Ultra High Energy Cosmic Rays and the Highest Energies Universe

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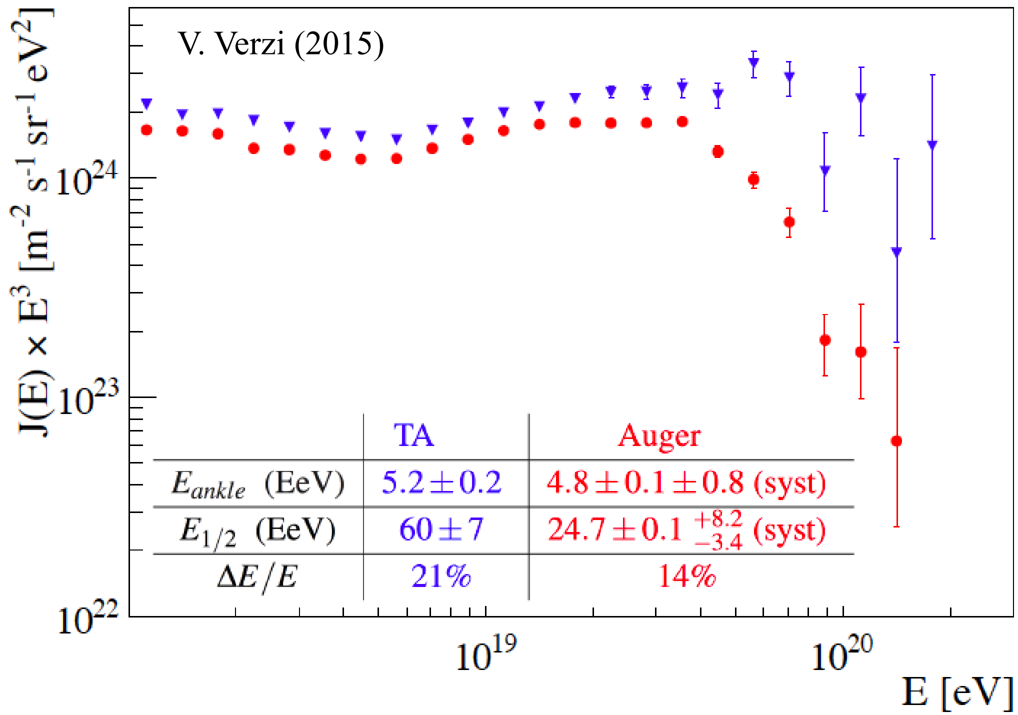
Outline of the talk

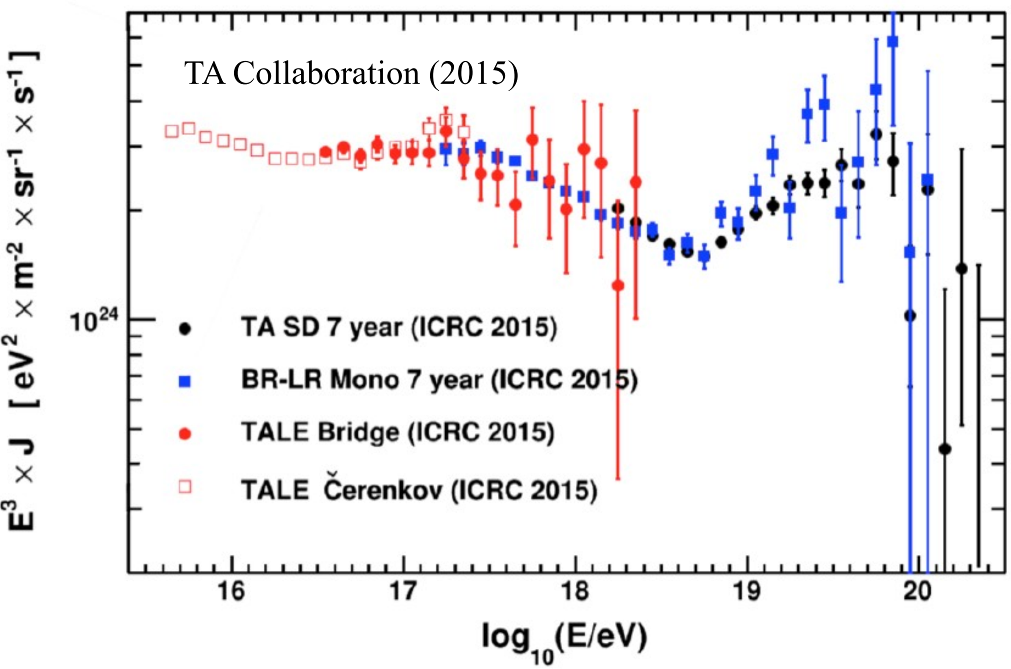
1. UHECR short recap of experimental evidences
2. Theoretical interpretations and possible sources
3. Looking farther away: cosmogenic neutrinos
4. UHECR and secondary gamma rays
5. Observations from space: the new HE frontier
6. Conclusions

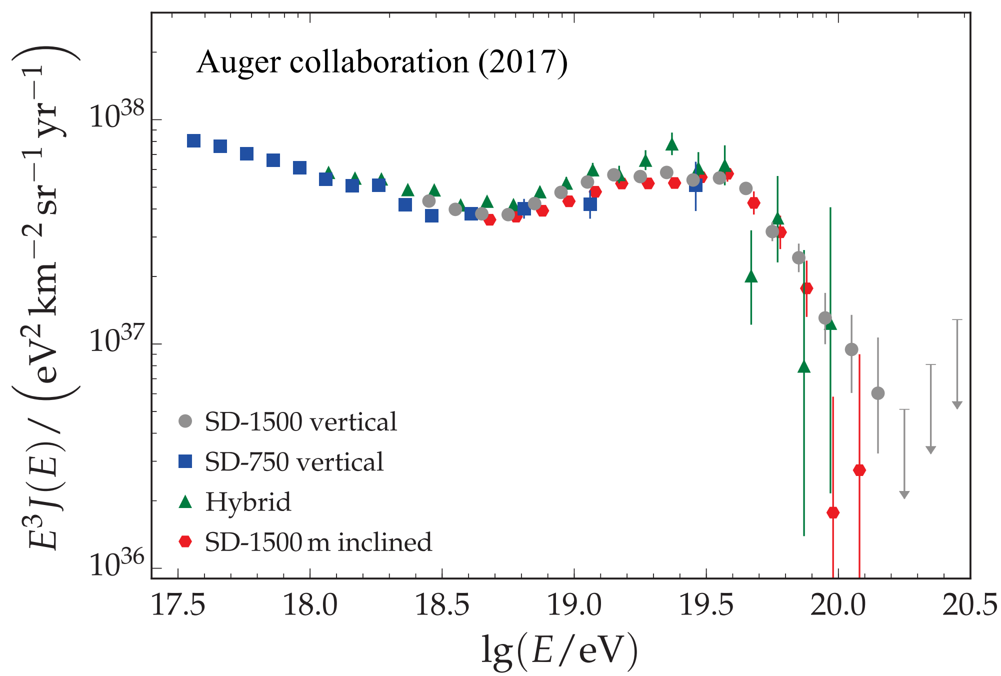
Ultra High Energies Cosmic Rays – Spectrum

As always in Cosmic Rays physics we can study sources and production mechanisms of UHECRs only through three basic observables

- ✓ **Spectrum**
- ✓ **Chemical Composition**
- ✓ **Anisotropy**

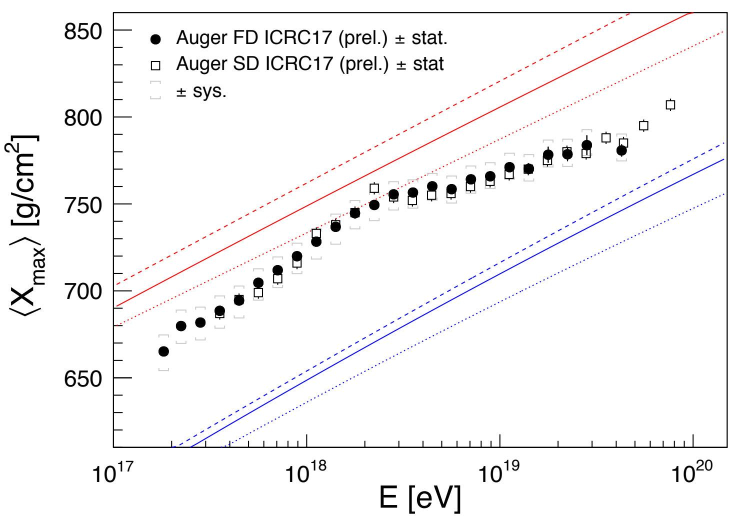


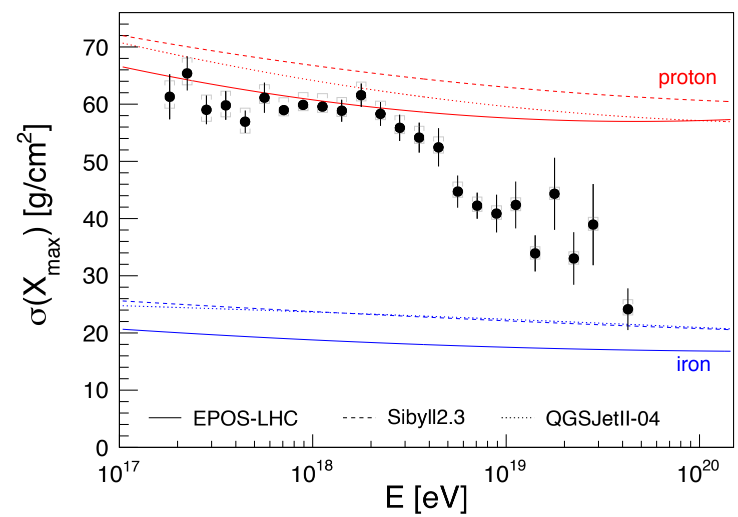




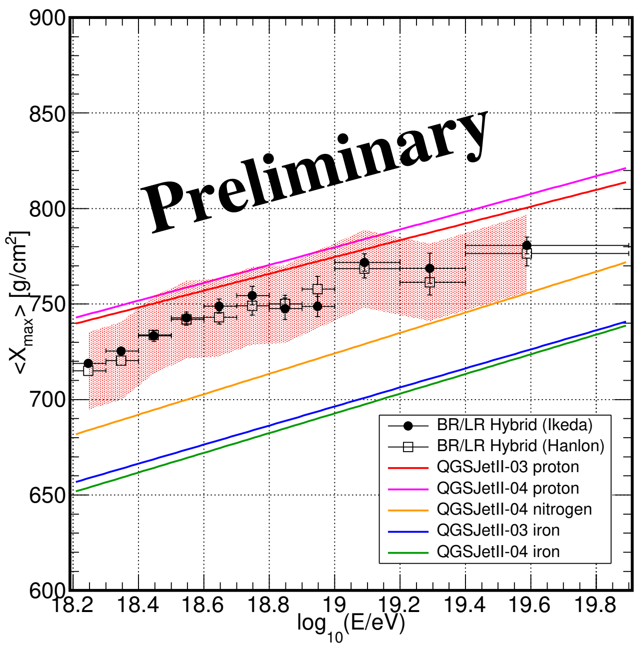
Ultra High Energies Cosmic Rays – Composition

Auger Collaboration (2017)

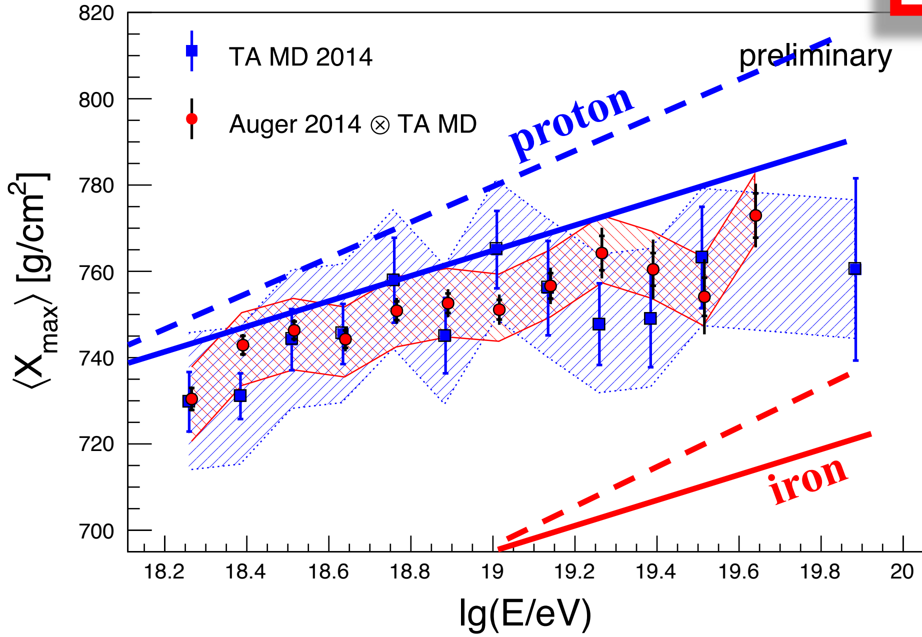




TA Collaboration (2017)



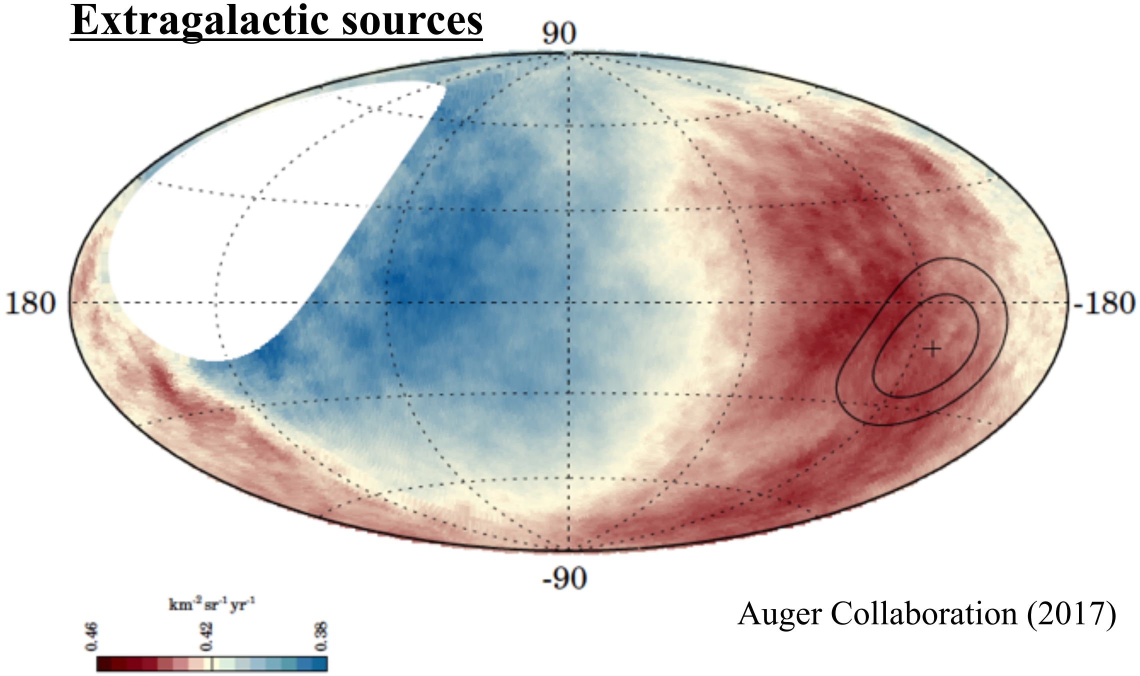
Auger-TA working group (2015)



- ✓ **Auger**: protons at low energy and heavier nuclei at high energy.
- ✓ **TA**: protons only.
- ✓ **Strong uncertainties due to the hadronic interaction model.**

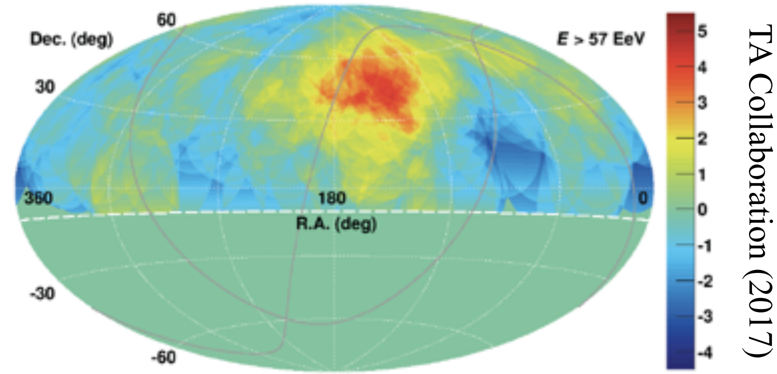
Ultra High Energies Cosmic Rays – Anisotropy

✓ Auger large scale anisotropy: dipole E>8 EeV (5.2σ)
Extragalactic sources



Auger Collaboration (2017)

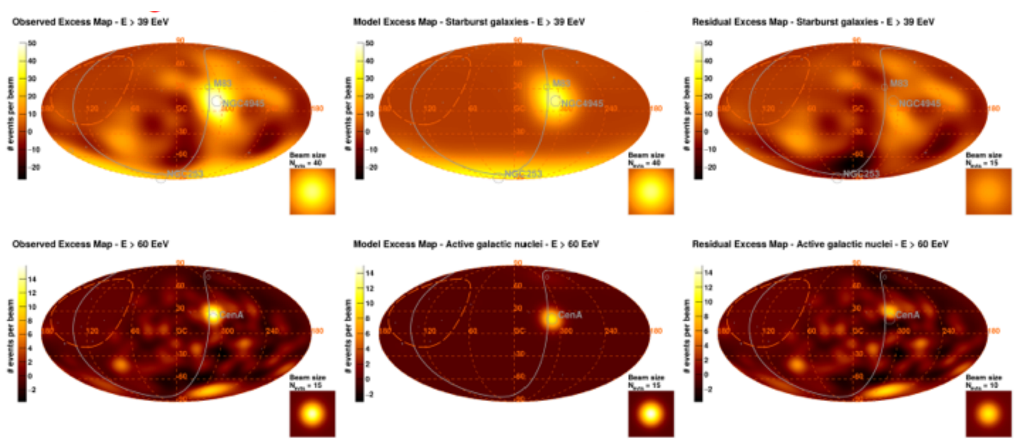
✓ TA: hotspot E>57 EeV (3σ)

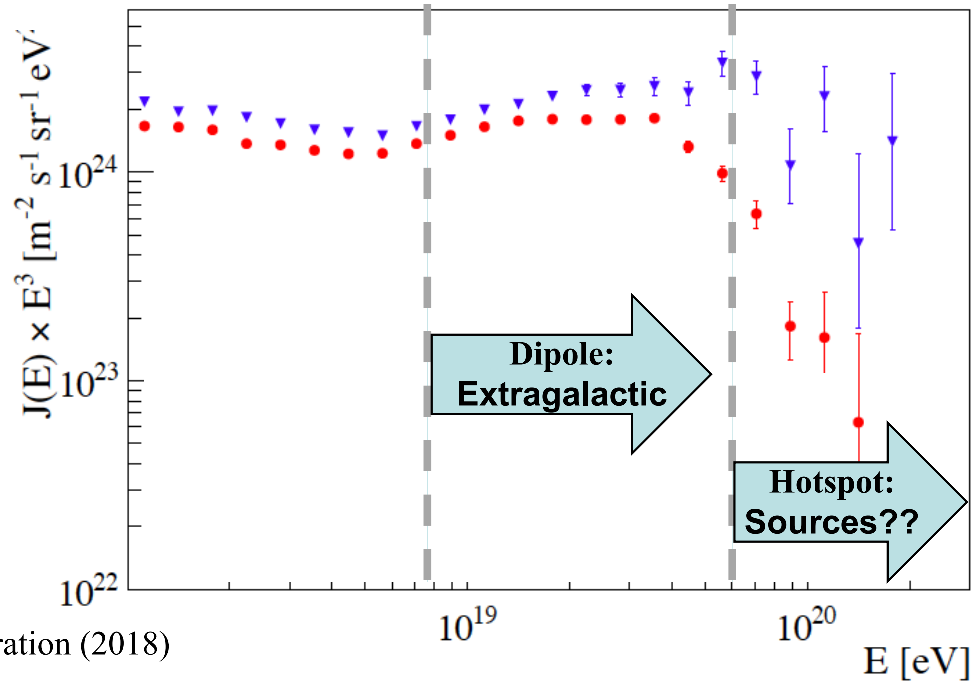


Total events: 143
Observed: 34
Expected : 13.5

Best circle center: RA=144.3°, Dec=+40.3°
Best circle radius: 25°
Local significance : 5 σ
Global significance : 3 σ

✓ Auger: starburst galaxy M83, E>39 EeV (4σ)

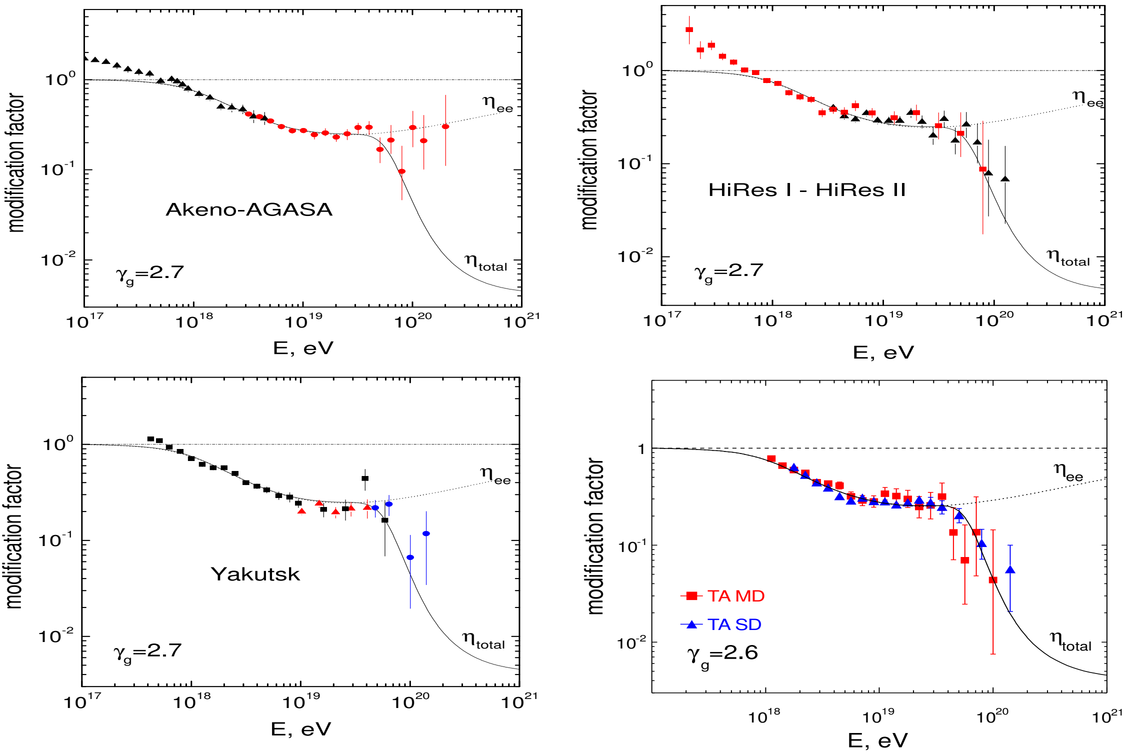




✓ Auger: Centaurus A, E>60 EeV (2.7σ)

Auger Collaboration (2018)

Dip Model

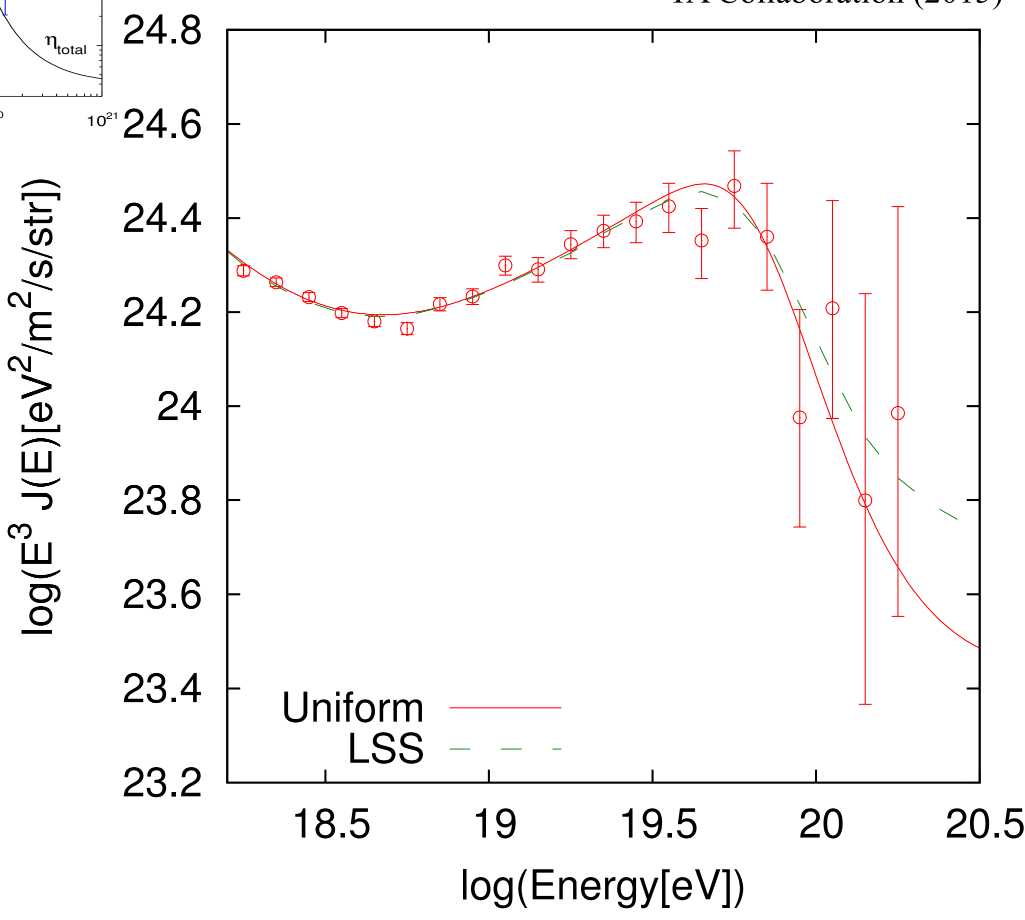


Berezinsky et al (2002-2007)

Protons footprint

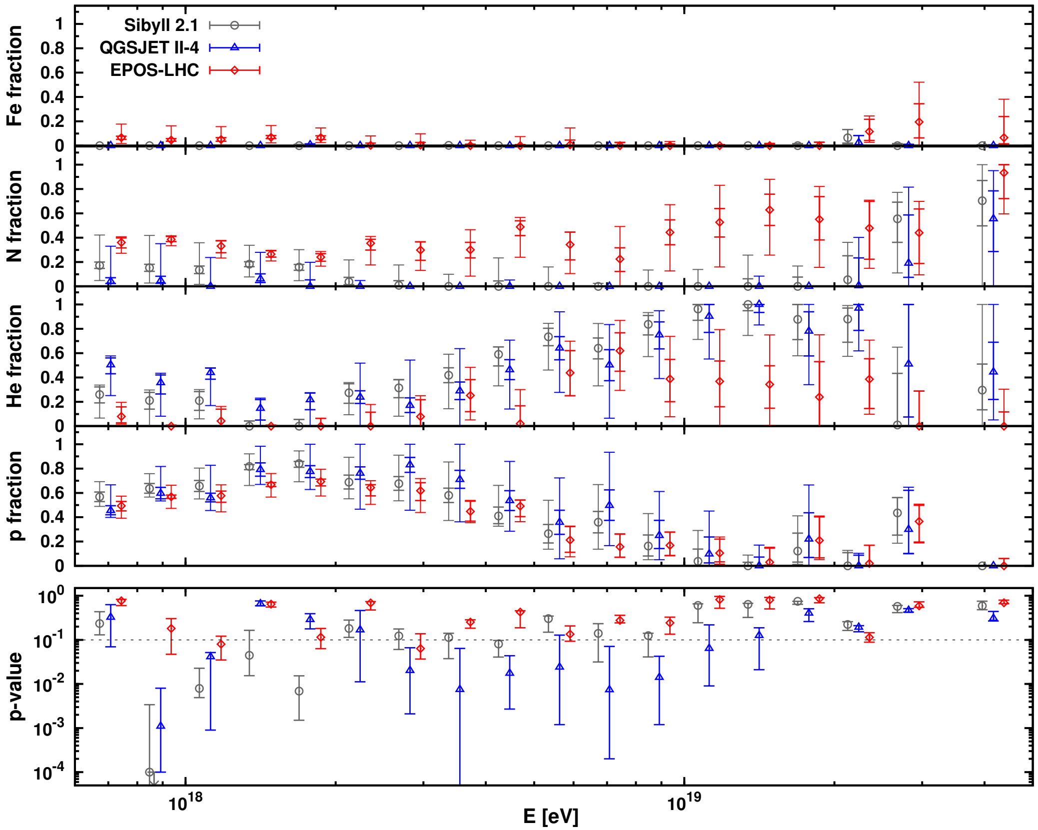
In the energy range 10^{18} - $5\mathrm{x}10^{19}$ eV the spectrum behavior is a signature of the pair production process of UHE protons on the CMB radiation field.

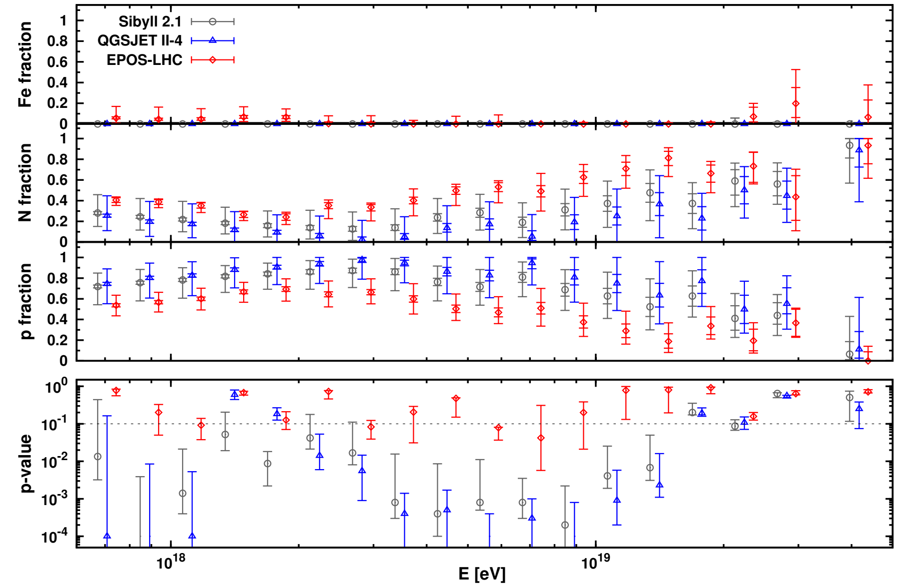
TA Collaboration (2015)



✓ TA surface detector events compared with theoretical expectation of the dip model, with uniformly distributed sources and with sources distributed according to large scale structures (LSS).

Auger Observatory – Composition





Auger Collaboration (2014)

Mixed Composition

Auger Collaboration (2016)

The hybrid events recorded by Auger enable the study of the correlation between depth of shower maximum and number of muons in the cascade. These correlations, in the energy range of the ankle log(E/eV)=18.5 – 19, seem to exclude a light composition made up of protons and helium nuclei.

Auger data at the ankle can be well explained only assuming a mixed composition with nuclei heavier than helium (A>4). **The dip model seems disfavored by this analysis**.

Caveats

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.

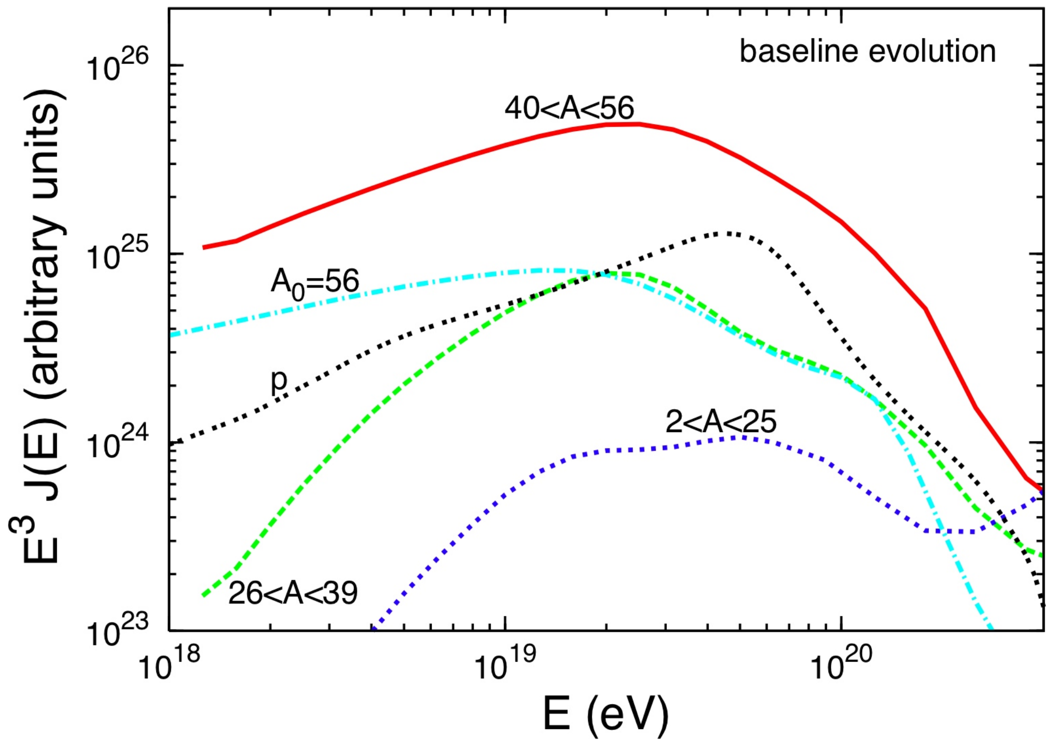
Critical Lorentz factor

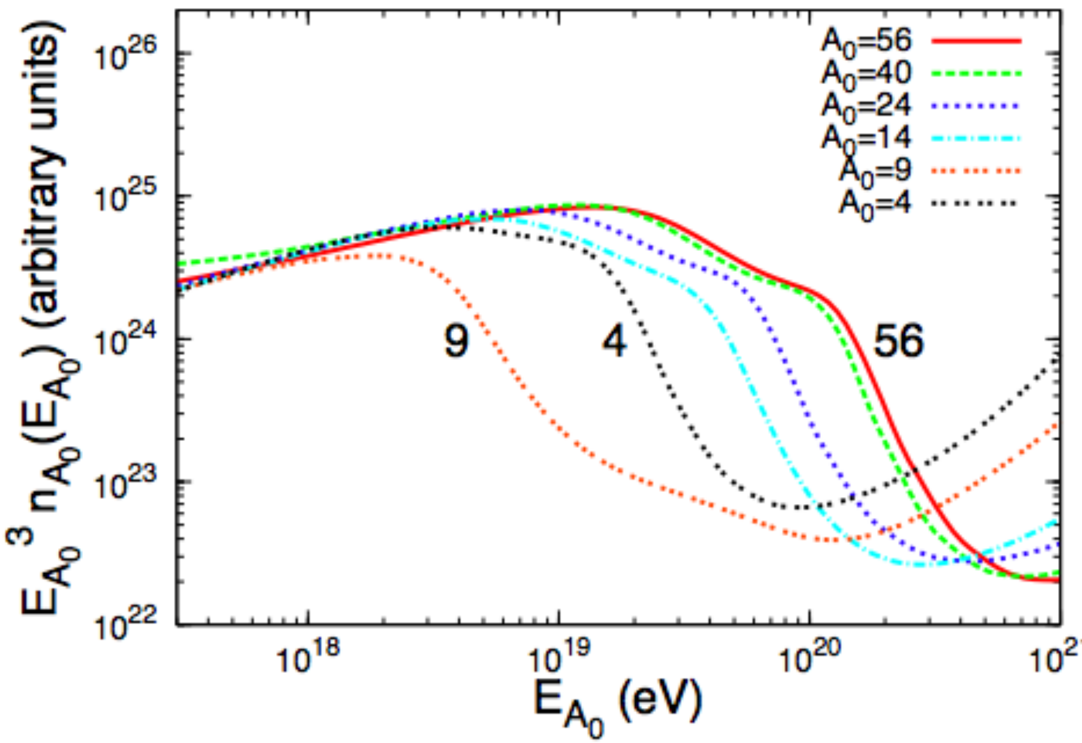
The critical Lorentz factor fixes the scale at which photo-disintegration becomes relevant, for heavy nuclei it is almost independent of the nuclei specie

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

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

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





RA, Berezinsky, Grigorieva (2009-2013)

Interaction vs maximum energy

The highest energy behavior of the fluxes is dominated by particles interaction with backgrounds (nuclei photo-disintegration or protons photo-pion) depending on the maximum acceleration energy at the sources.

✓ **Protons**

$$E^p_{max} > E_{GZK} \simeq 10^{20} eV$$

✓ **Nuclei**

$$E_{max}(A) = Z E^p_{max}$$

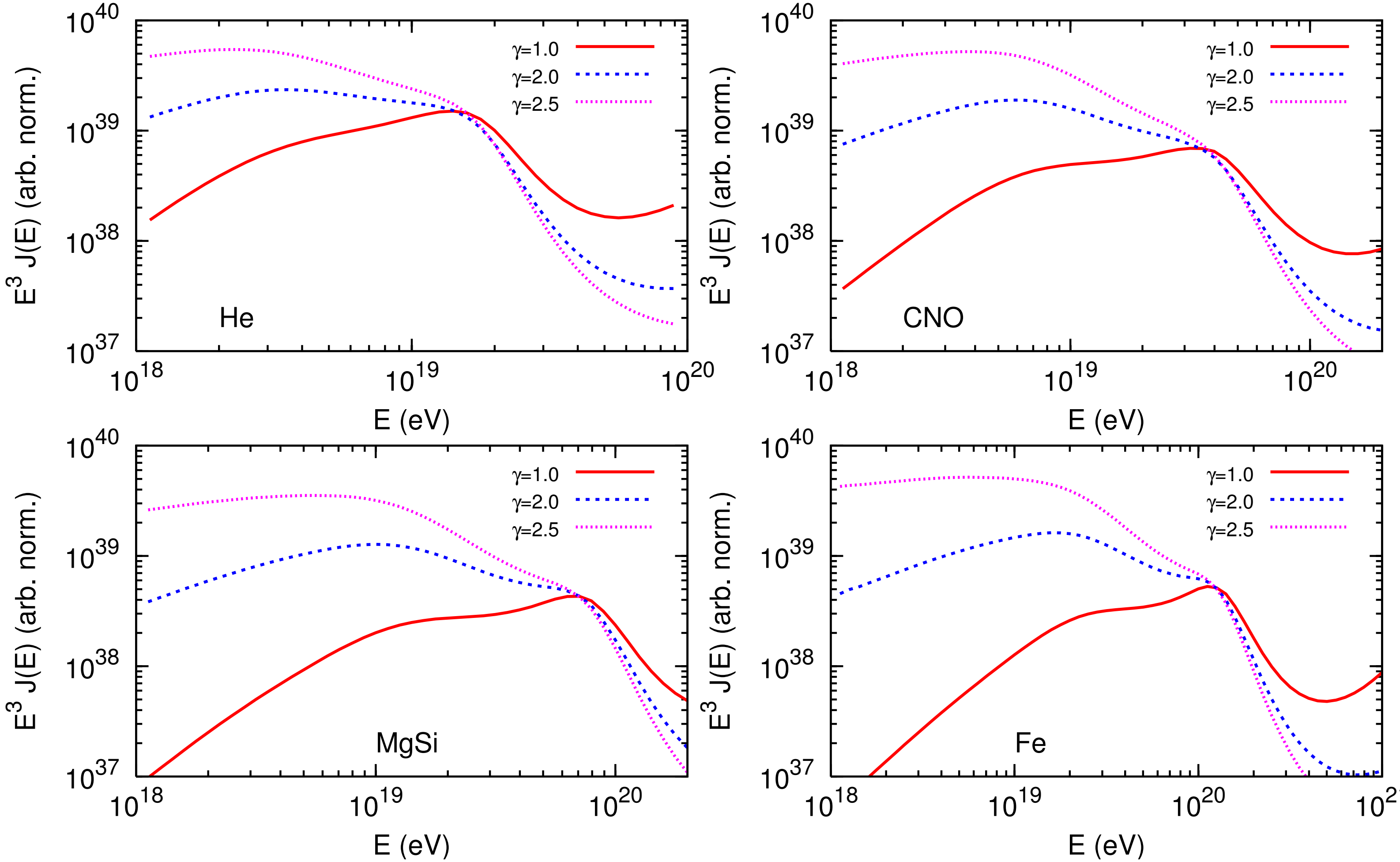
$$E_{max}(A) > E_{cut}(A)$$

$$E^p_{max} > \frac{A}{Z} m_N \Gamma_c \simeq 4 \times 10^{18} eV$$

✓ Only under these conditions the high energy flux is shaped by the protons photo-pion production process (GZK) or by the nuclei photo-disintegration process.

Injection of nuclei flat vs steep

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



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

Astrophysical sources

✓ **Hillas criterion**: fixes a relation between size and magnetic field of the acceleration site.

$$r_L(E) < R \qquad R > 0.1pc \left(\frac{E}{10^{20}\ eV}\right)\left(\frac{B}{1\ G}\right)^{-1}$$

✓ The Hillas criterion can be refined in terms of a lower limit on the required luminosity. Taking into account a moving source (as for shocks) the total ram pressure should be larger than the magnetic field energy density:

$$\epsilon_B = \frac{B^2}{4\pi} < \rho V^2 \qquad L = 4\pi R^2 V \frac{\rho V^2}{2} > 2\pi R^2 V \epsilon_B$$

- non-relativistic moving source

$$L > 3\times 10^{45}\frac{\beta}{Z^2}\left(\frac{E}{10^{20} eV}\right)^2 \frac{\text{erg}}{s}$$

- relativistic moving source

$$L > 4\pi R^2 c\Gamma^2 \epsilon_{B'} \simeq 10^{47}\frac{\Gamma^2}{Z^2}\left(\frac{E}{10^{20} eV}\right)^2 \frac{\text{erg}}{s}$$

✓ The observed UHECR flux fixes the scale of the source emissivity needed

$$J(E) \simeq \frac{c}{4\pi} Q(E)\tau_{loss}(E) \qquad \mathcal{L} = O(10^{45})\frac{\text{erg}}{\text{Mpc}^3\ \text{yr}}$$

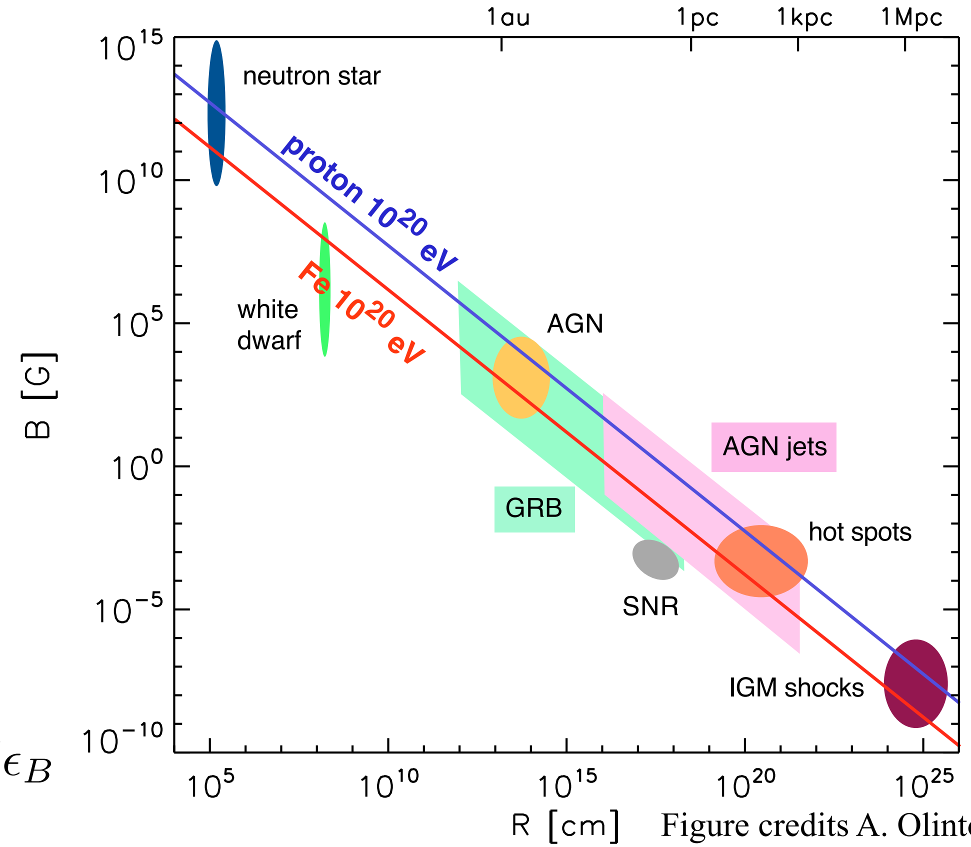
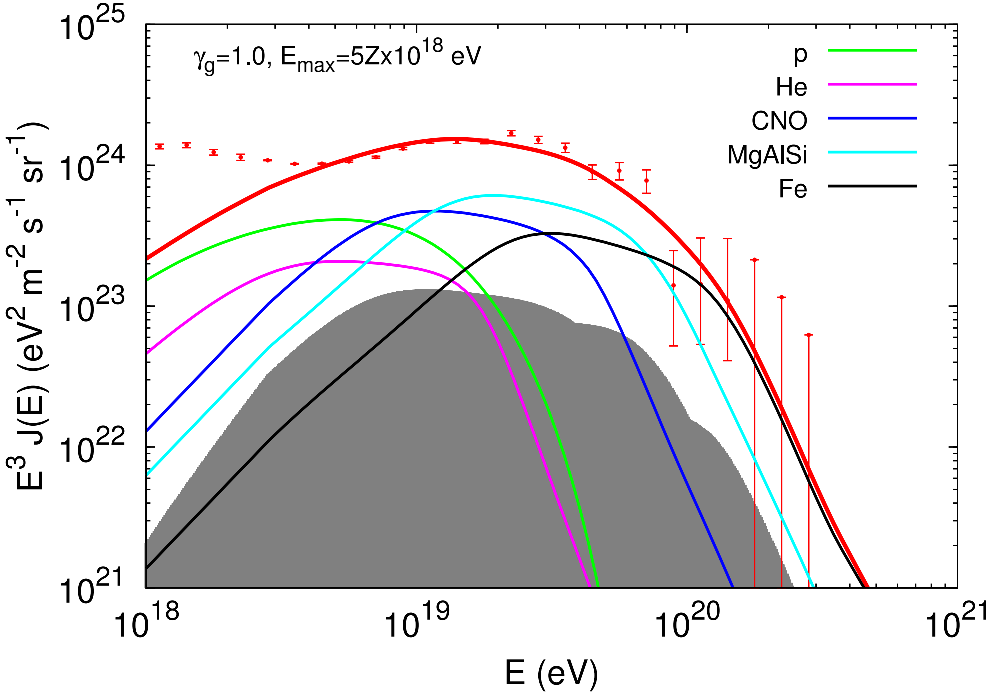


Figure credits A. Olinto

With typical bolometric luminosities and number densities in the range of **10^{43} – 10^{47} erg/s** and **10^{-5} – 10^{-4} Mpc^{-3}**, AGNs would meet the energetic requirements to produce UHECR if a fraction around 10^{-4} – 10^{-3} of their bolometric luminosity is converted into UHECR.

What we can learn from Auger data

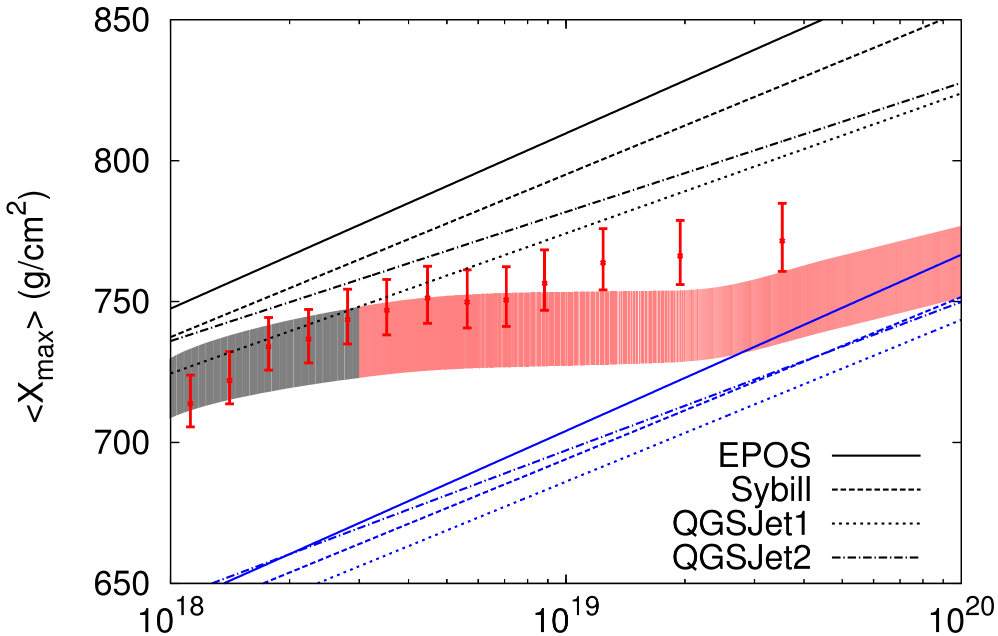


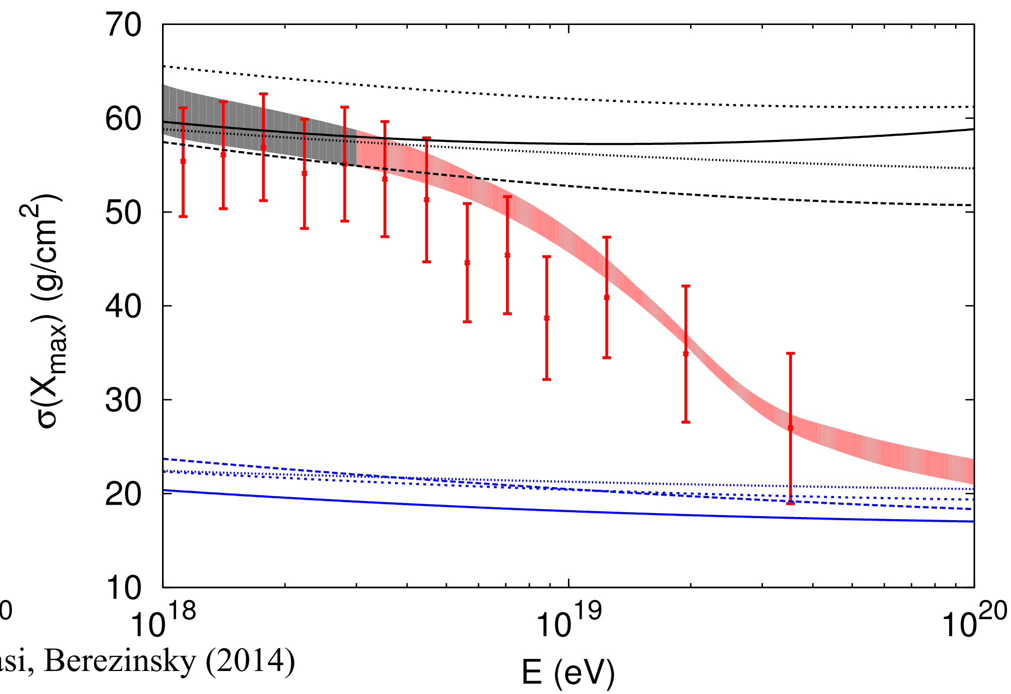
Auger chemical composition can be reproduced only assuming a very flat injection of primary nuclei

$$\gamma_g = 1.0 \div 1.5$$

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

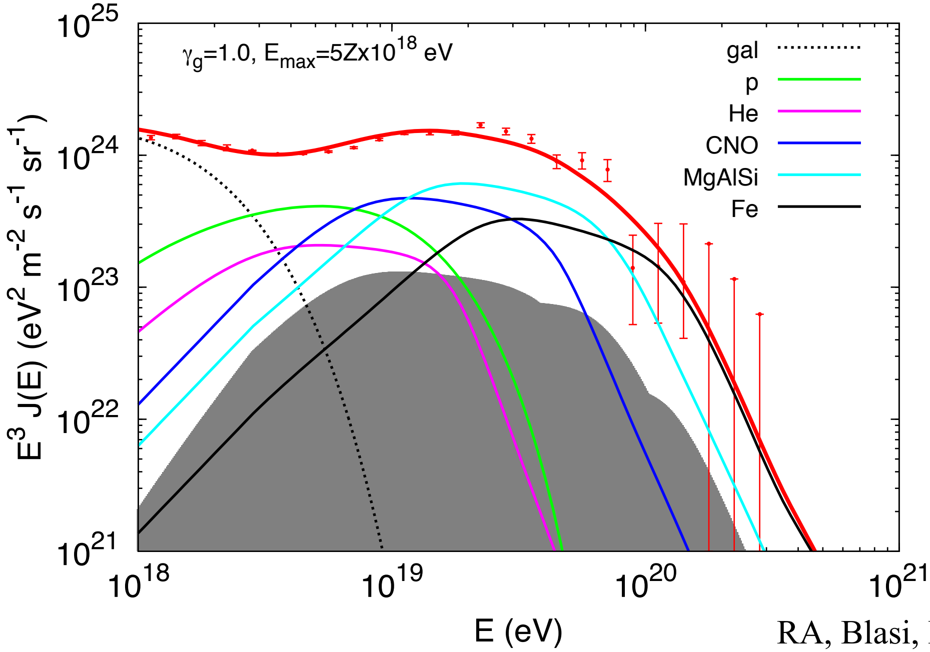
with a certain level of degeneracy in terms of the nuclei species injected





RA, Blasi, Berezinsky (2014)

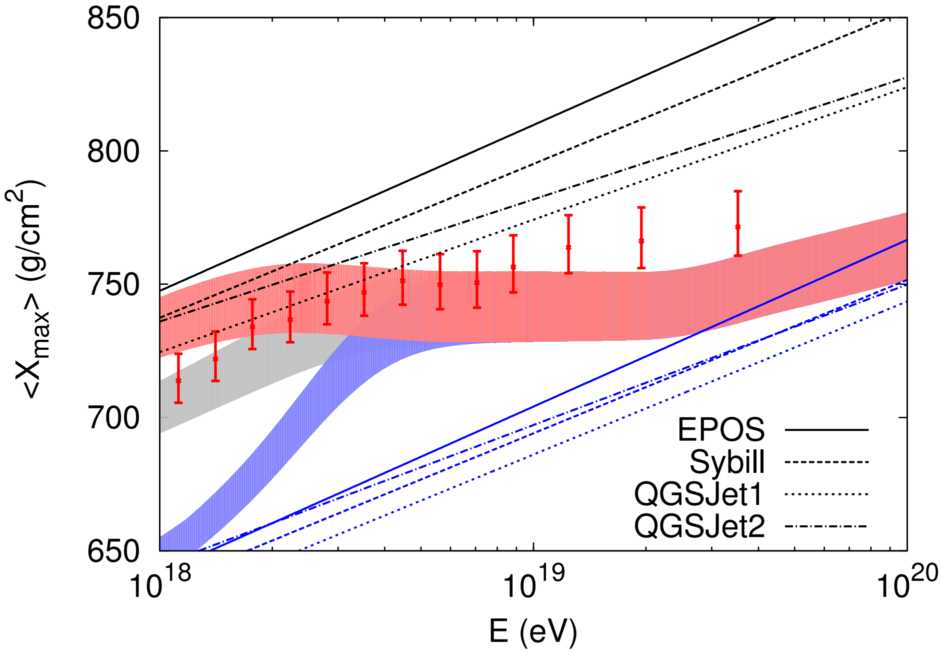
Extra Galactic Nuclei and Galactic light elements

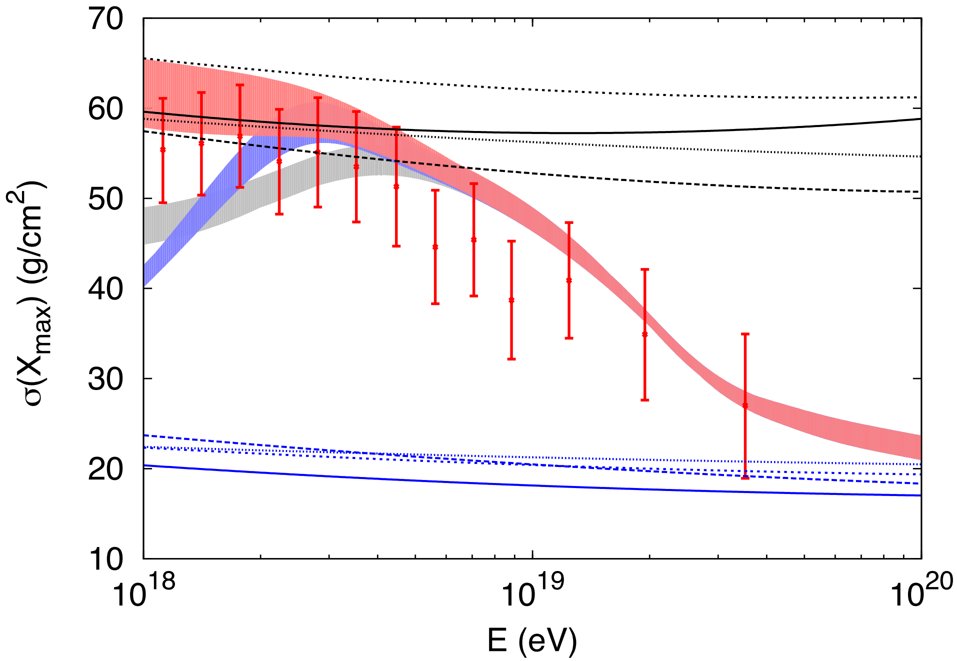


An additional galactic component can fill the gap in the spectrum.

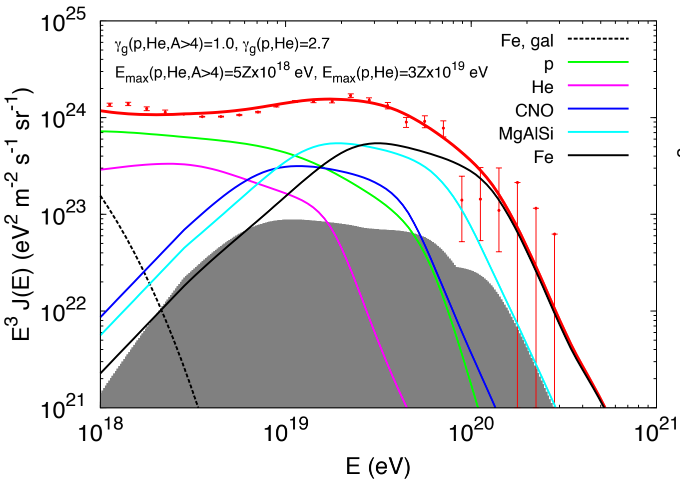
Composition issue. Mixture of 80% p and 20% He to reproduce Auger observations. Difficult to reconcile with galactic CR physics and anisotropy observations.

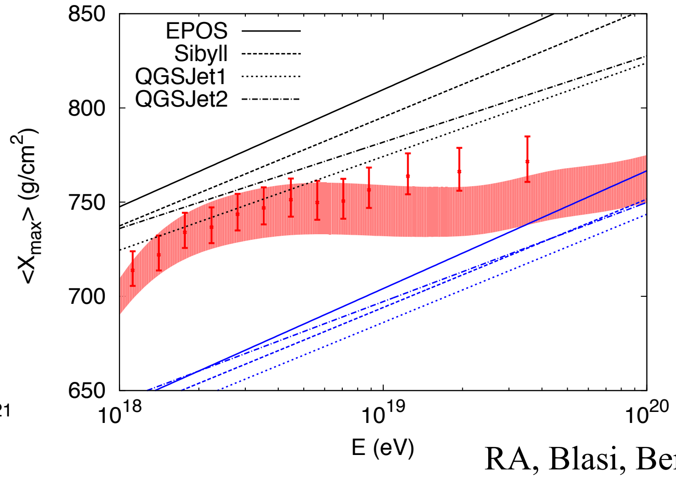
RA, Blasi, Berezinsky (2014)

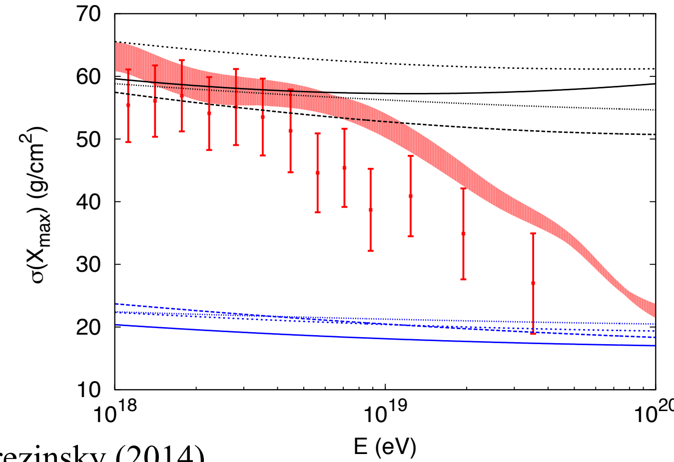




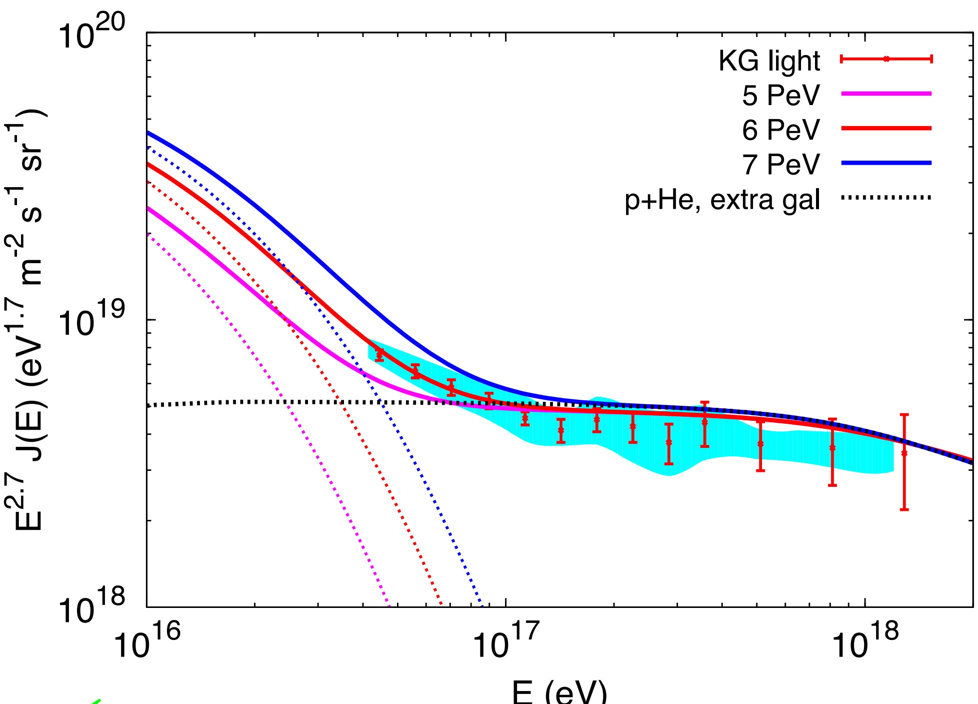
Different Classes of Extra Galactic Sources







RA, Blasi, Berezinsky (2014)



✓ light component steep injection ($\gamma_g>2.5$)

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

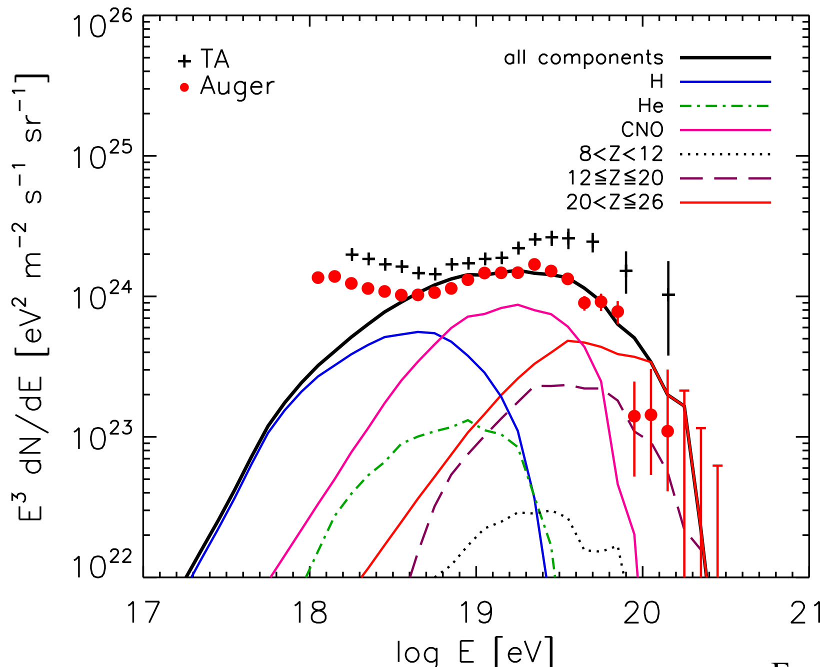
✓ heavy component flat injection ($\gamma_g<1.5$)

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

✓ **active galactic nuclei** can easily provide steep injection and the correct emissivity.

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

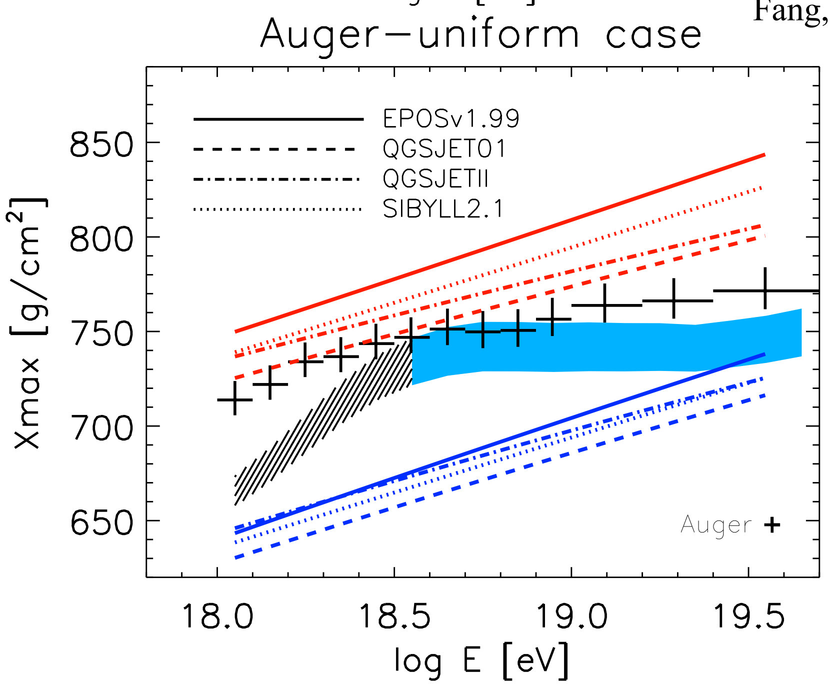
Pulsars, Extra Galactic and Galactic

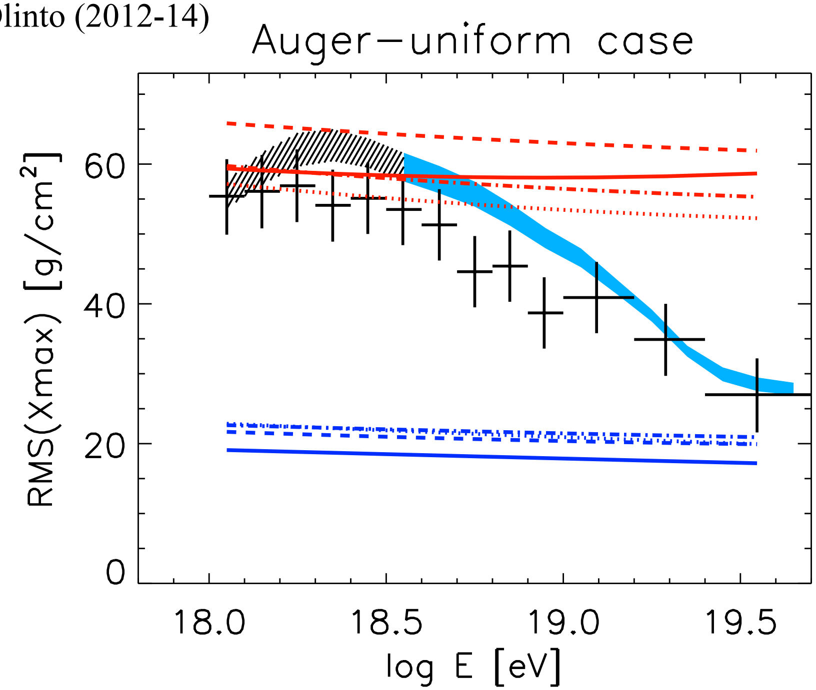


✔ Extragalactic pulsars with flat injection provide the observed spectrum and mass composition at energies > 3 EeV. A flat component from galactic pulsars fills the gap.

✔ <u>Problems</u> with chemical composition and anisotropy of the galactic pulsars contribution.

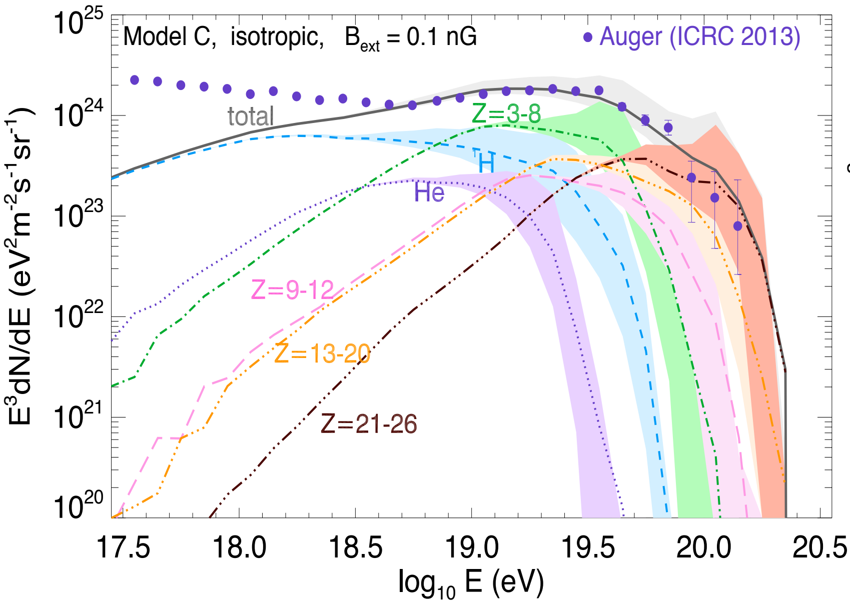
Fang, Kotera, Olinto (2012-14)

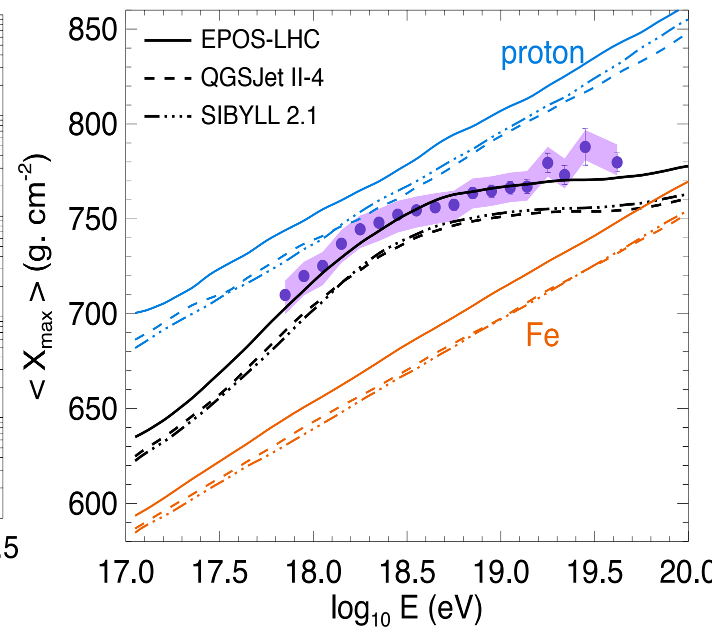




Specific dynamic at the sources

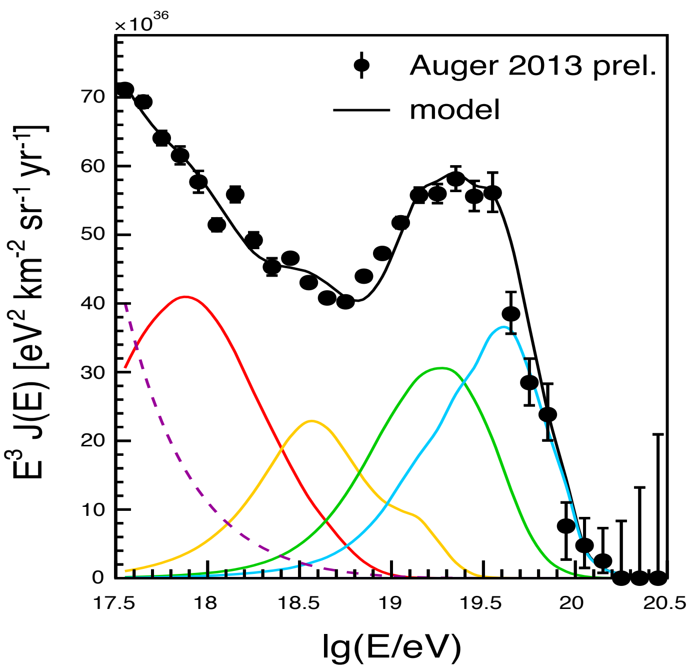
Globus, Allard, Parizot (2014-2015)

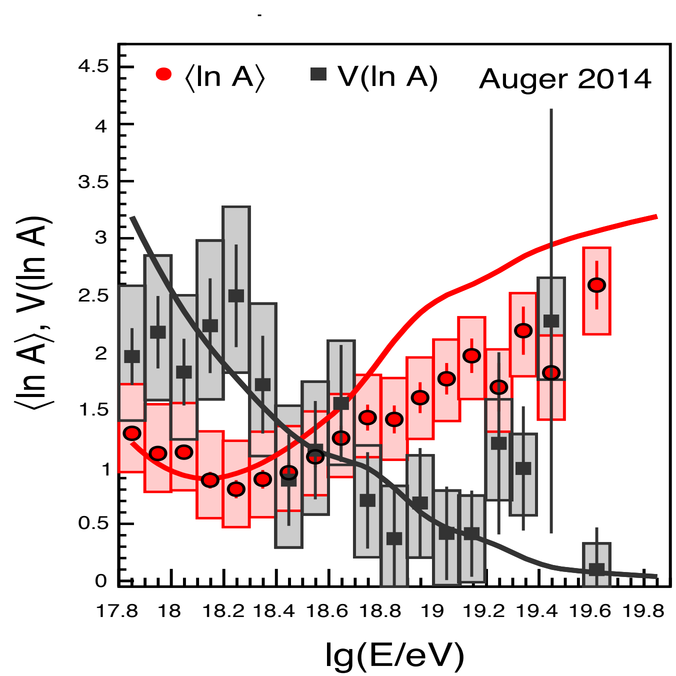




- ✓ Single class of EG sources: Mildly relativistic shocks in GRBs.
- ✓ <u>Problem</u> with Galactic CR maximum energy larger than 10^{16} eV

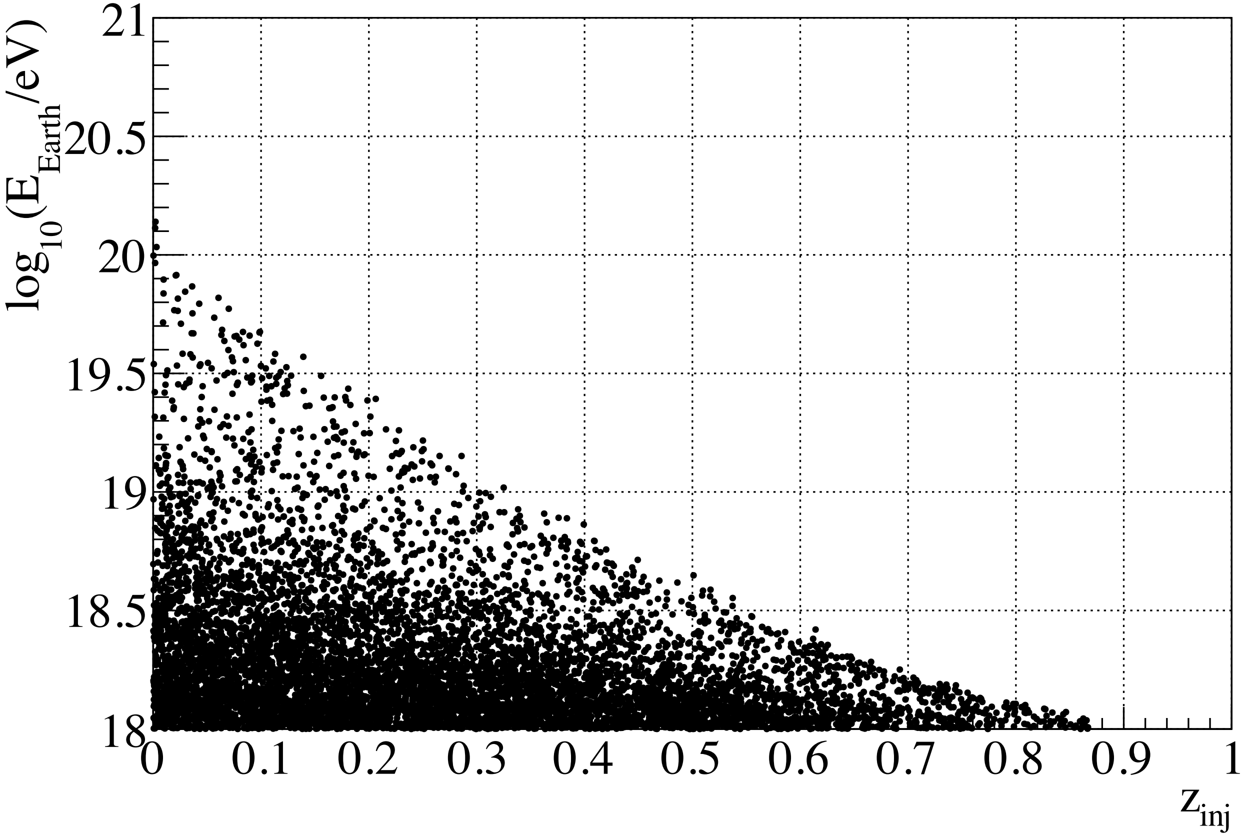
Unger, Farrar, Anchordoqui (2015)





- ✓ Photodisintegration at the source. Flat injection for nuclei ($\gamma \approx 1$) and steep for protons ($\gamma > 2$).
- ✓ Agreement with Kascade-Grande.

Looking farther away



- ✓ The universe accessible in UHECRs (protons or nuclei) is not larger than redshift z~1.

$$p\gamma \to \pi^{\pm} \to e^{\pm}, \nu$$

- ✓ Only the observation of secondary cosmogenic neutrinos can open up the far away universe (until the first stars redshift z~10) in the UHE window.

- ✓ Photo-hadronic interactions are less efficient in the case of nucleons bounded inside nuclei. The production of secondary cosmogenic neutrinos and gamma rays strongly tied to the UHECR mass composition.

Dip model – ν spectra

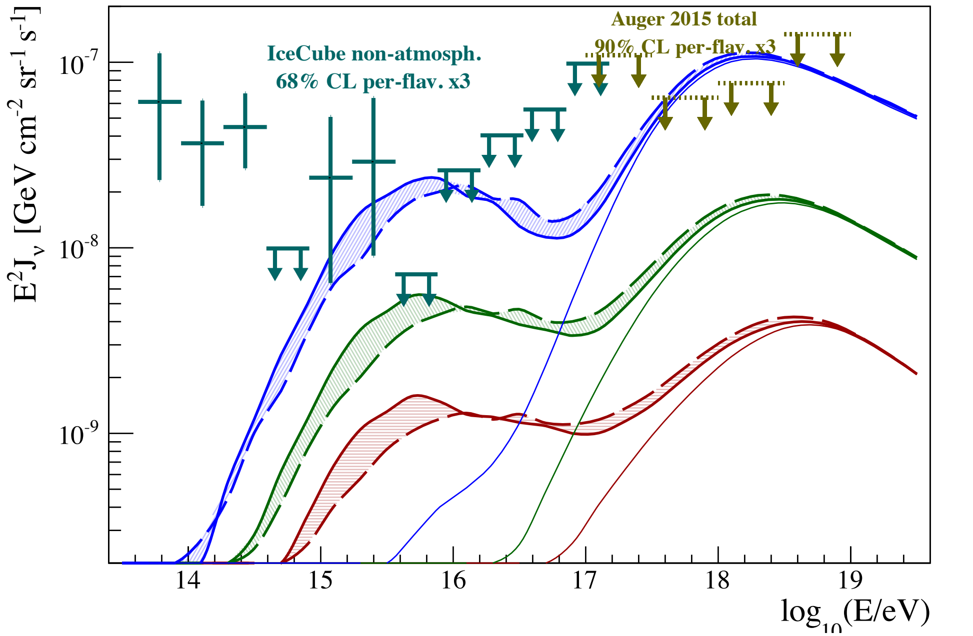
✓ Photo-pion production

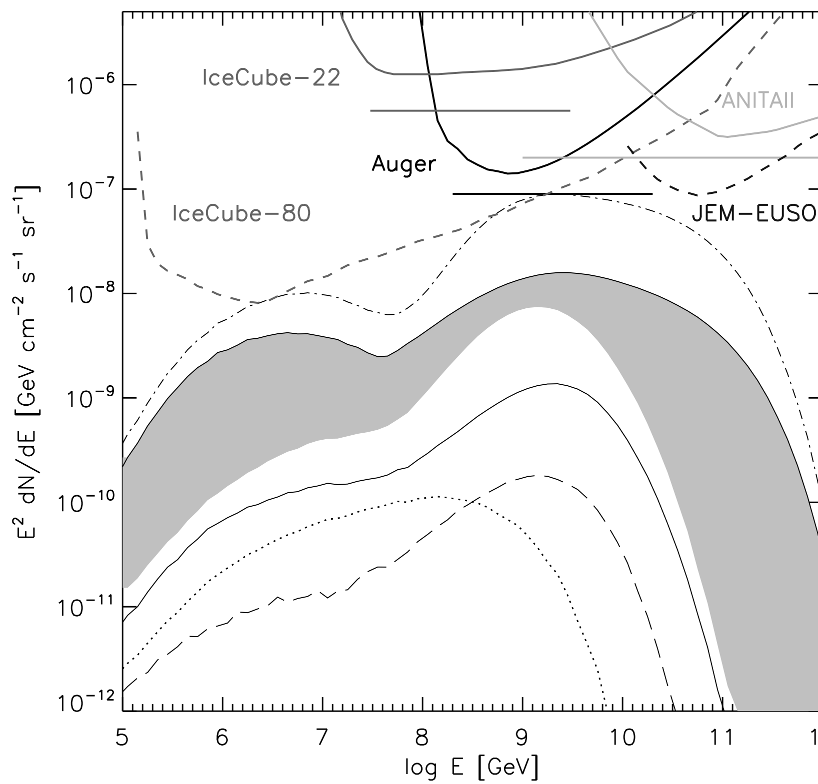
On EBL has a threshold of about 10^8 GeV, broadened by the energy distribution of EBL photons. The pion production by UHE protons on the EBL can account for the production of PeV neutrinos.

✓ Cosmological evolution

The result on the diffuse flux depends on the cosmological evolution assumed for the sources. The IceCube observations at PeV can be reproduced in the case of strong cosmological evolution (AGN like).

RA, Boncioli, di Matteo, Grillo, Petrera, Salamida (2015)

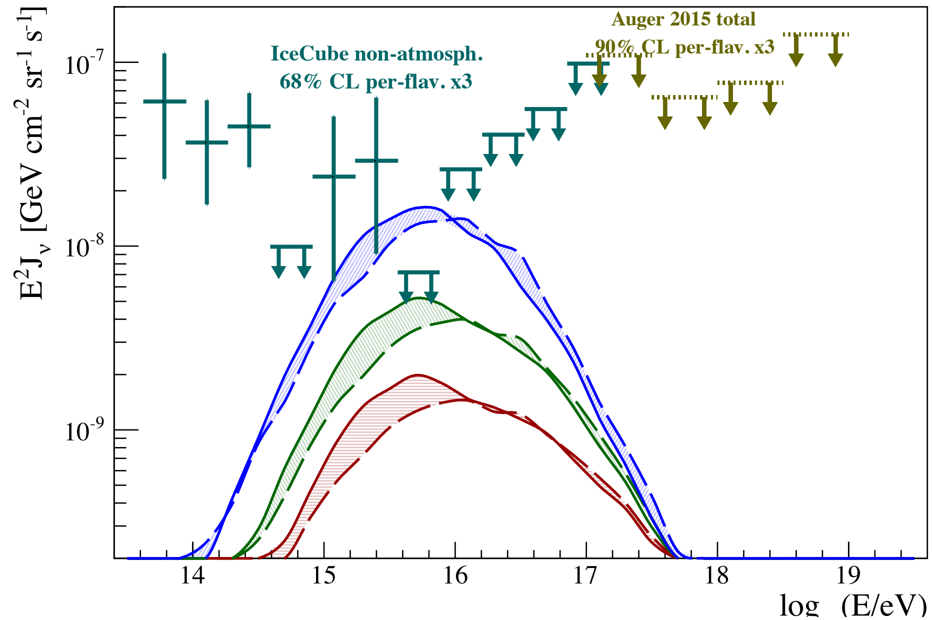




Kotera, Allard, Olinto (2011)

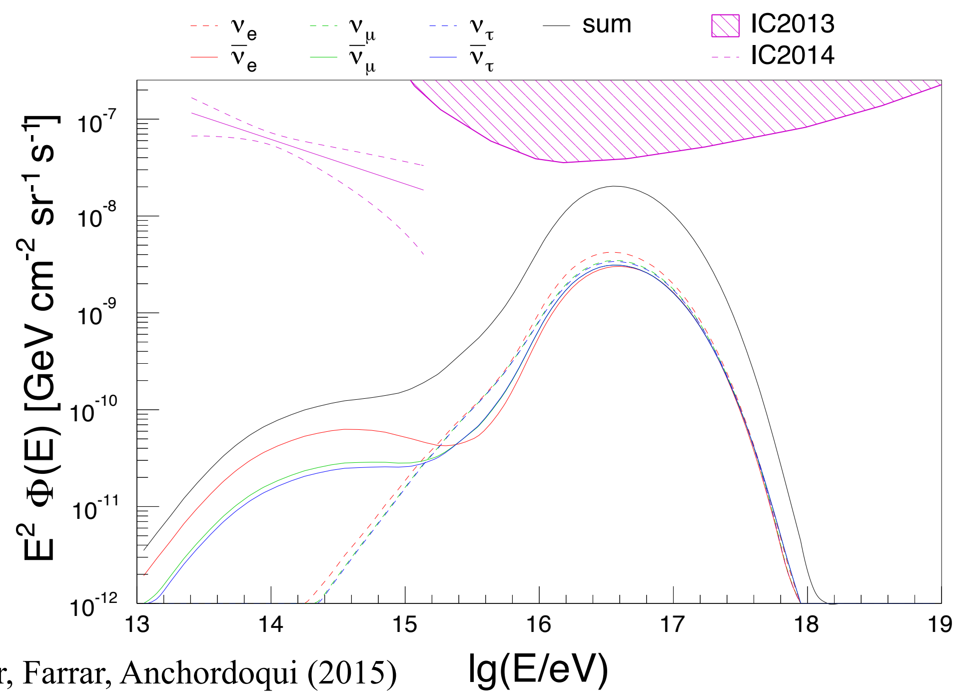
Mixed composition model – ν spectra

RA, Boncioli, di Matteo, Grillo, Petrera, Salamida (2015)



✓ EeV neutrinos

UHE nuclei suffer photo-pion production on CMB only for energies above AE_{GZK}. The production of EeV neutrinos strongly depends on the nuclei maximum energy. UHE neutrino production by nuclei practically disappears in models with maximum nuclei acceleration energy $E_{max} < 10^{21}$ eV.



✓ PeV neutrinos

PeV neutrinos produced in the photo-pion production process of UHECR on the EBL radiation field The IceCube observations at PeV can be marginally reproduced in the case of strong cosmological evolution (AGN like).

Unger, Farrar, Anchordoqui (2015)

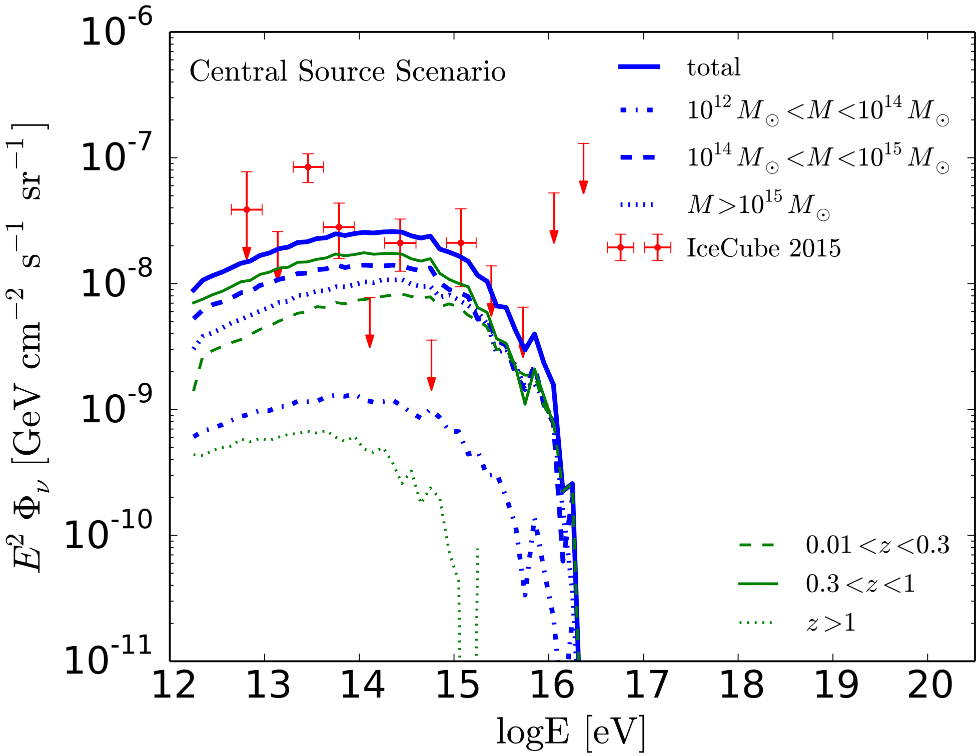
Clusters of Galaxies and PeV ν

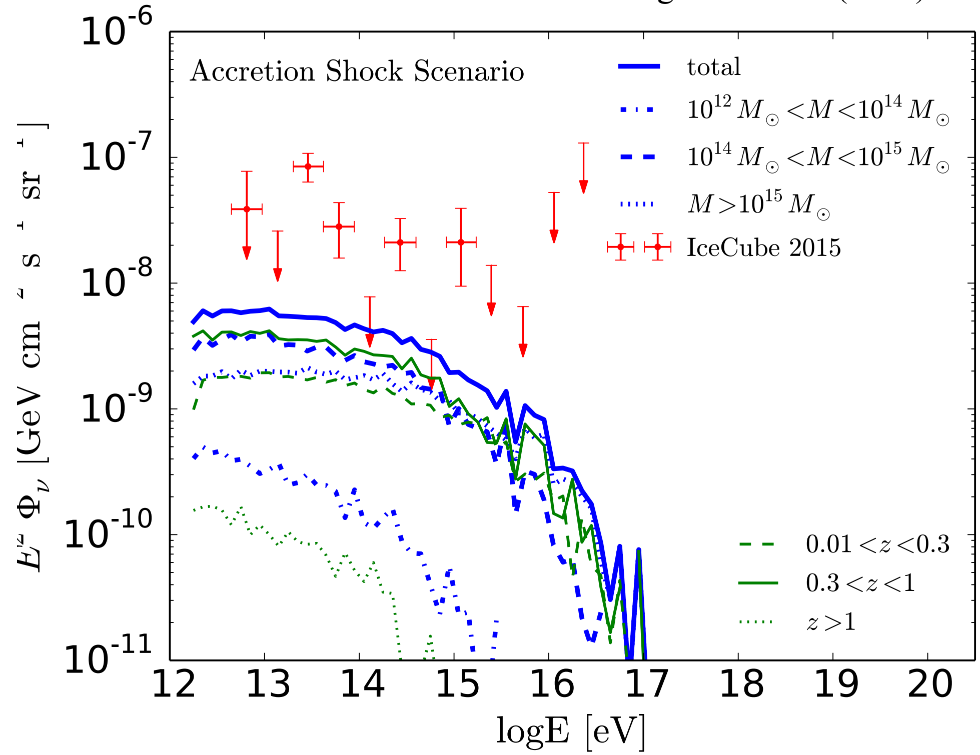
Berezinsky, Blasi and Ptuskin (1998)

- ✓ Because of their magnetic fields (at several μG level) clusters of galaxies are "storage rooms" for cosmic rays till energies $\sim 10^6 \div 10^8$ GeV, depending on the magnetic field turbulence.

- ✓ Depending on the CR acceleration mechanism inside clusters, pp and pγ interactions can account for the observed IceCube neutrino flux at energies larger than 10^{12} eV.

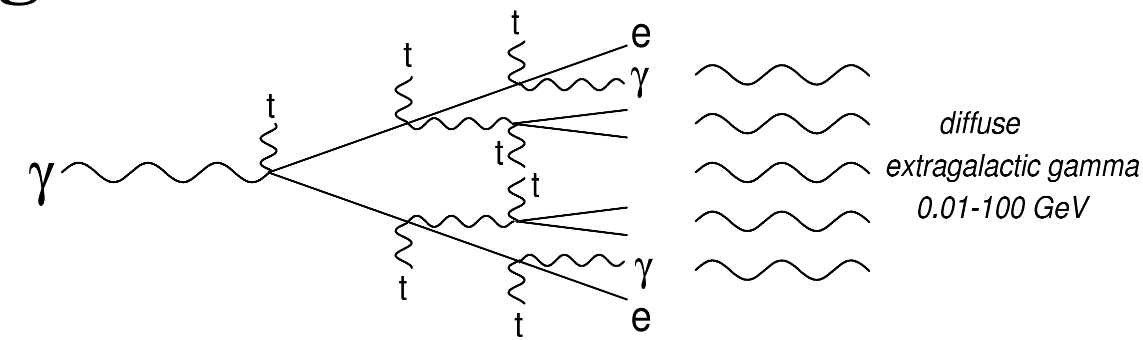
Fang and Olinto (2016)





Diffuse γ ray background

Cascade upper limit

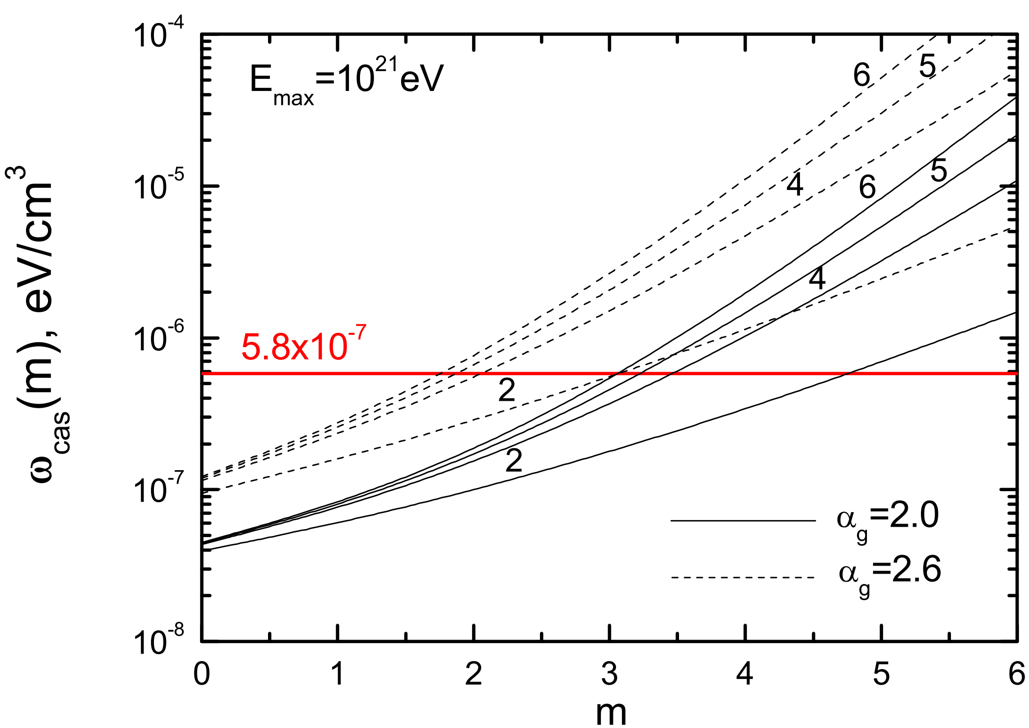


$$p\gamma \to e^{\pm}$$
$$p\gamma \to \pi^0 \to \gamma$$
$$p\gamma \to \pi^{\pm} \to e^{\pm}, \nu$$

Fermi-LAT data

$\omega_{cas} = 5.8\text{x}10^{-7}$ eV/cm^3

$$\omega_{cas}^{max} > \omega_{cas}^{\pi} > \frac{4\pi}{c}\int_E^\infty E' J_\nu(E')dE' > \frac{4\pi}{c} E_\nu J_\nu(> E)$$



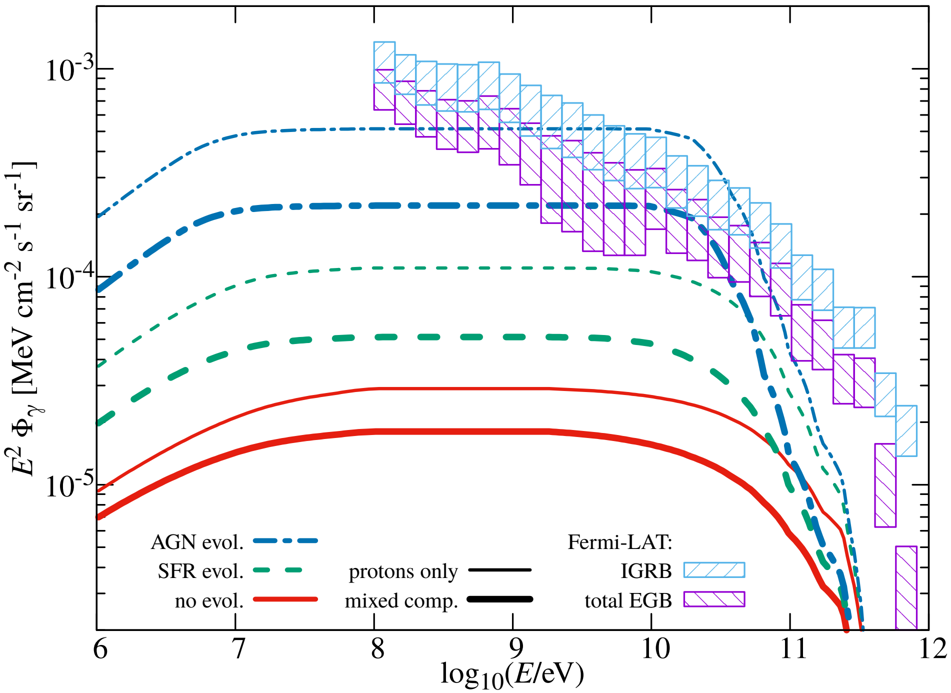
Berezinsky, Gazizov, Kachelriess, Ostapchenko (2011)

The cascade limit can be expressed in terms of the energy densities of photons and e^+e^- initiated cascades

$$E^2 J_\nu(E) \le \frac{c}{4\pi}\frac{\omega_{cas}^{max}}{\ln(E_{max}/E_{min})}\frac{1}{1+\omega_{cas}^{e^+e^-}/\omega_{cas}^{\pi}}$$

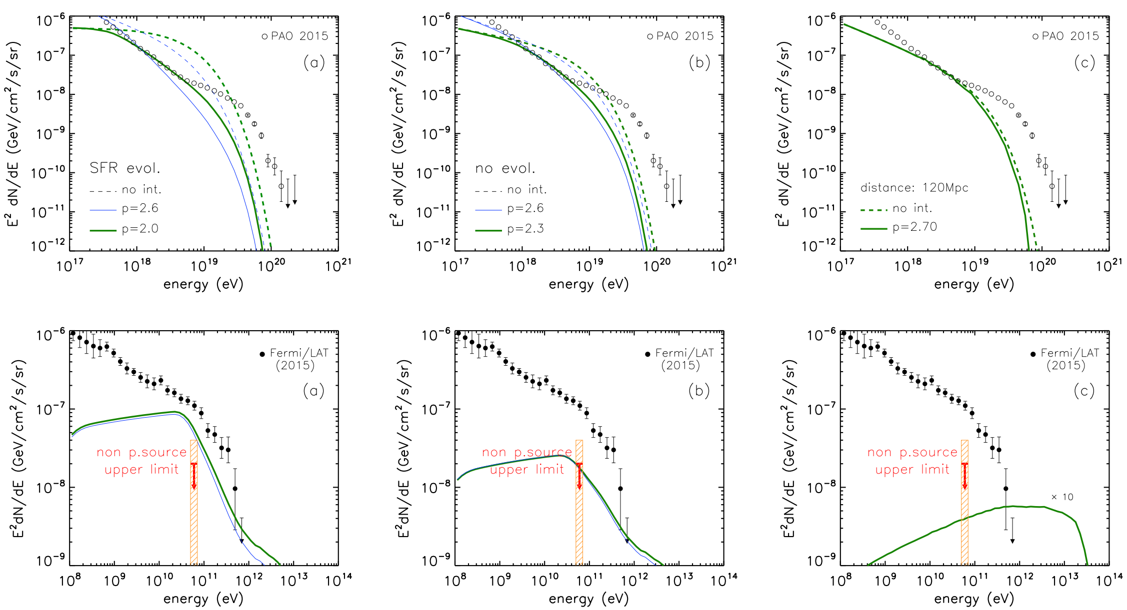
The cascade upper limit constrains the source parameters: cosmological evolution, injection power law and maximum acceleration energy.

$$Q(E) = Q_0(1+z)^m \left(\frac{E}{E_0}\right)^{\alpha_g} e^{-E/E_{max}}$$

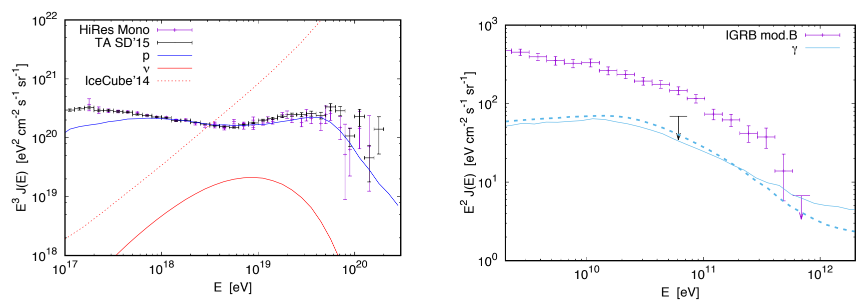


RA, Boncioli, di Matteo, Grillo, Petrera, Salamida (2017)

- ✓ Diffuse extragalactic gamma-ray flux at E ~ 1 TeV is a very powerful observable to constrain the fraction of protons in the UHECR spectrum.
- ✓ With the available statistics, given the poor knowledge of the galactic diffuse foregrounds and EBL, it is impossible to exclude a pure proton composition at (1 − 40) EeV.
- ✓ The observation of the diffuse extra-galactic gamma-ray background will be one of the important tasks for the future CTA observatory.



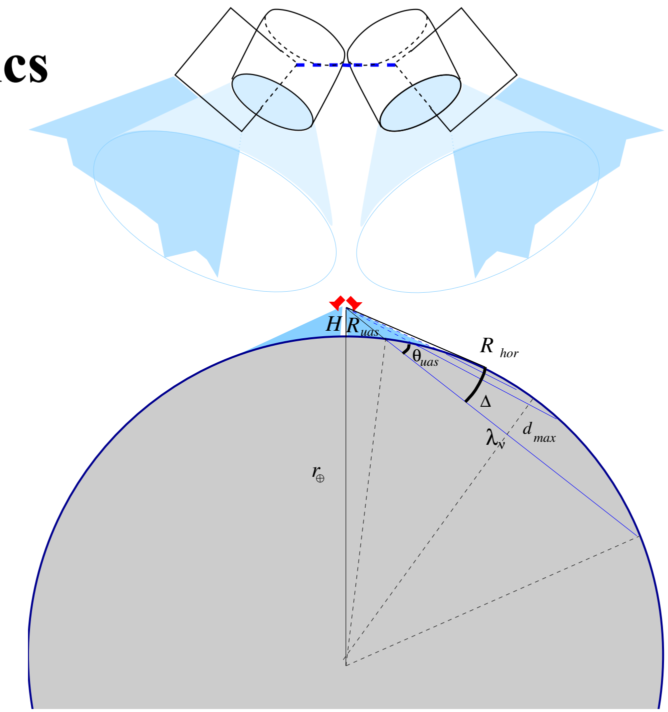
Liu, Taylor, Wang, Aharonian (2016)



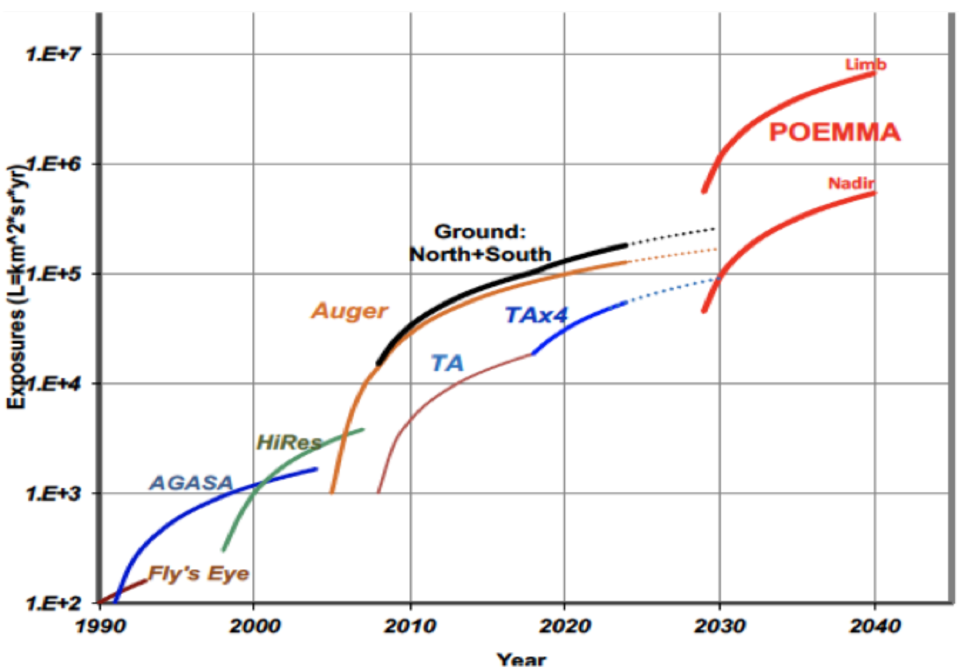
Berezinsky, Gazizov, Kalashev (2016)

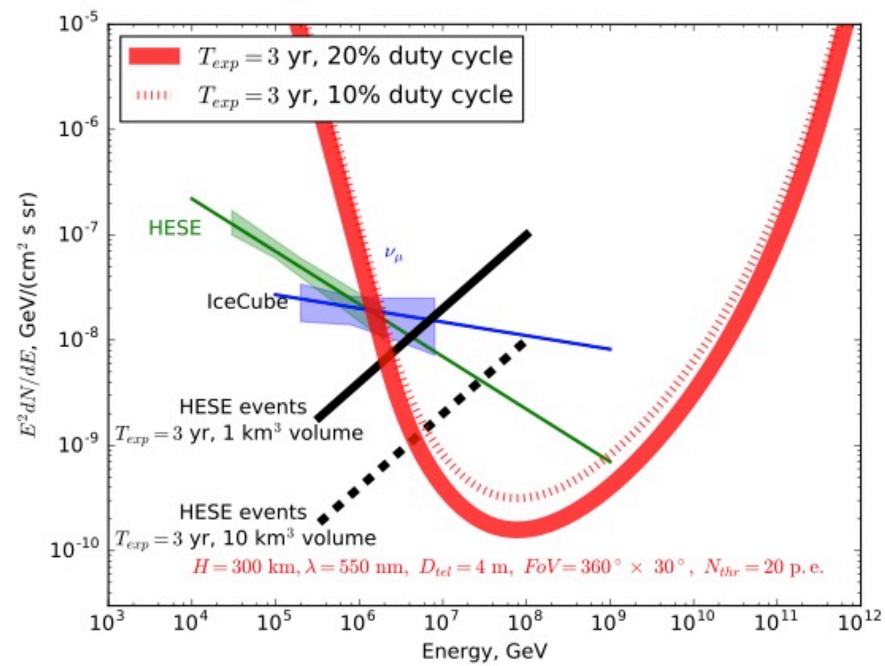
Astrophysical ν and UHECR from space

Probe of Extreme Multi-Messenger Astrophysics (POEMMA proposal)



- ✓ The observation of astrophysical neutrinos at energies E > few PeV can be achieved only from space.
- ✓ Only the observation of cosmogenic neutrinos (with E> PeV) can open up the far away universe in the UHE window (until the first stars redshift z~10).
- ✓ At the highest energies (E> 50 EeV), the required statistics to point back UHECR sources can be achieved only from space.





Conclusions

✓ UHECR Astrophysical models

A pure proton composition (dip model) seems strongly disfavored by Auger while still possible according to TA data:

- ✓ Steep injection ($\gamma_g > 2.5$). High maximum acceleration energies ($\sim 10^{20}$ eV).
- ✓ AGNs are strong candidate as UHECR source.
- ✓ Huge production of cosmogenic neutrinos and gamma rays.

Mixed composition, with nuclei heavier than He, imply a rich phenomenology:

- ✓ Flat injection ($\gamma_g < 1.5$). Dynamics at the source or non-shock acceleration.
- ✓ Low maximum acceleration energies $E_{max}(Z) < 5Z \times 10^{18}$ eV.
- ✓ Reduced flux of secondary cosmogenic neutrinos and gamma rays

Composition of UHECR is a fundamental observable:

- ✓ To identify possible astrophysical sources.
- ✓ To tag galactic-extragalactic transition.
- ✓ To quantify the expectations in terms of secondary cosmogenic neutrinos and gamma rays

✓ A simple thought: my personal view on the future

- ✓ The most important future achievements in order to make progresses in the physics of UHECRs are: univocal determination of mass composition (~ few g/cm^2 resolution), larger (> 1 order of magnitude) statistics at the highest energies.
- ✓ The observation of astrophysical neutrinos with energies larger than PeV is of paramount importance to open the high energy window on the faraway universe.
- ✓ To pursue these goals a step forward in the detection technologies is needed.
- ✓ To reach the required statistics on both UHECR and HE neutrinos observations from space can be the only option. Even if a substantial improvement in the detection techniques should be still achieved.

Thank you