Main results of the Pierre Auger Observatory and prospects for the upgrade AugerPrime

Carola Dobrigkeit for the Auger Collaboration - Brazil

The Pierre Auger Observatory

The Pierre Auger Collaboration

- International Collaboration of ~400 scientists from ~100 institutions in ~18 countries.
- Brazil participates since the beginning in 1994.
- Brazil: ~ 20 PhD physicists from 12 institutions and ~ 20 graduate students.

As for 2022:

- Ronald Shellard (CBPF)
- Bruno Lago (CEFET/RJ)
- Fernando Catalani, Carlos Todero Peixoto (EEL - USP)
- Rogério Menezes de Almeida (UFF)
- Jaime de Oliveira (IFRJ)
- Edivaldo Moura Santos (USP)
- Germano Guedes (UEFS)
- Marcelo Leigui de Oliveira (UFABC)
- Rita dos Anjos (UFPR)
- João Torres de Mello Neto (UFRJ)
- Anderson Fauth, José Augusto Chinellato, C. D. (UNICAMP)
- Vitor de Souza, Luan Bonneau Arbeletche (USP São Carlos)

Brazilian contributions over the years

- Construction and installation of main detectors: SD tanks, shutters and corrector lenses for the telescopes; installation of detectors for the upgrade AugerPrime;
- Participation in Fluorescence Shifts for data taking twice a year;
- Participation in regular shifts – surface array;
- Chair of the Collaboration Board – various mandates (R.S. & C.O.E);
- Chair of the Publication Committee (C.D. since 2013);
- Chair of the Conference Committee (V.S.), C.B. member;
- Task Leaders (conveners): J.M.N., C.O.E., E.M.S., V.S., C.B.
- Ombudsperson (C.D.)

Achievements

- 112 Papers published in International journals (some editor's suggestions and one Top10 Breakthrough 2017 from Physics World);
- 34 Ph.D. theses;
- 200 graduate/ undergraduate students enrolled;
- More than 50 presentations in national conferences / workshops;
- More than 400 presentations in international conferences, of which I highlight three in the latest ICRCs:

PROCEEDINGS OF SCIENCE

ICRC2021

Large-scale and multipolar anisotropies of cosmic rays detected at the Pierre Auger Observatory with energies above 4 EeV

R. M. de Almeida[a,*] **on behalf of the Pierre Auger**[b] **Collaboration**
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PROCEEDINGS OF SCIENCE

ICRC2019

Estimating the Depth of Shower Maximum using the Surface Detectors of the Pierre Auger Observatory

Carlos José Todero Peixoto[*a] **for the Pierre Auger Collaboration**[b†]

[a] *Escola de Engenharia de Lorena, Universidade de São Paulo, São Paulo, Brazil*

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E-mail: auger_spokespersons@fnal.gov

Full author list: http://www.auger.org/archive/authors_icrc_2019.html

PROCEEDINGS OF SCIENCE

ICRC2017

Testing the agreement between the $X_{\max}$ distributions measured by the Pierre Auger and Telescope Array Observatories

Vitor de Souza[*a] **for the Pierre Auger Collaboration**[b] **and the Telescope Array Collaboration**[c]

[a] *Instituto de Física de São Carlos, Universidade de São Paulo, São Paulo, Brazil*

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E-mail: auger_spokespersons@fnal.gov

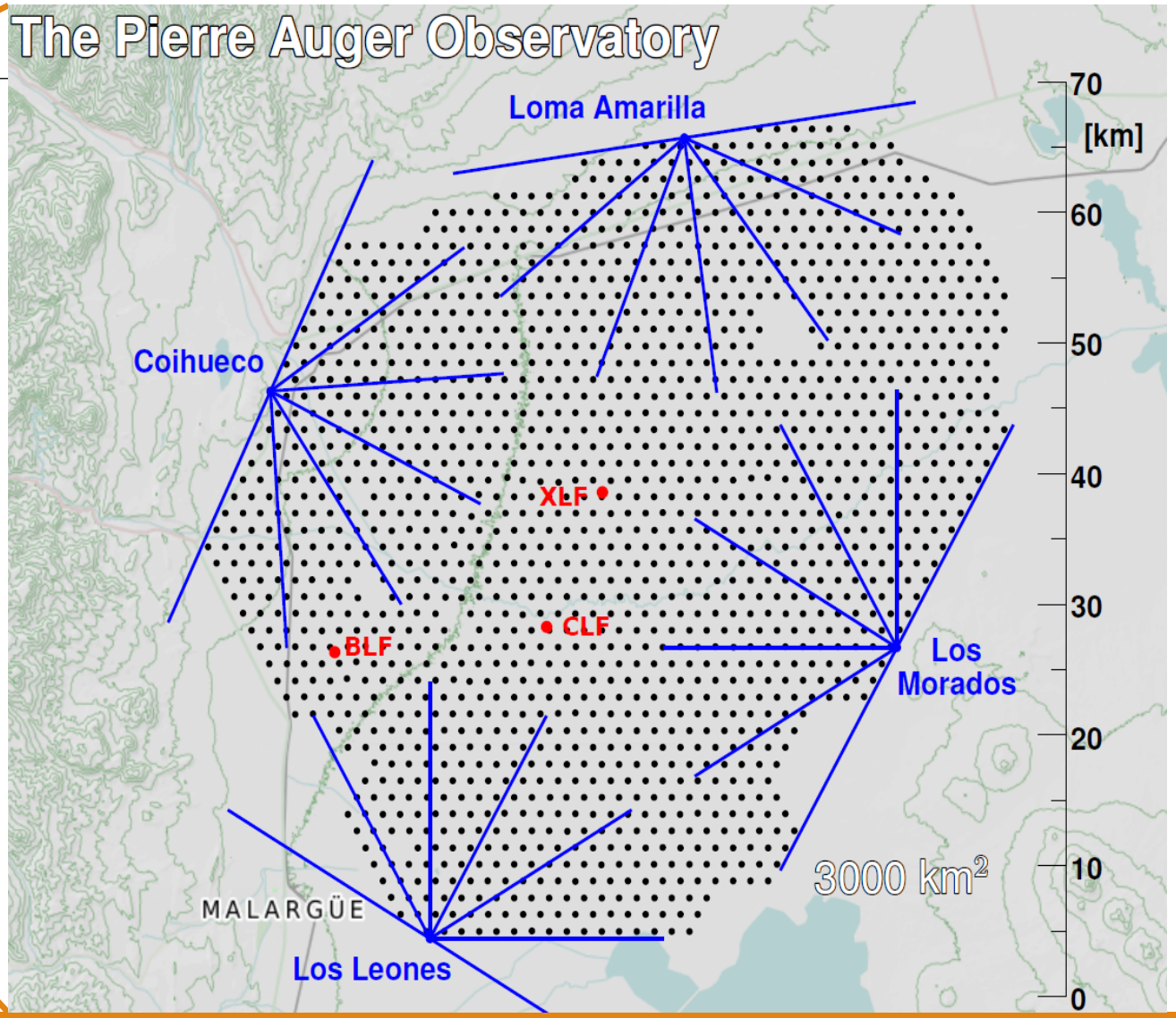
Full author list: http://www.auger.org/archive/authors_icrc_2017.html

[c] *Telescope Array Project, 201 James Fletcher Bldg, 115 S. 1400 East, Salt Lake City, UT 84112-0830, USA*

E-mail: ta-icrc@cosmic.utah.edu

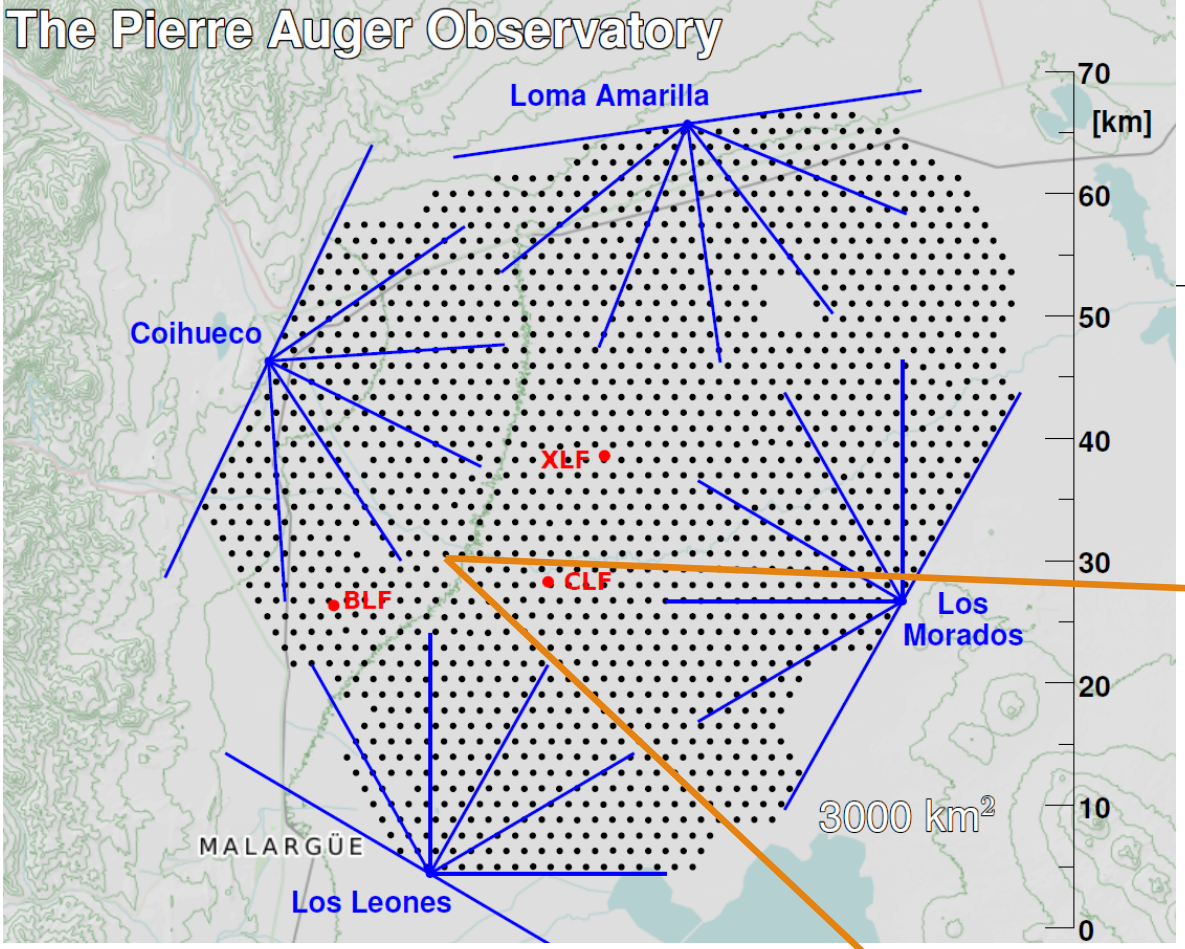
Full author list: http://www.telescopearray.org/research/colaborators

The Pierre Auger Observatory

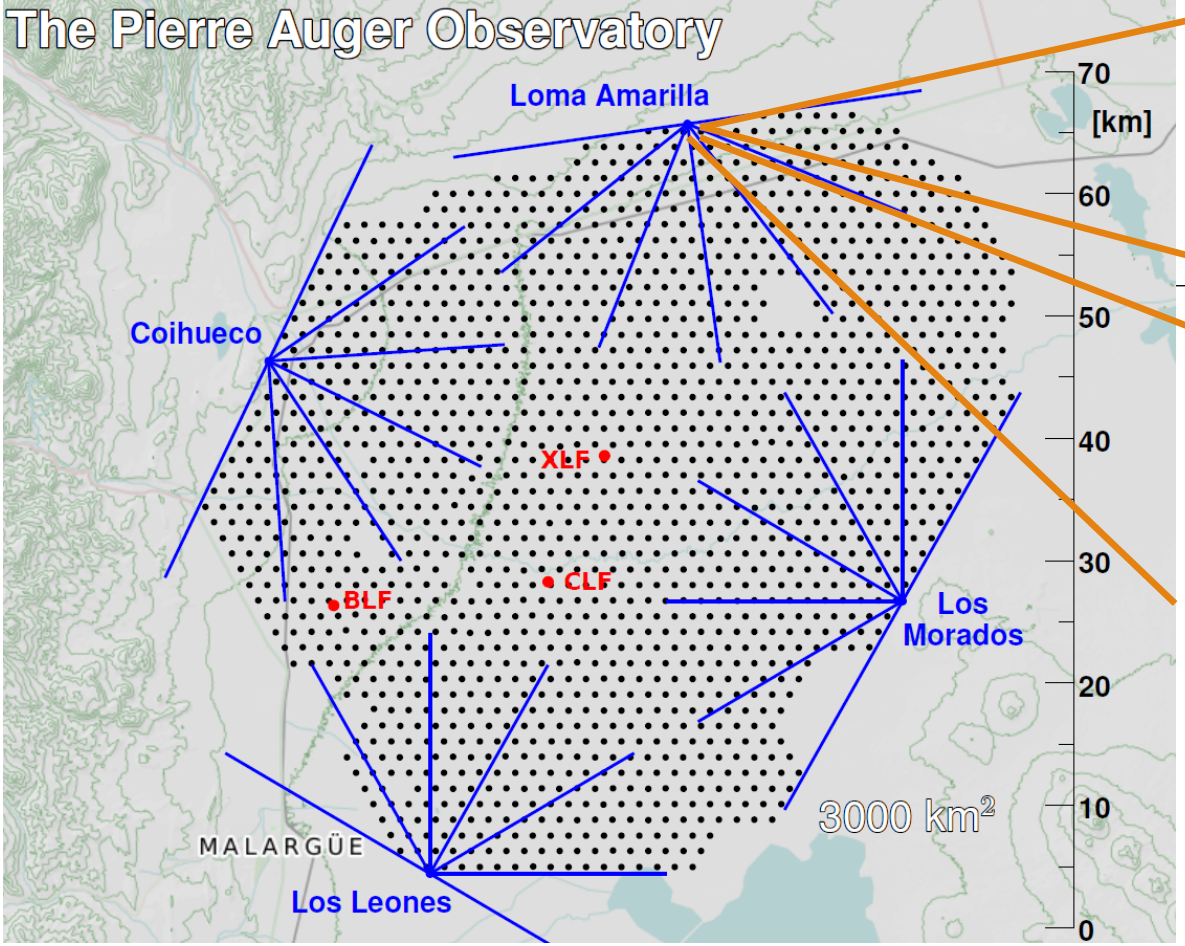


- Area: 3000 km^2 (2×São Paulo)
- Taking data since 01.01.2004

Main detectors

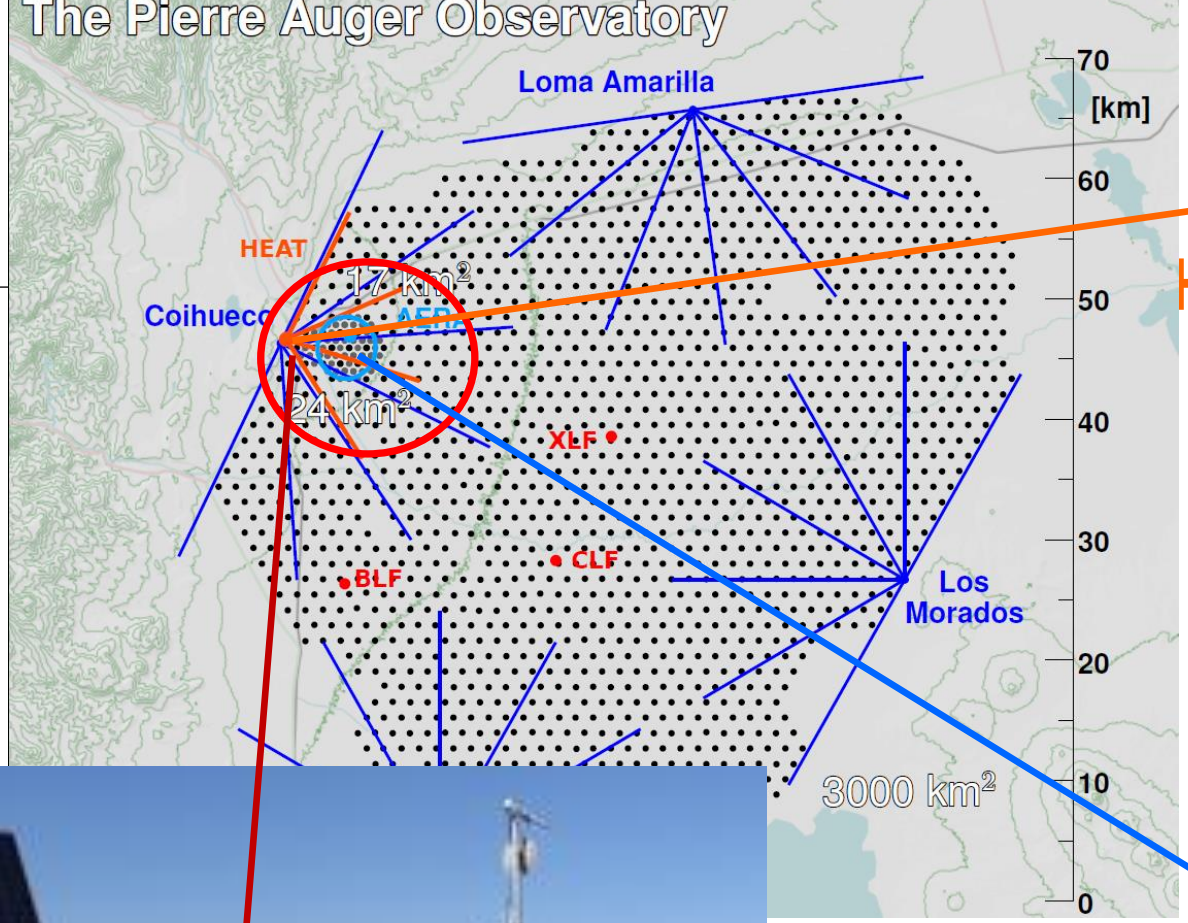


1600 water-Cherenkov stations
+ 60 water-Cherenkov stations
~ 100% duty cycle



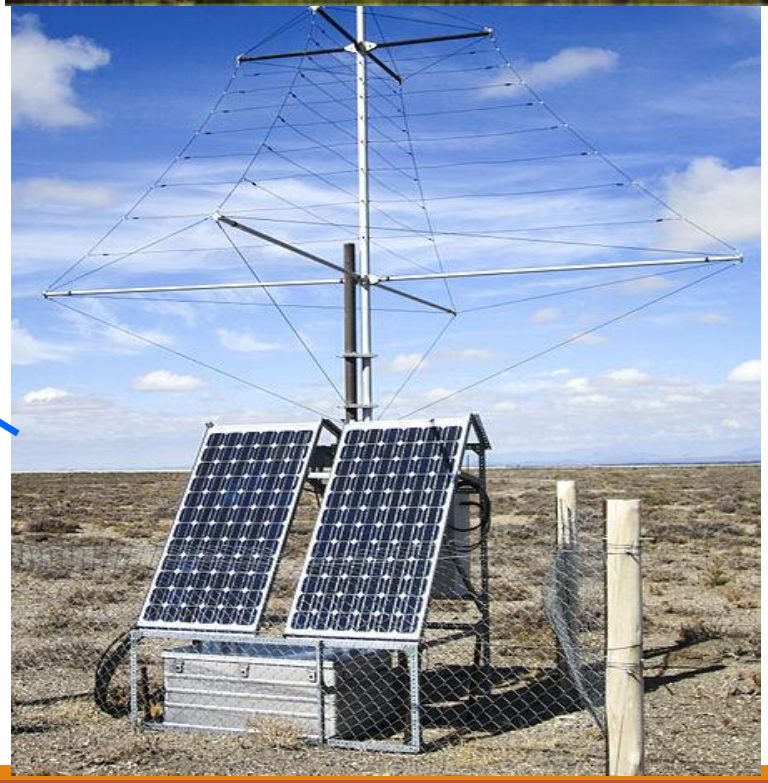
Four fluorescence sites with 6 Schmidt telescopes each (~15% duty cycle)

1600 water-Cherenkov stations
60 water-Cherenkov stations
~ 100% duty cycle



HEAT

AERA



AMIGA Underground Muon Detectors

Upgrade ongoing: **AugerPrime**

Main Goal:
higher accuracy in mass determination

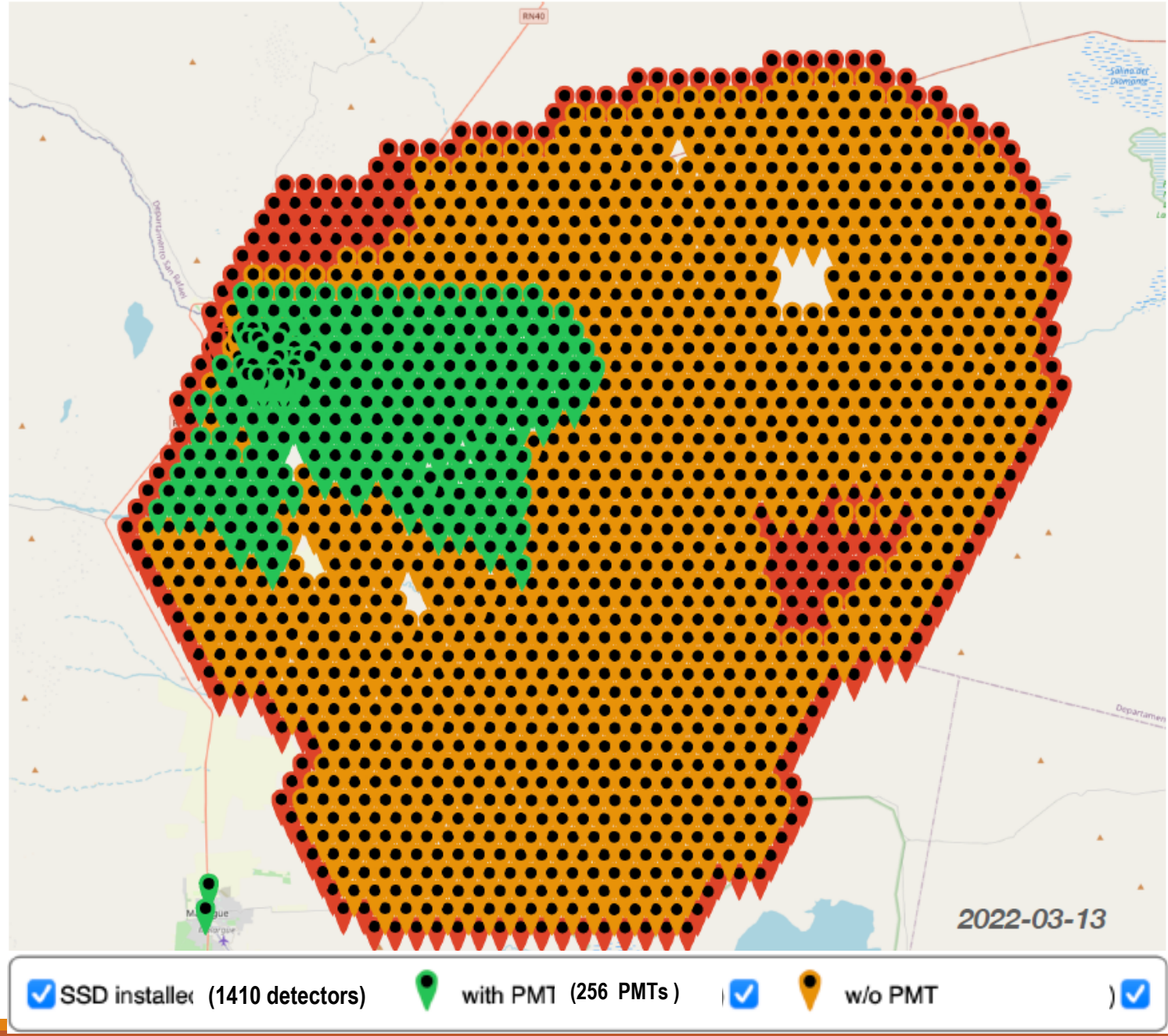
- **Adding 3.8 m^2 scintillators on top of the water-Cherenkov (WCD) detectors;**
- **Updating and modernizing the DAQ Electronics (120 MHz);**
- **Adding small PMTs in each WCD, improving the reconstruction of the most energetic showers, when normal PMTs saturate;**
- **Adding underground muon detectors and radio antennas for inclined showers;**
- **Extending the period of FD operation to periods of brighter night-sky background.**

Physics Motivation for AugerPrime

- **Composition sensitivity with 100% duty cycle**
- **Composition measurement up to 10^{20} eV**
- **Composition selected anisotropy**
- **Particle physics with air showers**
- **Much better understanding of new and old data**
- **Re-analysis of old data set (deep learning)**

Upgrade Status
(as for 13 March 2022)

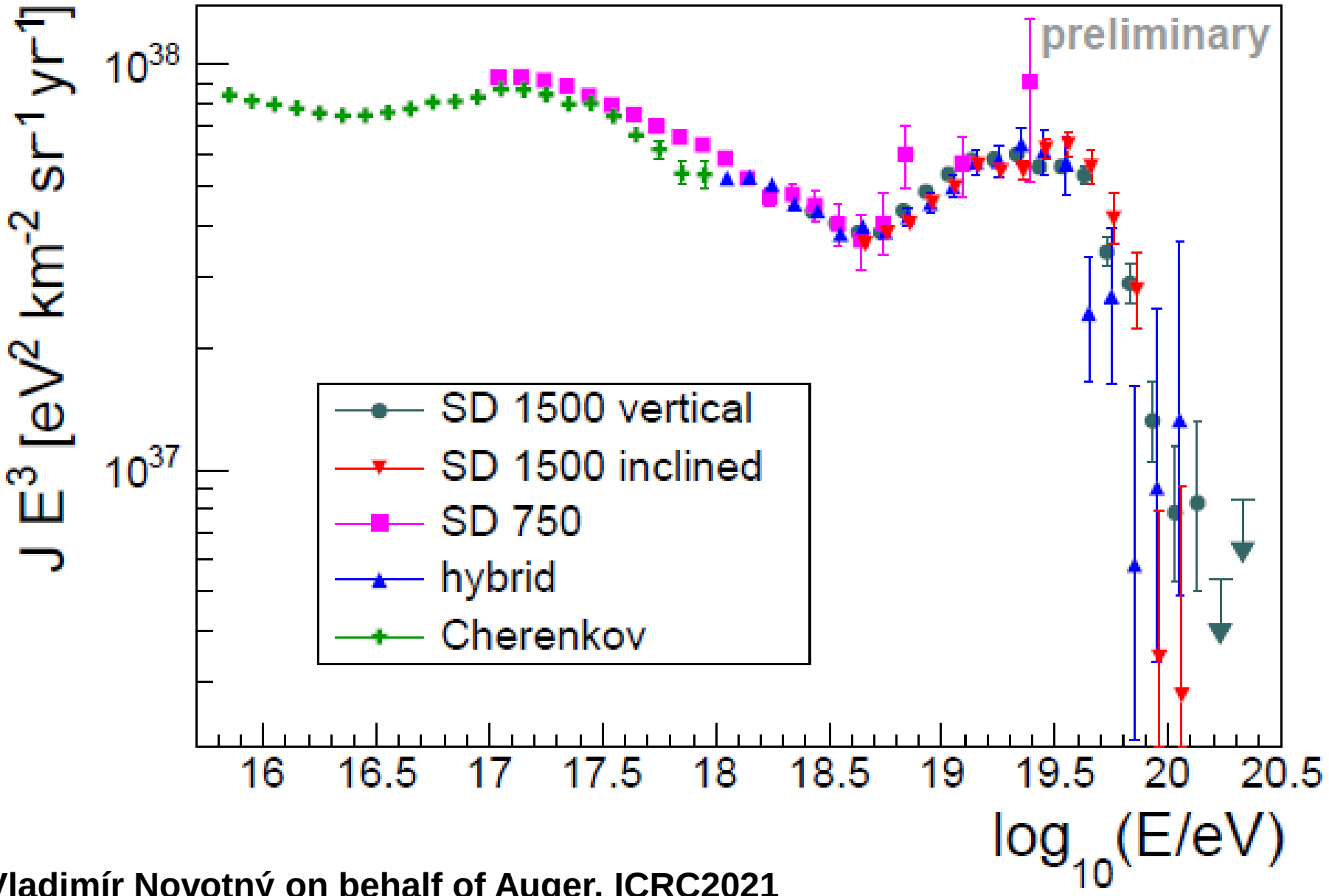
- SSD installation completed
- PMT installation ongoing
- Electronics arriving and being installed

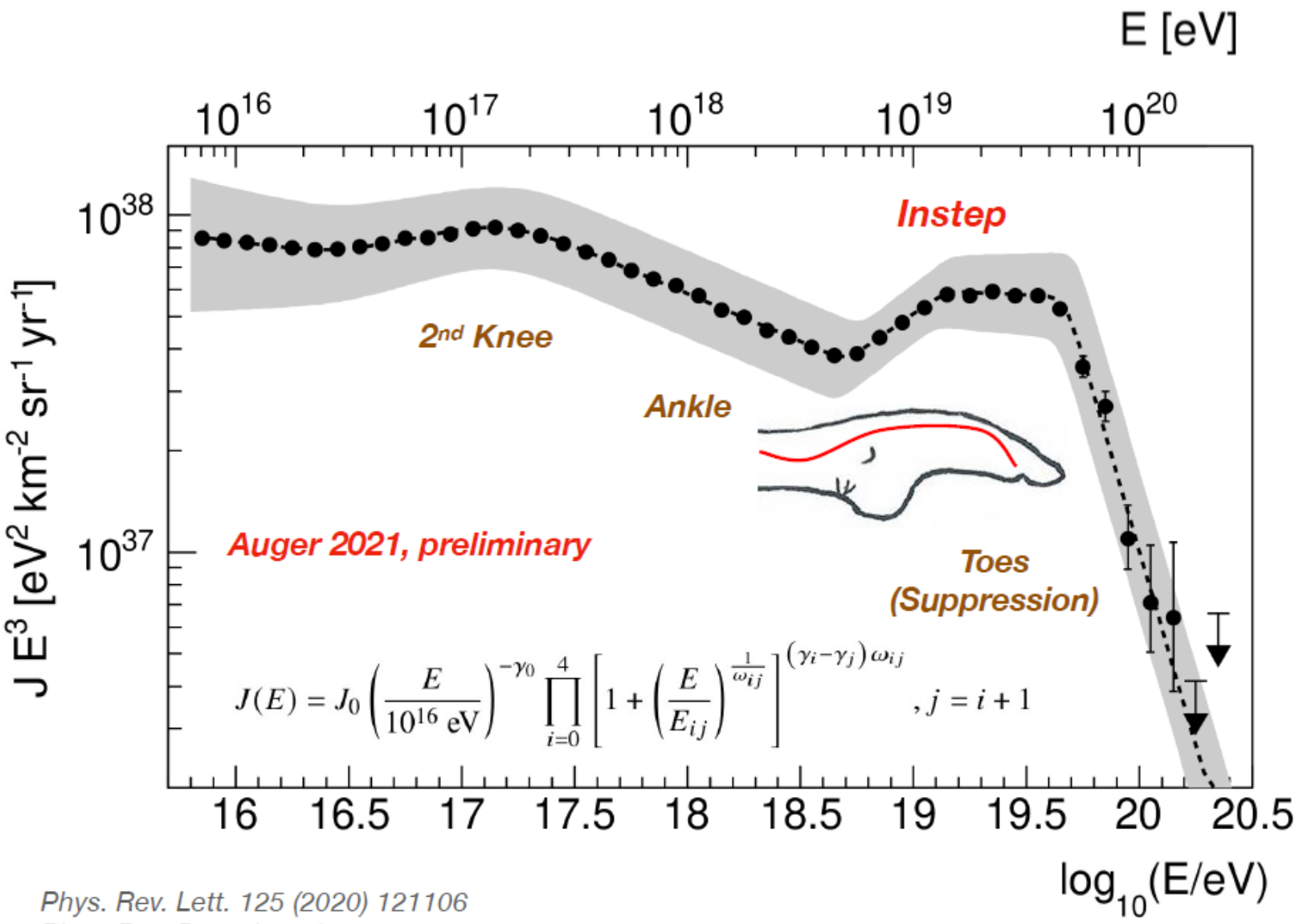


A Selection: a few recent results

(exposure ~120,000 km^2 sr yr)

Energy Spectrum over five decades





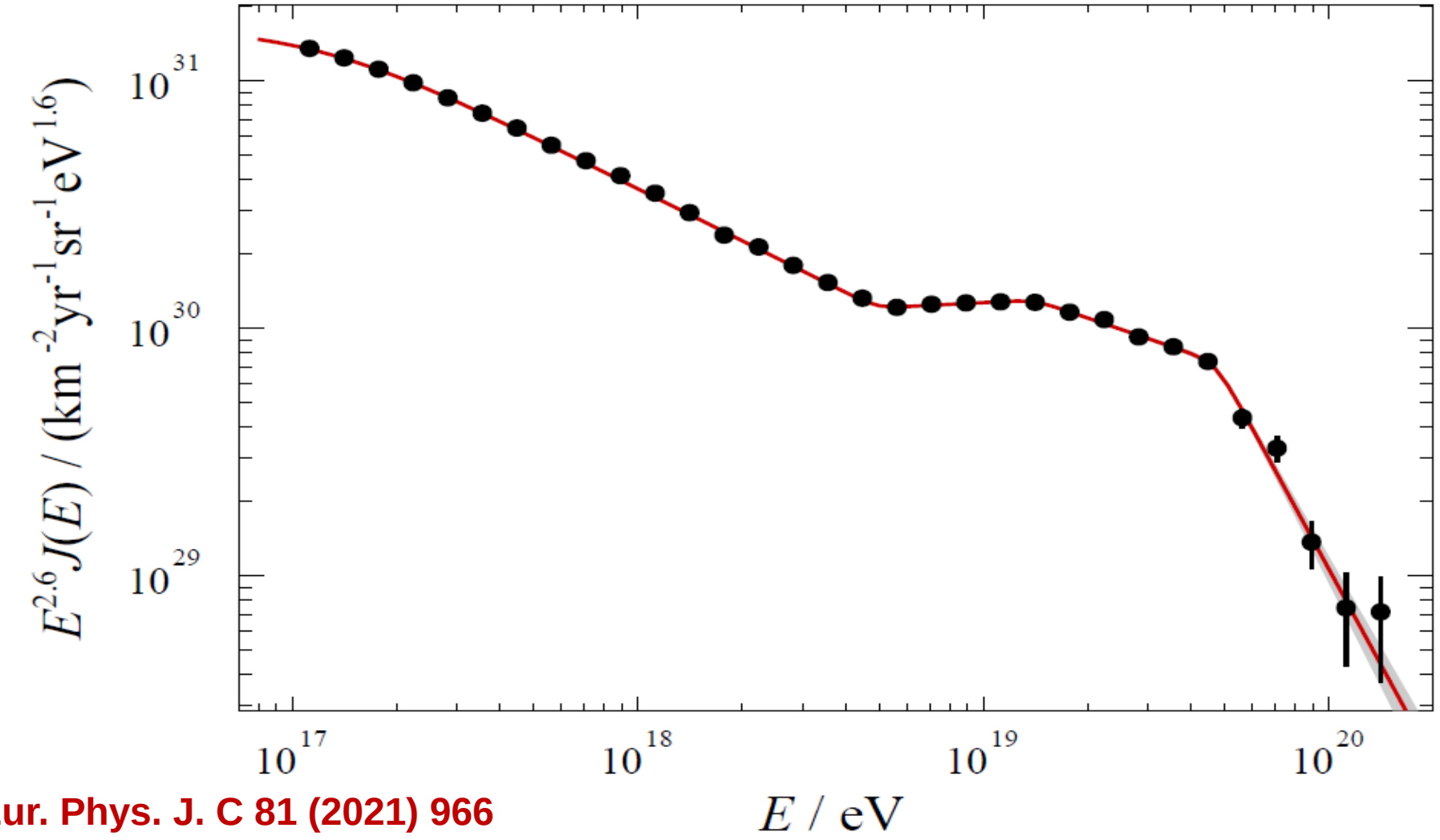
Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
submitted to Eur. Phys. J. C (2021)

(Vladimir Novotny)

Spectrum over five decades in energy

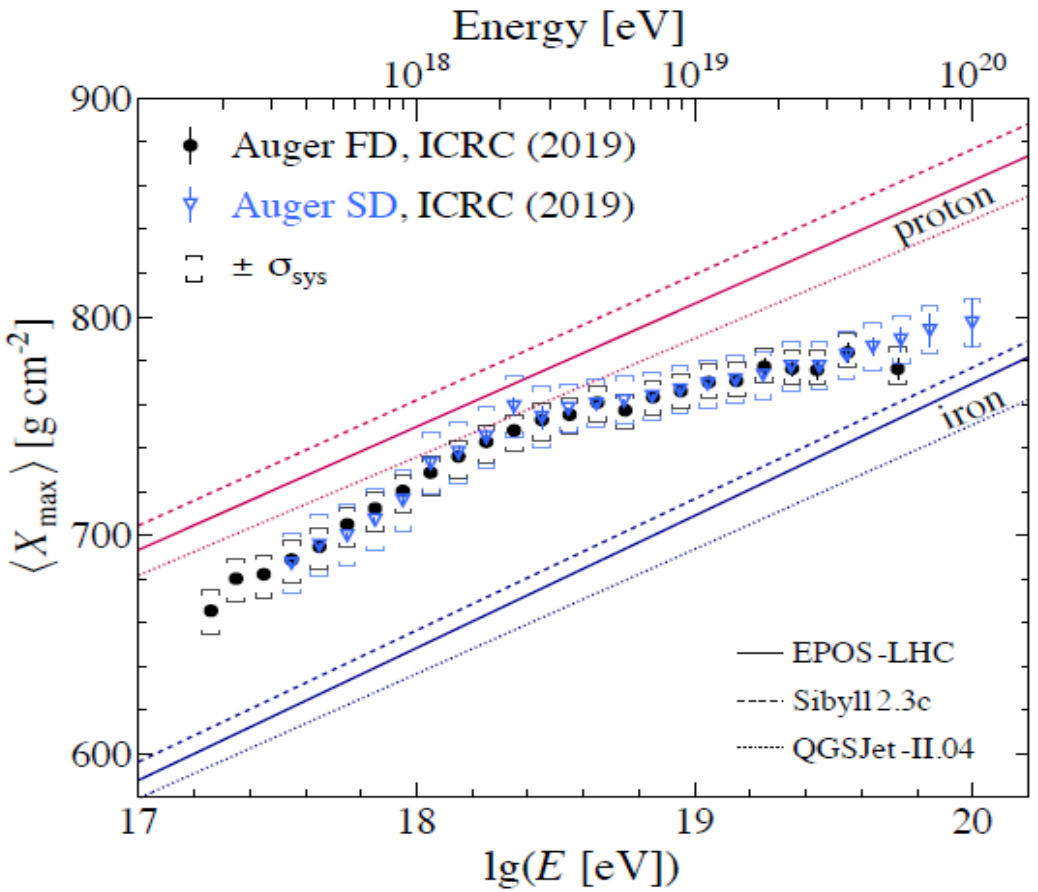
Figure from Ralph Engel, ICRC 2021 Highlights

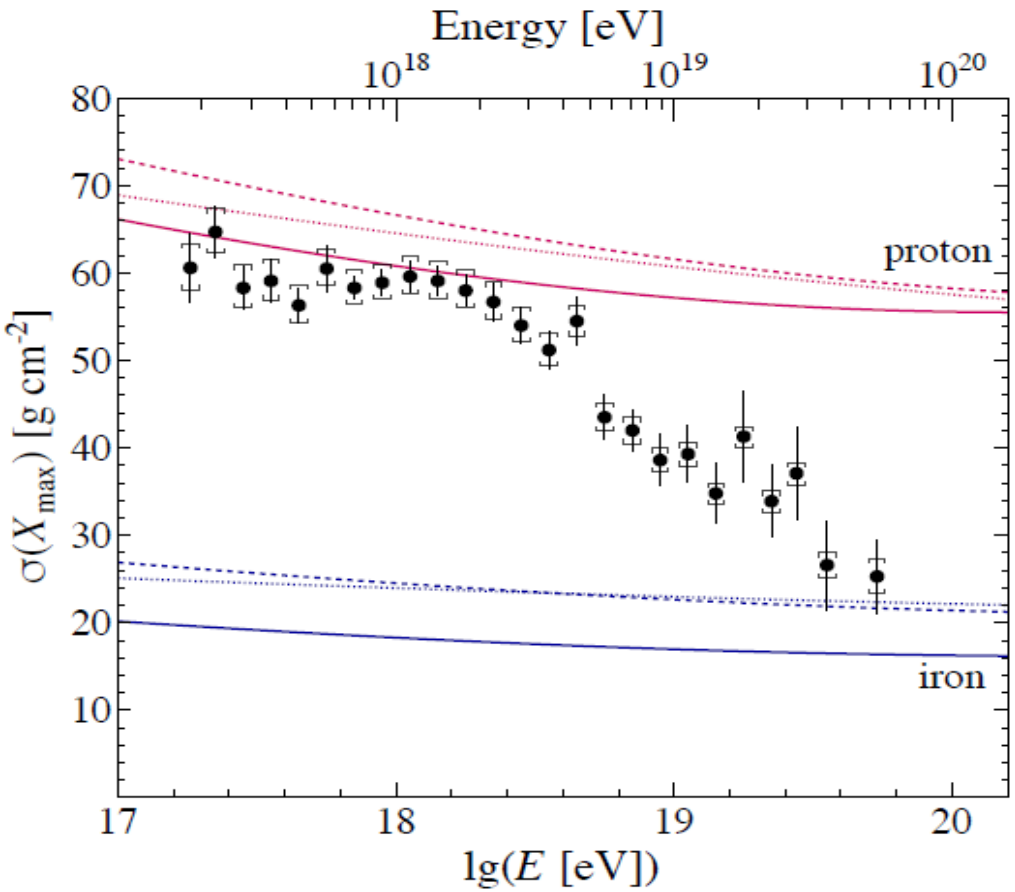
Energy Spectrum



Auger Collab., Eur. Phys. J. C 81 (2021) 966

Mass composition





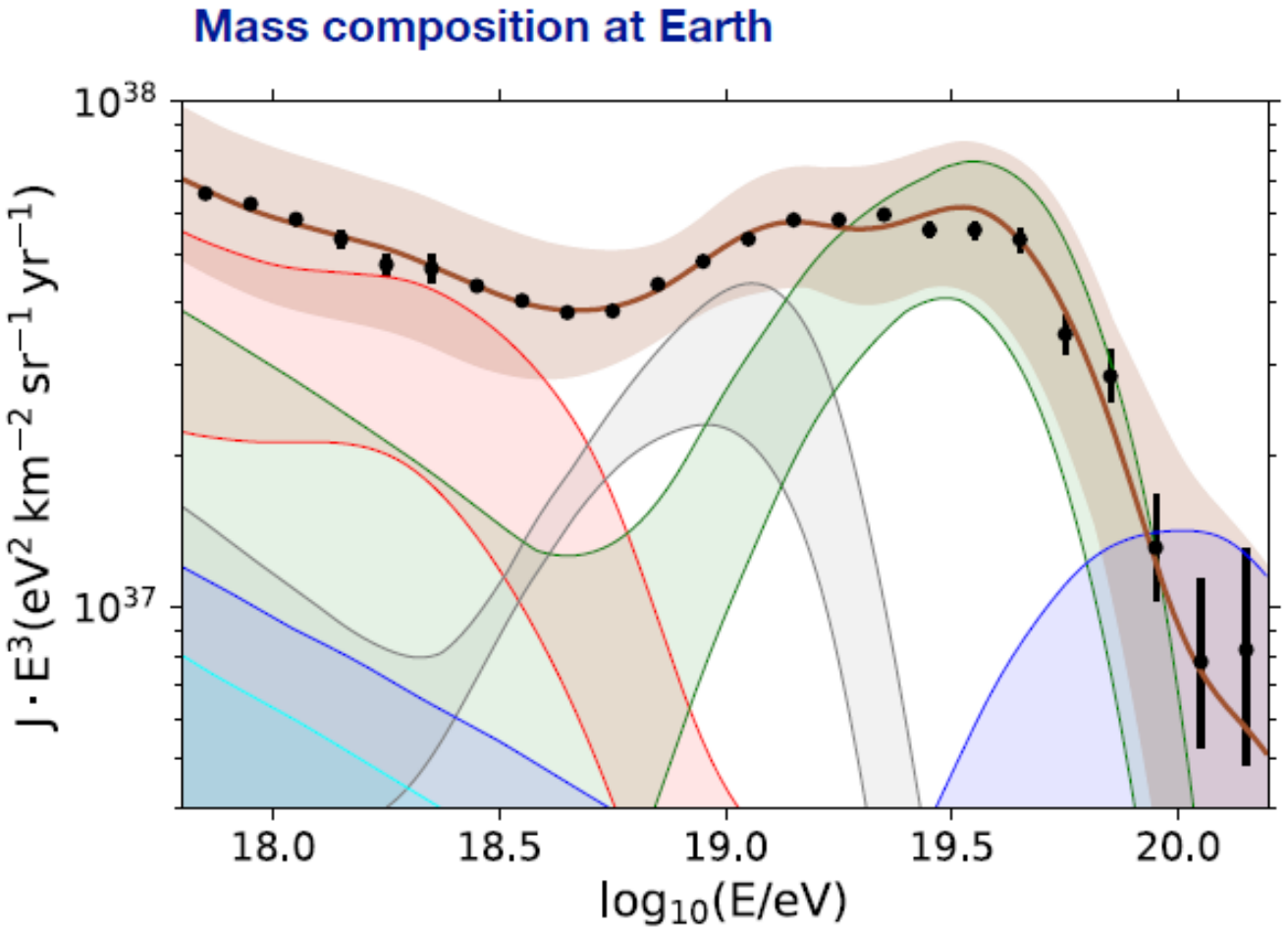
Ralph Engel, ICRC 2021 Highlights

Important: LHC-tuned interaction models used for interpretation

(Phys. Rev. D90 (2014), 122005 & 122005, updated ICRC 2019)

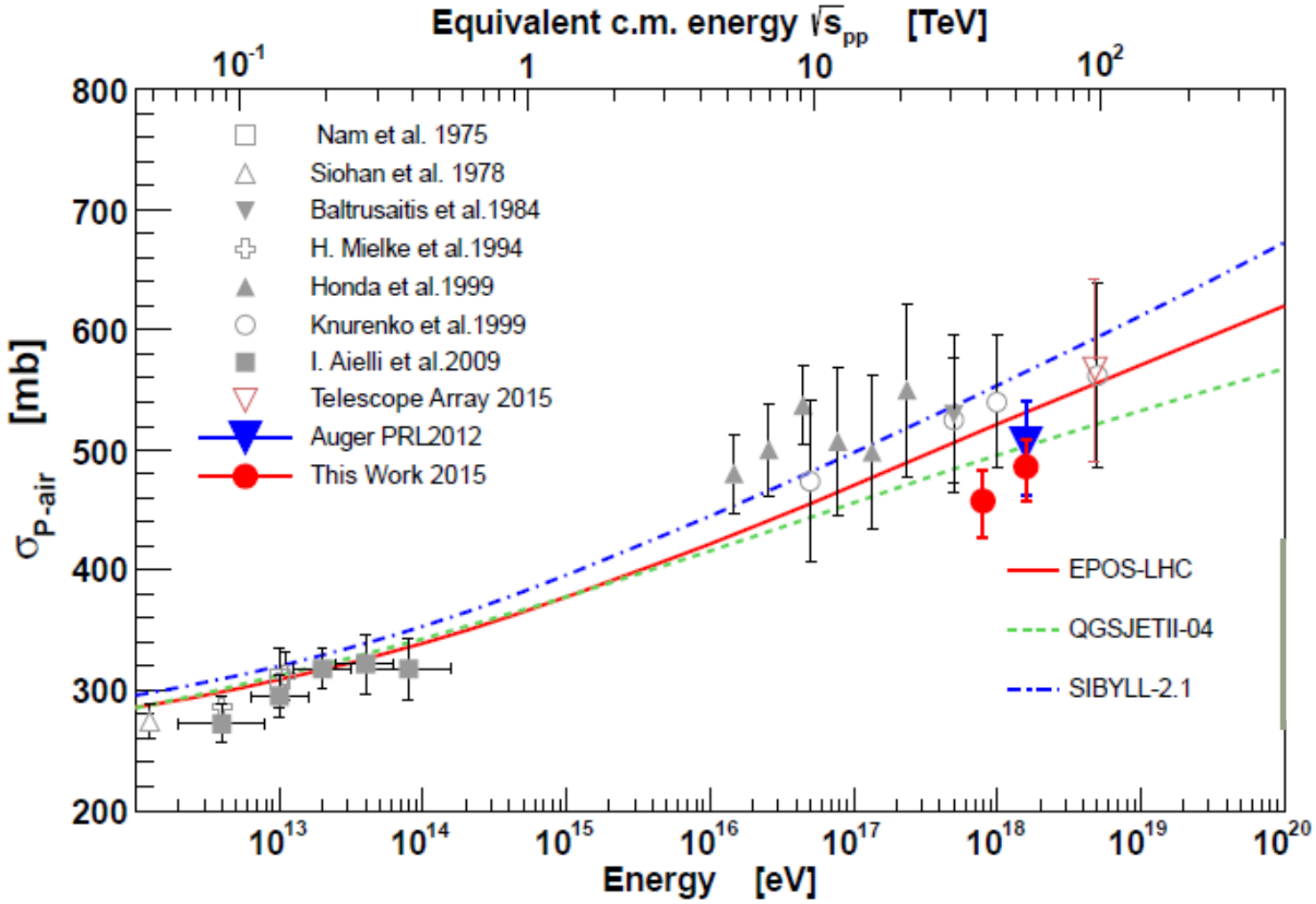
(Phys. Rev. D96 (2017), 122003)

Combining spectrum & mass composition



A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57

Eleonora Guido for Auger, ICRC 2021



Proton-air cross-section

in two energy intervals:

$10^{17.8}$ – 10^{18} eV

and

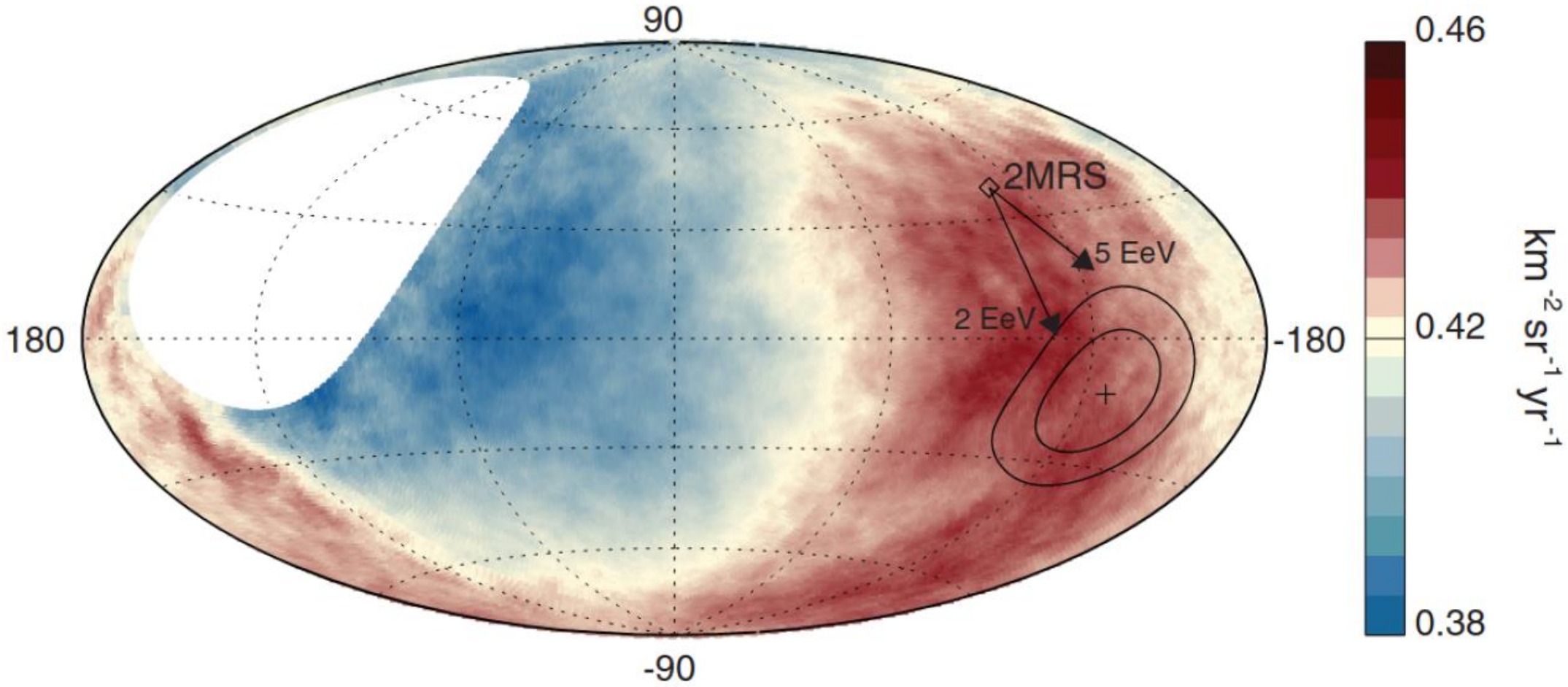
$10^{1.8}$ – $10^{18.5}$ eV

R. Ulrich for Auger, ICRC2015

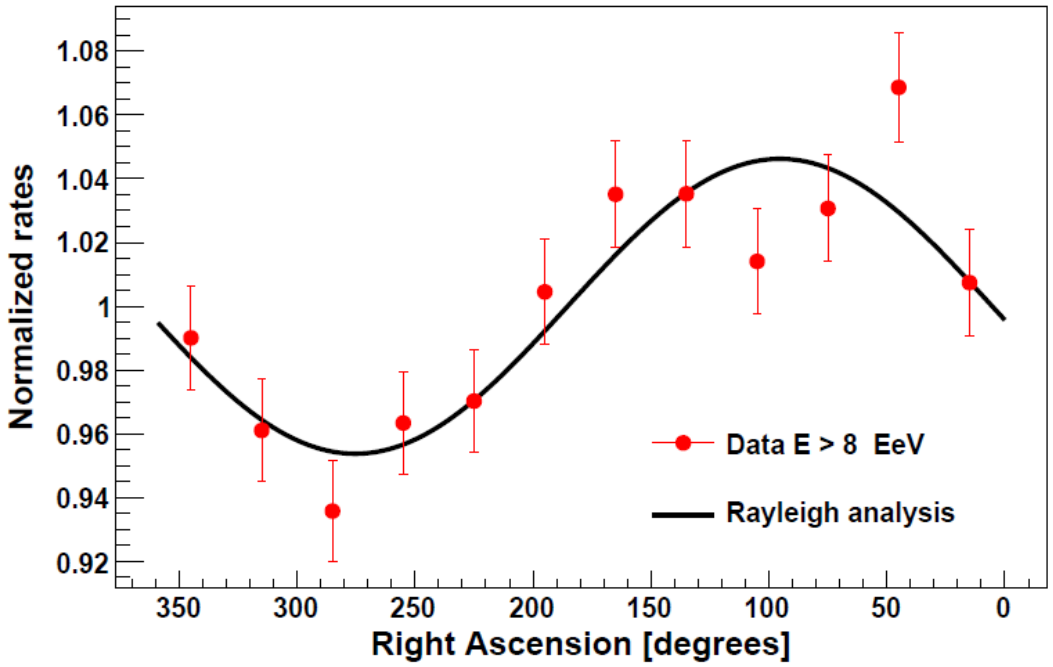
Large-scale anisotropy above 8 EeV

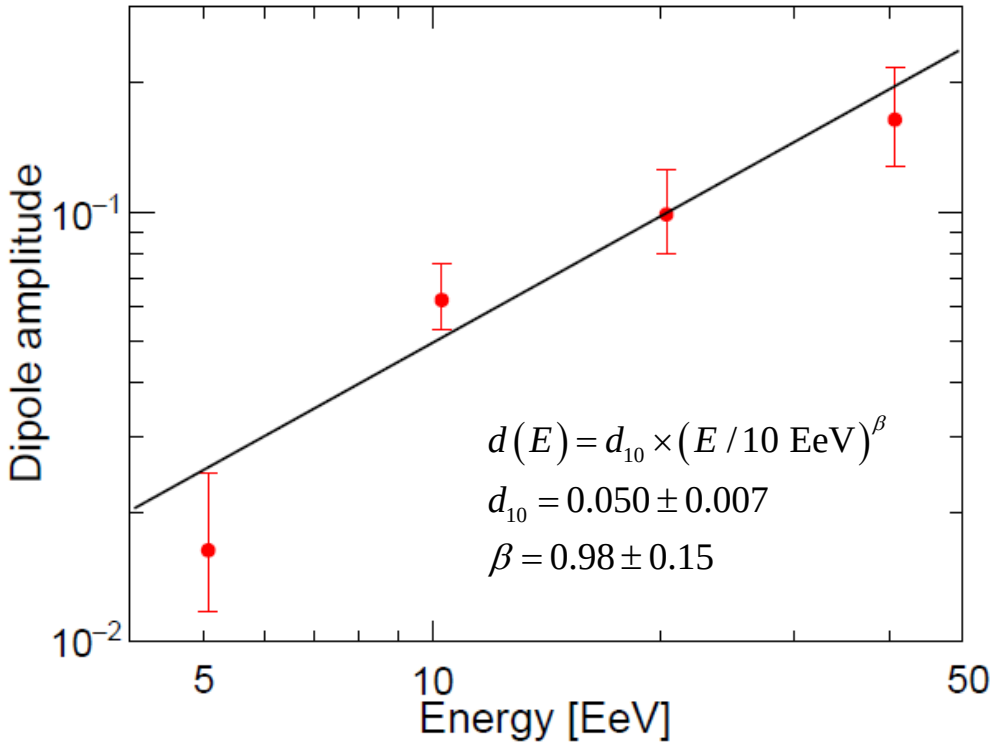
physicsworld TOP 10 BREAKTHROUGH 2017

6σ C.L. rejection of isotropy



Auger Collaboration, Science 357 (2017) 6357

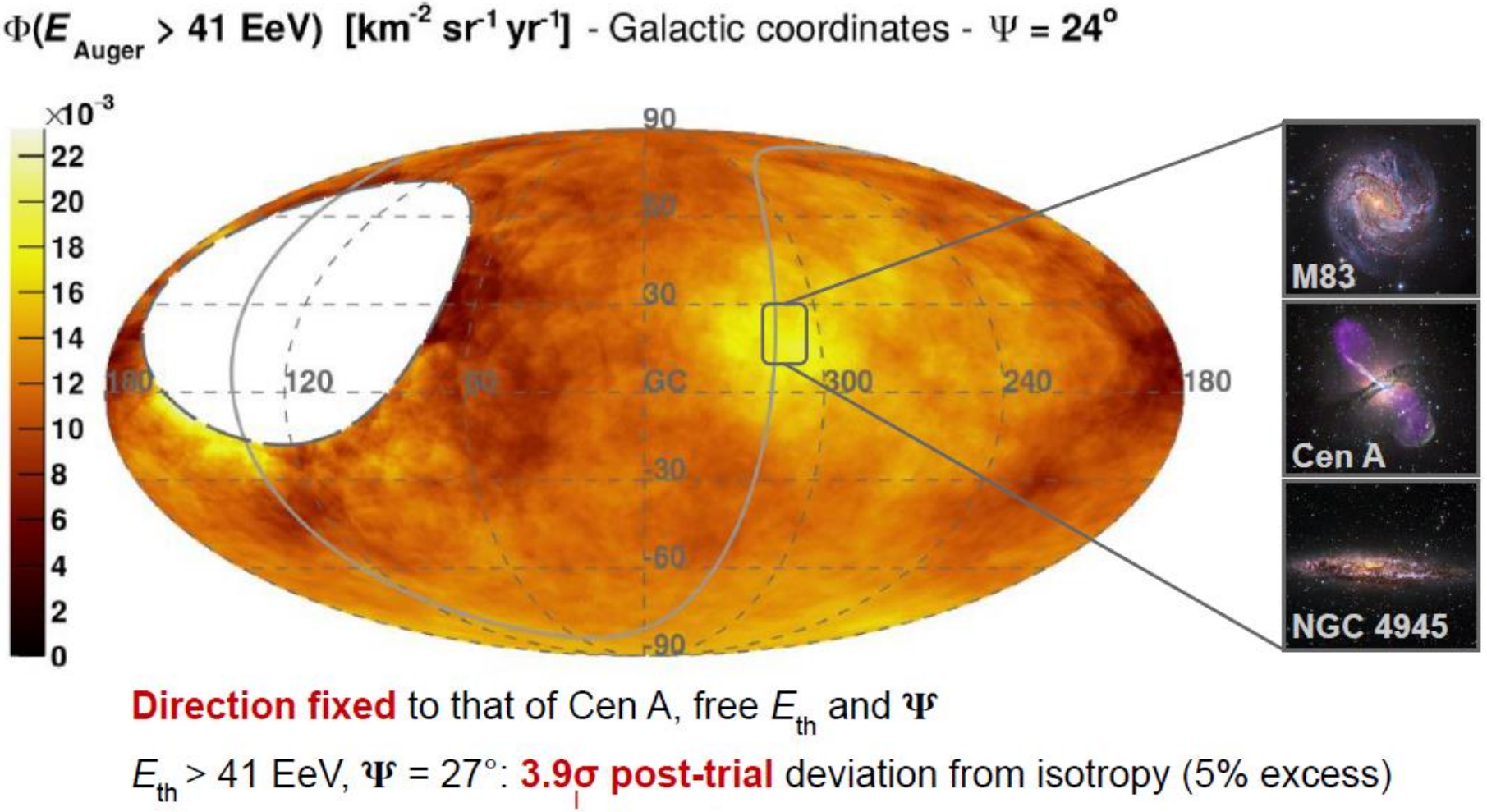




Observed dipole increases with energy

Rogério Menezes for Auger, ICRC2021

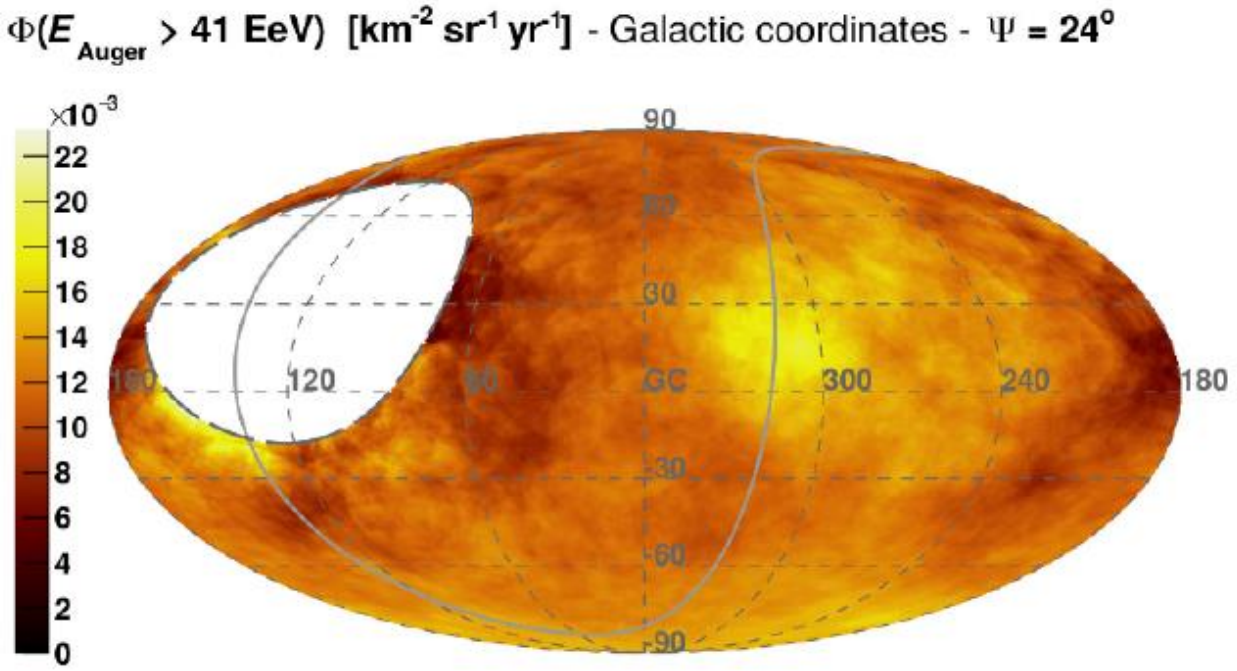
More anisotropy searches at higher energies and intermediate angular scale

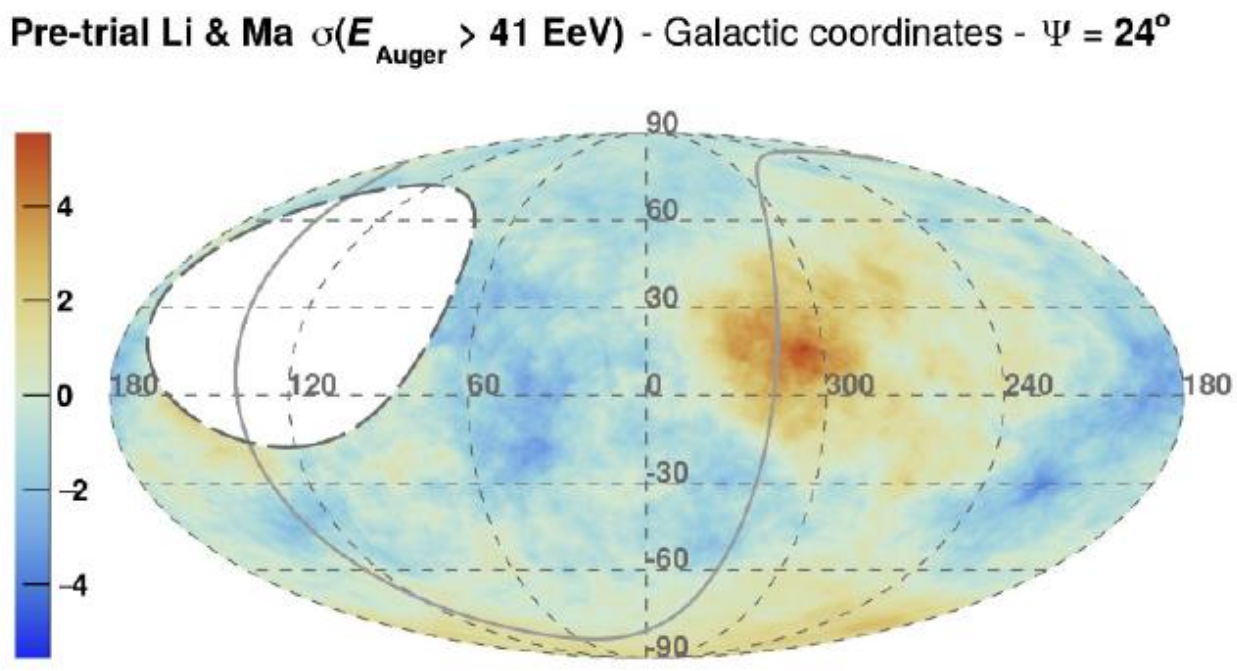


Direction fixed to that of Cen A, free E_{th} and Ψ

$E_{th} > 41$ EeV, $\Psi = 27°$: **3.9σ post-trial** deviation from isotropy (5% excess)

J. Biteau for Auger, ICRC2021, figure from R. Engel, ICRC2021

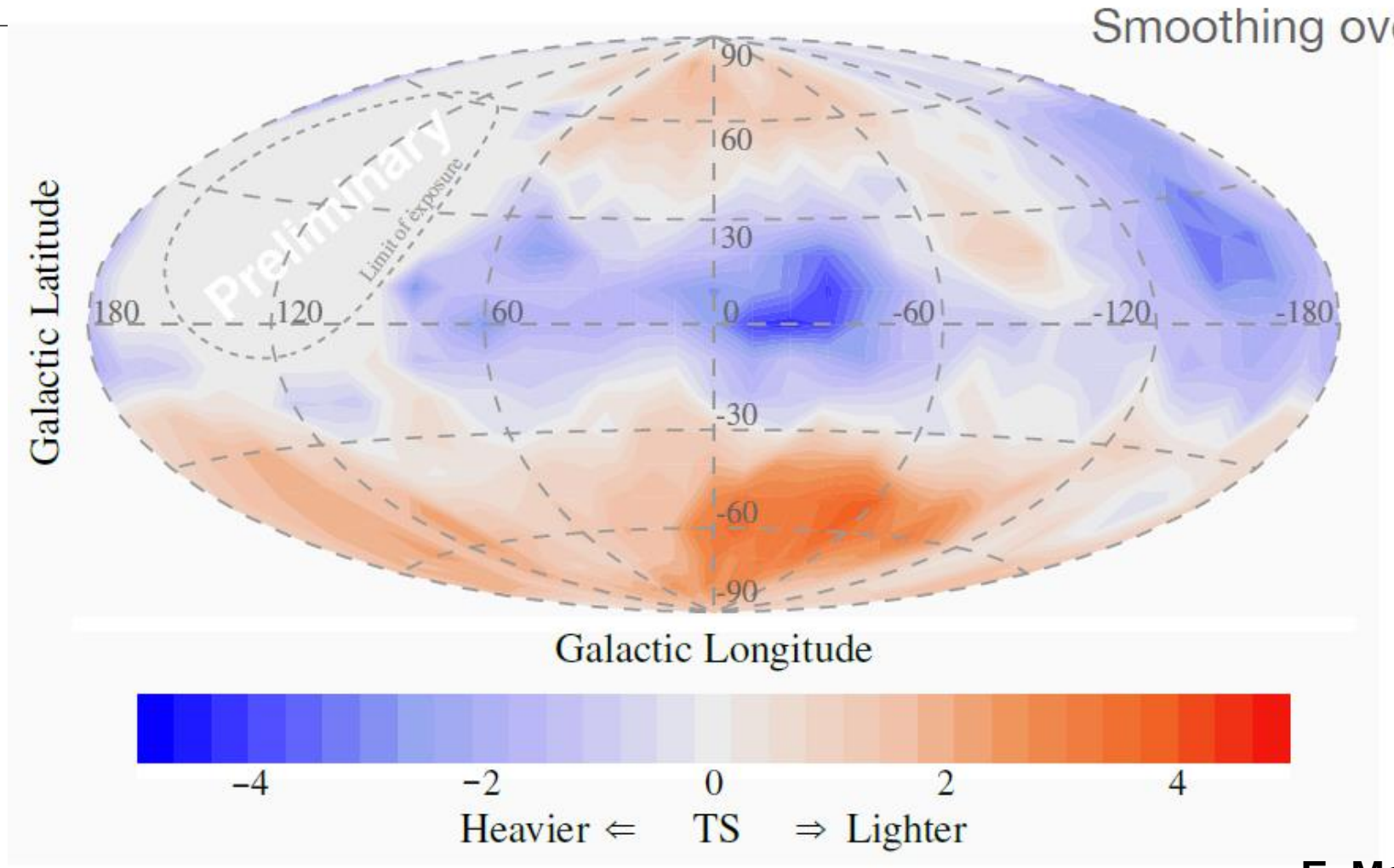




Anisotropy searches at higher energies

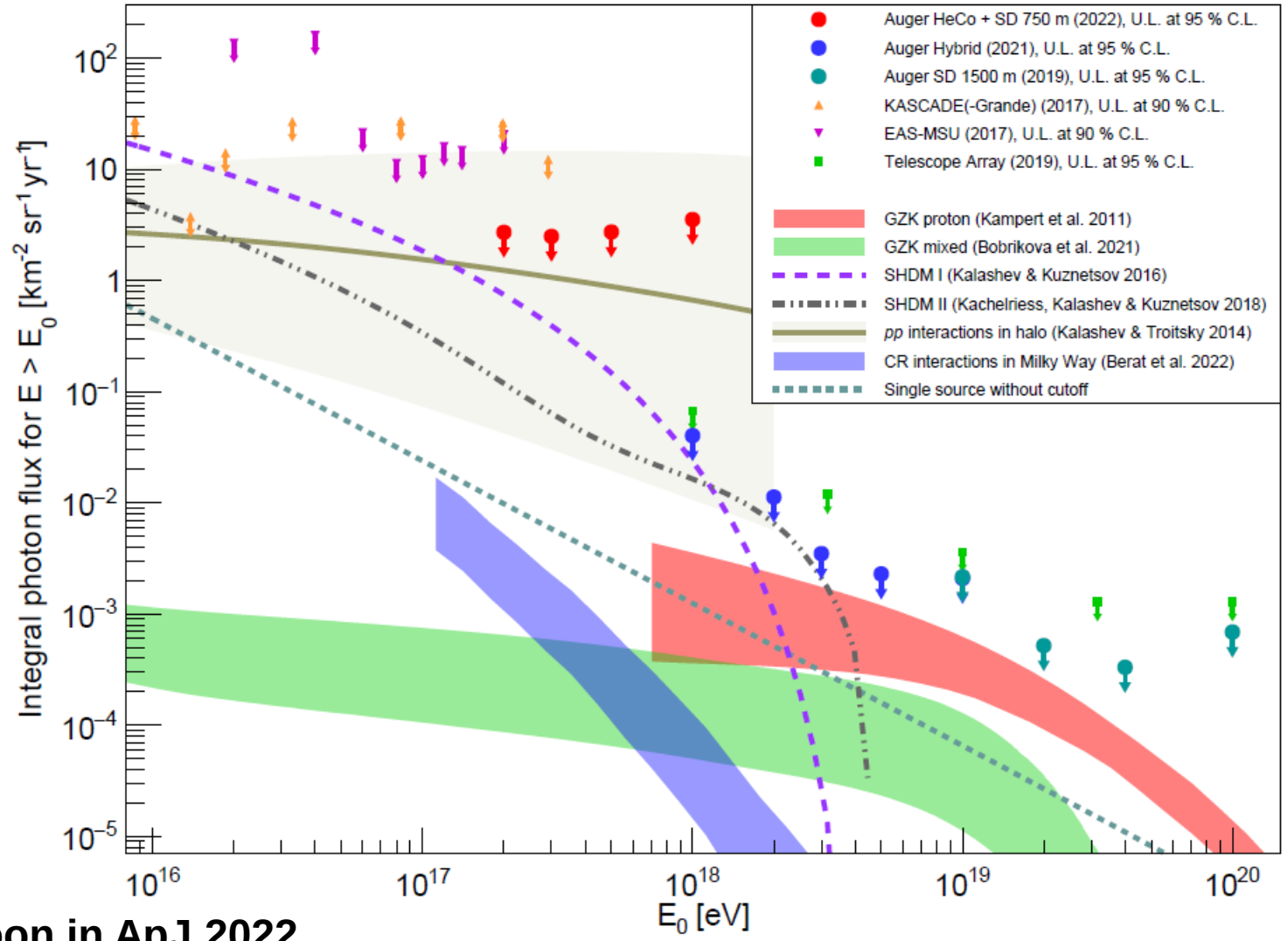
Left, flux of cosmic rays observed above 41 EeV observed at the Auger Observatory smoothed with a top-hat function of radius 24◦. Right: Associated Li-Ma pre-trial significance map. The solid gray line shows the supergalactic plane.

Vision of the future: first steps in anisotropy searches with composition information

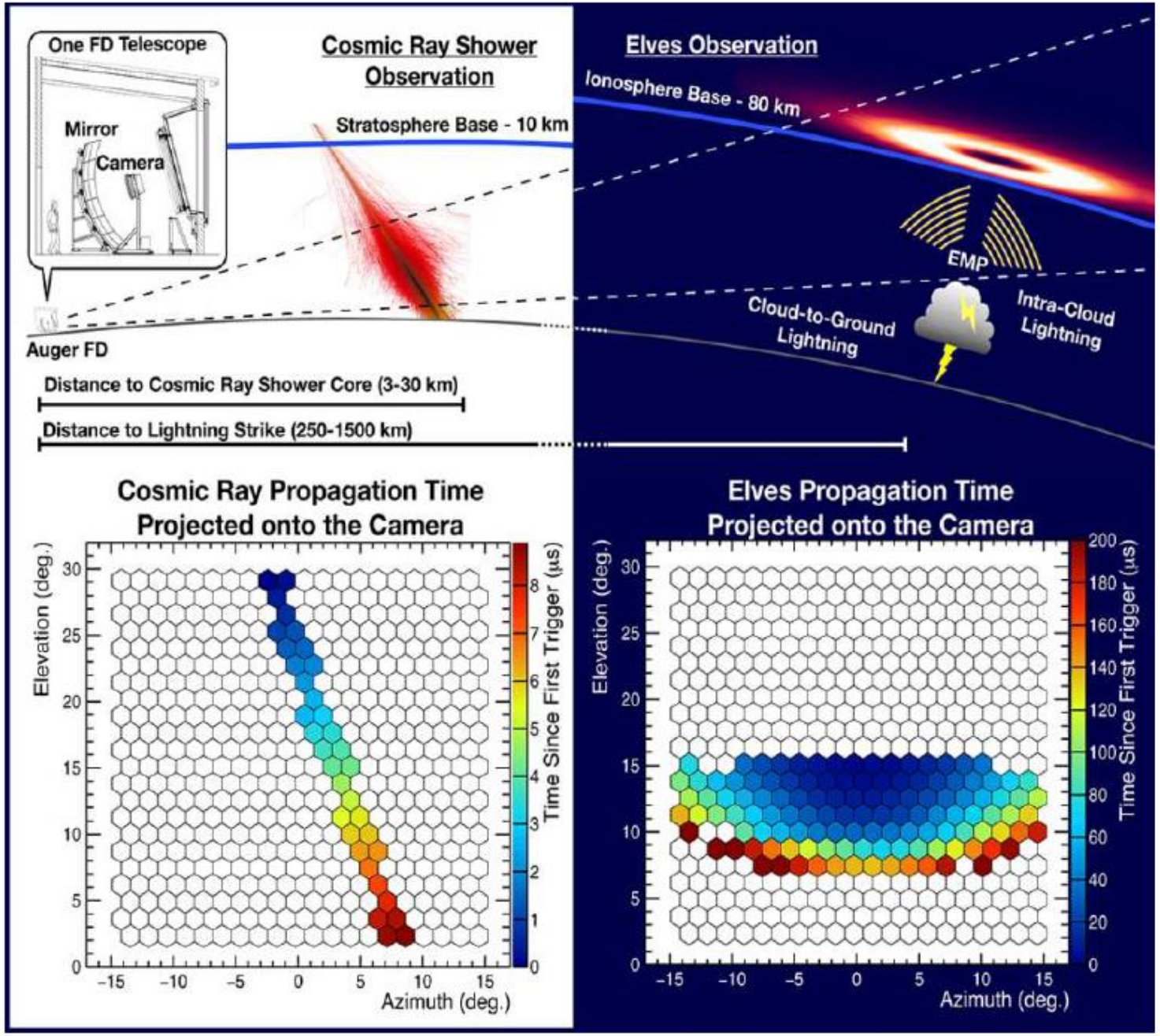


E. Mayotte for Auger, ICRC2021

Upper limits of photon flux



Auger, to appear soon in ApJ 2022



Detecting Elves with the fluorescence telescopes

***E**missions of **L**ight and **V**ery low frequency perturbations due to **E**lectromagnetic pulse **S**ources*

What else are we doing?

Exploring other topics as:

- Testing UHE **hadronic interaction models** using mass composition information.
- Testing **Lorentz Invariance Violation** in UHE cosmic-ray propagation/ **Constraining Lorentz Invariance Violation using the muon content in air showers.**
- **Constraining gravitationally-produced super-heavy dark matter particles in the early Universe.**
- **Applying deep learning techniques to obtain the depth of shower maxima or separating signal of muons in the detectors.**
- **Following up multimessenger searches (gravitational waves and HE neutrinos).**
- **Joint analyses with the Telescope Array Collaboration covering the whole UHECR sky.**

We acknowledge the support of: