GCR source composition and acceleration site(s)

a historical overview

and some conclusions

NP (2012a, A&A)
On the origin and composition of Galactic cosmic rays

NP (2012b, A&A)
Production and evolution of LiBeB isotopes in the Galaxy

ISSI team « GCR composition » internal report (2018)

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Galactic Cosmic Ray Odyssey

Energetic shocks

CR Source
Original Composition

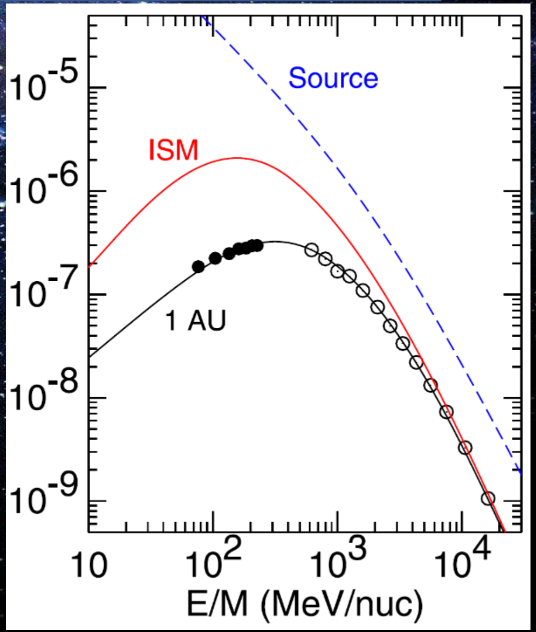
GCR + ISM ➔ LiBeB

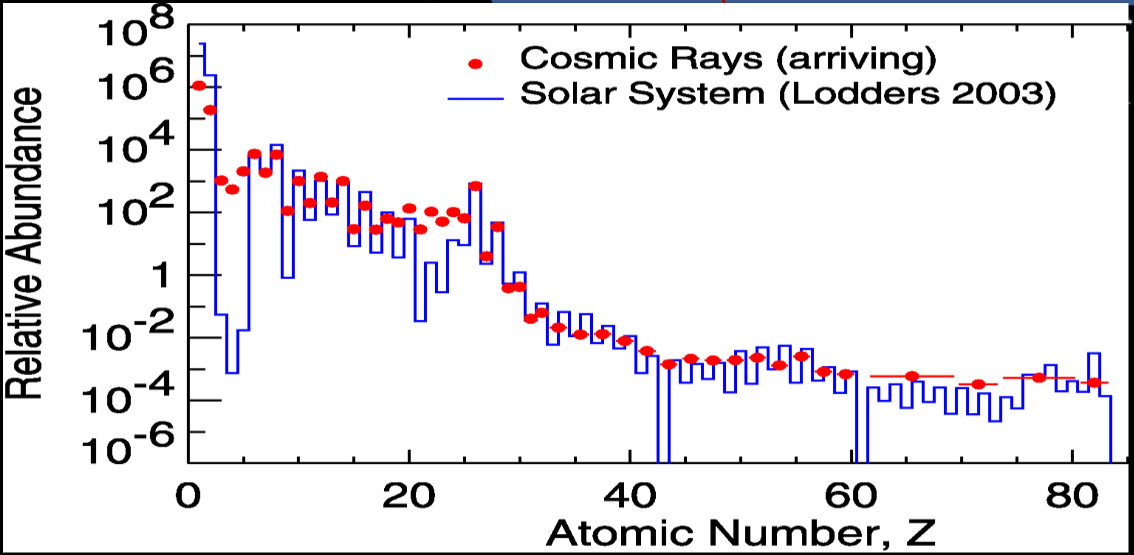
CR on Earth
Modulated spectrum
Observed Composition

CR Acceleration
Injection spectrum
Modified Source Composition

CR Propagation
(=equilibrium) spectrum

CR Transport
Losses *(ionisation, escape, nuclear) VS*
Gains *(reacceleration?,secondary nuclei)*





What do we learn from GCR source abundances ?

First Ionization Potential vs Condensation Temperature

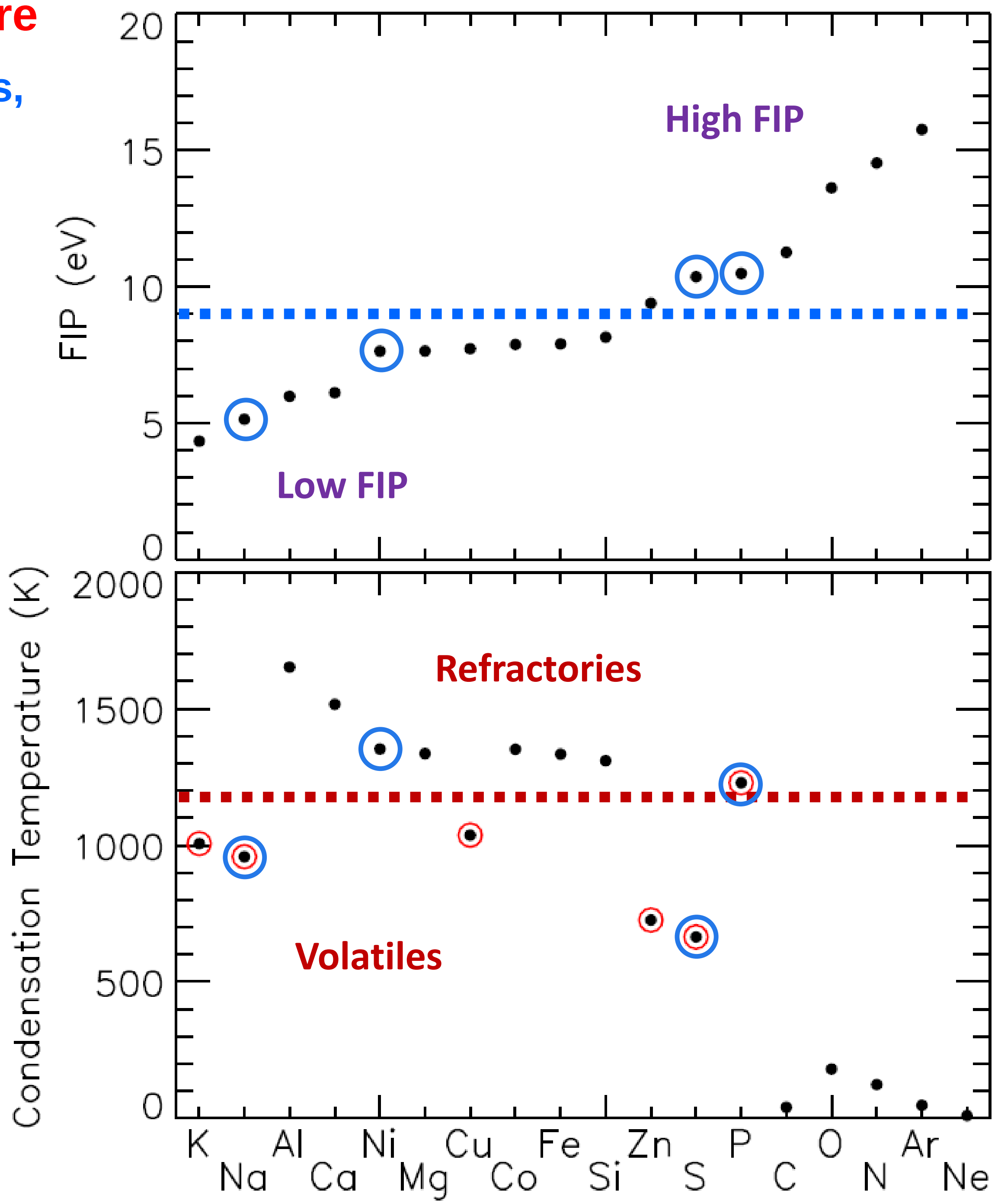
_1985_. Solar-stellar outer atmospheres and energetic particles, and galactic cosmic rays (_J. P. Meyer_)

The pattern involves an underabundance of heavy elements with first ionization potential (FIP) greater than about 9 eV relative to elements with lower FIP by factors of about 4-6. They were extracted from solar stellar coronae, with their compositions reflecting, to first order, that of their birthplace. ***GCRSs should be MeV-stellar energetic particles first injected by flares out of the coronae of unevolved, later-type stars, subsequently reaccelerated to high energy by strong interstellar shock waves****.*

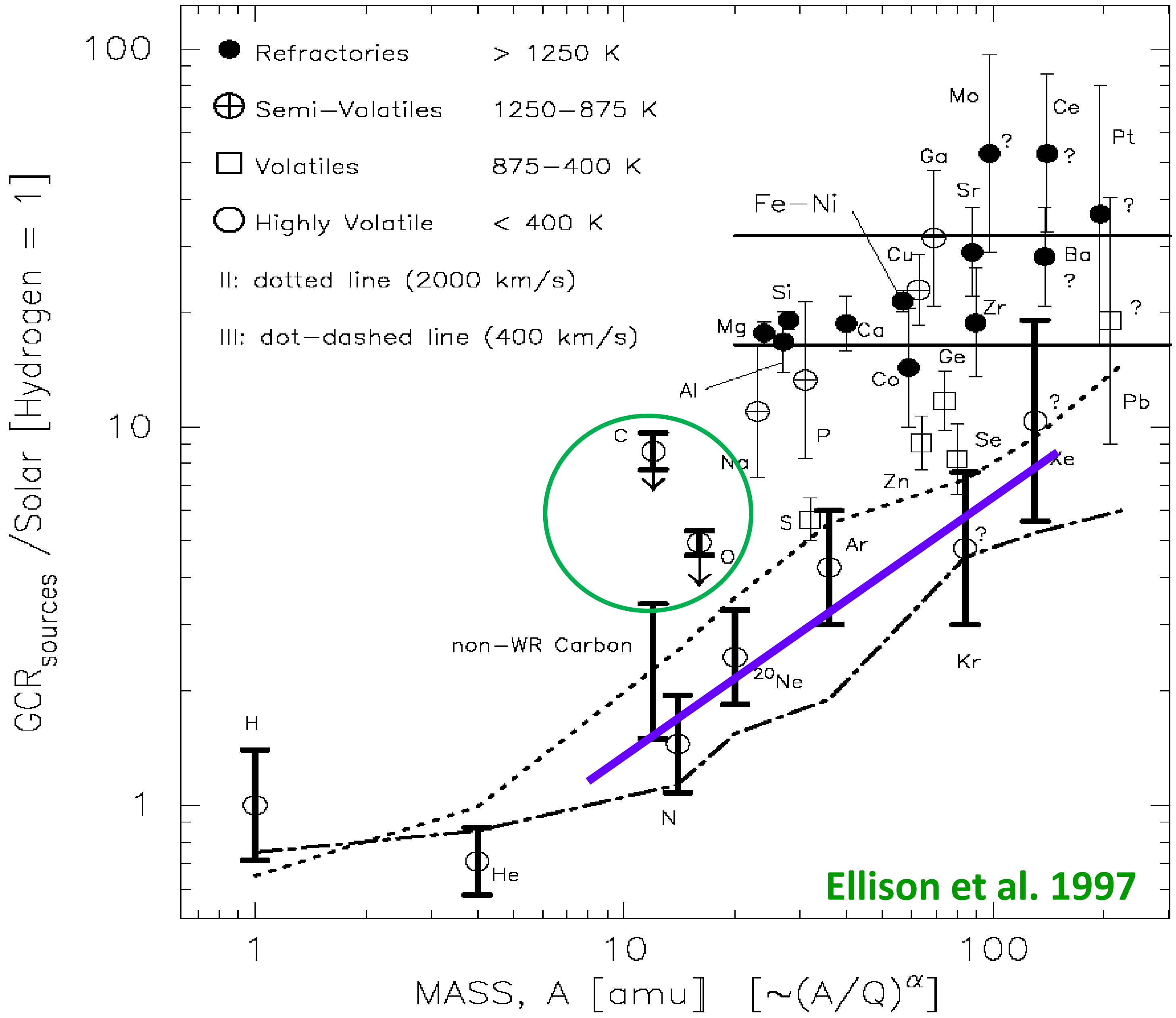
But: Na/Mg lower and P/S higher than expected

_1997._ Galactic Cosmic Rays from Supernova Remnants. II. Shock Acceleration of Gas and Dust (_Ellison, Drury, Meyer_)

So, in our current view, ***the great (Meyer 1985). similarity between*** *the GCR source composition (volatility-biased, because of preferential acceleration of grain material) and the solar coronal, solar wind, and solar energetic particle composition (FIP-biased, as a result of an ion-neutral fractionation in the D104 K solar chromosphere)* ***is purely coincidental!***



Galactic Cosmic Ray Source Composition



Is it solar ?

No, for elemental abundances
Selection effects due to mass and Volatility

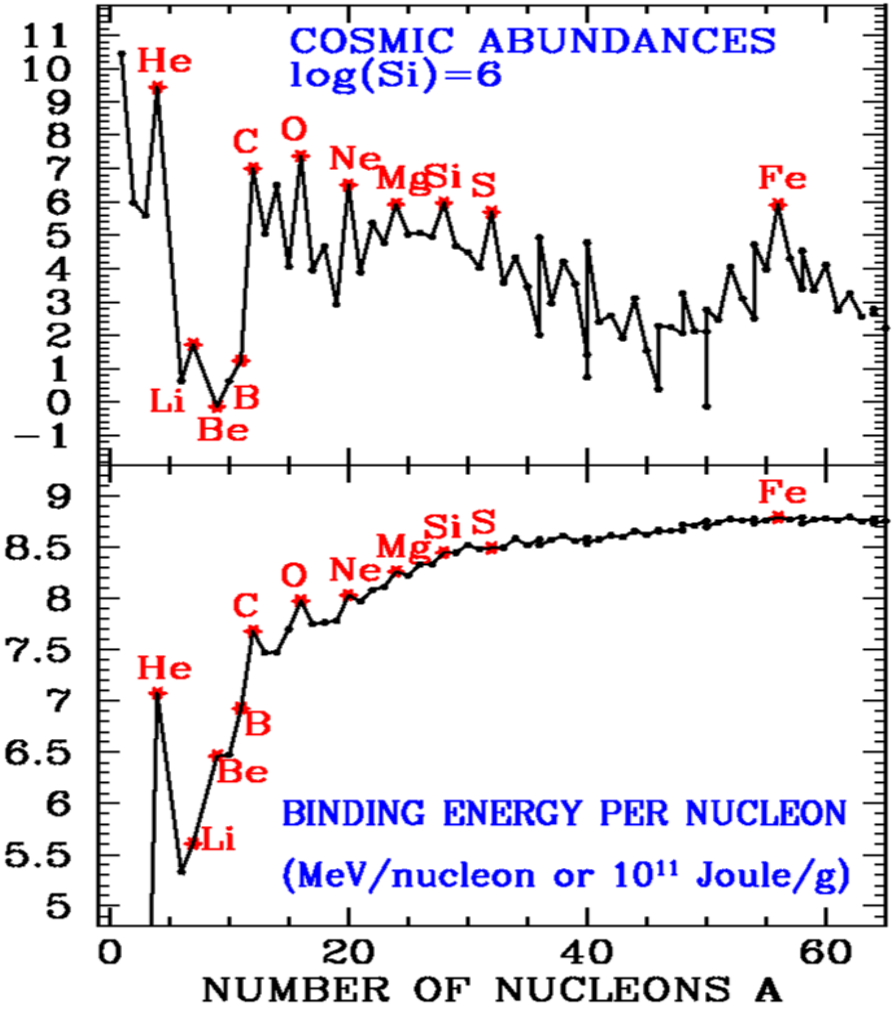
Volatiles: underabundant
abundance increasing with A/Q (mass to charge ratio)

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

***Forward SN shocks* accelerate both circumstellar gas *(volatiles)* AND sputtered grains (*refractories*)**

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

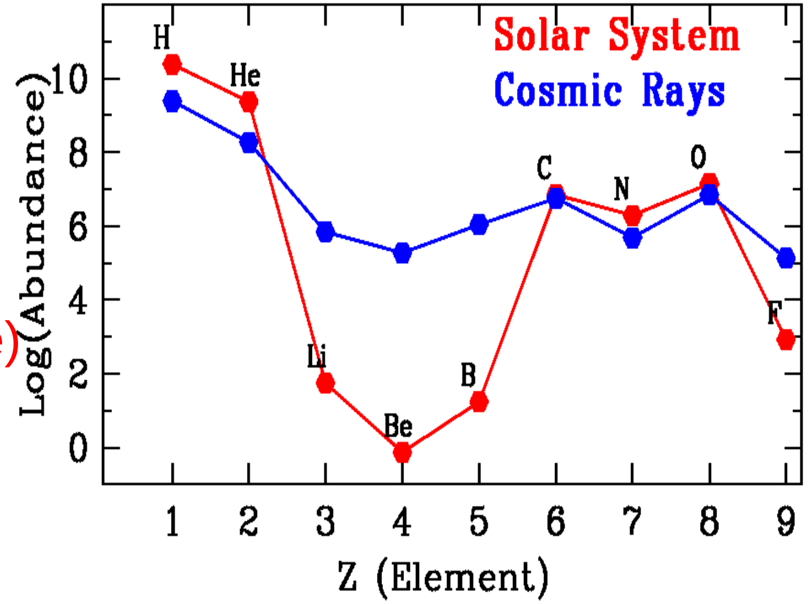
The light elements Li Be B and the composition of GCR



GCR are heavily enriched in Li, Be, B (~10^6 for Be and B)

Proto-Solar: X(Li) > X(B) > X (Be)

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

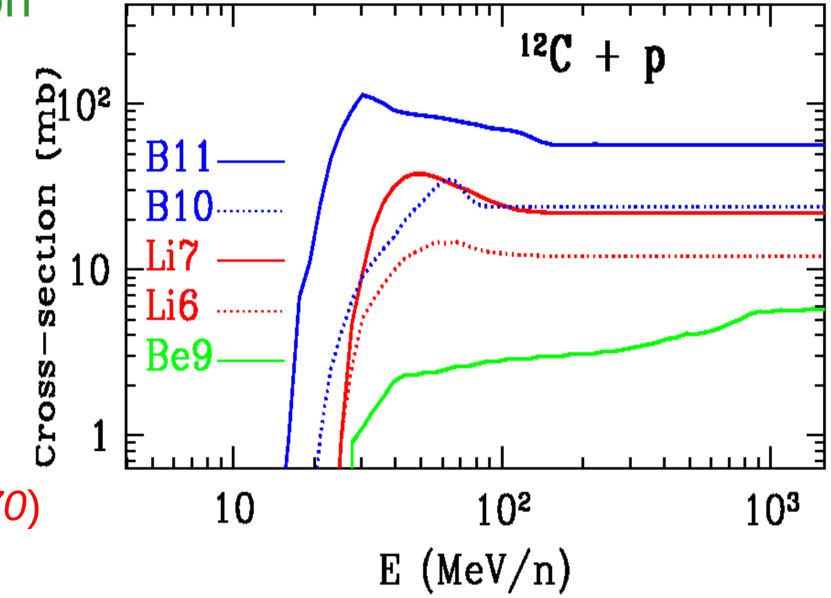


Same order as spallation cross sections of CNO ⇒ LiBeB:

σ(B) > σ(Li) > σ(Be)

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

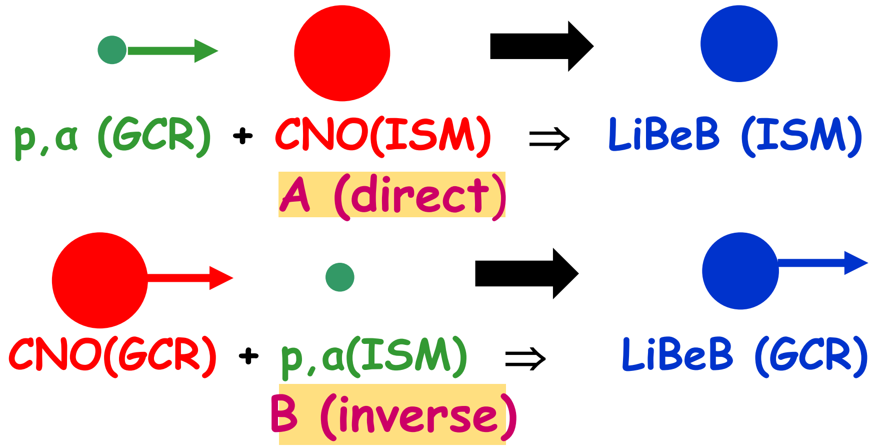
(*Reeves, Fowler, Hoyle 1970*)



The most fragile stable isotopes (*after D and He3*)

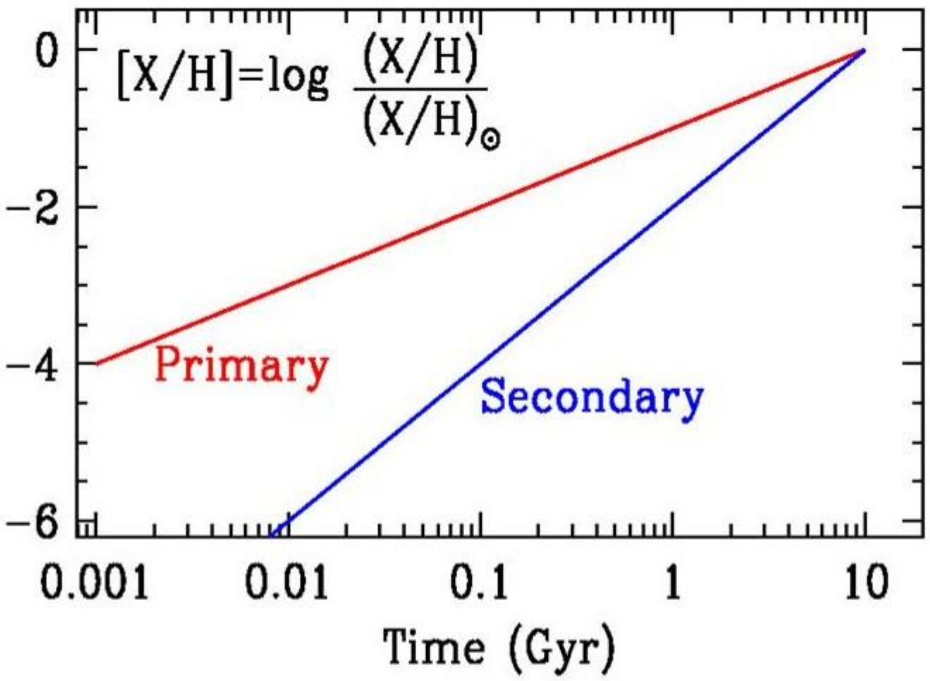
Always destroyed in stellar interiors T~ a few MK

(except for Li7, which is produced in special cases)



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

Definitions	Chemical evolution	GCR
Primary element	Stellar Yields ~constant with stellar metallicity	Produced in GCR source
Secondary element	Stellar Yields ~proportional to stellar metallicity	Produced from spallation of GCR during propagation



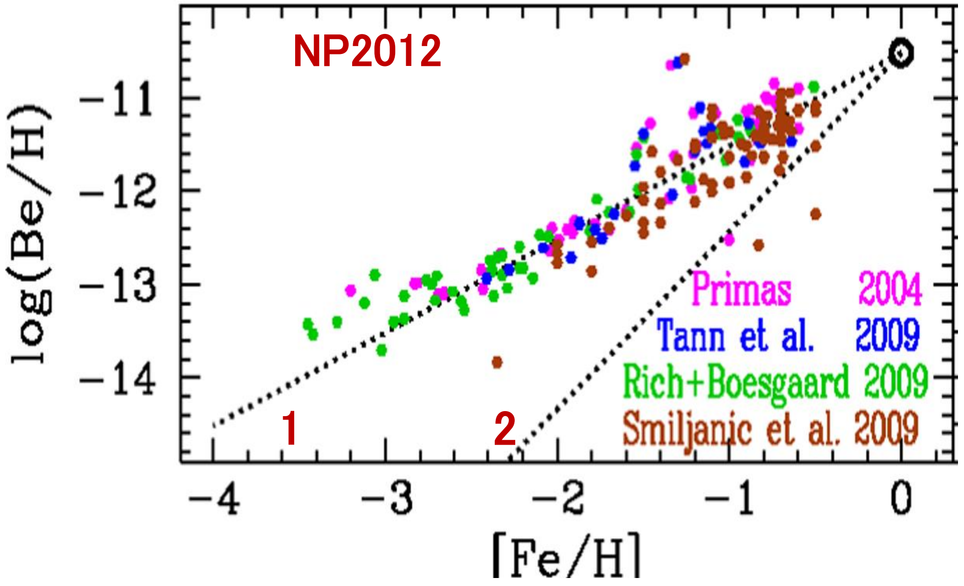
Primary: produced from initial H and He inside the star
Yield: independent of initial metallicity (Z)
Examples: C, O, Fe…

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): $X_S \propto t^2 \propto Z^2$

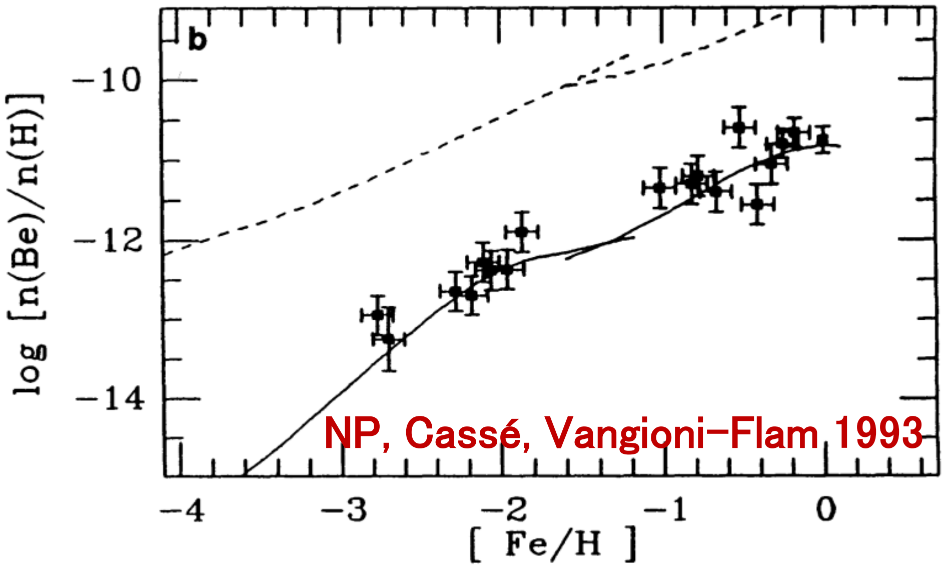
Evolution of Be

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



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

NP, Cassé, Vangioni−Flam 1993 : Galactic chemical evolution with GCR composition = ISM and leaky box model of propagation with escape length Λ ⇒ 1000 g/cm2 in early galaxy (confinement)



Notice, however, that if GCR have a *time-independent composition* (i.e., not following the metallicity of the ISM), then the second component of LiBeB production (i.e., GCR CNO nuclei impinging on ISM protons and alphas) had a much larger contribution in the past, its effect being similar to the one of $\alpha + \alpha$ reaction for ^{6,7}Li. Although this possibility (mentioned by Duncan et al. 1992) is contrary to current ideas on GCR source composition (i.e., Meyer 1985a, b), we think that it offers an interesting alternative (see, however, Prantzos, Ramaty, Kozlovsky, Lingelfelter & Reeves 1997

Energetics argument: Not enough energy in GCR
IF CNO is secondary, to produce ~constant Be/Fe
Only possibility: Primary CNO in GCR

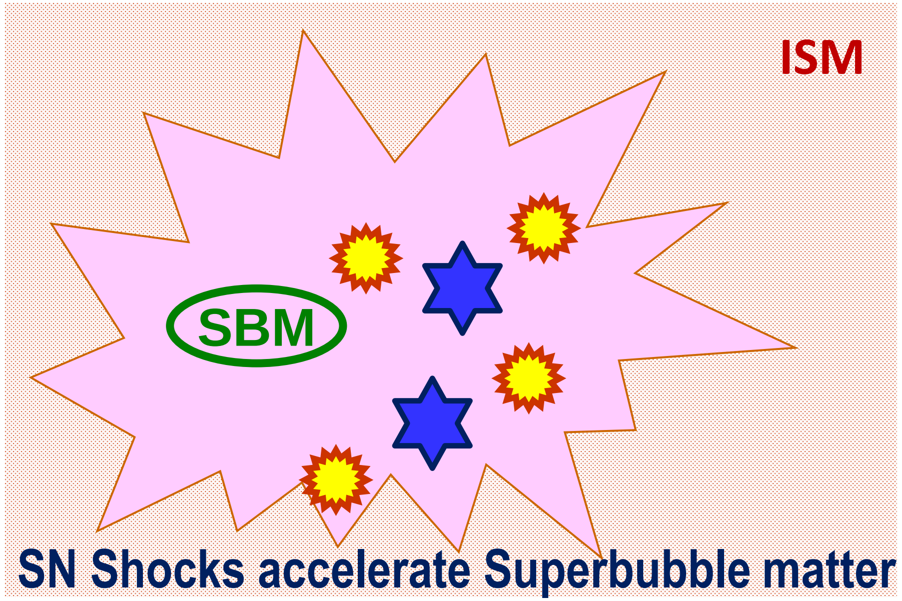
"*Observations of Be and B in low-metallicity halo stars formed during the first Gy of Galactic evolution strongly suggest that the cosmic-ray acceleration is related to* ***particles being accelerated out of freshly nucleosynthesized matter*** *before it mixes into the ambient, essentially nonmetallic interstellar medium".*

BUT *(Ellison+Meyer 1998)* Not enough energy in reverse SN shocks

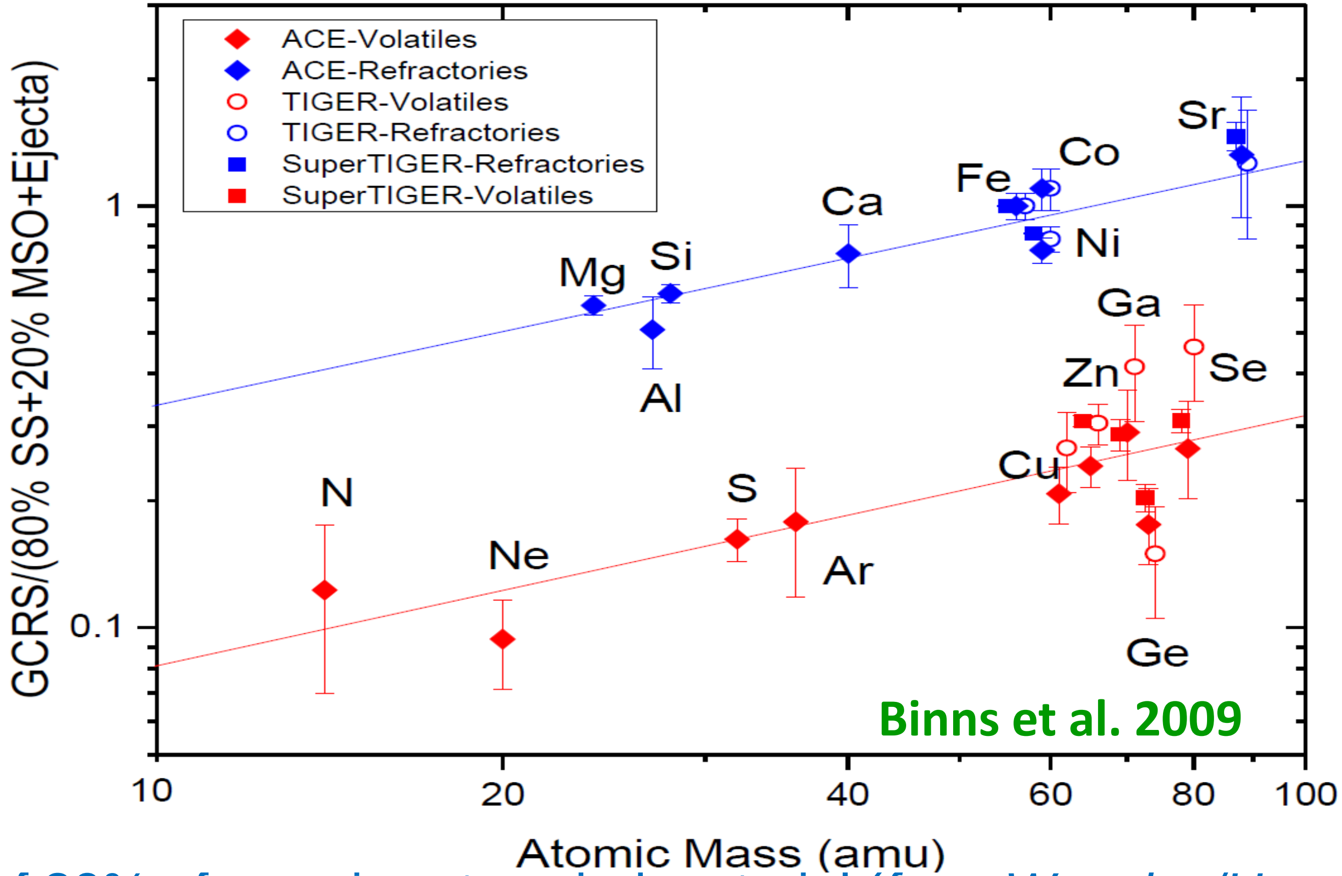
Higdon, Lingelfelter & Ramaty 1998

We suggest that the ***cosmic rays are accelerated primarily out of the supernova ejecta-enriched matter in the interiors of superbubbles.*** *… The bulk of these supernovae remnants, together with their metal-rich grain and gas ejecta and their cosmic-ray-accelerating shocks, are well confined within the cores of superbubbles.* ***These cores can thus provide a source of cosmic-ray matter of essentially constant metallicity*** *throughout the age of the Galaxy,* ***which is required to account for the constancy of cosmic-ray-produced Be***

Criticized in *Ellison&Meyer 1998*



Galactic Cosmic Ray Source Composition

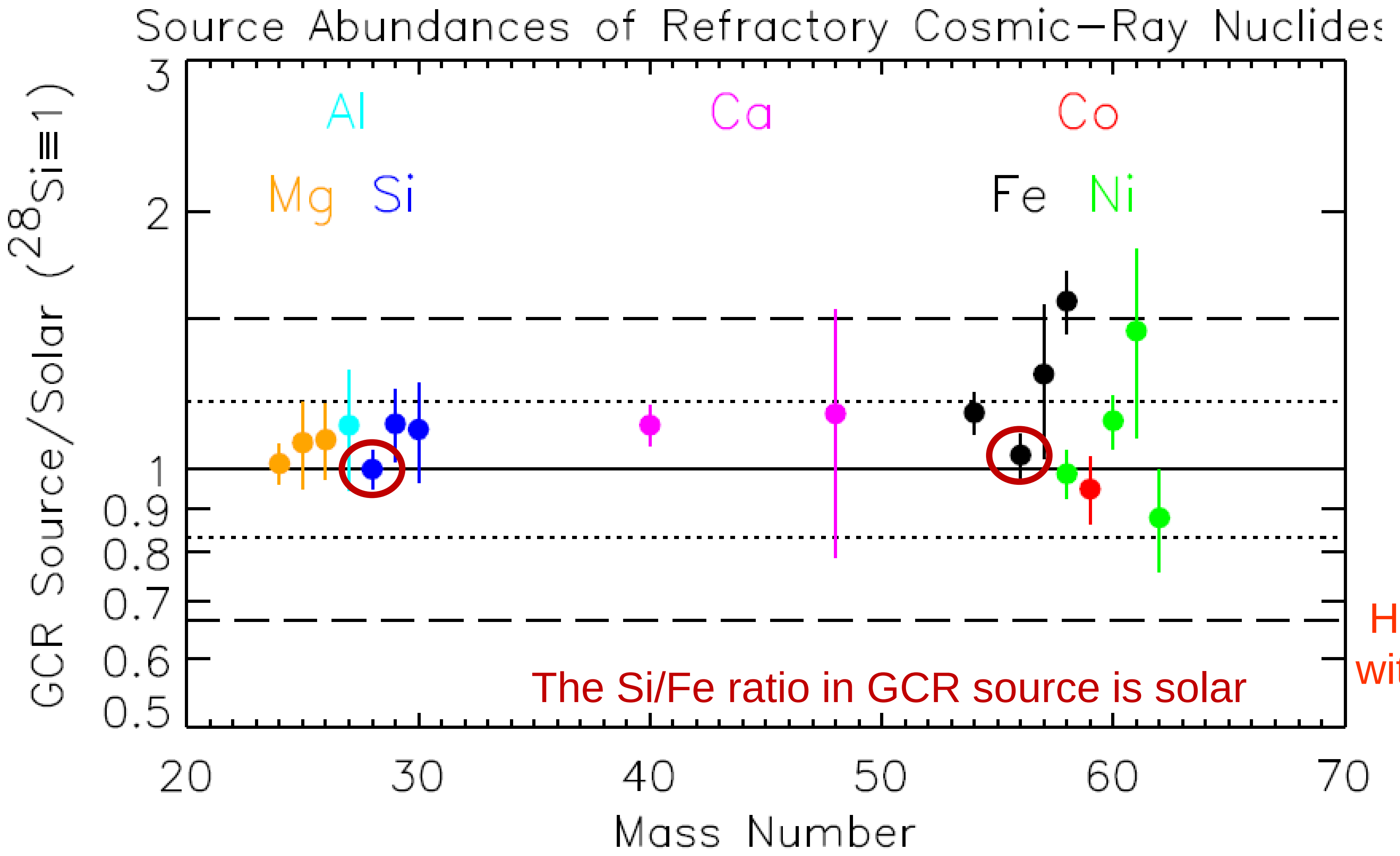


A mixture of 20% of massive star wind material (*from Woosley/Heger 2007*) with 80% of ISM allows for a better ordering of the GCR composition *assuming a clear separation in refractories and volatiles only*

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

20/80 ratio imposed from Ne22/Ne20 requirement

Ne22/Ne20~5.3 ⊙

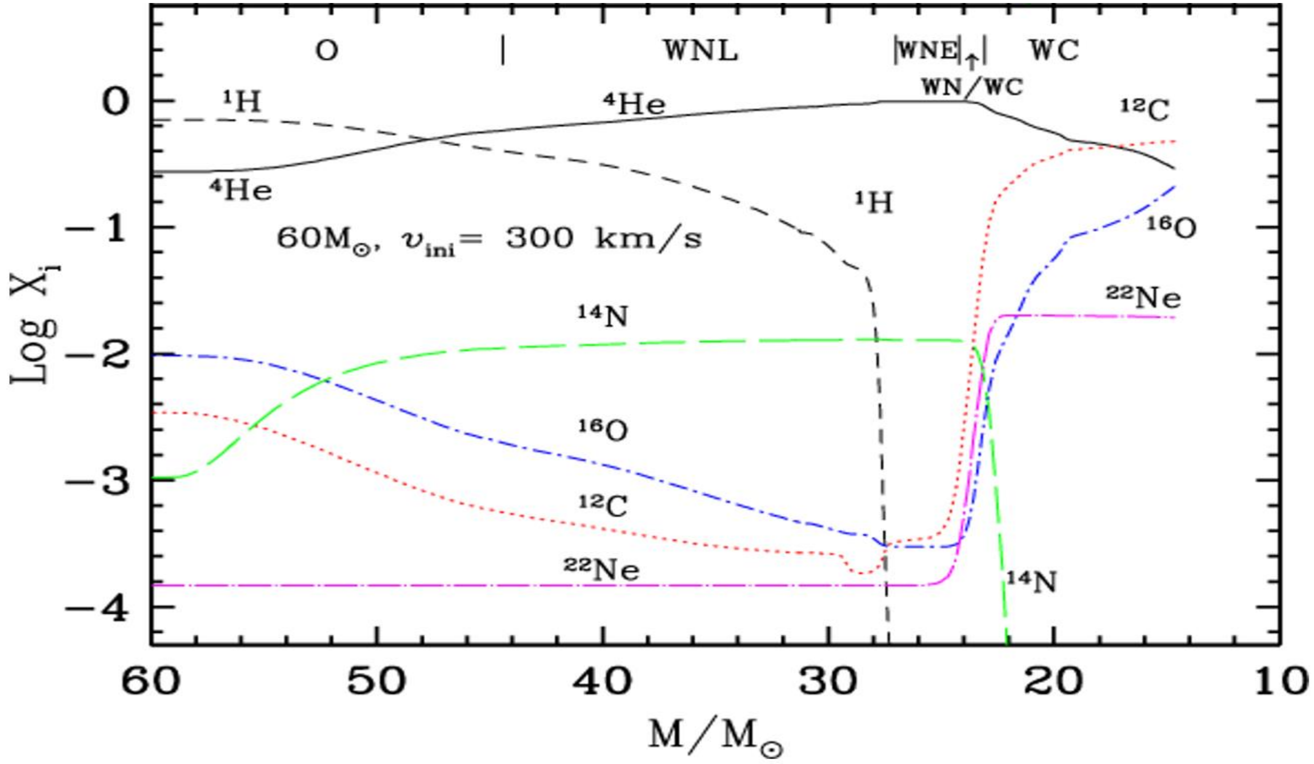


All refractory isotopic ratios are very close to solar

The best measured volatile isotopic ratio Ne22/Ne20 is 5.3 times solar

How to get a mix so close to solar, with so high Ne22/Ne20 anomaly ?

The most massive stars (M>30 M☉) have strong winds, expelling the H and He layers (WR stars) and ejecting Ne22 (*Cassé and Paul 1982*)



In H burning through CNO cycle, C+O turn into N14

In subsequent He-burning
N14+α ⇒ F18 ⇒ O18,   O18+α ⇒ Ne22

In the He-layer: Ne22/Ne20 ~100 solar

To obtain the GCRS ^{22}Ne/^{20}Ne enhancement factor of 4.4 ± 0.9, the He-burning component with ^{22}Ne/^{20}Ne enhancement of 140 must be highly diluted in a component with solar ^{22}Ne/^{20}Ne, by a factor of 140/[4.4 ± (0.9–1)] ≃ 44 ± 12. With

J.P.Meyer, D. Ellison L. Drury : 1997 ApJ

In the 2000ies, with full stellar models with mass loss, the « dilution factor » of the WR winds (Ne22 rich) with normal ISM (Ne22/Ne20 -normal) was evaluated to ~4 ***(Binns+2005)***

For some obscur reason, it was accepted that this occurs in superbubbles… ***(Higdon&Lingelfelter 2003,2005)***

Are GCR accelerated in superbubbles ?

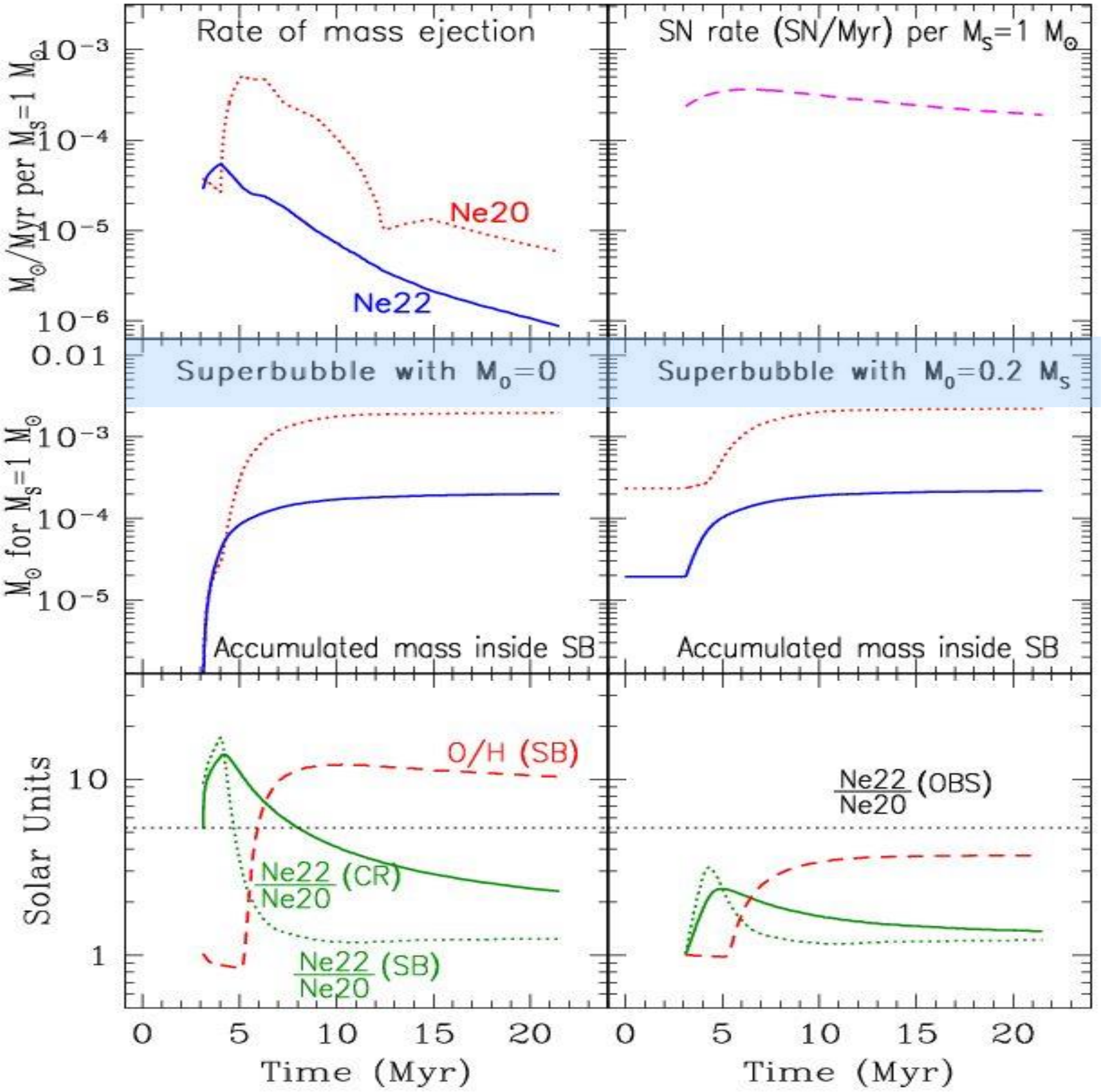
NP2012a : I DON'T THINK SO

Both Ne20 and Ne22 are produced
by massive stars (SN ejecta + winds)
and their ratio in a SB should be ~solar

In a superbubble, the time integrated Ne22/Ne20 ratio **remains as high as in GCR ONLY for a short early period** (when strong 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 inside the superbubble is expected supersolar (not observed)*

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



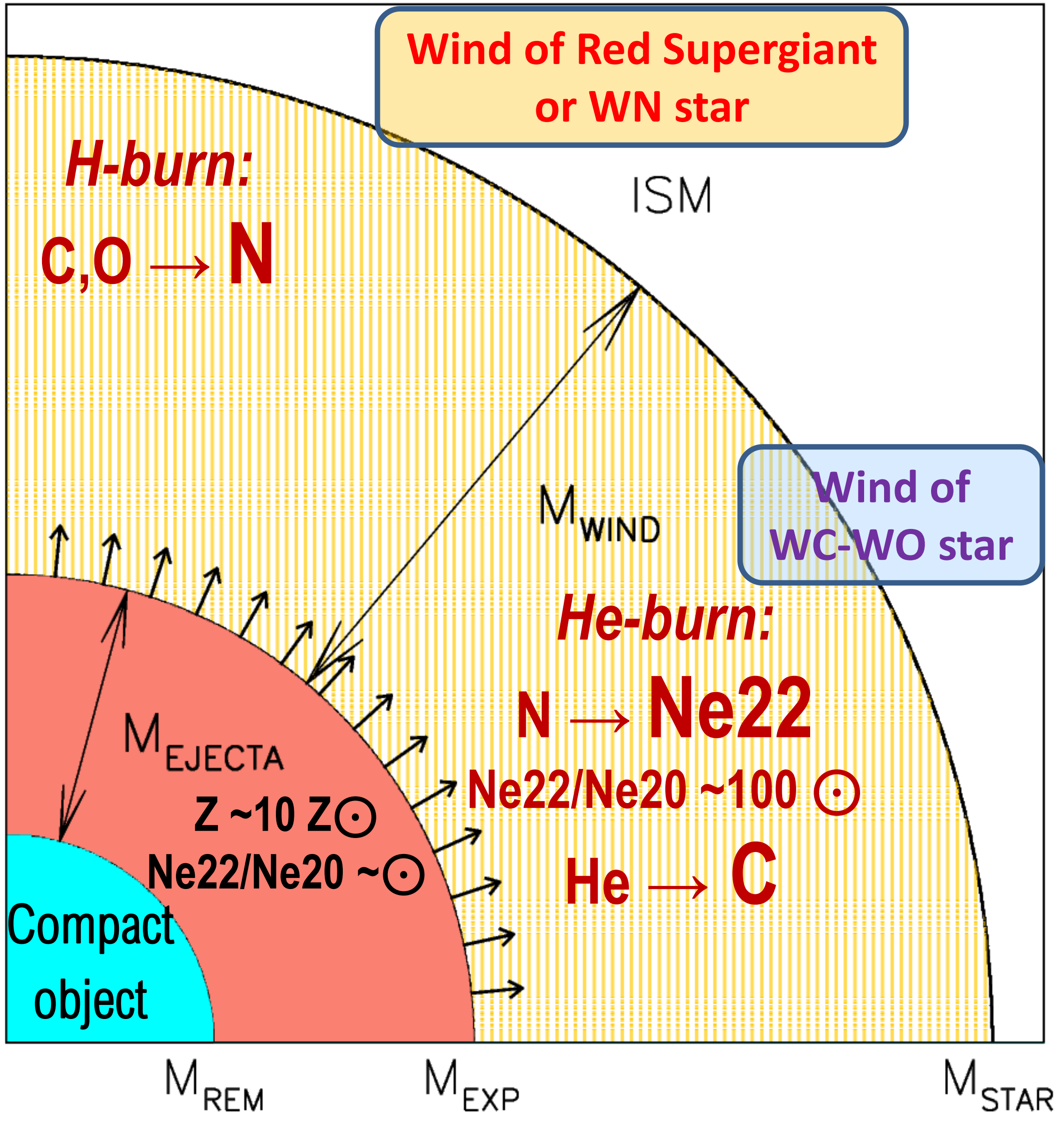
Are GCR accelerated in massive star winds ?

NP2012a: I THINK SO (BUT...)

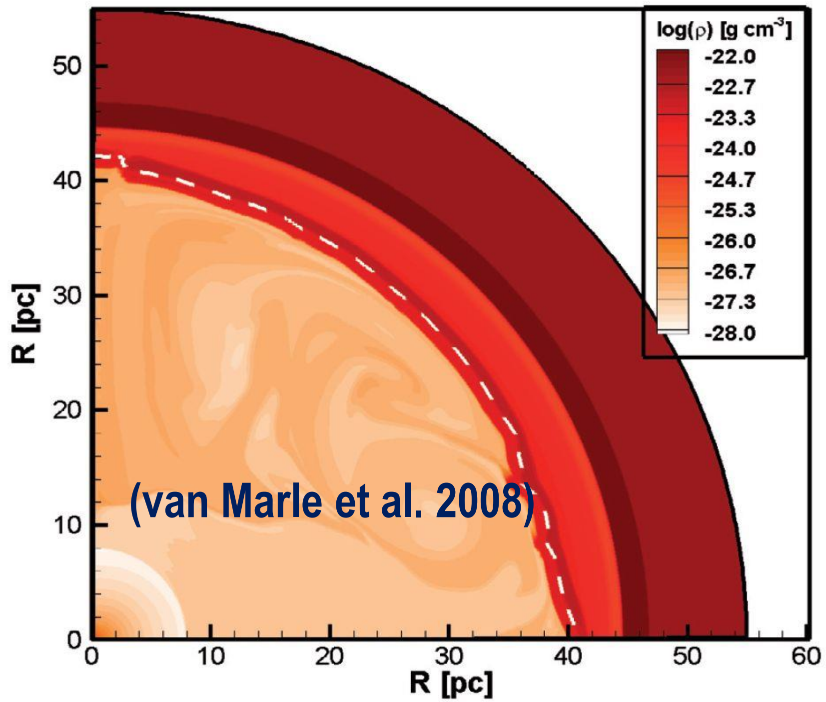
A forward shock (FS) is launched at M_{EXP}
and runs through the wind of the star,
which is enriched with products
of H- (Red SG or WN star)
and/or He- burning (WC-WO star)
and then – perhaps - in the interstellar medium.

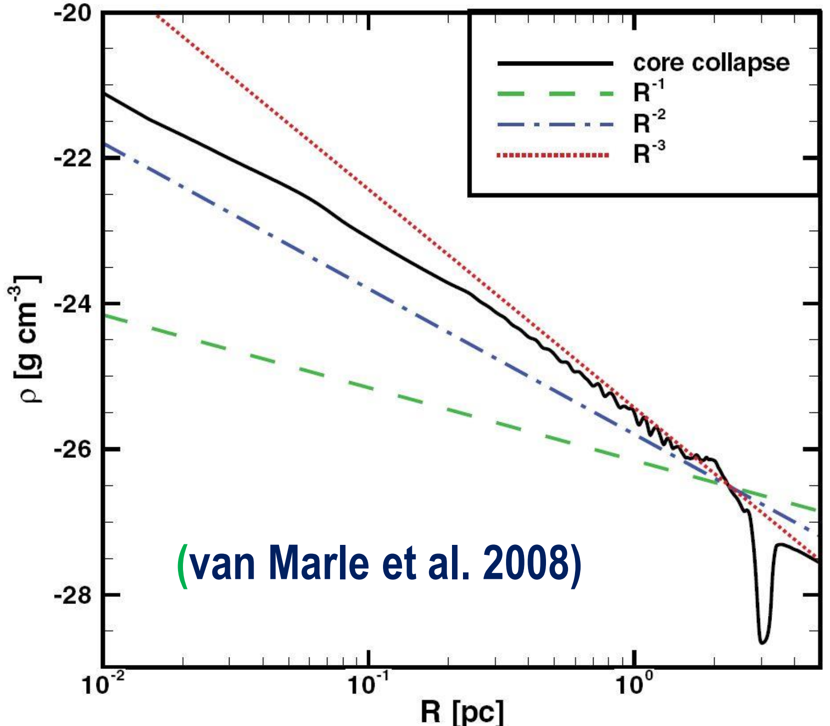
ASSUMPTION: Particle acceleration starts in the beginning of the Sedov-Taylor (ST) phase, when $M_{SWEPT} \sim M_{EJECTA}$

BUT: When does it stop ?



ASSUMPTION: 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.





Propagation of forward shock into a stellar wind of profile $\rho(r) \propto r^{-2}$

(*Ptuskin and Zirakhasvili 2005, Caprioli 2011*)

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

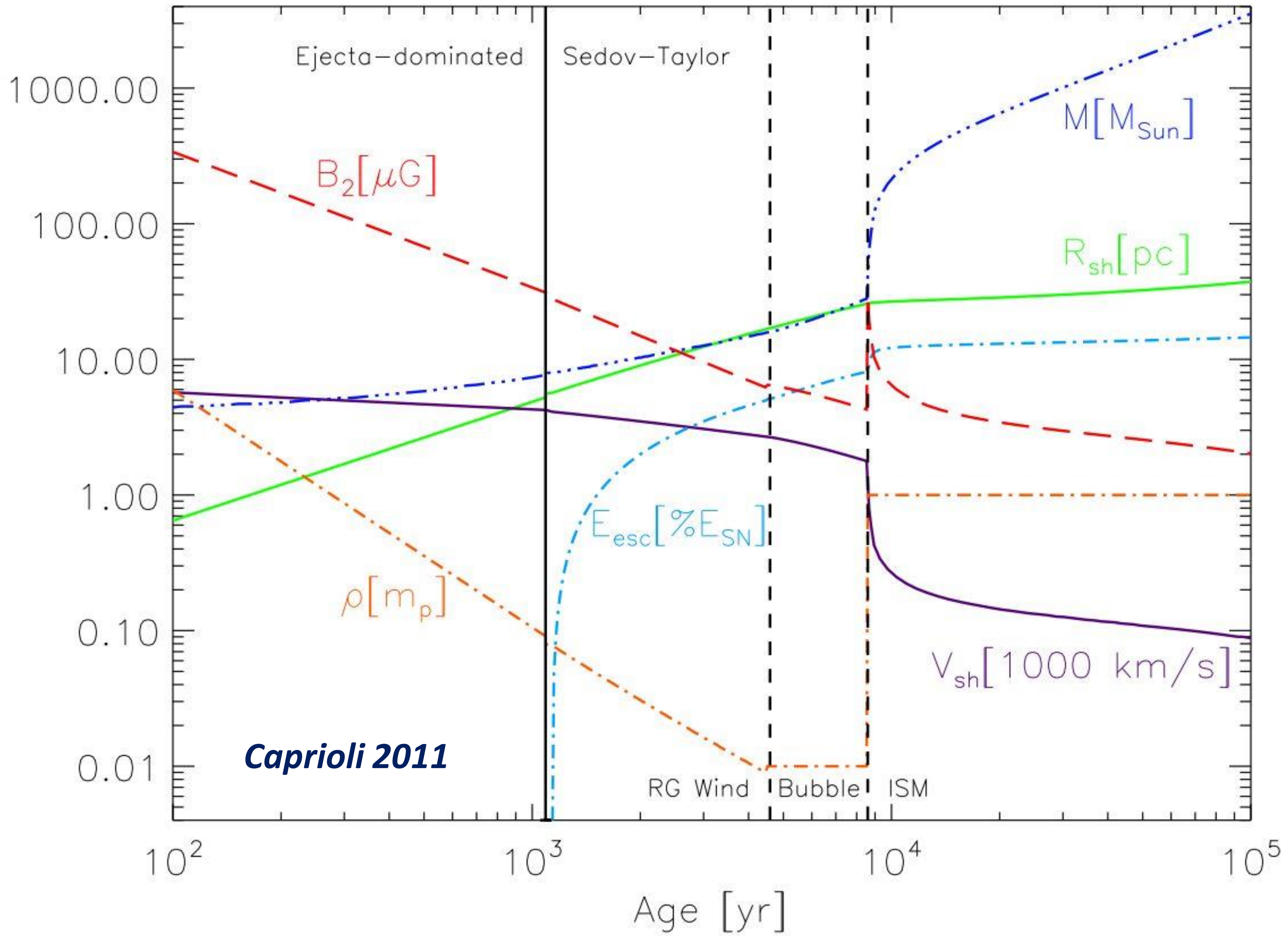
$$V_{\rm sh}(R_{\rm sh}) \simeq 8800 R_{\rm sh,pc}^{-1/7} \left(\frac{\mathcal{E}_{51}^{7/2} V_{w,6}}{\dot{M}_{-5,\odot} M_{\rm ej,\odot}^{5/2}} \right)^{1/7} \quad {\rm km\ s^{-1}}$$

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

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

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

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



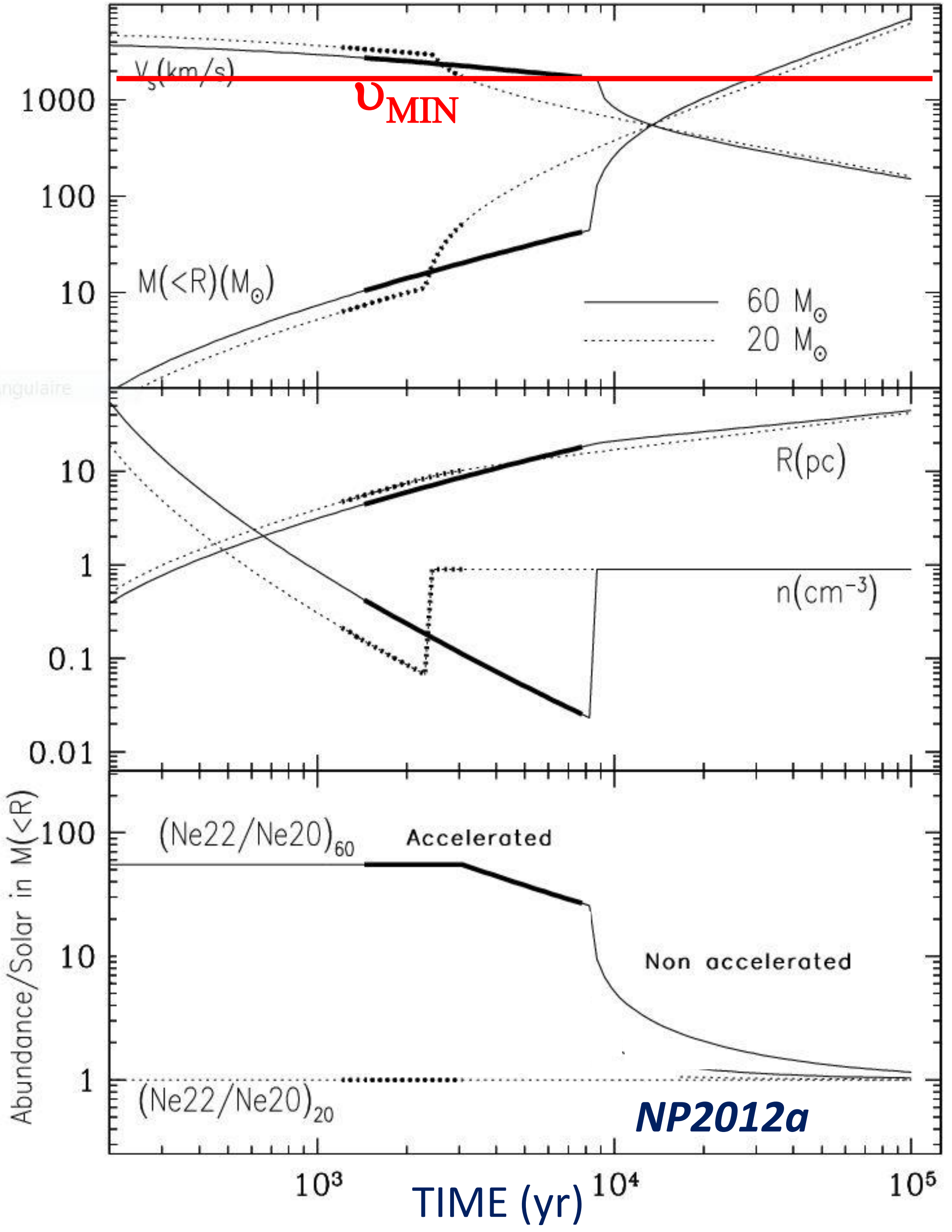
Ejecta−dominated
Sedov−Taylor
M[M_Sun]
B_2[μG]
R_sh[pc]
E_esc[%E_SN]
ρ[m_p]
V_sh[1000 km/s]
Caprioli 2011
RG Wind
Bubble
ISM
1000.00
100.00
10.00
1.00
0.10
0.01
10^2
10^3
10^4
10^5
Age [yr]

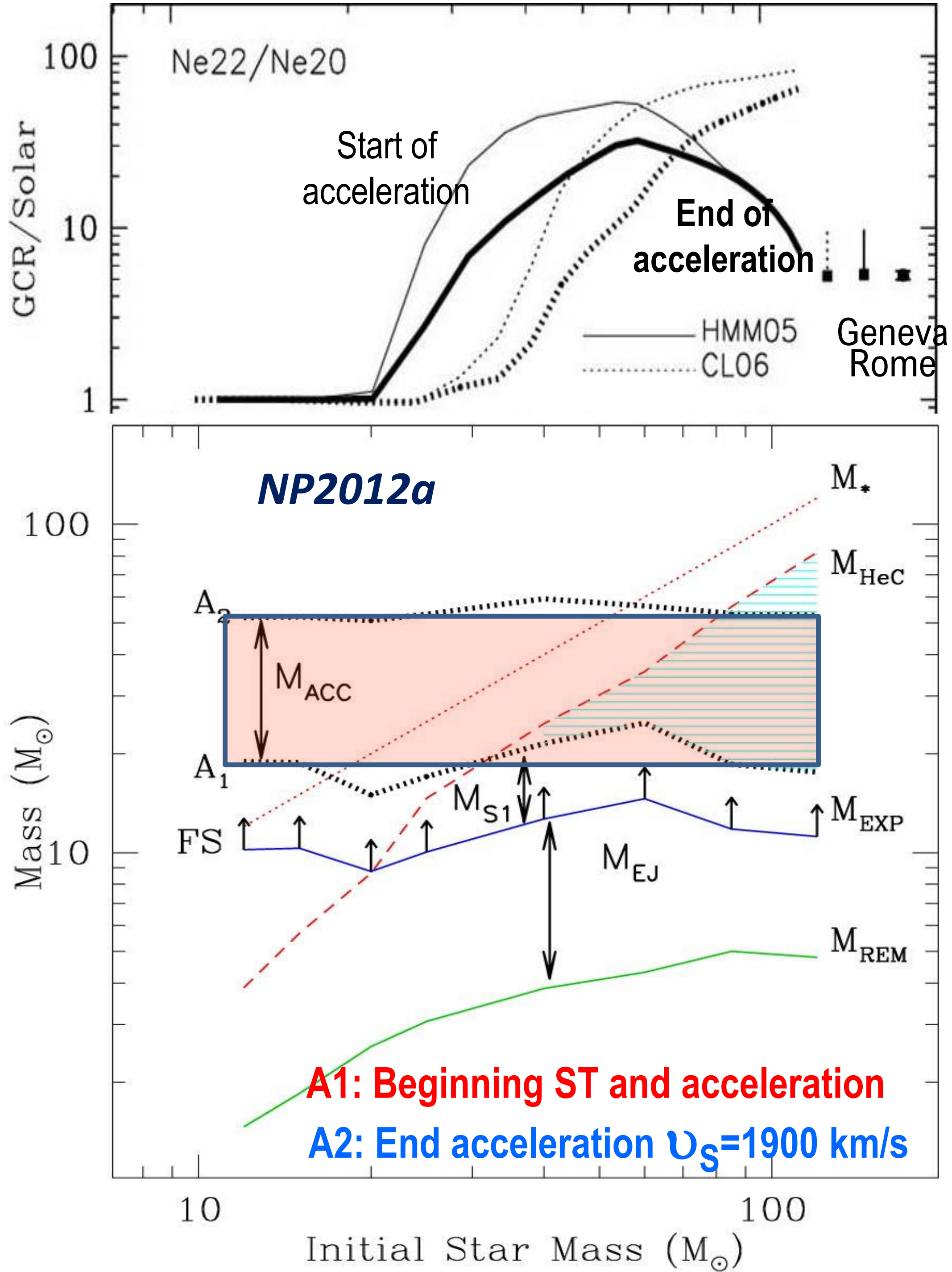
Particle acceleration starts in beginning of ST phase and is assumed here to stop when the velocity of the shock drops to υ_{MIN} ~1900 km/s chosen such as **the IMF averaged ratio Ne22/Ne20 of accelerated particles equals the observed one**

$$\mathbf{R = (Ne22/Ne20)_{GCR} = 5.3 \odot}$$

Note: here, efficiency of acceleration assumed constant

If assumed velocity dependent ($\propto \upsilon^2$) allowed υ_{MIN} is found smaller (1600 km/s) and allowed region of acceleration larger





The IMF averaged Ne22/Ne20 of accelerated particles equals the observational one for GCR sources **R = Ne22/Ne20)$_{GCR}$ = 5.3 ⊙** for **υ_{MIN}=1900 km/s** (for rotating star models of Geneva)

The composition of that material is :
stellar Envelope **(~solar with high C,N and Ne22/Ne20)**
plus a few times ISM **(=solar)**
(~ 20% WR Envelope + 80% ISM)

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**)

Efficiency of particle acceleration: $$W = \frac{m_{AP}}{M_{ACC}}$$

$$m_{AP} = \sum N_i A_i m_P,$$

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

$$Q(E) \propto \frac{p^{-s}}{\beta} \exp(-E/E_C)$$

Efficiency of particle acceleration: W = a few 10^{-6} to 10^{-5}

We estimated the **particle acceleration efficiency** in both SN shocks and WTS to be **of the order of 10^{-5}**, which is consistent with the prediction of the diffusive shock acceleration theory for strong shocks *(Tatischeff+2021)*

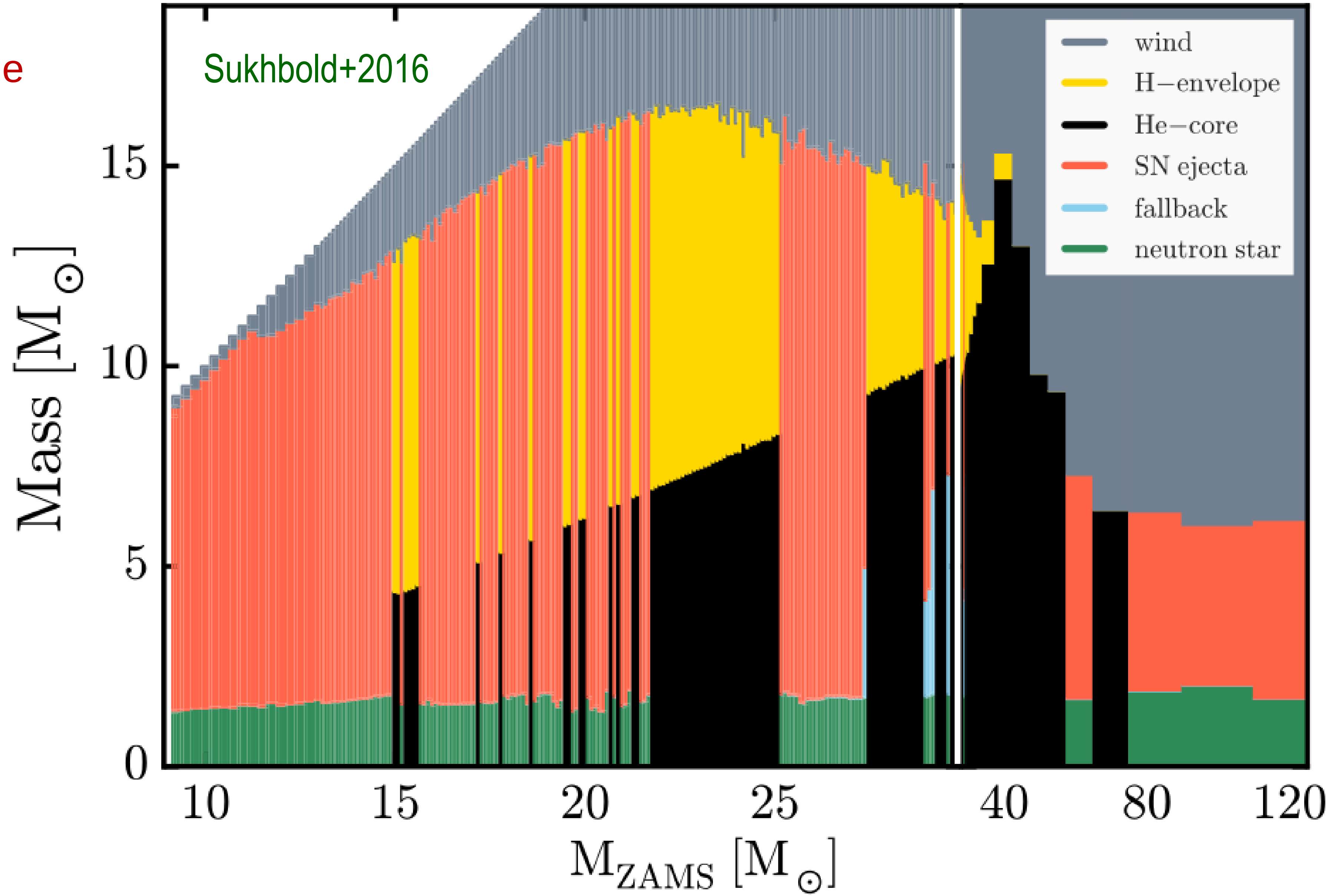
The fate of massive stars

Not all massive stars explode

Some of them end in black holes with no explosion

But some, even among the most massive ones may explode, leaving a neutron star

And they all have stellar winds

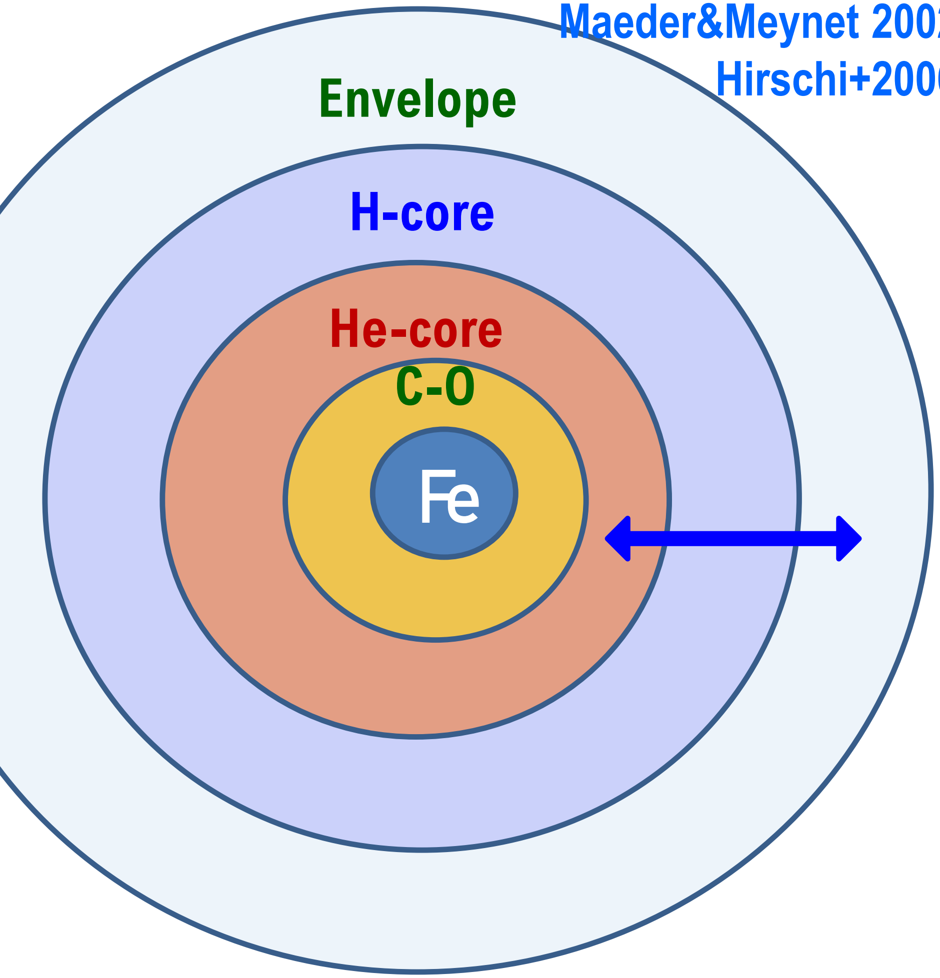


Back to Be evolution

Stellar Rotation stronger at low Z

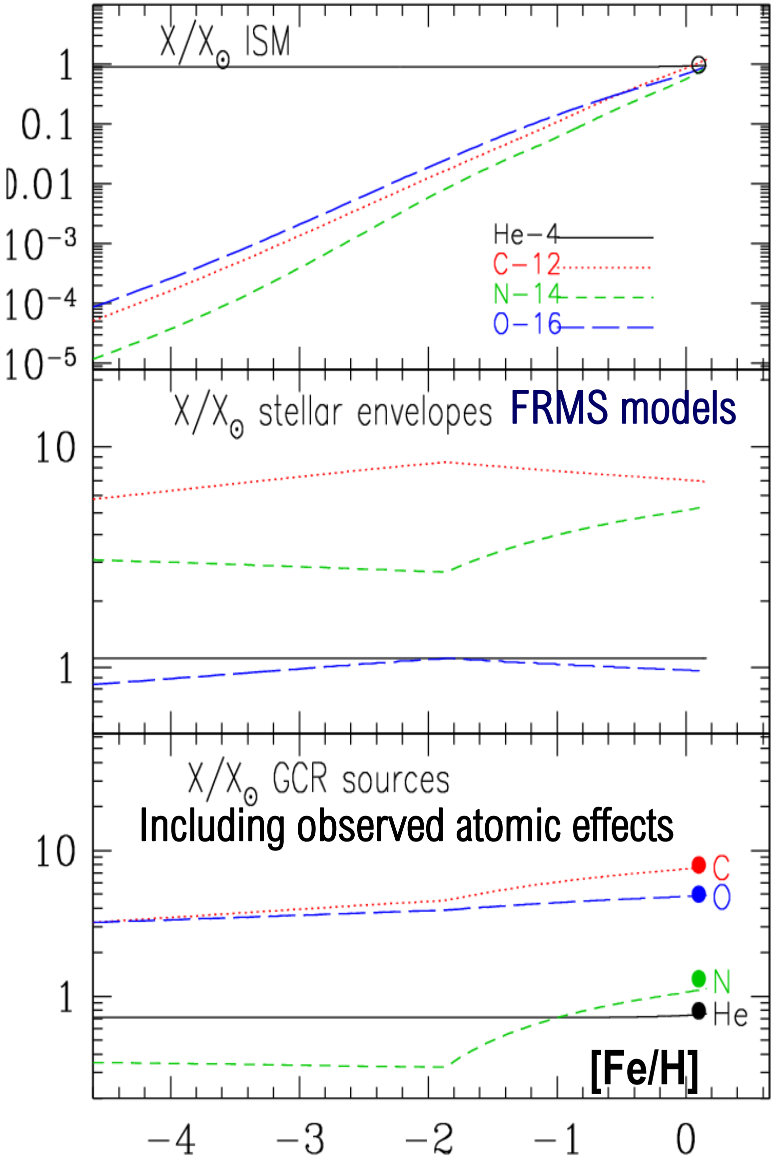
It mixes protons in He-burning regions
as well as products of H- and He-burning,

Maeder&Meynet 2002
Hirschi+2006

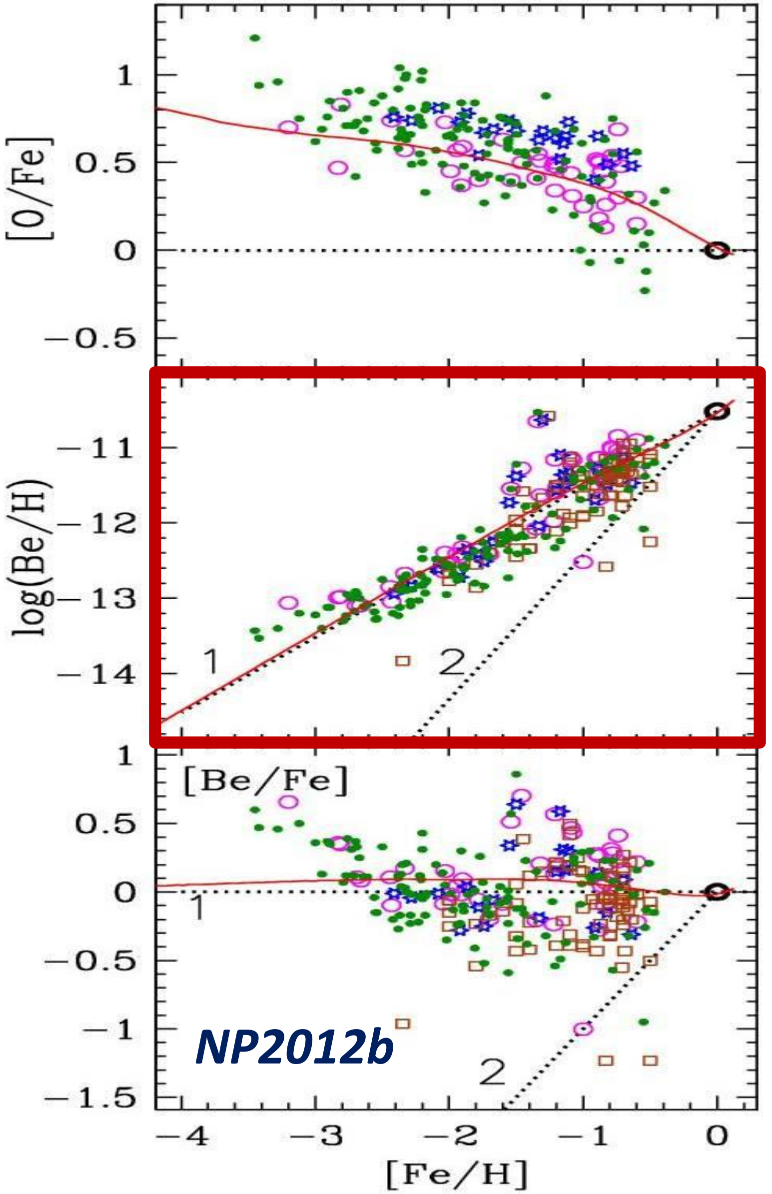


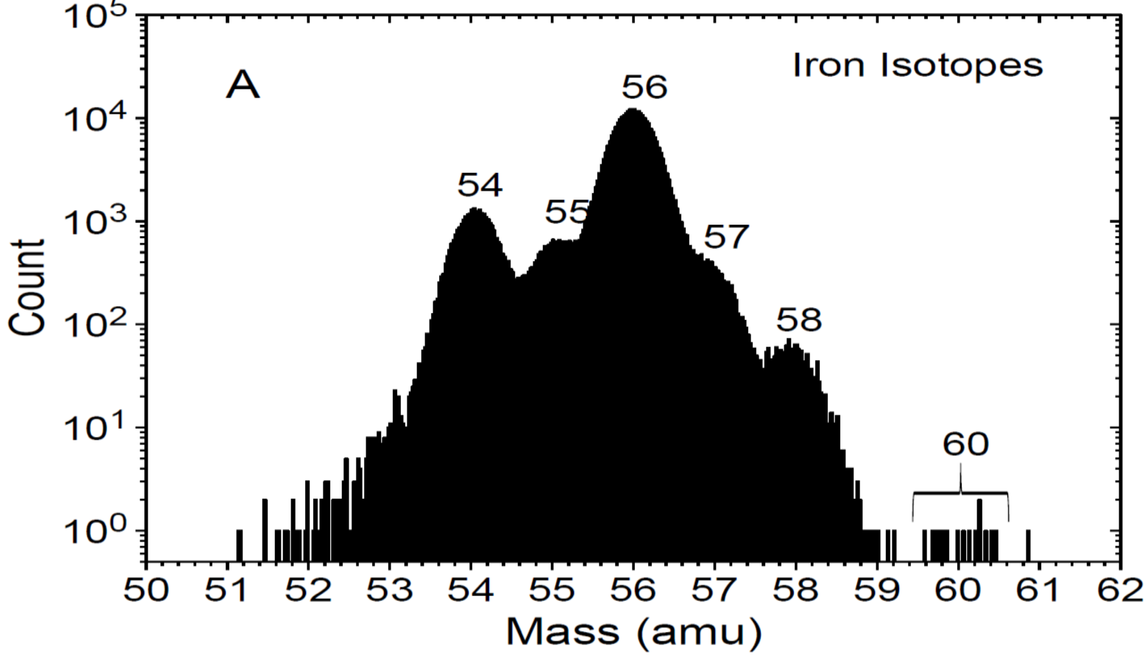
It boosts production of CNO, F, Ne22
and turns « *secondary* » elements
into « *quasi-primary* » ones (e.g. N, F)

NP2012b:Self-consistent calculation of evolving ISM composition AND of GCR accelerated in fast rotating massive star winds



"Physically motivated" GCR composition and proper GCR/SN energetics, produce naturally primary Be

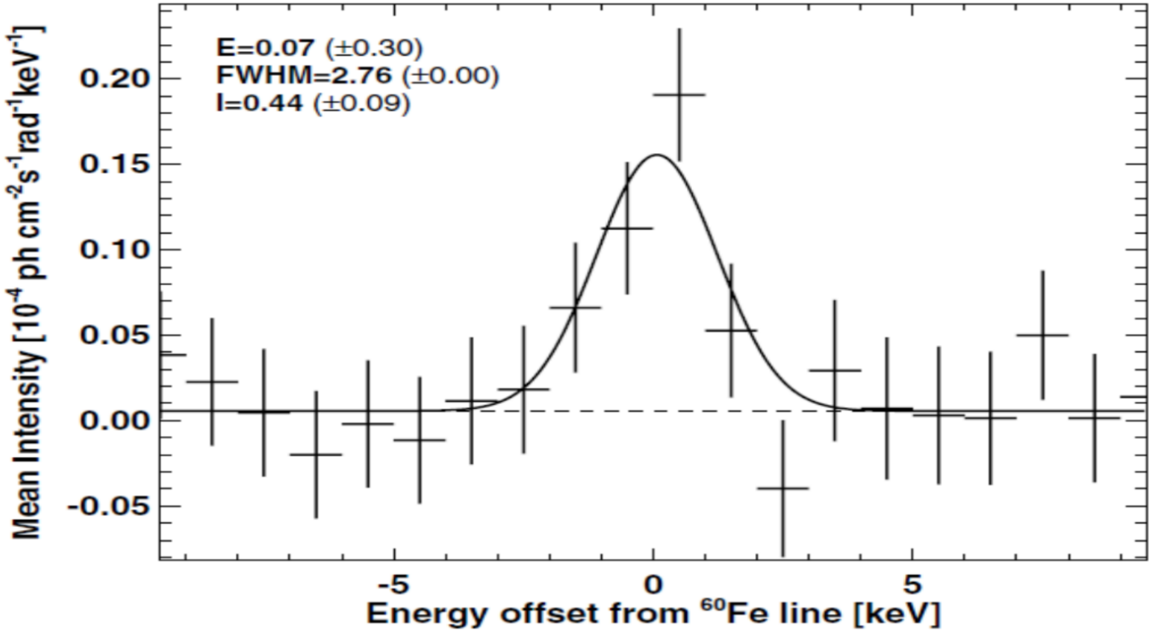




Radioactive Fe60 (τ~2.5 My) in GCR

GCR source Fe60/Fe56 ~ 10^{-4} *(Binns+2016)*

(see also: Morlino&Amato 2019)

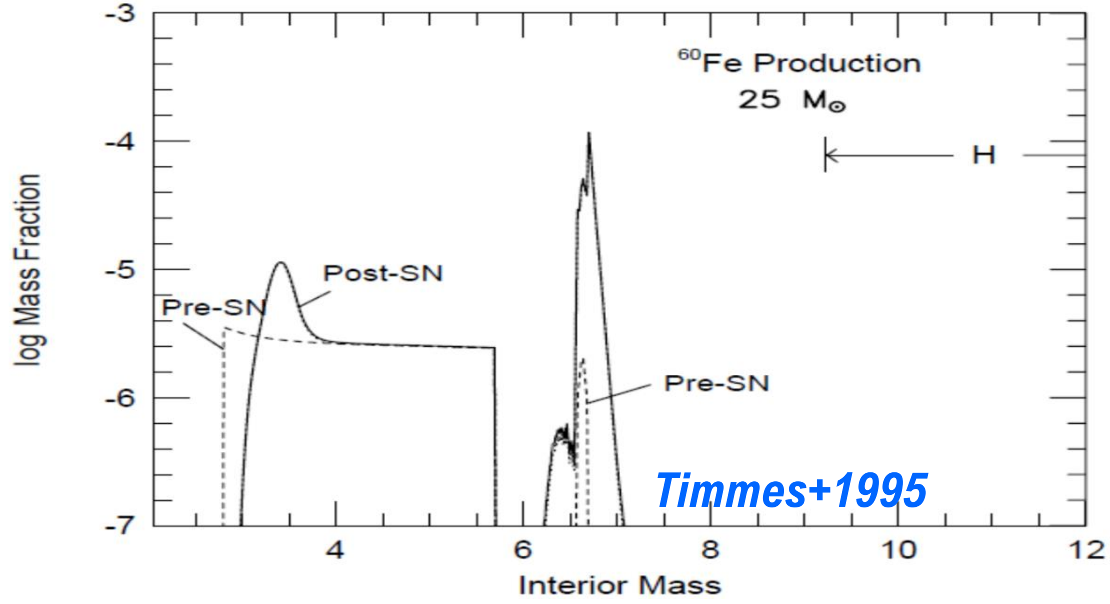


ISM (γ-rays): Fe60/Fe56 ~ 10^{-7}

(Wang +2015)

Fe60 is produced by explosive nucleosynthesis in the *inner layers of massive stars,* by neutron captures

<Fe60/Fe56>~2 10^{-3}



Timmes+1995

Constraints on GCR acceleration sites from Ne22 and Fe60

Ne22:

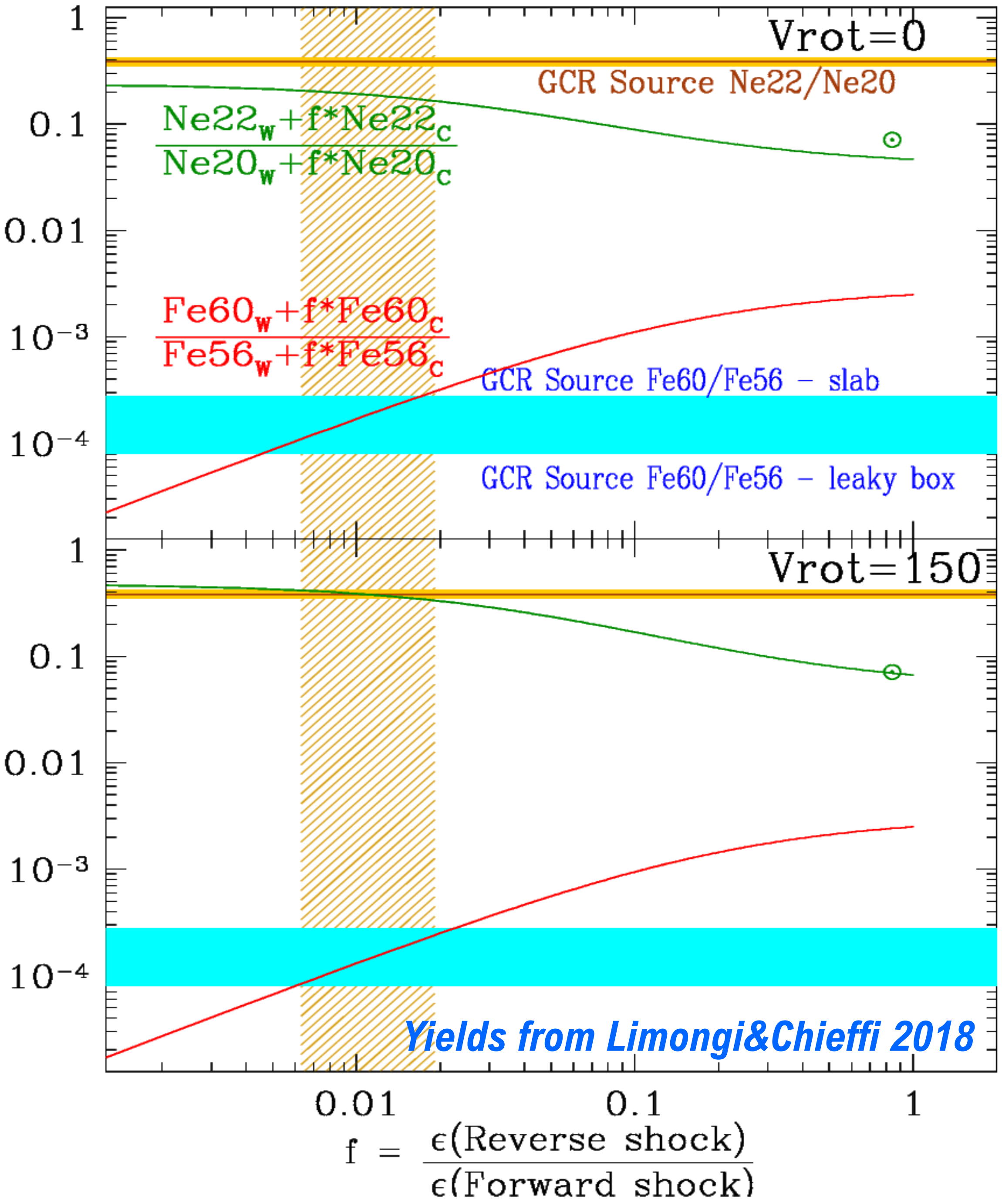
- Mostly massive star winds
- Little amount of core material required
- Little dilution with ISM required
  (to avoid Ne20 from core and ISM)

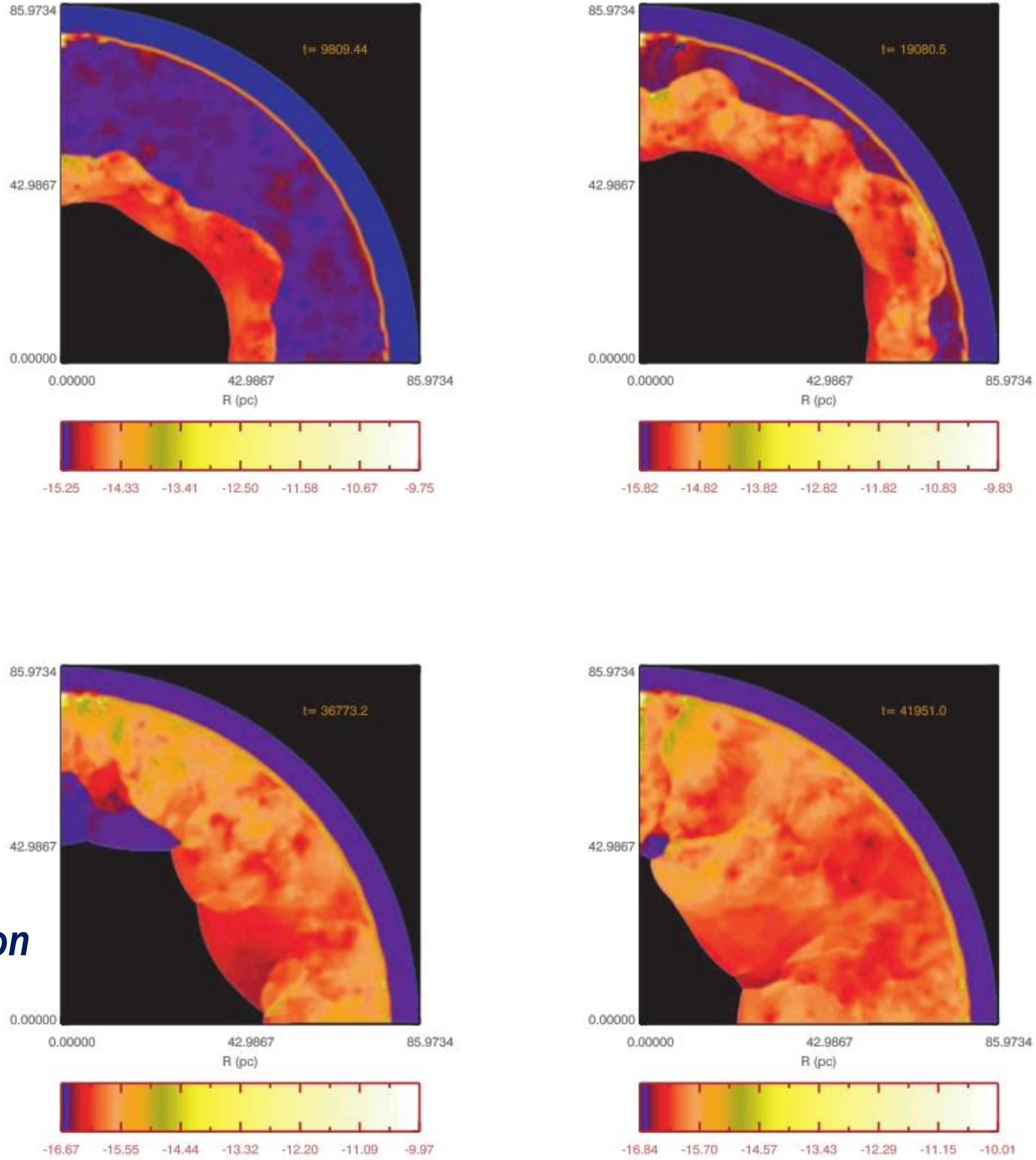
Fe60:

- Mostly core material
- More dilution with normal matter allowed

Perhaps possible:

Efficient forward shock through Ne22 wind, reflected in wind shell and accelerating core Fe60 (and Ne20) with much smaller efficiency

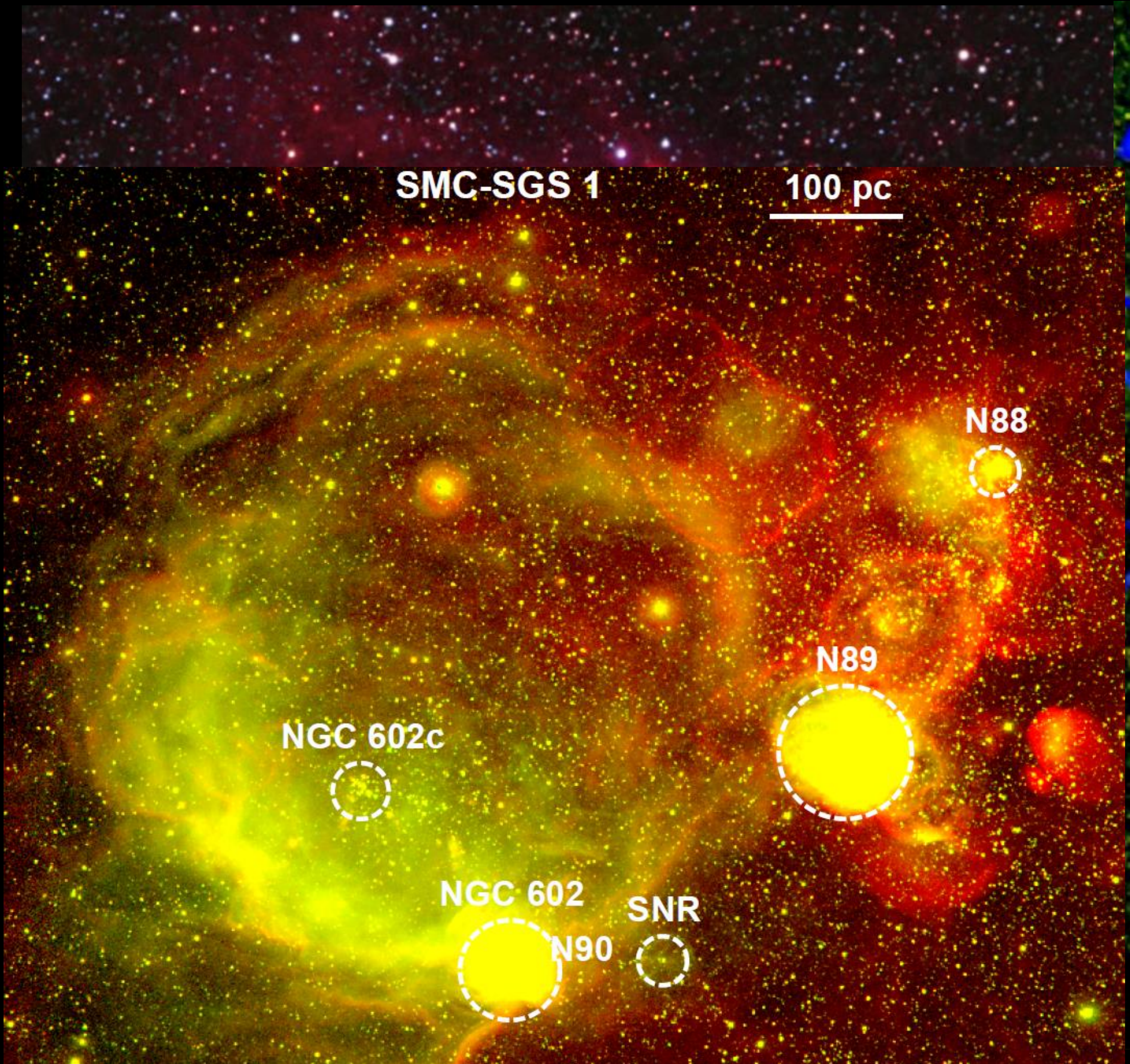


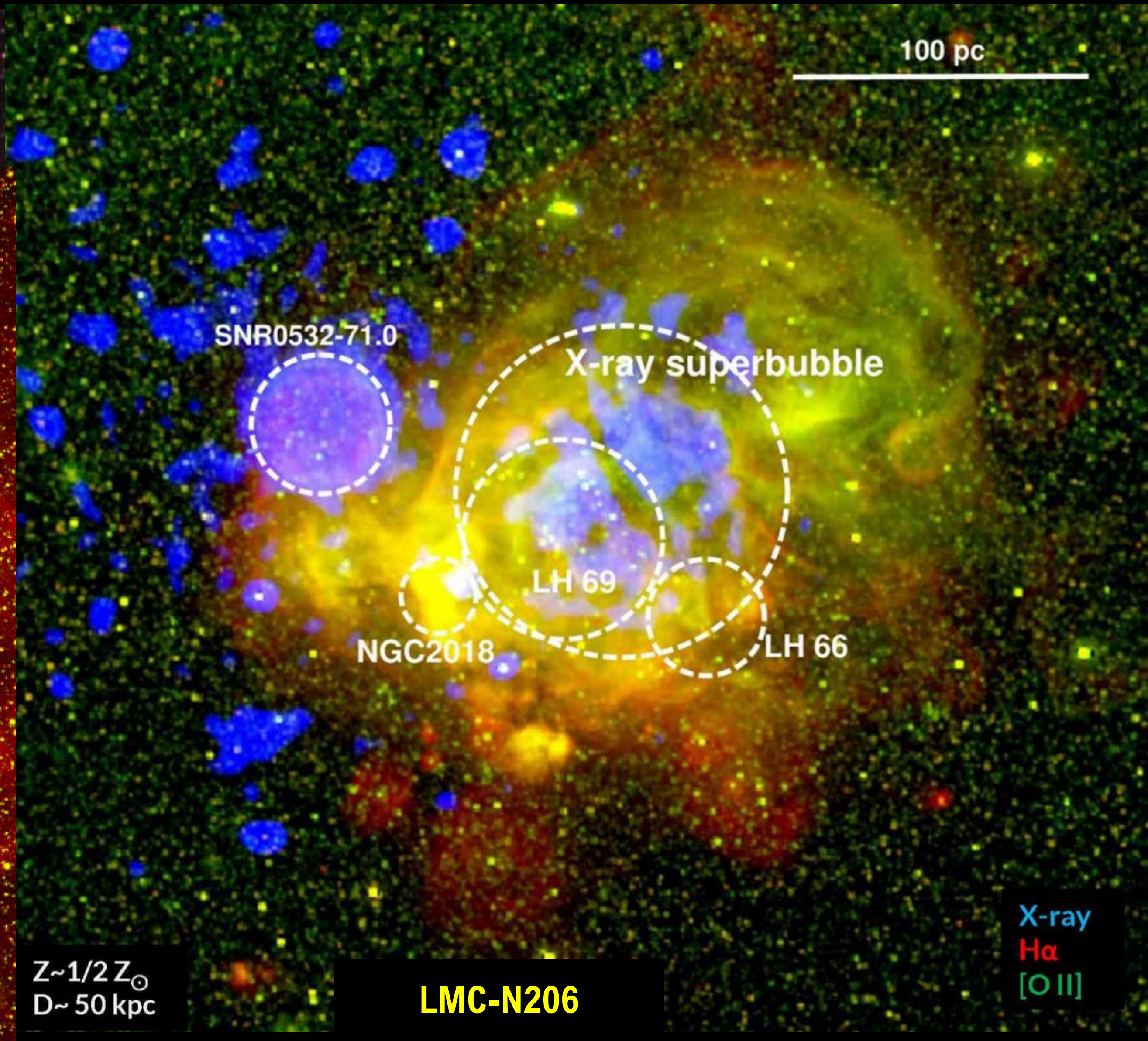


1D and 2D simulations suggest that
the forward SN shock propagating
In the wind nebula of a massive star
is reflected when reaching the wind shell,
accelerating particles inside the wind bubble
(Dwarkadas 2007),

perhaps more efficiently in the low density hot region of the wind (Ne22-rich) than in the higher density, cold inner region (Ne20 and Fe60-rich) ????

Superbubbles





Tatischeff+2021 **The origin of Galactic cosmic rays as revealed by their composition**

ABSTRACT

Galactic cosmic rays (GCRs) are thought to be accelerated in strong shocks induced by massive star winds and supernova explosions sweeping across the interstellar medium. But the phase of the interstellar medium from which the CRs are extracted has remained elusive until now. Here, we study in detail the GCR source composition deduced from recent measurements by the AMS-02, Voyager 1, and SuperTIGER experiments to obtain information on the composition, ionization state, and dust content of the GCR source reservoirs. We show that the **volatile elements** of the CR material are mainly accelerated from a plasma of temperature 2 MK, which is typical of the hot medium found in Galactic **superbubbles** energized by the activity of massive star winds and supernova explosions. Another GCR component, which is responsible for the **overabundance of 22Ne**, most likely arises from **acceleration of massive star winds in their termination shocks**. From the CR-related gamma-ray luminosity of the Milky Way, we estimate that the ion **acceleration efficiency** in both supernova shocks and wind termination shocks is **of the order of 10−5**. The GCR source composition also shows evidence for a preferential acceleration of refractory elements contained in interstellar dust. **We suggest** that the **GCR refractories are also produced in superbubbles**, from shock acceleration and subsequent sputtering of dust grains continuously incorporated into the hot plasma through **thermal evaporation of embedded molecular clouds**. Our model explains well the measured abundances of all primary and mostly primary CRs from H to Zr, including the overabundance of 22Ne.

Tatischeff+2021

	Model 1	Model 2	Model 3	Model 4	Model 5
GCR gas source of SC compo.	70 per cent WNM, 30 per cent WIM	SB	SB	60 per cent SB, 28 per cent WNM, 12 per cent WIM	60 per cent SB, 28 per cent WNM, 12 per cent WIM
^{22}Ne-rich GCR gas source	Accelerated winds	Winds in SB	Accelerated winds	Winds in SB	Accelerated winds
SB temperature $\log(T_{SB})$ [a]	–	6.50 ± 0.25	>6.45	$6.5^{+0.3}_{-0.2}$	>6.35
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}$ [b]	33.8 ± 13.4	26.0 ± 13.2	17.9 ± 9.7	27.0 ± 13.2	22.8 ± 10.6
W-R wind contribution x_w [c]	10.3 per cent	48.9 per cent	(5.1–6.1) per cent	$(55.6^{+1.3}_{-0.3})$ per cent	(7.3–7.9) per cent
χ^2_{min}(GCR dust source)[d]	24.6	26.9	25.9	26.0	24.8
χ^2_{min}(GCR gas source)[e]	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{SB})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}$ [b]	33.8 ± 13.4	23.2 ± 9.4	20.2 ± 7.2	24.6 ± 10.2	24.4 ± 9.2
W-R wind contribution x_w [c]	10.3 per cent	48.9 per cent	5.9 per cent	56.0 per cent	7.7 per cent
χ^2_{min}(GCR dust source)[d]	24.6	28.0	26.9	26.4	25.0
χ^2_{min}(GCR gas source)[e]	24.7	32.3	13.2	32.4	18.3

[a] Best-fitting values with 1σ errors of the SB temperature ($\log(T_{SB})$ with T_{SB} in K) as obtained from the GCR gas source data.

[b] Weighted mean of the best-fitting values obtained from the GCR gas and dust source data.

[c] Required mixing of W-R wind material with the reservoir of SC composition to get $^{22}Ne/^{20}Ne = 0.317$ in GCRs (Boschini et al. 2020).

[d] Minimum χ^2 from a least-squares fit of the $A_{dust}(f_d)$ data (equation 13) to a straight line.

[e] Minimum χ^2 from a least-squares fit of the $B_{gas}(f_g)$ data (equation 14) to a straight line.

Accelerated WR winds play a key role in understanding GCR composition

Origin of the 22-Ne-rich GCR source

The high 22Ne/20Ne ratio in the GCR composition has been used as an argument that GCRs originate in SBs, based on the assumption that SNR shocks within SBs should accelerate a medium enriched by W-R winds from the most massive stars of the parent OB association

Another problem faced by the SB model for the origin of GCR 22Ne is that it requires that the SB gas is strongly enriched in W-R wind material, at the level of $x_W \approx 50$ per cent (Table 4), which is not supported either by theory or by observations.

Moreover, such a level of mixing would imply that SB gas has a highly non-solar composition, which is not supported by X-ray observations. The latter show on the contrary that SB plasmas have a metallicity close to the ISM average.
Note NP: *OK for observations, but what is the metallicity of a SB in a SB model ? Close to SN ejecta or to ISM ? If the latter, then how to explain primary GCR CNO composition for evolution of Be as done by Ramaty+ ?*

The GCR composition data do not allow us to distinguish if the 22Ne-rich material is accelerated in winds of individual massive stars born in loosely-bound clusters or in collective WTSs formed by the overlap of stellar wind bubbles in massive and compact clusters

Superbubbles CANNOT BE at the origin of GCR Ne22/Ne20 because they SHOULD have Ne22/Ne~$\odot$ ***(NP2012a)***

Superbubbles cannot be the sources of the bulk of GCR Ne22

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>2/3 of Galactic WR stars are isolated, not in OB associations or clusters

Unlocking Galactic Wolf–Rayet stars with *Gaia* DR2 – II. Cluster and association membership

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ABSTRACT

Galactic Wolf–Rayet (WR) star membership of star-forming regions can be used to constrain the formation environments of massive stars. Here, we utilize *Gaia* DR2 parallaxes and proper motions to reconsider WR star membership of clusters and associations in the Galactic disc, supplemented by recent near-infrared studies of young massive clusters. We find that only 18–36 per cent of 553 WR stars external to the Galactic Centre region are located in clusters, OB associations or obscured star-forming regions, such that at least 64 per cent of the known disc WR population are isolated, in contrast with only 13 per cent of O stars from the Galactic O star Catalogue. The fraction located in clusters, OB associations or star-forming regions rises to 25–41 per cent from a global census of 663 WR stars including the Galactic Centre region. We use simulations to explore the formation processes of isolated WR stars. Neither runaways, nor low-mass clusters, are numerous enough to account for the low cluster membership fraction. Rapid cluster dissolution is excluded as mass segregation ensures WR stars remain in dense, well-populated environments. Only low-density environments consistently produce WR stars that appeared to be isolated during the WR phase. We therefore conclude that a significant fraction of WR progenitors originate in low-density association-like surroundings which expand over time. We provide distance estimates to clusters and associations host to WR stars, and estimate cluster ages from isochrone fitting.

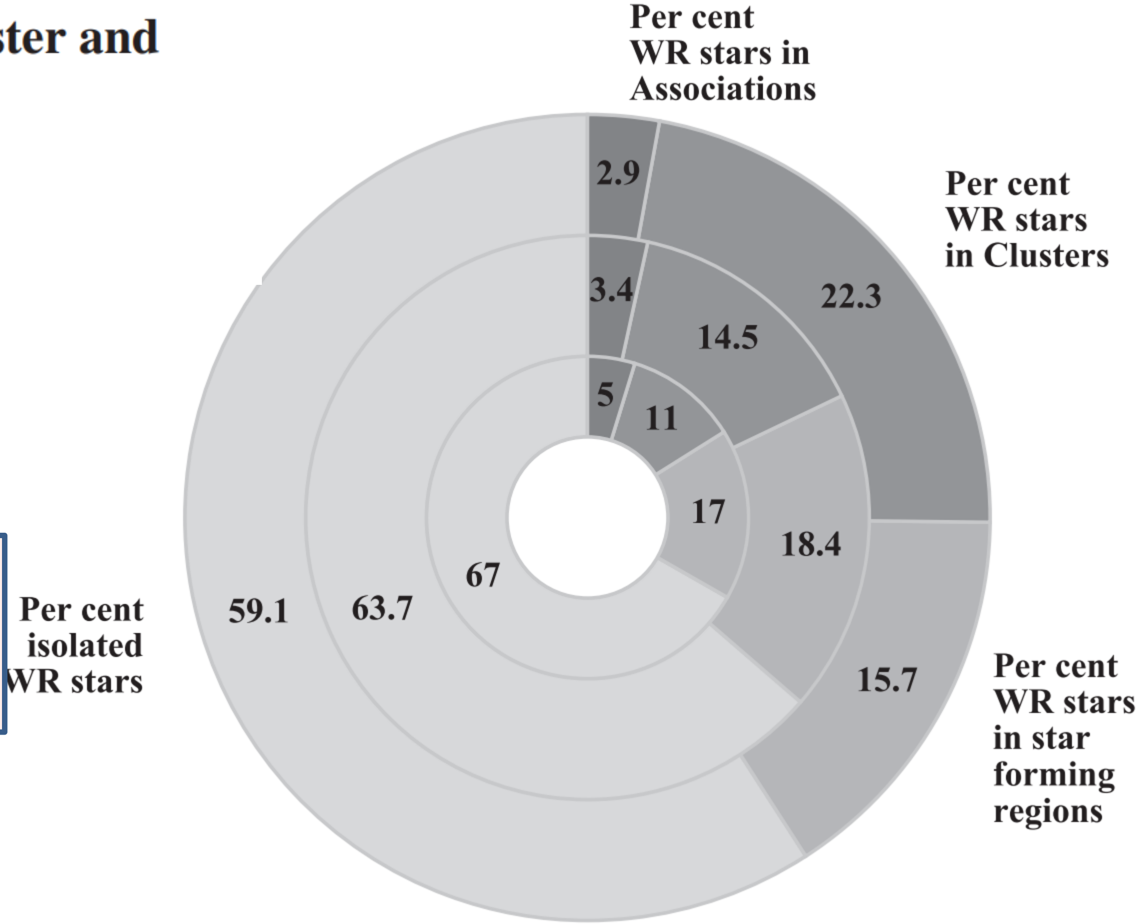

Figure 7. Doughnut chart showing the percentages of the WR stars with *Gaia* DR2 distances in clusters, associations, and star-forming regions and isolated environments (inner, 379 stars), *Gaia* plus embedded Galactic disc WR stars (middle, 553 stars), *Gaia* plus all embedded WR stars (outer, 663 stars).

Origin of the GCR refractories from dust grains

The GCR refractory elements most likely originate from the acceleration and sputtering of dust grains in SNR shocks.

The refractory element injection rate is expected to be less efficient in SBs than in the warm and denser ISM by a factor t_loss/t_SNR of the order of 6 (depending on the grain properties and the ambient medium density.

GCR refractories may also be significantly produced in the warm ISM. As we found that **SNe exploding outside SBs** can contribute up to 30 per cent to the GCR volatile composition, **these objects may in fact be the main source of the fast refractory elements**, depending on the relative efficiencies of dust acceleration in the different ISM phases

More work is needed to refine the grain acceleration model in the light of current knowledge about both interstellar dust and diffusive shock acceleration, and apply it to the different phases of the ISM.

We suggest that the GCR refractories could be mainly produced in SBs, ***if dust is continuously replenished in the SB interior t****hrough thermal evaporation of embedded molecular clouds swept up by SN shocks

Alternatively, the GCR refractories could be predominantly produced in SN shocks propagating in the WIM.

Superbubbles are not necessary to explain the GCR refractories

Origin of the GCR volatiles in Galactic superbubbles

We found that the CR volatiles are mostly accelerated in Galactic SBs, from SNR shocks sweeping up a plasma of temperature 2 × 106 K. **SNRs in the warm ISM contribute to the GCR volatile composition for less than 28 per cent,** whereas about 40 per cent of Galactic SNe occur in this phase and not in SBs.

This suggests that the limitation of GCR production in the WNM due to the NRF effect **is not enough to explain why the bulk of the GCR volatiles come from SBs. However, the relative contributions of SNRs in SBs and in the WIM depend directly on the values of V_SB s,min and V_WIM s,min , which are uncertain.**

Note NP*: Ellison, Meyer and Drury 1997 find that forward SN shocks in ISM can reproduce the A/Q dependence of volatiles*

Superbubble contribution to **GCR volatiles** is uncertain

Superbubbles are not necessary to explain the **GCR refractories**

Superbubbles cannot be the sources of the bulk of **GCR Ne22**

ARE SUPERBUBBLES MANDATORY ?

CONCLUSIONS (*subjective*)

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

2. The *bulk of GCR* may originate from material of
a) winds from individual massive (>25 Msun) WR stars (*Ne22-rich*) +
b) winds from individual less massive (<Msun) Red Supergiants *(=solar with dust grains*) +
c) little ISM *(=solar with dust grains*) +
d) fairly small (~1%) contribution of SN core ejecta (*Fe60-rich, through the reverse/reflected shock*)
Particle acceleration should be mostly made in the stellar winds, mixed with ISM (20% + 80%)
and an acceleration efficiency of ~10^{-5}

3. *If* stars at low metallicity are *fast rotating (near break-up velocity, Geneva models)*,
the resulting GCR source composition of CNO from fast rotating WR winds
can also explain the observed evolution of light elements Be and B *(NP 2012b)*

CONCLUSION (*intersubjective*)

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