On the Origin of Galactic Cosmic Rays

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with John C. Raymond, Jean Duprat, Stefano Gabici & Sarah Recchia

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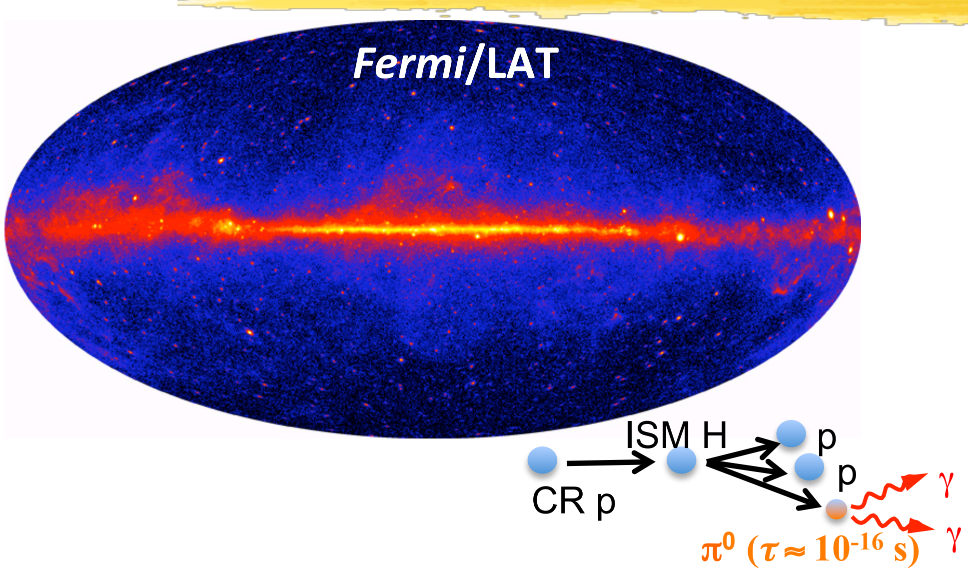
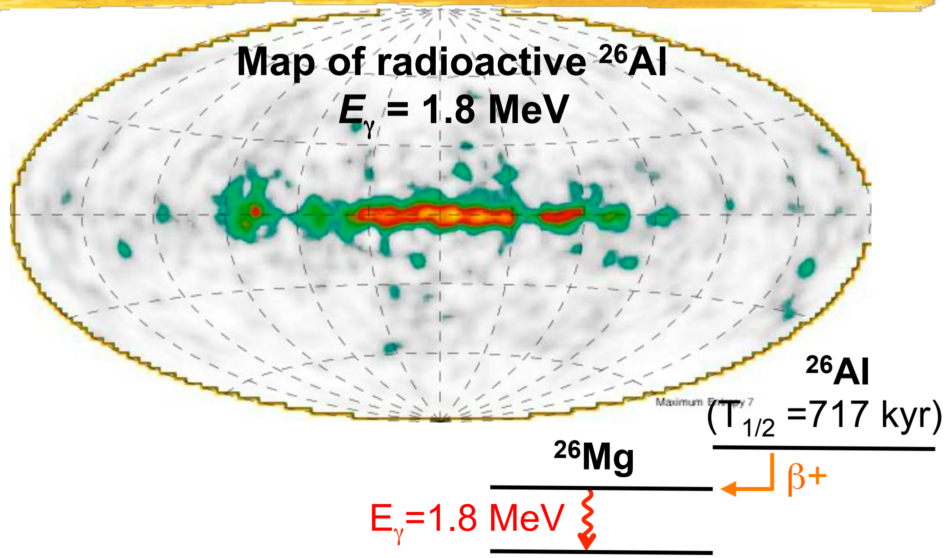
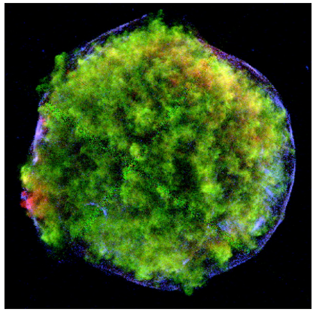
Galactic Cosmic Rays & supernova energetics



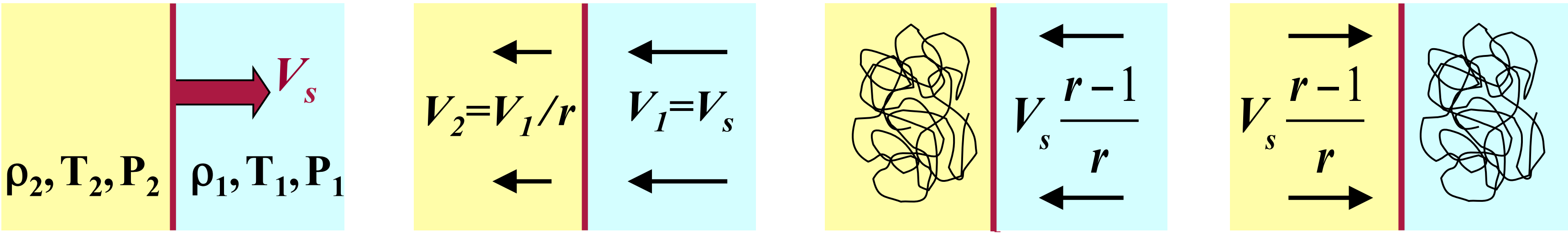


- GCRs are thought to be produced in **supernova remnants** (Baade & Zwicky 1934)
- Consistent with the cosmic-ray power and supernova energetics:
  - ✓ Kinetic power of CRs injected in the Galaxy: $\mathbf{L_{CR}} = L_\gamma / R_\gamma$ **$\sim 10^{41}$ erg/s**, where $R_\gamma \sim 0.004$ is the γ-ray radiation yield (= efficiency) for $p + p \rightarrow \pi^0 + X$ and L_γ from π^0 decay $\sim 5\times10^{38}$ erg/s (Fermi/LAT; see Strong et al. 2010)
  - ✓ Kinetic power supplied by supernovae: $\mathbf{L_{SN}} = E_{SN} \times f_{SN}$ **$\sim 6\times10^{41}$ erg/s**, where $E_{SN} \sim 1.5\times10^{51}$ erg is the mean energy of a SN and $f_{SN} \sim 1.3$ century^{-1} is the SN rate in the Milky Way (from the observed mass of ^{26}Al; Diehl+ 2021)

Diffusive shock acceleration in SN shocks



- High-velocity ejecta in supernova explosion: $\sim 10\,000$ km/s
- **Strong shock**, with initial sonic Mach number $M_S = V_s / c_S > 100$ with the sound speed $c_S \approx 100\ (T/10^6\ \mathrm{K})^{0.5}$ km/s
- First-order Fermi (1949) acceleration process in SN shock waves (Krymskii 1977; Bell 1978; Axford et al. 1978; Blandford & Ostriker 1978)
- Particle diffusion on magnetized turbulence on both sides of the SN shock



ref. frame: observer | shock front | downstream gas | upstream gas

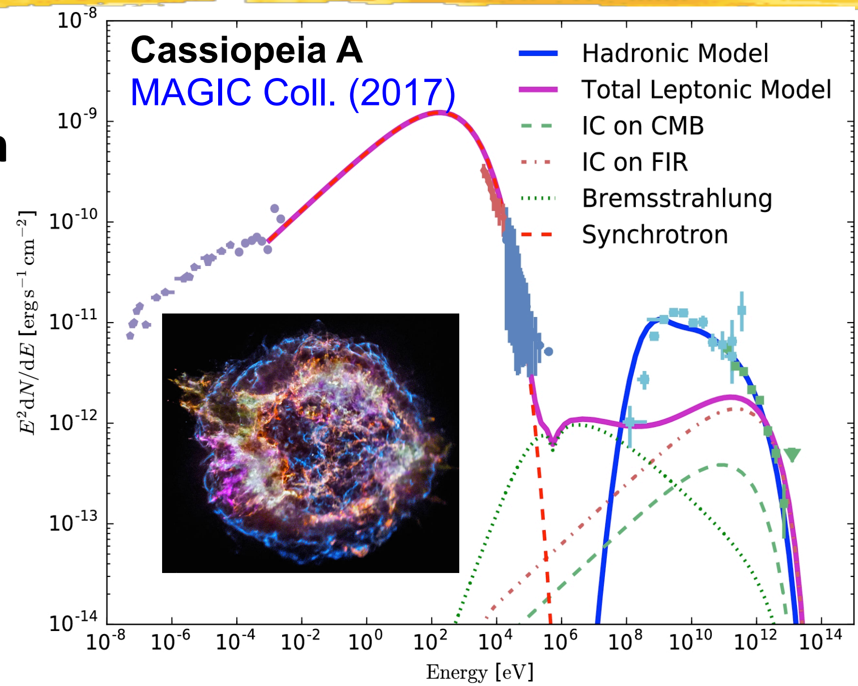
- Fractional momentum gain after each cycle up-down-up: $\frac{\Delta p}{p} = \frac{4}{3}\frac{r-1}{r}\frac{V_s}{v}$
- Particle momentum spectrum: $\mathrm{d}N/\mathrm{d}p(p) \propto p^{-q}$ with $q = (r+2)/(r-1)$
- For a test-particle strong shock $r = 4 \Rightarrow q = 2$; but observations suggest $q = 2.1 \ldots 2.4$ (?) (e.g. Gabici et al. 2019)

Maximum CR energy & γ-ray observations

- Maximum CR energy from the **rate of energy gain by diffusive shock acceleration** and the **finite age of SNR shock** (Lagage & Cesarsky 1983):

$$E_{\mathrm{max}} < 30\, Z\, B_{\mu\mathrm{G}}\ \mathrm{TeV}$$

⇒ E_{max} can reach the “knee” (3 PeV) if the B-field in the acceleration region is **amplified to $B \sim 100\ \mu\mathrm{G}$**

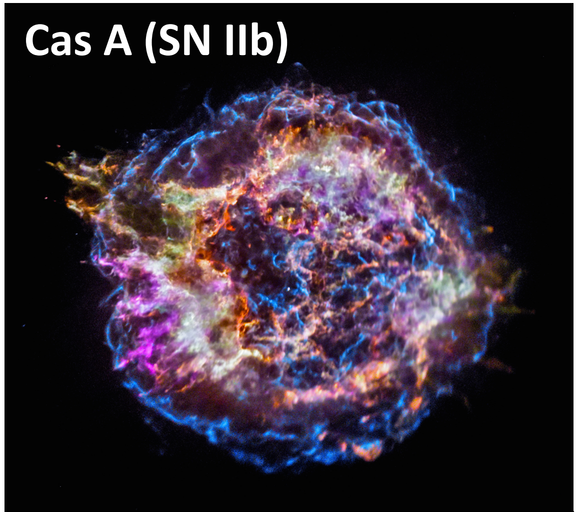


- **Gamma-ray observations of young SN remnants** confirm that cosmic rays are produced in SN shocks and constrain the proton **maximum energy** (J. Devin’s talk)

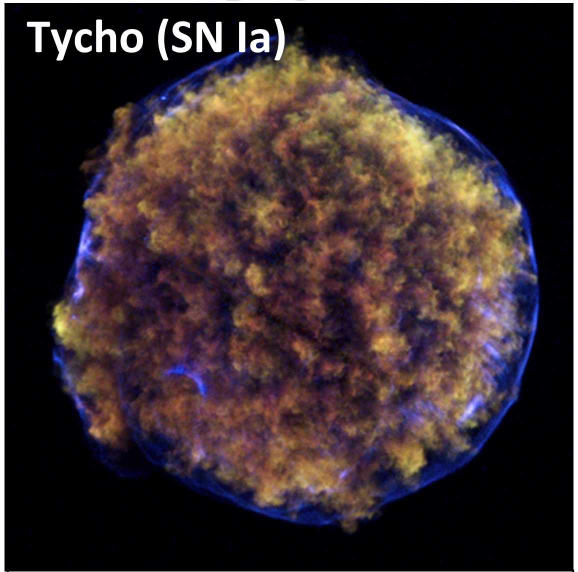
- Predicted maximum energy of protons (Schure & Bell 2013) vs. observations:

SNR Type	Age	R_s	u_s	$E_{\max}(\gamma\tau = 5)$	B_{sat}	B_{obs}	$E_{\max}$ (obs)
RSG (Cas A)	330 yr	2.2 pc	4900 km s^{-1}	283 TeV	243 μG	210–230 μG	~12 TeV (MAGIC 2017)
Tycho	440 yr	3.2 pc	3900 km s^{-1}	108 TeV	128 μG	200–230 μG	~10 TeV (VERITAS 2017)
SN1006	1000 yr	7.6 pc	4100 km s^{-1}	<60 TeV	< 35 μG	80–150 μG	~50 TeV (Condon et al. 2016)

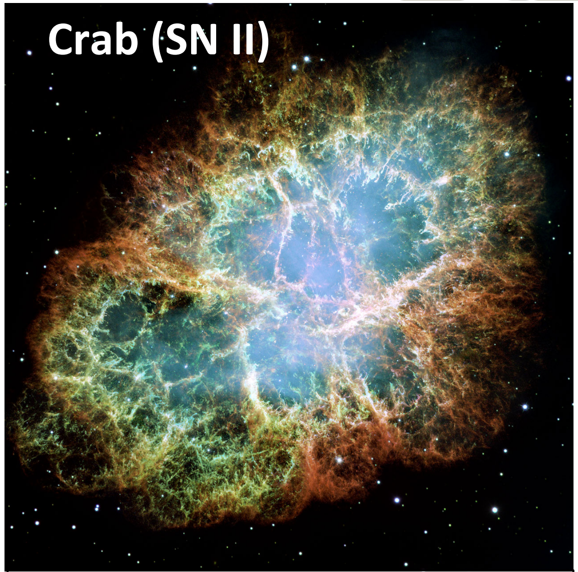
SN distribution in the ISM phases



SNR still interacting with stellar winds lost by the progenitor star

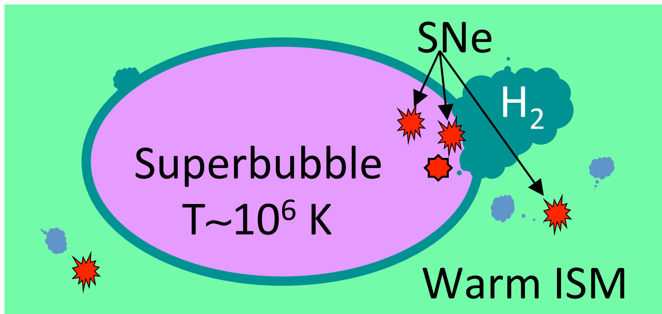


SNR evolves in a warm and partially ionised ISM



Explosion in a bubble of hot plasma

- Massive stars are born in **OB association** and their wind activities generate **superbubbles** (SBs) of hot plasma, where most core-collapse SNe explode ($\sim$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)



Galactic cosmic-ray 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?

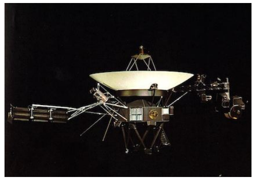
3. **Overabundance of the heavier volatile elements** compared to the lighter ones due to a **dependence of the acceleration efficiency on ion rigidity**

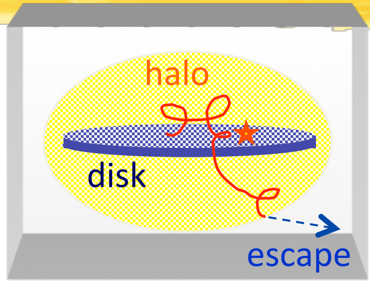
⇒ Expected from nonlinear DSA (Ellison+ 1981) and PIC simulations (Caprioli+ 2017), but ionisation states in shock precursors? **Depends on the ISM phases**

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





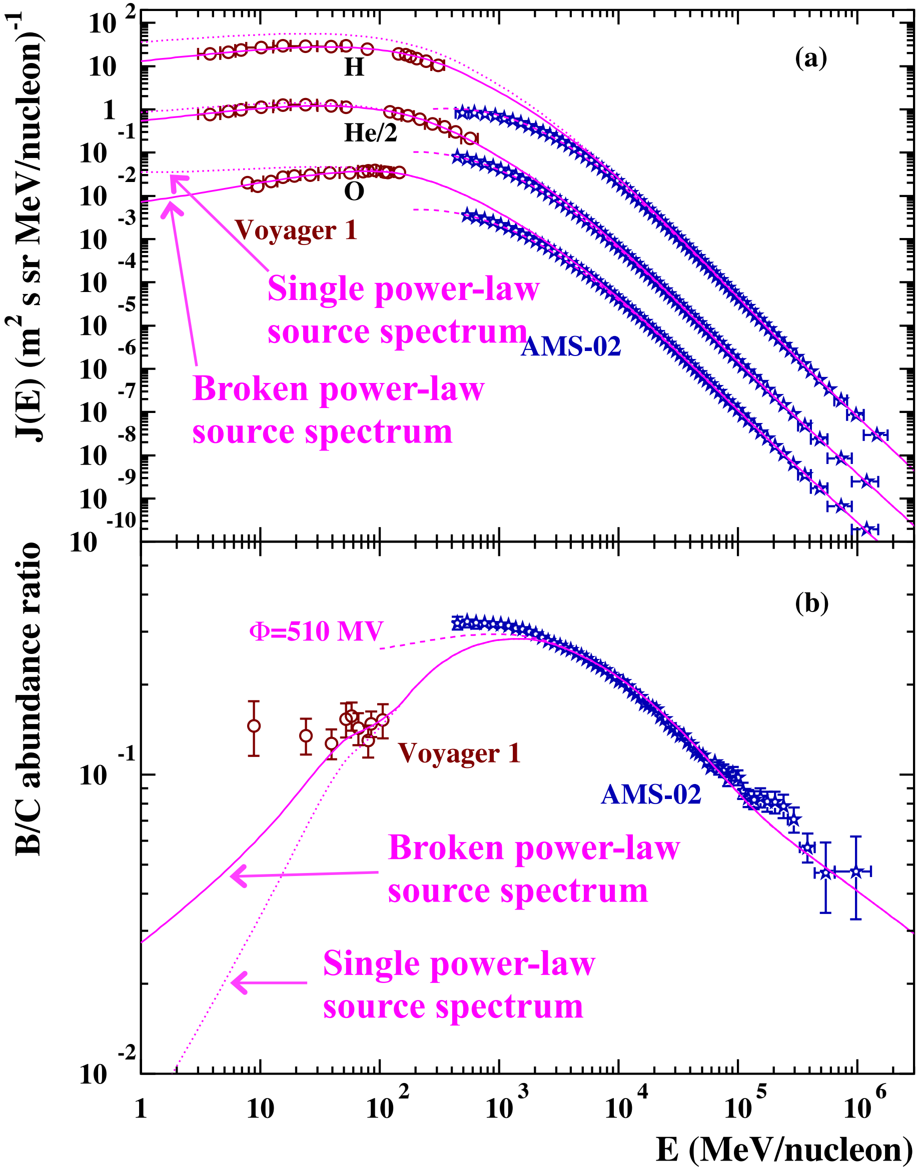
- Fit to **Voyager 1** and **AMS-02** data using a **1D advection-diffusion model** with homogeneous diffusion for the GCR propagation (Evoli et al. 2019)

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

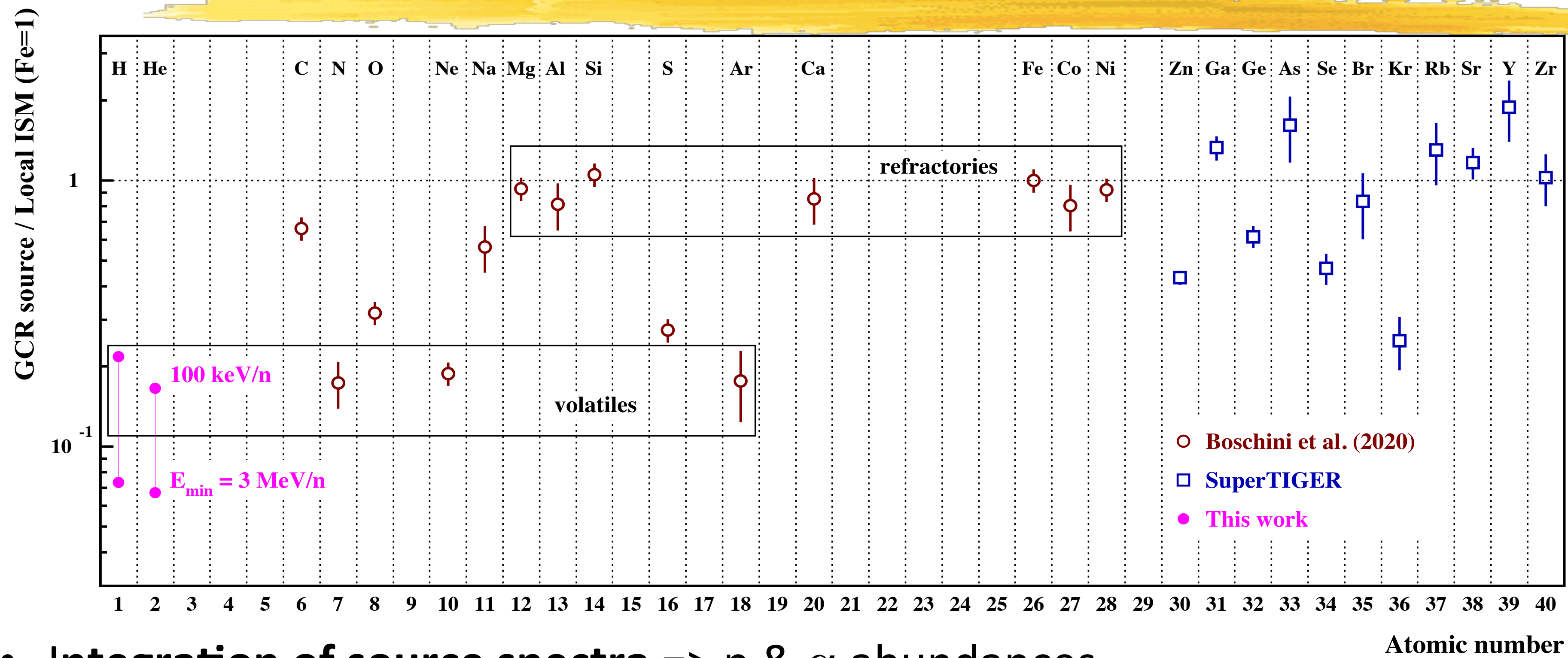
Table 2. CR source spectrum parameters (Eq. 2).

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.

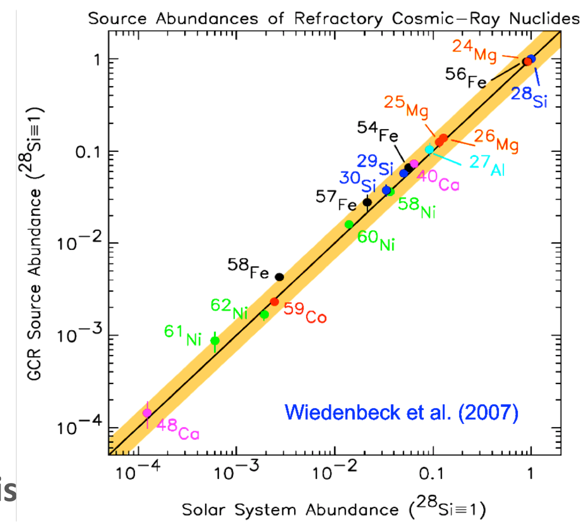
[a] Parameter fixed from Evoli et al. (2019).
[b] Minimum χ^2 from a fit of the propagated spectrum to Voyager 1 data.
[c] d.o.f.: degrees of freedom.



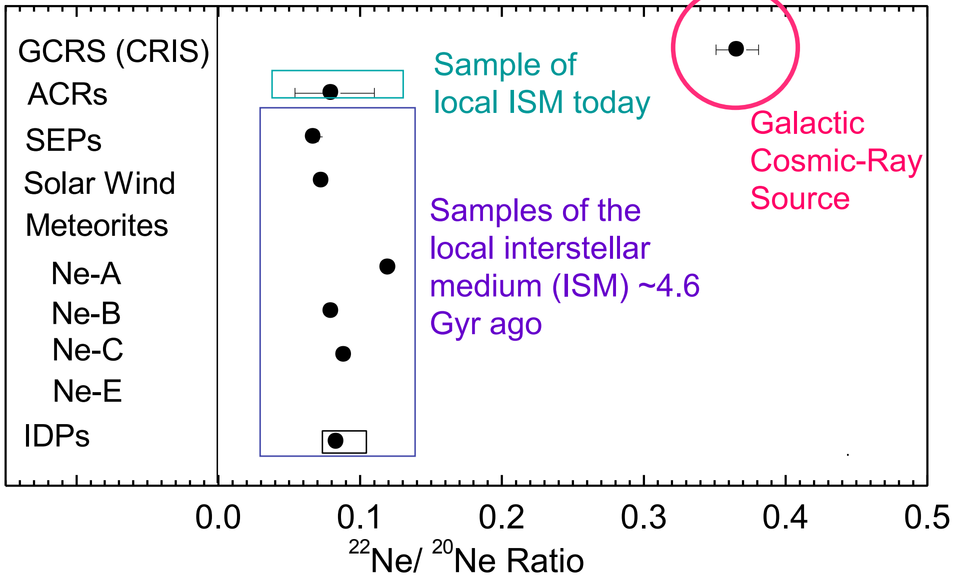
GCR abundance data

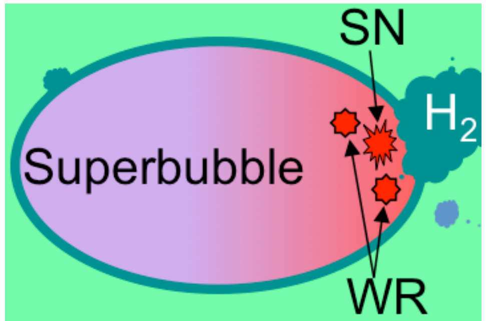


- **Integration of source spectra** => p & α abundances similar to those of the other volatiles N, Ne and Ar, provided that the **minimum CR source energy is of the order of a few hundred keV/n**
- Highly refractory elements Mg, Al, Si, Ca, Fe, Co, and Ni in solar system proportions => acceleration of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

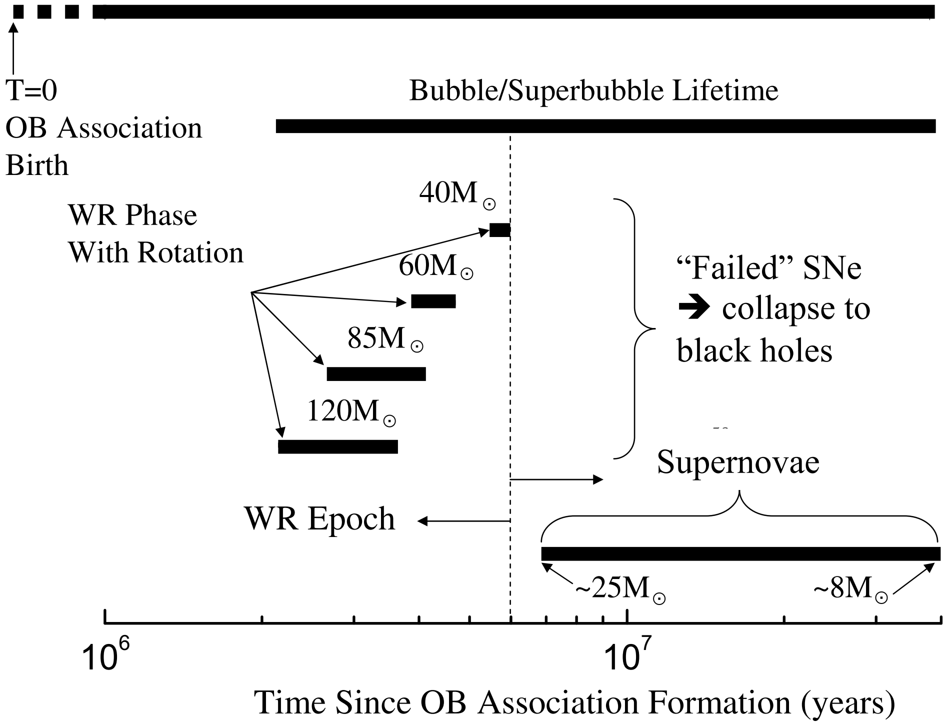


^{22}Ne abundance in GCRs





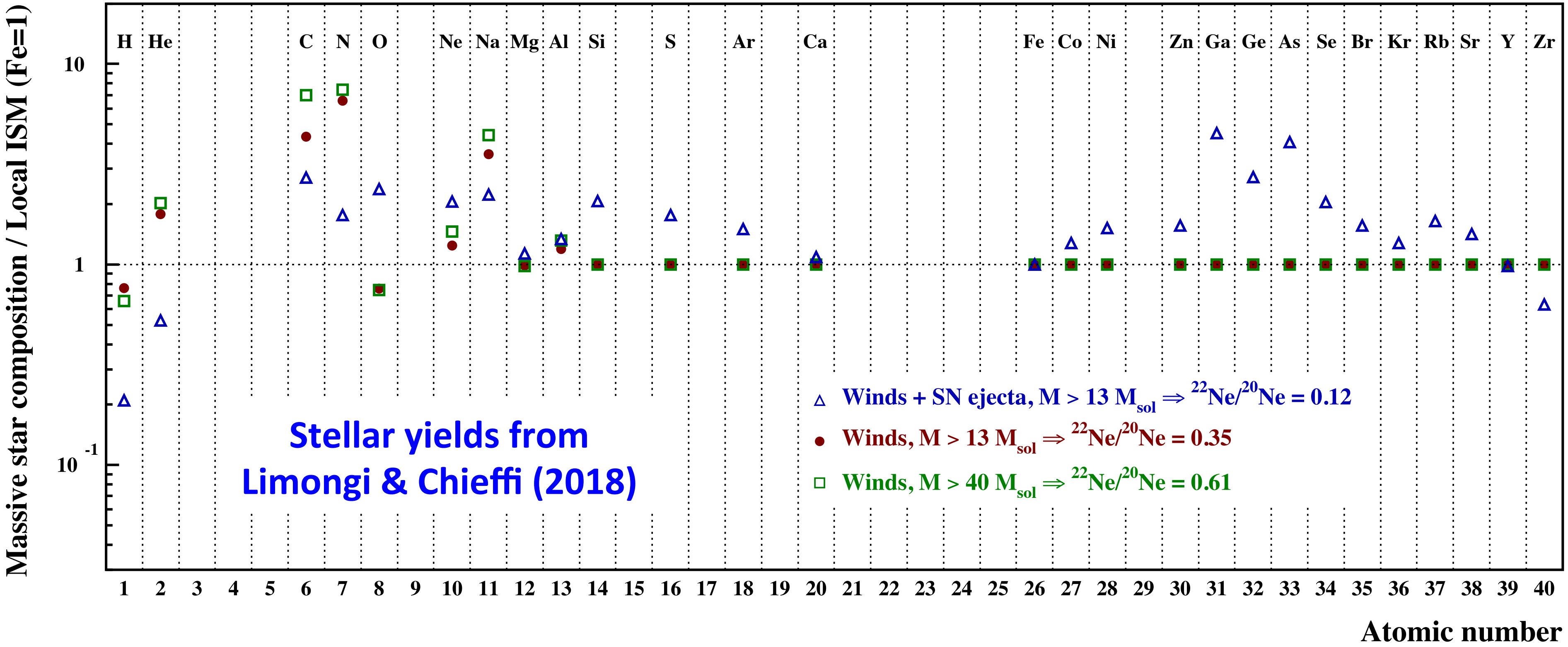
Adapted from Binns et al. (2008)



- 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(α,γ)^{18}F(β$^+$)^{18}O(α,γ)^{22}Ne during He burning)? (Cassé & Paul 1982)
- GCR origin in **superbubbles** enriched in ^{22}Ne from winds of massive stars?

GCR ^{22}Ne from enriched superbubble gas

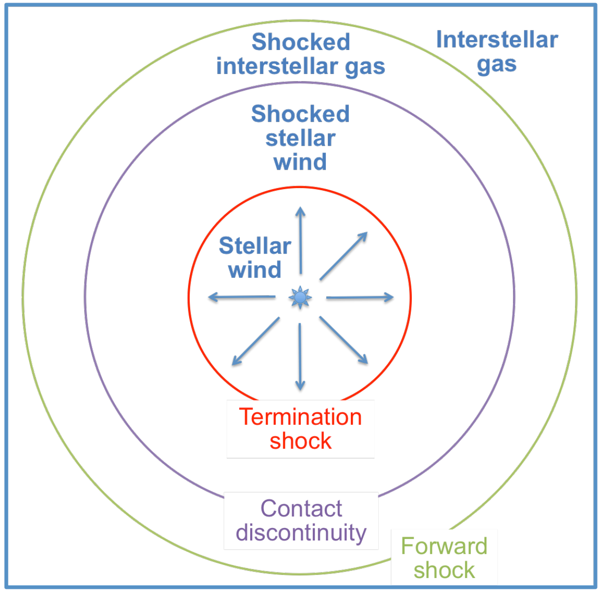
- Mix of **massive star winds and SN ejecta** in SB cores? **No, $^{22}Ne/^{20}Ne=0.12$**
  Ratio close to solar, because massive star winds and SN ejecta are the principal sources of both ^{20}Ne and ^{22}Ne in the Universe (Prantzos 2012)
- **Only massive star winds** in SB cores? **No, $^{22}Ne/^{20}Ne=0.35$**
- Winds from **very massive stars** ≥ 40 M_{sol}? **$^{22}Ne/^{20}Ne=0.61$, 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

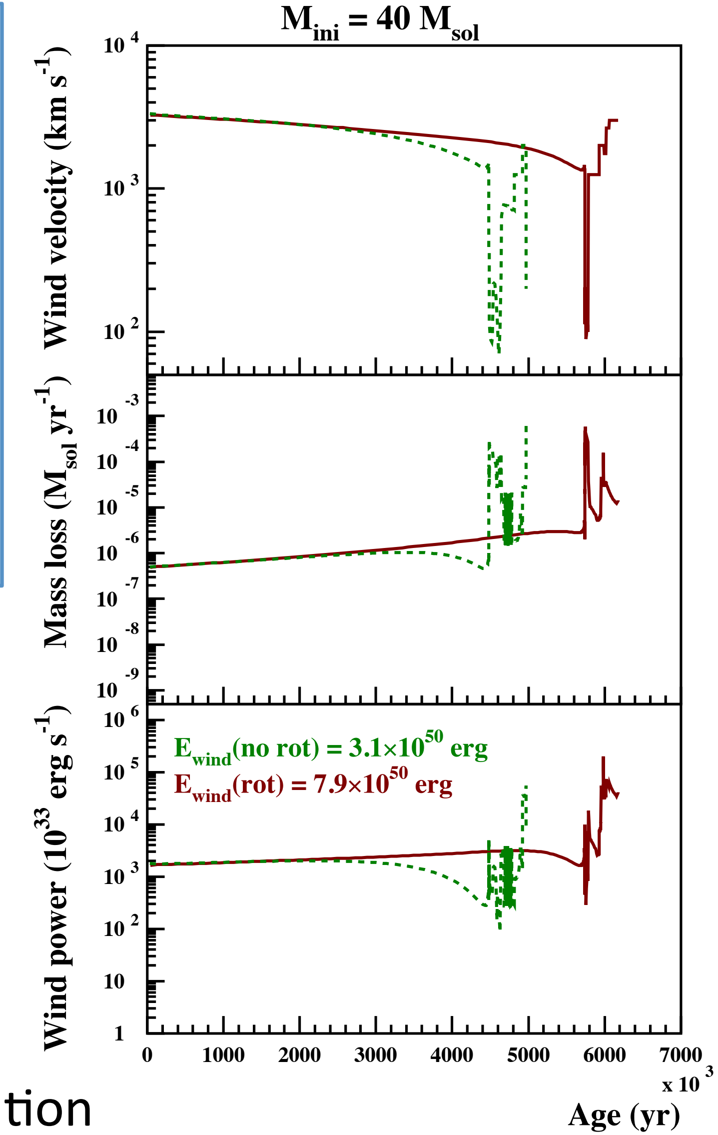
⇒ **^{22}Ne-rich** CR component (see also Kalyashova et al. 2019)



- Time-dependent yields, mass loss rates & stellar types 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 composition



GCR composition model

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

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

Elemental fraction in ISM dust

Global efficiency factors

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

Contribution of the Wolf-Rayet wind reservoir

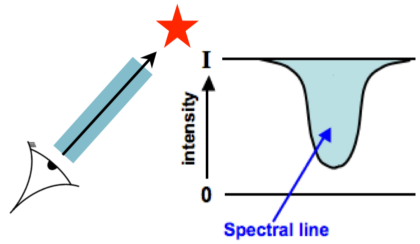
Enhancement of element i in the Wolf-Rayet wind reservoir

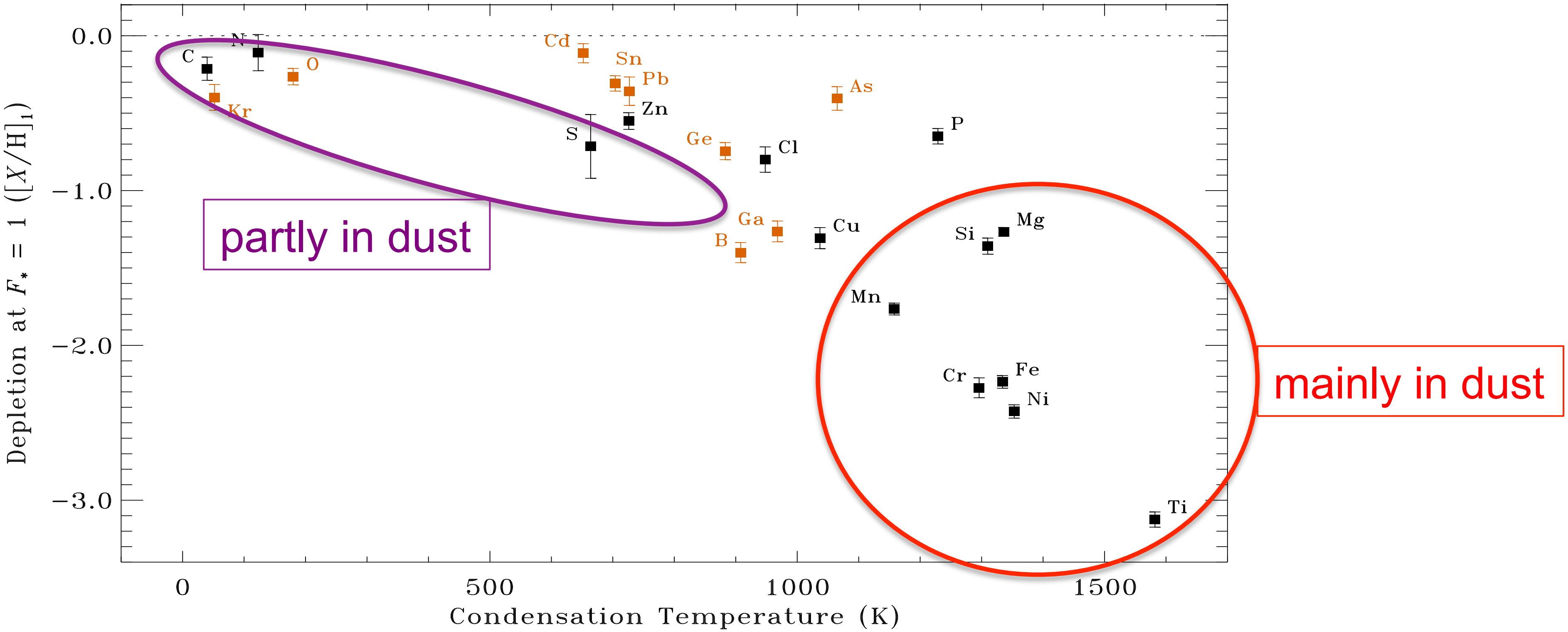
$f^j_{A/Q}(i) = (1 - X^j_{0,i}) A_i / Q^j_i$
where $X^j_{0,i}$, A_i and Q^j_i are the fraction of neutral atoms, atomic mass and mean ionic charge in shock precursors

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

Interstellar dust composition

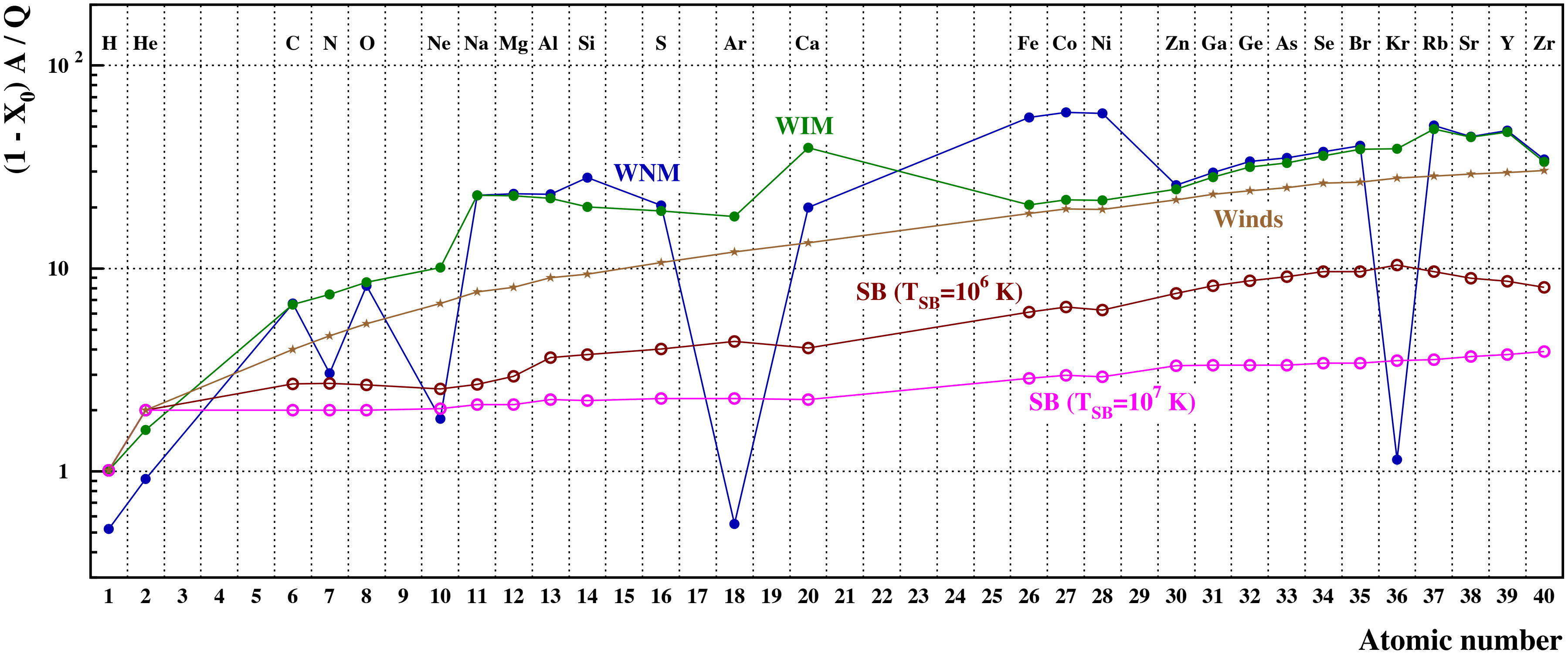
- **Average fraction in dust** for each element, $f_d(i)$, from
  - Gas-phase element **depletions** (Jenkins 2009, 2019; Ritchey et al. 2018)
  - The interstellar dust modeling framework **THEMIS** (Jones et al. 2017)
  - General properties of **primitive interplanetary dust**





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)



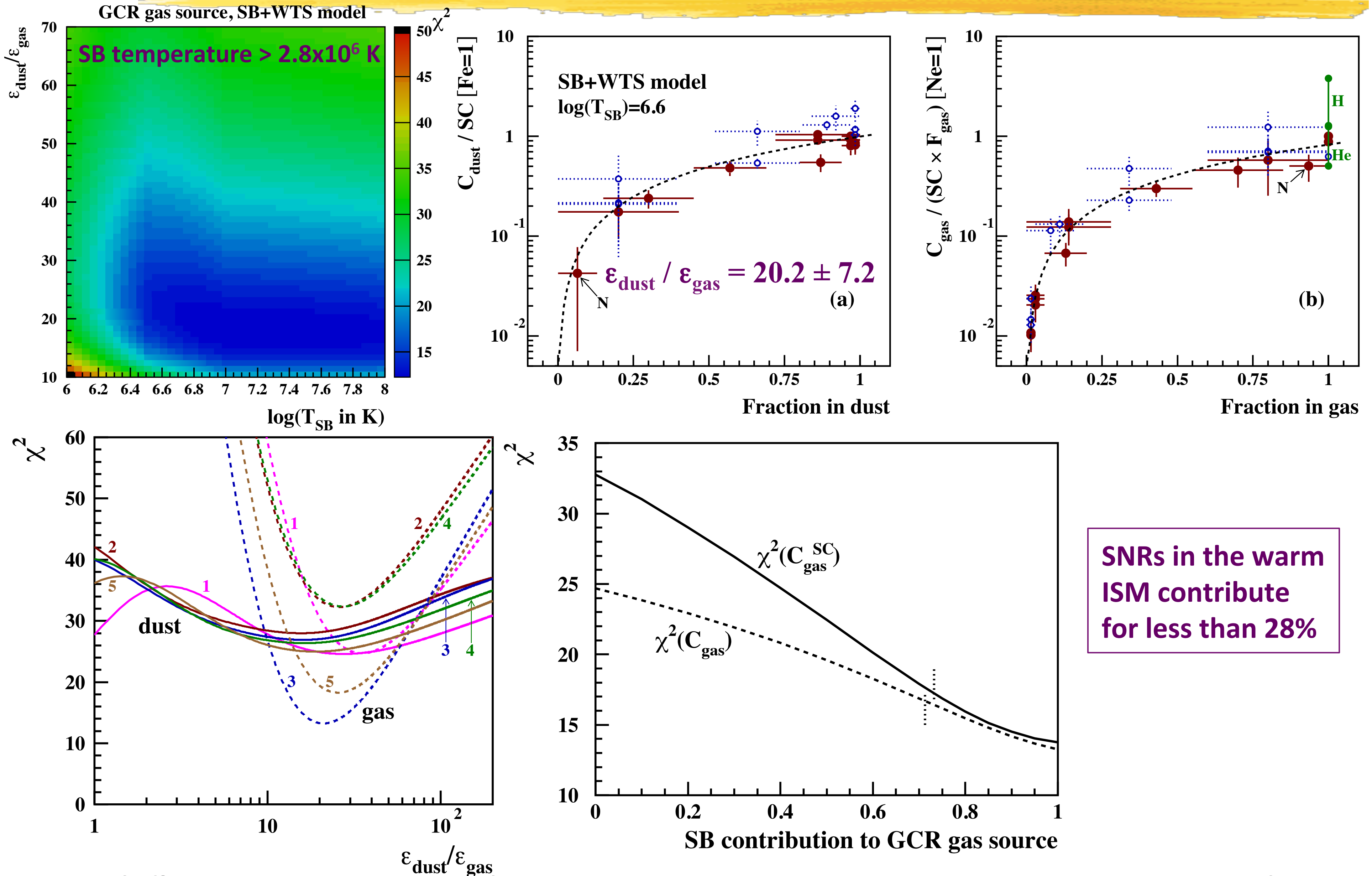
Results of the GCR composition model

	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 $\log(T_{\rm SB})^a$	–	6.50 ± 0.25	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{\rm dust}/\epsilon_{\rm gas}{}^b$	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)%
$\chi^2_{\rm min}$(GCR dust source)^d	24.6	26.9	25.9	26.0	24.8
$\chi^2_{\rm min}$(GCR gas source)^e	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{\rm SB})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{\rm dust}/\epsilon_{\rm gas}{}^b$	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%
$\chi^2_{\rm min}$(GCR dust source)^d	24.6	28.0	26.9	26.4	25.0
$\chi^2_{\rm min}$(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**

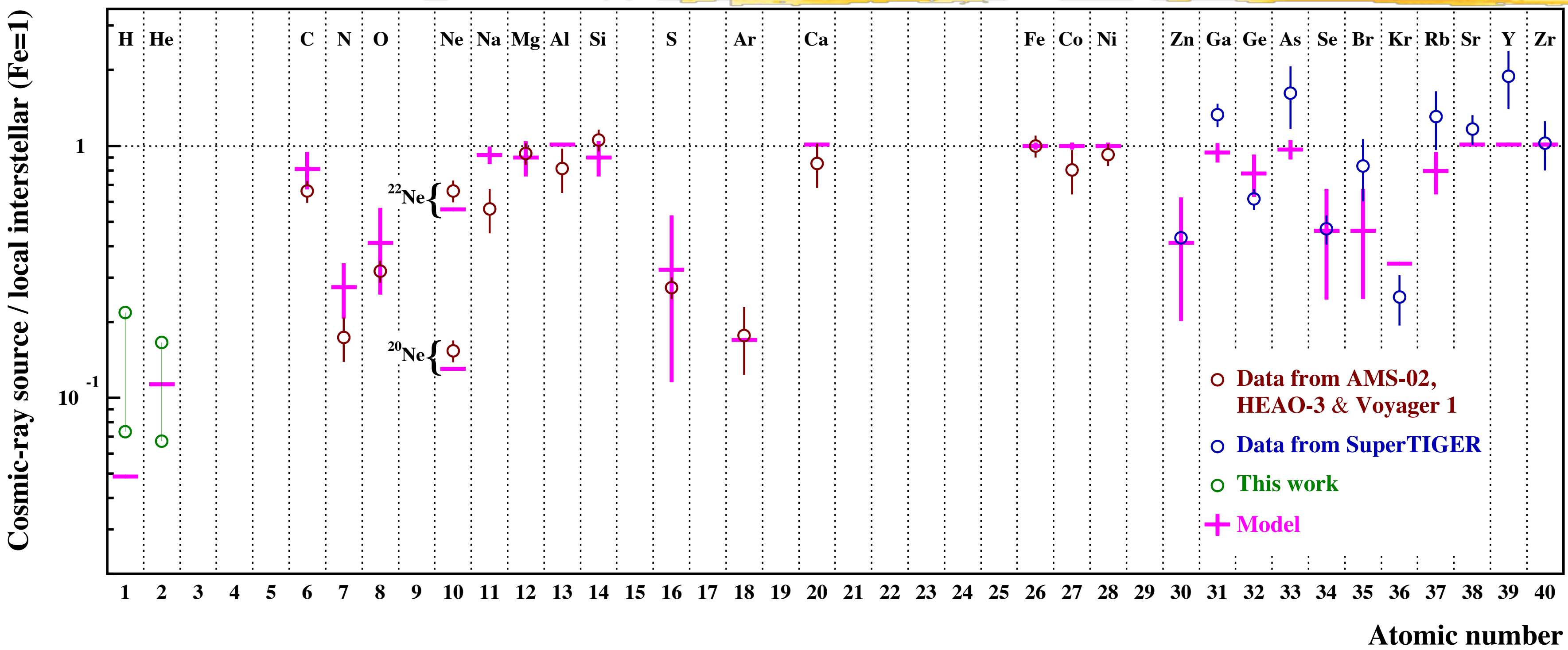
- Best-fit model: GCR volatiles accelerated in **superbubbles** + ^{22}Ne-rich component from acceleration in **wind termination shocks** ($x_w \approx 6\%$)

Results of the GCR composition model

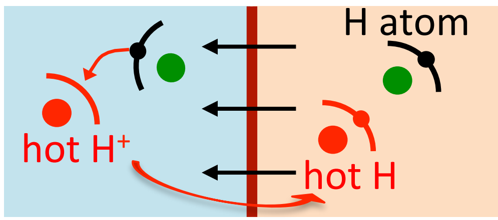


SNRs in the warm ISM contribute for less than 28%

Origin of GCR volatiles in superbubbles

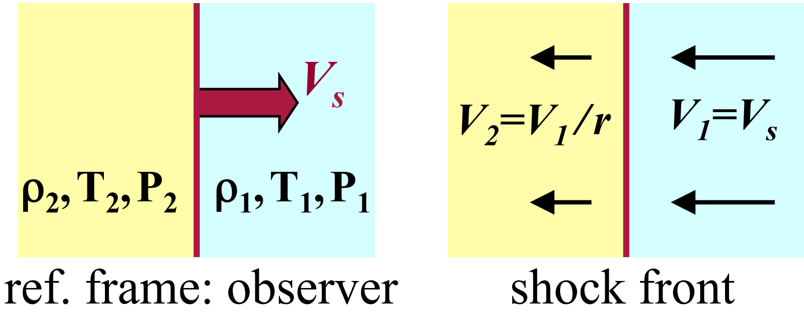


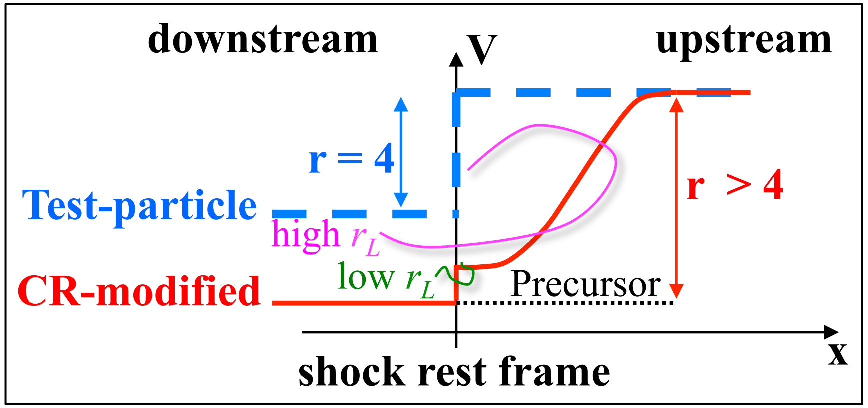
- SNRs in the warm ISM contribute to the GCR volatile composition for less than 28%, whereas ~ 40% of SNe occur in this phase and not in superbubbles (?)
- Effects of neutral atoms on the acceleration process: ion-neutral damping, **neutral return flux** (Morlino et al. 2013)?
  - ⇒ Heating of the upstream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



Acceleration of dust grains

- **Preferential 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)

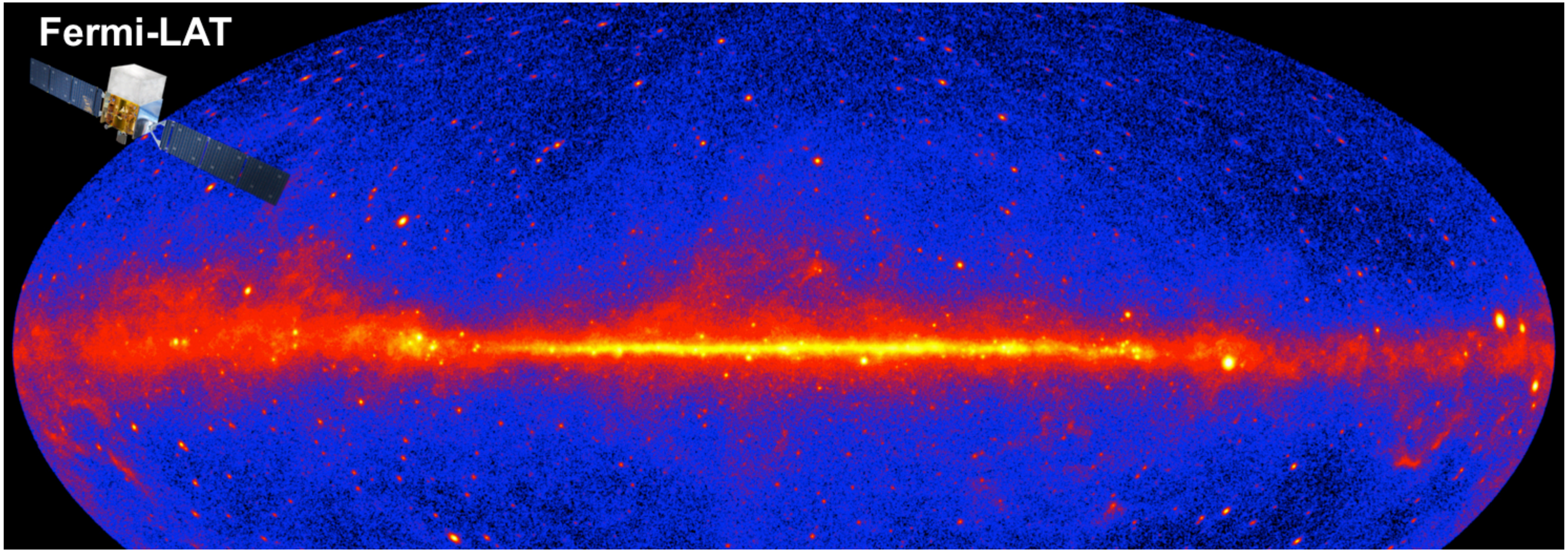




  i. **Grain acceleration**
  ii. **Grain sputtering** with ambient atoms
  iii. **Injection of the sputtered ions** in the acceleration process with the **supra-thermal velocity** of the parent grain

- **Can GCR refractories also be produced in superbubbles?**
  - ✓ **Dust is continuously replenished** in the Orion-Eradinus SB through thermal evaporation of embedded molecular clouds (Ochsendorf et al. 2015)
  - ✓ Timescale between two successive SNe in SBs, $t \lesssim 1$ Myr, **shorter than the destruction timescale** of silicate grains against thermal sputtering (Tielens et al. 1994) - *not true for nano carbonaceous grains and PAH molecules* (to be studied)

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**: $\eta_{dust} \gtrsim 10^{-4}$

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?

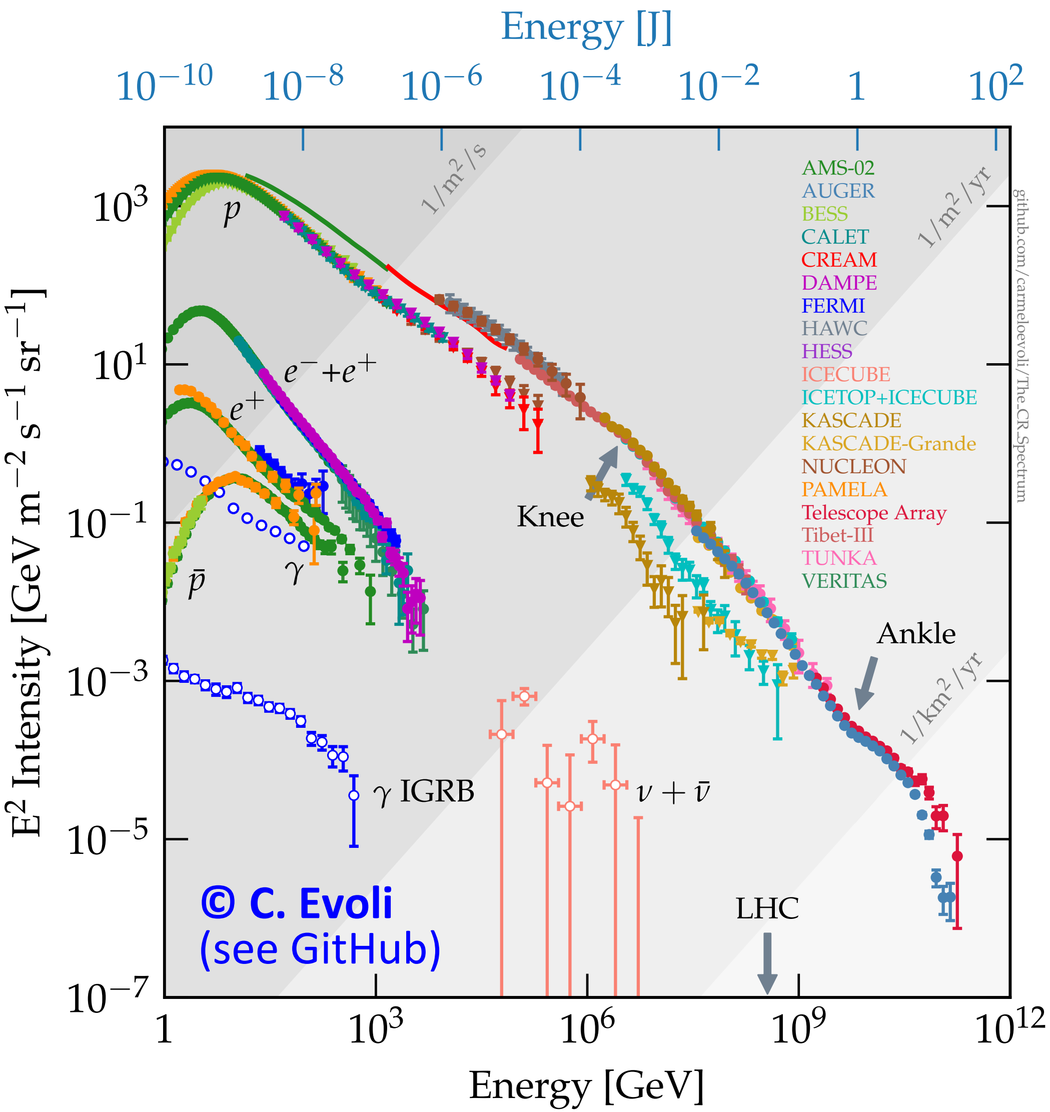
- CR volatiles are mostly accelerated in **Galactic superbubbles**, from SN shocks sweeping up a plasma of $T_{\mathrm{SB}} > 2.8$ MK
  ⇒ CR production in superbubbles up to and above 3×10^{15} eV (Vieu et al. 2022)?

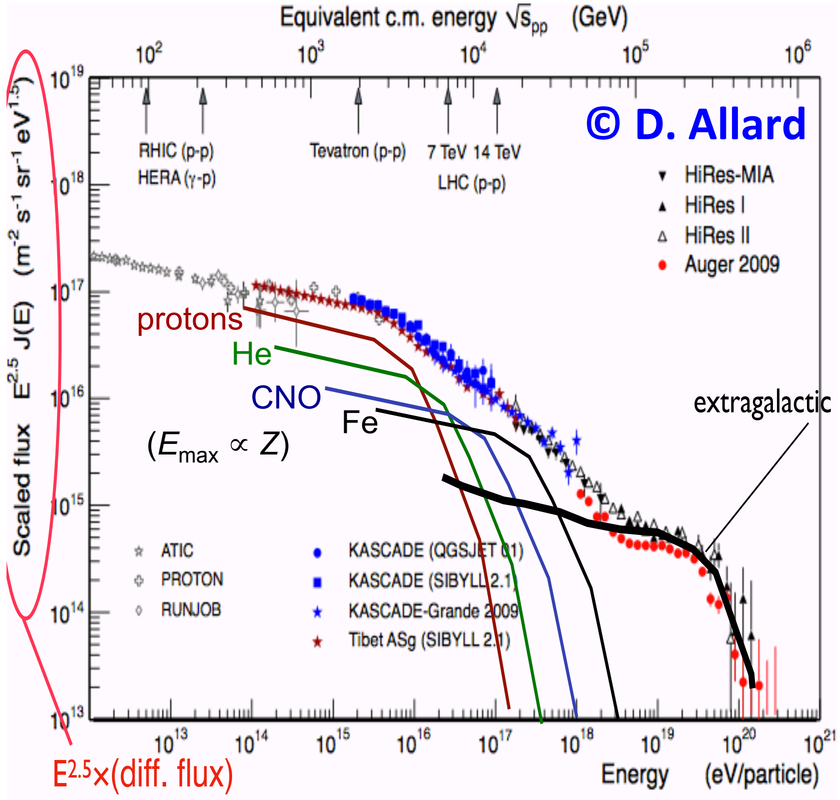
- The overabundance of ^{22}Ne is most likely due to a small ($x_w \approx 6\%$) contribution of particle acceleration in **wind termination shocks** of massive stars
  ⇒ Diffusive shock acceleration in wind termination shocks (Morlino et al. 2021)

- The GCR refractories, which originate from the **acceleration and sputtering of dust grains** in SNR shocks, may also be produced **in superbubbles**
  ⇒ Update of the grain acceleration model of Ellison et al. (1997) based on current knowledge of dust in the ISM (Cristofari et al., in preparation)

Extra slides

Cosmic Ray Spectrum





Cosmic rays are of Galactic origin up to the **"Knee" at ~ 3×10^{15} eV (3 PeV)** and probably even up to ~ **10^{18} eV**

GCR composition model

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

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

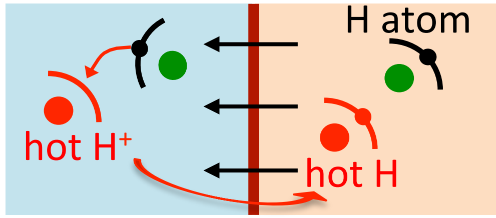
$$C_{\rm gas}(i) = \frac{C_{\rm mes}(i)}{\left(1 + \frac{f_d(i)}{1-f_d(i)} \cdot \frac{\epsilon}{x_w f_w(i) f_{A/Q}^{w}(i) + (1-x_w) f_{A/Q}^{\rm SC}(i)}\right)},$$

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

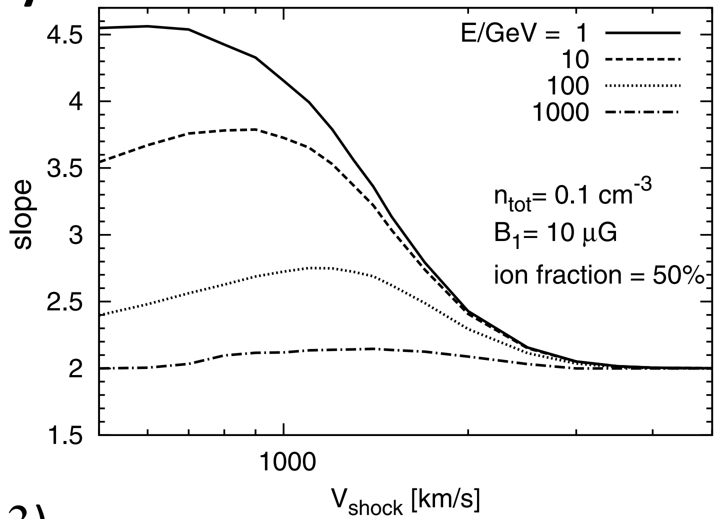
$$C_{\rm gas}^{\rm SC}(i) = \frac{C_{\rm mes}(i)}{\left(1 + \frac{f_d(i)}{1-f_d(i)} \cdot \frac{\epsilon}{(1-x_w) f_{A/Q}^{\rm SC}(i)} + \frac{x_w f_w(i) f_{A/Q}^{w}(i)}{(1-x_w) f_{A/Q}^{\rm SC}(i)}\right)}$$

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 $V_s > V_{s,\mathrm{min}}$ with
  - $V_{s,\mathrm{min}}(\mathrm{WNM}) = 3000$ km/s
  - $V_{s,\mathrm{min}}(\mathrm{WIM}) = 300$ km/s (ineffective acceleration in radiative shocks; Raymond et al. 2020)
  - $V_{s,\mathrm{min}}(\mathrm{SB}) = 600$ km/s (=> Mach number $M_{S,\mathrm{min}} = 3$)
- Swept-up masses in the adiabatic stage: $M^k_{\mathrm{s.-u.}} \approx 68\ \mathrm{M}_\odot \left(\frac{E_{\mathrm{SN}}}{10^{51}\ \mathrm{erg}}\right)\left(\frac{V^k_{s,\mathrm{min}}}{1000\ \mathrm{km\ s}^{-1}}\right)^{-2}$

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

Cosmic-ray production in superbubbles

- **Collective effects** should be taken into account in such energetics environments: **shock collisions**, particle **reacceleration** in multiple shocks and **hydromagnetic turbulence**... (Thibault Vieu's PhD thesis 2021)
- Production of cosmic rays **up to the knee of the spectrum and beyond?**