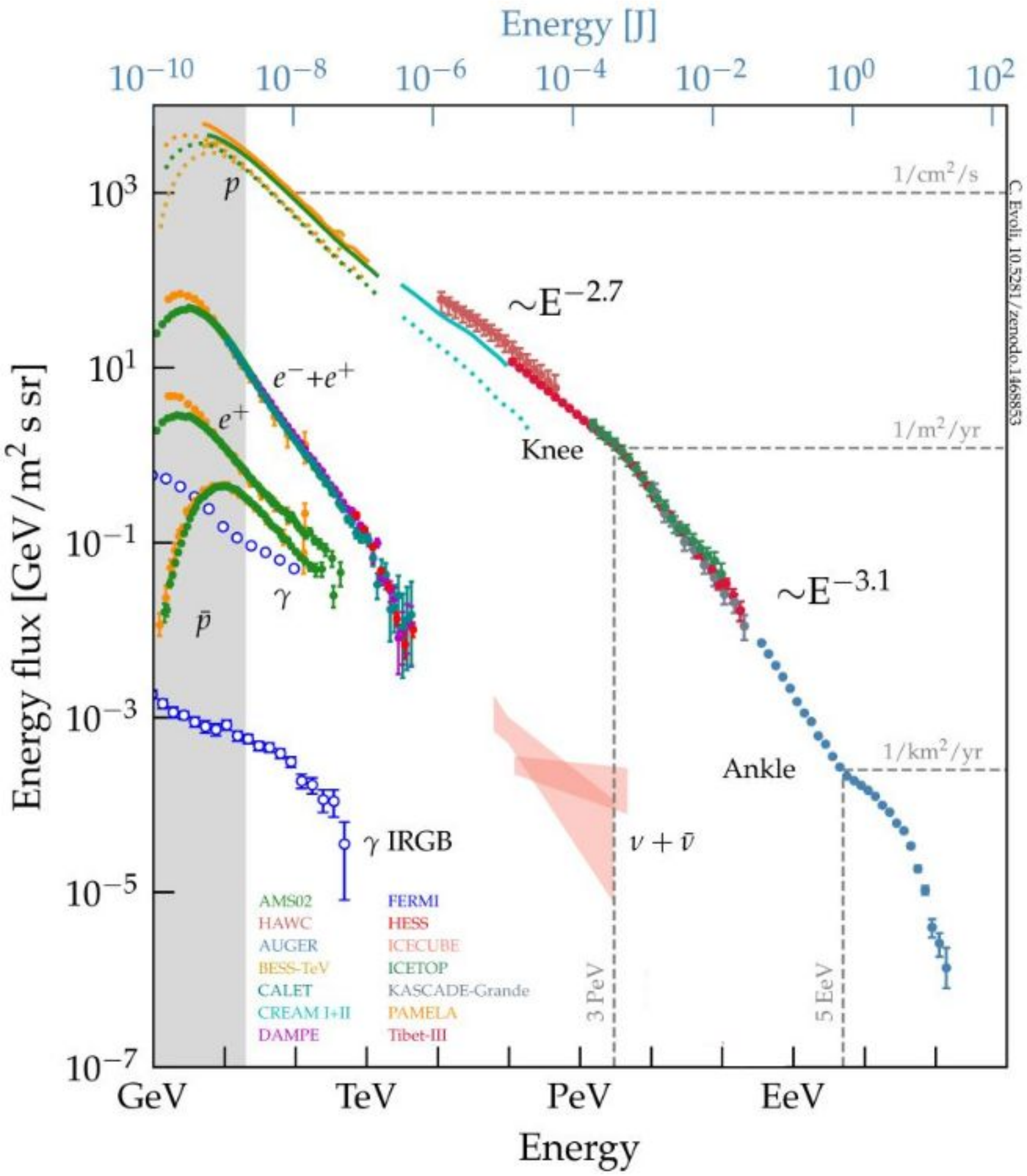
Friedrich-Alexander-Universität
Erlangen-Nürnberg

The origin of UHECR: a decades-long puzzle

Rodrigo Guedes Lang

High-energy astrophysics in the multi-messenger era workshop, 09/05/2023

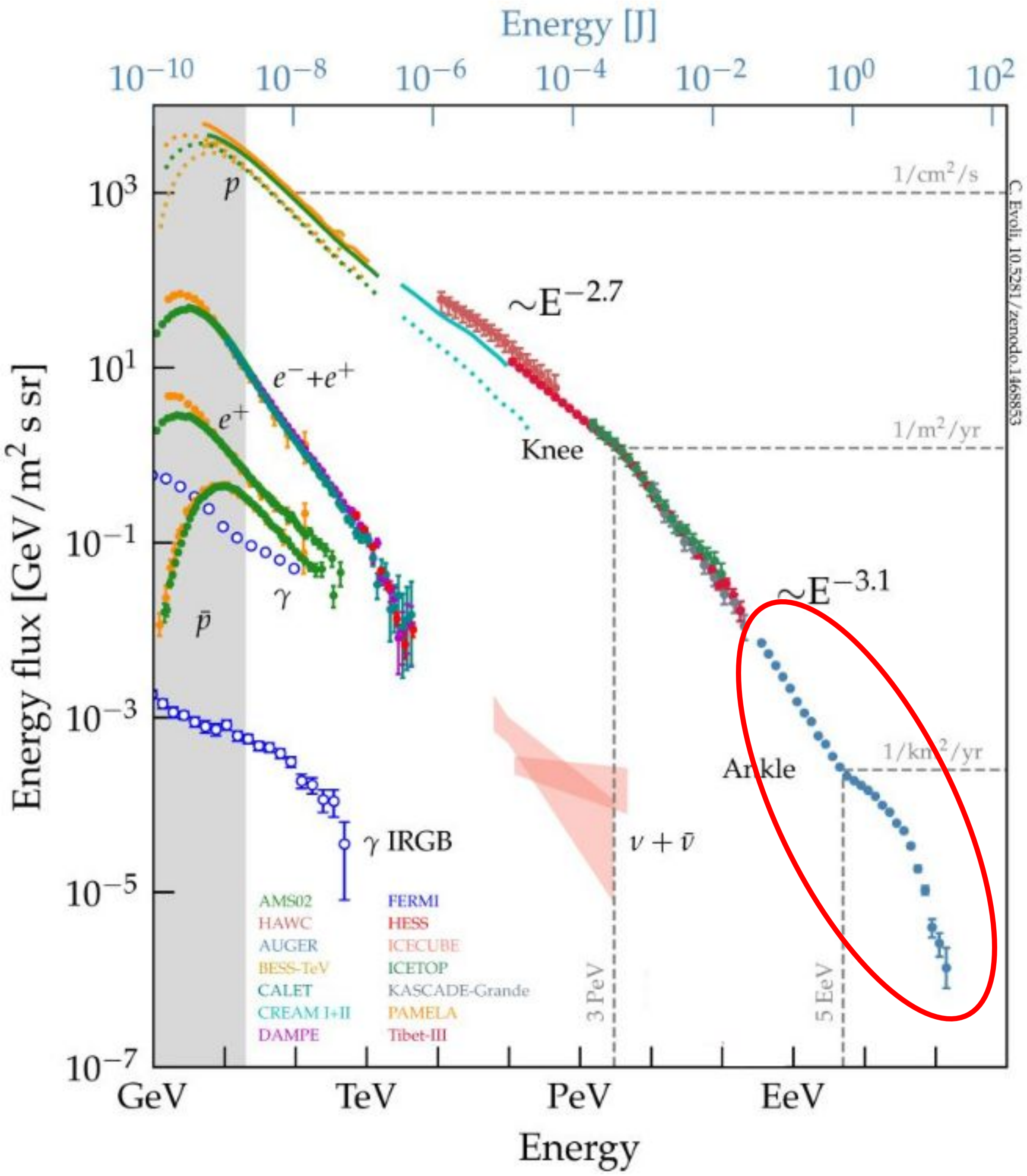
UHECR



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}
p
e^-+e^+
e^+
γ
$\bar{p}$
$\sim E^{-2.7}$
Knee
$\sim E^{-3.1}$
Ankle
γ IRGB
$\nu+\bar{\nu}$
1/cm^2/s
1/m^2/yr
1/km^2/yr
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

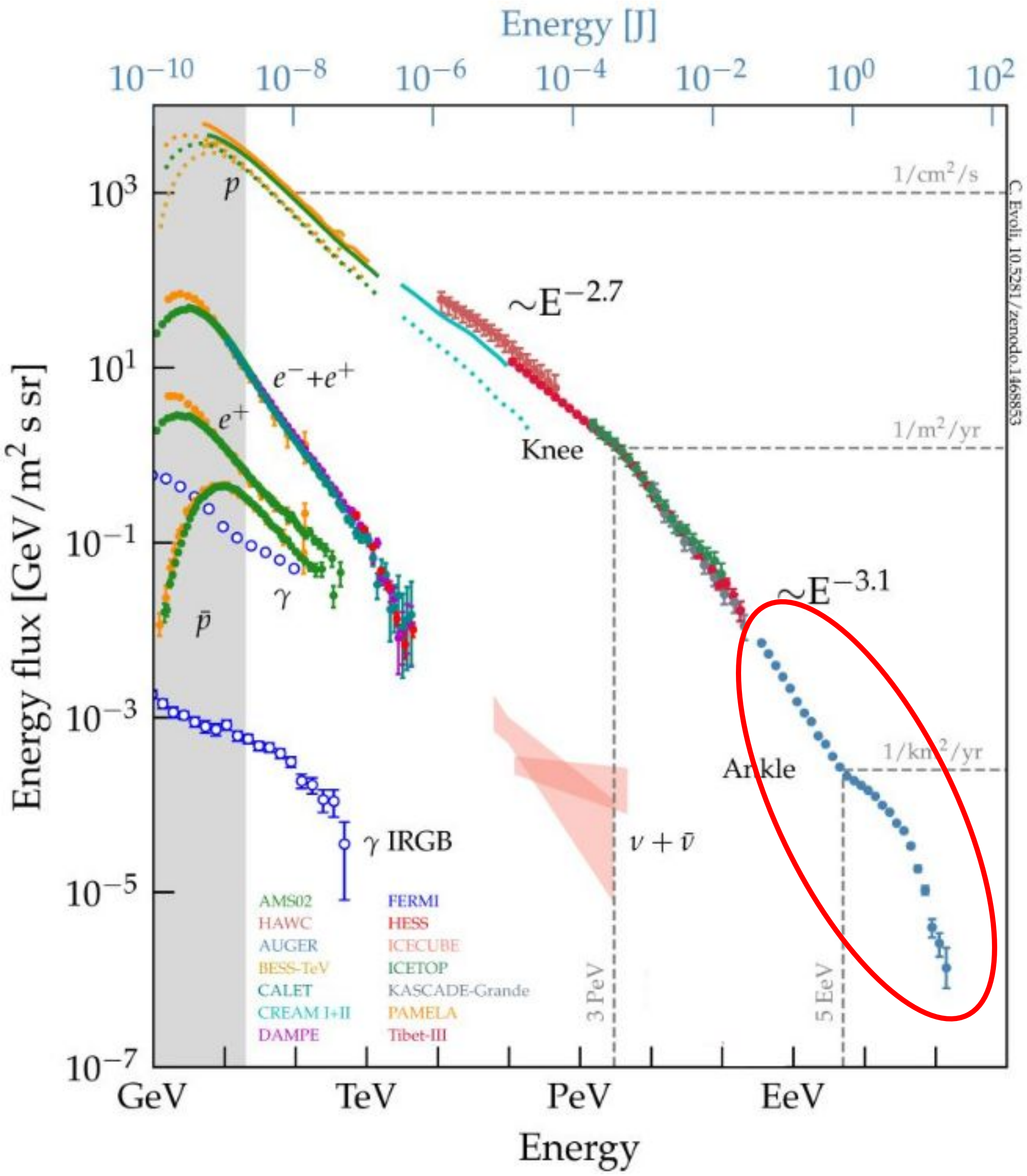
UHECR

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



UHECR

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



The puzzle: what are their origins?

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

The pieces: how do we get them?

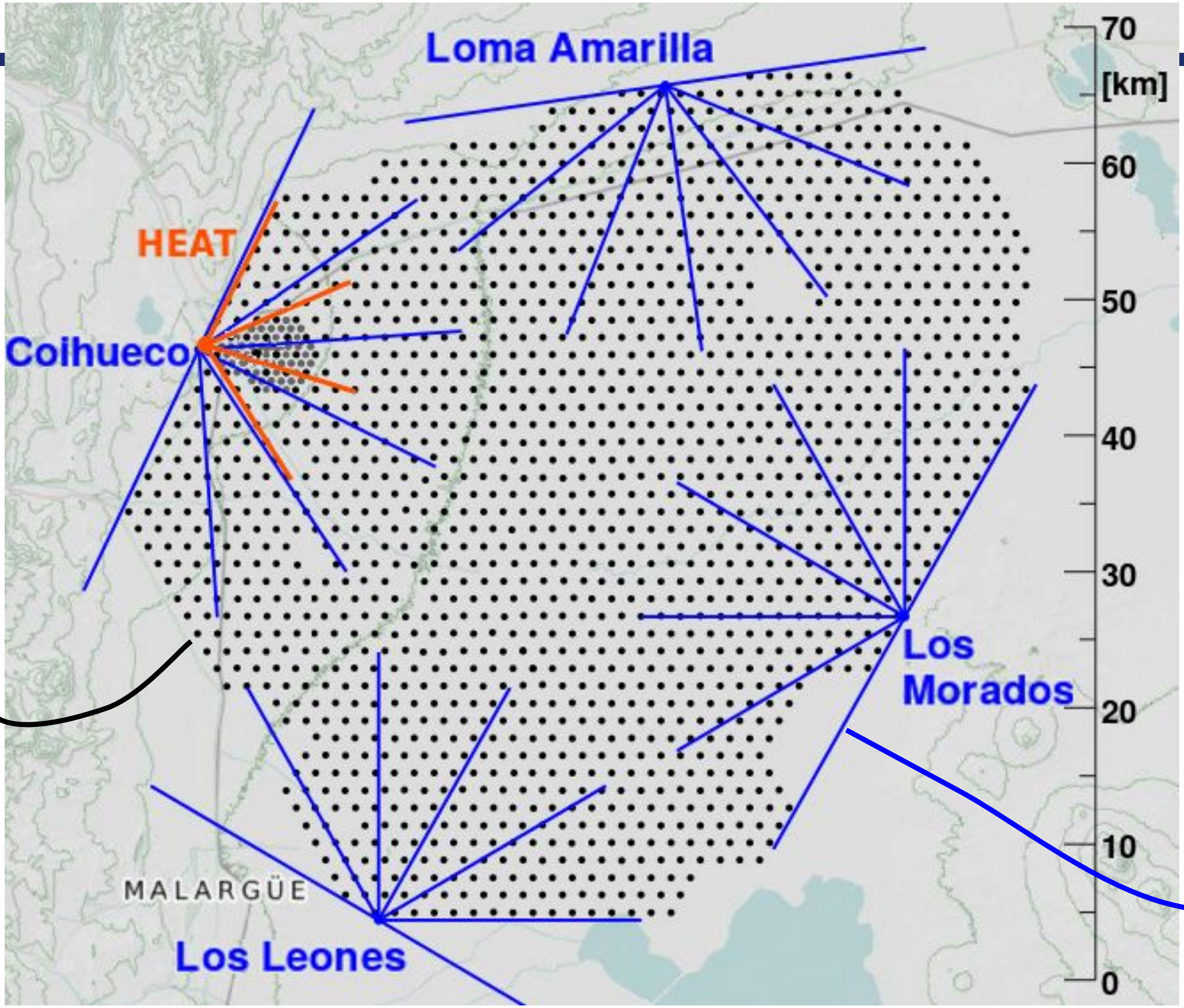
- Very low flux (< $1/km^2/year$);
- Huge ground-based experiments

The pieces: how do we get them?

- ➢ 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.

2x the area of the city of São Paulo!
3.3x the area of Berlin!

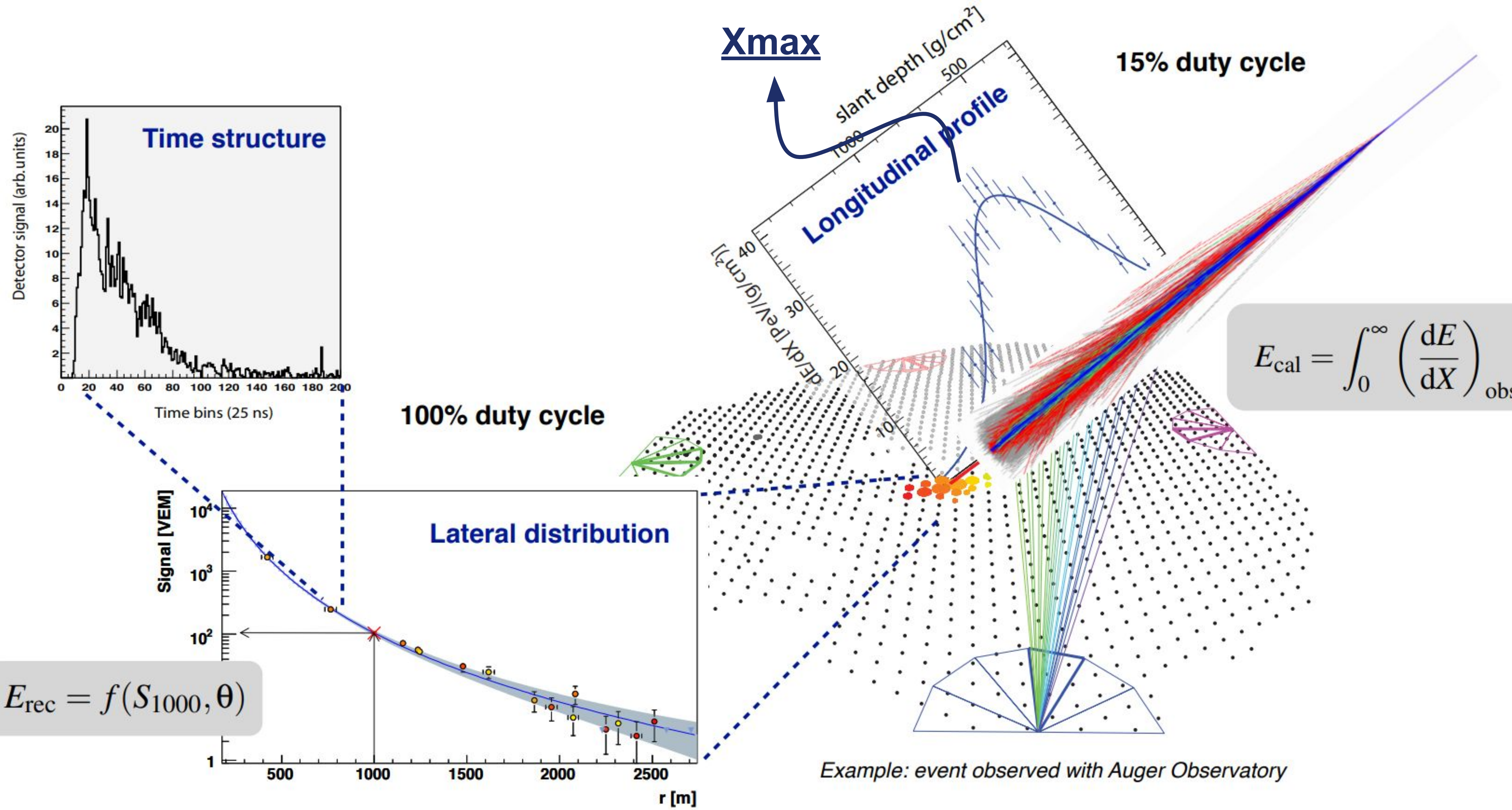
Pierre Auger Observatory



SD: 1660 water Cherenkov detectors

FD: 27 fluorescence telescopes

Hybrid technique



$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

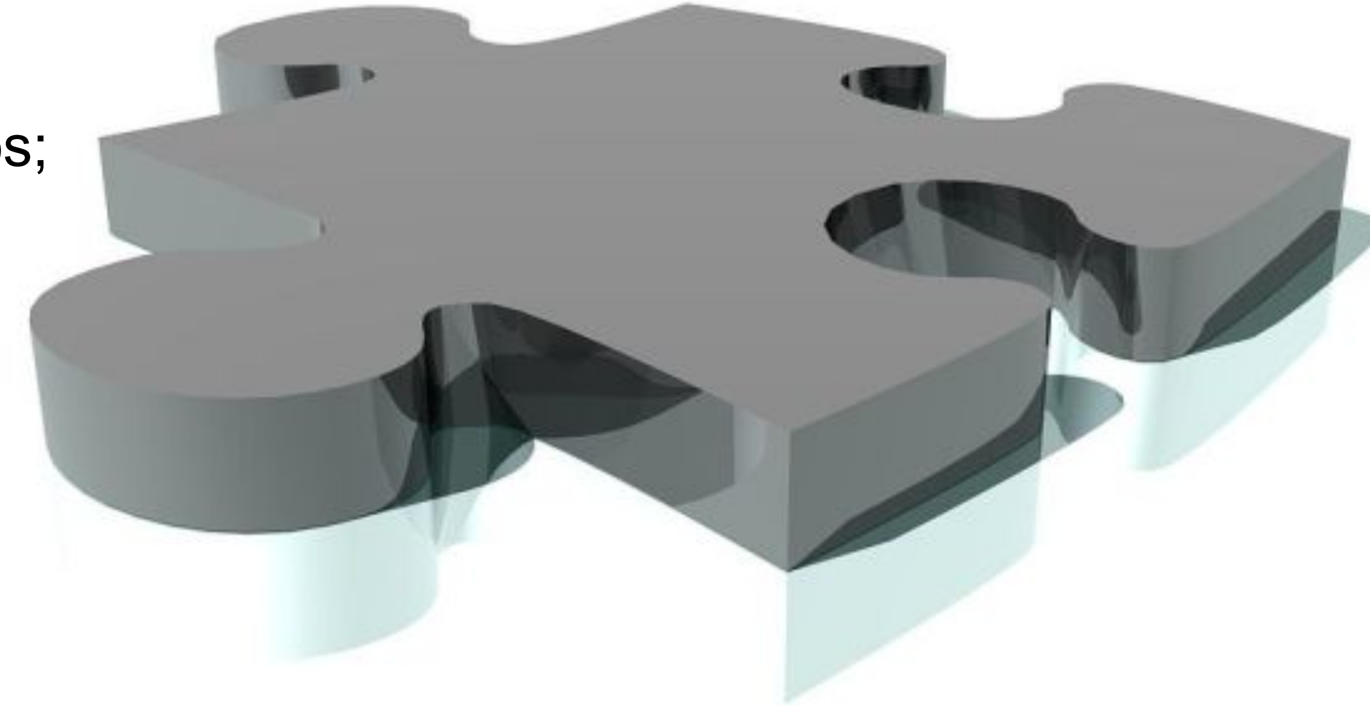
$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$

Example: event observed with Auger Observatory

Slide from Ralph Engel

The pieces: experimental data

- Three main CR observables:
  - Energy spectrum;
  - Mass composition;
  - Arrival directions;
- Plus flux of UHE photons and neutrinos;



The pieces: experimental data

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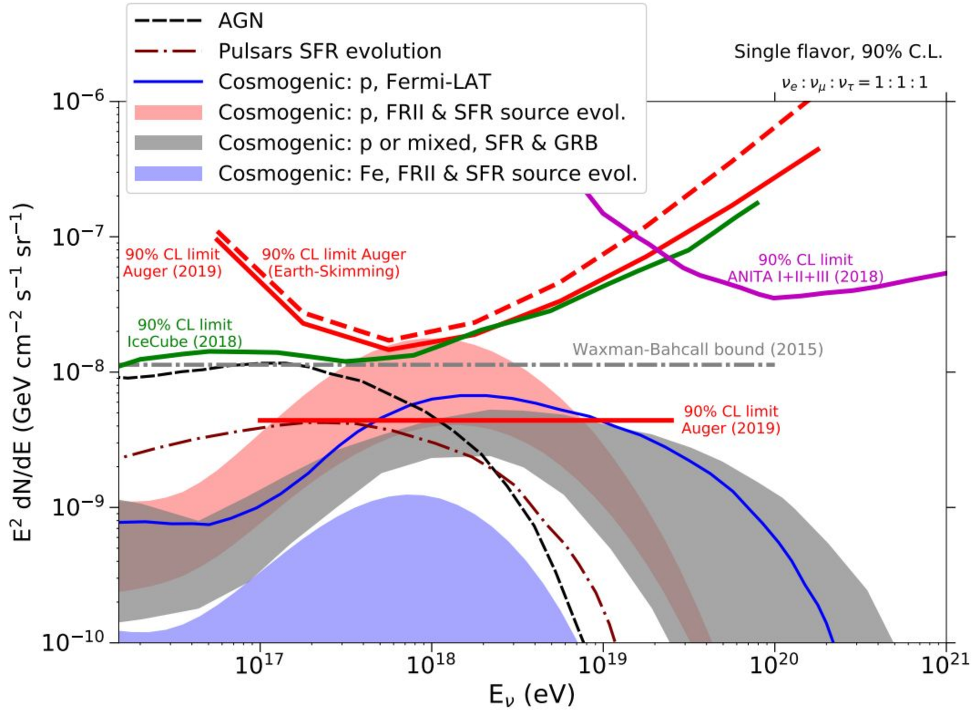
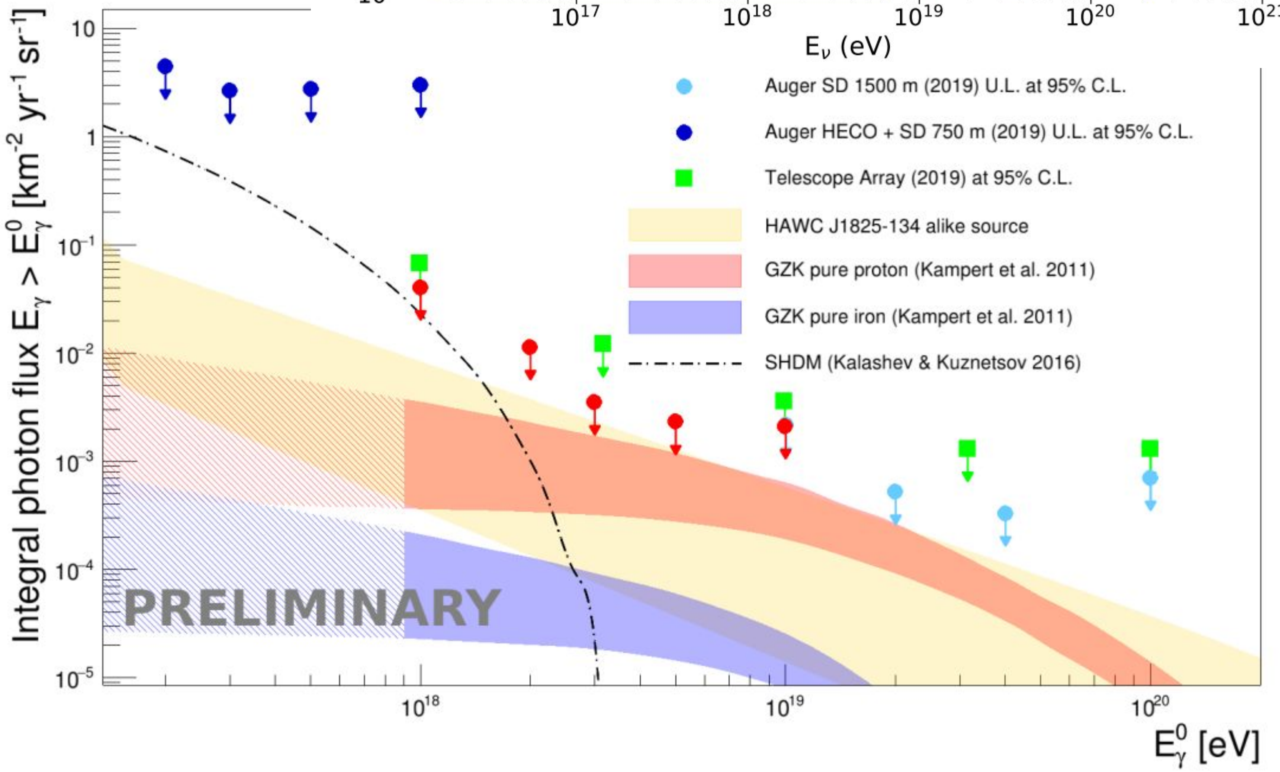
Pedreira, F., **ICRC 2019**





Savina, P., **ICRC 2021**

The pieces: experimental data

- ➢ Three main CR observables:
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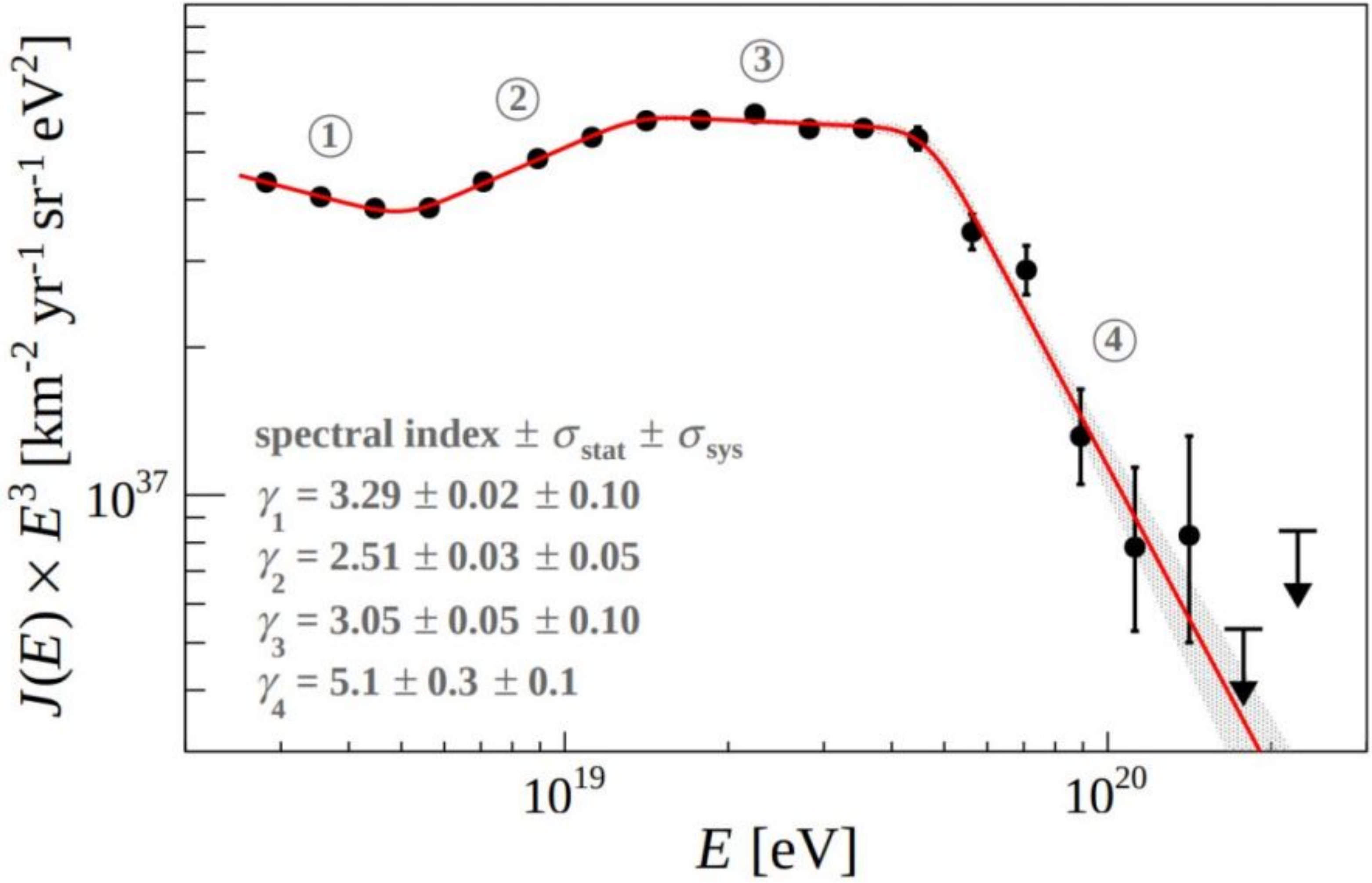
  - ○ Arrival directions;
- ➢ Plus flux of UHE photons and r



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

The pieces: experimental data

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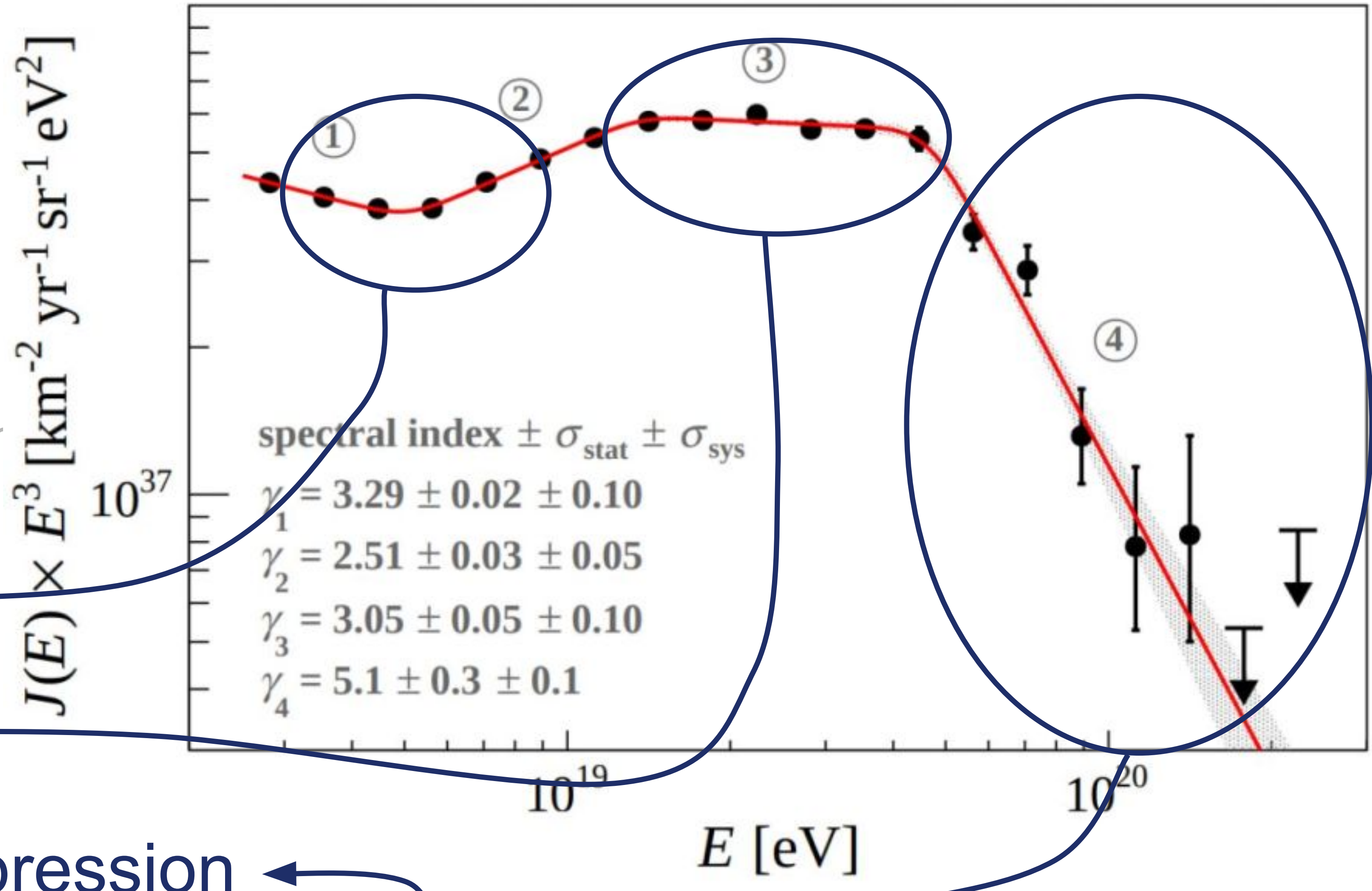


The Pierre Auger Collaboration, **Phys. Rev. Let.**, 2020

Ankle

Transition from galactic to extragalactic

Instep

To be described :)

Suppression

To be discussed still today

The pieces: experimental data

➢ Three main CR observables:

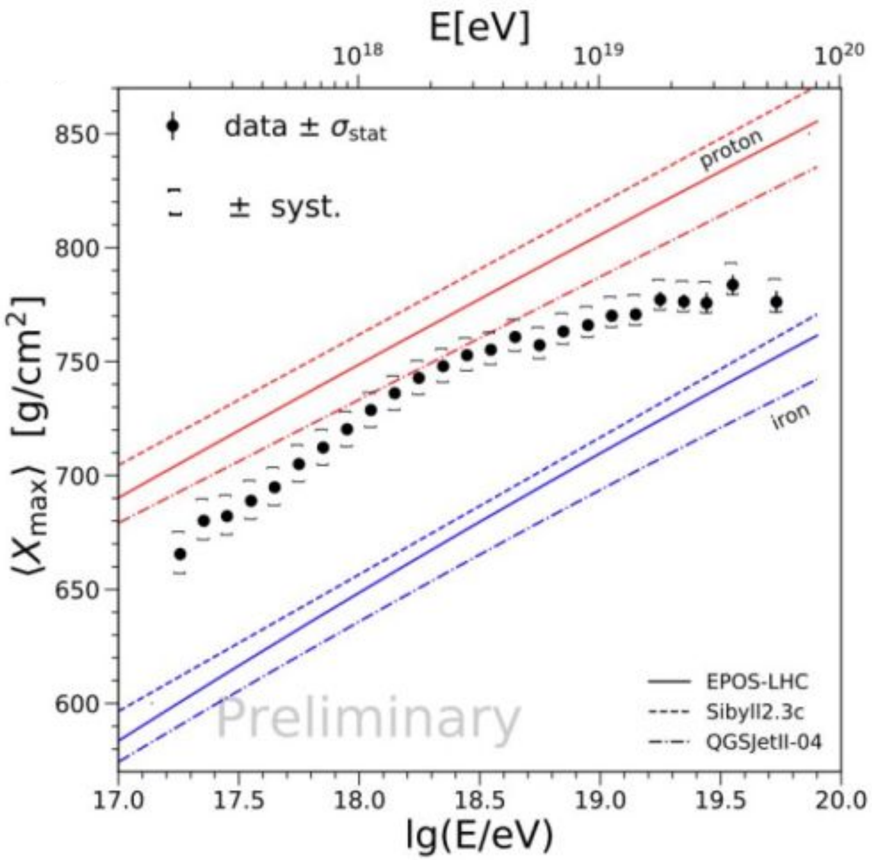
  ○ Energy spectrum;

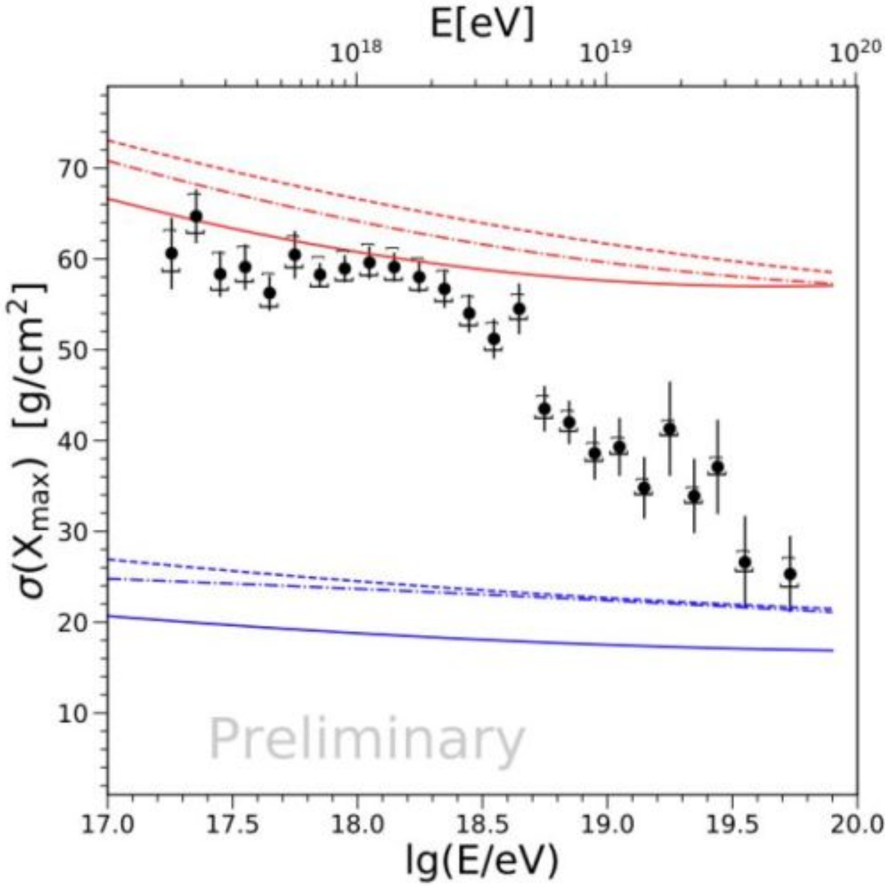
  ○ Mass composition;

  ○ Arrival directions;

➢ Plus flux of UHE photo

Yushkov, A., **ICRC 2019**



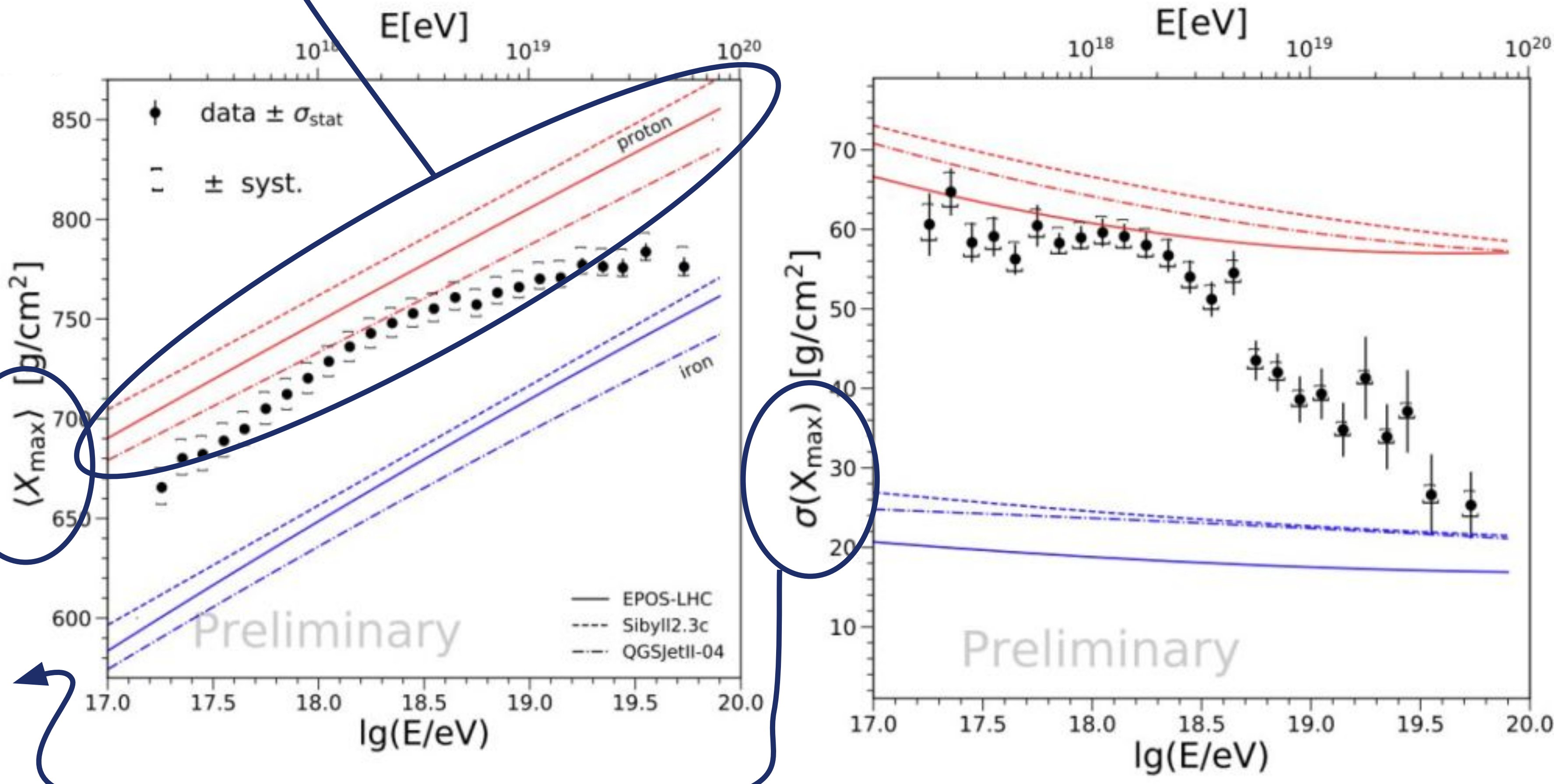


The pieces: experimental data

- Three main CR observables:
  - Energy spectrum;
  - Mass composition;
  - Arrival directions;
- Plus flux of UHE photo

Discrepancy between hadronic models

Yushkov, A., **ICRC 2019**



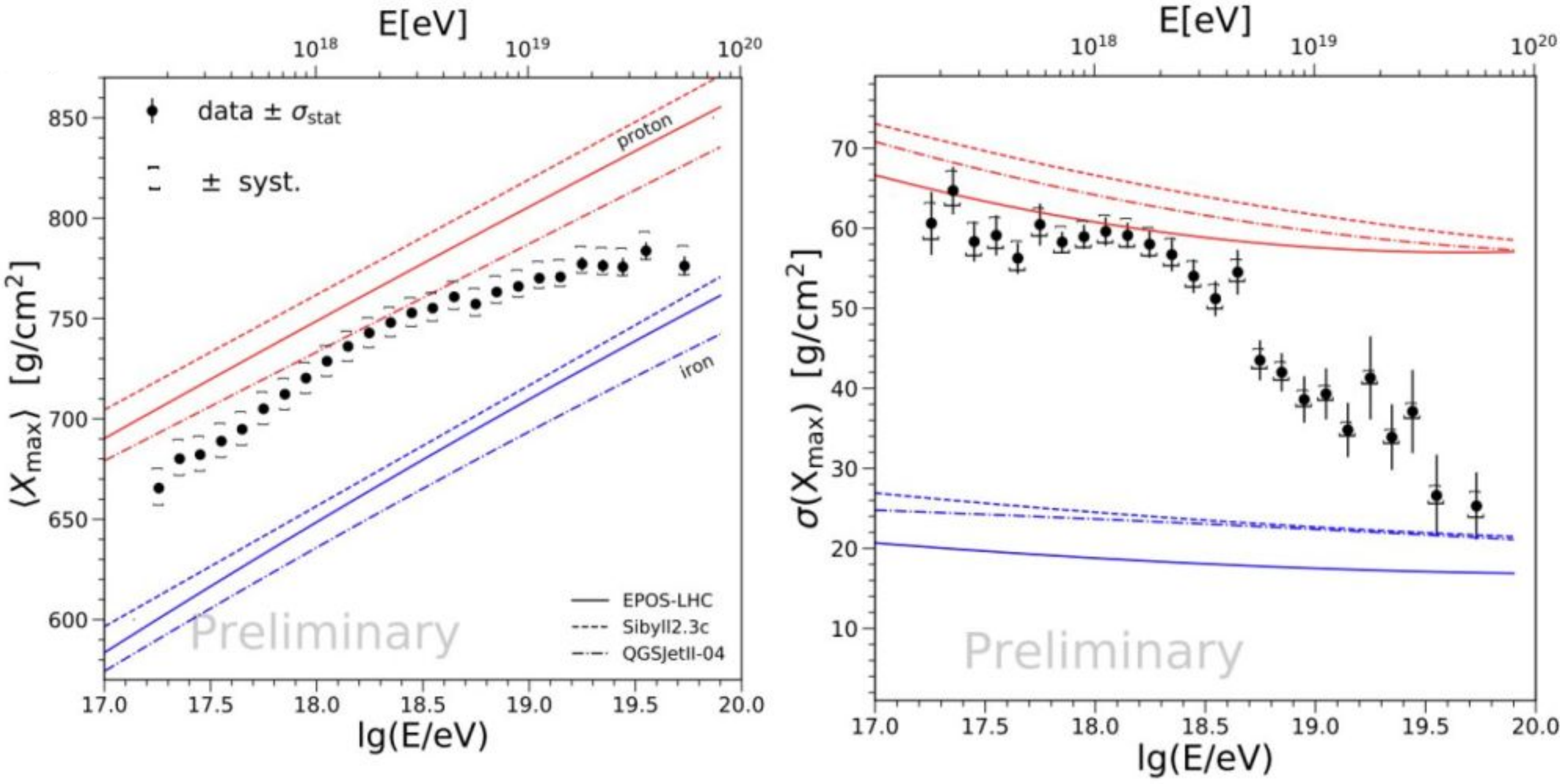
Not on an event-by-event basis

The pieces: experimental data

- Three main CR observables:
  - Energy spectrum;
  - Mass composition;
  - Arrival directions;
- Plus flux of UHE photo

Mixed composition!
Slightly lightening until near the ankle then becomes heavier;

Yushkov, A., **ICRC 2019**



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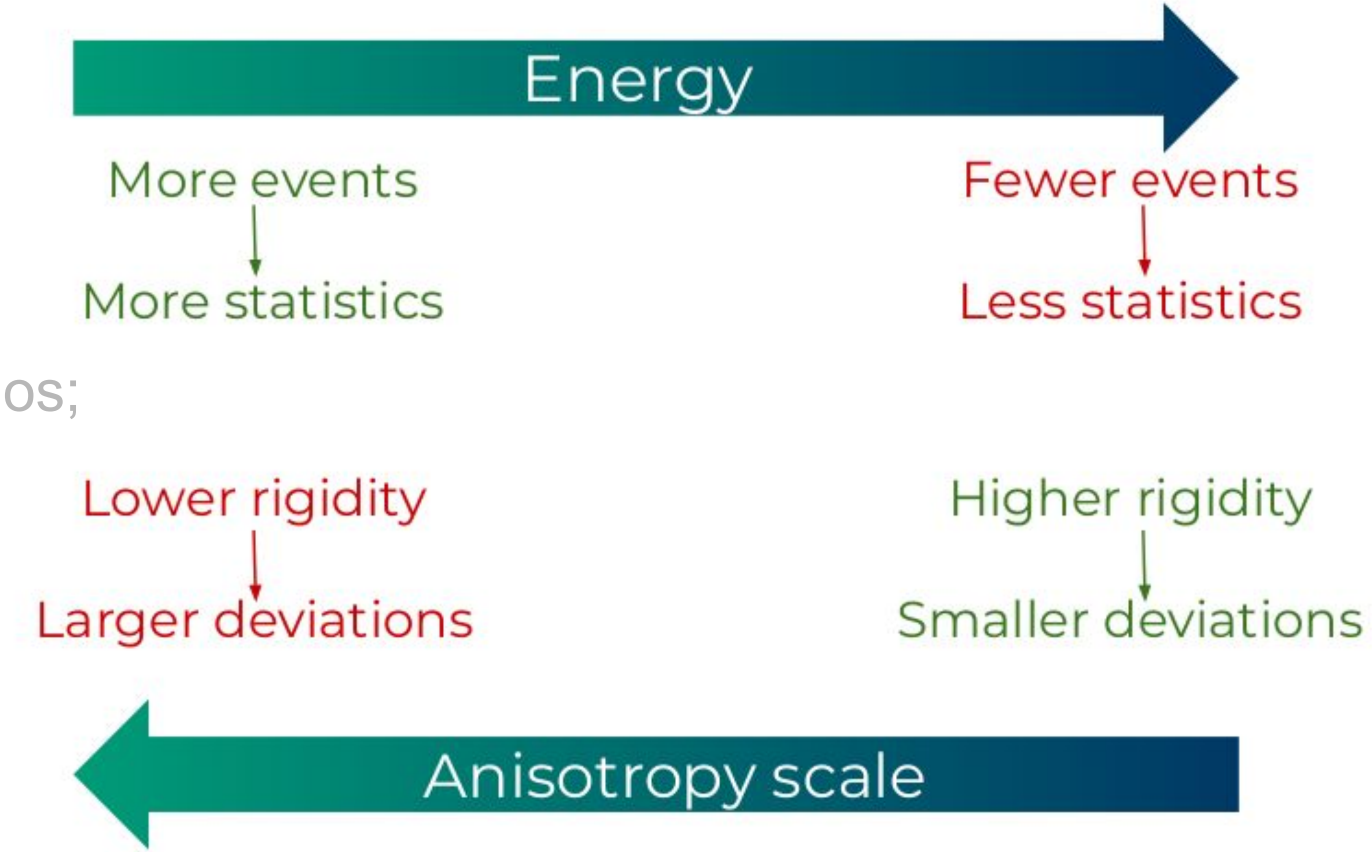
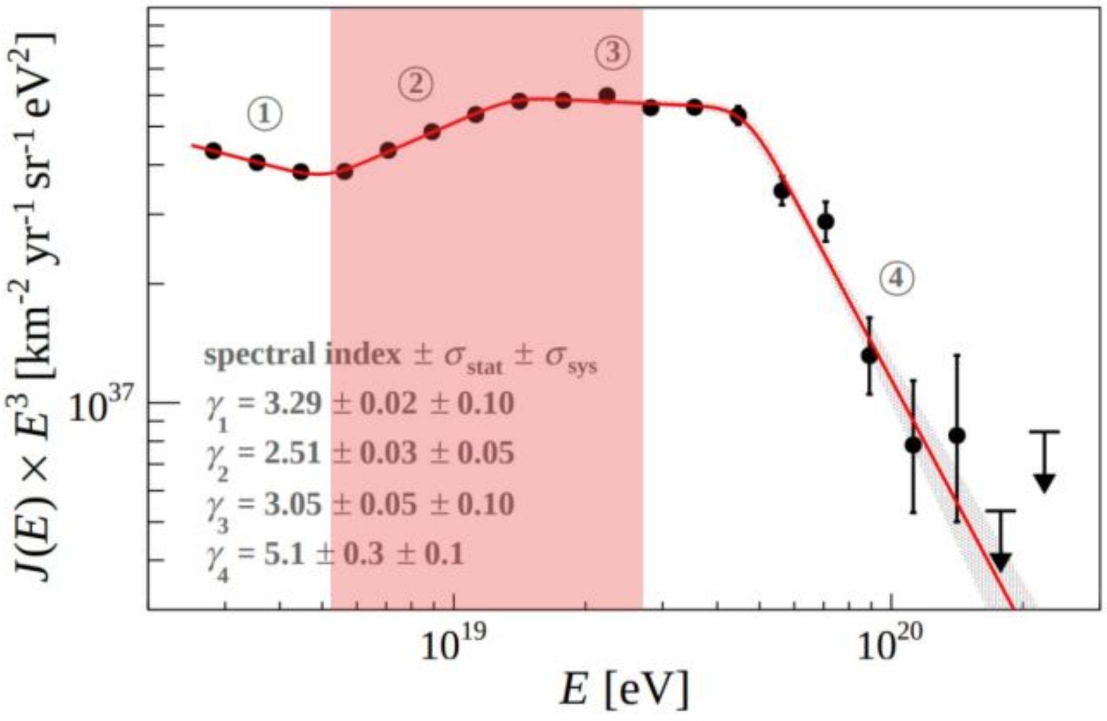
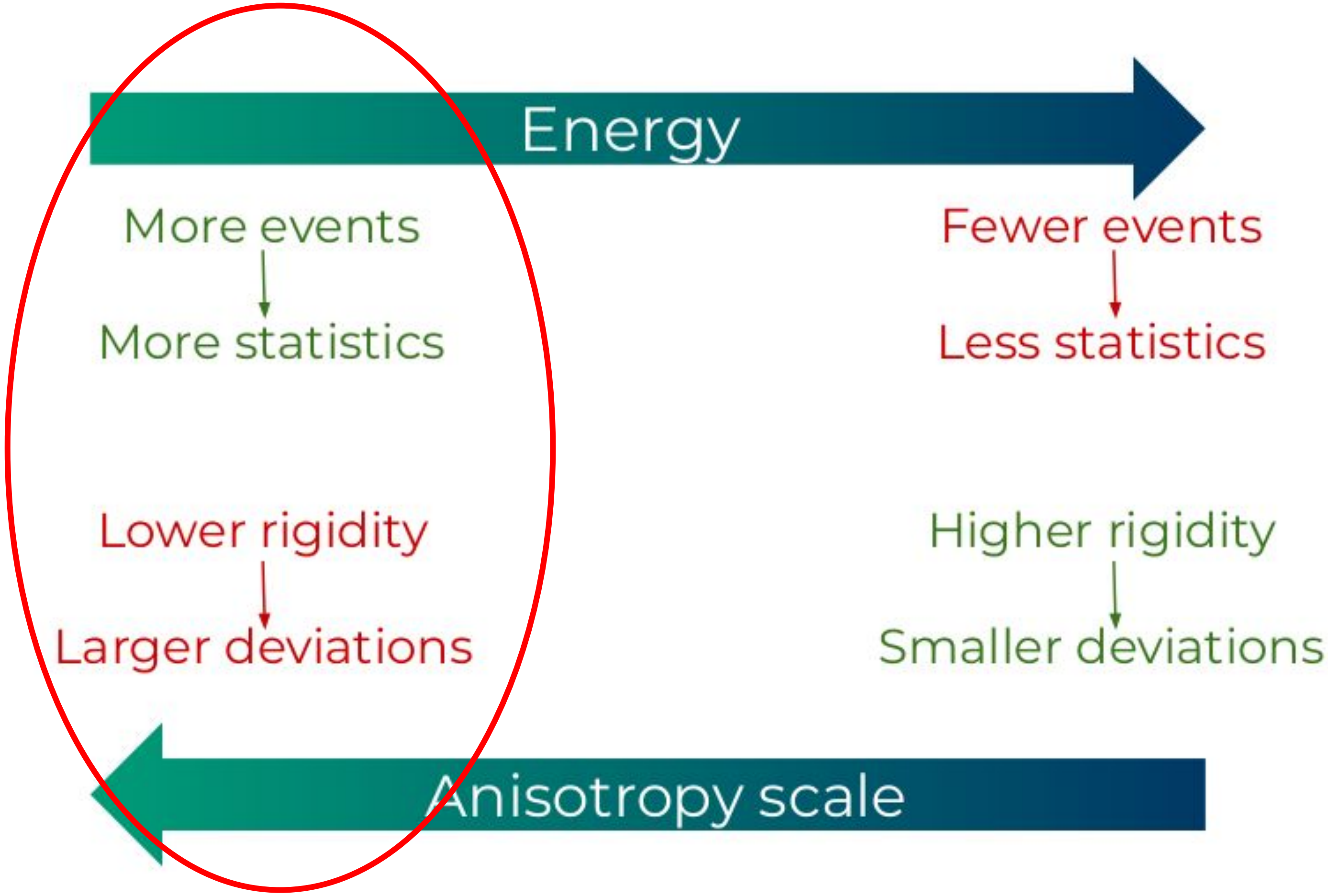


Low energies - large scale

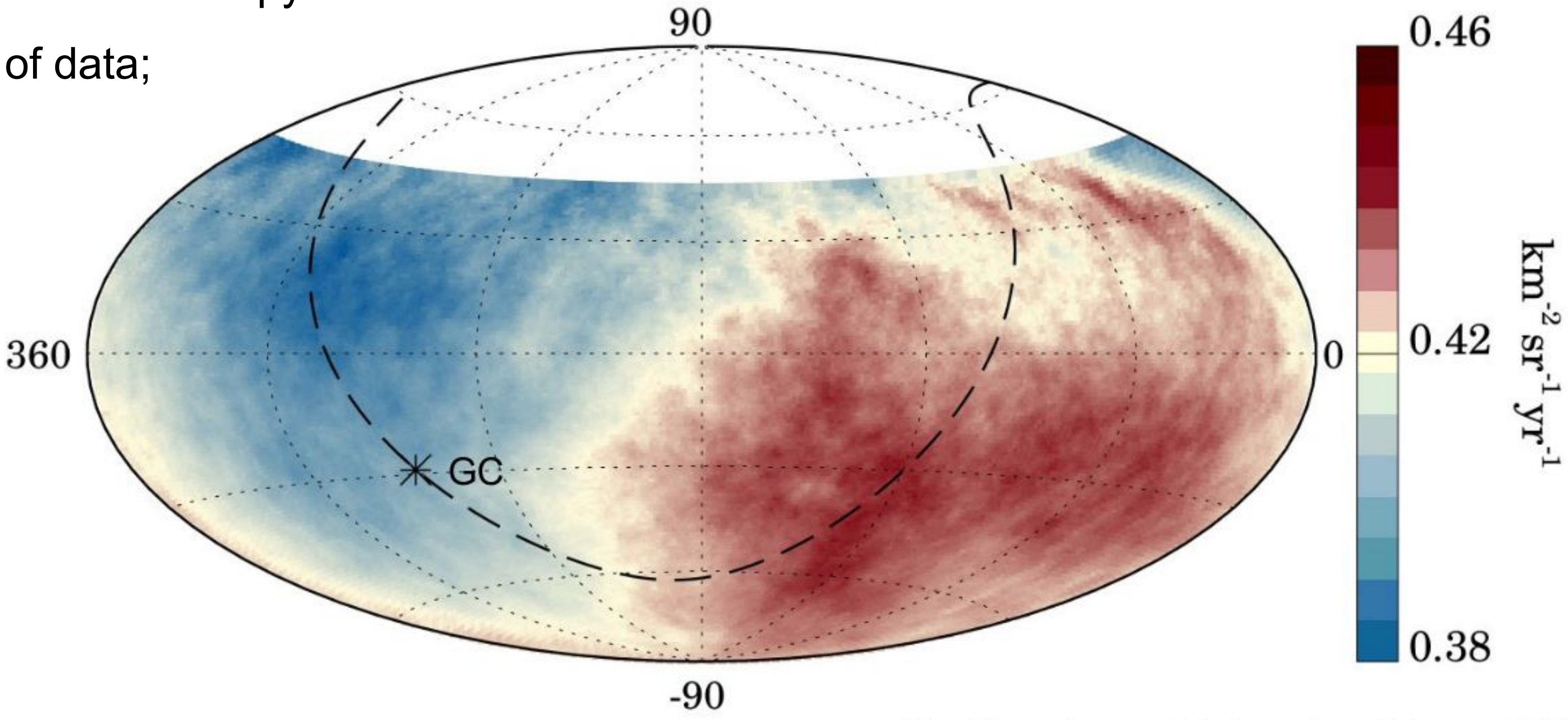


The Pierre Auger Collaboration, **Phys. Rev. Let.**, 2020



Low energies - large scale

- Auger's large scale anisotropy:
  - 12.5 years of data;
  - E > 8 EeV;



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

Low energies - large scale

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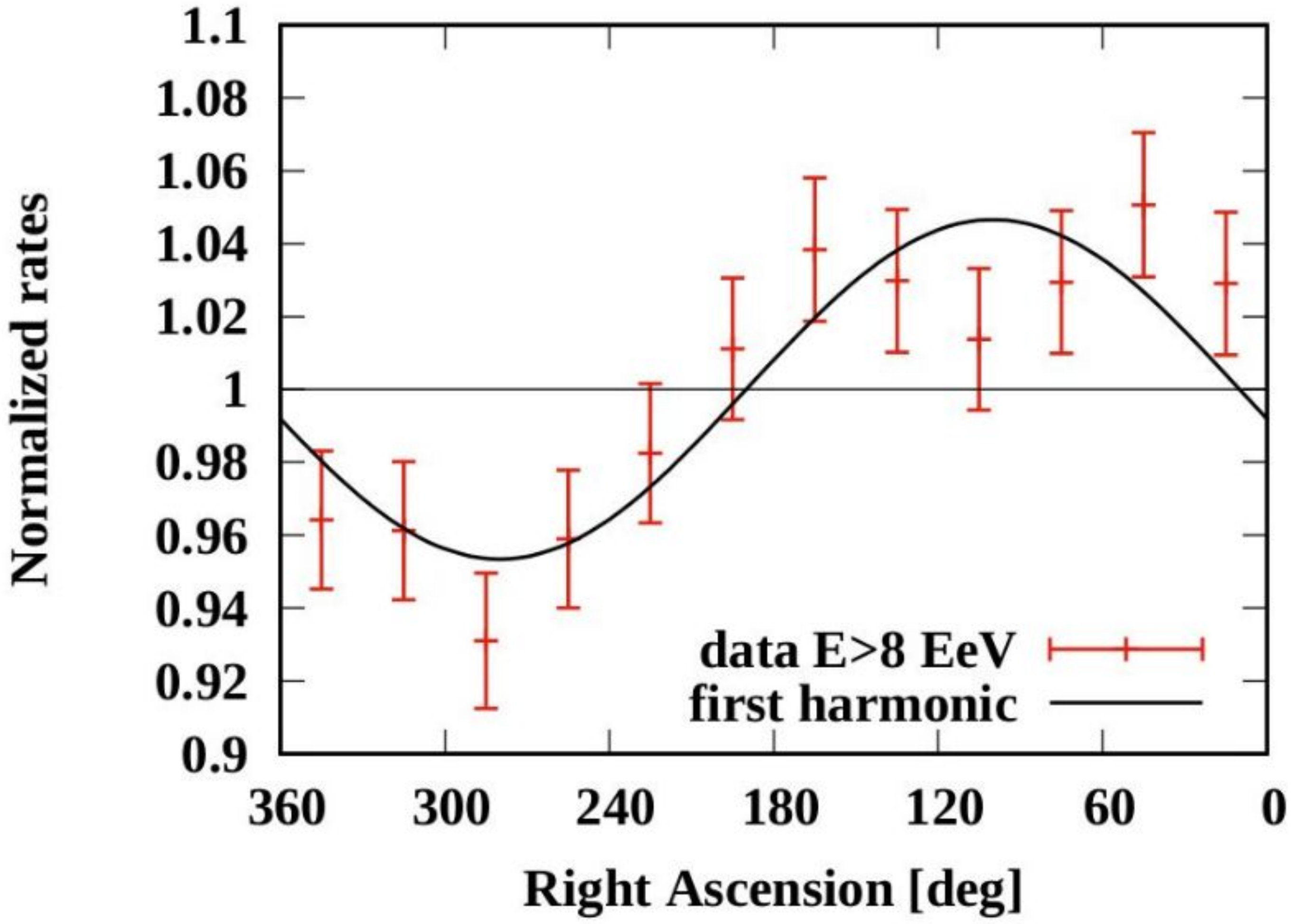
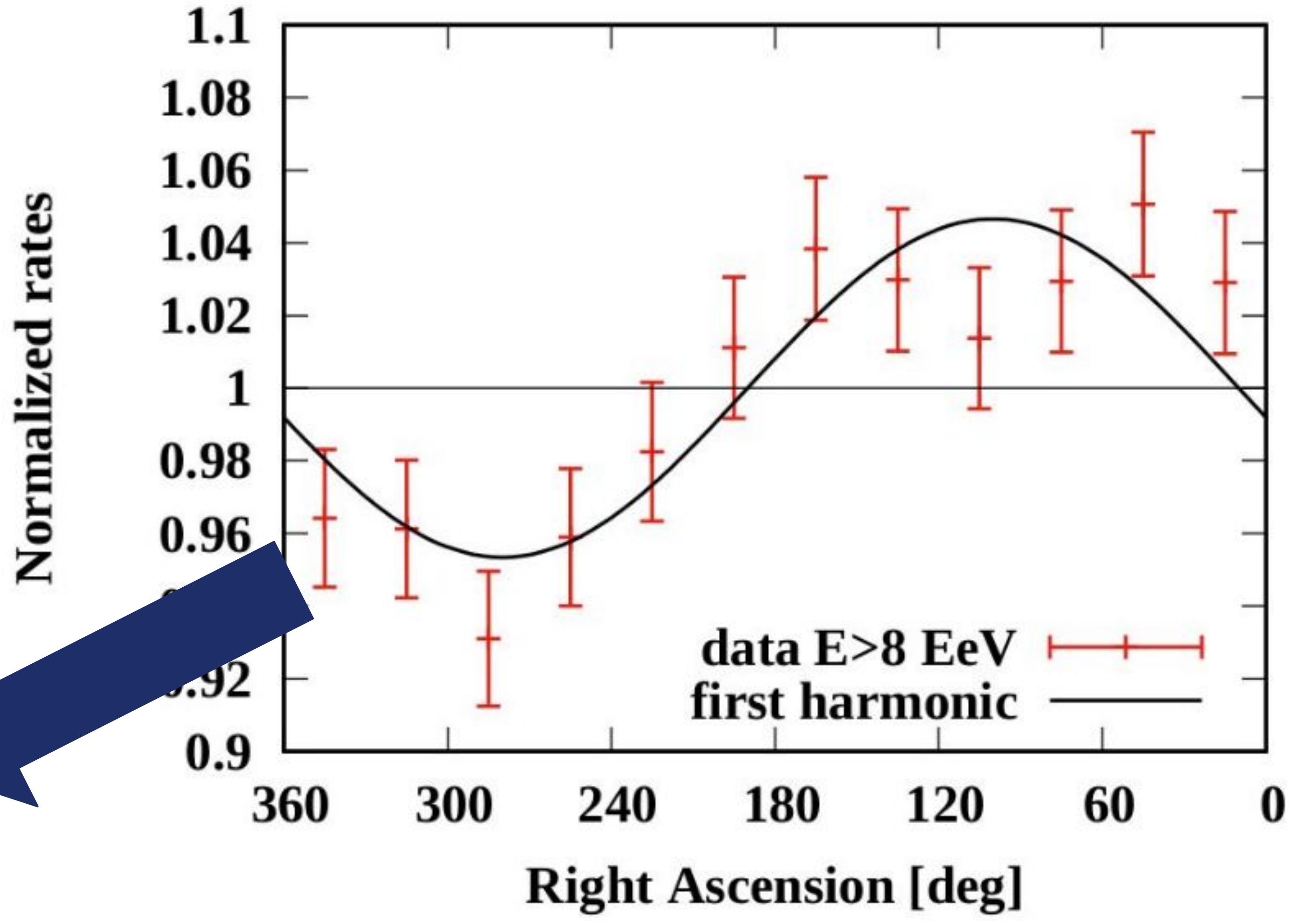


The Pierre Auger Collaboration, **Science**, 2017

Low energies - large scale

- Auger's large scale anisotropy:
  - 12.5 years of data;
  - E > 8 EeV;
  - Dipolar behavior;

$$\boxed{1 + d\cos\theta}$$



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

Low energies - large scale

➢ Auger's large scale anisotropy:

- 12.5 years of data;
- $E > 8$ EeV;
- Dipolar behavior;

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 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 energies - large scale

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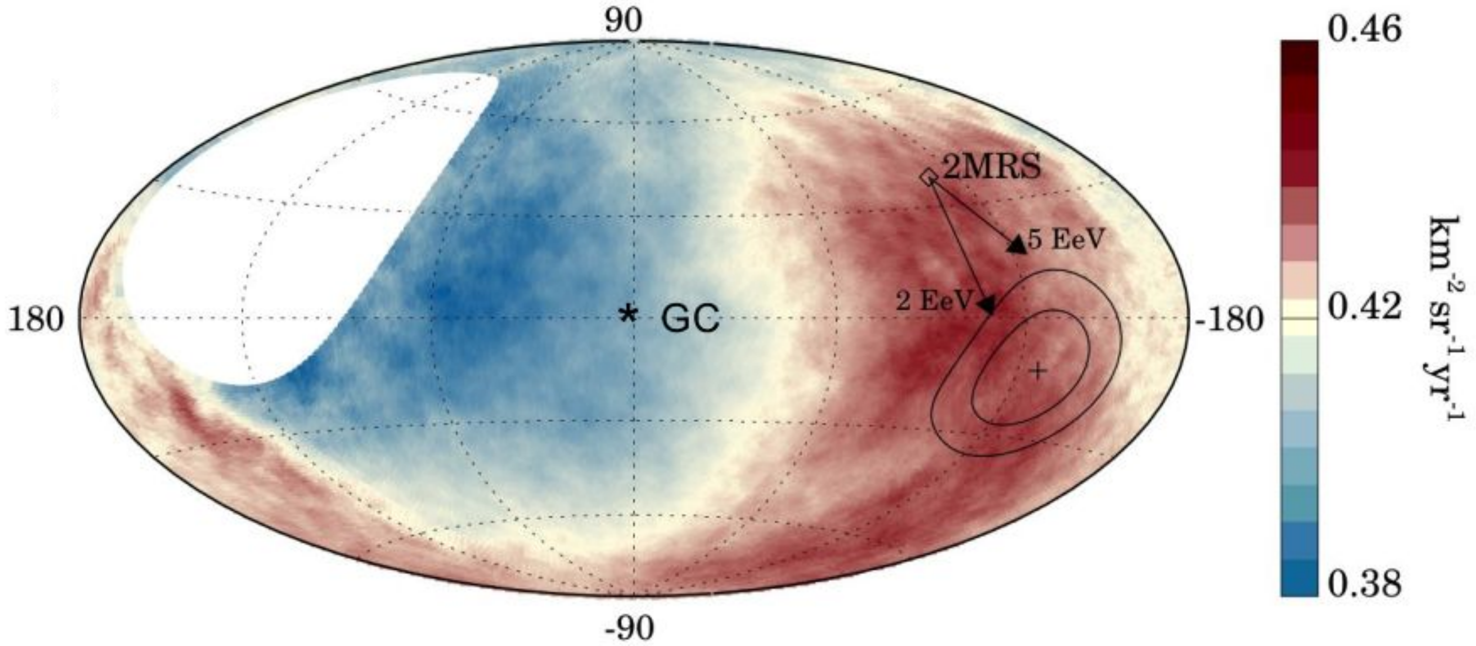
- 12.5 years of data;
- E > 8 EeV;
- Dipolar behavior;



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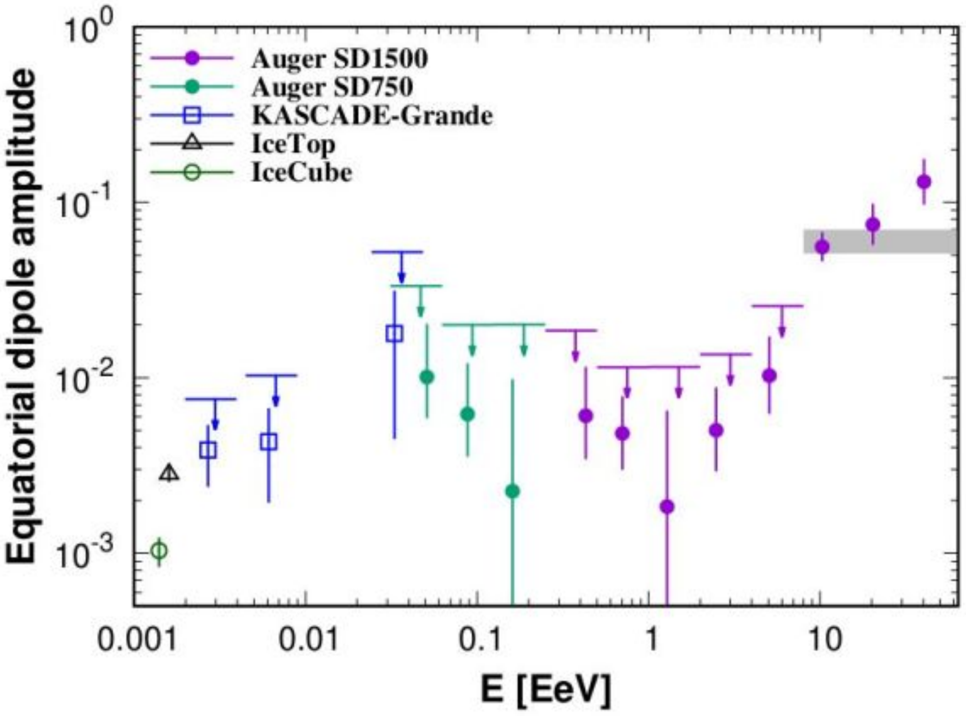
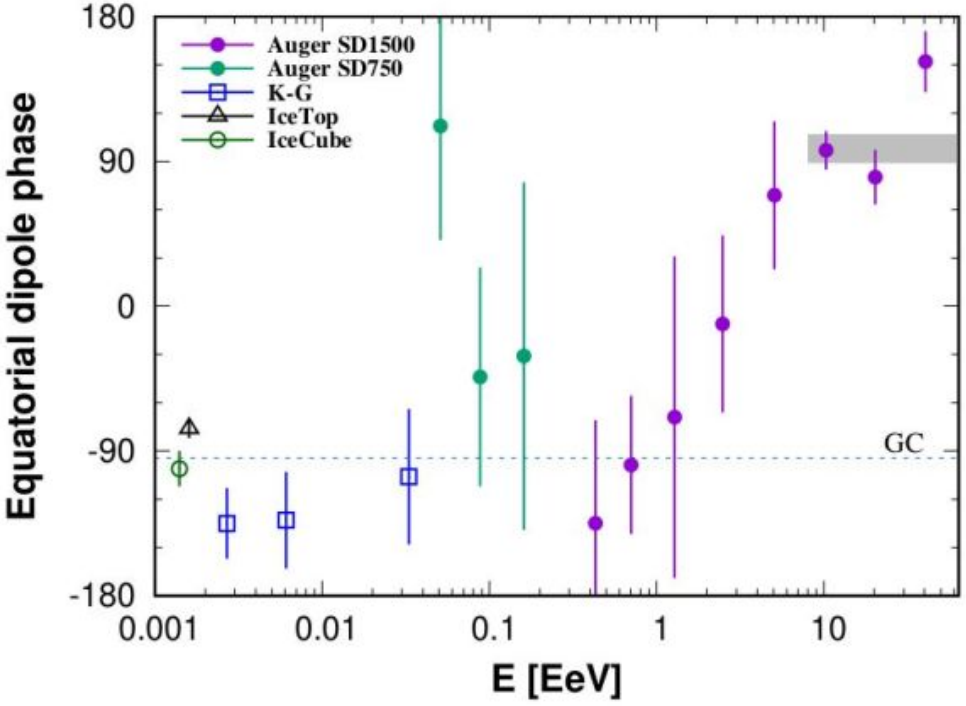
The Pierre Auger Collaboration, **Science**, 2017

outwards the galactic center

Low energies - large scale

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





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

Low energies - large scale

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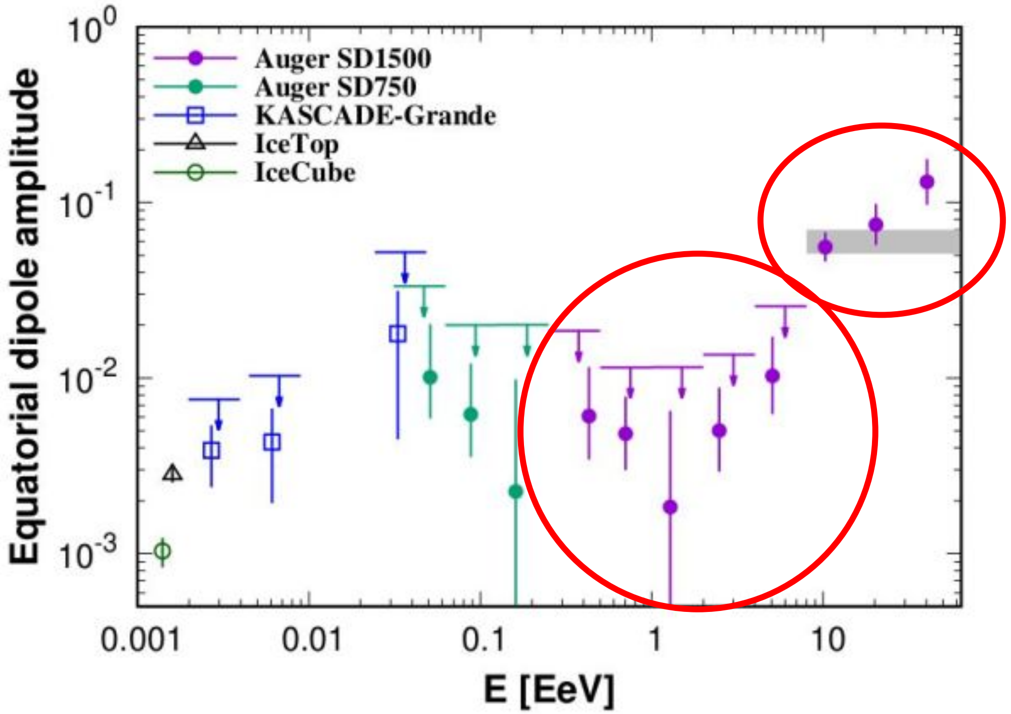
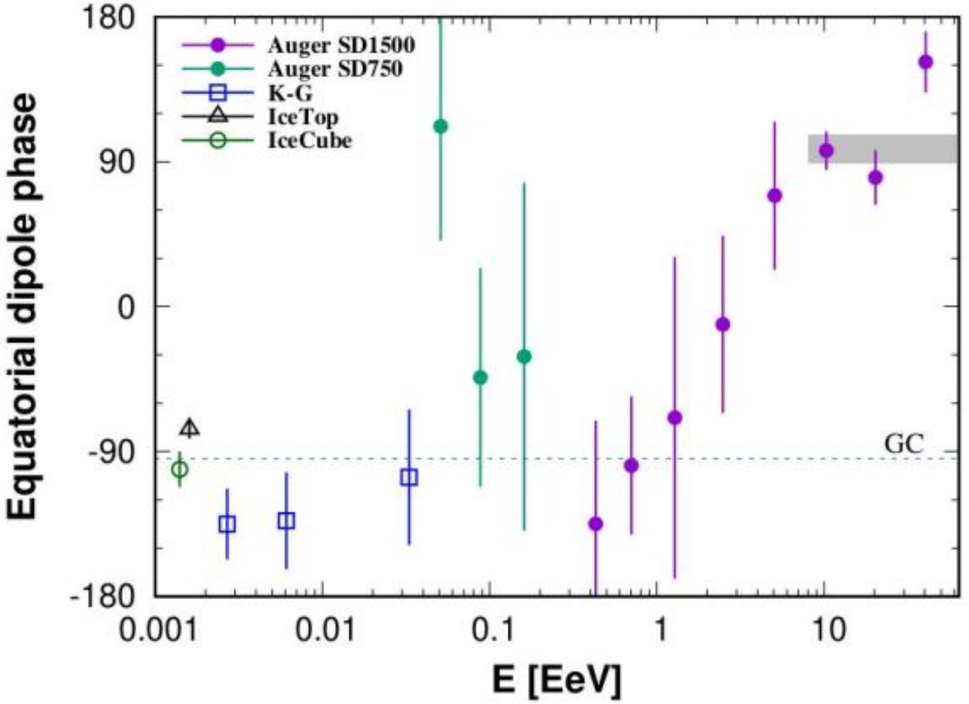


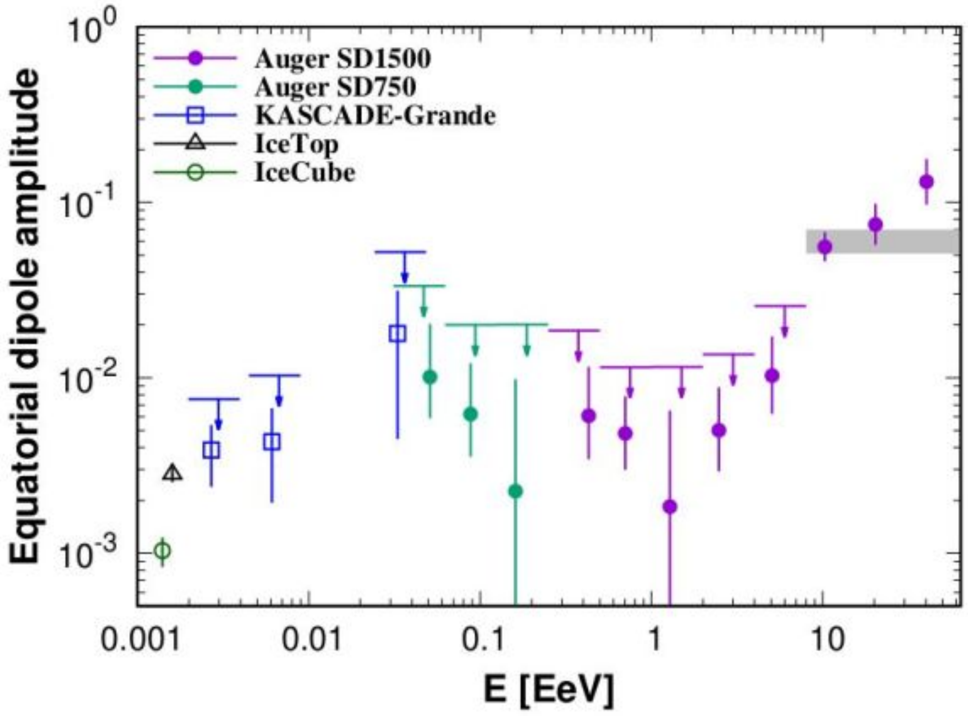


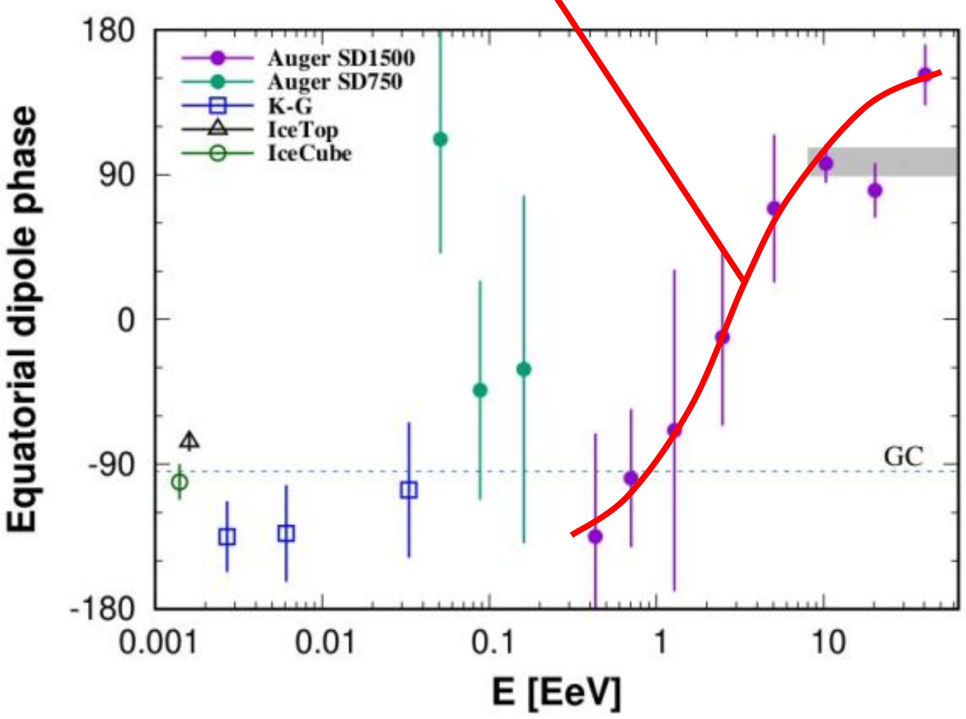
The Pierre Auger Collaboration, **Astrophys. J.**, 2020

Low energies - large scale

➢ Evolution with energy:
  ○ Dipole in right ascension;
  ○ 14.5 years of Auger data;

Evidence of a change from predominance of galactic to extragalactic sources

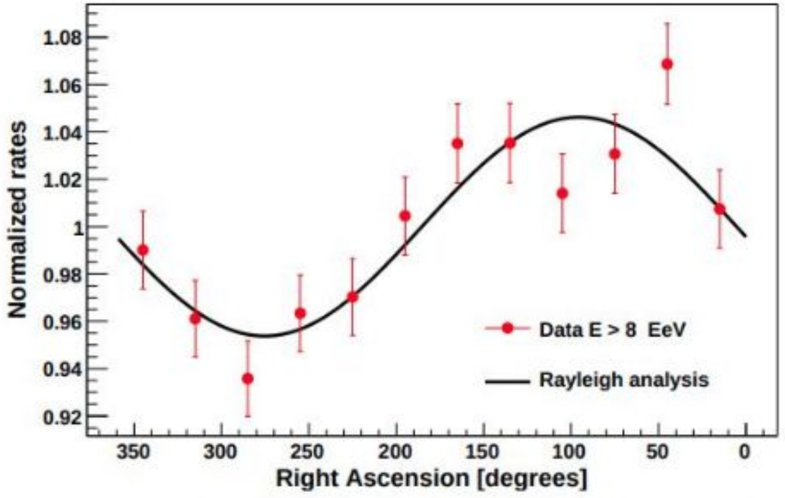


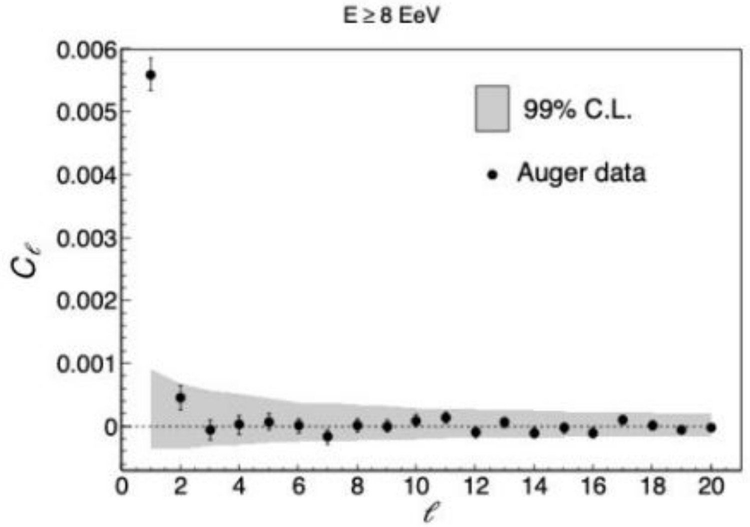


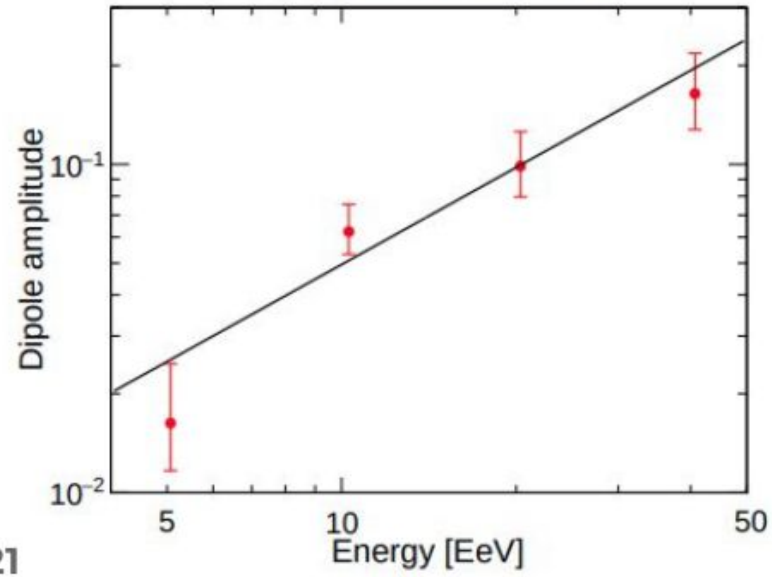
The Pierre Auger Collaboration, **Astrophys. J.**, 2020

Low energies - large scale

- Latest (for the next 90 days):
  - 7.3% with 6.6σ for E > 8 EeV;
  - Quadrupole not statistically significant;
  - New bin on energy evolution;
  - Angular power spectrum.



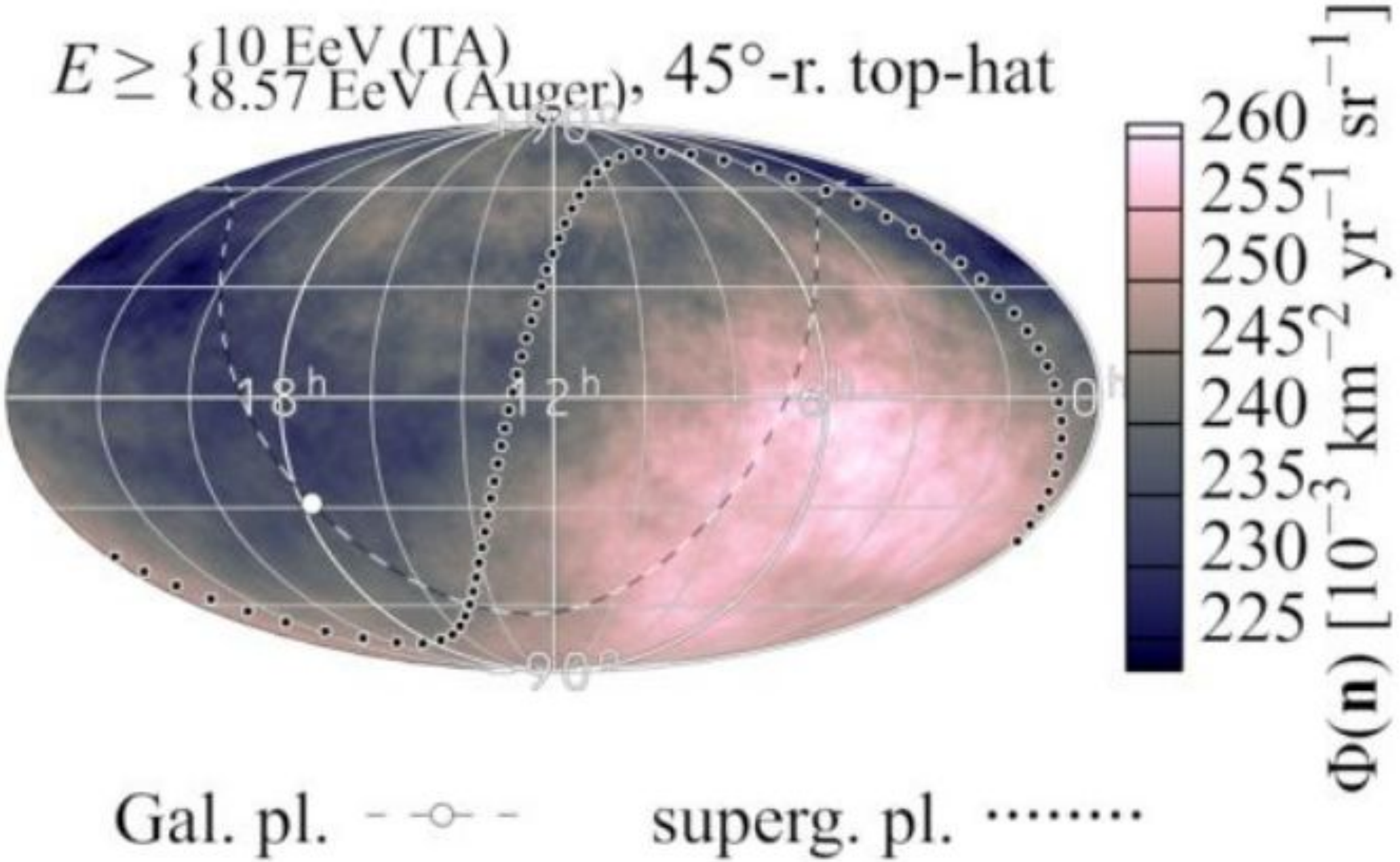




de Almeira, R. M. *et al.*, **ICRC 2021**

Low energies - large scale

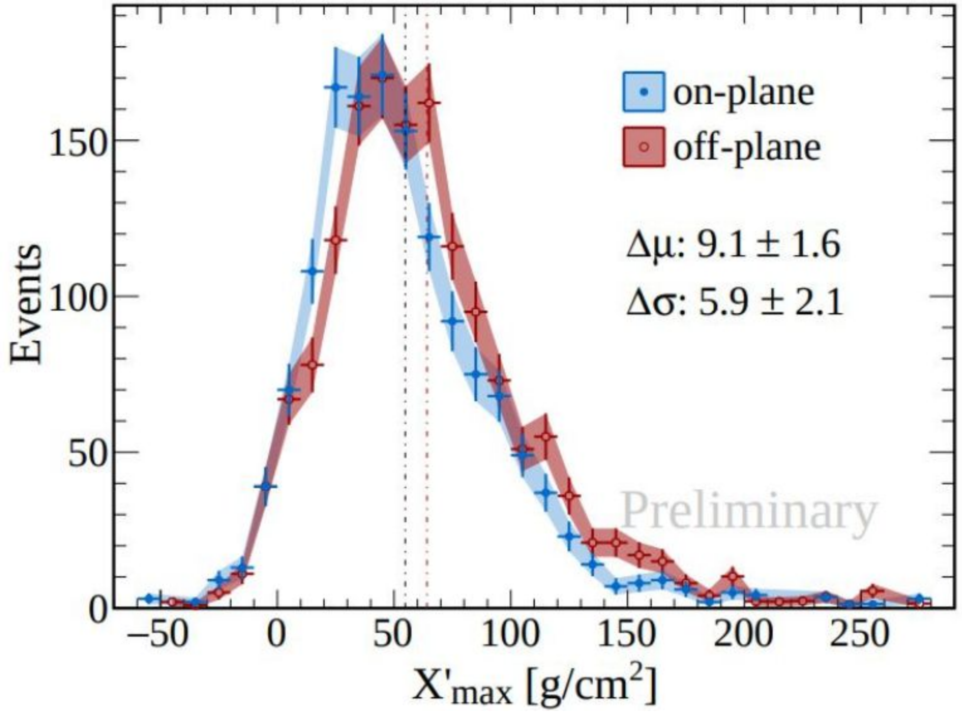
- Full sky:
  - Auger + TA;
  - Regardless of assumptions about multipoles;
  - Agrees with only Auger data;
  - Only dipole is statistically significant;

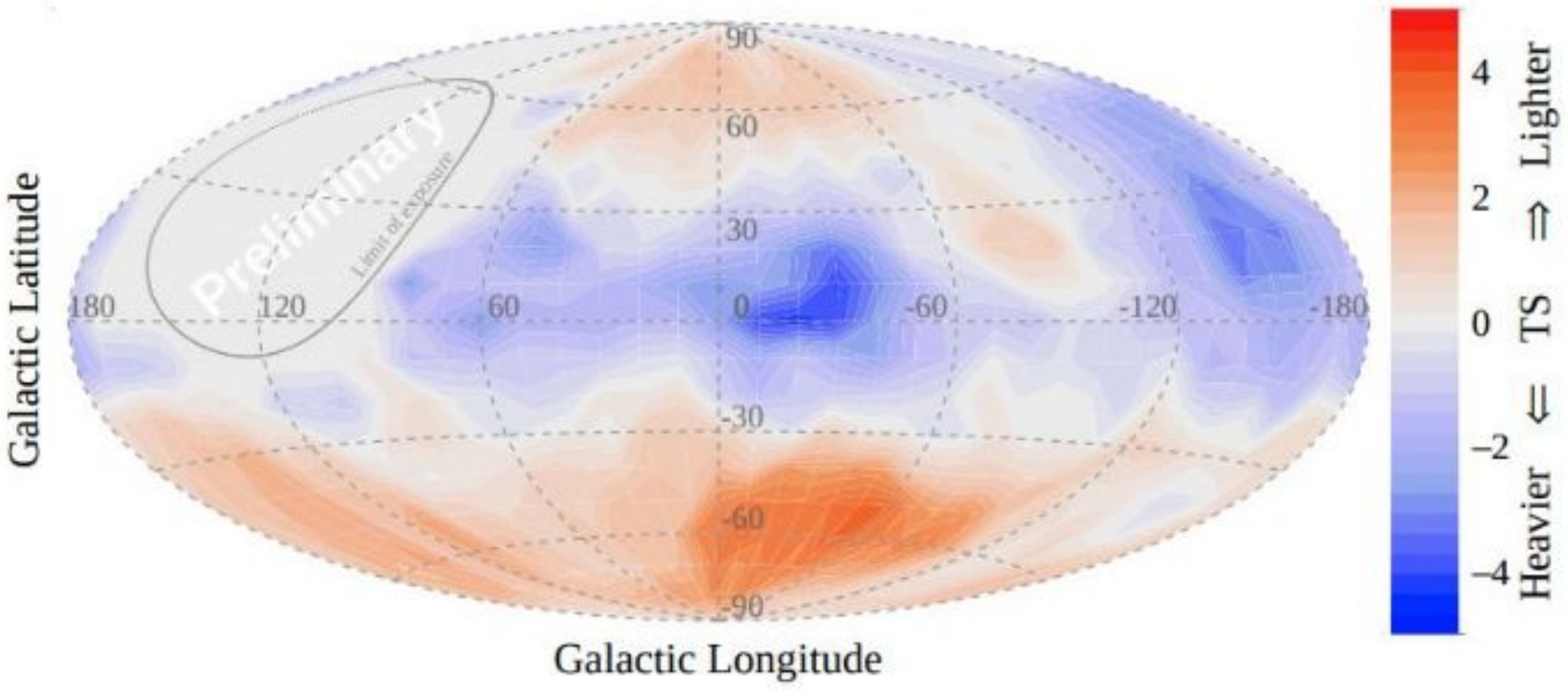


Tinyakov, P. *et al.*, **ICRC 2021**

Low energies - large scale

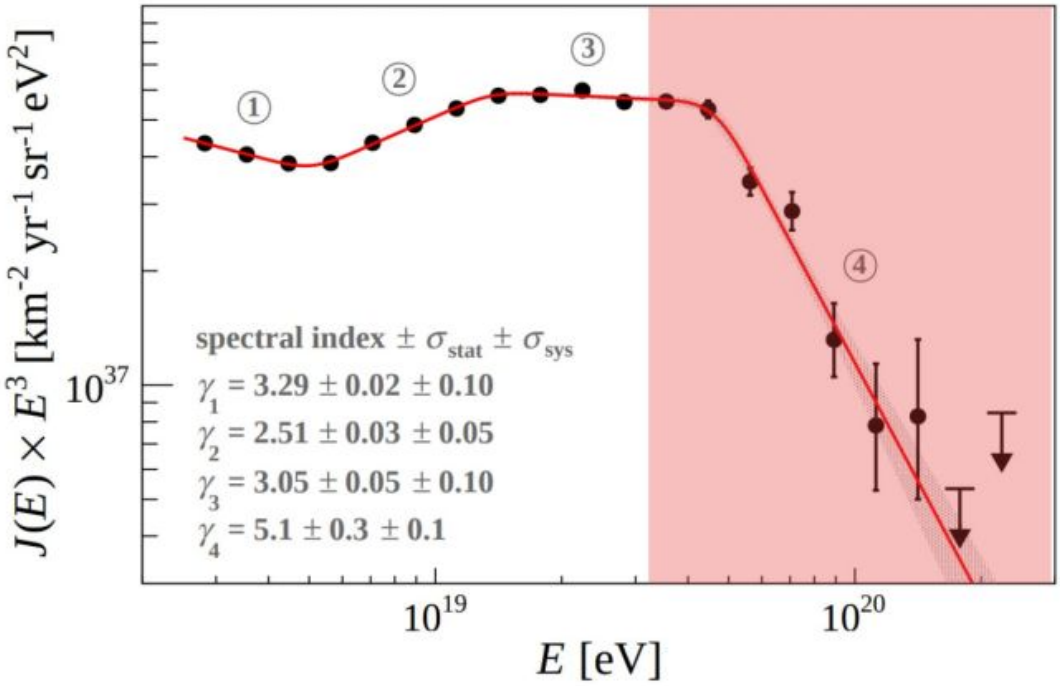
- Composition anisotropy:
  - 14 years of Auger data;
  - $E > 10^{18.7}$ eV;



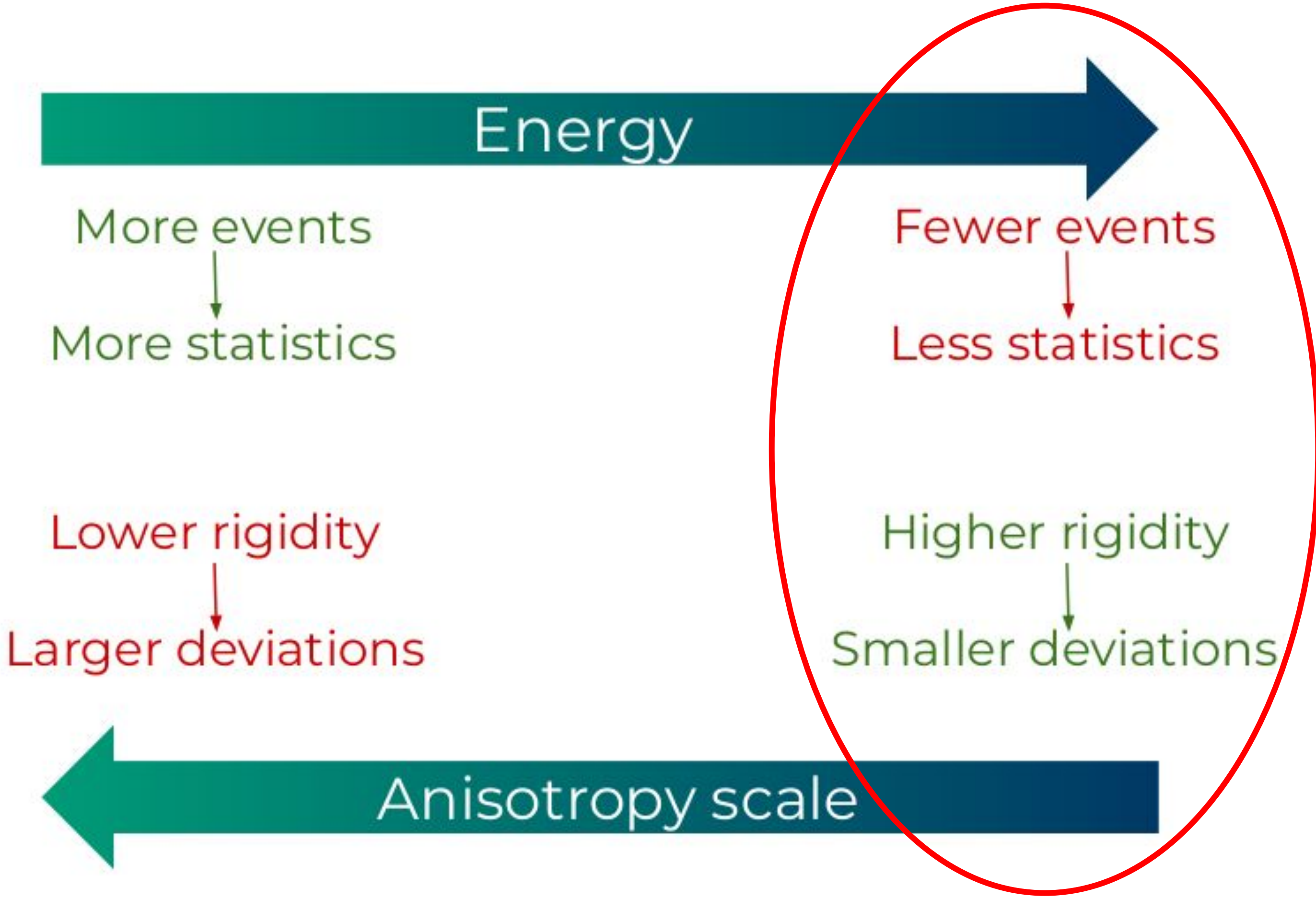


Mayotte, E., **ICRC 2021**

High energies - intermediate scale



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

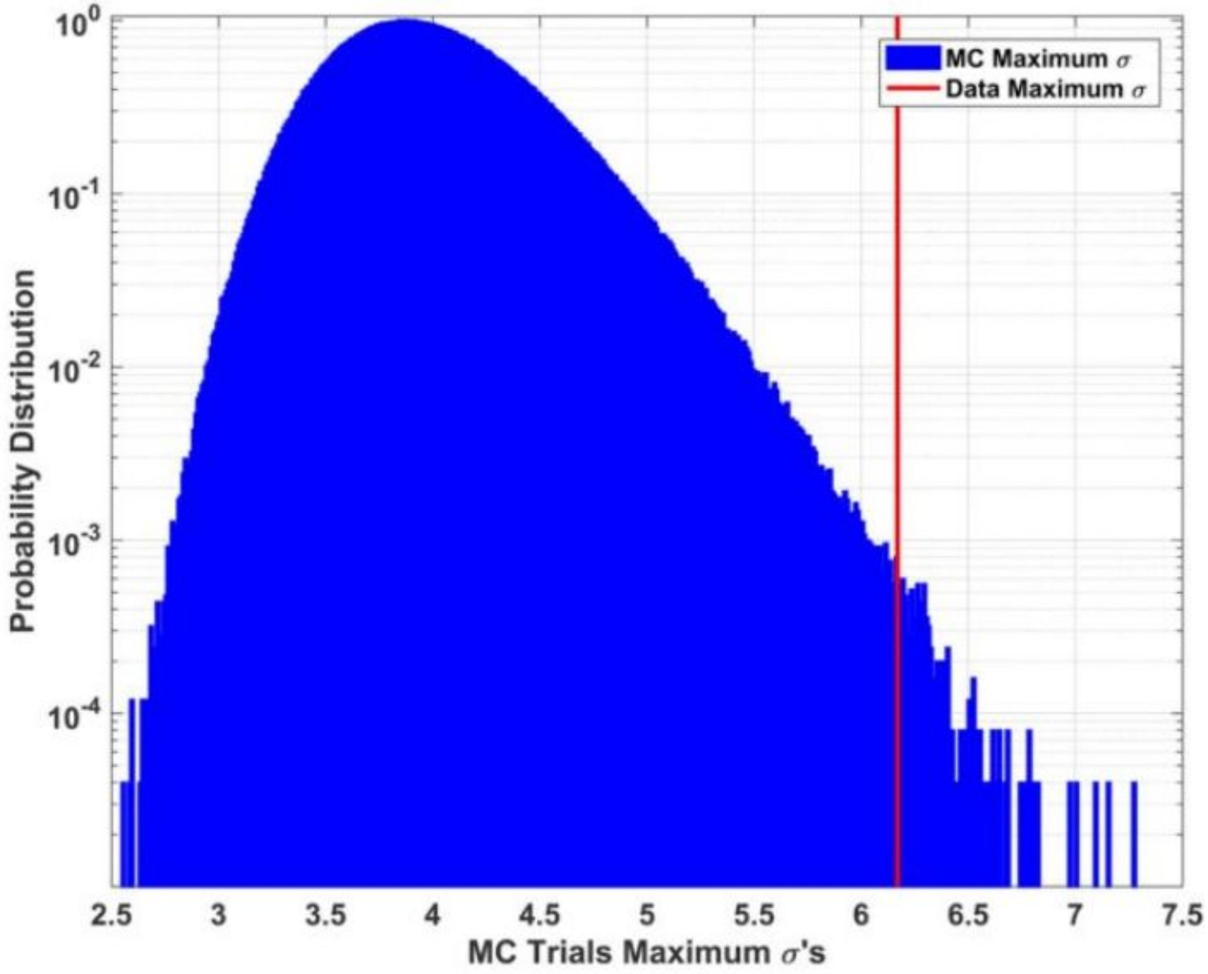


High energies - intermediate scale

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

High energies - intermediate scale

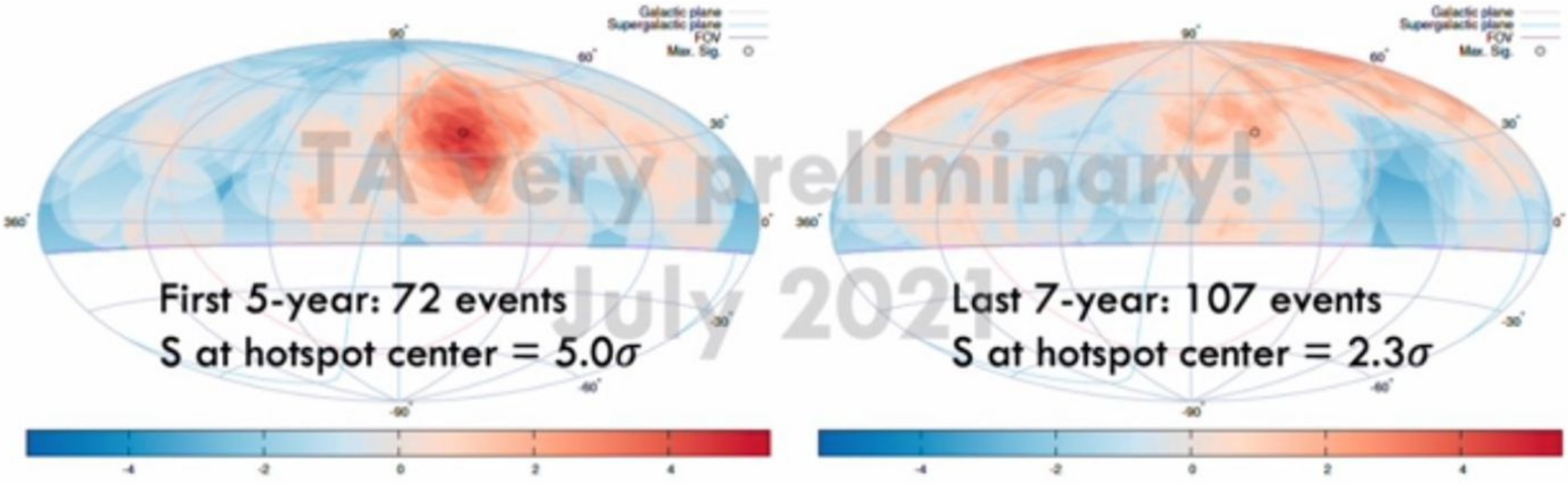
- TA hotspot:
  - What is the probability of such strong excess to appear if you do multiple searches?
  - Post-trial significance:
    - TA '14: 3.4σ;
    - TA '18: 3.74σ;
    - TA '19: 2.9σ;
    - TA '21: 3.2σ;



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

High energies - intermediate scale

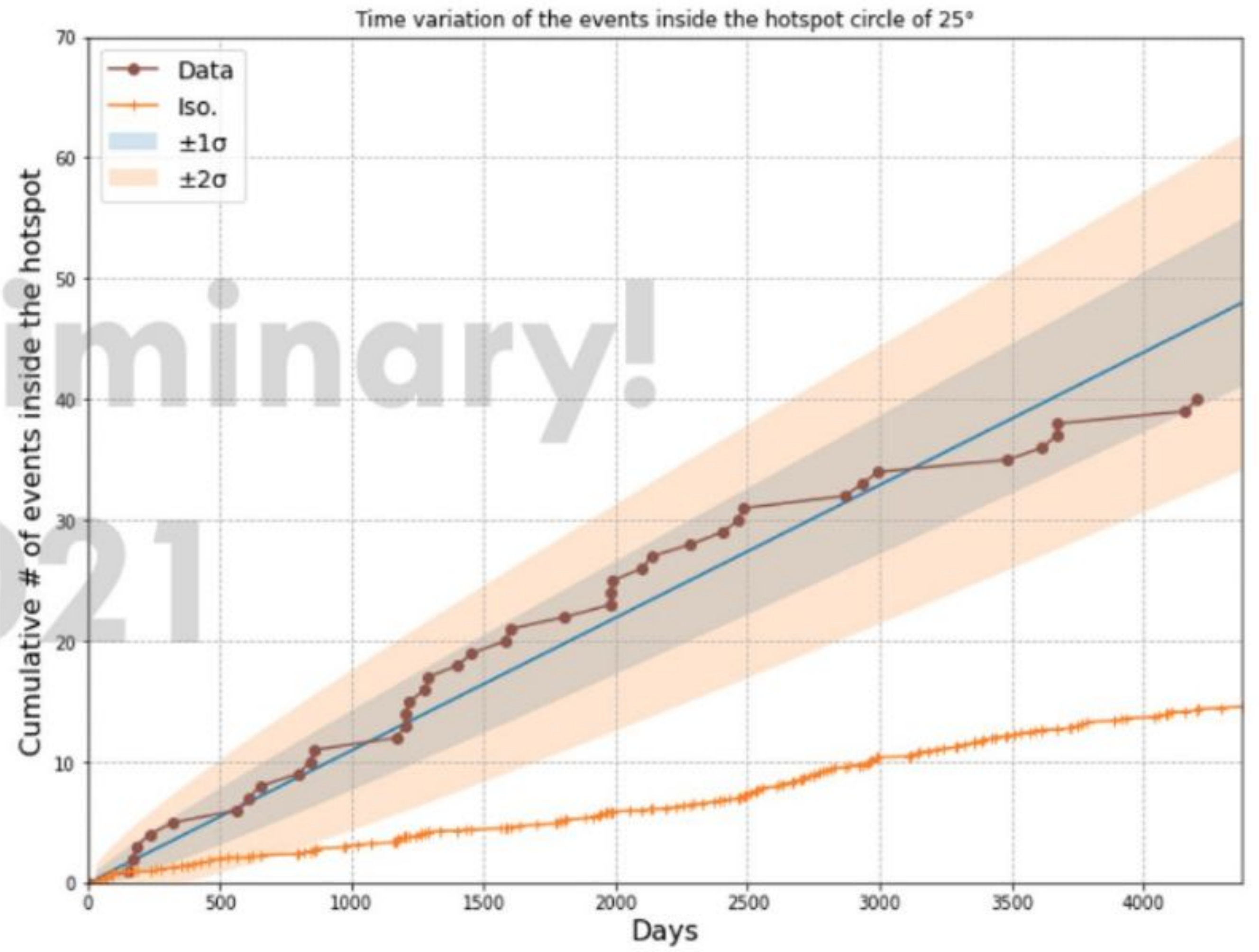
- TA hotspot:
  - Is the hotspot vanishing?



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

High energies - intermediate scale

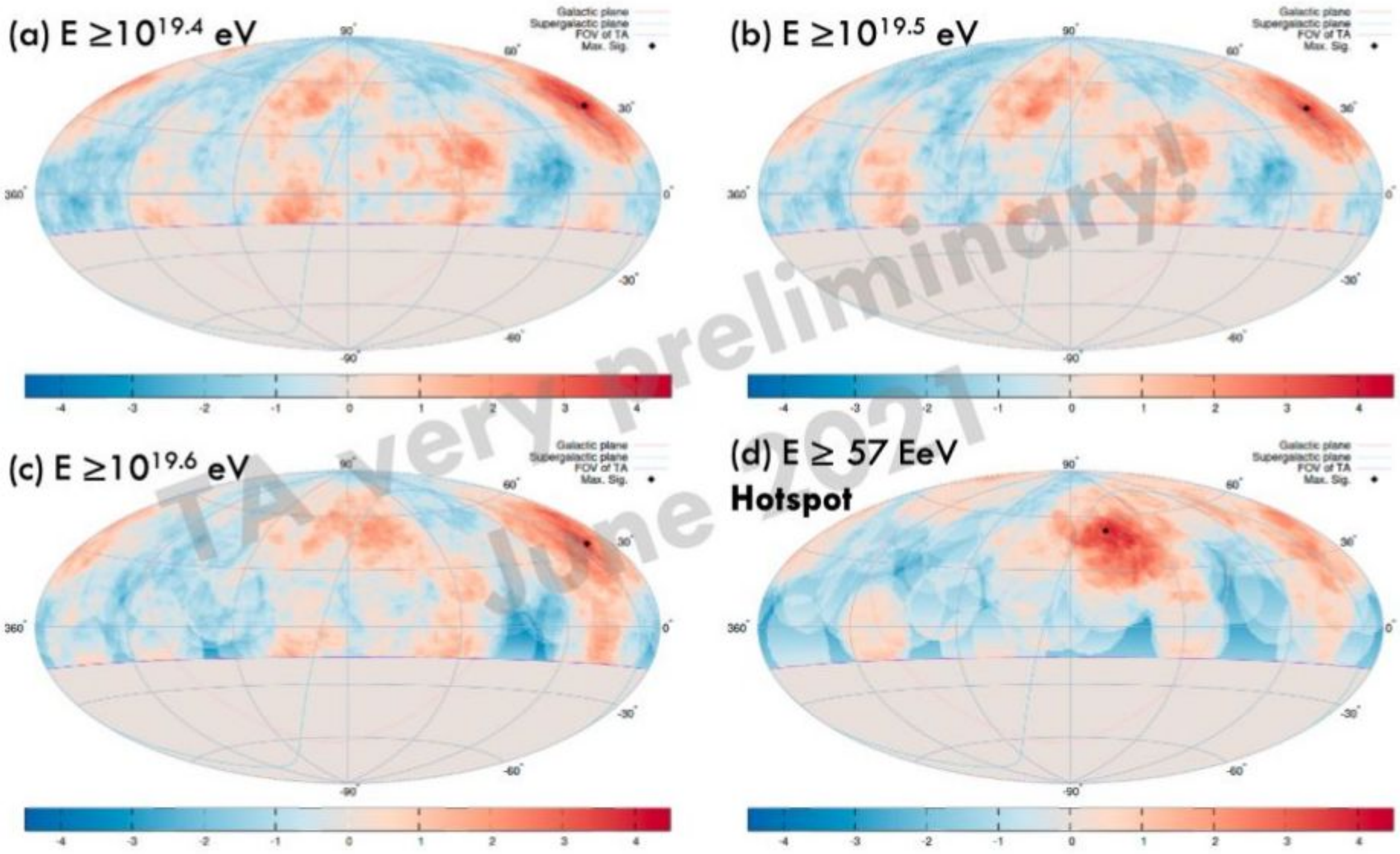
- TA hotspot:
  - Is the hotspot vanishing?
  - The growth is still fluctuating within 1σ;
  - We may just have been unlucky for a few years.



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 deg radius;
  - Near Perseus-Pisces cluster;
  - 3.6σ post-trial;

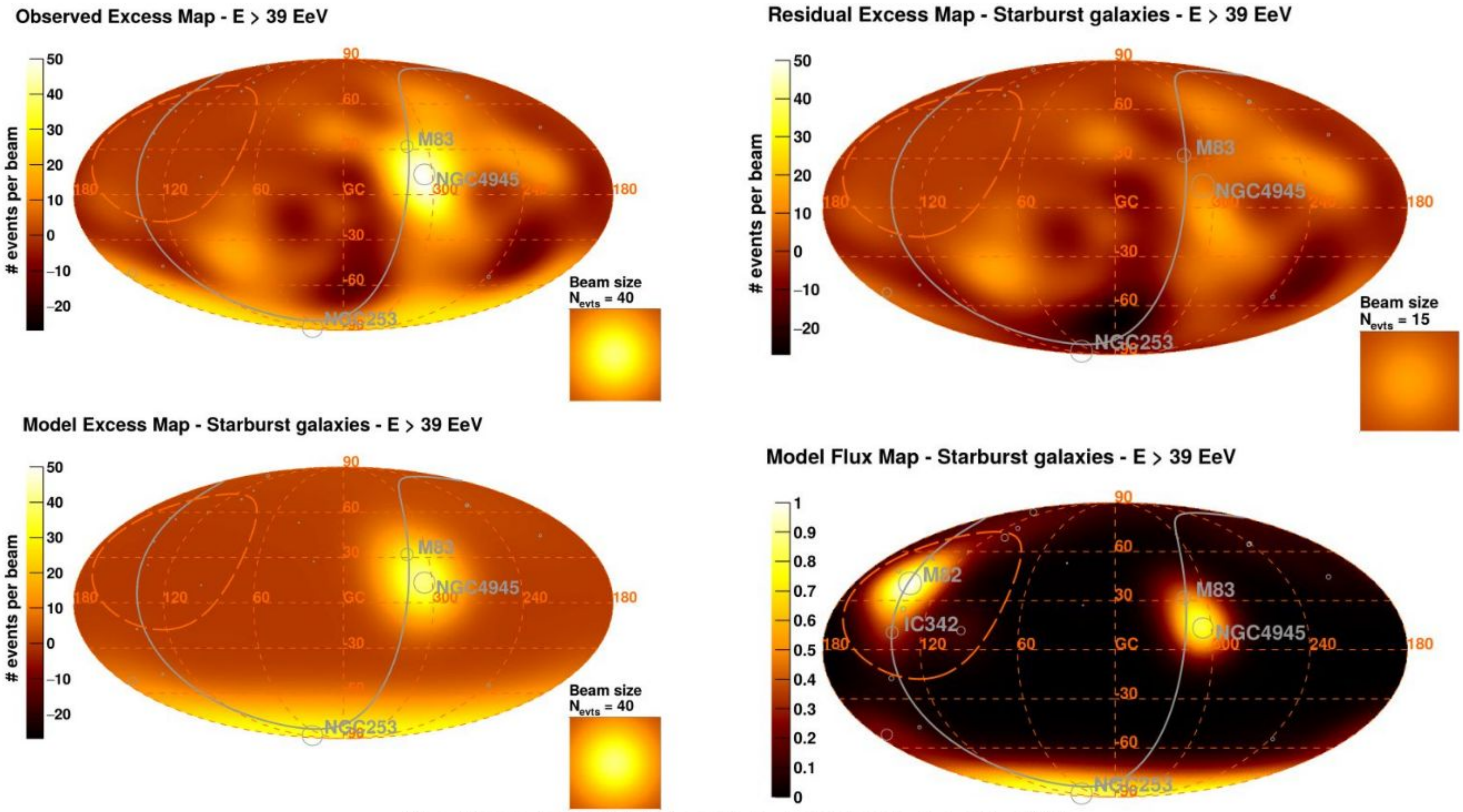


Kim, J. et al, ICRC 2021.

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 fractions;

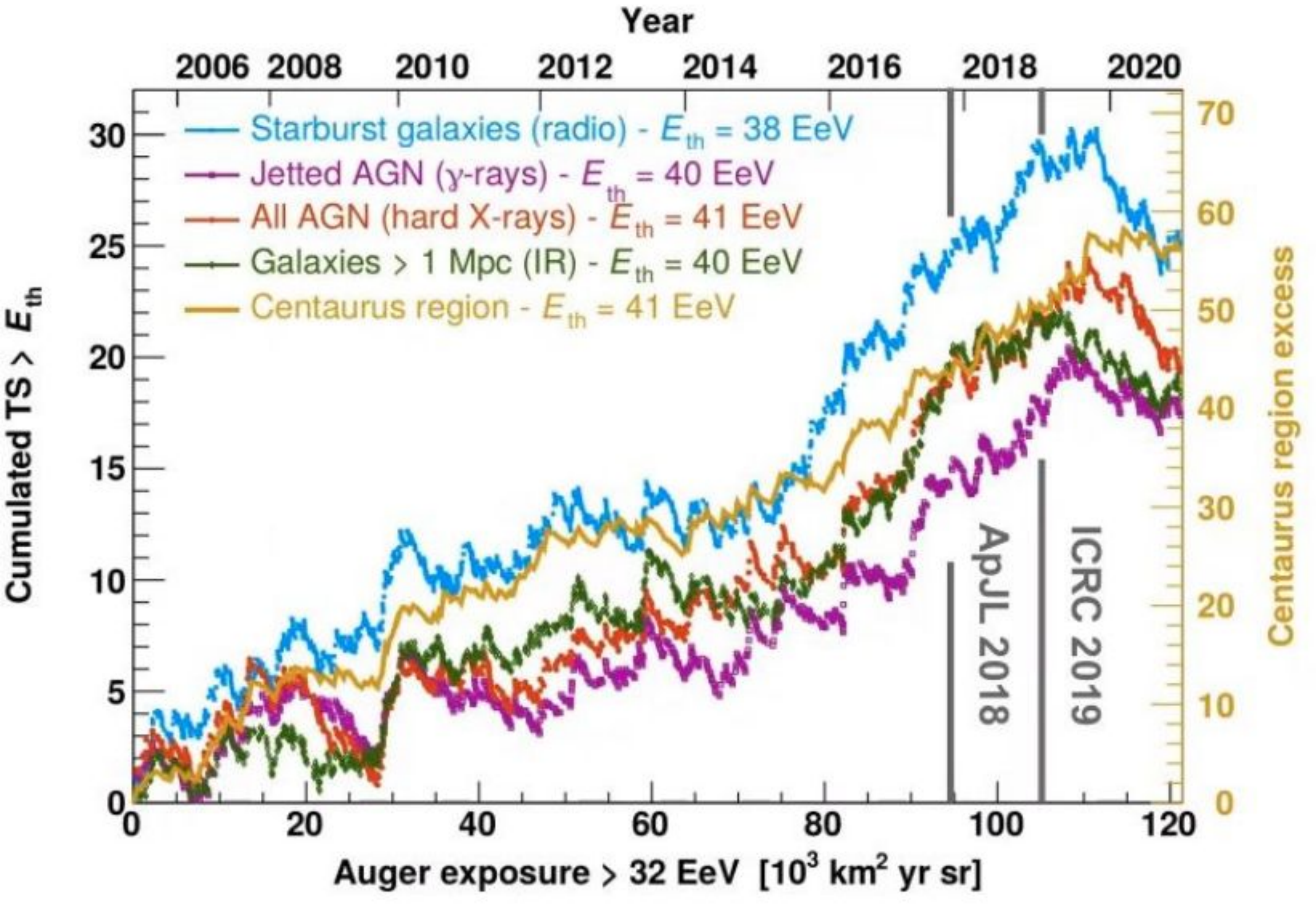
High energies - intermediate scale



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

High energies - intermediate scale

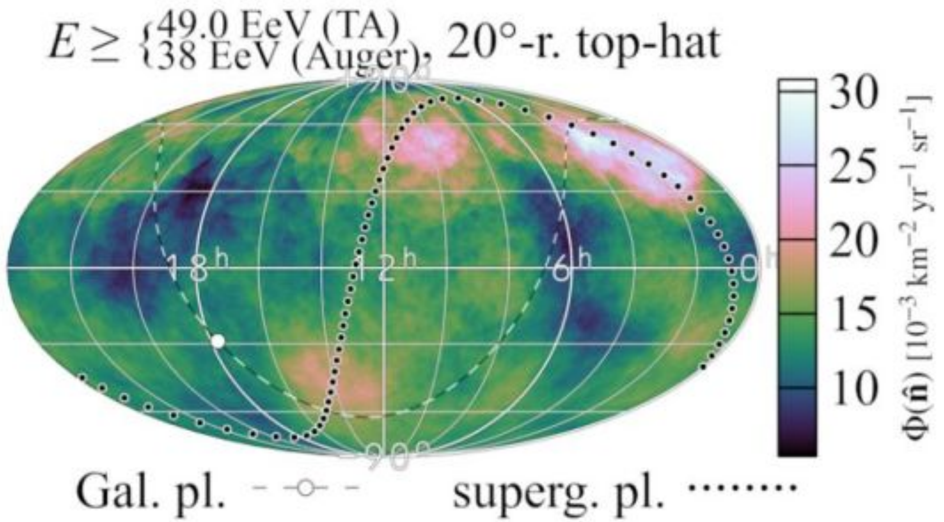
- Auger correlation maps - currently (for the next 90 days):
  - Jetted AGNs: 3.0σ;
  - SBGs: 4.0σ;
  - Centaurus region: 3.9σ;

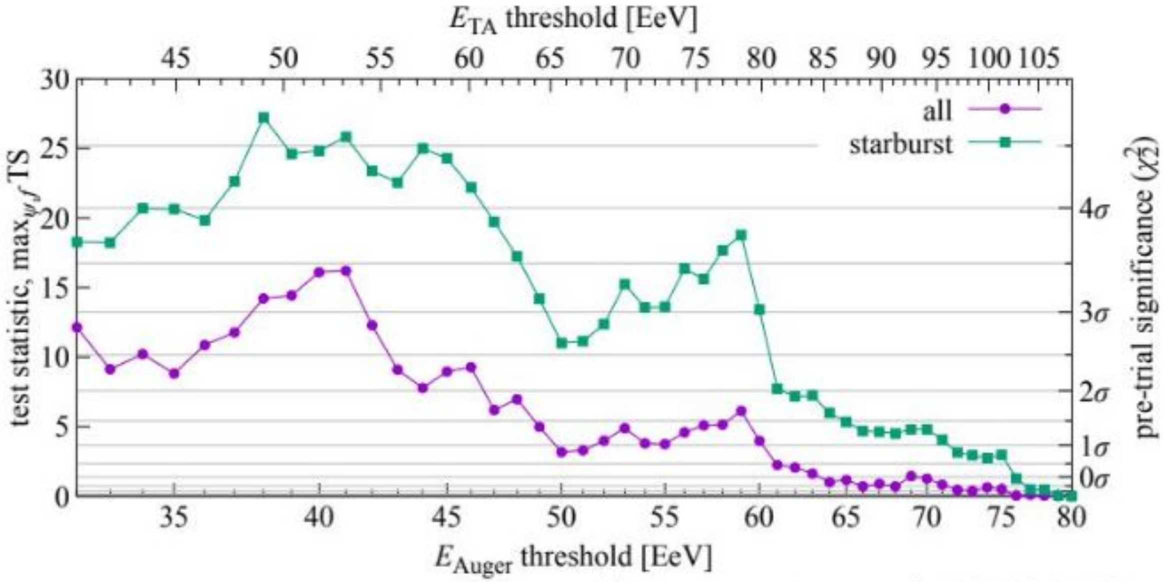


Biteau, J., **slides from ICRC 2021**.

High energies - intermediate scale

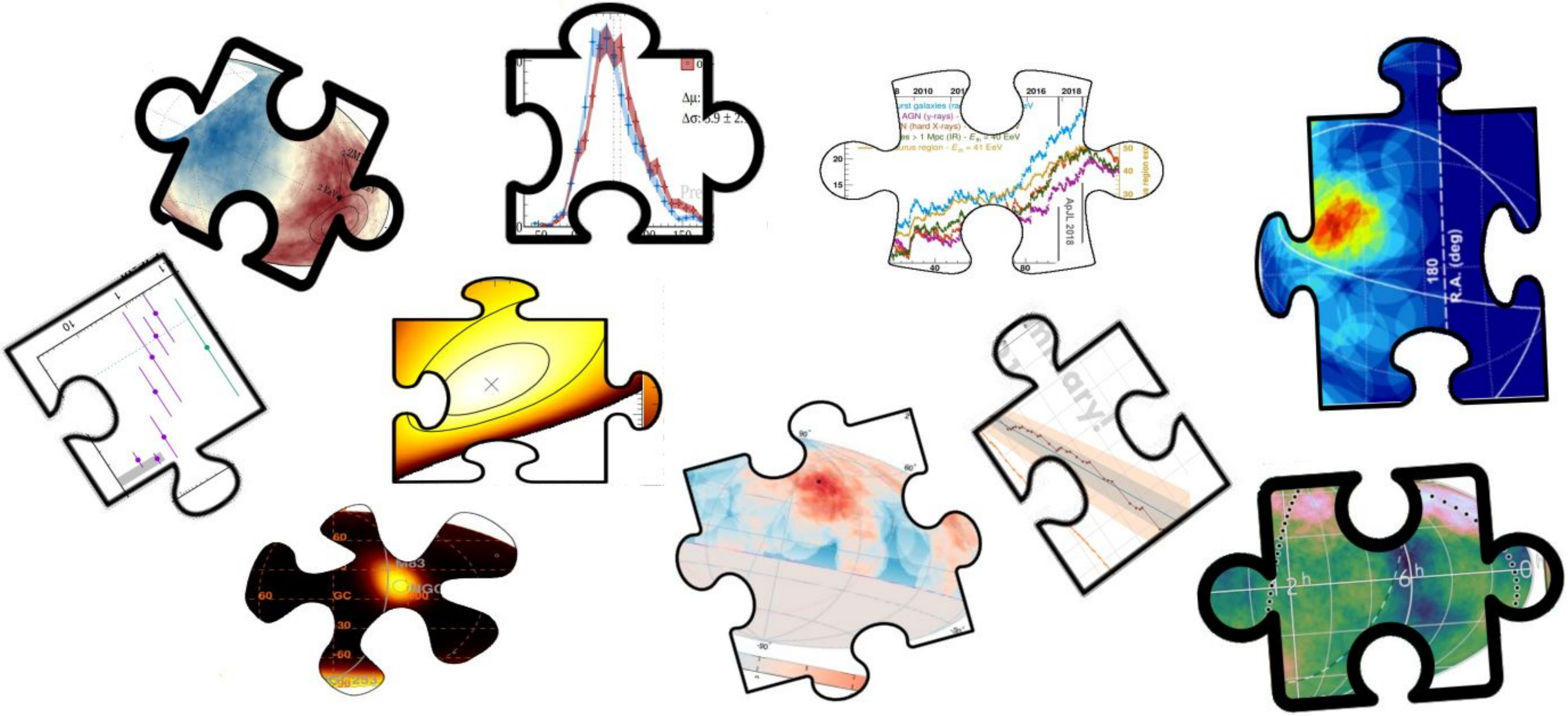
- Full sky:
  - Auger+TA;
  - Correlation with SBGs:
    - E > 38 EeV (Auger);
    - E > 49 EeV (TA);
    - 16 deg radius;
    - 4.0σ post-trial.





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

The pieces: experimental data



The assembly: phenomenology

➢ Several efforts in the last decade to model the experimental results;

The assembly: phenomenology

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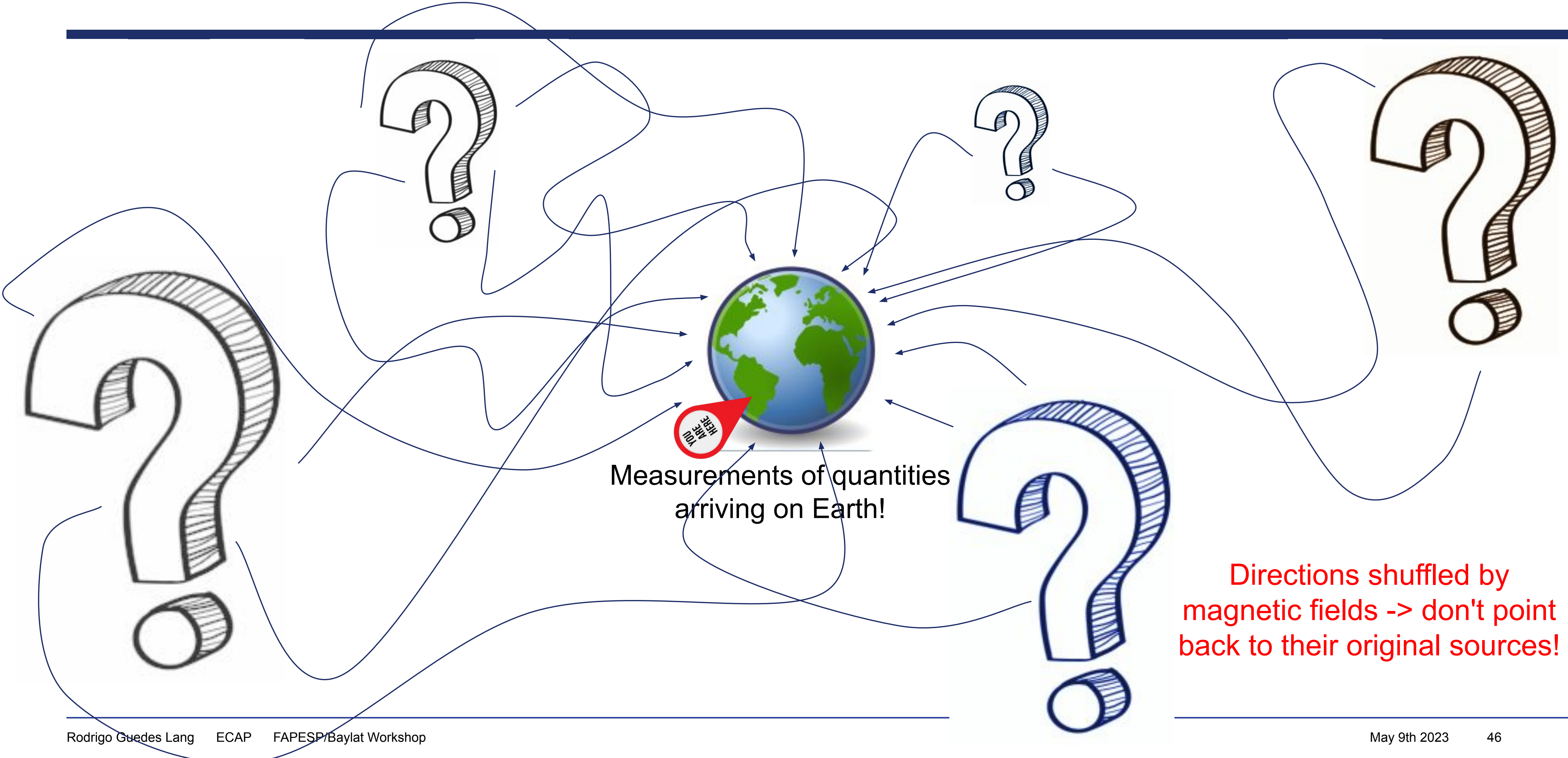
But not that easy…

The assembly: phenomenology

The assembly: phenomenology

Measurements of quantities
arriving on Earth!

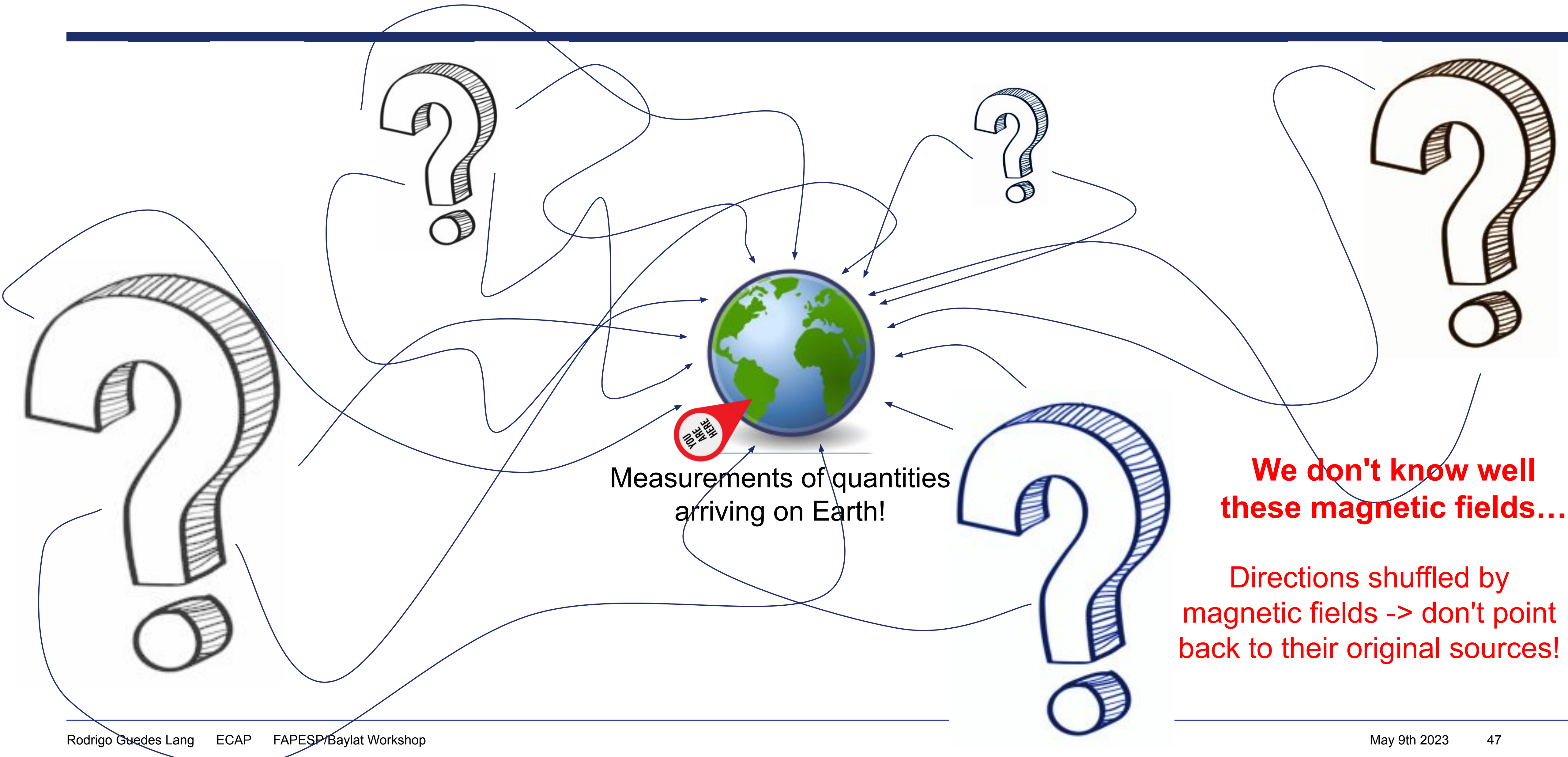
The assembly: phenomenology



Measurements of quantities arriving on Earth!

Directions shuffled by magnetic fields -> don't point back to their original sources!

The assembly: phenomenology



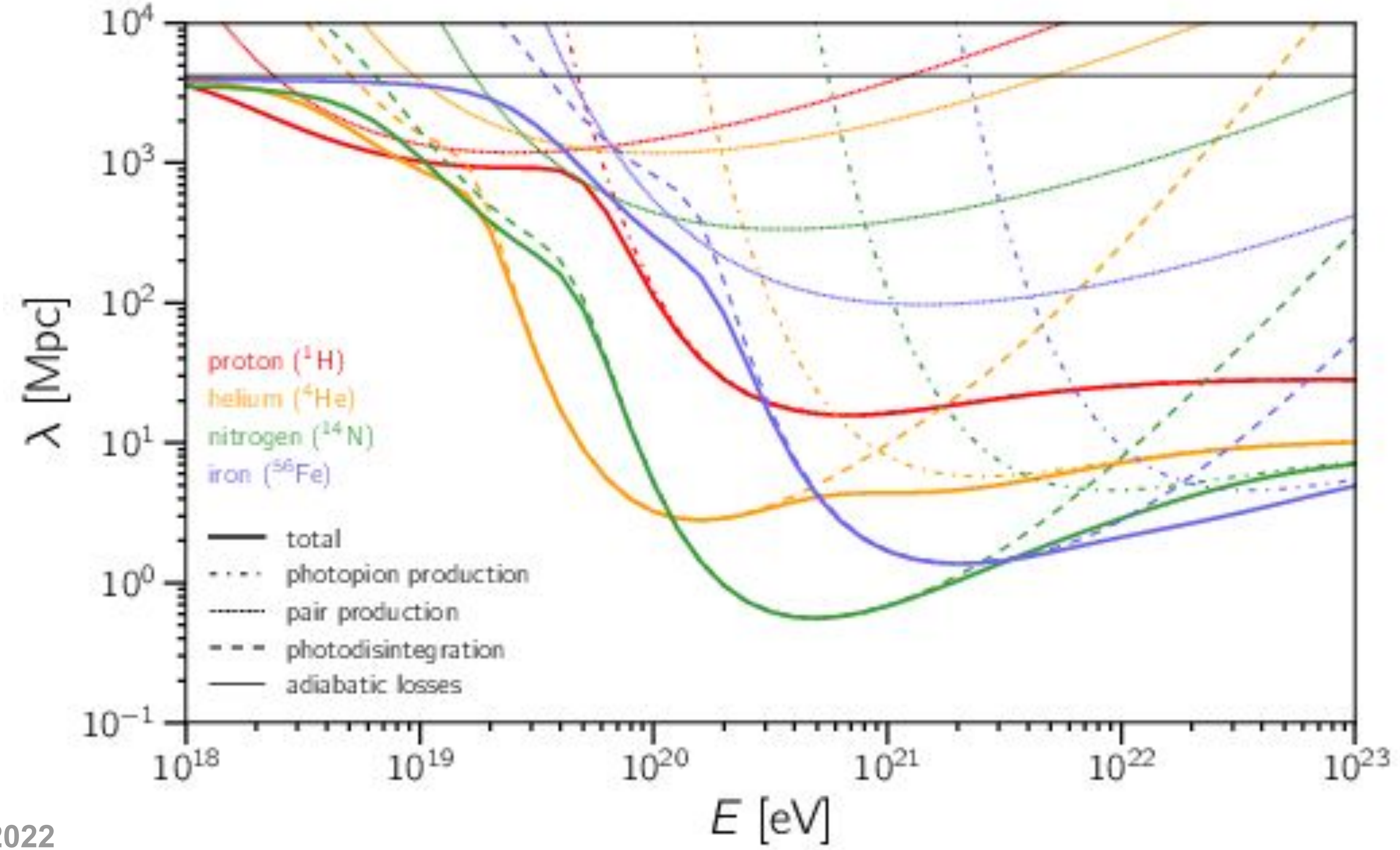
Measurements of quantities arriving on Earth!

We don't know well these magnetic fields…

Directions shuffled by magnetic fields -> don't point back to their original sources!

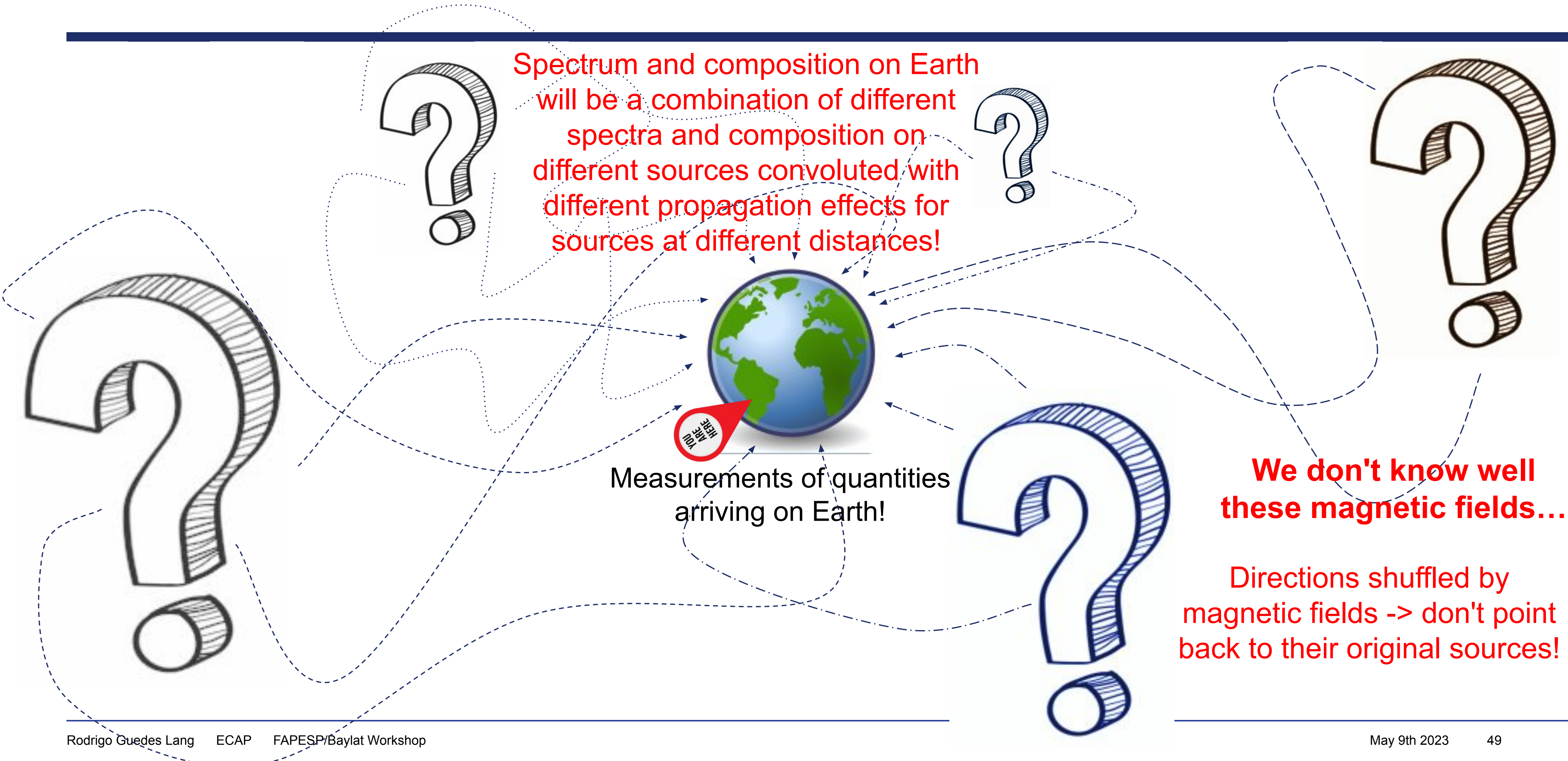
The assembly: phenomenology

- ➢ Energy loss dependent on energy and particle type;
- ➢ Composition and spectrum will be modified differently for sources at different energies;



Addazi, A. *et al.*, **Prog. Part. Nucl. Phys. 2022**

The assembly: phenomenology



Spectrum and composition on Earth will be a combination of different spectra and composition on different sources convoluted with different propagation effects for sources at different distances!

Measurements of quantities arriving on Earth!

We don't know well these magnetic fields…

Directions shuffled by magnetic fields -> don't point back to their original sources!

The assembly: phenomenology

Propagation systematics
EBL uncertainties
Hadronic models uncertainties

Spectrum and composition on Earth will be a combination of different spectra and composition on different sources convoluted with different propagation effects for sources at different distances!

Measurements of quantities arriving on Earth!

We don't know well these magnetic fields…

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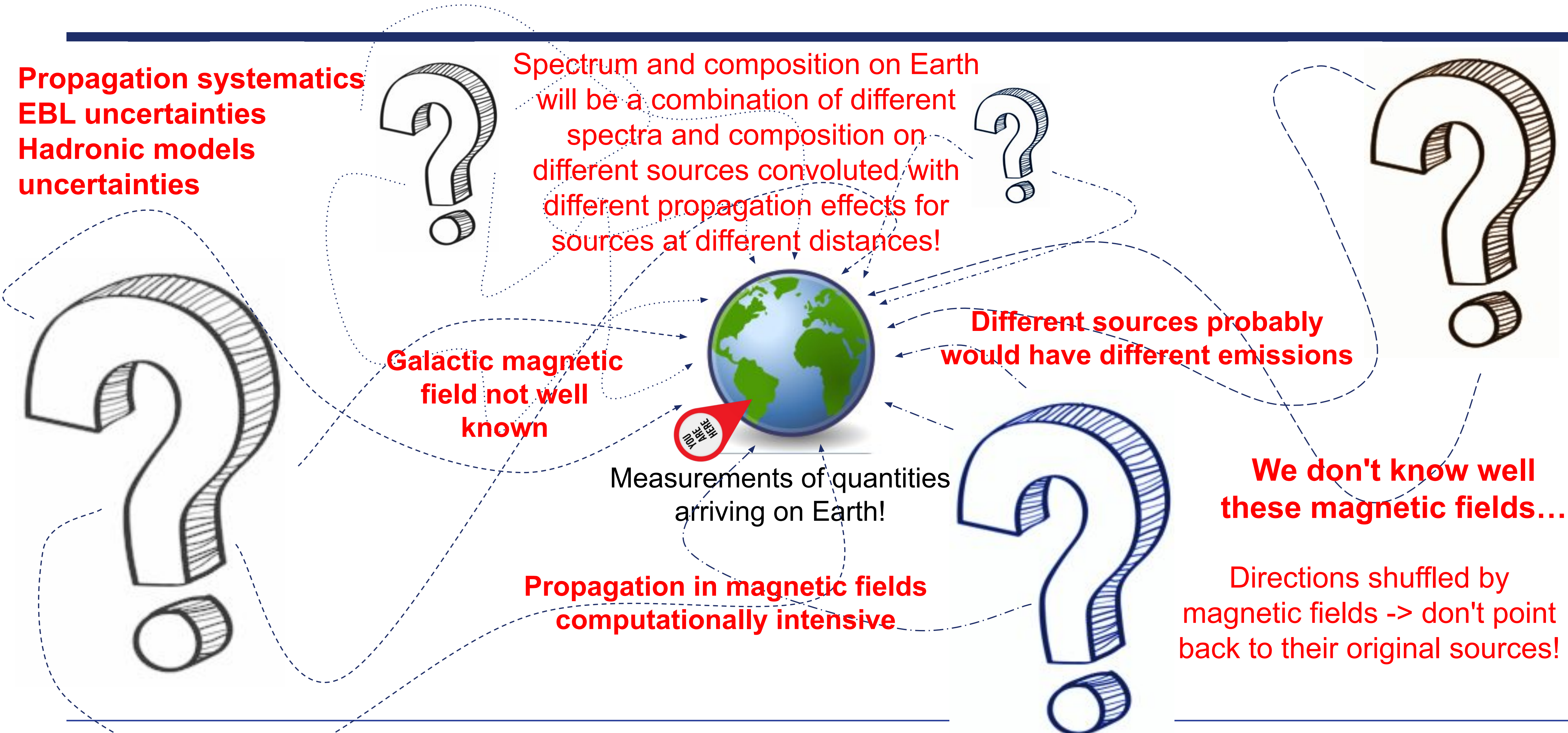
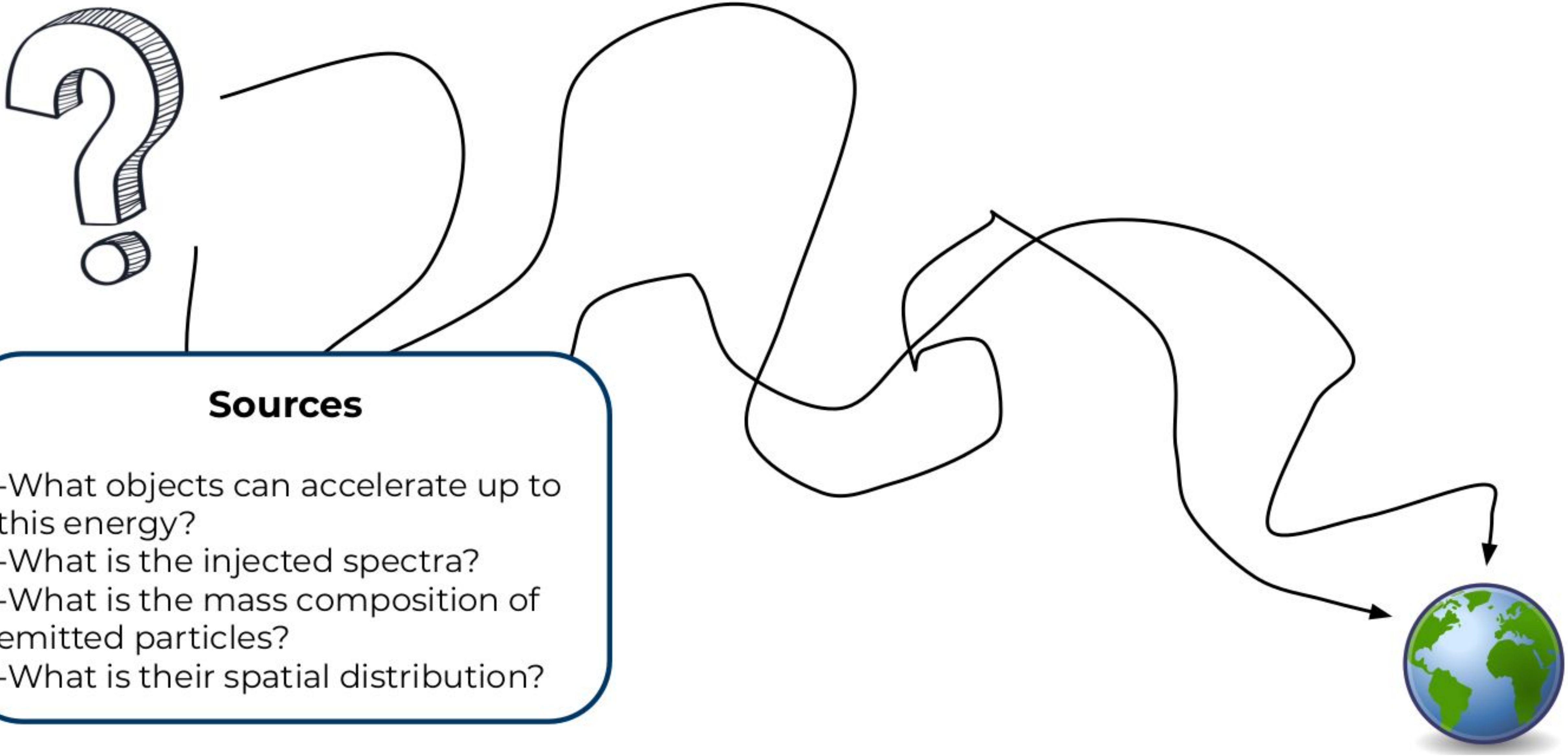


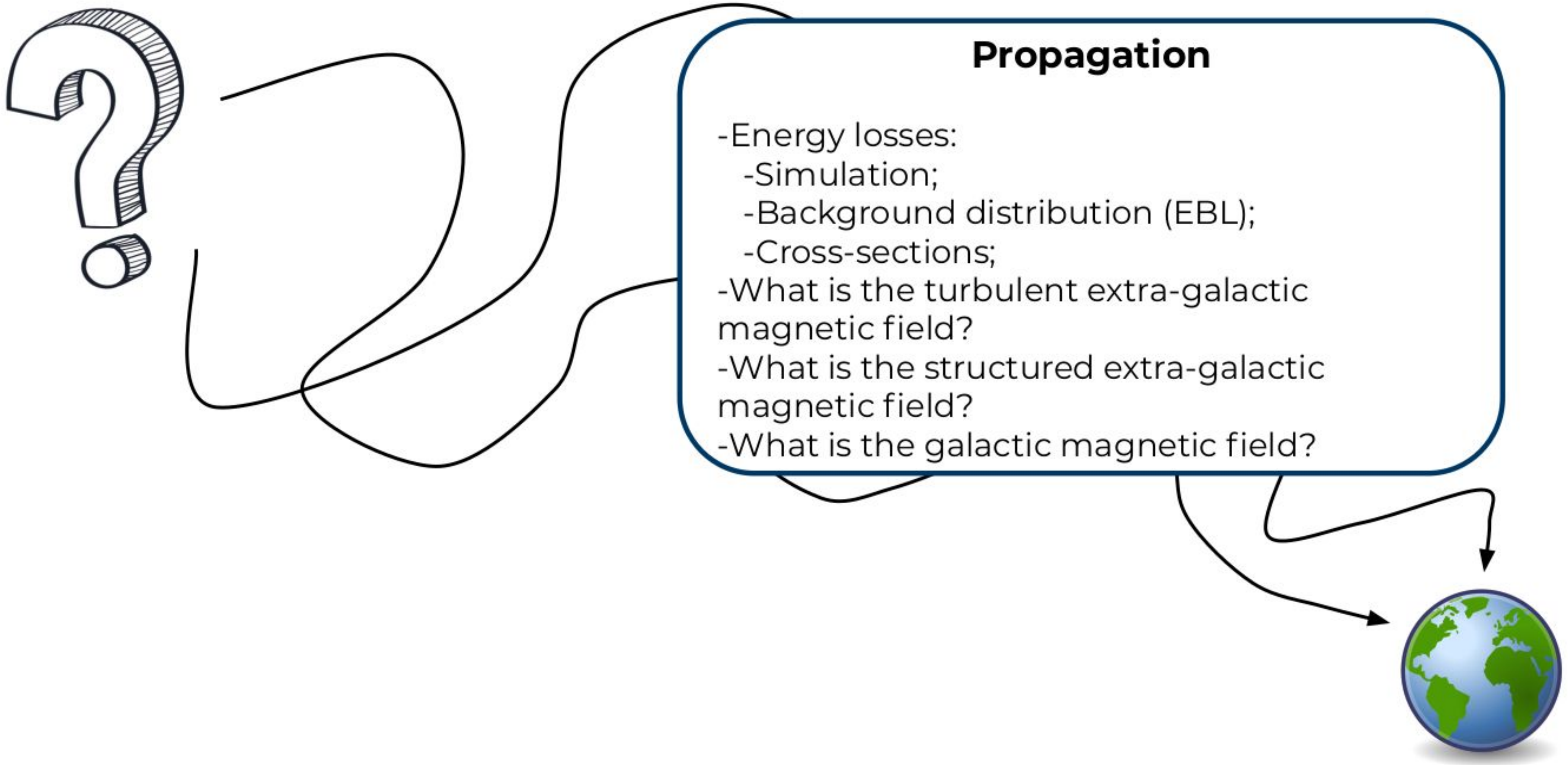
Hypotheses



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 -> strong model dependency;
  - Few hypotheses/many fit parameters -> no strong conclusions.

One approach -> Auger's combined fit

- Tries to fit energy spectrum and Xmax distribution at the same time;
- Simple source assumptions:
  - Homogeneous distribution;
  - Every source emitting with the same spectrum and composition (standard candle);
  - No magnetic field effects;

- fitted parameters

$$J(E) = f_A \left(\frac{E}{E_0}\right)^{-\gamma} e^{(-E/Z R_{\mathrm{max}})}$$

One approach -> Auger's combined fit

model	γ	$\log_{10}(R_{\rm cut}/{\rm V})$	D	$D(J)$	$D(X_{\max})$
SPG	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$	174.3	13.2	161.1
STG	$+0.77^{+0.07}_{-0.13}$	$18.62^{+0.02}_{-0.04}$	175.9	18.8	157.1
SPD	$-1.02^{+0.31}_{-0.26}$	$18.19^{+0.04}_{-0.03}$	187.0	8.4	178.6
CTG	$-1.03^{+0.35}_{-0.30}$	$18.21^{+0.05}_{-0.04}$	189.7	8.3	181.4
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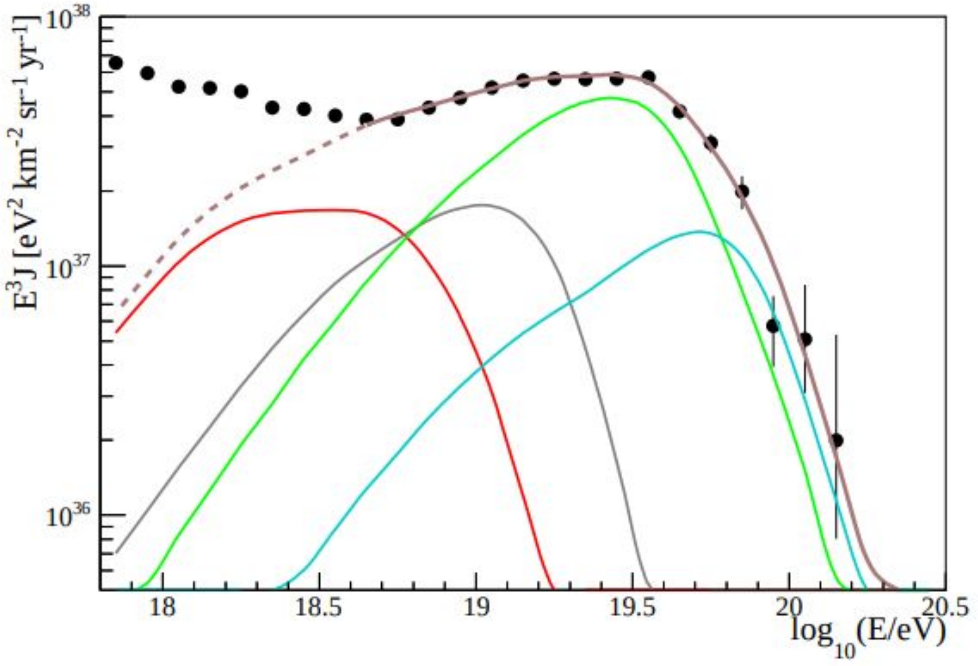
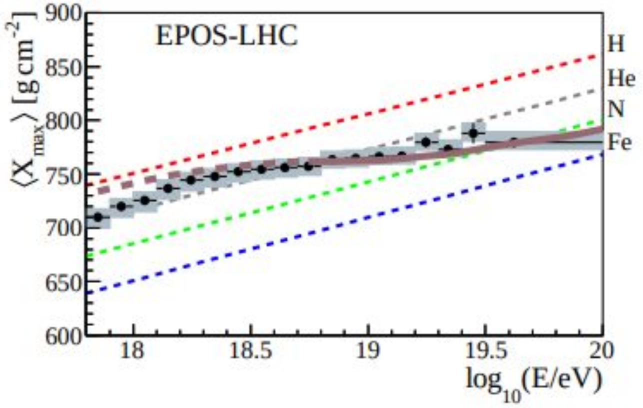
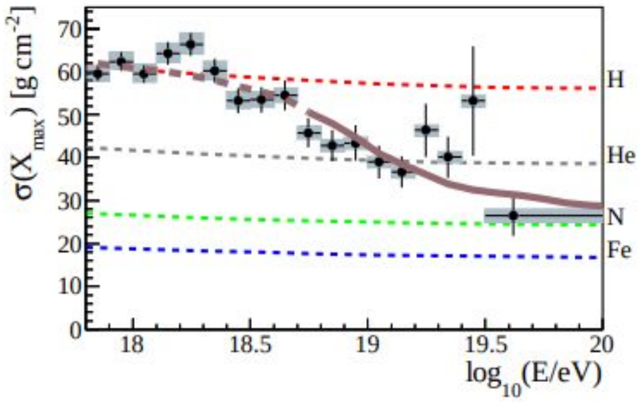
model	$f_{\rm H}$	$f_{\rm He}$	$f_{\rm N}$	$f_{\rm Si}$	$\frac{\mathcal{L}_{\rm H}}{\mathcal{L}_0}$	$\frac{\mathcal{L}_{\rm He}}{\mathcal{L}_0}$	$\frac{\mathcal{L}_{\rm N}}{\mathcal{L}_0}$	$\frac{\mathcal{L}_{\rm Si}}{\mathcal{L}_0}$
SPG	0%	67%	28%	5%	0%	33%	50%	17%
STG	0%	7%	85%	8%	0%	1%	81%	17%
SPD	63%	37%	0.6%	0.03%	9%	45%	30%	15%
CTG ($\gamma = -1.03$)	68%	31%	1%	0.06%	7%	26%	50%	18%
CTG ($\gamma = +0.87$)	0%	0%	88%	12%	0%	0%	77%	23%
CTD	45%	52%	3%	0.06%	1%	15%	70%	14%
CGD	90%	5%	4%	0.09%	5%	2%	79%	14%







Pierre Auger Collaboration, **JCAP 2017**

One approach -> Auger's combined fit

strongly dependent on the hypotheses

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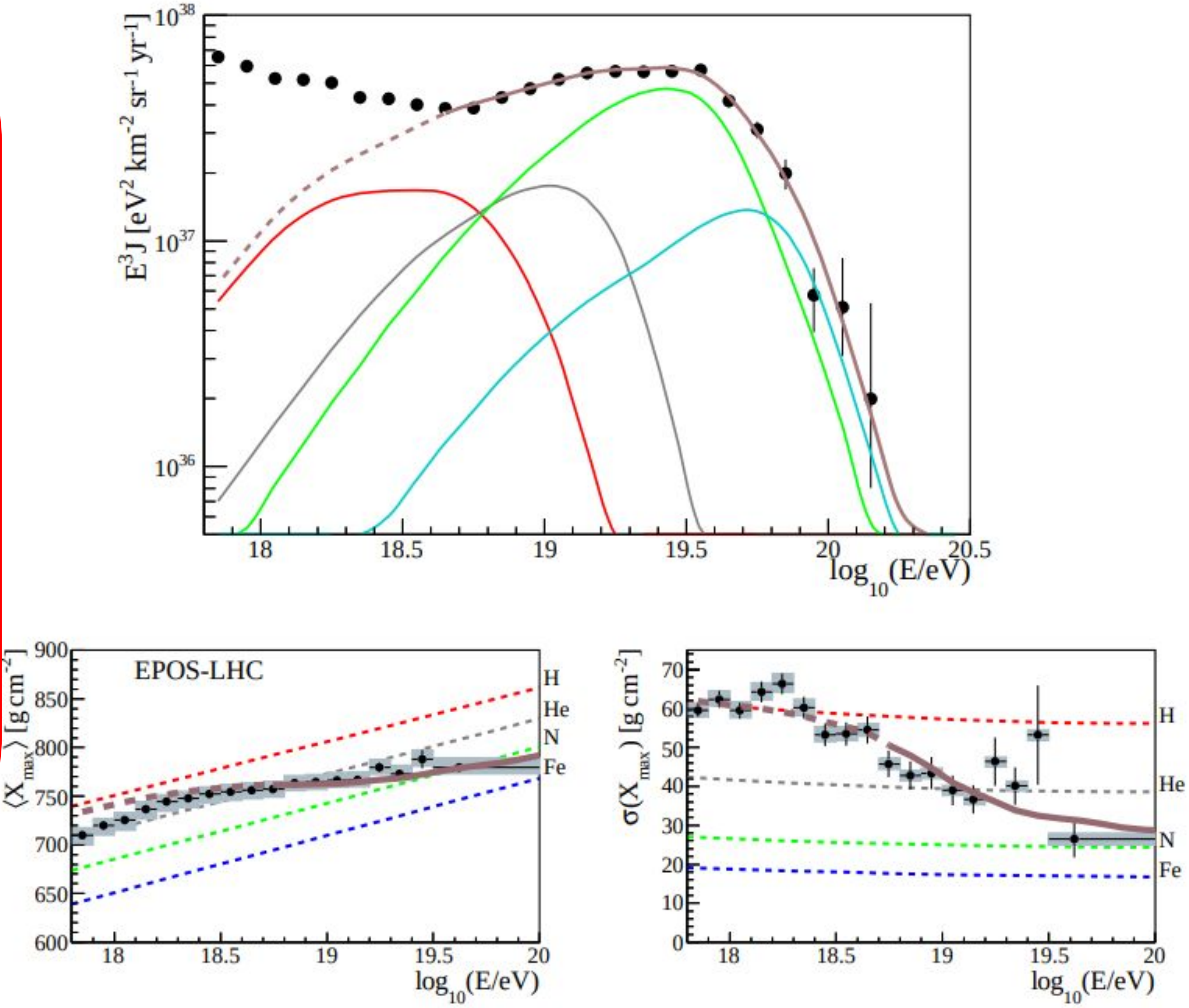
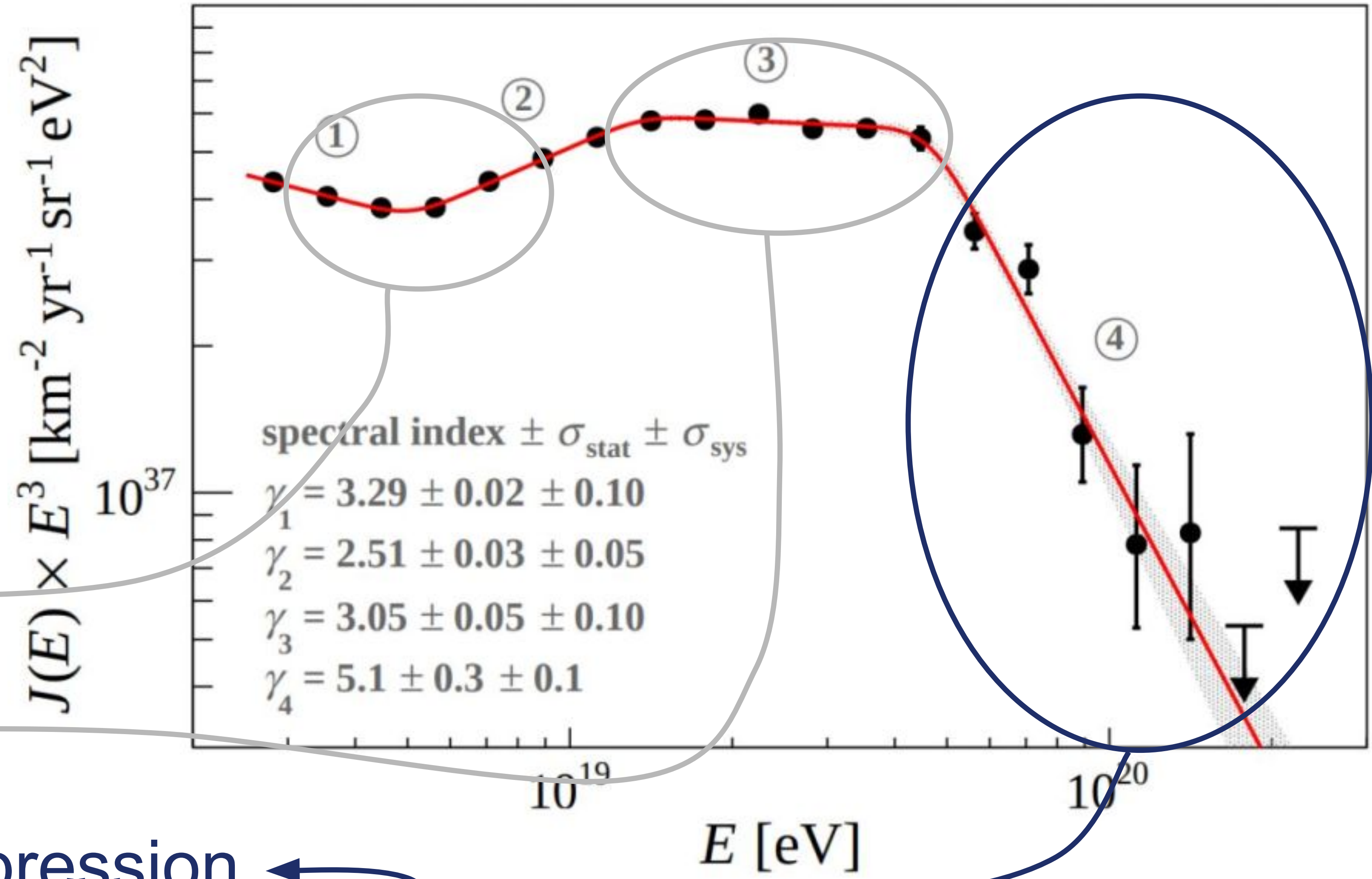


Pierre Auger Collaboration, **JCAP 2017**

One approach -> Auger's combined fit

➢ Something to be noted!



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

Ankle

Transition from galactic to extragalactic

Instep

To be described :)

Suppression

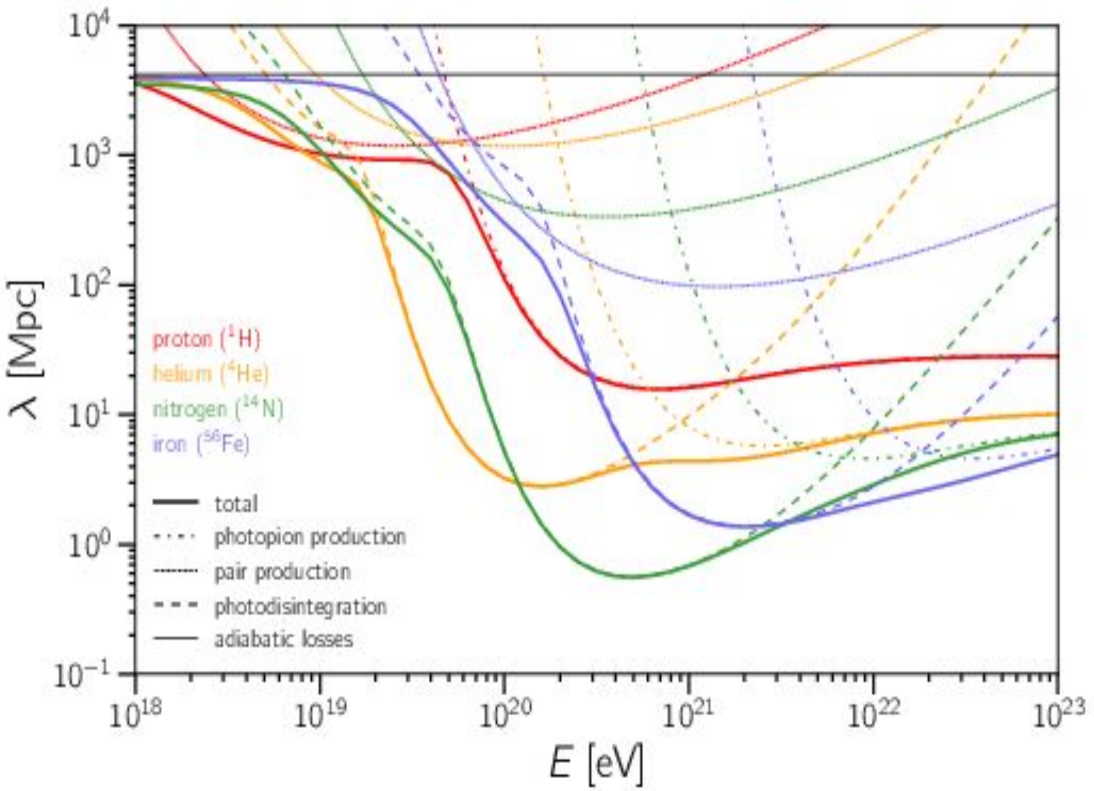
To be discussed still today

One approach -> Auger's combined fit

Maximum power of acceleration

$$J(E) = f_A \left(\frac{E}{E_0}\right)^{-\gamma} e^{(-E/Z R_{\max})}$$

GZK



Addazi, A. *et al.*, **Prog. Part. Nucl. Phys. 2022**

One approach -> Auger's combined fit

Maximum power of acceleration

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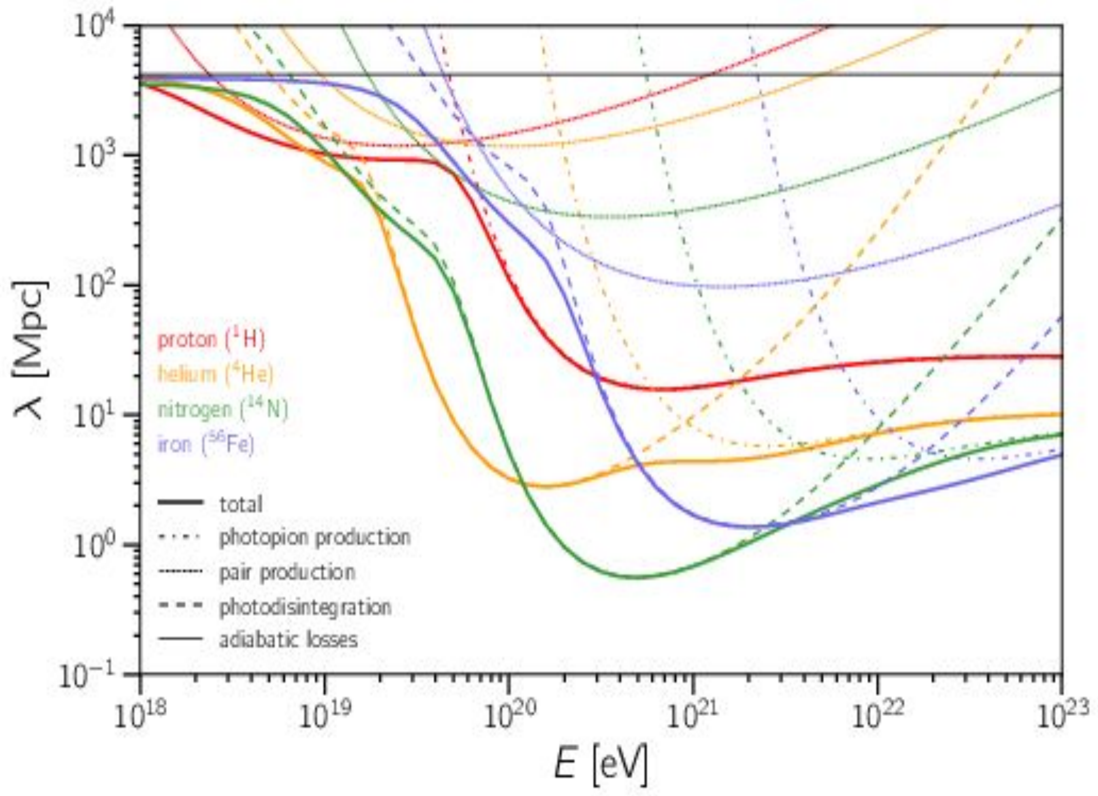
Both effects are present, but the importance of each is not yet fully understood!

GZK



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Both effects are present, but the importance of each is not yet fully understood!

Maximum power of acceleration preferred by most models!

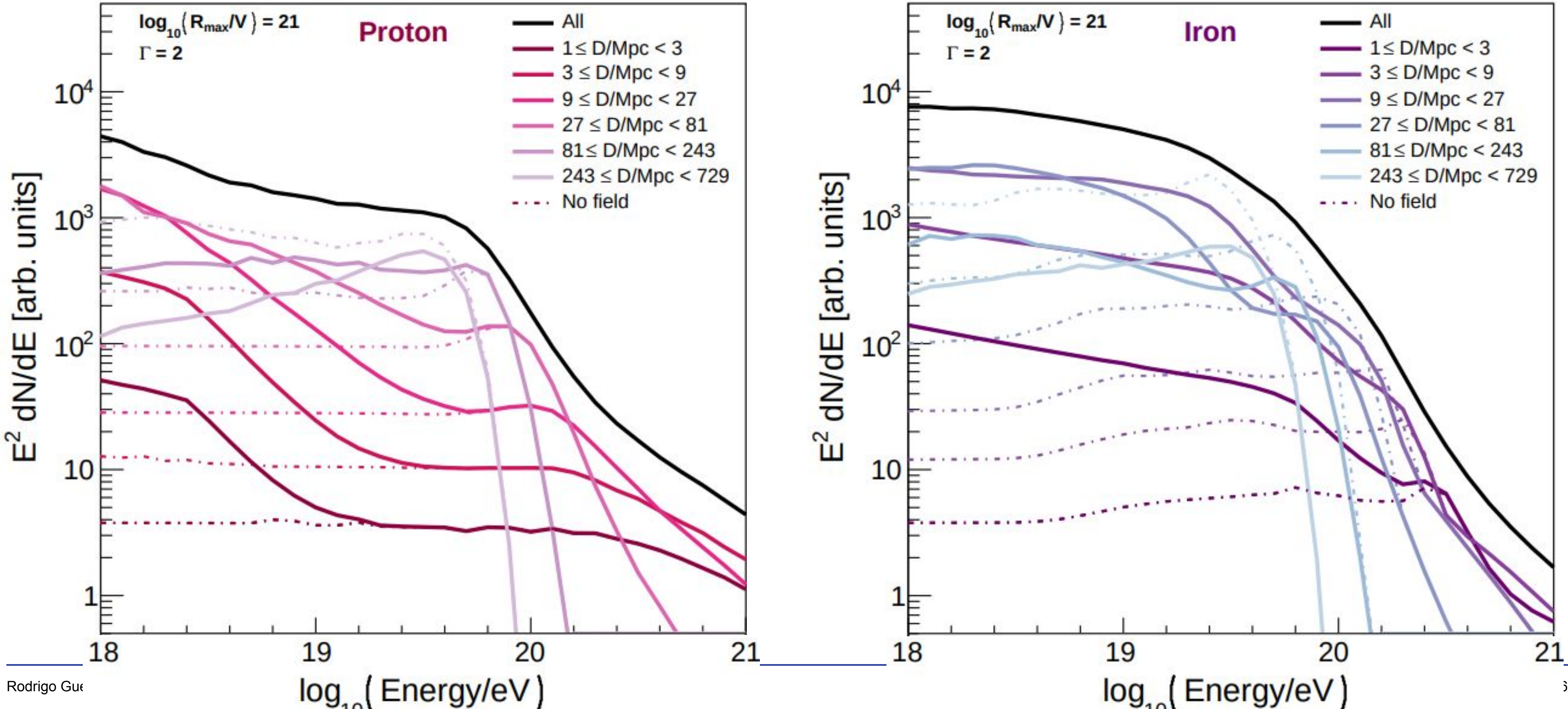
Starting with the borders

- 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

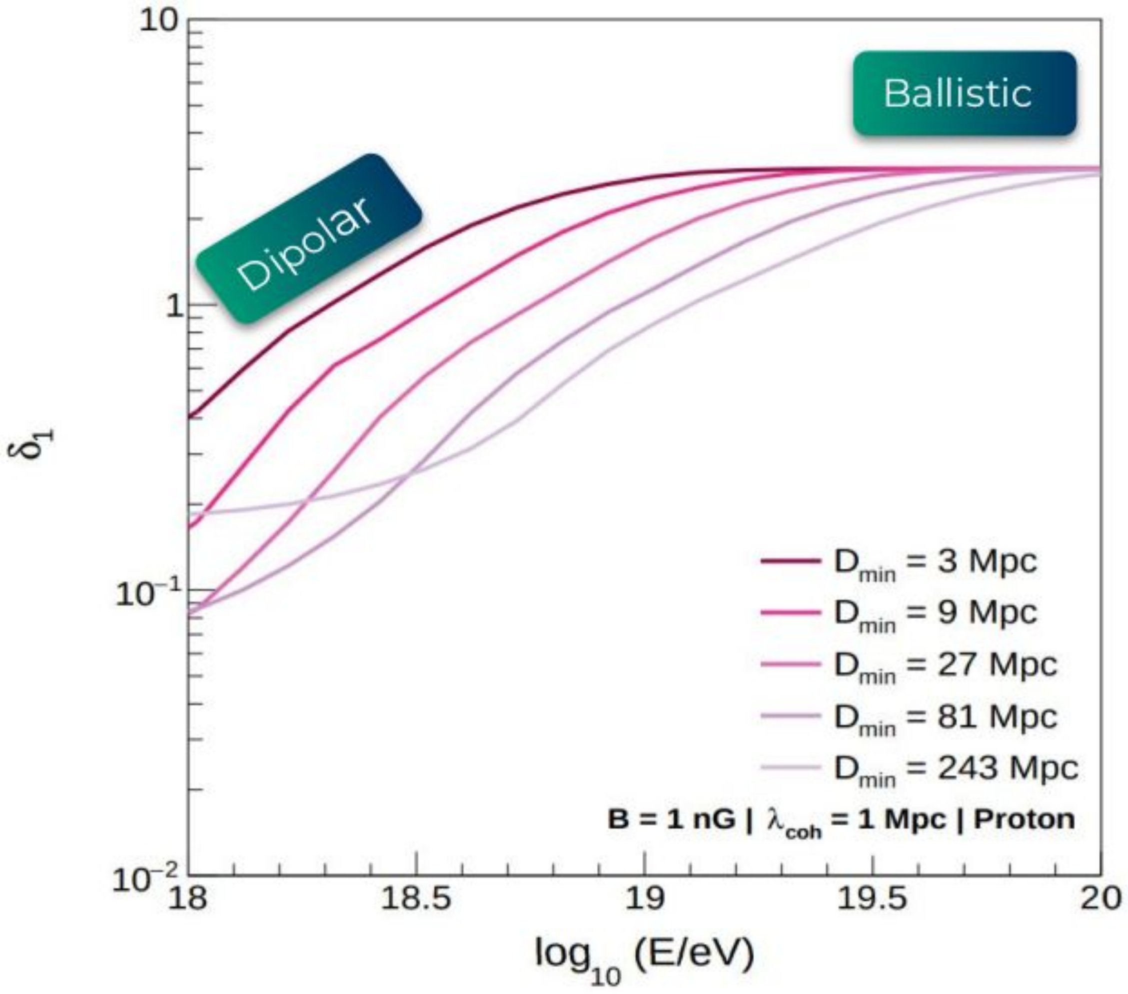
Lang, R.G. *et al.*, **Phys. Rev. D 2020**

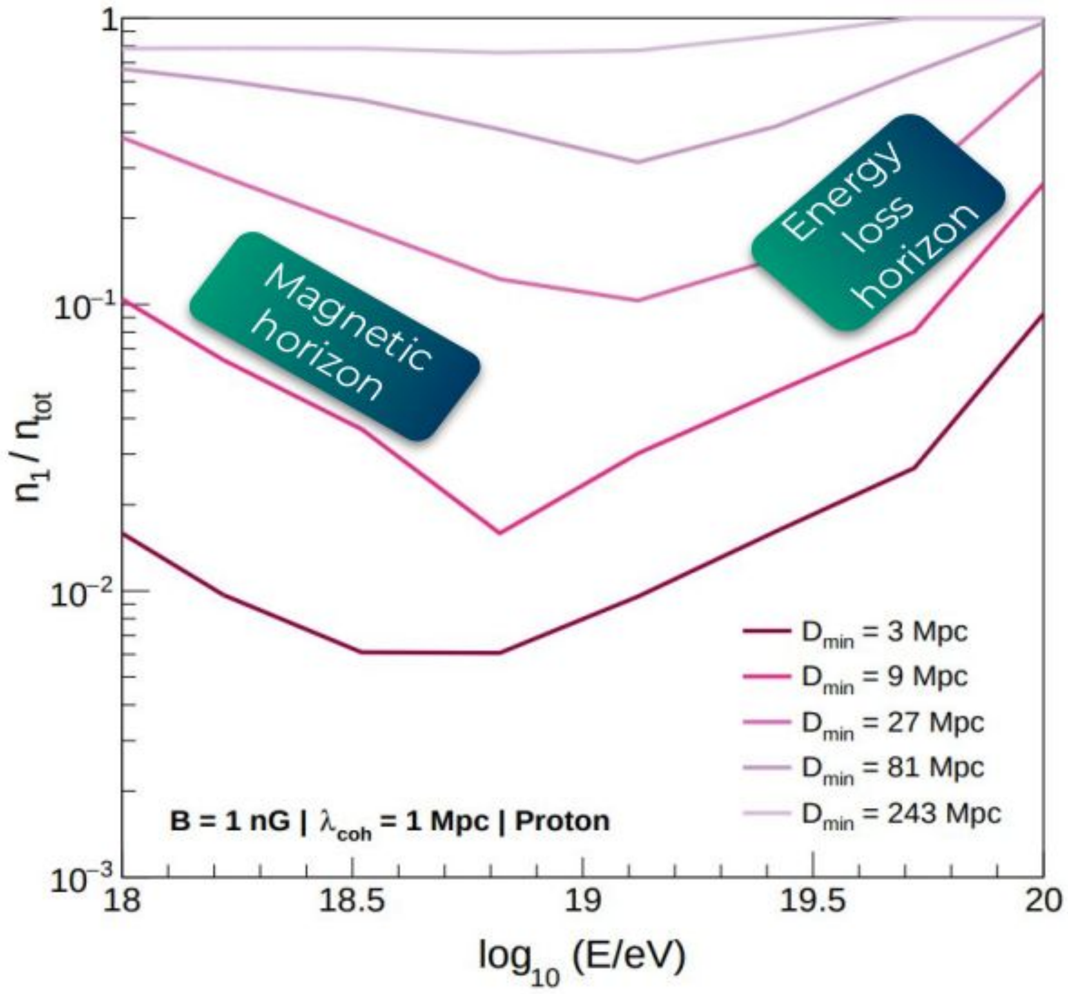


Starting with the borders

➢ Local sources

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





Starting with the borders

➢ Local sources

Closer sources have stronger dipoles

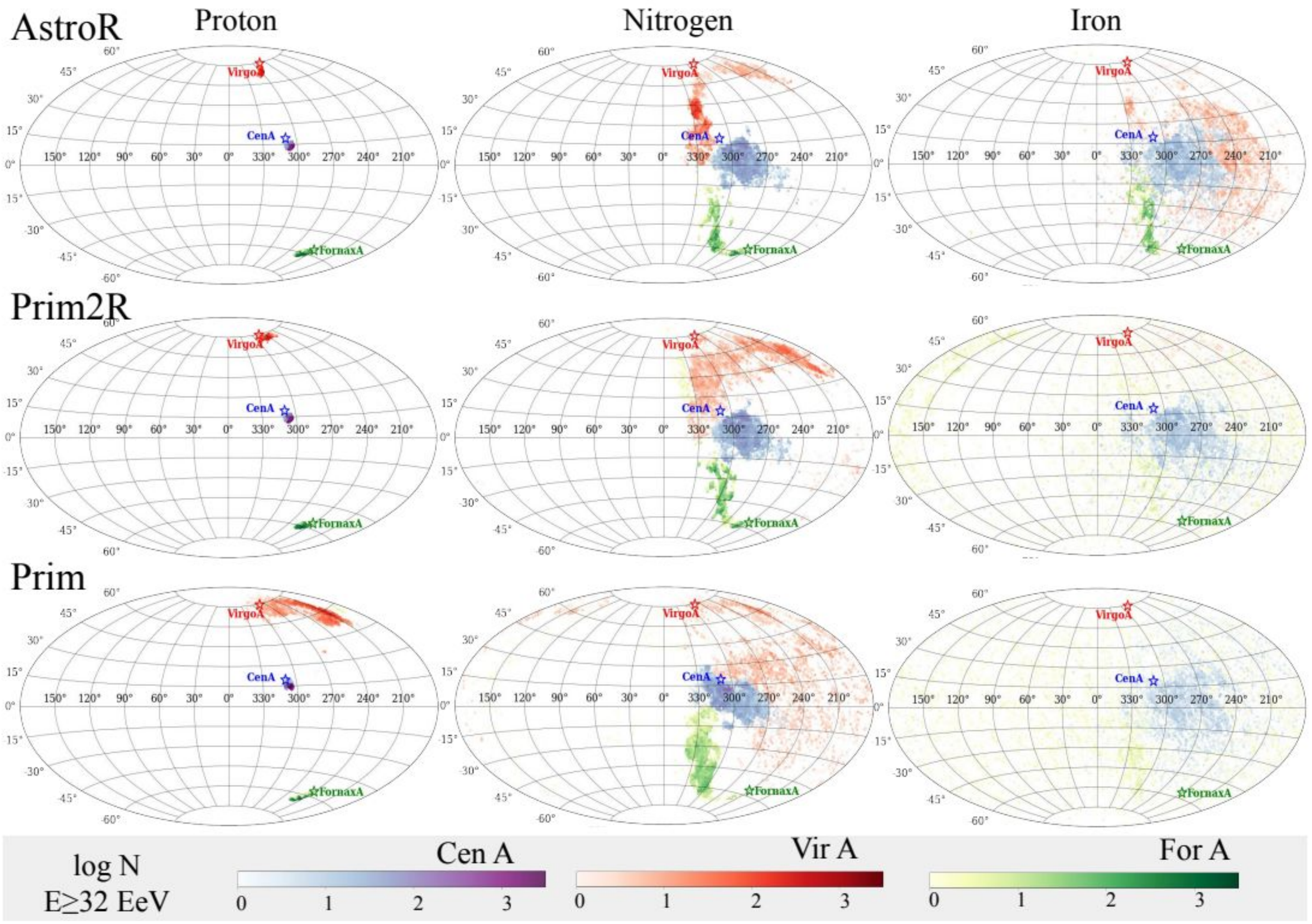
Larger densities lead to smaller dipoles

→

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

Starting with the borders

- ➢ Local sources
- ➢ Magnetic fields



de Oliveira & de Souza, **Astrophys. Journal 2021**

Current pieces and assembly status

- 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 Xmax 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;
  - Many extended fit approaches as well efforts to understand better the problem;

Can't we get more pieces?!

- More exposure of current experiments:
  - Correlation maps;
  - Energy evolution of the dipole;
  - Larger multipoles;
- Upgrade of current experiments:
  - AugerPrime: better discrimination of proton events -> better understanding of composition;
  - TAx4: more statistics;
- Future experiments:
  - JEM-EUSO, POEMMA, GCOS, …

ICRC is just around the corner!

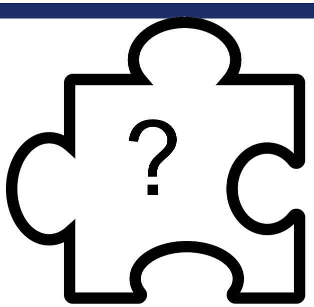
But why only UHECR?

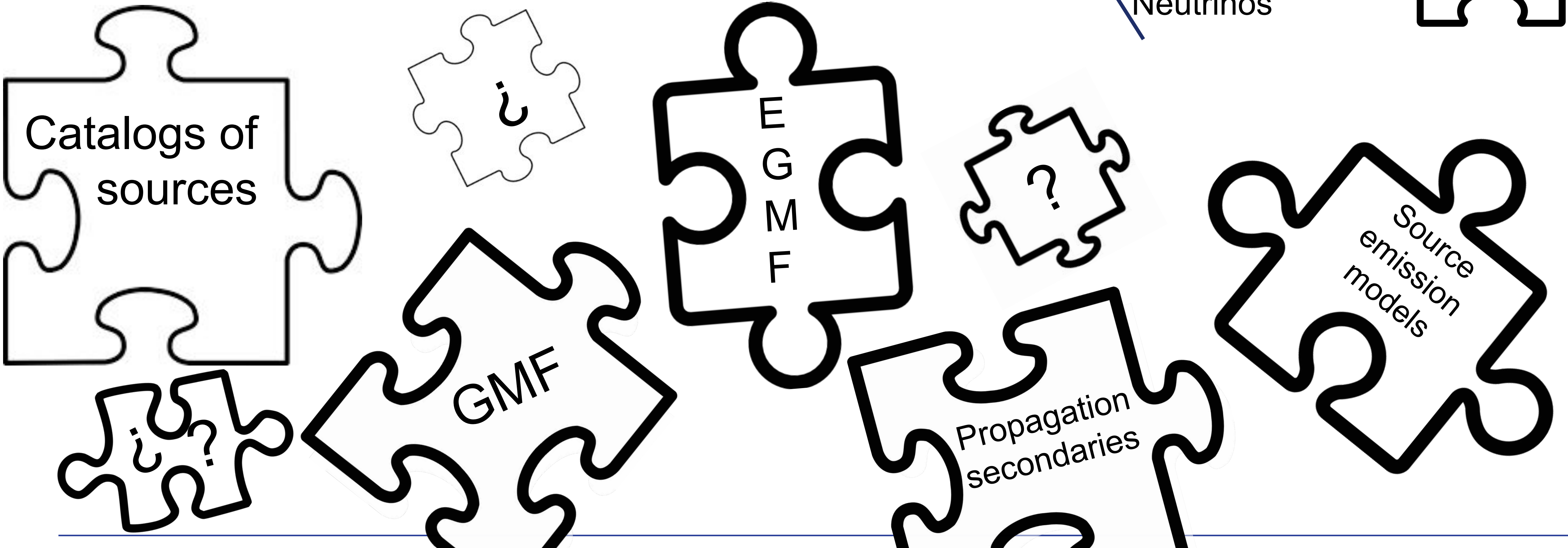
- ➢ Assembling puzzles is easier (and more fun!) in group!
- ➢ What can we learn/take advantage from other particles/energies?

For this workshop

- Assembling puzzles is easier (and more fun!) in group!
- What can we learn/take advantage from other particles/energies?

GeV-TeV γ rays
TeV-PeV γ rays
Neutrinos





Muito obrigado
Vielen Dank
Thank you very much
:D