Ultra High Energy Cosmic Rays Propagation and the Production of Secondary Cosmogenic Particles

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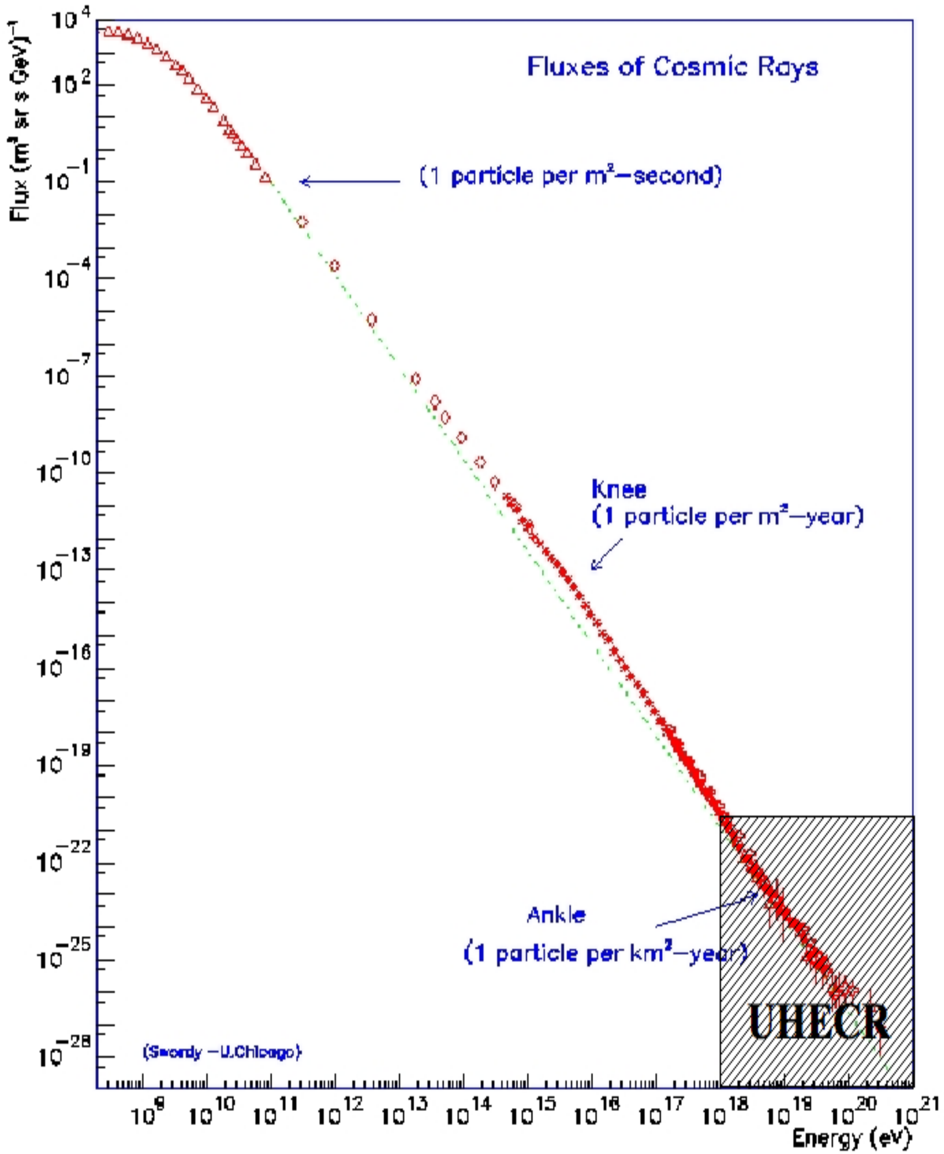
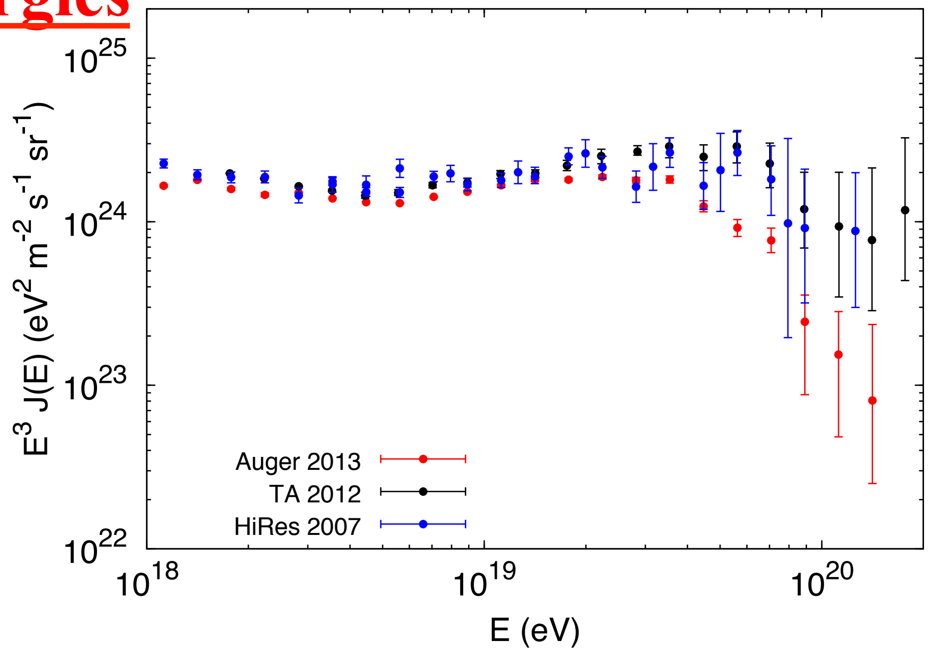
CR spectrum at Ultra High Energies



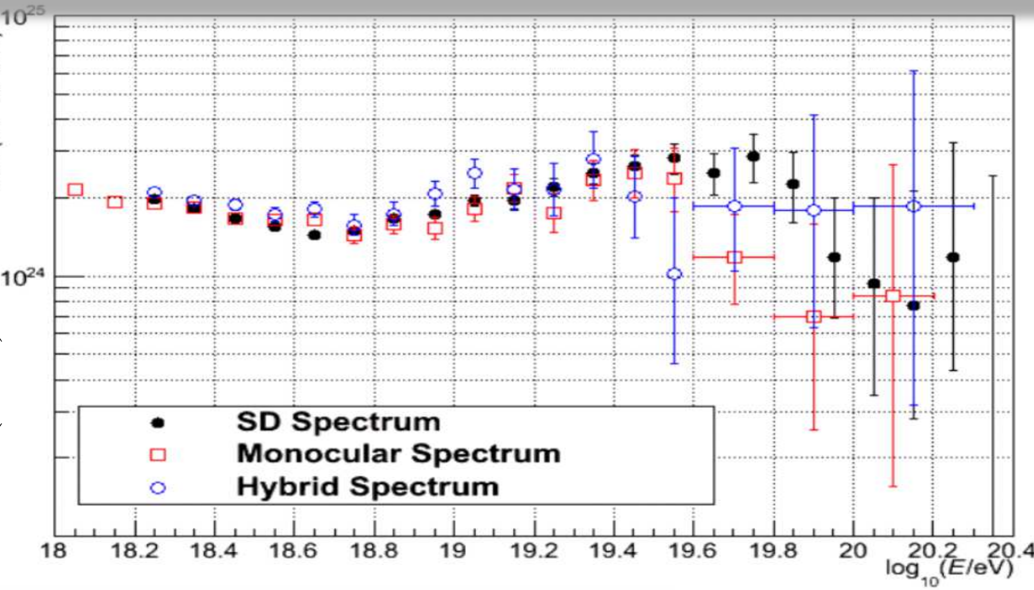


The observations on Earth are the result of the acceleration at the source (injection) and the propagation of particles in the background radiation (CMB & EBL) and possible intergalactic magnetic fields (IMF).

- ✓ **Spectrum**
- ✓ **Chemical Composition**
- ✓ **Anisotropy** (astronomy?)
- ✓ **Cosmogenic secondary particles**

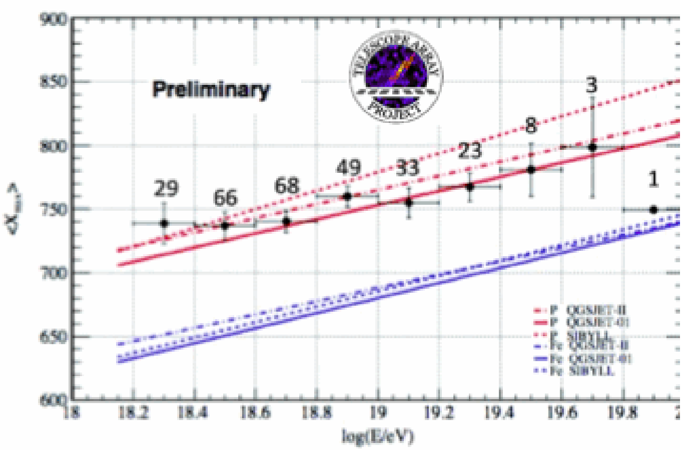
HiRes & Telescope Array – Energy Spectrum

The HiReS analysis confirms the expected Greisen Zatzepin Kuzmin suppression for protons with $E_{1/2}=10^{19.73\pm0.07}$ eV in fairly good agreement with the theoretically predicted value $E_{1/2}=10^{19.72}$ eV.



The new Telescope Array results, in agreement with HiRes, show a suppression in the spectrum compatible with the GZK feature.

TA collaboration (2013)

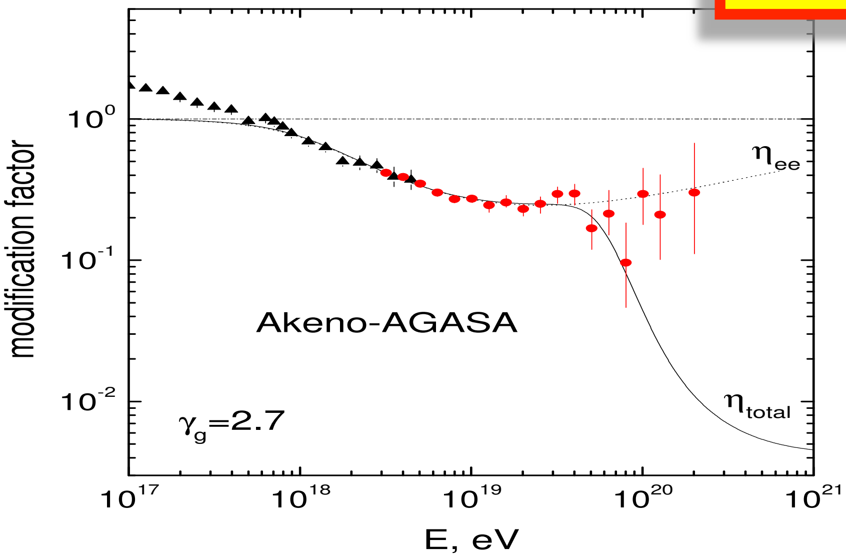


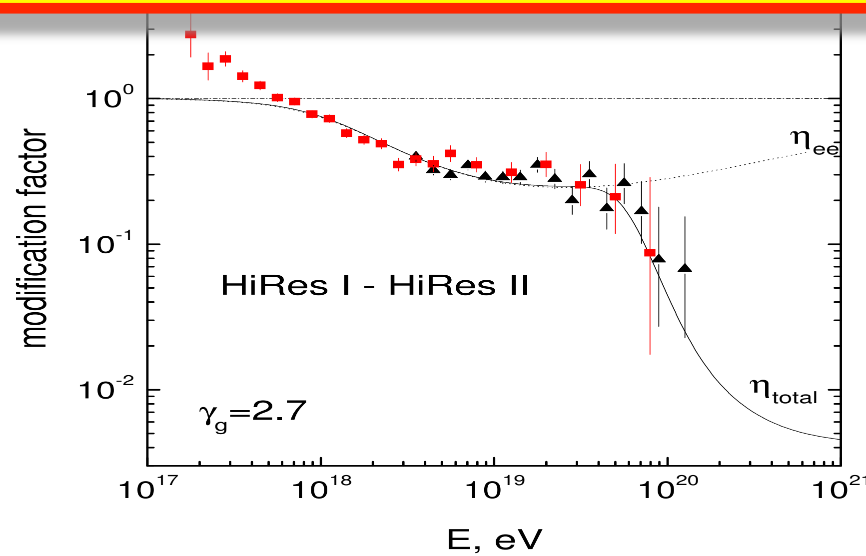
HiReS and Telescope Array observe a proton dominated spectrum at all energies, starting from 10^{18} eV up to the highest energies.

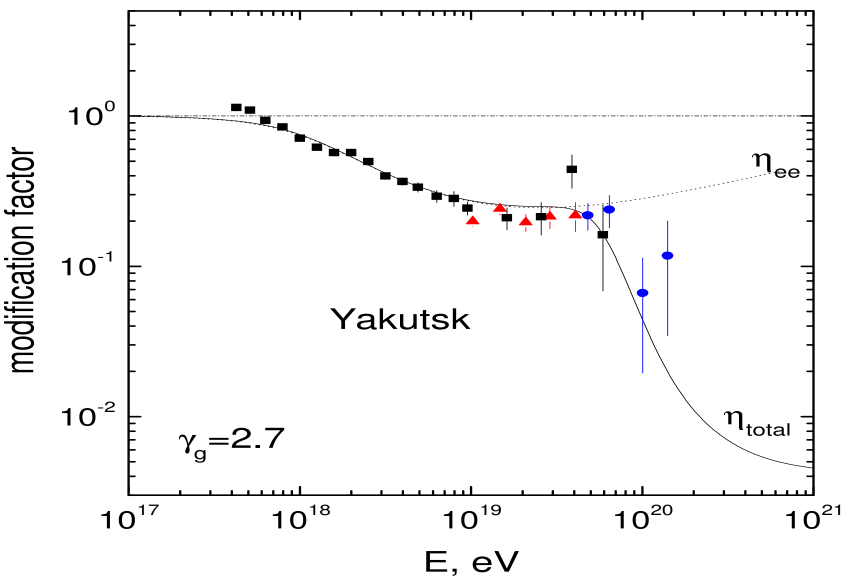
Dip Model

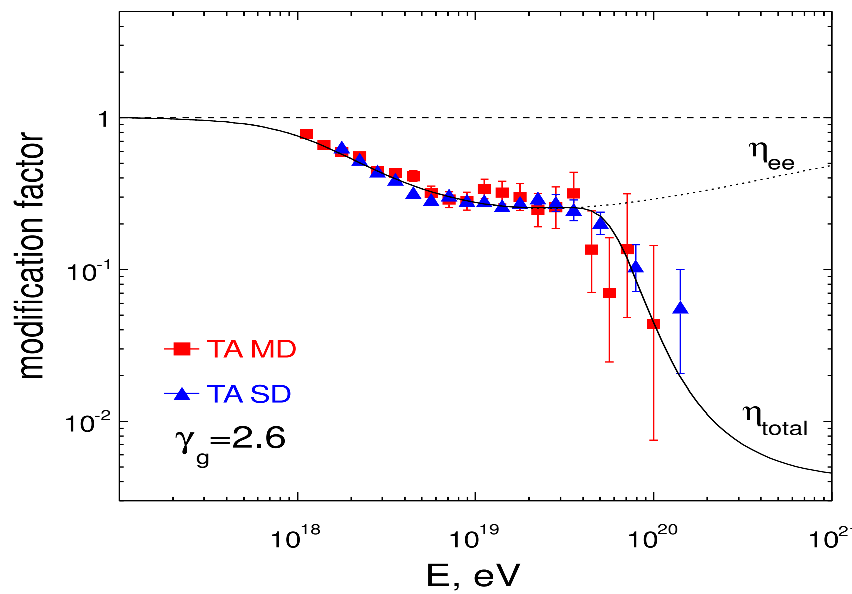
the protons footprint

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



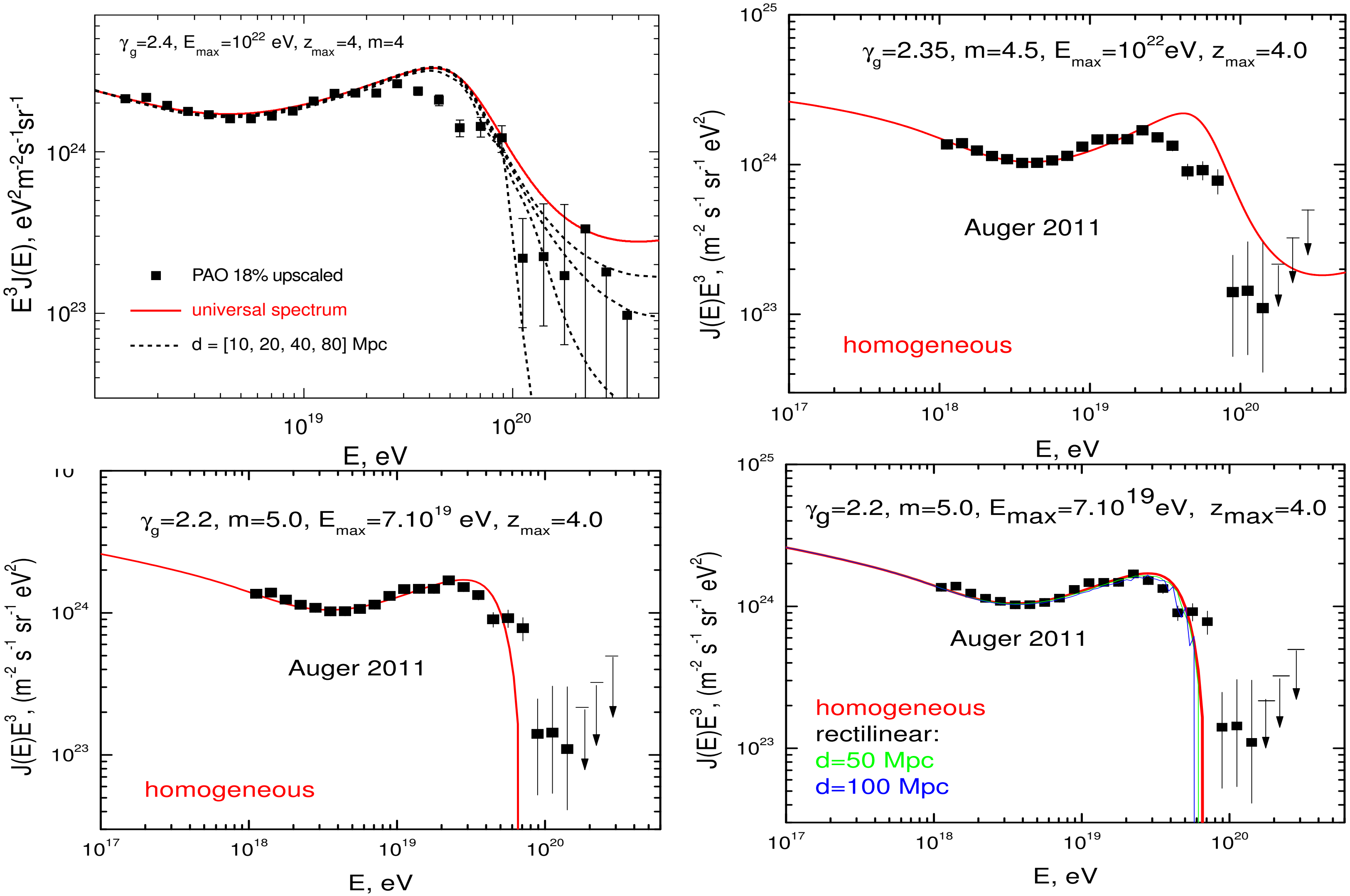






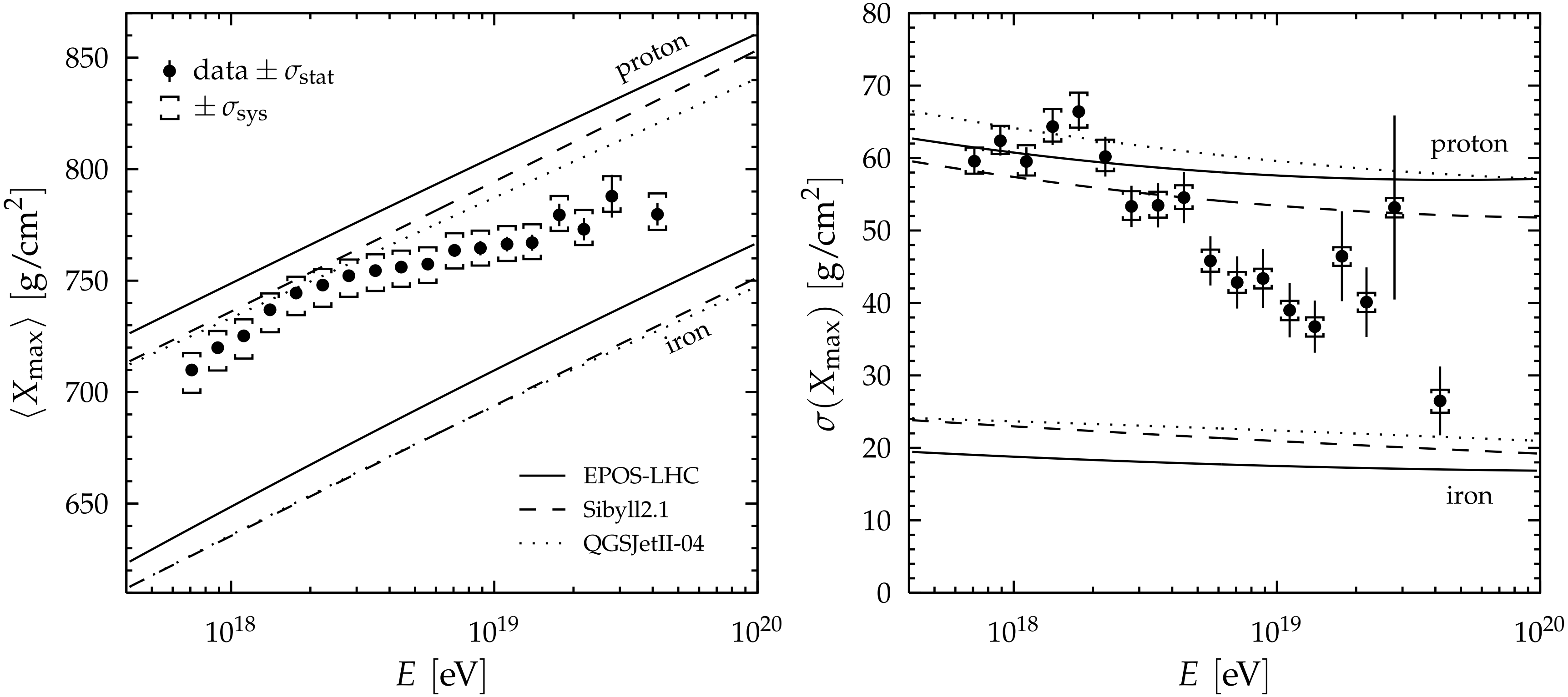
Berezinsky et al (2002) - RA et al. (2007-2012)

Auger Observatory – Energy Spectrum



it is very difficult to explain the Auger flux in the framework of the dip model. At the highest energies the flux suppression seems not compatible with the suppression of the proton flux (GZK). Signal of heavy nuclei.

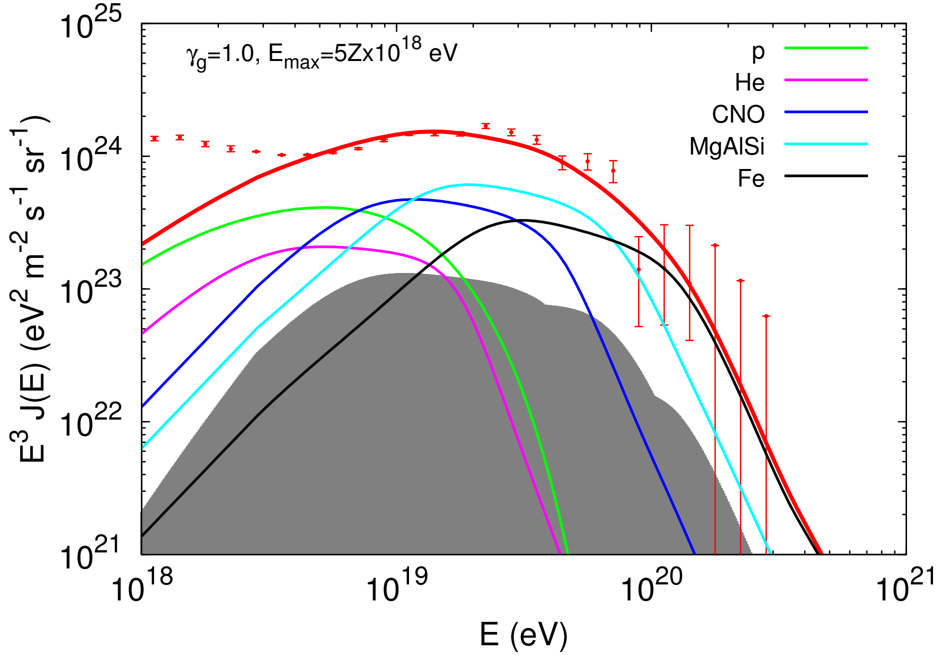
Auger chemical composition



Auger collaboration (2014)

The Auger observations on chemical composition show the tendency for a nuclei dominated flux at the highest energies.

What we can learn from Auger data

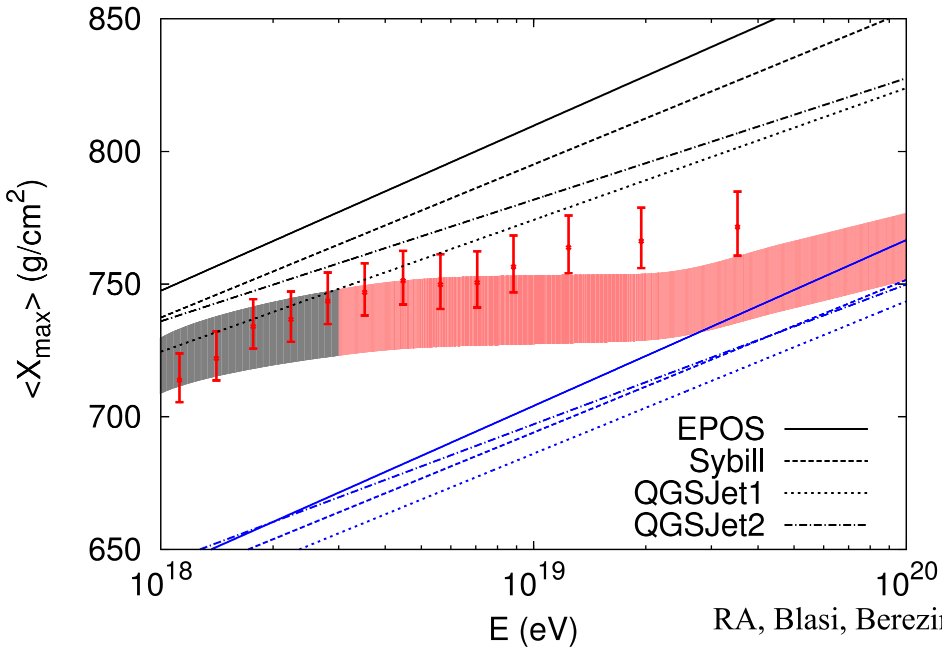


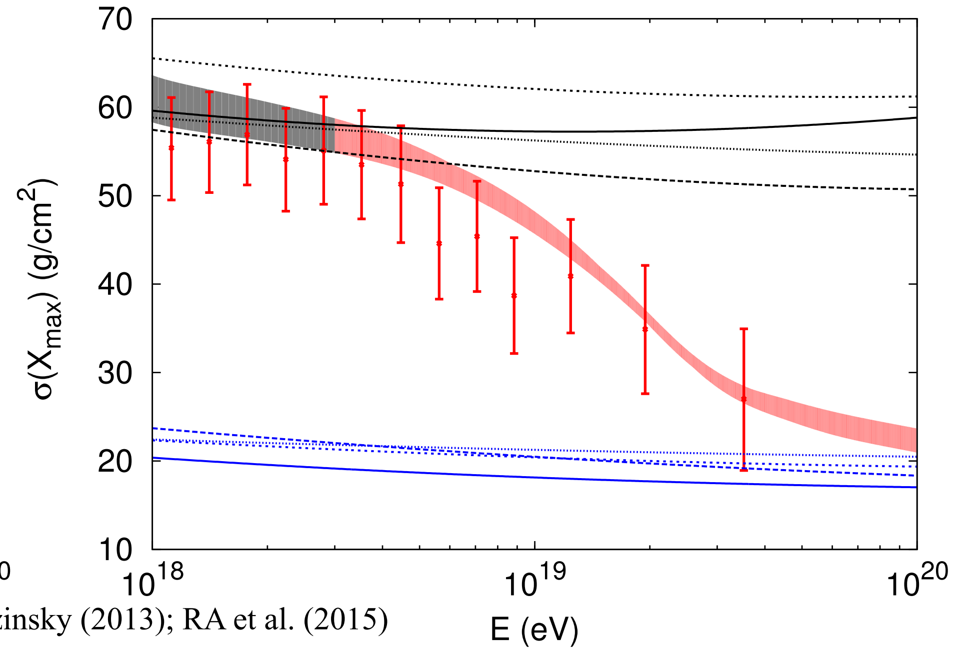
Auger chemical composition can be reproduced assuming a very flat injection of primary nuclei

$$\gamma_g = 1.0 \div 1.5$$

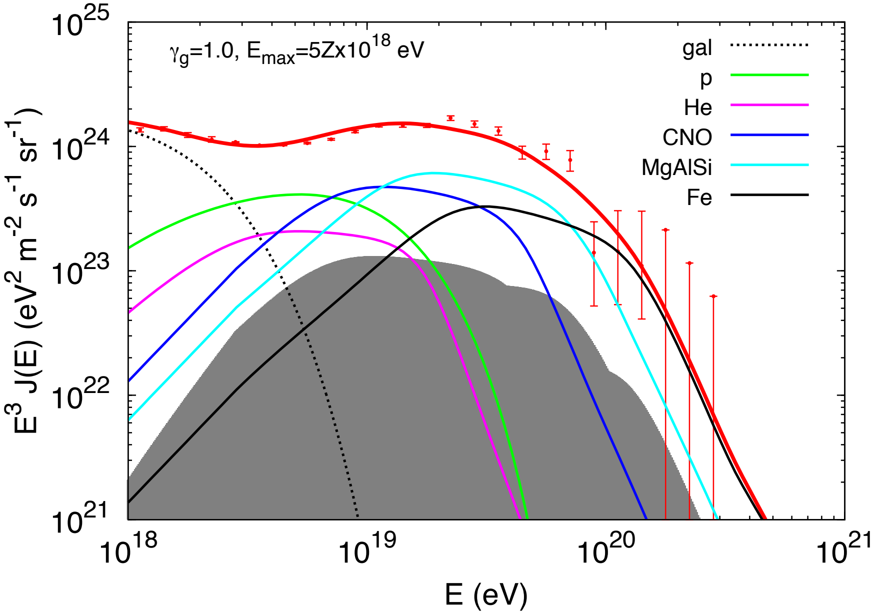
$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{y}}$$

75% p, 15% He, 5% CNO, 3% MgAlSi, 1% Fe.



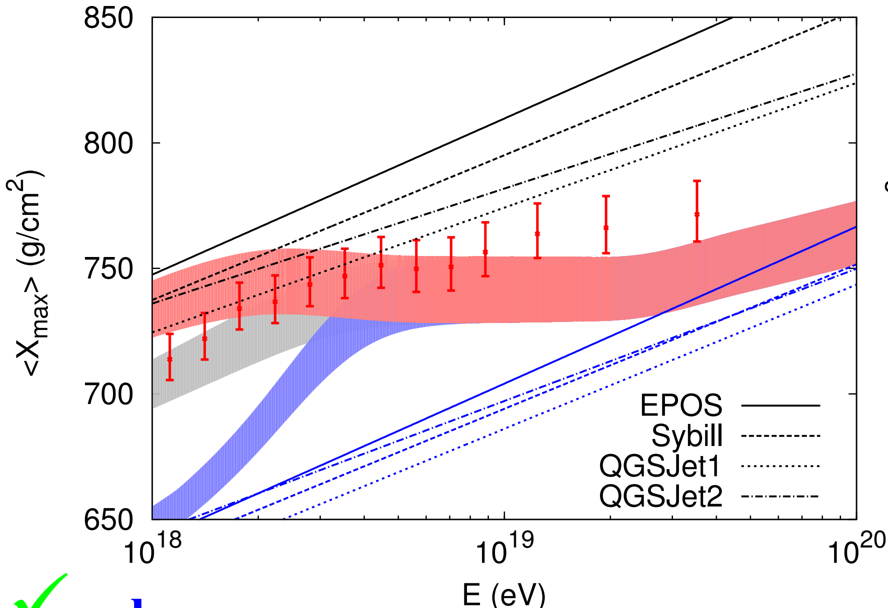


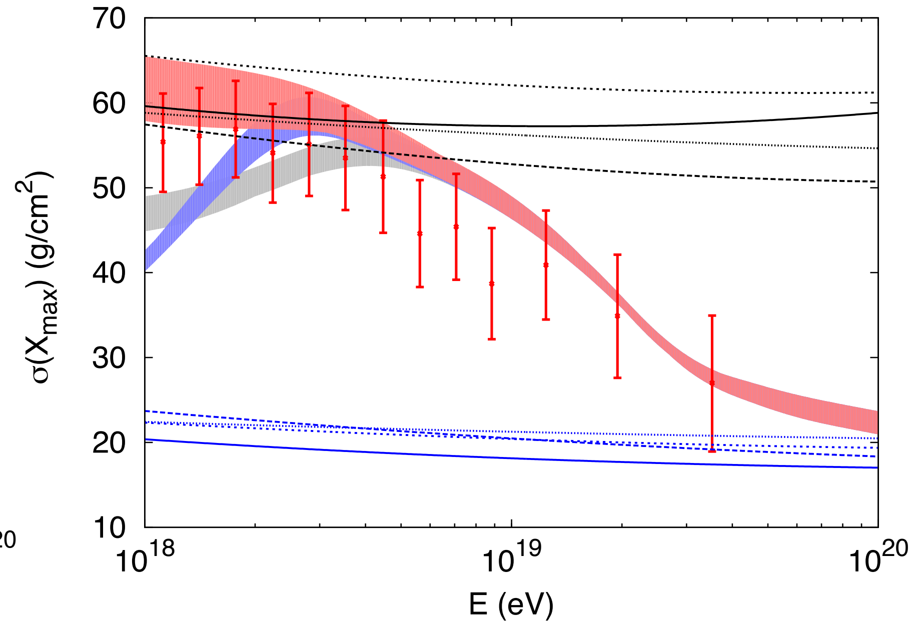
RA, Blasi, Berezinsky (2013); RA et al. (2015)



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.



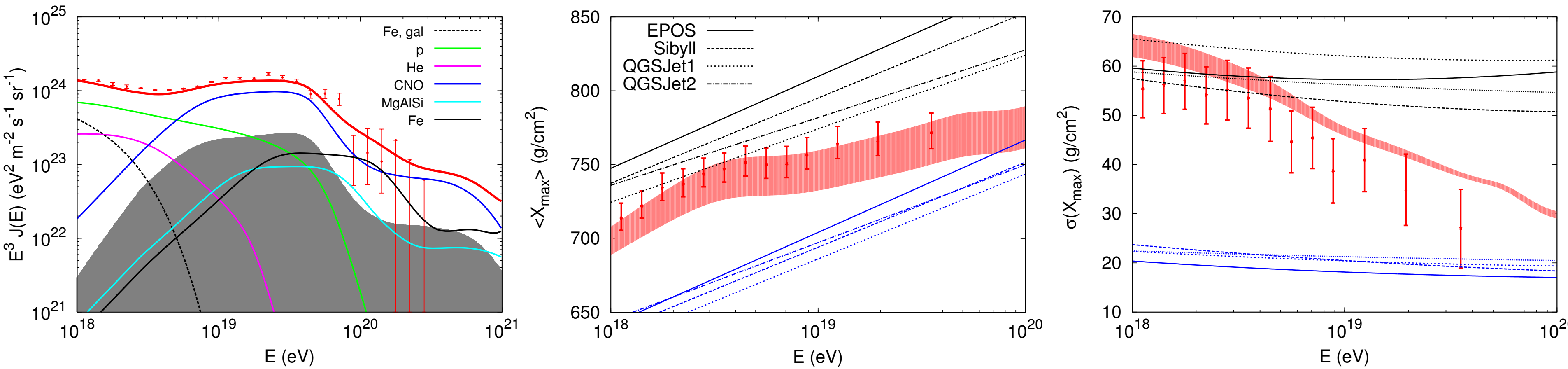


RA, Blasi, Berezinsky (2013)

✓ **pulsars**

flat component from galactic pulsars fills the gap, flat injection, correct emissivity, problems with chemical composition and anisotropy (Auger EeV anisotropy).

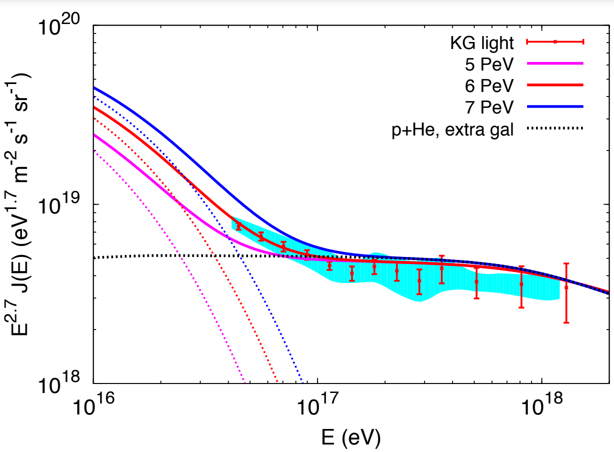
Fang et al. (2013)



Two types of extra-galactic sources:

- ✓ light component steep injection (γ_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 (γ_g<1.5) $\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{y}}$

RA, Blasi, Berezinsky (2013)



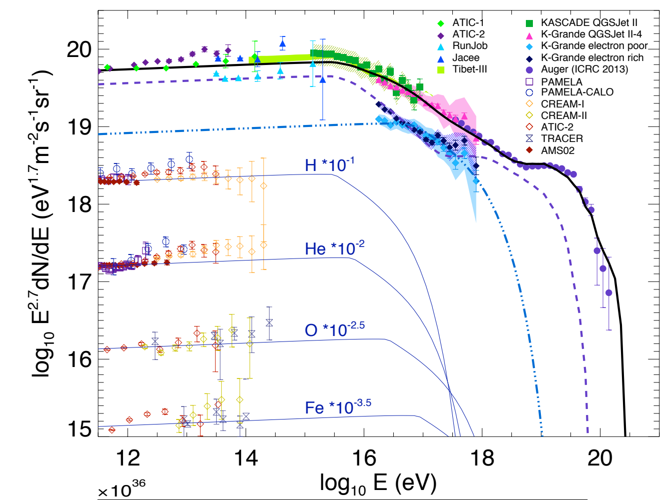
The latest observations of Kascade-Grande seem to confirm the presence of an extragalactic light component with a steep injection spectrum.

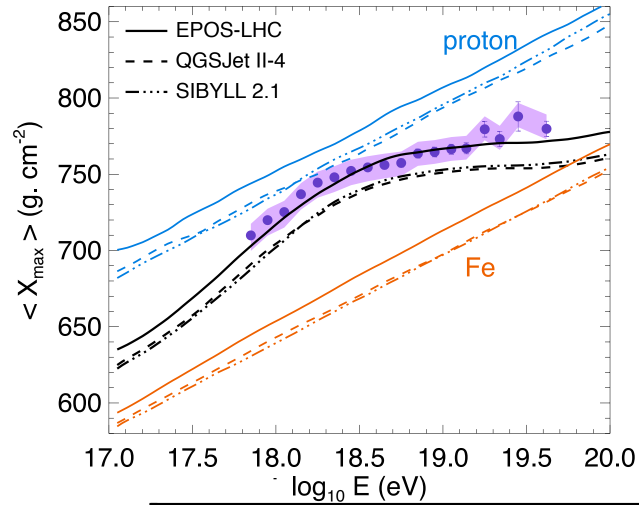
✓ **active galactic nuclei**

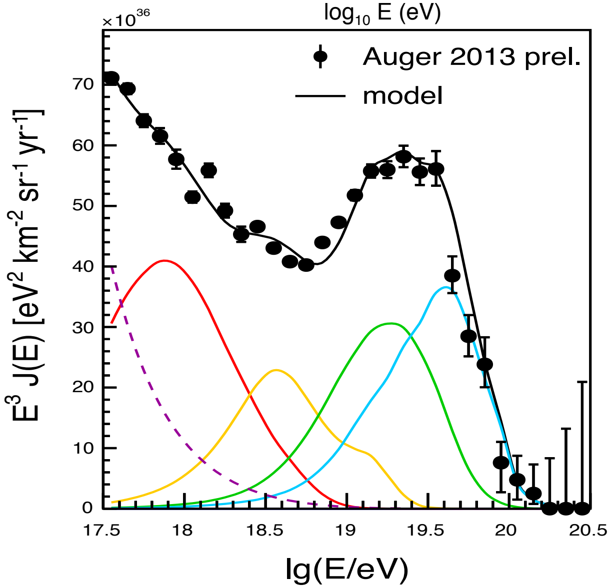
can easily provide steep injection, correct emissivity.

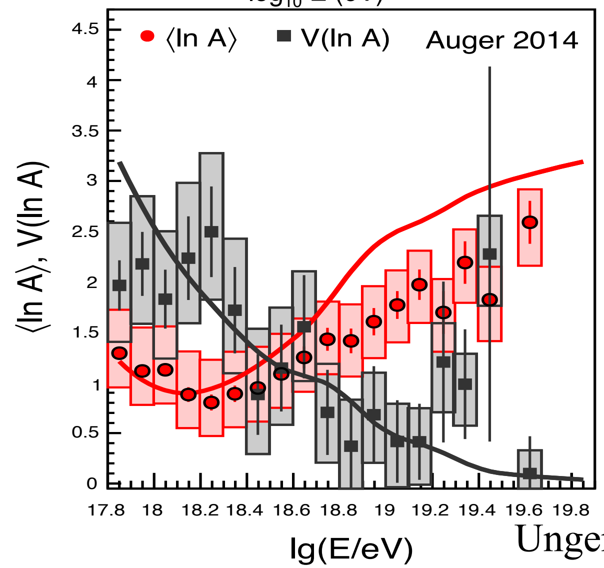
GRB and Galactic CR (pushed at high energies)

Globus, Allard, Parizot (2015)









Unger, Farrar, Anchordoqui (2015)

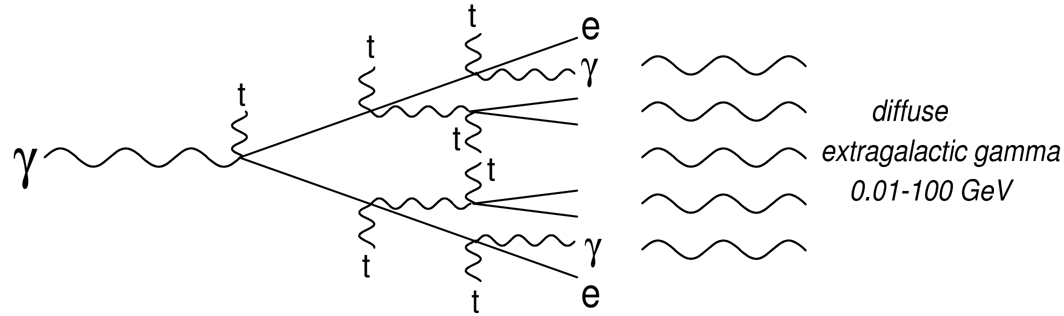
- ✓ Single class of extragalactic sources: Mildly relativistic shocks in GRBs.
- ✓ Photodisintegration at the source. Flat injection for nuclei ($\gamma \approx 1$) and steep for protons ($\gamma > 2$).
- ✓ Agreement with Kascade-Grande.

Galactic CR maximum acceleration energy pushed up to 10^{16} eV
difficult to reconcile with standard DSA in SNR.

Production of secondary γ ν

Cascade upper limit

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

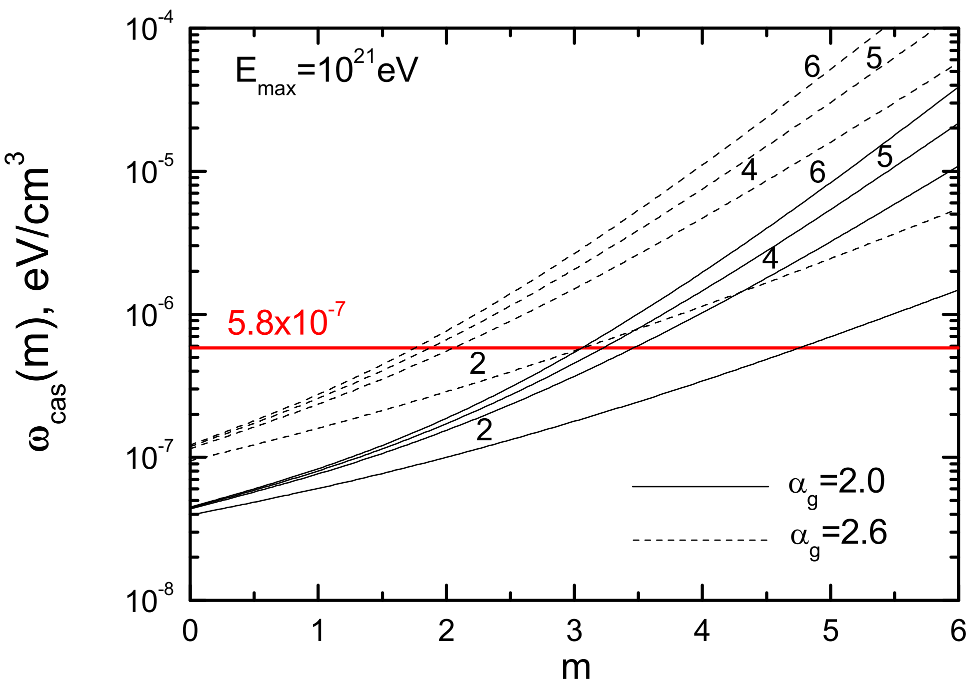


Berezinsky & Smirnov (1979)

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)

Assuming an E^{-2} neutrino flux , the cascade limit can be expressed in terms of the energy densities of photons and e^+e^- initiated cascades

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

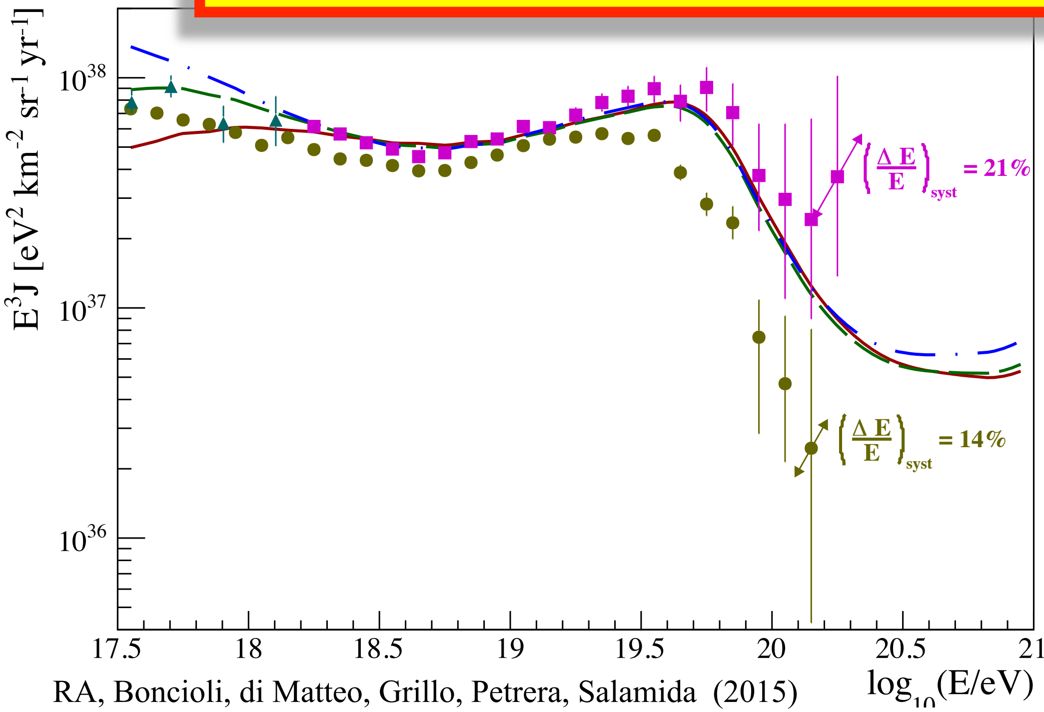
The cascade upper limit constrains the source parameters: cosmological evolution, injection power law and maximum acceleration energy.

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

Dip model – ν spectra

✓ **Injection**

$$Q_{inj}(\Gamma, z) \propto S(z) e^{-\Gamma/\Gamma_{max}} \begin{cases} 1/\Gamma^2 & \Gamma < \Gamma_0 \\ \frac{1}{\Gamma_0^2}\left(\frac{\Gamma}{\Gamma_0}\right)^{-\gamma_g} & \Gamma \geq \Gamma_0. \end{cases}$$



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

✓ **Cosmological evolution**

Star Formation Rate

$$S_{\rm SFR}(z) = \begin{cases} (1+z)^{3.4} & z < 1 \\ 2^{3.7}(1+z)^{-0.3} & 1 < z < 4 \\ 2^{3.7}5^{3.2}(1+z)^{-3.5} & z > 4 \end{cases}$$

Radio Loud AGN

$$S_{\rm AGN}(z) = \begin{cases} (1+z)^{5.0} & z < 1.7 \\ (1+1.7)^{5.0} & 1.7 < z < 2.7 \\ (1+1.7)^{5.0} 10^{(2.7-z)} & z > 2.7 \end{cases}$$

✓ The flux in the EeV region depends on the assumed cosmological evolution of sources.

✓ Transition galactic-extragalactic and production of cosmogenic neutrinos strongly depend on the cosmological evolution of sources

✓ 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.

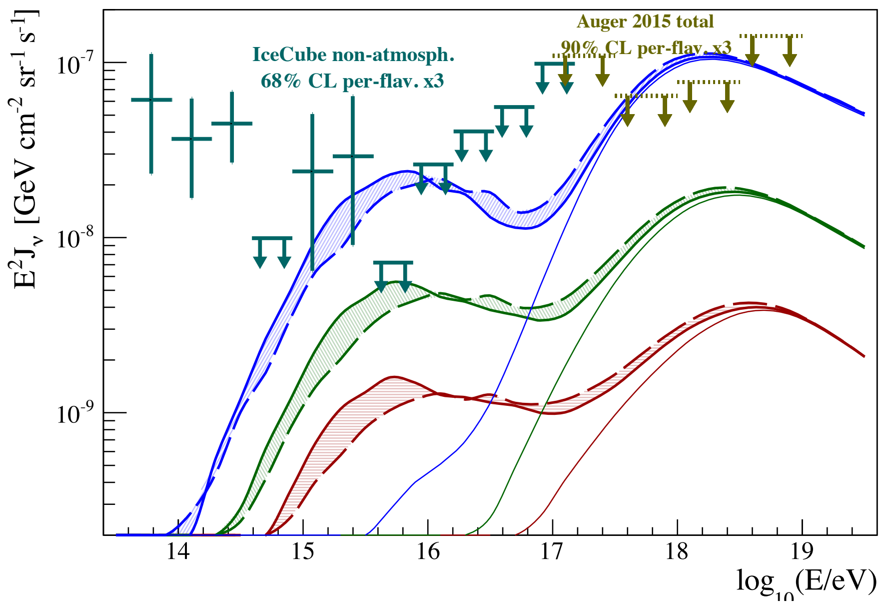
✓ Cosmological evolution

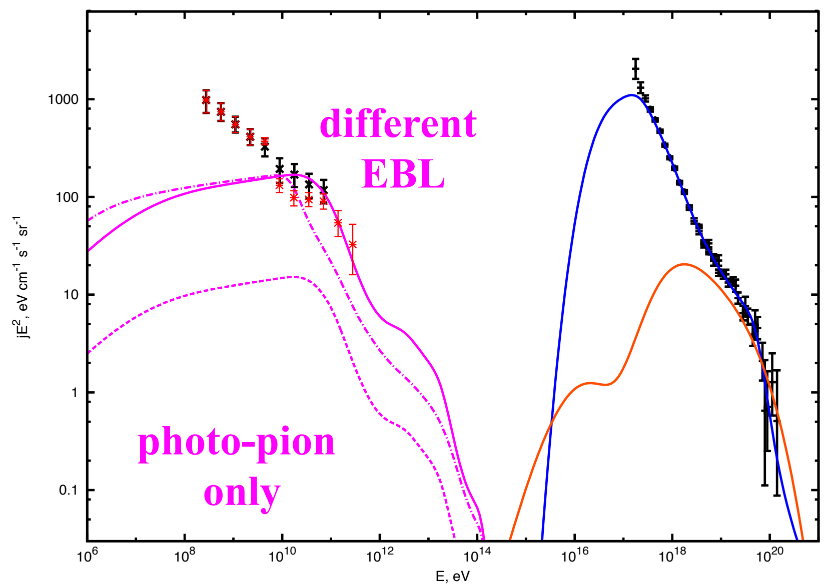
The result on the diffuse flux depends on the cosmological evolution assumed for the sources. The IceCube observations at PeV can be reproduced in the case of strong cosmological evolution (AGN like).

✓ Source constraints

The high energy neutrino flux provides another constraint to UHECR sources.

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



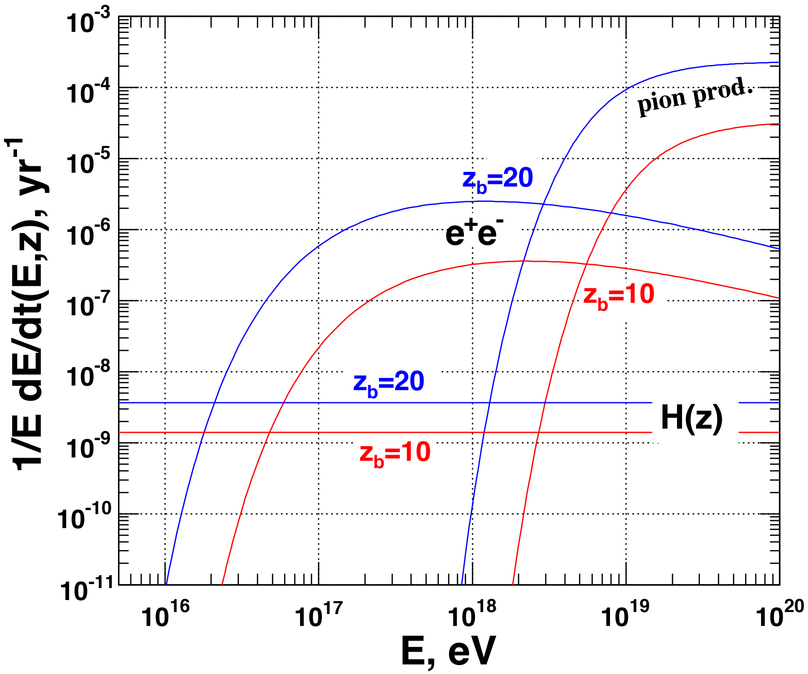


Gelmini, Kalashev, Semikoz (2012)

PeV neutrinos from pop III stars

- ✓ massive stars (100 M_{sol}) at $z \approx 10 \div 20$
- ✓ protons acceleration with $\gamma_g = 2.0 \div 2.3$
- ✓ $E_{max} = 10^{21}$ eV

Photo pion production responsible for the generation of neutrinos dominates at energy above the crossing of the pair-production and pion production curves.



$$E_\nu = \frac{1}{20}\frac{E_{p\gamma\to\pi}}{(1+z_b)^2} \simeq 7.5\times 10^{15}\left(\frac{20}{1+z_b}\right)^2\ eV$$

$$E_\nu^2 J_\nu(E_\nu) = 0.1\frac{c}{4\pi}\frac{\omega_p(z_b)}{(1+z_b)^4}\frac{1}{\ln(E_{max}/E_{min})}$$

$$\omega_p \gtrsim 10^{-6}\mathrm{eV/cm^3}$$

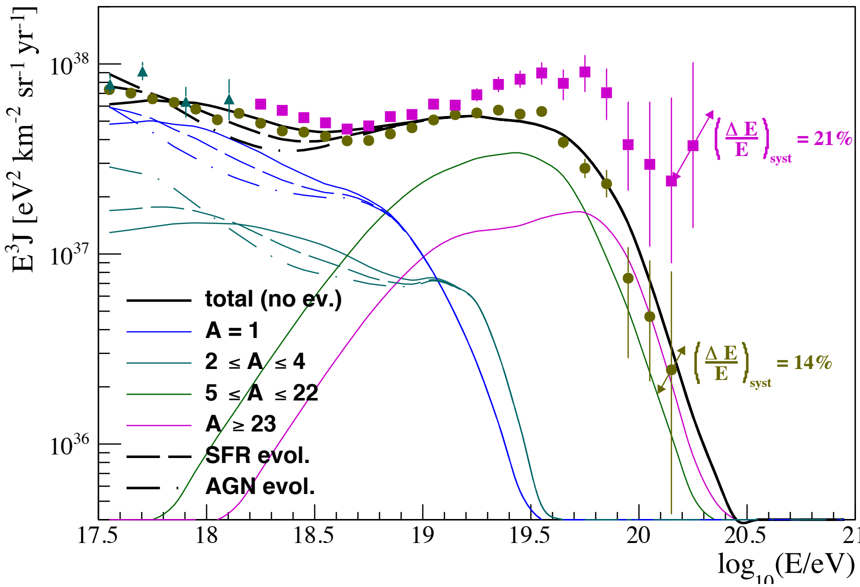
Ice Cube detectable

Berezinsky and Blasi (2012)

Mixed composition model – ν spectra

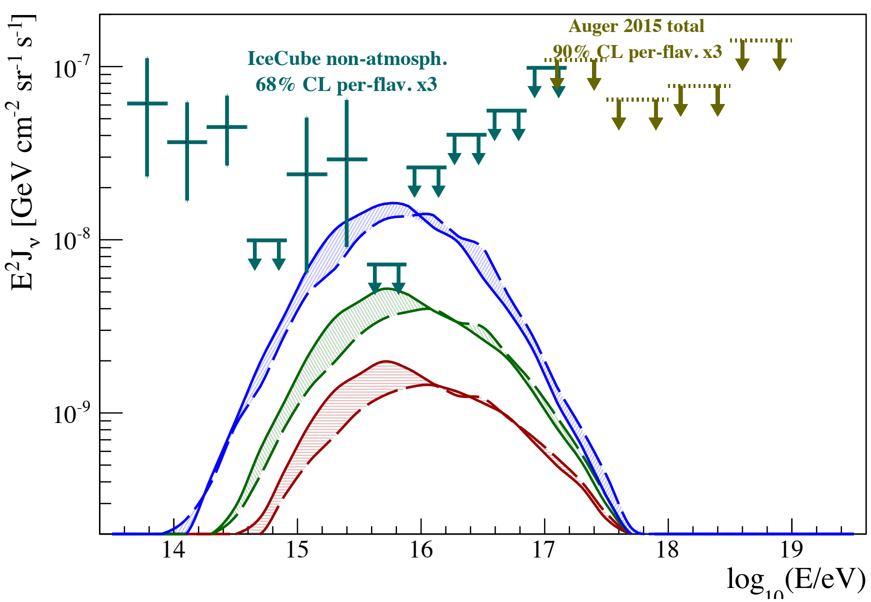
✓ **EeV neutrinos**

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).



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

γ from distant AGN

The observed high energy gamma ray signal by distant blazars may be dominated by secondary gamma rays produced along the line of sight by the interaction of UHE protons with background photons. This hypothesis solves the problems connected with the gamma ray flux observed by too distant AGN.

$$J_{\gamma,primary} \propto \frac{1}{d^2} exp^{-d/\lambda_\gamma}$$

$$J_{\gamma,secondary} \propto \frac{p\lambda_\gamma}{4\pi d^2}\left[1 - e^{-d/\lambda_\gamma}\right]$$

For sources at large distances the secondary gammas dominate.

$$\Delta\theta \simeq 0.1^\circ \left(\frac{B}{10^{-14}G}\right)\left(\frac{4\times 10^7 GeV}{E}\right)\left(\frac{D}{1Gpc}\right)\left(\frac{l_c}{1Mpc}\right)$$

$$\Delta t \simeq 10^4 y \left(\frac{B}{10^{-14}G}\right)^2\left(\frac{10^7 GeV}{E}\right)^2\left(\frac{D}{1Gpc}\right)^2\left(\frac{l_c}{1Mpc}\right)$$

this model requires low IMF at the level of femtogaus (10^{-15} G).

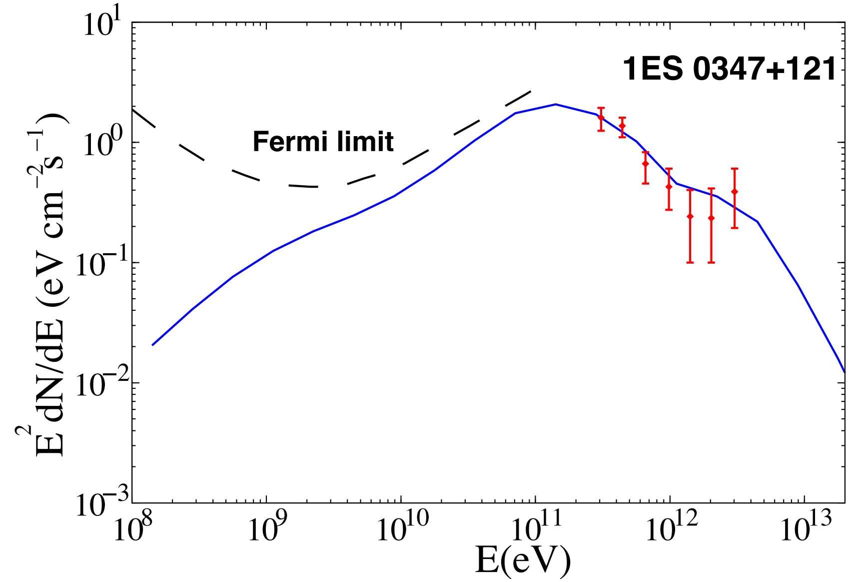
The spectrum of the final cascade is universal. The EM cascade behaves as a sort of calorimeter that redistribute the initial energy into gamma rays and neutrinos with a given spectrum.

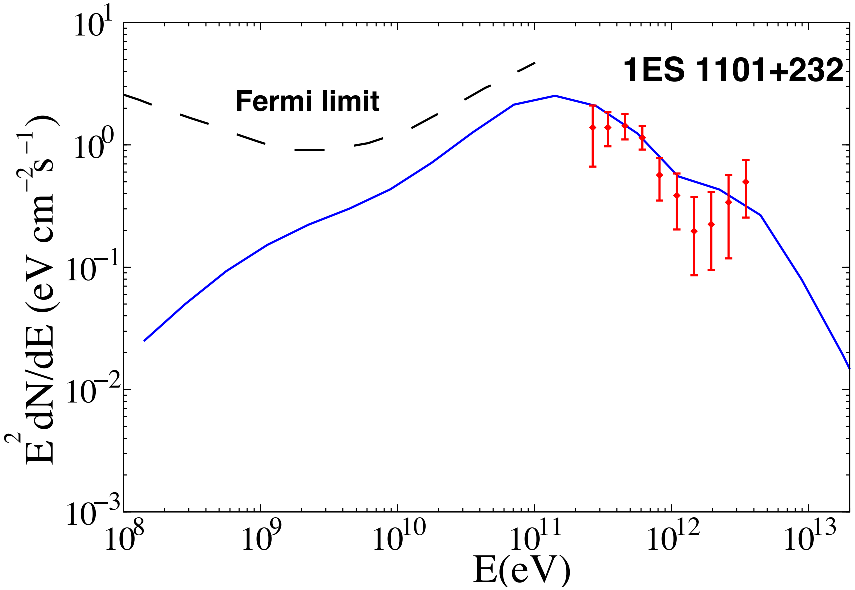
Ferrigno, Blasi, De Marco (2004) Essey, Kalashev, Kusenko, Beacom (2009-13)

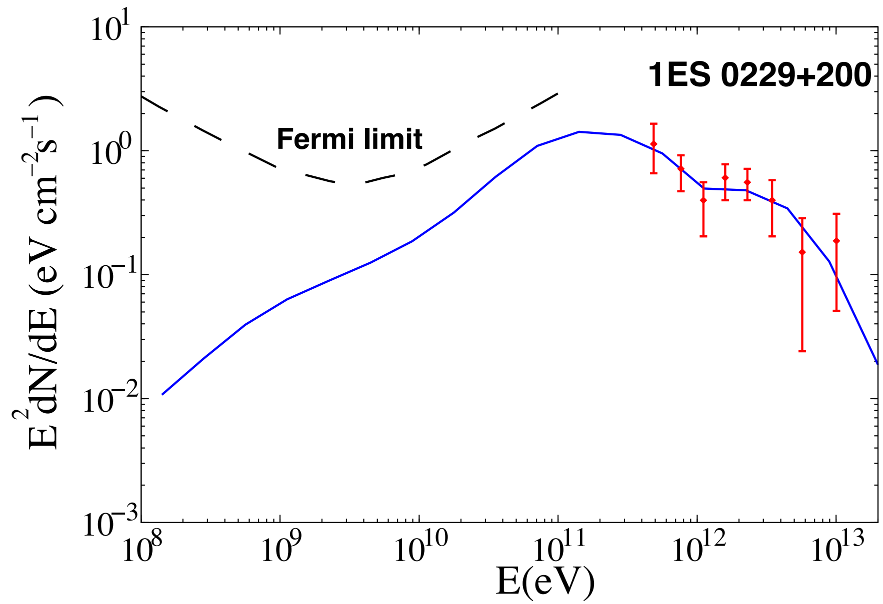
gamma rays (HESS)

The shape of the spectrum is fixed by the EBL, the overall height is proportional to the product of UHECR luminosity and the level of EBL.

The effect of different E_{max} is to change the relative contribution of the different reactions to the flux of secondaries. If E_{max} is large (>10 EeV) interaction on CMB dominates, otherwise photo-pion production on EBL plays a role (provided that $E_{max}>10^8$ GeV).







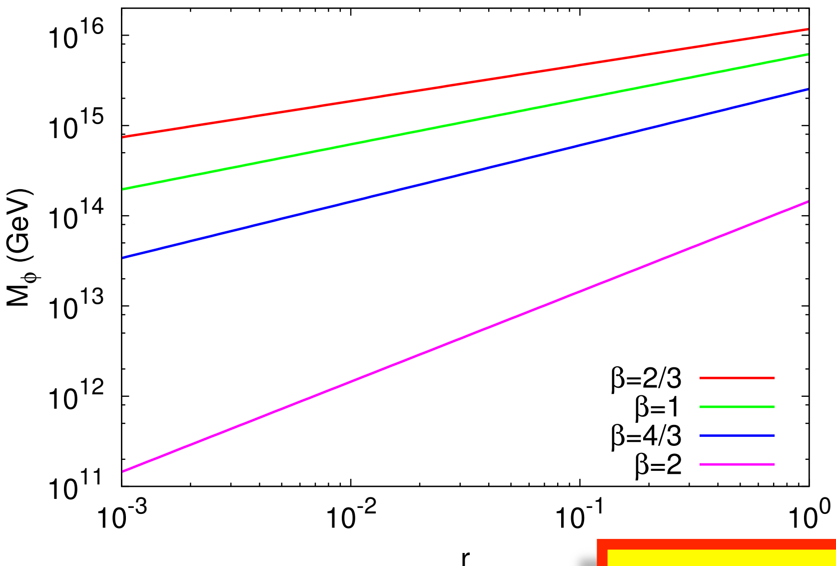
Essey, Kalashev, Kusenko, Beacom (2011)

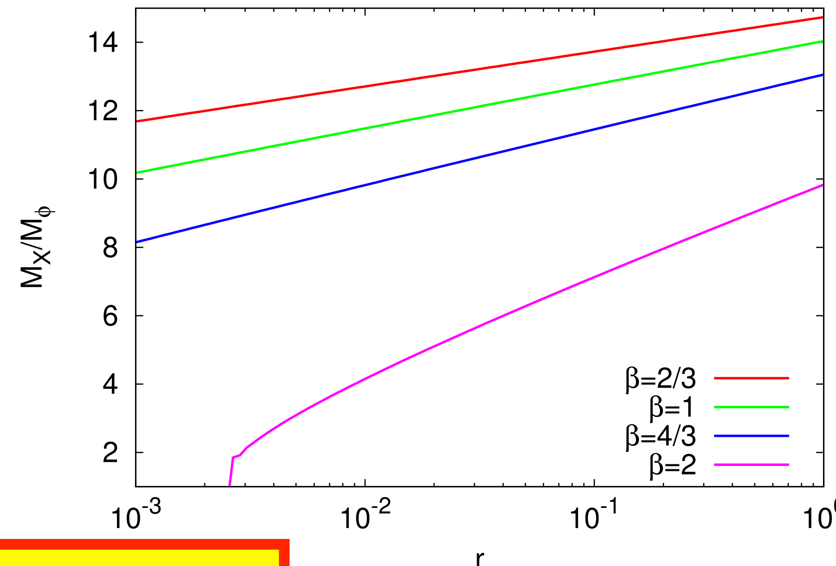
Extreme energies: Cosmology, DM, UHE γ & ν

The tensor-to-scalar ratio in CMB fluctuations (r) sets the scale for models where the dark matter is created at the inflationary epoch, the generically called super-heavy dark matter models. These scenarios can be constrained by ultrahigh energy cosmic ray, gamma ray and neutrino observations which set the limit on super-heavy dark matter particles lifetime. Super-heavy dark matter can be discovered by a precise measurement of r combined with future observations of ultra high energy cosmic rays, gamma rays and neutrinos.

$$V(\phi) = \frac{M_\phi^{4-\beta}}{\beta}\phi^\beta \qquad V_\star \simeq \frac{3\pi^2}{2}A_s r M_{Pl}^4 \simeq M_{GUT}^4\left(\frac{r}{r_0}\right)$$

$$\epsilon(\phi) = \frac{M_{Pl}^2}{16\pi}\left[\frac{V'(\phi)}{V(\phi)}\right]^2 = \frac{r}{16} \qquad \Omega_X(t_0) \simeq 10^{-3}\Omega_R\frac{8\pi}{3}\left(\frac{T_{RH}}{T_0}\right)\left(\frac{M_\phi}{M_{Pl}}\right)^2\left(\frac{M_X}{M_\phi}\right)^{5/2} e^{-2M_X/M_\phi}$$

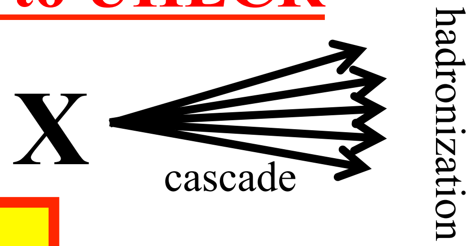




RA, Matarrese, Olinto (2015)

SHDM mass M_X determined assuming $\Omega_X = \Omega_{DM}$ today

From SHDM to UHECR

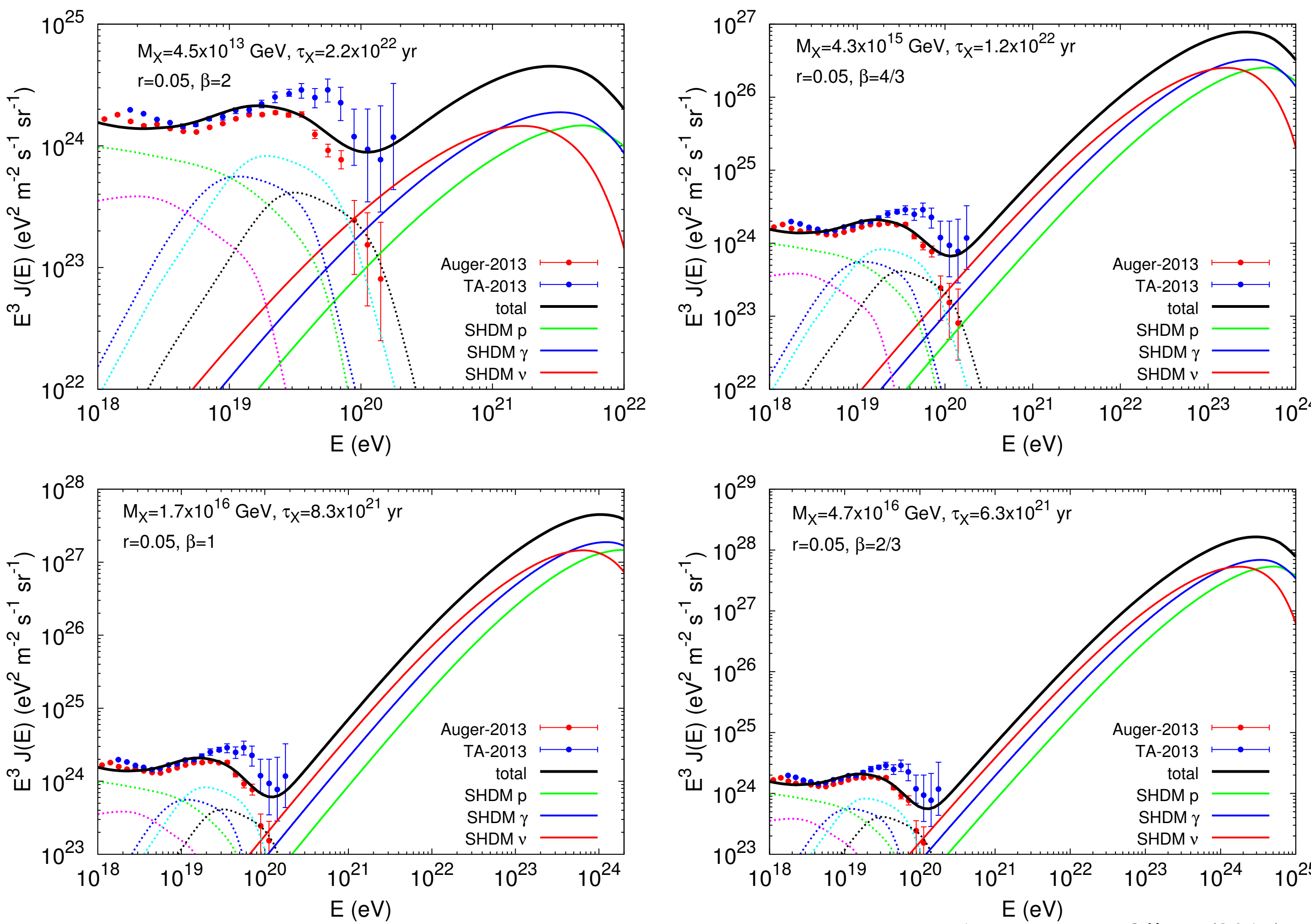


mainly π
therefore γ and ν

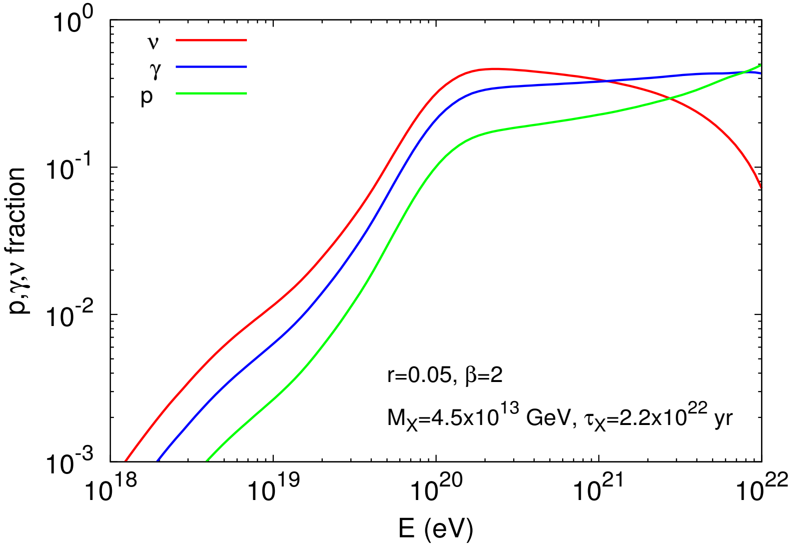
$$Q_{\nu,\gamma,p} \propto E^{-1.9}$$

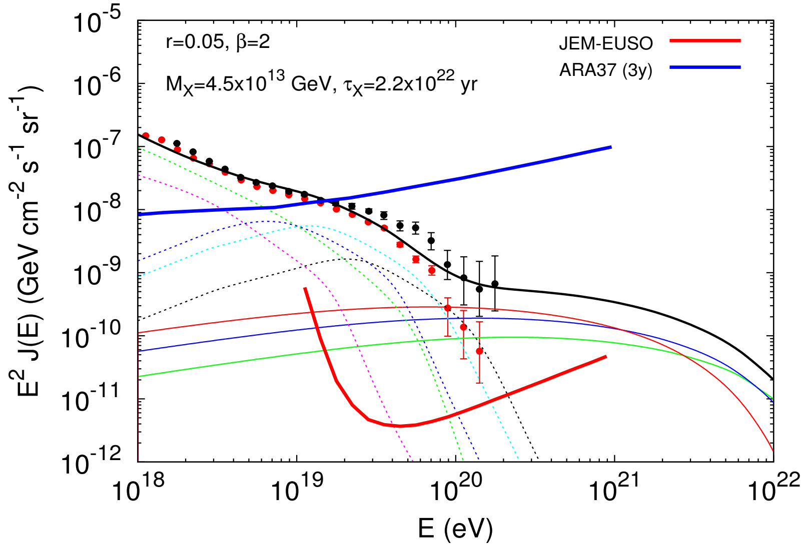
$$J_{\nu,\gamma,p} \propto \frac{1}{M_X \tau_X}$$

- ✓ SHDM lifetime τ_X regulates the expected CR flux.
- ✓ SHDM halo density profile (Moore in figs)
- ✓ Integrating over the whole sky.
- ✓ Taking into account the whole universe.

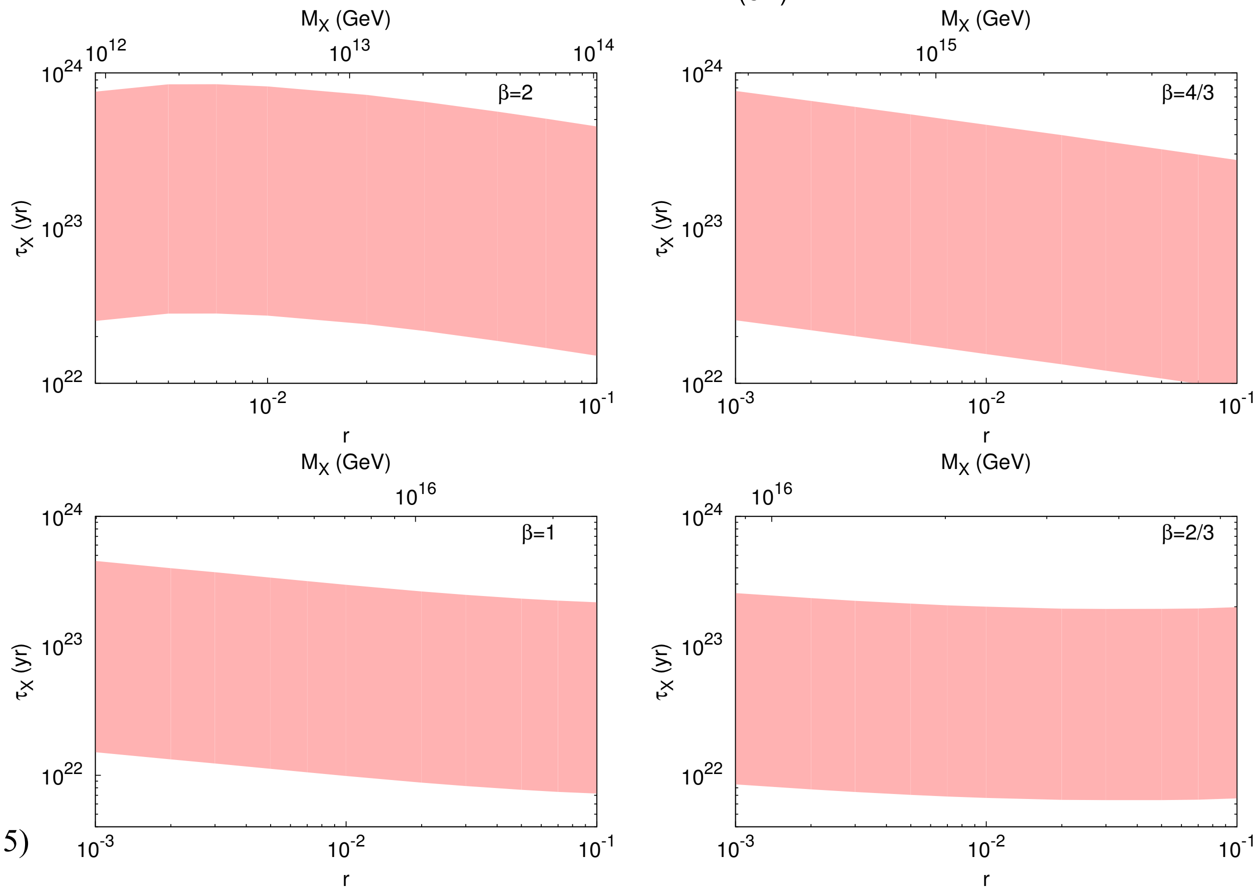


RA, Matarrese, Olinto (2015)





- ✓ UHECR experiments are more suitable to detect UHE particles produced by SHDM decays.
- ✓ JEM-EUSO has the capability of exploring SHDM till $\tau_X \sim 10^{24}$ yr.



RA, Matarrese, Olinto (2015)

Conclusions

Cosmogenic particles production

- Auger scenario (UHECR heavy composition) very low fluxes of gamma and neutrinos, impossible to detect at the highest energies. PeV neutrinos and 100 GeV gammas within reach IceCube and Fermi.
- HiRes/TA scenario (UHECR proton composition) fluxes of gamma and neutrinos detectable at all energies. Within reach the detection capabilities of Fermi, IceCube and Auger.
- PeV neutrinos can be produced by the interaction of low energy protons (10^{16} eV< E < 10^{18} eV, low energy tail of UHECR) with the EBL background (photo-pion production).
- EBL evolution models are important.

Super Heavy Dark Matter

- The observation of UHECR at extreme energies (E>10^{20} eV) can set stringent limits on the SHDM lifetime. SHDM can be discovered by a precise measurement of r combined with future observations of ultra high energy cosmic rays and neutrinos.