Star Formation Rate as a tracer of UHECRs?

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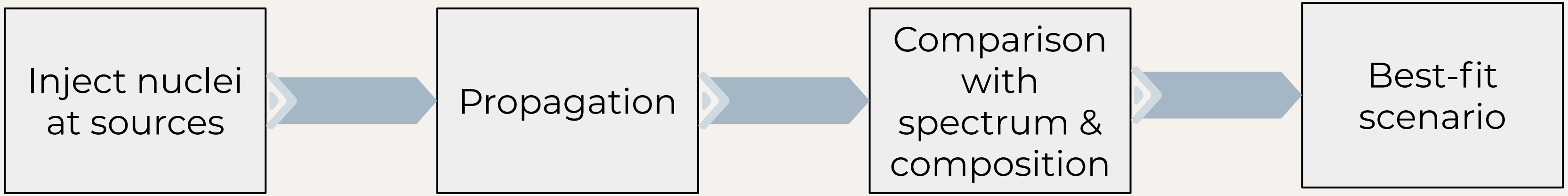
An astrophysical model: The Combined Fit

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

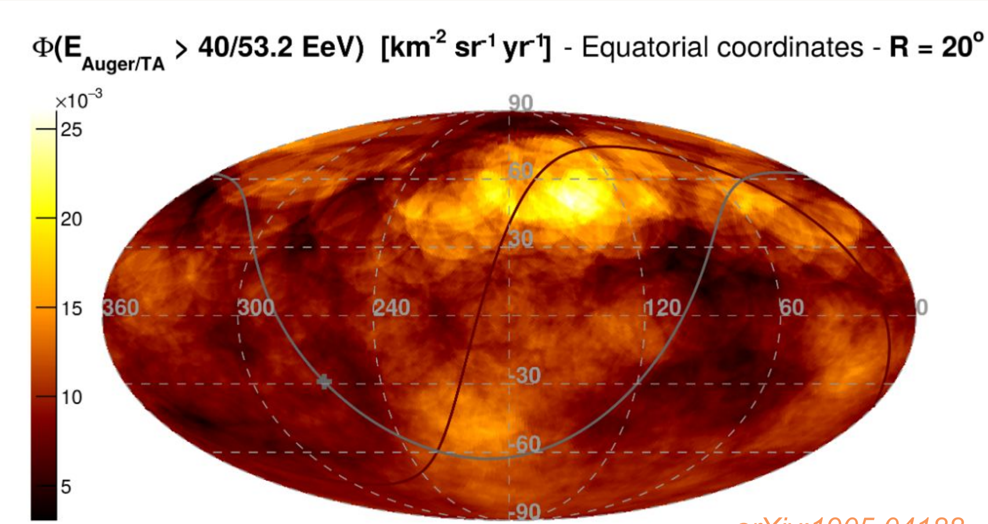


➔ 5 representatives masses injected at sources: **H**, **He**, **N**, **Si**, **Fe**

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

Combined Fit: How it works

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



[arXiv:1905.04188](https://arxiv.org/abs/1905.04188)

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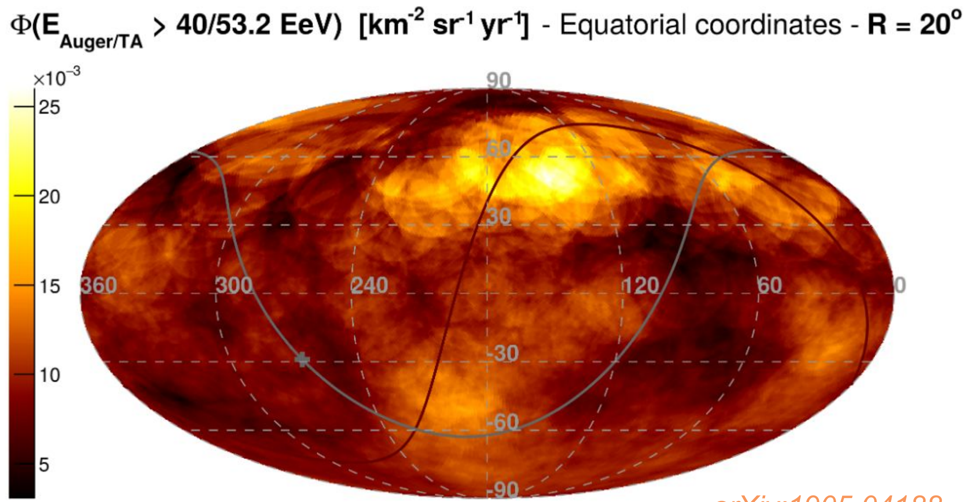

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Generation term

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.

$$q_A(E_\mathrm{g}, z) = \underbrace{\frac{dN_A}{dE_\mathrm{g}}(E_\mathrm{g})}_{\text{Gives the number of generated nuclei per source}} \times \underbrace{S(z)}_{\text{Gives the number of sources at a redshift z}}$$

Gives the number of generated nuclei per source

Gives the number of sources at a redshift z

Generation term: injected spectrum

Inject nuclei at sources

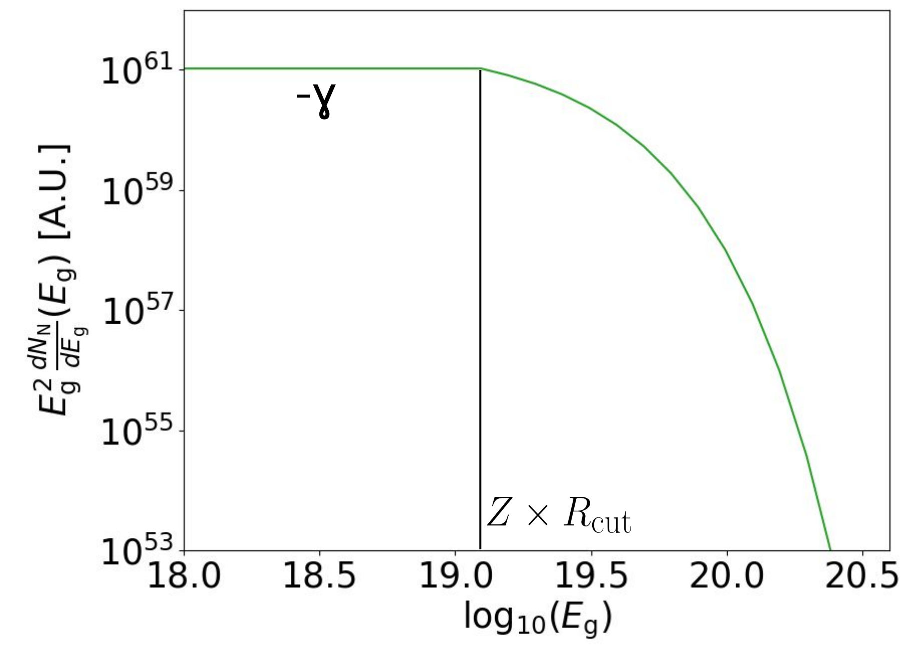
$$q_A(E_g, z) = \frac{dN_A}{dE_g}(E_g) \times S(z)$$

Gives the number of sources at a redshift z

Gives the number of generated nuclei per source

$$E_g \frac{dN_A}{dE_g}(E_g) = E_A \times \frac{E_g\, f(E_g)}{\int_0^\infty E_g\, f(E_g)\, dE_g}$$

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



Generation term: evolution of sources

Inject nuclei at sources

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

Gives the number of generated nuclei per source

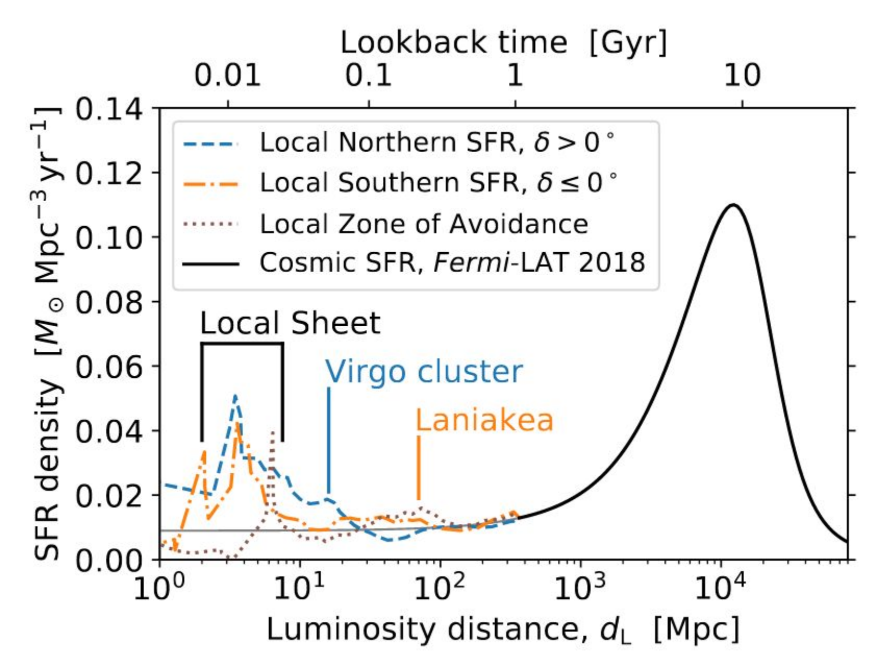
Gives the number of sources at a redshift z

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

$$S(z) = \boxed{k} \times \underbrace{\mathrm{SFRd(z)}}$$

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

$$[k] = \text{Number of sources per } \mathrm{M}_\odot$$



What are the free parameters ?

Inject nuclei at sources

- ➔ **γ** - 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 solar mass
- ➔ $\mathbf{E_{He} \times k}$ - Injected energy per injected solar mass
- ➔ $\mathbf{E_N \times k}$ - Injected energy per injected solar mass
- ➔ $\mathbf{E_{Si} \times k}$ - Injected energy per injected solar mass
- ➔ $\mathbf{E_{Fe} \times k}$ - Injected energy per injected solar mass

The total energy density

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

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

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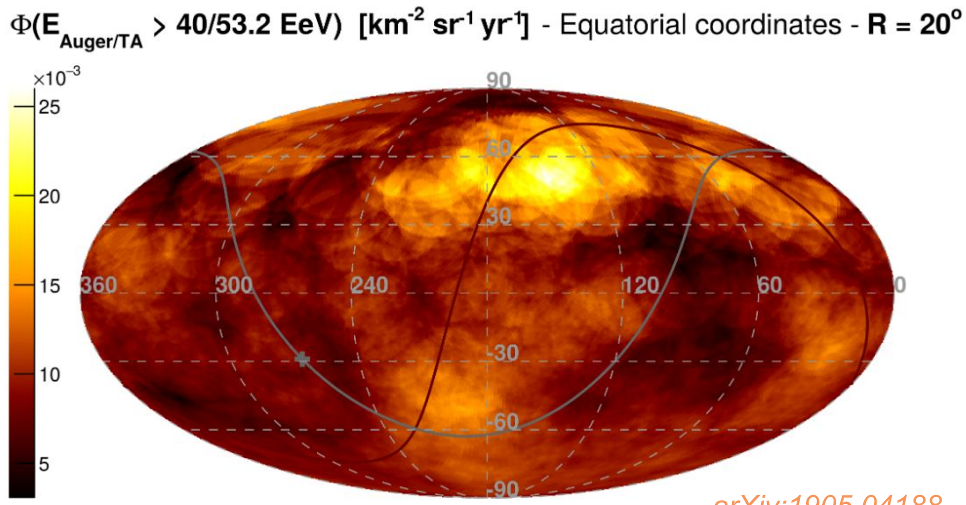

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Propagation: Tensor formalism

Propagation

- ➔ SimProp (arXiv:1705.03729) 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

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

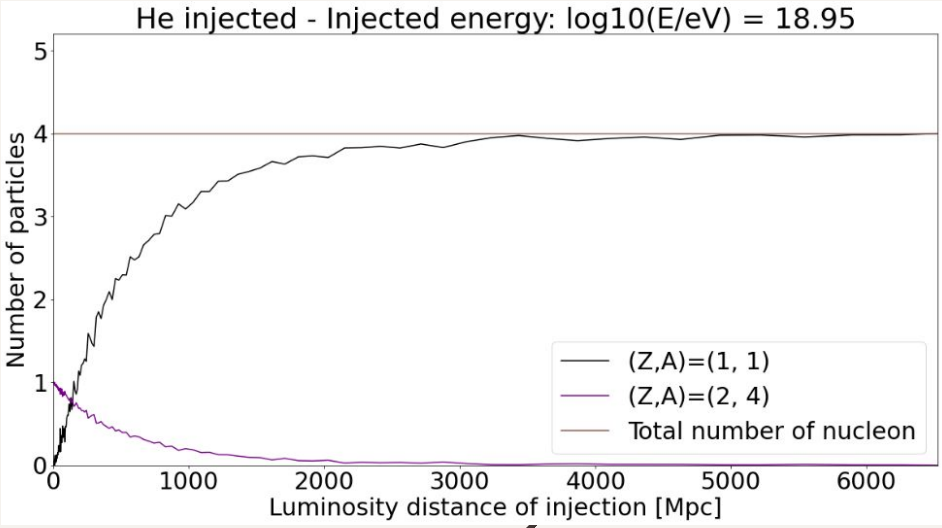
Injected mass

Injected energy

Injected redshift

Detected mass

Detected energy



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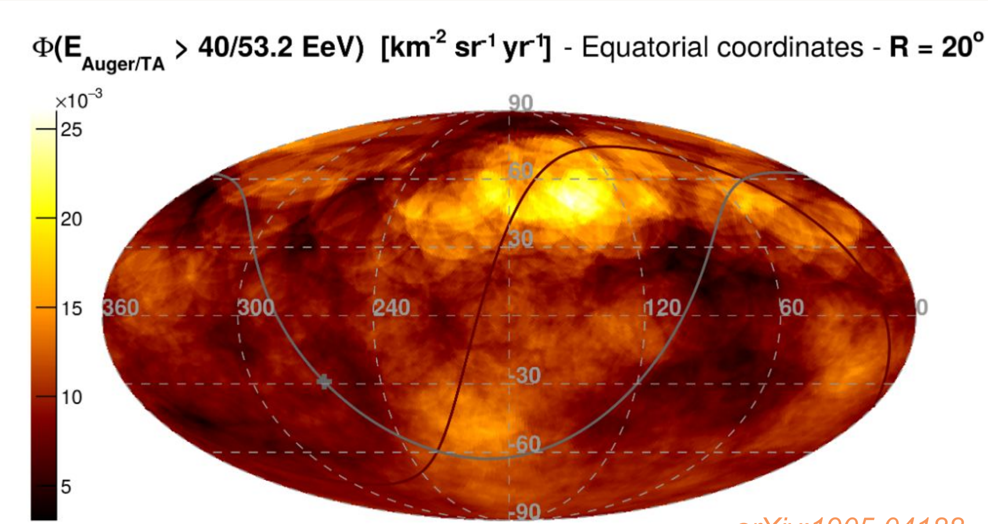

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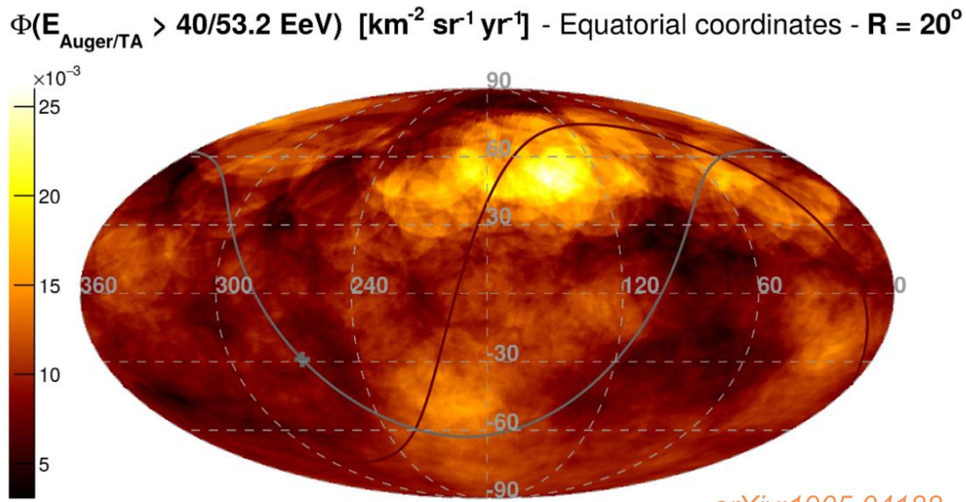

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Combined Fit: Minimization

Comparison with spectrum & **composition**

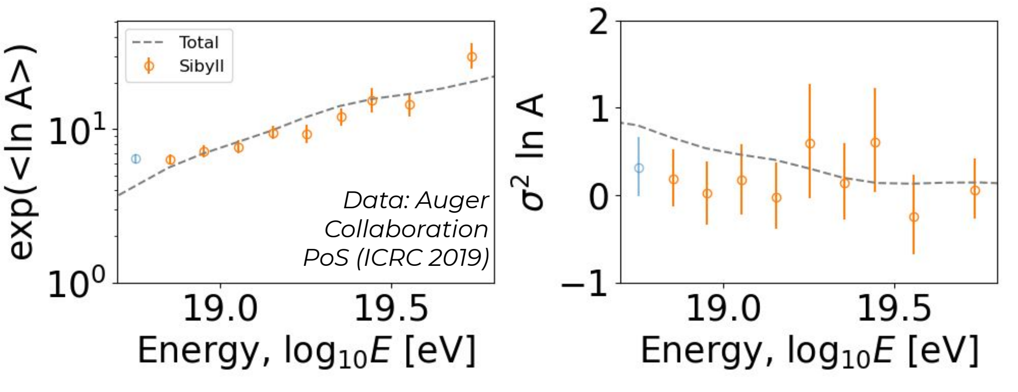
➔ **Tensor is contracted** to compute the flux of each detected nuclei

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

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

➔ Fit start at $\log_{10}E = 18.8$

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



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

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

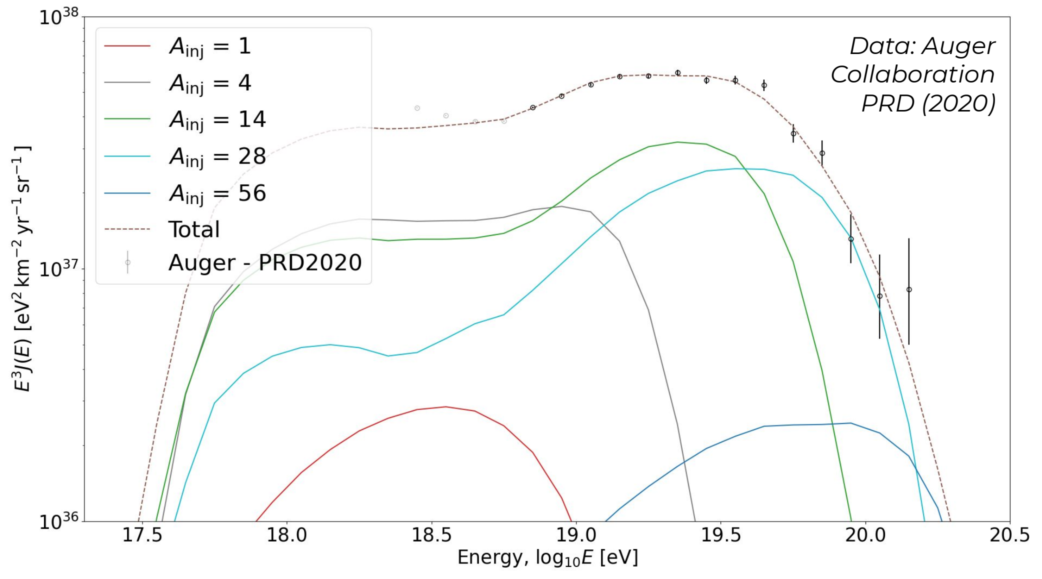
Combined Fit: Minimization

Comparison with **spectrum** & composition

➔ Tensor is contracted to compute the flux

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

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



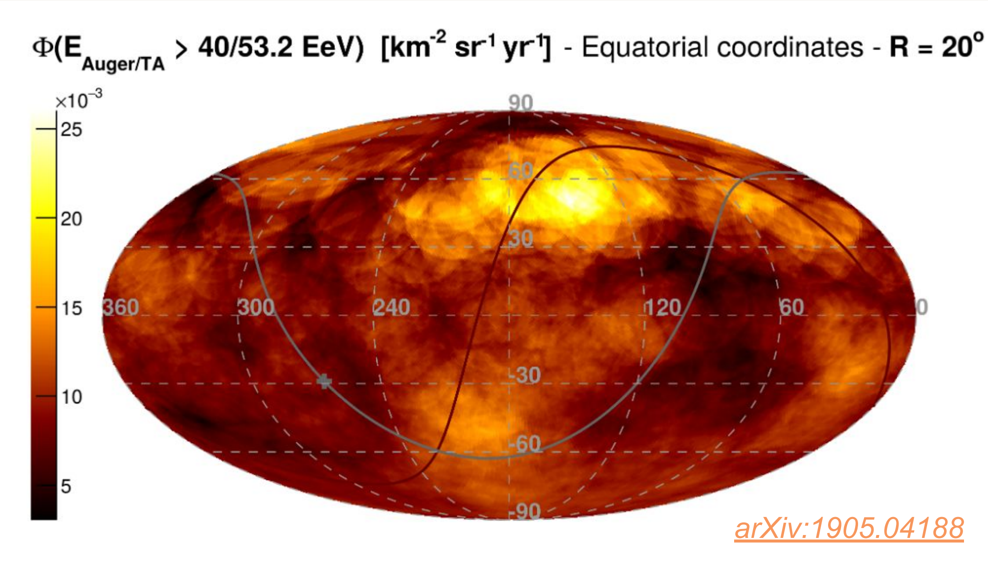
➔ Goodness of fit given by the deviance

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

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

Combined Fit: How it works

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



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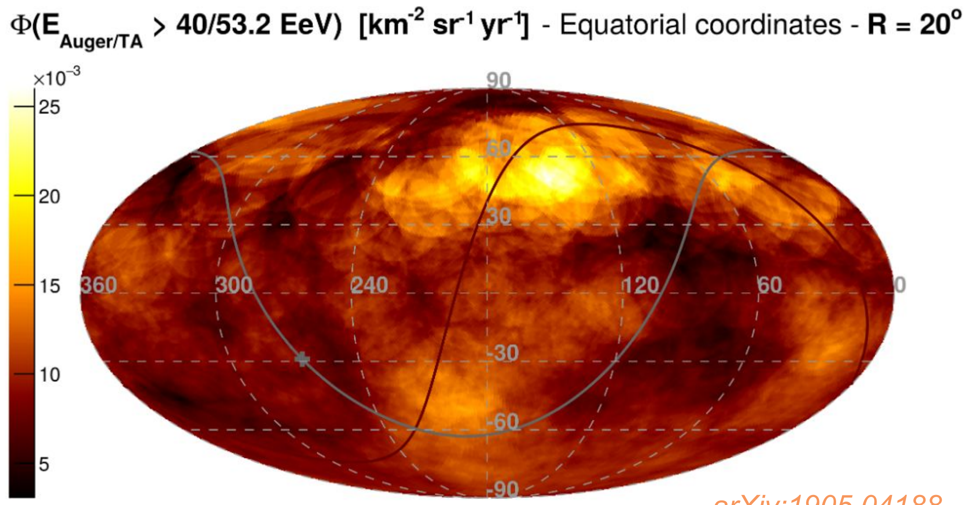

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Combined Fit: Best-fit scenario

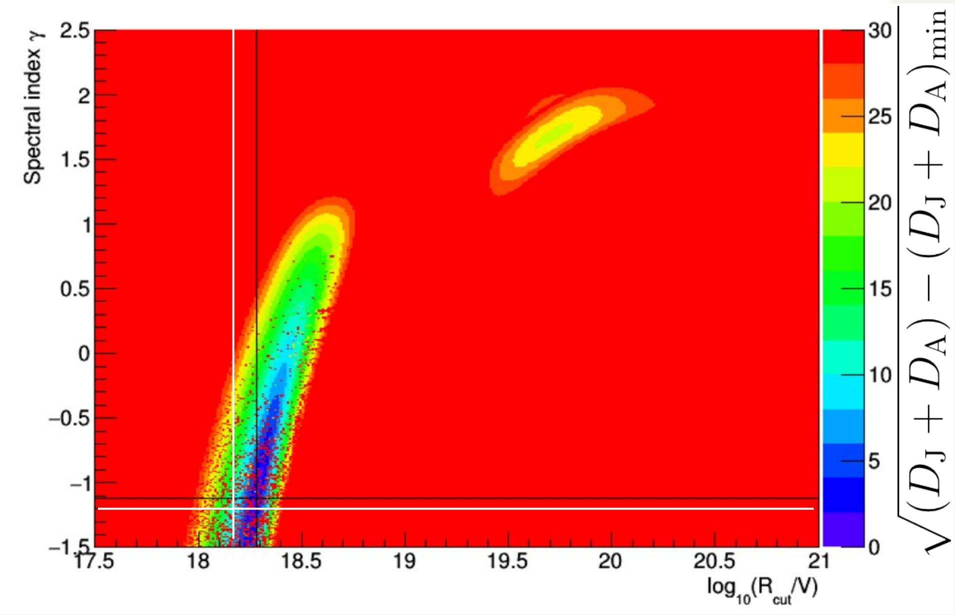
Comparison with spectrum & composition

- ➔ In agreement with previous work
- ➔ Reasonable deviance

R_{cut} (this work)	γ (this work)	R_{cut} (Q. Luce PhD)	γ (Q. Luce PhD)
18.2	-1.2	18.28 ±0.02	-1.12±0.12

D_J (num. of points) (this work)	D_A (num. of points) (this work)
20.6 (14)	14.8 (18)

Extracted from Q. Luce PhD:



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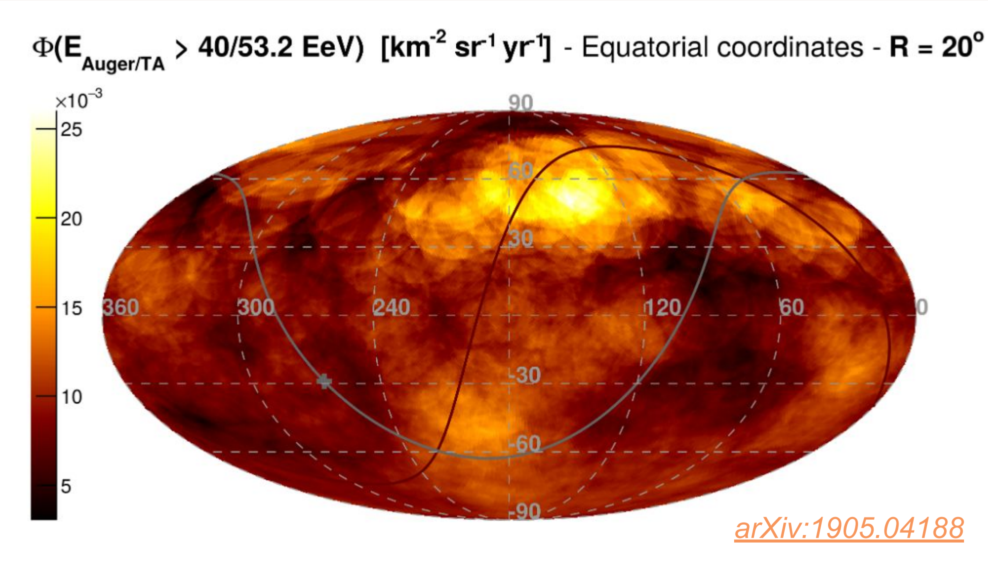

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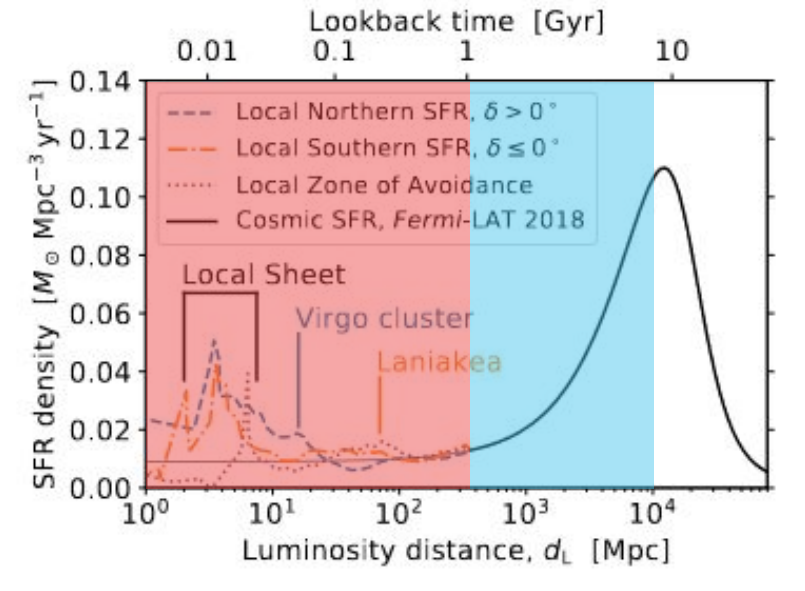
Consequences on arrival directions

Looking at arrival directions

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



- ➔ **Discrete:** Compute the flux for each galaxy from the catalogue (~400 000)
- ➔ **Continuous:** Compute the flux as before, from z=0.08 to z=2.5

$$J_{\rm A}(E)|_{\rm Gal} = \frac{1}{4\pi\, d_{\rm L}^2} \sum_{A_{\rm g}} \sum_{E_{\rm g}} S(z_{\rm Gal}) \times \frac{dN_{A_{\rm g}}}{dE_{\rm g}} \times T_A(E_{\rm g}, z, E_{\rm det}, (Z,A)_{\rm det}) \Delta E_{\rm g}$$

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

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

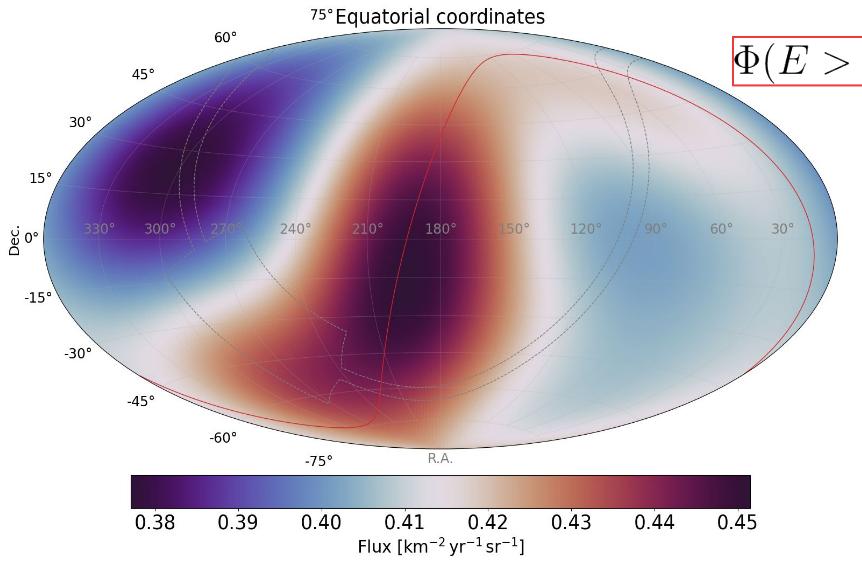
Result - Consequences on arrival directions

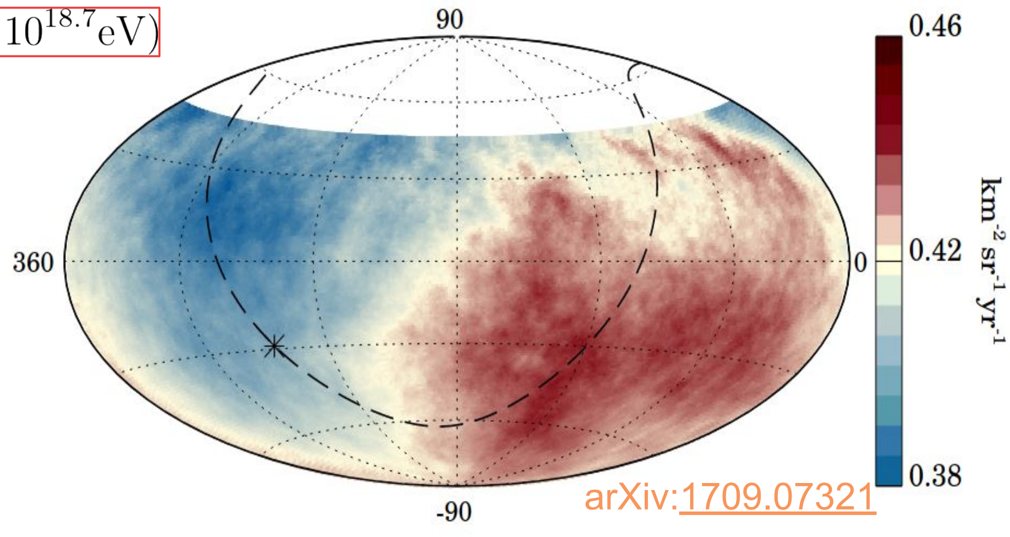
Looking at arrival directions

- ➔ Compute the flux in each pixel
- ➔ Do a **Fisher smoothing** with 30° radius

Model

Data from Auger (top-hat smoothing 45°)



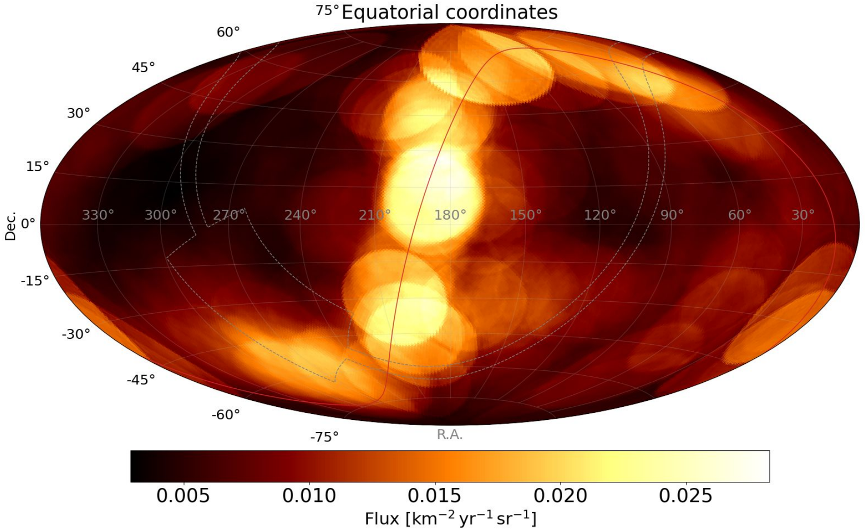


Result - Consequences on arrival directions (highest energies)

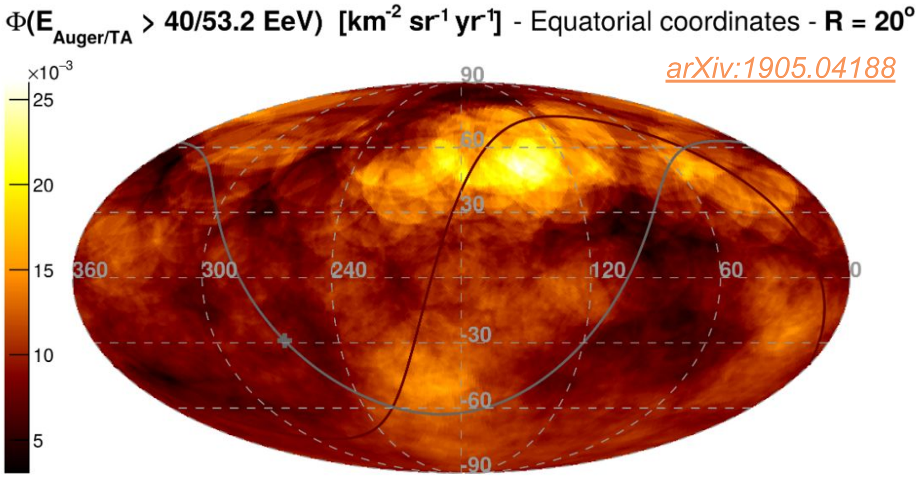
Looking at arrival directions

- ➔ Do a top-hat smoothing with **20° radius**
- ➔ Dominated by Laniakea, Shapley cluster, Virgo Cluster.

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



Data



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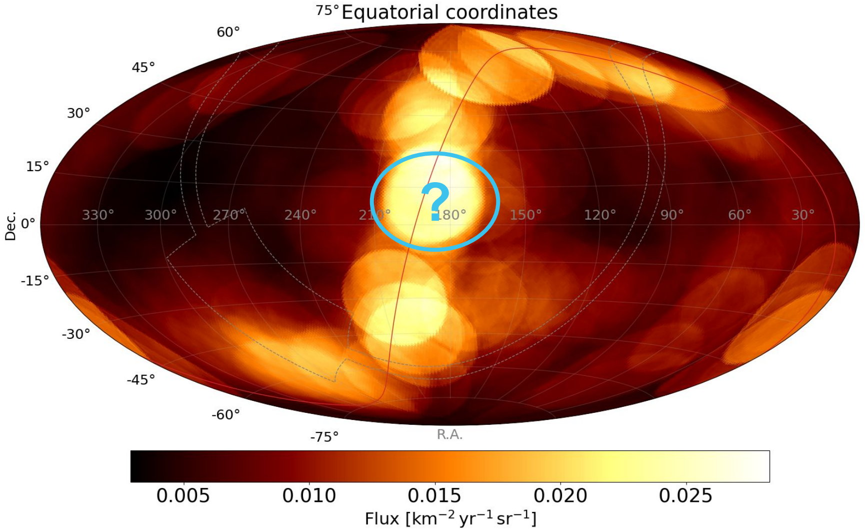

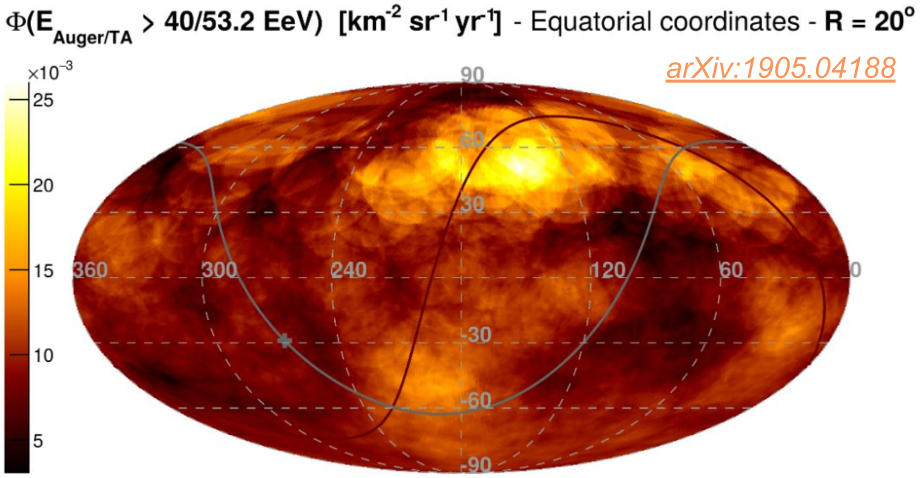

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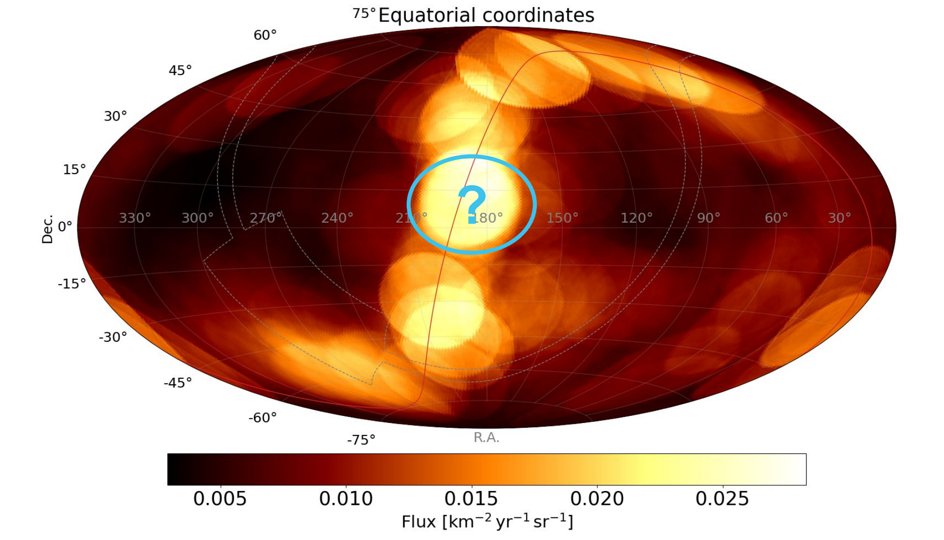


Conclusion:

- ➔ We are missing an ingredient

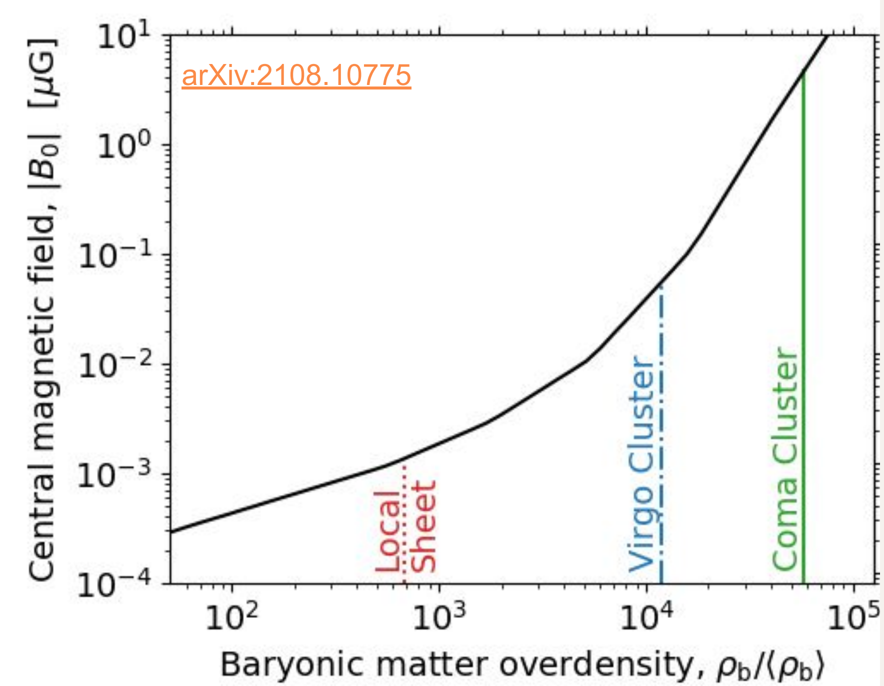
Idea, question:

- ➔ Is magnetic cluster field plays a major role explaining the unseen virgo cluster?

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

Definition rigidity:
$R = E/Z$

- ➔ **Depends on rigidity** of UHECR

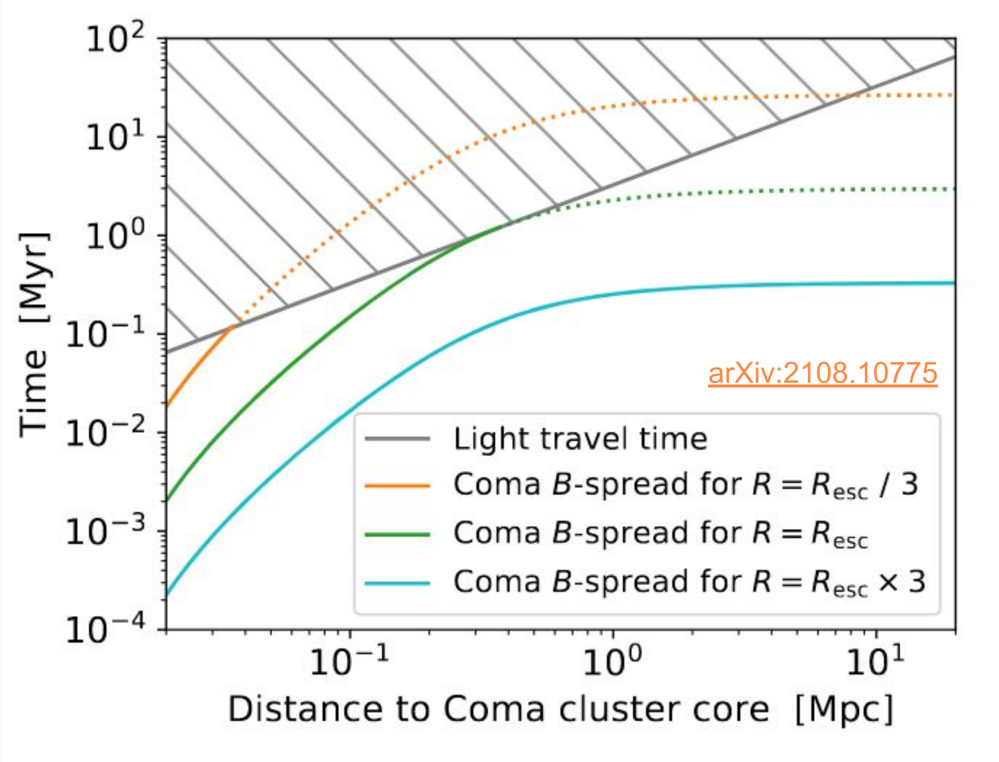
Time of spreading vs light travel time

Definition rigidity:
R = E/Z

- ➔ **Depends on rigidity** of UHECR

Hypothesis:

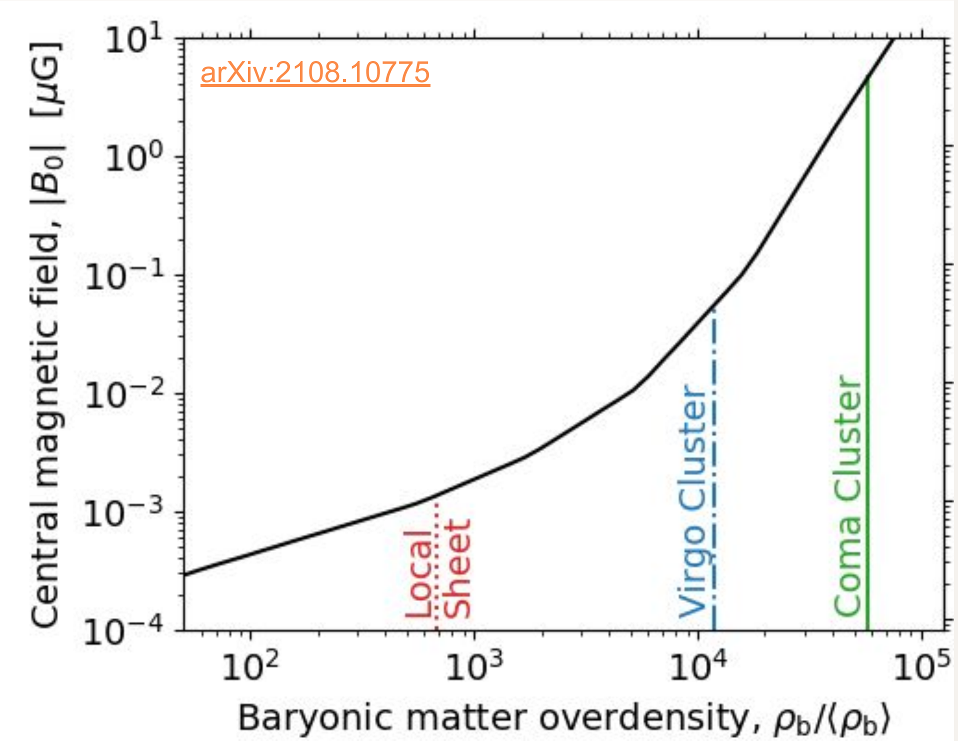
- ➔ If the time spend in the cluster due to magnetic field spread **is lower than the light travel time** → **UHECR escape**.
- ➔ If the time **is equal or bigger** → **UHECR get stuck**
- ➔ $\mathbf{R_{esc}}$ is defined as the rigidity where **times equal**



Magnetic confinement

Definition rigidity:
R = E/Z

Consequences:

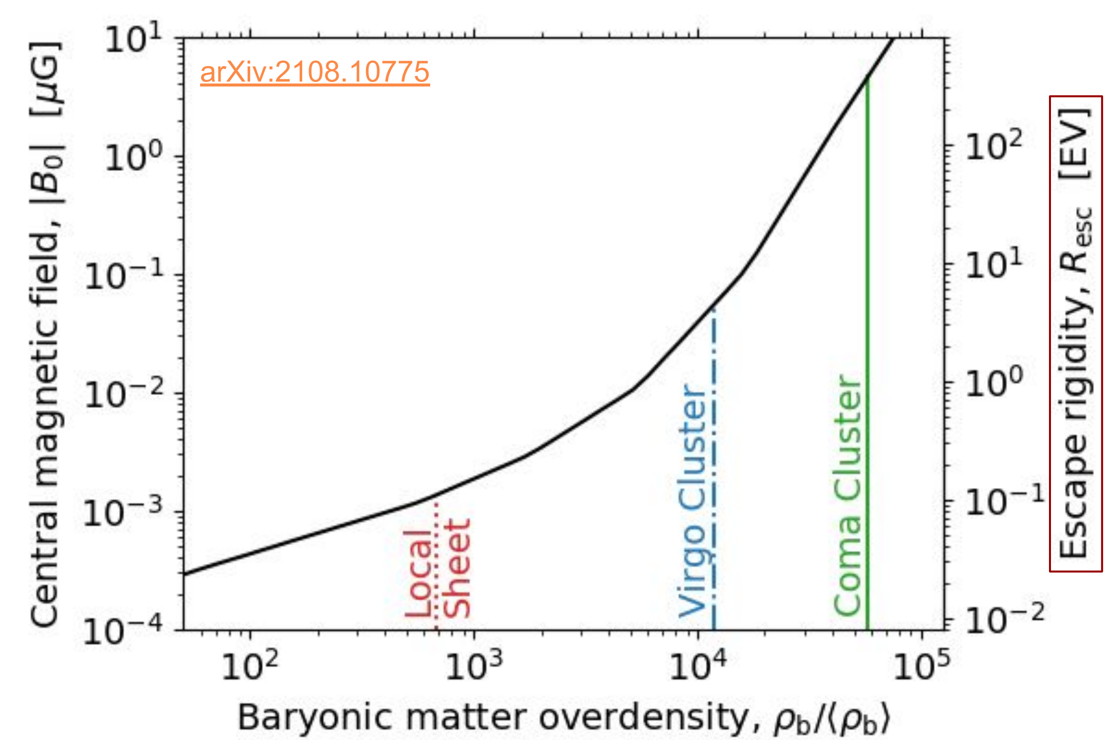


Magnetic confinement

Definition rigidity:
R = E/Z

Consequences:

➔ We can associate an **escape rigidity R_{esc}** for each cluster.



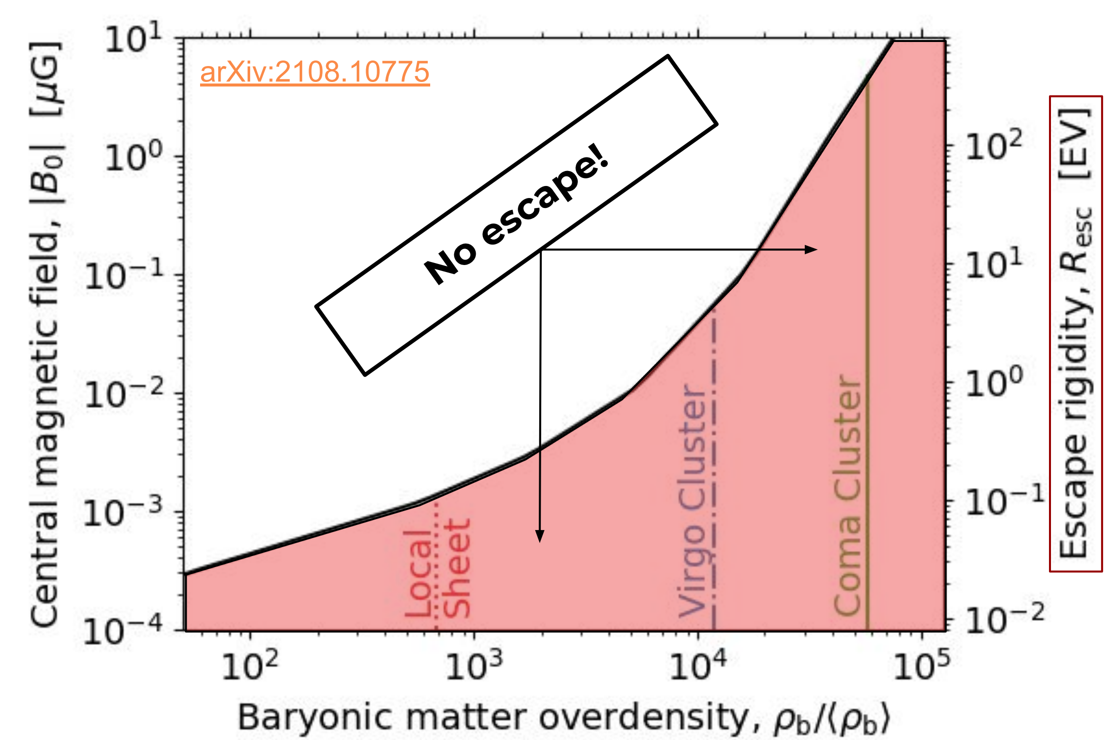
Magnetic confinement

Definition rigidity:
R = E/Z

Consequences:

➔ We can associate an **escape rigidity R_{esc}** for each cluster.

➔ **Conclusion:** Some clusters cannot be seen

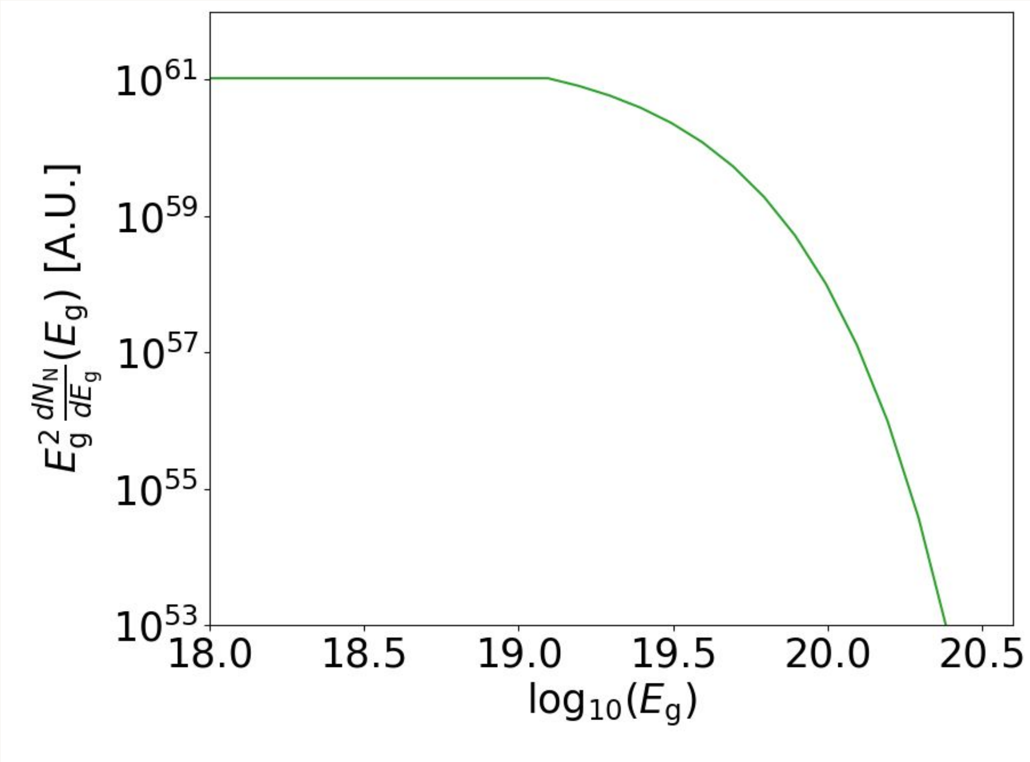


Back to injection spectrum

Consequences:

➔ One $\mathbf{R_{esc}}$ per galaxy

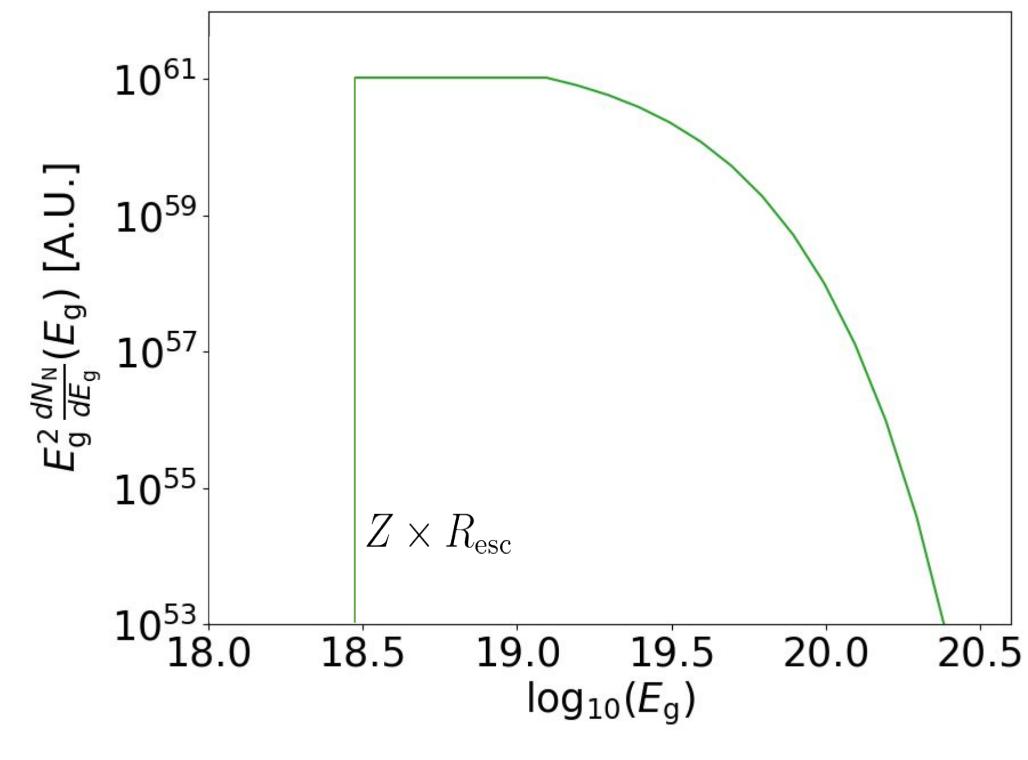
➔ The injection term is changed for **each galaxy** !



Back to injection spectrum

Consequences:

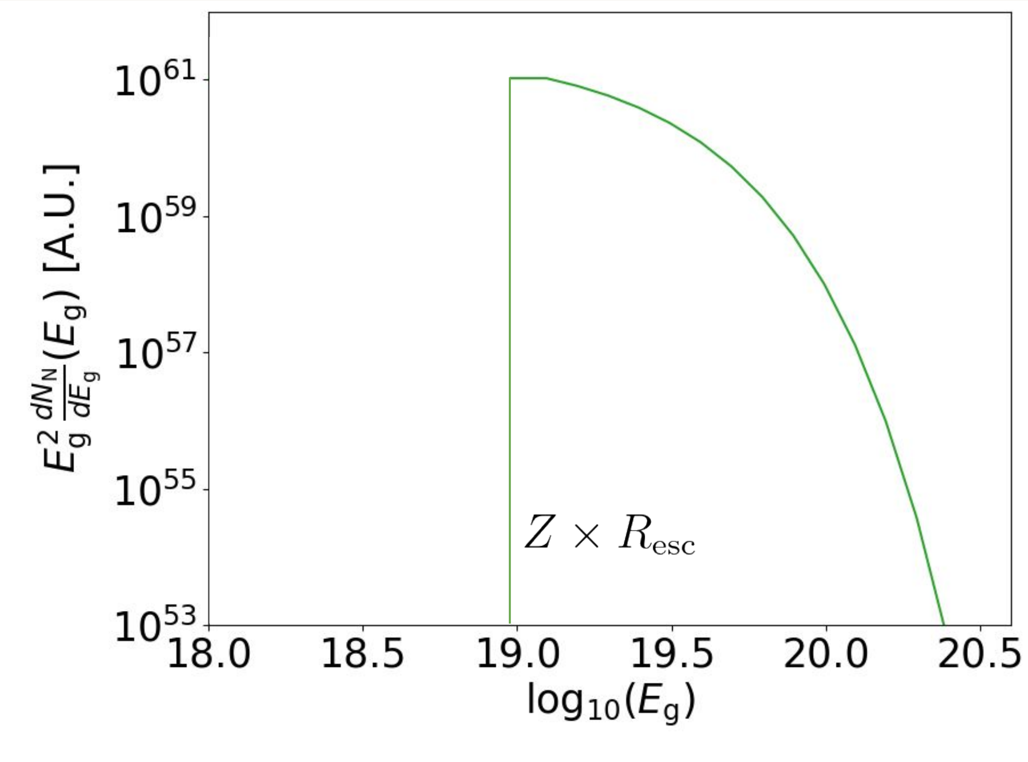
- ➔ One $\mathbf{R_{esc}}$ per galaxy
- ➔ The injection term is changed for **each galaxy** !
- ➔ **Example:** Galaxy A - “small” cluster magnetic field



Back to injection spectrum

Consequences:

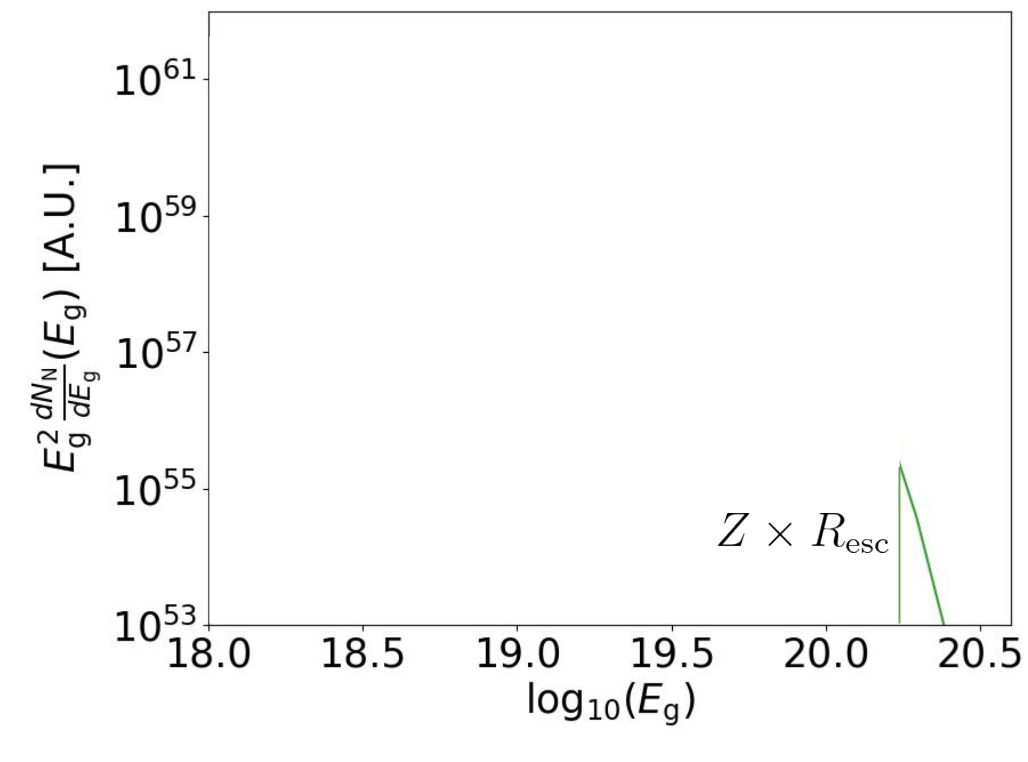
- ➔ One $\mathbf{R_{esc}}$ per galaxy
- ➔ The injection term is changed for **each galaxy** !
- ➔ **Example:** Galaxy B - “medium” cluster magnetic field



Back to injection spectrum

Consequences:

- One $\mathbf{R_{esc}}$ per galaxy
- The injection term is changed for **each galaxy** !
- **Example:** Galaxy C - "Huge" cluster magnetic field
  → No escape at all

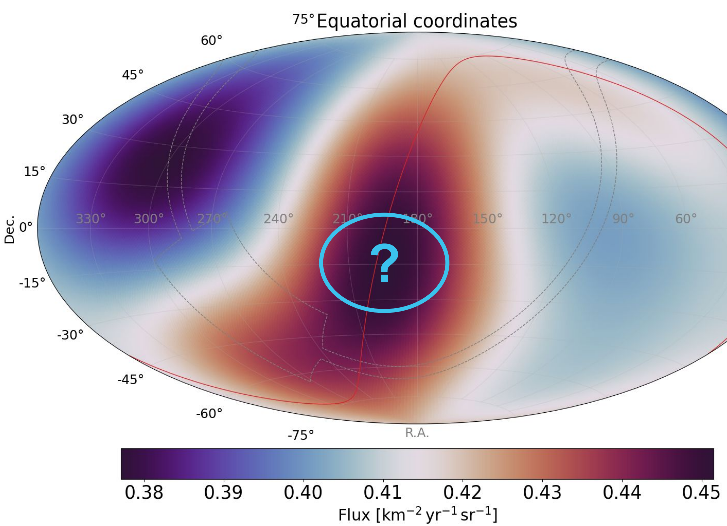


How will it affect the map?

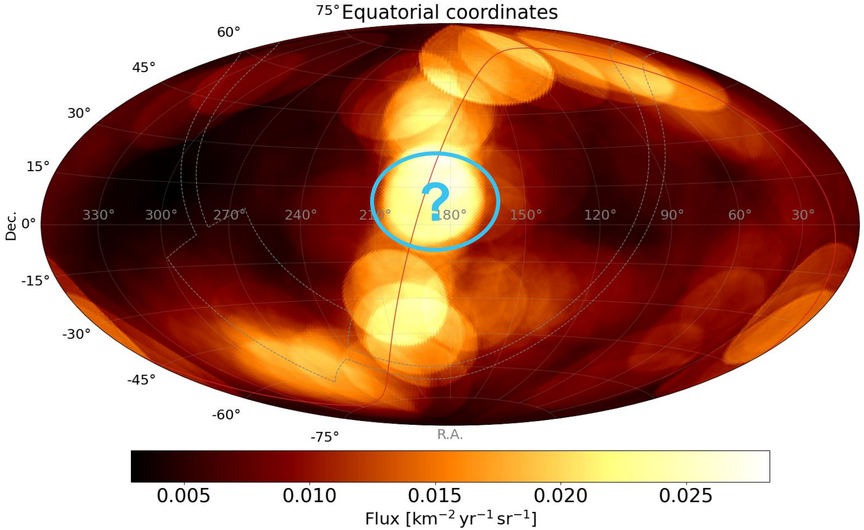
Looking at arrival directions

➔ Need to compute the map to see which clusters will contribute

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



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



Conclusion

- ➔ An astrophysical model that shows consequences on arrival directions

What's next?

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