L’origine des rayons cosmiques révélée par leur composition

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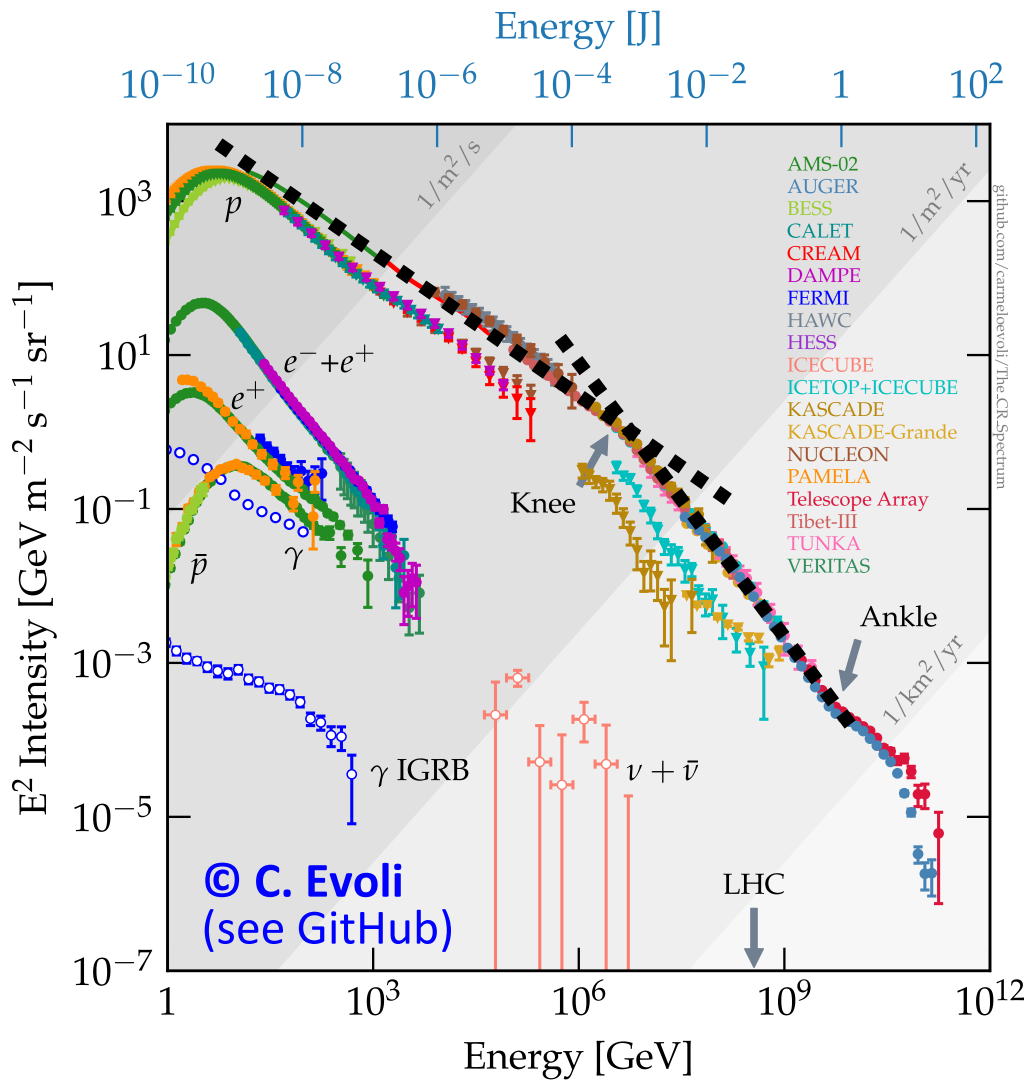
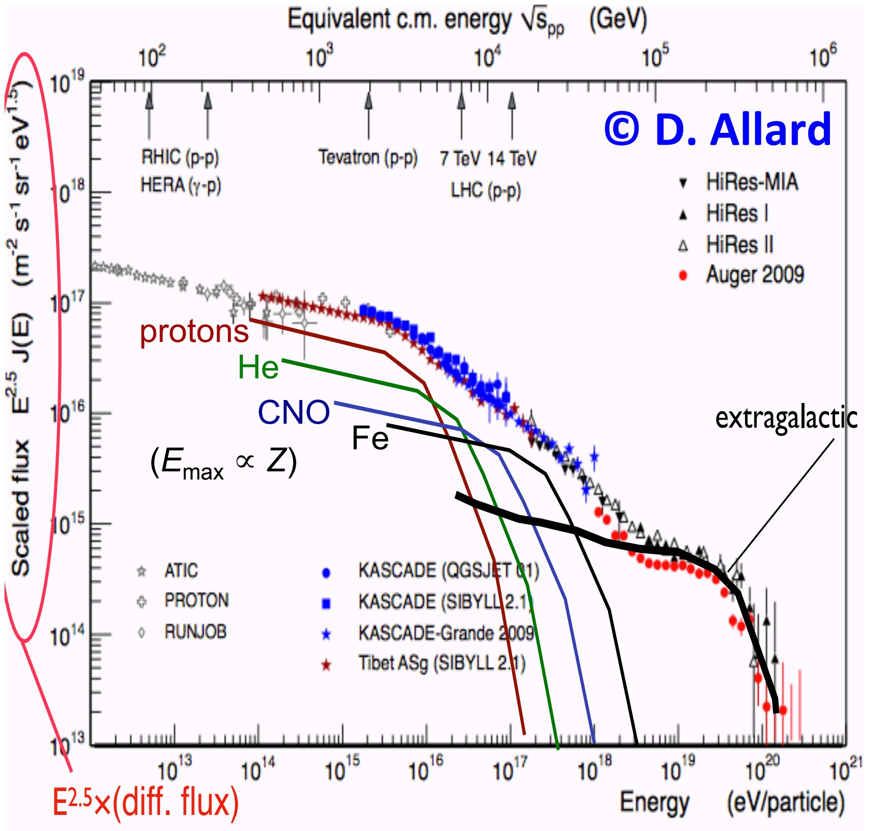
Cosmic ray spectrum

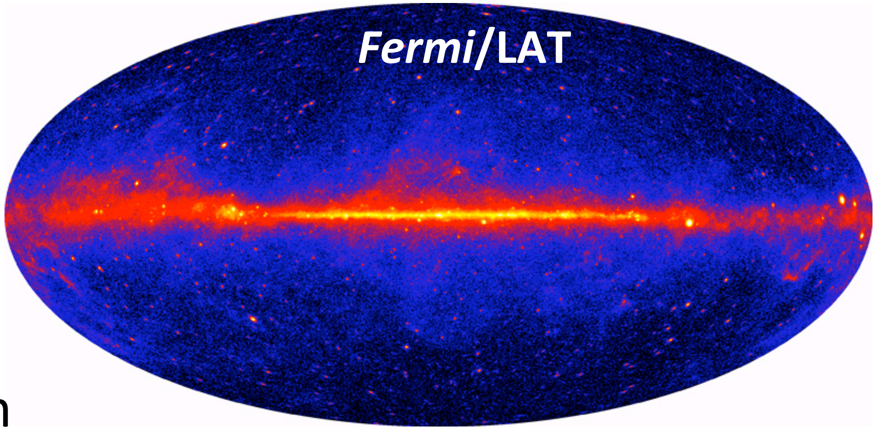




- Over 13 decades in energy and 30 decades in differential flux!
- Mostly protons (89%)

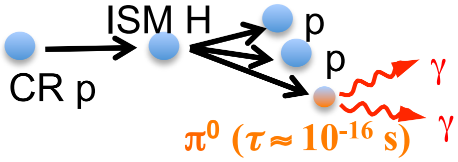
- Galactic origin up to the **“Knee” at ~3×10^{15} eV** and even probably up to **~10^{18} eV**

Galactic cosmic rays & supernovae



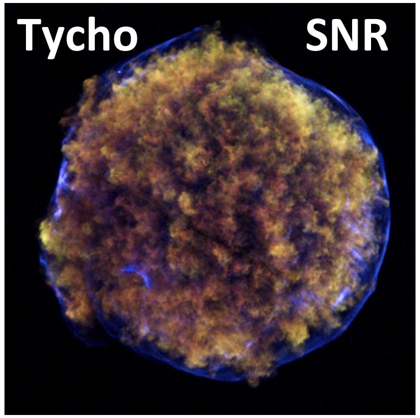
- GCRs are thought to be produced in **supernova remnants** (Baade & Zwicky 1934)

- Consistent with CR power and supernova energetics: $L_{CR} = L_\gamma / R_\gamma \sim 10^{41}$ **erg/s**, where $R_\gamma \sim 0.004$ is the γ-ray radiation yield (= efficiency) for $p + p \rightarrow \pi^0 + X$ and L_γ from π^0 decay $\sim 5\times10^{38}$ erg/s (Strong et al. 2010)



⇒ $L_{CR} \sim$ **10% of the kinetic power supplied by supernovae**

- **Diffusive shock acceleration in supernova shocks** = First-order Fermi (1949) process (Krymskii 1977; Bell 1978; Axford et al. 1978; Blandford & Ostriker 1978)



$V_{\text{SN ejecta}} \rightarrow 10^4$ km/s

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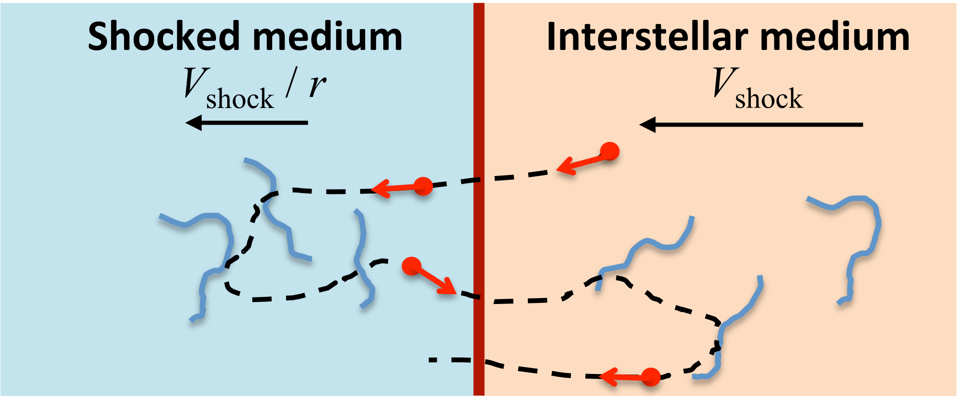
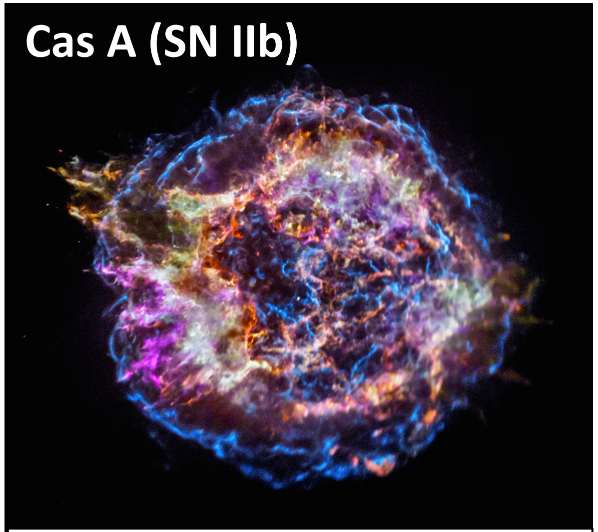
ISM sound speed $c_S \approx 100\ (T/10^6\ \text{K})^{0.5}$ km/s

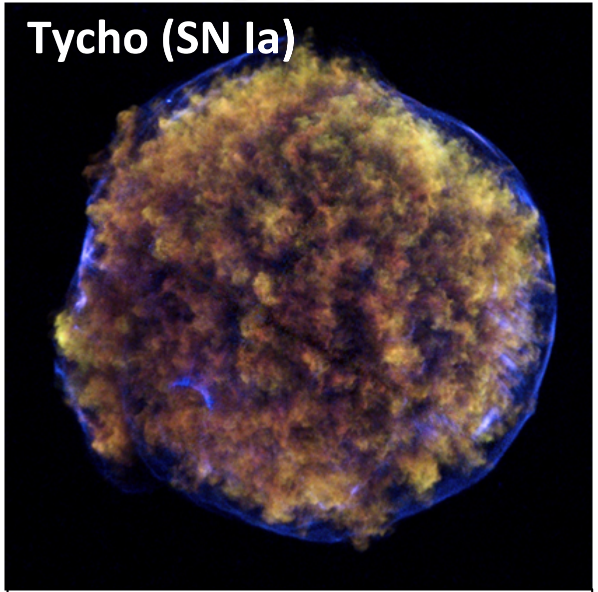
⇒ **Strong shock**



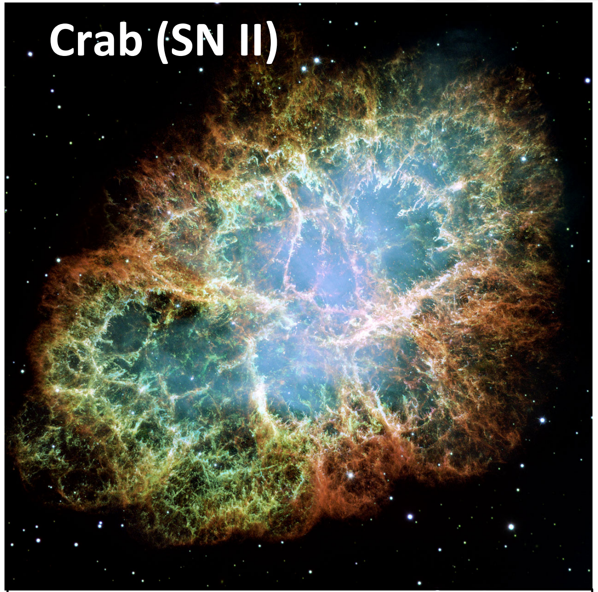
SN distribution in the ISM phases


Cas A (SN IIb)

SNR still interacting with stellar winds lost by the progenitor star

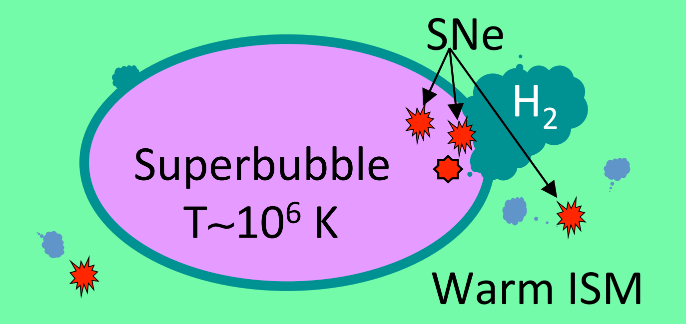

Tycho (SN Ia)

SNR evolves in a warm and partially ionised ISM

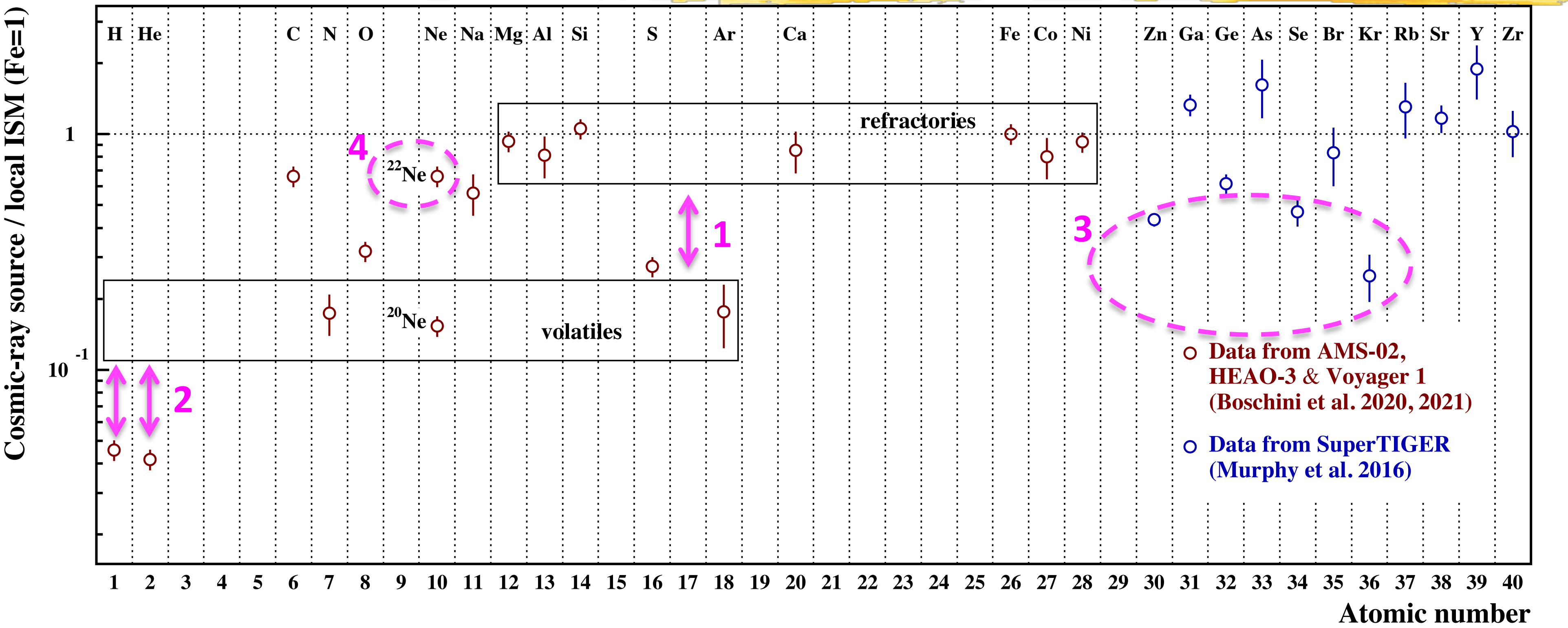

Crab (SN II)

Explosion in a bubble of hot plasma

- Massive stars are born in **OB association** and their wind activities generate **superbubbles** (SBs) of hot plasma, where most core-collapse SNe explode (~80%; Lingenfelter & Higdon 2007)
- With 25% of Galactic SNe of **Type Ia** occurring in the **warm ISM**: 60% of SNe in hot SBs, 40% in warm ISM (28% in WNM, 12% in WIM)

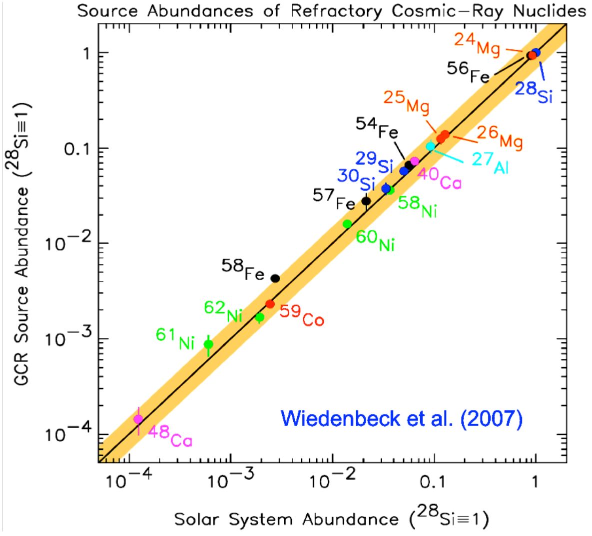


GCR source abundance data



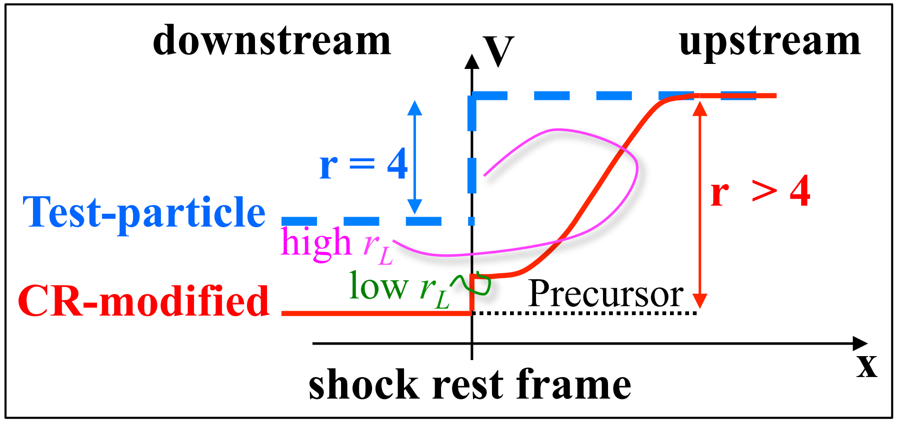
1. **Overabundance of refractory elements** over volatiles
2. **Under-abundance of protons and α-particles**
3. **Overabundance of heavier volatile elements** (Zn, Se, Kr...) compared to lighter ones (N, Ne, S, Ar...)?
4. **Overabundance of ^{22}Ne** (^{22}Ne/^{20}Ne is 5 times solar)

See Meyer, Drury & Ellison (1997)



1. Acceleration of dust grains

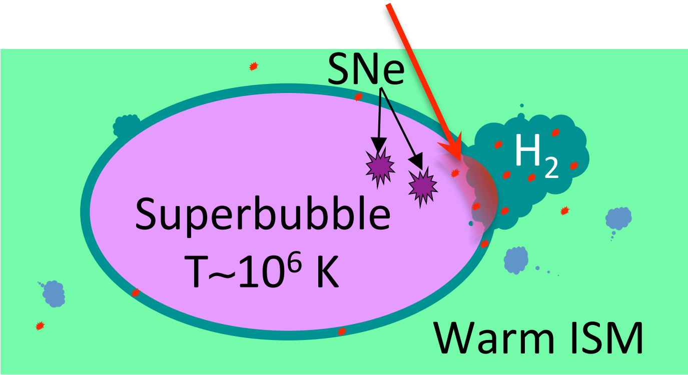
- **Higher efficiency of acceleration of dust grains** in SN shocks, because interstellar grains can have **very large $A/Q \sim 10^4$ - 10^8** and particles with a high rigidity ($R \propto A/Q$) feel a larger ΔV of the background plasma (Ellison et al. 1997, 1998)



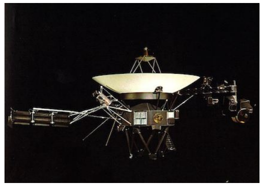
i. **Grain acceleration**
ii. **Grain sputtering** with ambient atoms
iii. **Injection of sputtered ions** with the **supra-thermal velocity** of the parent grain

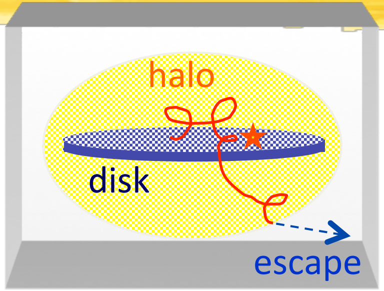
- **ISM phase where dust grains are accelerated?**
  - ✓ Diffuse shock acceleration occurs in **ionised media** (requires plasma waves)
  - ✓ But dust grains are mainly found in **cold molecular clouds** and the **warm ISM** (however, see Ochsendorf et al. (2015) for dust in the Orion-Eradinus superbubble)

Material enriched in dust grains evaporated off the SB shell and the parent molecular clouds



2. Protons, α-particles and O source spectra





- Fit to **Voyager 1** and **AMS-02** data using a **1D advection-diffusion model** with homogeneous diffusion for the GCR propagation (Evoli et al. 2019)
- **Broken power law source spectra** from a fit of propagated spectra to the data

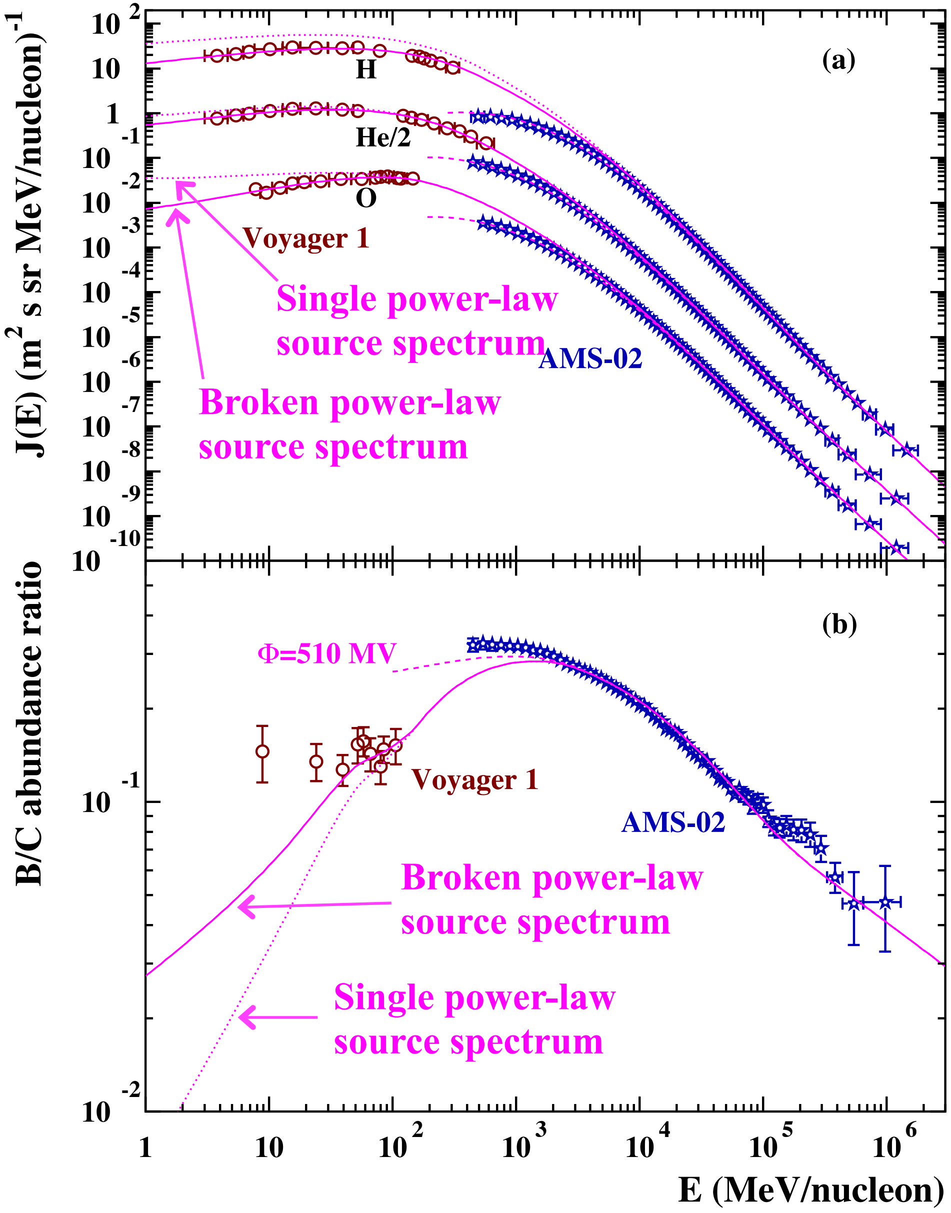
Table 2. CR source spectrum parameters (Eq. 2).

Parameter	H	He	O
E_{break}	10 ± 2 GeV/n	200^{+160}_{-120} MeV/n	160^{+40}_{-30} MeV/n
$\gamma_{\mathrm{l.e.}}$	4.10 ± 0.03	$3.98^{+0.08}_{-0.20}$	$3.32^{+0.18}_{-0.24}$
$\gamma_{\mathrm{h.e.}}{}^{a}$	4.31	4.21	4.26
$\chi^2_{\mathrm{min}}{}^{b}$	16.0 for 13 d.o.f.[c]	7.3 for 14 d.o.f.	5.9 for 12 d.o.f.

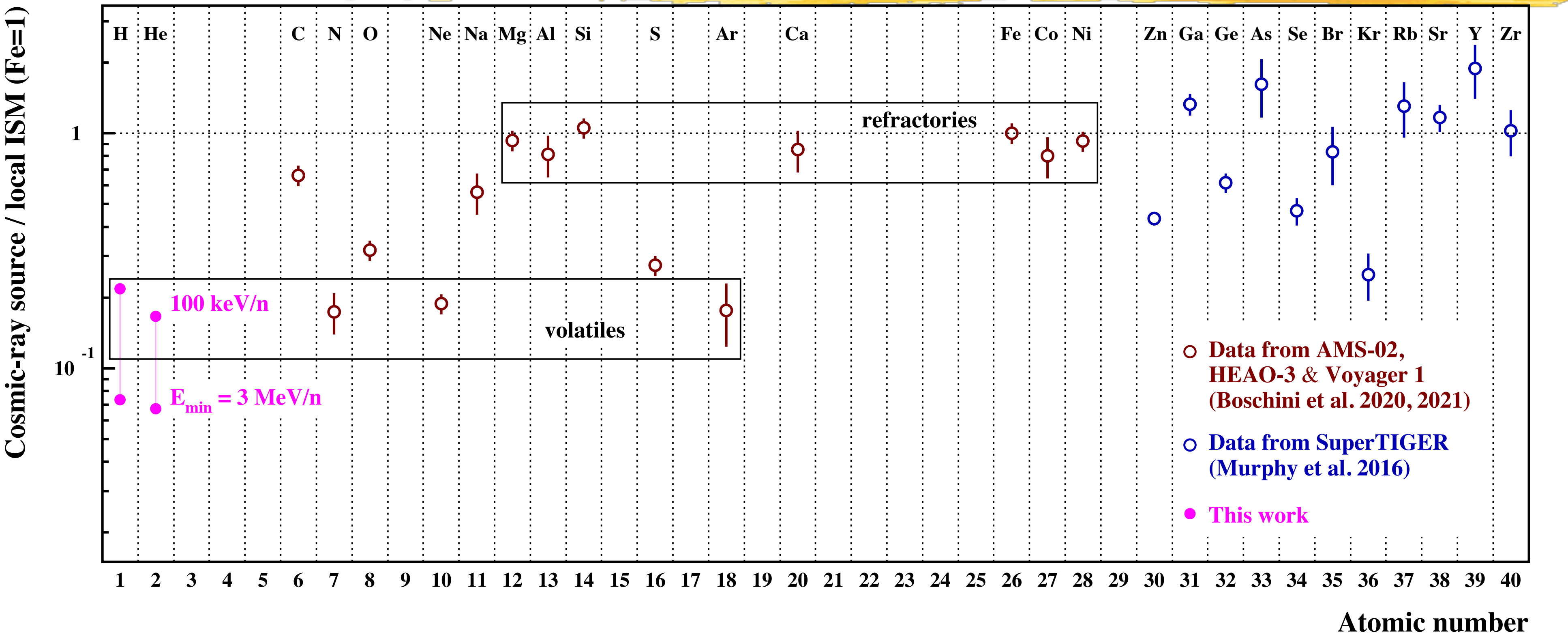
[a] Parameter fixed from Evoli et al. (2019).

[b] Minimum χ^2 from a fit of the propagated spectrum to Voyager 1 data.

[c] d.o.f.: degrees of freedom.



2. p and α-particles in the GCR composition

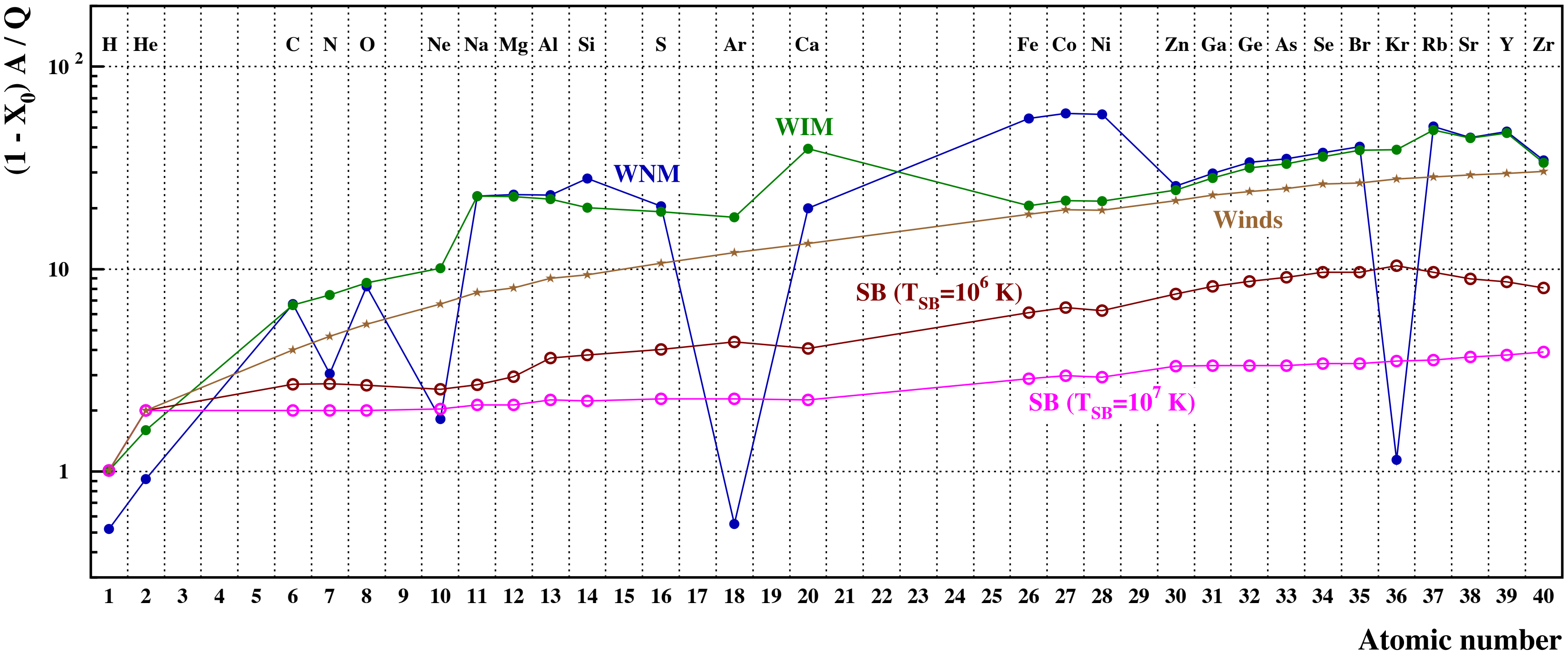


- **Integration of source spectra** => p & α abundances similar to those of the other volatiles N, Ne and Ar, provided that the **minimum CR source energy is of the order of a few hundred keV/n**
- **Escape of low-energy CR from their sources (see Schroer et al. 2022)? Source spectrum differences between p, α-particles and heavy nuclei?**

3. Charge dependence of GCR volatile abundances

○ Volatile element abundances in the GCR source composition depend on **ionisation states in shock precursors**, i.e. on **ISM phases**, because **acceleration efficiency depends on ion rigidity** (Ellison et al. 1981; Caprioli et al. 2017)

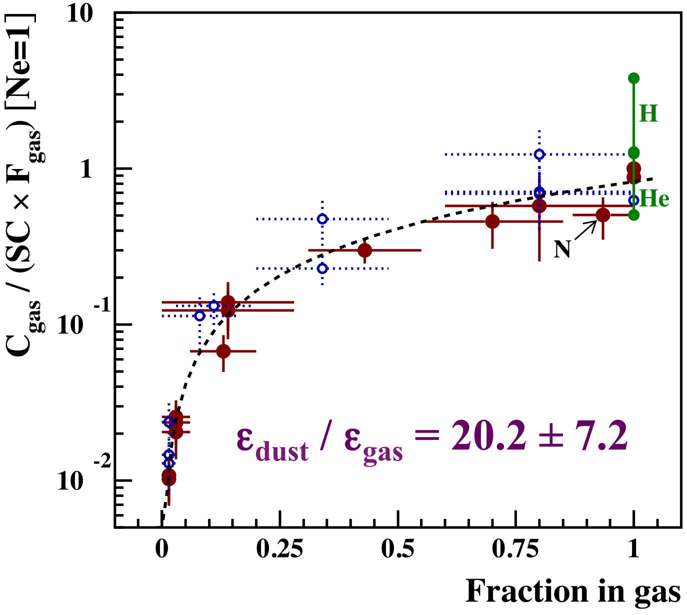
- **Warm ISM**: **photoionization precursors** mainly produced by He I and He II photons from the post-shock region (Ghavamian et al. 2000; Medina et al. 2014)
- **Superbubbles**: collisional ionisation in a hot plasma (negligible photoionization)

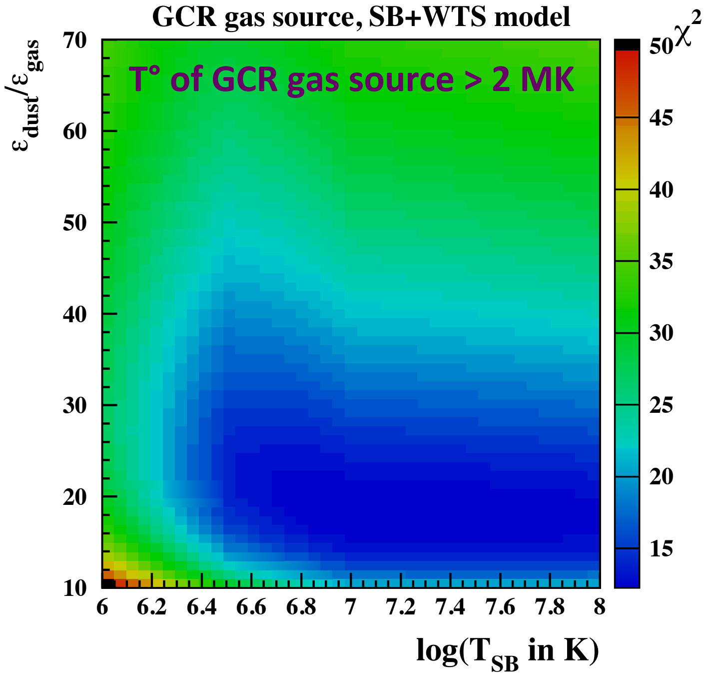


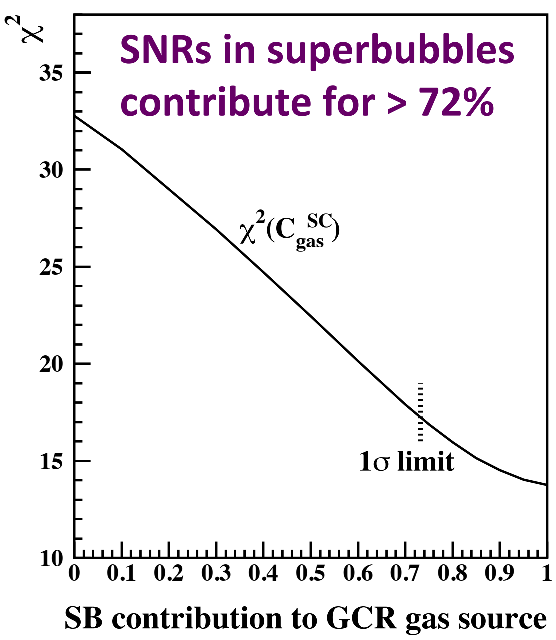
GCR source composition model

- ○ Model of GCR source abundances fitted to data (AMS-02, SuperTIGER...) from
  - ✓ **Mean composition of the local ISM** (B-type stars + solar system)
  - ✓ **Ionisation states in SNR shock precursor**
  - ✓ **Elemental fraction in ISM dust** - mainly from gas-phase element **depletions** (Jenkins 2009, 2019; Ritchey et al. 2018)

VT, J. C. Raymond, J. Duprat, S. Gabici, S. Recchia (2021)



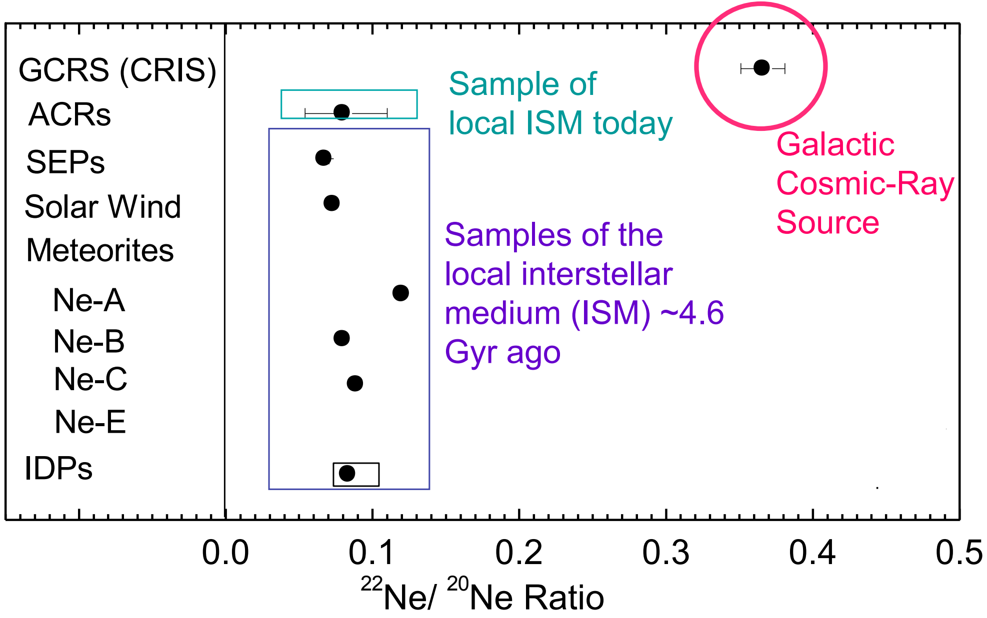


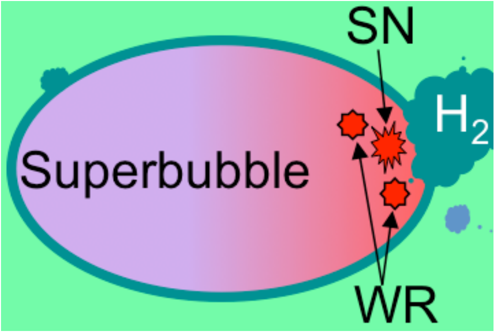


⇒ **Preferential acceleration of the GCR volatile elements in superbubbles**

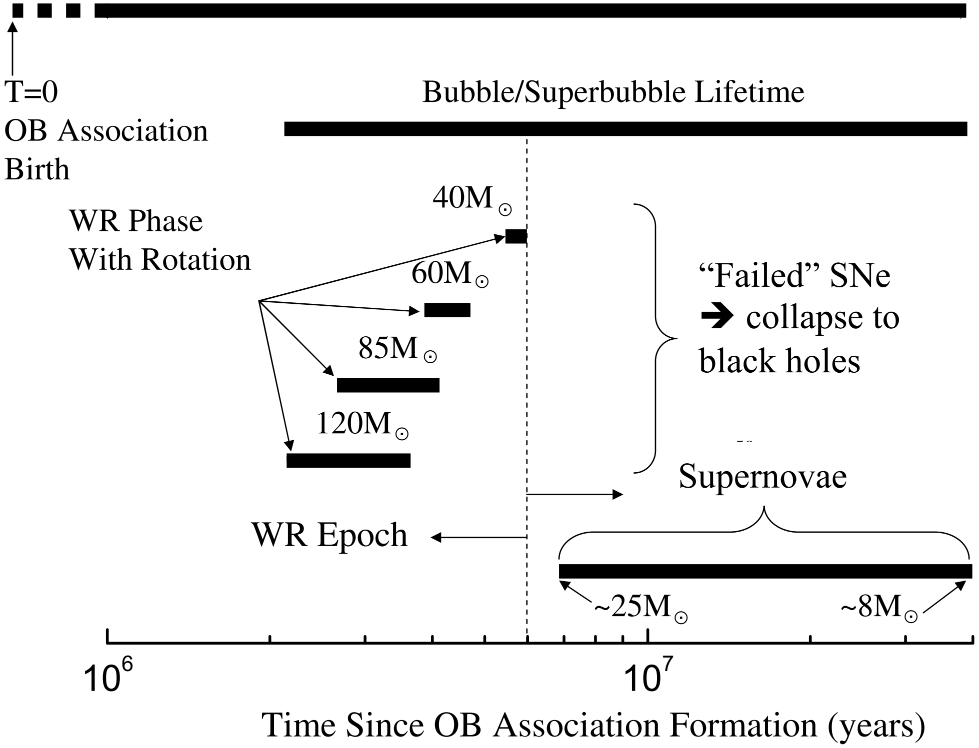
- ○ Effects possibly limiting the efficiency of shock acceleration in the warm ISM: **ion-neutral damping, neutral return flux** (Morlino et al. 2013)?

4. ^{22}Ne abundance in GCRs



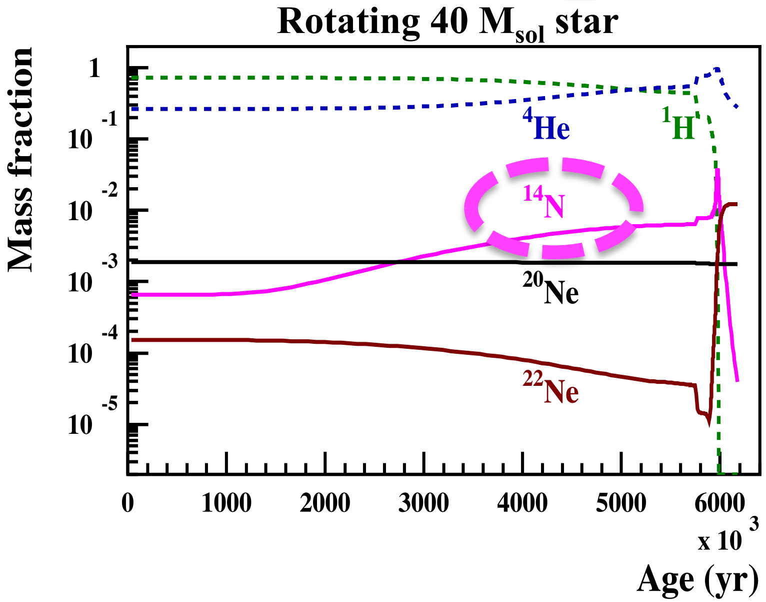


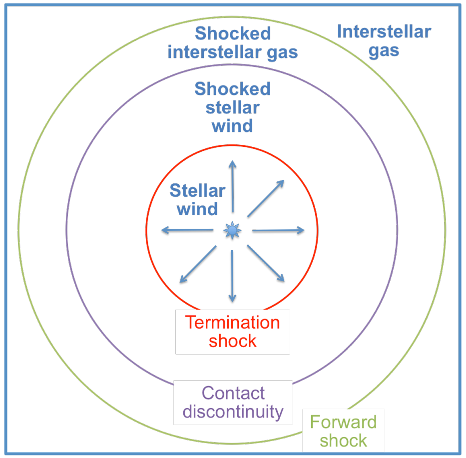
Adapted from Binns et al. (2008)

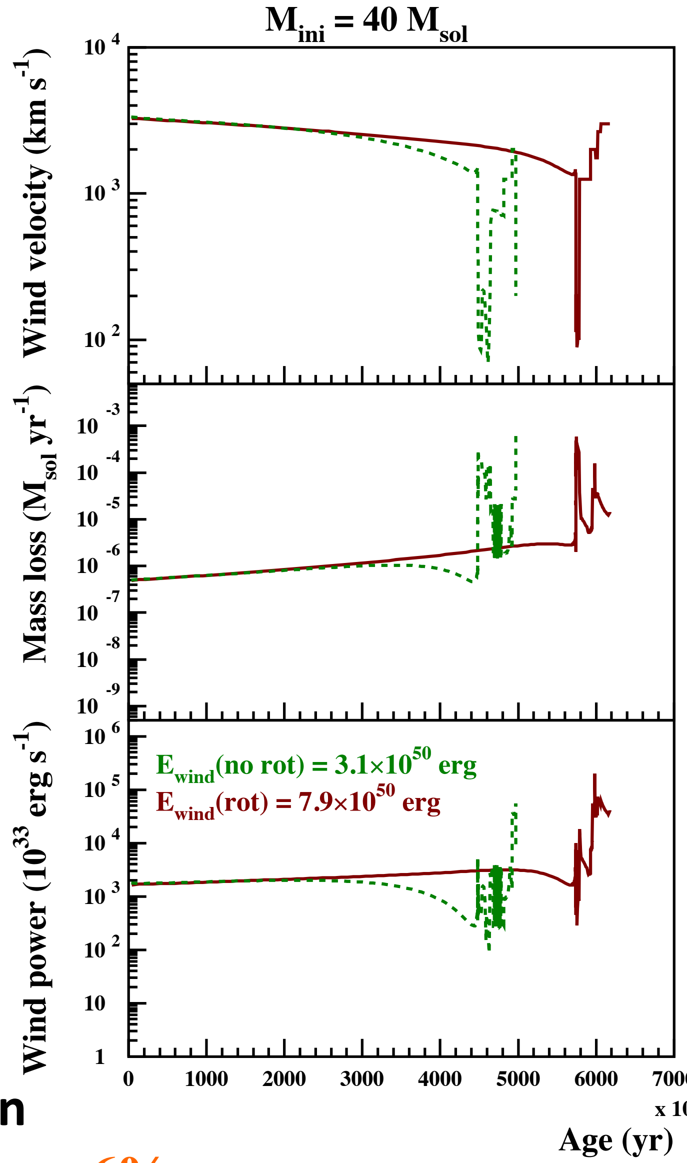


- GCR ^{22}Ne/^{20}Ne ratio ≈ 0.35, i.e **~ 5 times the solar ratio** (Garcia-Munoz et al. 1970; Binns et al. 2005)
- Contribution to GCRs of **Wolf-Rayet wind material** ($^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne$ during He burning)? (Cassé & Paul 1982)
- GCR origin in **superbubbles** enriched in ^{22}Ne from winds of massive stars?

4. GCR ^{22}Ne from wind termination shocks







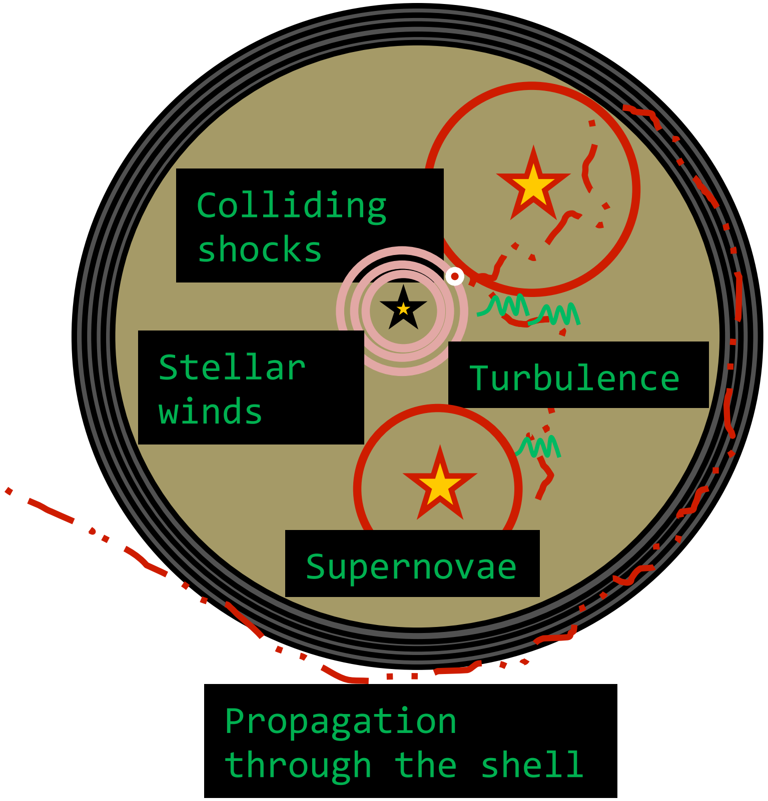
From the Geneva Observatory database

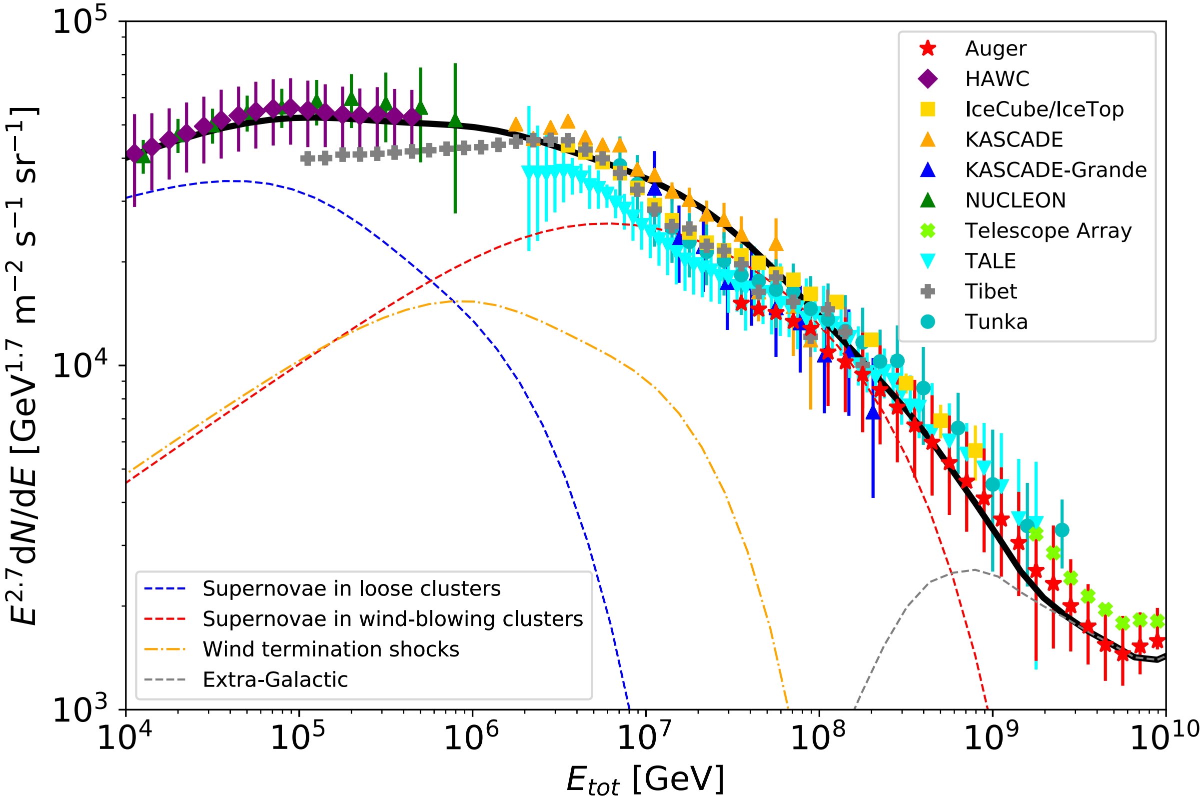
- **GCR ^{22}Ne not from enriched superbubble gas**, because overproduction of ^{14}N (main sequence): **$(N/Ne)_{wind}$=2.6 => 5.5x the ratio in the GCR source**
- More likely ^{22}Ne is produced by shock acceleration in **wind termination shocks** (see Morlino et al. 2021)
- Assuming the acceleration efficiency in WTS to be proportional to the **wind mechanical power:**

⇒ **^{22}Ne/^{20}Ne=1.56** in the **accelerated wind composition**

⇒ **Small contribution** to the GCR source composition: $x_w \approx 6\%$

Cosmic-rays from massive star clusters and superbubbles





- ○ Vieu et al. (2020, 2022a, 2022b, 2022c): detailed theory of **cosmic-ray production in superbubbles** from stellar winds, supernova remnants and turbulence, taking into account the nonlinear feedback of the accelerated particles
  => CR are mainly accelerated in SNRs, only **5 - 10% of CRs are produced in WTS**

- ○ Vieu & Reville (2022): explain the **Galactic CR population up to hundreds of PeV**

Conclusions

- Composition of Galactic cosmic rays is **key to understanding their origin** and their effects in the ISM and in cosmology (atelier S07)

- Measured source abundances of **primary and mostly primary CRs from H to Zr** point to an origin in **superbubble environment**, mainly from **acceleration in SN shocks**, with a small contribution of acceleration in **wind termination shock**s ($x_w \approx 6\%$) to explain the ^{22}Ne overabundance

- More work is needed to understand the origin of the GCR refractories - acceleration of **dust grains in superbubbles?** (atelier S10)

- CR production in massive star clusters and superbubbles up to 10^{18} eV? => **Cherenkov Telescope Array**, **LHAASO**