IGFAE Retreat - July 5, 2022

SA2: Cosmic particles & fundamental physics

SA2-AUGE: Extremely energetic cosmic rays & neutrinos - Large exposure experiments

Highlights 2020-2021

IGFAE Instituto Galego de Física de Altas Enerxías

USC Universidade de Santiago de Compostela

Xunta de Galicia

Enrique Zas – Catedrático USC

Gonzalo Parente – Catedrático USC

Jaime Álvarez – Titular USC

SA2-AUGE group

Lorenzo Cazón

Ramón y Cajal Researcher – Sept. 2021 →

Marvin Gottowik

Postdoctoral Fellow – July 2022 →

Felix Riehn

Marie Sklodowska Curie Fellowship – Sept. 2022 →

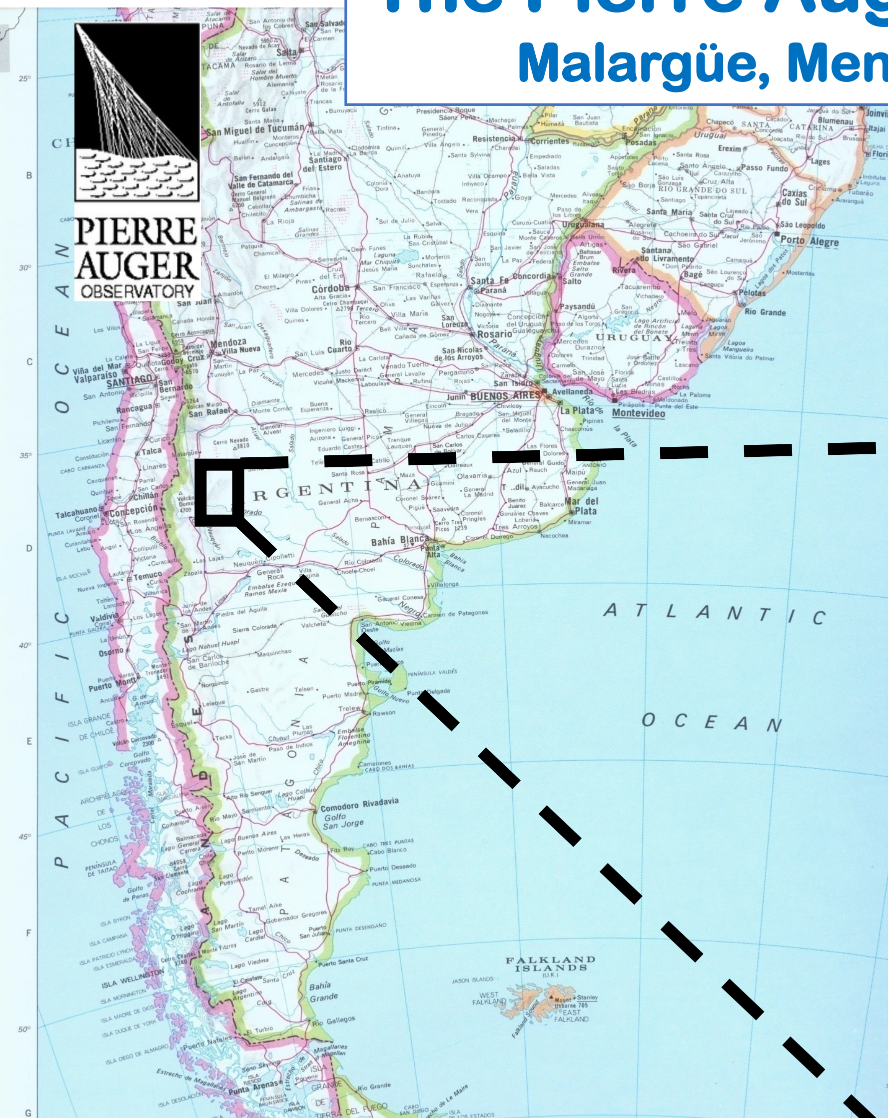
Juan Ammerman

IGFAE (MdM) FPI – Sept. 2021 →

Miguel A. Martins

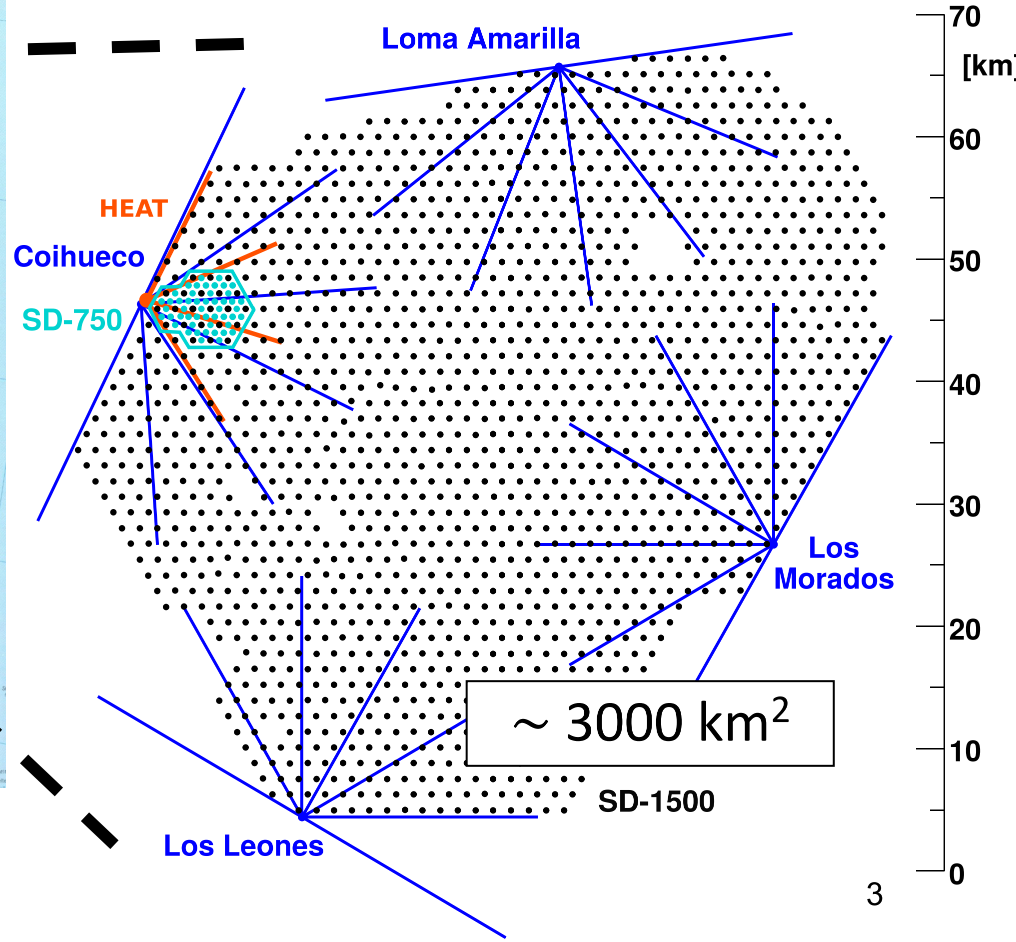
INPHiNIT La Caixa – Jan. 2022 →

The Pierre Auger Observatory
Malargüe, Mendoza (Argentina)



- **SD1500** = Surface Detector array of 1600 water Cherenkov stations (~ 3000 km^2)
- **SD 750** = 61 water Cherenkov stations (~ 25 km^2)

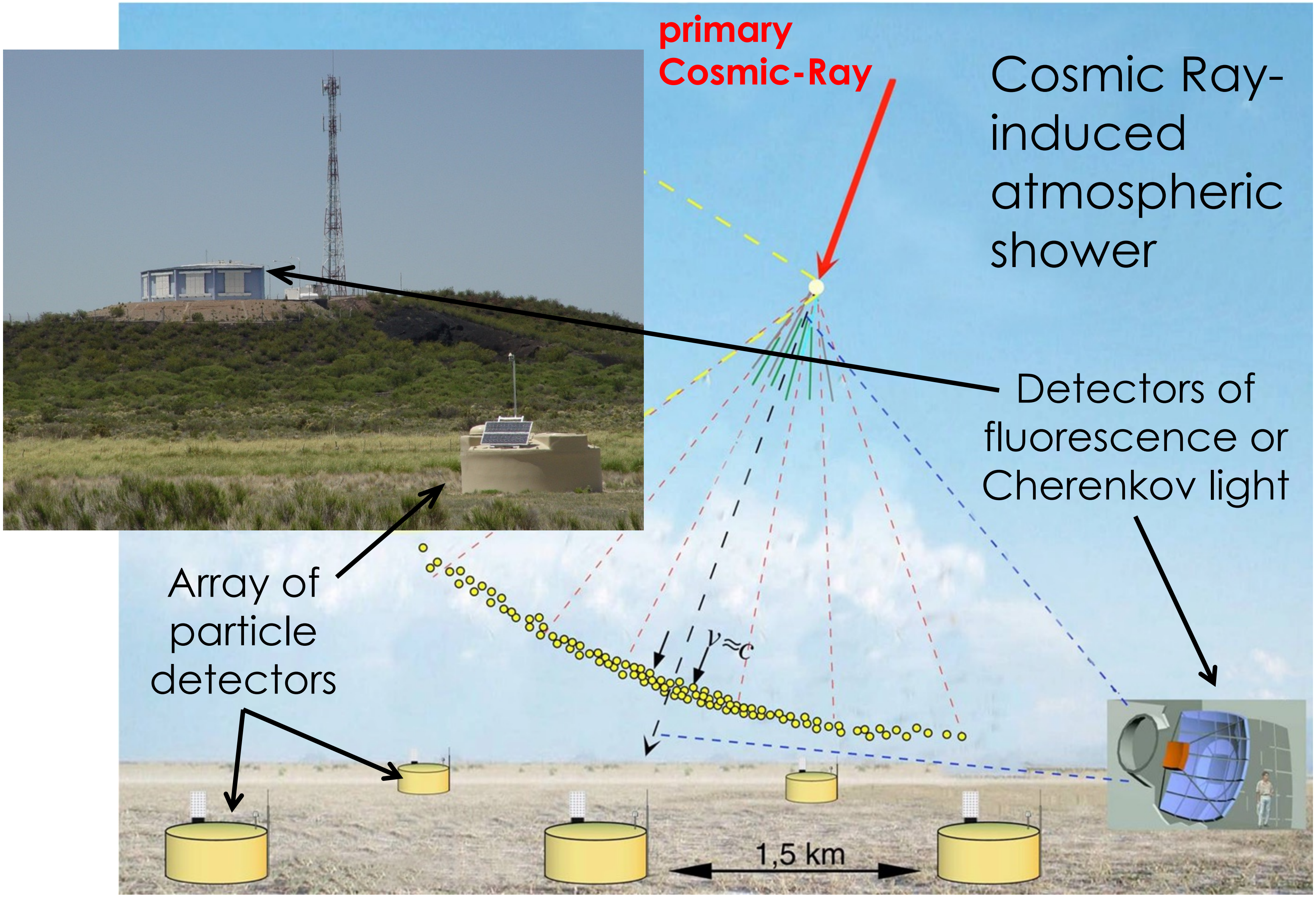
FD = 4 Fluorescence buildings (24 + 3) detectors



35.5º S, 69.3º W
1400 m a.s.l. (870 g cm^{-2})

Pierre Auger, NIMA **798** (2015) 172–213

Detection of UHECR-induced showers



Had we built Auger centered in Santiago…

Role of IGFAE in Auger

The "Auger house"
Analysis tasks

Detector Performance and Science Coordination
I.Lhenry-Yvon, F.Salamida
L.Cazon, B.Dawson

CR Phenomenology
D.Boncioli, E.Roulet
Astrophysical scenarios, magnetic fields, LIV,…

Multimessenger
K.-H.Kampert, E.Zas
Multi-wavelength observations, triggers, alerts, data sharing…

Air Shower Physics
R.Conceicao, T.Pierog
Muons and multiparticle production, new physics,…

Cosmo-geophysics
R.Mussa, D.Veberic
Atmo phenomena, correlation with solar activity and space weather,…

Energy Spectrum
F.Fenu, V.Verzi
SD-vertical, SD-inclined, hybrid, radio

Mass Composition
E.Mayotte, A.Yushkov
Mass estimators and composition

Neutral Particles
J.Alvarez-Muniz, M.Niechciol
ν and γ searches

Arrival Directions
L.Caccianiga, G.Golup
Large and intermediate scale anisotropy, point sources

Calibration
D.Schmidt, G.Salina, N.N. (radio)
FD calib database, VEM/MIP, muon number…

Monitoring
C.Berat, J.Rautenberg
Definition and preparation of tools for performance checks

Long Term Performance
R.Caruso, I.Maris
Detectors stability, shifts report

Atmospheric Conditions
B.Keilhauer, L.Valore
Atmo database, VAOD, data monitoring,…

Monte Carlo Simulations
R.Colalillo, E.Santos
Shower and detector simulation libraries

Analysis Foundations
J.Bellido, T.Huege, M.Roth
High quality data for analysis

Machine Learning
J.Glombitza, N.N.
Deep learning methods, algorithms

Main goal of Pierre Auger Observatory:

Determine **origin** (sources), **nature** (composition) and **acceleration mechanisms** of Ultra-High-Energy Cosmic Rays (UHECR) above ~ 1 EeV (10^{18} eV), through measurements of:

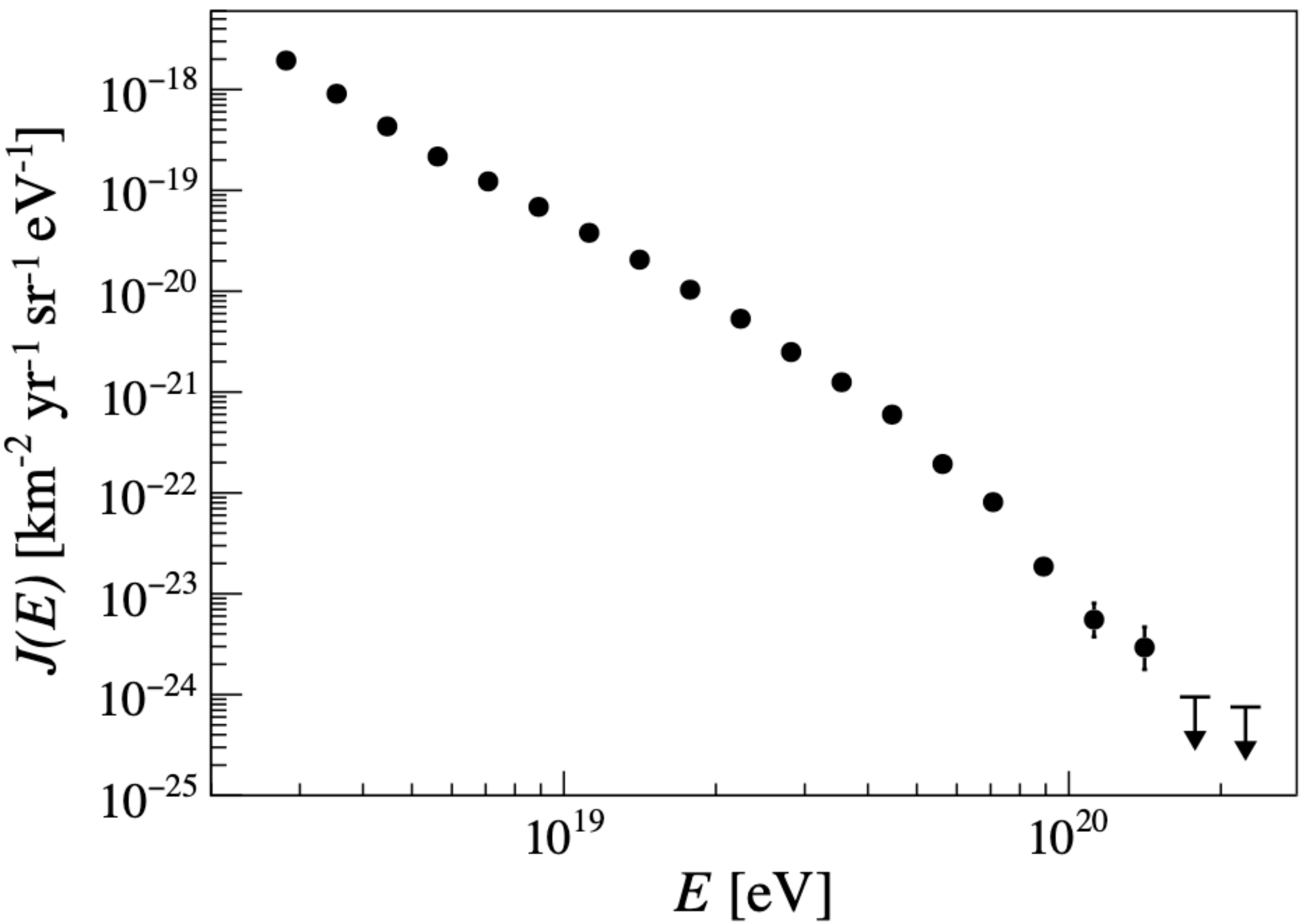
- **energy spectrum**
- primary composition
- distribution of arrival directions
- gamma-ray and **neutrino content** of the UHE particle flux

Auger data also **probes hadronic interactions** at the energy frontier

See International Cosmic Ray Conference 2021, Berlin, July 2021 for latest results. https://pos.sissa.it/395

Energy spectrum of UHE Cosmic Rays

Most precise measurement of the cosmic-ray energy spectrum at UHE



215,030 events above 2.5 x 10^{18} eV

Flux above 5 x 10^{19} eV is 0.5 km^{-2} century

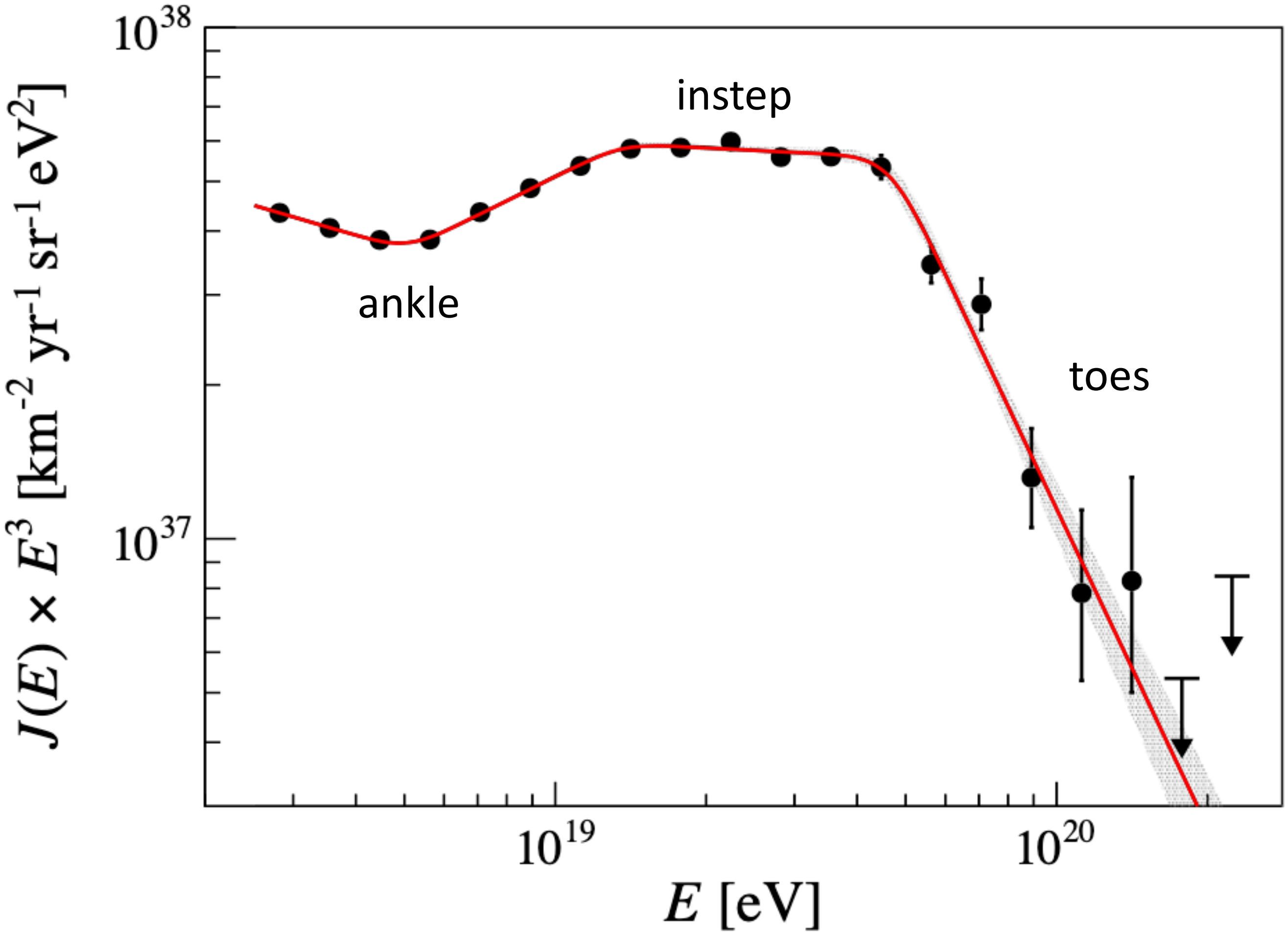
15 events detected with E>10^{20} eV (16 Joules)

Highest energy event is 100 million times more energetic than a LHC proton

Pierre Auger, Phys. Rev. Lett. **125**, 121106 (2020)
Pierre Auger, Phys. Rev. D **102**, 062005 (2020)

Energy spectrum of UHE Cosmic Rays

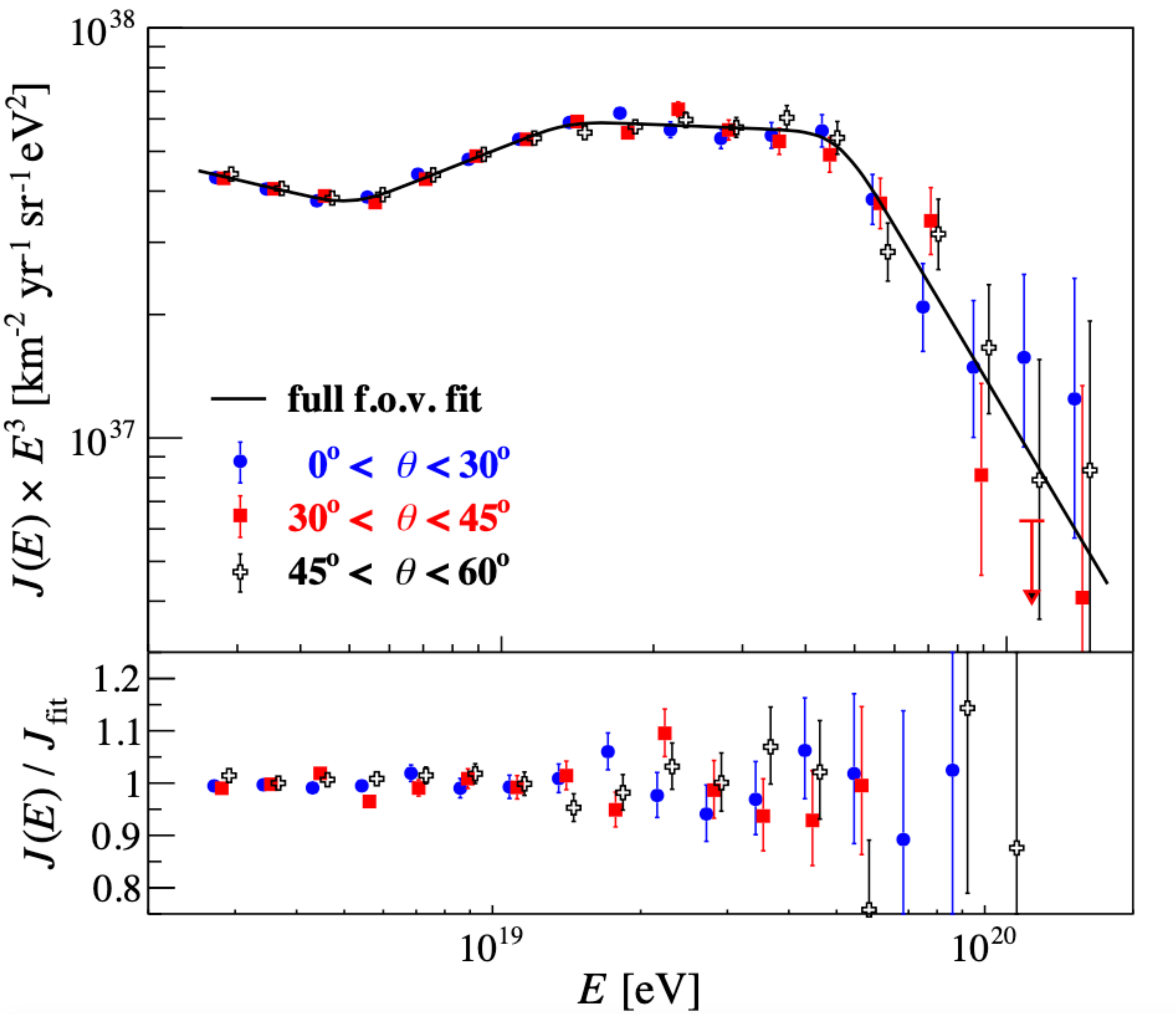
Most precise measurement of the cosmic-ray energy spectrum at UHE



Rich structure.
New feature discovered: the ”instep”
(compatible with the change of composition from light to heavy as E increases)

Pierre Auger, Phys. Rev. Lett. **125**, 121106 (2020)
Pierre Auger, Phys. Rev. D **102**, 062005 (2020)

Declination dependence of UHECR spectrum



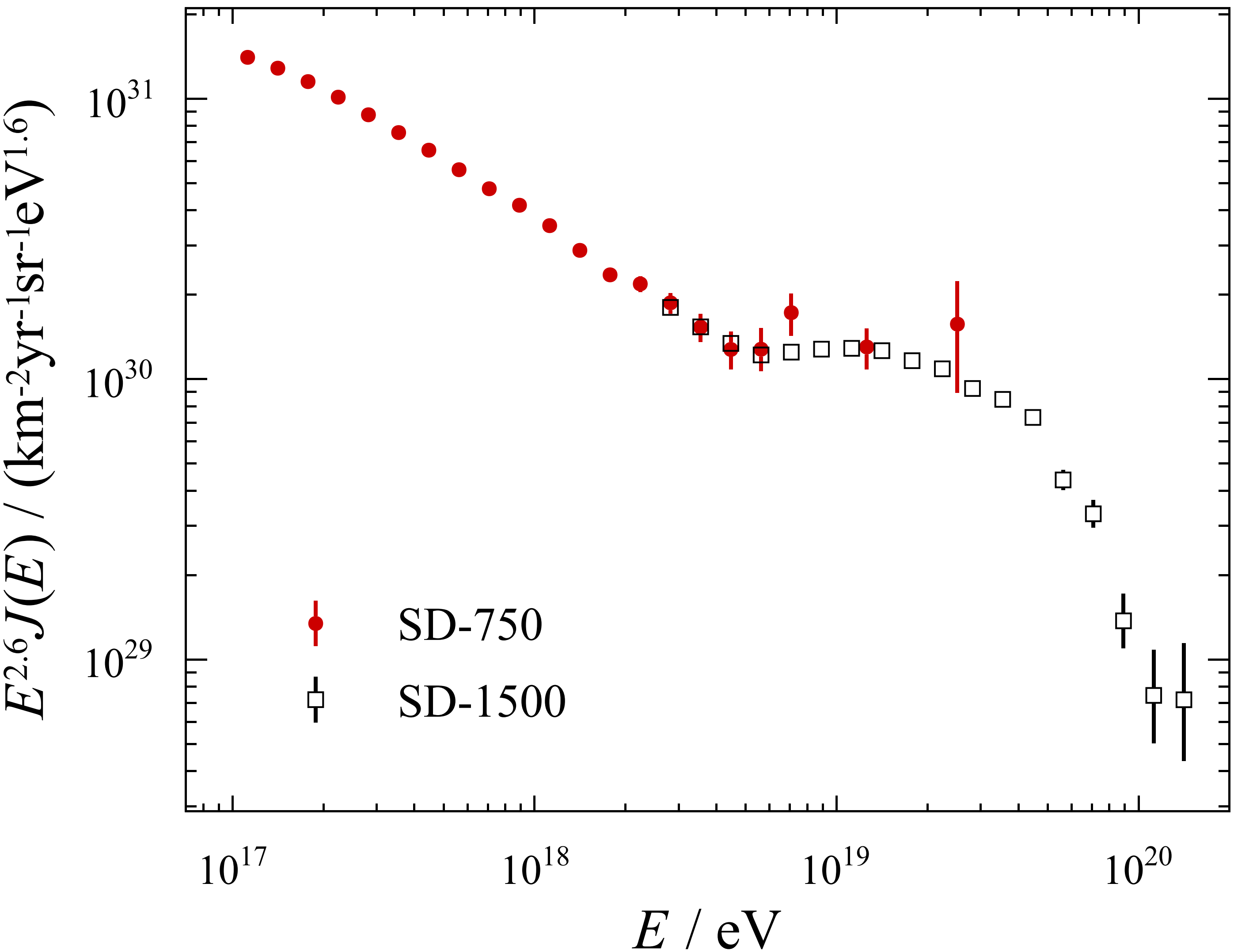
No dependence of flux on declination i.e.

Flux is the same in different parts of the sky (within the FoV of Auger)

Disfavours a single or a small number of sources in the sky responsible for the flux

Pierre Auger, Phys. Rev. Lett. **125**, 121106 (2020)
Pierre Auger, Phys. Rev. D **102**, 062005 (2020)

UHECR spectrum above 10^{17} eV

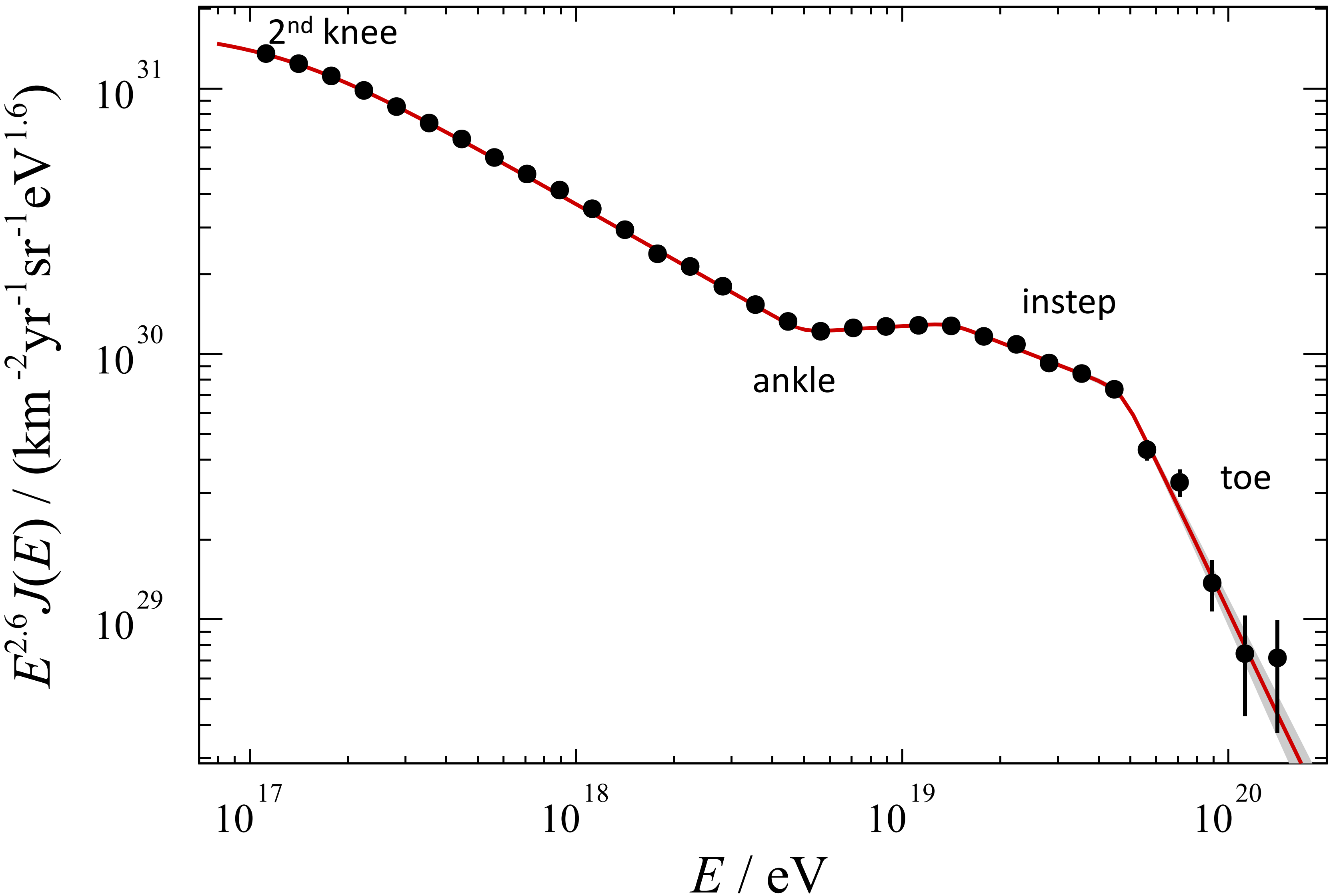


Measured with the smaller more compact SD750 array

560,000 events with $\theta < 40$ deg.
$E > 10^{17}$ eV

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

Unified HECR spectrum above 10^{17} eV



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

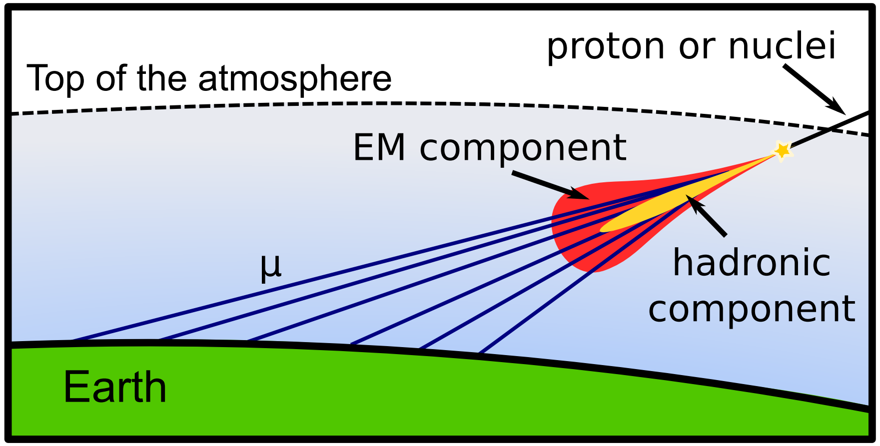
Inclined air showers & number of muons in Auger

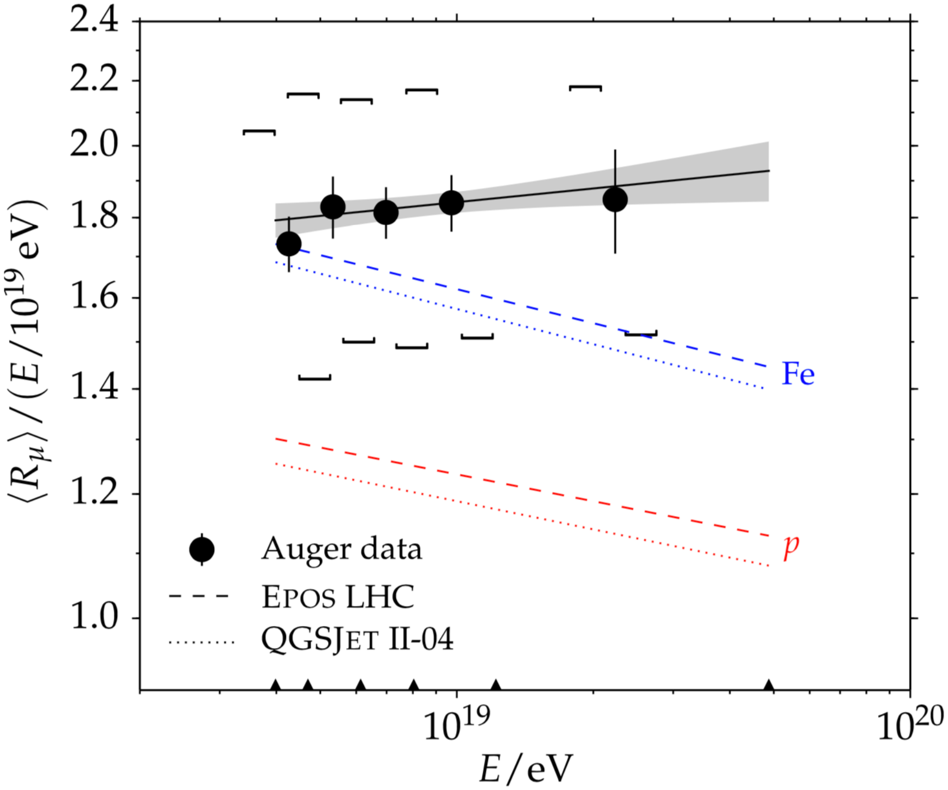
Inclined showers → muon-dominated ⇒

clean & direct measurement of number of muons.

Pierre Auger, Phys. Rev. D **91**, 032003 (2015)

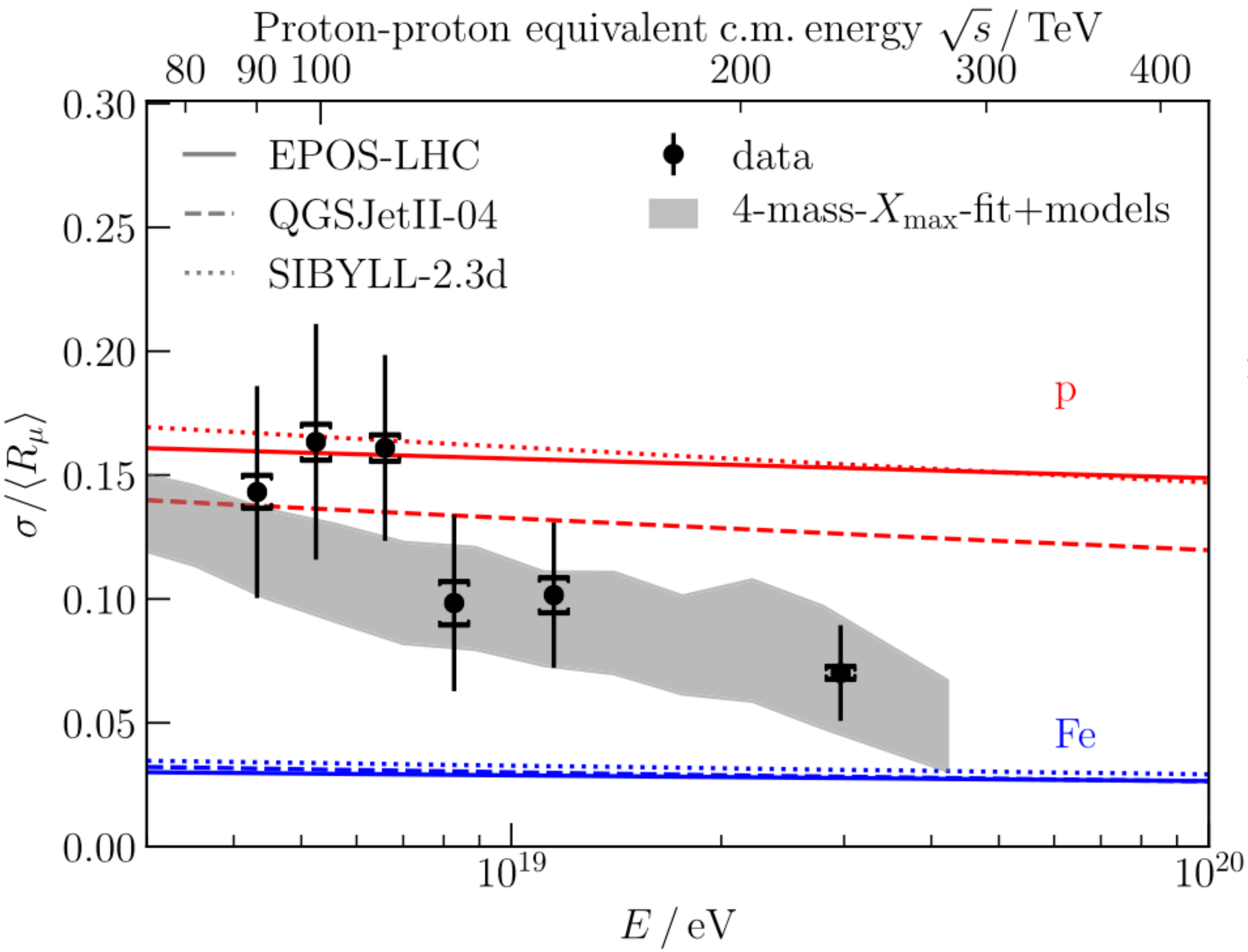
Inclined cosmic-ray Shower





Hadronic interaction models of multiparticle production predict 30% - 80% less muons than observed in Auger data

First measurement of the (relative) fluctuations in the muon content of air showers at ultra-high energy



Pierre Auger, Phys. Rev. Lett. **126**, 152002 (2021)

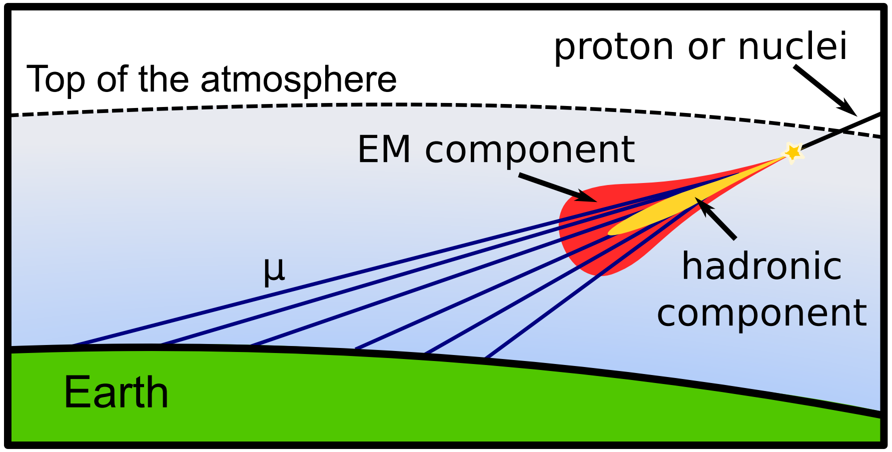
Fluctuations well reproduced by hadronic interaction models =>

Compatible with muon deficit originating from small deviations in predictions from hadronic models that accumulate as showers develop.

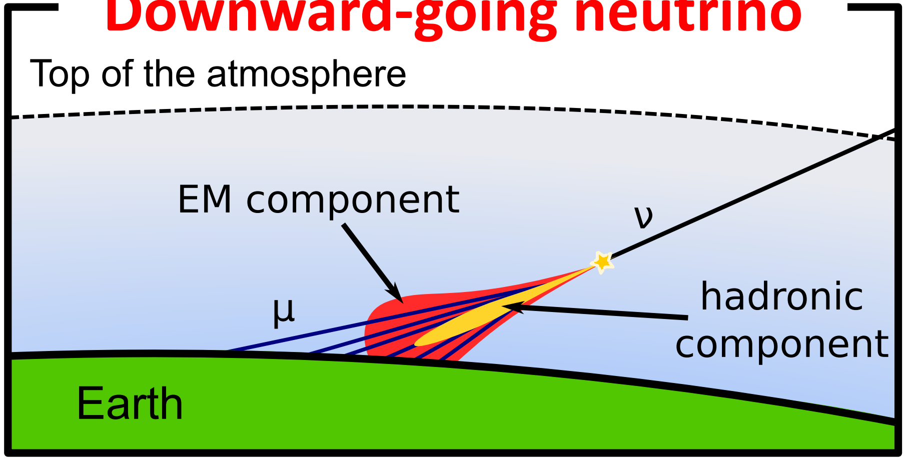
Search for UHE neutrinos with Auger Surface Detector SD1500

- **Pierre Auger is not a dedicated neutrino observatory** but ...
- **UHE neutrinos** induce showers that **can be distinguished** from background charged CR showers:

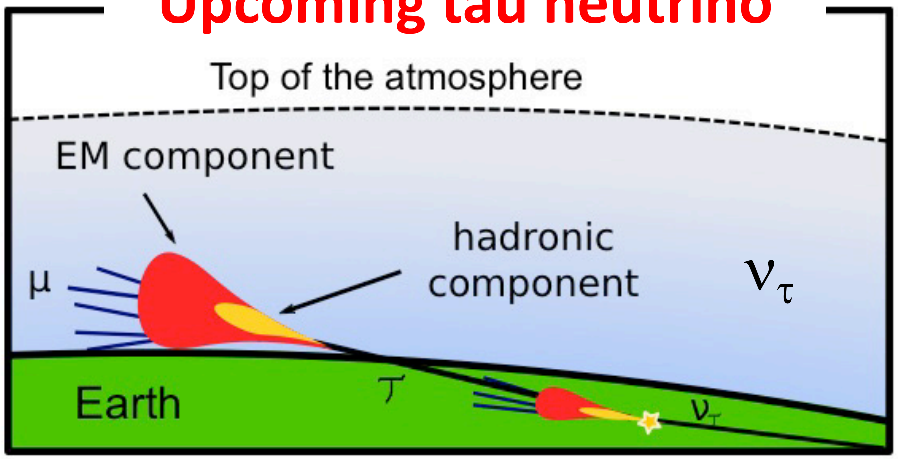
Cosmic Ray



Downward-going neutrino



Upcoming tau neutrino



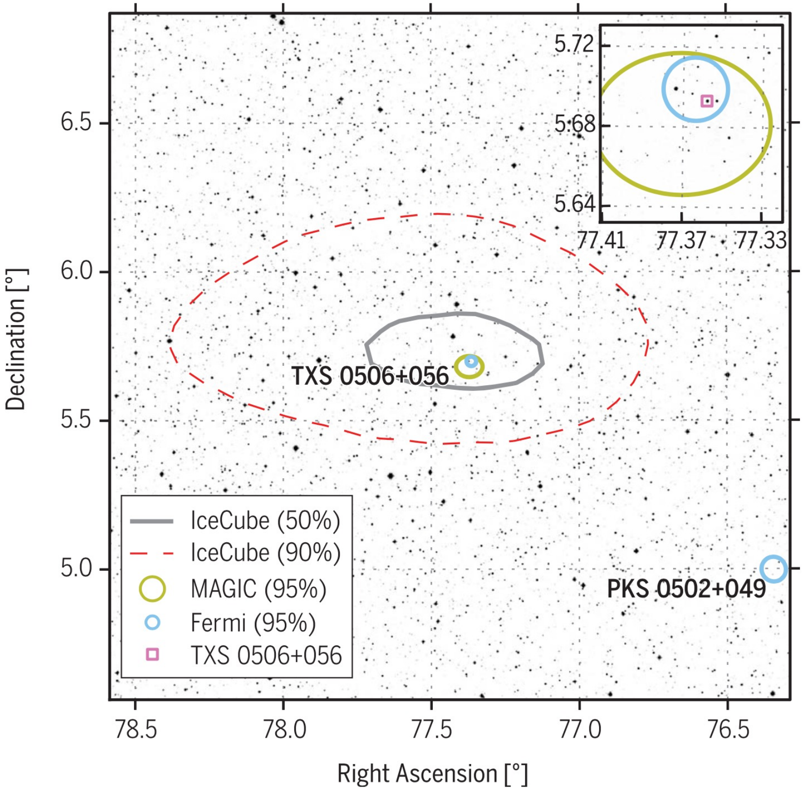
Neutrino signature ⇒ **inclined showers** that develop close to ground

High-Energy ν discovered by IceCube directionally coincident with a blazar (AGN)

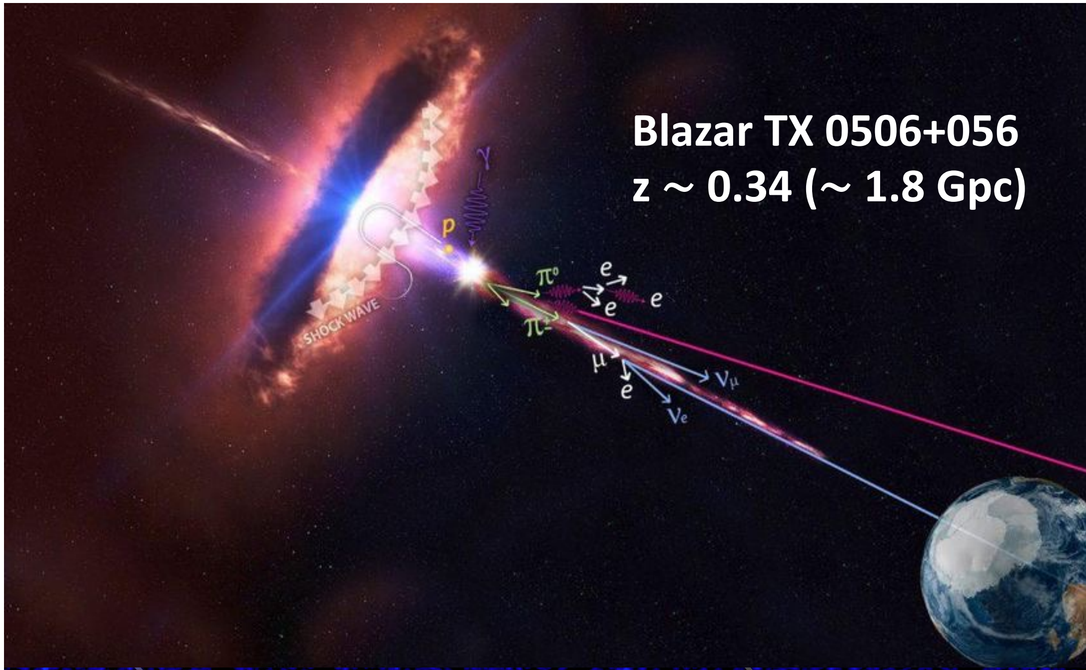
22 Sep. 2017 ~ 300 TeV ν within 0.1° of γ-ray source TXS 0506+056 (blazar) in a flaring state of activity

Excess of 13+/-5 events (3.5 σ) in a window of 110 days around 13 Dec 2014 coincident with TXS 0506+056.

IceCube Collab. et al. Science 361, 146 (2018)
IceCube Collab. Science 361, 147-151 (2018)



First identified source of high-energy astrophysical neutrinos

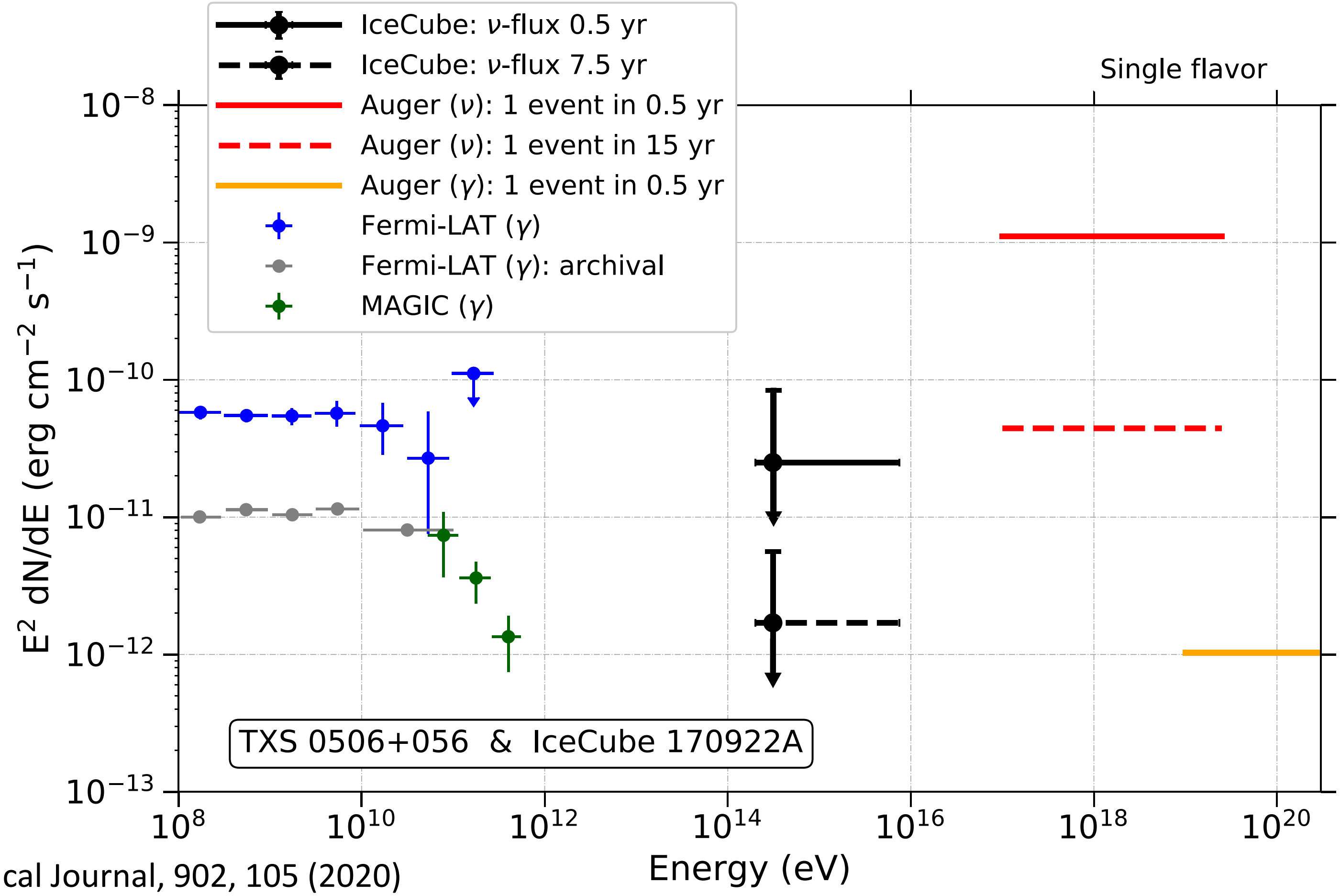


Auger limit to UHEν from TXS 0506+056

Multimessenger Astronomy

IGFAE is responsible for follow-up of transient events in UHE neutrinos

No candidate neutrinos from direction of TXS at EeV energies in Auger
First upper limits to the UHE neutrino flux from an identified ν source



Pierre Auger.
The Astrophysical Journal, 902, 105 (2020)

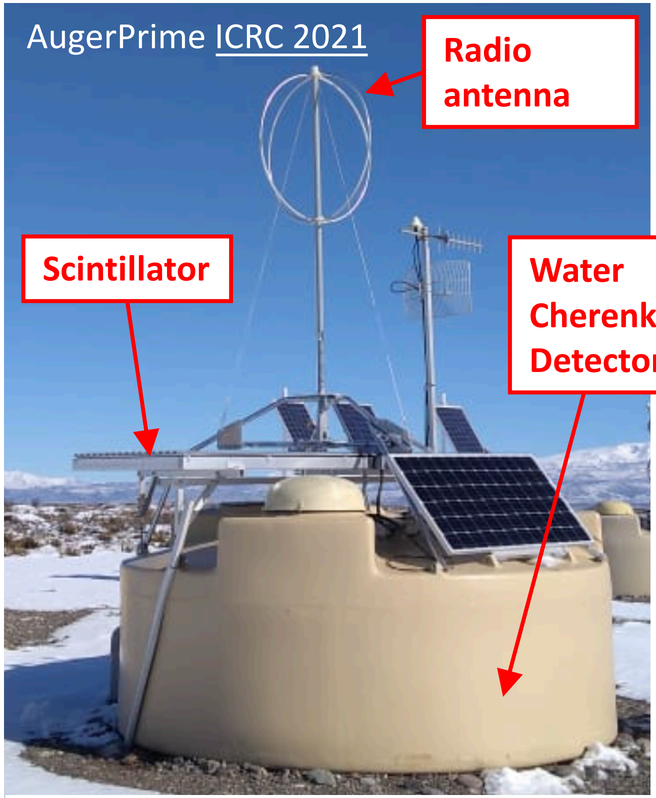
Progress in AugerPrime

Extension/Upgrade of the Pierre Auger Observatory

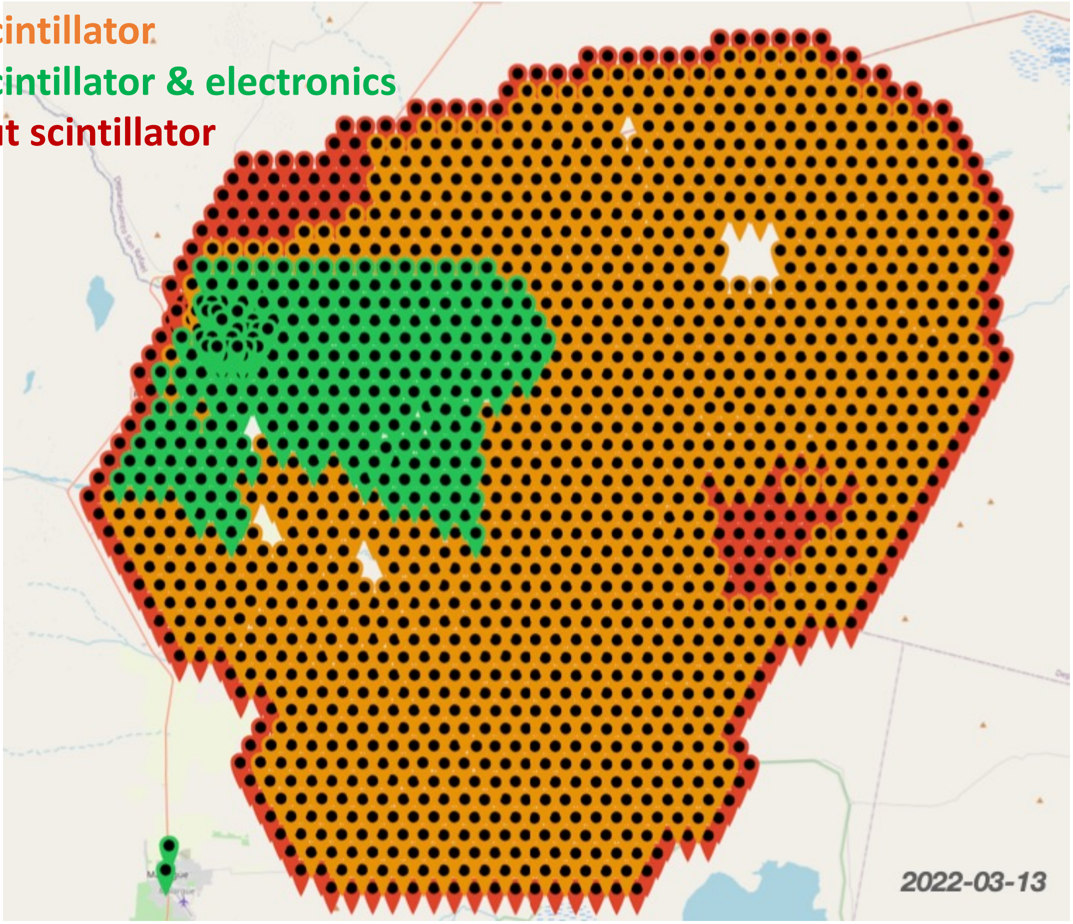
Instrument water-Cherenkov stations with ~4 m^2 **scintillators & antennas on top**

Improve composition determination on shower-by-shower basis

Status & timeline: Data taking with full upgraded array until **2025 (extension to 2030 ?)**



Fully-equipped AugerPrime Surface Detector station

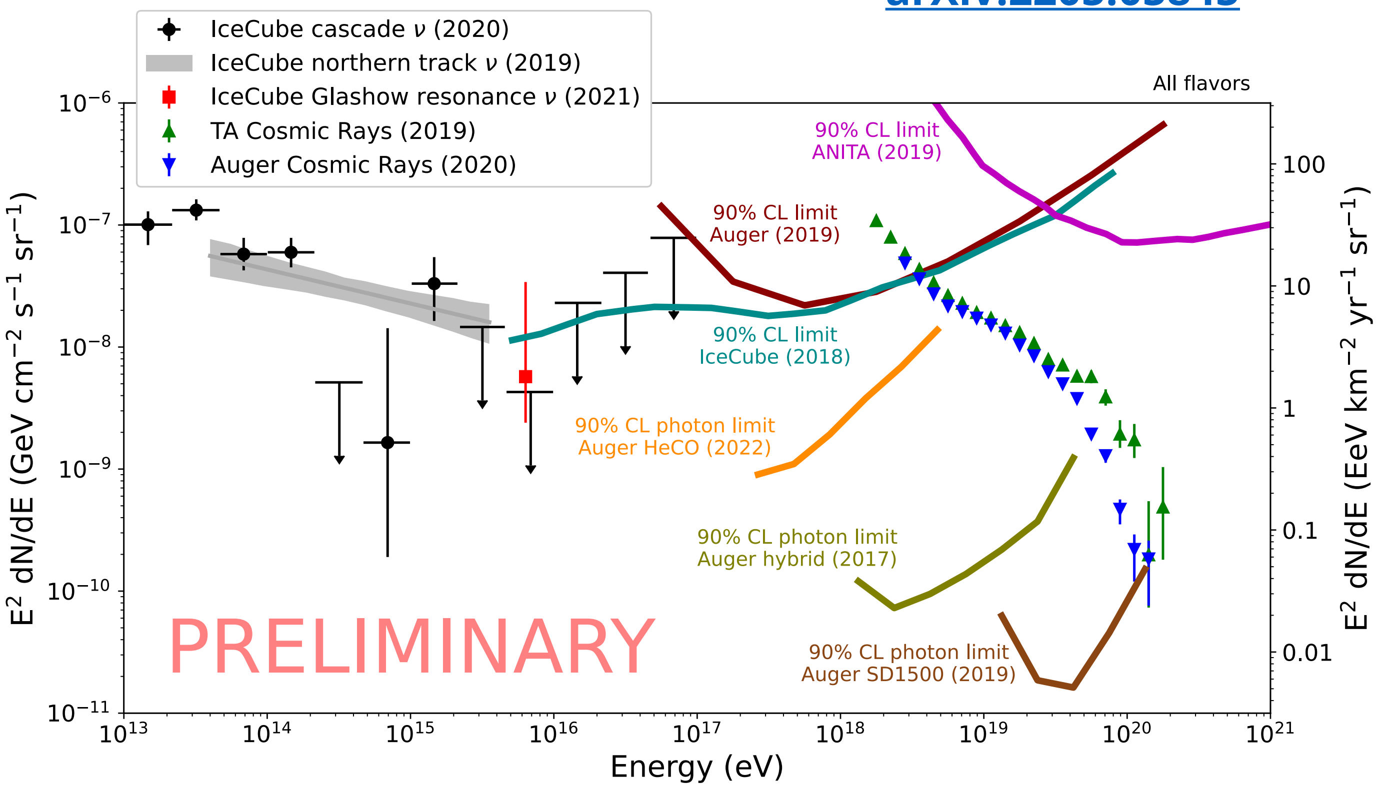


Contributions to Snowmass 2021 as coordinators / main authors

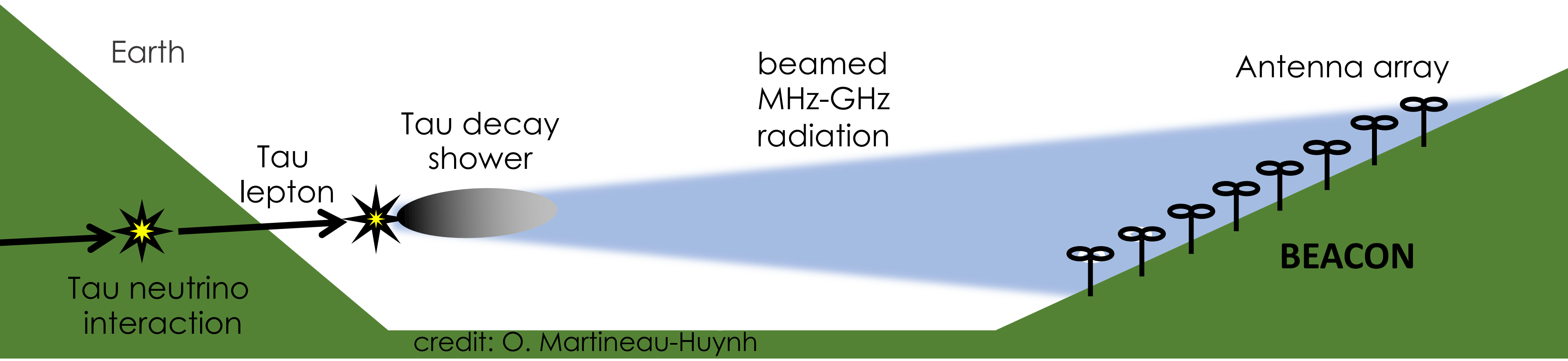
“Ultra-High Energy Cosmic Rays (UHECRs): The Intersection of the Cosmic and Energy Frontiers”

arXiv:2205.05845

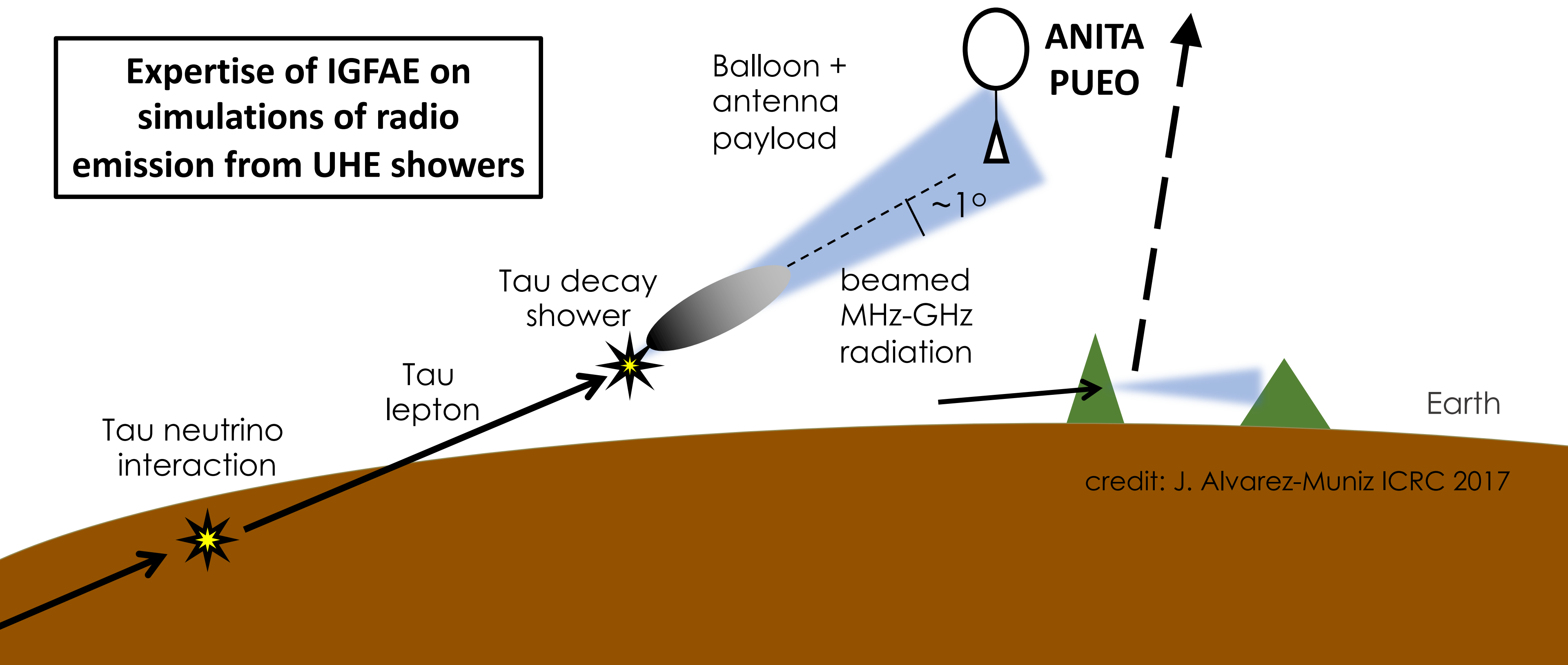
Multimessenger summary plot showing together Auger **differential** photon and neutrino limits in comparison to UHECR spectrum and IceCube fluxes and limits



Radio detection of tau neutrinos

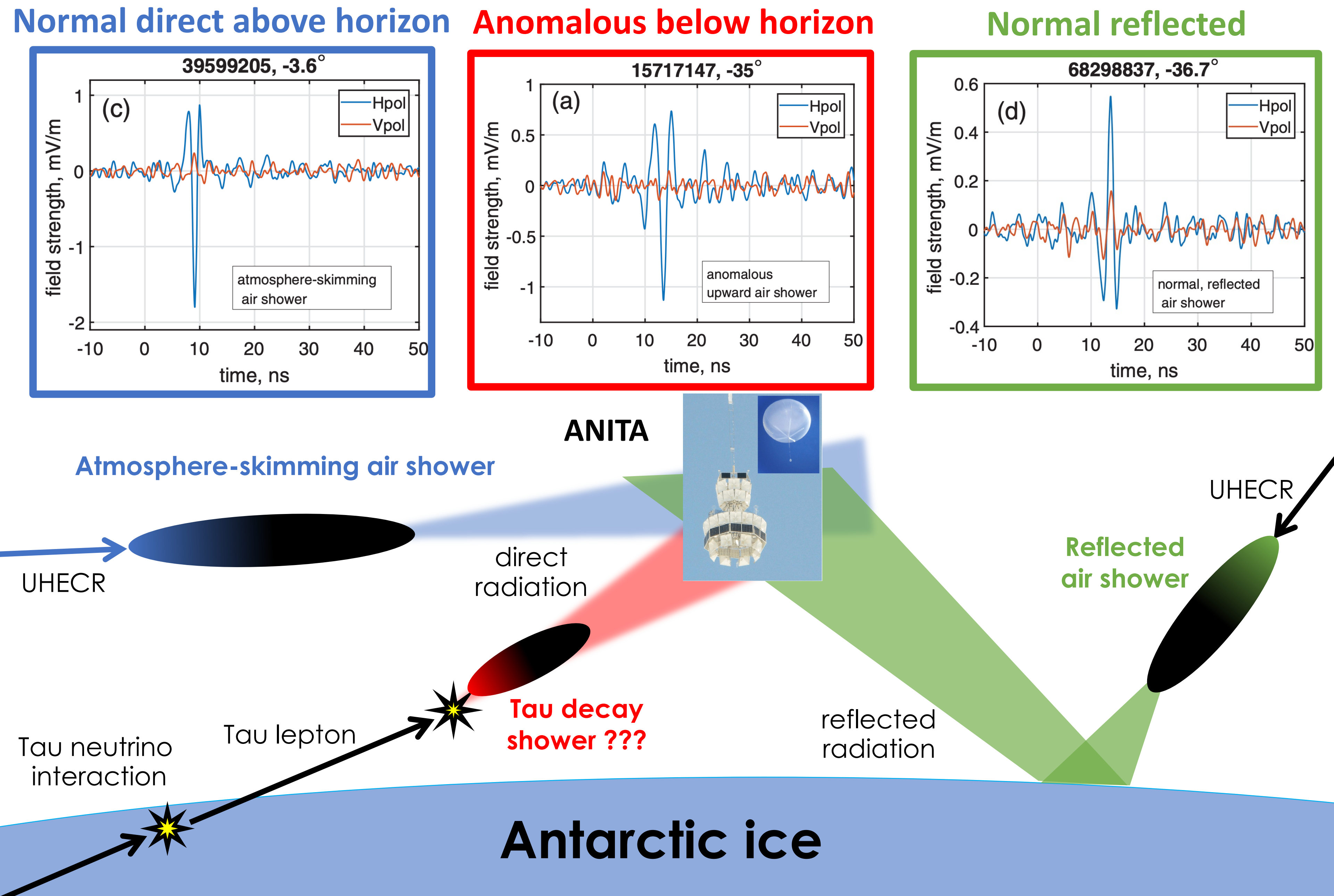


Expertise of IGFAE on simulations of radio emission from UHE showers



ANITA normal & "anomalous" events

ANITA. PRL **117**, 071101 (2016)
ANITA. PRL **121**, 161102 (2018)
ANITA. PRL **126**, 071103 (2021)

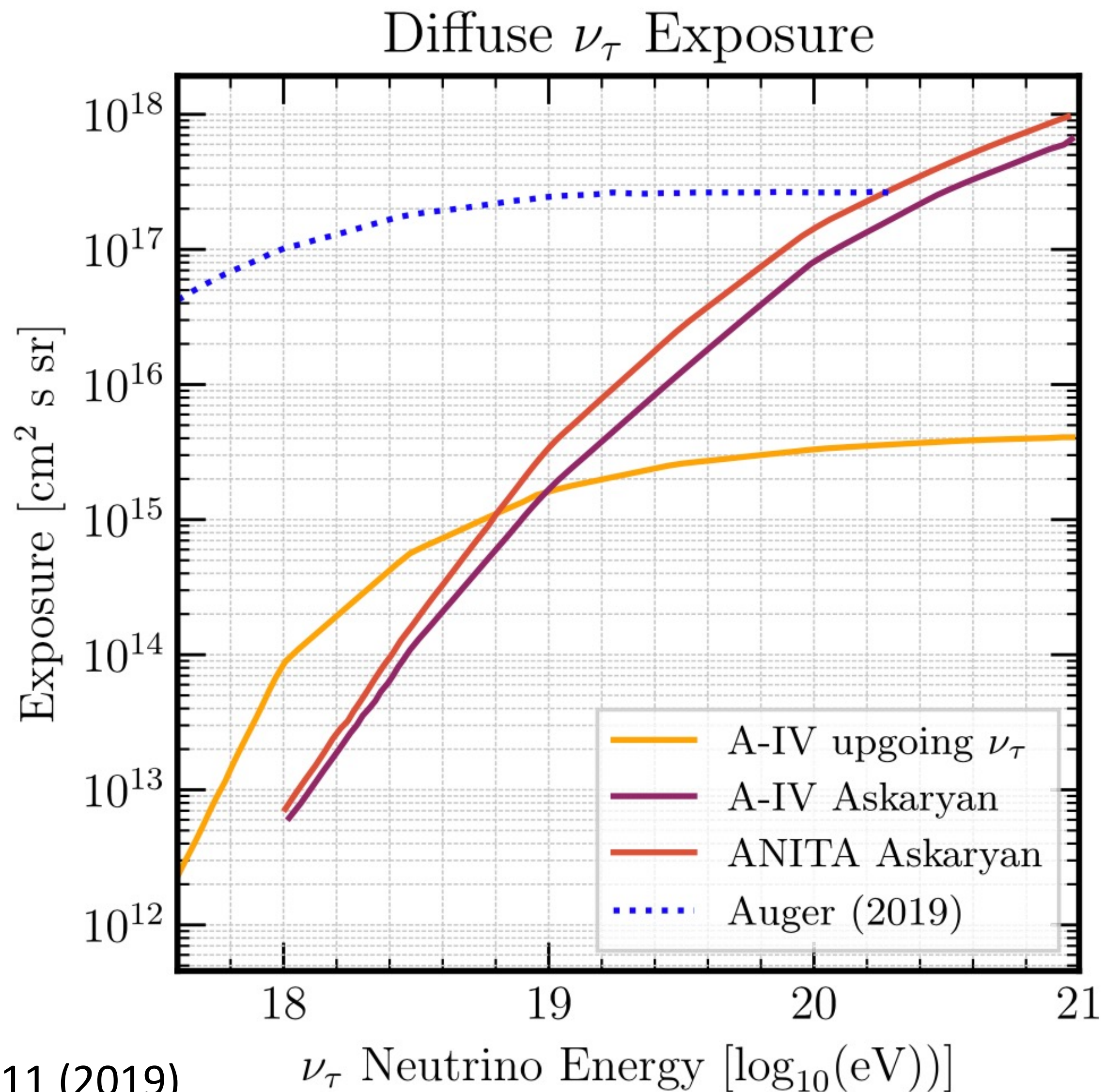


ANITA I, III and IV saw 6 ”anomalous” events

If ANITA ”anomalous” events are due to tau neutrinos interacting in the Earth

⇩

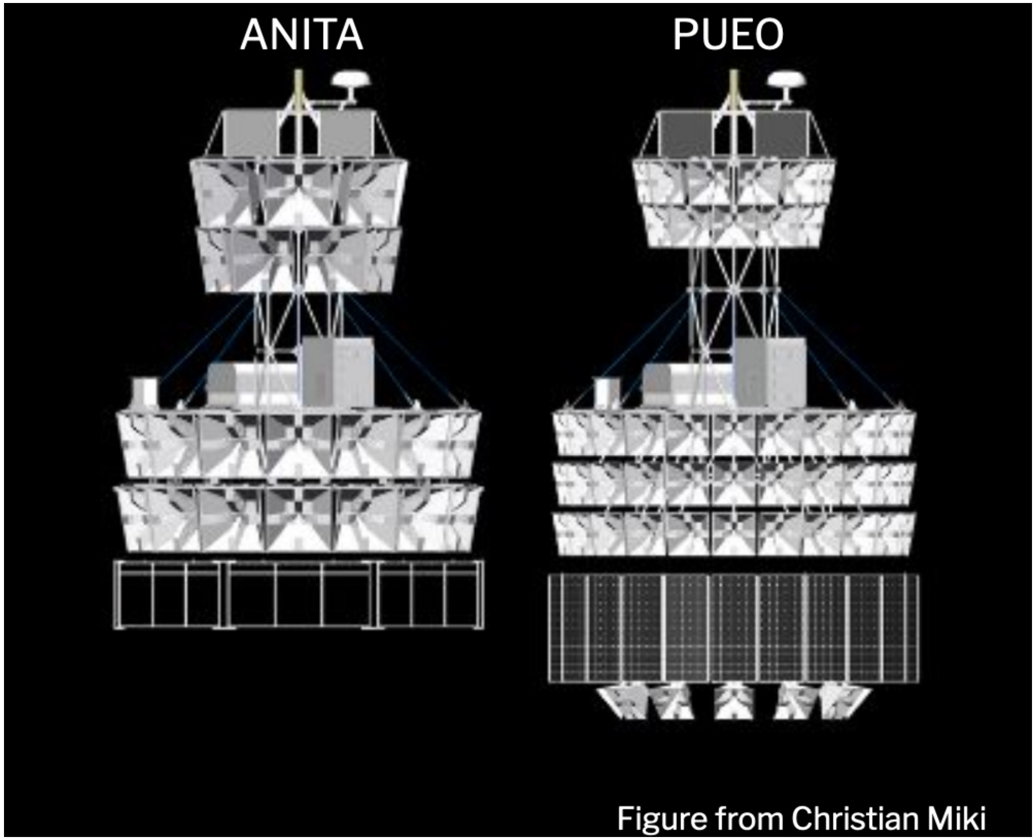
Auger and IceCube should have already detected hundreds of tau neutrino events !!



ANITA & IGFAE, Phys. Rev. D **99**, 063011 (2019)
ANITA & IGFAE, Phys. Rev. D 105, 042001 (2022)

PUEO – Payload for Ultra-high Energy Observations

- PUEO builds on the success of the previous ANITA experiment.
- > 10 x more sensitive than ANITA at 10 EeV
- To be launched from Antarctica in 2024 (30-day flight expected)



The Payload for Ultrahigh Energy Observations (PUEO): A White Paper.
JINST 16 (2021) 08, P08035 (participation of IGFAE)

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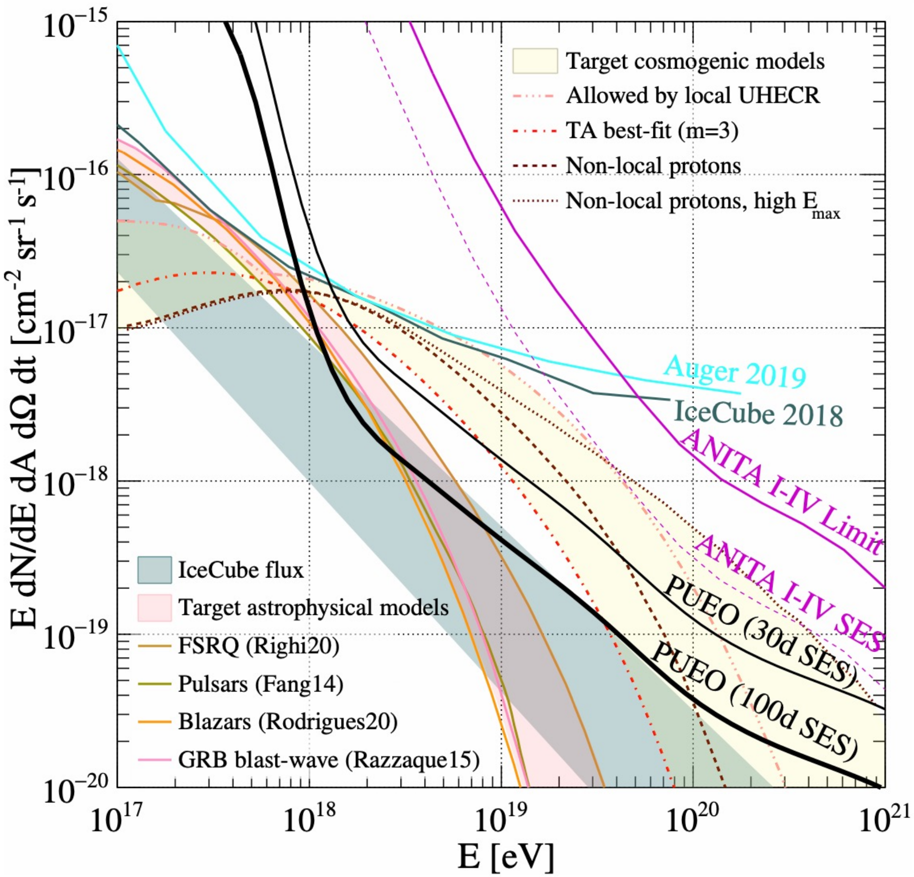
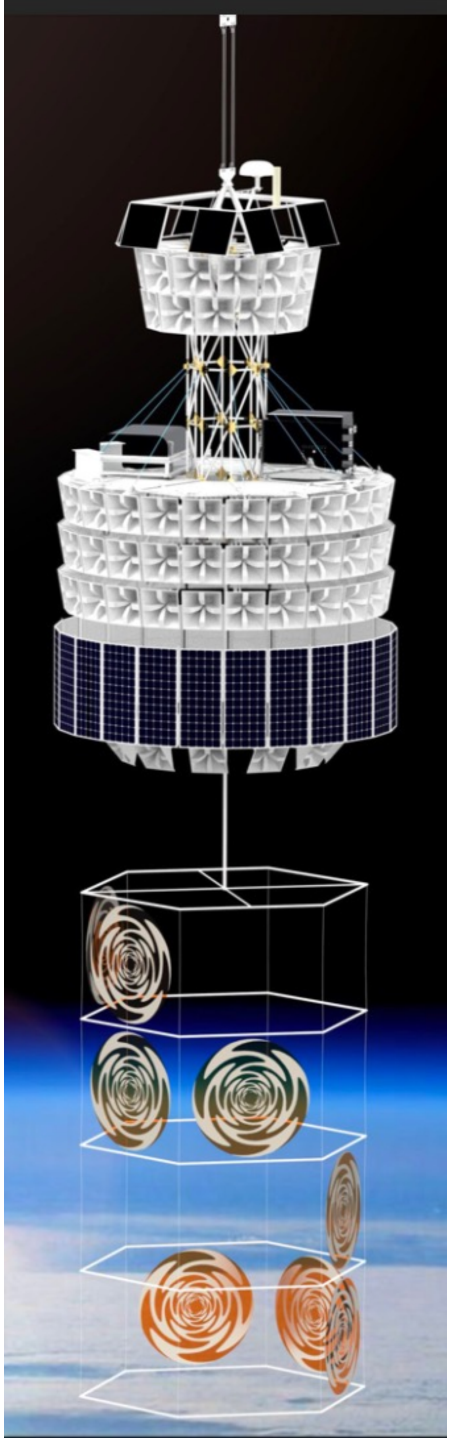
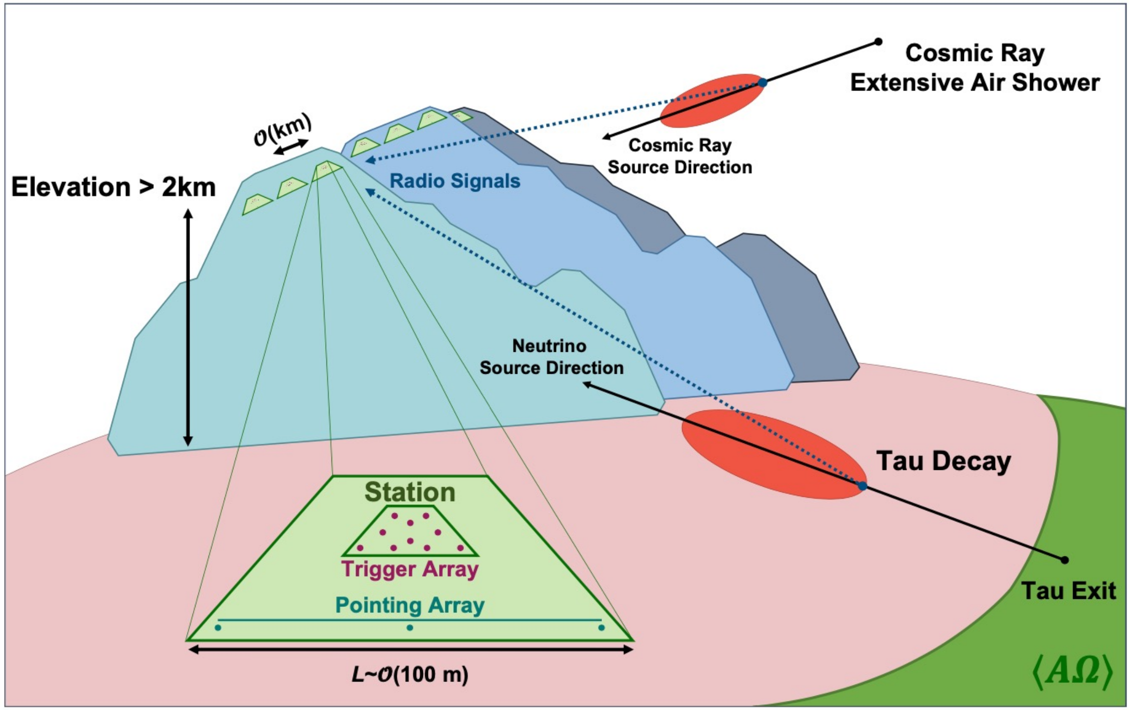




The Payload for Ultrahigh Energy Observations (PUEO): A White Paper.
JINST 16 (2021) 08, P08035 (participation of IGFAE)

BEACON: Beamforming Elevated Array for Cosmic Neutrinos



BEACON prototype (4 antennas 30-80 MHz) in the White Mountains in California, USA at 3.8 km altitude. Cosmic-Ray candidate detected

BEACON with 100 stations & 3 years of data can improve existing limits by a factor of 3.

BEACON & IGFAE – JCAP 11 (2020) 069. BEACON prototype arXiv:2206.09660

Contributions to Snowmass 2021 as coordinators / main authors

"Tau Neutrinos in the Next Decade: from GeV to EeV"

arXiv:2203.05591

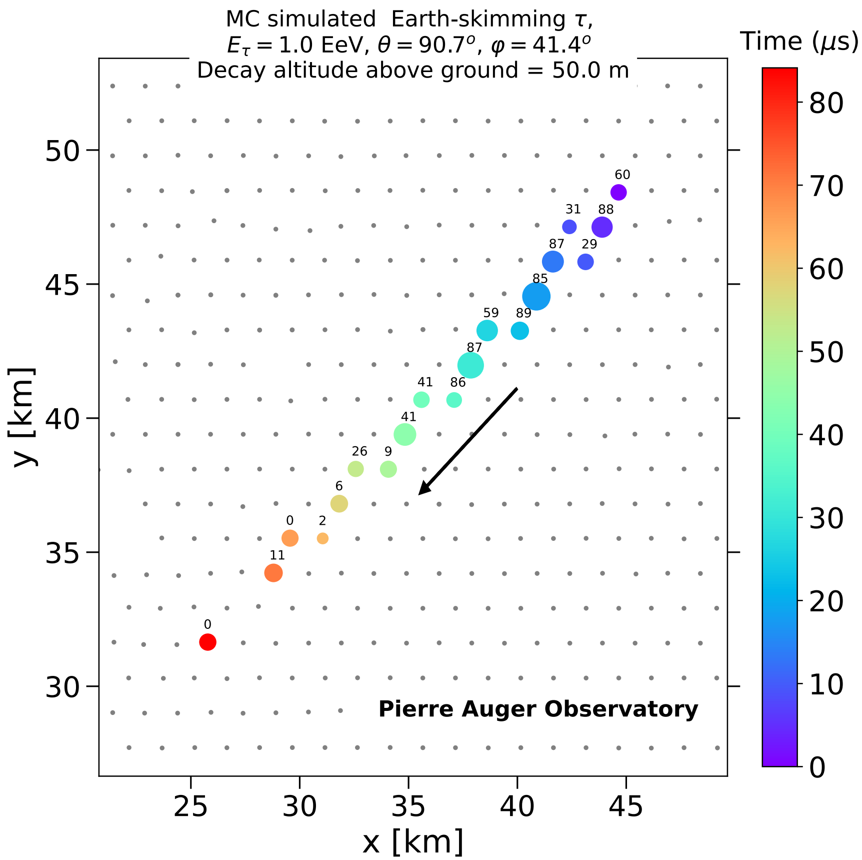
Landscape of operating and planned experiments sensitive to tau neutrinos

				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediterranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational		Date full operations began
Prototype		Date protoype operations began or begin
Planning		Projected full operations

Contributions to Snowmass 2021 as coordinators / main authors

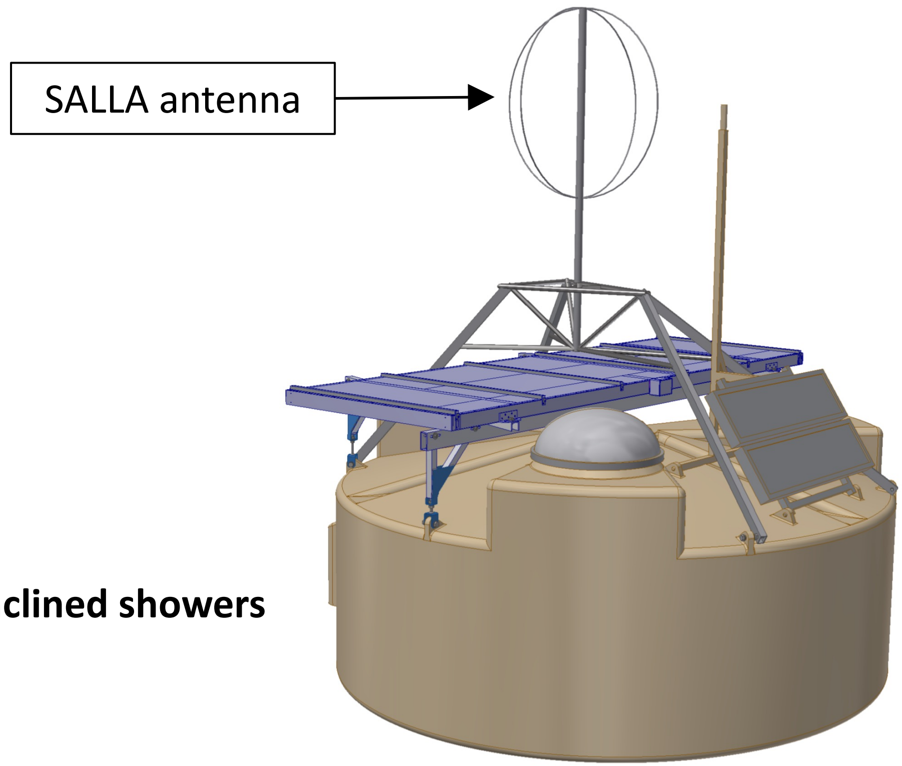
"High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper" [arXiv:2203.08096]



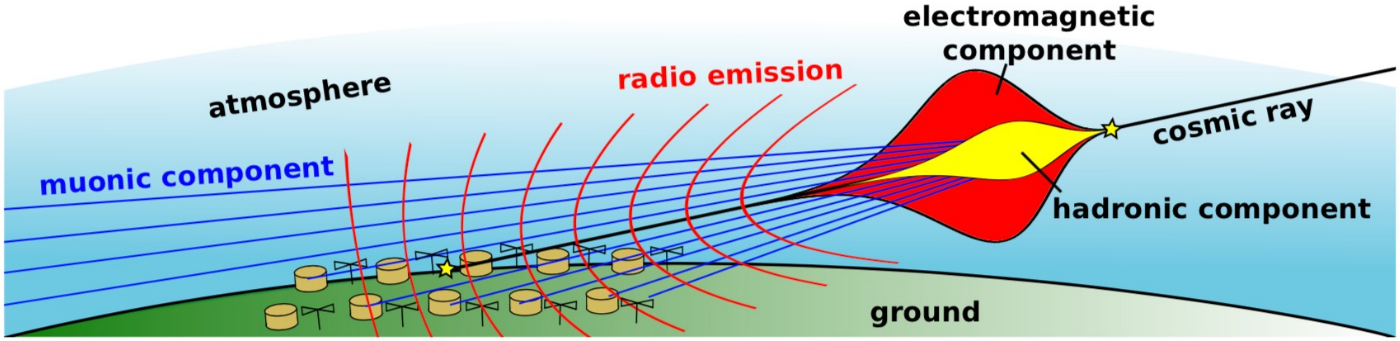
Example of a simulated 10^{18} eV Earth-Skimming (θ=90.7 deg.) tau neutrino in Auger

More information

Radio extension of Auger



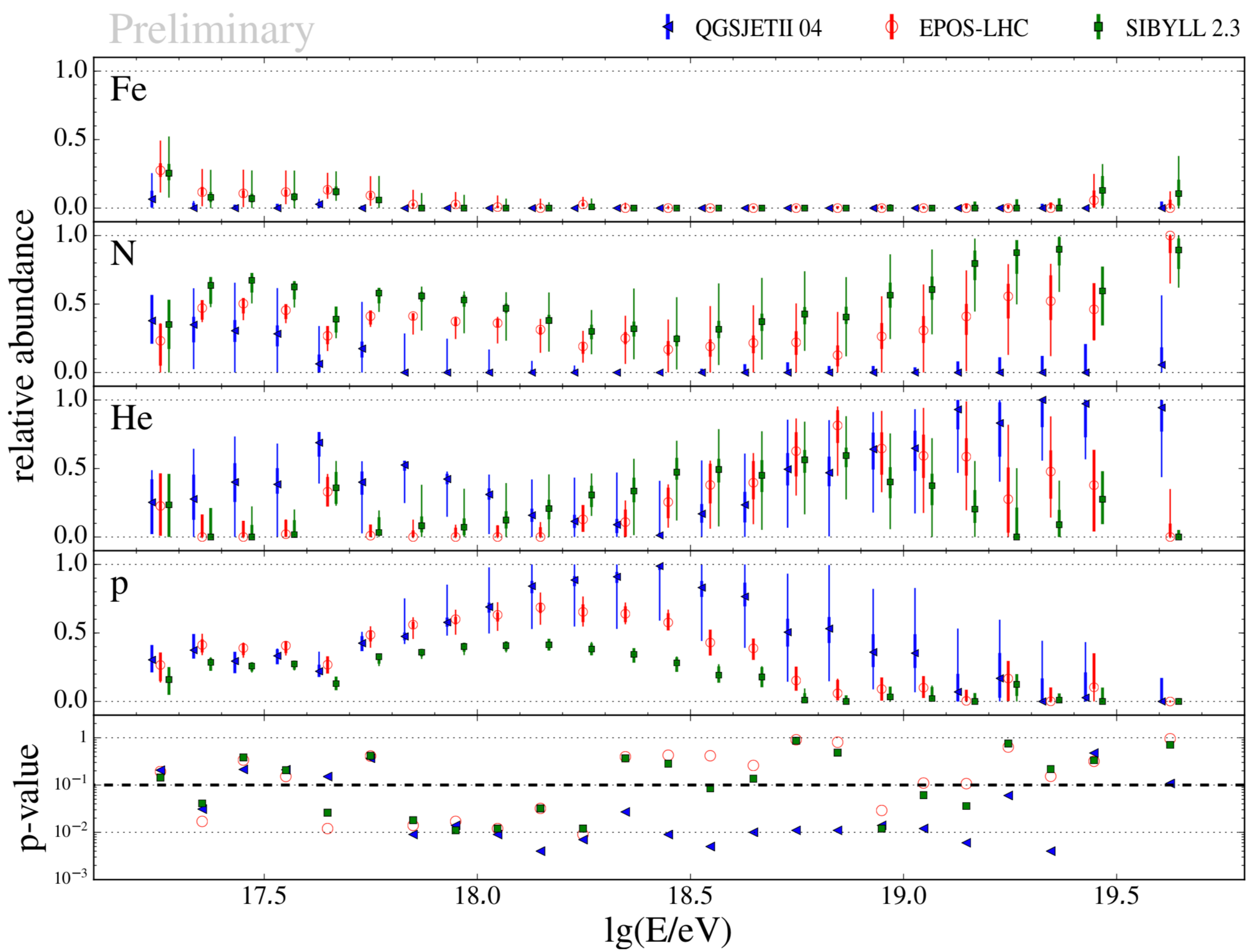
- Add **radio antennas (30-80 MHz)** to the 1600 water-Cherenkov stations
- **Goals:**
  - **em/muon separation in inclined showers**
  - **shower-by-shower mass sensitivity with inclined showers**
  - increase sky coverage



- **Status:**
  - **100% of the funds secured** (Advanced ERC + Netherlands Organiz. for Scientifc Research).
  - Project implementation currently ongoing. Prototyping.

UHECR composition with Auger

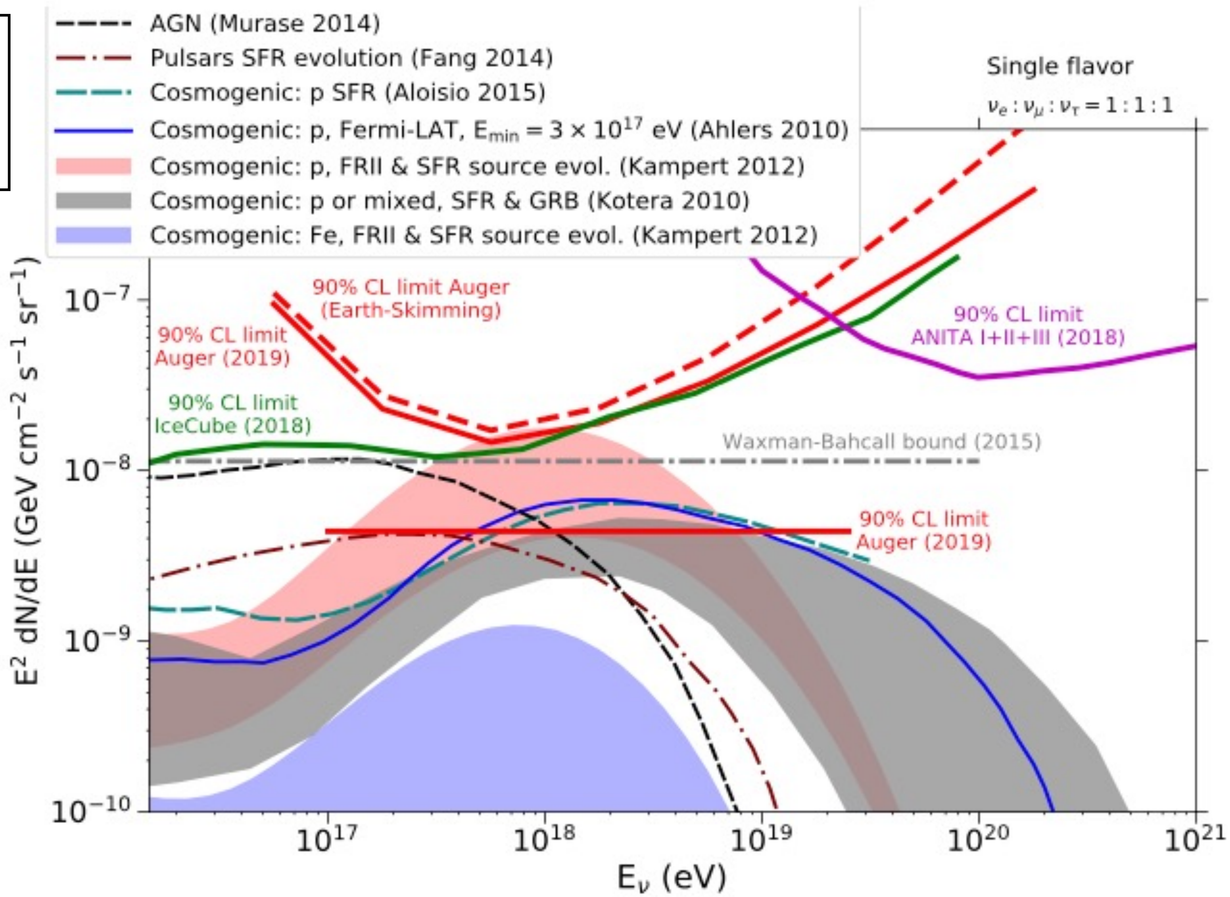
Complex evolution of mass composition between $10^{17.2}$ and 10^{20} eV



Pierre Auger Coll., PRD **90** (2014) 12, 122006; update at ICRC17

Upper limit to diffuse flux of UHE neutrinos

Auger data:
1 Jan 2004 –
30 June 2018

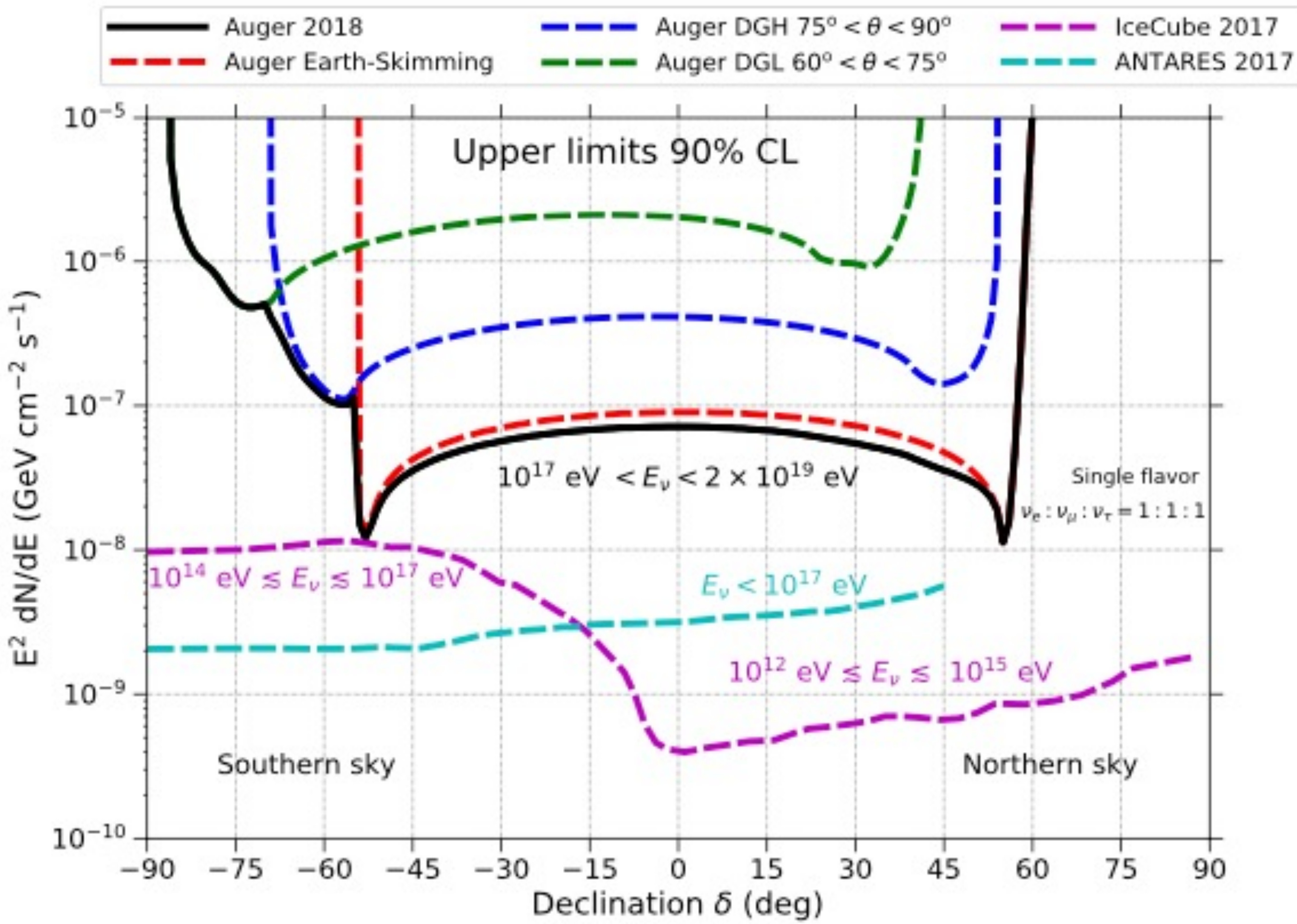


Pierre Auger
JCAP 10 (2019) 022

- **No neutrino candidates** in data Jan 04 – June 18 => restrictive upper limits to neutrino flux in cosmic beam
- UHE neutrinos are produced in UHECR interactions & Auger limits constrain models assuming pure proton primary cosmic beam
- Very small background to ν identification => Auger sensitivity limited by exposure

Limits to point-like & steady neutrino sources

Broad range in declination where ν can be efficiently identified with Auger: two ”sweet” spots around declinations -55° and +55°



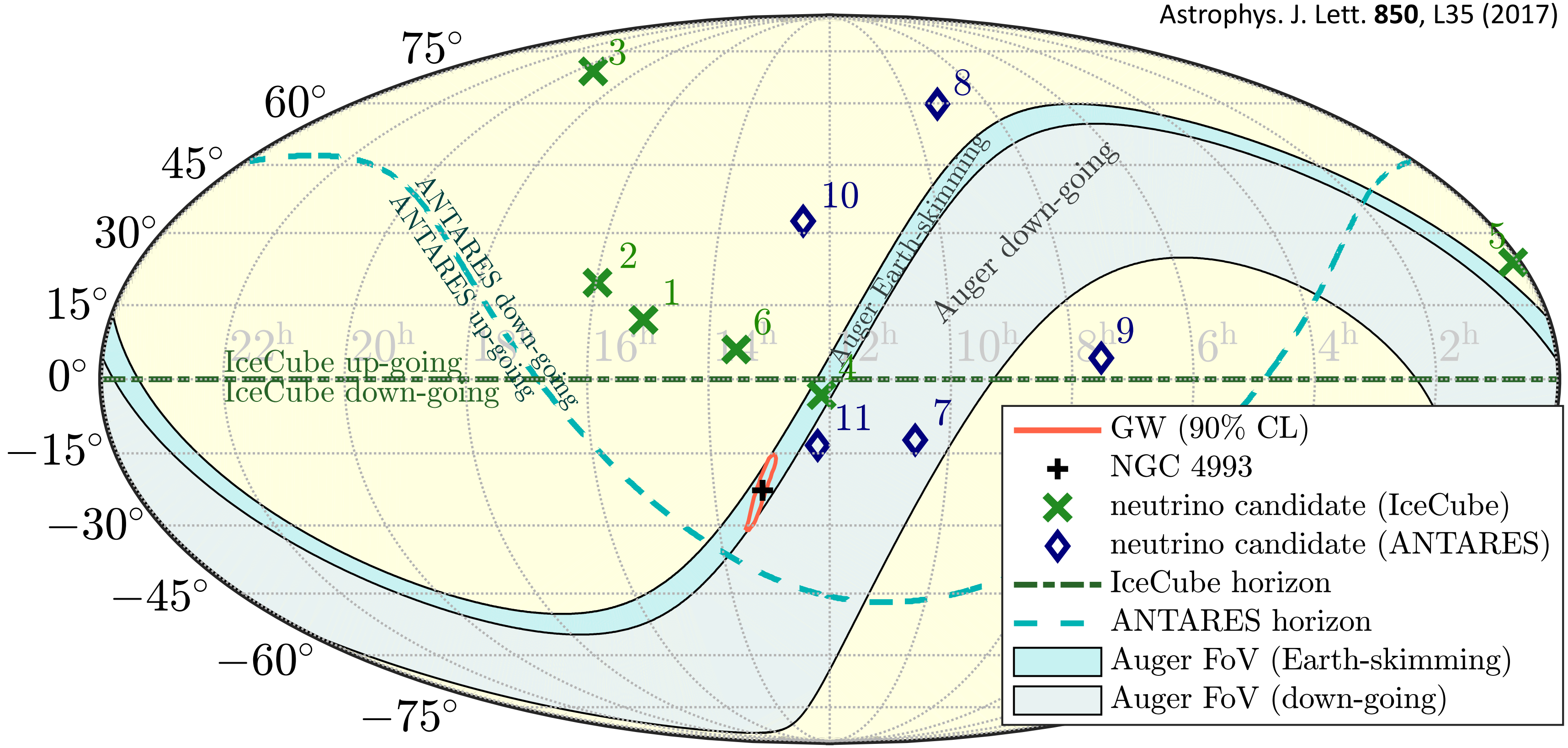
Pierre Auger
JCAP 11 (2019) 004

NOTE **complementary** energy ranges of experiments

IceCube, Astrophys.J. **835**, 151 (2017)   ANTARES, PRD **96**, 082001 (2017)

Follow-up of GW170817 in neutrinos
Binary Neutron Star Merger + short GRB

ANTARES, IceCube, Auger, LIGO & Virgo
Astrophys. J. Lett. **850**, L35 (2017)



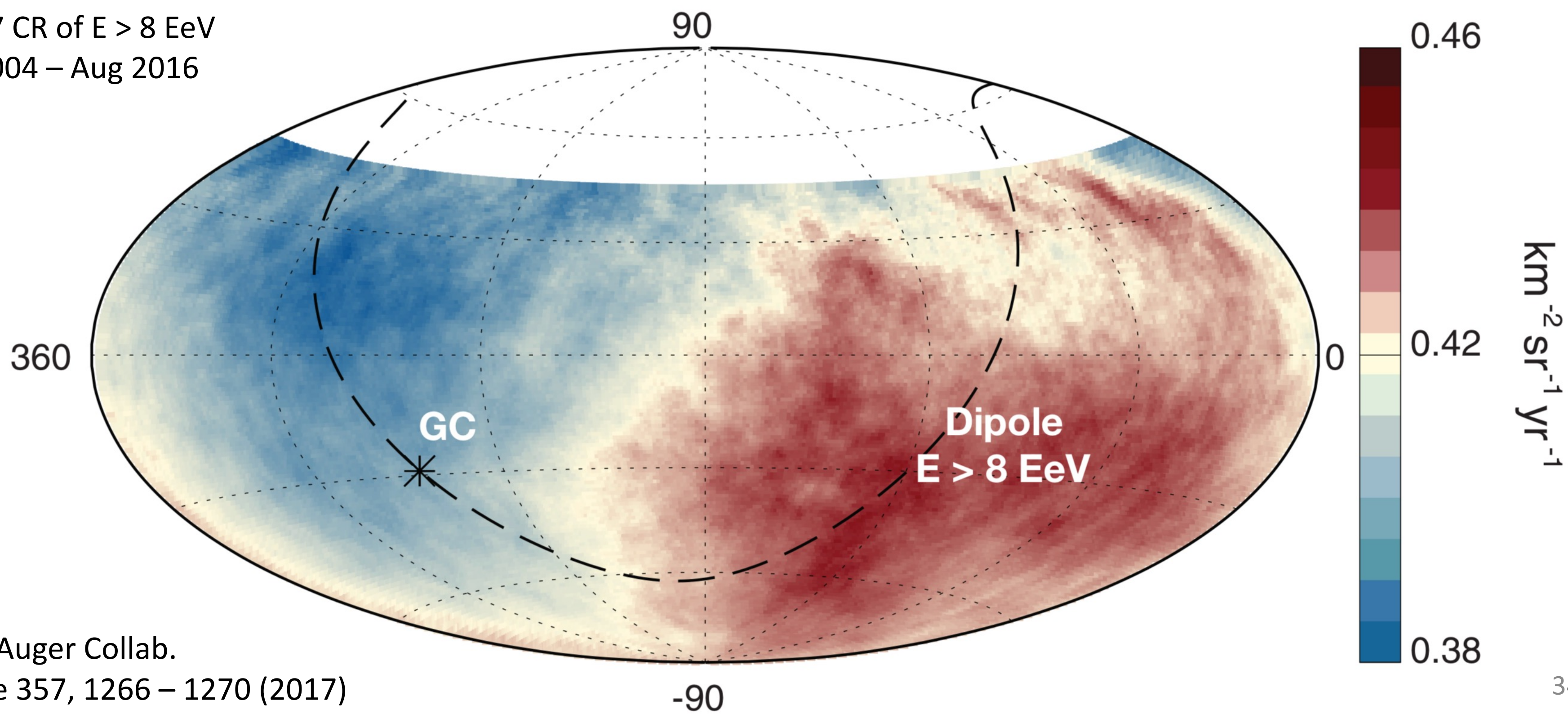
The NS-NS merger was in an **optimal position** for the detection of UHE tau neutrinos from Auger at the instant of emission of GW170817

Dipolar anisotropy of UHECR at $E > 8\ 10^{18}$ eV

- In 2017 Auger discovered an anisotropy in the arrival direction of cosmic rays with energies above 8 EeV
- Anisotropy well represented by a dipole (> 5 σ) with amplitude 6.5% and direction pointing ~ 125° away from Galactic Center.
- Anisotropy supports hypothesis of extragalactic origin for UHECR, rather than sources within Galaxy.

Flux map above 8 EeV in equatorial coordinates

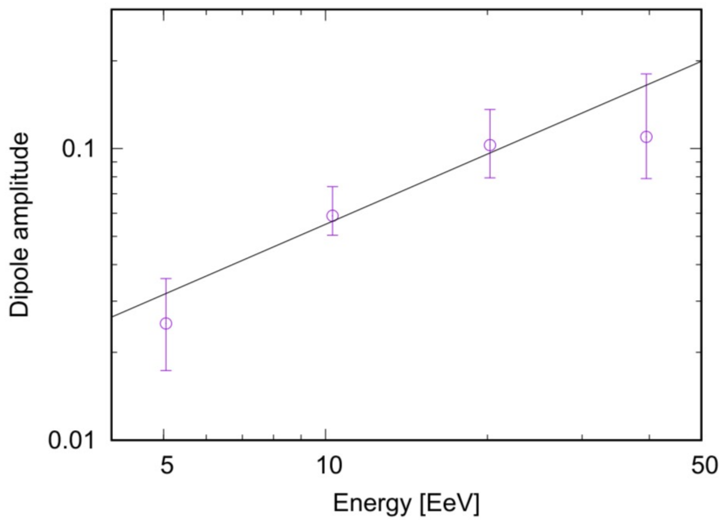
32,187 CR of E > 8 EeV
Jan 2004 – Aug 2016



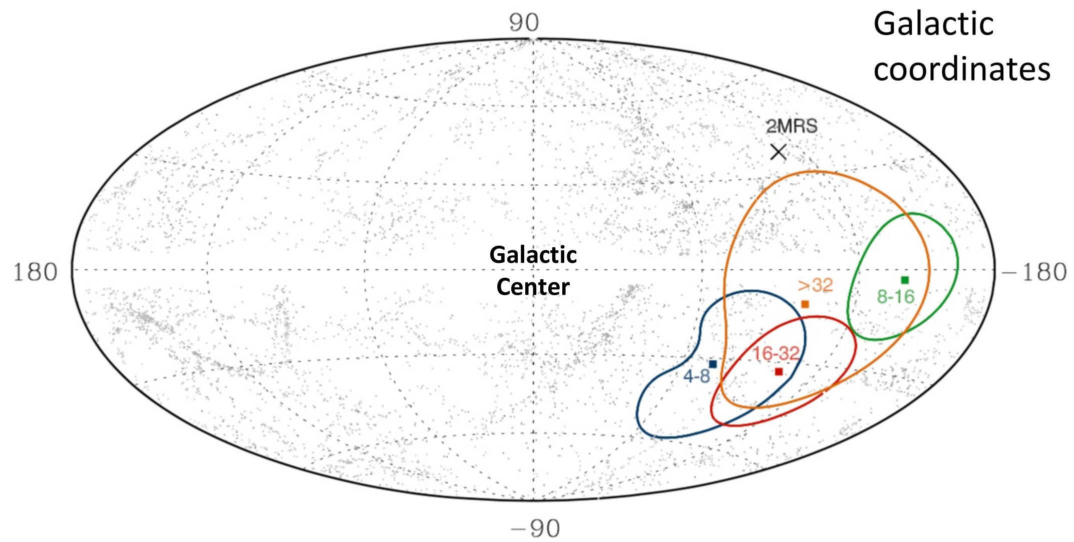
Pierre Auger Collab.
Science 357, 1266 – 1270 (2017)

Energy evolution of dipolar anisotropy

- In 2018 **evolution of the anisotropy with energy** was studied:
  - **amplitude of dipole increases with energy** as expected owing to smaller magnetic deflections suffered by CR at higher energy
  - directions of reconstructed dipoles **consistent with extragalactic origin** of anisotropies at all energies (all point at least 80° away from Galactic Center).
  - quadrupolar components of anisotropy not statistically significant



Evolution with energy of the amplitude of dipole



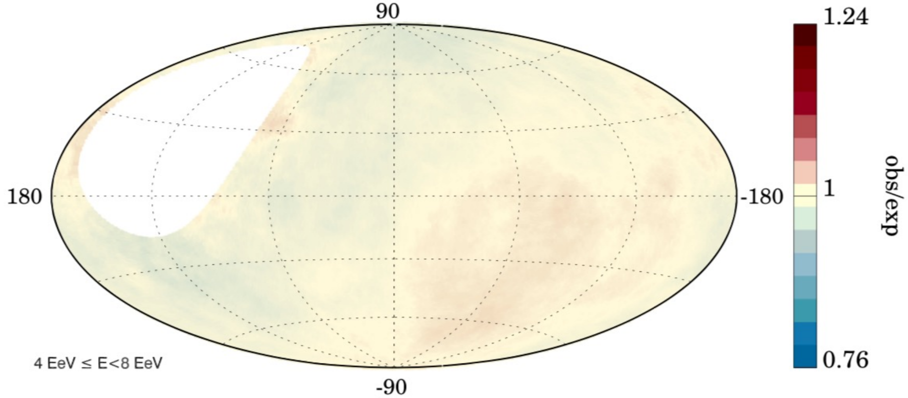
Direction of dipole determined in different energy bins above 4-8, 8-16, 16-32 & > 32 EeV.
(Dots represent direction toward galaxies in the 2MRS catalog at D < 100 Mpc)

Pierre Auger Collab. Astrophysical Journal **868** (2018)

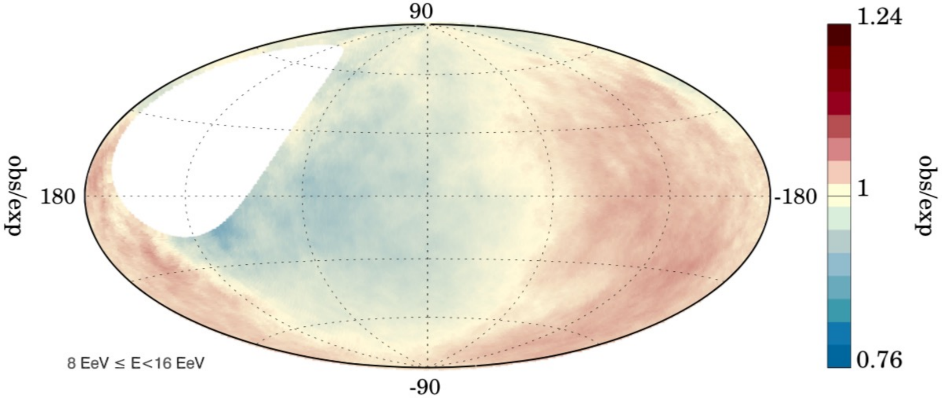
Energy evolution of dipolar anisotropy

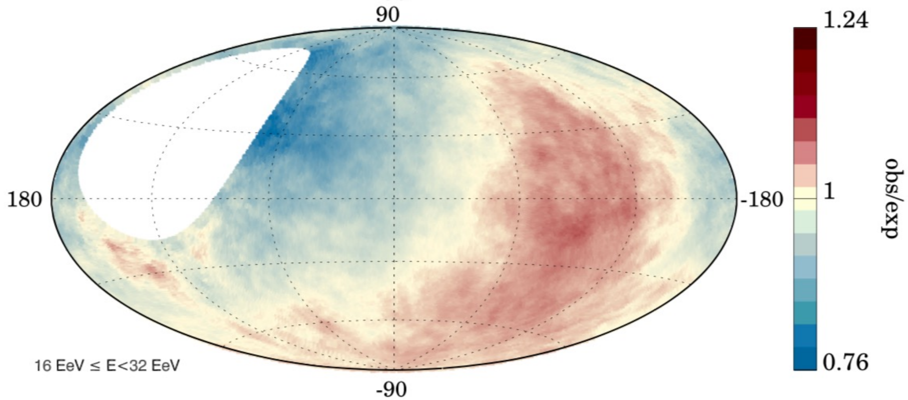
Sky maps, in Galactic coordinates, of the ratio between the observed flux and that expected for isotropic distribution

4 EeV < E < 8 EeV

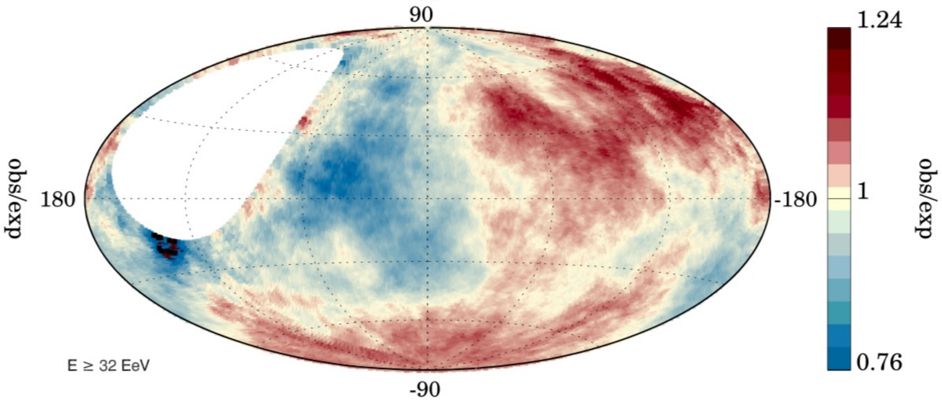


8 EeV < E < 16 EeV





16 EeV < E < 32 EeV



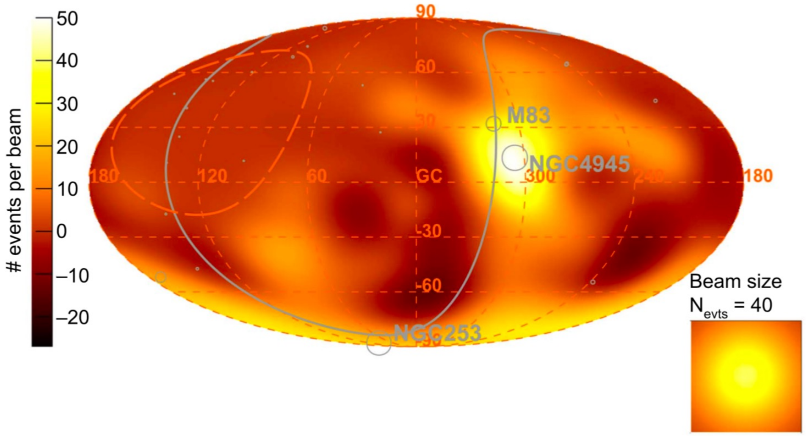
E > 32 EeV

Pierre Auger Collab. Astrophysical Journal **868** (2018)

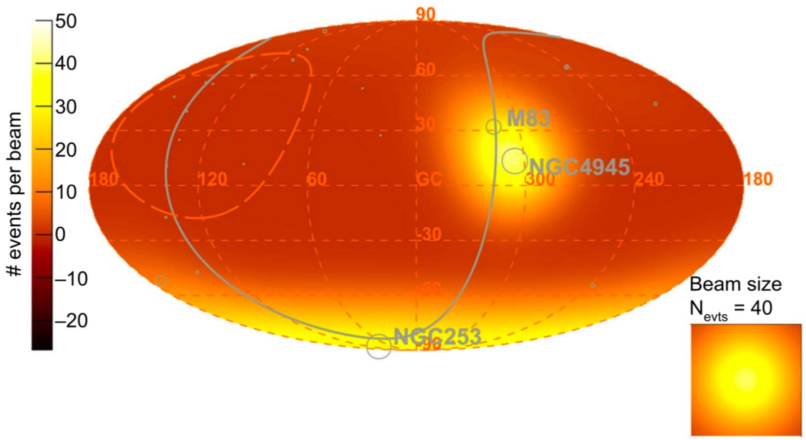
Anisotropy above 40 EeV: StarBurst Galaxies & UHECR

Pierre Auger Collaboration,
Astrophysical Journal Letters **853**, L29 (2018)

Observed Excess Map - E > 39 Eev



Model Excess Map - Starburst galaxies - E > 39 EeV



Comparison between sky model of cosmic-ray excess from StarBurst galaxies & measured one

- Observed pattern of UHECR arrival directions is best matched by a model in which ~ 10% of UHECR arrive from directions clustered around positions of bright, nearby **StarBurst Galaxies***
- **Isotropy of UHECRs is disfavored with 4.0 σ confidence.**
- **Indications of excess arrivals from strong, nearby (a few Mpc) sources.**

***StarBurst Galaxies:**
galaxies of intense star formation with increased rates of gamma-ray bursts, hypernovae & magnetars.

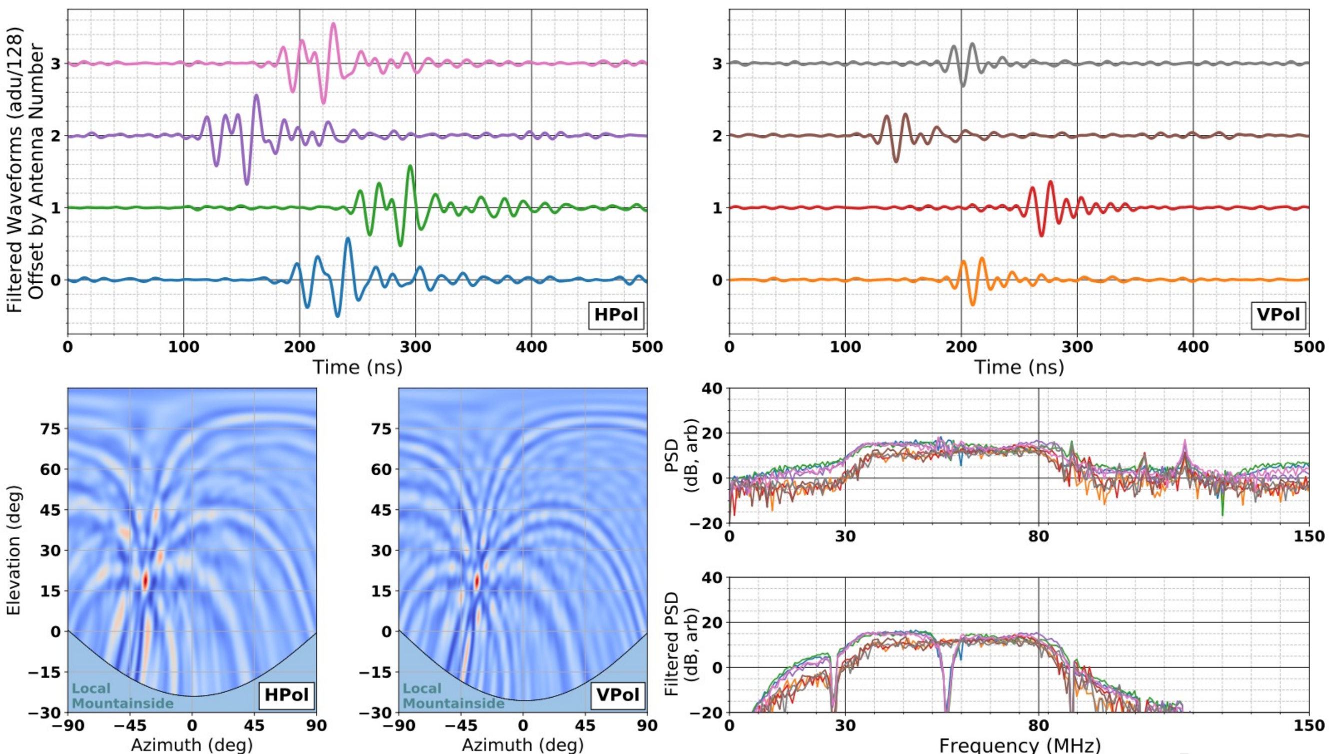
Source candidates of UHECR.

A conclusion from Auger studies on arrival directions of UHECR

- The observation of a significant (5.2 σ) dipole at large angular scales and of indications at 4 σ level of anisotropies at mid-angular scales, together with the lack of significant anisotropies at small angular scales, implies that the Galactic and/or extragalactic magnetic fields have a non-negligible effect on UHECR trajectories. This is, in fact, expected in scenarios with mixed composition where the CRs are heavier for increasing energies, in agreement with the trends in the composition that have been inferred for energies above a few EeV.

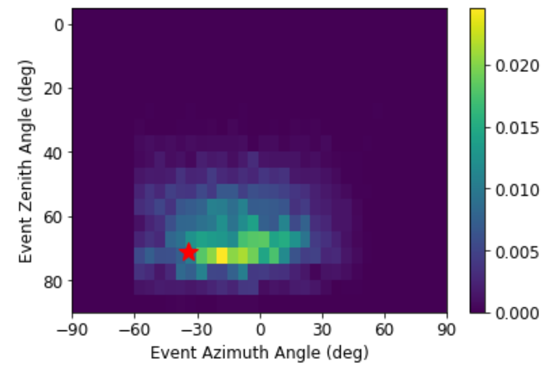
UHECR candidate detected with BEACON prototype

Data

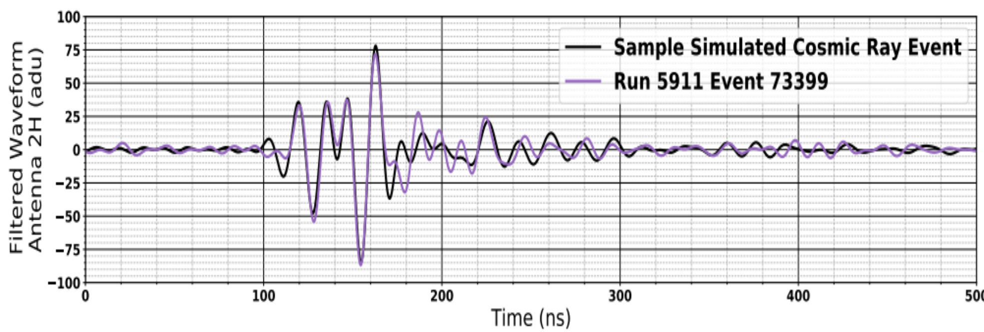


$\hat{v}\times\hat{B}$ Polarization Angle: $\sim 30°$

Measured Polariz. Angle: $\sim 27°$



Data vs Simulation



BEACON prototype arXiv:2206.09660 (participation of IGFAE).