Aims of Galactic Chemical Evolution (GCE) studies

To check / constrain our understanding of stellar nucleosynthesis
(i.e. stellar yields), either ***statistically*** (mean, dispersion) or in ***individual objects***

To establish a chronology of events in a given system
e.g. ***when*** metallicity reached a given value, or ***when*** some stellar source (SNIa, AGB etc.) became important contributor to the abundance of a given isotope / element

To infer how a system was formed
(***Star Formation Rate, large scale gas mouvements***)
e.g. slow infall of gas in case of solar neighborhood

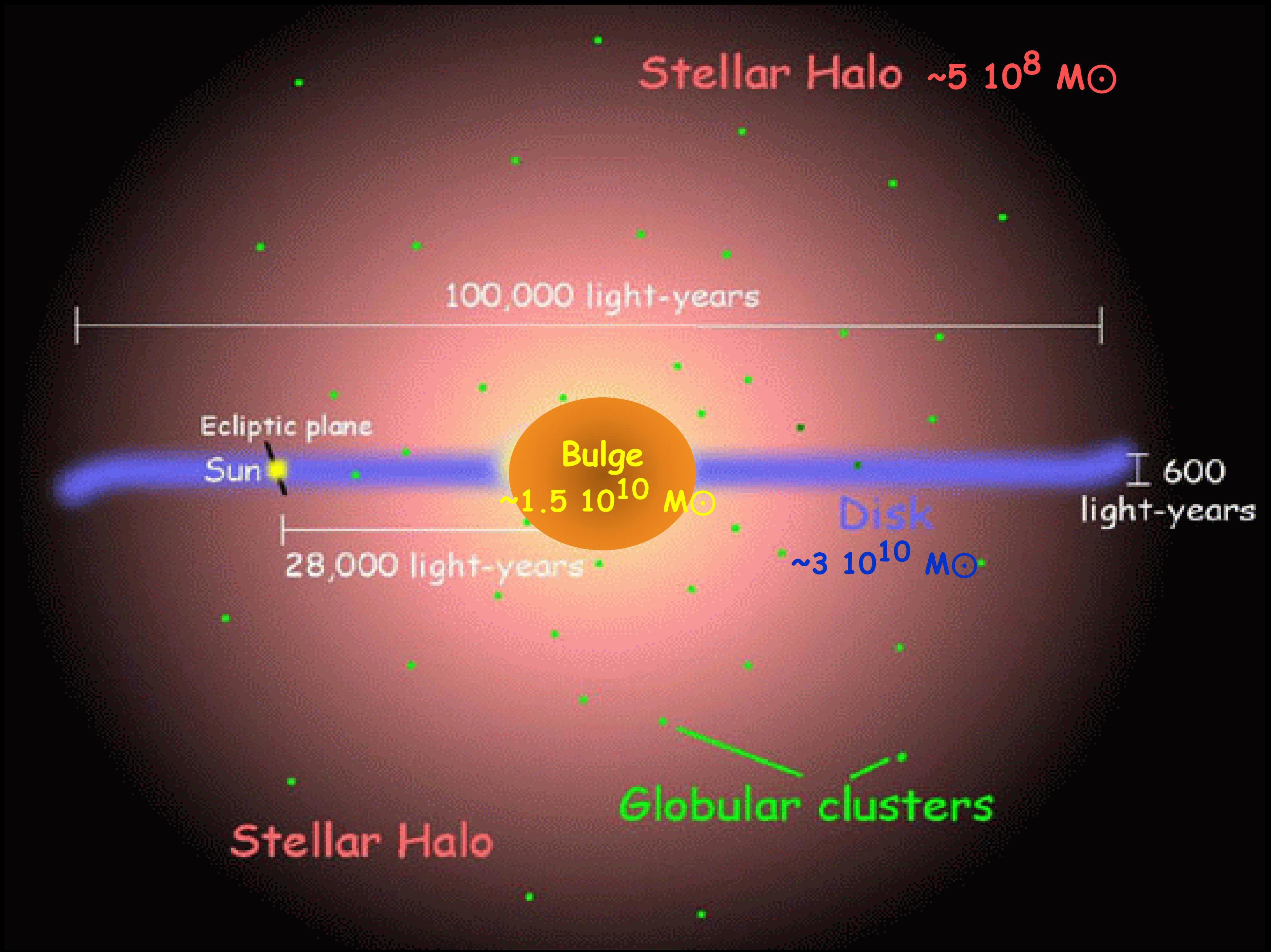
Assumptions of Galactic Chemical Evolution (GCE) studies

It is assumed that the system is chemically homogeneous at any time, i.e. all its parts have the same chemical composition.

This allows one to use e.g. [Fe/H] as a proxy for time.

1) **The system is well mixed at any time**
(mixing time scale much smaller than evolutionary timescale of metal producers)

2) **The system is sufficiently small that all its parts evolve at the same rate.**

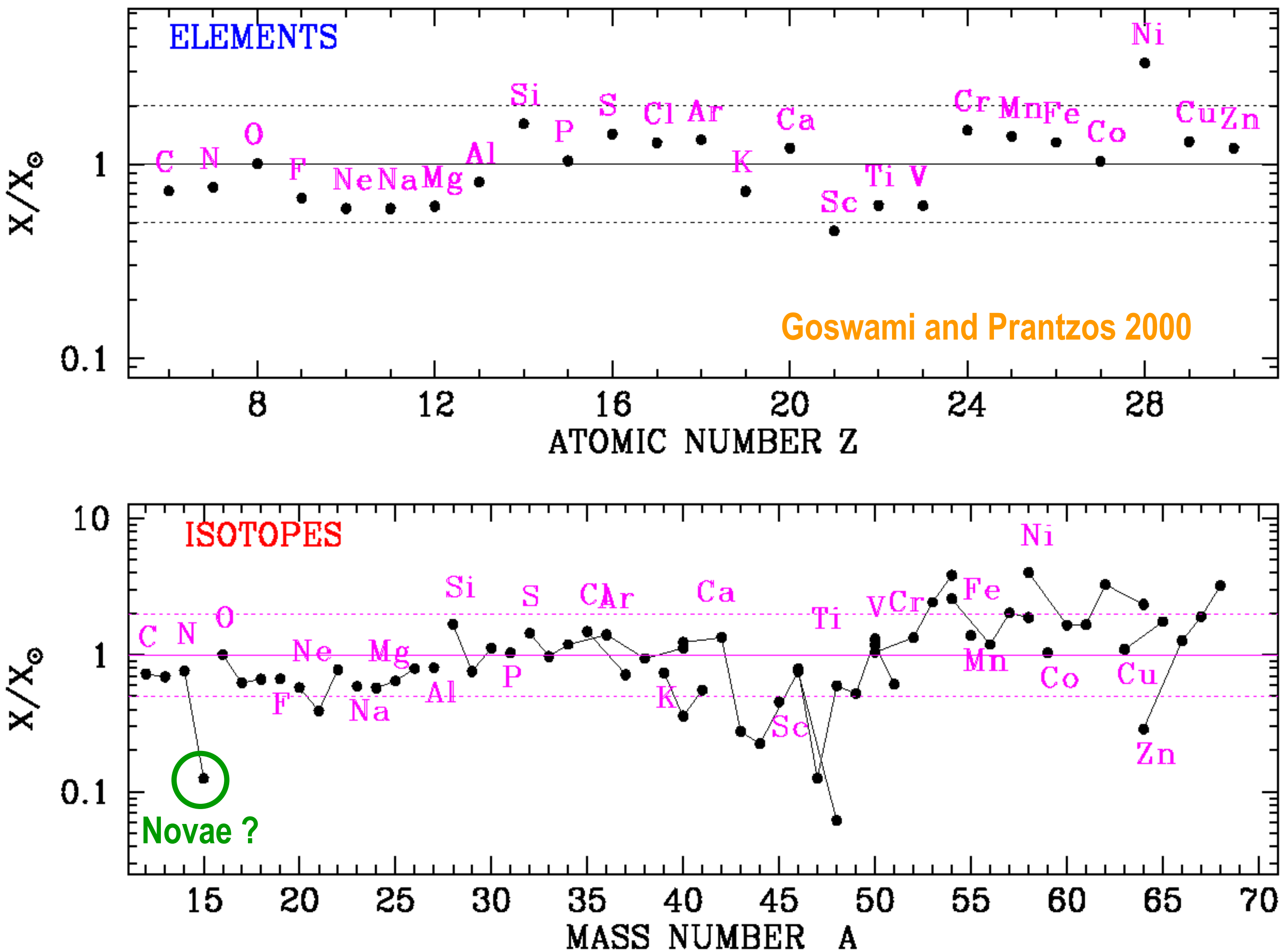


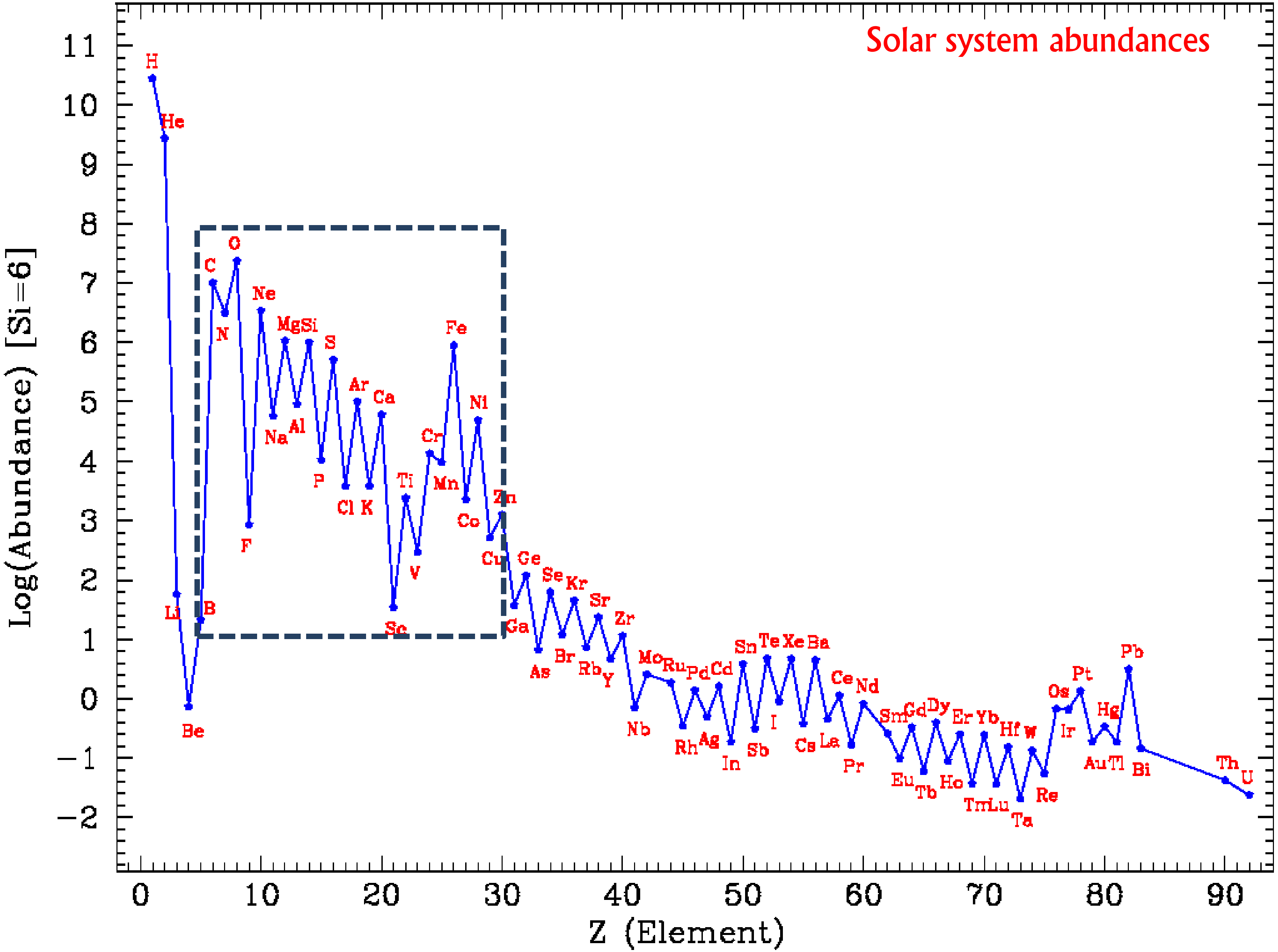
Stellar Halo ~5 10^8 M☉
100,000 light-years
Ecliptic plane
Sun
Bulge
~1.5 10^10 M☉
Disk
~3 10^10 M☉
600
light-years
28,000 light-years
Globular clusters
Stellar Halo

The Solar Neighborhood

Abundances at Solar system formation

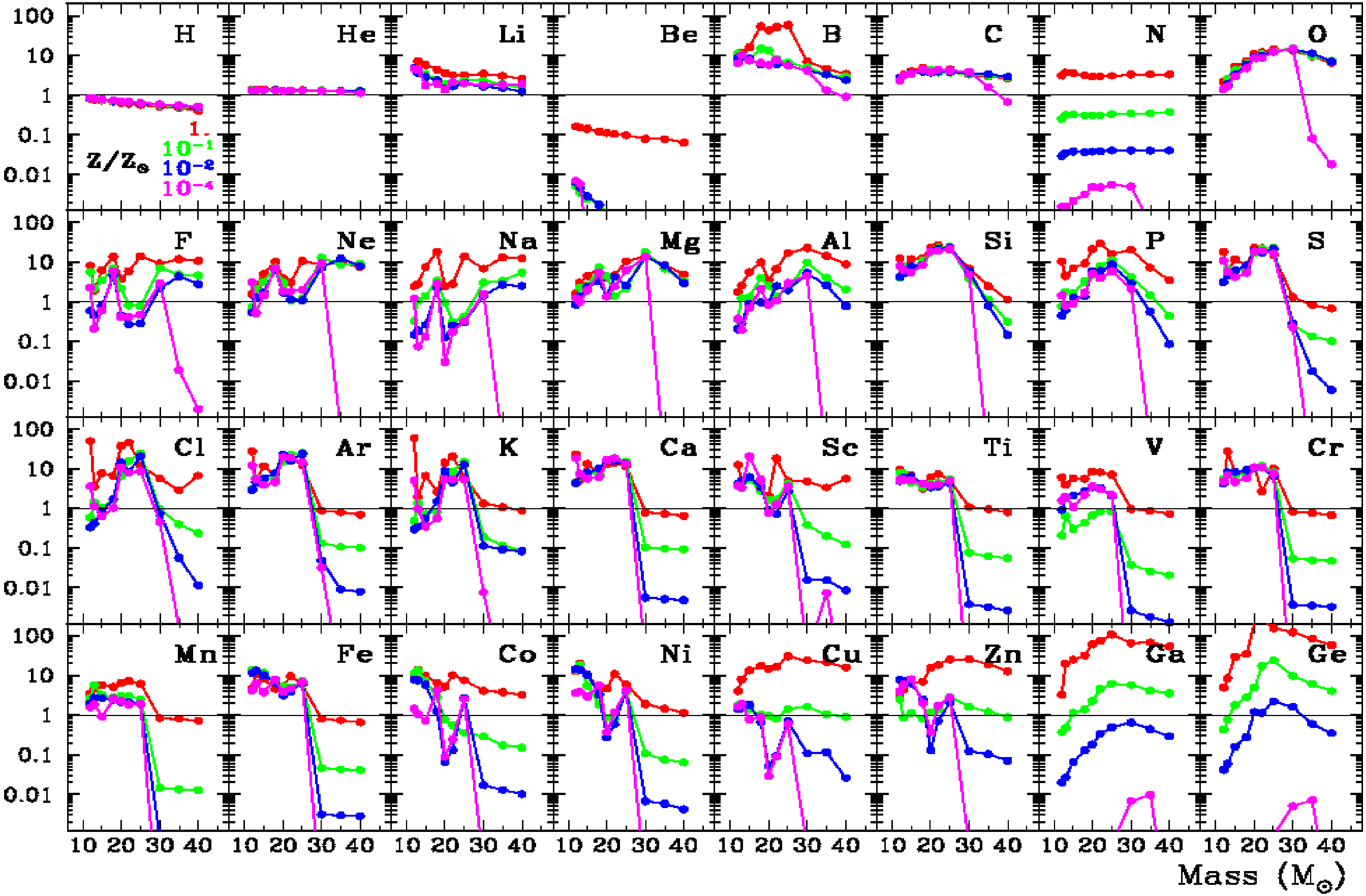
(Massive stars: *Woosley+Weaver 1995*; Intermediate mass stars: *van den Hoek+Gronewegen 1997*; SNIa: *Iwamoto et al. 2000*)

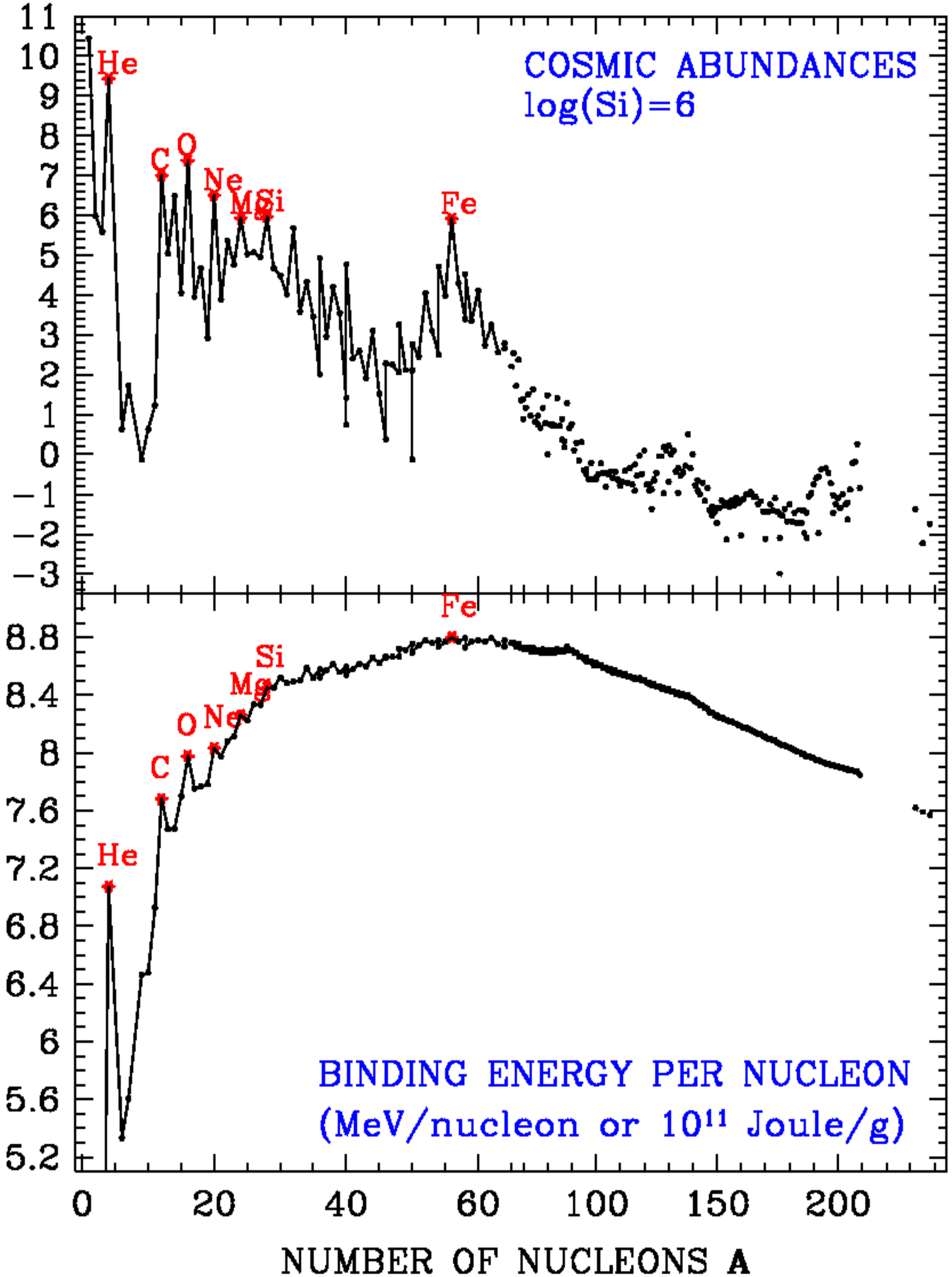



Solar system abundances
Log(Abundance) [Si=6]
Z (Element)
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Yields of massive stars

Woosley and Weaver 1995: **Yields** (overproduction factors) for various initial metallicities



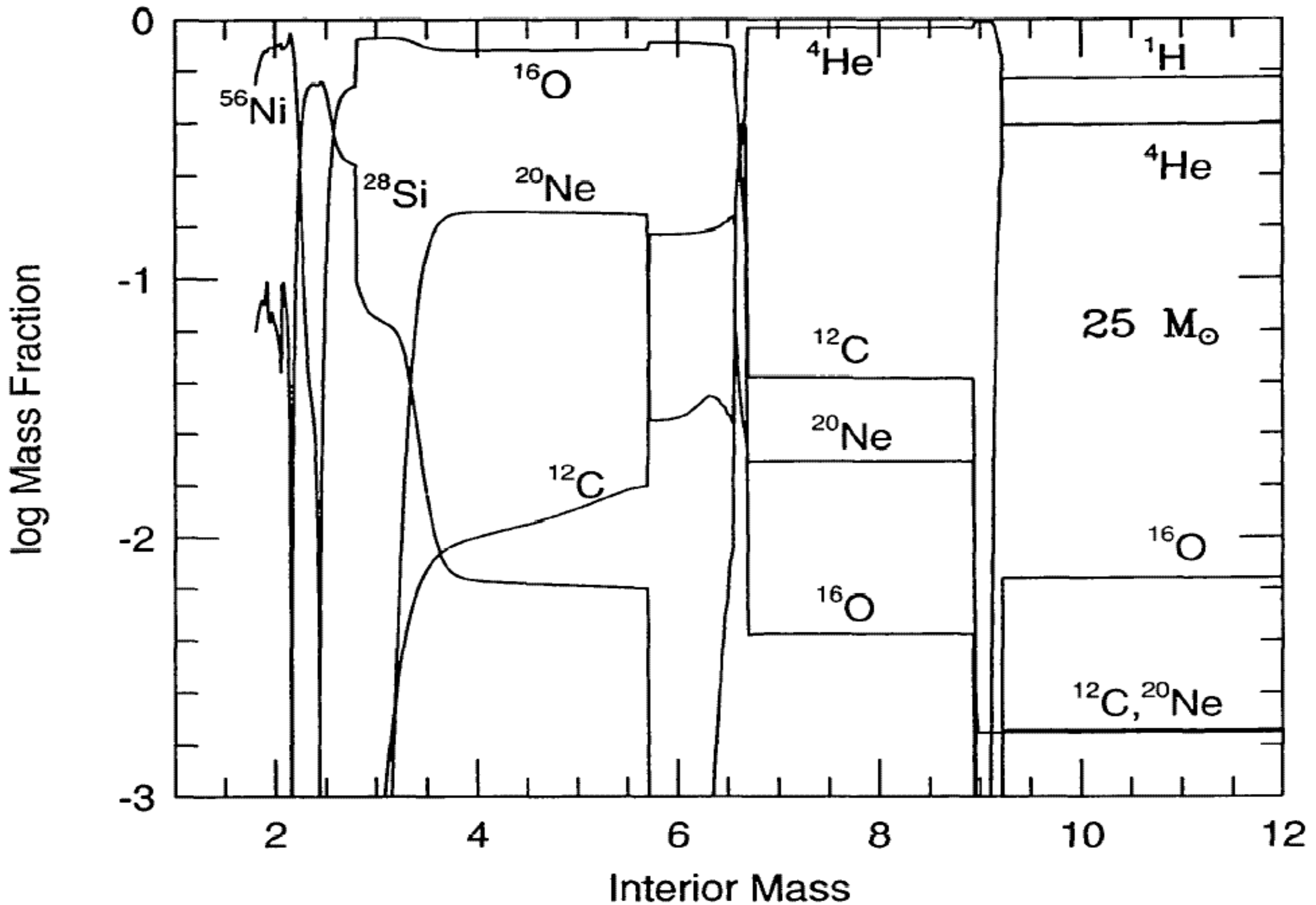


Cosmic abundances
of nuclides are **locally**
correlated with
nuclear stability

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

Nuclear processes
have shaped the
cosmic abundances
of the chemical elements

Yields of massive stars



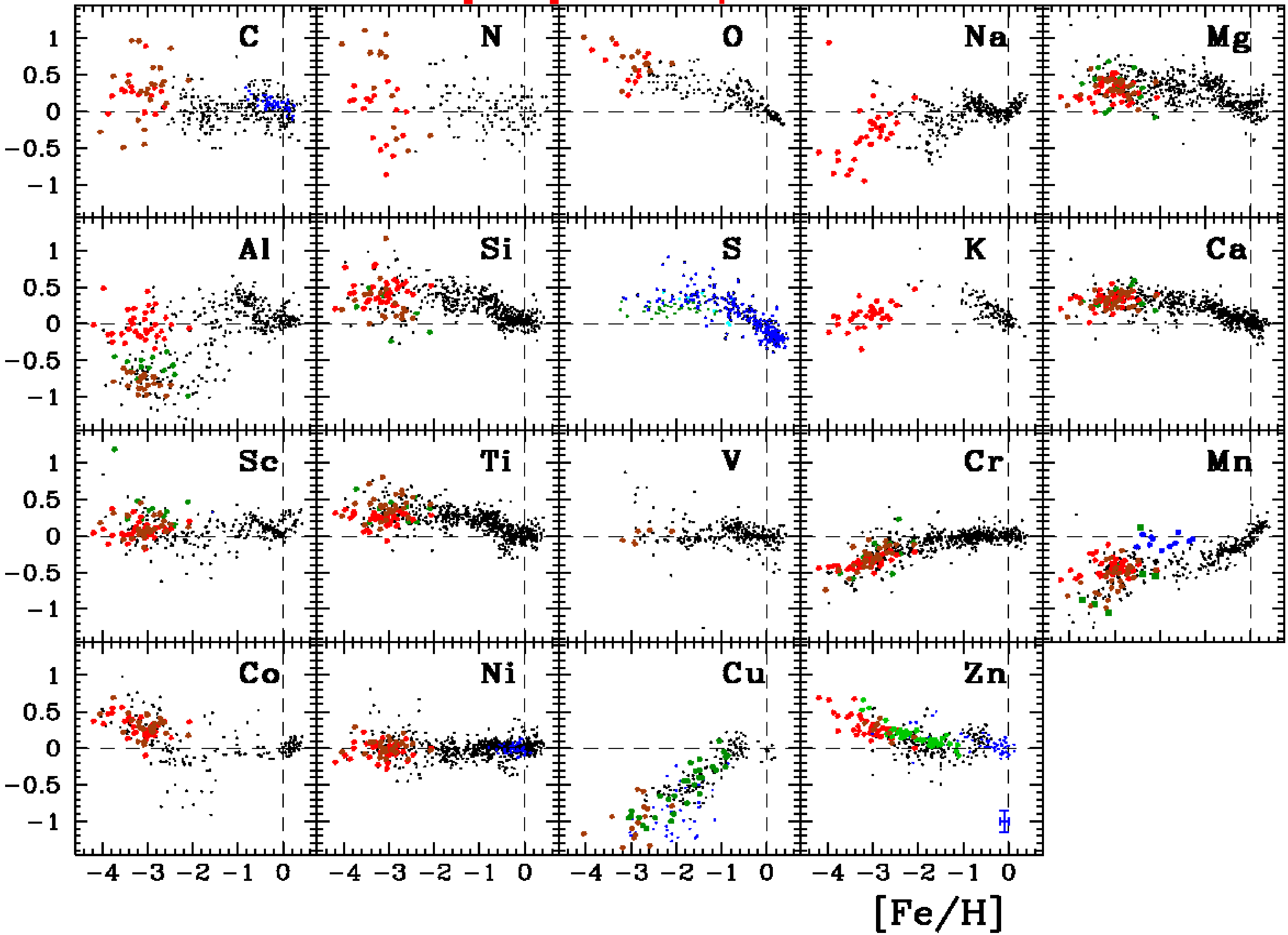
Most abundant nuclei ejected by a star of 25 M⊙

(WW95)

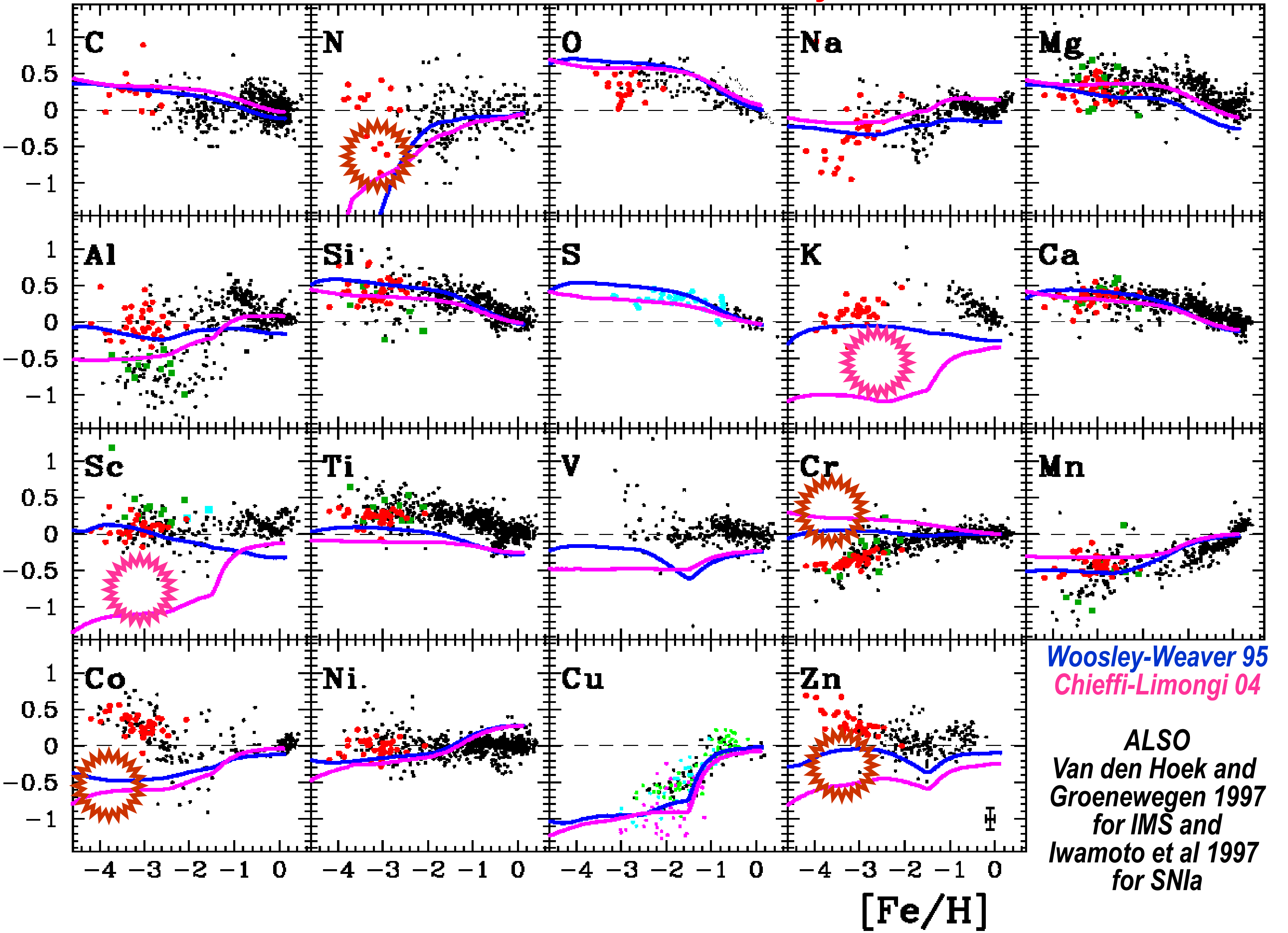
Thickness of layers depends on assumptions about **convection** and **mixing processes**
Abundances in each layer depend on adopted **nuclear reaction rates**
Abundances in **inner layers** depend also on **explosion mechanism**
Overall structure/evolution also depends on **rotation, mass loss** etc.

Large uncertainties still affecting the supernova yields (amounts of elements ejected)

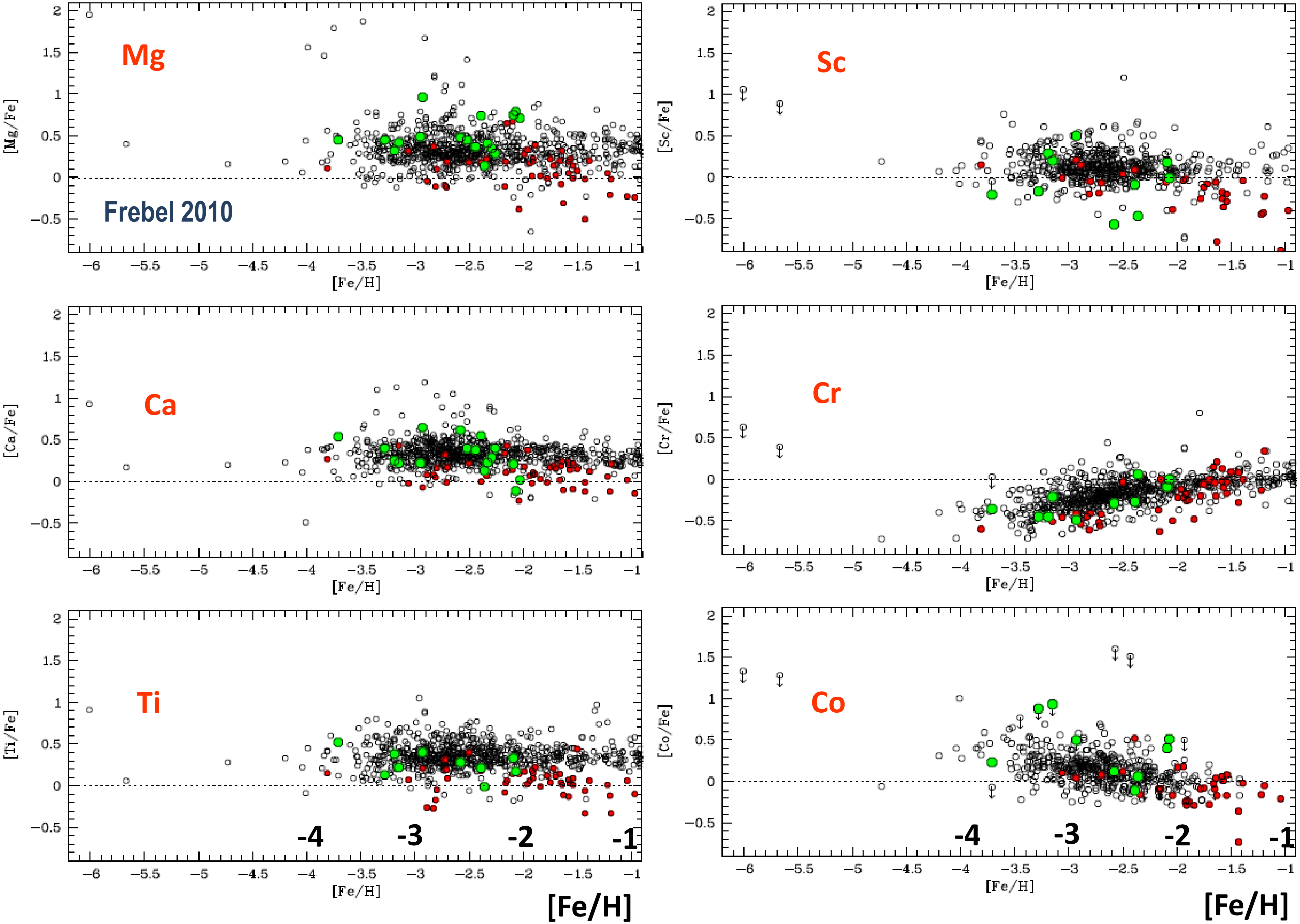
Abundances [X/Fe] in metal poor stars of the Halo



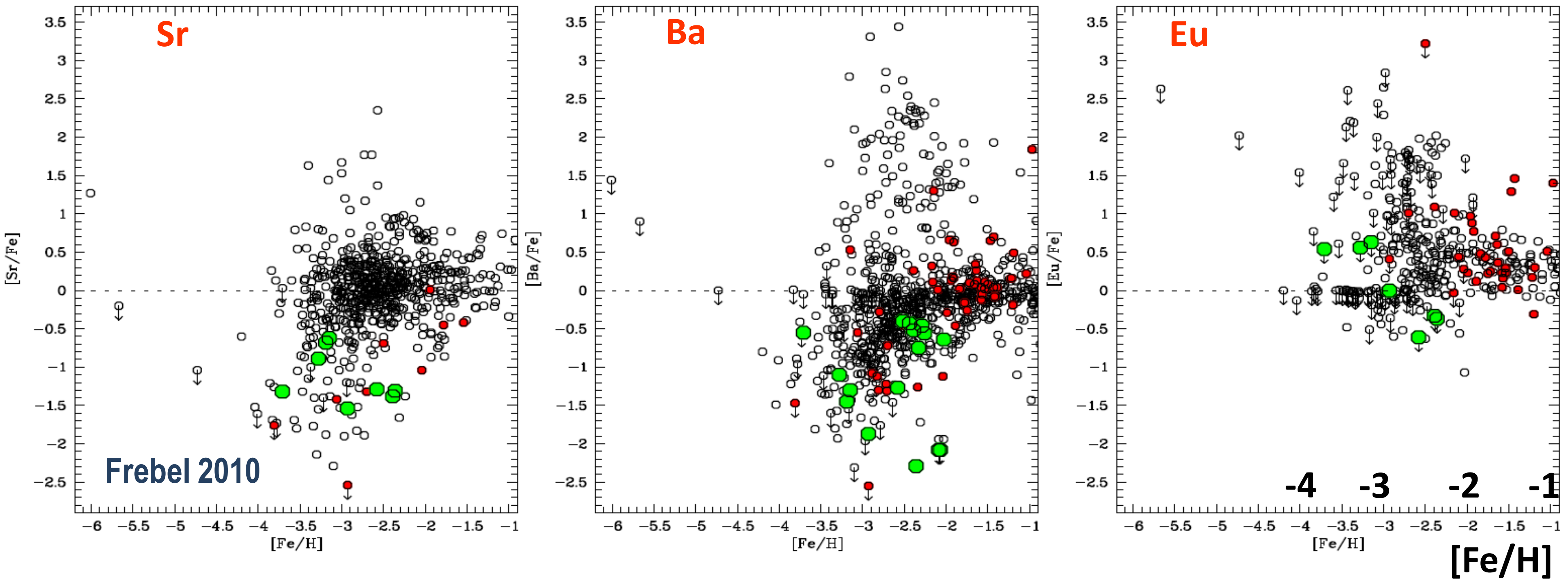
Chemical evolution from C to Zn : theory vs observations



Surprisingly little (or no) dispersion of X/Fe even at very low metallicities for elements up to Fe peak



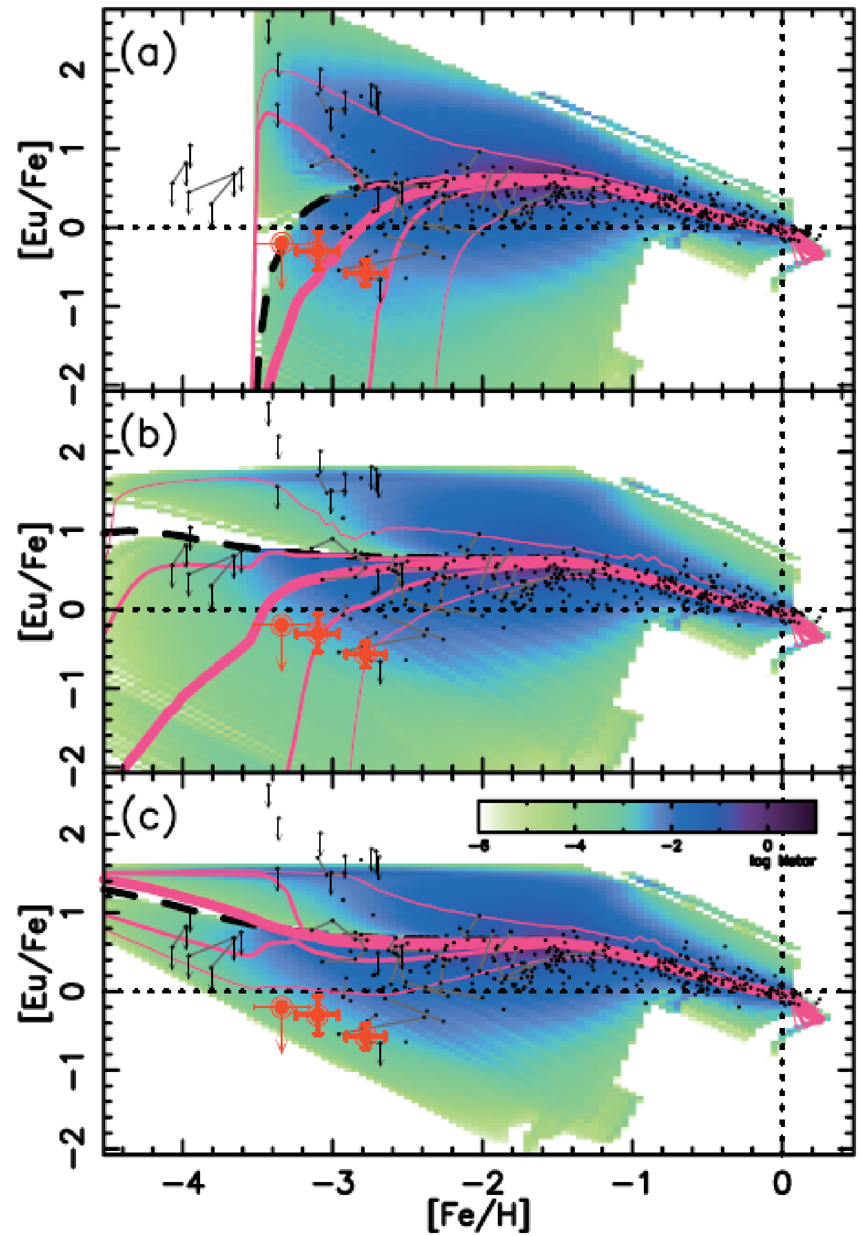
Large dispersion of X/Fe for elements heavier than Fe peak (s- or r-)



Despite the different nature of s- and r- processes,
and the difference in the lifetimes of the corresponding sources,
both r/Fe and s/Fe ratios display large scatter early on

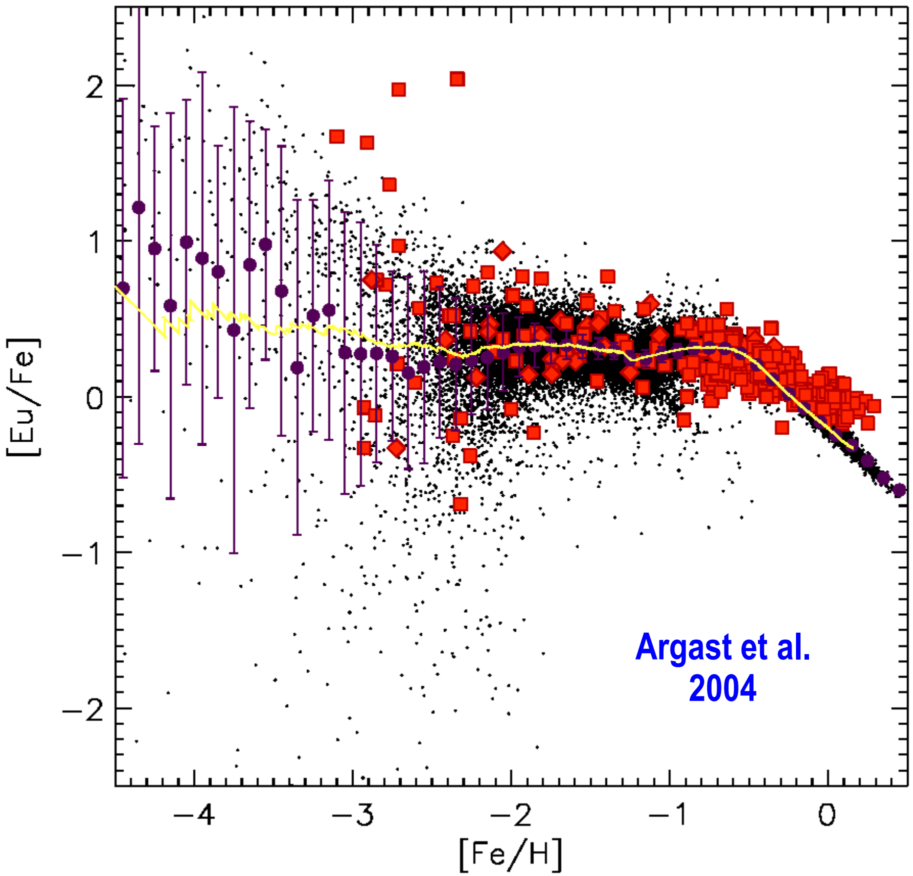
Large dispersion of X/Fe for elements heavier than Fe peak (s- or r-)

For r-elements, this could imply
inhomogeneous evolution :
that they are produced
ONLY in massive stars stars
of a limited mass range
(say, 8-10 $M_{\odot}$ or 25-30 $M_{\odot}$)
not well mixed with other ejecta…

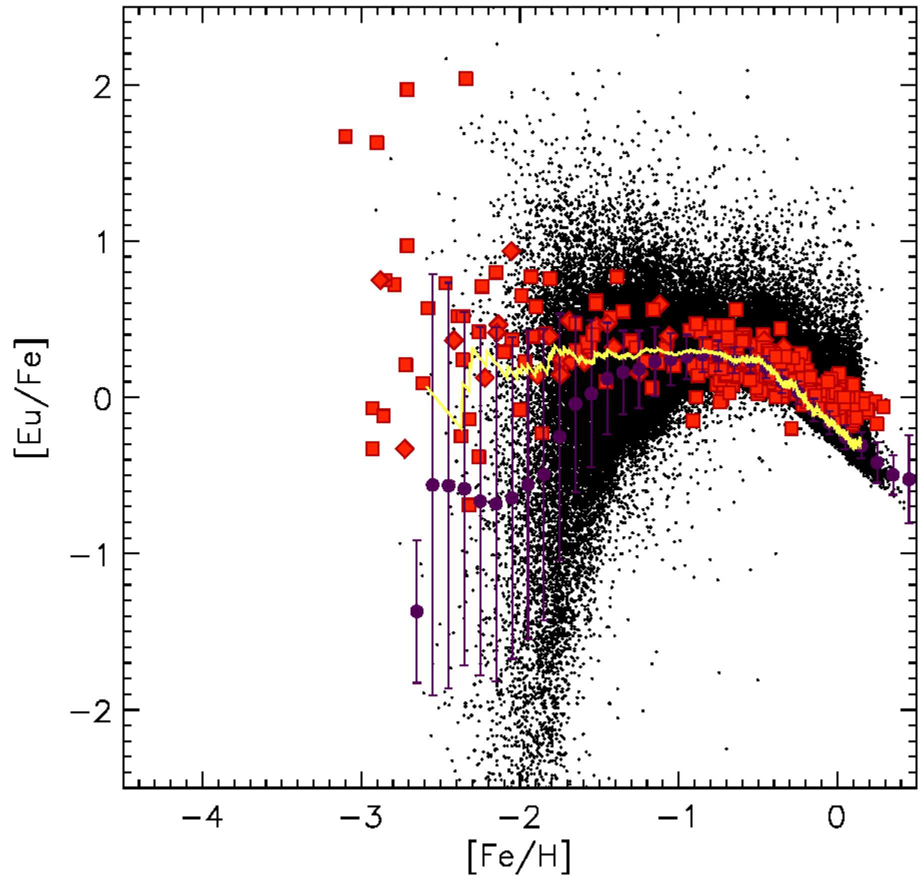


Another possibility: neutron star mergers

Core collapse Supernovae
(*high frequency, low r- yield*)



Neutron star mergers
(*low frequency, high r- yield*)



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

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 (MD)

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

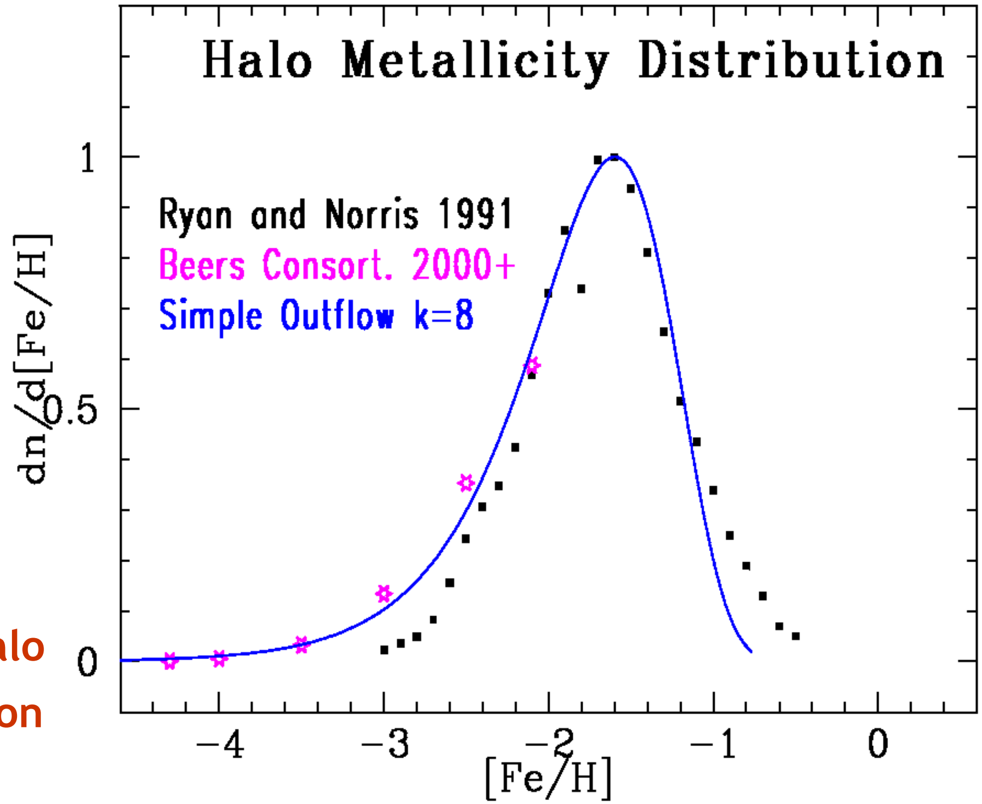
1) *A peak at [Fe/H] = -1.6* implying a **reduced effective yield**

$p_{EFF} \sim p_0/9$

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 ?



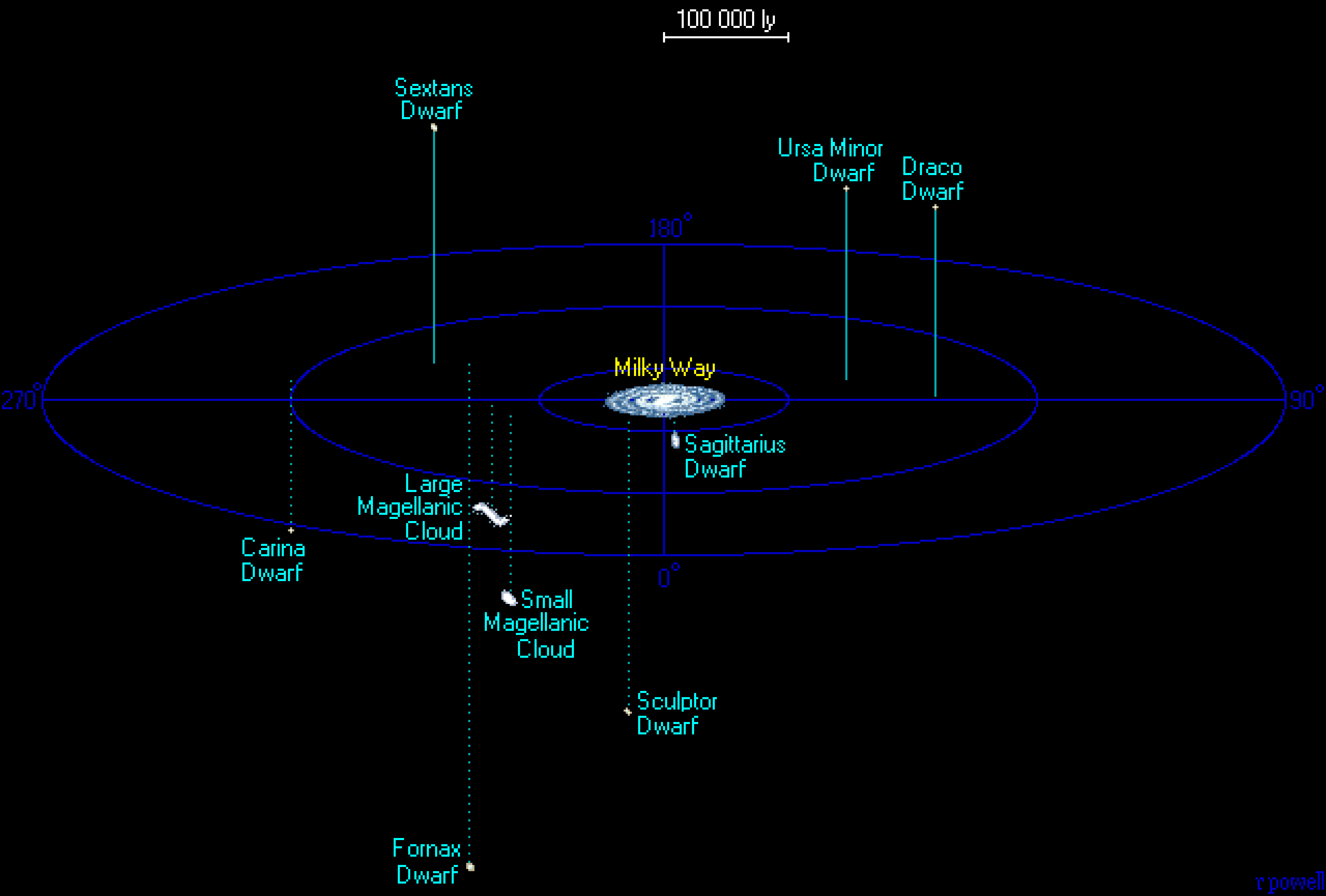
Ingredients required to evaluate the halo MD as a sum of MDs of sub-haloes in the hierarchical merging paradigm :

1) Shape of sub-halo MD

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

3) Baryon mass distribution of sub-haloes

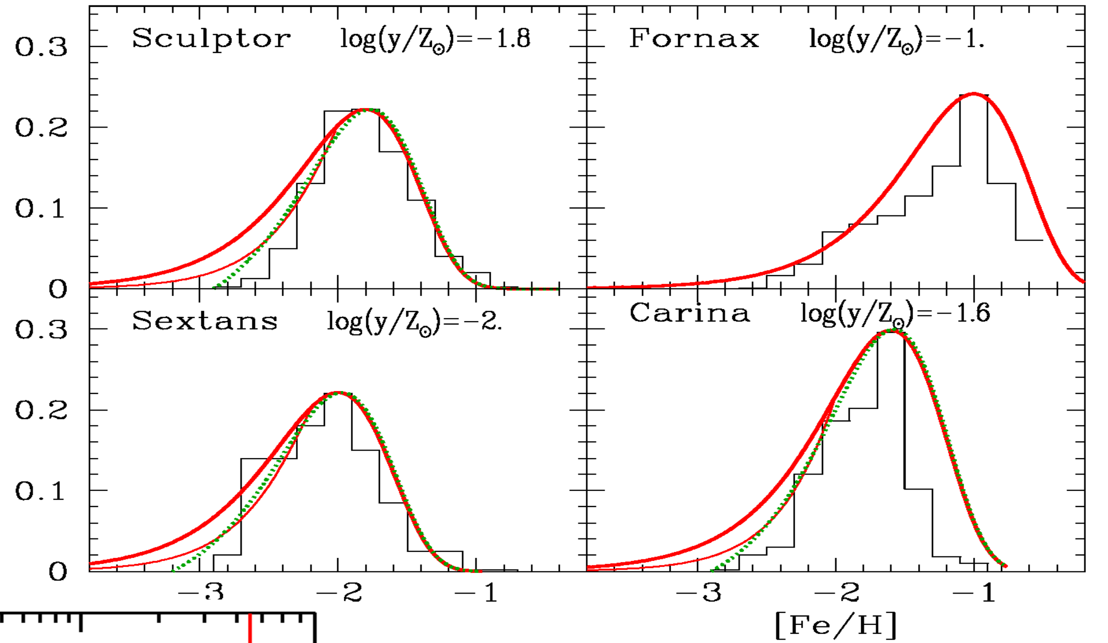
For the former two ingredients, one may get inspiration by observations of nearby dwarf galaxies (satellites of Milky Way)

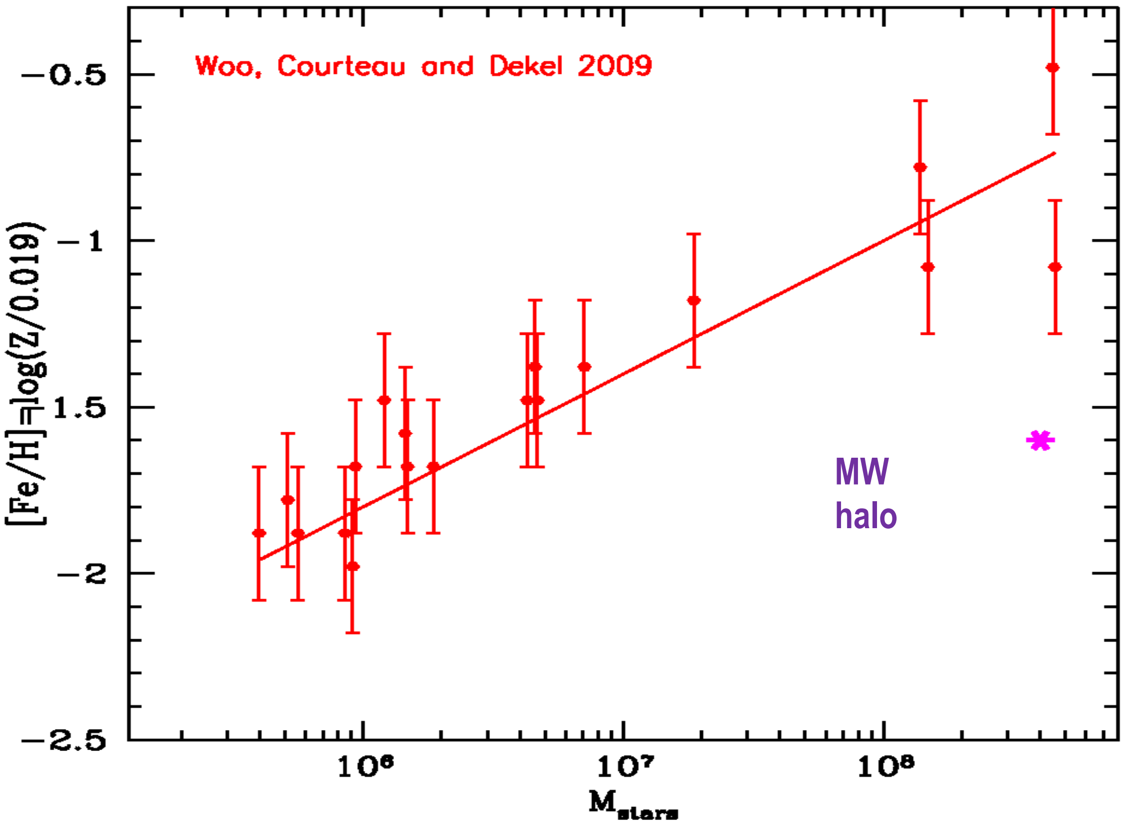


100 000 ly
Sextans Dwarf
Ursa Minor Dwarf
Draco Dwarf
180°
270°
90°
0°
Milky Way
Sagittarius Dwarf
Large Magellanic Cloud
Carina Dwarf
Small Magellanic Cloud
Sculptor Dwarf
Fornax Dwarf
r powell

Metallicity distributions of nearby 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 *(NP 2007)*
- both *(Salvadori et al. 2008)*





The peak of the MD can be obtained from the observed *Mass - Metallicity relationship* of dwarf spheroidals as a function of their mass

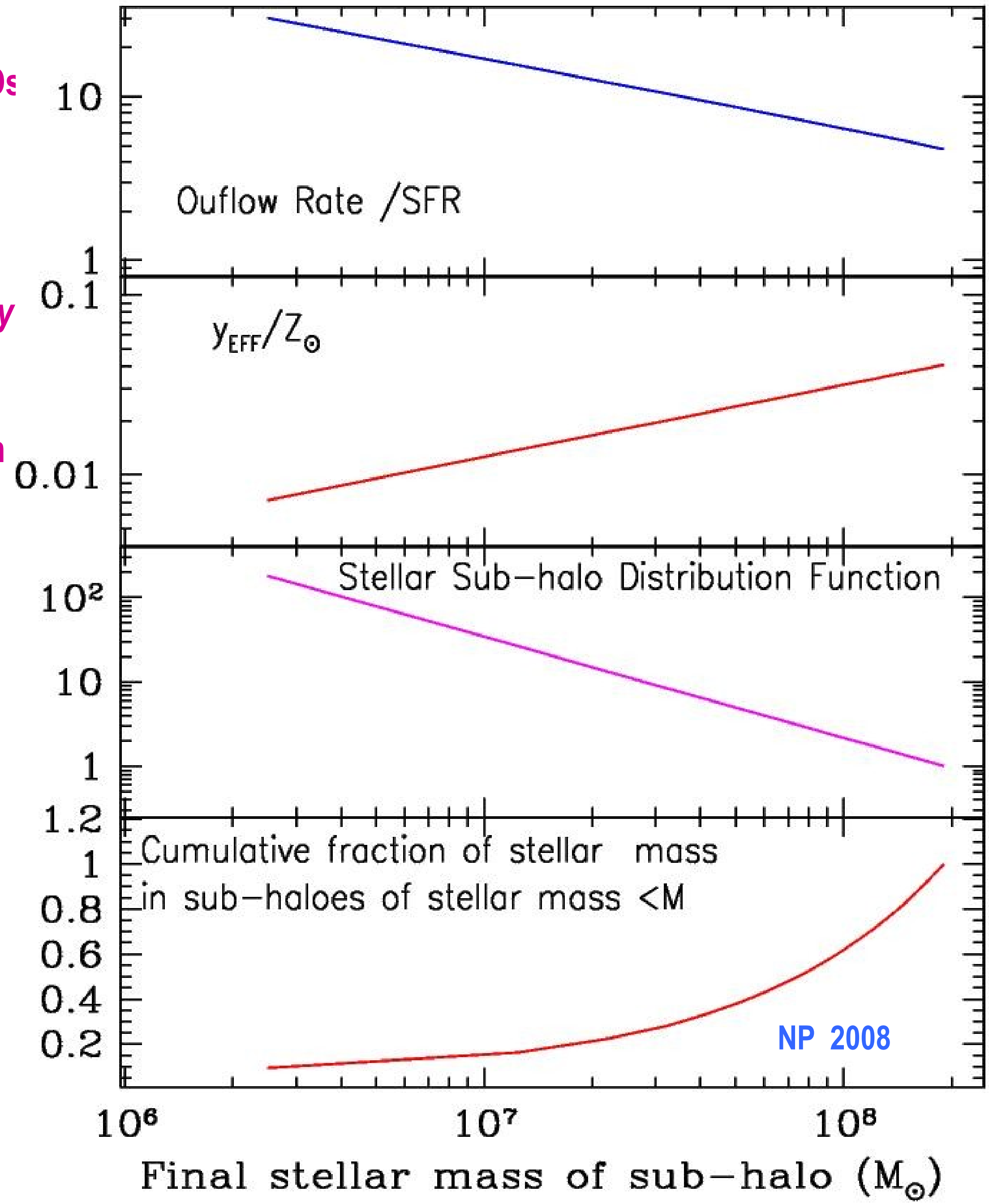
(The MW halo lies far below that relation)

Properties of toy-model stellar subhaloes

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 (from cosmological simulations)



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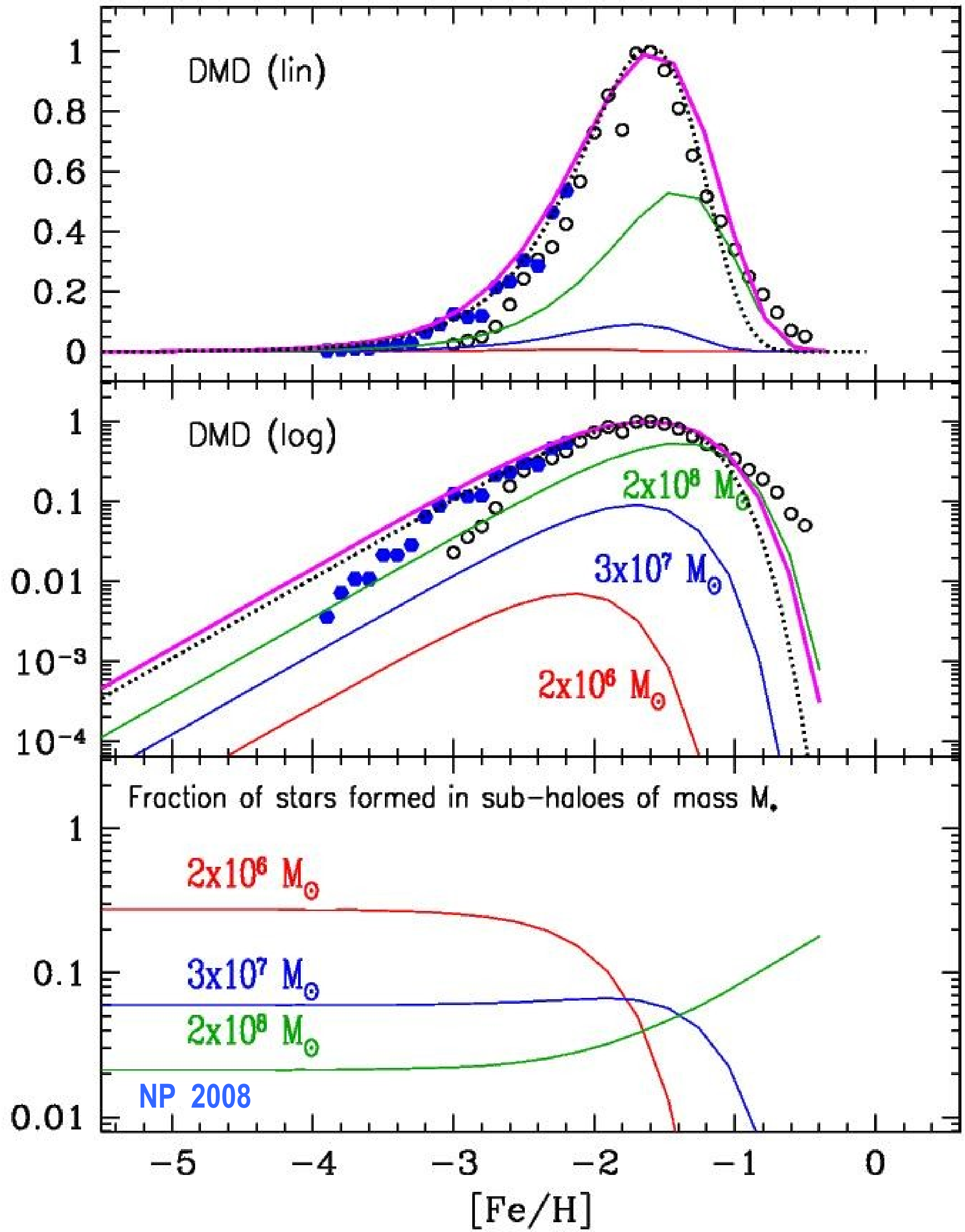
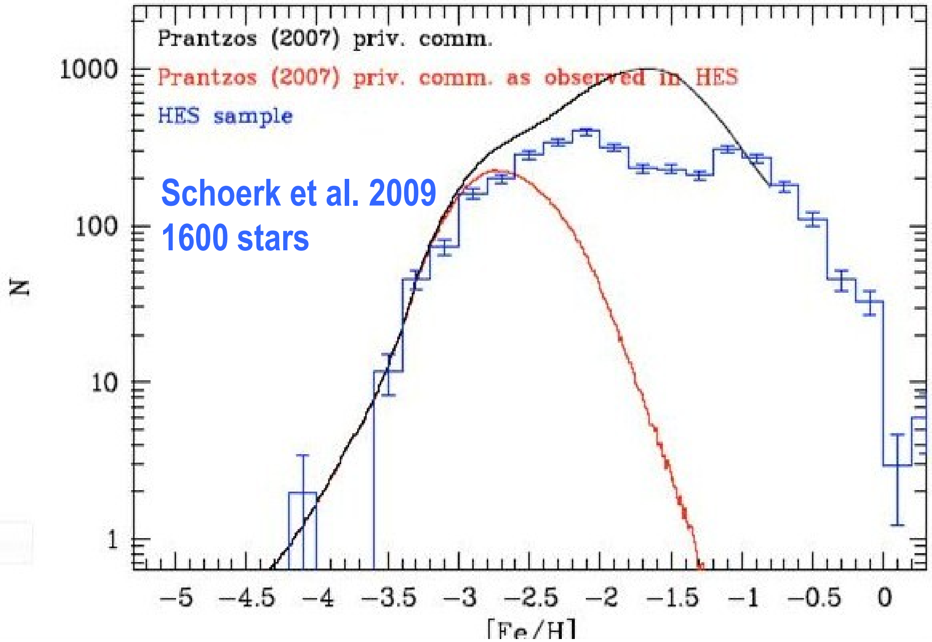
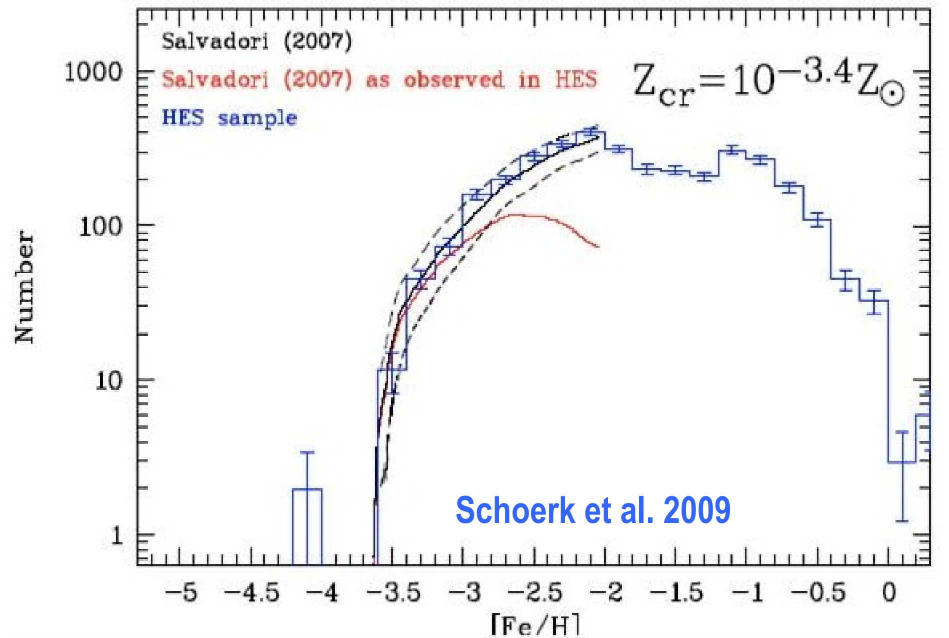
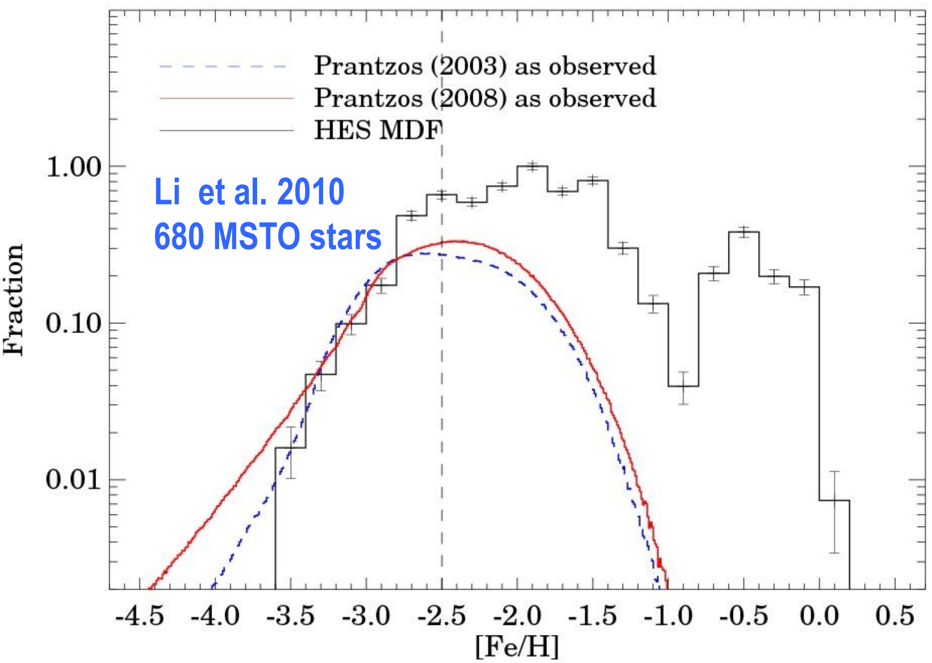
Most of the lowest metallicity stars of the halo ([Fe/H]<-2) have been formed in the numerous, smallest sub-haloes, while its high metallicity tail was formed in a COUPLE of relatively massive, sub-haloes



Comparison of Halo Metallicity Distribution (MD) to Hamburg-ESO survey

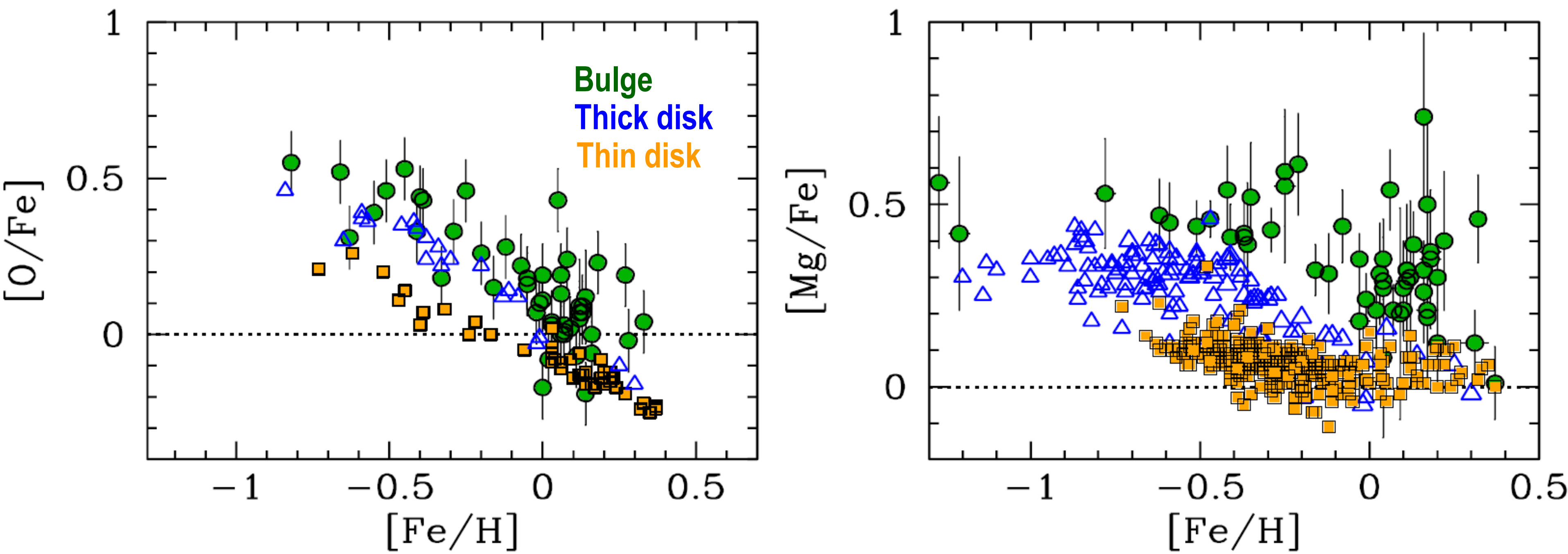






Assuming the MW halo was indeed formed from a few hundred sub-haloes,
each one of them evolving on a different timescale:
What are the implications for the evolution of abundance ratios ?

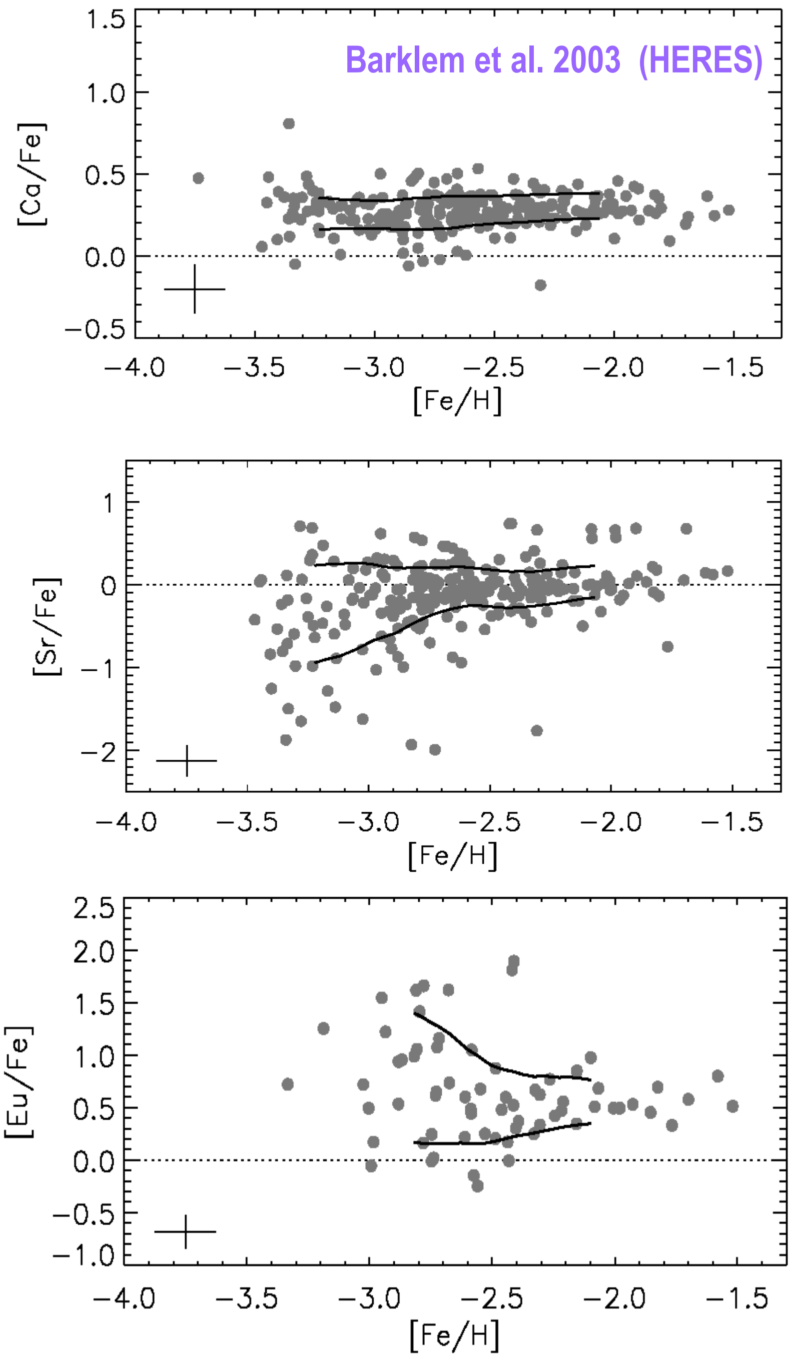
[Fe/H] is no more an absolute "clock" for the whole halo:
the same value of [FeH] may be reached on
very different timescales in different sub-haloes
(depending on their star formation and outflow histories)
even if each sub-halo evolved homogeneously



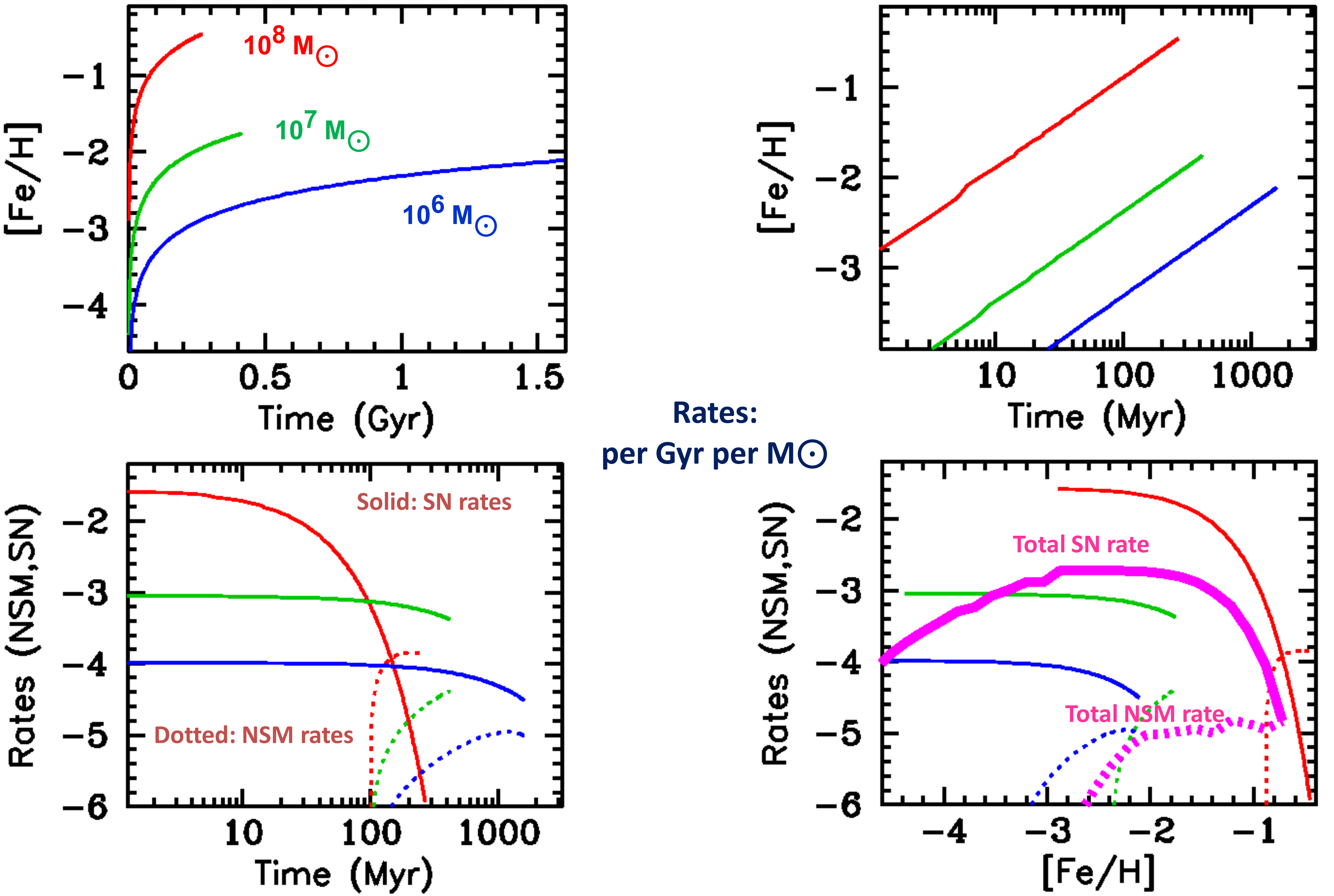
Elements produced in the same site
(e.g. α-elements and Fe, both in SNII)
will display a uniform abundance ratio
(no dispersion, at all [Fe/H]),
assuming efficient mixing with ISM

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

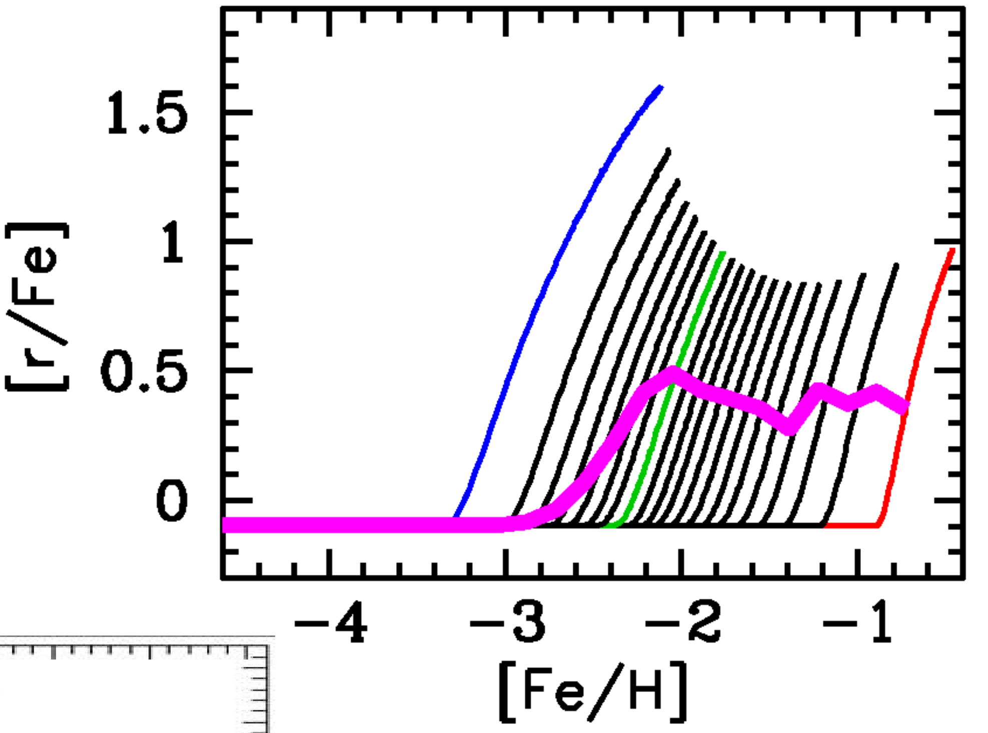
Could this explain
the early dispersion in Eu/Fe ?
[assuming that r – elements are produced
in both, short (SNII) and long (NS mergers)
timescales]

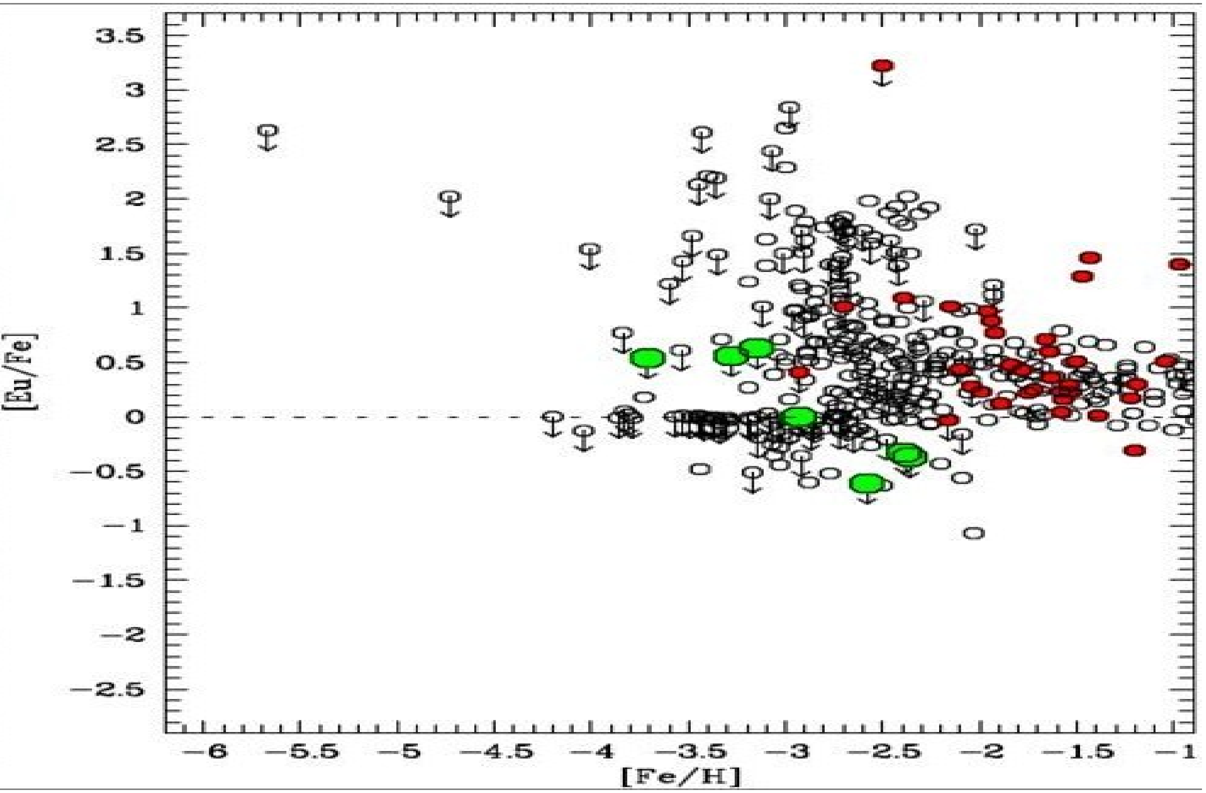


A toy model: constructing the halo as a sum of sub-haloes of different properties (masses and evolutionary histories) constrained by the observed metallicity distribution



The average r/Fe
rises at [Fe/] slightly below -3
and displays a dispersion
slightly larger at lowest metallicities
(*even though each sub-halo
evolves homogeneously*)

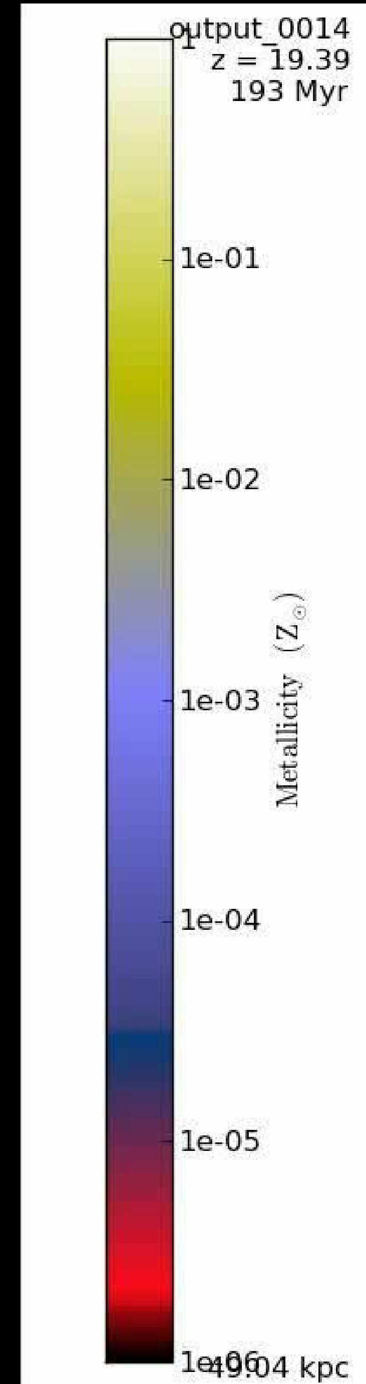


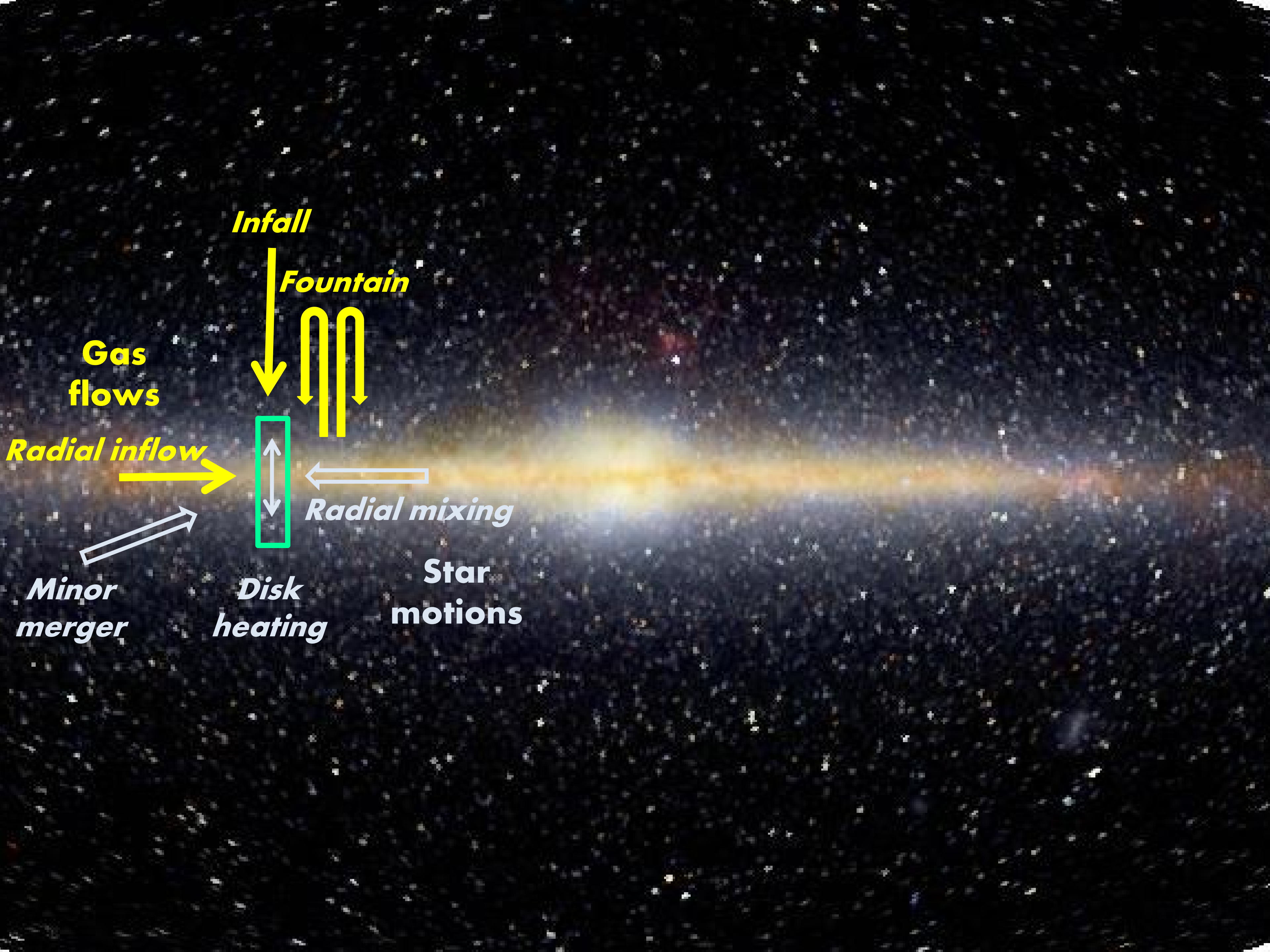


In qualitative agreement
with observations

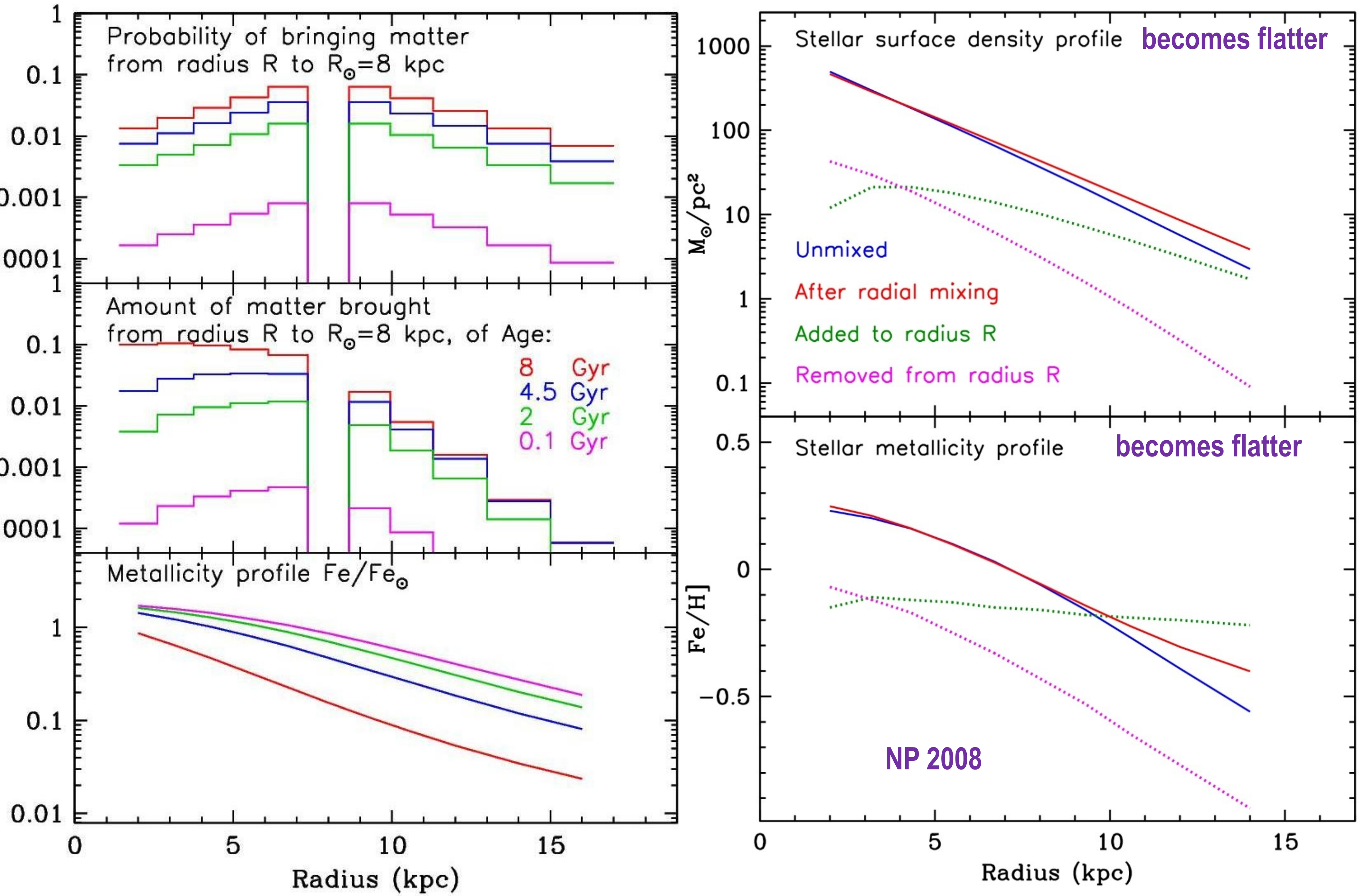
z 19.39

Wise et al. 2011

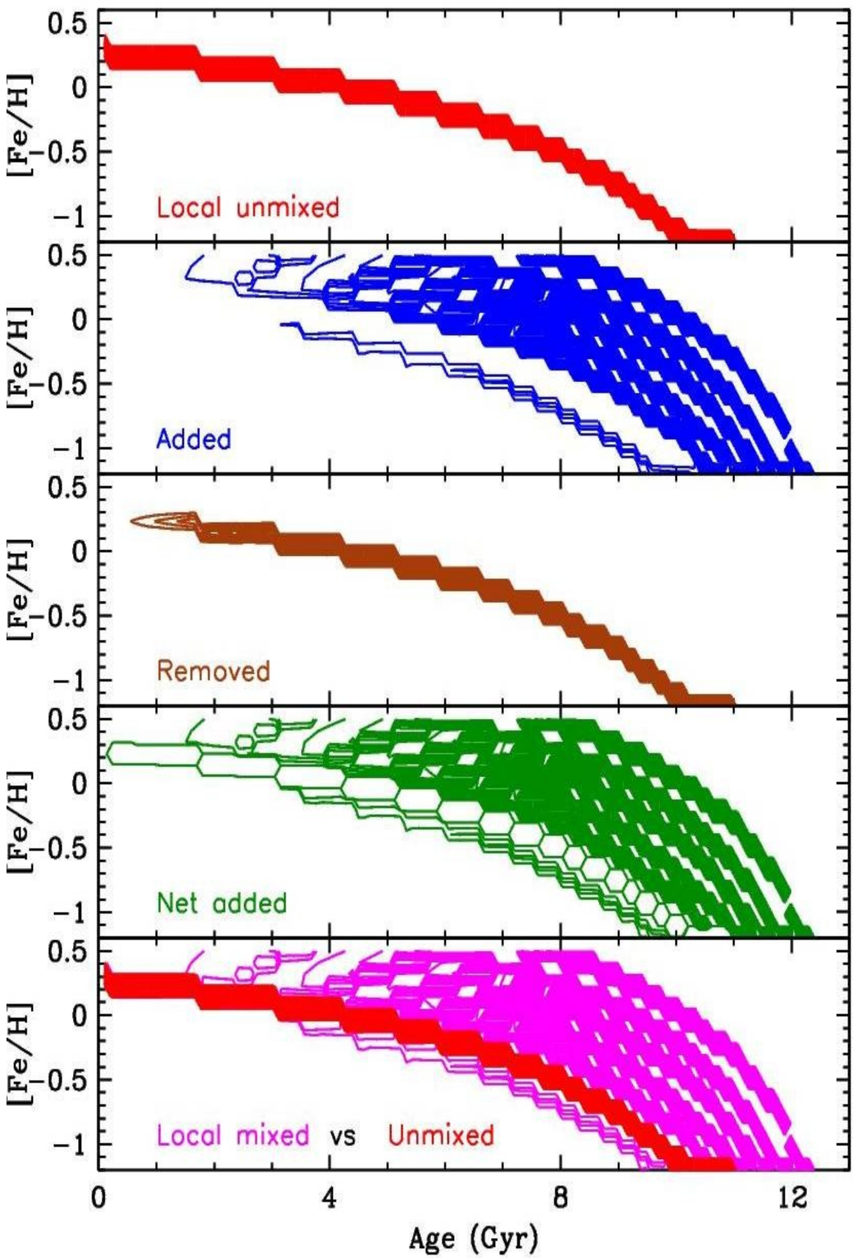


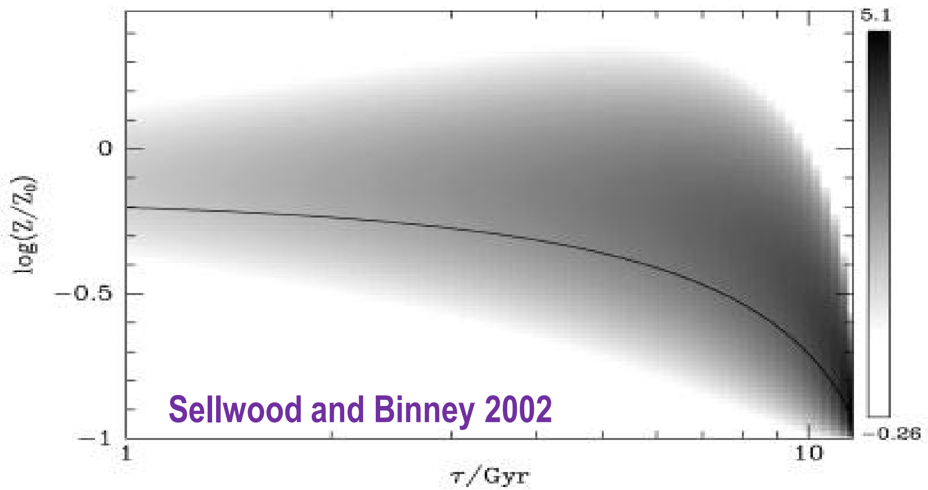

Infall
Fountain
Gas flows
Radial inflow
Radial mixing
Minor merger
Disk heating
Star motions

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 alter the average local age-metallicity relation

It also modifies the stellar metallicity distribuition (*Schoenrich and Binney 2009*)

It renders classical methods of dating the disk (***nucleocosmochronology, white dwarf cooling***) inapplicable !

Conclusions

Hierarchical galaxy formation offers a much richer (and complex) framework for chemical evolution

Elements produced in sites evolving on different timescales should display variations in abundance ratios,, even if the ISM was locally well mixed.