

**ORIGIN AND EVOLUTION
OF THE
SPALLOGENIC NUCLIDES
(Li6, Li7, Be9, B10, B11)**

N. Prantzos

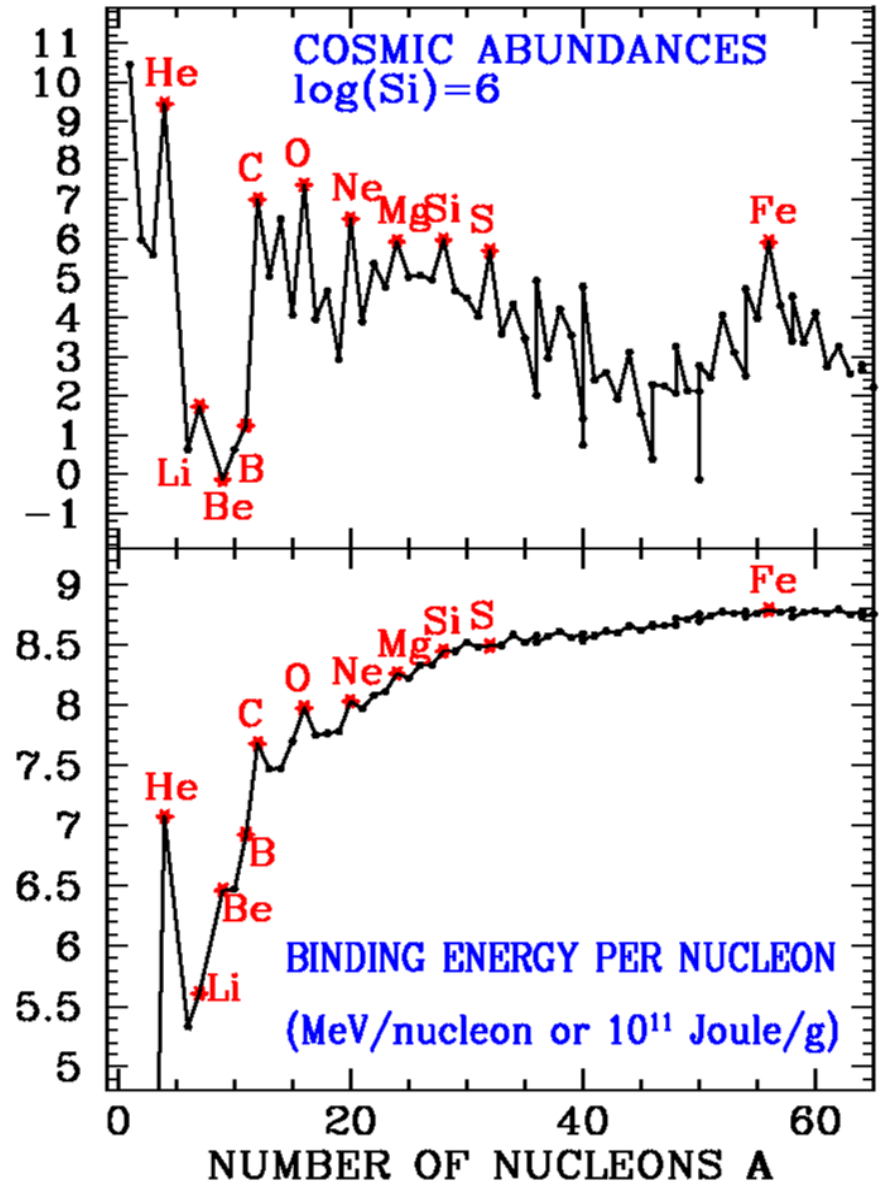
Institut d'Astrophysique de Paris

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

The most fragile
stable isotopes in nature
(after D and He3)

Always destroyed in stellar interiors

$T(\text{H-burn}) = 2.2 \text{ MK for Li (1.5 for Li6)}$
 3.5 MK for Be
 4.5 MK for B



REVIEWS OF MODERN PHYSICS

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Synthesis of the Elements in Stars*

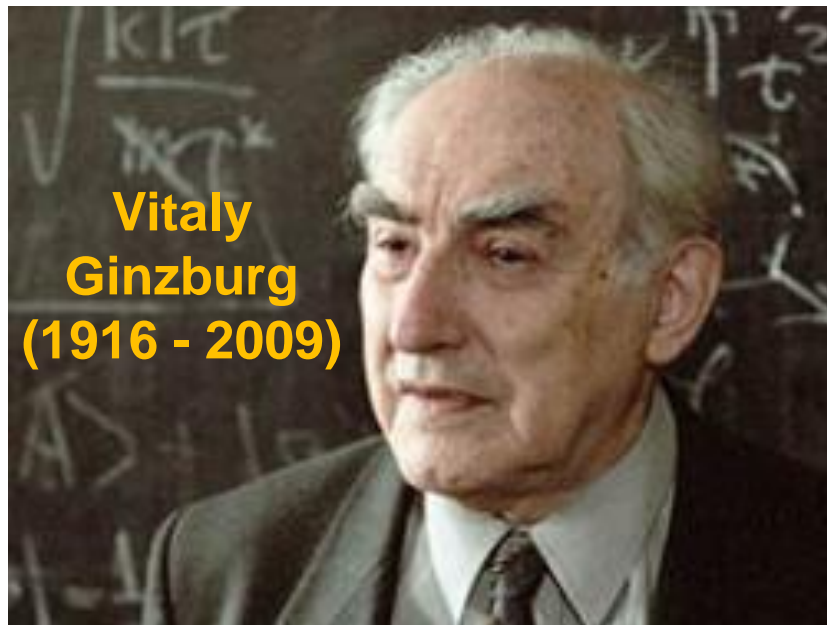
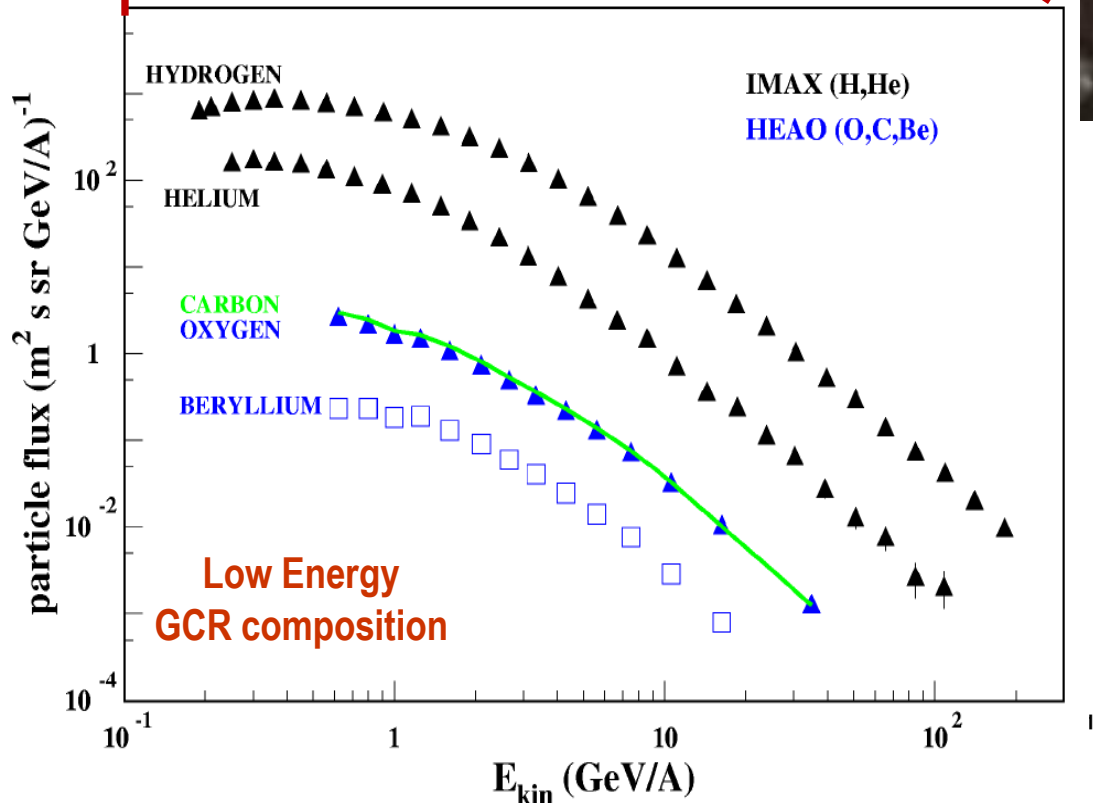
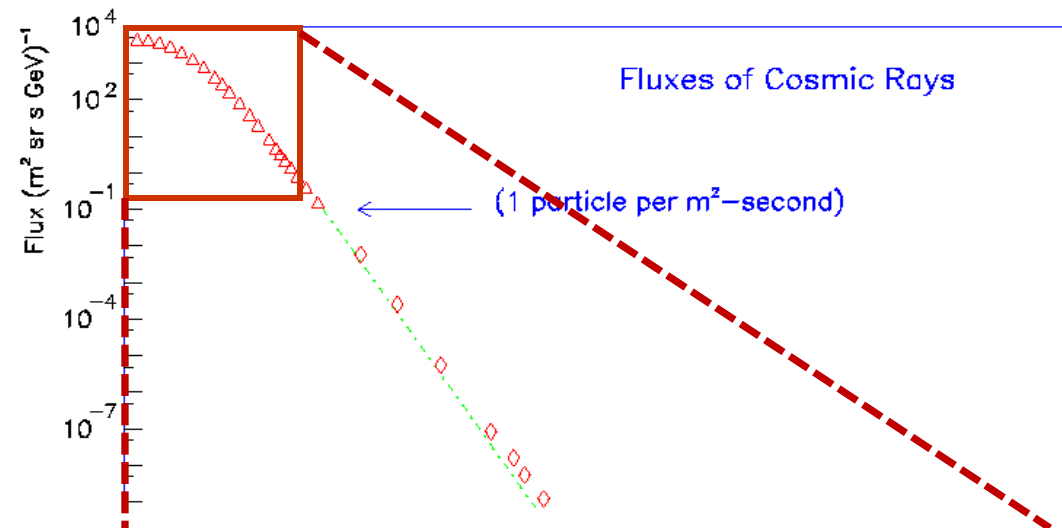
E. MARGARET BURBIDGE, G. R. BURBIDGE,
WILLIAM A. FOWLER, AND F. HOYLE

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

X. α PROCESS

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

Galactic Cosmic Rays (GCR)



Vitaly Ginzburg
(1916 - 2009)

GCR Energetics in Milky Way:

Power(GCR) $\sim 10^{41}$ erg/s

Power(Supernovae): $\sim 10^{42}$ erg/s

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

OK if $E(\text{GCR}) \sim 10\% E_{KIN}(\text{SN})$

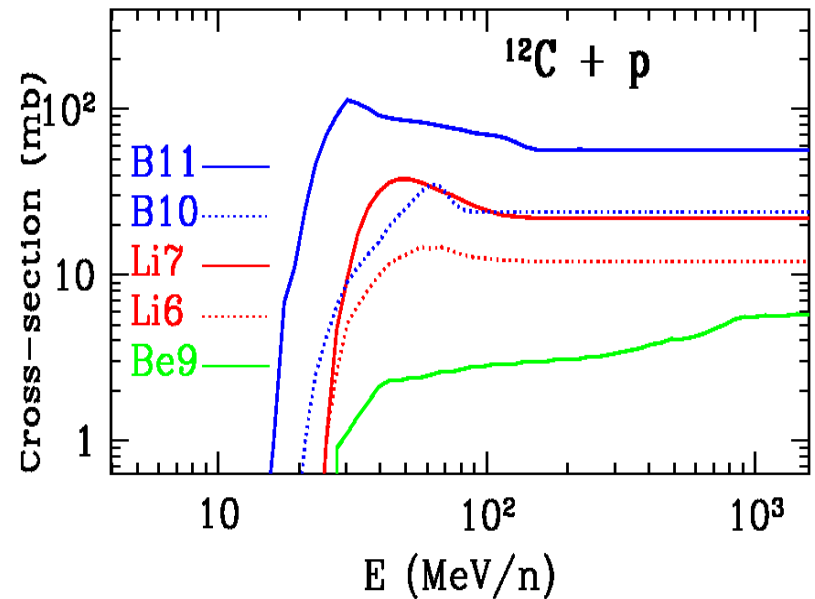
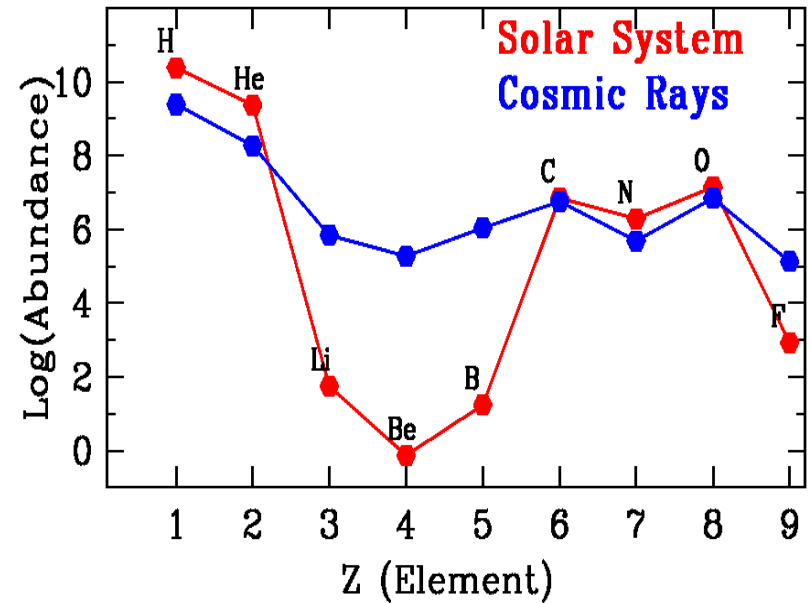
GCR composition is heavily enriched in Li, Be, B
 (a factor $\sim 10^6$ for Be and B)

Solar composition: $X(\text{Li}) > X(\text{B}) > X(\text{Be})$

GCR composition: $X(\text{B}) > X(\text{Li}) > X(\text{Be})$

Same order as spallation cross sections of CNO \Rightarrow LiBeB: $\sigma(\text{B}) > \sigma(\text{Li}) > \sigma(\text{Be})$

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



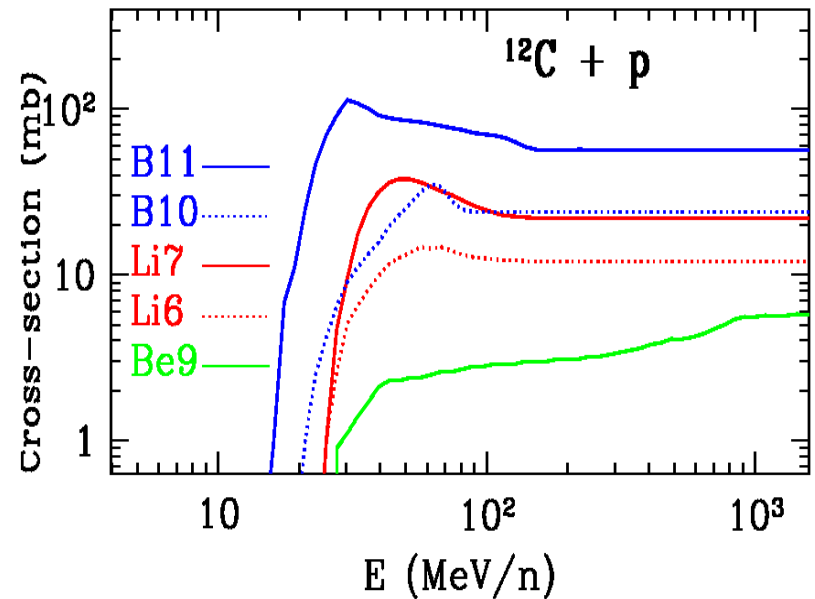
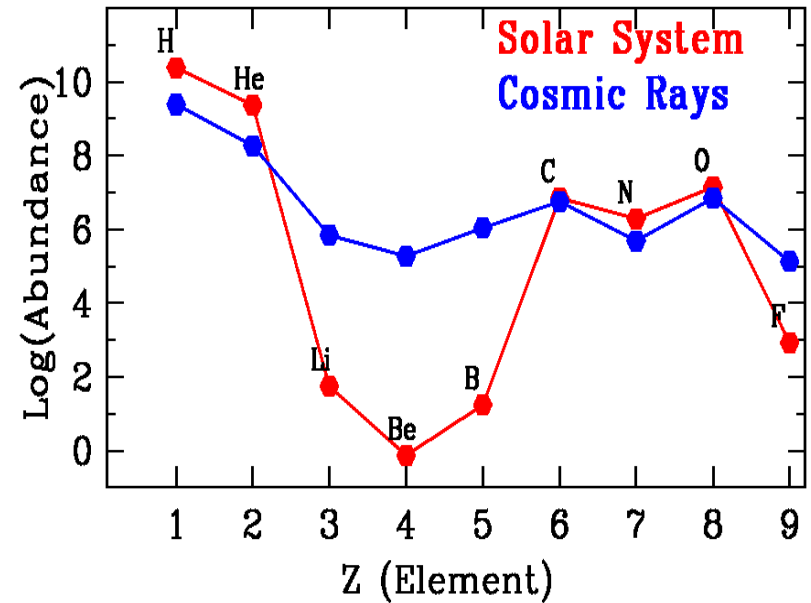
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The Production of the Elements Li, Be, B by Galactic Cosmic Rays in Space and its Relation with Stellar Observations

M. MENEGUZZI*, J. AUDOUZE* and H. REEVES*

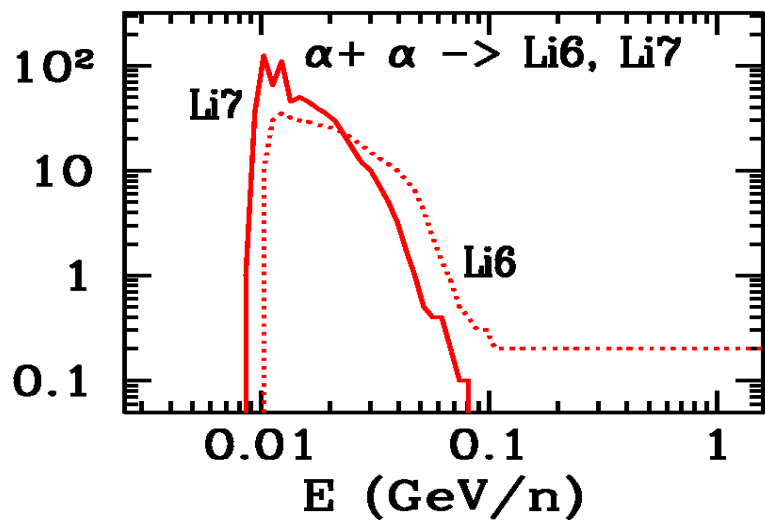
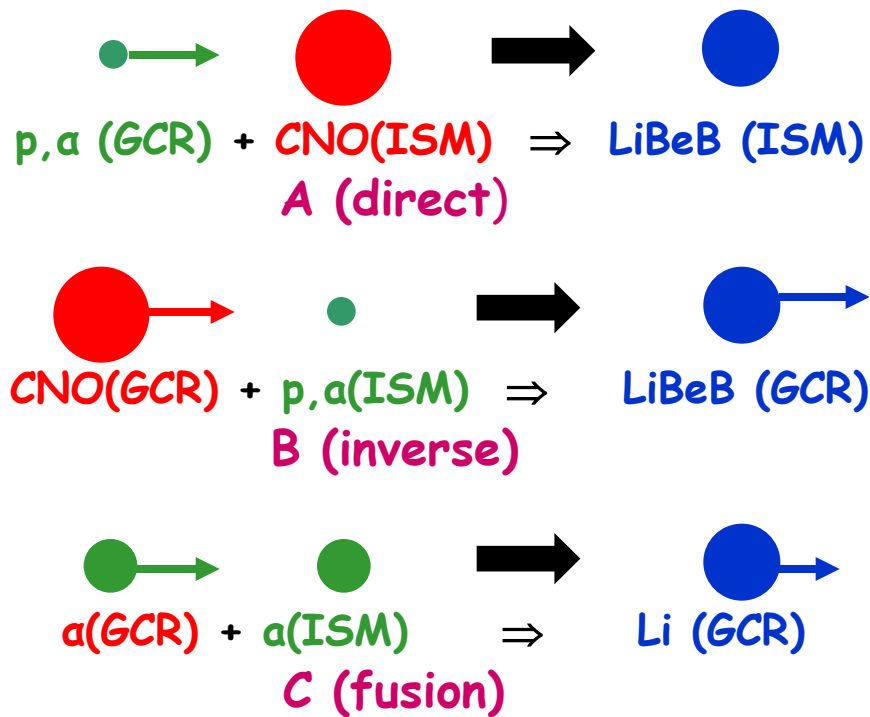
Service d'Electronique Physique, Saclay, and Institut d'Astrophysique de Paris

Received May 28, 1971

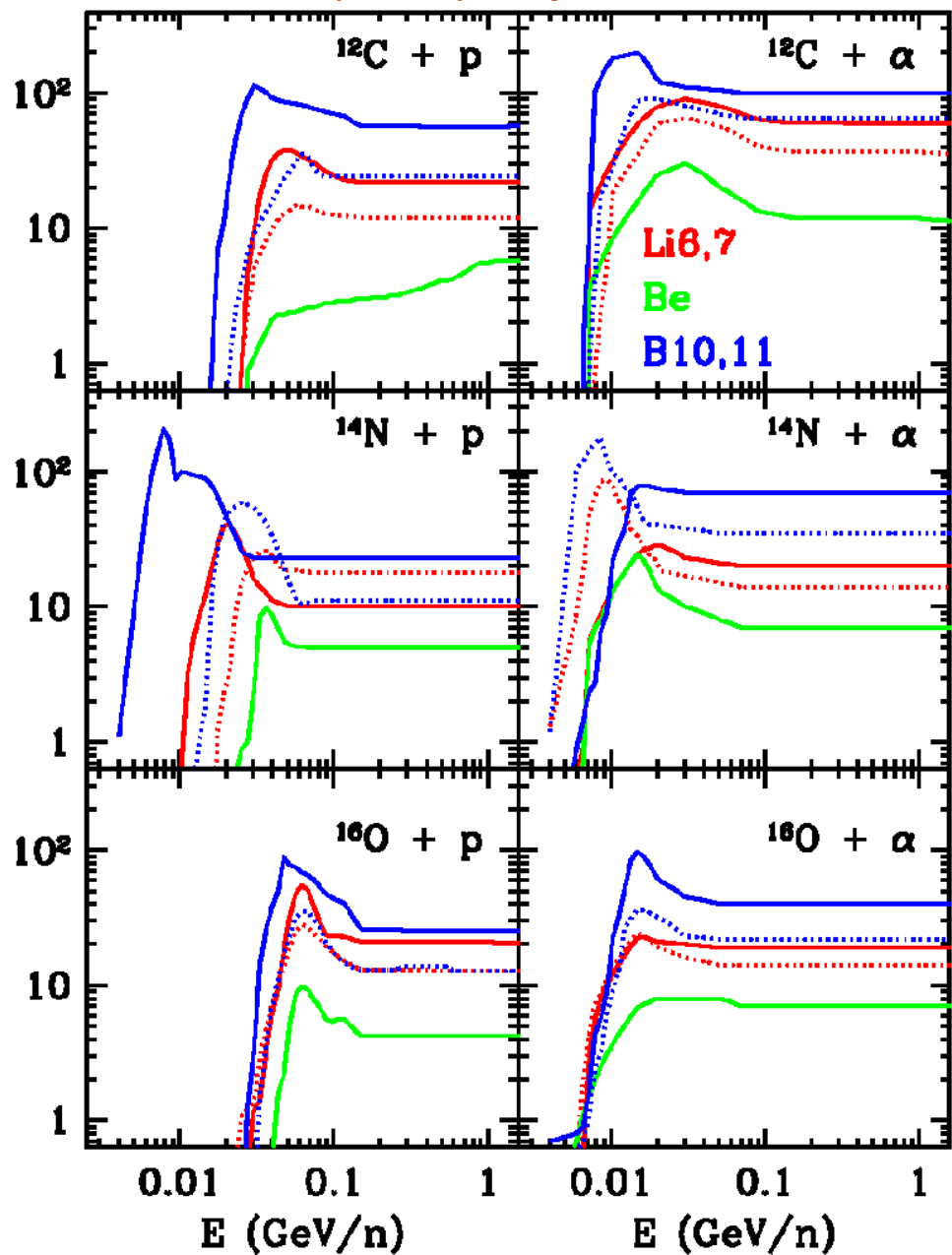
The L-element (Li, Be, B) contamination rate of the interstellar gas by nuclear reactions induced by the Galactic Cosmic Rays (G.C.R.) is calculated using a diffusion model of fast moving particles in the Galaxy. The presence of helium in the G.C.R. flux and in the interstellar gas is taken into account.

It is found that most of the stellar and meteoritic data is in agreement with a model which otherwise gives a reasonable account of the G.C.R. observations. This model assumes an injection spectrum in total energy power ($W^{-2.6}$) diffusing in a leaking galaxy with an escape range of 6.3 g cm^{-2} . The intensity, the composition at the source and the spectral shape have remained the same for the last 10^{10} years.

However a large part of the ${}^7\text{Li}$ must come from another source. Two possibilities are discussed: a) thermonuclear ${}^7\text{Li}$ ejected from Giant Stars in "dirty" regions of our Galaxy, b) spallative ${}^7\text{Li}$ generated from an intense low energy component of the G.C.R.



Cross sections (in mb) of $p, \alpha + \text{CNO} \Rightarrow \text{LiBeB}$



Galactic Cosmic Ray Odyssey

CR Source
(Composition)

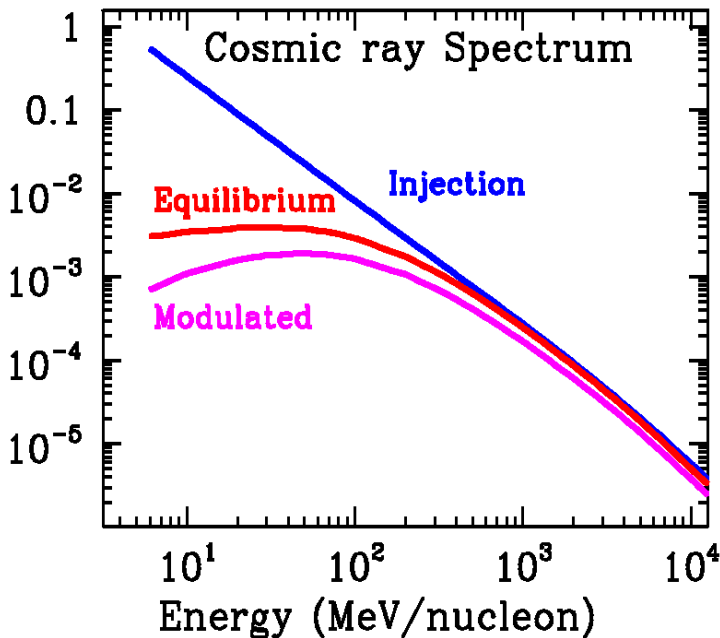
Losses
(Ionisation, Escape
Nuclear Reactions)

CR Propagation
(Equilibrium Spectrum)

CR Acceleration
(Injection Spectrum,
Modified source comp.)

LiBeB

CR on Earth
(Modulated Spectrum,
Observed composition)

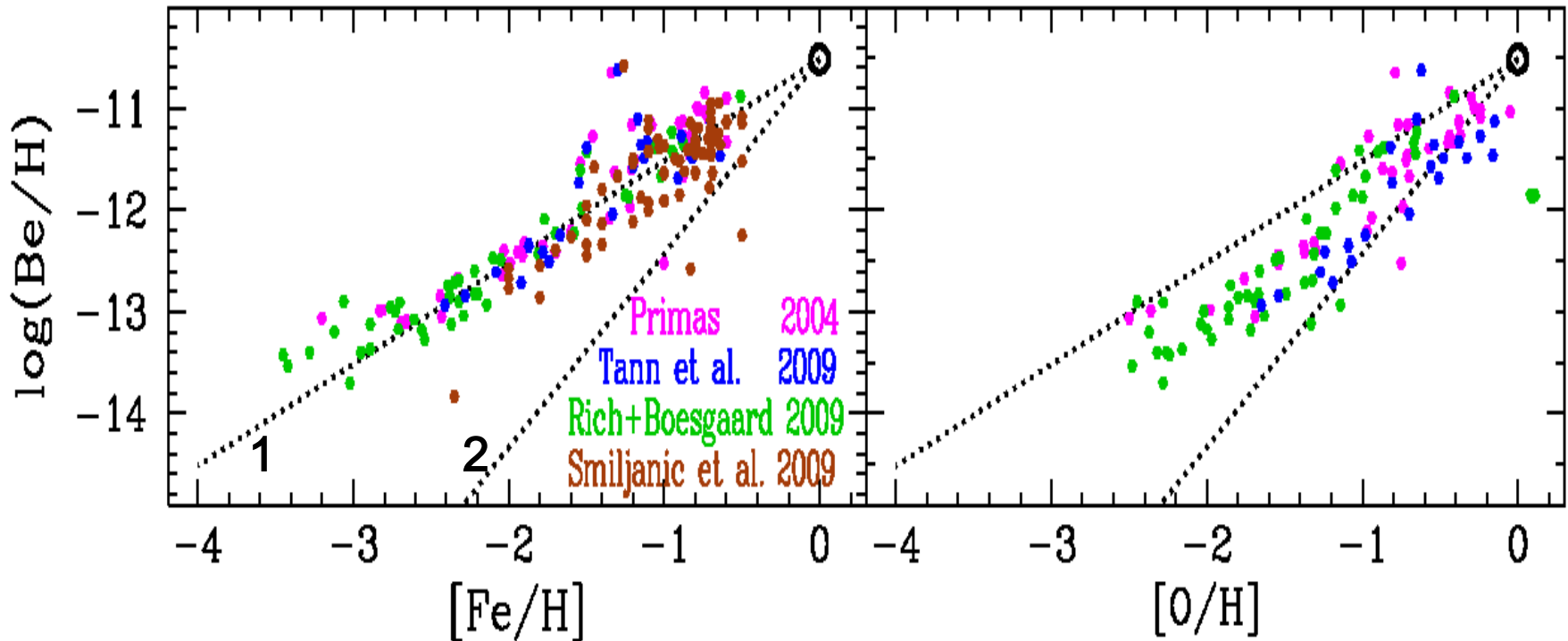


Theory of GCR acceleration:
injection spectra : power laws
in total energy or momentum (per nucleon)

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

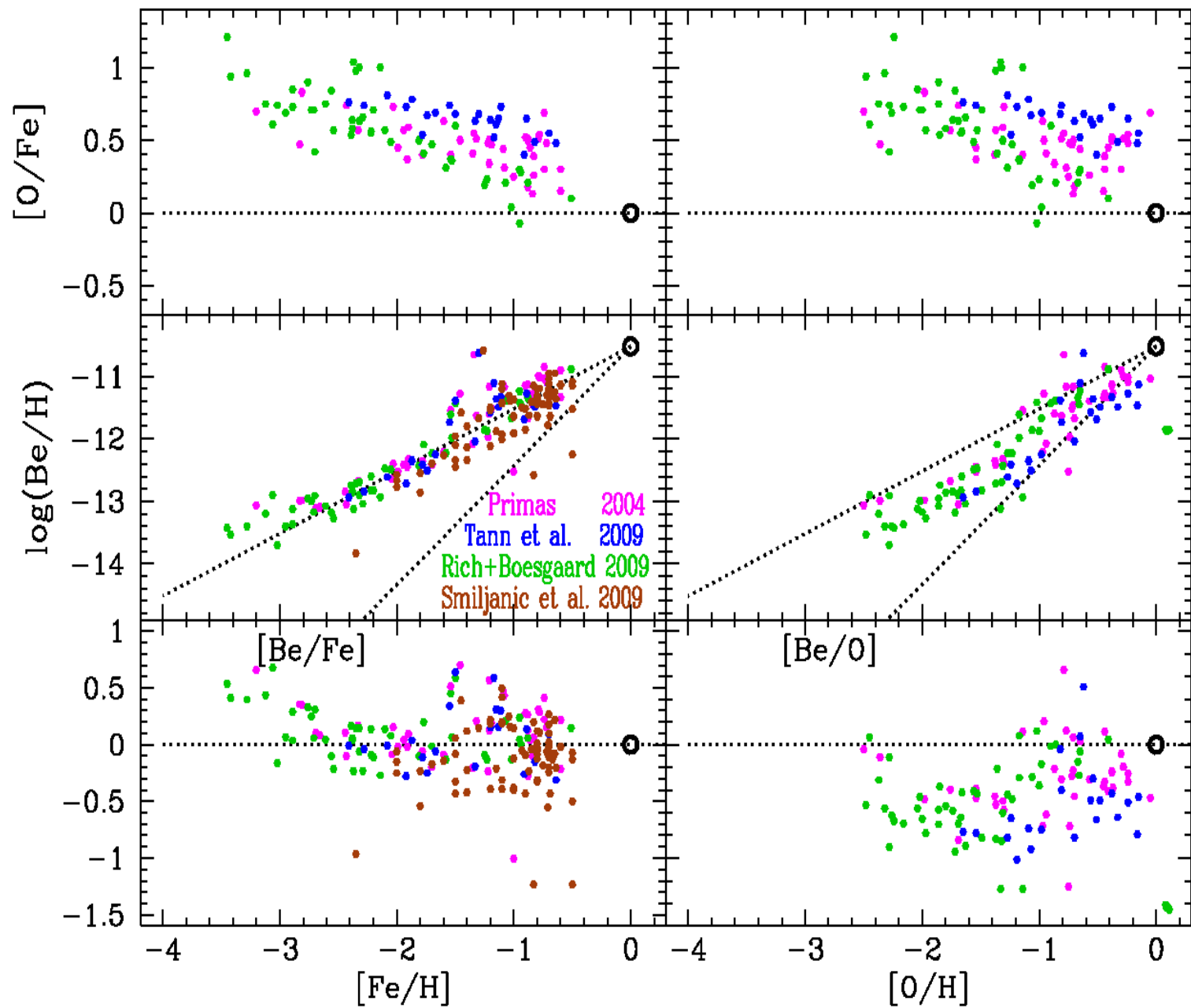
Evolution of Be

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

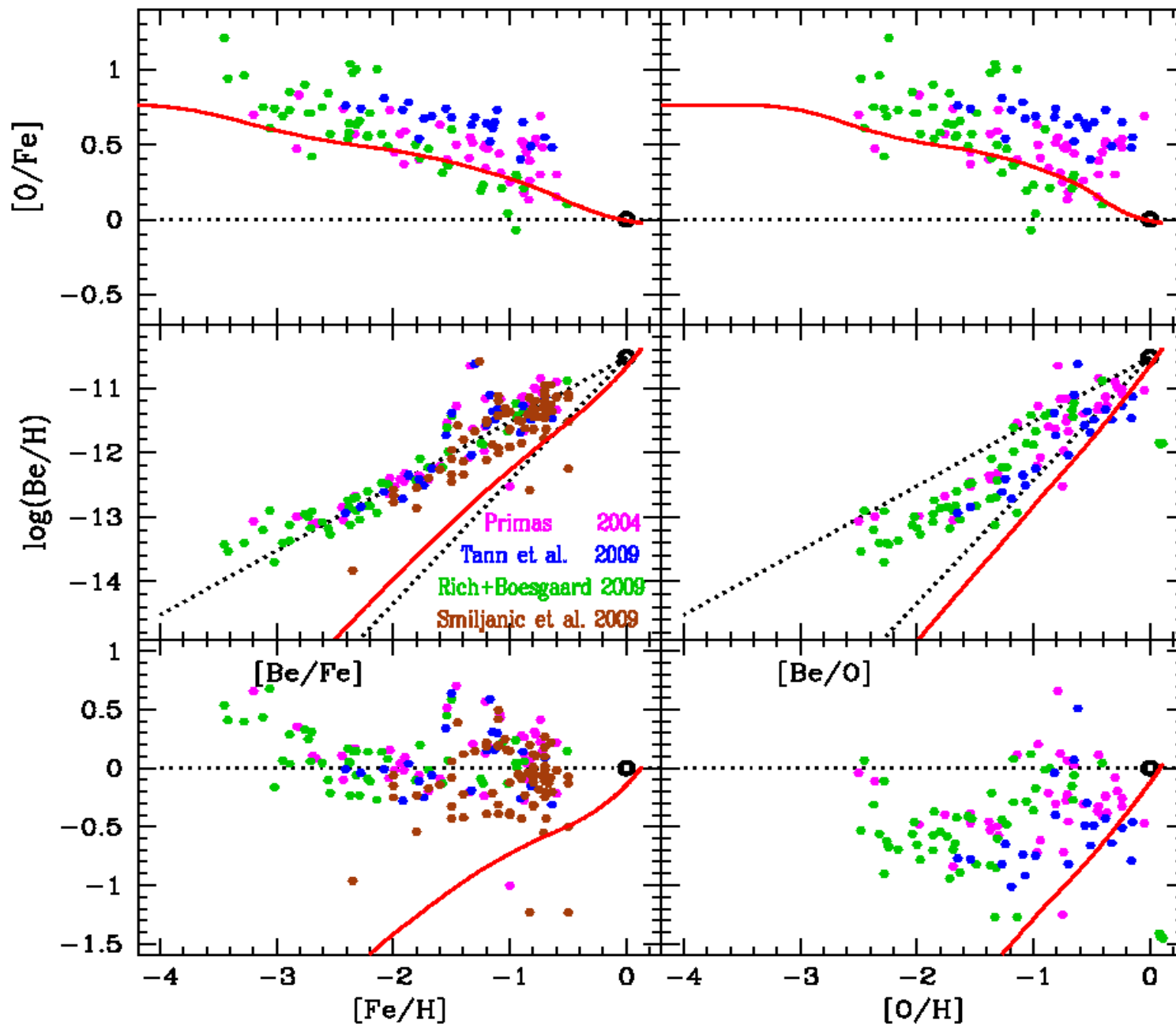


Be abundance evolves (as expected, since it is not primordial)

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



“Standard” chemical evolution of Be and B
[Standard GCR spectra and $X_{\text{CNO}}(\text{GCR},t) \propto X_{\text{CNO}}(\text{ISM},t)$]



~~Higher Λ_{ESCAPE}
in early
Galaxy?
(Prantzos et al. 1993)~~

~~Higher O/Fe
in early
Galaxy?~~

Reverse
GCR component
(fast CNO)
MUST have a
time-independent
composition
(Duncan, Lemke and
Lambert, 1993)

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

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 ($\sim 0.1 M_{\odot}$) and

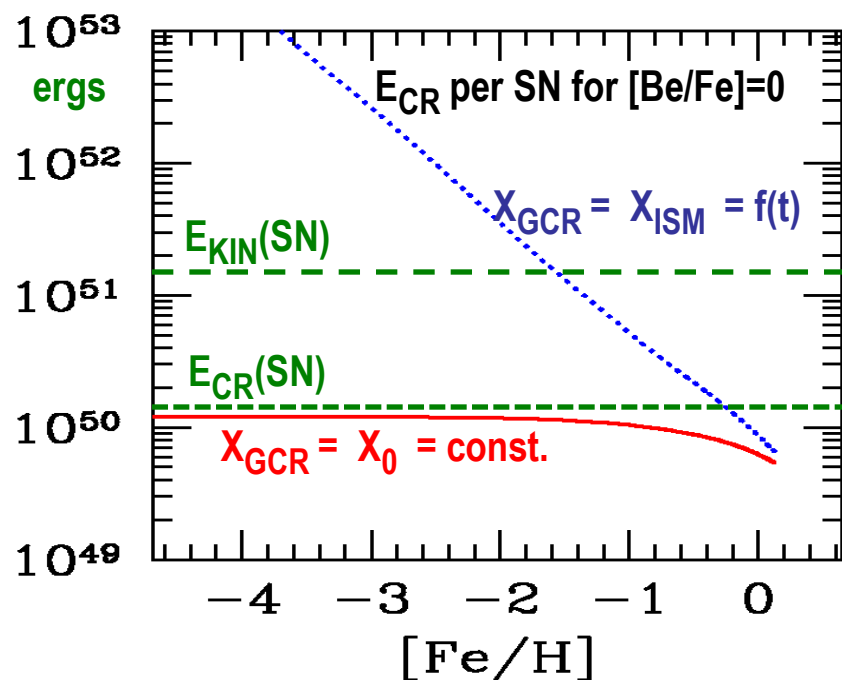
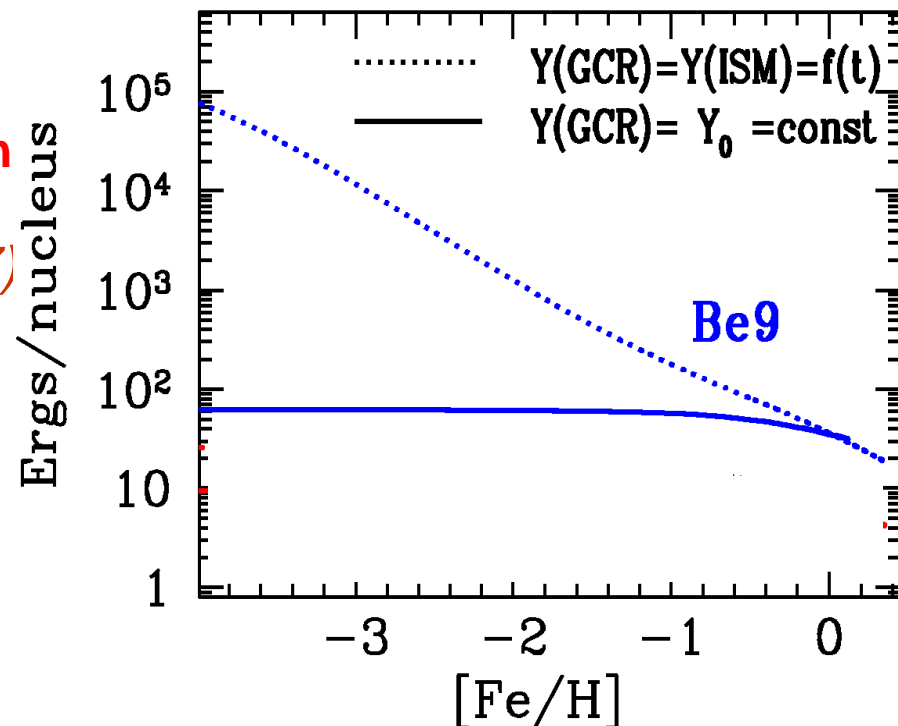
energy ($\sim 10^{50}$ ergs) for GCR acceleration

3) If the composition of GCR

$X(\text{GCR}, t) \propto X(\text{ISM}, t) \ll X_0$ at early times,

there is simply not enough energy in early GCR
accelerated by SN to maintain Be/Fe \sim const.

We need $X(\text{GCR}, t) \sim X_0$ always



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

1. Standard ISM accelerated by forward shock

$X(\text{GCR}) = X(\text{ISM})$
Secondary BeB



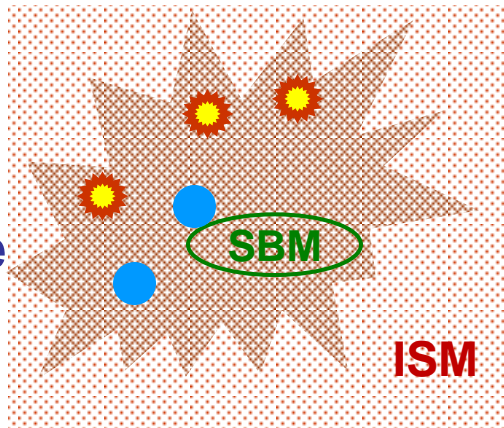
2. SN interior accelerated by reverse shock (RS)

$X(\text{GCR}) = X(\text{SN})$
Primary BeB



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

$X(\text{GCR}) \sim X(\text{SN})$
Primary BeB



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

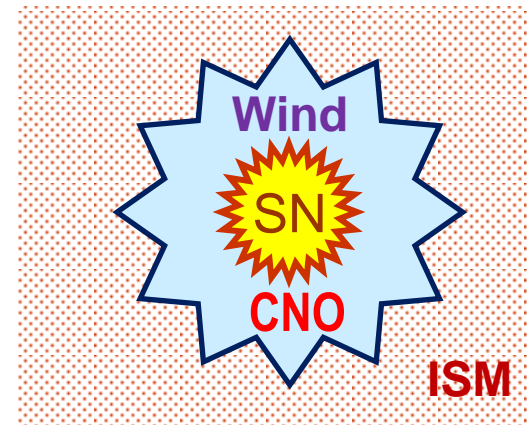
B) SN are observationally associated with HII regions, with widely different metallicities

A) Energetically unfeasible (reverse shock too weak)

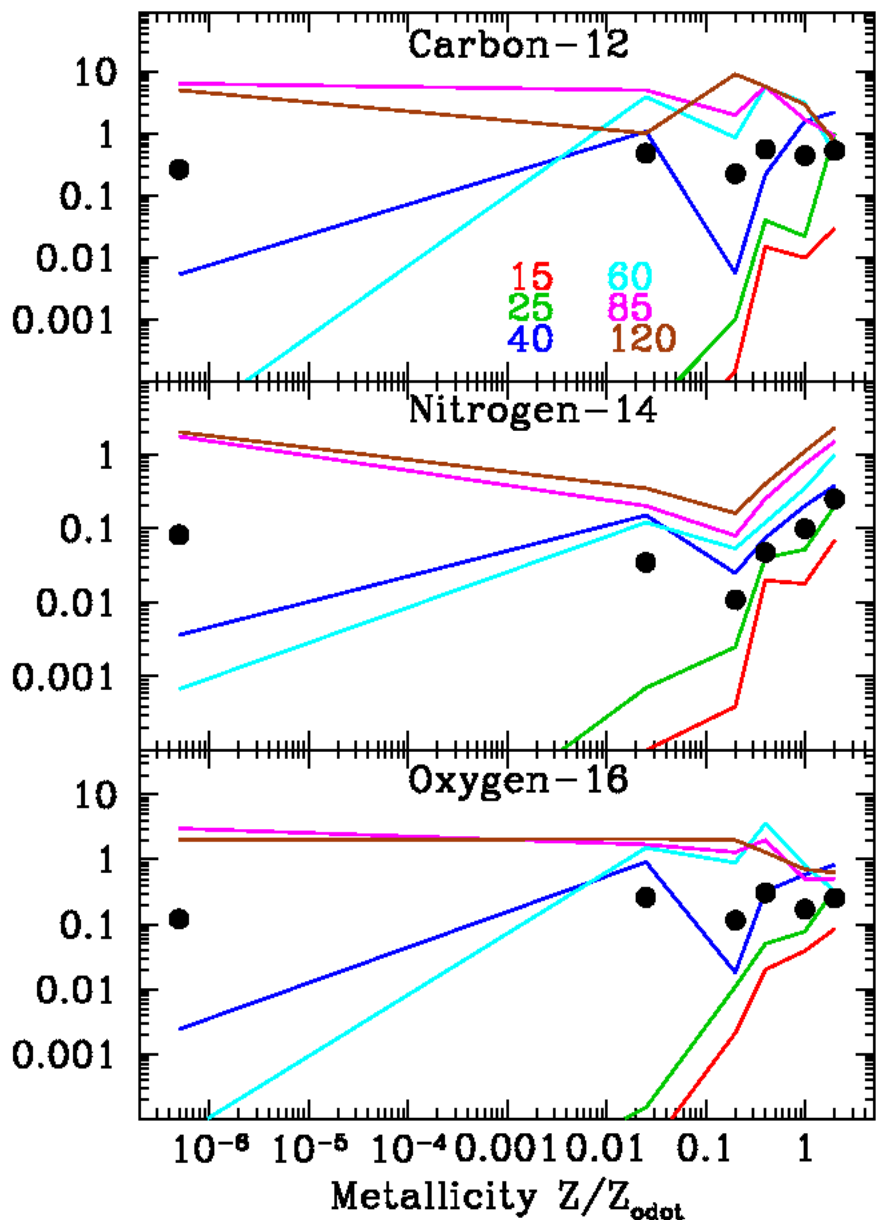
B) Absence of radioactive Ni59 ($\tau \sim 10^5$ yr) in observed GCR (Wiedenbeck et al. 1998) requires $\Delta t > 3 \cdot 10^5$ yr between SN explosion and GCR acceleration

4. Massive star wind accelerated by forward shock

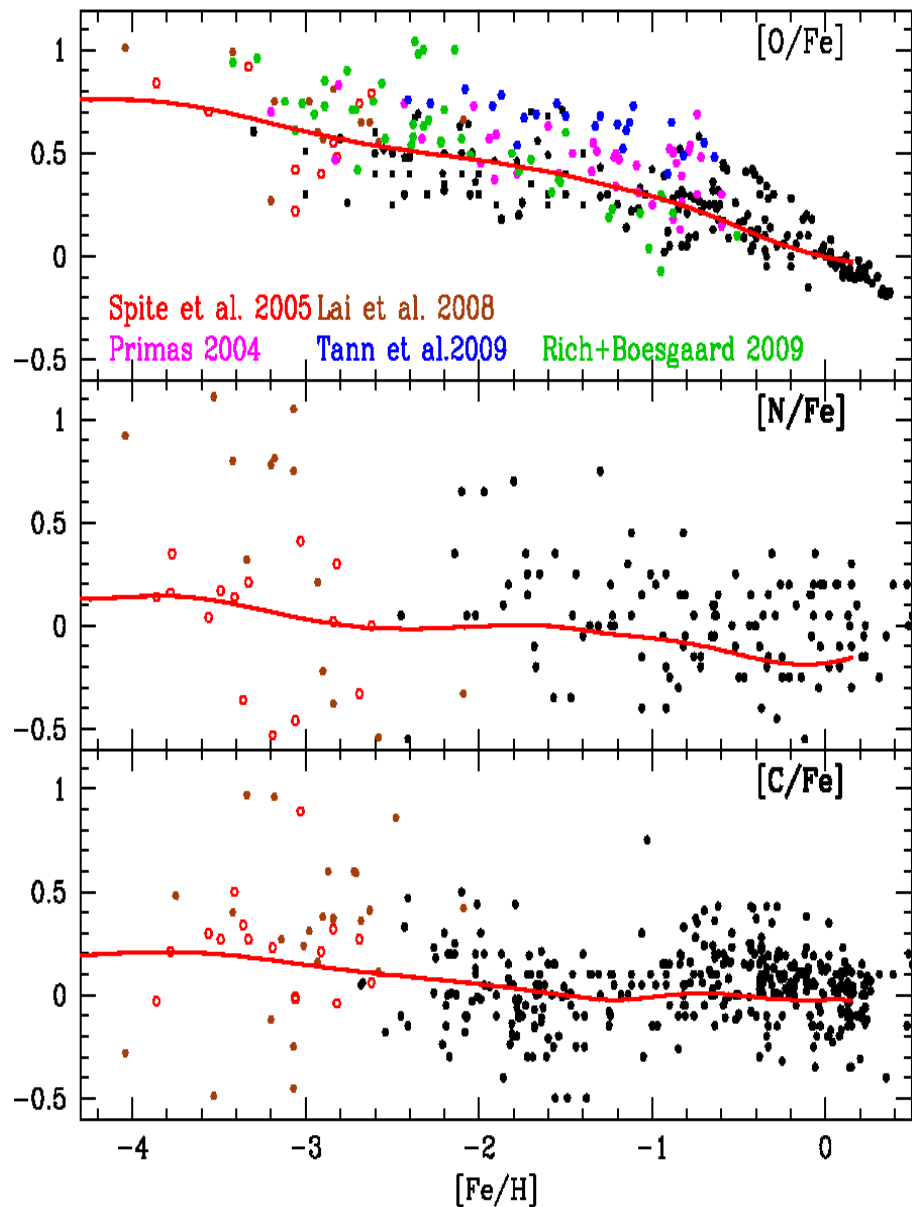
$X_{\text{CNO}}(\text{GCR}) \sim X_{\text{CNO}}(\text{Wind})$
Primary BeB
BUT $X_{\text{Heavy}}(\text{GCR}) \neq X_{\text{Heavy}}(\text{ISM})$



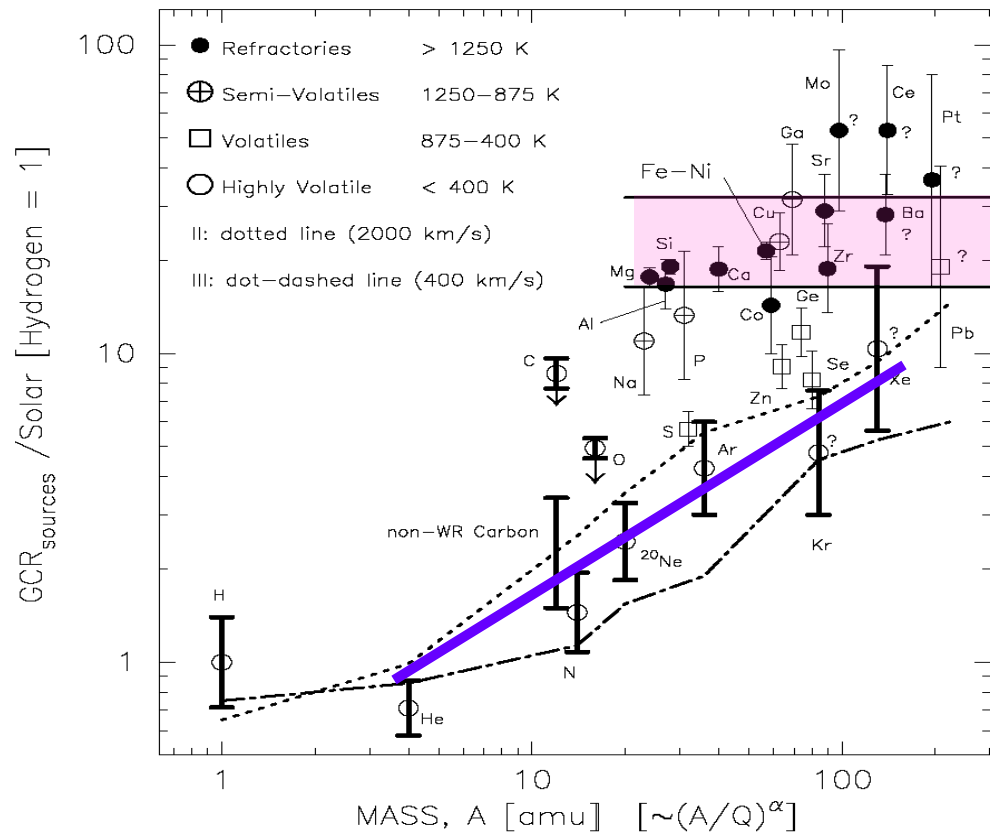
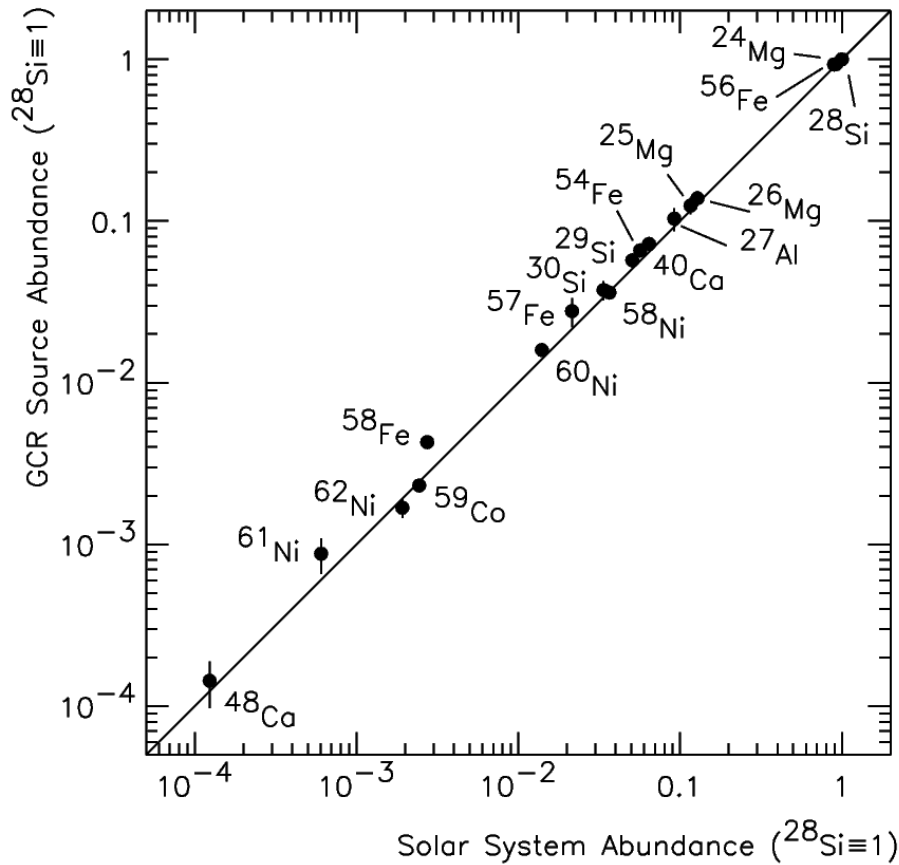
Yields of CNO (in M_{\odot}) in winds of massive rotating stars (*Geneva models*)



Such yields explain naturally the observations of primary N in early Galaxy



Galactic Cosmic Ray SOURCE composition



Is it solar ? **Yes, for most isotopic ratios** **Volatiles:** elements with high A/Q (mass to charge) favored

No, for elemental ratios \Rightarrow **Selection effects** **Refractories:** overabundant, but no clear trend with A/Q

Ellison, Meyer, Drury (1997): SN shocks accelerate ISM gas (volatiles) and sputtered grains (refractories)

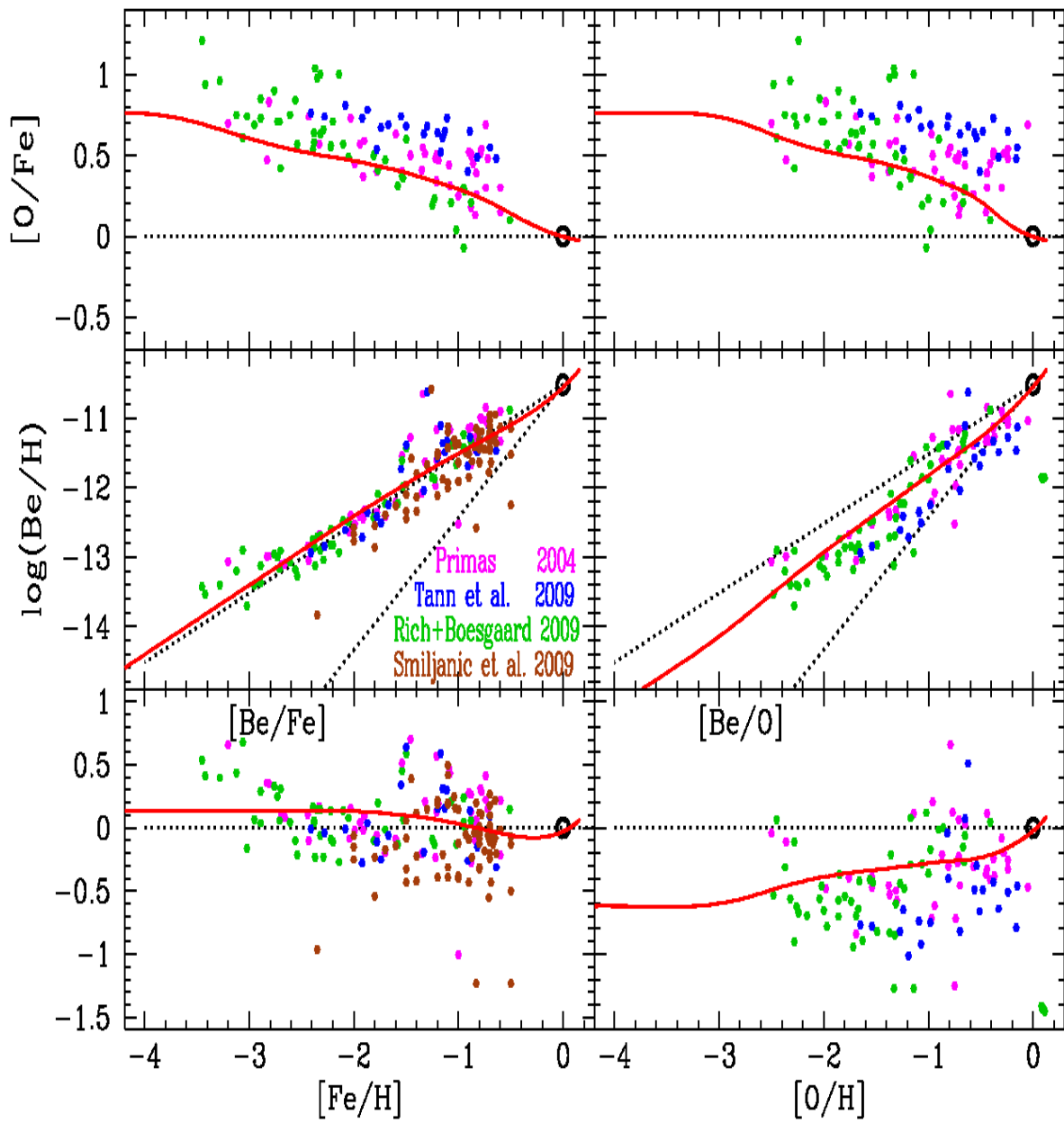
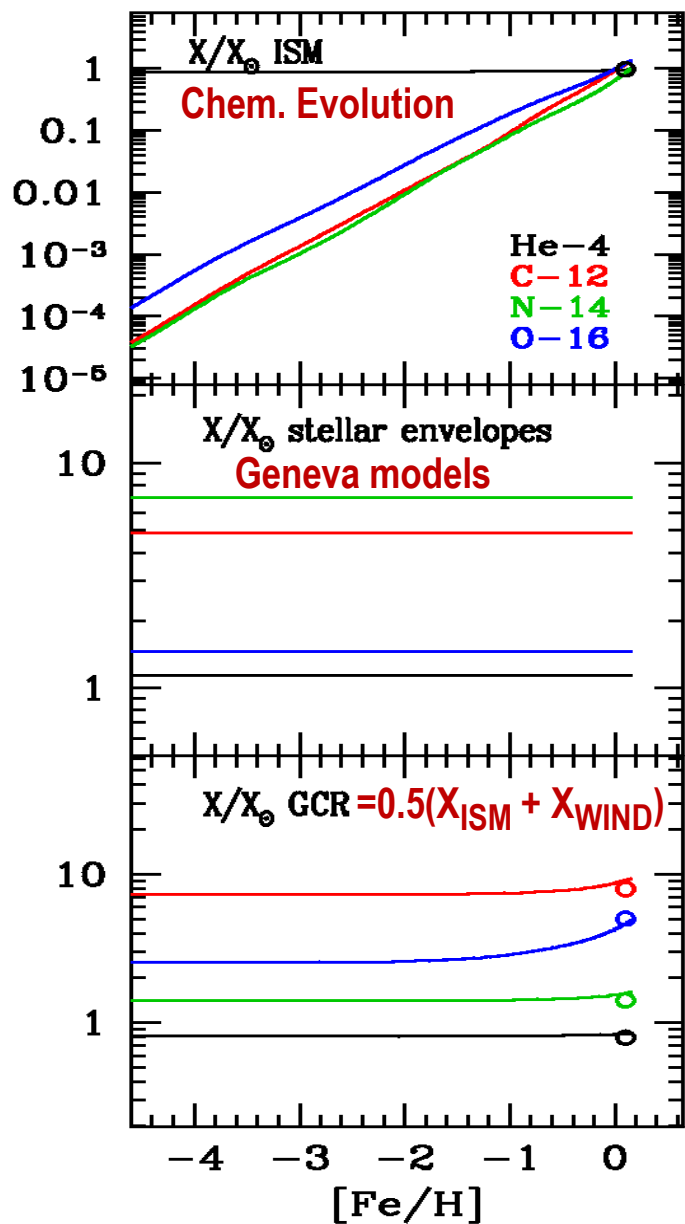
CNO overabundant by ~ 1.5 to 8 ; Most excess CNO attributed to WR stars

After taking into account several selection effects, it seems that the Source composition of GCR today is \sim solar.

What about the GCR metallicity in the early Galaxy ?

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

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



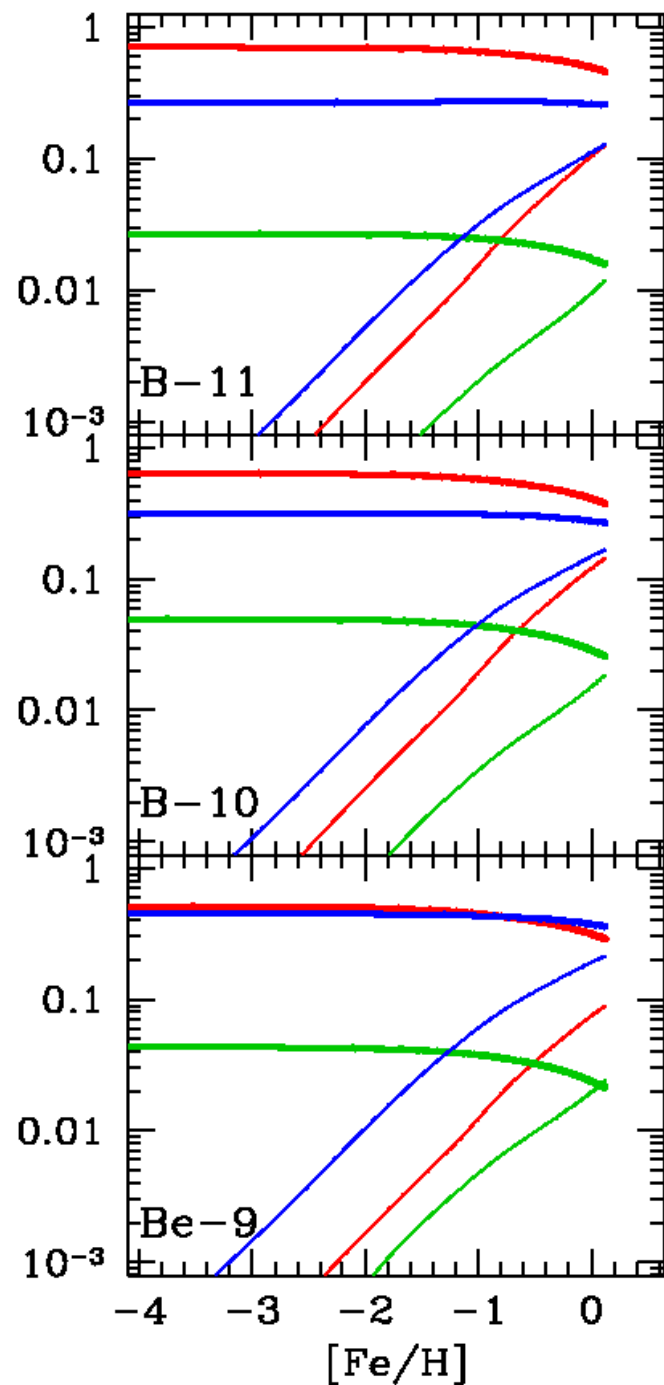
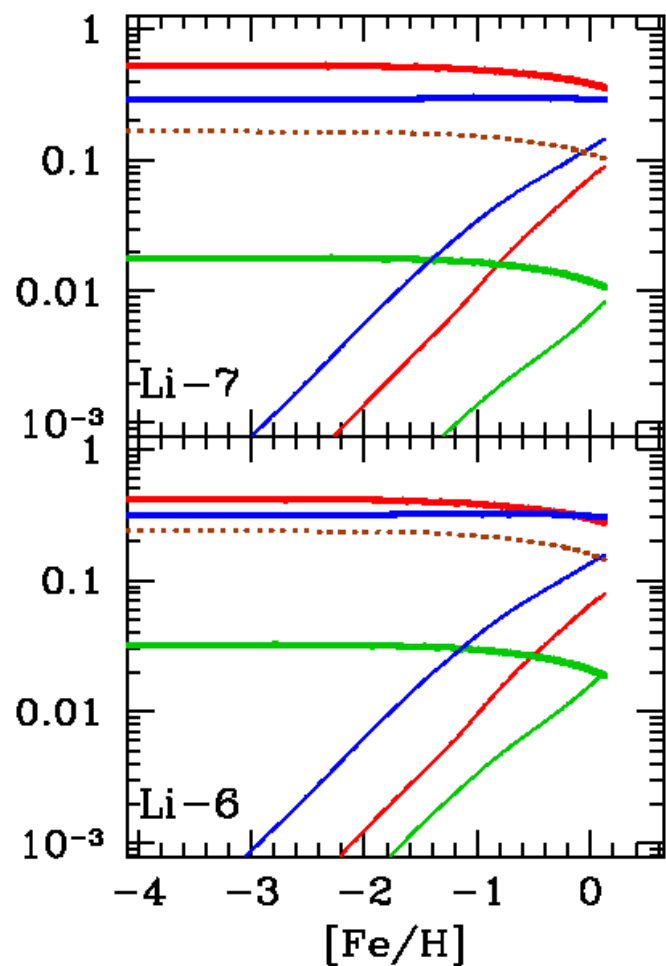
Components of LiBeB from GCR

Fast CNO

Fast p, α

C N O

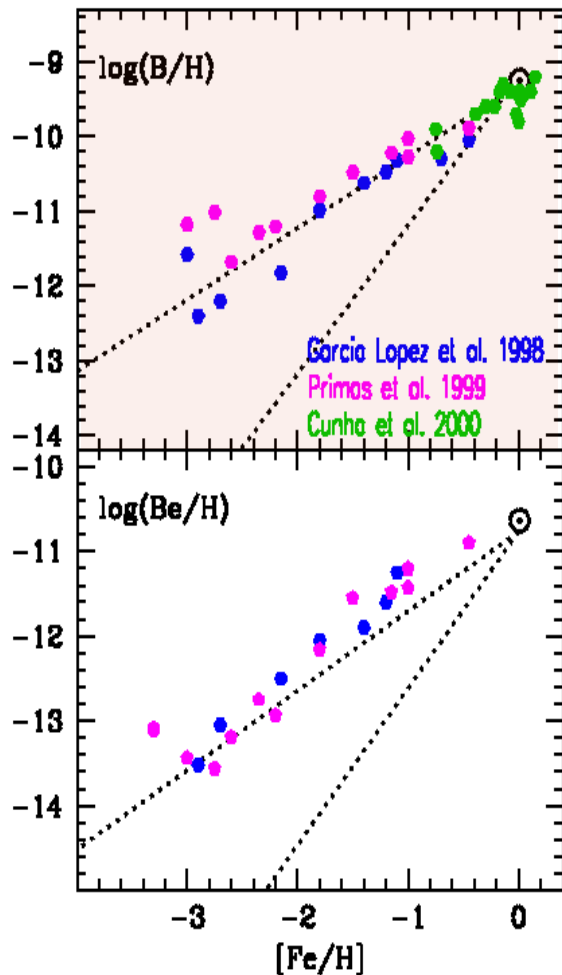
$\alpha + \alpha$



**Boron observations
(< 2000)**

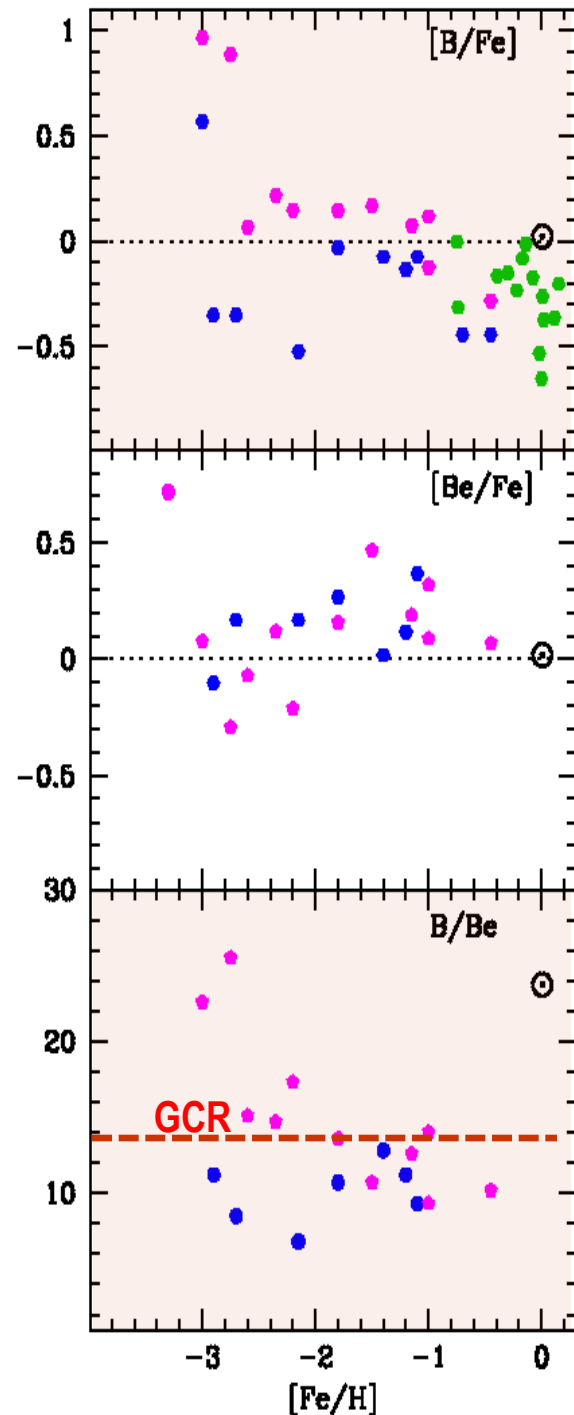
Primary, as Be

(fewer data, larger scatter)

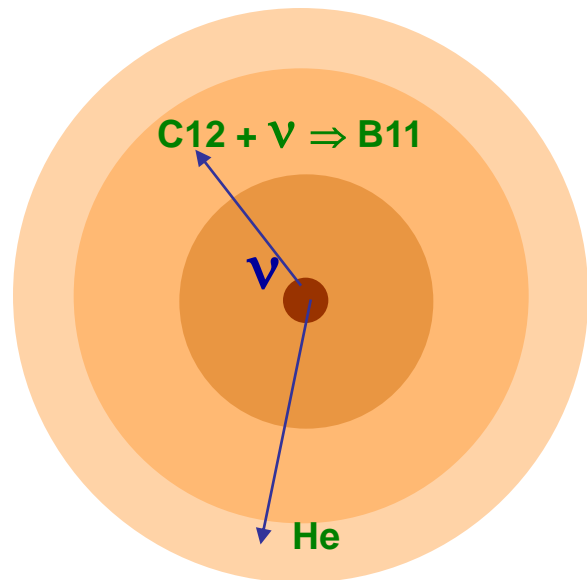


**B/Be ratio vs Fe/H ~ 14 (just from GCR)
albeit with VERY large error bars**

But Solar B/Be ~ 24 !



**Production of primary B11
(and some Li7) in CCSN by
neutrino-induced
nucleosynthesis
(Woosley et al. 1990)**

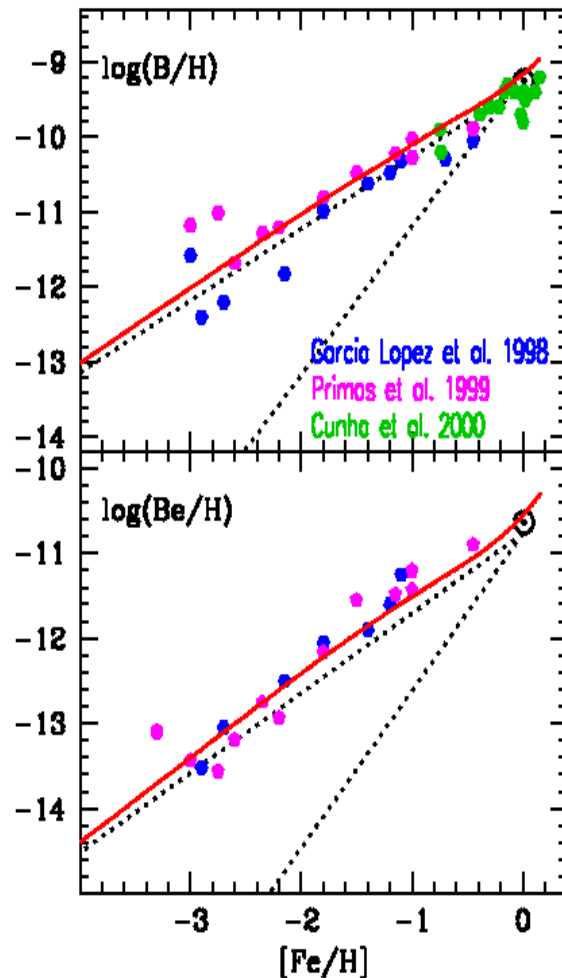


**Neutrinos from CCSN spallate C12
in C-shell and produce B11 (primary)
and He4 in He-shell and produce He3**

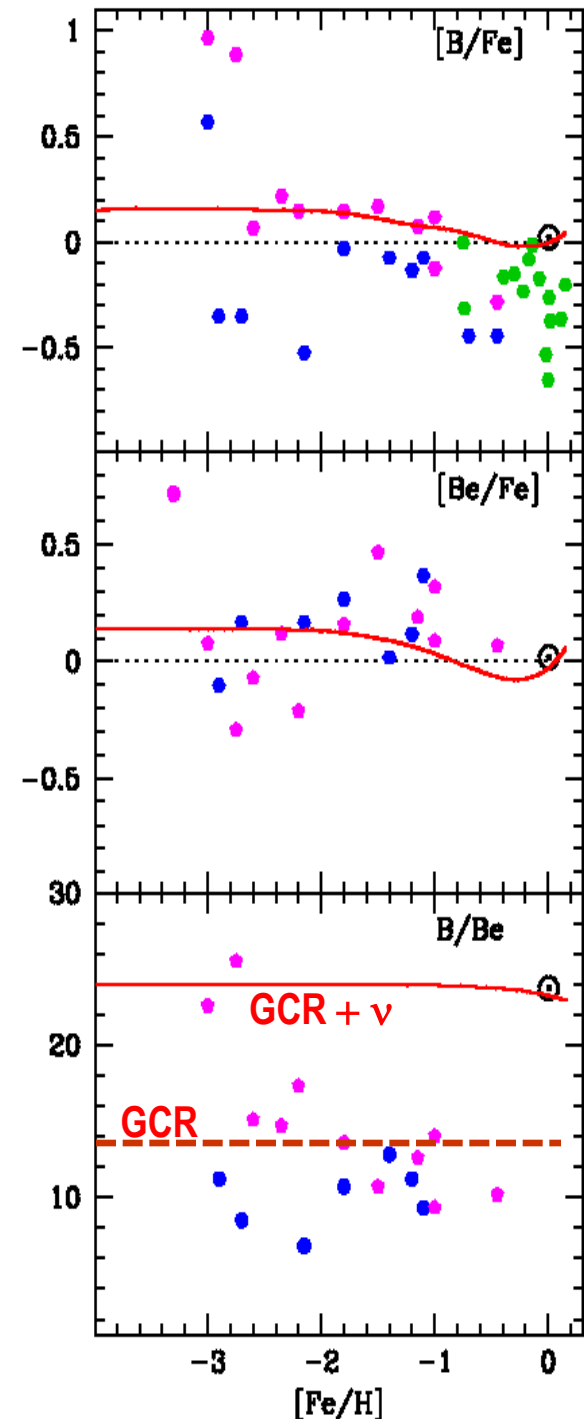
then : He3 + He4 → Li7 (primary)

**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] ?**



Evolution of Li isotopes

What is the pre-galactic Li_{TOTAL} ?

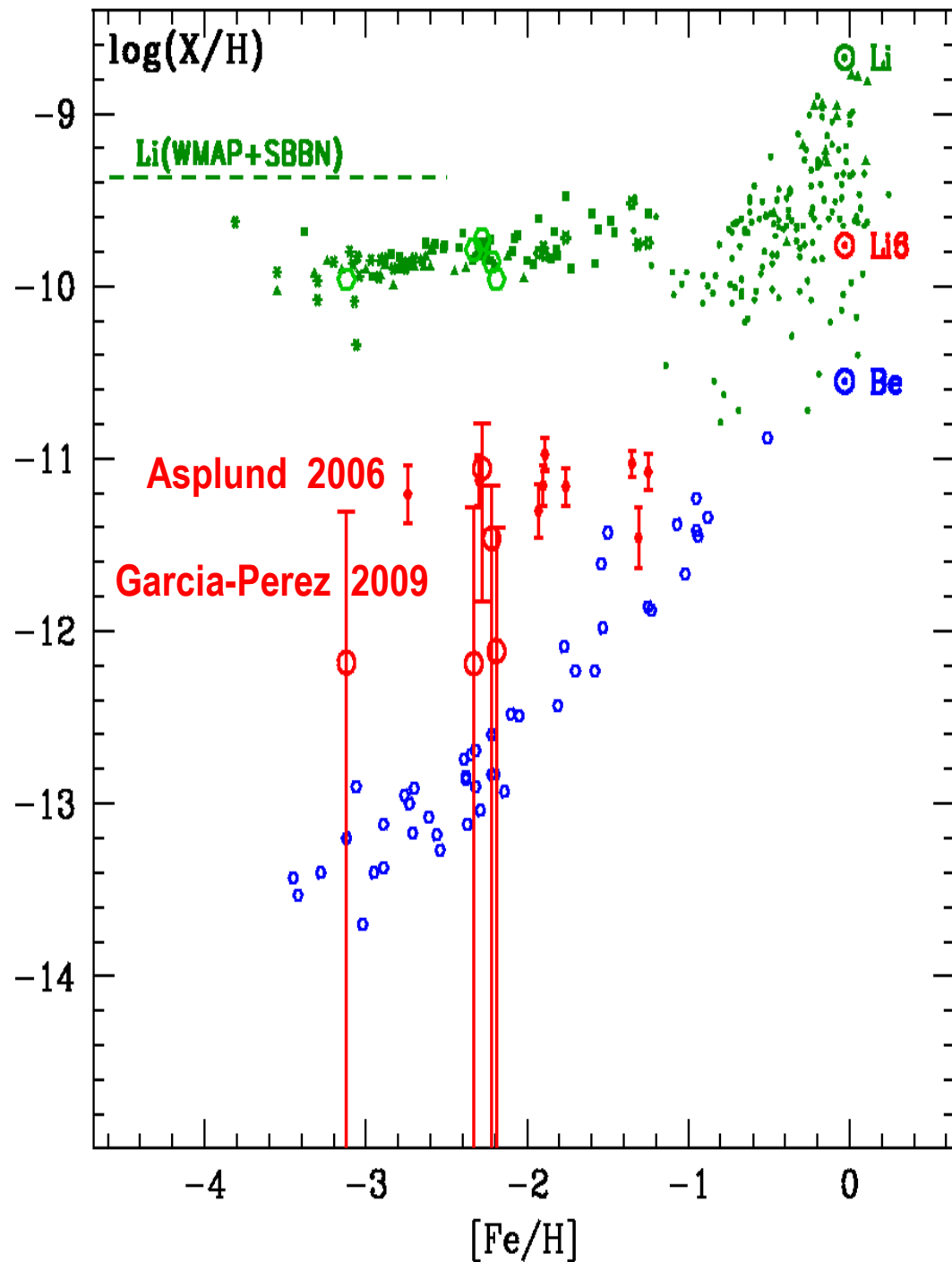
WMAP (Li-7) or "Spite plateau"?

What is the early Li6 value ?

Asplund "upper envelope"?

Lower ?

None et all ?



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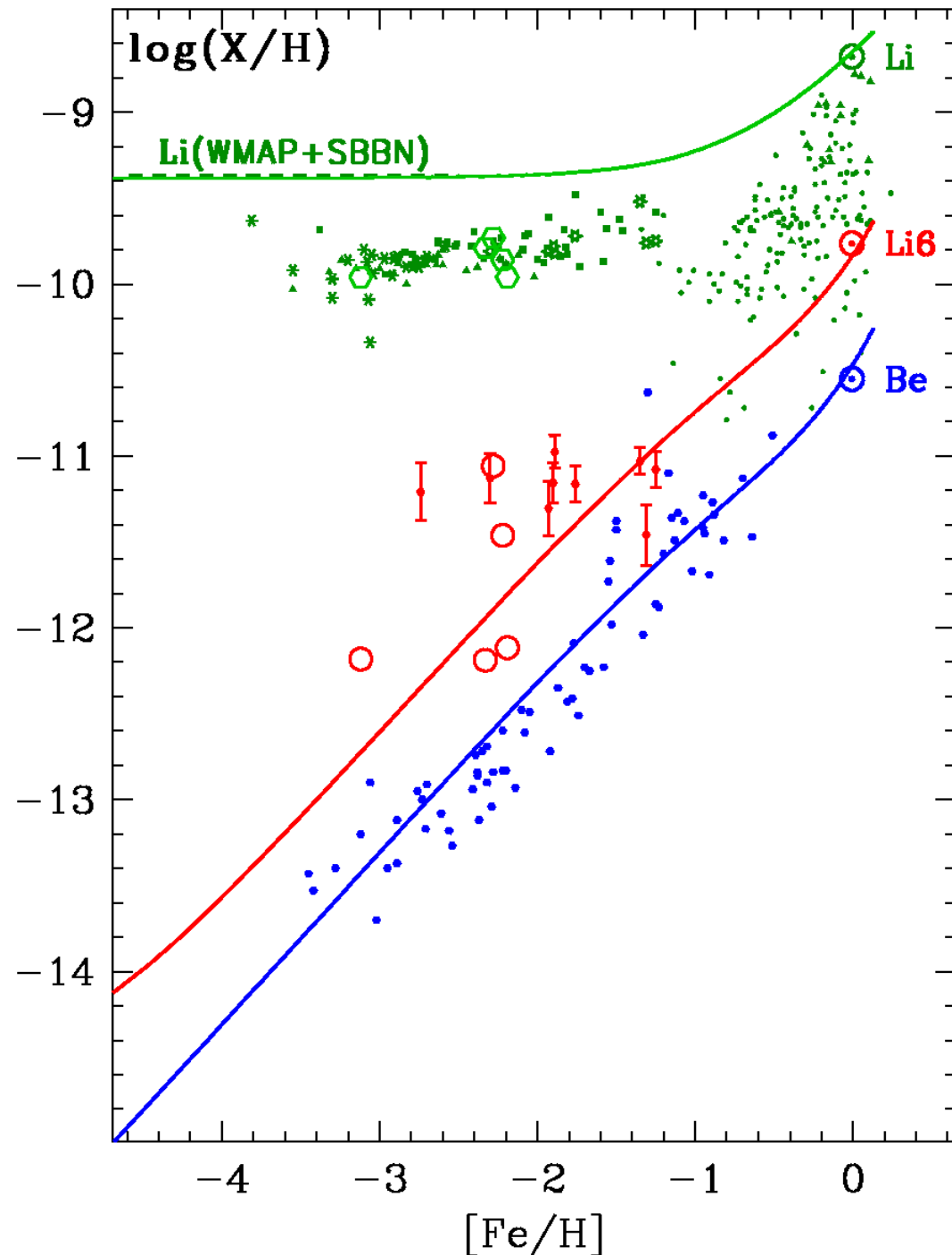
Lower ?

None et all ?

Standard GCR (reproducing Be9)

fail by >10 to reproduce

Asplund06 Li6 at $[\text{Fe}/\text{H}] = -2.7$



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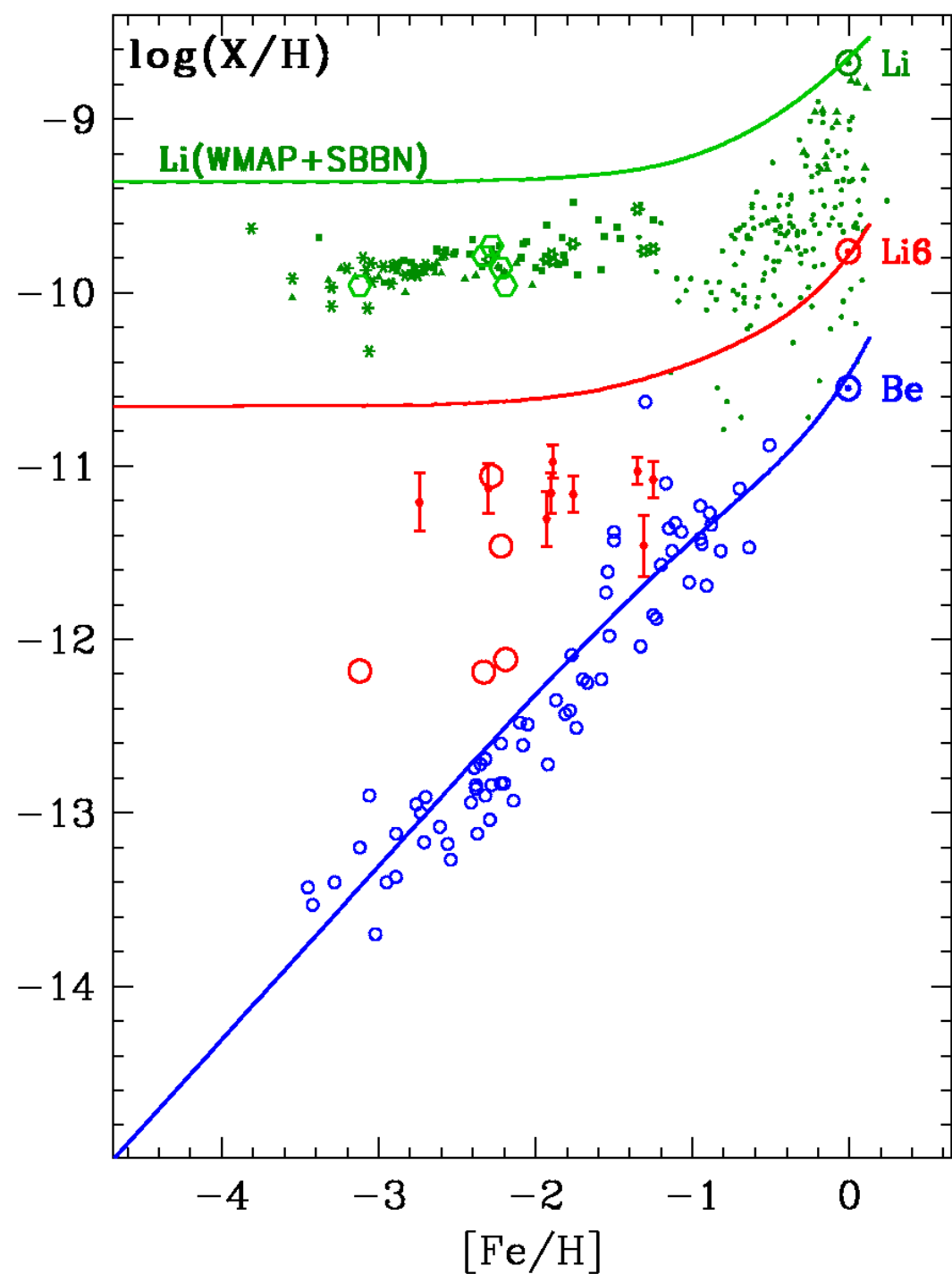
Standard GCR (reproducing Be9)

fail by >10 to reproduce

Asplund06 Li6 at $[\text{Fe}/\text{H}] = -2.7$

and by a much larger amount if

$\text{Li}(\text{WMAP})$ is correct



Energetics of early Li6 formation (*Prantzos 2006*)

Energy required (Normal CR spectrum, only $\alpha+\alpha$): 16 erg/Li6

For $\text{Li6/H} = 10^{-11}$: Energy required: 10^{14} erg/gr (= 10^{14} erg in fast particles for each gr of ISM)

Note: for a spectrum of Low Energy particles, (10-50 MeV/N) ~ 3 times less energy required

Mass of MW halo : $5 \cdot 10^8 M_{\odot} \sim 10^{42}$ gr

Energy (for $\text{Li6/H} \sim 10^{-11}$) $\sim 10^{56}$ erg , or 10^5 CCSN

If normal CCSN (10^{51} erg and $0.1 M_{\odot}$ of Fe), they enrich the ISM to $[\text{Fe/H}] \sim -1$

They have to eject normal kinetic energy but 50 times less metals than normal SN!

Shocks from structure formation (*Suzuki and Inoue 2002*)

Velocity $V_{\text{Virial}} \sim (GM/R)^{1/2} \sim 400 (M_{\text{DarkHalo}}/10^{13} M_{\odot})^{1/3}$ km/s

In Milky Way: $M_{\text{DarkHalo}} \sim 10^{12} M_{\odot}$, $V_{\text{Virial}} \sim 200$ km/s

$E_{\text{shock}} \sim \frac{1}{2} m v^2$ and energy per unit mass $\varepsilon \sim 2 \cdot 10^{14}$ erg/gr

OK, for an efficiency of 50% (normal spectrum) but full DM halo NOT in place so early !

Collapse to black hole: Energy extracted (jet or wind \Rightarrow shock) = $\eta M_{\text{BlackHole}} c^2$, $\eta \sim 0.1$

For Milky Way: $M_{\text{BlackHole}} \sim 3 \cdot 10^6 M_{\odot} \Rightarrow$ Energy $\sim 5 \cdot 10^{59}$ erg

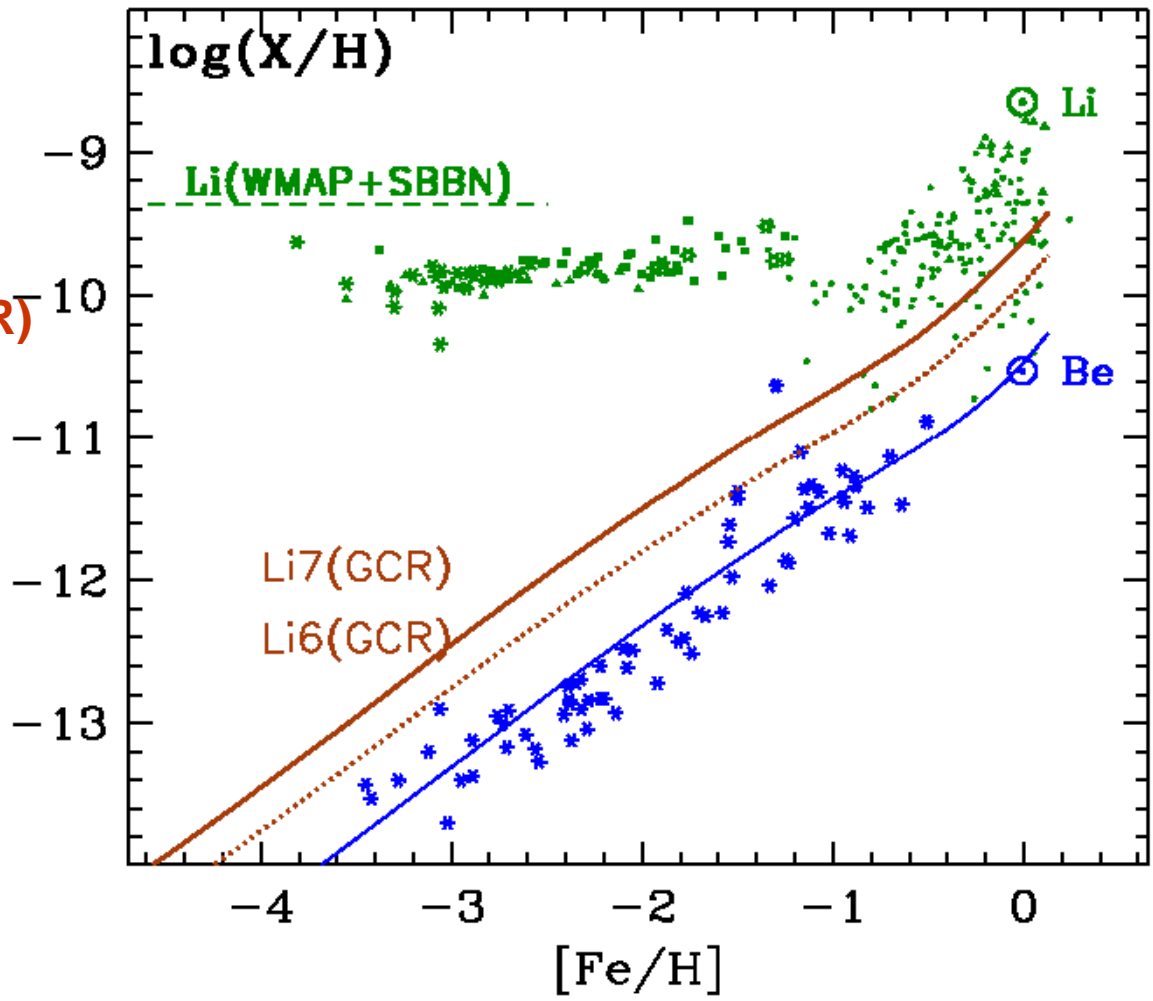
For M_{Gas} (Milky Way) $\sim 5 \cdot 10^{10} M_{\odot} \sim 10^{44}$ gr, Specific energy \sim Energy/ $M_{\text{Gas}} \sim 5 \cdot 10^{15}$ erg/gr

Chromospheric activity on surfaces of low mass stars (*Tatischeff and Thibaud 2007*)

Evolution of Li_{TOTAL}

$$\text{Li}_{\text{TOTAL}} = \text{Li7(GCR)} + \text{Li6(GCR)}$$

(Calibrated on Be9)

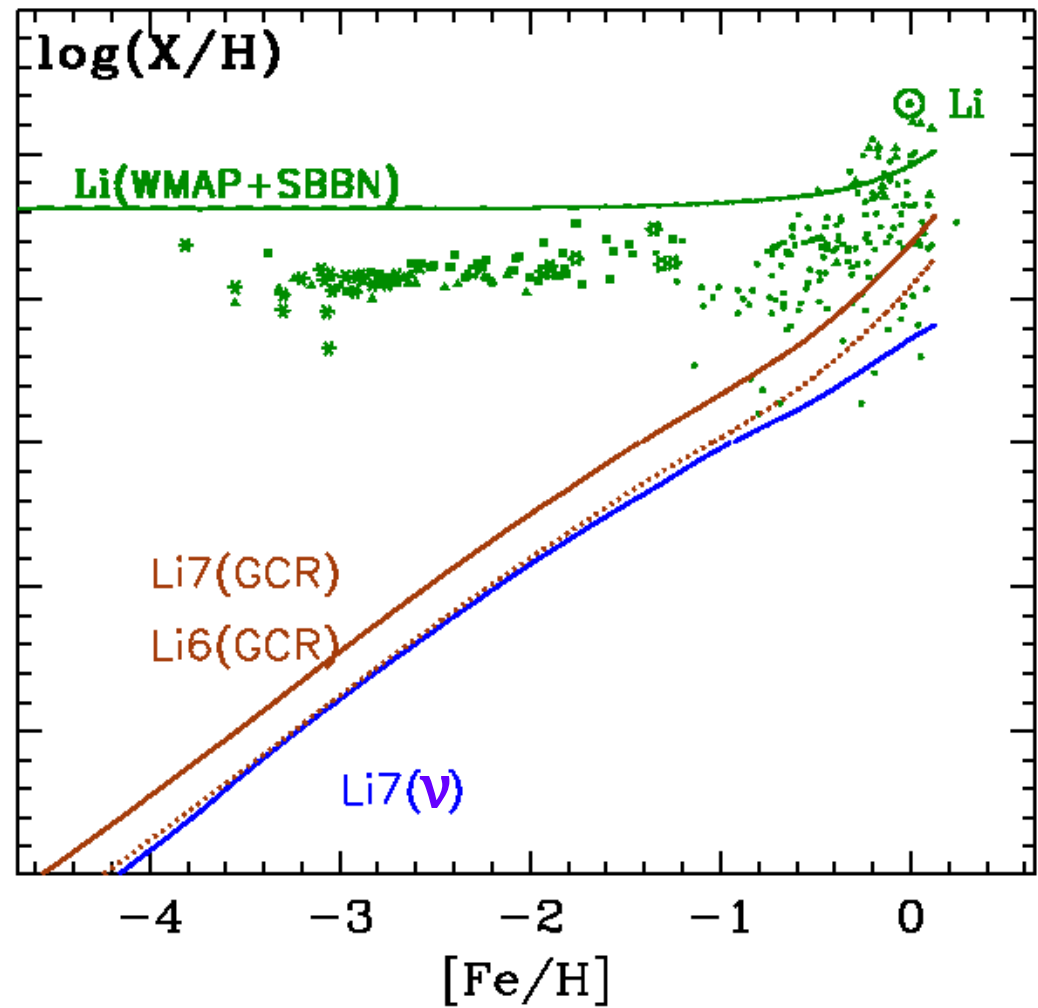


Evolution of Li_{TOTAL}

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

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

+ Li7 (pre-galactic)



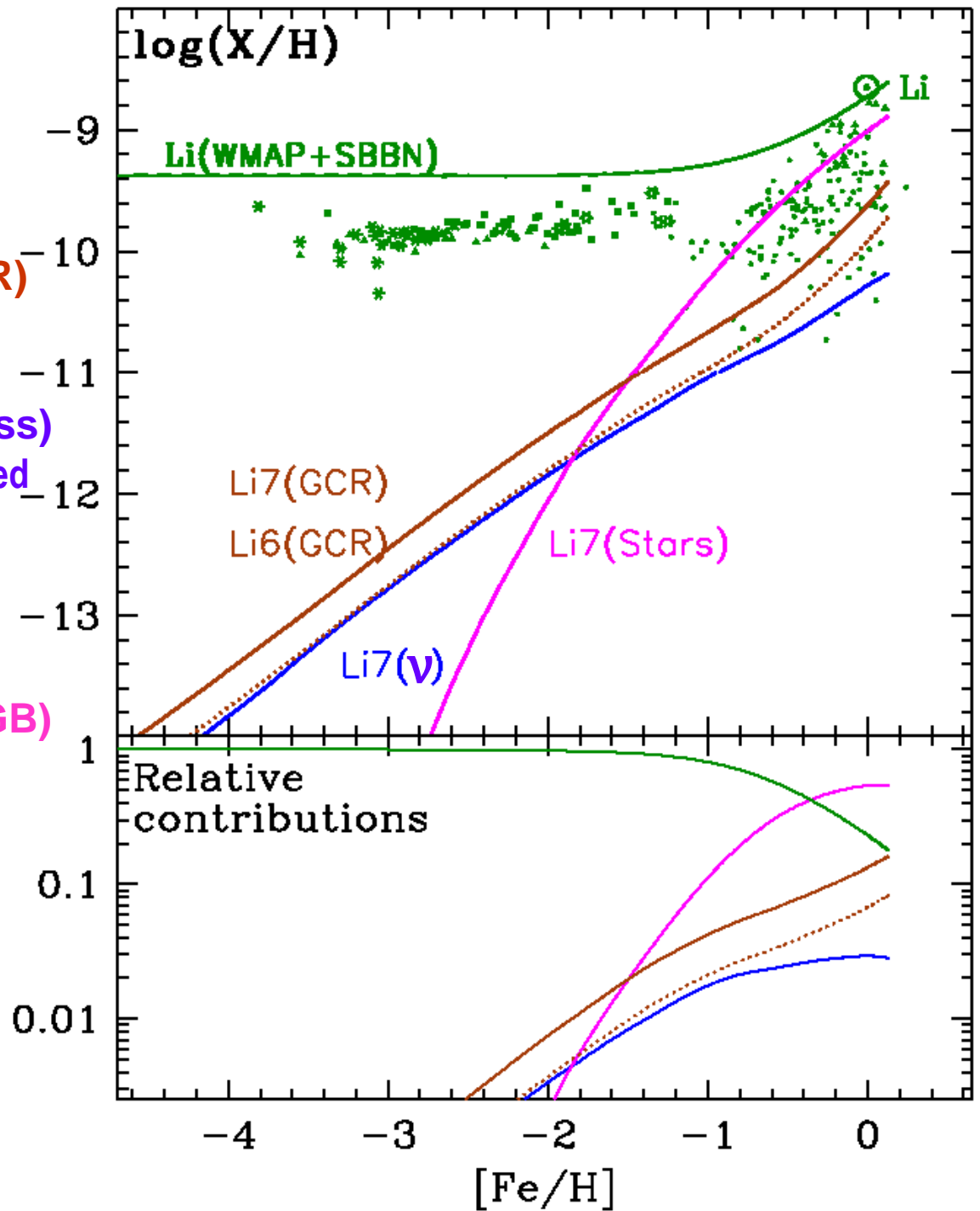
If $\text{Li7}(\text{pre-galactic}) = \text{Li7}(\text{WMAP+SBBN})$
 ~50% of solar Li is still missing

If $\text{Li7}(\text{pre-galactic}) = \text{Li7}(\text{Spite plateau})$
 ~65% of solar Li is still missing

Need for another (late) stellar source

Evolution of Li_{TOTAL}

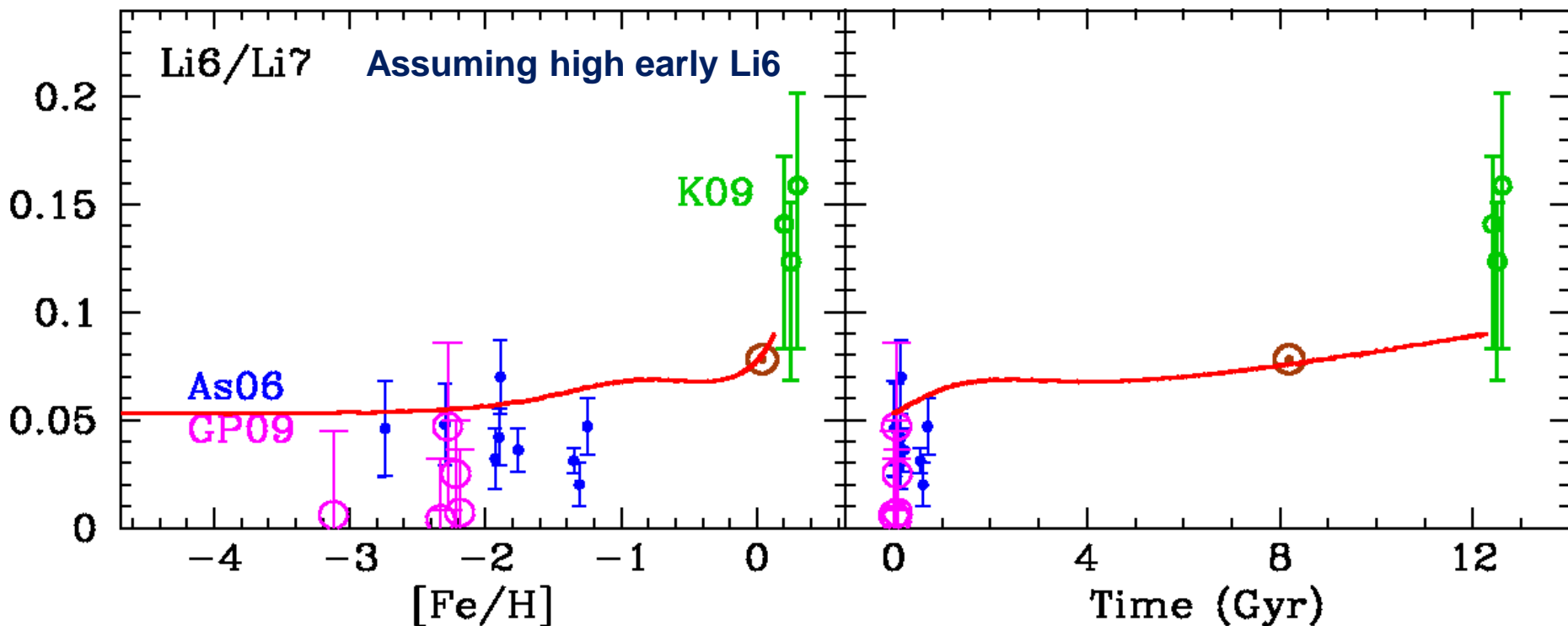
- $\text{Li}_{\text{TOTAL}} = \text{Li7(GCR)} + \text{Li6(GCR)}$
 (Calibrated on Be9)
- + Li7(neutrino process)
 (SN yields of Li7 reduced by 6, as for B-11 yields)
 - + Li7 (pre-galactic)
 - + Li7 (nova and/or AGB)



Observations of Li6/Li7 in local ISM (Kawanomoto et al. 2009)

provide some hints for
differential evolution of Li6 vs Li7
in past 4.6 Gyr

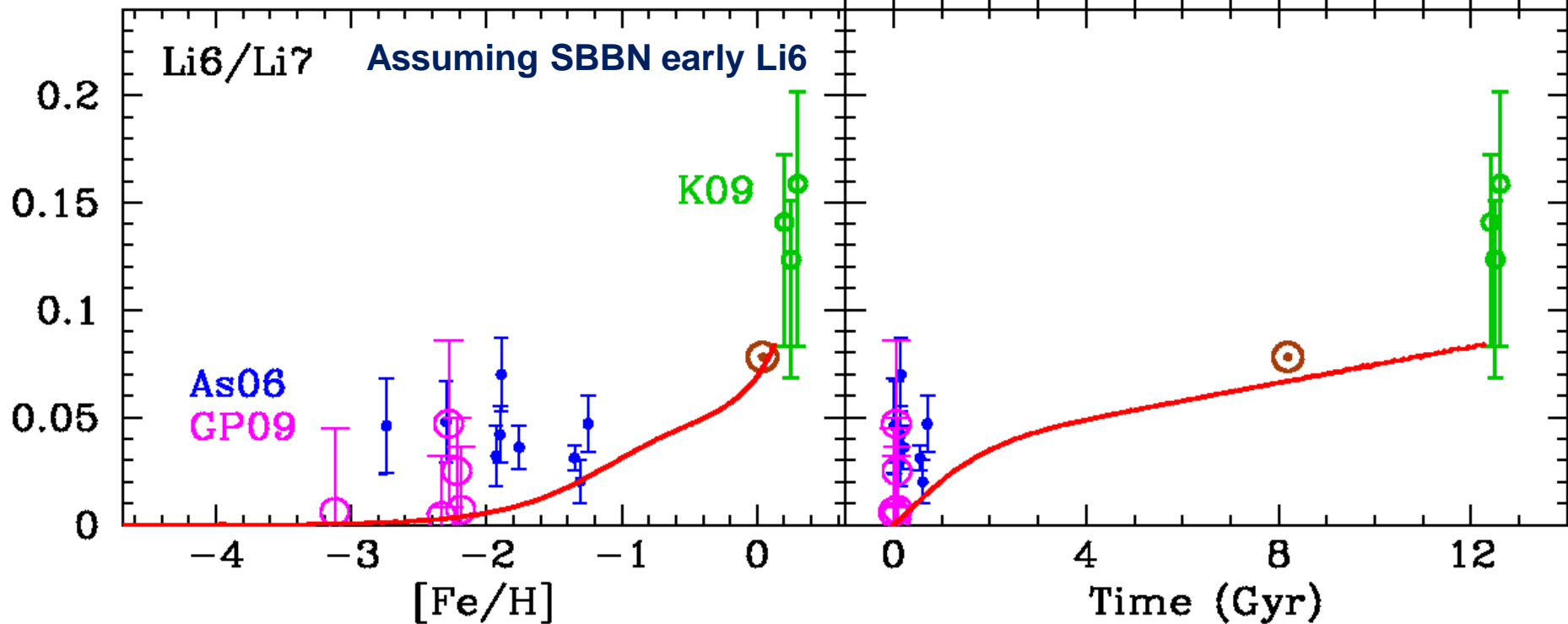
**GCE models DO PREDICT
a SMALL effect**



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GCE models DO PREDICT
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Contributions (%) of nucleosynthesis processes to SOLAR LiBeB

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