Study of the origins of ultra high energy cosmic rays

Sullivan Marafico
sullivan.marafico@u-psud.fr

Supervisors: Olivier Deligny, Jonathan Biteau

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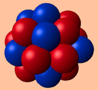
What are Ultra High Energy Cosmic Rays (UHECR) ?

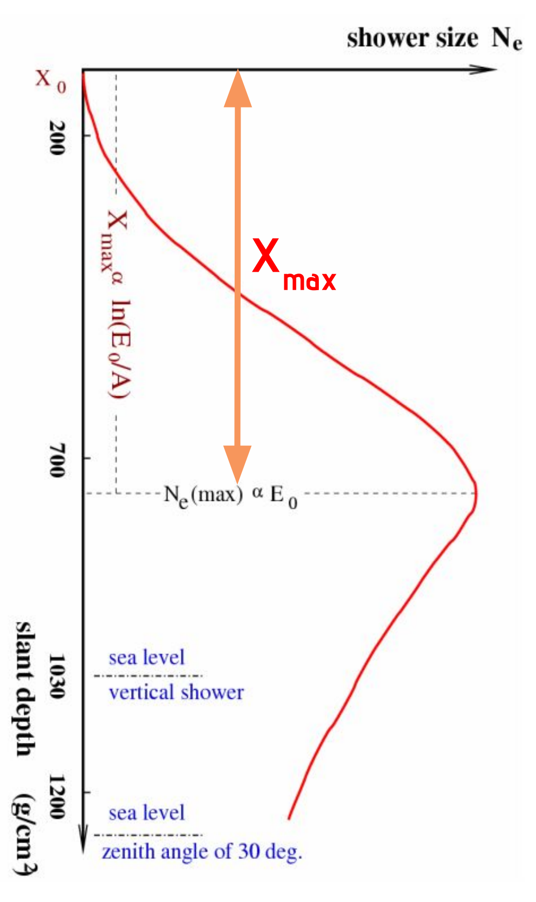
UHECR are nuclei which are accelerated up to 10^{21} eV.
(>10^{18} eV)

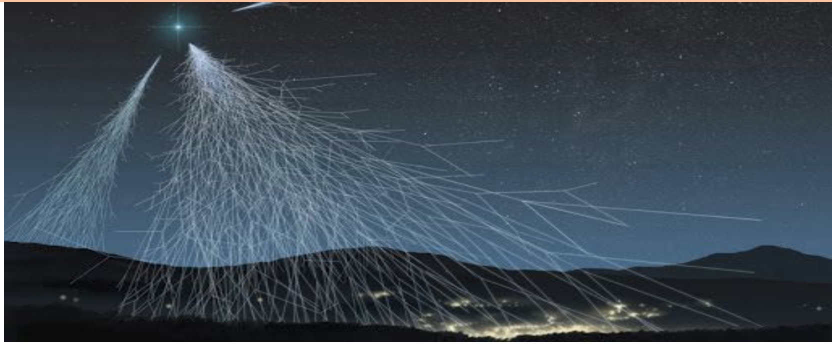


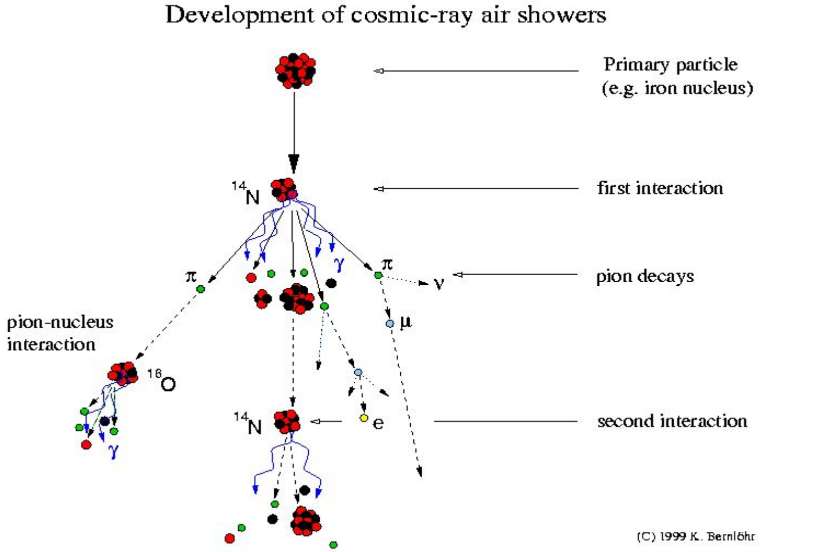
Nuclei reaches the earth

↓

Hadronic shower







Three main observables:

⟶ Arrival directions
⟶ Energy
⟶ X_{max}, Depth of maximum shower (characteristic length of the shower, linked to the mass)

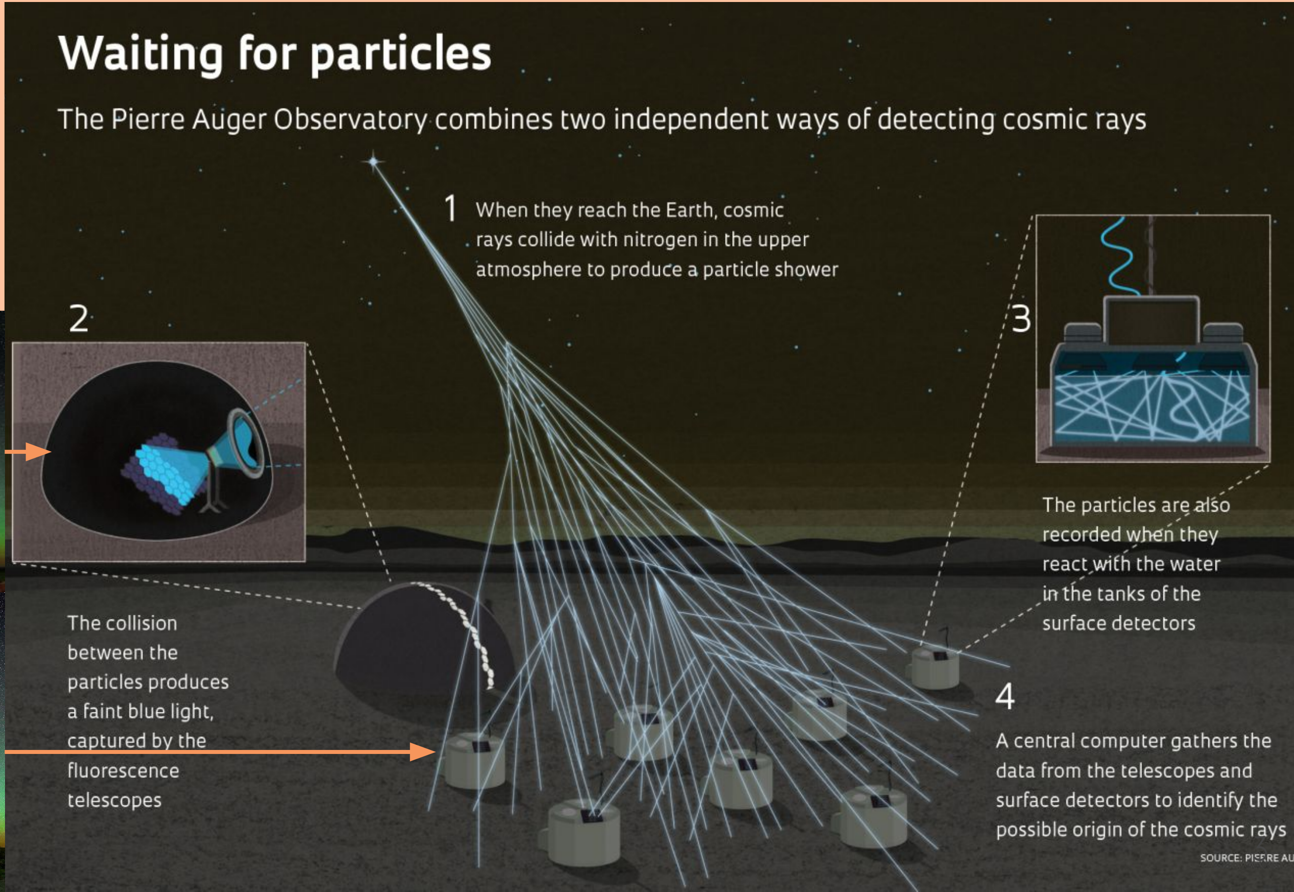
The Pierre Auger Observatory

Two detectors:

3 000 km^2, 30 times Paris

→ Telescopes measures X_{max}, energy, arrival directions

→ Surface detectors measures the energy and the arrival directions



Arrival directions: An extragalactic origin ? (Science 2017)

Evidence of extragalactic origins

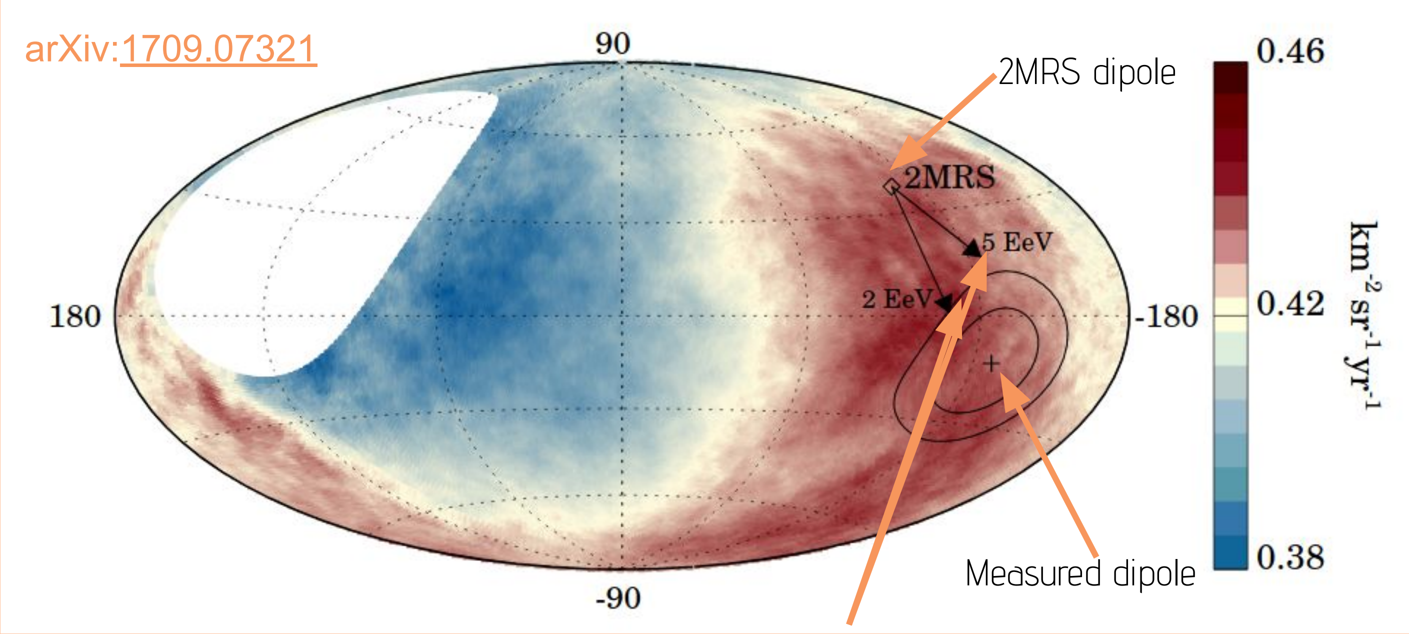
At **E > 8 EeV**, a dipole is observed at more than the **5.2σ** level of significance.

The cosmic ray dipole points **55° away** from the 2MRS dipole

Definition rigidity:
R = E/Z

with
E, the energy
Z, the charge

Measured flux for events above 8 EeV, galactic coordinates



Galactic magnetic field effect for
R = 2 EV & R = 5 EV

February 2021: Auger Open Data: http://auger.org/opendata/

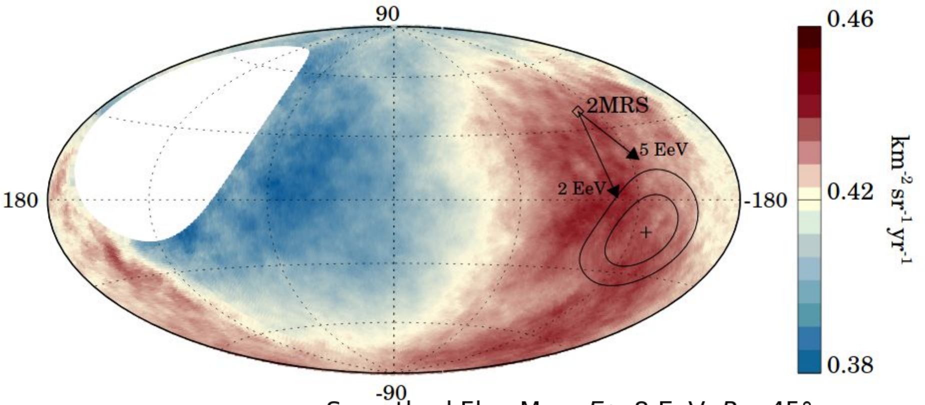
The collaboration decided to release **10%** of the data.

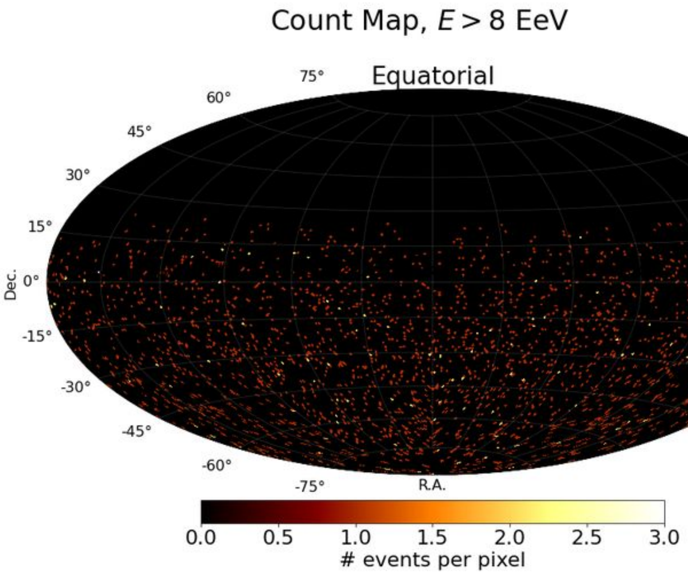
→ Creation of the UHECR Sky notebook (Basically follows Science paper)

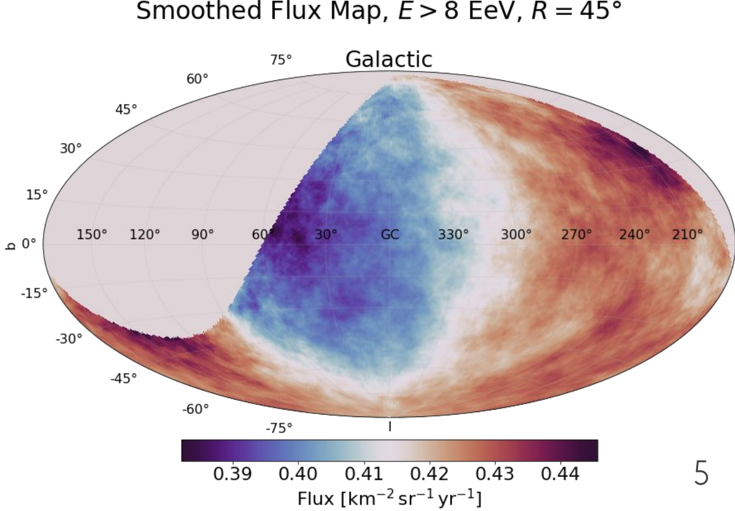
```
# Plot the count map
Emin = 8 # EeV
galCoord = False
dataset = LoadShapedData(galCoord, Emin) # data Emin

nside = 64
count_map = LoadCountMap(dataset, nside)

title=f"Count Map, $E > {Emin}$ EeV"
color_bar_title = "# events per pixel"
PlotHPmap(count_map, nside, galCoord, title, color_bar_title)
```







Xmax: Study the composition

Goal: Get an idea of the composition of observed cosmic rays

Method: For a given range in energy,
Xmax histogram is reconstructed.

Xmax histograms are **fitted using 4 representatives** masses: **H**, **He**, **CNO**, **Fe**

$$g_{tot}(X_{max}) = \sum_A f_A \, g_A(X_{max})$$

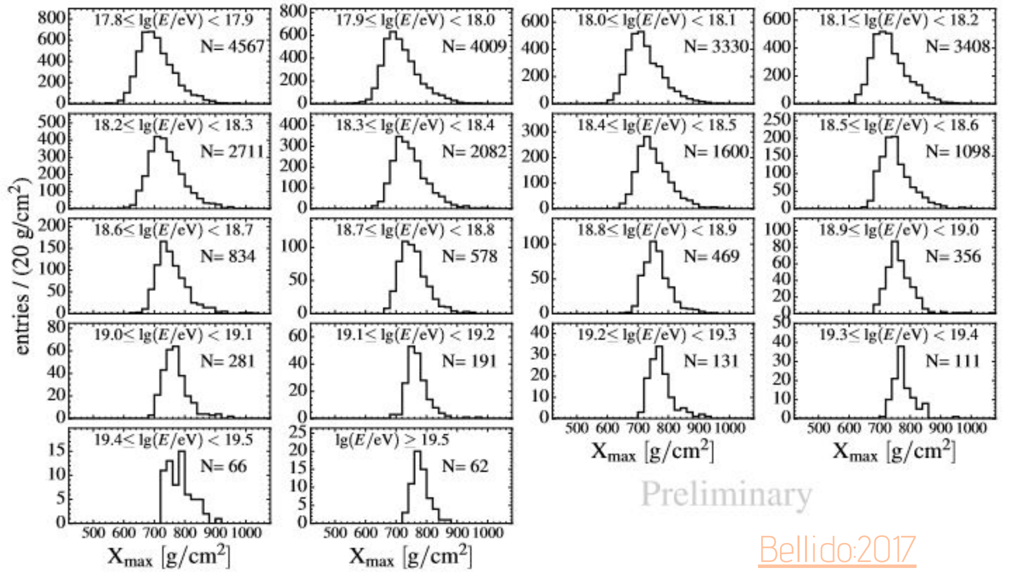
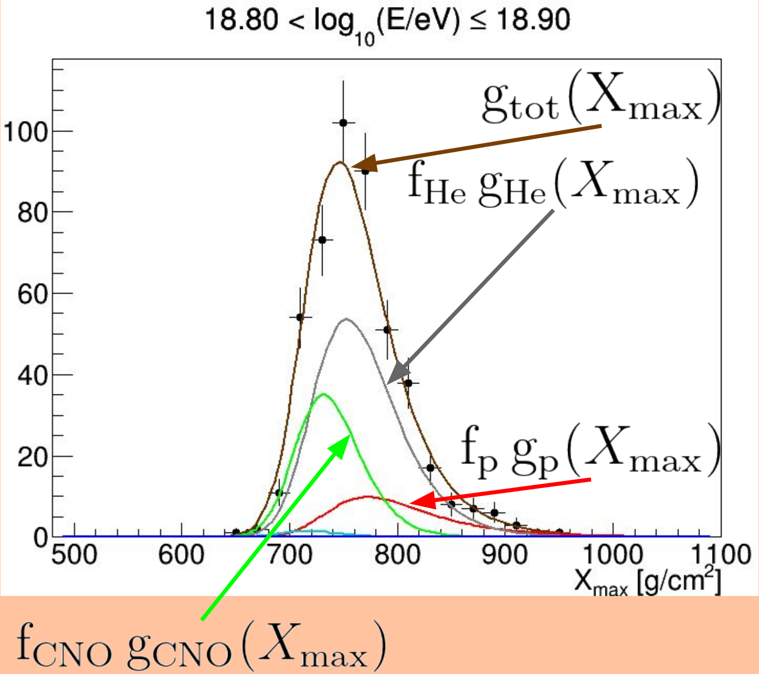
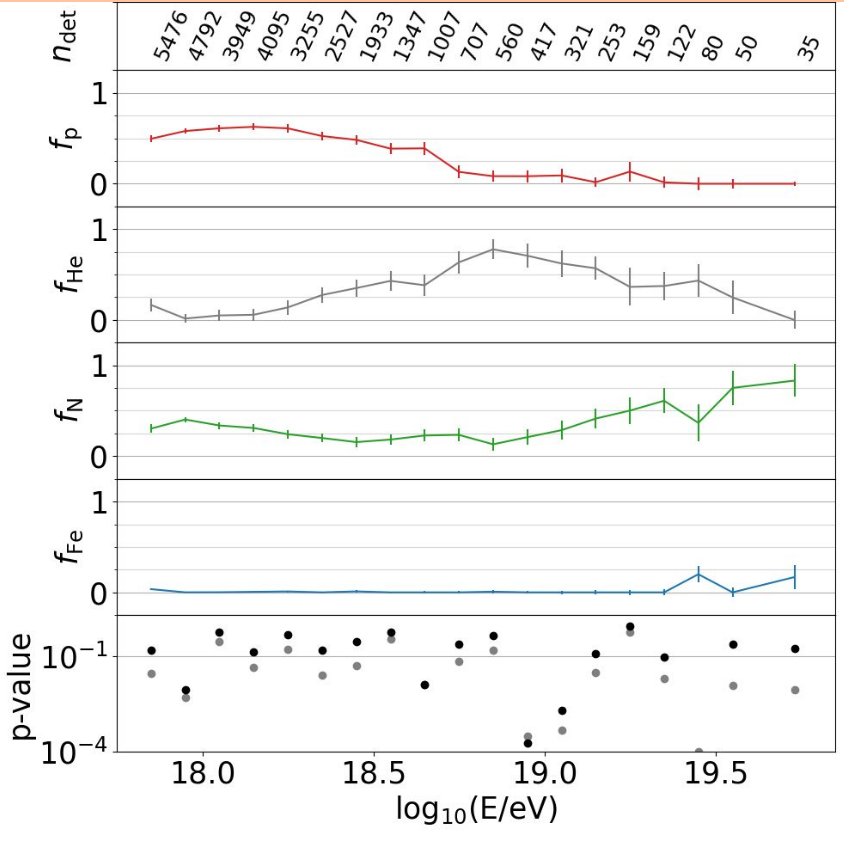


Figure 3: X_{max} distributions for different energy intervals from the HeCo (top) and Standard-FD (bottom) datasets. The number of events in each energy bin is indicated.



Xmax: Study the composition

Results: Scan on all energy bin



Hadronic model:
EPOS-LHC

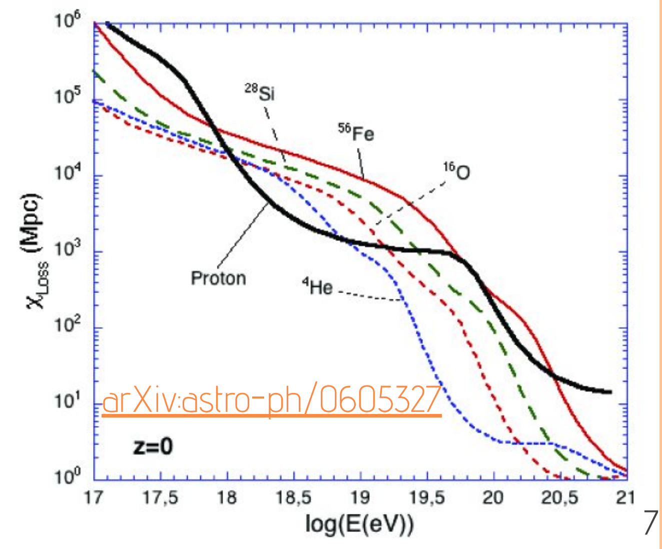
p-value:

→ Black dots: consider empty bins
C-Statistics
arXiv:1912.05444

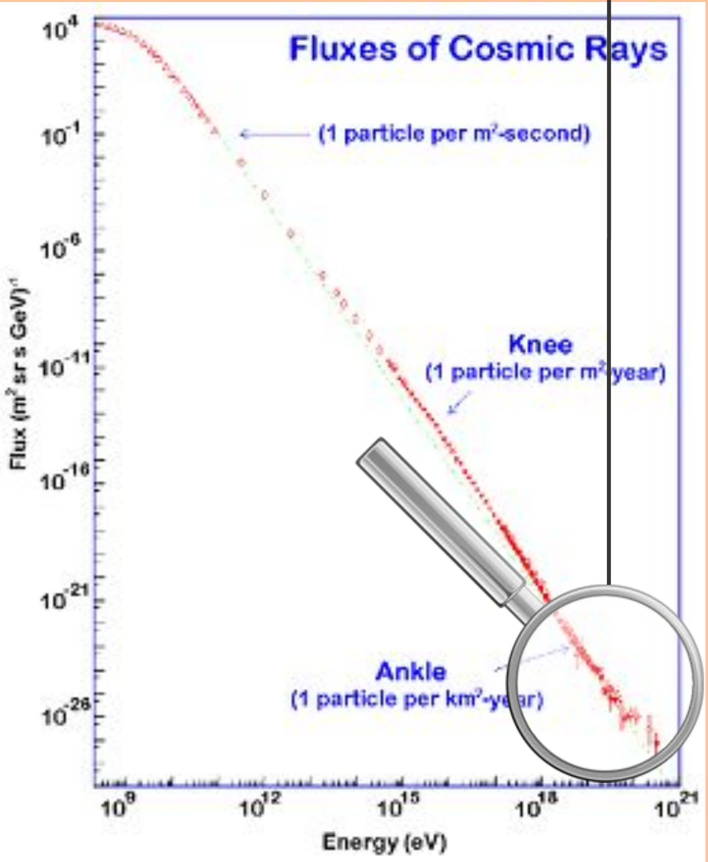
→ Grey dots: Classical χ^2

Reason:
The energy and the composition gives an information about the distance of the sources.

□$_{Loss}$ is the attenuation length



Energy spectrum



Energy spectrum, composition & model

×E^3

Astrophysical model:

Goal: Describe the Xmax data and the energy spectrum with a model.

Combined Fit:

→ Assuming a **1D distribution of sources** of UHECR, S(z).

→ **Inject representative masses** at the sources. (**H**, **He**, **CNO**, **Si**, **Fe**) given a **production rate** q_{gen}.

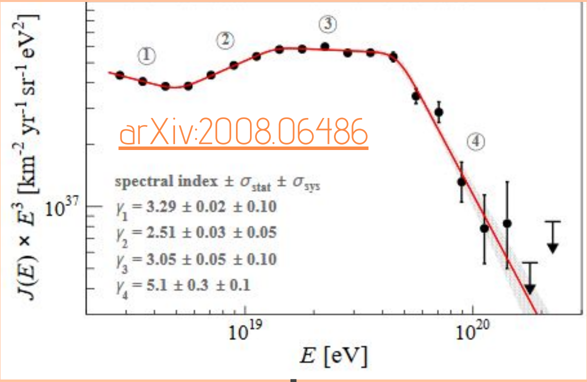
→ **Propagate nuclei** through cosmic microwave and infrared backgrounds

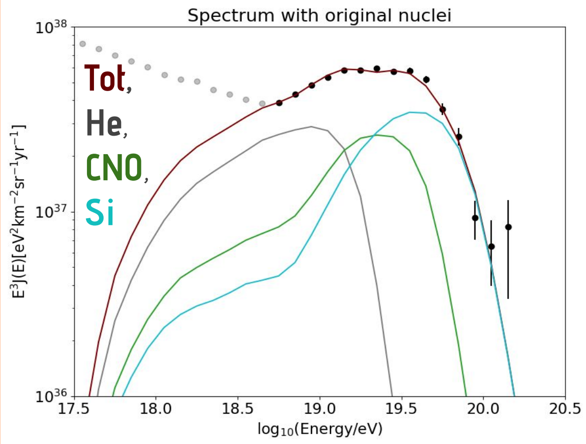
→ **Compare** the propagated nuclei with the spectrum and the Xmax distribution.

Parameters:

→ f_A, fraction of injected elements

→ Two parameters for q_{gen}





Combined Fit: 1D distribution of sources

The Cosmic Star Formation History is given by Madau & Dickinson (2014):

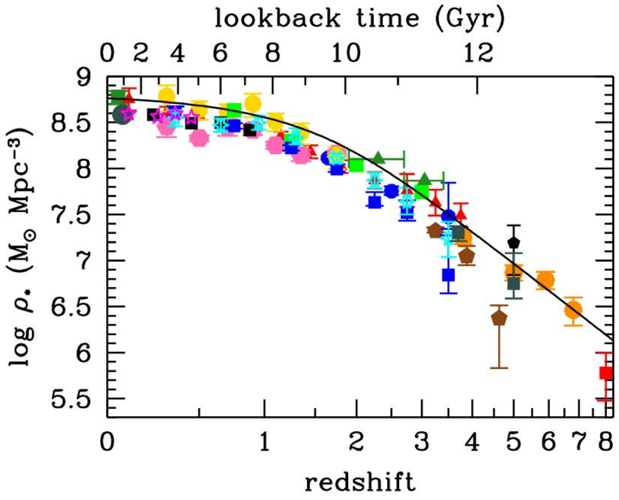
$$\mathrm{CSFH}^{\mathrm{cosmo}}(\mathrm{z}) \propto \frac{(1+\mathrm{z})^{2.7}}{1+[(1+\mathrm{z})/2.9]^{5.6}}$$

The cosmic stellar density is given by:

$$\rho_*^{\mathrm{cosmo}}(z) \propto \int_z^{\infty} CSFH_{\mathrm{cosmo}}(z') \frac{dz'}{H(z')(1+z')}$$

1D distribution of sources S(z):

$$S(z) \propto \rho_*^{\mathrm{cosmo}}(z)$$

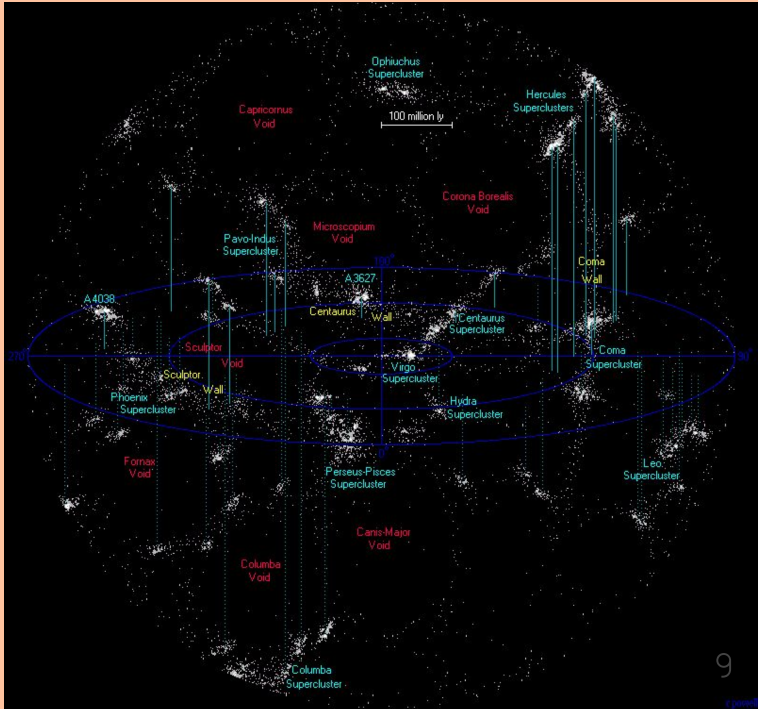


P. Madau & M. Dickinson arXiv:1403.0007

Figure 11: The evolution of the stellar mass density. The data points with symbols are given in Table 2. The solid line shows the global stellar mass density obtained by integrating the best-fit instantaneous star-formation rate density $\psi(z)$ (Equations 2 and 15) with a return fraction $R = 0.27$.

An inhomogeneous universe ?

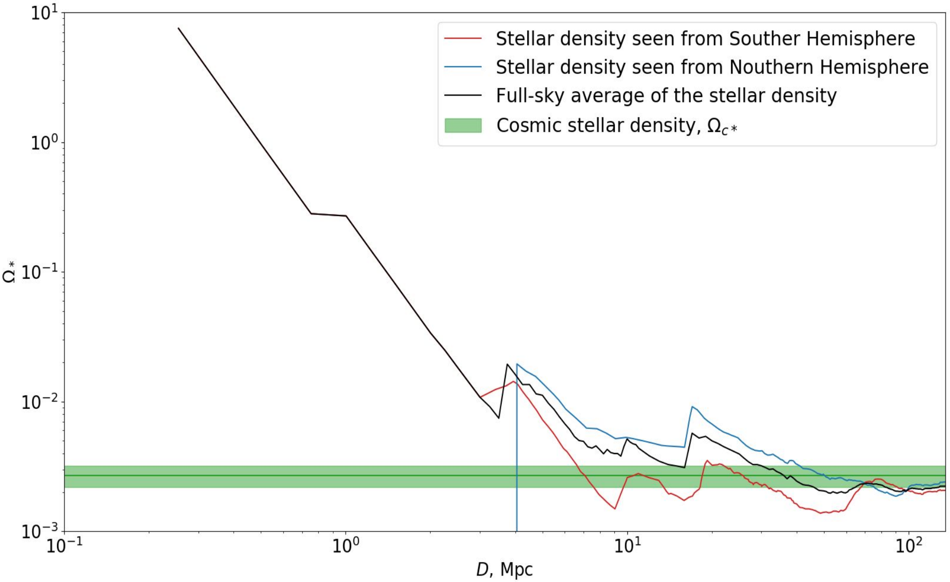
~30 Mpc

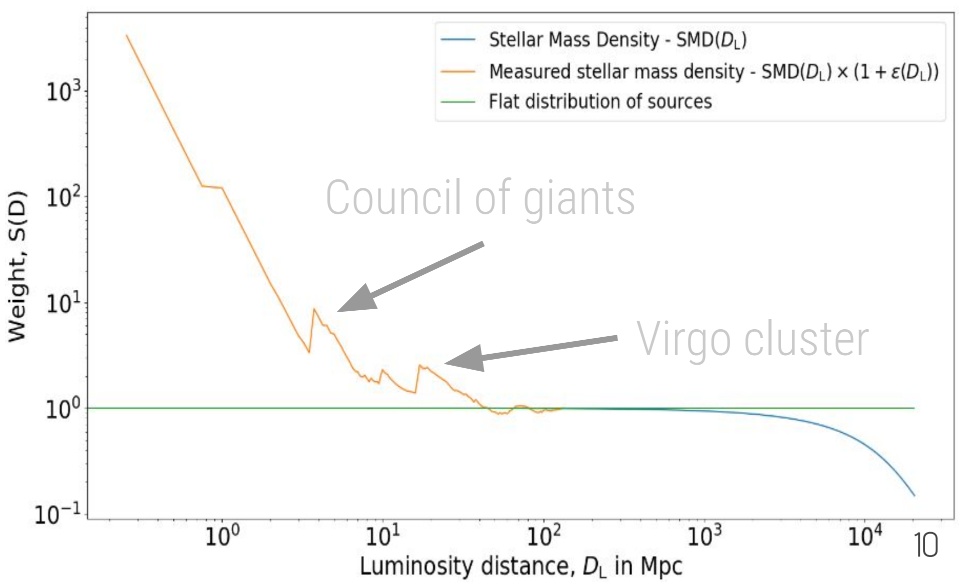


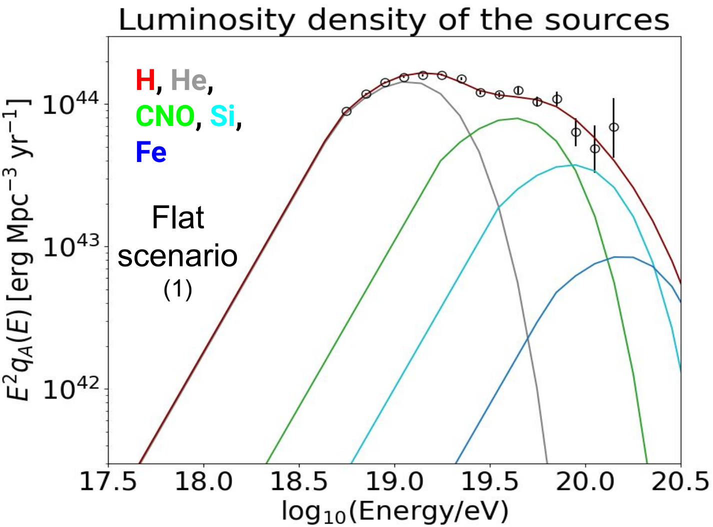
An inhomogeneous universe: Need to modelize the local universe

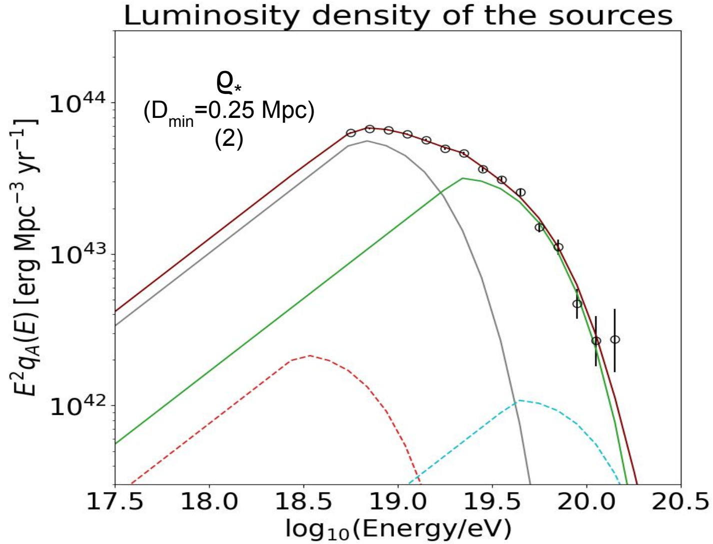
Idea: Extract the stellar density from the Local Volume (Karachentsev arxiv:1810.06326)

Reconstructed source evolution, S(D): Describe the stellar density from 0 to 10^4 Mpc (D_L) (orange & blue lines)









Results

→ The stellar density describes the data using only He & CNO !

→ Deviance improved (~80 units)

	Results	Flat scenario (1)	ϱ* (D_{min}=0.25 Mpc) (2)
Emissivities per injected elements	$\mathscr{L}_H$ [10^{43} erg Mpc^{-3} yr^{-1}]	0.00 ± 0.01	0.7 ± 0.5
	$\mathscr{L}_{He}$ [10^{43} erg Mpc^{-3} yr^{-1}]	23.2 ± 4.3	**11.4 ± 0.3**
	$\mathscr{L}_N$ [10^{43} erg Mpc^{-3} yr^{-1}]	12.8 ± 1.0	**6.0 ± 0.3**
	$\mathscr{L}_{Si}$ [10^{43} erg Mpc^{-3} yr^{-1}]	6.0 ± 1.0	0.9 ± 1.0
	$\mathscr{L}_{Fe}$ [10^{43} erg Mpc^{-3} yr^{-1}]	1.4 ± 0.5	0. ± 10^{-3}
	D_{tot} / ndf	**312.5 / 129**	**234.6 / 129**
	D_j / N_j	29.5 / 15	23.0 / 15
	D_{Xmax} / N_{Xmax}	283.0 / 121	211.6 / 121
Production rate (q_{gen}) parameters	γ	-0.35 ± 0.02	0.96 ± 0.04
	R_{cut}	18.36 ± 0.01	18.45 ± 0.00

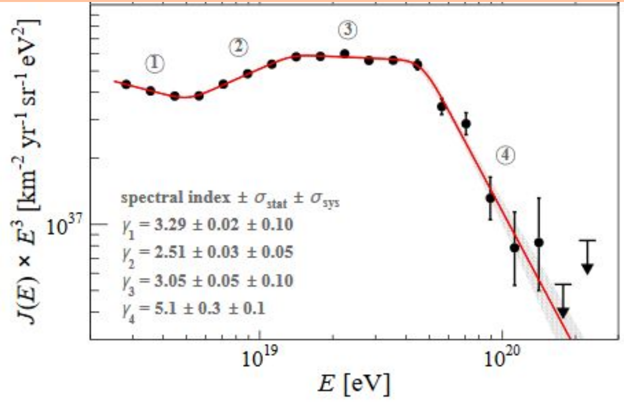
The next step

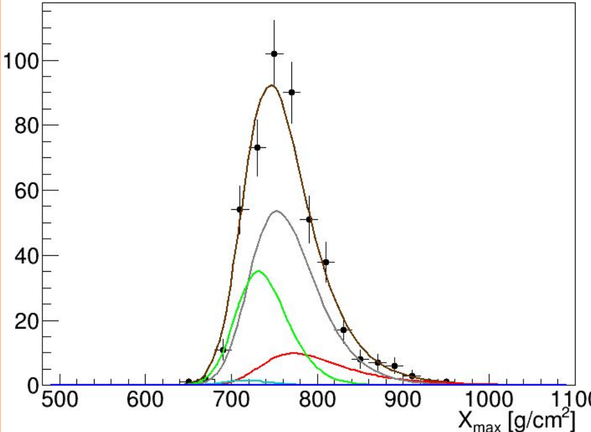
Goal: Have an astrophysical model which describes the **three observables**.

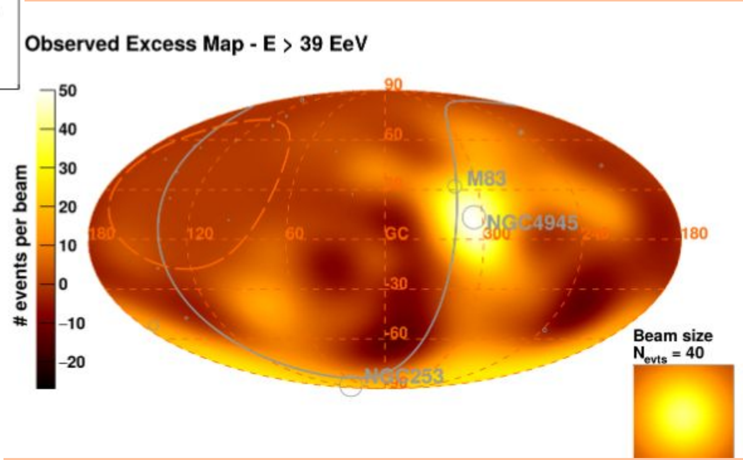
Idea: Implement anisotropy studies in the Combined Fit.

1D → 3D

Hypothesis: Source follows the Star Formation Rate computed from 400,000 galaxies within 350 Mpc







Indication of mass anisotropy ?

PRELIMINARY

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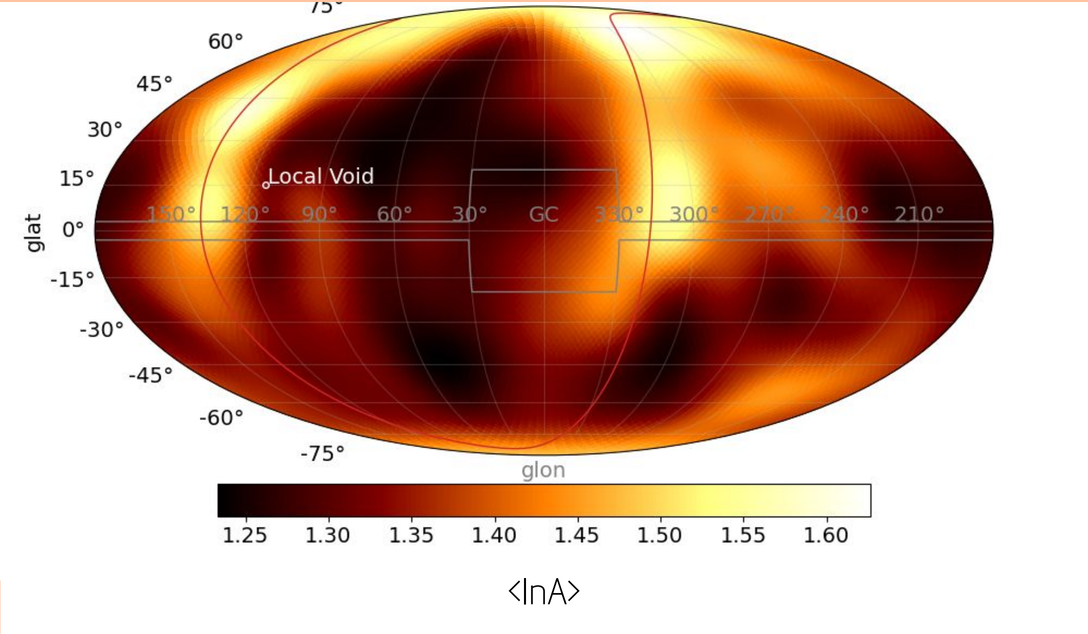


Conclusion

- The anisotropies studies make us think, we are near discovering the host of UHECR sources.
- Using stellar density as source evolution for the combined fit is in good agreement with the data
- Having a astrophysical model which can describes the three observables could constrain the sources in an unprecedented way.

Thank you for listening :)

Arrival directions: An indication of the hosts galaxies ? (2018)

Comparing flux patterns

Idea: Compare the measured flux with the sky-map of extragalactic gamma-ray sources!.

Here: sky-map of starburst galaxies (SBG) compare to observed

Starburst galaxies = High Star Formation rate

4.0σ level of significance.

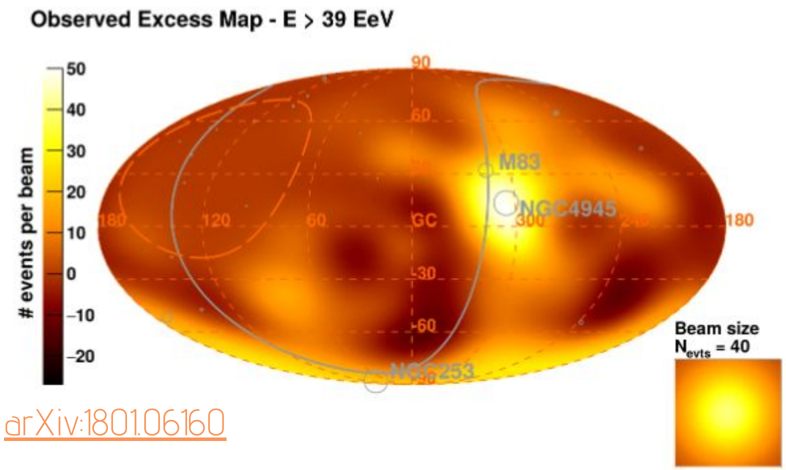
Model:

$$\Phi_{model} = \alpha\, \Phi_{isotropy} + (1-\alpha)\, \Phi_{SBG}$$

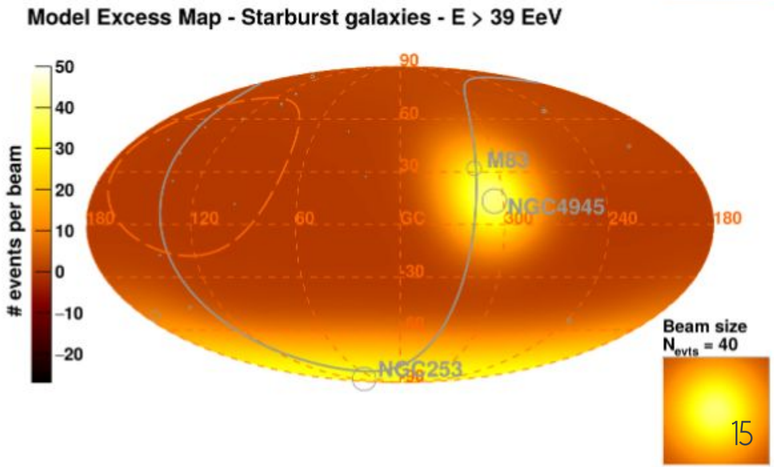
Two free parameters:

α, the isotropy fraction

Beam size

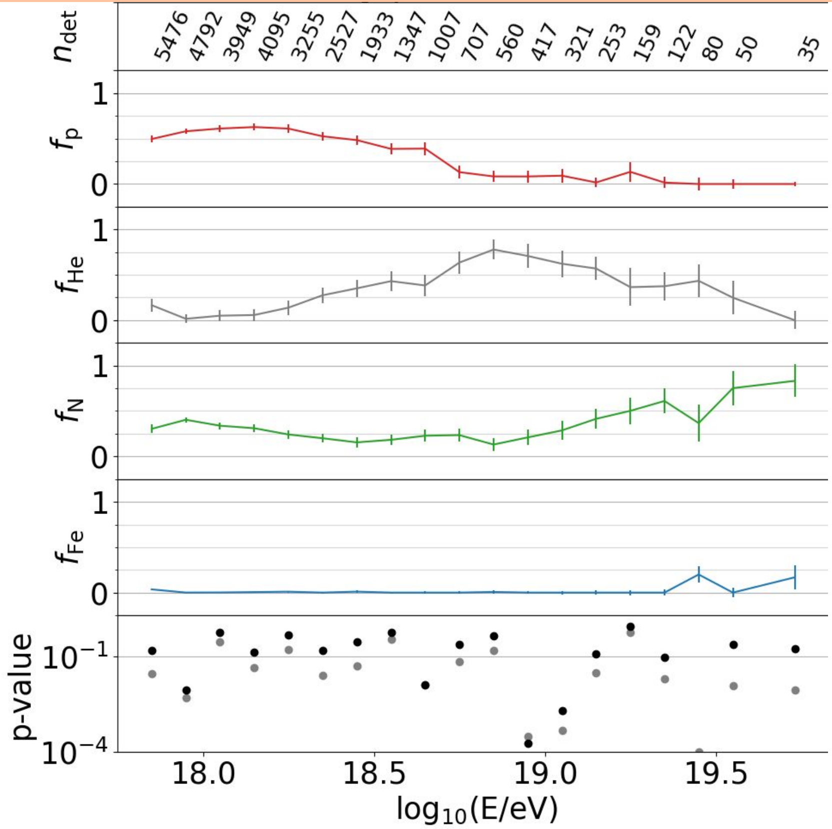


arXiv:1801.06160



Xmax: Study the composition

EPOS-LHC



Sybill2.3d