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Laboratoire de Physique des 2 Infinis

Starburst Galaxies as possible sources of UHECRs and neutrinos

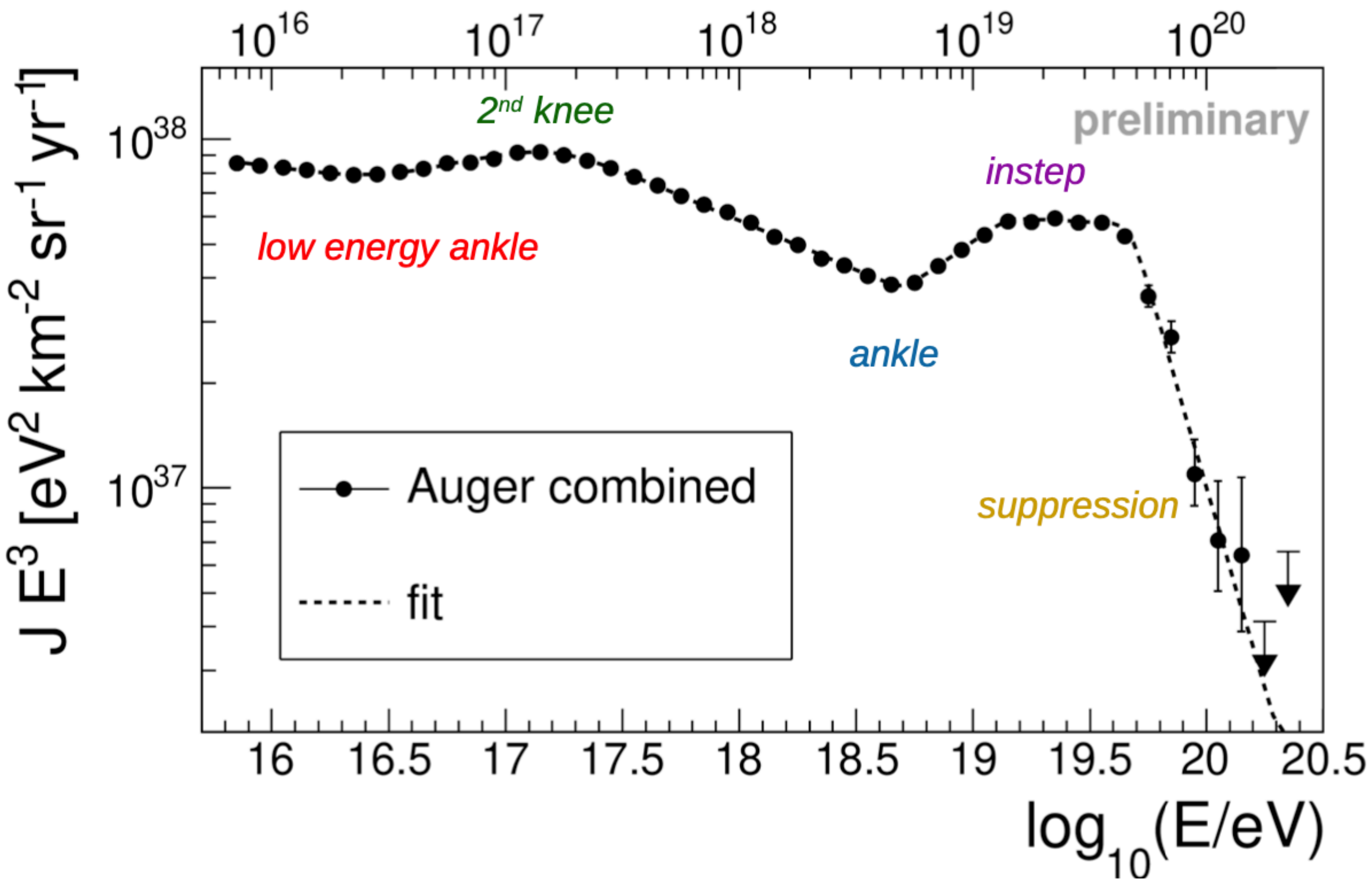
A. Condorelli

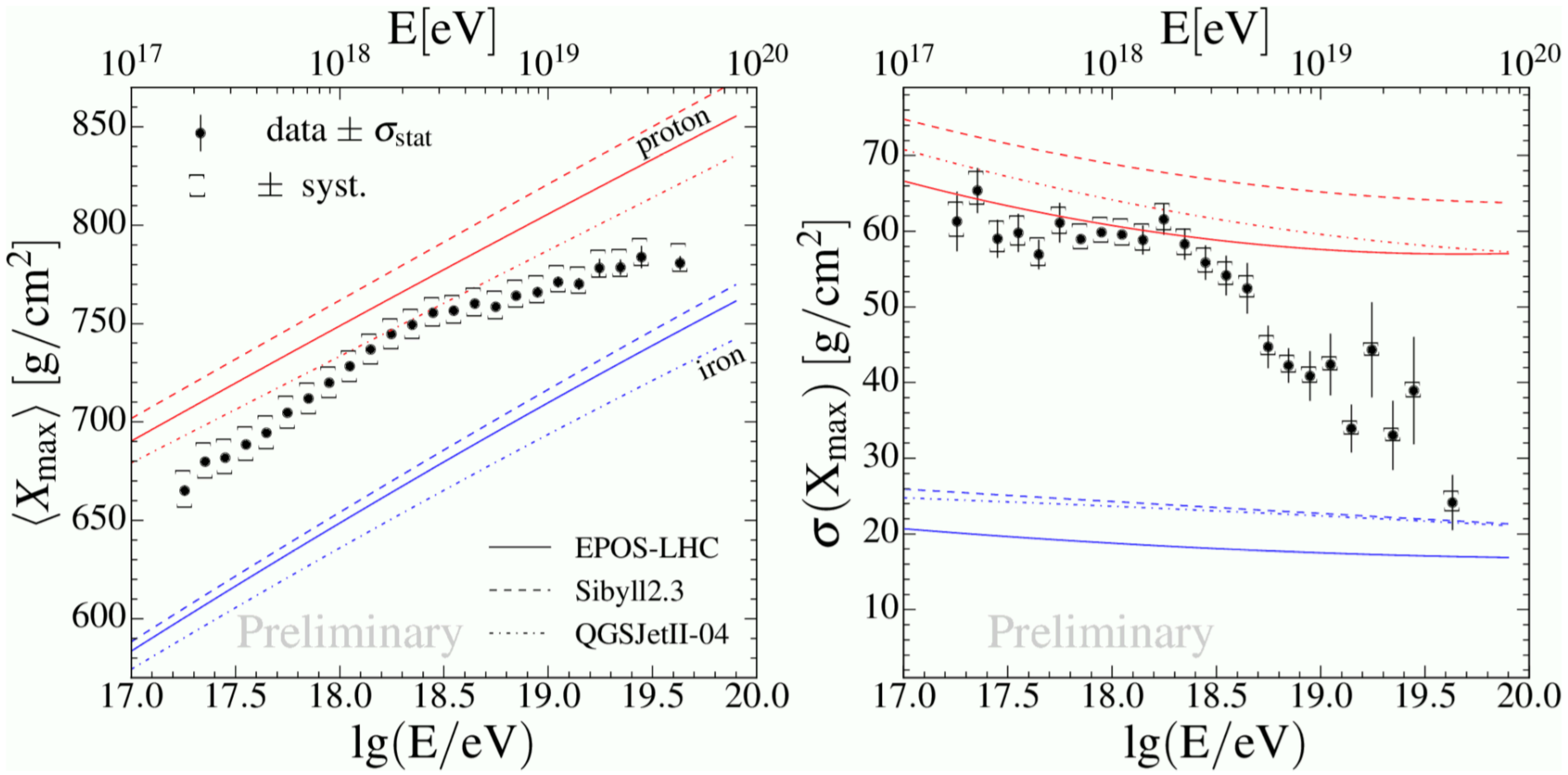
Nuclear Physics in the Cosmos, 10/02/202

Outline

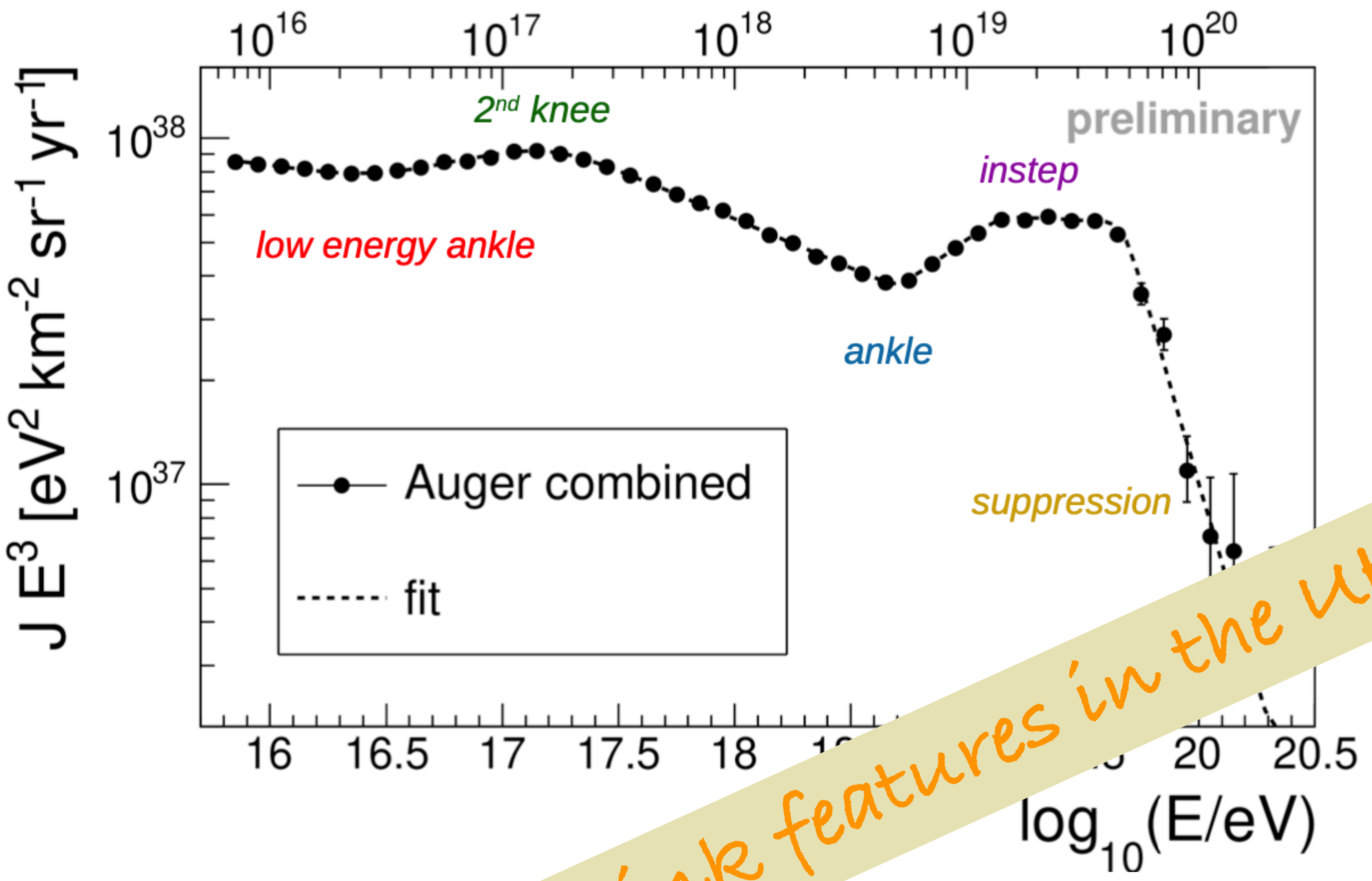
- Motivation: astrophysical interpretation of UHECRs measurements
- Extra-galactic propagation of UHECRs
- Source-propagation model in Starburst Galaxies
- Conclusions and future perspectives

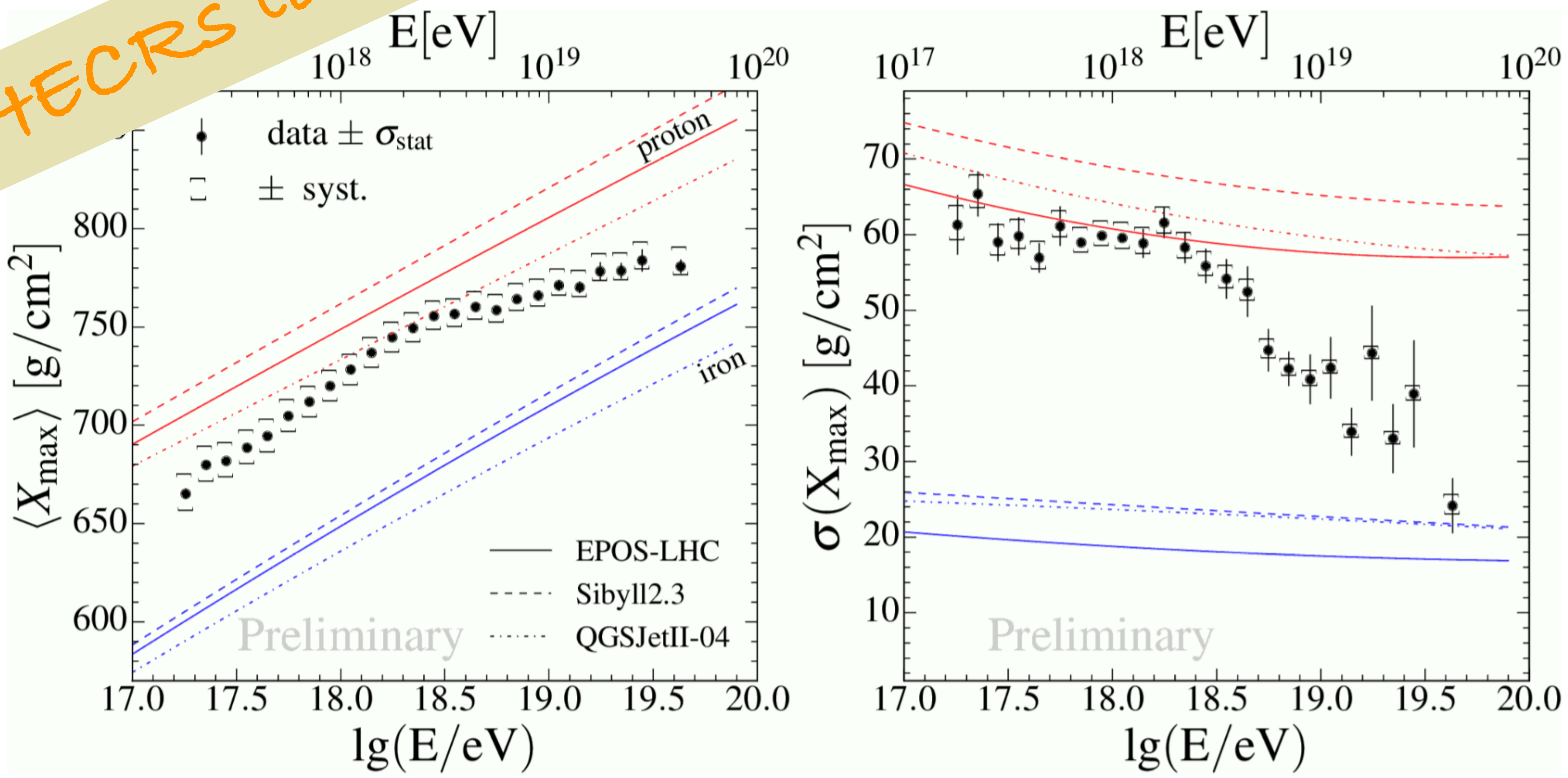
UHECRs measurements





UHECRs measurements



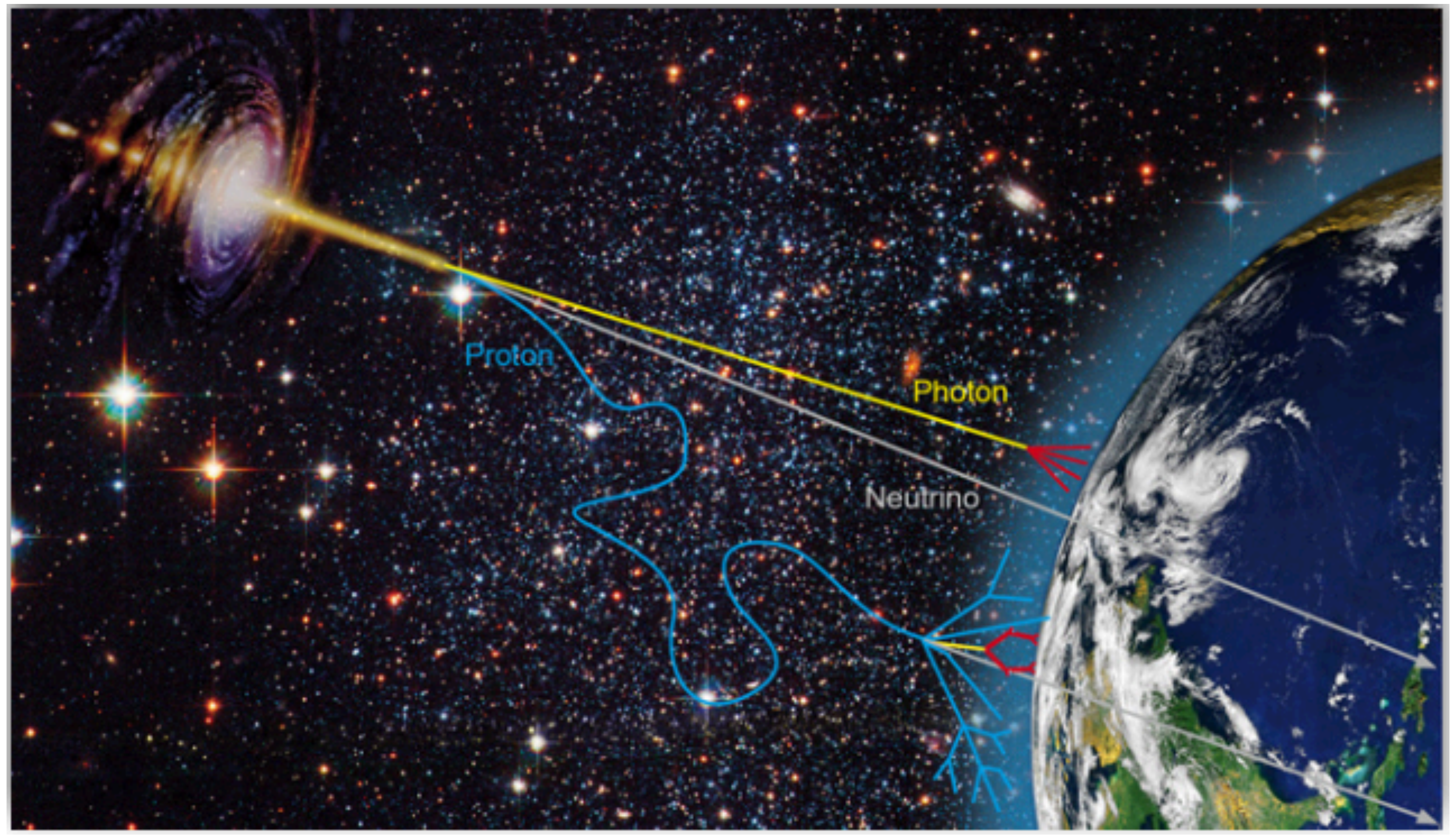


It is possible to link features in the UHECRs to astrophysical processes?

V. Novothny for the Pierre Auger collaboration, ICRC2021

A. Yushkov for the Pierre Auger collaboration, ICRC2019

UHECRs sources



- ✴Class of UHECR sources still unidentified.
- ✴Connection of observables at Earth to theoretical models including UHECR properties, in order to infer UHECR characteristics at the sources.

Several codes for UHECR propagation available:

- ✴SimProp (Aloisio, Boncioli, di Matteo, Grillo, Petrera & Salamida, JCAP 2017)
- ✴ CRPropa (Alves Batista, Dundovic, Erdmann, Kampert, Kuempel, Muller, Sigl, van Vliet, Walz & Winchen, JCAP 2016)

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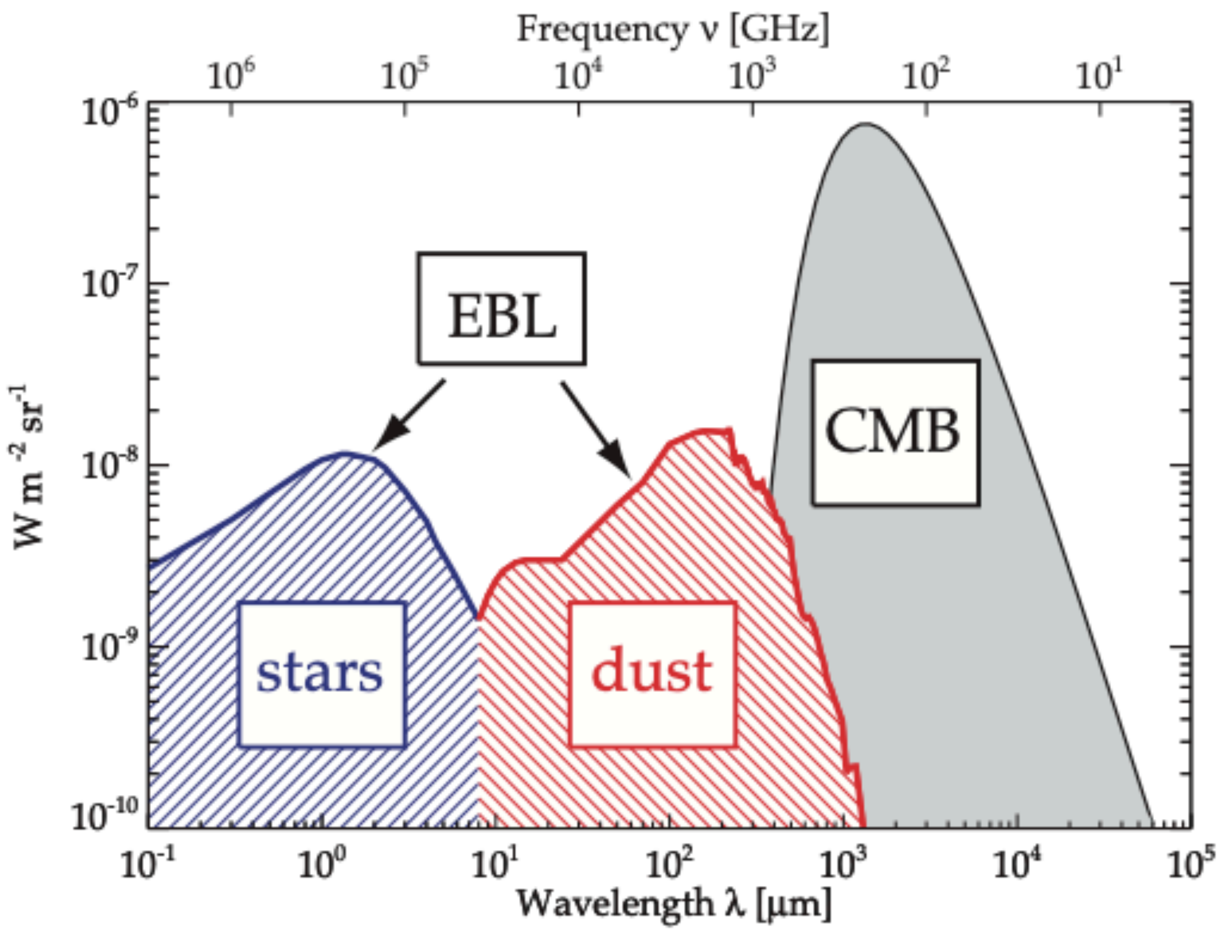
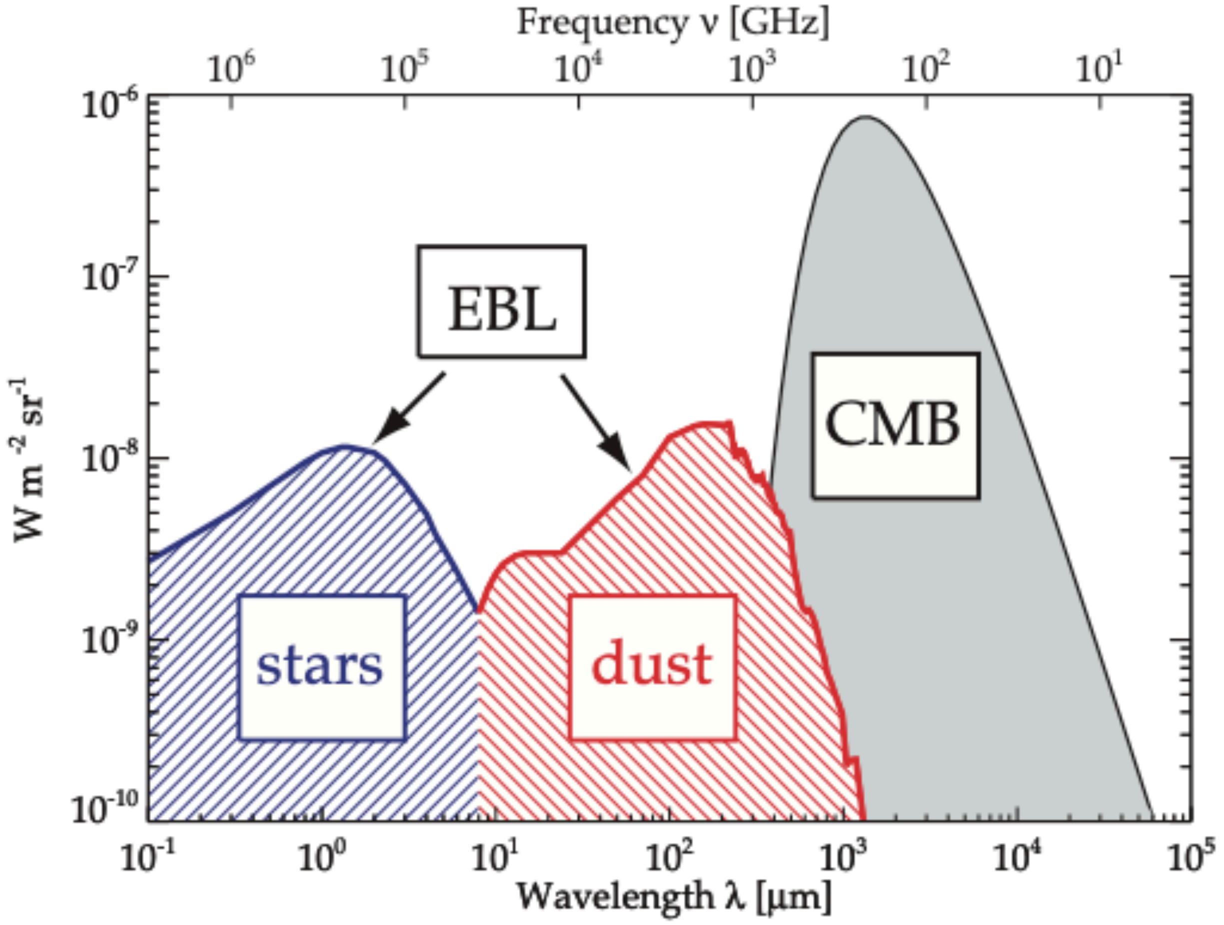
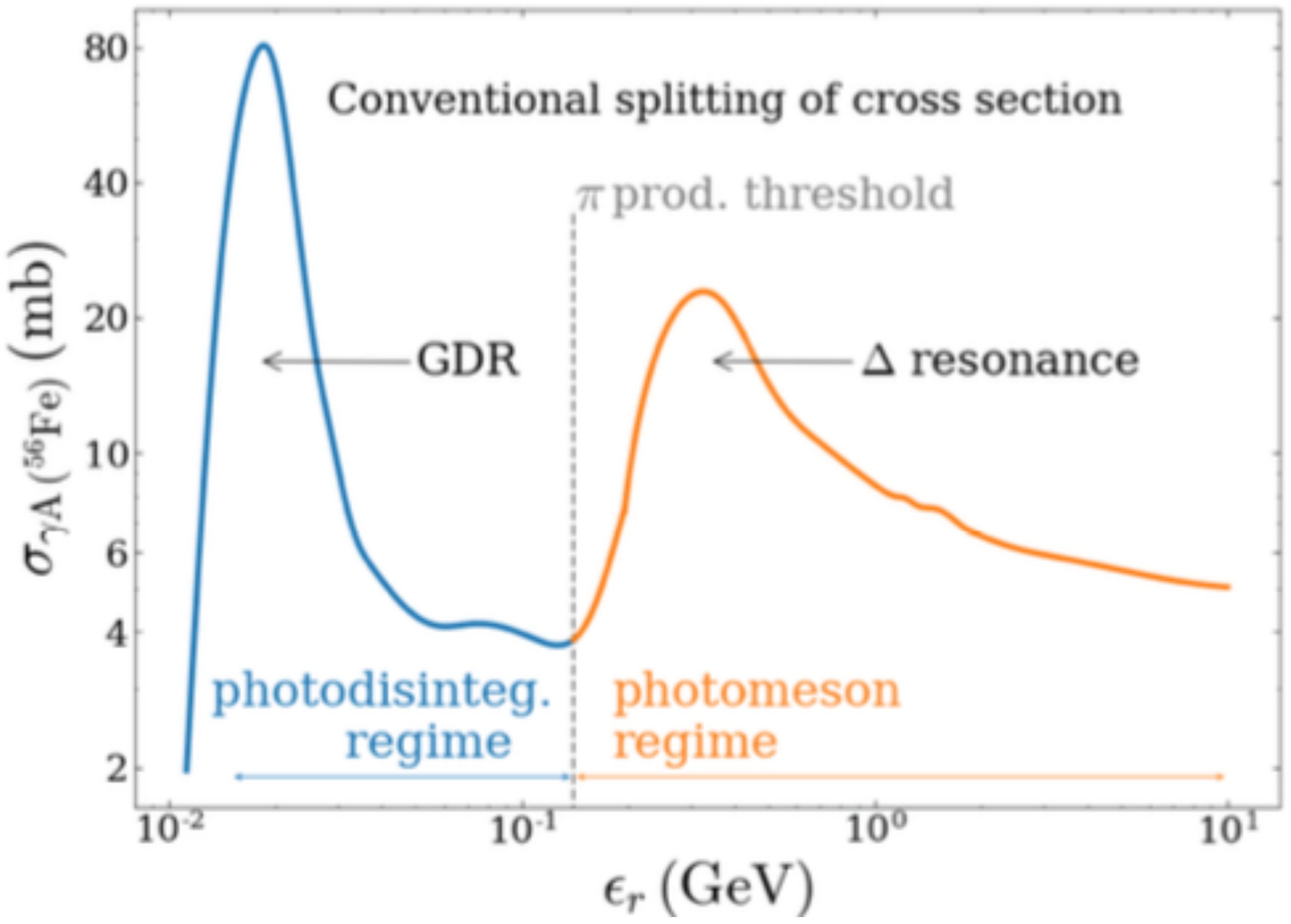
Astrophysics and Nuclear Physics inputs



Astrophysics and Nuclear Physics inputs

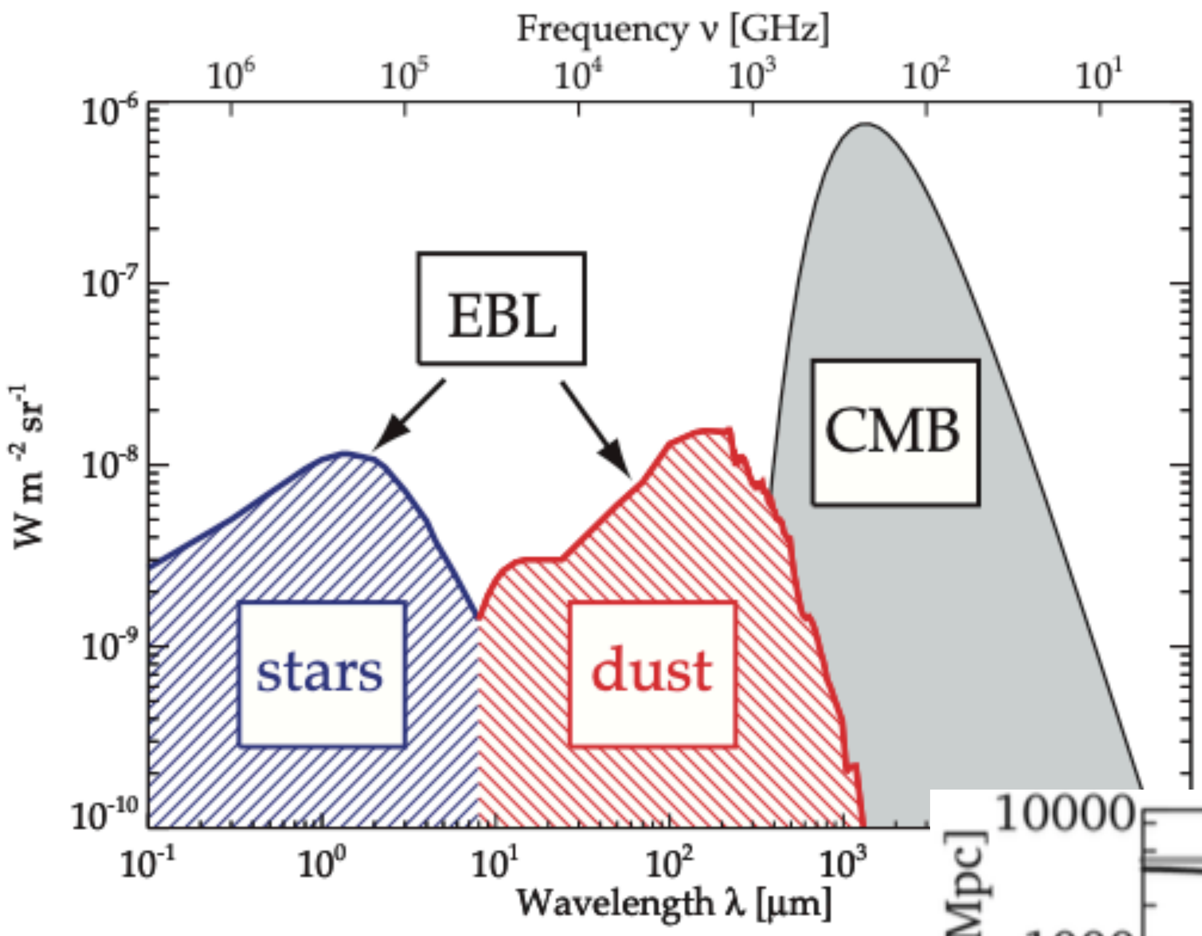


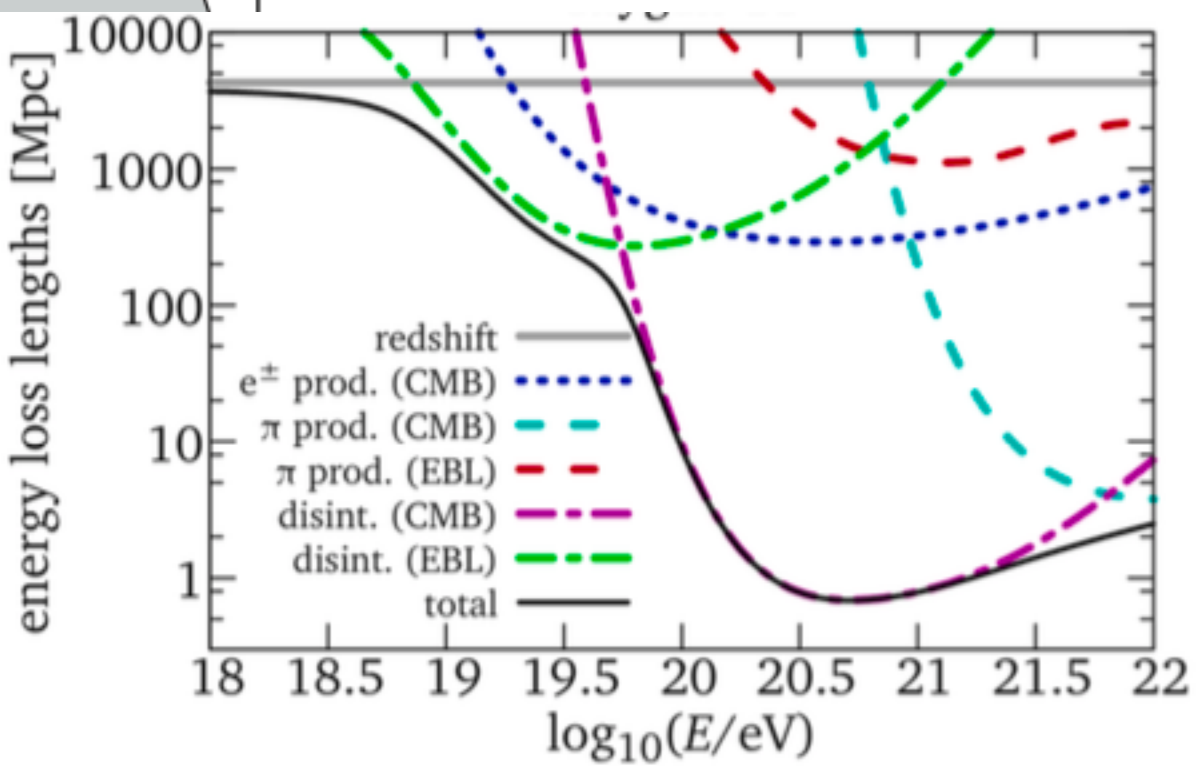


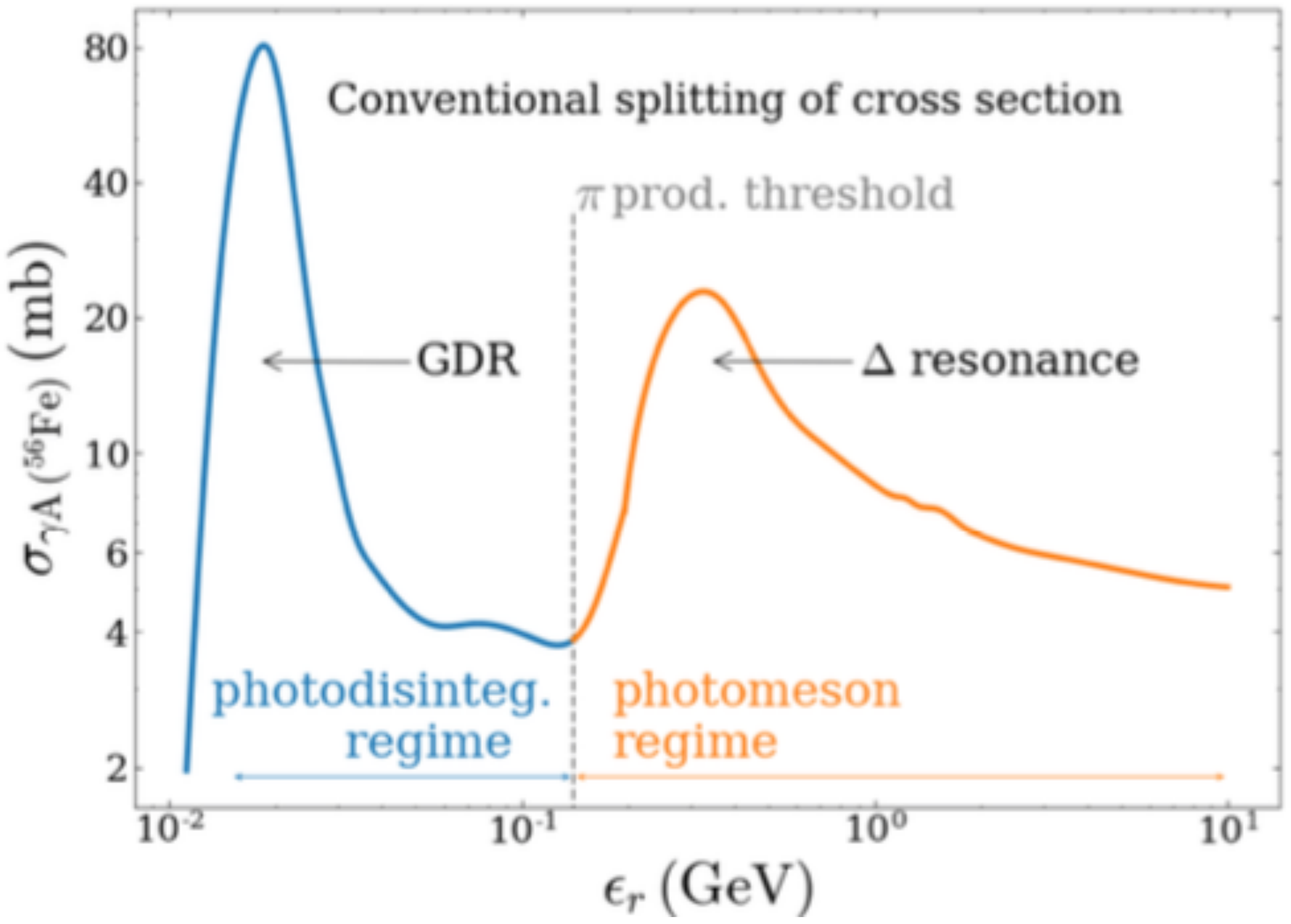
A.Condorelli, PhD thesis

Morejon et al, JCAP 2019

Astrophysics and Nuclear Physics inputs





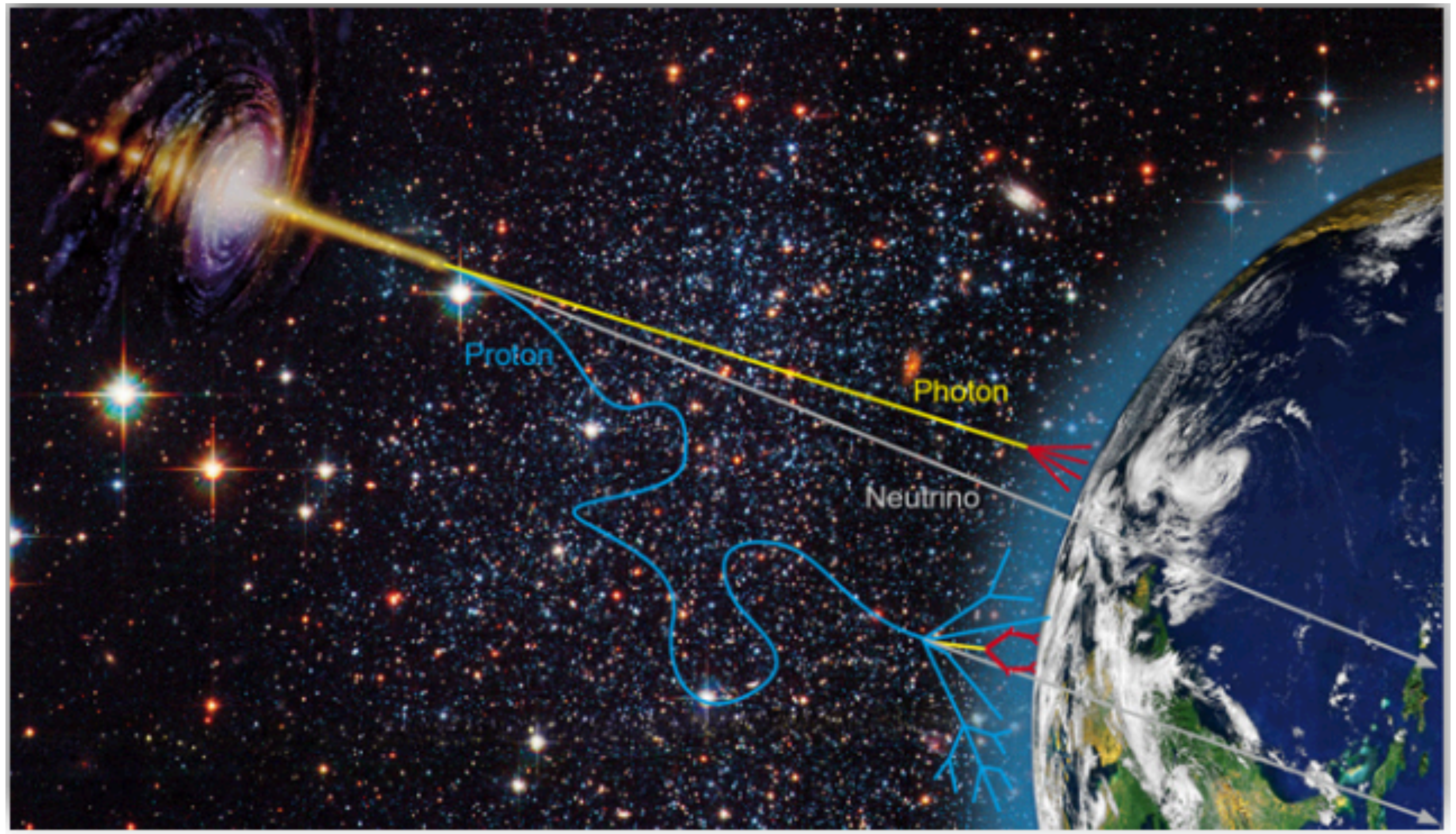


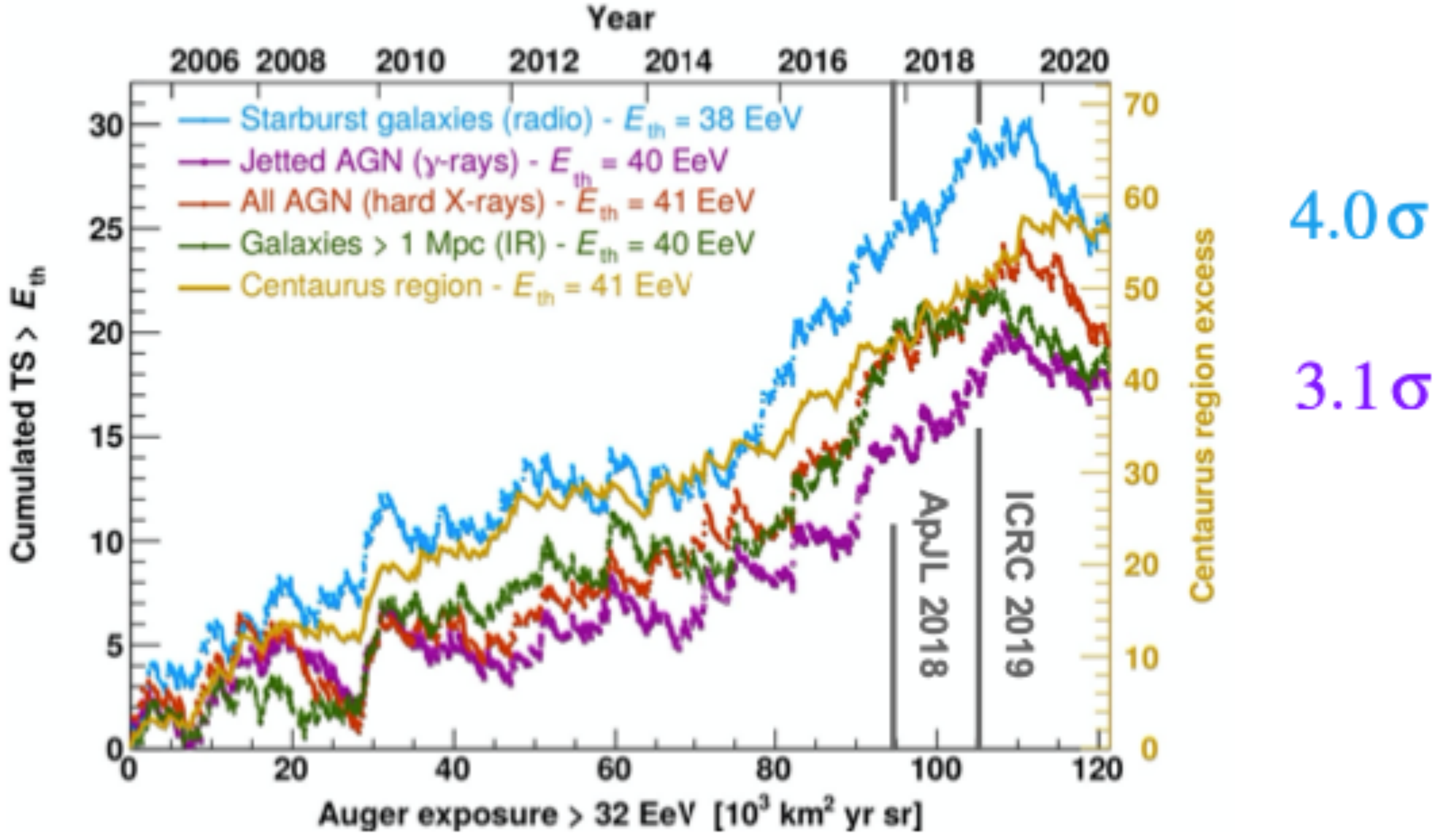
$$\frac{1}{\tau} = \frac{1}{2\Gamma^2} \int_{\epsilon'_{\min}}^{2\Gamma\epsilon} \int_{\epsilon=0}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} \, d\epsilon \, \sigma(\epsilon')\epsilon' \, d\epsilon'$$

A.Condorelli, PhD thesis

Morejon et al, JCAP 2019

Source-propagation in SBGs

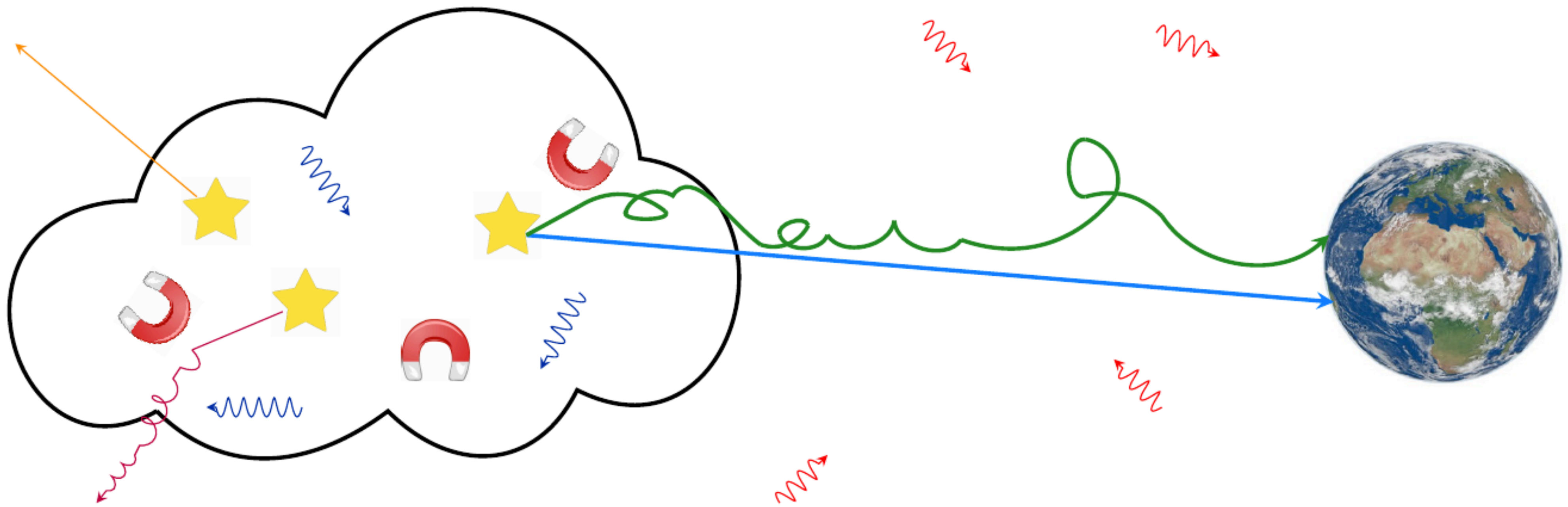




J. Biteau for the Pierre Auger Collaboration, ICRC2021

Source-propagation model in Starburst Galaxies

- Accelerated particles confined in the environment surrounding the source;
- Presence of photon and gas density;
- High energy particles–> escape with no interaction;
- Low energy particles –> Pile-up of nucleons at lower energies.



M. Unger, G.R. Farrar and L.A. Anchordoqui, Phys. Rev. D 92, 123001 (2015)

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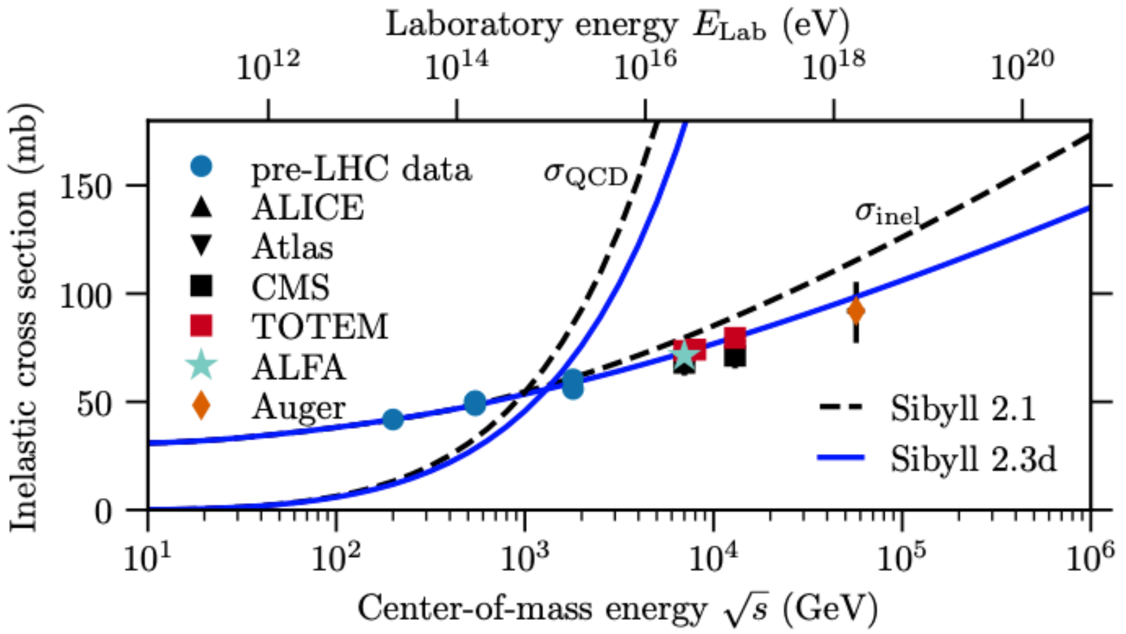
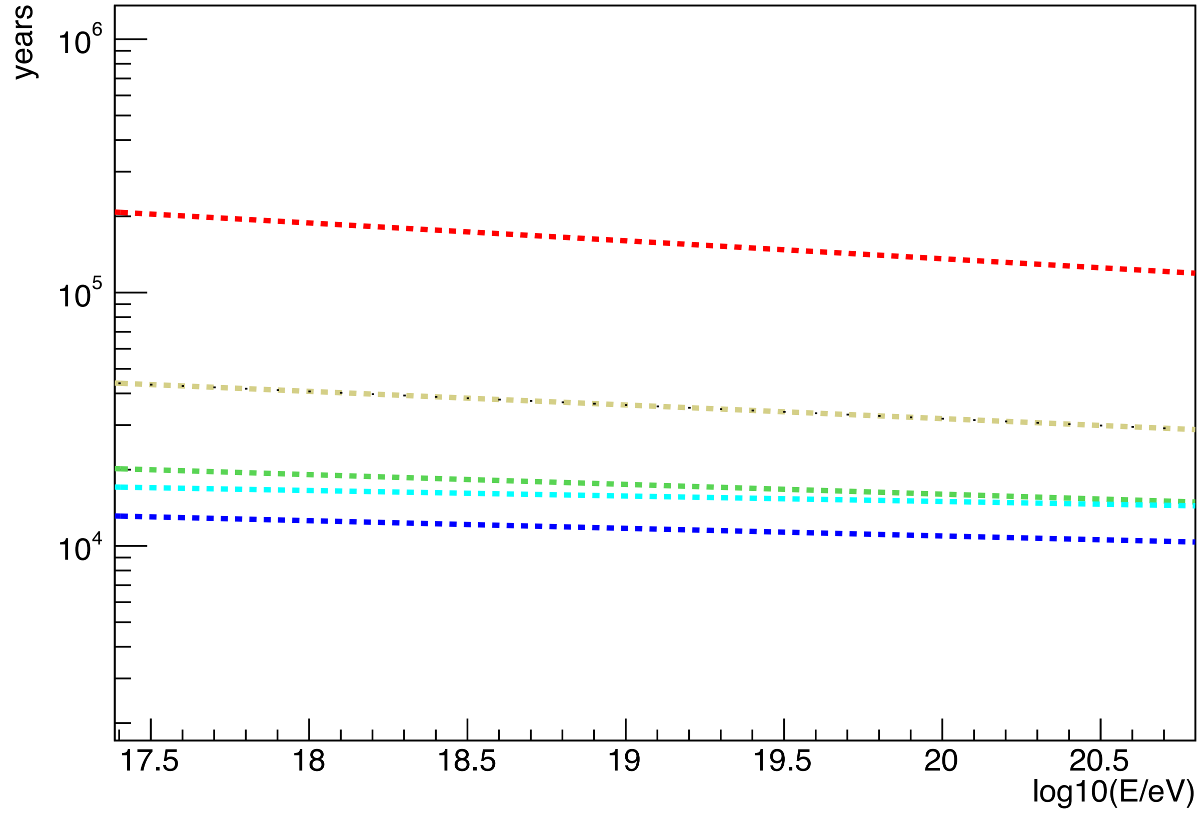
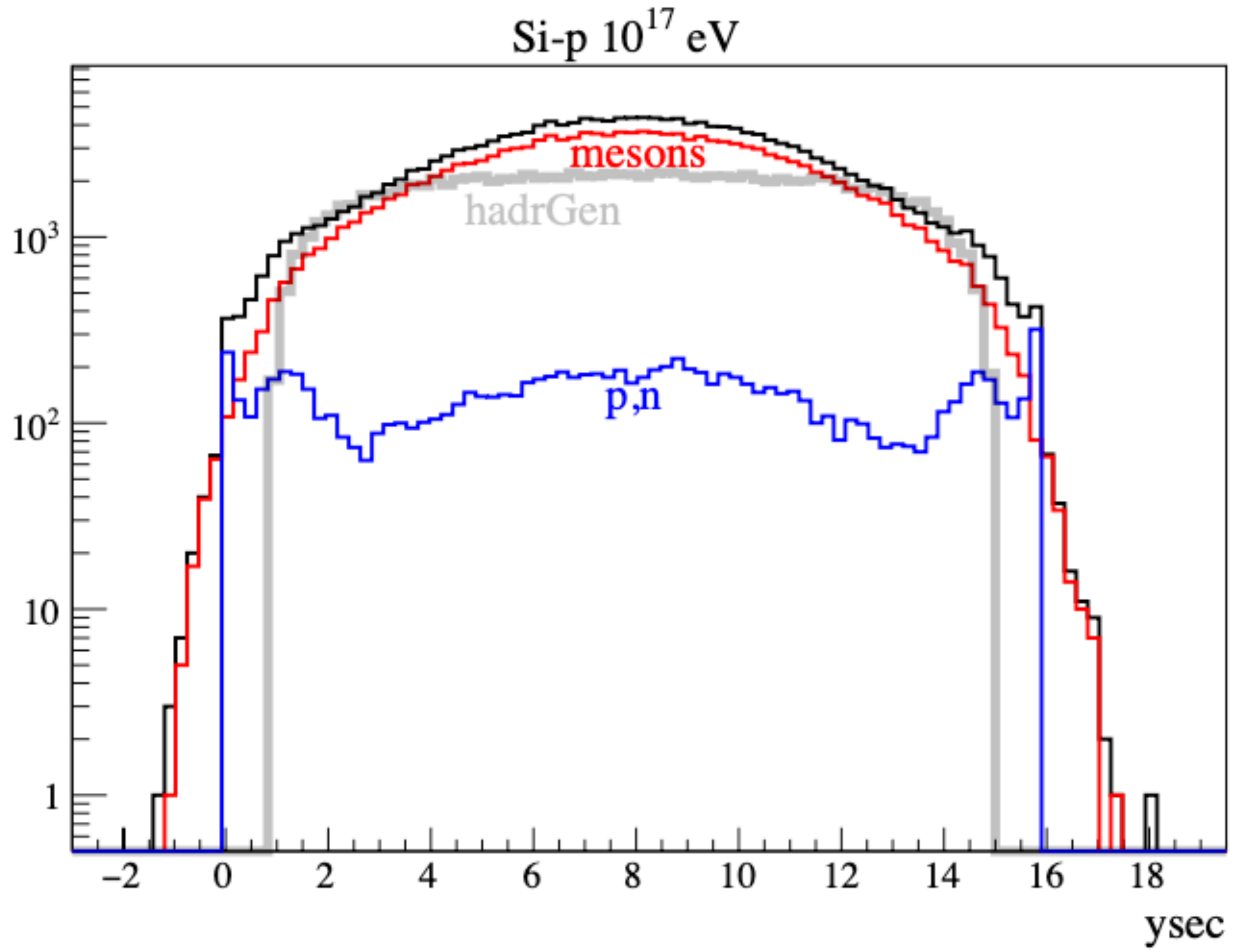
Including spallation time in SimProp

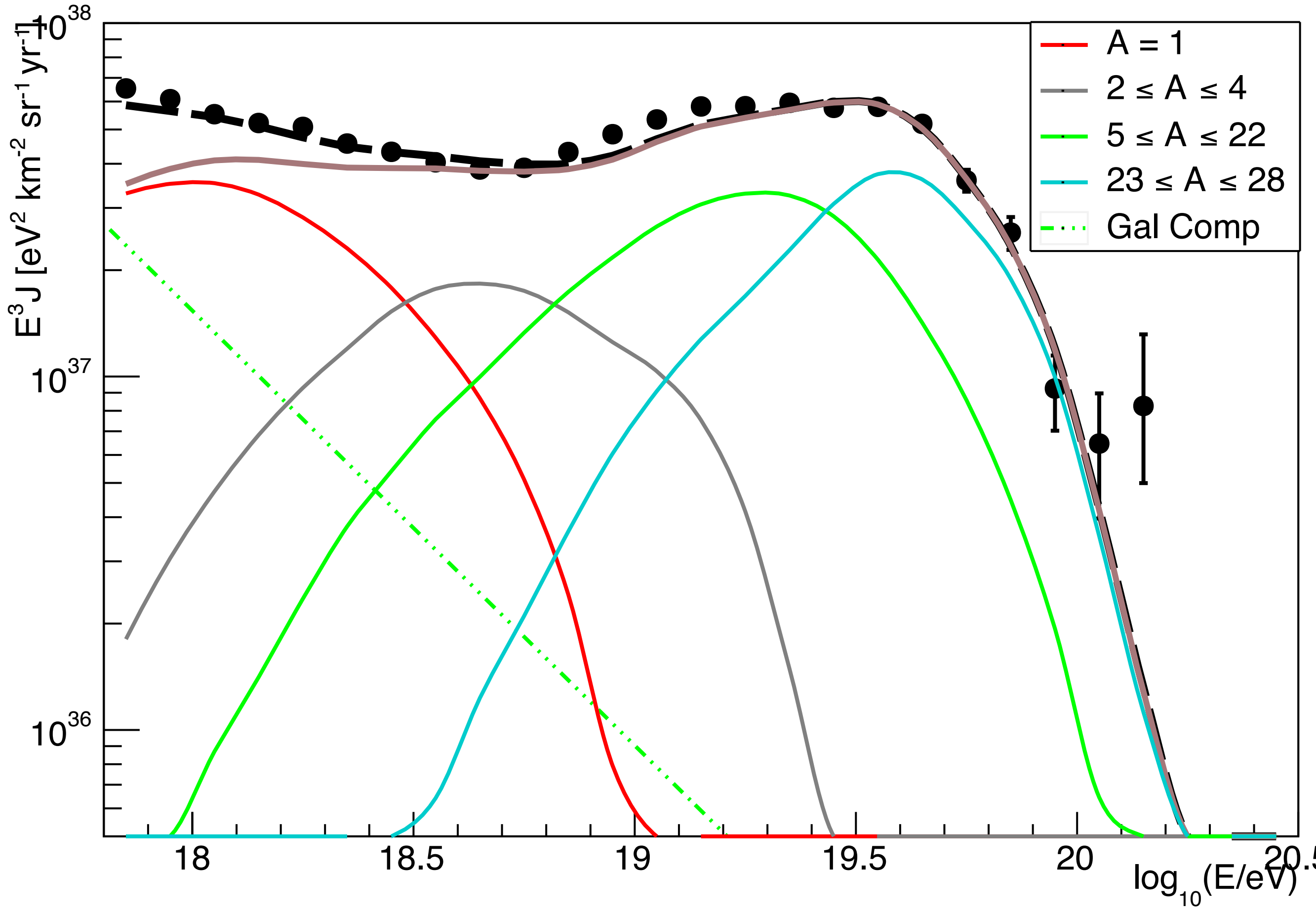


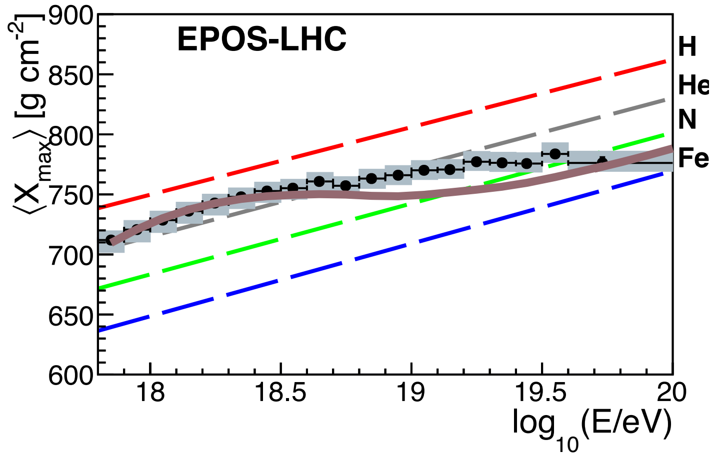


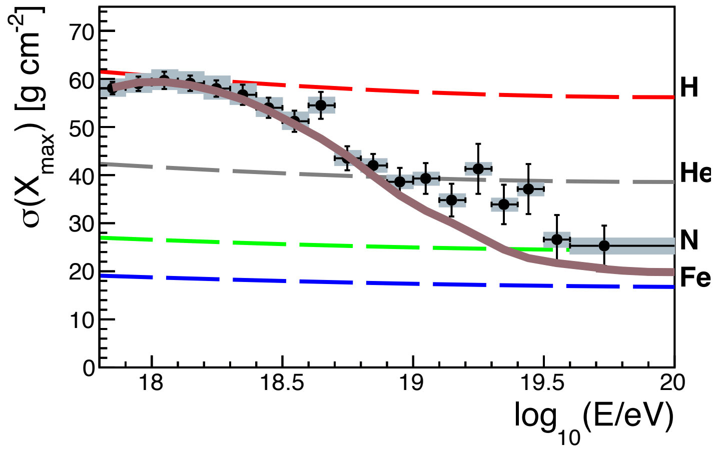


F. Riehn et al, Phys. Rev. D 102, 063002 (2020),

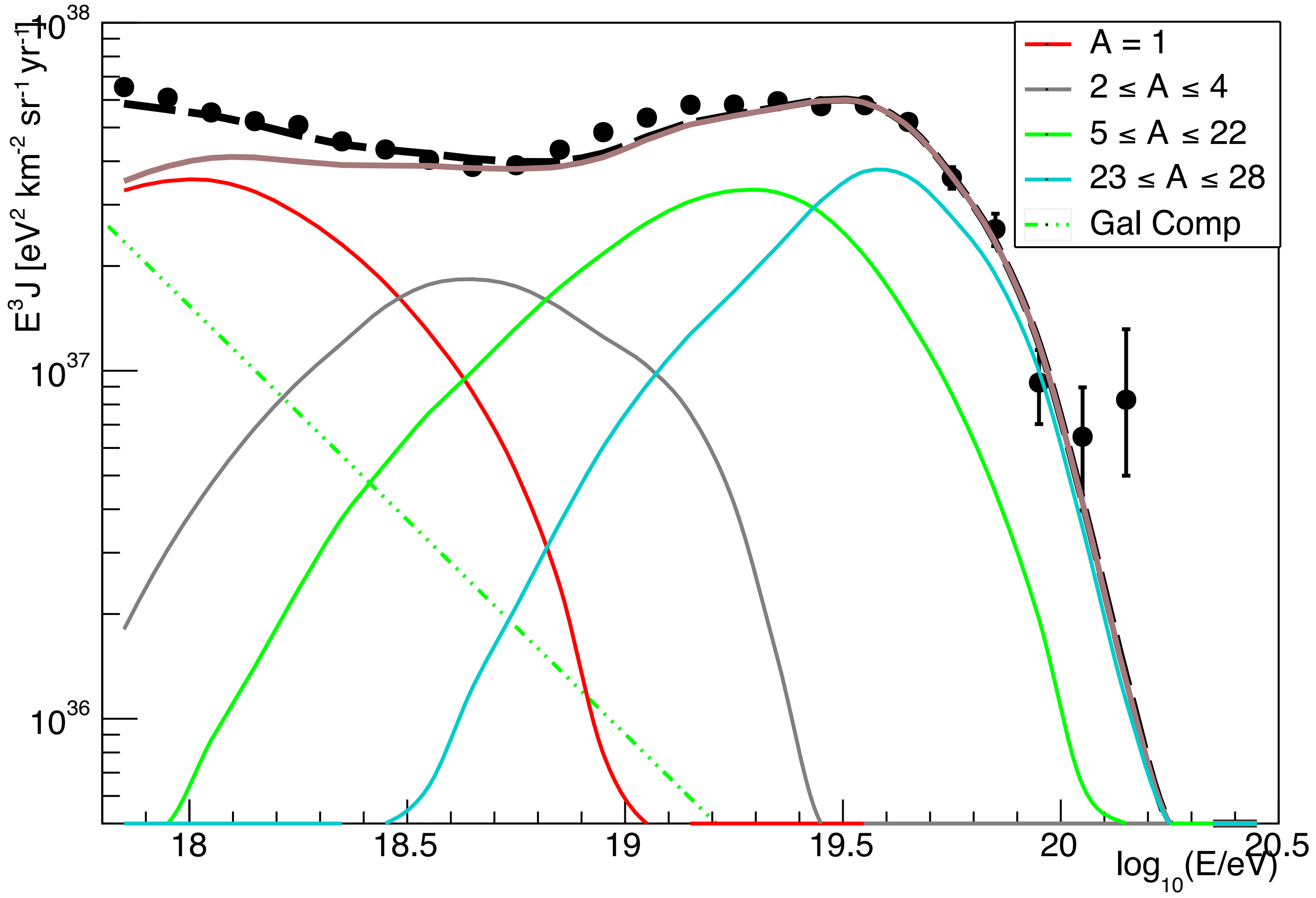
Comparison to the experimental data

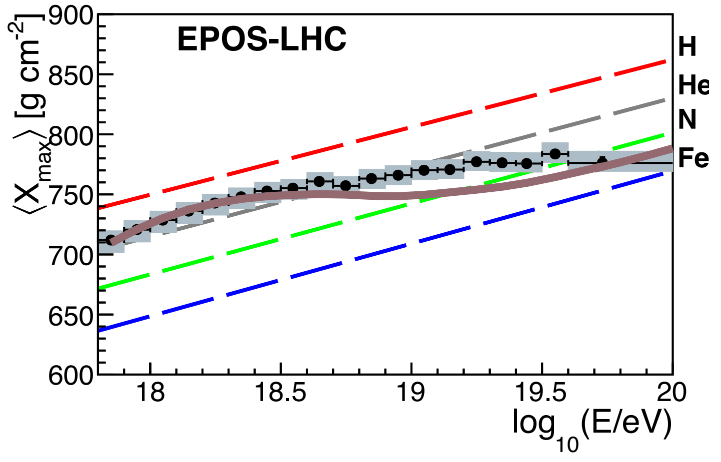


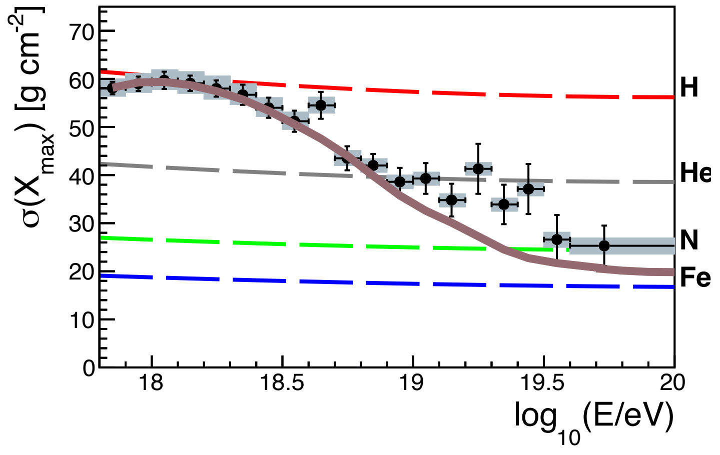


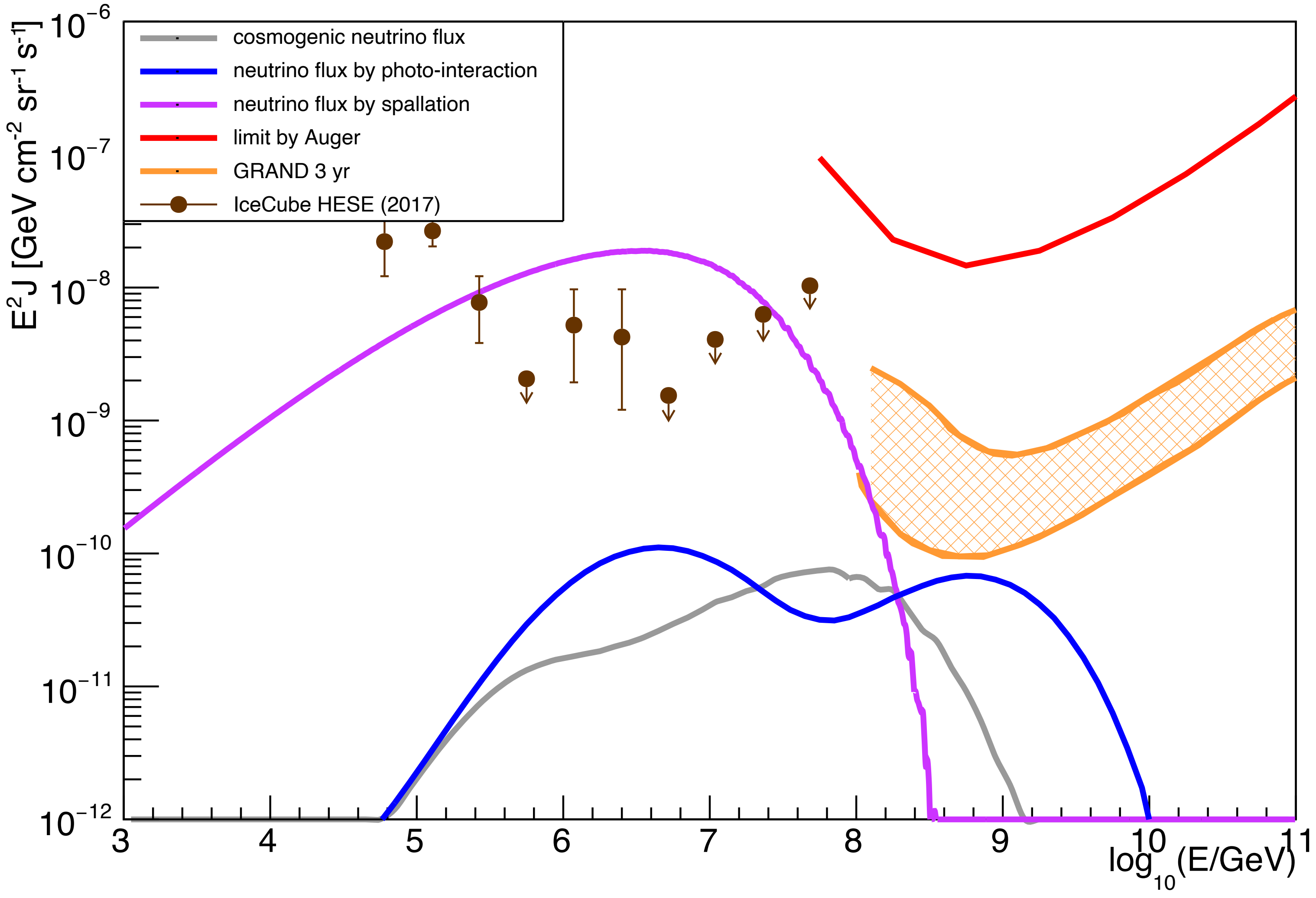


Comparison to the experimental data









Summary

- ☑ Source-propagation model in a Starburst Galaxy;
- ☑ Computing interaction times for hadronic and photo-interactions;
- ☑ Cosmogenic and source neutrino fluxes for each interaction;
- ☑ Exploiting the importance of hadronic interactions inside the source environment.

Summary

- ☑ Source-propagation model in a Starburst Galaxy;
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- ☑ Exploiting the importance of hadronic interactions inside the source environment.

Merci pour votre attention!

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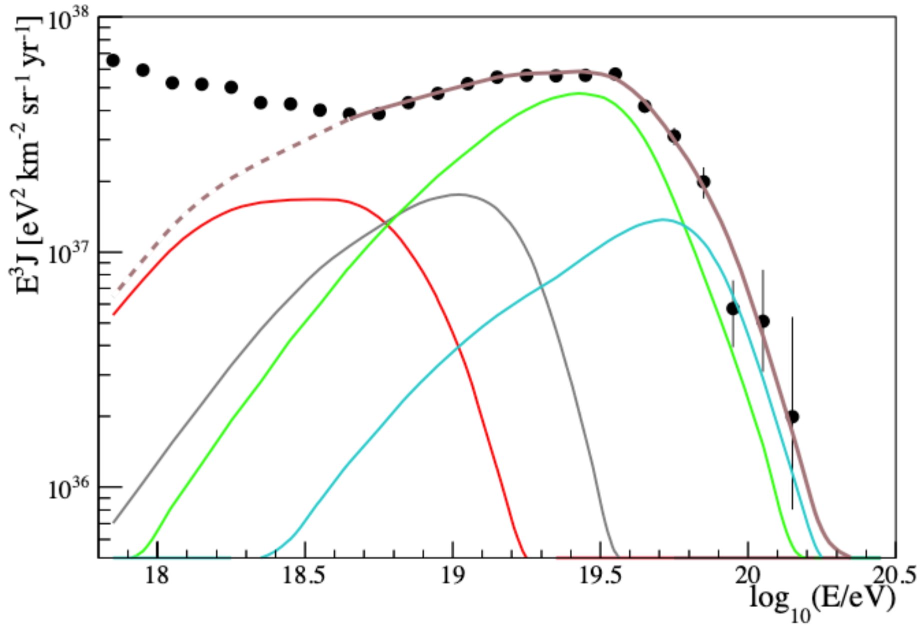
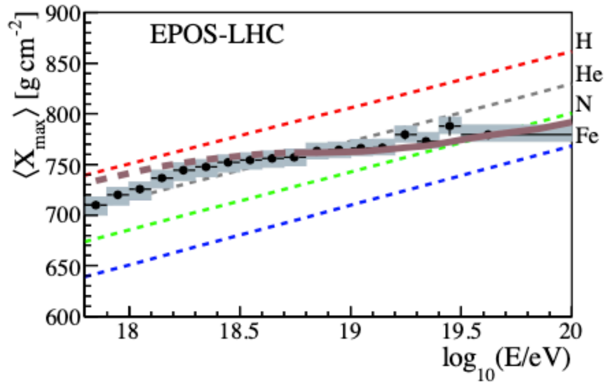
Back-up slides!

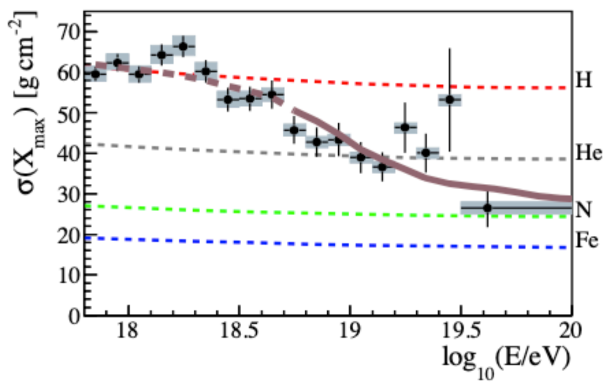
Astrophysical interpretation of Auger data

Fitting both the spectrum and composition, one can infer information about the source scenarios which are compatible to data.

Combined fit







- ✳ Nuclei are accelerated at the sources.
- ✳ A hard injection spectrum at the sources is required.
- ✳ Suppression due to photo-interactions and by limiting acceleration at the sources, while the ankle feature is not easy to accomodate.

The UHECRs phenomenology is a mess!

Particles of unknown chemical composition are accelerated through unknown mechanisms by astrophysical objects of uncertain nature with uncertain spatial distribution and temporal evolution, achieving an unknown injection energy spectrum; then they travel through intergalactic space, interacting with photon backgrounds with poorly known energy density at certain wave-lengths, in processes with unknown cross sections for certain channels, and may be deflected by poorly known intergalactic and galactic magnetic fields; then they reach Earth and generate particle cascades in the atmosphere through nuclear interactions whose behaviour is uncertain; finally they are detected by apparatuses with partly uncertain characteristics.

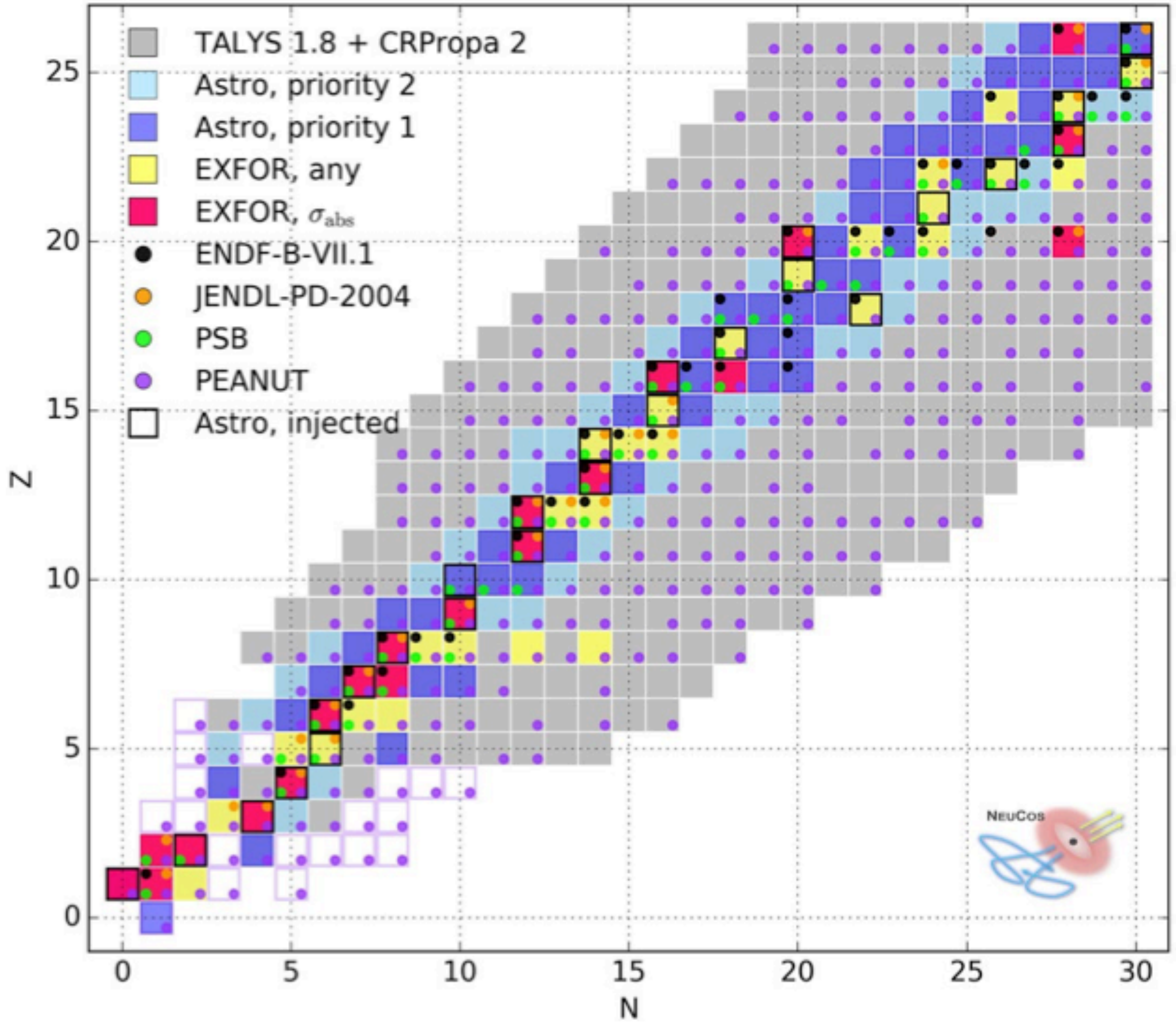
The UHECRs phenomenology is a mess!

In spite of all this, thanks to years of study by hundreds of scientists, there are a few solid results:

- ✳ UHECRs are atomic nuclei and most of them are protons or light nuclei except possibly at the highest energies.
- ✳The UHECR energy spectrum is approximately a power law except for an ankle feature at 5 EeV and a cutoff above 40 EeV (with a new feature to be studied).
- ✳Their arrival directions are distributed nearly isotropically, except for a dipole moment.

Combining different information is the key to infer something about the astrophysical sources.

Methodology of source-propagation model



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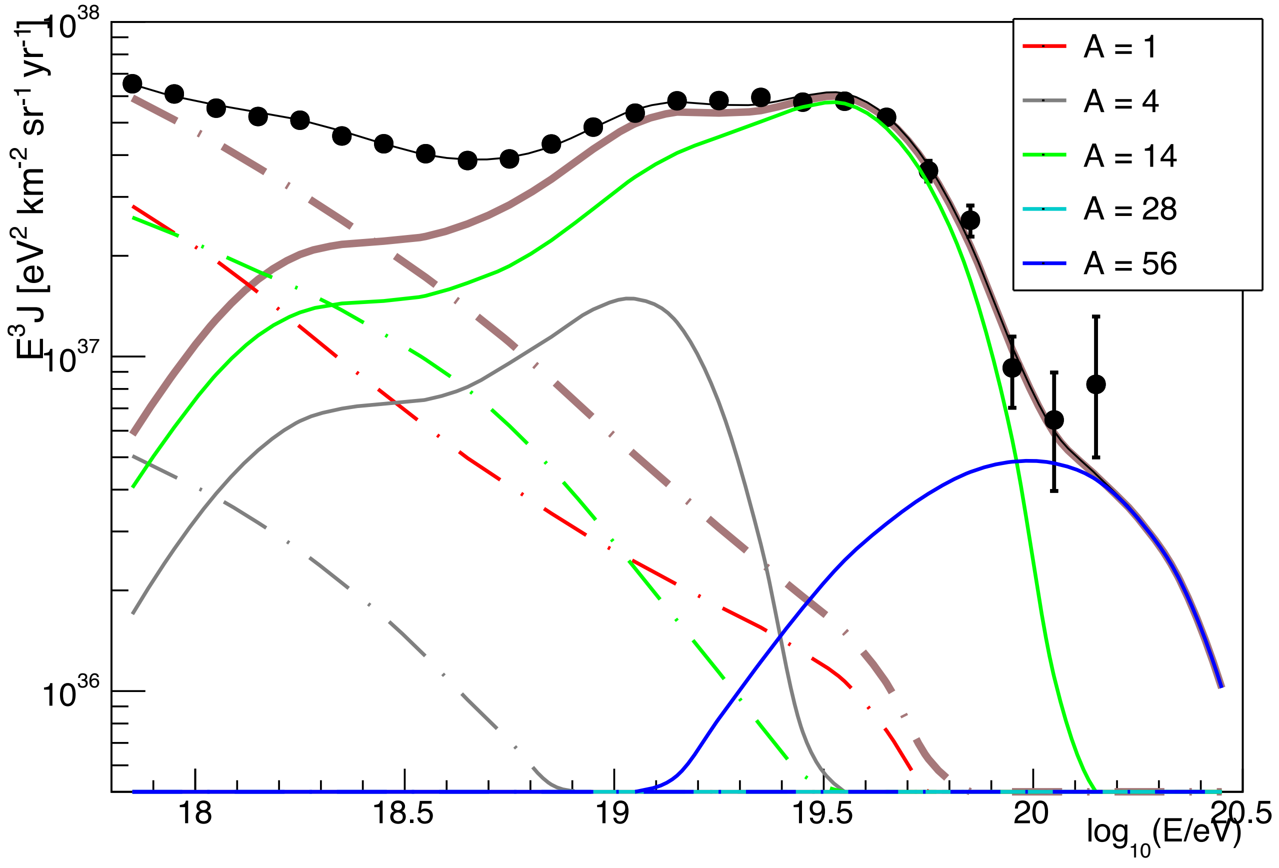
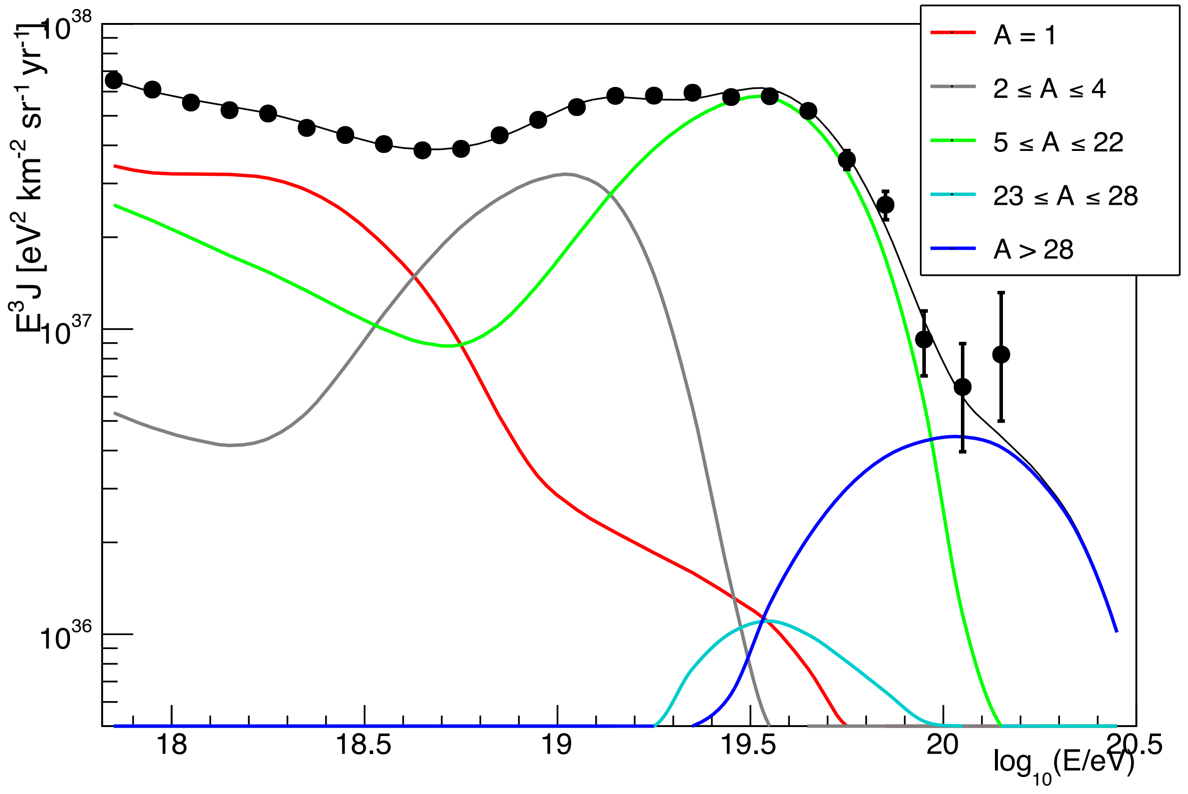
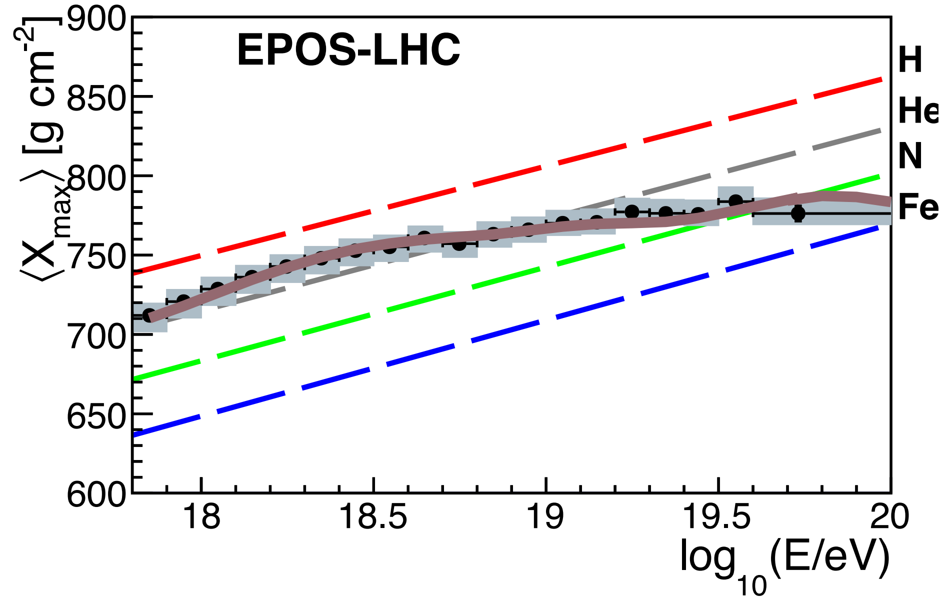
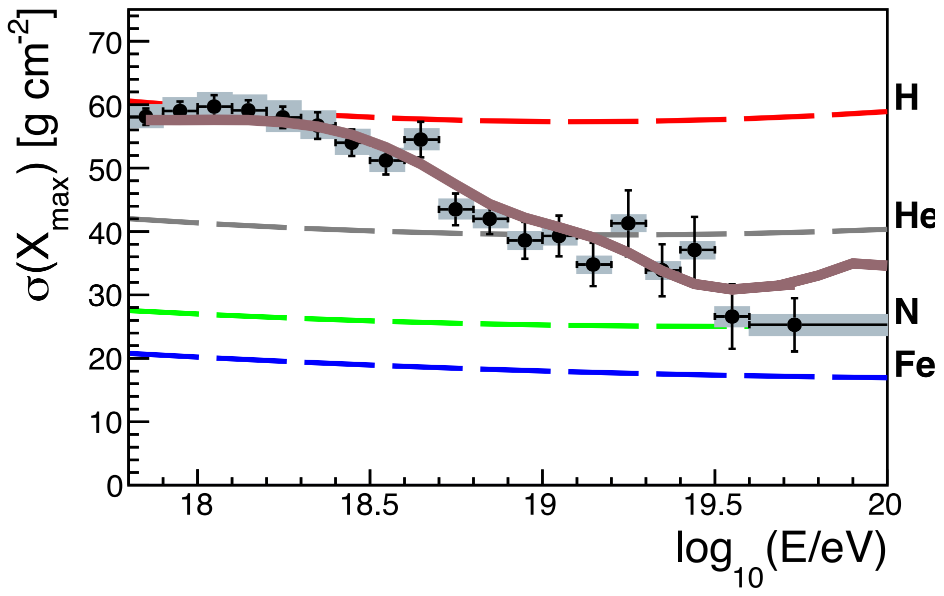
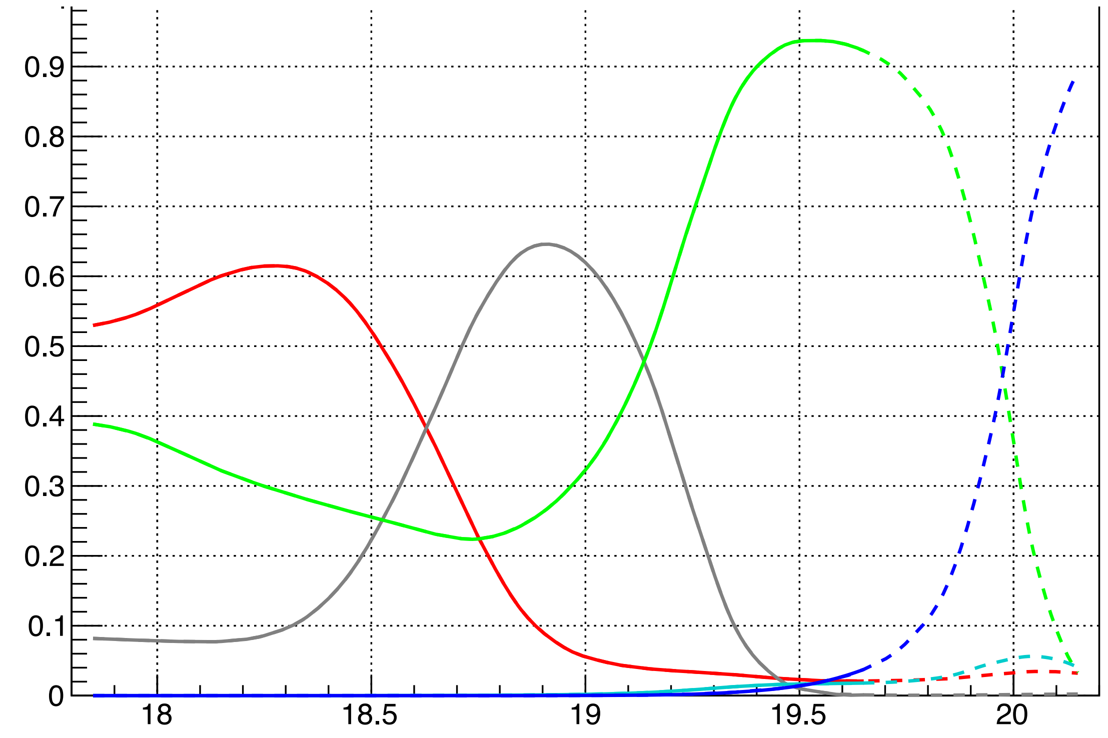
Second extra-galactic component











Combined fit above the ankle: ingredients

- Assuming point-like sources identical and uniformly distributed;
- Acceleration of five representative masses: Hydrogen, Helium, Nitrogen, Silicon and Iron.
- The injected flux for each mass is a power law with a broken-exponential cutoff.

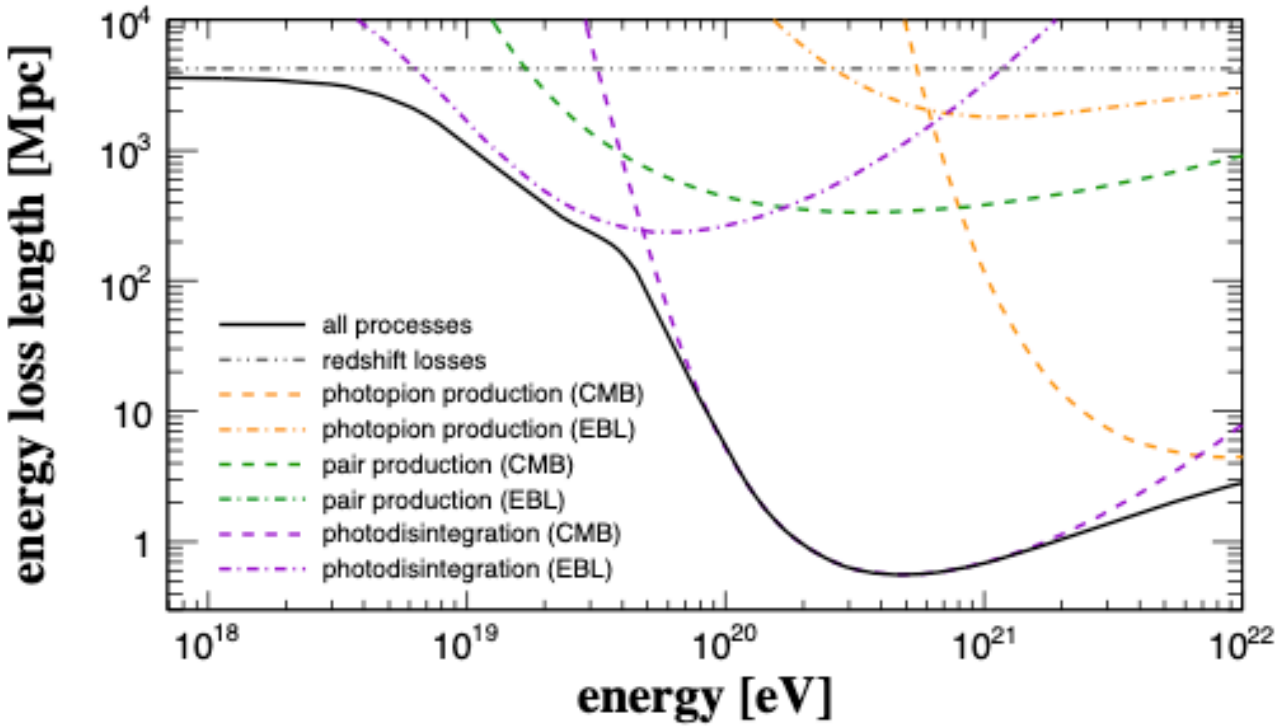
$$J_k(E_i) = f_k J_0 \left(\frac{E_i}{E_0}\right)^{-\gamma} \cdot f_{\rm cut}(E_i, Z \cdot R_{\rm cut})$$

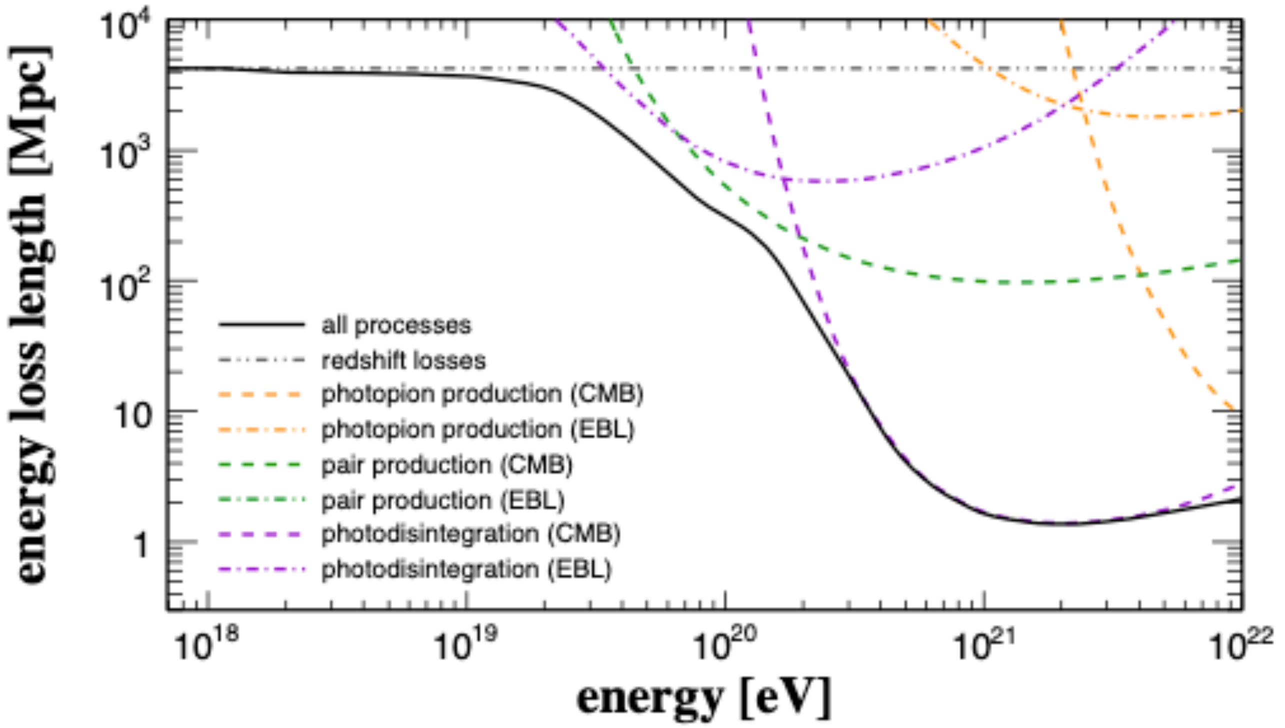
$$f_{\rm cut}(E_i, Z \cdot R_{\rm cut}) = \begin{cases} 1 & E_i < Z\ R_{\rm cut} \\ \exp\left(1 - \frac{E_i}{Z \cdot\ R_{\rm cut}}\right) & E_i > Z\ R_{\rm cut} \end{cases}$$

- The injected flux are propagated through the extra-galactic space and fitted to the Auger energy spectrum and composition.
- Free parameters of the fit are: $J_0, \gamma, R_{\rm cut}$ and $(N-1)\ f_k$.
- The total deviance is considered as the sum of the deviance of the spectrum and the deviance of the composition.

Simulation of extra-galactic propagation

To interpret the measured spectrum and mass composition data in terms of astrophysical scenarios, some tools are needed in order to take into account the role of the propagation.





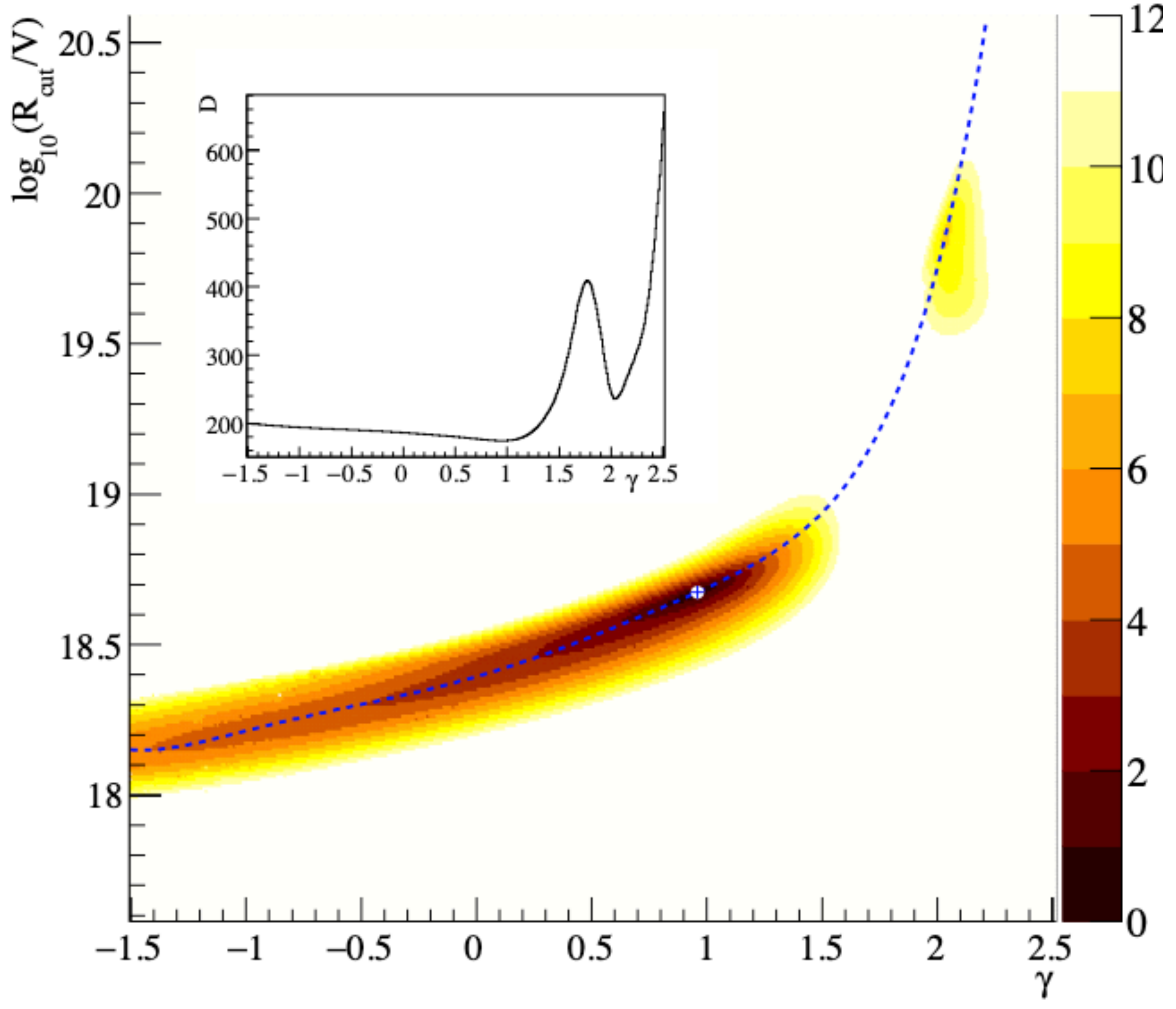
The SimProp software

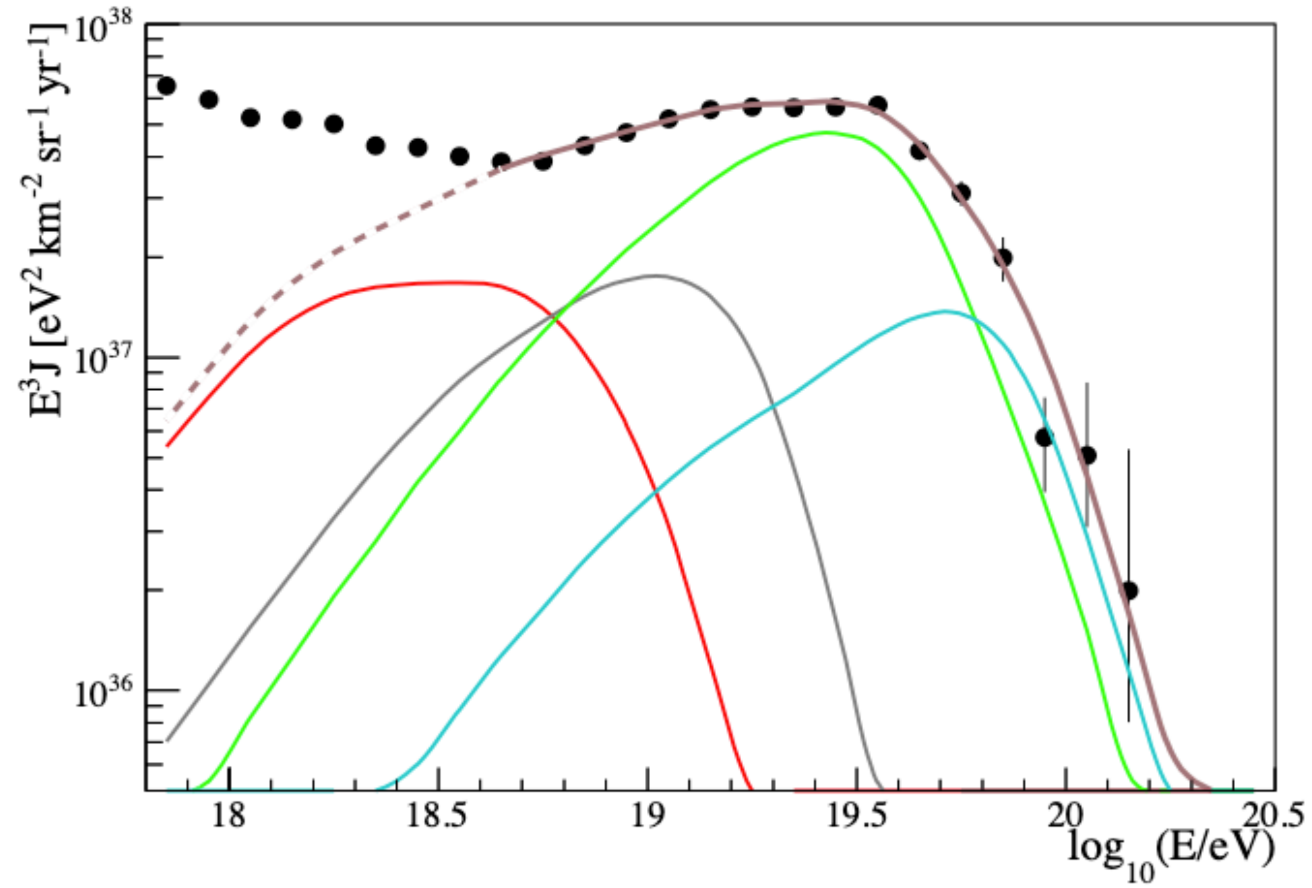
- SimProp is a Monte Carlo simulation code for the propagation of UHECRs through the Universe.
- Particles injected with a flat distribution in energy and source redshift uniformly distributed.
- The propagation of particles is followed, along with that of the secondary particles produced during propagation.
- Different models for the Photo-disintegration cross section and EBL model.

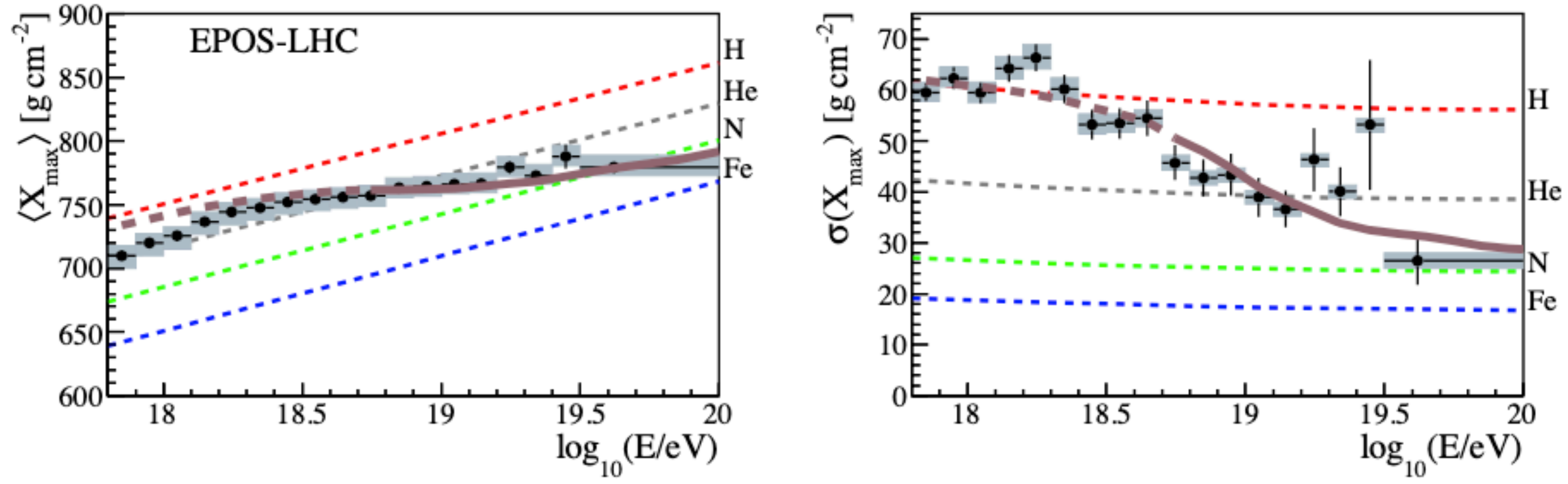
R. Aloisio et al. JCAP11(2017)009

R. Alves Batista et al, JCAP10(2015)063

Combined fit above the ankle: results



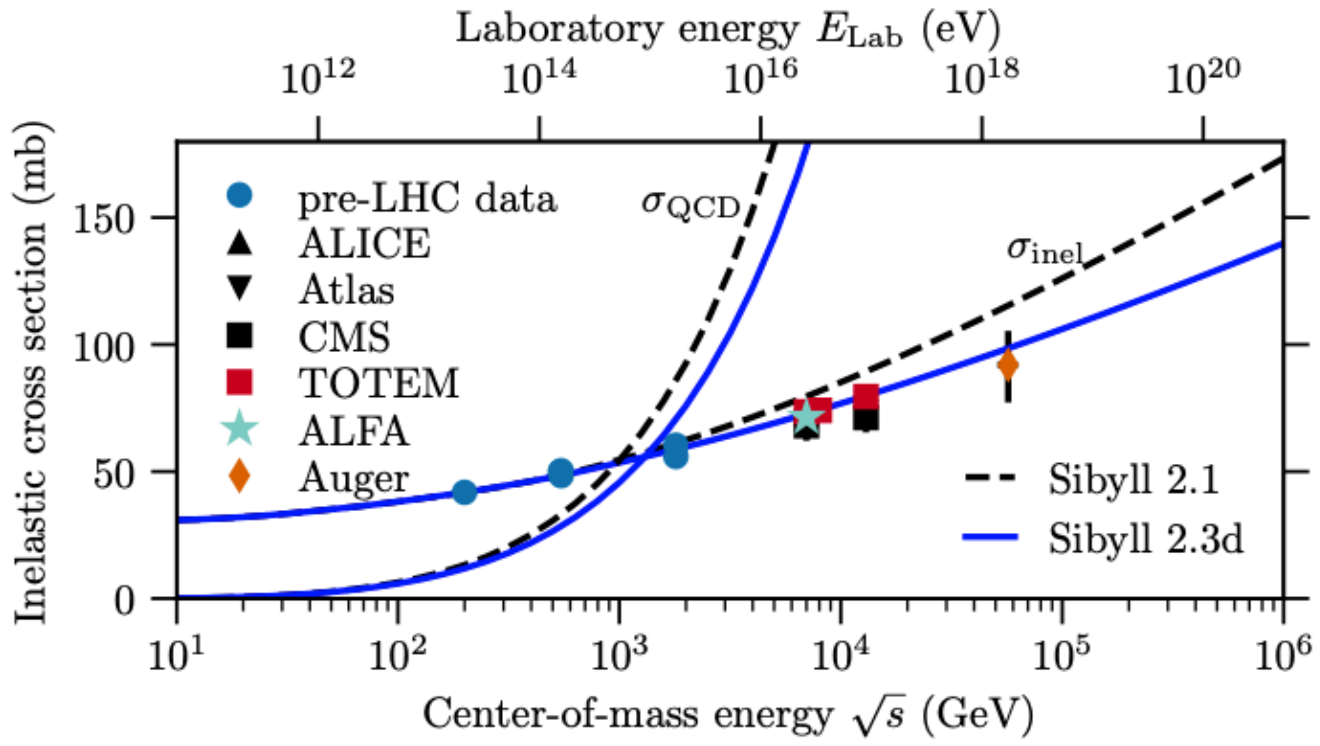




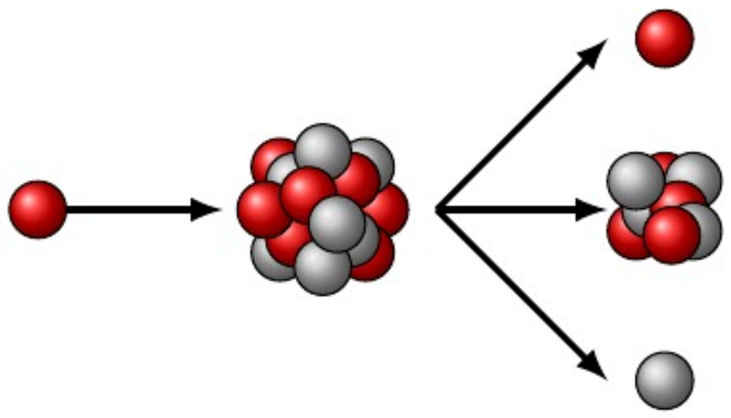
A.Aab et al. (The Pierre Auger Collaboration), JCAP04(2017)038

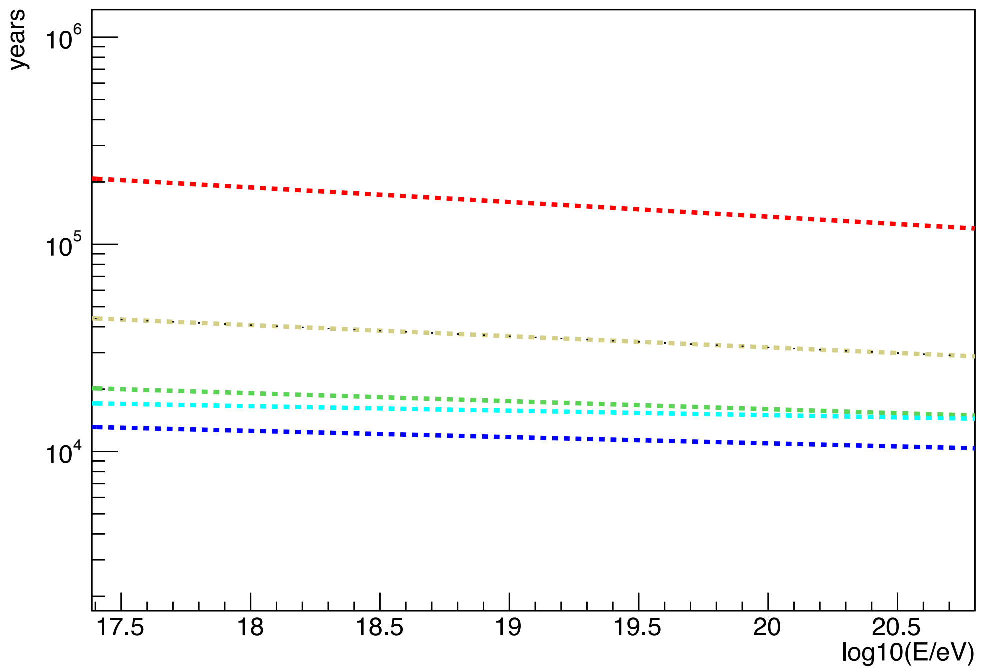
Including hadronic interactions

- The p-p and p-A cross section σ are used to calculate the interaction time
- If a hadronic interaction happens, then the interacting nucleus A is disintegrated in a nucleus $A_{\mathrm{frag}} < A$, producing $A - A_{\mathrm{frag}}$ nucleons.
- For each interaction a certain number of charged pions $N_{\pi^{\pm}}$ are produced according to a flat distribution in rapidity.



σ, A_{frag} and $N_{\pi^{\pm}}$ are obtained using Sibyll 2.3d.





F. Riehn et al, Phys. Rev. D 102, 063002 (2020),