Ultra High Energy Cosmic Rays Origin, Composition and Spectrum

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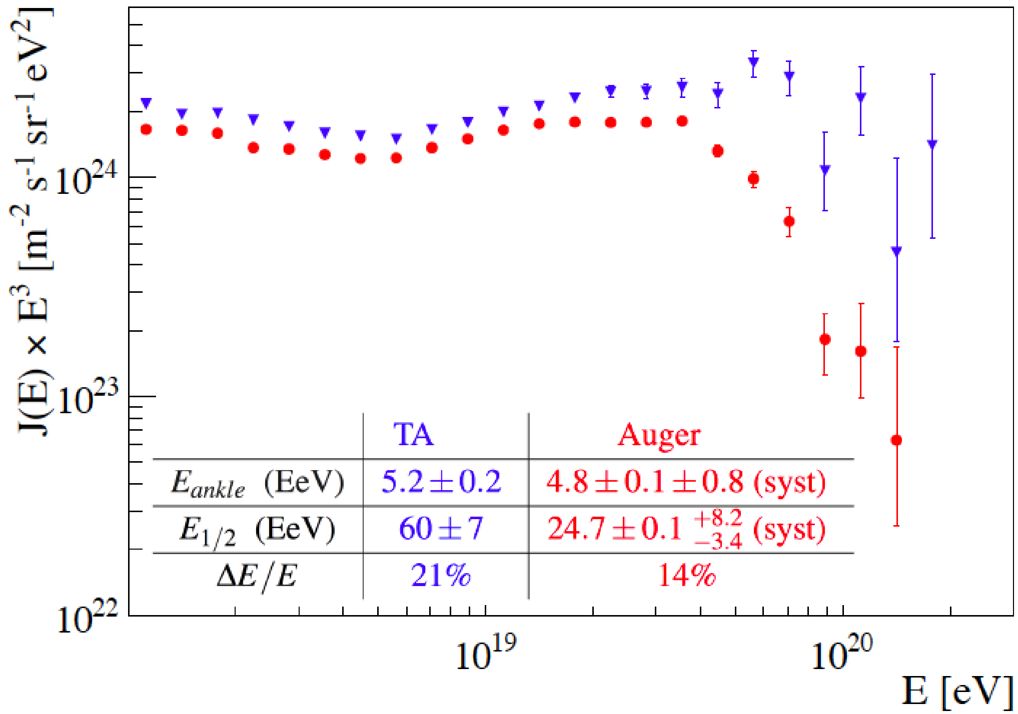
Outline of the talk

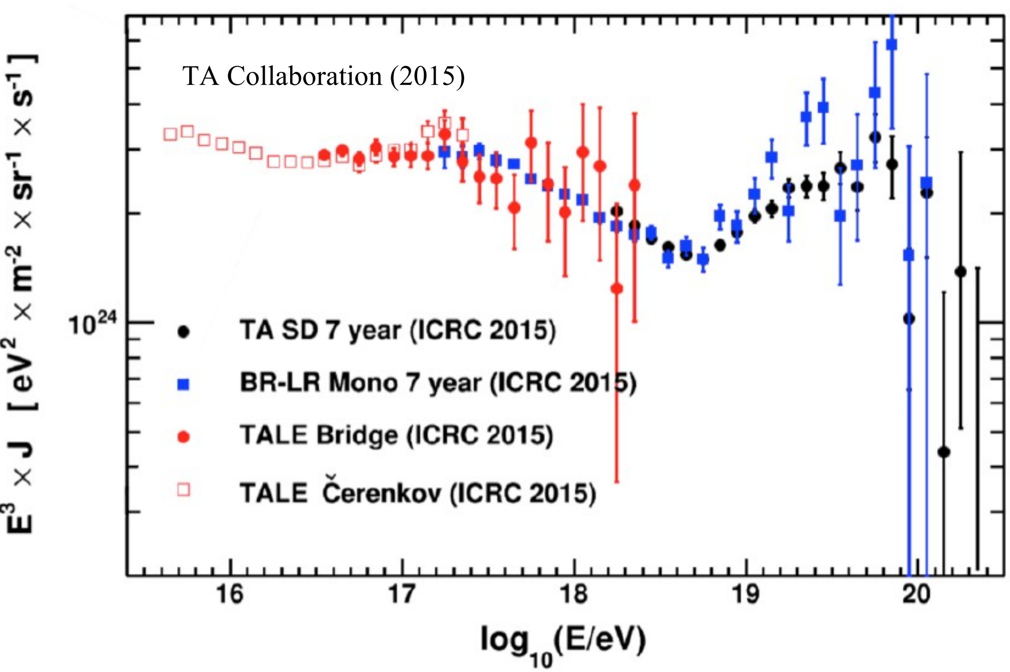
1. UHECR short recap of experimental evidences
2. Theoretical interpretations and possible sources
3. UHECR and secondary gamma rays
4. UHECR and secondary neutrinos
5. UHECR and neutrino observations from space
6. Conclusions

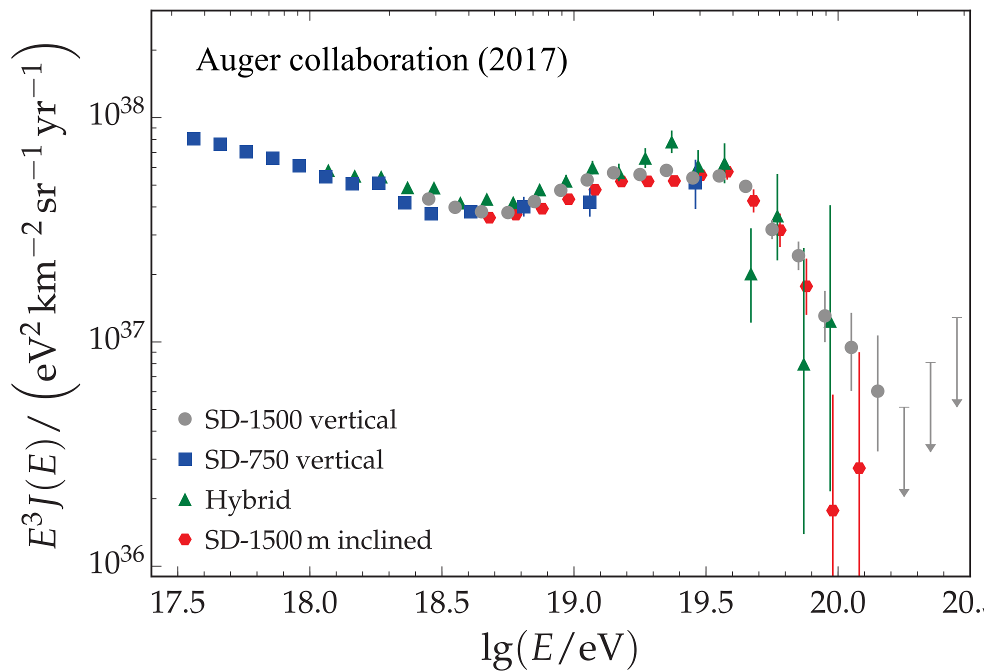
Ultra High Energies Cosmic Rays – Spectrum

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

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

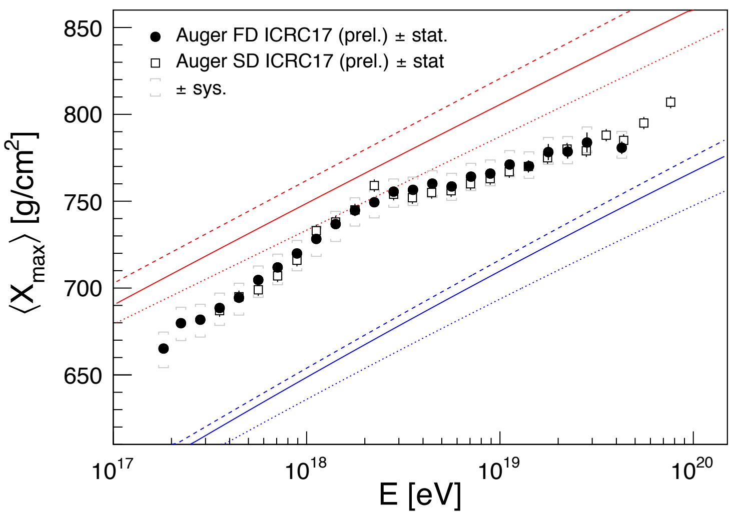


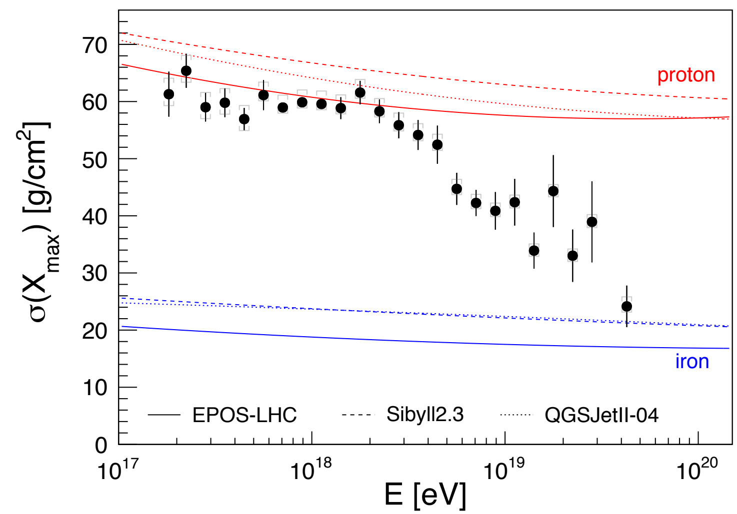




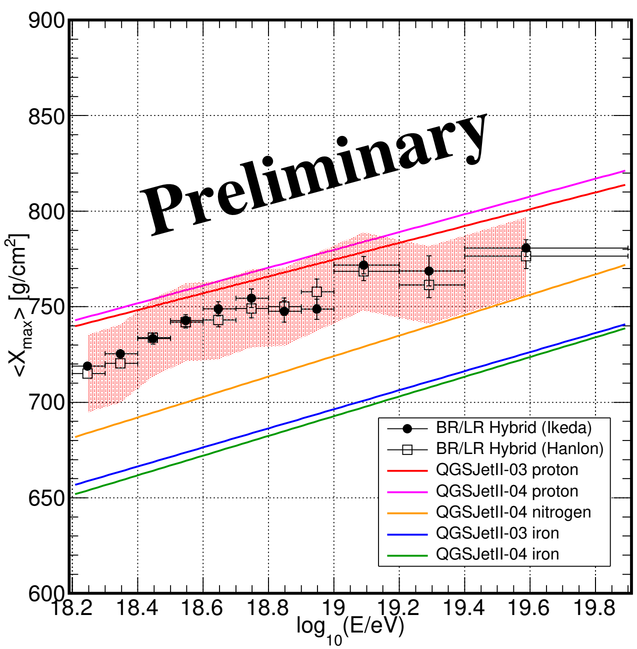
Ultra High Energies Cosmic Rays – Composition

Auger Collaboration (2017)

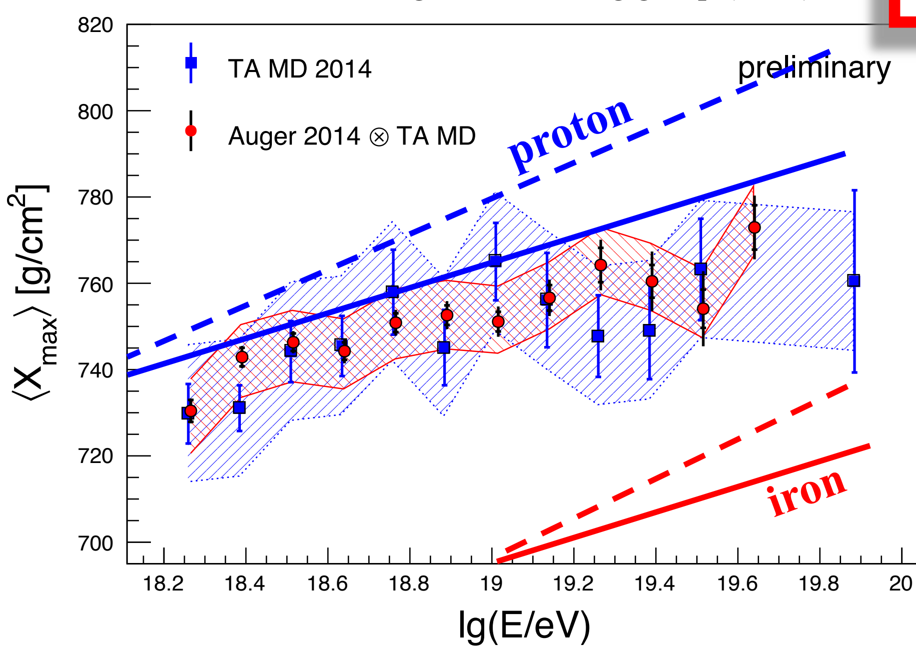




TA Collaboration (2017)

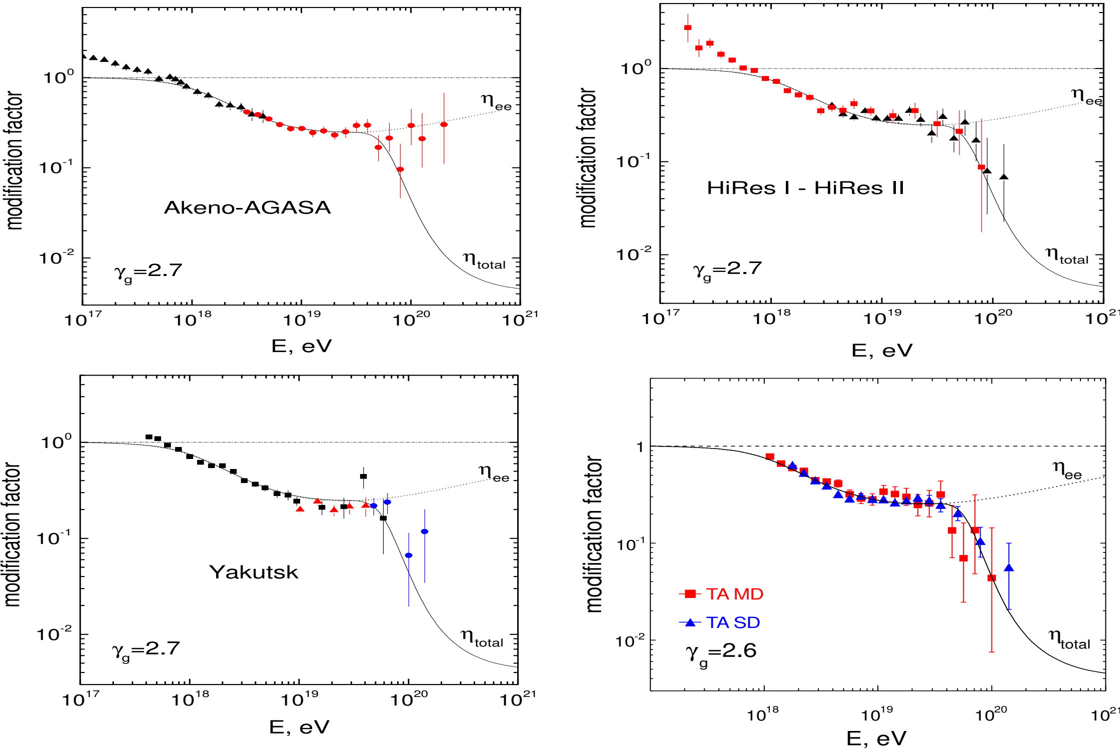


Auger-TA working group (2015)



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

Dip Model

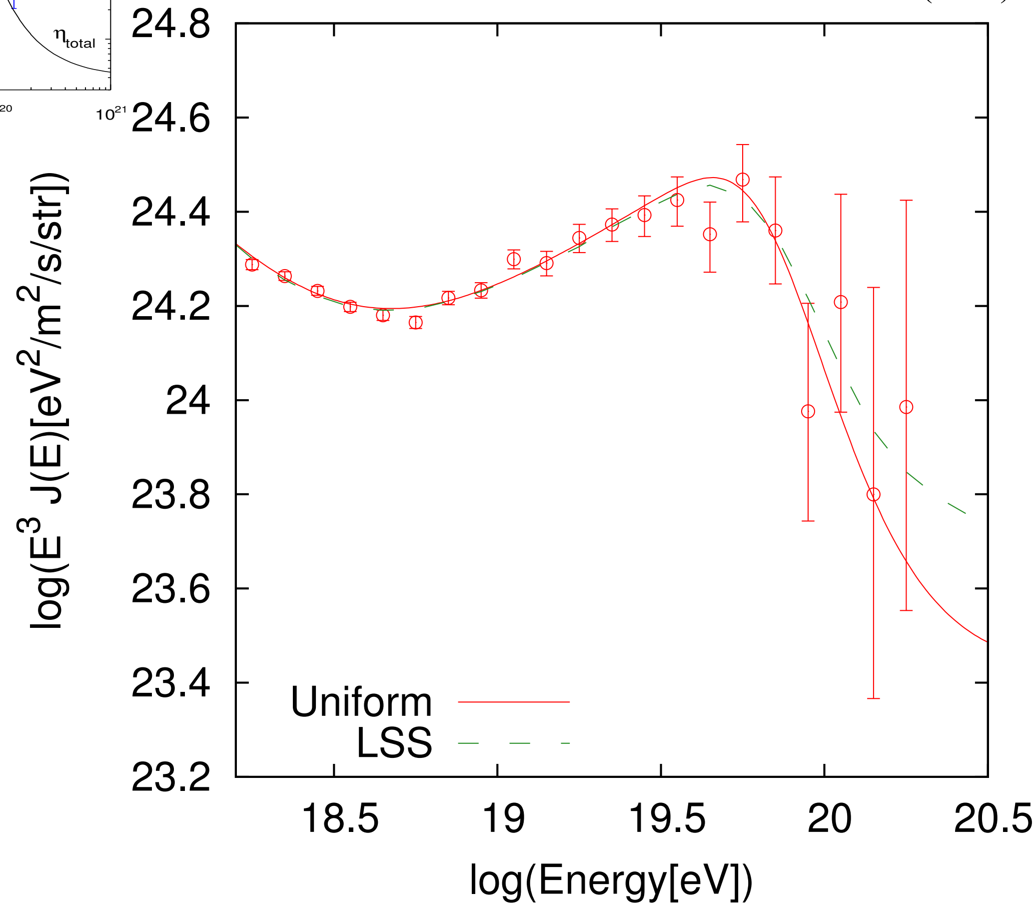


Berezinsky et al (2002-2007)

Protons footprint

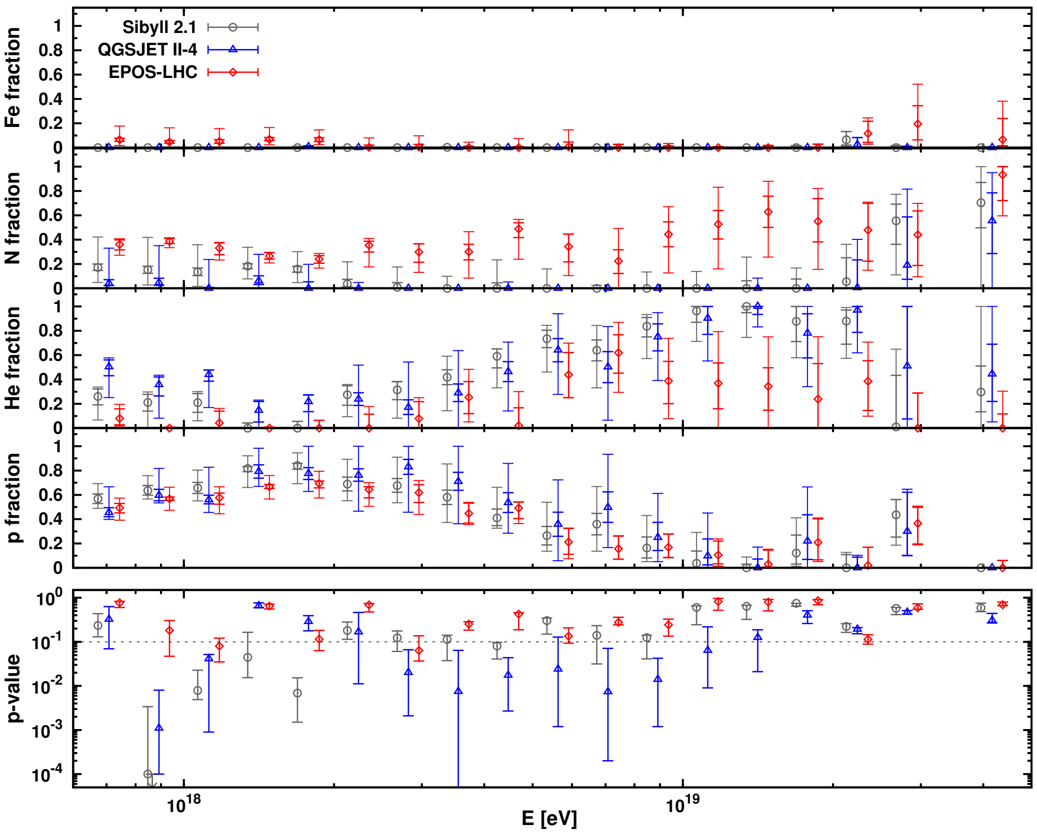
In the energy range 10^{18} - $5\text{x}10^{19}$ eV the spectrum behavior is a signature of the pair production process of UHE protons on the CMB radiation field.

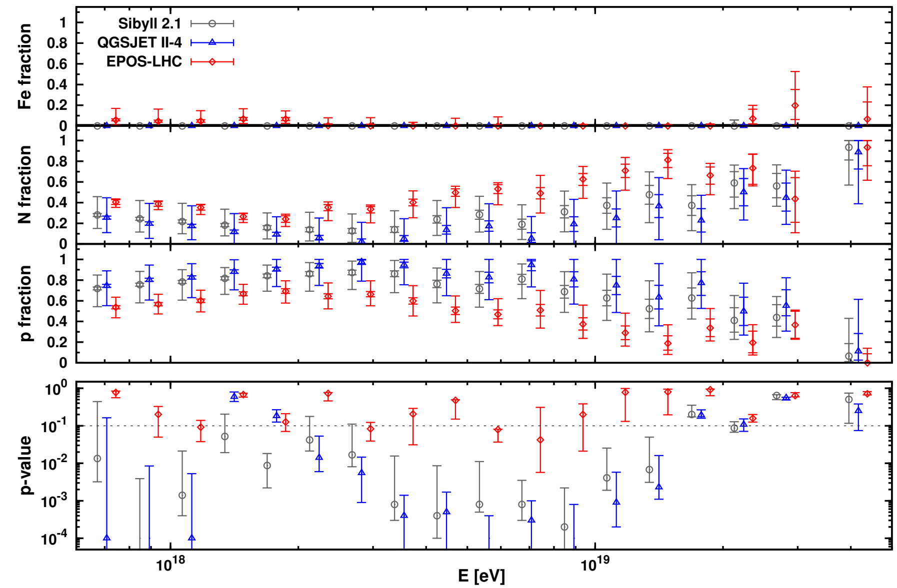
TA Collaboration (2015)



✓ 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 excluded by this analysis**.

Caveats

Composition

It is <u>impossible</u> 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.

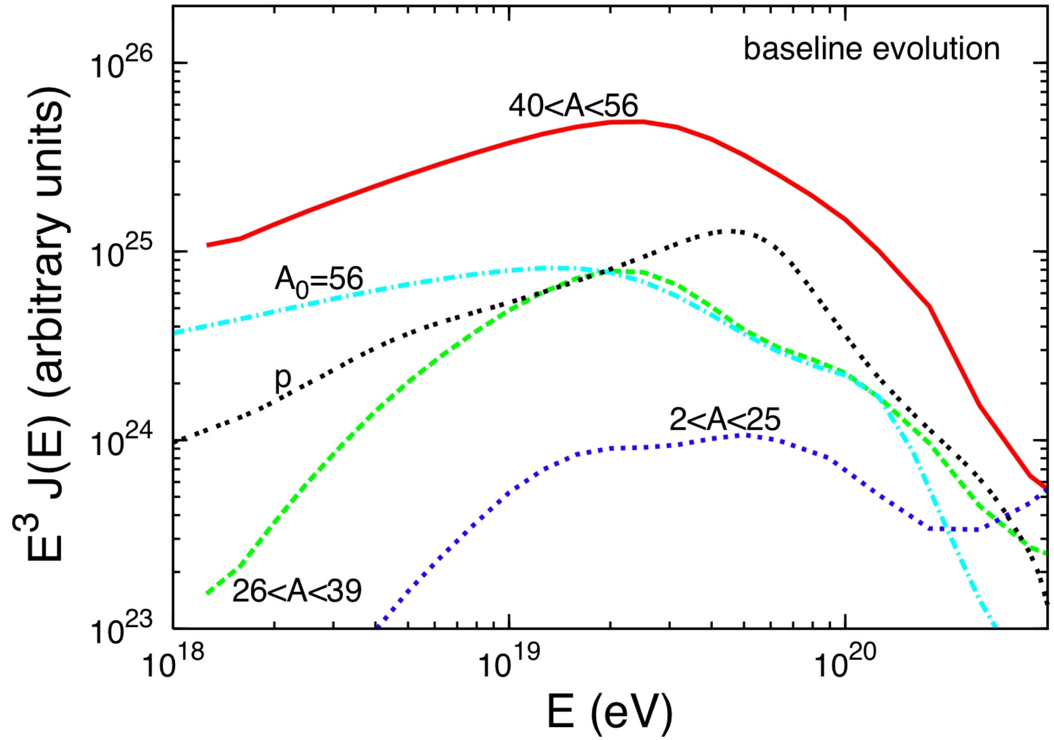
Critical Lorentz factor

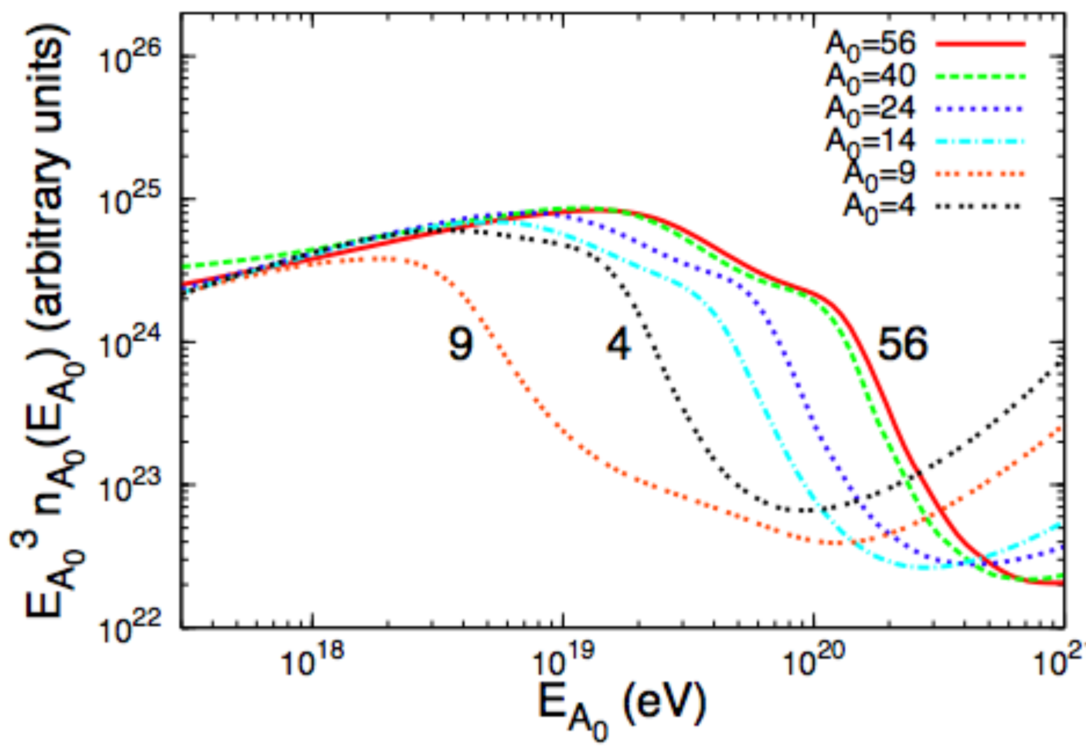
The critical Lorentz factor fixes the scale at which photo-disintegration becomes relevant, for heavy nuclei it is almost independent of the nuclei specie

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

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

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





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.

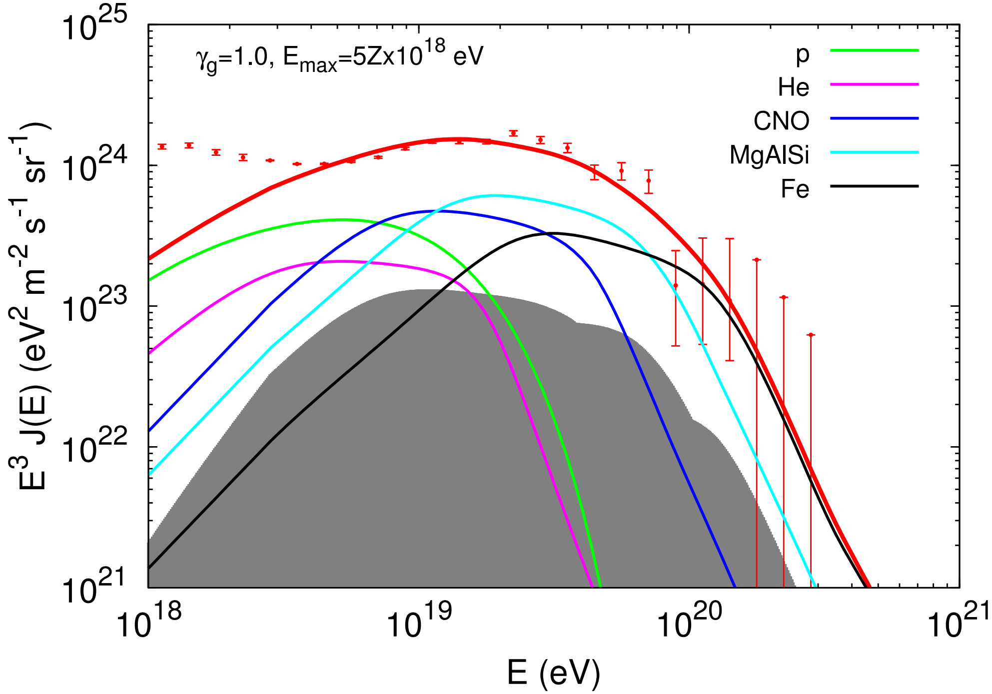
- **Protons**

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

- **Nuclei**

$$E^A_{max} > E_{cut}(A) = A m_N \Gamma_c \simeq 2A \times 10^{18} eV$$

What we can learn from Auger data

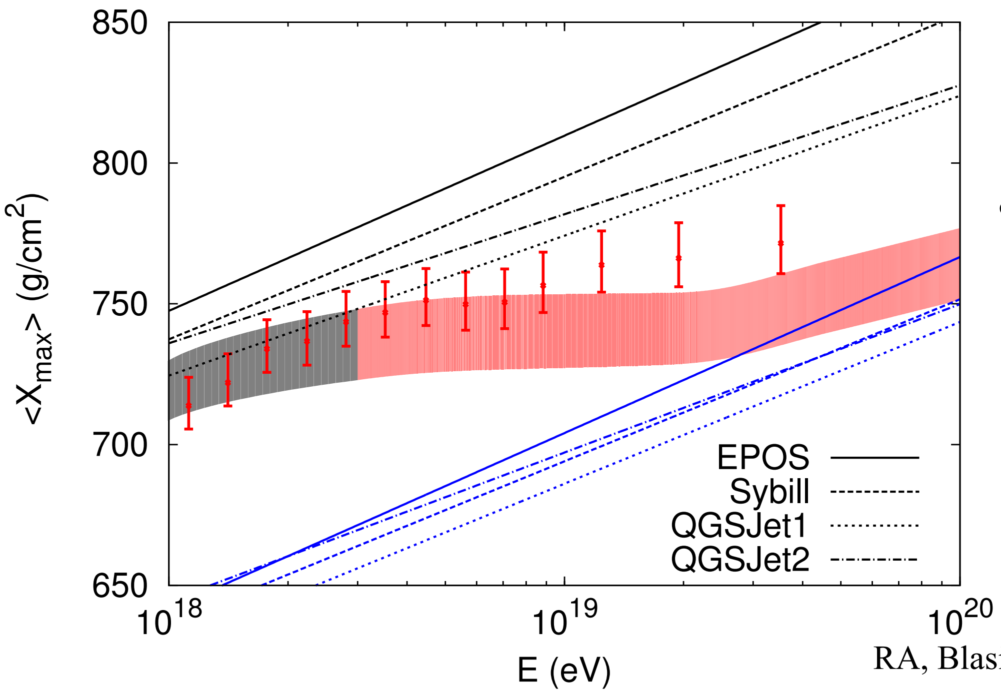


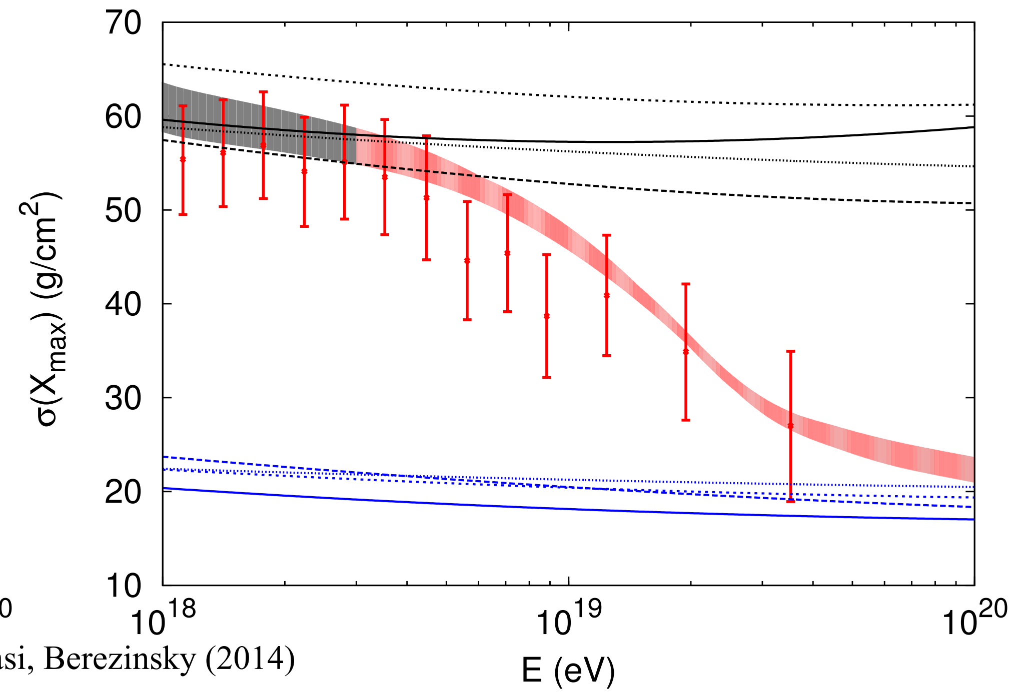
Auger chemical composition can be reproduced only assuming a very flat injection of primary nuclei

$$\gamma_g = 1.0 \div 1.5$$

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

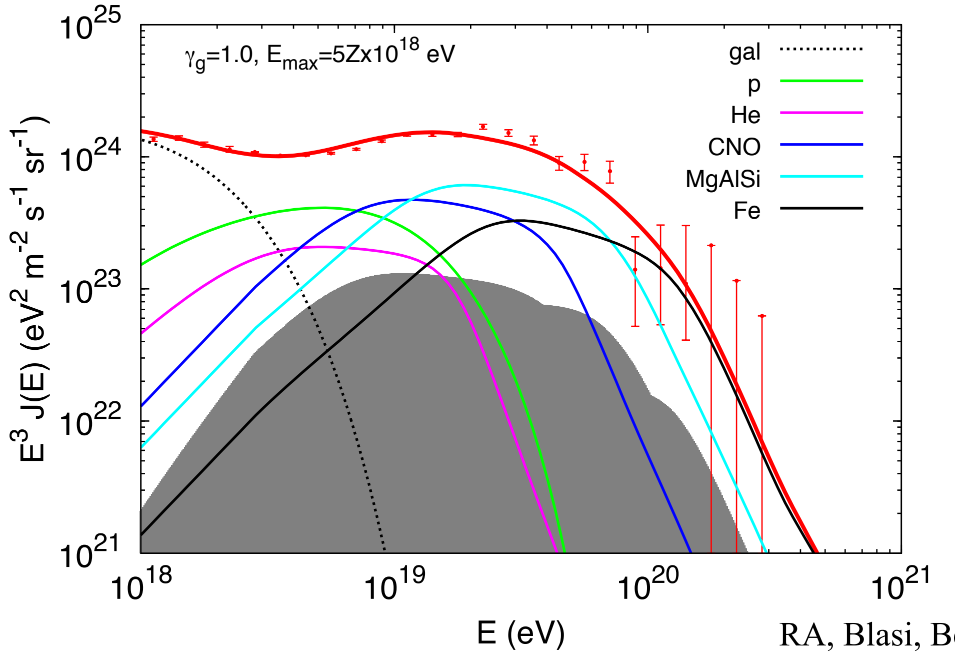
with a certain level of degeneracy in terms of the nuclei species injected





RA, Blasi, Berezinsky (2014)

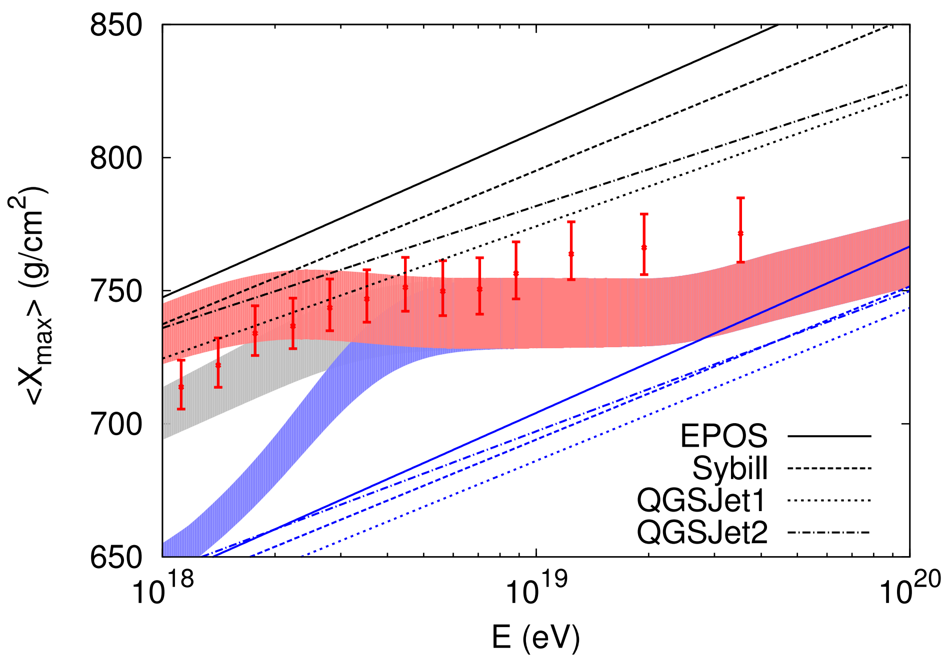
Extra Galactic Nuclei and Galactic light elements

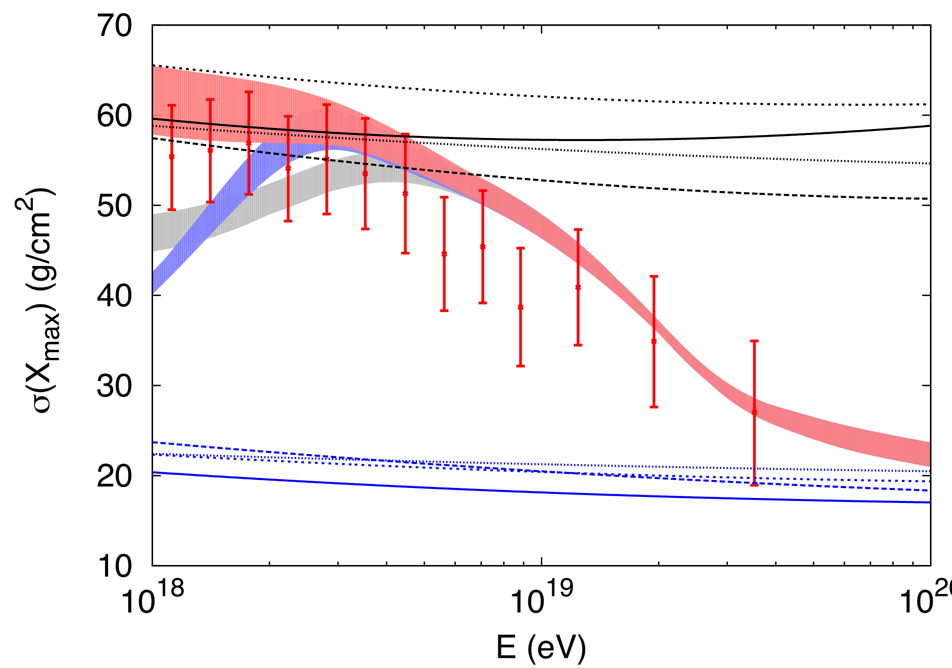


An additional galactic component can fill the gap in the spectrum.

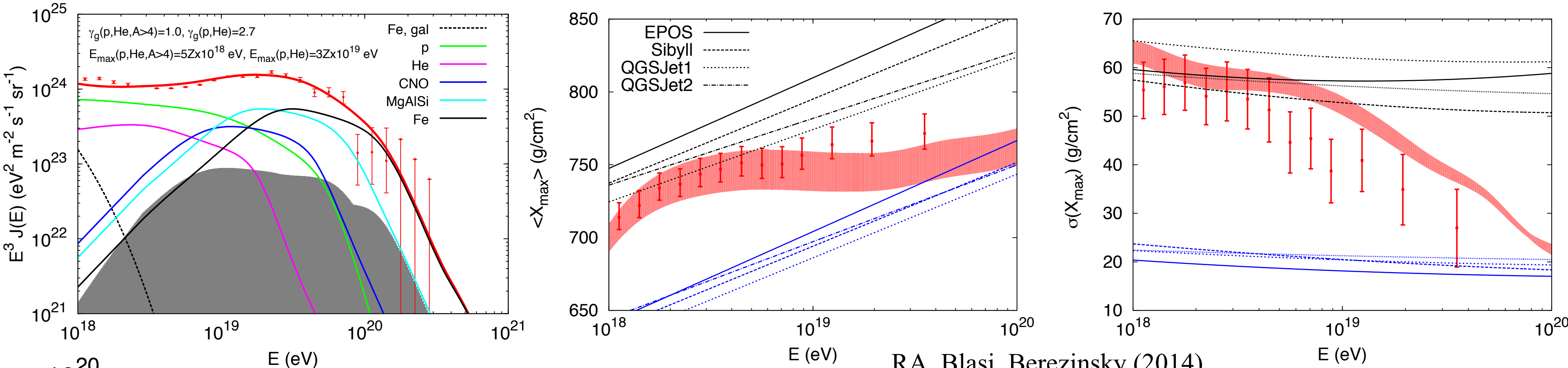
Composition issue. Mixture of 80% p and 20% He to reproduce Auger observations. Difficult to reconcile with galactic CR physics and anisotropy observations.

RA, Blasi, Berezinsky (2014)

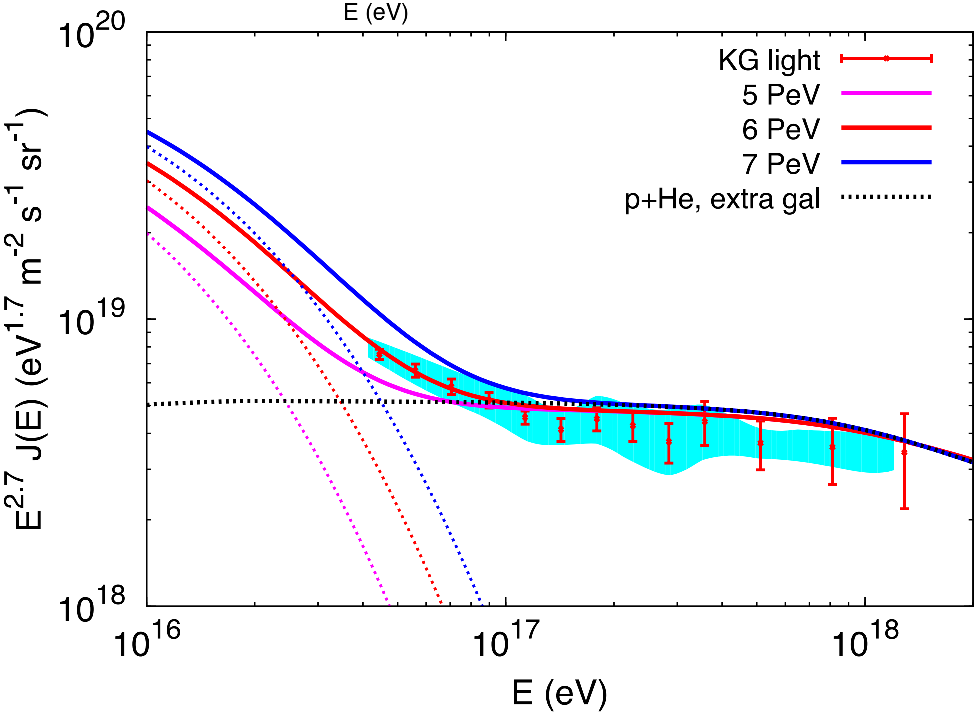




Different Classes of Extra Galactic Sources



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)

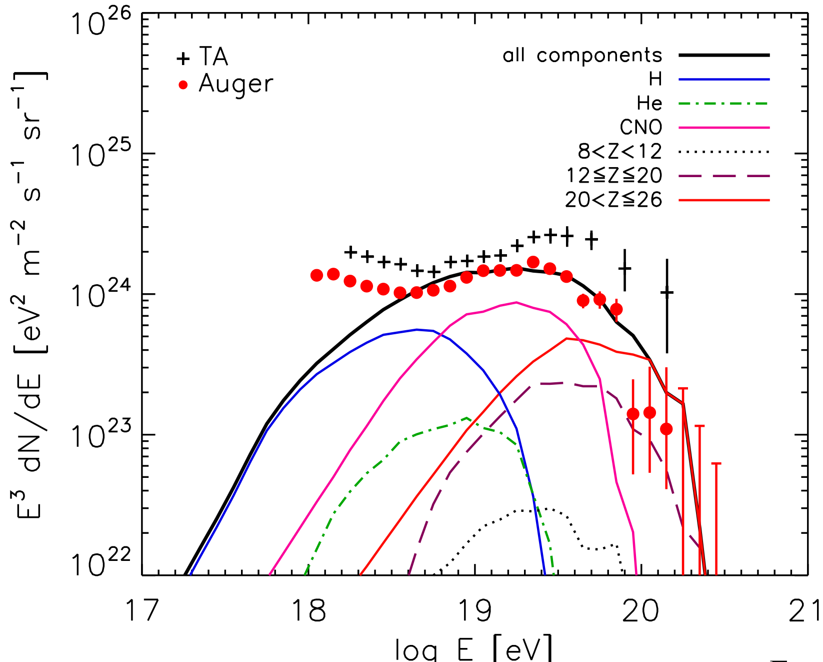
$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3 \mathrm{y}}$$

✓ **active galactic nuclei**

can easily provide steep injection and the correct emissivity.

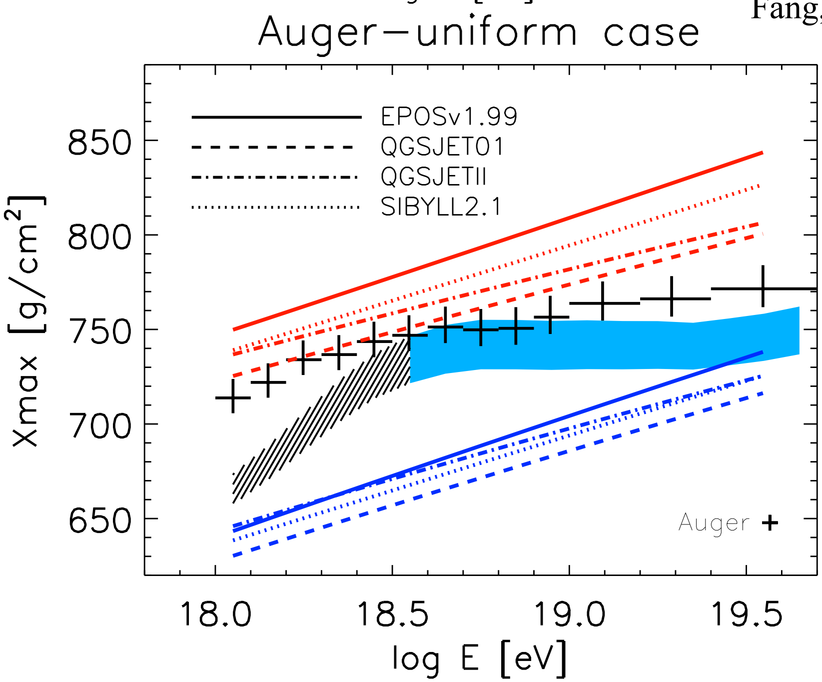
The Kascade-Grande observations seem to confirm the presence of an extragalactic light component with a steep injection spectrum.

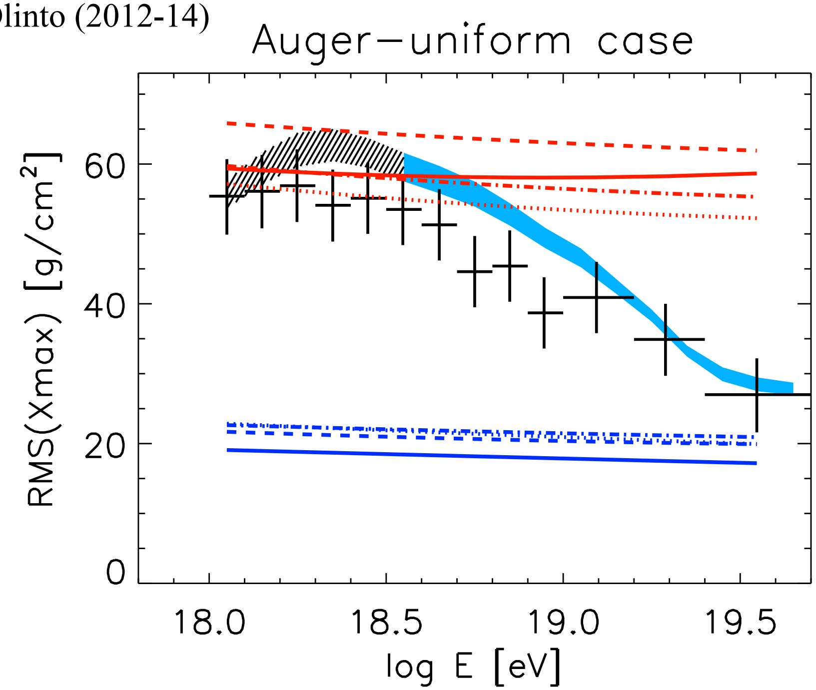
Pulsars, Extra Galactic and Galactic



- ✓ 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.
- ✓ Problems with chemical composition and anisotropy of the galactic pulsars contribution.

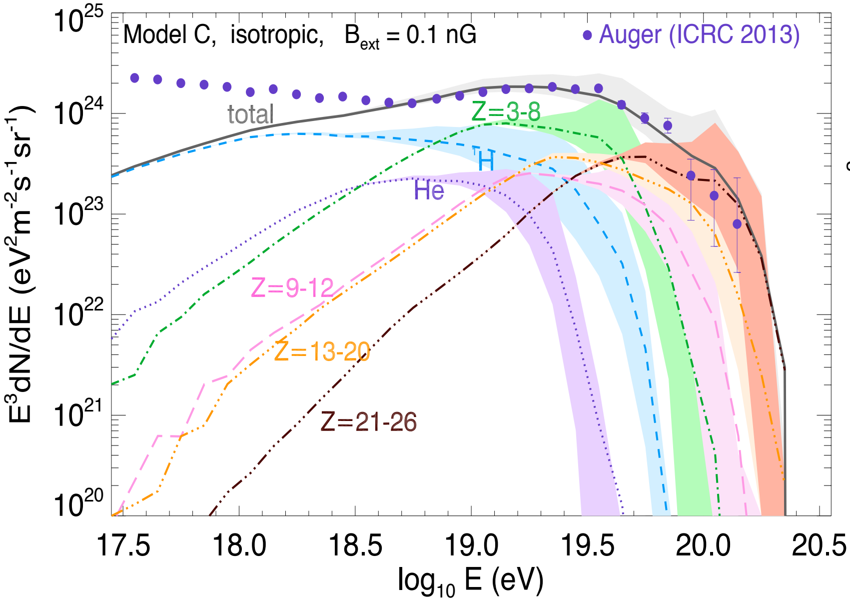
Fang, Kotera, Olinto (2012-14)

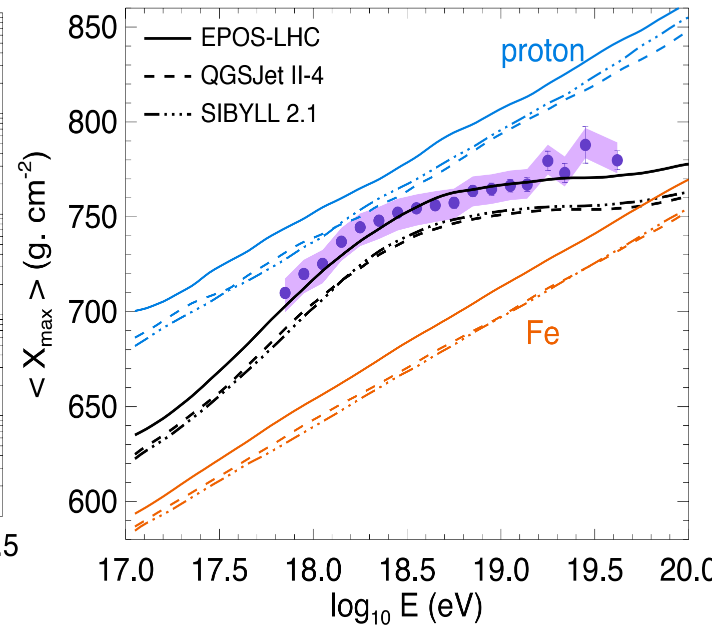




Specific dynamic at the sources

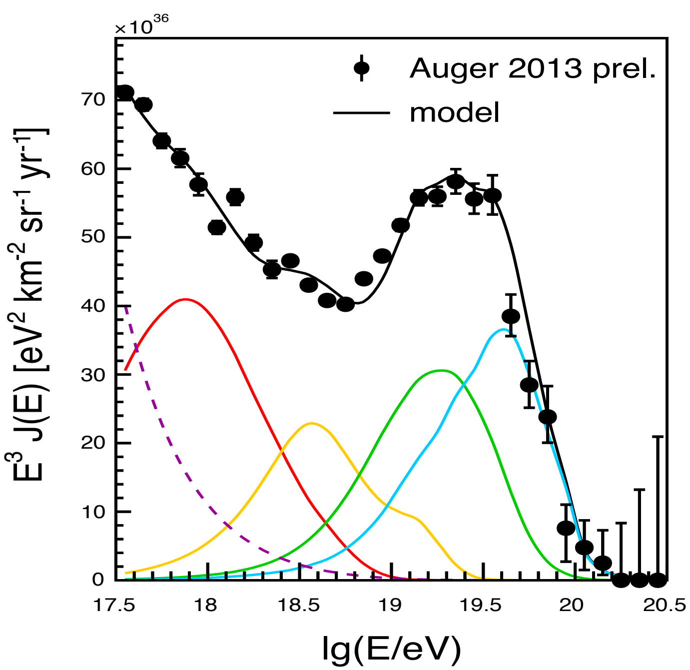
Globus, Allard, Parizot (2014-2015)

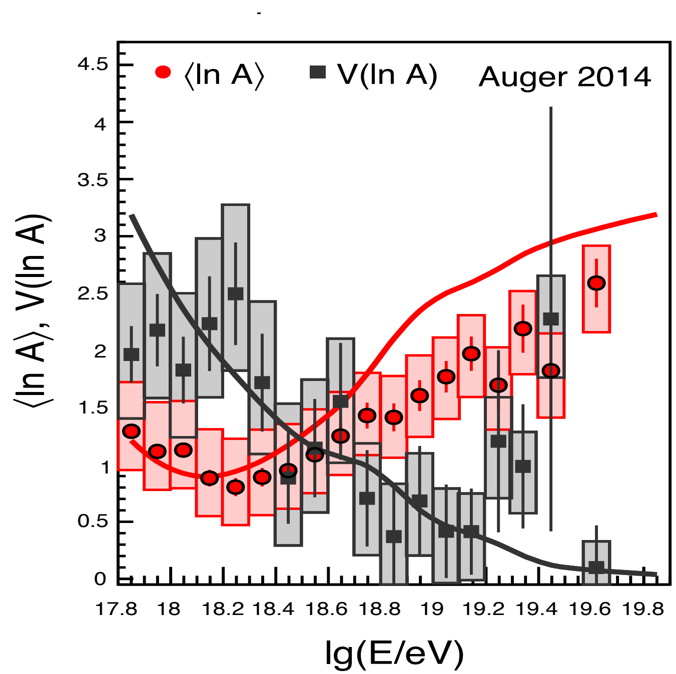




- ✓ Single class of EG sources: Mildly relativistic shocks in GRBs.
- ✓ Problem with Galactic CR maximum energy larger than 10^{16} eV

Unger, Farrar, Anchordoqui (2015)



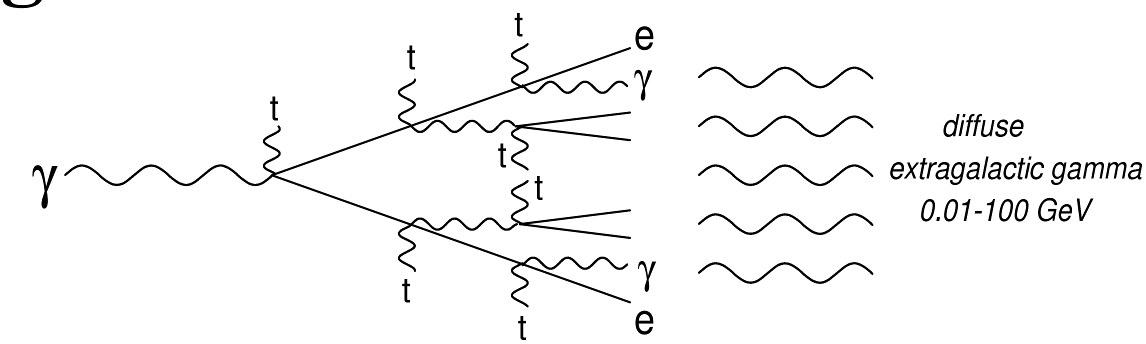


- ✓ Photodisintegration at the source. Flat injection for nuclei ($\gamma \approx 1$) and steep for protons ($\gamma > 2$).
- ✓ Agreement with Kascade-Grande.

Diffuse γ ray background

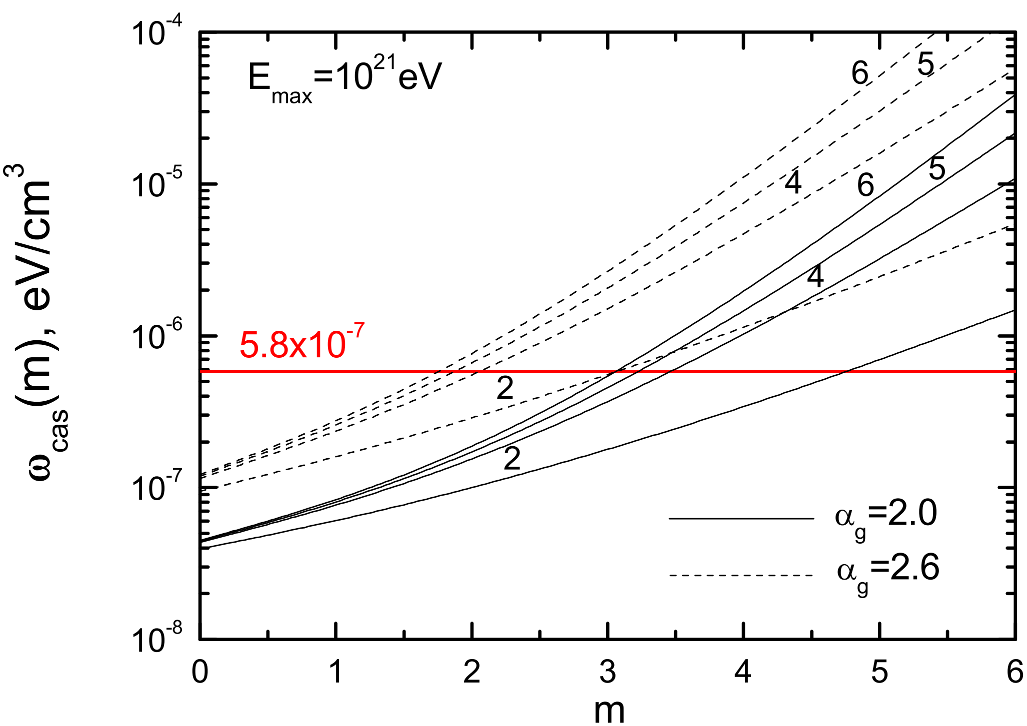
Cascade upper limit

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



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)

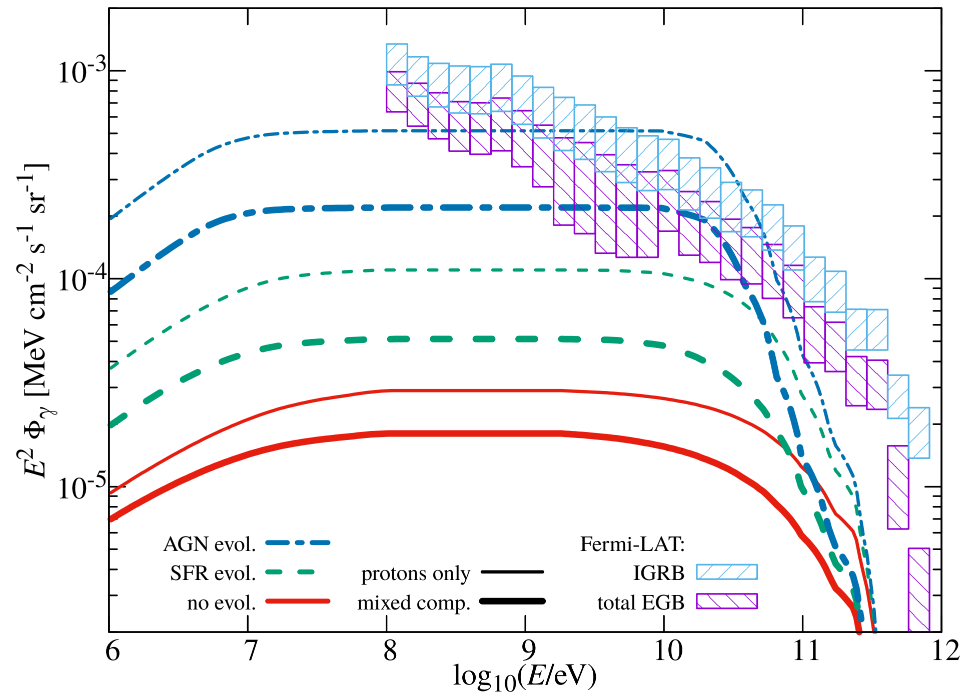
The cascade limit can be expressed in terms of the energy densities of photons and e^+e^- initiated cascades

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

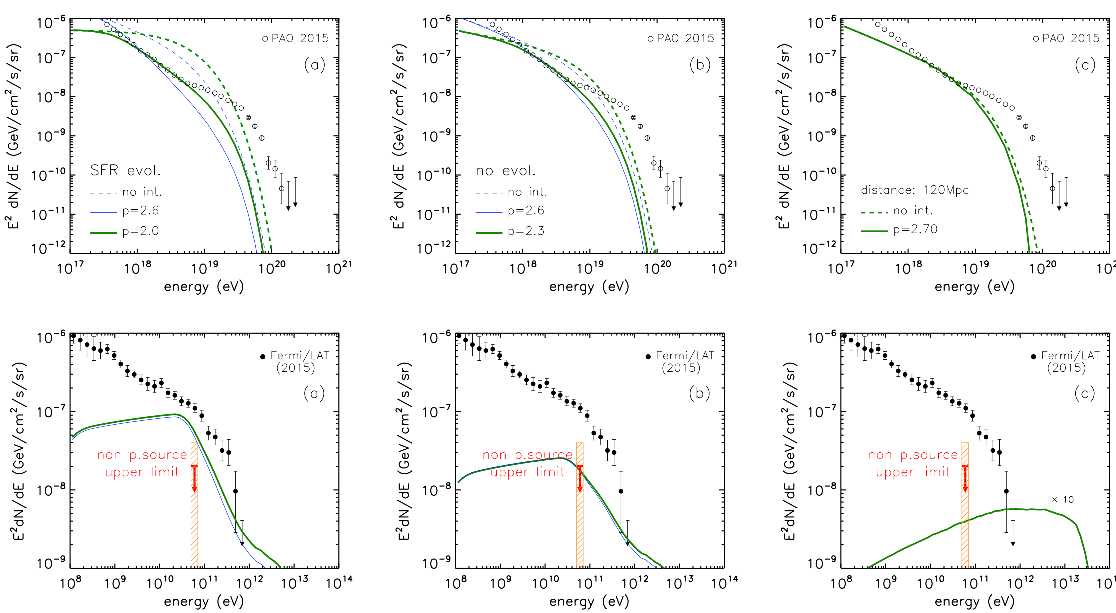
The cascade upper limit constrains the source parameters: cosmological evolution, injection power law and maximum acceleration energy.

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

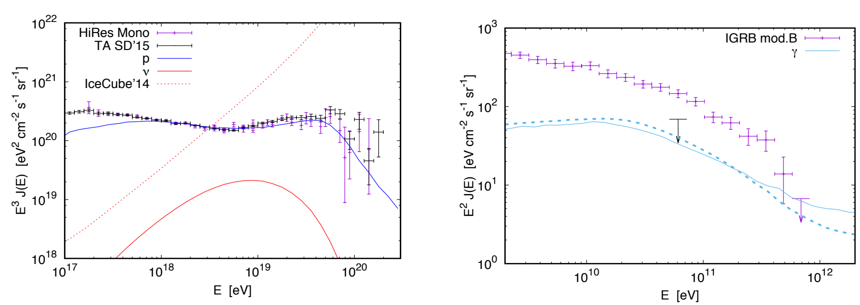
RA, Boncioli, di Matteo, Grillo, Petrera, Salamida (2017)



- ✓ 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 gamma rays observation.

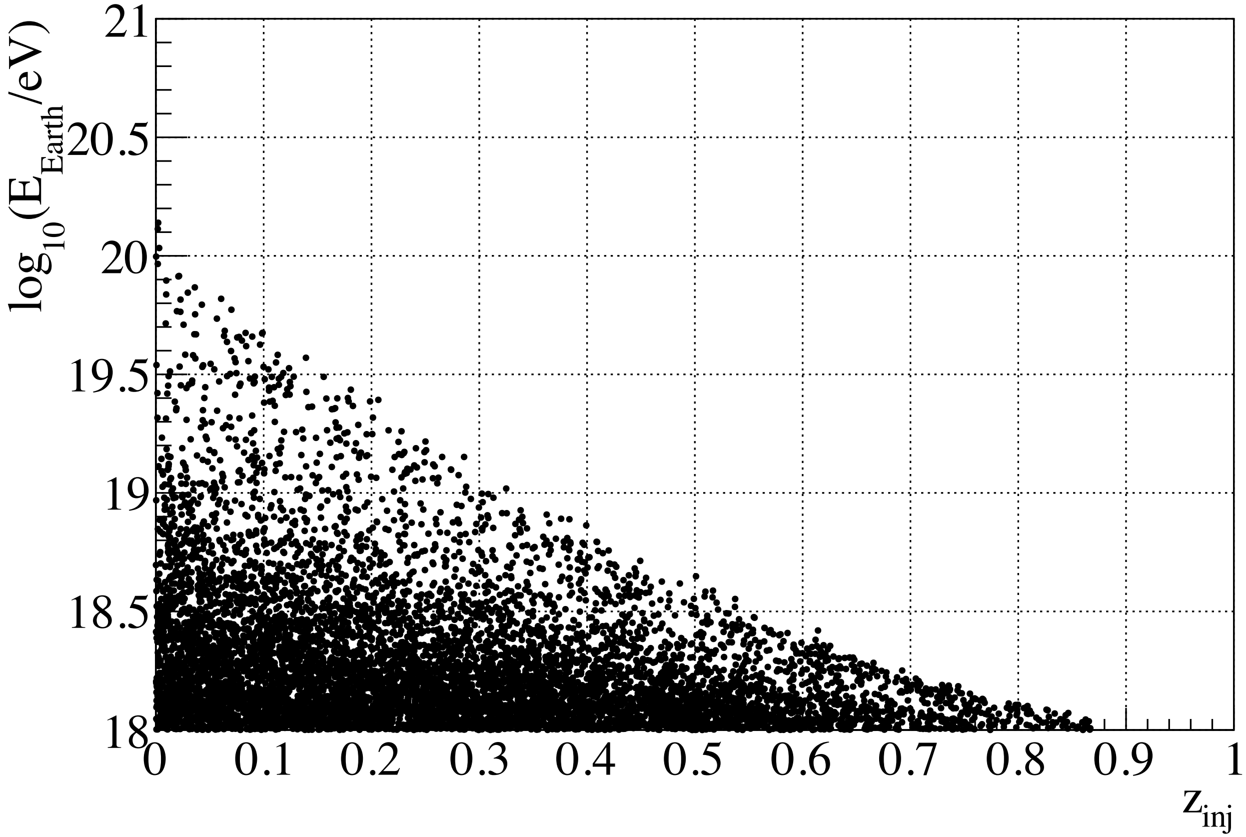


Liu, Taylor, Wang, Aharonian (2016)



Berezinsky, Gazizov, Kalashev (2016)

Looking farther away



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

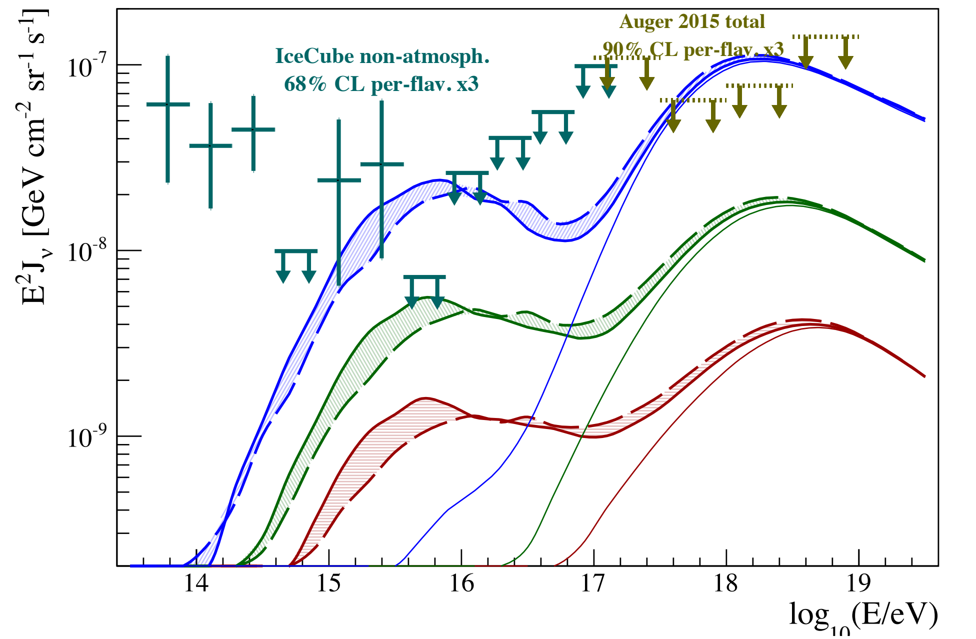
$$p\gamma \to \pi^{\pm} \to e^{\pm}, \nu$$

- ✓ 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 UHECR mass composition.

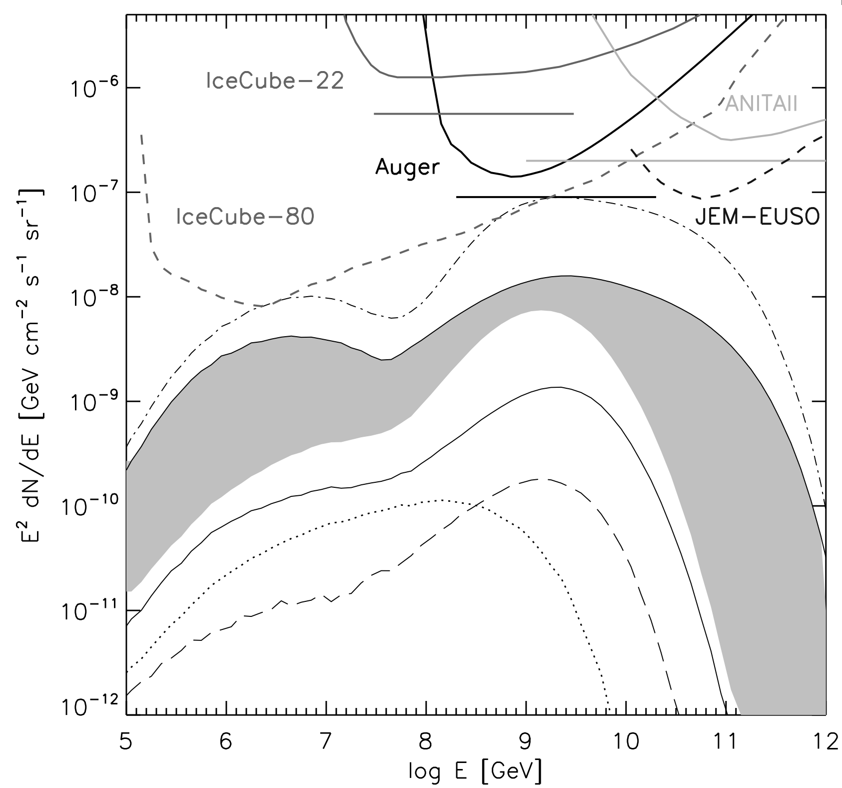
Dip model – ν spectra

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



✓ 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.



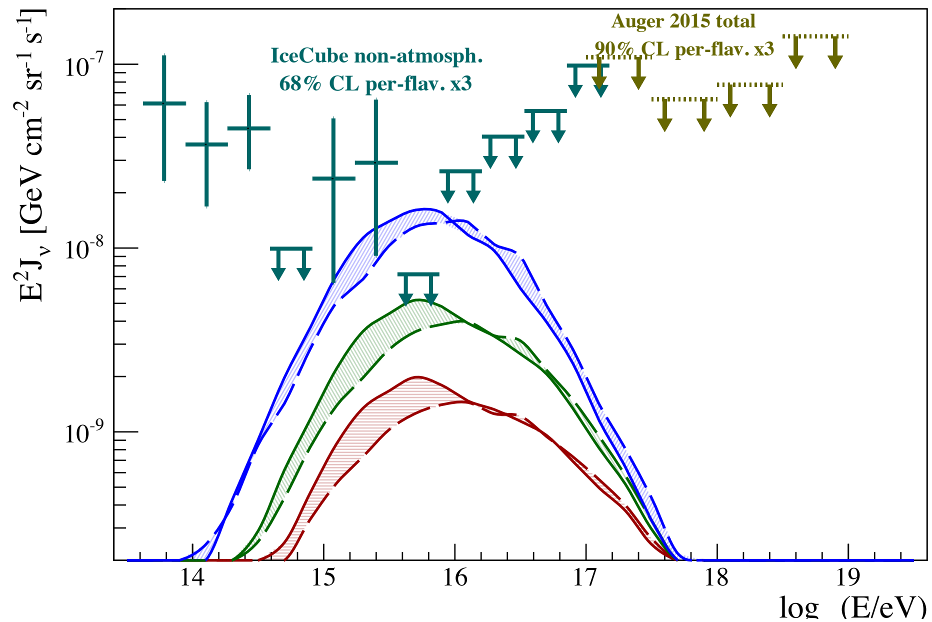
Kotera, Allard, Olinto (2011)

✓ 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).

Mixed composition model – ν spectra

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

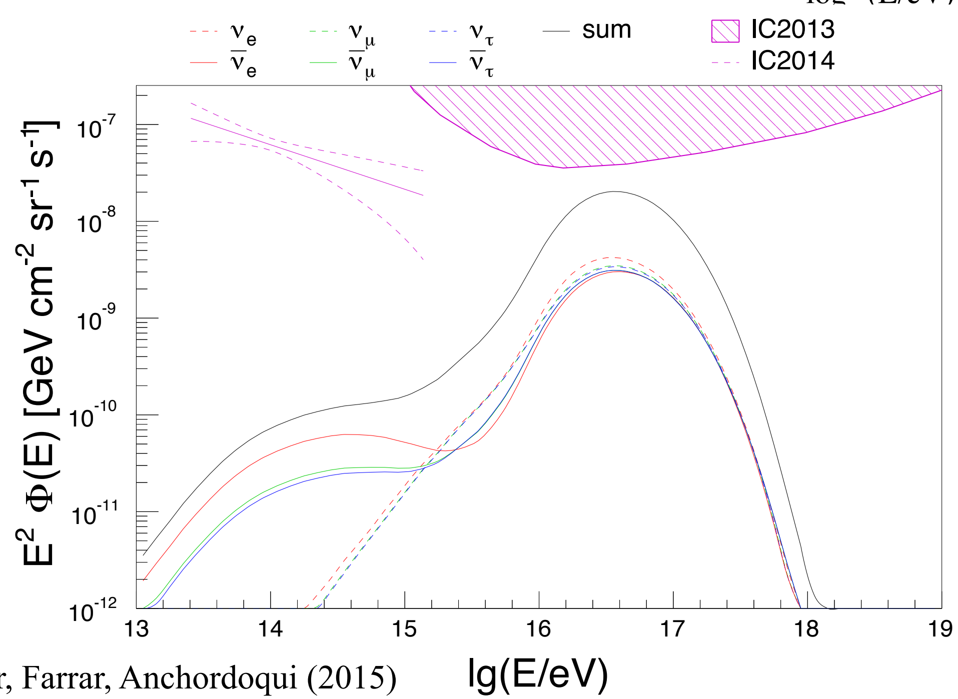


✓ EeV neutrinos

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)

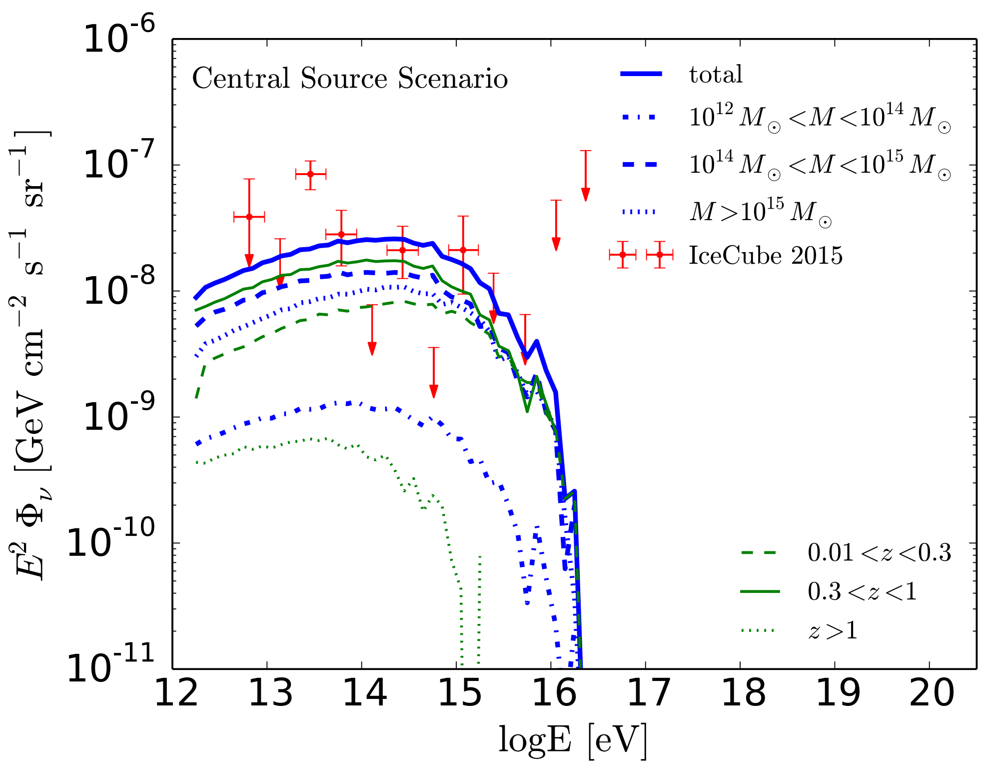
Clusters of Galaxies and PeV ν

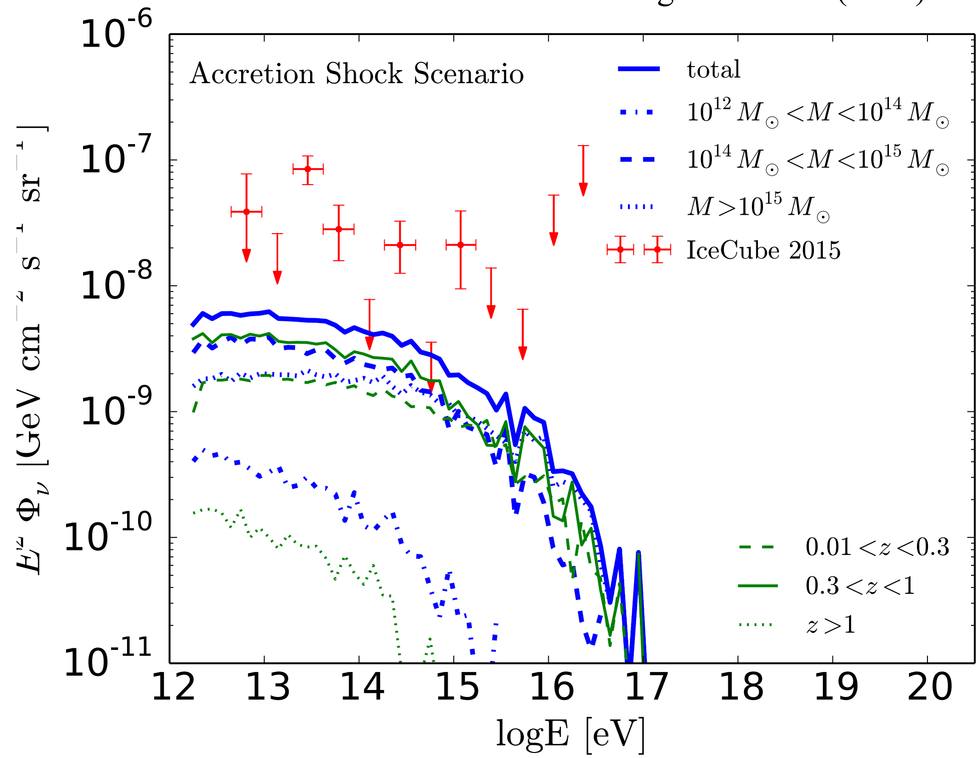
✓ Because of their magnetic fields (at several μG level) clusters of galaxies are “storage rooms” for cosmic rays till energies ~$10^6 \div 10^8$ GeV, depending on the magnetic field turbulence.

✓ 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.

Berezinsky, Blasi and Ptuskin (1998)

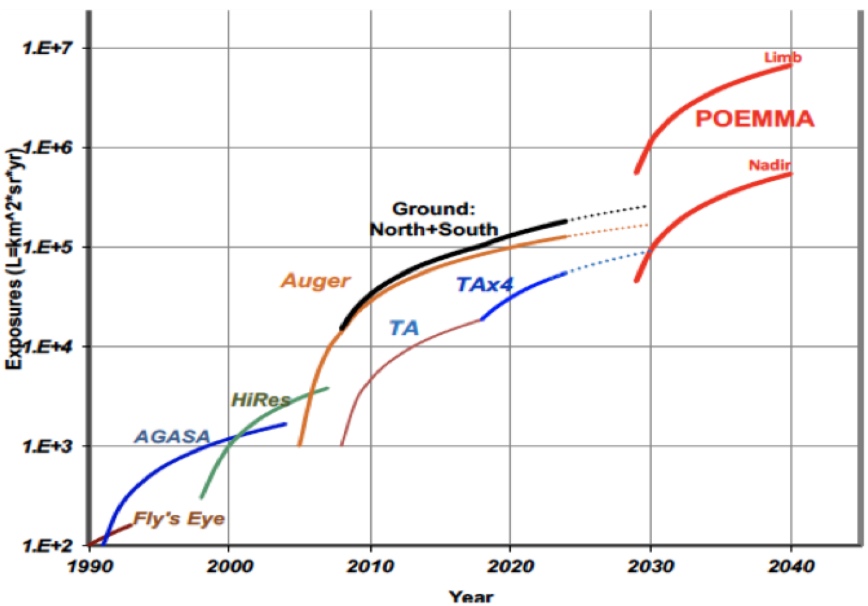
Fang and Olinto (2016)



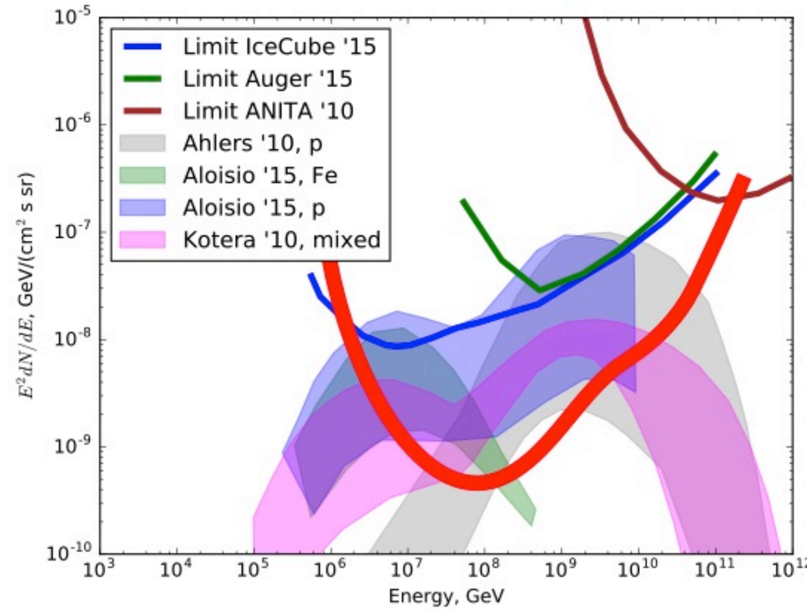


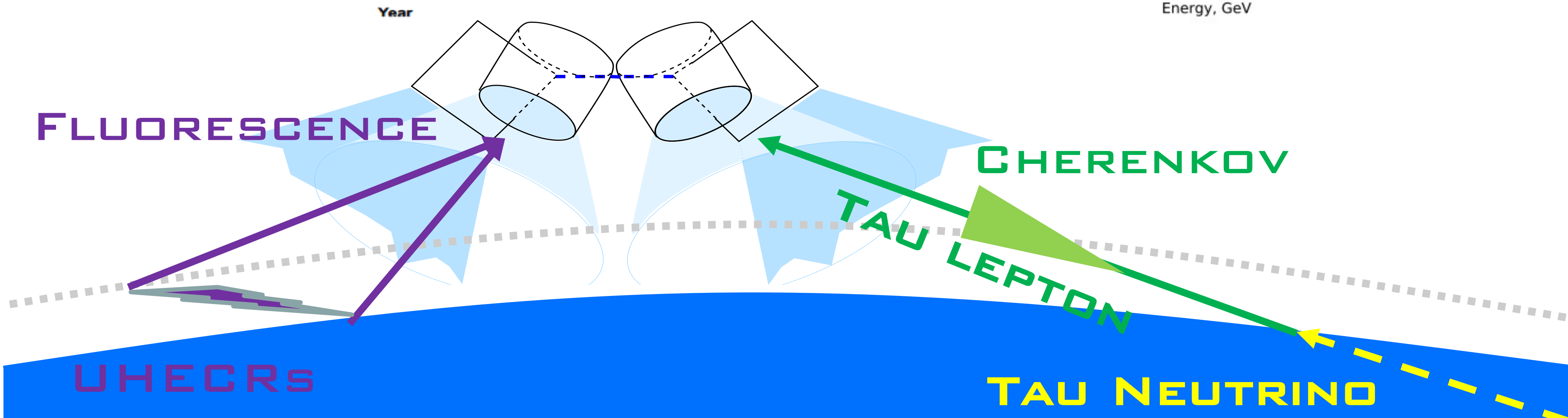
POEMMA - Probe Of Extreme Multi Messenger Astrophysics

- ✓ The observation of astrophysical neutrinos (E > few PeV) can be achieved only from space.
- ✓ Only the observation from space enables the needed statics to study the high energy tail of UHECR flux and to probe new physics.



J.H. Adams et al. 2017





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, 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 HE 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 UHECR and to observe HE astrophysical neutrinos, the observation from space seems the only option.

Thank you