The Origin of Galactic Cosmic Rays as Revealed by their Composition

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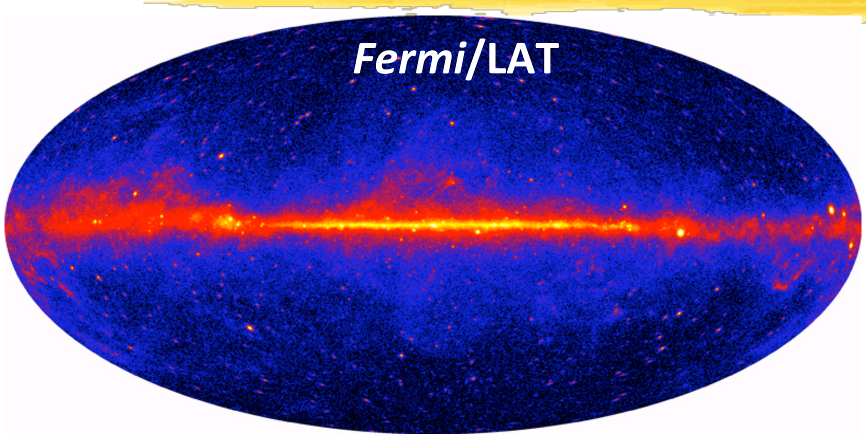
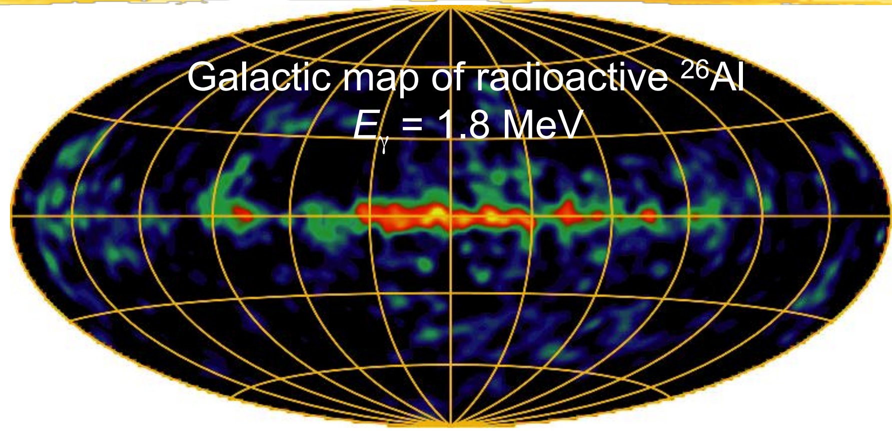
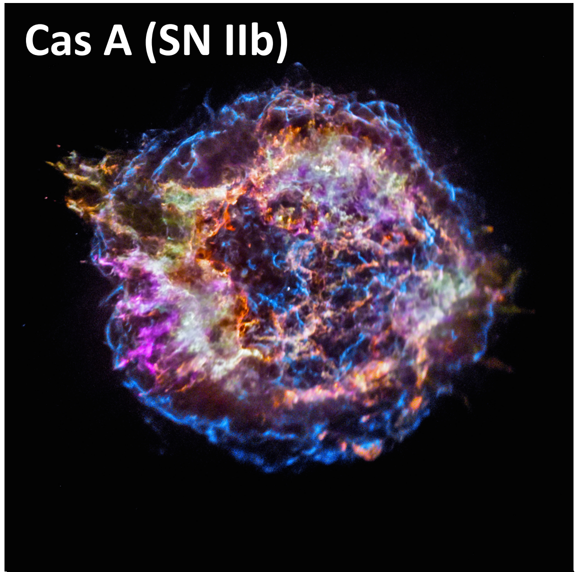
On the origin of Galactic Cosmic Rays



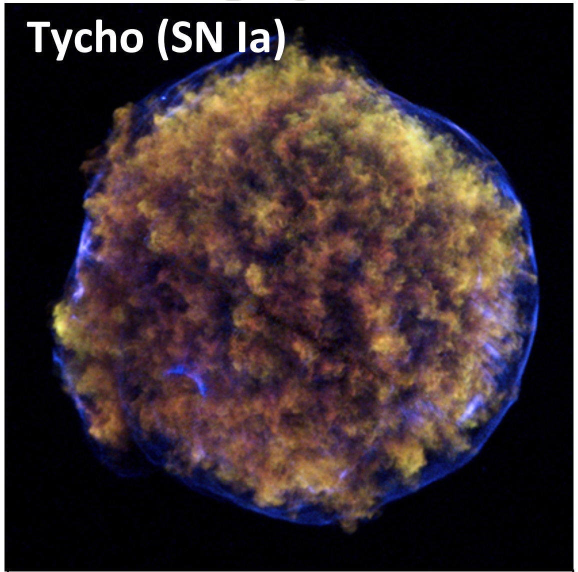


- GCRs are thought to be produced in **supernova remnants** (Baade & Zwicky 1934)
- Consistent with the cosmic-ray power and supernova energetics:
  - ✓ Kinetic power of CRs injected in the Galaxy: $\boldsymbol{L_{CR}} = L_\gamma / R_\gamma$ **~ $\mathbf{10^{41}}$ erg/s**, where $R_\gamma \sim 0.004$ is the γ-ray radiation yield (= efficiency) for $p + p \rightarrow \pi^0 + X$ and L_γ from π^0 decay $\sim 5{\times}10^{38}$ erg/s (Fermi/LAT; see Strong et al. 2010)
  - ✓ Kinetic power supplied by supernovae: $\boldsymbol{L_{SN}} = E_{SN} \times f_{SN}$ **~ $\mathbf{10^{42}}$ erg/s**, where $E_{SN} \sim 1.5{\times}10^{51}$ erg is the mean energy of a SN and $f_{SN} \sim 50$ yr^{-1} is the SN rate in the Milky Way (from the present-day mass of ^{26}Al; Diehl+ 2006)
- (Kinetic power supplied by massive star winds: $\boldsymbol{L_{wind} \sim L_{SN}}$ **/ 4**; Seo et al. 2018)
- **From which phase(s) of the ISM are the CRs extracted? => GCR composition**

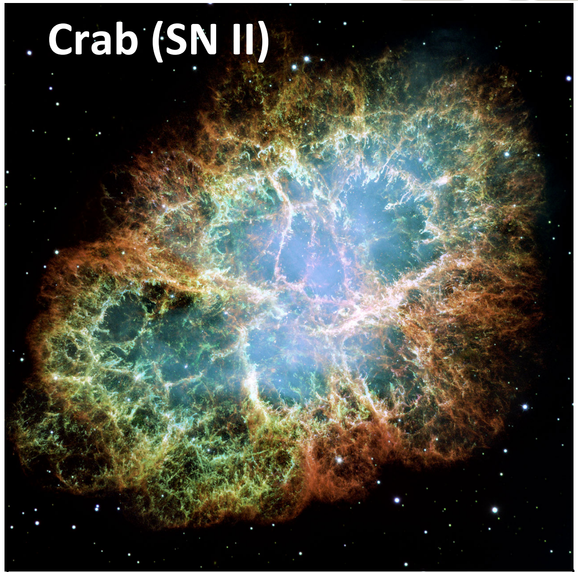
SN distribution in the ISM phases



SNR still interacting with stellar winds lost by the progenitor star



SNR evolves in a warm and partially ionised ISM



Explosion in a bubble of hot gas

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

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? From which ISM phase(s) are they accelerated?

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

⇒ Expected from nonlinear DSA (Ellison+ 1981) and PIC simulations (Caprioli+ 2017), 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?

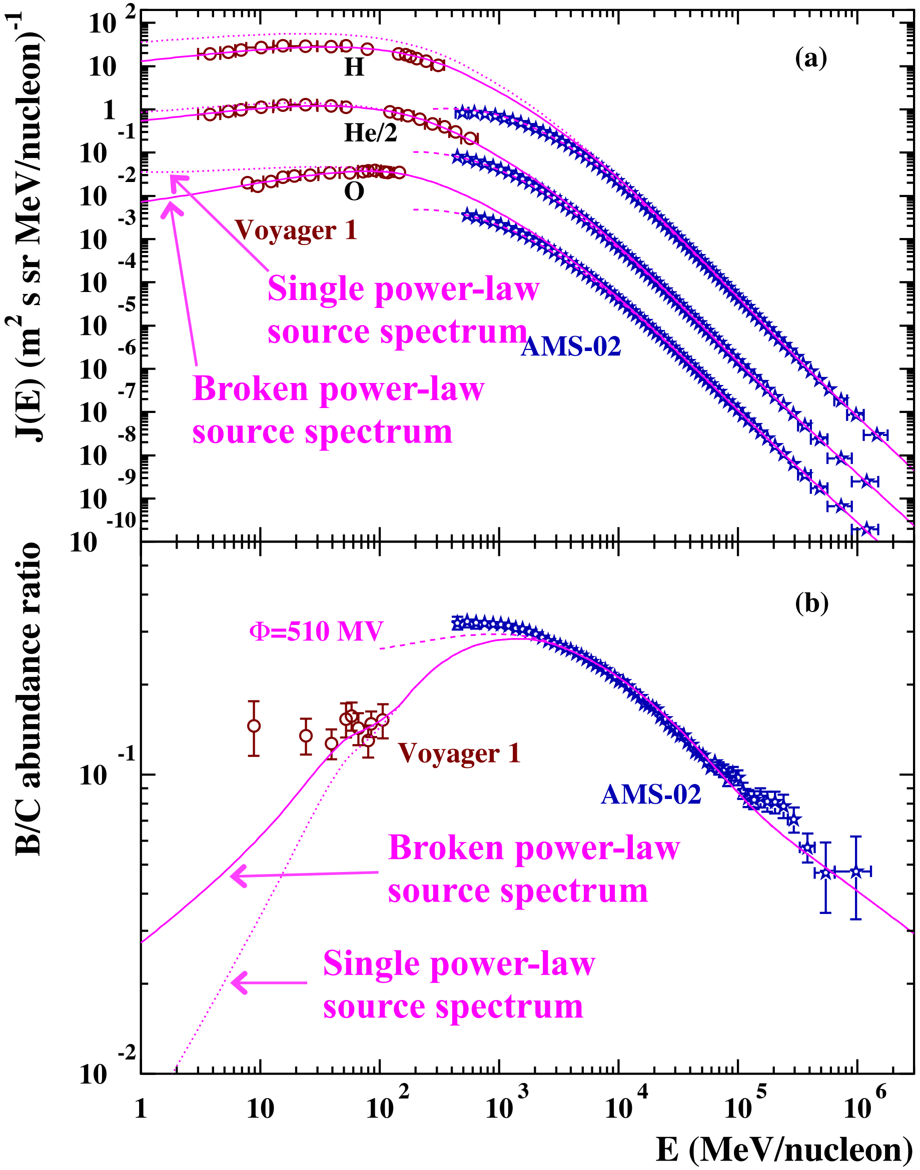
Protons, α-particles and O source spectra

- 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

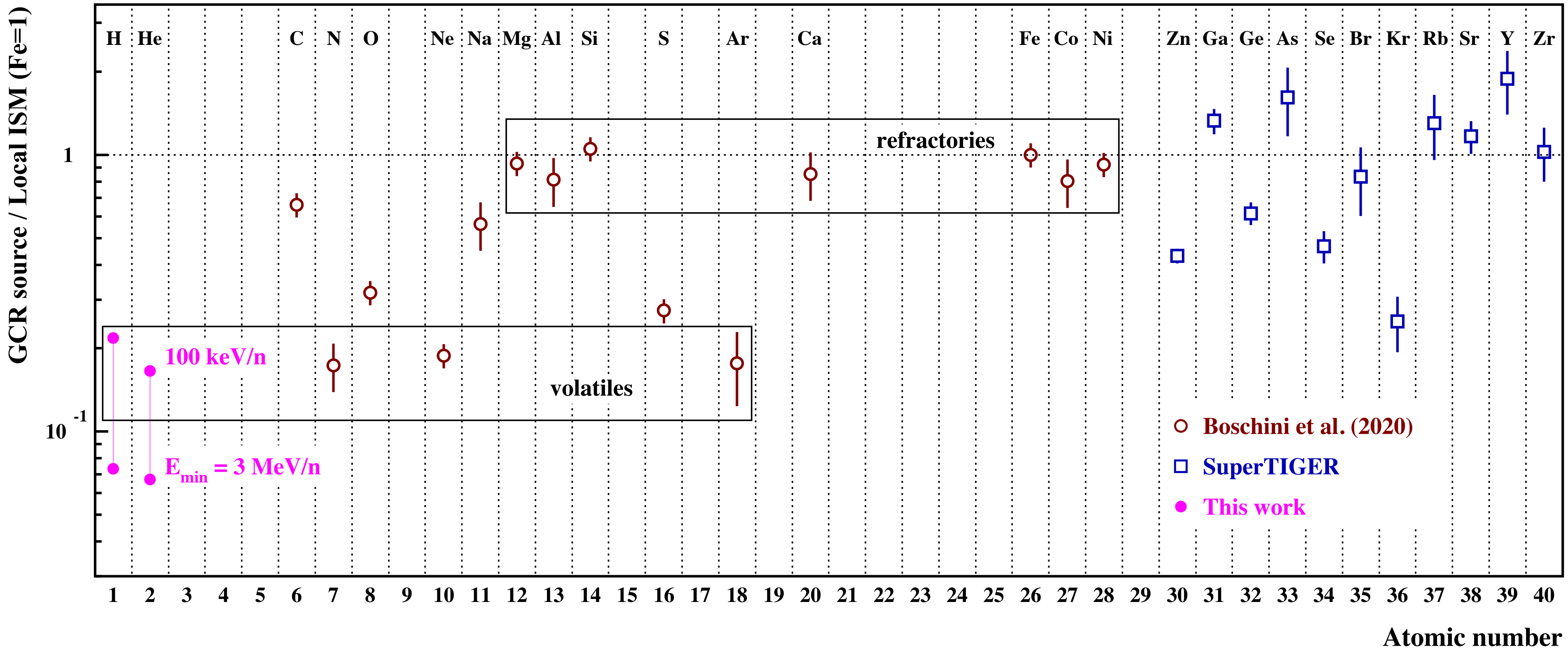
Table 2. CR source spectrum parameters (Eq. 2).

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

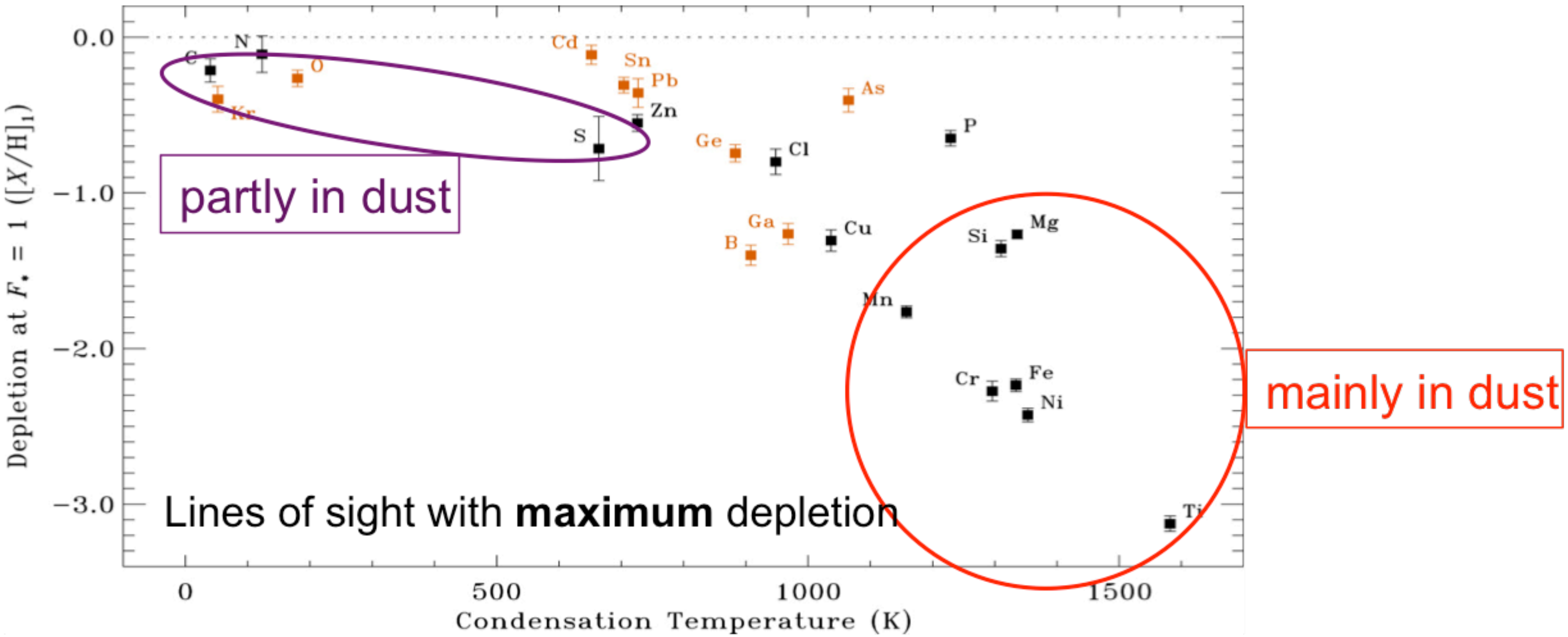
$f^{j}_{A/Q}(i) = (1 - X^{j}_{0,i}) A_i / Q^{j}_i$

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 x_w, $\epsilon = \epsilon_{\mathrm{dust}}/\epsilon_{\mathrm{gas}}$, as well as constraints on the **GCR source reservoirs** (e.g. their temperature)

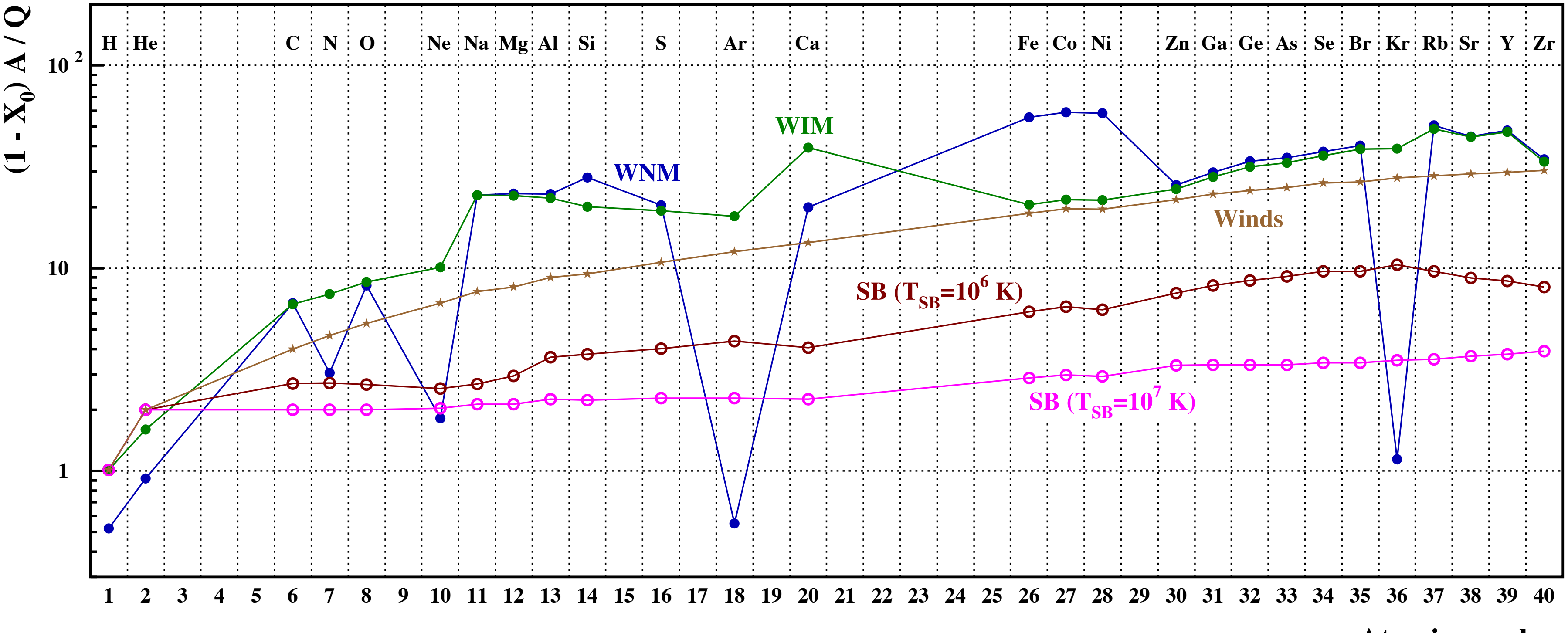
Interstellar dust composition

- **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**



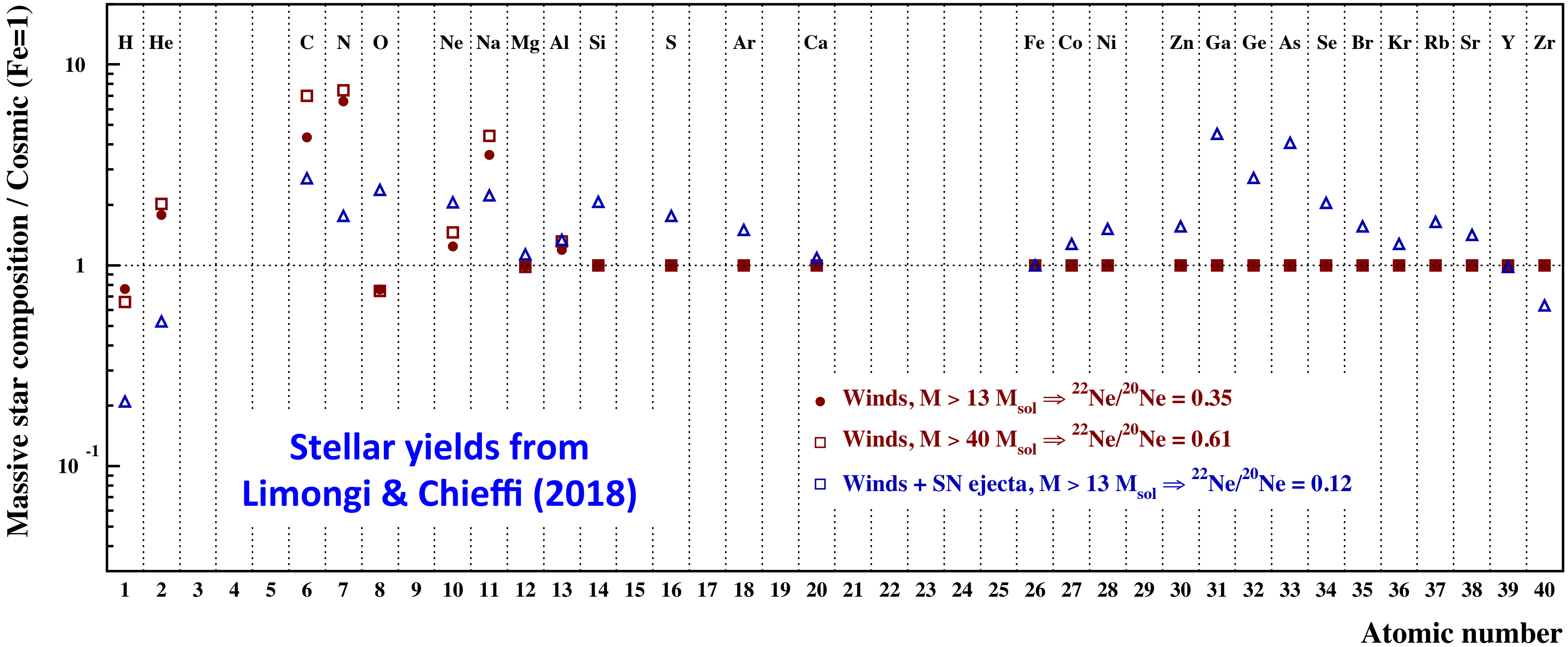
Ionisation states in shock precursors

- **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

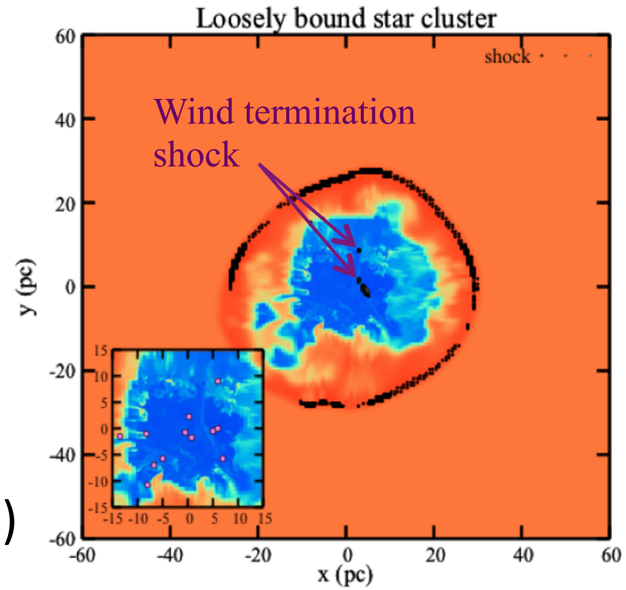
- GCR $^{22}Ne/^{20}Ne = 0.317$ (Boschini et al. 2020), i.e. ~ **5 times the solar ratio**
- Mix of **massive star winds and SN ejecta** in SB cores? **No, $^{22}Ne/^{20}Ne$ too low**
- **Only massive star winds** in SB cores? **No, $^{22}Ne/^{20}Ne$ still too low**
- Winds from **very massive stars**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

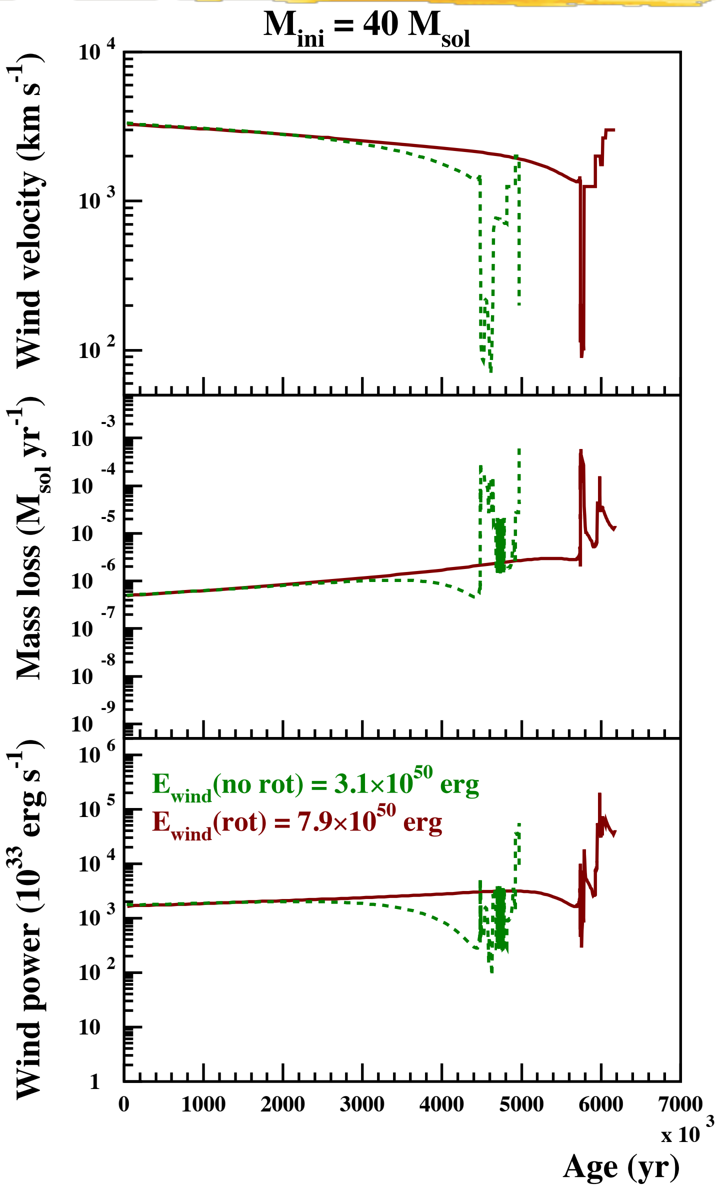


GCR ^{22}Ne from wind termination shocks

- 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**

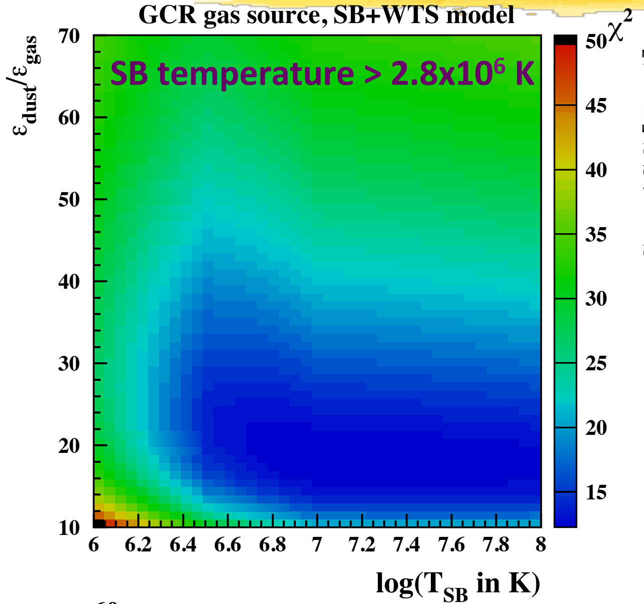
⇒ **^{22}Ne/^{20}Ne=1.56** in the accelerated wind compo.

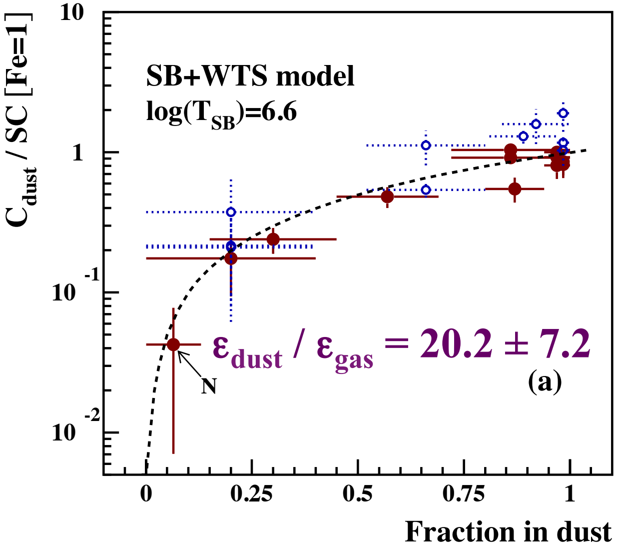
Results of the GCR composition model

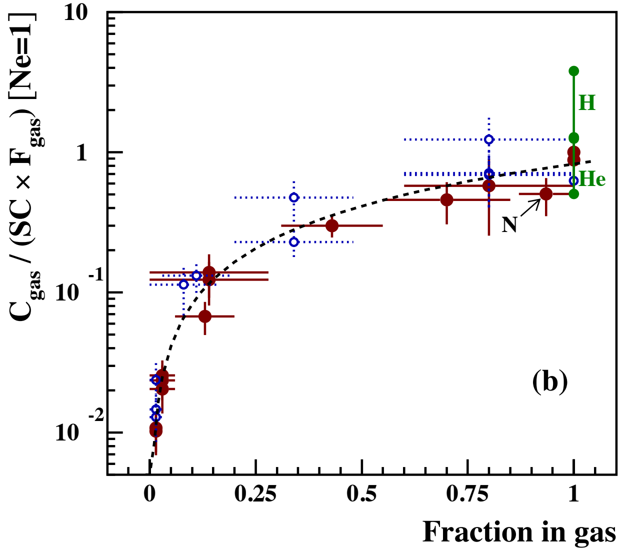
	Model 1	Model 2	Model 3	Model 4	Model 5
GCR gas source of SC compo.	70% WNM, 30% WIM	SB	SB	60% SB, 28% WNM, 12% WIM	60% SB, 28% WNM, 12% WIM
^{22}Ne-rich GCR gas source	Accelerated winds	Winds in SB	Accelerated winds	Winds in SB	Accelerated winds
SB temperature $\log(T_{SB})^a$	–	6.50 ± 0.25	> 6.45	$6.5^{+0.3}_{-0.2}$	> 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%	48.9%	(5.1 – 6.1)%	$(55.6^{+1.3}_{-0.3})$%	(7.3 – 7.9)%
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%	48.9%	5.9%	56.0%	7.7%
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

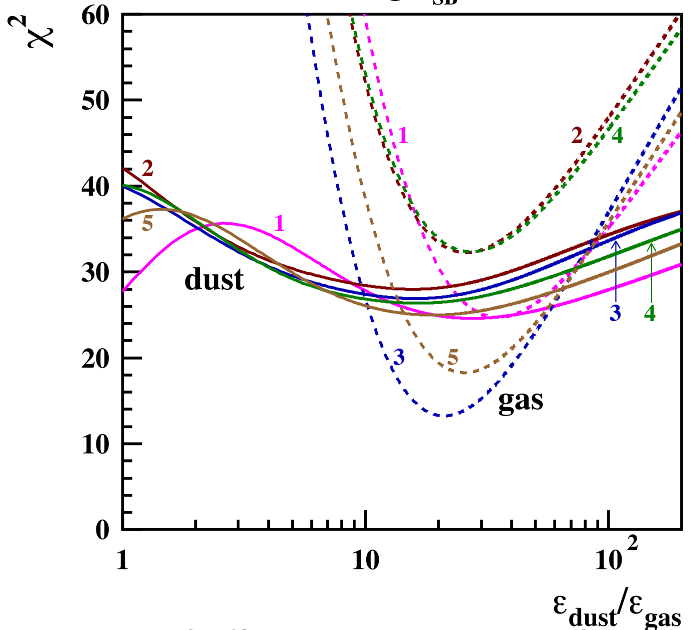
- Five models depending on the relative weights of the **ISM phases** in the GCR volatile production, and the **origin of GCR ^{22}Ne**
- Best-fit model: GCR volatiles accelerated in **superbubbles** + ^{22}Ne-rich component from acceleration in **wind termination shocks** ($x_w \approx 6\%$)

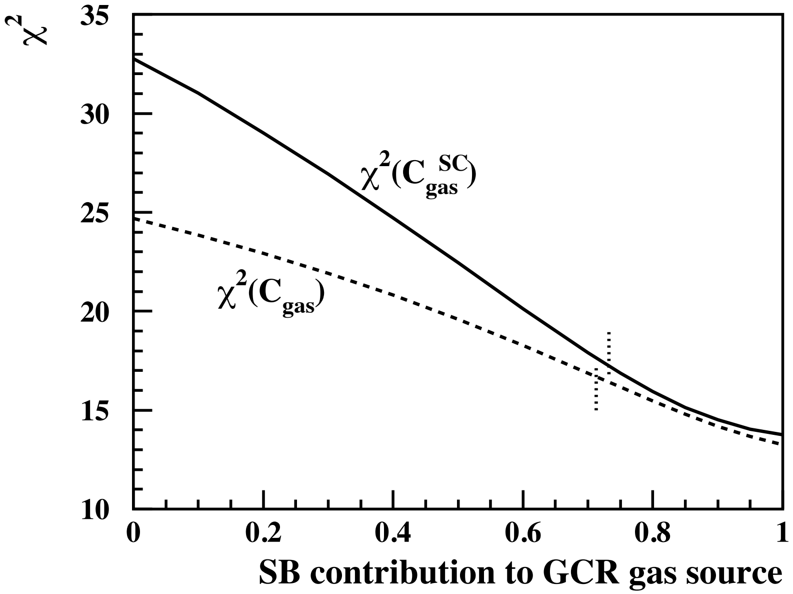
Results of the GCR composition model





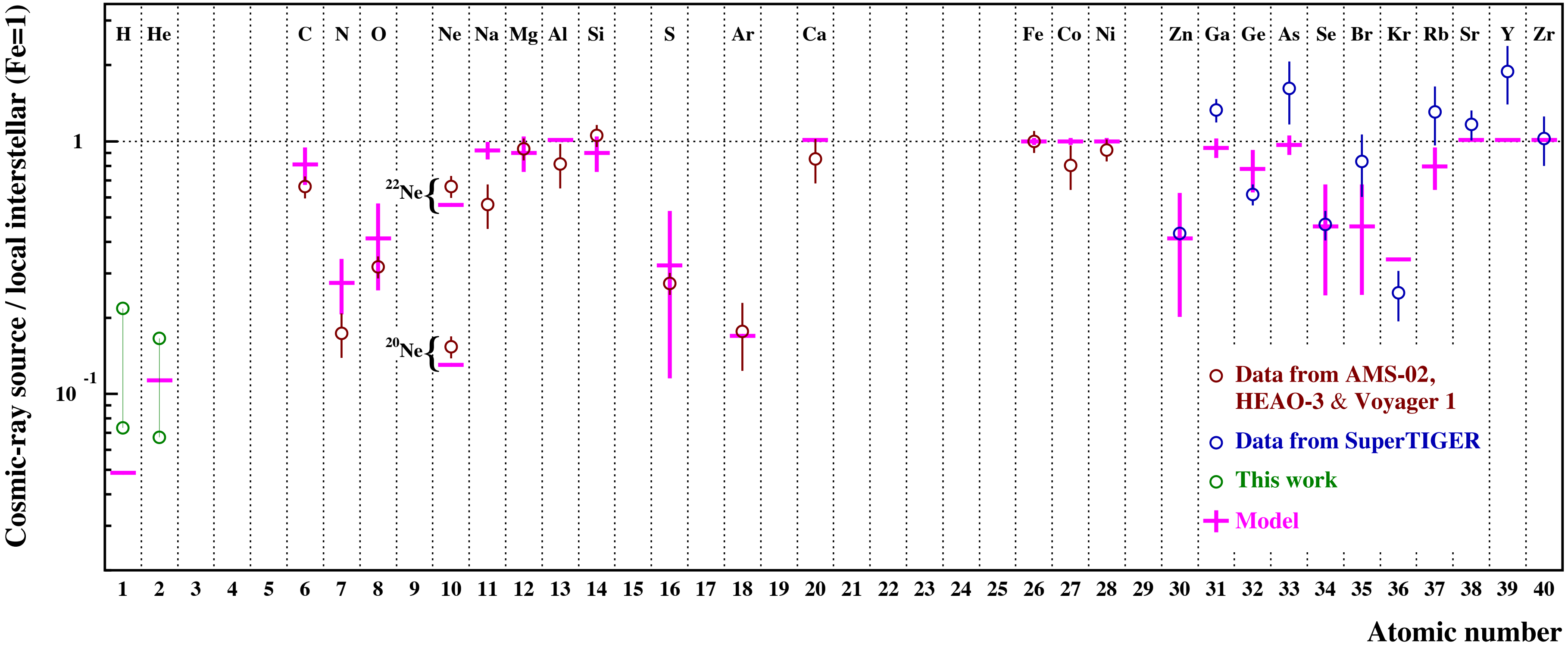






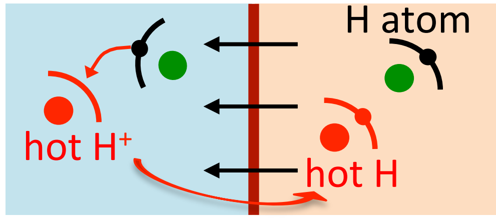
SNRs in the warm ISM contribute for less than 28%

GCR origin in superbubbles

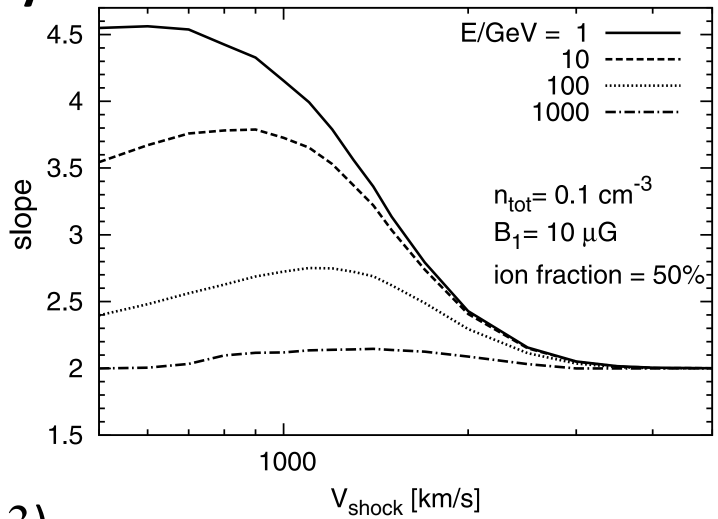


- SNRs in the warm ISM contribute to the GCR volatile composition for less than 28% , whereas ~40% of SNe occur in this phase and not in SBs => **effects of neutral atoms on the acceleration process** (e.g. neutral return flux; Morlino et al. 2013)?
- **GCR refractories might also be produced in SBs**, if dust is continuously replenished in SB interior through thermal evaporation of molecular clouds in contact with the hot plasma (see Ochsendorf et al. 2015 for the Orion-Eradinus SB)

Effects of the neutral return flux



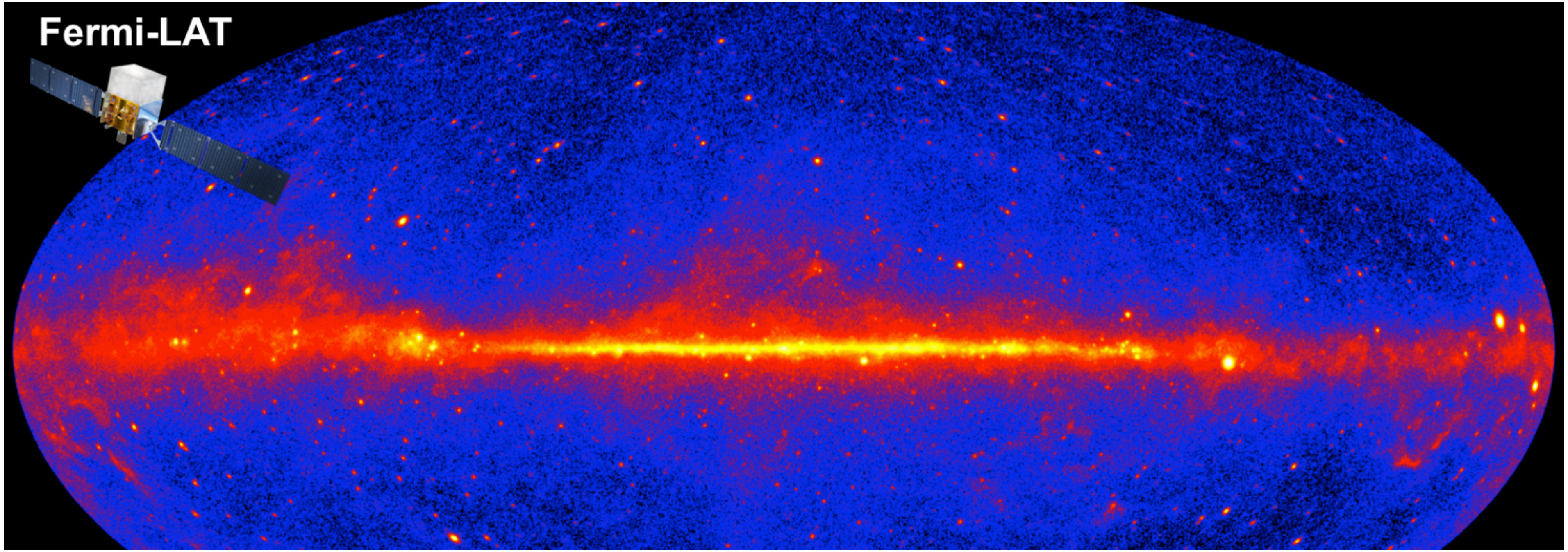
- Production of hot neutral hydrogen that may deposit kinetic energy in the shock upstream medium
  - ⇒ Heating of the upstream plasma
  - ⇒ Reduction of the shock Mach number
  - ⇒ **Reduction of the particle acceleration efficiency**



- For a neutral fraction of $\sim 50\%$ (WNM), significant effects of the NRF for shock velocities $\lesssim 3000$ km/s (Blasi et al. 2012; Morlino et al. 2013)
- Assuming CR production only for $V_{\rm s} > V_{\rm s,min}$ with
  - $V_{\rm s,min}$(WNM) = 3000 km/s
  - $V_{\rm s,min}$(WIM) = 300 km/s (ineffective acceleration in radiative shocks; Raymond et al. 2020)
  - $V_{\rm s,min}$(SB) = 600 km/s (=> Mach number $M_{\rm S,min} = 3$)
- Swept-up masses in the adiabatic stage: $M^k_{\rm s.-u.} \approx 68\ {\rm M}_\odot \left(\frac{E_{\rm SN}}{10^{51}\ {\rm erg}}\right)\left(\frac{V^k_{s,\rm min}}{1000\ {\rm km\ s^{-1}}}\right)^{-2}$

⇒ Relative contribution of the ISM phases to the GCR volatile production: $f_{\rm SB}$=55%, $f_{\rm WIM}$=44%, $f_{\rm WNM}$=1% ⇒ **no good fit to the data** ($\chi^2_{\rm min}$=24.0)

GCR acceleration efficiency



- Efficiency of GCR production from the **γ-ray luminosity of the Milky Way** and the proton source spectrum: $N_{GCR}(p) \approx (0.2 - 1.5)\times10^{45}$ protons s^{-1}

- 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

- 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}**
  ⇒ Escape of low-energy CR from their sources? Source spectrum differences between p, α-particles and heavy nuclei?

- CR volatiles are mostly accelerated in **Galactic superbubbles**, from SN shocks sweeping up a plasma of $T_{\rm SB} > 2.8$ MK
  ⇒ CR production in superbubbles, up to and above 10^{15} eV (Vieu et al. 2021)?

- 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
  ⇒ Diffusive shock acceleration in wind termination shocks (Morlino et al. 2021)

- The GCR refractories most likely originate from the **acceleration and sputtering of dust grains** in SNR shocks, and might be produced in superbubbles as well
  ⇒ Update of the grain acceleration model of Ellison et al. (1997) based on current knowledge of dust in the ISM

Extra slides

GCR composition model

- Relative contributions of the ISM dust and gas reservoirs in the measured GCR abundances:

$$C_{\rm dust}(i) = \frac{C_{\rm mes}(i)}{\left(1 + \frac{1-f_d(i)}{f_d(i)} \cdot \frac{x_w f_w(i) f_{A/Q}^{w}(i) + (1-x_w) f_{A/Q}^{\rm SC}(i)}{\epsilon}\right)},$$

$$C_{\rm gas}(i) = \frac{C_{\rm mes}(i)}{\left(1 + \frac{f_d(i)}{1-f_d(i)} \cdot \frac{\epsilon}{x_w f_w(i) f_{A/Q}^{w}(i) + (1-x_w) f_{A/Q}^{\rm SC}(i)}\right)},$$

- GCR abundances arising from the gas reservoir of standard cosmic composition:

$$C_{\rm gas}^{\rm SC}(i) = \frac{C_{\rm mes}(i)}{\left(1 + \frac{f_d(i)}{1-f_d(i)} \cdot \frac{\epsilon}{(1-x_w) f_{A/Q}^{\rm SC}(i)} + \frac{x_w f_w(i) f_{A/Q}^{w}(i)}{(1-x_w) f_{A/Q}^{\rm SC}(i)}\right)}$$