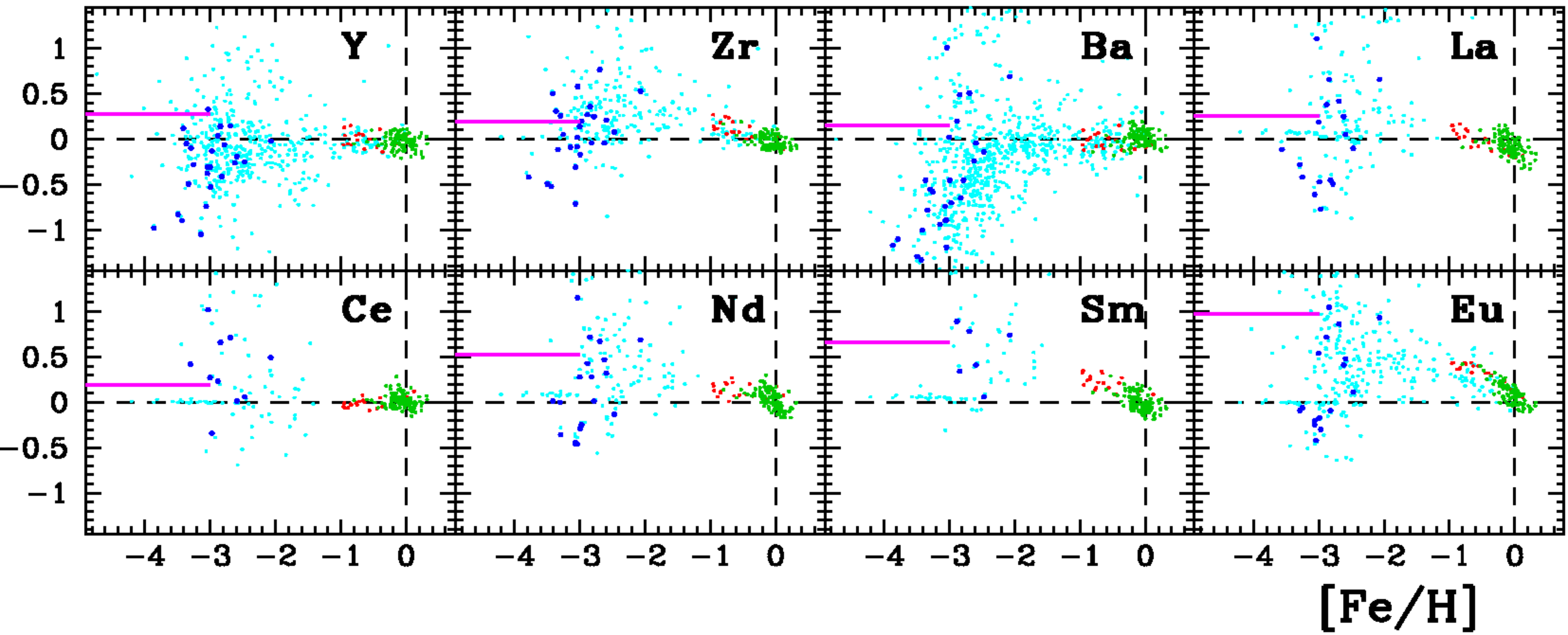
Impossible to reproduce observed linearity of Be/H vs Fe/H with metallicity dependent GCR composition



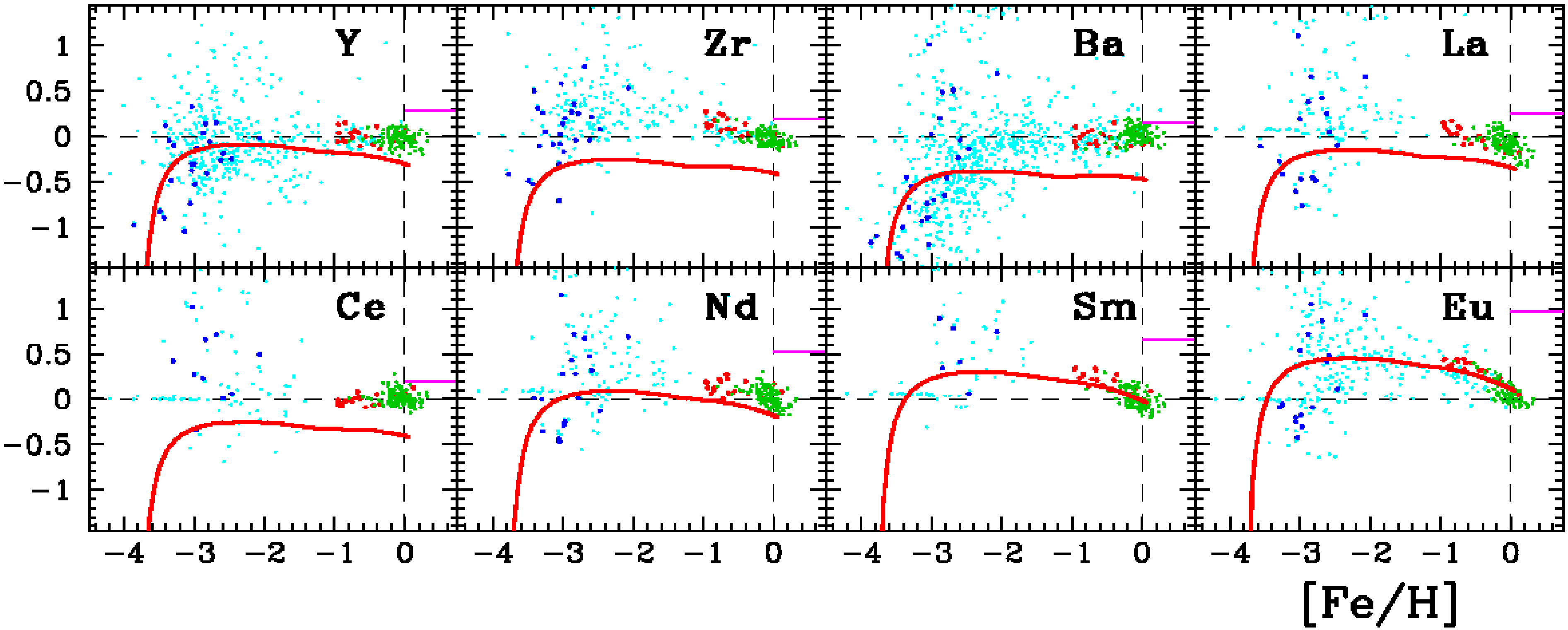


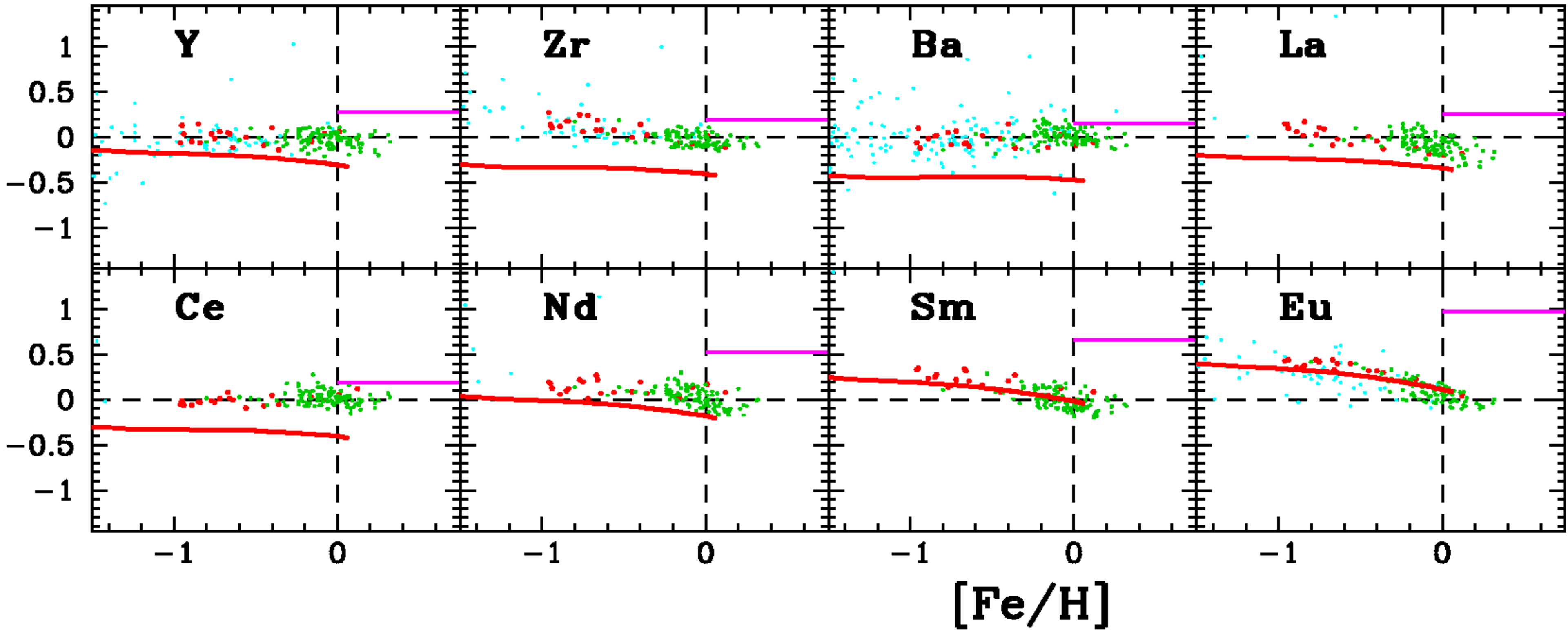
ELEMENTS
X/X⊙
1
0.1
0
10
20
30
40
50
60
70
80
90
ATOMIC NUMBER Z
H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Se Br Kr Rb Sr Y Mo Sn Sb Te I Xe Cs Ba La Ce Pr Nd Eu Gd Tb Dy Ho Er Yb Hf W Ta Re Os Ir Pt Au Hg Pb Bi Th U


ISOTOPES
X/X⊙
10
1
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 Cu Zn Ga Ge As Se Br Kr
0 10 20 30 40 50 60 70 80
MASS NUMBER A
X/X⊙
10
1
0.1
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
80 90 100 110 120 130 140 150 160
MASS NUMBER A
X/X⊙
10
1
0.1
Er Ho Tm Yb Lu Hf Ta Re Os Ir Pt Au Hg Tl Pb Bi Th U
160 170 180 190 200 210 220 230 240
MASS NUMBER A



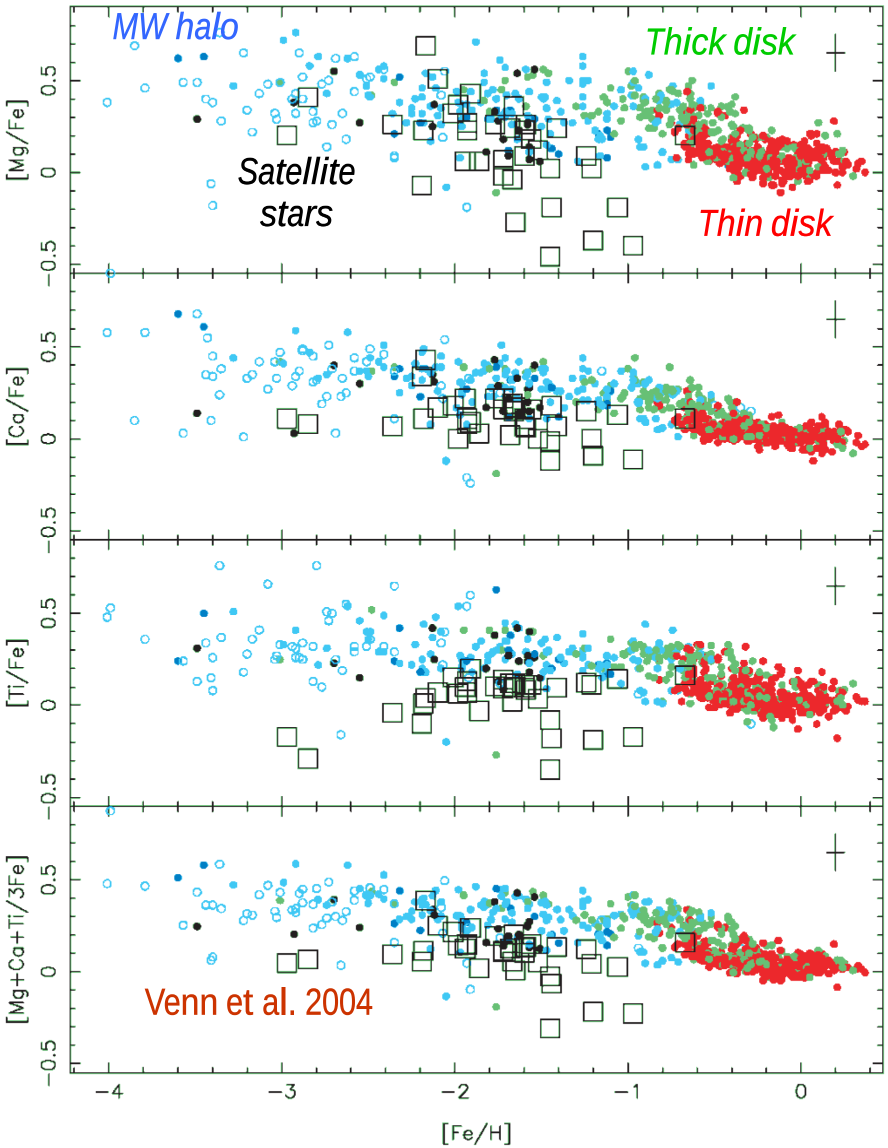
Y
Zr
Ba
La
Ce
Nd
Sm
Eu
1
0.5
0
−0.5
−1
−4
−3
−2
−1
0
[Fe/H]


Y
Zr
Ba
La
Ce
Nd
Sm
Eu
1
0.5
0
−0.5
−1
−4
−3
−2
−1
0
[Fe/H]



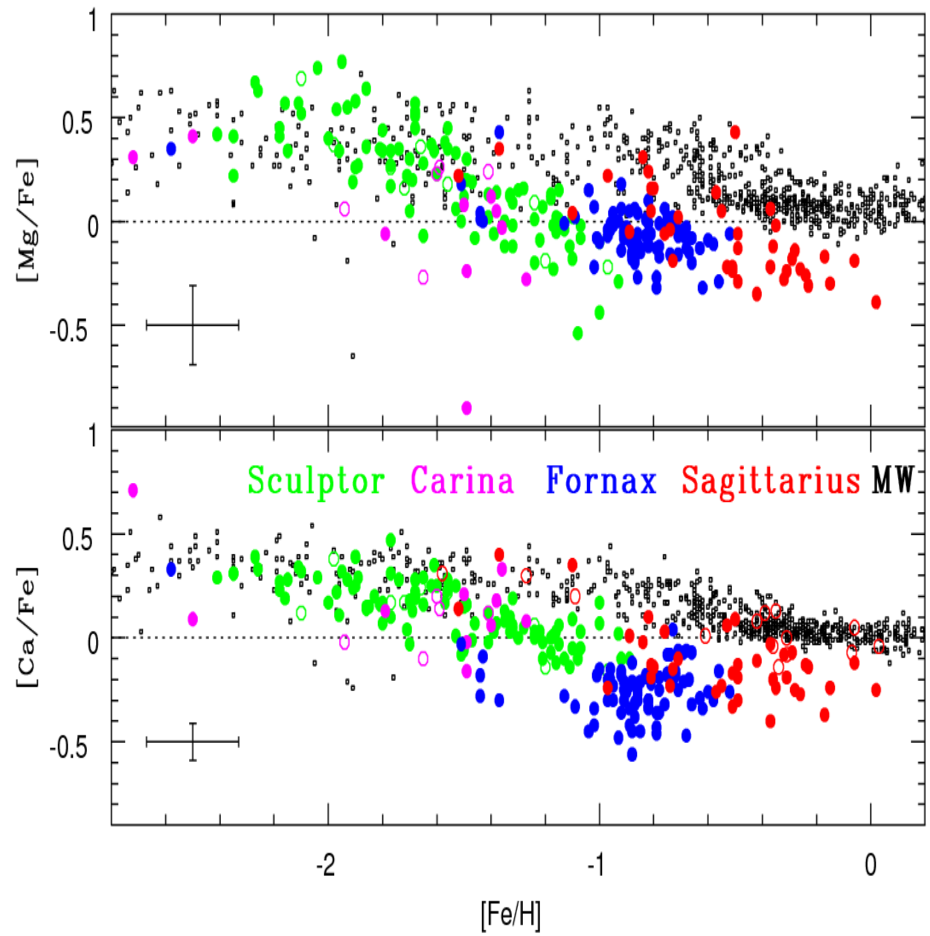
Y
Zr
Ba
La
Ce
Nd
Sm
Eu
1
0.5
0
−0.5
−1
−1
0
[Fe/H]

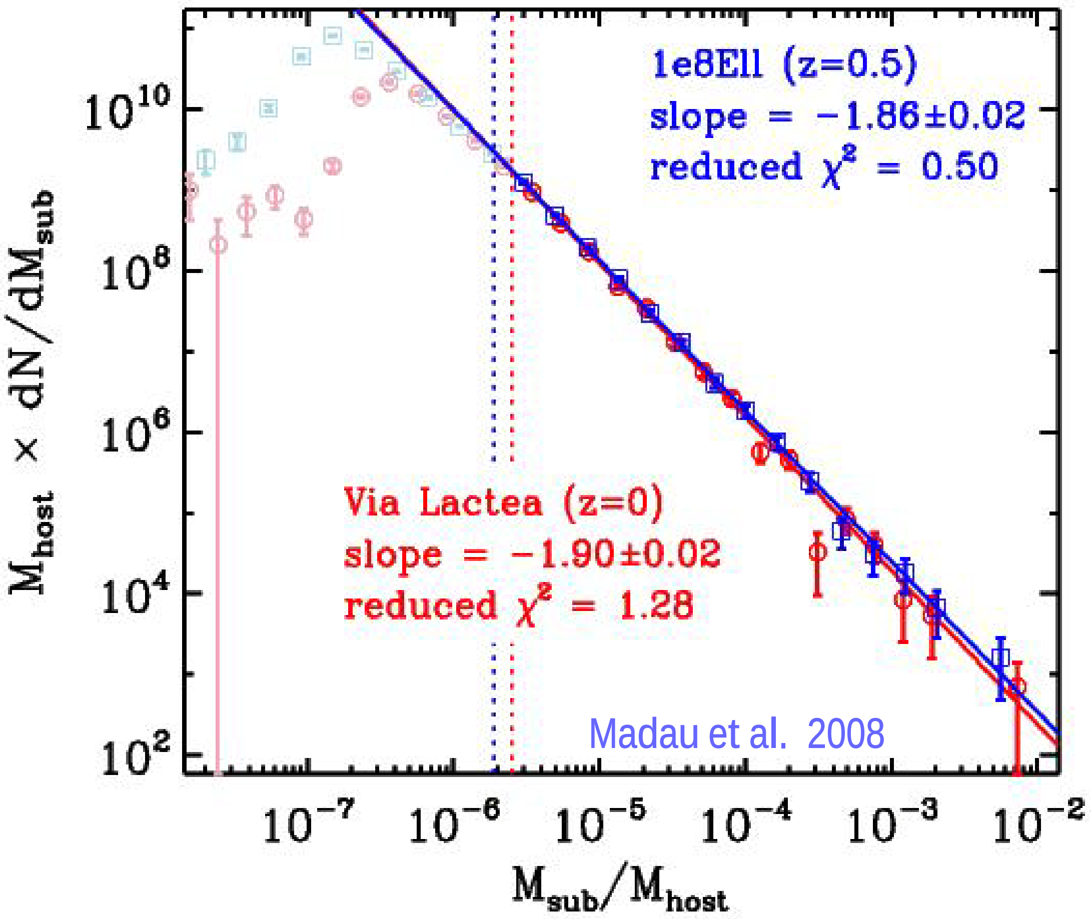
Present day dwarf satellites of MW cannot be the building blocks of MW halo *(abundance ratios: Fe from SNIa)*



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)



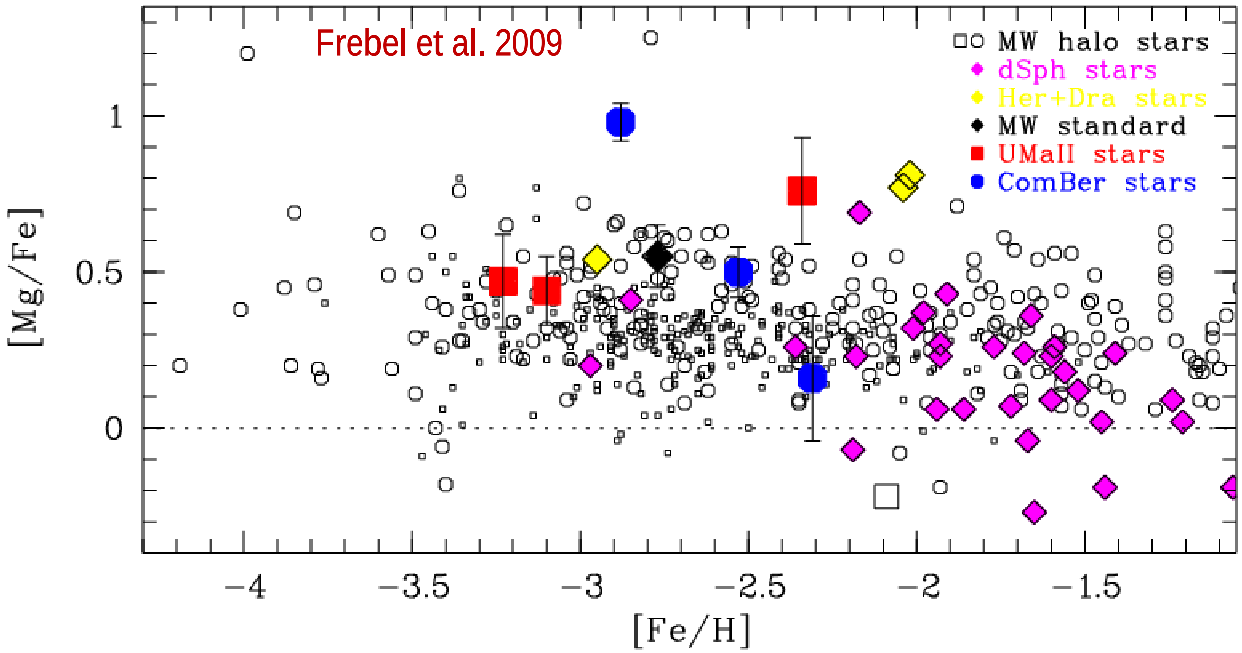


Dark halo distribution function

Simulations find that for the dark matter sub-haloes

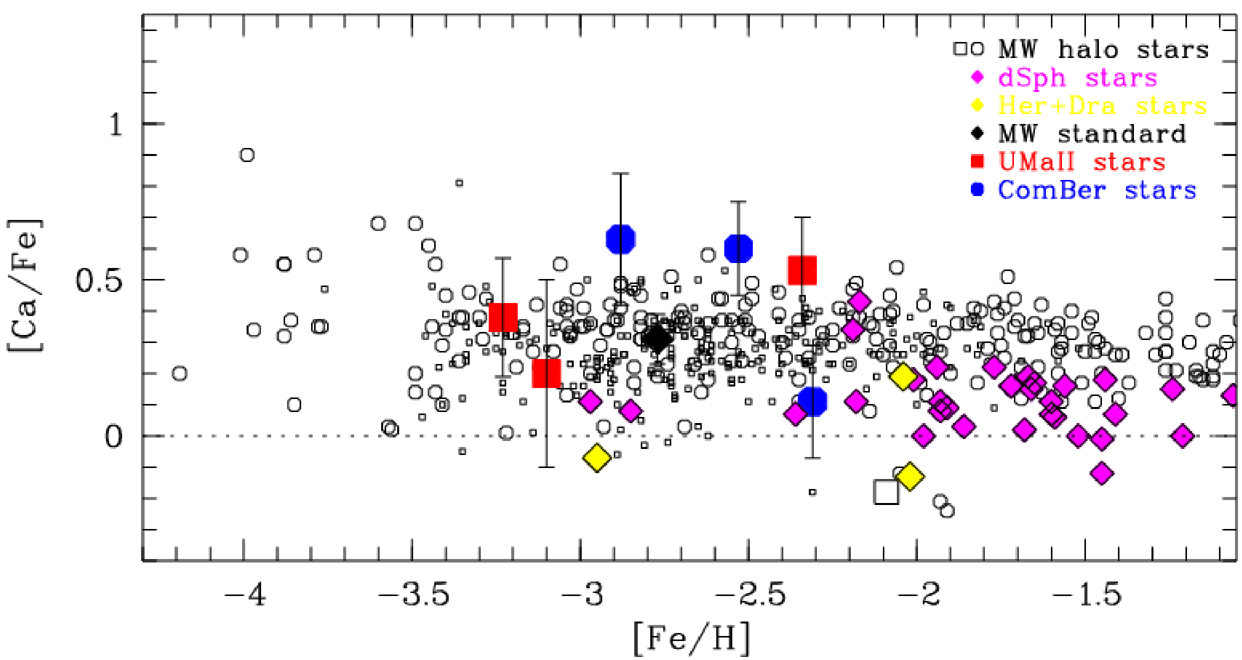
$$dN/dM \propto M^{-2}$$

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



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 ???