Ultra High Energy Cosmic Rays an Overview

Roberto Aloisio

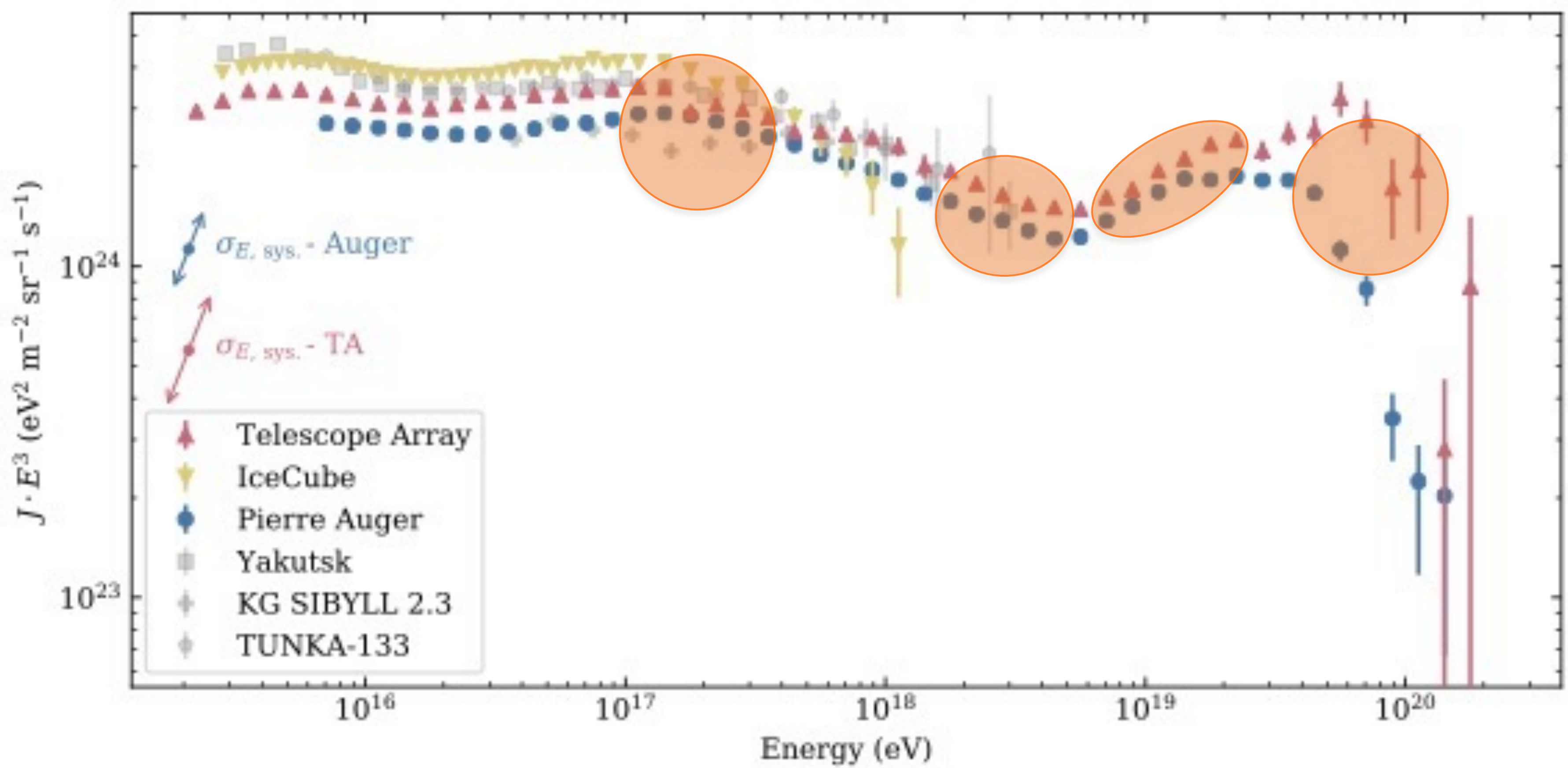
Gran Sasso Science Institute

INFN – Laboratori Nazionali del Gran Sasso

12th Cosmic Rays International Seminar

12-16 September 2022, Napoli, Italy

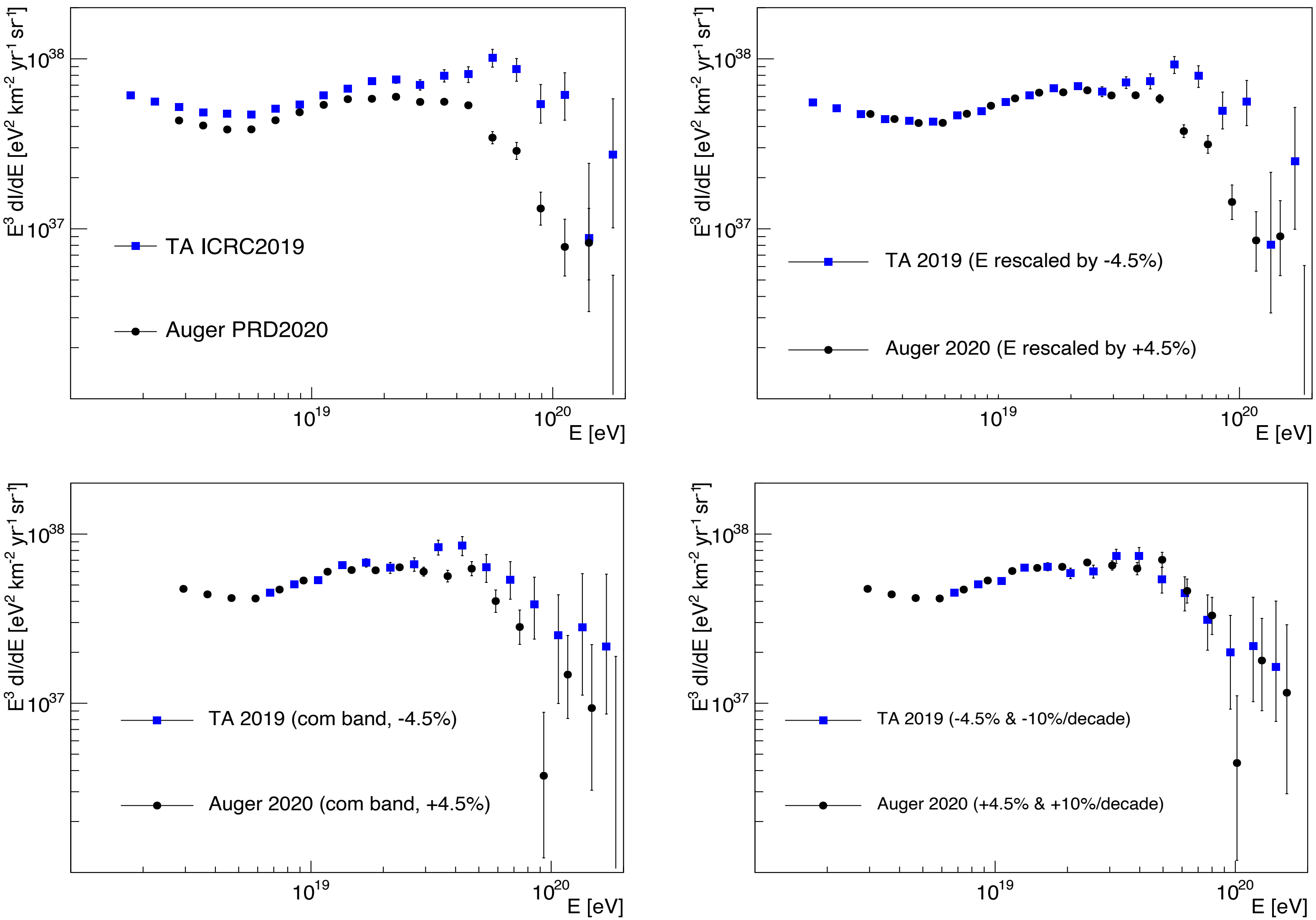
Ultra High Energy Cosmic Rays – Spectrum



Spectral features

- ✓ Second knee: ~2x10^{17} eV
- ✓ Ankle: ~3x10^{18} eV
- ✓ Instep: ~10^{19} eV
- ✓ Flux suppression ~5x10^{19} eV

✓ The difference between Auger and TA observed energy spectra can be understood in terms of the systematics in the energy determination of the two observatories.



Full field of view

Auger
$-90^\circ \leq \delta \leq 24.8^\circ$

TA
$-15.7^\circ \leq \delta \leq 90^\circ$

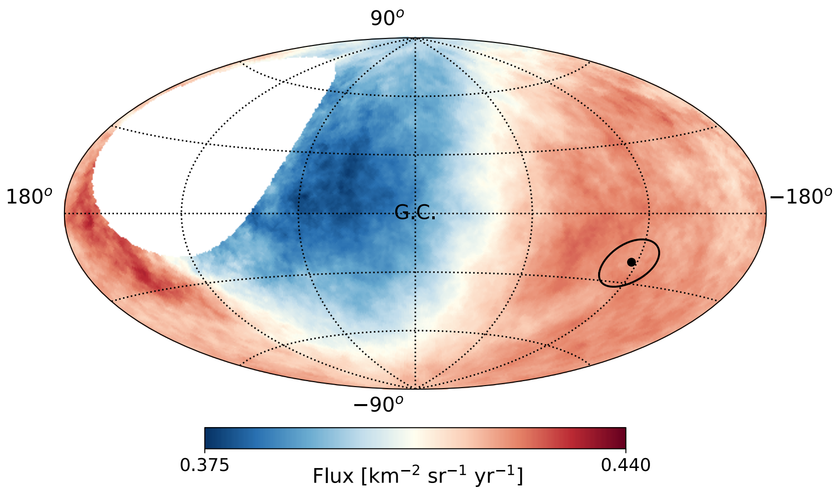
common declination band

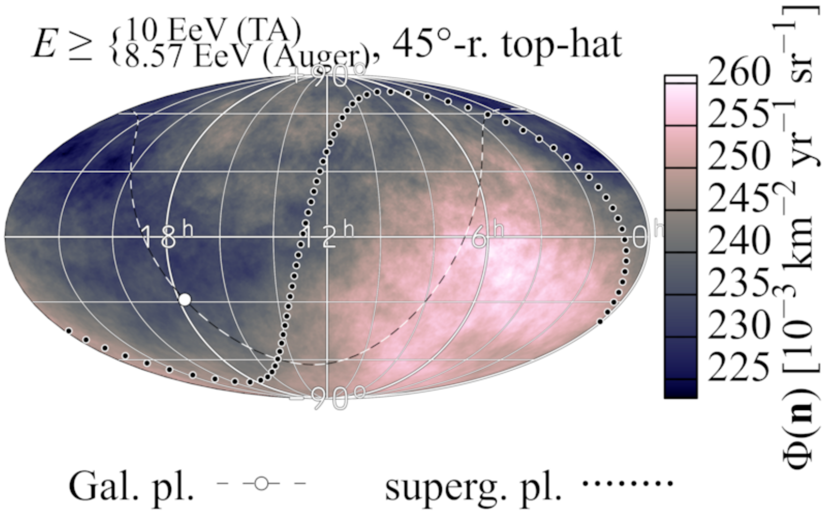
$-15.7^\circ \leq \delta \leq 24.8^\circ$

Auger and TA Collaborations (2021)

Ultra High Energy Cosmic Rays – Anisotropy

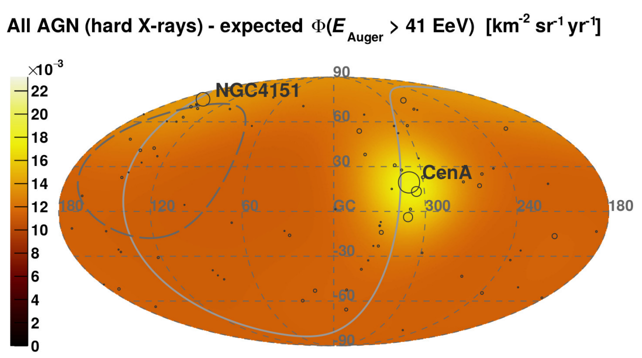
✓ Large scale anisotropy: dipole E>8 EeV (5.2σ). Solid evidence of **Extragalactic origin**

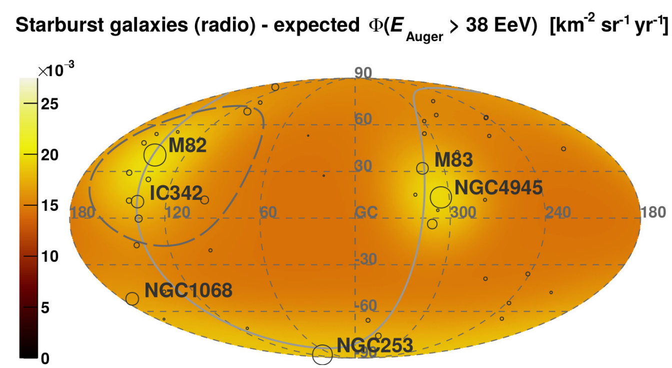


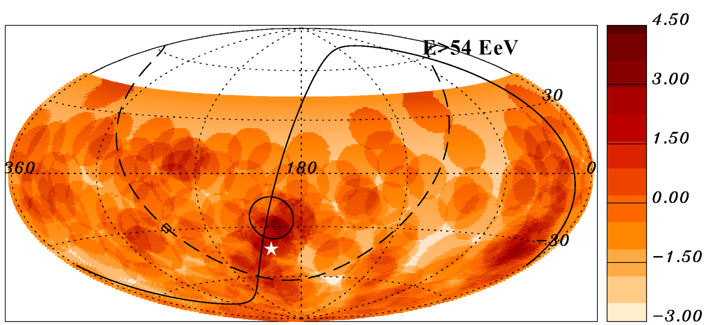


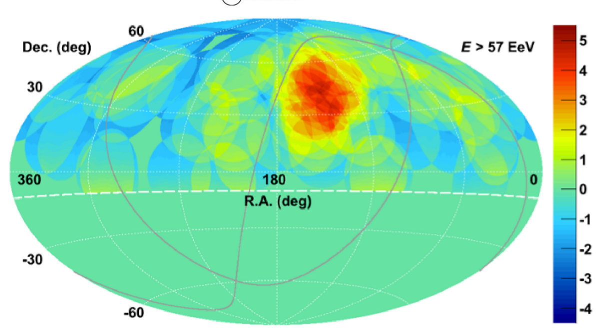
Auger and TA Collaborations (2021)

✓ Small-scale anisotropy: **Hints of sources (?)**



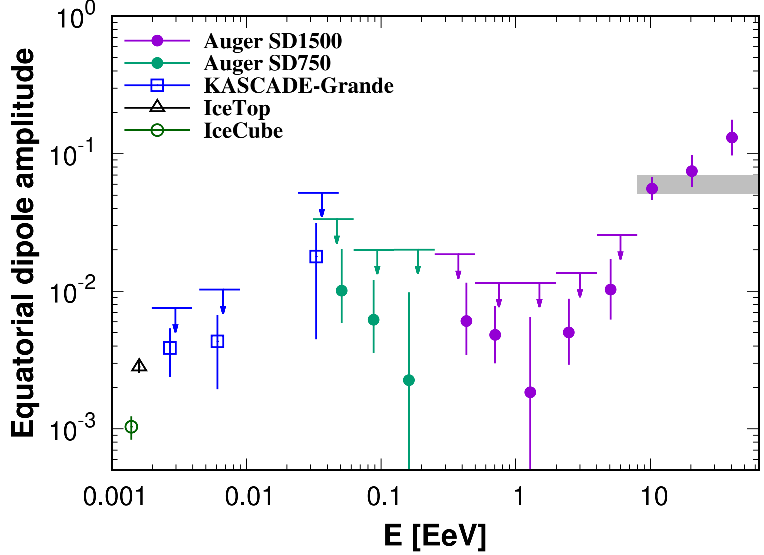


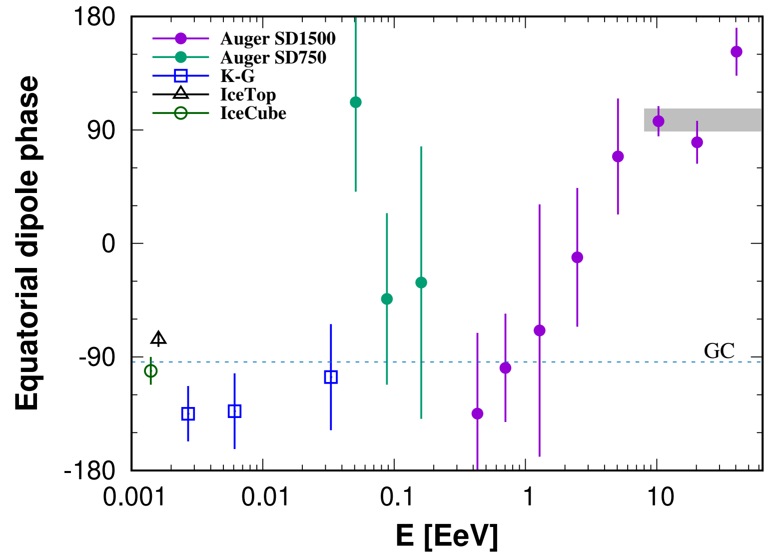




✓ Small-scale anisotropy still insufficient to draw conclusions as to the UHECR sources.

✓ Lack of multiplets at E>40 EeV constrains the apparent number density of sources: $n_0 \geq 10^{-5}$ Mpc^{-3}

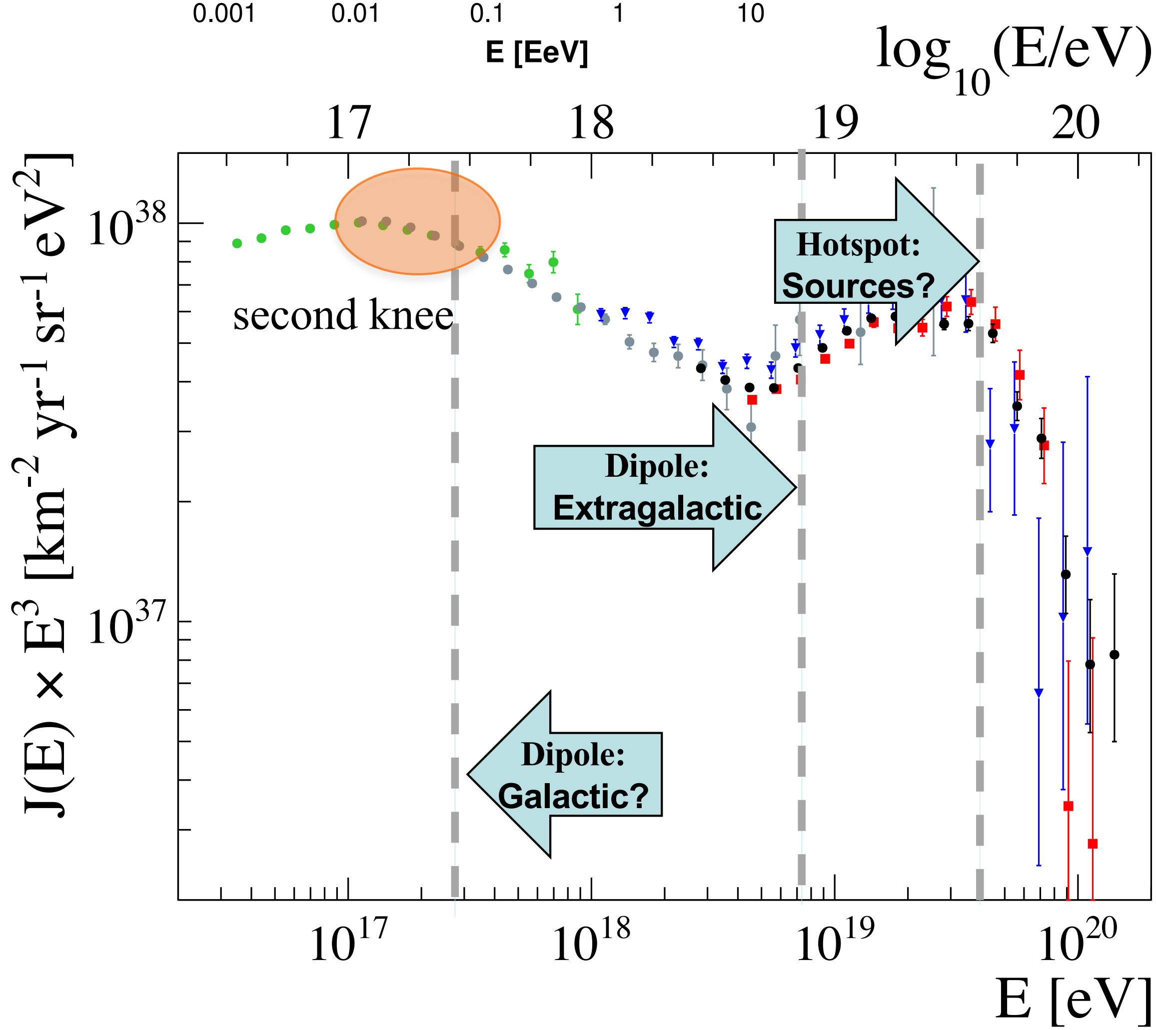




Auger Collaboration (2020)

Right ascension anisotropies

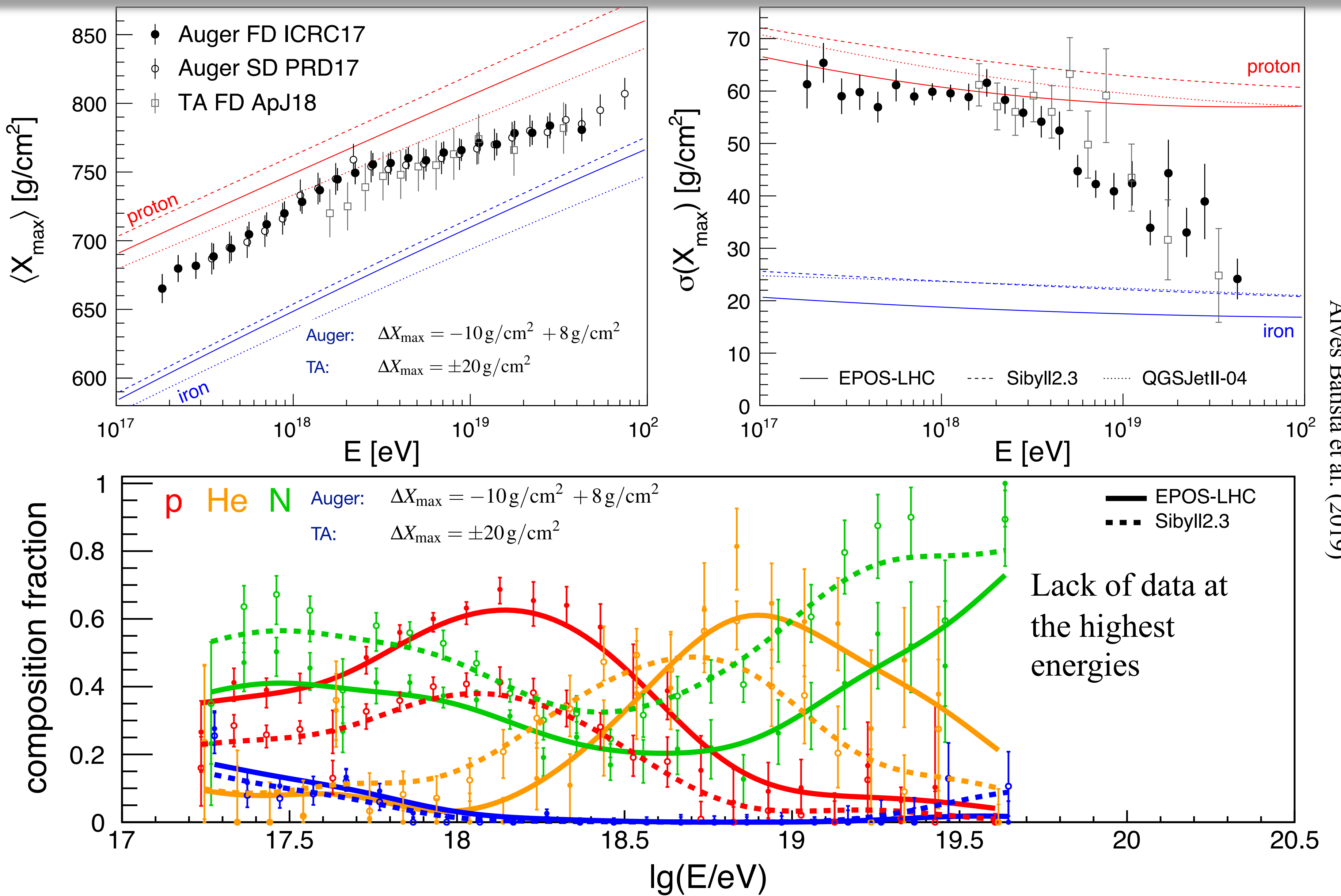
- Above 8 EeV, $d_\perp = 6.0^{+1.0}_{-0.9}$ % with a phase pointing toward the galactic anticenter. Signal of a possible extragalactic origin.
- Below 8 EeV, only upper bounds on $d_\perp$ at the level of 1%
- Below 0.3 EeV, amplitude is not significant, the phase is not far from the right ascension of the galactic center. Signal of a possible galactic origin (?).

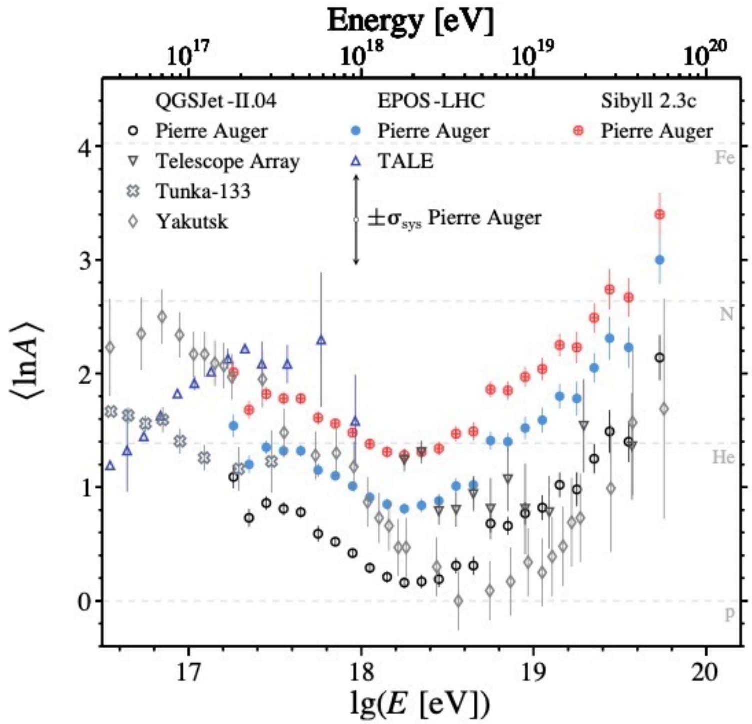


Ultra High Energy Cosmic Rays – Composition

Mixed Composition

Starting at 10^{17} eV the light fraction increases till $3x10^{18}$ eV where it dominates the flux. At energies larger then $3x10^{18}$ eV, both Auger and TA data show a mass fraction progressively heavier with increasing energy.

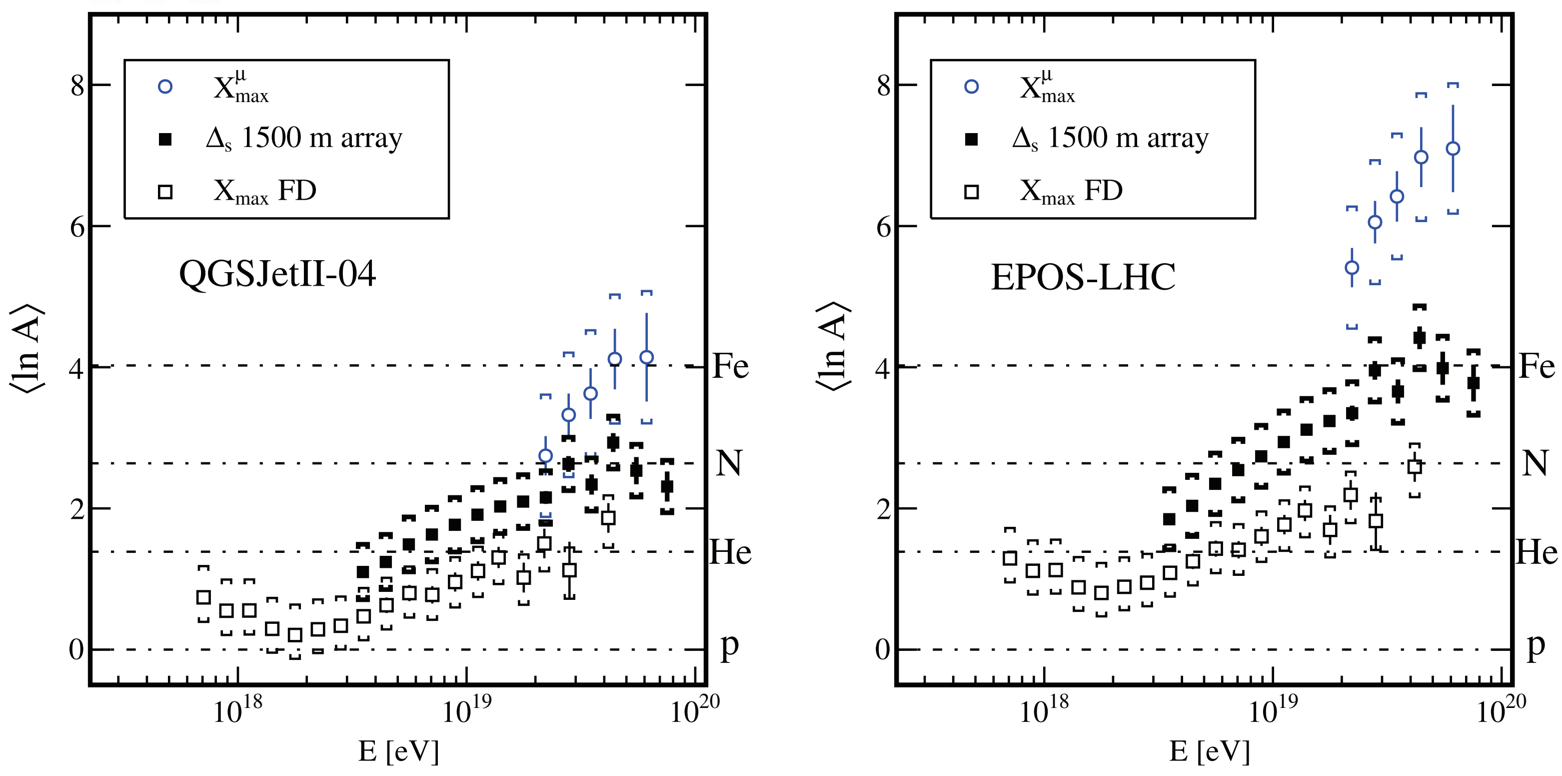




UHECR Snowmass white paper (2022)

- ✓ Uncertainties due to the hadronic interaction model considered.
- ✓ Problems in the self-consistency of hadronic models, likely connected to an inadequate description of the muon production mechanisms in air showers.

Auger Collaboration (2013-2017)



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.

High Energies

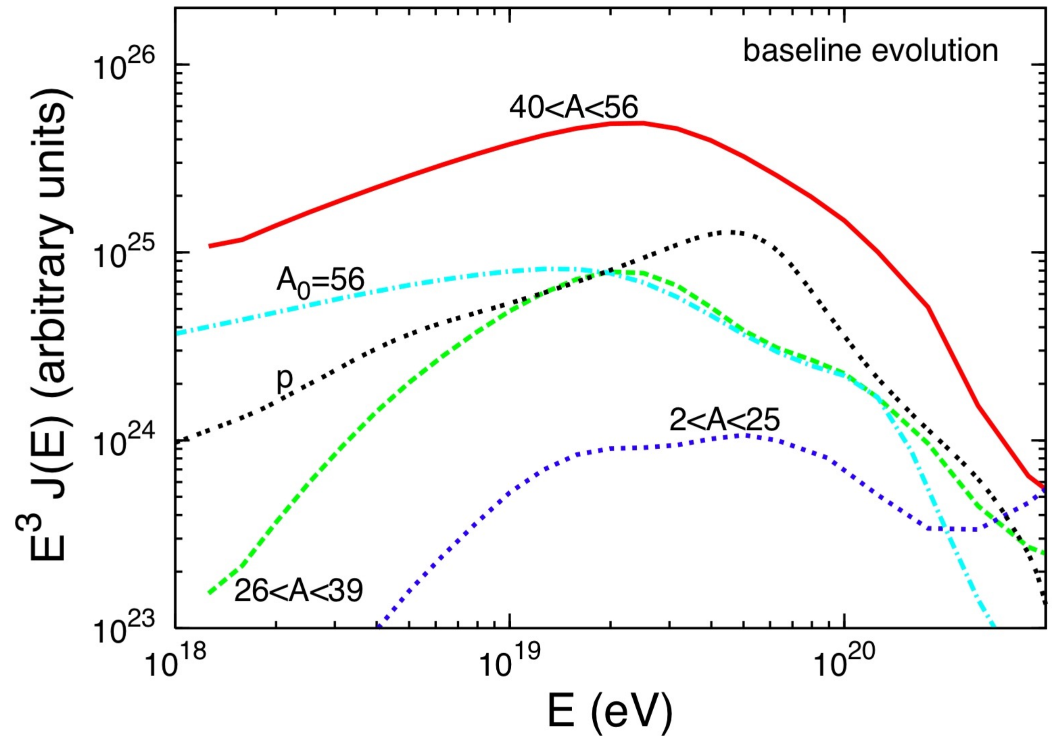
The scale at which photo-disintegration becomes relevant, for heavy nuclei, it is almost independent of the nuclei specie

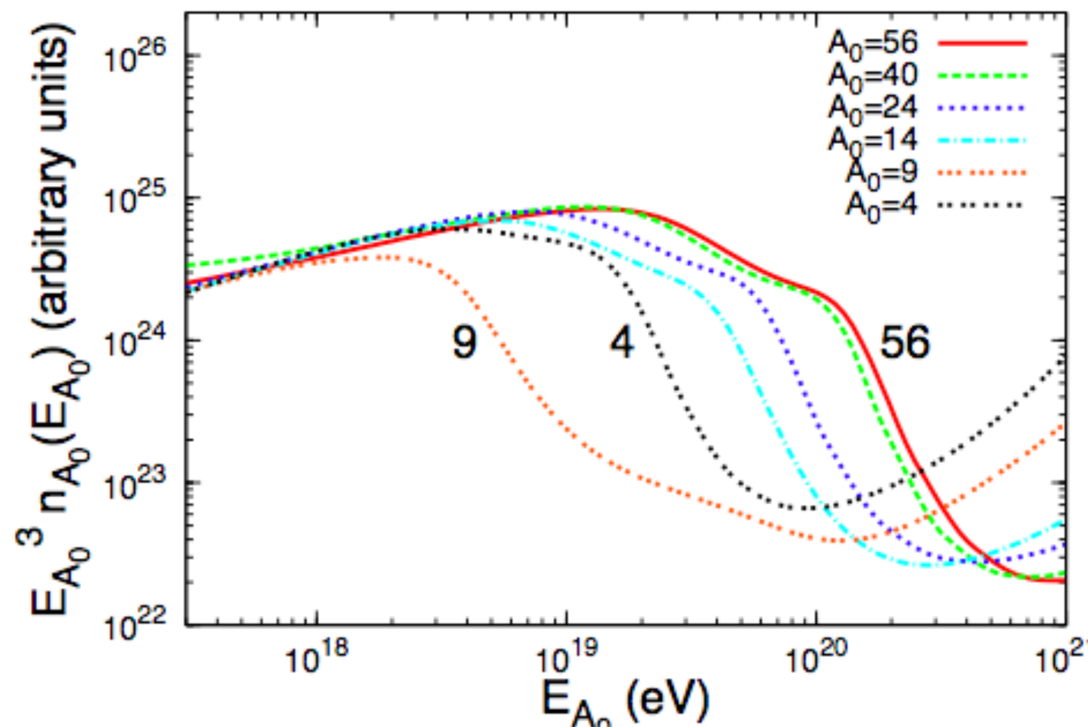
$$\beta^{A}_{e^+e^-}(\Gamma, t) + H_0(t) = \beta^{\Gamma}_{dis}(A, t)$$

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

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

The highest energies behavior is fixed by the interplay between E_{cut} and the maximum energy at the source E_{max}.



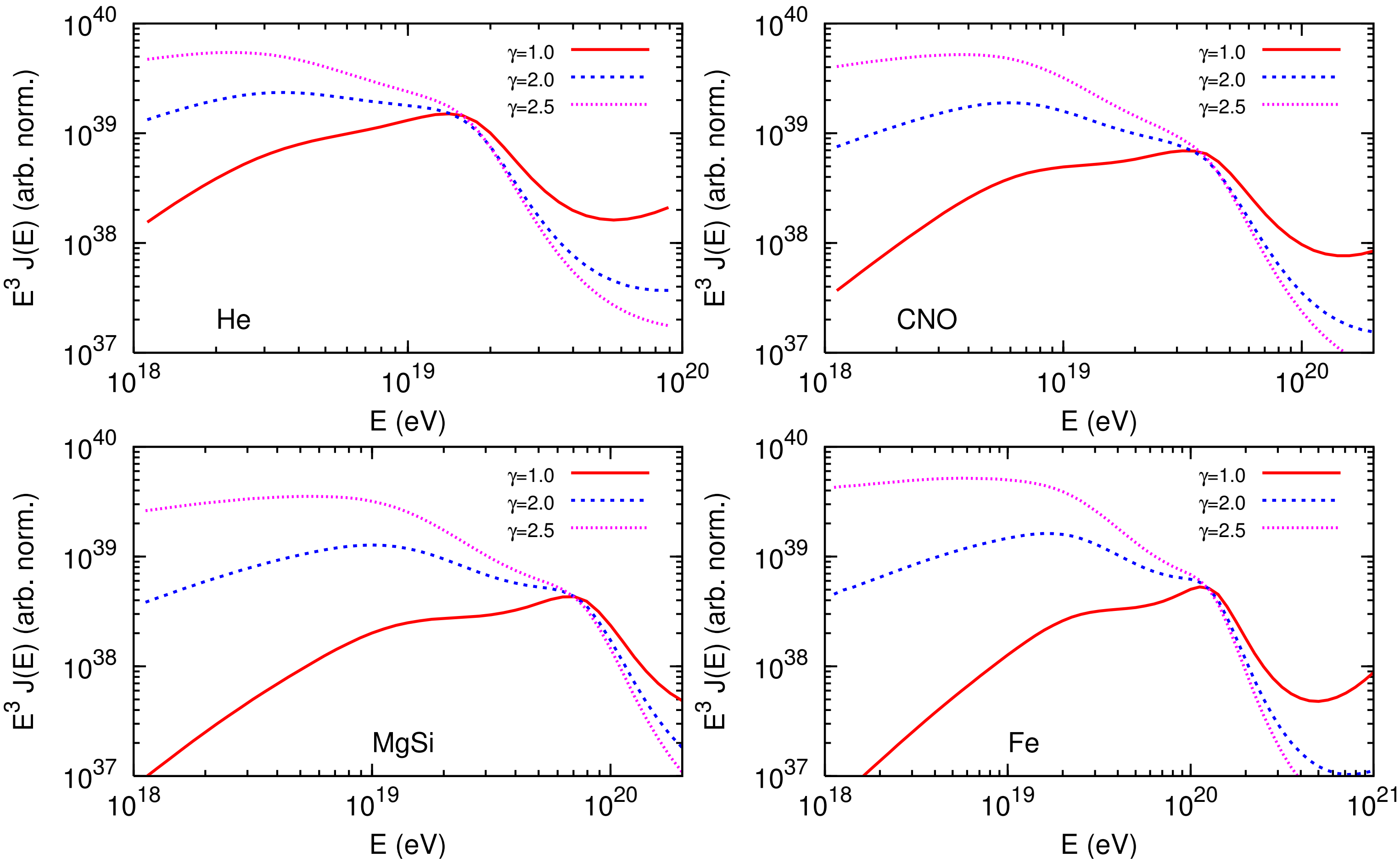


RA, Berezinsky, Grigorieva (2009-2013)

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

$$Q_A(\Gamma) = Q_0 e^{-\Gamma/\Gamma_{max}} \left(\frac{\Gamma}{\Gamma_0}\right)^{-\gamma_g}$$



Note

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

Astrophysical sources

✓ **Hillas criterion**: relation between (comoving) size and magnetic field of the acceleration site.

$$E < E_{max} = \beta ZeBR\Gamma$$

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

$$L = 4\pi R^2 V \frac{1}{2}\rho V^2 > 4\pi R^2 V \frac{B^2}{8\pi}$$

- non-relativistic moving source

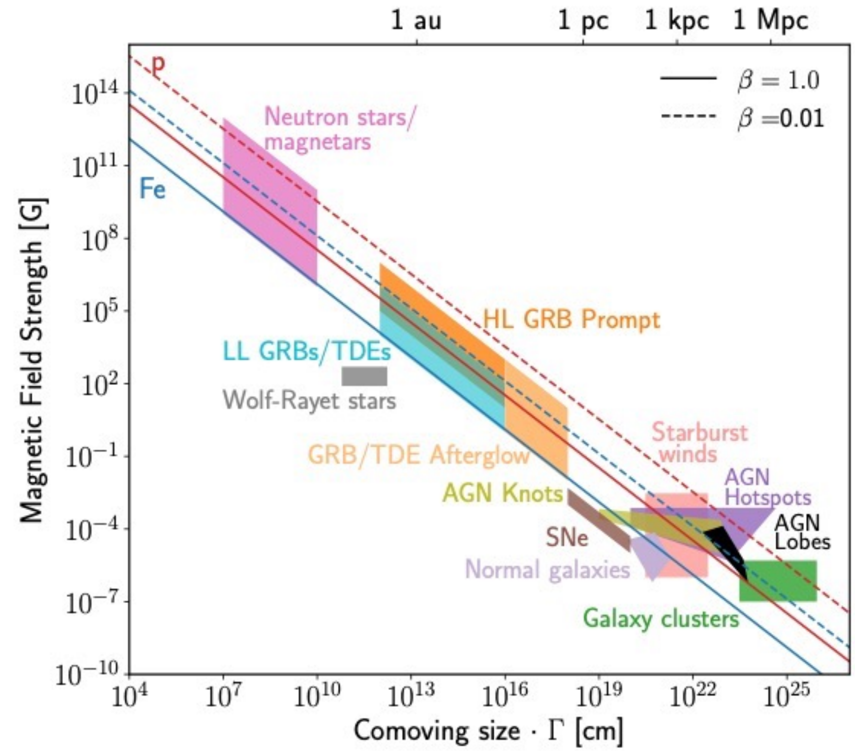
$$L > 3 \times 10^{45} \frac{\beta}{Z^2} \left(\frac{E}{10^{20} eV}\right)^2 \frac{\text{erg}}{s}$$

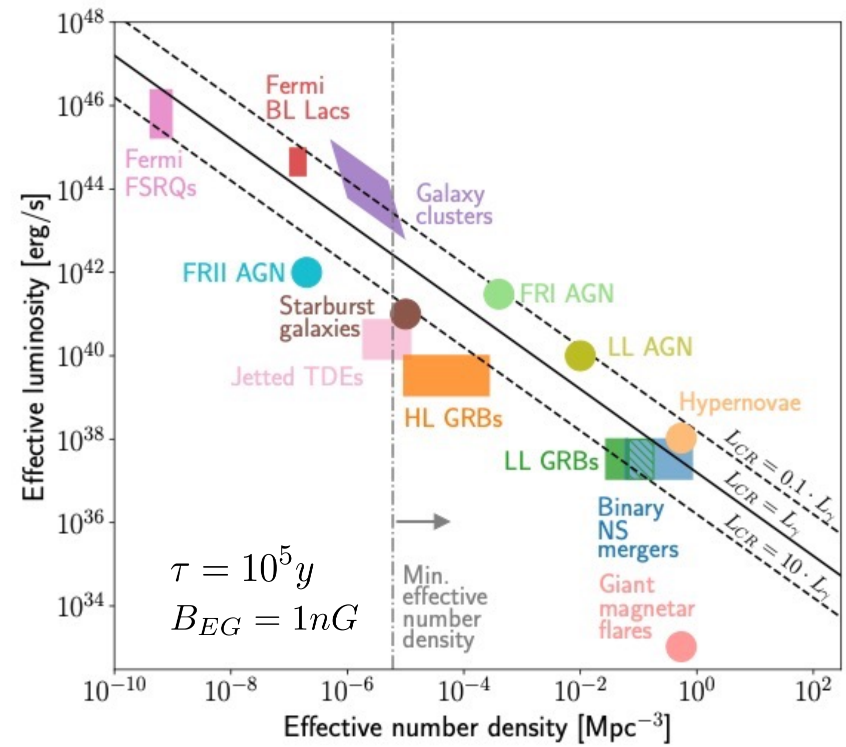
- relativistic moving source

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

✓ The observed UHECR flux fixes the scale of the source emissivity ($\mathscr{L}$= L·n) needed

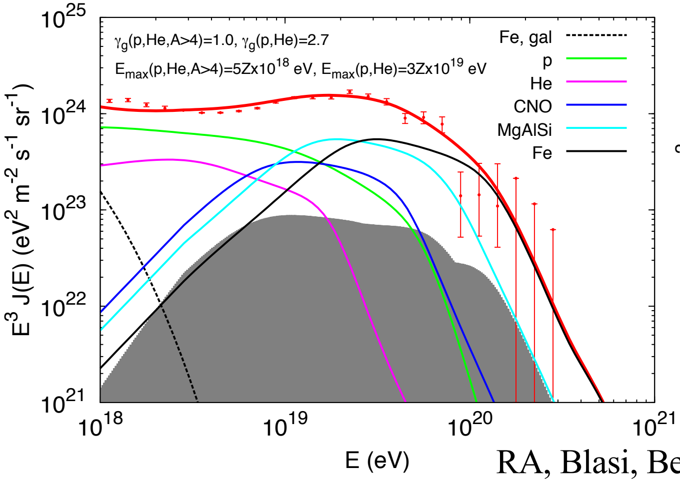
$$J(E) \simeq \frac{c}{4\pi} Q(E) \tau_{loss}(E) \qquad \mathcal{L} = O(10^{37}) \frac{\text{erg}}{\text{Mpc}^3 \text{s}}$$

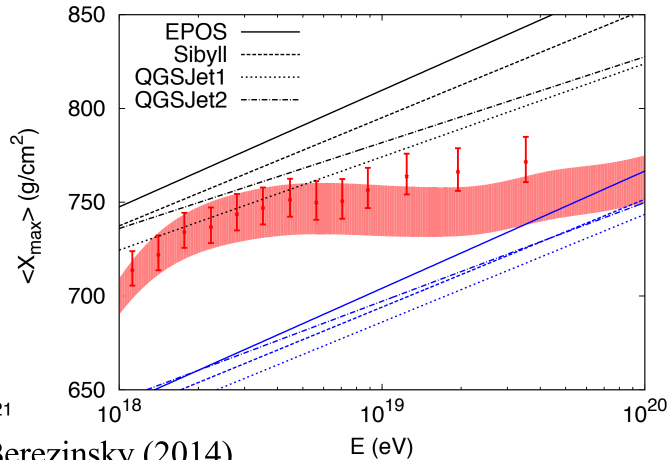


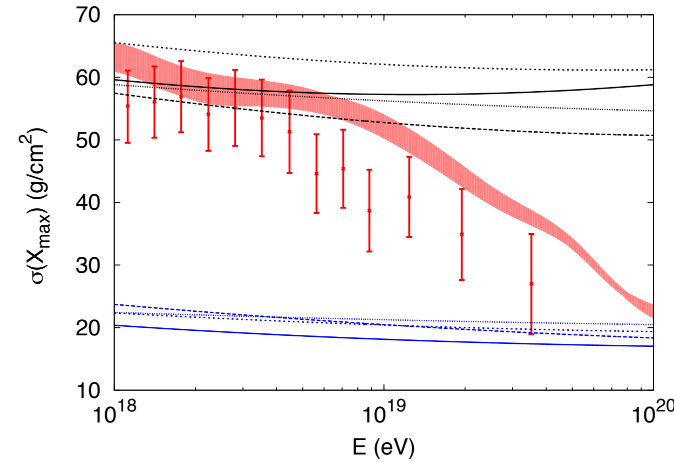


Alves Batista et al. (2019)

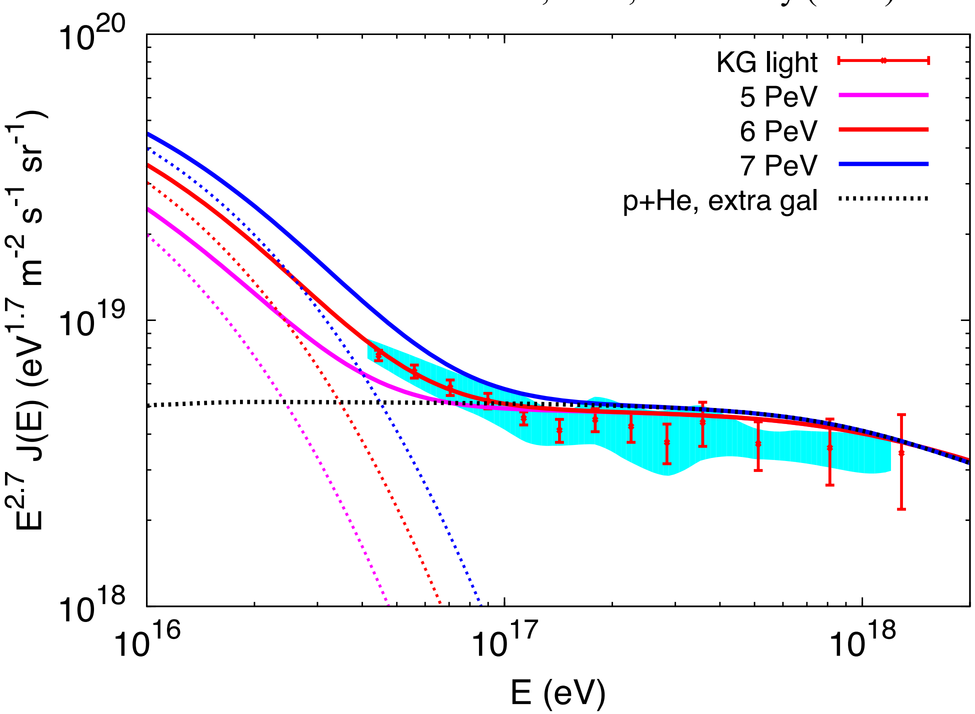
Mass Composition – Different Classes of Injection







RA, Blasi, Berezinsky (2014)



✓ Light component steep injection ($\gamma_g \geq 2.5$)

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

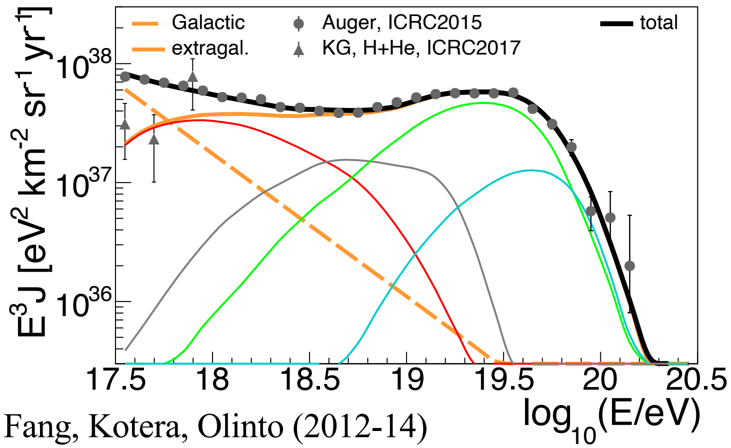
✓ Heavy component flat injection ($\gamma_g \leq 2.0$)

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

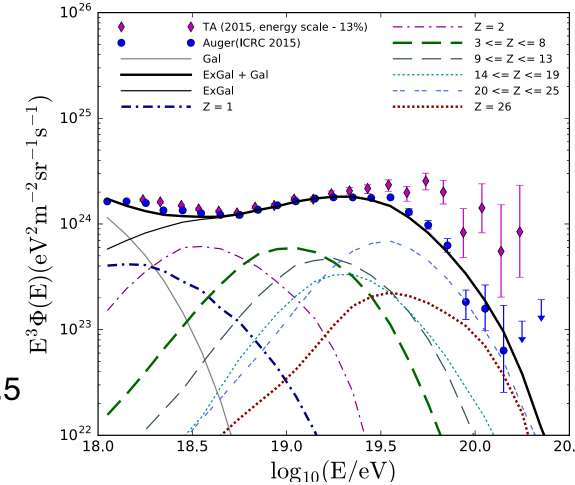
The Kascade-Grande observations seem to confirm the presence at high energy of an (extragalactic?) additional light component with a steep injection spectrum.

Astrophysical models

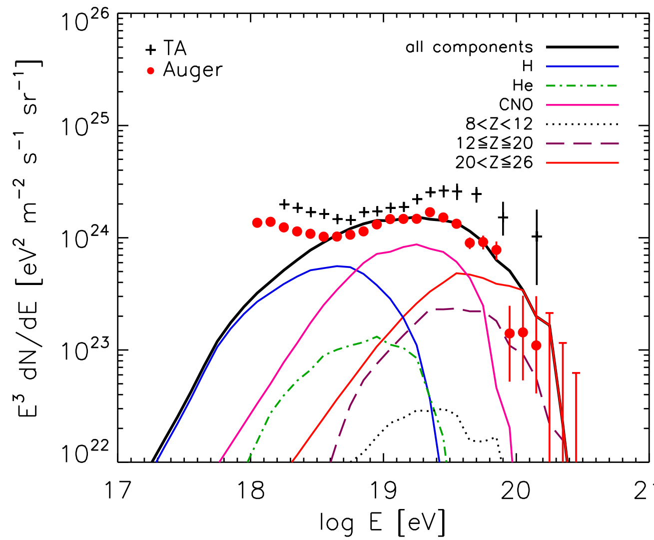
Boncioli, Bhiel, Winter (2018)



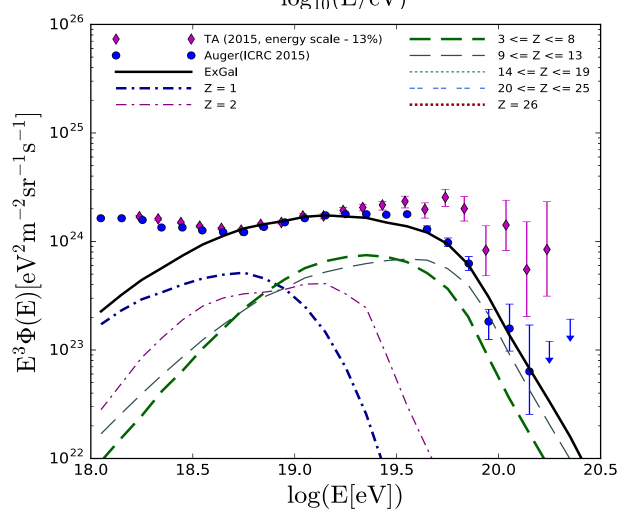
Kimura, Murase, Zang (2018)



Fang, Kotera, Olinto (2012-14)



Zang, Murase, Oikonomou, Li (2017)



✓ At EeV energies it should be filled the gap. A galactic component challenges GCR acceleration, anisotropy and composition.

✓ Specific dynamics in the environment of the extragalactic source: interaction with local matter and radiation fields (in-source photo-disintegration hardens nuclei injection).

- ✓ **Gamma Ray Burst**
  UHECR heavy composition favors LL-GRB with a large number density (vs HL-GRB) and mildly relativistic jets. [Transient]
- ✓ **Active Galactic Nuclei**
  different models of acceleration: termination shock, compact regions at the base of the jet, shear acceleration. [Steady]
- ✓ **Pulsar**
  very hard spectra $\gamma\sim1$, heavy composition due to internal dynamics at the source. [Steady]
- ✓ **Tidal Disruption Events**
  easily reach the needed energies and luminosities, recently associated with high energy neutrinos. [Transient]
- ✓ **Starburst galaxies.**
  no consensus reached on this scenario, hints of an excess in the Auger data at E>38 EeV. [Steady]

Neutral secondaries – UHE neutrinos and γ rays

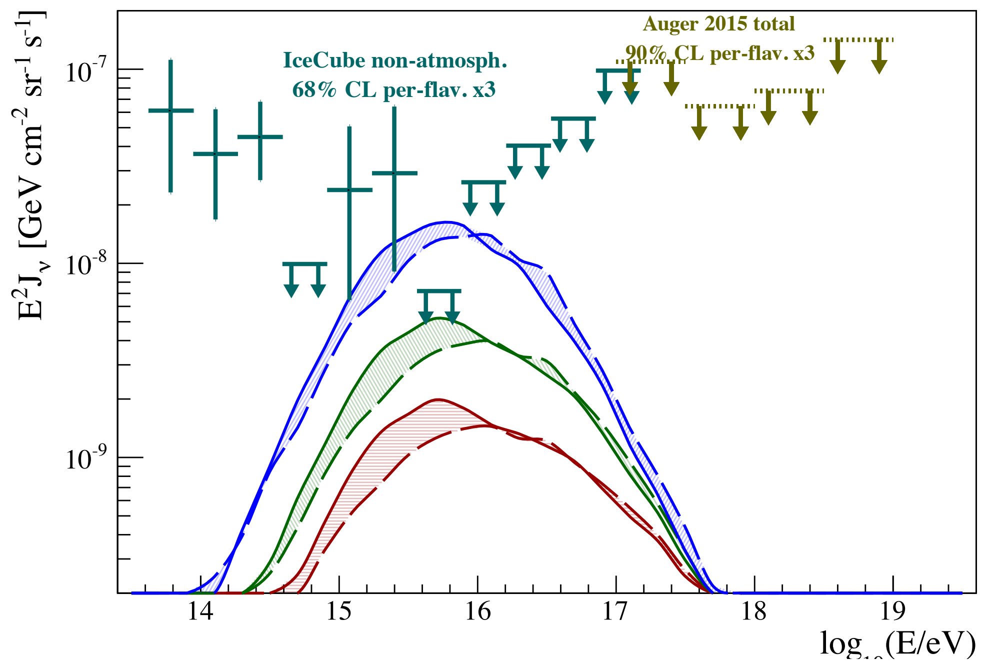
✓ EeV neutrinos

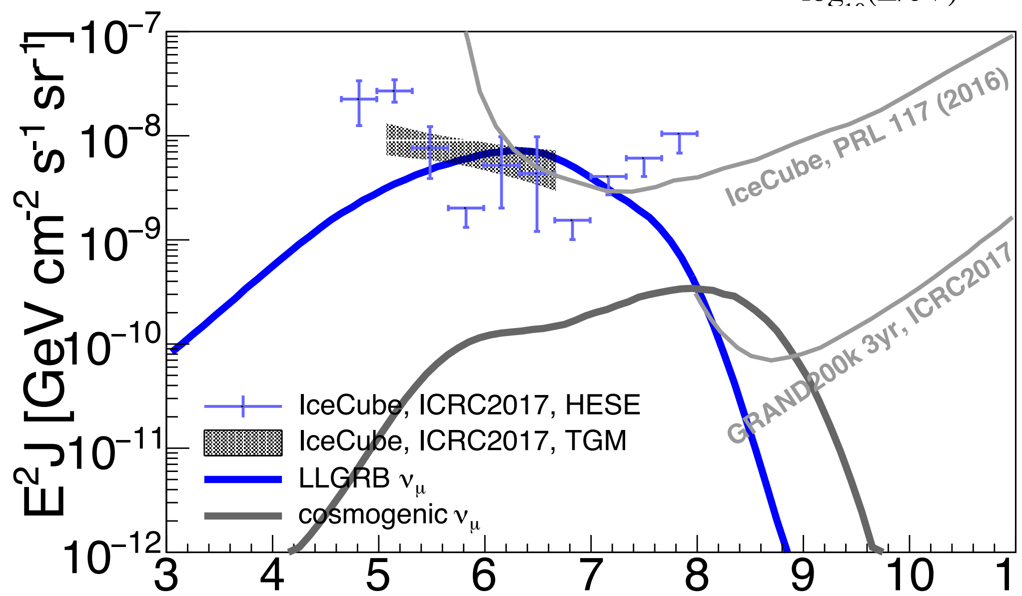
UHE nuclei suffer photo-pion production on CMB only for energies above AE_{GZK} . The production of EeV neutrinos strongly depends on the nuclei maximum energy.
UHE neutrino production by nuclei practically disappears in models with maximum nuclei acceleration energy $E_{max} < 10^{21}$ eV.

✓ PeV neutrinos

PeV neutrinos are generated by the photo-pion production process of UHECR on the EBL (cosmogenic component) and by in-source interactions. IceCube observations can be marginally explained by the cosmogenic component while can be better reproduced by in-source photo-disintegration processes (as in GRB).

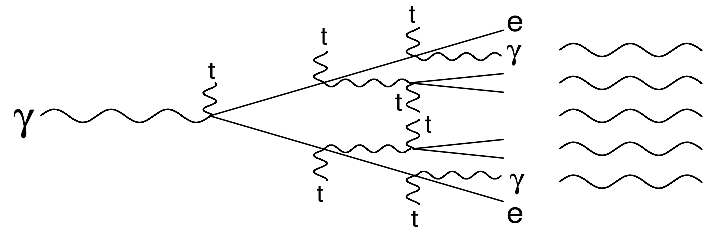
RA, Boncioli, di Matteo, Grillo, Petrera, Salamida (2015)





Boncioli, Bhiel, Winter (2018)

$p(A) + \gamma \to e^{\pm}$
$p(A) + \gamma \to \pi^0 \to \gamma$
$p(A) + \gamma \to \pi^{\pm} \to e^{\pm}, \nu$



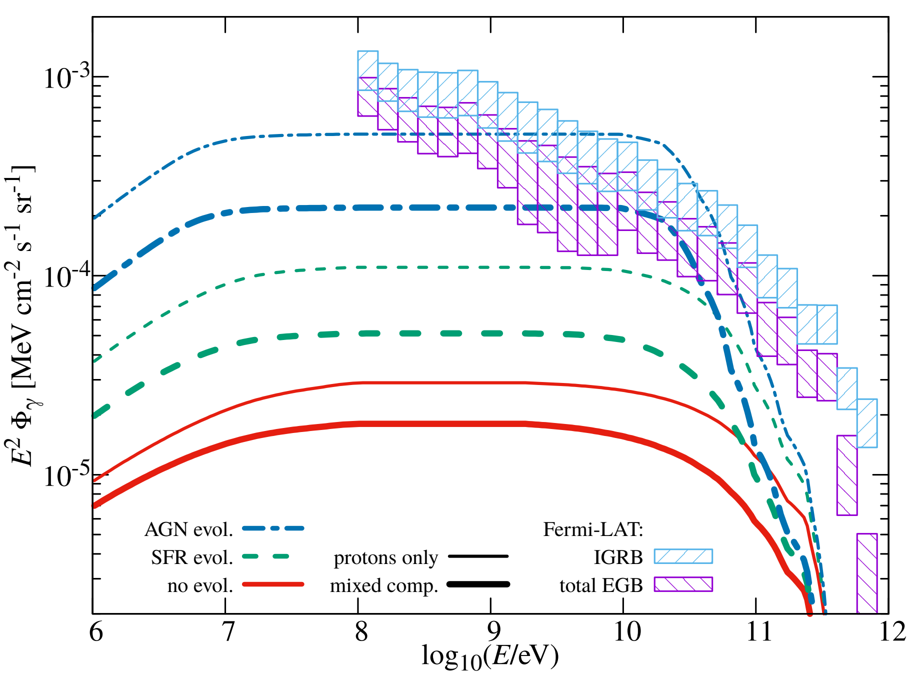
diffuse extragalactic γ ray background (10^{-2}-10^{2} GeV).

- ✓ Pair and photo-pion production are less efficient in the case of UHE nuclei respect to protons (single nucleon interaction, energy/nucleon, higher energy required).
- ✓ Electromagnetic cascades show a universal behavior independent of the spectrum of primaries (which just fixes the normalization).

$$n_\gamma(E_\gamma) \propto \begin{cases} E_\gamma^{-3/2} & E_\gamma < \mathcal{E}_X \\ E_\gamma^{-2} & \mathcal{E}_X \leq E_\gamma \leq \mathcal{E}_{EBL} \end{cases}$$

$$\mathcal{E}_X = \frac{\mathcal{E}_{EBL}}{3}\frac{\epsilon_{CMB}}{\epsilon_{EBL}} \simeq 10^7 \text{ eV}$$

$$\mathcal{E}_{EBL} \simeq 2.5 \times 10^{11} eV$$
$$\mathcal{E}_{CMB} \simeq 2.5 \times 10^{14} eV$$



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, only models with strong cosmological evolution and light composition are excluded.
- ✓ The future CTA observatory will improve the constrains on UHECR composition and cosmological evolution of sources.

UHECR, DM and Cosmology

- ✓ Supermassive particles, with mass M>10^8 GeV, can be easily generated in the early universe by time-dependent gravitational fields and through gravitational (direct) coupling to the inflaton field and/or to SM fields.
- ✓ Supermassive particles can be long-lived and compose the observed DM. The decay of SHDM is driven by high order suppressed interaction with SM fields or through non-perturbative instanton effect.
- ✓ The SHDM scenario can be constrained by UHE CR, γ ray and neutrino observations.
- ✓ SHDM implies primordial gravitational waves production and links UHECR physics to cosmology and CMB observations (tensor to scalar ratio).

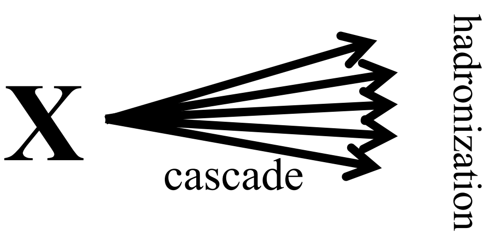
$$X \to q\bar{q} \to N, \gamma, \nu, \bar{\nu}$$

✓ High order suppressed interaction

$$\mathcal{L}_{int} = \frac{g_{X\Theta}}{\Lambda^{n-4}} X\Theta \qquad \tau_X = \frac{V_n}{4\pi M_X \alpha_{X\Theta}} \left(\frac{\Lambda}{M_X}\right)^{2n-8} \qquad \alpha_{X\Theta} = \frac{g^2_{X\Theta}}{4\pi}$$

✓ Instanton decay

$$\tau_X \simeq \frac{1}{M_X} e^{4\pi/\alpha_X} \qquad \alpha_X = \frac{g^2_X}{4\pi}$$

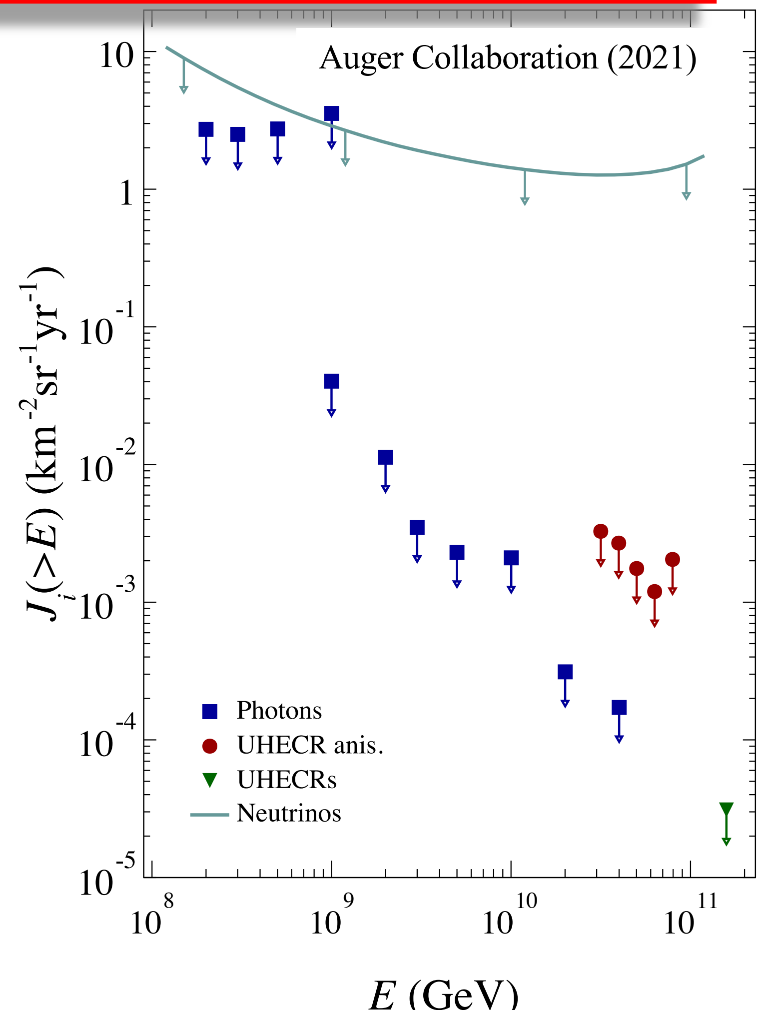


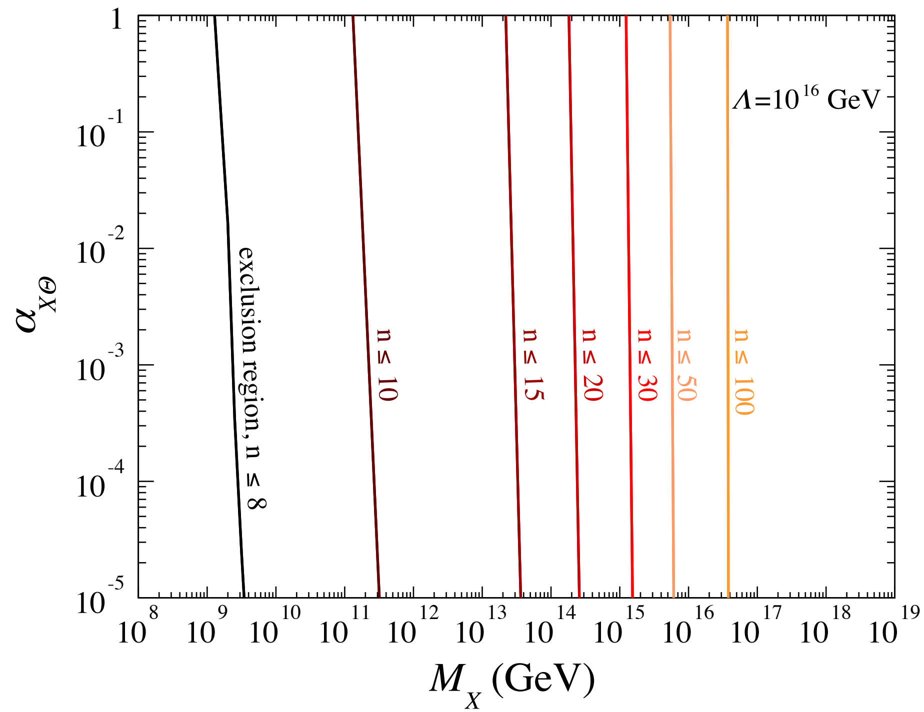
mainly π
therefore γ and ν

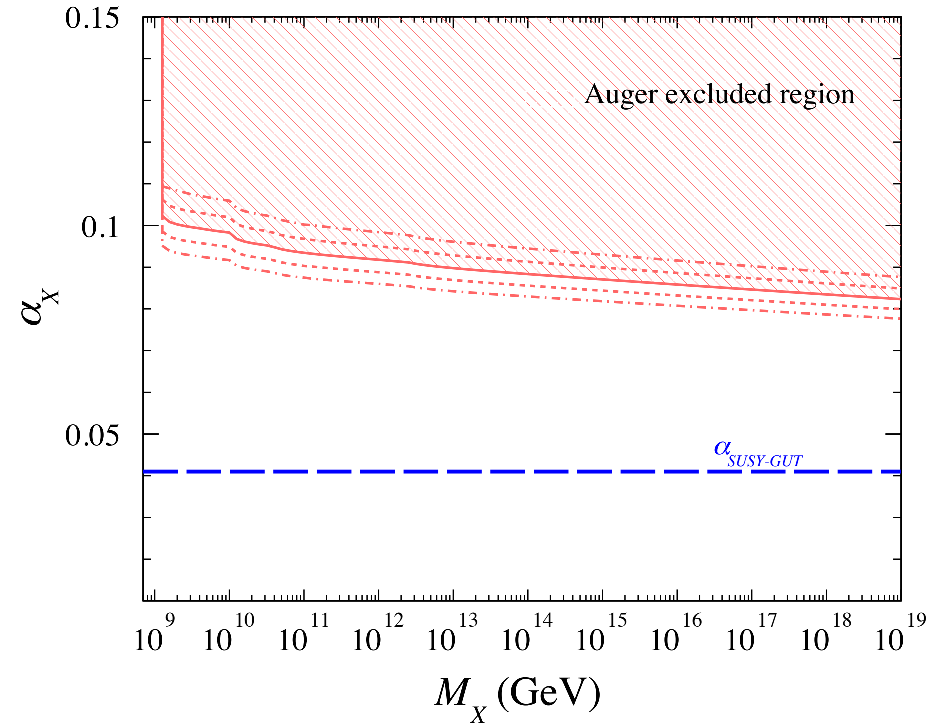
$$Q_{\nu,\gamma,p} \propto E^{-1.9}$$

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

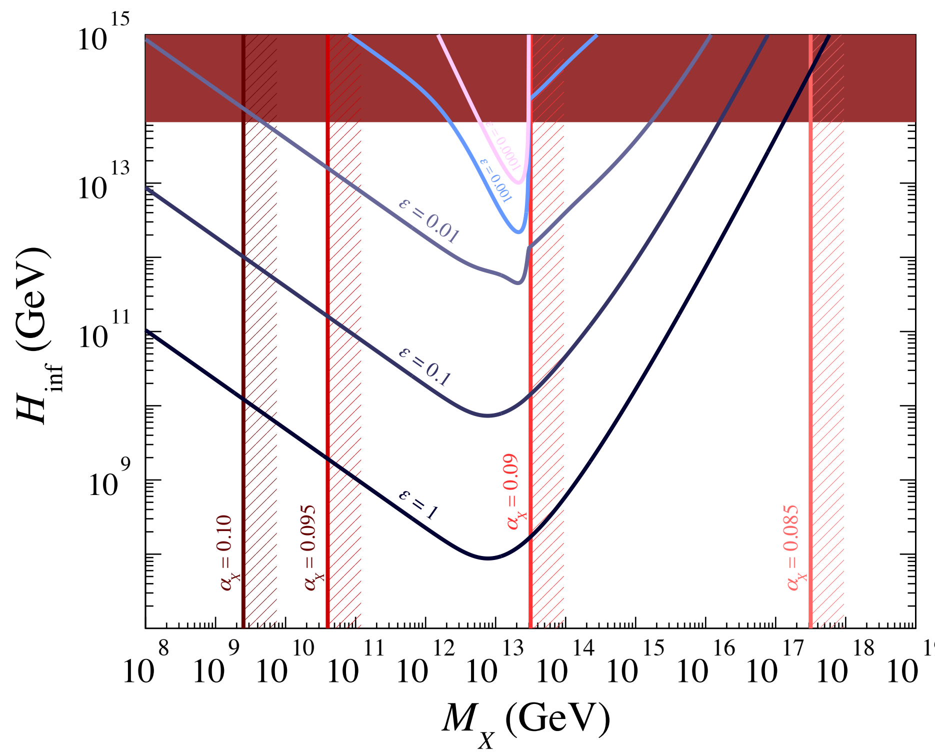
$$J_{SHDM}(E,\theta) = \frac{1}{4\pi M_X \tau_X} Q(E) \int_0^{r_{max}(\theta)} dr n_X(R(r))$$







Auger Collaboration (2022)



✓ The limits on M_x and $\boldsymbol{\tau}_X$ can be rewritten in terms of the cosmology parameters H_{inf} and $\boldsymbol{\varepsilon}$. The Hubble parameter at the end of inflation H_{inf} is bounded by the CMB tensor to scalar ratio

$$H_{inf} \lesssim 6.6 \times 10^{-6} M_P \left(\frac{r}{0.1}\right)^{1/2}$$

The reheating efficiency $\boldsymbol{\varepsilon}$ can be expressed in terms of the inflaton decay amplitude Γ_φ

$$\epsilon = \sqrt{\frac{\Gamma_\phi}{H_{inf}}}$$

Conclusions

In the past 20 years the physics of UHECR experienced a paradigm shift. Thanks to the measurements of PAO and TA, the simple picture of protons at the highest energies has been replaced by a more complex (and phenomenologically richer) one with heavy nuclei dominating the highest energies.

- ✓ Mass determination is currently limited by the uncertainties in the predictions of hadronic models and muon content in the EAS.
- ✓ Precise mass determination till the highest energies will be of paramount importance in the future. The necessary step forward should be disentangling the all-particle energy spectrum into that of individual mass groups (p, He, CNO, MgAlSi, Fe). The clearest path to event-by-event primary mass reconstruction lies in a high-resolution independent reconstruction of both X_{max} and N_{μ} coupled to a high-resolution energy reconstruction.
- ✓ The origin of the flux suppression at the highest energies is still uncertain (energy losses or maximum energy at the source). Solving this puzzle requires individual mass groups energy spectra.
- ✓ Identifying individual sources would be possible only at the highest energies and with light primaries, calling for a shower-by-shower determination of the mass and energy of the primary particle.
- ✓ To study the properties of a single source, to probe BSM physics and cosmological models it is needed larger statistics at the highest energies ($\sim 10^{20}$ eV).

In the next 5-10 years, the upgrades of the Auger and TA observatories, together with new potential next-generation detectors, will provide larger statistics and refined measurement of the energy spectrum, mass and anisotropy to the point where several of the above problems can be solved.