

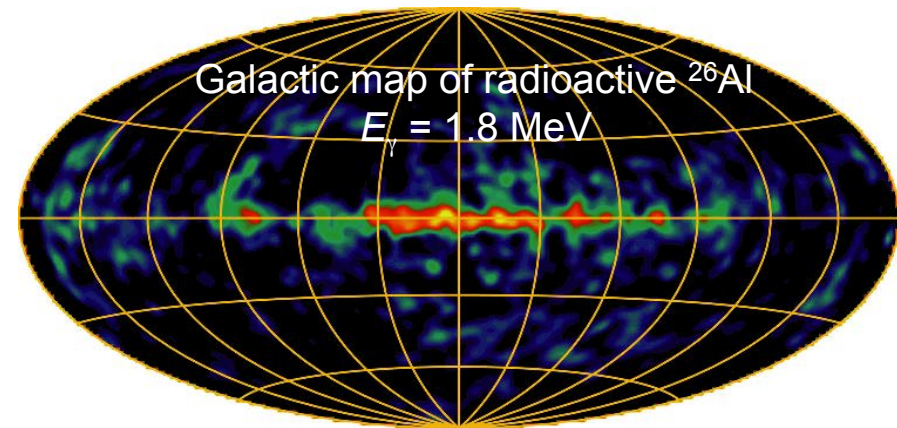
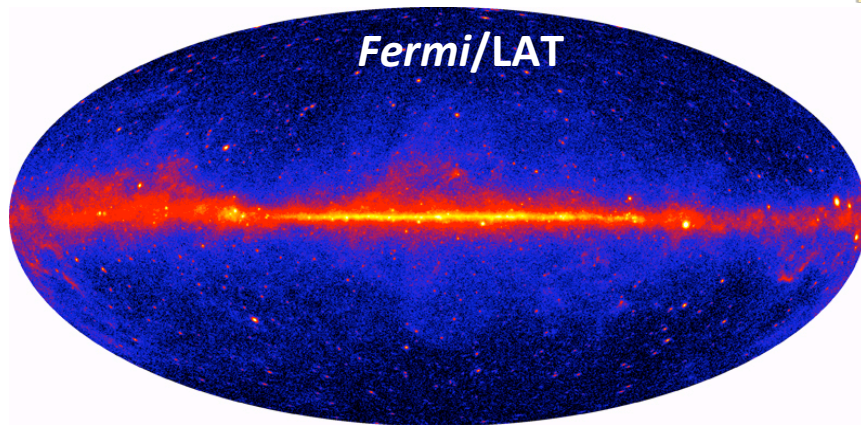
The background of the slide is a deep space image featuring a dark field filled with numerous stars of varying brightness. A prominent, vibrant nebula with swirling patterns of purple, pink, and orange is visible in the lower half of the frame. A thick, horizontal yellow brushstroke is positioned above the main title.

The Origin of Galactic Cosmic Rays as Revealed by their Composition

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Stefano Gabici & Sarah Recchia*
MNRAS, in press ([arXiv:2106.15581](https://arxiv.org/abs/2106.15581))

On the origin of Galactic Cosmic Rays

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- 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: $L_{\text{CR}} = L_\gamma / R_\gamma \sim 10^{41} \text{ erg/s}$,
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 $\sim 5 \times 10^{38} \text{ erg/s}$ (Fermi/LAT; see Strong et al. 2010)
 - ✓ Kinetic power supplied by supernovae: $L_{\text{SN}} = E_{\text{SN}} \times f_{\text{SN}} \sim 10^{42} \text{ erg/s}$,
where $E_{\text{SN}} \sim 1.5 \times 10^{51} \text{ erg}$ is the mean energy of a SN and $f_{\text{SN}} \sim 50 \text{ yr}^{-1}$ is the
SN rate in the Milky Way (from the present-day mass of ^{26}Al ; Diehl+ 2006)
- **From which phase(s) of the ISM are the CRs extracted? Do all supernovae contribute equally to the CR production? => GCR composition**

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

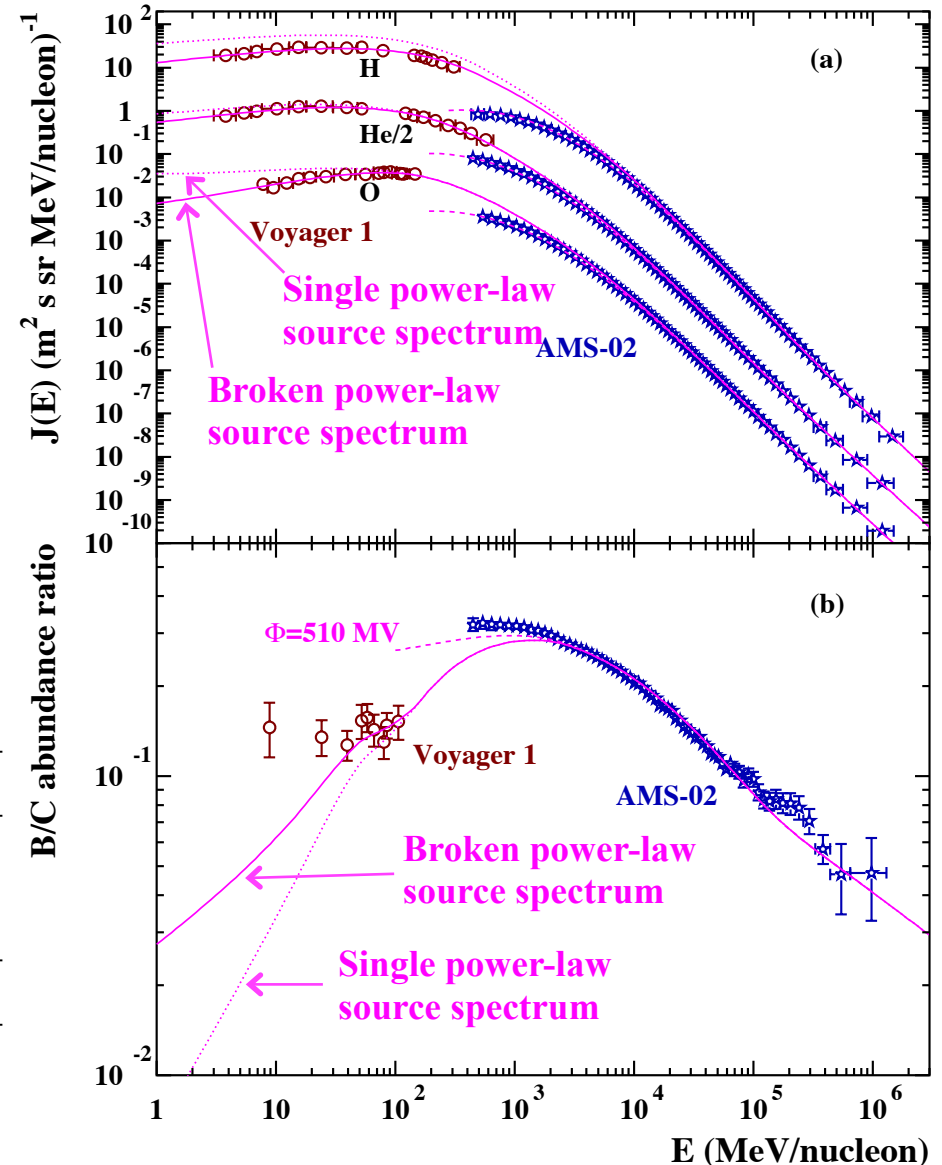
Table 2. CR source spectrum parameters (Eq. 2).

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

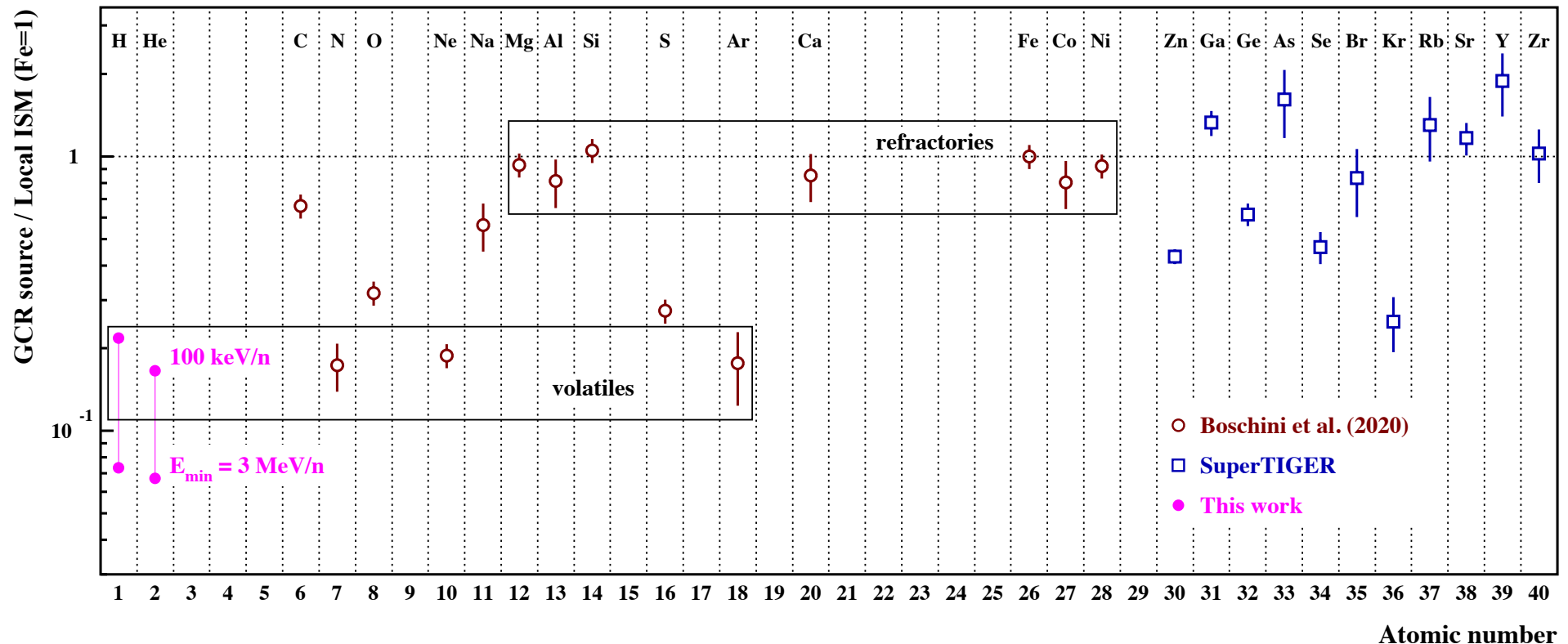
^a Parameter fixed from [Evoli et al. \(2019\)](#).

^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

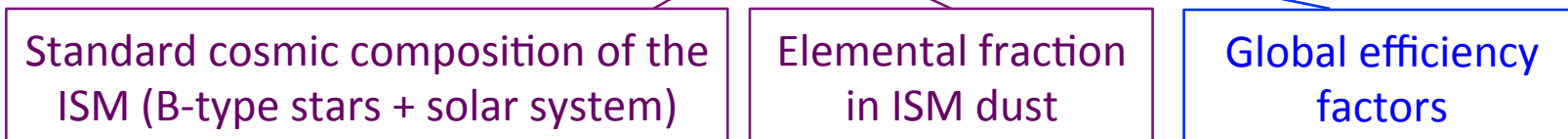


- Abundances from **integration of source spectra** => the abundances of H and He are similar to those of the other volatiles N, Ne and Ar, provided that the **minimum CR source energy is of the order of a few hundred keV/n**
- Highly refractory elements Mg, Al, Si, Ca, Fe, Co, and Ni are in solar system proportions => acceleration of various **dust grains of the ISM mix**

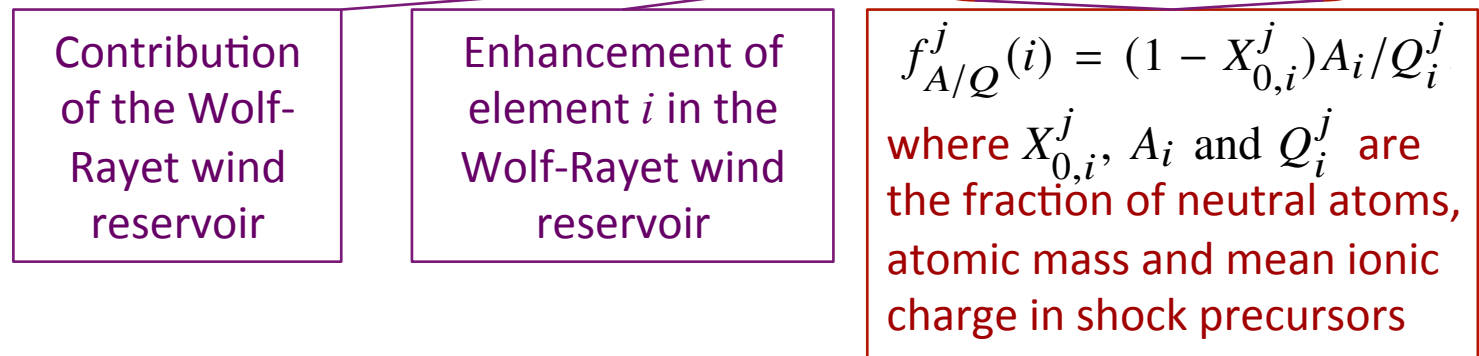
GCR composition model

- Measured GCR source abundances: $C_{\text{mes}}(i) = C_{\text{gas}}(i) + C_{\text{dust}}(i)$

- Dust contribution: $C_{\text{dust}}(i) = \text{SC}(i) f_d(i) \epsilon_{\text{dust}}$



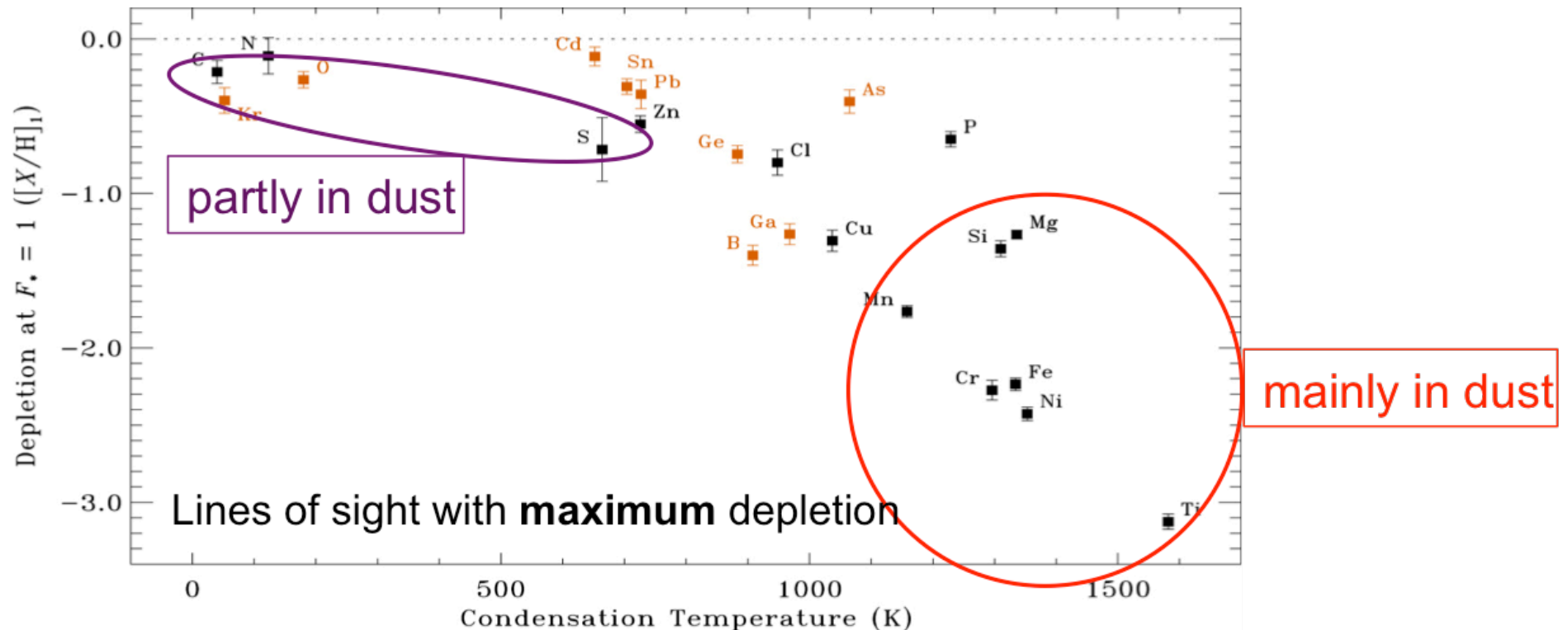
- Gas contribution: $C_{\text{gas}}(i) = \text{SC}(i)(1 - f_d(i)) \epsilon_{\text{gas}} [x_w f_w(i) f_{A/Q}^w(i) + (1 - x_w) f_{A/Q}^{\text{SC}}(i)]$



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

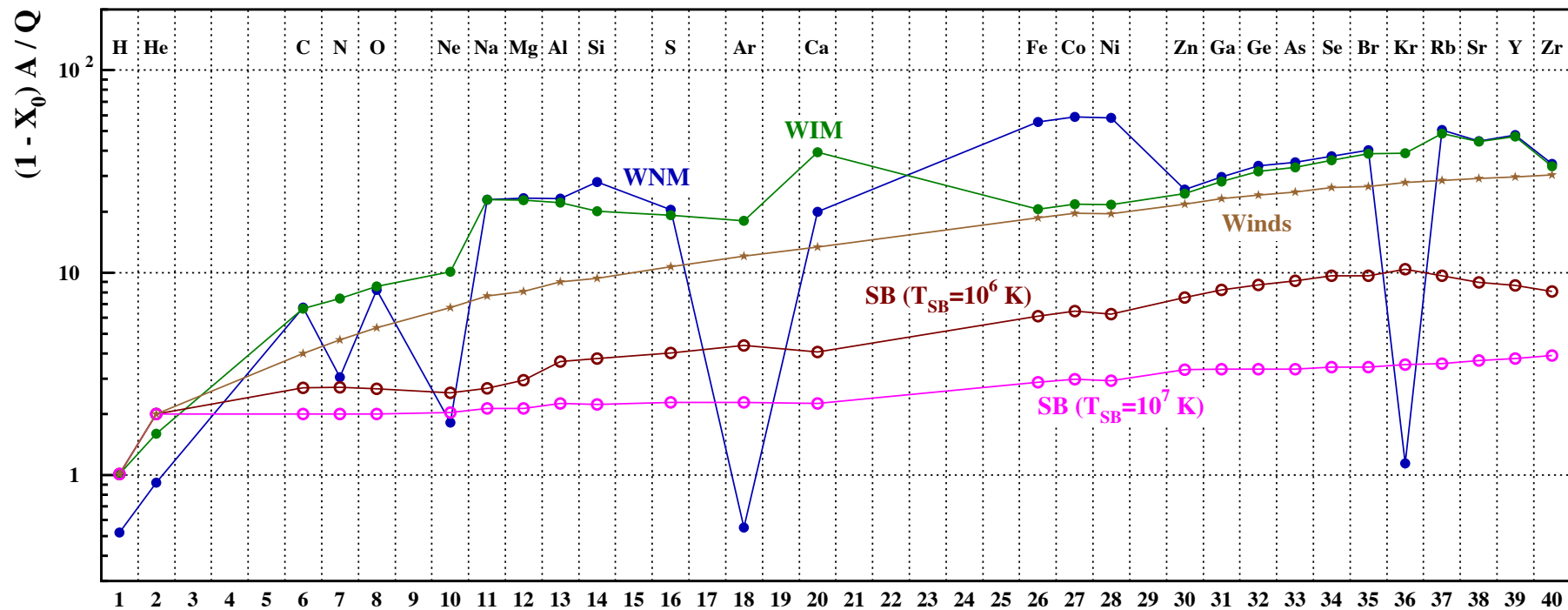
Interstellar dust composition

- **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**



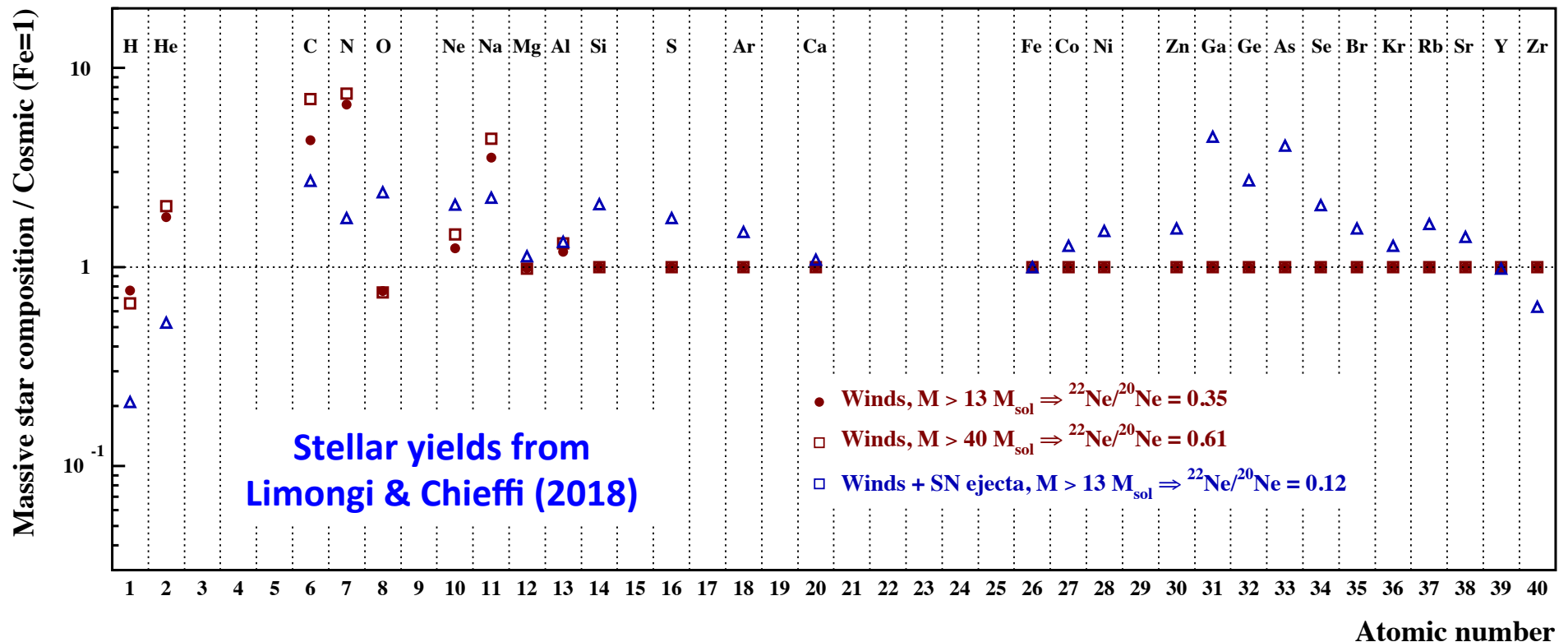
Ionisation states in shock precursors

- **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 gas⁹

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



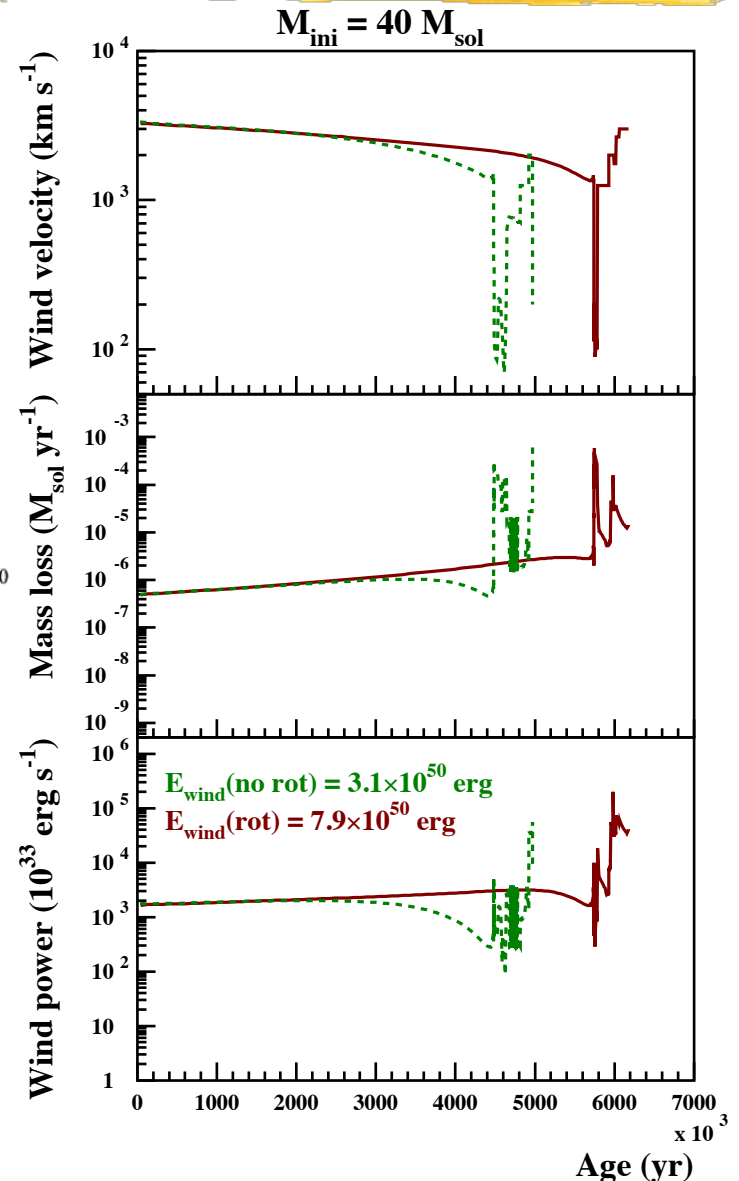
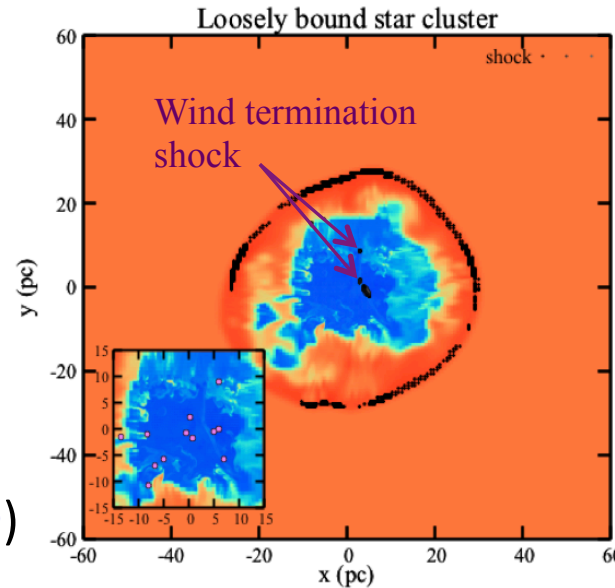
GCR ^{22}Ne from wind termination shocks ¹⁰

- 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**

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

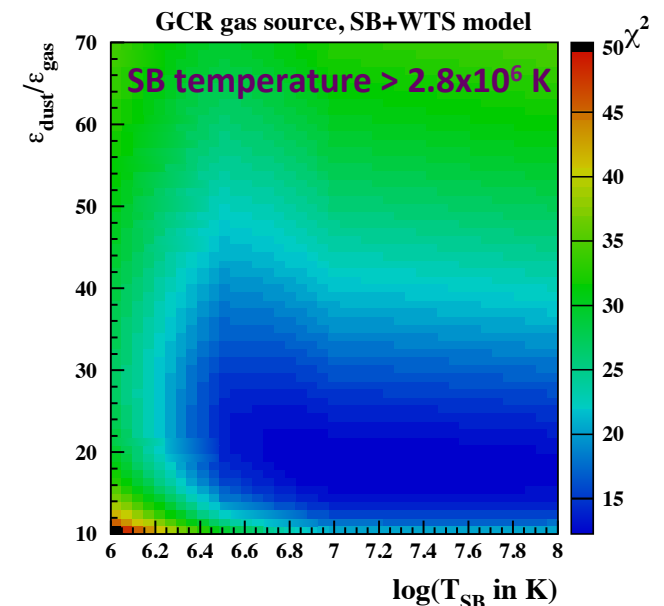
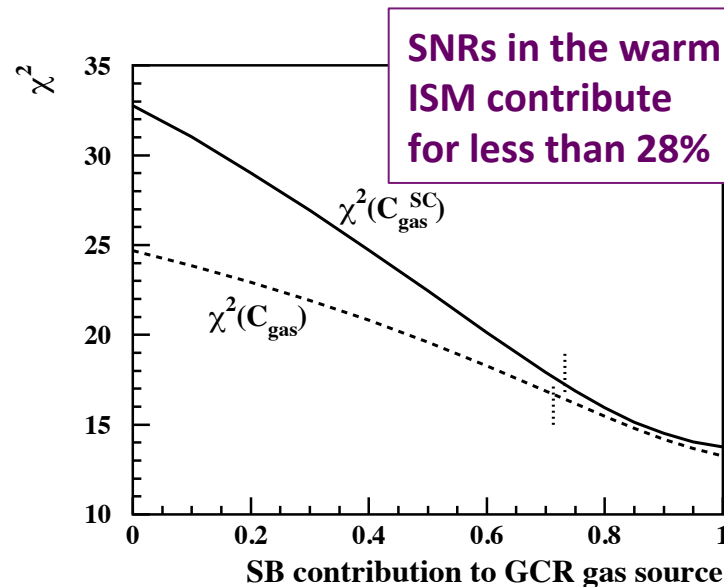
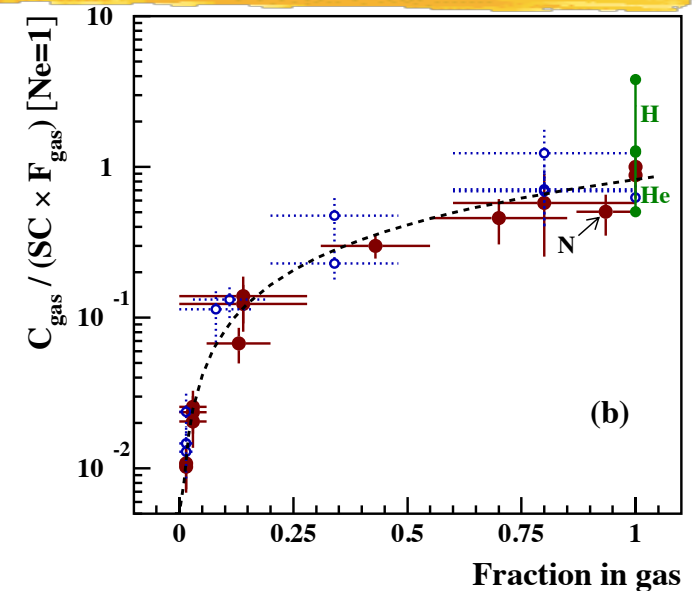
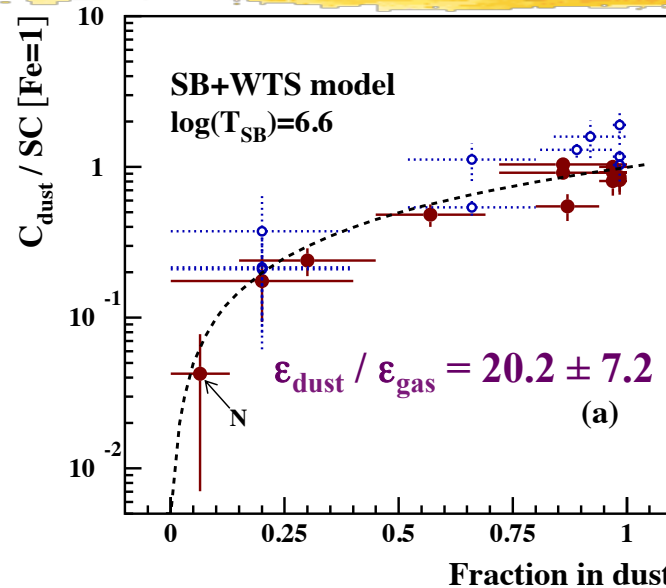


Some results of the GCR composition model

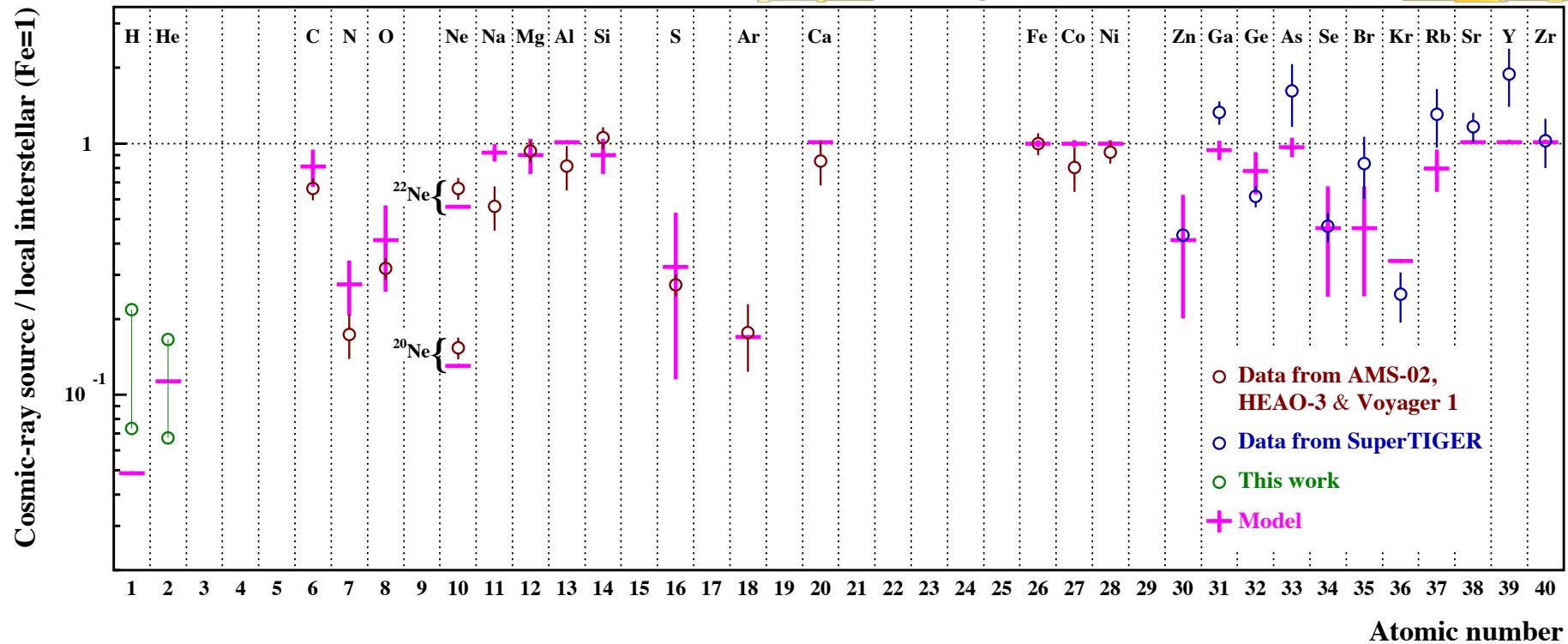
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- Various models depending on the relative weights of the **ISM phases** in the GCR production, and the **origin of GCR ^{22}Ne**

- Best-fit model:
GCR accelerated in **superbubbles** + ^{22}Ne -rich component from acceleration in **wind termination shocks** ($x_w \approx 6\%$)

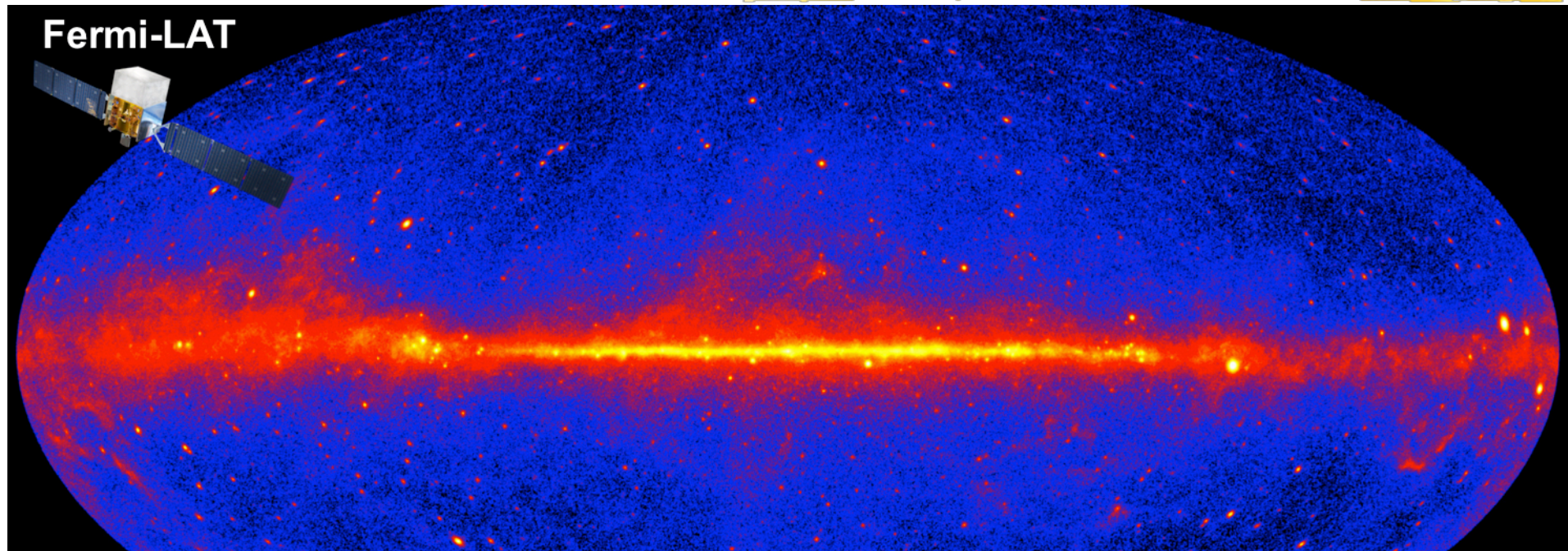


GCR origin in superbubbles



- 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-Eridanus SB)

GCR acceleration efficiency



- Efficiency of GCR production from the **γ -ray luminosity of the Milky Way** and the proton source spectrum: $N_{GCR}(p) \approx (0.2 - 1.5) \times 10^{45} \text{ protons s}^{-1}$
- Estimating the **mass of gas swept up by interstellar shocks**, we get:
 - Efficiency of acceleration of **SB gas by SN shocks**: $\eta_{SB} \approx (0.4 - 2.3) \times 10^{-5}$
 - 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**
⇒ **CR escape from their sources?**
- CR volatiles are mostly accelerated in **Galactic superbubbles**, from SN shocks sweeping up a plasma of $T_{\text{SB}} > 2.8 \text{ MK}$
⇒ **CR production in superbubbles, up to and above 10^{15} eV ?**
- 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**
- 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**