The Origin of Galactic Cosmic Rays as Revealed by their Composition

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On the GCR composition

Refs: Meyer, Drury & Ellison (1997); Ellison, Drury & Meyer (1997)

1. **Overabundance of elements with $Z > 2$** relative to H and He (as compared with the solar system composition)

⇒ **Not necessarily**, because CR protons and α-particles have different source spectra than the other elements (e.g. Tatischeff & Gabici 2018)

2. **Overabundance of refractory elements** over volatiles due to the more **efficient acceleration** of material locked in **dust grains**

⇒ OK, but which dust grains?

3. **Overabundance of the heavier volatile elements** compared to the lighter ones due to a **dependence of the acceleration efficiency on ion rigidity**

⇒ Confirmed by PIC simulations (Caprioli et al. 2017; Hanusch et al. 2019), but ionisation states in shock precursors? **Depends on the ISM phases**

4. **Overabundance of ^{22}Ne** due to the acceleration of **Wolf-Rayet wind** material enriched in He-burning products

⇒ OK, but how exactly Wolf-Rayet wind material is incorporated in GCRs?

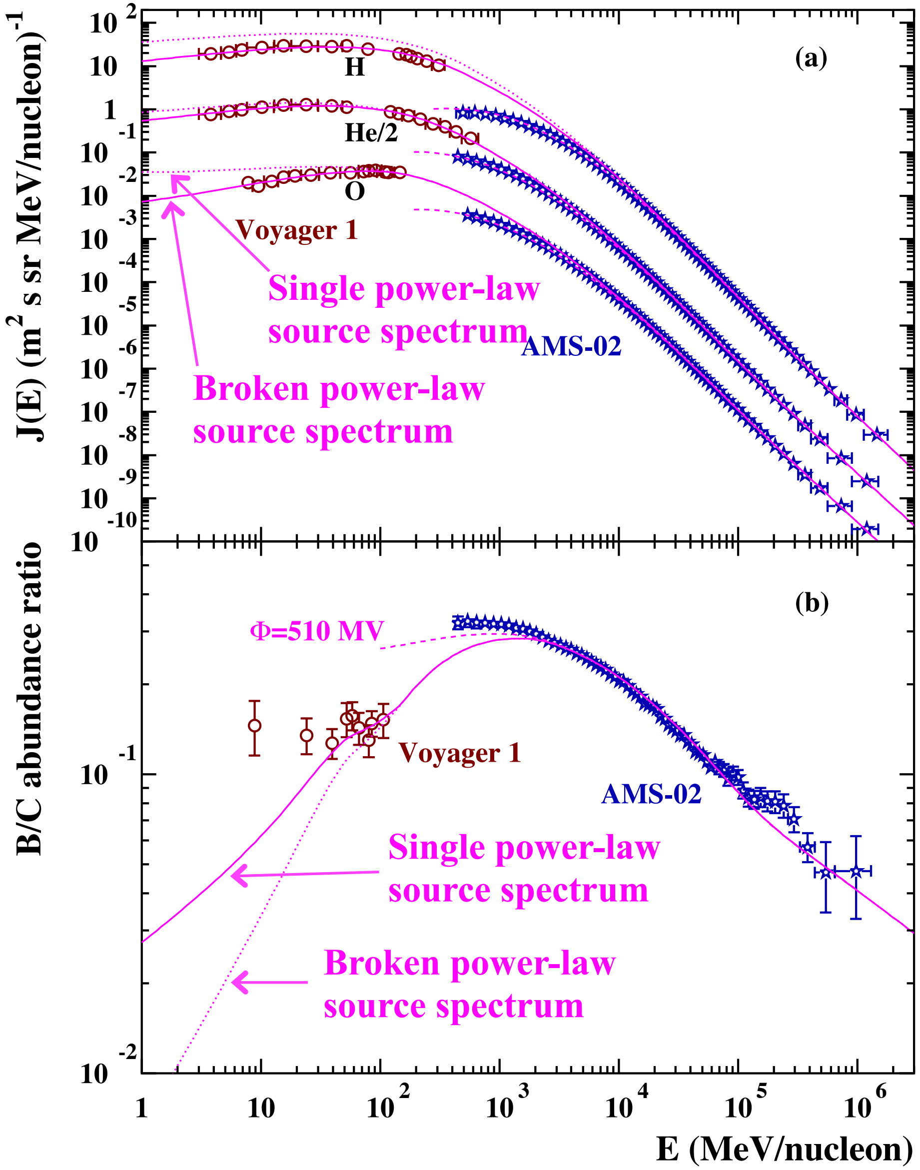
Protons, α-particles and O source spectra

- 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)
- Updated cross section database to be published
- **Broken power law source spectra** from a fit of propagated spectra to the data

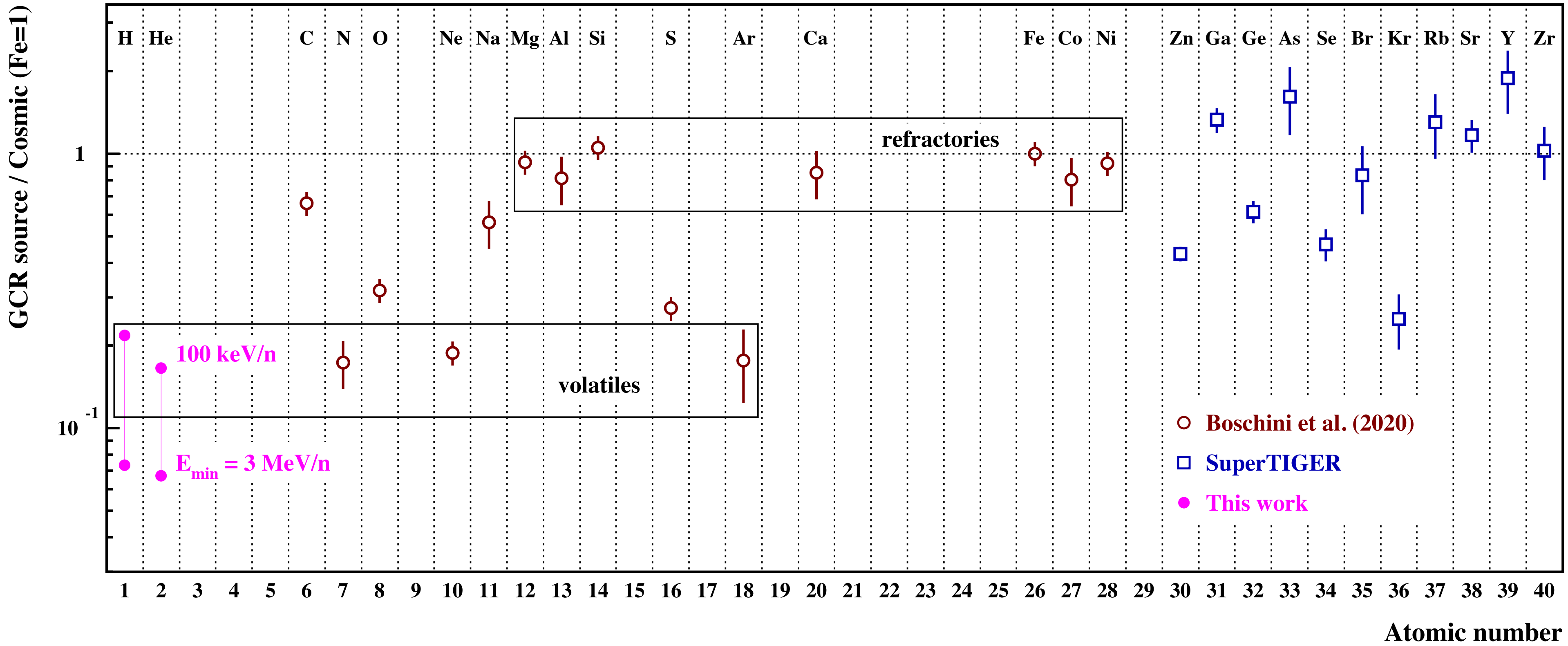
Table 2. CR source spectrum parameters (Eq. 2).

Parameter	H	He	O
$E_{\rm break}$	10 ± 2 GeV/n	200^{+160}_{-120} MeV/n	160^{+40}_{-30} MeV/n
$\gamma_{\rm l.e.}$	4.10 ± 0.03	$3.98^{+0.08}_{-0.20}$	$3.32^{+0.18}_{-0.24}$
$\gamma_{\rm h.e.}$ [a]	4.31	4.21	4.26
$\chi^2_{\rm min}$ [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.



GCR abundance data



- Abundances from **integration of source spectra** => the abundances of H and He are 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**
- Highly refractory elements Mg, Al, Si, Ca, Fe, Co, and Ni are in solar system proportions => acceleration of various **dust grains of the ISM mix**

GCR composition model

- Measured GCR source abundances: $C_{\mathrm{mes}}(i) = C_{\mathrm{gas}}(i) + C_{\mathrm{dust}}(i)$
- Dust contribution: $C_{\mathrm{dust}}(i) = \mathrm{SC}(i) f_d(i) \epsilon_{\mathrm{dust}}$

Standard cosmic composition of the ISM (B-type stars + solar system) | Elemental fraction in ISM dust | Global efficiency factors

- Gas contribution: $C_{\mathrm{gas}}(i) = \mathrm{SC}(i)(1-f_d(i))\epsilon_{\mathrm{gas}}[x_w f_w(i) f^w_{A/Q}(i) + (1-x_w) f^{\mathrm{SC}}_{A/Q}(i)]$

Contribution of the Wolf-Rayet wind reservoir | Enhancement of element i in the Wolf-Rayet wind reservoir |

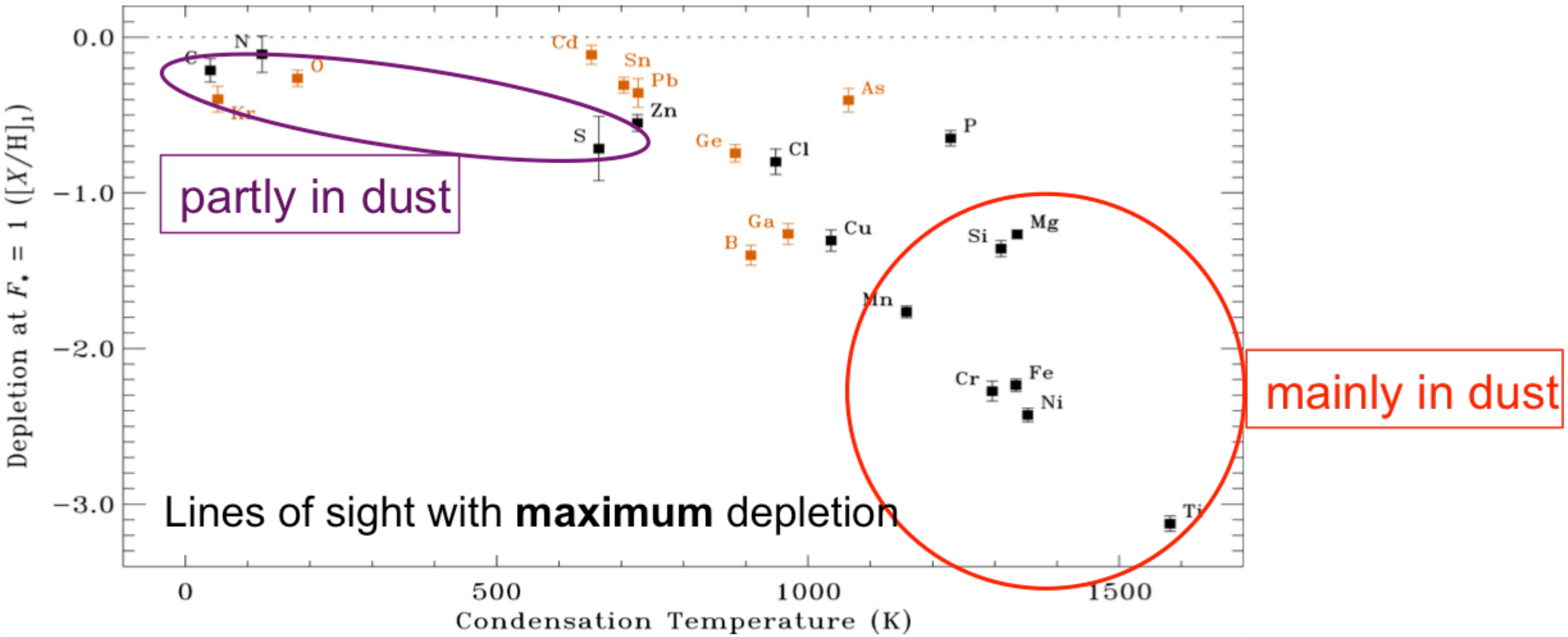
$f^j_{A/Q}(i) = (1 - X^j_{0,i}) A_i / Q^j_i$

where $X^j_{0,i}$, A_i and Q^j_i are the fraction of neutral atoms, atomic mass and mean ionic charge in shock precursors

- If the gas reservoir includes several phases of the ISM: $f^{\mathrm{SC}}_{A/Q}(i) = \sum_k a_k f^{\mathrm{SC},k}_{A/Q}(i)$
- Fitting theoretical abundances to data to derive $\epsilon = \epsilon_{\mathrm{dust}}/\epsilon_{\mathrm{gas}}$, as well as constraints on the **GCR source reservoirs**

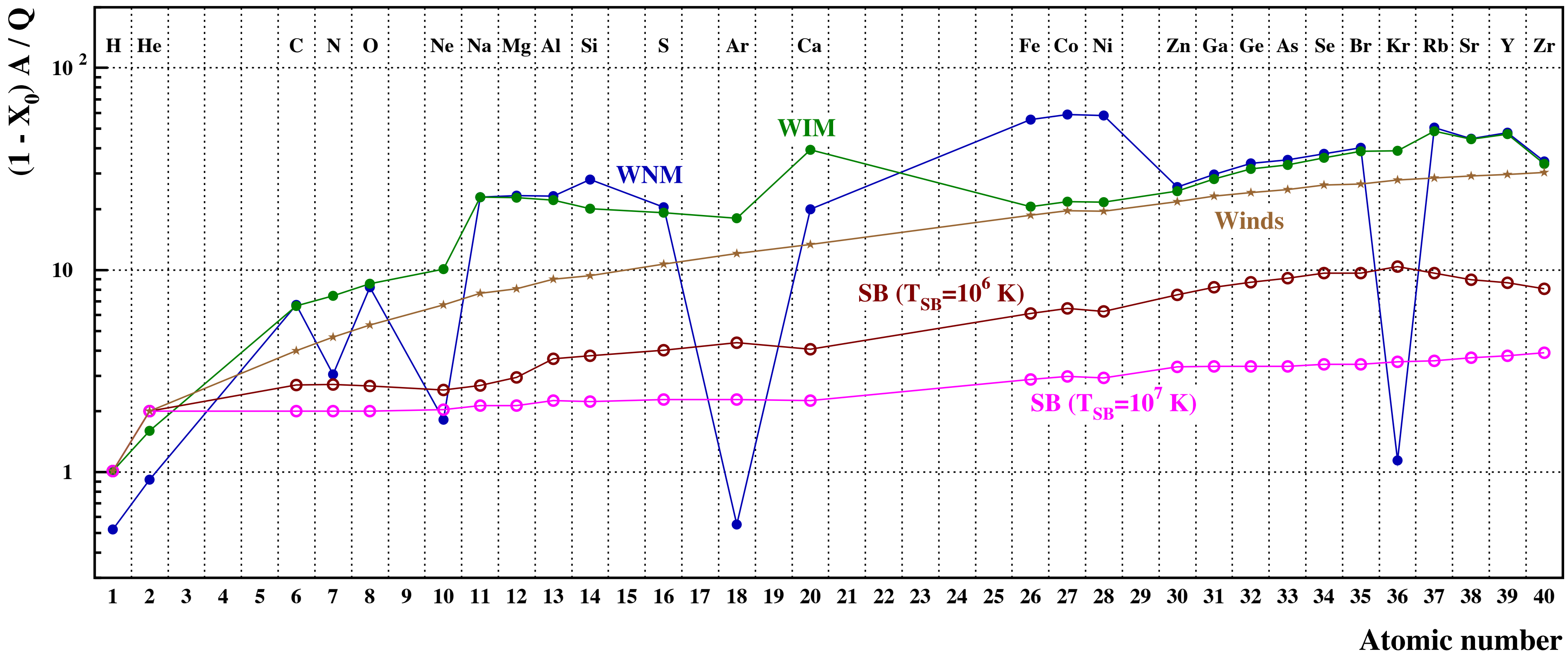
Interstellar dust composition

- **Average fraction in dust** for each element, $f_d(i)$, from
  - Gas-phase element **depletions** (Jenkins 2009, 2019; Ritchey et al. 2018)
  - The interstellar dust modeling framework **THEMIS** (Jones et al. 2017)
  - General properties of **primitive interplanetary dust**



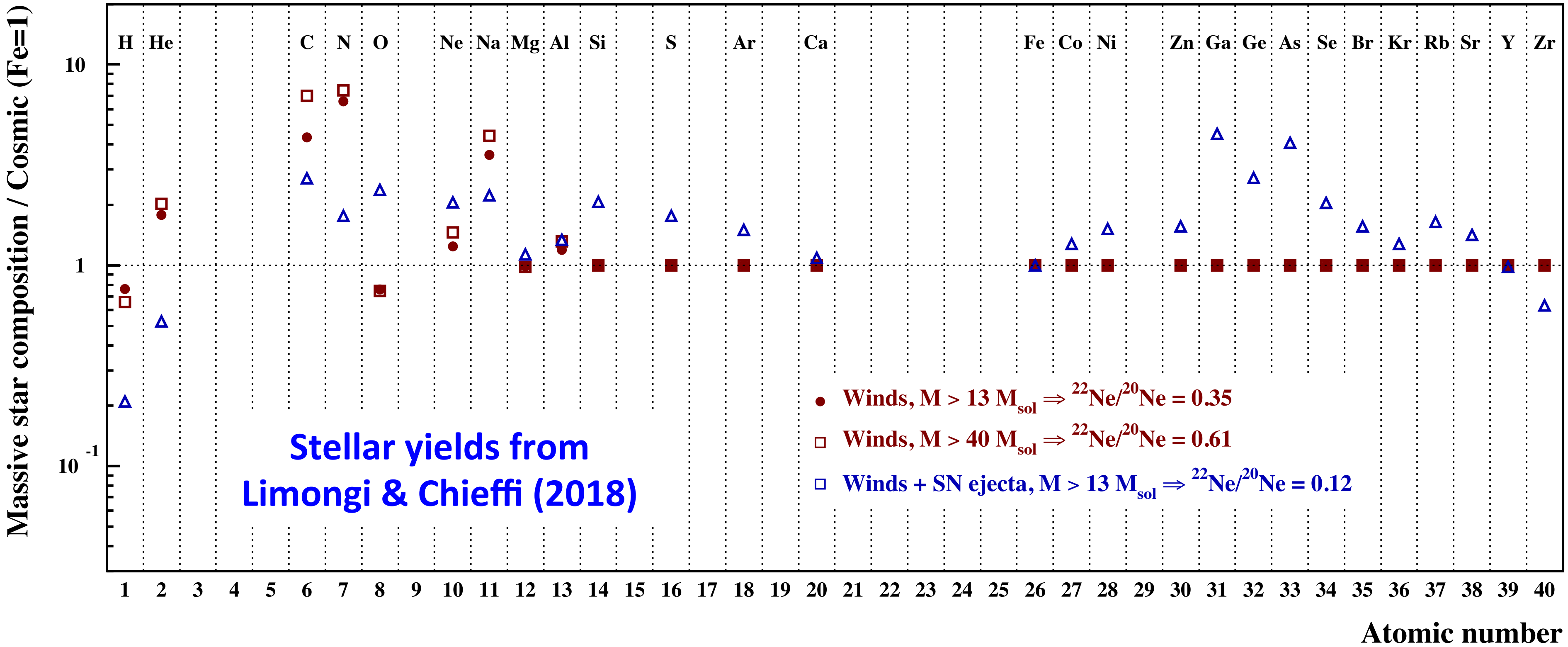
Ionisation states in shock precursors

- **Warm ISM**: Ionisation states of the WIM and the WNM from absorption/emission line measurements (e.g. Sembach et al. 2000; Madsen et al. 2006)
  + **photoionisation precursors** mainly produced by He I and He II photons from the thin ionisation zone behind the shock (Ghavamian et al. 2000; Medina et al. 2014)
- **Superbubbles**: collisional ionisation in a hot plasma (negligible photoionisation)
- **Stellar winds**: photoionisation by the EUV radiation of hot stars + EUV and X-rays from shocks in the winds => heavy elements mostly triply ionised (e.g. Hillier 2020)



GCR ^{22}Ne from enriched superbubble gas

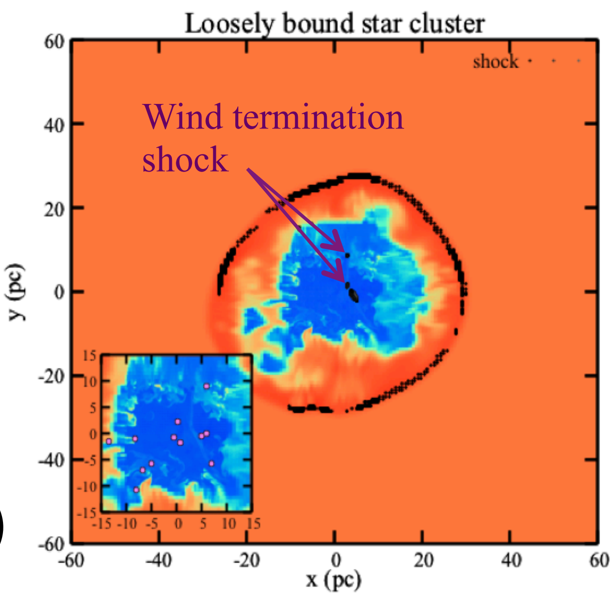
- GCR $^{22}Ne/^{20}Ne = 0.317$ (Boschini et al. 2020), i.e. ~ **5 times the solar ratio**
- Mix of **massive star winds and SN ejecta** in SB cores? **No, $^{22}Ne/^{20}Ne$ too low**
- **Only massive star winds** in SB cores? **No, $^{22}Ne/^{20}Ne$ still too low**
- Winds from **very massive stars** ≥ 40 M_{sol} (e.g. Binns et al. 2008)? **Maybe...**

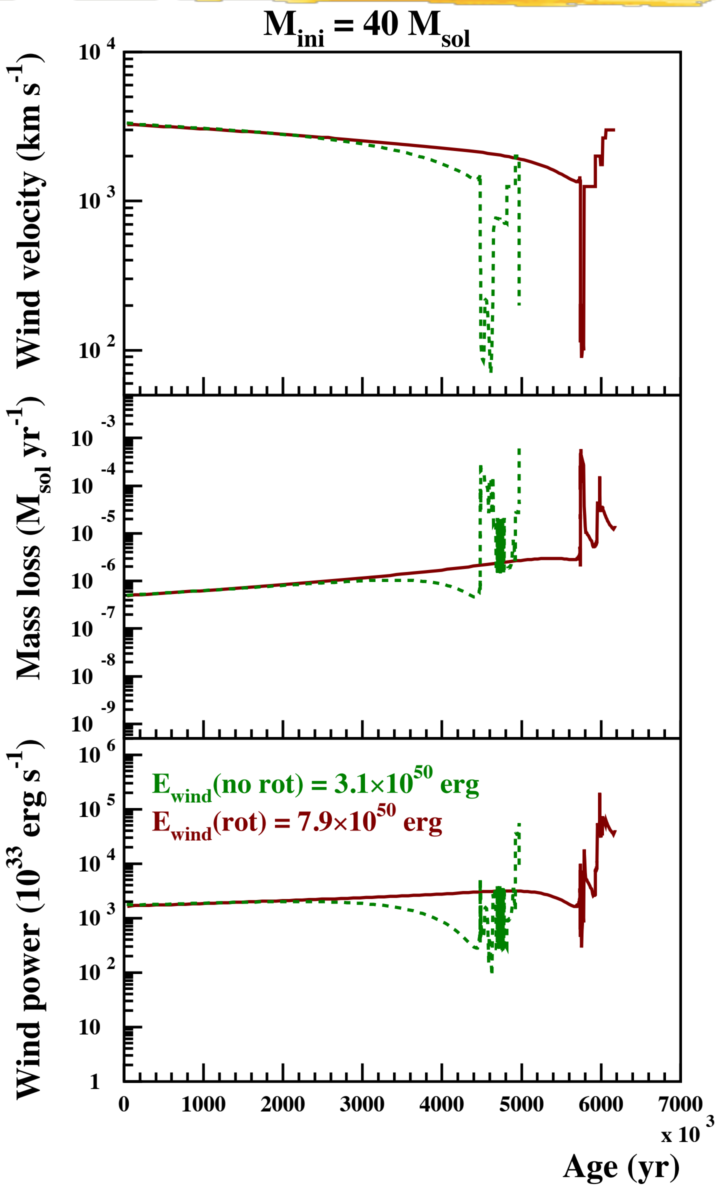


GCR ^{22}Ne from wind termination shocks

- Gupta et al. (2020): WTSs can contribute **more than 25% of the CR production** in massive star clusters

⇒ **^{22}Ne-rich** CR component (see also Kalyashova et al. 2019)





- Time-dependent yields and mass loss rates from the **Geneva Observatory database** (e.g. Ekström et al. 2012)

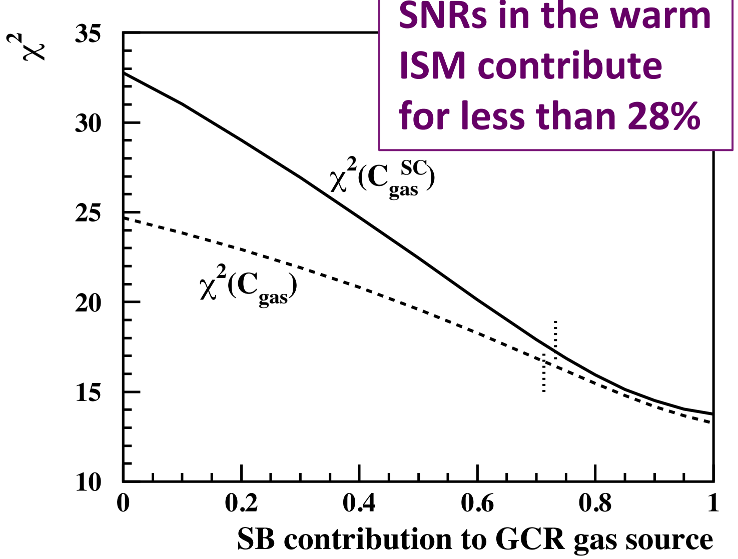
- Instantaneous acceleration efficiency in WTS assumed to be proportional to the **wind mechanical power**

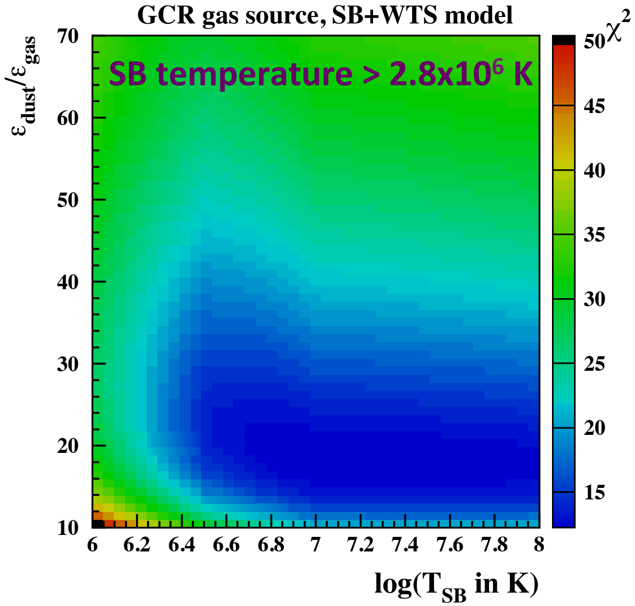
⇒ ^{22}Ne/^{20}Ne=1.56 in the accelerated wind compo.

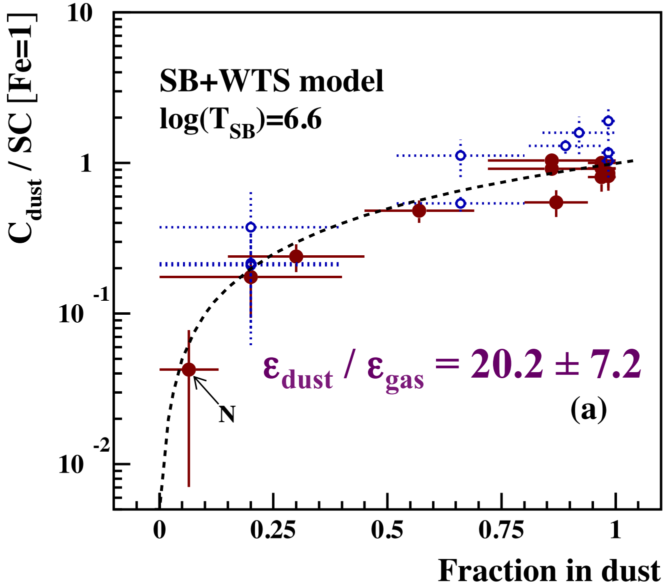
Some results of the GCR composition model

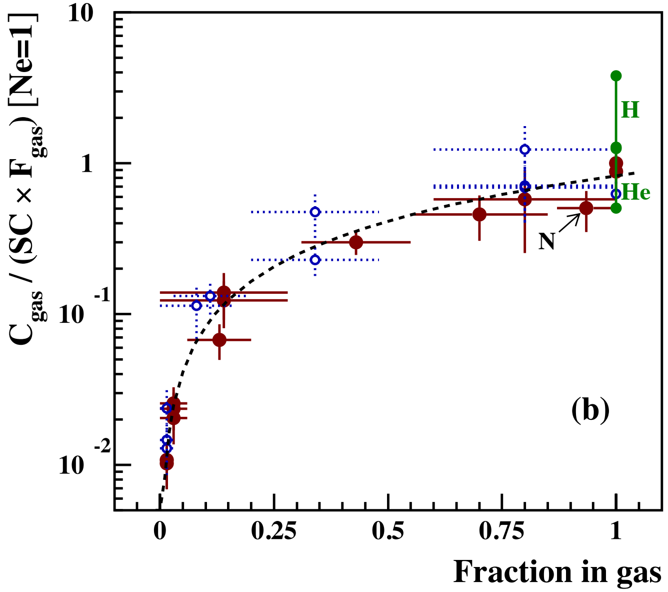
- 5 models depending on the relative weights of the **ISM phases** in the GCR production, and the **origin of GCR ^{22}Ne**
- Best-fit model: GCR accelerated in **superbubbles** + ^{22}Ne-rich component from acceleration in **wind termination shocks** ($x_w \approx 6\%$)

SNRs in the warm ISM contribute for less than 28%

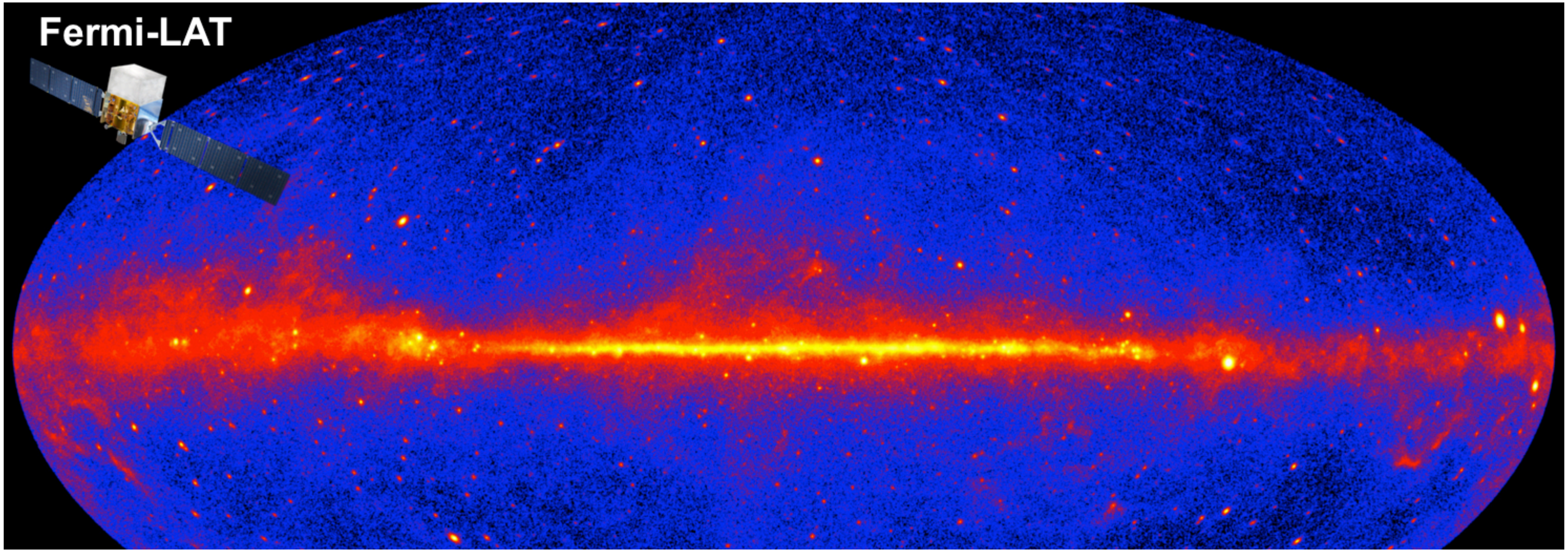








GCR acceleration efficiency



- The efficiency of GCR acceleration can be estimated from the **γ-ray luminosity of the Milky Way** => $W_p(0.1\text{- } 100 \text{ GeV}) \approx 7\times10^{40}$ erg/s (Strong et al. 2010)

- Estimating the mass of gas swept up by interstellar shocks, we get:
  - Efficiency of acceleration of **SB gas by SN shocks**: $\eta_{SB} \approx (0.4 - 2.3)\times10^{-5}$
  - Efficiency of acceleration of **wind material by WTSs**: $\eta_{wind} \approx 0.8\ \eta_{SB}$
  - Efficiency of acceleration of GCR **refractories from dust grains**: $\eta_{dust} \gtrsim 10^{-4}$

Conclusions (see arXiv:2106.15581)

- Measured source abundances of all primary and mostly primary CRs **from H to Zr are well explained**, including the overabundance of ^{22}Ne
- **No overabundance of elements with *Z* > 2** relative to H and He, if the **minimum CR source energy is of the order a few hundred keV nucleon^{-1}**
- CR volatiles are mostly accelerated in **Galactic superbubbles**, from SN shocks sweeping up a plasma of $T_{\rm SB} > 2.8$ MK. SNRs in the warm ISM contribute to the GCR volatile composition for less than 28%
- The overabundance of ^{22}Ne is due to a small ($x_w \approx 6\%$) contribution of particle acceleration in **wind termination shocks** of massive stars
- The GCR refractories most likely originate from the **acceleration and sputtering of dust grains** in SNR shocks. They might be produced in superbubbles (SBs) as well, if dust is continuously replenished in SB interior