Cosmic rays from Galactic star clusters

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Siena

Outline of my talk

- Introduction.
- General picture of cosmic-ray origin.
- Issues/concerns of cosmic-ray properties between 10^{16}-10^{18} energies.
- How star clusters (as cosmic-ray sources) can fit into this?
- Results on the cosmic-ray spectrum and composition with star clusters.
- Summary.

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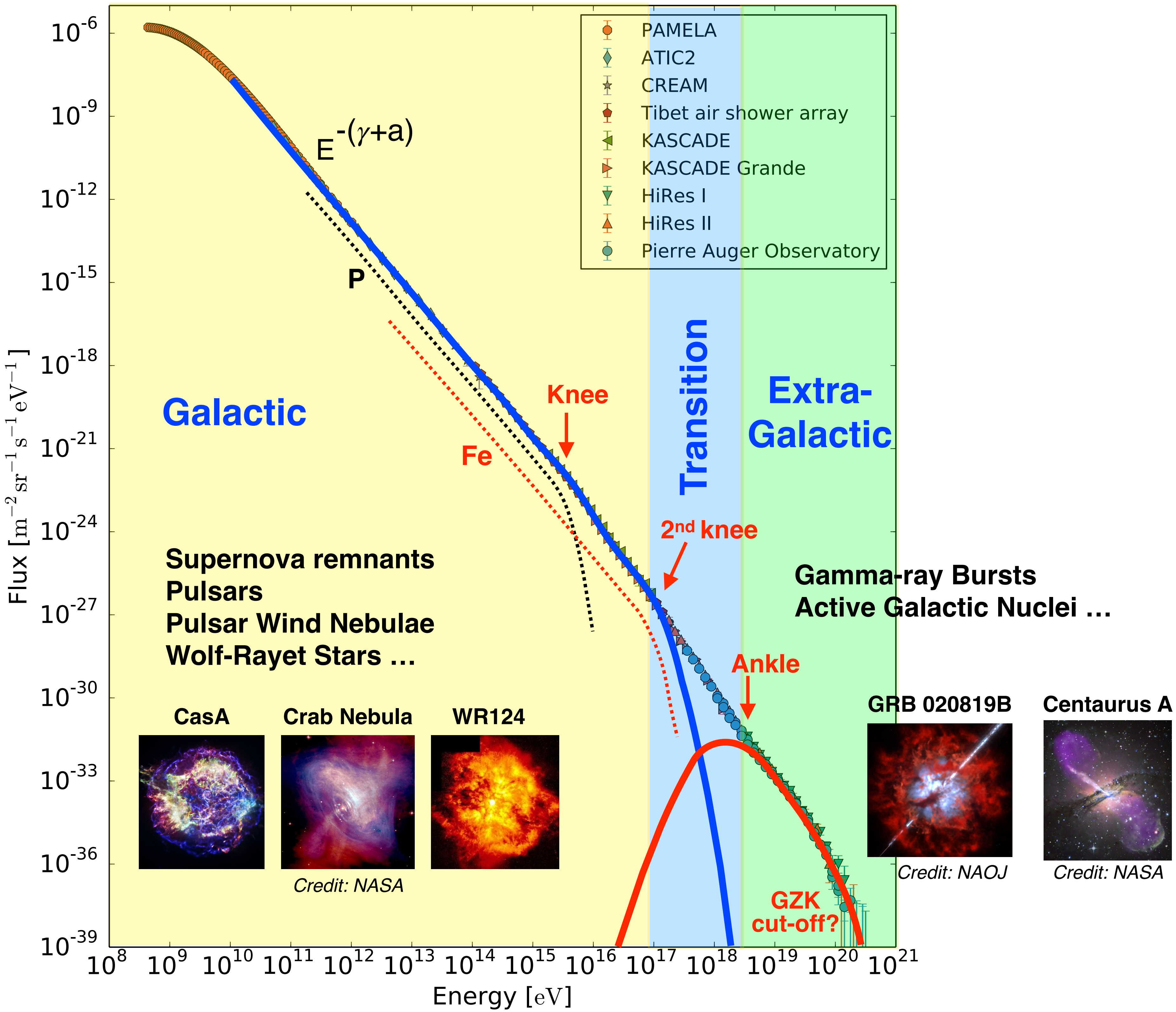
Origin of Cosmic rays: The general picture



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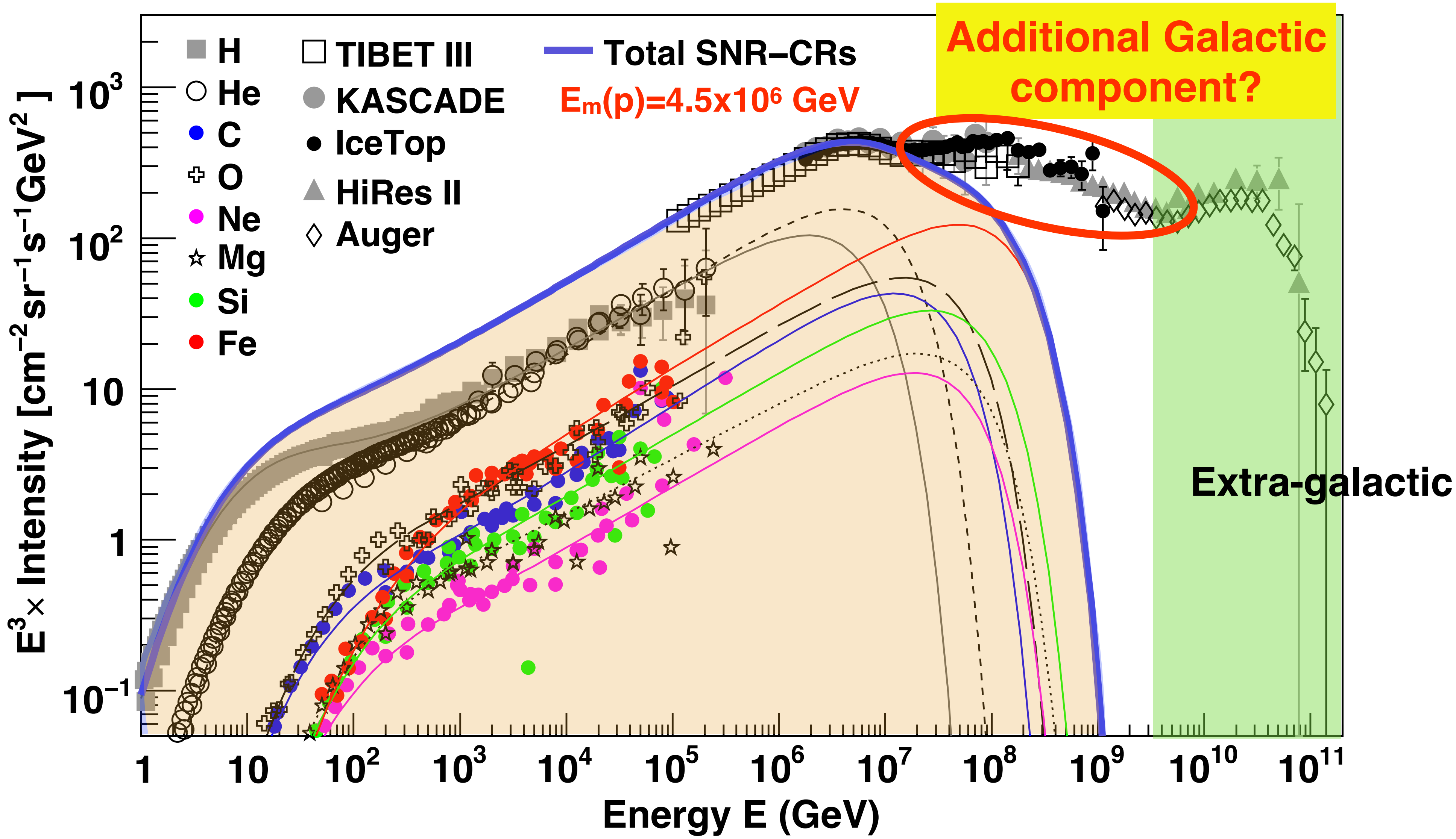
Contribution of Regular Supernova remnants to the CR spectrum



- The “knee” is dominated by helium nuclei, not by proton.
- Maximum energy: E_m (Fe)= 26 E_m(p) =1.17×10^8 GeV.
- Prediction close to the “second knee”, but not enough in intensity.
- **Regular SNRs alone cannot account for CRs above ~2×10^{16} eV. They contribute only ~30% at 10^8 GeV (10^{17} eV).**

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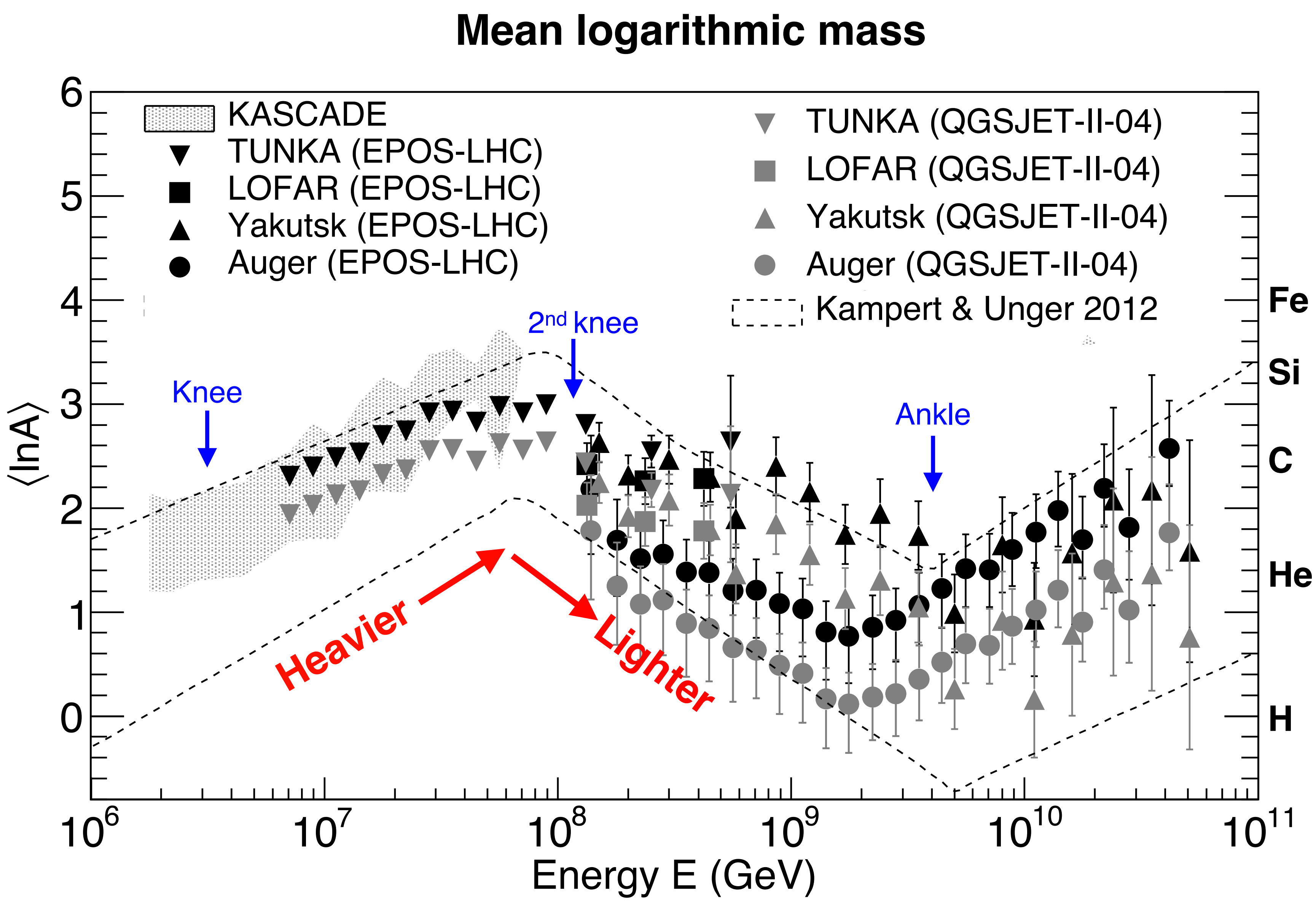
Thoudam+ 2016, A&A, 595, A33

Measured CR mass composition above the knee



✦ Below ~ 10^{17} eV, composition becomes heavier, as expected.

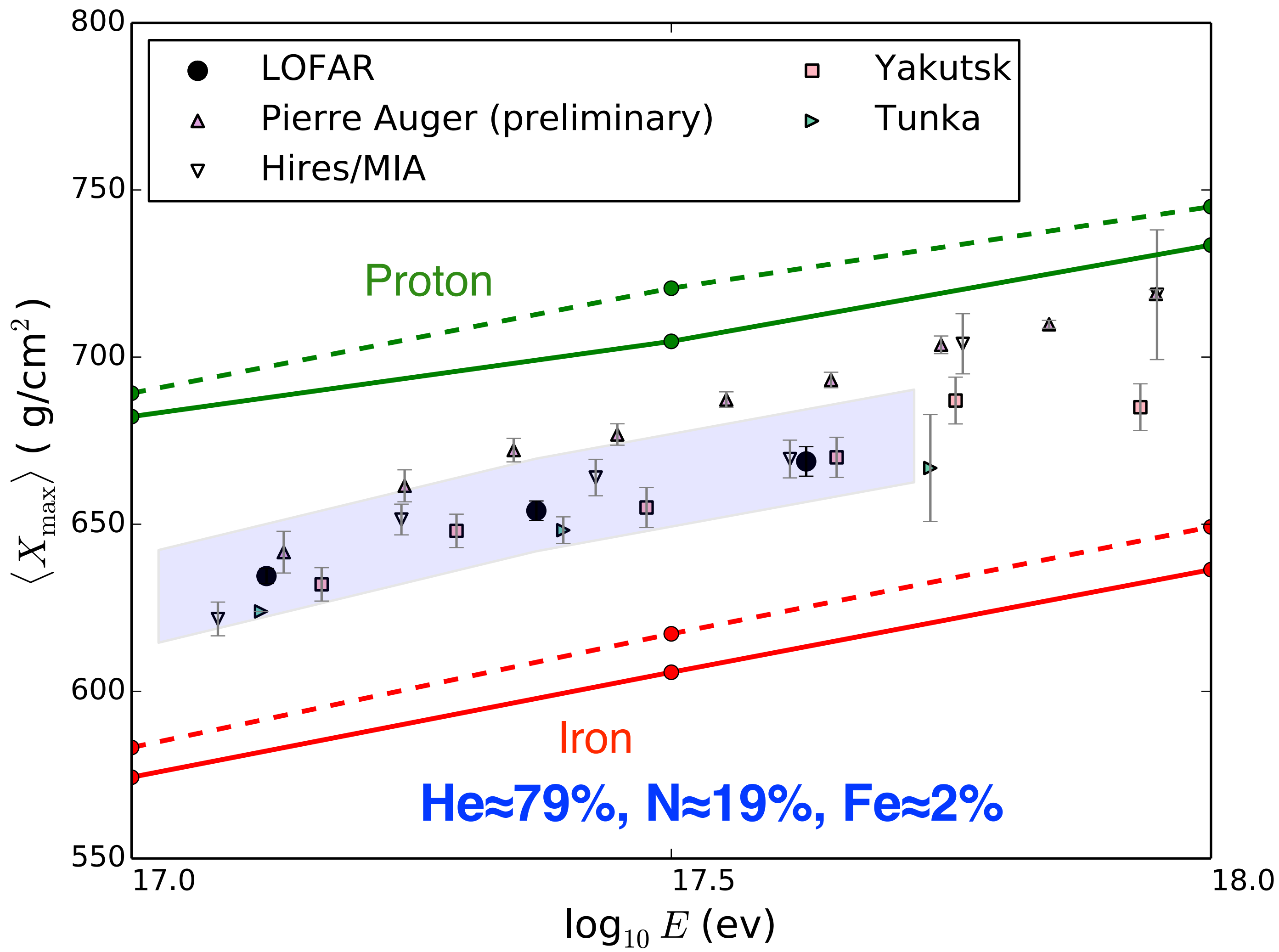
✦ **Above ~ 10^{17} eV, composition becomes lighter.**

Thoudam+ 2016, A&A, 595, A33

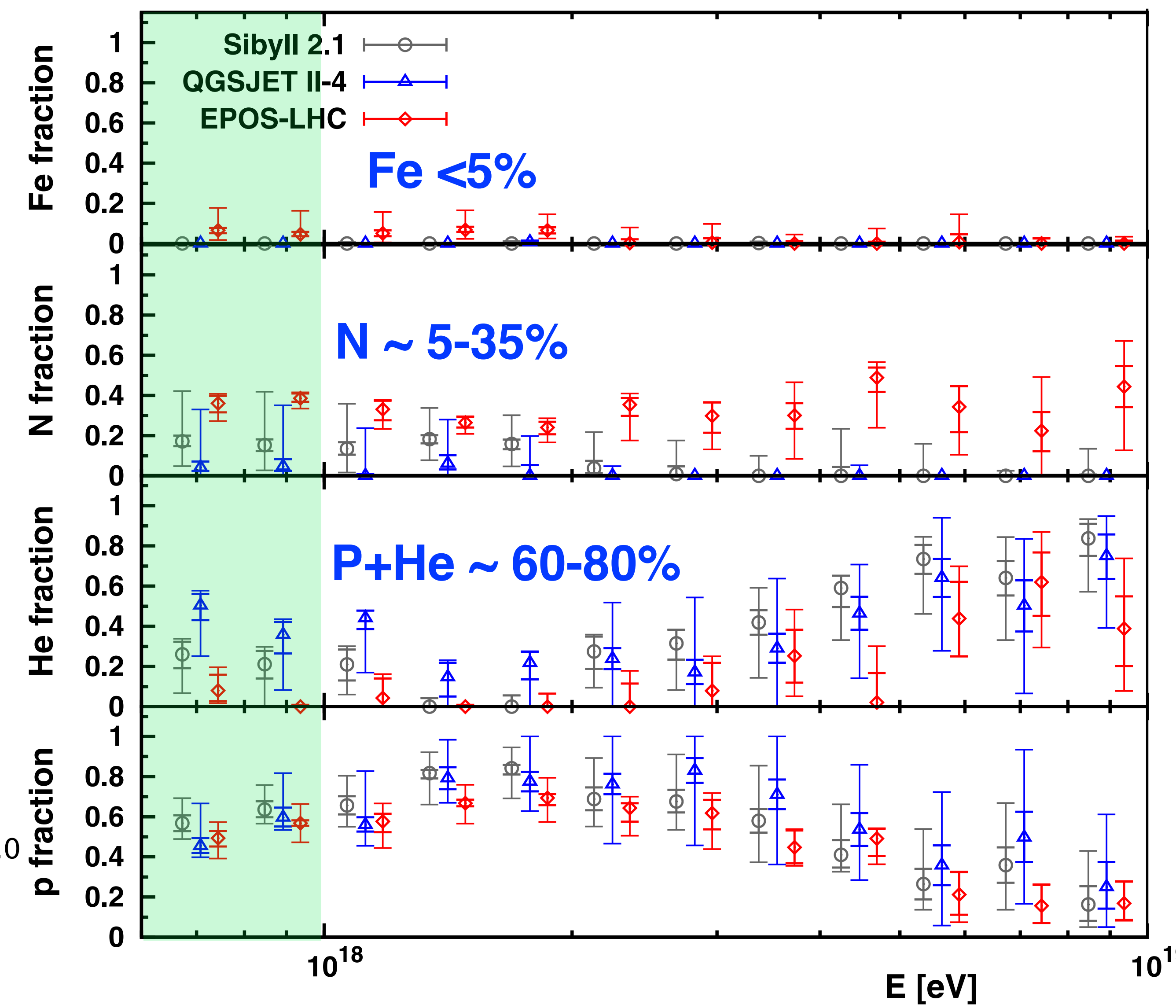
Measured CR mass composition above the knee

Elemental fraction at 10^{17}-10^{19} eV

LOFAR Collaboration
2016, Nature, 531, 70



Pierre Auger Collaboration
2014, PRD, 90, 122006



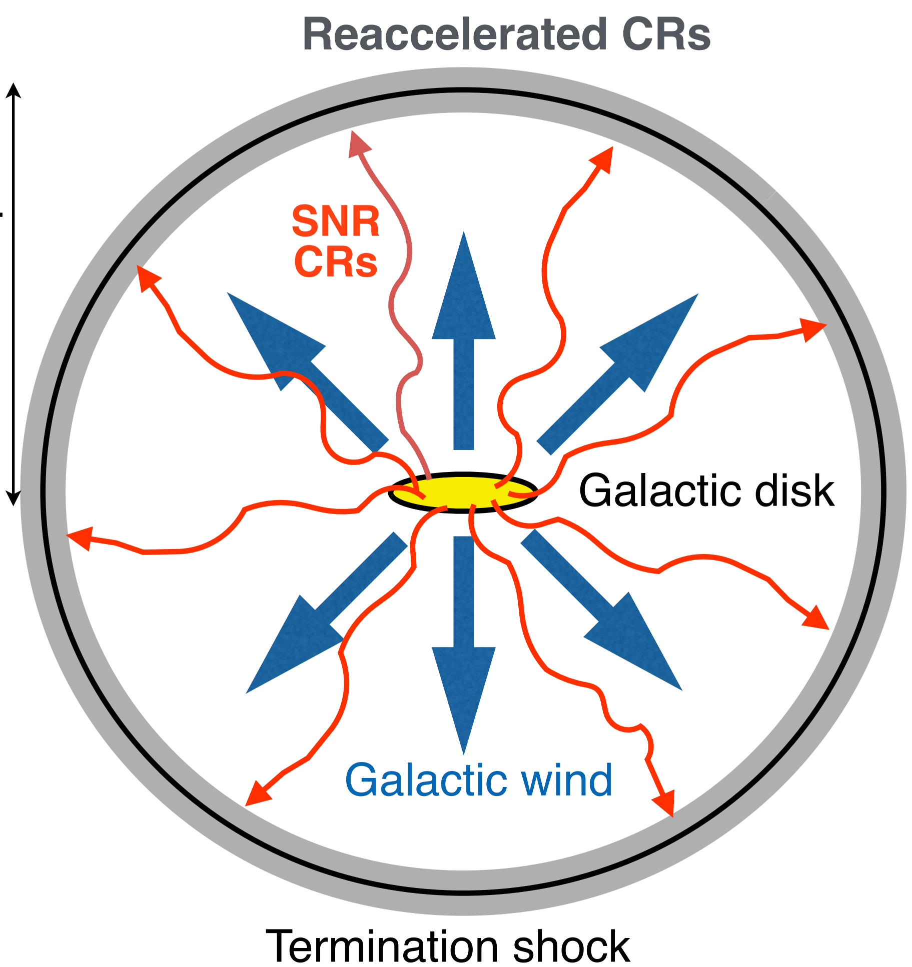
✦ Both LOFAR and Pierre-Auger measurements show light elements (P+He).

✦Theoretically expected to be iron or heavy-element dominant.

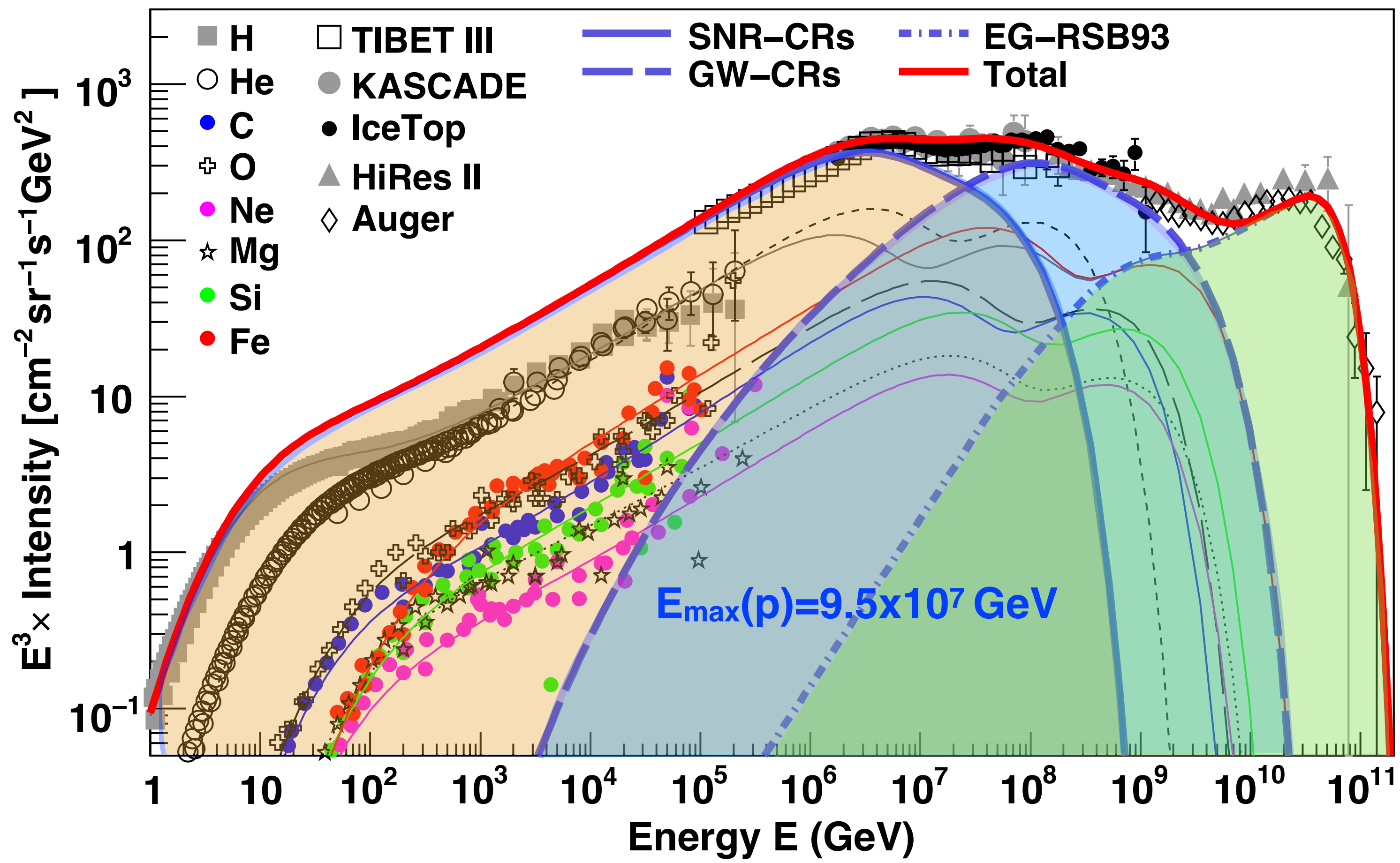
✦ Extra-galactic component unlikely to extend down to 10^{17} eV (*Thoudam+ 2016, A&A, 595, A33*)

✦ **A second/additional Galactic component above ~ 10^{17} eV?** *(e.g. Hillas 2005, J. Phys. G, 31, R95)*

Additional Galactic component:
Reacceleration by Galactic wind termination shocks (GW-CRs)



Thoudam+ 2016, A&A, 595, A33



See also:
Bustard+ 2017, ApJ, 835, 72
Merten+ 2018, ApJ, 859, 63
Mukhopadhyay+ 2023, ApJ, 953, 49

D_w=10 D_{gal}
$V=V_0 r$, V_0=15 km/s/kpc
f_{inj} =14.5%
E_{max}(p)=9.5x10^7 GeV

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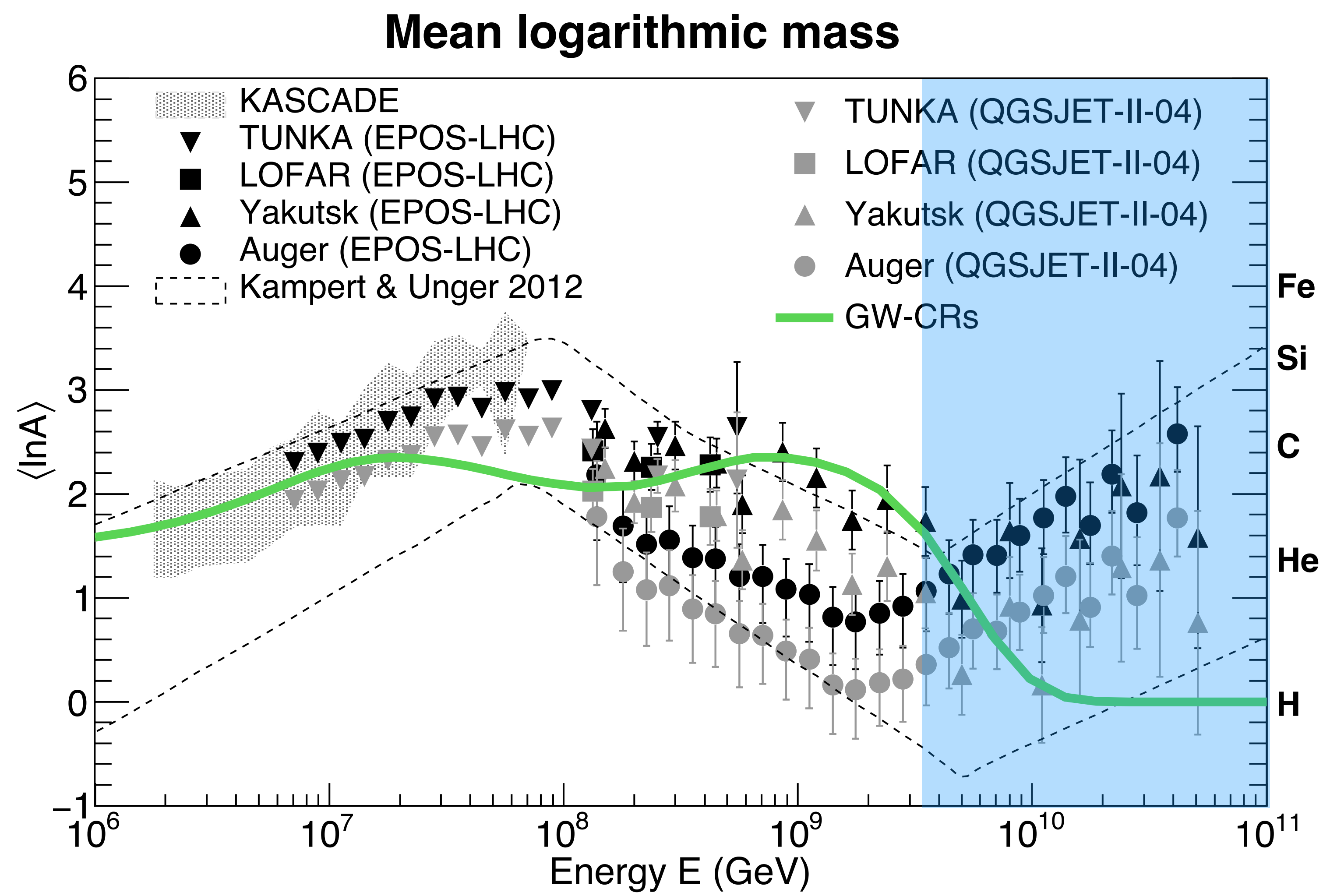
Additional Galactic component:
Reacceleration by Galactic wind termination shocks (GW-CRs)



- **Galactic wind scenario has tension when compared with the observed composition at ~ 10^{16} - 10^{18} eV.**
- **This is mainly due the large proton fraction at these energies.**
- Bad fit above the Ankle is due to the all-proton extra-galactic model *(Rachen, Stanev, & Biermann, 1993, A&A, 273, 377)*

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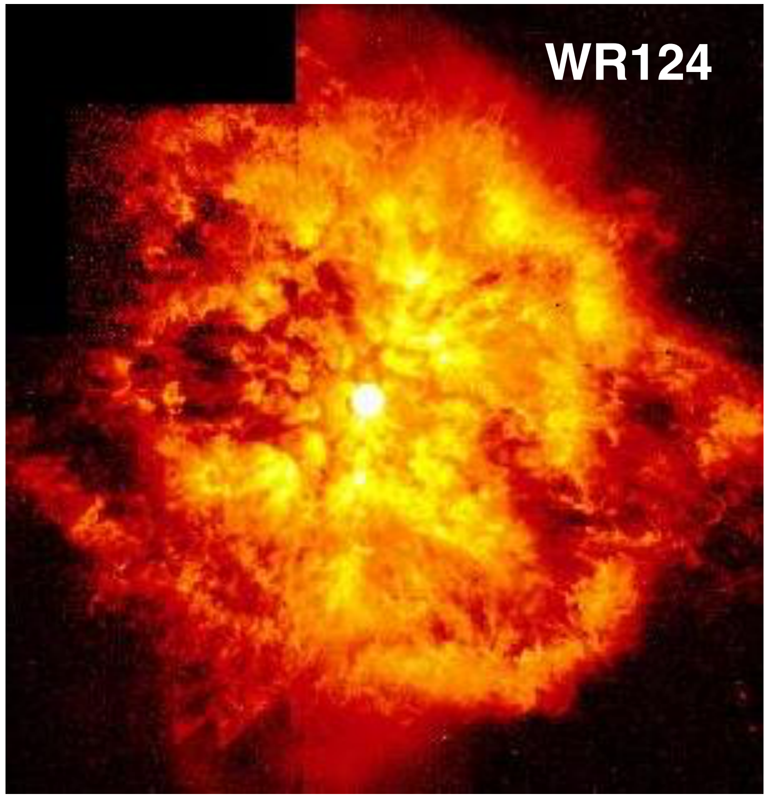
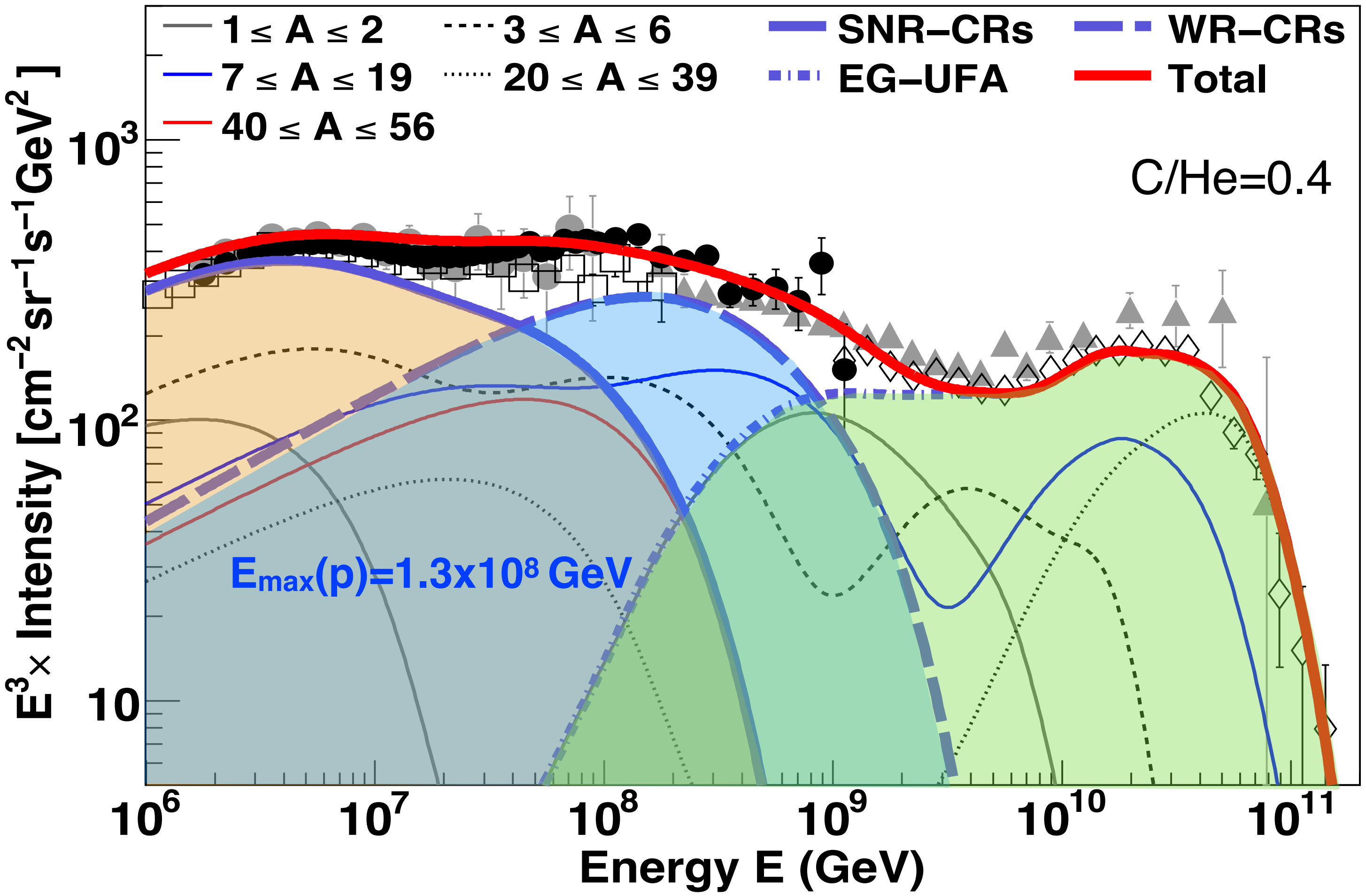
Thoudam+ 2016, A&A, 595, A33

Additional Galactic component:
Cosmic rays from Wolf-Rayet star supernova explosions (WR-CRs)

- Mostly located in the Galactic disk like the regular supernova remnants.
- Rare, massive stars with fast winds; mass~ 20 M_s and frequency ~1/210 yr^{-1} = 1/7 SNe
- **Lack of hydrogen (proton) in the wind.**
- Short-lived before exploding into supernova.
- High magnetic field, ~ 100 G or even more (*Chevrotiere+ 2013, 2014*).
- Accelerate particles up to ~ 10^{18} eV (*Biermann & Cassinelli 1993, Stanev+ 1993*).



Credit: NASA, HST



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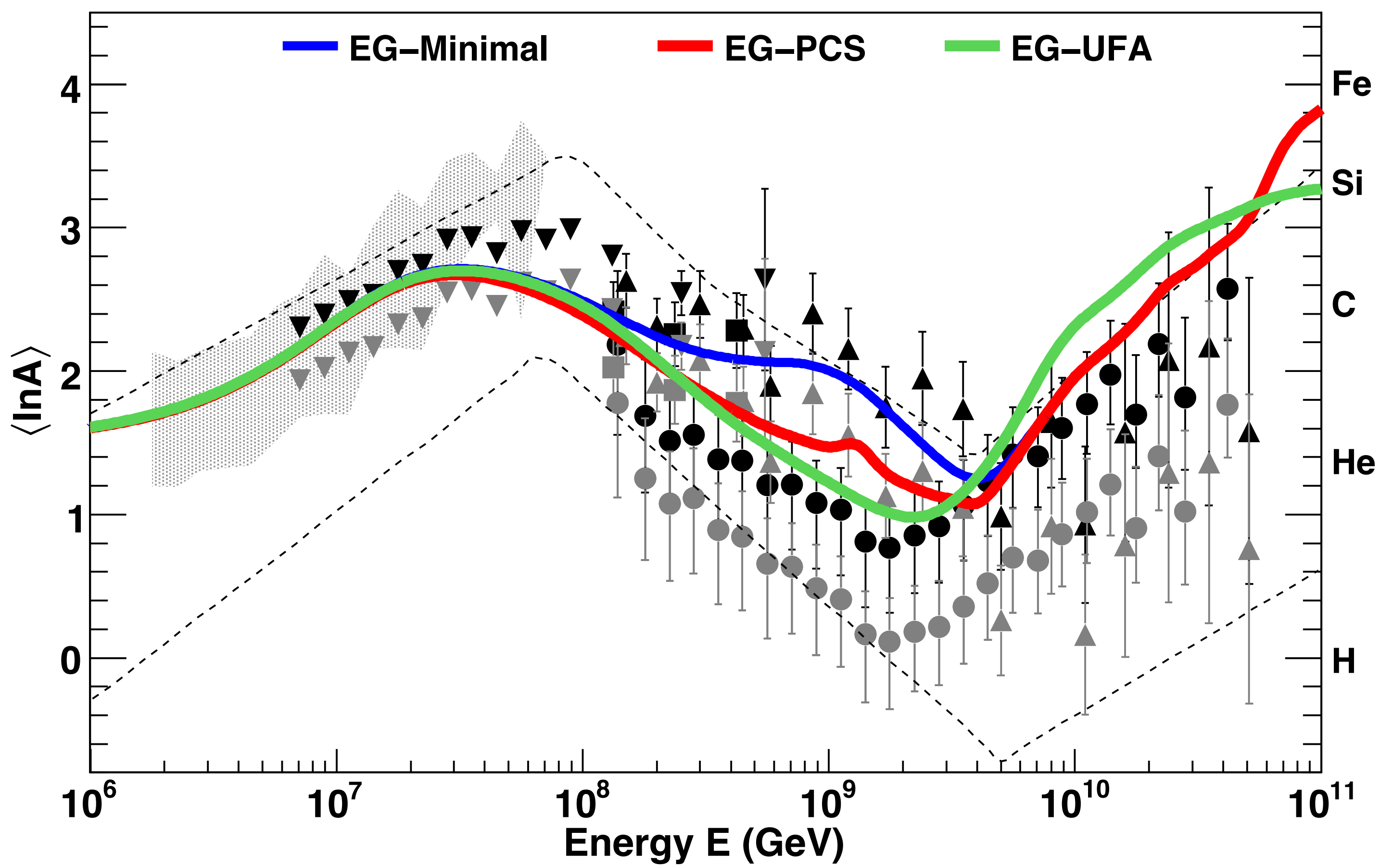
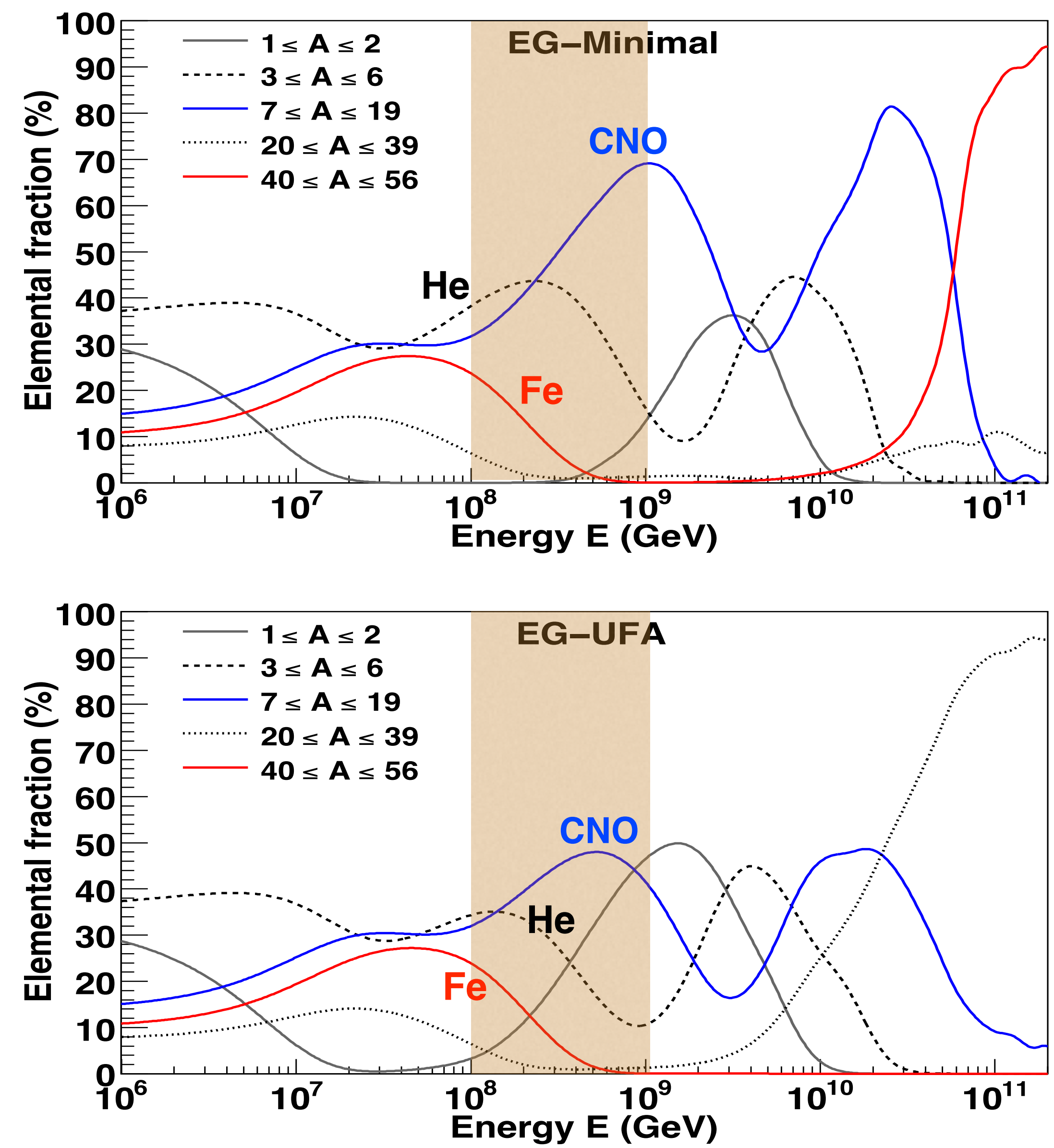
Additional Galactic component:
Cosmic rays from Wolf-Rayet star supernova explosions (WR-CRs)

Mean logarithmic mass
(with different extra-galactic CR models)



Elemental fraction



- ✤ **Wolf-Rayet scenario can reproduce the observed composition much better (at 10^{16} - 10^{18} eV)**
- ✤ **This is because of NO proton in WR winds.**
- ✤ (He+CNO) composition is favorable.
- ✤ This result is quite robust to the model of the extra-galactic cosmic rays.

Thoudam+ 2016, A&A, 595, A33

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Why star clusters as the second galactic component?

- Most stars are expected to evolve in clusters.
- Potential candidates for CRs beyond the knee (*Knödlseder 2013; Bykov 2014; Aharonian+ 2019*).
- Very-high-energy gamma rays detected from several massive young star clusters (*Abeysekara+ 2021; Cao+ 2021*).
- Complex environment: Massive stars, supernova explosions, turbulent medium, superbubbles, fast stellar winds, wind termination shocks, …..
- Possible multiple sites for CR acceleration (*Cesarsky & Montmerle 1983; Webb+ 1985; Gupta+ 2018; Bykov+ 2020, Morlino+ 2021, Vieu+ 2022*).

Westerlund 1

Credit: ESO/VPHAS+ Survey/N. Wright

Cygnus OB2

Credit: Chandra X-ray Observatory

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CR acceleration in star clusters

✤ **Superbubble surrounding star cluster**

Acceleration in the highly turbulent, low diffusivity, highly inflated region (e.g. *Bykov+, 2020, SSRv, 216, 42*)

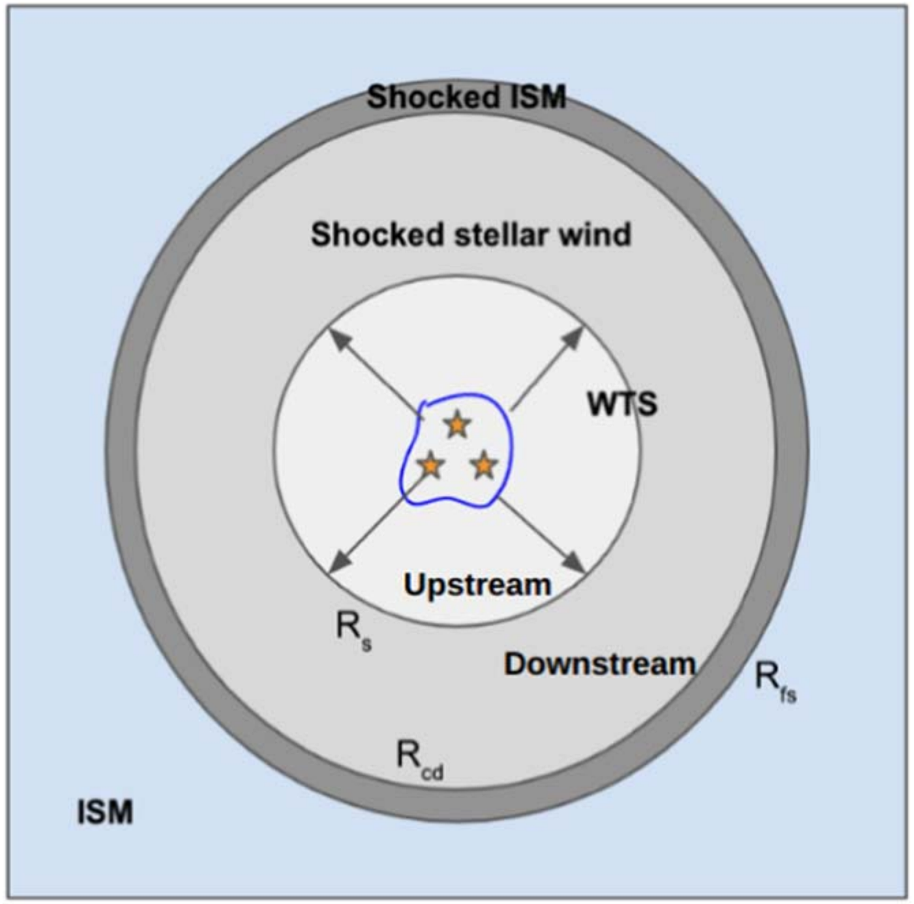
✤ **Supernove shocks embedded in stellar winds**

Acceleration by supernova shocks running through stellar winds of young compact clusters (e.g. *Vieu & Reville, 2023, MNRAS, 519, 136*).

✤ **Wind termination shocks**

Acceleration at the wind termination shocks produced by the collective wind effect (e.g. *Morlino+ 2021, MNRAS, 504, 6096; Vieu+ 2022, MNRAS, 515, 2256; Bhadra, Thoudam+ 2024, ApJ, 961, 215*)

Schematic of a star cluster environment



[In the following, I will mainly focus on wind termination shocks case.]

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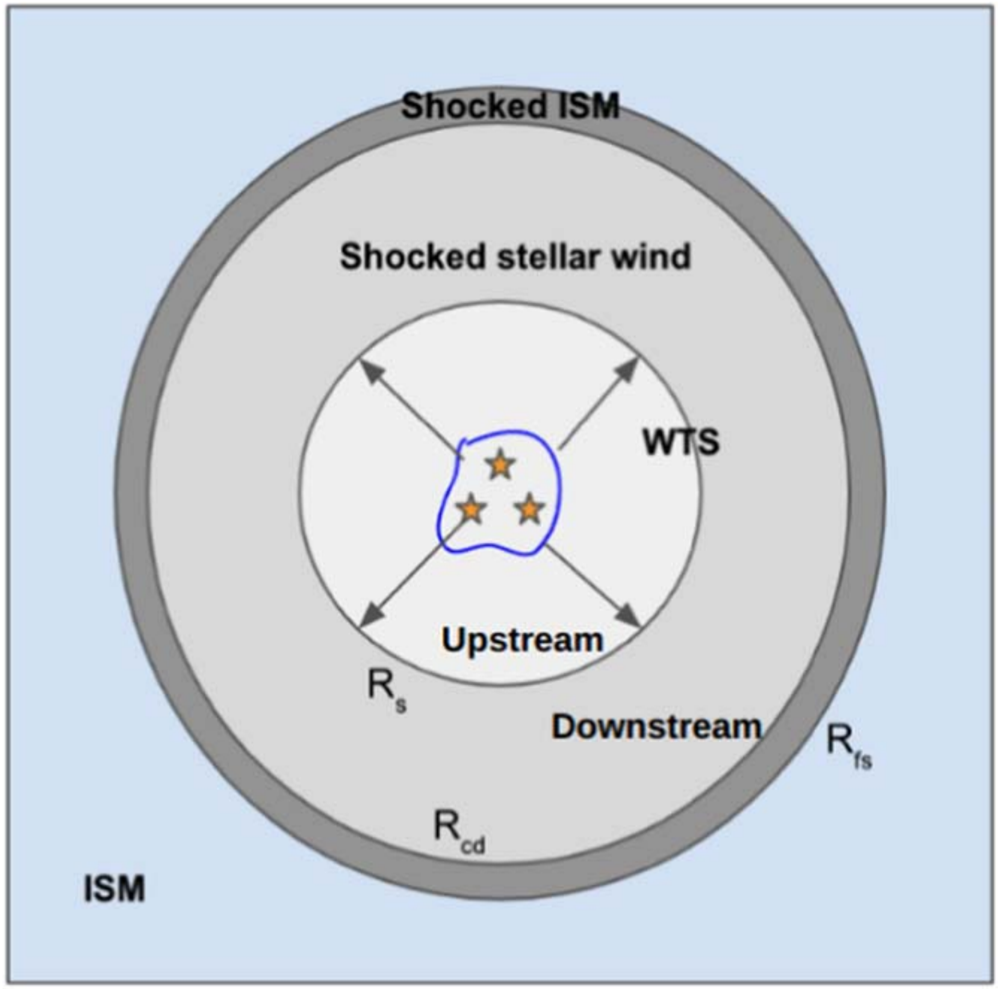
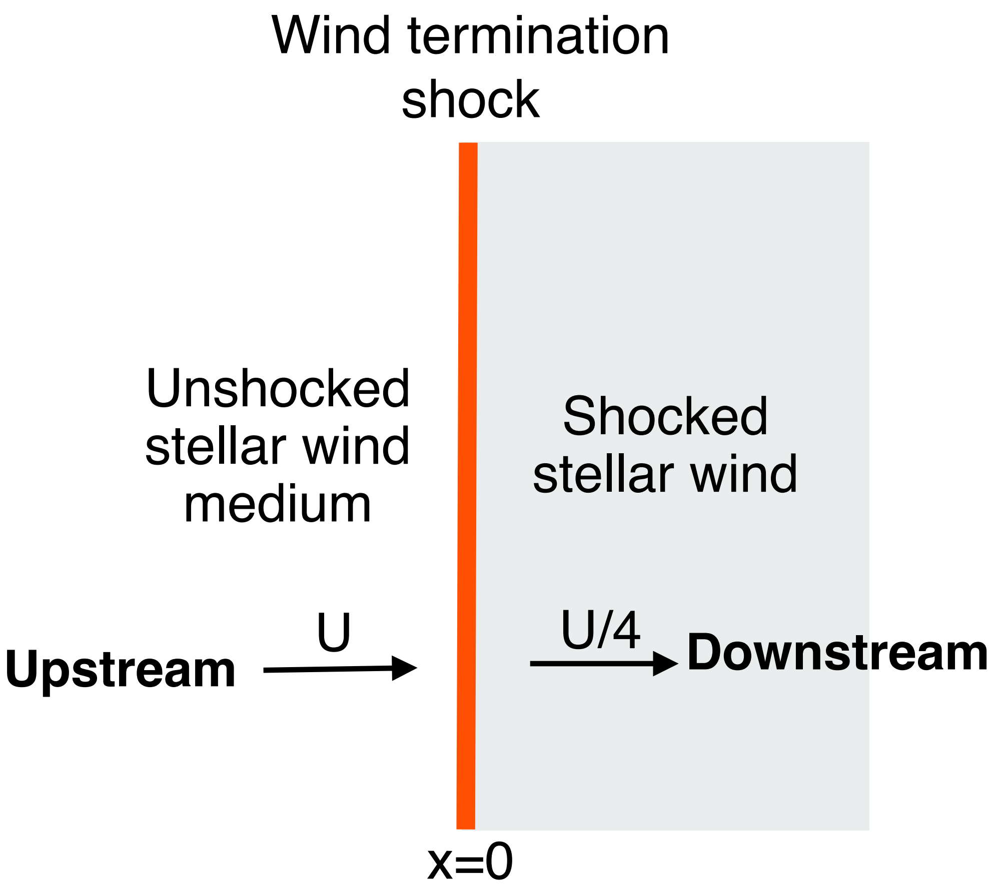
CR acceleration in star clusters

CR acceleration at the wind termination shocks

- Collective wind flow leads to a wind termination shock.
- CRs can be accelerated at the termination shock (*Bhadra, Thoudam+ 2024, ApJ, 961, 215*).
- Maximum CR energy depends on the cluster size, magnetic field and the wind speed.

Schematic of a star cluster environment





$$f(p) \sim p^{-\gamma},\ \gamma \sim 4 \text{ for strong shocks}$$

CR acceleration in star clusters

Maximum energy of CRs produced by Wind Termination Shocks (Hillas criterion):

$$E_{\max} \sim \zeta\, q\, B_{\rm WTS}\, R_{\rm WTS}\, \frac{V_w}{c}.$$

where,
$B_{\rm WTS}$: Magnetic field at the WTS
$R_{\rm WTS}$: Size of the WTS
$V_{\rm w}$: Wind velocity
q: Charge of CR

=> $$E_{\max} \sim \zeta\, q\, B_c\, R_c\, \frac{V_w}{c}.$$

[For a Parker's magnetic field model, $B \propto 1/R$, (Parker 1958)]

where,
$B_{\rm C}$: Magnetic field at the cluster
$R_{\rm C}$: Size of the cluster
$V_{\rm w}$: Wind velocity

- For $B_{\rm C}$ = 150 uG, $R_{\rm C}$ = 1 pc, $V_{\rm w}$ = 2000 km/s, $E_{\max} \approx 6$ PeV.
- In our work, $E_{\max}$ is obtained based on the observed all-particle spectrum (data driven approach).

Gupta+ 2020, MNRAS, 493, 3159
Morlino+ 2021, MNRAS, 504, 6096
Vieu+ 2022, MNRAS, 515, 2256

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Average kinetic luminosity of star clusters

- Certain fraction of the total wind kinetic energy injects into CRs.
- Injection fraction kept as a parameter.
- Mechanical luminosity function of OB star association: $\phi(L) \propto L^{-2}$

(*Oey & Clarke, 1997, MNRAS, 289, 570*)

- **Average mechanical (kinetic) luminosity:**

$$\langle L_w \rangle = \frac{\int_{L_{\min}}^{L_{\max}} \phi(L) L \, dL}{\int_{L_{\min}}^{L_{\max}} \phi(L) dL} \sim 4.5 \times 10^{37} \text{ erg s}^{-1}$$

where

$L_{\min} = 10^{37}$ erg/s (Corresponding to $N_{OB} = 10$ stars in a cluster)

$L_{\max} = 10^{39}$ erg/s (Corresponding to $N_{OB} = 1000$ stars)

Note: For spectrum calculation, we take $N_{OB} = 10$ stars.

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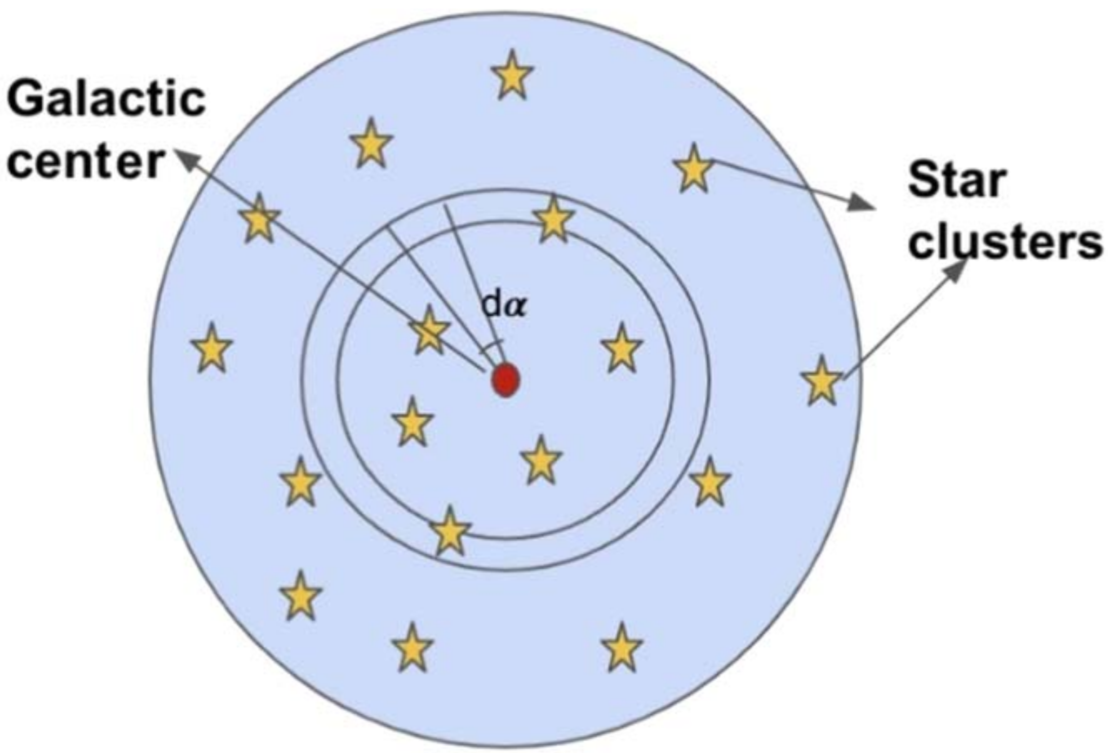
Bhadra, Thoudam+ 2024, ApJ, 961, 215

Distribution of star clusters in the Galactic plane

Schematic of star cluster distribution in the Galactic plane

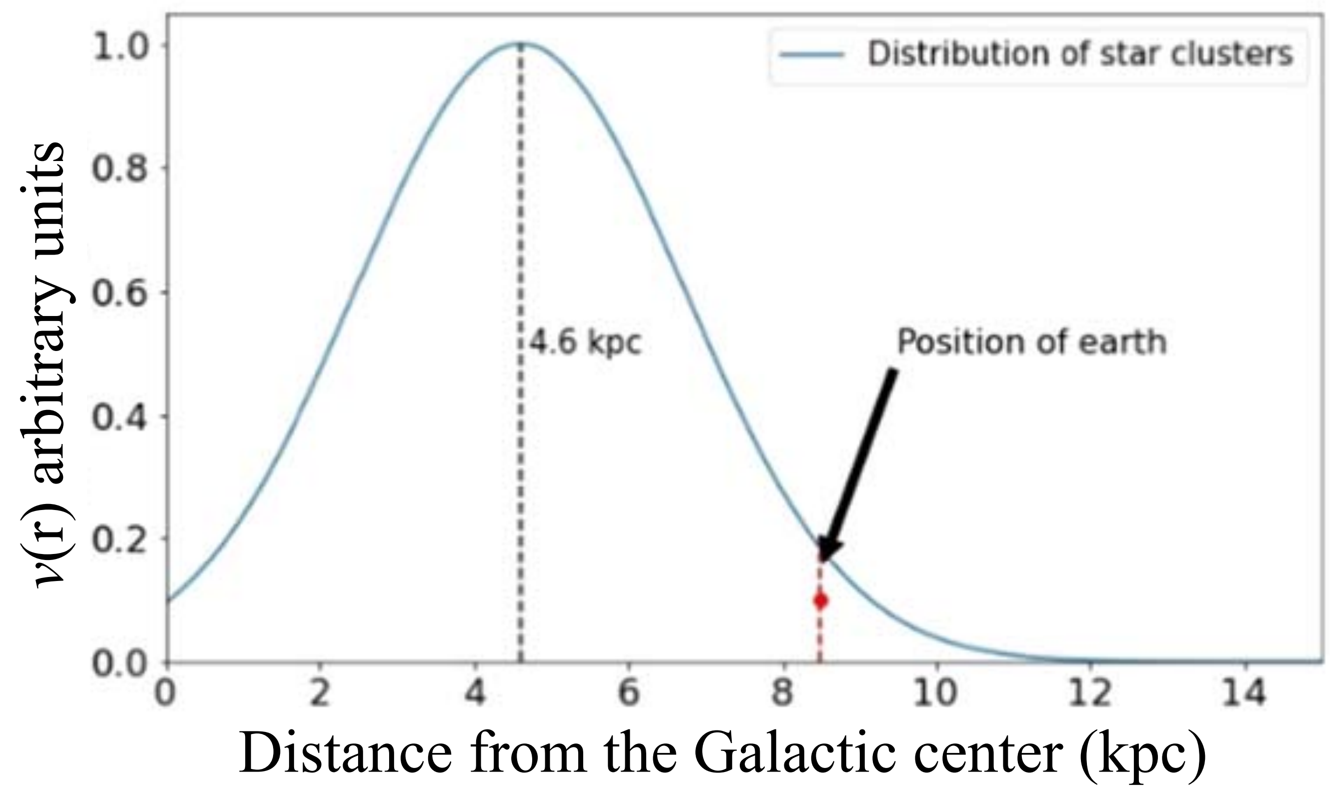


No. of OB stars in a cluster:

$N_{OB} = 10 - 1000$

Surface density profile of star clusters

Bhadra, Thoudam+ 2024, ApJ, 961, 215



$$\nu(r) = \Sigma_0 \, e^{\frac{(-r-R_p)^2}{\sigma^2}}$$

Bronfman+ 2000, A&A, 358, 521

$\Sigma_0 \sim 14 \text{ kpc}^{-2}$

$\sigma = 3$ kpc

$R_\text{p} = 4.6$ kpc

Nath & Eichler 2020, MNRAS, 499, L1

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Elemental abundance in star cluster winds

- Initial mass function of stars: $\beta(m) \propto m^{-2.35}$ *(Salpeter, 1955, ApJ, 121, 161).*
- Obtain elemental mass-loss rate $\dot{m}_w(X, m, t')$ of massive stars in the form of winds using nucleosynthesis model (*Roy+ 2021, MNRAS, 502, 4359*).
- Obtain total mass of element X injected by a star of mass m over an age t as

$$M_w(X, m, t) = \int_0^t \dot{m}_w(X, m, t')dt'$$

Bhadra, Thoudam+ 2024, ApJ, 961, 215

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$$M_w(X, m, t) = \int_0^t \dot{m}_w(X, m, t')dt'$$

- Elemental fraction injected by a single star of mass m:

$$f(X, m) = \frac{M_w(X, m, t)}{M_{w,\mathrm{tot}}(m, t)} = \frac{\int_0^t \dot{m}_w(X, m, t')dt'}{\int_0^t \dot{m}(m, t')dt'}.$$

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Bhadra, Thoudam+ 2024, ApJ, 961, 215

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- Star-mass weighted elemental fraction is obtained by convolving with the Salpeter function:

$$\langle f(X)\rangle = \frac{\int_0^m f(X, m)Am^{-2.35}dm}{\int_0^m Am^{-2.35}dm}.$$

where A is a constant.

Bhadra, Thoudam+ 2024, ApJ, 961, 215

Elemental abundance in star cluster winds

Elements	Γ	Fractional Abundances in Winds
Proton	2.25	0.86
Helium	2.23	0.13
Carbon	2.20	3.32×10^{-3}
Oxygen	2.24	8.51×10^{-4}
Neon	2.24	8.83×10^{-5}
Magnesium	2.28	3.62×10^{-5}
Silicon	2.24	3.42×10^{-5}
Iron	2.24	3.72×10^{-5}

Bhadra, Thoudam+ 2024, ApJ, 961, 215

- ✦ Note the dominant proton fraction.
- ✦ CR spectral index (Γ) values taken to be same as that of the regular supernova remnants.
- ✦ Elemental CR injection fraction scaled with the fractional abundance in the wind material.
- ✦ Total CR injection energy obtained based on the all-particle spectrum.

Bhadra, Thoudam+ 2024, ApJ, 961, 215

Transport of cosmic rays in the Galaxy

$$\nabla \cdot (D\nabla N) - [\bar{n}v\sigma + \xi]\,\delta(z)N + \left[\xi s p^{-s}\int_{p_0}^{p} du\; N(u)u^{s-1}\right]\delta(z) = -Q\delta(z)$$

Diffusion

$D(p) \propto p^a$

- p → Particle momentum

Loss:

Re-acceleration ξ
+
Inelastic $\bar{n}v\sigma$

- $\bar{n}$ → ISM matter density
- v → Velocity of CRs
- σ → Interaction crossection

Gain:

Re-acceleration

$\xi \propto V\nu$

- V → Volume of SNR
- ν → Rate of SN explosion

Source

$Q(p) \propto \nu p^{-\Gamma} \exp\left(-\frac{p}{Zp_{\mathrm{m}}}\right)$

- Z → Charge of nuclei
- p_{m} → Proton cut-off momentum

- **Propagation parameters:** D_0, p_0, a } **(Based on Boron-to-Carbon ratio)**
- **Reacceleration parameters:** V, s }
- **Source parameters:** Γ **(Based on elemental spectra)**
  p_{m} **(Based on All-particle spectrum)**

Thoudam & Hörandel 2014, A&A, 567, A33

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Results on the CR spectrum and composition

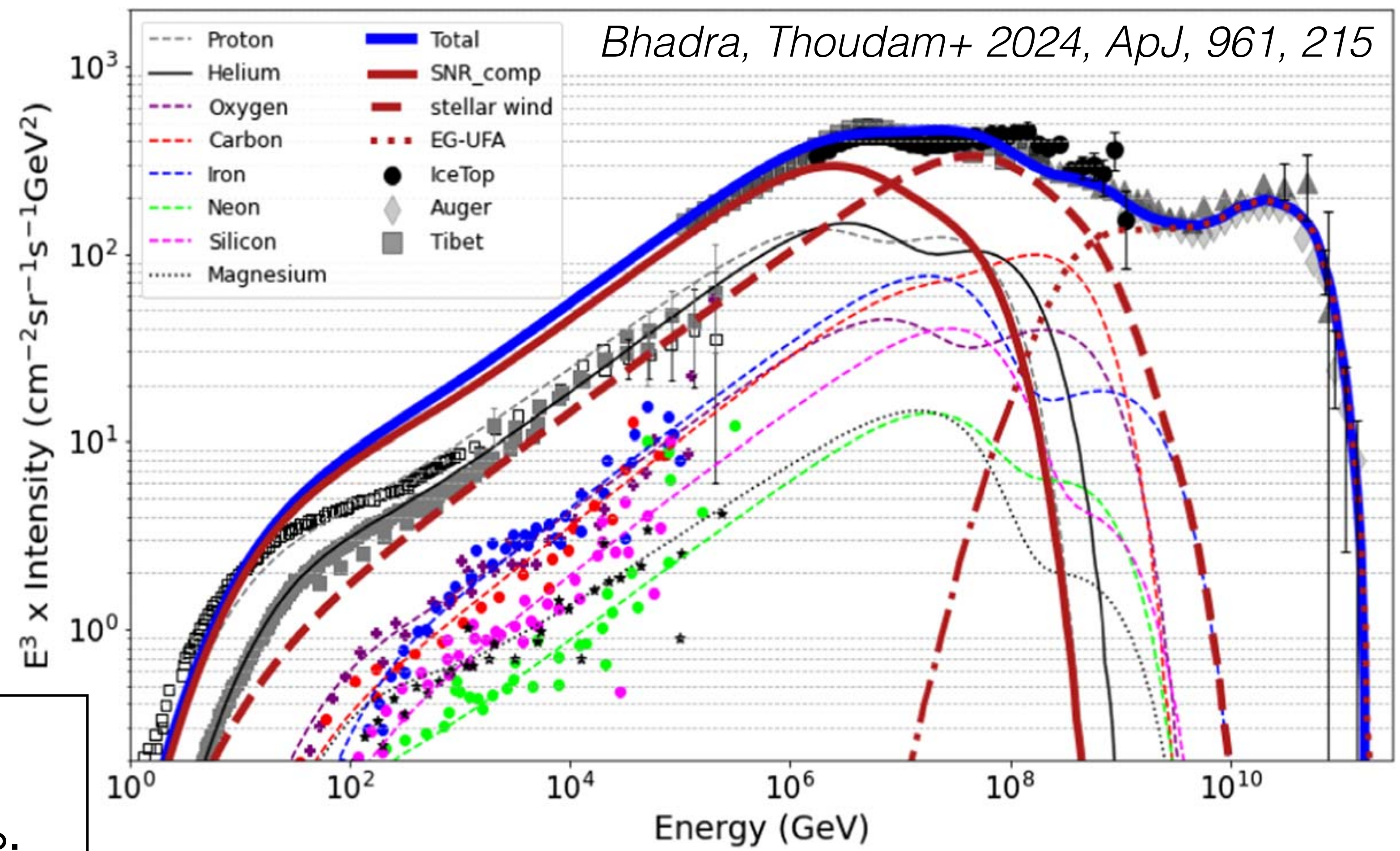
Regular SNRS *(Thoudam+ 2016)*

+

Star clusters *(Bhadra+ 2024)*

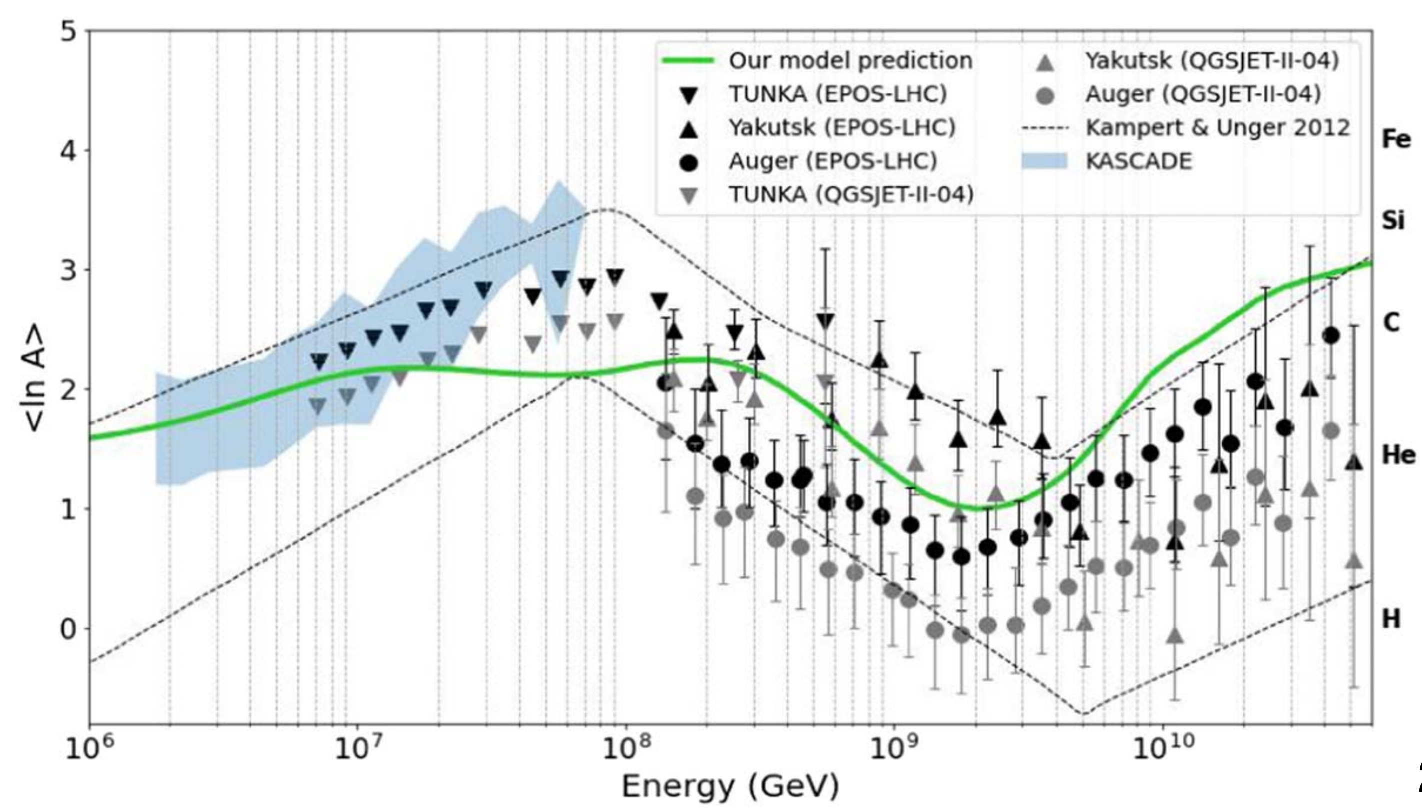
+

Extra-galactic *(Unger+ 2015)*



Parameters for the star cluster comp.

- ✦ Wind energy injected into protons ~ 5%.
- ✦ E_{max} ~ 5 x10^7 Z GeV, which is about an order of magnitude larger than the simple theoretical estimate.
- ✦ Predicted <lnA> within the observed band, but has some tension at ~ 10^{16}-10^{17} eV.



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Summary

- Young massive star clusters have been proposed as potential sources of CRs above the knee.
- Star clusters seem to have the potential to explain the observed all-particle CR spectrum (when combined with a low-energy galactic component and an extra-galactic component having dominant light nuclei below the ankle).
- Requires a maximum CR energy which is about an order of magnitude higher than theoretical value (at least for the wind termination shock).
- Also, composition shows some tension at ~ 10^{16}-10^{17} eV, which results mainly from a dominant proton fraction.

Thanks for your attention!

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