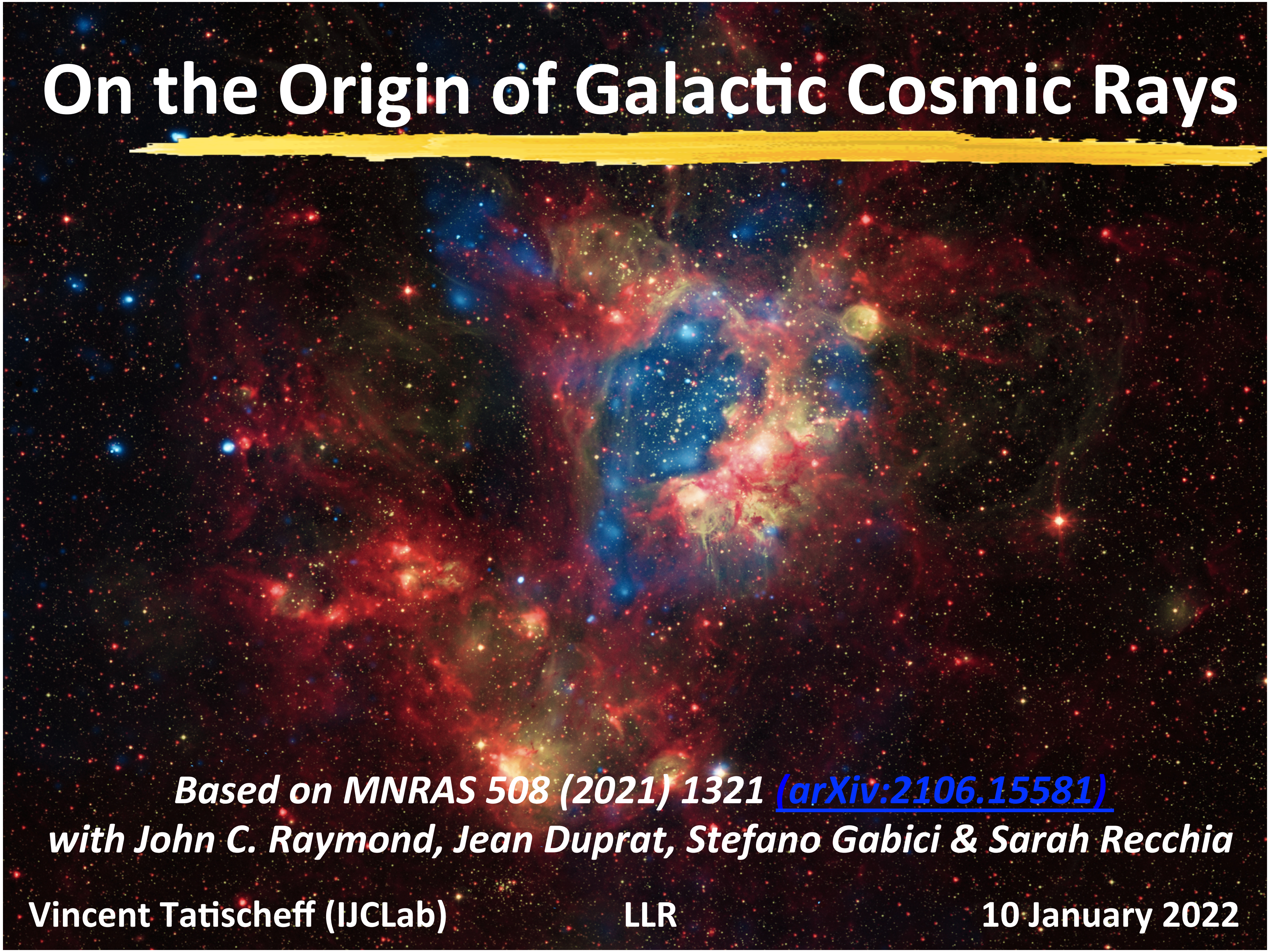
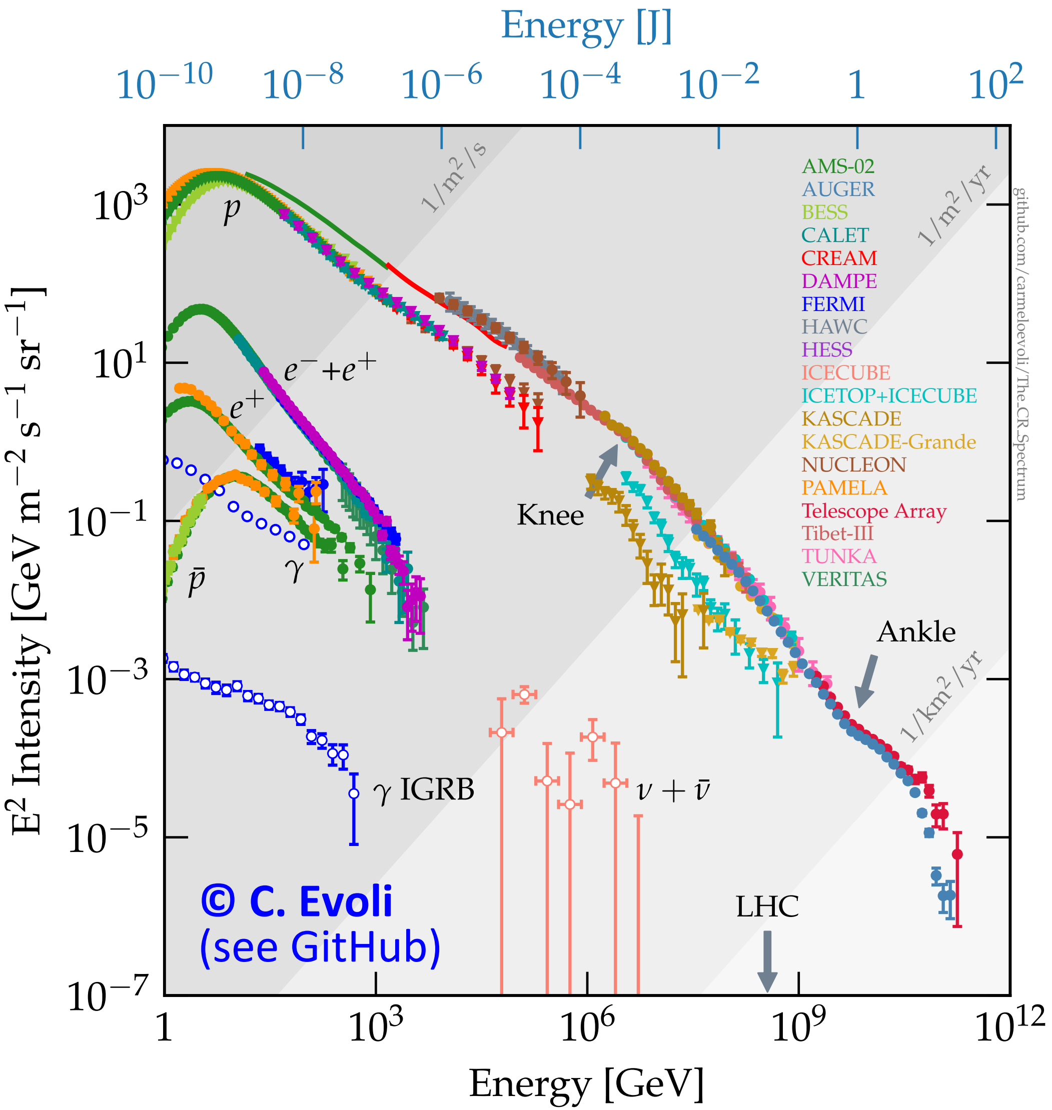


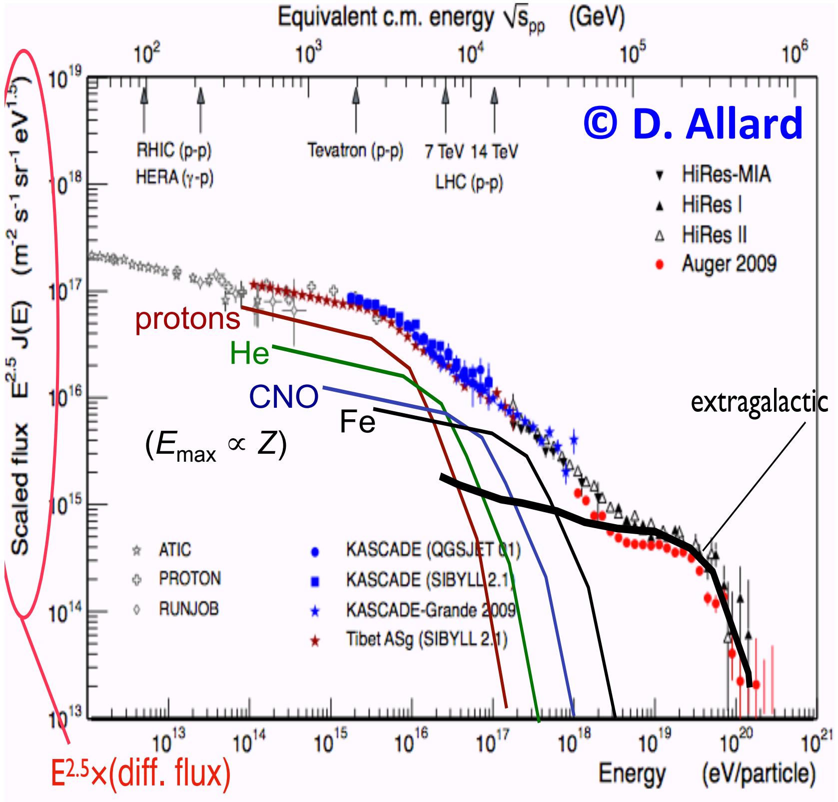
On the Origin of Galactic Cosmic Rays

Based on MNRAS 508 (2021) 1321 [(arXiv:2106.15581)](arXiv:2106.15581)
with John C. Raymond, Jean Duprat, Stefano Gabici & Sarah Recchia

Vincent Tatischeff (IJCLab) **LLR** **10 January 2022**

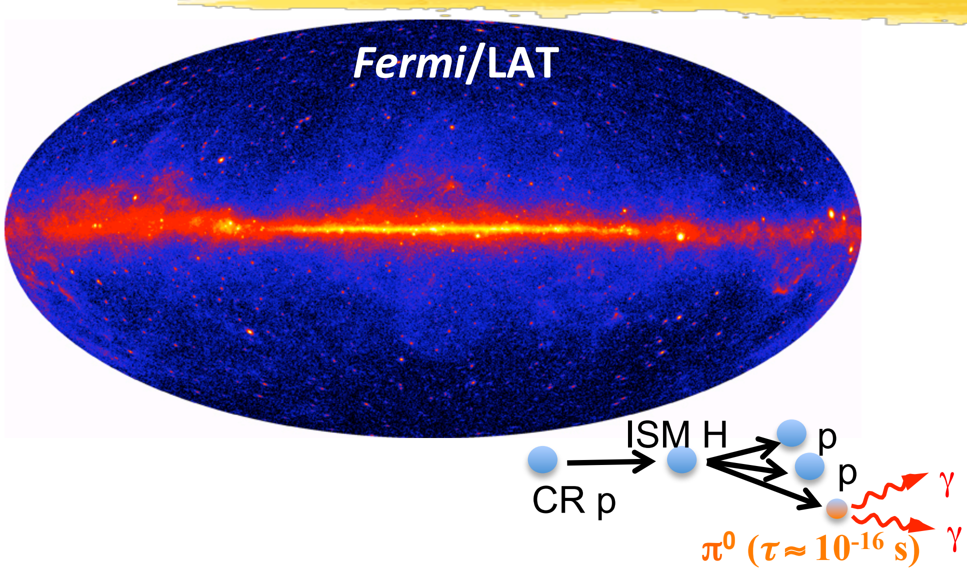
Cosmic Ray Spectrum

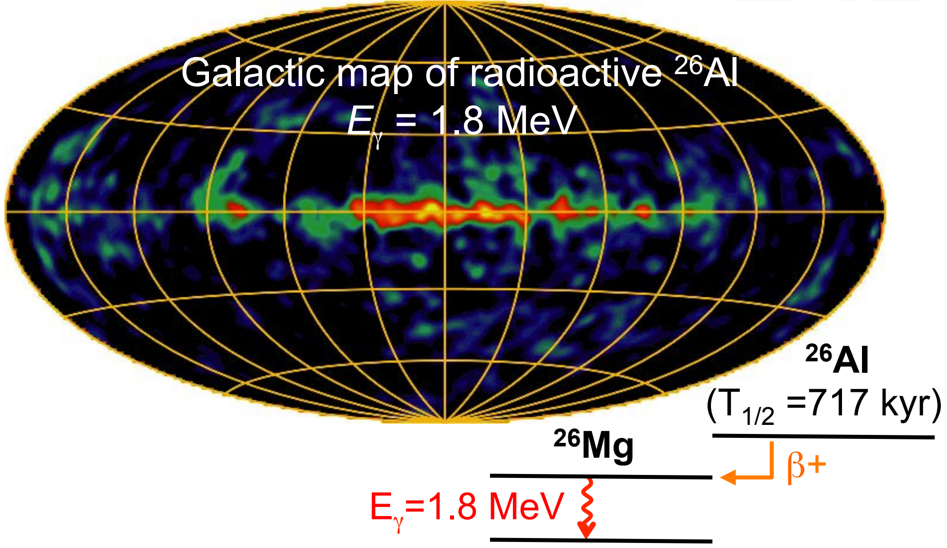




Cosmic rays are of Galactic origin up to the **"Knee" at ~ 3×10^{15} eV (3 PeV)** and probably even up to ~ **10^{18} eV**

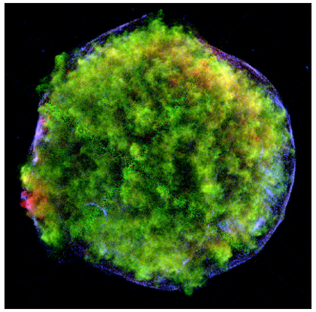
Galactic Cosmic Rays & supernova energetics



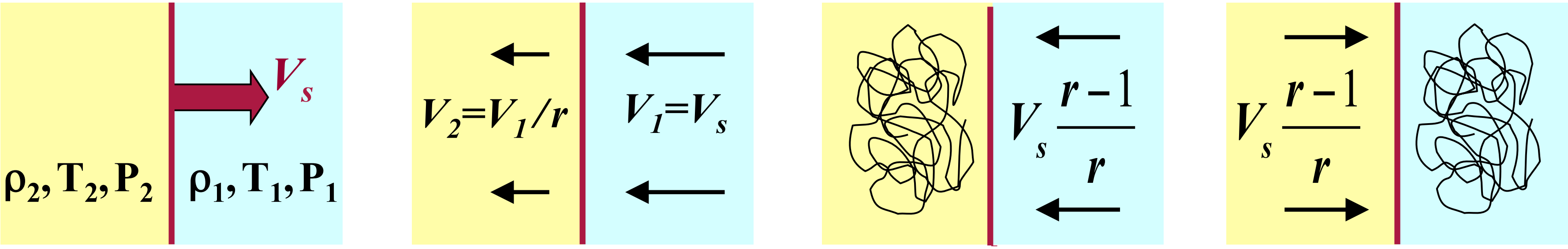


- GCRs are thought to be produced in **supernova remnants** (Baade & Zwicky 1934)
- Consistent with the cosmic-ray power and supernova energetics:
  - ✓ Kinetic power of CRs injected in the Galaxy: $\boldsymbol{L_{CR}} = L_\gamma / R_\gamma \boldsymbol{\sim 10^{41}}$ **erg/s**, where $R_\gamma \sim 0.004$ is the γ-ray radiation yield (= efficiency) for $p + p \rightarrow \pi^0 + X$ and L_γ from π^0 decay $\sim 5 \times 10^{38}$ erg/s (Fermi/LAT; see Strong et al. 2010)
  - ✓ Kinetic power supplied by supernovae: $\boldsymbol{L_{SN}} = E_{SN} \times f_{SN} \boldsymbol{\sim 10^{42}}$ **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)

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

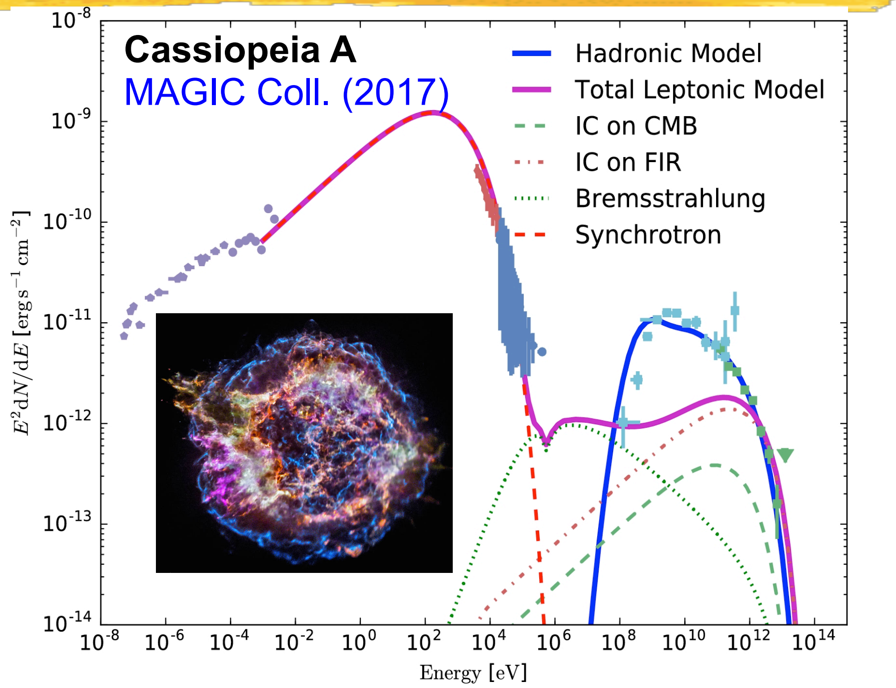
- Fractional momentum gain after each cycle up-down-up: $\frac{\Delta p}{p} = \frac{4}{3}\frac{r-1}{r}\frac{V_s}{v}$
- Particle momentum spectrum: $\mathrm{d}N/\mathrm{d}p(p) \propto p^{-q}$ with $q = (r+2)/(r-1)$ (for a test-particle strong shock $r = 4 \Rightarrow q = 2$)

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 $B \sim 100\ \mu\mathrm{G}$**

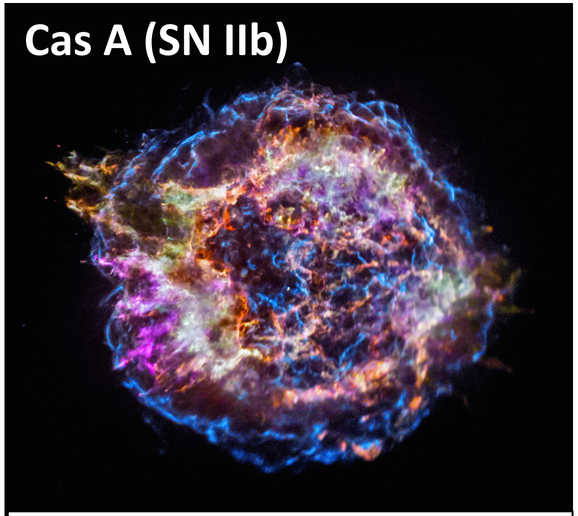


- **Gamma-ray observations of young SN remnants** confirm that cosmic rays are produced in SN shocks and constrain the proton maximum energy

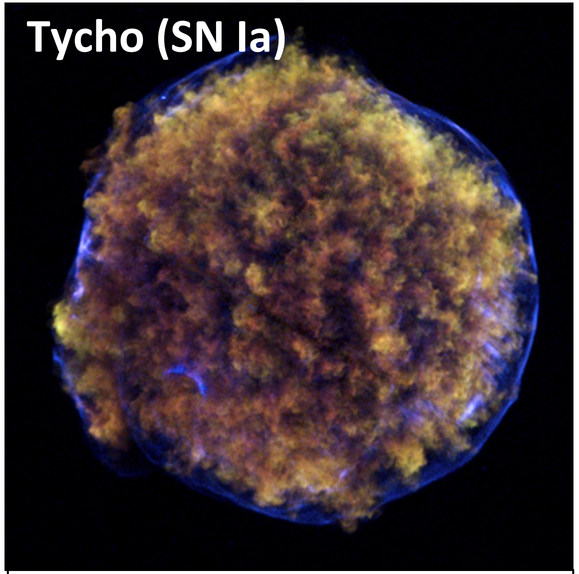
- Predicted maximum energy of protons (Schure & Bell 2013) vs. observations:

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)

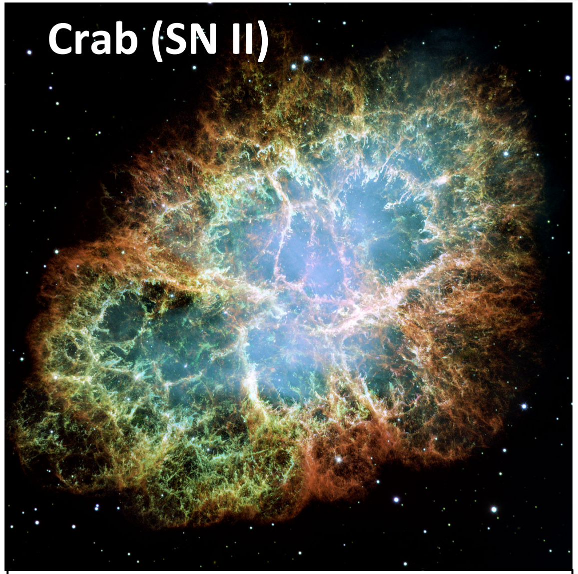
SN distribution in the ISM phases



SNR still interacting with stellar winds lost by the progenitor star

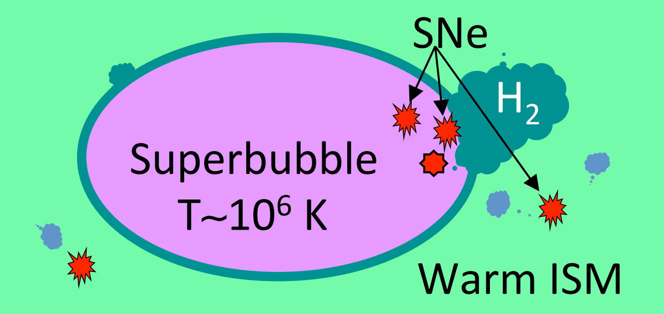


SNR evolves in a warm and partially ionised ISM



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?

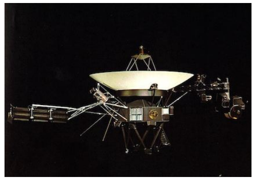
3. **Overabundance of the heavier volatile elements** compared to the lighter ones due to a **dependence of the acceleration efficiency on ion rigidity**

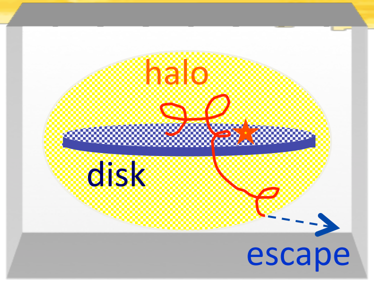
⇒ Expected from nonlinear DSA (Ellison+ 1981) and PIC simulations (Caprioli+ 2017), but ionisation states in shock precursors? **Depends on the ISM phases**

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

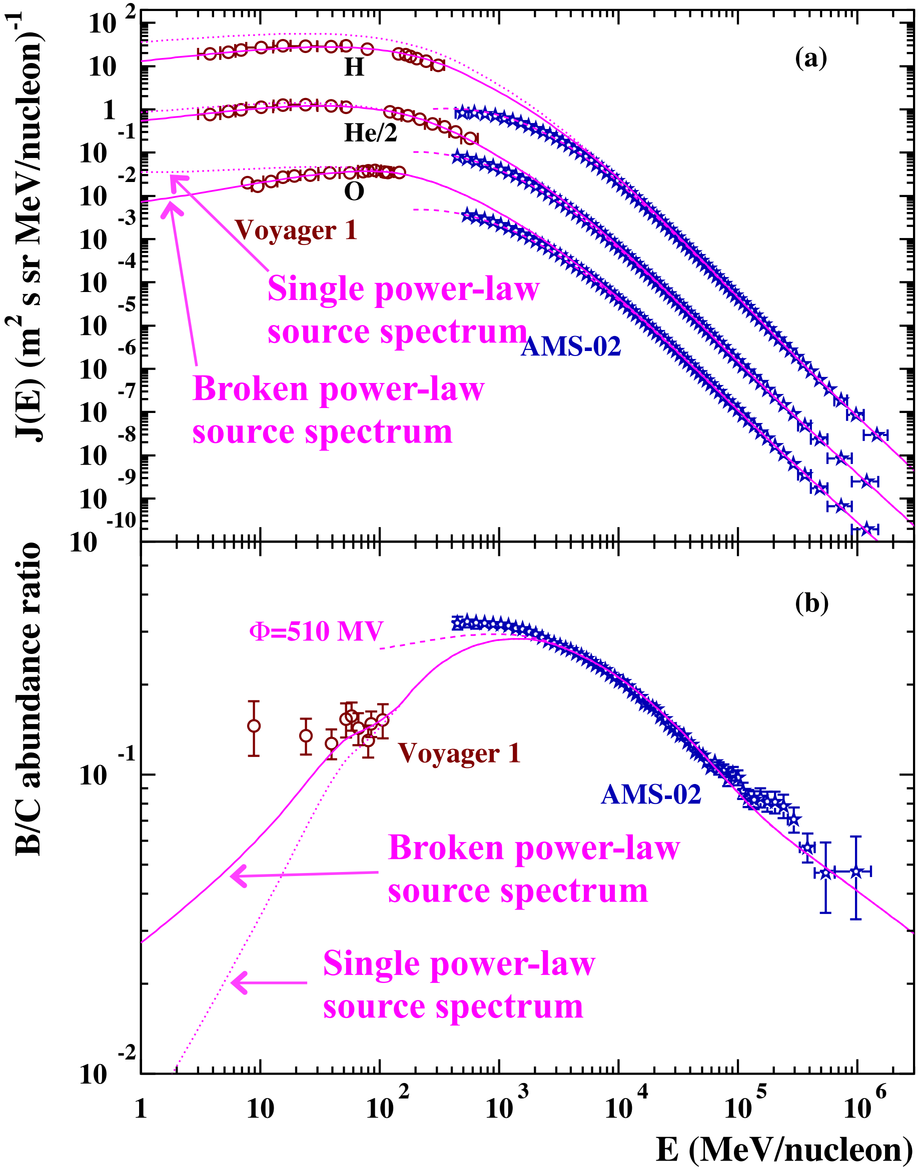
Table 2. CR source spectrum parameters (Eq. 2).

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

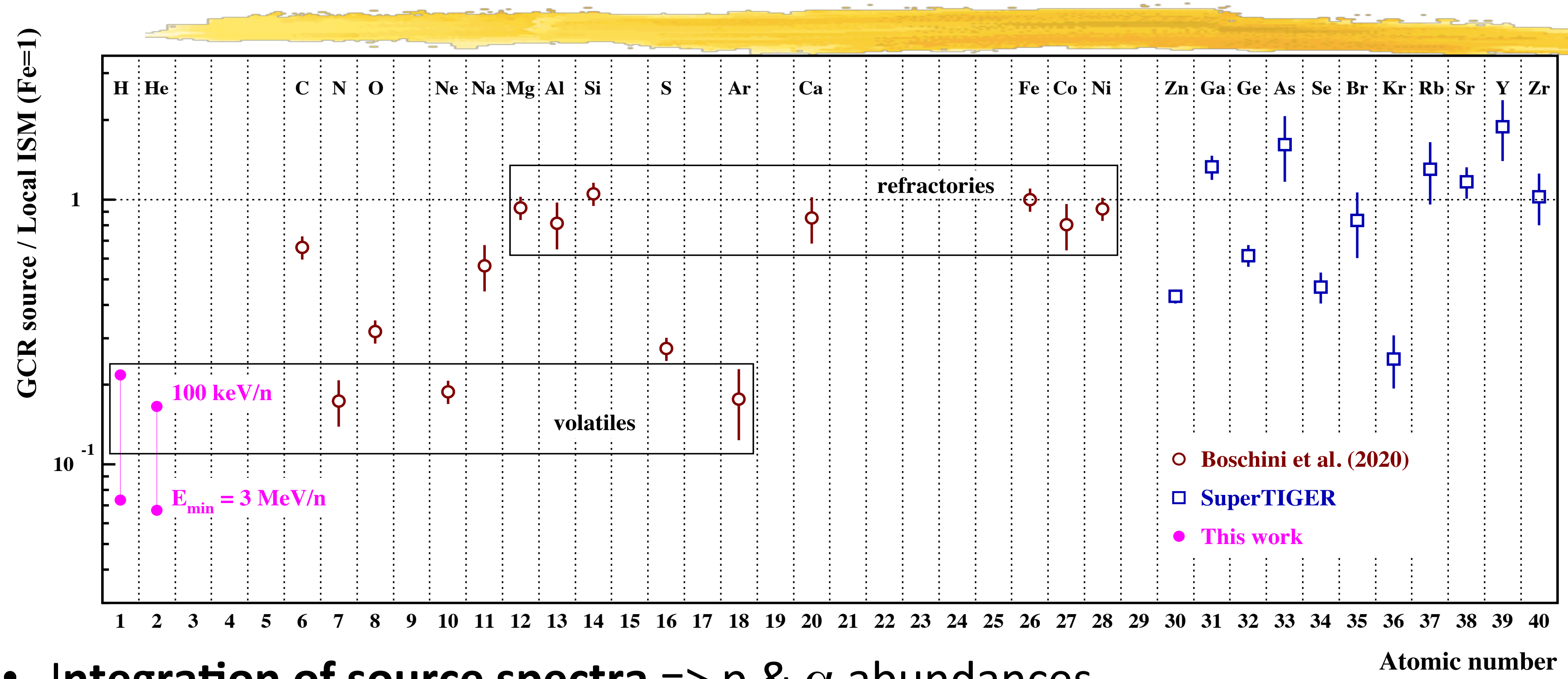
[a] Parameter fixed from Evoli et al. (2019).

[b] Minimum χ^2 from a fit of the propagated spectrum to Voyager 1 data.

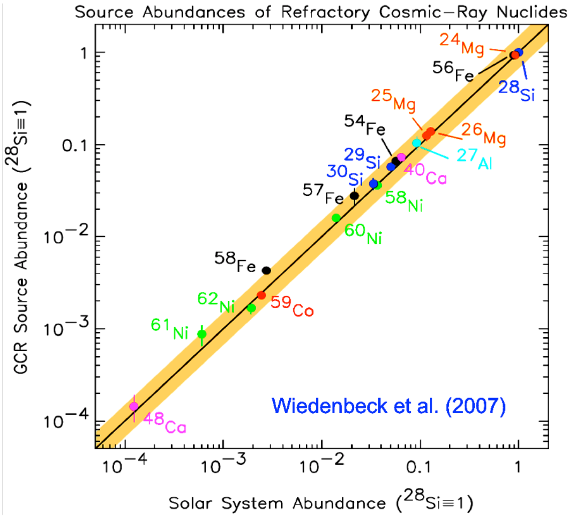
[c] d.o.f.: degrees of freedom.



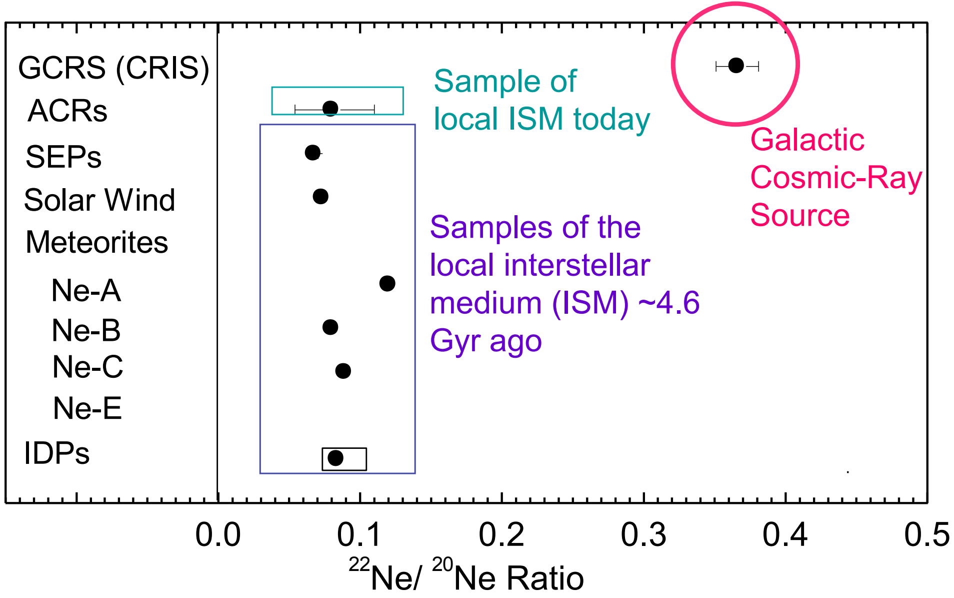
GCR abundance data

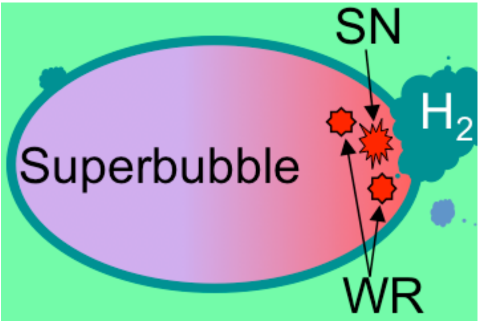


- **Integration of source spectra** => p & α abundances similar to those of the other volatiles N, Ne and Ar, provided that the **minimum CR source energy is of the order of a few hundred keV/n**
- Highly refractory elements Mg, Al, Si, Ca, Fe, Co, and Ni in solar system proportions => acceleration of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

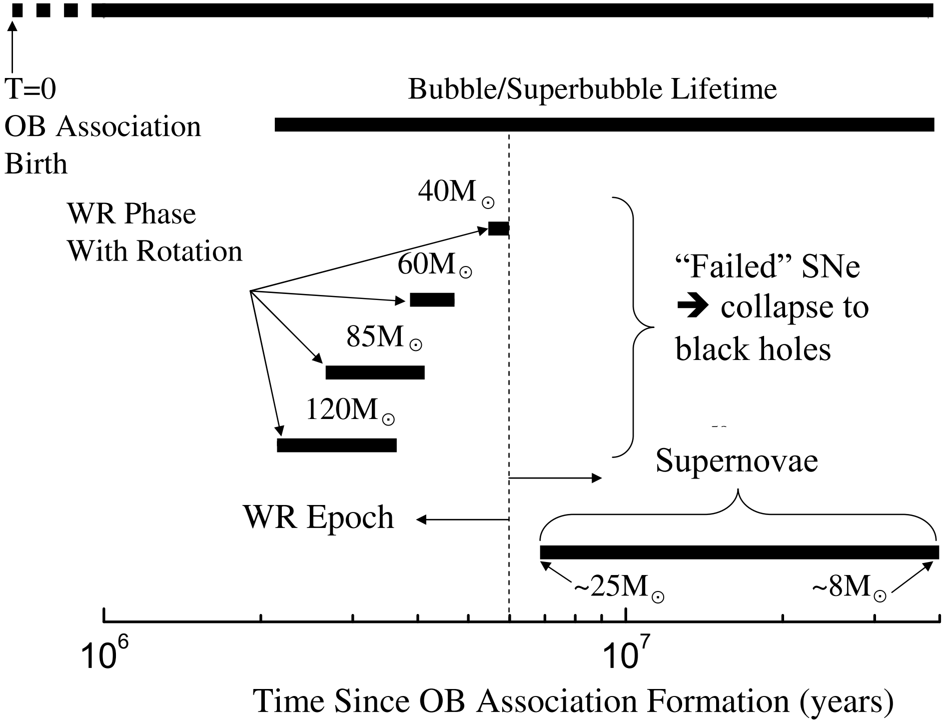


^{22}Ne abundance in GCRs





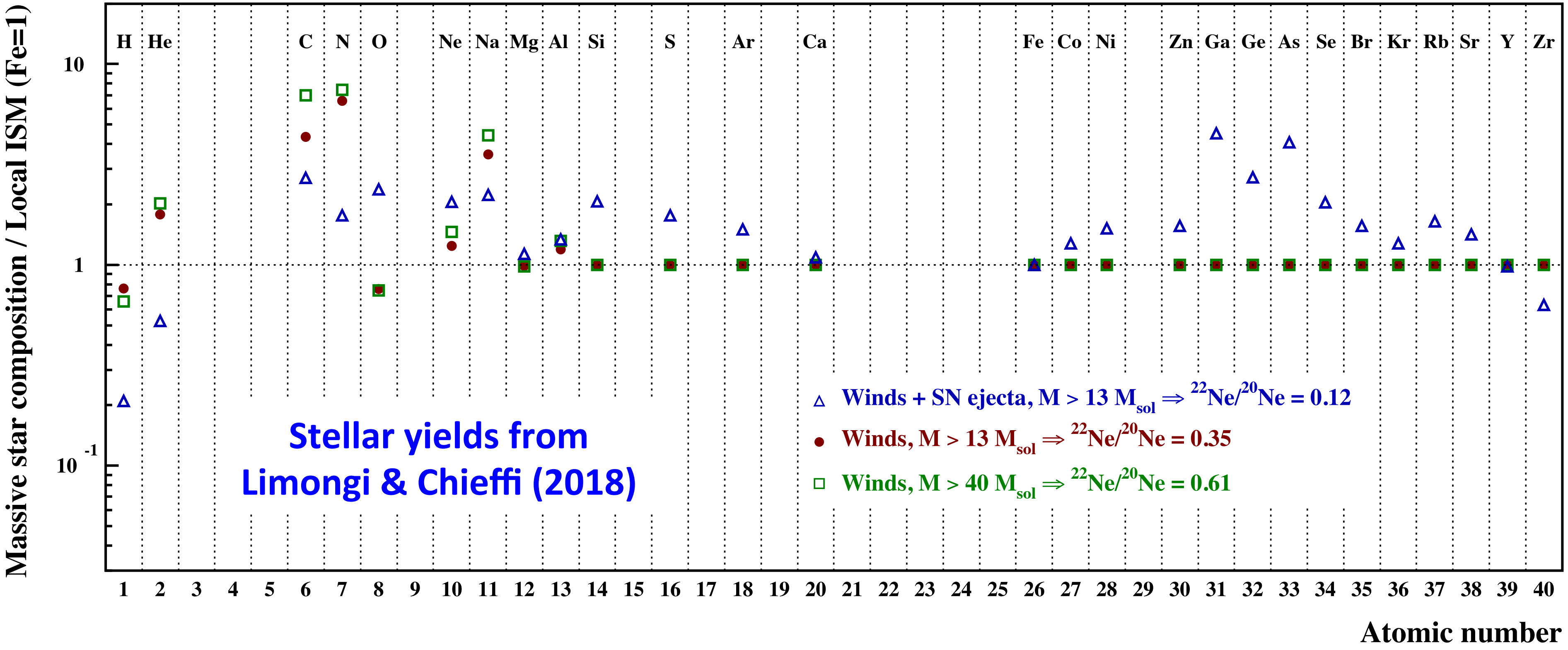
Adapted from Binns et al. (2008)



- 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$(\alpha,\gamma)^{18}$F$(\beta^+)^{18}$O$(\alpha,\gamma)^{22}$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** (close to solar as 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…**

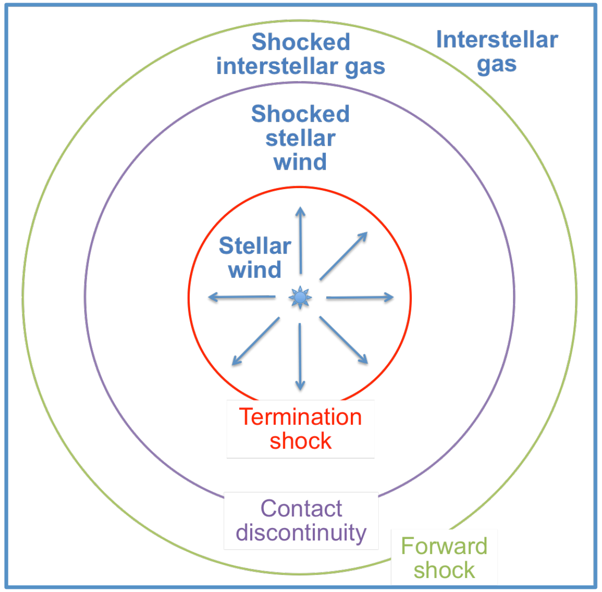


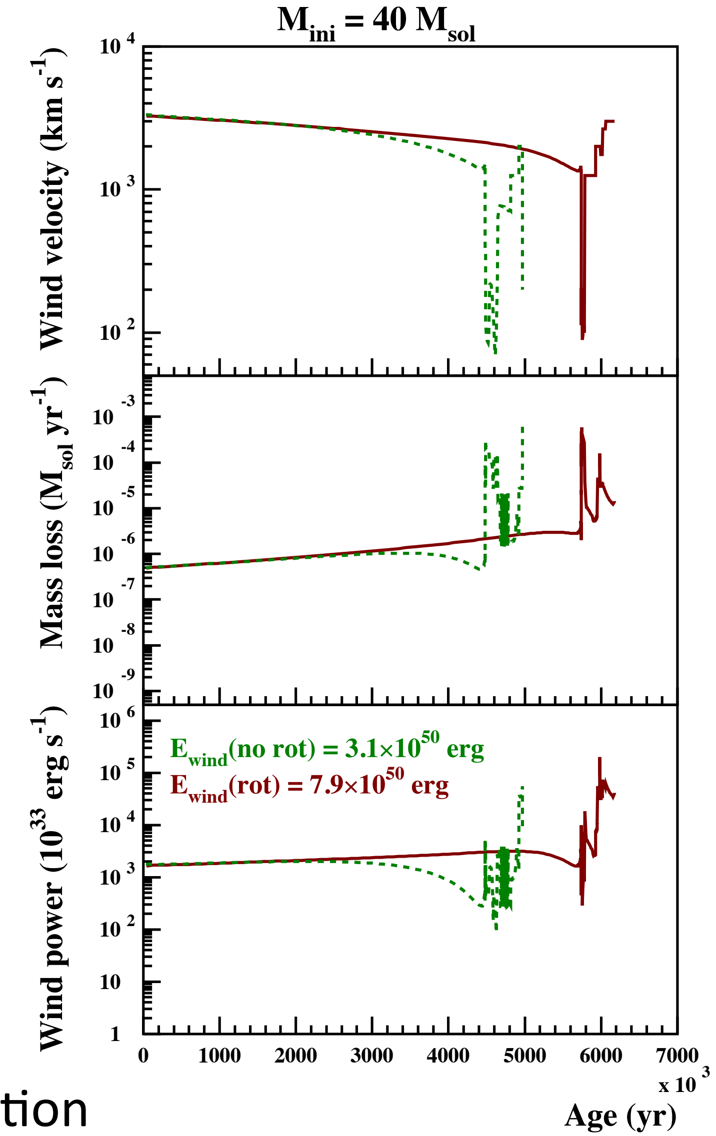
Stellar yields from Limongi & Chieffi (2018)

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)





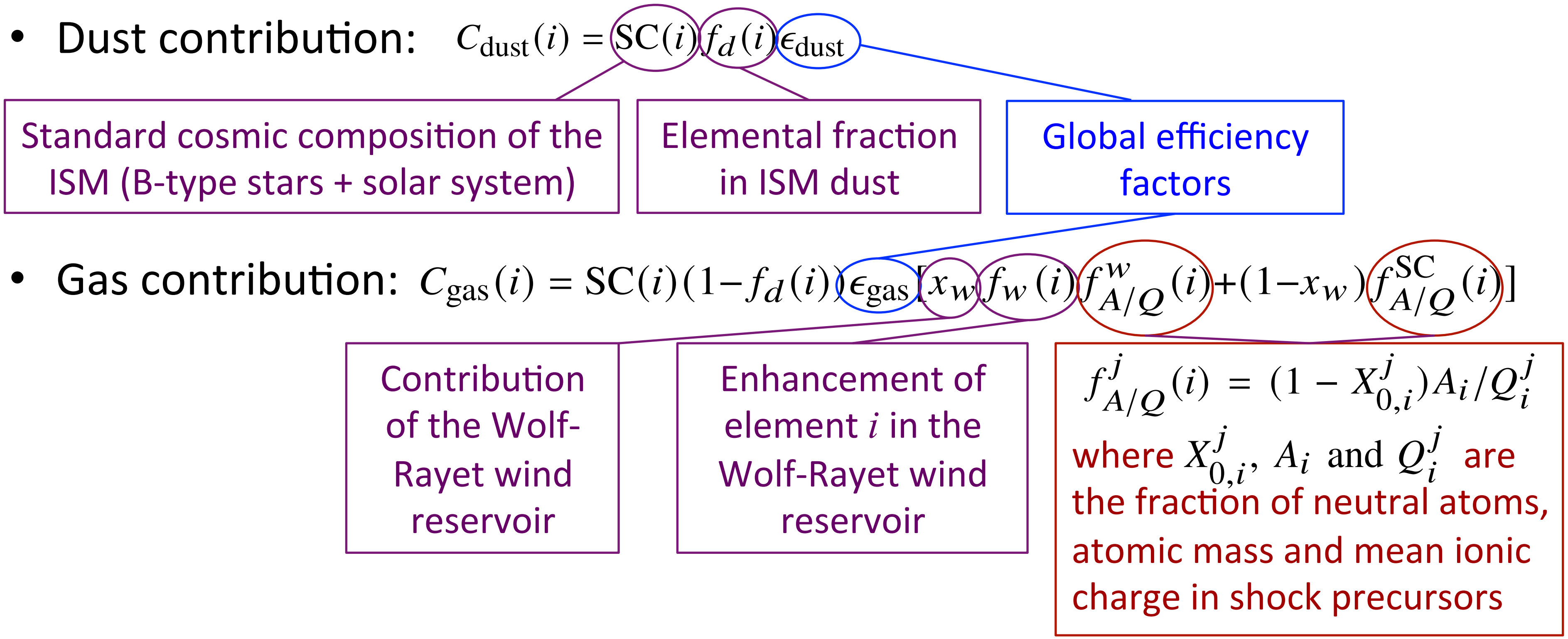
- Time-dependent yields, mass loss rates & stellar types from the **Geneva Observatory database** (e.g. Ekström et al. 2012)

- 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

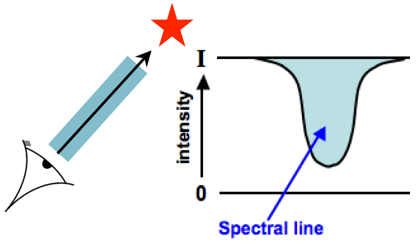
$$f^j_{A/Q}(i) = (1 - X^j_{0,i}) A_i / Q^j_i$$

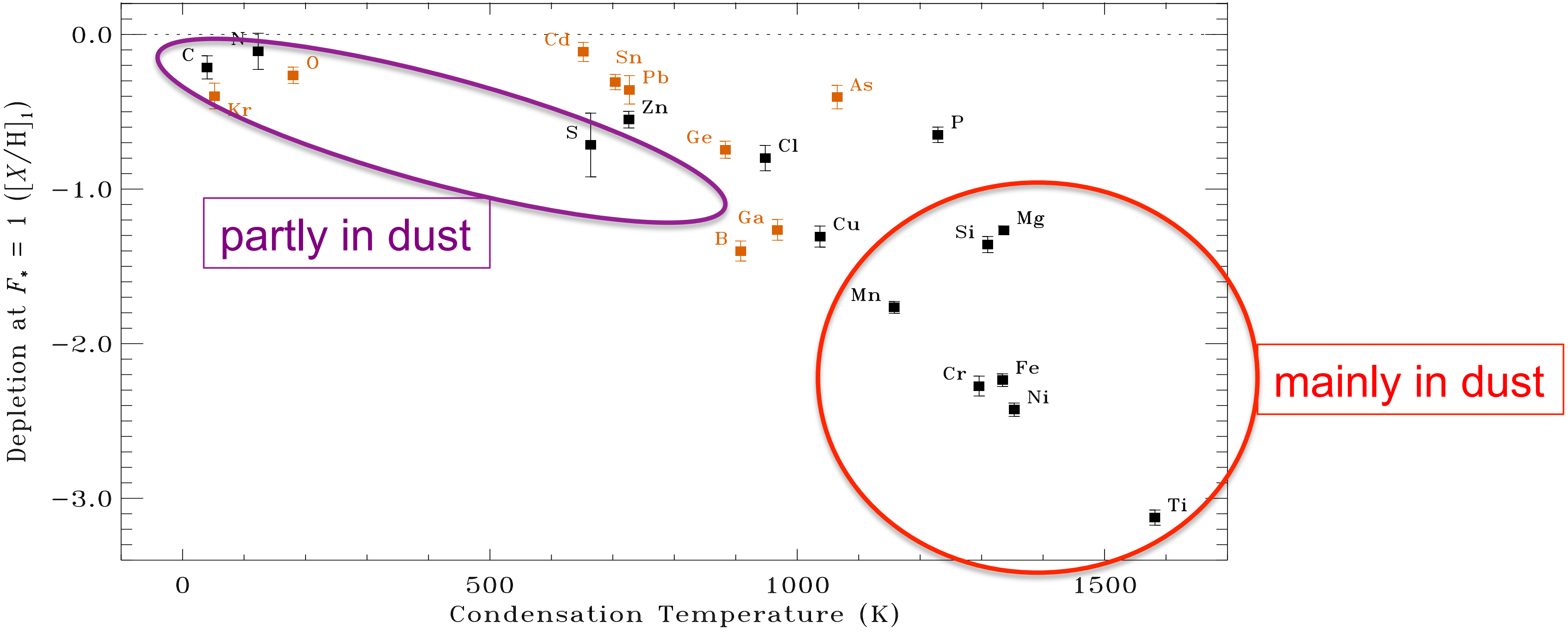
where $X^j_{0,i}$, A_i and Q^j_i are the fraction of neutral atoms, atomic mass and mean ionic charge in shock precursors

- 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**



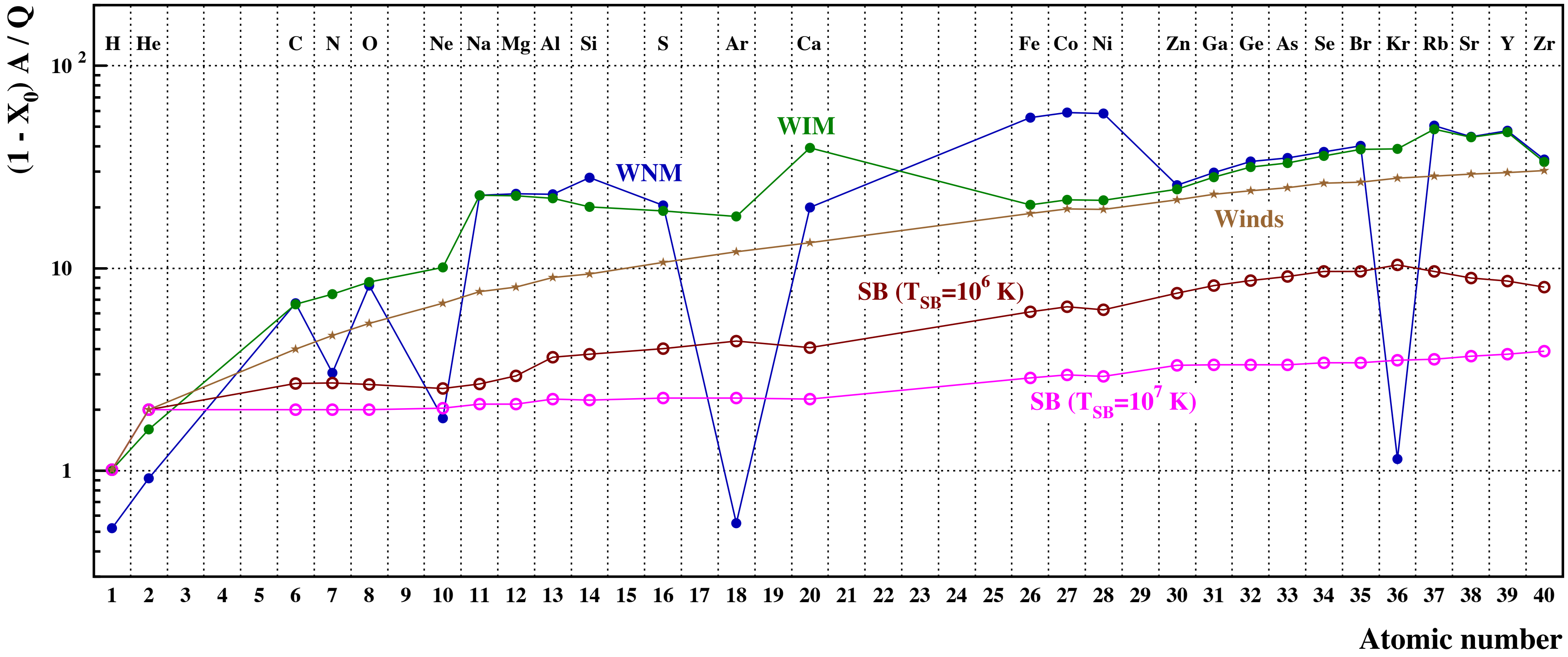


partly in dust

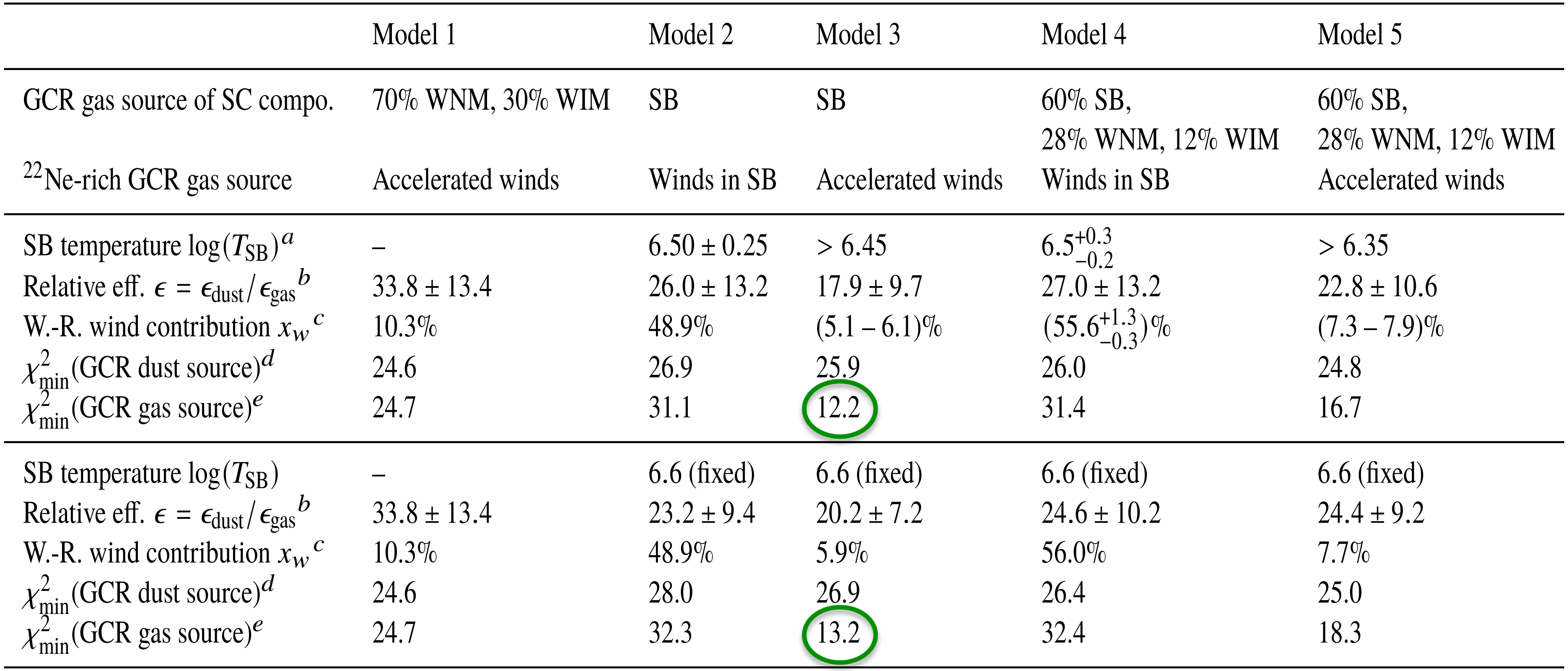
mainly in dust

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

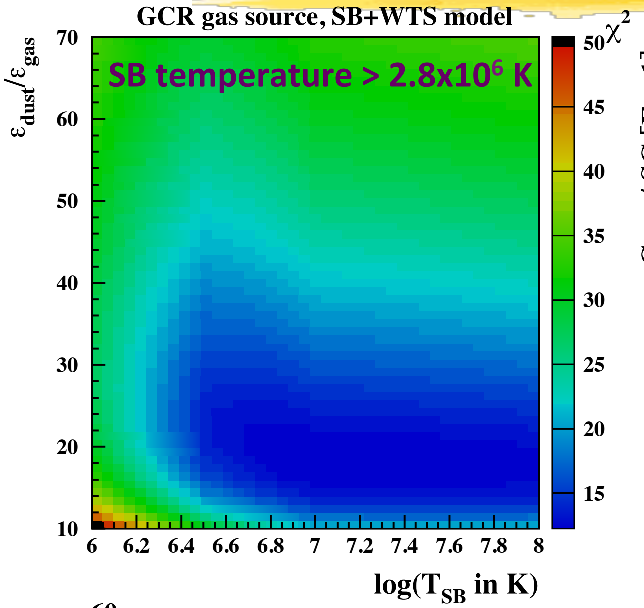


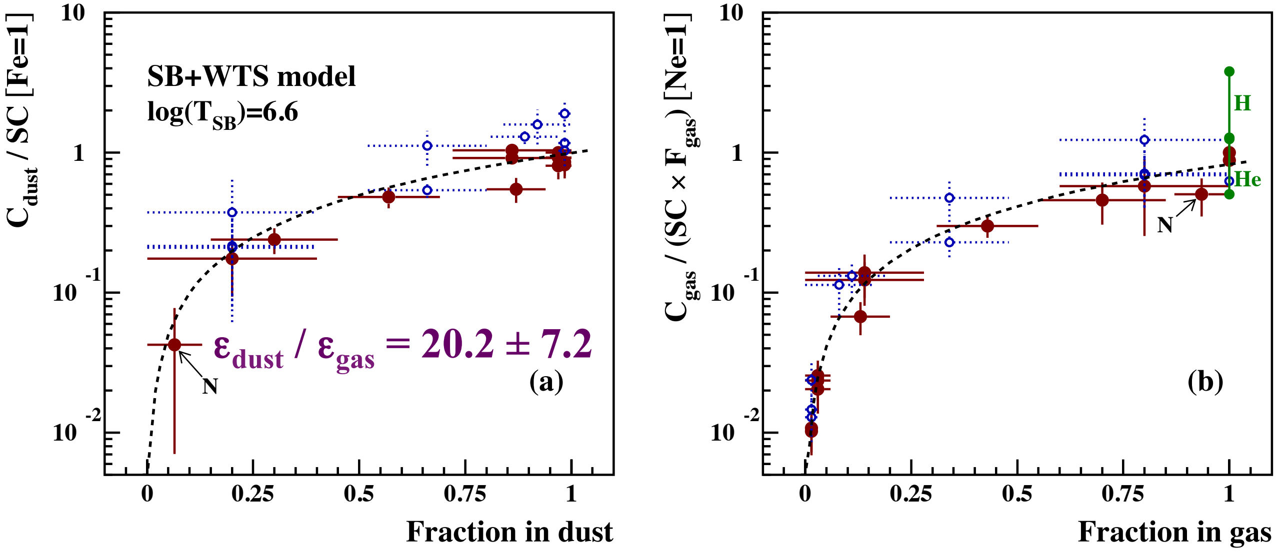
	Model 1	Model 2	Model 3	Model 4	Model 5
GCR gas source of SC compo.	70% WNM, 30% WIM	SB	SB	60% SB, 28% WNM, 12% WIM	60% SB, 28% WNM, 12% WIM
^{22}Ne-rich GCR gas source	Accelerated winds	Winds in SB	Accelerated winds	Winds in SB	Accelerated winds
SB temperature $\log(T_{\mathrm{SB}})$[a]	–	6.50 ± 0.25	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{\mathrm{dust}}/\epsilon_{\mathrm{gas}}$[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 $\log(T_{\mathrm{SB}})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{\mathrm{dust}}/\epsilon_{\mathrm{gas}}$[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

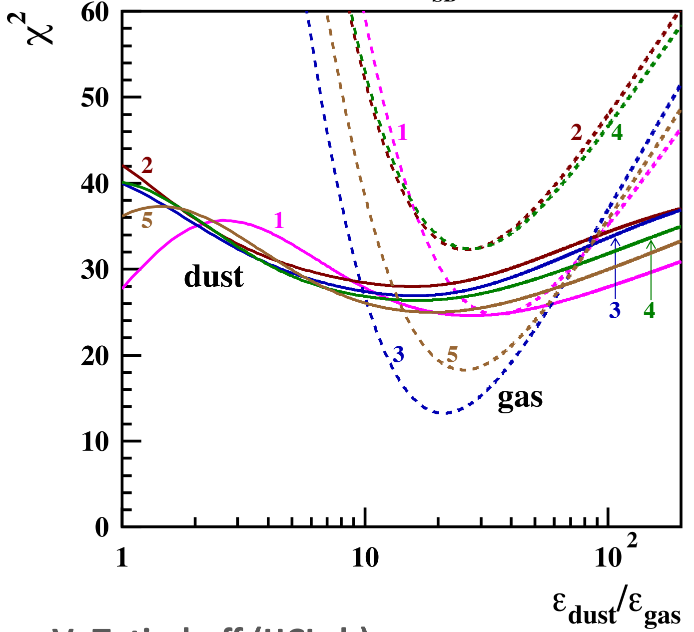
- Five models depending on the relative weights of the **ISM phases** in the GCR volatile production, and the **origin of GCR ^{22}Ne**

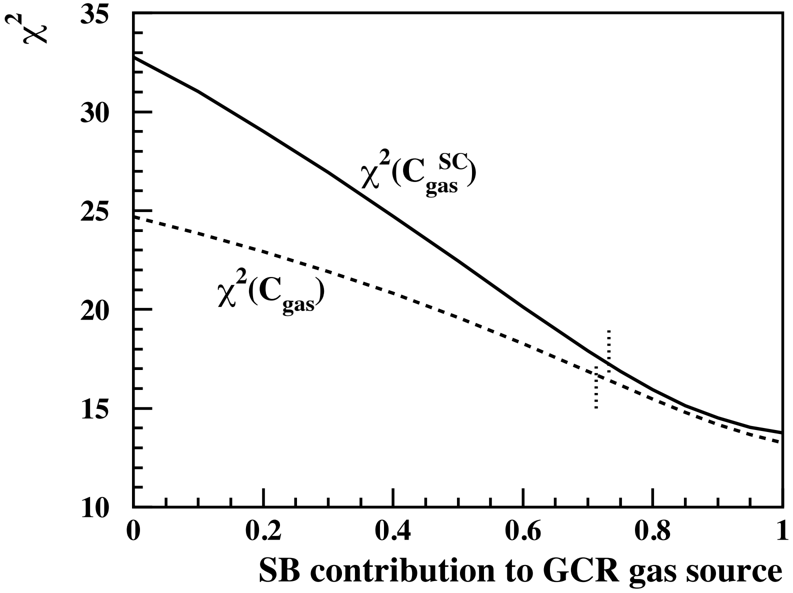
- Best-fit model: GCR volatiles accelerated in **superbubbles** + ^{22}Ne-rich component from acceleration in **wind termination shocks** ($x_w \approx 6\%$)

Results of the GCR composition model


SB temperature > 2.8x10^6 K

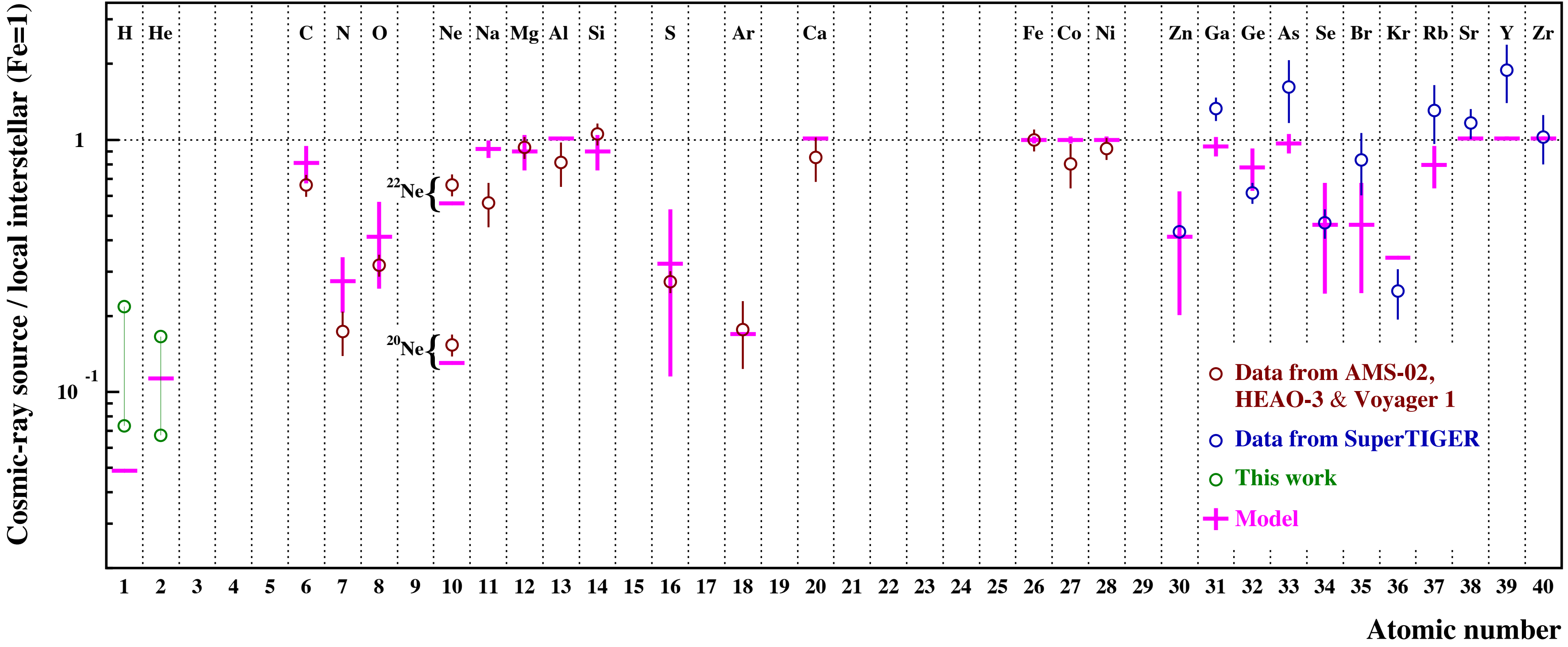

$\varepsilon_{dust} / \varepsilon_{gas} = 20.2 \pm 7.2$





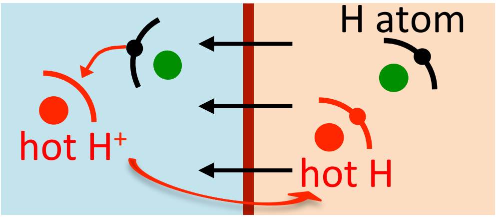
SNRs in the warm ISM contribute for less than 28%

Origin of GCR volatiles in superbubbles



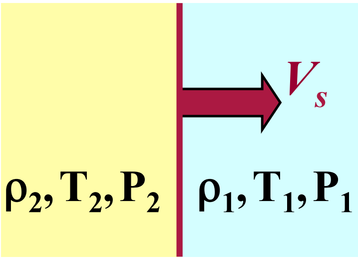
- ○ SNRs in the warm ISM contribute to the GCR volatile composition for less than 28%, whereas ~ 40% of SNe occur in this phase and not in superbubbles (?)

- ○ 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**

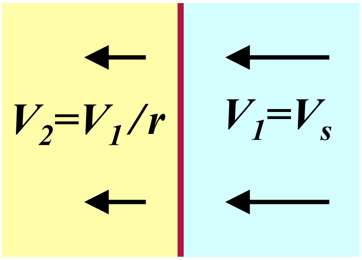


Acceleration of dust grains

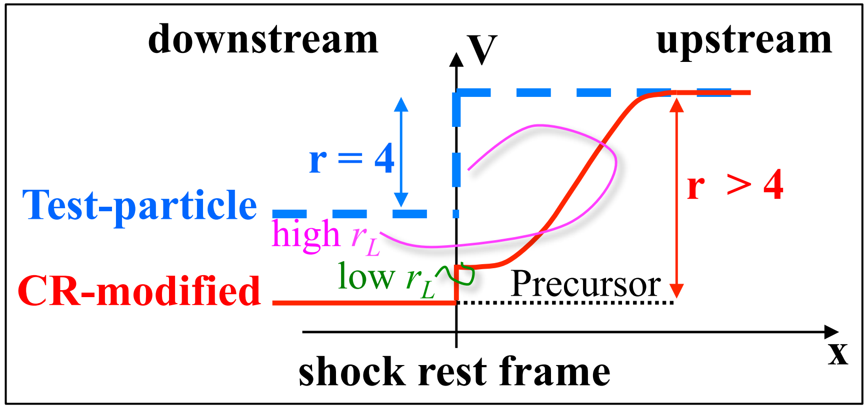
- **Preferential acceleration of dust grains** in SN shocks, because interstellar grains can have **very large $A/Q \sim 10^4$ - 10^8** and particles with a high rigidity ($R \propto A/Q$) feel a larger ΔV of the background plasma (Ellison et al. 1997, 1998)
  i. **Grain acceleration**
  ii. **Grain sputtering** with ambient atoms
  iii. **Injection of the sputtered ions** in the acceleration process with the **supra-thermal velocity** of the parent grain



ref. frame: observer

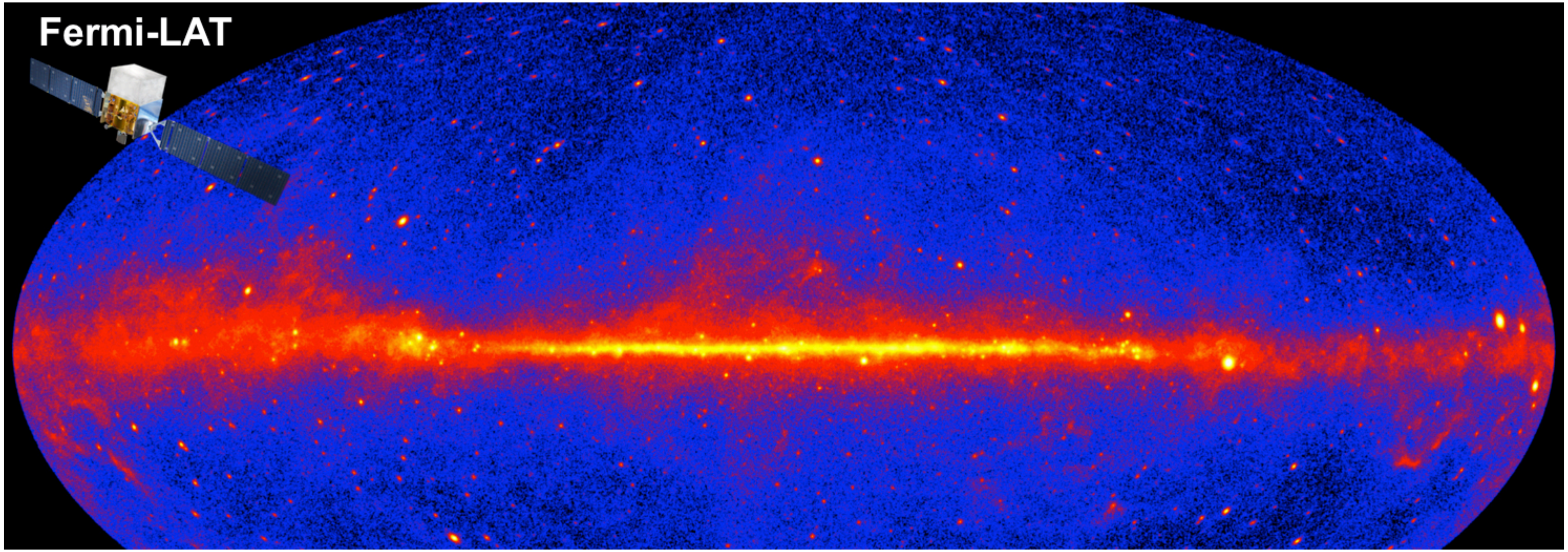


shock front



- **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)

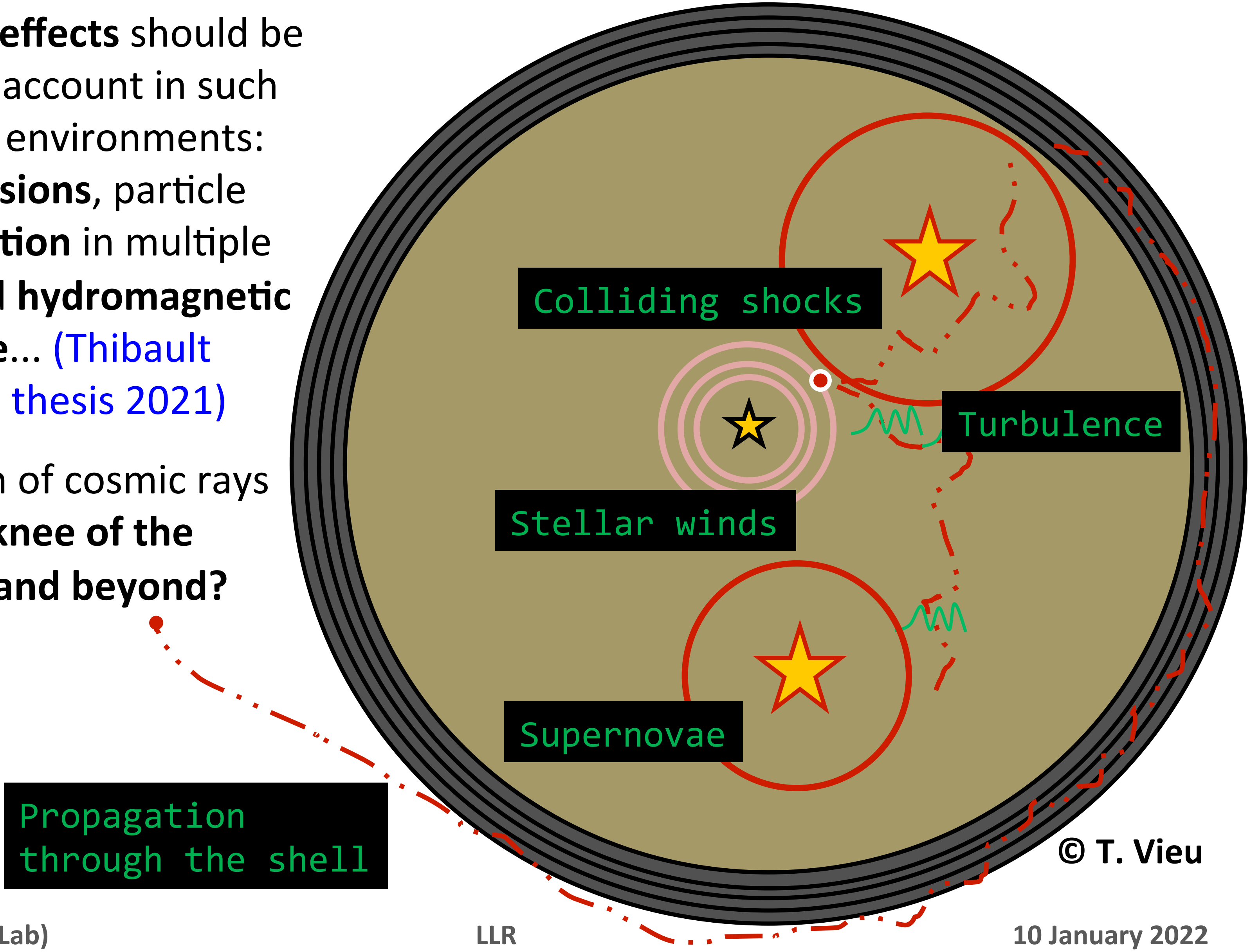
GCR acceleration efficiency



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

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?**



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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 3×10^{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 (Cristofari et al., in prep.)