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

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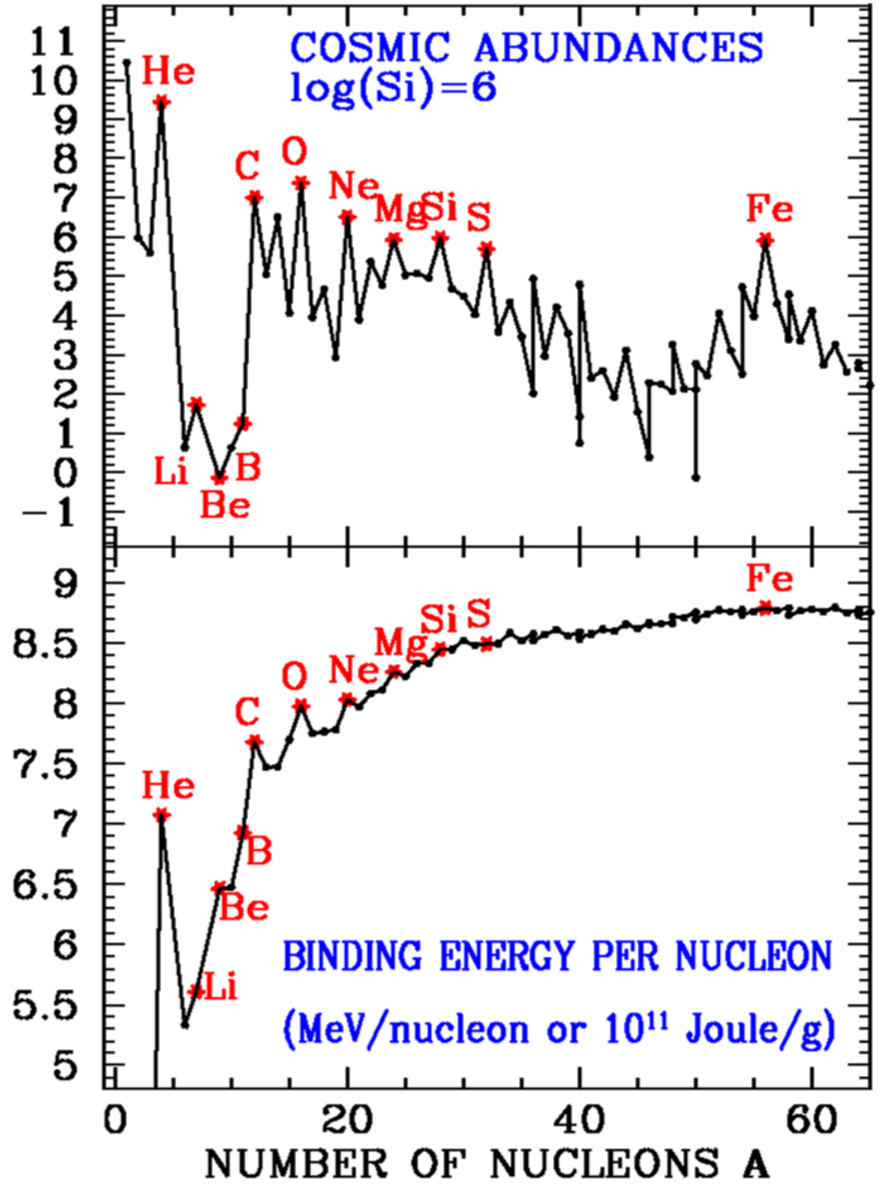
The light elements Li Be B
(Li6, Li7, Be9, B10, B11)

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

Always destroyed in stellar interiors

T(H-burn) = 2.2 MK for Li (1.5 for Li6)
3.5 MK for Be
4.5 MK for B



REVIEWS OF
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Synthesis of the Elements in Stars*

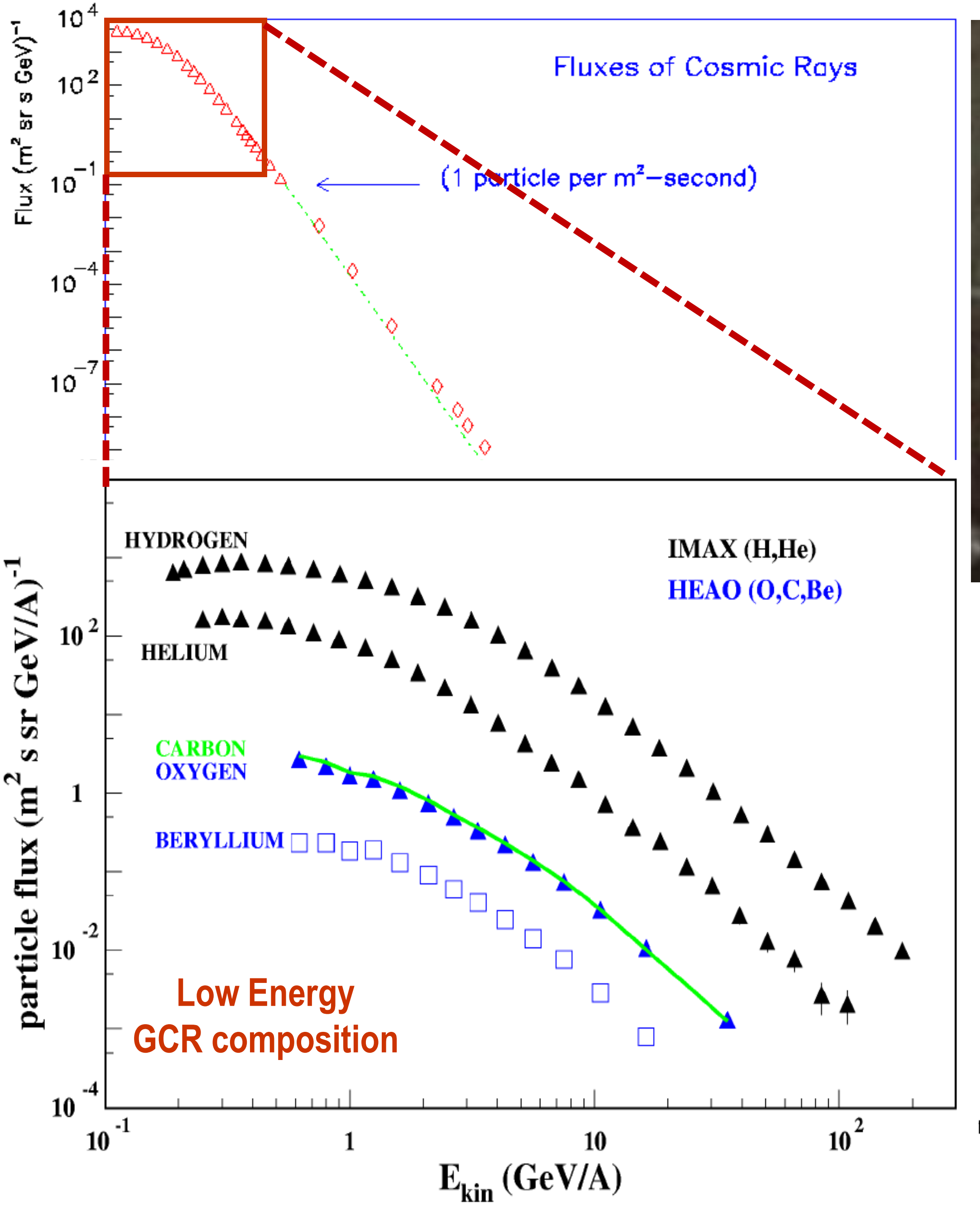
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

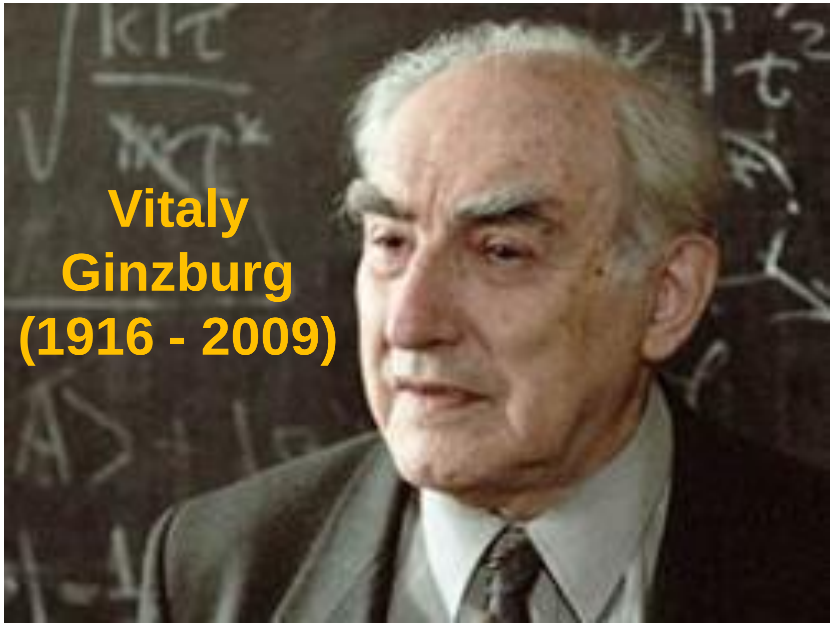
X. x PROCESS

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)





GCR Energetics in Milky Way:

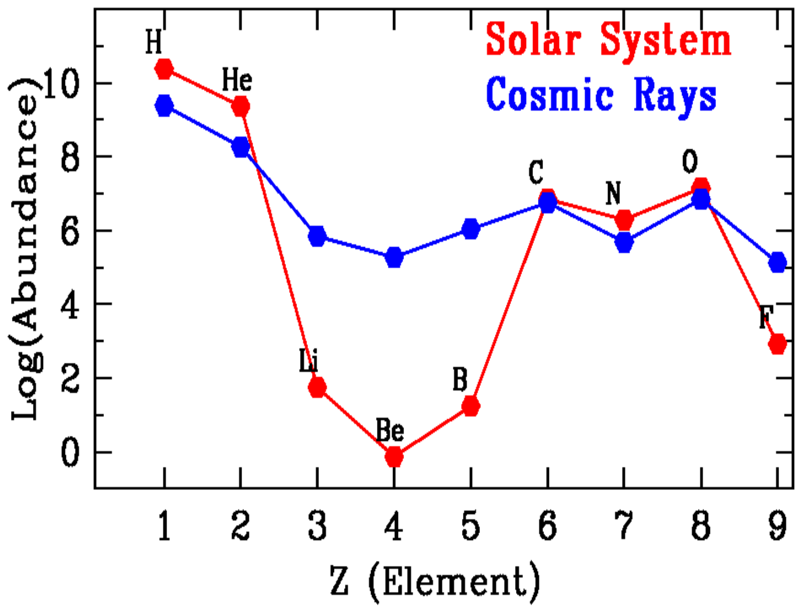
Power(GCR) ~10^{41} erg/s

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

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

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

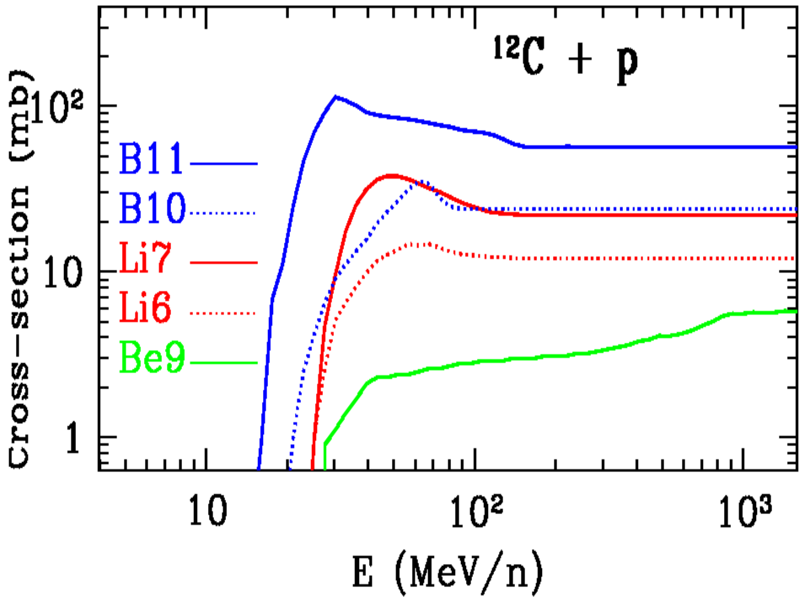
GCR composition is heavily enriched in Li, Be, B (a factor ~10^6 for Be and B)



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*)

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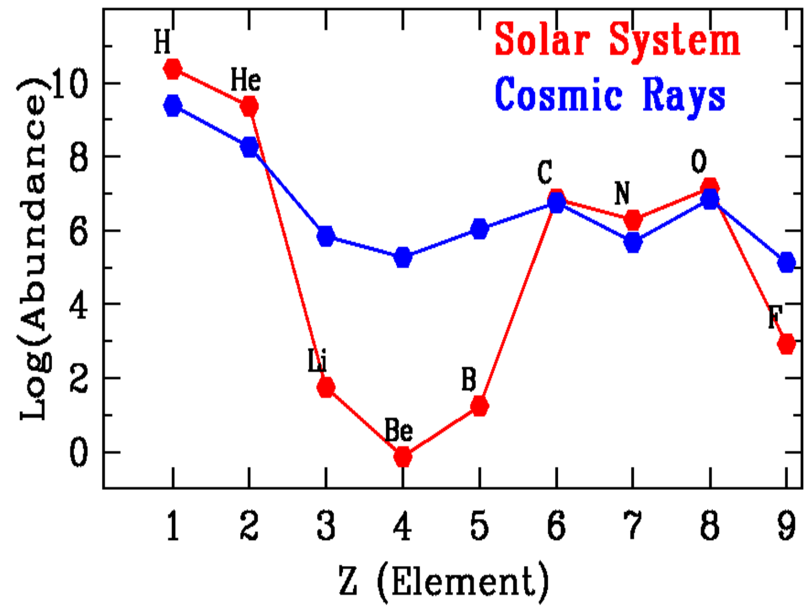

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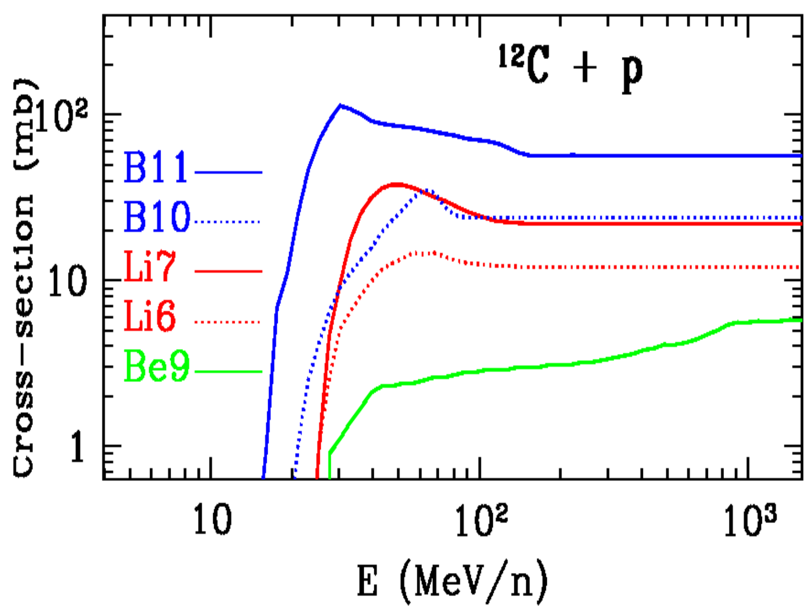


LiBeB is produced by spallation of CNO as GCR propagate in the Galaxy (*Reeves, Fowler, Hoyle 1970*)

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*

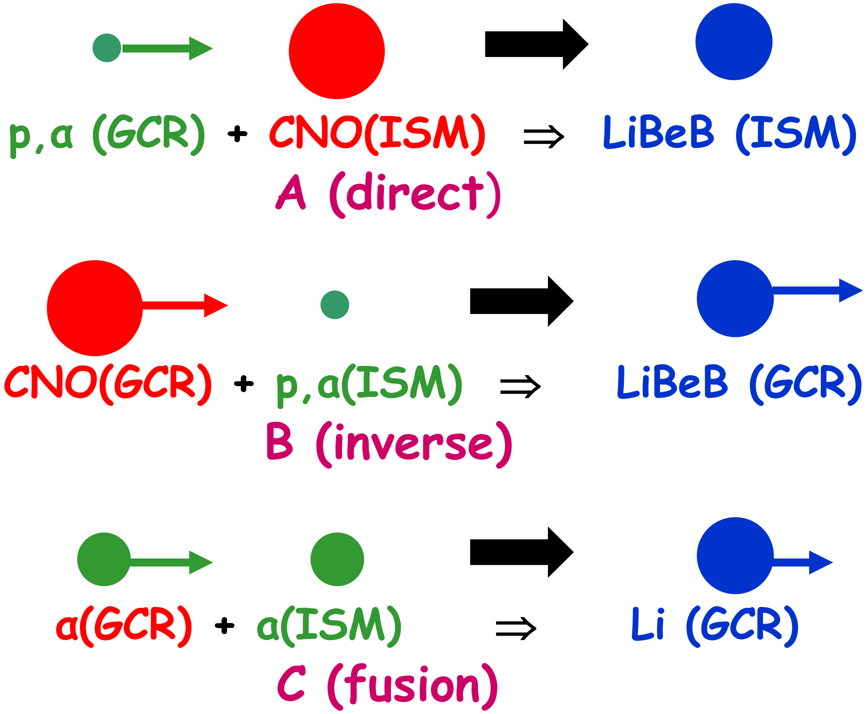
Service d'Electronique Physique, Saclay, and Institut d'Astrophysique de Paris

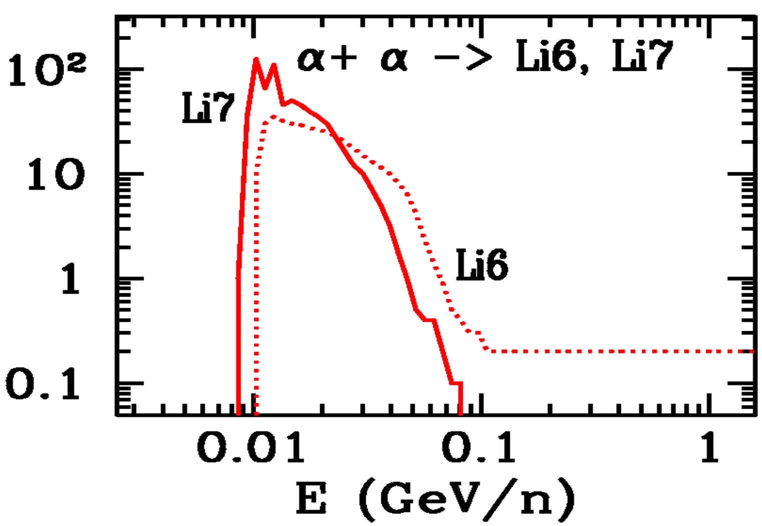
Received May 28, 1971

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.

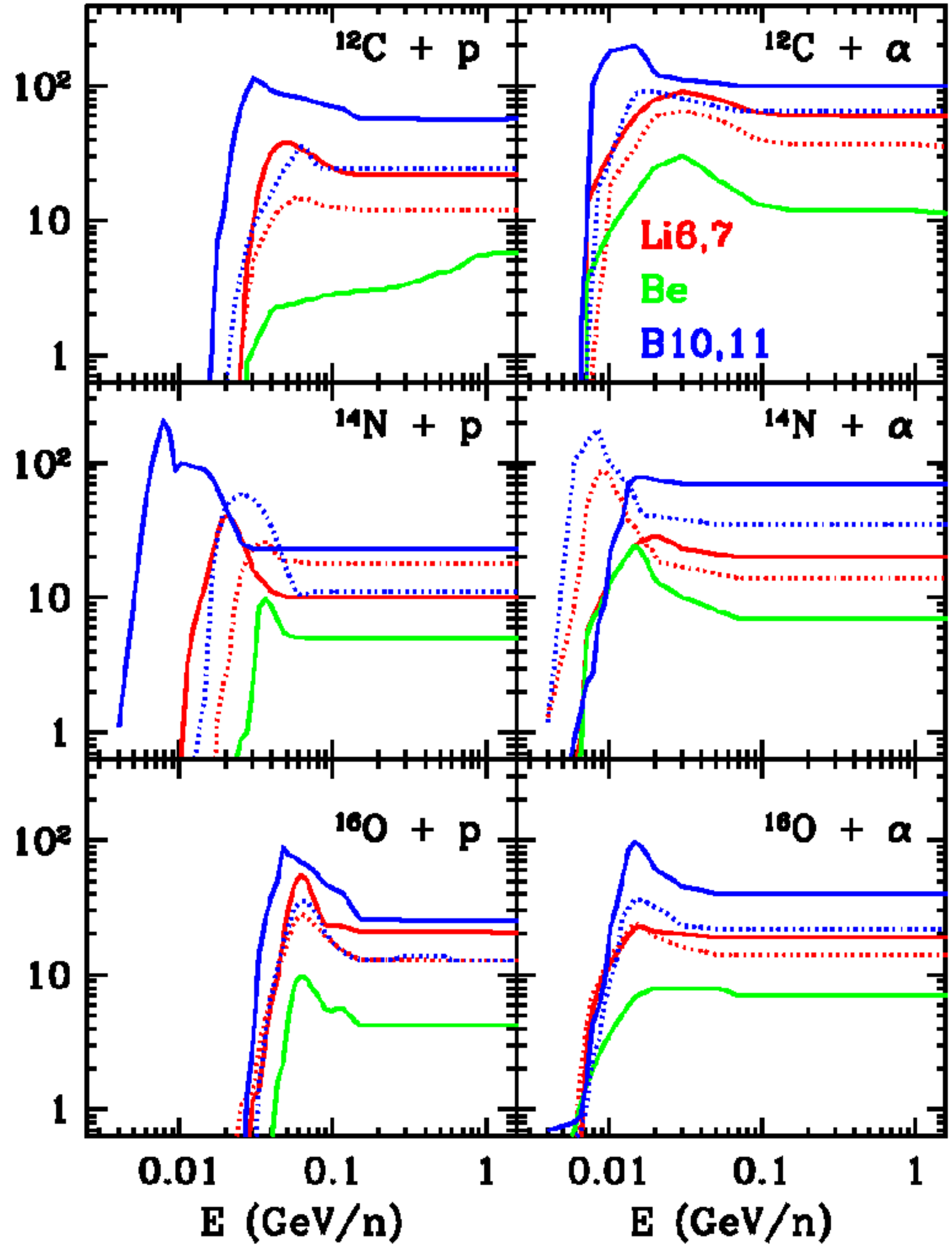
It is found that most of the stellar and meteoritic data is in agreement with a model which otherwise gives a reasonable account of the G.C.R. observations. This model assumes an injection spectrum in total energy power ($W^{-2.6}$) diffusing in a leaking galaxy with an escape range of 6.3 g cm^{-2}. 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}Li must come from another source. Two possibilities are discussed: a) thermonuclear ^{7}Li ejected from Giant Stars in "dirty" regions of our Galaxy, b) spallative ^{7}Li generated from an intense low energy component of the G.C.R.

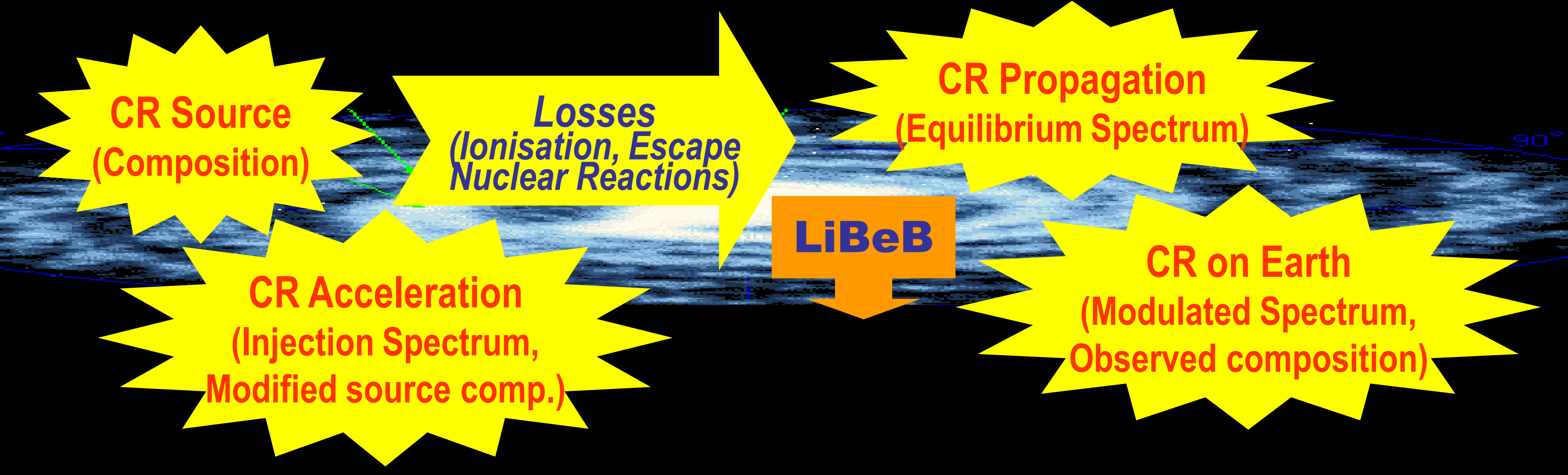


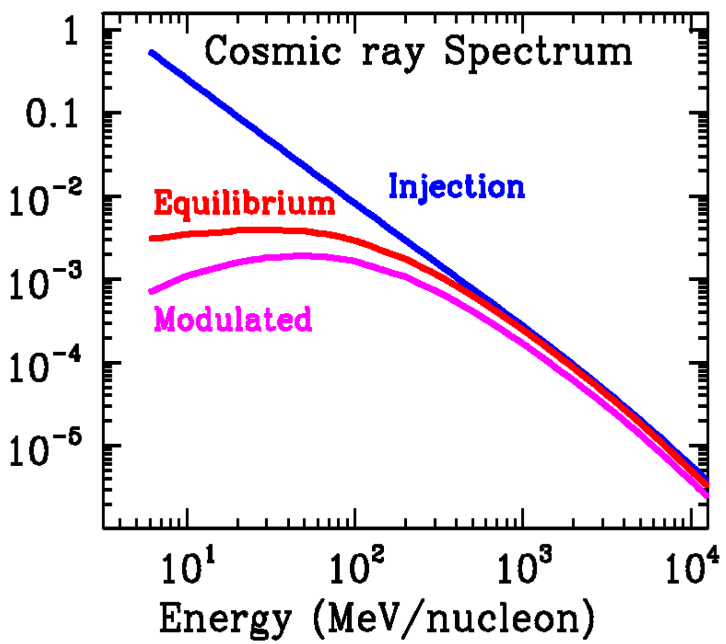


Cross sections (in mb) of p,a + CNO ⇒ LiBeB



Galactic Cosmic Ray Odyssey



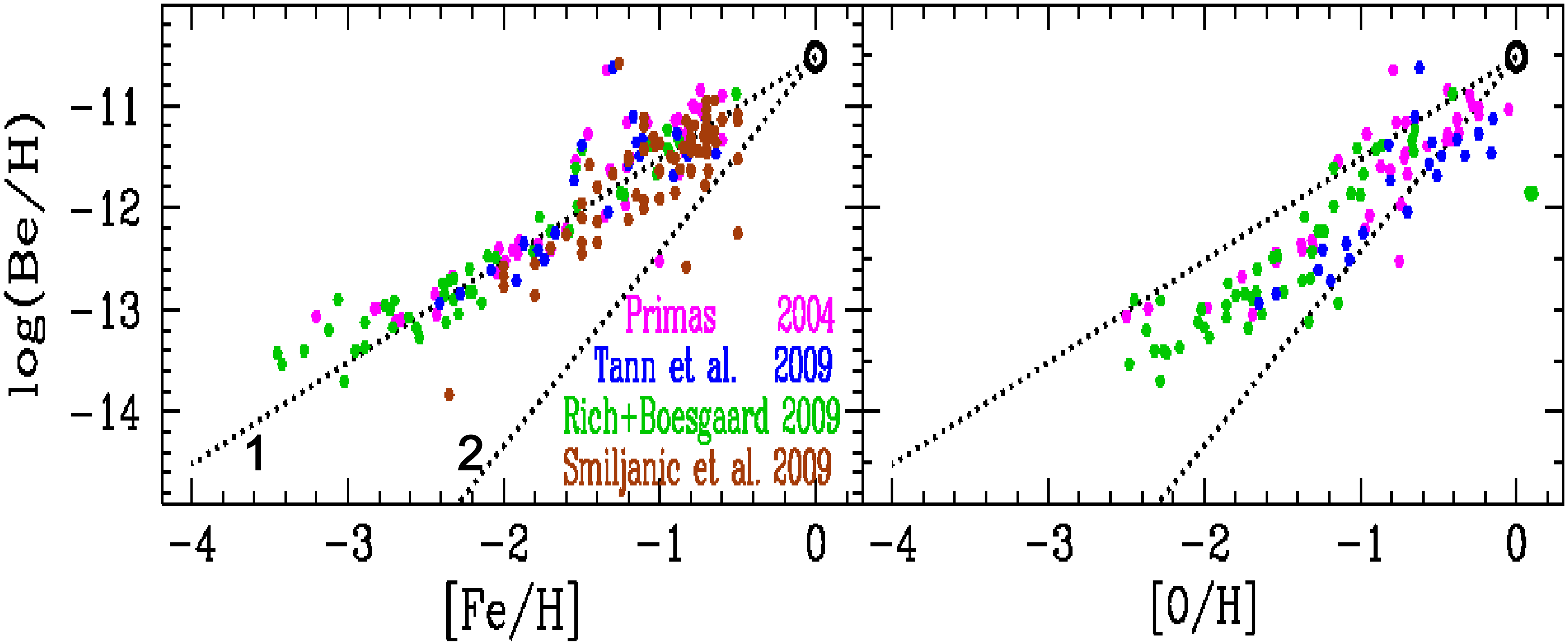


***Theory of GCR acceleration*:**
injection spectra : power laws
in total energy or momentum (per nucleon)

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

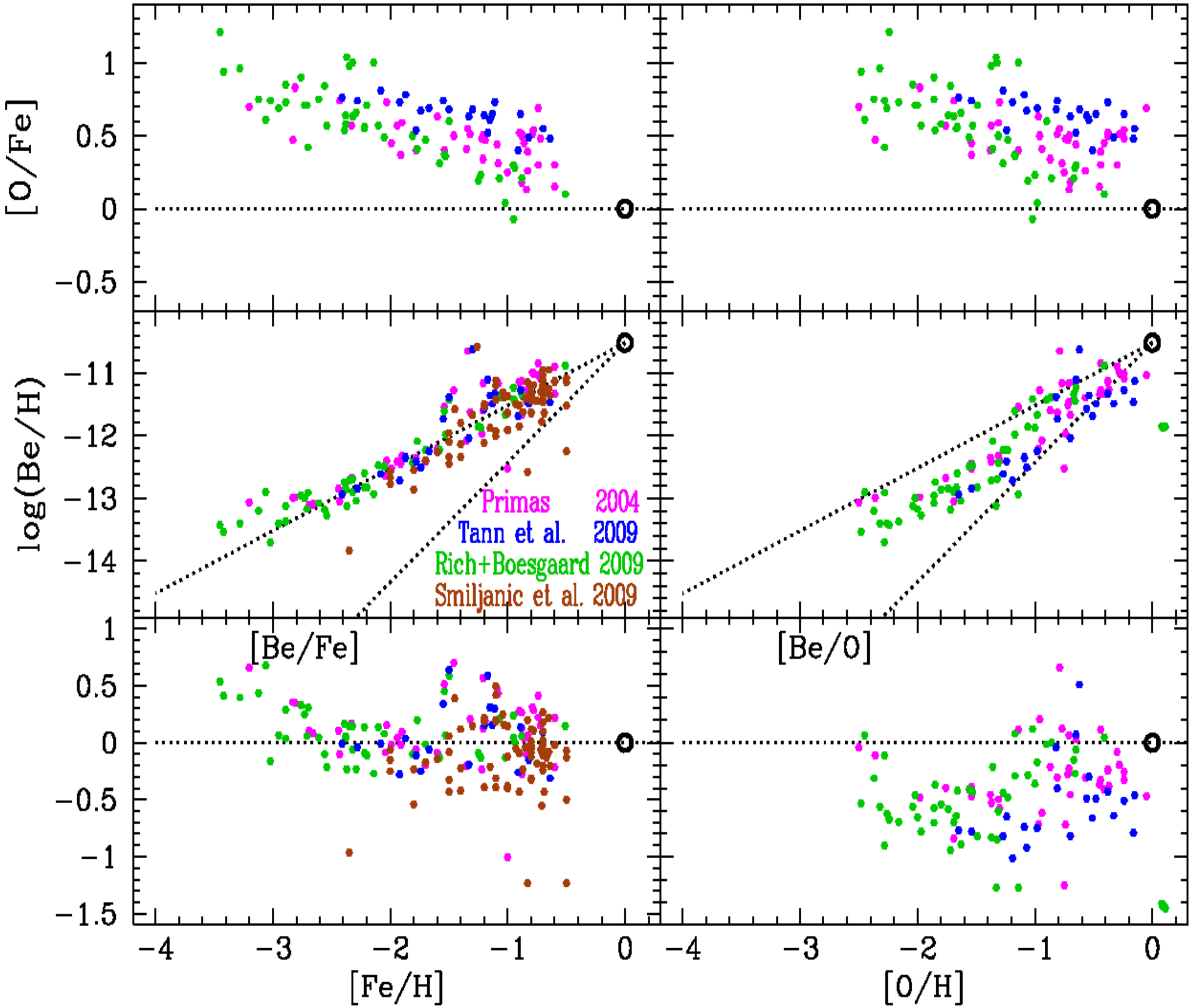
Evolution of Be

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



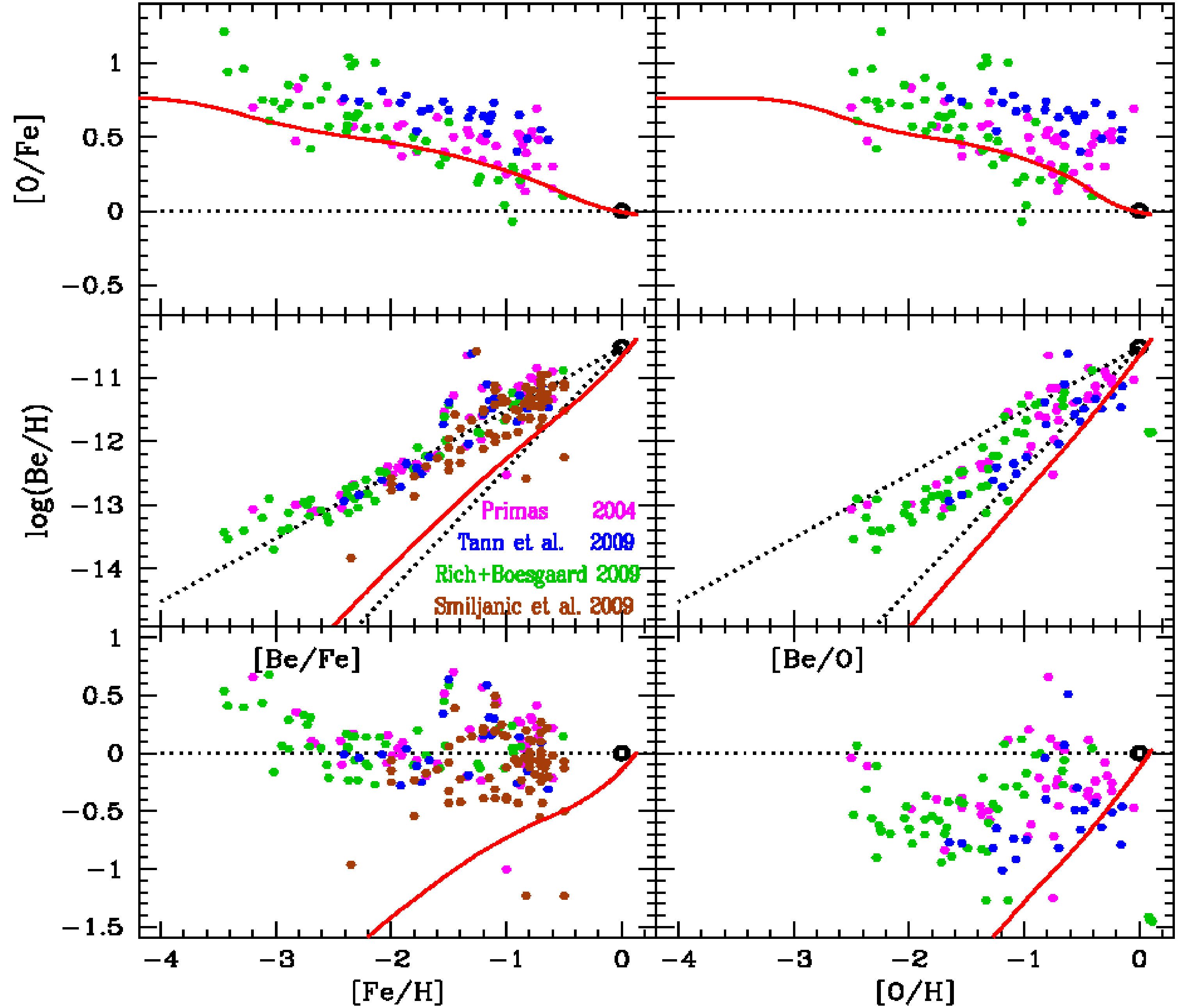
Be abundance evolves (as expected, since it is not primordial)

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


[O/Fe]
log(Be/H)
[Be/Fe]
[Be/O]
[Fe/H]
[O/H]
Primas 2004
Tann et al. 2009
Rich+Boesgaard 2009
Smiljanic et al. 2009

"Standard" chemical evolution of Be and B

[Standard GCR spectra and $X_{CNO}(GCR,t) \propto X_{CNO}(ISM,t)$]



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

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

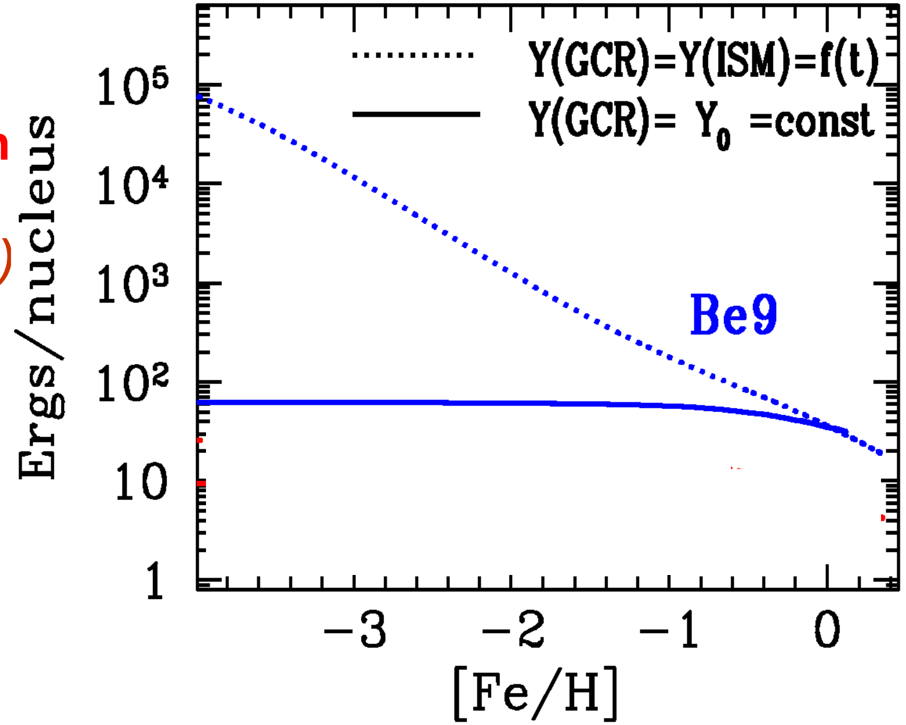
3) If the composition of GCR

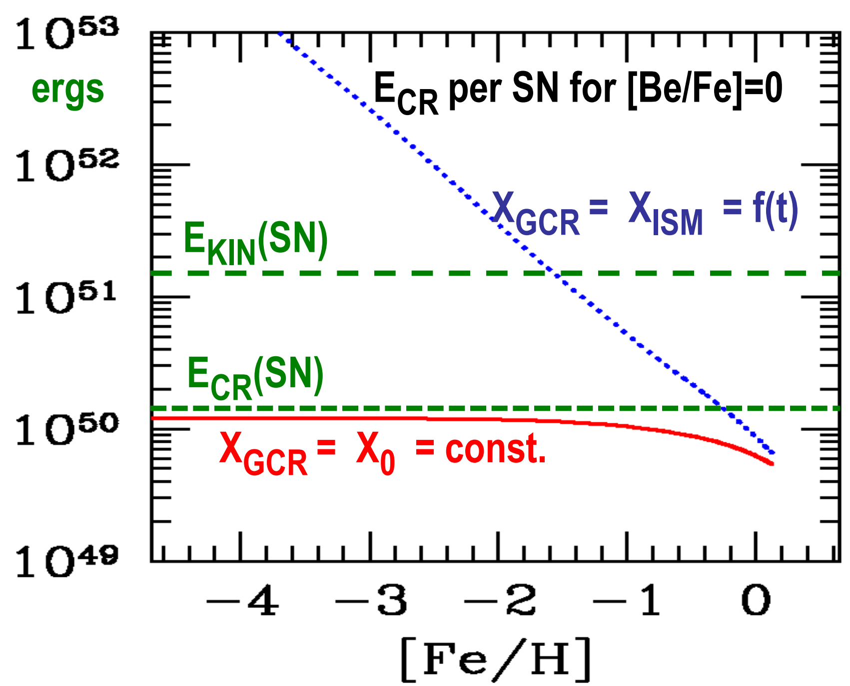
X(GCR,t) ∝ X(ISM,t) << $X_{\odot}$ at early times,

there is simply not enough energy in early GCR

accelerated by SN to maintain Be/Fe ~ const.

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





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

1. Standard ISM accelerated by forward shock

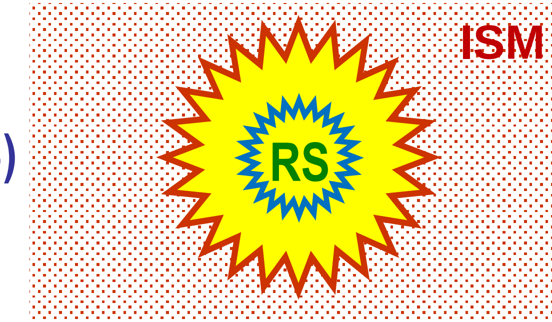
$X(GCR) = X(ISM)$

Secondary BeB

2. SN interior accelerated by reverse shock (RS)

$X(GCR) = X(SN)$

Primary BeB



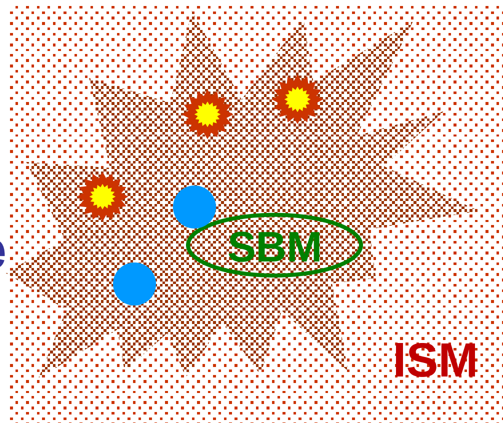
A) Energetically unfeasible (reverse shock too weak)

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

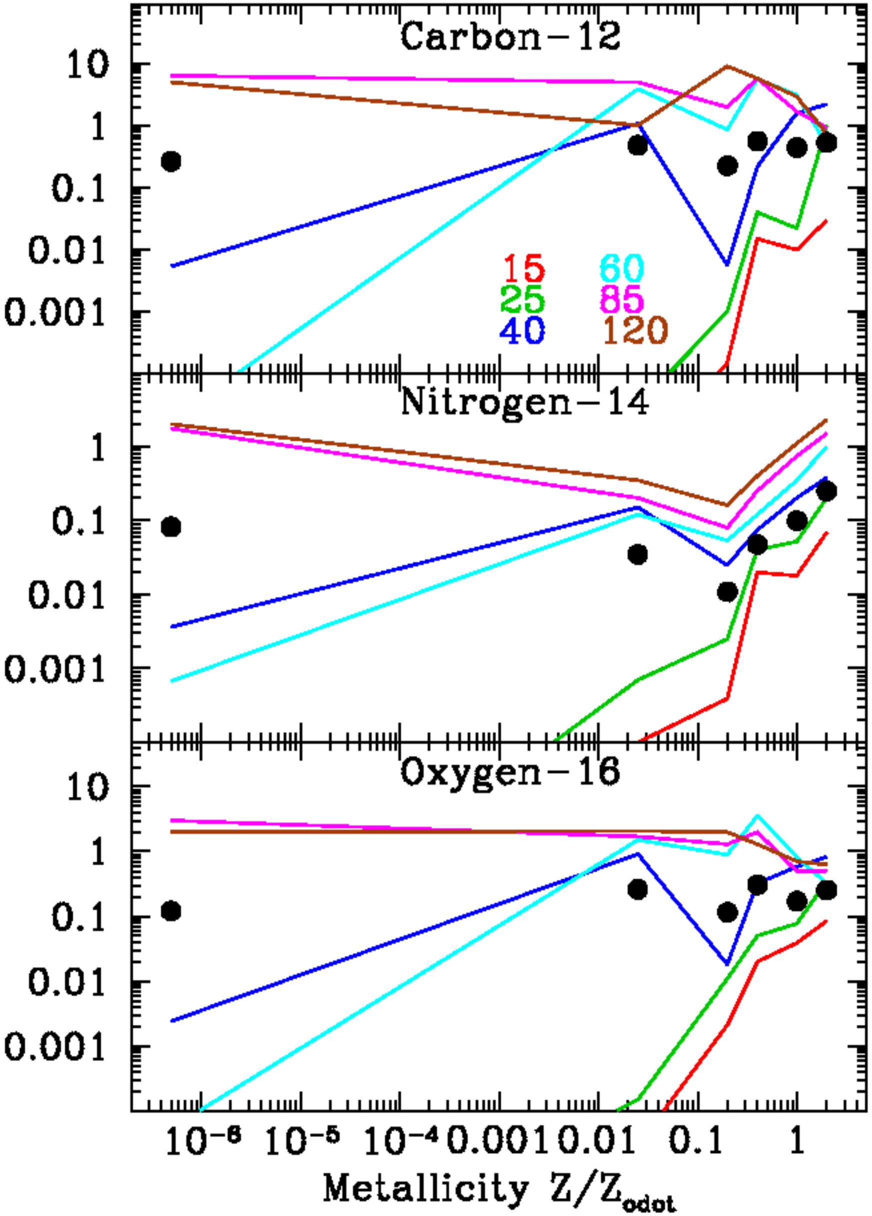
4. Massive star wind accelerated by forward shock

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

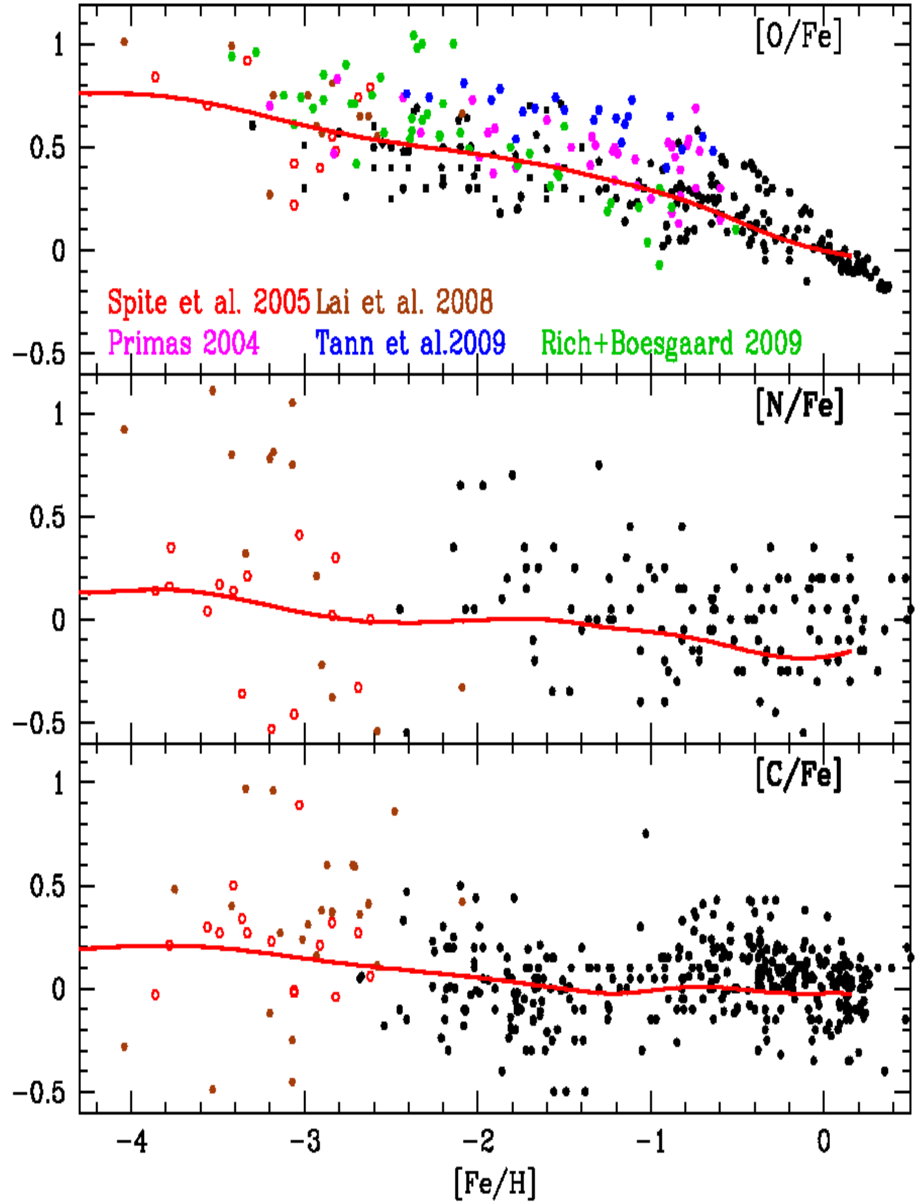
Primary BeB

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

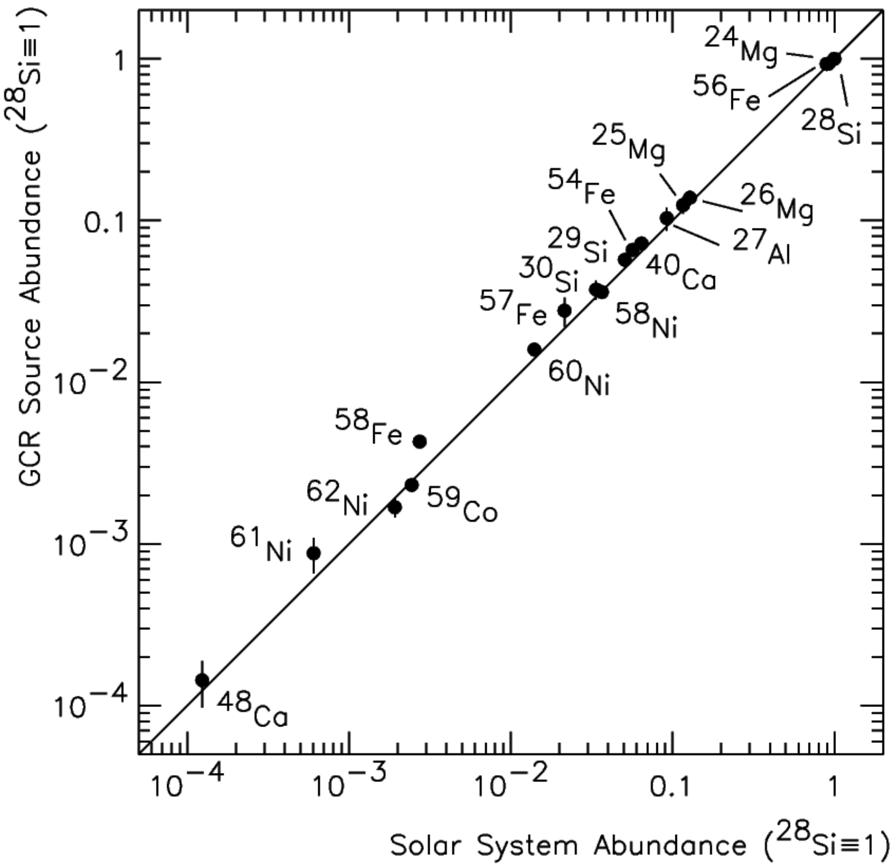
Yields of CNO (in M⊙) in winds of massive rotating stars (*Geneva models*)

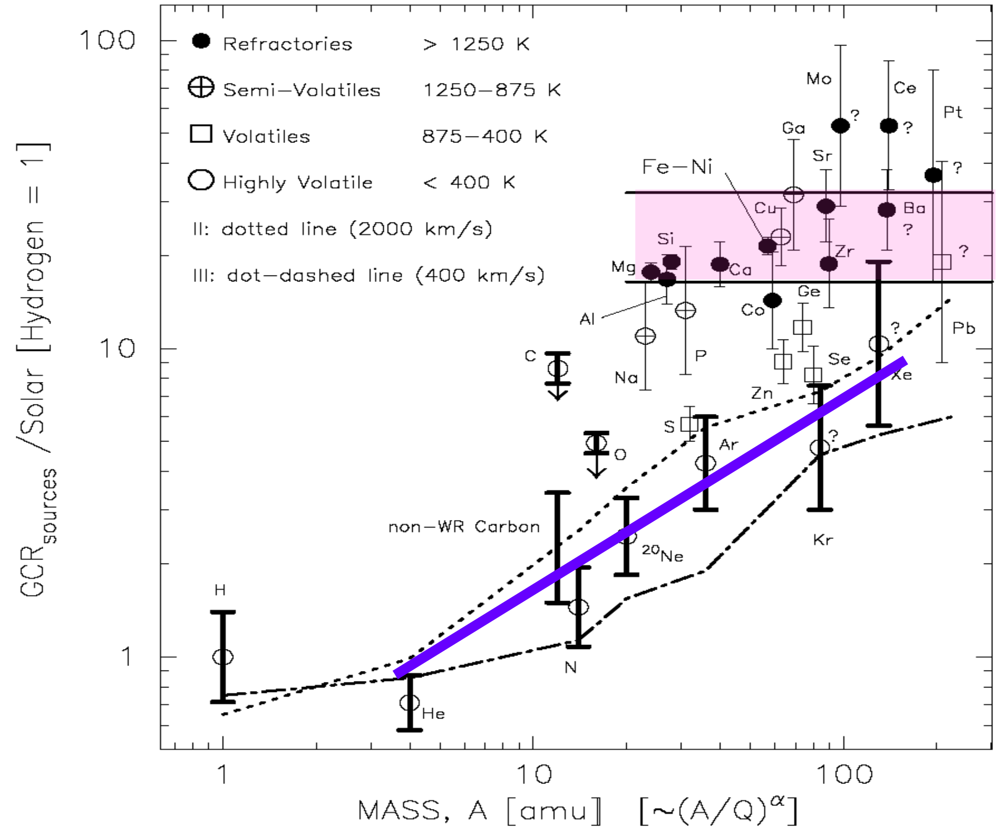


Such yields explain naturally the observations of primary N in early Galaxy



Galactic Cosmic Ray SOURCE composition





Is it solar ? *Yes,* for most isotopic ratios

No, for elemental ratios ⇒ ***Selection effects***

Volatiles: elements with high A/Q (mass to charge) favored

Refractories: overabundant, but no clear trend with A/Q

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

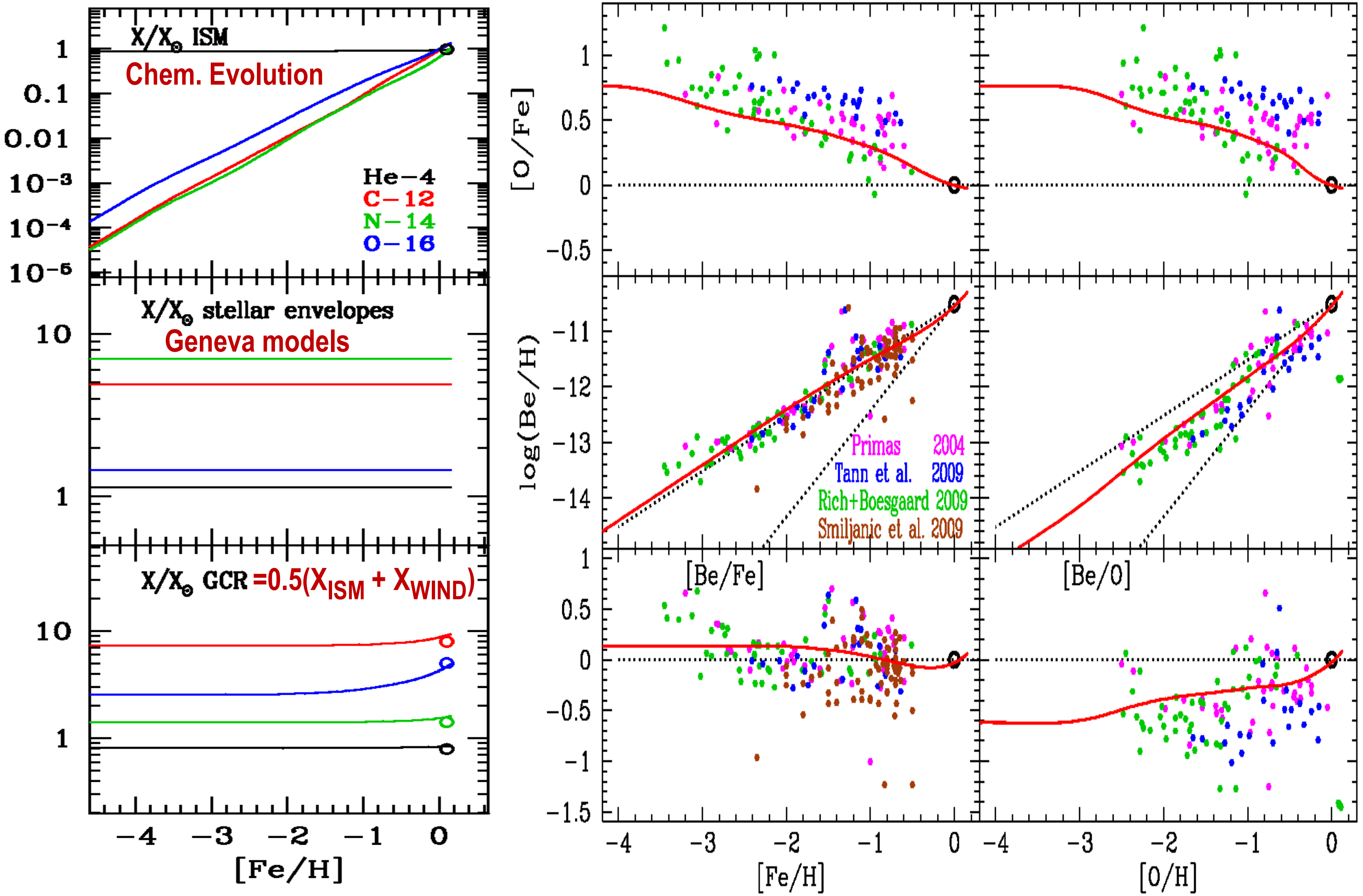
CNO overabundant by ~1.5 to 8 ; Most excess CNO attributed to WR stars

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

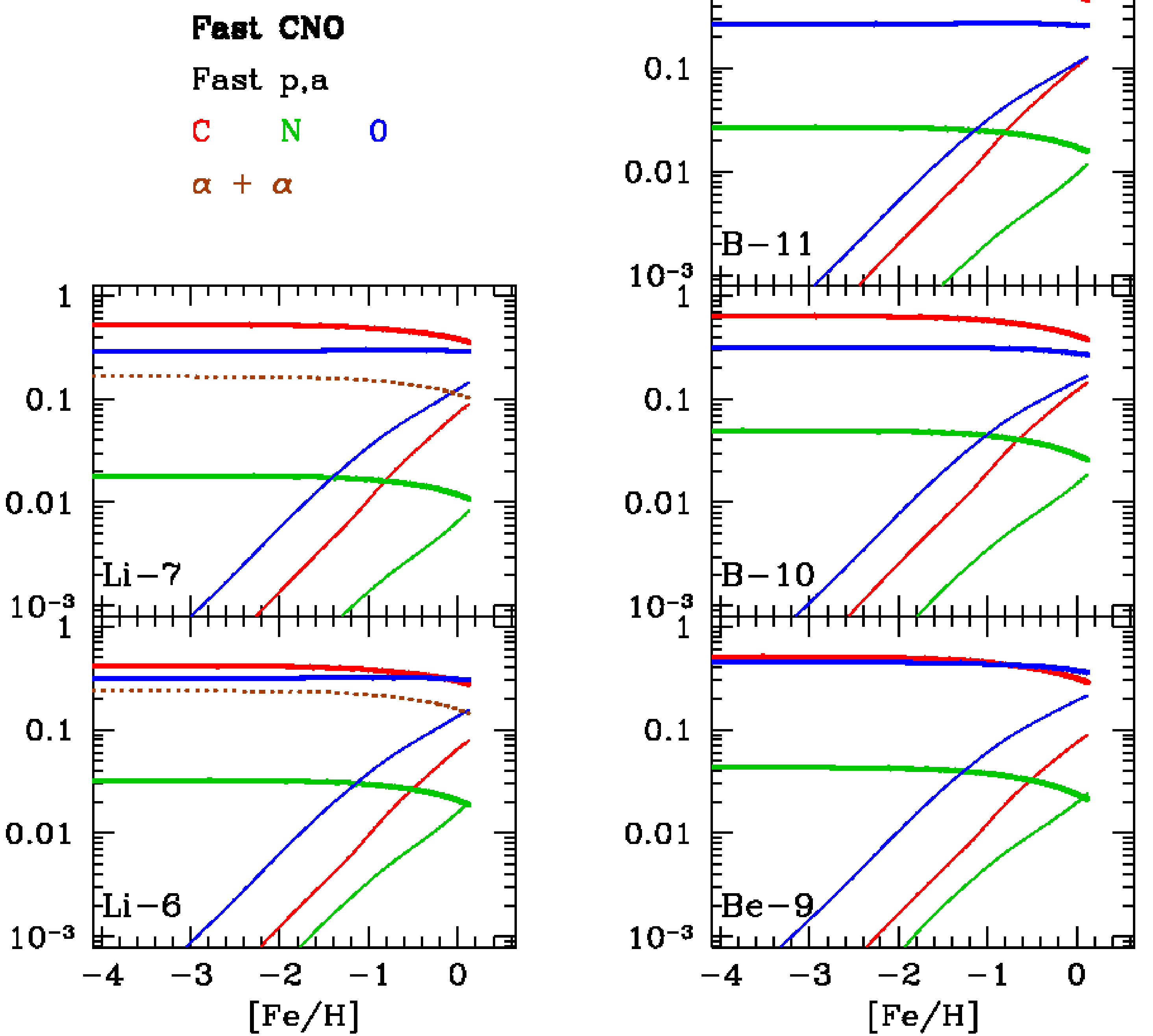
What about the GCR metallicity in the early Galaxy ?

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



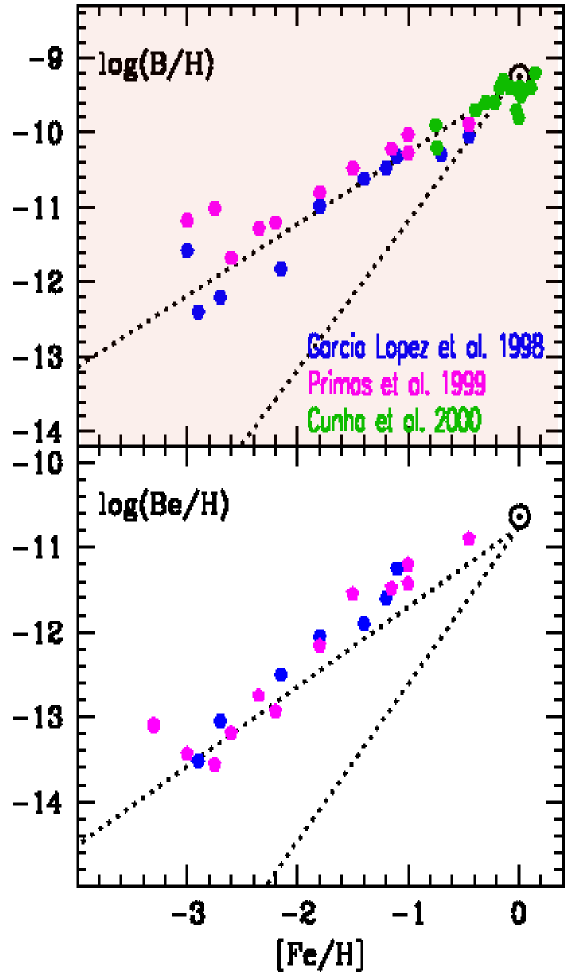
Components of LiBeB from GCR

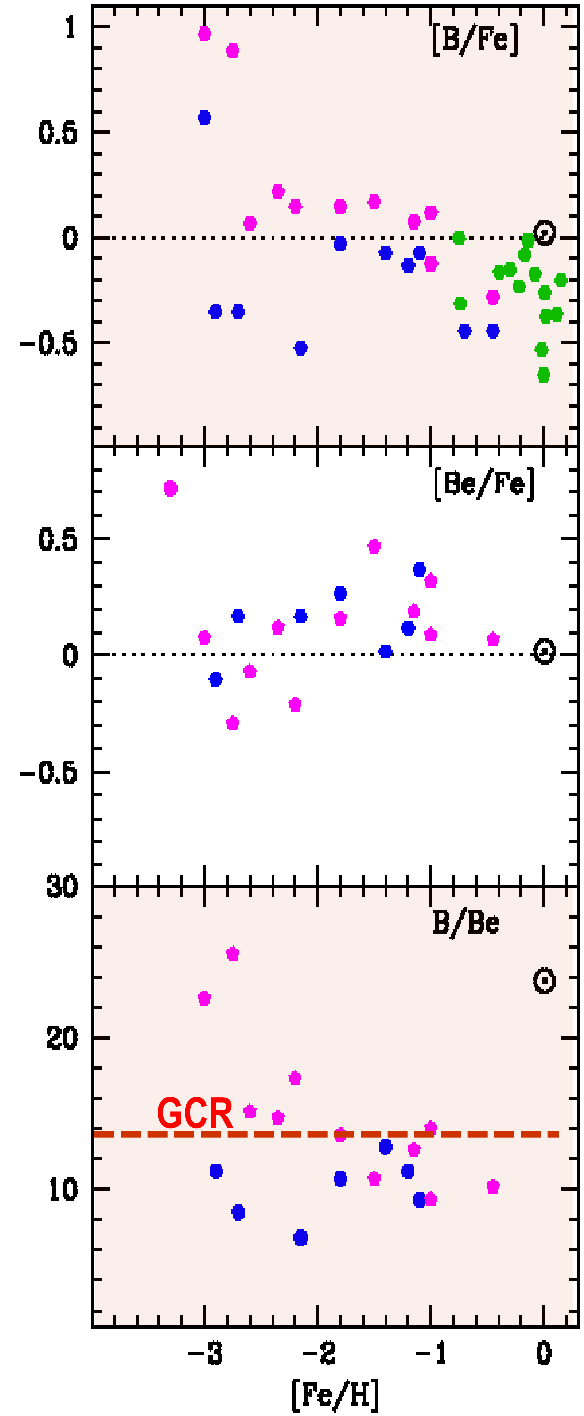


Boron observations (< 2000)

Primary, as Be

(fewer data, larger scatter)



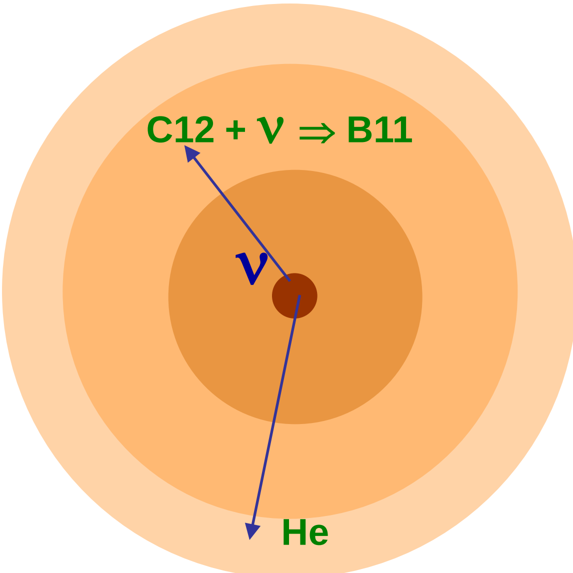


B/Be ratio vs Fe/H ~ 14 (just from GCR)
albeit with VERY large errror bars

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

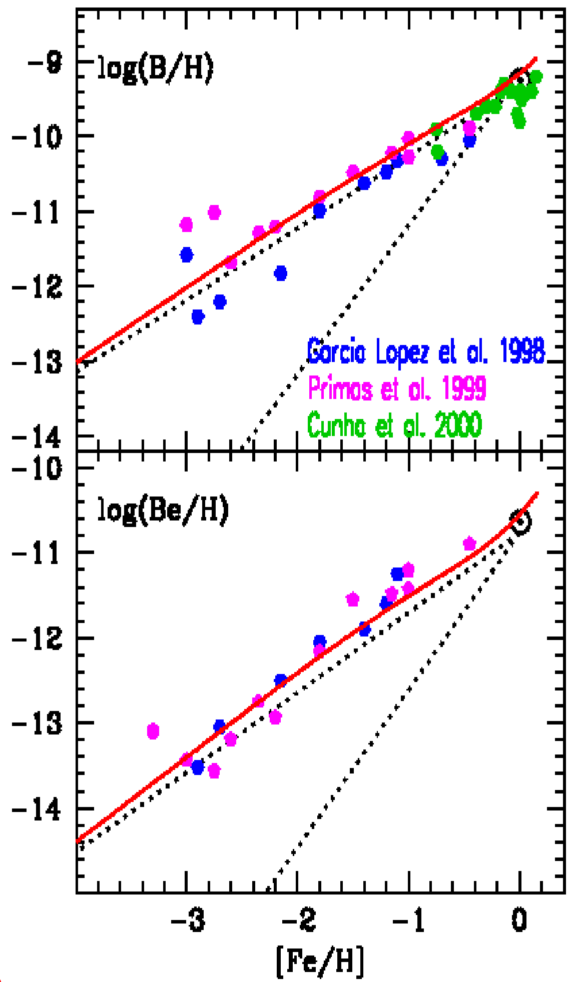
in C-shell and produce **B11 (primary)**

and He4 in He-shell and produce He3

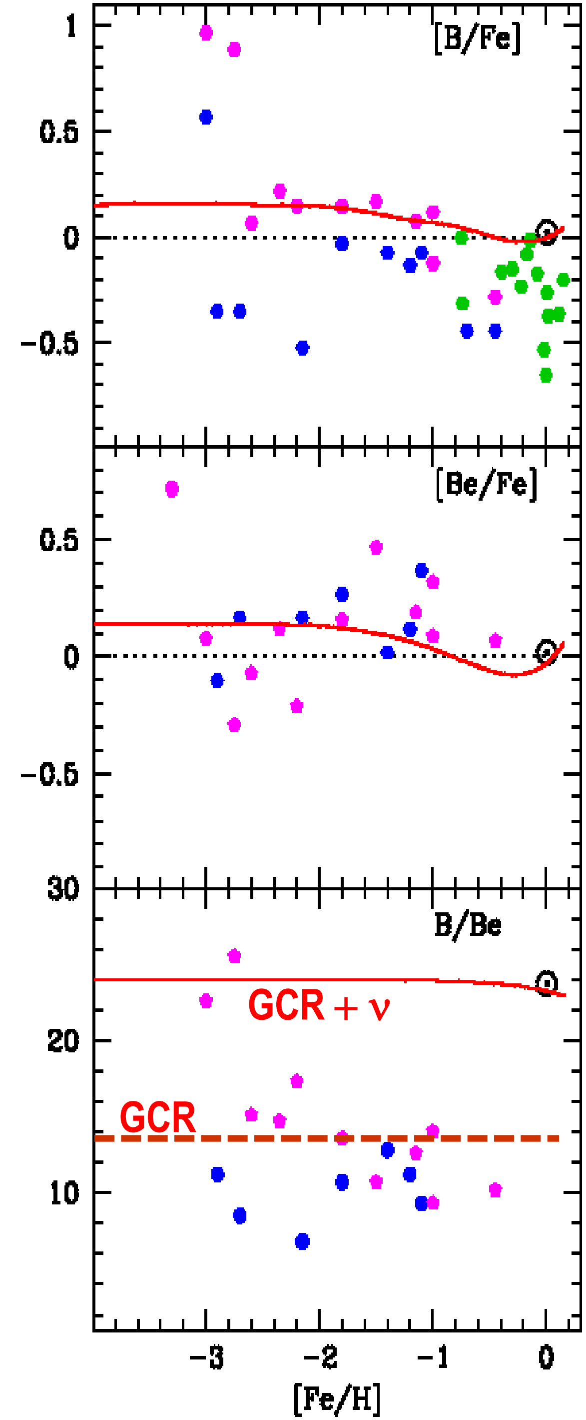
then : He3 + He4 → **Li7 (primary)**

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] ?



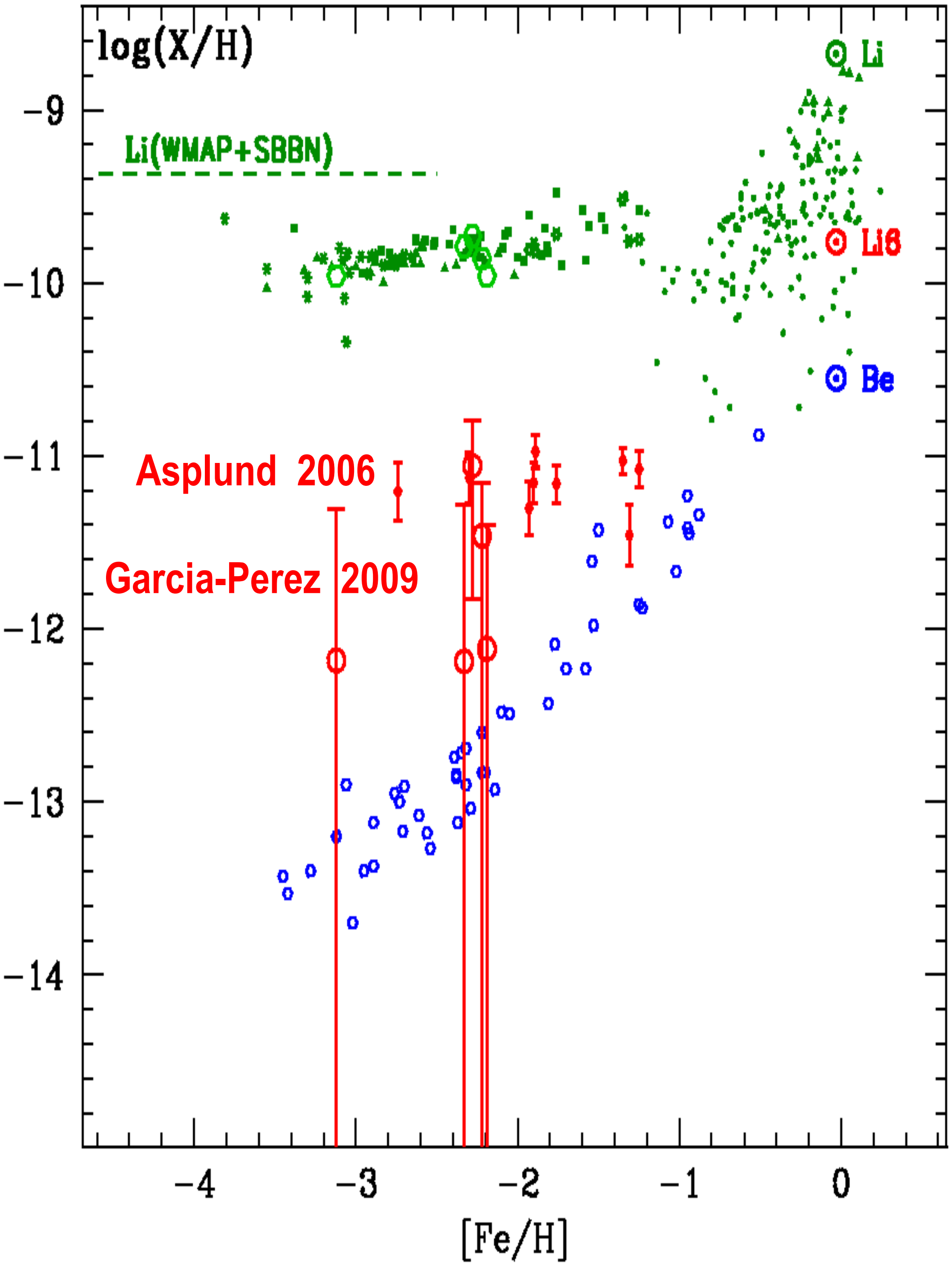
Evolution of Li isotopes

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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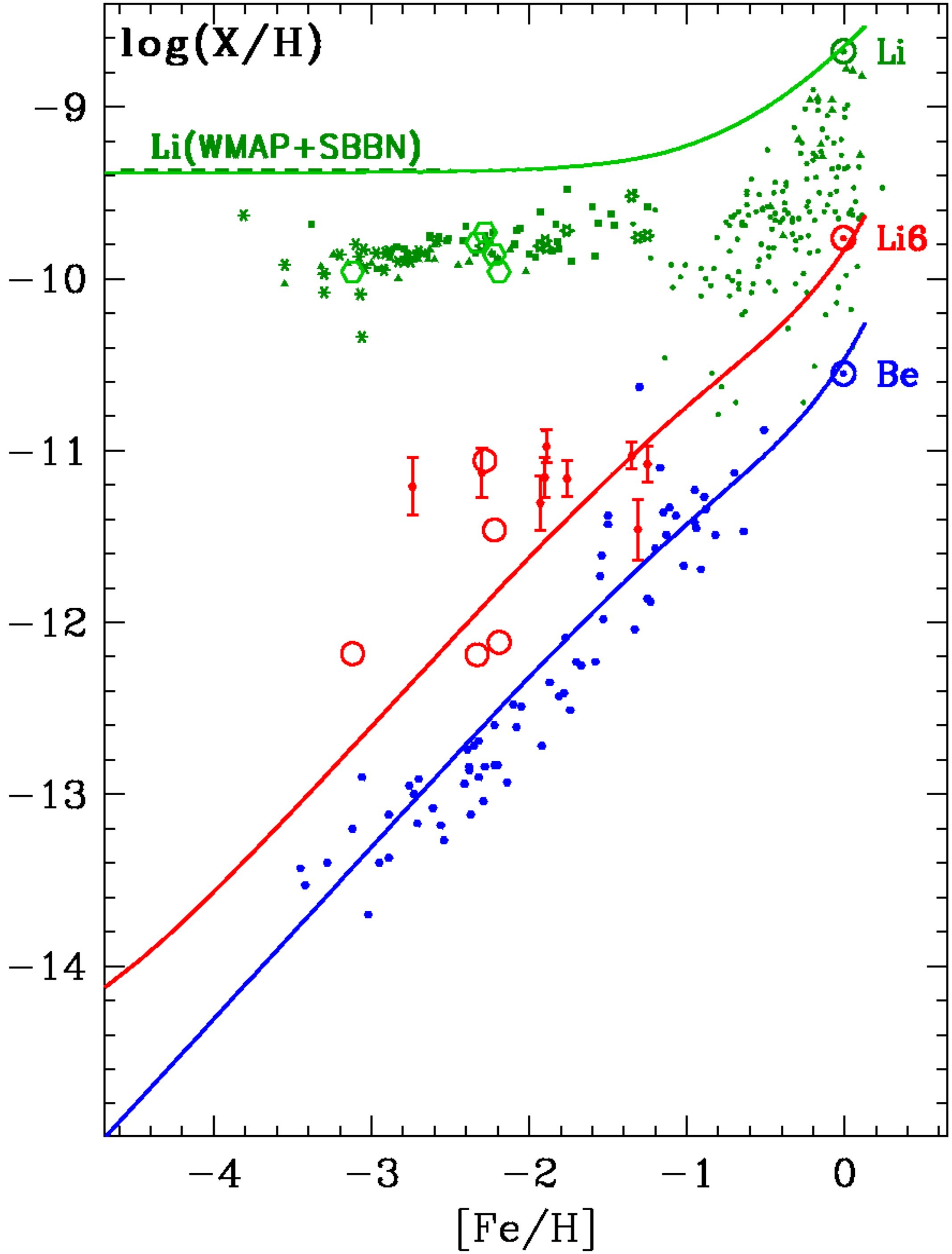
Standard GCR (reproducing Be9)
fail by >10 to reproduce
Asplund06 **Li6 at [Fe/H] = -2.7**



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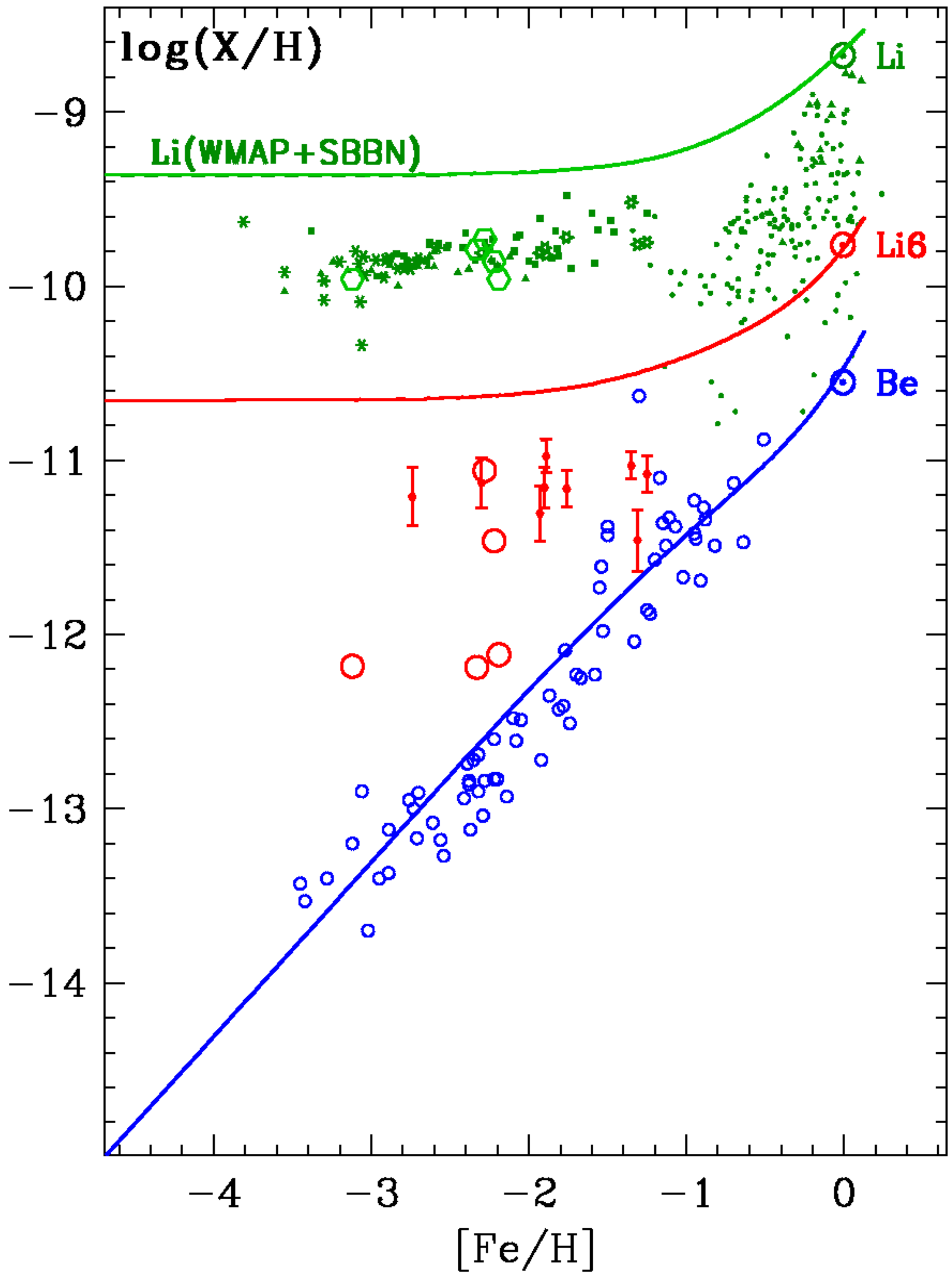
fail by >10 to reproduce
Asplund06 Li6 at [Fe/H] = -2.7

and by a much larger amount if
Li(WMAP) is correct



Energetics of early Li6 formation (*Prantzos 2006*)

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

For 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 10^8 $M_\odot$ ~ 10^{42} gr

Energy (for Li6/H~ 10^{-11}) ~ 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 [Fe/H] ~ -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_{Virial} ~ $(GM/R)^{1/2}$ ~ 400 $(M_{DarkHalo}/10^{13}\ M_\odot)^{1/3}$ km/s

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

E_{shock}~ ½ m v^2 and energy per unit mass ε~2 10^{14} erg/gr

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

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

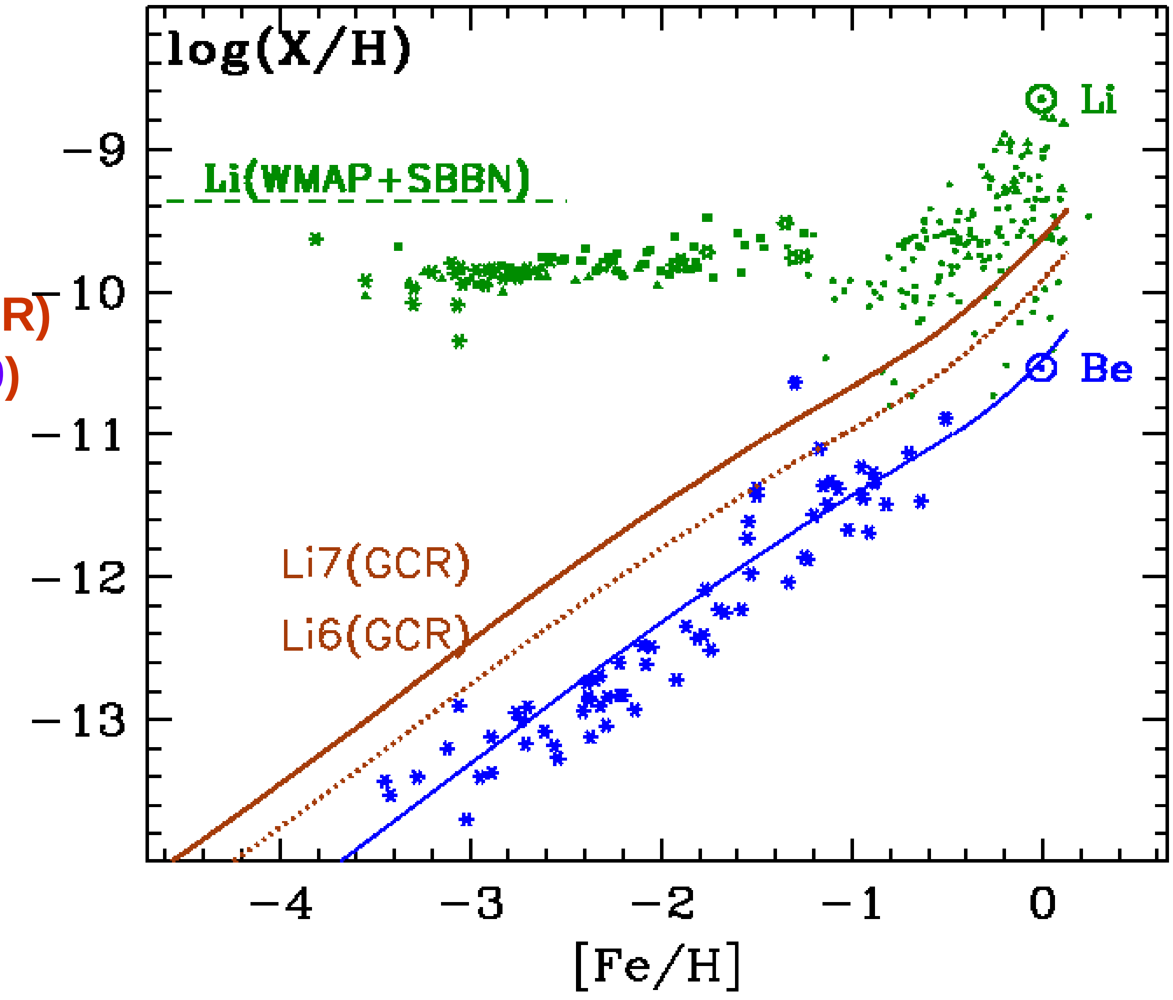
For Milky Way: $M_{BlackHole}$ ~ 3 10^6 $M_\odot$ ⇒ Energy ~5 10^{59} erg

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

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

Evolution of Li_{TOTAL}

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



Evolution of Li_{TOTAL}

Li_{TOTAL} = Li7(GCR) + Li6(GCR)
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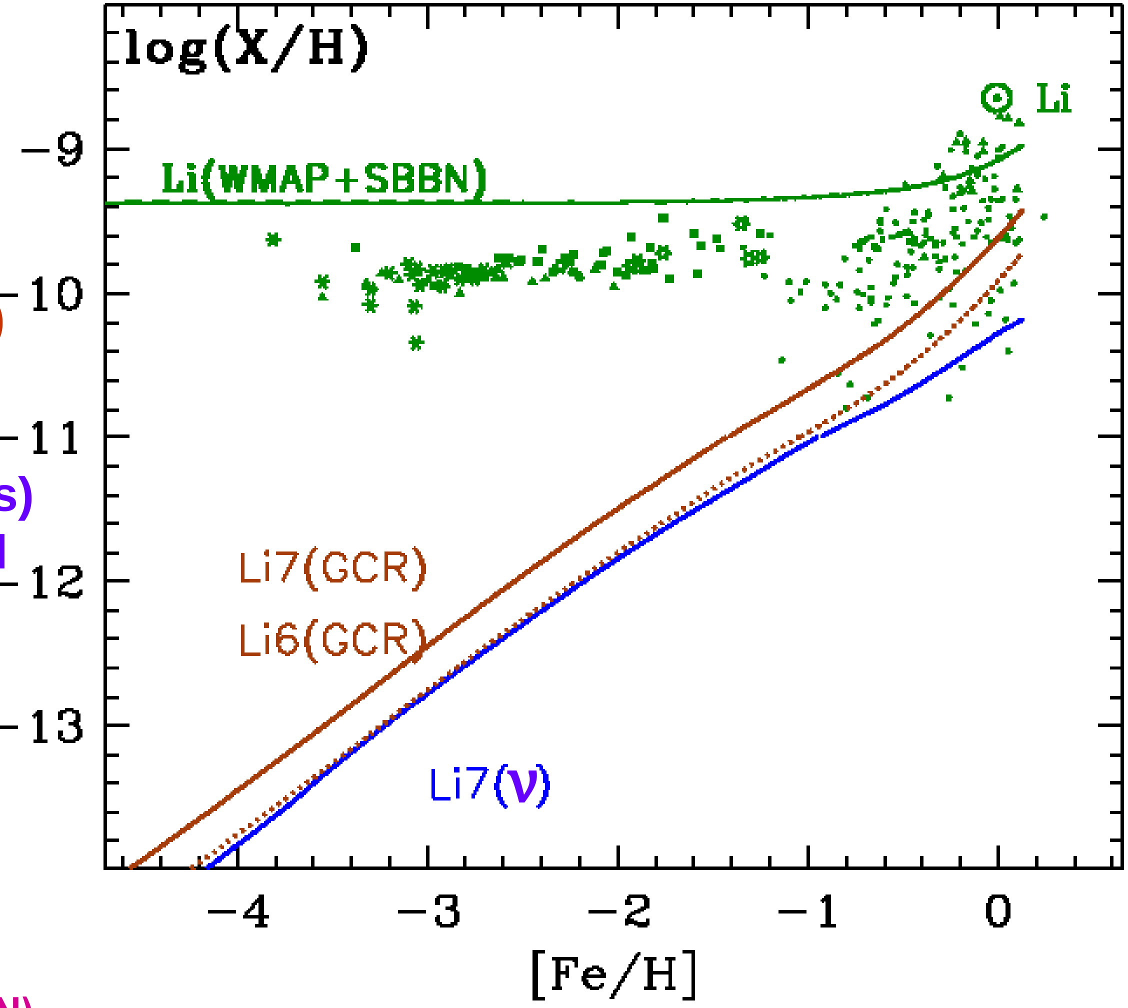
+ Li7(neutrino process)
(SN yields of Li7 reduced by 6, as for B-11 yields)

+ 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

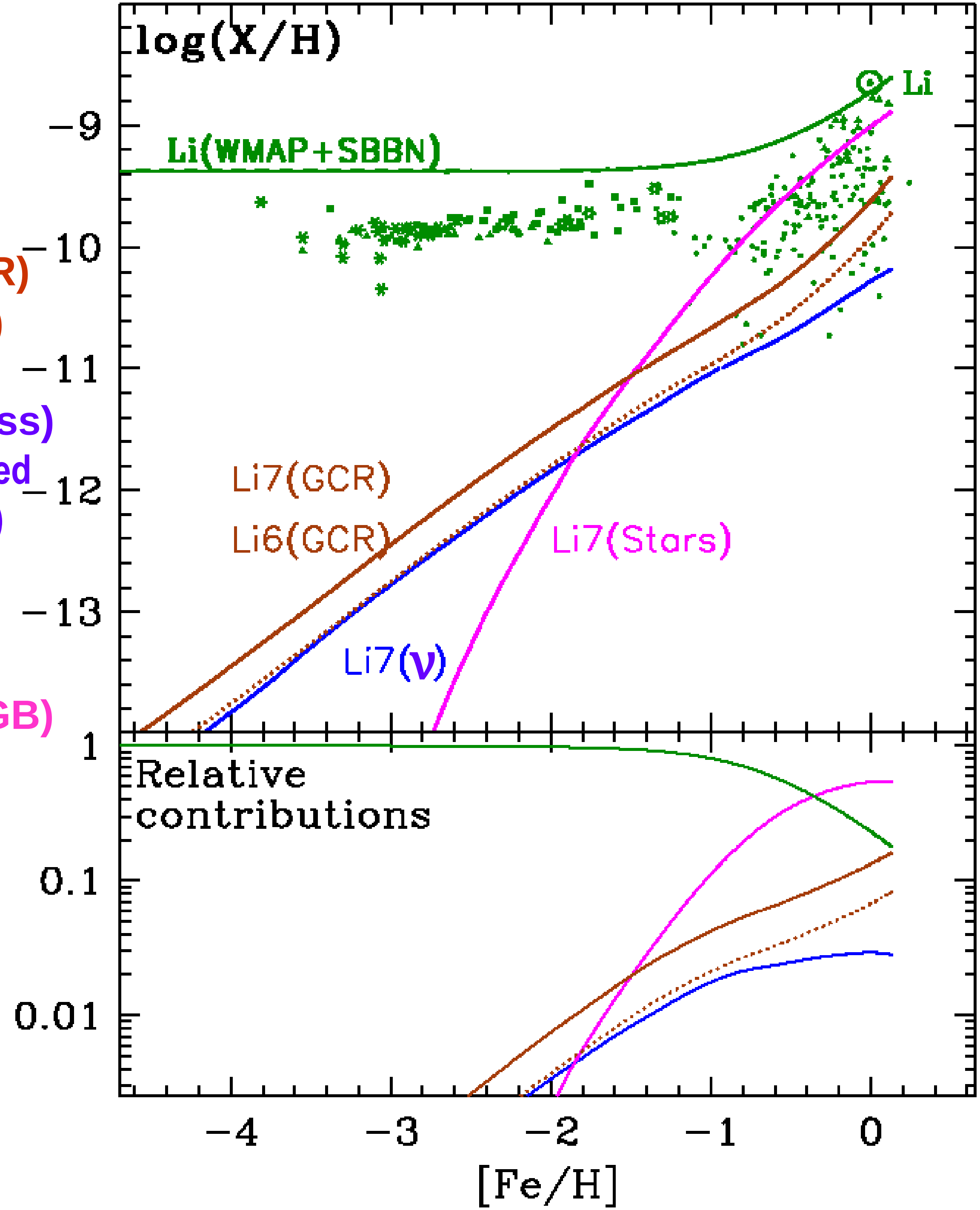
Evolution of Li_{TOTAL}

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)

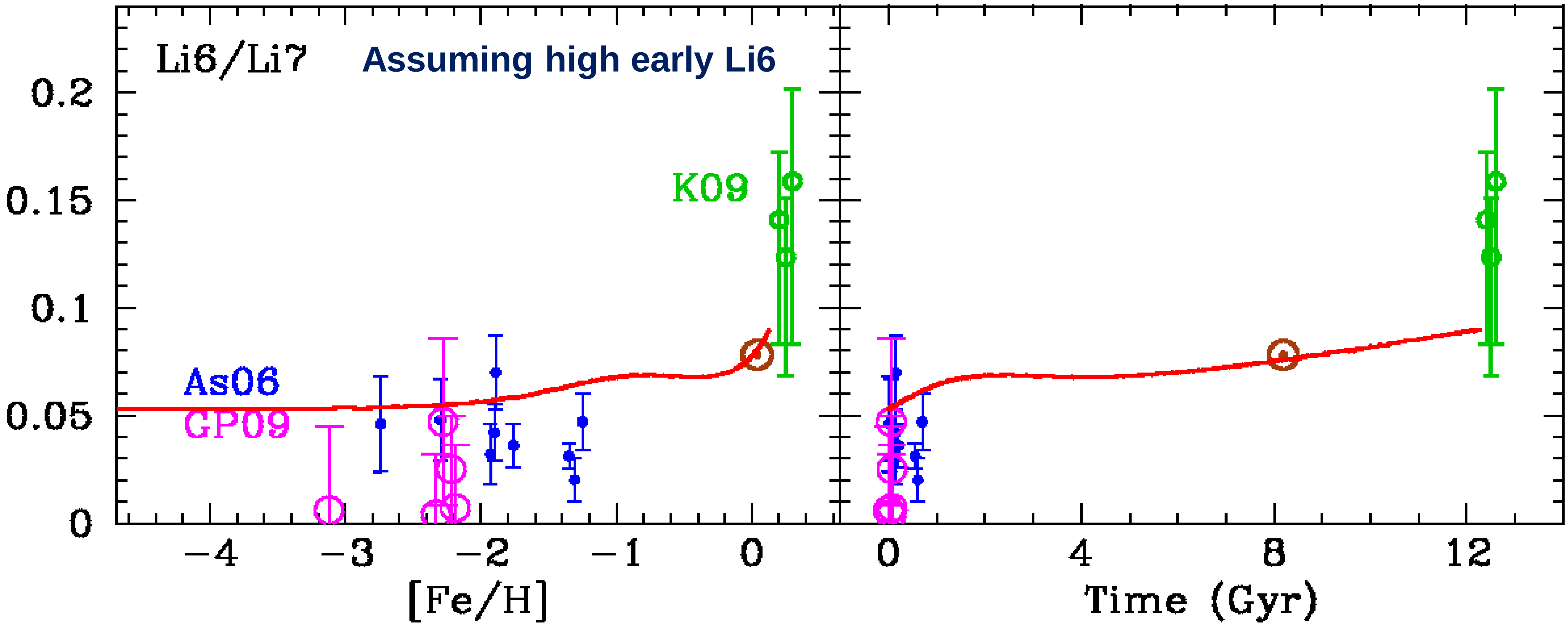
+ Li7 (nova and/or AGB)



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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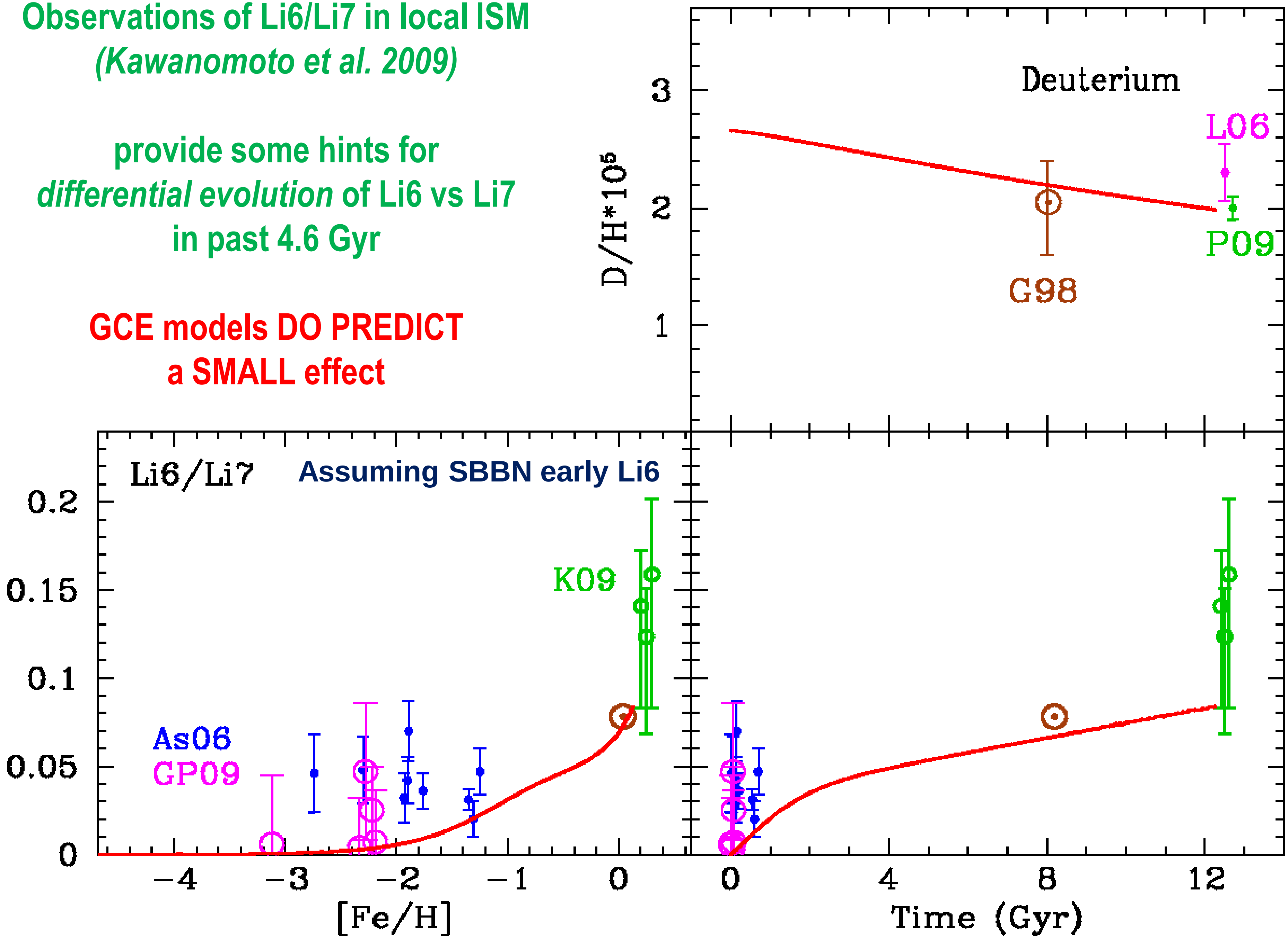

Contributions (%) of nucleosynthesis processes to SOLAR LiBeB

	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 ???						