Testing astrophysical model to interpret the Auger data

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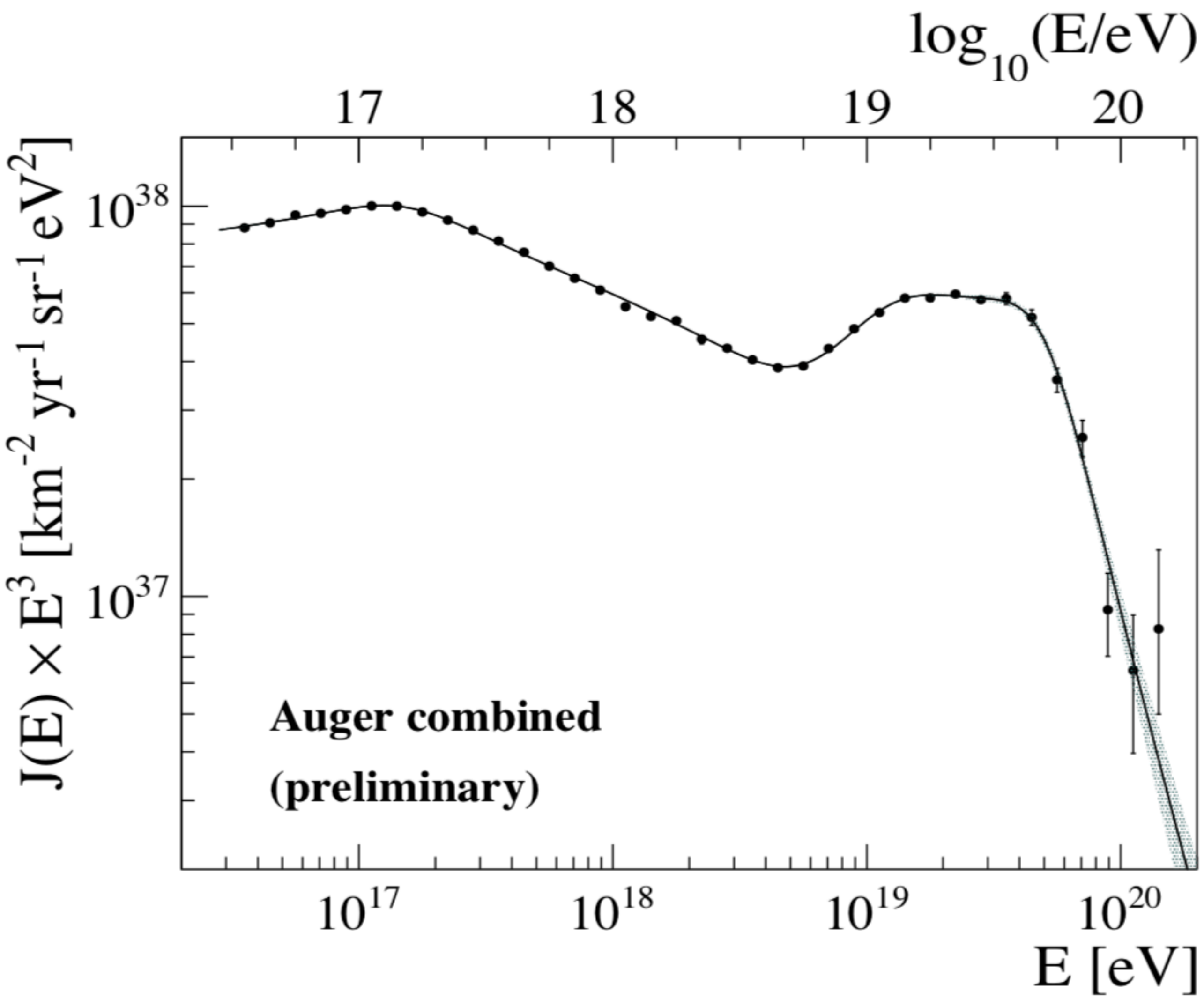
Outline

- Restyling of the Combined fit;
- Application to a mass composition study;
- Interpretation of the ankle feature;
- Source effect mechanism;
- Conclusion and future perspectives;

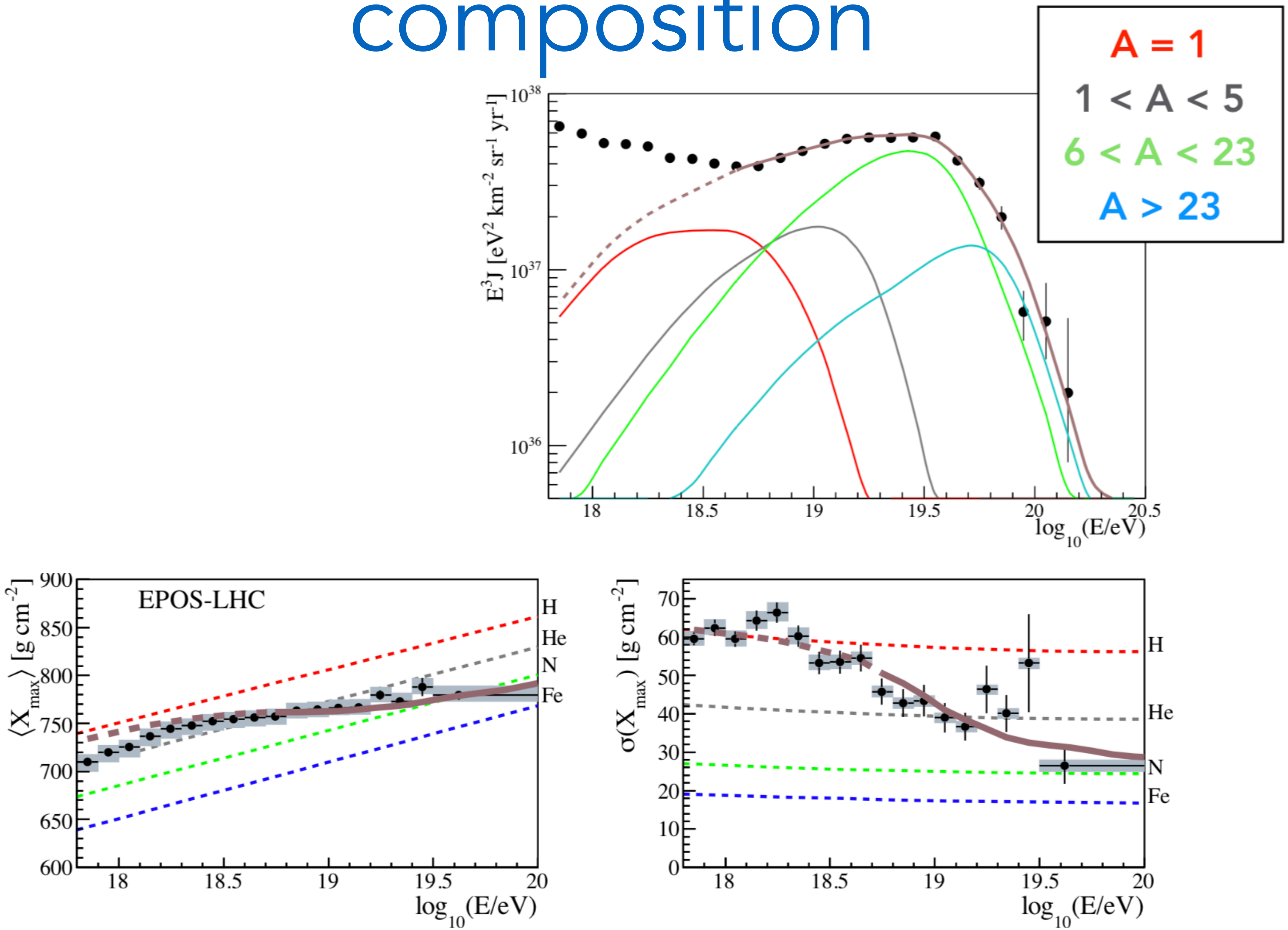
Auger spectrum



- *What is the origin of the cosmic-ray features in the energy spectrum?*
- *Energy spectrum alone remains ambiguous concerning interpretation.*

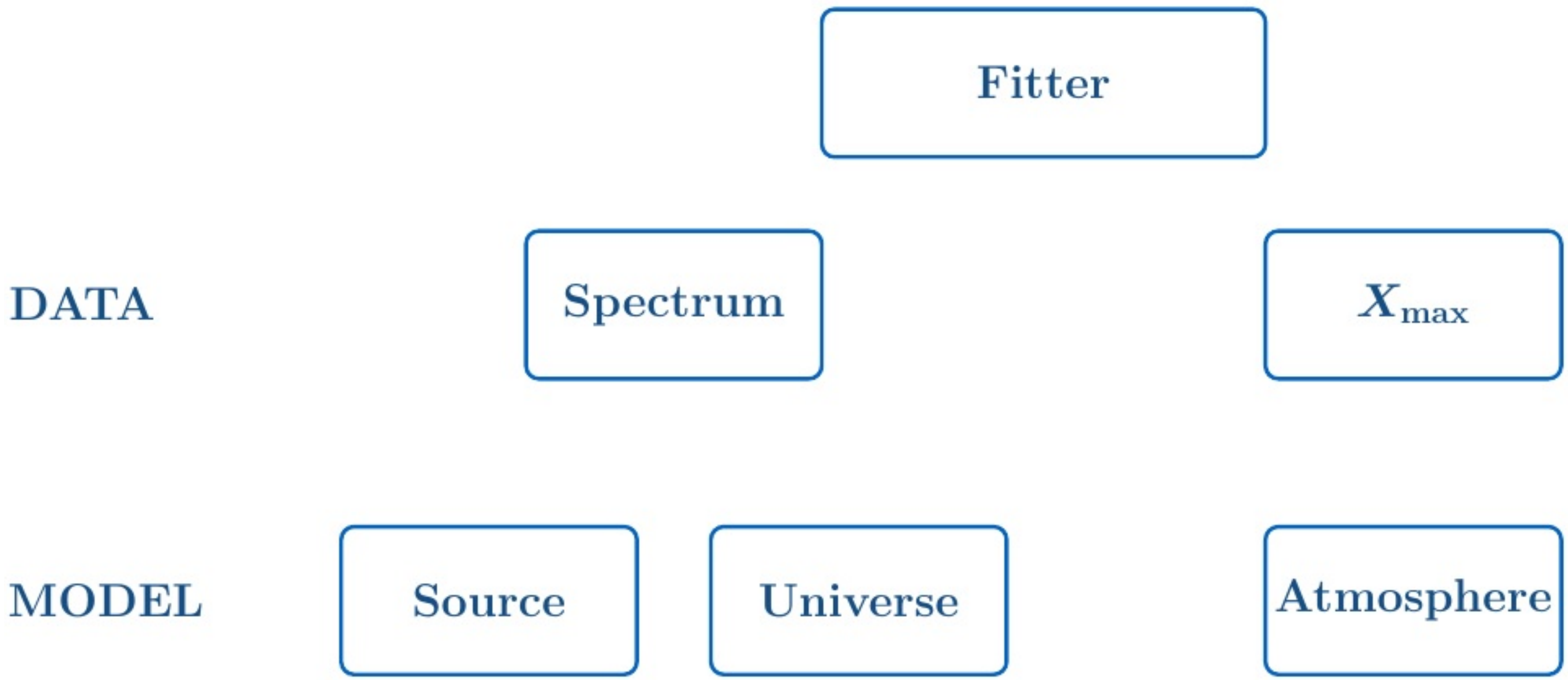
V.Verzi [PierreAugerColl.], PoS(ICRC2019)450

Combined fit of both spectrum and composition

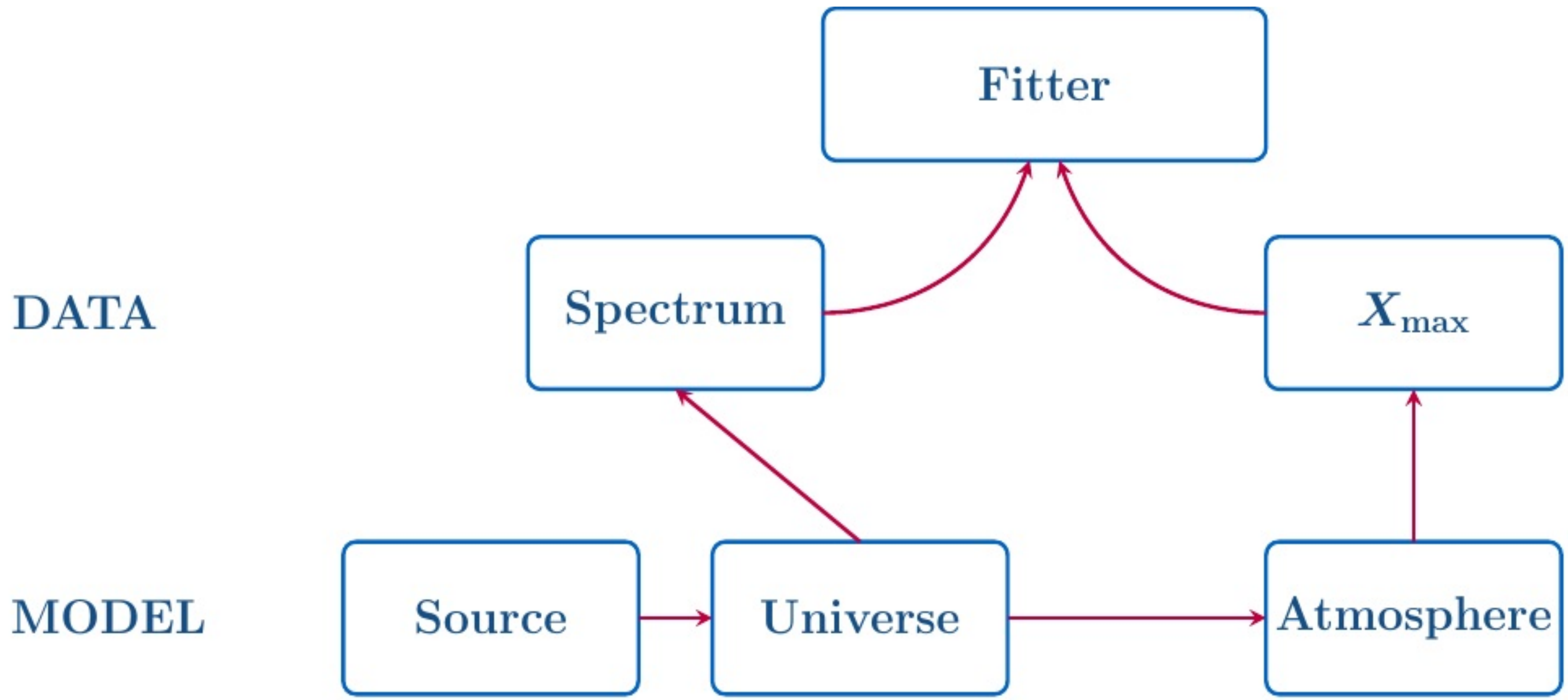


A. Aab et al .,JCAP04(2017)038,arXiv:1612.07155v3

Update of the combined fit

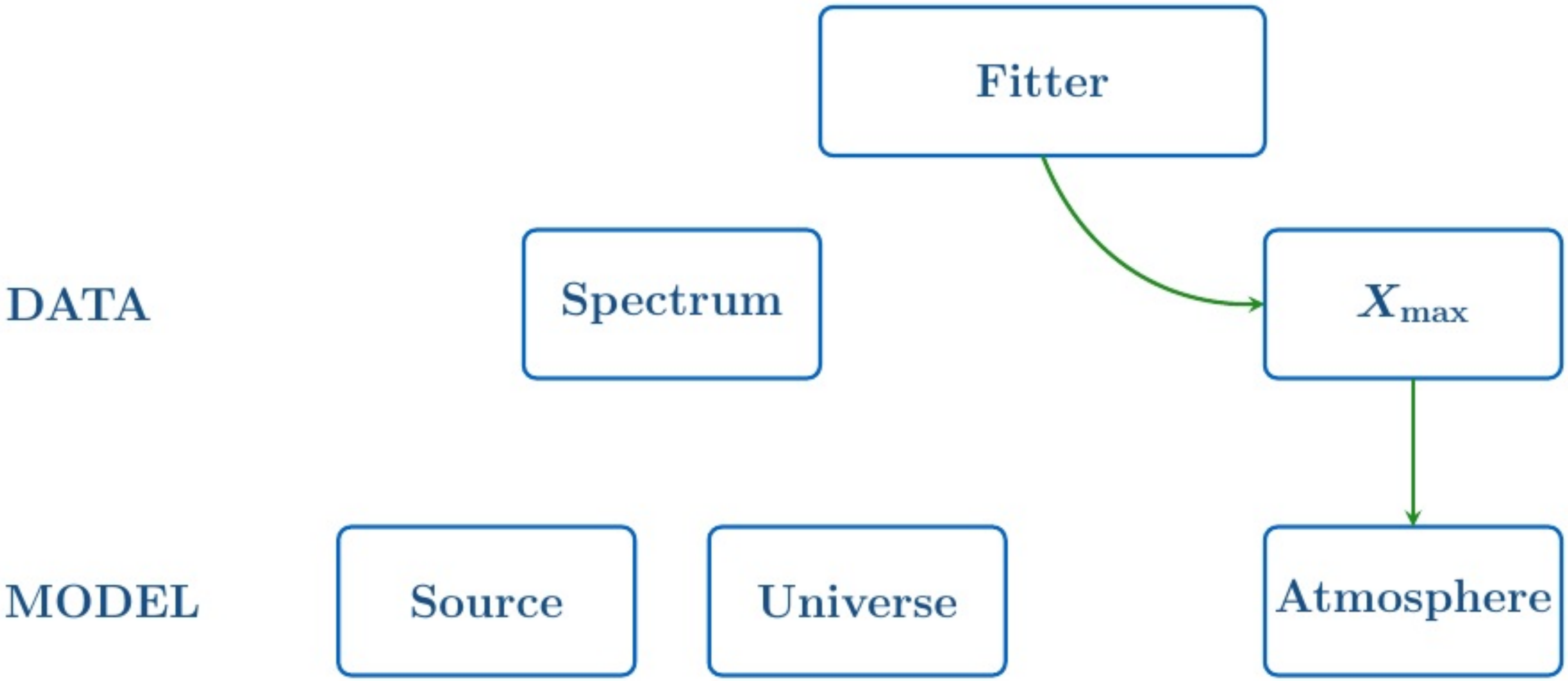


Update of the combined fit



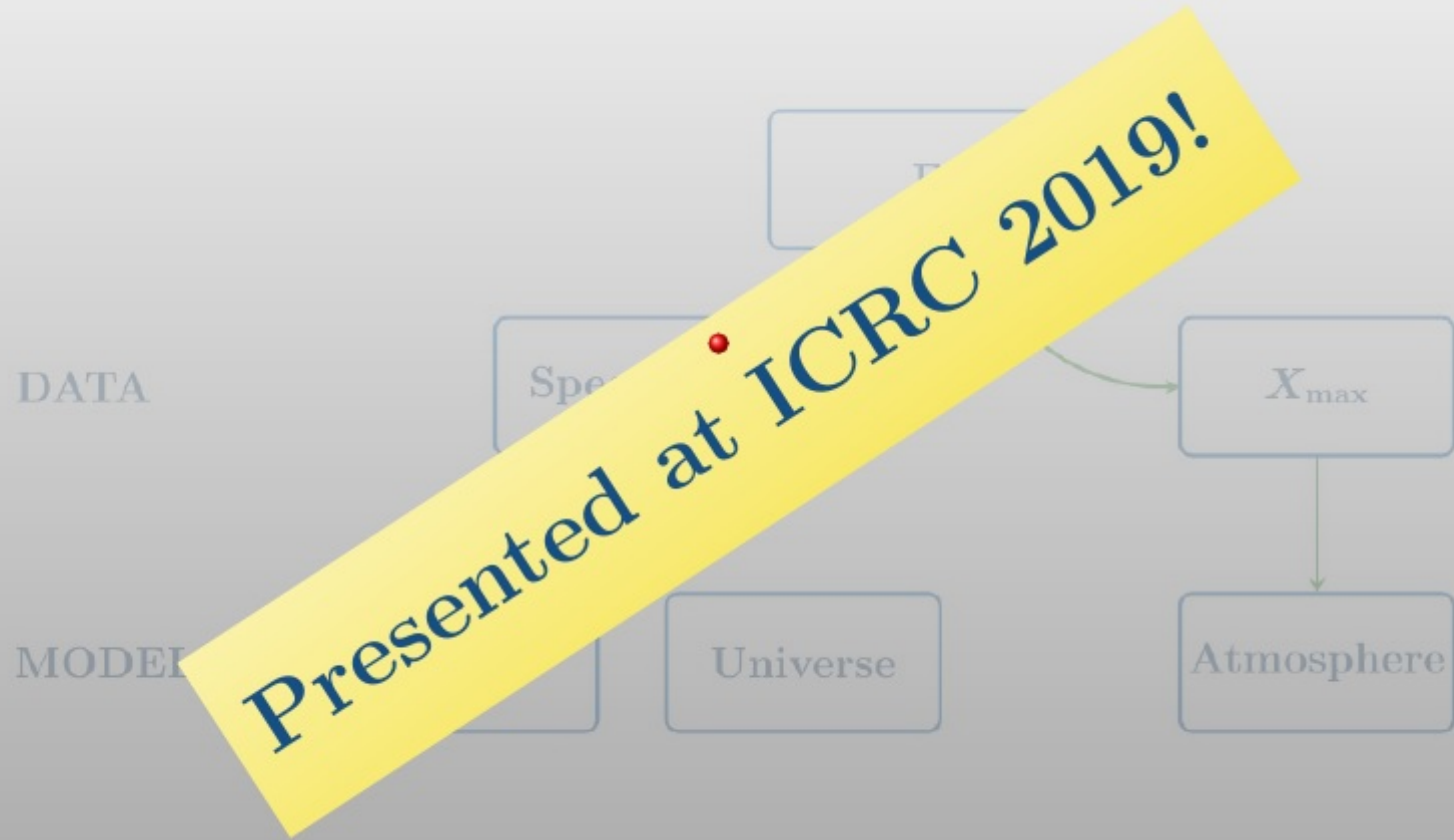
Working principle of the combined fit

Update of the combined fit



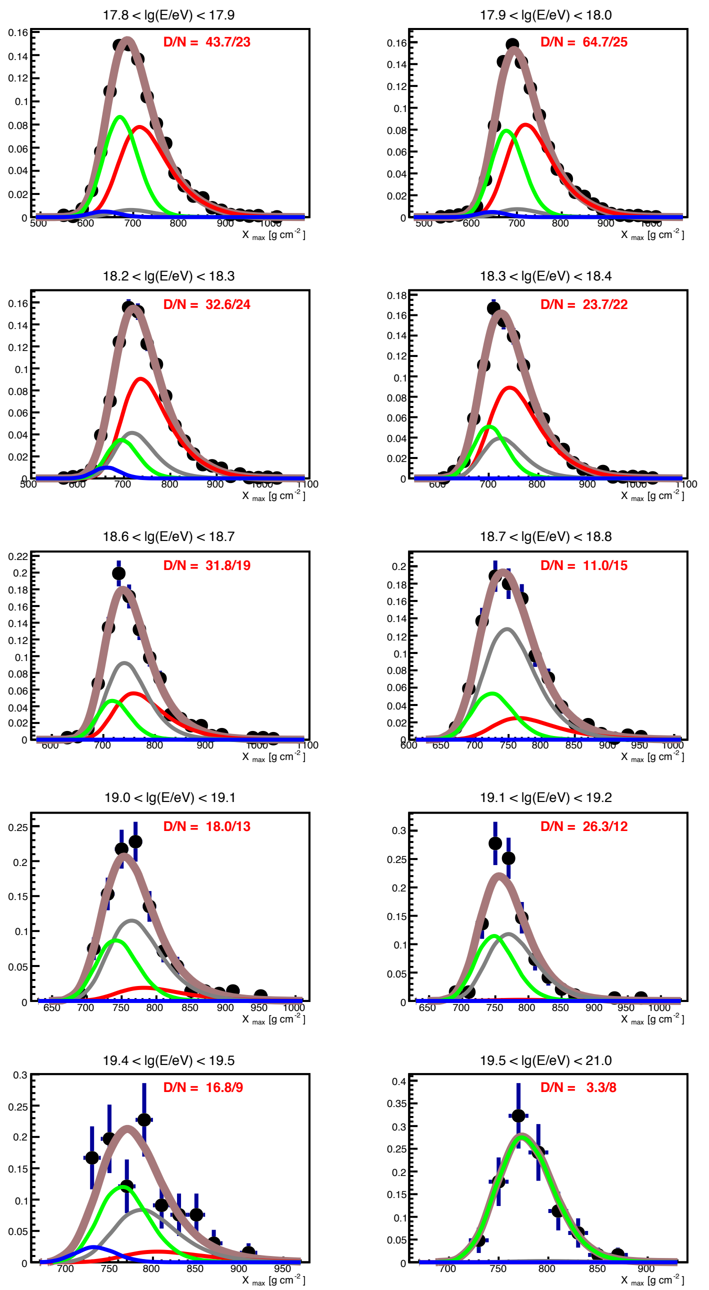
Working principle of the fraction fit

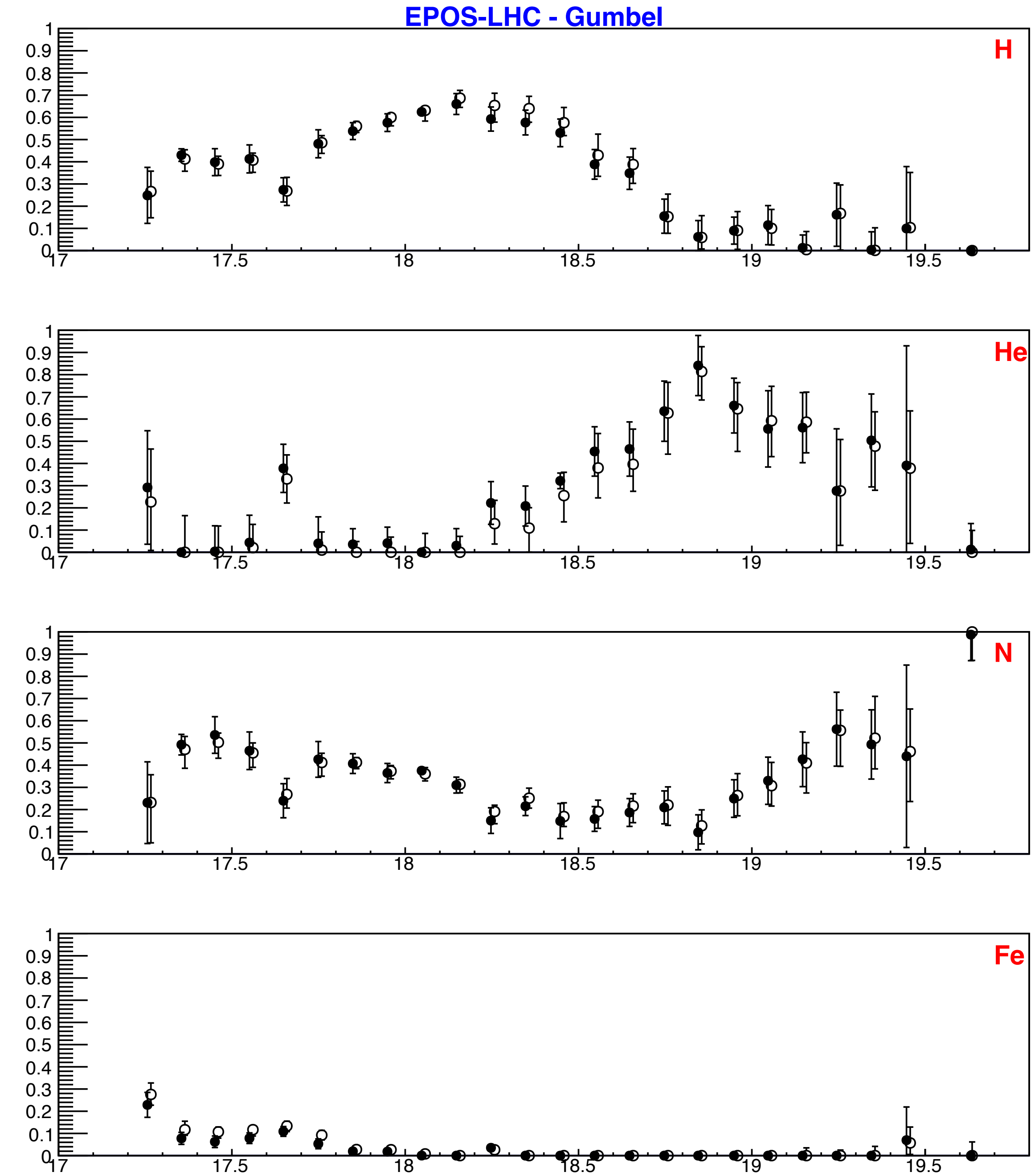
Update of the combined fit



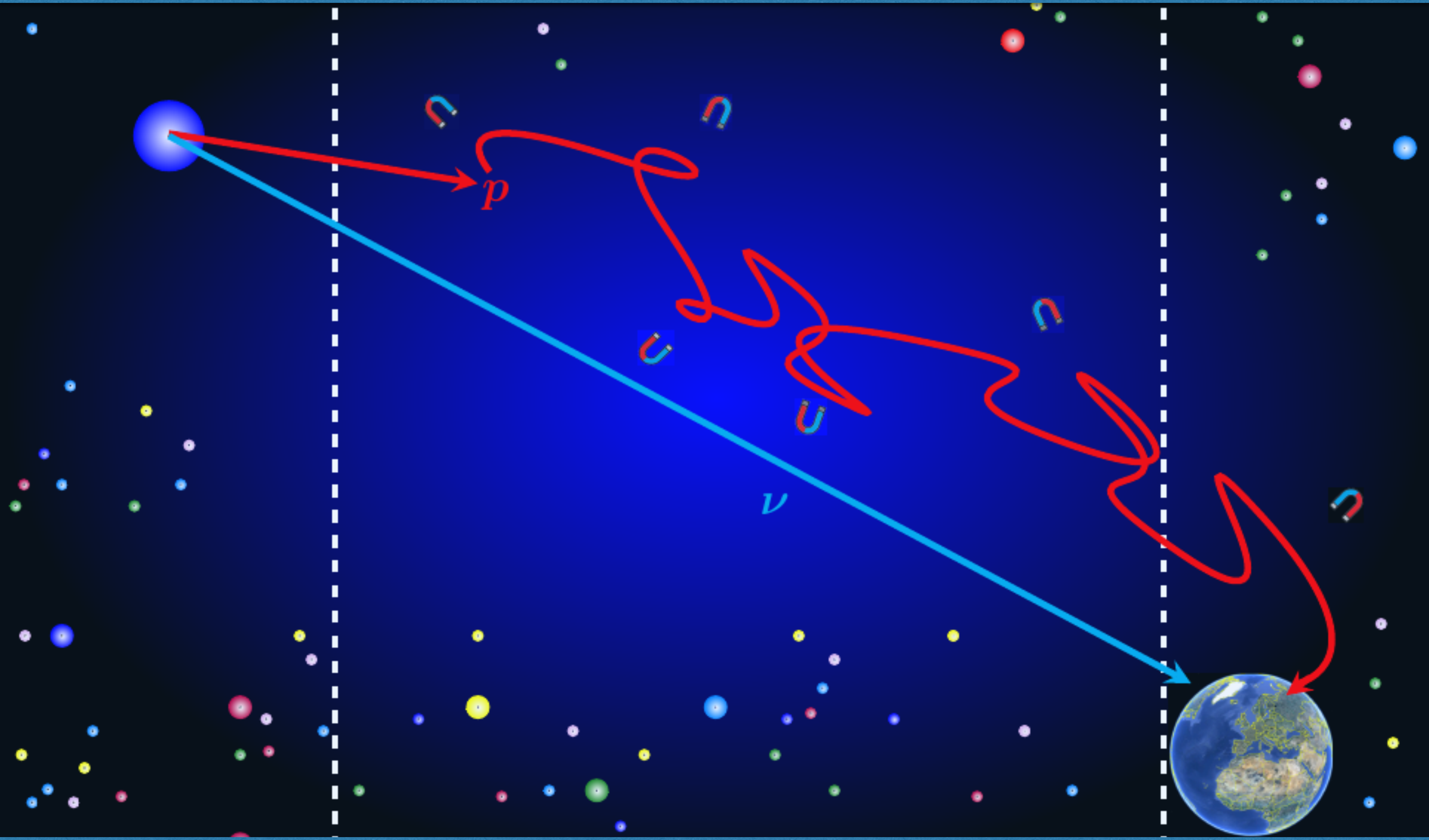
A.Yushkov [PierreAugerColl.], PoS(ICRC2019)482

Results of fraction fit

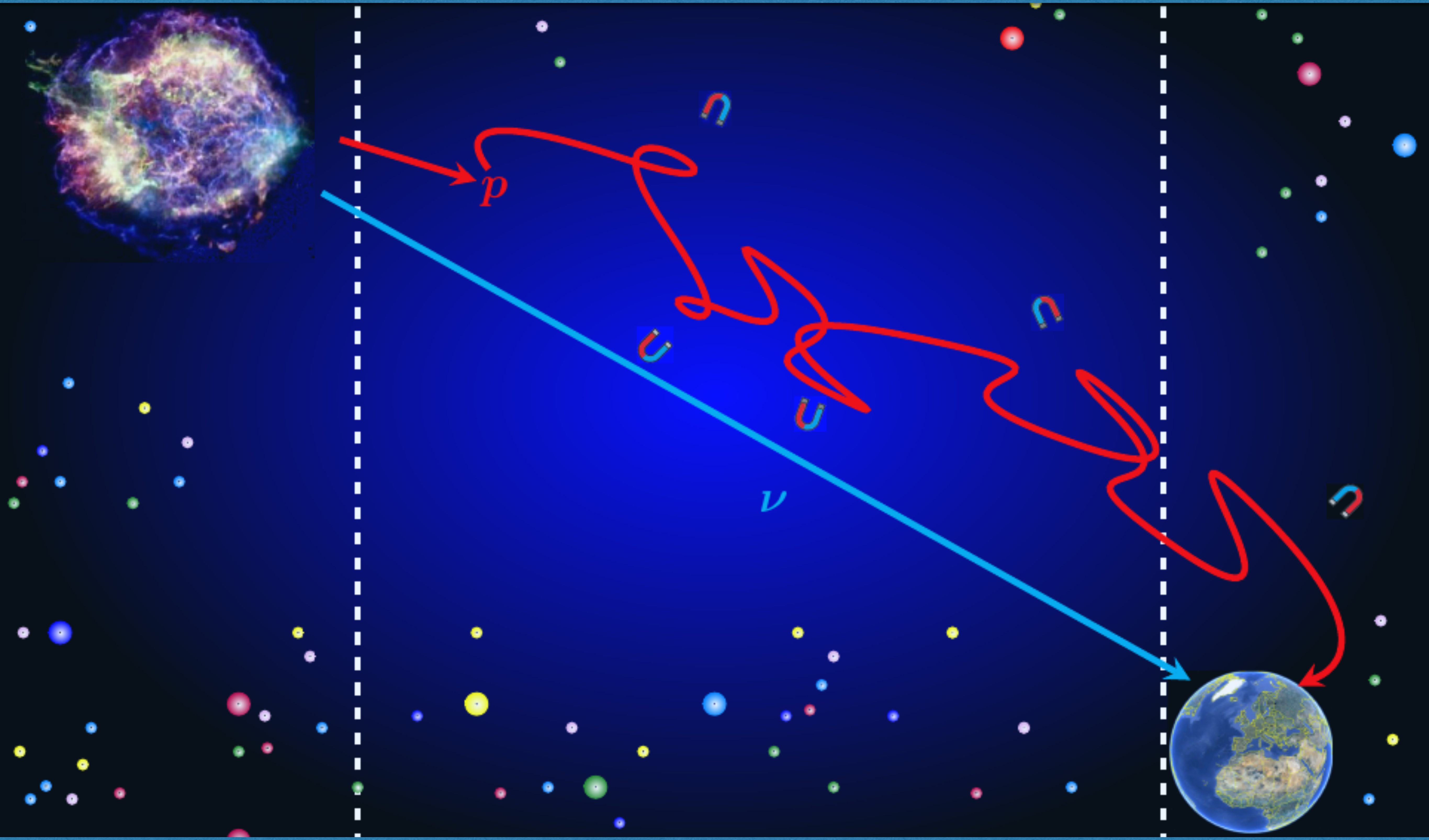




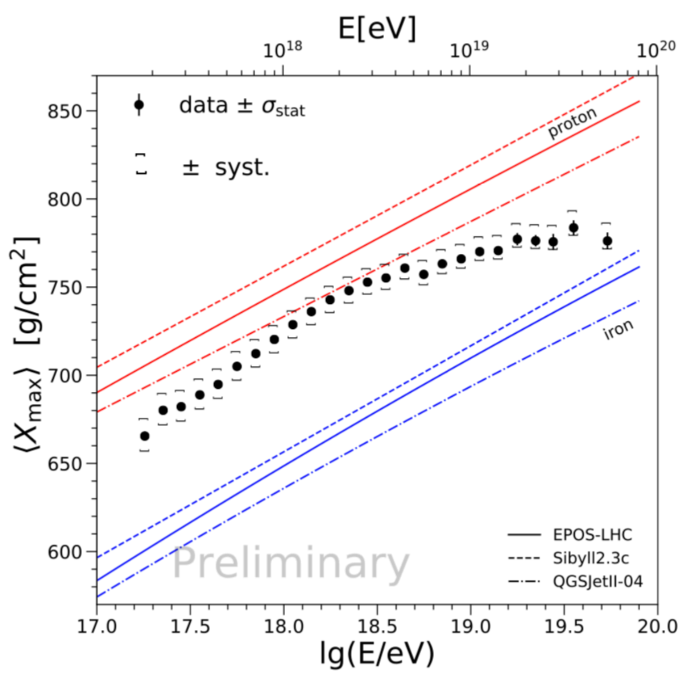
Testing source effect mechanism

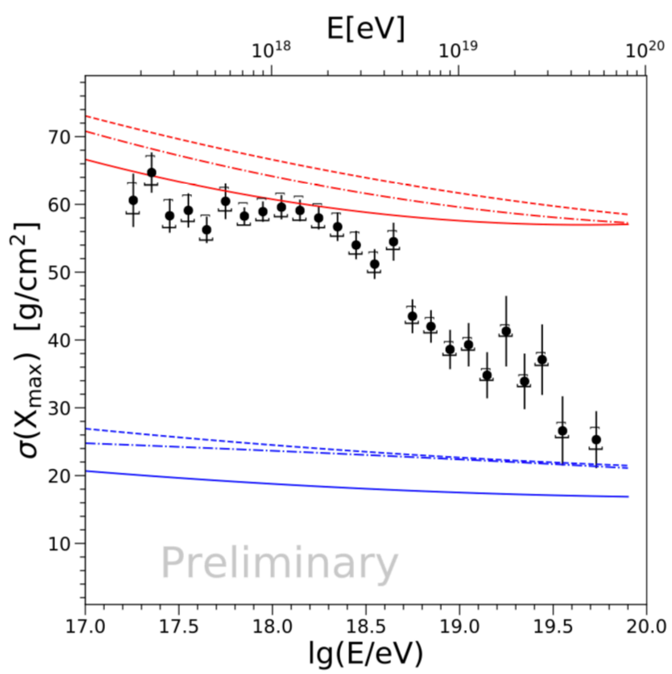


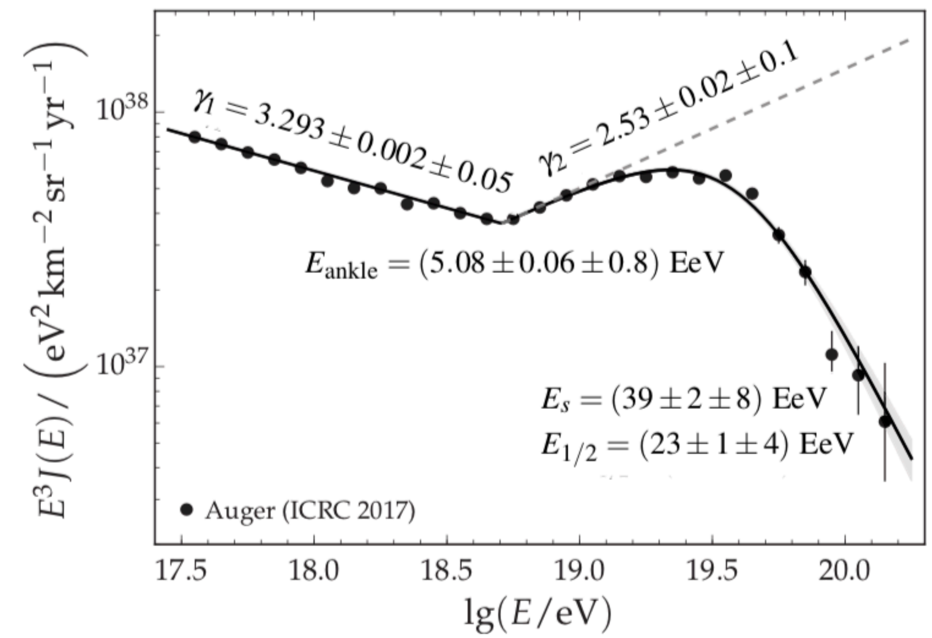
Testing source effect mechanism



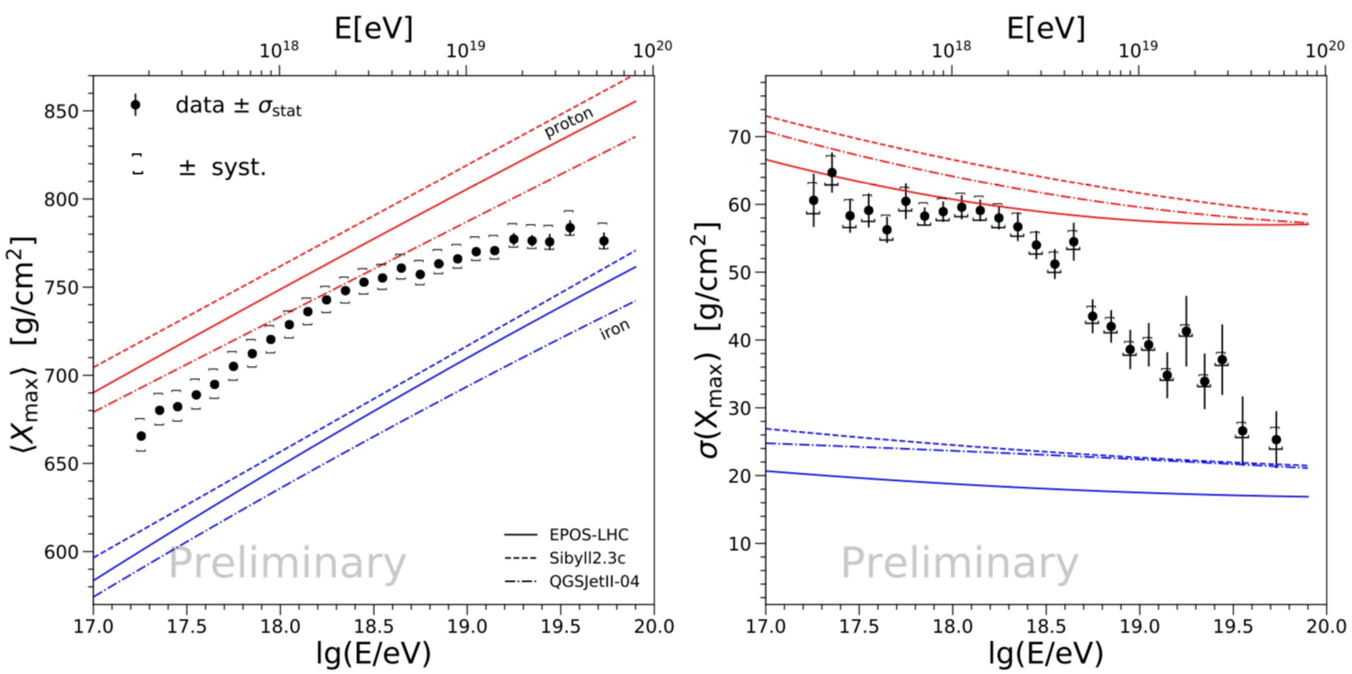
Auger measurements

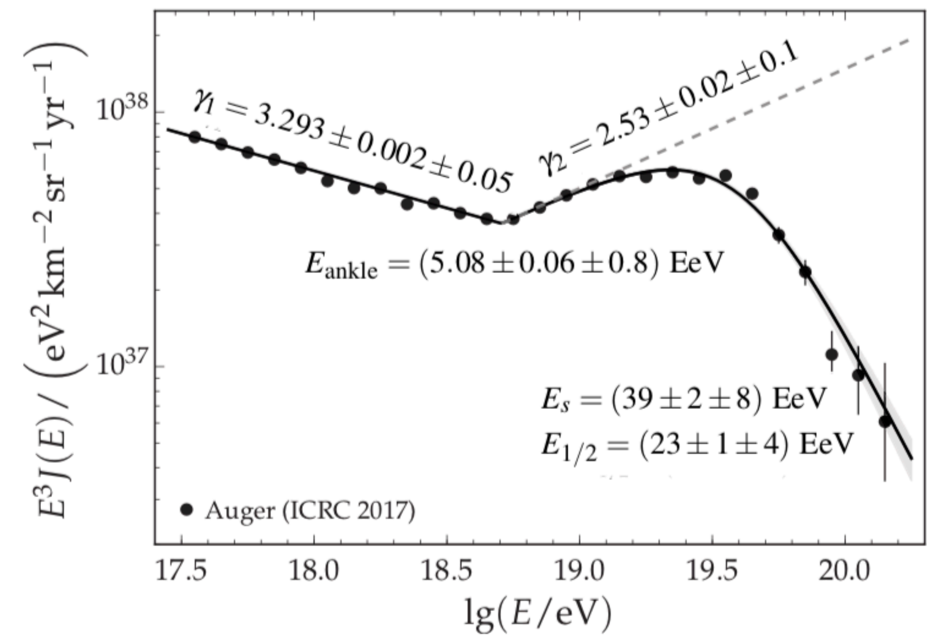






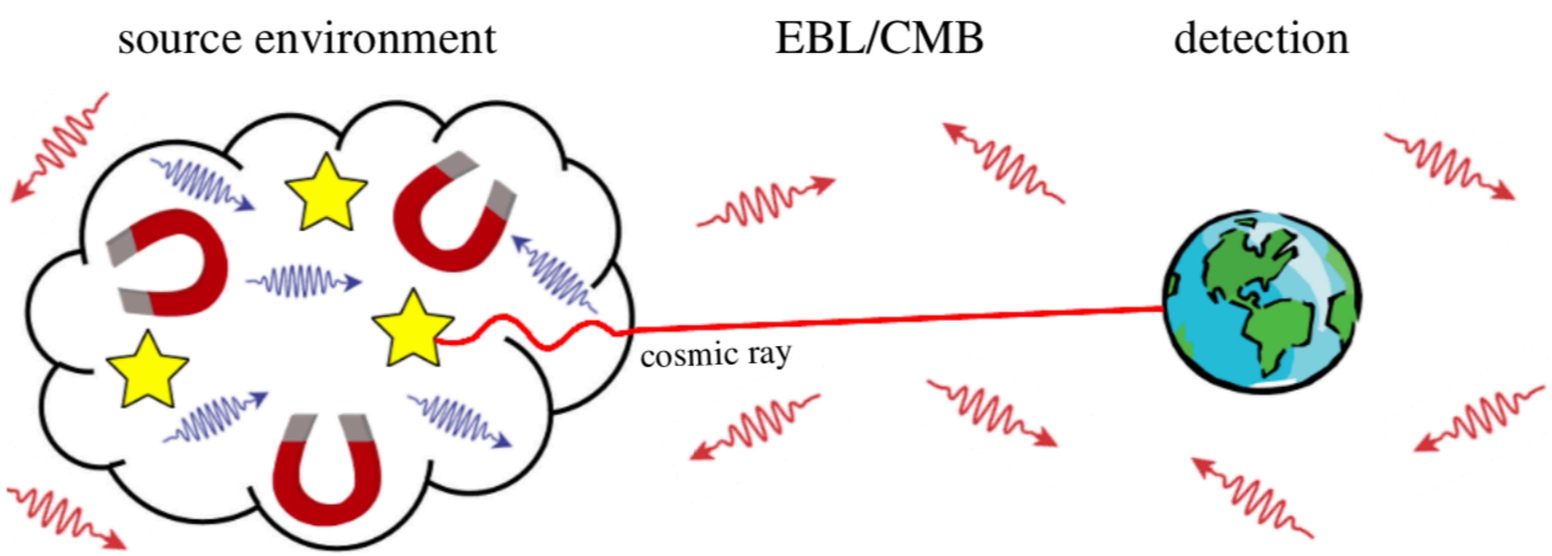
What is the ankle?





- ❑ If we assume only proton spectrum—> feature of the propagation;
- ❑ Transition point between galactic and extragalactic cosmic rays;
- ❑ Two extragalactic components;
- ❑ Source mechanism;

Testing a model



- Consider a system in which the accelerator (also referred to as the source) is embedded in an environment in which the cosmic rays are confined by magnetic fields while interacting with the ambient radiation field.

- The lower the energy, the more time the nuclei have to interact before escaping, leading to a hardening of the spectrum and lightening of the composition of nuclei escaping the region surrounding the source.

Origin of the ankle in the ultrahigh energy cosmic ray spectrum and of the extragalactic protons below it, M.Unger, G. Farrar, L. Anchordoqui, arXiv:1505.02153v2

SimProp

What ?

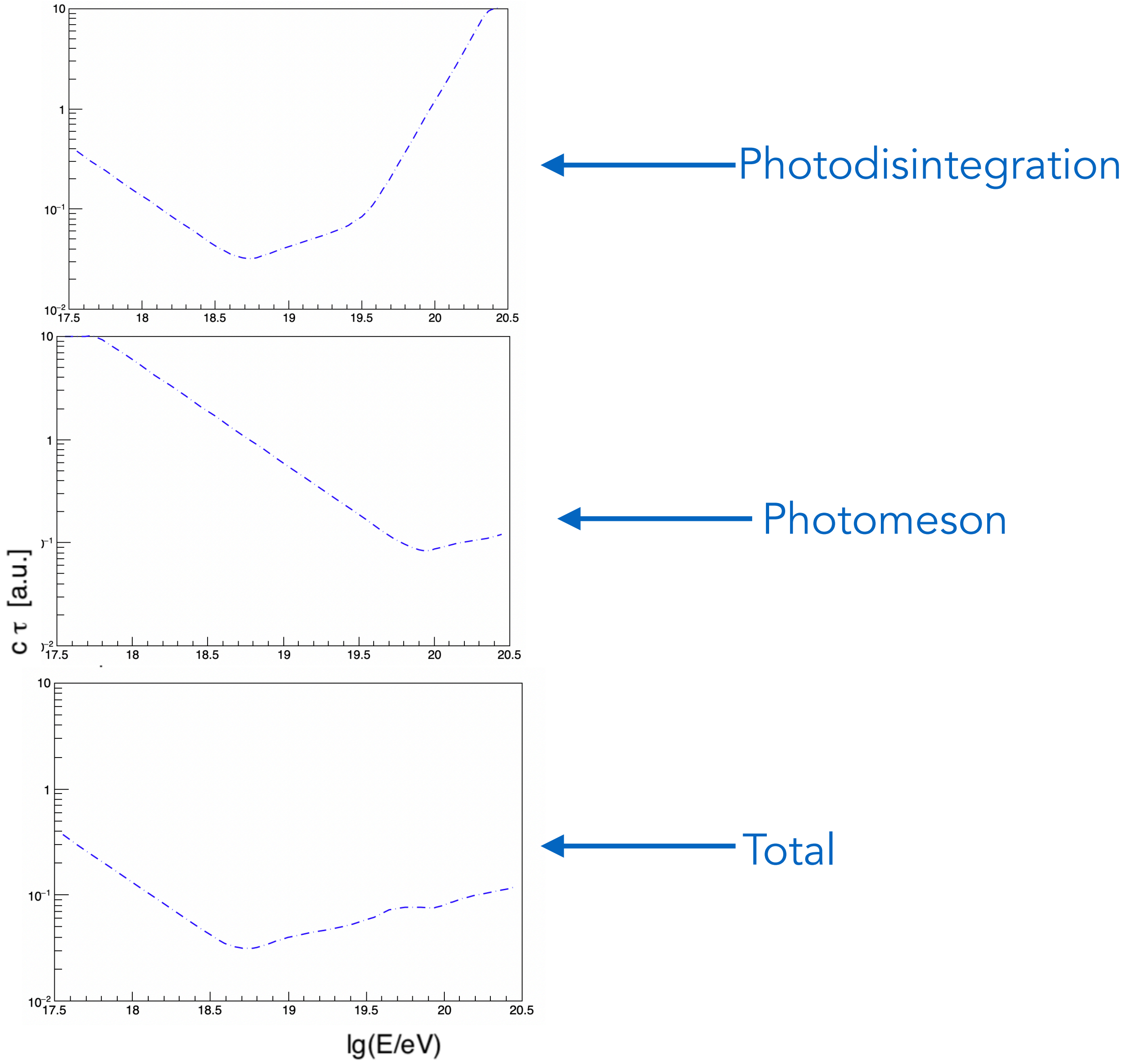
- MonteCarlo code for propagation of particle through the Universe;
- Generation of a primary (proton or nucleus) and its propagation from the source to the observer;
- Taking into account all possible energy losses;

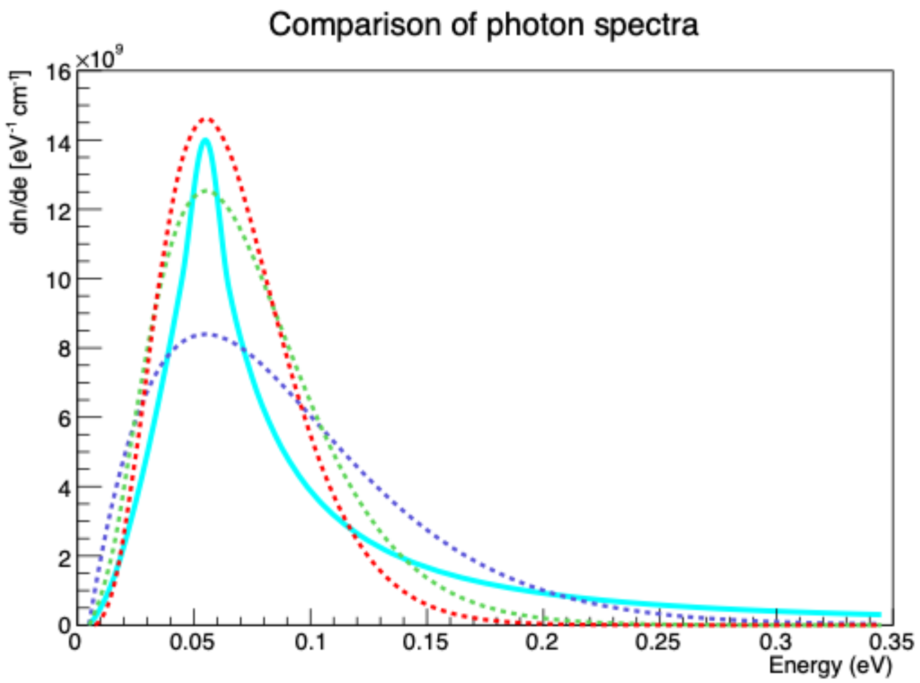
Why?

- Interaction time easy to compute;
- Propagation and production of secondary particles;
- ☑ Implementation of a generic photon field;
- ☑ A single code for propagation inside and outside the source;

SimProp v2r4: Monte Carlo simulation code for UHECR propagation, R.Aloisio, D.Boncioli, A.Di Matteo, A.F. Grillo, S.Petrera, F.Salamida, arXiv:1705.03729 .

Interaction and escape time

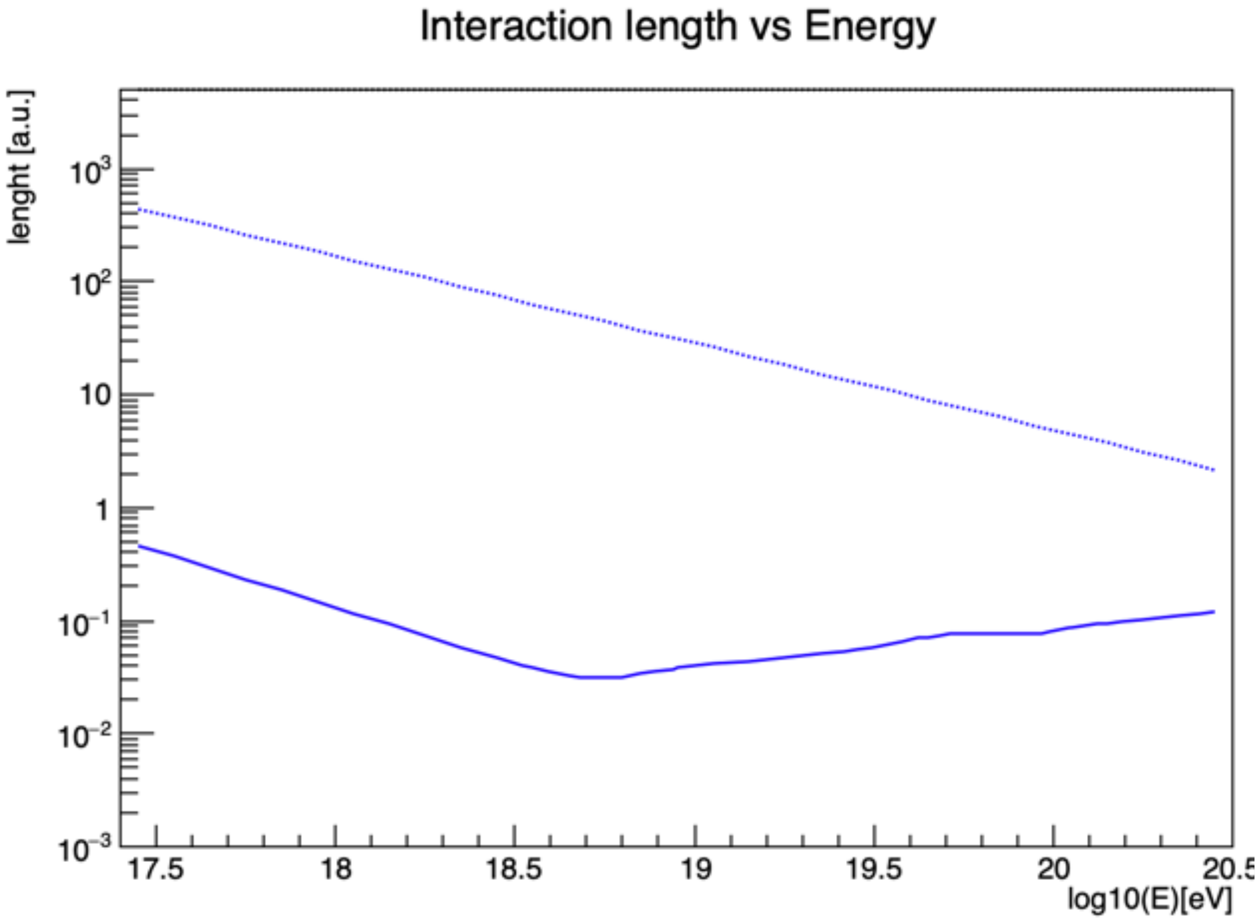


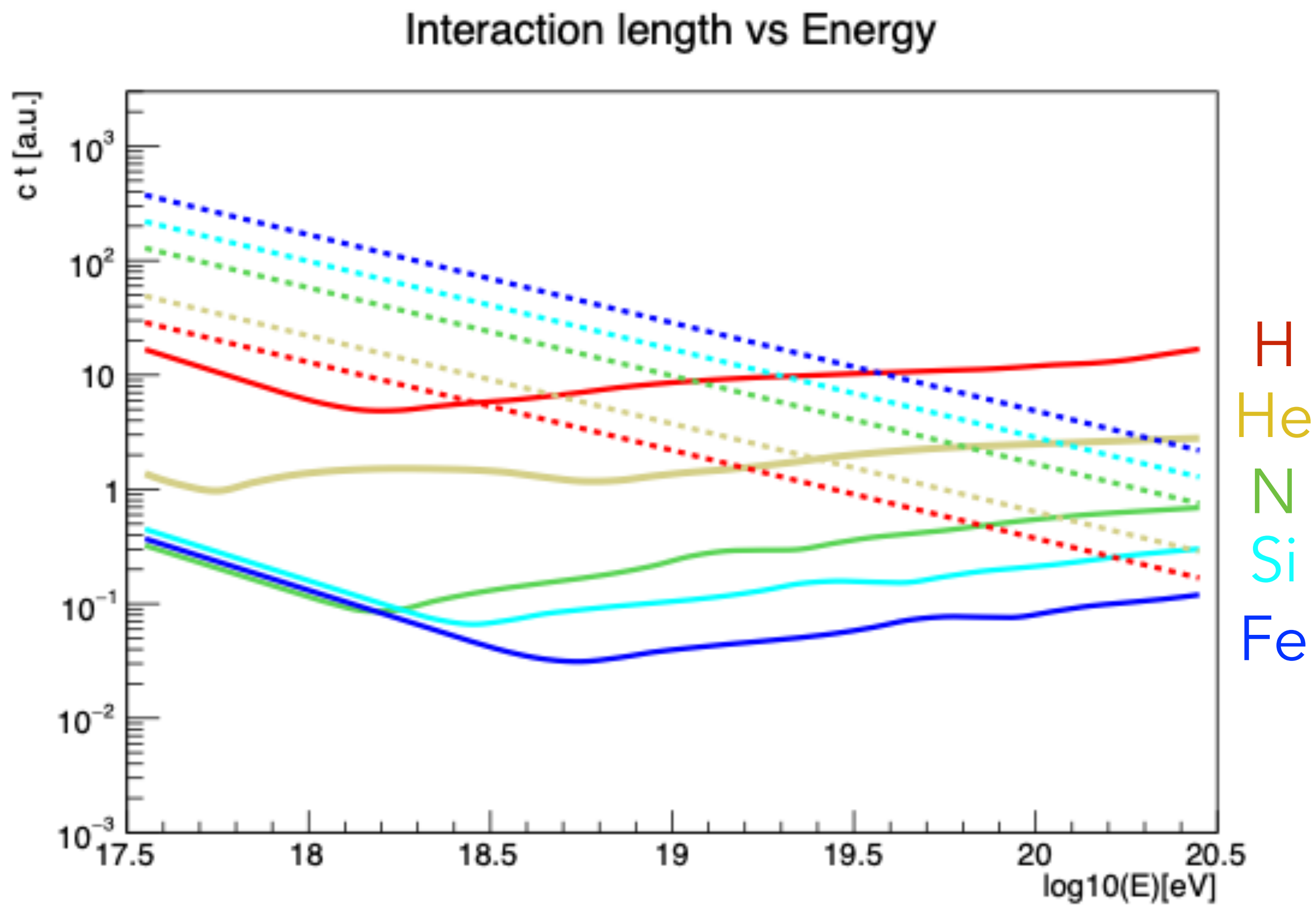


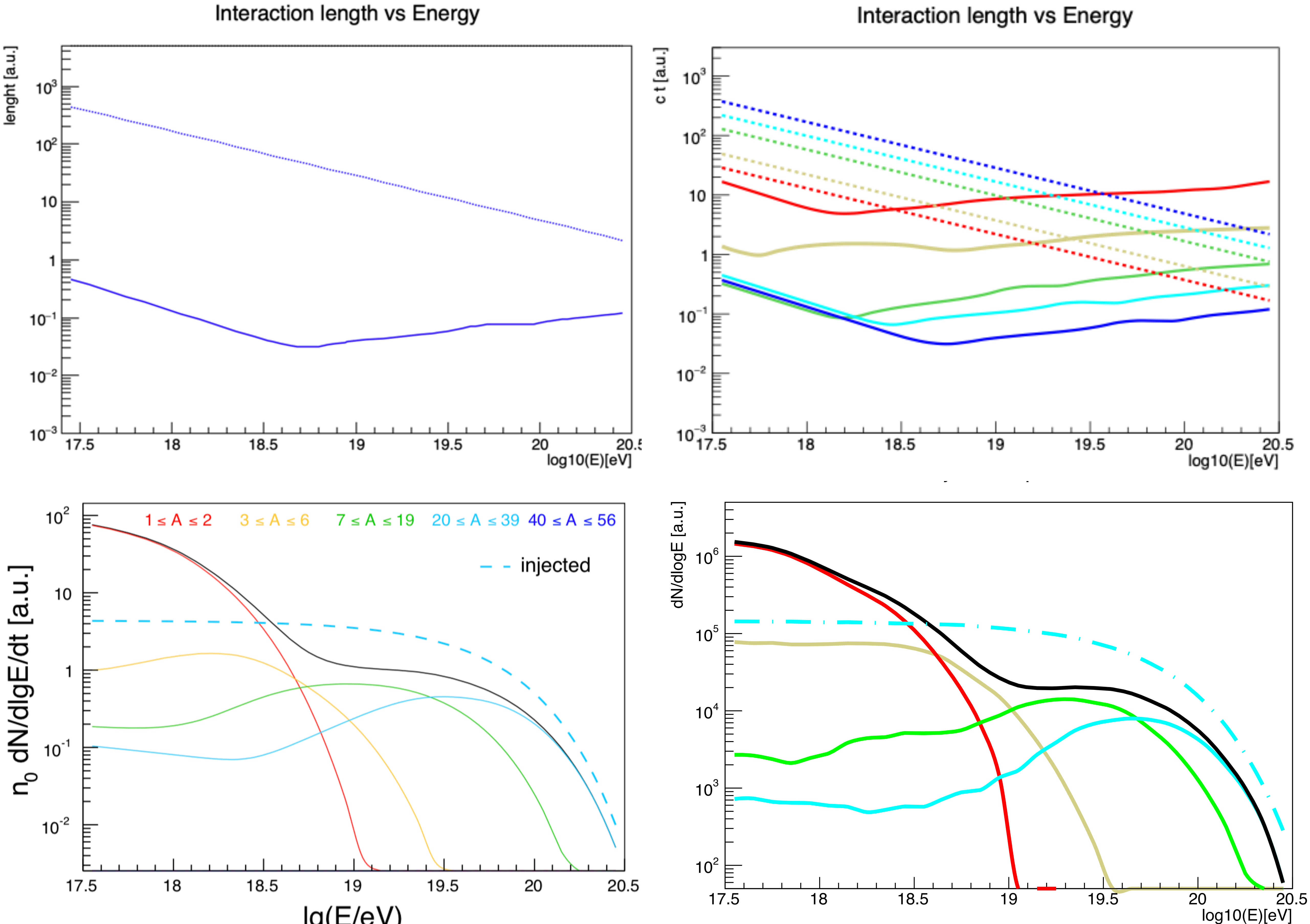
$$\frac{1}{\tau} = \frac{1}{2\Gamma^2}\int_{\epsilon'_{min}}^{2\Gamma\epsilon}\int_{\epsilon=0}^{+\infty}\frac{n_\gamma(\epsilon)}{\epsilon^2}\,d\epsilon\,\sigma(\epsilon')\epsilon'\,d\epsilon'$$

$$\tau_{esc} = \tau_0\left(\frac{EZ^{-1}}{E_0}\right)^{\delta}$$

- The shape of the spectrum of the target photons is needed.
- The interaction time is given by the double integral on the cross sections and on the photon field;
- The escaping time is just a power law on rigidity.


Interaction length vs Energy
lenght [a.u.]
log10(E)[eV]

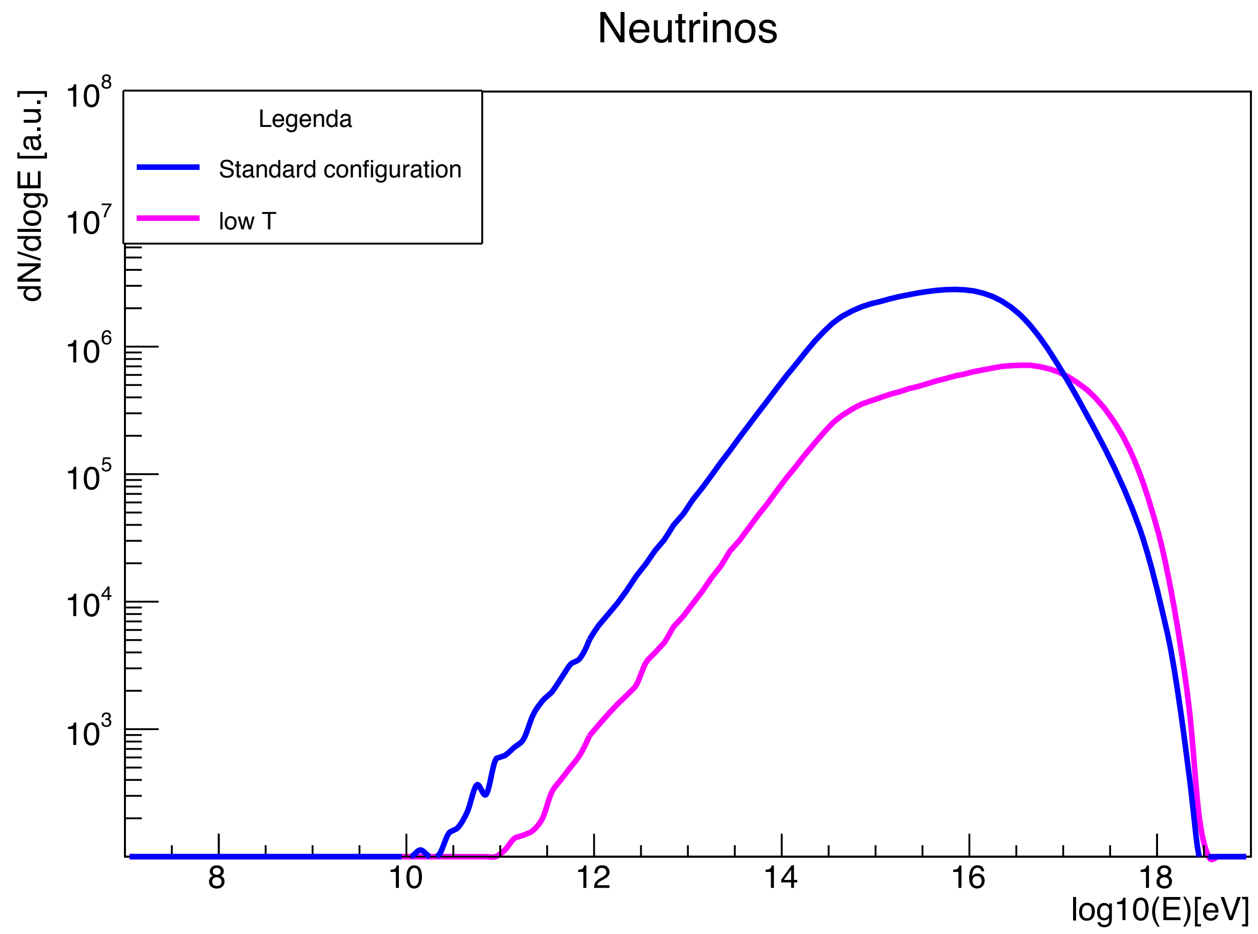

Interaction length vs Energy
c t [a.u.]
log10(E)[eV]
H
He
N
Si
Fe

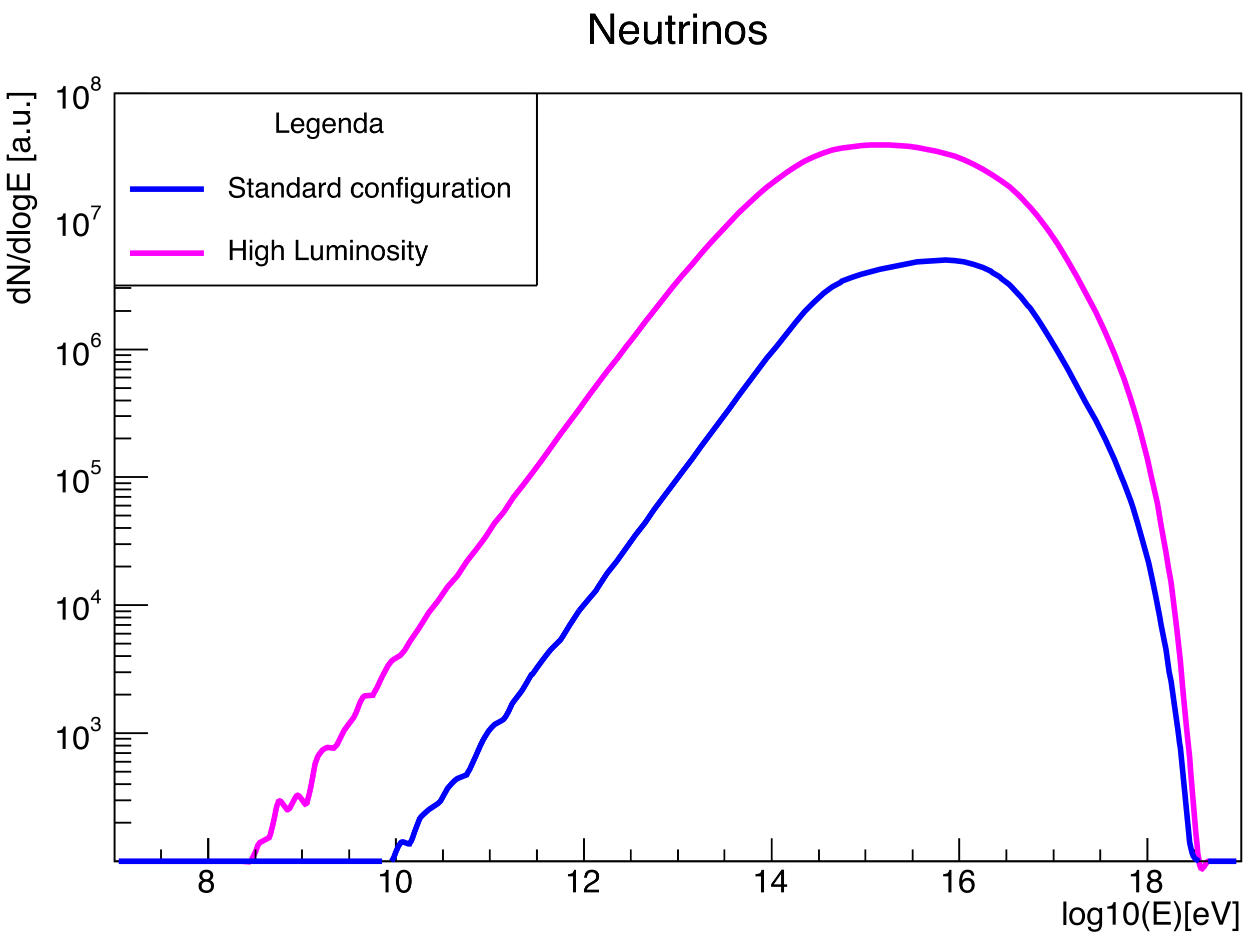


Origin of the ankle in the ultrahigh energy cosmic ray spectrum and of the extragalactic protons below it, M.Unger, G. Farrar, L. Anchordoqui, arXiv:1505.02153v2

Neutrino spectrum from the source

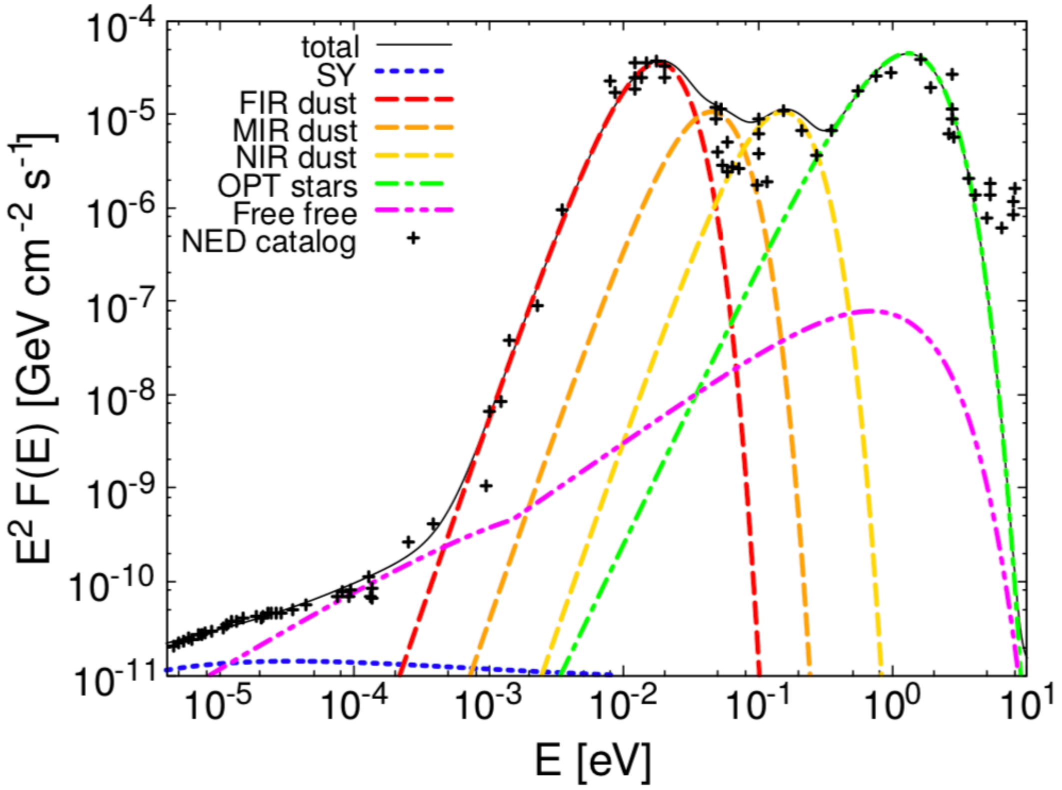
Decreasing temperature by a factor 10 →

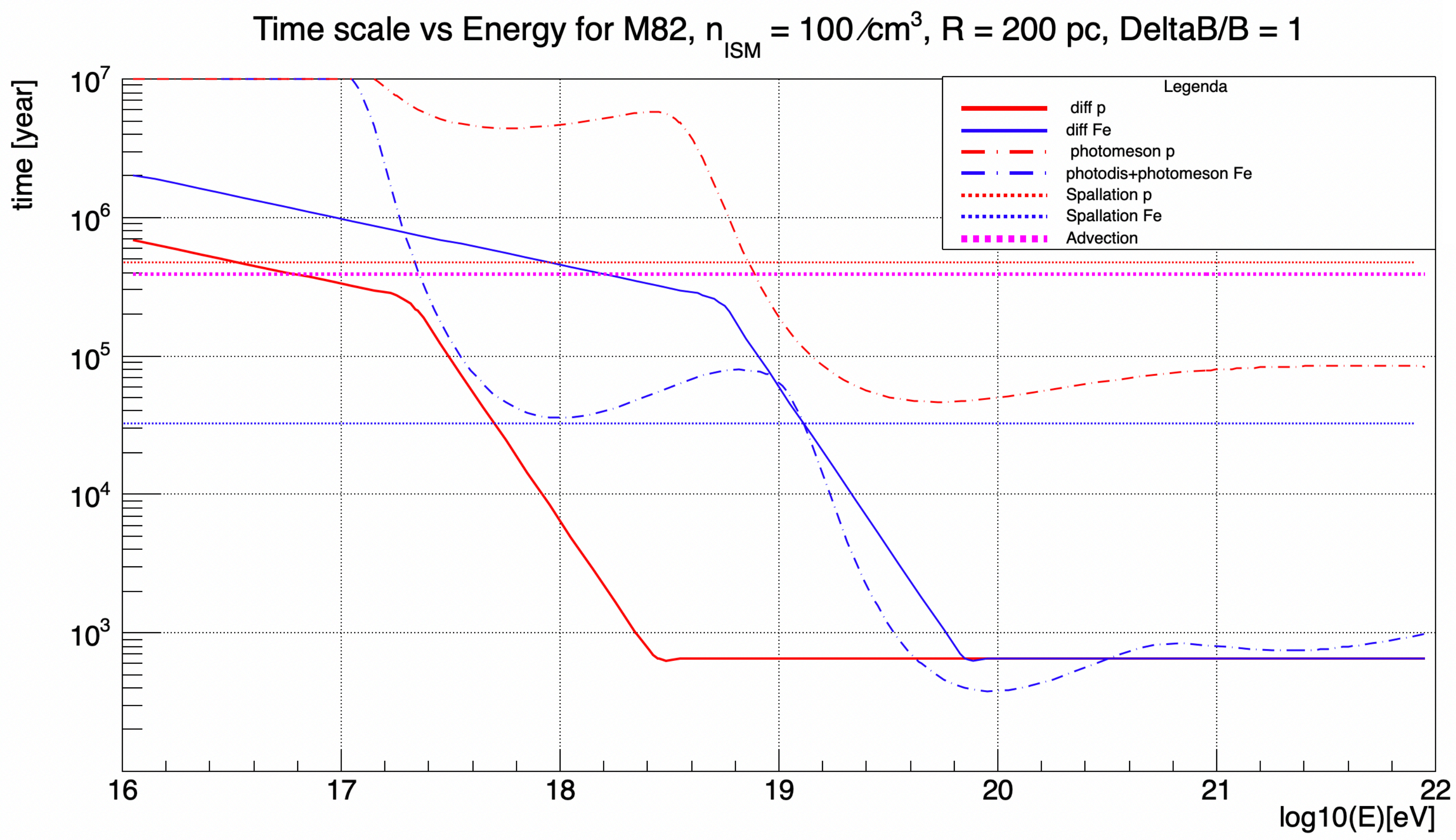




← **Increasing luminosity by a factor 10**

Application of source mechanism to SBGs





Cosmic ray transport and radiative processes in nuclei of starburst galaxies, E.Peretti, P.Blasi, F.Aharonian, G.Morlino. arXiv:1812.01996v2

Summary and future perspectives

Tools

- [x] Organizing combined fit code according to a logic structure and applications;
- [ ] Fit using two components.

Source mechanism

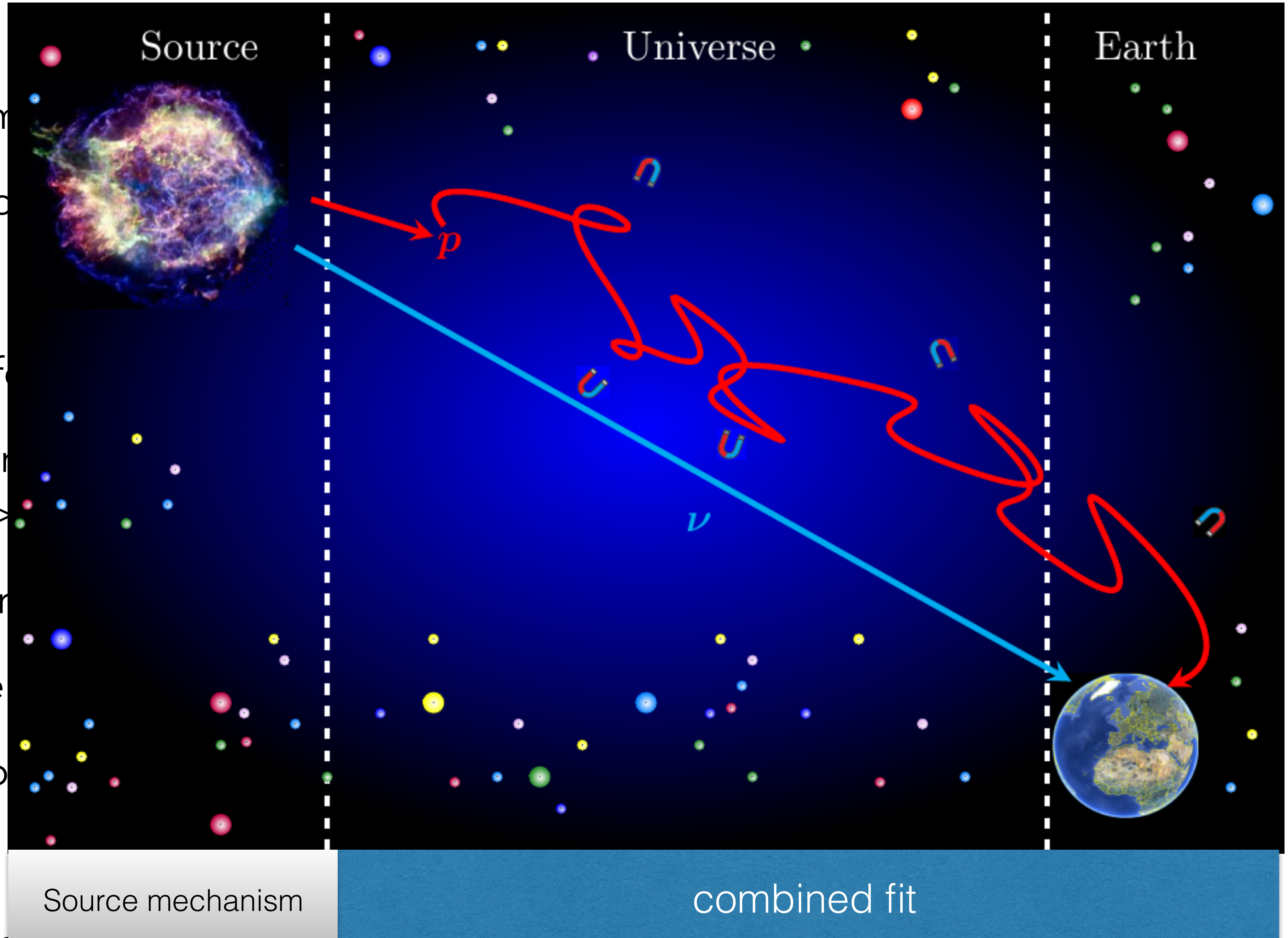
- [x] A single code for propagation inside and outside the source;
- [x] How the neutrino flux (produced in the source) changes according to the source parameters —> Additional observables with respect to cosmogenic neutrinos.
- [x] Studying of parameter space for real sources;
- [ ] Studying of the diffusion process inside the source;
- [ ] Development of simplified analytical approach;

Interpretation

- [ ] Fit at the source.

Summary and future perspectives

- ☑ Organizing com
- ☐ Fit using two co
- ☑ A single code f
- ☑ How the neutri
  parameters —>
- ☑ Studying of par
- ☐ Studying of the
- ☐ Development o

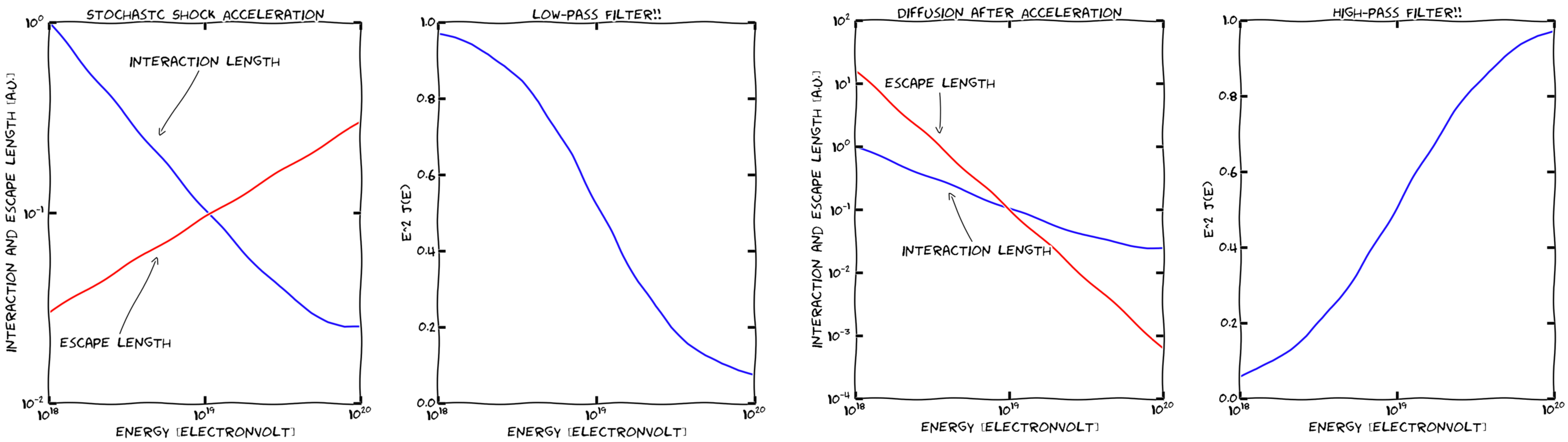


- ☐ Fit at the source.

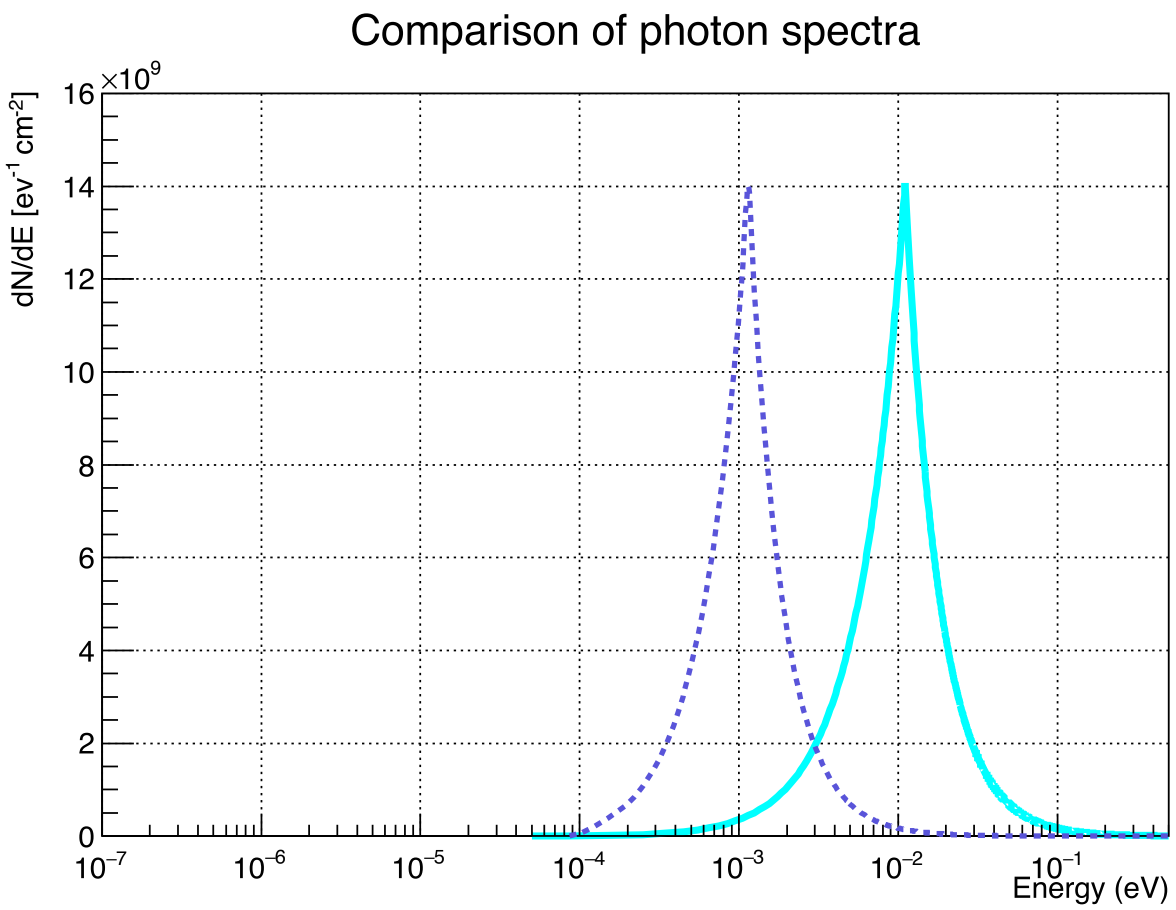
back-up slides

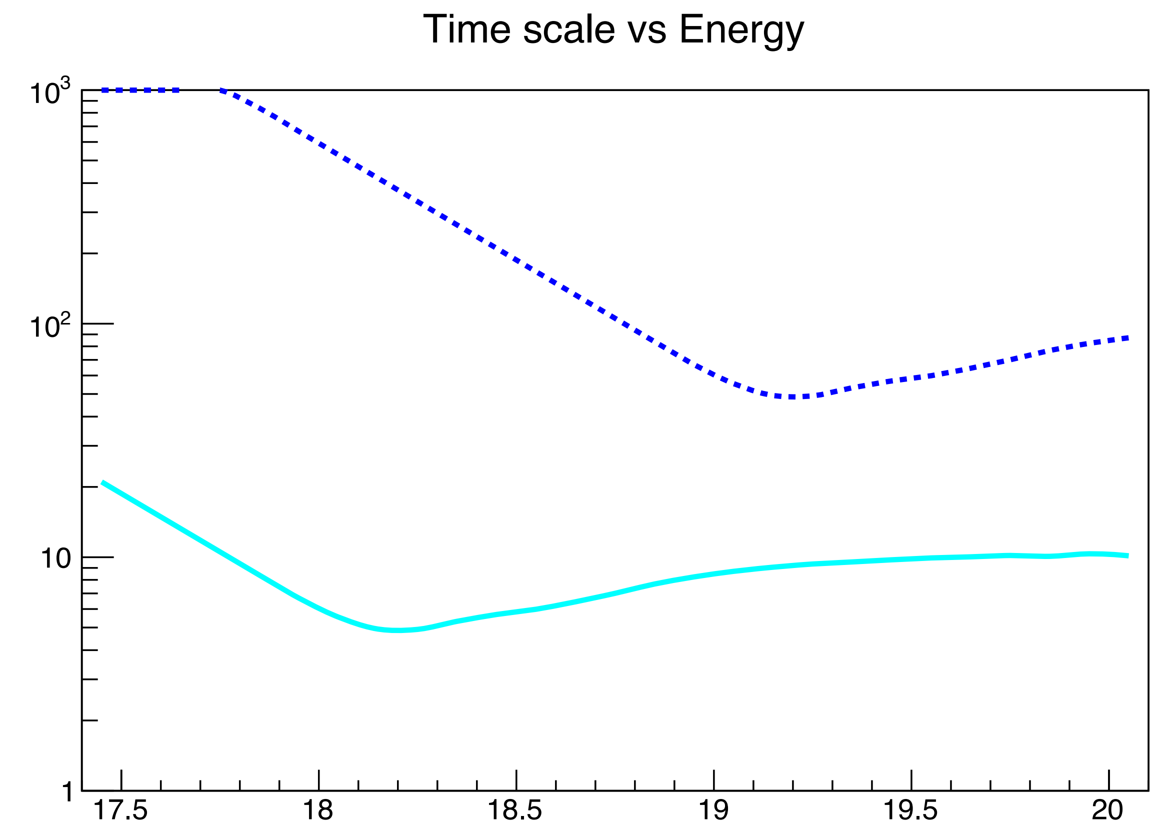
Assumptions

1. A fast acceleration mechanism and a low photon density inside the accelerator;
2. No energy is lost except through an interaction, and whenever a nucleus interacts it loses one or more nucleons by photo-disintegration or photo-pion production (in this case the nucleus loses a fraction of its energy corresponding to the reduction in its nuclear mass);
3. A cosmic ray either escapes without changing energy, with a rate τ_{esc} or the cosmic ray interacts one or more times before escaping, with a rate τ_{int};

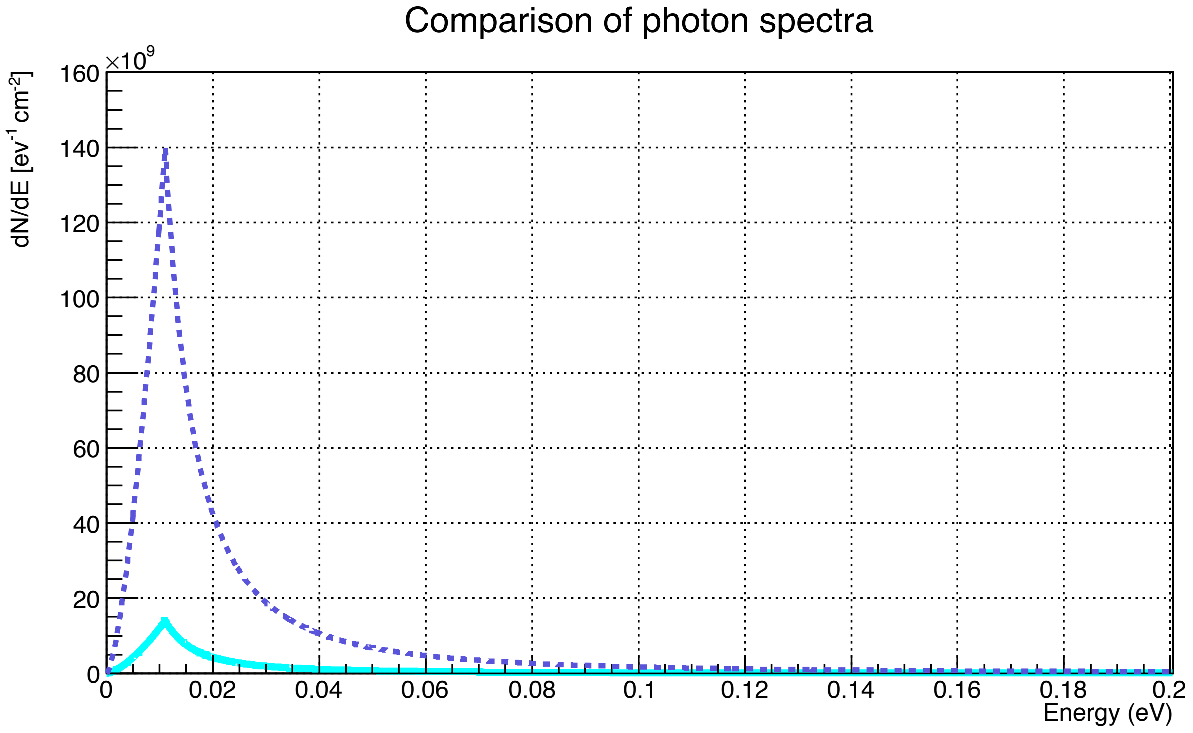


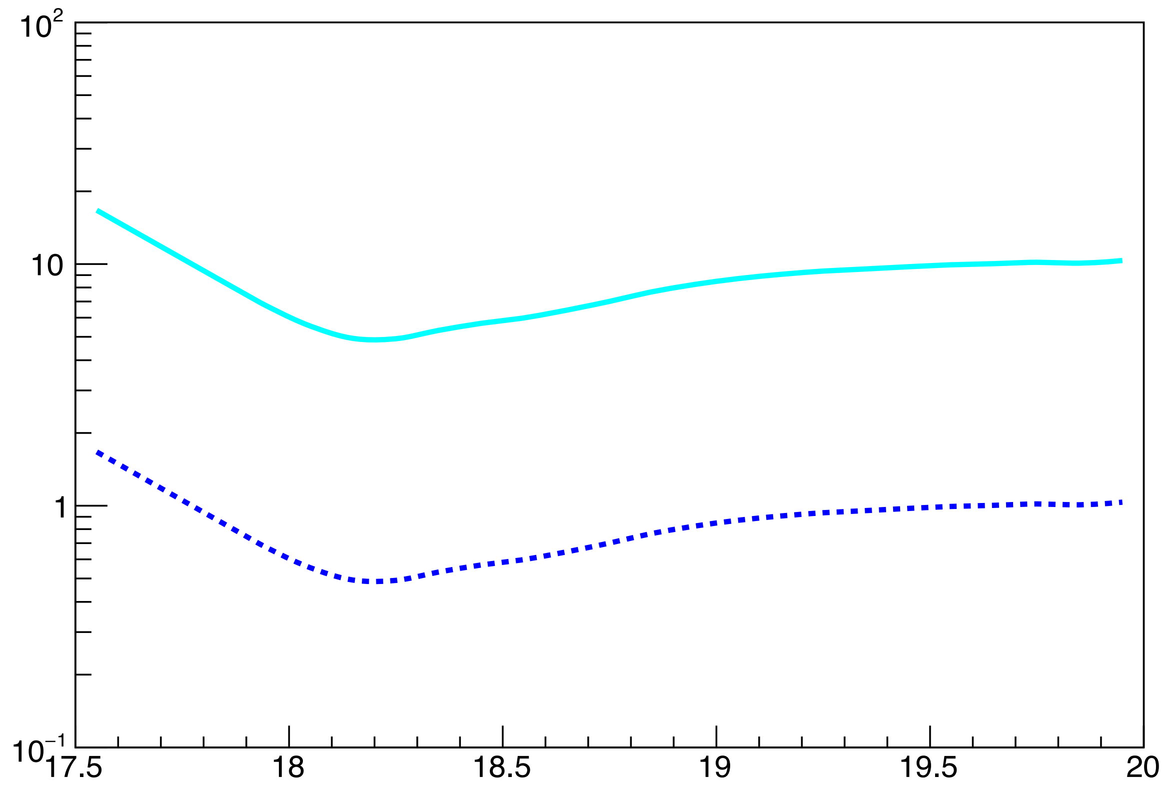
Changing the temperature





Changing the luminosity

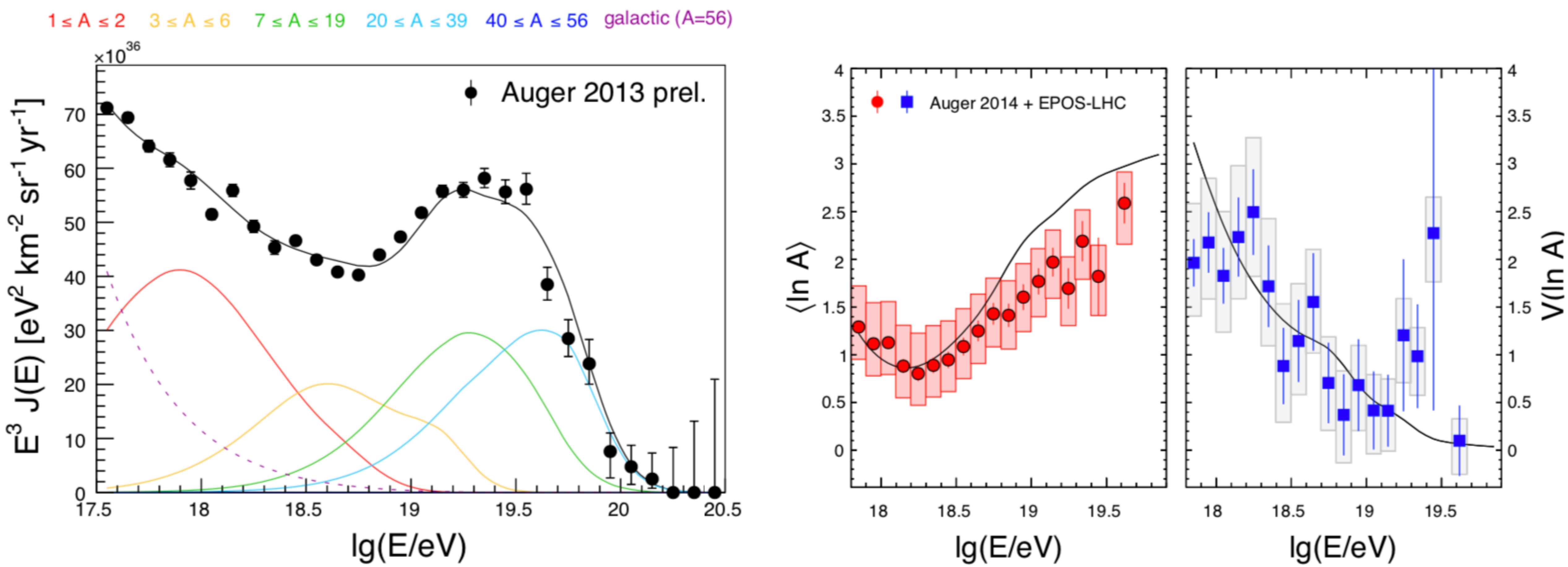




Parameters in the fit

source parameters			
power law index of injected nuclei	γ	fix	-1
mass number of injected nuclei	A	free	28 (29)
maximum energy	$E^p_{\max}$	free	$10^{18.5\,(18.6)}$ eV
cosmic ray power density, $E > 10^{17.5}$ eV	$\dot{\epsilon}_{17.5}$	free	9.2 (13) $\times 10^{44}$ erg Mpc^{-3} yr^{-1}
evolution	$\xi(z(t))$	fix	star formation rate [60]
source environment			
energy of maximum of photon field density	ε_0	free	0.11 (0.07) eV
power law index of photon spectrum ($\varepsilon < \varepsilon_0$)	α	fix	$+\frac{3}{2}$
power law index of photon spectrum ($\varepsilon \geqslant \varepsilon_0$)	β	fix	-2
power law index of escape length	δ	free	-0.77 (-0.94)
ratio of interaction and escape time	R^{Fe}_{19}	free	4.4 (3.7) $\times 10^2$
propagation to Earth			
infra-red photon background	–	fix	Gilmore12 [61]
spectrum of Galactic cosmic rays			
power law index at Earth	γ_{gal}	free	-4.2 (-3.7)
mass number of Galactic nuclei	A_{gal}	fix	56
flux fraction at $10^{17.5}$ eV	f_{gal}	free	57 (72) %

Fit the Auger Data



(a) Flux at Earth

(b) Composition at Earth

Injection

$$J_A(E) = f_A \cdot J_0 \cdot \left(\frac{E}{10^{18}\ \text{eV}}\right)^{-\gamma} \cdot f_{cut}(E, Z_A \cdot R_{cut})$$

$$f_{cut}(E, Z_A \cdot R_{cut}) = \begin{cases} 1 & E < Z_A R_{cut} \\ \exp\left(1 - \frac{E}{Z_A R_{cut}}\right) & E > Z_A R_{cut} \end{cases}$$

To obtain the spectral parameters, the combined spectrum is fitted with the function

$$J_{unf}(E) = \begin{cases} J_0 \left(\frac{E}{E_{ankle}}\right)^{-\gamma_1} & ; E \leq E_{ankle} \\ J_0 \left(\frac{E}{E_{ankle}}\right)^{-\gamma_2} \left[1 + \left(\frac{E_{ankle}}{E_s}\right)^{\Delta\gamma}\right] \left[1 + \left(\frac{E}{E_s}\right)^{\Delta\gamma}\right]^{-1} & ; E > E_{ankle} \end{cases} \quad (4.1)$$

The spectrum, the fit and the optimized parameters are plotted in Fig. 5. An ankle is found at $E_{ankle} = (5.08 \pm 0.06(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{18}$ eV, while the suppression is at $E_s = (3.9 \pm 0.2(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{19}$ eV. The energy $E_{1/2}$ at which the integral spectrum drops by a factor of two below what would be the expected with no steepening is $E_{1/2} = (2.26 \pm 0.08(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{19}$ eV. The spectral indexes are: $\gamma_1 = 3.293 \pm 0.002(\text{stat.}) \pm 0.05(\text{syst.})$, $\gamma_2 = 2.53 \pm 0.02(\text{stat.}) \pm 0.1(\text{syst.})$ while $\Delta\gamma = 2.5 \pm 0.1(\text{stat.}) \pm 0.4(\text{syst.})$.

Advection and diffusion time

- *Advection time: just the ratio between the size of the source R and the velocity of the wind.*
  $v = 500$ *Km/s;* $R = 300$ *pc*

- *Diffusion time is given by*

$$t_D = \frac{R^2}{D}$$

$$D = \frac{1}{3}\frac{R_L c}{F(k)} = \frac{1}{3(d-1)} \cdot \left(\frac{B}{\Delta B}\right)^2 \cdot {L_0}^{d-1} \cdot {R_L}^{2-d} \cdot c$$

Where:

- $d = 5/3$;
- $L_0 = 1$ *pc;*
- $R = 300$ *pc;*
- $(\Delta B/B) = 1$

- *if* $(R_L > L_0)$ *we multiply the diffusion coefficient* D_0 *by a factor* $(R_L/L_0)^2$
- *If* $(t_{diff} < R/c)$ $t_{diff} = R/c$