ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

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


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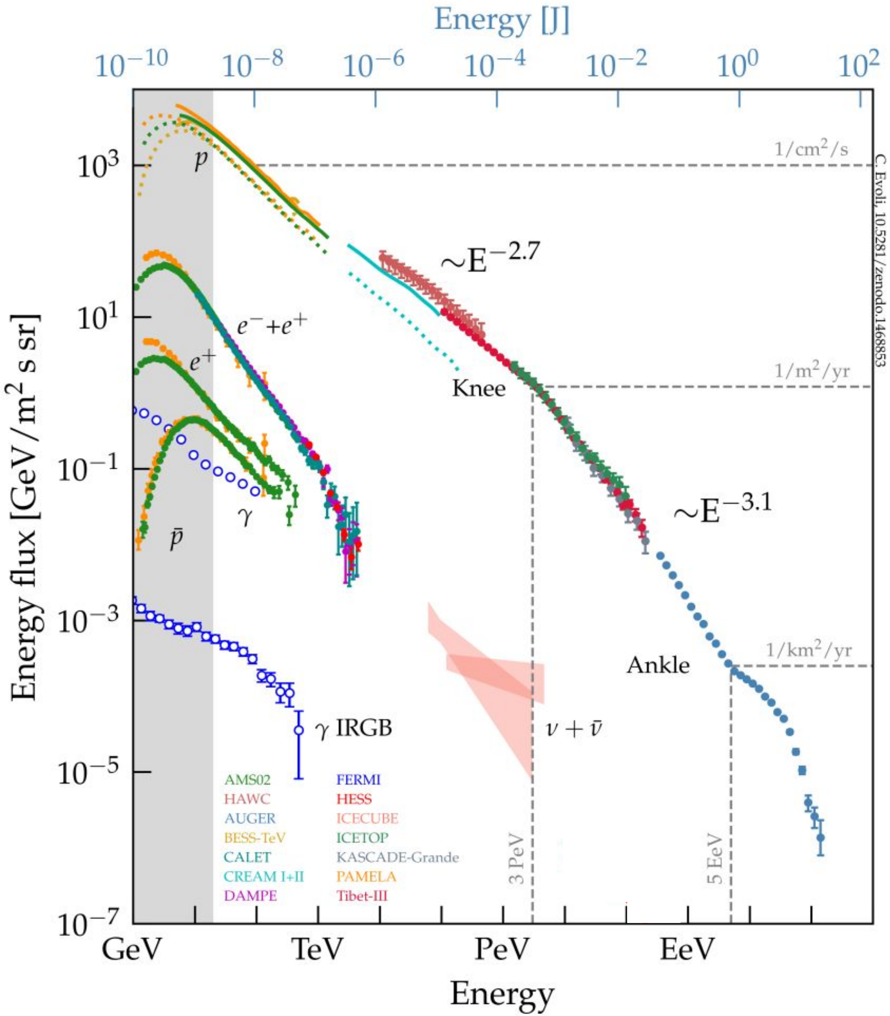
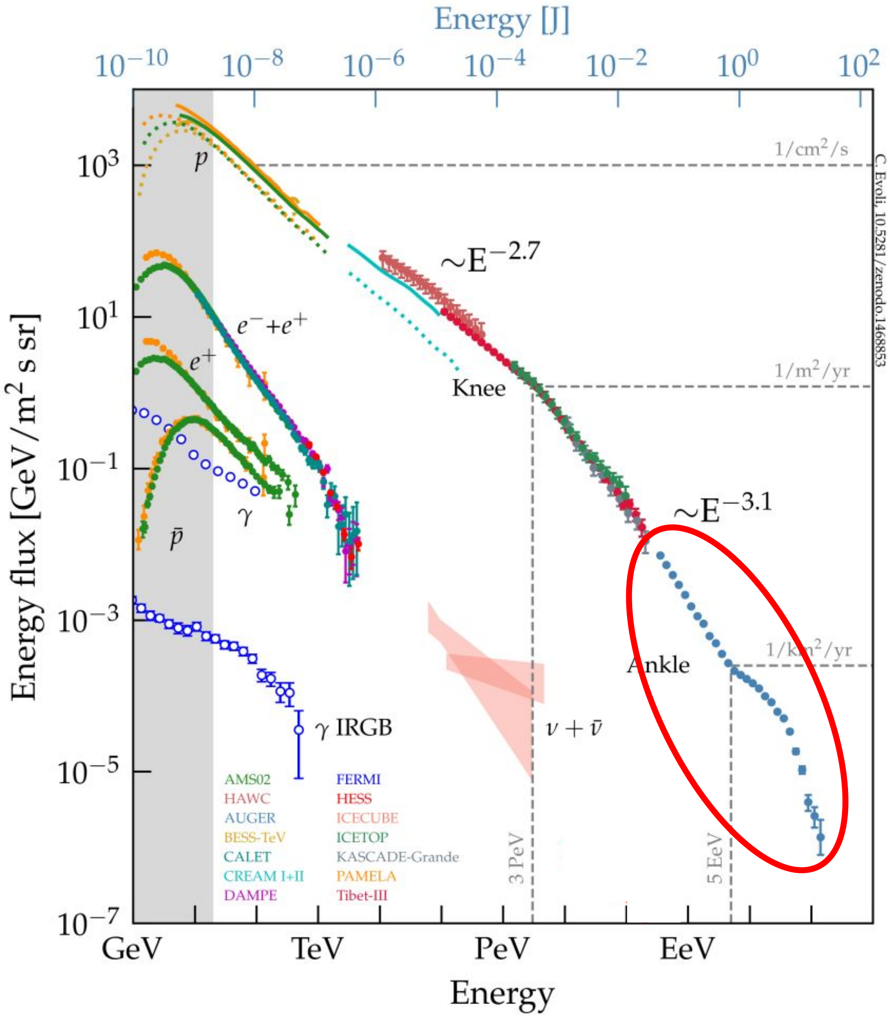
# UHECR



Energy [J]
$10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^{0}$ $10^{2}$
Energy flux [GeV/m$^2$ s sr]
$10^3$ $10^1$ $10^{-1}$ $10^{-3}$ $10^{-5}$ $10^{-7}$
1/cm$^2$/s
1/m$^2$/yr
1/km$^2$/yr
$p$
$e^-+e^+$
$e^+$
$\bar{p}$
$\gamma$
$\sim$E$^{-2.7}$
Knee
$\sim$E$^{-3.1}$
Ankle
$\gamma$ IRGB
$\nu + \bar{\nu}$
3 PeV
5 EeV
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASCADE-Grande
PAMELA
Tibet-III
GeV TeV PeV EeV
Energy
C. Evoli, 10.5281/zenodo.1468853

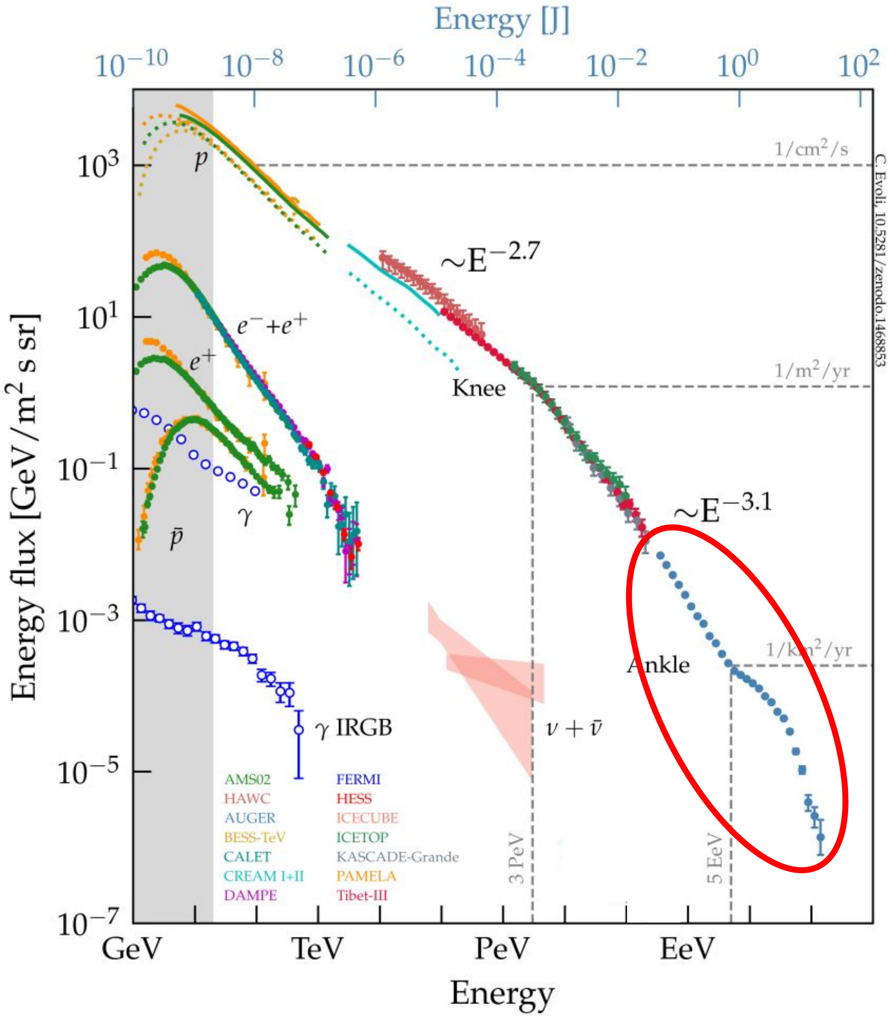
# UHECR

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



# UHECR

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



# The puzzle: what are their origins?

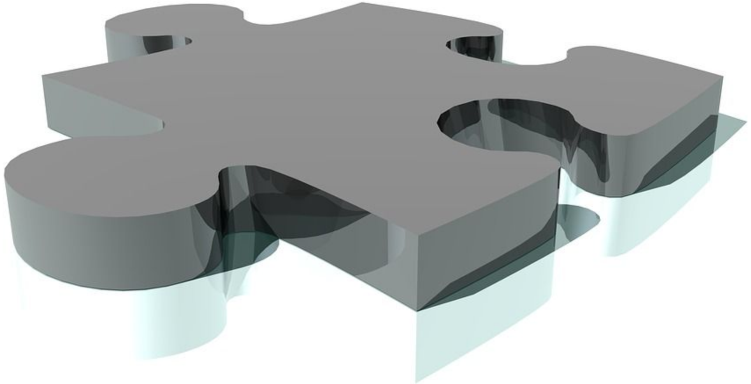
- Astroparticles in the EeV range;
- Most energetic known particles:
  - Probes to the extremes of the Universe;
- Charged:
  - Don't point directly back to their sources.

# The pieces: experimental data

- Very low flux (< 1/km$^2$/year);
- Huge ground-based experiments:
  - Pierre Auger Observatory:
    - 3000 km$^2$ in the southern hemisphere;
  - Telescope Array:
    - 762 km$^2$ in the northern hemisphere.

# The pieces: experimental data

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



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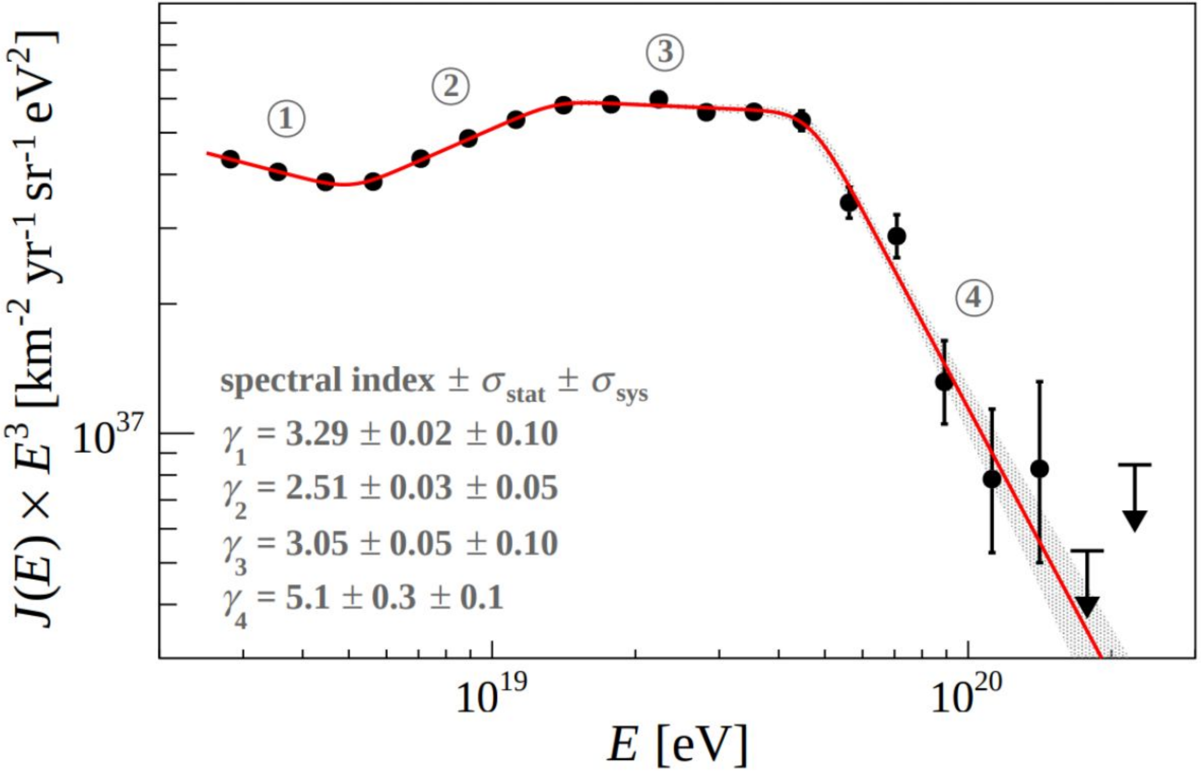


The Pierre Auger Collaboration, **Phys. Rev. Let.**, 2020

# The pieces: experimental data

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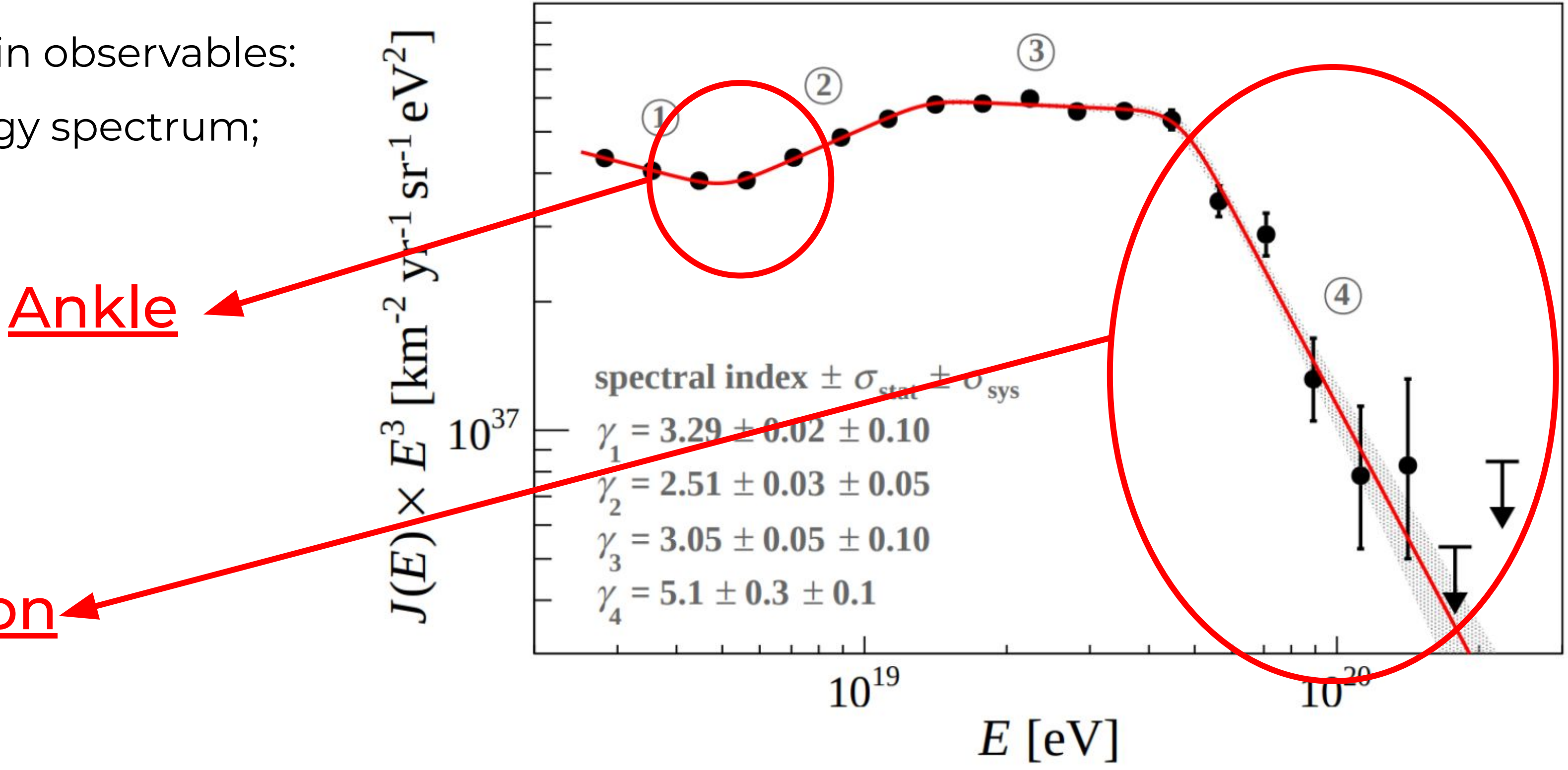


The Pierre Auger Collaboration, **Phys. Rev. Let.**, 2020

# The pieces: experimental data

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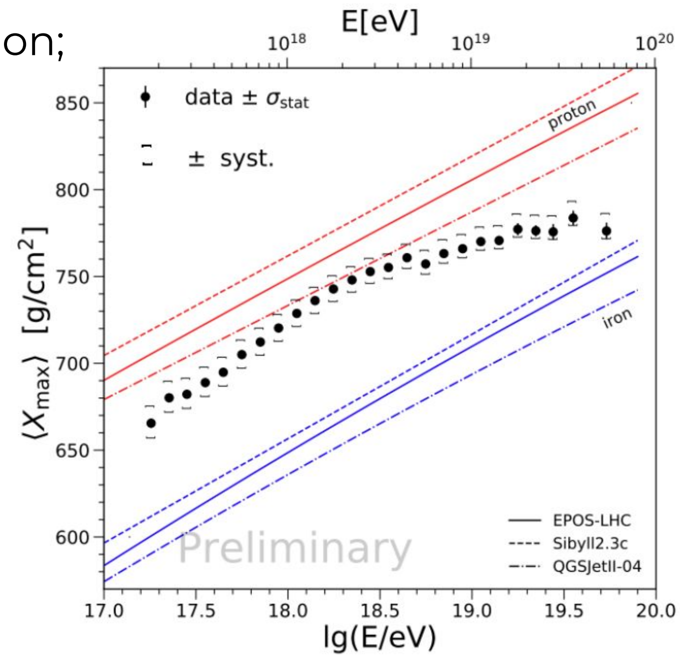
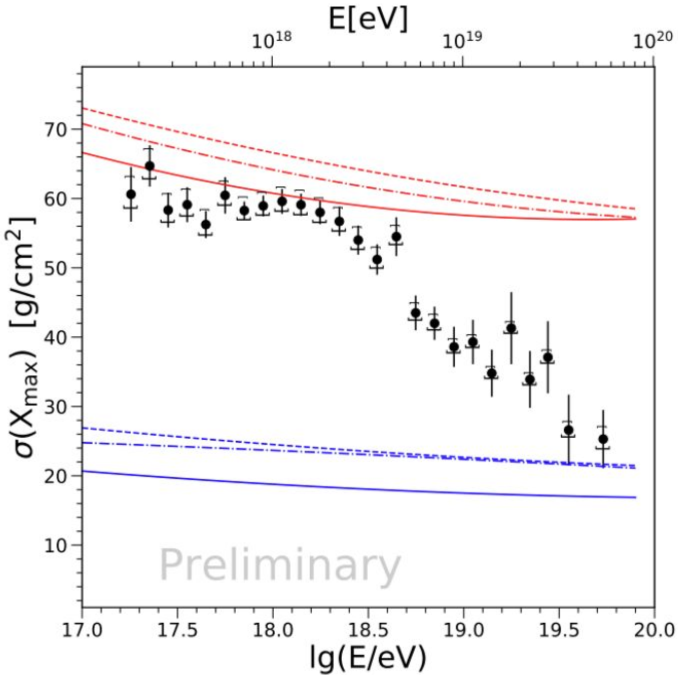
Yushkov, A., **ICRC 2019**



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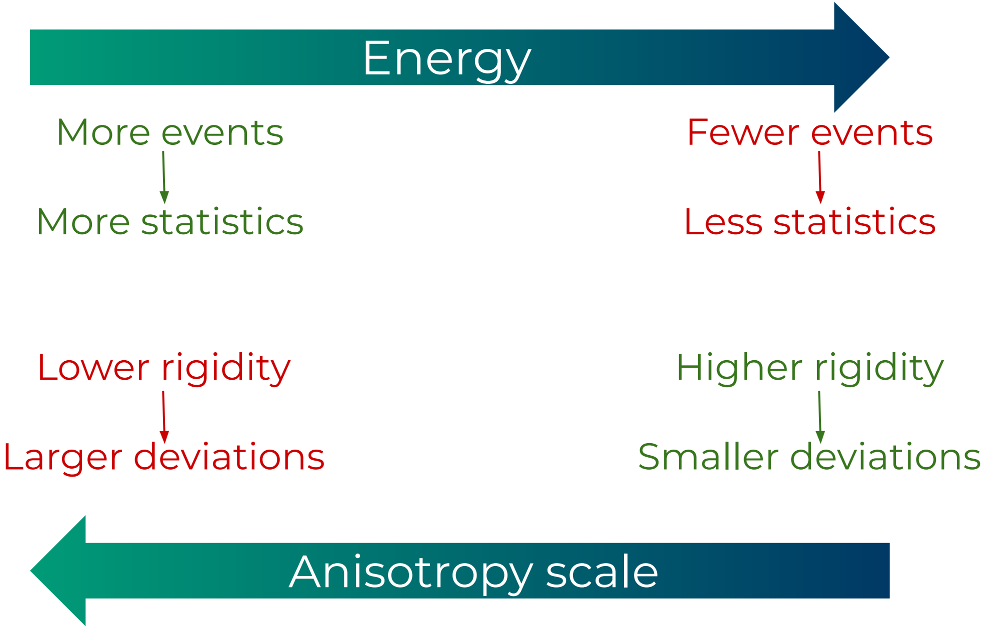
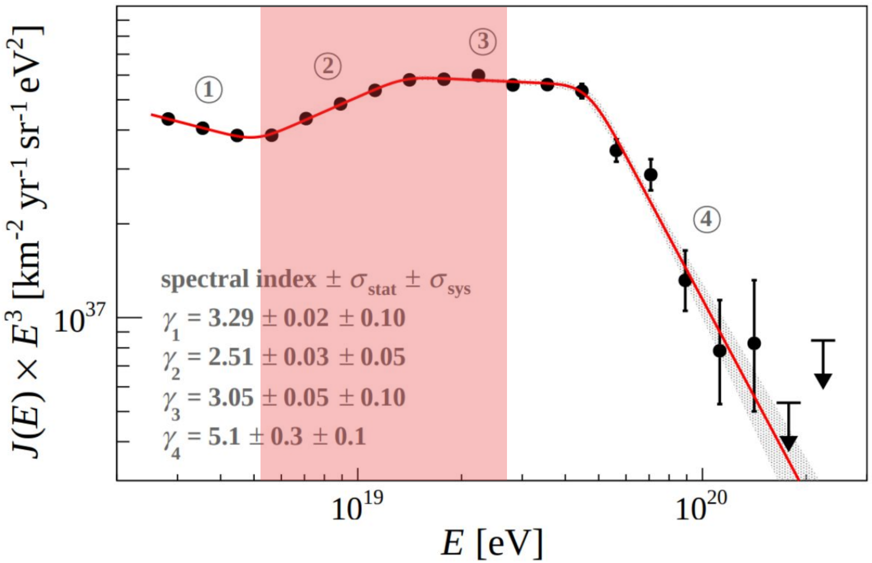
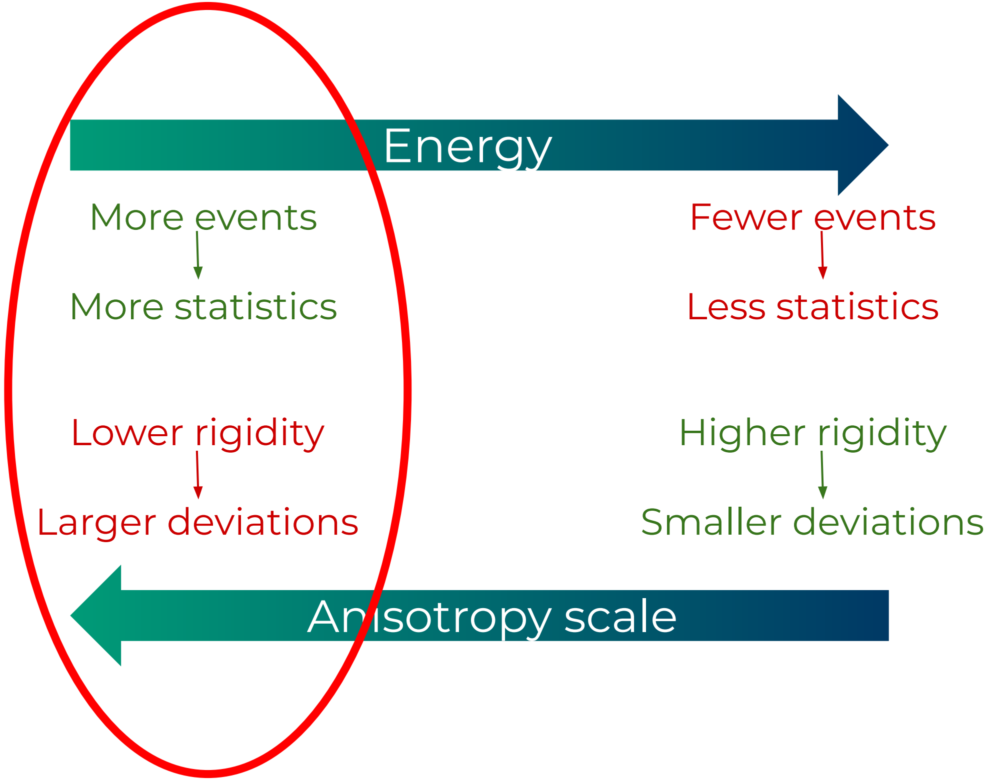


# Low energies - large scale

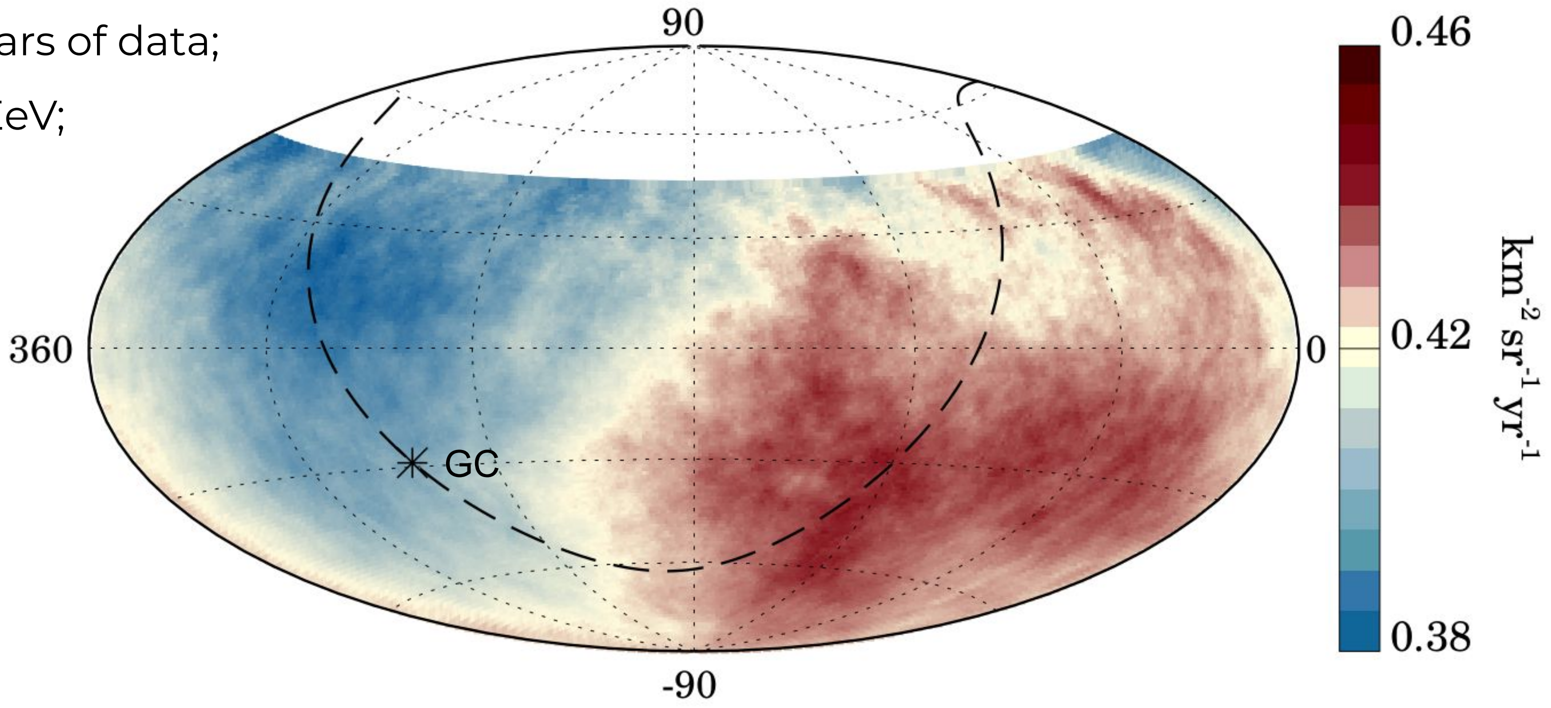



The Pierre Auger Collaboration, **Phys. Rev. Let.**, 2020



# Low energies - 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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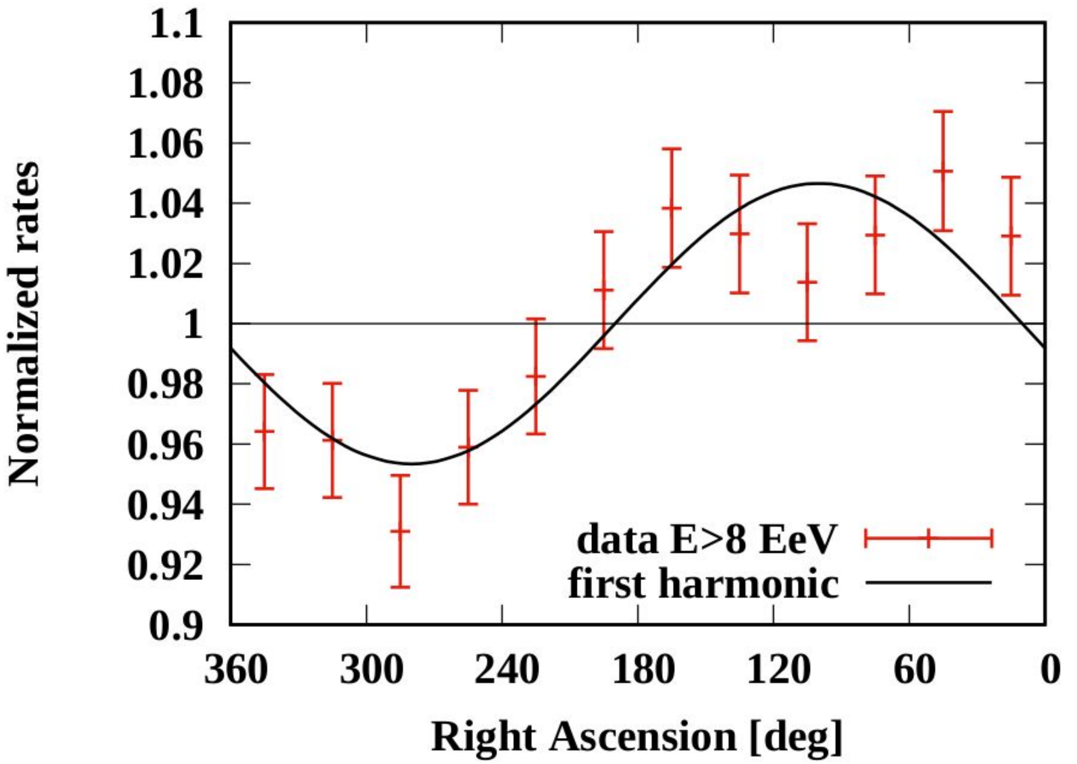
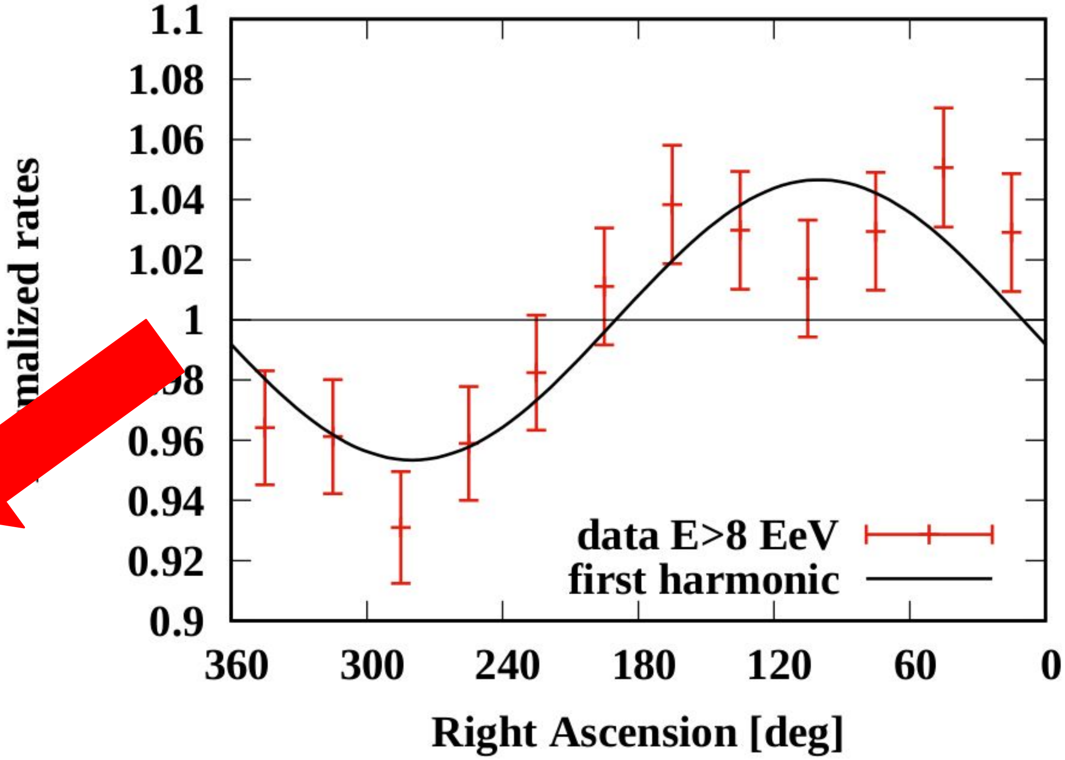



The Pierre Auger Collaboration, **Science**, 2017

# Low energies - 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 energies - large scale

- Auger's large scale anisotropy:
  - 12.5 years of data;
  - E > 8 EeV;
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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 energies - 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 $\delta_d$ [°] | Dipole right ascension $\alpha_d$ [°] |
|---|---|---|---|---|---|
| 4 to 8 | $-0.024 \pm 0.009$ | $0.006^{+0.007}_{-0.003}$ | $0.025^{+0.010}_{-0.007}$ | $-75^{+17}_{-8}$ | $80 \pm 60$ |
| 8 | $-0.026 \pm 0.015$ | $0.060^{+0.011}_{-0.010}$ | $0.065^{+0.013}_{-0.009}$ | $-24^{+12}_{-13}$ | $100 \pm 10$ |

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

*d*>0 with 5.2σ

# Low energies - large scale

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  - 12.5 years of data;
  - E > 8 EeV;
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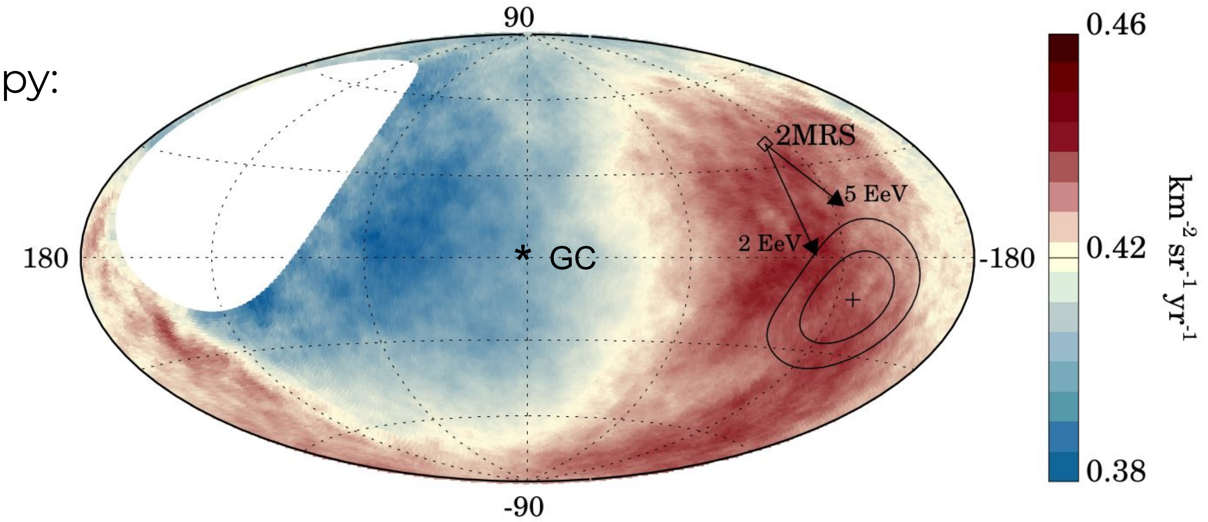


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The Pierre Auger Collaboration, **Science**, 2017

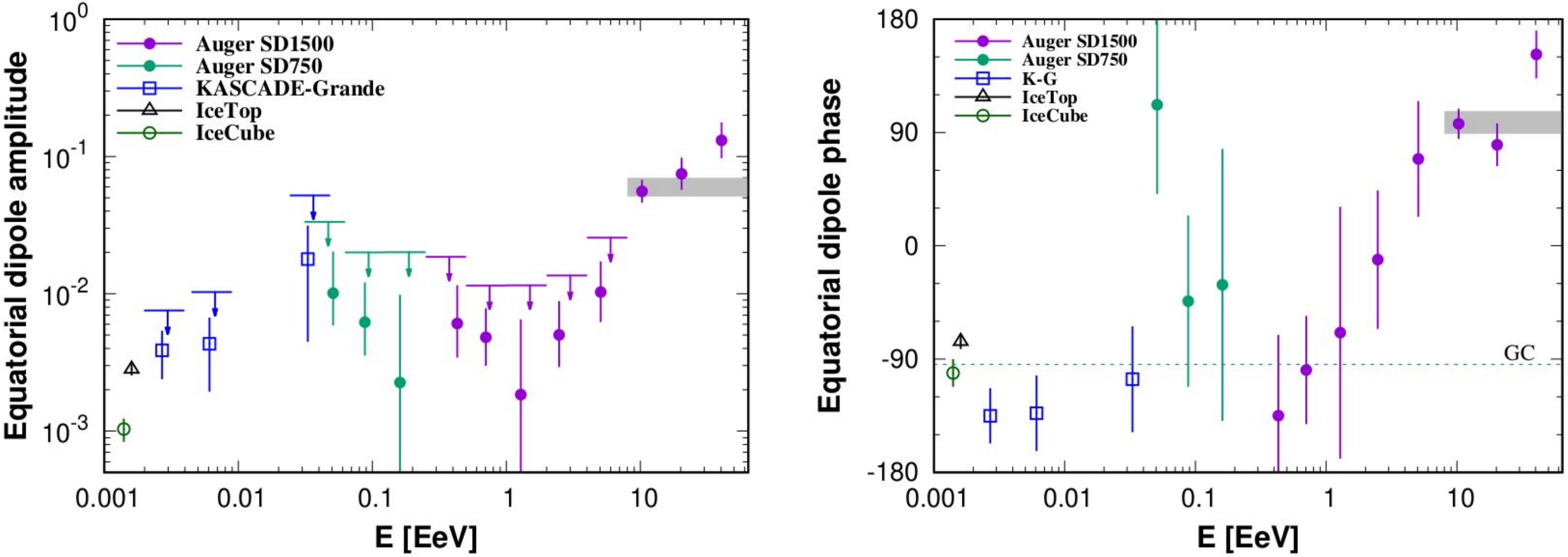
outwards the galactic center

# Low energies - 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 energies - large scale

➢ Evolution with energy:
- Dipole in right ascension;
- 14.5 yr of Auger data;




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

# Low energies - large scale

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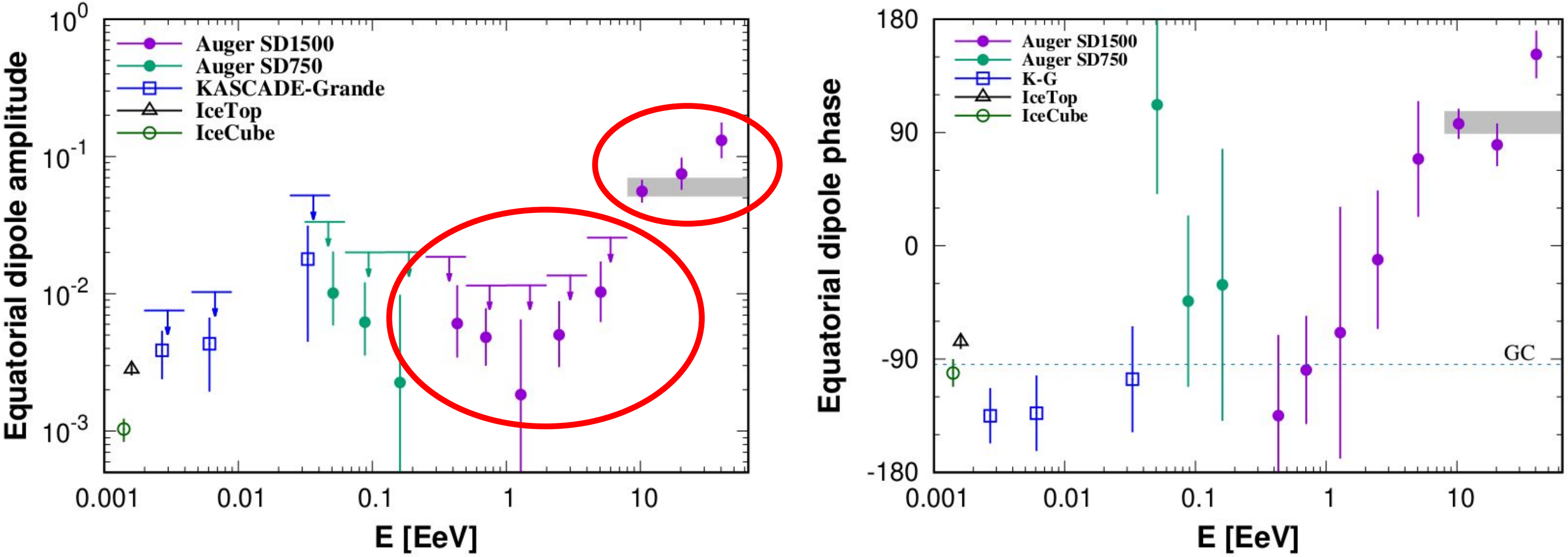
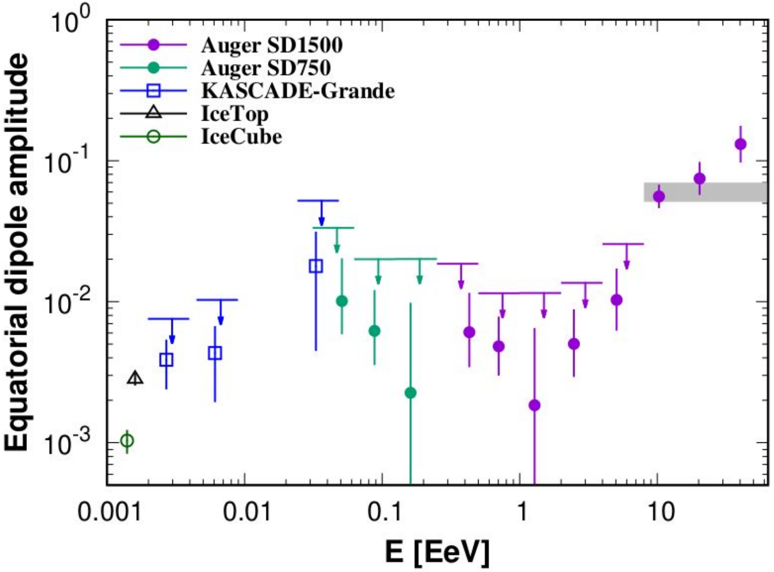


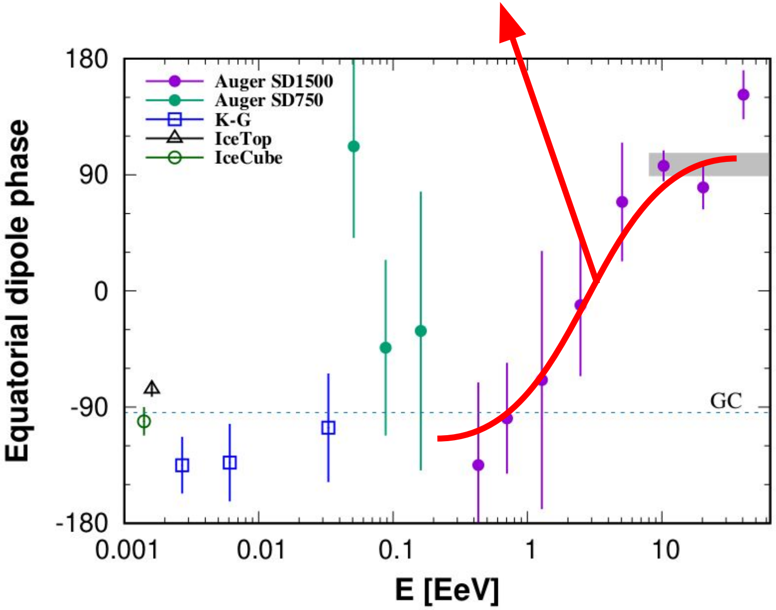

The Pierre Auger Collaboration, **Astrophys. J.**, 2020

# Low energies - 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

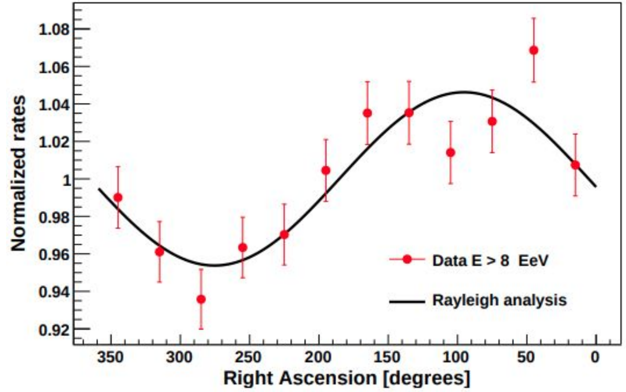


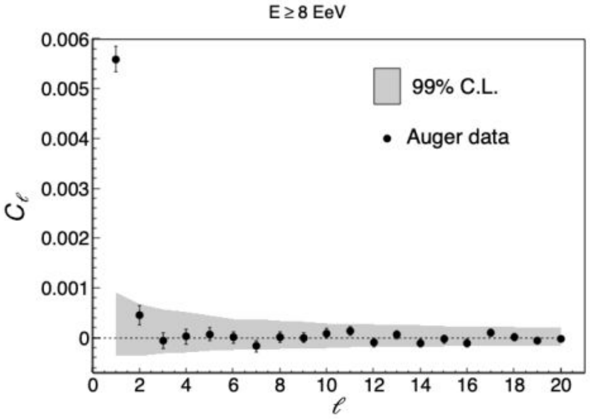



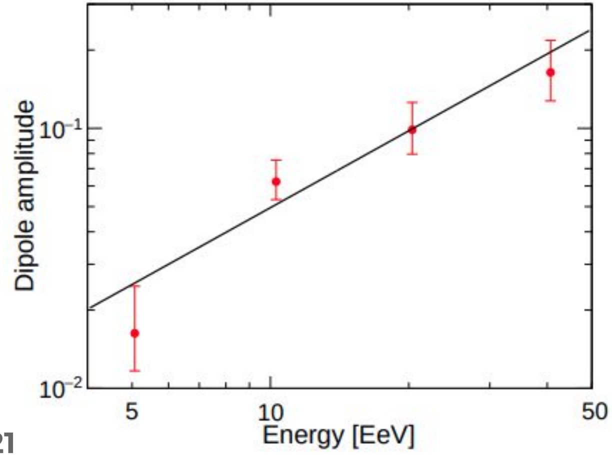

The Pierre Auger Collaboration, **Astrophys. J.**, 2020

# Low energies - large scale

➢ Auger's large scale anisotropy:
  - 7.3% with 6.6σ for E > 8 EeV;
  - Quadrupole not statistically significant;
  - Evolution with energy;
  - Angular power spectrum.



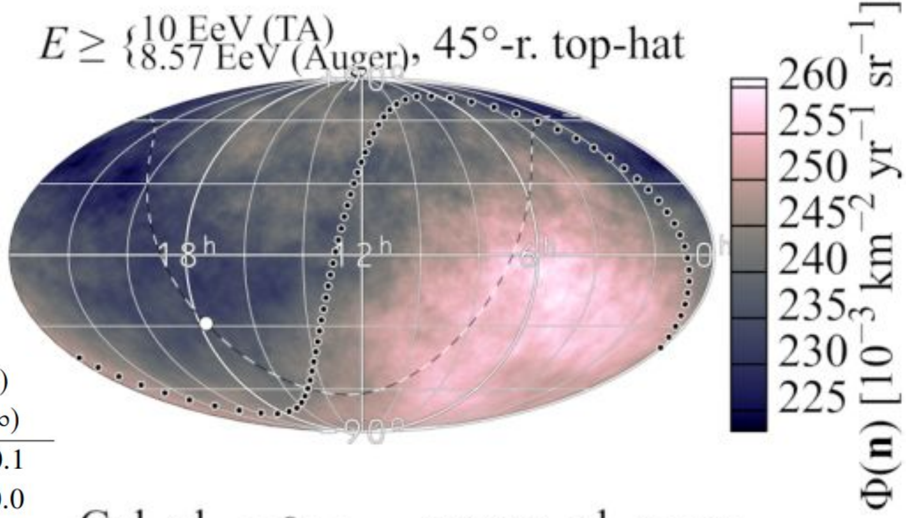





de Almeira, R. M. *et al.*, **ICRC 2021**

# Low energies - large scale

- Full sky:
  - Auger + TA;



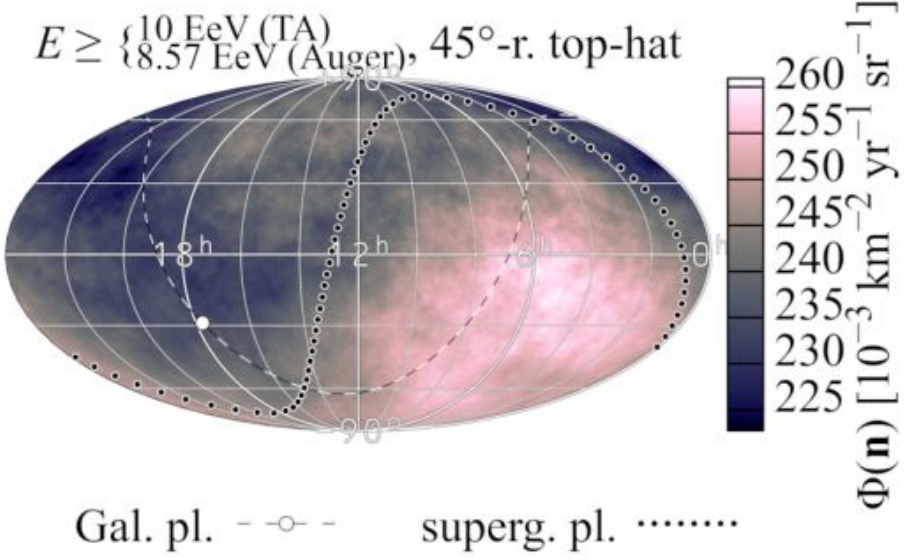

Tinyakov, P. *et al.*, **ICRC 2021**

| energies (Auger)<br>energies (TA) | [8.57 EeV, 16 EeV)<br>[10 EeV, 19.47 EeV) | [16 EeV, 32 EeV)<br>[19.47 EeV, 40.8 EeV) | [32 EeV, +∞)<br>[40.8 EeV, +∞) |
|---|---|---|---|
| $d_x$ [%] | −0.7 ± 1.1 ± 0.0 | +1.6 ± 2.0 ± 0.0 | −5.3 ± 3.9 ± 0.1 |
| $d_y$ [%] | +4.8 ± 1.1 ± 0.0 | +3.9 ± 1.9 ± 0.1 | +9.7 ± 3.7 ± 0.0 |
| $d_z$ [%] | −3.3 ± 1.4 ± 1.3 | −6.0 ± 2.4 ± 1.3 | +3.4 ± 4.7 ± 3.6 |
| $Q_{xx} - Q_{yy}$ [%] | −5.1 ± 4.8 ± 0.0 | +13.6 ± 8.3 ± 0.0 | +43 ± 16 ± 0 |
| $Q_{xz}$ [%] | −3.9 ± 2.9 ± 0.1 | +5.4 ± 5.1 ± 0.0 | +5 ± 11 ± 0 |
| $Q_{yz}$ [%] | −4.9 ± 2.9 ± 0.0 | −9.6 ± 5.0 ± 0.1 | +11.9 ± 9.8 ± 0.2 |
| $Q_{zz}$ [%] | +0.5 ± 3.3 ± 1.7 | +5.2 ± 5.8 ± 1.7 | +20 ± 11 ± 5 |
| $Q_{xy}$ [%] | +2.2 ± 2.4 ± 0.0 | +0.2 ± 4.2 ± 0.1 | +4.5 ± 8.1 ± 0.1 |
| $C_1$ [$10^{-3}$] | 4.8 ± 2.0 ± 1.2 | 7.6 ± 4.6 ± 2.2 | 19 ± 12 ± 4 |
| $C_2$ [$10^{-3}$] | 0.85 ± 0.66 ± 0.02 | 3.1 ± 2.2 ± 0.2 | 15.5 ± 8.9 ± 2.4 |

LATEST NEWS

# Low energies - large scale

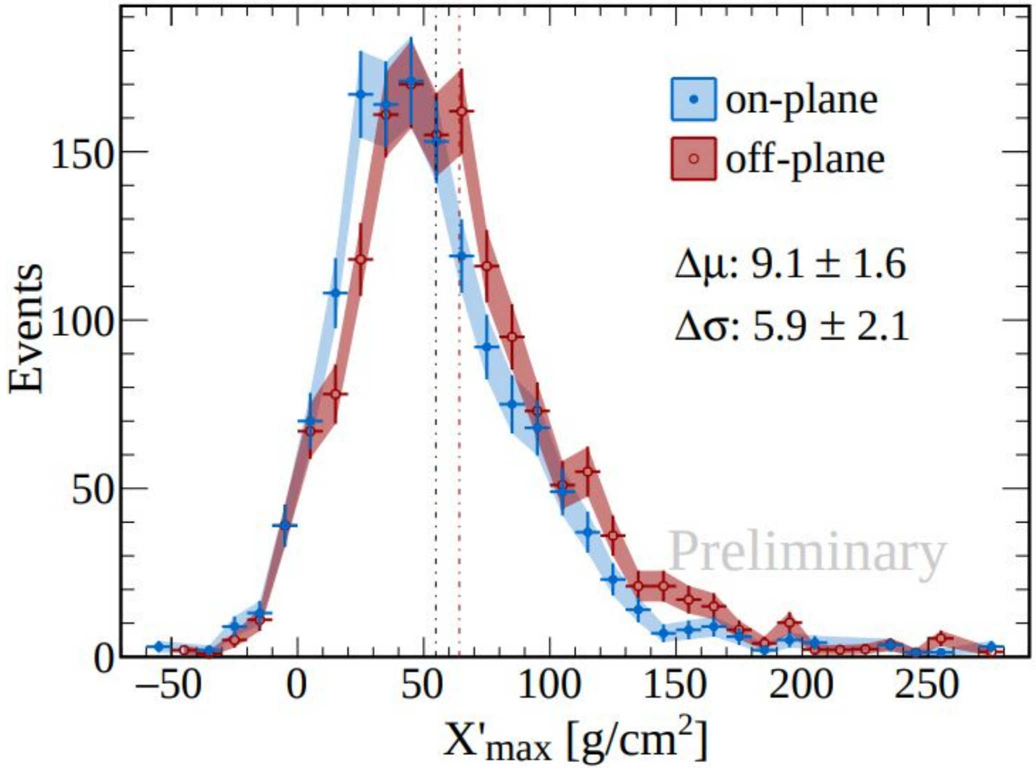
- Full sky:
  - Auger + TA;
  - Regardless of assumptions about multipoles;
  - Agreement with only Auger data;
  - Only dipole is statistically significant.




Tinyakov, P. *et al.*, **ICRC 2021**

# Low energies - large scale

➢ Composition anisotropy:
  ○ 14 years of Auger data;
  ○ $E > 10^{18.7}$ eV;


Mayotte, E., **ICRC 2021**

# Low energies - large scale

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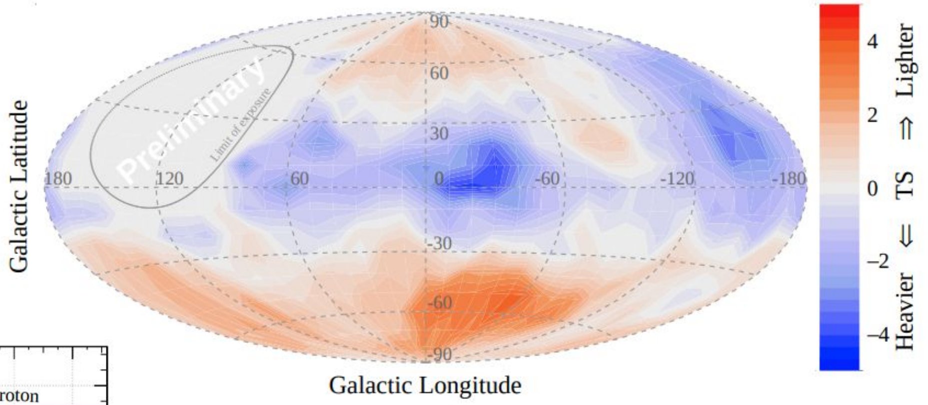
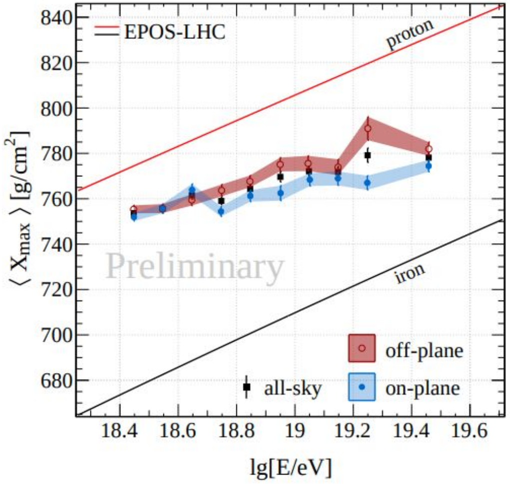
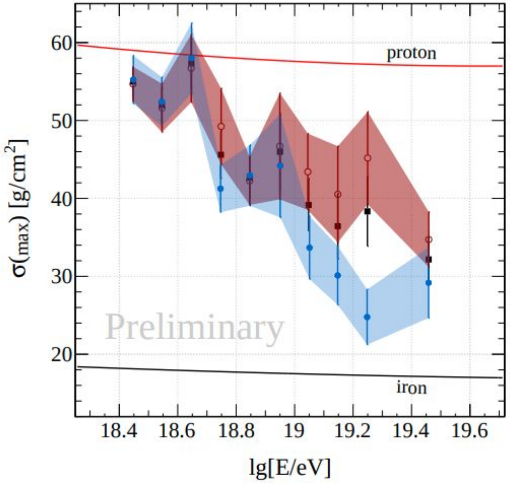



Mayotte, E., **ICRC 2021**

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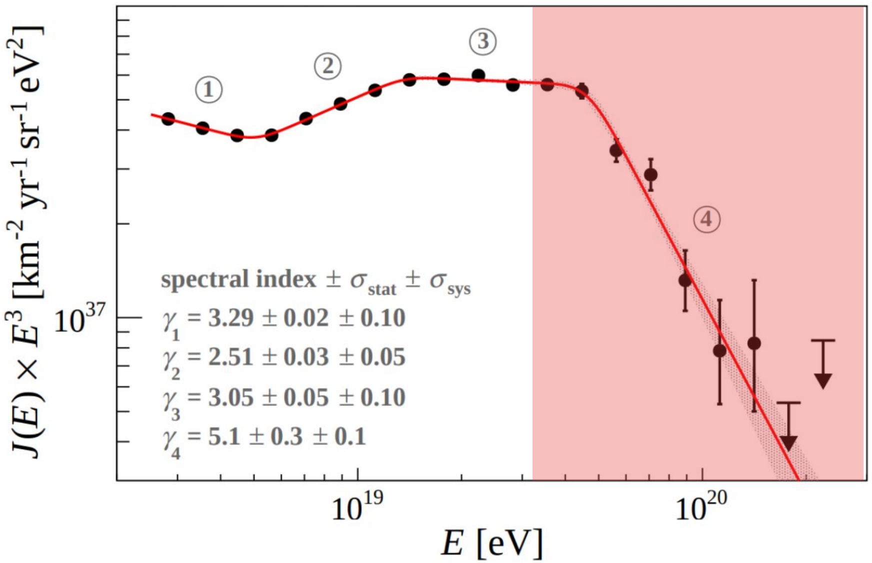
# High energies - intermediate scale




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

Energy →

More events → More statistics

Fewer events → Less statistics

Lower rigidity → Larger deviations

Higher rigidity → Smaller deviations

← Anisotropy scale

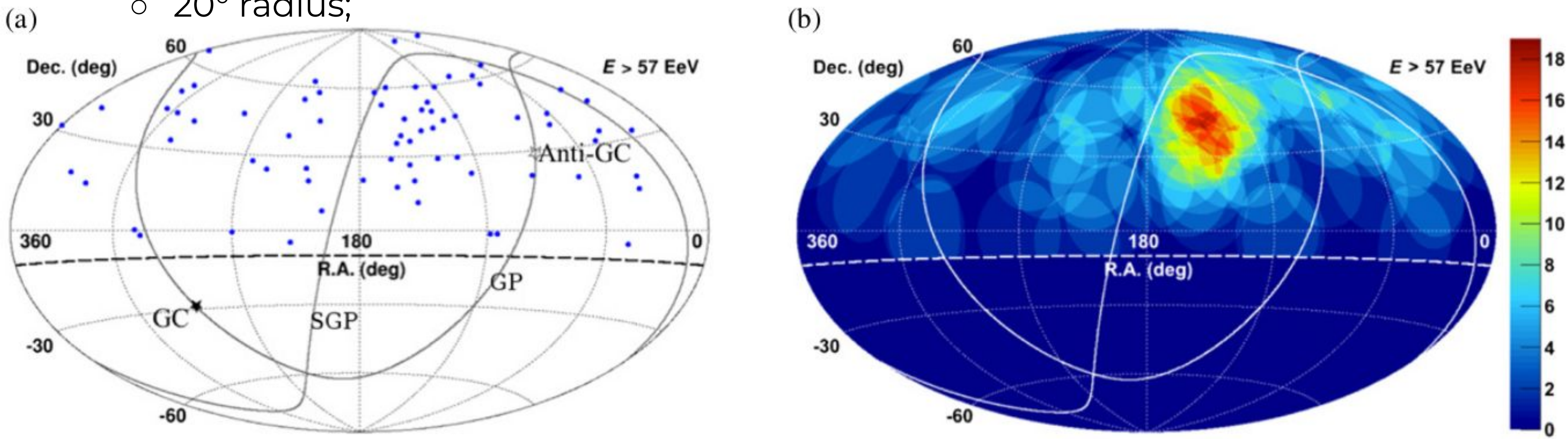
# High energies - intermediate scale

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

# High energies - intermediate scale

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

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



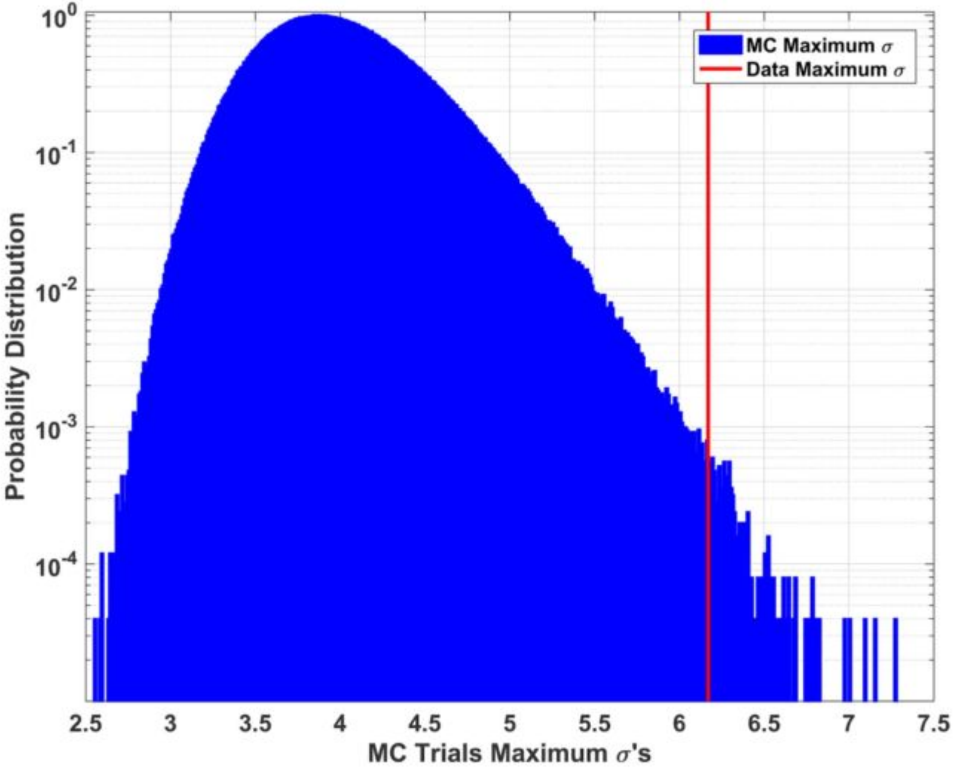

Telescope Array Collaboration, **Astrophys. J. Lett.**, 2014

# High energies - intermediate scale

- TA hotspot - significance:
  - What is the probability of such strong excess appearing if you do multiple searches?

# High energies - intermediate scale

- TA hotspot - significance:
  - What is the probability of such strong excess appearing if you do multiple searches?
  - Post-trial significance:
    - TA '14: 3.4σ;
    - TA '18: 3.74σ;
    - TA '19: 2.9σ;
    - TA '21: 3.2σ.




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

# High energies - intermediate scale

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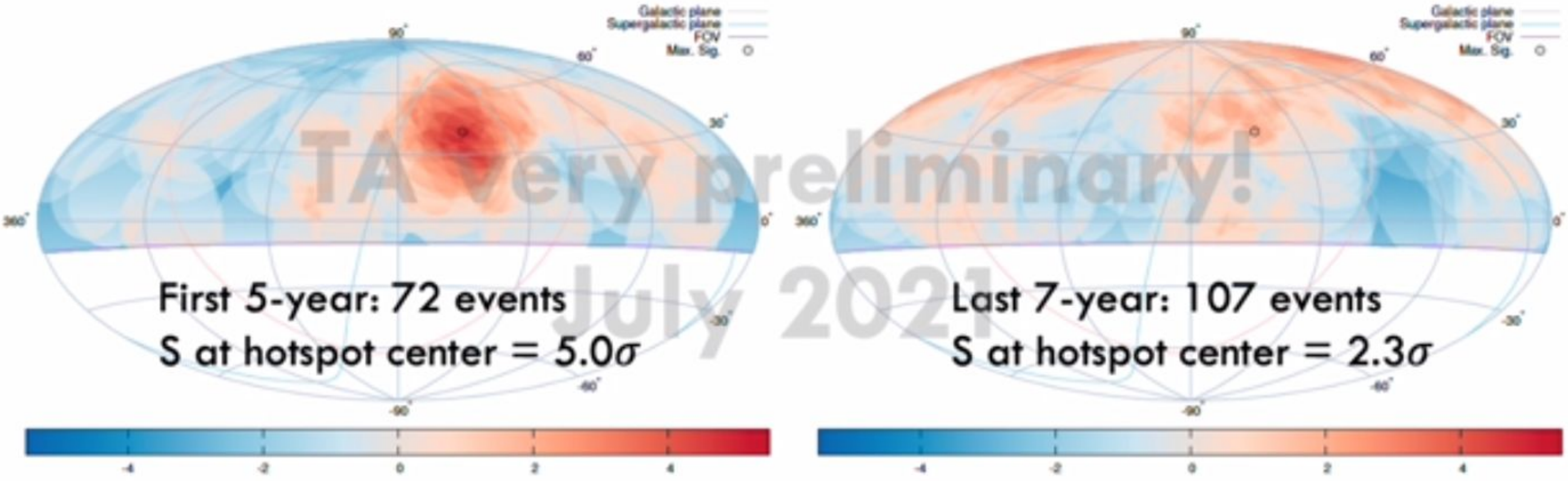
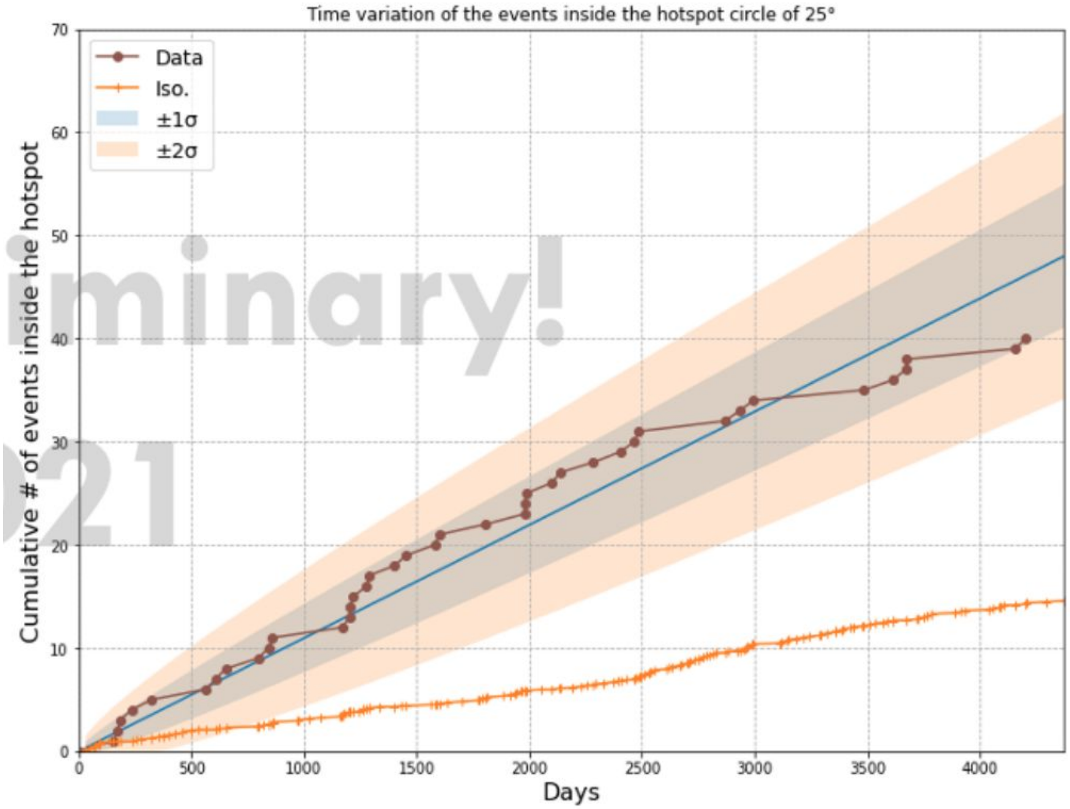
- TA hotspot - significance:
  - Is the hotspot vanishing?




Kim, J., **slides from ICRC 2021**.

# High energies - intermediate scale

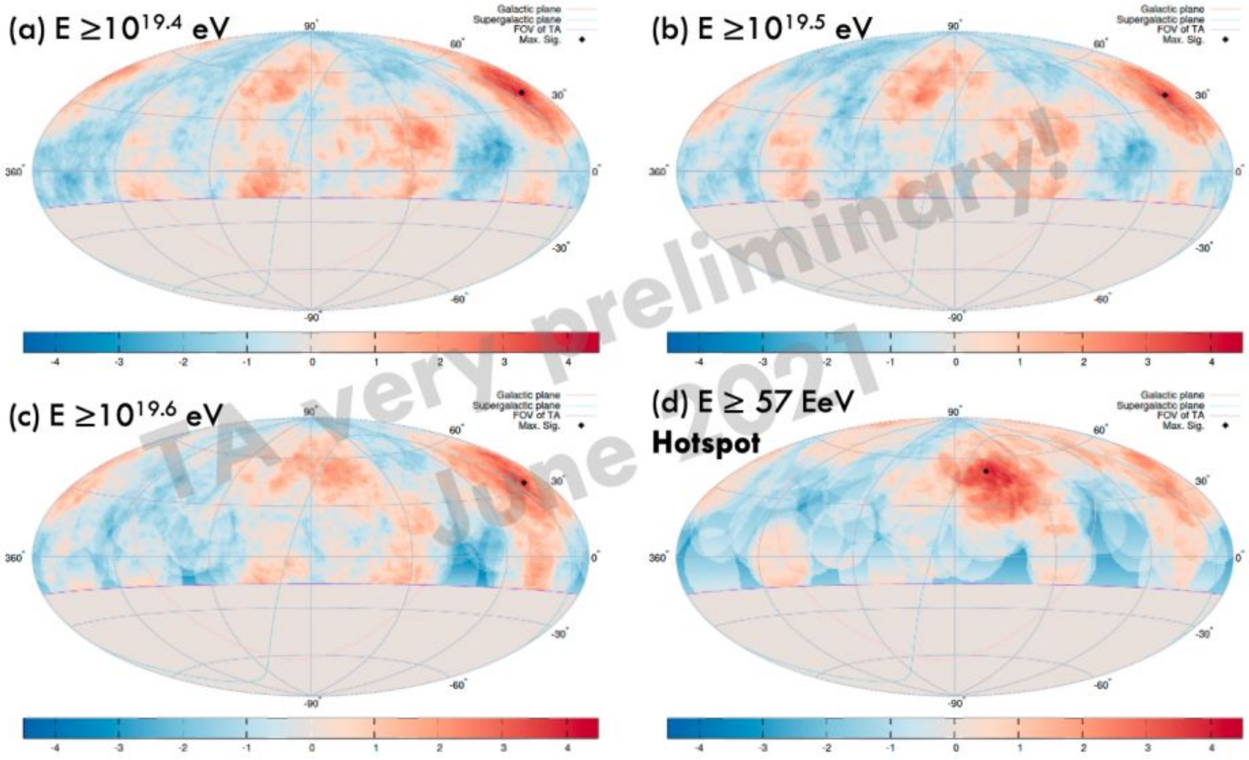
➢ TA hotspot - significance:
  - Is the hotspot vanishing?
  - The growth of events is still fluctuating within 1σ;
  - We might have just been unlucky.


Kim, J. *et al*, **ICRC 2021**.

# High energies - intermediate scale

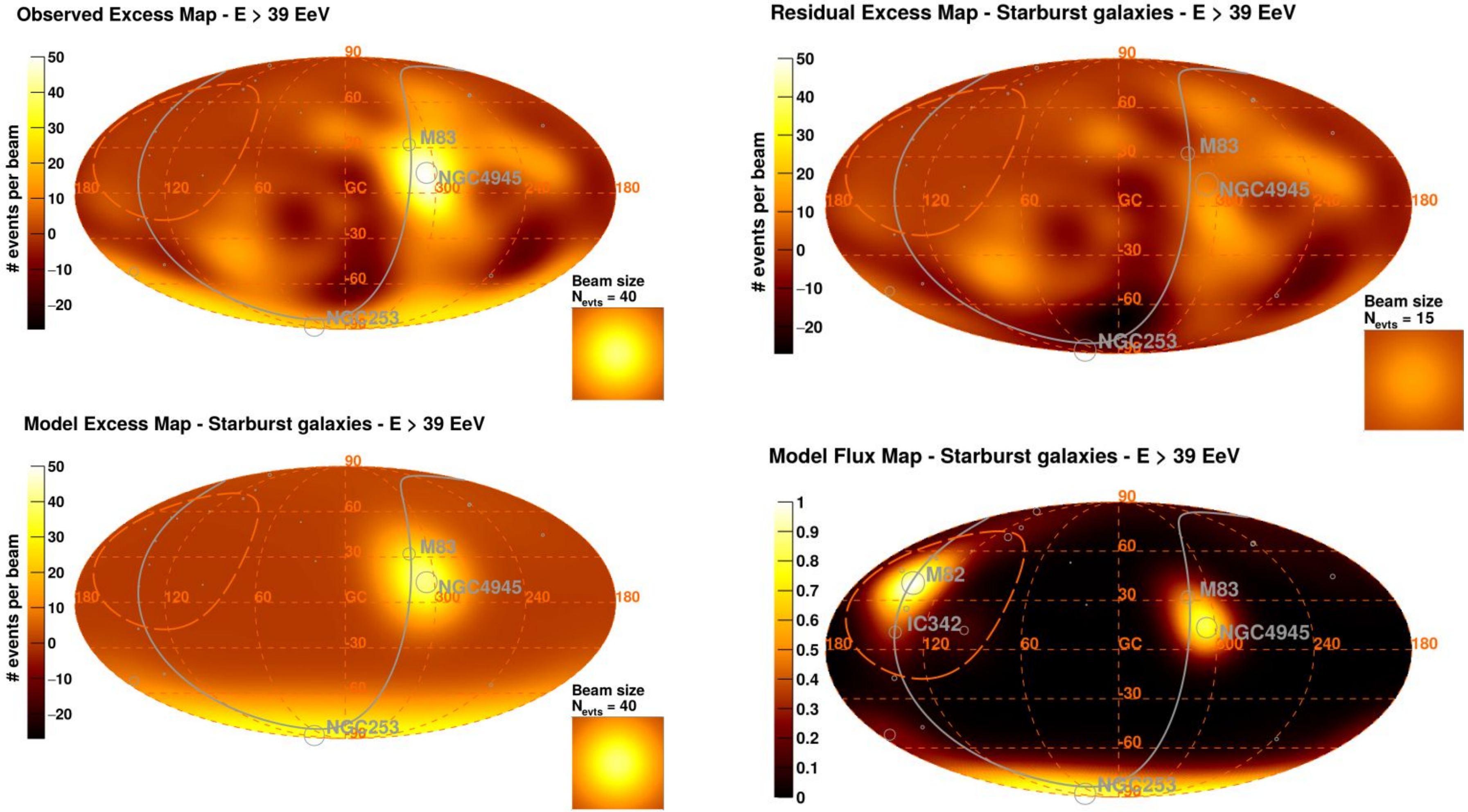
- (A new) TA hotspot:
  - 12 years of data;
  - E > $10^{19.4\text{-}19.6}$ EeV;
  - 20° radius;
  - Hotspot near Perseus-Pisces cluster;
  - 3.6σ post-trial;


Kim, J. *et al*, **ICRC 2021**.

# High energies - intermediate scale

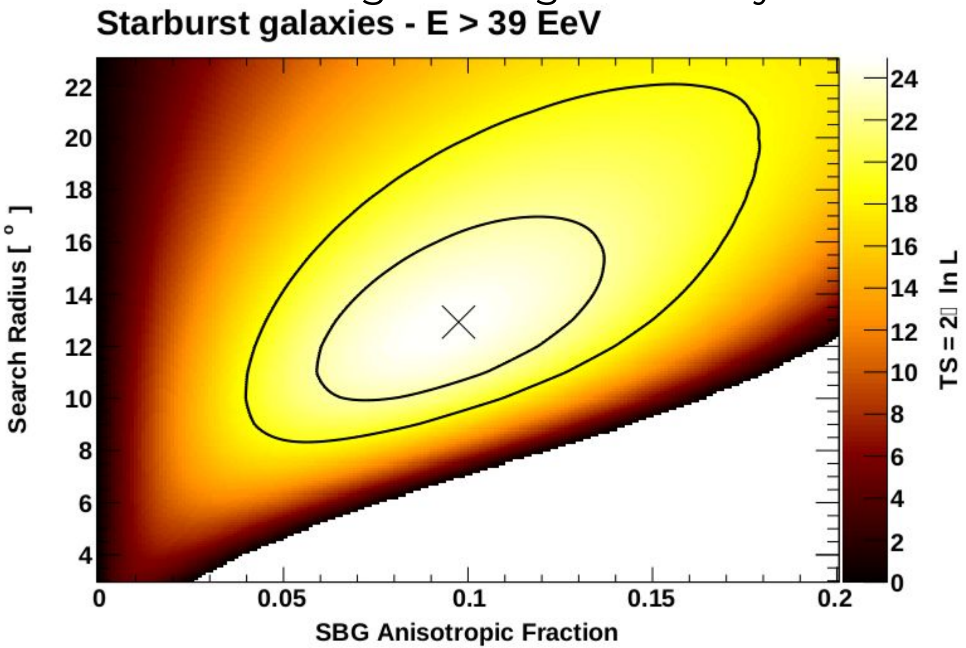
- Auger correlation maps:
  - Search for correlations of excesses with known extragalactic gamma-ray sources:
    - Active galactic nuclei (AGNs);
    - Starburst galaxies (SBGs);
  - Search variables:
    - Minimum energy;
    - Radius;
    - Anisotropic fraction.




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

# High energies - intermediate scale

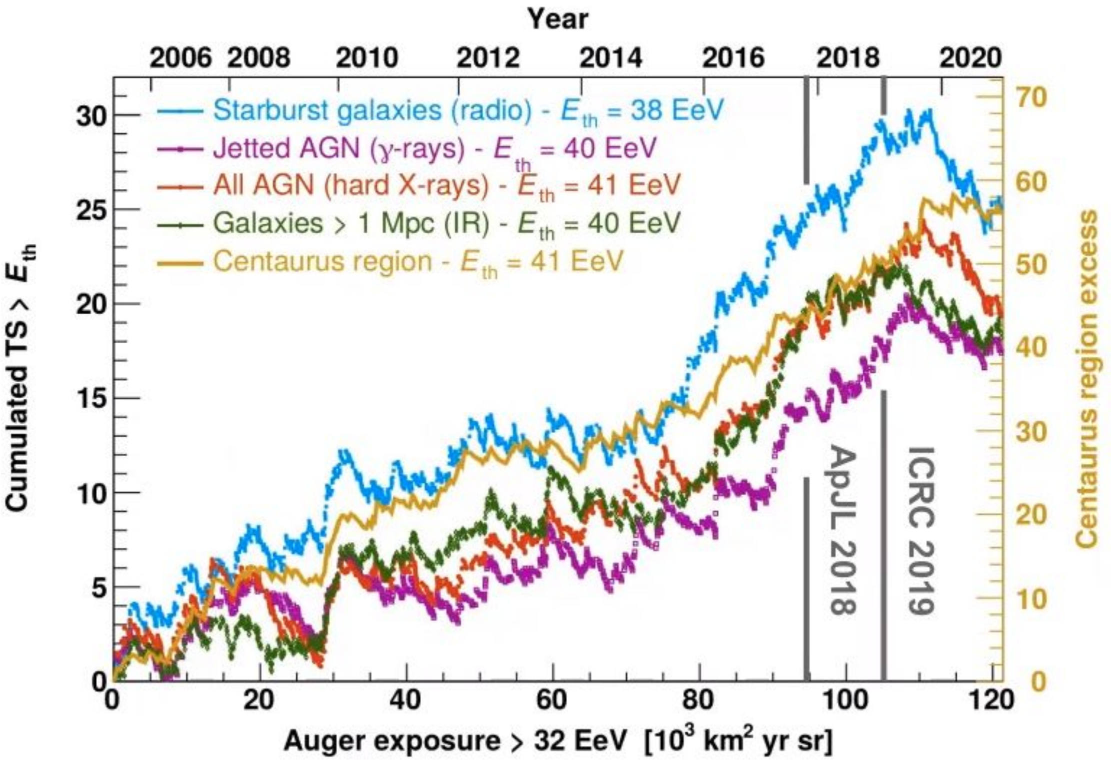
- Auger correlation maps:
  - Search for correlations of excesses with known extragalactic gamma-ray sources:
    - Active galactic nuclei (AGNs);
    - Starburst galaxies (SBGs);
  - Correlations:
    - AGNs: 2.7σ;
    - AGNs+SBGs: 3.7σ;
    - SBGs: 4.0σ.




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

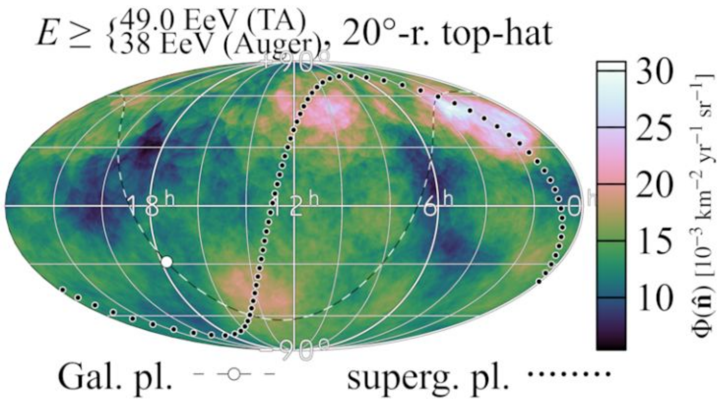
# High energies - intermediate scale

- Auger correlation maps:
  - Currently:
    - Jetted AGNs: 3.0σ;
    - SBGs: 4.0σ;
    - Centaurus region: 3.9σ;

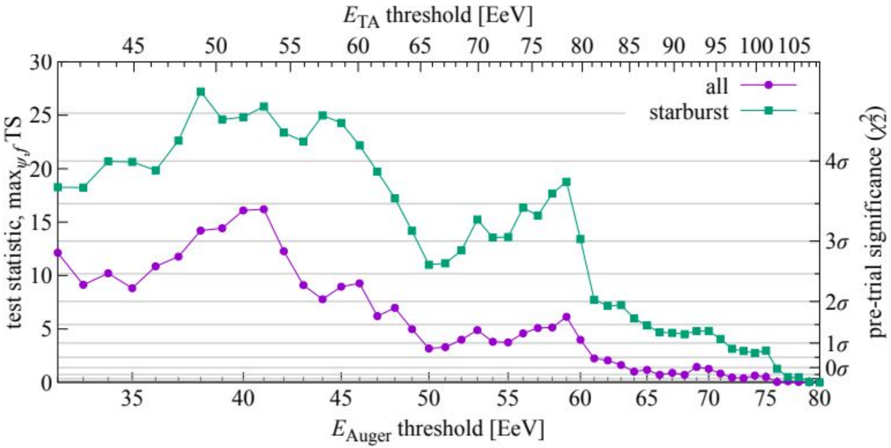




Biteau, J., **slides from ICRC 2021**.

# High energies - intermediate scale

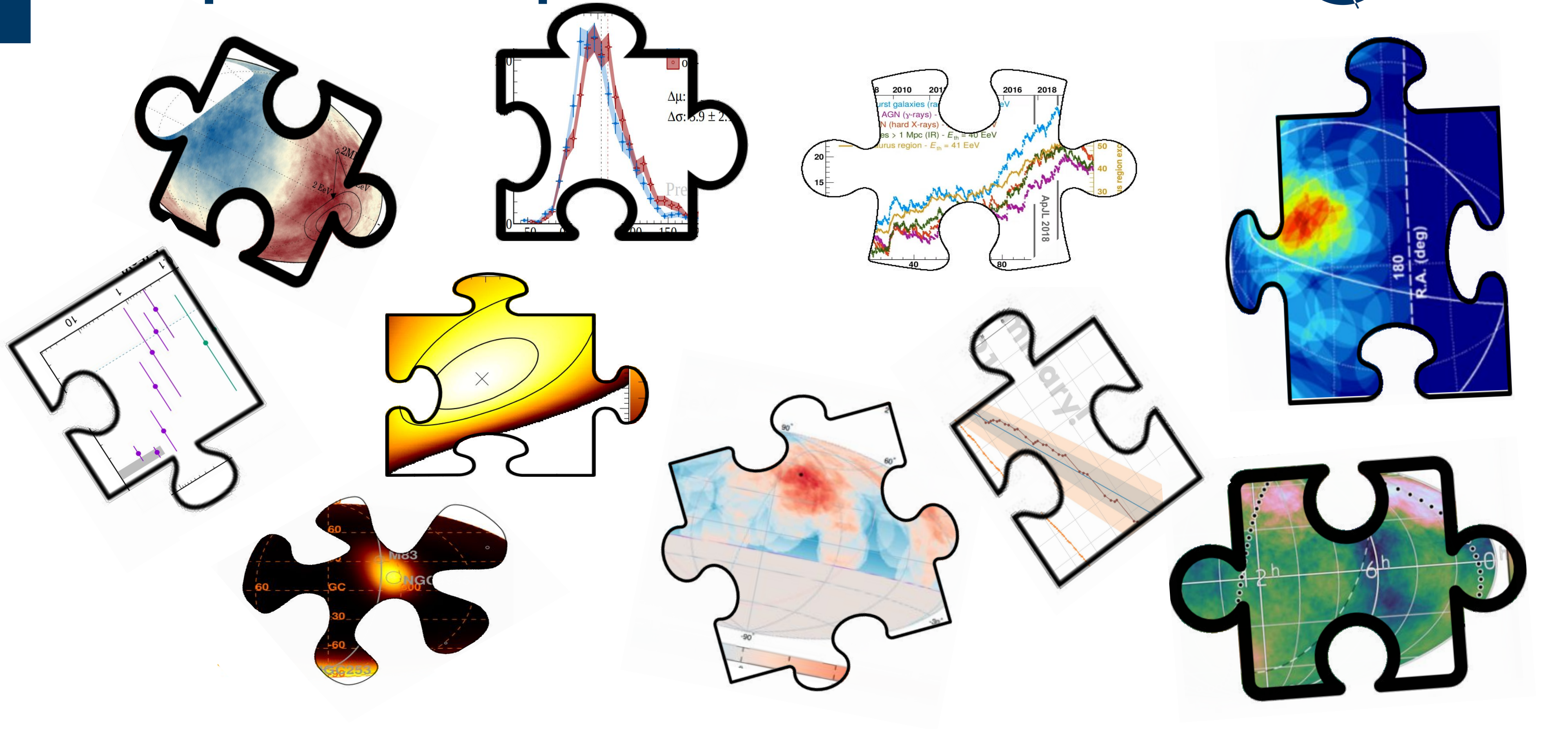



- ➢ Full sky:
  - ○ Auger+TA;
  - ○ Correlation with SBGs:
    - ■ E>38 EeV (Auger);
    - ■ E>49 EeV (TA);
    - ■ 16° radius;
    - ■ 4.0σ post-trial.




di Matteo, A. *et al.*, **ICRC 2021**.

# The pieces: experimental data



# The assembly: phenomenology

➢ Several efforts to describe the experimental results:

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

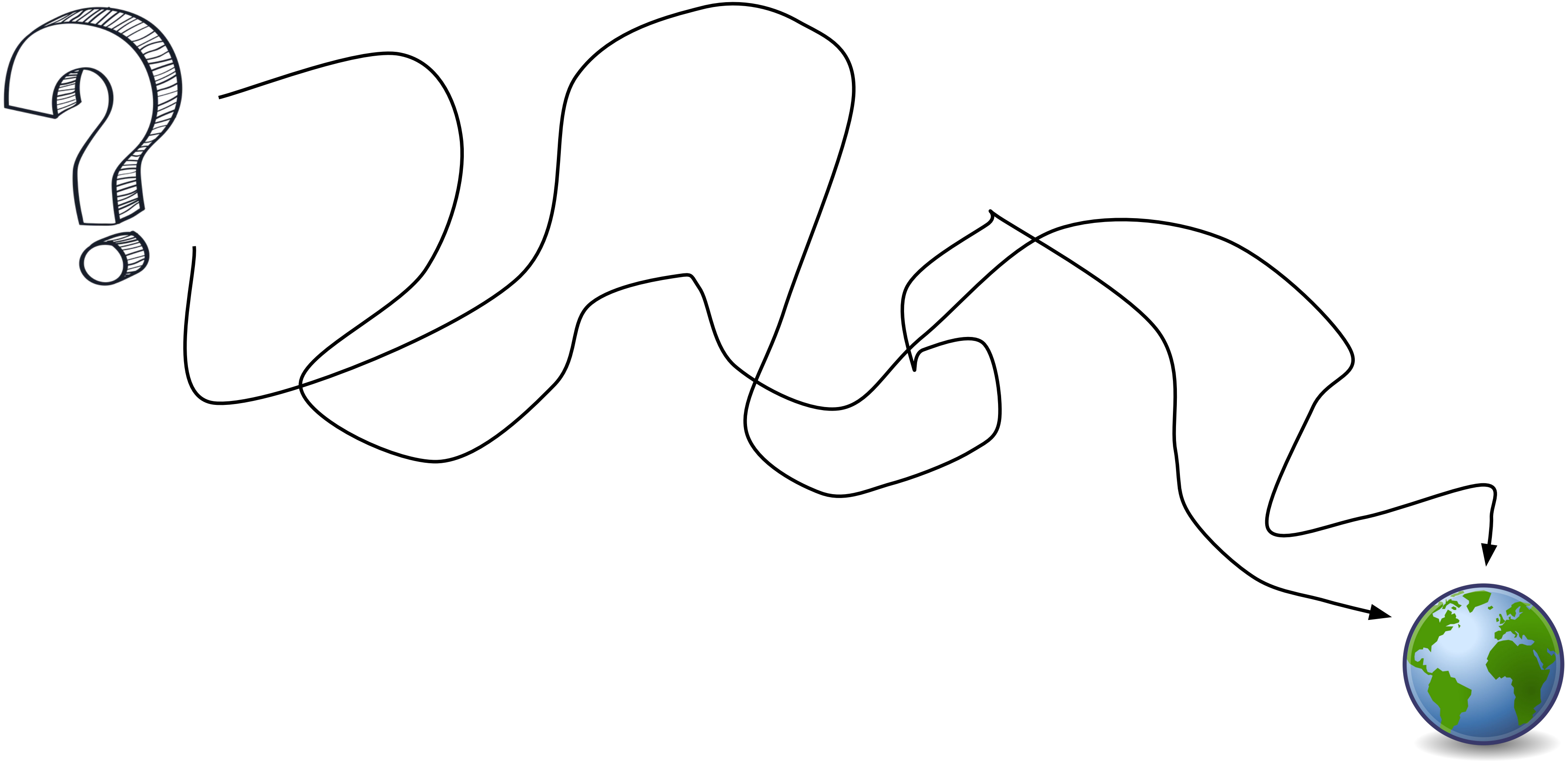
Bister, T. *et al.*, **Astropart. Phys.**, 2021

de Oliveira, C. *et al.*, **Eur. Phys. J. C**, 2021

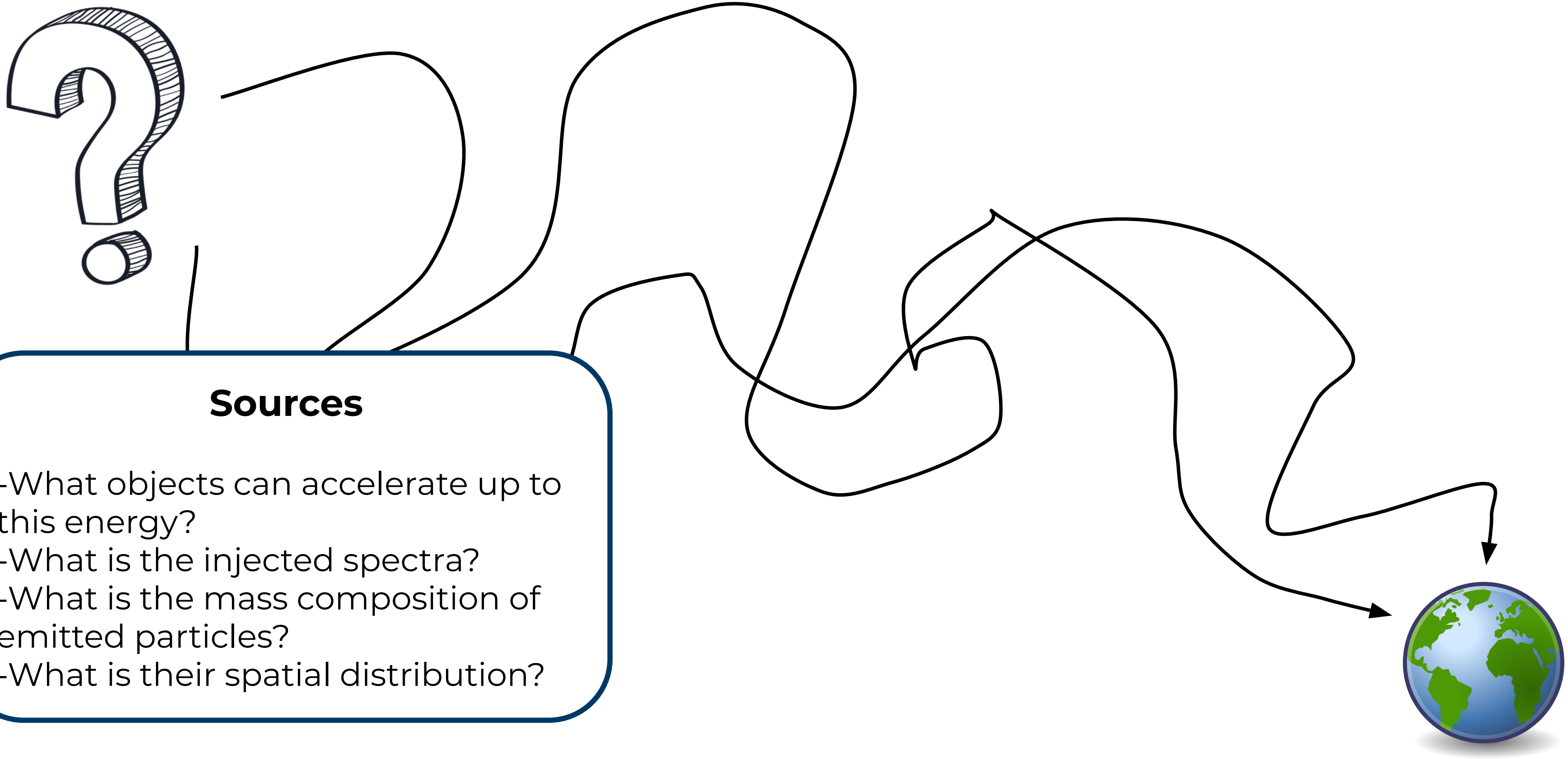
Muzio, M. *et al.*, **ICRC 2021**

**(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

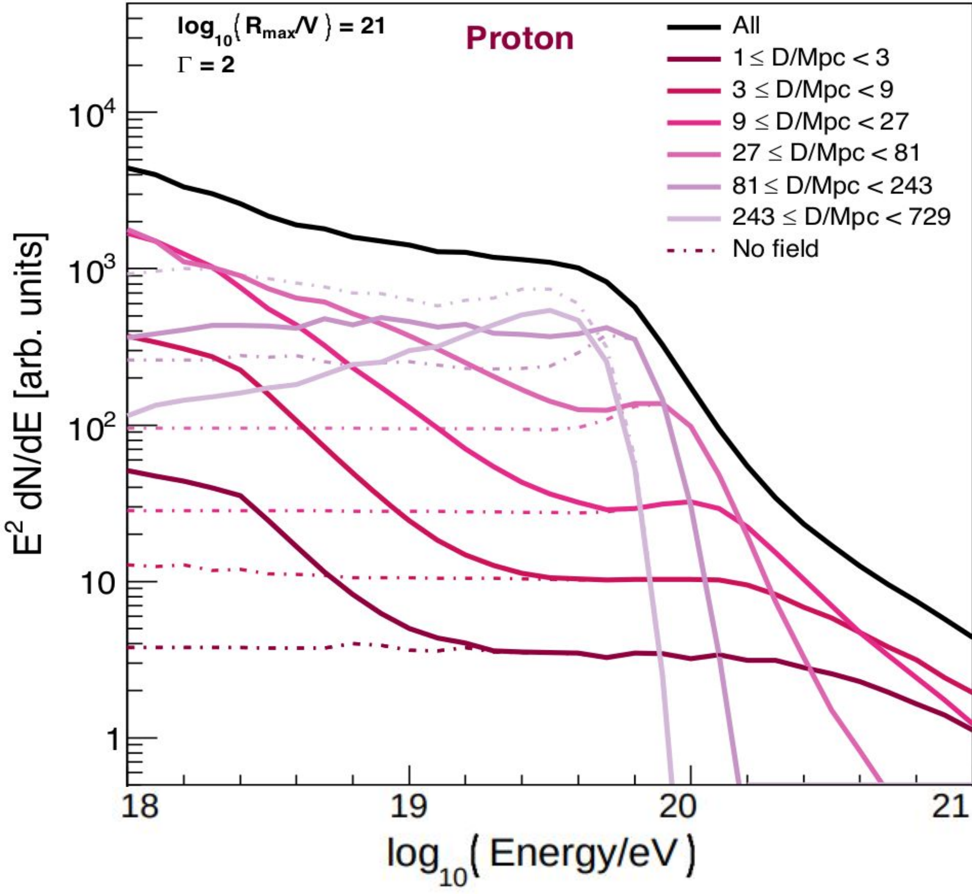
- Lots of unknowns -> lots of hypotheses needed;
- We need to find a balance between:
  - Many hypotheses/Few fit parameters -> model dependency;
  - Few hypotheses/Many fit parameters -> no strong conclusions.

# Starting with the borders

- A possible (good) approach:
  - Understand the intrinsic behavior of the measurements and how they depend on each assumption;
  - Find variables which don't strongly rely on given hypotheses;

# Starting with the borders

➢ Local sources;

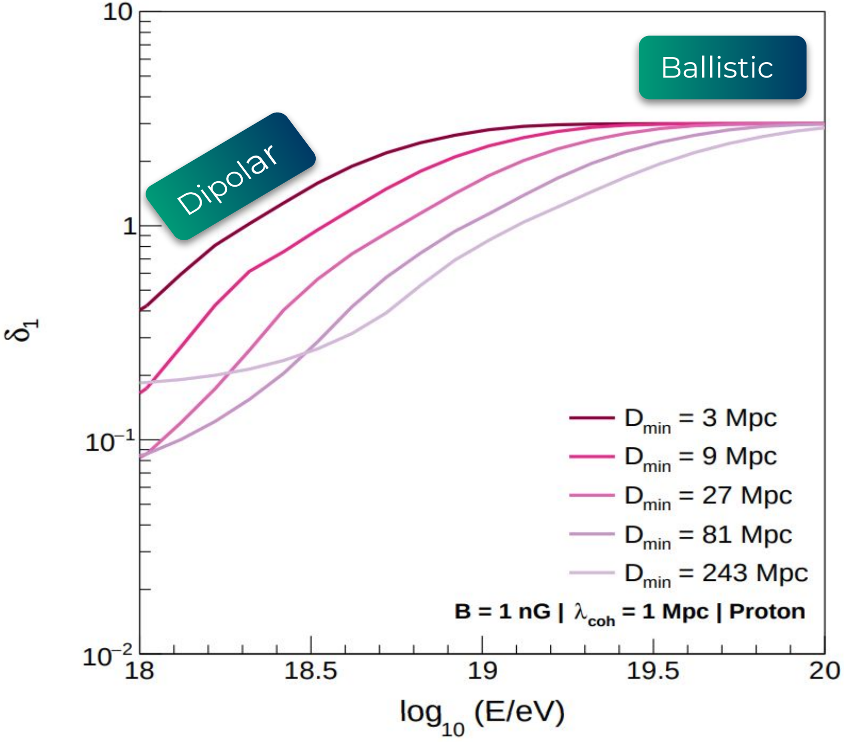


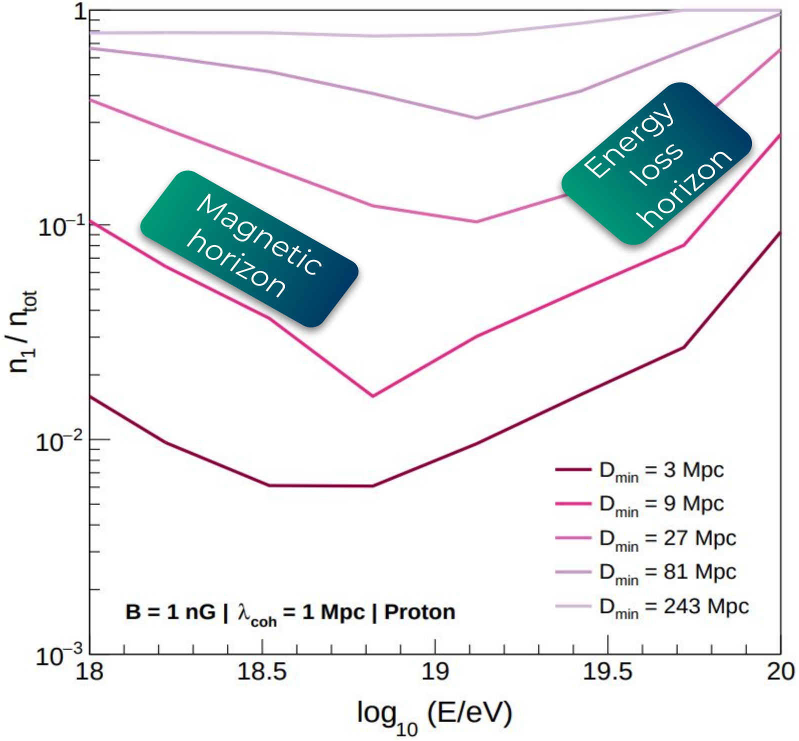

Lang, R. G. *et al.*, **Phys. Rev. D**, 2020

# Starting with the borders

- ➢ Local sources;

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



# Starting with the borders

- Local sources;

Closer sources have stronger dipoles

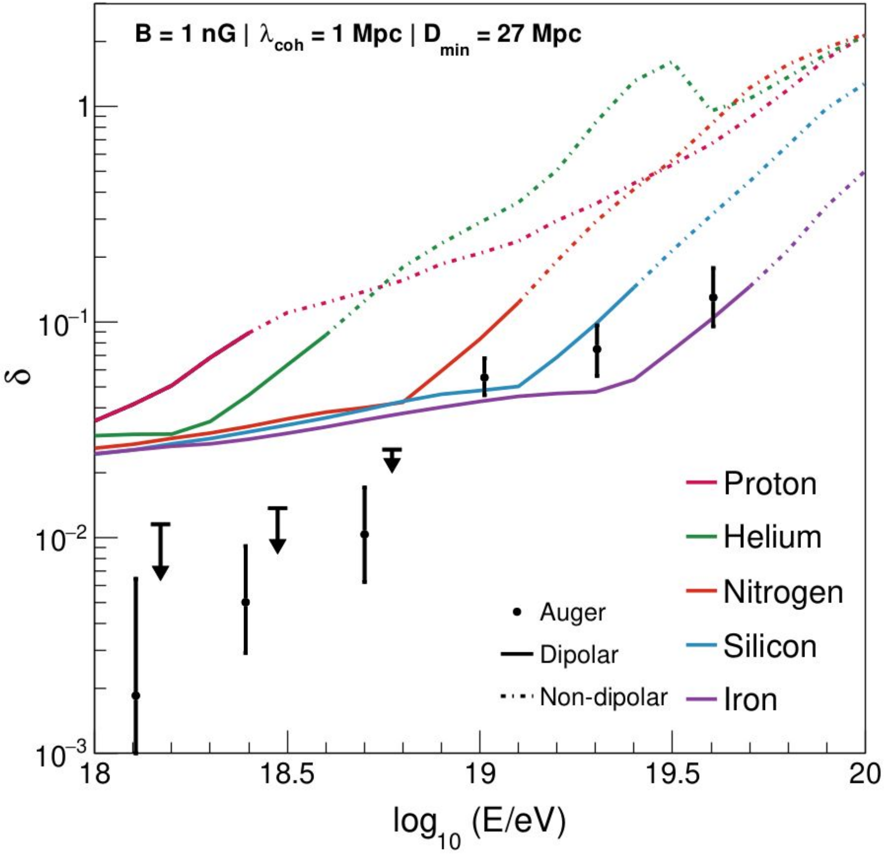
Larger densities lead to smaller dipoles

⇒

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

# Starting with the borders

- ➢ Local sources;
- ➢ Composition;




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

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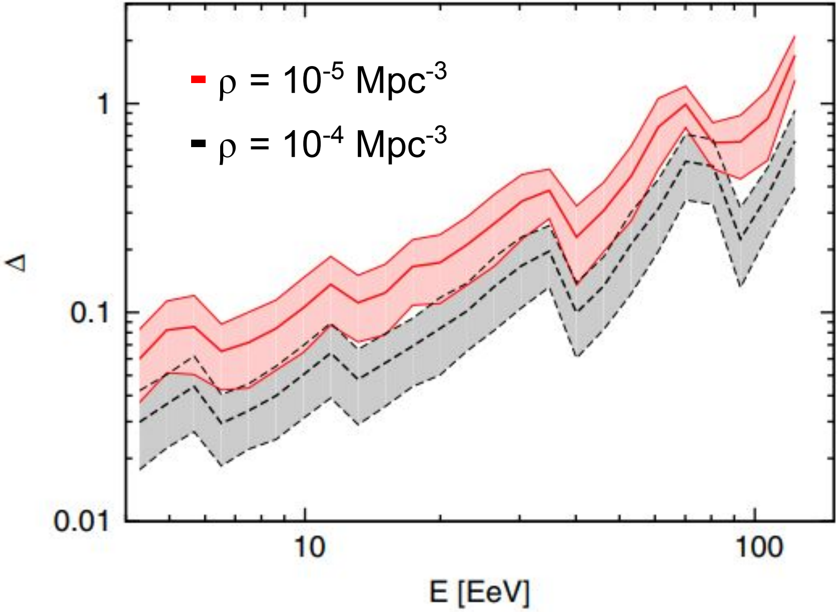
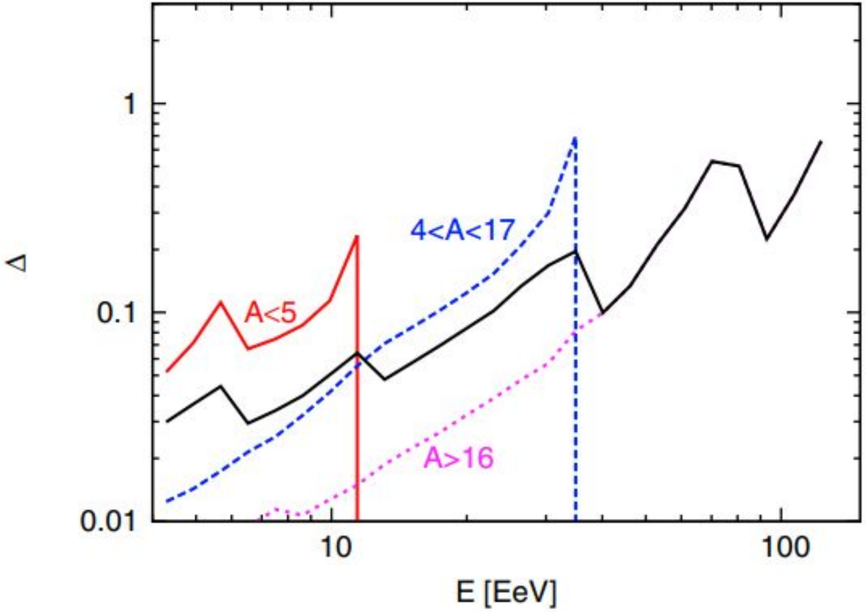
- ➢ Composition;

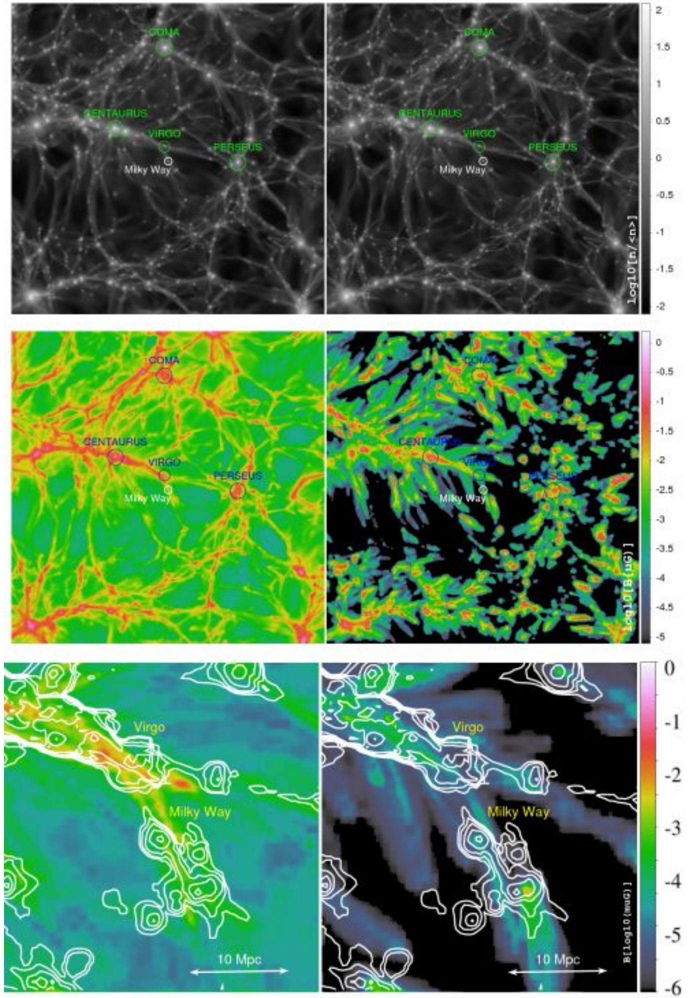



Harari, D. *et al.*, **Phys. Rev. D**, 2015

# Starting with the borders

- ➢ Local sources;
- ➢ Composition;
- ➢ Magnetic fields;




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

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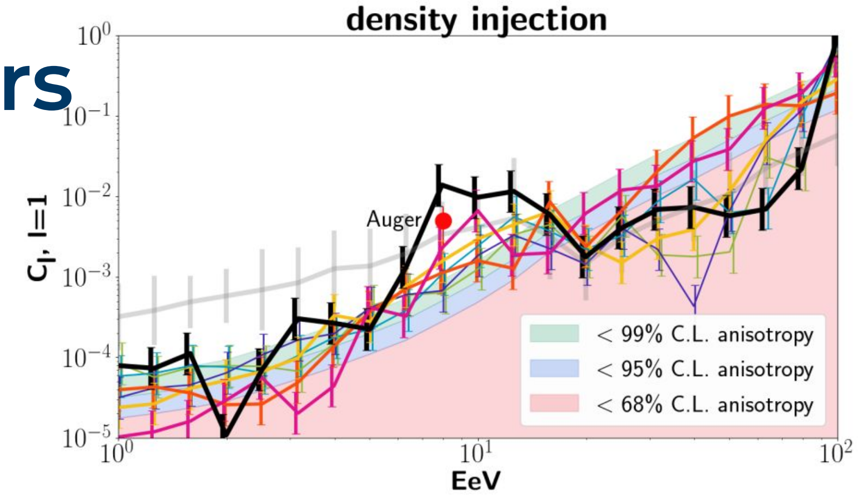


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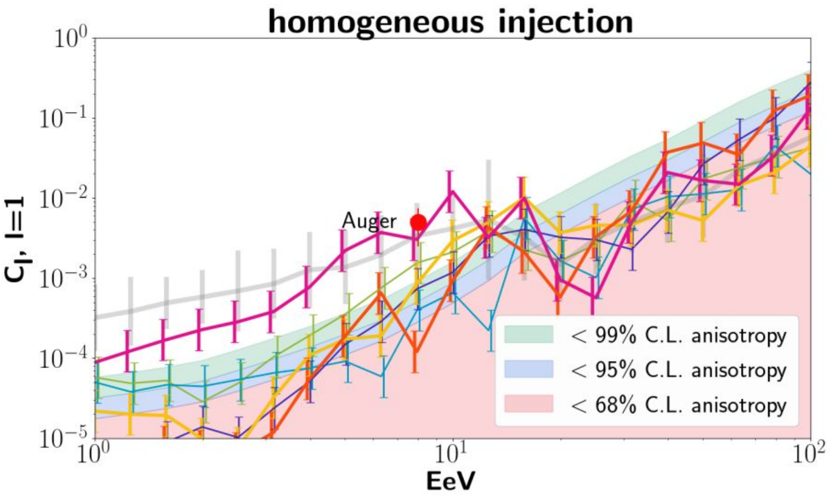


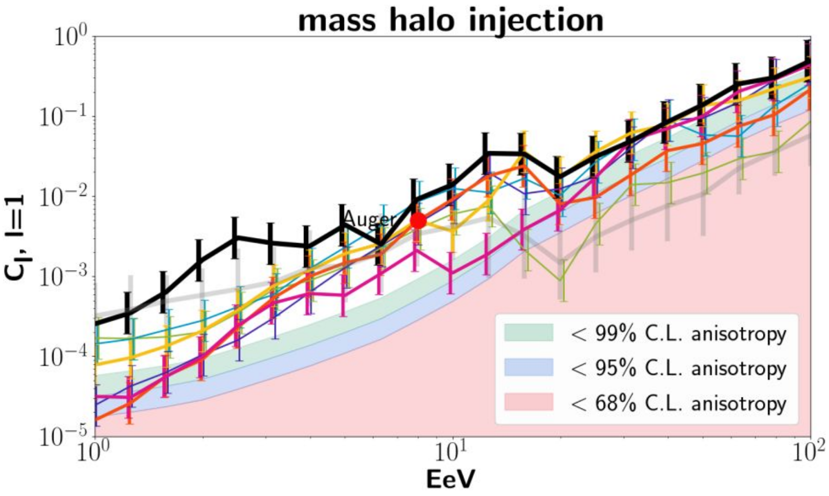

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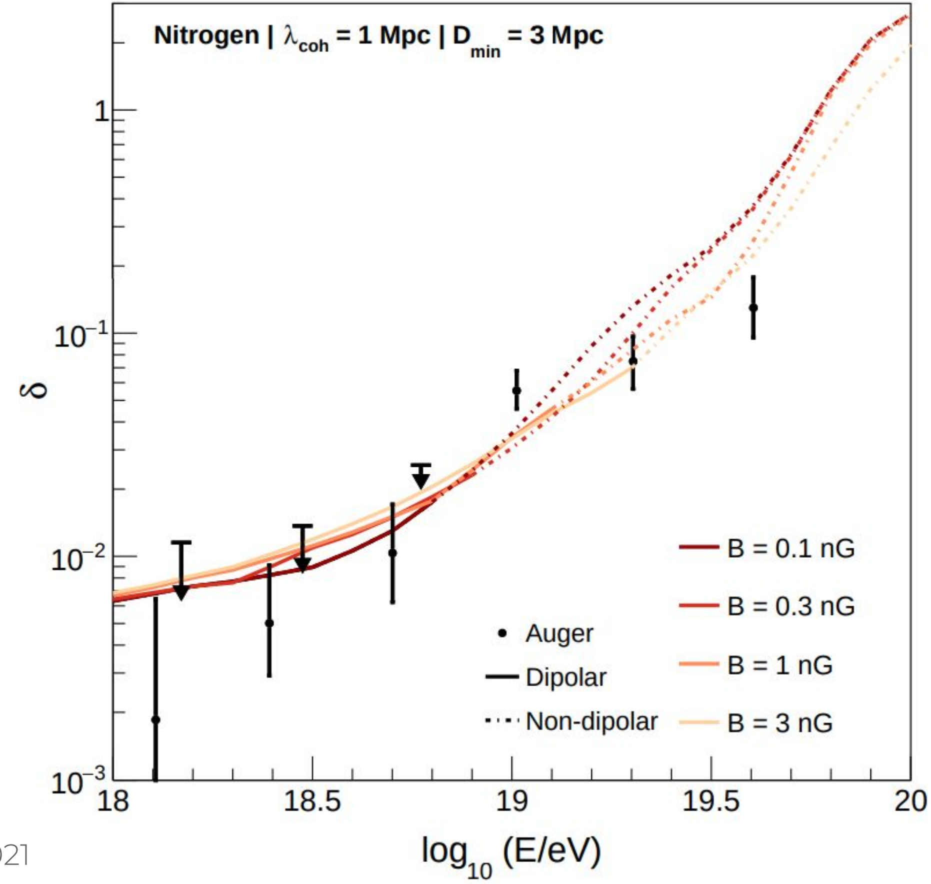


Lang, R. G. *et al.*, **Phys. Rev. D**, 2021

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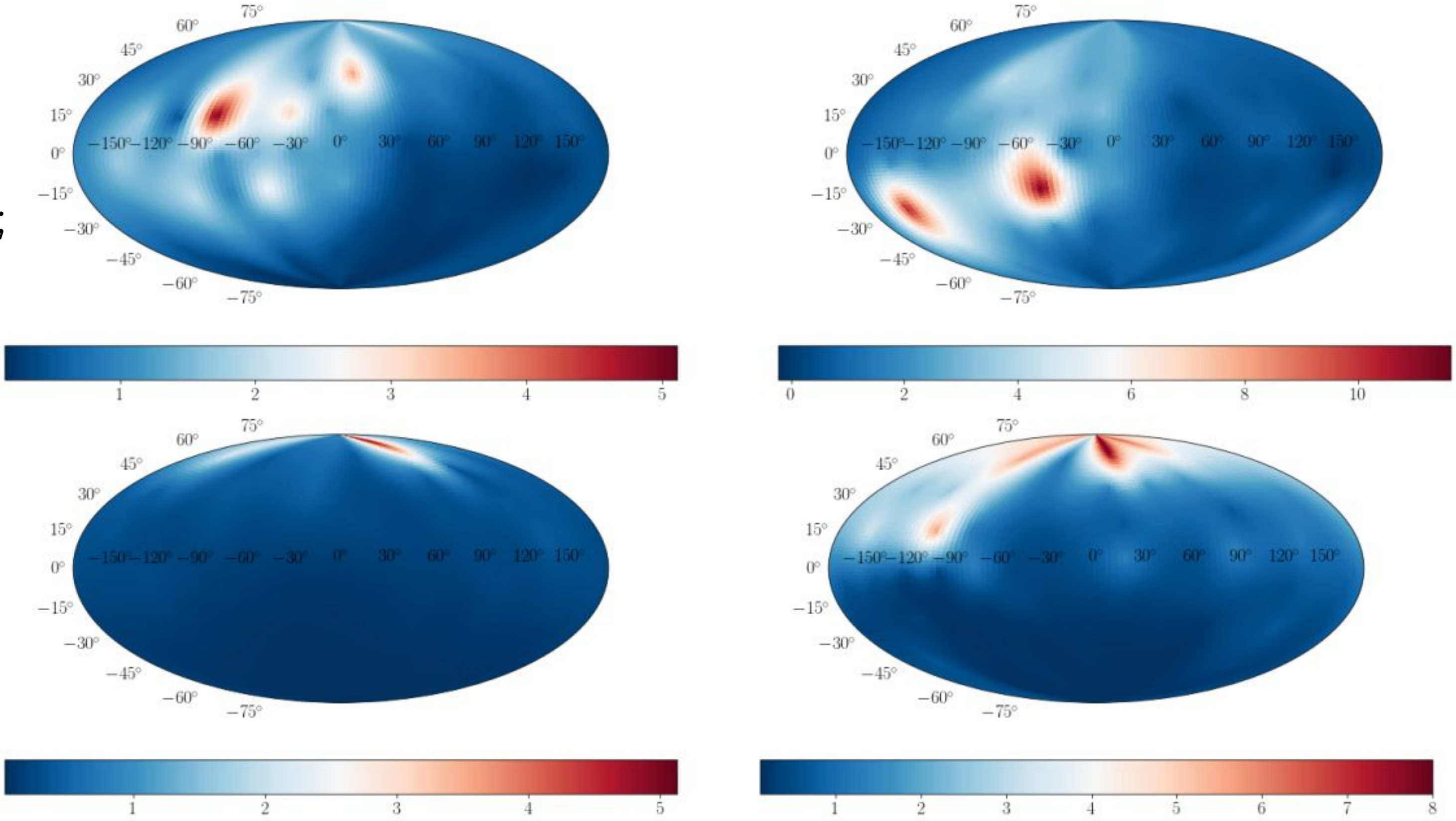

Dundovic, A. *et al.*, **JCAP**, 2019

# Current status of the puzzle

- Recent data show deviations from isotropy:
    - ~7.3% dipole at E>8 EeV pointing outwards the galactic center;
    - Evolution of dipole amplitude and phase with energy;
    - Hotspots at the highest energies;
    - (Strong) hints of a correlation with Starburst Galaxies;
    - Differences in $X_{max}$ on and off the galactic plane;
- Several analysis trying to describe such deviations:
    - Heavily dependent on astrophysical hypotheses about things we don't know very well.

# Future of the puzzle: next pieces

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

# Future of the puzzle: assembly

- Better understanding the processes involved:
  - Constrain possible hypothesis;
- Further development of analysis techniques:
  - Understand the model dependency of the analyses;
  - Find variables which are decoupled from some (most) of the hypotheses;
  - Understand the astrophysical origins of the behaviour of the measured data;

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# Thank you and stay safe!

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