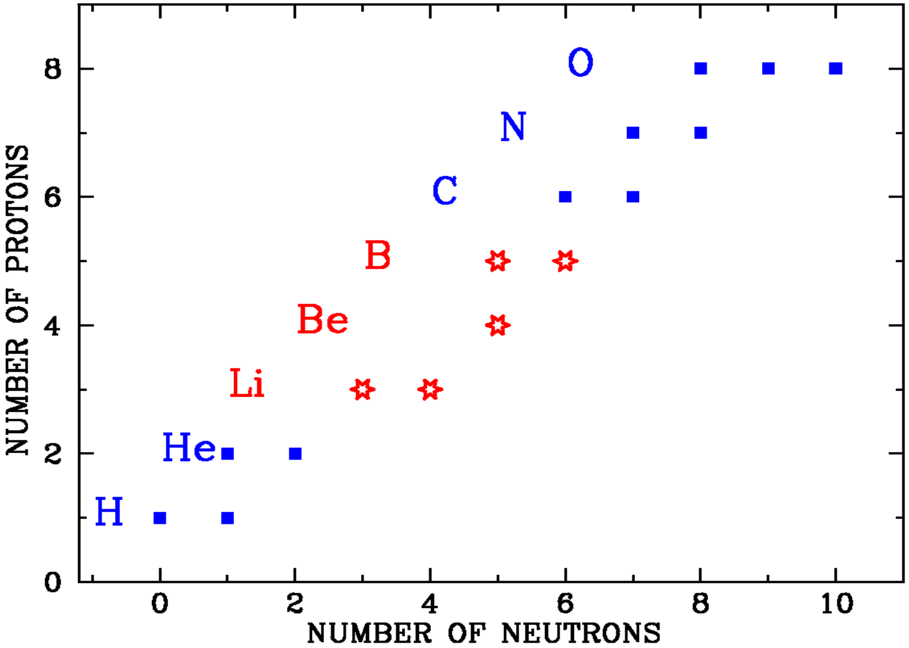
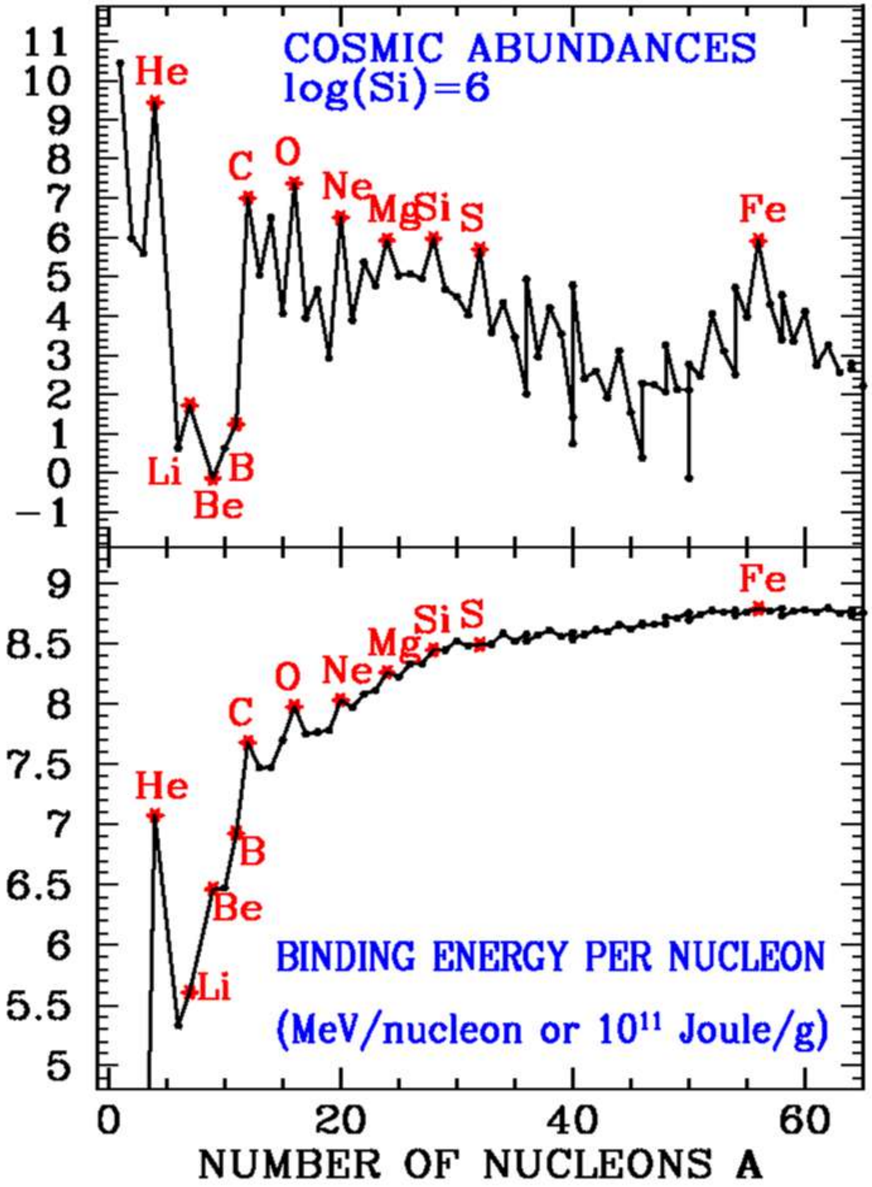
# The light elements Li Be B (Li6, Li7, Be9, B10, B11)

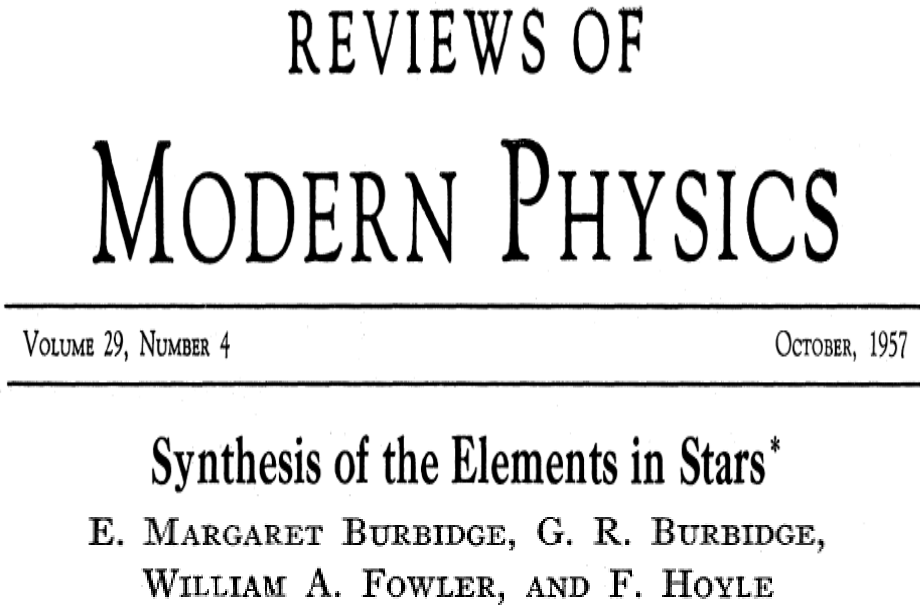




The most fragile stable isotopes in nature
(after D and He3)

Always destroyed in stellar interiors

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



REVIEWS OF
MODERN PHYSICS

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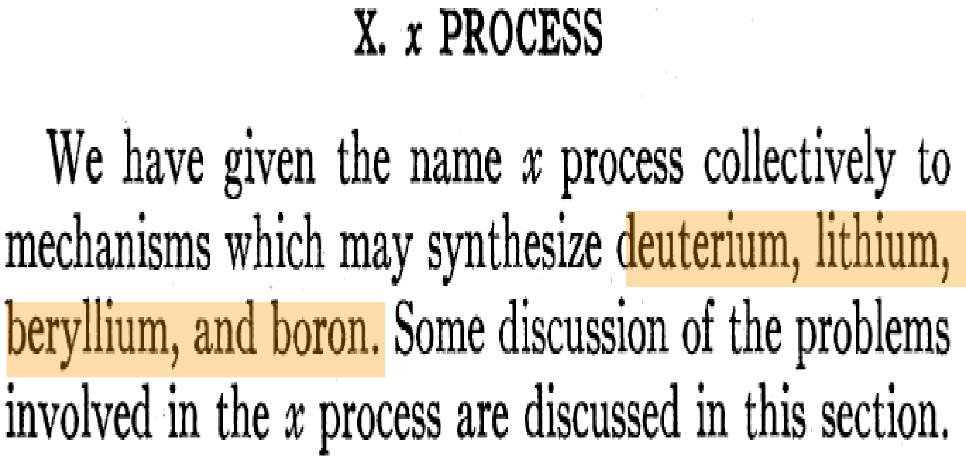
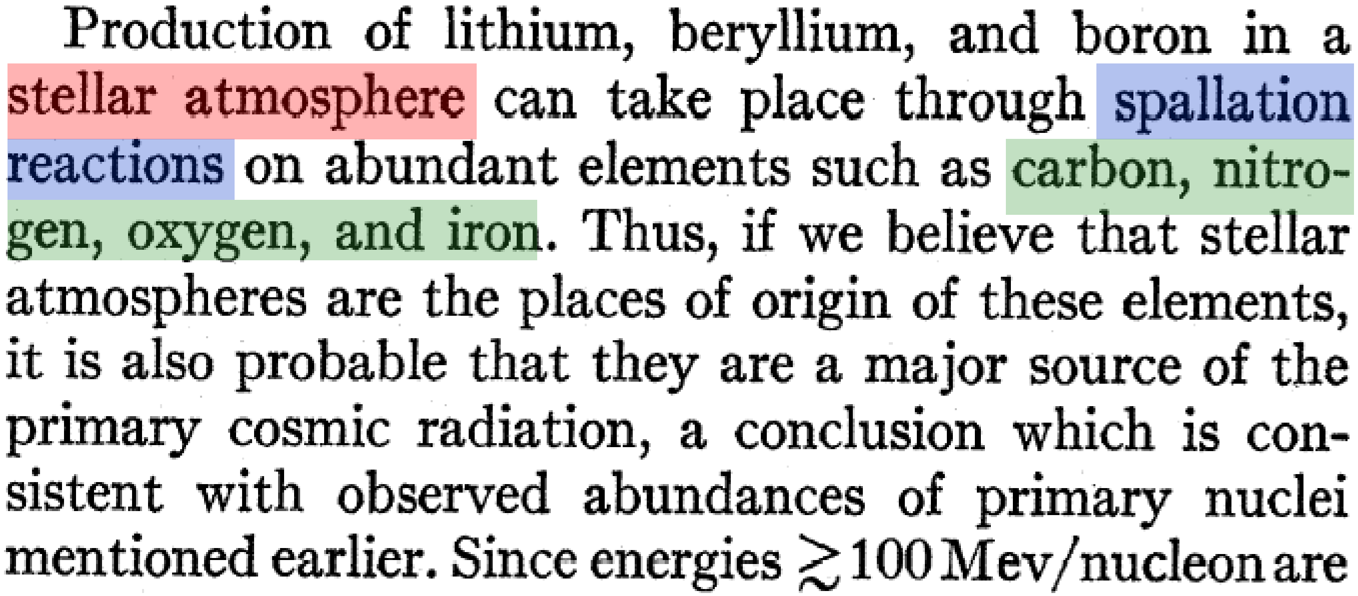
# Synthesis of the Elements in Stars*

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



## 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

# 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

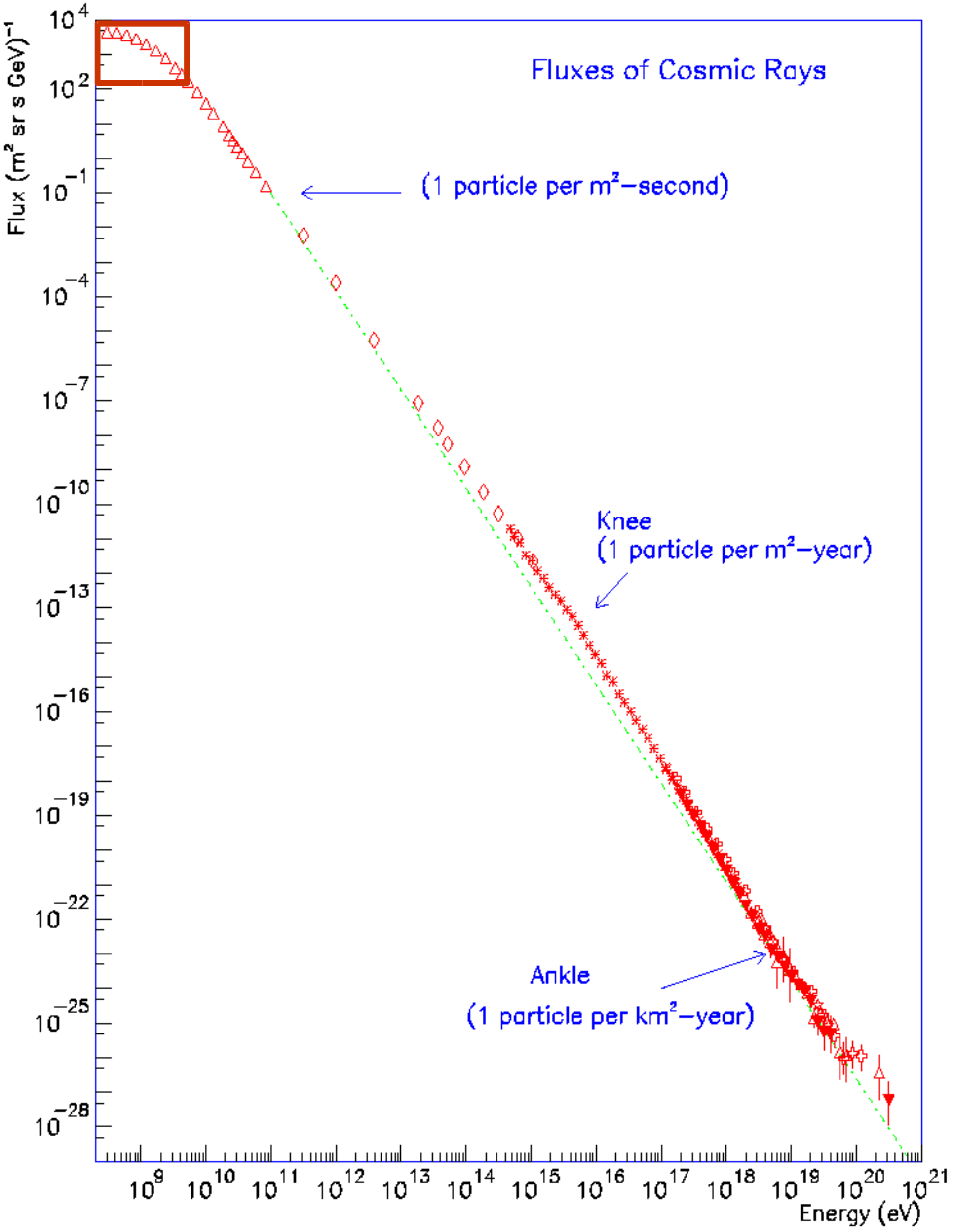
Received May 28, 1971

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.

# Galactic Cosmic Rays (GCR)



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$^7$ yrs

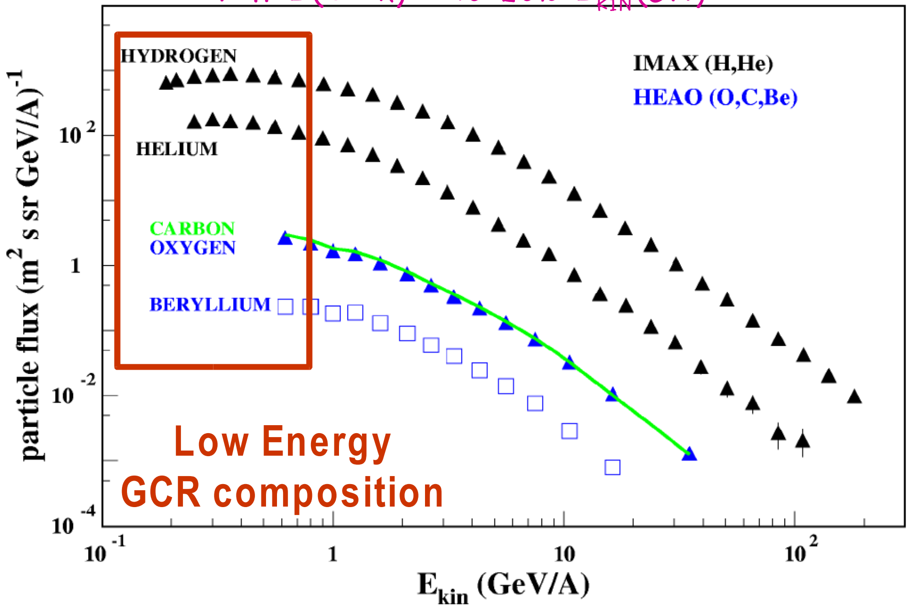
GCR Energetics in Milky Way:

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) ~ 10-20% $E_{KIN}$(SN)



GCR composition is heavily

enriched in Li, Be, B

(a factor ~$10^6$ for Be and B)

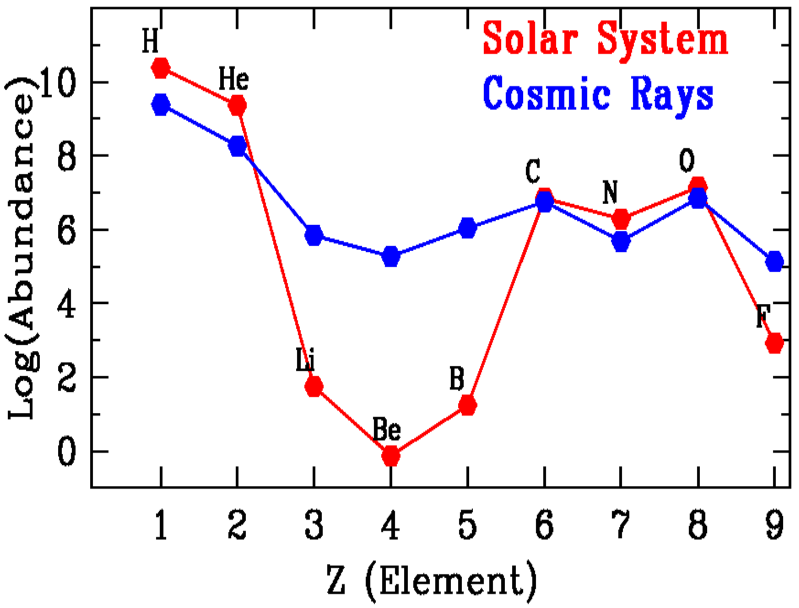
Solar composition: X(Li) > X(B) > X (Be)

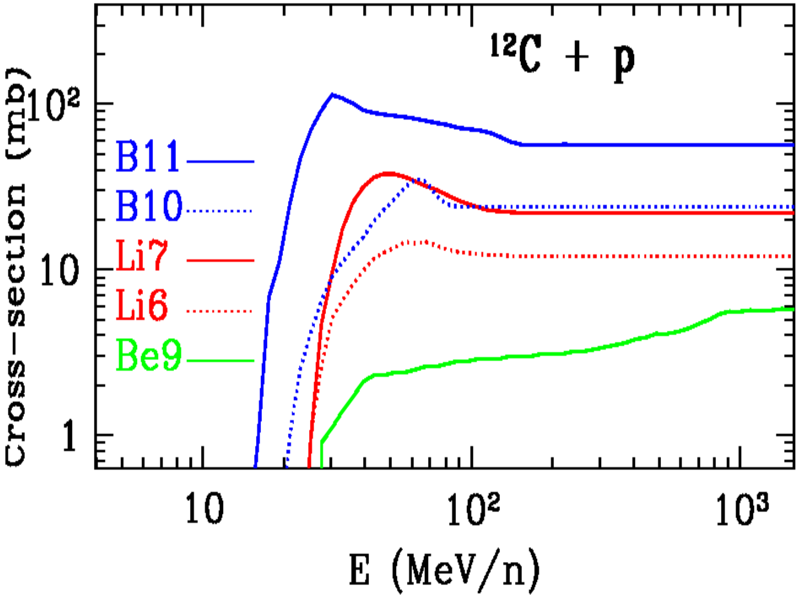
GCR composition: X(B) > X(Li) > X(Be)

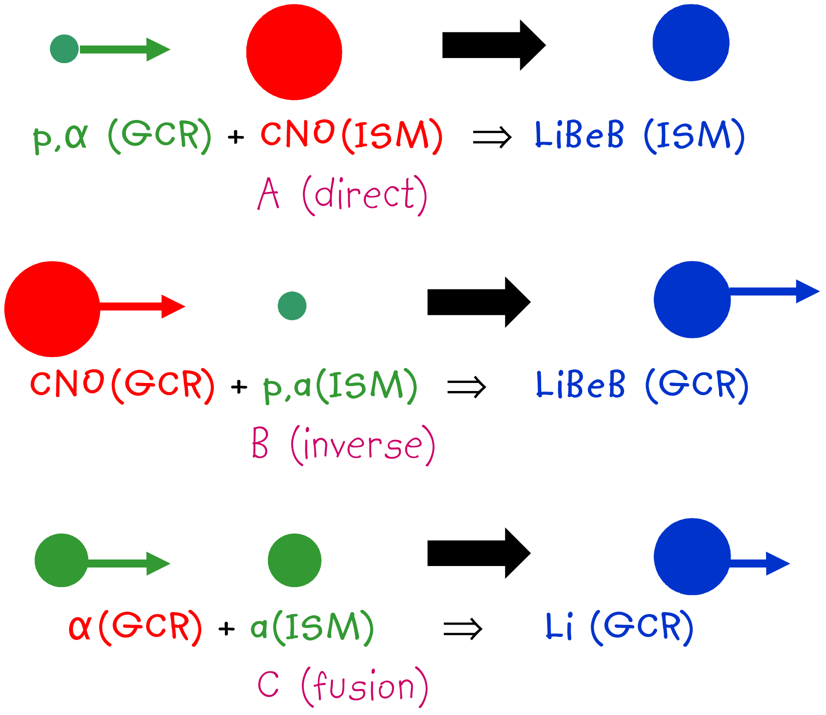
Same order as **spallation cross sections**

of CNO $\Longrightarrow$ LiBeB: σ(B) > σ(Li) > σ(Be)

LiBeB is produced by spallation of CNO
as GCR propagate in the Galaxy







p,α (GCR) + CNO(ISM) ⇒ LiBeB (ISM)

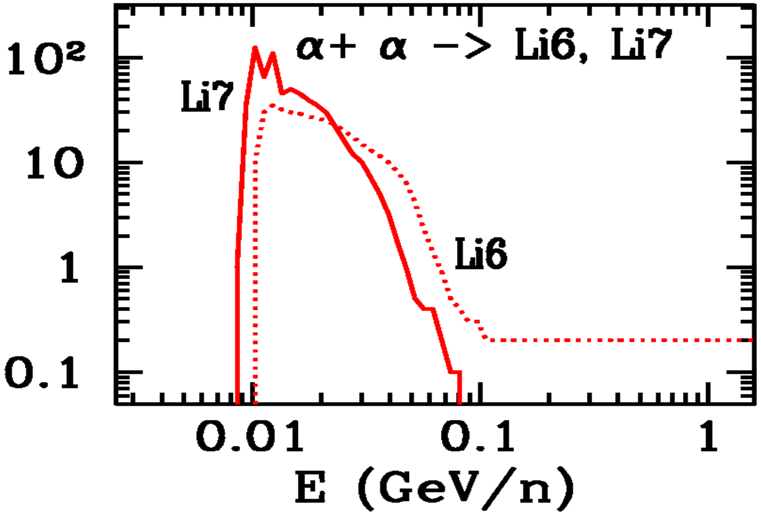
A (direct)

CNO(GCR) + p,a(ISM) ⇒ LiBeB (GCR)

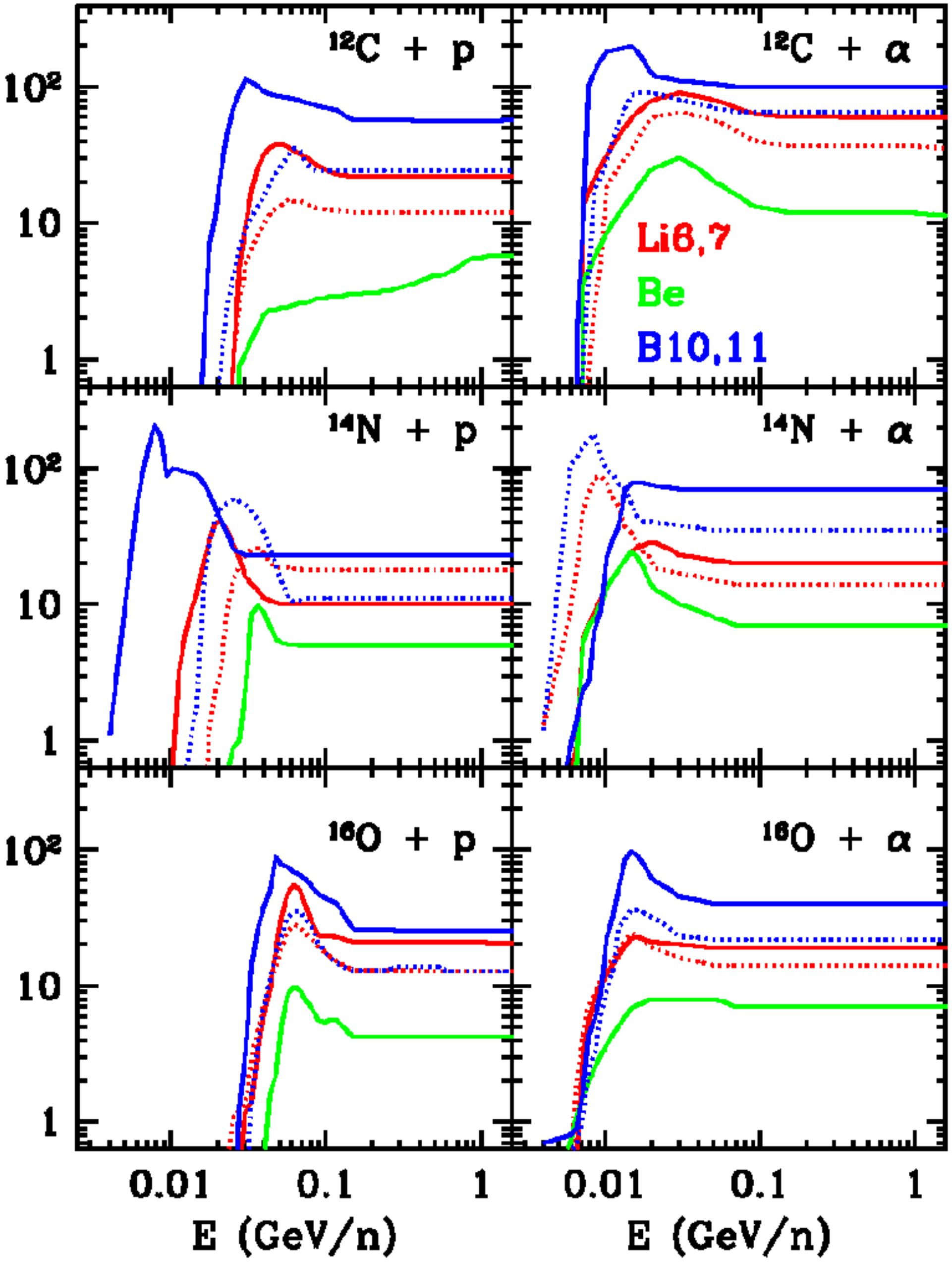
B (inverse)

α(GCR) + a(ISM) ⇒ Li (GCR)

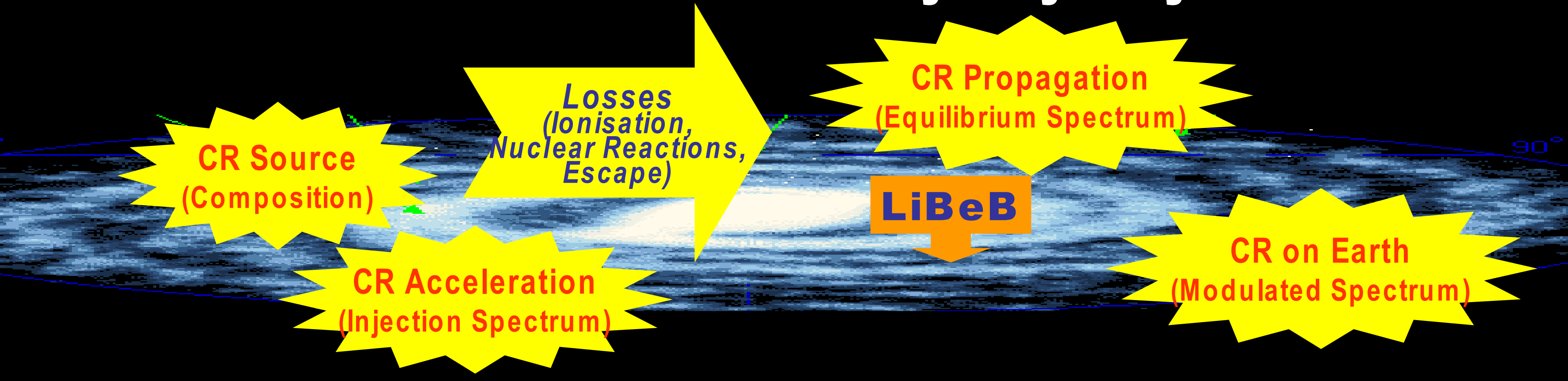
C (fusion)



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



# Galactic Cosmic Ray Odyssey



**CR Source**
(Composition)

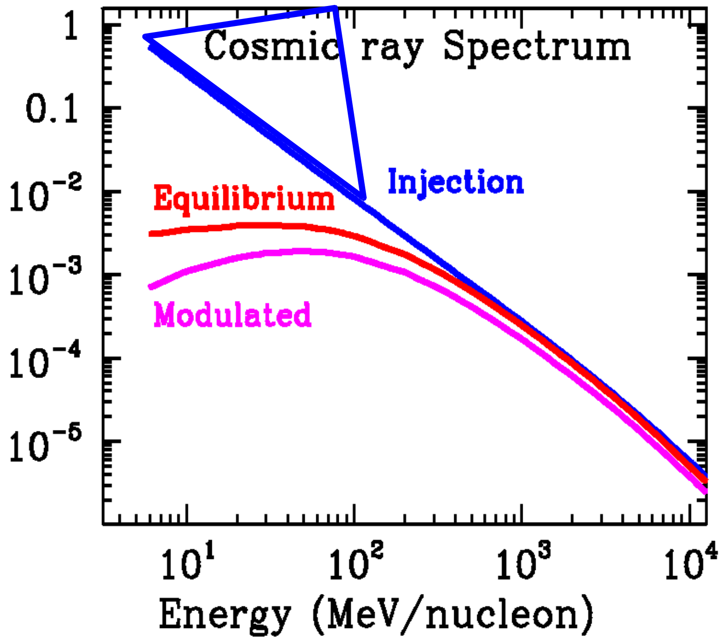
**Losses**
(Ionisation,
Nuclear Reactions,
Escape)

**CR Acceleration**
(Injection Spectrum)

**CR Propagation**
(Equilibrium Spectrum)

**LiBeB**

**CR on Earth**
(Modulated Spectrum)



Observations: modulated spectrum
the demodulated (=equilibrium) one may be derived
under some assumptions

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

However: neither theory nor GCR observations
can settle the question of a hypothetical low-energy
(<100 MeV/n) GCR component (short-ranged, i.e. local)
which may be very important for LiBeB
(Meneguzzi and Reeves 1975)

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

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

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

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

$\sigma_{p\alpha+CNO \Rightarrow Be} \sim 10\ mb$

$(10^{-26}\ cm^2)$

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

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

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

~OK for

Li6, Be, B10, B11

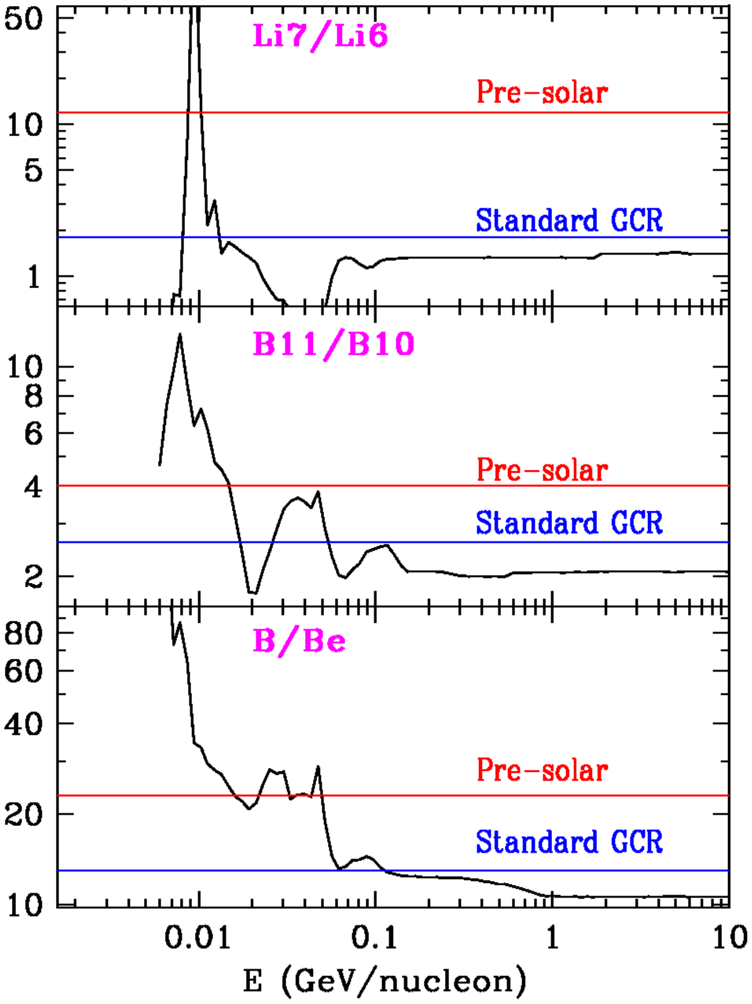
(Reeves, Fowler, Hoyle 1970)

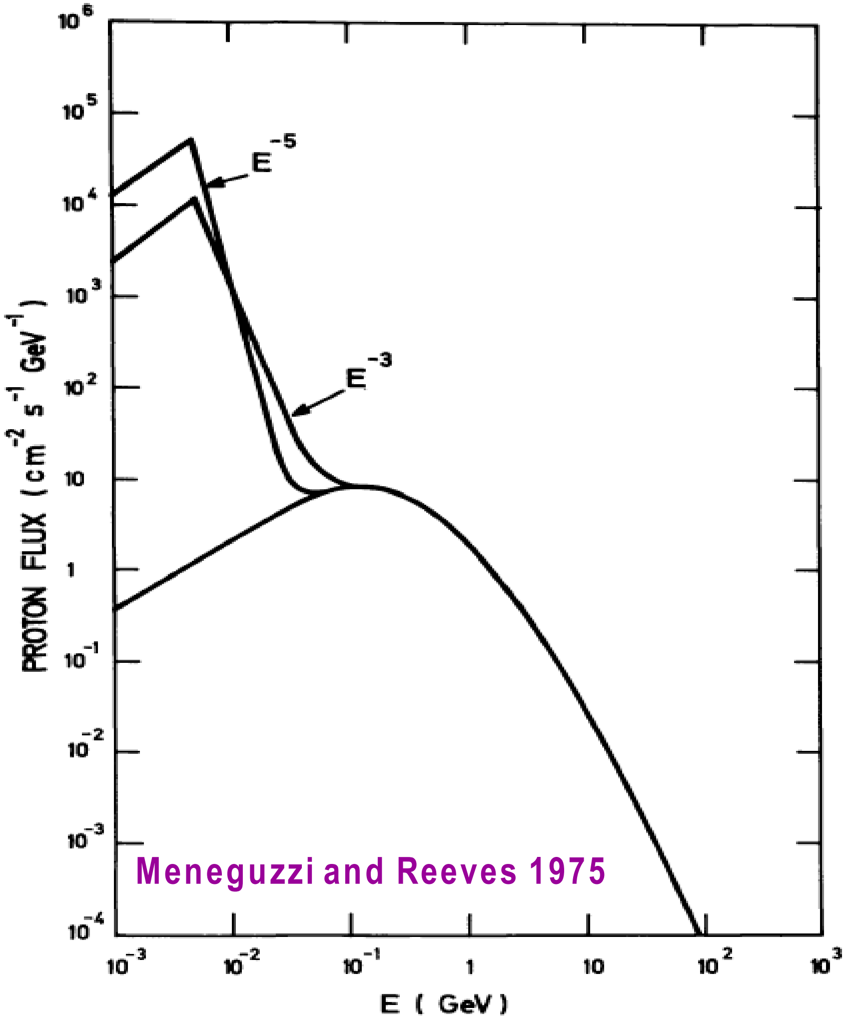
BUT

(Meneguzzi, Audouze and Reeves 1971)

| "Standard" GCR Production | Solar Values |
|---|---|
| Li7/Li6 ~ 2 | ~ 12 |
| B11/B10 ~ 2.5 | ~ 4 |
| B/Be ~ 14 | ~ 23 |

# LiBeB abundance ratios



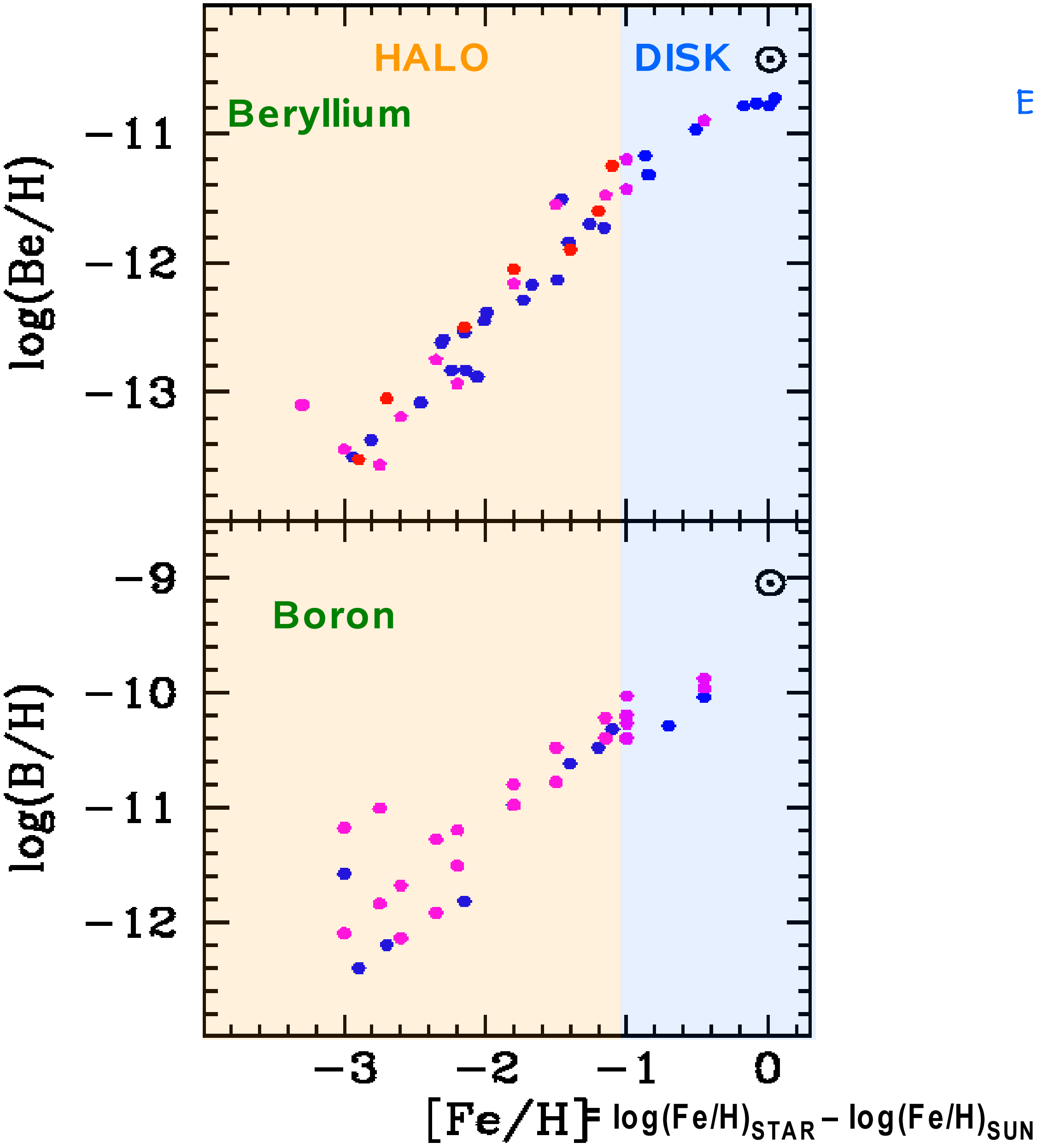


Discrepancies between results of standard GCR and pre-solar values could – perhaps - be cured by assuming a (substantial) Low Energy Component (LECR) in the region of 10-50 MeV

LECR should ionize considerably the ISM, should be local and should excite C and O nuclei, resulting in MeV γ-ray line emission

But none has been detected up to now

# Evolution of Be and B



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

Their abundances evolve

(as expected, since they are not primordial)

BUT, they evolve exactly as Fe

(unexpected, since they are produced from CNO and they should behave as secondaries)

# 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: O17, s-nuclei...

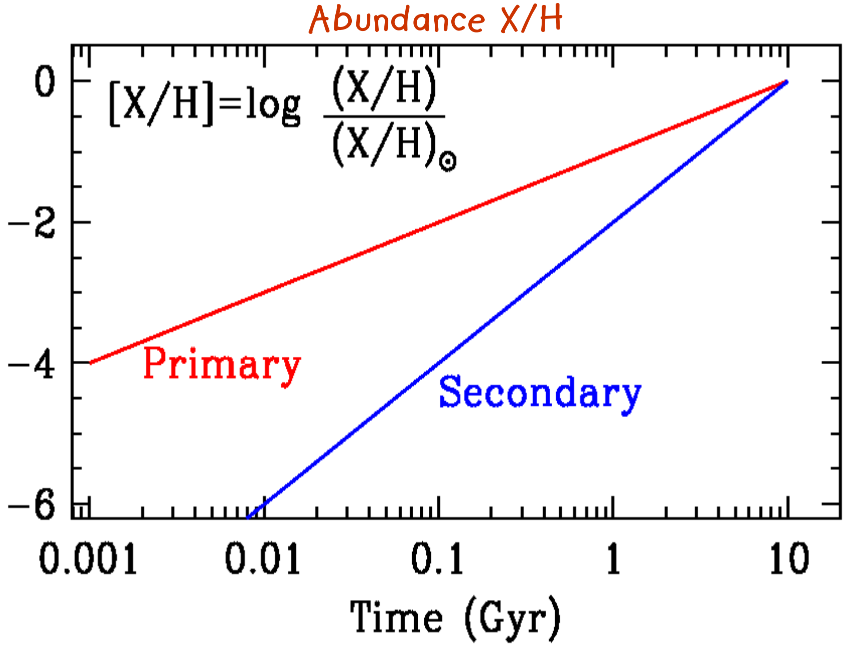
Abundance(primary): $X_p \propto t \propto Z$

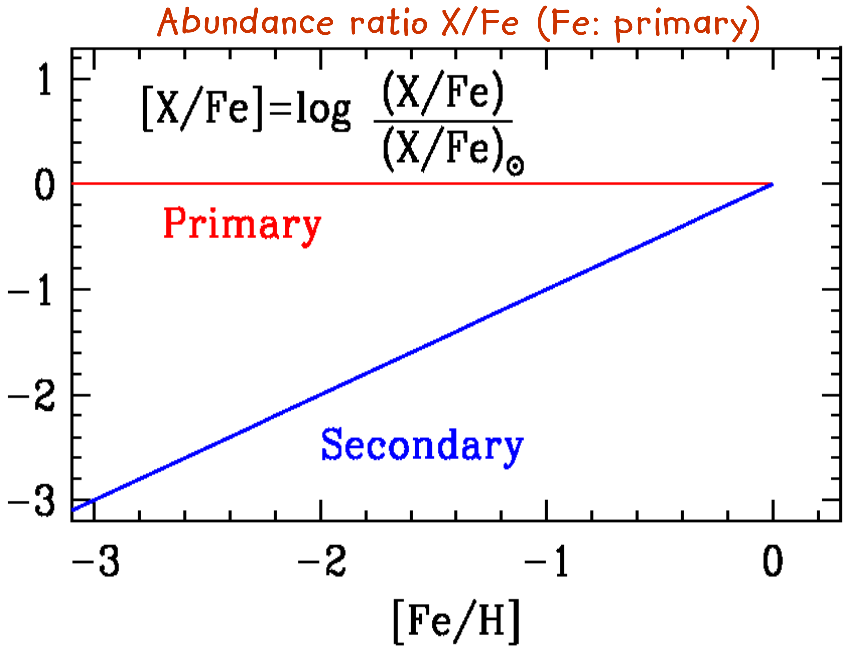
Abundance(secondary): $X_S \propto t^2 \propto Z^2$

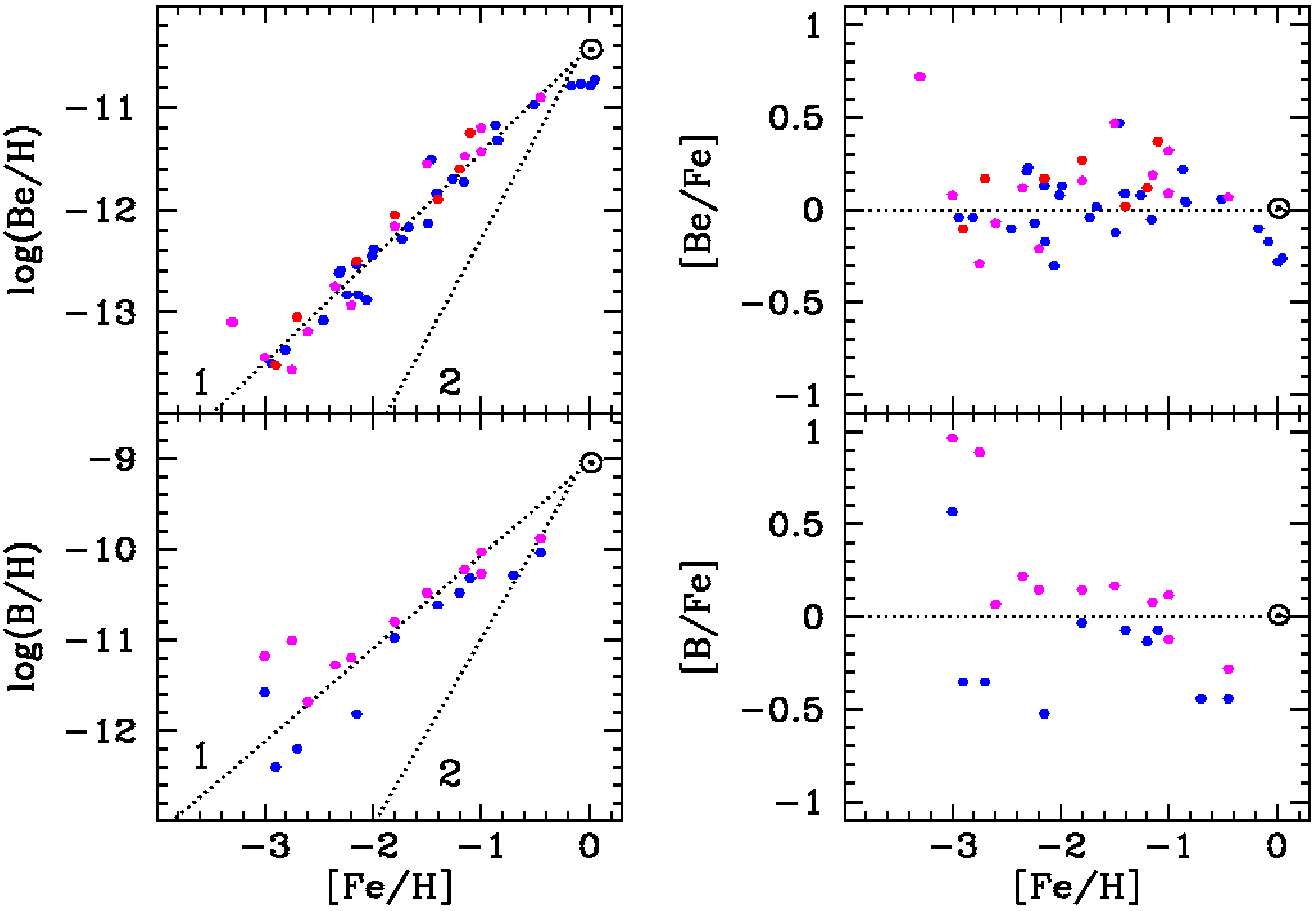
Abundance ratio

P/P : ~constant

S/P : $\propto X_P$


Abundance X/H


Abundance ratio X/Fe (Fe: primary)



Be and B behave as primaries (slope of Be/H vs Z : s=1 and of Be/Fe vs Z: s=0)
They should not !

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

Flux Composition Rate(Supernova)

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

$Y_{pa}(GCR,t)$ ~Const. : Cannot affect Be vs Fe behaviour

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

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

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

Always secondary LiBeB

Secondary LiBeB

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

Primary LiBeB

IF $Y_{CNO(GCR)} \sim$ const $\sim Y_{CNO}$

(Duncan, Lemke and Lambert 1992)

Always primary Li6,7

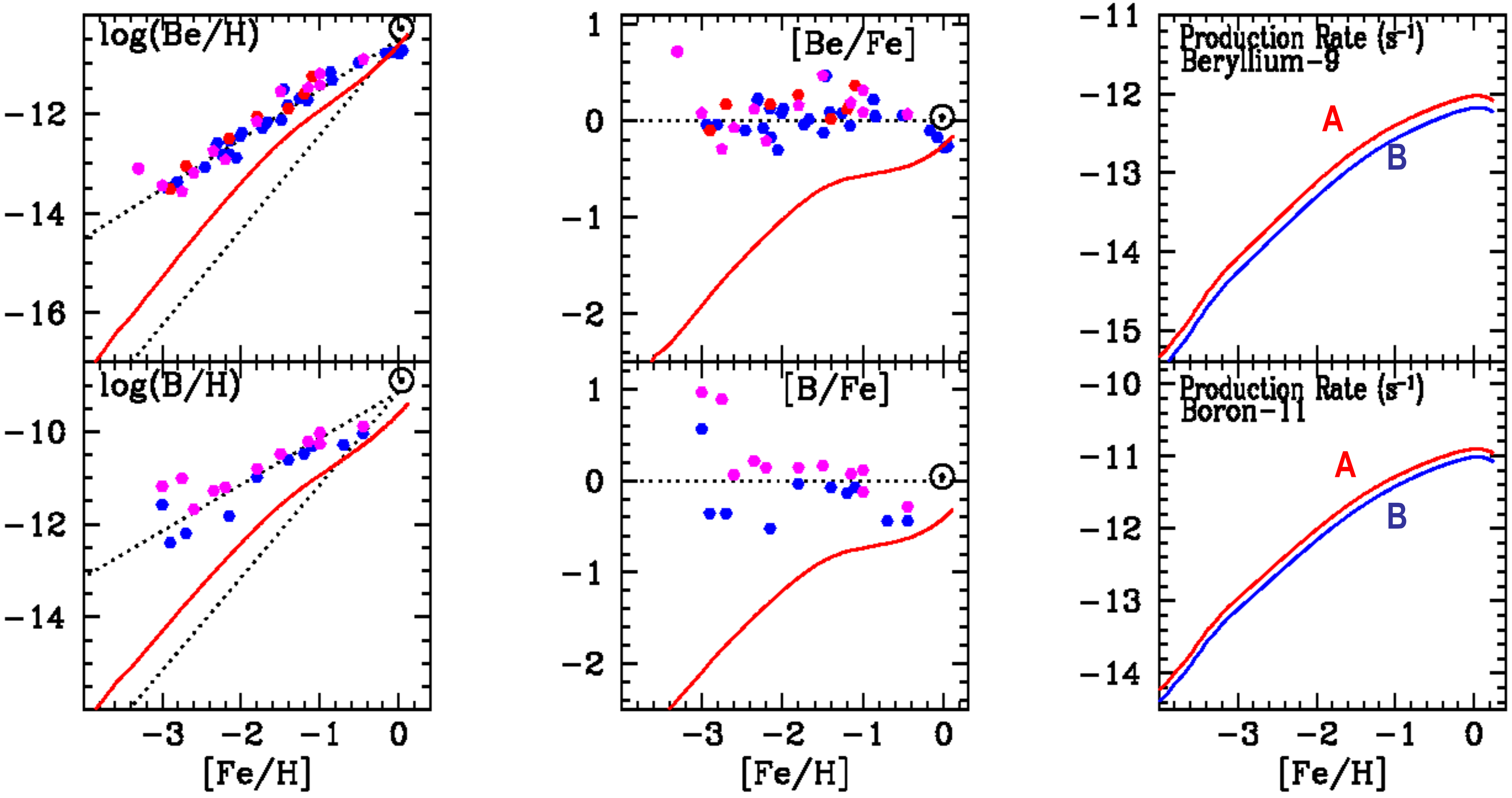
(Steigman and Walker 1992)

Standard GCRs: $\Phi_{p\alpha CNO(GCR,t)} \propto$ Rate SN(t) and $Y_{CNO(GCR)} \sim Y_{CNO(ISM)}$

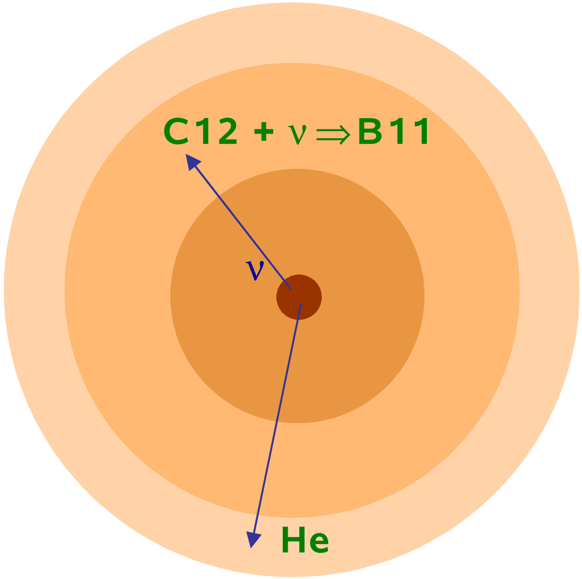
Always produce **secondary** **Be B**

# Standard chemical evolution of Be and B

[Standard GCR spectra and $X(GCR,t) \propto X(ISM,t)$ ]



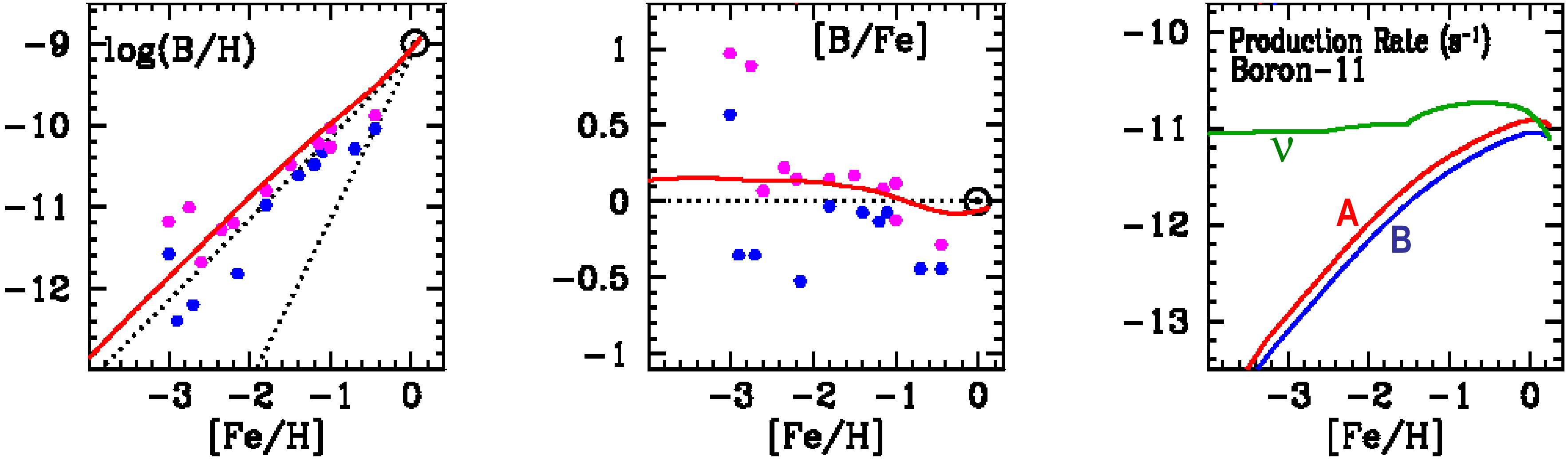
## Production of primary B11 (and little Li7) in SNII through neutrino-induced nucleosynthesis (Woosley et al. 1990)



Neutrinos from cooling of stellar core spallate :

- C12 in C-shell and produce B11 (primary)
- He4 in He-shell and produce He3;
- then : He3 + He4 → Li7 (primary)

Note : Neutrino spectra of core-collapse SN
are very uncertain;
So are the yields of B11 and Li7
of Woosley and Weaver (1995)



May completely account for B observations (80% of solar B is B11)
and for solar B11/B10 BUT not for evolution of Be...

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

**Energetics argument** (Ramaty et al. 1997)

1) SN produce Fe (~0.1 M ) and energy (~$10^{50}$ ergs ) for GCR acceleration

2) Producing one atom of Be by GCR requires a certain amount of energy, which depends on composition

**3) If X(GCR,t) ∝ X(ISM,t) << X at early times, there is simply not enough energy in early GCR accelerated by SN to maintain Be/Fe ~ const.**

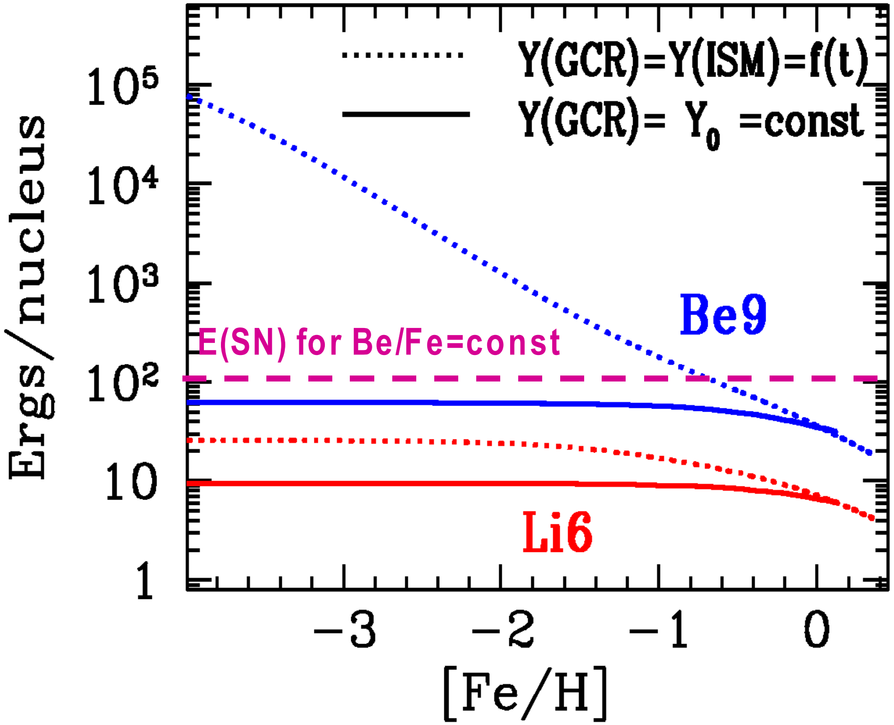
**We need X(GCR,t) ~ X always**

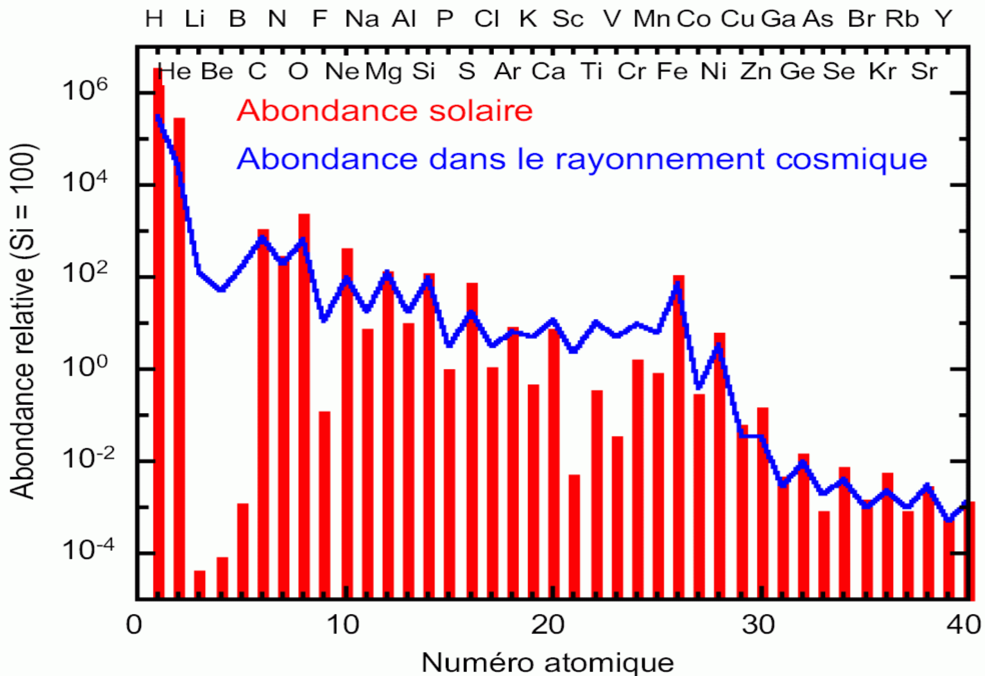
**Today, the source composition of GCR is ~Solar (once selection effects are taken into account)**

**But it is also SN, since elements from C to Fe peak are produced in SN**

**What is the GCR Source composition X(GCR,t) ?**

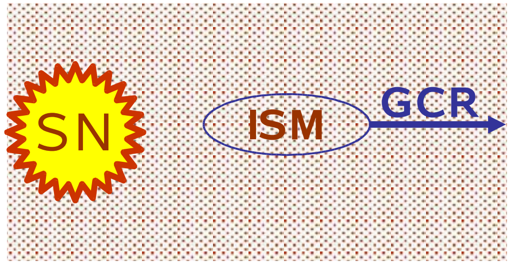
**What is the GCR Source ?**





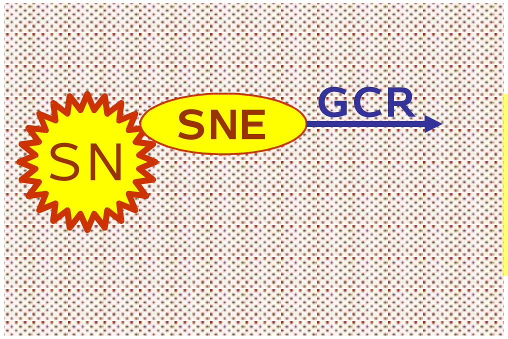
# Source Composition of Galactic Cosmic Rays

1) Standard ISM



$X_{CNO}(GCR,t) = X_{CNO}(ISM,t)$ Secondary LiBeB

2) Supernova ejecta (SNE)

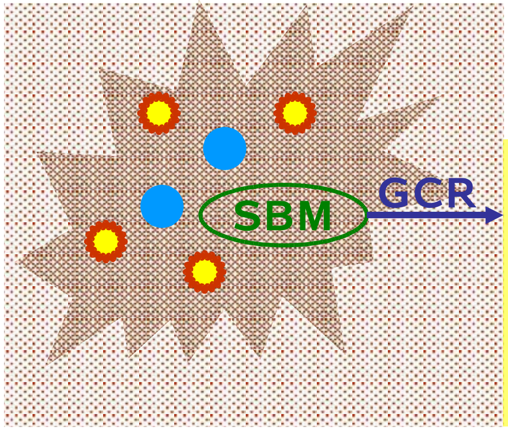


$X_{CNO}(GCR,t) = X_{CNO}(SNE,t) = \mathrm{Const.}$ Primary LiBeB

BUT: Absence of radioactive Ni59 ($\tau \sim 10^5$ yr) from observed GCR (Wiedenbeck et al. 1998) requires $\Delta t > 3\ 10^5$ yr between SNE explosion and GCR acceleration

SN cannot accelerate their own ejecta

3) SuperBubble matter (SBM), always enriched to ~Z from its own supernovae... (Higdon et al. 1998)



$X_{CNO}(GCR,t) = X_{CNO}(SBM,t) = \mathrm{Const.}$ Primary LiBeB

OK with Ni59 if $\Delta t$(between SN) $> 3\ 10^5$ yr

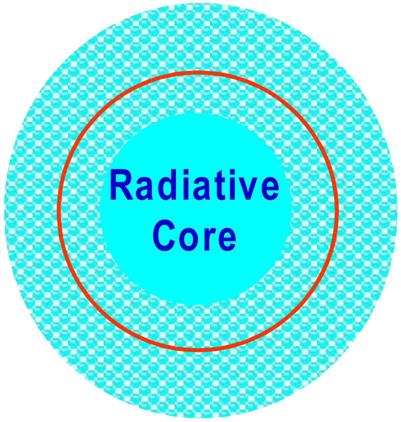
BUT: in Superbubbles, massive star winds continuously accelerate SBM, and do not allow Ni59 to decay

ALSO: SN are observationally associated with HII regions, with widely different metallicities

The SBM scenario has even more serious problems than the SNE one...

# Surface Li abundance of Main Sequence stars

## Cool stars



Deep
convective
envelope

**Radiative Core**

Li
depleted
at surface

T (Li-burn)
~2 $10^6$ K

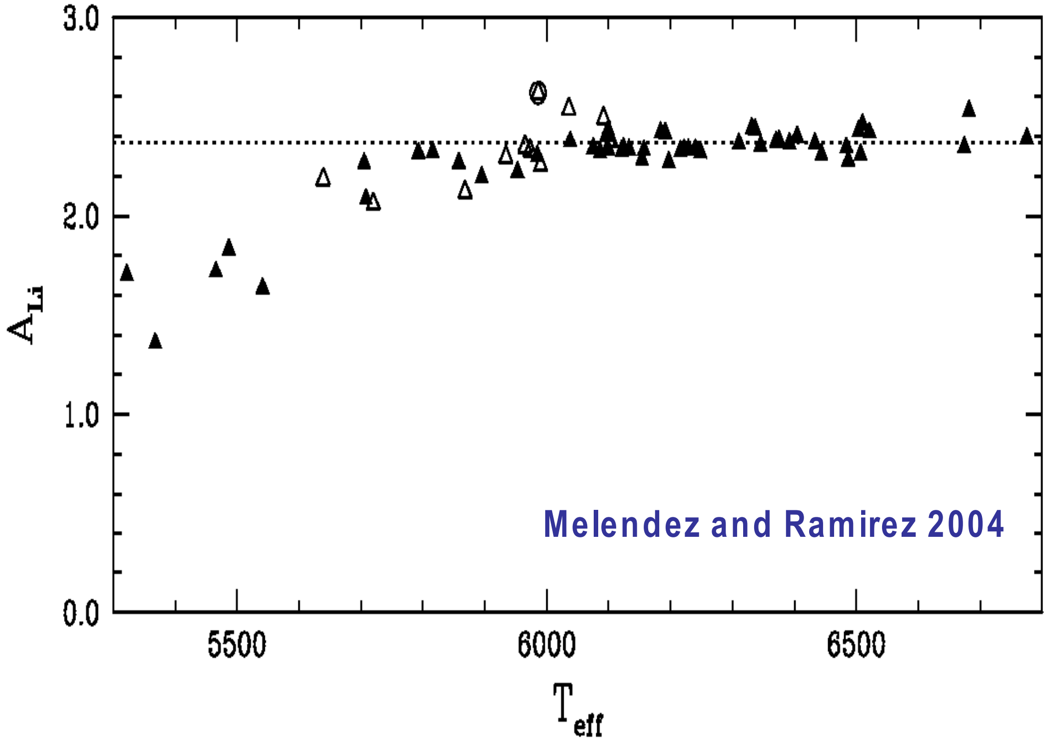
## Hot stars

Swallow
convective
envelope

**Radiative Core**

Li
preserved
at surface

T (Li-burn)
~2 $10^6$ K

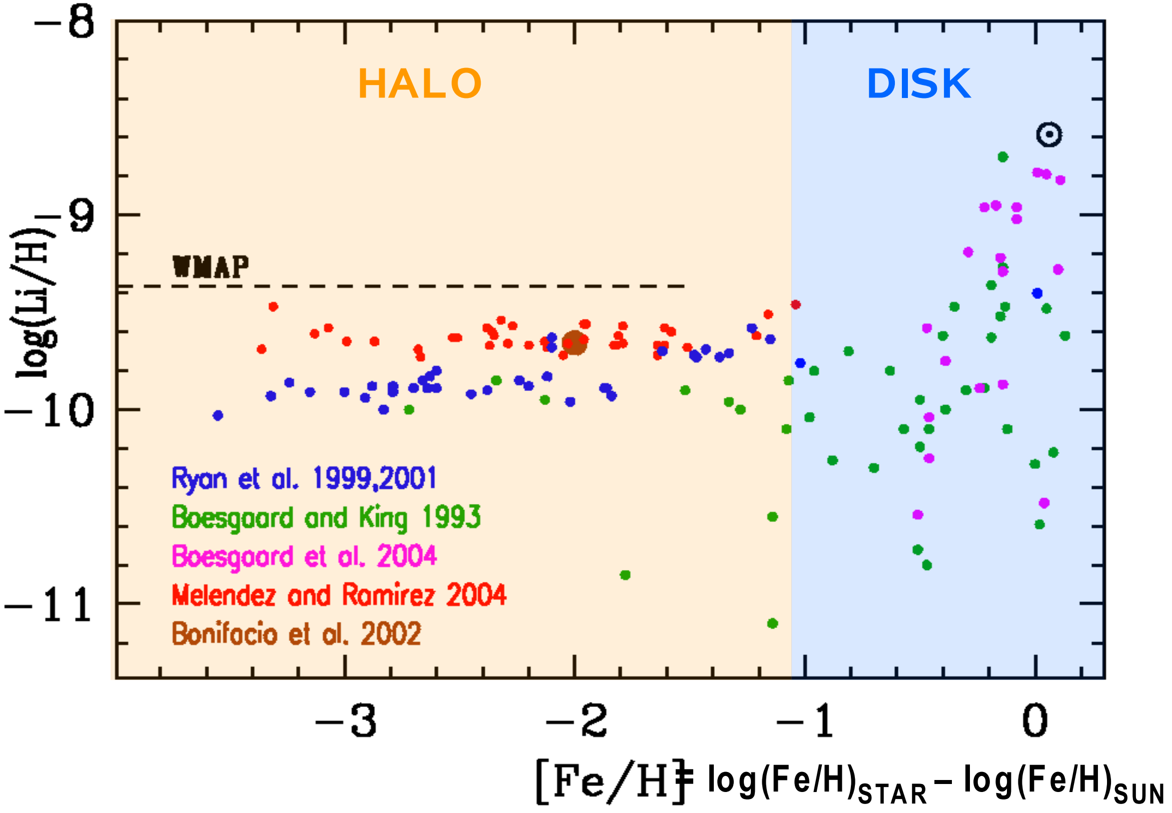


**Melendez and Ramirez 2004**

Stars with $T_{EFF}$ > 6000 K
(hopefully) display
at their surface
their initial Li content,
the one of the gas from which
they were formed

They may be used as tracers of
the chemical evolution of Li

# Observations of Li



The Li "plateau" observed in
old, low metallicity, stars
of the galactic halo
(M. and F. Spite 1982)
with its low dispersion, suggests
a pregalactic/primordial origin

BUT

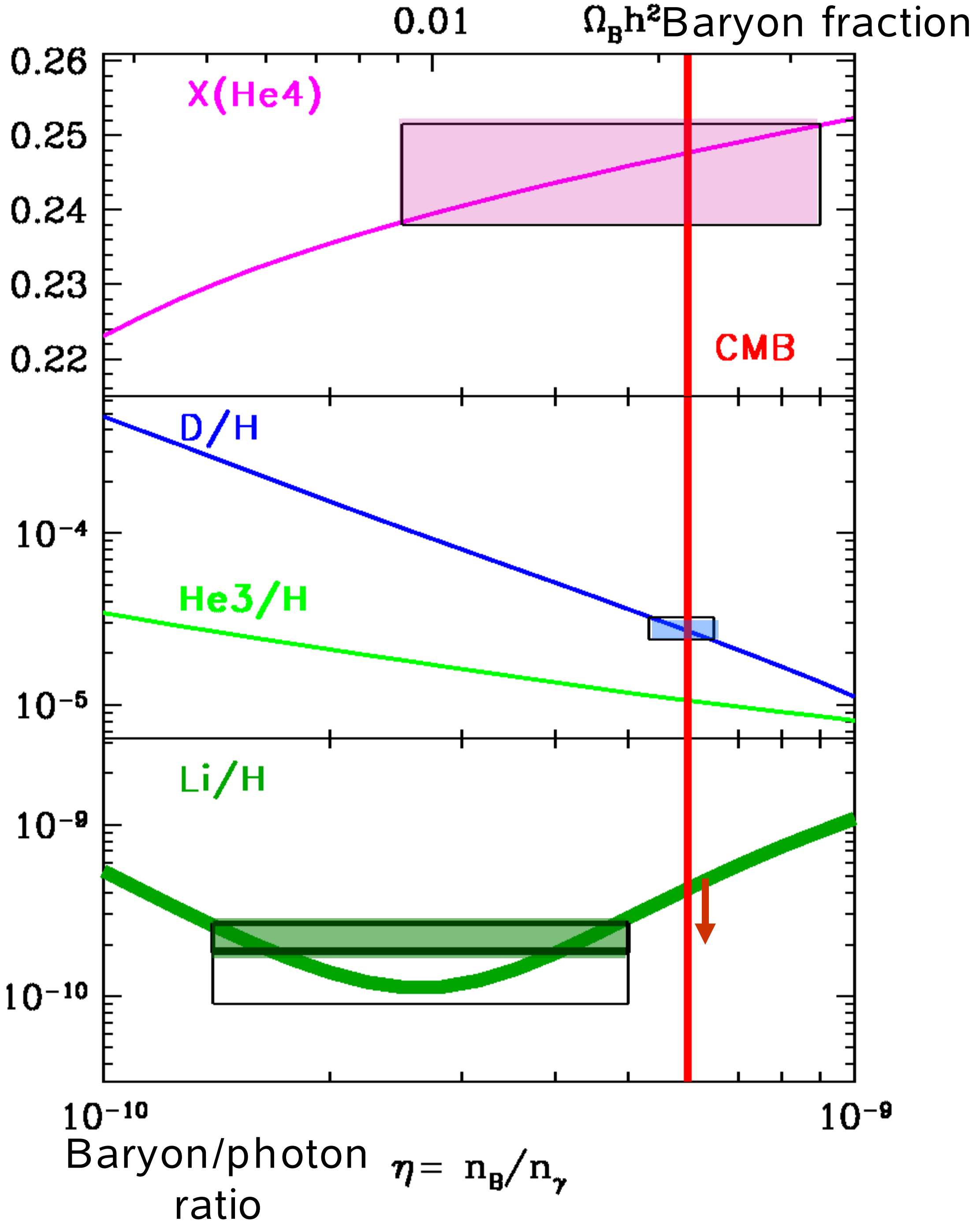
What is the true
primordial value ?

Current plateau lower than
suggested by WMAP + standard
Big Bang Nucleosynthesis (BBN)

Problem No 1 (Observations): Measurements affected by systematic errors
(stellar atmosphere models: 1D vs 3D, LTE vs NLTE, $T_{EFF}$ scale)

Problem No 2 (Stellar physics): If standard BBN calculations are correct, then
WMAP results imply some Li surface depletion, even for such "hot" stars… BUT:
Stellar models fail to deplete by required factors 2-3 AND with such small dispersion

Problem No 3 (BBN Nuclear Physics): Perhaps, Li destruction is underestimated;
BBN calculations may become compatible with observed plateau,
even for WMAP baryonic density



Calculations of
primordial nucleosynthesis
and determination
of baryonic density
by WMAP

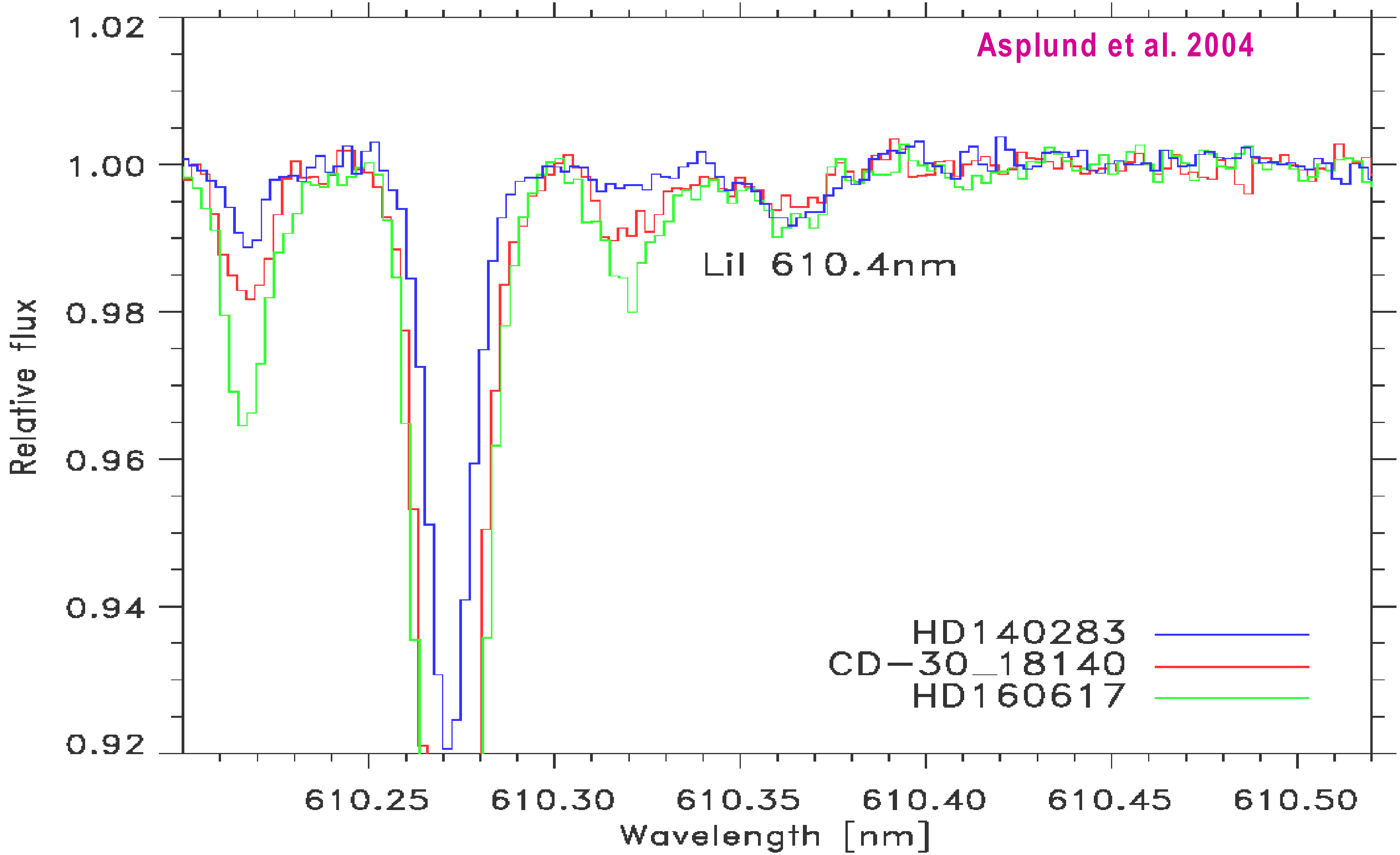
-are consistent with
observed "primordial" D
in high redshift gas clouds

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

-suggest a value of
primordial Li
~2 times higher
than the observed
"plateau" in halo stars

Perhaps Li destruction is
underestimated in standard BBN
(Coc et al. 2004)

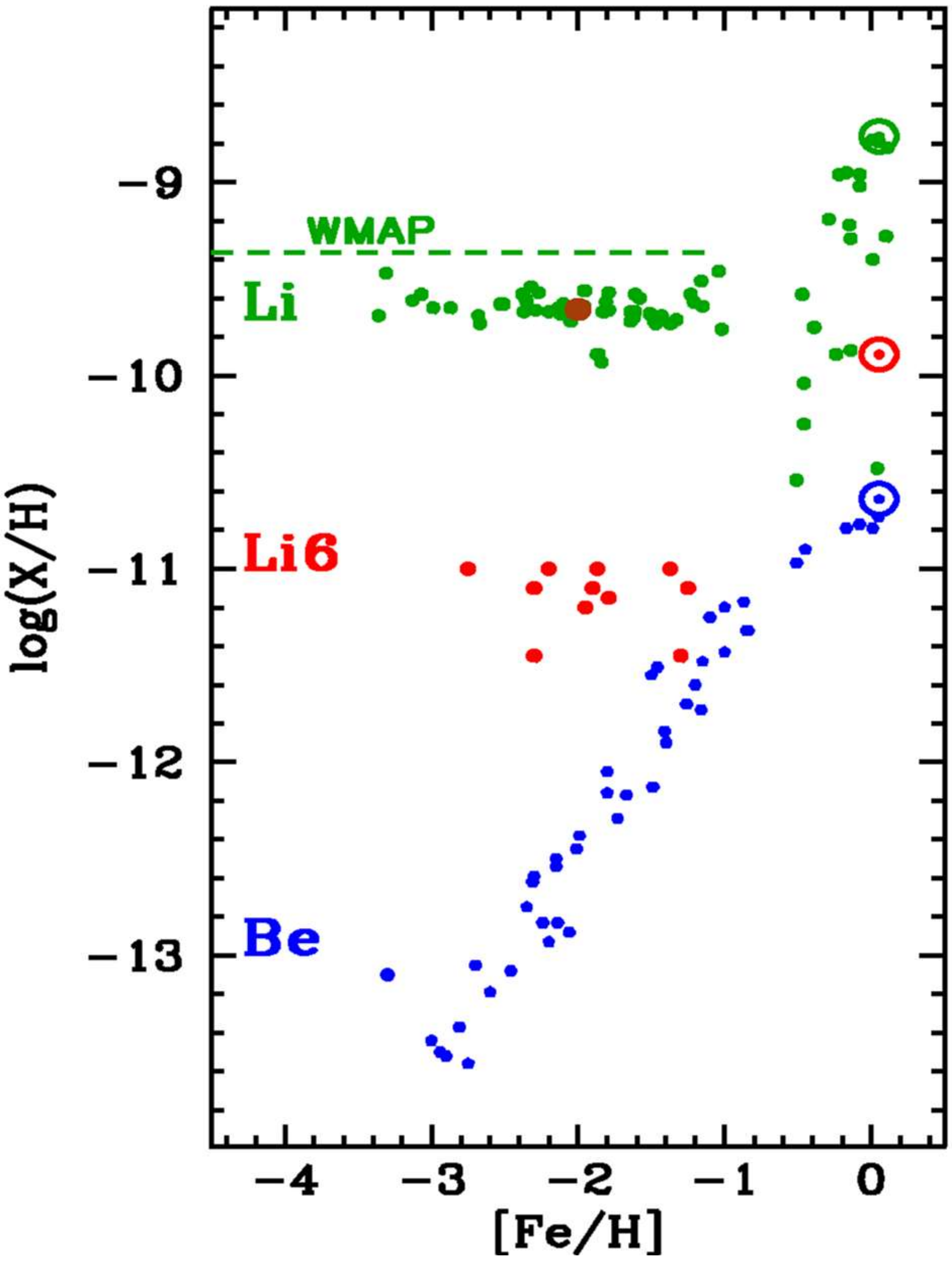
# Observations of Li6 in low metallicity halo stars



Apparently, a Li6 plateau,
at log(Li6/H) = -11
Much higher than primordial
$\log(\mathrm{Li6/H})_{SBBN} \sim -14$

If Li depleted in stars
(by factor 2, from WMAP value)
Li6 should be depleted
at least as much

Li6 plateau value should be
even higher
than log(Li6/H) = -11

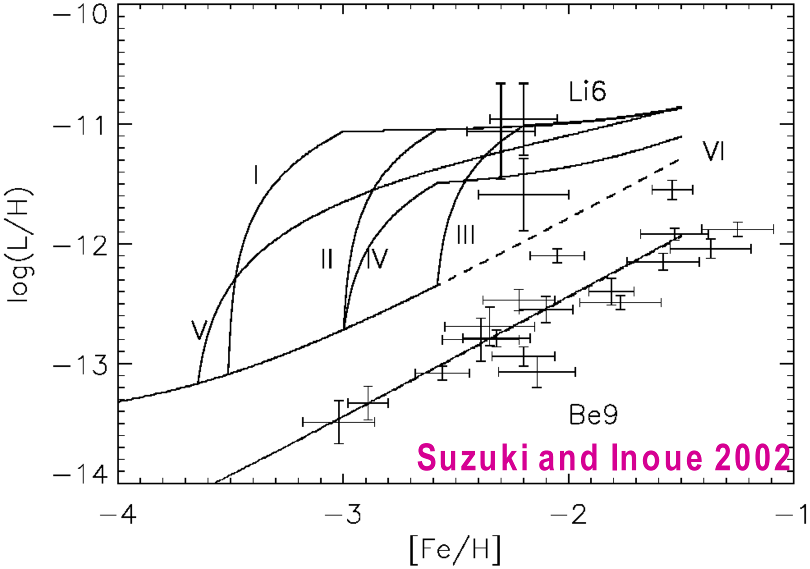


Neither the Li6 plateau,
nor its high value
can be explained by
Standard GCR production
of Li6 ( primary, from $\alpha + \alpha$ )

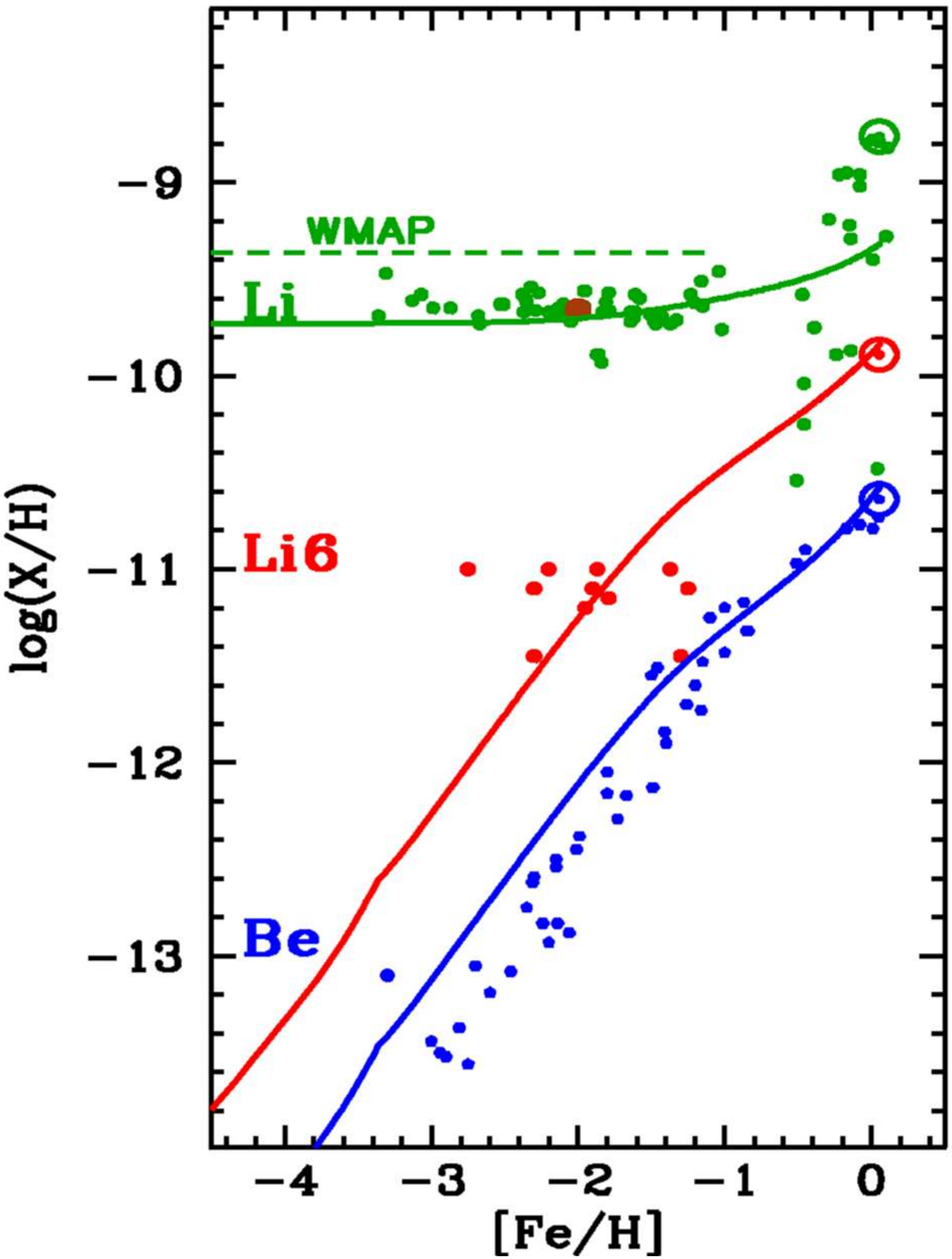
Pregalactic Li6 production suggested
either through

1) Modification of BBN, induced by
decay of unstable particles
(Jedamzik 2004)

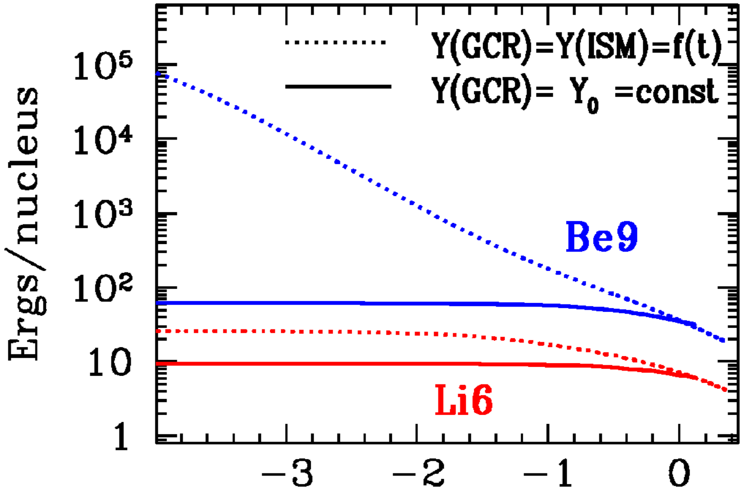
2) $\alpha+\alpha$ accelerated by shocks induced
by early cosmic structure formation
(Suzuki and Inoue 2002)
BUT it must stop before the formation
of the first stars...



Suzuki and Inoue 2002



# Energetics of early Li6 formation



Energy required (Normal spectrum and $\alpha+\alpha$): 20 erg/Li6

@ 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,

(LECR, 10-50 MeV/N) ~3 times less energy required

Normal SN: $E_{SN}$(CR) = 2 $10^{50}$ erg, producing $10^{49}$ Li6 nuclei ; to obtain Li6/H~$10^{-11}$,

dilution into $10^{60}$ H atoms or $10^3$ M is required

But each SN produces $M_{SN}$(Fe)~0.1 M , so that X(Fe)~ $10^{-4}$ ~0.07 X (Fe) or [Fe/H]~-1.3

Normal SN can produce Li6/H ~$10^{-11}$ but only at [Fe/H] ~ -1.3; at [Fe/H]~-3, only Li6/H ~5 $10^{-13}$

Shocks from structure formation: Velocity $V_{Virial}$ ~ $(GM/R)^{1/2}$ ~ 400 $(M_{DarkHalo}/10^{13}\ M\ )^{1/3}$ km/s

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

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

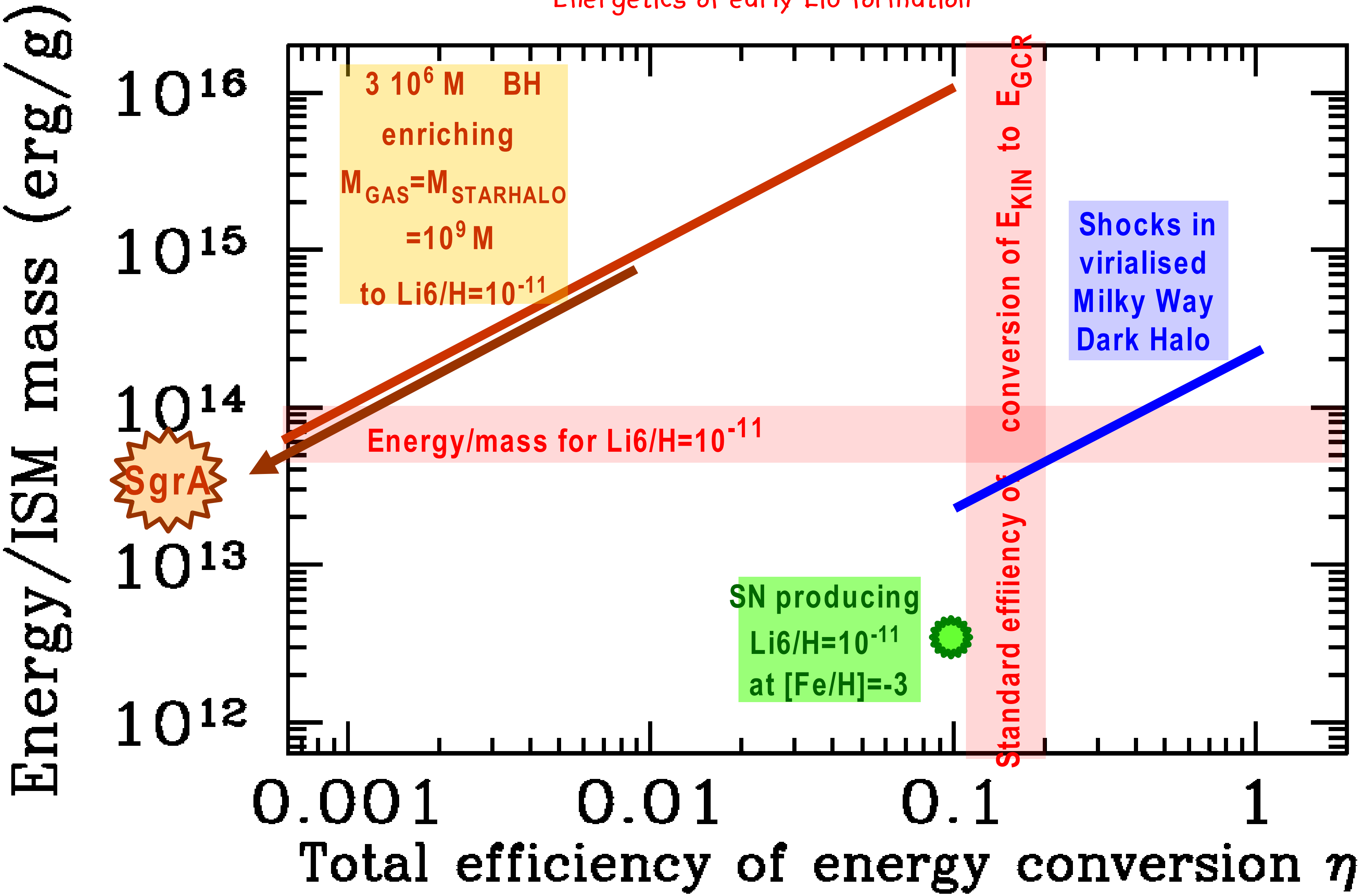
OK, for an efficiency of 50% (normal spectrum) or 20% (LECR spectrum)

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

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

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

# Energetics of early Li6 formation



Energetics of early Li6/H=$10^{-11}$ are quite demanding

No energy source appears really efficient enough

If the Li6 plateau is real and
Li6 is pregalactic, then some
metallicity dependent depletion
should operate in stars
([Fe/H] ~ -2 to -1)
in order to Keep Li6/H flat

## CONCLUDING QUESTIONS

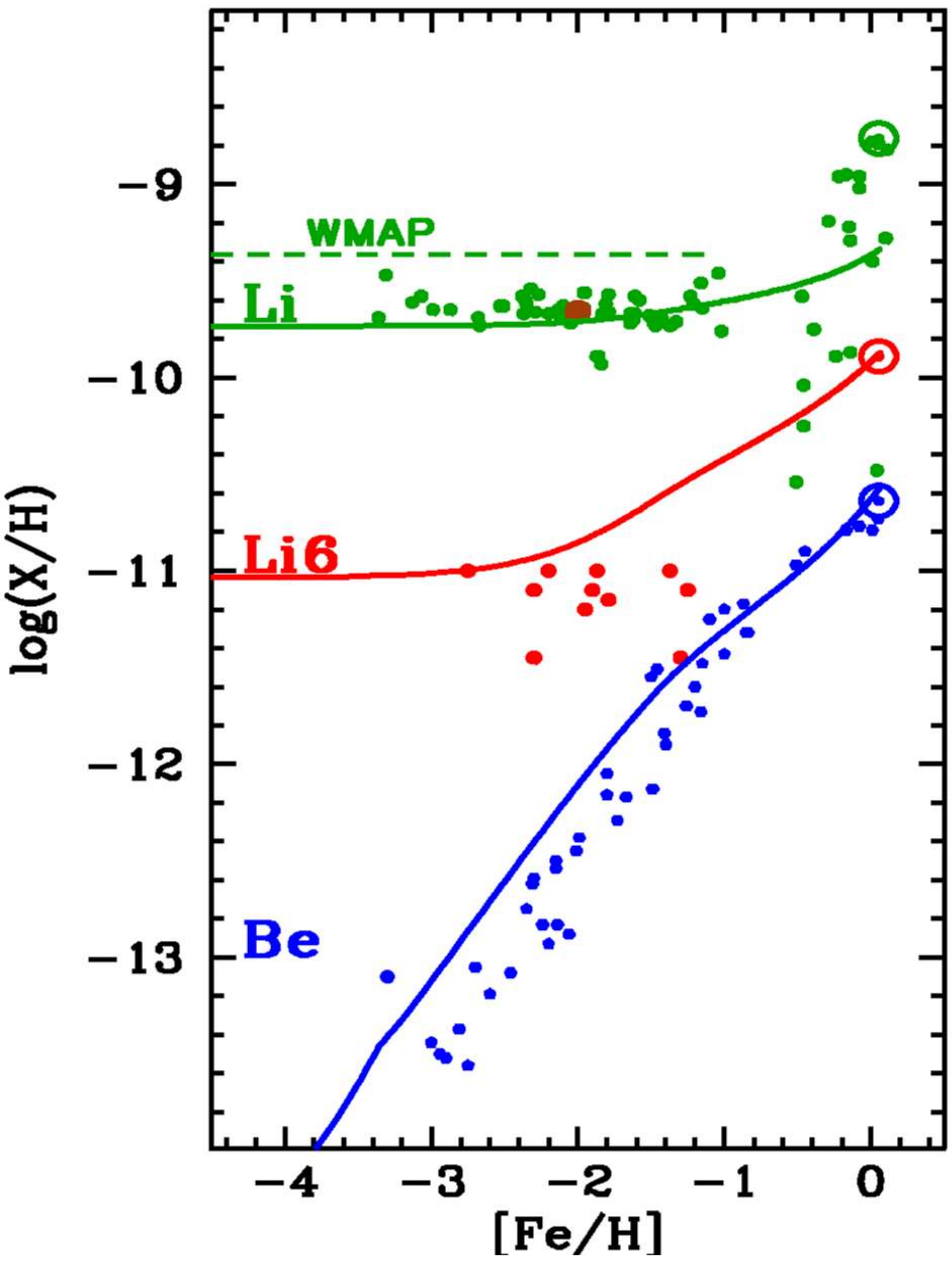
1) What is the true Li plateau value and how was it made ?
(BBN vs stellar depletion)

2) What is the late source of Li7?
(AGB stars or novae?)

3) IF there is a Li6/H plateau, how to explain its origin (energetics) and flatness at [Fe/H] ~ -2 to -1 ?

4) How to explain primary Be (and B) ?

X(GCR,t)=const required,
but HOW is it obtained?



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# The x-process of B2FH turned out to be incredibly rich in astrophysical implications

cosmic rays
(GCR source, acceleration and propagation,
"standard"and "low energy" CR,
Galactic and pre-galactic)

primordial nucleosynthesis

stellar depletion
(convection, rotation, diffusion)

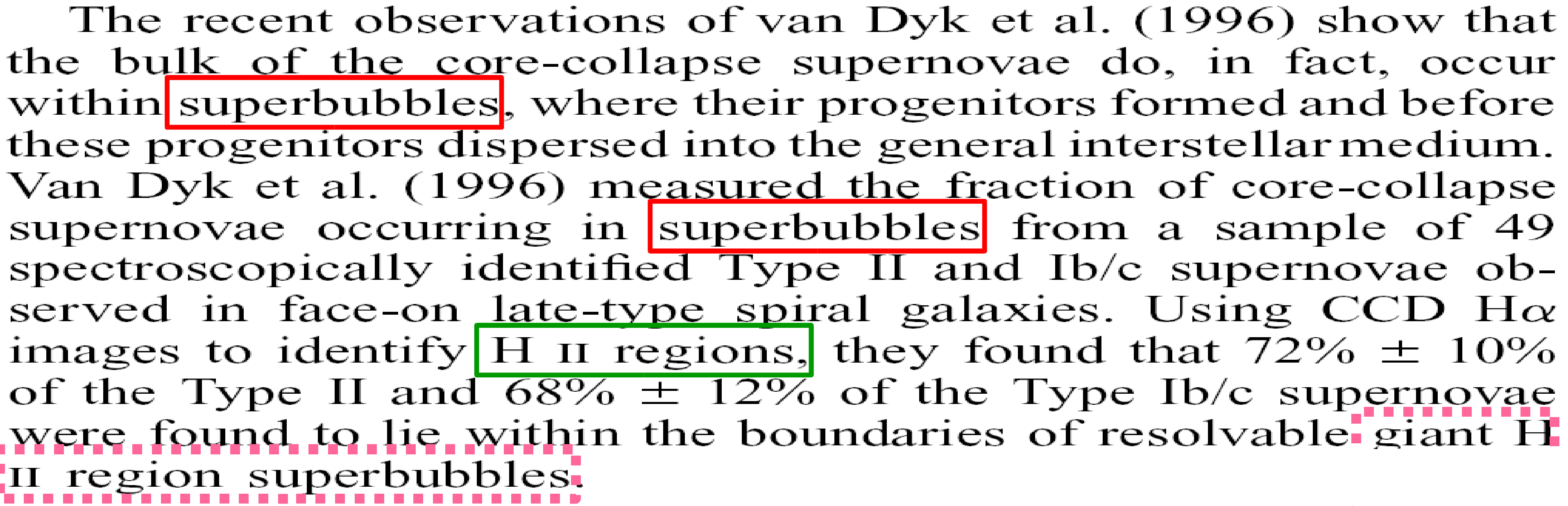
stellar nucleosynthesis
- hydrostatic: novae, AGB
- explosive : $\nu$ in SNII

galactic chemical evolution

(perhaps) cosmic structure formation...

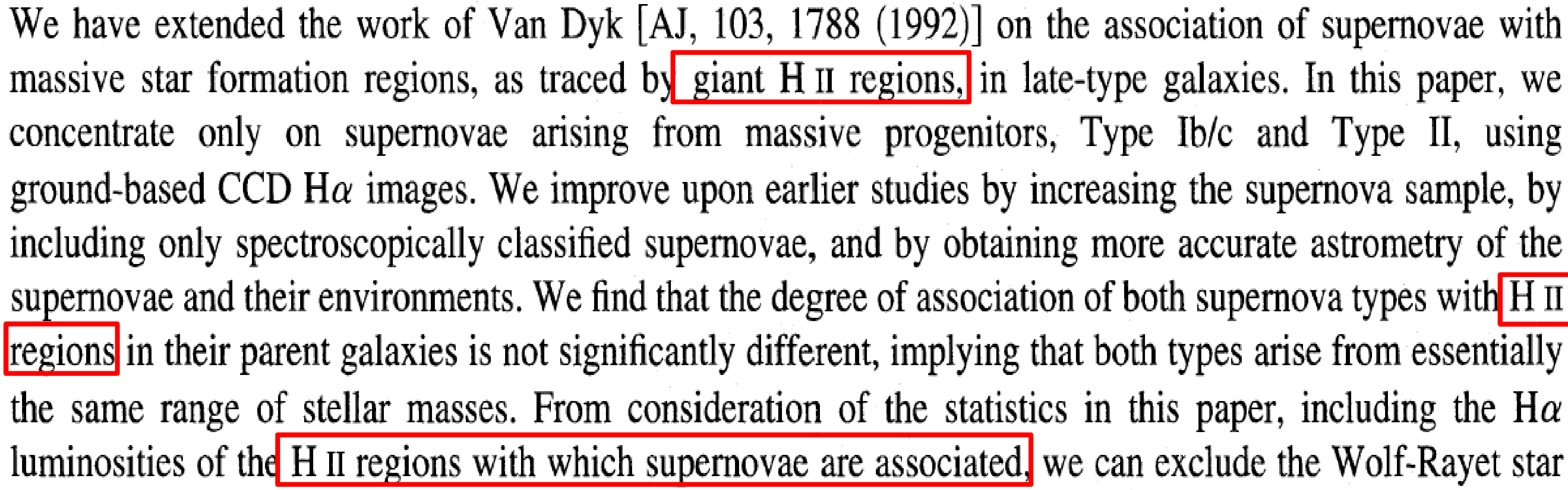
In fact, the richest of all nucleosynthesis processes !
Many more man-years of study required !

Higdon, Lingenfelter and Ramaty 1998



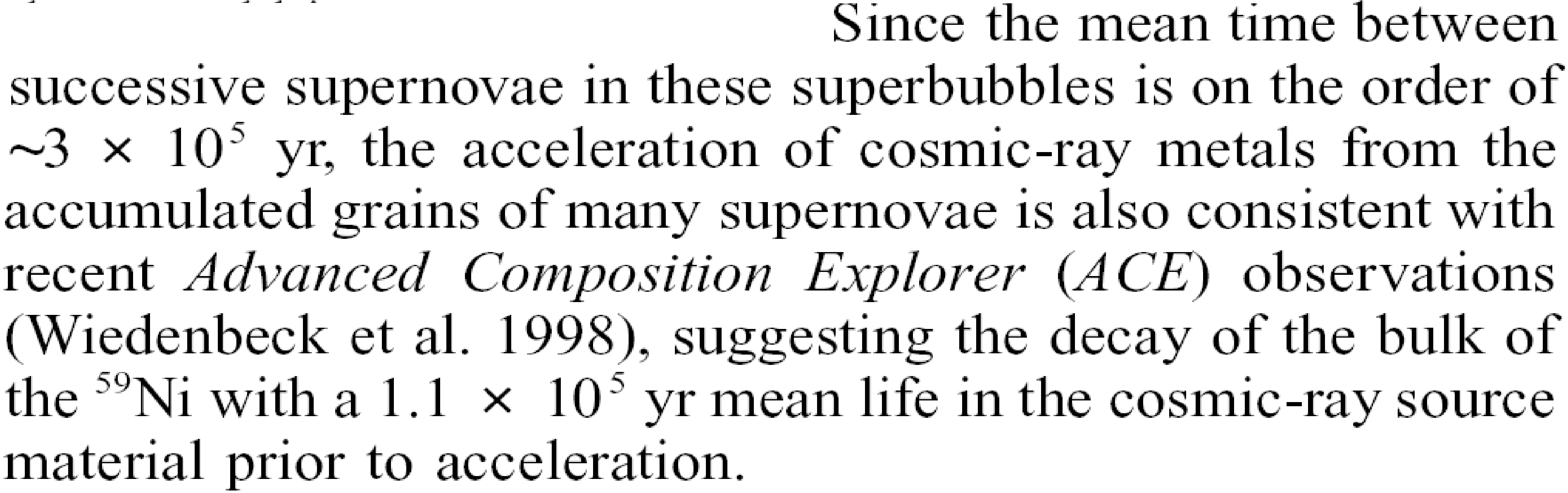
The recent observations of van Dyk et al. (1996) show that the bulk of the core-collapse supernovae do, in fact, occur within superbubbles, where their progenitors formed and before these progenitors dispersed into the general interstellar medium. Van Dyk et al. (1996) measured the fraction of core-collapse supernovae occurring in superbubbles from a sample of 49 spectroscopically identified Type II and Ib/c supernovae observed in face-on late-type spiral galaxies. Using CCD H$\alpha$ images to identify H II regions, they found that 72% ± 10% of the Type II and 68% ± 12% of the Type Ib/c supernovae were found to lie within the boundaries of resolvable giant H II region superbubbles.

Van Dyk, Hamuy and Fillipenko 1996



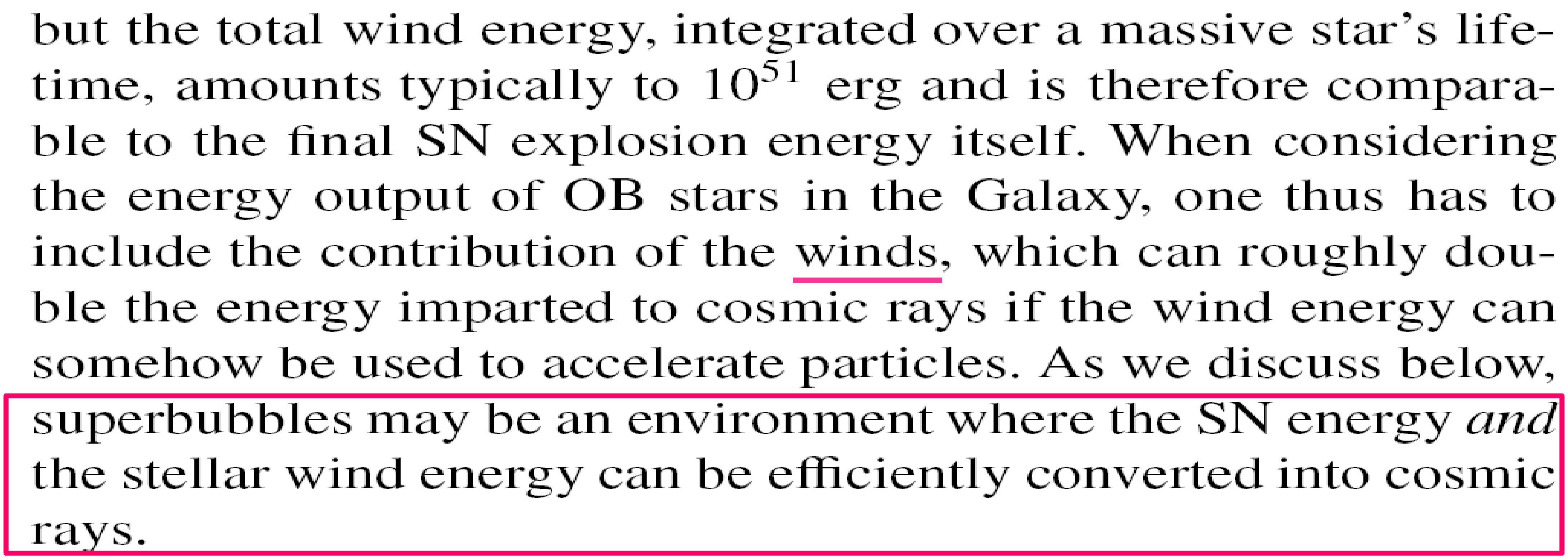
We have extended the work of Van Dyk [AJ, 103, 1788 (1992)] on the association of supernovae with massive star formation regions, as traced by giant H II regions, in late-type galaxies. In this paper, we concentrate only on supernovae arising from massive progenitors, Type Ib/c and Type II, using ground-based CCD H$\alpha$ images. We improve upon earlier studies by increasing the supernova sample, by including only spectroscopically classified supernovae, and by obtaining more accurate astrometry of the supernovae and their environments. We find that the degree of association of both supernova types with H II regions in their parent galaxies is not significantly different, implying that both types arise from essentially the same range of stellar masses. From consideration of the statistics in this paper, including the H$\alpha$ luminosities of the H II regions with which supernovae are associated, we can exclude the Wolf-Rayet star

Higdon, Lingenfelter and Ramaty 1998



Since the mean time between successive supernovae in these superbubbles is on the order of ~3 × $10^5$ yr, the acceleration of cosmic-ray metals from the accumulated grains of many supernovae is also consistent with recent *Advanced Composition Explorer* (*ACE*) observations (Wiedenbeck et al. 1998), suggesting the decay of the bulk of the $^{59}$Ni with a 1.1 × $10^5$ yr mean life in the cosmic-ray source material prior to acceleration.

Parizot, Markowith, Bykov et al 2004



but the total wind energy, integrated over a massive star's lifetime, amounts typically to $10^{51}$ erg and is therefore comparable to the final SN explosion energy itself. When considering the energy output of OB stars in the Galaxy, one thus has to include the contribution of the winds, which can roughly double the energy imparted to cosmic rays if the wind energy can somehow be used to accelerate particles. As we discuss below, superbubbles may be an environment where the SN energy *and* the stellar wind energy can be efficiently converted into cosmic rays.