Composition of GCR and production of Li, Be and B in the Galaxy

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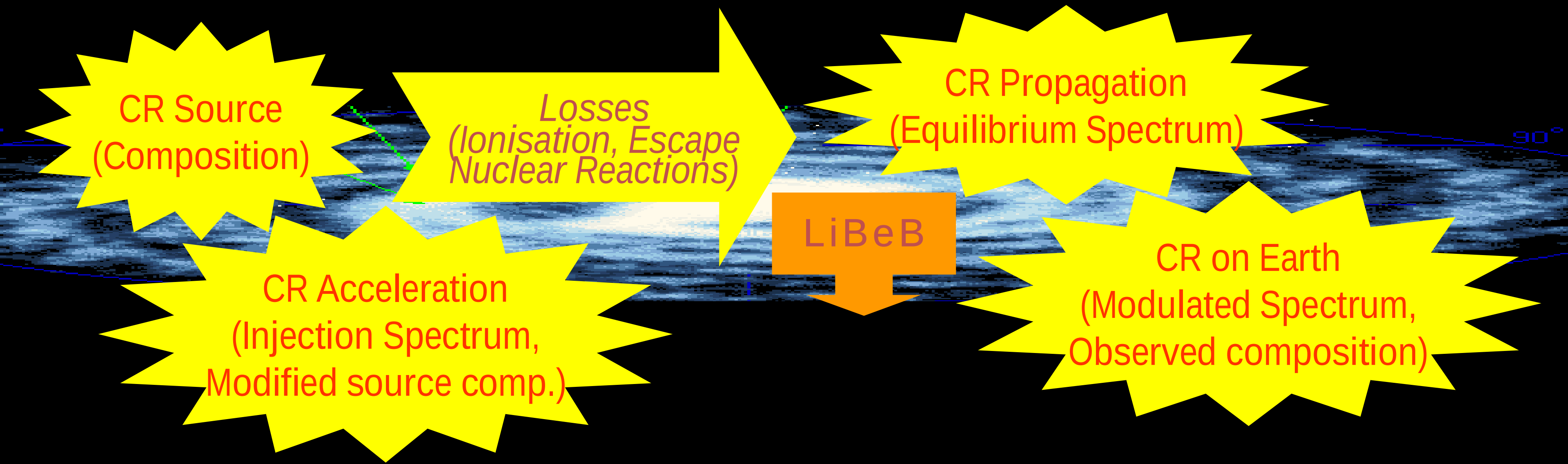
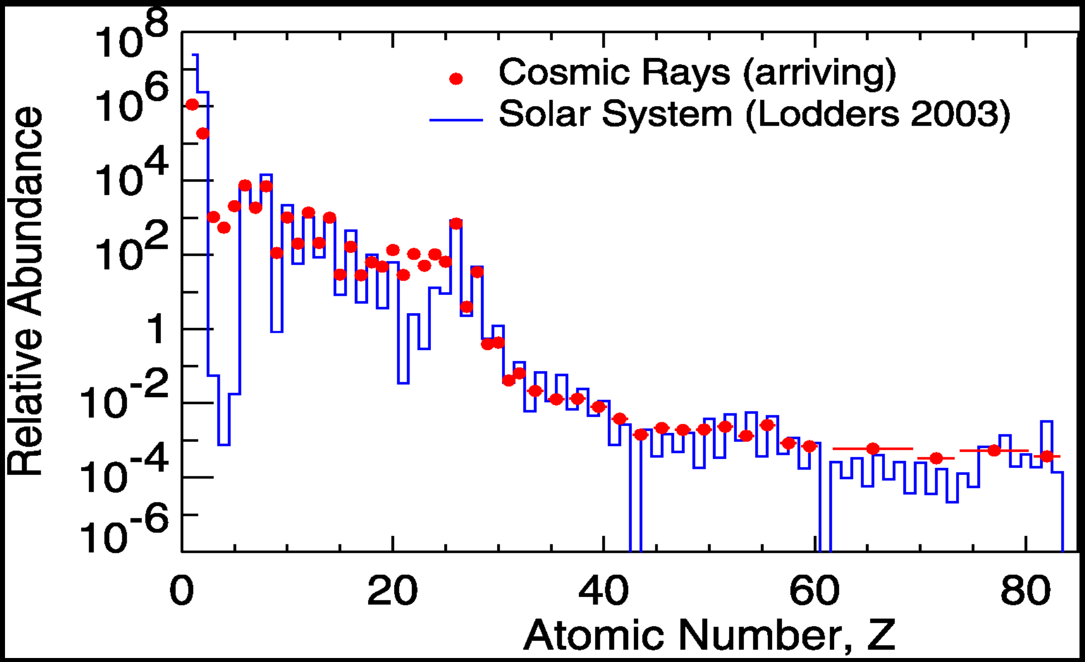
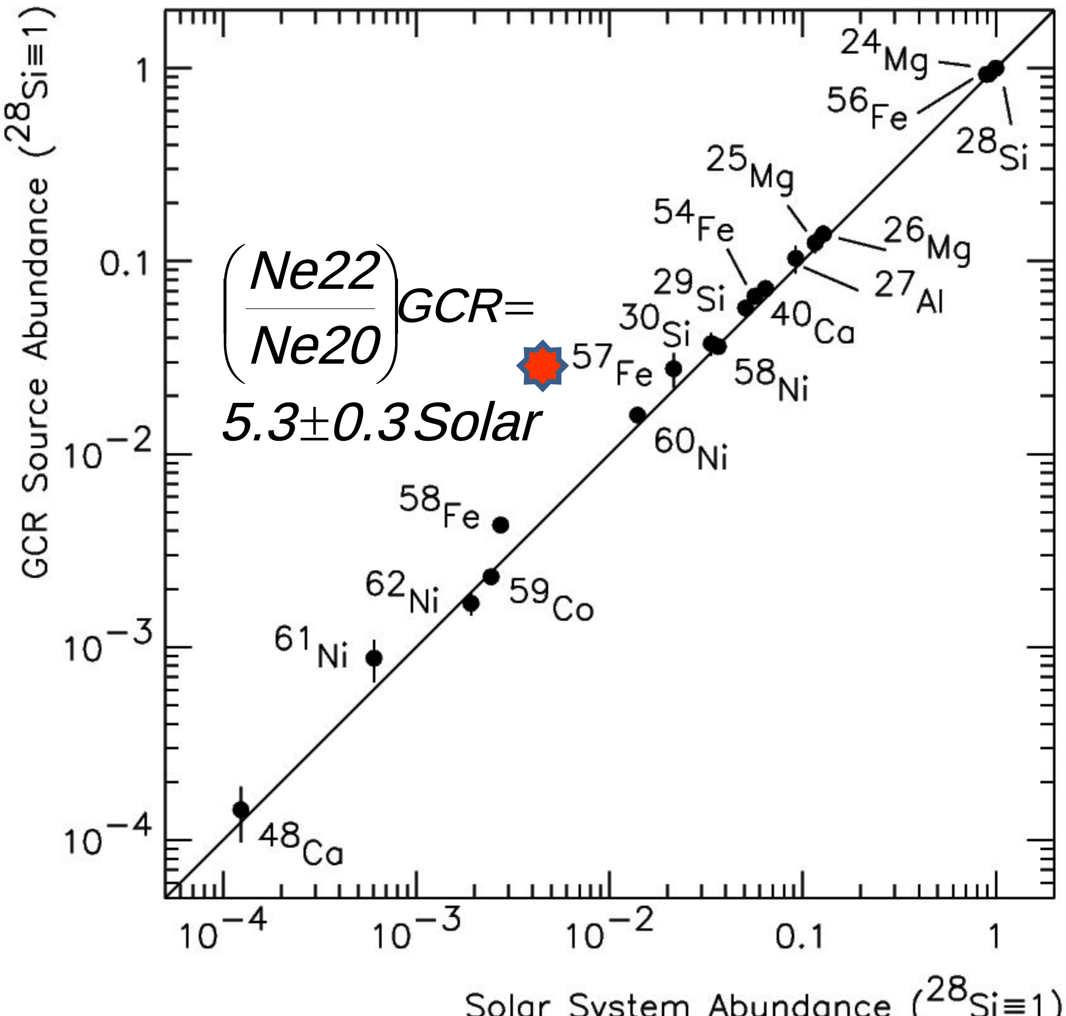
Galactic Cosmic Ray Odyssey





What do we learn from GCR source abundances ?

Galactic Cosmic Ray Source Composition



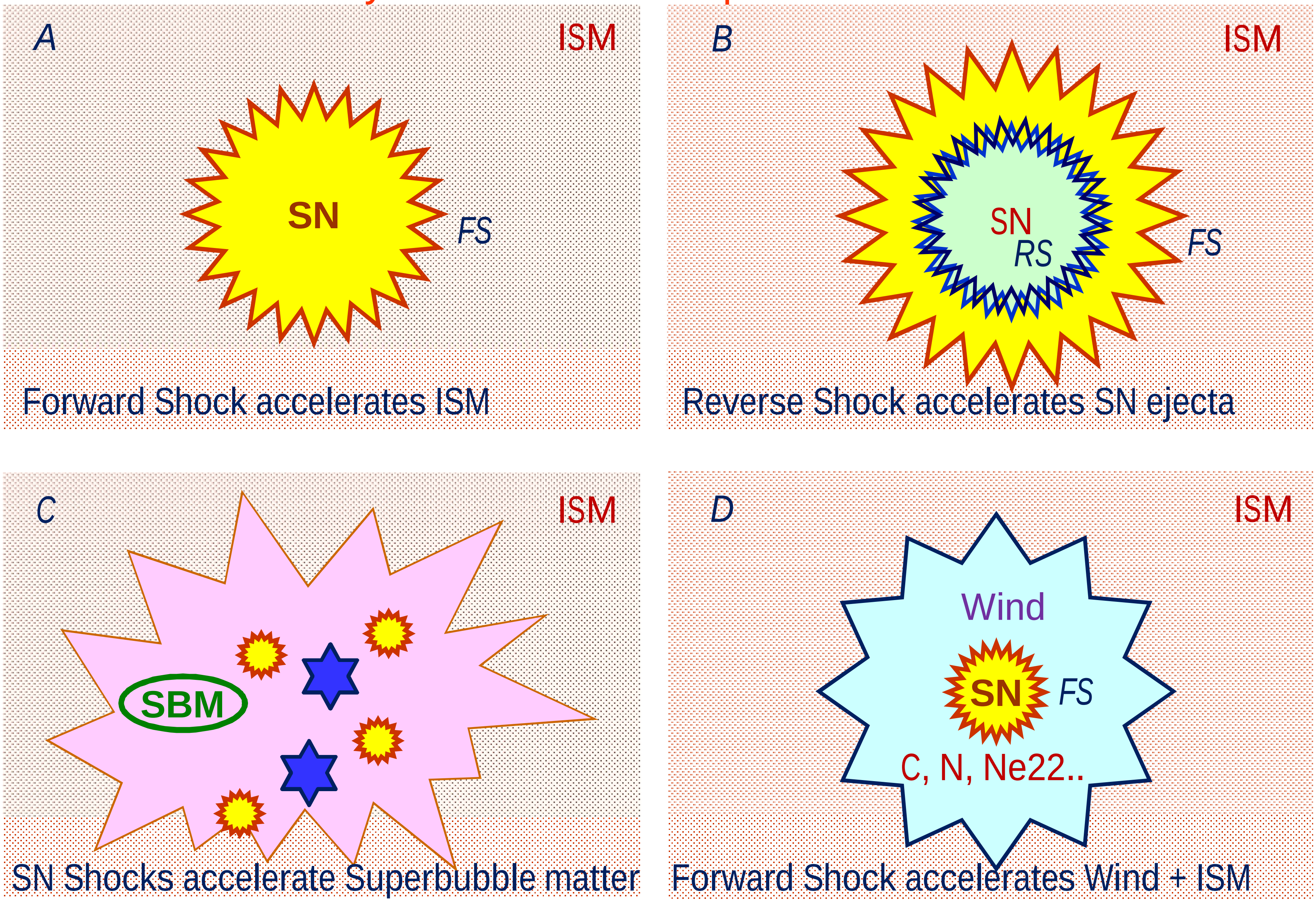
Is it solar ? *Yes,* for most isotopic ratios

No, for elemental ratios $\Rightarrow$ *Selection effects*

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

Except for some excess C and Ne22/Ne20 from WR star winds (*Cassé and Paul 1982)*

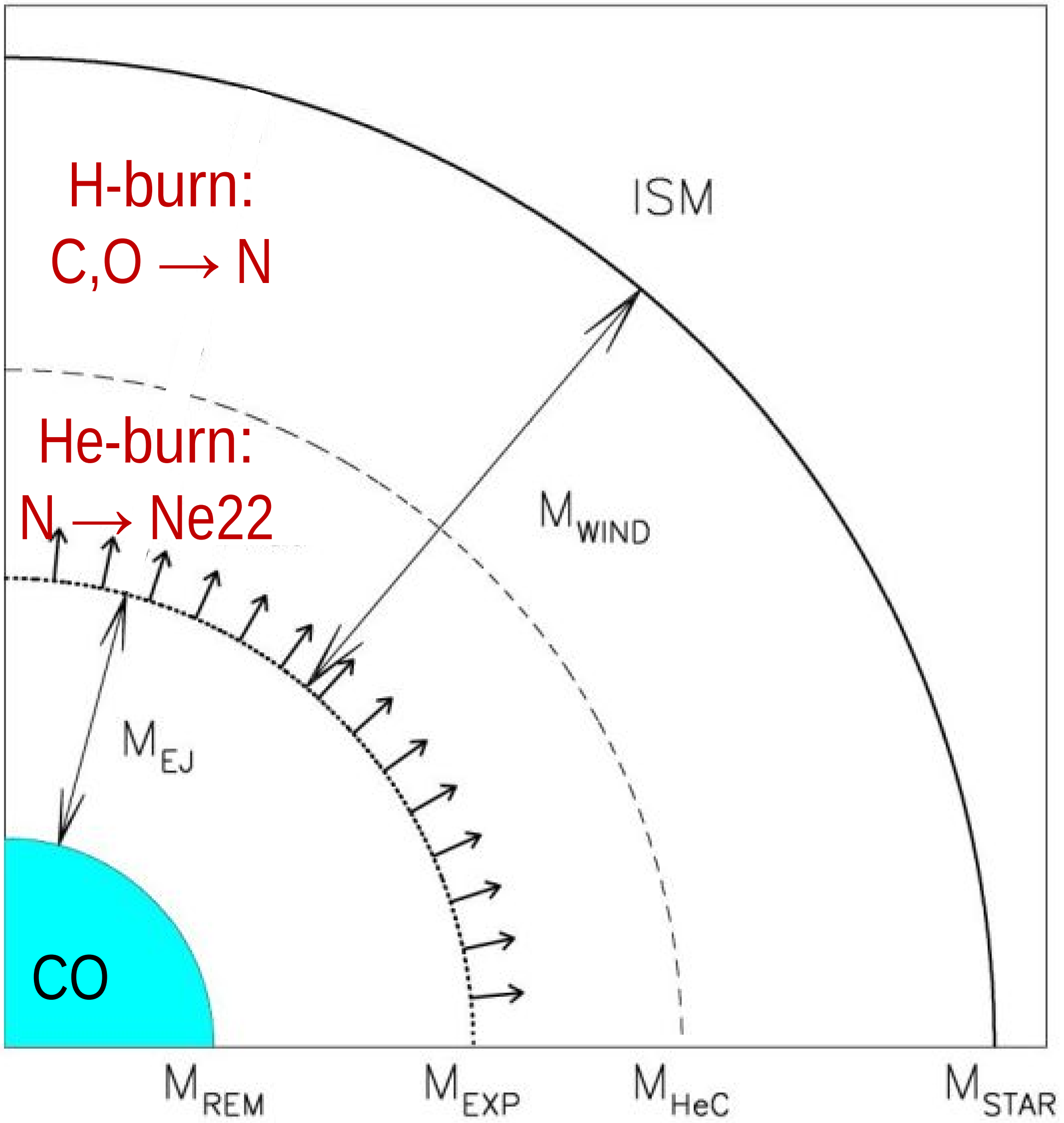
Galactic Cosmic Rays : what is the composition of accelerated matter ?



A forward shock (FS)is launched at M_{EXP} and runs through the wind of the star, enriched with products of H- and/or He- burning, and finally in the interstellar medium.

ASSUMPTION: Particle acceleration starts in the beginning of the Sedov-Taylor (ST) phase, when $M_{SWEPT} \sim M_{EJEC}$

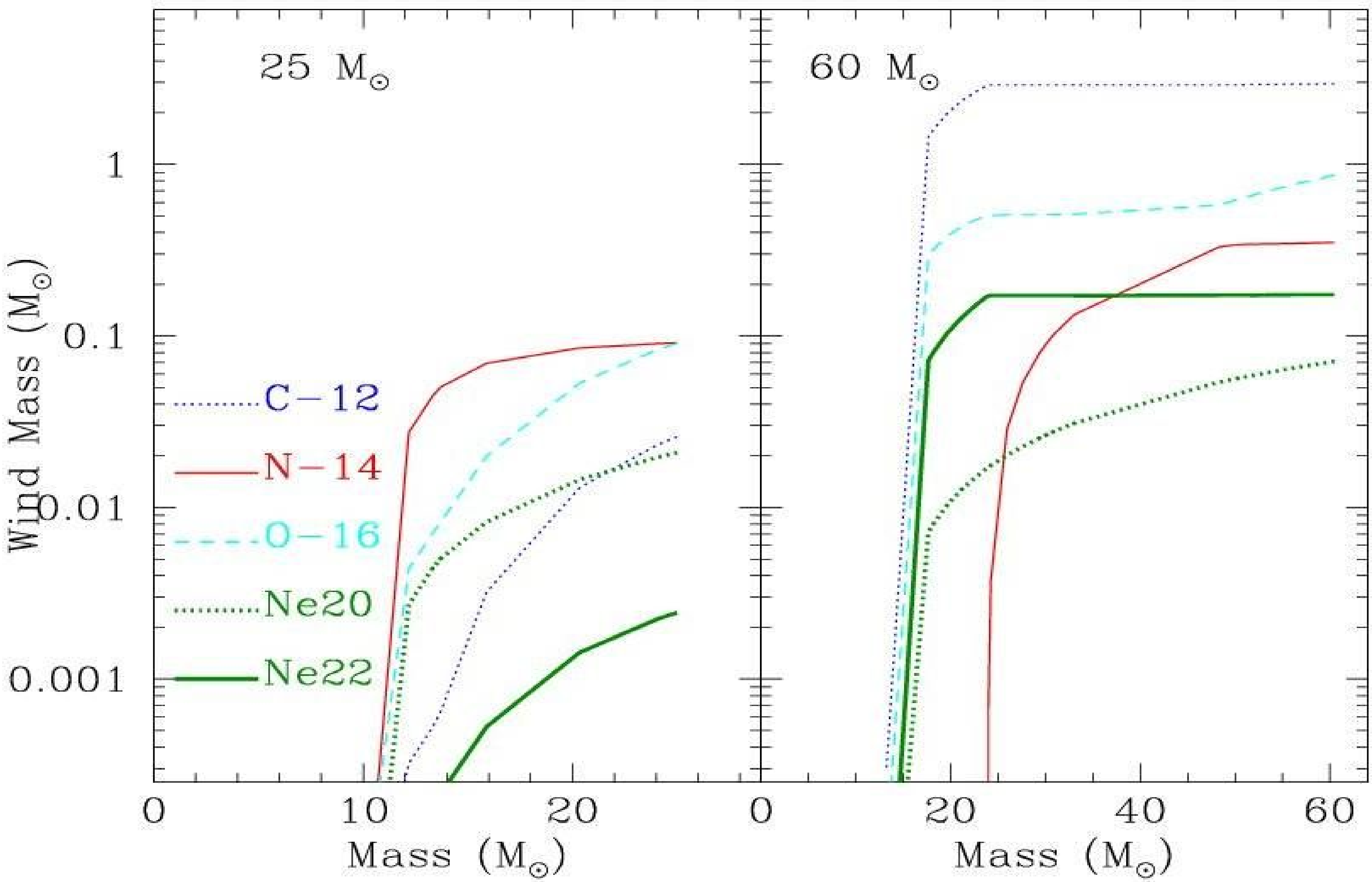
(BUT: When does it stop ?)



Depending on the previous mass loss of the star, acceleration may occur when the shock is still *within the wind (more massive stars)* or *in the ISM (less massive stars),*

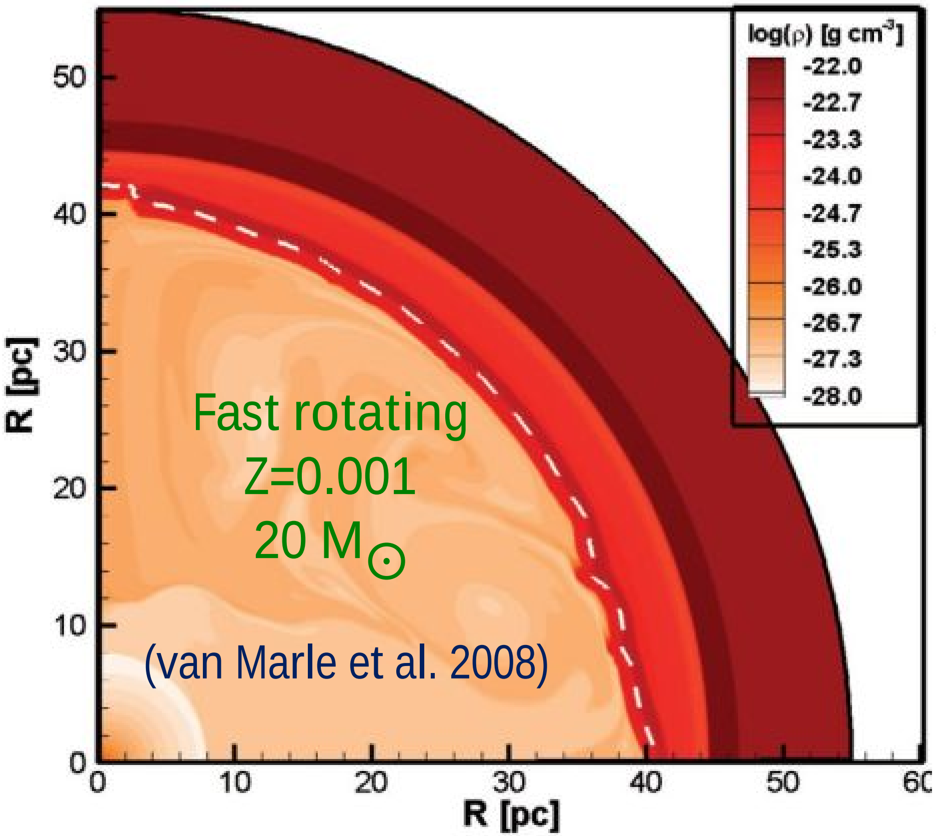
thus affecting the composition of accelerated particles.

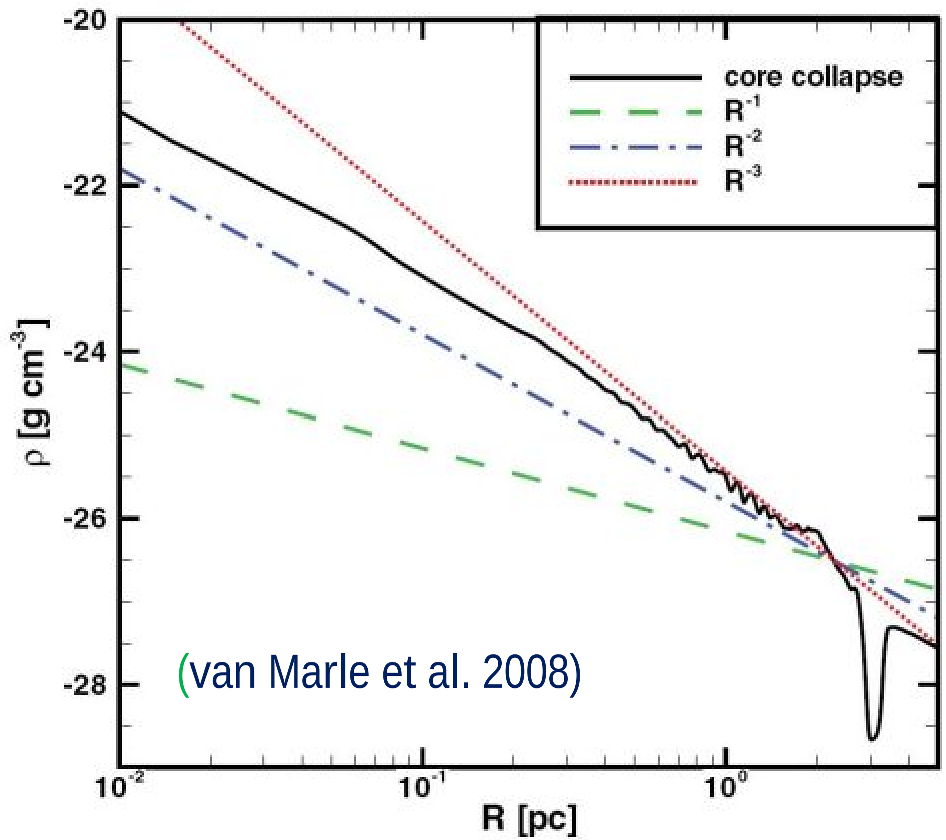
Stellar models with mass loss and rotation (*Hirschi et al. 2005*)



Integrated mass swept up by the forward shock, as it moves outwards

The circumstellar environment of mass losing stars





For a steady stellar wind, the density profile can be approximated by

Density ∝ Radius^{-2}

with $4ù \,\dot{}\, \grave{}\, ú(r)r^{2}dr = M_{Wind}$

Propagation of forward shock into a stellar wind of profile $\rho(r) \propto r^{-2}$ (*Ptuskin and Zirakhasvili 2005, Caprioli 2011*)

$$t(R_{\rm sh}) \simeq 99 R_{\rm sh,pc}^{8/7} \left(\frac{\mathcal{E}_{51}^{7/2} V_{w,6}}{\dot{M}_{-5,\odot} M_{\rm ej,\odot}^{5/2}} \right)^{-1/7} \text{yr}$$

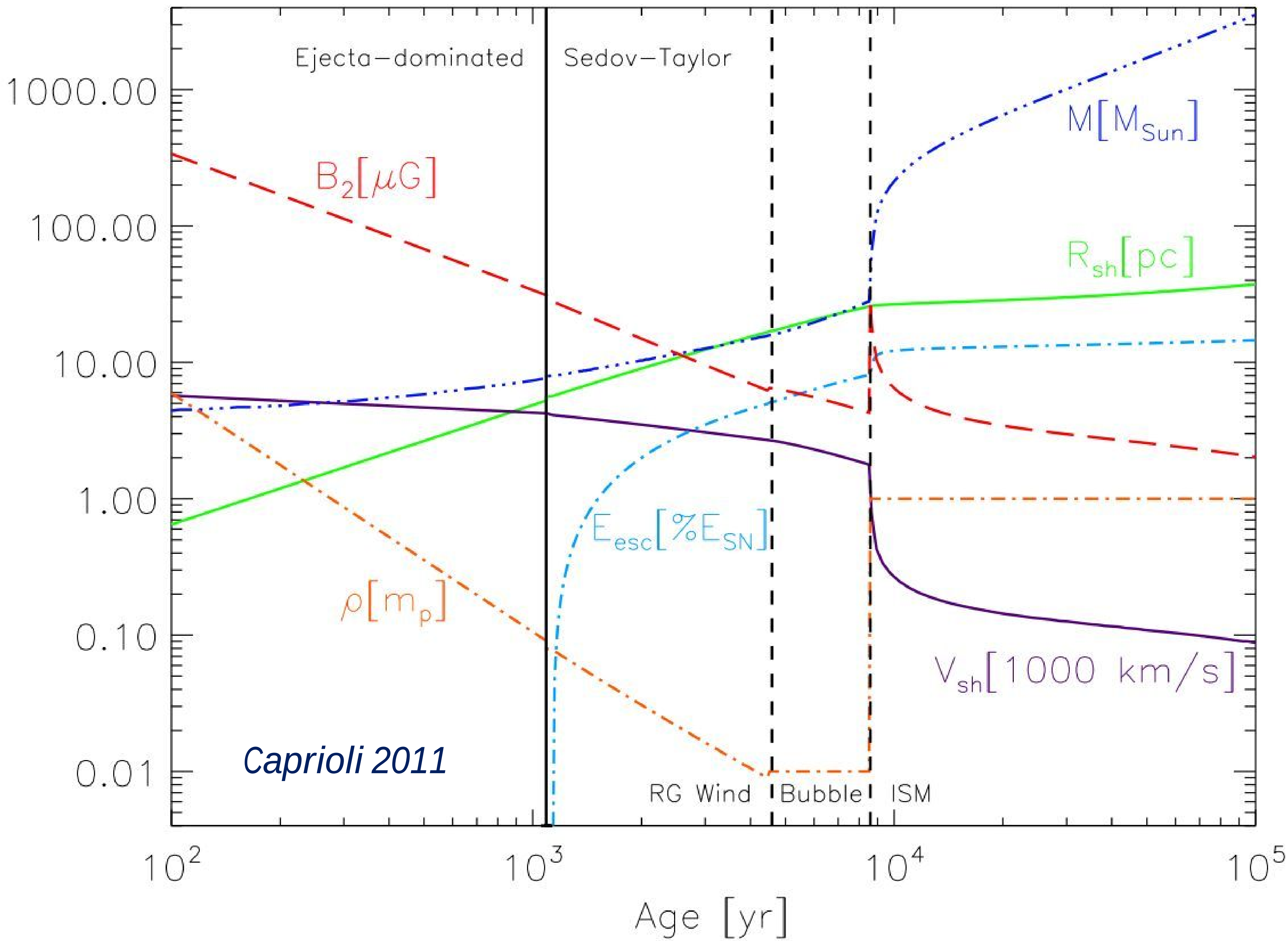
$$V_{\rm sh}(R_{\rm sh}) \simeq 8800 R_{\rm sh,pc}^{-1/7} \left(\frac{\mathcal{E}_{51}^{7/2} V_{w,6}}{\dot{M}_{-5,\odot} M_{\rm ej,\odot}^{5/2}} \right)^{1/7} \text{km s}^{-1}$$

$$M(R_{\rm sh}) = M_{\rm ej} + 4\pi \int_0^{R_{\rm sh}} \mathrm{d}r r^2 \rho(r);$$

$$\mathcal{E}(R_{\rm sh}) = \mathcal{E}_{SN} - 4\pi \int_0^{R_{\rm sh}} \mathrm{d}r r^2 \mathcal{F}_{\rm esc}(r);$$

$$t(R_{\rm sh}) = \int_0^{R_{\rm sh}} \frac{\mathrm{d}r}{V_{\rm sh}(r)}; \qquad \lambda = 6 \frac{\gamma_{\rm eff} - 1}{\gamma_{\rm eff} + 1}$$

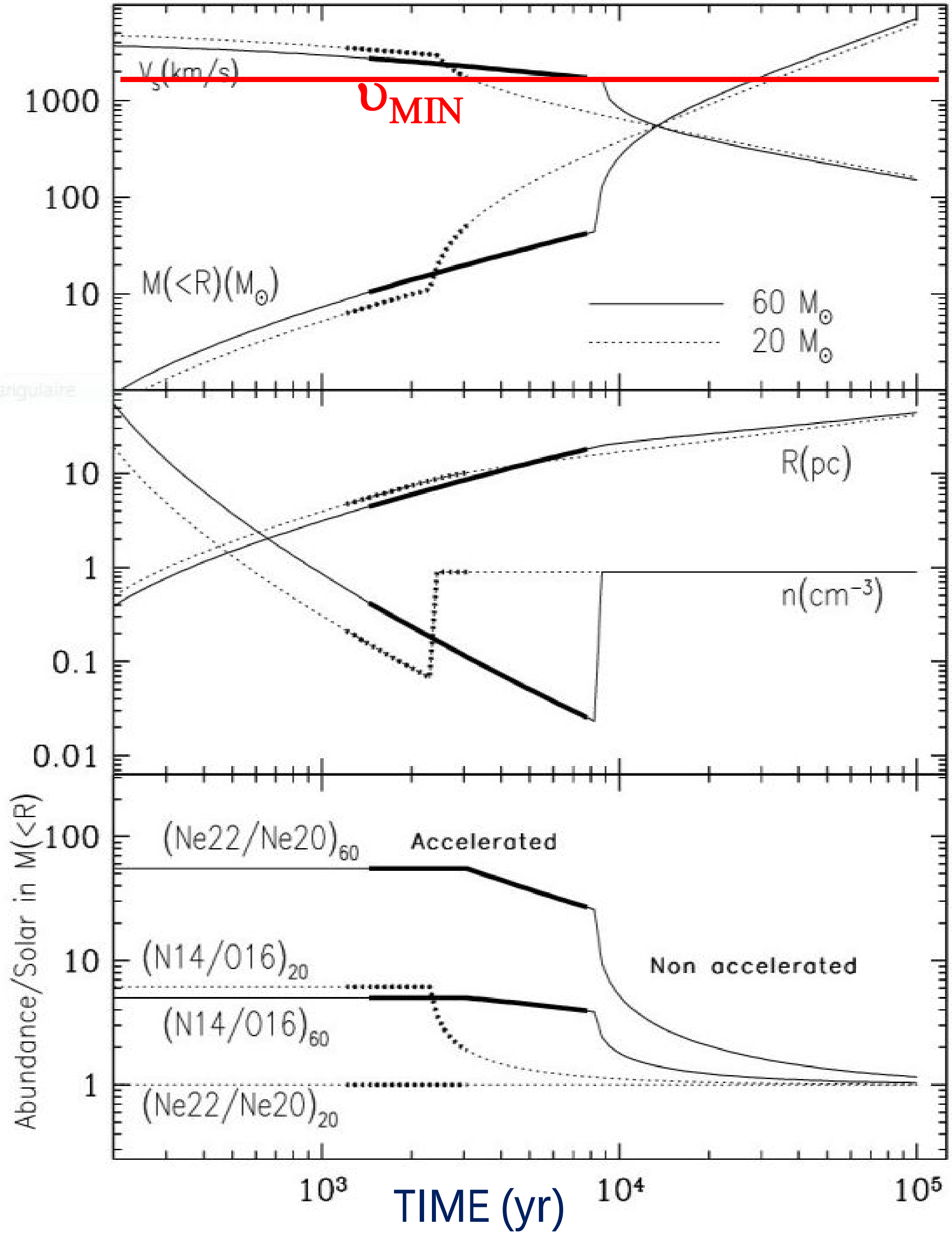
$$V_{\rm sh}(R_{\rm sh}) = \frac{\gamma_{\rm eff} + 1}{2} \left[\frac{2\lambda}{M^2(R_{\rm sh}) R_{\rm sh}^{\lambda}} \int_0^{R_{\rm sh}} \mathrm{d}r r^{\lambda - 1} E(r) M(r) \right]^{1/2}$$

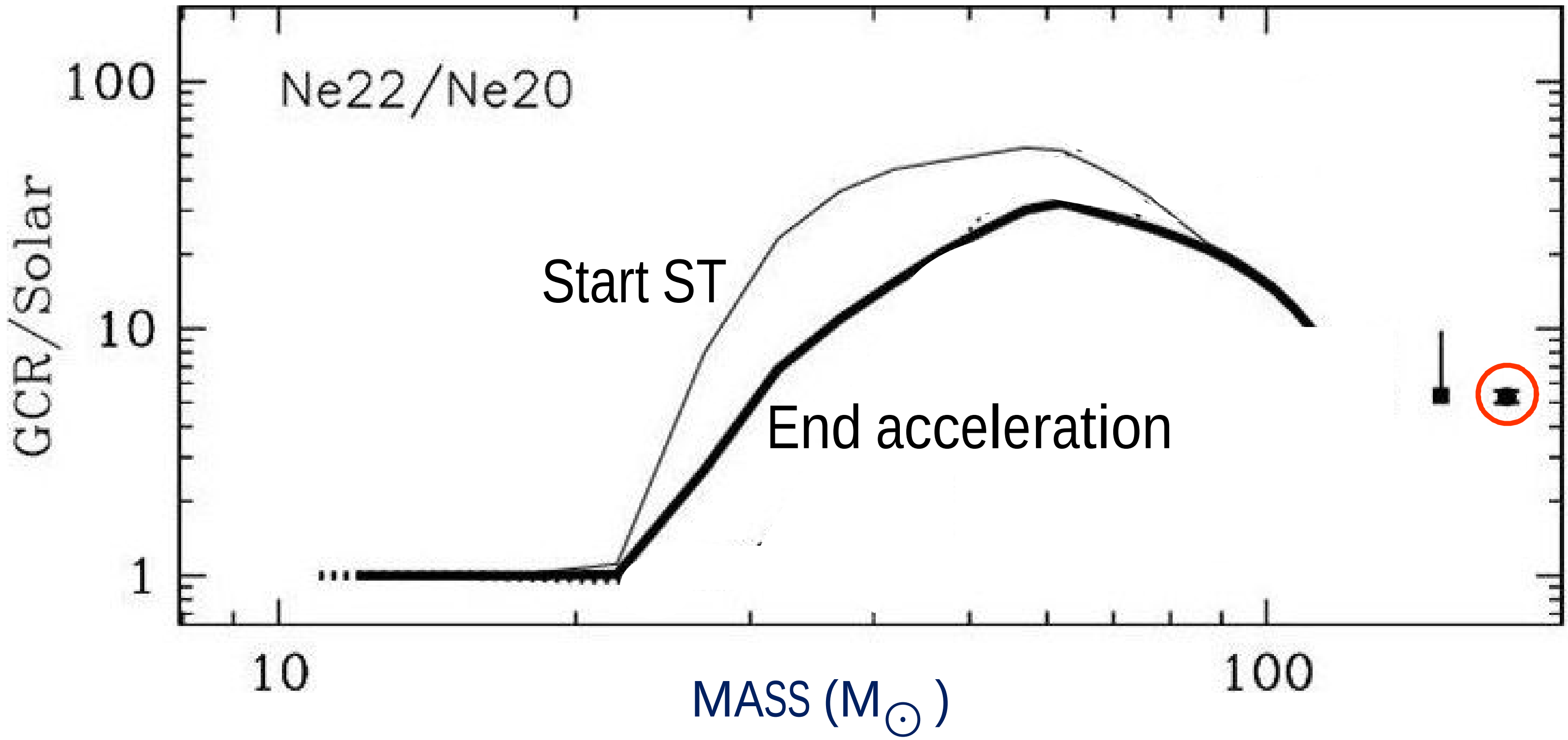


Ejecta−dominated
Sedov−Taylor
M[M_Sun]
B_2[μG]
R_sh[pc]
E_esc[%E_SN]
ρ[m_p]
V_sh[1000 km/s]
Caprioli 2011
RG Wind
Bubble
ISM
1000.00
100.00
10.00
1.00
0.10
0.01
10^2
10^3
10^4
10^5
Age [yr]

Particle acceleration
starts in beginning of ST
and is assumed
to stop when the velocity
of the shock drops to υ_{MIN}

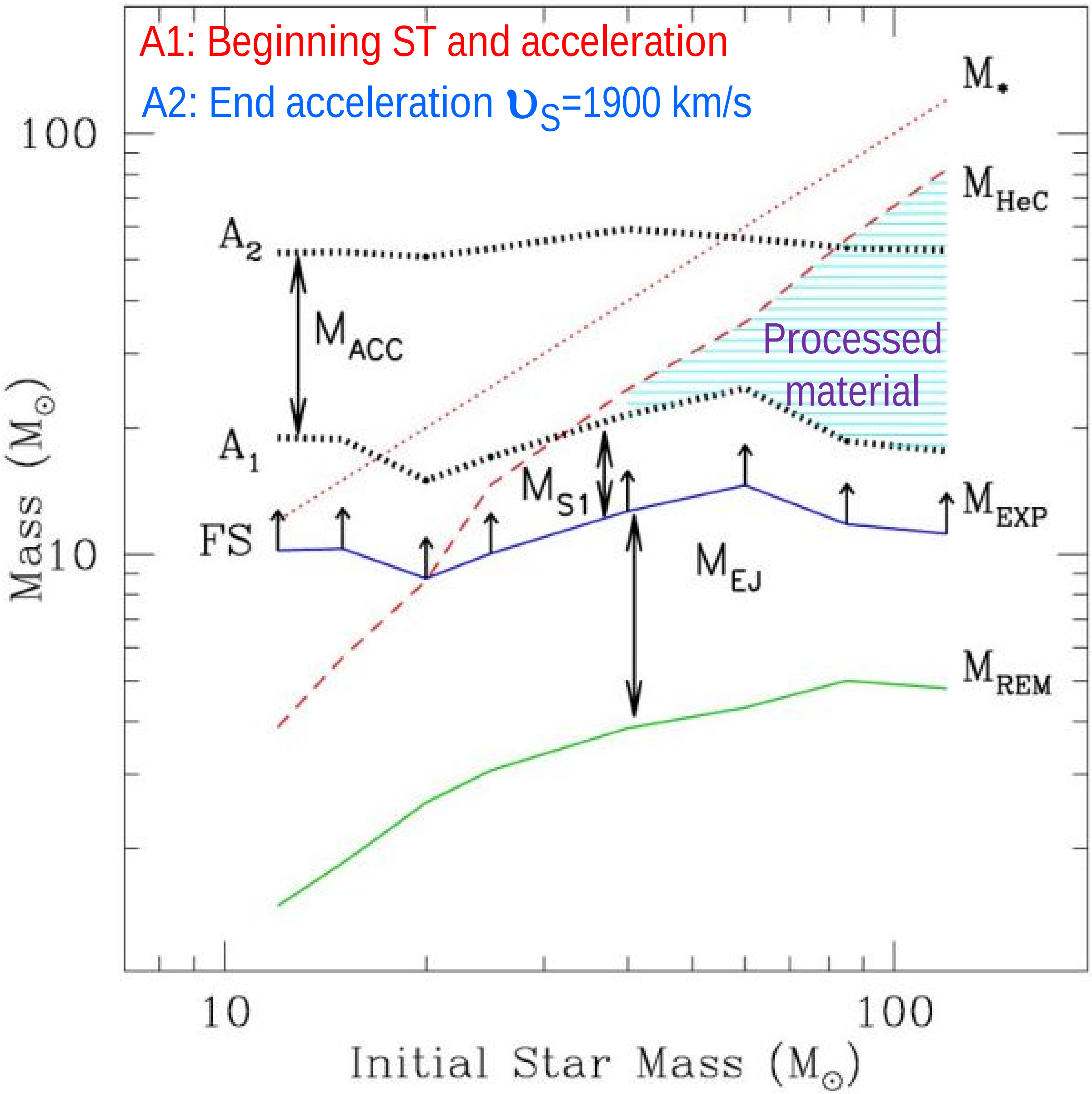
chosen such as
the IMF averaged ratio
Ne22/Ne20
of accelerated particles
equals the observed one
$R = (Ne22/Ne20)_{GCR} = 5.3 \odot$





The IMF averaged ratio Ne22/Ne20
of accelerated particles equals the observationally derived one
for GCR sources
$R = (Ne22/Ne20)_{GCR} = 5.3\ \odot$

for υ_{MIN}=1900 km/s for rotating models
(and 2400 km/s for non-rotating ones)



The forward shock accelerates particles from a pool of mass

$$M_{ACC} = A2 - A1$$

between the beginning of ST (A1) and υ=1900 km/s (A2)

Energy of accelerated particles

$$\sum N_i A_i \int_0^\infty E\, Q(E)\, dE = f\, E_0$$

E_0 = 1.5 10^{51} erg

f = 0.1

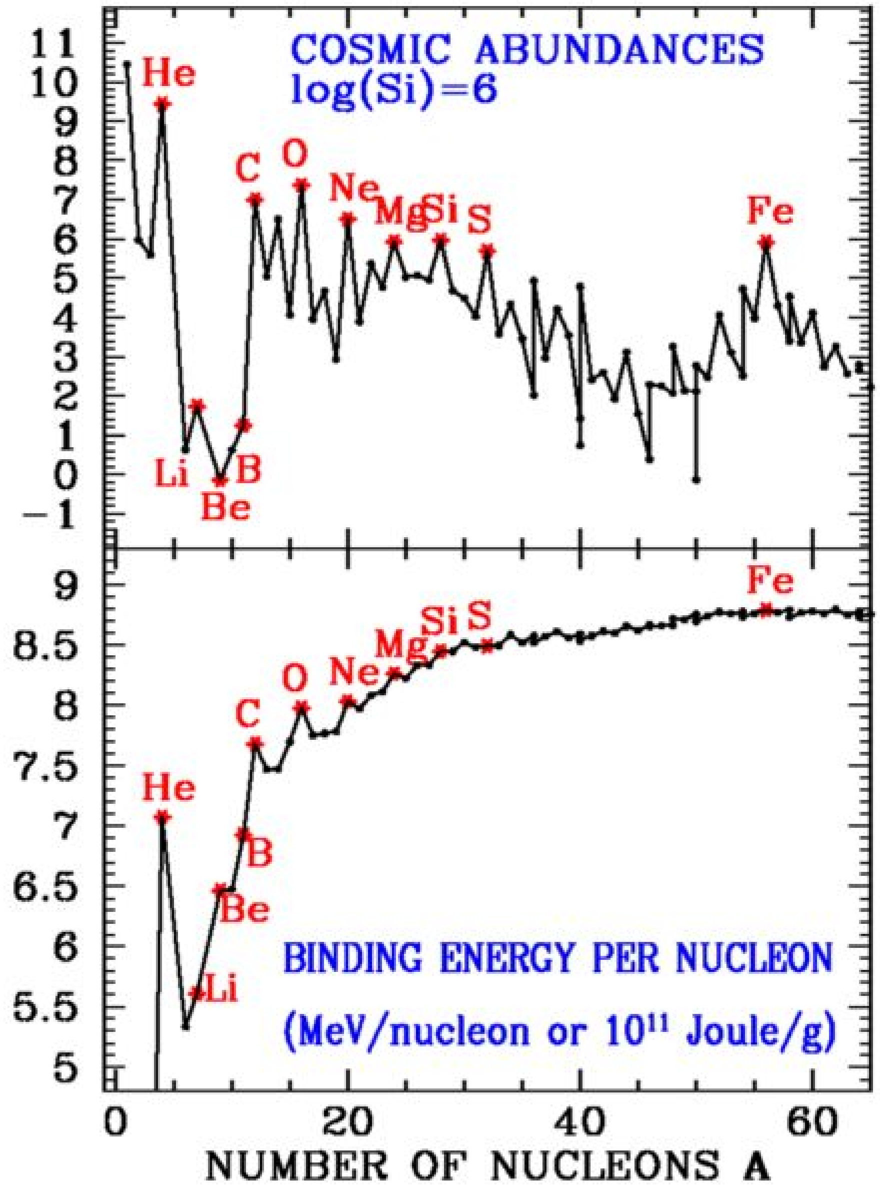
Mass of accelerated particles

$$m_{ACC} = \sum N_i A_i$$

Efficiency of acceleration

$$\Omega = \frac{m_{ACC}}{M_{ACC}} = \text{a few } 10^{-6}$$

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

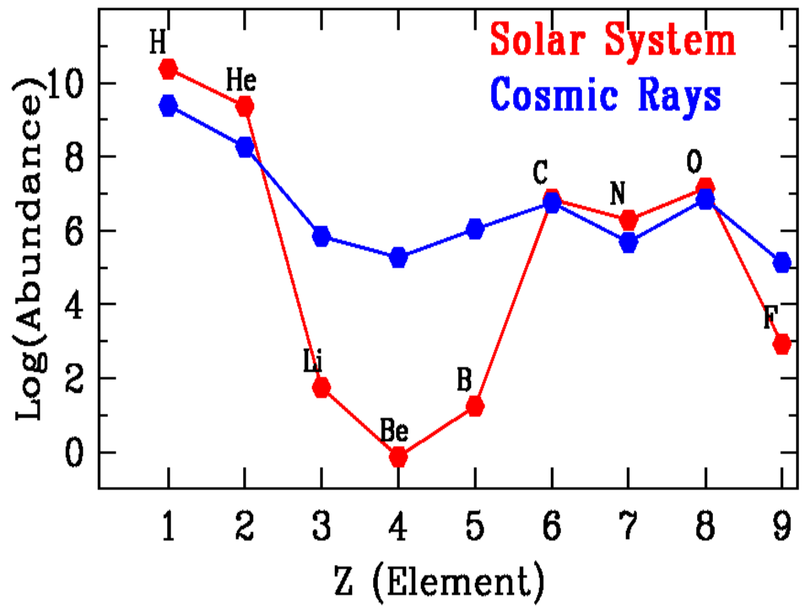


The most fragile stable isotopes in nature (after D and He3)

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

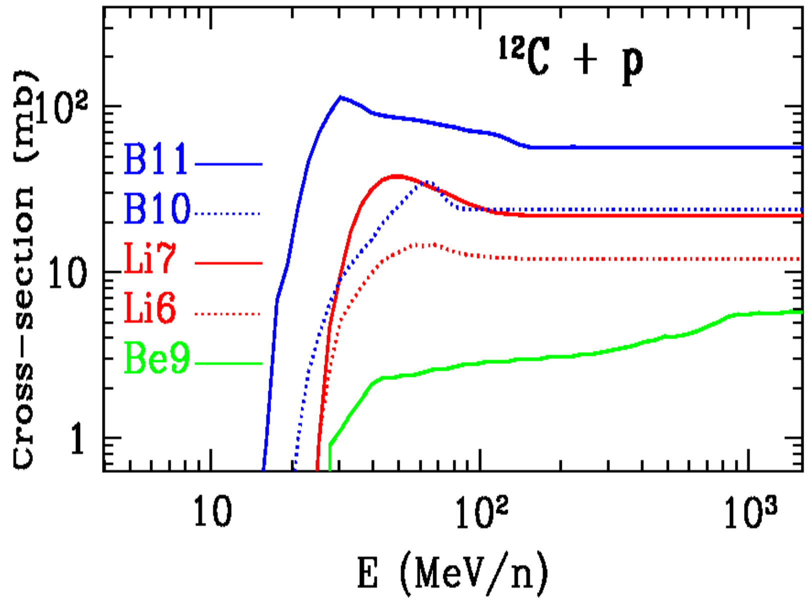
GCR composition is heavily enriched in Li, Be, B (a factor ~10^6 for Be and B)



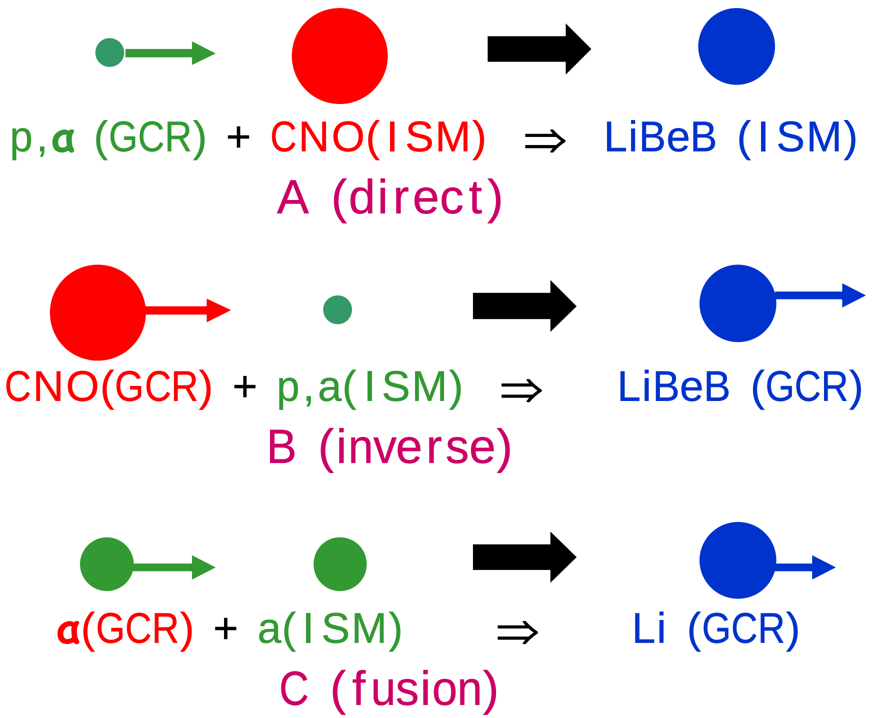
Solar composition: X(Li) > X(B) > X (Be)

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

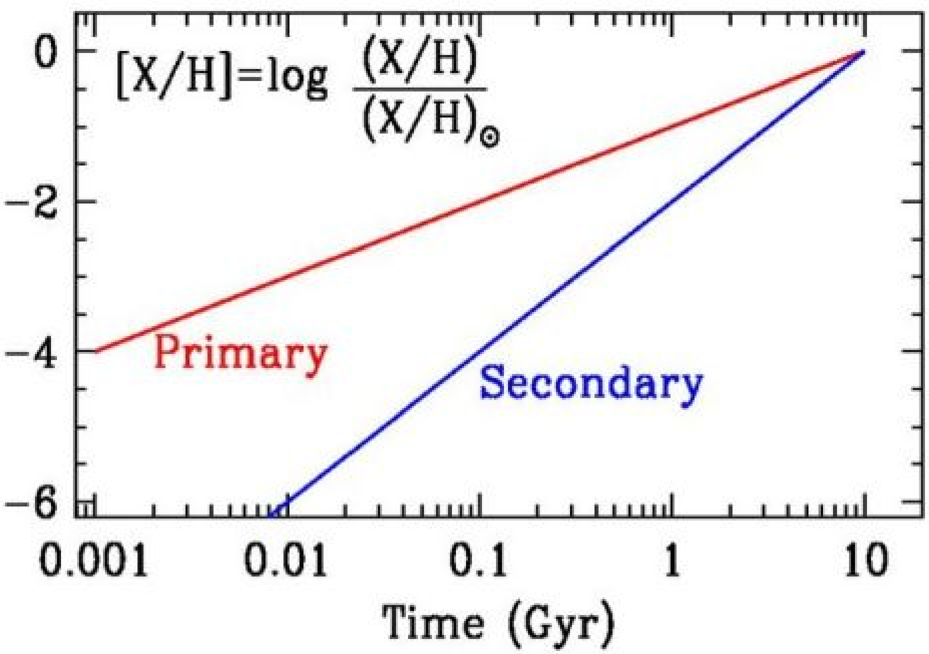
Same order as spallation cross sections of CNO ⇒ LiBeB: σ(B) > σ(Li) > σ(Be)



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



The composition of GCR determines whether Be is produced as PRIMARY or SECONDARY



Primary: produced from initial H and He inside the star
Yield: independent of initial metallicity (Z)
Examples*:* C, O, Fe…

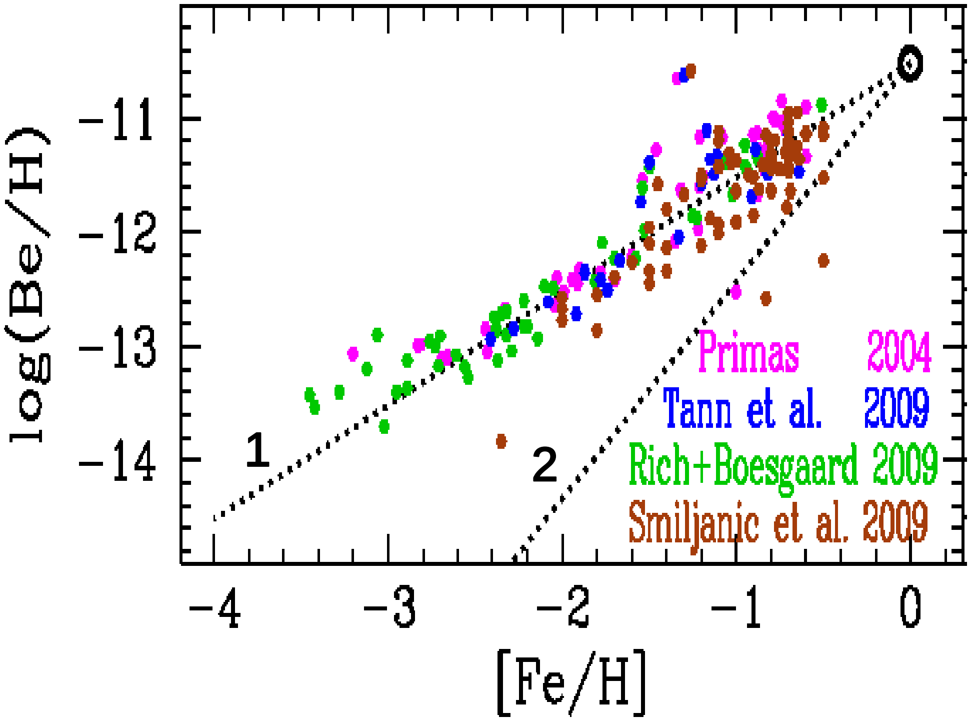
Secondary: produced from initial metals (Z) inside the star
Yield**:** proportional to initial metallicity (Z)
Examples: N14, O17, s-nuclei…

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

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

Evolution of Be

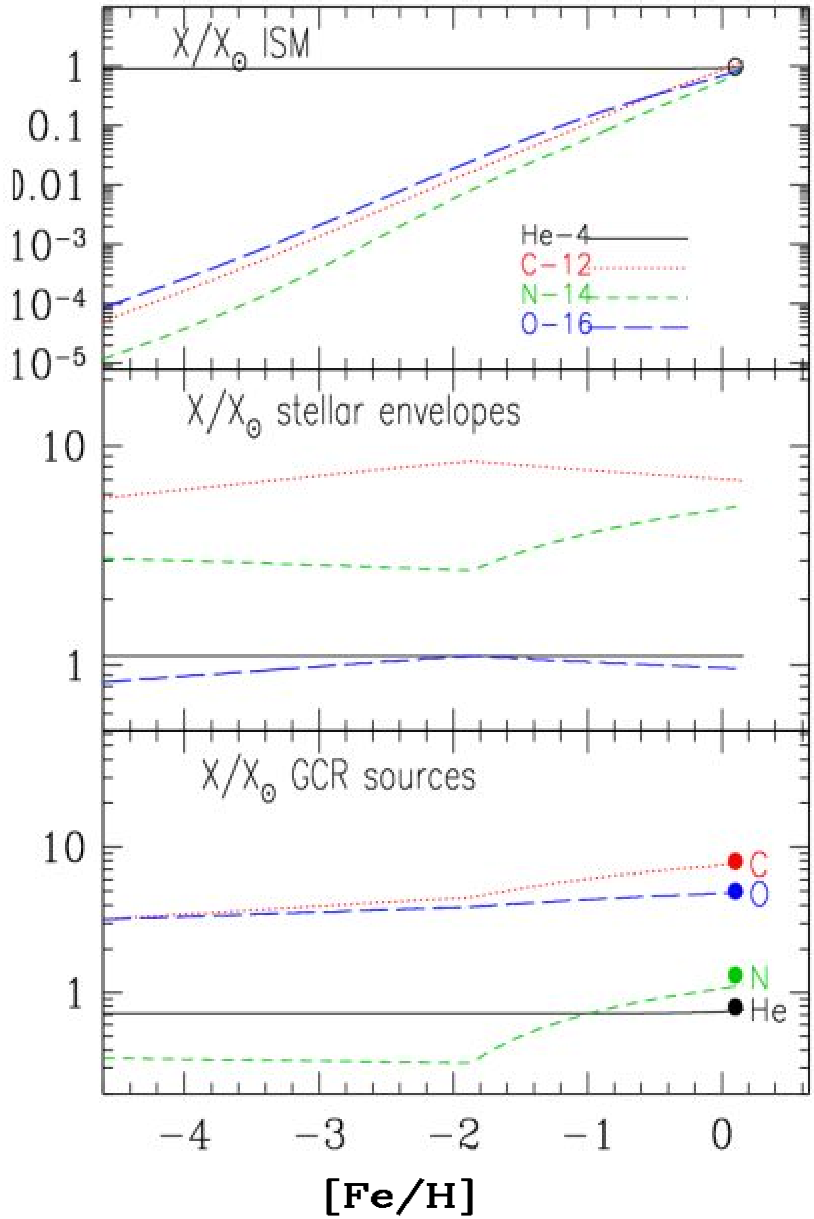
Early 90ies: Be (and B) observations in low metallicity halo stars



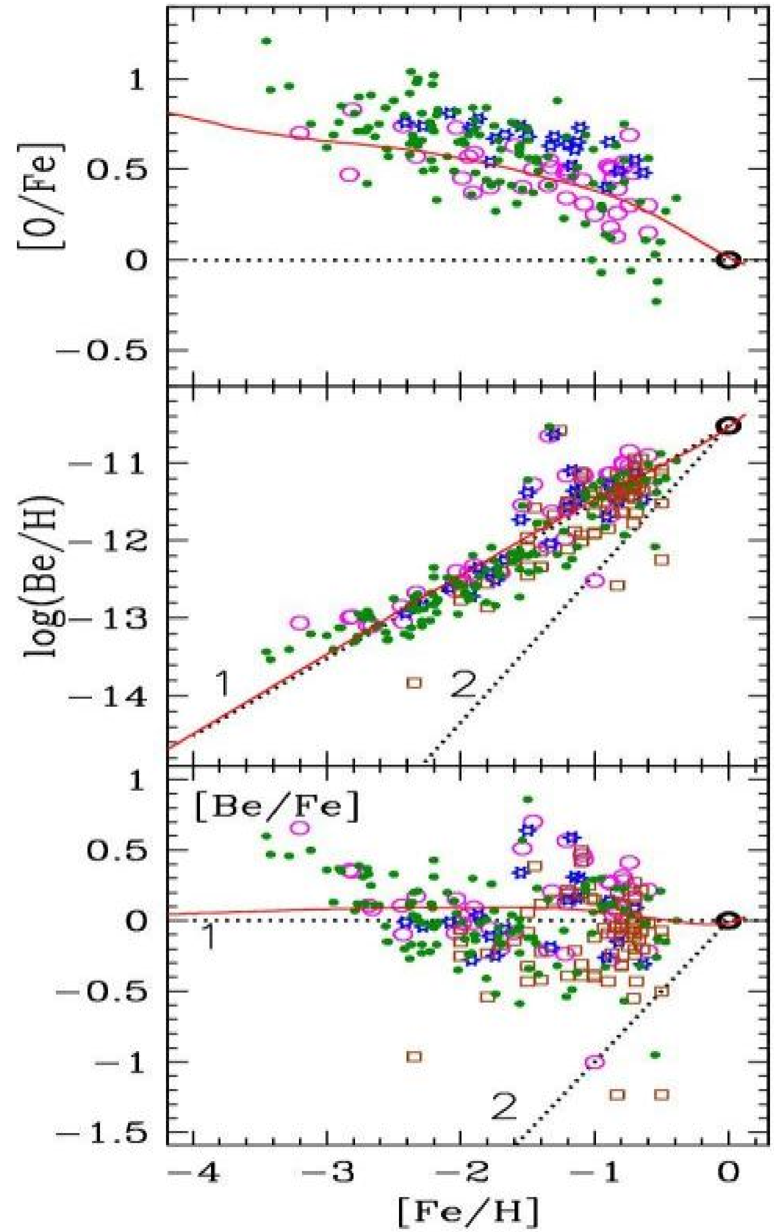
Be abundance evolves exactly as Fe (unexpected, since it is produced from CNO in GCR and it should behave as secondary, not as primary !)

Was the CNO fraction of GCR ~constant in the past ?
PERHAPS… IF from ROTATING massive stars

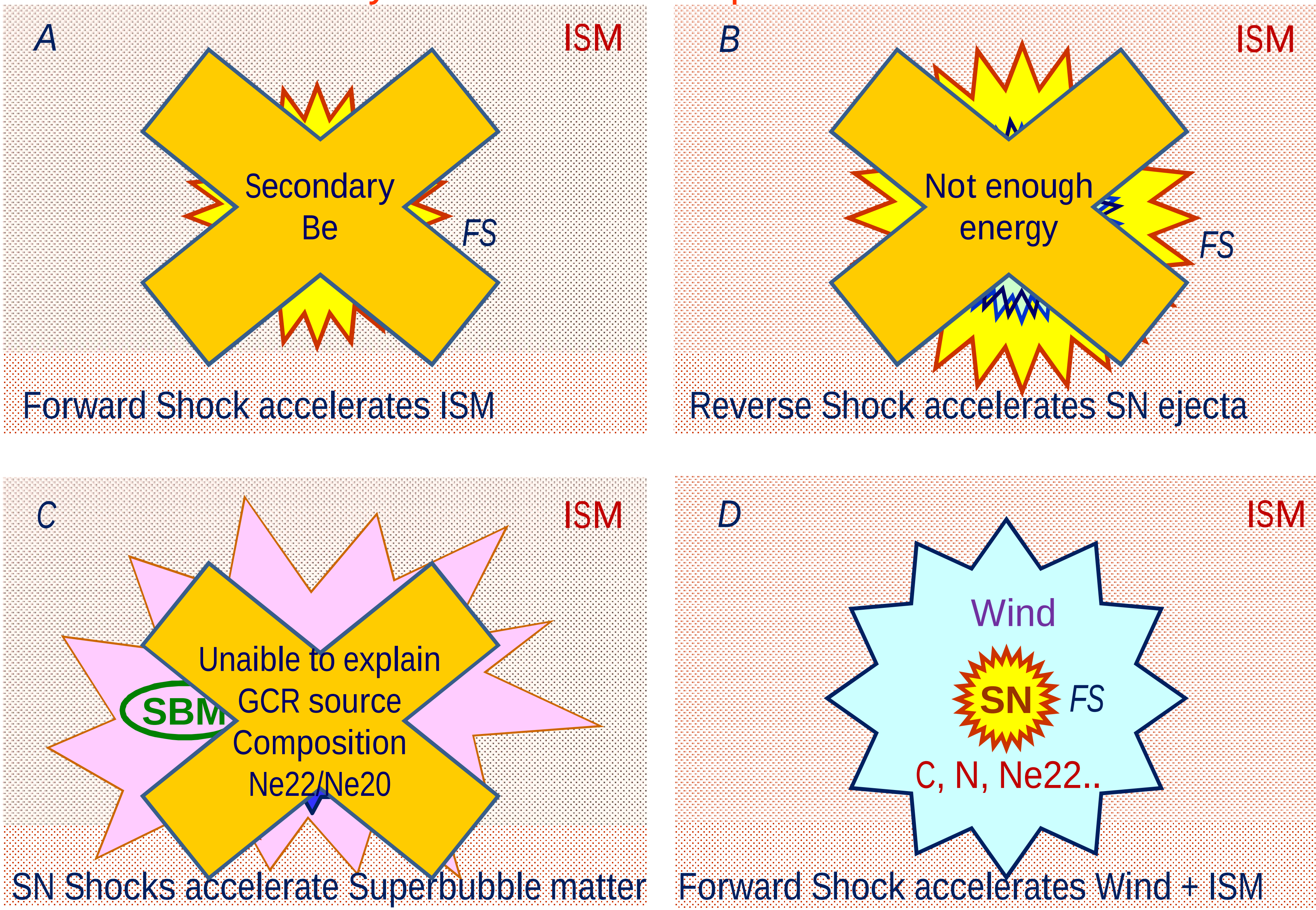
Self-consistent calculation of evolving composition of ISM AND GCR



With this, "physically motivated" composition of GCR and proper GCR/SN energetics, primary Be is naturally obtained`in GCE models

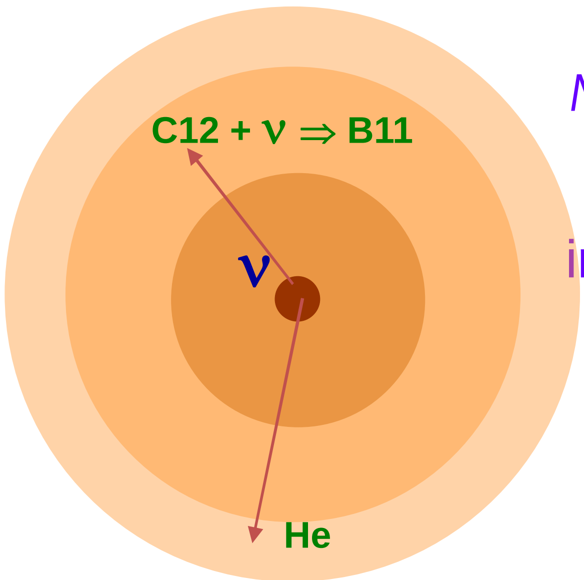


Galactic Cosmic Rays : what is the composition of accelerated matter ?

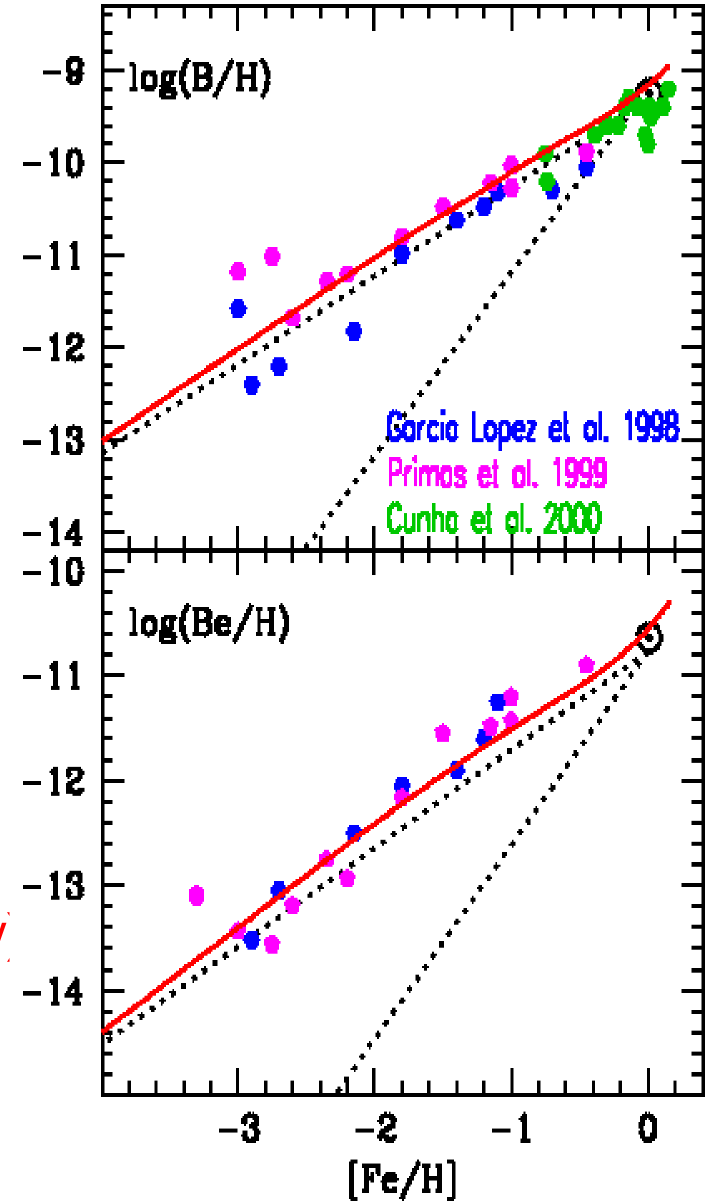


PRIMARY Be

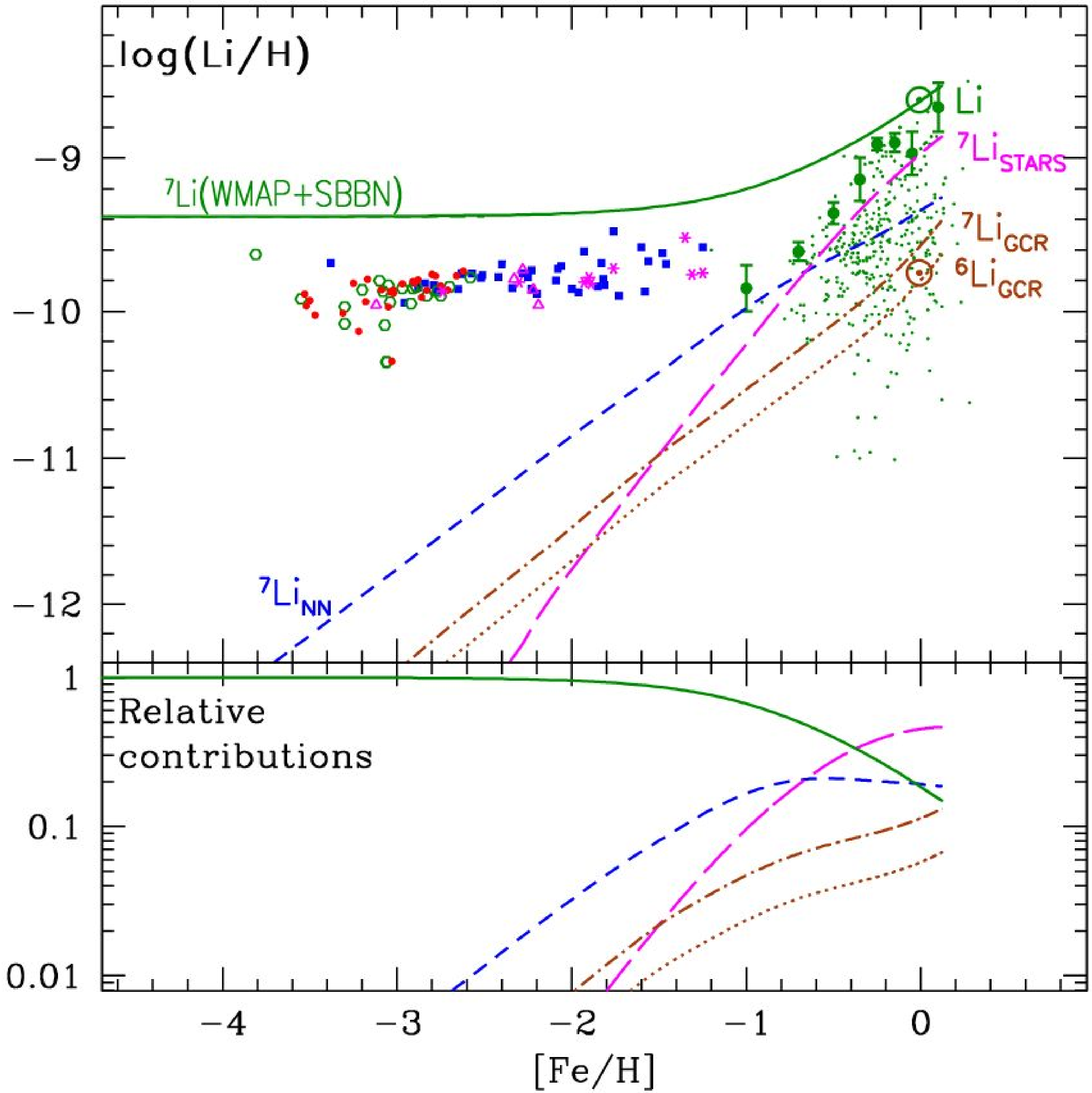
Production of primary B11 by GCR
BUT ALSO in CCSN by
neutrino-induced nucleosynthesis
(*Woosley et al. 1990*)



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



log(Li/H)
Li
^{7}Li$_{STARS}$
^{7}Li(WMAP+SBBN)
^{7}Li$_{GCR}$
^{6}Li$_{GCR}$
^{7}Li$_{NN}$
−9
−10
−11
−12
1
0.1
0.01
Relative
contributions
−4
−3
−2
−1
0
[Fe/H]

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 ???						

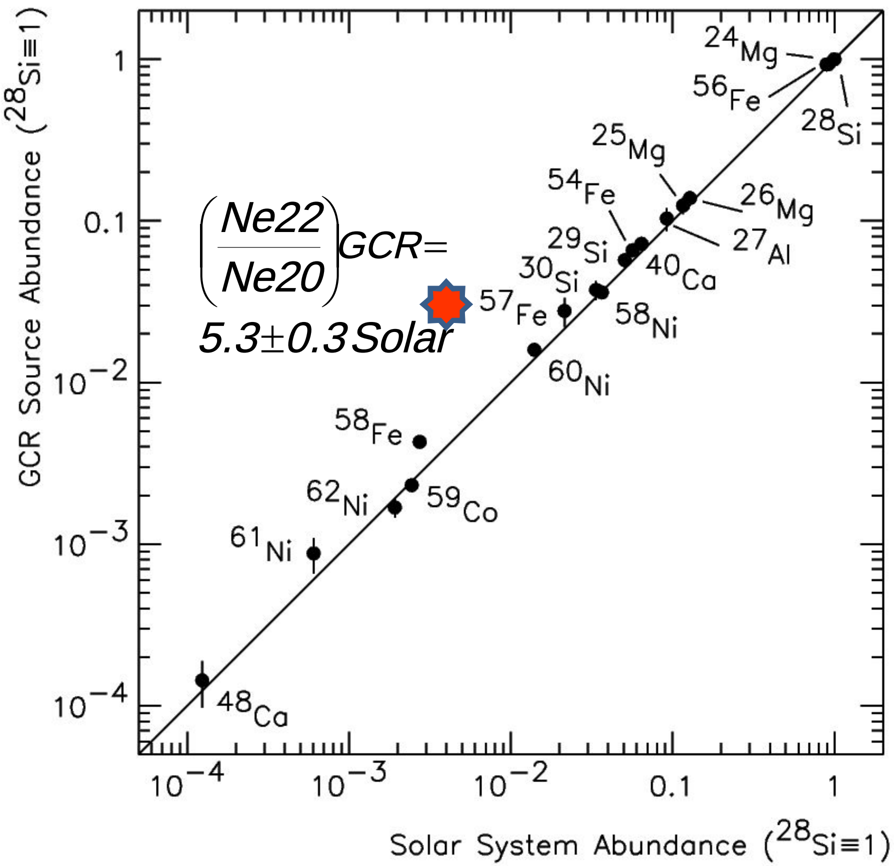
SUMMARY

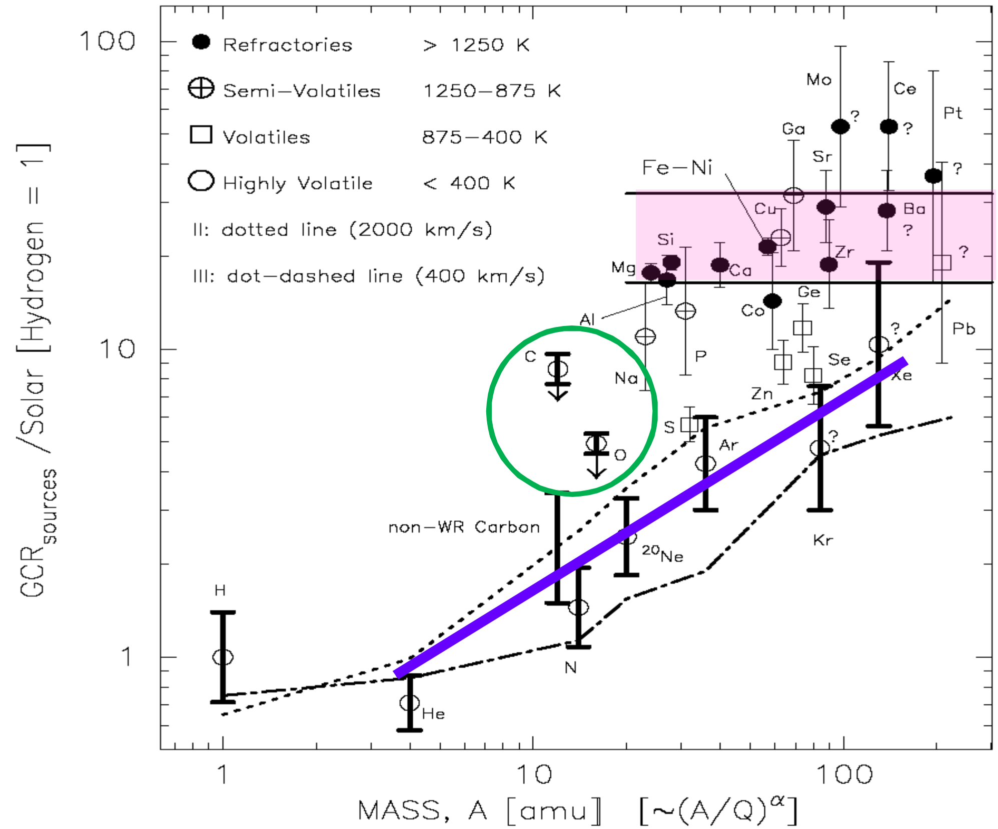
GCR composition (*Ne22/Ne20)* best understood
if GCR accelerated for a few 1000 years
by forward shocks of CCSN explosions
hitting massive star winds and ISM

Stellar models suggest that *rotating* massive star winds
have always ~same CNO content ;
If GCR accelerated from such material,
then Be evolution understood.

GCR Ne22/Ne20: NP, 2012 *Astronomy and Astrophysics*, 538, 80
GCR and LiBeB : NP, 2012 *Astronomy and Astrophysics*, in press

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.

Except for some excess C and Ne22/Ne20 from WR star winds (*Cassé and Paul 1982)*