Transition from Galactic to Extragalactic Cosmic Rays

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Symposium
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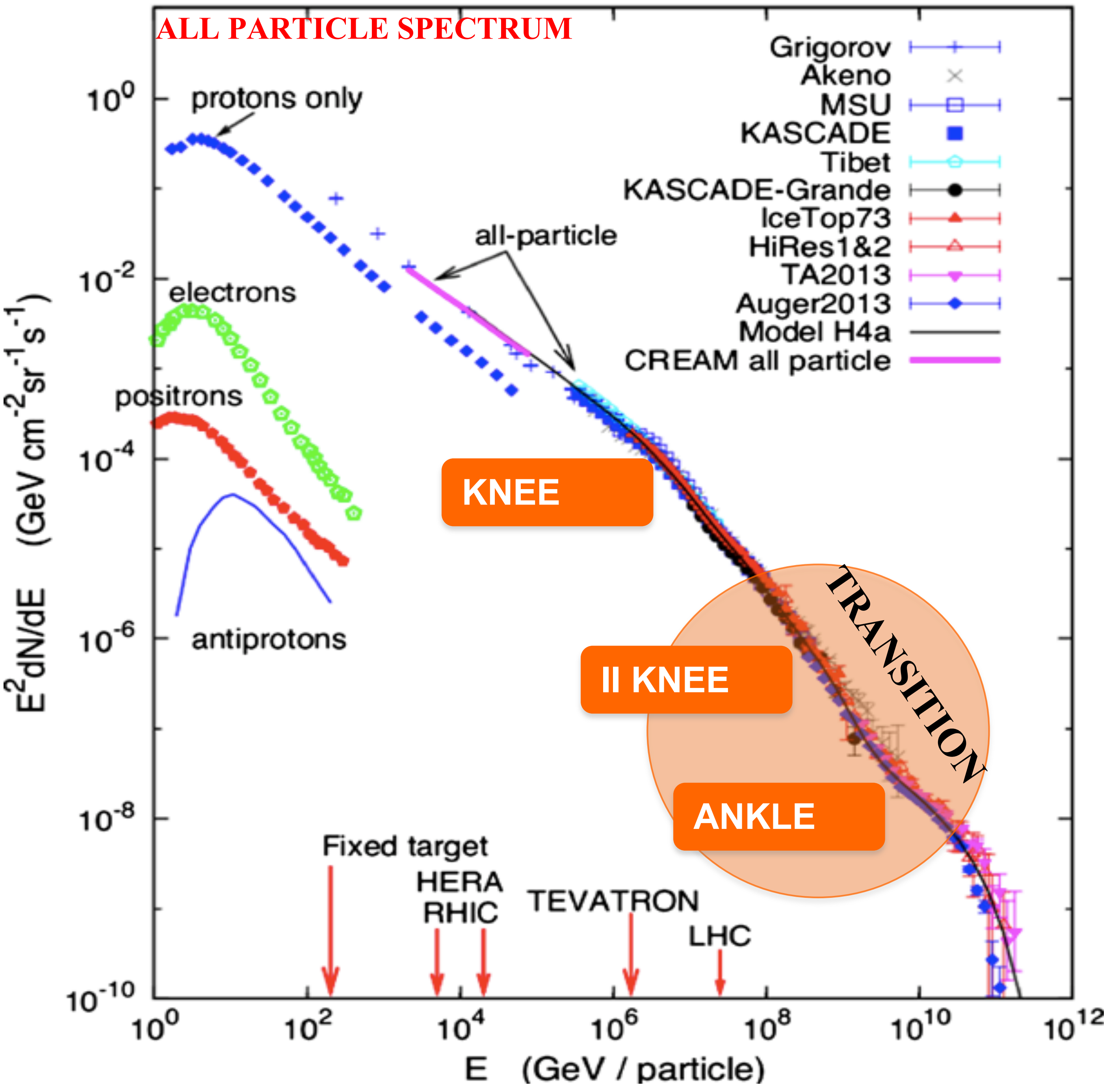
14-16 November 2019, Malargue, Mendoza Province, Argentina.

CR Observations and the transition GCR-EGCR

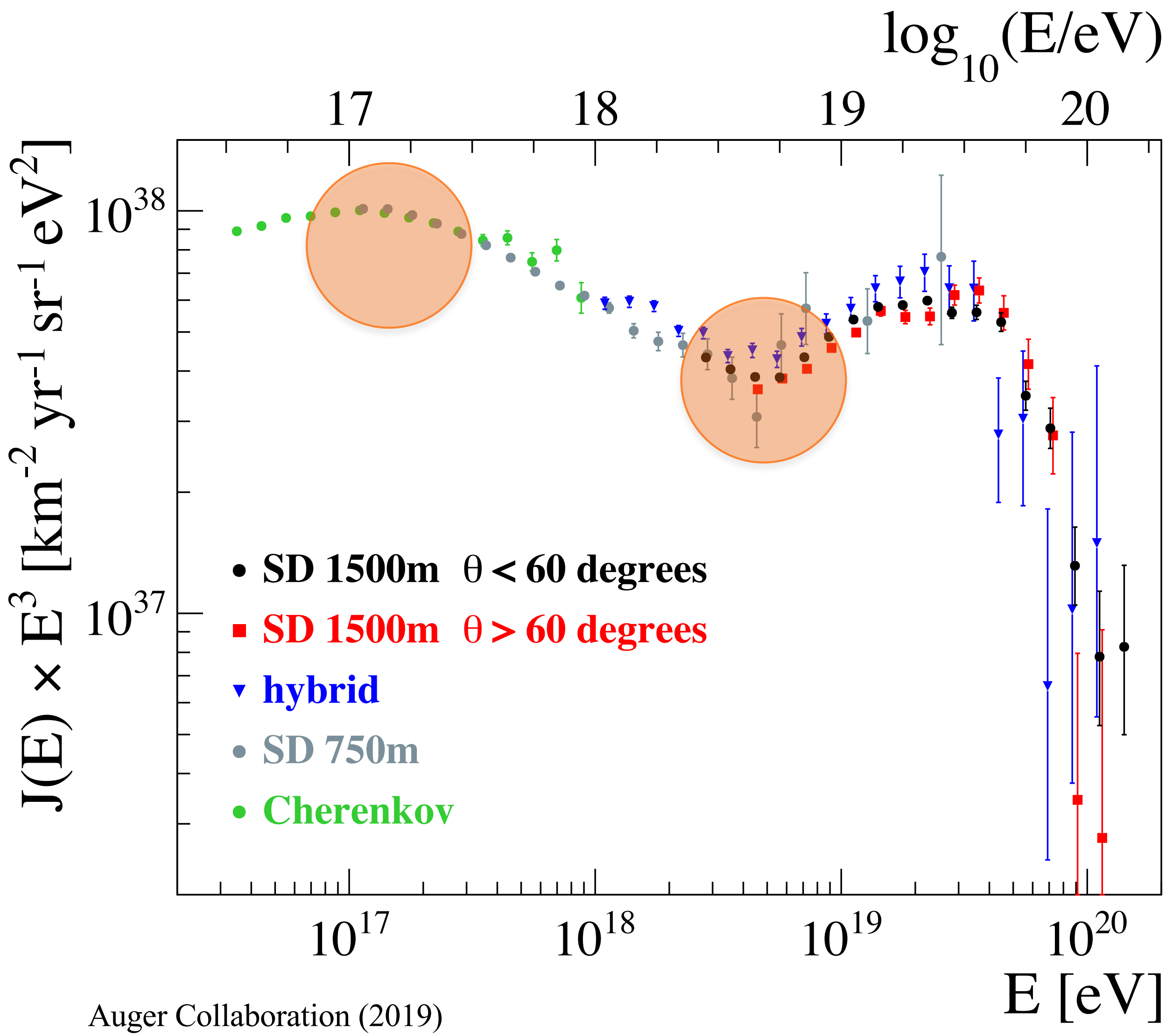
In Cosmic Rays physics we can study sources, production mechanisms and the physics of propagation only through three basic observables

- ✓ **Spectrum**
- ✓ **Anisotropy**
- ✓ **Mass composition**



✓ The all particle spectrum is a broken power law with few structures: knee, second knee, ankle, strong suppression at UHE.

Ultra High Energy Cosmic Rays – Spectrum



Auger Collaboration (2019)

Spectral features

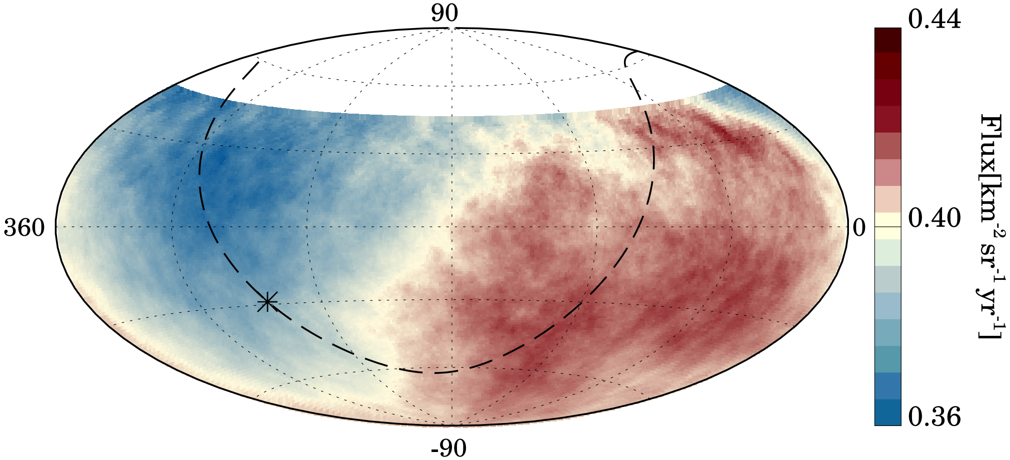
- ✓ Second knee: ~2x10^{17} eV
- ✓ Ankle: ~3x10^{18} eV

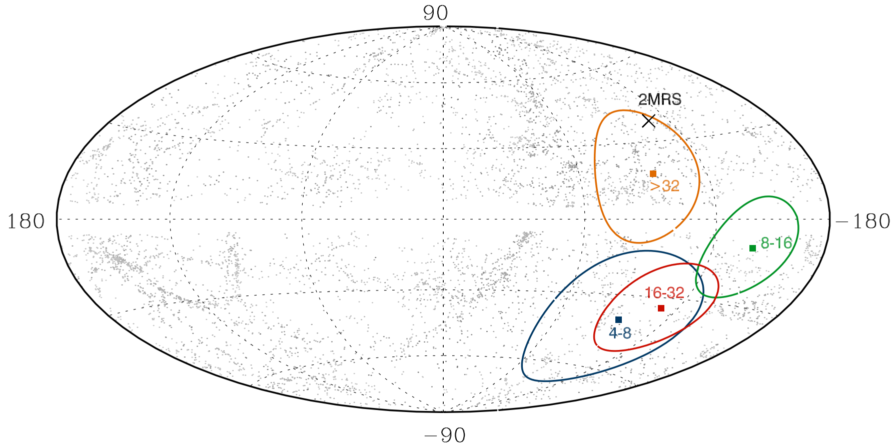
Transition GCR-EGCR

- ✓ Expected changes in the mass composition across the transition region: from heavy to light (see later).
- ✓ Anisotropy observations can provide stringent limits on the transition region.

Ultra High Energy Cosmic Rays – Anisotropy

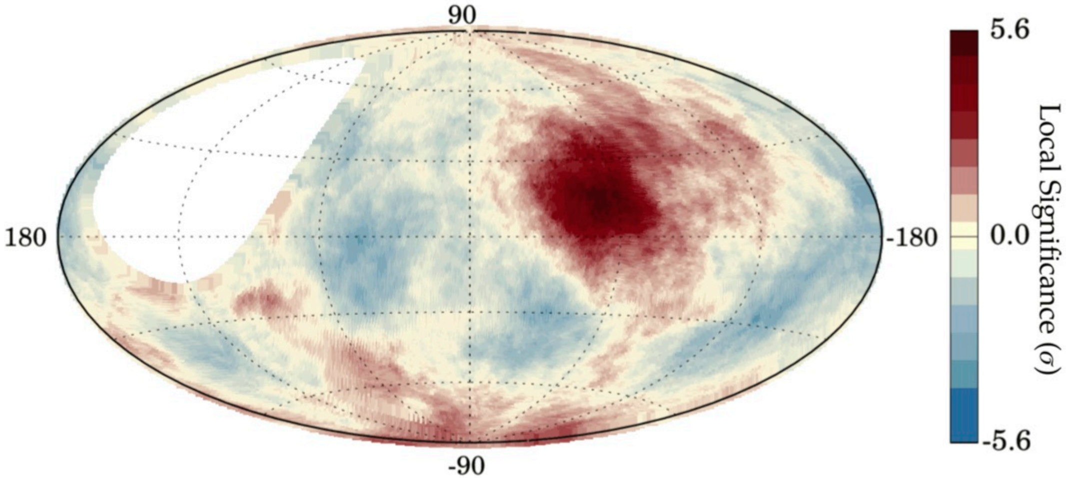
✓ Large scale anisotropy: dipole E>8 EeV (5.2σ) **Extragalactic origin**

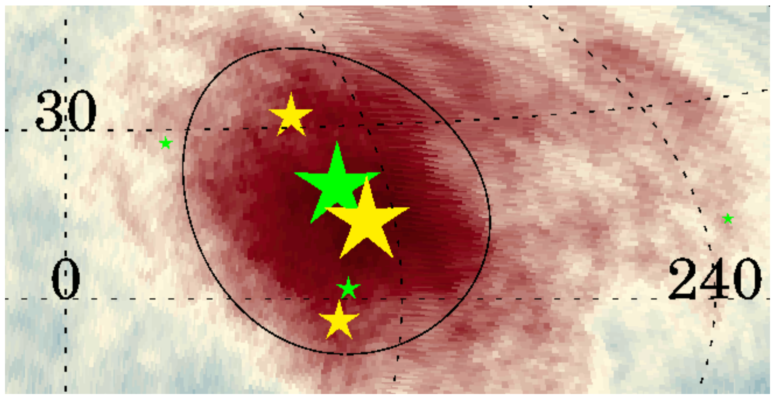


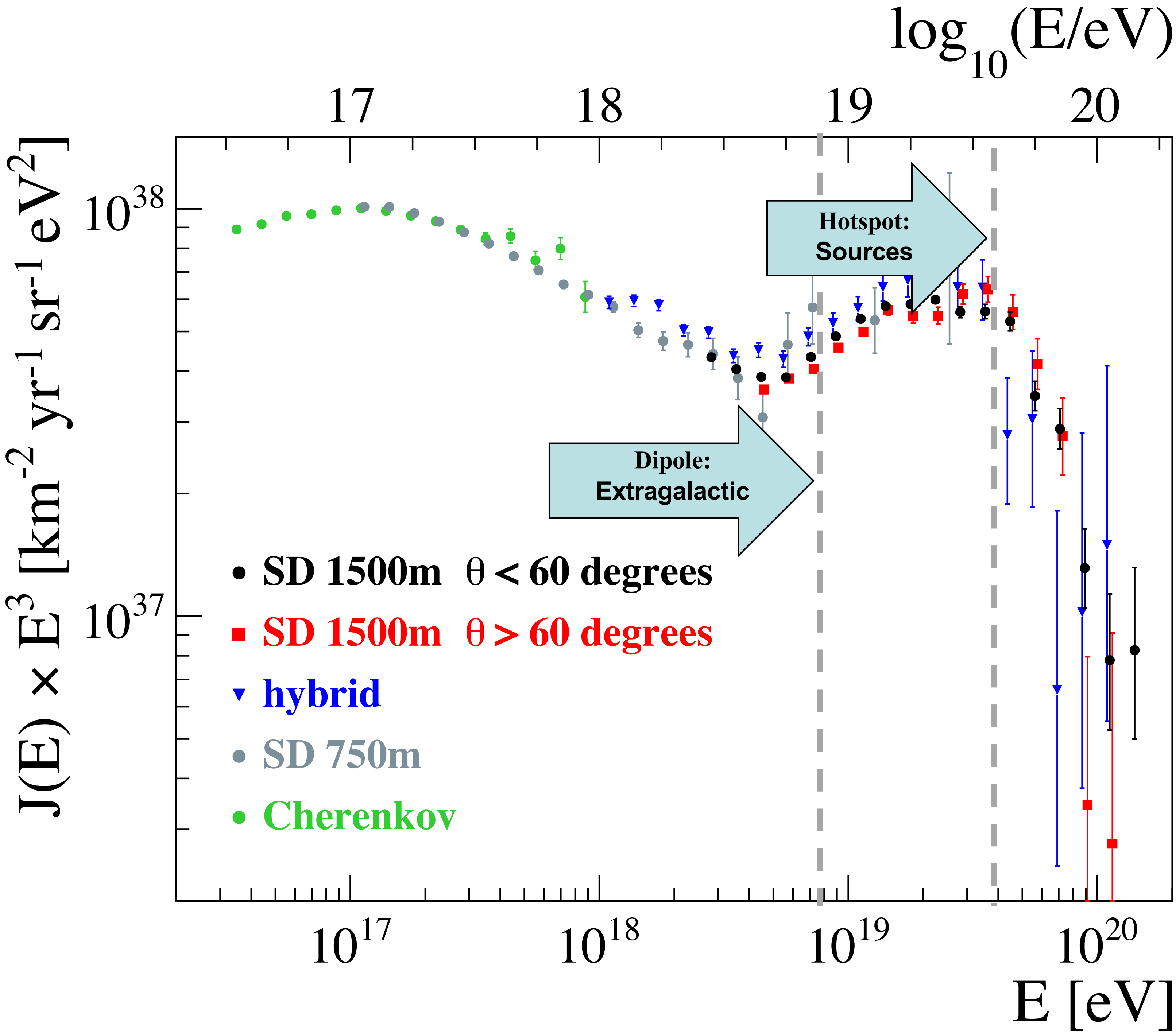


Auger Collaboration (2019)

✓ Intermediate anisotropy: E>38 EeV (3.8σ) **Hints of sources (Starburst, AGN)**

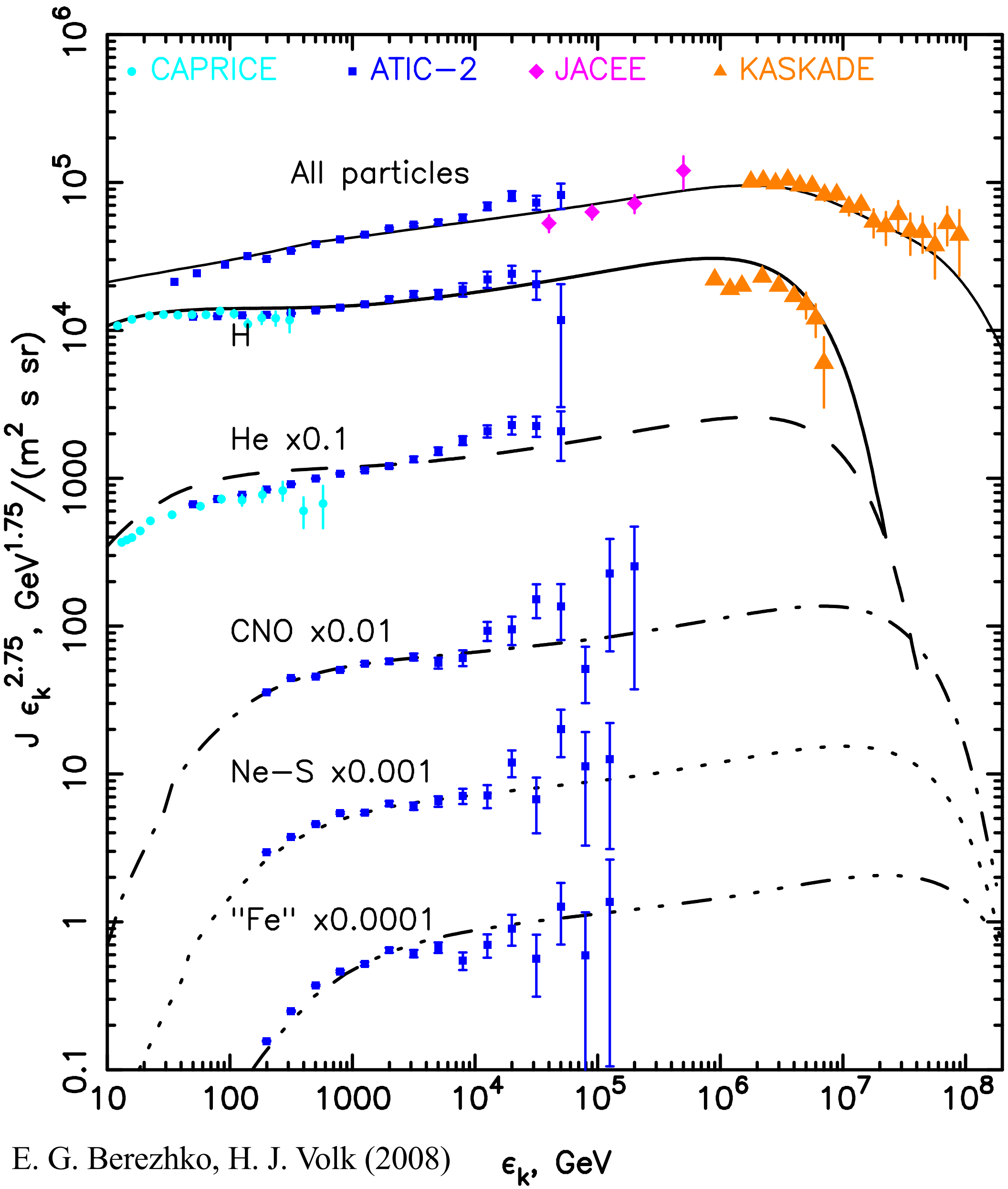






log10(E/eV)
17
18
19
20
J(E) × E3 [km-2 yr-1 sr-1 eV2]
10^38
10^37
Hotspot:
Sources
Dipole:
Extragalactic
SD 1500m θ < 60 degrees
SD 1500m θ > 60 degrees
hybrid
SD 750m
Cherenkov
10^17
10^18
10^19
10^20
E [eV]

Galactic CR: knees and acceleration



E. G. Berezhko, H. J. Volk (2008)

✓ The knee as a signature of a rigidity dependent acceleration

✓ The all particle spectrum is the result of the sum of the spectra of different species, with a cut-off energy rigidity dependent

$$E_Z = Z E_0^p$$

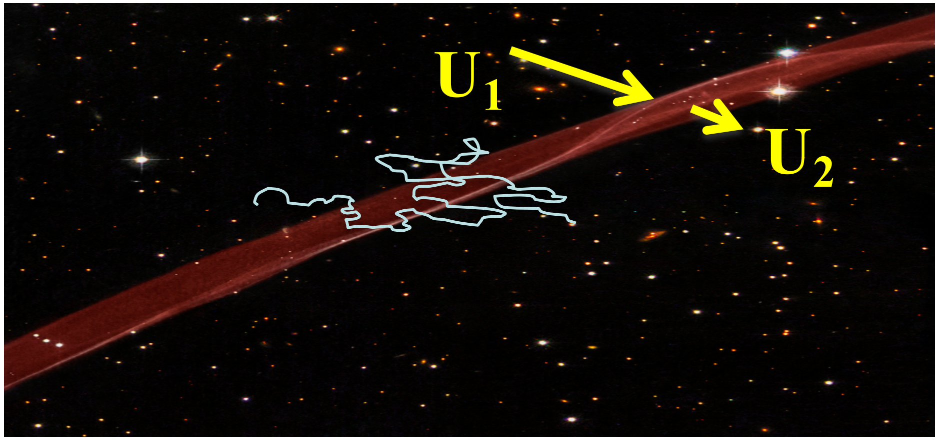
$$\frac{d\Phi_Z}{dE}(E) = \Phi_X^0 E_Z^\gamma \left[1 + \left(\frac{E}{E_Z}\right)^{\epsilon_c}\right]^{-\frac{\Delta\gamma}{\epsilon_c}}$$

J.R. Horandel et al. (2003)

✓ Maximum energy of accelerated protons (need for "Pevatron" sources)

$$E_0^p \gtrsim 1\text{PeV}$$

Diffusive Shock Acceleration

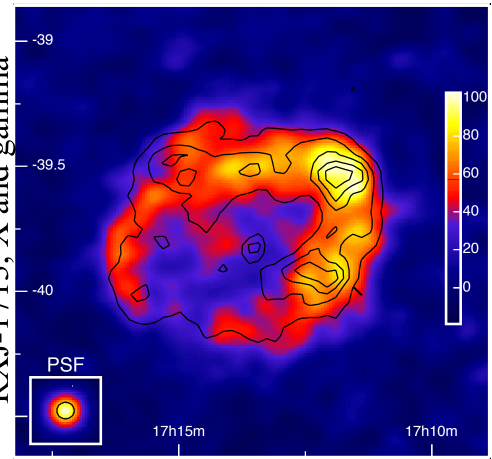


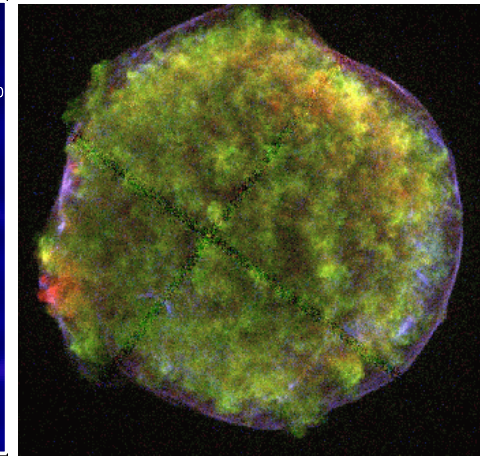
- Diffusion of charged particles back and forth through the shock leads to

$$\Delta E \simeq E(4/3)(U_1 - U_2)/c$$

- Particles are accelerated to a power law spectrum $$Q(E) \propto E^{-\gamma}$$
- The slope of the spectrum depends only on the shock compression factor, in the case of strong shock (M>>1) $Q{\sim}E^{-2}$.
- The maximum acceleration energy depends only on diffusion in the shock region. The ISM magnetic turbulence (as it follows from B/C observation) is too low (providing only CR at GeV energy). It is needed additional turbulence to reach E_{max} ~10^5-10^6 GeV.

RXJ-1713, X and gamma





Tycho, X

X-rays observations

Typical size of the observed filaments ~ 10^{-2} parsec

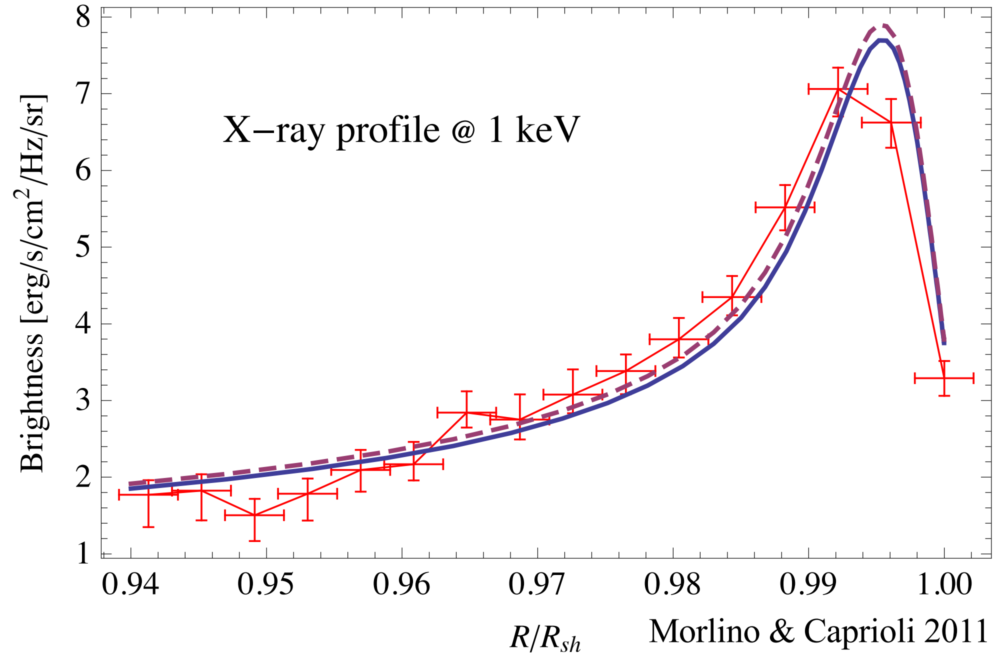
$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \text{pc}$$

Comparison with the observed thickness leads to a B-field estimate

$$B \simeq \mathrm{O}(100\mu\mathrm{G})$$

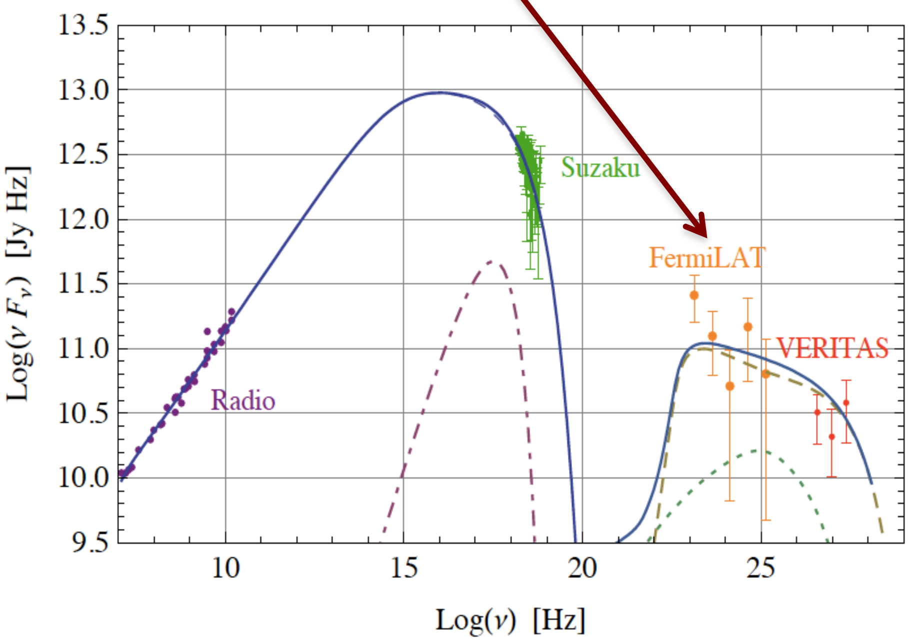
The case of Tycho

- SNIa exploded in roughly homogeneous ISM (regular spherical shape)
- From X-ray observations B~300 μG
- Maximum energy protons E_{max}~500 TeV



Morlino & Caprioli 2011

Steep spectrum hard to explain with leptonic emission



Morlino & Caprioli 2011

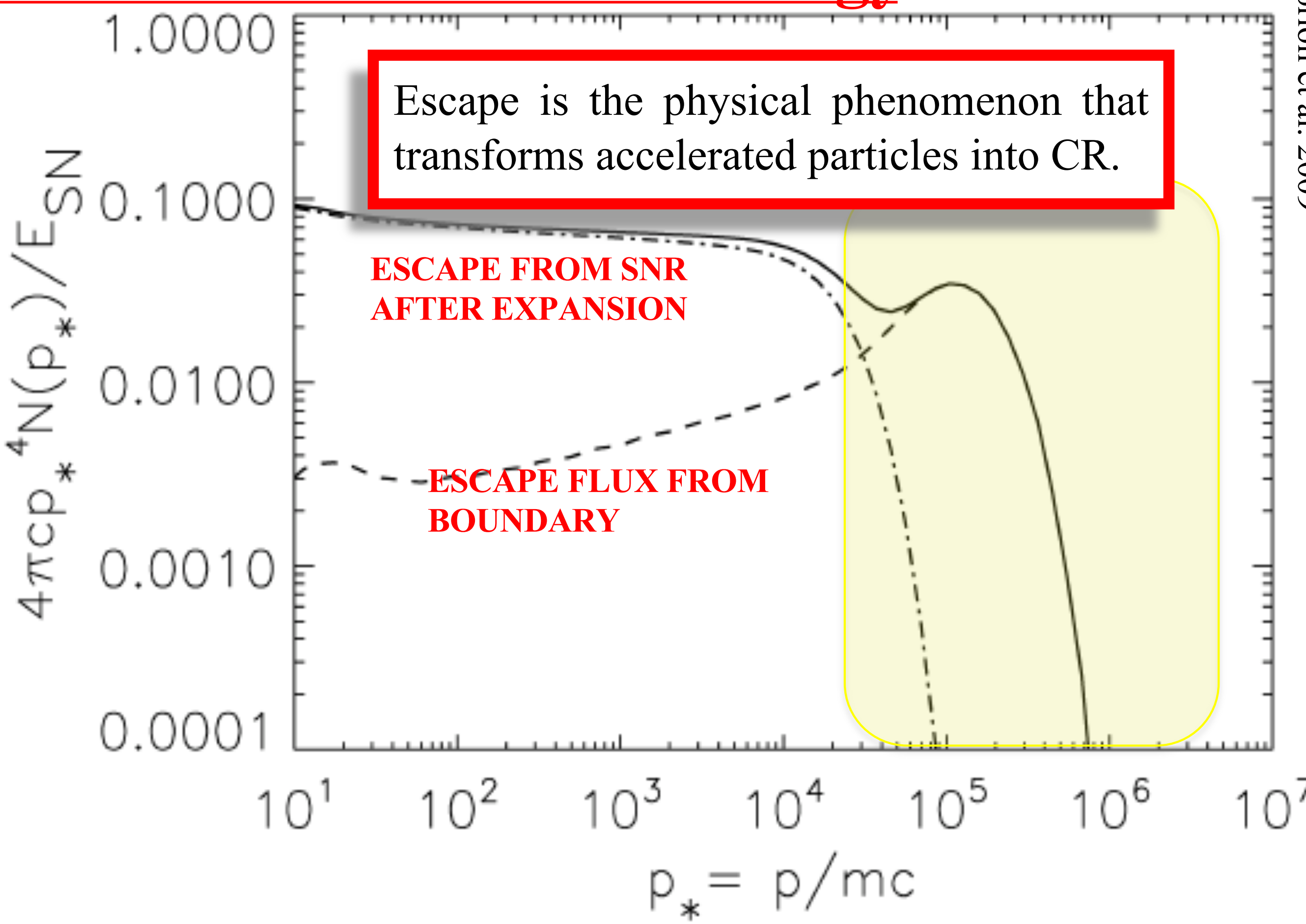
- Leptonic emission. ICS of relativistic electrons on photon background has a flatter spectrum respect to CR: $E^{-(\gamma+1)/2}$
- Hadronic emission. pp→π^0→γγ conserves the same spectrum of CR: $E^{-\gamma}$
- Important experimental confirmation of the credibility level of theories based on DSA. Space resolved gamma ray observations would test different theoretical hypothesis.

Escape of CR from accelerator – maximum energy

Caprioli et al. 2009

Streaming instability

Super-Alfvenic streaming of CR leads to the excitation of magnetic turbulence δB at the resonant wavenumber $k=1/r_L$. Locally at the shock front this turbulence can reach δB/B ~ 50, while in the ISM δB/B<<1.



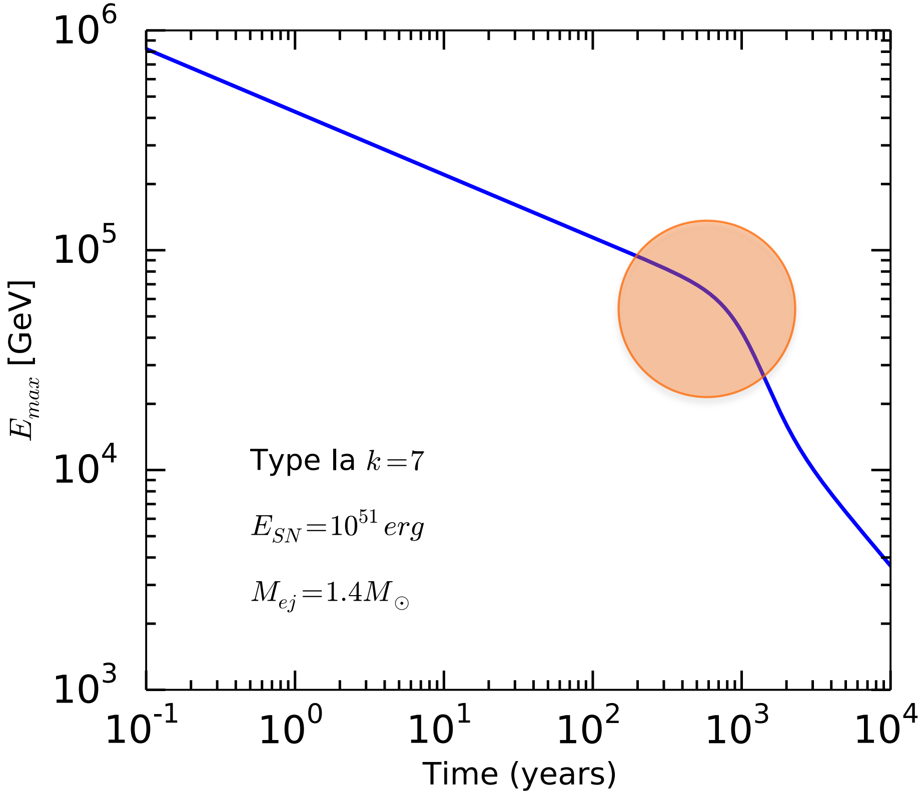
Escape is the physical phenomenon that transforms accelerated particles into CR.

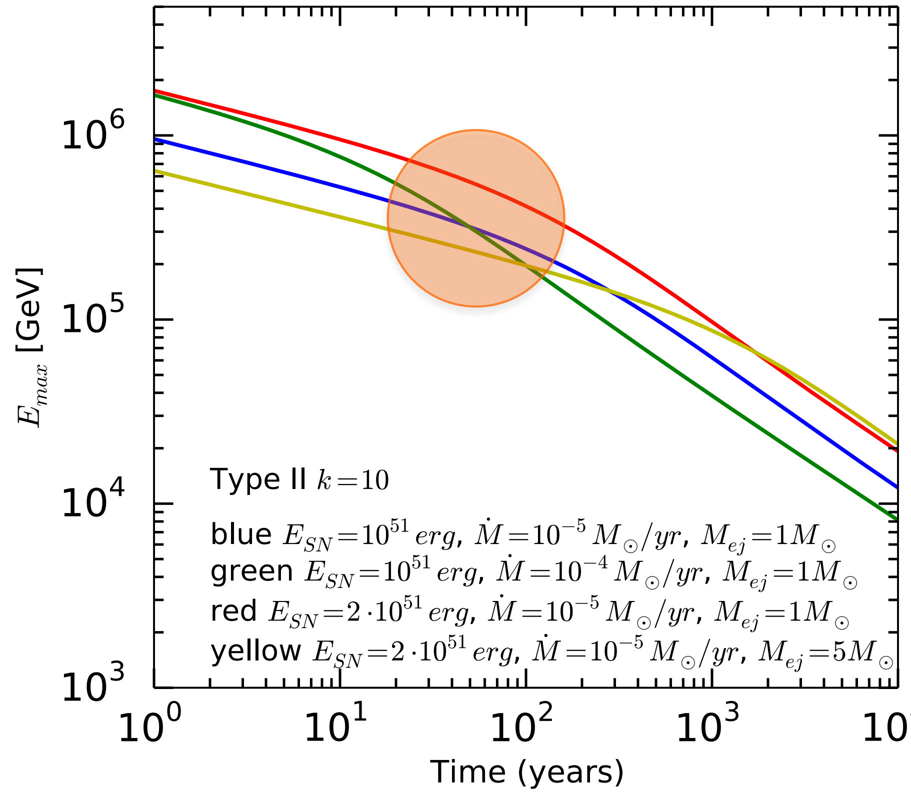
CR injected

- ✓ particles escaped during the free expansion and Sedov-Taylor phases (emission peaked on p_{max})
- ✓ particles released in the ISM after expansion

Maximum energy

- ✓ particles escape $$\frac{D(E_{max})}{V_{sh}} \simeq \chi R_{sh} \qquad \chi < 1$$
- ✓ NOTE: Hillas criterion $r_L(E_{max}) = R_{sh}$ is an upper limit, overestimates the actual maximum energy by a factor of c/V_{sh}





Blasi 2019

- ✓ Type Ia SN

$$E^p_{max} = 0.05\left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-2/3}\left(\frac{E_{SN}}{10^{51}erg}\right)\left(\frac{n_{ISM}}{cm^{-3}}\right) PeV$$

- ✓ Type II SN core collapse in its own wind

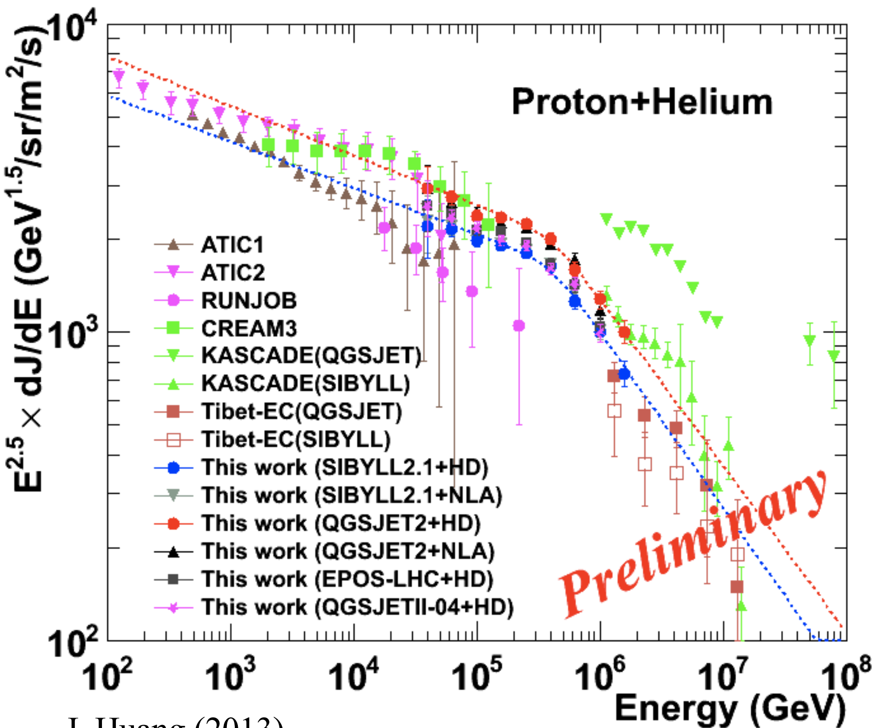
$$E^p_{max} = 0.3\left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-1}\left(\frac{\dot{M}}{10^{-5}M_\odot yr^{-1}}\right)^{1/2}\left(\frac{E_{SN}}{10^{51}erg}\right)\left(\frac{V_w}{10kms^{-1}}\right) PeV$$

Galactic CR acceleration

- ✓ In the framework of DSA in SNRs the maximum attainable energy seems somewhat lower than needed.

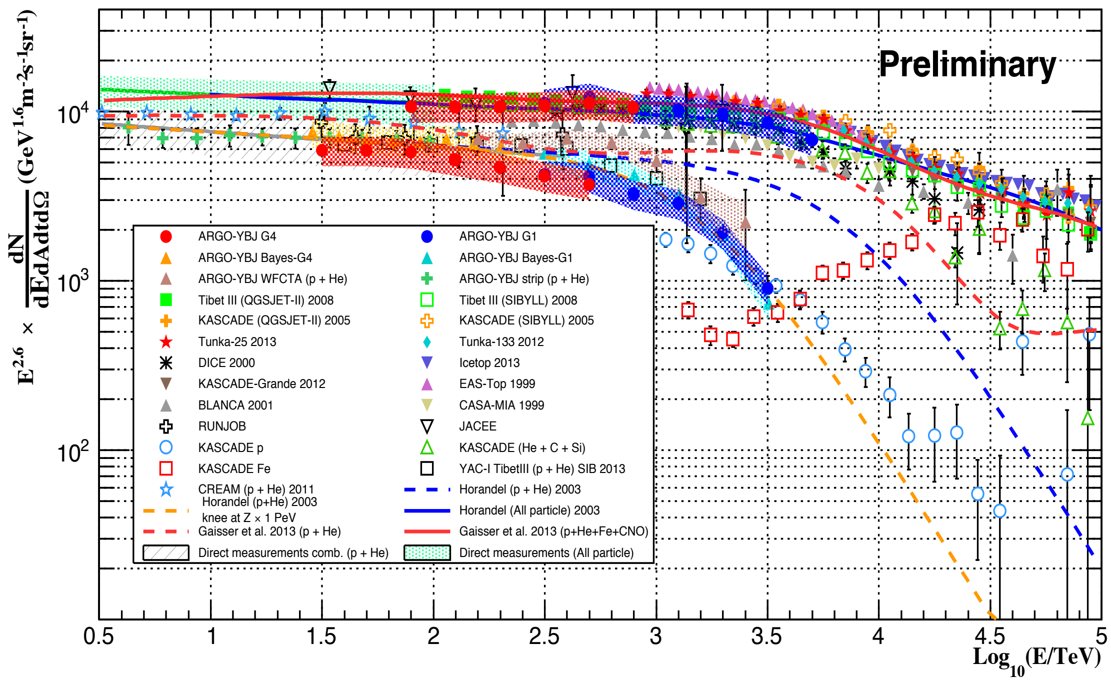
Galactic Cosmic Rays – The knee structure

P+HE SPECTRUM (YAC1-Tibet)



J. Huang (2013)

All particle and light components (Argo-YBJ)

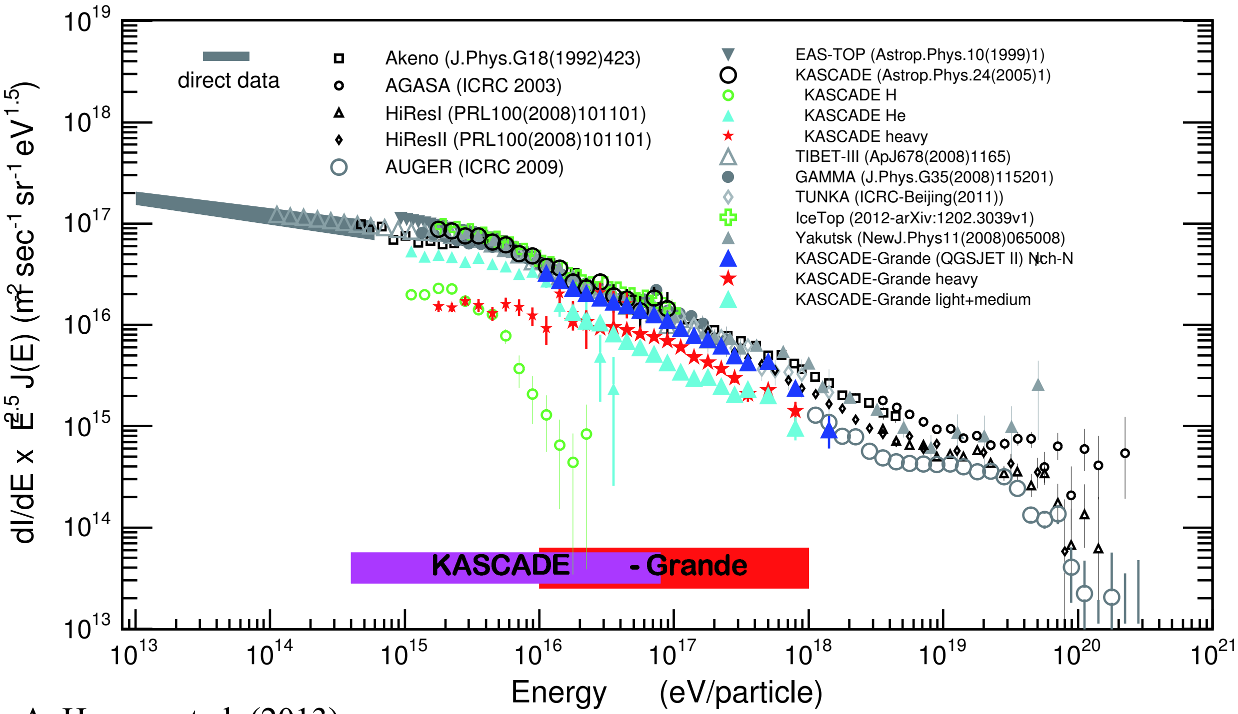


I. De Mitri, A. D'Amone, L. Perrone, A. Surdo (2016)

YAC1-Tibet and Argo-YBJ

- ✓ Knee in the all particle spectrum ~ 2 PeV
- ✓ Knee in the light component ~ 0.1 PeV

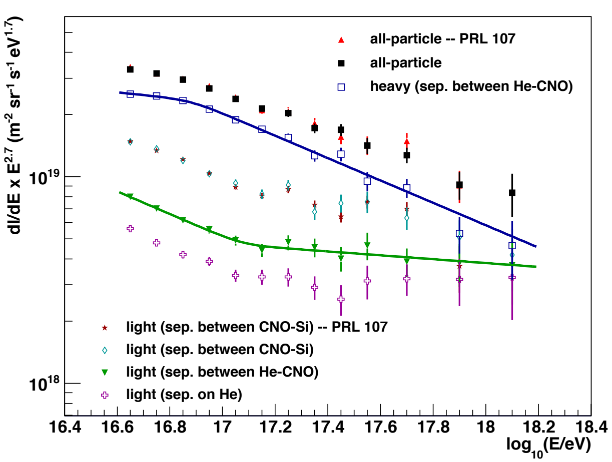
Kascade and Kascade-Grande

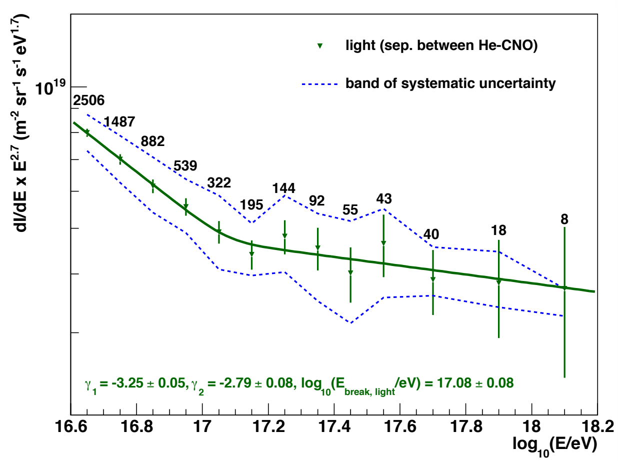


A. Haungs et al. (2013)

Kascade and Kascade -Grande

- ✓ Knee in the all particle spectrum ~ 2 PeV
- ✓ Knee in the heavy component ~ 80 PeV
- ✓ "Recovery" in the light component ~ 100 PeV

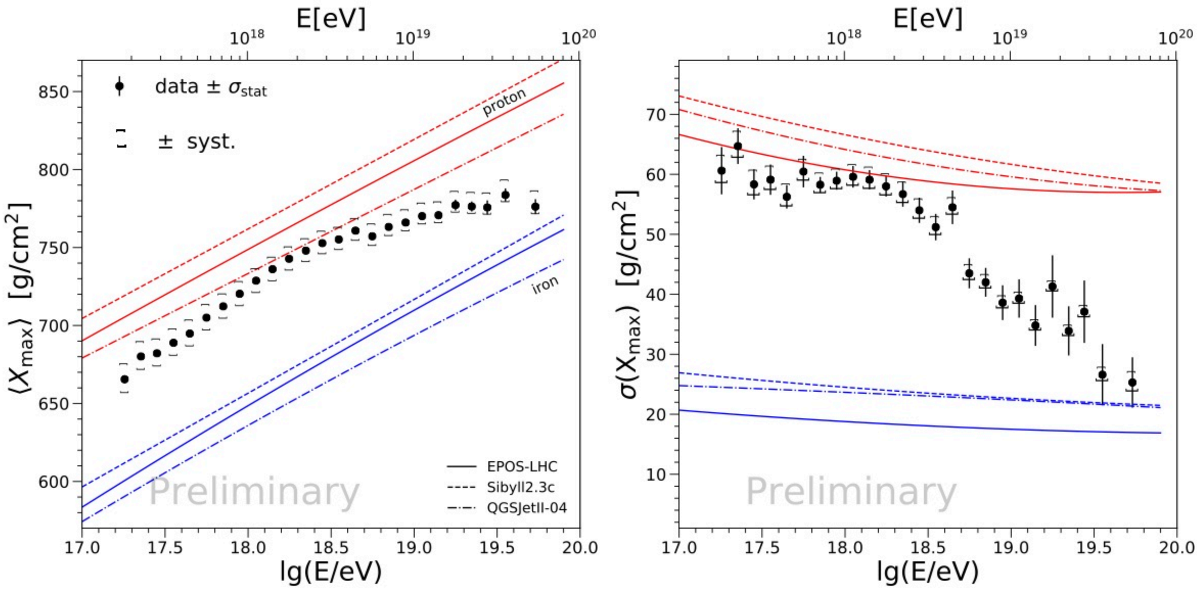


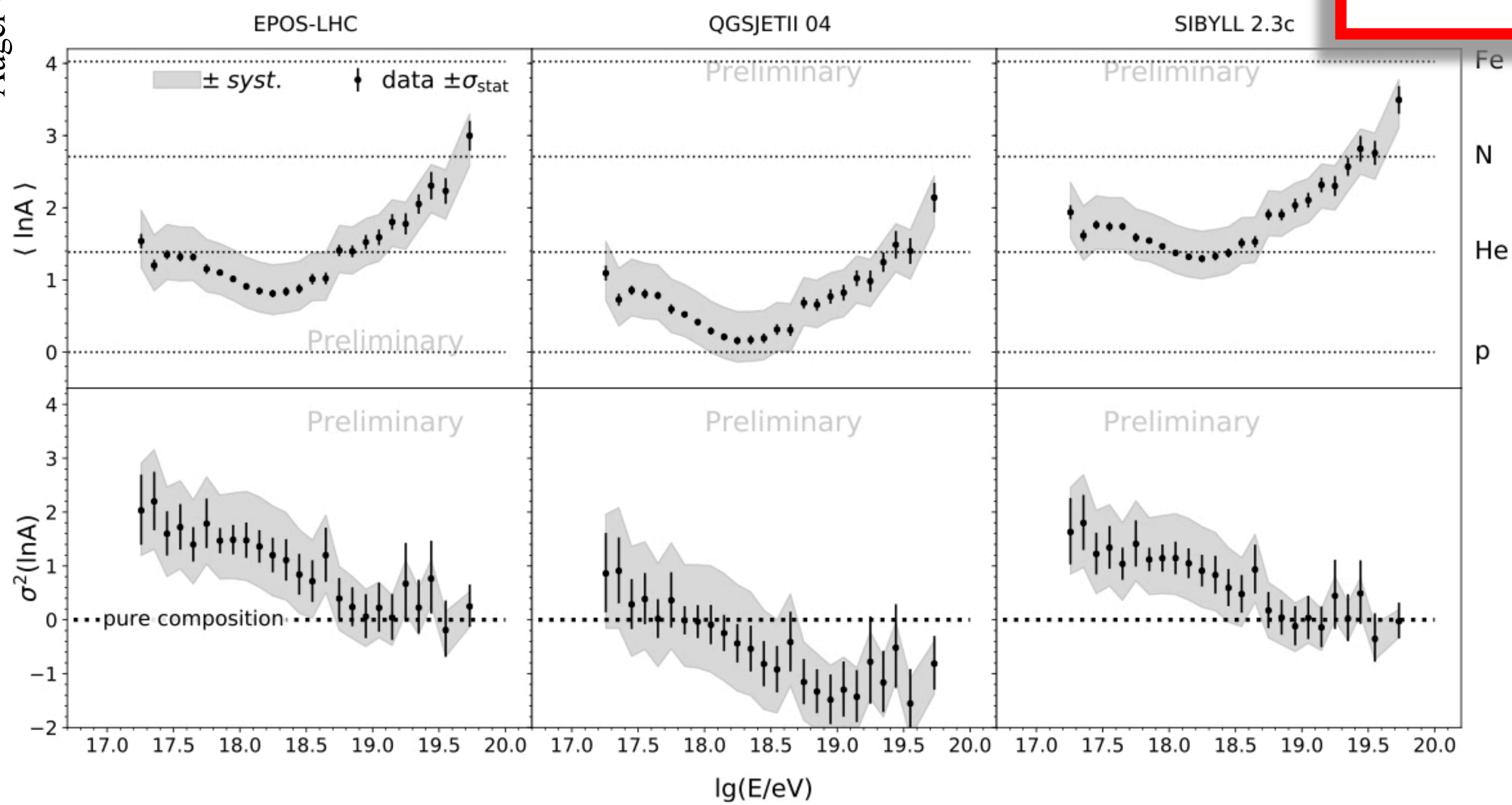


W.D. Apel et al. (2013)

- ✓ The position of the p+He knee is not clearly determined, discrepancies among experiments (high vs low altitudes?)
- ✓ Uncertainties in the hadronic interaction models
- ✓ Uncertainty in the maximum acceleration energy of galactic CR.

Ultra High Energy Cosmic Rays – Composition





Auger Collaboration (2019)

Mixed Composition

At the lowest energies log(E/eV)=17.5 an increasing light component till log(E/eV)=18.5, with increasing energy the composition turns heavier. Uncertainties due to the hadronic interaction model assumed.

Caveats on UHE nuclei

Composition

It is impossible to observe at the Earth a pure heavy nuclei spectrum, even if sources inject only heavy nuclei of a fixed specie at the Earth we will observe all secondaries (protons too) produced by photo-disintegration.

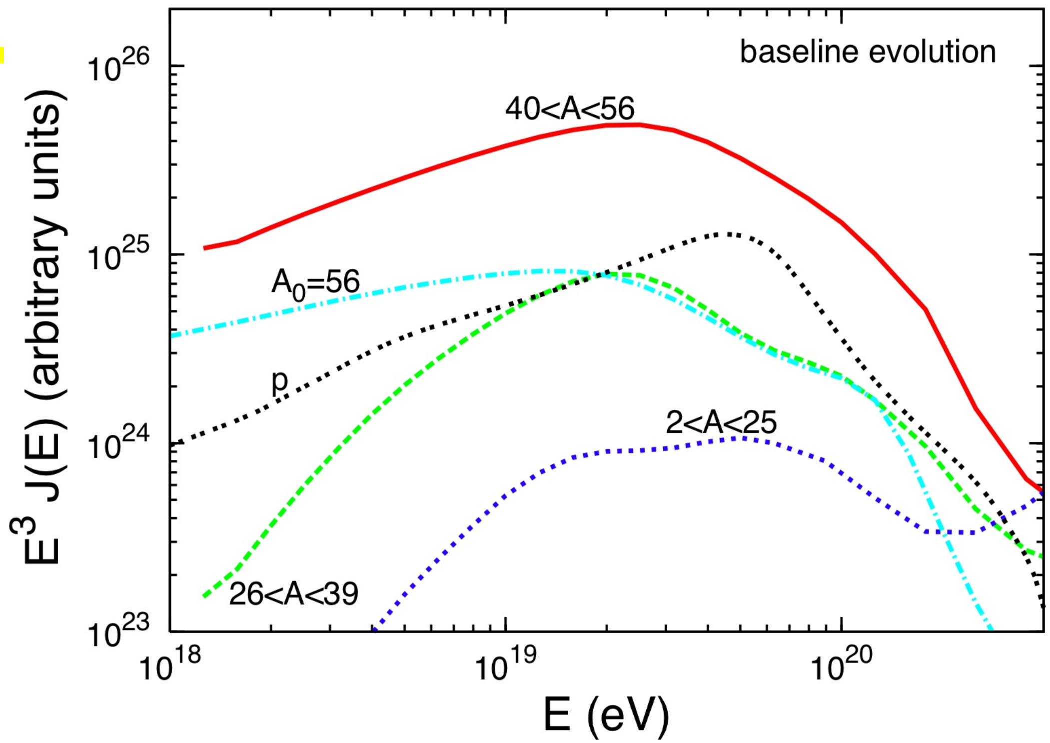
Critical Lorentz factor

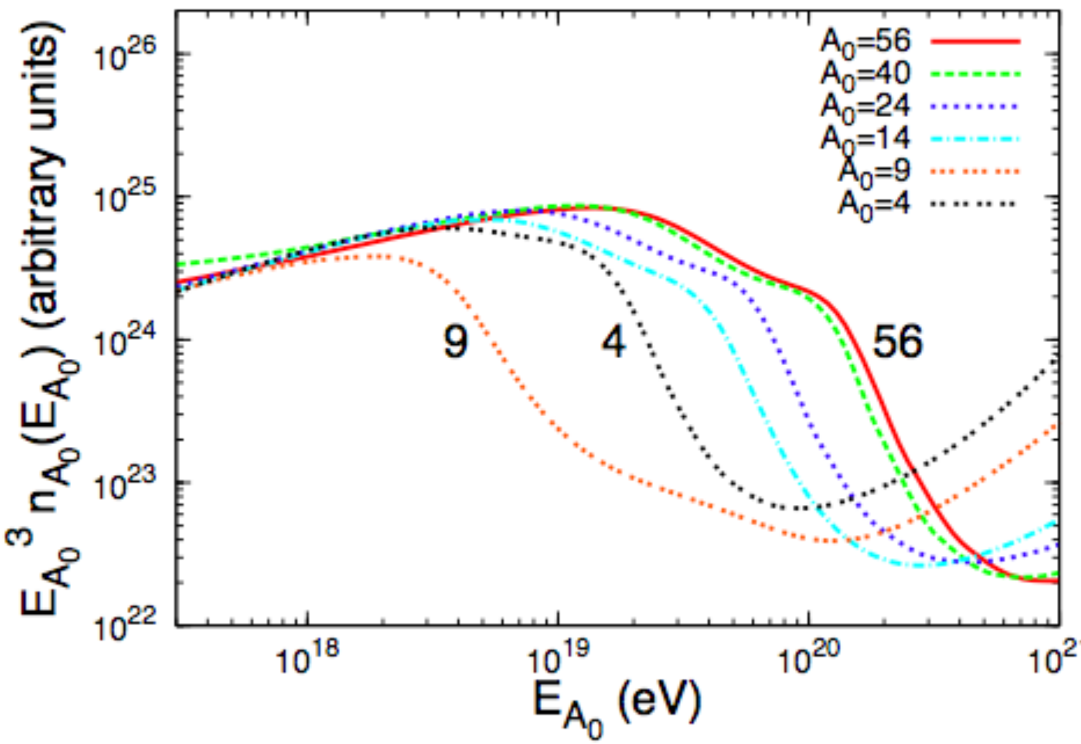
The critical Lorentz factor fixes the scale at which photo-disintegration becomes relevant, for heavy nuclei it is almost independent of the nuclei specie

$$\beta^{A}_{e^+e^-}(\Gamma,t) + H_0(t) = \beta^{\Gamma}_{dis}(A,t)$$

$$E_{cut}(A) = A m_N \Gamma_c$$

$$\Gamma_c \simeq 2 \times 10^9$$



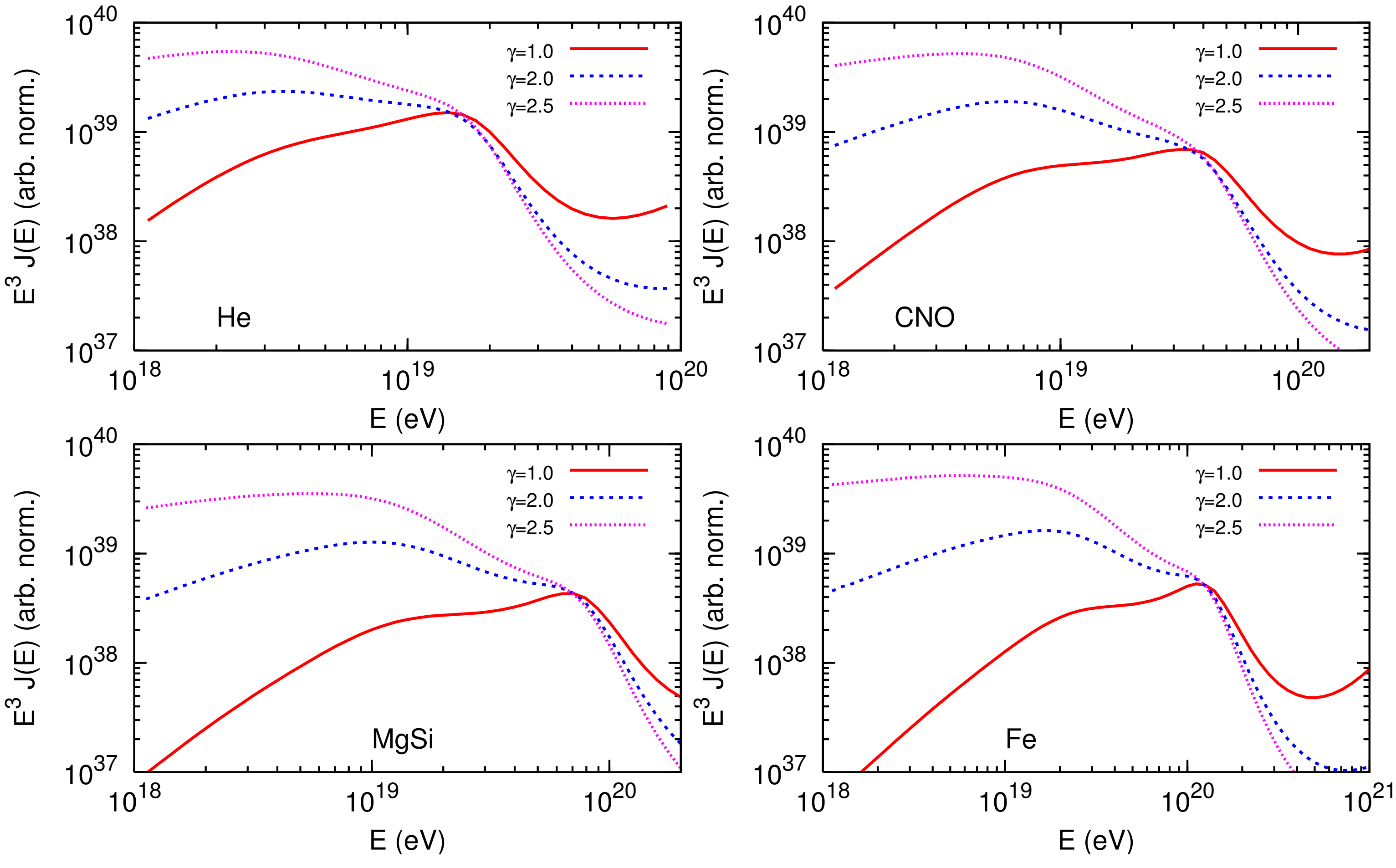


RA, Berezinsky, Grigorieva (2009-2013)

Injection of nuclei: flat vs steep

The combined effect of nuclei energy losses, mainly photo-disintegration, and injection implies that a steep injection increases the low energy weight of the mass composition

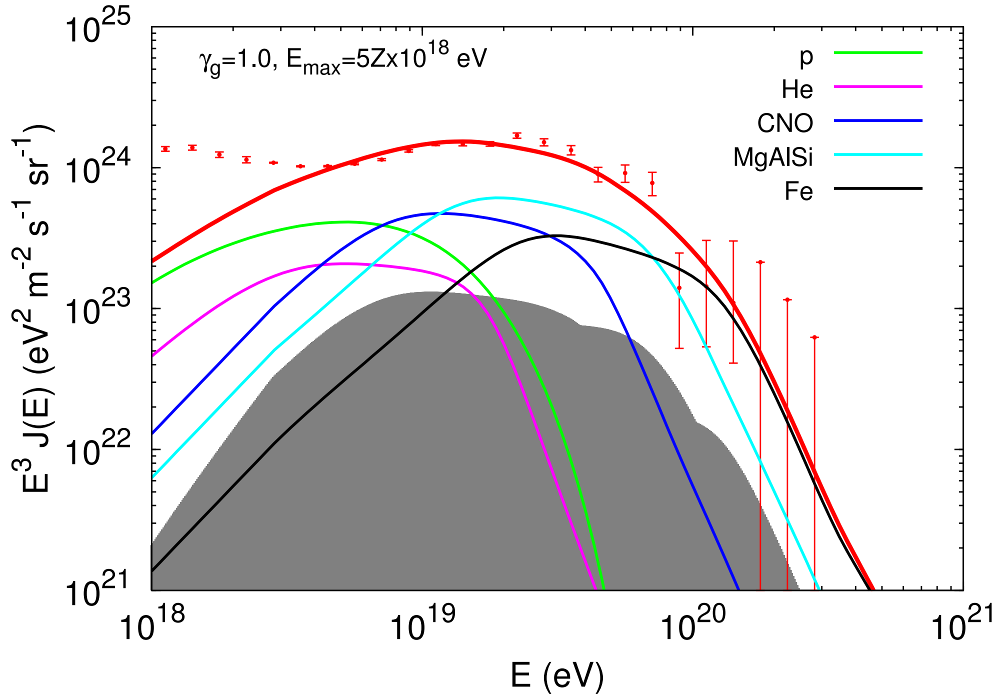
$$Q_A(\Gamma) = Q_0 e^{-\Gamma/\Gamma_{max}} \left(\frac{\Gamma}{\Gamma_0}\right)^{-\gamma_g} \qquad \mathcal{L}_0 = n_{UHE} L_{UHE} = A m_N \int_1^{\Gamma_{max}} d\Gamma \Gamma Q_A(\Gamma)$$



Note

The effect of an Intergalactic Magnetic Field (IMF) can mitigate the conclusion on flat spectra allowing for steeper spectra γ≈2.

What we can learn from Auger data

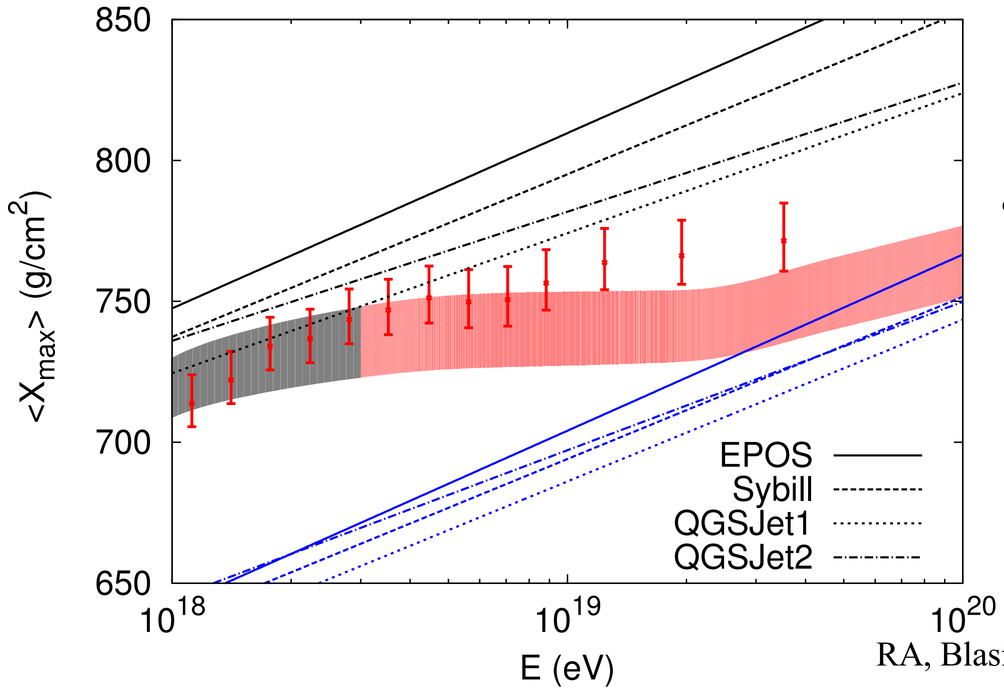


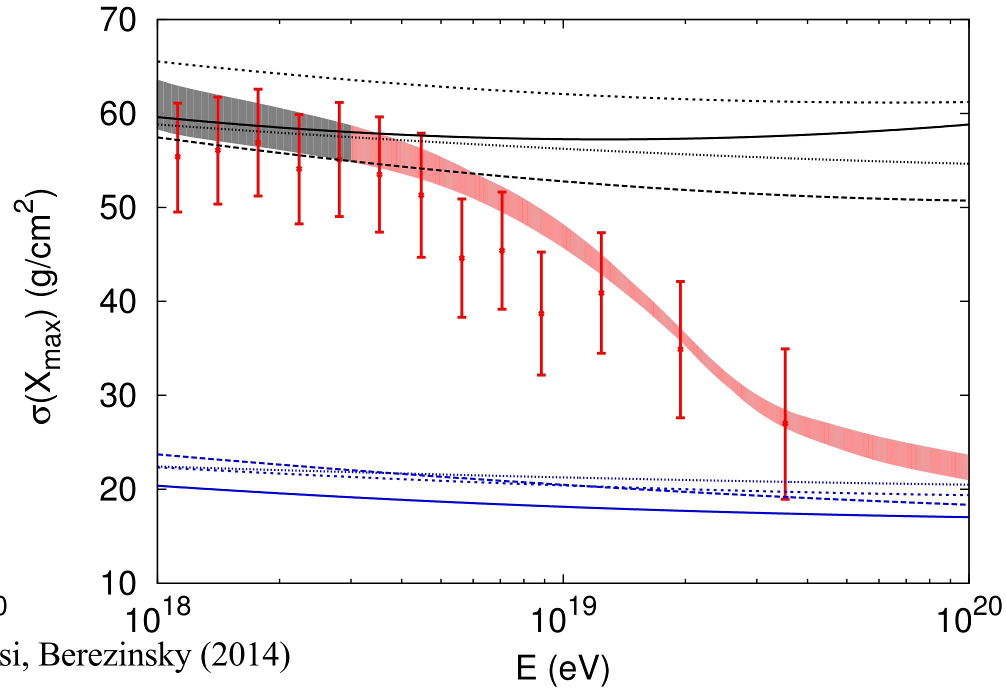
Auger chemical composition can be reproduced only assuming a very flat injection of primary nuclei

$$\gamma_g = 1.0 \div 1.5$$

$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{y}}$$

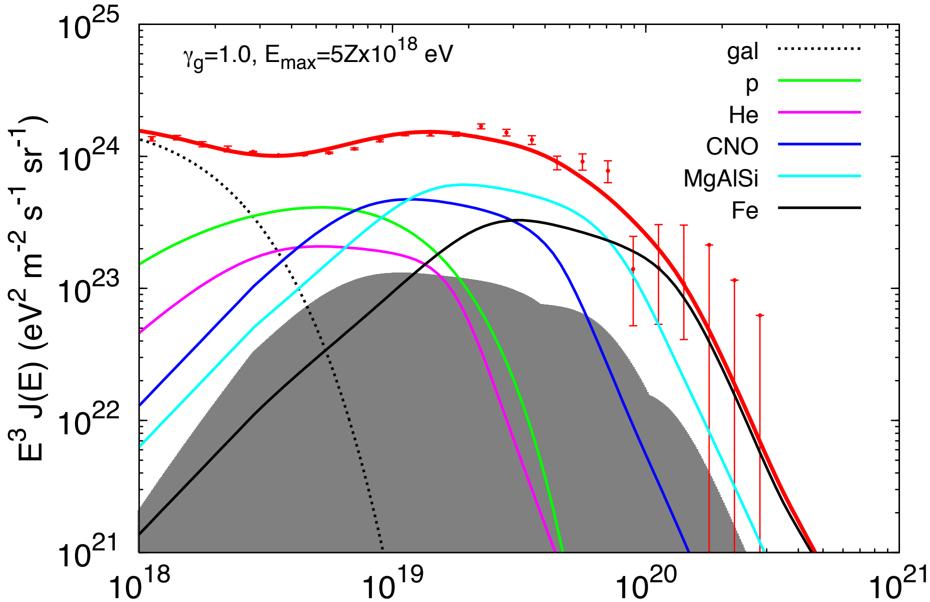
with a certain level of degeneracy in terms of the nuclei species injected





RA, Blasi, Berezinsky (2014)

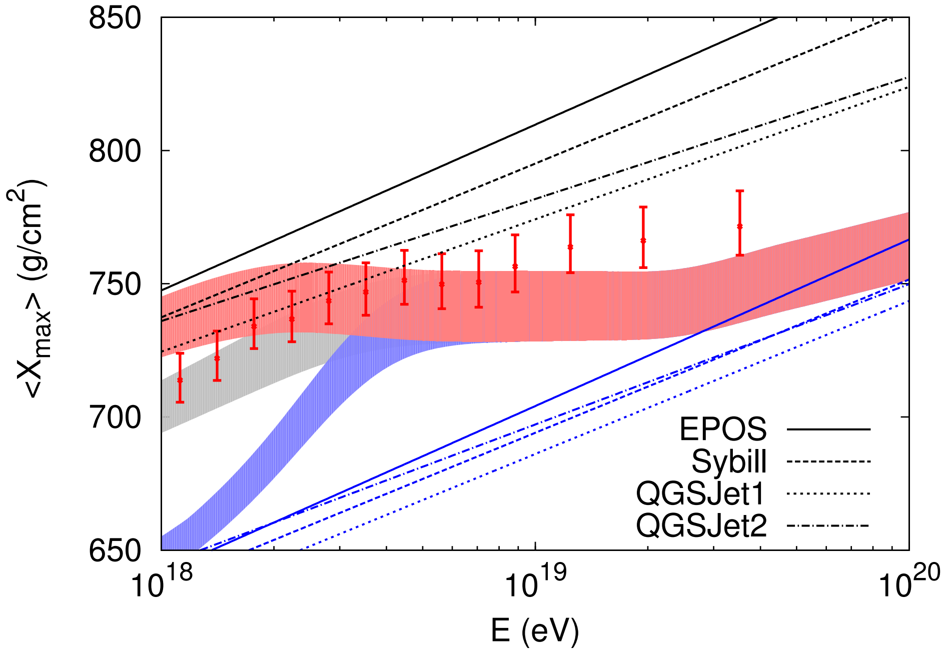
Extra Galactic Nuclei and Galactic light elements

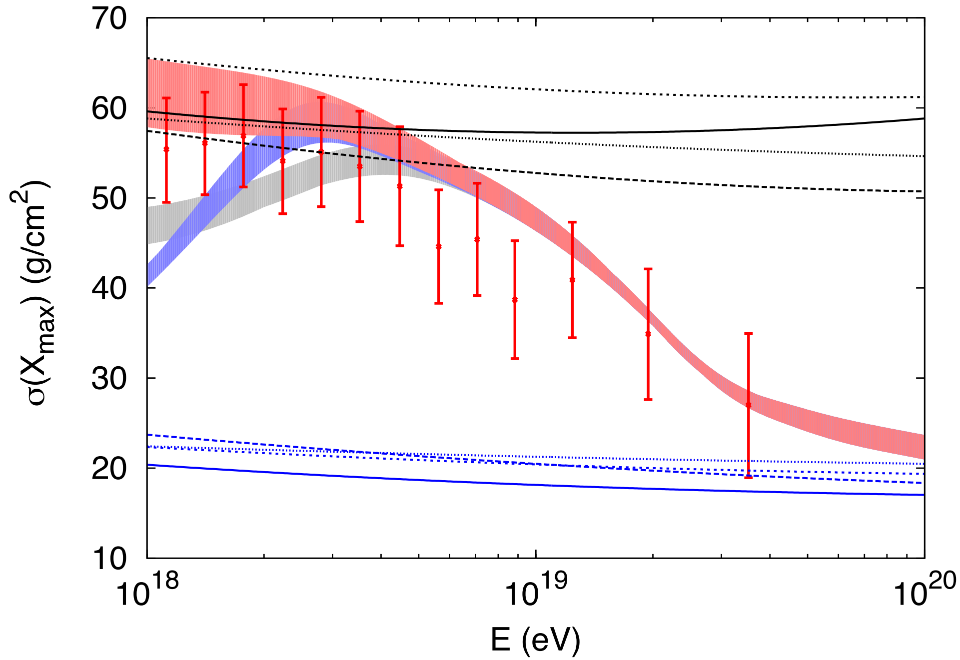


An additional galactic component can fill the gap in the spectrum.

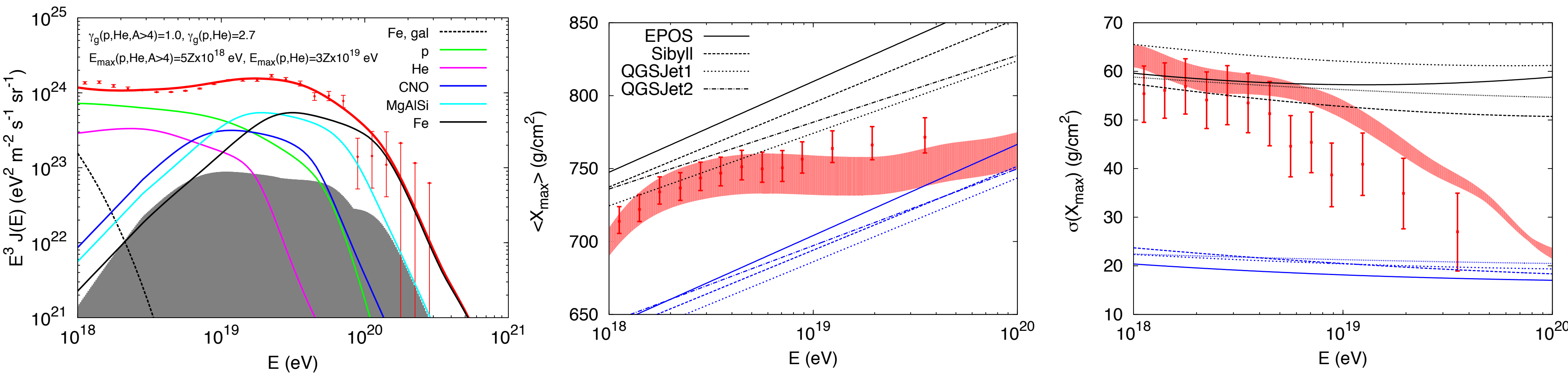
Composition issue. Mixture of 80% p and 20% He to reproduce Auger observations. Difficult to reconcile with DSA acceleration and anisotropy observations.

RA, Blasi, Berezinsky (2014)

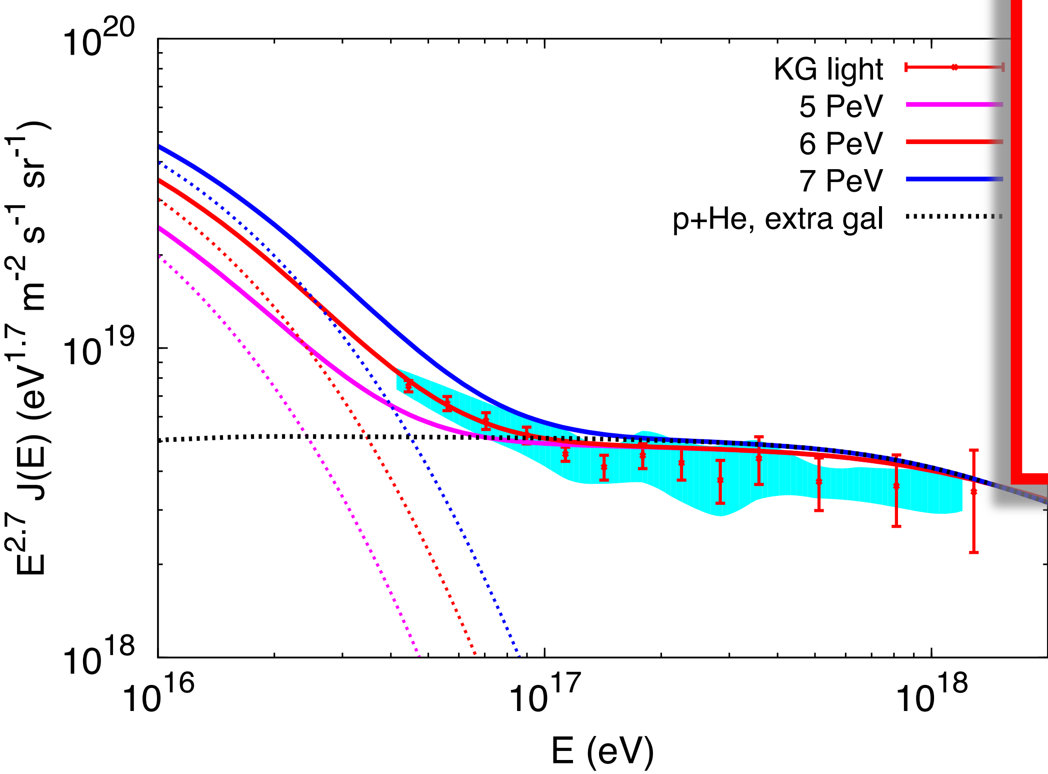




Different Classes of Extra Galactic Sources



RA, Blasi, Berezinsky (2014)



✓ light component steep injection (γ_g>2.5)

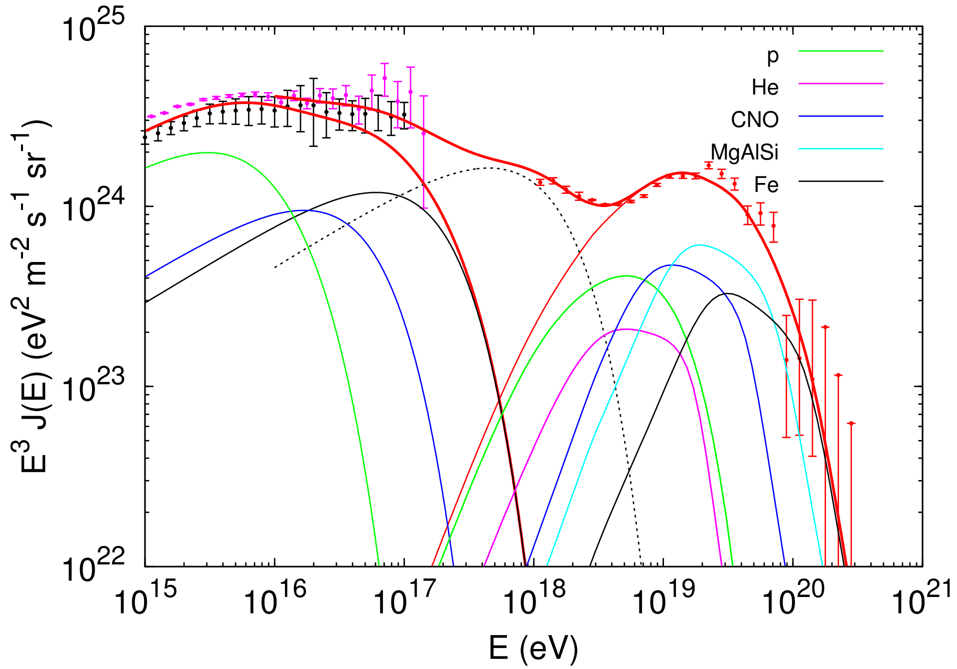
$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{47} \frac{\mathrm{erg}}{\mathrm{Mpc}^3 \mathrm{y}}$$

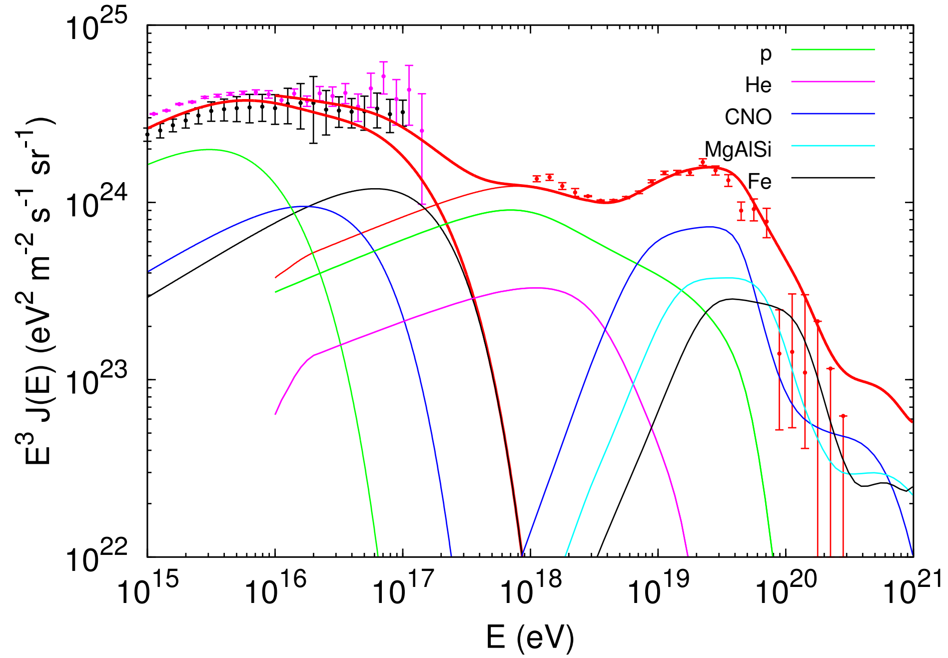
✓ heavy component flat injection (γ_g<1.5)

$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3 \mathrm{y}}$$

The Kascade-Grande observations seem to confirm the presence of an extragalactic light component with a steep injection spectrum.

Conclusions





Unlikely possibility

Transition at the ankle

- ✓ Galactic light component between 0.1 EeV<E< 1 EeV.
- ✓ Difficult to reconcile with anisotropy and mass composition observations.
- ✓ New kind of galactic very high energy sources. Not compatible with the standard model of DSA.

Transition at the II knee

- ✓ Different injection light/heavy (steep/flat) (Two classes of extragalactic sources and/or specific dynamics at the source).
- ✓ Compatible with Kascade-Grande observations.
- ✓ Not too demanding respect to the standard model of DSA.