ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

NATURWISSENSCHAFTLICHE FAKULTÄT

The origin of UHECR: current status of a decades-long puzzle

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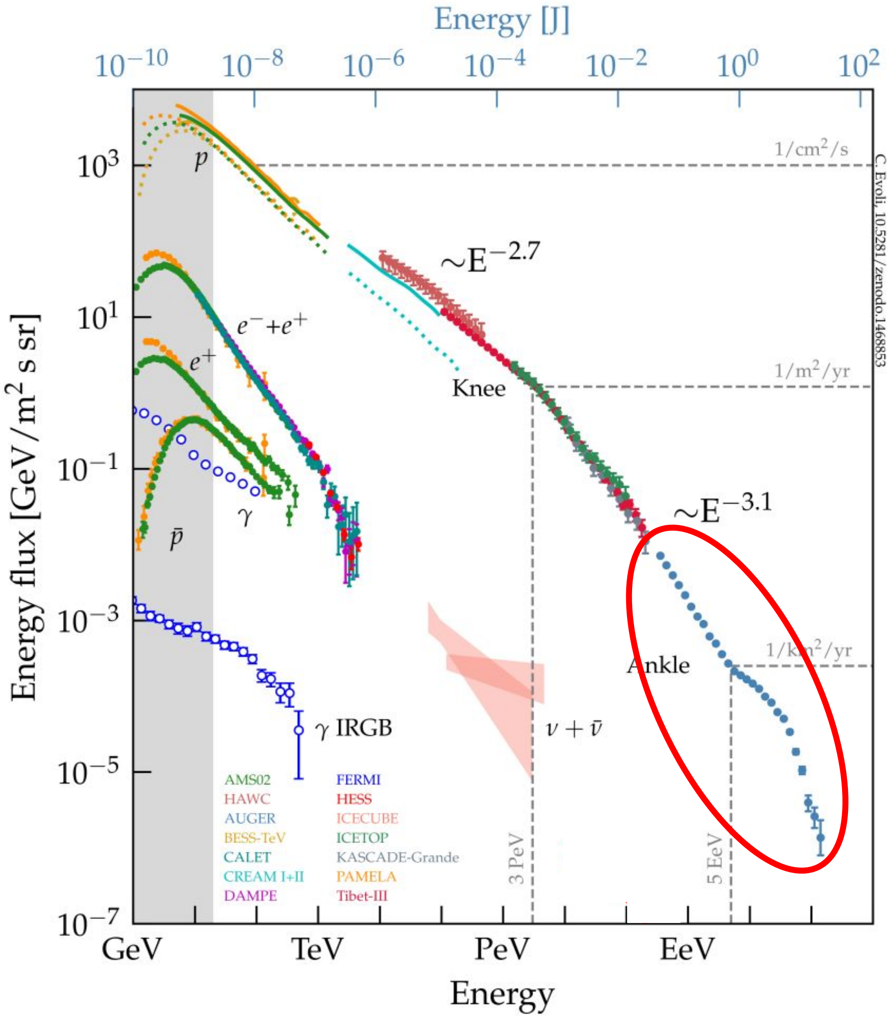
Friday, May 7th, 2020

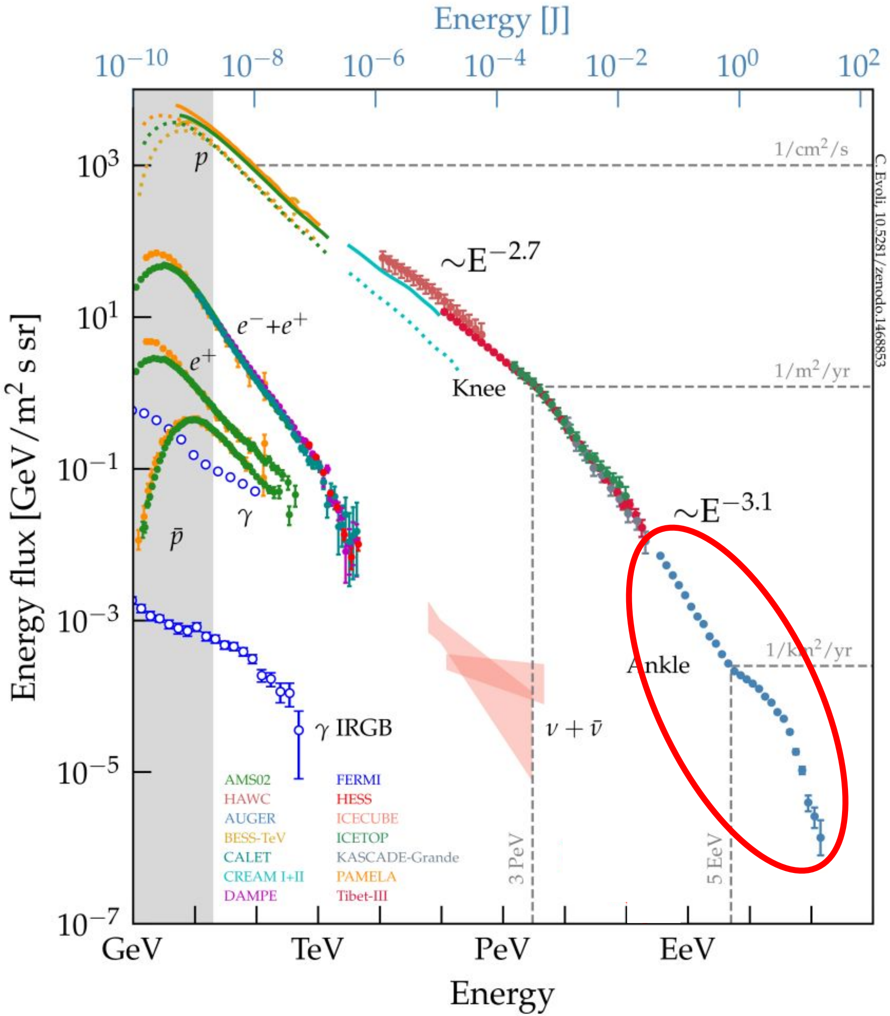
UHECR

- ➢ Astroparticles in the EeV range;
- ➢ Most energetic known:
  - ○ Probes to the extremes of the Universe;



UHECR

- ➢ Astroparticles in the EeV range;
- ➢ Most energetic known:
  - ○ Probes to the extremes of the Universe;
- ➢ Charged:
  - ○ Don't point directly back to their sources.



The puzzle: what are their origins?

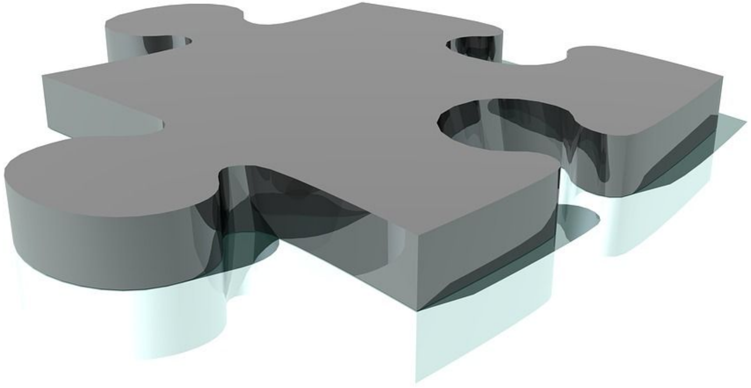
- Astroparticles in the EeV range;
- Most energetic known:
  - Probes to the extremes of the Universe;
- Charged:
  - Don't point directly back to their sources.

The pieces: experimental data

- ➢ Very low flux (< 1/km²/year);
- ➢ Huge ground-based experiments:
  - ○ Pierre Auger Observatory:
    - ■ ~3000 km^2;
    - ■ Argentina;
  - ○ Telescope Array:
    - ■ 762 km^2;
    - ■ USA.

The pieces: experimental data

- Three main observables:
  - Energy spectrum;
  - Mass composition;
  - Arrival directions.



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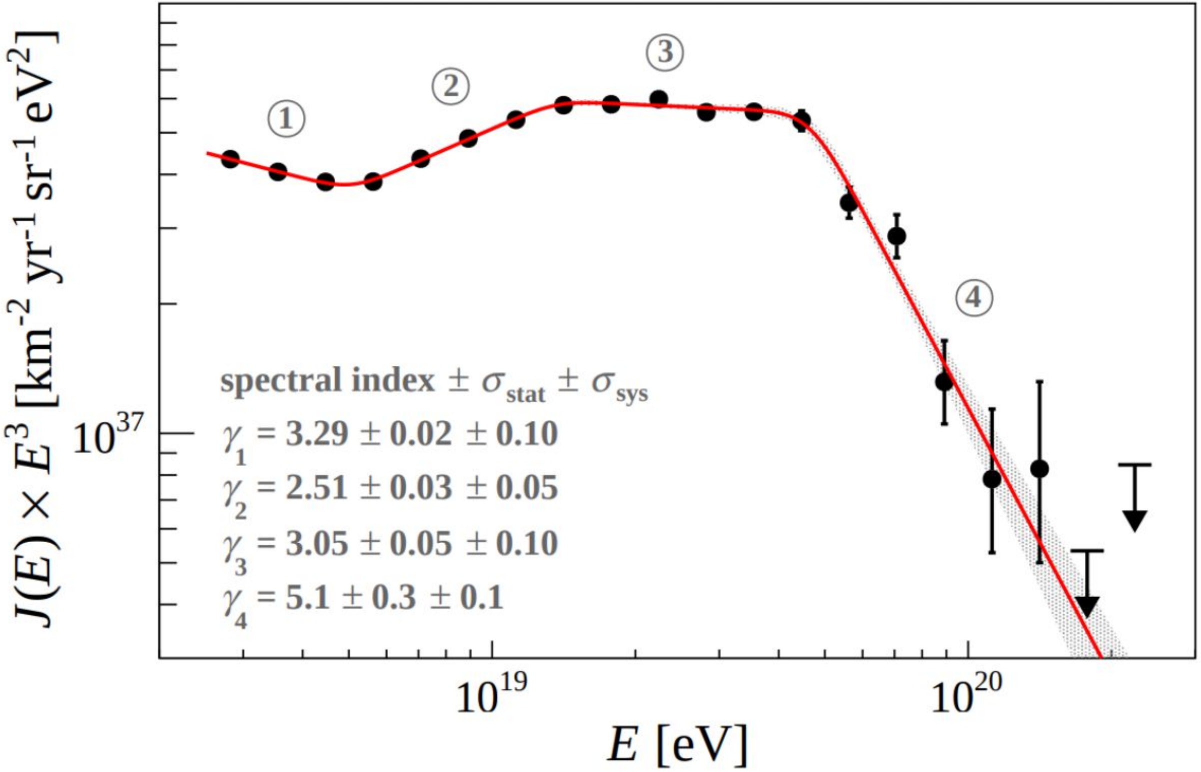


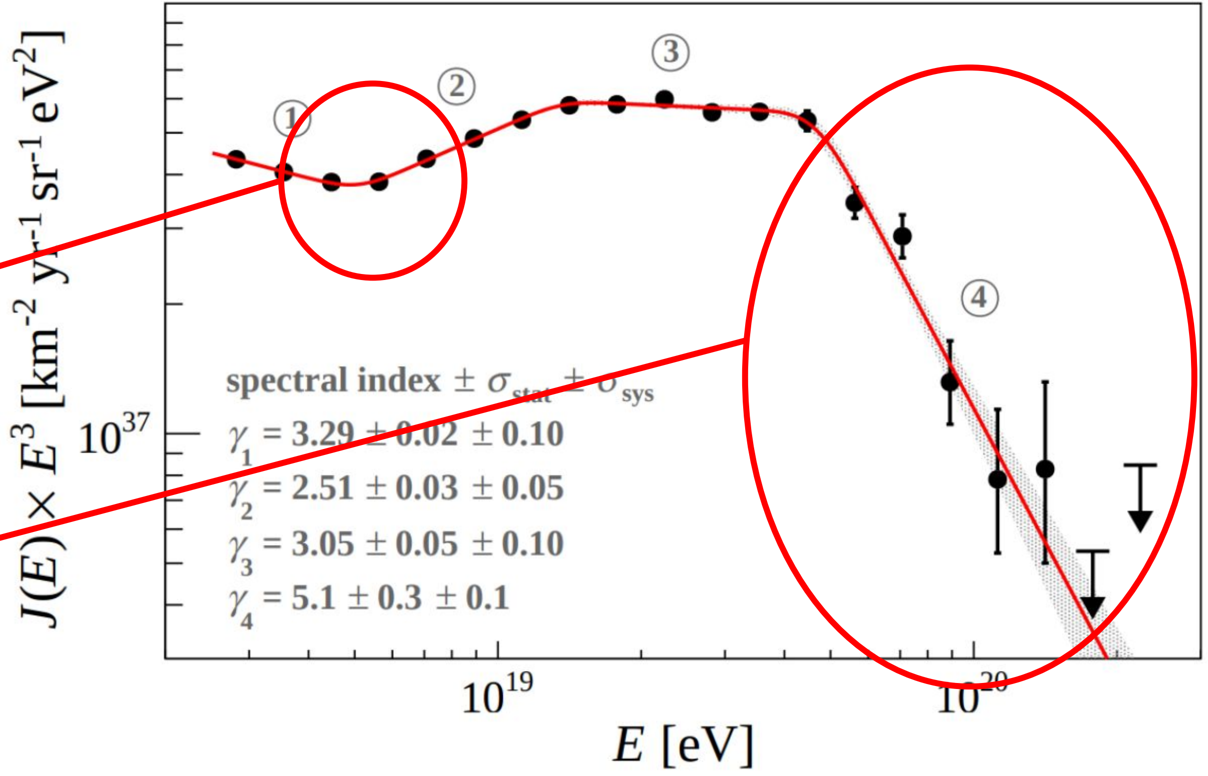
The Pierre Auger Collaboration, **Phys. Rev. Let.**, 2020

The pieces: experimental data

- Three main observables:
  - Energy spectrum;

Ankle

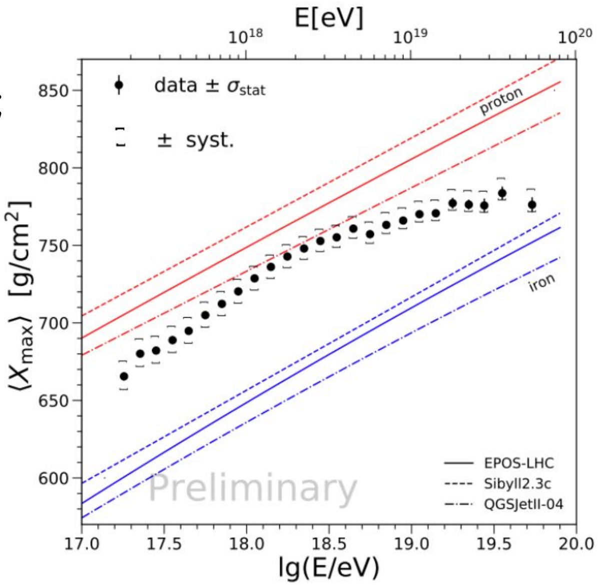
Suppression

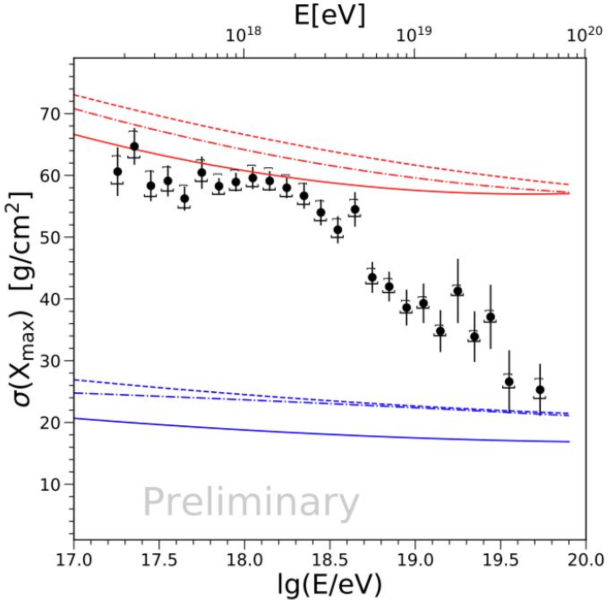


The Pierre Auger Collaboration, **Phys. Rev. Let.**, 2020

The pieces: experimental data

- Three main observables:
  - Energy spectrum;
  - Mass composition;
    - Not event by event;
    - Intermediate mass for the highest energies;
    - Relies on models for the hadronic interactions.





Yushkov, A., **ICRC 2019**

The pieces: experimental data

- Three main observables:
  - Energy spectrum;
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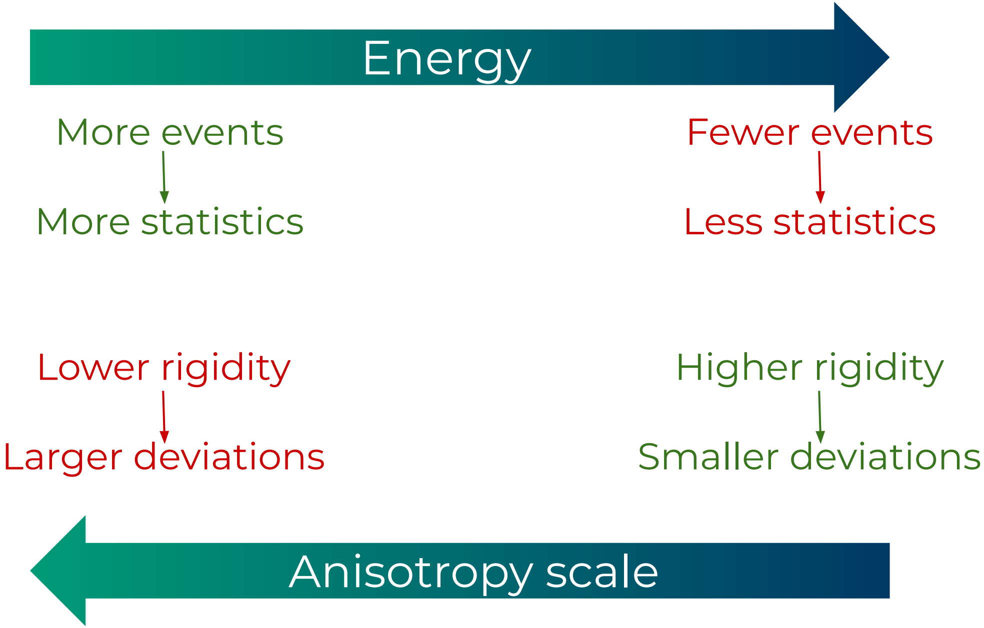
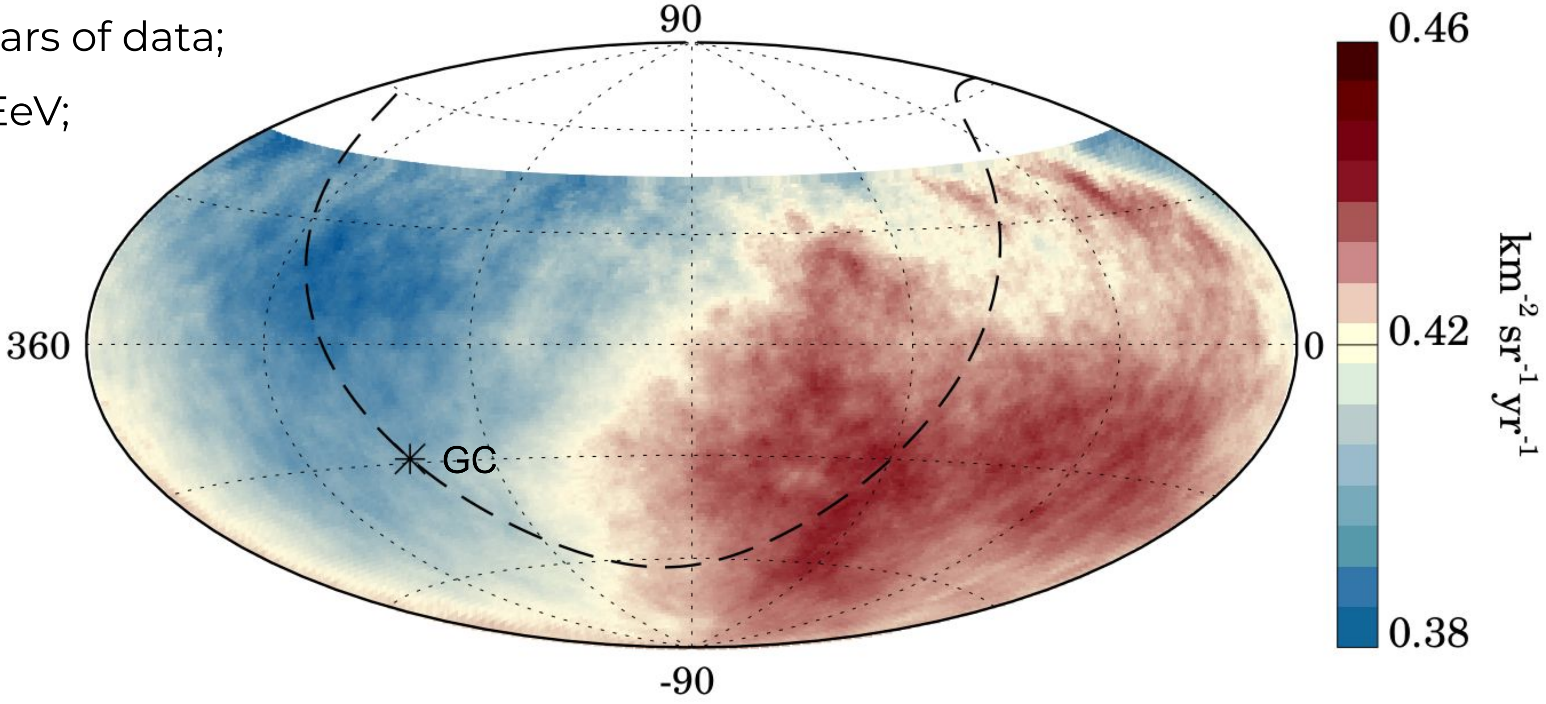


Low energy - large scale

➢ Auger's large scale anisotropy:
  - 12,5 years of data;
  - E > 8 EeV;



The Pierre Auger Collaboration, **Science**, 2017

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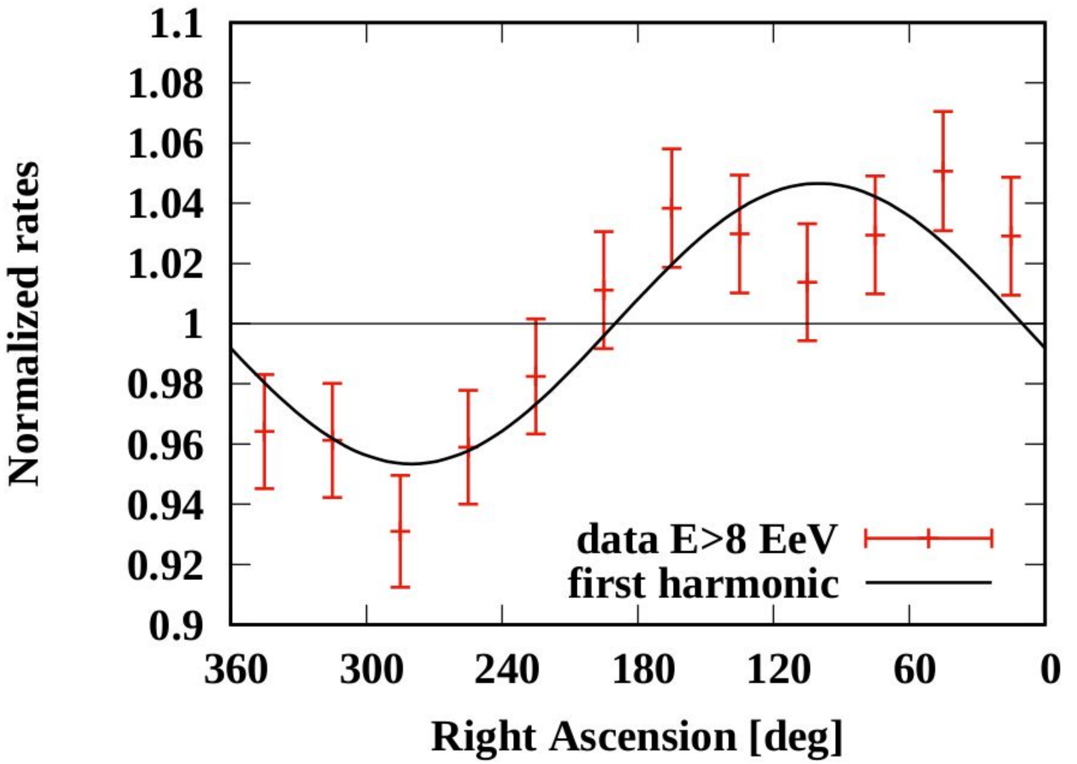


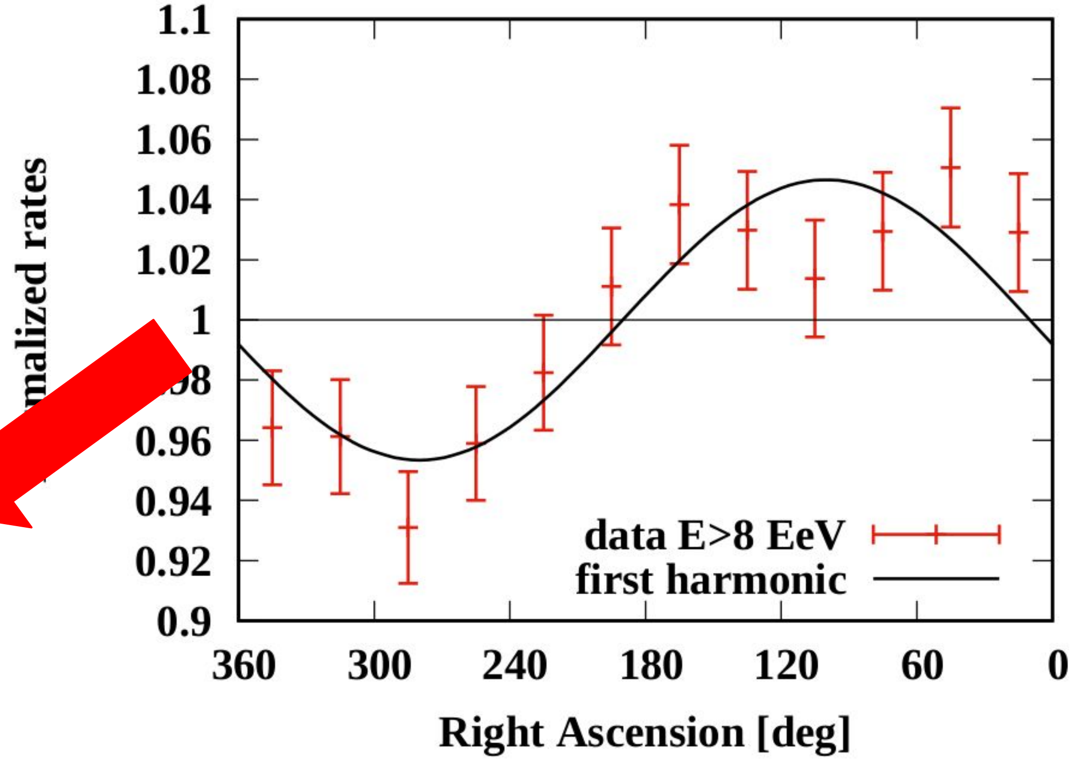
The Pierre Auger Collaboration, **Science**, 2017

Low energy - large scale

➢ Auger's large scale anisotropy:

- 12,5 years of data;
- E > 8 EeV;
- Dipolar behavior;

$$1 + d\cos\theta$$



The Pierre Auger Collaboration, **Science**, 2017

Low energy - large scale

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Rayleigh Analysis

$$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos \alpha_i, \qquad b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin \alpha_i$$

$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}, \qquad \tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$

The Pierre Auger Collaboration, **Science**, 2017

Low energy - large scale

➢ Auger's large scale anisotropy:

- 12,5 years of data;
- E > 8 EeV;
- Dipolar behavior;

Statistically consistent with *d*=0

Energy [EeV]	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d [°]	Dipole right ascension α_d [°]
4 to 8	-0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
8	-0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

The Pierre Auger Collaboration, **Science**, 2017

d>0 with 5.2σ

Low energy - large scale

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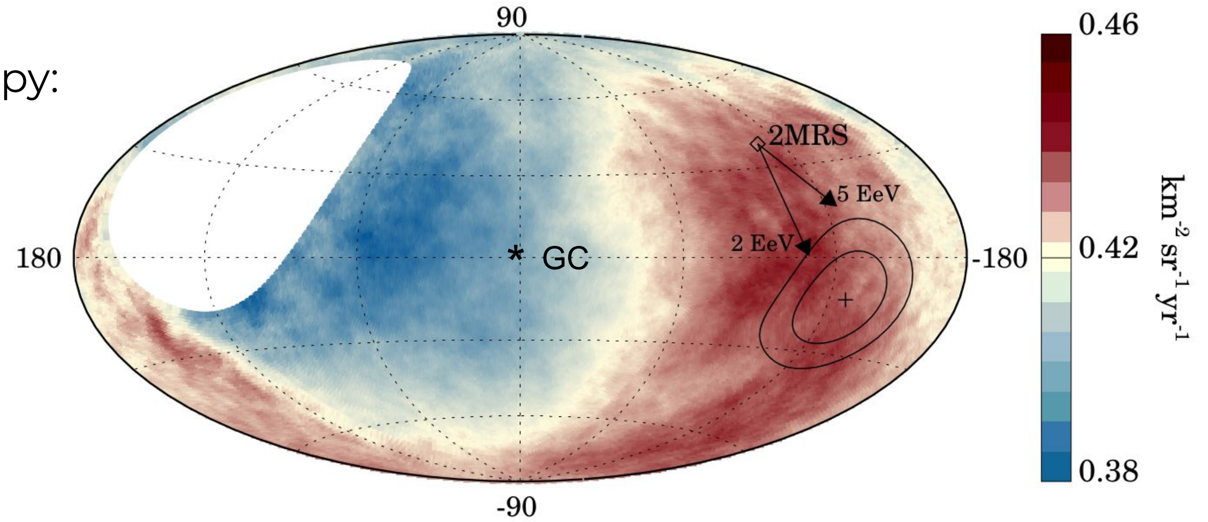
  - 12,5 years of data;
  - E > 8 EeV;
  - Dipolar behavior;



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The Pierre Auger Collaboration, **Science**, 2017

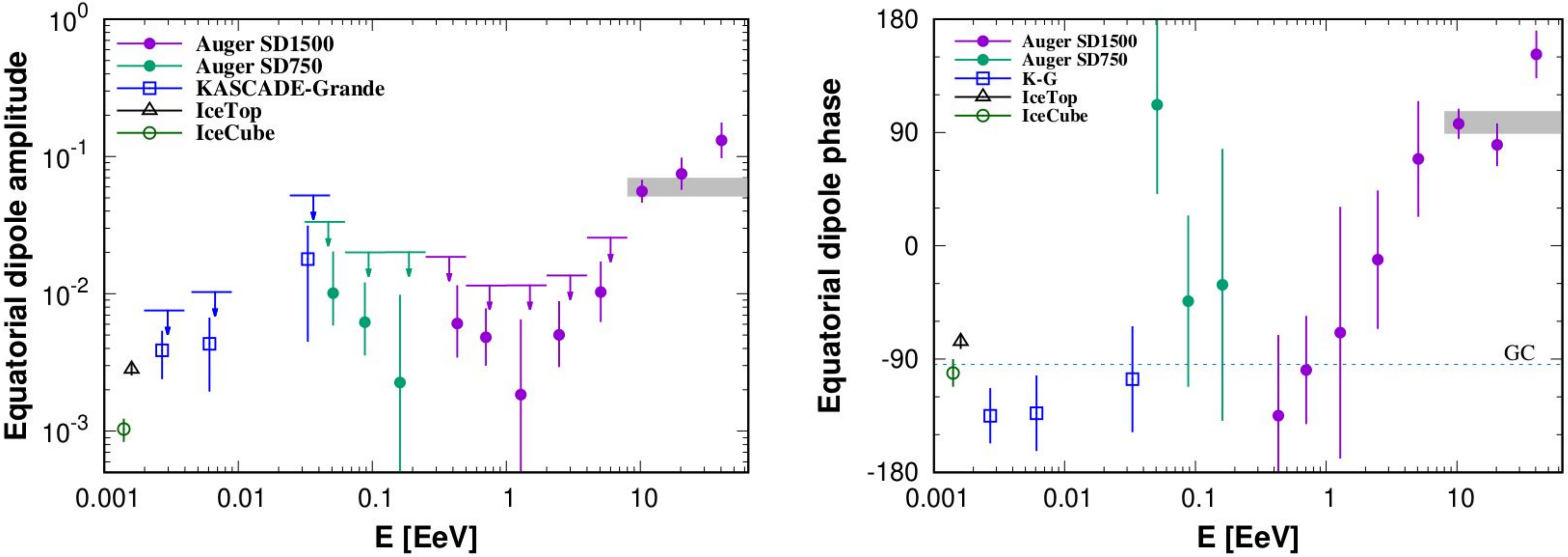
outwards the galactic center

Low energy - large scale

- Auger's large scale anisotropy:
  - 12,5 years of data;
  - E > 8 EeV;
  - Dipolar behavior:
    - 6.5% amplitude;
    - points outward the GC;

Low energy - large scale

- Evolution with energy:
  - Dipole in right ascension;
  - 14,5 yr of Auger data;



The Pierre Auger Collaboration, **Astrophys. J.**, 2020

Low energy - large scale

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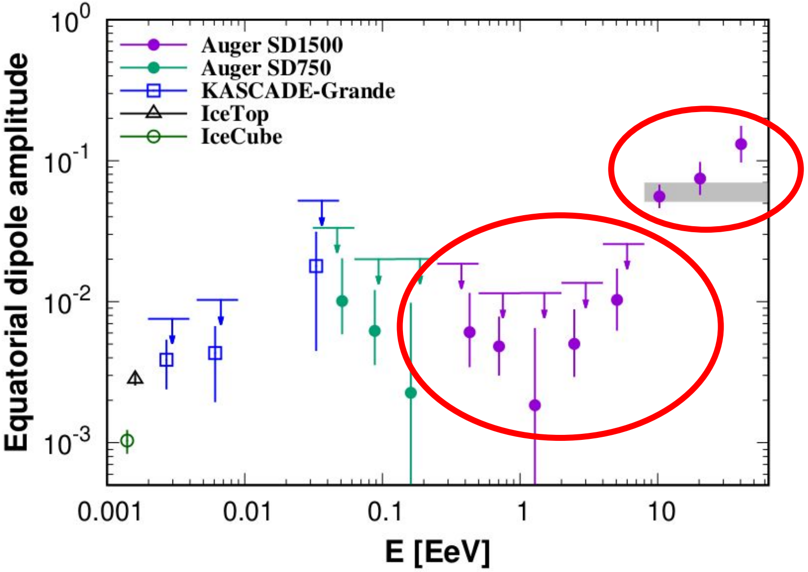
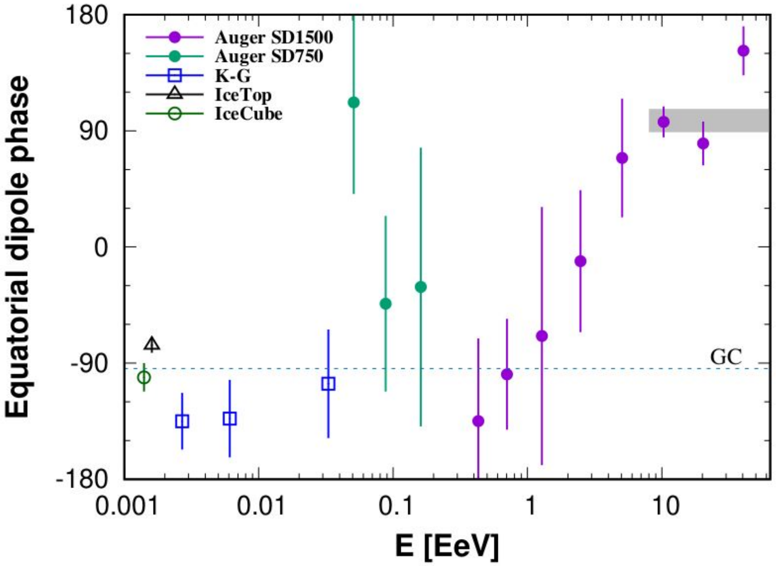


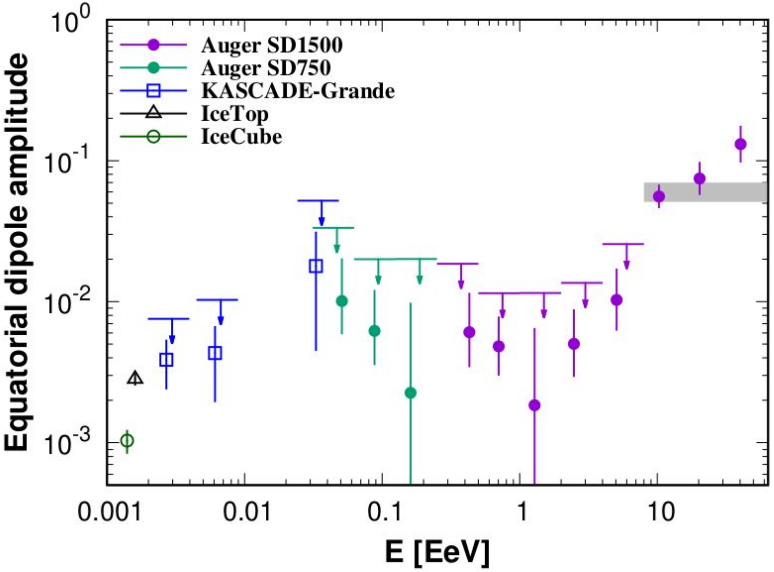


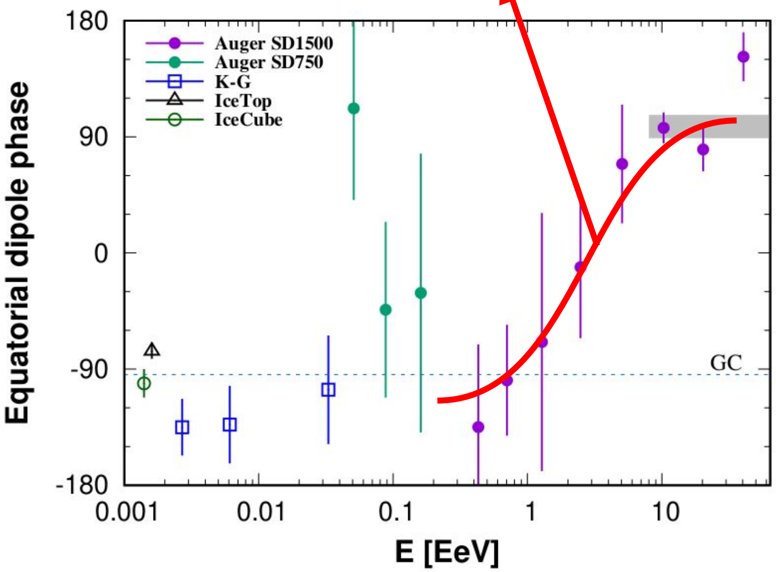
The Pierre Auger Collaboration, **Astrophys. J.**, 2020

Low energy - large scale

- Evolution with energy:
  - Dipole in right ascension;
  - 14,5 yr of Auger data;

Evidence of a change from predominance of galactic to extragalactic sources

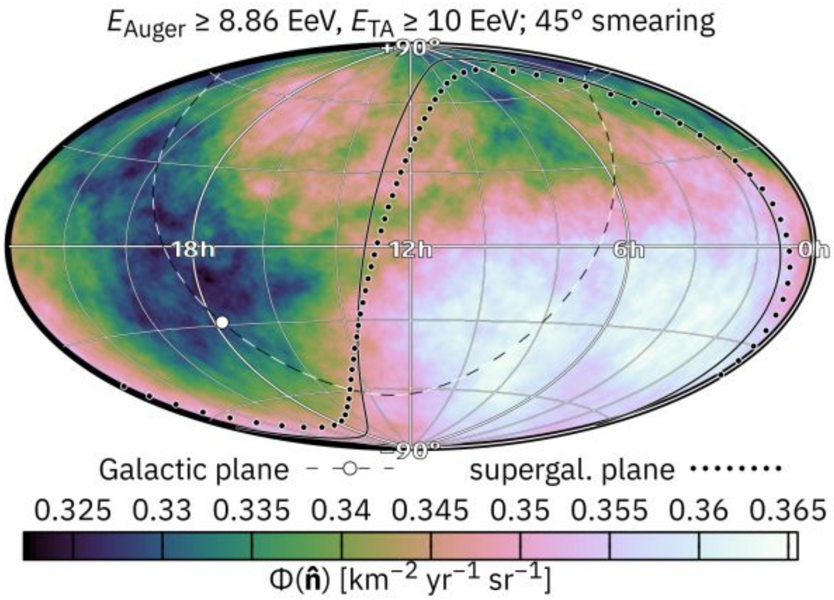




The Pierre Auger Collaboration, **Astrophys. J.**, 2020

Low energy - large scale

- Full sky:
  - Auger + TA;



This work	$d_x = (-0.7 \pm 1.1 \pm 0.01)\%$	
	$d_y = (+4.2 \pm 1.1 \pm 0.04)\%$	
	$d_z = (-2.6 \pm 1.3 \pm 1.4)\%$	
Auger [5] ≥ 8 EeV	$d_x = (-1.0 \pm 1.0)\%$	
	$d_y = (+5.9 \pm 1.0)\%$	$\ell_{max} = 1$
	$d_z = (-2.6 \pm 1.5)\%$	
	$d_x = (-0.3 \pm 1.3)\%$	
	$d_y = (+5.0 \pm 1.3)\%$	$\ell_{max} = 2$
	$d_z = (-2 \quad \pm 4)\%$	

di Matteo, A. *et al.*, **ICRC 2019**

Low energy - large scale

- Full sky:
  - Auger + TA;
  - Regardless of higher multipoles;
  - Slightly lower dipole: 4.99%

This work	$d_x = (-0.7 \pm 1.1 \pm 0.01)\%$	
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di Matteo, A. *et al.*, **ICRC 2019**

High energy - intermediate scale

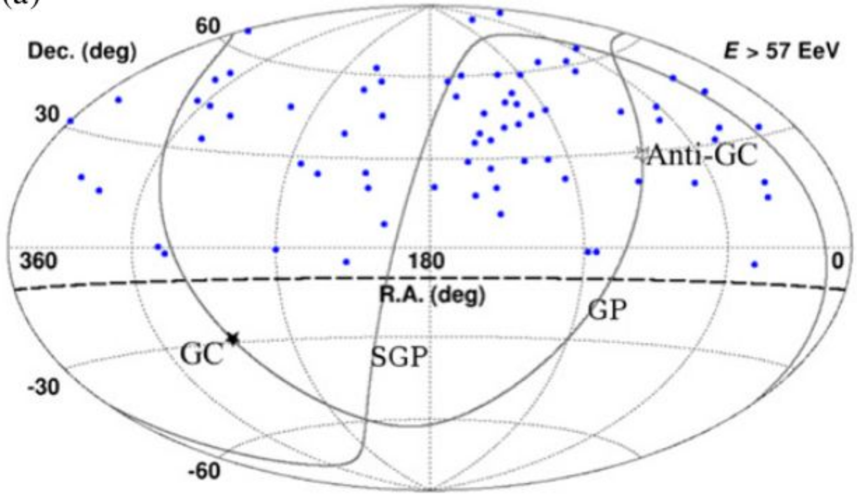
- Higher energy - intermediate scales:
  - Fewer events;
  - Smaller deflections;
  - Search for excesses w.r.t. isotropic expectations:
    - Minimum energy;
    - Radius;

High energy - intermediate scale

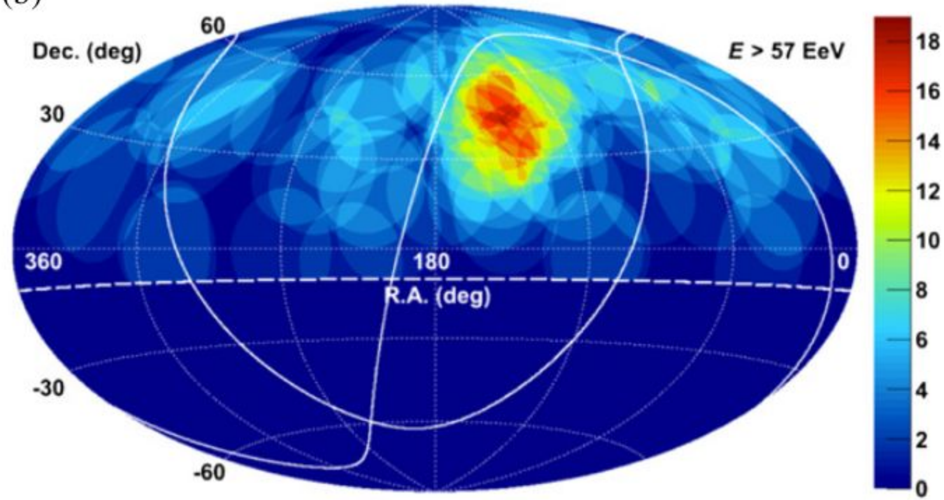
➢ TA hotspot:
  - 5 years of data;
  - E > 57 EeV;
  - 20° radius;

- No known sources;
- ~19° from the supergalactic plane

(a)



(b)

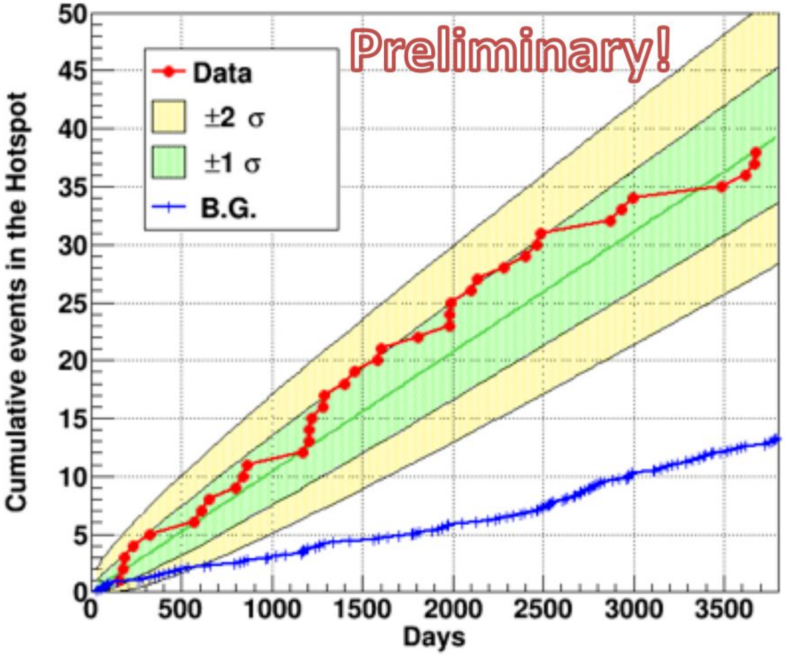


Telescope Array Collaboration, **Astrophys. J. Lett.**, 2014

High energy - intermediate scale

➢ TA hotspot - significance:

Before penalizations



Kawata, K. *et al.*, **ICRC 2019**

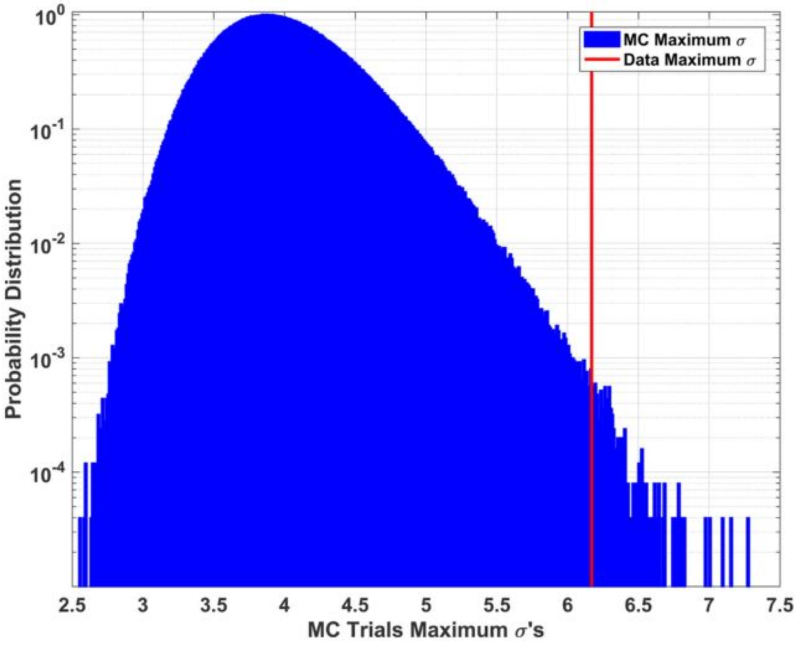
➢ Excess over background increasing over time;

➢ What is the probability of such strong excess appearing if you do different searches?

High energy - intermediate scale

➢ TA hotspot - significance:

Monte Carlos simulations



Telescope Array Collaboration, **Astrophys. J.**, 2018.

➢ Excess over background increasing over time;

➢ What is the probability of such strong excess appearing if you do different searches?

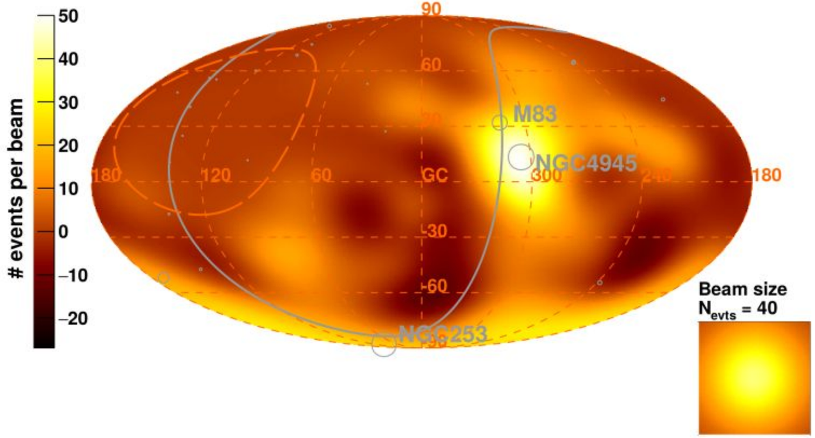
➢ Post-trial significance:

- TA '14: 3.4σ;
- TA '18: 3.74σ;
- TA '19: 2.9σ.

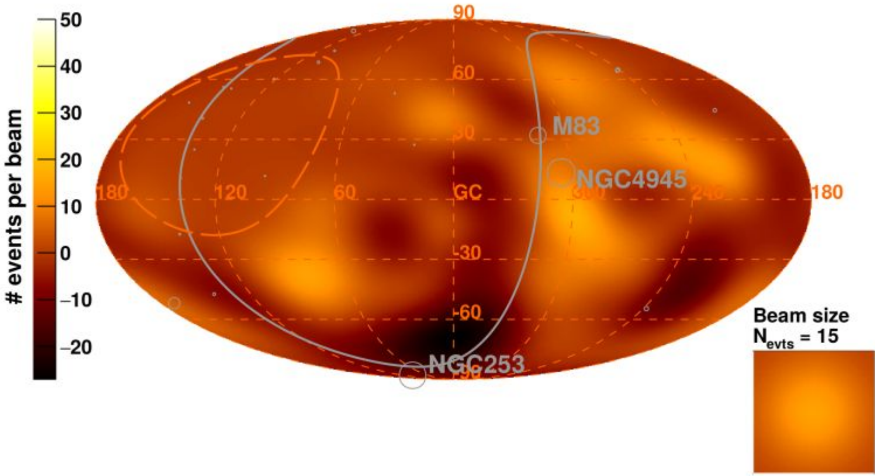
High energy - intermediate scale

- Auger correlation maps:
  - Search for correlations of excesses with known extragalactic gamma-ray sources:
    - Active galactic nuclei (AGNs);
    - Starburst galaxies (SBGs);
  - Search variables:
    - Minimum energy;
    - Radius;
    - Anisotropic fraction.

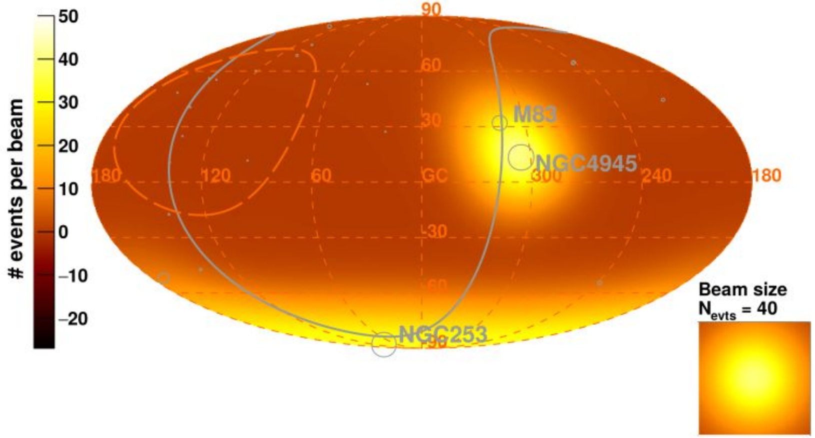
Observed Excess Map - E > 39 EeV



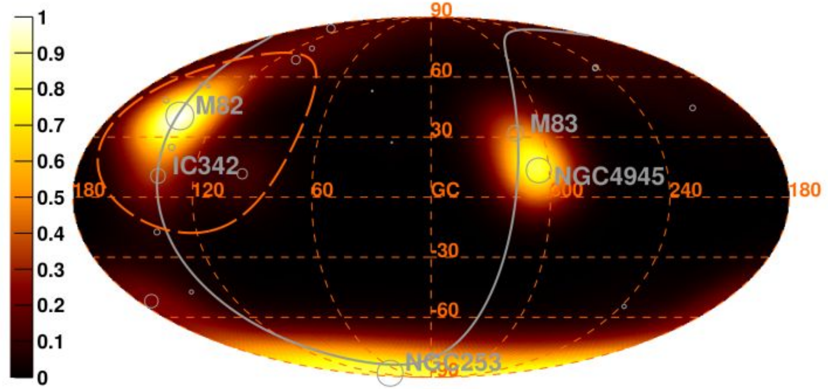
Residual Excess Map - Starburst galaxies - E > 39 EeV



Model Excess Map - Starburst galaxies - E > 39 EeV



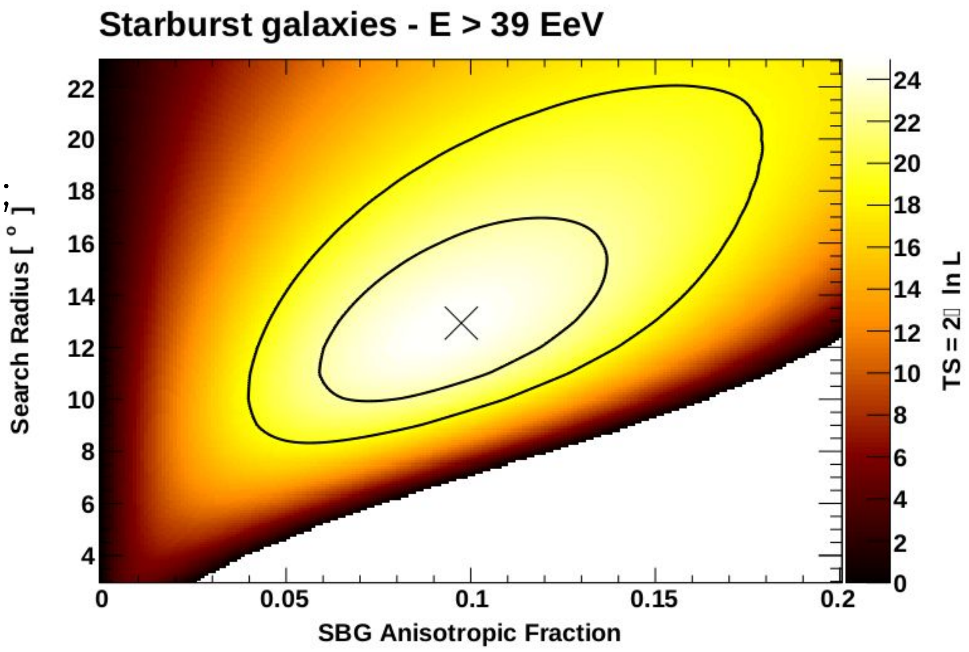
Model Flux Map - Starburst galaxies - E > 39 EeV



The Pierre Auger Collaboration, **Astrophys. J. Lett.**, 2018.

High energy - intermediate scale

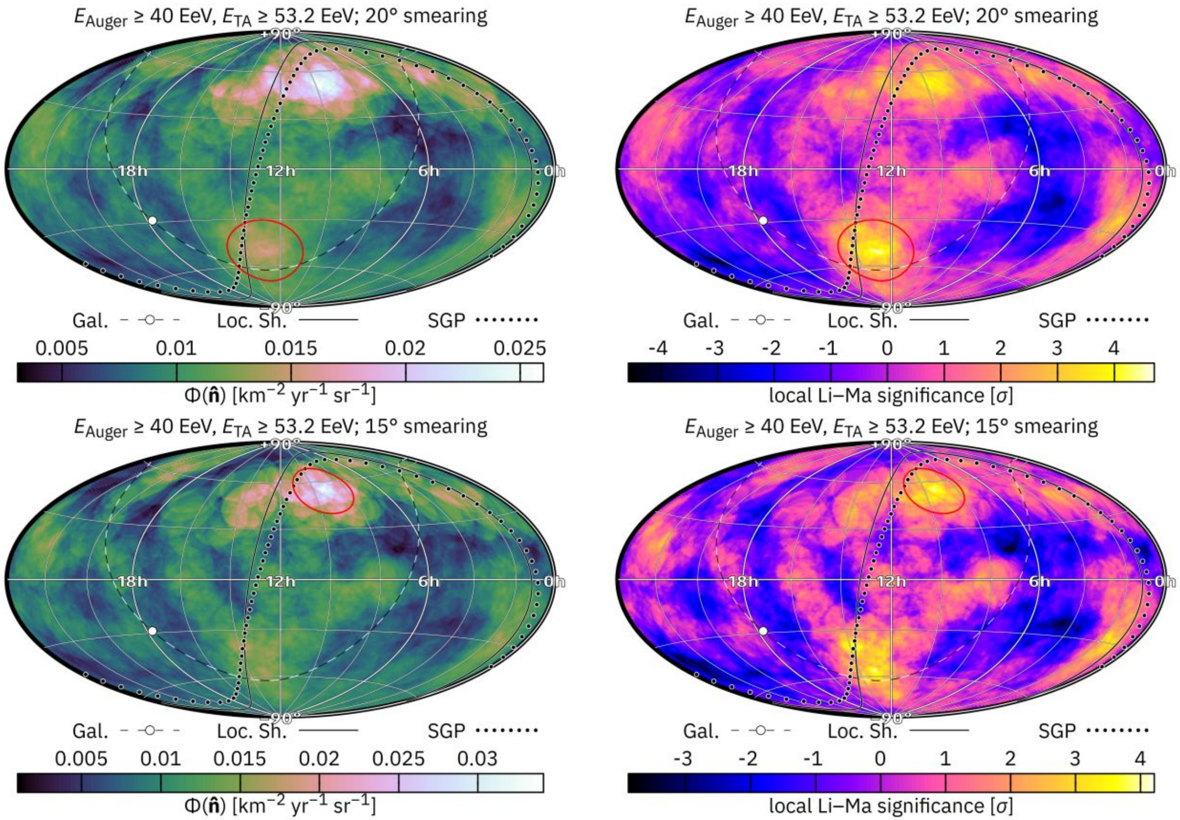
- ➢ Auger correlation maps:
  - Search for correlations of excesses with known extragalactic gamma-ray sources:
    - Active galactic nuclei (AGNs);
    - Starburst galaxies (SBGs);
  - Correlations:
    - AGNs: 2.7σ;
    - AGN+SBG: 3.7σ;
    - SBG: 4.0σ.



Pierre Auger Collaboration, **Astrophys. J. Lett.**, 2018.

High energy - intermediate scale

- Full sky:
  - Auger+TA;
  - Two hotspots;
    - Local significances:
      - 4.7σ;
      - 4.2σ;
    - Post-trial signif.:
      - 2.2σ;
      - 1.5σ;



di Matteo, A. *et al.*, **ICRC 2019**

The assembly: phenomenology

➢ Several efforts to describe the experimental results:

Taylor, A. *et al.*, **Phys. Rev. D**, 2011

Harari, D. *et al.*, **Phys. Rev. D**, 2015

Globus, N. *et al.*, **Astrophys. J. Lett.**, 2017

di Matteo, A. *et al.*, **MNRAS**, 2018

Hackstein, S. *et al.*, **MNRAS**, 2018

Wittkowski, D. *et al.*, **Astrophys. J. Lett.**, 2018

Dundovic, A. *et al.*, **JCAP**, 2019

Lang, R.G. *et al.*, **Phys. Rev. D**, 2020

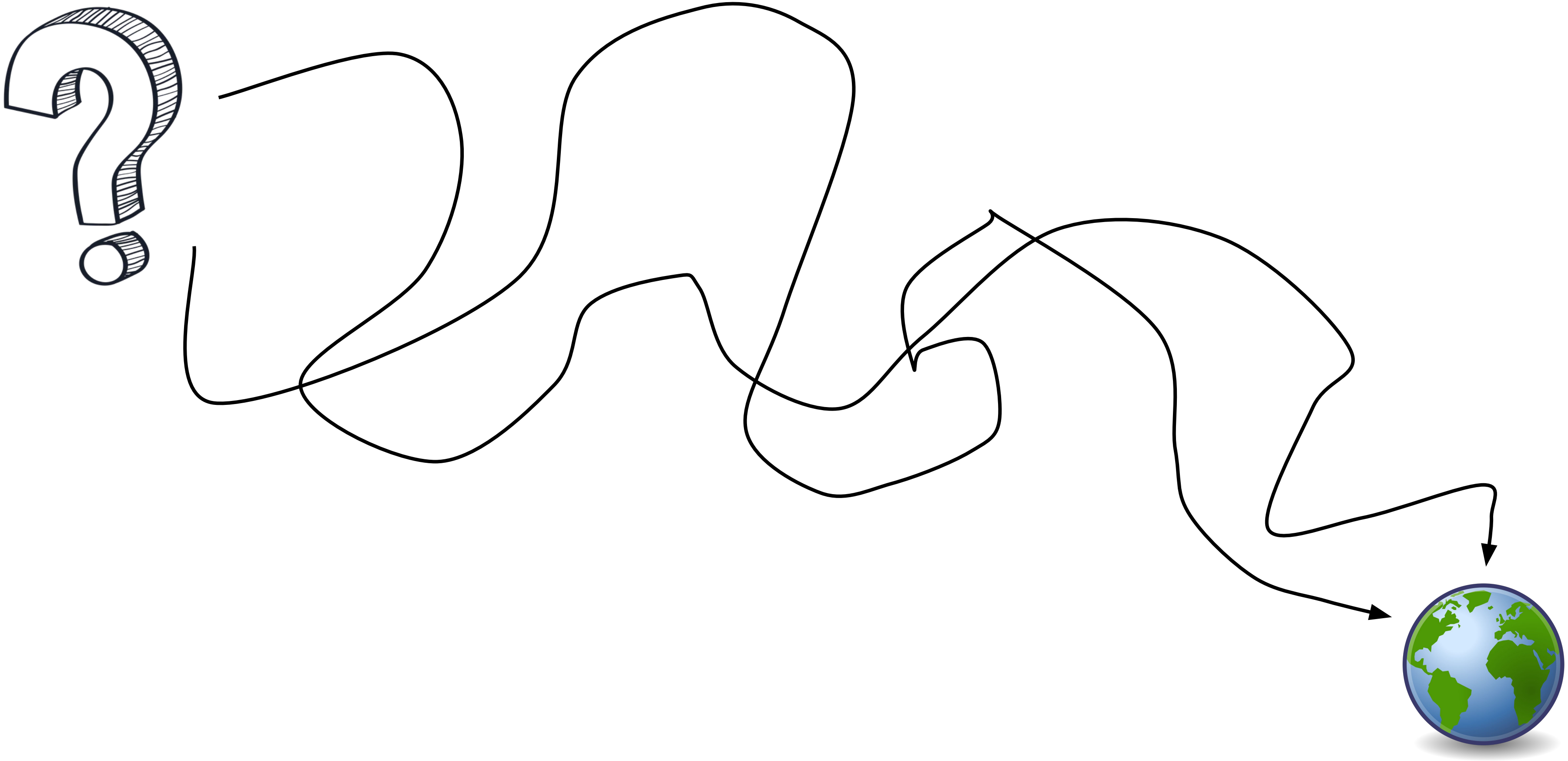
Mollerach, S. *et al.*, **Phys. Rev. D**, 2020

Lang, R.G. *et al.*, **Phys. Rev. D**, 2021

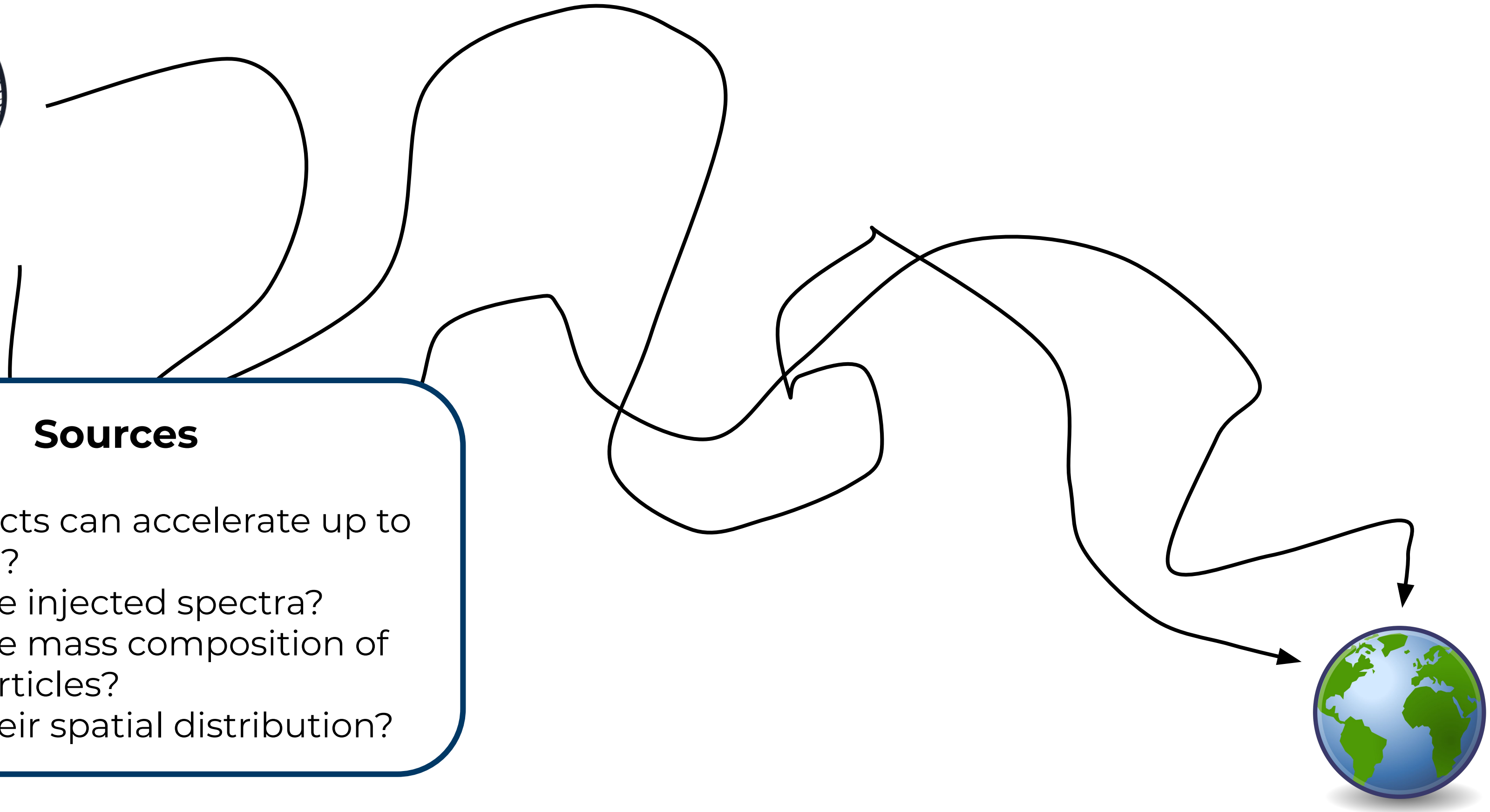
Bister, T. *et al.*, **Astropart. Phys.**, 2021

(amongst many others)

Hypotheses



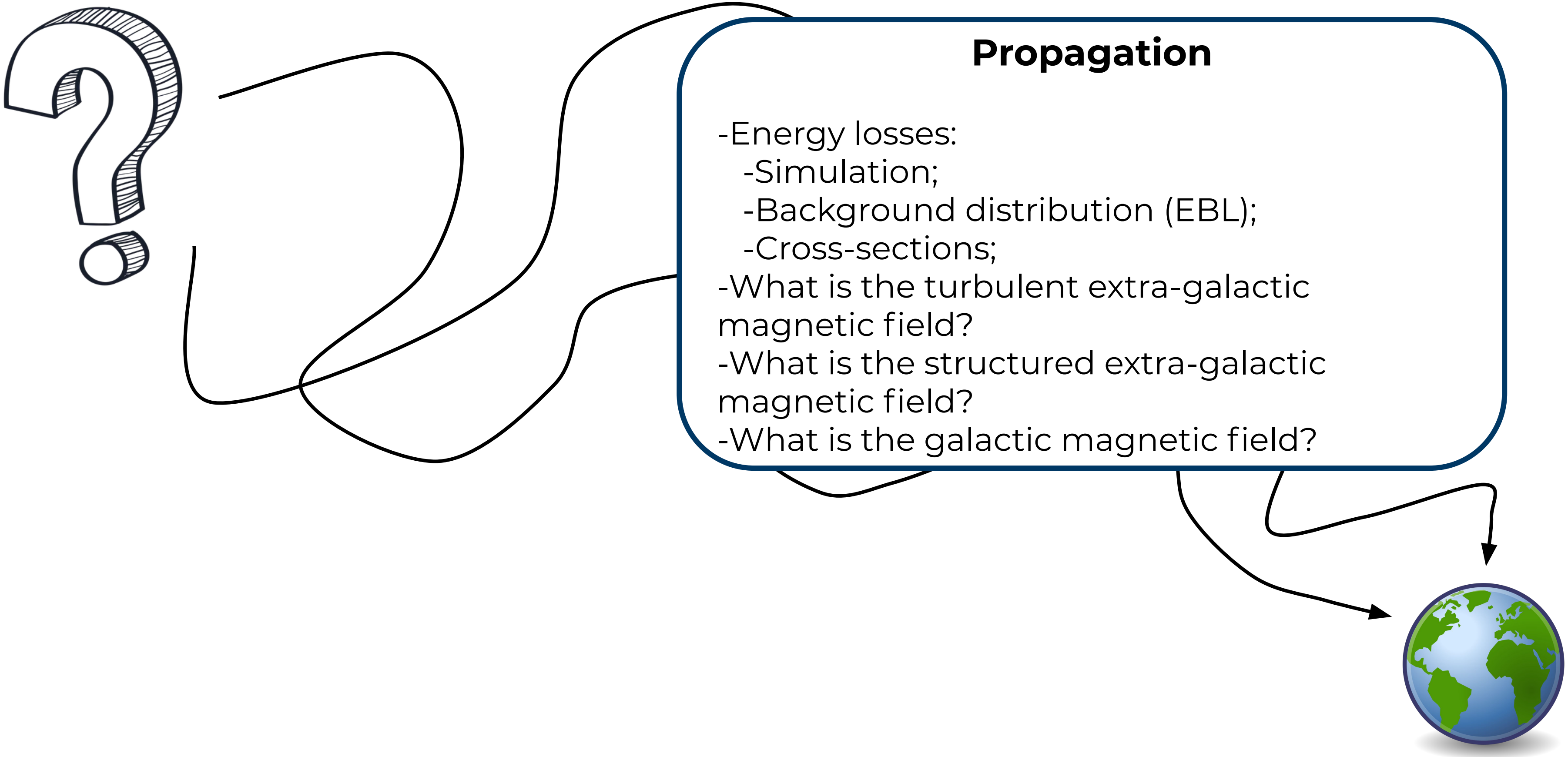
Hypotheses



Sources

-What objects can accelerate up to this energy?
-What is the injected spectra?
-What is the mass composition of emitted particles?
-What is their spatial distribution?

Hypotheses



Propagation

-Energy losses:
  -Simulation;
  -Background distribution (EBL);
  -Cross-sections;
-What is the turbulent extra-galactic magnetic field?
-What is the structured extra-galactic magnetic field?
-What is the galactic magnetic field?

Hypotheses

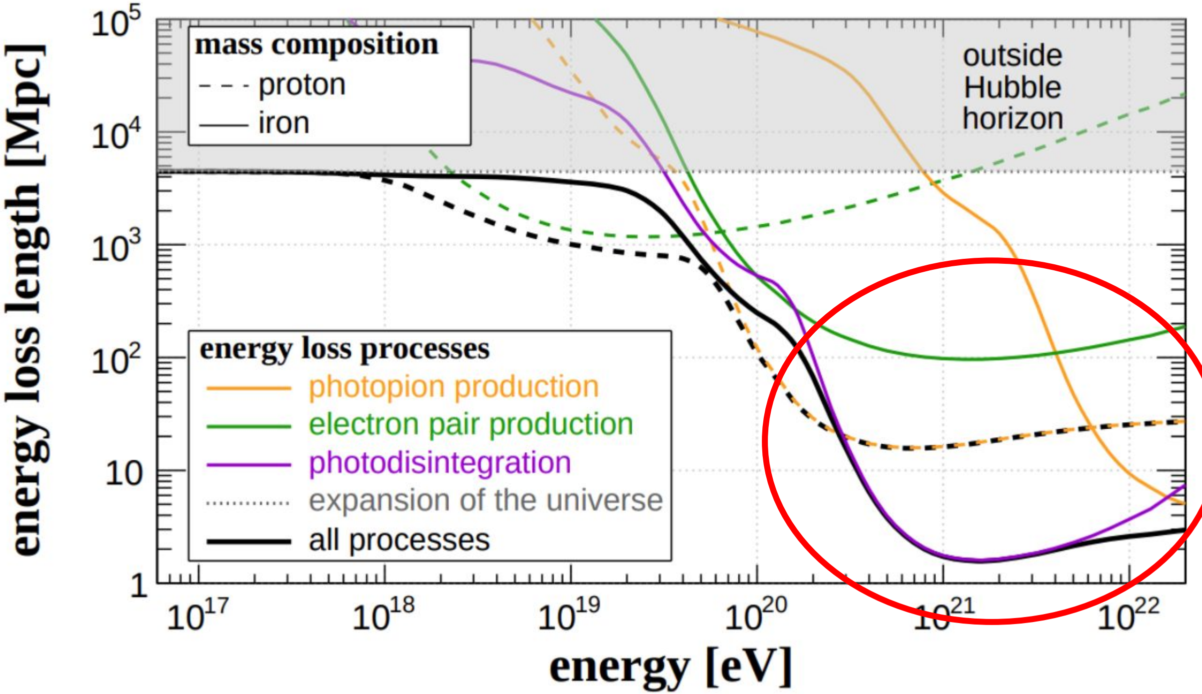
- ➢ Lots of hypothesis needed;
- ➢ We need to find a balance between:
  - Many hypotheses/Few fit parameters -> model dependency;
  - Few hypotheses/Many fit parameters -> no strong conclusions.

Starting with the borders

- ➢ A possible (phenomenological) approach:
  - ○ Understand the behavior of the measurements and how they depend on each assumption;
  - ○ Find variables which don't strongly rely on the hypotheses.
- ➢ One (of many) case:
  - ○ Understand the role of local sources in the dipole;

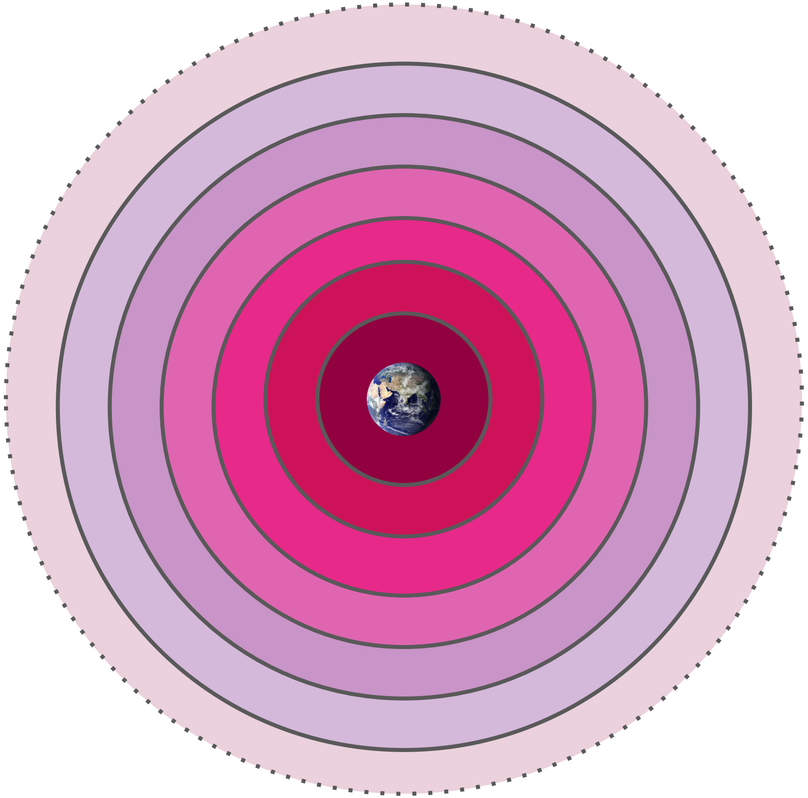
A (possible) "border": Local sources

- ➢ Energy-dependent losses;
- ➢ Propagation horizon;
- ➢ How much important are they?



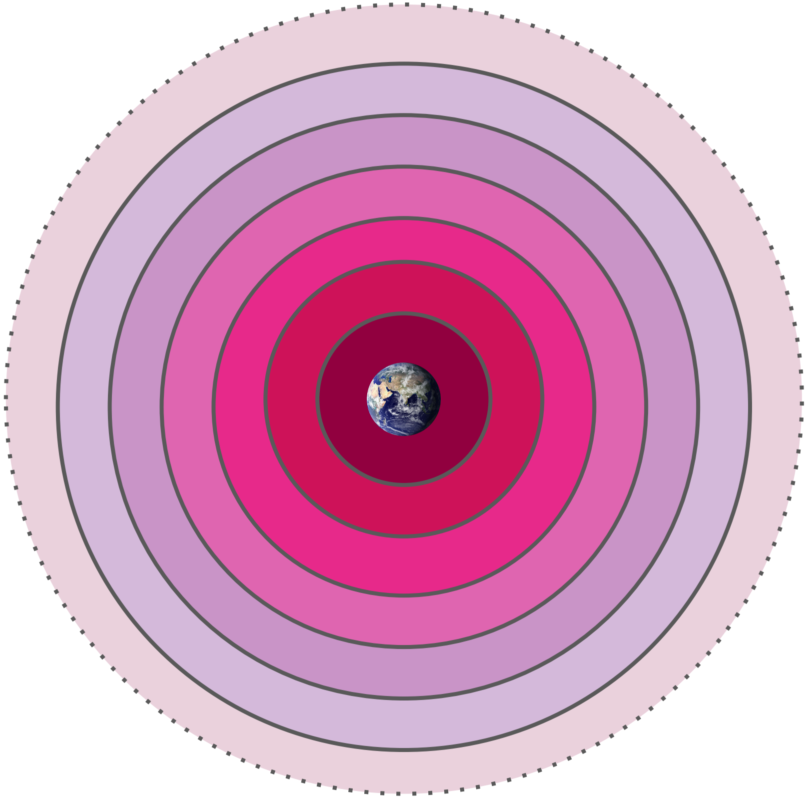
Batista, R. A., **Ph.D. Thesis**, 2015

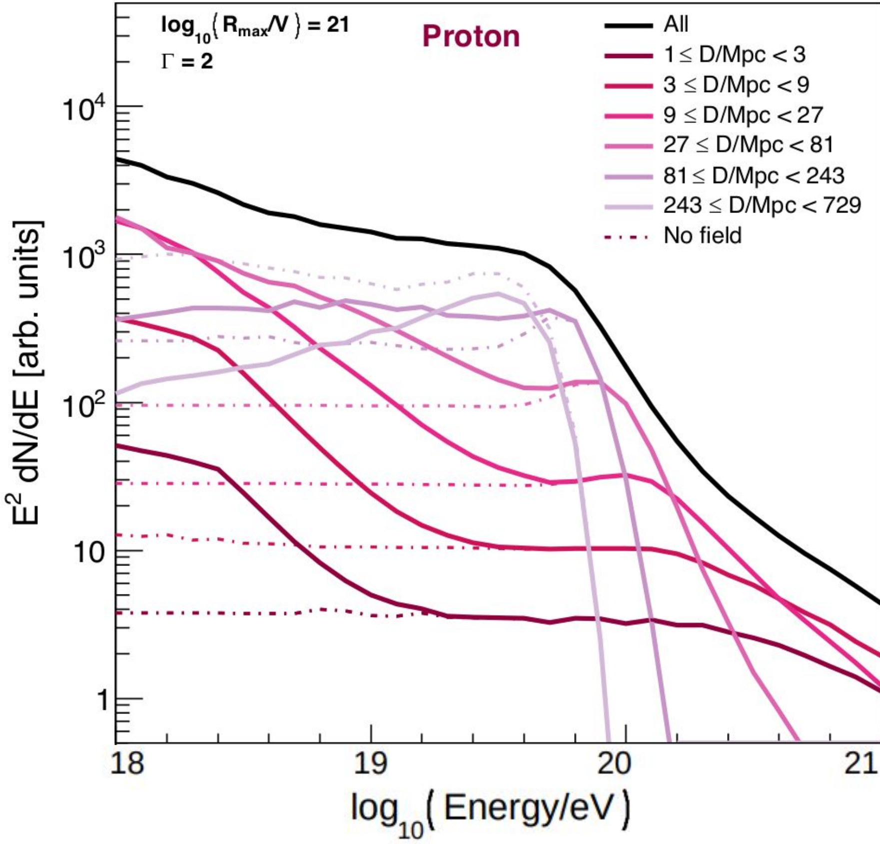
A (possible) "border": Local sources



- ➢ Contribution from different distance shells;
- ➢ Example spectrum;
- ➢ Semi-analytical method;
- ➢ Turbulent EGMF.

A (possible) "border": Local sources





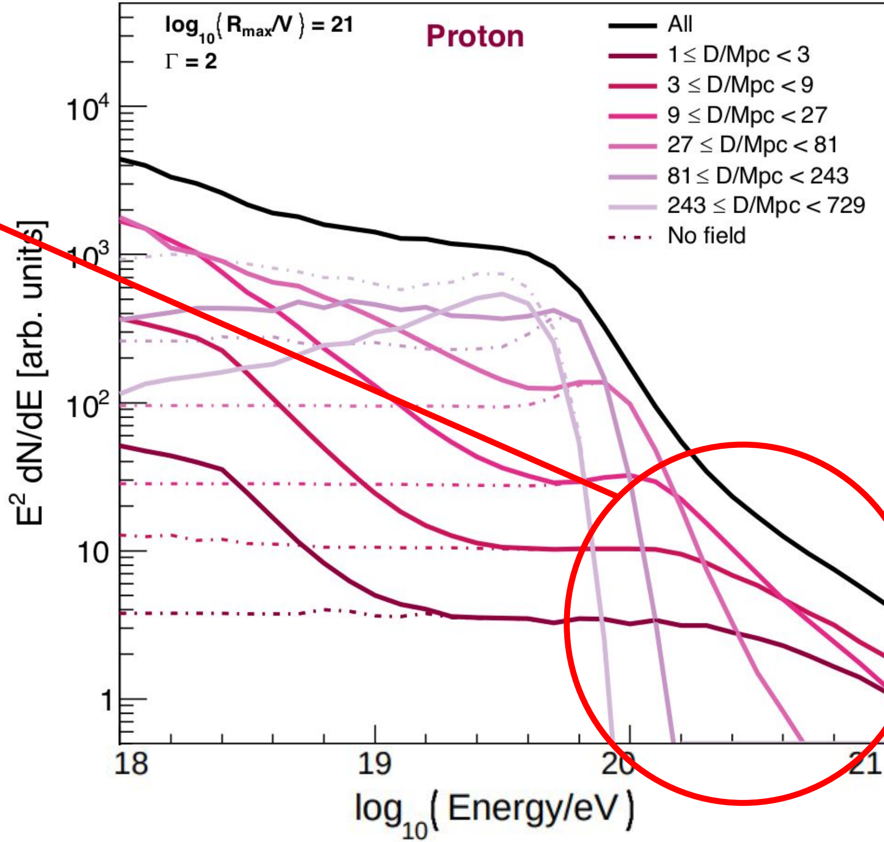
Lang, R. G. *et al.*, **Phys. Rev. D**, 2020

A (possible) "border": Local sources

Energy

➢ Propagation horizon:

dominated by local sources;

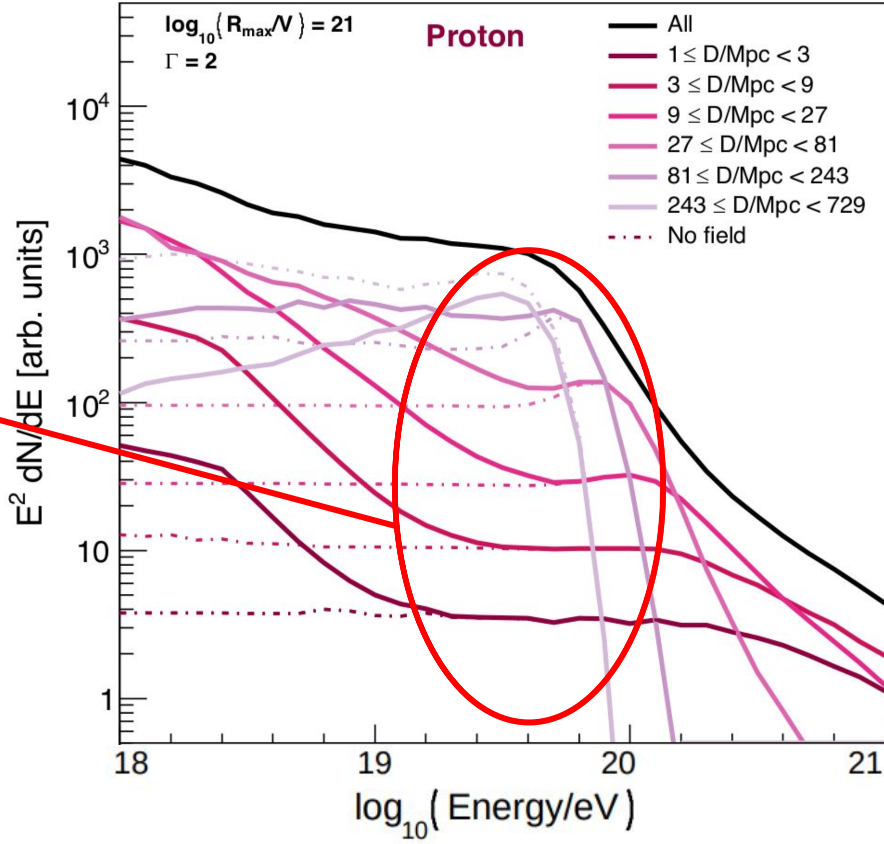


Lang, R. G. *et al.*, **Phys. Rev. D**, 2020

A (possible) "border": Local sources

Energy

- ➢ Propagation horizon: dominated by local sources;
- ➢ Ballistic propagation: dominated by far sources;

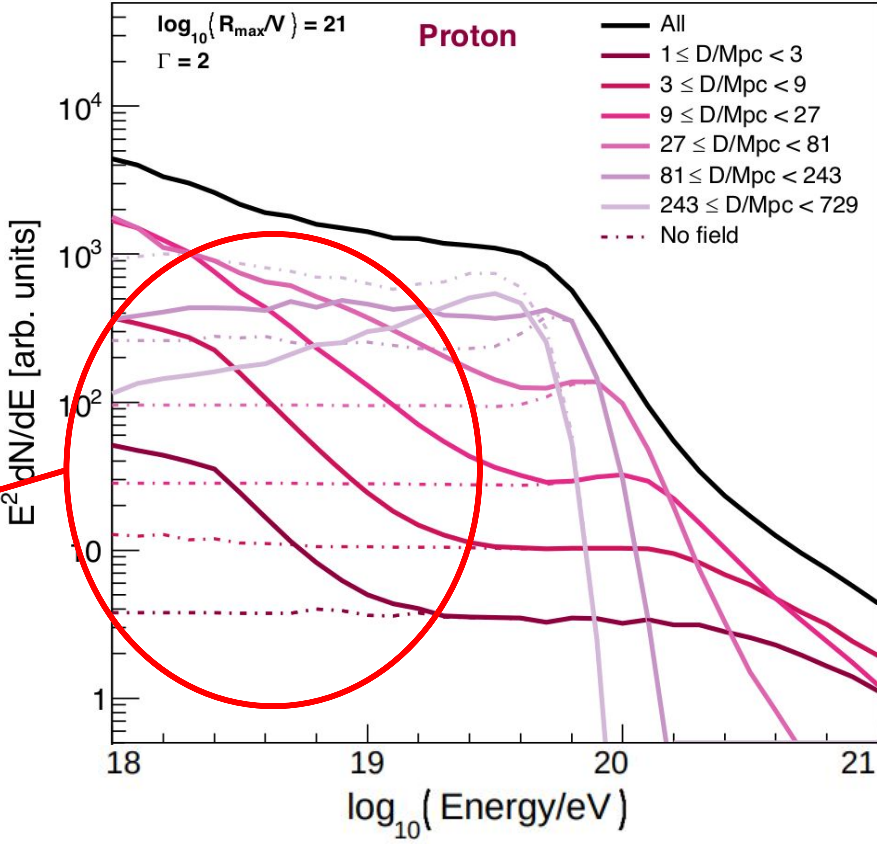


Lang, R. G. *et al.*, **Phys. Rev. D**, 2020

A (possible) "border": Local sources

Energy

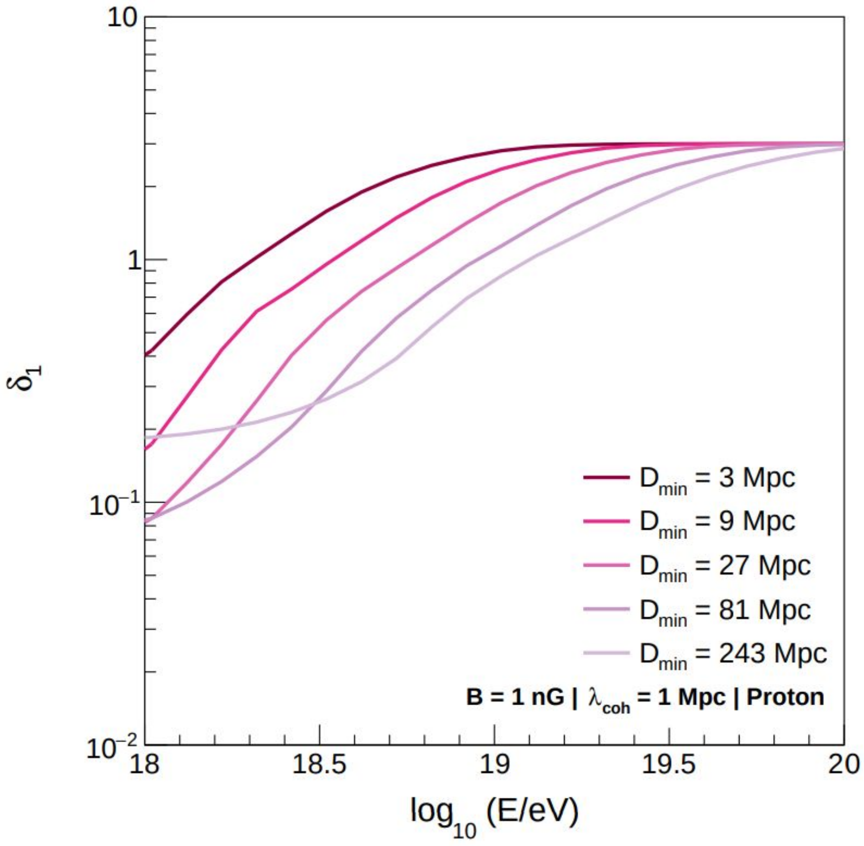
- ➢ Propagation horizon: dominated by local sources;
- ➢ Ballistic propagation: dominated by far sources;
- ➢ EGMF effects: recovery of local sources.



Lang, R. G. *et al.*, **Phys. Rev. D**, 2020

A (possible) "border": Local sources

- Dipole for a single source:
  - Turbulent EGMF;
  - Semi-analytical propagation;
  - Example scenario.

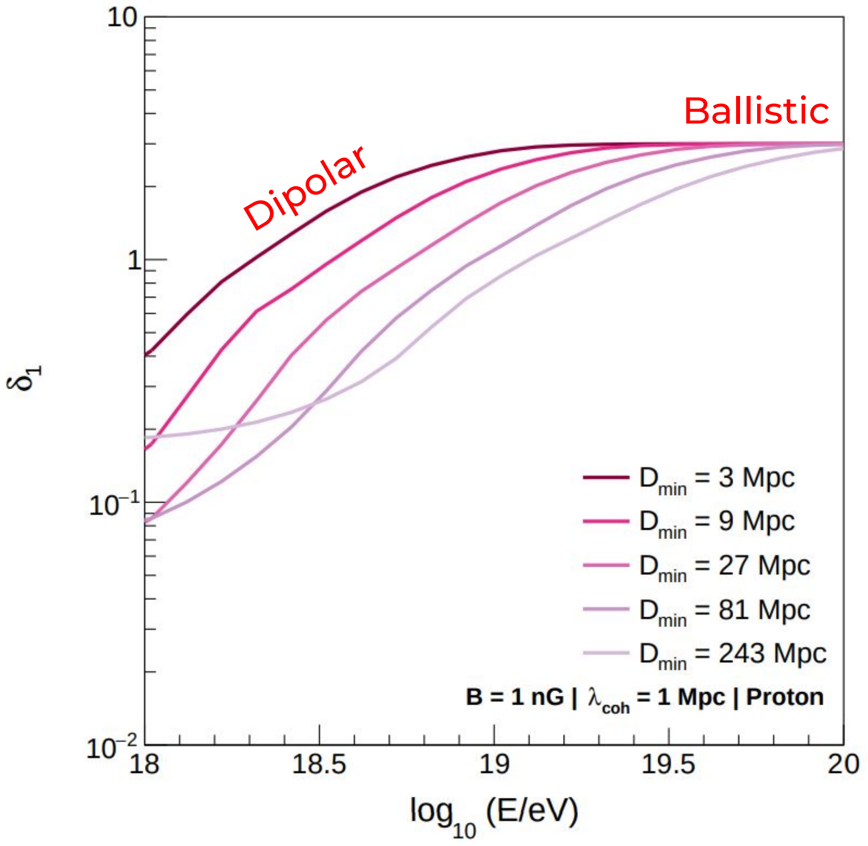


Lang, R. G. *et al.*, **Phys. Rev. D**, 2021

A (possible) "border": Local sources

➢ Dipole for a single source:
  - Turbulent EGMF;
  - Semi-analytical propagation;
  - Example scenario.

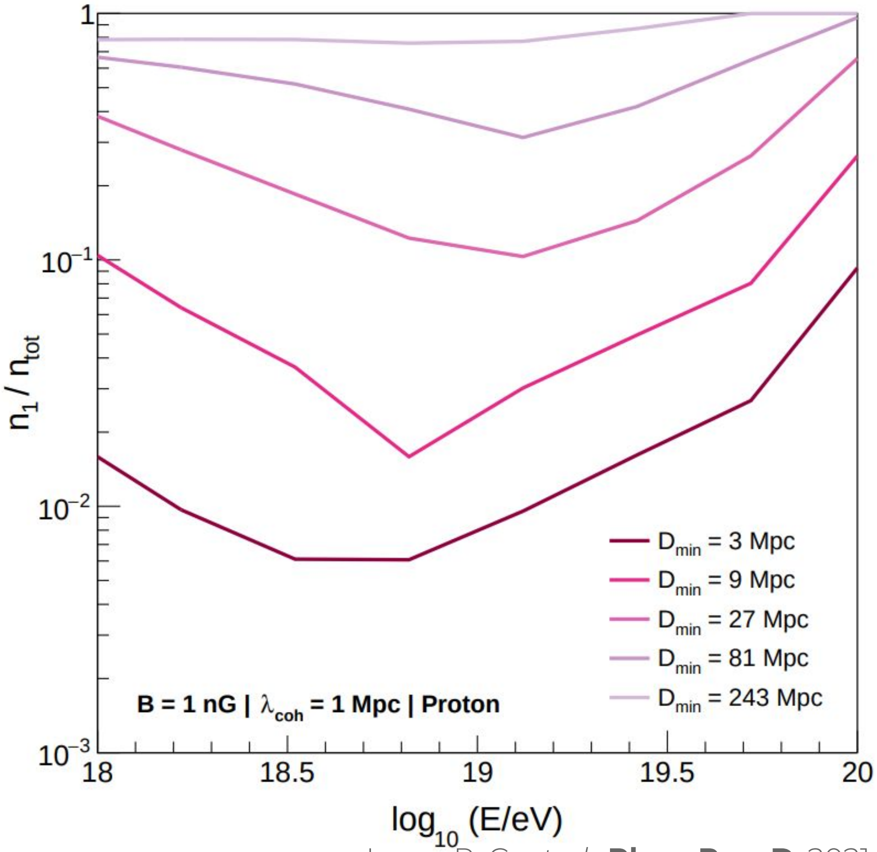
Closer sources have stronger dipoles



Lang, R. G. *et al.*, **Phys. Rev. D**, 2021

A (possible) "border": Local sources

- For a homogeneous distribution of sources:
  - D_{min} related to density;

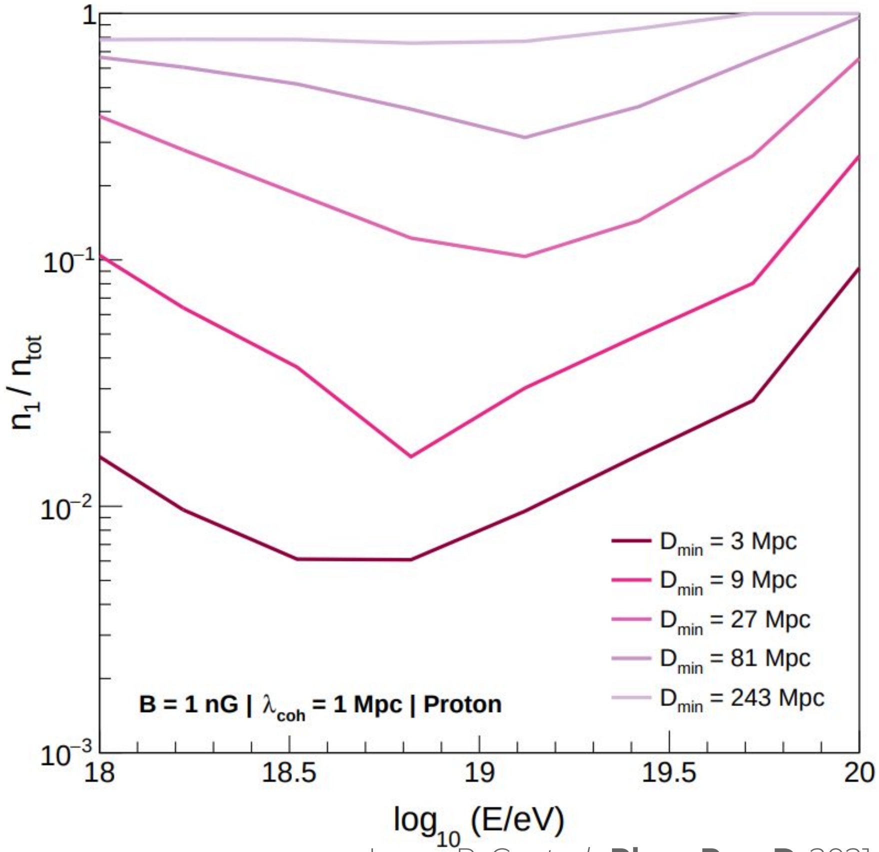


Lang, R. G. *et al.*, **Phys. Rev. D**, 2021

A (possible) "border": Local sources

- For a homogeneous distribution of sources:
  - D_{min} related to density;

Larger densities lead to smaller dipoles



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A (possible) "border": Local sources

Closer sources have stronger dipoles

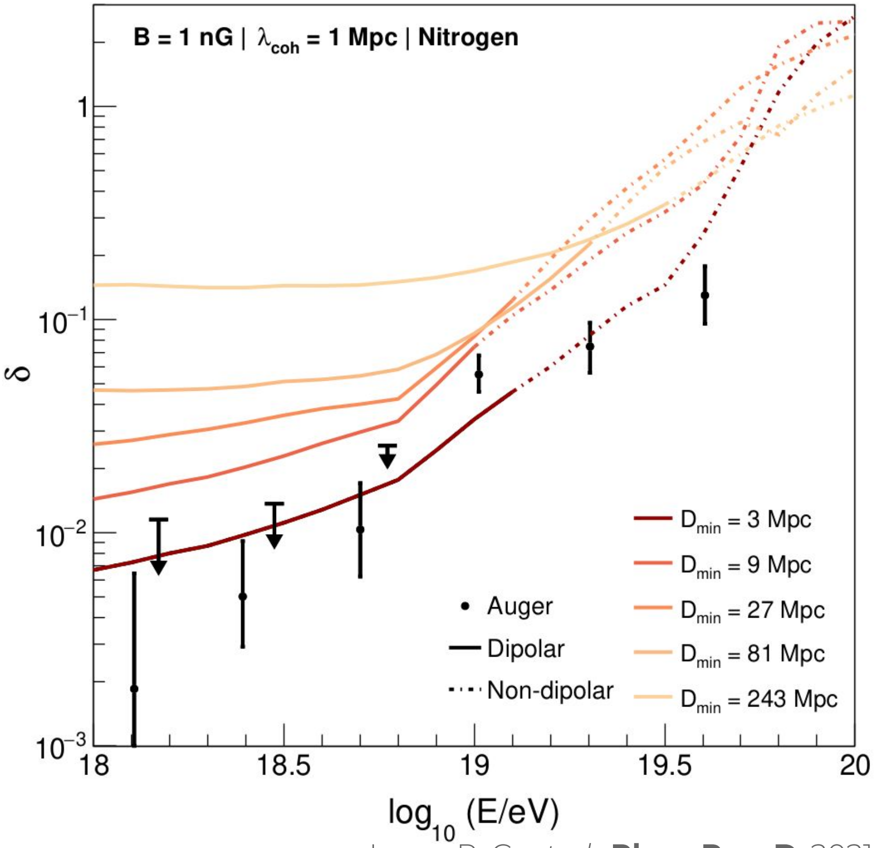
Larger densities lead to smaller dipoles

→

The dipole is driven by the closest sources and diluted by the farther ones

A (possible) "border": Local sources

➢ Evolution with energy:
  - Homogeneous and random distribution of sources;
  - Turbulent EGMF;
  - Semi-analytical propagation;
  - Example spectra.



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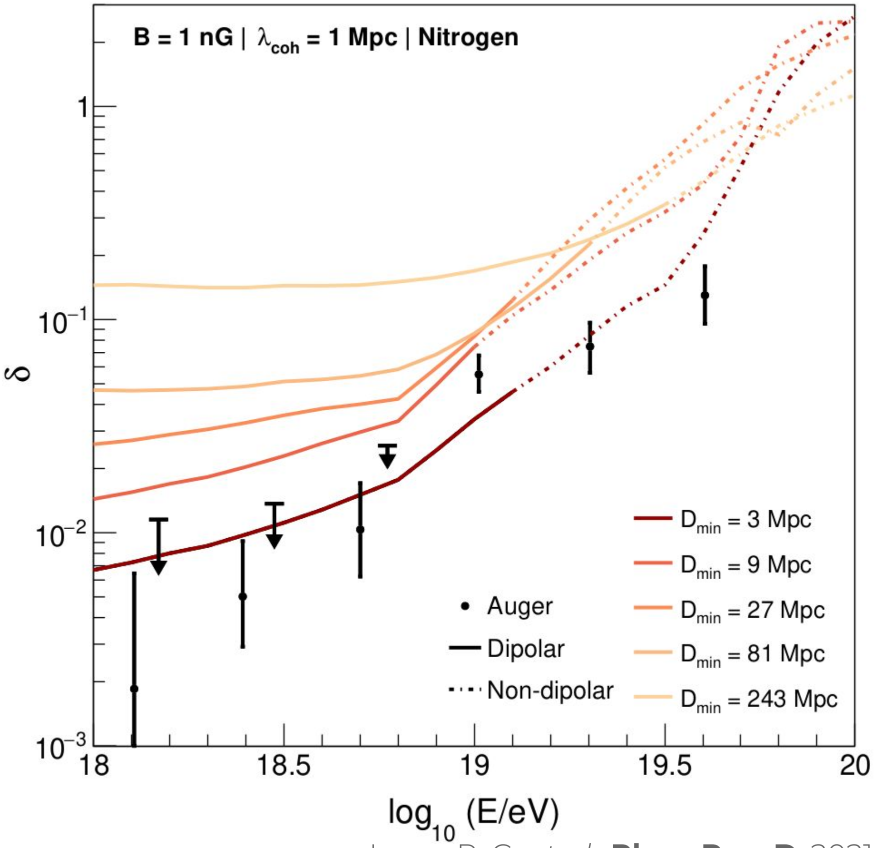
A (possible) "border": Local sources

➢ Evolution with energy:
  - Can be understood from the contribution of each distance shell;
  - Distance to the nearest source and density dictate the amplitude.



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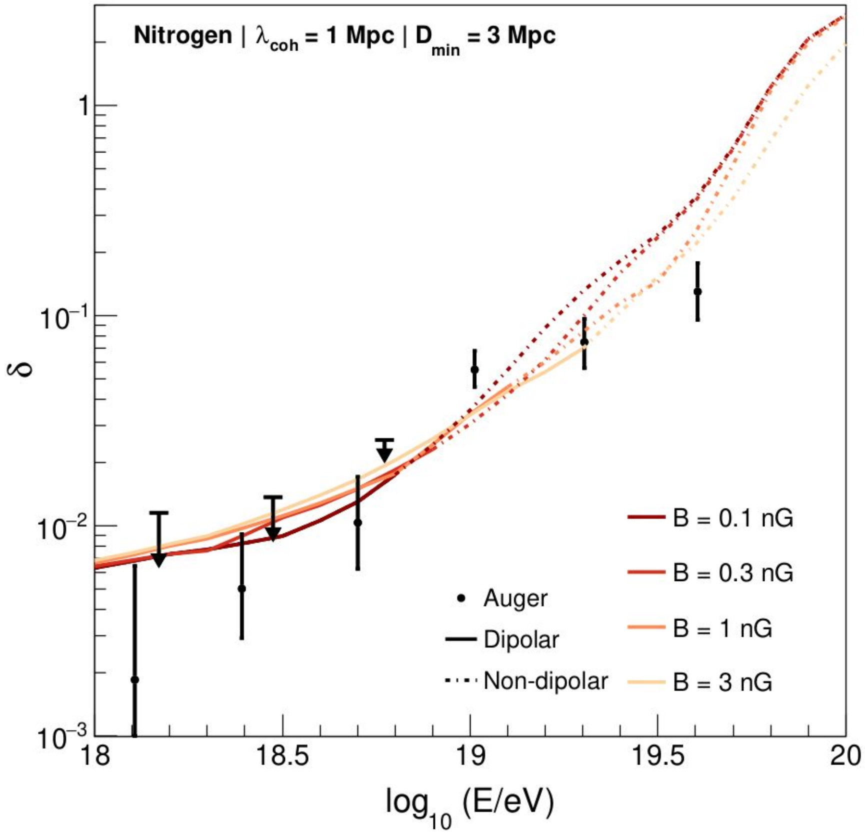
A (possible) "border": Local sources

➢ Dependencies:
  - EGMF intensity;



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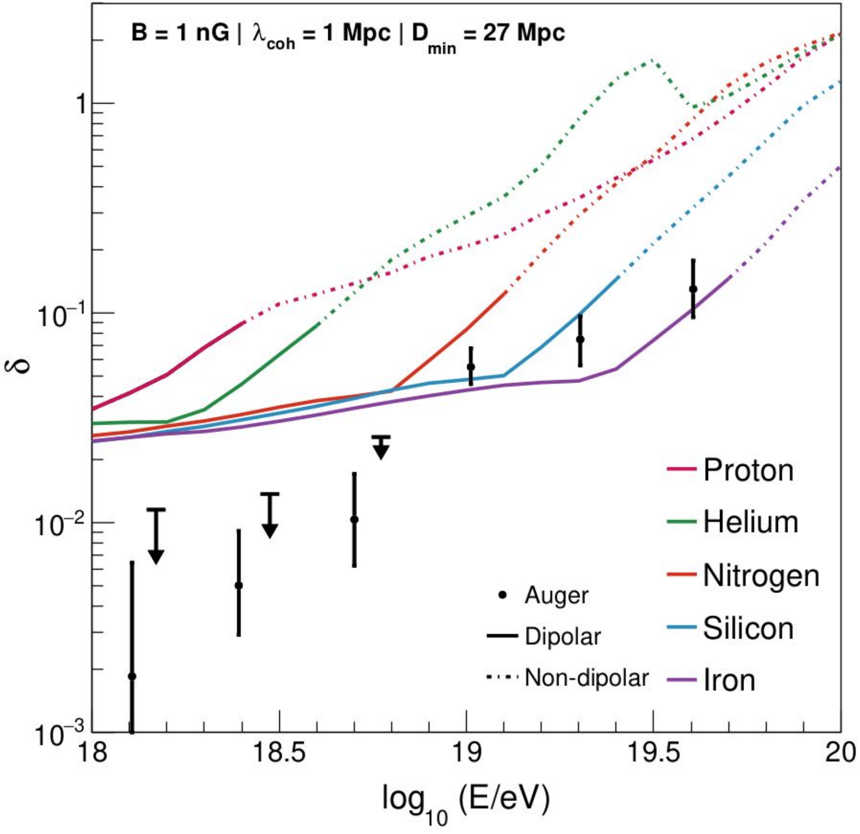
A (possible) "border": Local sources

- Dependencies:
  - EGMF intensity;
  - Composition:
    - Changes in evolution with energy;
    - Transition from dipolar to non-dipolar;
    - More realistic: mixed composition.



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A (possible) "border": Local sources

- Next to this border:
  - Position (and distance) of local sources;
  - Source density;
  - Composition;
  - Power spectrum.

Current status of the puzzle

- Recent data show deviations from isotropy:
  - ~6% dipole at E>8 EeV pointing outwards the galactic center;
  - Evolution of dipole amplitude and phase with energy;
  - Hotspots at the highest energies;
  - Hints of a correlation with Starburst Galaxies;
- Several analysis trying to describe such deviations:
  - Heavily dependent on astrophysical hypotheses about things we don't know well;

Future of the puzzle: experiments

- Multimessenger approach:
  - Source catalogs;
  - EGMF and GMF;
  - Secondaries;
- Future experiments (e.g. AugerPrime, TAx4, JEM-EUSO, POEMMA):
  - Composition;
  - Better statistics.

Future of the puzzle: theory

➢ Better understanding the processes involved;

➢ Further development of analysis techniques:

  - Understand the model dependency of the analyses;
  - Find variables which are decoupled from some (most) of the hypotheses.

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Thank you and stay safe!

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