Sur l’origine des rayons cosmiques

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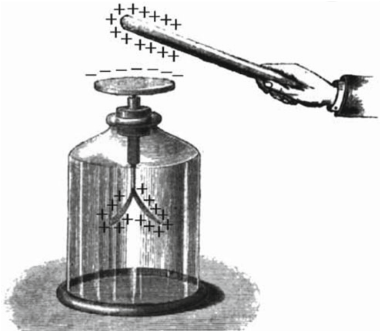
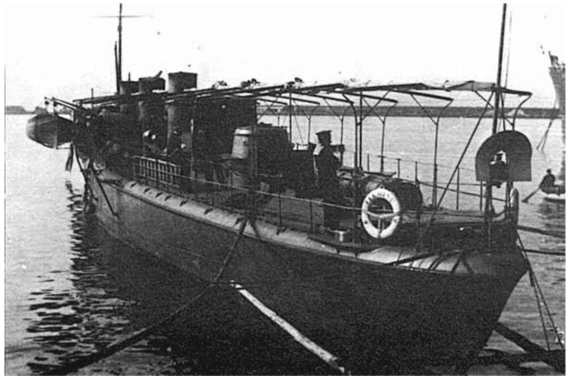
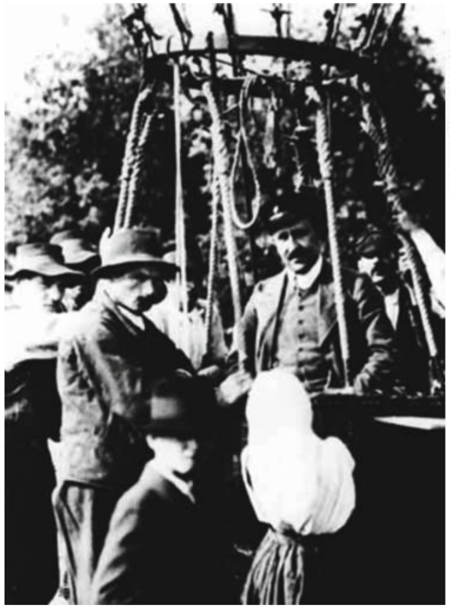
Discovery of cosmic rays

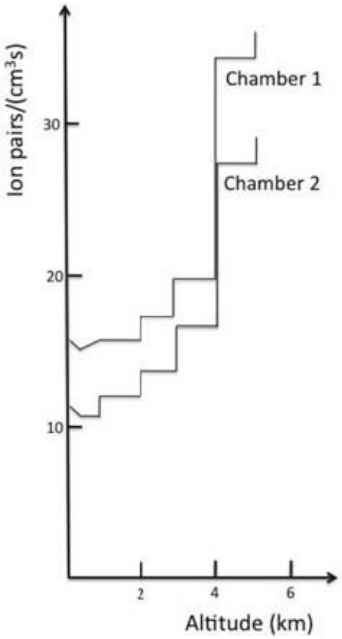


Pacini's first mission in 1907

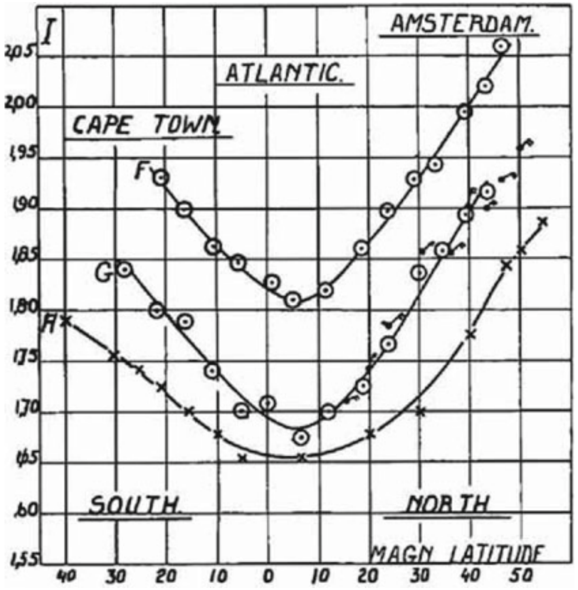


Hess' balloon flight in 1912

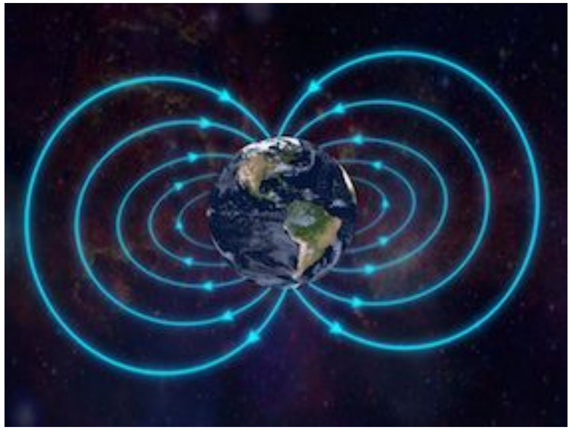




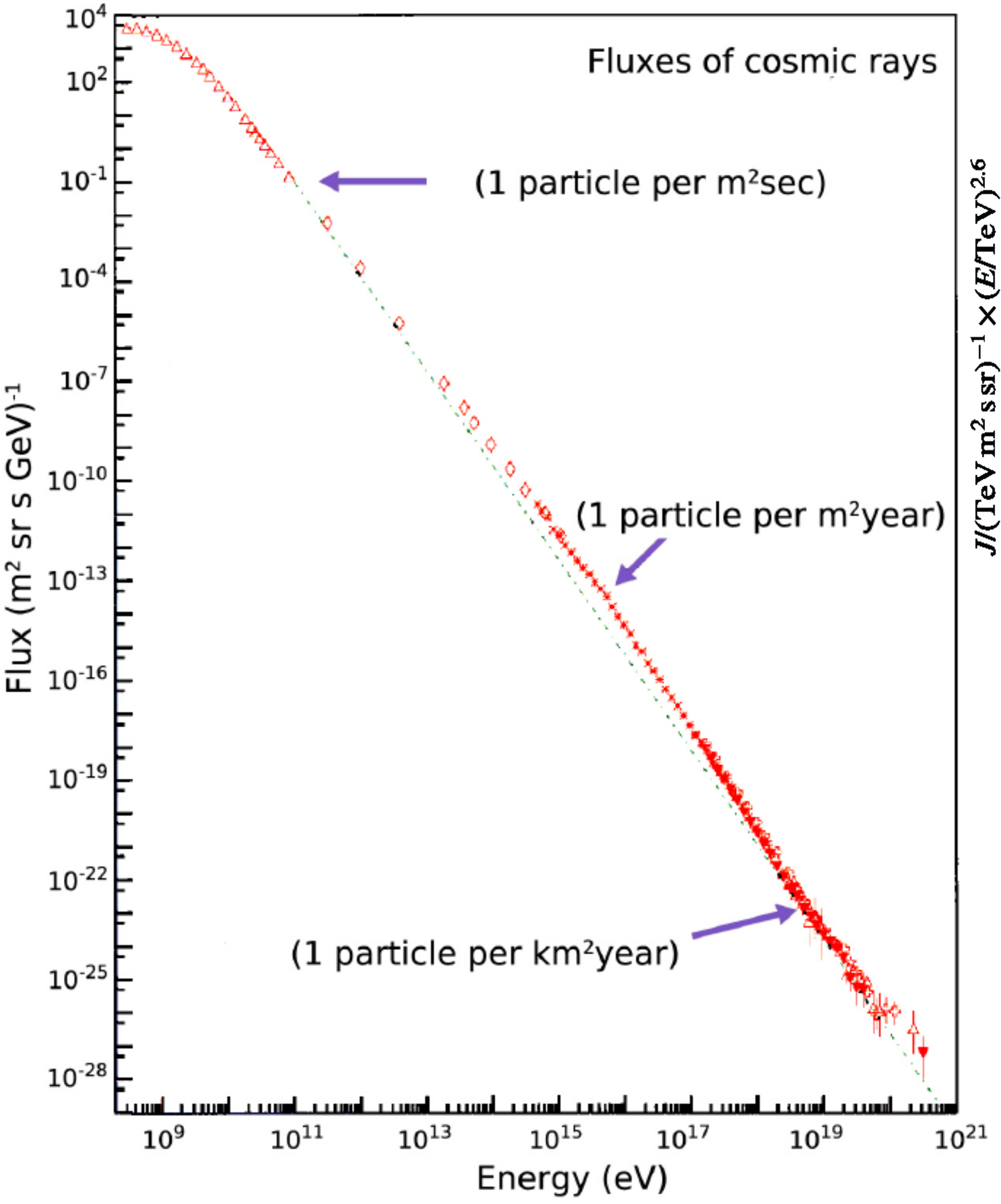
Measurements by Clay et al.

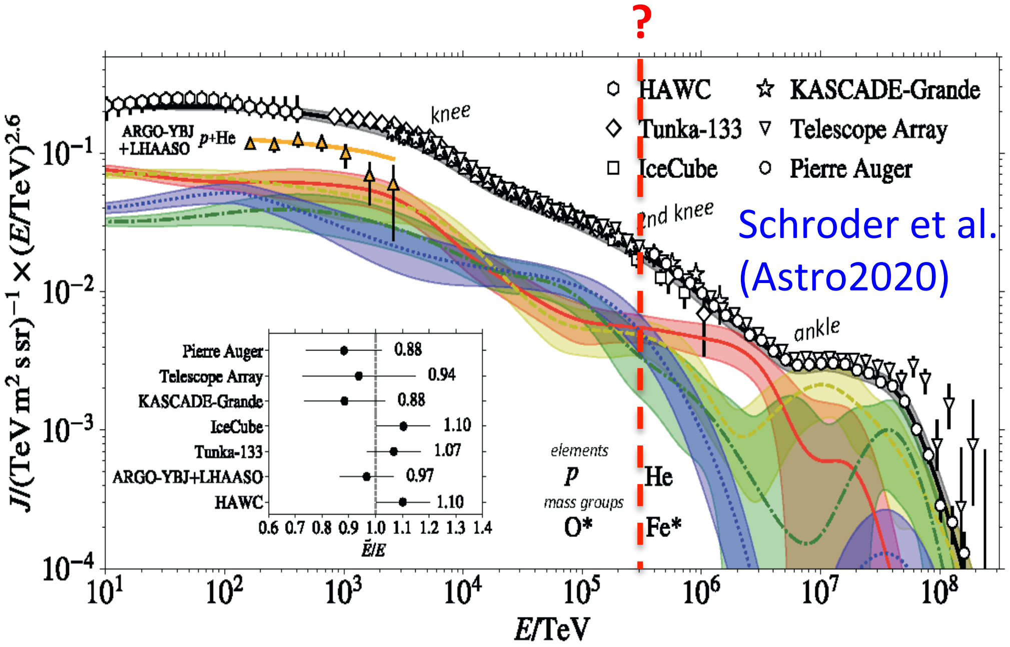


- **1785 Coulomb**: spontaneous discharge of electroscopes
- **Early 20th century**: effect is due to **ionizing radiation**
- **1907 - 1911 D. Pacini**: measurements away from Earth's crust, then underwater => **not terrestrial radioactivity**
- **1912 V. Hess** (Nobel price in 1936): increase in ionization with height => **cosmic origin**
- **1928 J. Clay**: increase in ionization with latitude => **charged particles**



Cosmic ray spectrum

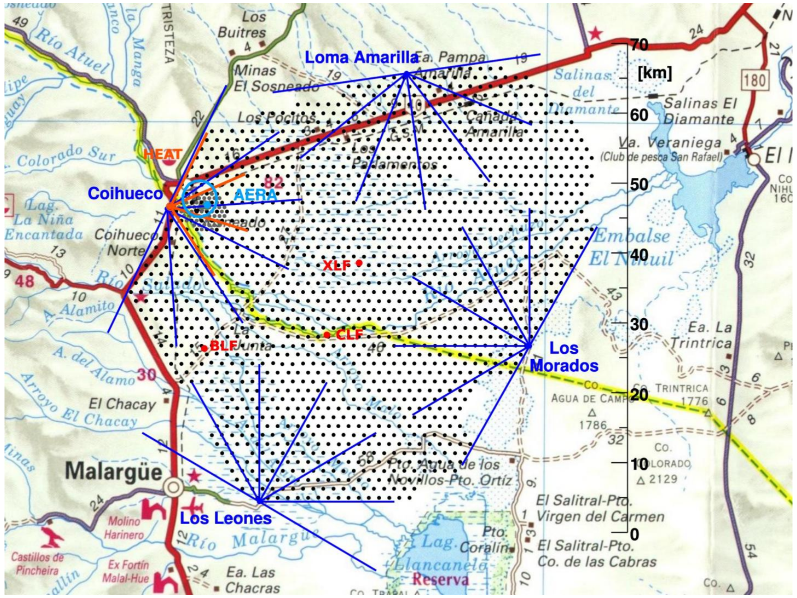




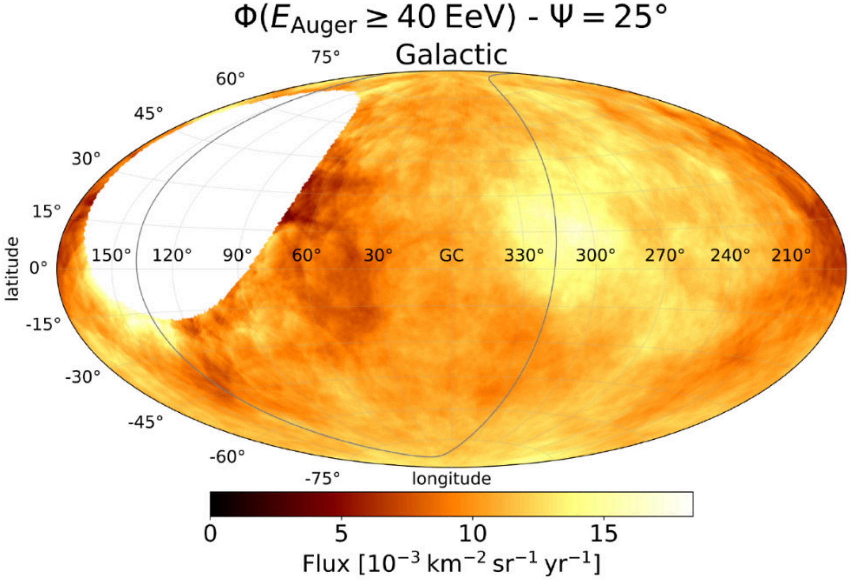
Schroder et al. (Astro2020)

- Almost a power law over **13 decades in energy and 31 decades in flux**!
- At low energies, **mostly protons** (89%) + 9% α-particles, 1% heavier nuclei and 1% electrons
- Transition from Galactic to extragalactic origin around **~ 3 × 10^{17} eV (?)**

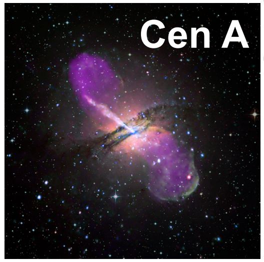
Ultra-high-energy cosmic rays



The Pierre Auger Collaboration (2022)



- Nearly 20 years of data from the **Pierre Auger Observatory** (3000 km^2)
- Confirmation of the **extragalactic origin** of UHECRs, **significant anisotropy** at large scale
- Mixed composition, **increasingly heavier above 2 × 10^{18} eV**
- <u>Possible sources</u>: **jetted active galactic nuclei**, starburst galaxies...



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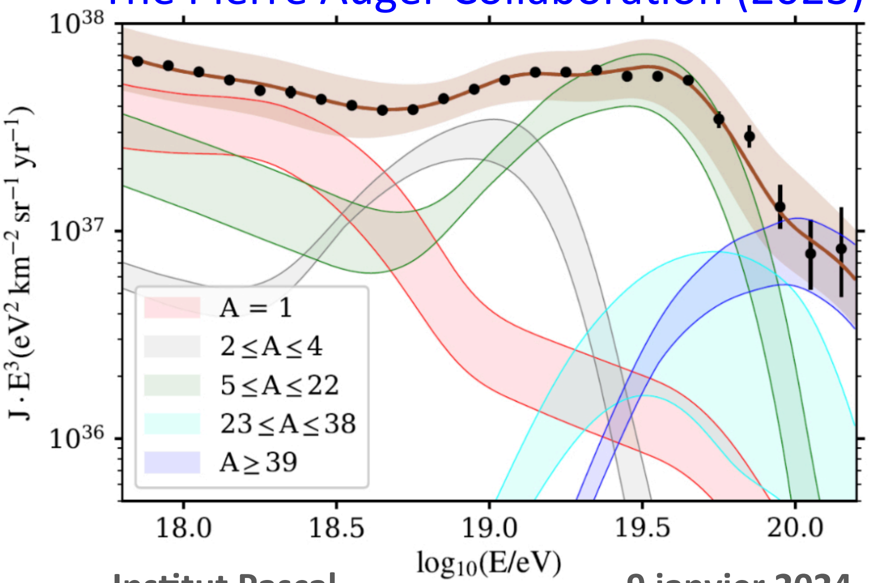
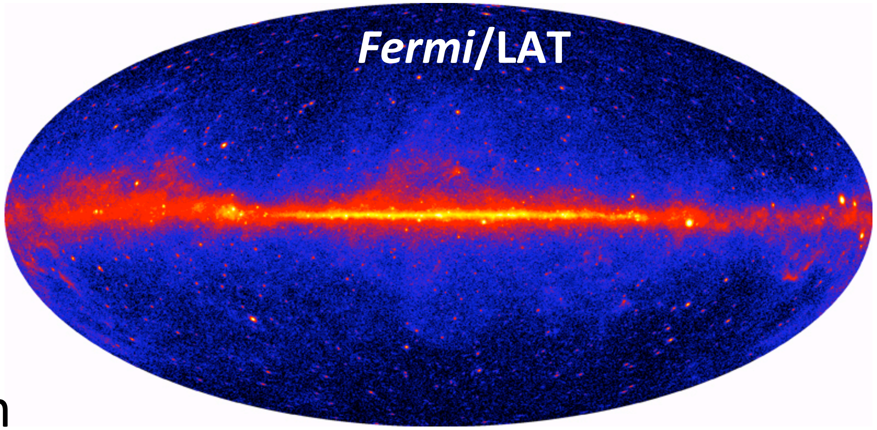
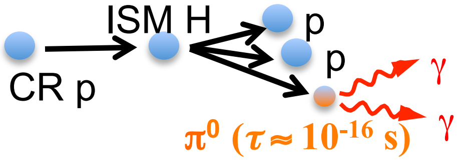


Galactic cosmic rays & supernovae



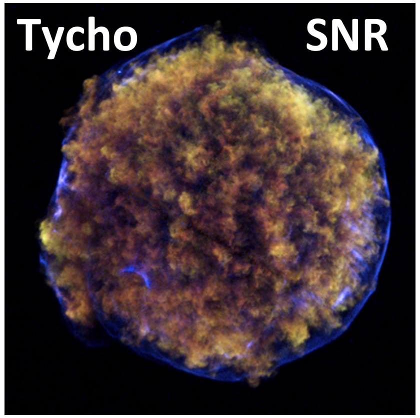
- GCRs are thought to be produced in **supernova remnants** (Baade & Zwicky 1934)

- Consistent with CR power and supernova energetics: $L_{\mathrm{CR}} = L_\gamma / R_\gamma \sim 10^{41}$ **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 (Strong et al. 2010)



⇒ $L_{\mathrm{CR}} \sim$ **10% of the kinetic power supplied by supernovae**

- **Diffusive shock acceleration in supernova shocks** = First-order Fermi (1949) process (Krymskii 1977; Bell 1978; Axford et al. 1978; Blandford & Ostriker 1978)



$V_{\text{SN ejecta}} \rightarrow 10^4$ km/s

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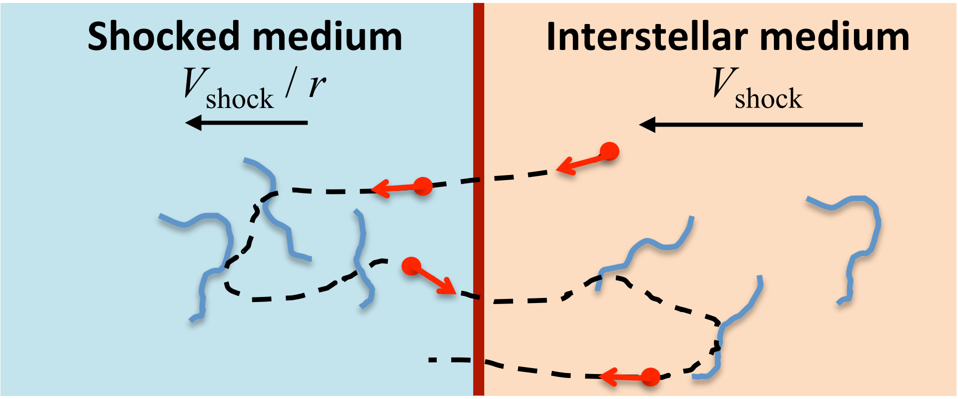
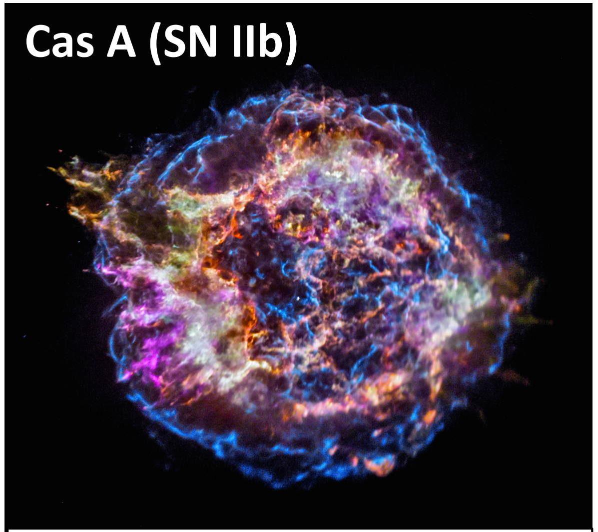
ISM sound speed $c_S \approx 100\ (T/10^6\ \mathrm{K})^{0.5}$ km/s

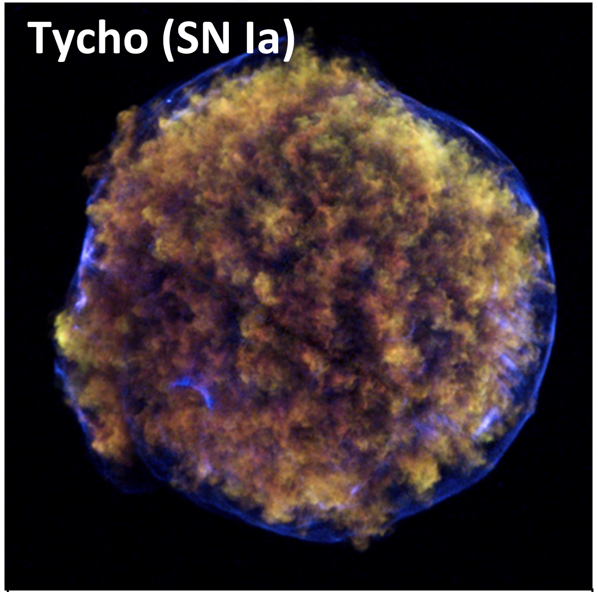
⇒ **Strong shock**



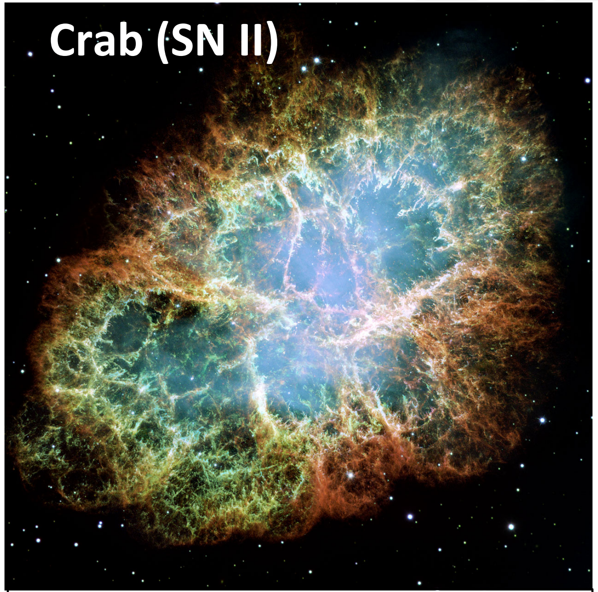
Supernova distribution in the ISM phases



SNR still interacting with stellar winds lost by the progenitor star

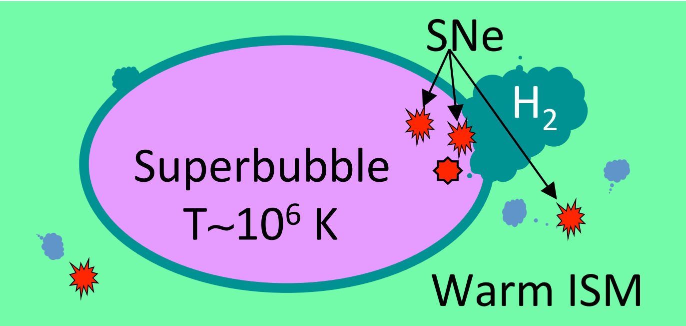


SNR evolves in a warm and partially ionised ISM

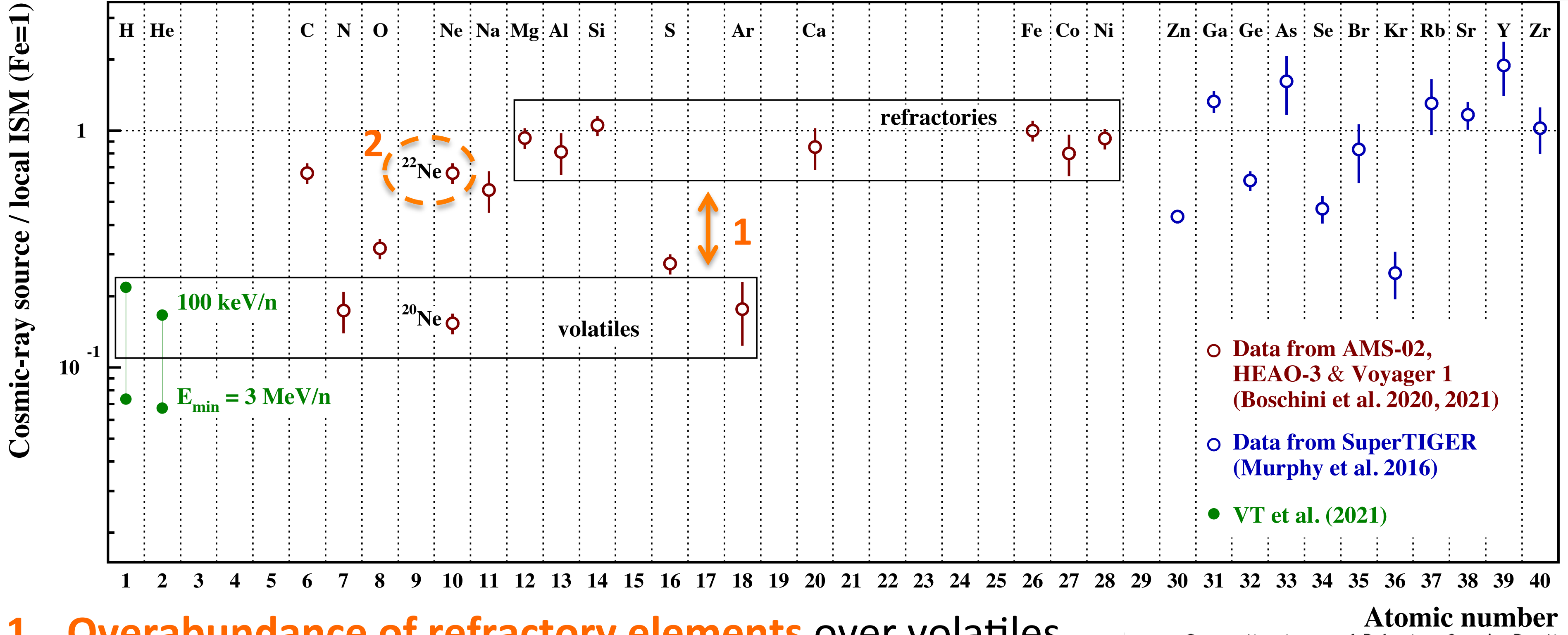


Explosion in a bubble of hot plasma

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

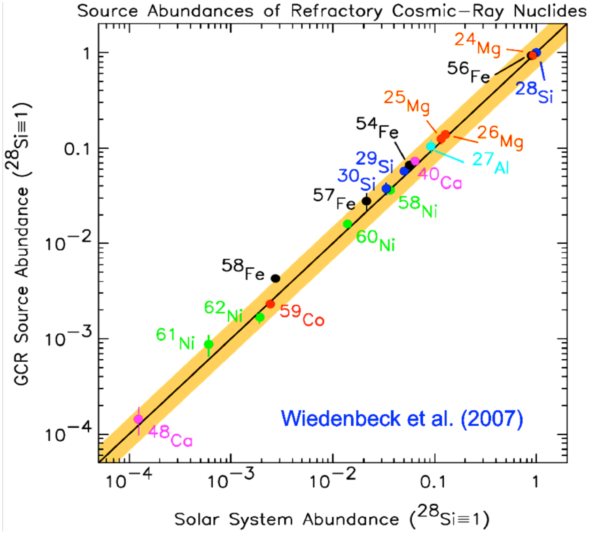


Galactic CR source abundance data



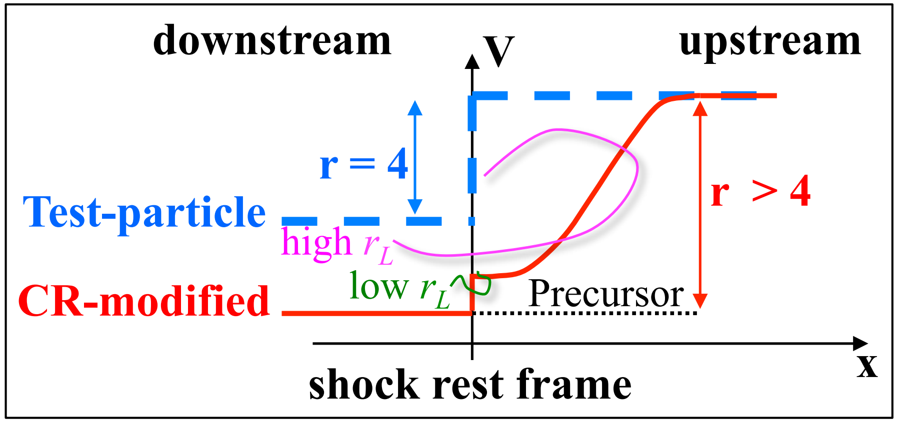
1. **Overabundance of refractory elements** over volatiles in the GCR composition => **preferential acceleration of dust grains** (in the interstellar medium, refractory elements are mainly found in dust)
2. **Overabundance of ^{22}Ne** (^{22}Ne/^{20}Ne is 5 times solar) => contribution of material from **massive star winds**

See **Meyer, Drury & Ellison (1997)**



Acceleration of dust grains

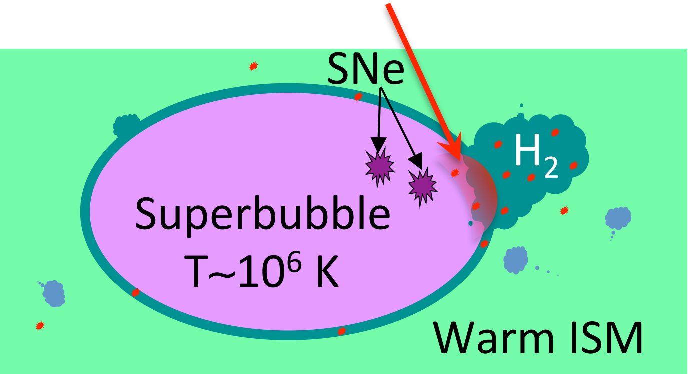
- **Higher efficiency of acceleration of dust grains** in SN shocks, because interstellar grains can have **very large** $A/Q \sim 10^4$ **-** 10^8 and particles with a high rigidity ($R \propto A/Q$) feel a larger ΔV of the background plasma (Ellison et al. 1997, 1998)



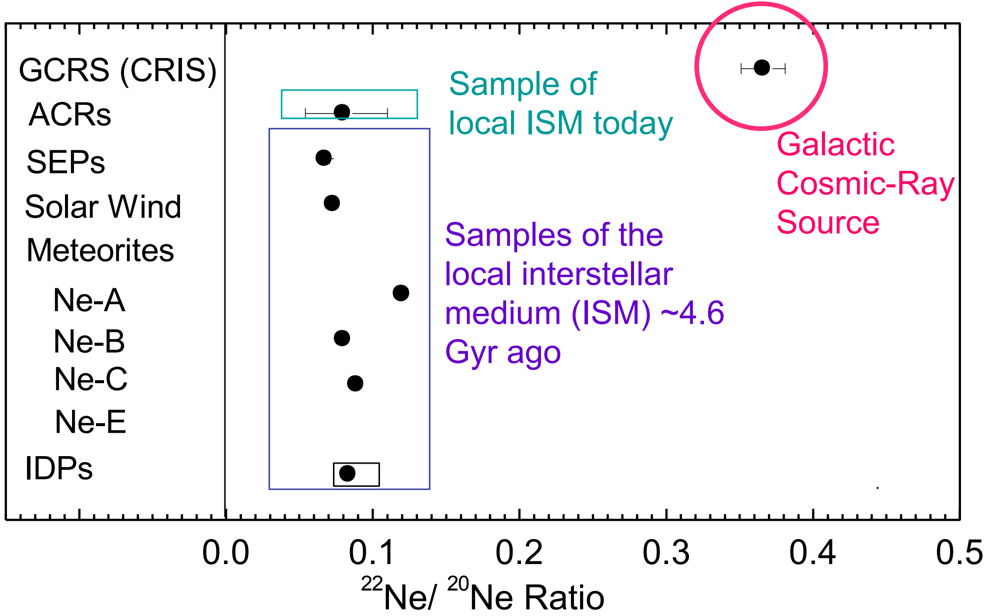
i. **Grain acceleration**
ii. **Grain sputtering** with ambient atoms
iii. **Injection of sputtered ions** with the **supra-thermal velocity** of the parent grain

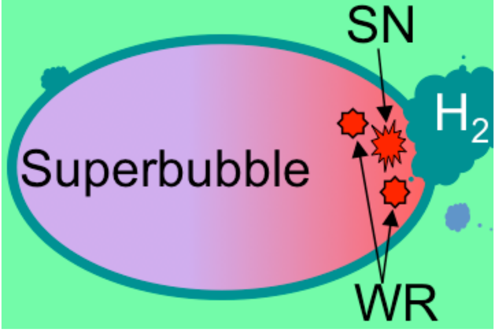
- **ISM phase where dust grains are accelerated?**
  - ✓ Diffuse shock acceleration occurs in **ionised media** (requires plasma waves)
  - ✓ But dust grains are mainly found in **cold molecular clouds** and the **warm ISM** (however, see Ochsendorf et al. (2015) for dust in the Orion-Eradinus superbubble)

Material enriched in dust grains evaporated off the SB shell and the parent molecular clouds

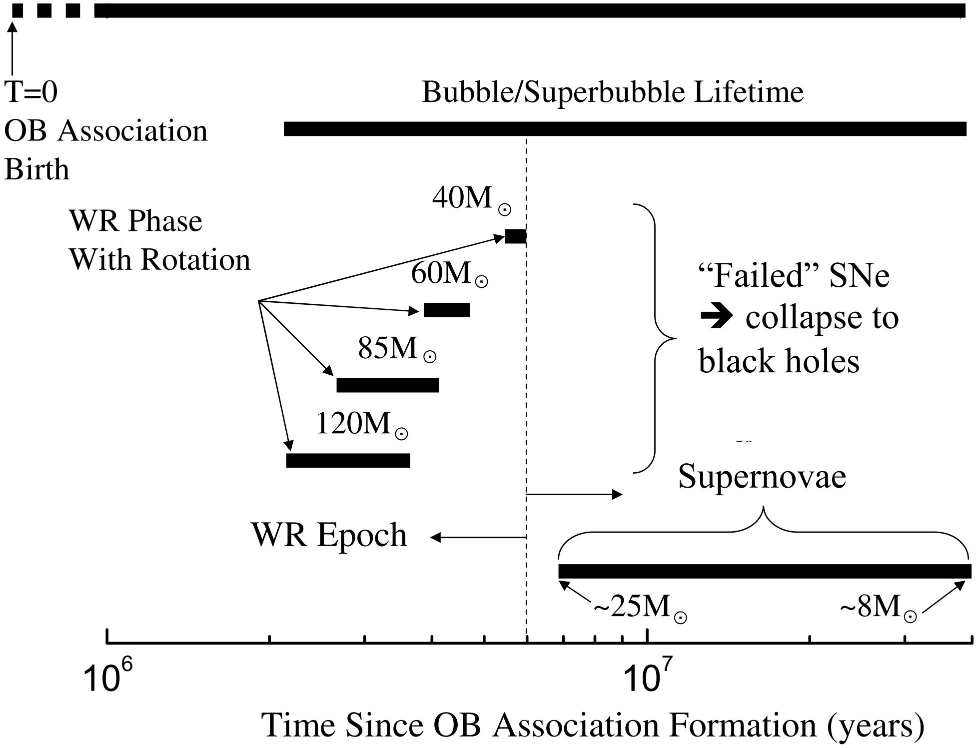


^{22}Ne overabundance in Galactic CRs



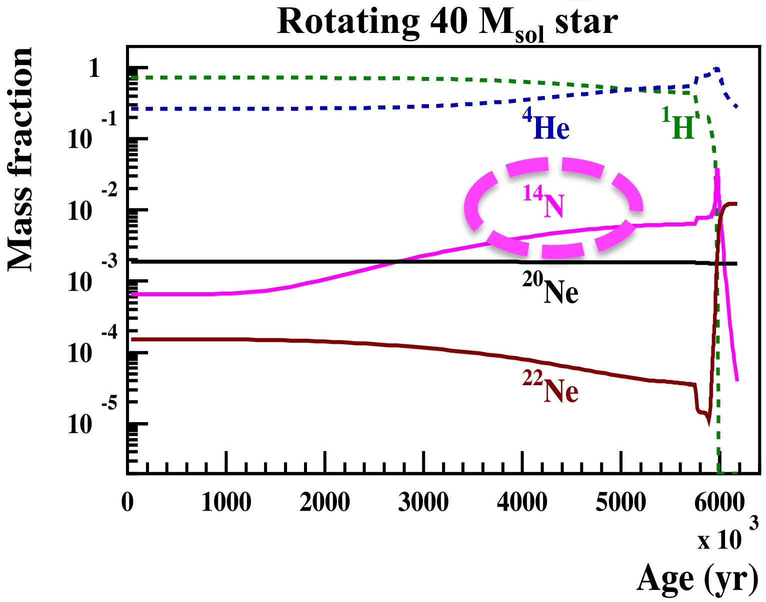


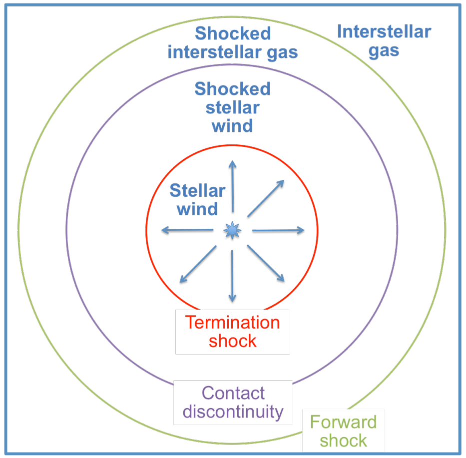
Adapted from Binns et al. (2008)

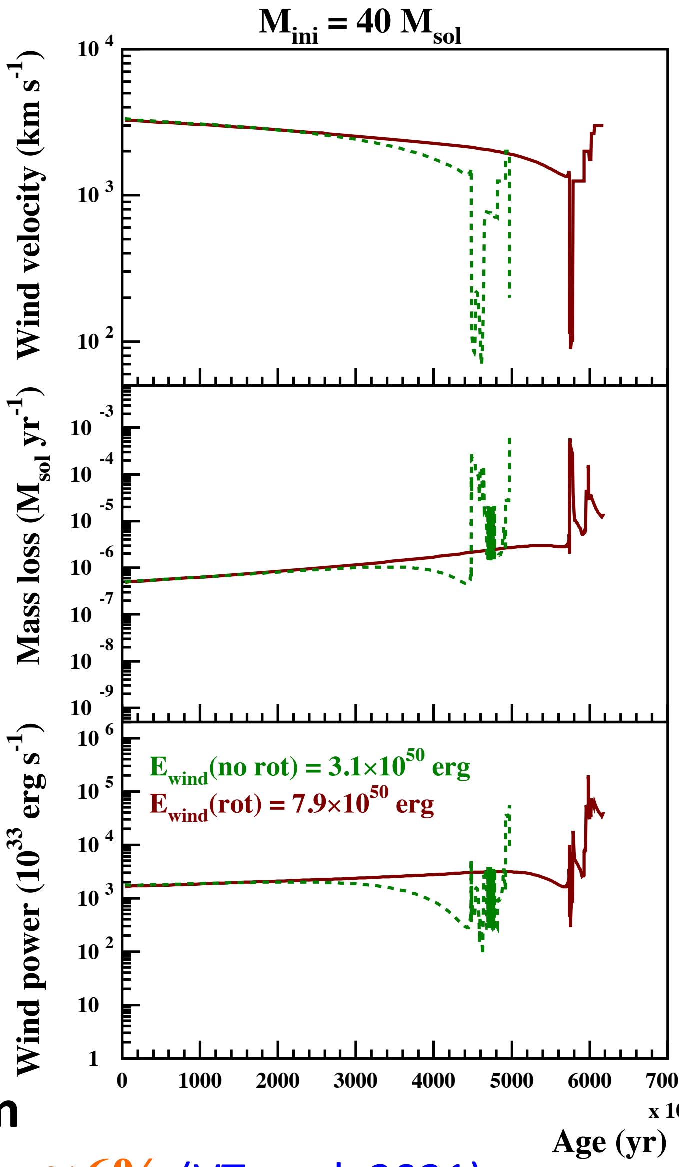


- GCR ^{22}Ne/^{20}Ne ratio ≈ 0.35, i.e **~ 5 times the solar ratio** (Garcia-Munoz et al. 1970; Binns et al. 2005)
- Contribution to GCRs of **Wolf-Rayet wind material** ($^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne$ during He burning)? (Cassé & Paul 1982)
- GCR origin in **superbubbles** enriched in ^{22}Ne from winds of massive stars?

GCR ^{22}Ne from wind termination shocks







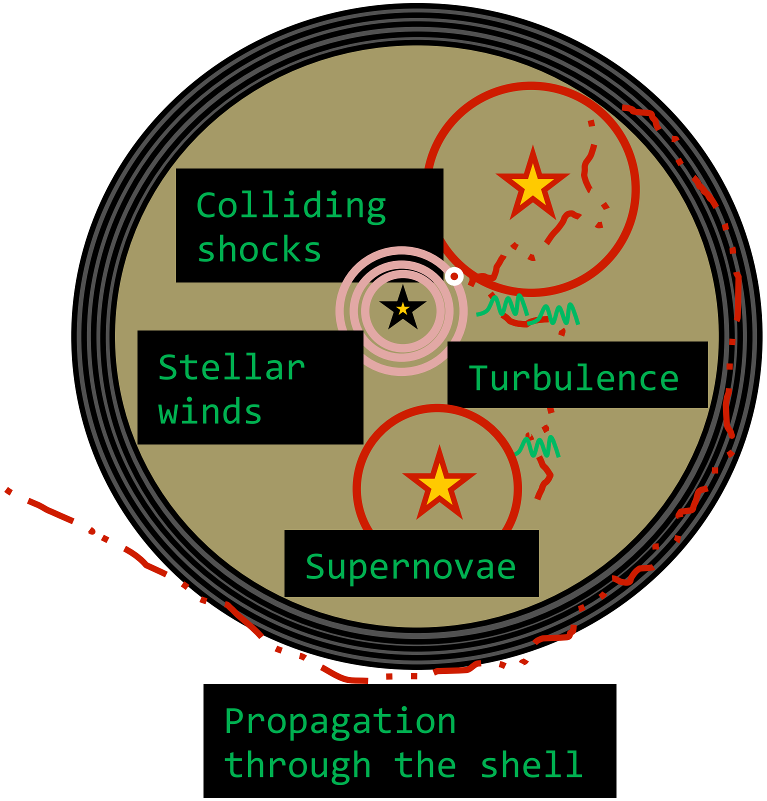
From the Geneva Observatory database

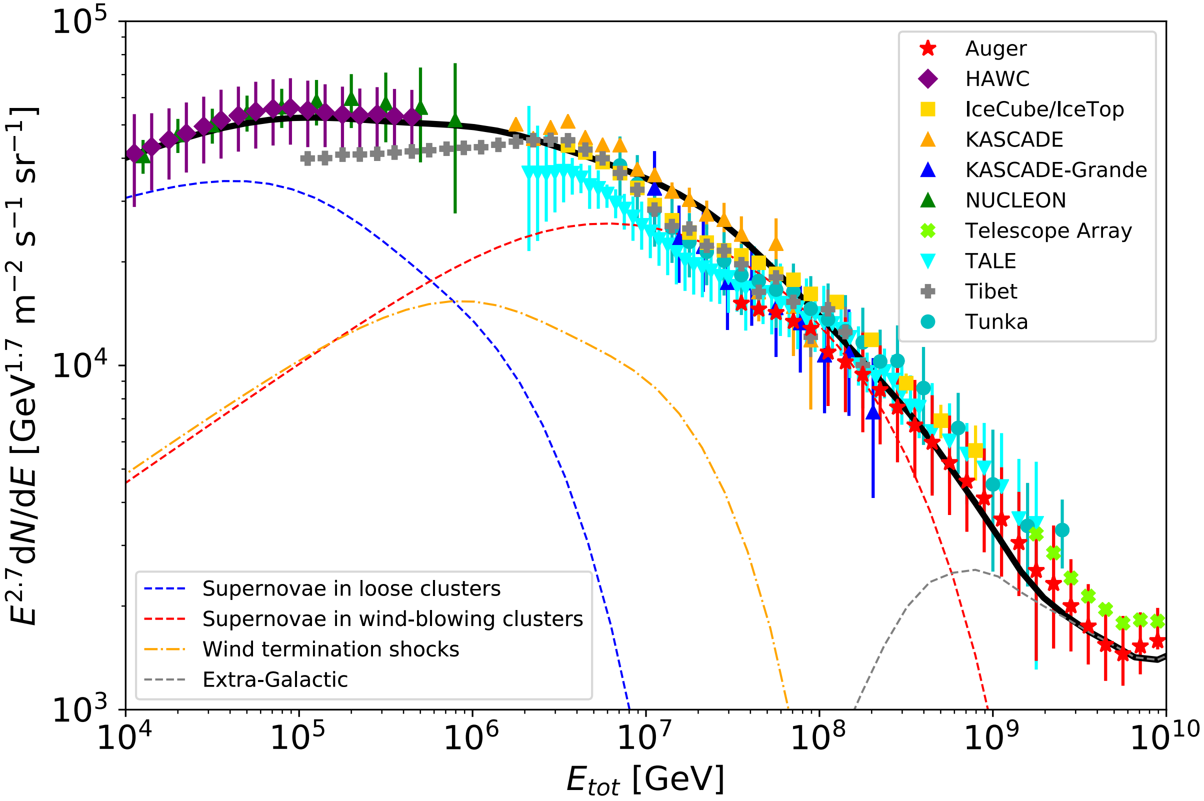
- **GCR ^{22}Ne not from enriched superbubble gas**, because overproduction of ^{14}N (main sequence): **(N/Ne)$_{wind}$=2.6 => 5.5x the ratio in the GCR source**
- More likely ^{22}Ne is produced by shock acceleration in **wind termination shocks** (see Morlino et al. 2021)
- Assuming the acceleration efficiency in WTS to be proportional to the **wind mechanical power:**

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

⇒ **Small contribution** to the GCR source composition: $x_w \approx 6\%$ (VT et al. 2021)

Cosmic-rays from massive star clusters and superbubbles





- ○ Vieu et al. (2020, 2022): 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**

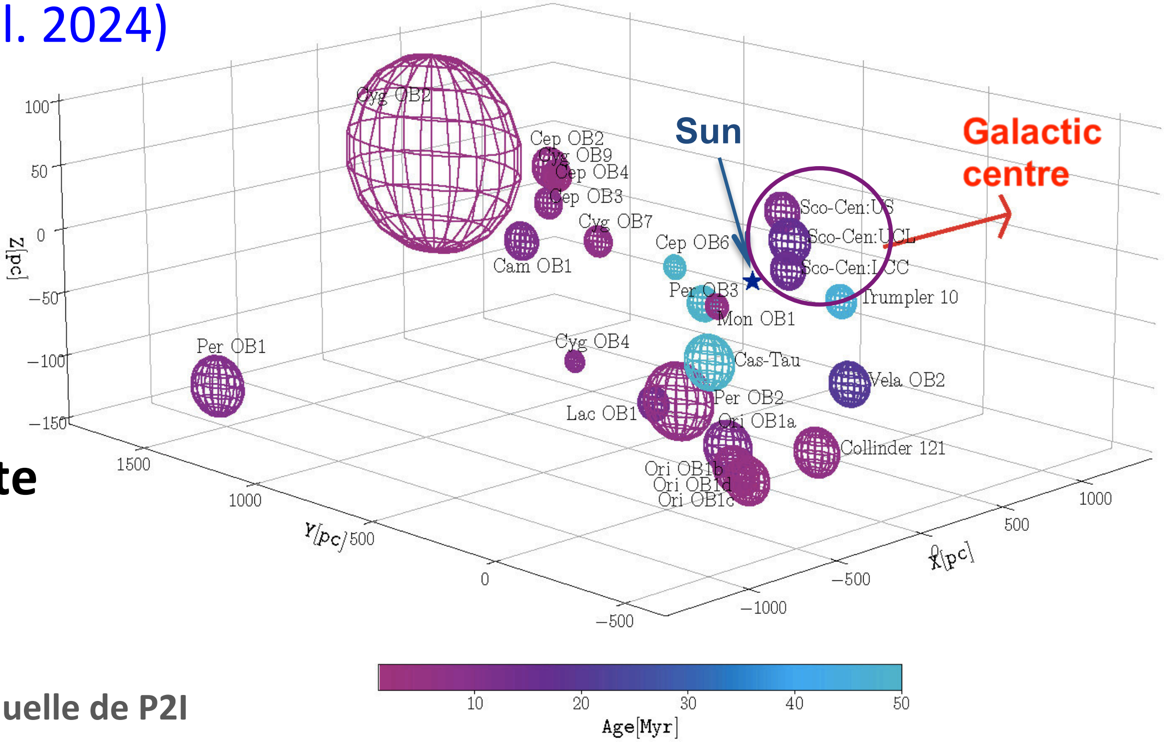
Local origin of ^{60}Fe in Galactic CRs

- Detection of **15 nuclei of ^{60}Fe (lifetime $\tau_{60}=3.8$ 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**
- Approximate maximum distance of the source(s): $L \sim (6\, D\, \gamma\, \tau_{60})^{1/2} \sim 2$ **kpc** with $D \sim 4 \times 10^{28}$ cm^2 s^{-1} the CR diffusion coefficient and $\gamma = 1.6$ the Lorentz factor

⇒ Model of **^{60}Fe synthesis and acceleration in the 25 nearest OB associations** based on ***Gaia*** census (De Séréville et al. 2024)

⇒ Most probable origin of ^{60}Fe: **recent supernova (≤ 500 kyr) in the Sco-Cen association** (~140 pc), from explosion of a star with initial M = 13−20 M_{sol}

⇒ **Local OB associations contribute ~ 20% of (stable) ^{56}Fe GCRs**



Conclusions

- Composition of Galactic cosmic rays is **key to understanding their origin**
- Measured source abundances point to an origin in **superbubbles**, mainly from **acceleration in SN shocks**, but with a small contribution of acceleration in **wind termination shocks** ($x_w \approx 6\%$) to explain the ^{22}Ne overabundance
- ^{60}Fe in the GCRs likely comes from a **recent supernova (≤ 500 kyr) in the Sco-Cen OB association**
- More work is needed to understand the origin of the GCR refractories - acceleration of **dust grains in superbubbles?**
- CR production in superbubbles up to ~ 3×10^{17} eV?
  => **LHAASO** & **Cherenkov Telescope Array** gamma-ray observatories