UHECR with CRPropa3: Understanding the effects of astrophysical hypothesis and source distance

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CRPropa face-to-face meeting

Zeuthen - Monday, September 30th, 2019

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São Carlos Institute of Physics

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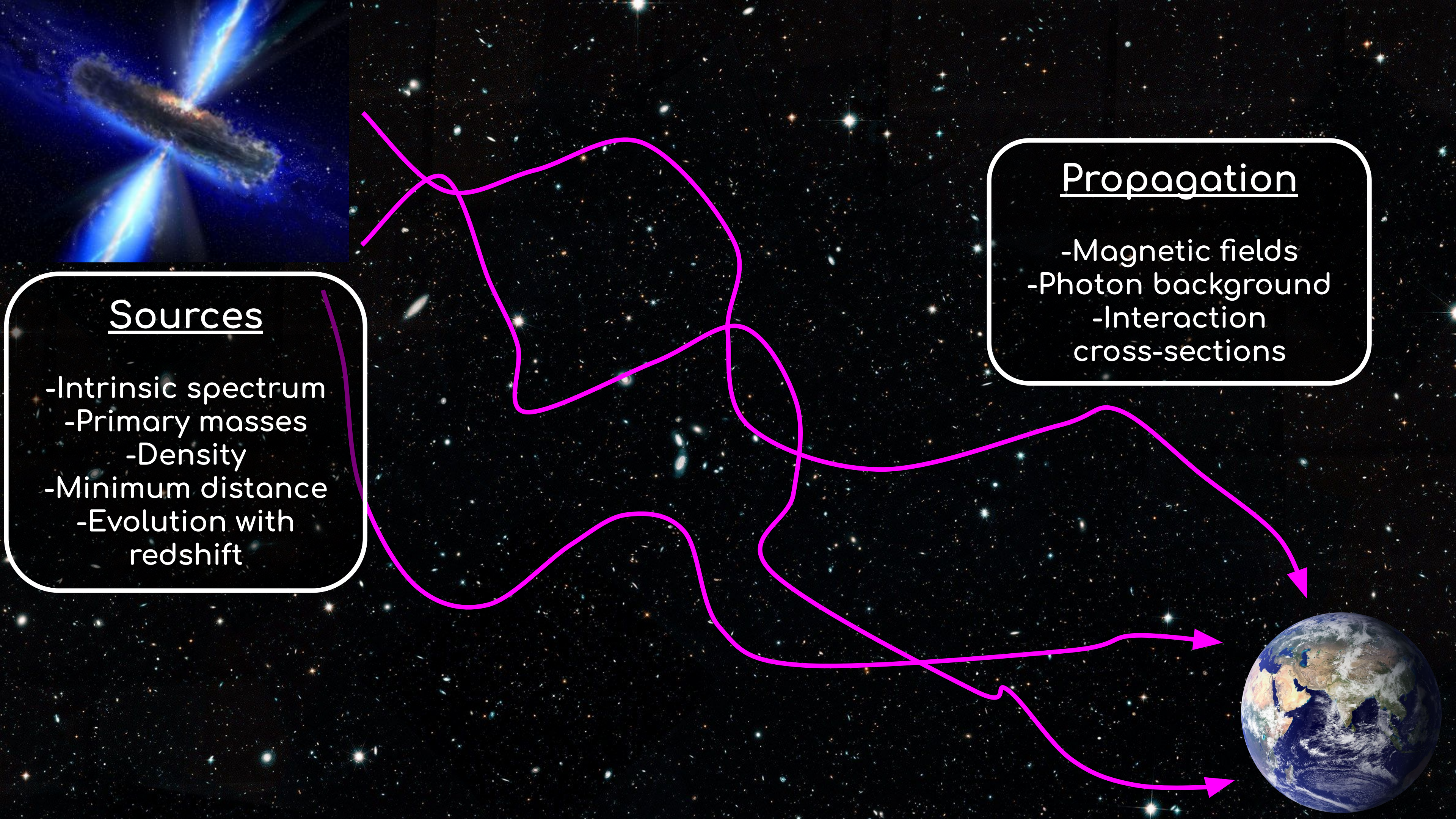
FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

UHECR spectrum

- Reproducing the UHECR spectrum is the main goal of several works;
- Different astrophysical and computational hypotheses are needed;
- In this work we evaluate the effects of a few of them.


Sources
-Intrinsic spectrum
-Primary masses
-Density
-Minimum distance
-Evolution with redshift


Sources
-Intrinsic spectrum
-Primary masses
-Density
-Minimum distance
-Evolution with redshift
Propagation
-Magnetic fields
-Photon background
-Interaction cross-sections

Source spectrum

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} e^{-E/(Z R_{max})} \times f_A$$

Spectral index

Normalization

Maximum rigidity

Primary fraction

Source spectrum

- Usually fitted to data:
  - Fixed values simulated;
  - Events weighted for each combination of parameters.

$$\left\{ \begin{array}{c} N_0 \\ \Gamma \\ R_{max} \\ f_A \end{array} \right.$$

Source spectrum

- In this work:
  - Fixed values;
  - Pure composition;
  - Easier to visualize the effects.

$N_0 \rightarrow$ arbitrary

$\Gamma = 1.7$

$R_{max} = 10^{19.5}$ V

$f_A \rightarrow$ p, He, N, Si, Fe

Hypotheses

Sources

-Maximum energy

-Maximum distance

-Source evolution

-Source distribution

Propagation

-Energy losses

-Adiabatic losses

-Pair production

-Pion production

-EBL models

Astrophysical
Computational

Maximum simulated energy

Sources

-Energy

-Distance

-Evolution

-Distribution

Propagation

-Losses

-Adiabatic

-Pair prod.

-Pion prod.

-EBL models

- Higher energies increase heavily the computational cost;
- Most energetic events don't contribute to the spectrum due to the power-law (with exponential cutoff) behaviour;
- $E_{max} = \{10^{21}, 10^{22}, 10^{23}\}$ eV

p

He

N

Si

Fe

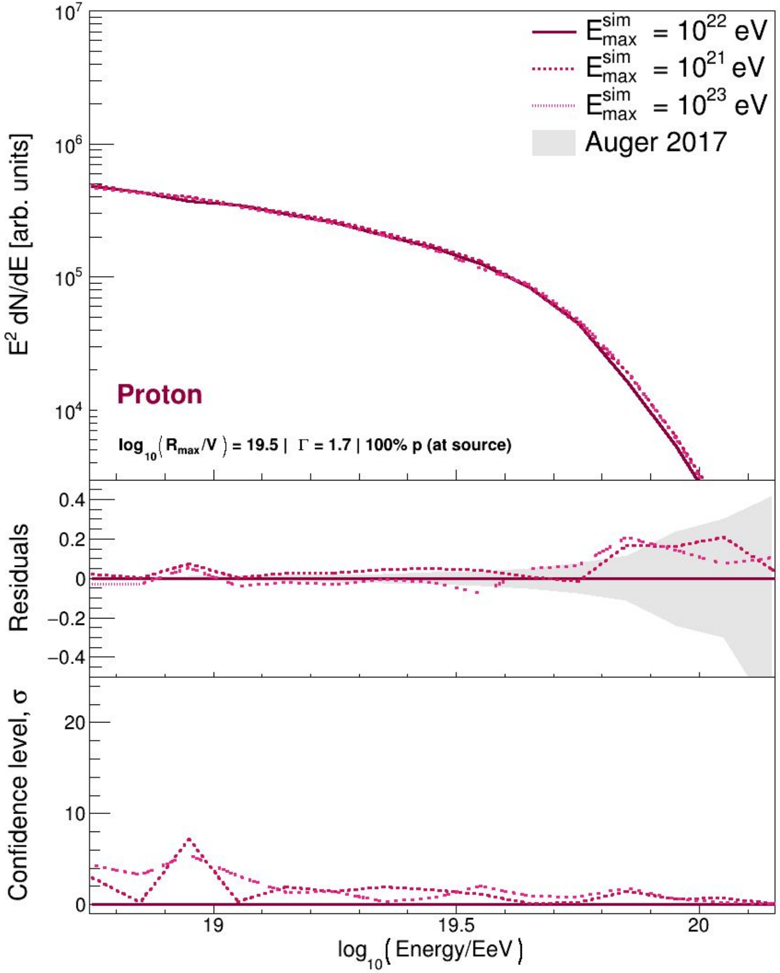
Sources

-Energy

-Distance

-Evolution

-Distribution



Propagation

-Losses

-Adiabatic

-Pair prod.

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-EBL models

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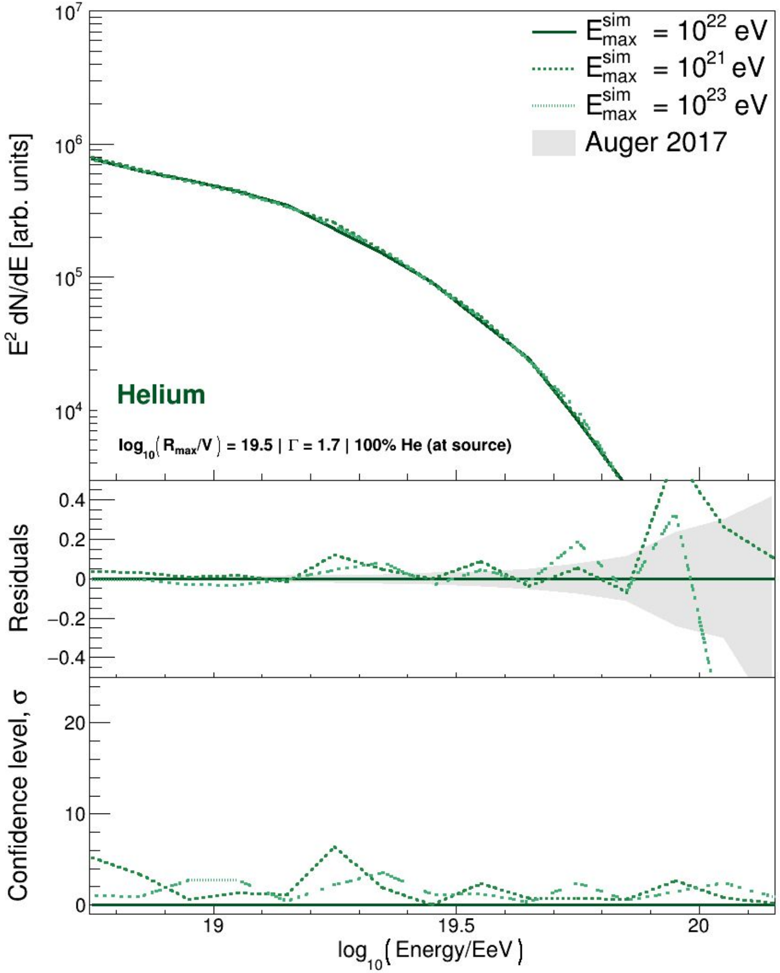

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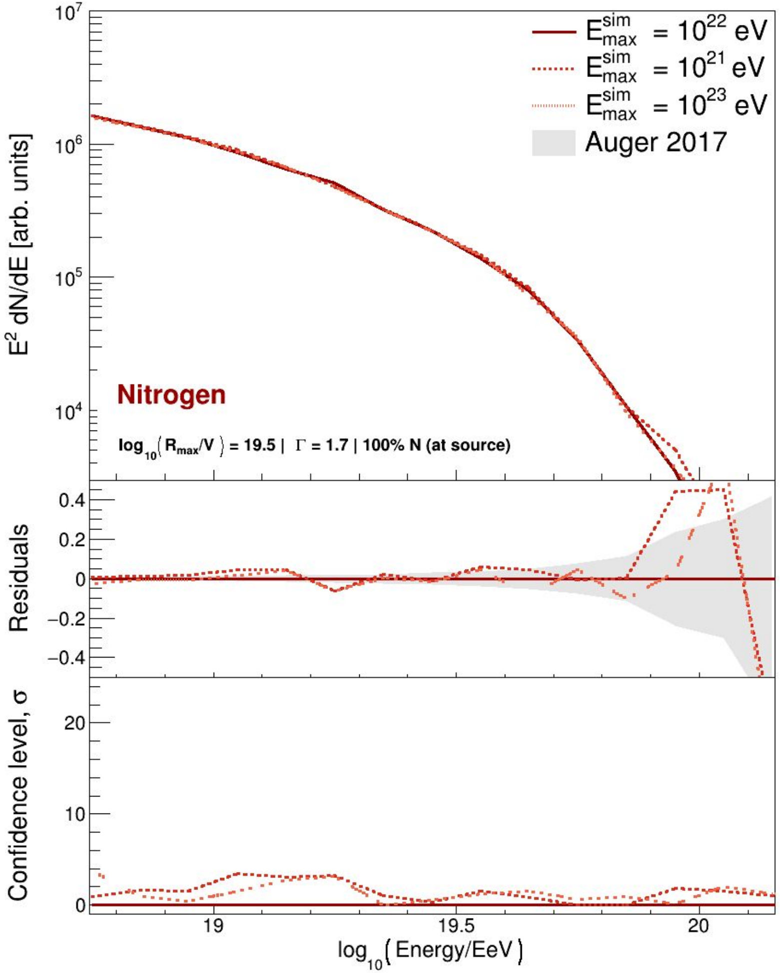

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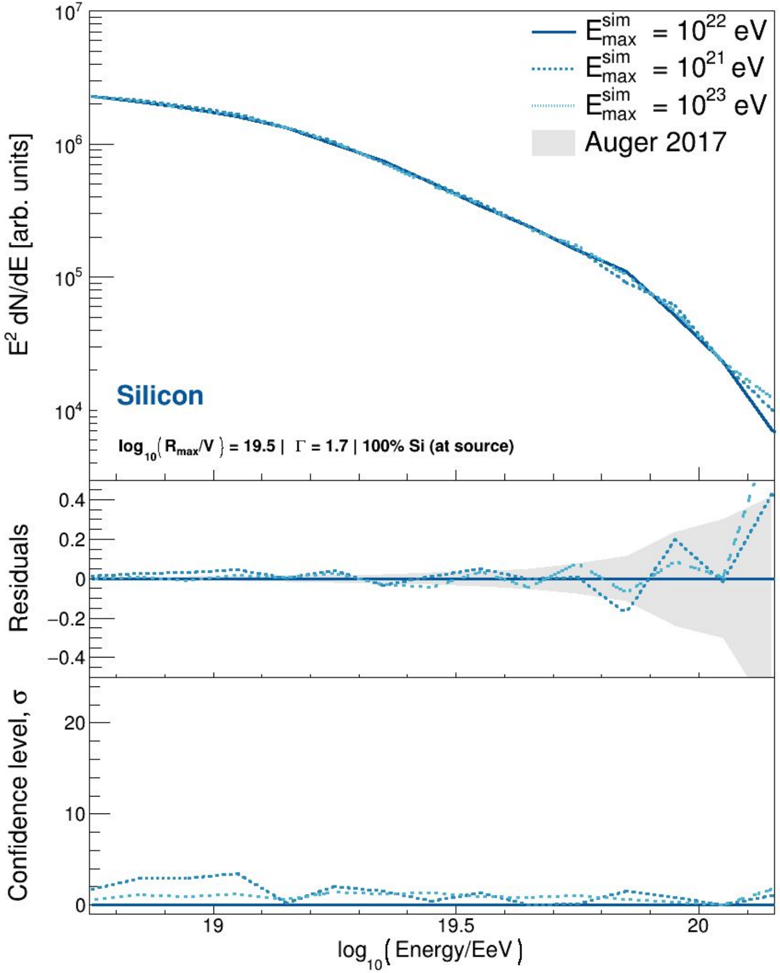

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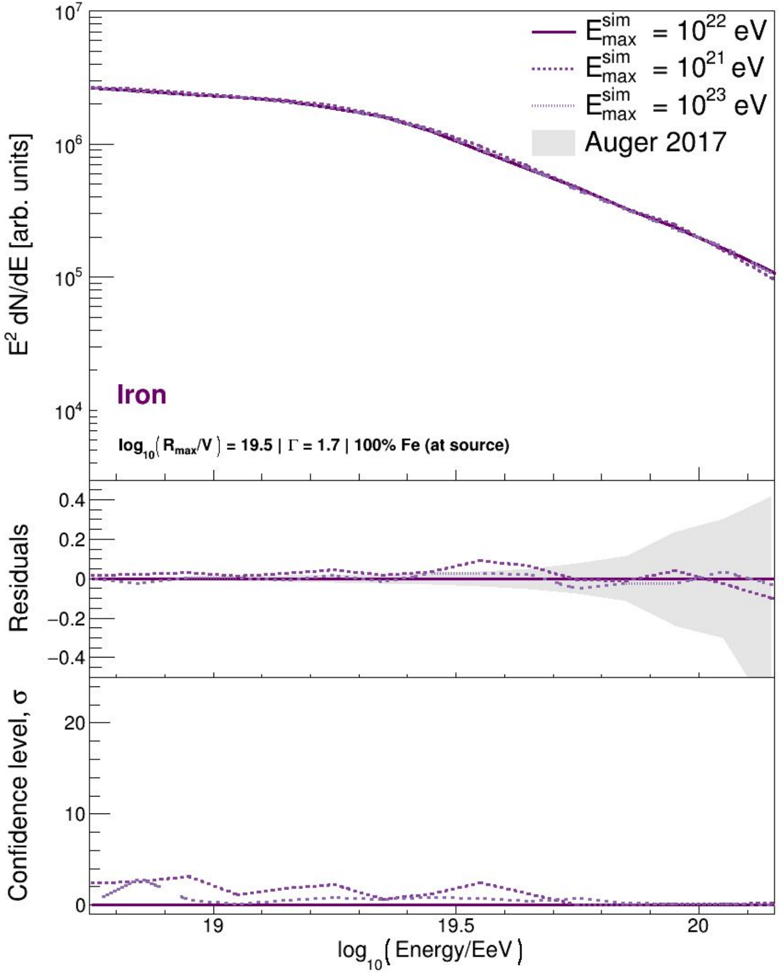

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Maximum simulated energy

p

He

N

Si

Fe

- For reasonable spectral indexes ($-\Gamma < 0$) and maximum rigidities ($R_{max} < 10^{20}$ V), $E_{max} = 10^{21}$ eV is still fine and $E_{max} = 10^{22}$ eV is surely a safe choice.

Maximum simulated distance

Sources

-Energy

-Distance

-Evolution

-Distribution

Propagation

-Losses

-Adiabatic

-Pair prod.

-Pion prod.

-EBL models

- Further distances increase heavily the computational cost;
- Most of the far events don't contribute to the spectrum due to energy losses;
- z_{max} = {0.1, 0.5, 1, 1.5, 2}

p

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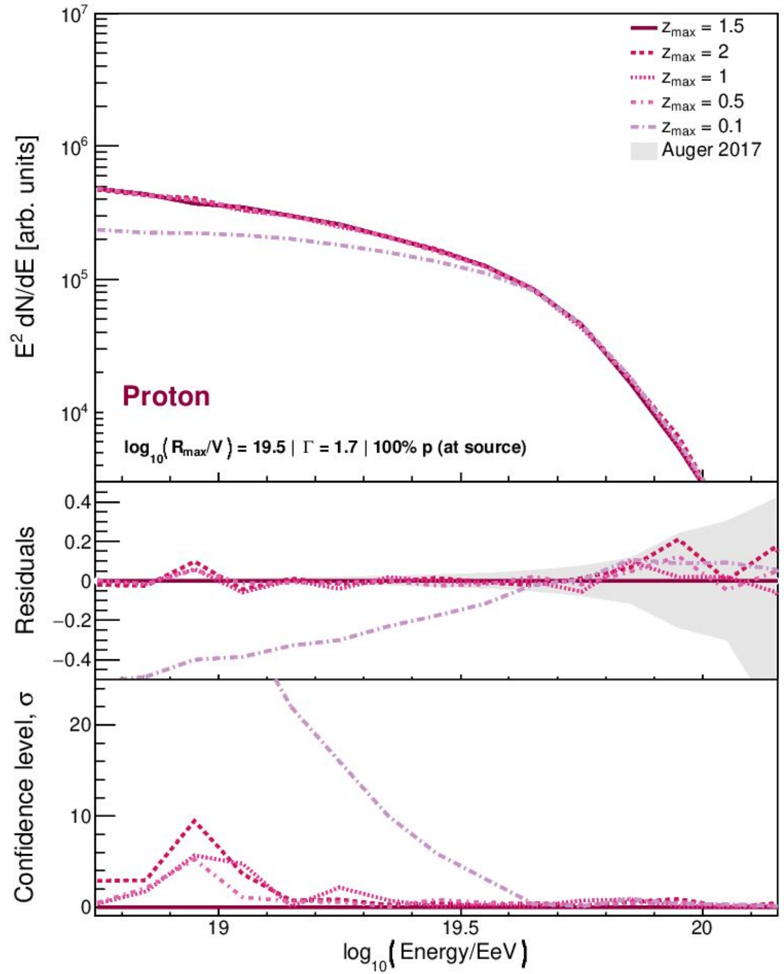

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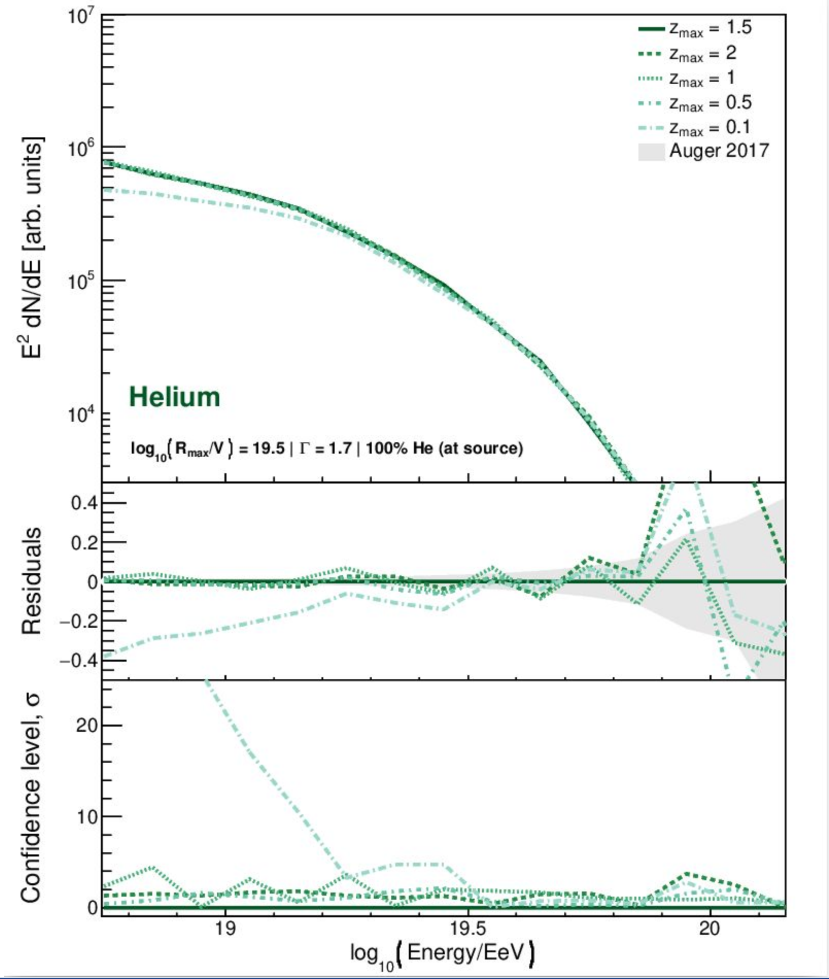

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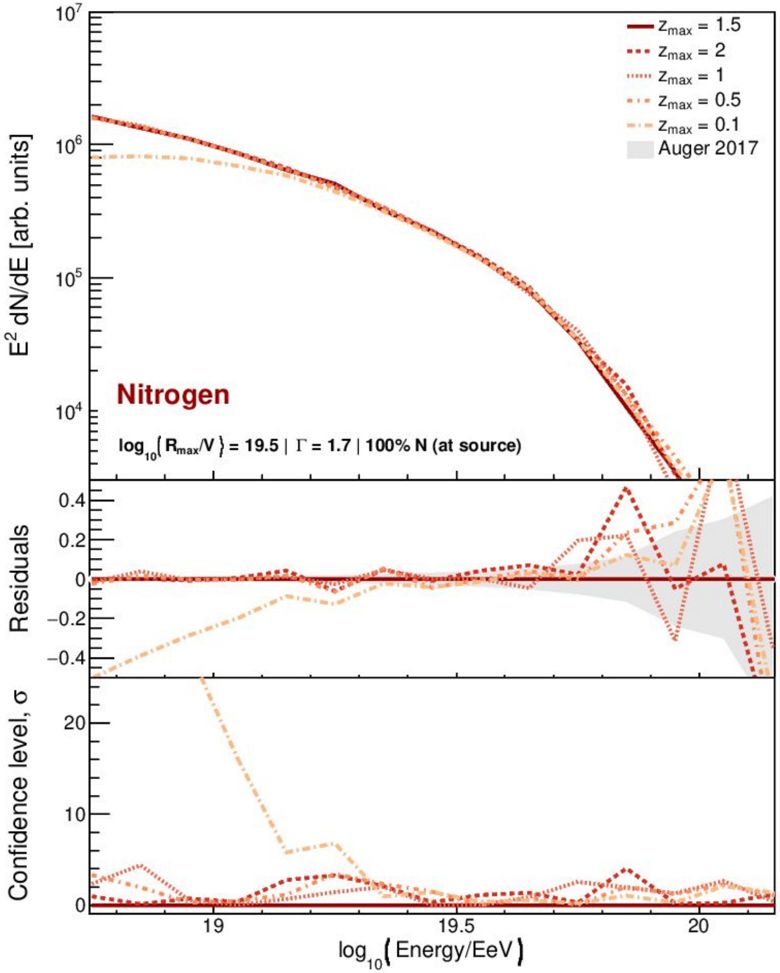

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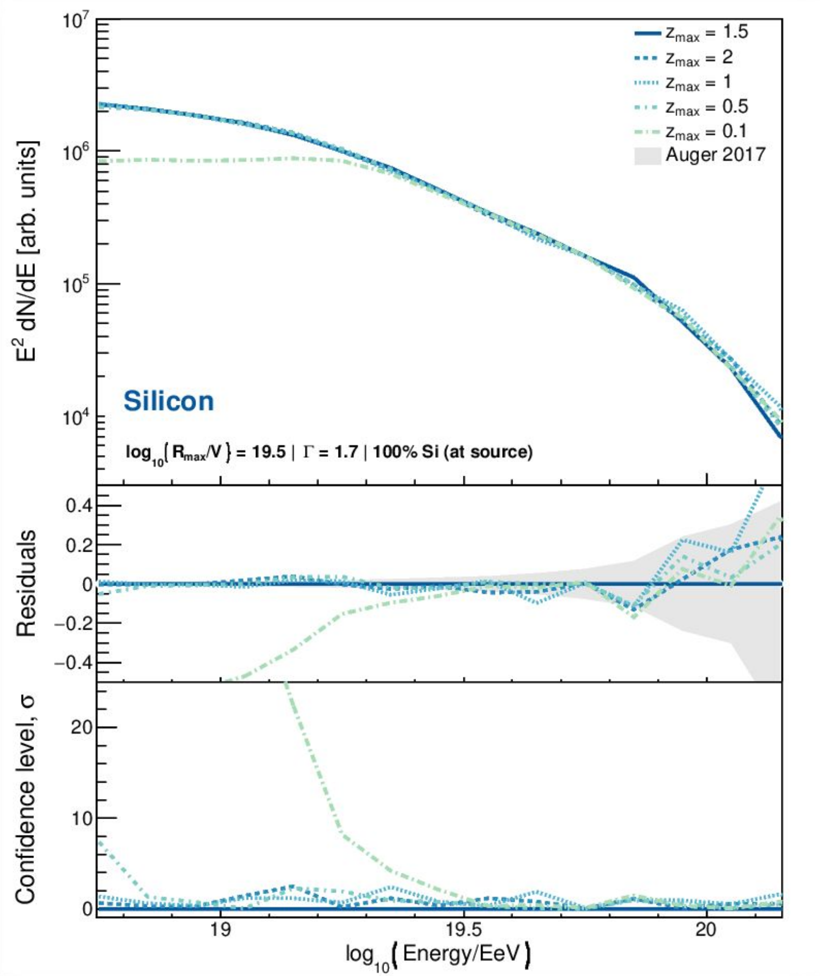

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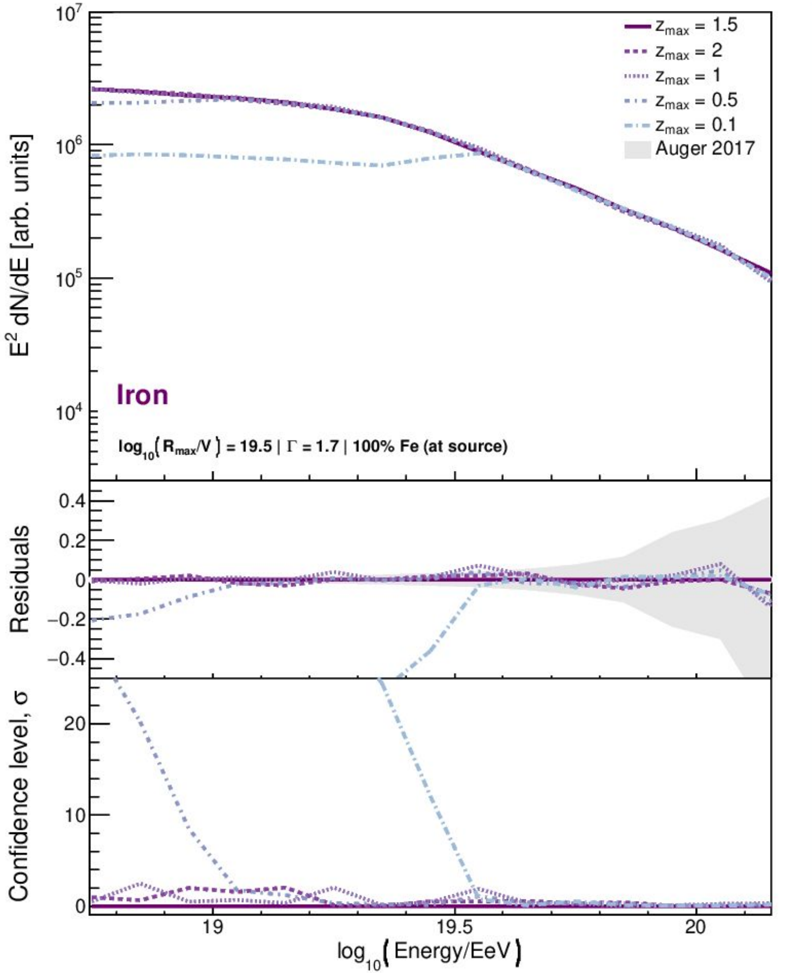

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Maximum simulated distance

Sources

-Energy

-Distance

-Evolution

-Distribution

Propagation

-Losses

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-Pion prod.

-EBL models

- When looking only at the UHECR even small redshifts like $z_{max} = 0.5$ seem to be enough. $z_{max} = 1$ is surely a safe choice;
- If secondaries are of interest, larger redshifts should be considered.

p

He

N

Si

Fe

Source evolution with redshift

Sources

-Energy

-Distance

-Evolution

-Distribution

- The distribution of sources may increase/decrease with redshift;
- Usually an evolution of the form $(1+z)^m$ is taken;
- $m = \{-3, -1, 0, 1, 3\}$

Propagation

-Losses

-Adiabatic

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-Pion prod.

-EBL models

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Sources

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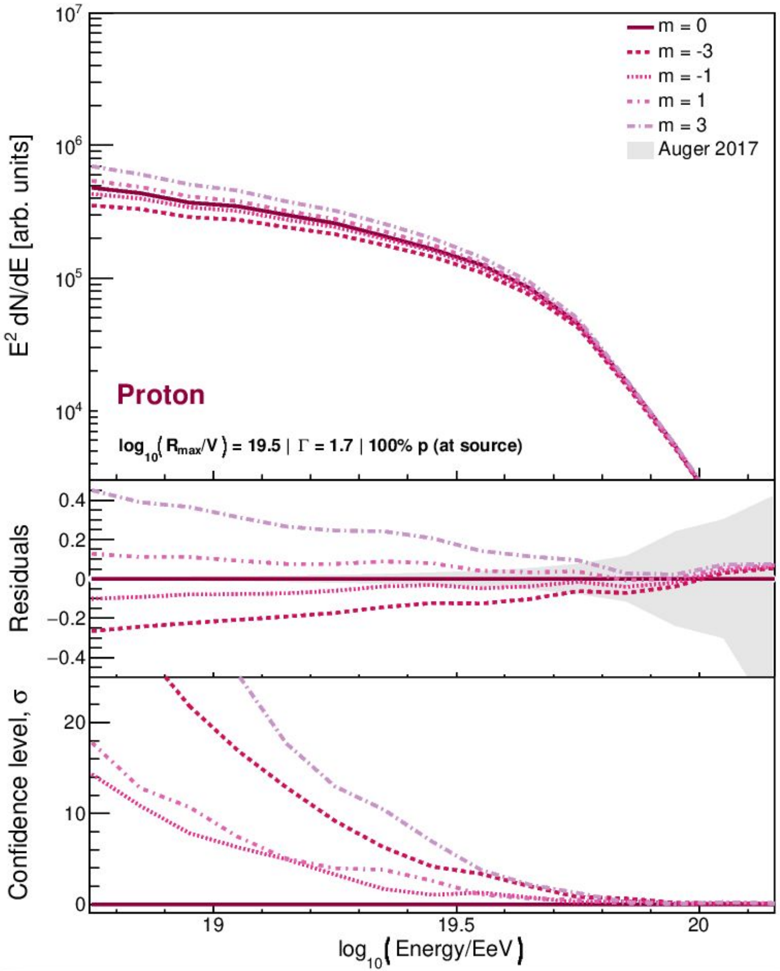

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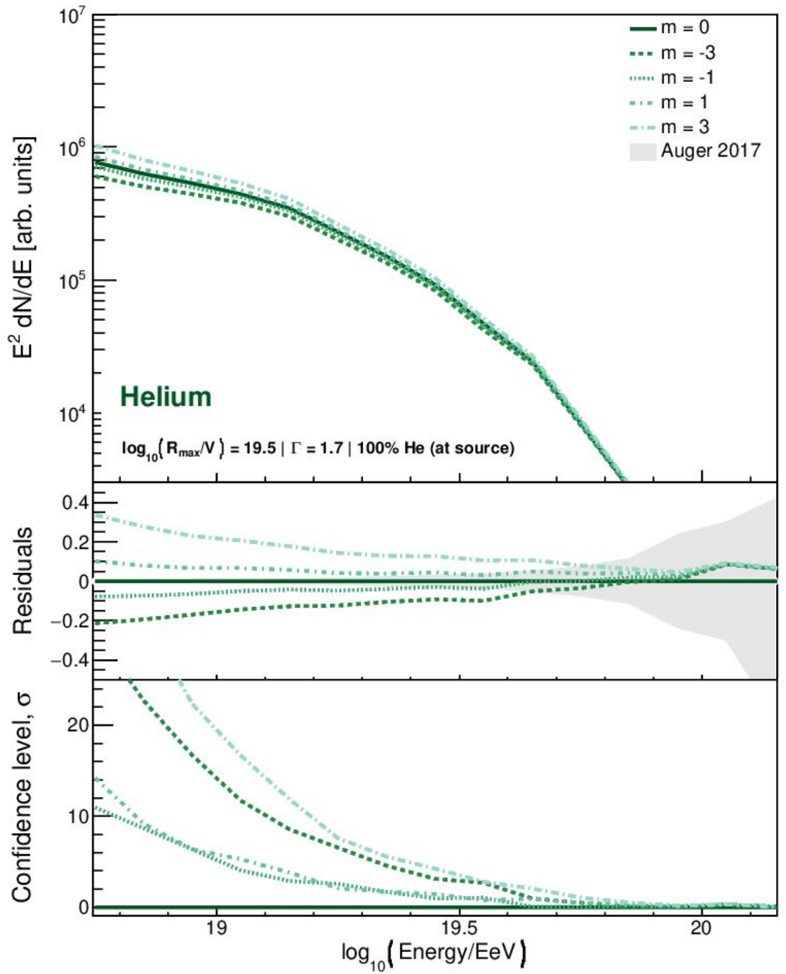

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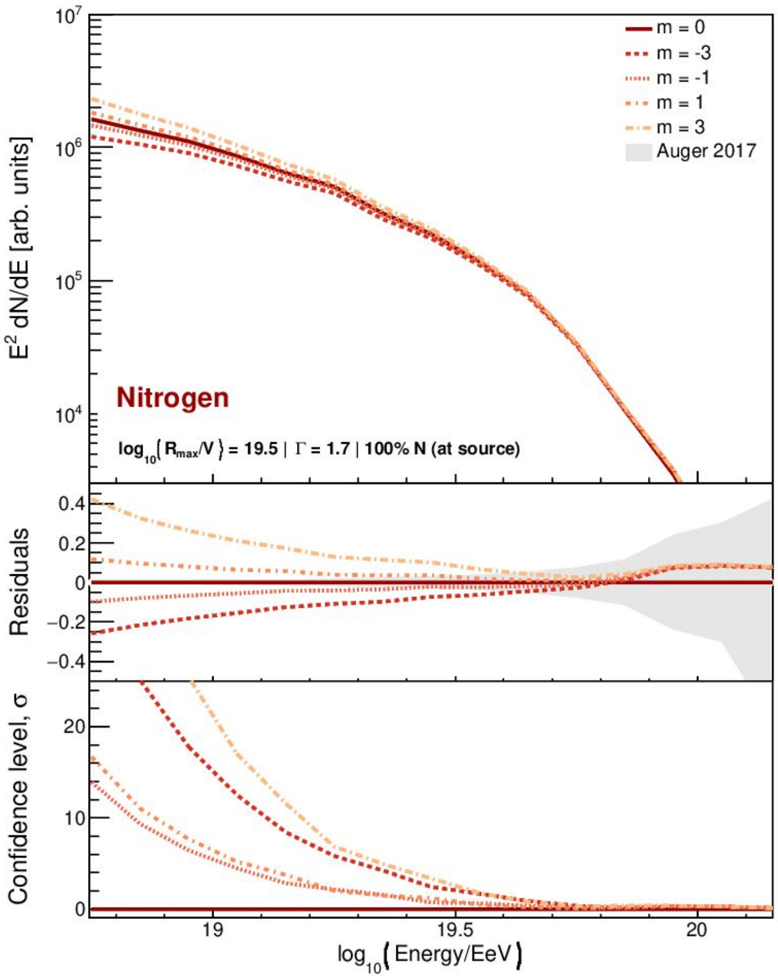

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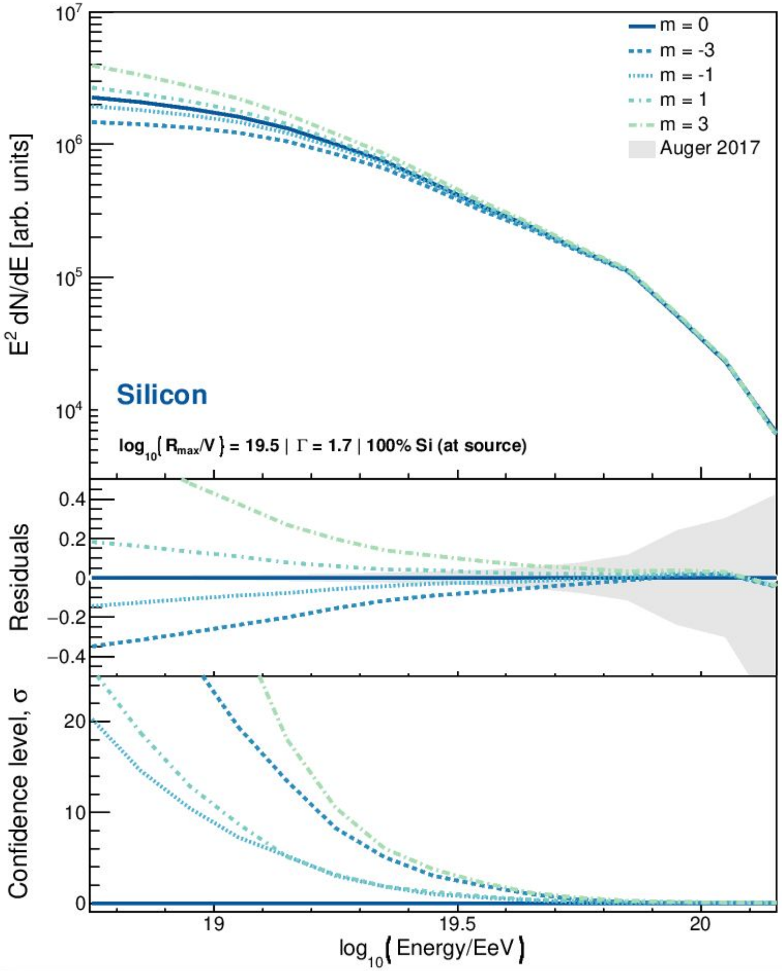

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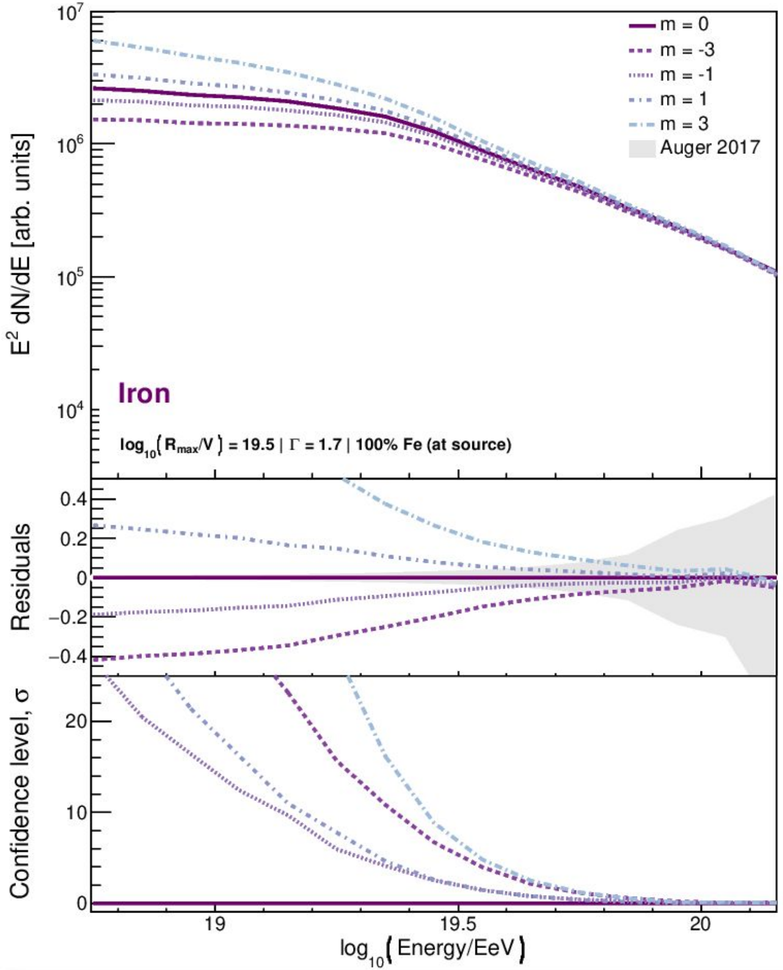

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Source evolution with redshift

Sources

-Energy

-Distance

-Evolution

-Distribution

Propagation

-Losses

-Adiabatic

-Pair prod.

-Pion prod.

-EBL models

- The source evolution plays a very important role in the low energy end of the spectrum;
- This effect is strong for larger masses going up to ~$10^{19.7}$ eV for iron;
- This may introduce a decent systematic uncertainty on some analysis.

p

He

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Fe

Source distribution

Sources

- -Energy
- -Distance
- -Evolution
- -Distribution

Propagation

- -Losses
- -Adiabatic
- -Pair prod.
- -Pion prod.
- -EBL models

p

He

N

Si

Fe

- It is usual to have sources uniformly distributed;
- Sources can be uniformly distributed in comoving distance (χ) or light-travel distance (cdt);
- In CRPropa 3 those are implemented in the option *withCosmology* in *SourceUniform1D*;

$$\frac{dN}{cdt} = (1 + z)\frac{dN}{d\chi}$$

Sources

-Energy

-Distance

-Evolution

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Propagation

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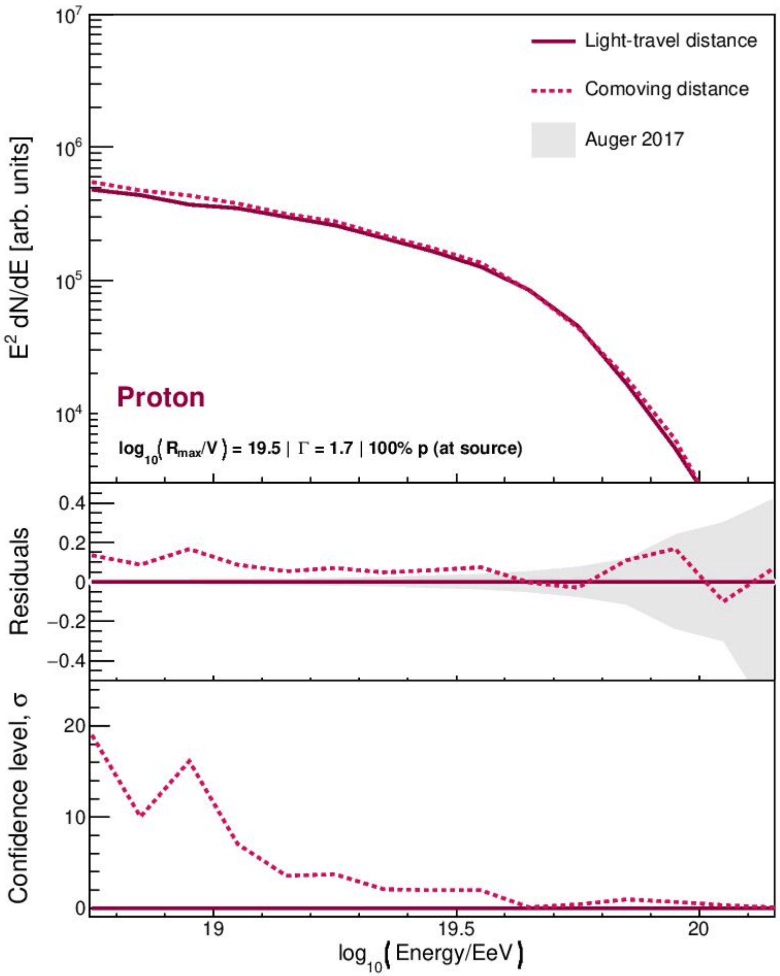

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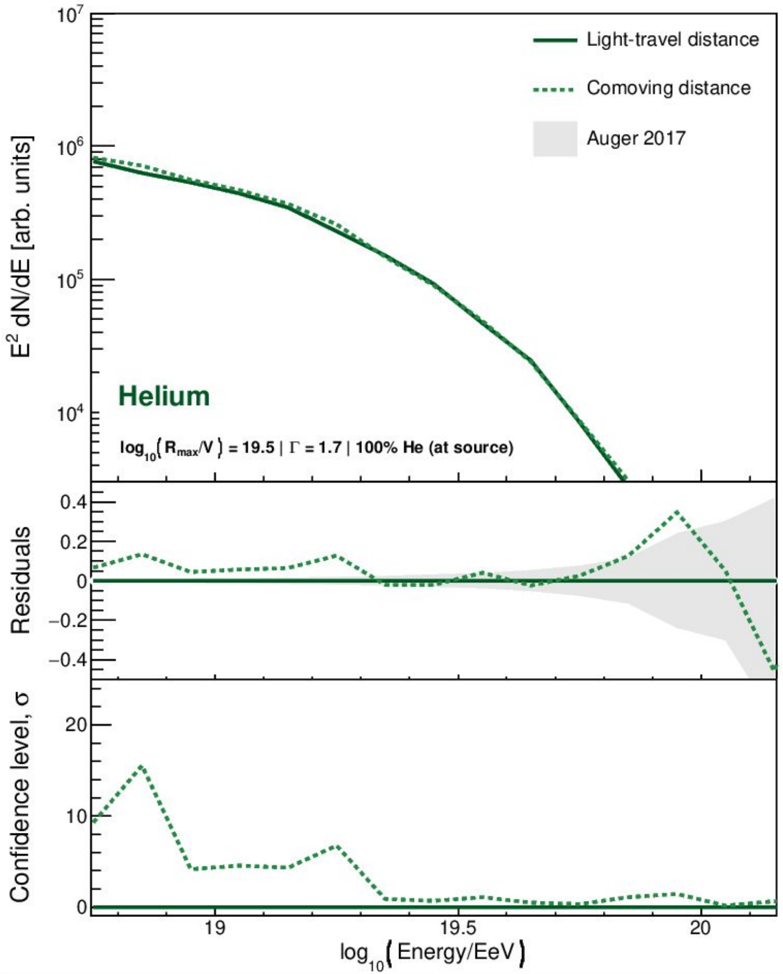

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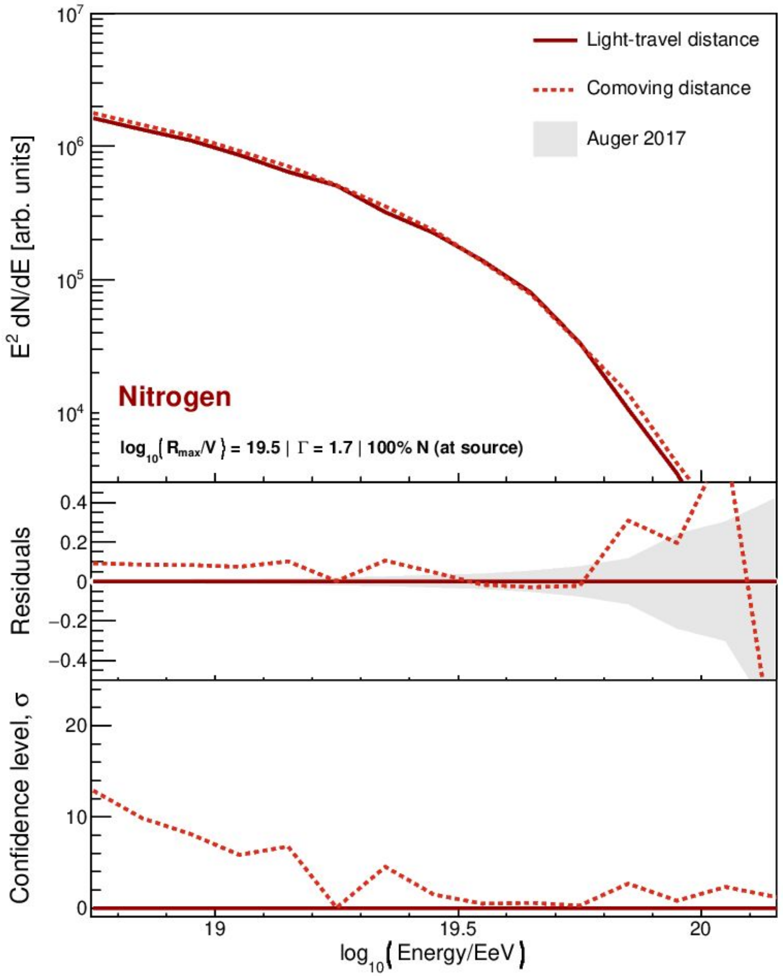

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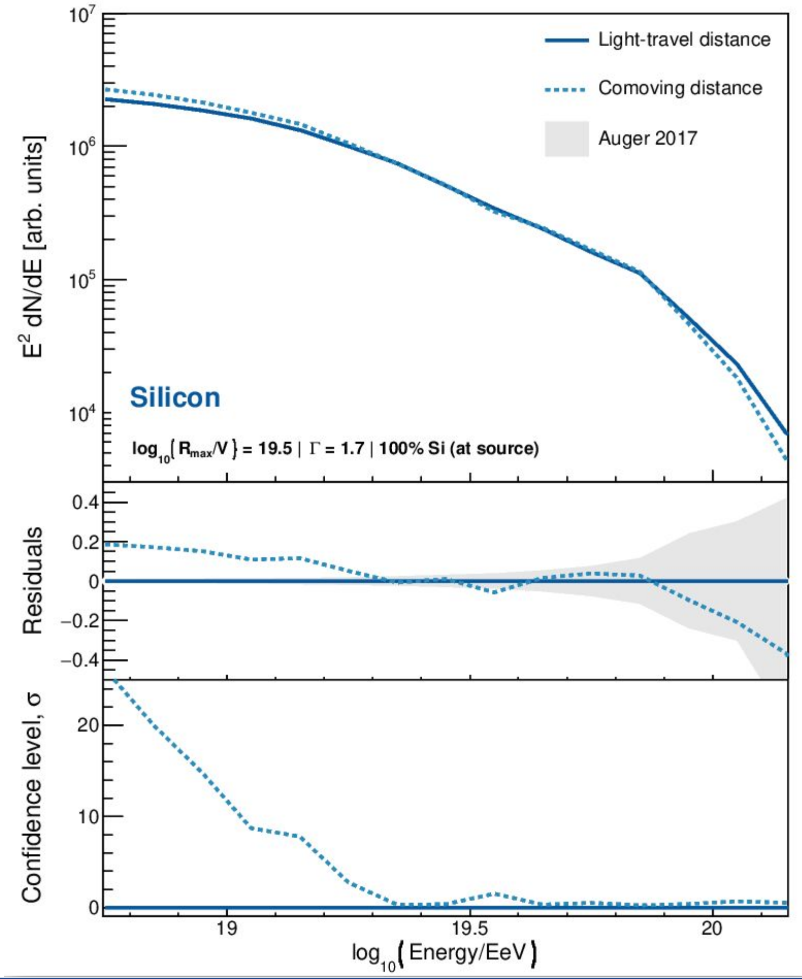

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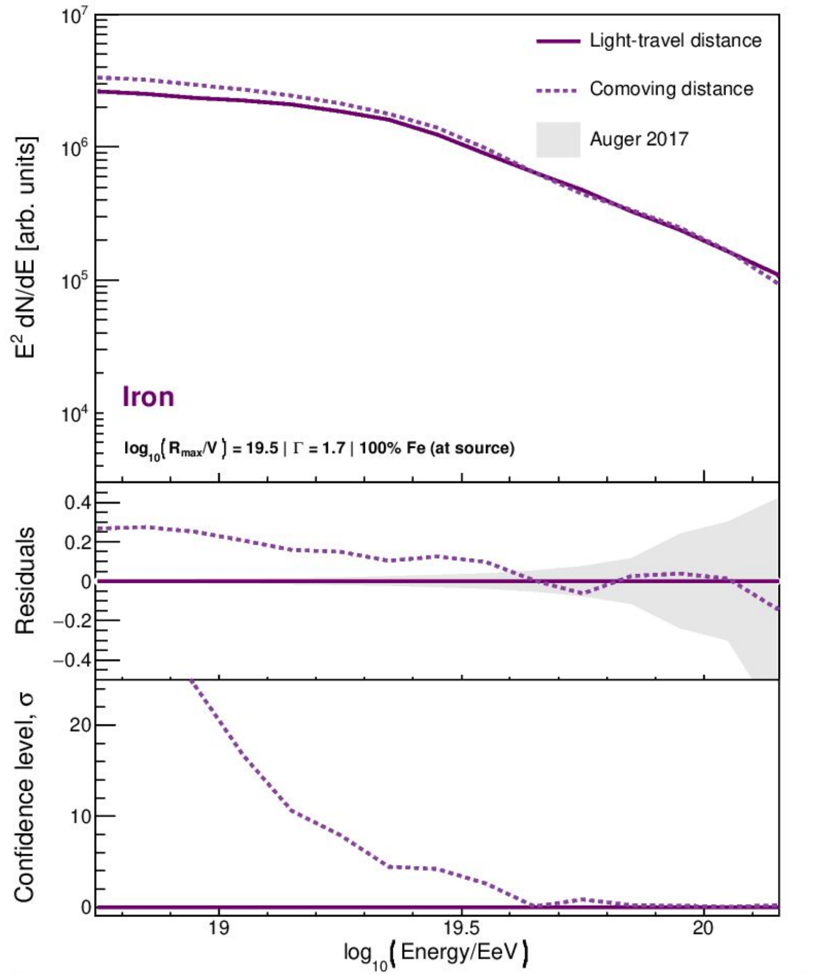

Propagation

-Losses

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Source distribution

Sources

-Energy

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-Evolution

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Propagation

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-EBL models

- Effects similar to those of the source evolution with redshift;
- Why does the option *withCosmology=true* uses a uniform distribution in light-travel distance and *withCosmology=false* uses a uniform distribution in comoving distance?

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Si

Fe

Energy losses

- Propagating UHECR lose energy via:
  - Adiabatic losses;
  - Pair production;
  - Pion production;
  - Photodisintegration;
- Each interaction is dominant for each particle mass and energy.

p
He
N
Si
Fe

Sources

-Energy

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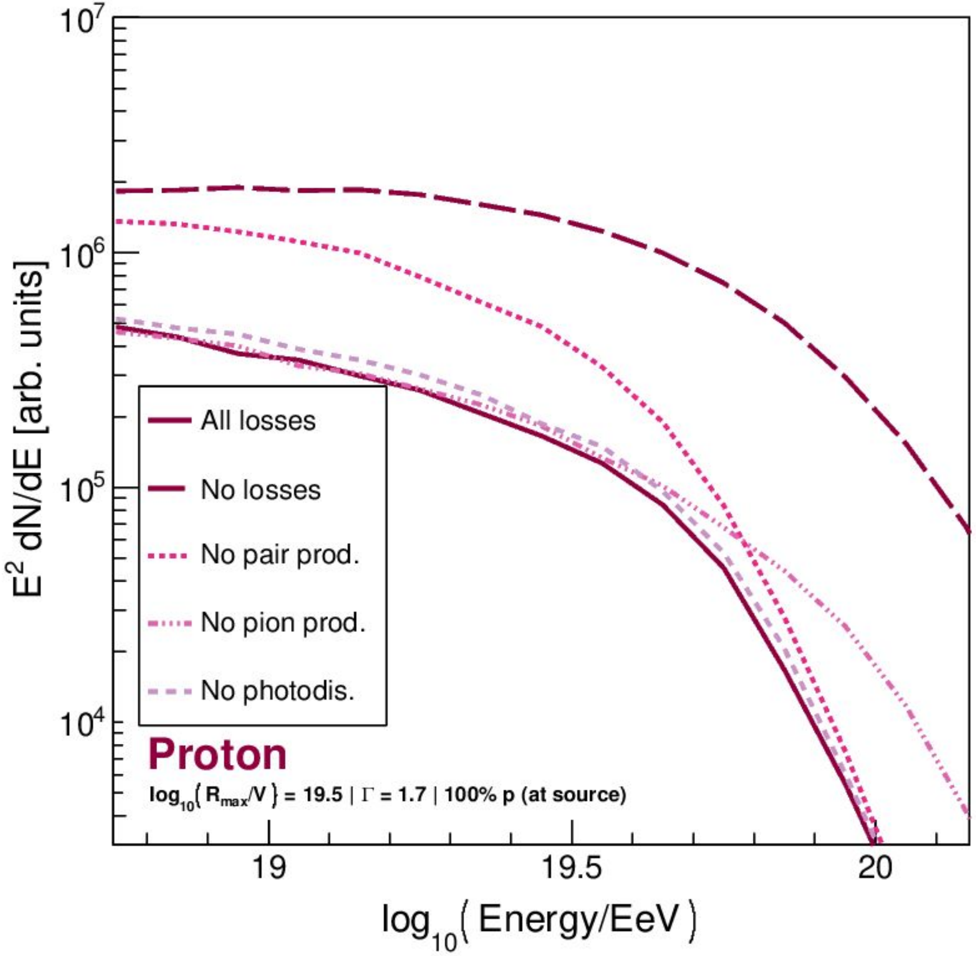

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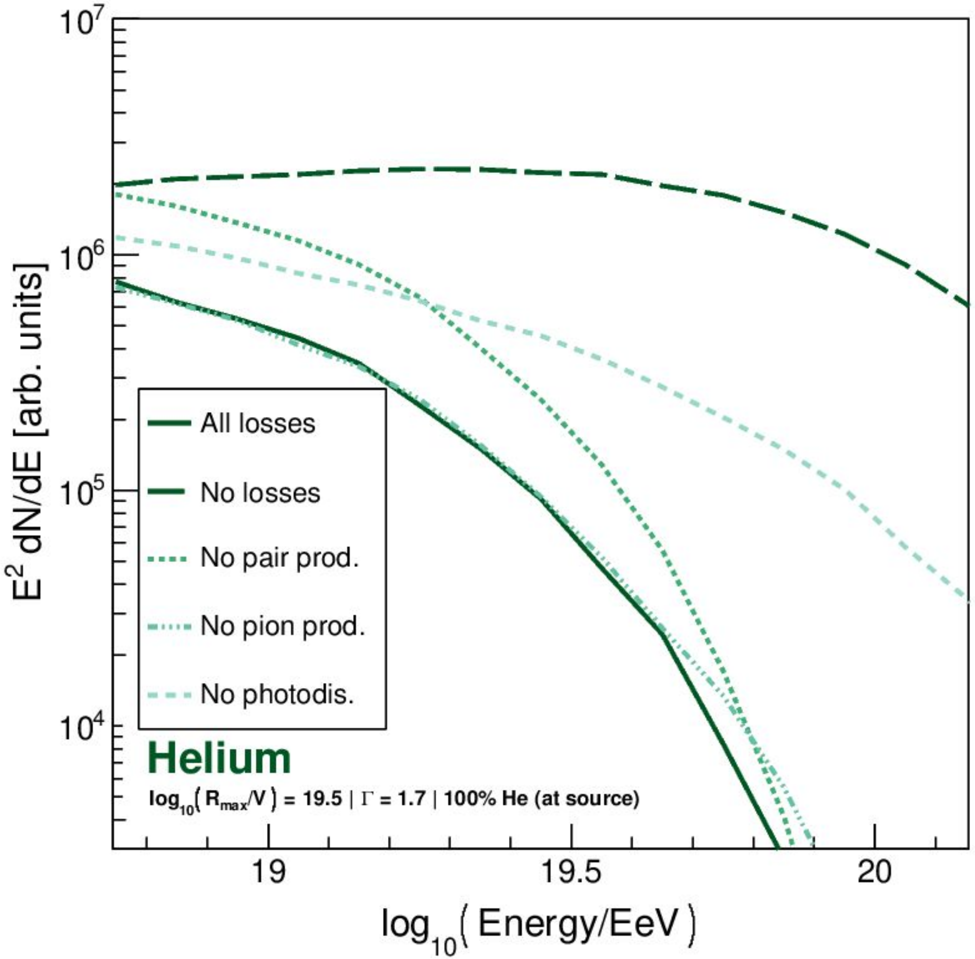

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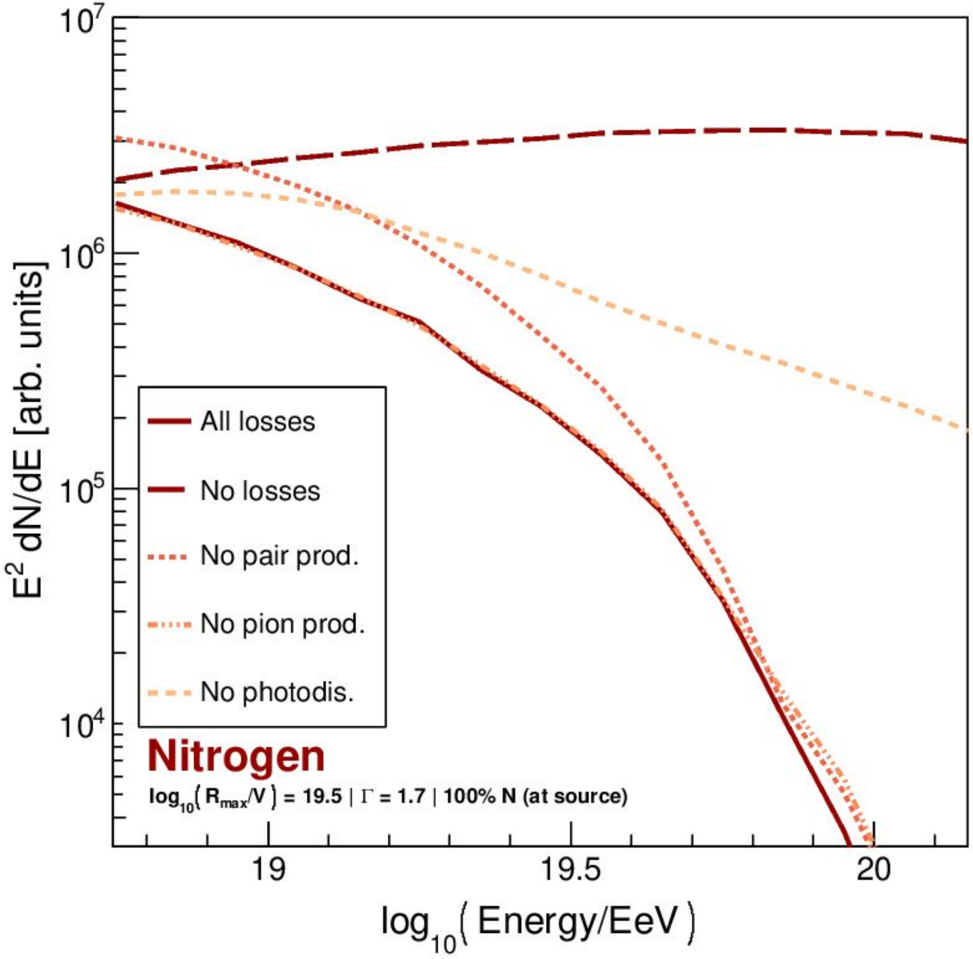

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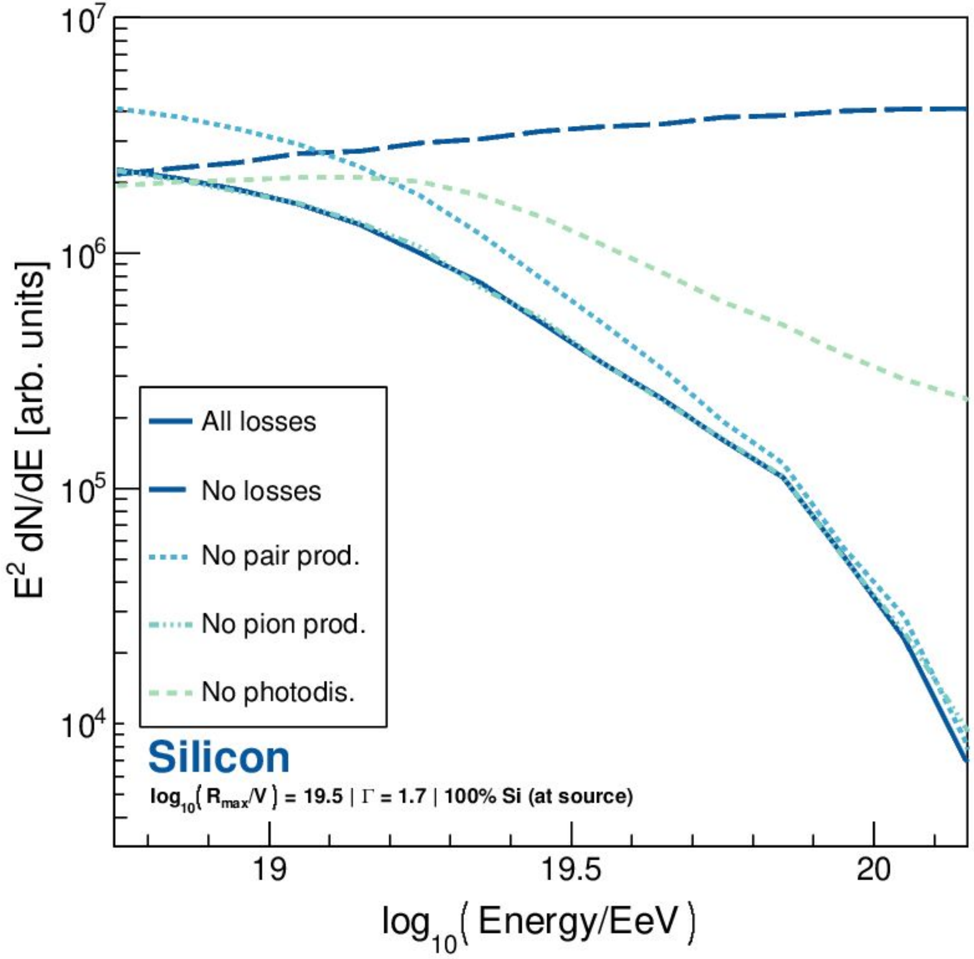

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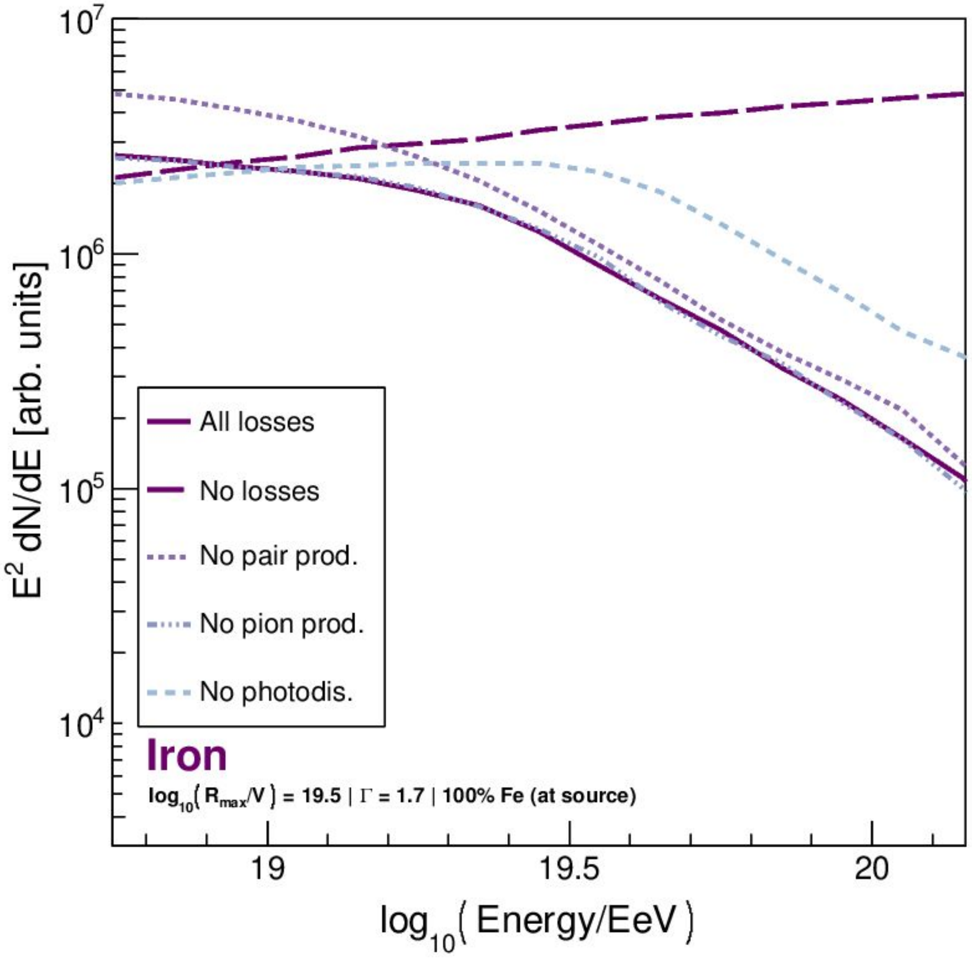

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Adiabatic losses

- Propagating UHECR lose energy adiabatically due to the expansion of the universe;
- In CRPropa3, there are two options for this energy loss: *Redshift()* and *FutureRedshift()*;
- The effect of using or not the option *SourceRedshift1D()* is also tested;

Sources

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Propagation

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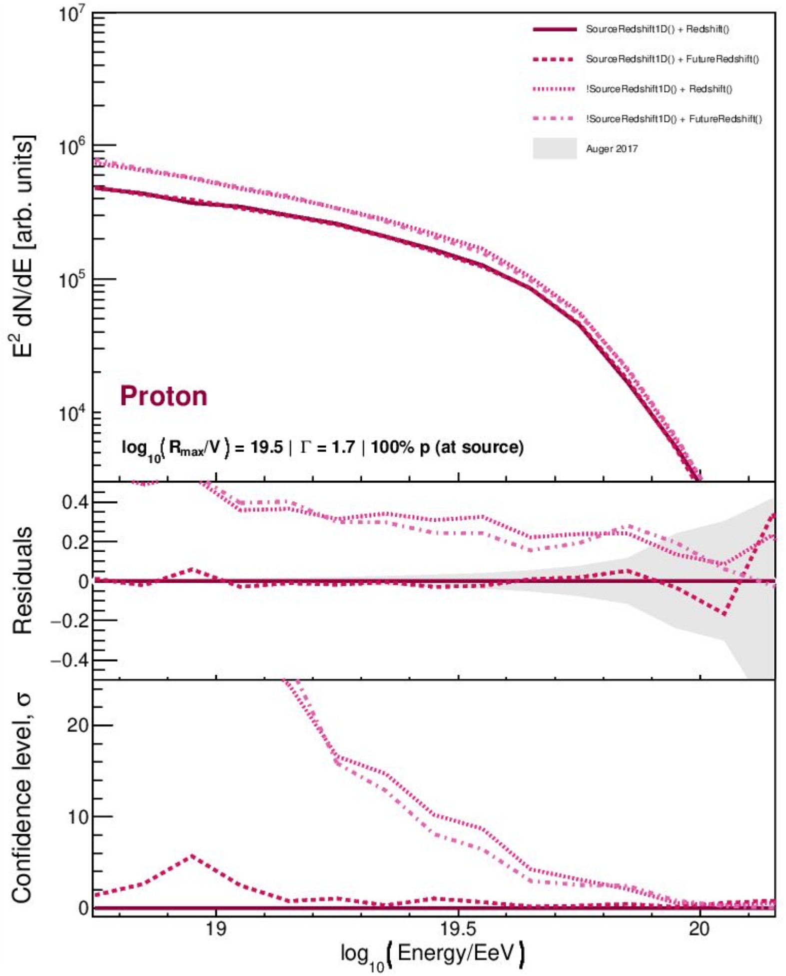

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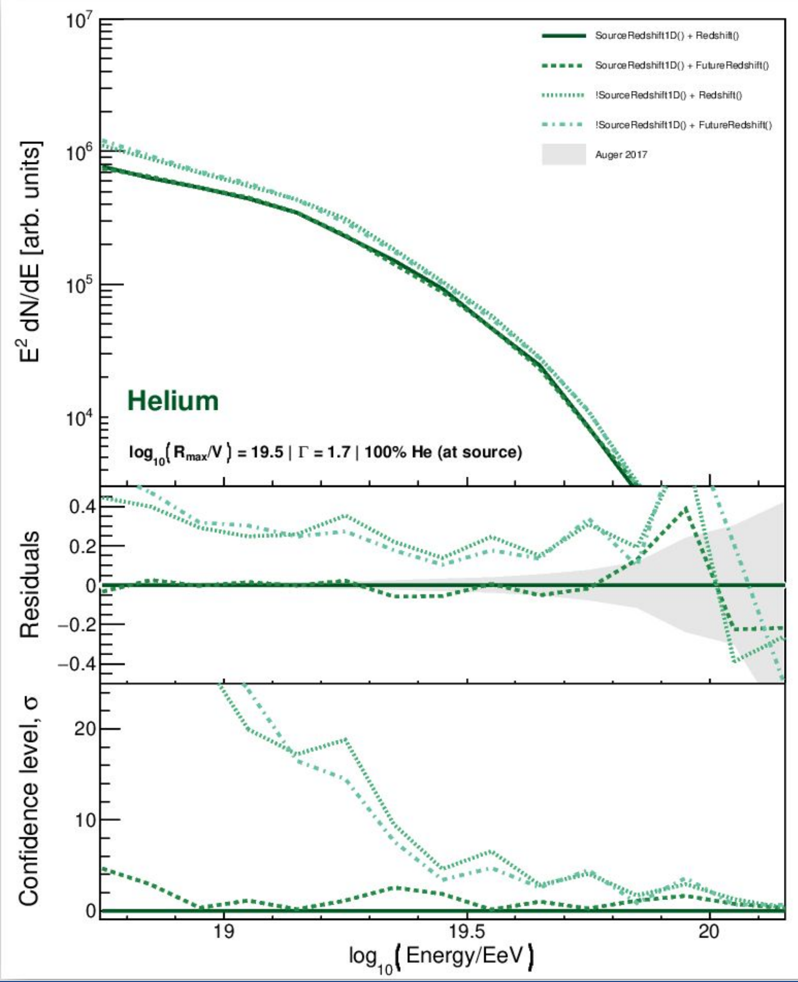

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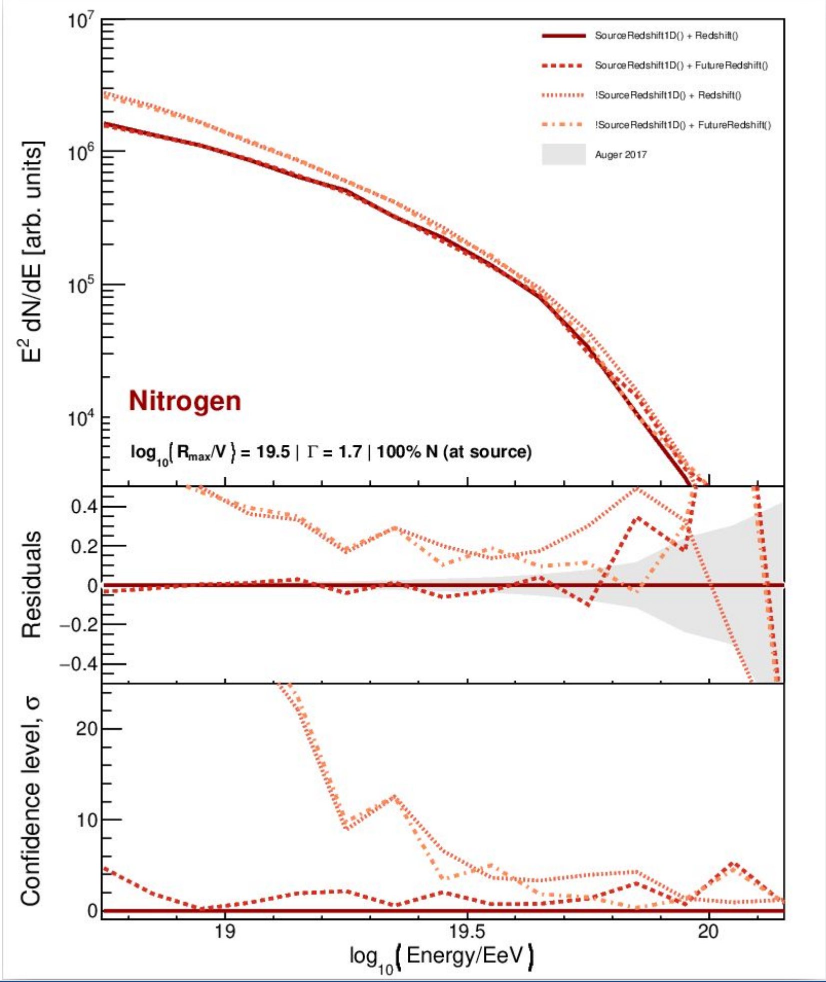

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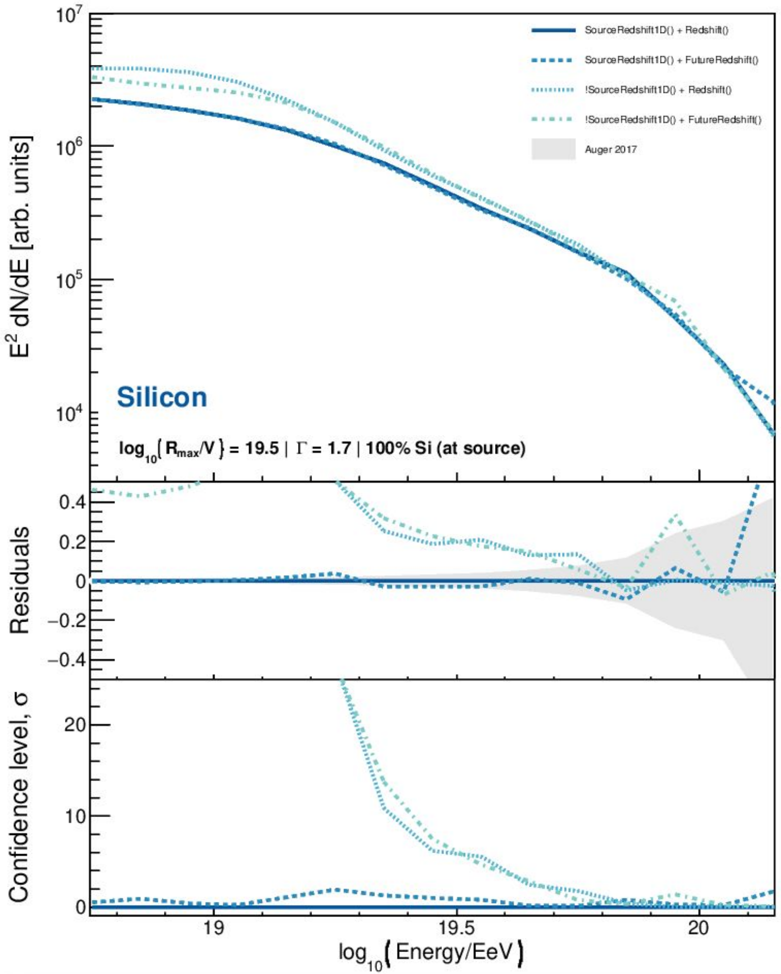

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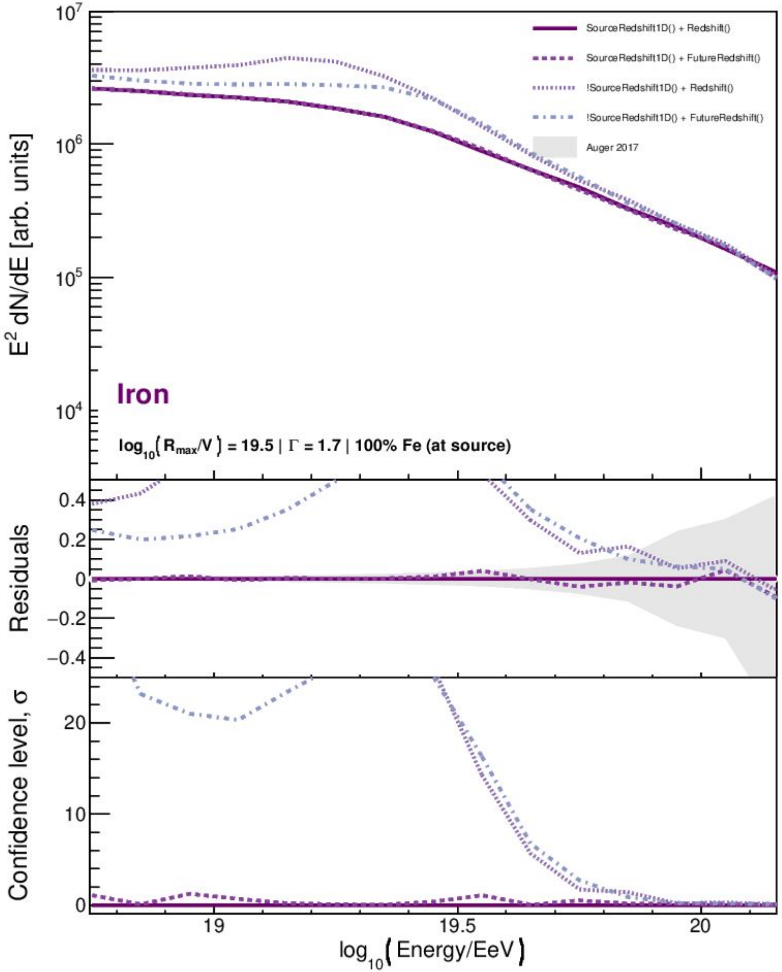

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Adiabatic losses

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- *SourceRedshift1D()* **must be used** not only to obtain the right adiabatic losses, but most importantly to get the right EBL evolution;
- If *SourceRedshift1D()* is used, *Redshift()* and *FutureRedshift()* produce identical results;
- Not using *SourceRedshift1D()* and using *FutureRedshift()* results in a non-sense behavior - there is a sharp energy loss above a given distance;

p

He

N

Si

Fe

Pair production

Sources

-Energy

-Distance

-Evolution

-Distribution

- Propagating UHECR interact with the photon background producing pairs;
- Photon background = {CMB, CMB+EBL}

Propagation

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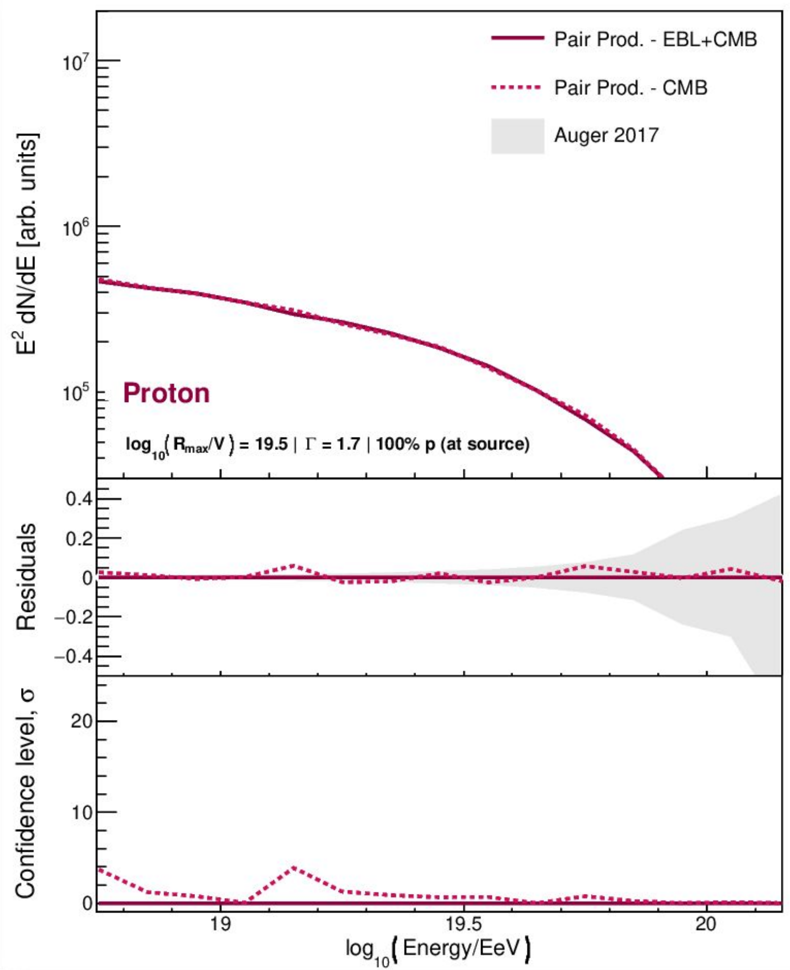

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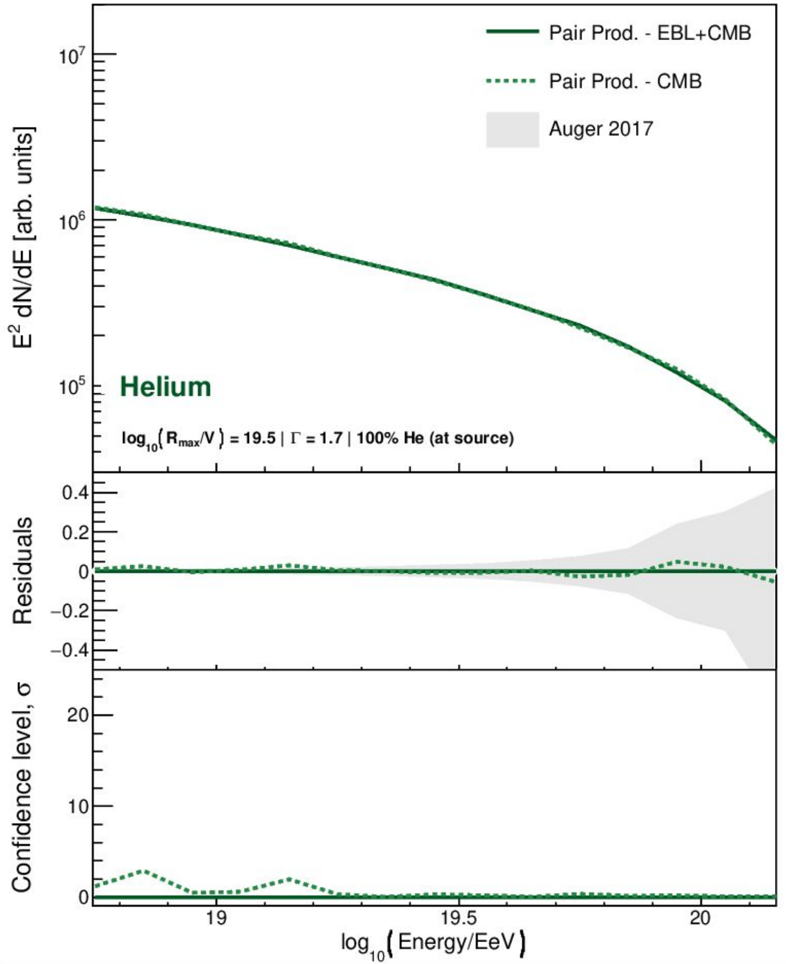

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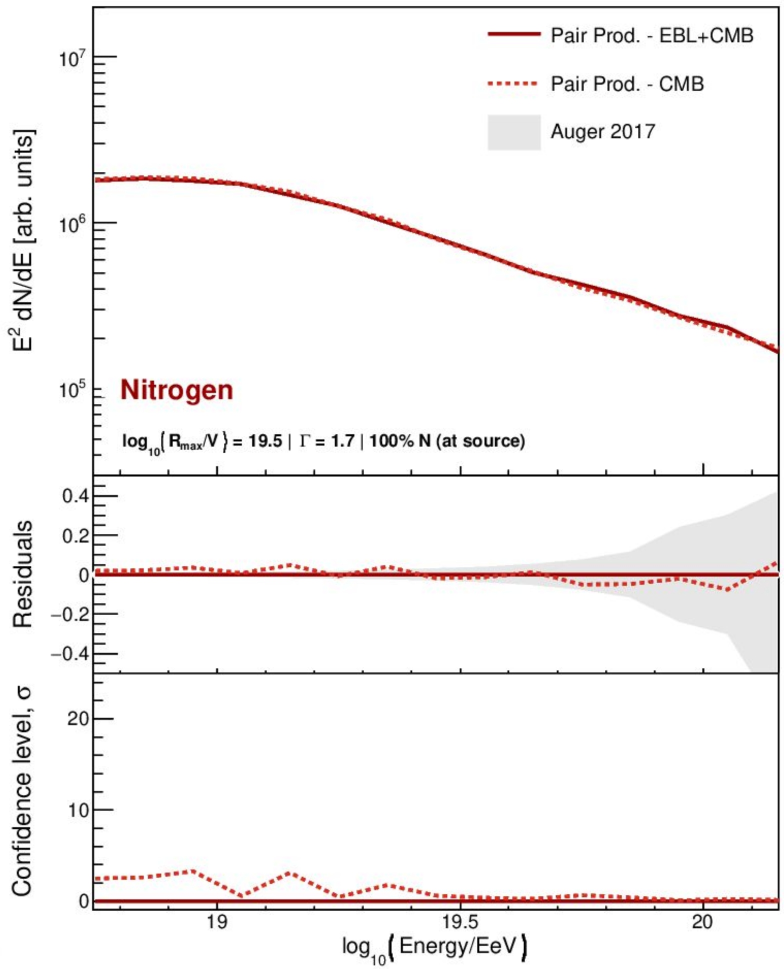

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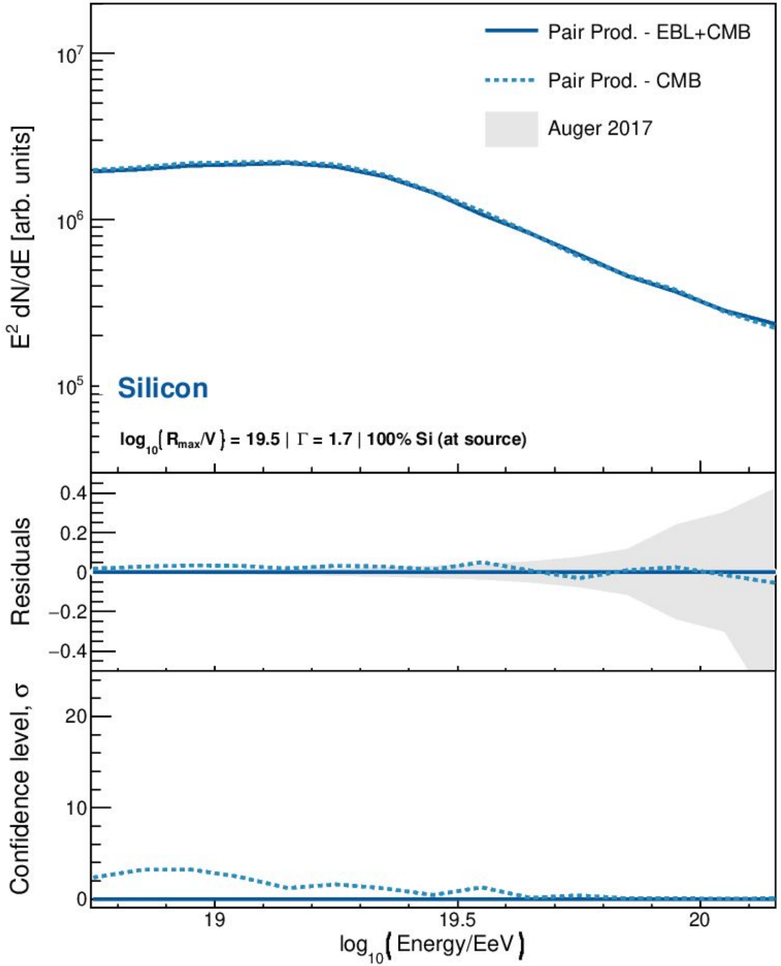

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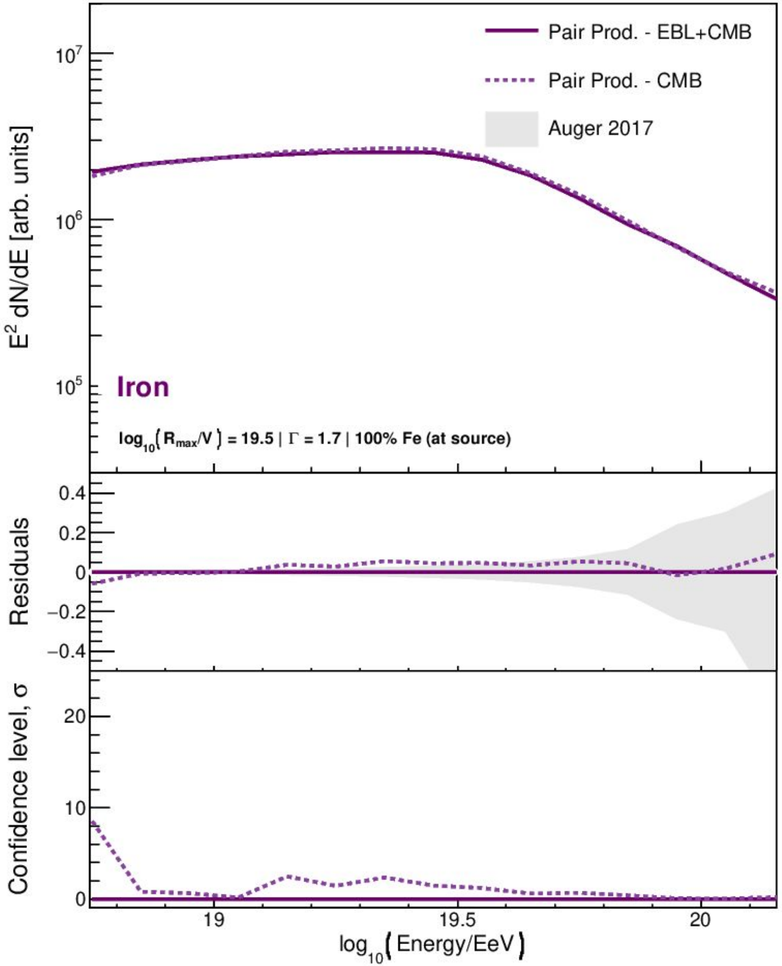
-Losses

-Adiabatic

-Pair prod.

-Pion prod.

-EBL models



p

He

N

Si

Fe

Pair production

Sources

-Energy

-Distance

-Evolution

-Distribution

Propagation

-Losses

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-Pair prod.

-Pion prod.

-EBL models

- Small but non-negligible effects are found by no using the EBL;
- The effects are stronger for a pure iron composition;

p

He

N

Si

Fe

Pion production

Sources

-Energy

-Distance

-Evolution

-Distribution

- Photon background = {CMB, CMB+EBL};
- CRPropa 3 has the option *haveRedshiftDependence* for the pion production;

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Propagation

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-EBL models

Sources

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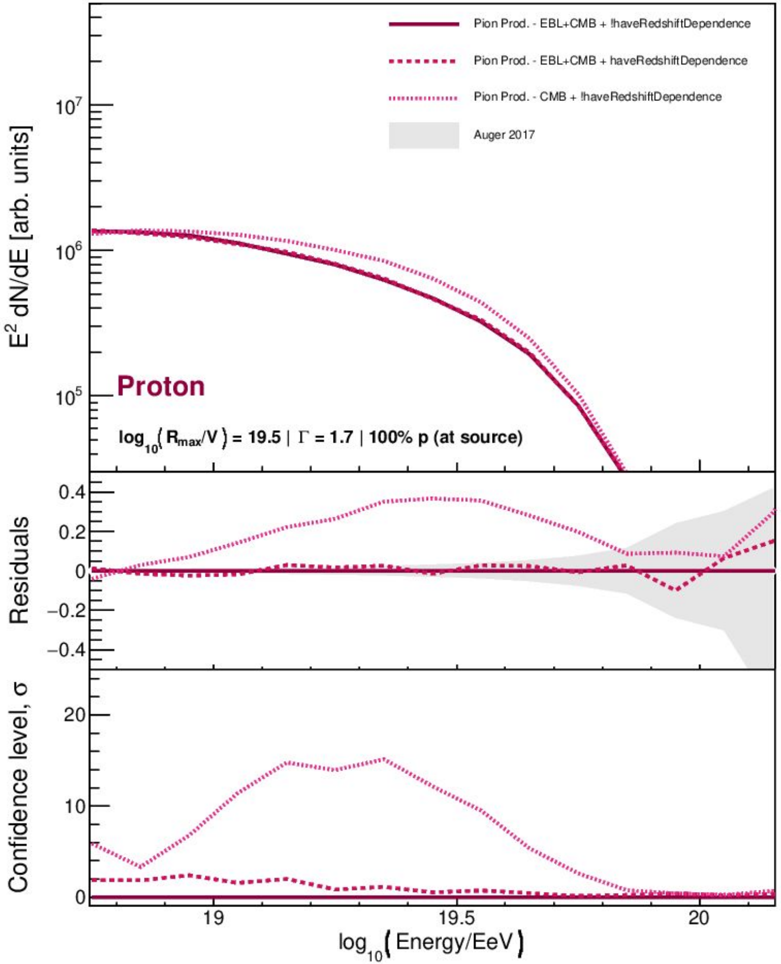
-Evolution

-Distribution



Propagation

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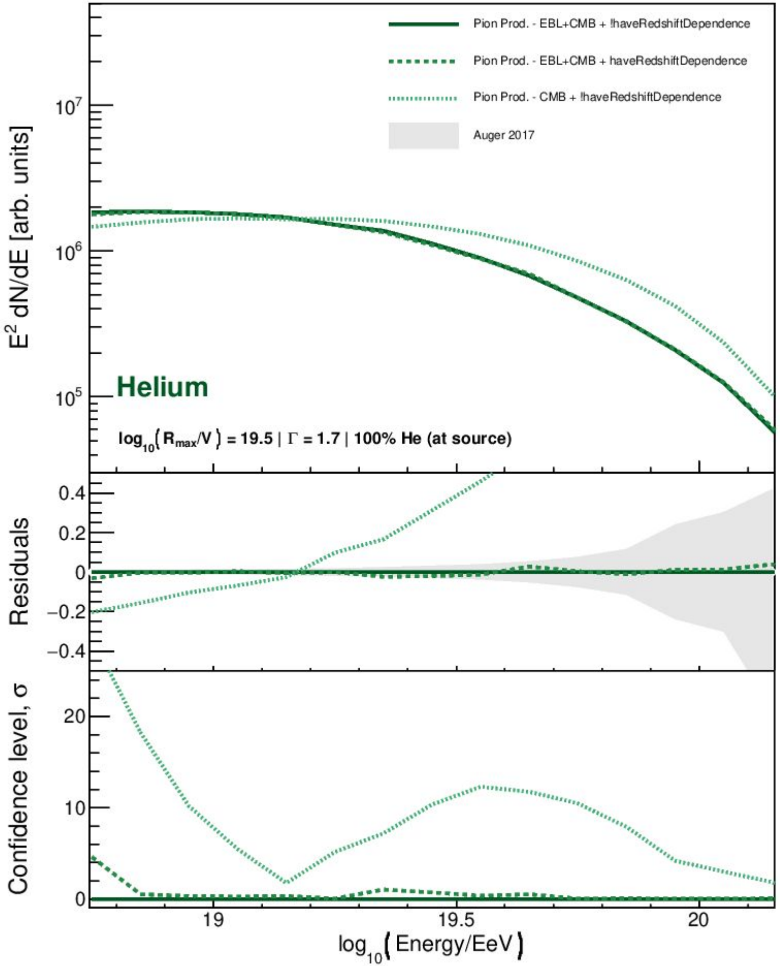

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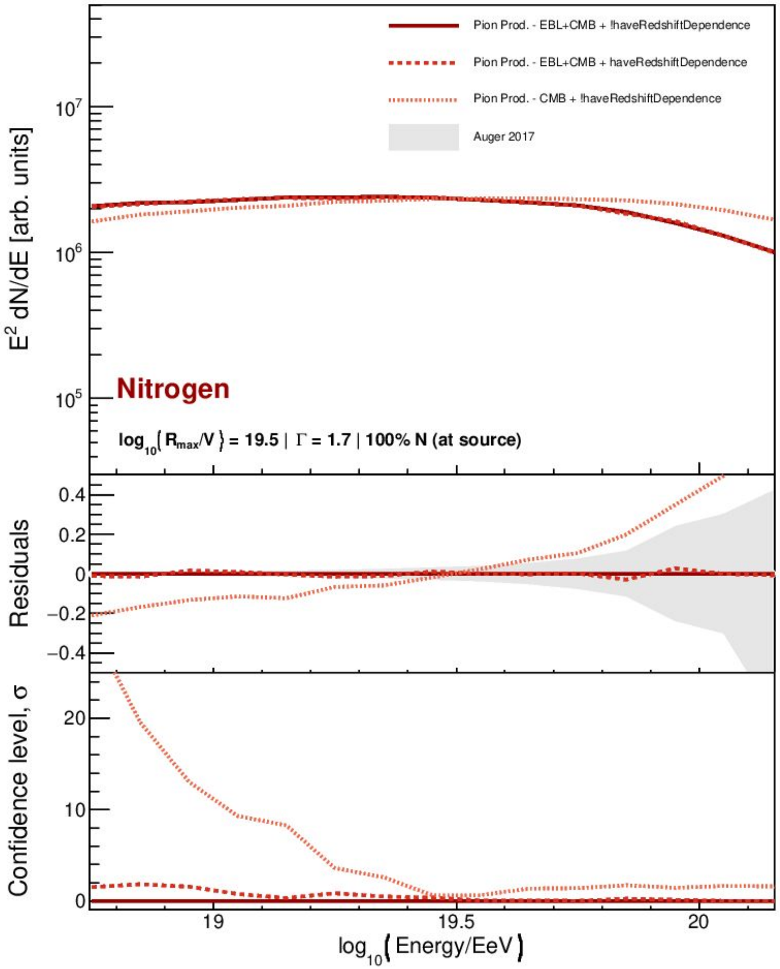

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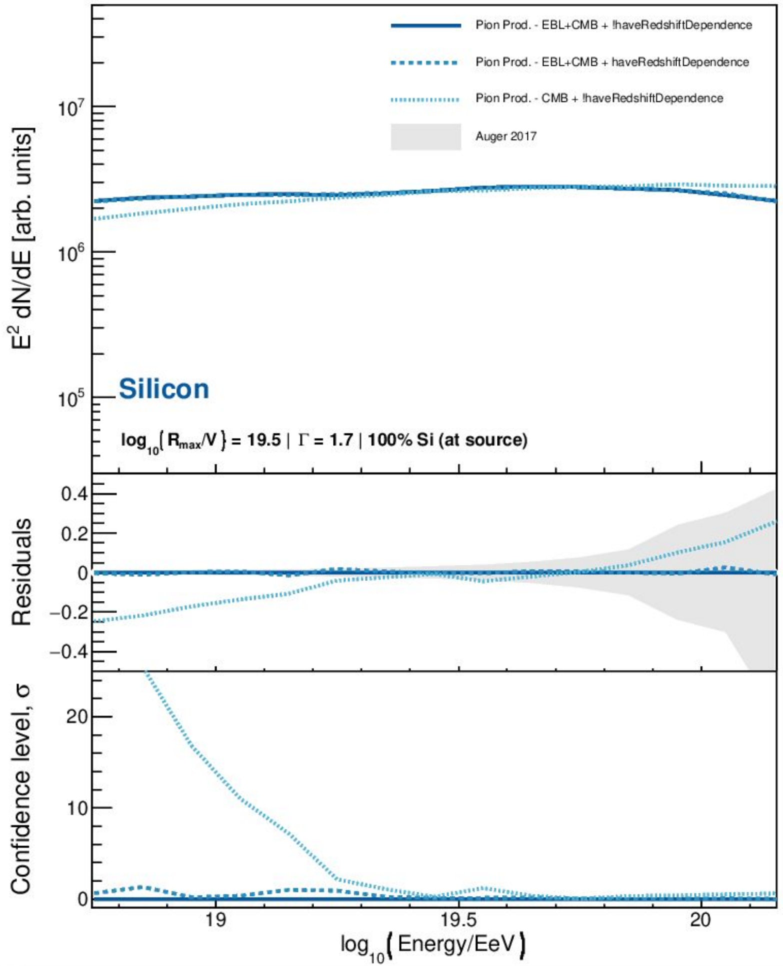

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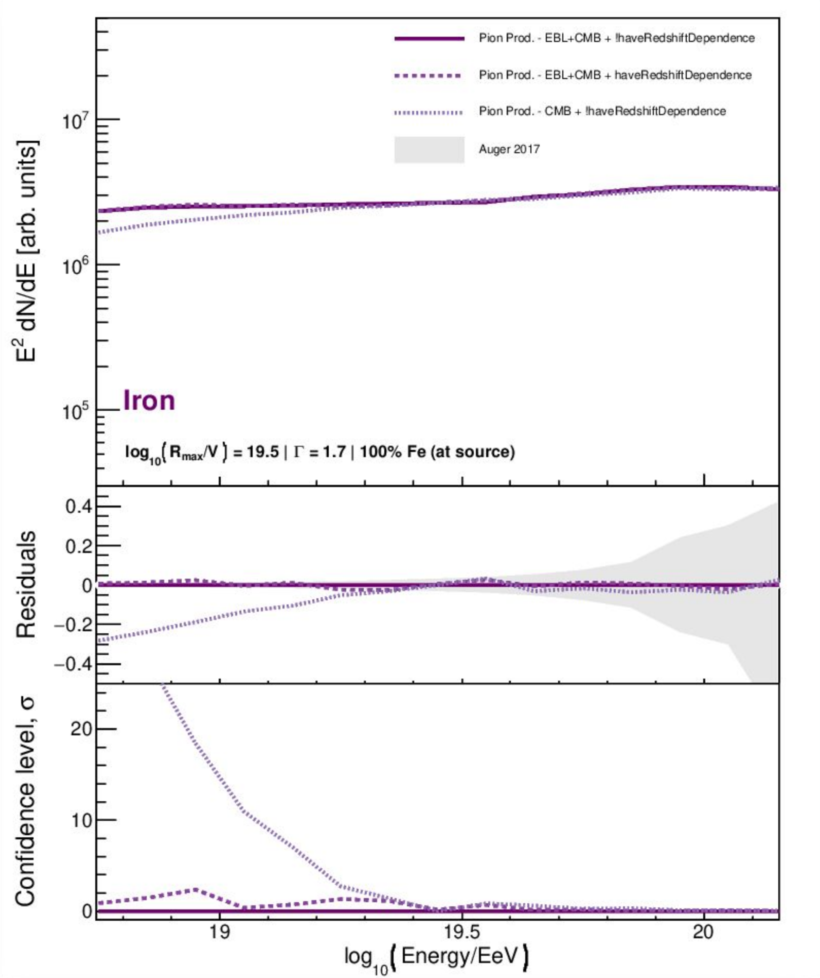

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Pion production

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Fe

- Not considering the EBL has a much stronger effect than in the pair production;
- The *haveRedshiftDependence* option has a smaller effect but not completely non-negligible;
- Why isn't the default

  haveRedshiftDependence = true??

EBL models

Sources

-Energy

-Distance

-Evolution

-Distribution

Propagation

-Losses

-Adiabatic

-Pair prod.

-Pion prod.

-EBL models

- There are a lot of uncertainties on the description of the EBL distribution;
- There are several competitive models;
- Models = {Kneiske08 (default), Stecker16_lower, Stecker16_upper}

p

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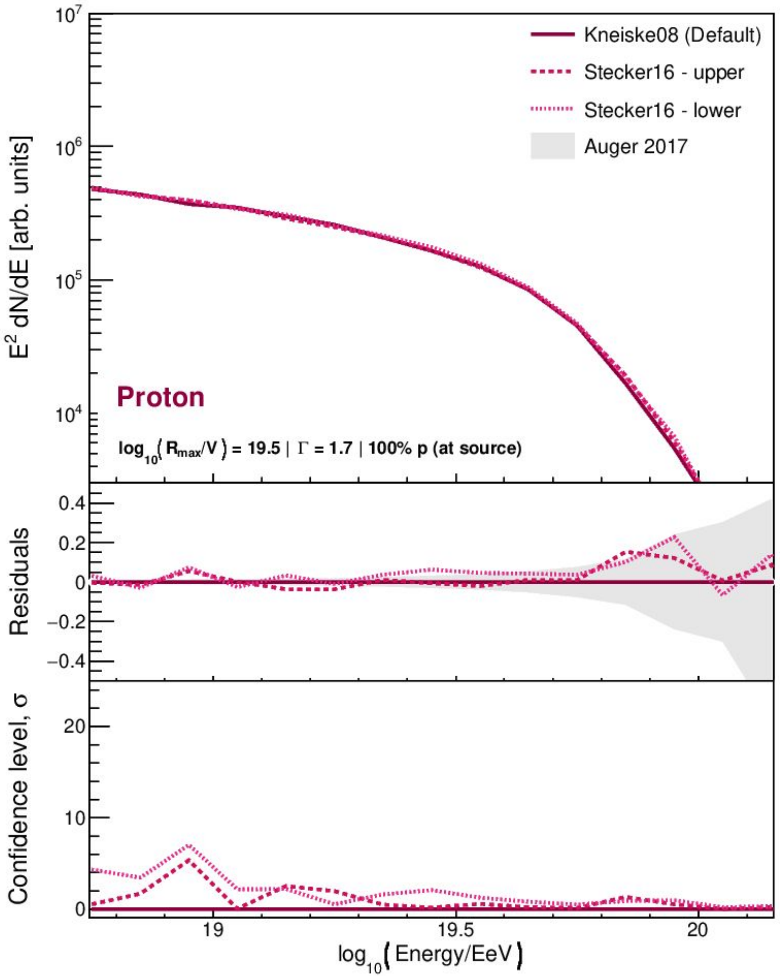

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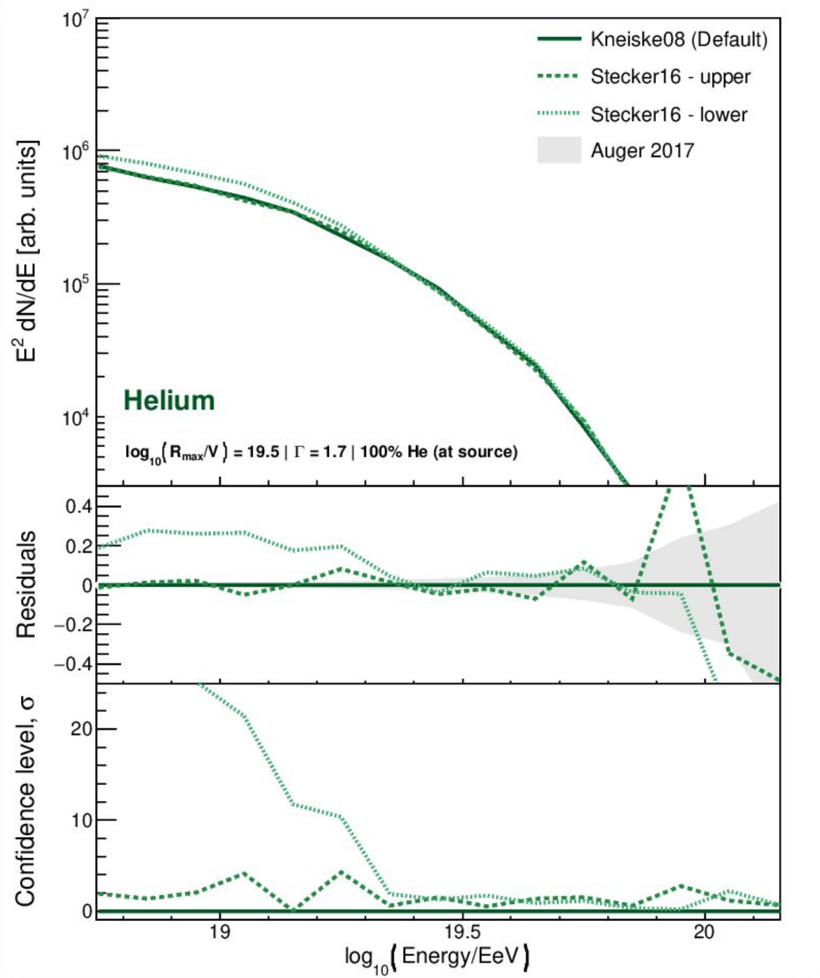

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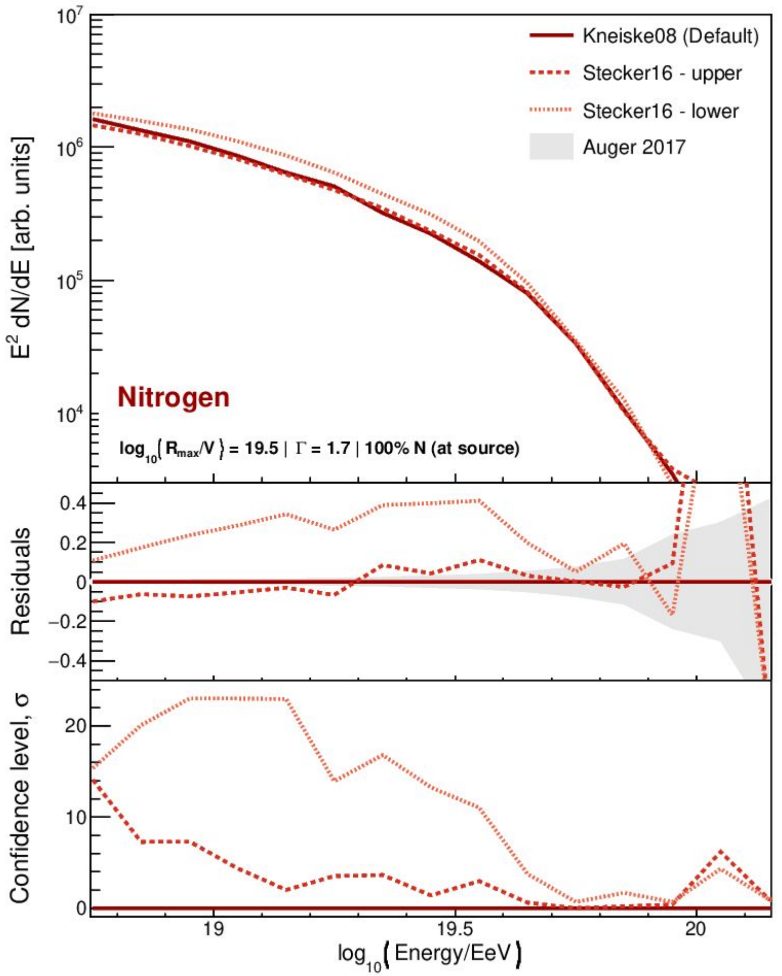

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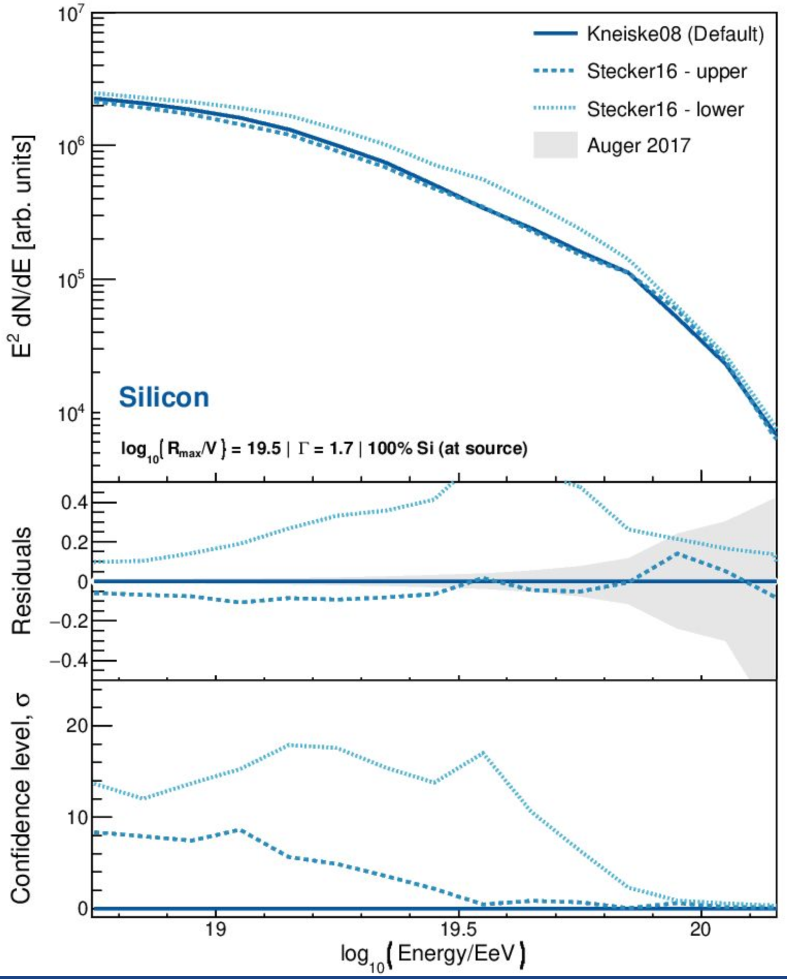

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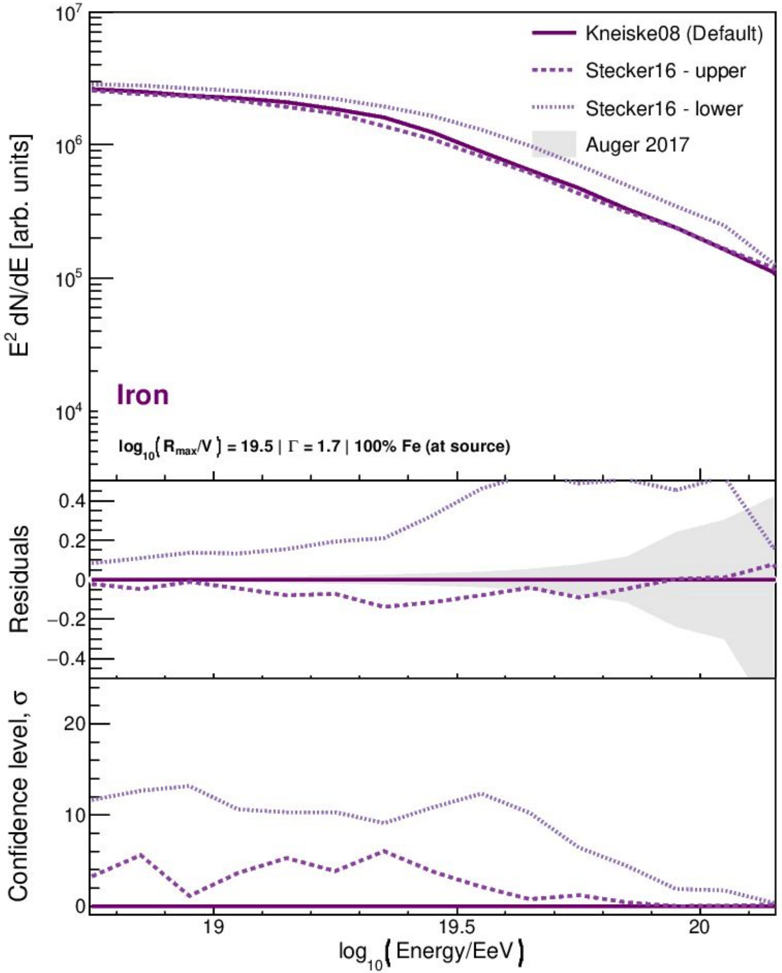

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EBL models

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-EBL models

- Different EBL models introduce huge differences in the spectrum up to the highest energies;
- It is very important to address this systematic uncertainty in the analyses.

p

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Si

Fe

Conclusions

- Several hypotheses and approximations need to be made in order to simulate the UHECR spectrum;
- Computational (mostly related to speeding up the simulation): it is important to be sure that there is no effect in the analysis;
- Astrophysical: it is very important to understand how to treat them:
    - Let them as fit parameters -> may lead to a huge number of free parameters;
    - Set a value -> need to understand what is the resulting systematic uncertainty in each analysis.