Subir-fest: Oxford 11 – 13 September 2023

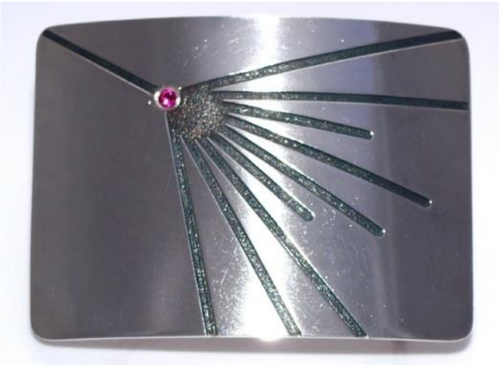
Subir, High Energy Neutrinos and the Pierre Auger Observatory

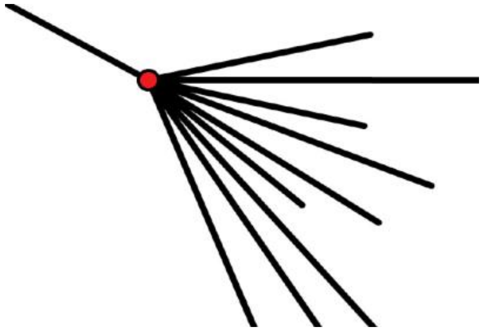
– friend and fellow neutrino hunter

Alan Watson

University of Leeds, UK

a.a.watson@leeds.ac.uk





International School of Cosmic Ray Astrophysics, Erice 1978

Later meeting 21st School in 2018

Fred Reines

Dave Schramm

Peter Fowler

John Linsley

John Simpson

....

ELSEVIER
Astroparticle Physics 23 (2005) 11–17
www.elsevier.com/locate/astropart

The impact of heavy nuclei on the cosmogenic neutrino flux

Dan Hooper [a], Andrew Taylor [a], Subir Sarkar [b,*]

[a] *Astrophysics, University of Oxford, Oxford OX1 3RH, UK*
[b] *Theoretical Physics, University of Oxford, Oxford OX1 3NP, UK*

Received 2 August 2004; received in revised form 21 October 2004; accepted 3 November 2004
Available online 8 December 2004

Web of Science
85 citations
Inspire
125

ELSEVIER
Astroparticle Physics 23 (2005) 19–29
www.elsevier.com/locate/astropart

Cosmogenic neutrinos from ultra-high energy nuclei

M. Ave [a,d], N. Busca [a,c], A.V. Olinto [a,b,d,*], A.A. Watson [e], T. Yamamoto [a,d]

[a] *Kavli Institute of Cosmological Physics, The University of Chicago, 5640 S. Ellis, Chicago, IL 60637, USA*
[b] *Department of Astronomy and Astrophysics, The University of Chicago, 5640 S. Ellis, Chicago, IL 60637, USA*
[c] *Department of Physics, The University of Chicago, 5640 S. Ellis, Chicago, IL 60637, USA*
[d] *Enrico Fermi Institute, The University of Chicago, 5640 S. Ellis, Chicago, IL 60637, USA*
[e] *Department of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK*

Received 14 September 2004; received in revised form 6 November 2004; accepted 8 November 2004
Available online 7 December 2004

Web of Science
99 citations
Inspire
142

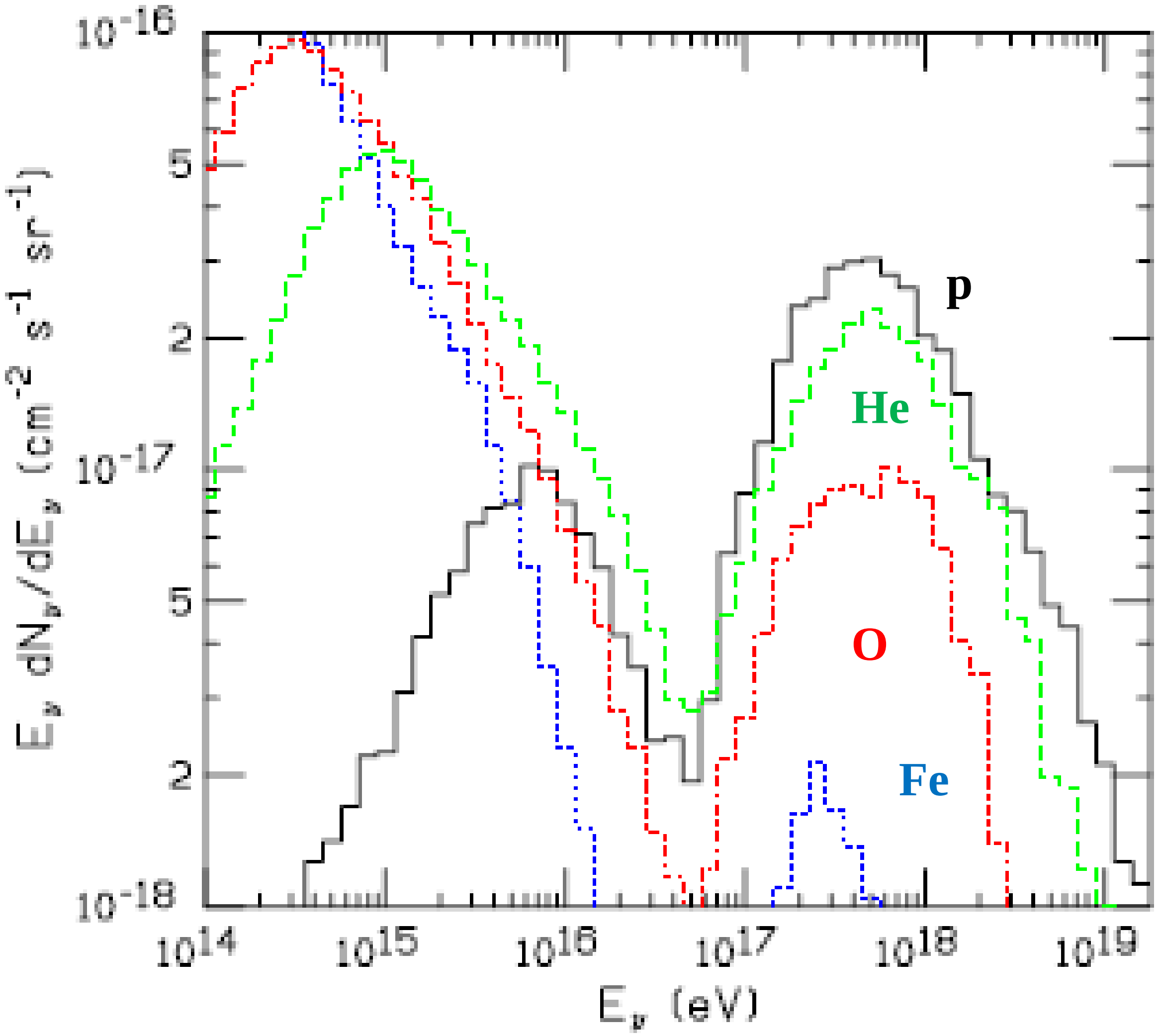
Neutrino flux very dependent on primary mass

$$p + \gamma_{2.7\,K} \rightarrow \Delta^+ \rightarrow p + \pi^0$$

or $n + \pi^+$

$$Fe^{56} + \gamma_{2.7\,K,\,ir} \rightarrow Fe^{55} + n$$

GZK effects:
Greisen (1966)
Zatsepin and Kuzmin (1966)



From Hooper, Taylor and Sarkar 2005

Member of Auger Collaboration 2006 – 2012, with main interest in the search for neutrinos


OBSERVATORIO
PIERRE AUGER

Paper started on Auger Shift: PRD 74 043008 2006

Probing low-x QCD with cosmic neutrinos at the Pierre Auger Observatory

Luis A. Anchordoqui,[1,2] Amanda M. Cooper-Sarkar,[3] Dan Hooper,[4] and Subir Sarkar[5]

[1] *Department of Physics, Northeastern University, Boston, MA 02115, USA*
[2] *Department of Physics, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53201, USA*
[3] *Particle Physics, Denys Wilkinson Laboratory, University of Oxford, Keble Road, Oxford, OX1 3RH, UK*
[4] *Particle Astrophysics Center, Fermilab, P.O. Box 500, Batavia, IL 60510, USA*
[5] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, Oxford, OX1 3NP, UK*

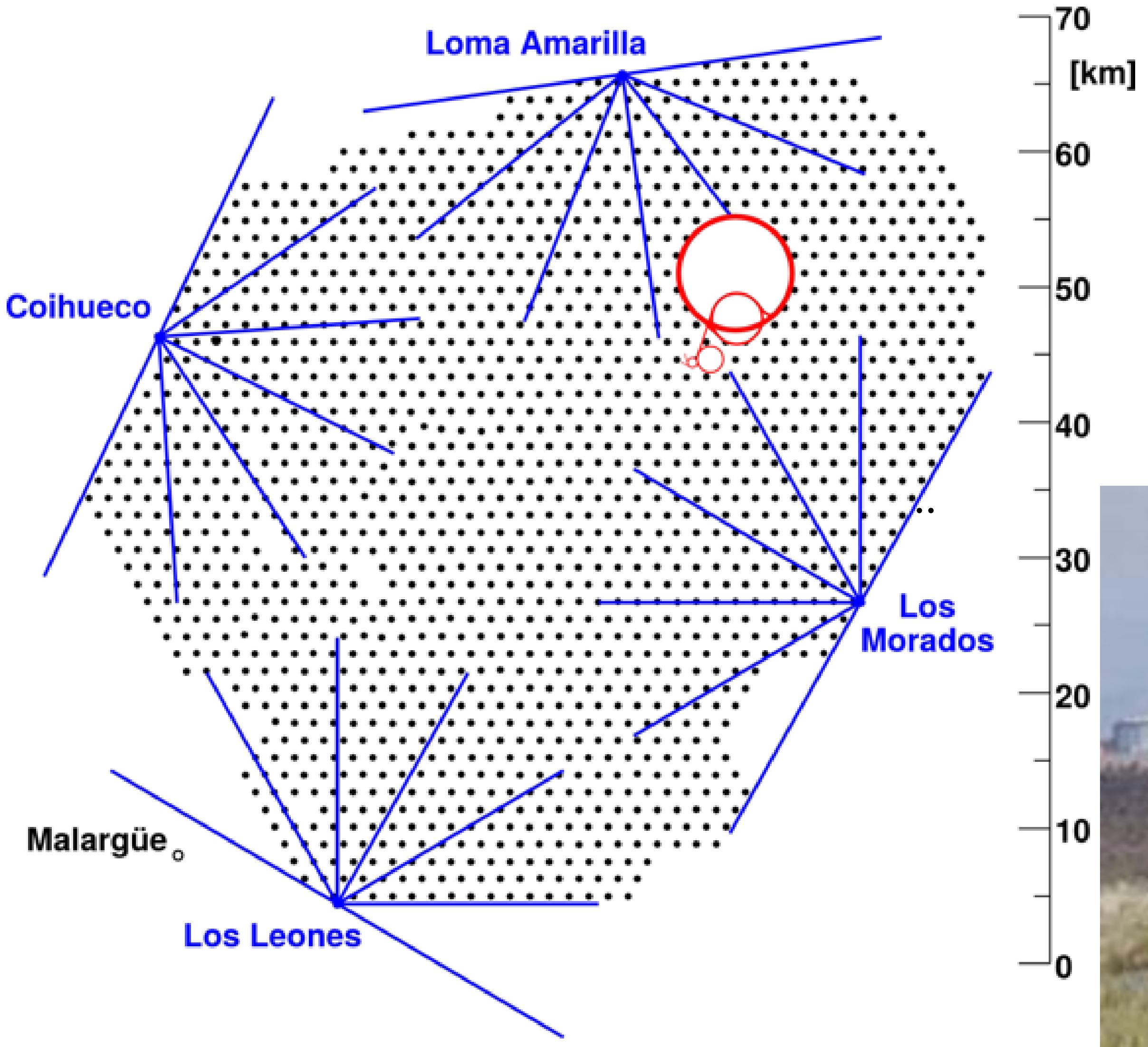
(Dated: June 4, 2018)

The sources of the observed ultra-high energy cosmic rays must also generate ultra-high energy neutrinos. Deep inelastic scattering of these neutrinos with nucleons on Earth probe center-of-mass energies $\sqrt{s} \sim 100$ TeV, well beyond those attainable at terrestrial colliders. By comparing the rates for two classes of observable events, any departure from the benchmark (unscreened perturbative QCD) neutrino-nucleon cross-section can be constrained. Using the projected sensitivity of the Pierre Auger Observatory to quasi-horizontal showers and Earth-skimming tau neutrinos, we show that a 'Super-Auger' detector can thus provide an unique probe of strong interaction dynamics.

'Super-Auger' x8 present size!

LAA is partially supported by NSF Grant No. PHY-0457004. DH is supported by the DOE and by NASA Grant NAG5-10842. SS acknowledges a PPARC Senior Research Fellowship (PPA/C506205/1). We wish to thank Jim Cronin and Alan Watson for discussions and encouragement.

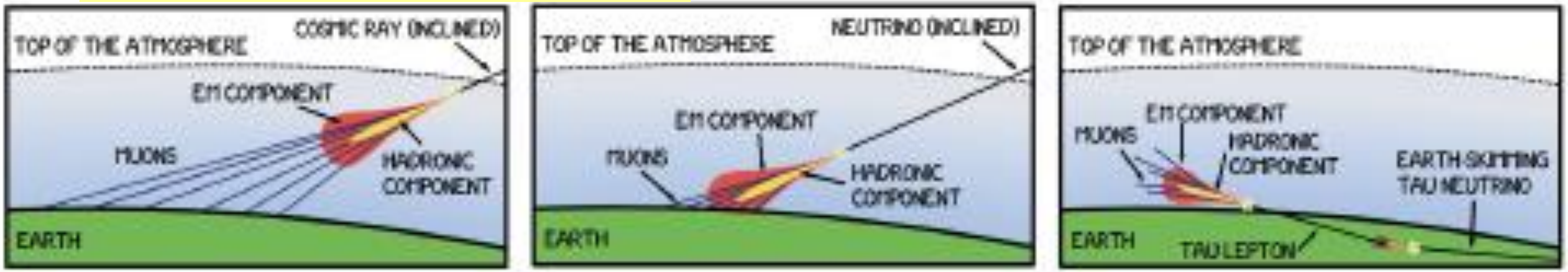
The Pierre Auger Observatory: Malargüe, Argentina



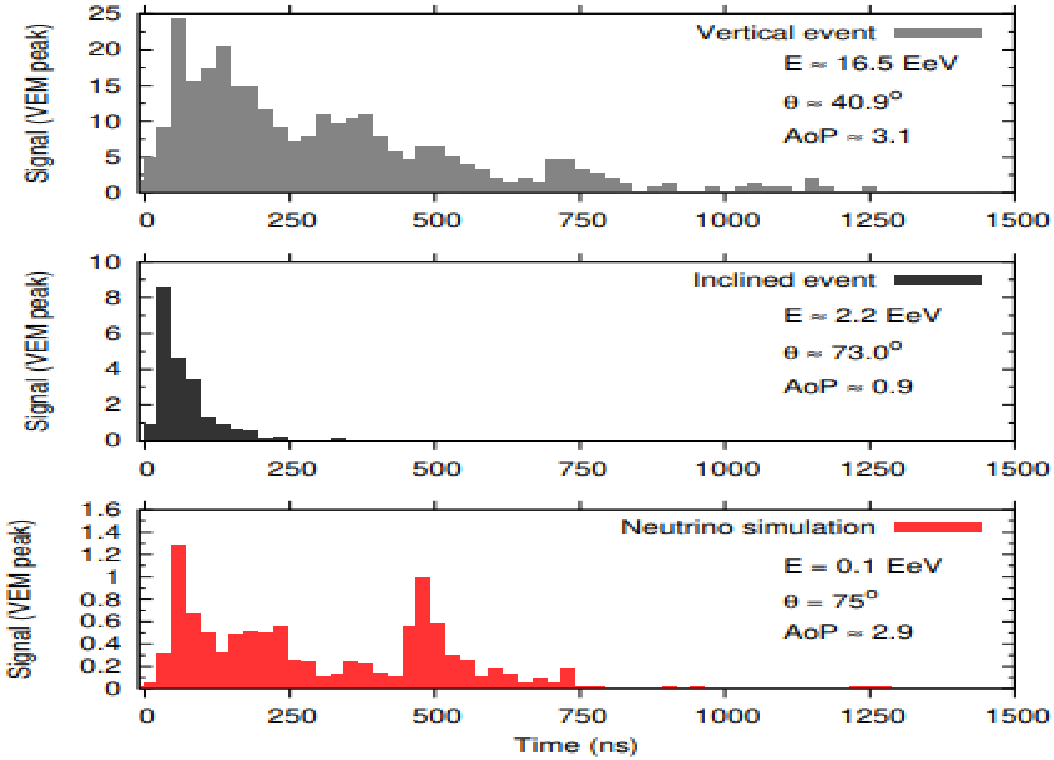
- $3000\ km^2$: area of West Yorkshire
- 1400 m ($875\ g\ cm^{-2}$)
- 1600 water-Cherenkov detectors: $10\ m^2 \times 1.2\ m$
- Fluorescence detectors at 4 locations

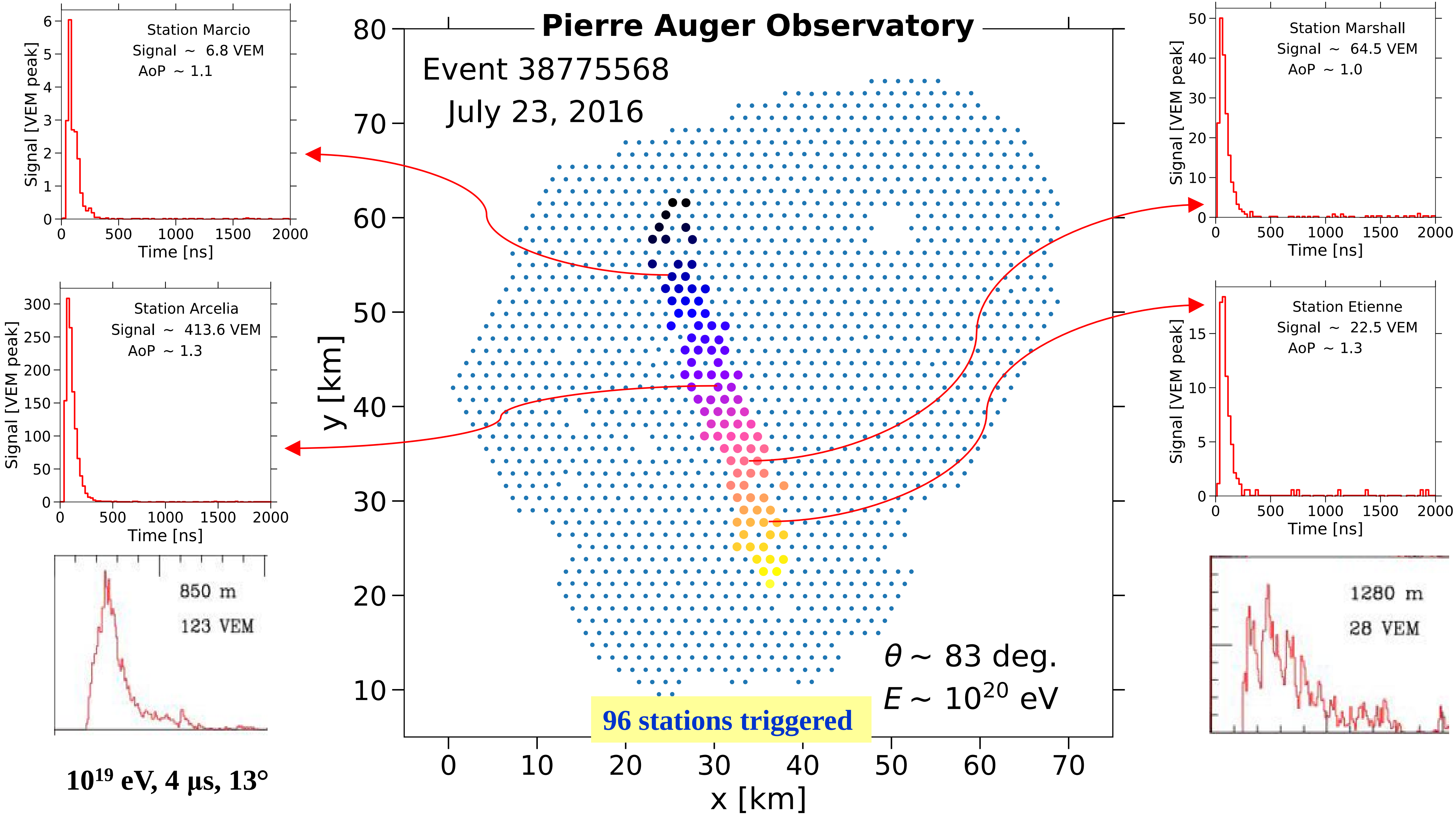
Telescope Array in Northern Hemisphere is ¼ size

Principles of neutrino detection



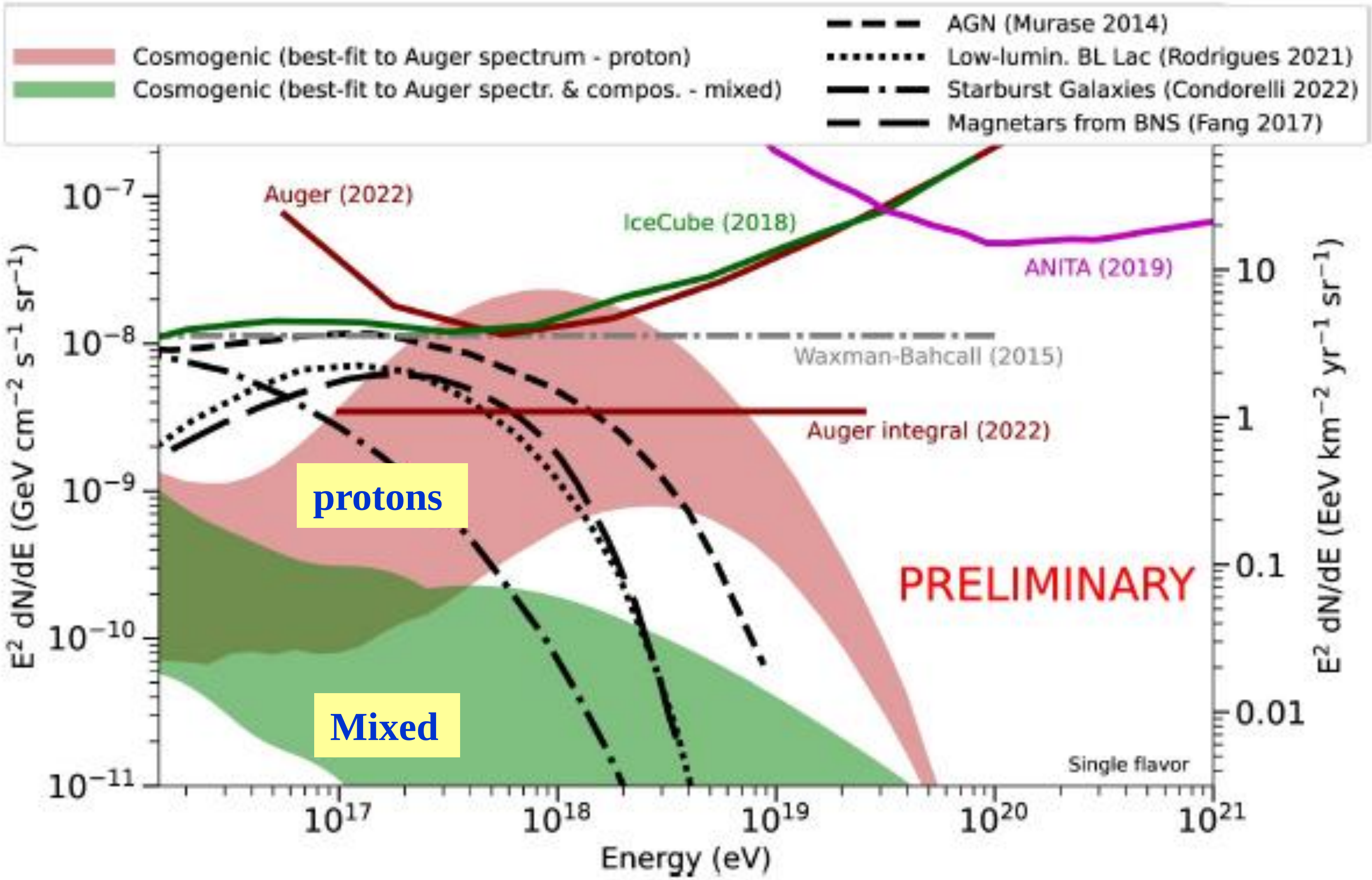
Simulations





10^{19} eV, 4 µs, 13°

Neutrino limits: as at ICRC 2023

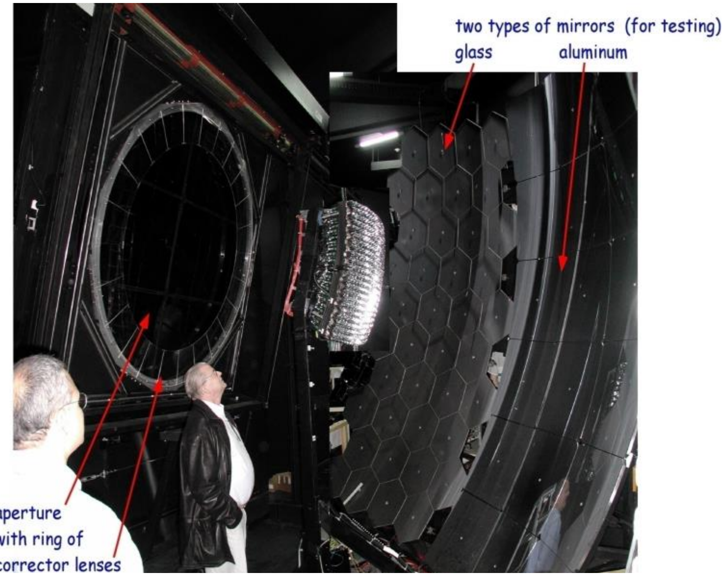


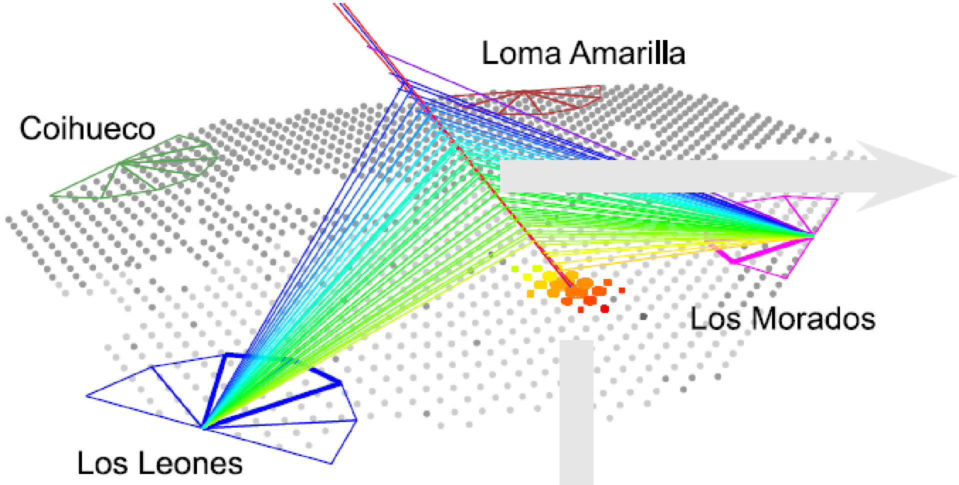
Recent results from Pierre Auger Observatory

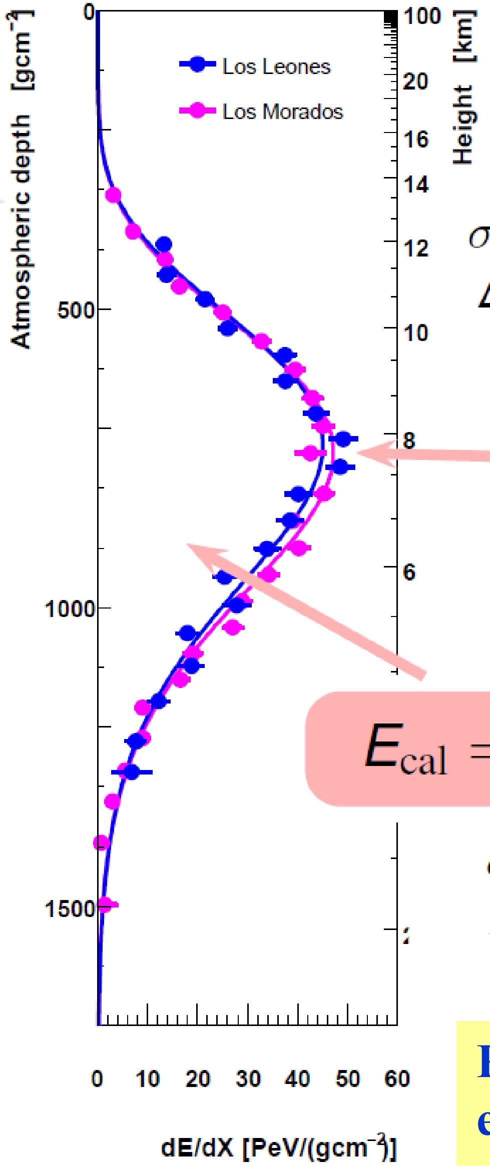
– or what Subir missed by joining IceCube

- **Energy Spectrum**
- **Mass Composition**
- **Distribution of arrival directions - Anisotropy**

Hybrid Detection of Air Showers







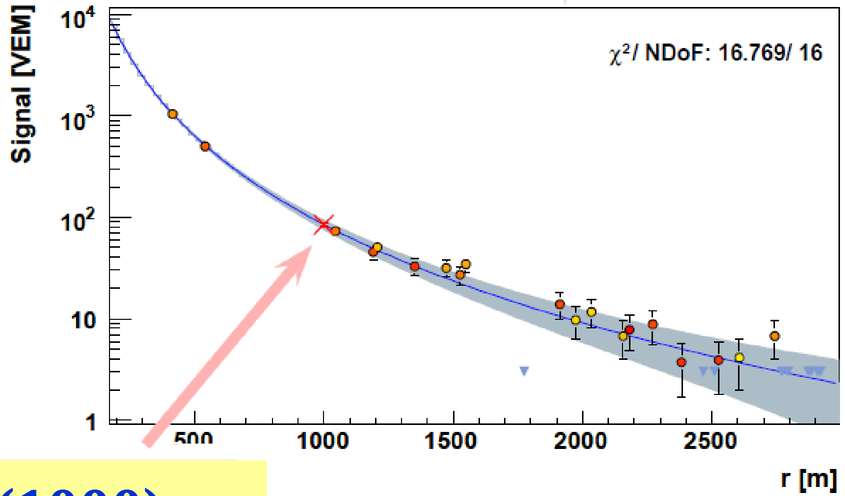
$\sigma_{X_{\rm max}} \lesssim 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \lesssim 10\,{\rm g/cm^2}$

$X_{\rm max}$

$E_{\rm cal} = \int \frac{dE}{dX}\,dX$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 15\,\%$

Hybrid detection of showers is a key feature of the Observatory



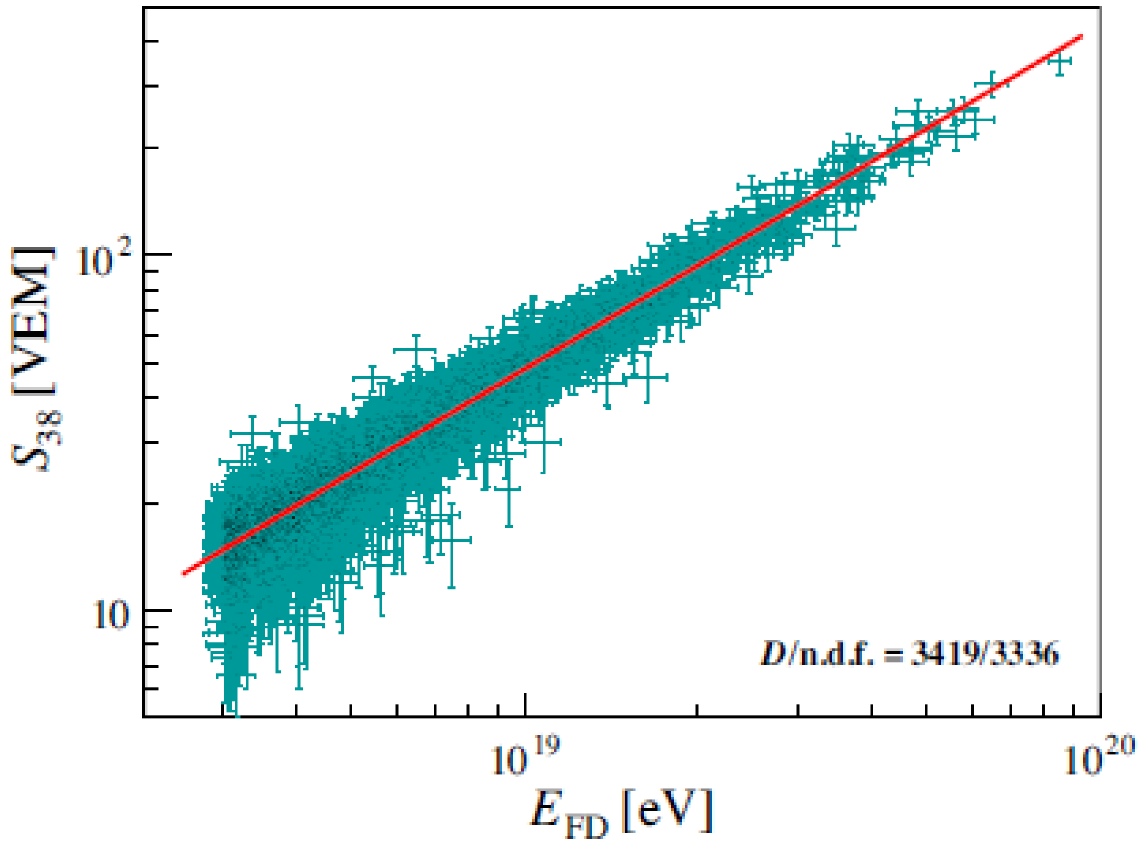
S(1000)

$E_{\rm surface} = f(S_{1000},\ \theta)$

Plus ‘invisible energy’ ~10% at 10 EeV

1. Measurement of the Energy Spectrum

- Determine size of each shower: $S_{38}(1000)$, signal at 1000 m adjusted to 38°
- Account for 'Invisible Energy' (neutrinos and muons dying out in earth)
- Calibrate the energy of S_{38} using hybrid events in which there is also a measurement of the longitudinal development from the fluorescence detector



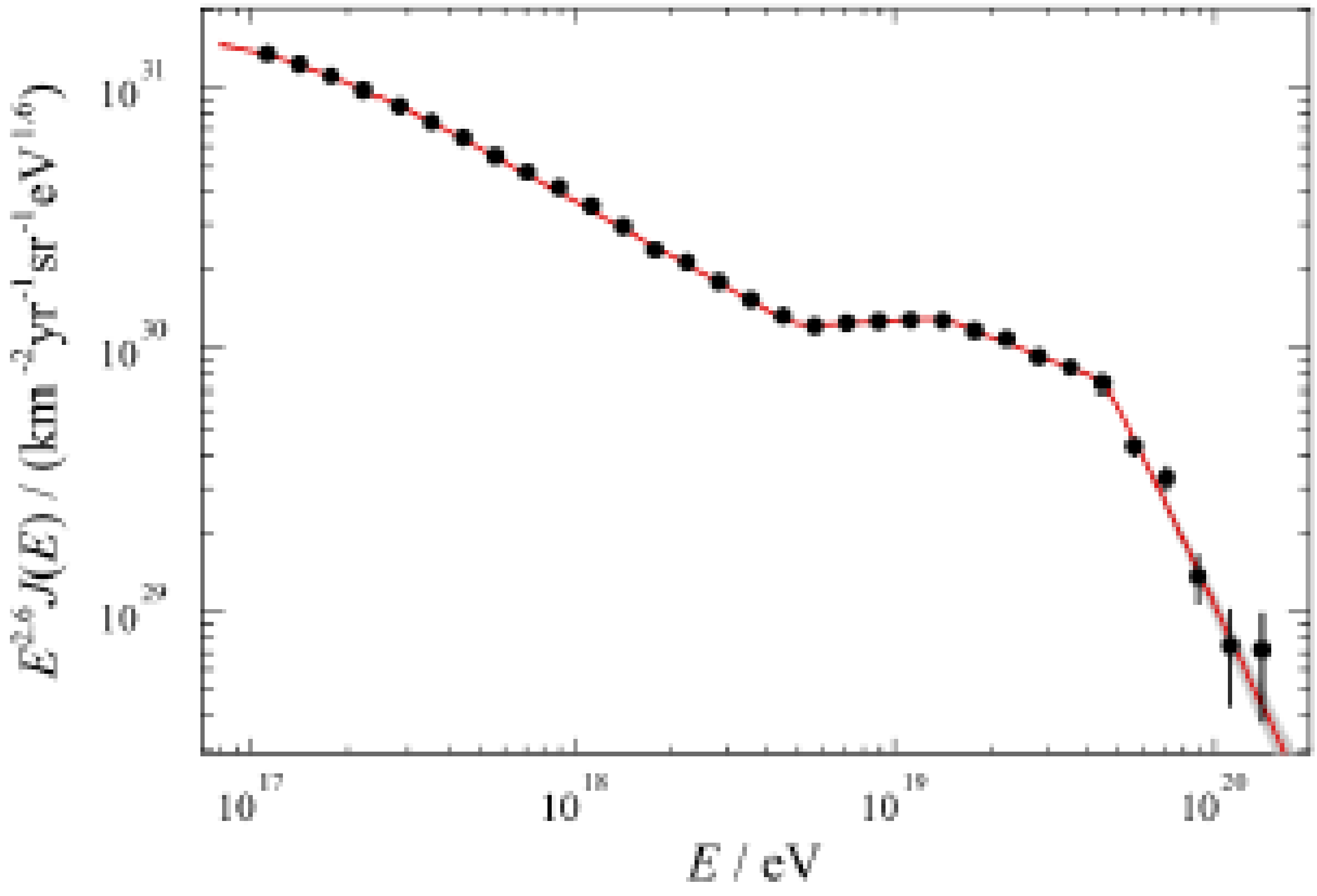


Figure 1 – Energy spectrum of UHECRs, scaled by $E^{2.6}$.

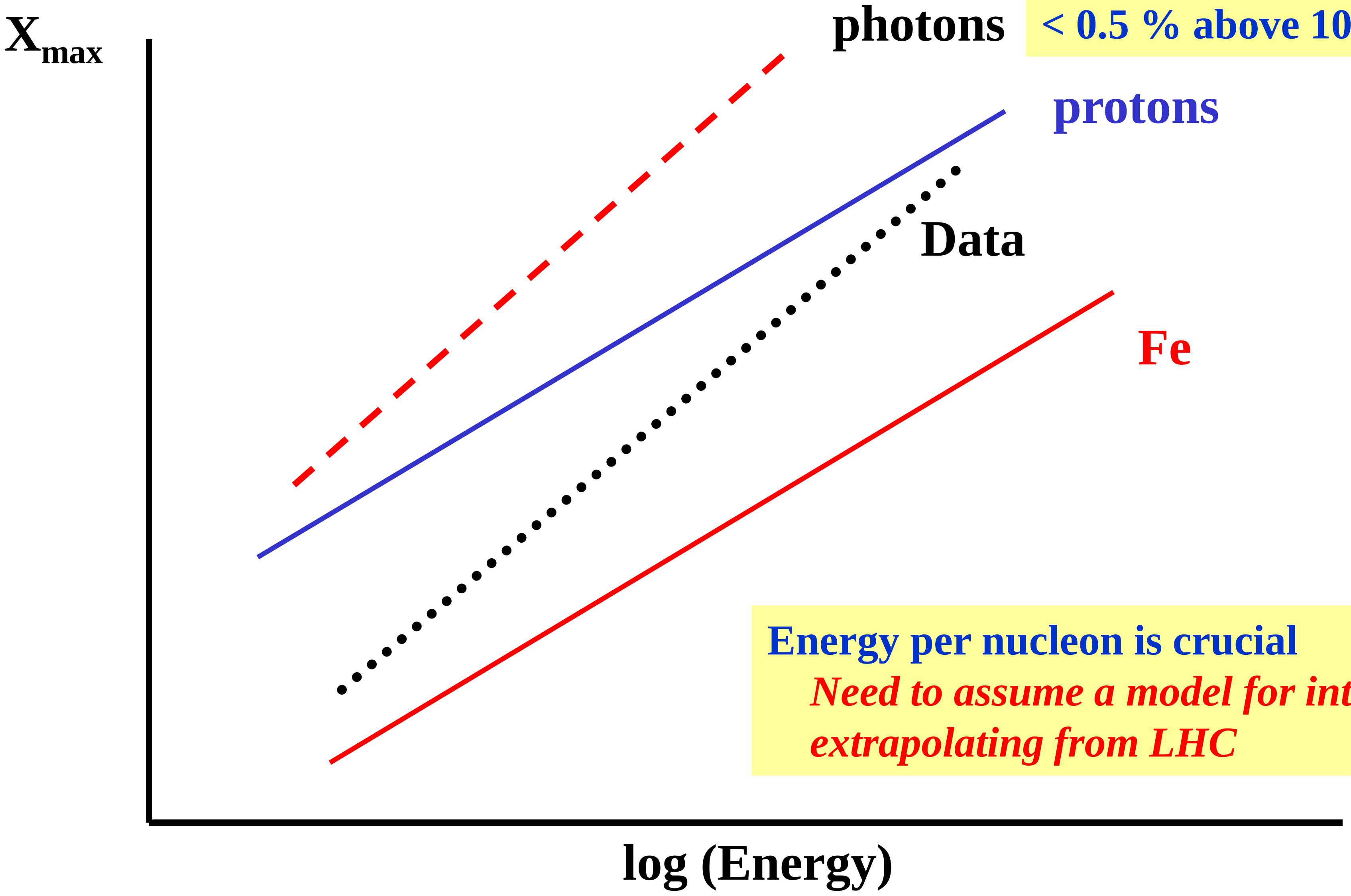
- **Energy Spectrum is measured, independent of assumptions about hadronic interactions**
- **Limited by systematic uncertainties up to about 30 EeV**
- **Exposure above 3 EeV:**

  60 x 10^3 km^2 sr yr

  760 x 10^3 events

  ~1/3 above 3 EeV

2. Estimate of mass composition is obtained from measurement of X_{max}

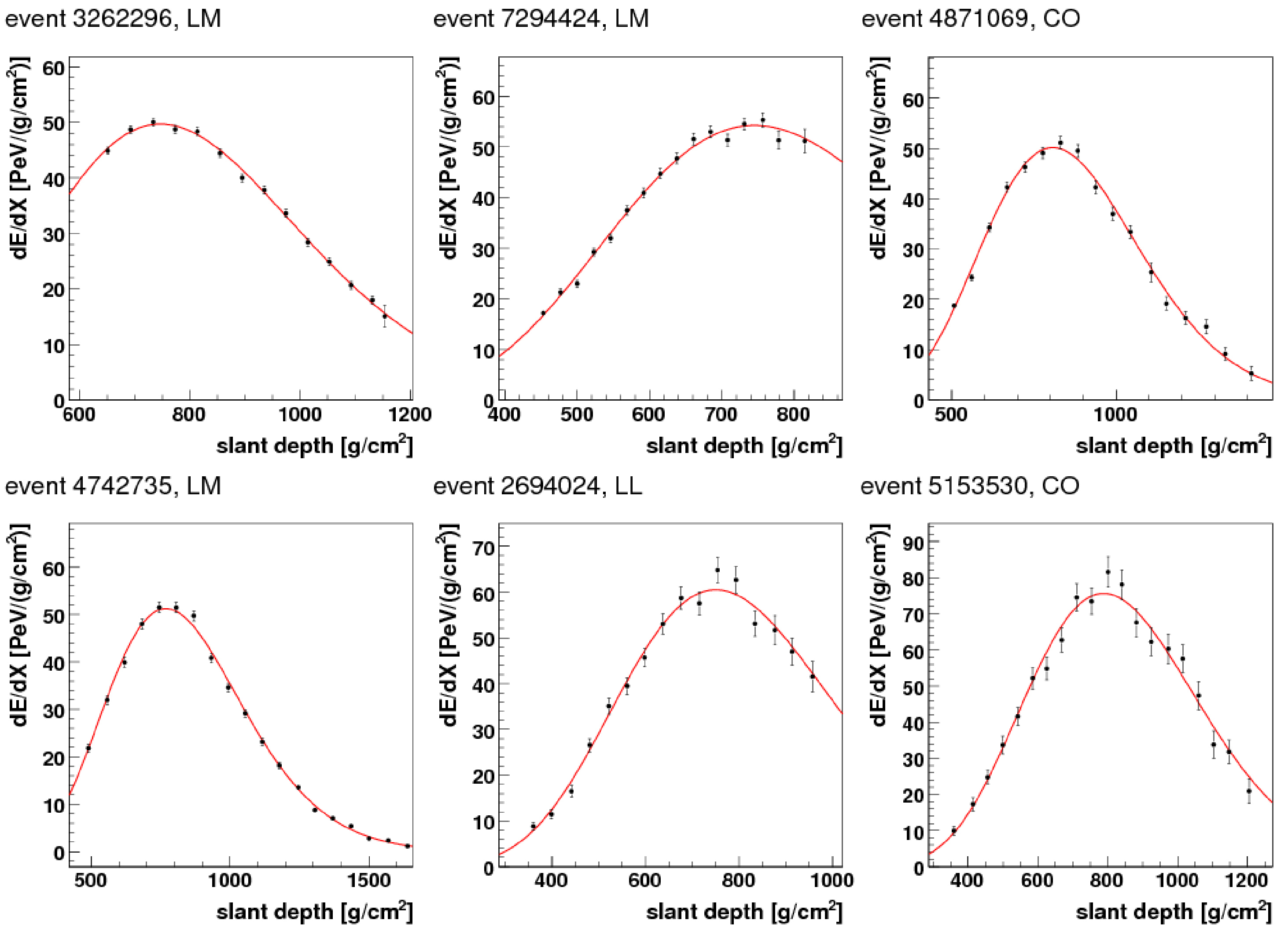


< 0.5 % above 10 EeV

Energy per nucleon is crucial

Need to assume a model for interactions extrapolating from LHC

Reconstructed longitudinal profiles



rms uncertainty in X_{max} < 20 g cm^{-2} from stereo measurements

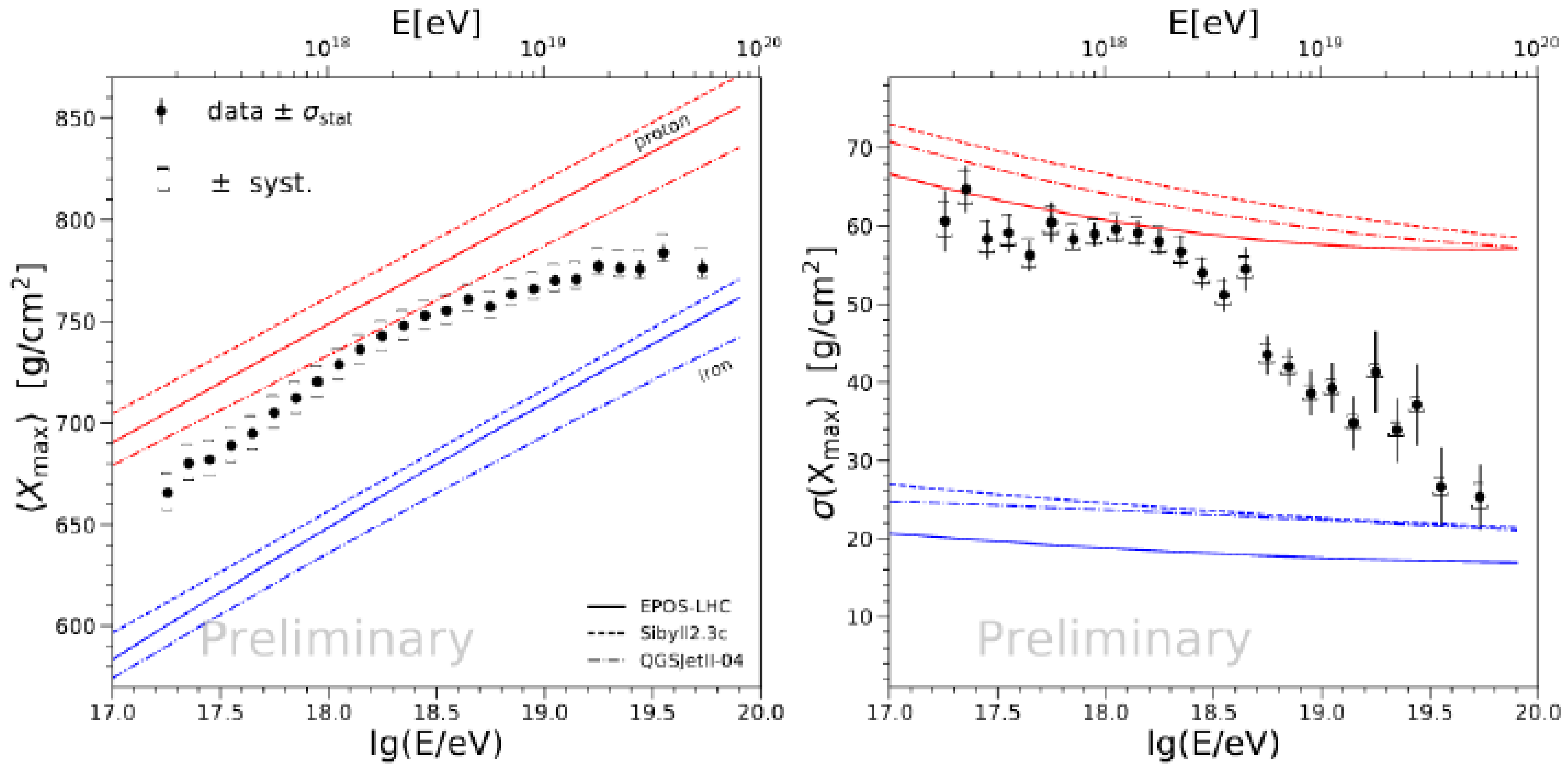
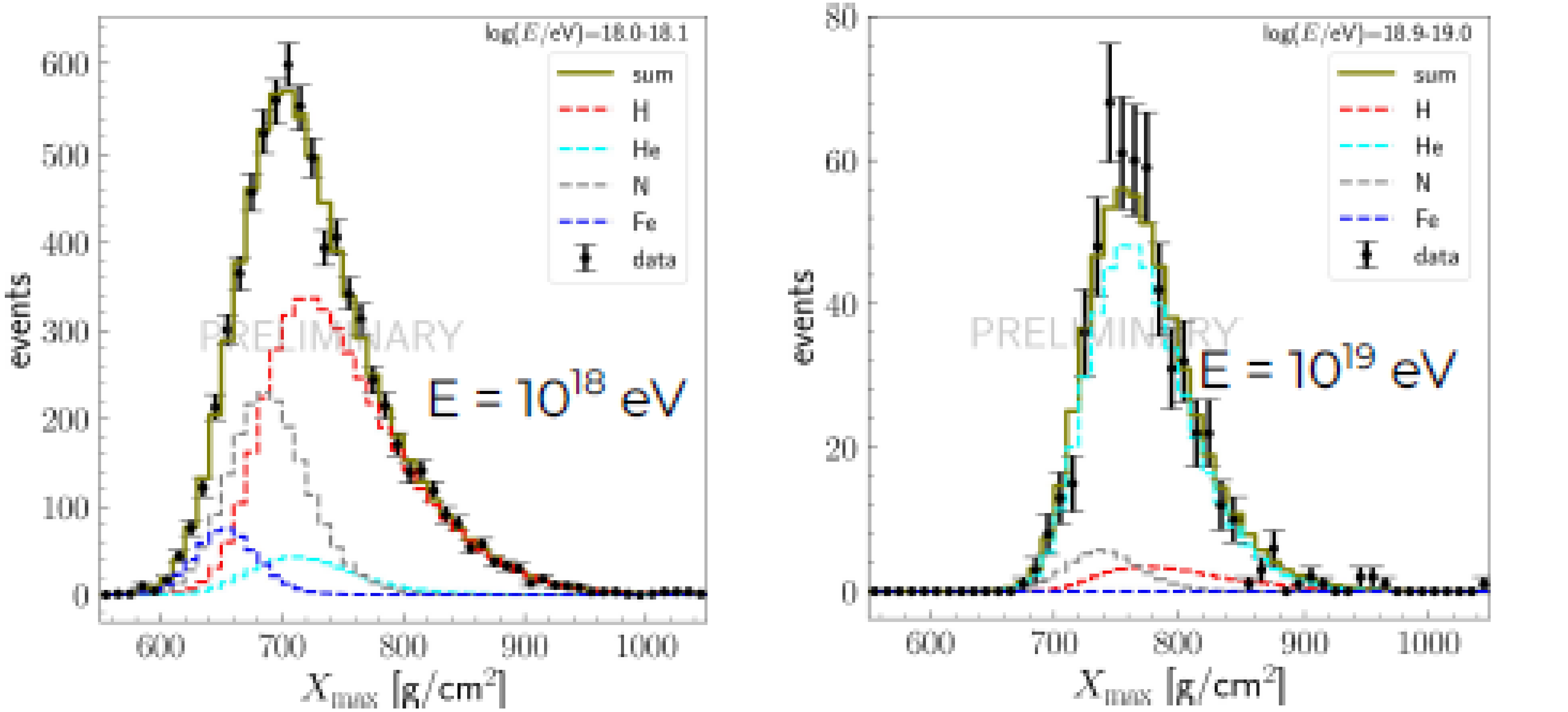


Figure 2 – Measurements of $\langle X_{\max} \rangle$(left) and $\sigma(X_{\max})$ (right) compared to the predictions for proton and iron nuclei of the hadronic models EPOS-LHC, Sibyll 2.3c and QGSJetII-04.

An unexpected result:

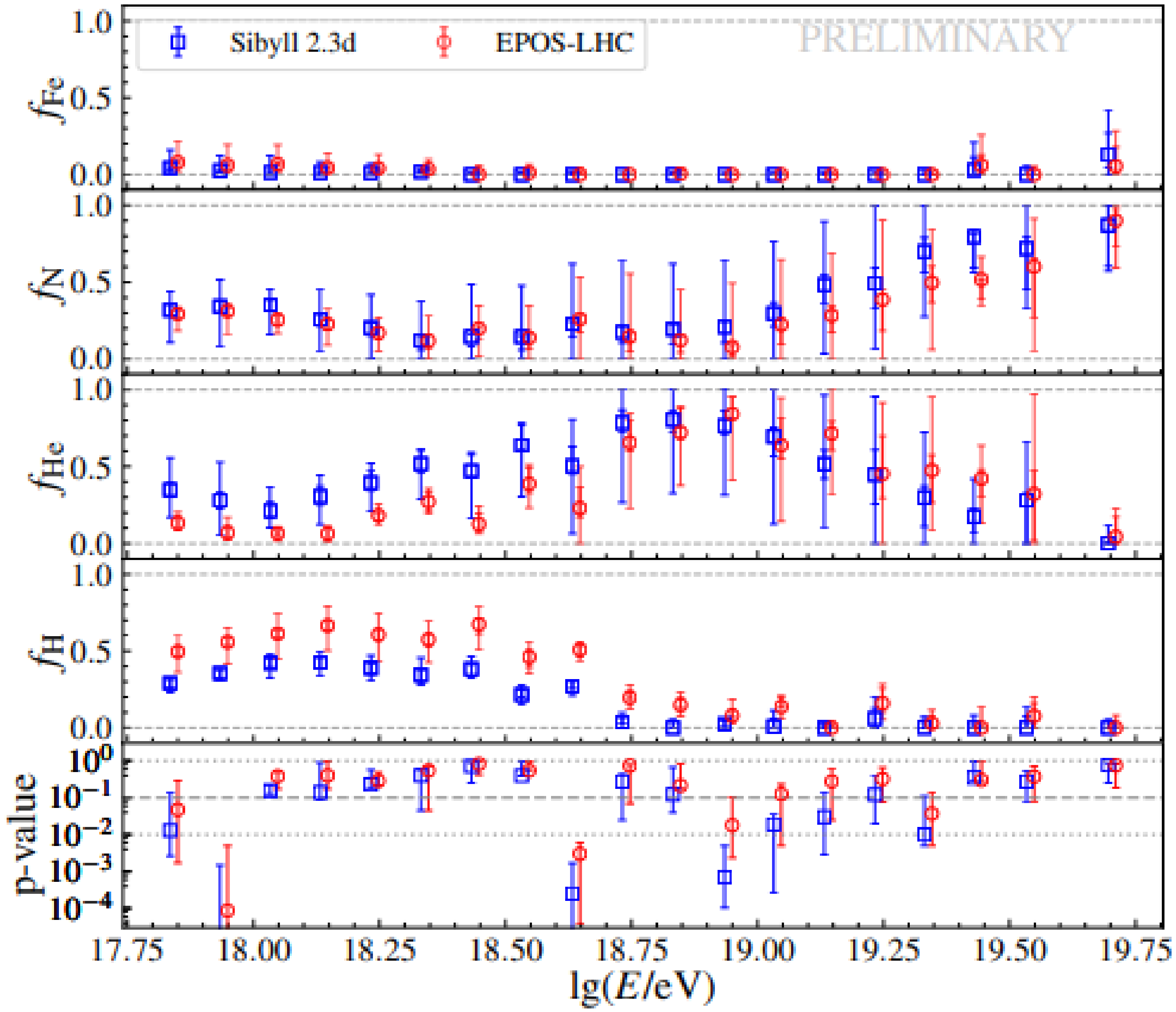
dogma – going back to the 1950s - was that protons dominated at high energies

Orwellian-like 'group think'



log(E/eV)=18.0-18.1
sum
H
He
N
Fe
data
PRELIMINARY
E = 10^18 eV
events
X_max [g/cm^2]
log(E/eV)=18.9-19.0
sum
H
He
N
Fe
data
PRELIMINARY
E = 10^19 eV
events
X_max [g/cm^2]

Mass Composition as function of energy



He and Nitrogen dominant above 10 EeV

Little evidence so far of protons or iron nuclei

- but highest energy ~50 EeV

More detailed mass estimates will come with upgrade, AugerPrime

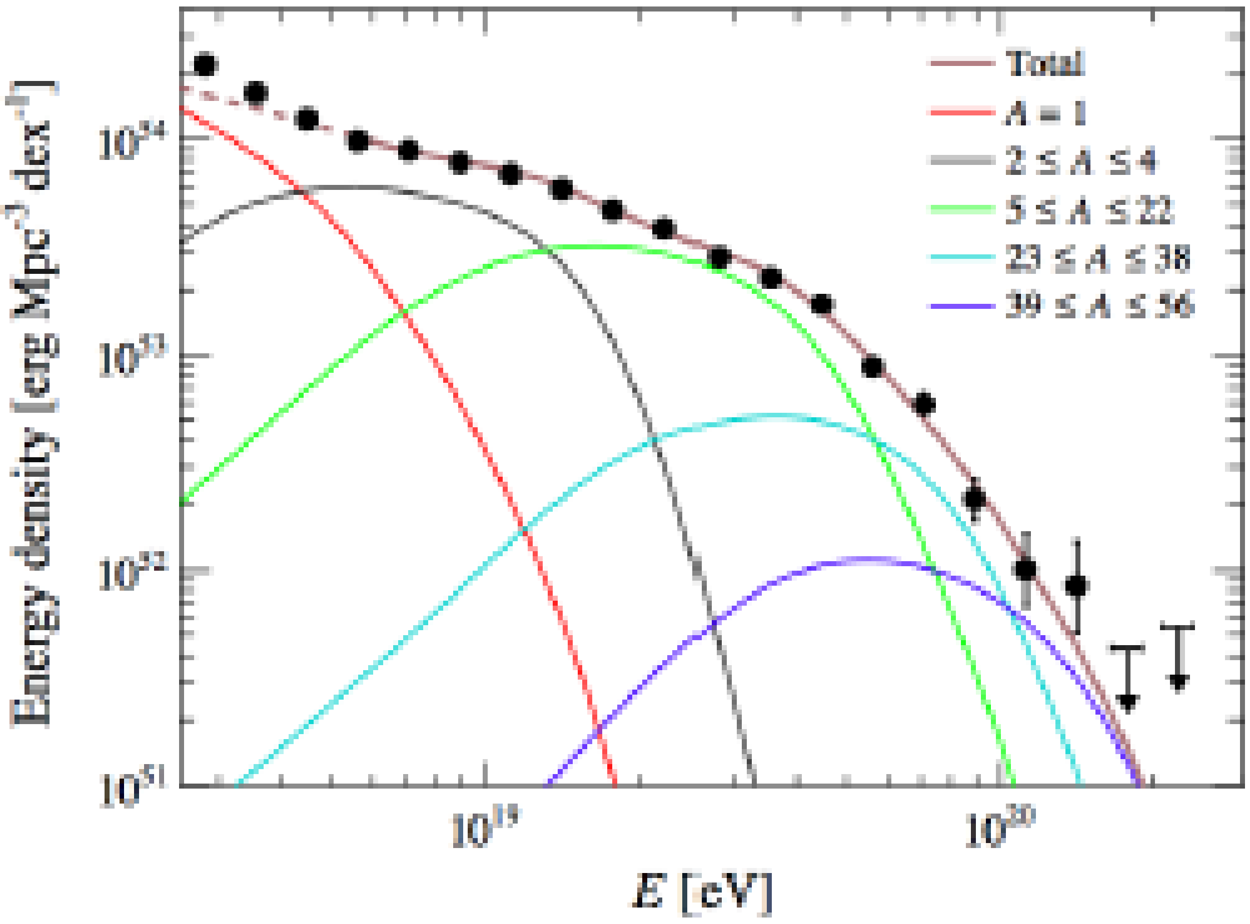


Figure 4 – Energy density obtained with the best fit parameters of the benchmark scenario described in PRL 125 12106 2020

Data as yet insufficient to give definitive explanation
But:
'proton domination' excluded

1. $E_{1/2}$ = 53 EeV predicted, (22 ±1 ±3) EeV observed

2. In ankle region, (3 -5) EeV, protons not dominant

Data can be explained with stationary and uniform sources with E_{max} ~ Z

Using data on X_{max} and the spectrum, one can make a fit

But surely not unique –
and anisotropy information still to be added

3. Distribution of Arrival Directions

1. Large scale Anisotropies

2. Small scale anisotropies at higher energies

6.9 sigma from 123×10^3 km^2 sr yr

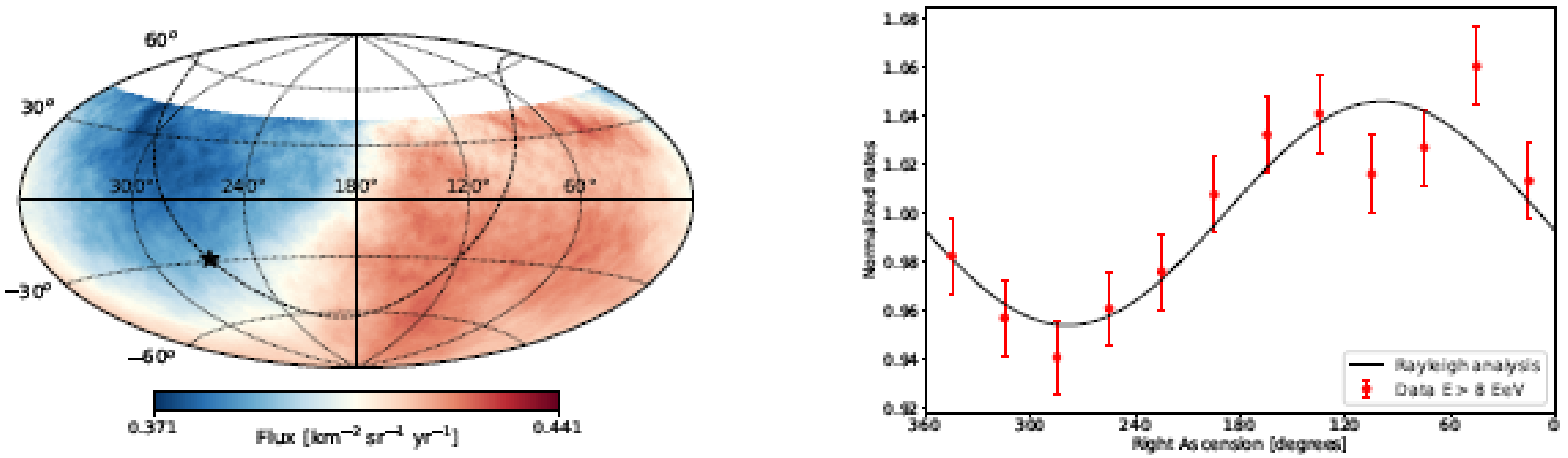
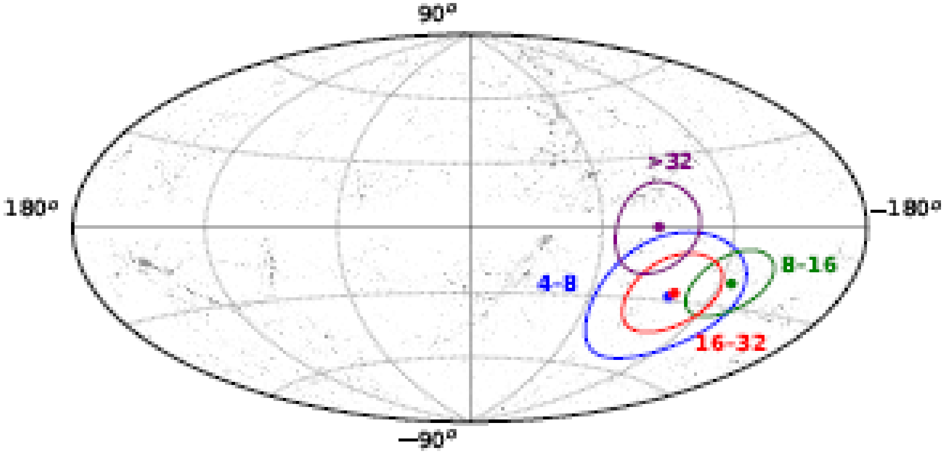
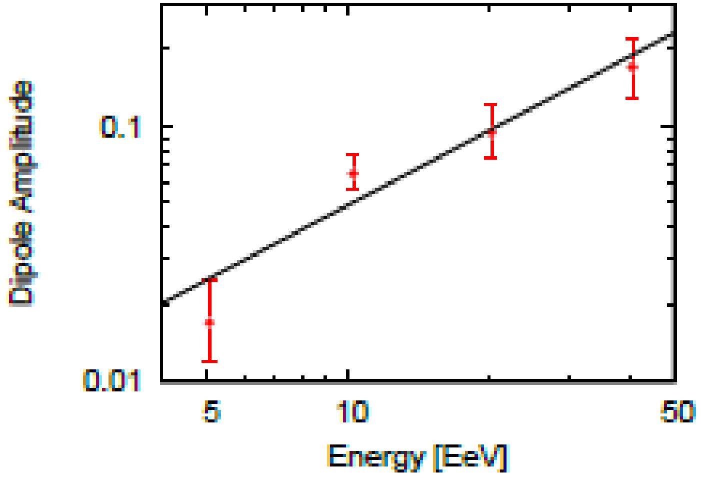


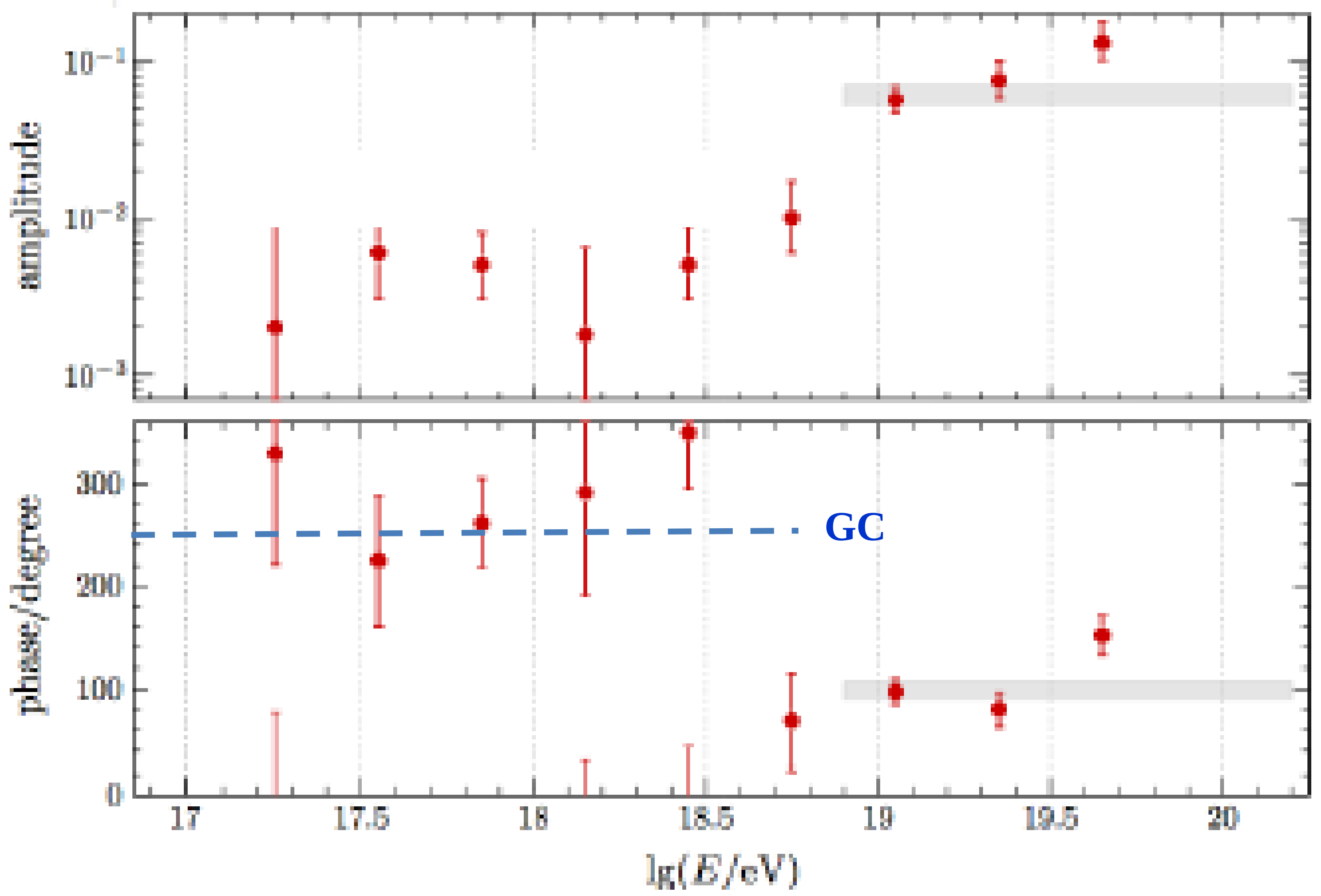
Figure 4: Flux above 8 EeV, smoothed by a top-hat window of 45°, in equatorial coordinates (left panel). The position of the Galactic Center is shown with a star and the Galactic Plane is indicated with a dashed line. Distribution in R.A. of the normalized rates of events with $E \geq 8$ EeV (right panel). The black line

After allowing for galactic magnetic field, reasonable agreement with dipole in distribution of 2MRS infra red galaxies

Position of excess does not change much with energy: mass must change?







Change in phase of anisotropy supports idea that cosmic rays > 8 EeV are dominantly extragalactic

Higher energies, E> 32 EeV:
ApJ 935 170 2022

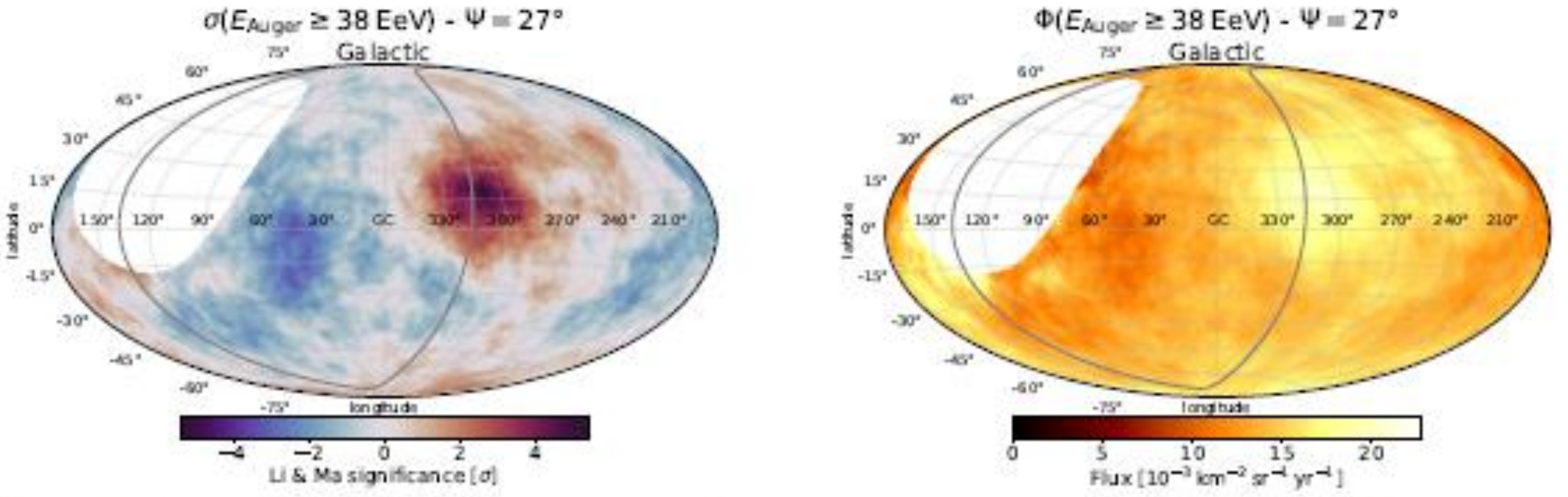


Figure 1: Local Li-Ma significance map within a top-hat window of 27° radius (left panel) and flux map (right panel) with $E \geq 38$ EeV in Galactic coordinates. The supergalactic plane is shown with a gray line.

As reported at ICRC 2023:

Centaurus region (~4 sigma effect) contains
Cen A: powerful AGN
NGC 4945: AGN and Seyfert Galaxy
M83: Starburst galaxy

For small scale anisotropy:

- **~20% of events appear to be associated with SBG and AGNs**
- **Strong hint of anisotropy associated with Cen A region**

Catalog	$E_{\rm th}$ [EeV]	Ψ [°]	α [%]	TS	Post-trial p-value
All galaxies (IR)	38	24^{+15}_{-8}	14^{+8}_{-6}	18.5	6.3×10^{-4}
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}
Jetted AGNs (γ-rays)	38	23^{+8}_{-7}	6^{+3}_{-3}	19.2	4.6×10^{-4}

Table 3: Most significant results of the catalog-based searches. We show the threshold energy, $E_{\rm th}$, the equivalent top-hat radius, Ψ, the signal fraction, α, the local test statistic, TS, and the post-trial p-value.

But can SGBs accelerate particles to beyond 10 EeV?

Anchordoqui – YES

but others (Blandford, Bell, …) less sure

Cen A may have the right credentials

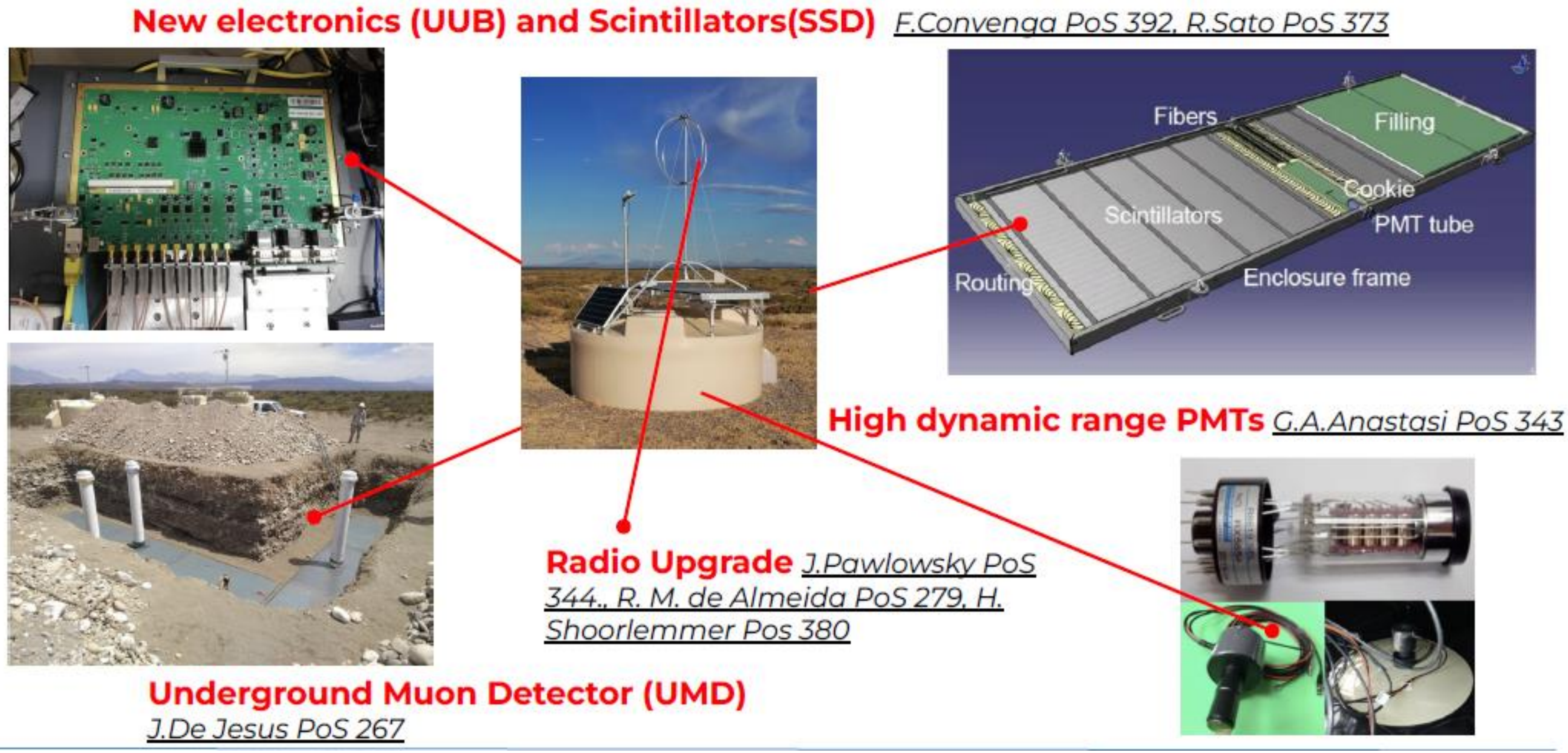
An intriguing suggestion for role of Cen A in explaining the data

Bell, Matthews and Taylor – the Echo Model

Cen A is the dominant local accelerator with signals apparently from SGBs in fact reflections. Several of the systems in the 'Council of Giants' are SGBs – talk by Andrew Taylor

Major upgrade to improve measurements of mass initiating events on an event-by event basis

Anisotropy as function of mass?



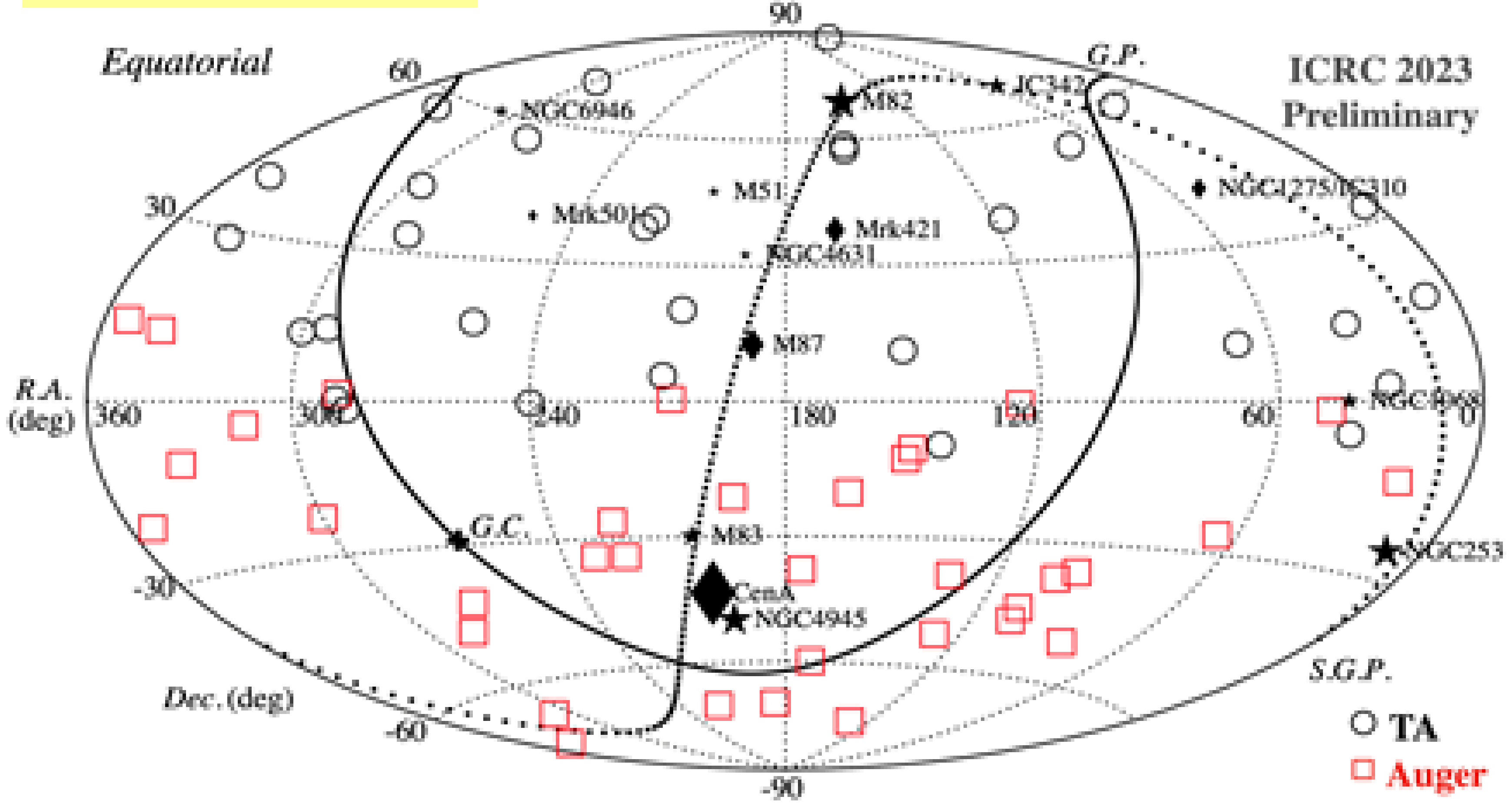
Other science at the Auger Observatory

- **Particle physics:**
  - p-p cross-section at $\sqrt{s}$ = 57 TeV
  - anomalous muon content
- **Photon limits**
- **Atmospheric Science:**
  - Thunderstorms
  - Elves
- **Space Weather: e.g. Forbusch decreases**
- **Beyond Standard Model: e.g: upward-going events (ANITA-like) not seen**

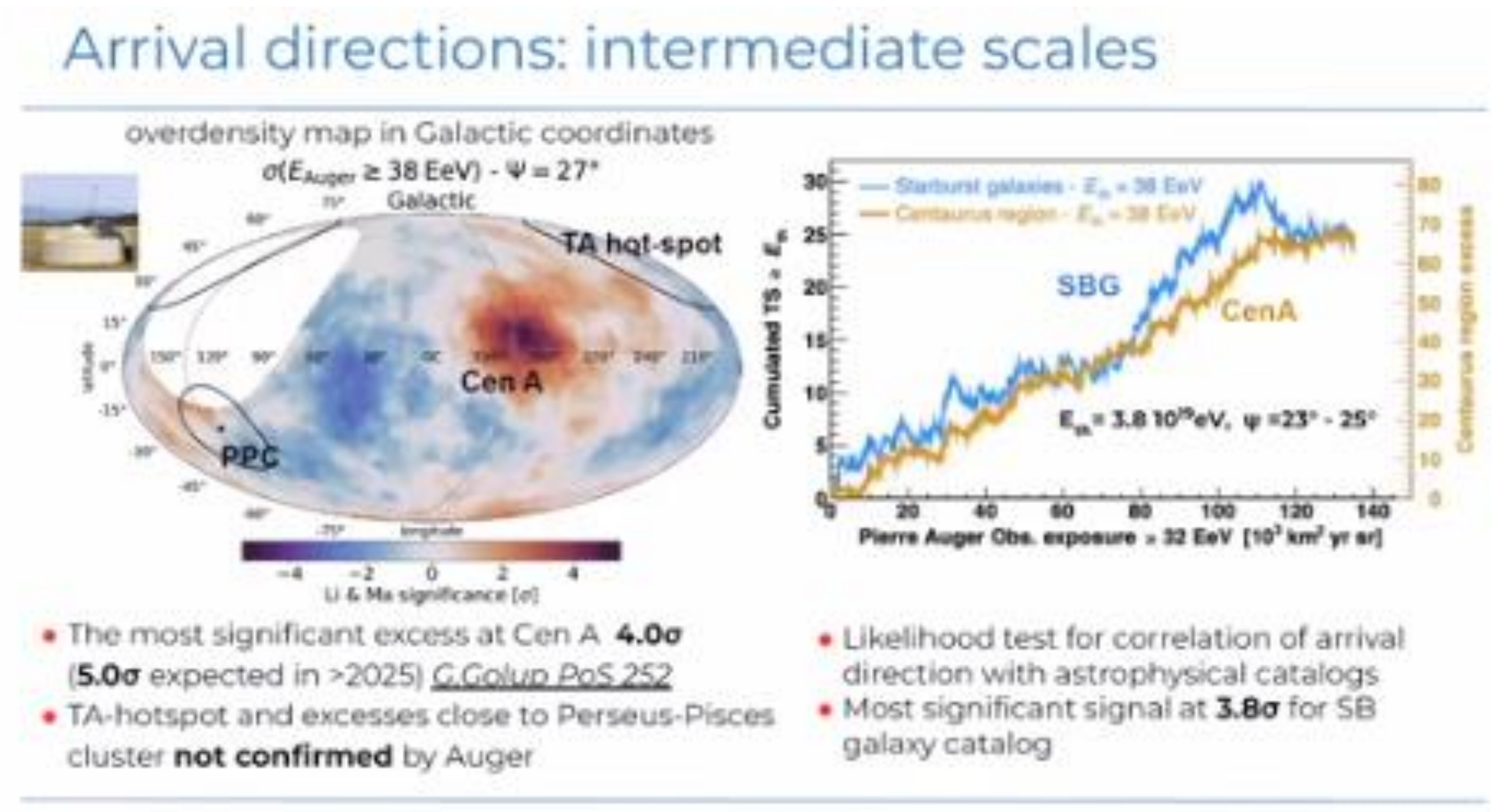
A rich harvest that I hope Subir might help us to explain

Back up Slides

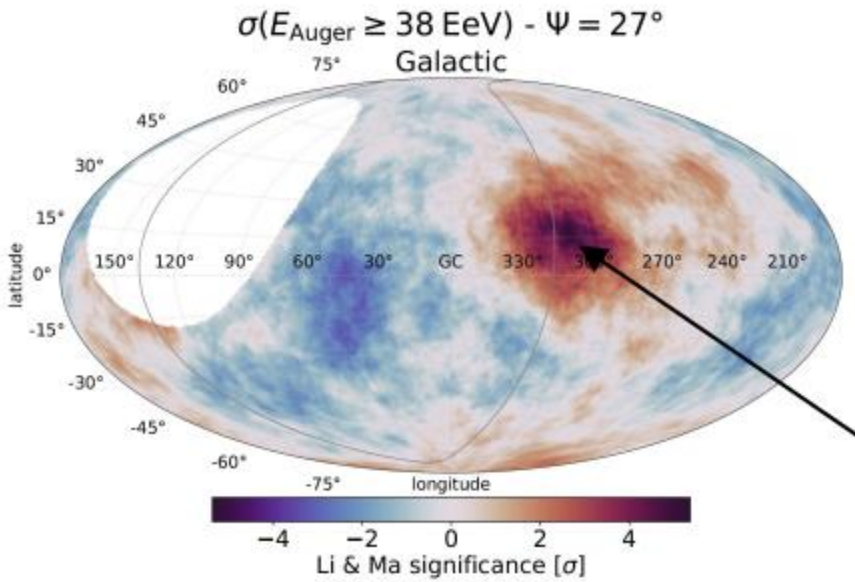
Events above 100 EeV



Ref: T. Fujii, Cosmic Ray Indirect Rapporteur at ICRC 2023

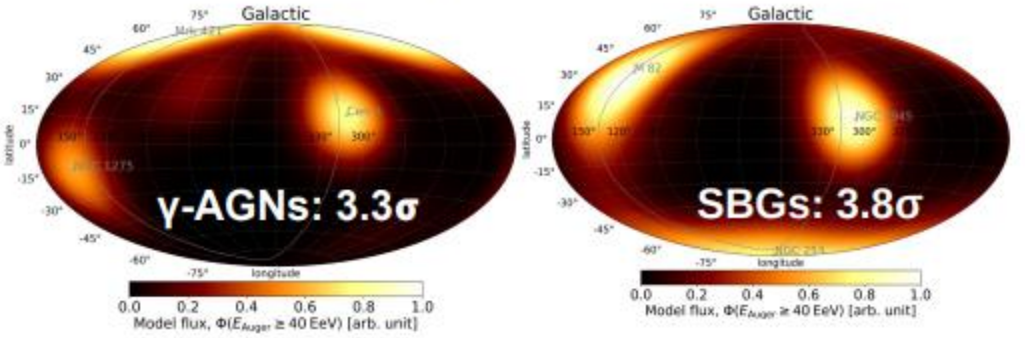


Arrival directions: intermediate scales
overdensity map in Galactic coordinates
σ(E_Auger ≥ 38 EeV) - Ψ = 27°
Galactic
TA hot-spot
Cen A
PPC
−4 −2 0 2 4
Li & Ma significance [σ]
SBG
CenA
E_th = 3.8 10^19 eV, ψ = 23° - 25°
Cumulated TS × E_th
Pierre Auger Obs. exposure > 32 EeV [10^3 km^2 yr sr]
Centaurus region excess
The most significant excess at Cen A 4.0σ (5.0σ expected in >2025) G.Golup PoS 252
TA-hotspot and excesses close to Perseus-Pisces cluster not confirmed by Auger
Likelihood test for correlation of arrival direction with astrophysical catalogs
Most significant signal at 3.8σ for SB galaxy catalog



search for overdensities in the UHECR flux measured at the Pierre Auger Observatory

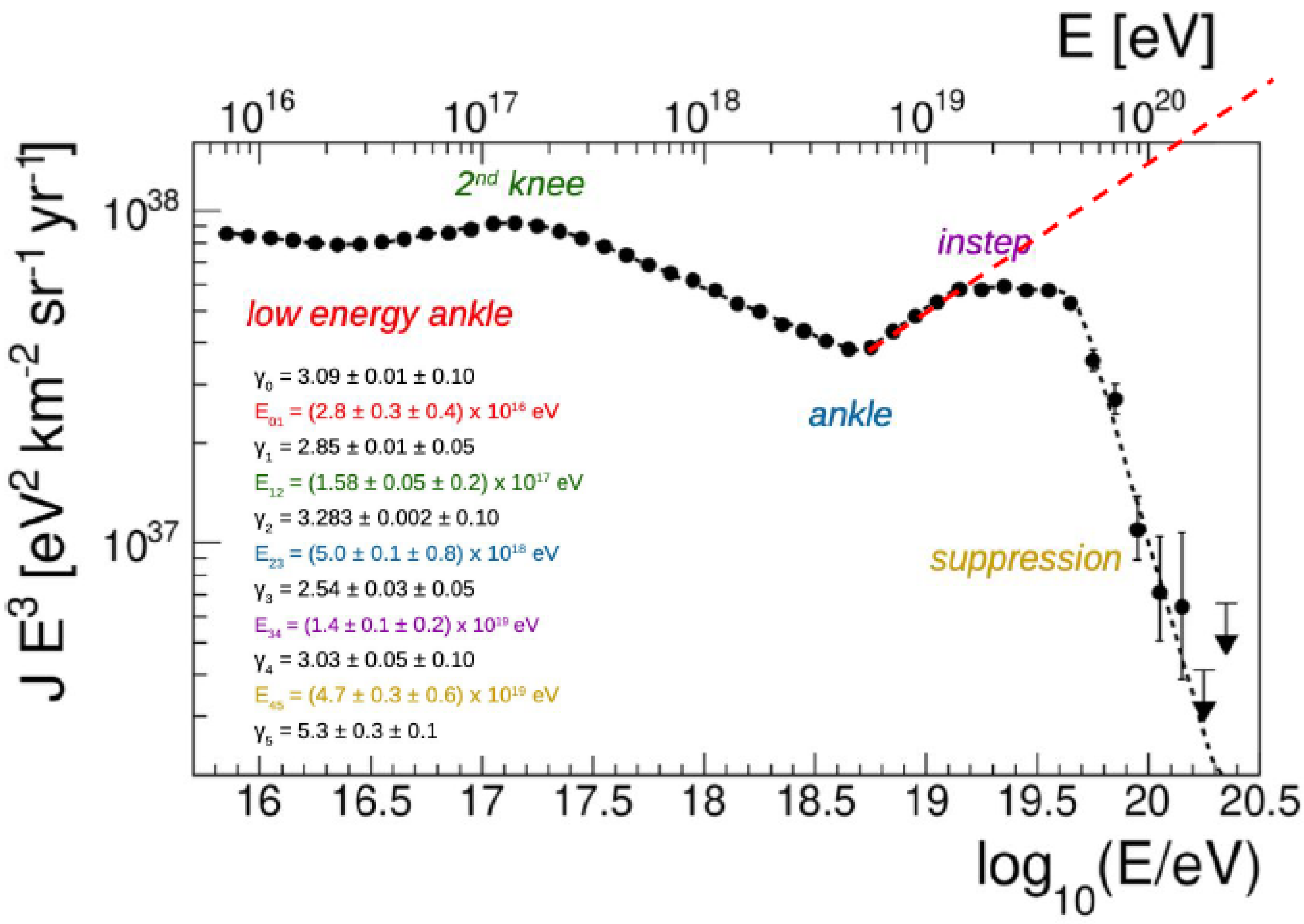
- intermediate-scale anisotropies in UHECR flux correlate with catalogs of source candidates:



- correlation with Cen A: 4.0σ

Centaurus region contains

Cen A: powerful AGN
NGC 4945: AGN and Seyfert Galaxy
M83: Starburst galaxy



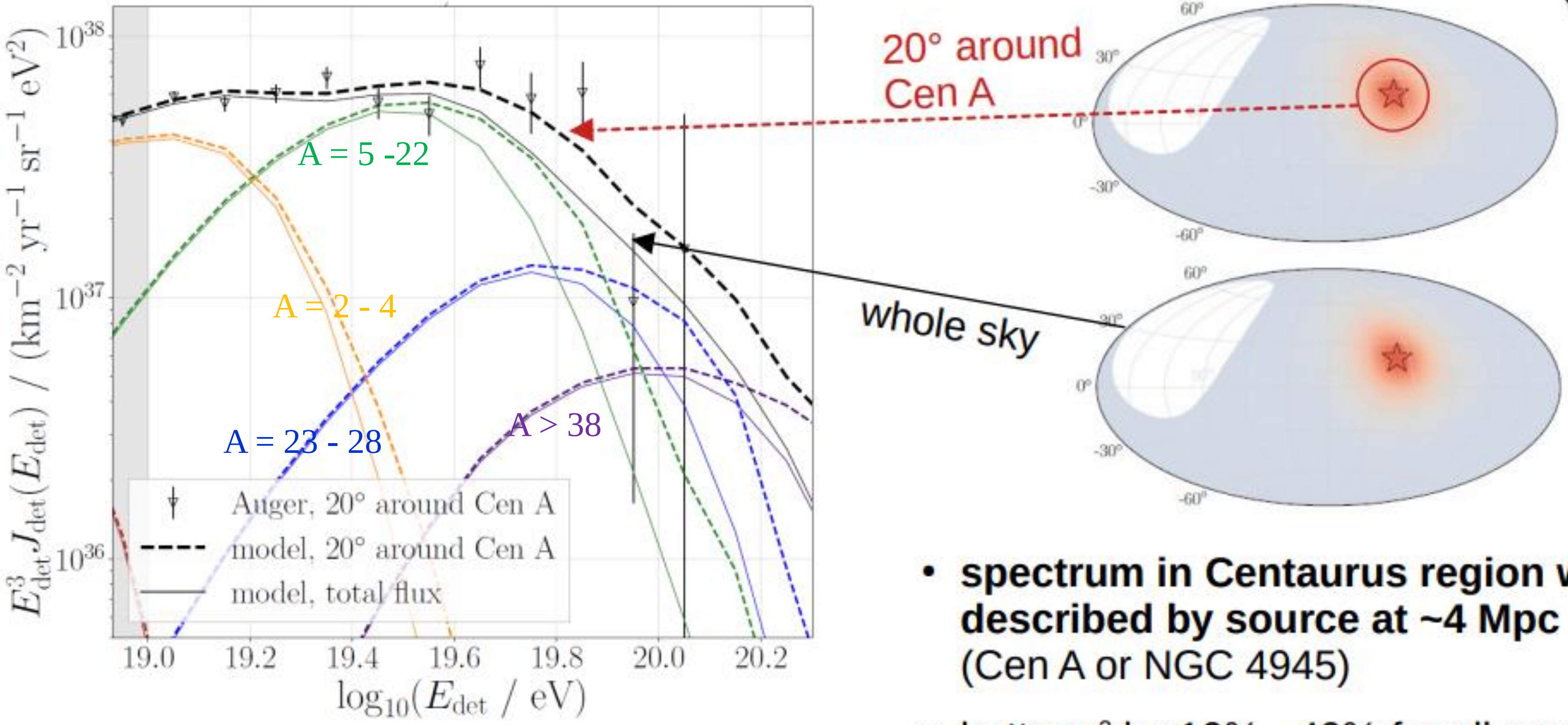
SPECTRUM FEATURES

- **Strong suppression at ~ 5 10^{19} eV**
- **New feature "instep" at ~ 10^{19} eV**
- **Ankle at ~ 5 10^{18} eV**
- **2nd knee at ~ 2 10^{17} eV**
- **Hint for low energy ankle at ~ 10^{17} eV**

Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
PoS(ICRC 2021) 324

Measurement of Energy Spectrum is entirely *DATA DRIVEN*

Spectrum in Cen A region



- **spectrum in Centaurus region well described by source at ~4 Mpc** (Cen A or NGC 4945)
- better χ^2 by 10% - 40% for all angles

$$Q_{inj}(E_{inj}, A_{inj}) = Q_0\, a_A \left(\frac{E_{inj}}{10^{18}\,eV}\right)^{-\gamma} \cdot \begin{cases} 1, & Z_A R_{cut} > E_{inj}; \\ \exp\left(1 - \frac{E_{inj}}{Z_A R_{cut}}\right), & Z_A R_{cut} \le E_{inj};\,. \end{cases}$$

Submitted to JCAP: arXiv 2305.16693