High Energy Cosmic Rays and the production of cosmogenic neutrinos and gamma rays

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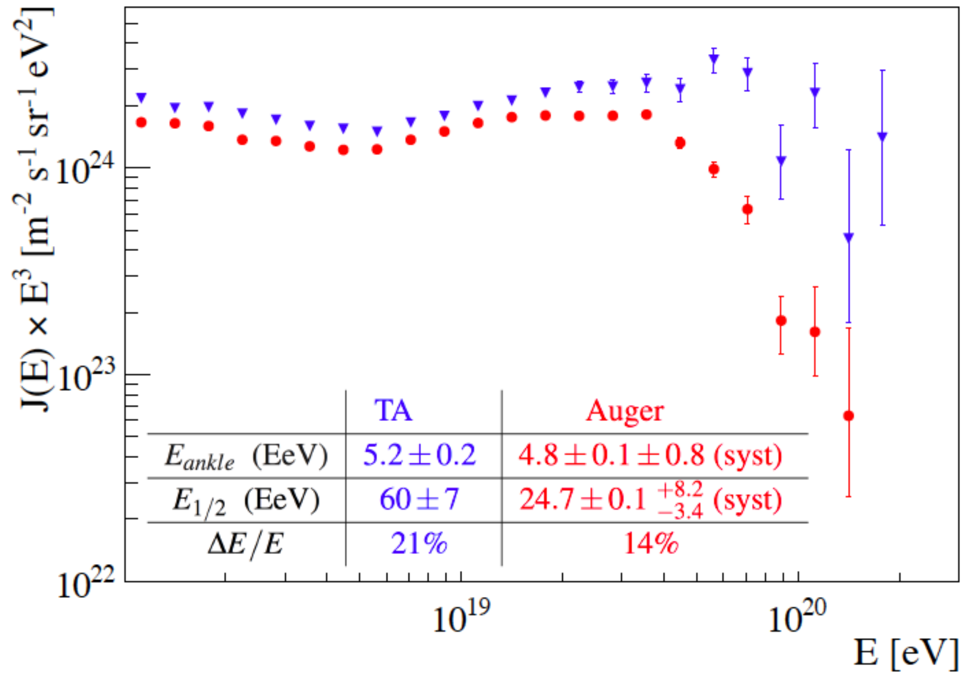
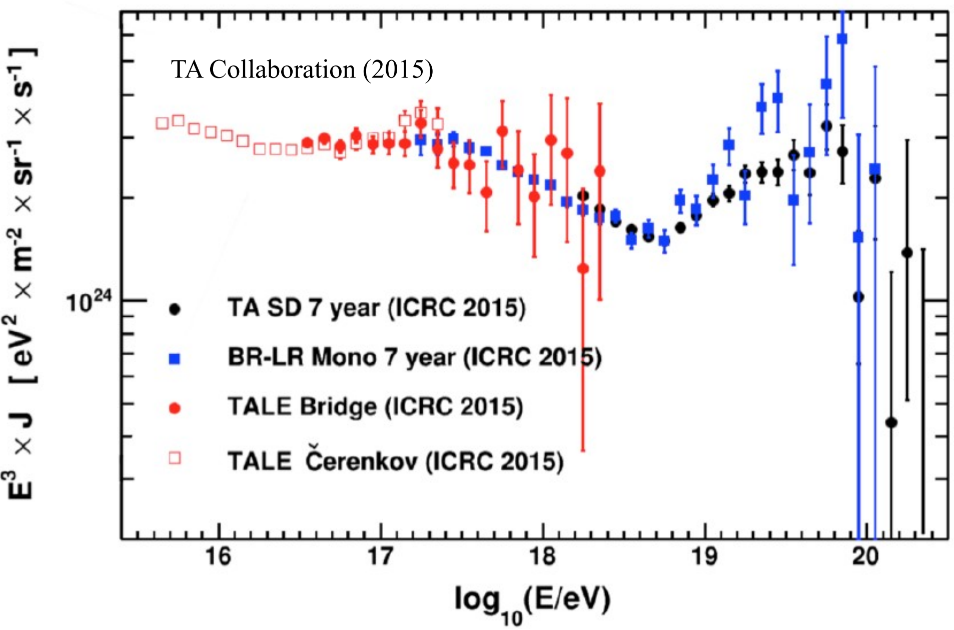
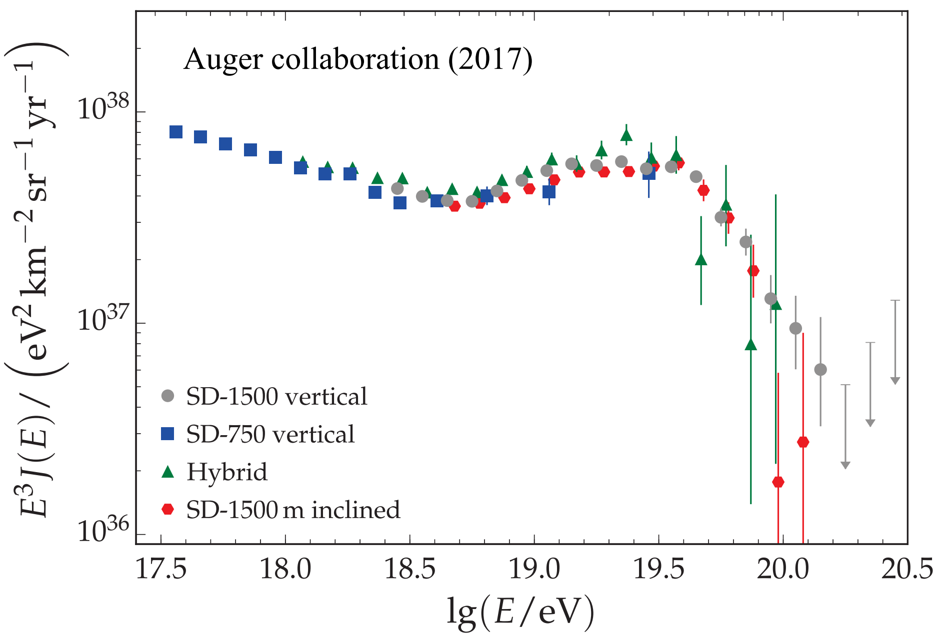
Ultra High Energies Cosmic Rays – Spectrum

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

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

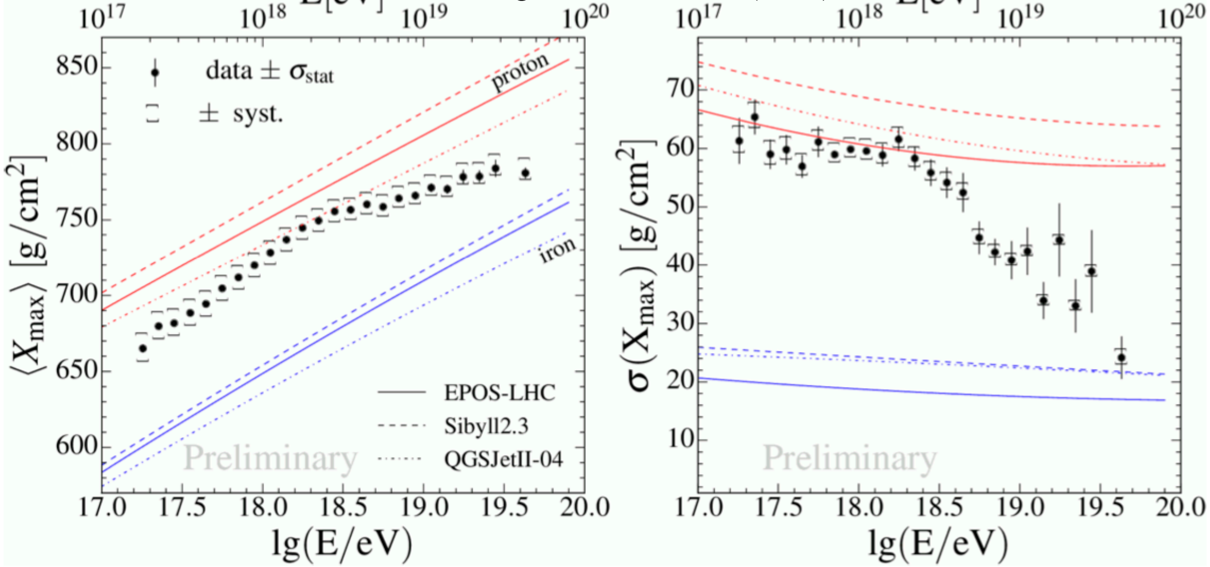




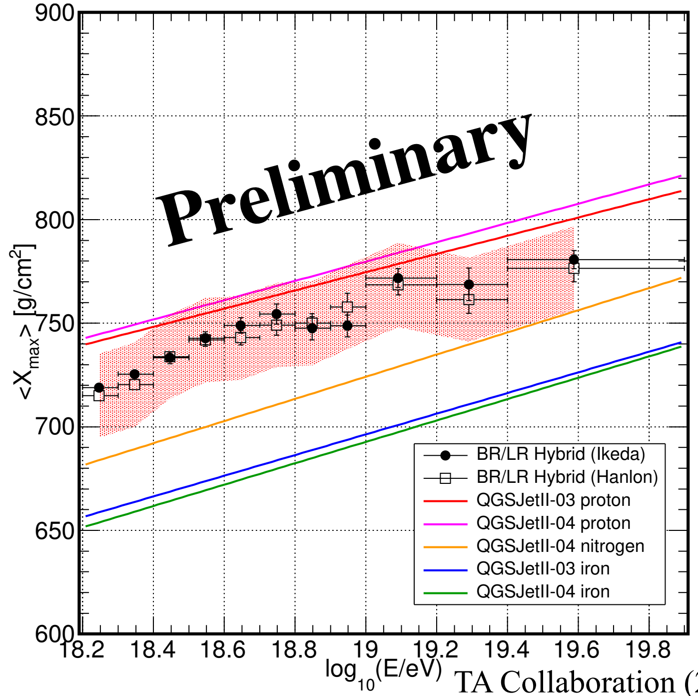


Ultra High Energies Cosmic Rays – Composition

Auger Collaboration (2017)

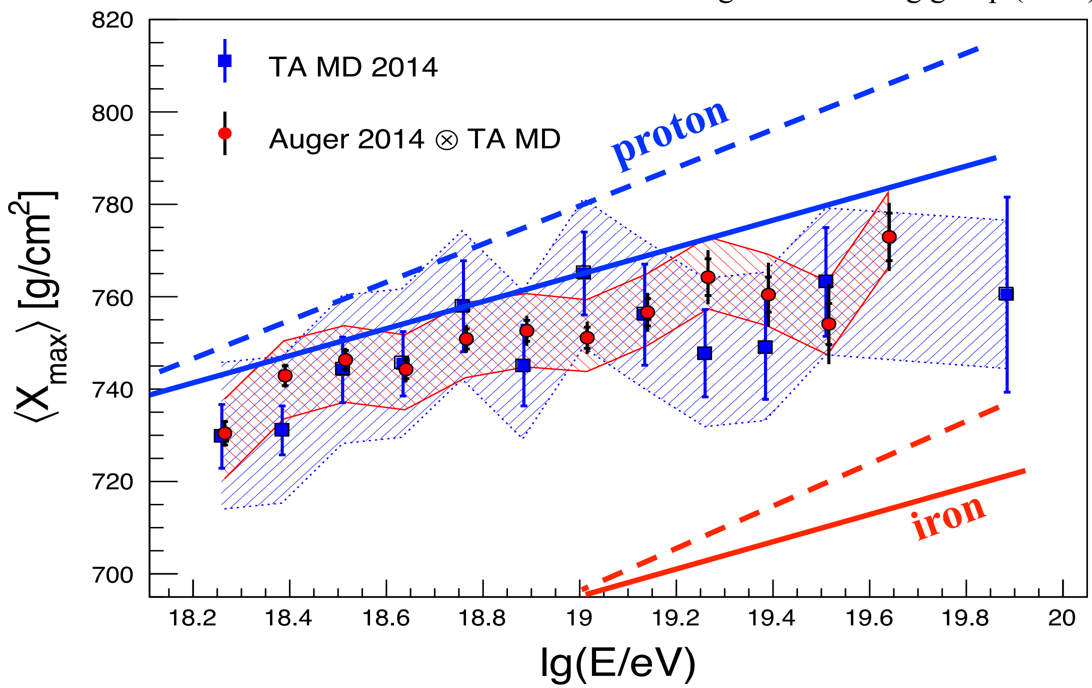


- ✓ **Auger**: protons at low energy and heavier nuclei at high energy.
- ✓ **TA**: protons only.
- ✓ **Strong uncertainties due to the hadronic interaction model.**

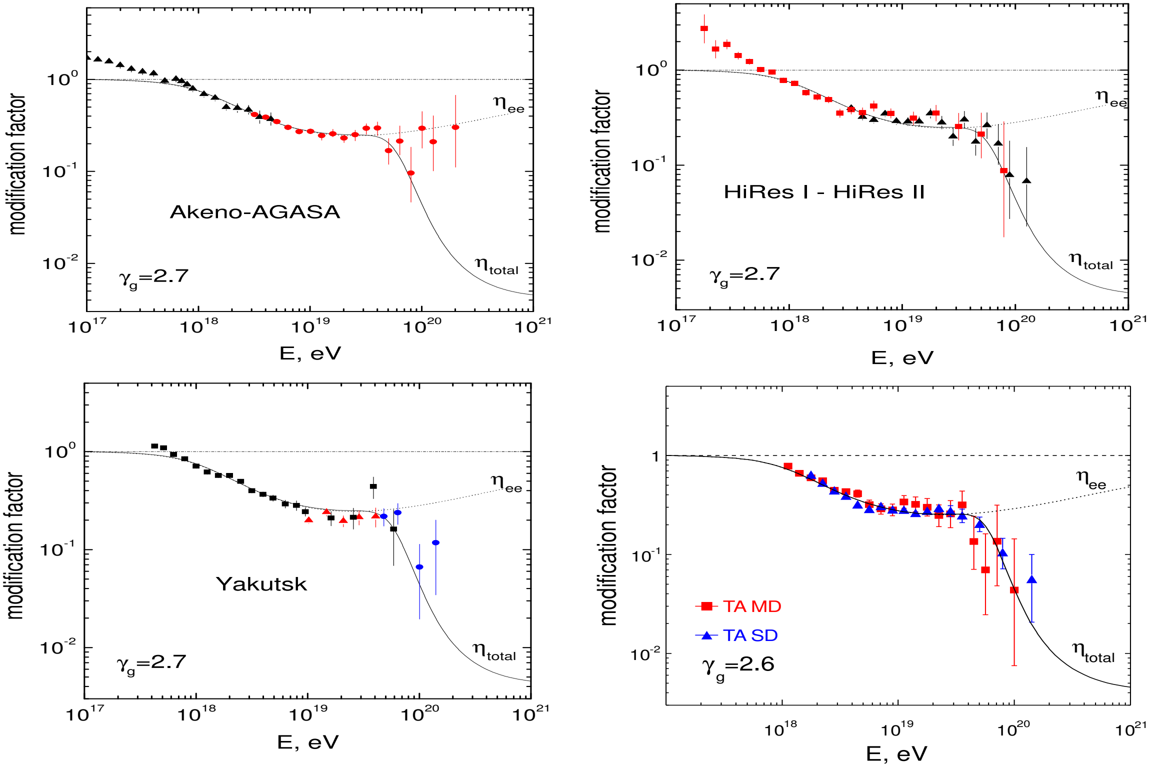


TA Collaboration (2(

Auger-TA working group (2015)



Dip Model

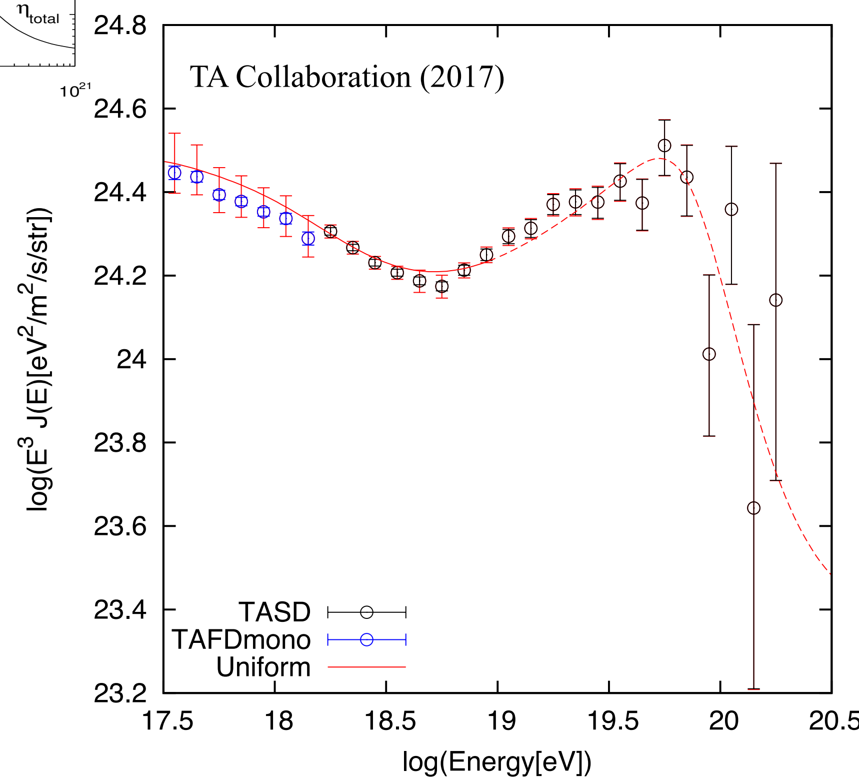


Berezinsky et al (2002-2007)

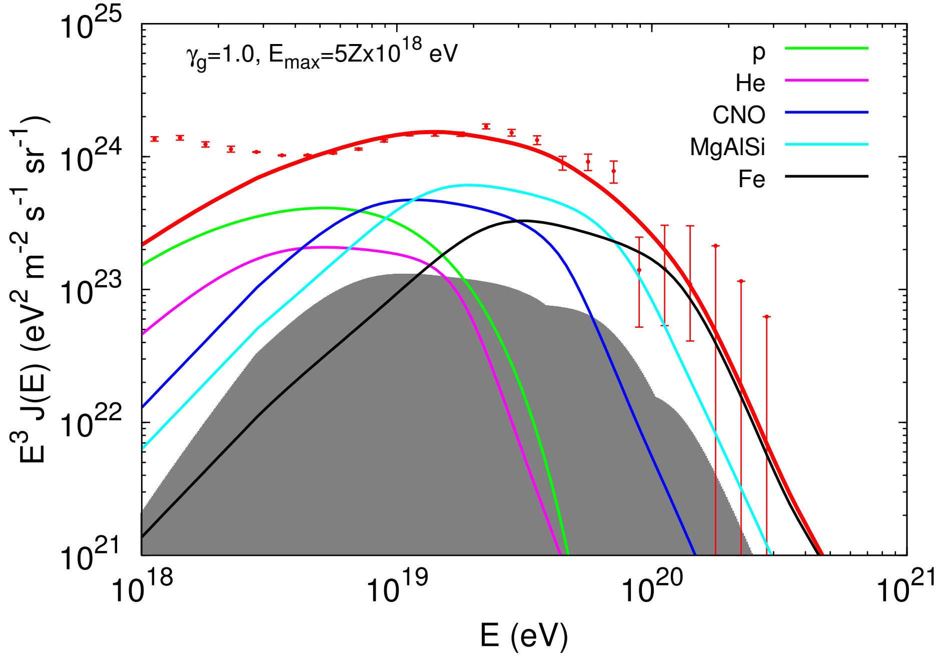
Protons footprint

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. The dip model requires: (i) steep injection (γ>2.5) and (ii) large maximum energy (E_{max}>10^{20} eV).

✓ TA surface detector events compared with theoretical expectation of the dip model, with uniformly distributed source.



What we can learn from Auger data

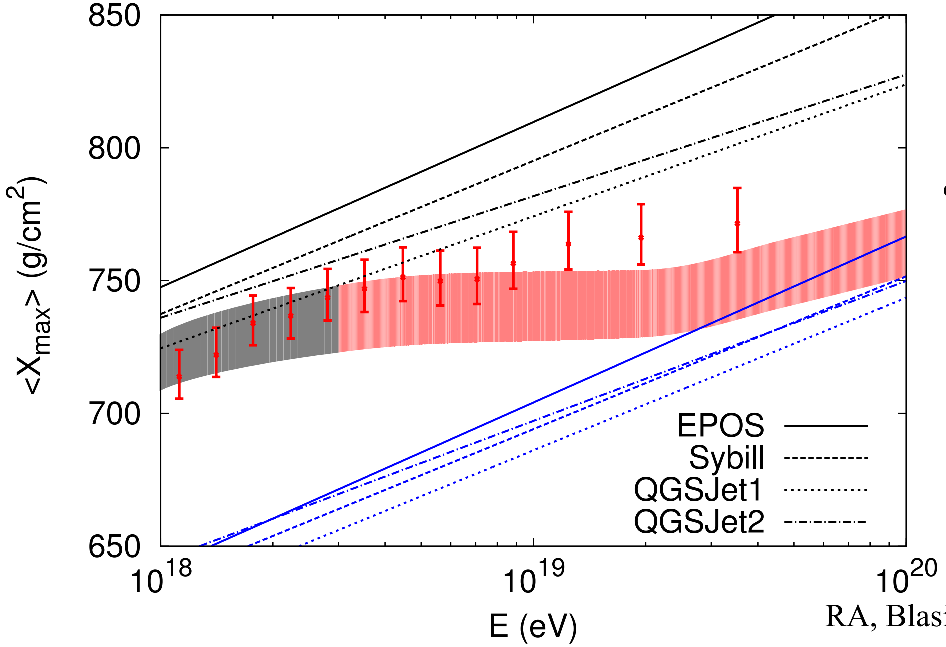


Auger chemical composition can be reproduced only assuming a very flat injection of primary nuclei

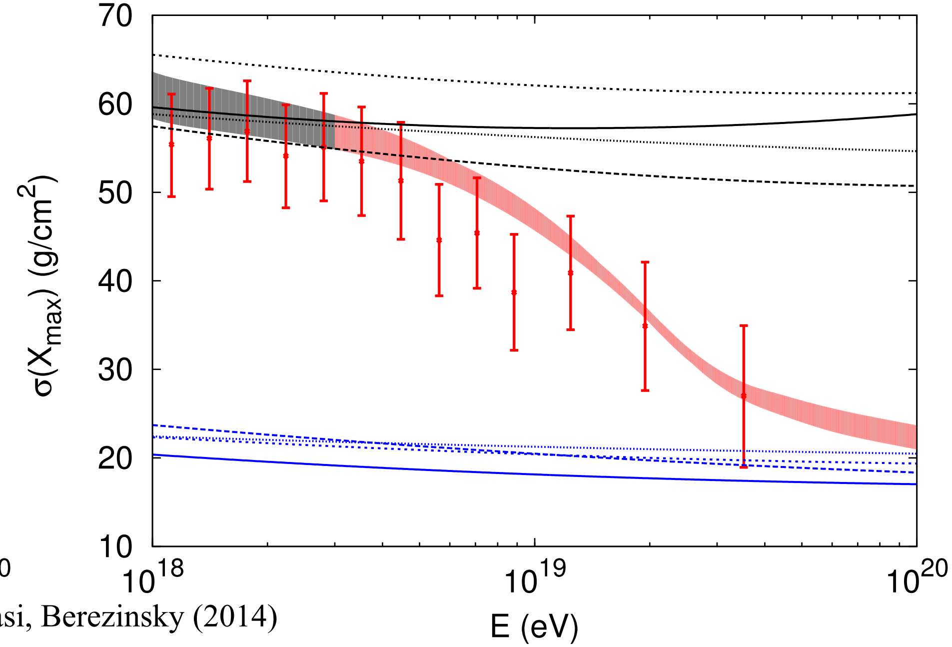
$$\gamma_g = 1.0 \div 1.5$$

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

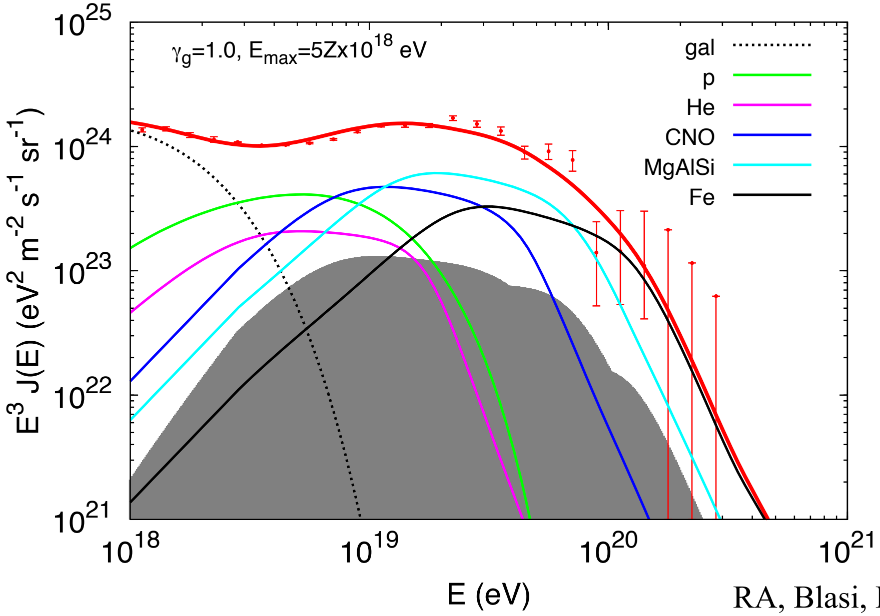
with a certain level of degeneracy in terms of the nuclei species injected



RA, Blasi, Berezinsky (2014)



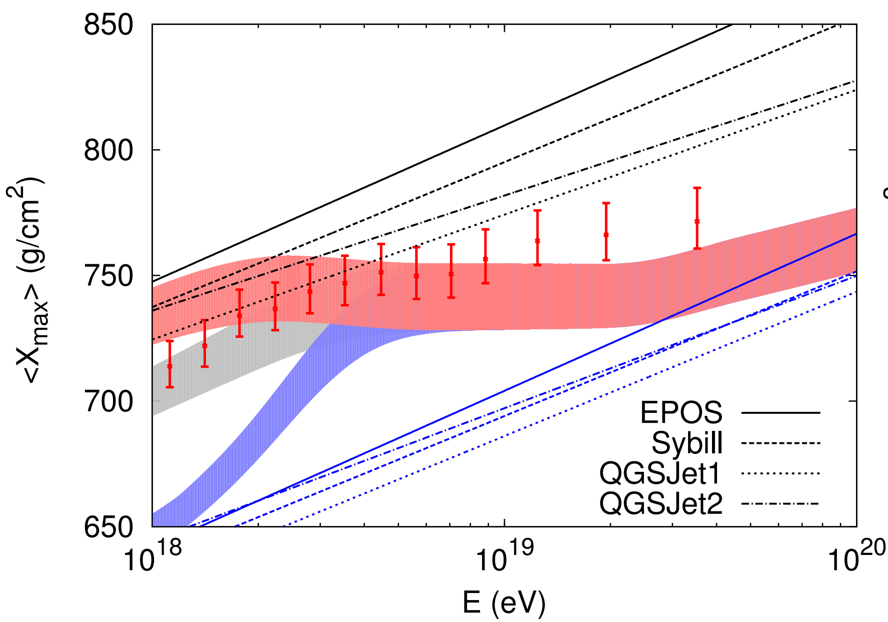
Extra Galactic Nuclei and Galactic light elements

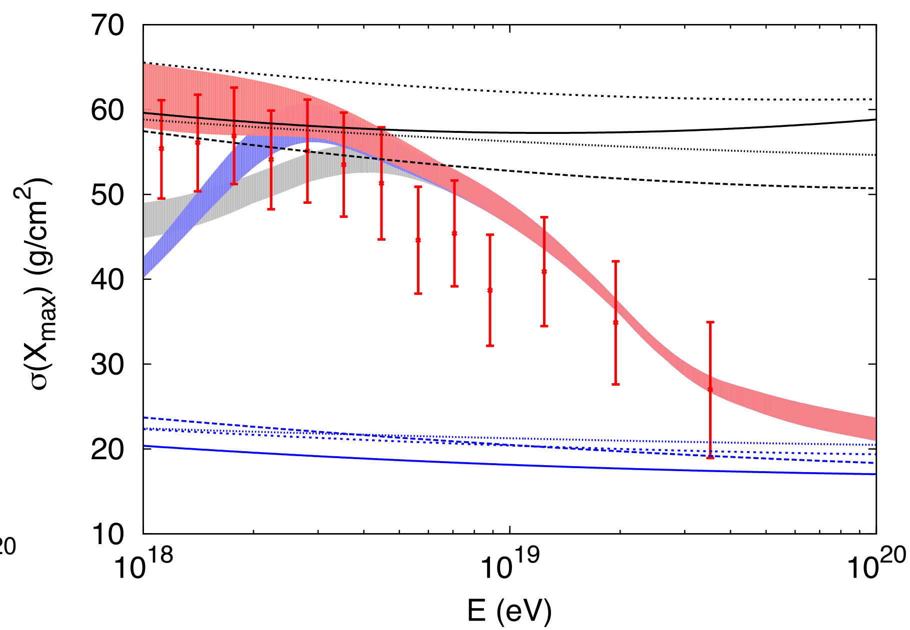


An additional galactic component can fill the gap in the spectrum.

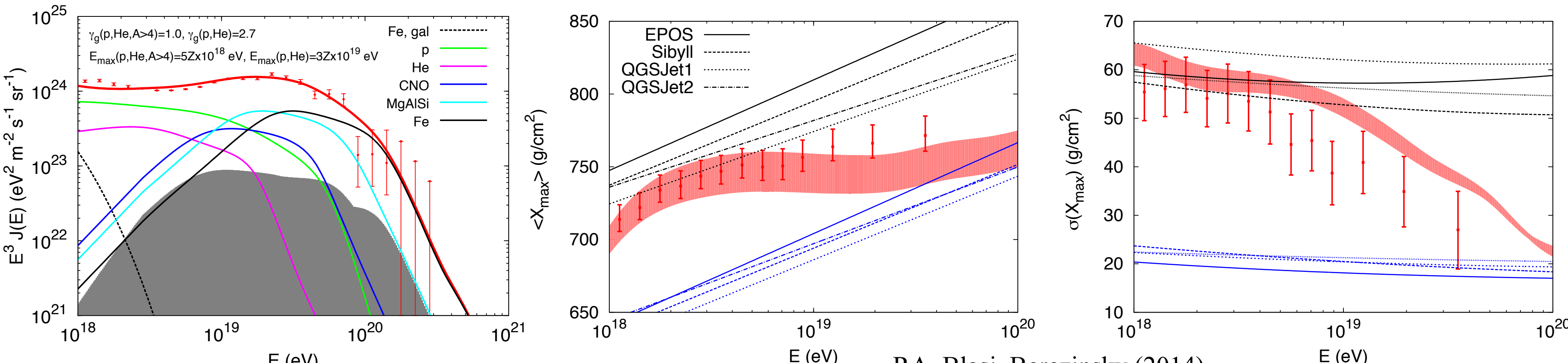
Composition issue. Mixture of 80% p and 20% He to reproduce Auger observations. Difficult to reconcile with galactic CR physics and anisotropy observations.

RA, Blasi, Berezinsky (2014)

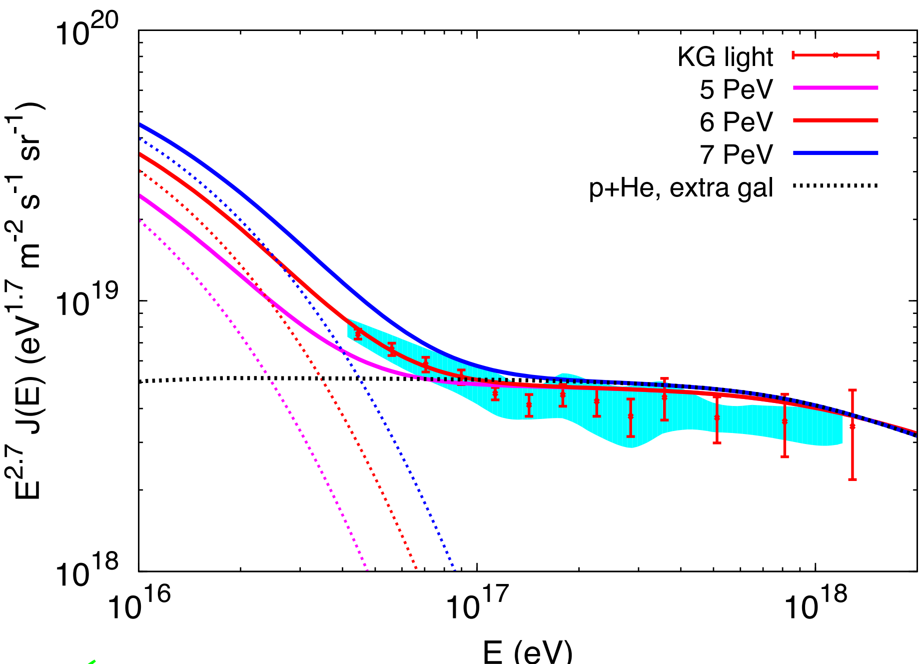




Different Classes of Extra Galactic Sources



RA, Blasi, Berezinsky (2014)



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

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

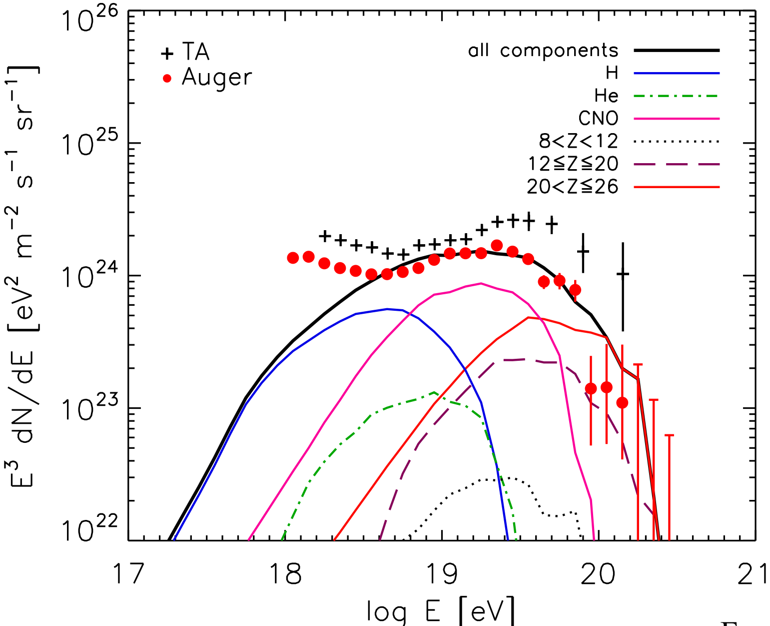
✓ heavy component flat injection ($\gamma_g<1.5$)

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

✓ **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.

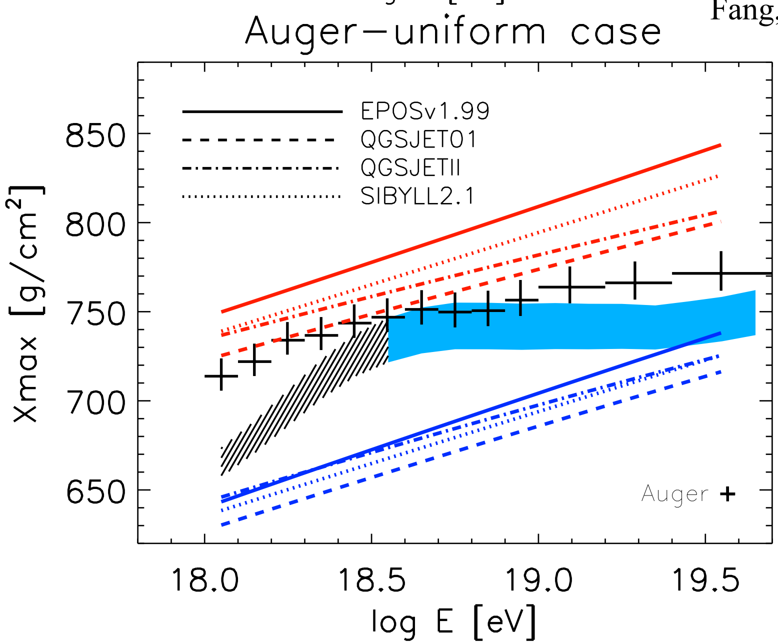
Pulsars, Extra Galactic and Galactic

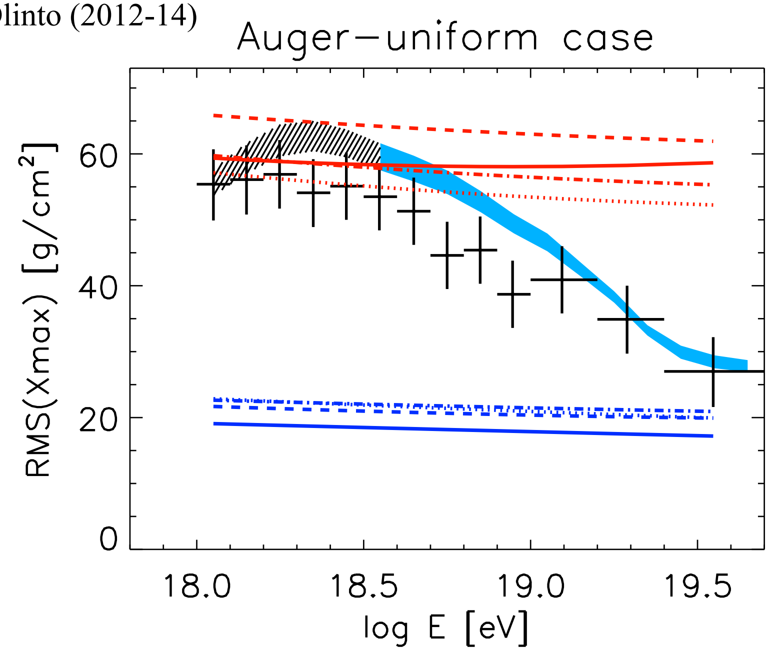


✓ Extragalactic pulsars with flat injection provide the observed spectrum and mass composition at energies > 3 EeV. A flat component from galactic pulsars fills the gap.

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

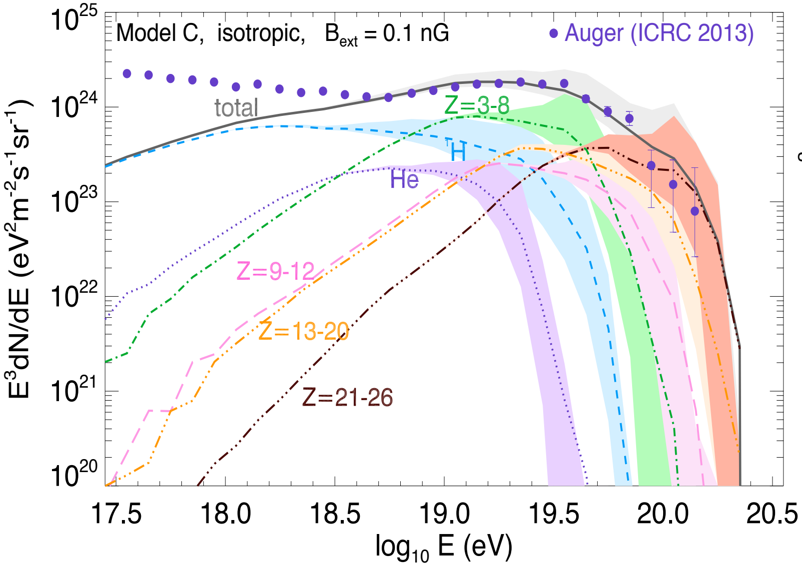
Fang, Kotera, Olinto (2012-14)

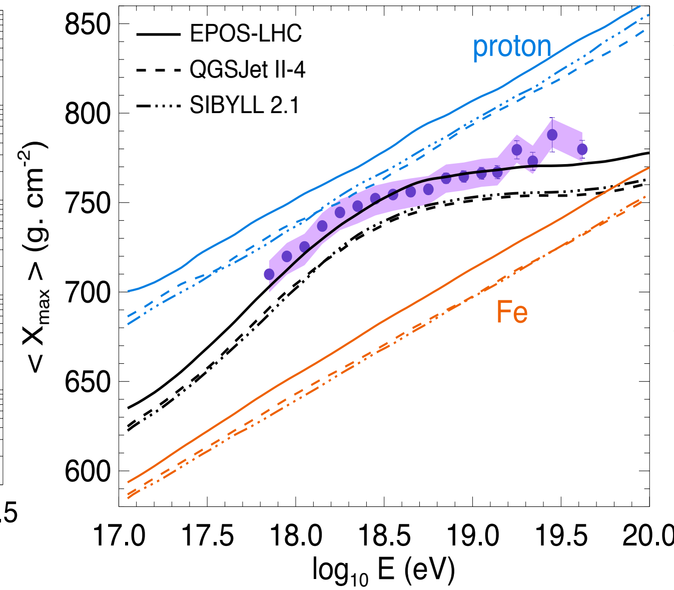




Specific dynamic at the sources

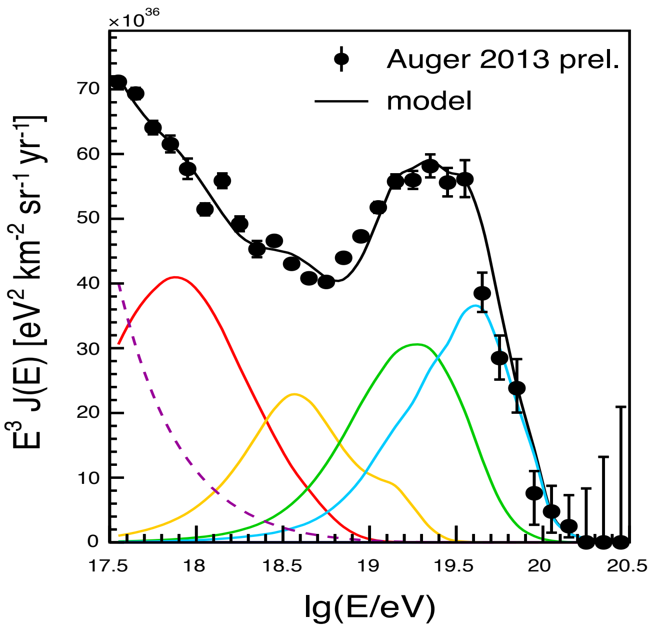
Globus, Allard, Parizot (2014-2015)

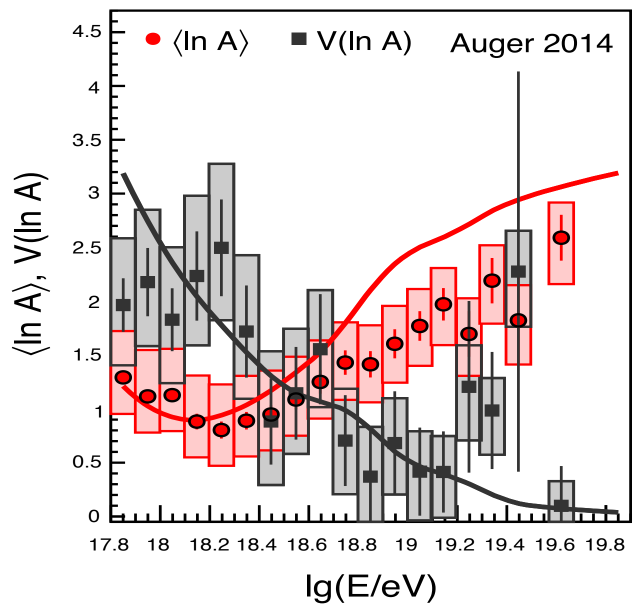




- ✓ Single class of EG sources: Mildly relativistic shocks in GRBs.
- ✓ Problem with Galactic CR maximum energy larger than 10^{16} eV

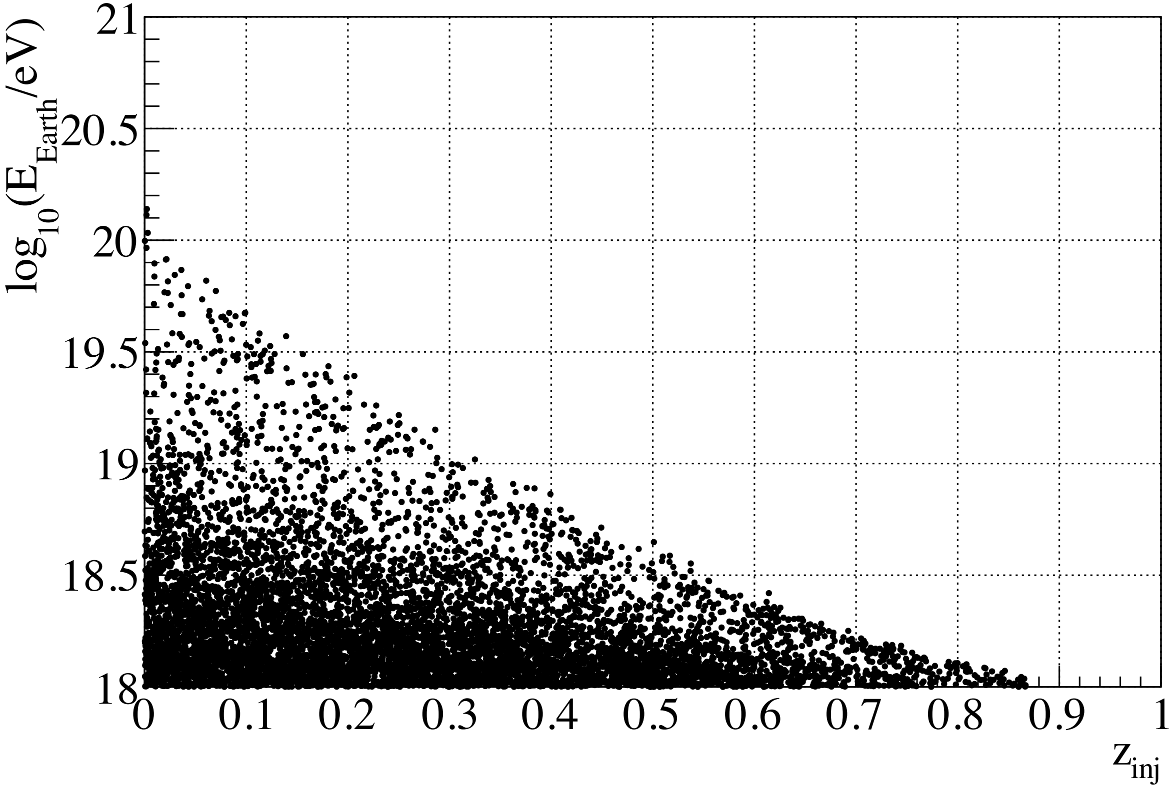
Unger, Farrar, Anchordoqui (2015)





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

Looking farther away



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

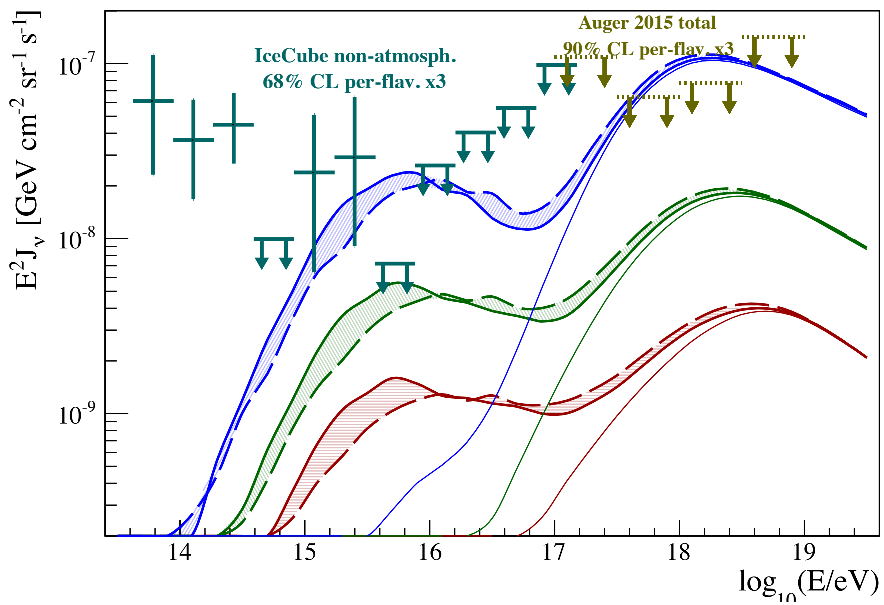
$$p\gamma \to \pi^{\pm} \to e^{\pm}, \nu$$

✓ 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.

ν spectra – Dip model

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

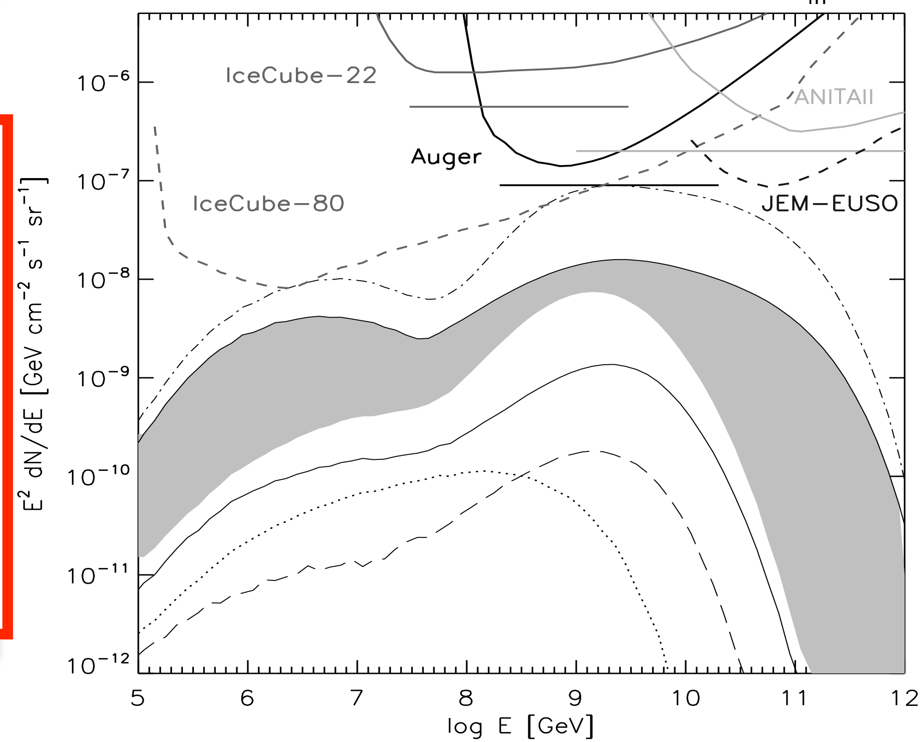


✓ Photo-pion production

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.

✓ Cosmological evolution

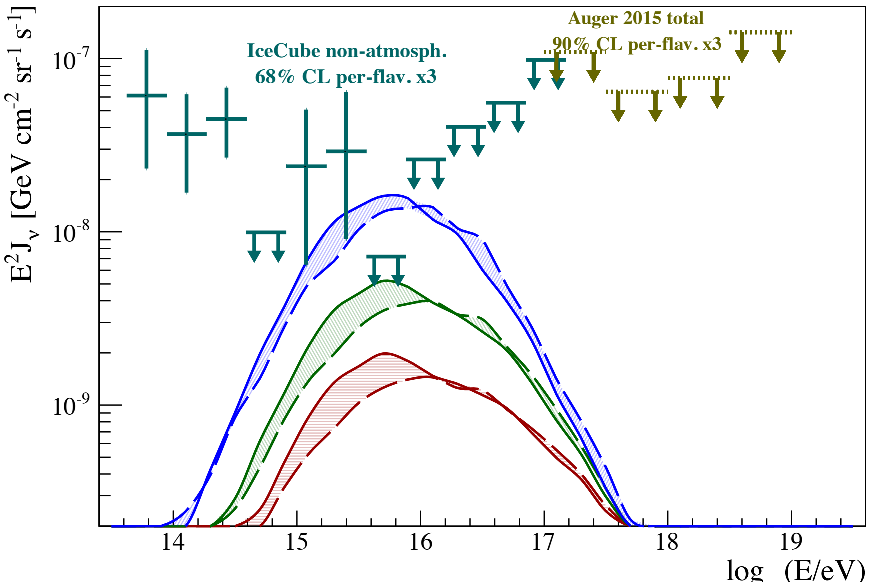
The result on the diffuse flux depends on the cosmological evolution assumed for the sources. The IceCube observations at PeV can be marginally reproduced only in the case of strong cosmological evolution (AGN like).



Kotera, Allard, Olinto (2011)

ν spectra – Mixed composition model

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

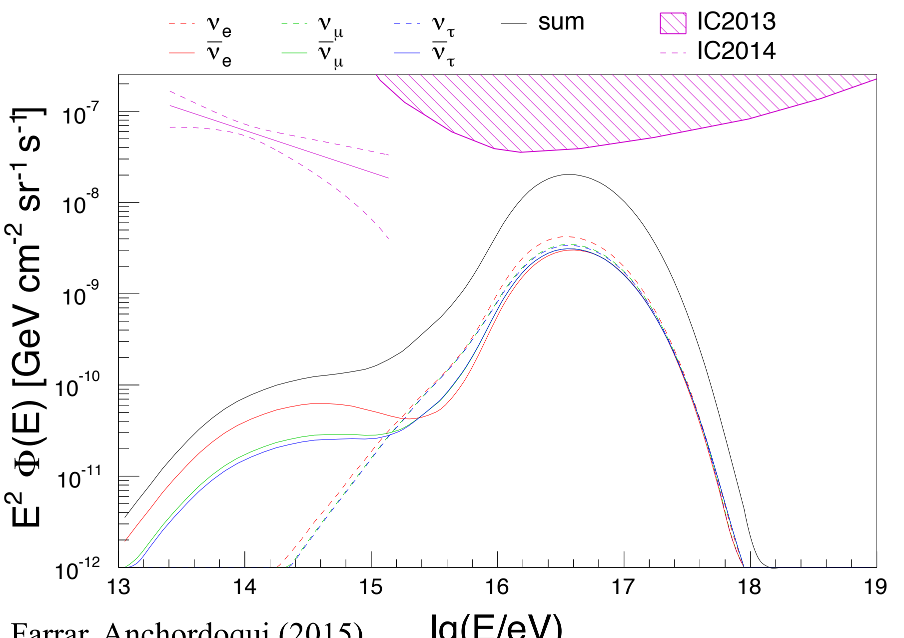


✓ EeV neutrinos

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 only in the case of strong cosmological evolution (AGN like).



Unger, Farrar, Anchordoqui (2015)

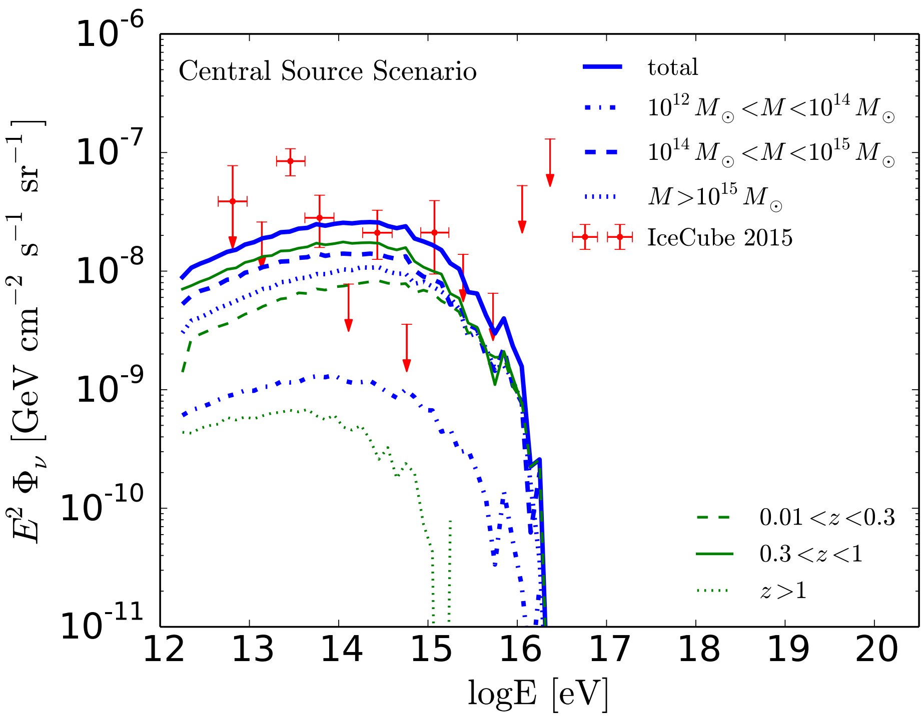
Clusters of Galaxies and PeV ν

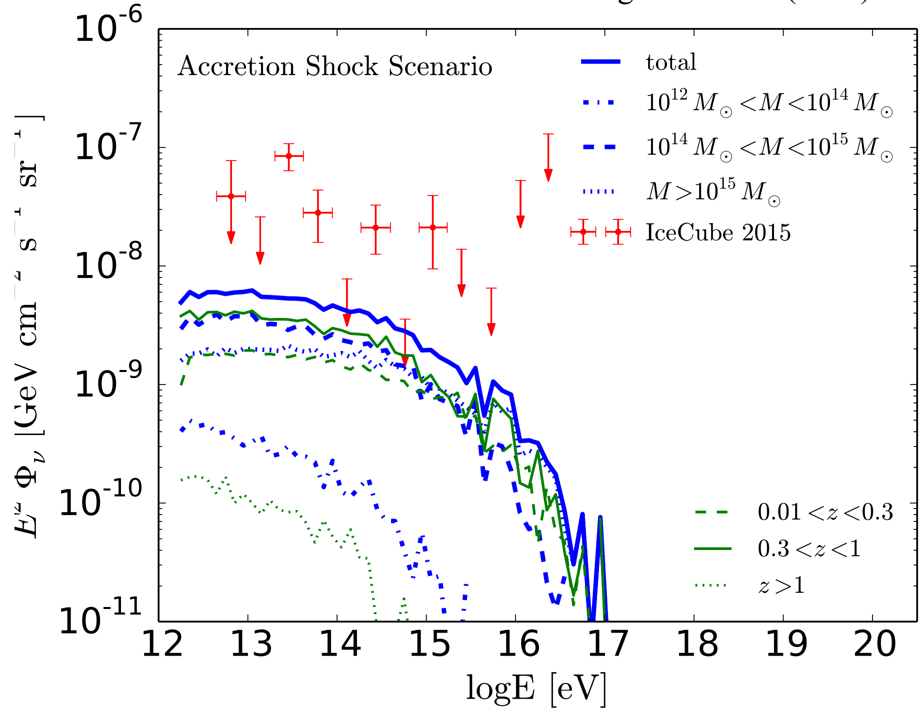
- ✓ Because of their magnetic fields (at several μG level) clusters of galaxies are "storage rooms" for cosmic rays till energies $\sim 10^6 \div 10^8$ GeV, depending on the magnetic field turbulence.

- ✓ 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.

Berezinsky, Blasi and Ptuskin (1998)

Fang and Olinto (2016)

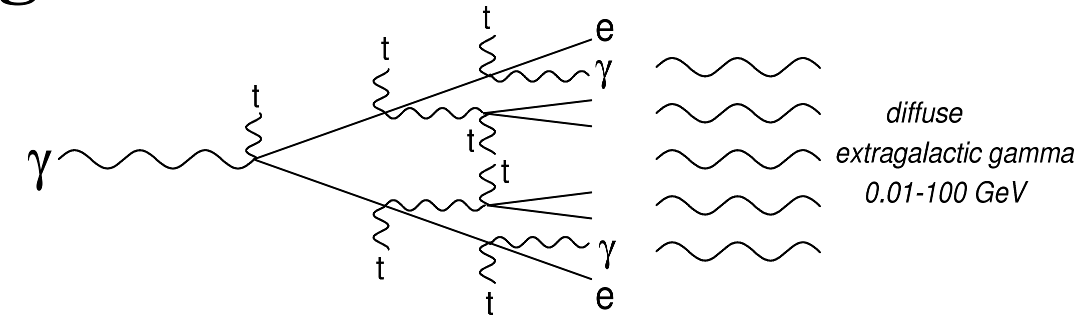




Diffuse γ ray background

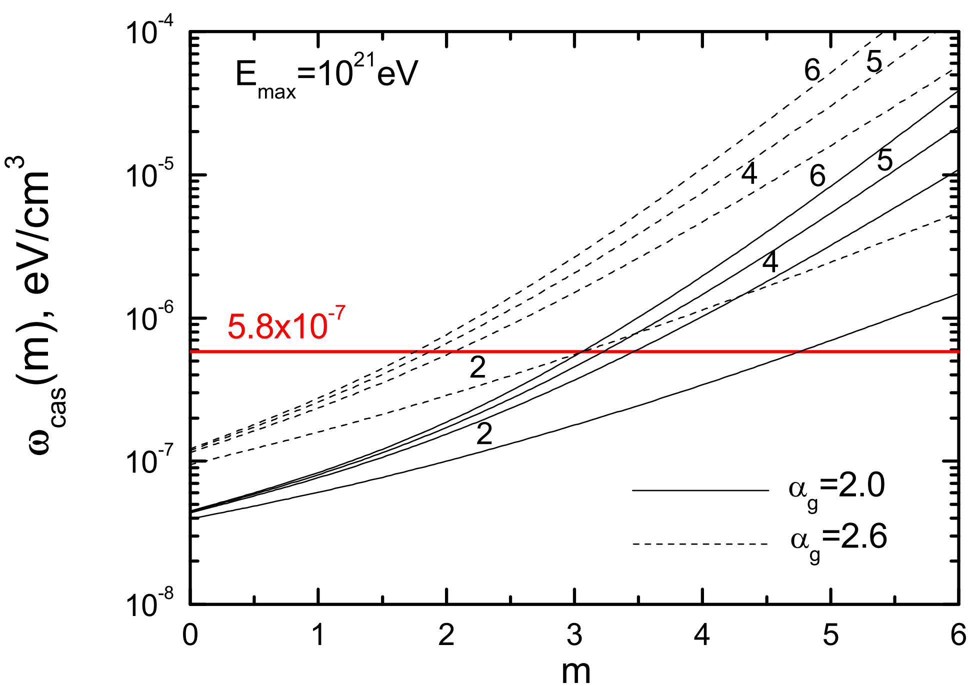
Cascade upper limit

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



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)

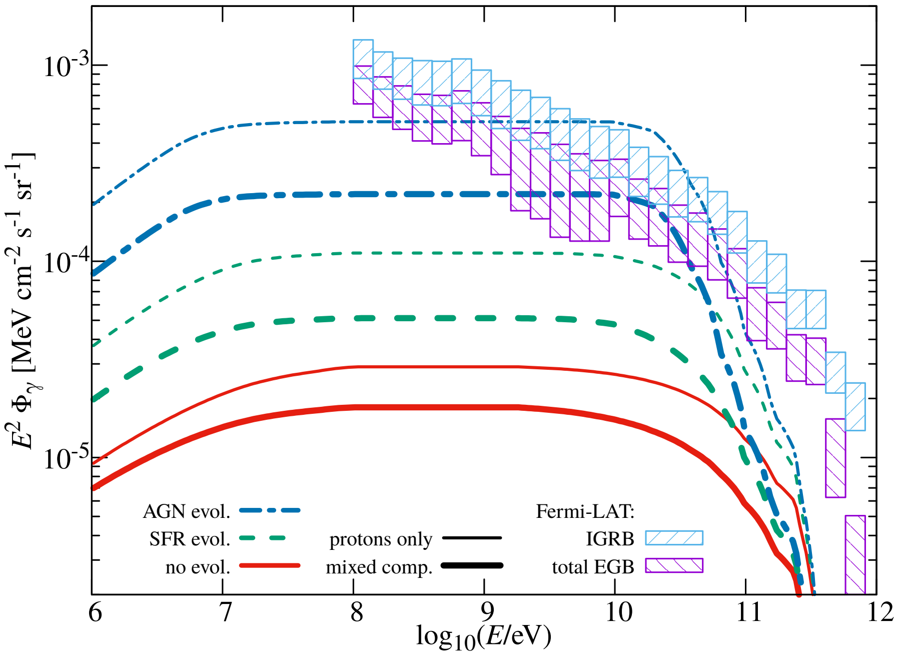
The cascade limit can be expressed in terms of the energy densities of photons and e^+e^- initiated cascades

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

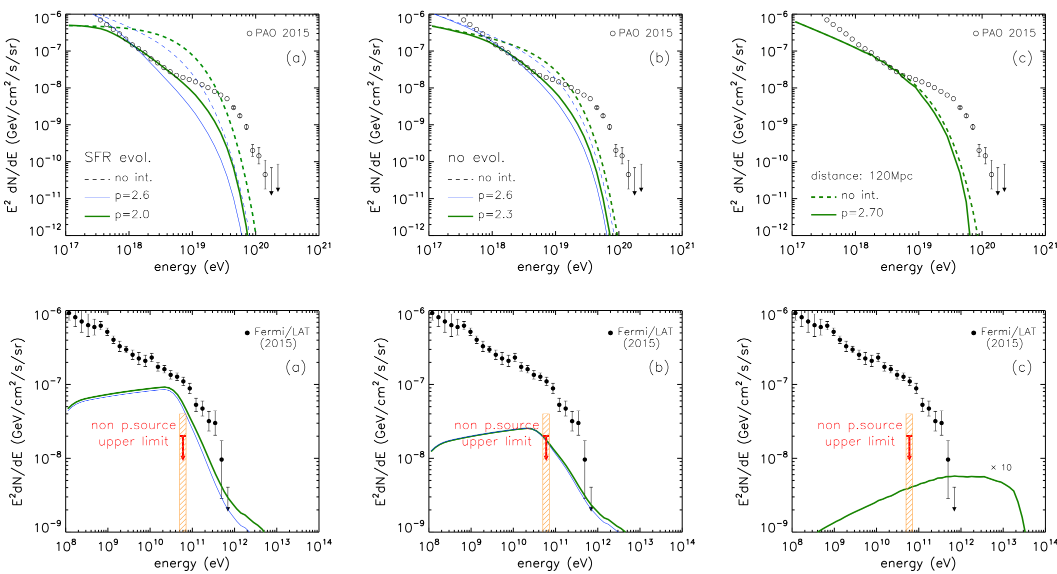
The cascade upper limit constrains the source parameters: cosmological evolution, injection power law and maximum acceleration energy.

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

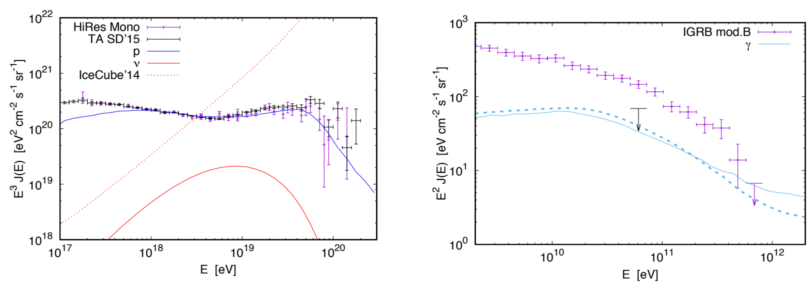
RA, Boncioli, di Matteo, Grillo, Petrera, Salamida (2017)



- ✓ 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)

Super Heavy Dark Matter

- ✓ Supermassive particles with mass comparable with the inflaton mass can be generated in the early universe by time-dependent gravitational fields or through direct coupling to the inflaton field. [Schrodinger (1939), Zeldovich & Starobinsky (1972), Kofman, Linde & Starobinsky (1994), Felder, Kofman & Linde (1998), Chung, Kolb & Riotto (1998), Kuzmin & Tkachev (1998)]
- ✓ They can be long-lived if their decay is inhibited by some discrete symmetry (such as R-parity for SUSY neutralinos). [Berezinsky, Kachelriess & Vilenkin (1997), Kuzmin & Rubakov (1997)]

In this case SH relics can be dark matter candidates (SHDM)

WIMP vs SHDM

- ➢ WIMP naturally produced in SUSY models (new physics supra-TeV, naturalness).
- ➢ SHDM naturally produced at inflation (always out of local thermal equilibrium)
- ➢ Both require additional (weakly broken) symmetries to prevent fast decays.
- ➢ WIMP can be experimentally tested through: production (LHC), direct detection (underground labs), indirectly (SM secondary in Astrophysical observations).
- ➢ SHDM can be experimentally tested only indirectly through cosmological (CMB) observations and UHECR observations.

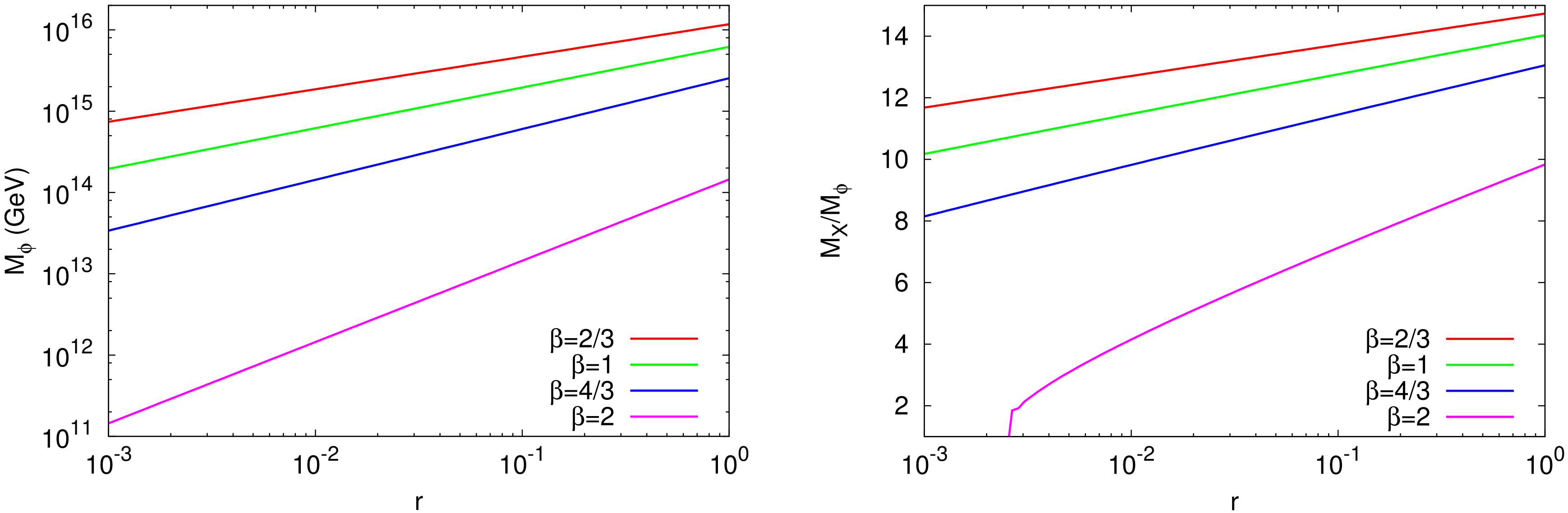
SHDM and Inflation

- ✓ Being out of local thermal equilibrium SHDM naturally produces tensor modes.

- ✓ The observed tensor-to-scalar ratio in CMB fluctuations sets the scale for SHDM.

$$\Omega_X(t_0) \simeq 10^{-3}\Omega_R \frac{8\pi}{3}\left(\frac{T_{RH}}{T_0}\right)\left(\frac{M_\phi}{M_{Pl}}\right)^2\left(\frac{M_X}{M_\phi}\right)^{5/2} e^{-2M_X/M_\phi}$$

$$V(\phi) = \frac{M_\phi^{4-\beta}}{\beta}\phi^\beta \qquad V_\star \simeq \frac{3\pi^2}{2}A_s r M_{Pl}^4 \simeq M_{GUT}^4\left(\frac{r}{r_0}\right) \qquad \epsilon(\phi) = \frac{M_{Pl}^2}{16\pi}\left[\frac{V'(\phi)}{V(\phi)}\right]^2 = \frac{r}{16}$$



RA, Matarrese, Olinto (2015)

- ✓ the observation of a non zero fraction of tensor modes in the CMB fluctuations pattern, already at the level of 10^{-3}, confirms that the gravitational production of SHDM particles is a viable mechanism to explain the DM problem, assuring a density of SHDM today at the observed level.

SHDM flux contribution

✓ SHDM accumulates in the halo of our own galaxy with an over-density δ given by:

$$\delta = \frac{\delta_X^{halo}}{\rho_X^{extr}} = \frac{\rho_{DM}^{halo}}{\Omega_{DM}\rho_c} \simeq 2 \times 10^5$$

Berezinsky, Kachelriess, Vilenkin (1997)

UHECR flux

$$J_{SHDM}(E,\theta) = \frac{1}{4\pi M_X \tau_X} Q(E) \int_0^{r_{max}(\theta)} dr n_X(R(r))$$

Particle Physics and Cosmology

Fix the spectrum and mass composition. The observed flux selects a sub-space of the SHDM parameter space, through

$$r_X = \Omega_X \frac{t_0}{\tau_X}$$

signature of the model

Astrophysics

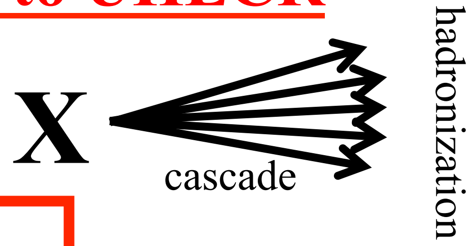
Galactic DM halo fixes the geometrical behavior of the SHDM emission, (increased emission from the GC direction)

$$n_X(R) = \frac{n_0}{(R/R_s)^\alpha (1 + R/R_s)^{3-\alpha}}$$

α=1 NFW, α=3/2 Moore density profile

signature of the model

From SHDM to UHECR



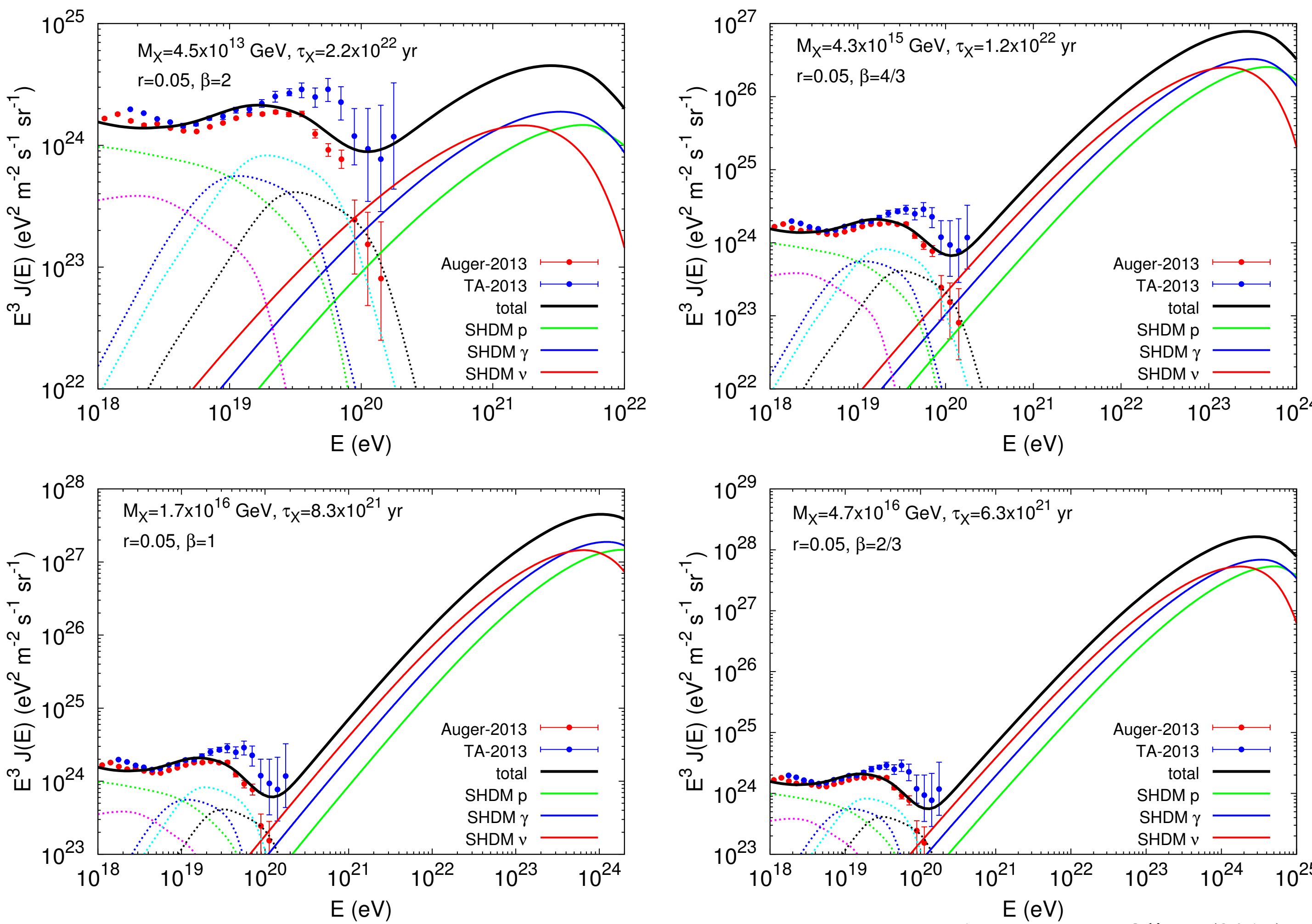
mainly π
hence γ and ν

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

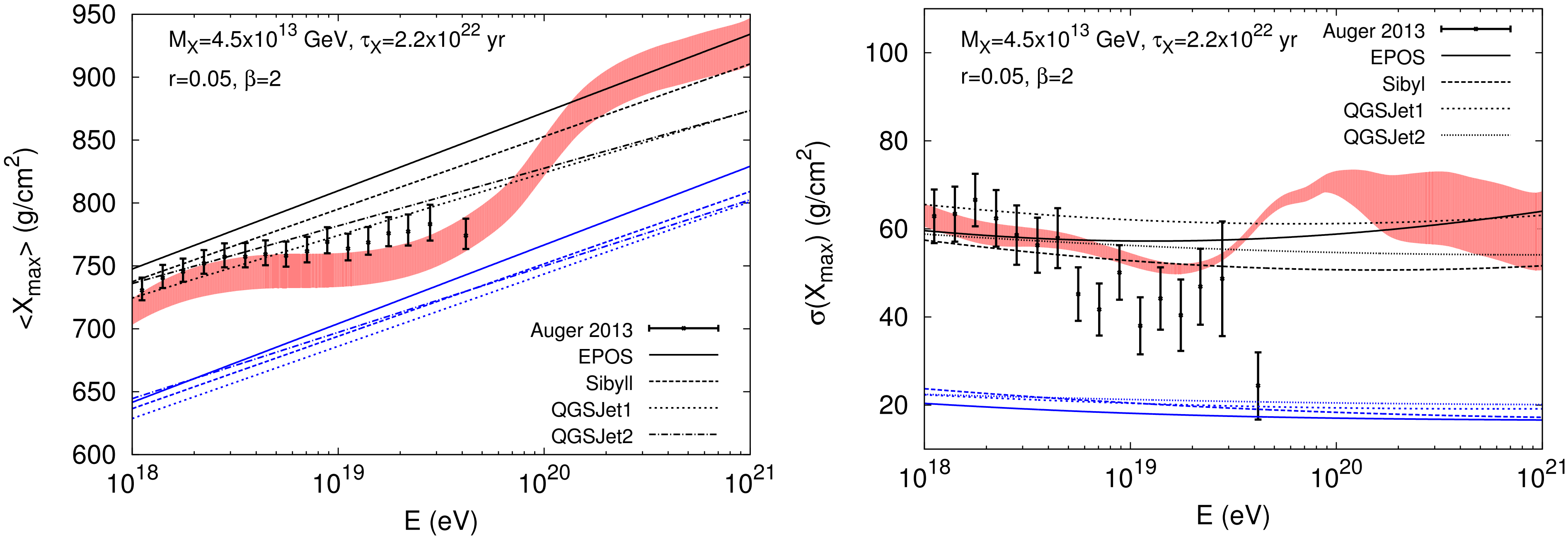
$$J_{\nu,\gamma,p} \propto \frac{1}{M_X \tau_X}$$

RA, et al (2004-2007)

- ✓ 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.



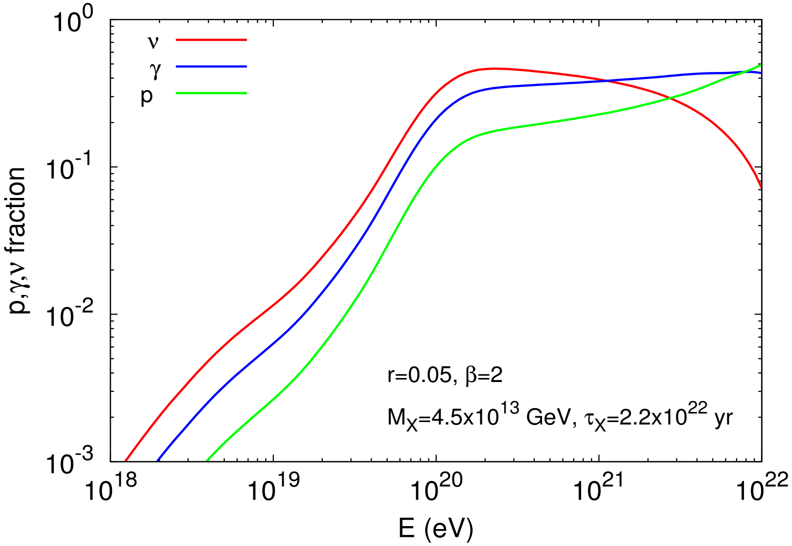
RA, Matarrese, Olinto (2015)

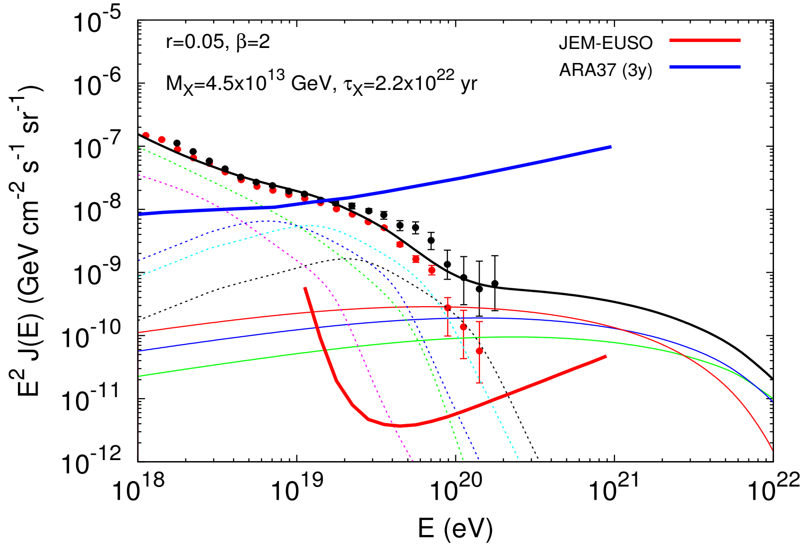


RA, Matarrese, Olinto (2015)

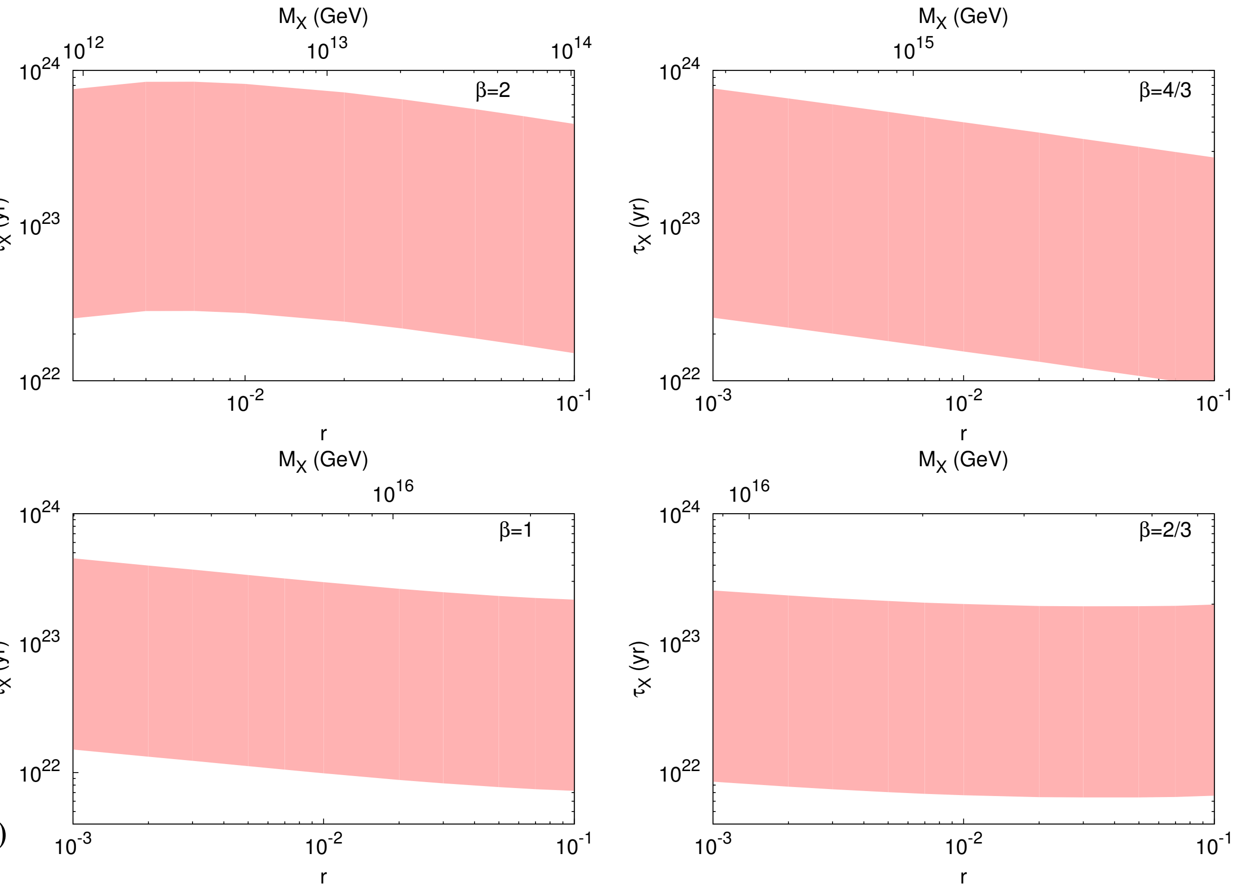
The most constraining observations that limit (from below) τ_X are

- ✓ Mass composition of UHECR
- ✓ Photons fraction at E>10^{19} eV below 1 %





- ✓ 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

✓ UHECR Astrophysical models

A pure proton composition is 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 candidates as UHECR sources.
- ✓ 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

✓ 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 future precise cosmological measurements combined with future observations of UHECR and neutrinos at extreme energies.
- ✓ Large statistics at energies around 10^{20} eV and higher are also instrumental to detect the faint signal of anisotropy expected by the decay of SHDM.

Thank you