Understanding the sources of Ultra High Energy Cosmic-rays

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JRJC 18/10/2021

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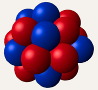
What are Ultra High Energy Cosmic Rays (UHECR) ?

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

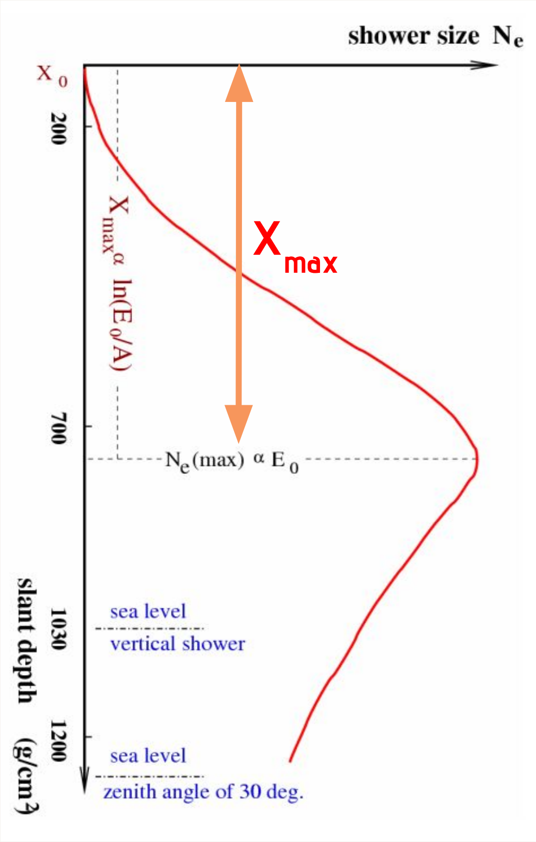


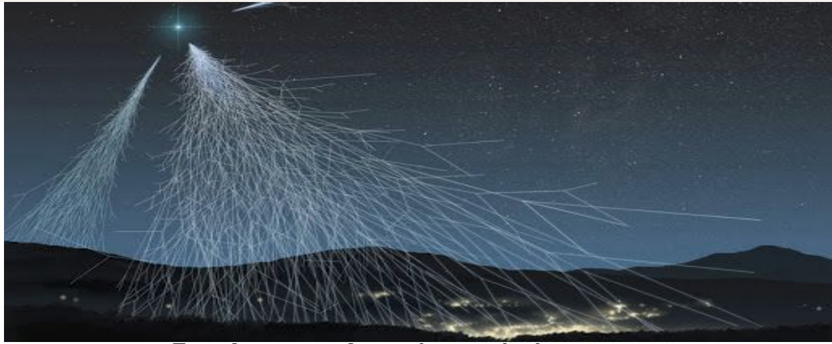
Nuclei reach the earth

Hadronic shower

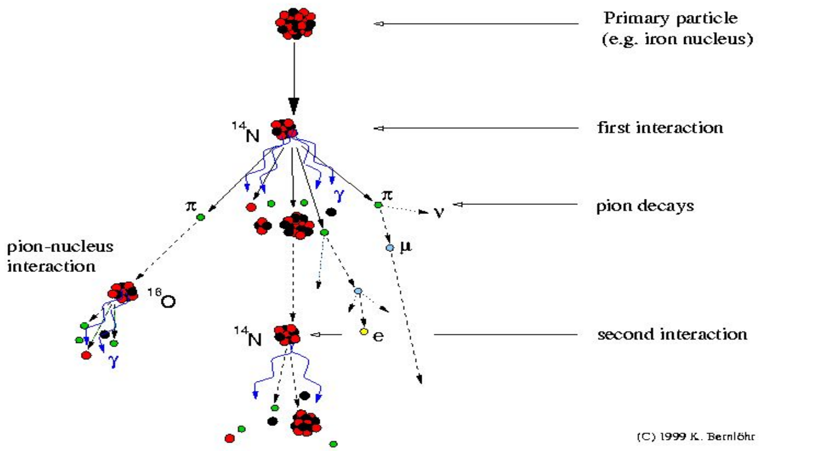
Three main observables:

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





Development of cosmic-ray air showers



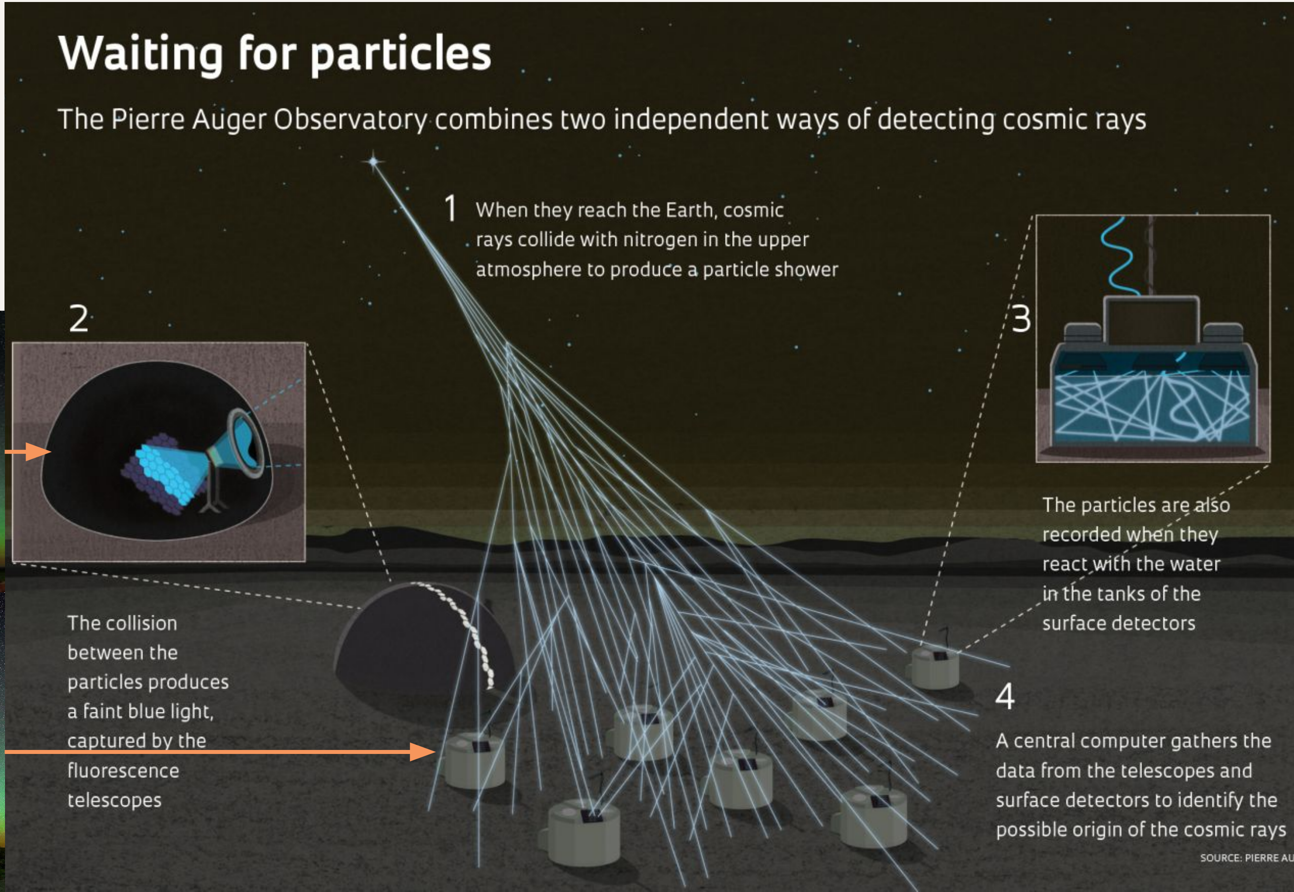
The Pierre Auger Observatory

3 000 km^2, 30 times Paris

Two detectors:

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

→ Surface detectors measures the energy and the arrival directions



State of the art

Arrival directions: An extragalactic origin ? (2017)

Evidence of extragalactic origins

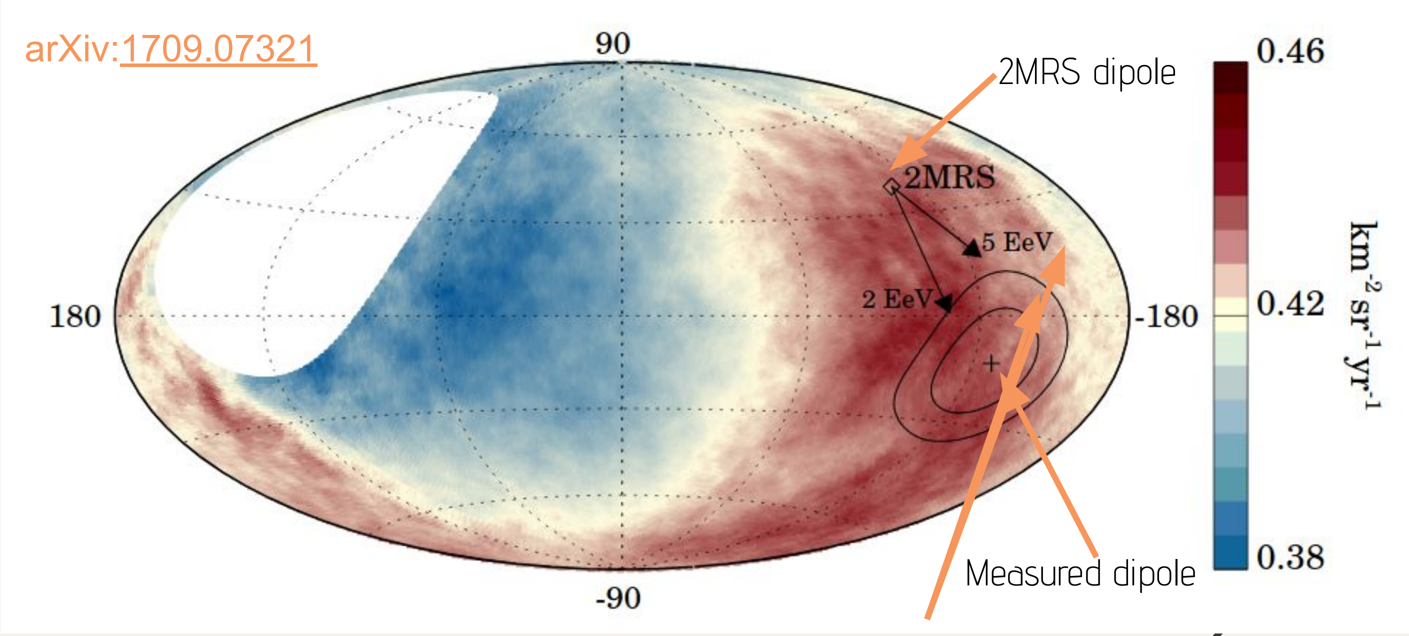
At **E > 8 EeV,** a dipole is observed at more than the **5.2σ** level of significance.

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

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.

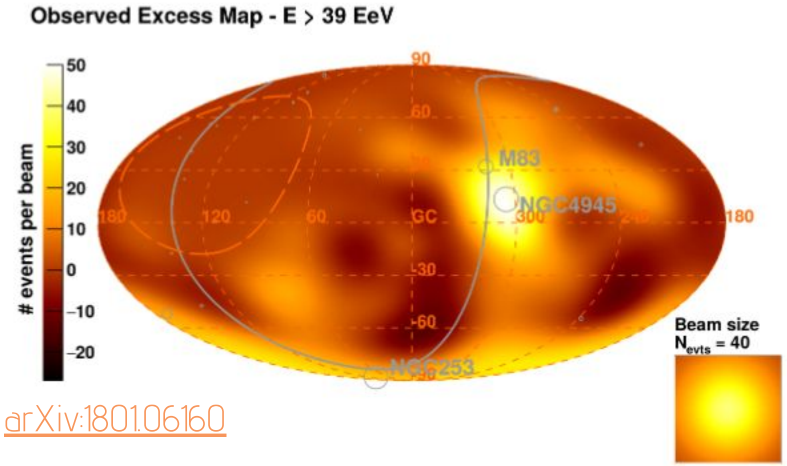
Model:

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

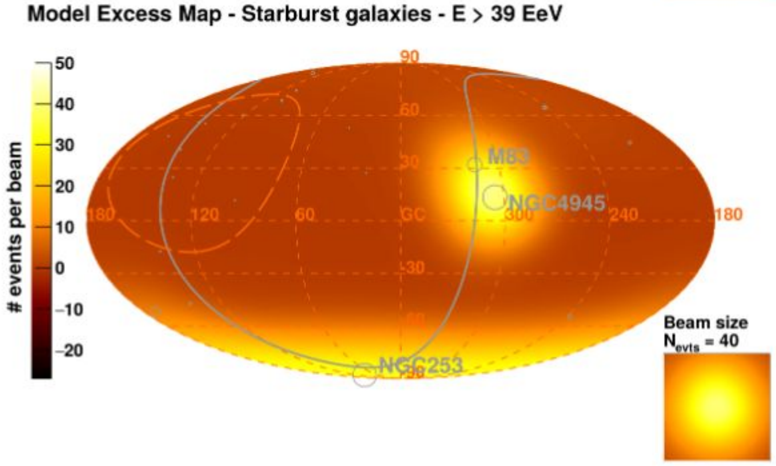
Two free parameters:

α, the isotropy fraction

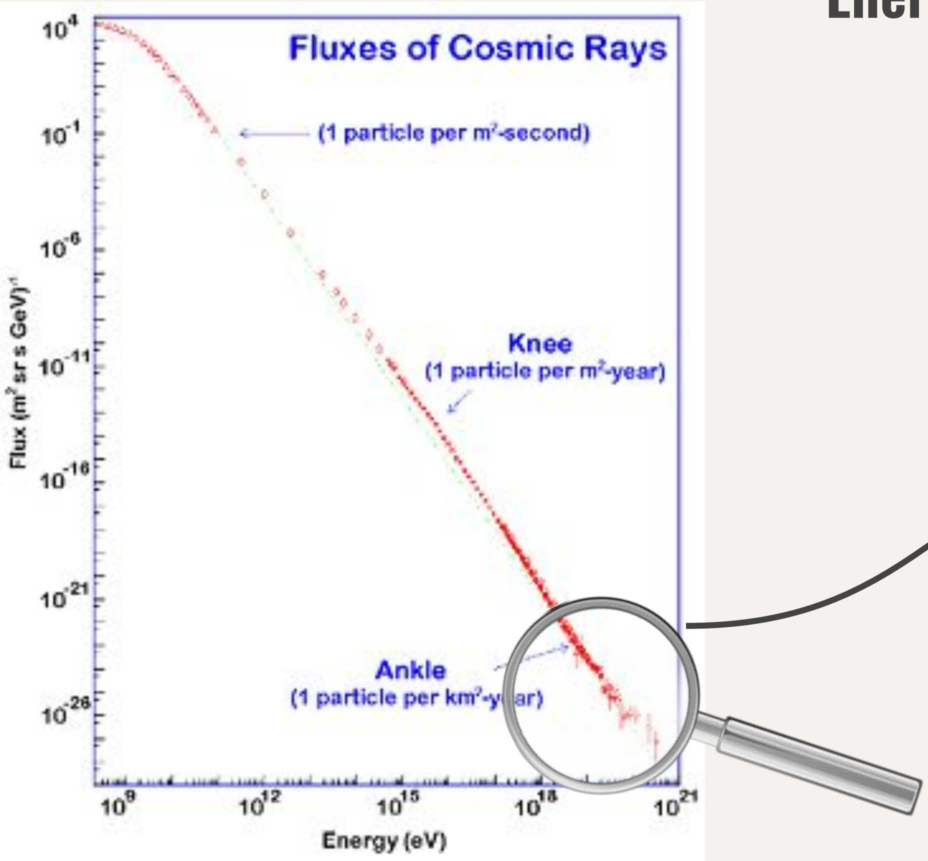
Beam size



arXiv:1801.06160

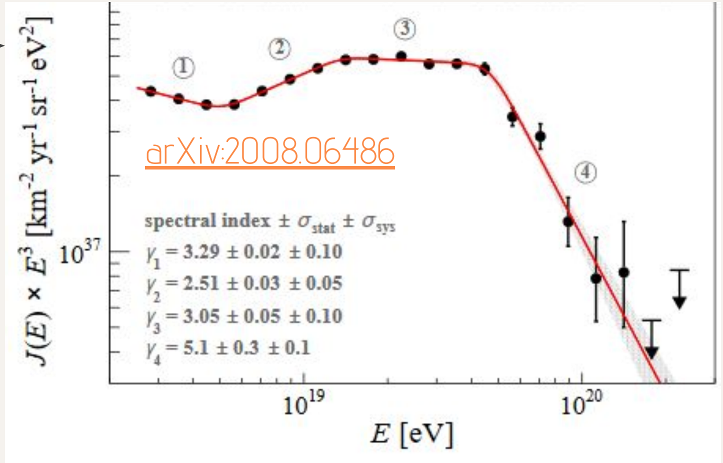


Energy Spectrum



$\times E^3$

The energy spectrum is given in the unit of [#.km^{-2}.yr^{-1}.sr^{-1}.eV^{-1}]

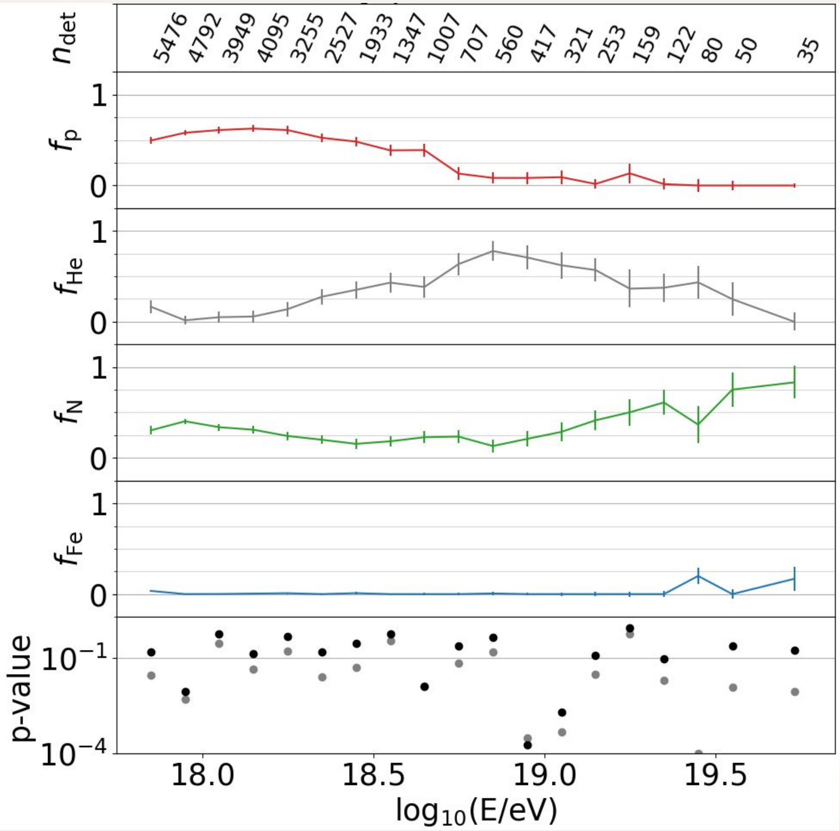


Xmax: Study the composition

Hadronic model:
EPOS-LHC

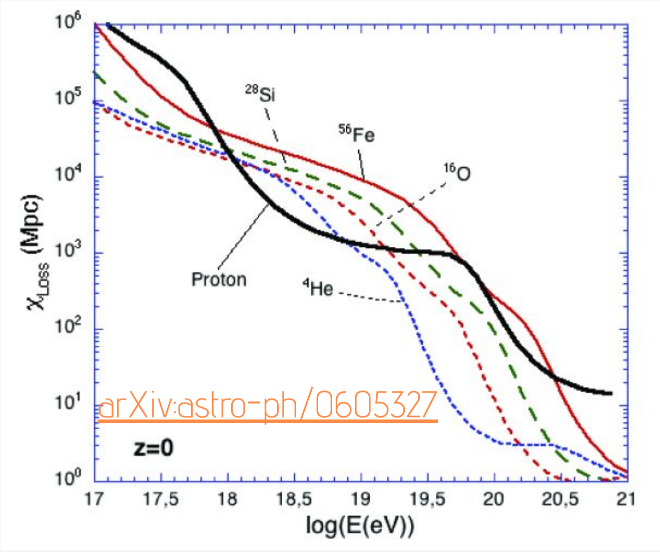
p-value:
→ Black dots: consider empty bins
C-Statistics
arXiv:1912.05444

→ Grey dots: Classical χ^2



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

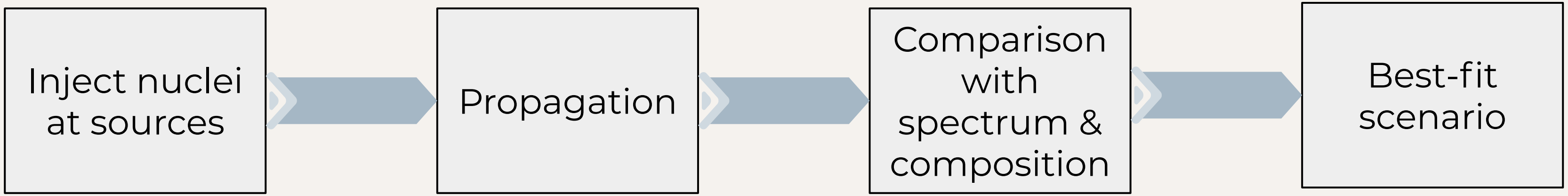
□$_{Loss}$ is the attenuation length



Towards an astrophysical model

Towards an astrophysical model: Combined Fit

➔ The combined fit is an **astrophysical model** trying to describe the composition and the energy spectrum of Ultra High Energy Cosmic Ray (UHECR).



➔ 5 representatives masses injected at sources: **H**, **He**, **N**, **Si**, **Fe**

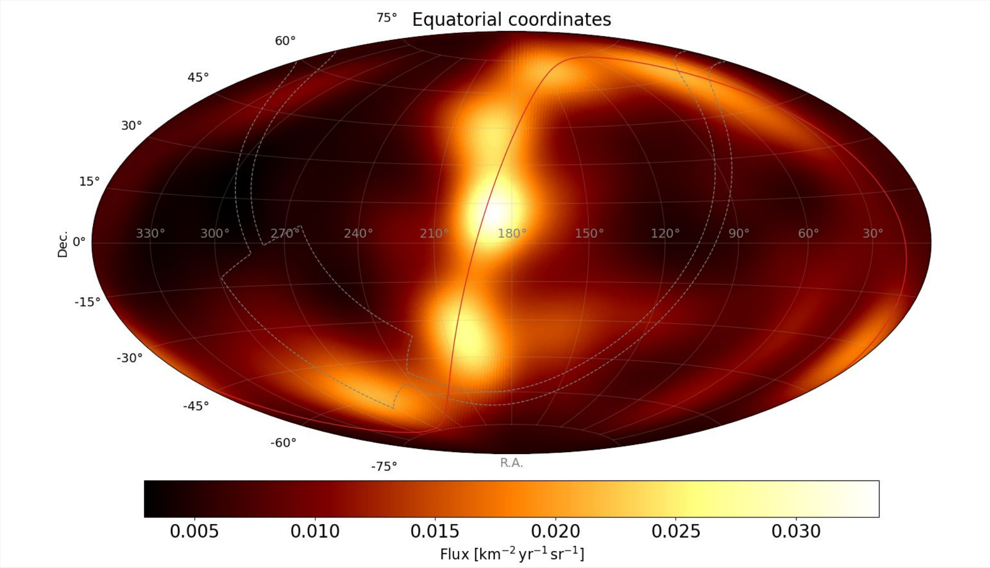
➔ 7 parameters of injection (5 for masses, 2 for the shape of the spectrum)

Hypothesis:

➔ **Transient scenario**: UHECR come from transient sources

Combined Fit: How it works

Inject nuclei at sources → Propagation → Comparison with spectrum & composition → Best-fit scenario → Looking at arrival directions



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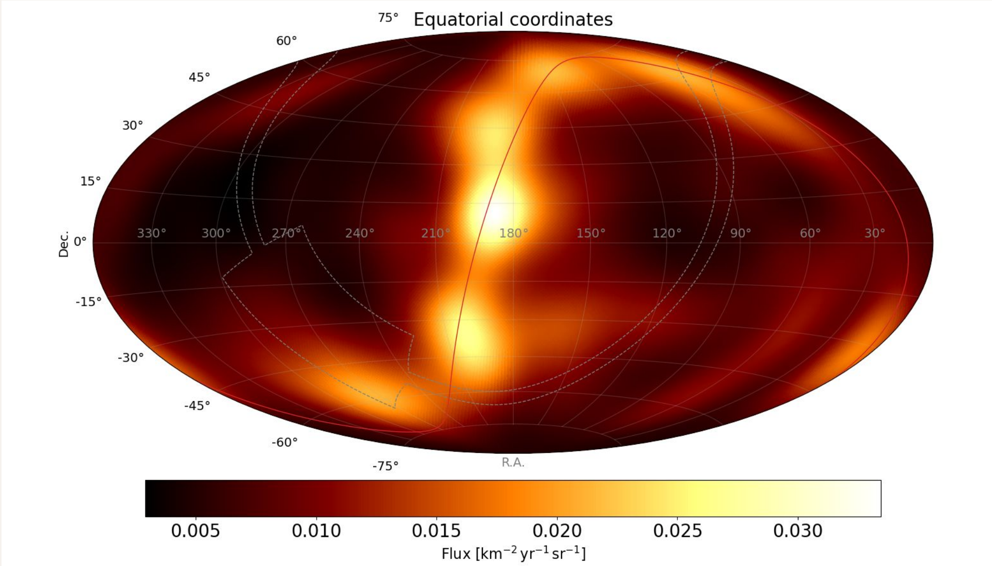


Generation term

Inject nuclei at sources

- Start from a generation term: $q_A(E_\mathrm{g}, z)$
  - Number of particles created
    - Per unit of energy
    - Per second
    - Per covolume $[q_A(E_\mathrm{g}, z)] = \mathrm{eV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{Mpc}^{-3}$
    - For a given specie A, at given energy, at a redshift z.

$$q_A(E_\mathrm{g}, z) = \frac{dN_A}{dE_\mathrm{g}}(E_\mathrm{g}) \times S(z)$$

Gives the number of generated nuclei per source

Gives the number of source at a redshift z

Generation term: injected spectrum

Inject nuclei at sources

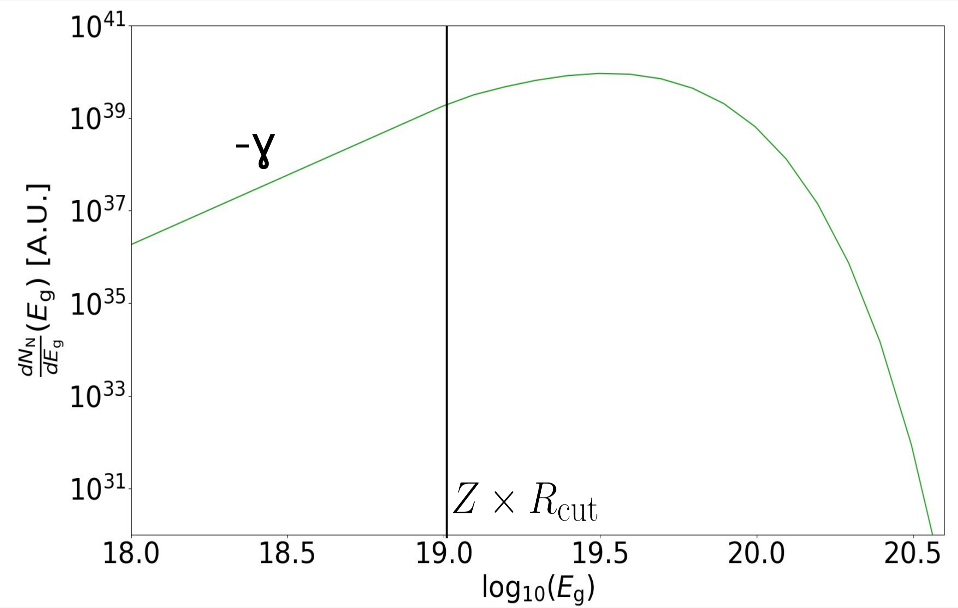
$$q_A(E_\mathrm{g}, z) = \frac{dN_A}{dE_\mathrm{g}}(E_\mathrm{g}) \times S(z)$$

Gives the number of source at a redshift z

Gives the number of generated nuclei per source

$$E_\mathrm{g}\frac{dN_A}{dE_\mathrm{g}}(E_\mathrm{g}) = E_A \times \frac{E_\mathrm{g}\, f(E_\mathrm{g})}{\int_0^\infty E_\mathrm{g}\, f(E_\mathrm{g})\, dE_\mathrm{g}}$$

$$f(E_\mathrm{g}) = \left(\frac{E}{E_\mathrm{ref}}\right)^{-\gamma} \times \begin{cases} 1 & E \leq Z \times R_\mathrm{cut} \\ e^{1-\frac{E_\mathrm{g}}{Z\times R_\mathrm{cut}}} & E > Z \times R_\mathrm{cut} \end{cases}$$



Generation term: evolution of sources

Inject nuclei at sources

$$q_A(E_g, t) = \frac{dN_A}{dE_g}(E_g) \times S(t)$$

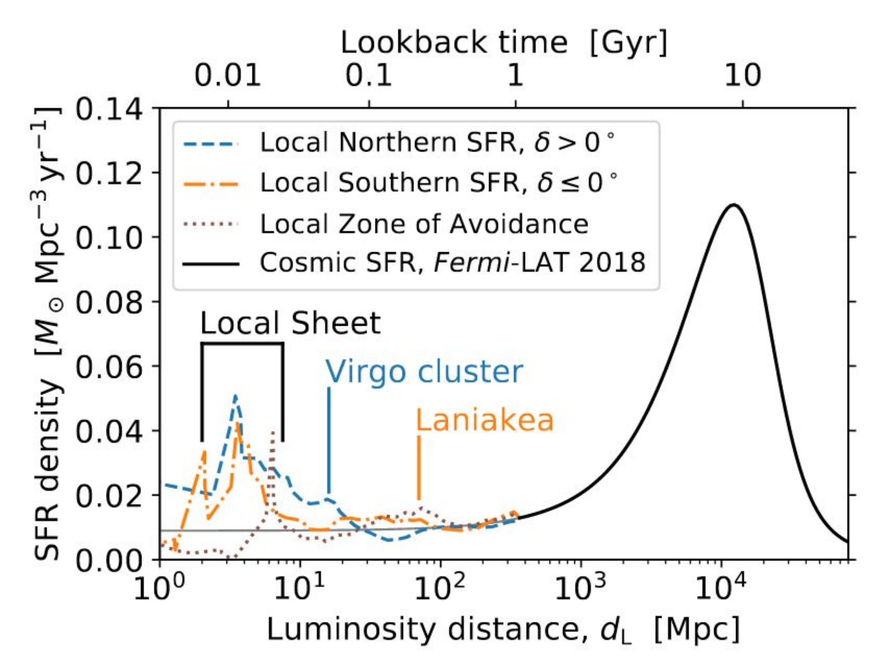
Gives the number of burst at a time t

Gives the number of generated nuclei per burst

S(t) describes the **evolution of sources** in time (or redshift).
Hypothesis: S(t) follows the Star Formation rate density

$$S(t) = k \times \mathrm{SFRd(t)}$$

Extracted from *Biteau(2021)* *Astrophys.J.Suppl. 256*



What are the free parameters ?

Inject nuclei at sources

- ➔ **ɣ** - Power of the power law of the injected spectrum at the sources
- ➔ $\mathbf{R_{cut}}$ - Cut in injection
- ➔ $\mathbf{E_H \times k}$ - Injected energy per injected stellar mass
- ➔ $\mathbf{E_{He} \times k}$ - Injected energy per injected stellar mass
- ➔ $\mathbf{E_N \times k}$ - Injected energy per injected stellar mass
- ➔ $\mathbf{E_{Si} \times k}$ - Injected energy per injected stellar mass
- ➔ $\mathbf{E_{Fe} \times k}$ - Injected energy per injected stellar mass

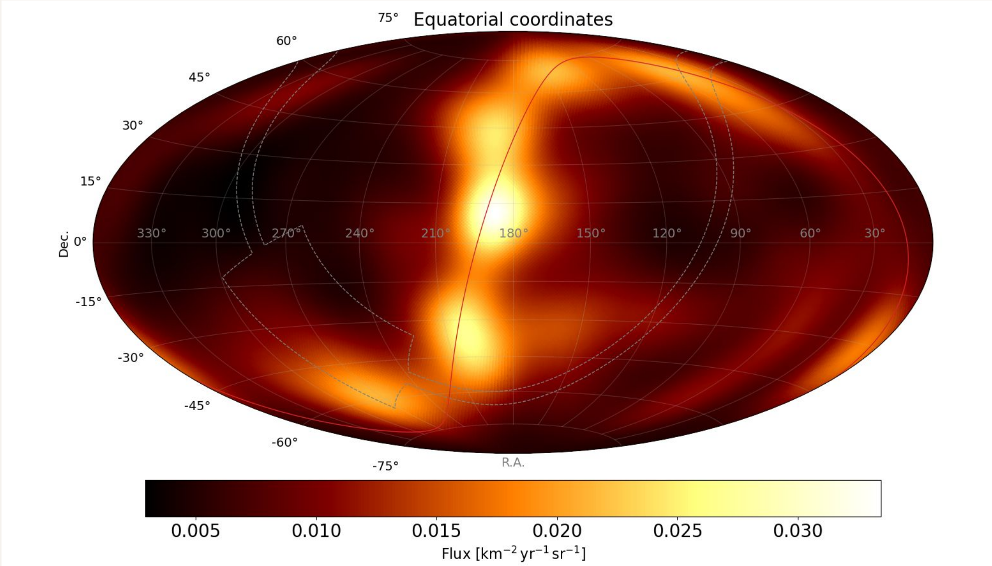
The total energy density

$$u = \sum_A E_A k \times \frac{\rho_*(z=0)}{(1-R)}$$

$$[E_A] = \text{erg per source} \quad [k] = \text{Number of sources per M}_\odot$$

Combined Fit: How it works

Inject nuclei at sources → Propagation → Comparison with spectrum & composition → Best-fit scenario → Looking at arrival directions



Propagation: Tensor formalism

Propagation

- ➔ SimProp simulations of 2 500 000 nuclei per injected A
- ➔ Nuclei propagate through CMB & EBL.
- ➔ Store in five 4D tensor.
- ➔ Tensor gives the **average number of detected nuclei per detected energy**

- **EBL:** Gilmore et al. 2012 fiducial
- **Photodisintegration cross sections:** PSB (Puget et al.)
- **Photoproduction of pion:** EBL+CMB

$$T_A(E_g, z, E_{det}, (Z, A)_{det})$$

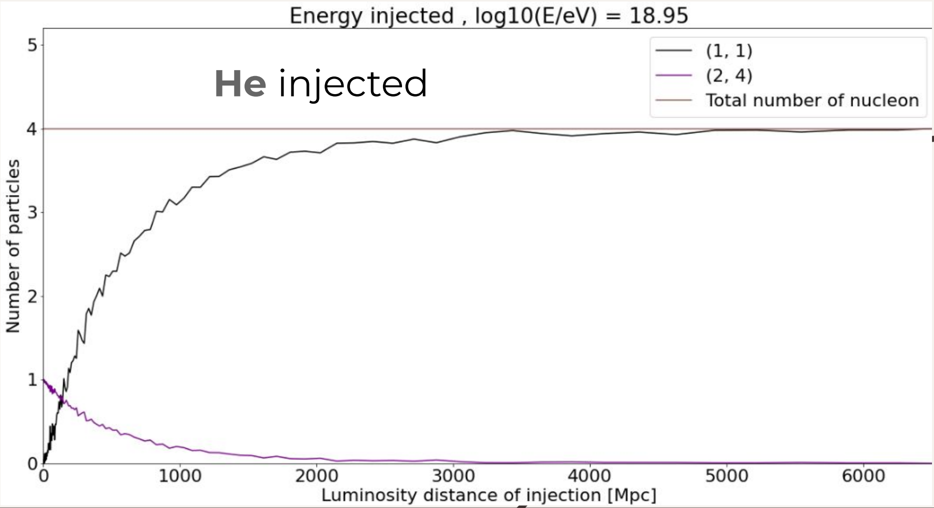
Injected mass

Injected energy

Injected redshift

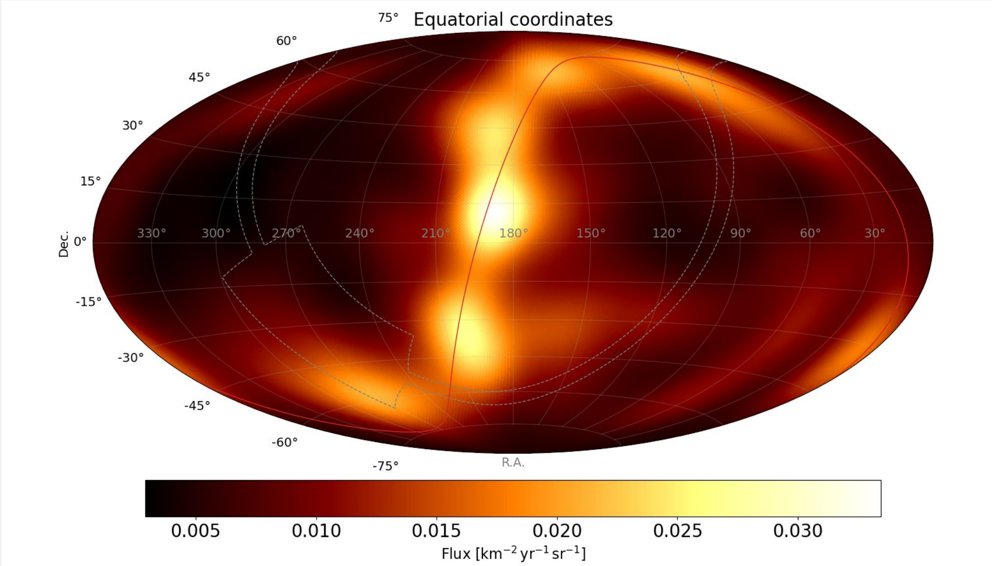
Detected mass

Detected energy



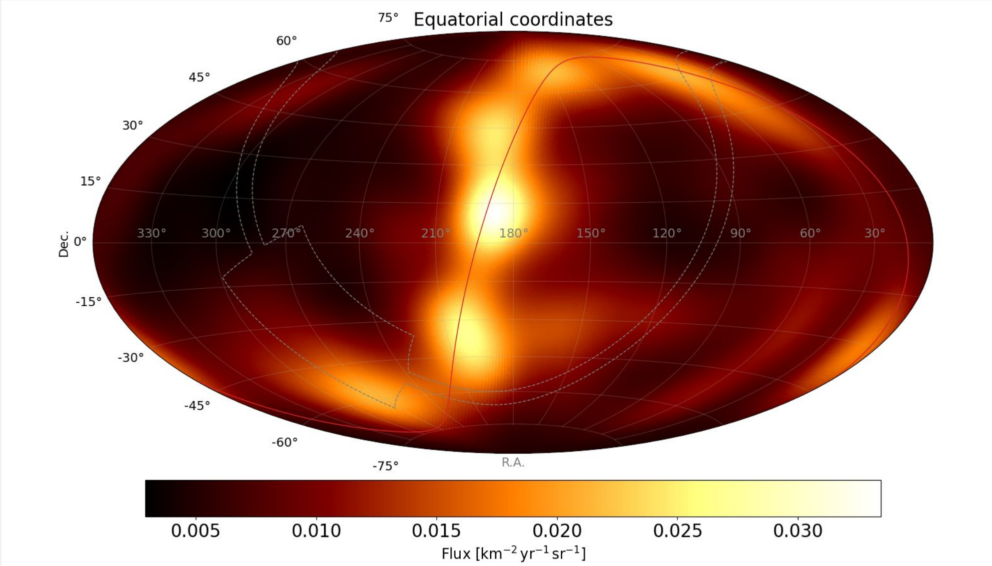
Combined Fit: How it works

Inject nuclei at sources → Propagation → Comparison with spectrum & composition → Best-fit scenario → Looking at arrival directions



Combined Fit: How it works

Inject nuclei at sources → Propagation → Comparison with spectrum & composition → Best-fit scenario



Looking at arrival directions

Combined Fit: Minimization

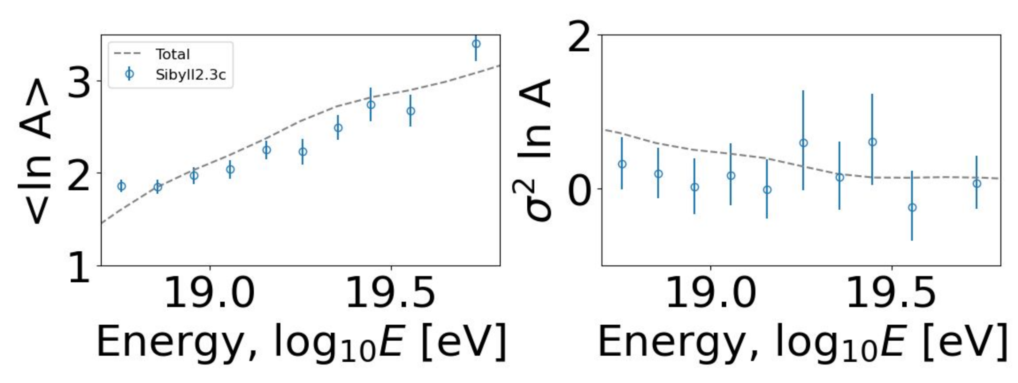
Comparison with spectrum & **composition**

➔ **Tensor is contracted** to compute the flux of each detected nuclei

$$J_{\rm A}(E) = \frac{c}{4\pi} \sum_{A_{\rm g}} \sum_{E_{\rm g}} \sum_{0}^{z=2.5} \Delta z \left|\frac{\Delta t}{\Delta z}\right| S(z) \times \frac{dN_{A_{\rm g}}}{dE_{\rm g}} \times T_A(E_{\rm g}, z, E_{\rm det}, (Z, A)_{\rm det}) \Delta E_{\rm g}$$

➔ **Compare** to <ln A> and **σ**^{2} ln A using **Gaussian likelihood**

$$\mathcal{L}_{\rm A} = \prod_j \frac{1}{\sigma(< \ln_{\rm A} >)_j^{\rm data}\sqrt{2\pi}} \times \exp\left(-\frac{1}{2}\left(\frac{< \ln_{\rm A} >_j^{\rm data} - < \ln_{\rm A} >_j^{\rm model}}{\sigma(< \ln_{\rm A} >)_j^{\rm data}}\right)^2\right) \times \frac{1}{\sigma(\sigma^2 \ln_{\rm A})_j^{\rm data}\sqrt{2\pi}} \times \exp\left(-\frac{1}{2}\left(\frac{\sigma^2 \ln_{{\rm A}_j}^{\rm data} - \sigma^2 \ln_{{\rm A}_j}^{\rm model}}{\sigma(\sigma^2 \ln_{\rm A})_j^{\rm data}}\right)^2\right)$$



➔ The **goodness of fit** is given by the deviance:

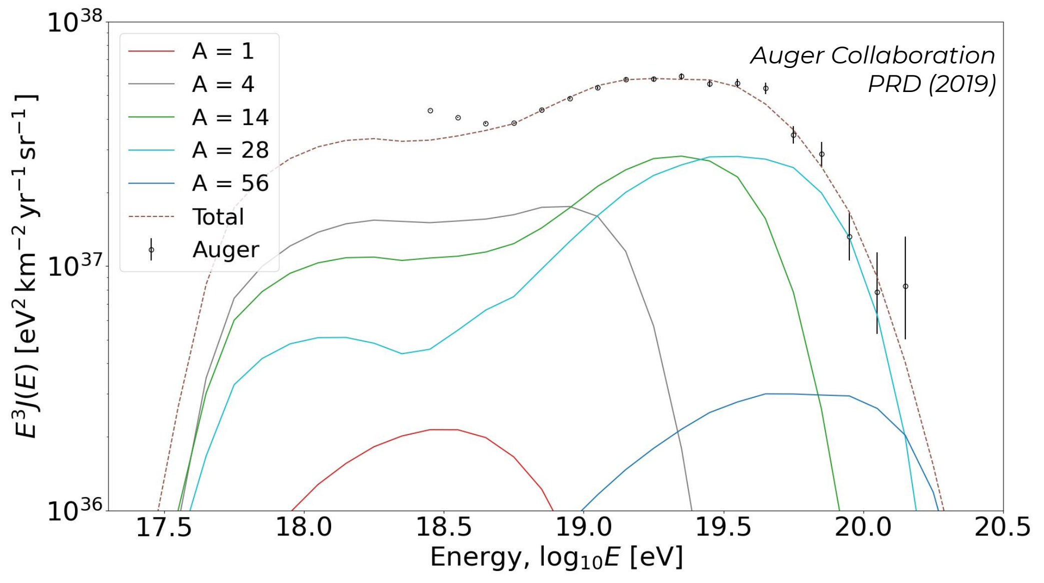
$$D_{\rm A} = -2 \ln \mathcal{L}_{\rm A} / \mathcal{L}_{\rm A}^{\rm sat}$$

Combined Fit: Minimization

Comparison with **spectrum** & composition

➔ Tensor is contracted to compute the flux

➔ **Compare to Auger spectrum** using Gaussian likelihood



$$\mathcal{L}_{\mathrm{J}} = \prod_j \frac{1}{\sigma_j^{\mathrm{data}}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{J_j^{\mathrm{data}} - J_j^{\mathrm{model}}}{\sigma_j^{\mathrm{data}}}\right)^2\right)$$

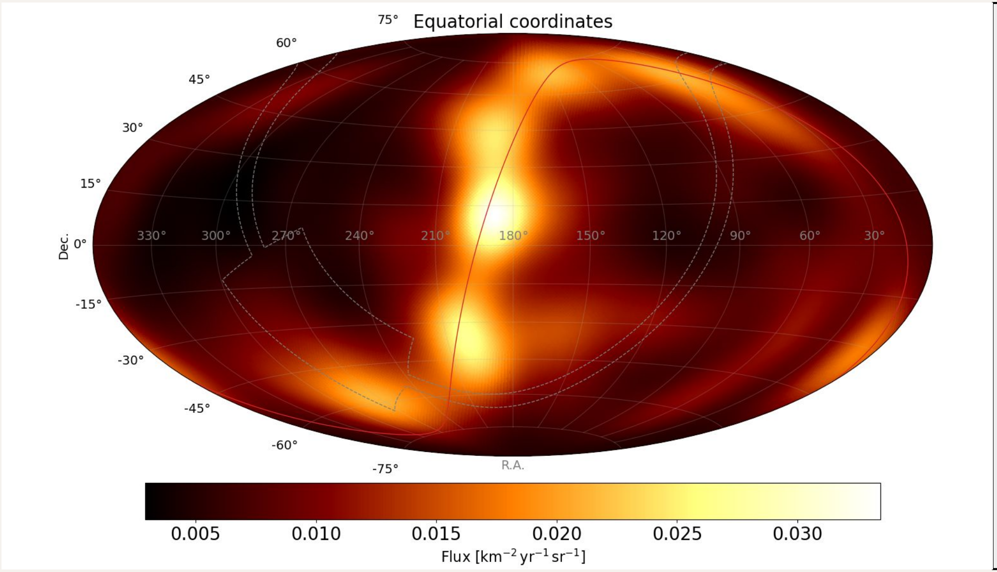
➔ Goodness of fit given by the deviance

$$D_J = -2\ln \mathcal{L}_J / \mathcal{L}_J^{\mathrm{sat}}$$

$$D_{\mathrm{tot}} = D_{\mathrm{J}} + D_{\mathrm{A}}$$

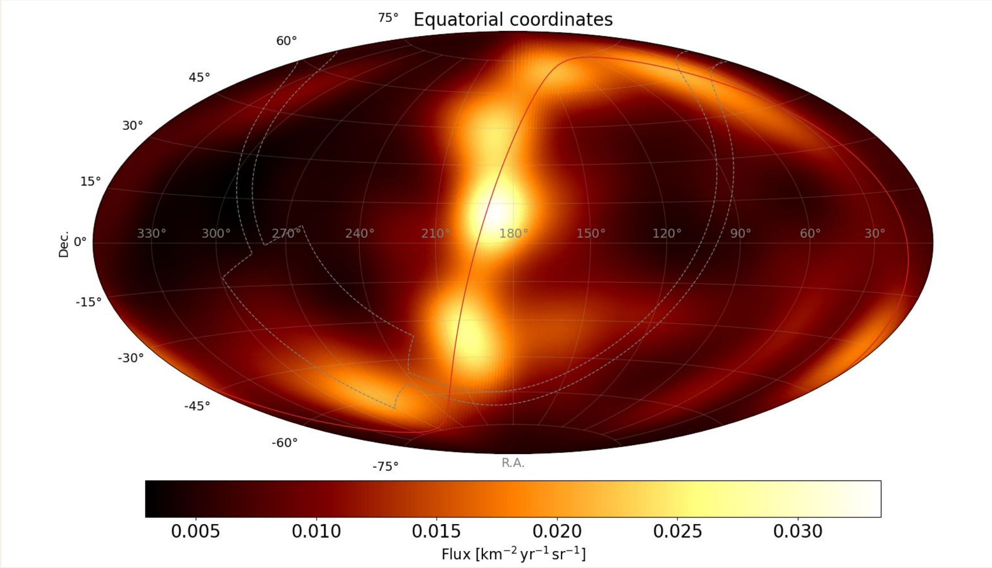
Combined Fit: How it works

Inject nuclei at sources → Propagation → Comparison with spectrum & composition → Best-fit scenario → Looking at arrival directions



Combined Fit: How it works

Inject nuclei at sources → Propagation → Comparison with spectrum & composition → **Best-fit scenario** → Looking at arrival directions

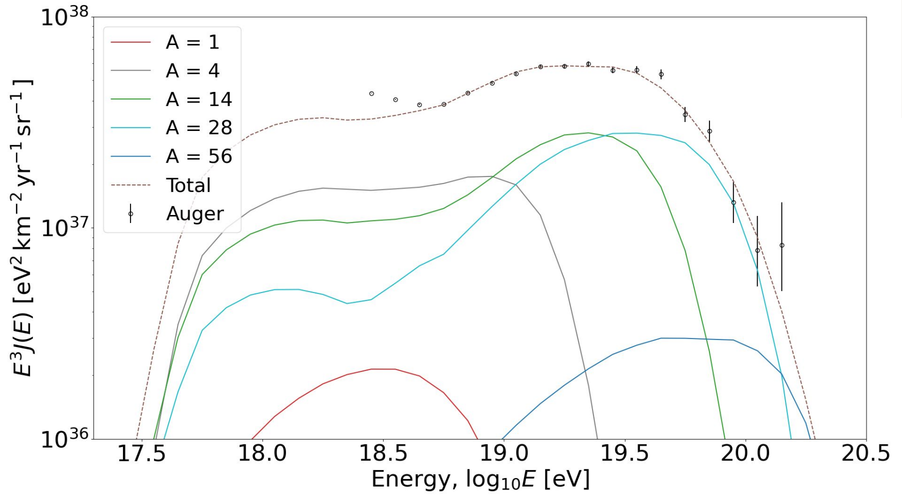


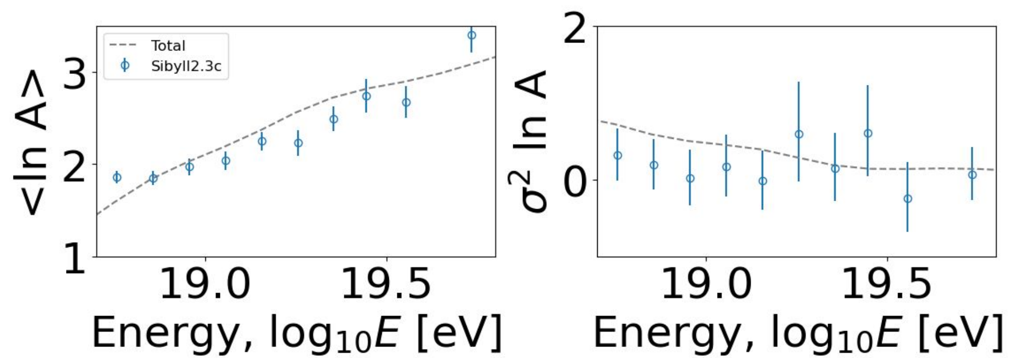
Combined Fit: Best-fit scenario

Comparison with spectrum & composition

R_{cut}	γ	$E_H \times k$ [A.U]	$E_{He} \times k$ [A.U]	$E_N \times k$ [A.U]	$E_{Si} \times k$ [A.U]	$E_{Fe} \times k$ [A.U]
18.2	-1.2	1.3	11.1	10	6.3	0.5

D_J (num. of points)	D_A (num. of points)
18.9 (15)	20 (20)





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Plus d'infos

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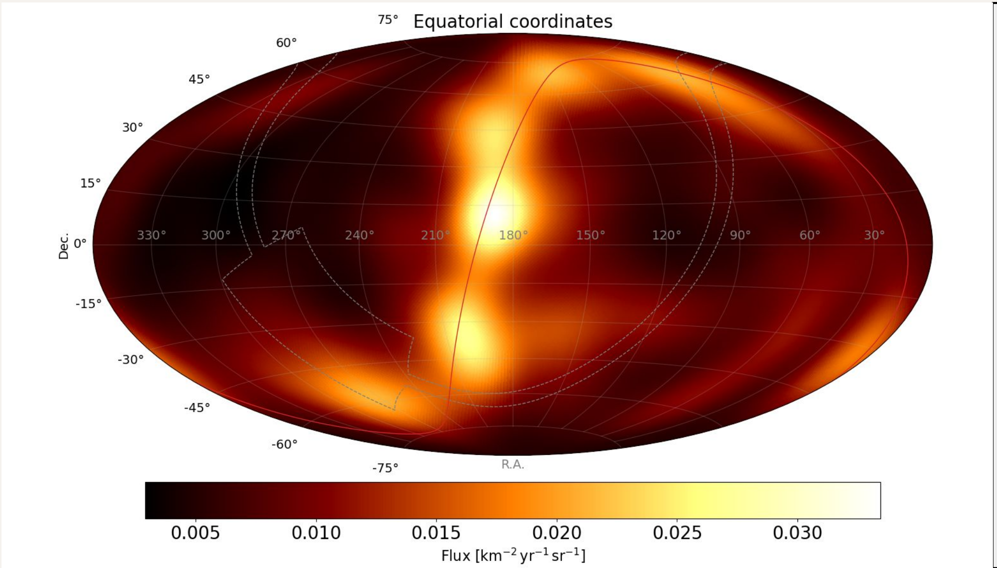
30,00 € bourriche - 48 huîtres

Plus d'infos

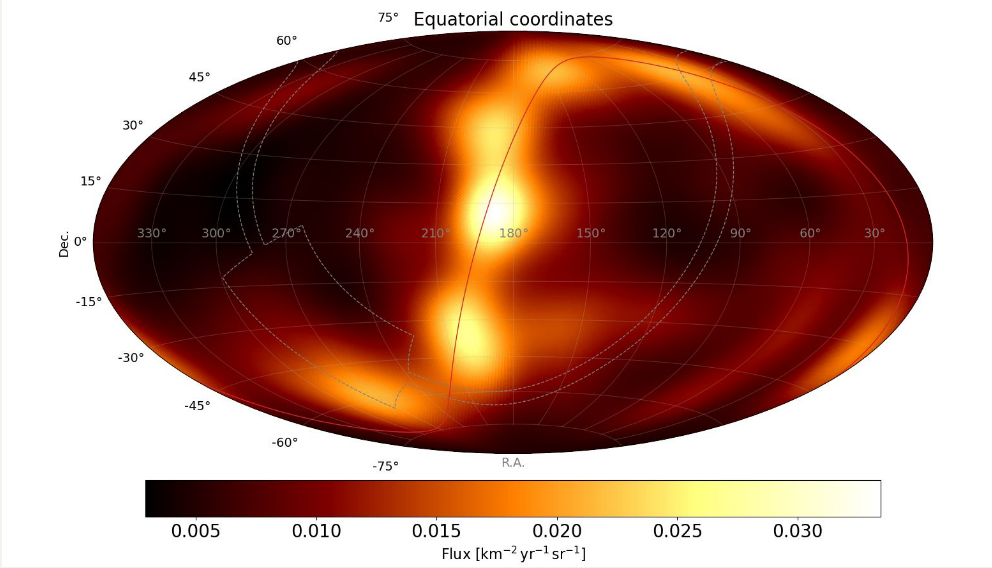
Combined Fit: How it works

Inject nuclei at sources → Propagation → Comparison with spectrum & composition → Best-fit scenario → Looking at arrival directions



Combined Fit: How it works

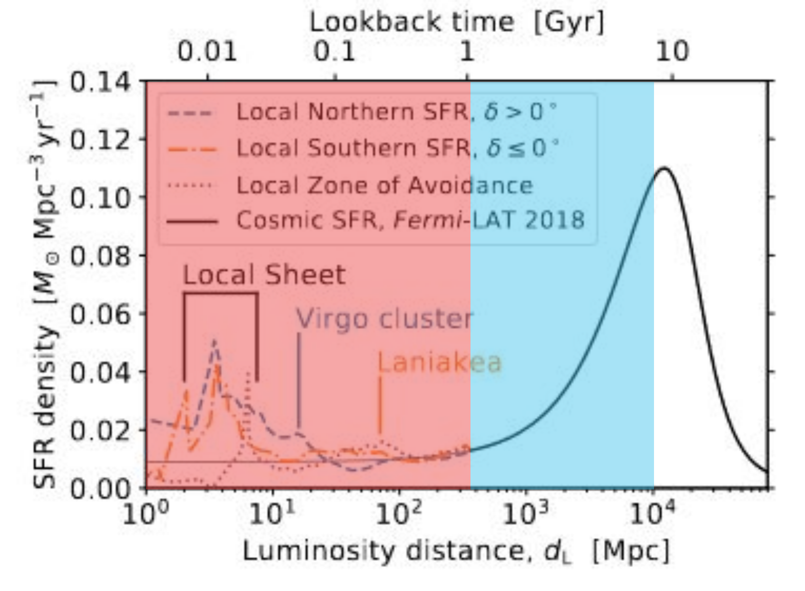
Inject nuclei at sources → Propagation → Comparison with spectrum & composition → Best-fit scenario → Looking at arrival directions



Consequences on arrival directions

Looking at arrival directions

➔ **Split** the code in 2
➔ Uses the full Catalogue of *Biteau(2021) Astrophys.J.Suppl. 256*



➔ **Compute the flux for each galaxy from the catalogue (~400 000)**

➔ **Compute the flux as before, from z=0.08 to z=2.5**

$$J_A(E)|_{\rm Gal} = \frac{1}{4\pi\, d_L^2} \sum_{A_g} \sum_{E_g} S(z_{\rm Gal}) \times \frac{dN_{A_g}}{dE_g} \times T_A(E_g, z, E_{\rm det}, (Z,A)_{\rm det}) \Delta E_g$$

$$J_A(E)|_{z=0.08\to 2.50} = \frac{c}{4\pi} \sum_{A_g} \sum_{E_g} \sum_{z=0.08}^{z=2.50} \Delta z \left|\frac{\Delta t}{\Delta z}\right| S(z) \times \frac{dN_{A_g}}{dE_g} \times T_A(E_g, z, E_{\rm det}, (Z,A)_{\rm det}) \Delta E_g$$

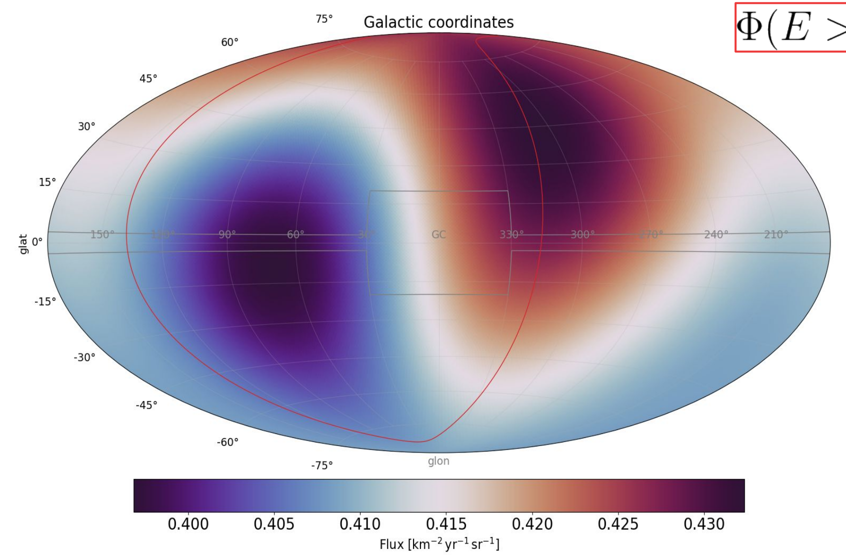
$$J_A(E) = J_A(E)|_{z=0.08\to 2.50} + \frac{J_A(E)|_{z=0.0\to 0.08}}{\sum_{\rm Gal} J_A(E)|_{\rm Gal}} J_A(E)|_{\rm Gal}$$

Result - Consequences on arrival directions

Looking at arrival directions

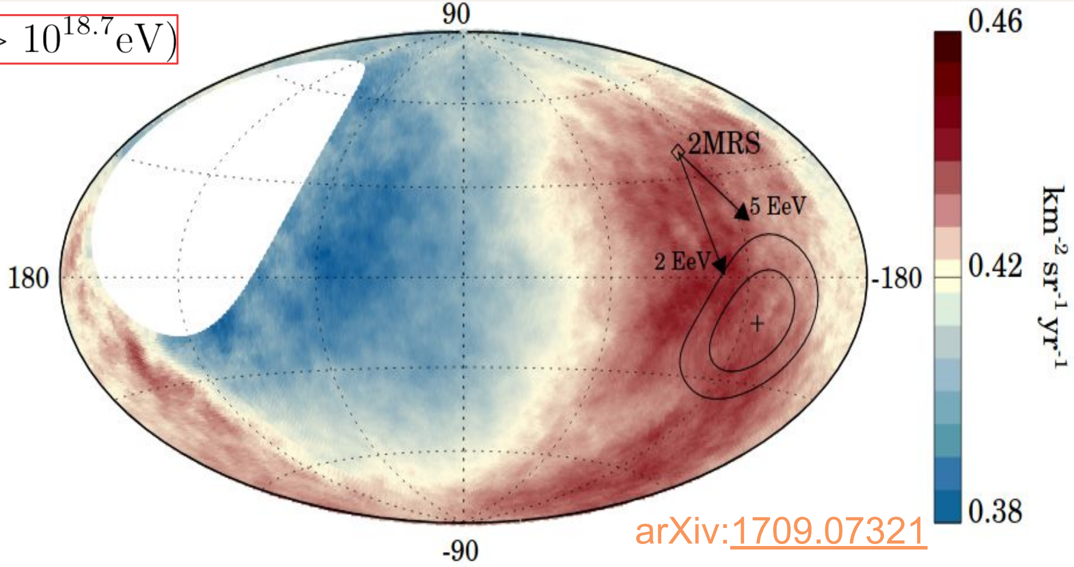
- ➔ Compute the flux in each pixel
- ➔ Do a **top-hat smoothing** with 45° radius

Model



$\Phi(E > 10^{18.7}\mathrm{eV})$

Data from Auger



arXiv:[1709.07321](1709.07321)

Result - Consequences on arrival directions

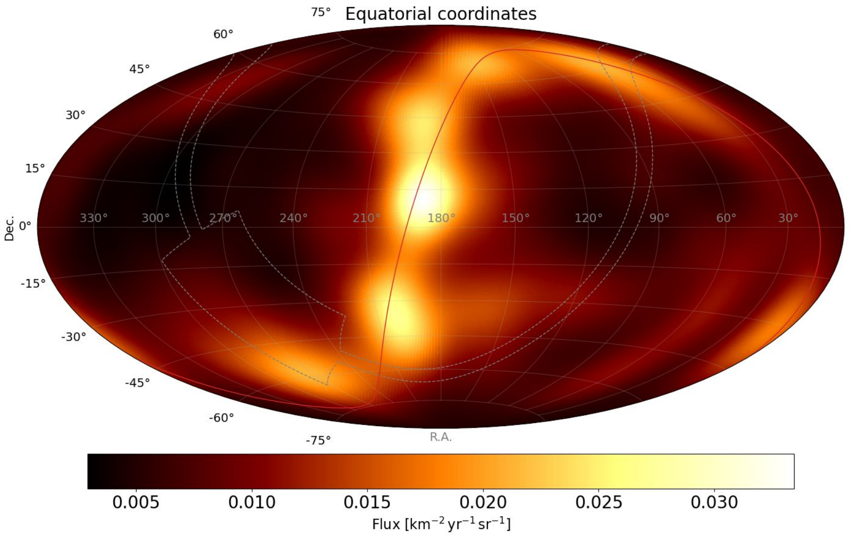
Looking at arrival directions

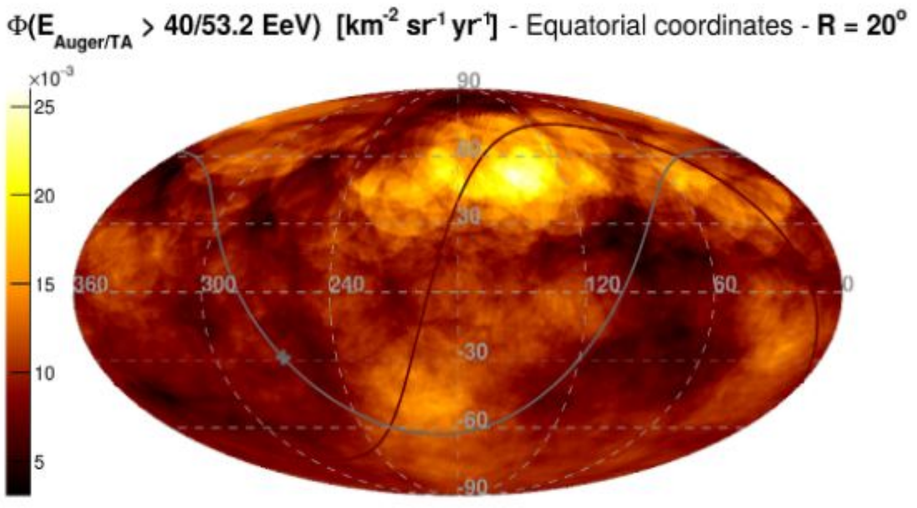
- ➔ Compute the flux in each pixel
- ➔ Do a top-hat smoothing with **10° radius**

➔ Dominated by Laniakea, Shapley cluster, Virgo Cluster.

Model $\Phi(E > 10^{19.6}\mathrm{eV})$

Data





Result - Consequences on arrival directions

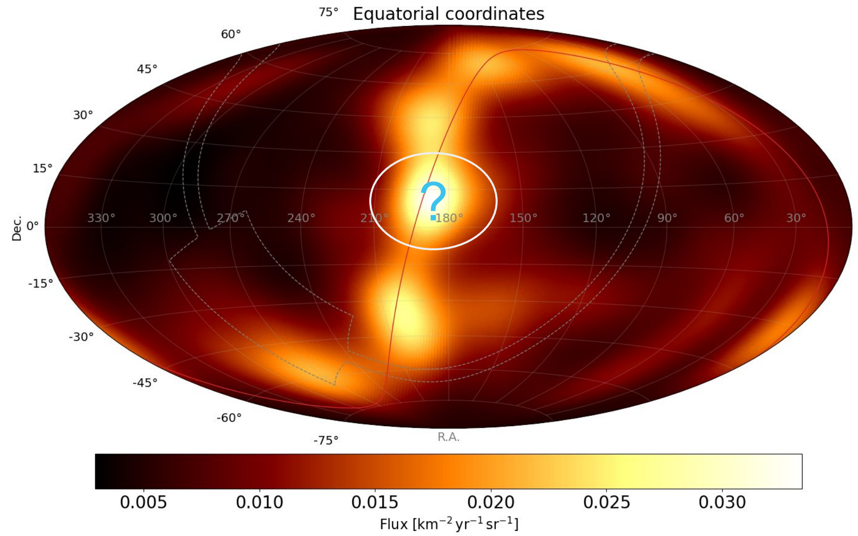
Looking at arrival directions

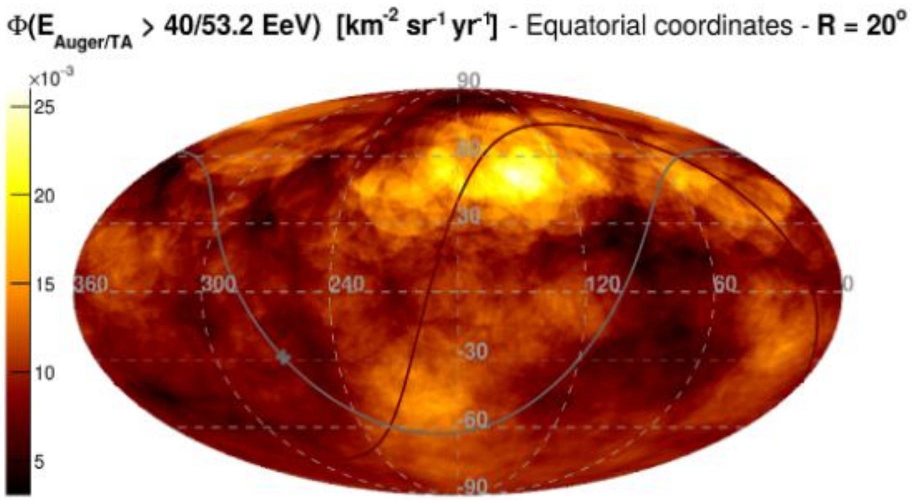
- ➔ Compute the flux in each pixel
- ➔ Do a top-hat smoothing with **10° radius**

➔ Dominated by Laniakea, Shapley cluster, Virgo Cluster.

Model $\Phi(E > 10^{19.6}\text{eV})$

Data





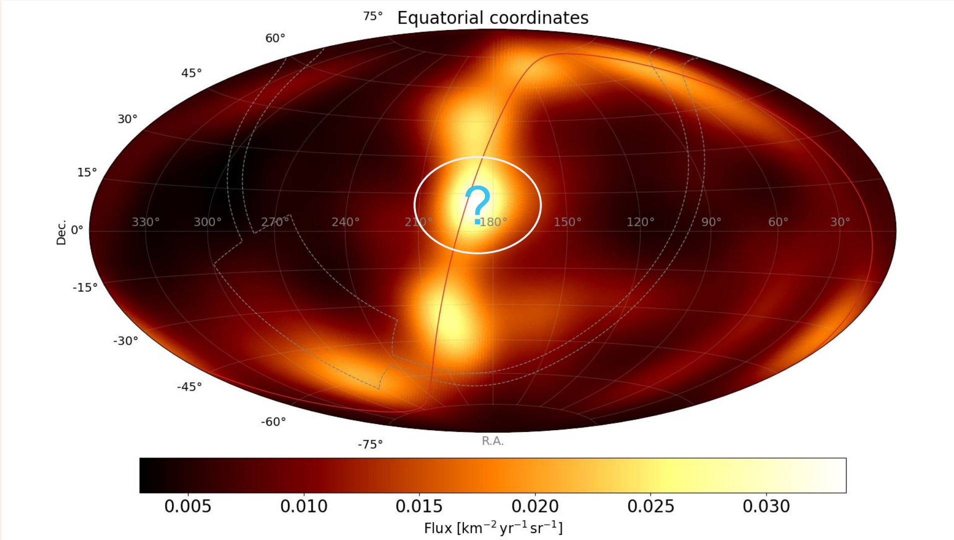
Result - Consequences on arrival directions

Looking at arrival directions

➔ Compute the flux in each pixel
➔ Do a top-hat smoothing with **10° radius**

➔ Dominated by Laniakea, Shapley cluster, Virgo Cluster.

Model $\Phi(E > 10^{19.6}\text{eV})$



Conclusion:

➔ Model that can describe the expected flux above any energy !

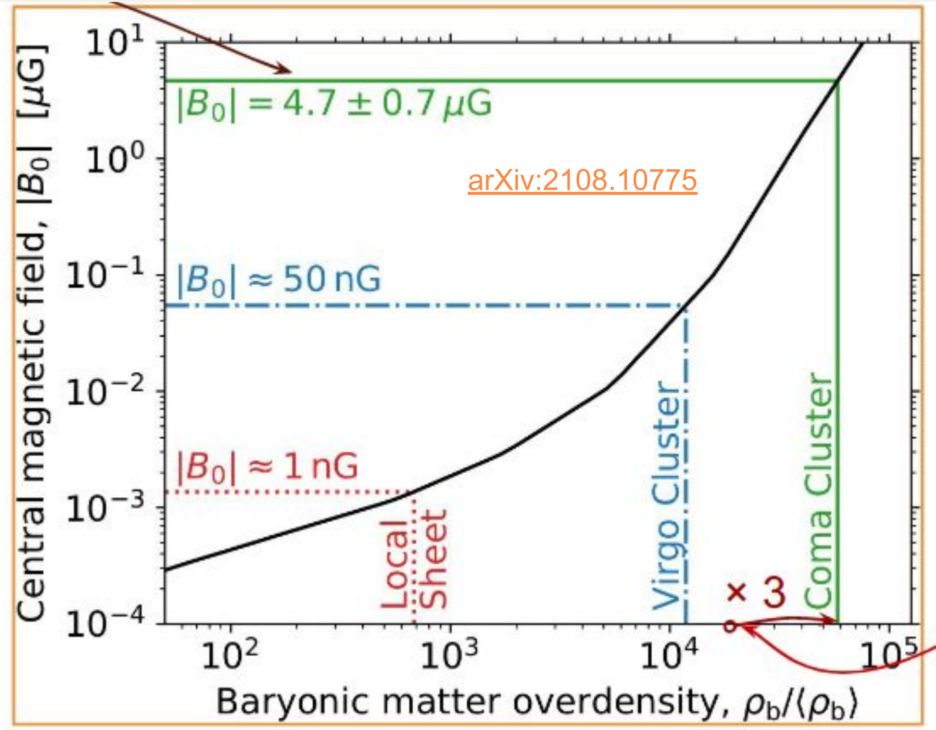
Question:

➔ Does UHECR escape from all clusters ?

Compute magnetic field of clusters

Idea:

- ➔ Compute cluster's magnetic field from baryonic matter overdensity based on MHD simulation (*Donnert+ 2018*)
- ➔ Check if UHECR can escape from the magnetic field of the cluster

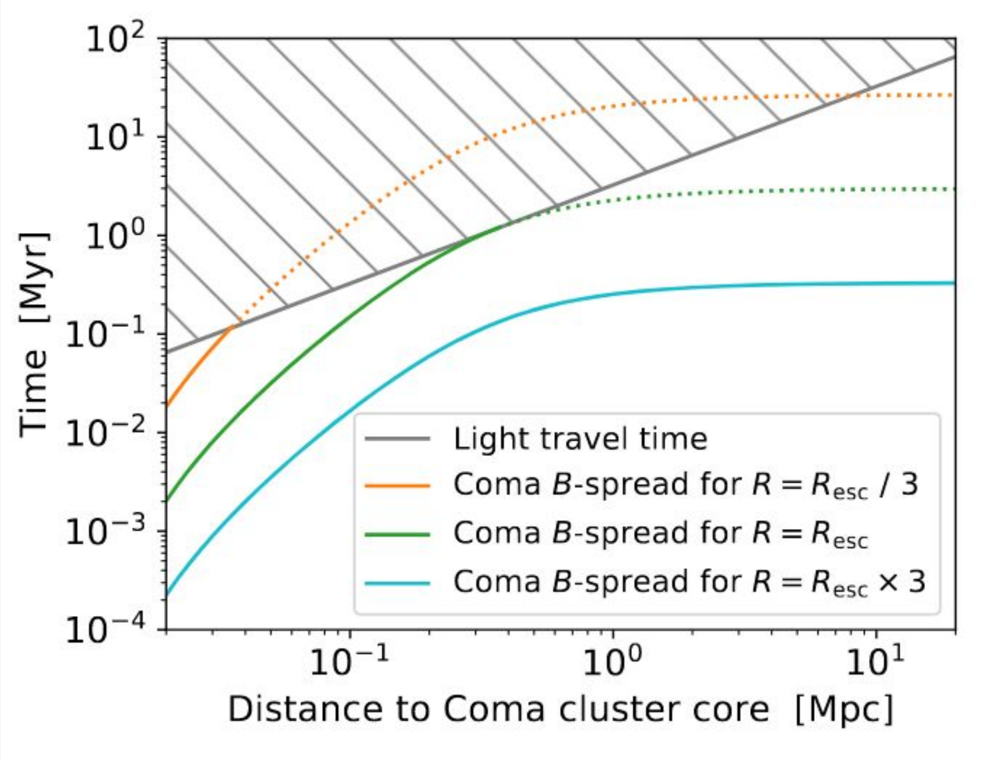


Time of spreading vs light travel time

Hypothesis:

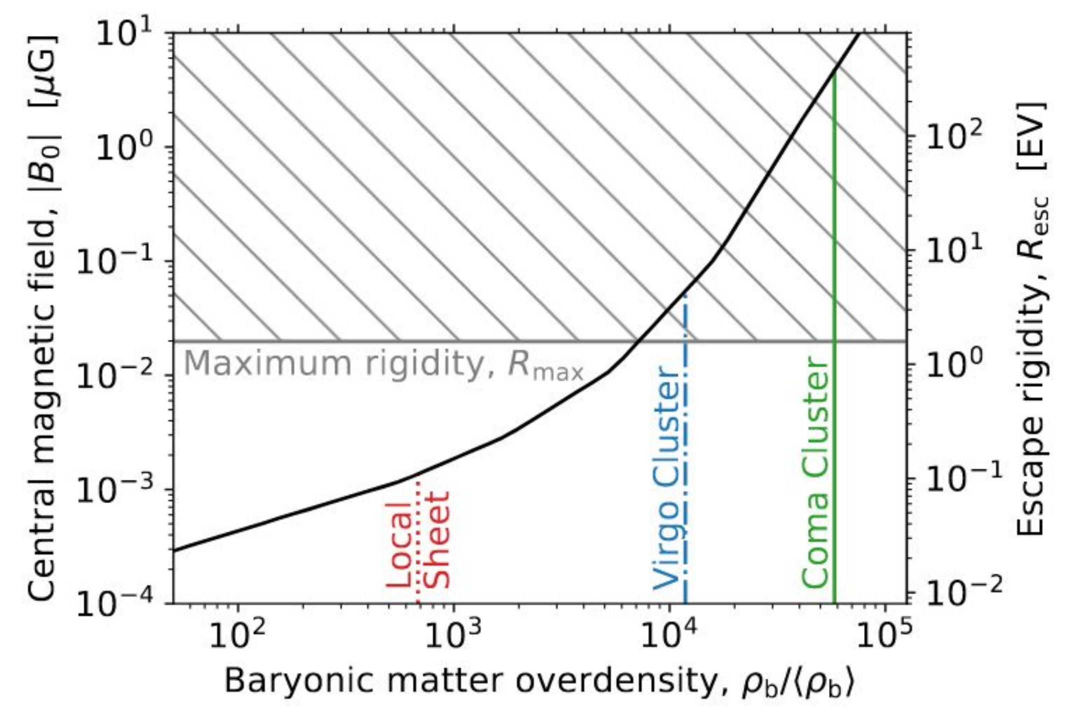
➔ If the time spend in the cluster due to magnetic field spread **is lower than the light travel time** → UHECR escape.

➔ If the time **is equal or bigger** → **UHECR get stuck**



Magnetic confinement

Definition rigidity:
R = E/Z



Consequences:

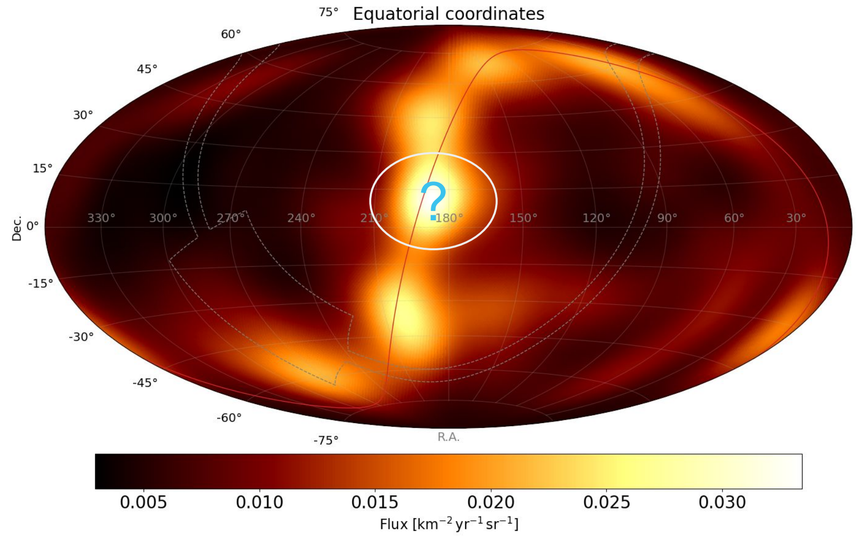
- ➔ The magnetic field will confine UHECR:
- ➔ If UHECR are injected up to a maximum rigidity R_{max}, the clusters with an escape rigidity above R_{max} do not contribute.
- ➔ **Conclusion:** Some clusters cannot be seen

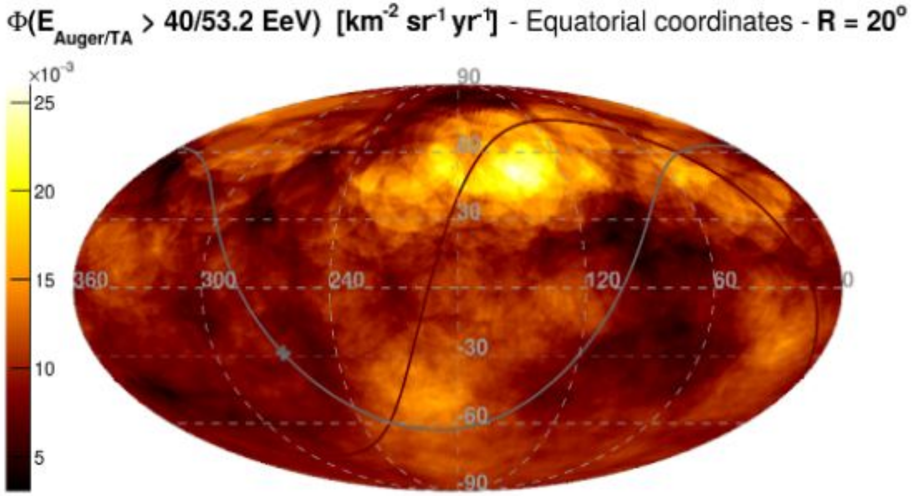
Result - Consequences on arrival directions

Looking at arrival directions

- ➔ Compute the flux in each pixel
- ➔ Do a top-hat smoothing with **10° radius**
- ➔ Dominated by Laniakea, Shapley cluster, Virgo Cluster.

Model $\Phi(E > 10^{19.6}\mathrm{eV})$ Data



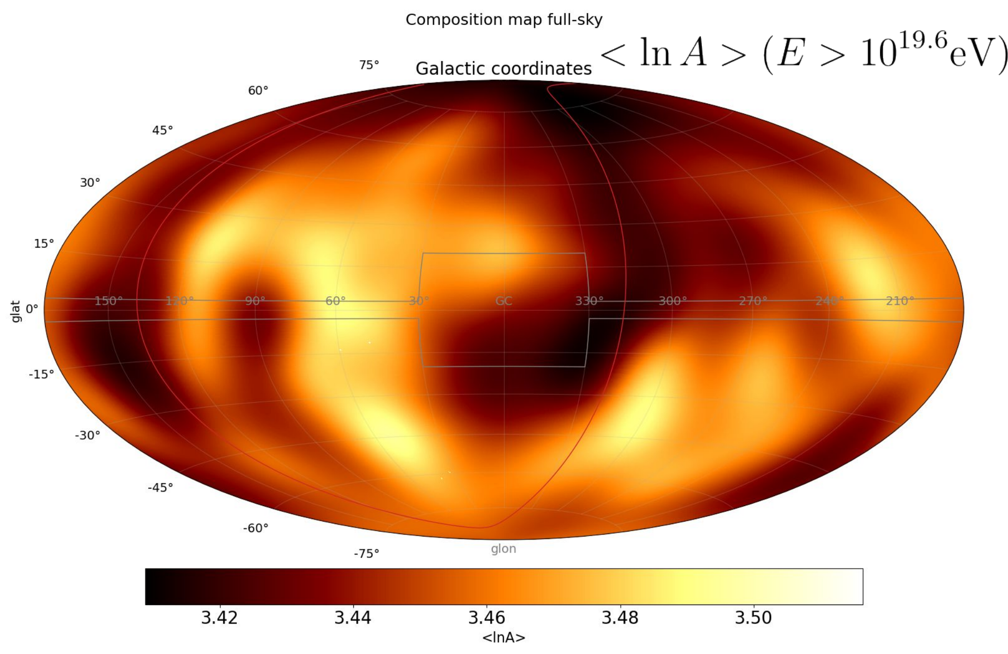


Conclusion

- ➔ An astrophysical model that shows consequences on arrival directions

What's next?

- ➔ We are implementing full X_{max} distribution into the code
- ➔ Magnetic confinement & screening is being implemented
- ➔ Give a composition map



Pub

Je contrôle les télescopes du plus grand observatoire à rayons cosmiques au monde !

992 vues • il y a 5 mois

SulliBoy

Je suis doctorant en astrophysique des hautes énergies. Dans cette vidéo, je vous embarque avec moi en Argentine dans la ...

Vous voulez savoir comment se passe un shift à l'observatoire Auger ! Allez voir ma vidéo ! :D

Thank you for your attention