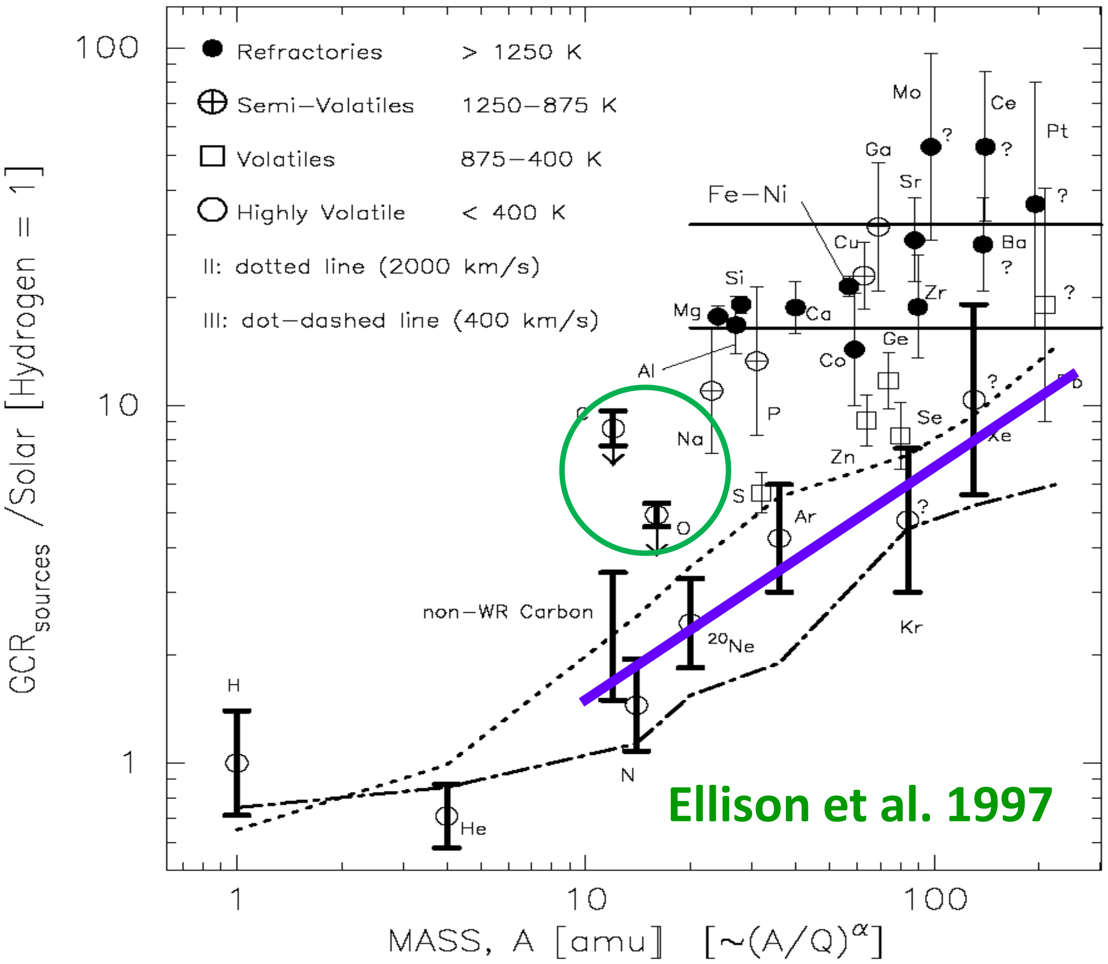
GCR source composition and acceleration site(s):

the role of the observed GCR source abundances of Ne22, Fe60 and Be evolution

Galactic Cosmic Ray Source Composition



Is it solar ? ***No,* for elemental abundances BUT: *Selection effects***

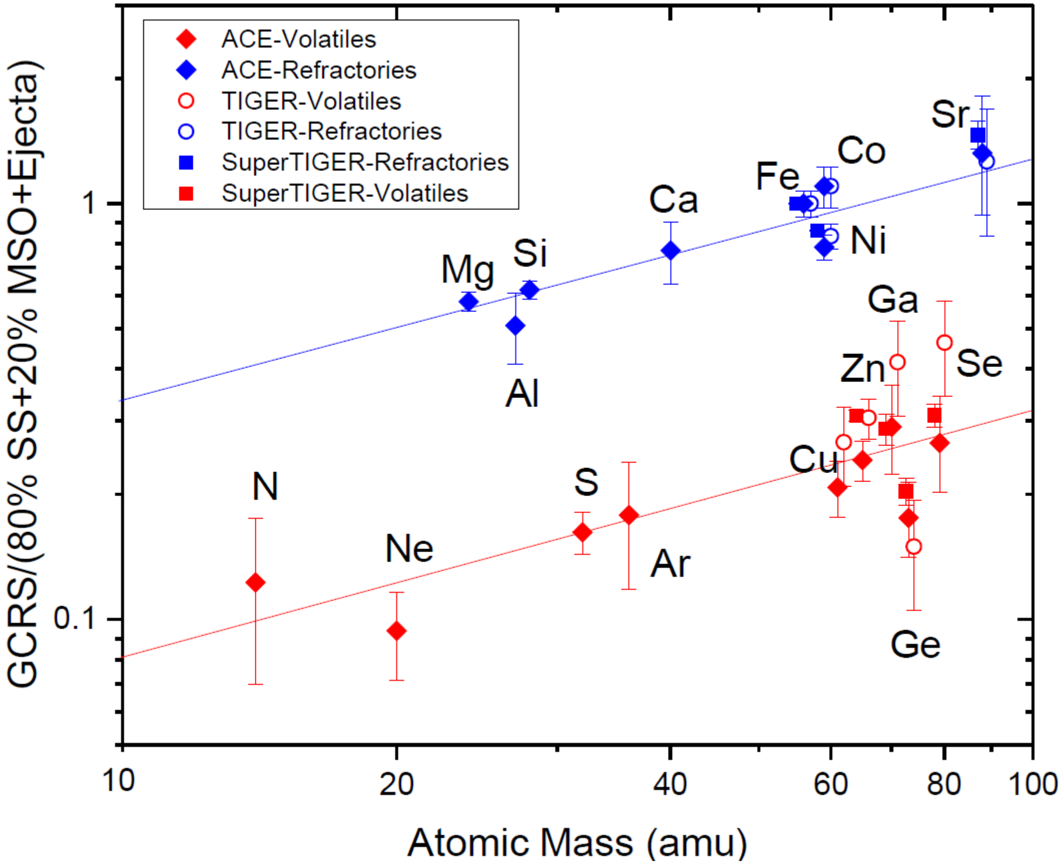
Volatiles: abundance increasing with A/Q (mass to charge ratio)

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

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

C,O overabundant by ~1.5 to 8 ; Most excess C attributed to WR stars

Galactic Cosmic Ray Source Composition (update)

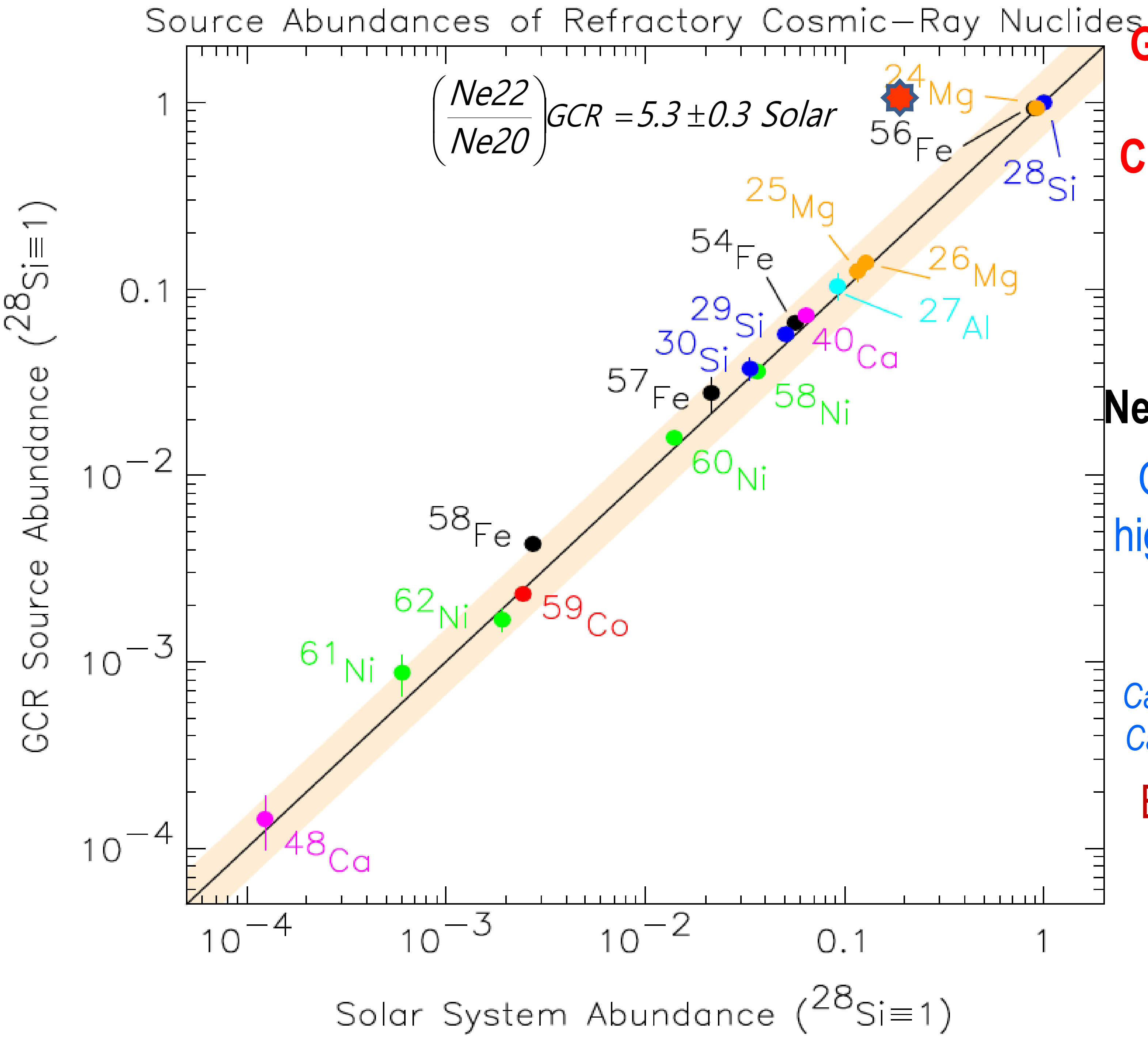


Binns et al. 2009

A mixture of 20% of massive star wind material (*from Woosley/Heger 2007*) with 80% of ISM allows for a better ordering of the GCR composition *assuming a clear separation in refractories and volatiles only*

(unclear for intermediate cases: semi-volatiles, like O ?
It does not work well with other sets of massive star yields)

For some obscure reason, it is concluded that this necessarily happens
In a superbubble environment



GCR Source Isotopic Composition: SOLAR (≡ ISM)

Exception: Ne22/Ne20~5 ⊙

Only site with high Ne22/Ne20

Winds of WR stars

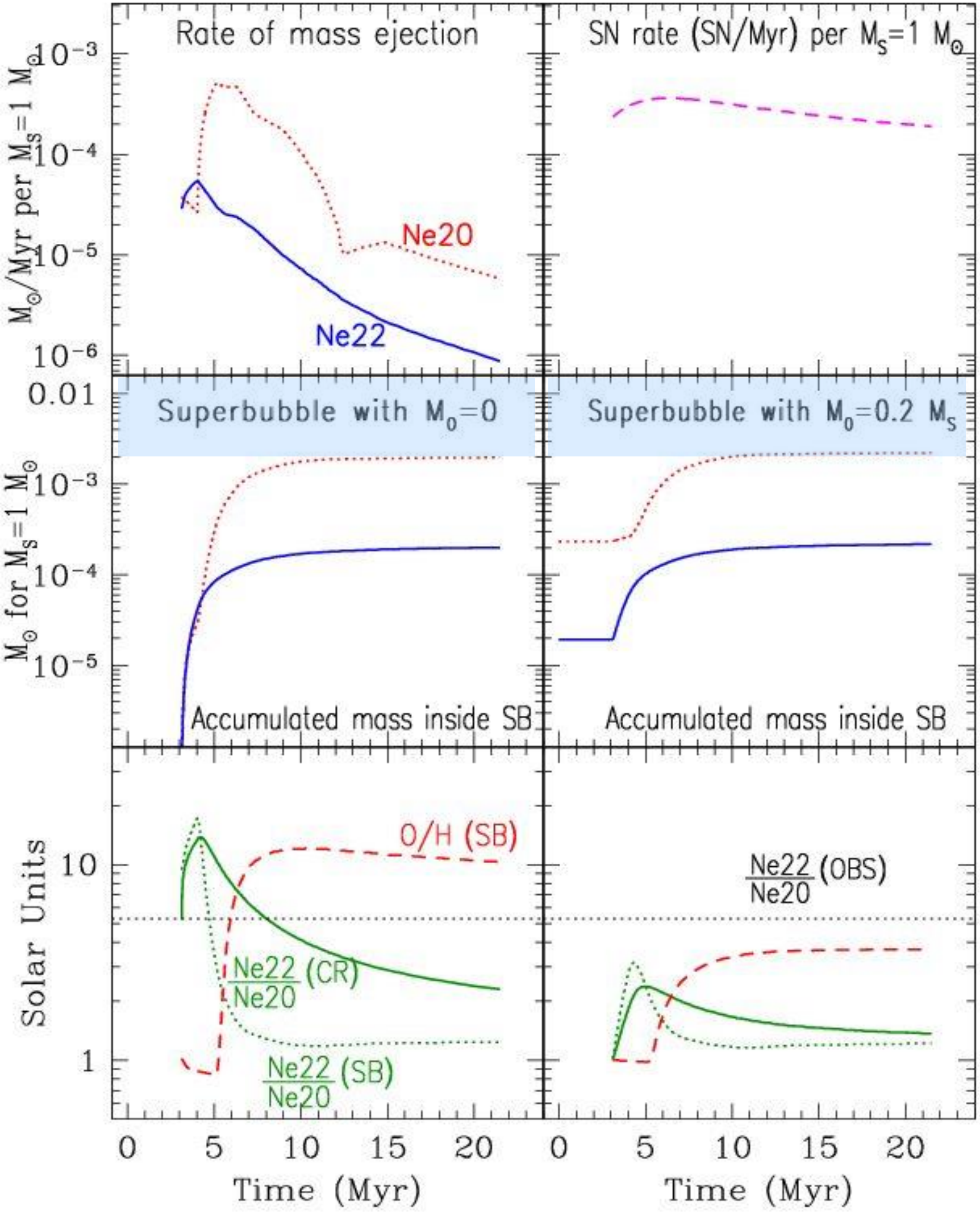
Cassé & Goret 1978
Cassé & Paul 1982)

BUT WHERE AND HOW does the mixture occur?

Are GCR accelerated in superbubbles ?

In a superbubble (OB association)
the time integrated
Ne22/Ne20 ratio
remains as high as
the observed GCR one
ONLY for a short early period
(when winds are important)
and **ONLY if no original gas**
is left over after star formation.
Most of the time,
and in realistic conditions
Ne22/Ne20 is close to solar
and ***metallicity is highly***
supersolar (not observed)

Superbubbles CANNOT BE at
the origin of GCR Ne22/Ne20
nor at the origin
of the bulk of GCR *(NP2012a)*



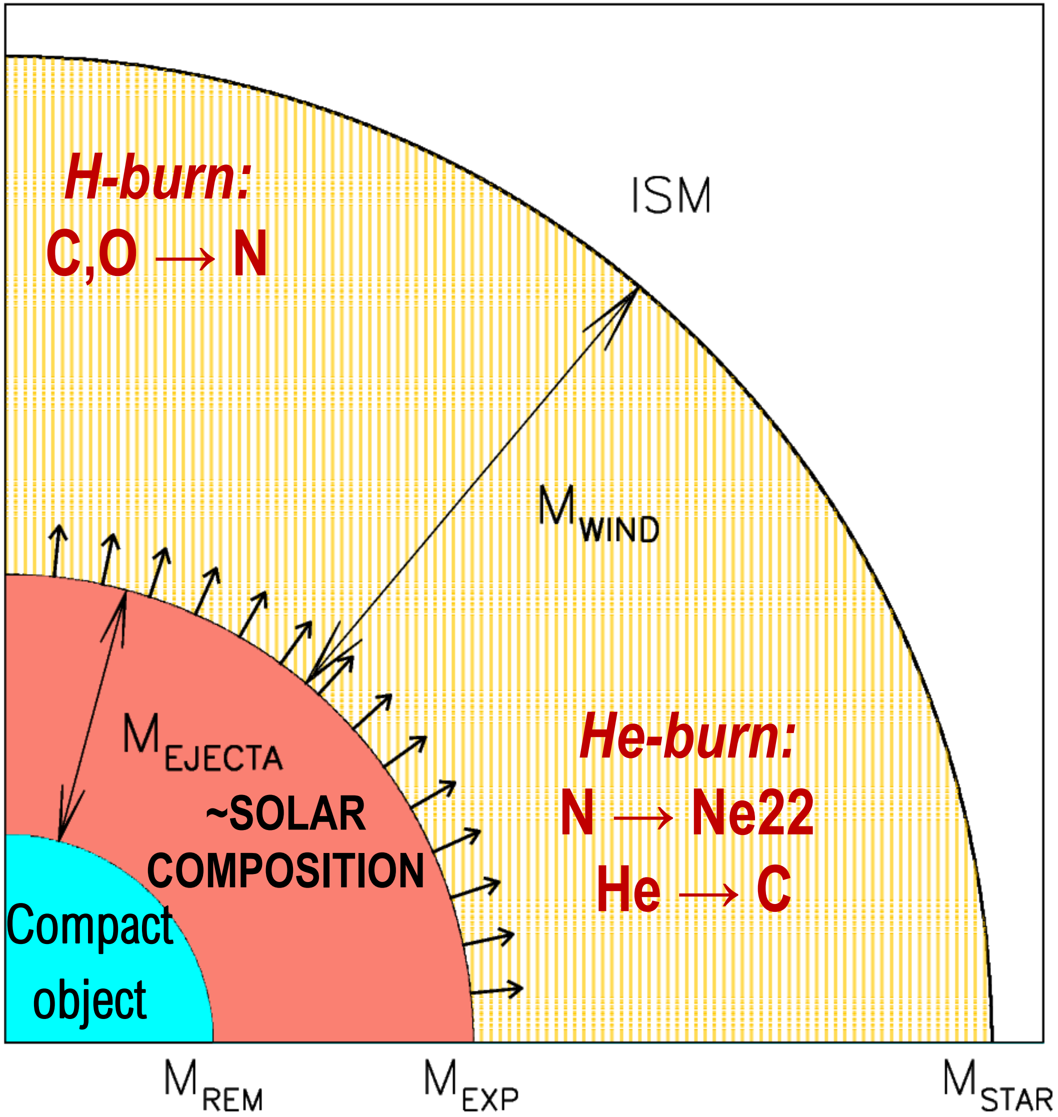
Are GCR accelerated in massive star winds ?

(I STILL THINK SO)

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

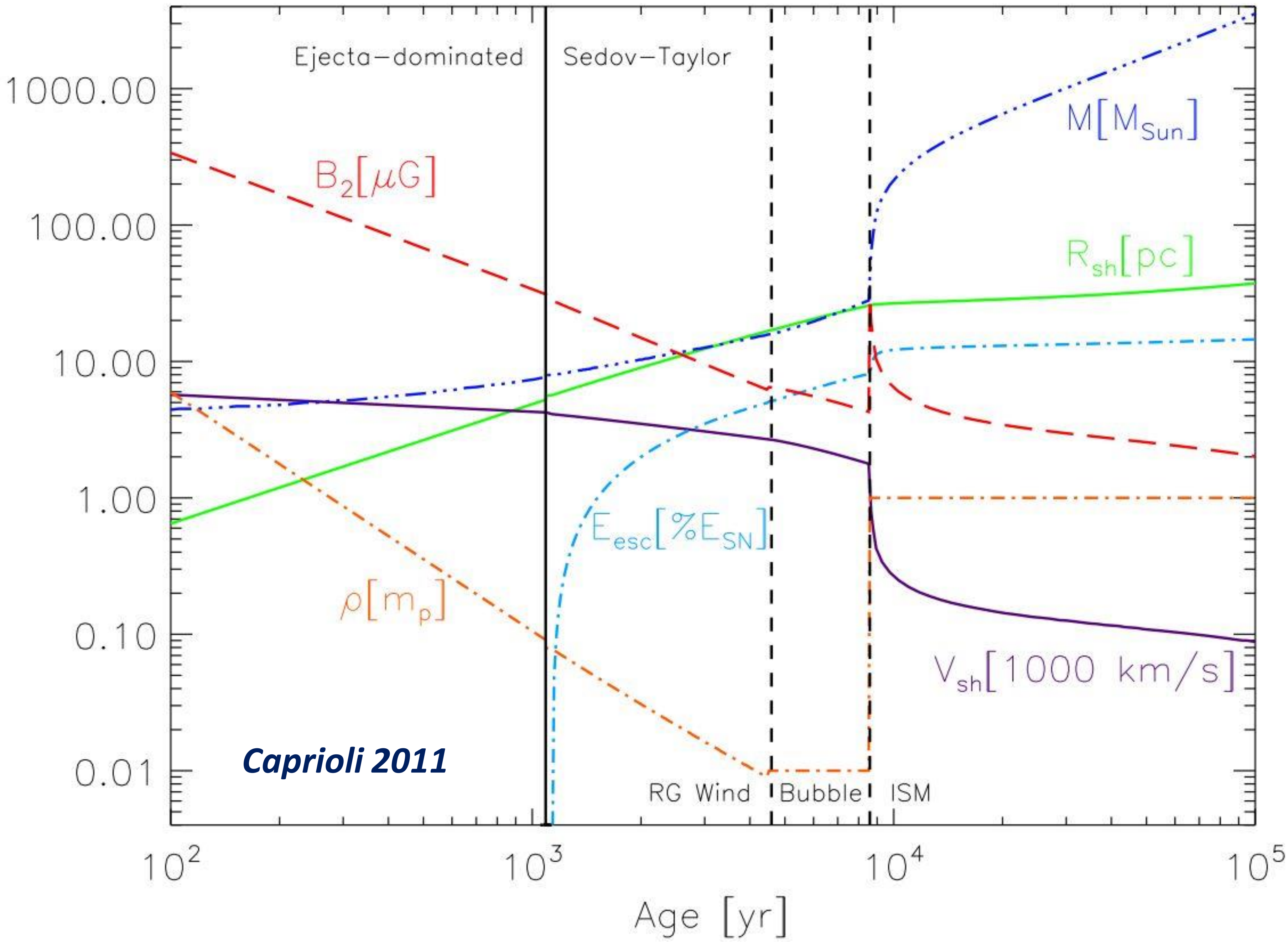
ASSUMPTION: Particle acceleration starts in the beginning of the Sedov-Taylor (ST) phase, when $M_{SWEPT} \sim M_{EJECTA}$

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.

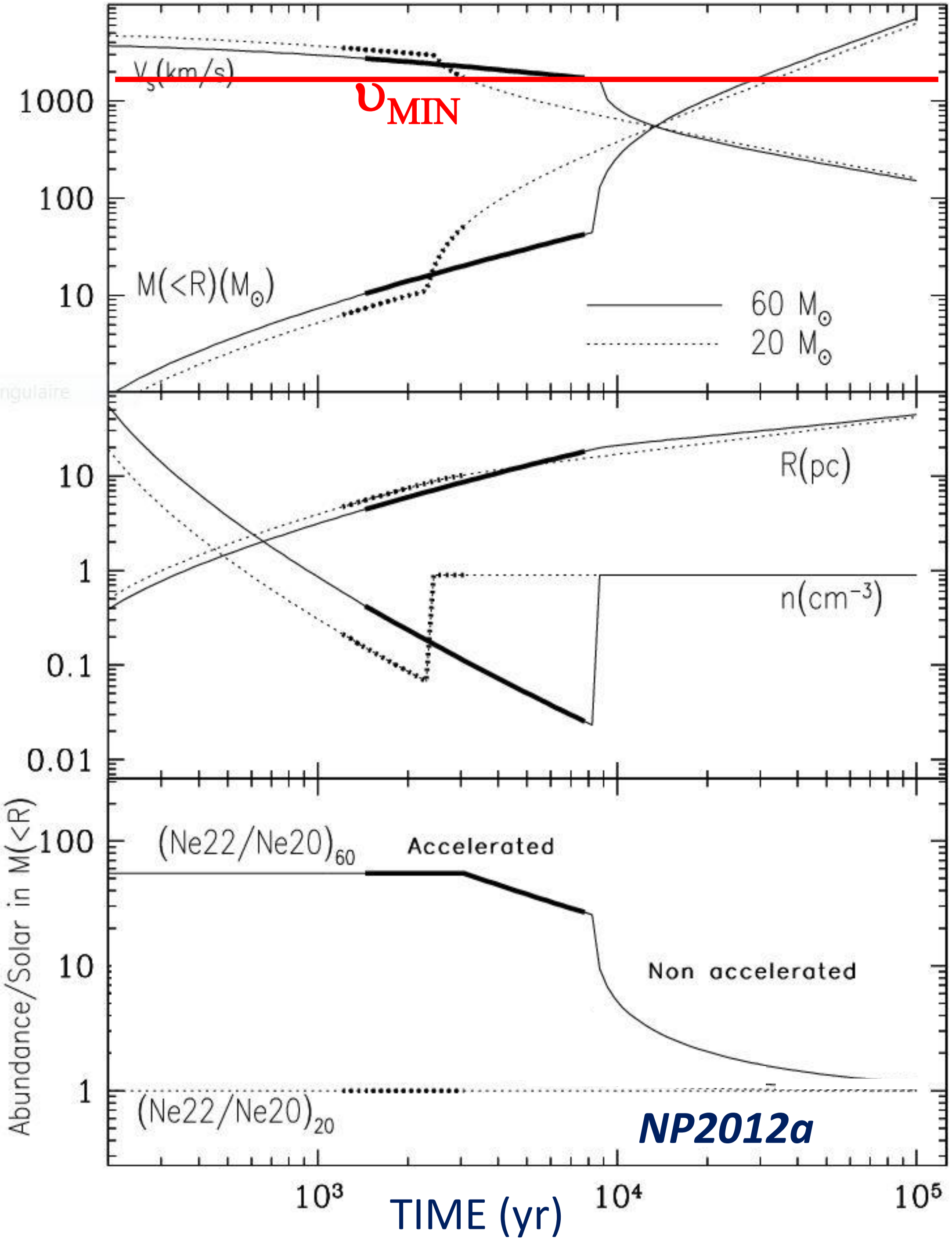


Caprioli 2011

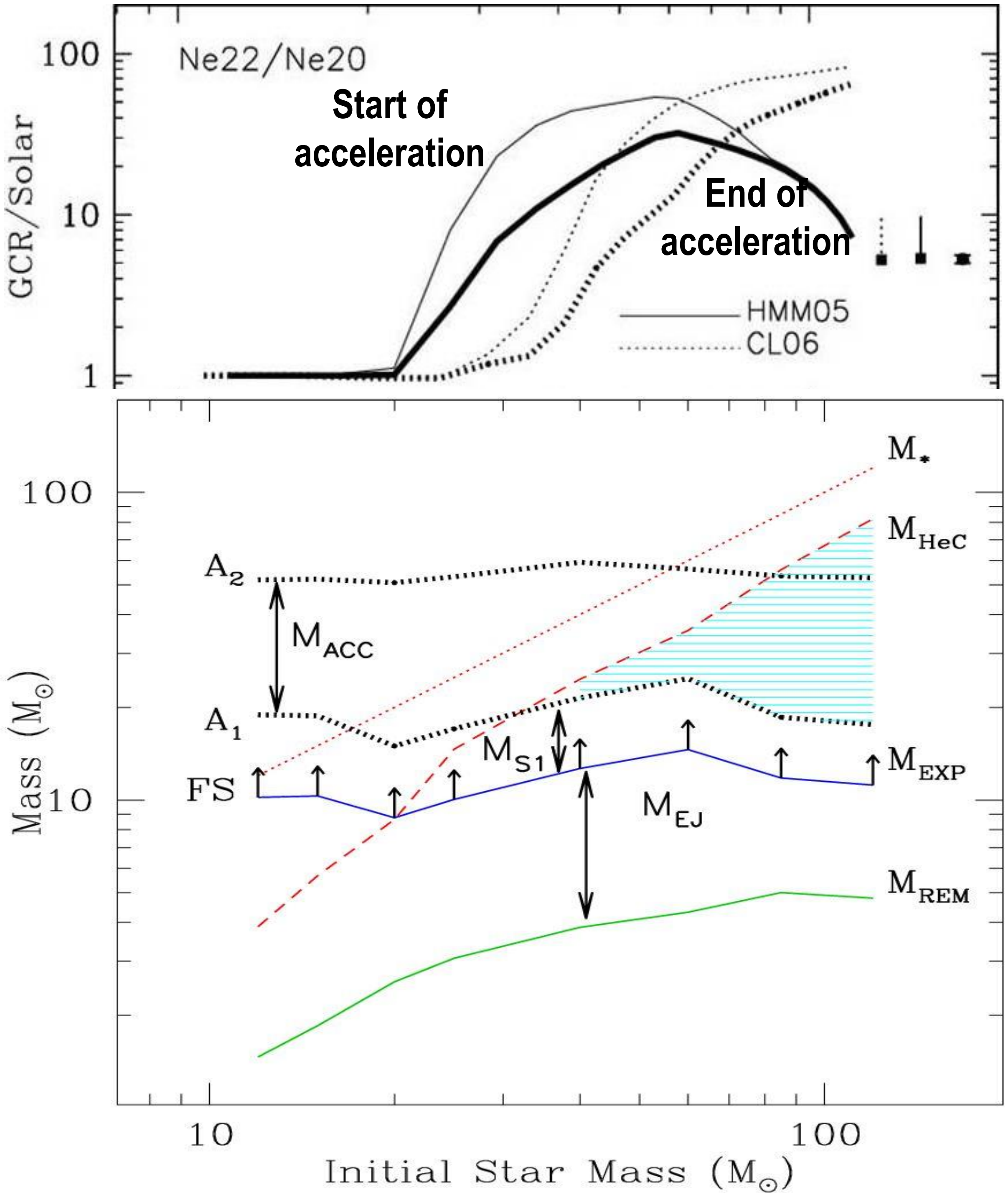
Particle acceleration starts in beginning of ST and **is assumed to stop when the velocity of the shock drops to υ_{MIN}**

chosen such as **the IMF averaged ratio Ne22/Ne20 of accelerated particles equals the observed one**

R = $(Ne22/Ne20)_{GCR}$ = 5.3 ⊙



NP2012a



The IMF averaged 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 star models of Geneva)

The forward shock accelerates particles from a pool of mass

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

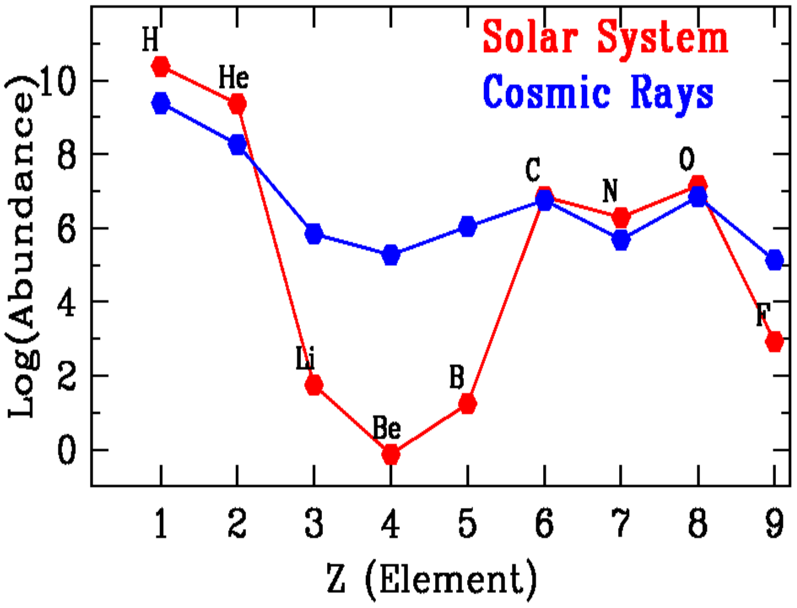
between the beginning of ST (**A1**) and υ=1900 km/s (**A2**)

The composition of that material is : stellar Envelope (~solar with high Ne22/Ne20) plus a few times ISM (=solar)

The 20% (winds)/ 80% (ISM) proportion is easily obtained *(with Geneva, not Roma, models)*

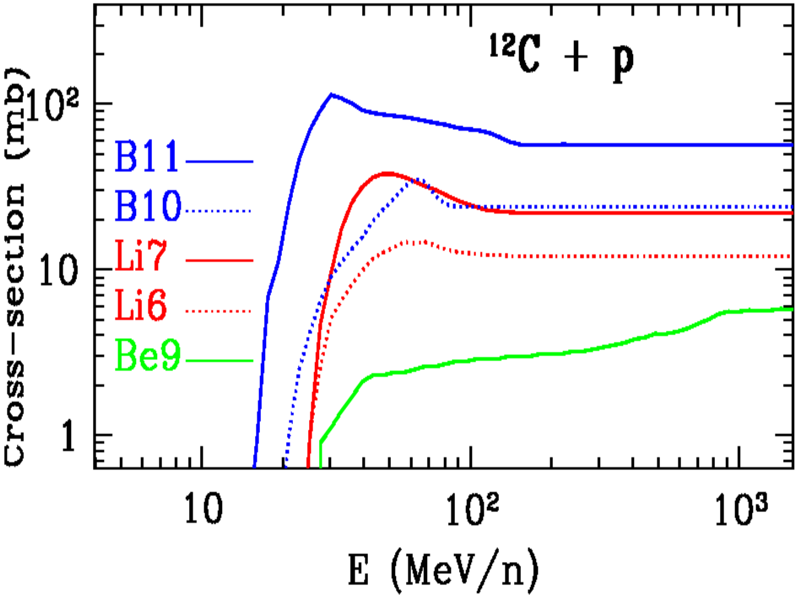
GCR composition is heavily enriched in Li, Be, B

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



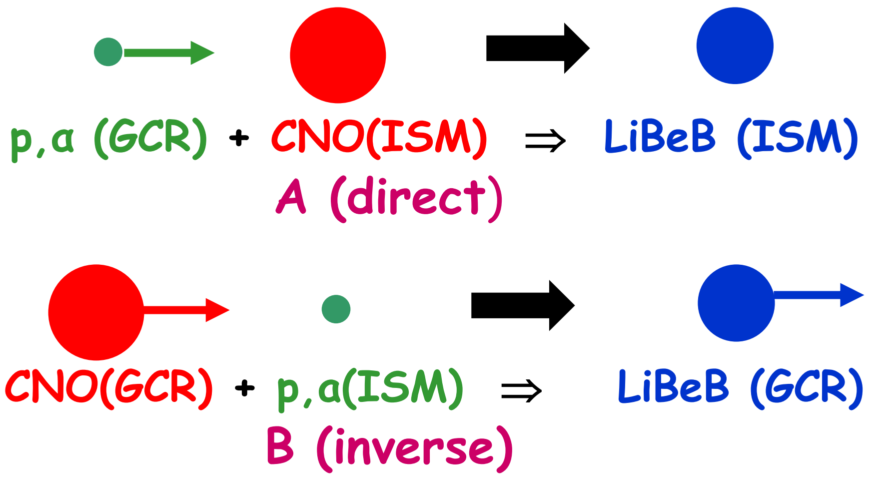
Solar composition: X(Li) > X(B) > X (Be)

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*)



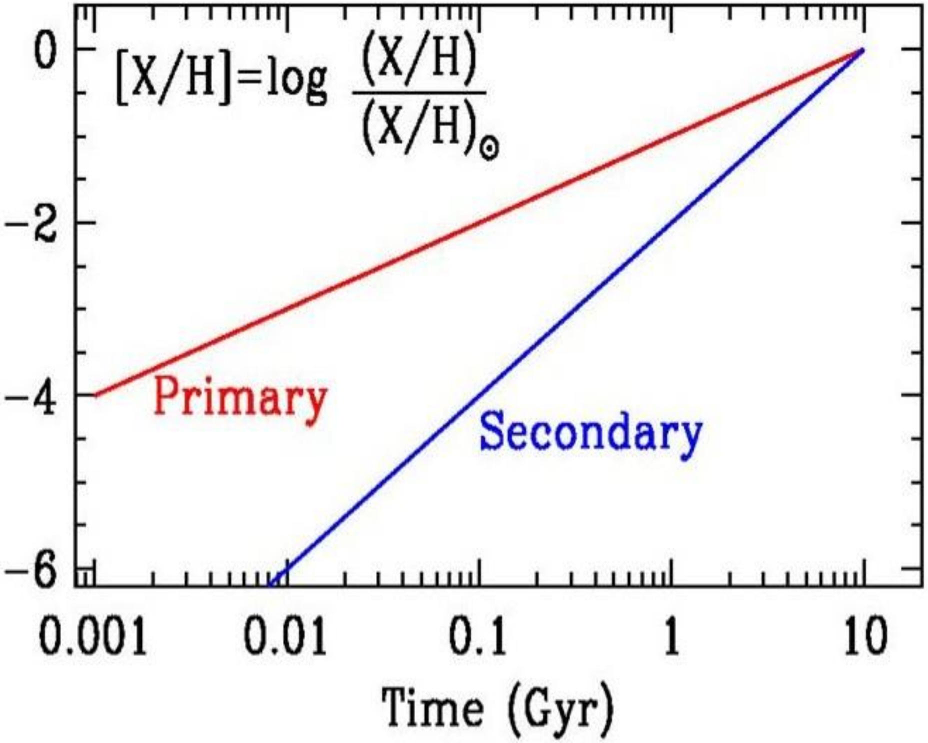
p,α (GCR) + CNO(ISM) ⇒ LiBeB (ISM)

A (direct)

CNO(GCR) + p,α(ISM) ⇒ LiBeB (GCR)

B (inverse)

The composition of GCR determines whether Be is produced as PRIMARY or SECONDARY during galactic chemical evolution



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)

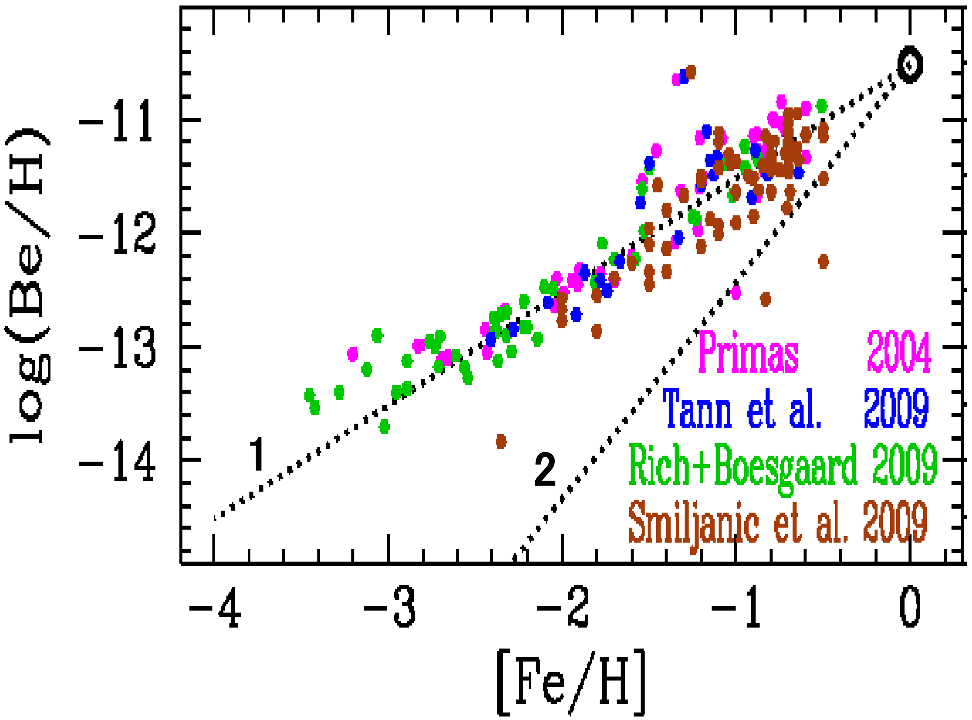
Examples: N14, O17, s-nuclei…

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

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

Evolution of Be

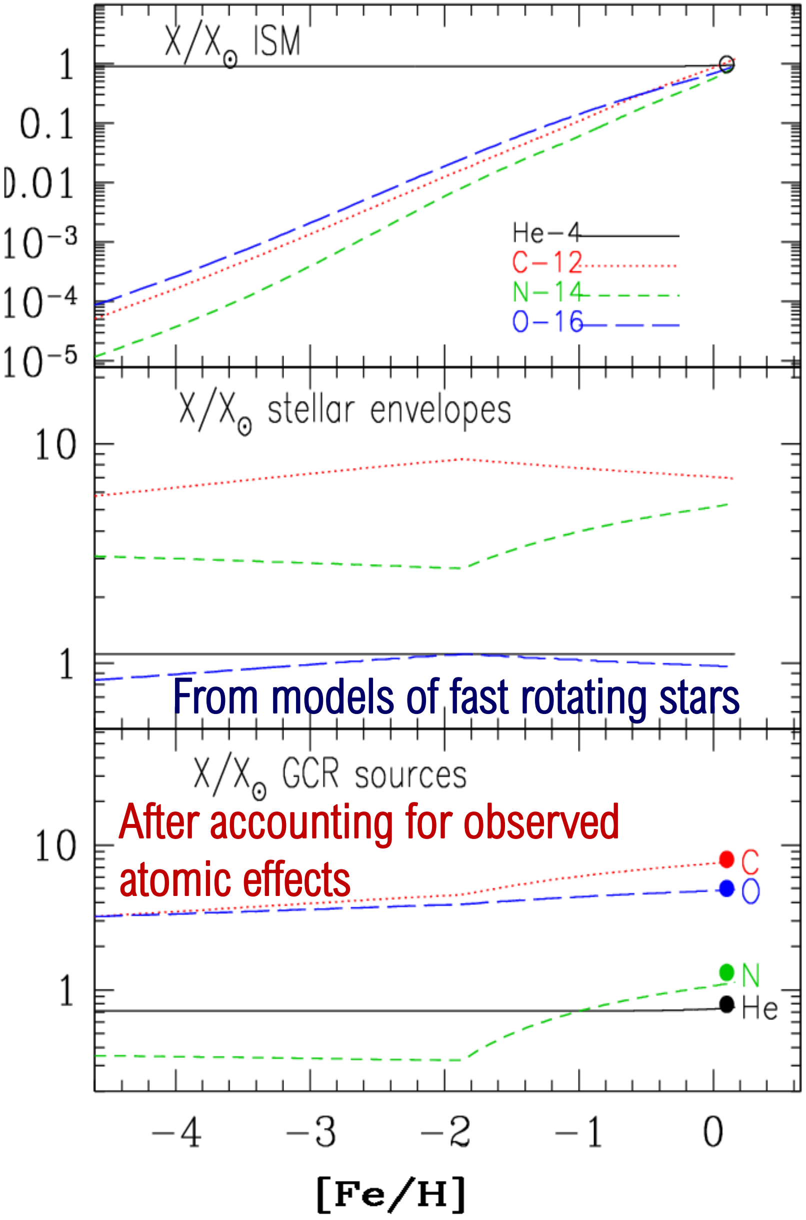
Early 90ies: Be (and B) observations in low metallicity halo stars



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

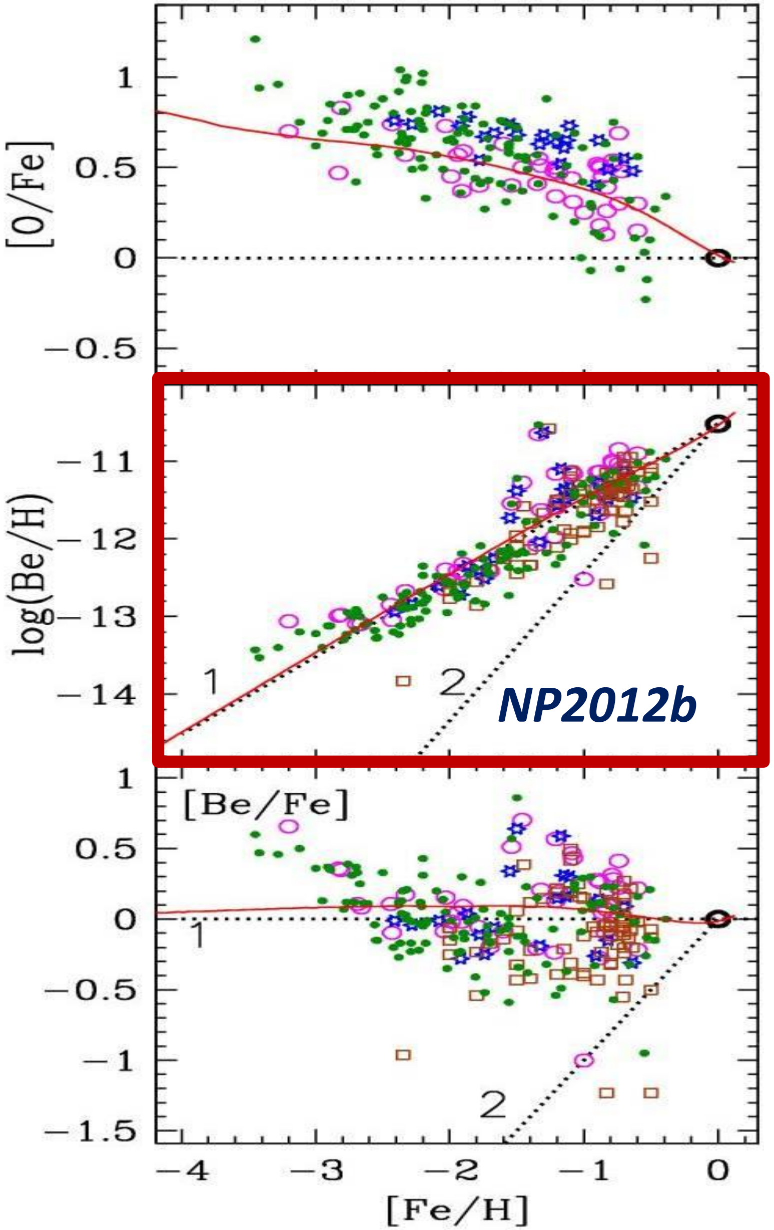
Self-consistent calculation of evolving composition of ISM AND GCR



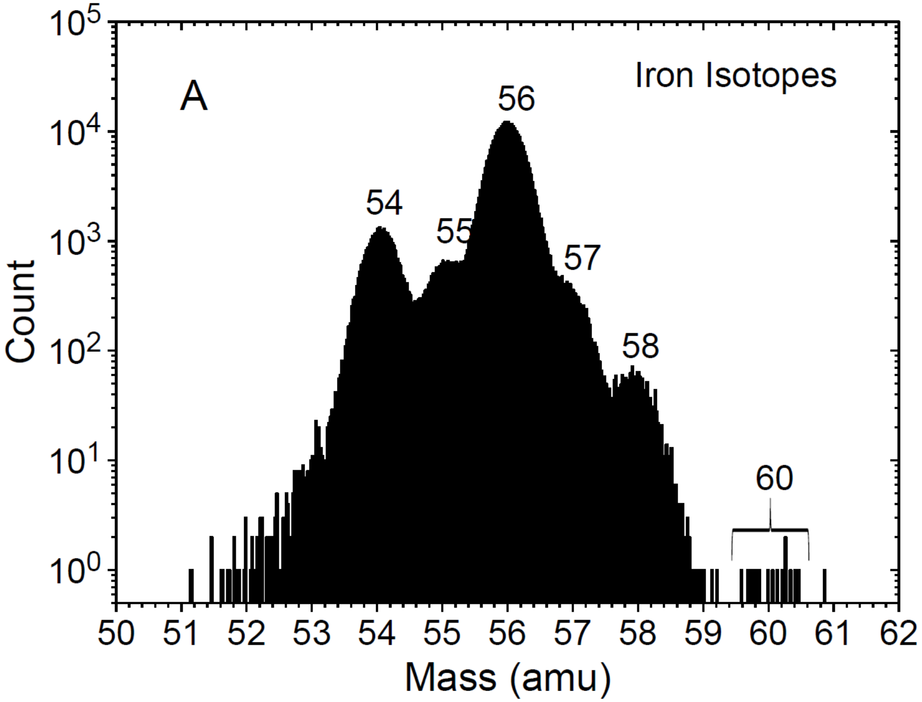
From models of fast rotating stars

After accounting for observed atomic effects

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



NP2012b



Radioactive Fe60 (τ~2.5 My) in GCR

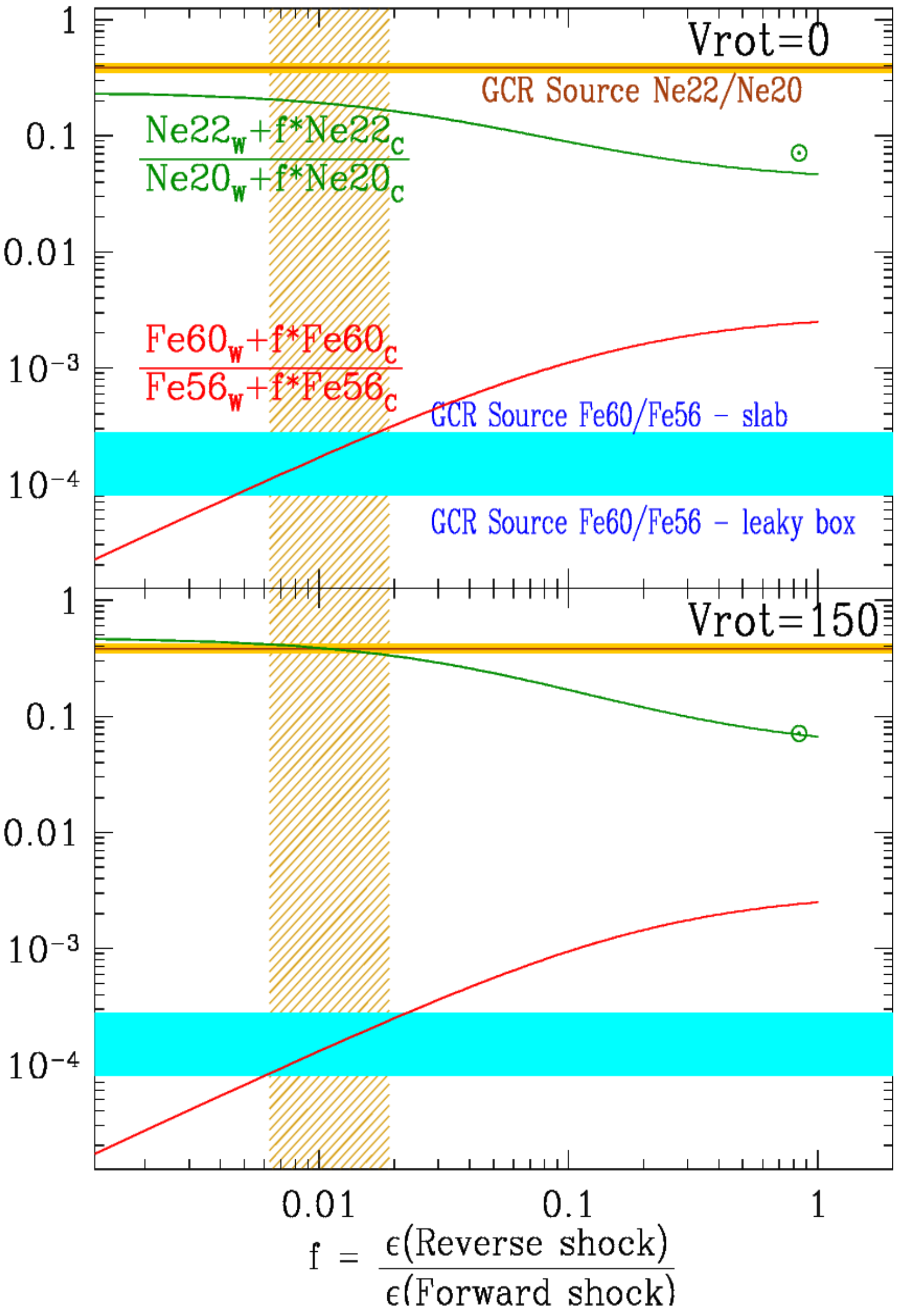
GCR source Fe60/Fe56 ~ 10^{-4}

(Binns et al. 2016)

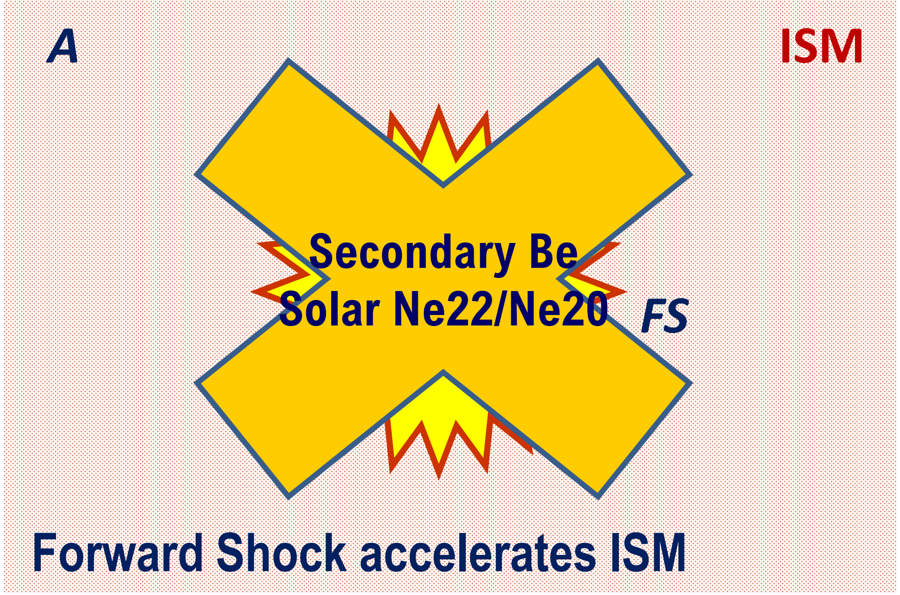
Stellar models: Fe60/Fe56 ~ 2 10^{-3}

in the core (Chieffi/Limongi 2018)

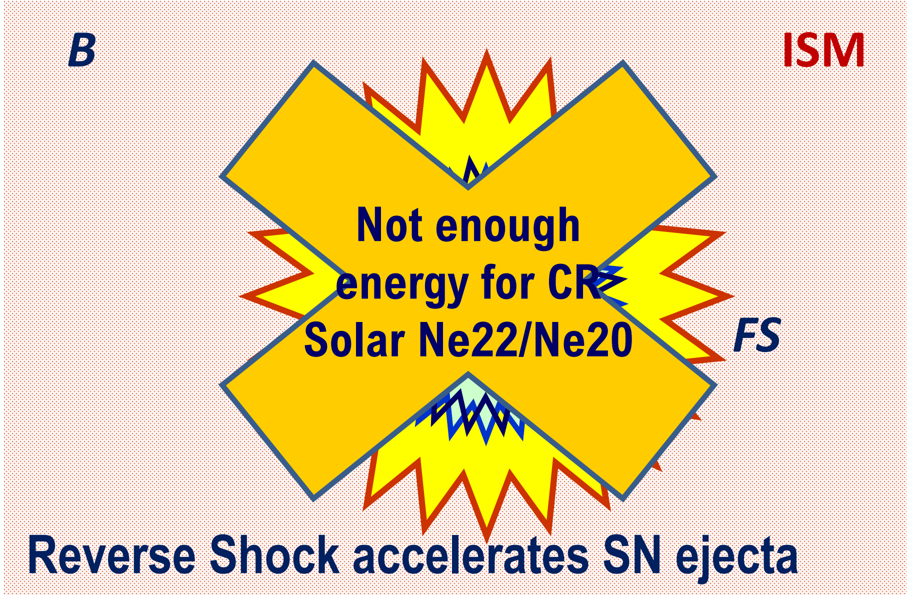
Some mixture of wind (Ne22 rich)
with little (a few %)
core material (Fe60 rich)
of rotating stars Is required



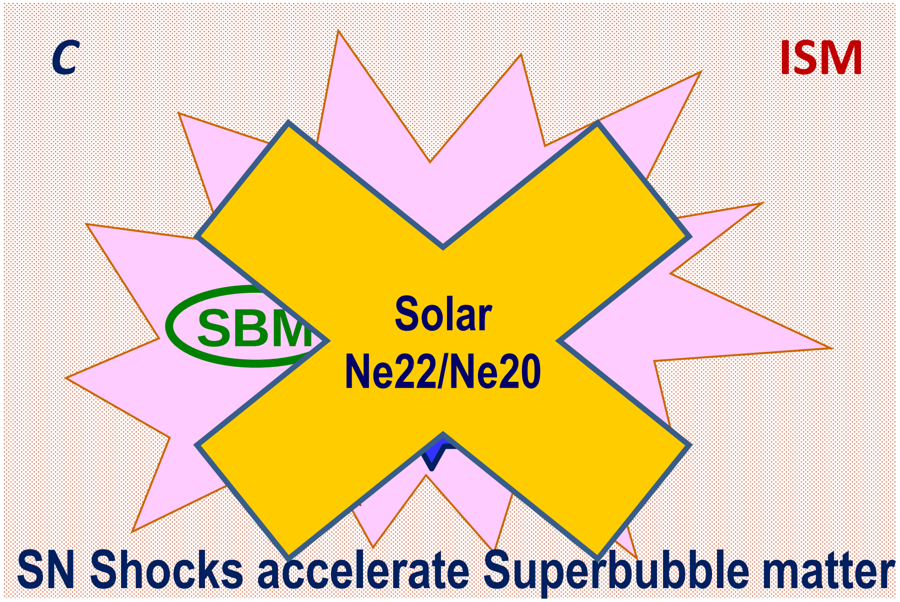
Galactic Cosmic Rays : what is the composition of accelerated matter ?



Forward Shock accelerates ISM

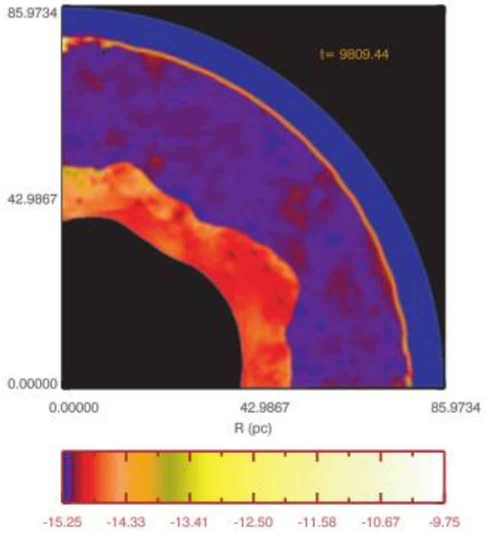


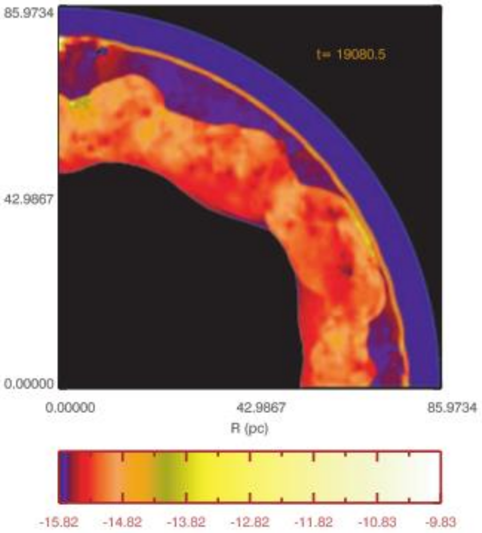
Reverse Shock accelerates SN ejecta



SN Shocks accelerate Superbubble matter

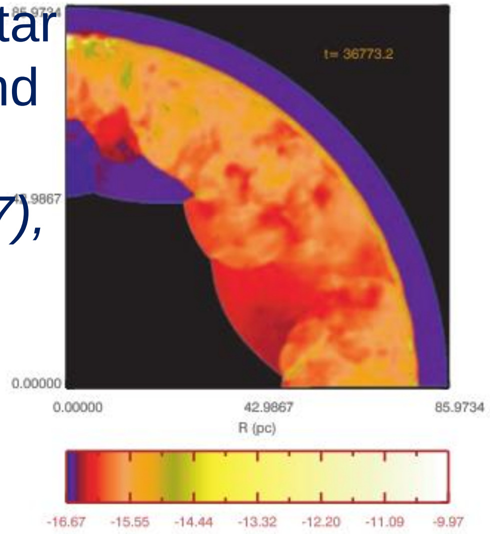
Forward Shock accelerates Wind+little ISM

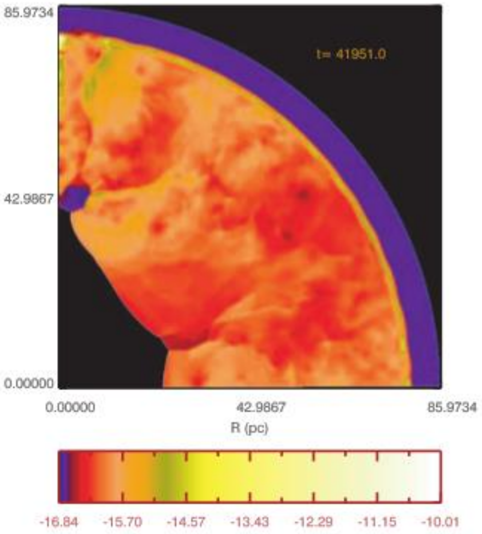




1D and 2D simulations suggest that the forward SN shock propagating In the wind nebula of a massive star is reflected when reaching the wind shell accelerating particles inside the wind bubble *(Dwarkadas 2007),*

perhaps more efficiently in the low density hot region of the wind (Ne22) than in the higher density, cold inner region (Fe60)





CONCLUSIONS *(assumption dependent)*

Assumption 1: Observed GCR source Ne22 and Fe60 are universal (not local)

1. The bulk of GCR cannot originate from SuperBubble material
(where WR and SN ejecta of the whole IMF are mixed)
otherwise the GCR source ratio Ne22/Ne20 should be ~solar *(NP 2012a)*

2. The *bulk of GCR* may originate from material
of winds from individual massive stars (Ne22-rich)
+ little ISM (=solar) and a little contribution of core ejecta
(Fe60-rich, through the reverse/reflected shock)
Particle acceleration should be essentially confined in the stellar wind

3. If stars at low metallicity are *fast rotating*
(near break-up velocity, Geneva models),
the resulting GCR source composition can also explain
the observed evolution of light elements Be and B *(NP 2012b)*
(if moderately rotating – Roma models – BeB evolution not explained)

CONCLUSIONS *(assumption dependent)*

Assumption 2: Observed GCR source Ne22 and Fe60 are local (not universal)

1. **The bulk of GCR can originate either from pure ISM accelerated from forward shocks (optimal) or from Superbubble material mixed « carefully » with ISM**
(Superbubbles have higher α/Fe than ISM (most Fe-peak coming from SNIa) and are defficient in s-elements (most of them coming from AGB stars)

2. **The *local component of GCR* may originate from wind material from an individual local/recent massive star (Ne22-rich) + little ISM (=solar) and a small contribution of its core ejecta (Fe60-rich, through the reverse/reflected shock)**
Accelerated particles should be little diluted with bulk of GCRs

3. ***Hard to explain observed evolution of BeB:***
Substantial amount of « gymnastics » required

CONCLUSION (*final*)

The observed source composition of GCR,

(enriched in stable Ne22 and radioactive Fe60

and more in refractories than in volatiles),

and the evolution of spallogenic Be

provide important, yet undeciphered, clues to

the site and the physics of GCR acceleration