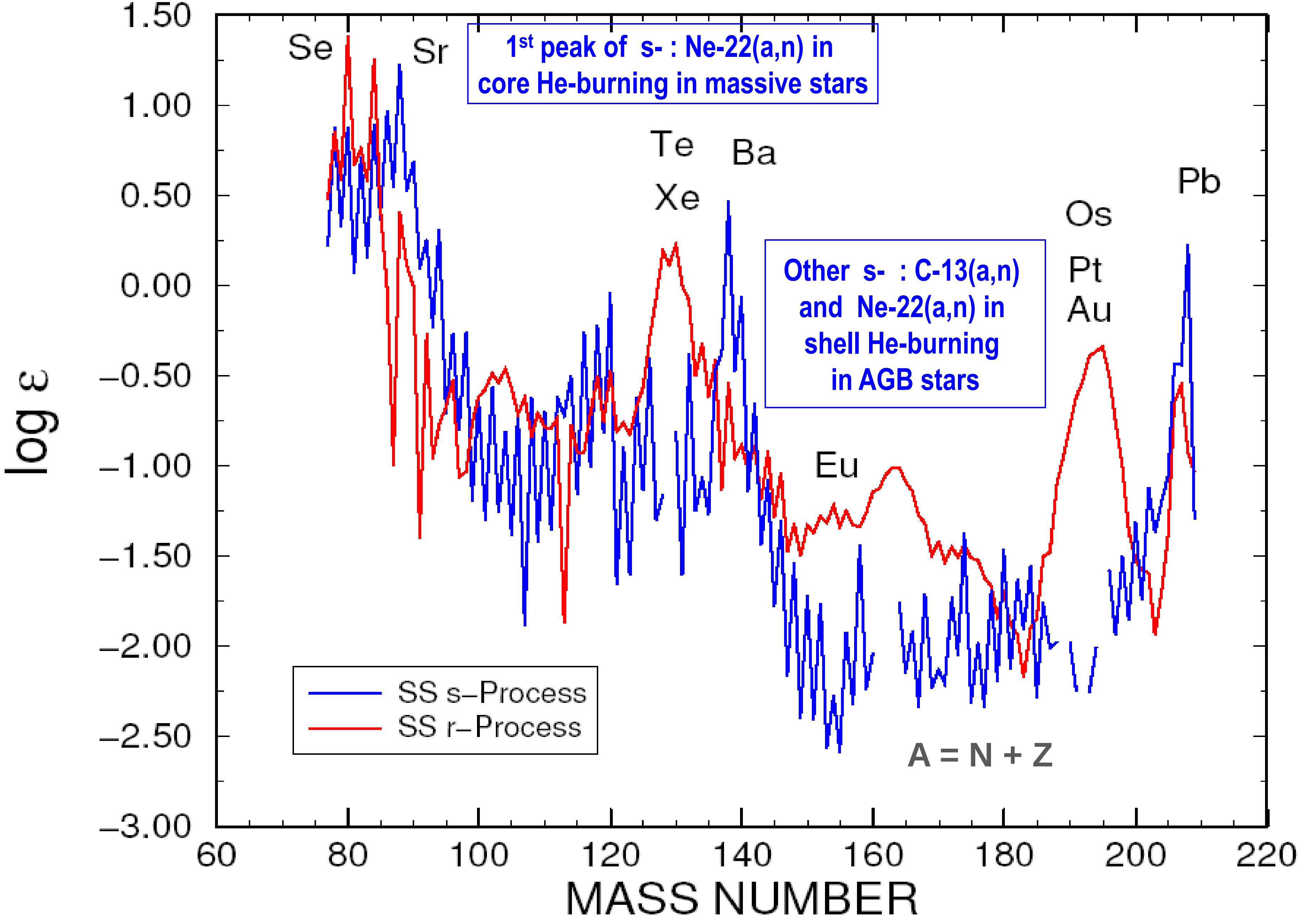
GALACTIC CHEMICAL EVOLUTION

Part III : The Milky Way

C: The Heavier than Fe Elements

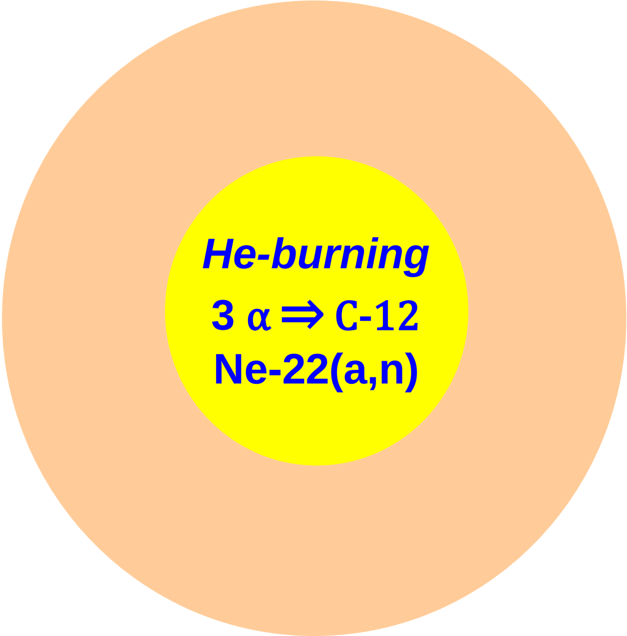
Abundances of heavier than Fe nuclei



1st peak of s- : Ne-22(a,n) in core He-burning in massive stars

Other s- : C-13(a,n) and Ne-22(a,n) in shell He-burning in AGB stars

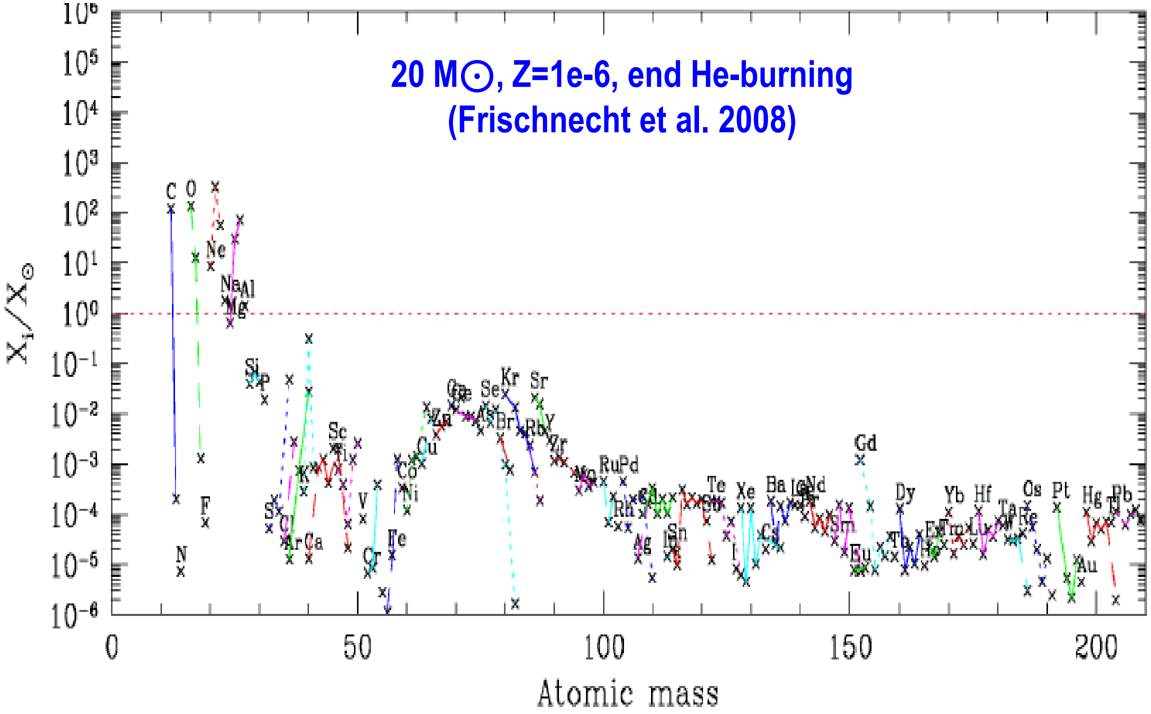
A = N + Z



He-burning

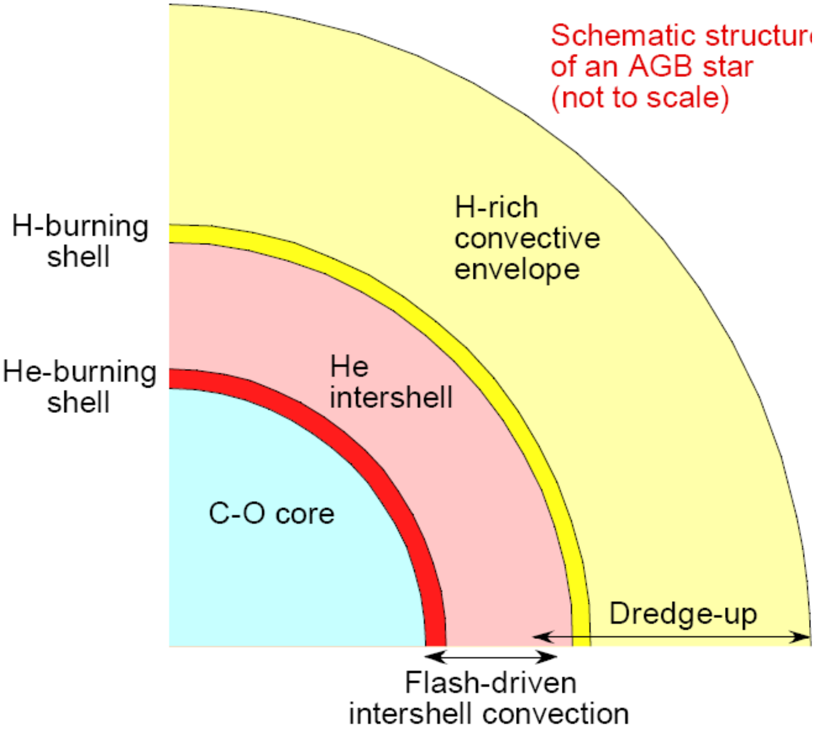
3 α ⇒ C-12

Ne-22(a,n)

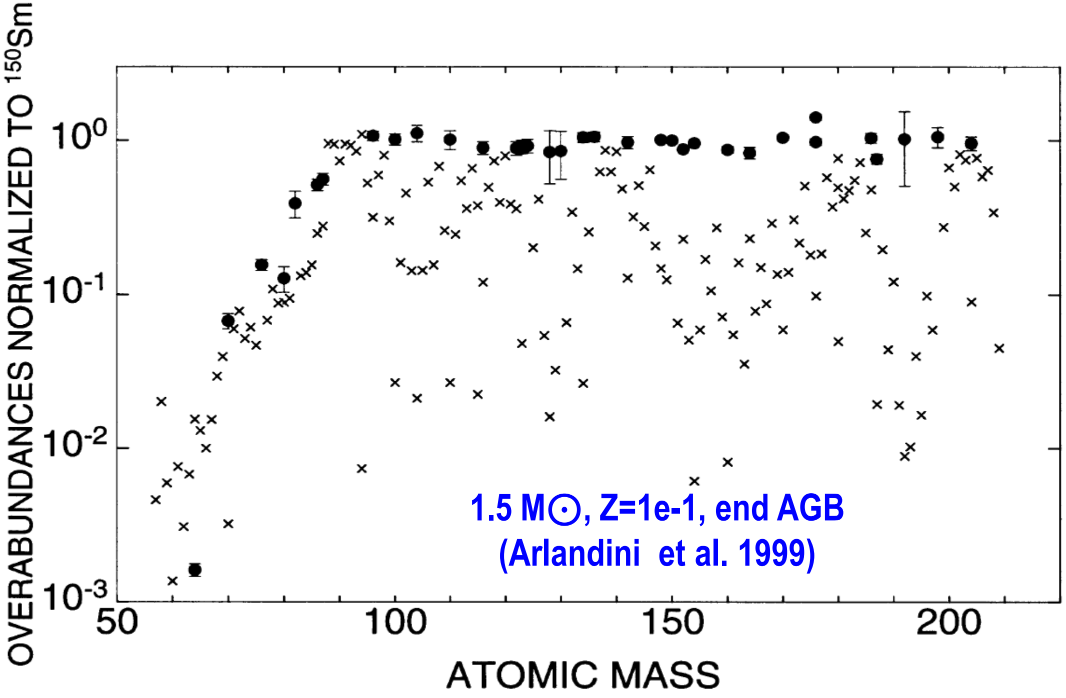


20 M⊙, Z=1e-6, end He-burning

(Frischnecht et al. 2008)



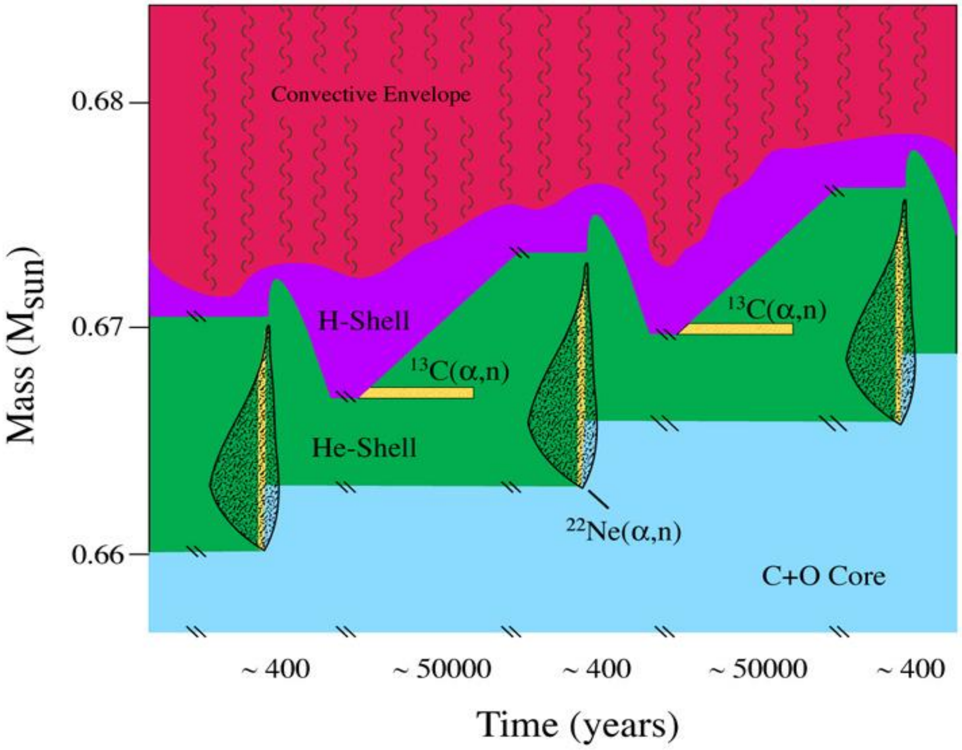
Schematic structure of an AGB star (not to scale)



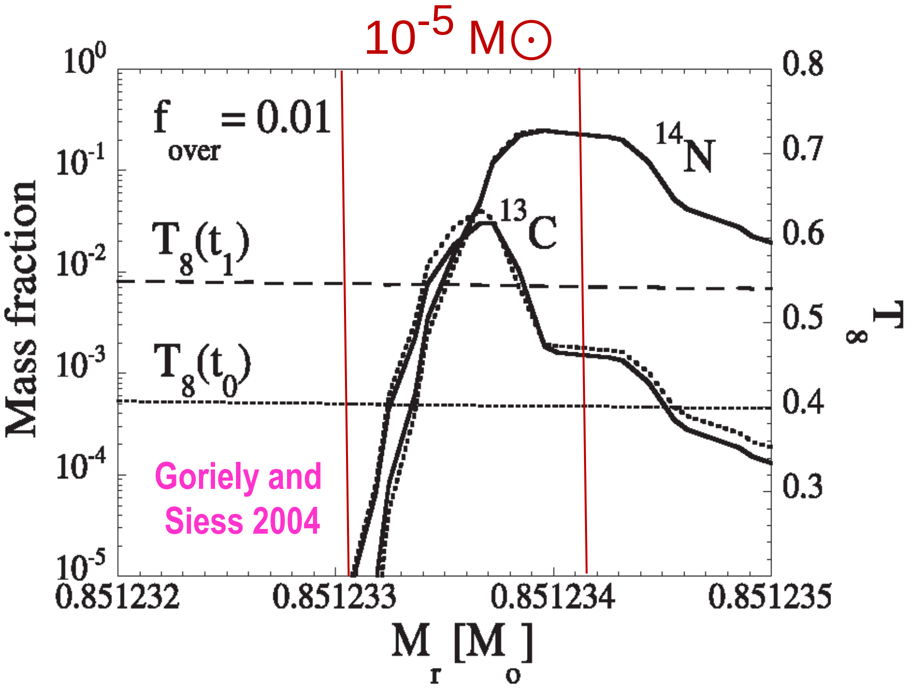
1.5 M⊙, Z=1e-1, end AGB

(Arlandini et al. 1999)

S- process in Low Mass (<2 M⊙) thermally pulsing AGB stars: neutrons from Radiative burning of C-13 (low neutron densities, for Main s-component) and convective burning of Ne-22 (higher neutron densities, for some branching points)



No consistent model for the formation of the C13 "pocket"

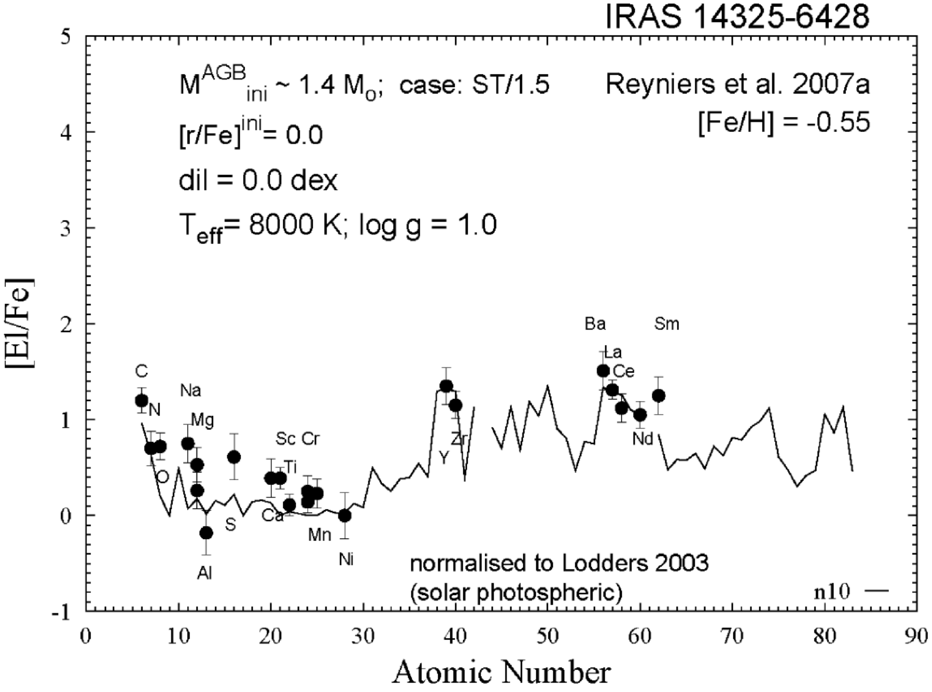


Goriely and Siess 2004

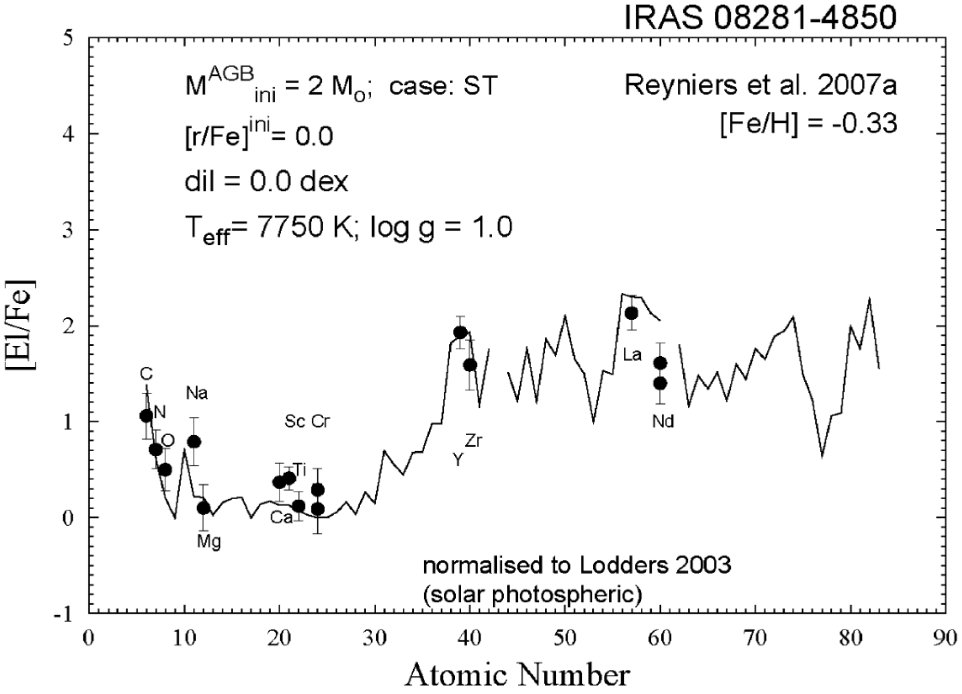
C13 created either "by hand" or by C12(p,γ)N13(β)C13

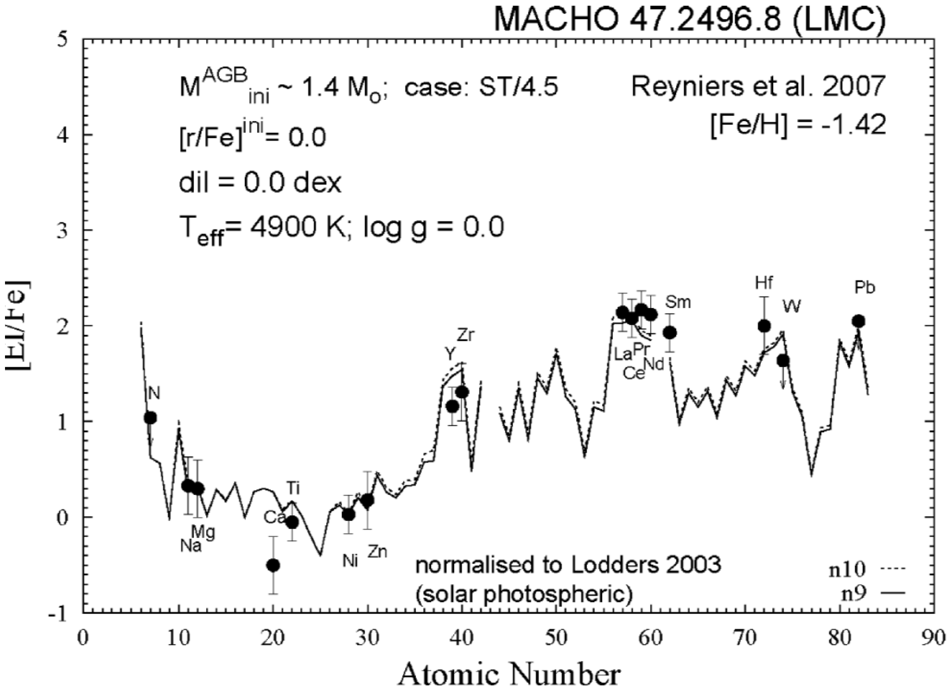
Protons must be introduced from the H shell, in He-zones (rich in C12), but HOW ?

Convective overshoot ? Rotational mixing ? Gravity waves ?



Parametrized models
of the s-process
in that site
reproduce succesfully
several observables



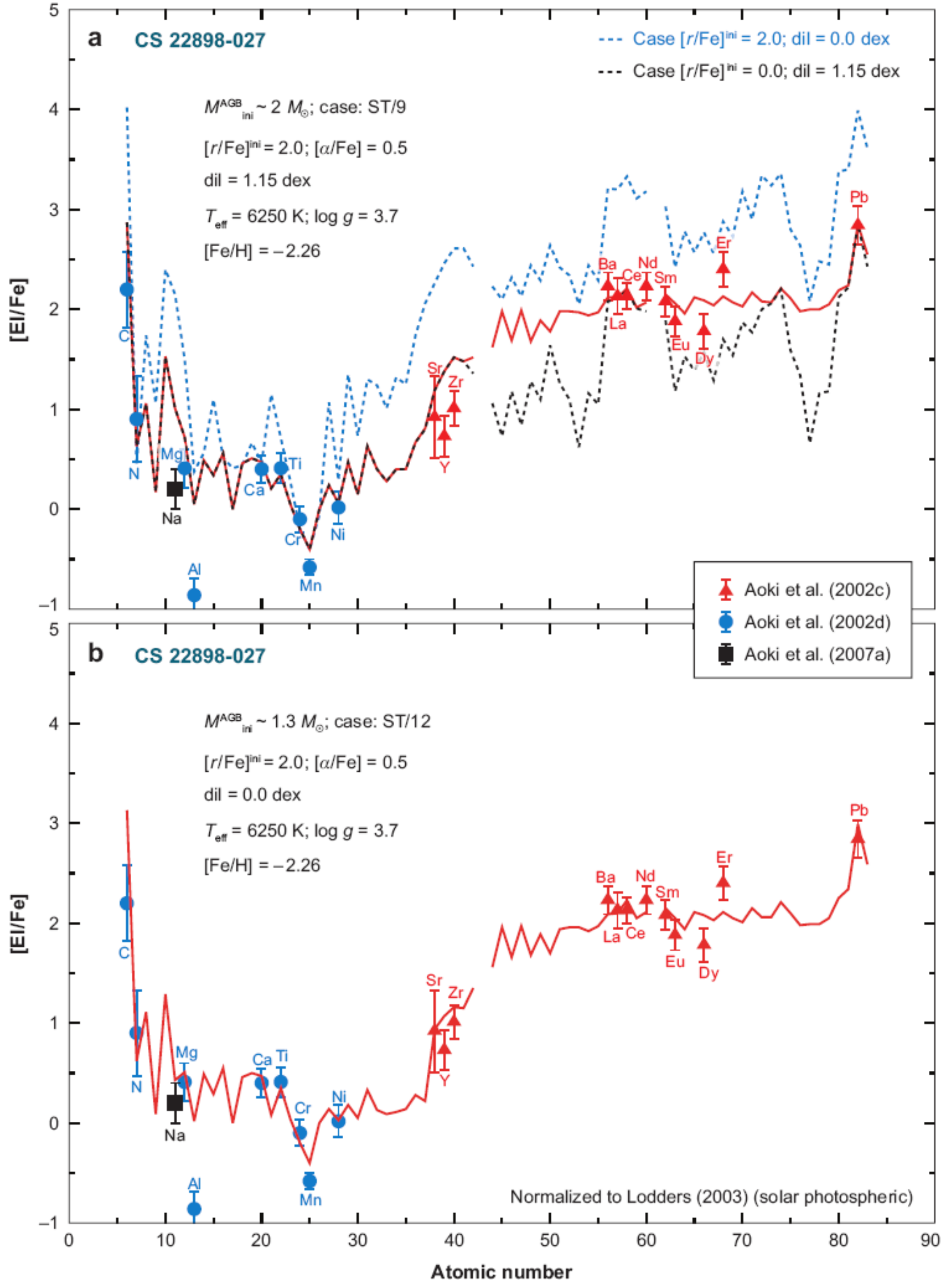


S-nuclei: in principle, *secondary*
(produced by n-captures on
abundant Fe-56 nuclei)

However, 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)

Somewhat counterintuitively,
the s-process efficiency
may be higher at low metallicities,
producing e.g. Pb-208
(Clayton 1988)

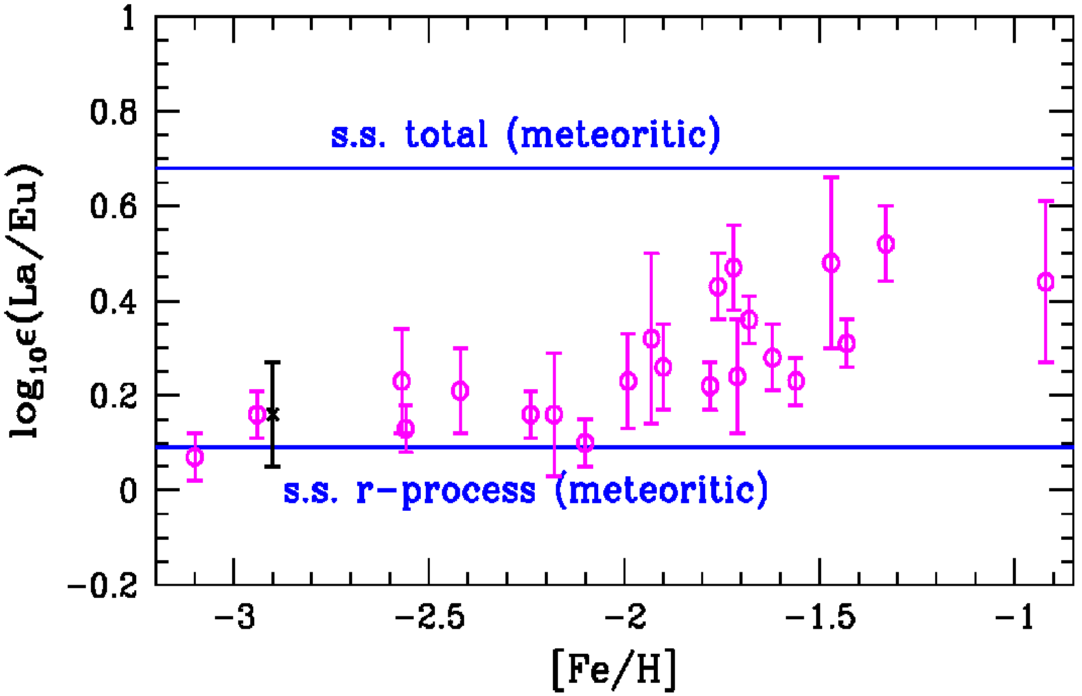


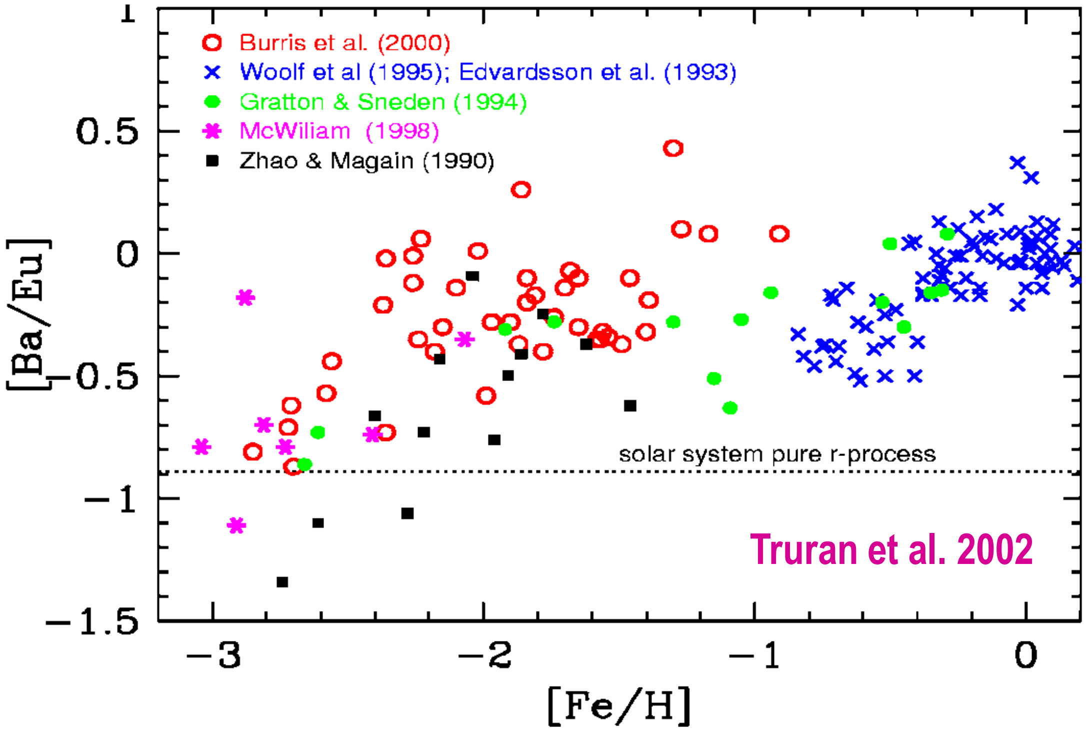
As we go back in time (low Z), the [s/Fe] ratio should decrease,

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

but 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)

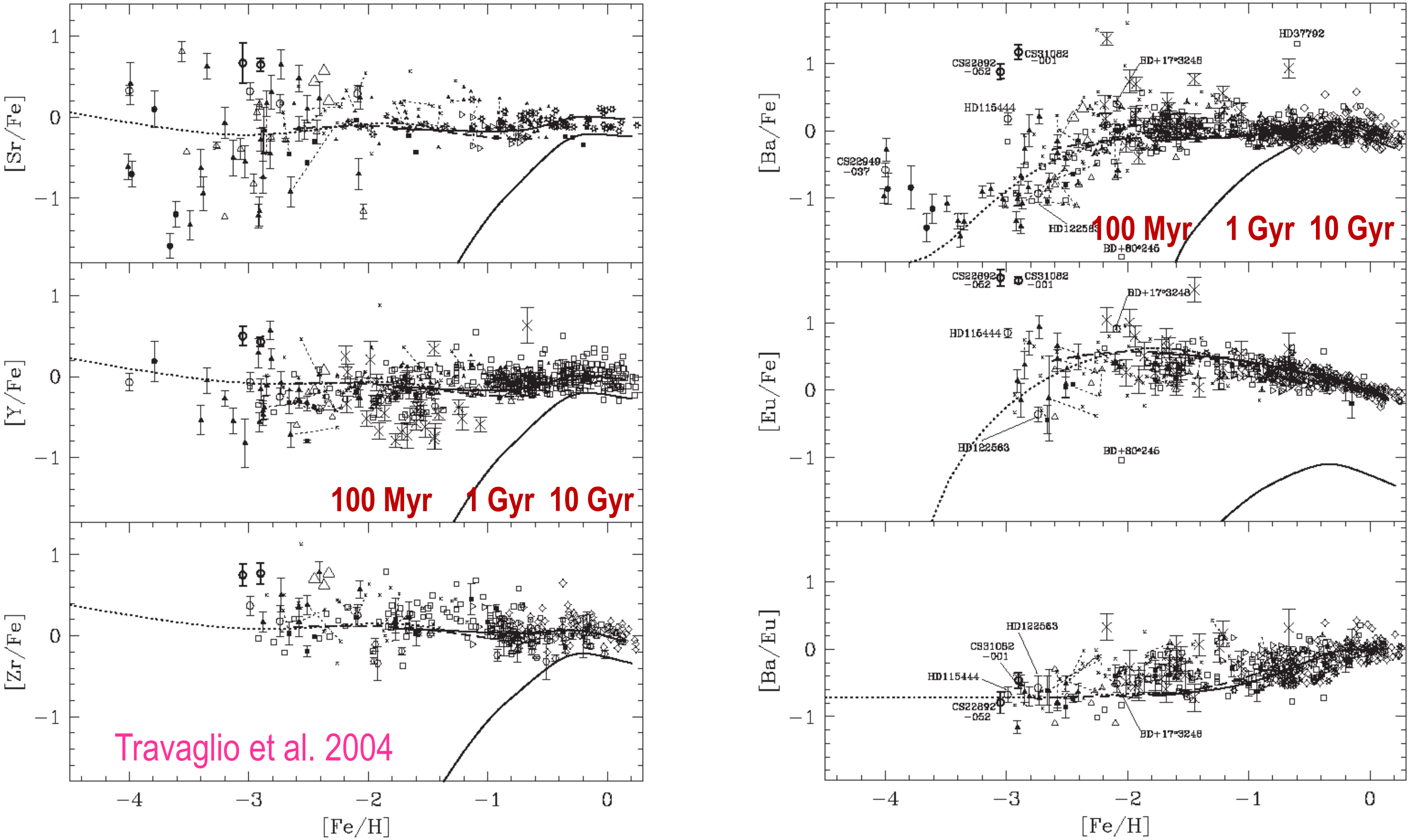




Truran et al. 2002

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

Hints for source lifetimes / yields

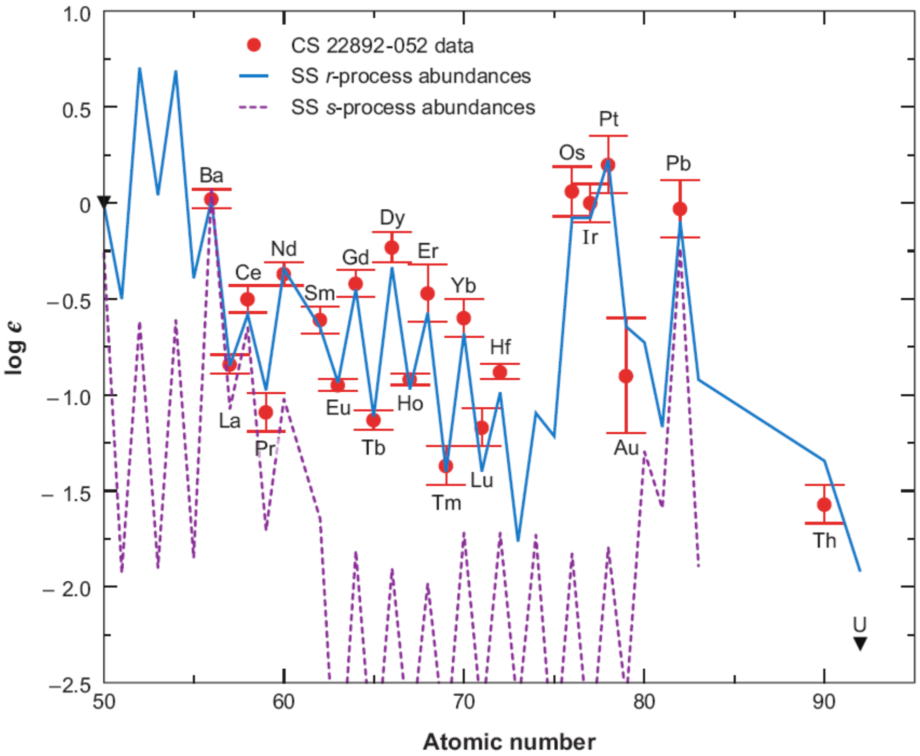


100 Myr 1 Gyr 10 Gyr

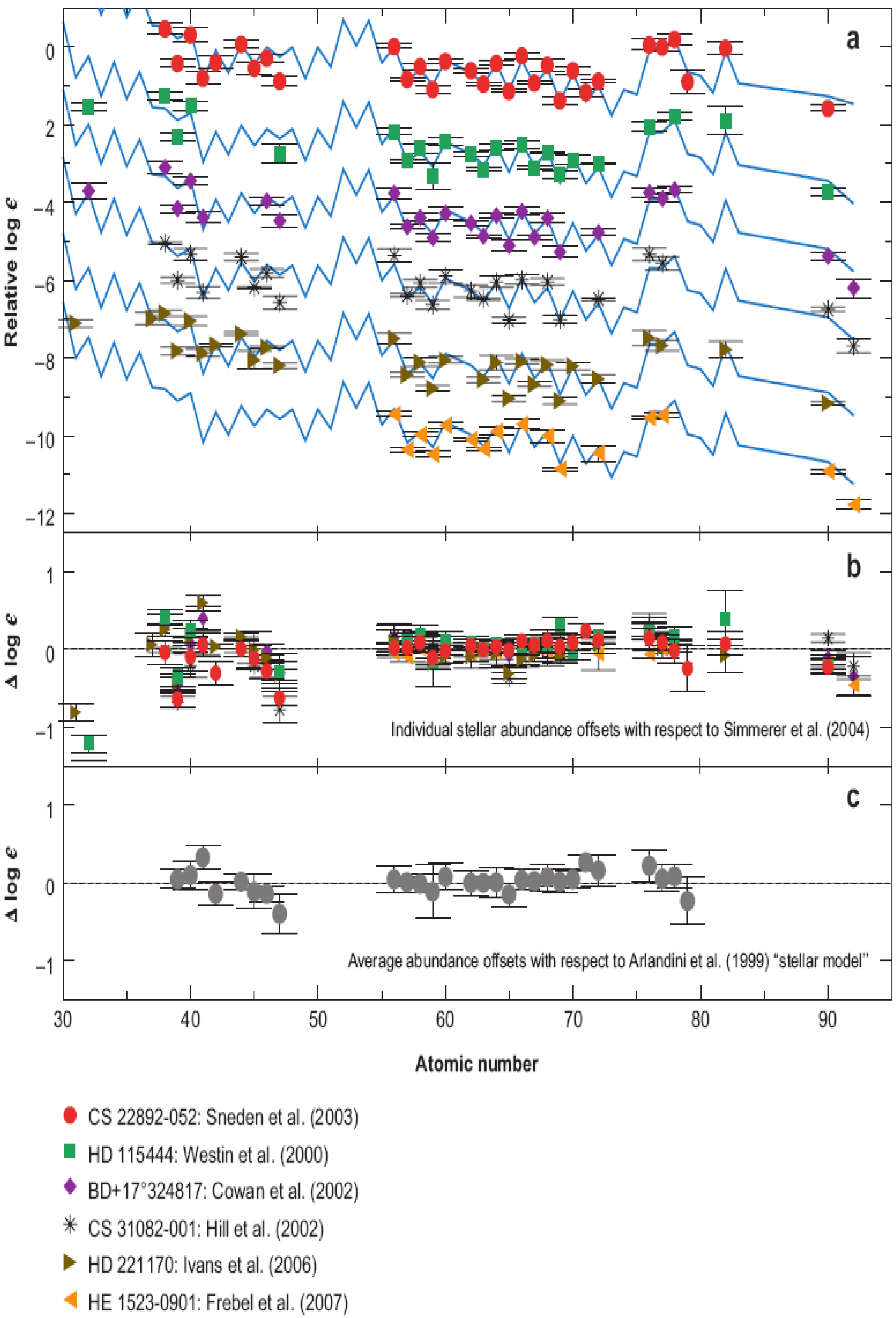
100 Myr 1 Gyr 10 Gyr

Travaglio et al. 2004

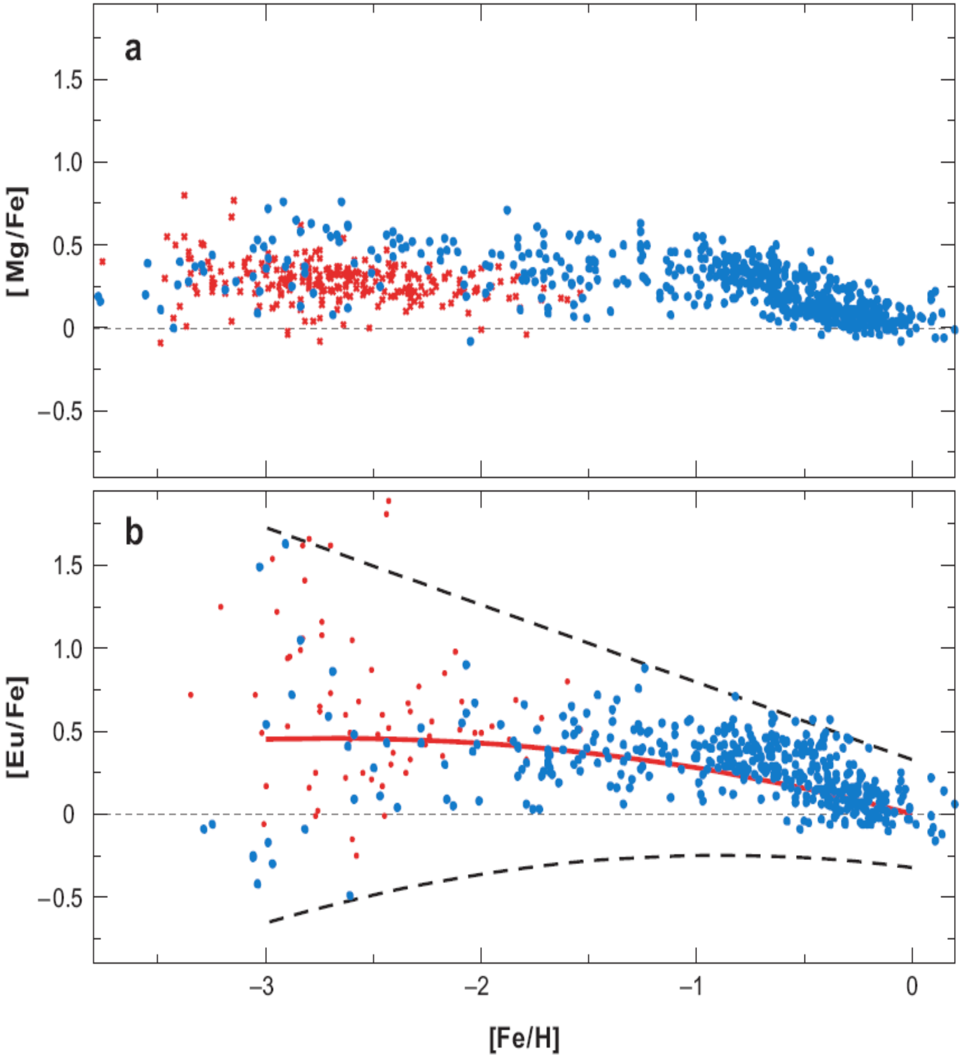
If low mass stars (<2 M⊙) are indeed at the origin of the
main s-process (2nd and 3d peaks) ,
how to explain the early appearance of the s-elements ?



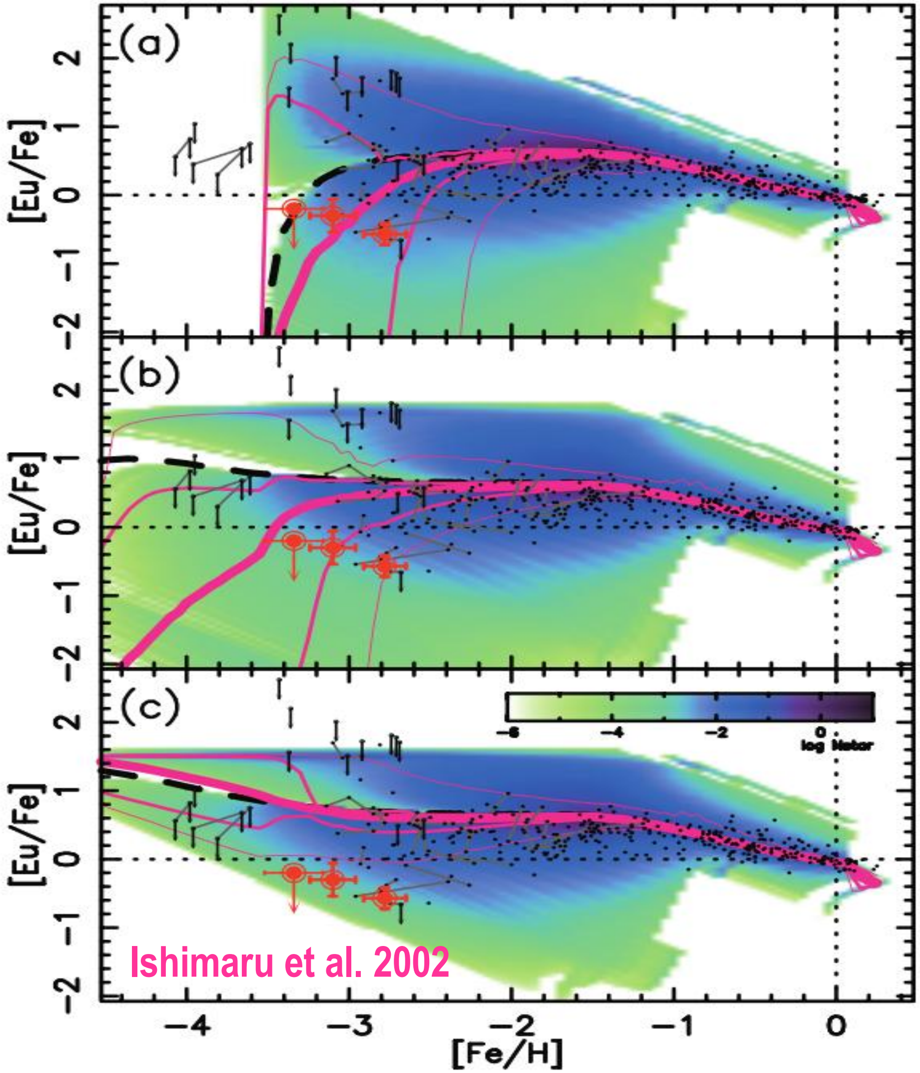
Contrary to s-process,
the r-process appears
(from observations)
to be extremely robust



BUT, contrary to C-Fe peak elements,
heavier than Fe elements
(both s- and r-) show dispersion
increasing at low metallicities…



Fo r-elements, this could imply
that they are produced
ONLY in stars of a limited
mass range (say, 8-10 $M_\odot$ or 25-30 $M_\odot$)



Ishimaru et al. 2002

Summary for heavy elements

S-elements

Main site (AGB) / conditions (shell He-burning*)* *identified*
Neutron source [C13(a,n)] identified BUT *put by hand*
Yields y(M,Z) NOT available

Secondary nature of process blurred by:
-large ages of sites (many 10^8 yr)
- metallicity dependence of: n-source, n-poison, S-seed

Comparison to observations:
OK for individual stars, Not OK for evolution

R-elements

Main site (CCSN) identified (?) BUT conditions (ν-wind?*)* *not identified*
Yields y(M,Z) NOT available

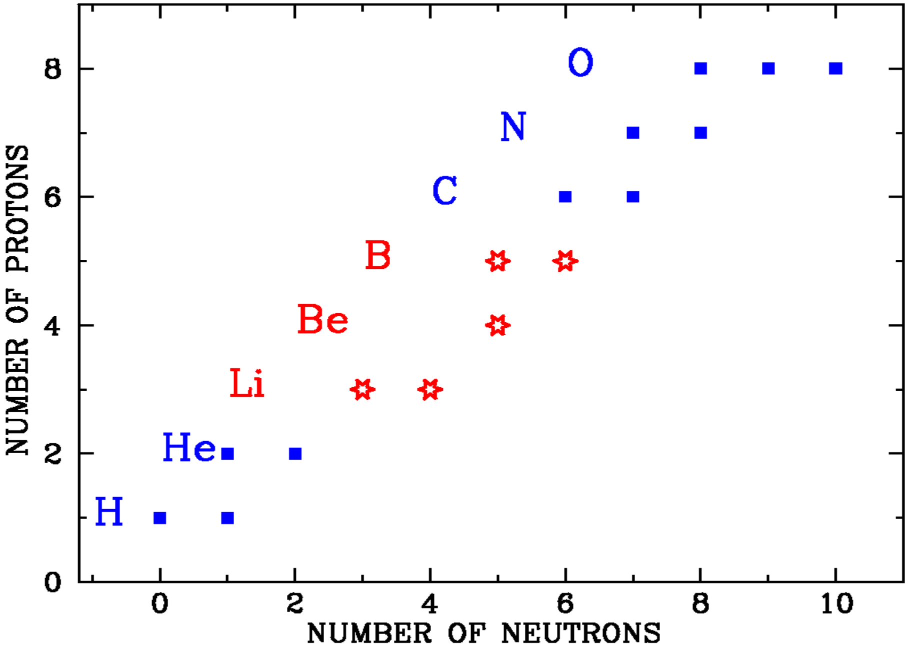
Primary process, but observed scatter R/Fe *poorly understood*

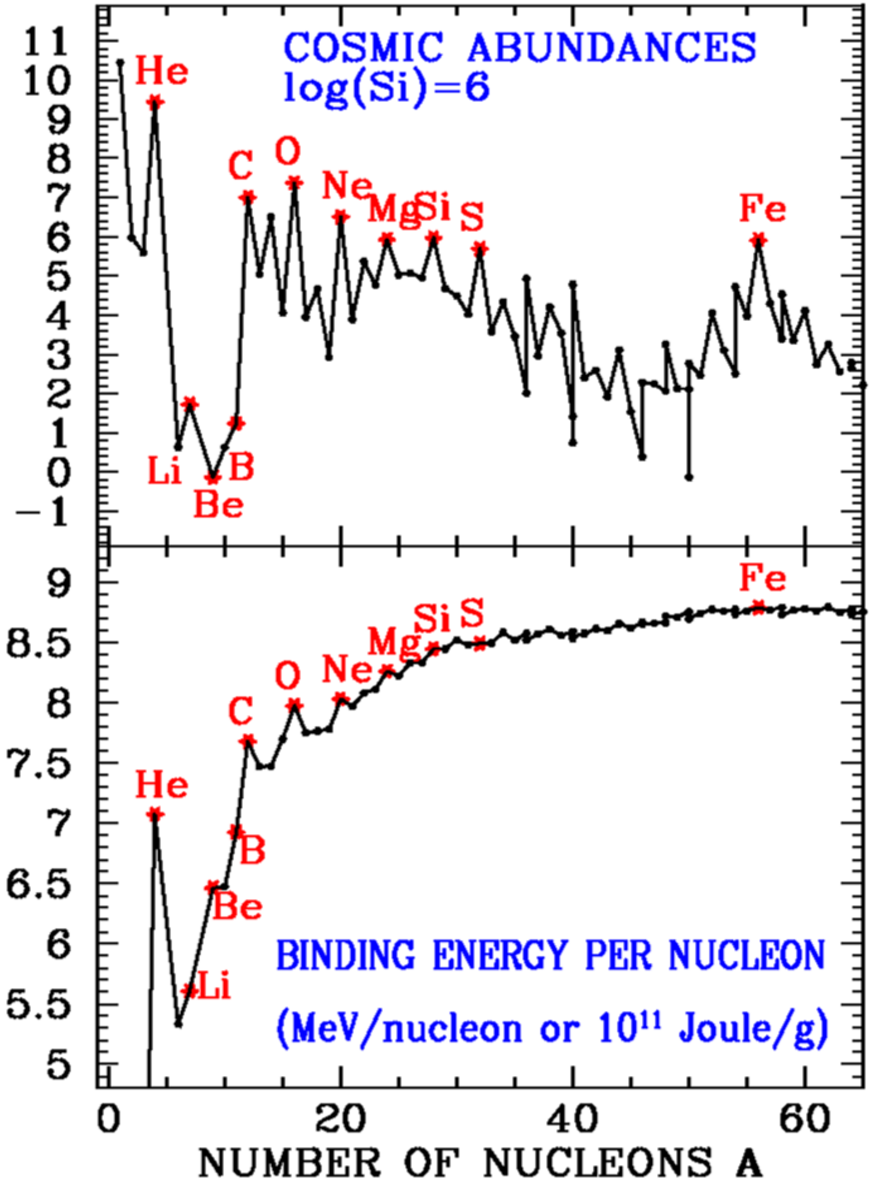
GALACTIC CHEMICAL EVOLUTION

Part III : The Milky Way

D: The Light Elements

The light elements Li Be B (Li6, Li7, Be9, B10, B11)

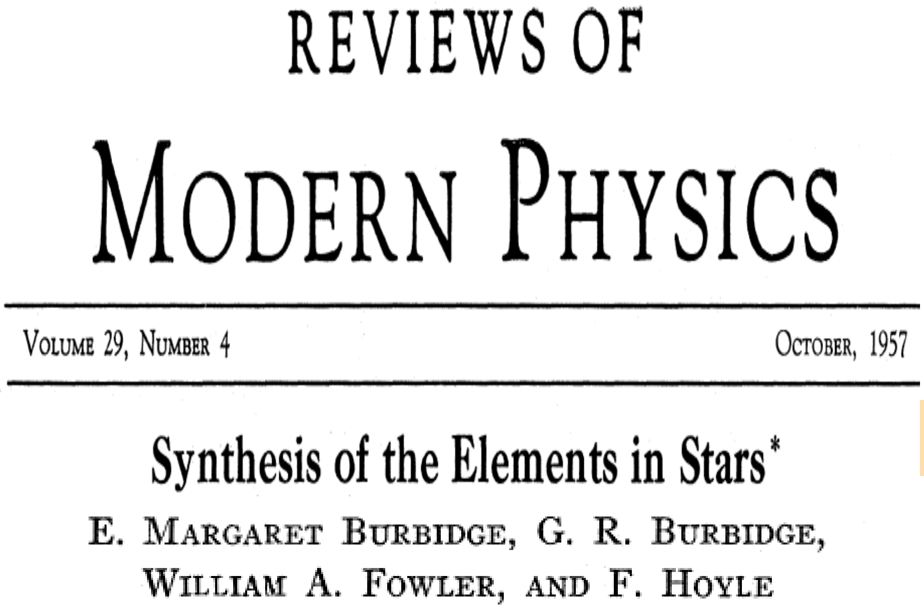




The most fragile stable isotopes in nature
(after D and He-3)

Destroyed in stellar interiors

T(burn) = 2 MK for Li (1.5 for Li6)
2.5 MK for Be
3 MK for B

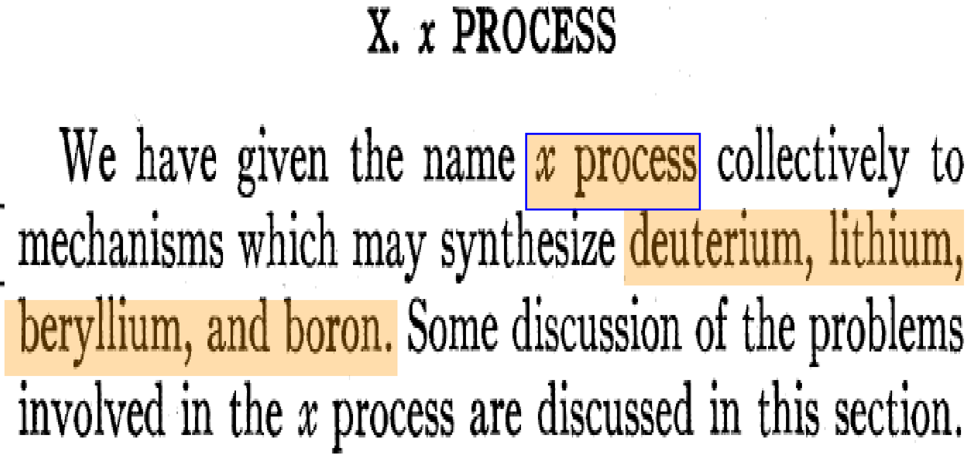


REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

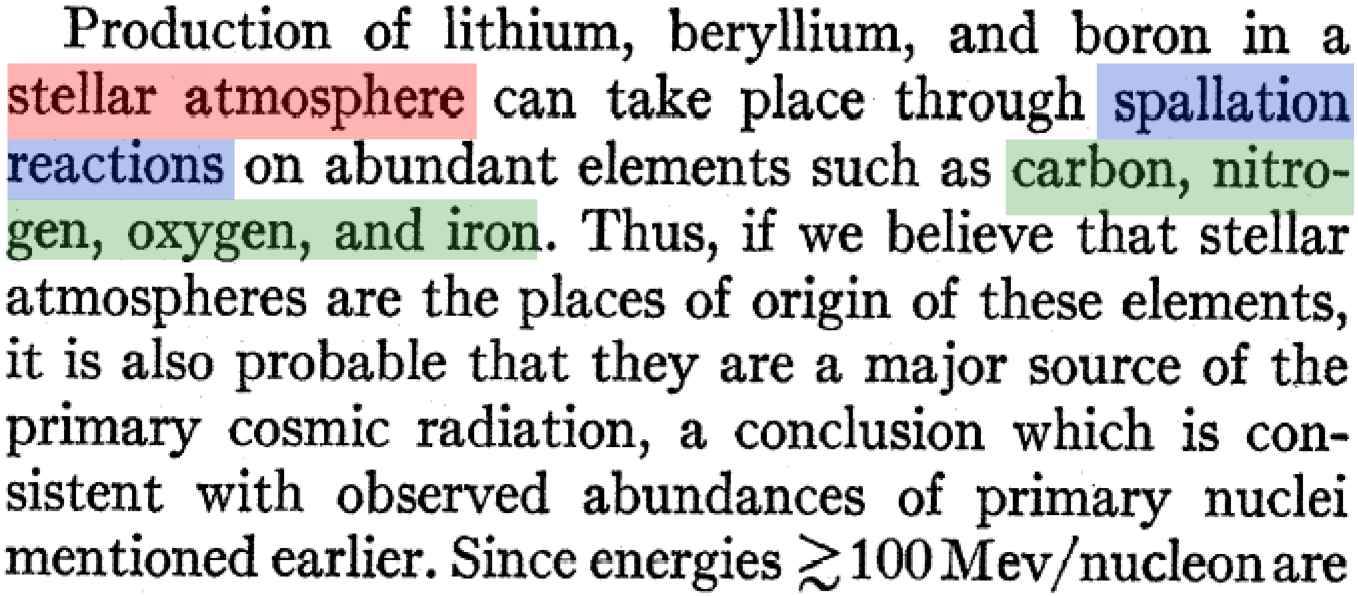
Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE,
WILLIAM A. FOWLER, AND F. HOYLE



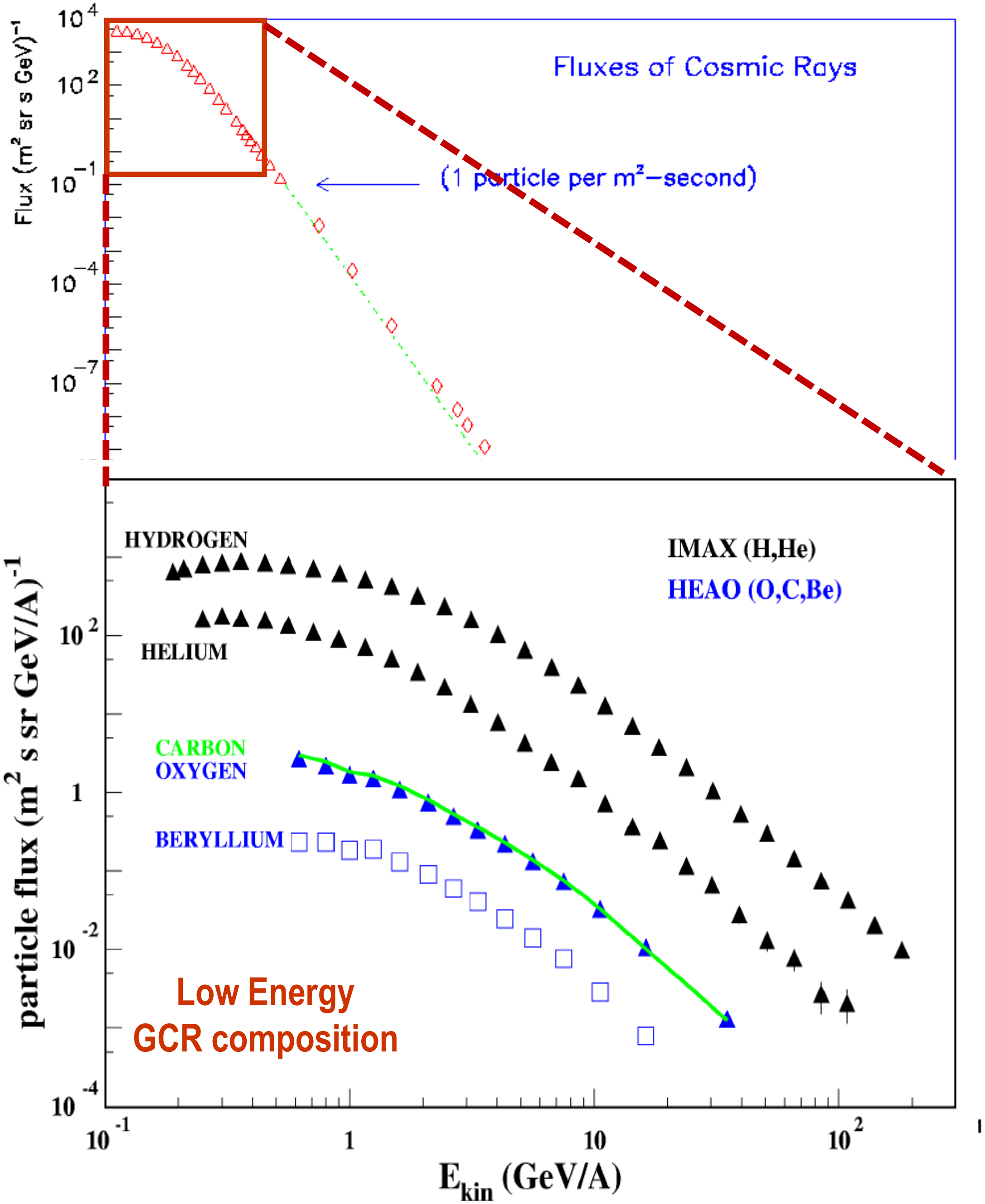
X. *x* PROCESS

We have given the name *x* process collectively to mechanisms which may synthesize deuterium, lithium, beryllium, and boron. Some discussion of the problems involved in the *x* process are discussed in this section.



Production of lithium, beryllium, and boron in a stellar atmosphere can take place through spallation reactions on abundant elements such as carbon, nitrogen, oxygen, and iron. Thus, if we believe that stellar atmospheres are the places of origin of these elements, it is also probable that they are a major source of the primary cosmic radiation, a conclusion which is consistent with observed abundances of primary nuclei mentioned earlier. Since energies $\gtrsim 100$ Mev/nucleon are

Galactic Cosmic Rays (GCR)



Low Energy
GCR composition

Local GCR Flux: 10 p/cm^2/s

GCR Energy density: 1 eV/cm^3

GCR particle density:10^{-9} particles/cm^3

(Particle density ratio GCR/ISM ~ 10^{-9})

Escape (confinement) time: ~10^7 yr

GCR Energetics in Milky Way:

Power(GCR) ~10^{41} erg/s

Power(Supernovae): ~10^{42} erg/s

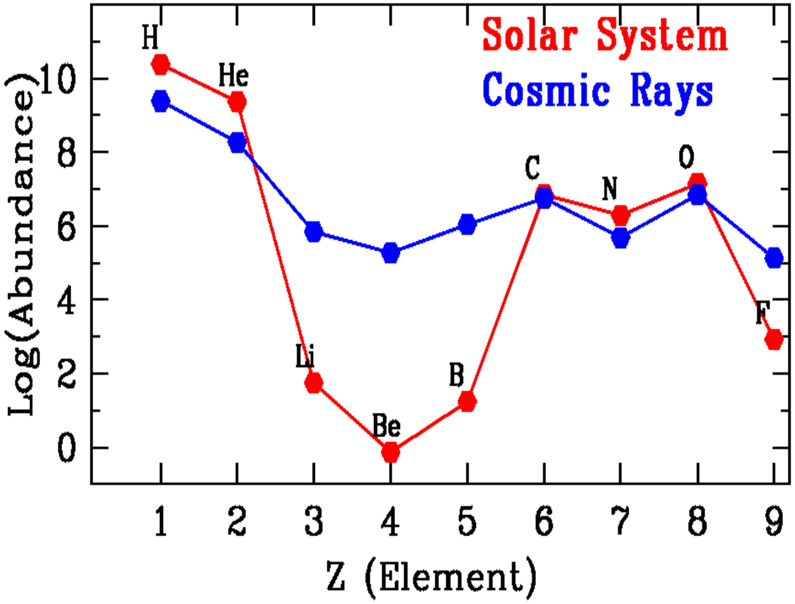
(~3 SN /100 yr @ E_{KIN}~10^{51} erg)

OK if E(GCR) ~ 10 % E_{KIN}(SN)

GCR composition is heavily
enriched in Li, Be, B
(a factor ~10^6 for Be and B)

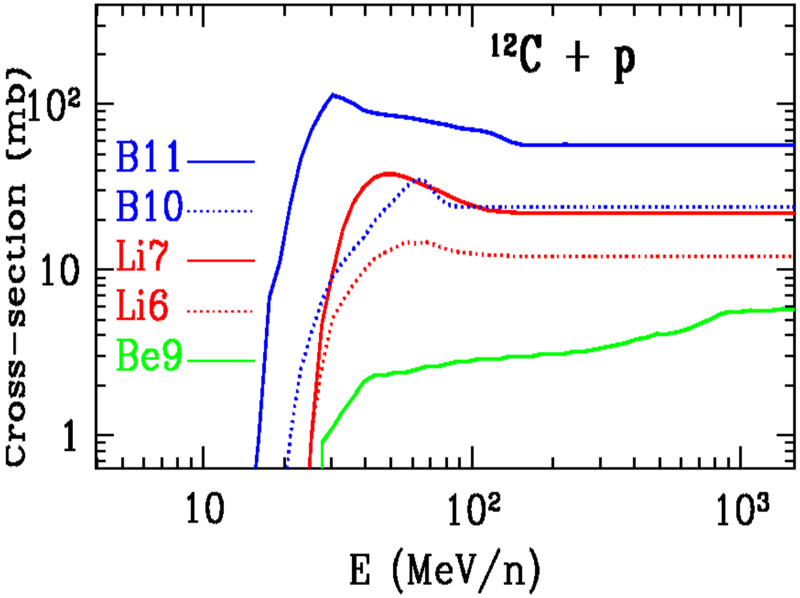
Solar composition: X(Li) > X(B) > X (Be)

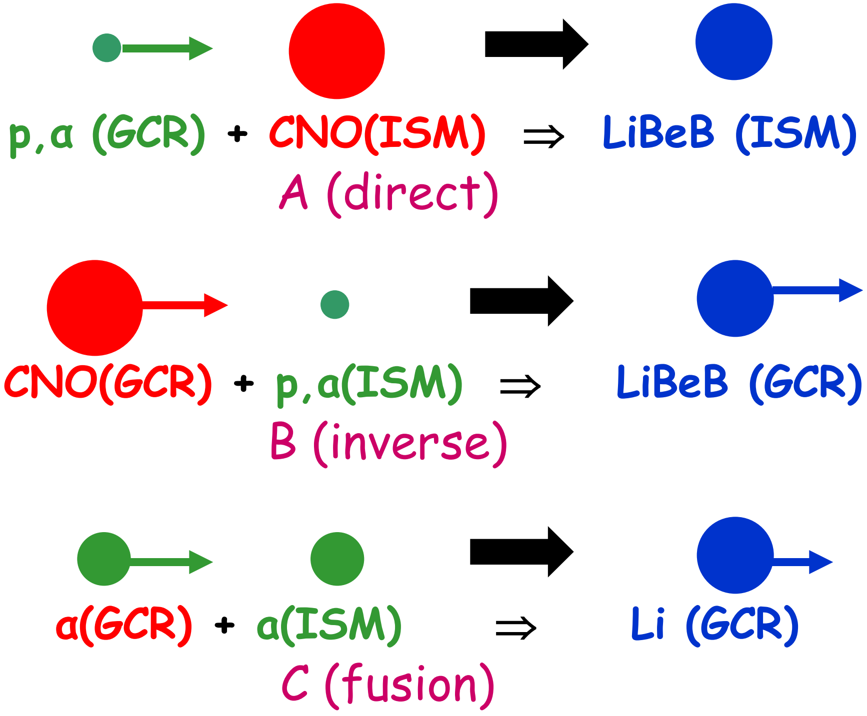
GCR composition: X(B) > X(Li) > X(Be)



Same order as spallation cross sections
of CNO ⇒ LiBeB: σ(B) > σ(Li) > σ(Be)

LiBeB is produced by spallation of CNO
as GCR propagate in the Galaxy
(*Reeves, Fowler, Hoyle 1970*)





p,α (GCR) + CNO(ISM) ⇒ LiBeB (ISM)

A (direct)

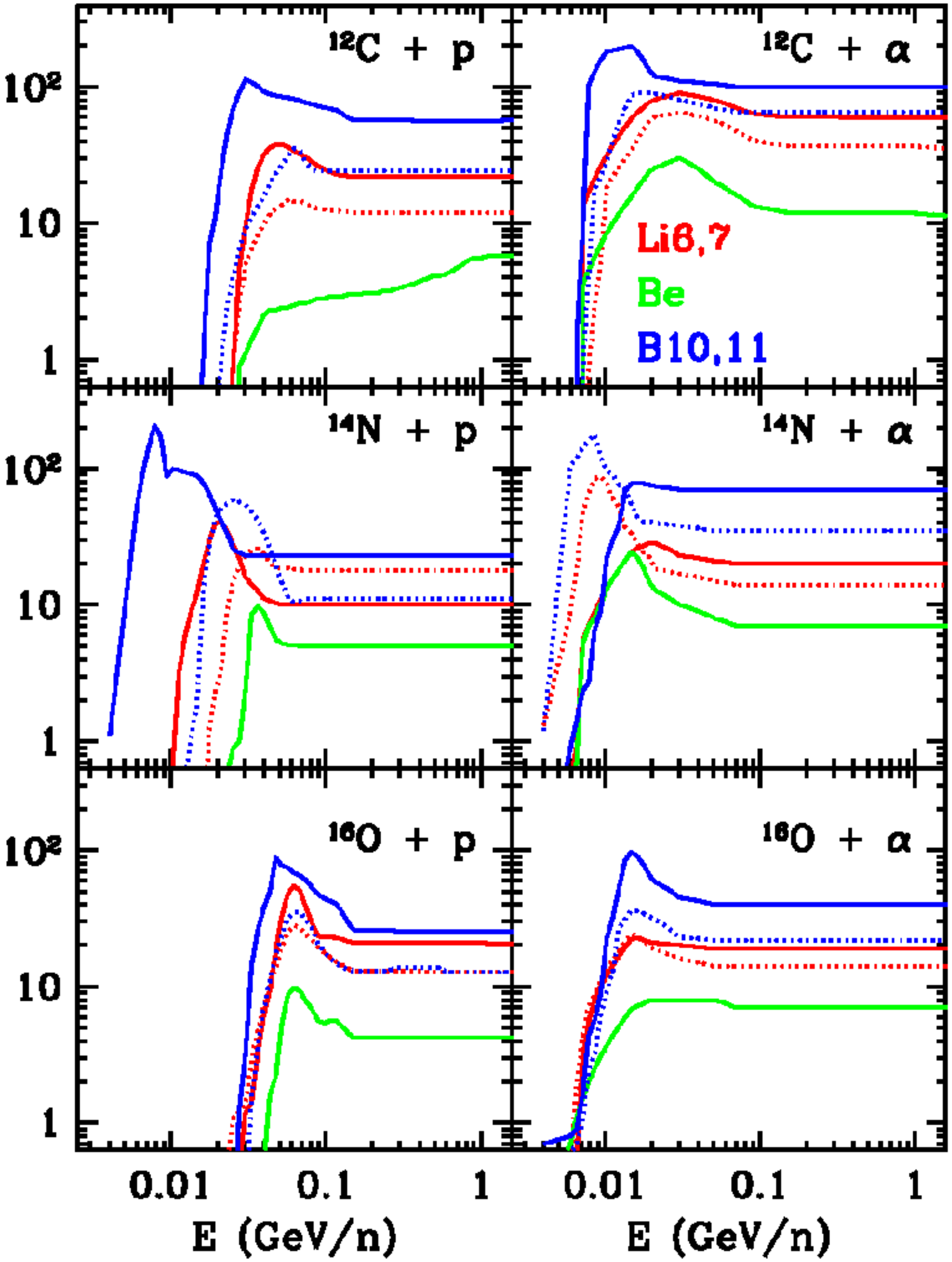
CNO(GCR) + p,α(ISM) ⇒ LiBeB (GCR)

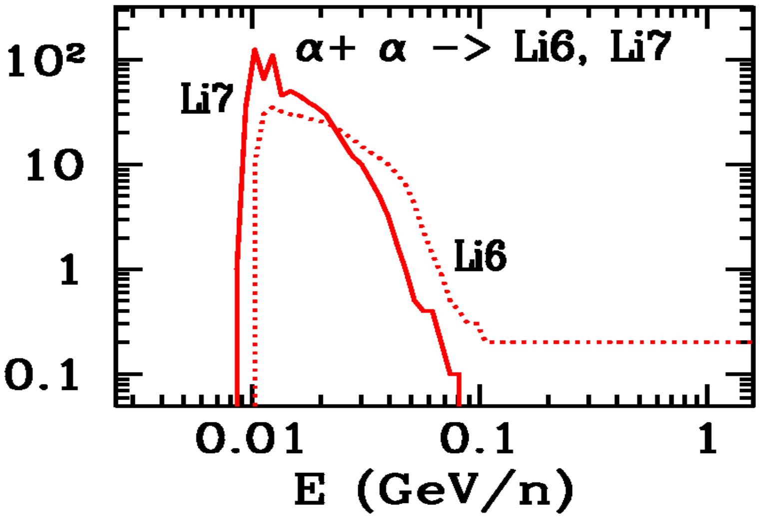
B (inverse)

α(GCR) + α(ISM) ⇒ Li (GCR)

C (fusion)

Cross sections (mb) of p,α + CNO ⇒ LiBeB





Solar abundances of Li Be B and production by Galactic Cosmic Rays (GCR)

Solar $Y_{Be} = N_{Be} / N_H \sim 3\ 10^{-11}$

Solar $Y_{CNO} = N_{CNO} / N_H \sim 10^{-3}$

Flux p cm^{-2} s^{-1}	Cross-section cm^2	Abundance

$$\frac{dY_L}{dt} = \Phi_{p\alpha(GCR)}\ \sigma_{p\alpha+CNO}\ Y_{CNO(ISM)} + \Phi_{CNO(GCR)}\ \sigma_{p\alpha+CNO}\ Y_{p\alpha(ISM)} + \Phi_{\alpha(GCR)}\ \sigma_{\alpha+\alpha}\ Y_{\alpha(ISM)}$$

A (direct)

B (inverse)

C (fusion) *Li only*

$\Phi_{p\alpha(GCR)} \sim 10$ p/cm^2/s

$\sigma_{p\alpha+CNO \Rightarrow Be} \sim 10$ mb (10^{-26} cm^2)

$Y_{CNO(ISM)} \sim 0.5\ Y_{CNO(\odot)}$

$\Delta t \sim 10^{10}$ ys

$\Rightarrow Y_{Be} \sim 2\ 10^{-11}$

~OK for

Li6, Be, B10, B11

(*Reeves, Fowler, Hoyle 1970*)

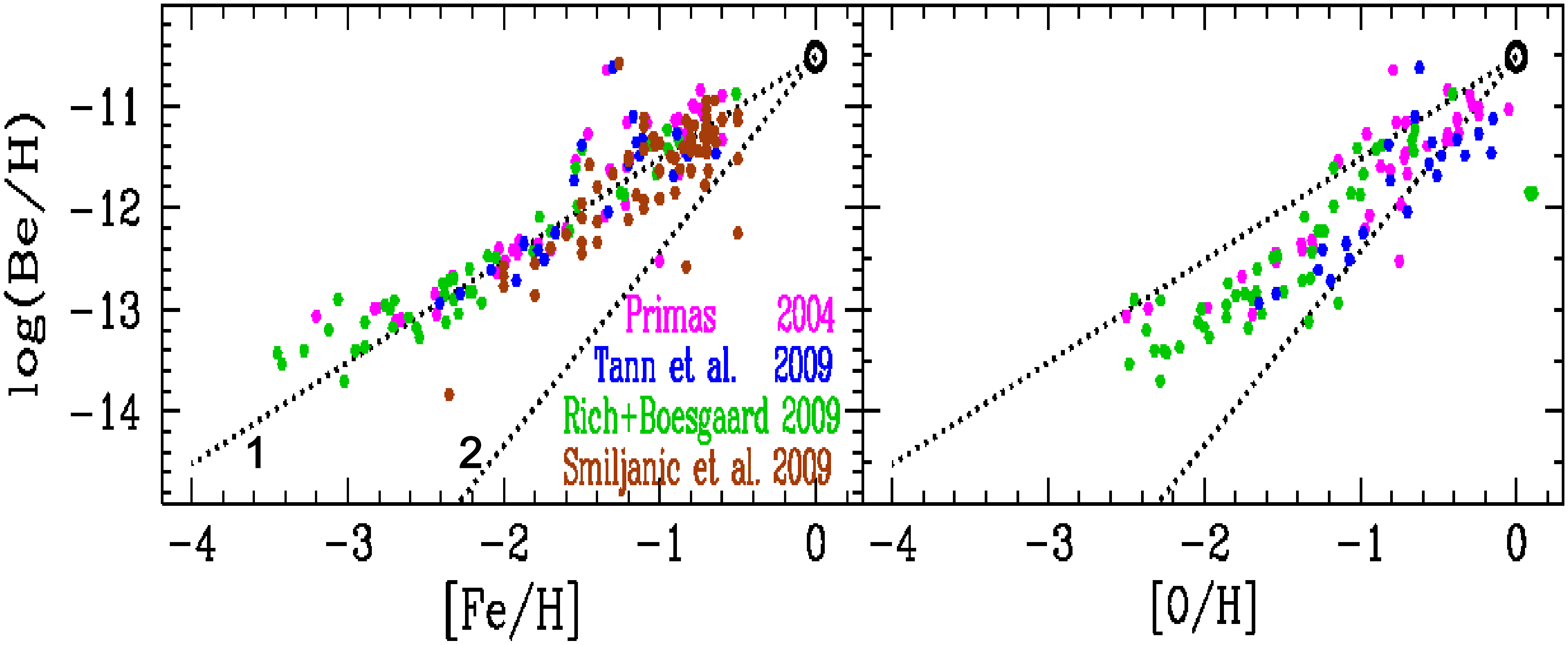
BUT

(*Meneguzzi, Audouze and Reeves 1971*)

"Standard" GCR Production	*Solar Values*
Li7/Li6 ~ 1.5	~ 12
B11/B10 ~ 2.5	~ 4
B/Be ~ 14	~ 23

Evolution of Be

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



Be abundance evolves (as expected, since it is not primordial)

BUT, it evolves exactly as Fe
(unexpected, since it is produced from CNO
and it should behave as secondary)

$$\Phi(GCR,t) \quad \propto \quad Y(GCR,t) \quad SN_{Rate}(t)$$

Flux Composition Rate(Supernova)

$SN_{Rate}(t)$: Cannot affect Be vs Fe behaviour (produces both Fe and GCR)

$Y_{pa}(GCR,t)$ ~Const. : Component A (direct) produces secondary LiBeB
Component C produces primary Li isotopes

$$Y_{CNO}(GCR,t) = ???$$

To account for observations, production rate should be **independent of metallicity**. How is it possible?

$$\frac{dY_L}{dt} = \Phi_{p\alpha(GCR)}\,\sigma_{p\alpha+CNO}\,Y_{CNO(ISM)} + \boxed{\Phi_{CNO(GCR)}}\,\sigma_{p\alpha+CNO}\,Y_{p\alpha(ISM)} + \Phi_{\alpha(GCR)}\,\sigma_{\alpha+\alpha}\,Y_{\alpha(ISM)}$$

A (direct) B (inverse) C (fusion)

Always secondary LiBeB

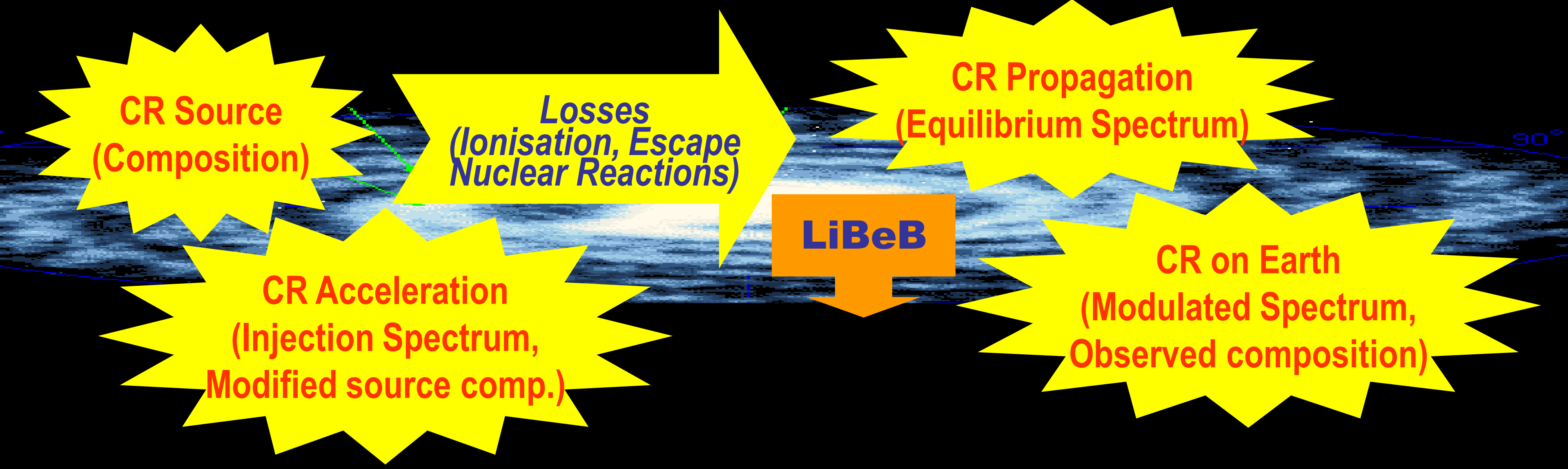
Secondary LiBeB
IF $Y_{CNO(GCR)} \sim Y_{CNO(ISM)}$

Always primary Li6,7
(Steigman and Walker 1992)

Primary LiBeB

IF $Y_{CNO(GCR)} \sim \text{const} \sim Y_{CNO\odot}$
(Duncan, Lemke and Lambert 1992)

Galactic Cosmic Ray Odyssey



CR Source
(Composition)

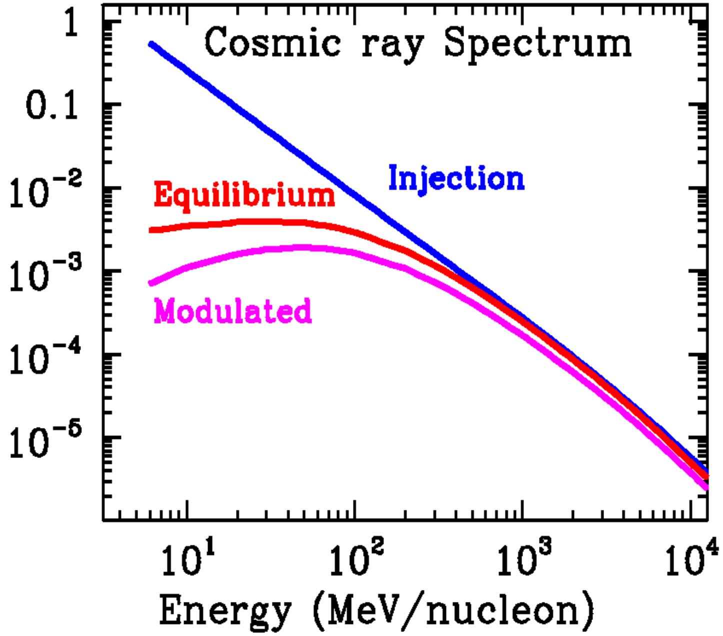
Losses
(Ionisation, Escape
Nuclear Reactions)

CR Propagation
(Equilibrium Spectrum)

LiBeB

CR Acceleration
(Injection Spectrum,
Modified source comp.)

CR on Earth
(Modulated Spectrum,
Observed composition)



Theory of GCR acceleration:
injection spectra : power laws
in total energy or momentum (per nucleon)

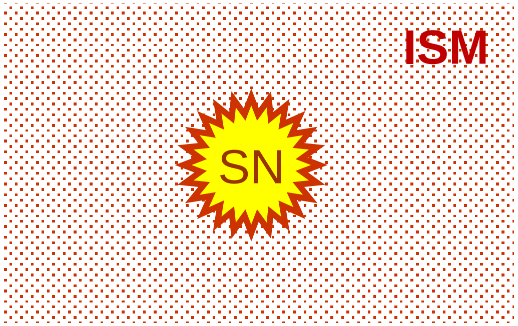
From theoretical *i*njection spectrum
the propagated (=equilibrium) one may be derived
under some assumptions (e.g. "*leaky box*" model)

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

1. Standard ISM accelerated by forward shock

$X(GCR) = X(ISM)$

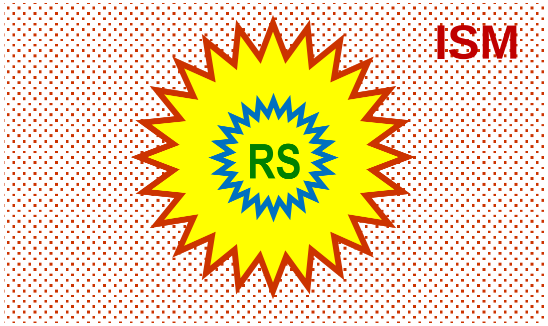
Secondary BeB



2. SN interior accelerated by reverse shock (RS)

$X(GCR) = X(SN)$

Primary BeB



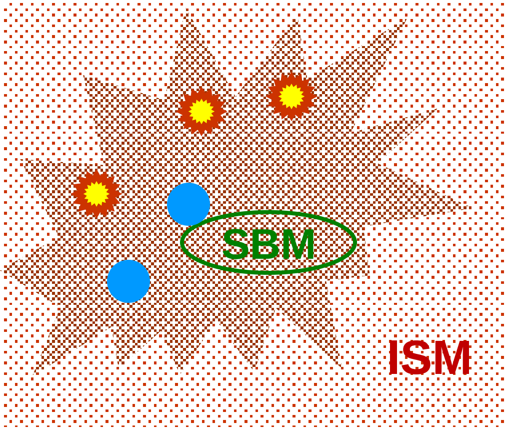
A) Energetically unfeasible (reverse shock too weak)

B) Absence of radioactive Ni59 ($\tau \sim 10^5$ 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 $\sim Z_\odot$ from its own Supernovae (*Higdon et al. 1998*)

$X(GCR) \sim X(SN)$

Primary BeB



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

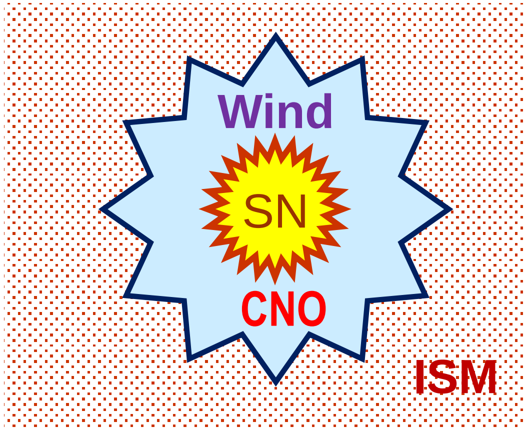
B) SN are observationally associated with HII regions, with widely different metallicities

4. Massive star wind accelerated by forward shock

$X_{CNO}(GCR) \sim X_{CNO}(Wind)$

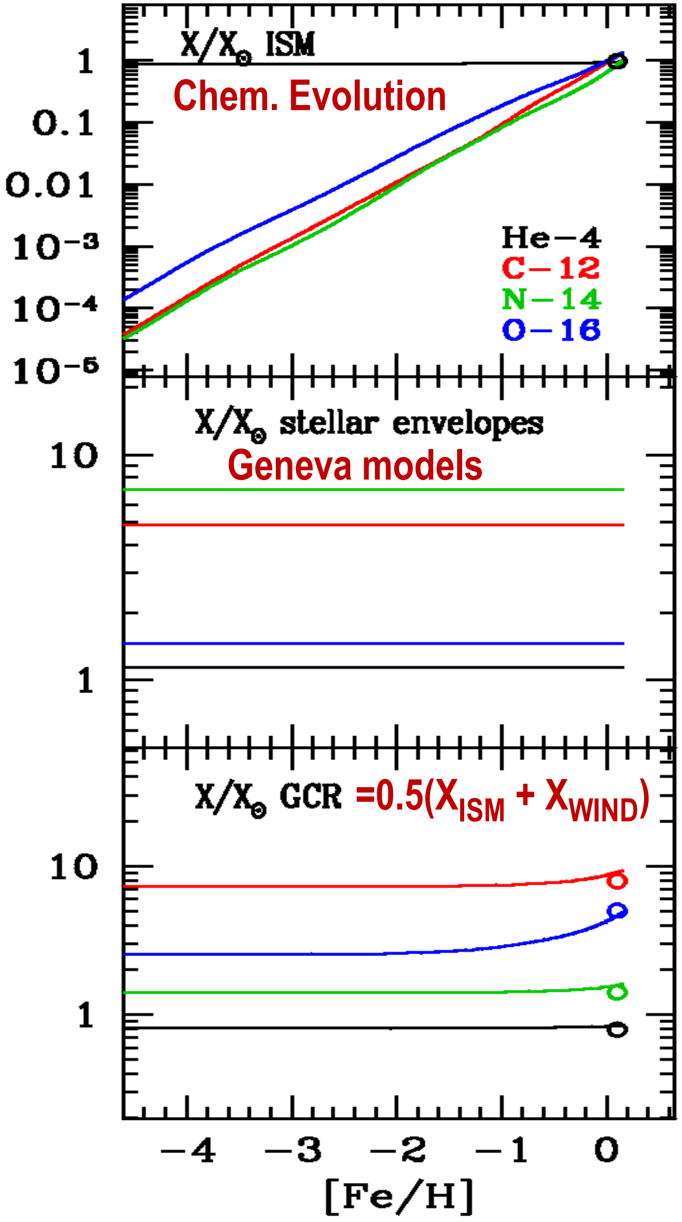
Primary BeB

BUT $X_{Heavy}(GCR) \neq X_{Heavy}(ISM)$

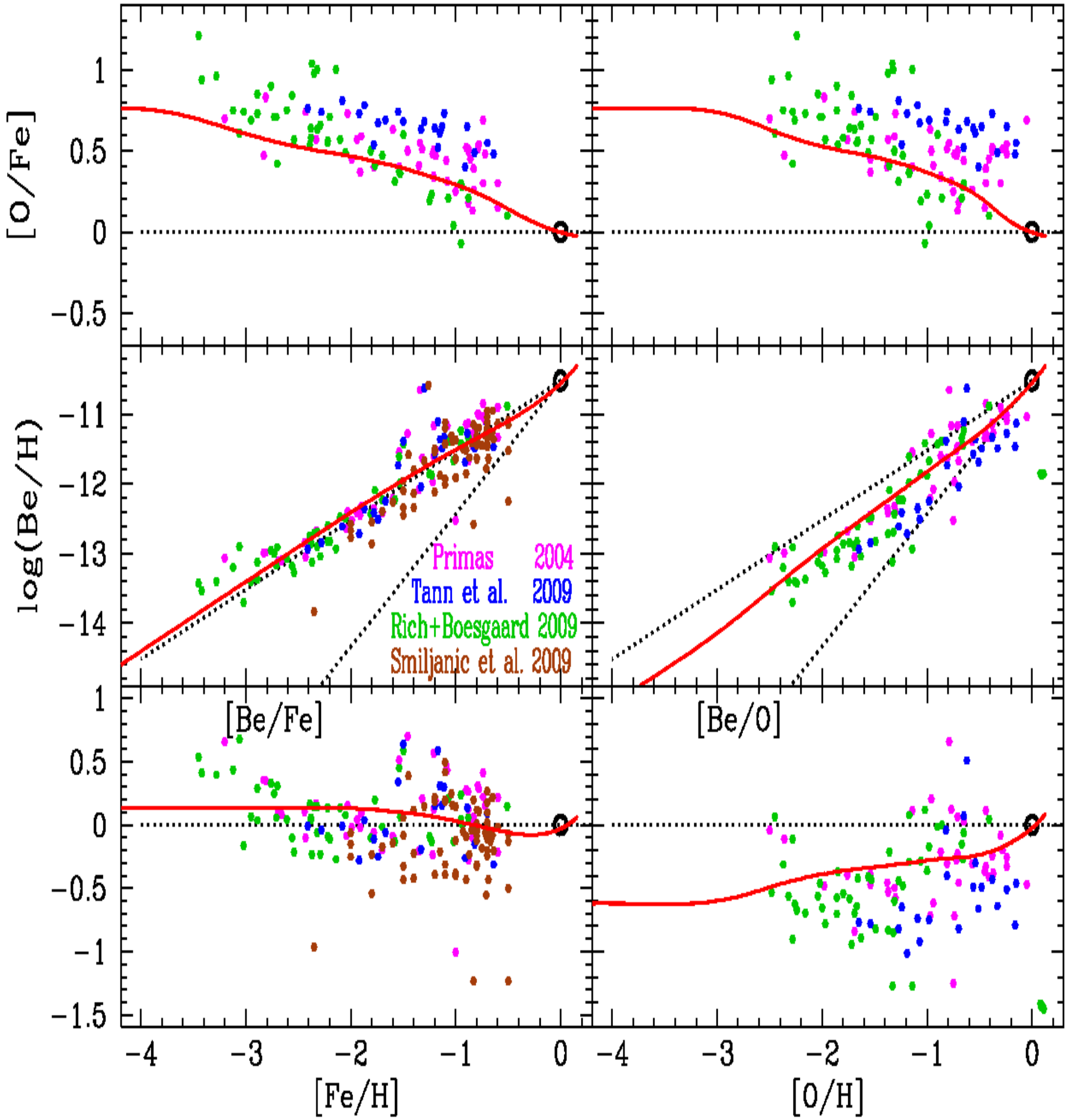


Assumed composition of GCR :

$X_{GCR}(t) = 0.5\,(X_{WIND}(t) + X_{ISM}(t))$

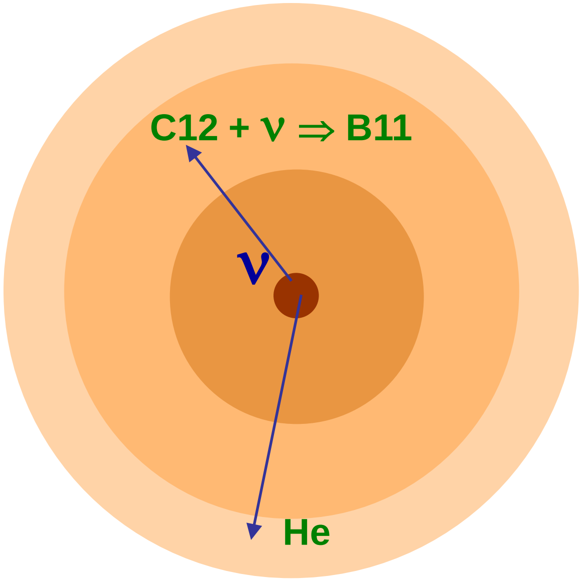


With this, “physically motivated” GCR composition AND proper GCR/SN energetics, primary Be is naturally obtained



Production of primary B11 (and some Li7) in CCSN by neutrino-induced nucleosynthesis

(*Woosley et al. 1990*)



Neutrinos from CCSN spallate C12

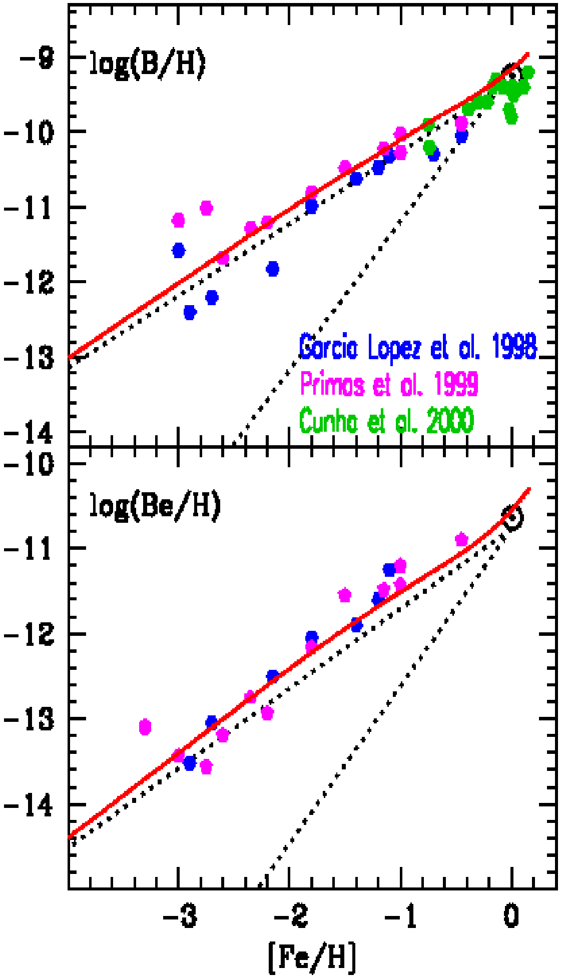
in C-shell and produce **B11 (primary)**

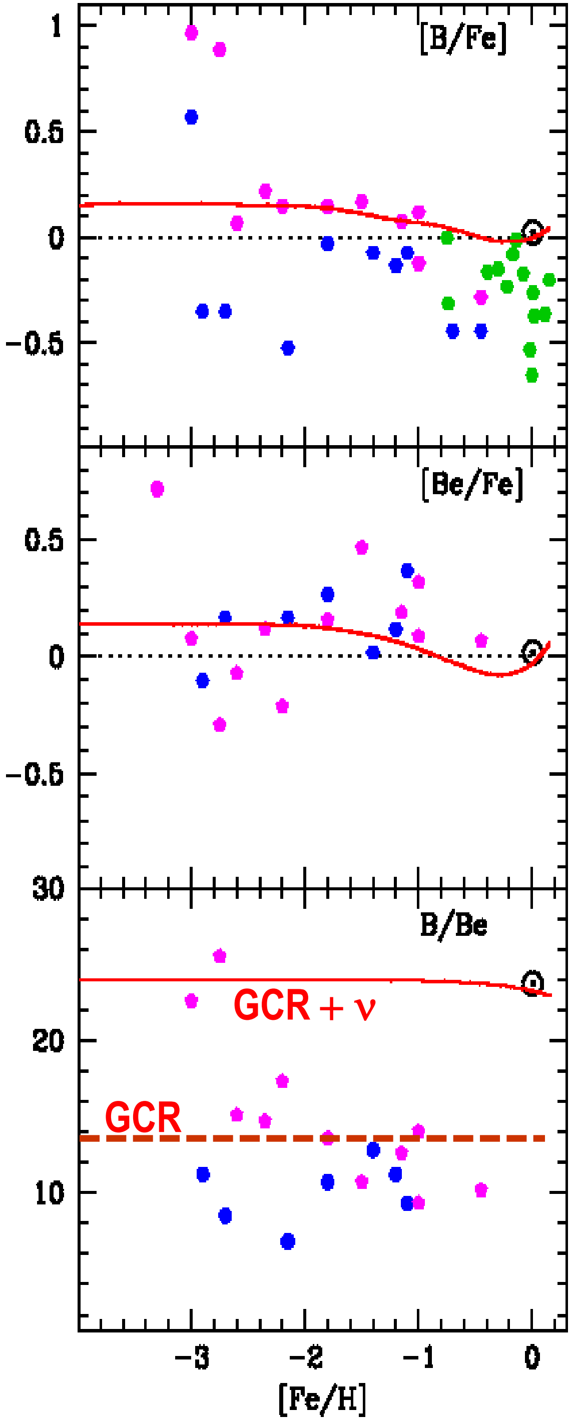
and He4 in He-shell and produce He3

then : He3 + He4 → **Li7 (primary)**

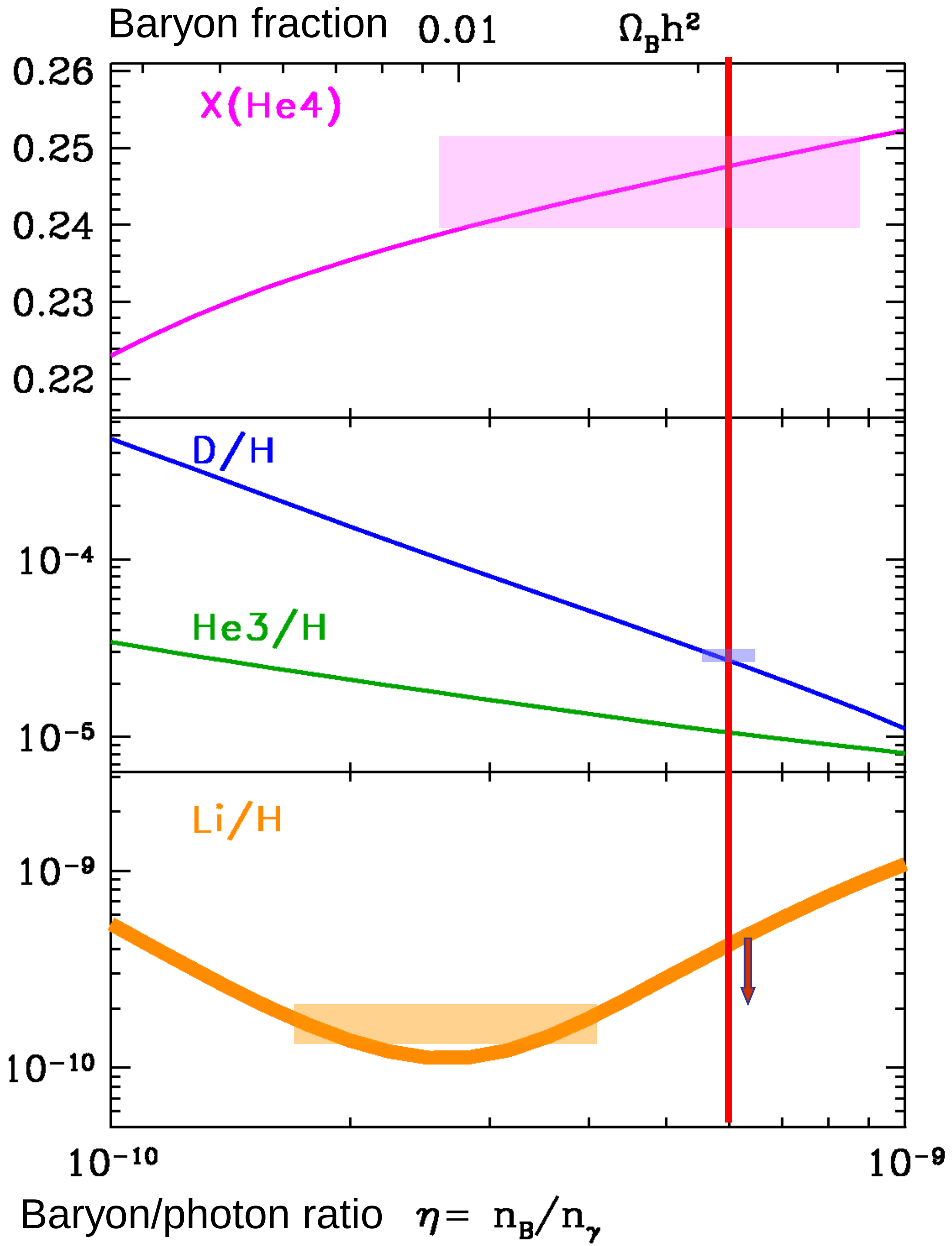
BUT: Neutrino spectra of core-collapse SN are very uncertain;

So are the yields of B11 and Li7





What is the true B/Be ratio at low [Fe/H] ?



Calculations of primordial nucleosynthesis and determination of baryonic density from Cosmic Microwave Background by WMAP

-are consistent with observed “primordial” D in high redshift gas clouds

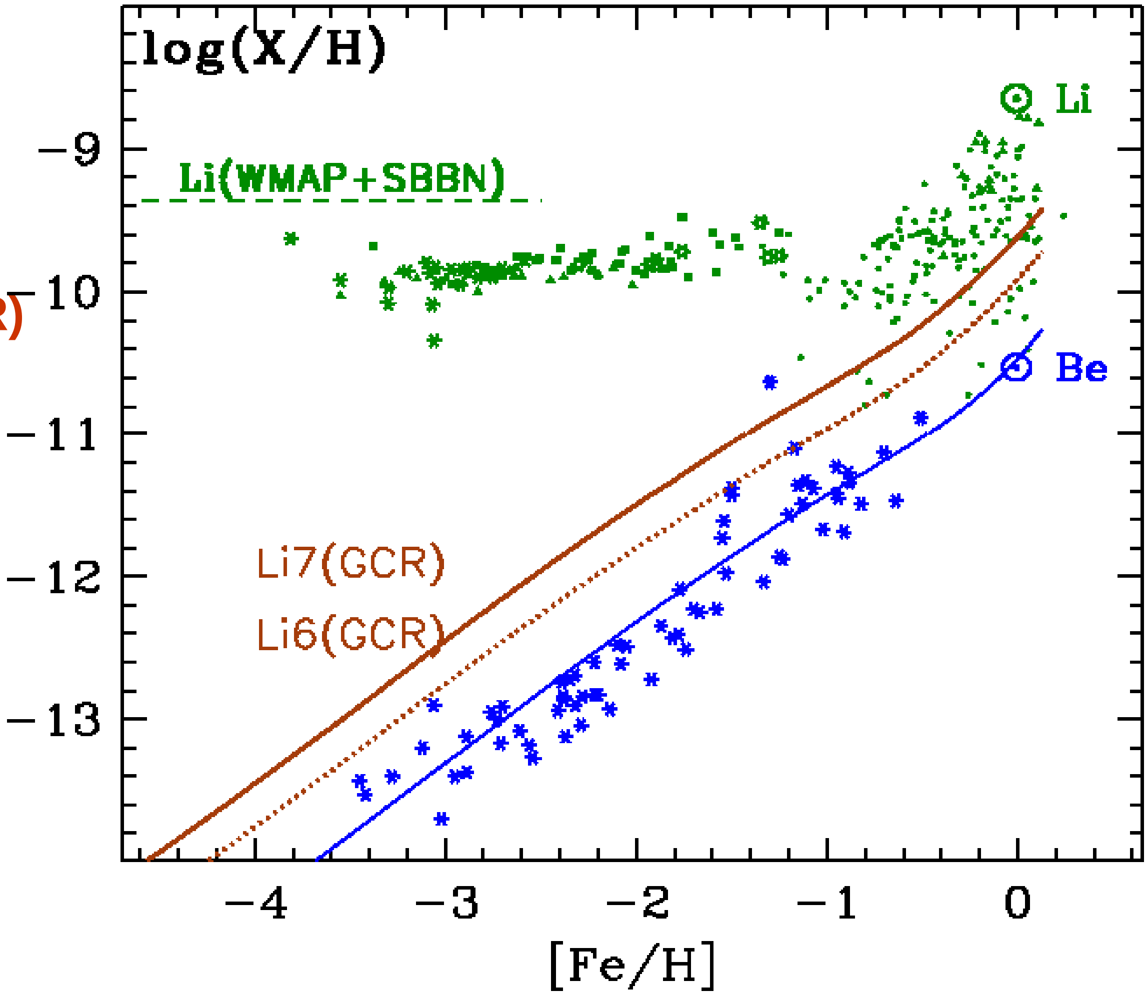
-are consistent with observationally derived primordial He4 (with large systematic errors)

-suggest a value of primordial Li7 ~2-3 times higher than the observed “plateau” in halo stars

Is Li7 destruction underestimated in standard BBN ?
Rather not : *Angulo et al. 2005*

Evolution of Li$_{\mathrm{TOTAL}}$

Li$_{\mathrm{TOTAL}}$ = Li7(GCR) + Li6(GCR)
(Calibrated on Be9)

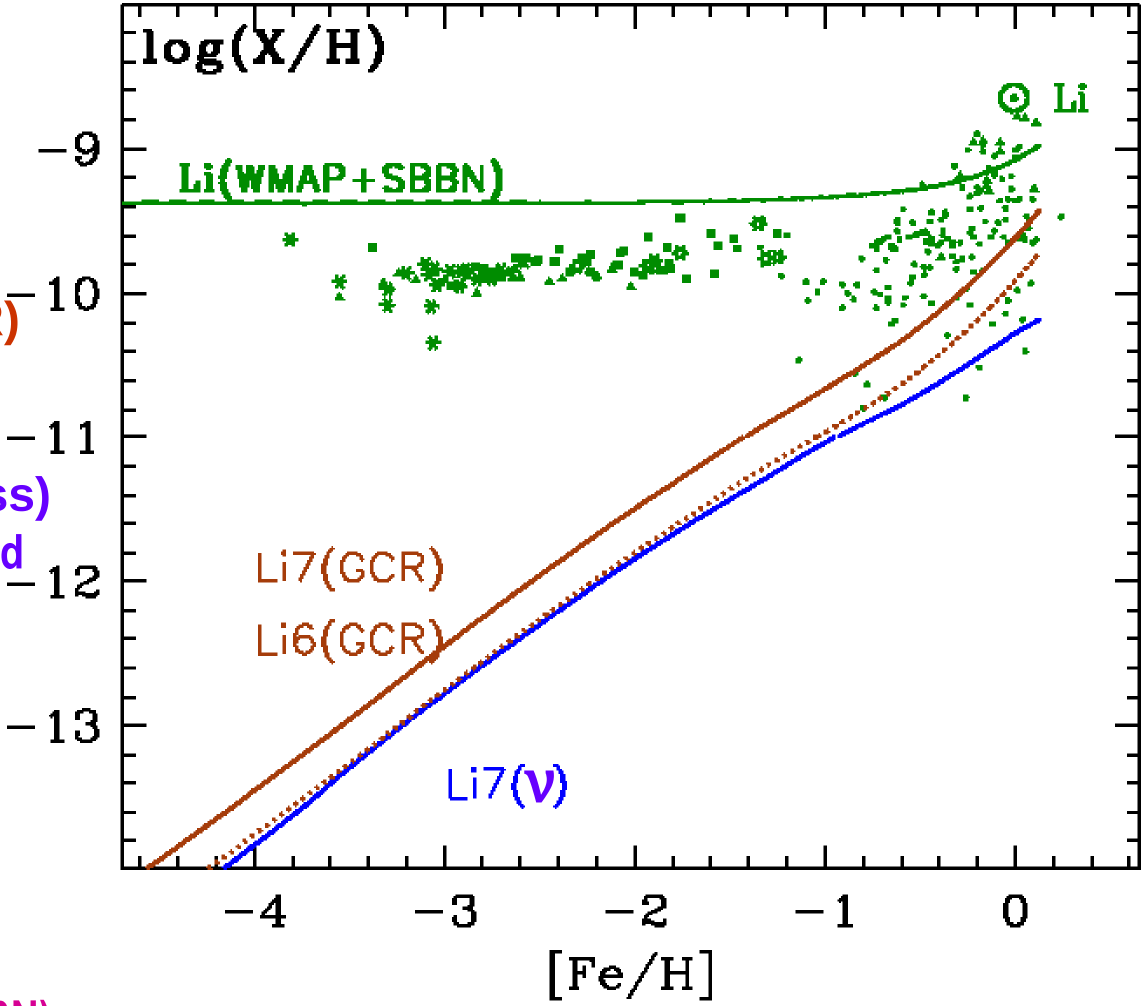


Evolution of $\mathrm{Li}_{\mathrm{TOTAL}}$

$\mathrm{Li}_{\mathrm{TOTAL}}$ = Li7(GCR) + Li6(GCR)
(Calibrated on Be9)

+ Li7(neutrino process)
(SN yields of Li7 reduced by 6, as for B-11 yields)

+ Li7 (pre-galactic)



If Li7(pre-galactic) = Li7(WMAP+SBBN)
~50% of solar Li is still missing

If Li7(pre-galactic) = Li7(Spite plateau)
~65% of solar Li is still missing

Need for another (late) stellar source

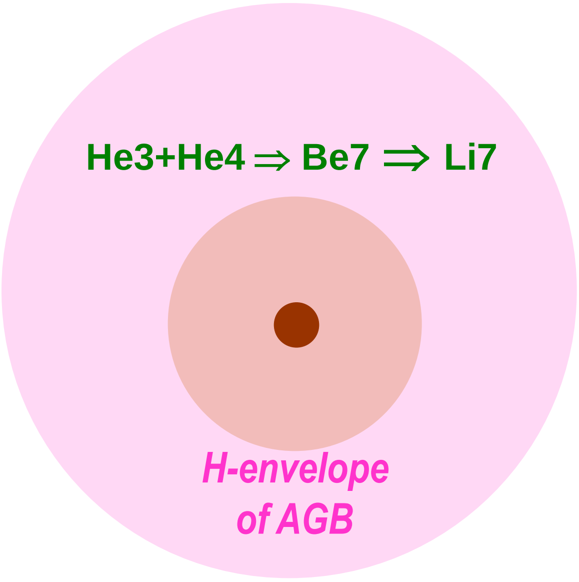
Evolution of Li_{TOTAL}

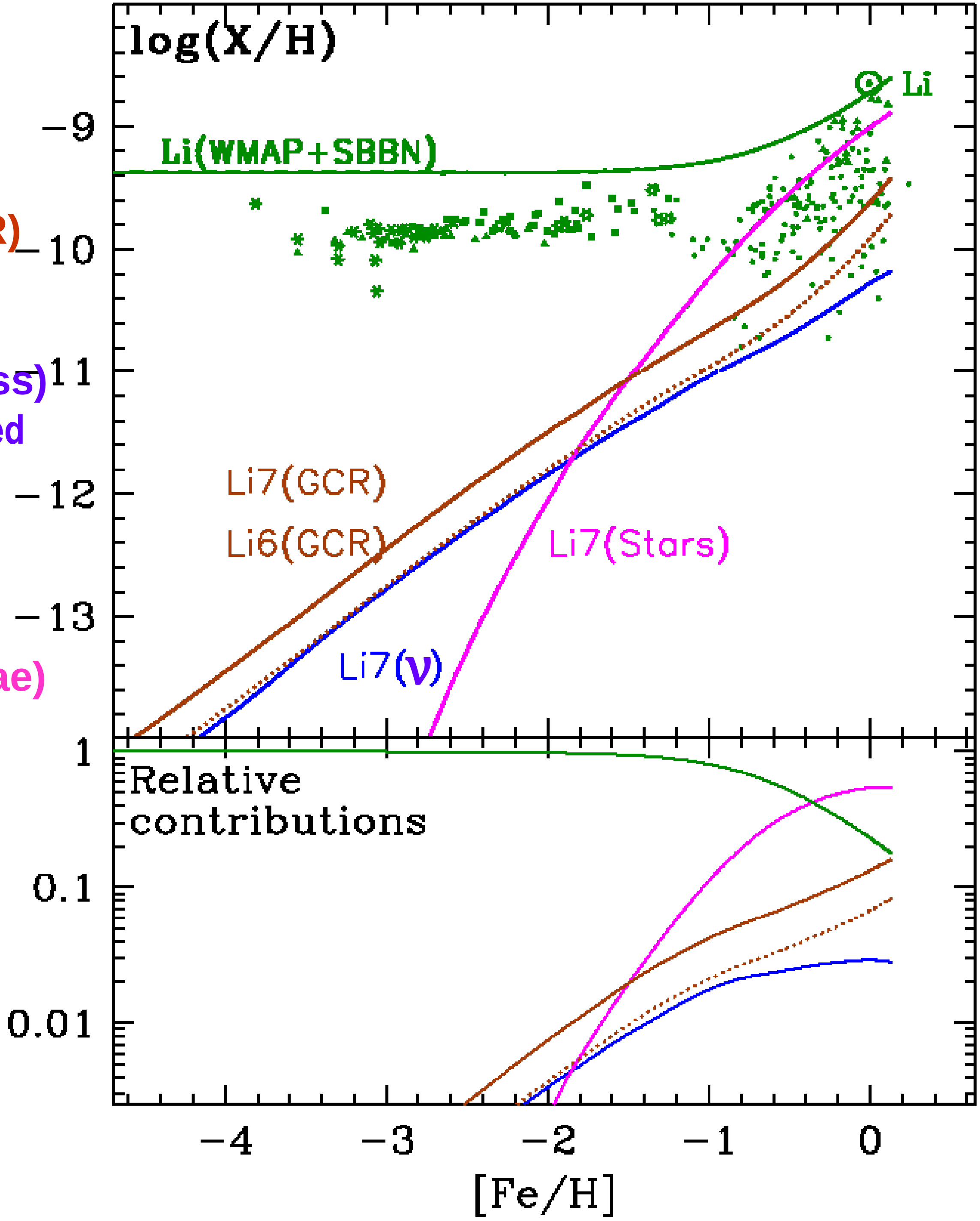
Li_{TOTAL} = Li7(GCR) + Li6(GCR)
(Calibrated on Be9)

+ Li7(neutrino process)
(SN yields of Li7 reduced
by 6, as for B-11 yields)

+ Li7 (pre-galactic)

+ Li7 (AGB stars/novae)





Summary for light elements

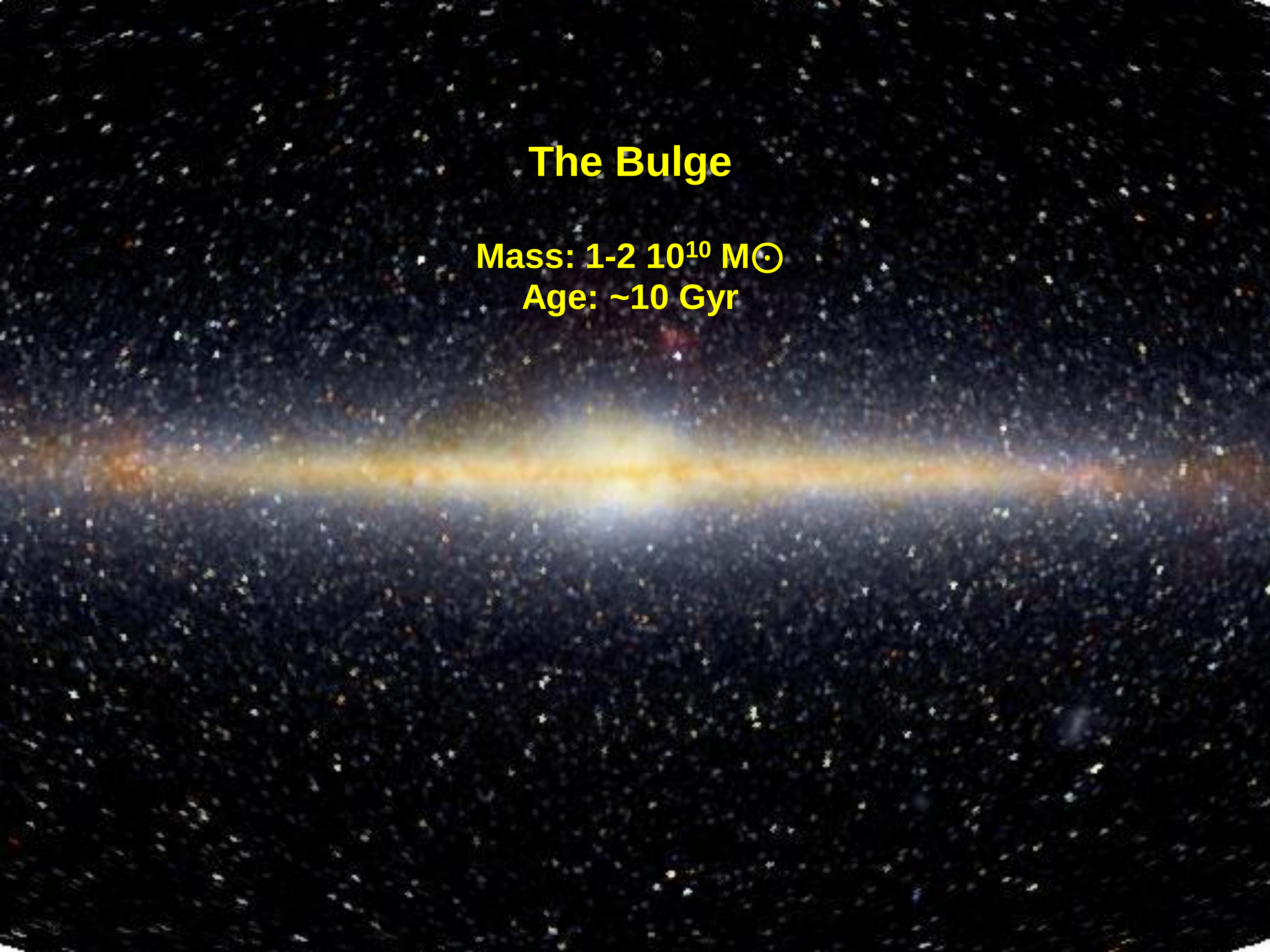
Source: mostly GCR but
-Li-7 partly from BBN *and* stellar sources
-B-11 partly from stellar source (ν-process?)
- Problems with observations of early Li
-Observed linearity of Be vs Fe implies composition of GCR always the same (how ?)

	Li-6	Li-7		Be-9	B-10	B-11
Big Bang	0	8 *Spite*	20 *WMAP*	0	0	0
GCR	100	25	20	100	100	60
ν-process		<10				40
AGB/novae		65	55			
Other ???						

GALACTIC CHEMICAL EVOLUTION

Part III : The Milky Way

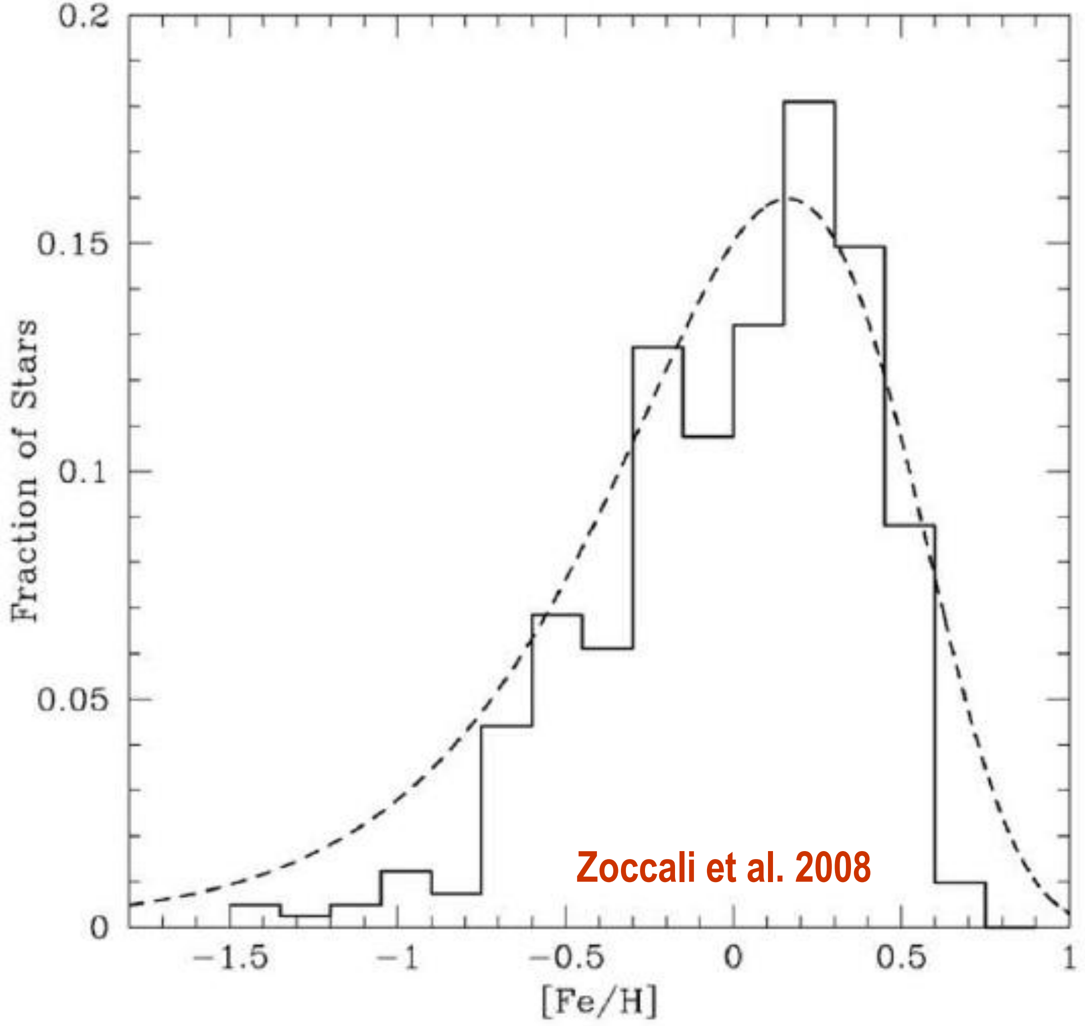
F: The Bulge



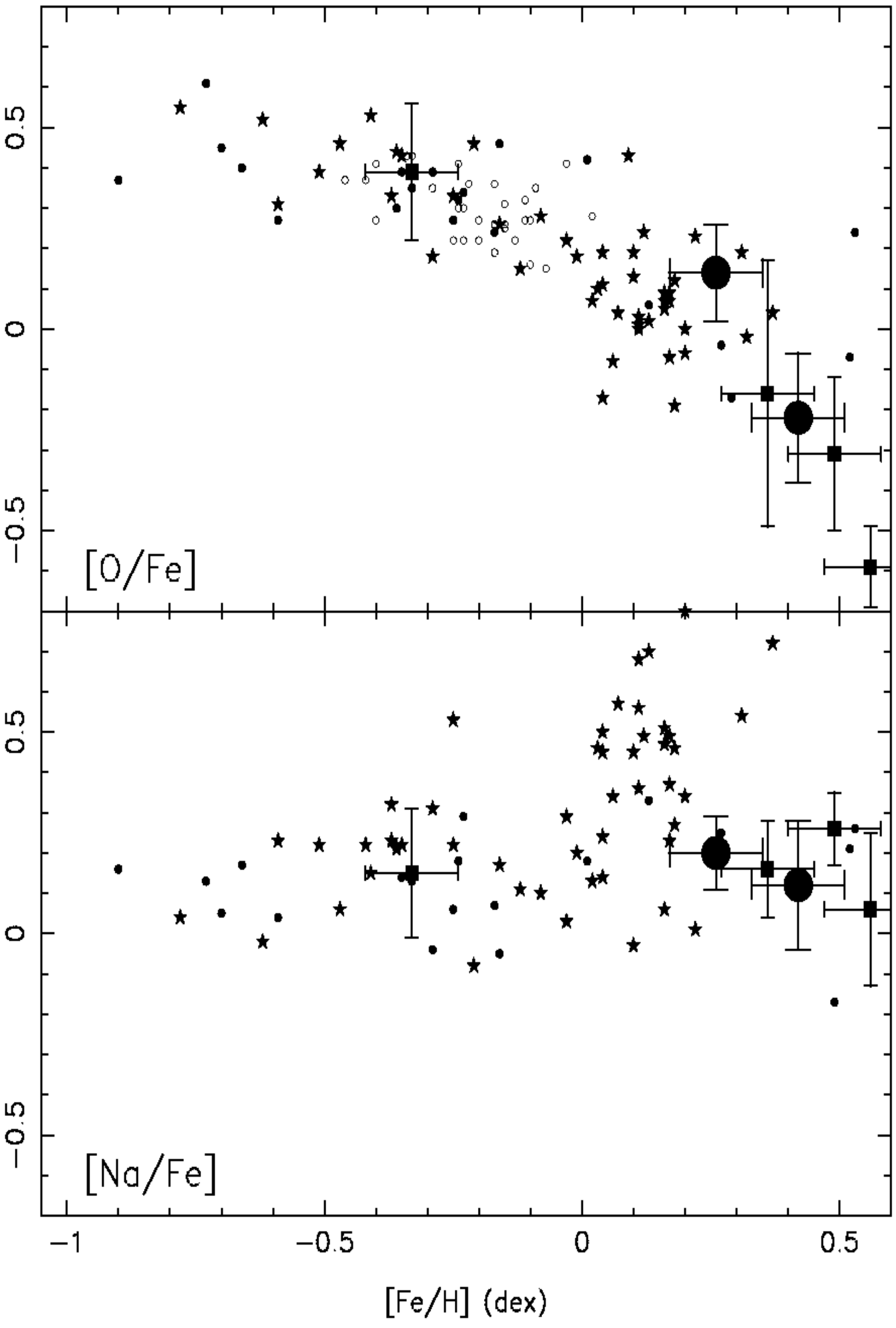
The Bulge

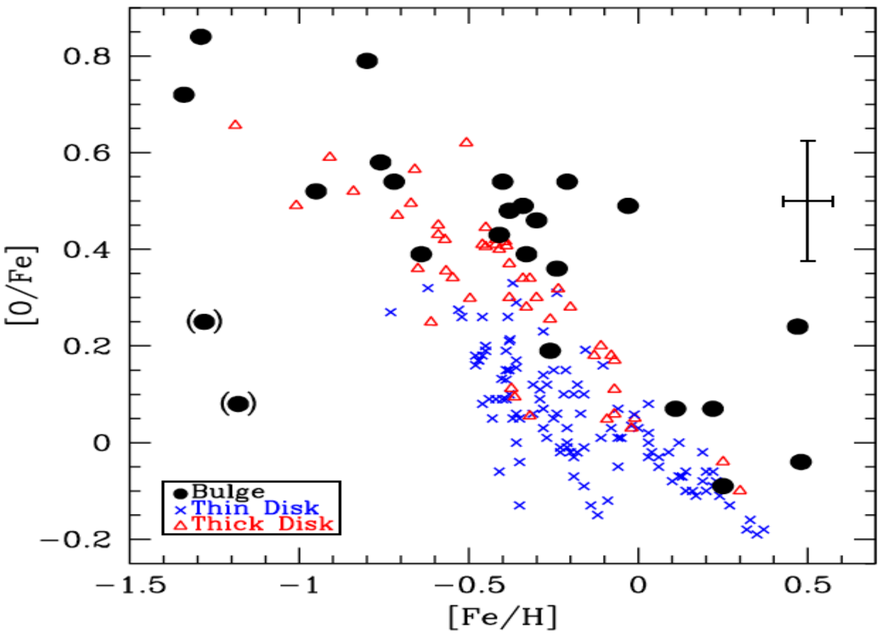
Mass: 1-2 10^{10} M⊙
Age: ~10 Gyr

Bulge metallicity distribution suggests evolution as closed box



and mean metallicity slightly higher than in solar neighborhood

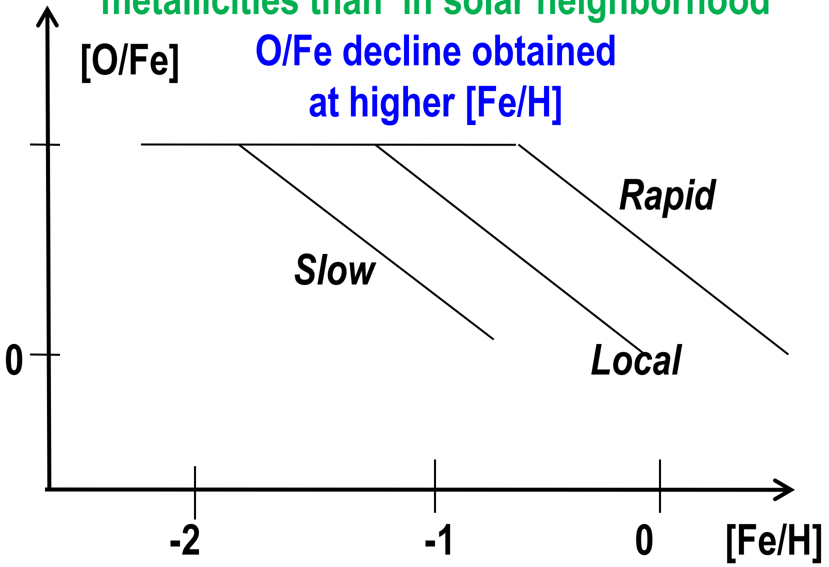


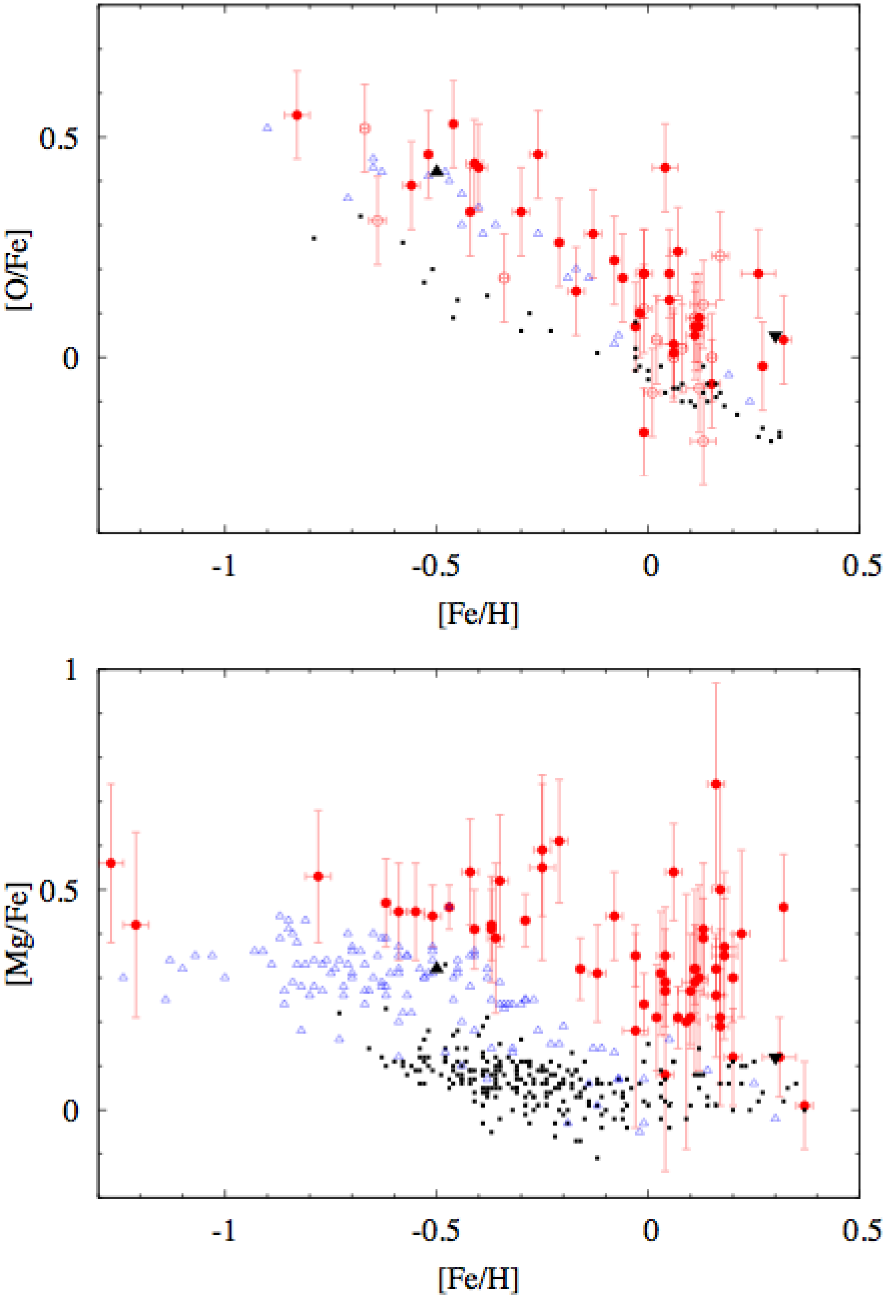


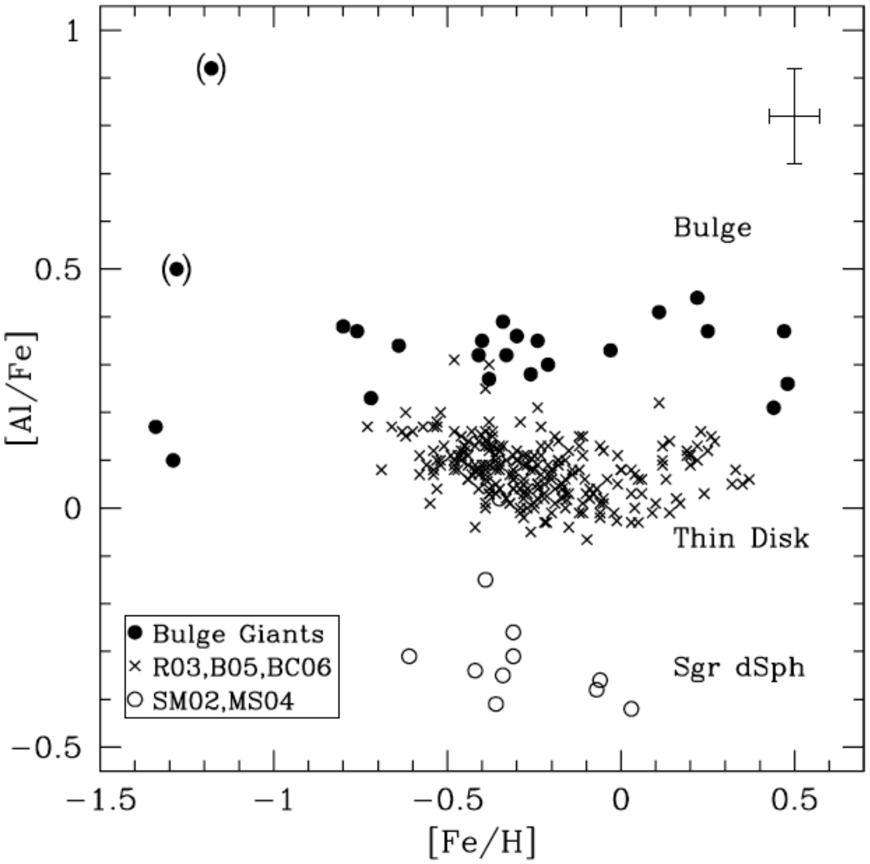
Because of rapid evolution, metallicity increases rapidly.

SNIa start producing Fe at higher metallicities than in solar neighborhood

O/Fe decline obtained at higher [Fe/H]




[O/Fe]
0.5
0
-1
-0.5
0
0.5
[Fe/H]
[Mg/Fe]
1
0.5
0
-1
-0.5
0
0.5
[Fe/H]


[Al/Fe]
1
0.5
0
−0.5
−1.5
−1
−0.5
0
0.5
[Fe/H]
Bulge
Thin Disk
Sgr dSph
● Bulge Giants
× R03,B05,BC06
○ SM02,MS04