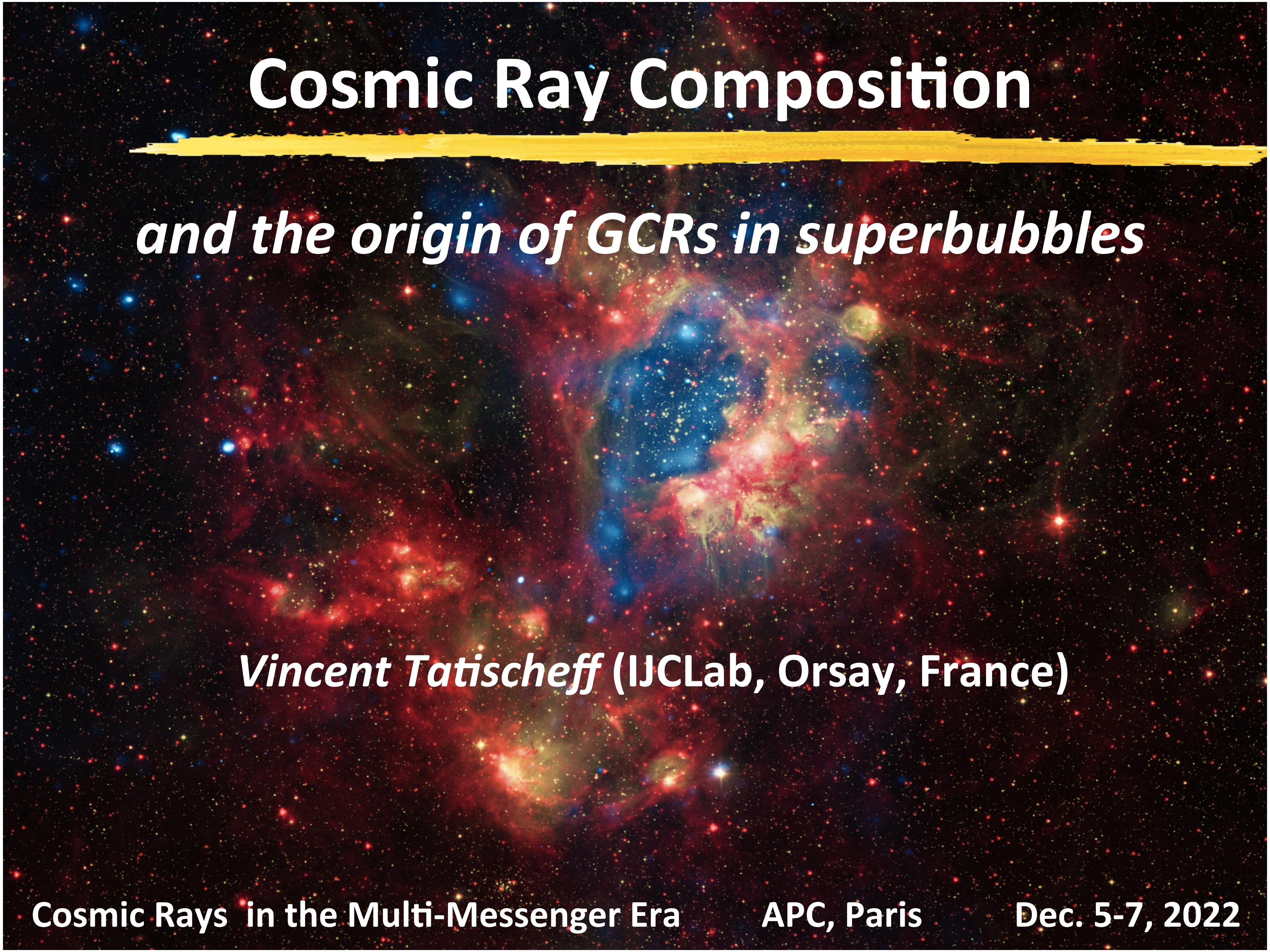


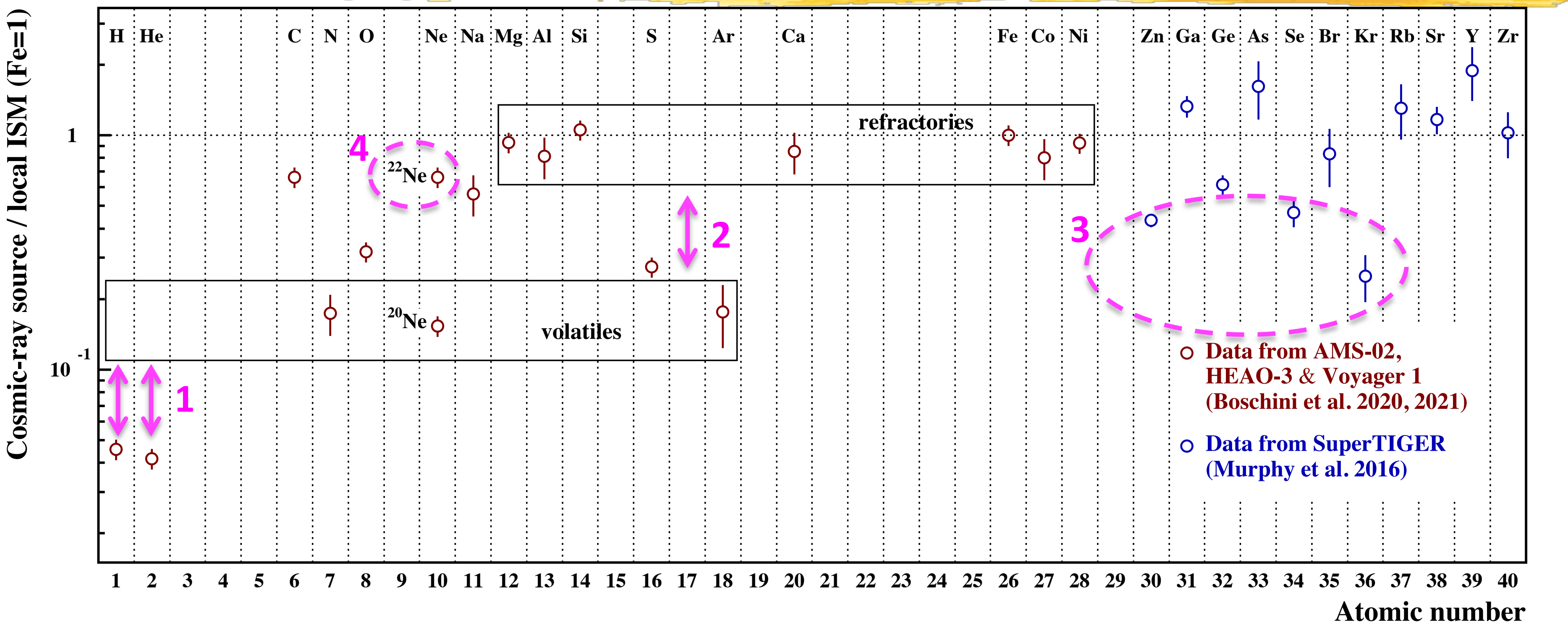
Cosmic Ray Composition

and the origin of GCRs in superbubbles

Vincent Tatischeff (IJCLab, Orsay, France)

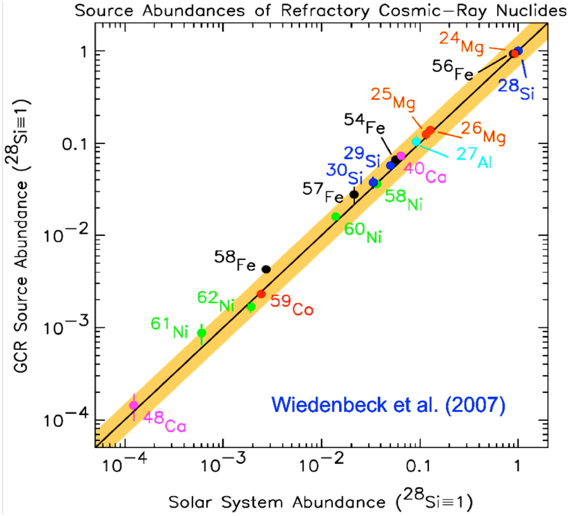
Cosmic Rays in the Multi-Messenger Era APC, Paris Dec. 5-7, 2022

GCR abundance data

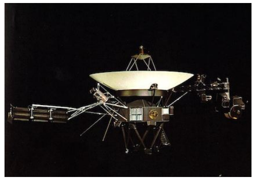


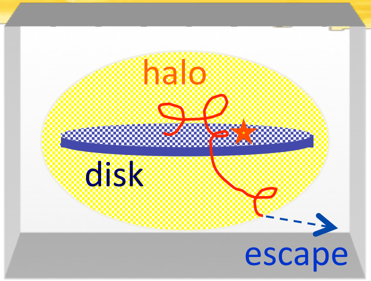
1. **Under-abundance of protons and α-particles**
2. **Overabundance of refractory elements** over volatiles
3. **Overabundance of heavier volatile elements** (Zn, Se, Kr...) compared to lighter ones (N, Ne, S, Ar...)
4. **Overabundance of ^{22}Ne**

See Meyer, Drury & Ellison (1997)



Protons, α-particles and O source spectra





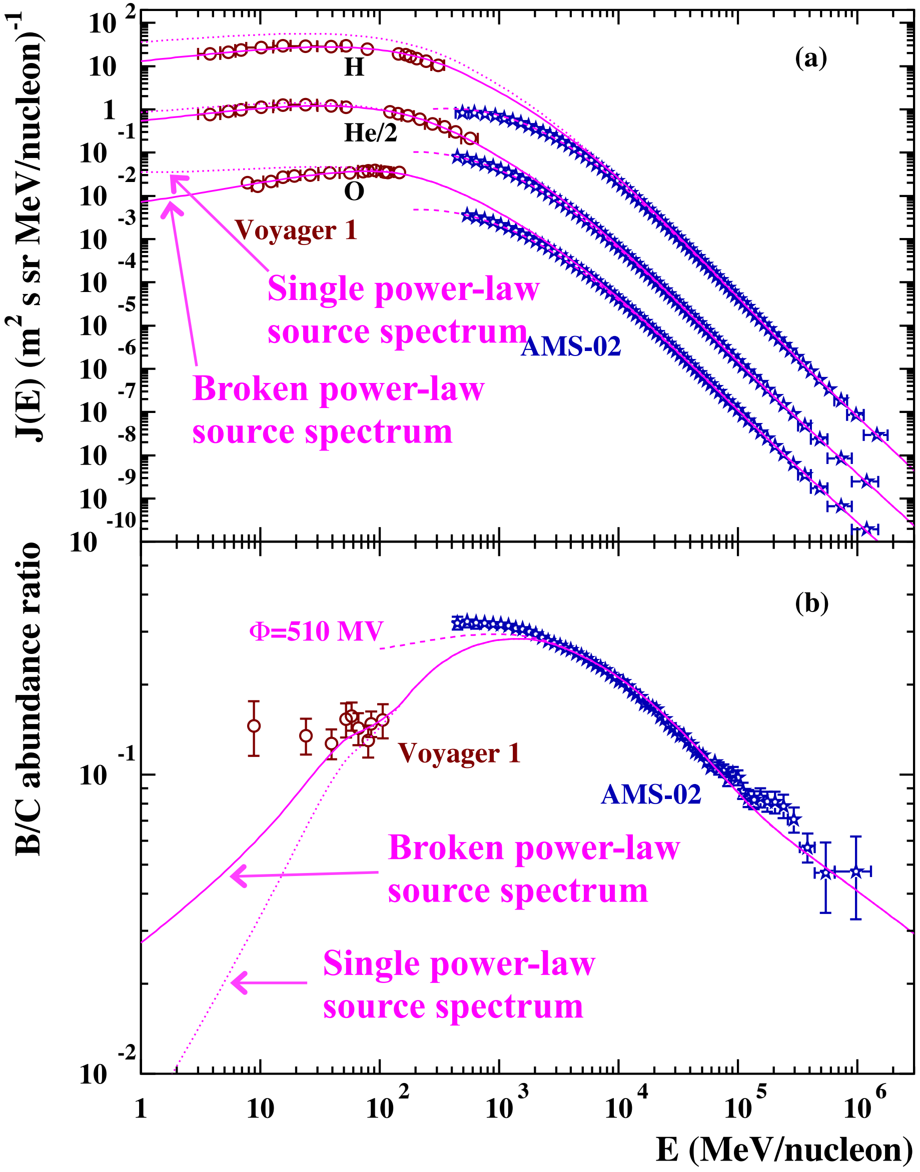
- Fit to **Voyager 1** and **AMS-02** data using a **1D advection-diffusion model** with homogeneous diffusion for the GCR propagation (Evoli et al. 2019)

- **Broken power law source spectra** from a fit of propagated spectra to the data

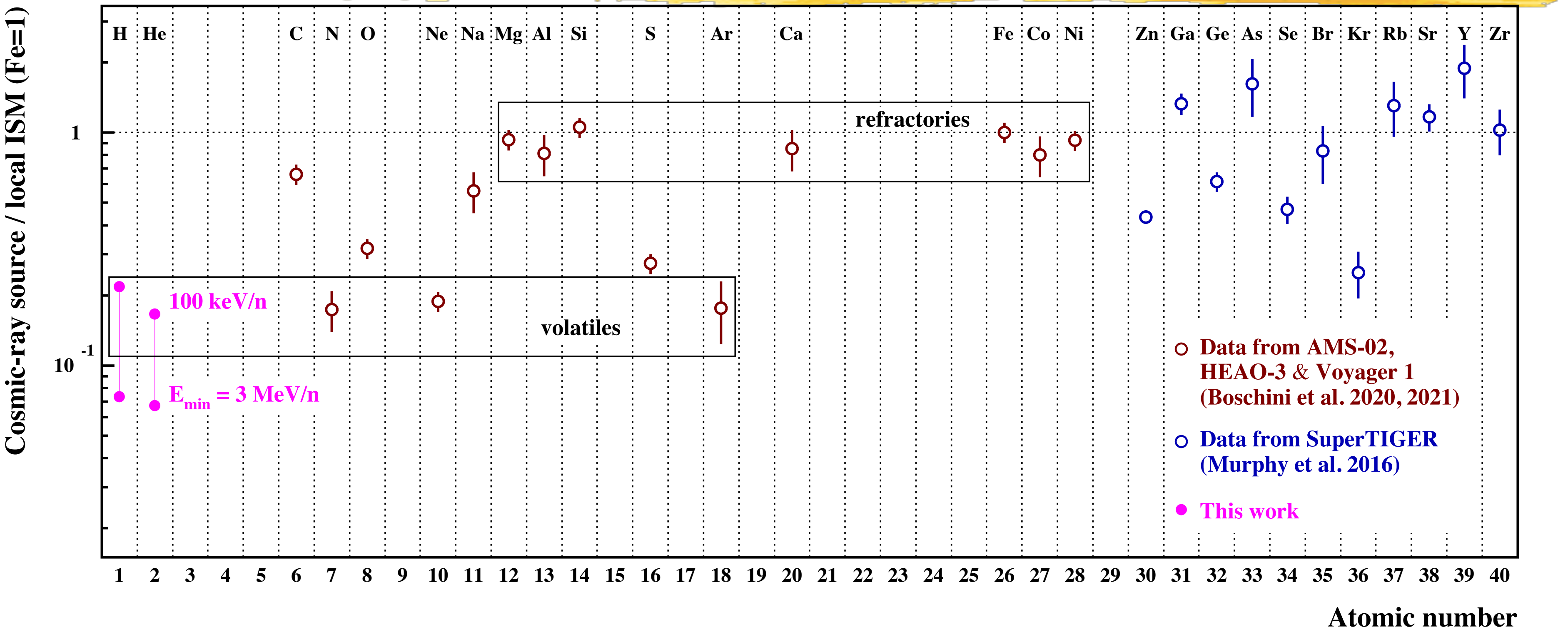
Table 2. CR source spectrum parameters (Eq. 2).

Parameter	H	He	O
$E_{\rm break}$	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.



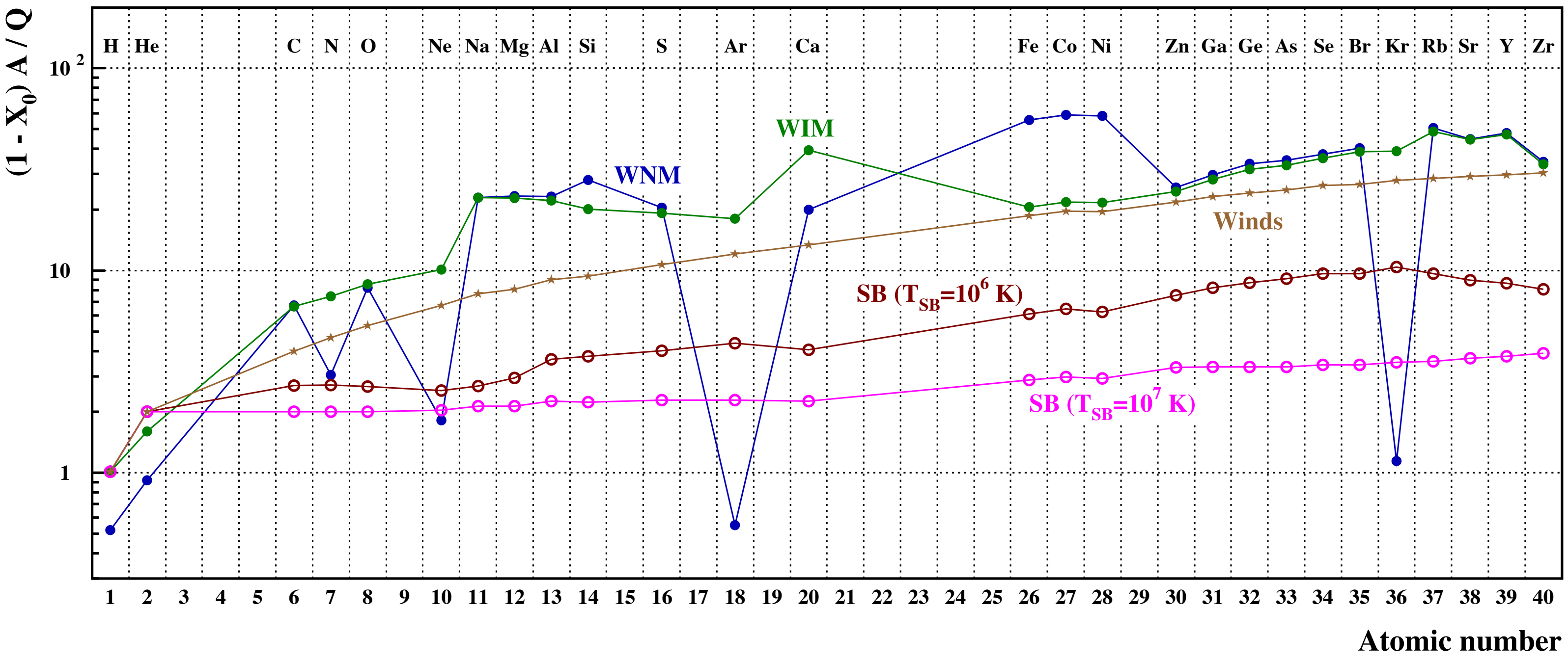
p and α-particles in the GCR composition



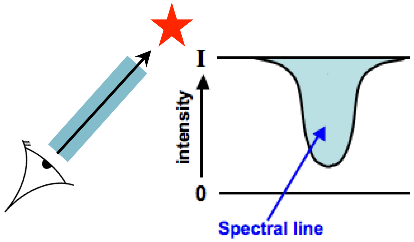
- **Integration of source spectra** => p & α abundances similar to those of the other volatiles N, Ne and Ar, provided that the **minimum CR source energy is of the order of a few hundred keV/n**
- **Escape of low-energy CR from their sources (see Schroer et al. 2022)? Source spectrum differences between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

Ionisation states in shock precursors

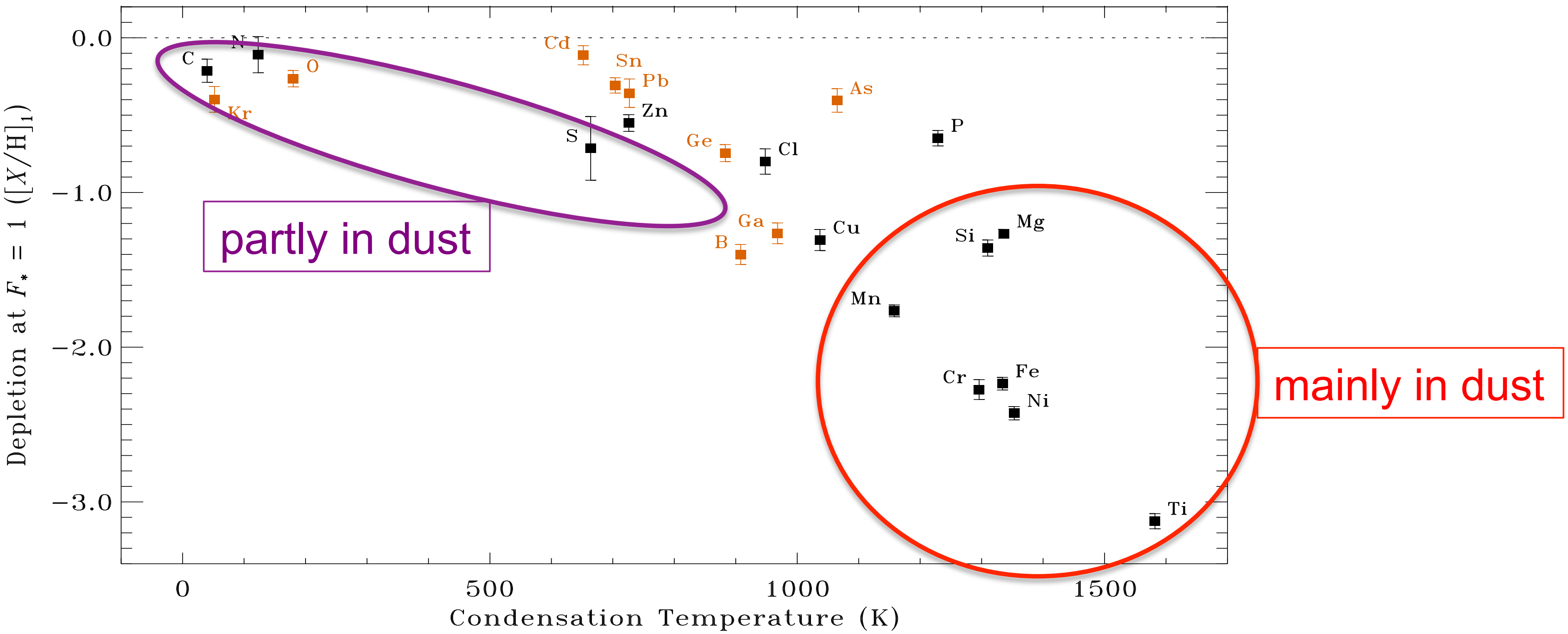
- **Dependence of acceleration efficiency on ion rigidity** expected from **nonlinear DSA** (Ellison+ 1981) and **PIC simulations** (Caprioli+ 2017) => volatile element abundances depend on **ionisation states in shock precursors** (i.e. ISM phases)
  - **Warm ISM**: **photoionization precursors** mainly 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)
  - **Stellar winds**: photoionization by EUV radiation of hot stars + EUV and X-rays from shocks in the winds => heavy elements mostly triply ionised (e.g. Hillier 2020)



Interstellar gas and 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**



partly in dust

mainly in dust

GCR composition model

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

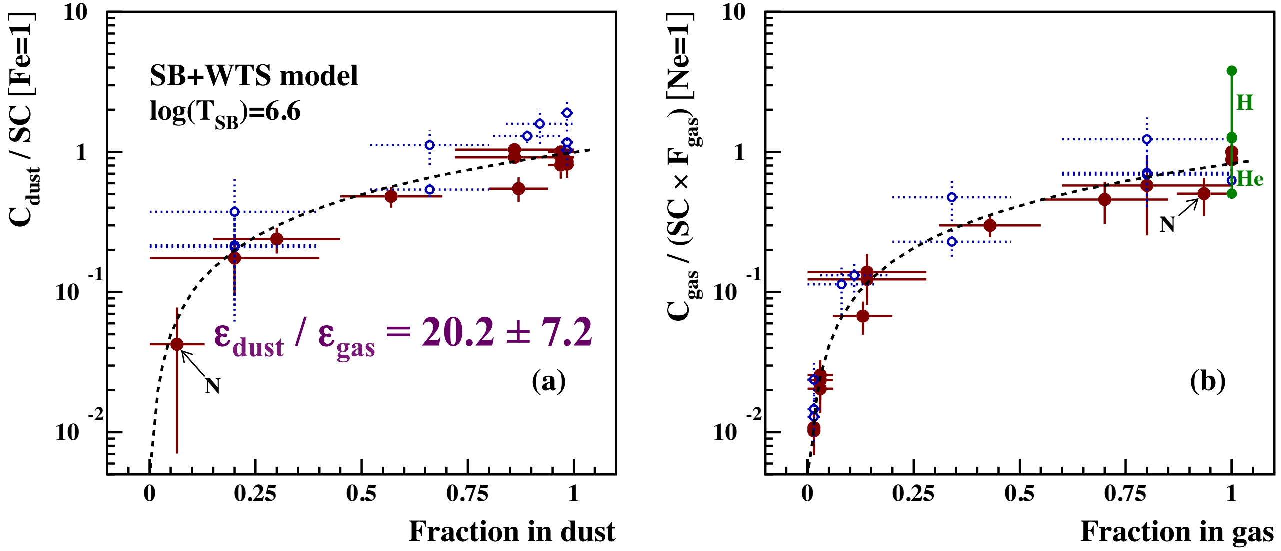
Standard cosmic composition of the ISM (B-type stars + solar system)

Elemental fraction in ISM dust

Global efficiency factors

- Gas contribution: $C_{\mathrm{gas}}(i) = \mathrm{SC}(i)(1-f_d(i))\epsilon_{\mathrm{gas}}[x_w f_w(i) f^{w}_{A/Q}(i) + (1-x_w) f^{\mathrm{SC}}_{A/Q}(i)]$
- Model inputs: **weights of ISM phases** in GCR volatile production, composition of ^{22}**Ne-rich reservoir** ($fw(i)$)

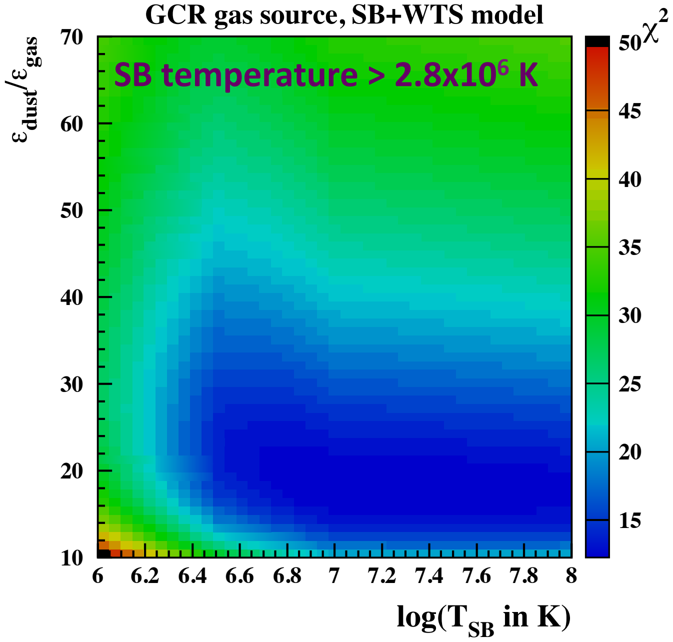
Ratio of atomic mass A to mean ionic charge in shock precursors Q, corrected to fraction of neutral atoms



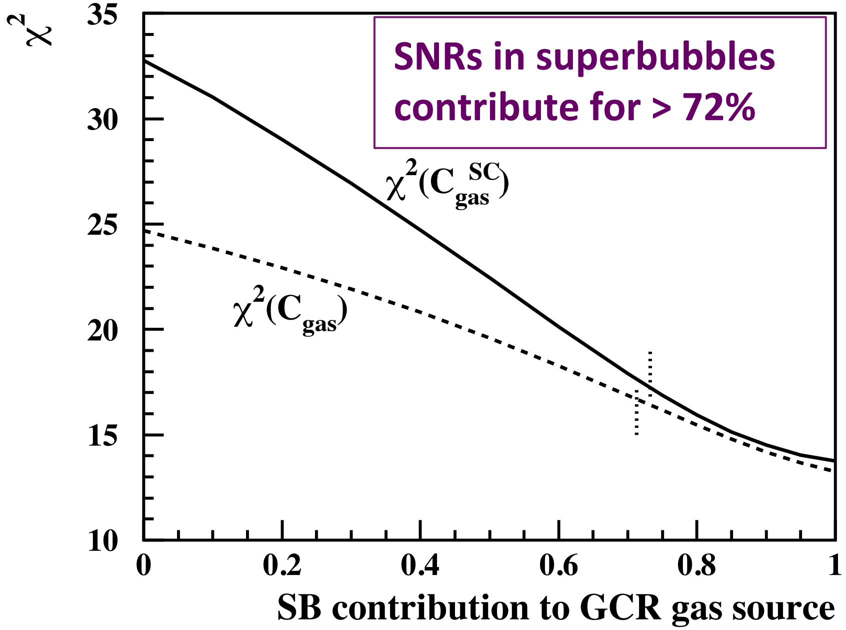
VT, J. C. Raymond, J. Duprat, S. Gabici, S. Recchia (2021)

See also Eichmann & Rachen (2021)

Origin of GCR volatiles in superbubbles

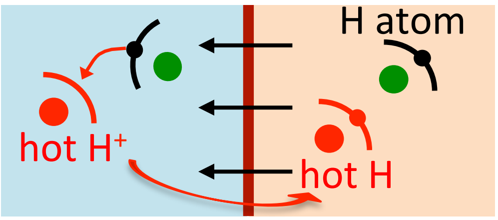


SB temperature > 2.8×10^6 K

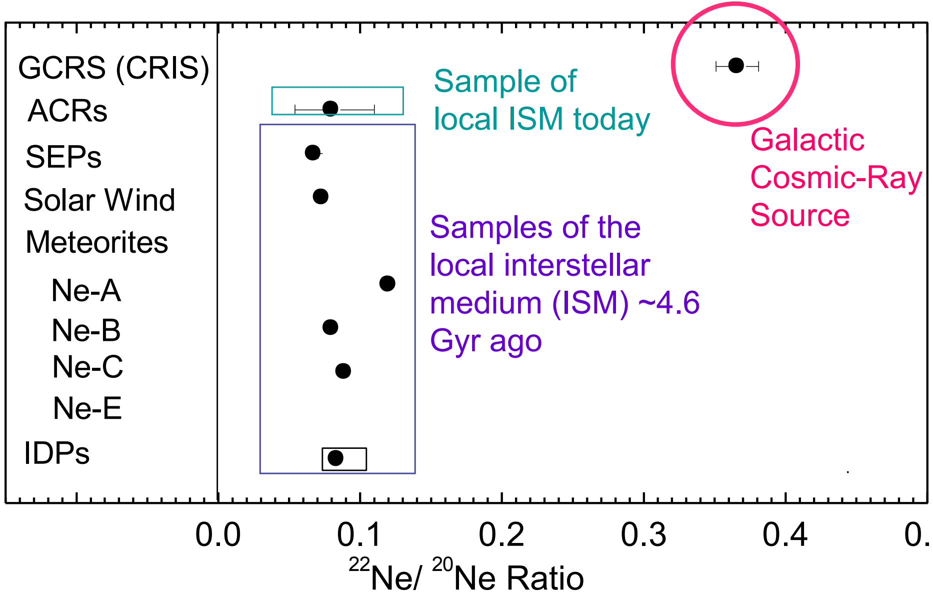


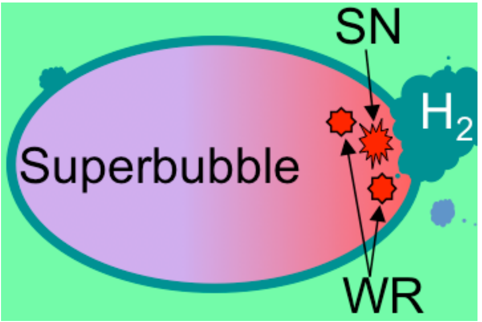
SNRs in superbubbles contribute for > 72%

- SNRs in warm ISM contribute to the GCR volatile composition for < 28%, whereas ~ 40% of SNe occur in this phase and not in SBs (e.g. Lingenfelter & Higdon 2007)
- Effects of neutral atoms on the acceleration process: ion-neutral damping, **neutral return flux** (Morlino et al. 2013)?
  ⇒ Heating of the upstream plasma
  ⇒ Reduction of the shock Mach number
  ⇒ **Reduction of the particle acceleration efficiency**

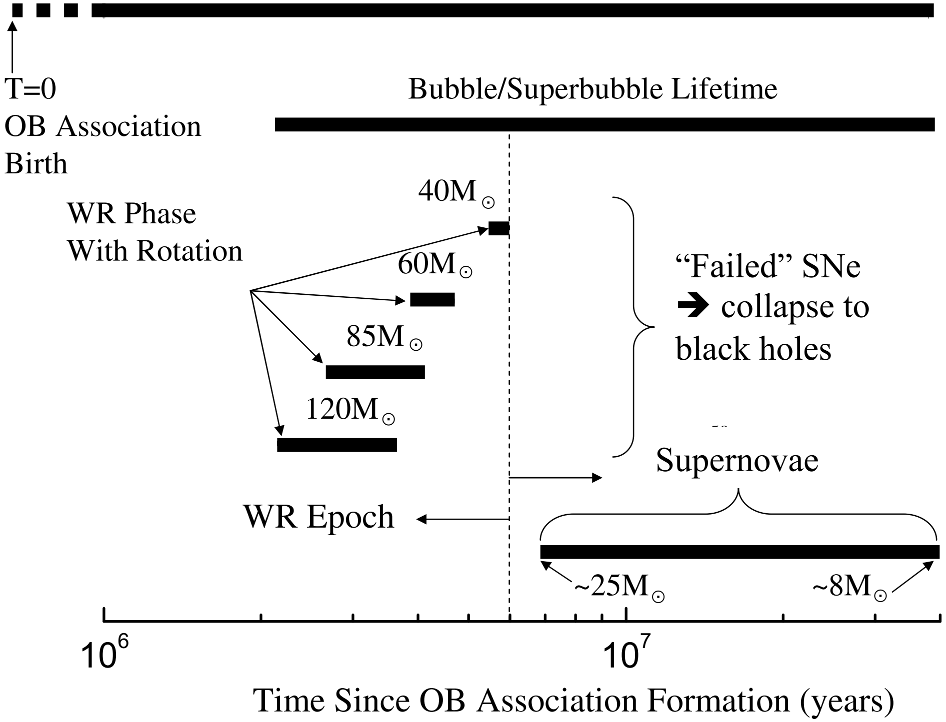


^{22}Ne abundance in GCRs





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** ($^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ during He burning)? (Cassé & Paul 1982)
- GCR origin in **superbubbles** enriched in ^{22}Ne from winds of massive stars?

GCR ^{22}Ne NOT from enriched superbubble gas

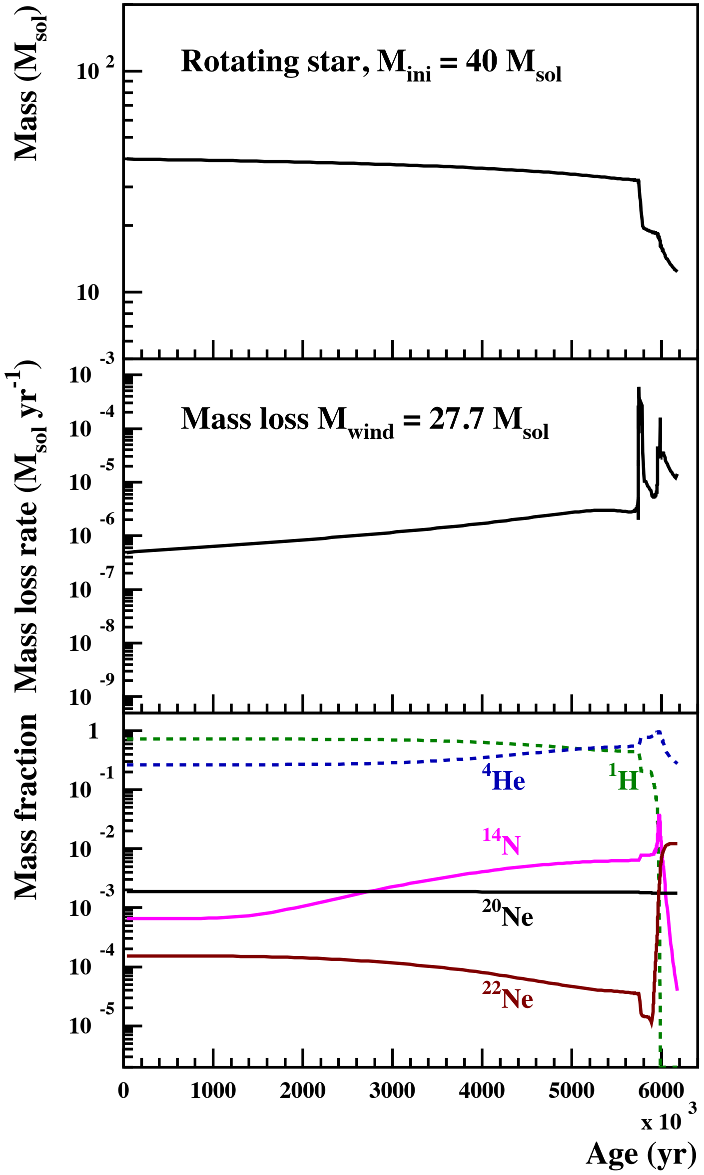
- Composition of **massive star (MS) winds and supernova (SN) ejecta** from stellar yields of Limongi & Chieffi (2018)

⇒ **(^{22}Ne/^{20}Ne)$_{\text{wind+SN}}$=0.12**, close to solar, as MS winds and SN ejecta are the main sources of ^{20}Ne and ^{22}Ne in the Universe (Prantzos 2012)

- Enrichment of superbubble gas only by winds from **MS ≥ 40 M$_{\text{sol}}$** (Binns et al. 2008)

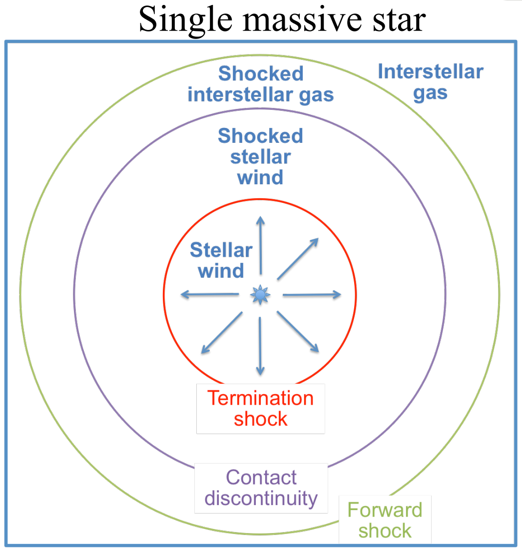
⇒ **(^{22}Ne/^{20}Ne)$_{\text{wind}}$=0.61**, would require $x_w \approx 50\%$ mixing of MS winds with material of solar composition, but a **high metallicity of SB gas is not supported by X-ray observations** (e.g. Kavanagh 2020)

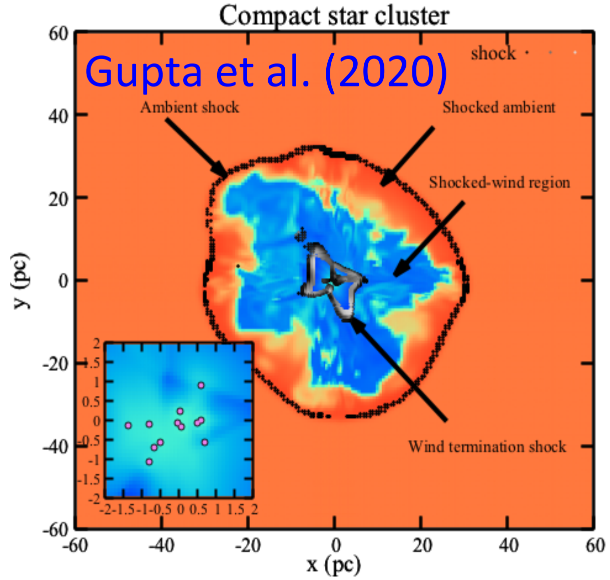
⇒ **(N/Ne)$_{\text{wind}}$=2.6**, **5.5x the ratio in the GCR source composition**, as MS loose **large amounts of ^{14}N** during the main sequence, and Wolf-Rayet WN phases

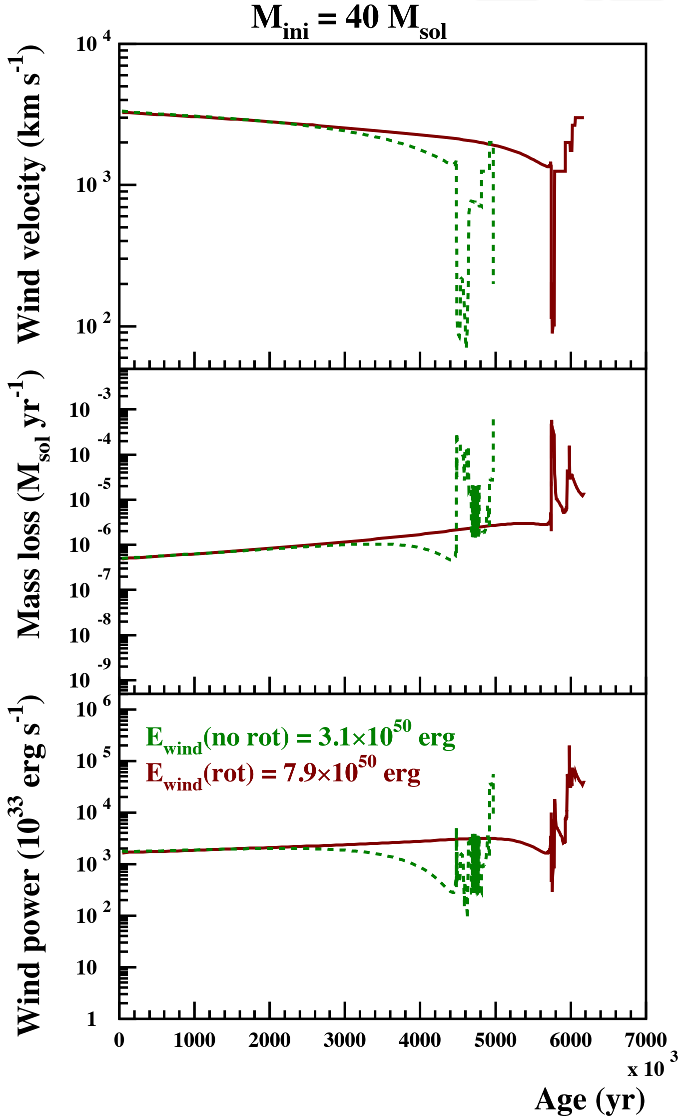


From the Geneva Observatory database

GCR ^{22}Ne from wind termination shocks




Gupta et al. (2020)



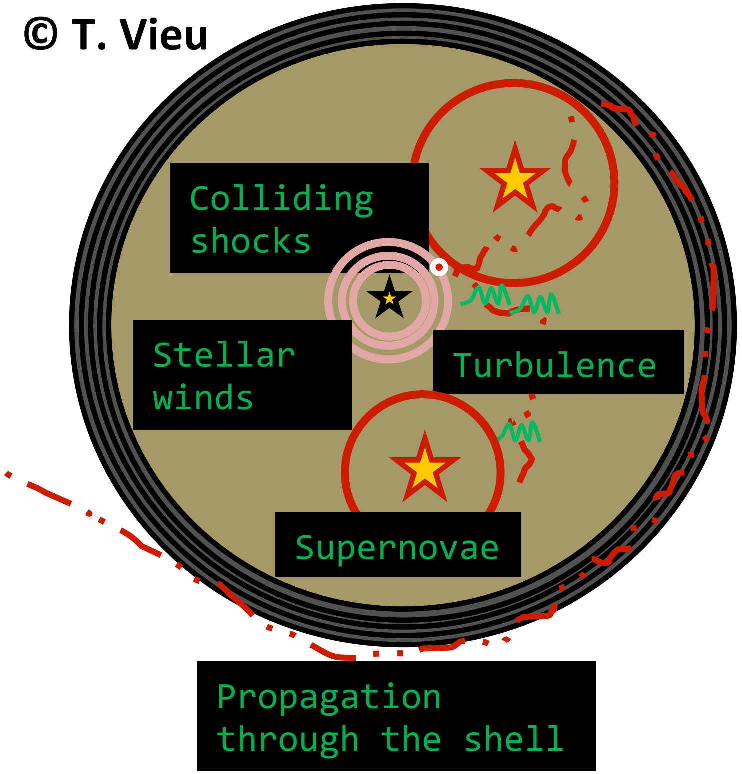
- Shock acceleration in WTS, see Morlino et al. (2021)
- Yields, mass loss rates & stellar types from **Geneva Observatory's database** (e.g. Ekström et al. 2012)
- Acceleration efficiency in WTS assumed to be proportional to the **wind mechanical power** (see also Kalyashova et al. 2019)

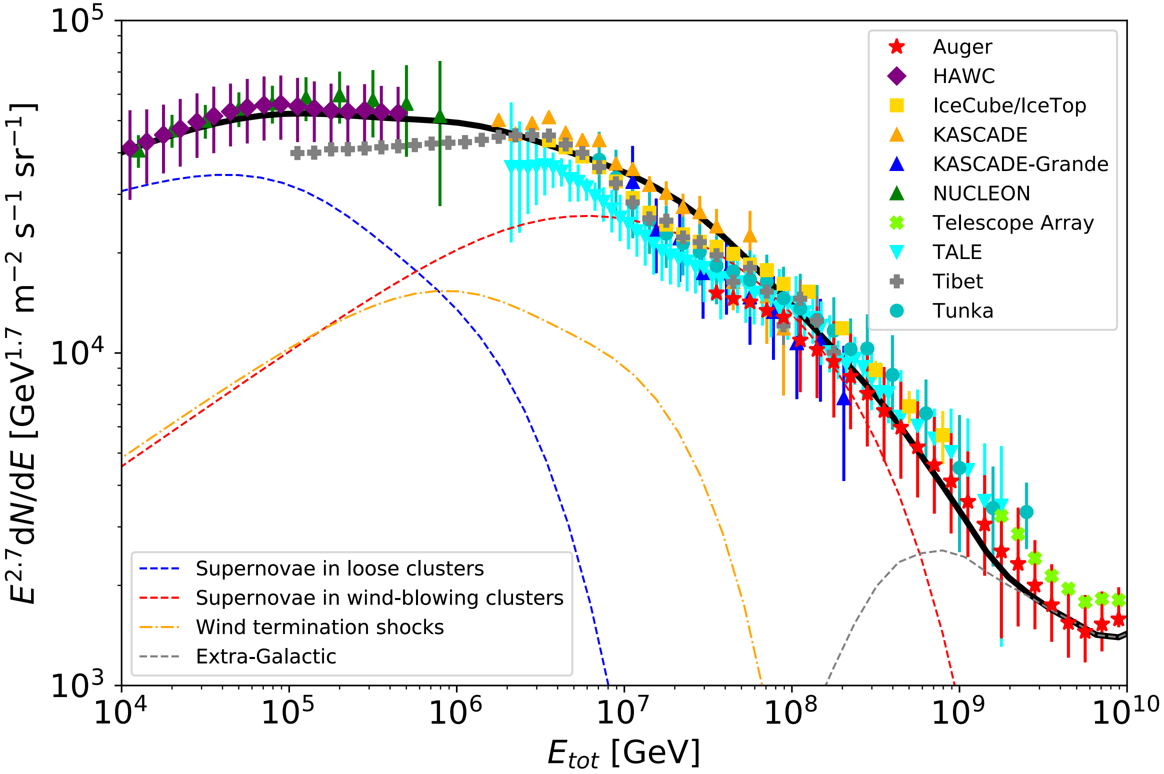
⇒ ^{22}Ne/^{20}Ne=1.56 in the **accelerated wind composition**

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

Cosmic-rays from massive star clusters and superbubbles

© T. Vieu

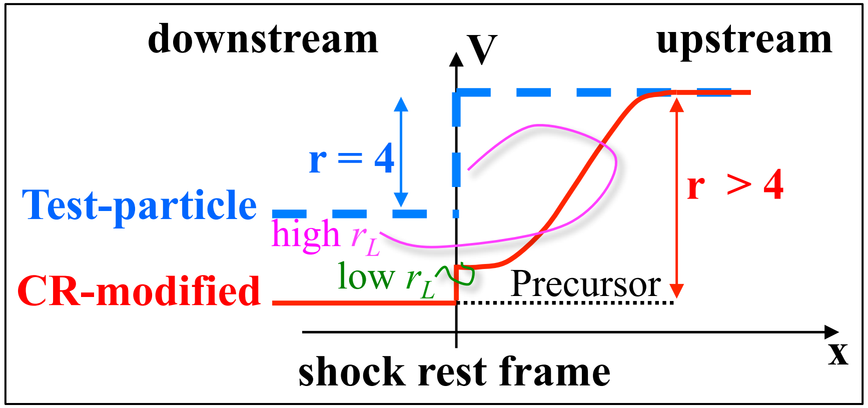




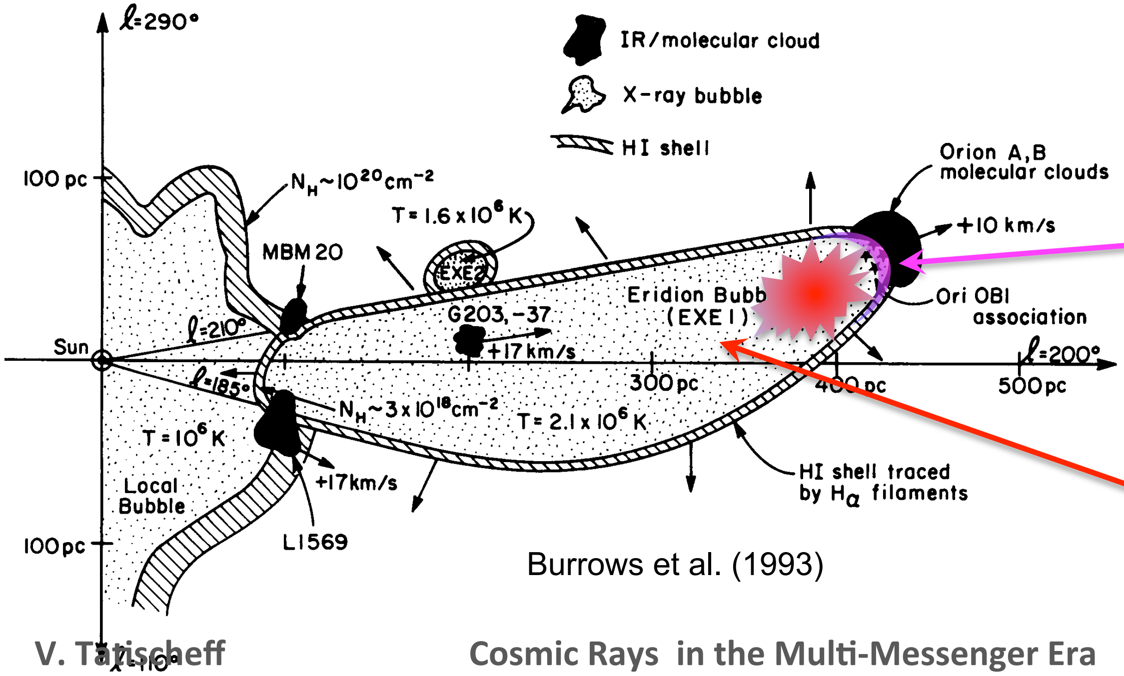
- Vieu et al. (2020, 2022a, 2022b, 2022c): detailed theory of **cosmic-ray production in superbubbles** from stellar winds, supernova remnants and turbulence, taking into account the nonlinear feedback of the accelerated particles
  => CR are mainly accelerated in SNRs, only **5 - 10% of CRs are produced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

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

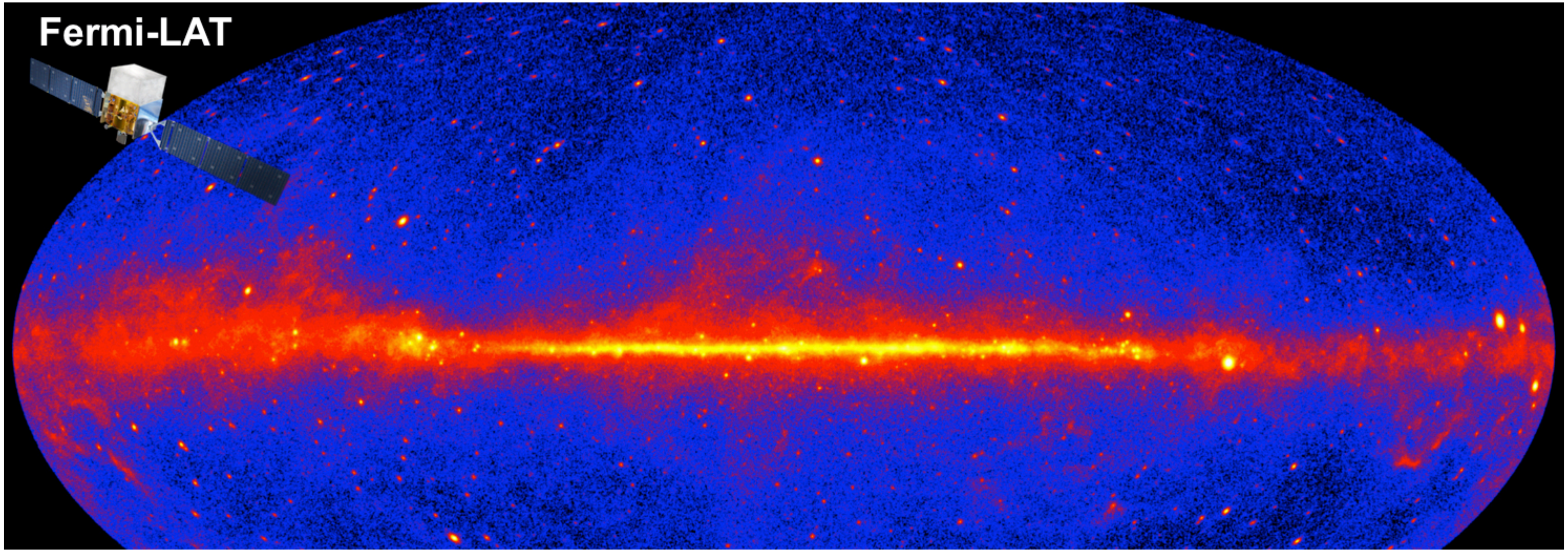


Burrows et al. (1993)

Material evaporated off the SB shell and the parent molecular clouds, enriched in dust grains => **acceleration of refractories**

Acceleration of volatile elements from the hot superbubble plasma

GCR acceleration efficiency

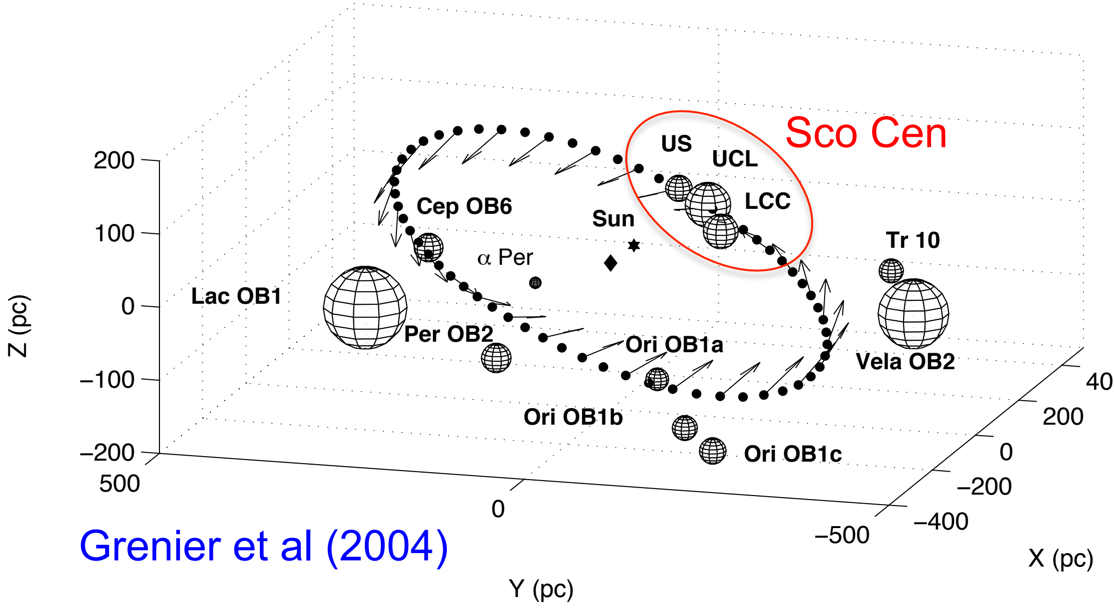


- Efficiency of GCR production from the **γ-ray luminosity of the Milky Way** and the proton source spectrum: $N_{GCR}(p) \approx (0.2 - 1.5)\times10^{45}$ protons s^{-1}
- Estimating the **mass of gas swept up by interstellar shocks**, we get:
  - Acceleration efficiency of **superbubble gas by SN shocks**: $\eta_{SB} \approx (0.4 - 2.3)\times10^{-5}$
  - Acceleration efficiency of **wind material by WTSs**: $\eta_{wind} \approx 0.8\ \eta_{SB}$
  - Acceleration efficiency of GCR **refractories from dust grains**: $\eta_{dust} \gtrsim 10^{-4}$

Origin of ^{60}Fe in GCRs

- Detection of **15 nuclei of ^{60}Fe (lifetime τ_{60}=3.8 Myr)** and 2.95×10^5 ^{56}Fe with **16.8 yr of data of ACE/CRIS** (Binns et al. 2016)
- ^{60}Fe produced in core-collapse SNe and released in **superbubbles** (Diehl et al. 2021) => can **be accelerated by subsequent SNe before decay** (De Séréville et al., in prep.)
- Approximate maximum distance of the source(s): $L \sim (6\ D\ \gamma\ \tau_{60})^{1/2} \sim 2$ **kpc** where $D \sim 4 \times 10^{28}$ cm^2 s^{-1} is the CR diffusion coefficient at ~500 MeV/nucleon (e.g. Evoli et al. 2019) and $\gamma = 1.6$ the Lorentz factor

⇒ Unique constraint on the **contribution of local source(s) to the total GCR flux**



Grenier et al (2004)

- Nearest OB association: **Scorpius-Centaurus** (~ 140 pc), at the origin of the **Local Hot Bubble** from ~ **15 SNe in the last ~ 14 Myr** (Zucker et al. 2022)
- Maximum CR energy density from a recent SN in Sco-Cen: $\varepsilon_{CR} = 10^{50}$ erg / V_{SC} = **0.2 eV cm^{-3}**

Conclusions

- Composition of Galactic cosmic rays is **key to understanding their origin**

- 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 shocks** ($x_w \approx 6\%$) to explain the ^{22}Ne overabundance