25 Years of the Pierre Auger Observatory: the evolving harvest of an evolving “hybrid” instrument

Piera L. Ghia (CNRS, IJCLab, Orsay) for the Pierre Auger Collaboration

25 Years of the Pierre Auger Observatory: the evolving harvest of an evolving "hybrid" instrument

Outline

Evolution of instruments: from one water tank and one telescope to a multi-detector facility

Evolution of observations (and methods)

Evolution of scopes: from cosmic-ray to interdisciplinary physics

Evolution of instruments

25 years ago: the seed of a hybrid observatory

2000: the first detectors

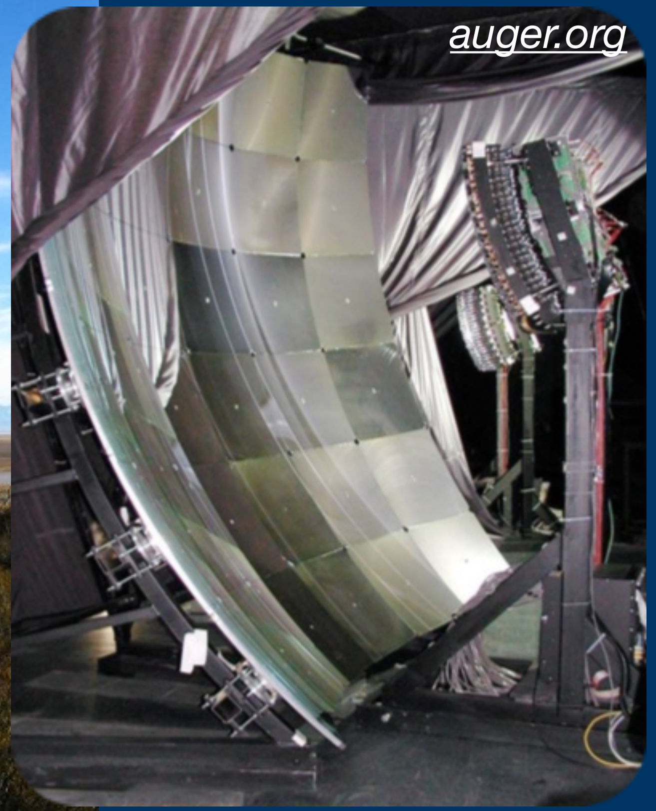
The first Water-Cherenkov detector

(Priscilla)

12 t water
3 PMTs
10 m² area
1.2 m height
Acceptance up to 90°

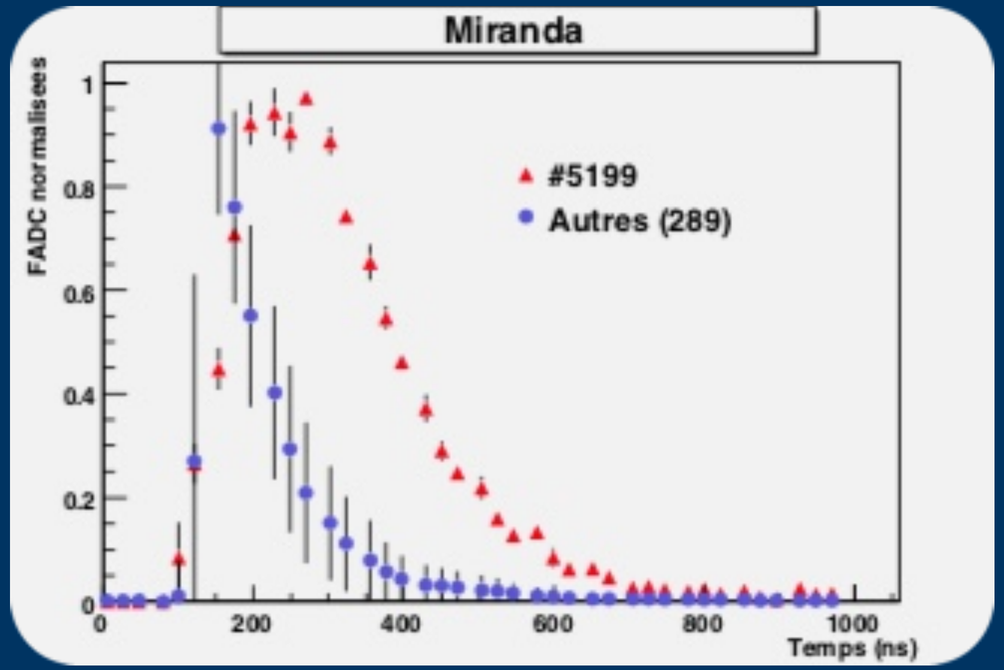
The first Fluorescence telescope

(Los Leones)

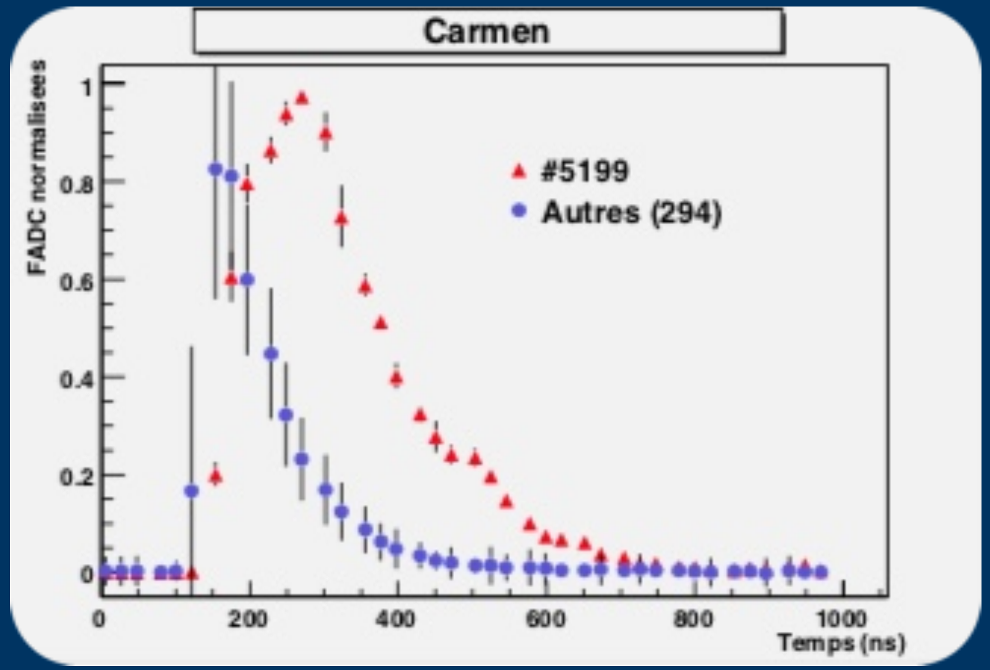


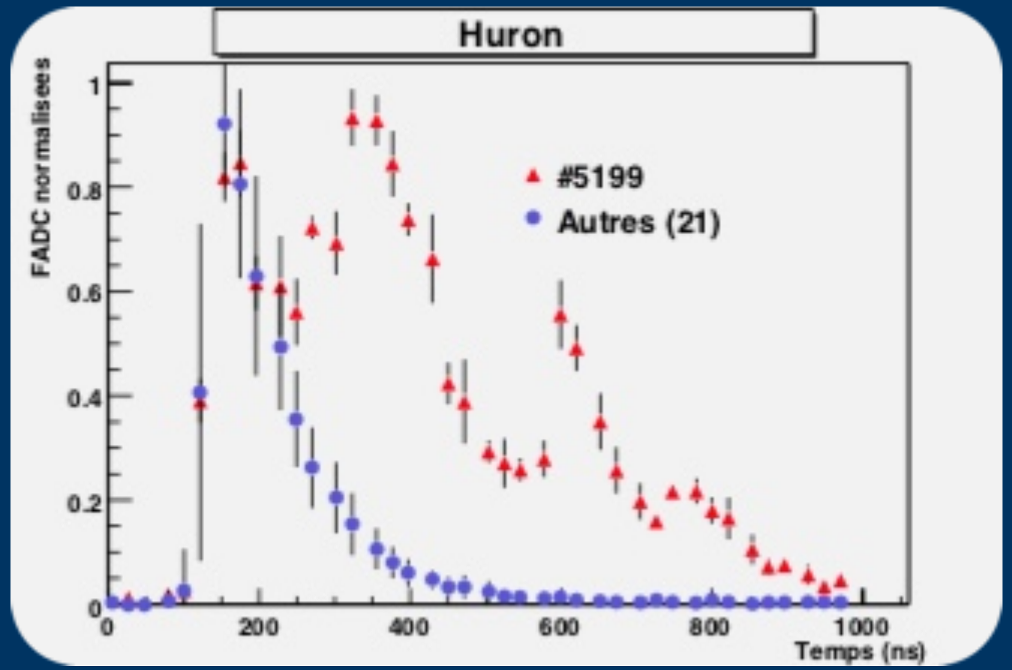
13 m² mirror
440 PMTs camera
30°x30° FoV

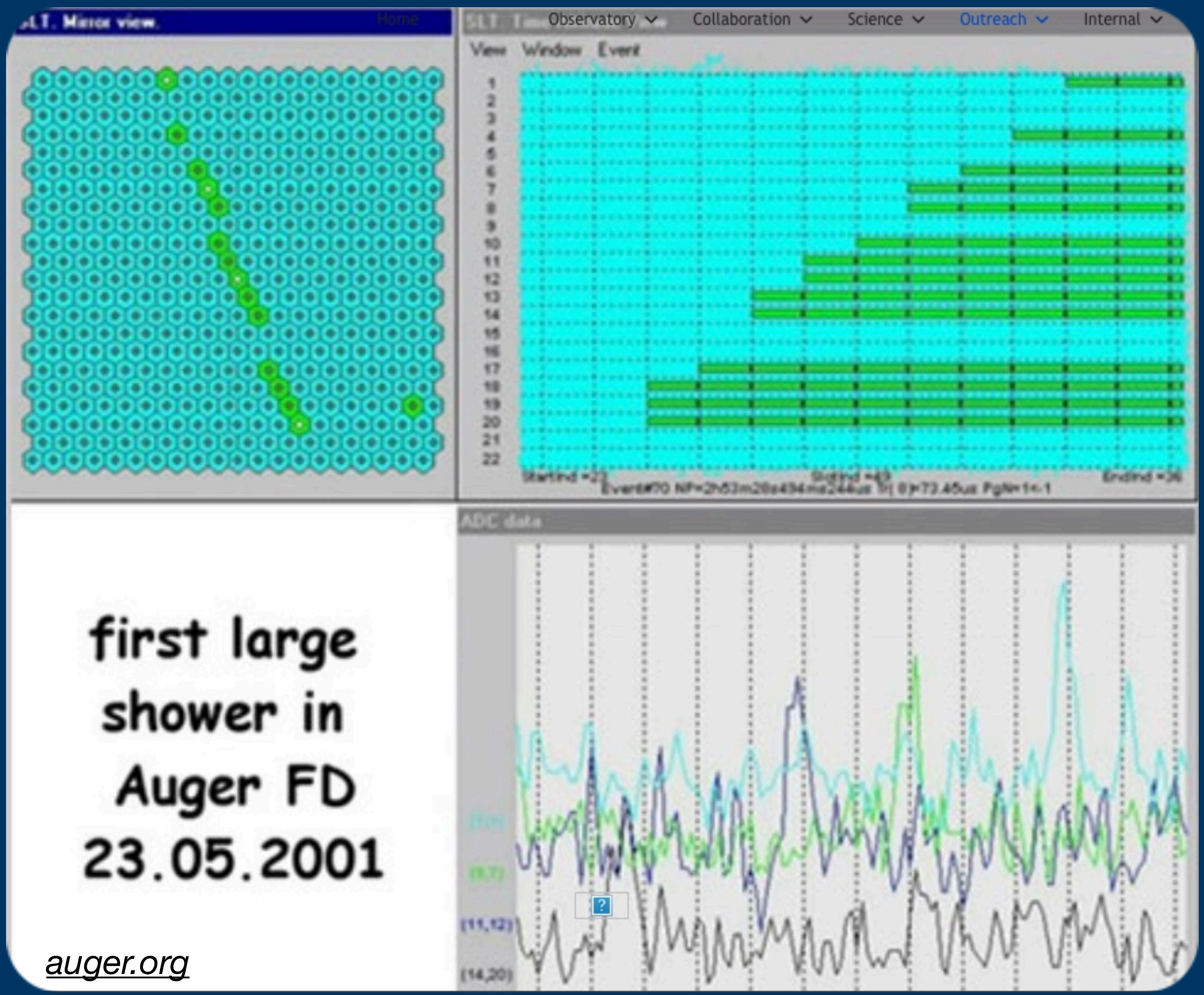
2001: the first light



Courtesy of X. Bertou



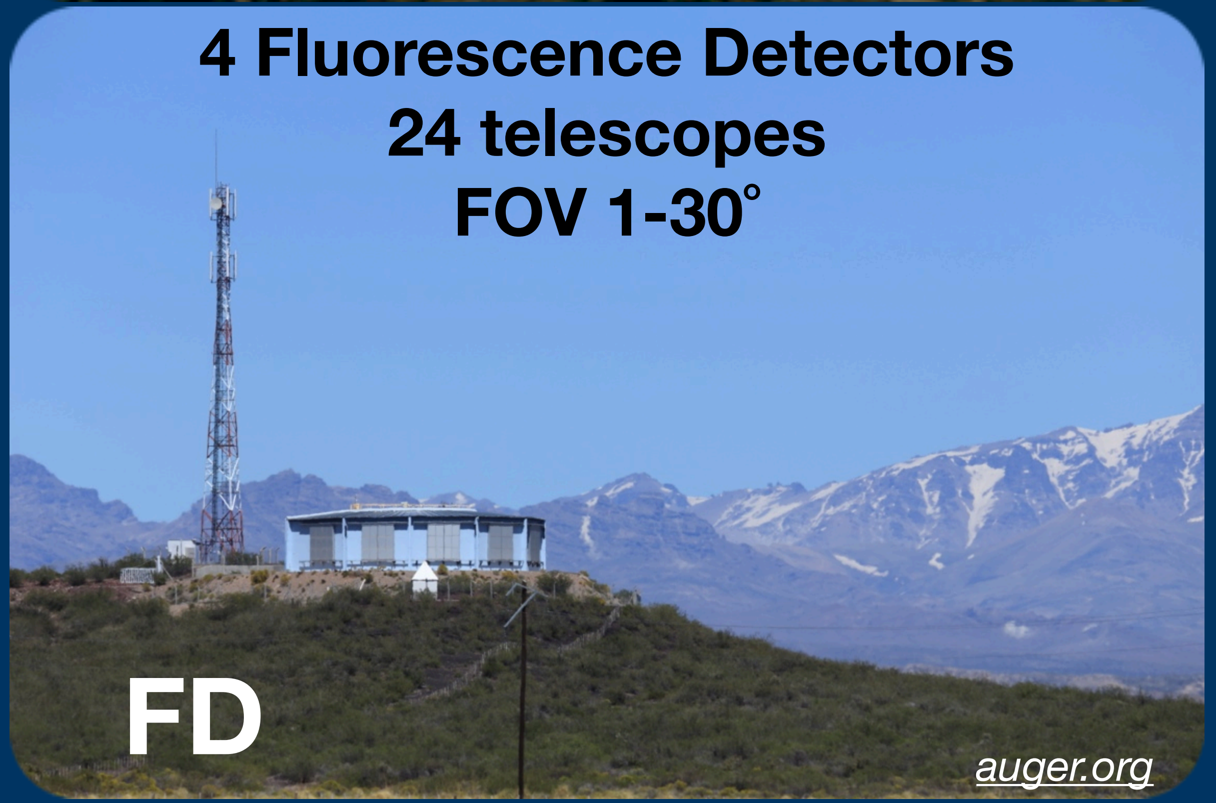


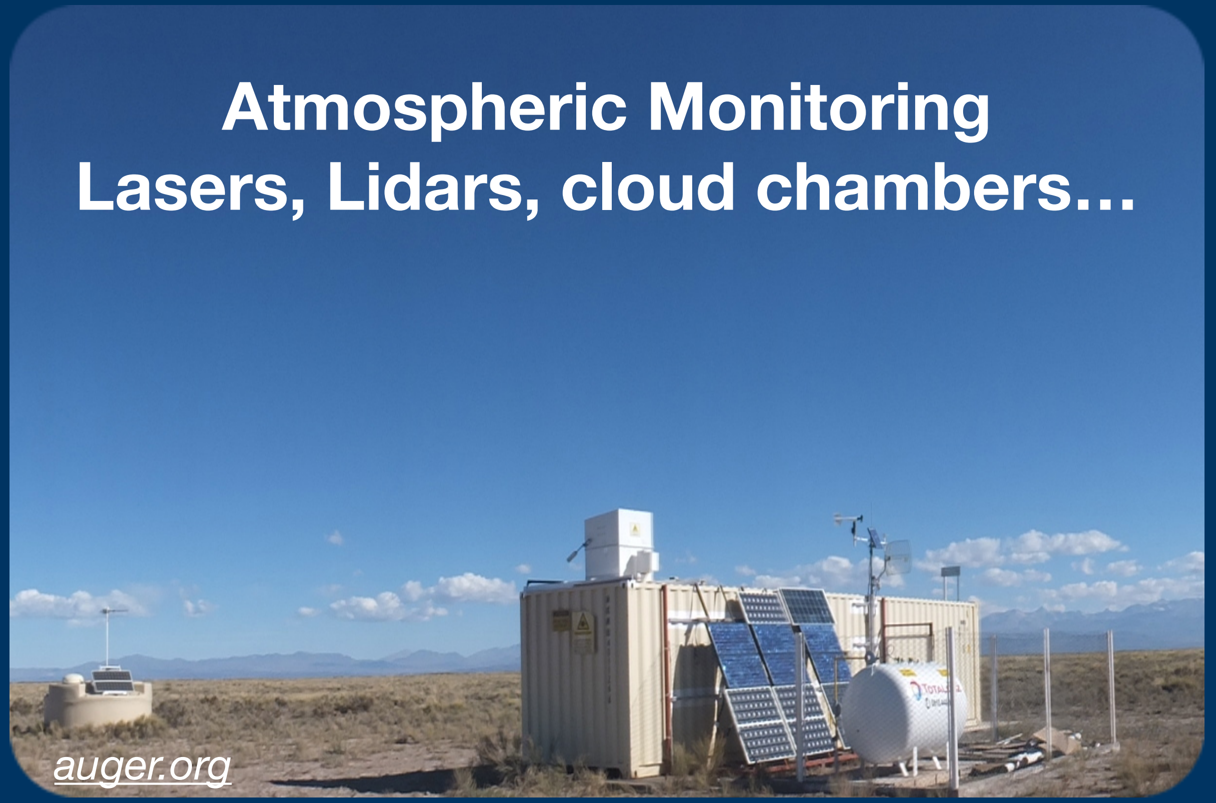


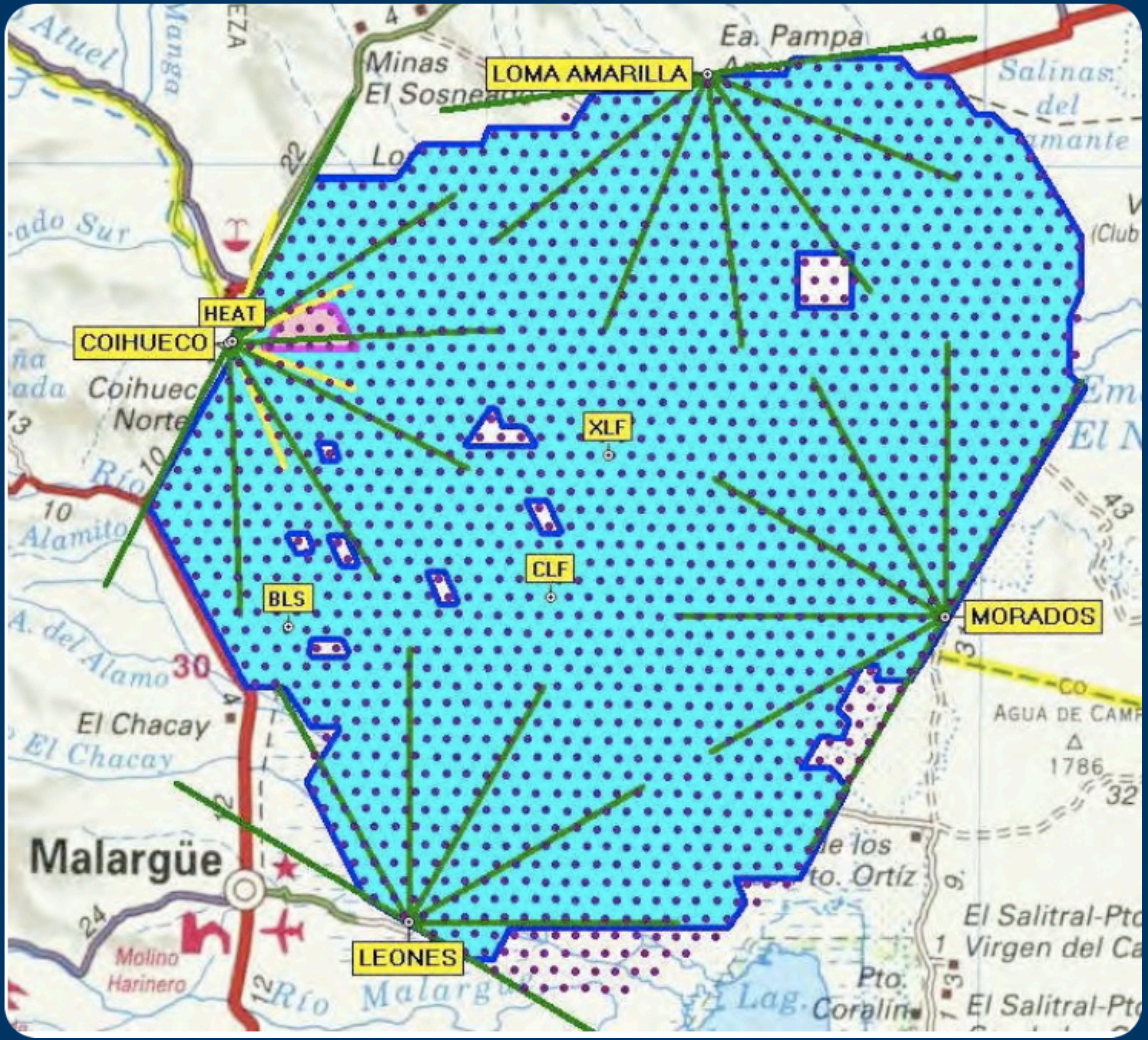
Official data-taking start: 1 January 2004 (with 154 WCDs and 6 telescopes)

From the seed to the full Observatory (2008)

Energy threshold: 10^{18} eV

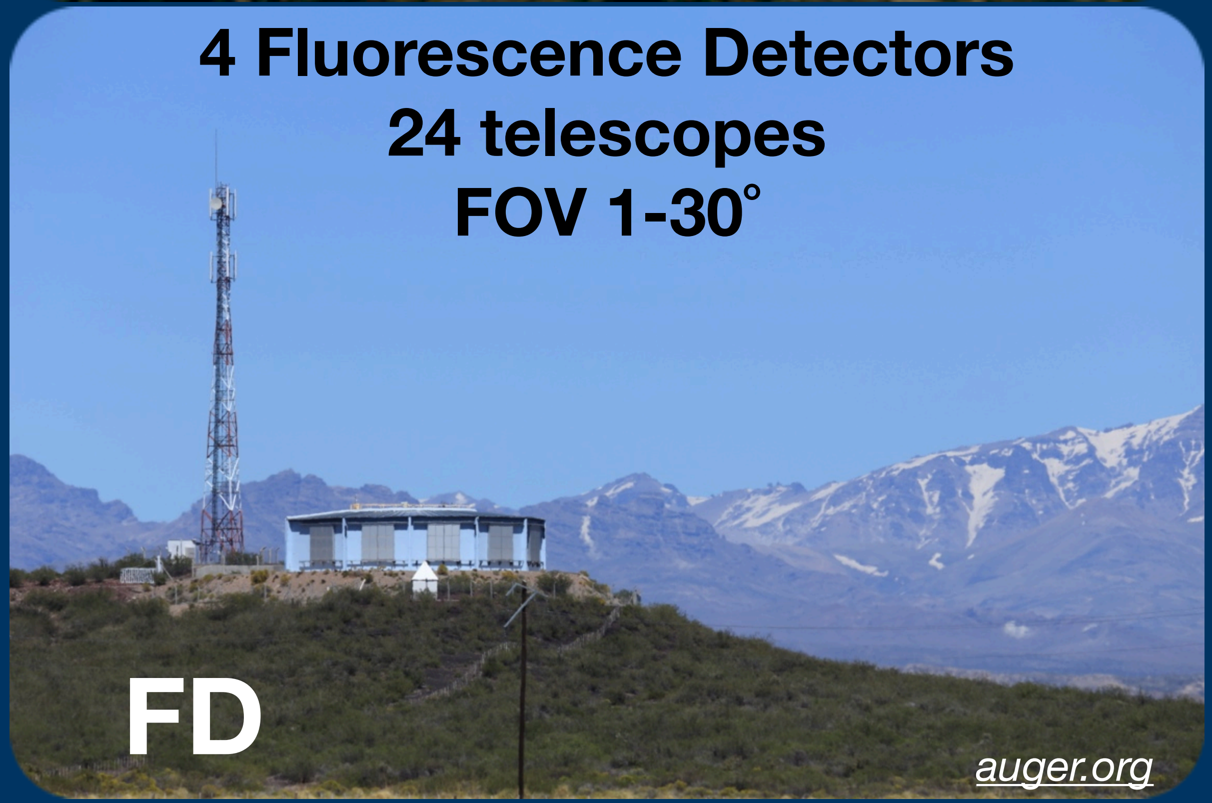


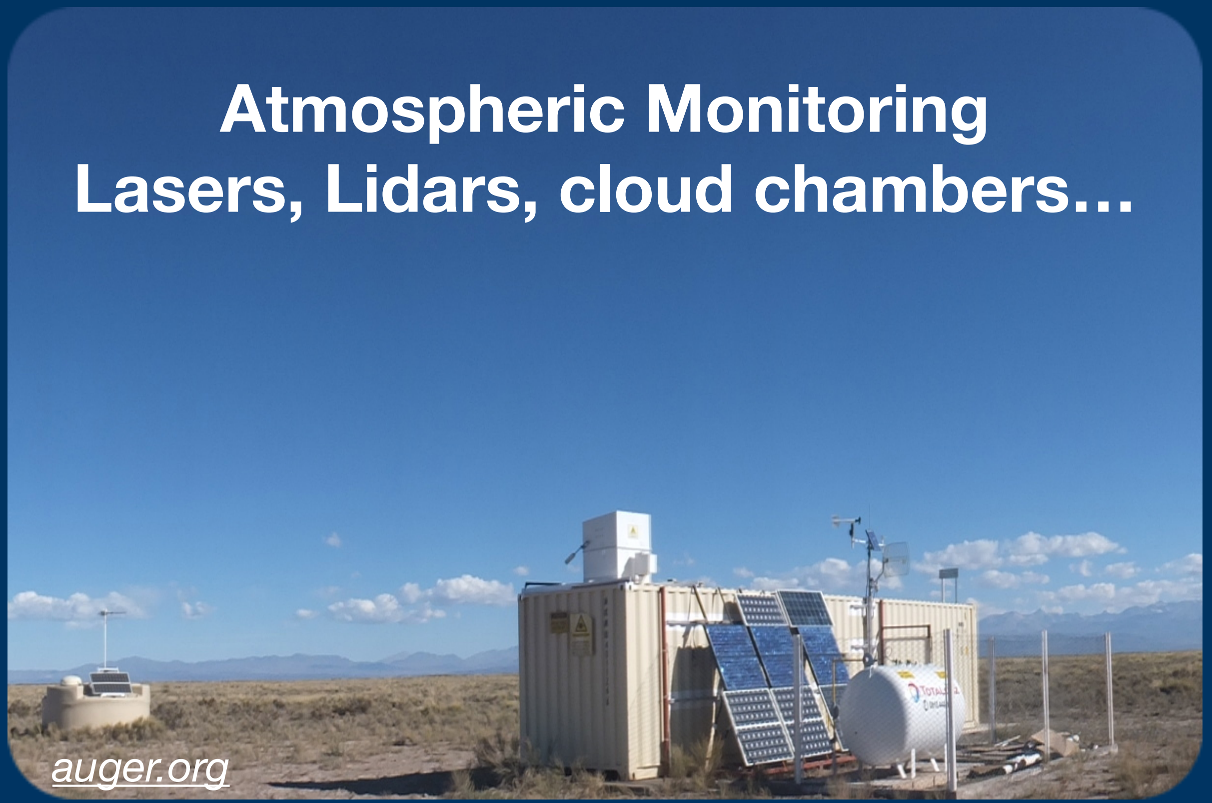


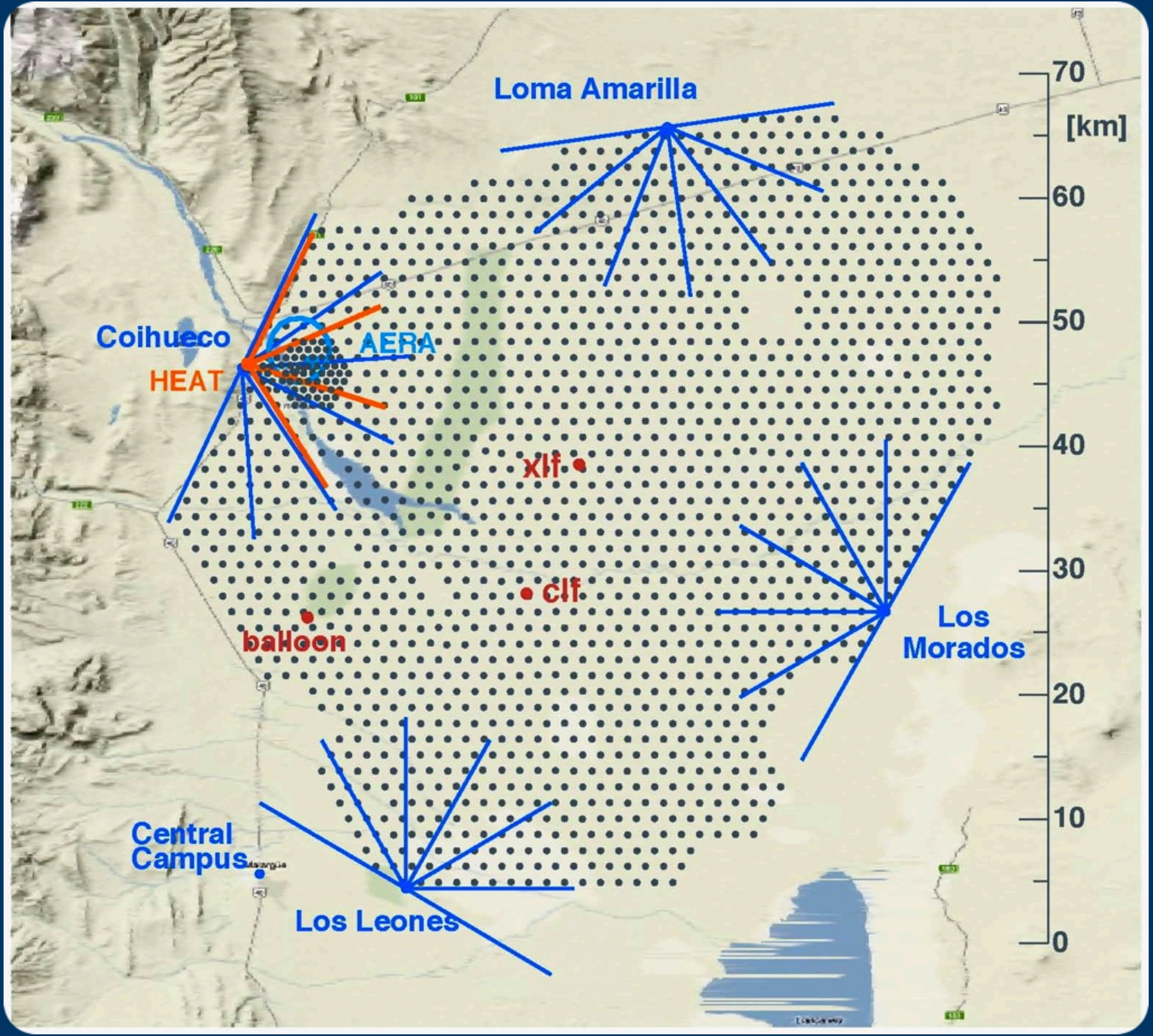


Extension to reach lower energies (2015)

Energy threshold: 10^{17} eV







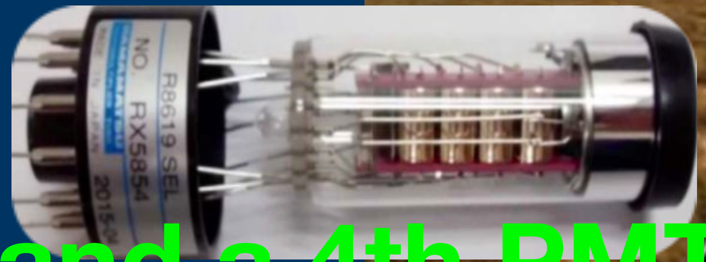
From 2 to 3 instruments: + Radio →

And, finally, a “multi-hybrid” instrument (2022)

From 2 to 5 instruments: FD+SD+RD+SSD+UMD

+ Radio antenna (RD)

+ new electronics…



…and a 4th PMT
in the WCD

+ Scintillator (SSD)

+ underground scintillators in the SD-433 and SD-750 areas (UMD)

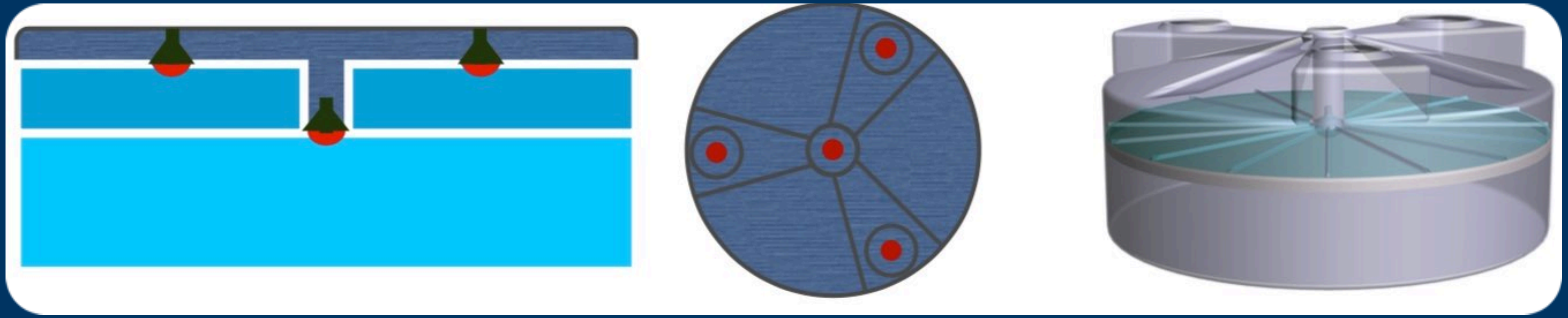
(Much) more in Rossella Caruso’s talk

Not only a "multi-hybrid" instrument, but also a research facility

The Fluorescence detector Array of Single-pixel Telescopes : a next-generation UHECR experiment

One of three prototype arrays for the GRAND project: 10 repurposed AERA antennas

Prototypes of radio antennas and scintillators for IceCube-Gen2 surface array



Double layer WCDs: R&D for GCOS and PEPS projects

And others to come….

Evolution of methods and observations

Original physics case and mission

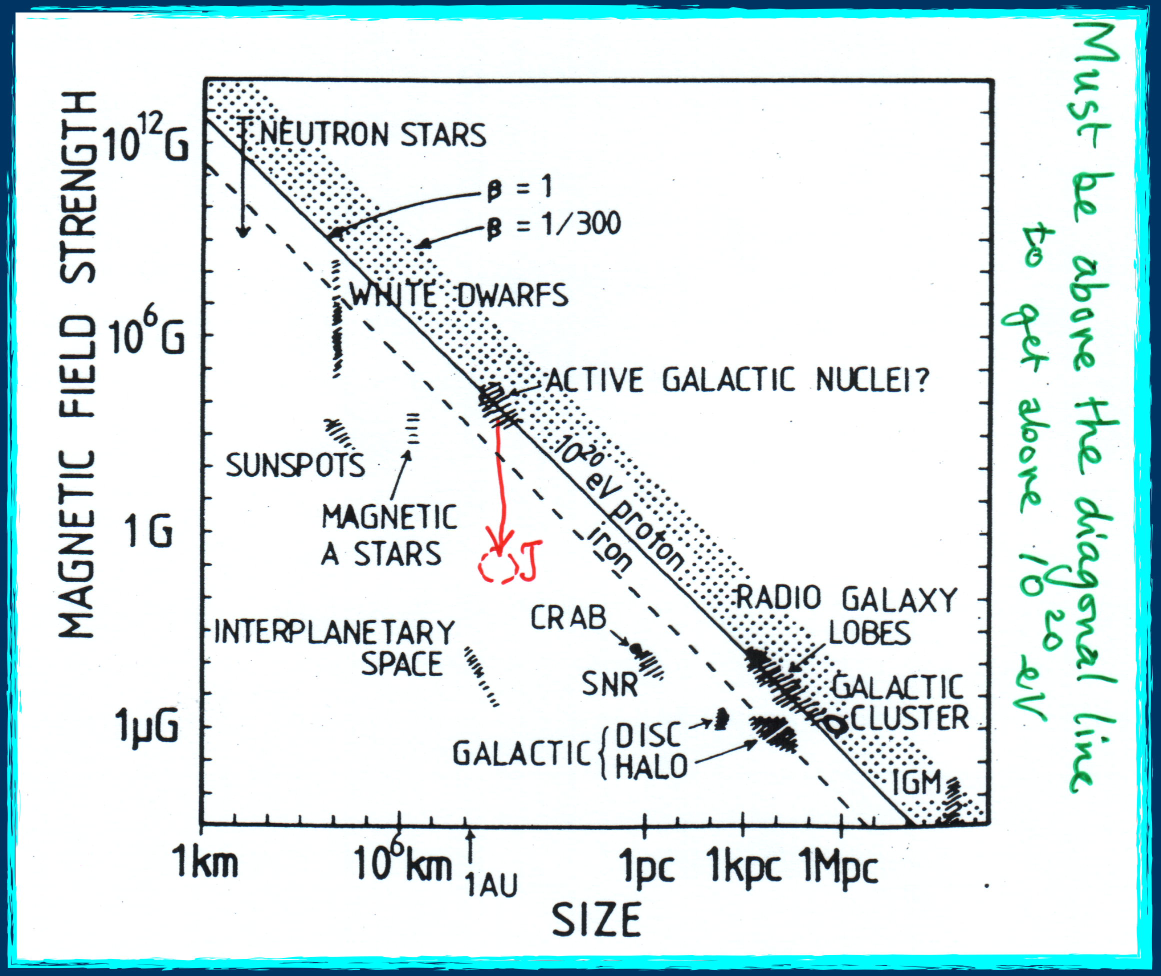
Physics case

Energy spectrum. One prediction only: suppression at ≈ 4×10^{19} eV, due to UHECR interactions with CMB, whether cosmic rays are protons or heavier nuclei.

Corollary: UHE neutrinos and γ-rays expected too as secondary particles from UHECR propagation.

Arrival directions. Hillas criteria, based on acceleration principles: a (limited) variety of possible UHECR sources (AGNs, Magnetars, GRBs, radio-galaxies…)

Mass: no prediction but prejudice -> **all protons**



“Hillas plot”

The mission

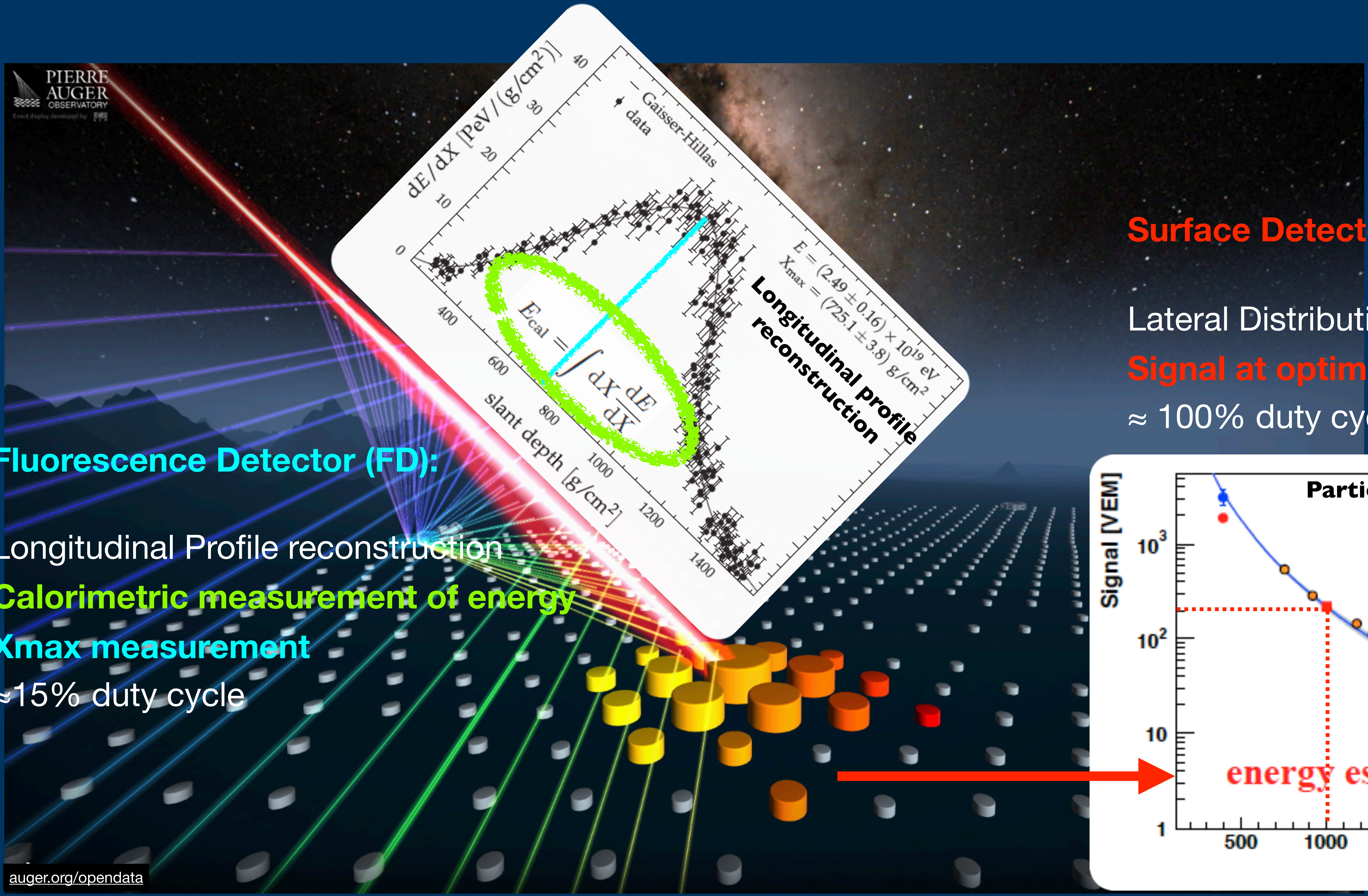
1. Precise reconstruction of the **energy spectrum (with the high statistics of SD): test the suppression prediction**

2. **Mass inference (with FD Xmax measurements): : test proton prejudice.** Inferences on mass composition drawn from the study of shower properties that might **constrain hadronic interaction models** at energies well beyond the reach of accelerator-based experiments

3. If suppression found, limited horizon ≈ 100 Mpc in which look for the sources via systematic study of **arrival directions**, that may indicate if there is anisotropy in the distribution and/or clusters and/or association with Hillas-proposed source-catalogues -> if all protons, small deflections, “proton-astronomy”

A “simple” mission, just need statistics: 3000 km2!

The essence of the hybrid approach (SD & FD)



Fluorescence Detector (FD):

Longitudinal Profile reconstruction

Calorimetric measurement of energy

Xmax measurement

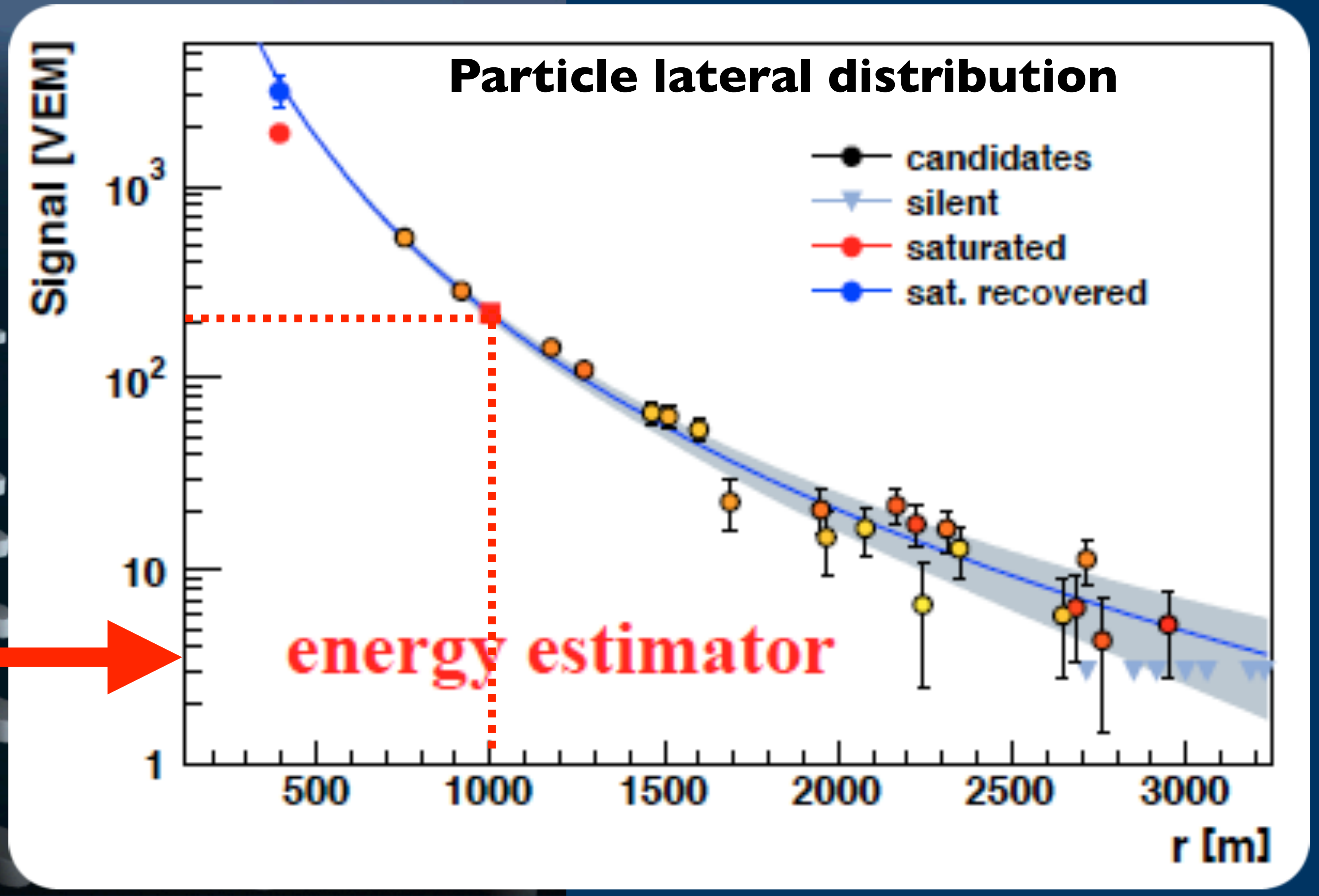
≈15% duty cycle

Surface Detector (SD):

Lateral Distribution reconstruction

Signal at optimal distance (1000 m)

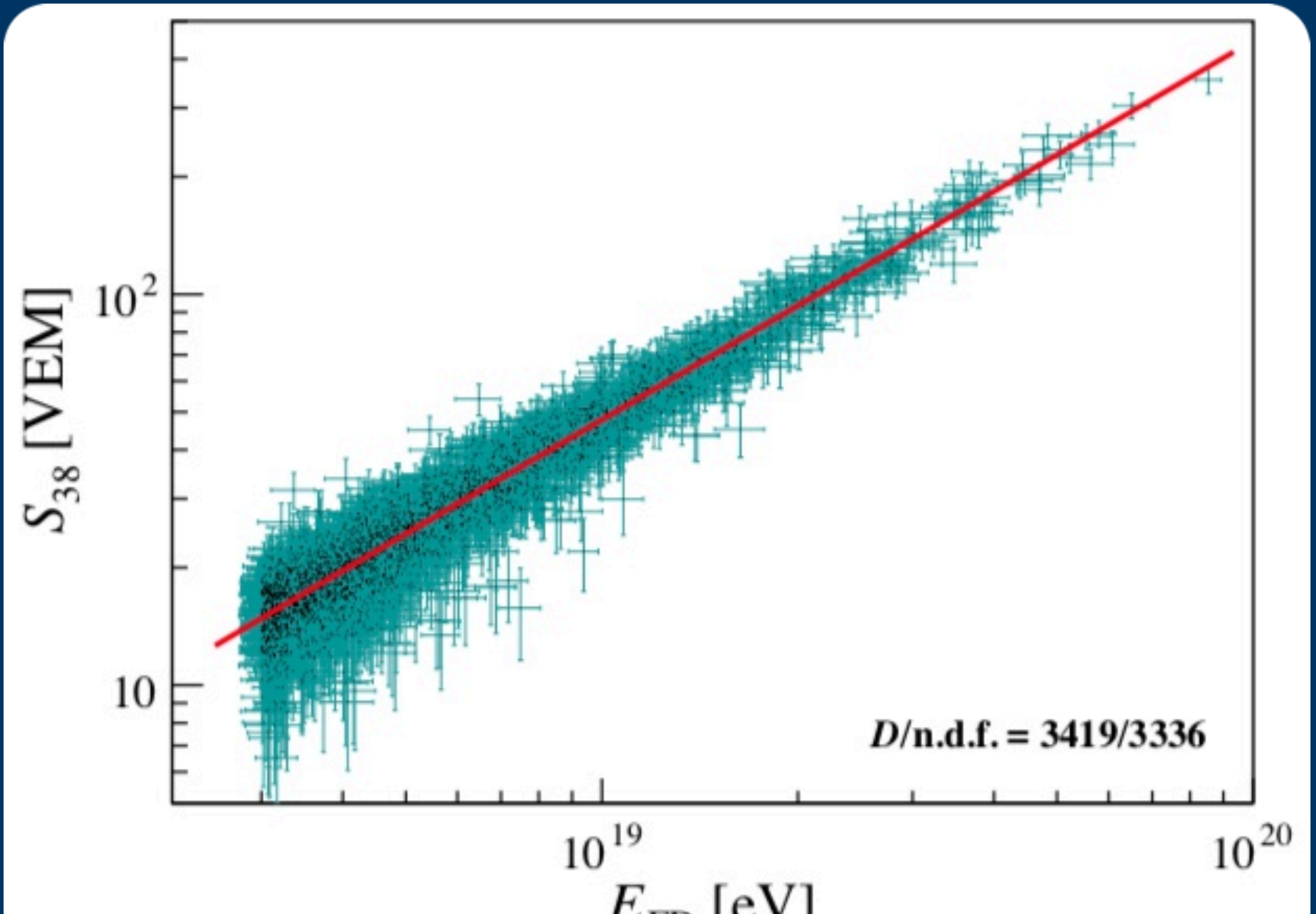
≈ 100% duty cycle



The essence (and evolution) of the hybrid approach (FD & SD & RD)

Data-driven (and not MC-driven) energy calibration

Calibration of SD energy estimator with the FD calorimetric energy

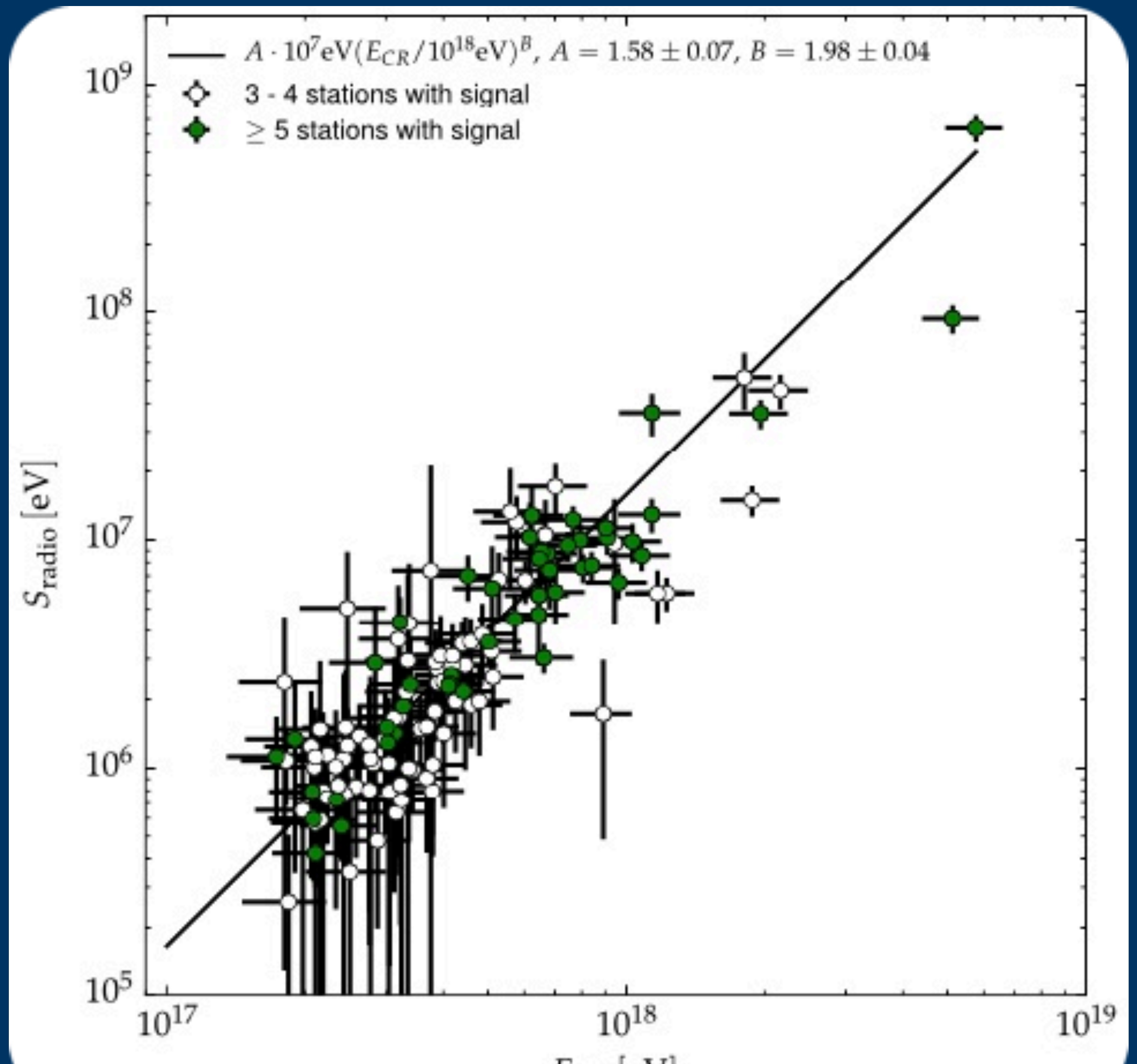


PRD 102, 062005 (2020)

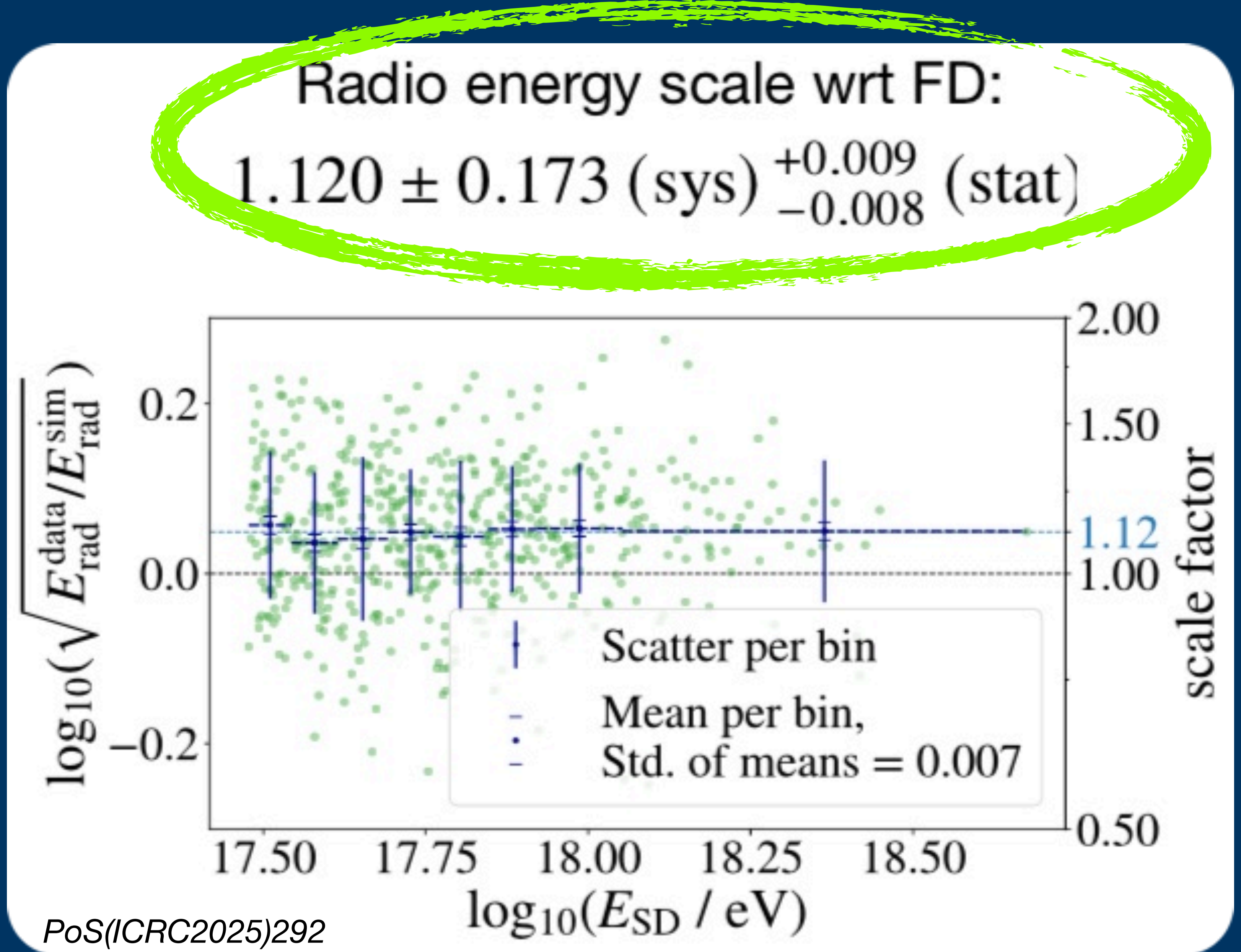
The FD sets the energy scale for all 3 SD arrays: systematic uncertainty 14%

(N.B. Evolution from early years, when it was 22%)

Radio Detector (RD): Independent determination of energy



PRD 93, 122005



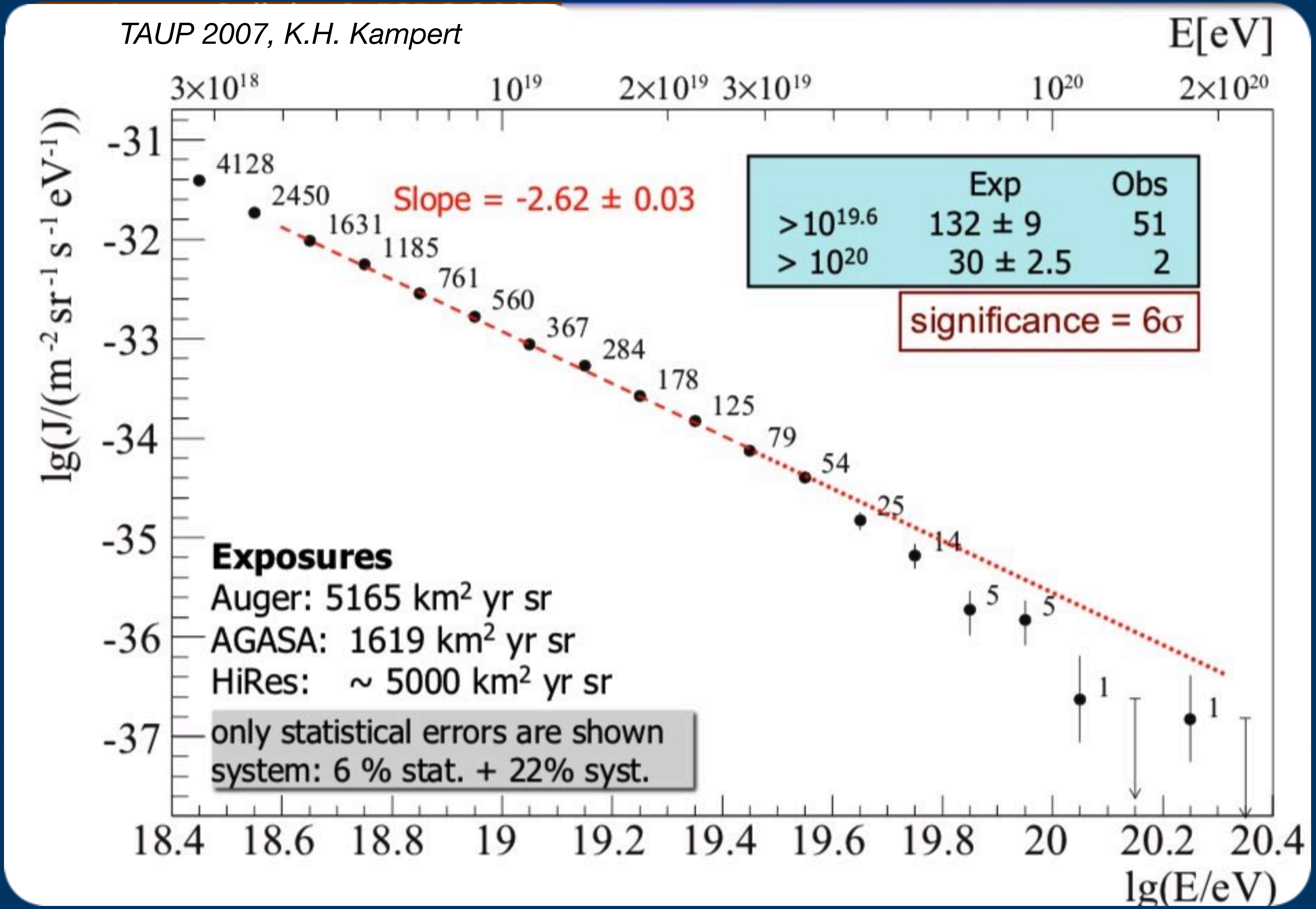
PoS(ICRC2025)292

FD and RD energy scale well-consistent with systematic uncertainties

Energy spectrum, from ≈ 5000 km² sr y to ≈100000 km² sr y

A 20x exposure allows the discovery of a new feature in the energy spectrum…

2007



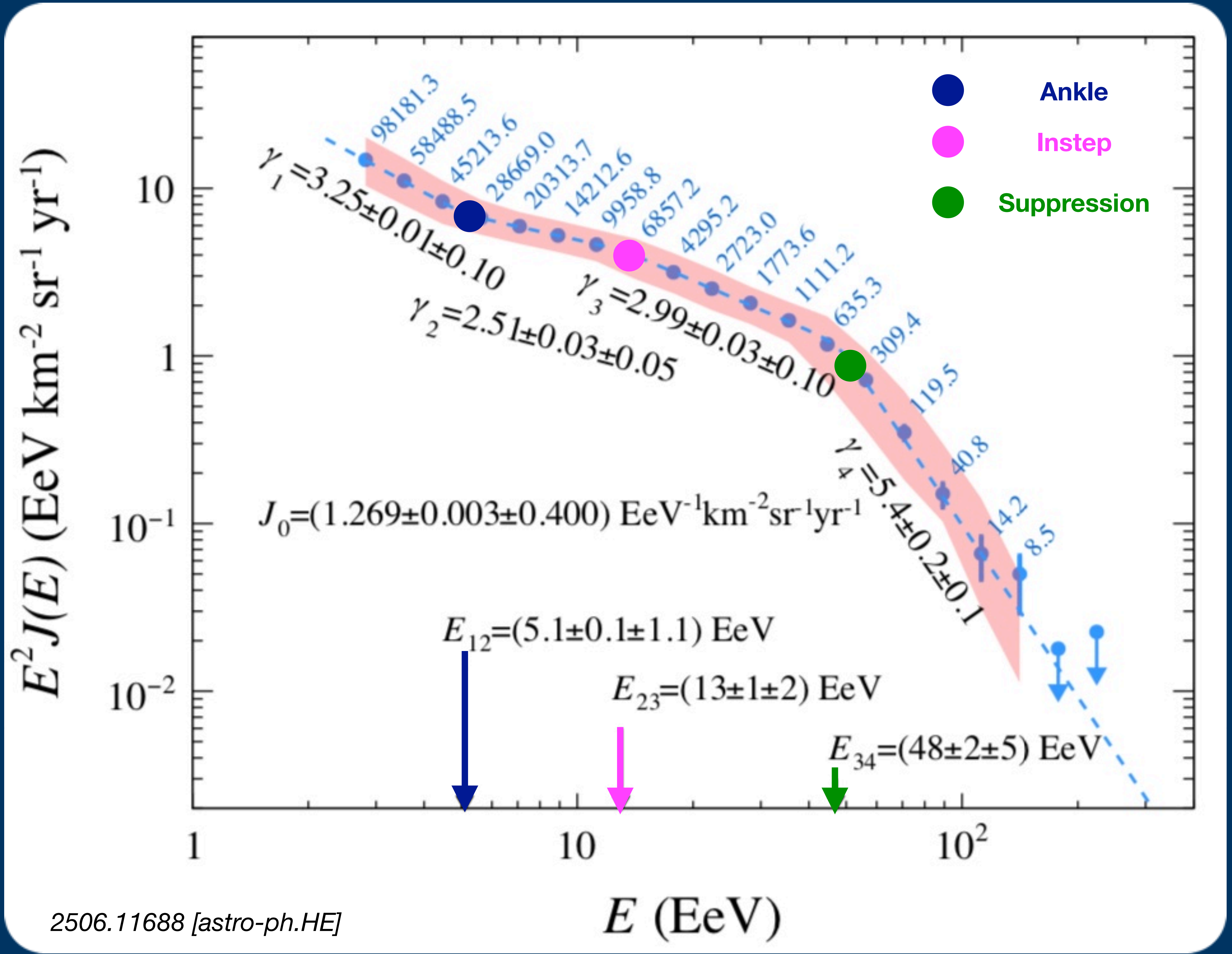
SD-1500: Full efficiency at 3×10^{18} eV

≈ **5000** km² sr y (AGASAx3)

≈ **12000** events (0-60°)

Observation of a suppression at ≈ 5 x 10^{19} eV (6 σ)

2025



SD: Full efficiency at 3×10^{18} eV

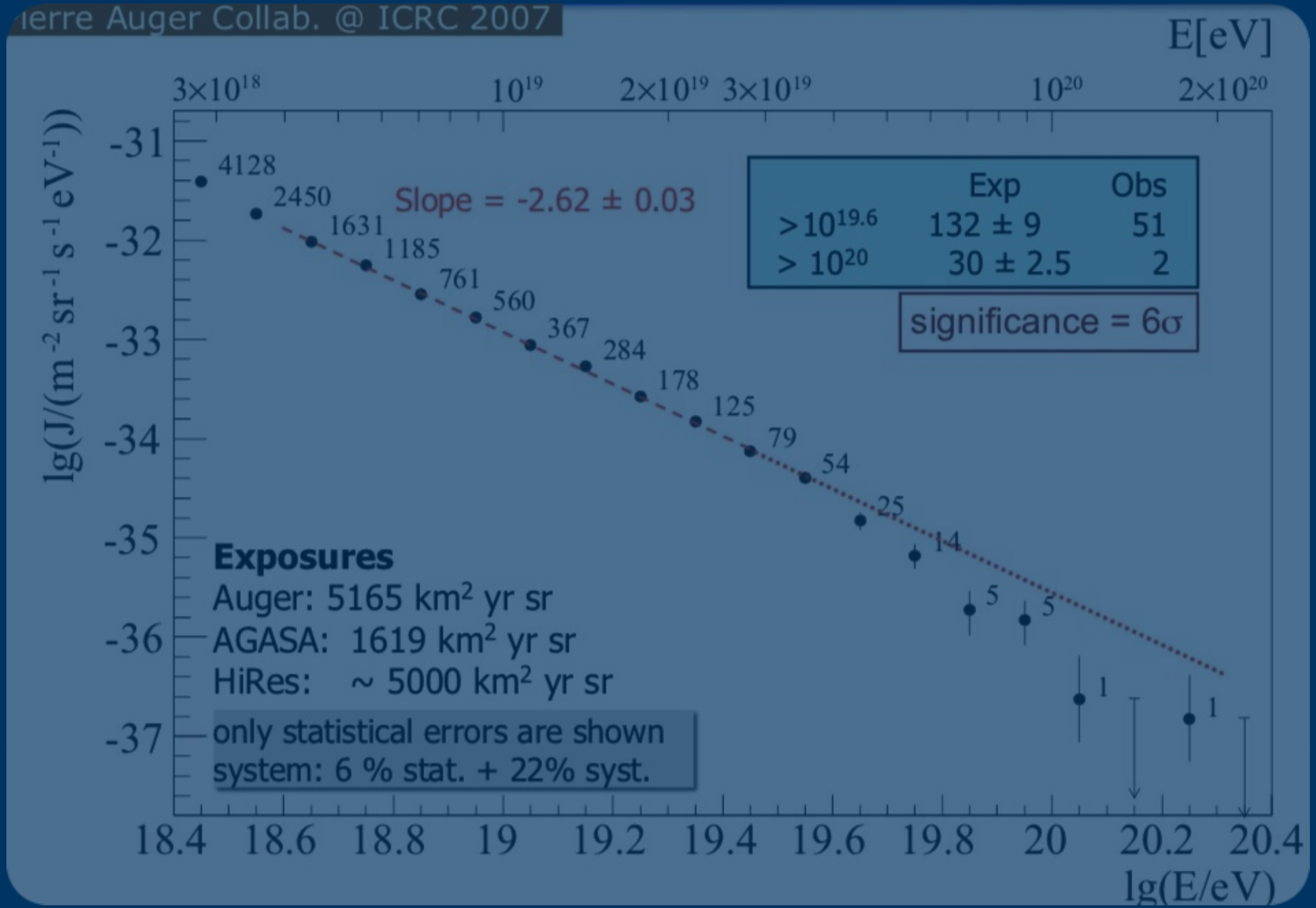
≈ **105000** km² sr y [20x]

≈ **310000** events (0-80°) [25x]

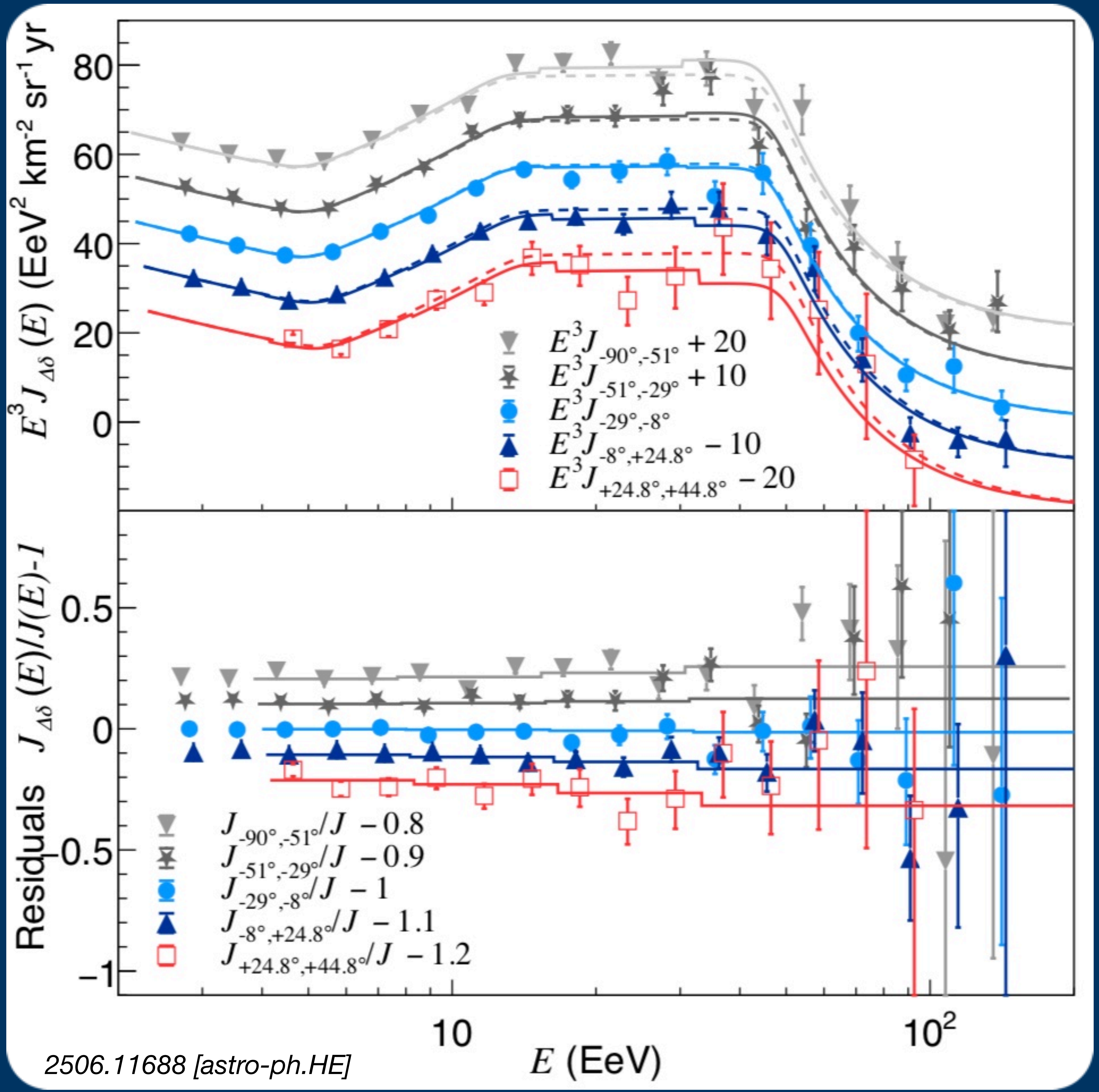
Discovery of a new feature (instep, 5.5 σ)

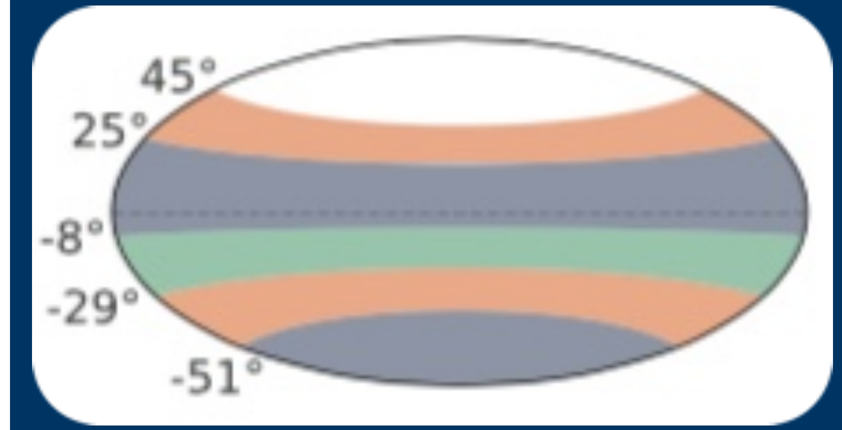
Energy spectrum, from ≈ 5000 km² sr y to ≈100000 km² sr y

…and the investigation of the spectrum behaviour versus declination over 3/4 of the sky



2025





Energy spectrum in 5 declination bands (-90° to +45°)

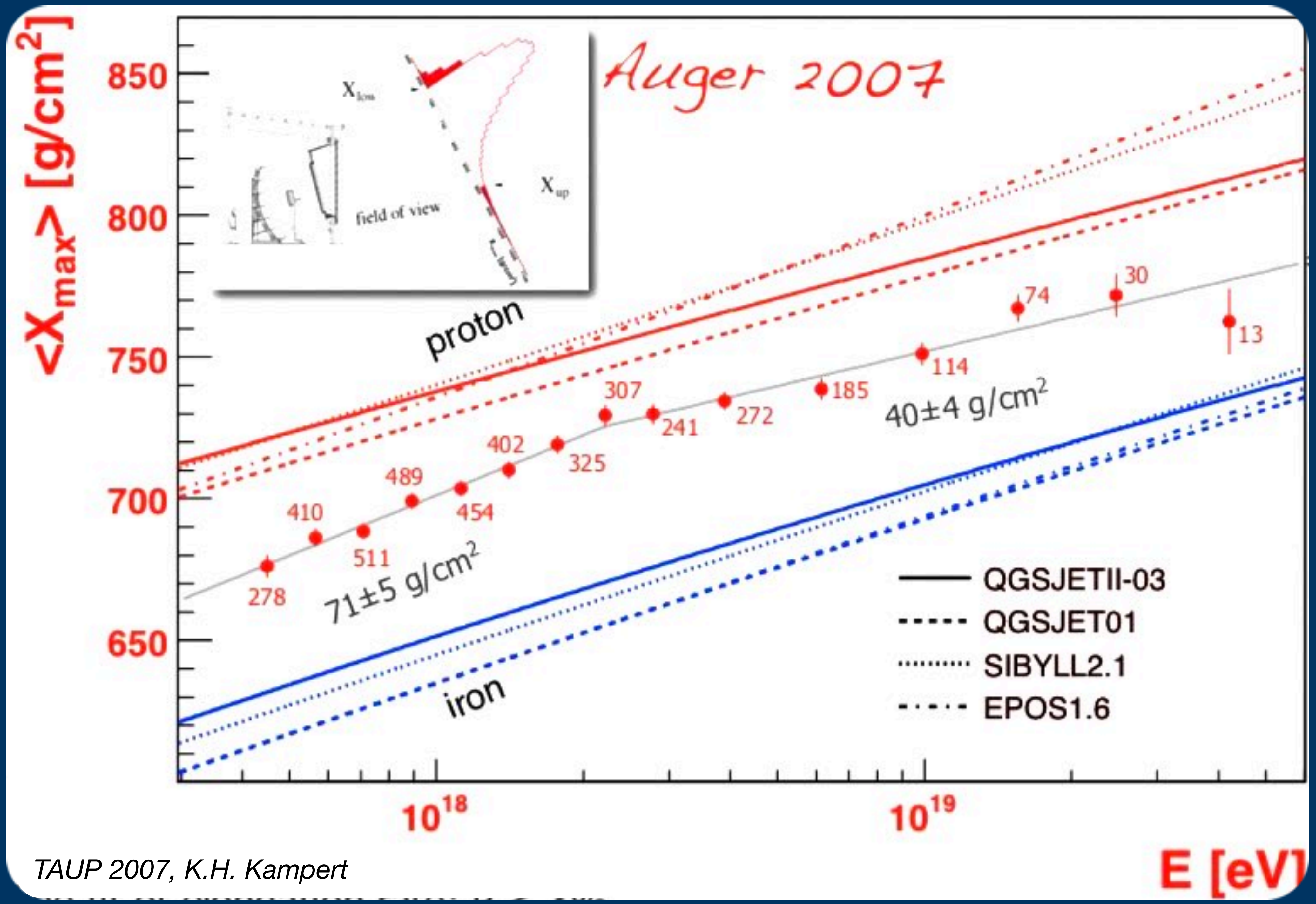
No declination dependence after accounting for well-known dipolar anisotropy

The quasi-uniformity across declinations disfavors an instep origin from a few distinctive sources

Depth of shower maximum: data (and methods) evolution

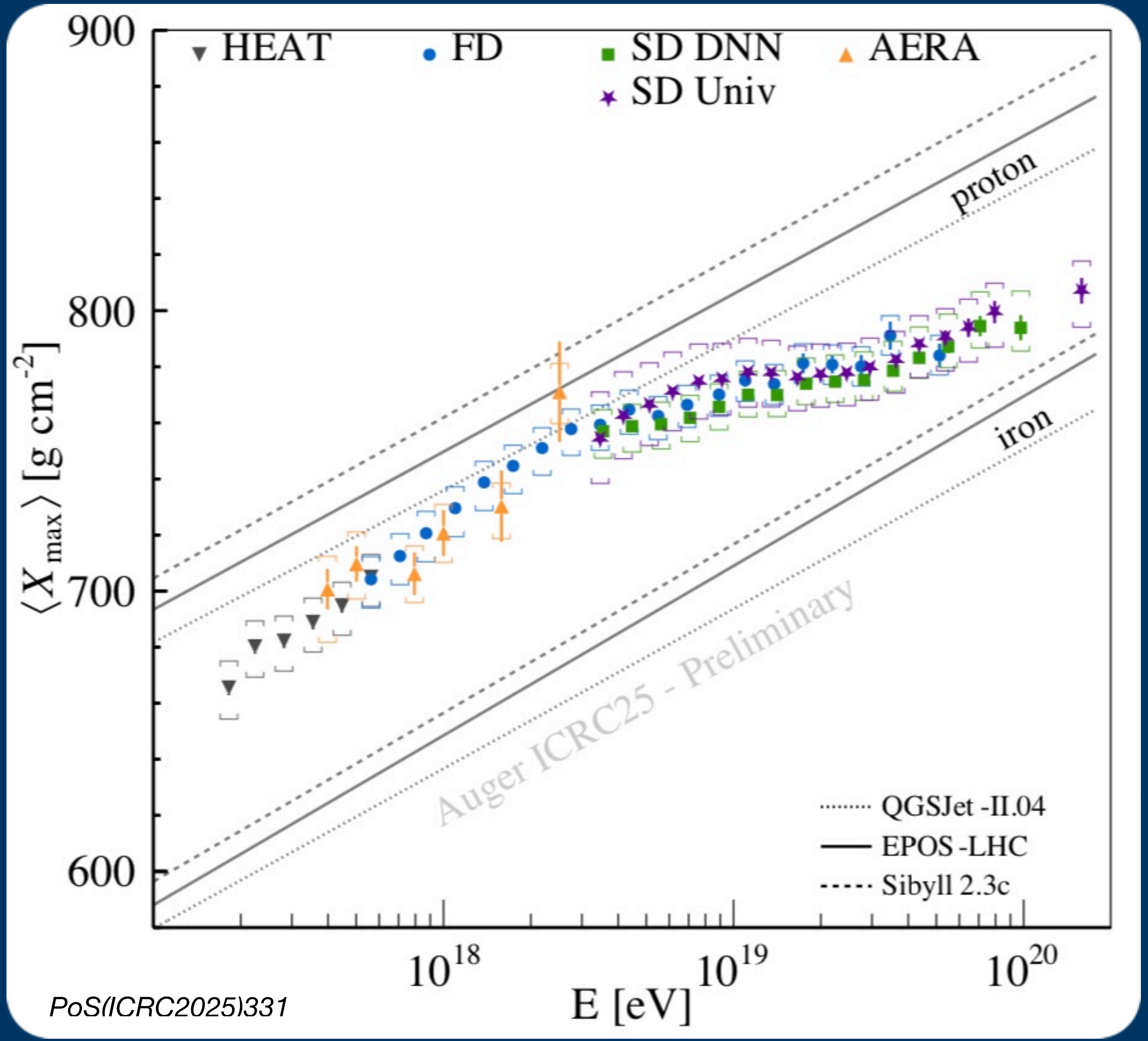
Depth of shower maximum premiere observable for mass composition studies
Mass inference relies on hadronic models (evolving too: <Xmax> deeper by ≈ 30 g/cm2)

2007



TAUP 2007, K.H. Kampert

2025



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Xmax not only from **FD** but also from **SD** (new methods) and **RD-AERA**

Mixed (mean) composition favoured at all energies
in spite of large uncertainties of hadronic models

A simple linear fit to elongation rate does not describe data well: pure composition excluded?

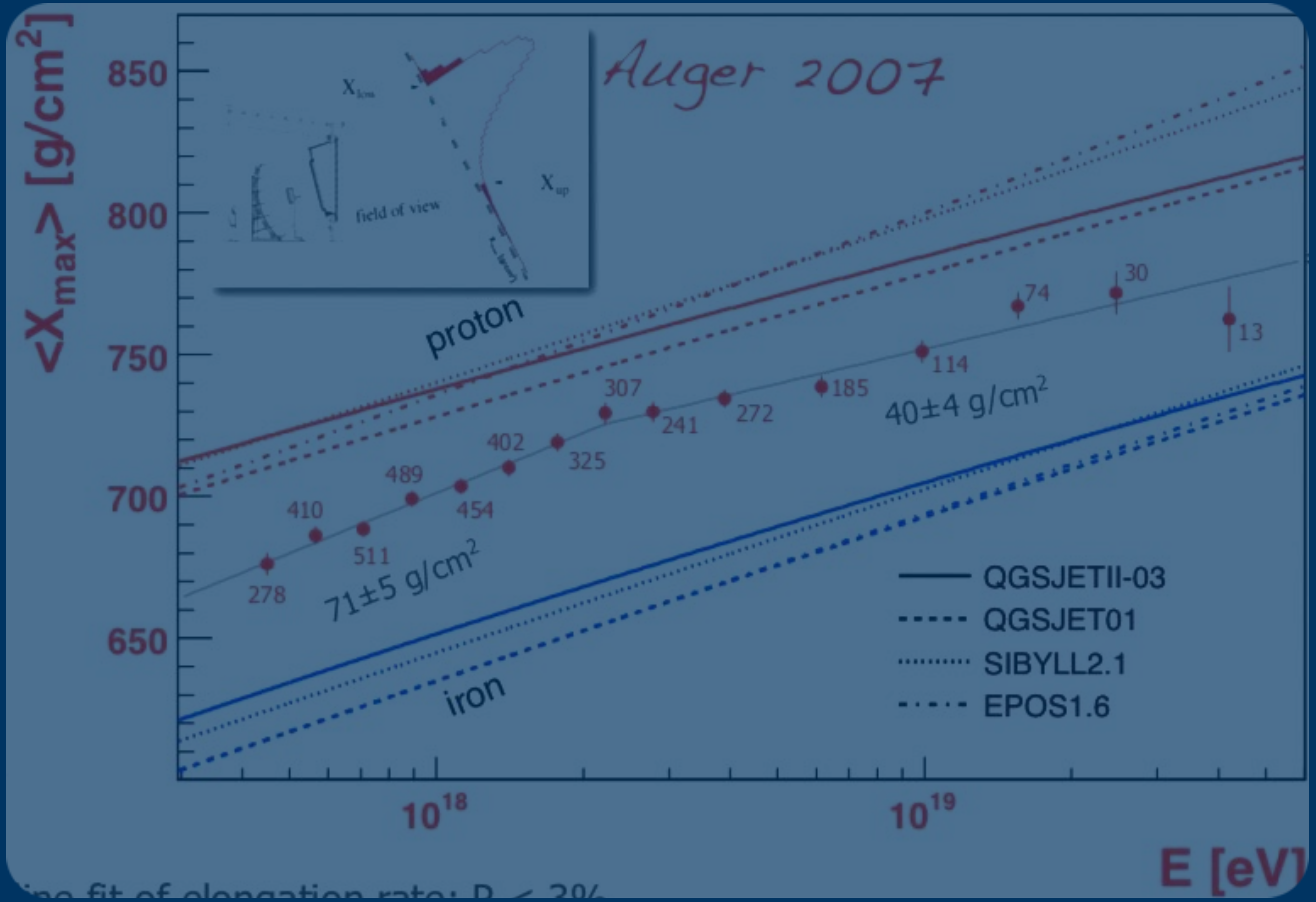
Mean composition gets lighter up to ≈ $10^{18.3}$ eV and heavier and heavier above

Constant elongation rate excluded at 4.6 σ

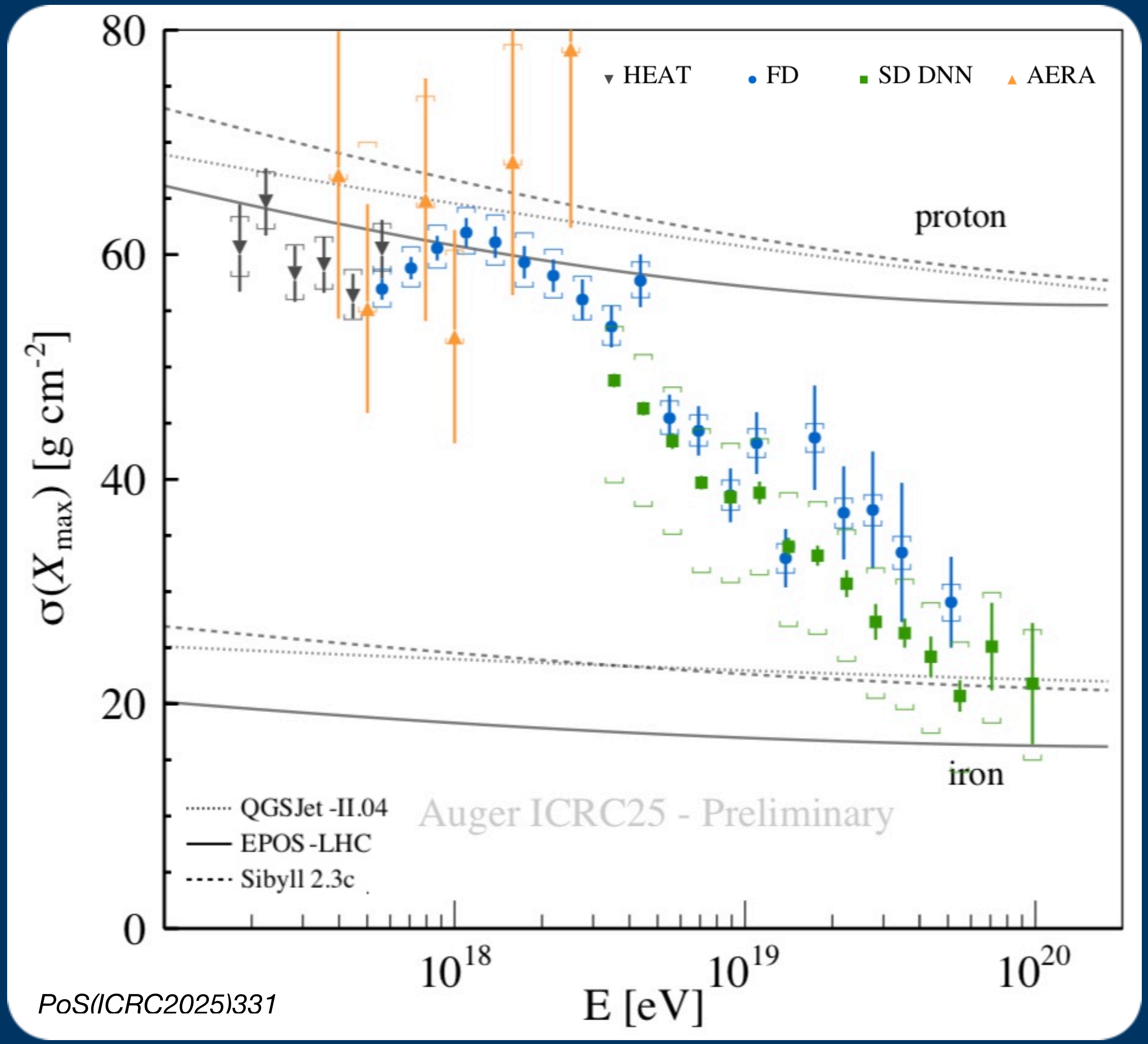
<Xmax> well-consistent for FD, SD, RD

Depth of shower maximum: data (and methods) evolution

Depth of shower maximum premiere observable for mass composition studies
Mass inference relies on hadronic models (evolving too: Xmax deeper by ≈ 30 g/cm2)



2025



Xmax not only from FD but also from SD (new methods) and RD-AERA

Xmax spread decrease with energy: heavier (and less mixed, purer) composition

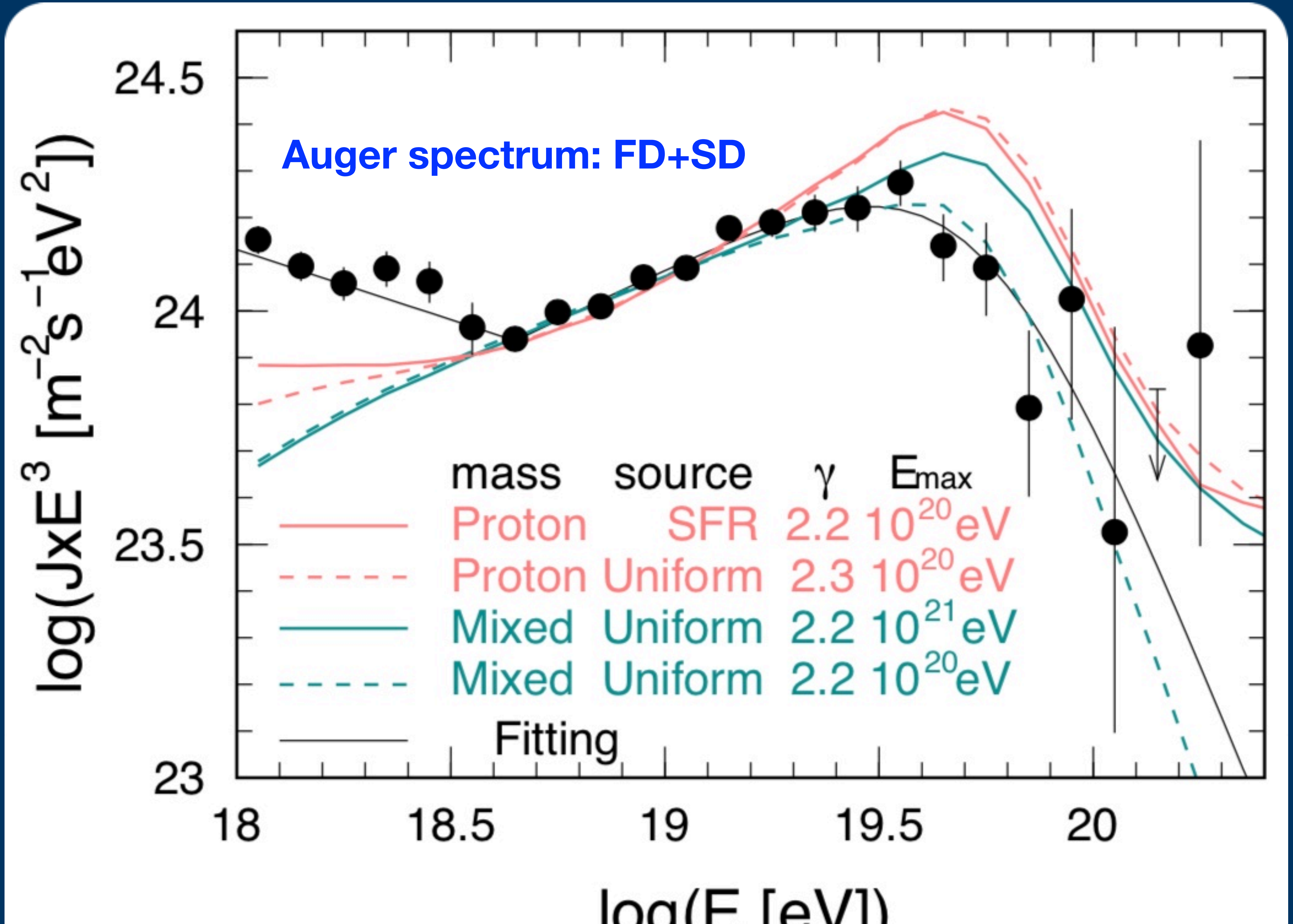
At the highest energies, very (very) small fraction of protons

Evolution of astrophysical interpretation

In early times, models probed with spectrum only (due to FD statistics)
Now more refined models, e.g., including spectrum data and Xmax distributions

(Much) more in Teresa Bister's talk

2007

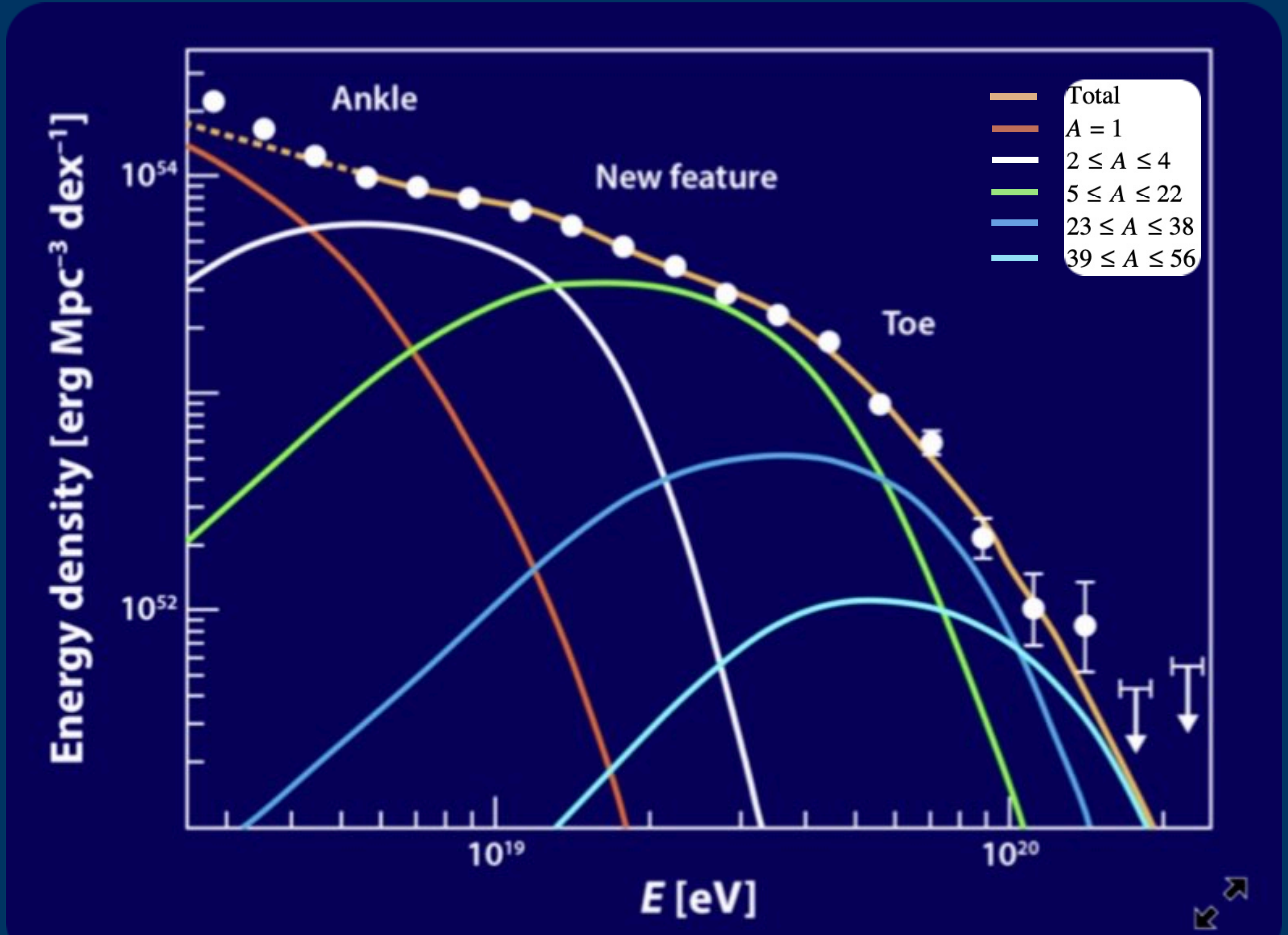


ICRC 2007

Models assuming all protons at the source disfavoured, favouring mixed compositions

NB. All models pointing to a "missing" component at the ankle (Galactic component?)

2025



2020 Physics 13, 145; PRL 125 (2020) 121106

Elements at the source dominated by intermediate-mass nuclei escaping with a very hard spectrum and low rigidity cutoff (E_{max} (Z) = Z × 5×10^{18} eV)

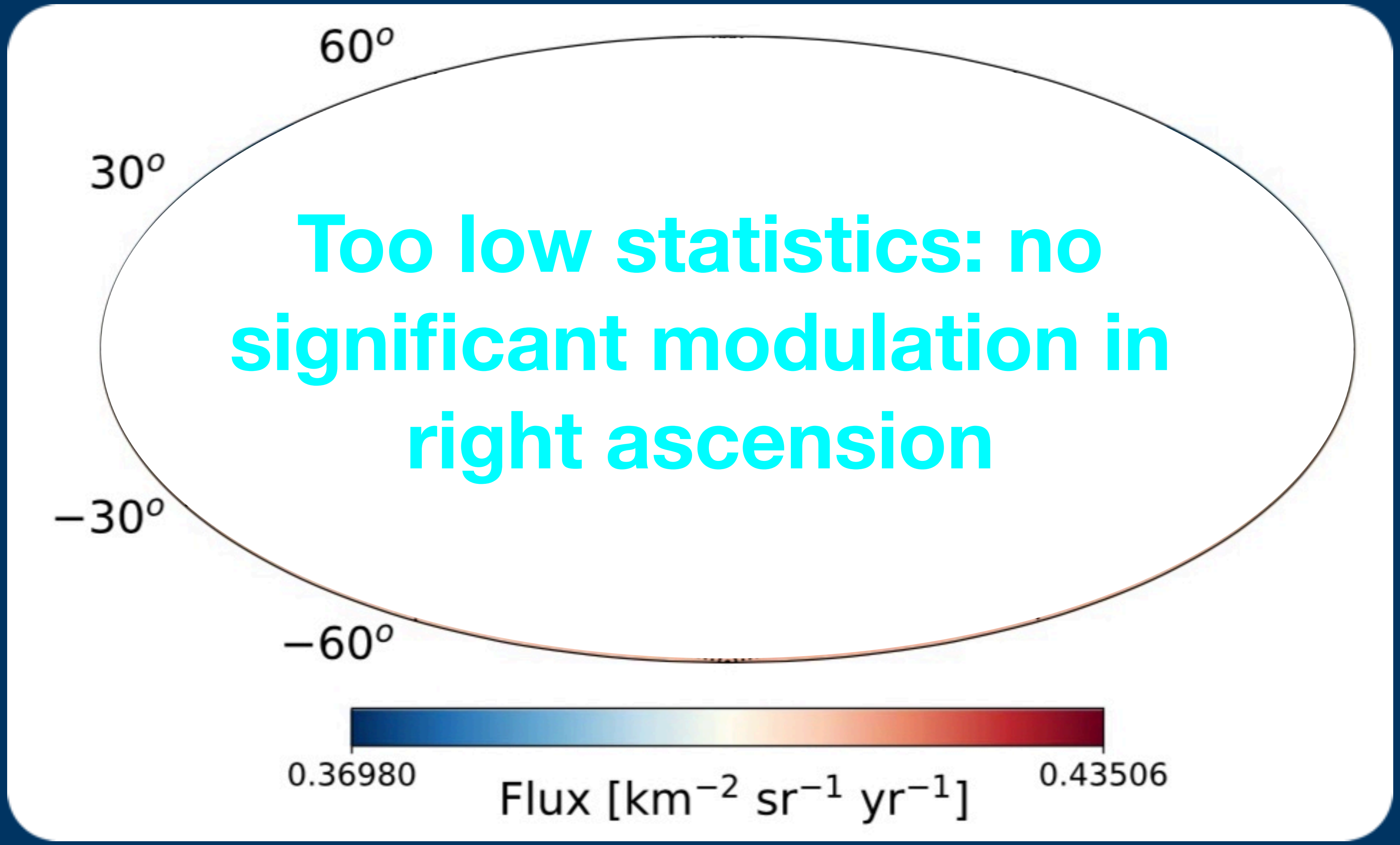
Suppression = Emax + propagation; instep = transition between He and CNO group

Evolution of the sky view

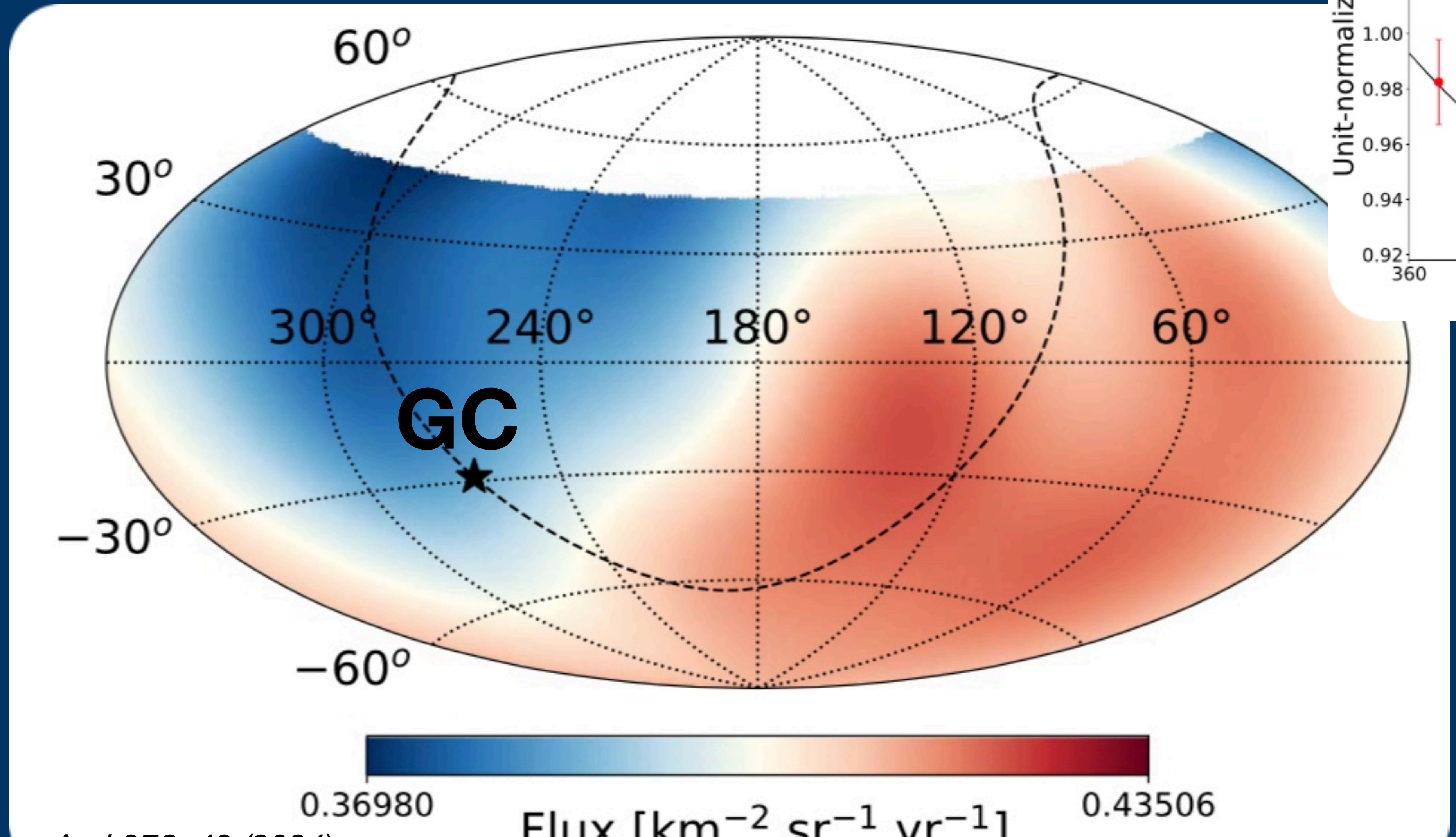
Discovery of a dipole and evidence of a growing excess in the Centaurus region

Large scale

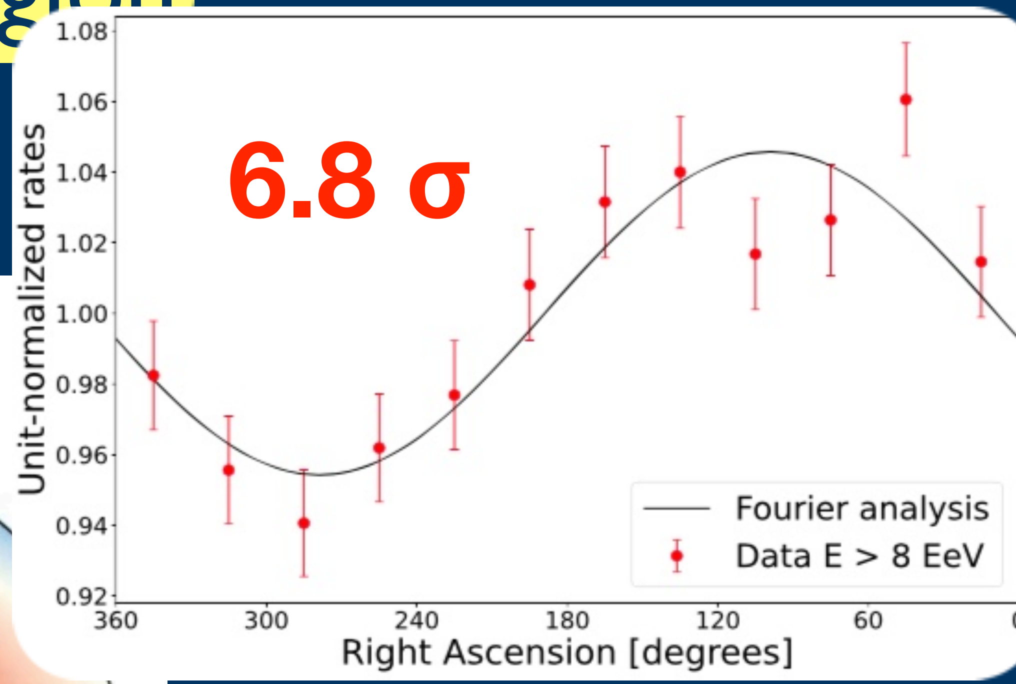
2007



2025



ApJ 976, 48 (2024)



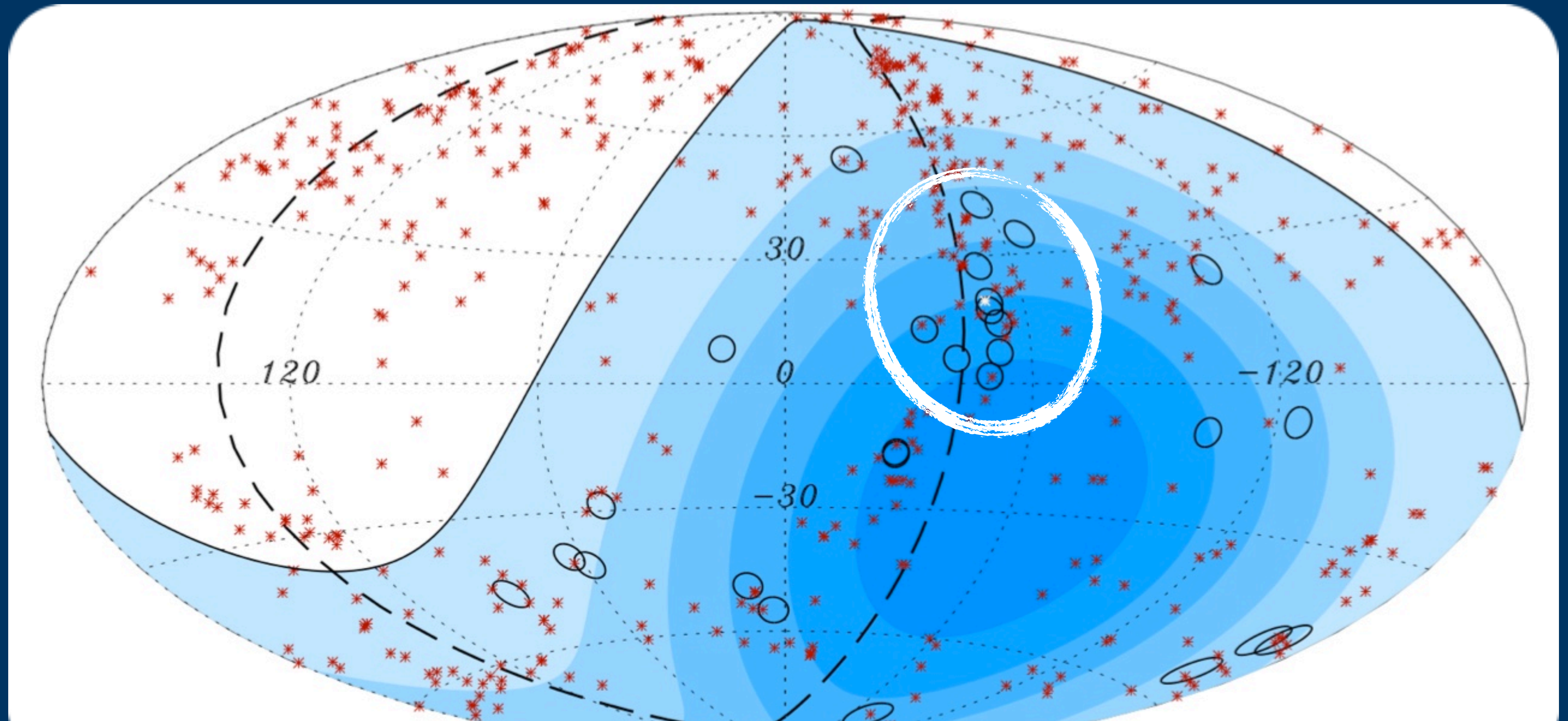
Dipolar anisotropy

Amplitude: ≈ 6.5%

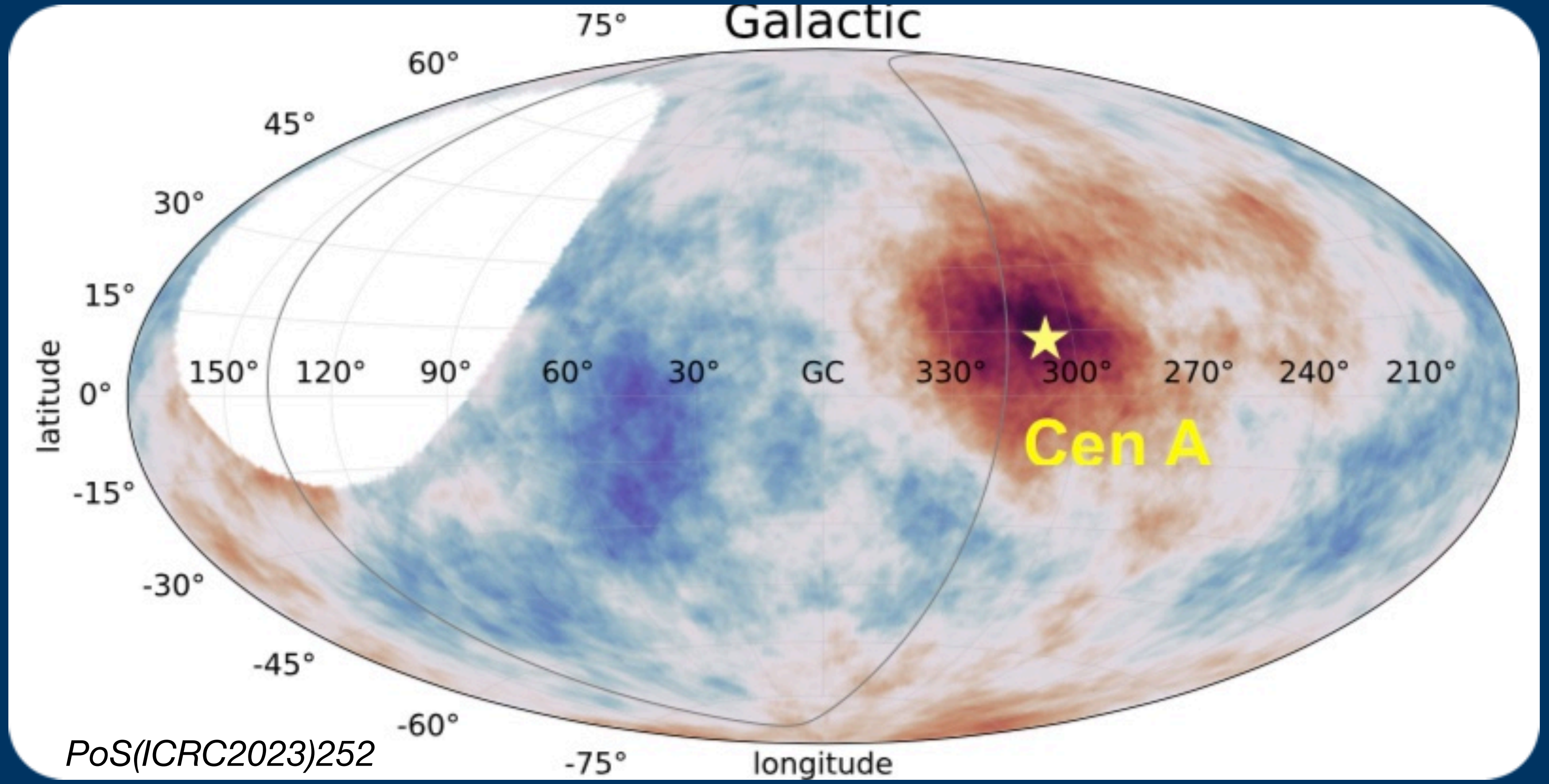
Direction: ≈ 113° away from the G.C.

Extragalactic origin

Small/Intermediate scale



Science 318, 938 (2007)



PoS(ICRC2023)252

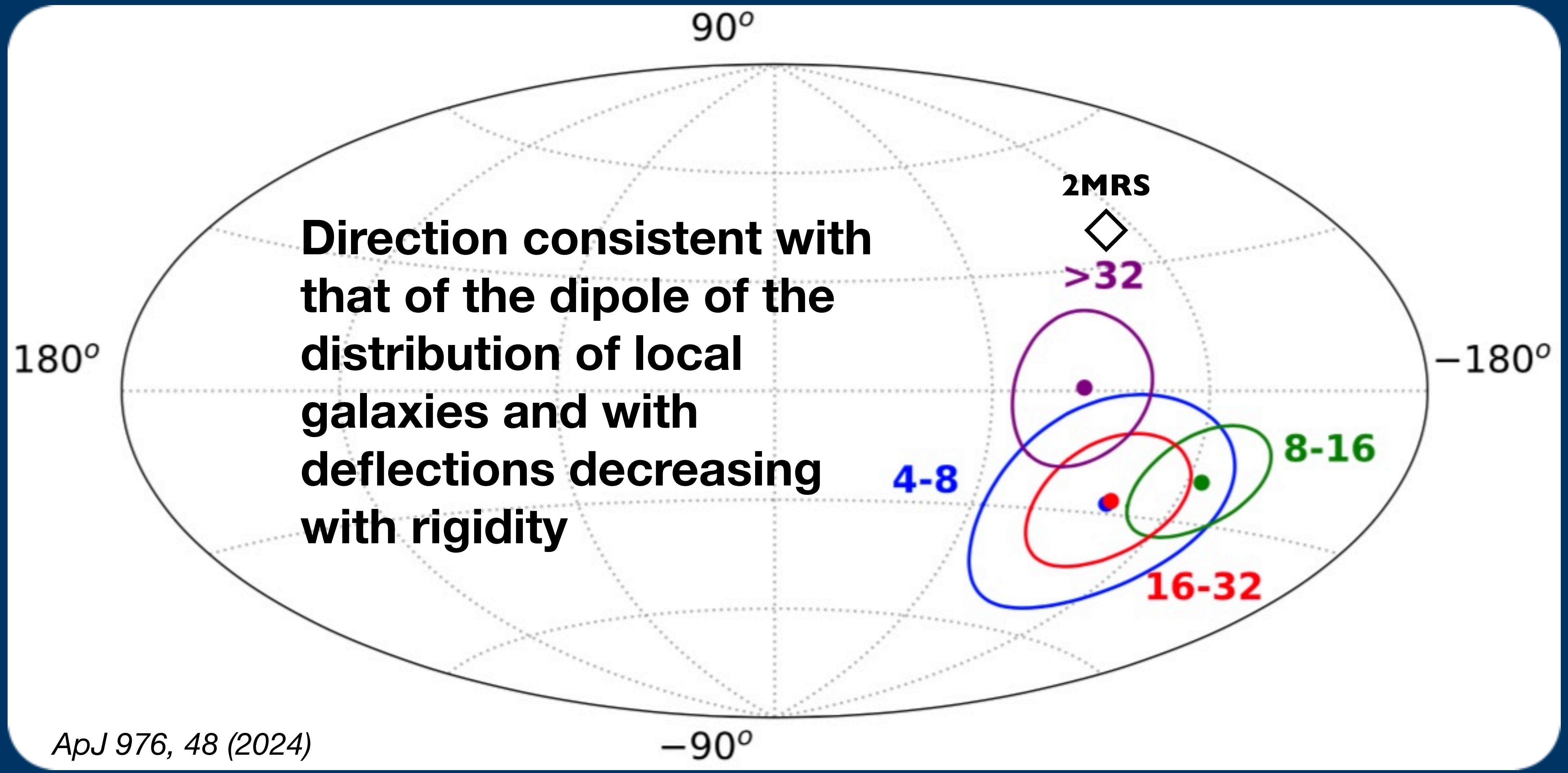
An old excess growing with time:

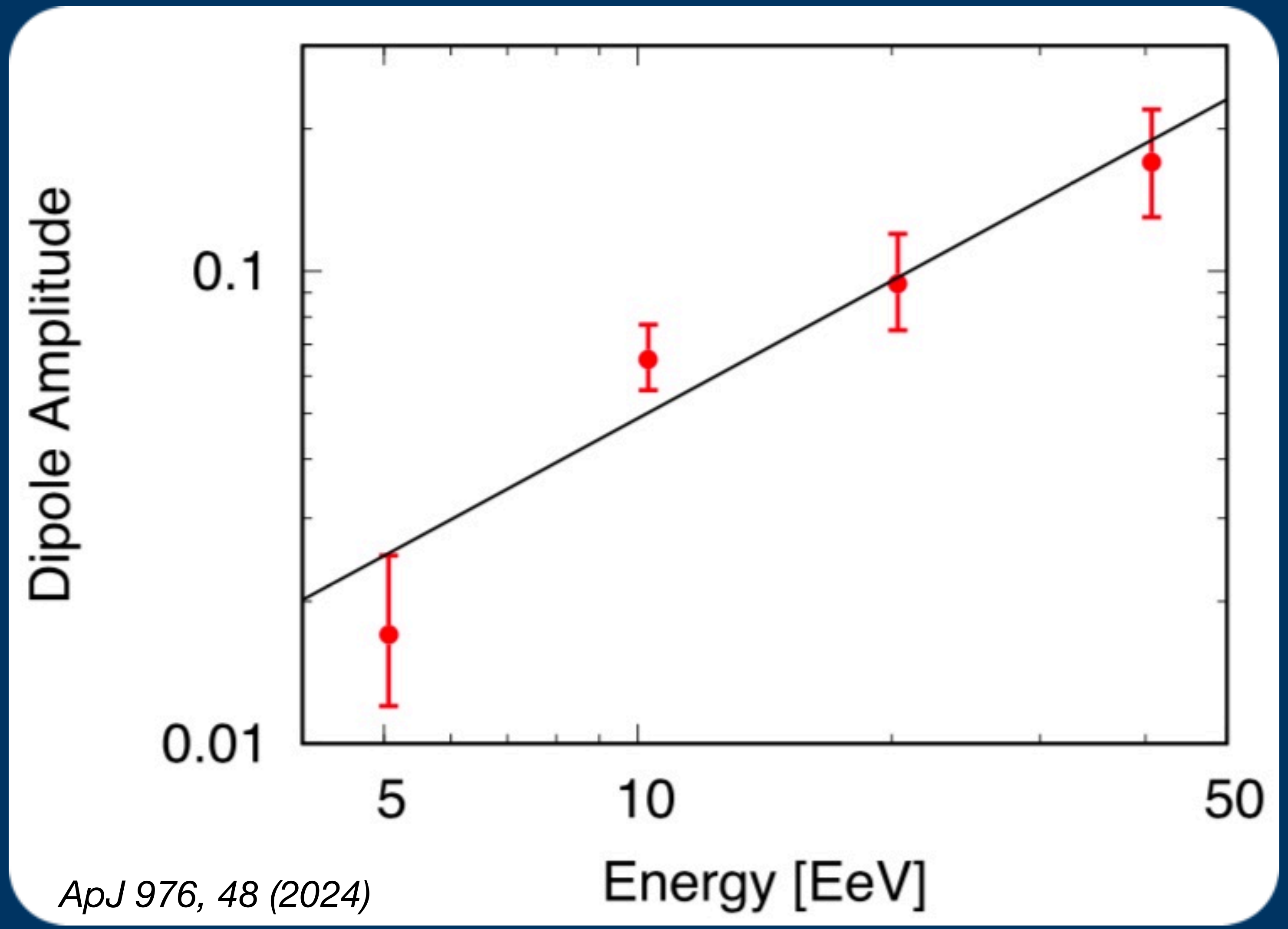
Max excess above 38 EeV, in a window of 27° radius: 4 σ post trial

Evolution of the sky view

Discovery of a dipole and evidence of a growing excess in the Centaurus region

Large scale

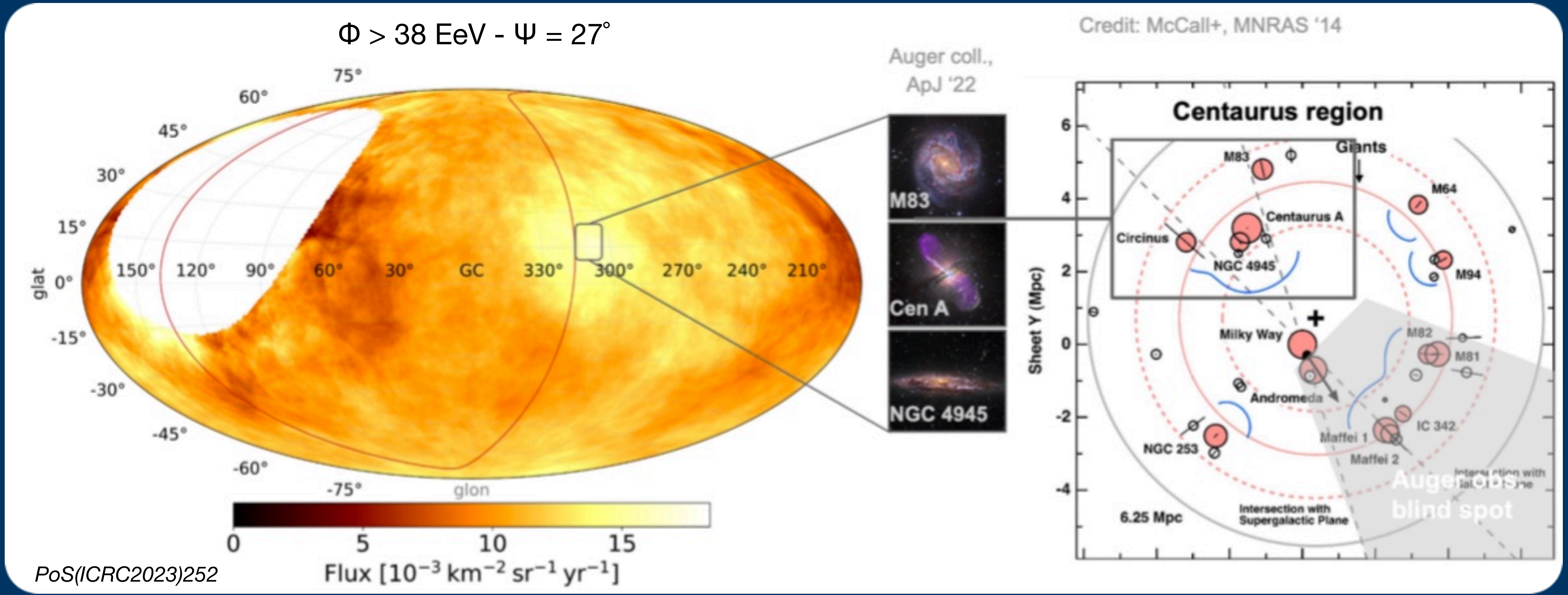




Amplitude increasing with energy: contribution from more and more nearby sources (shrinking horizon) as E increases.

Also: higher rigidities, smaller deflections, larger dipole.

Small/Intermediate scale



Test of different models (Cen-A, AGNs, Starburst Galaxies): all models capture the excess at the Centaurus region (Cen A or NGC4945+M83).

The SBG model also fits the mild excess in the SGP (NGC 253)

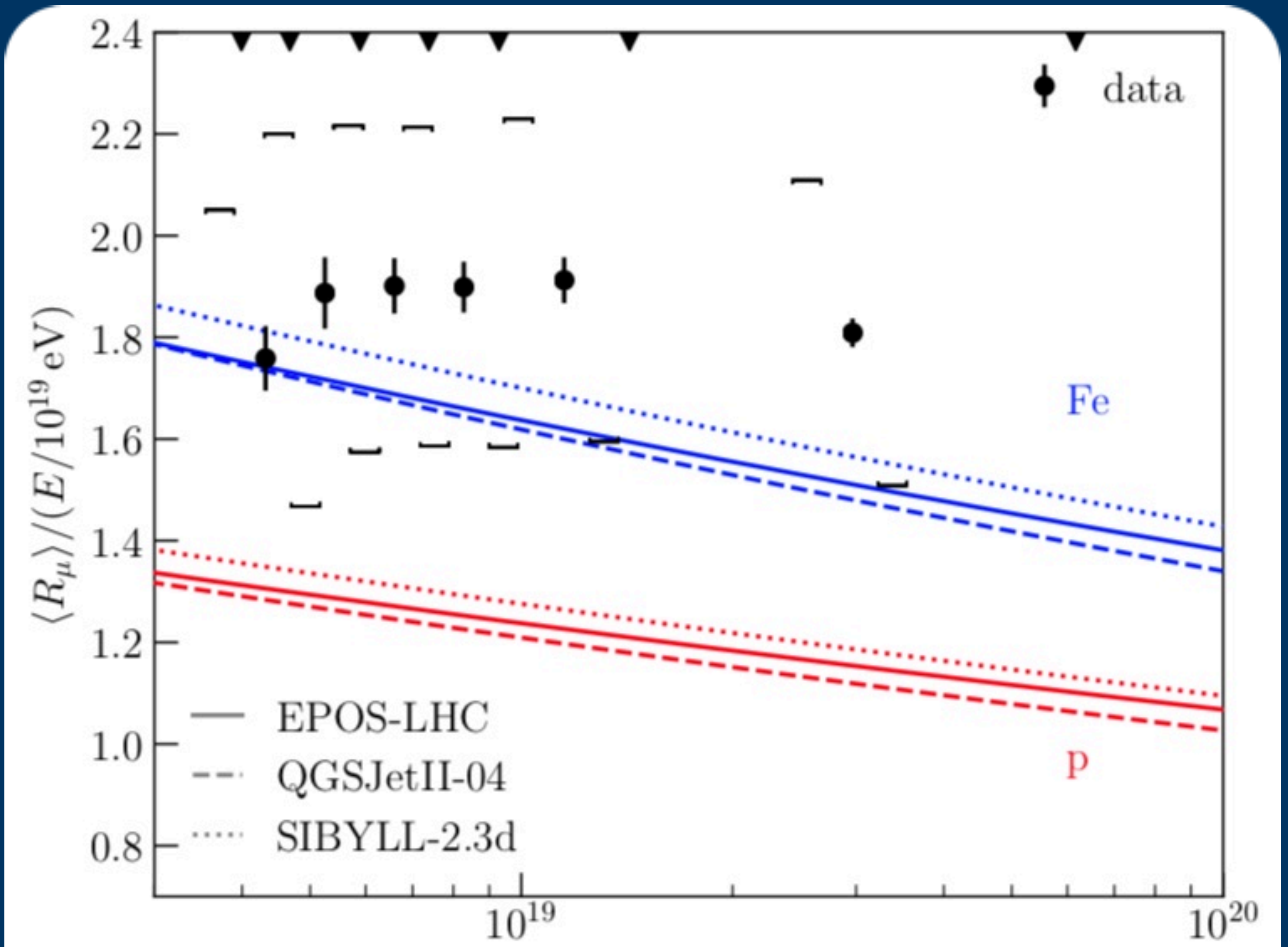
Evolution of scopes

Probing (evolving) hadronic-interaction models and particle physics

Hadronic models have evolved thanks to inputs from LHC but also from UHE CR instruments

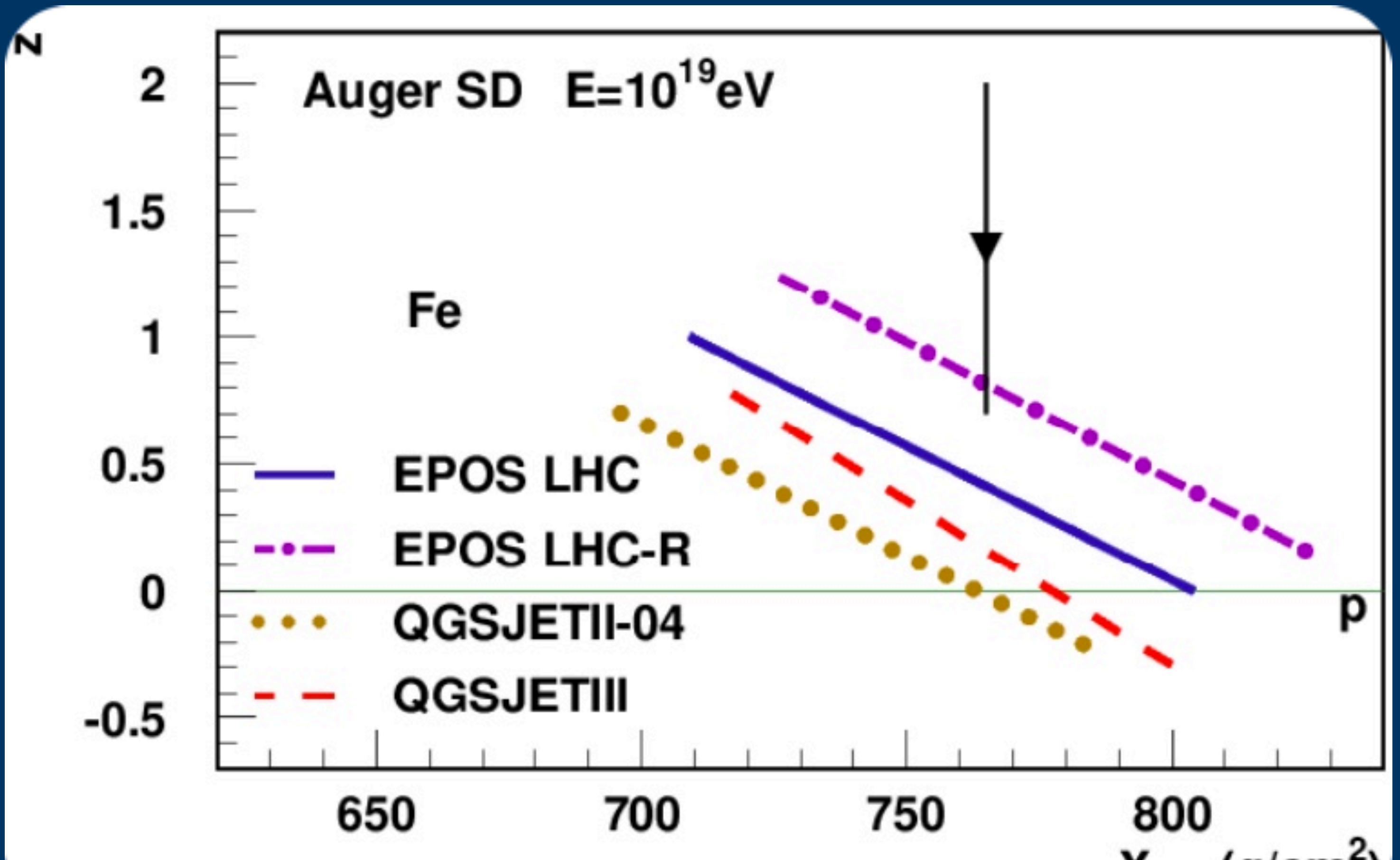
(Much) more in Eva Santos' talk

Discrepancy on mean number of shower muons between Auger data and predictions from hadronic models (too few muons)



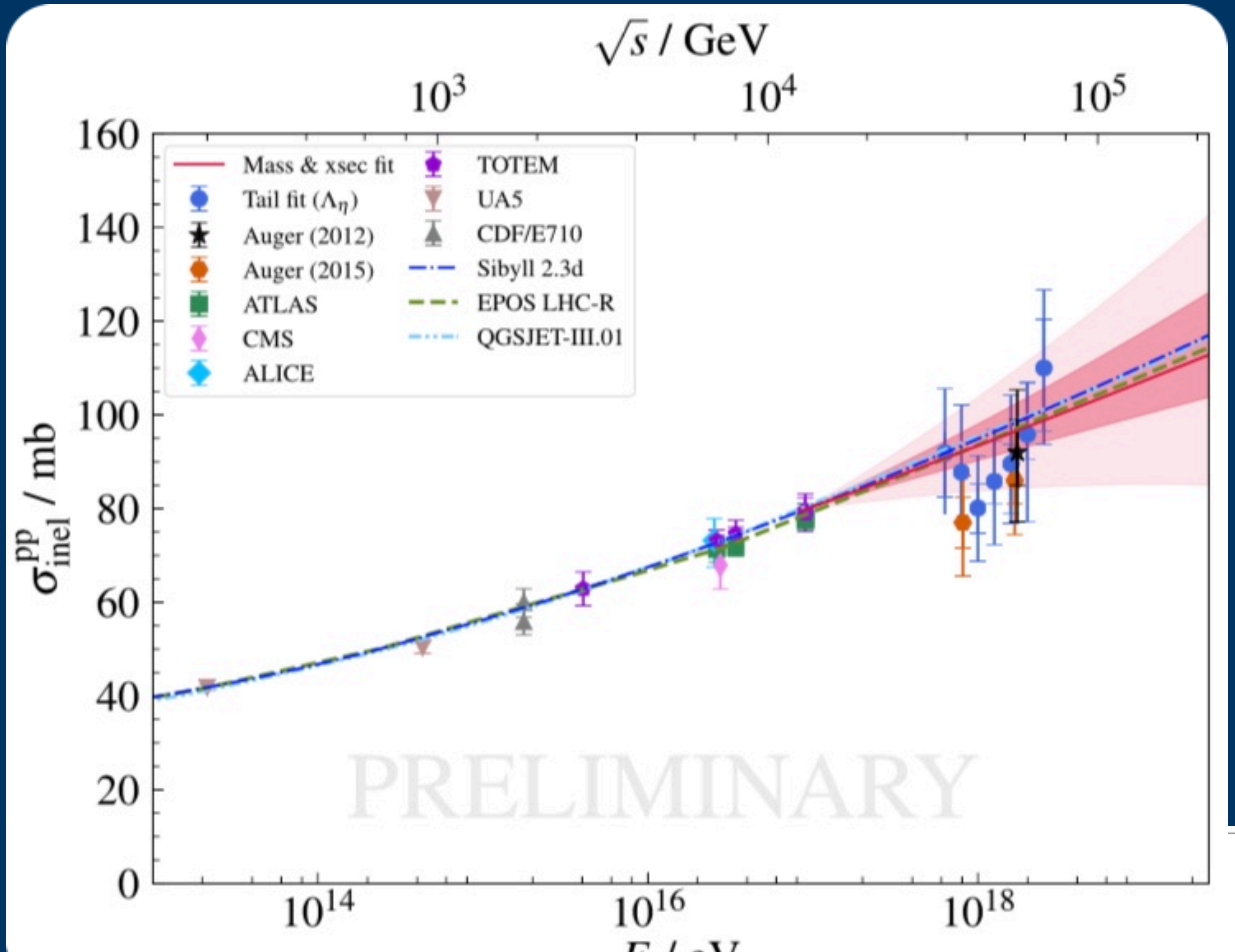
PRD 91, 032003 (2015)

Recently tuned models (EPOS LHC-R) seem to alleviate the discrepancy



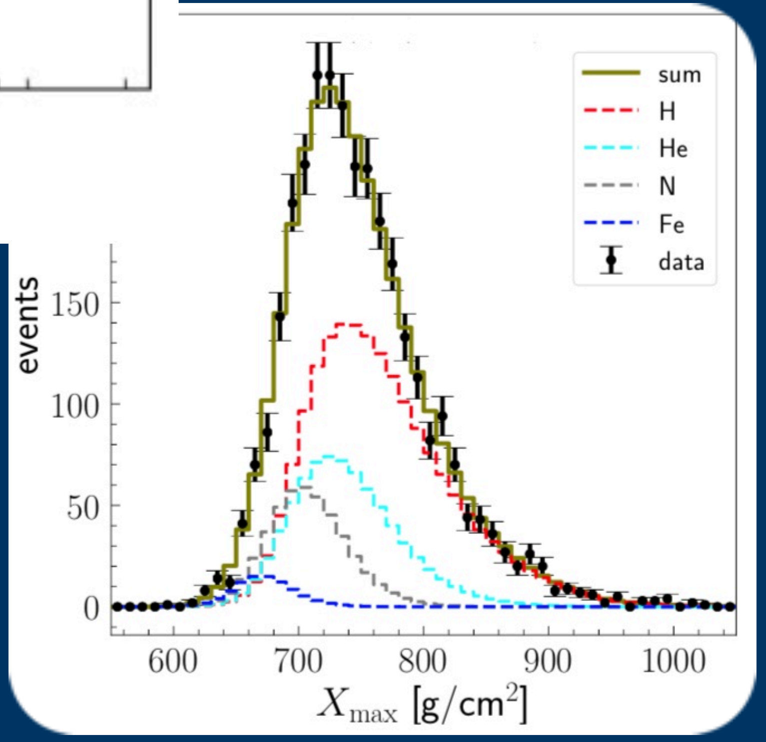
T.Pierog, ICRC 2025

Proton-proton cross-section at √s ≥ 40 TeV



POS(ICRC2025)416

Old Auger pp cross-section measurements (2012-2015) used the tail of the Xmax distribution, at energies where protons dominate



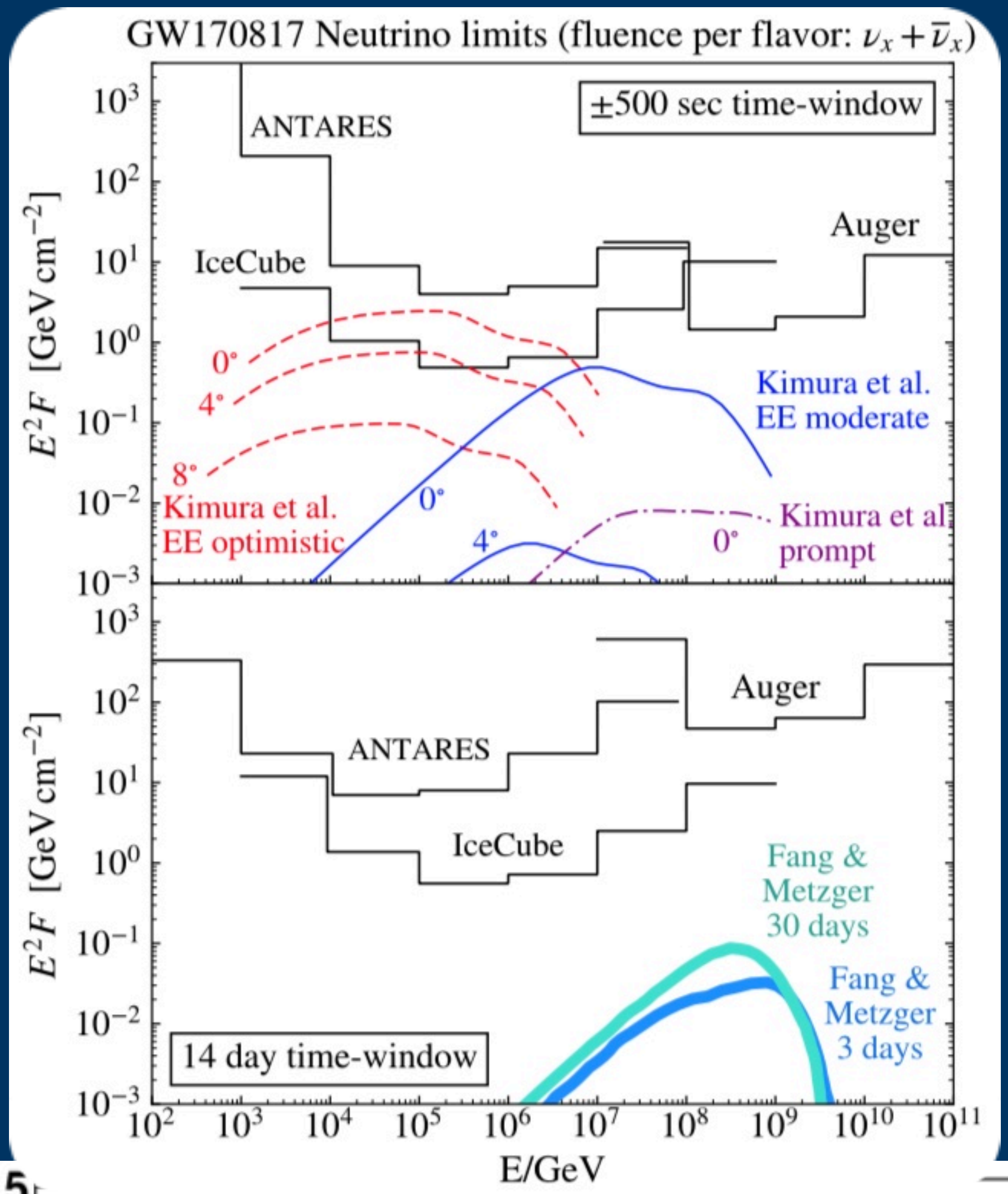
Novel method and measurement: use the full Xmax distribution vs energy, by fitting at the same time composition and cross-section

Evolving as an actor in multi-messenger astronomy

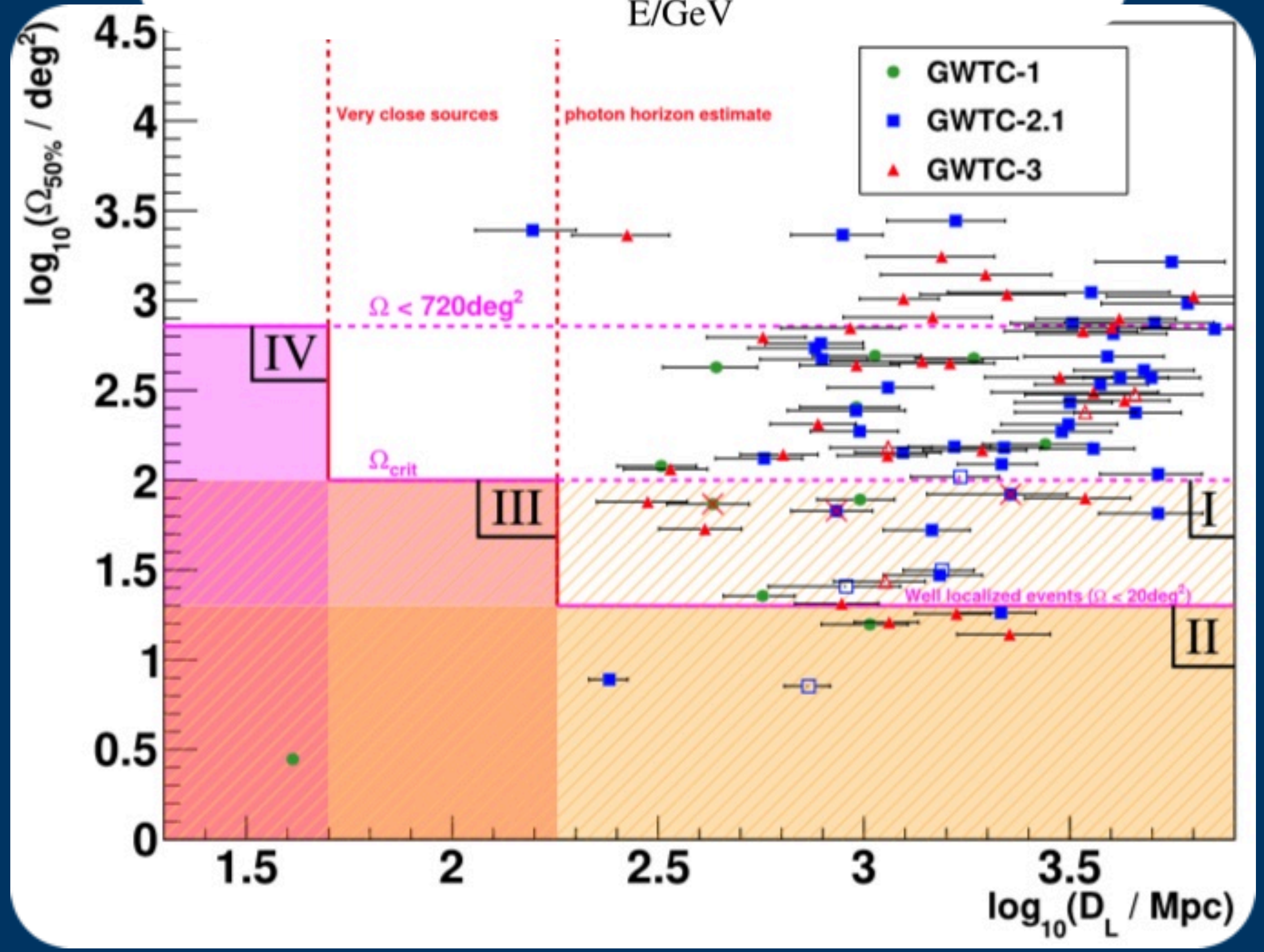
Auger as a neutrino and gamma-rays (potential) observatory too

(Much) more in Fiona Ellwanger's talk

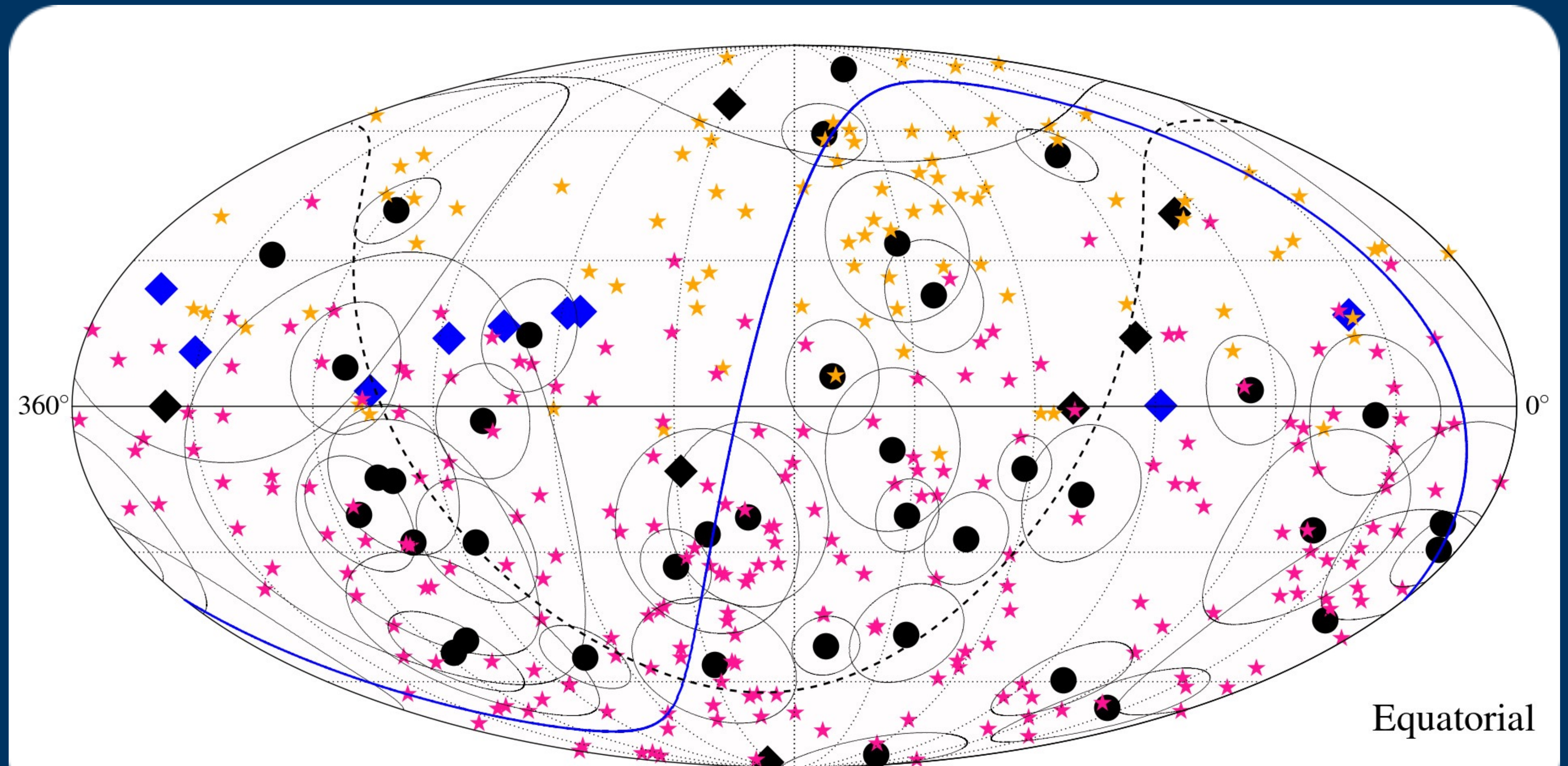
Search for UHE neutrinos from GW170817



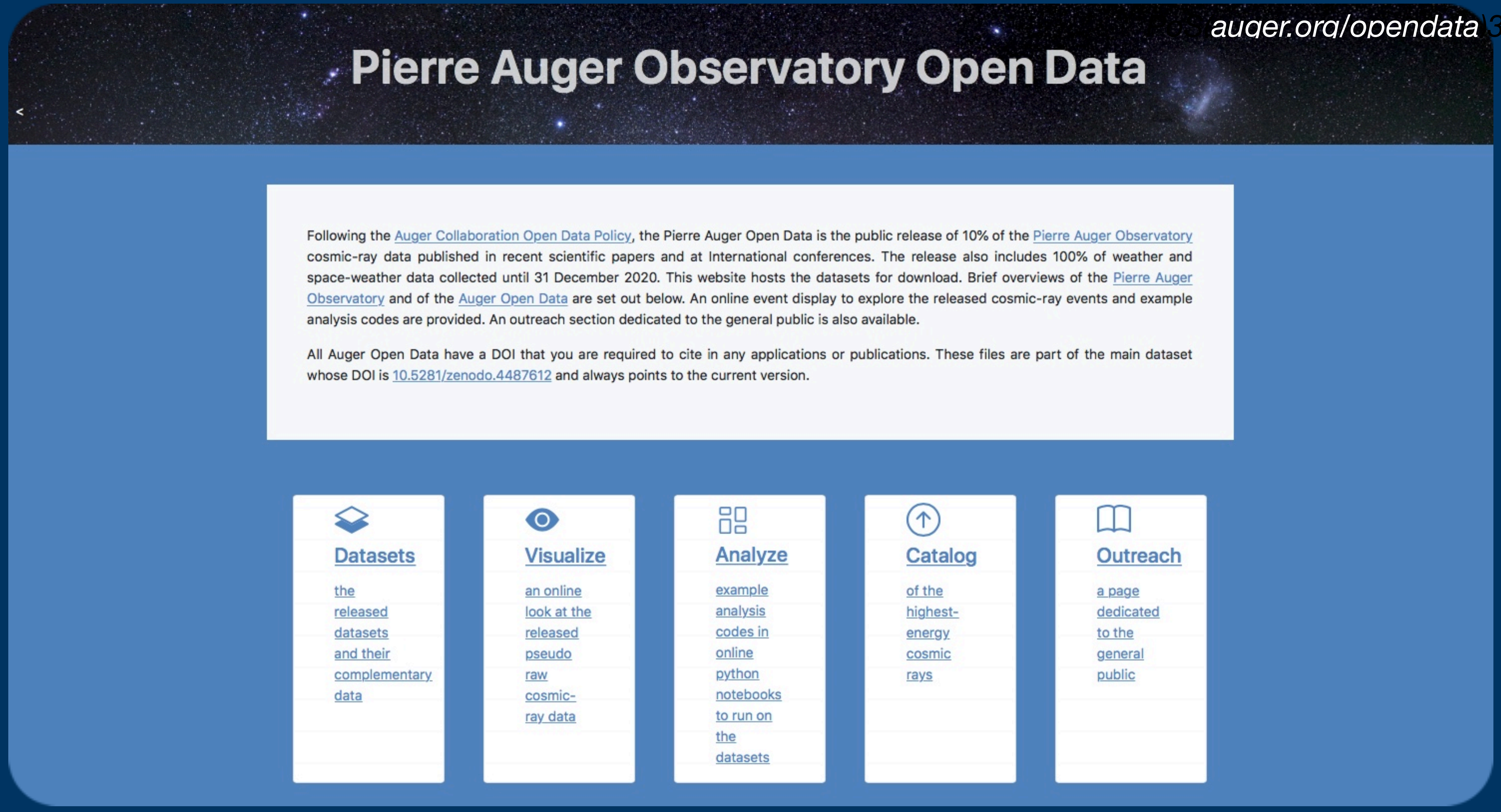
Search for UHE gamma-rays from (close-by) GWs from O1-2-3



Search for correlations between UHECRs (Auger & TA) and HE neutrinos (IceCube)



JCAP 1601 (2016) 037



Data accessible for MM studies:

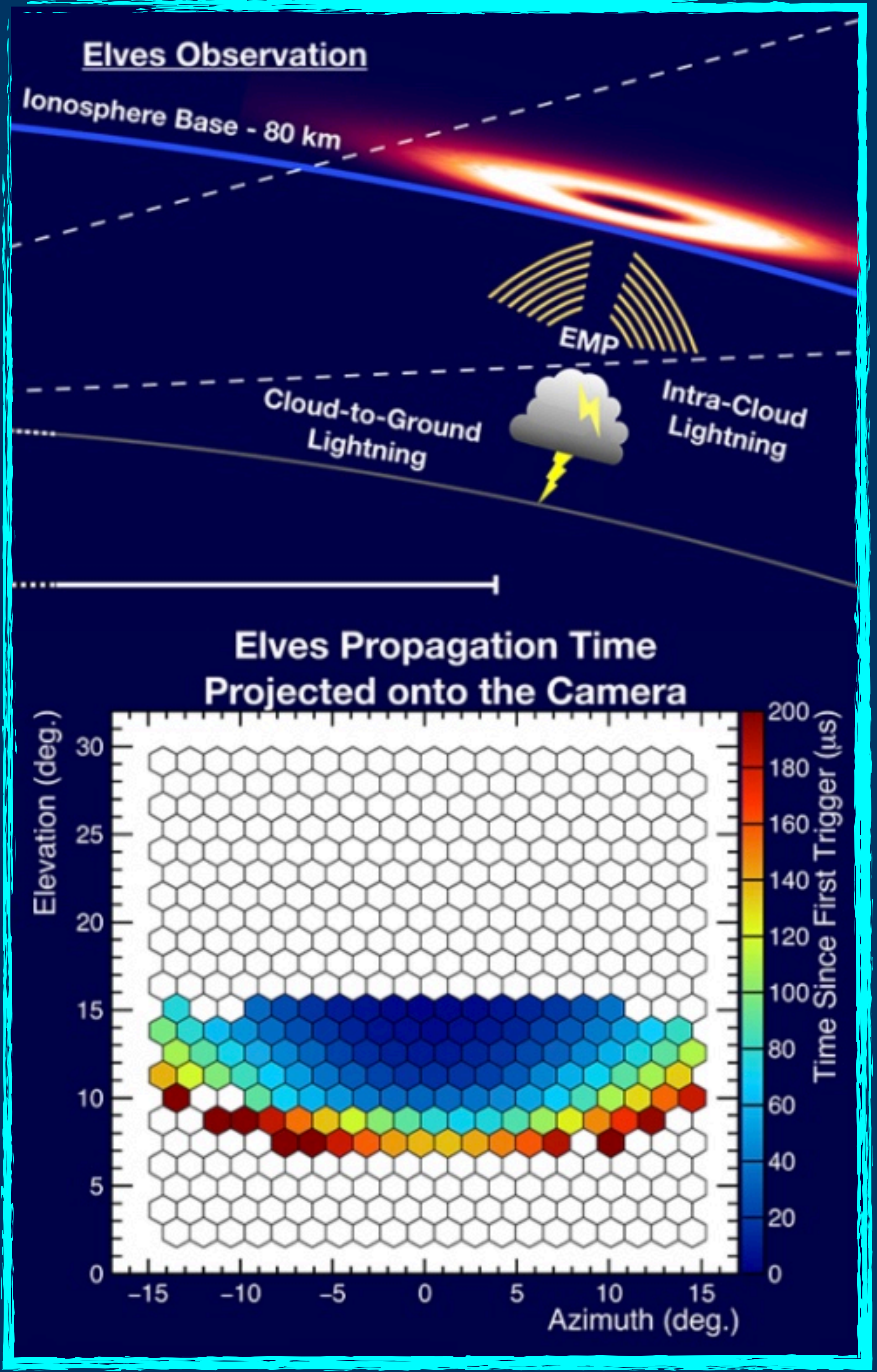
10% of data public since 2021, 30% very soon

Access via ACME and VO in the future

Geo and solar physics

Serendipitous discovery of atmospheric-electricity phenomena recorded with FD and SD
Sun activity monitor

Elves with FD



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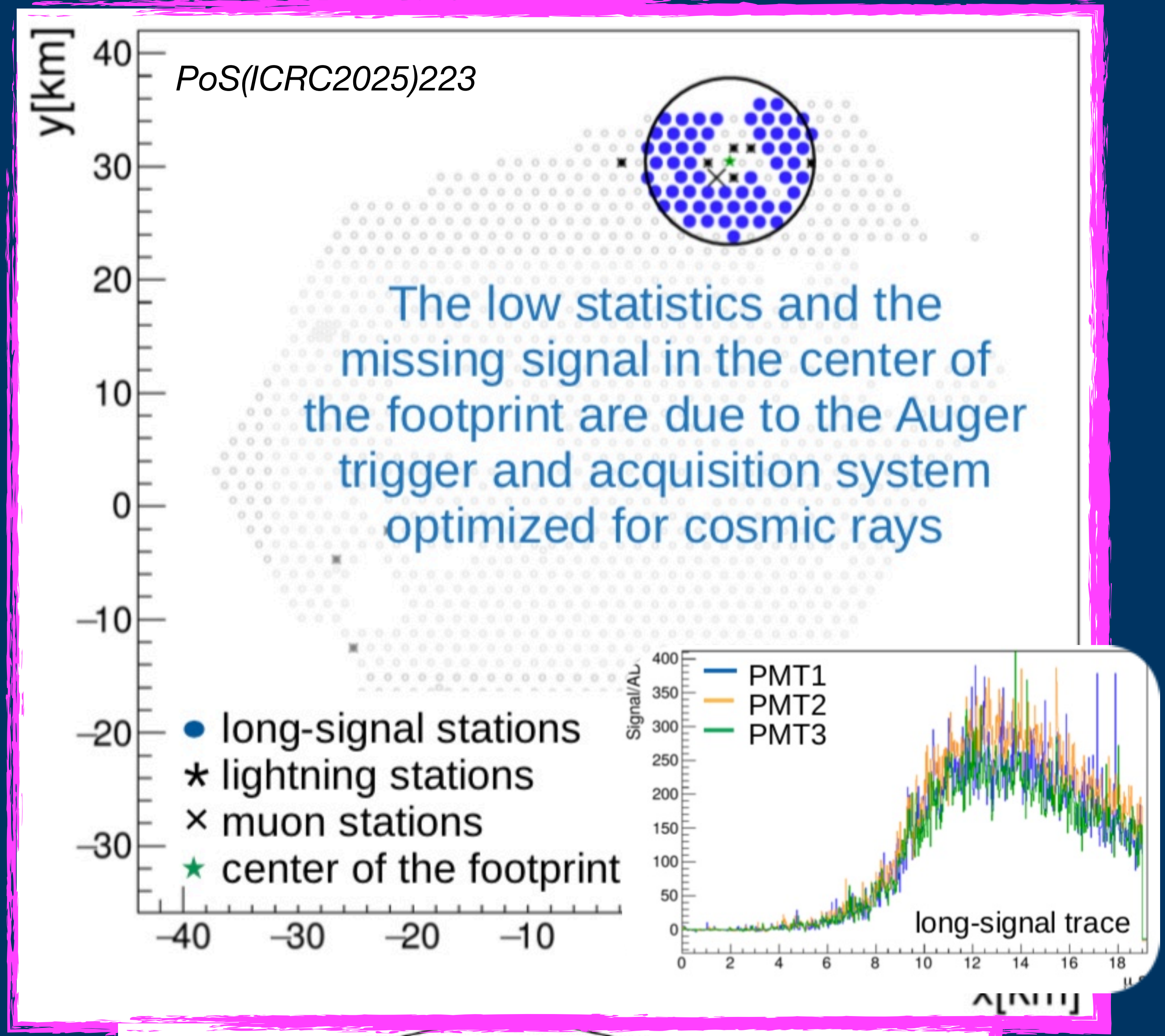
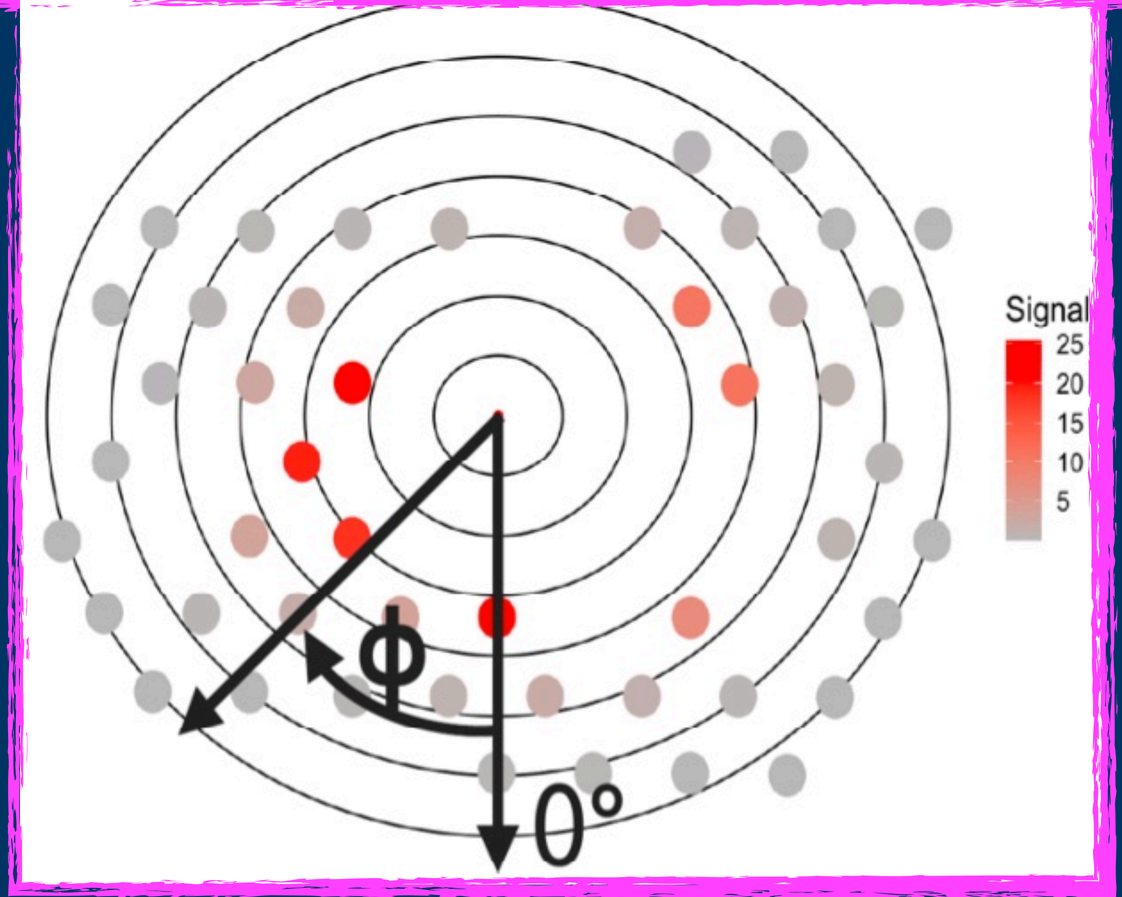
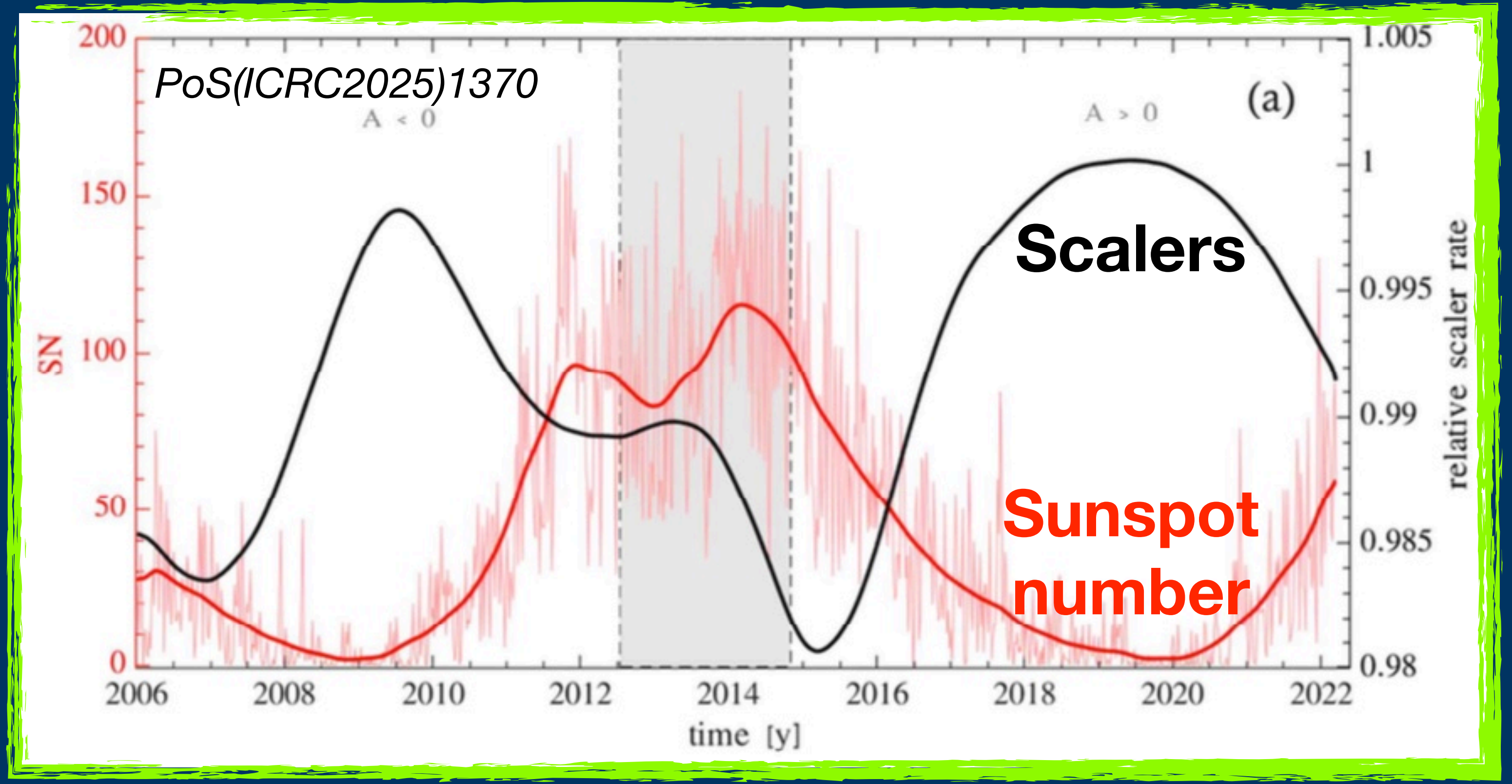
TGFs with SD

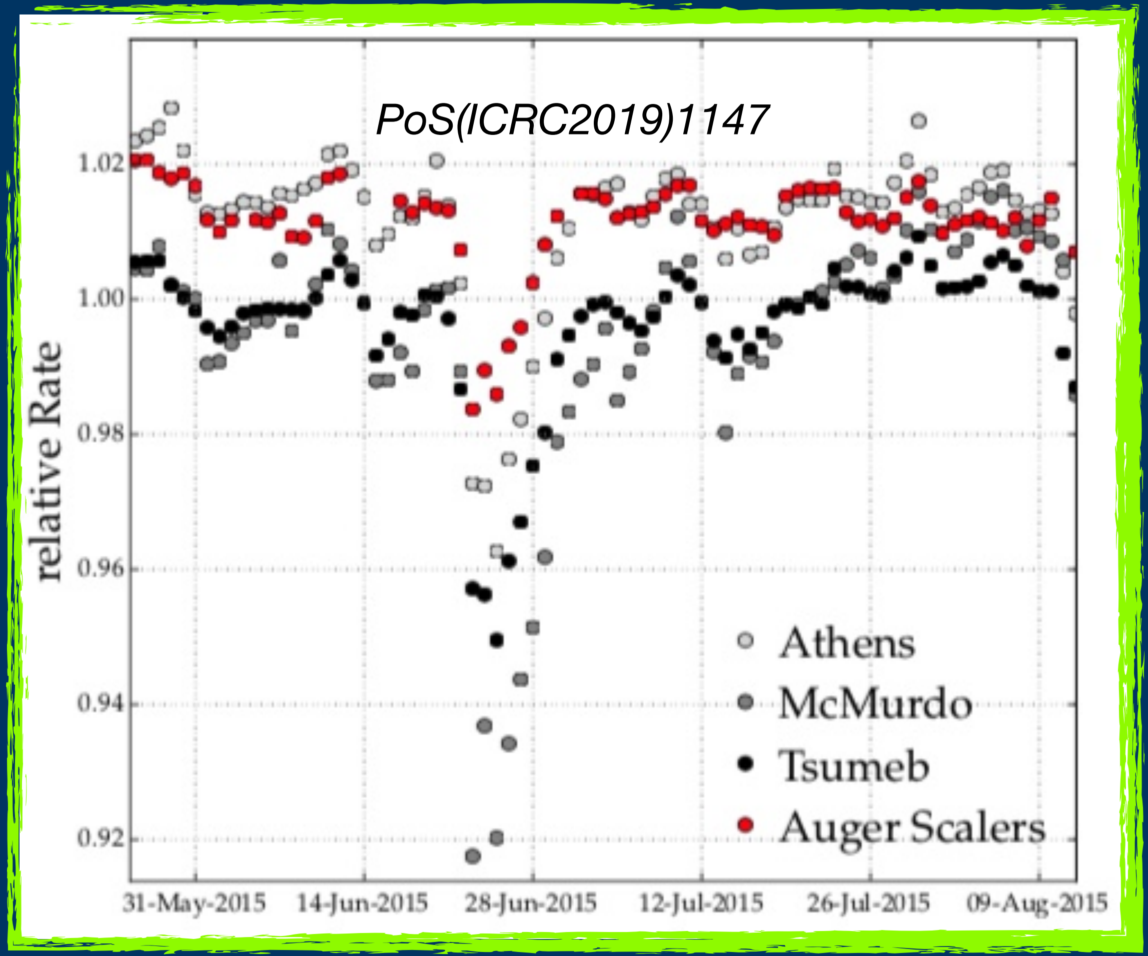




Sun with SD (scalers)



Decadal cycle (≈ 2 cycles)



Forbush decrease
(Coronal mass ejection)

25 years after: outcome and outlook

Mission not as simple after all: nature does not do what we wish for ;-)

Outcome

1. Precise reconstruction of all-particle energy spectrum (with the high statistics of SD): ***mission accomplished*** (a new feature even discovered)

2. Mass inference (with FD): **no pure protons, but indications of a mixed composition getting purer and purer (and heavier) at UHE. Mission partly accomplished: lacking statistics at UHE**

3. Mass inference consistent over time, even with evolving hadronic models. Auger data **probed models** and helped them to evolve**. Mission accomplished.**

4. **A non-predicted large-scale anisotropy discovered**, but origin still to be clarified. At smaller scales, **a 4σ excess within ≈ 30°** has been developing over years, but even it gets 5σ, it will prove anisotropy, not origin. **Mission not accomplished**

Outlook

Energy spectrum. Reconstruction of spectrum of elements

Corollary. Keep looking for UHE neutrinos and γ-rays, with better discrimination vs hadrons.

Arrival directions. *Study distributions by discriminating elements (lighter vs heavier, smaller vs larger deflections). Include magnetic fields (evolving models for those too)*

Mass: extend Xmax measurement with SD, using different detectors (multi-hybrid) that probe different shower components.

Hadronic models: keep probing them, help them evolve, **always use most modern models**

The new, not simple, mission of the upgraded Pierre Auger Observatory

Not only instruments, results and science, but also, above all, relentless people

THANKS