Research Line 4:

Extremely energetic cosmic rays & neutrinos
Large exposure experiments

Highlights 2018

IGFAE
Instituto Galego de Física de Altas Enerxías

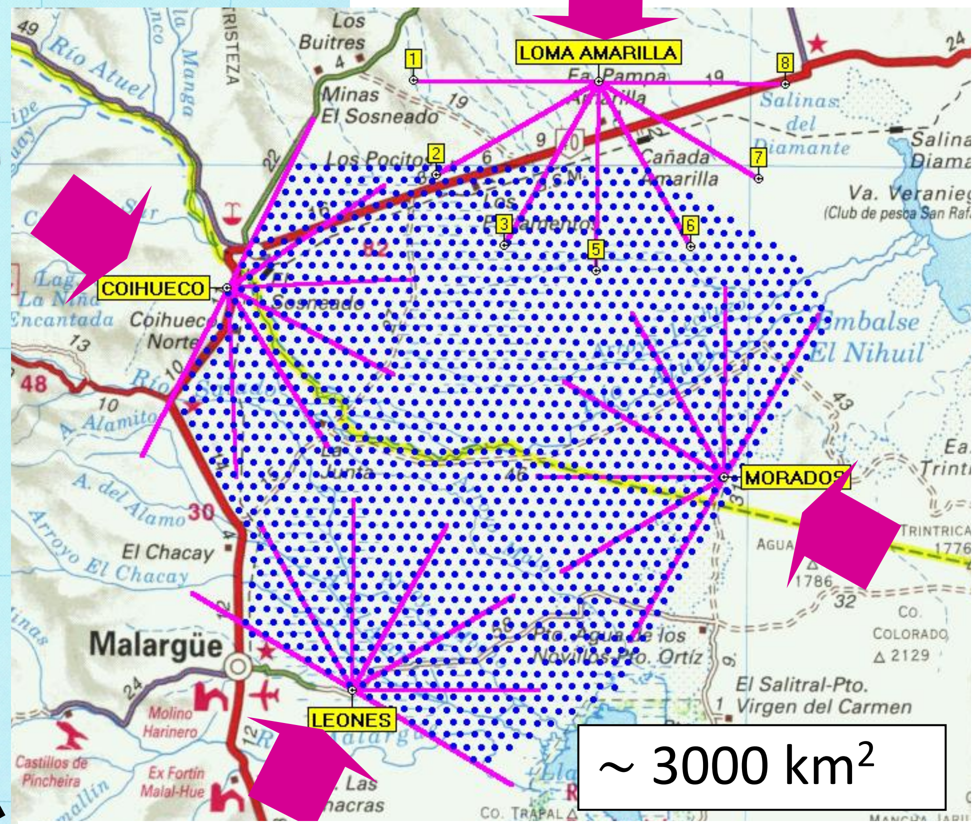
USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

XUNTA DE GALICIA

The Pierre Auger Observatory
Malargüe, Mendoza (Argentina)

35.5º S, 69.3º W
1400 m a.s.l. (880 g cm^{-2})

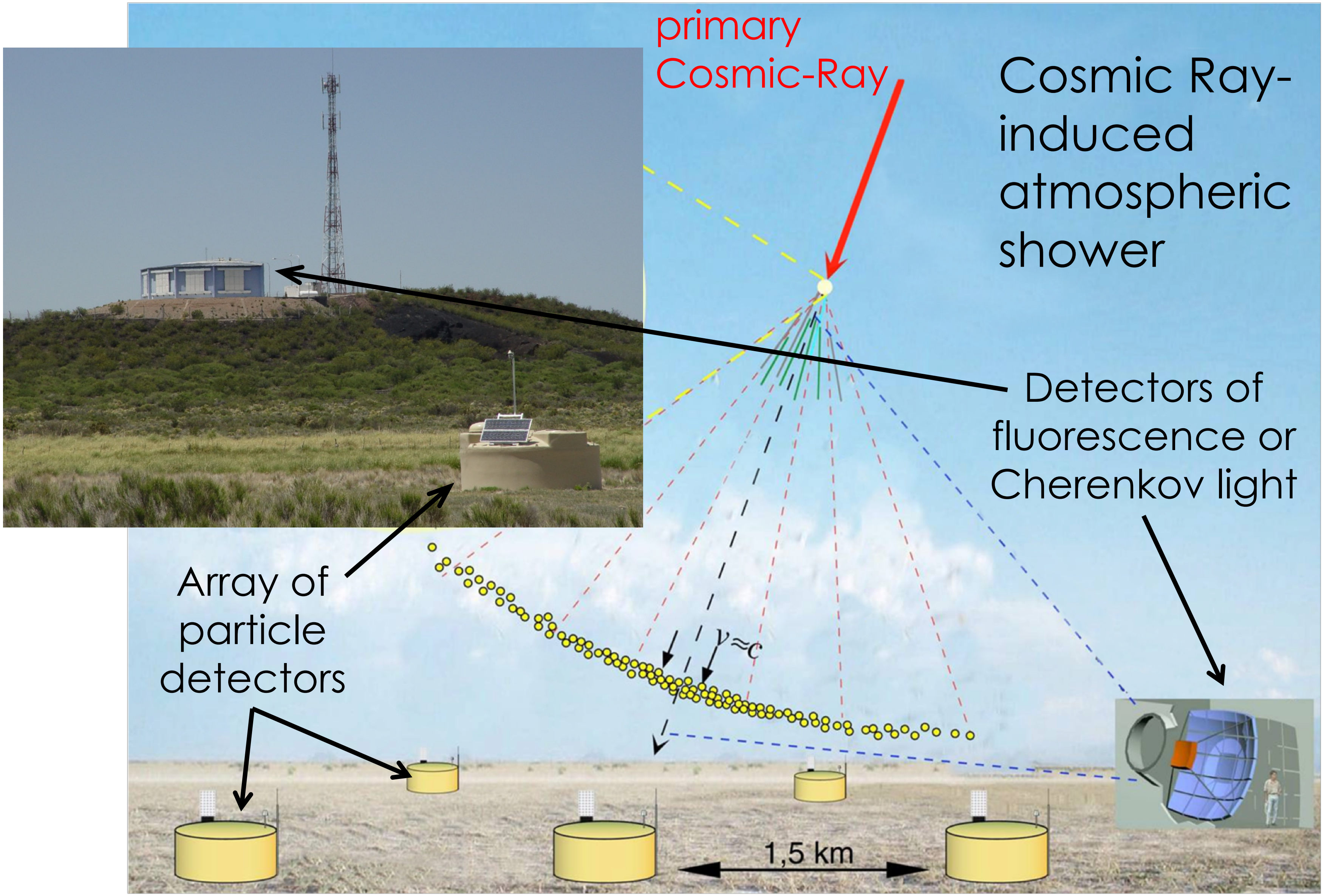
SD 1500 = Surface Detector array of 1600 water Cherenkov stations (3000 km^2)
FD = 4 Fluorescence buildings (24 + 3) detectors



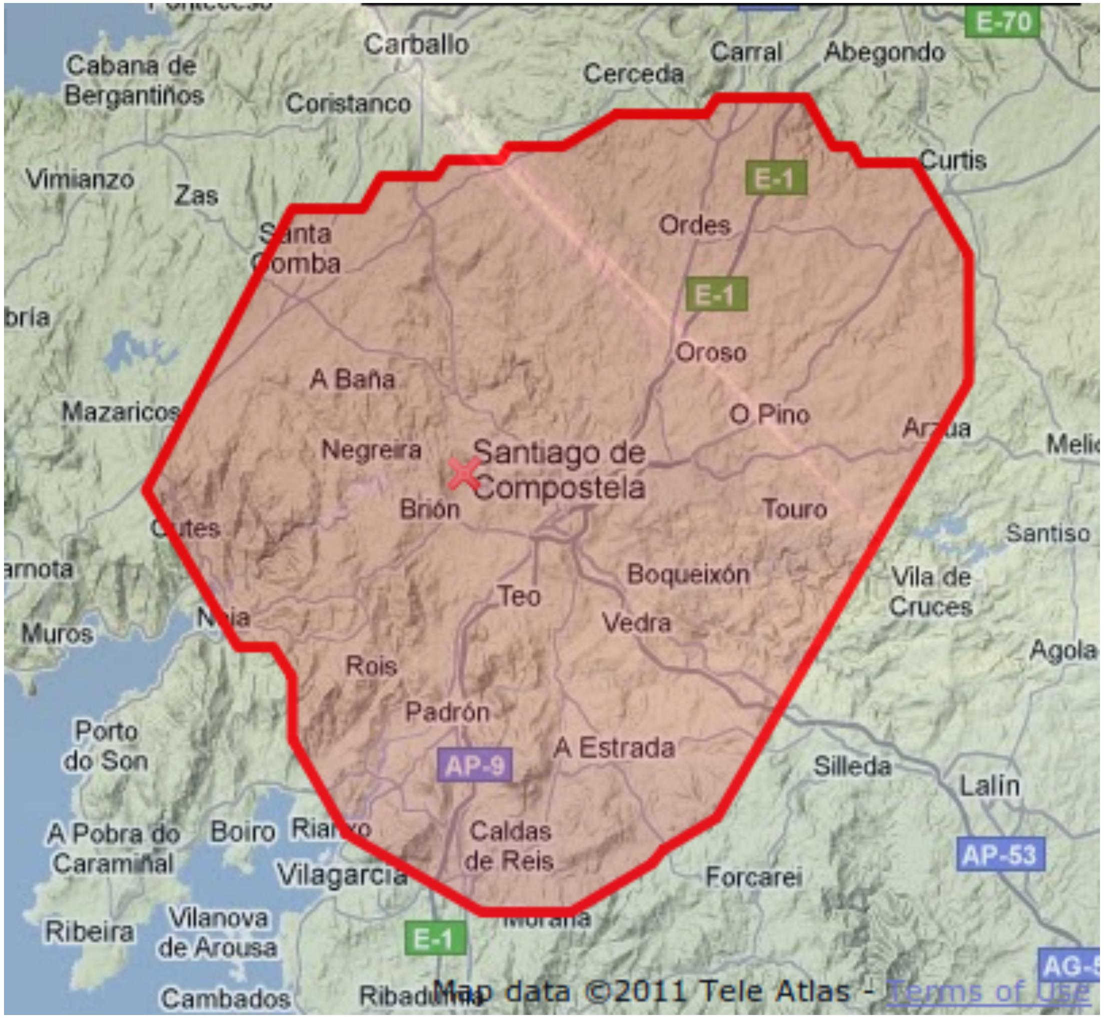
+ SD 750 = 61 water Cherenkov stations (~ 25 km^2)
+ AERA = Array of 153 antennas (~ 17 km^2)
+ AMIGA = Array of 61 buried muon detectors (~ 23.5 km^2)

Pierre Auger, Nuclear Instruments & Methods in Physics Research A **798** (2015) 172–213

Detection of UHECR-induced showers



If the center of Auger was in Santiago...



Main goal of Pierre Auger Observatory:

Determine **origin** (sources), **nature** and **acceleration mechansims** 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

See UHECR 2018 conference, Paris, Oct. 2018 for latest results

Distribution of arrival directions of UHECR

- **Provides most direct evidence of location of sources.**

- UHECR directions determined in Auger with ≤ 1 deg. angular resolution

- Identifying sources is however very challenging because:
  - UHECR experience E-dependent **magnetic deflections** in the NOT perfectly known Galactic & extragal. B-fields (do not point directly to sources).
  - UHECR **composition is NOT known**: Auger results => mixed mass from light (p/He) to heavy (CNO, Fe?) as energy increases.
  - UHECR **flux falls rapidly** with increasing energy => small statistics

- Despite of all these difficulties an important conclusion in 2018:

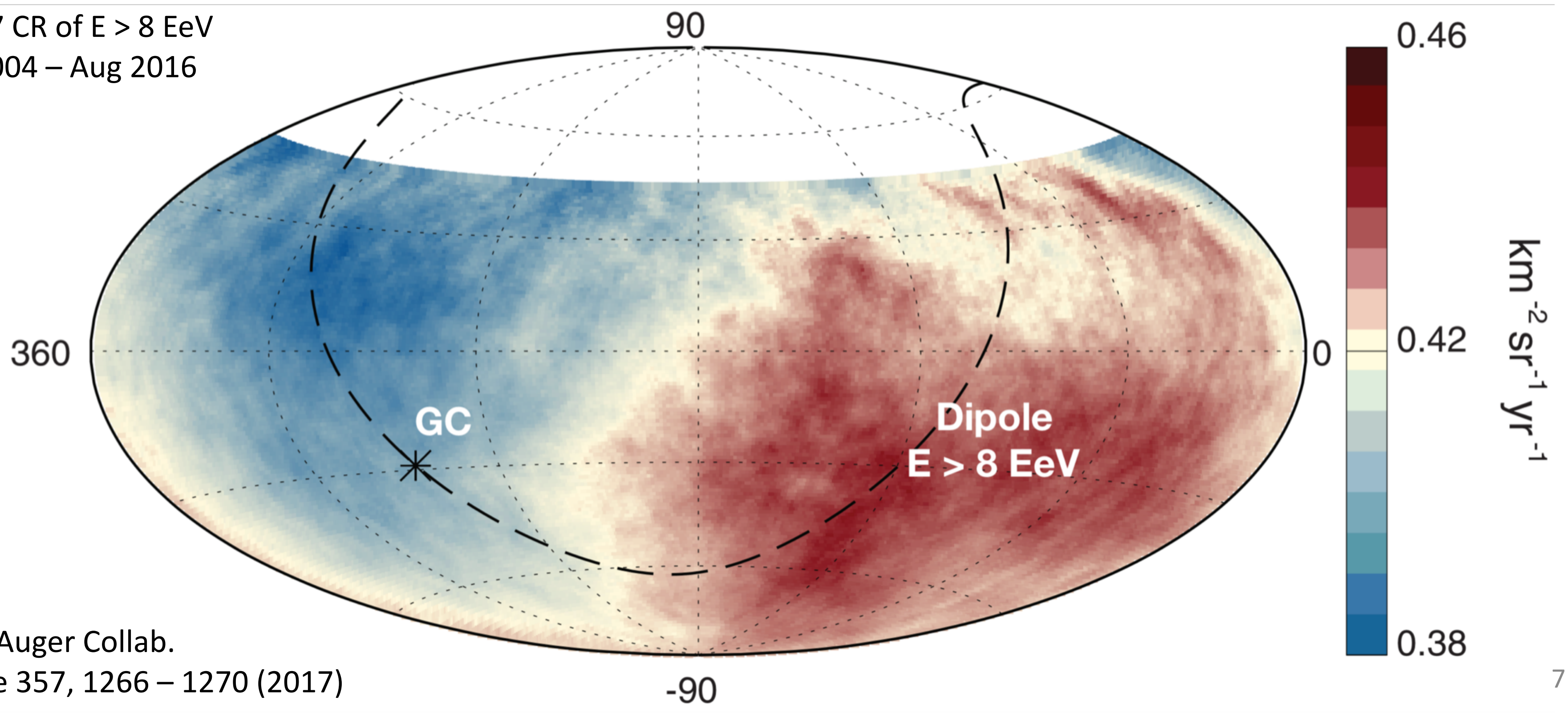
Anisotropies in the distribution of arrival directions of UHECR are arising as energy increases

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

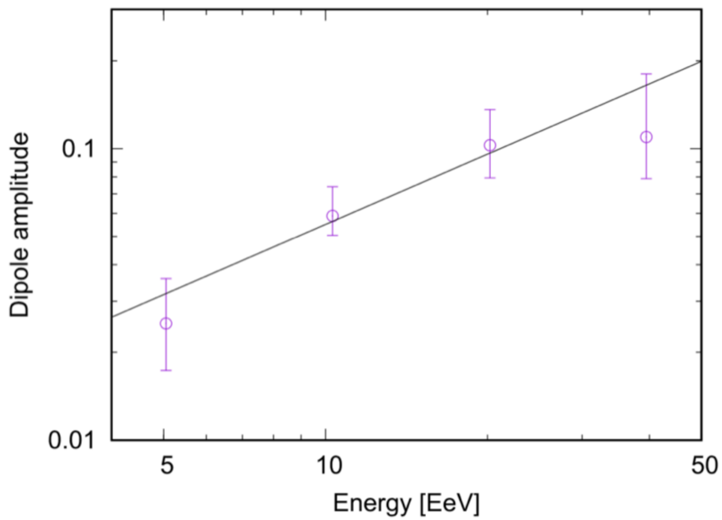
32,187 CR of E > 8 EeV
Jan 2004 – Aug 2016



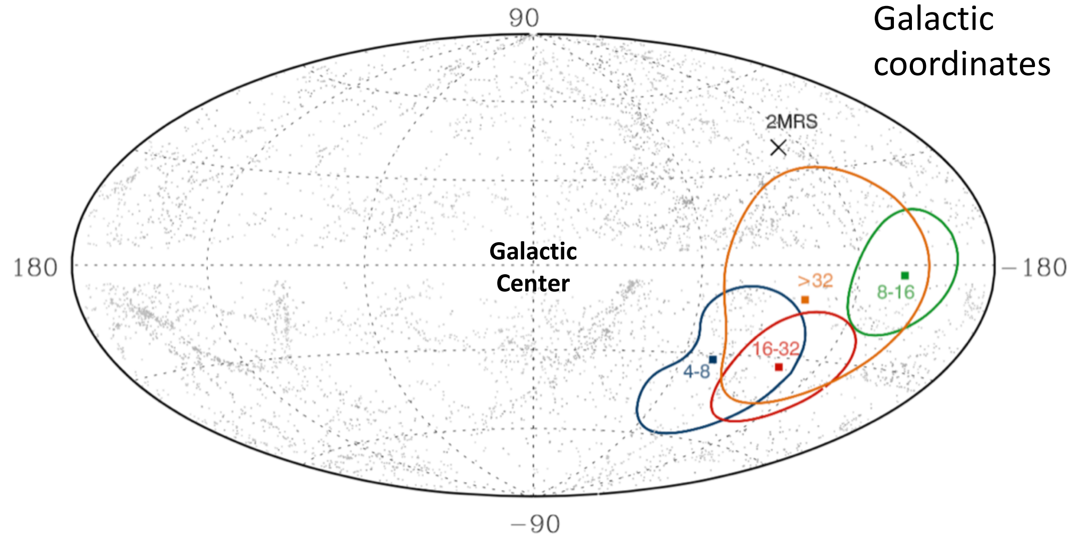
Pierre Auger Collab.
Science 357, 1266 – 1270 (2017)

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

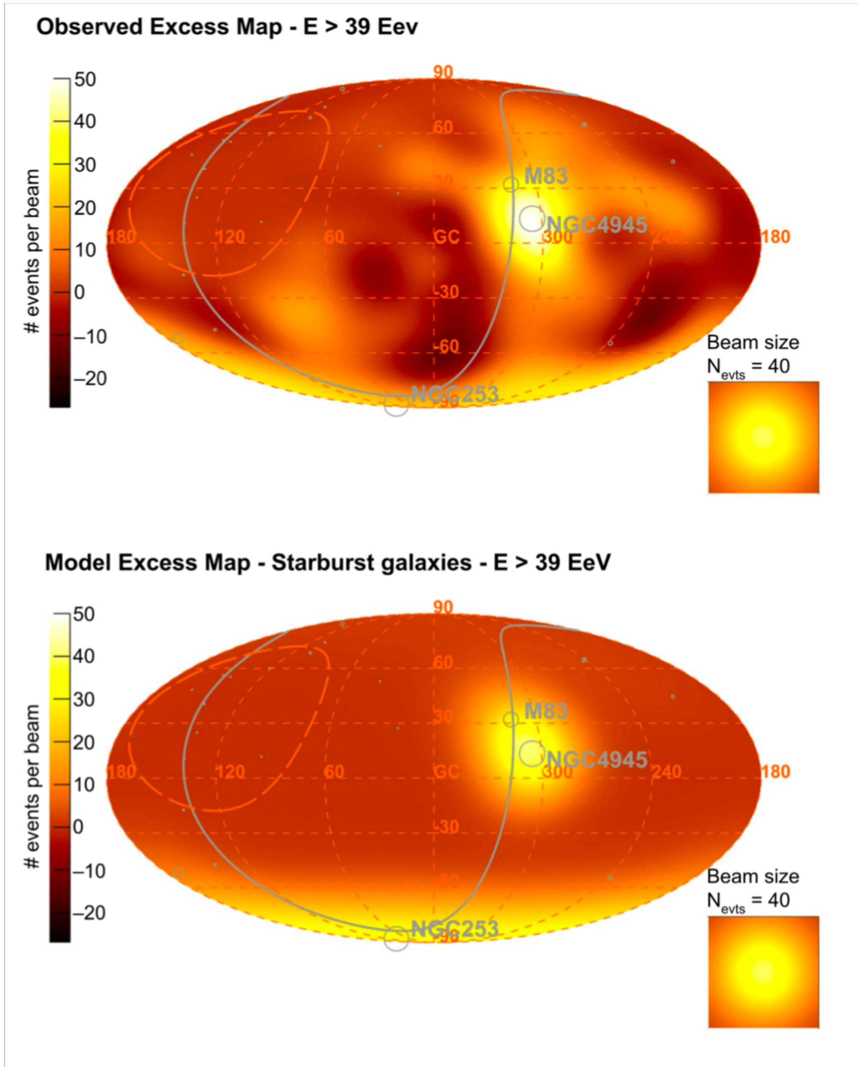


Direction of dipole determined in different energy bins above 4-8, 8-16, 16-32 & > 32 EeV.
(Dots represent direction toward galaxies in the 2MRS catalog at D < 100 Mpc)

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

Anisotropy above 40 EeV: StarBurst Galaxies & UHECR

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



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

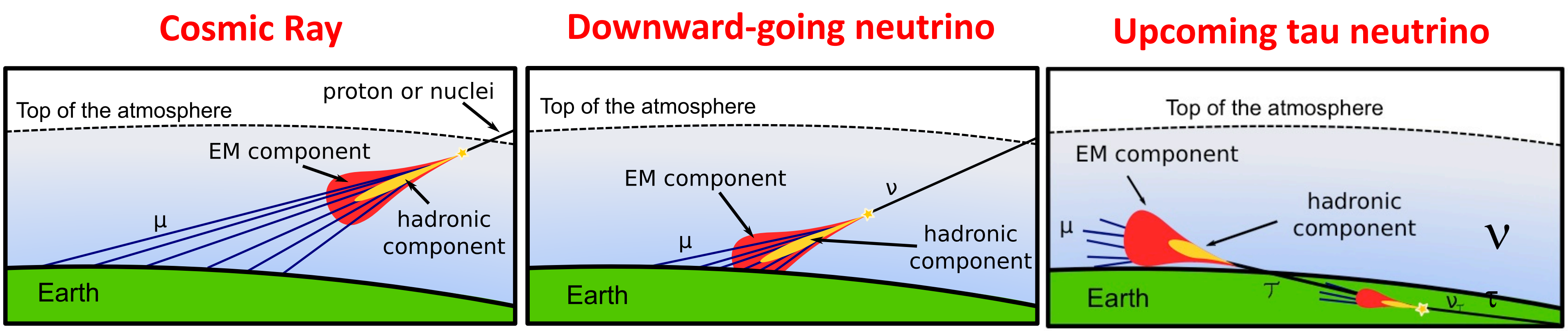
- Observed pattern of UHECR arrival directions is best matched by a model in which ~ 10% of UHECR arrive from directions clustered around positions of bright, nearby **StarBurst Galaxies***
- **Isotropy of UHECRs is disfavored with 4.0 σ confidence.**
- **Indications of excess arrivals from strong, nearby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

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

Source candidates of UHECR.

Search for UHE neutrinos with Auger Surface Detector

- **Pierre Auger is not a dedicated neutrino observatory** (main aim is characterizing the properties UHECR) but ...
- **UHE neutrinos** induce showers that **can be distinguished** from background charged CR showers:

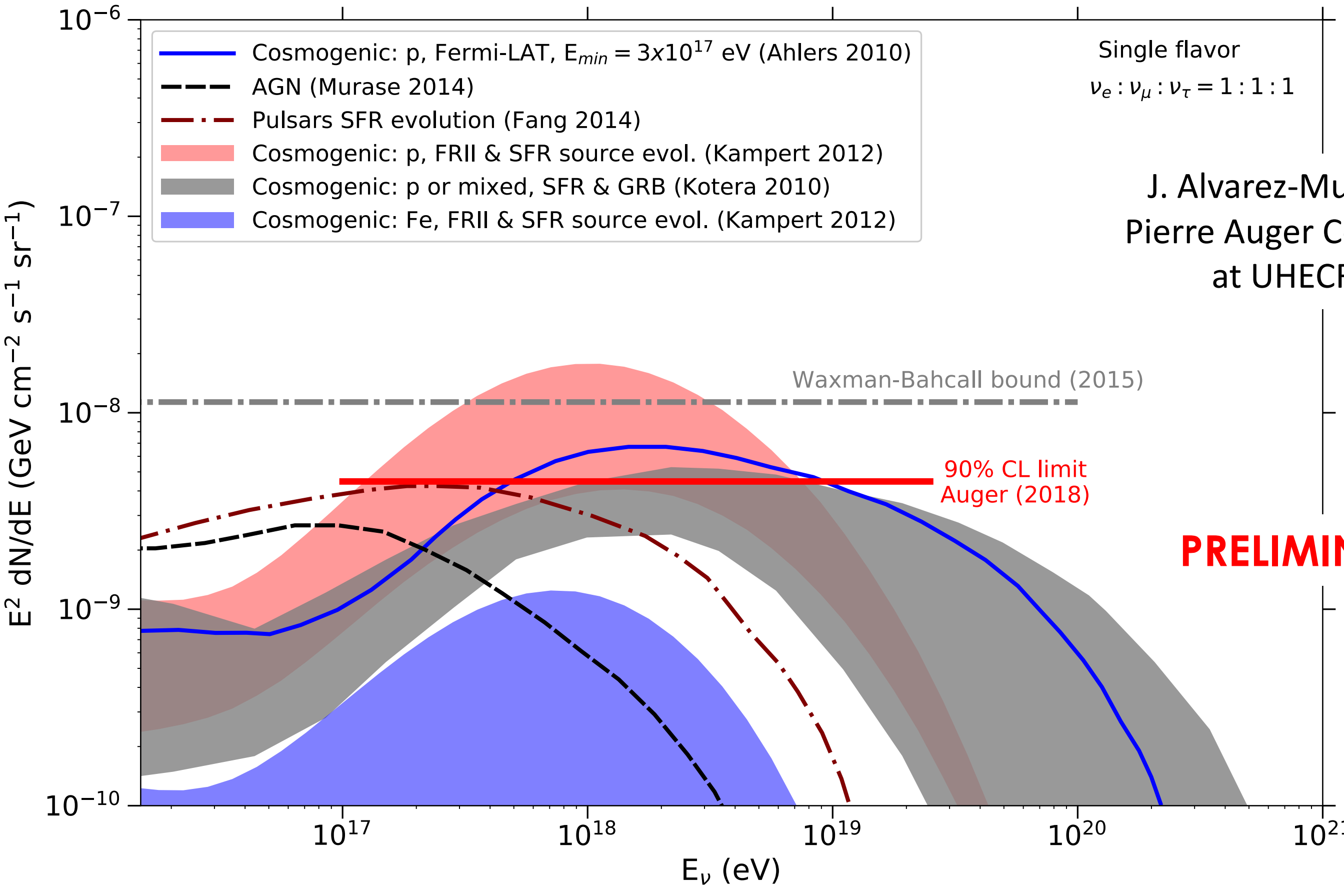


Neutrino signature ⇒ **inclined showers** that develop close to ground

3 dedicated analysis (with strong involvement of Auger-IGFAE) are used to perform these searches – see Pierre Auger Collaboration, Phys. Rev. D 91, 092008 (2015)

Upper limit to diffuse flux of UHE neutrinos

Auger data:
1 Jan 2004 –
30 June 2018



J. Alvarez-Muniz for the Pierre Auger Collaboration at UHECR 2018

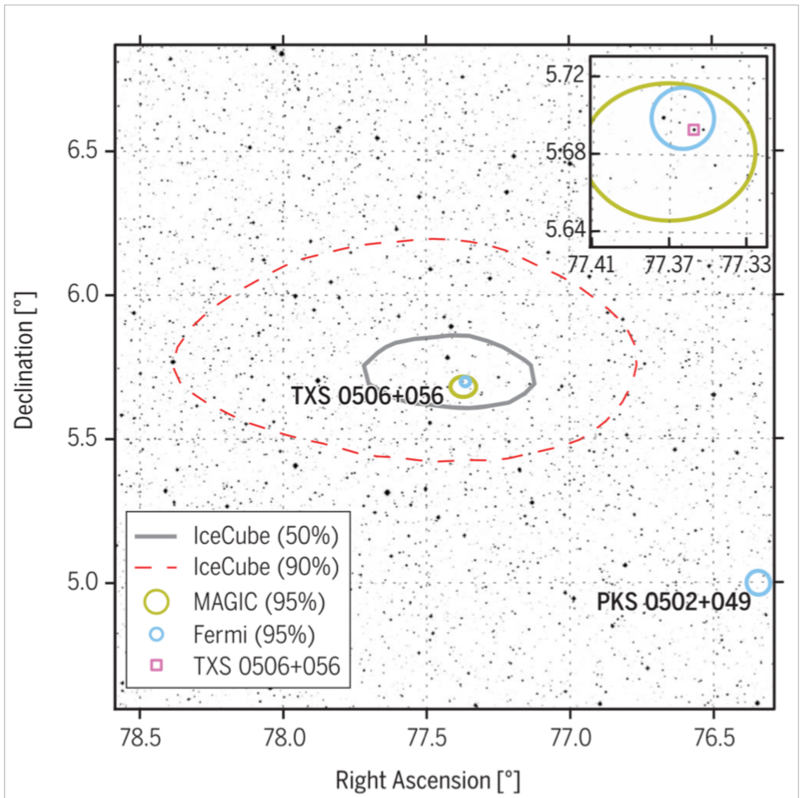
PRELIMINARY

Paper to appear in 2019

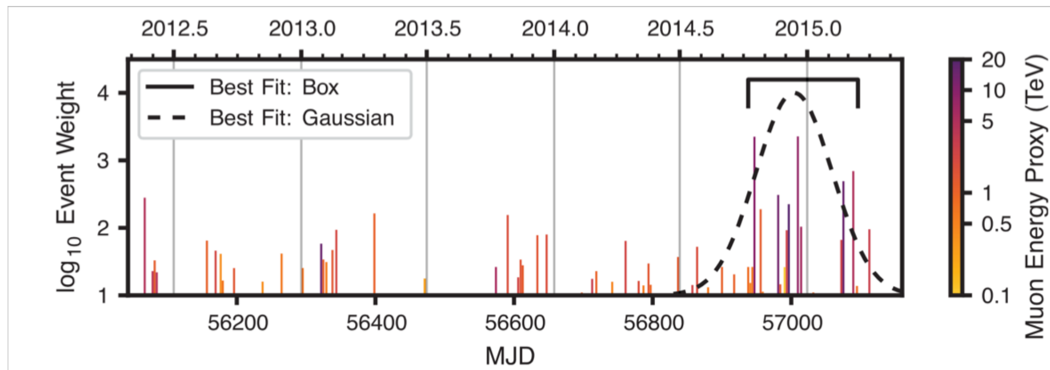
- **No neutrino candidates** found in data Jan 04 – June 18 => restrictive upper limits to neutrino flux in cosmic beam
- UHE neutrinos are produced in UHECR interactions & Auger limits constrains models assuming pure proton primary cosmic beam
- Very small background to ν identification => Auger sensitivity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

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

- **IceCube** detected a ~ 300 TeV ν on 22 Sep. 2017
- Within 0.1° of γ-ray source TXS 0506+056 (blazar) in a flaring state of activity
- Very far away source: z ~ 0.34 (~ 1.8 Gpc)



- In a time window of 110 days around 13 Dec 2014 IceCube found:
- Excess of 13+/-5 events (above atmospheric background) consistent with the position of TXS 0506+056. Significance 3.5 σ

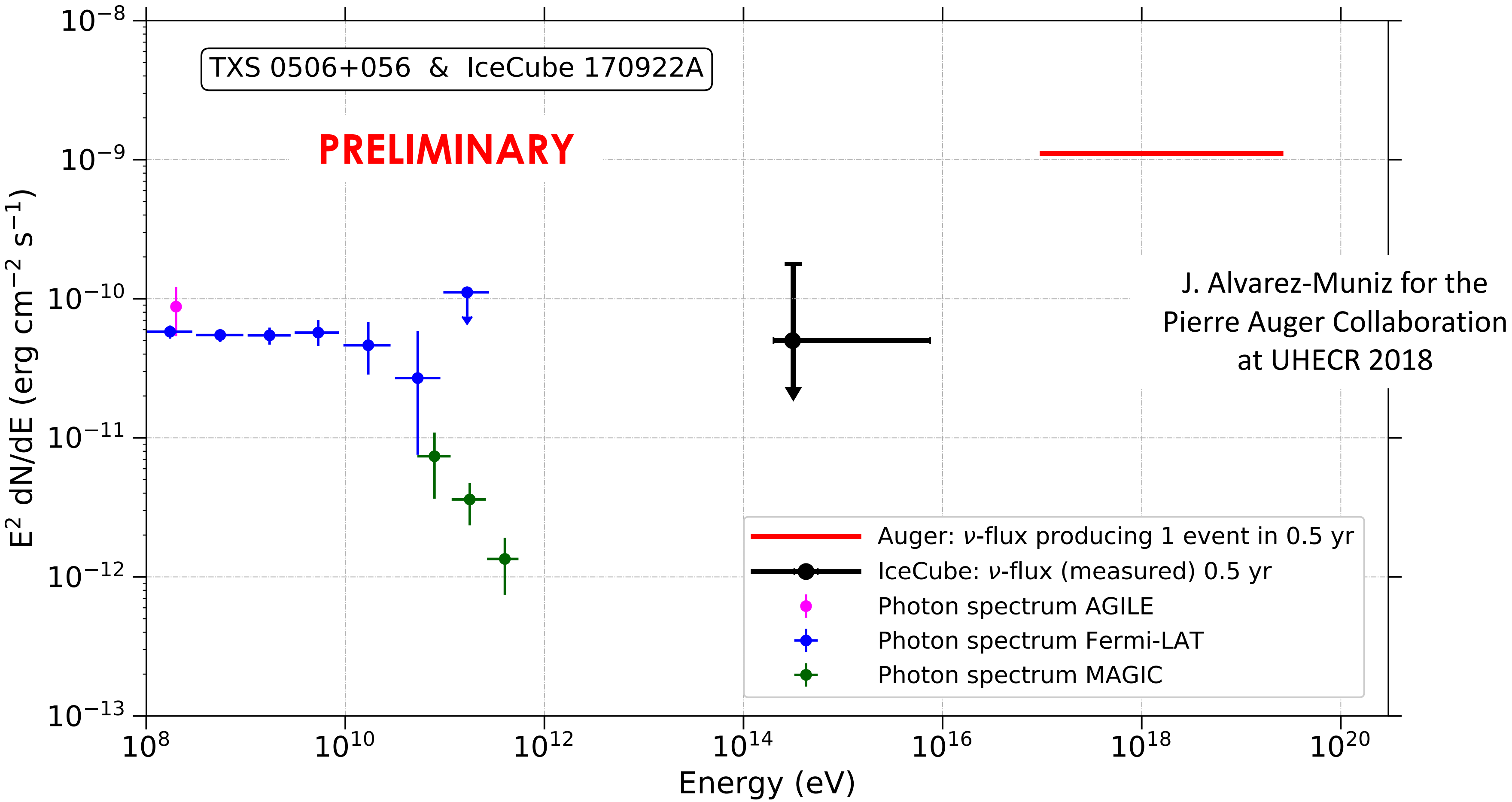


NOTE: IceCube has also detected tens of neutrinos of astrophysical origin but this is the **first identified potential source of high-energy astrophysical neutrinos**

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

IceCube ν flux & Auger limit from TXS 0506+056

No candidate neutrinos from direction of TXS at EeV energies in Auger

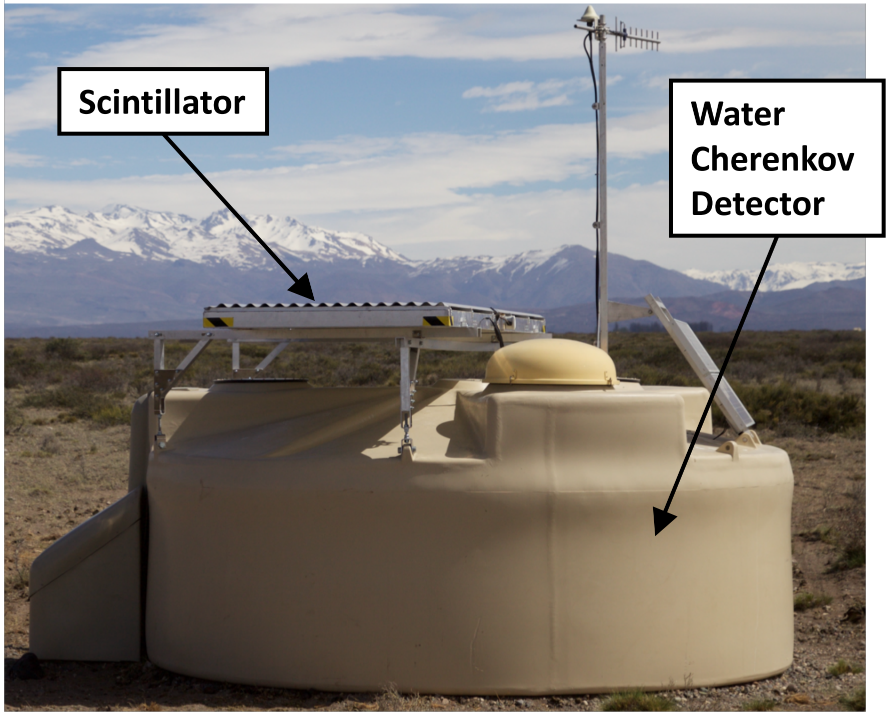


Paper to appear in 2019

First upper limits to the neutrino flux from an identified source of neutrinos at EeV energies

Progress in AugerPrime

D. Martello, Pierre Auger Collab. PoS (ICRC2017) 383
A. Castellina at UHECR 2018 meeting in Paris



- **Extension** of Pierre Auger Observatory

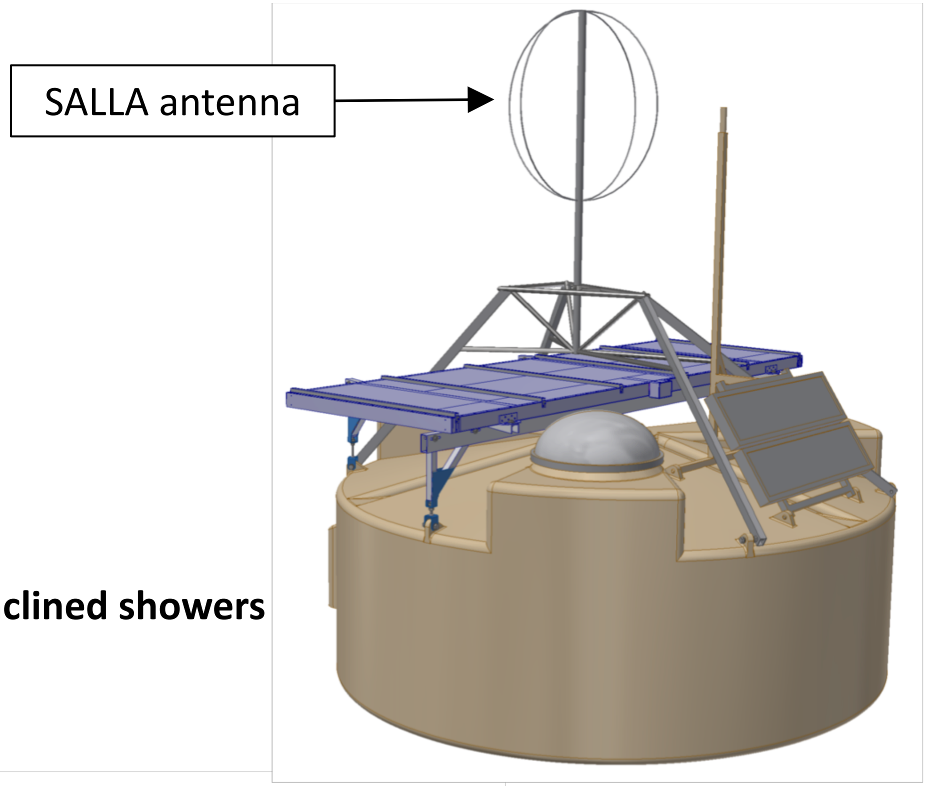
- Instrument 1600 water-Cherenkov

stations with ~ 4 m^2 **scintillators on top,** plus:
  - improvements in electronics
  - new triggers lowering energy threshold
  - direct muon buried detector (AMIGA)
  - extension of Fluorescence detector duty cycle

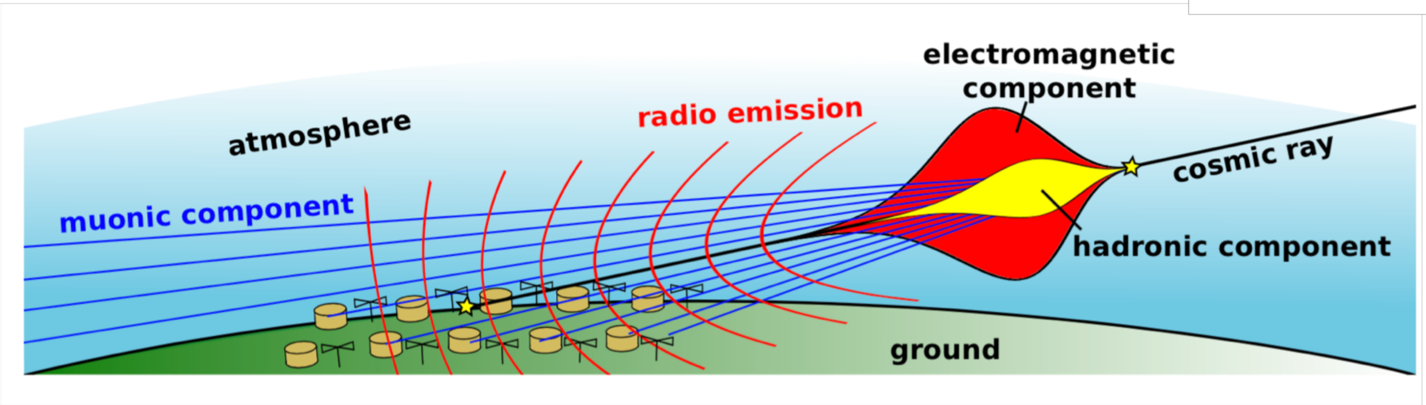
- **Goals:**
  - **Improve discrimination of muon & electromagnetic components in showers**
  - Improve **composition determination** on shower-by-shower basis to understand
    - origin of flux suppression above 50 EeV
    - evaluation of proton contribution above 50 EeV for charged particle astronomy
    - test of hadronic interactions

- **Status & timeline:**
  - **80% of the funds secured.**
  - Engineering array (12 stations) working since 2016. 30 stations being installed. 800 detectors being assembled.
  - **Full deployment end of 2019**. Data taking with full upgraded array **2020-2025**

Radio extension of Auger



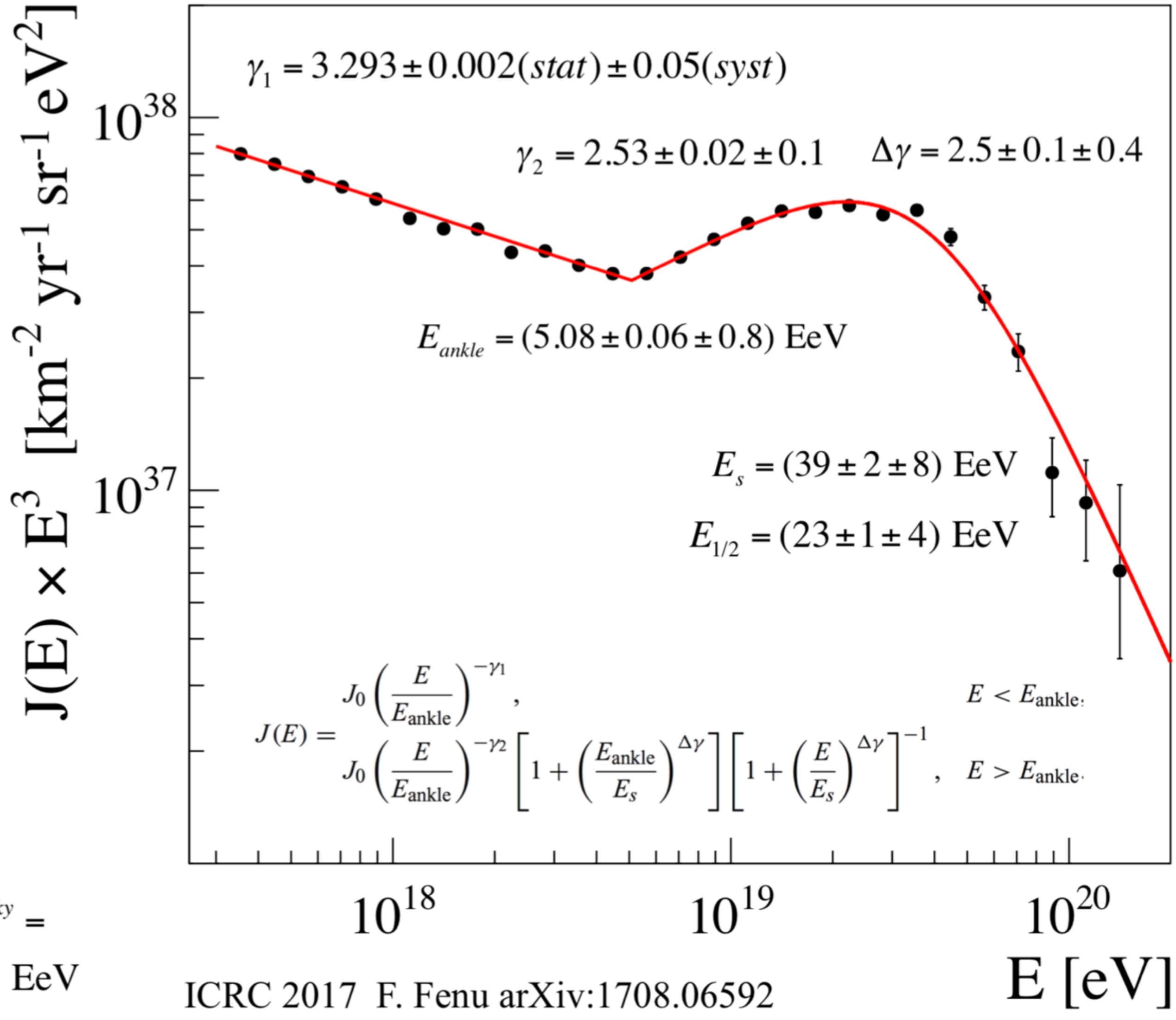
- Add **radio antennas (30-80 MHz)** to the 1600 water-Cherenkov stations
- **Goals:**
  - **em/muon separation in inclined showers**
  - **shower-by-shower mass sensitivity with inclined showers**
  - increase sky coverage



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

More information

Energy spectrum of UHECR in Auger

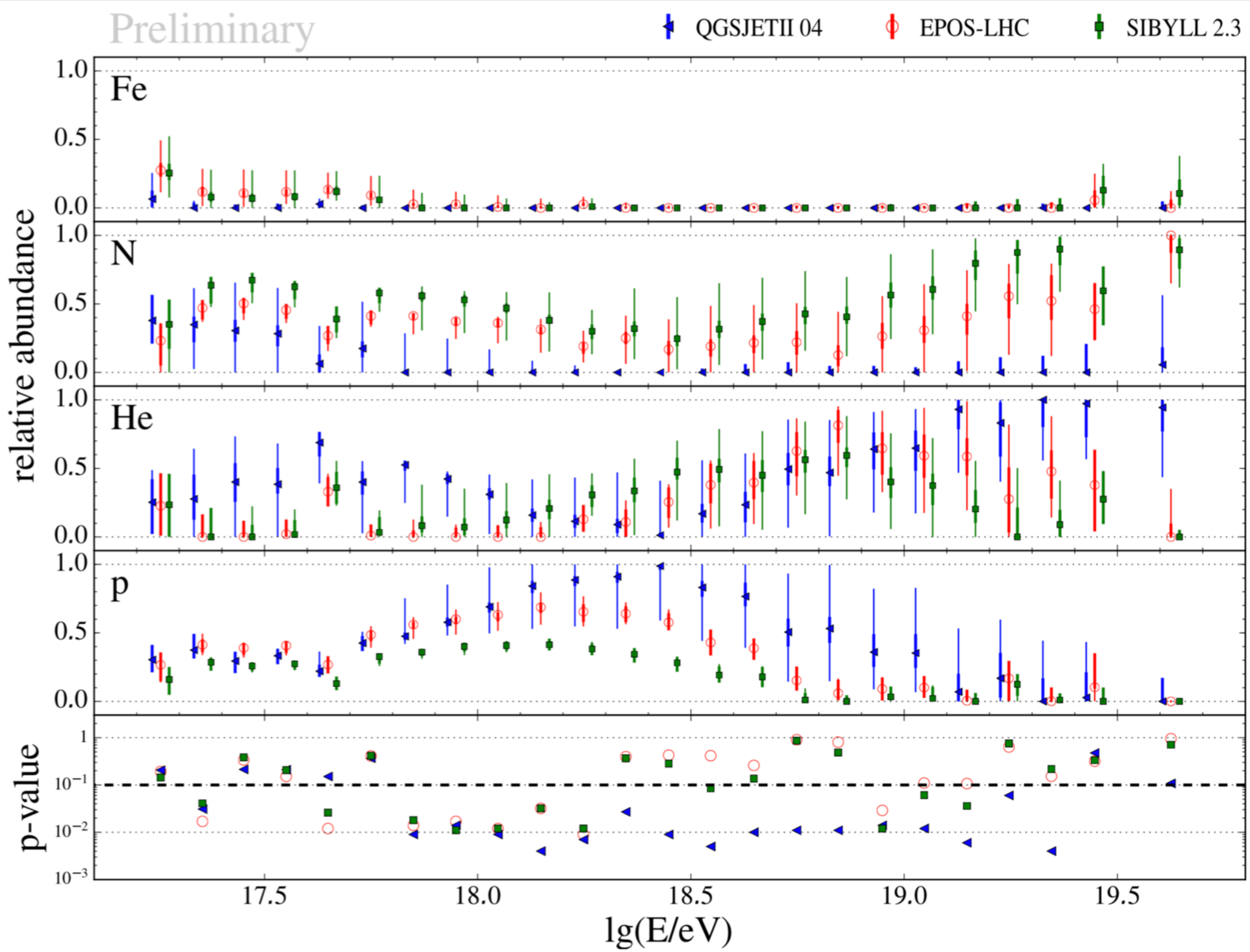


$E_{1/2}^{Berezinsky} =$
50 – 60 EeV

ICRC 2017 F. Fenu arXiv:1708.06592

UHECR composition with Auger

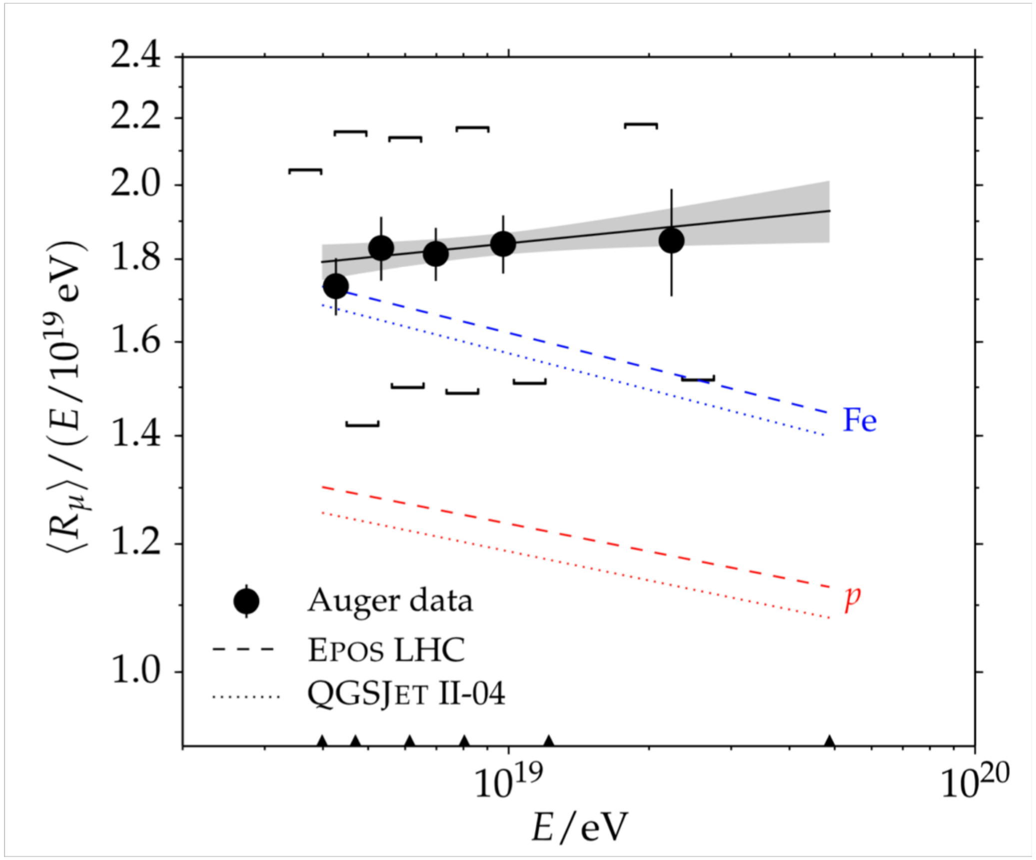
complex evolution of mass composition between $10^{17.2}$ and 10^{20} eV



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

Muons in air showers in Auger

- Inclined showers -> muon-dominated => clean & direct measurement of number of muons.



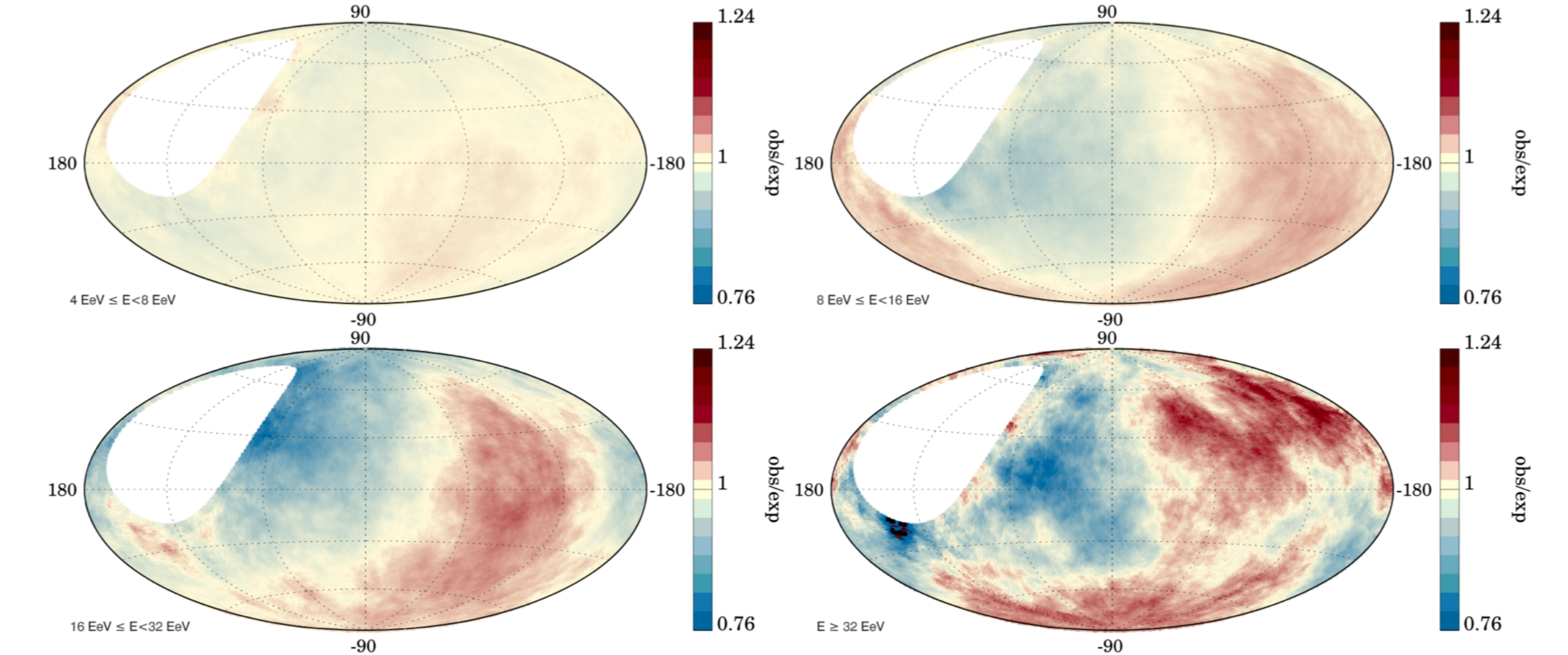
- Simulations fall short of muons when compared to Auger data by a large factor

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

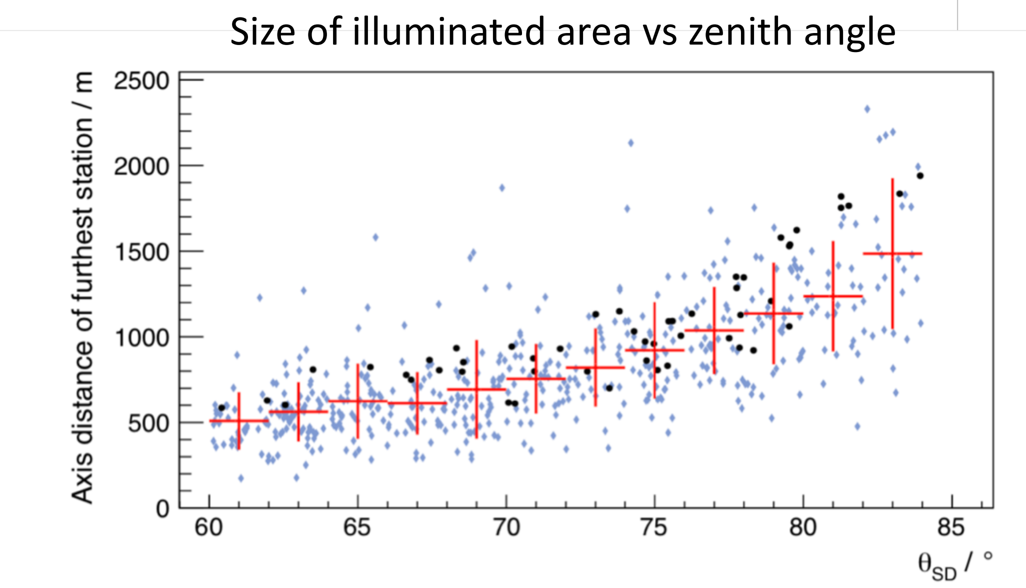
Pierre Auger Collab. Astrophysical Journal **868** (2018)

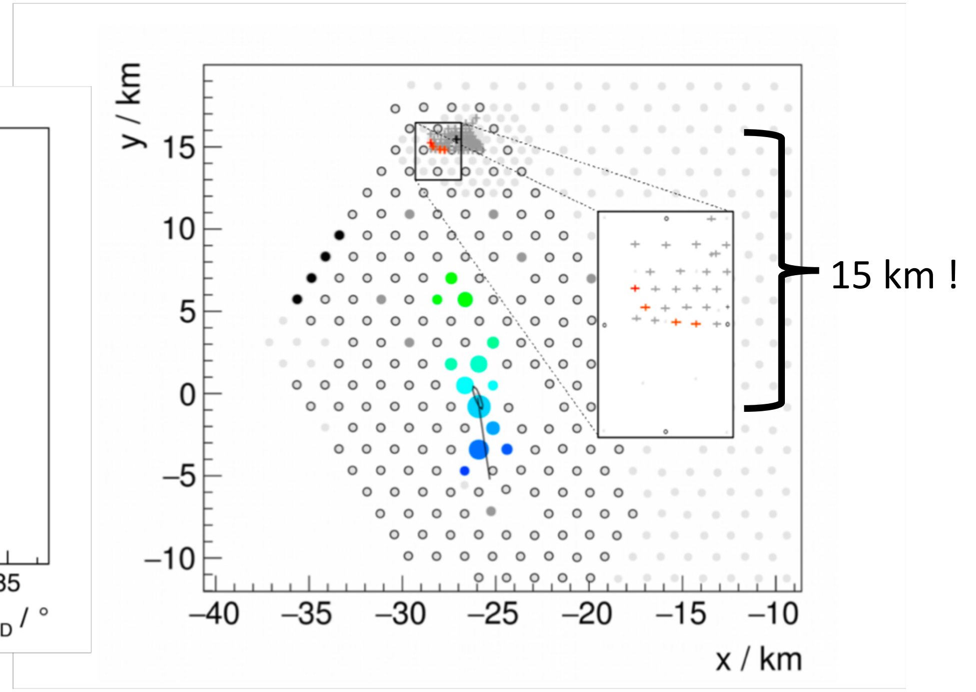
A conclusion from Auger studies on arrival directions of UHECR

- 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.

Radio detection of inclined showers in AERA

- **AERA** = Auger Engineering Radio Array (17 km^2, 153 antennas in the 30 - 80 MHz band)
- Radio emission from 561 air showers at EeV with zenith angles [60^o, 84^o]



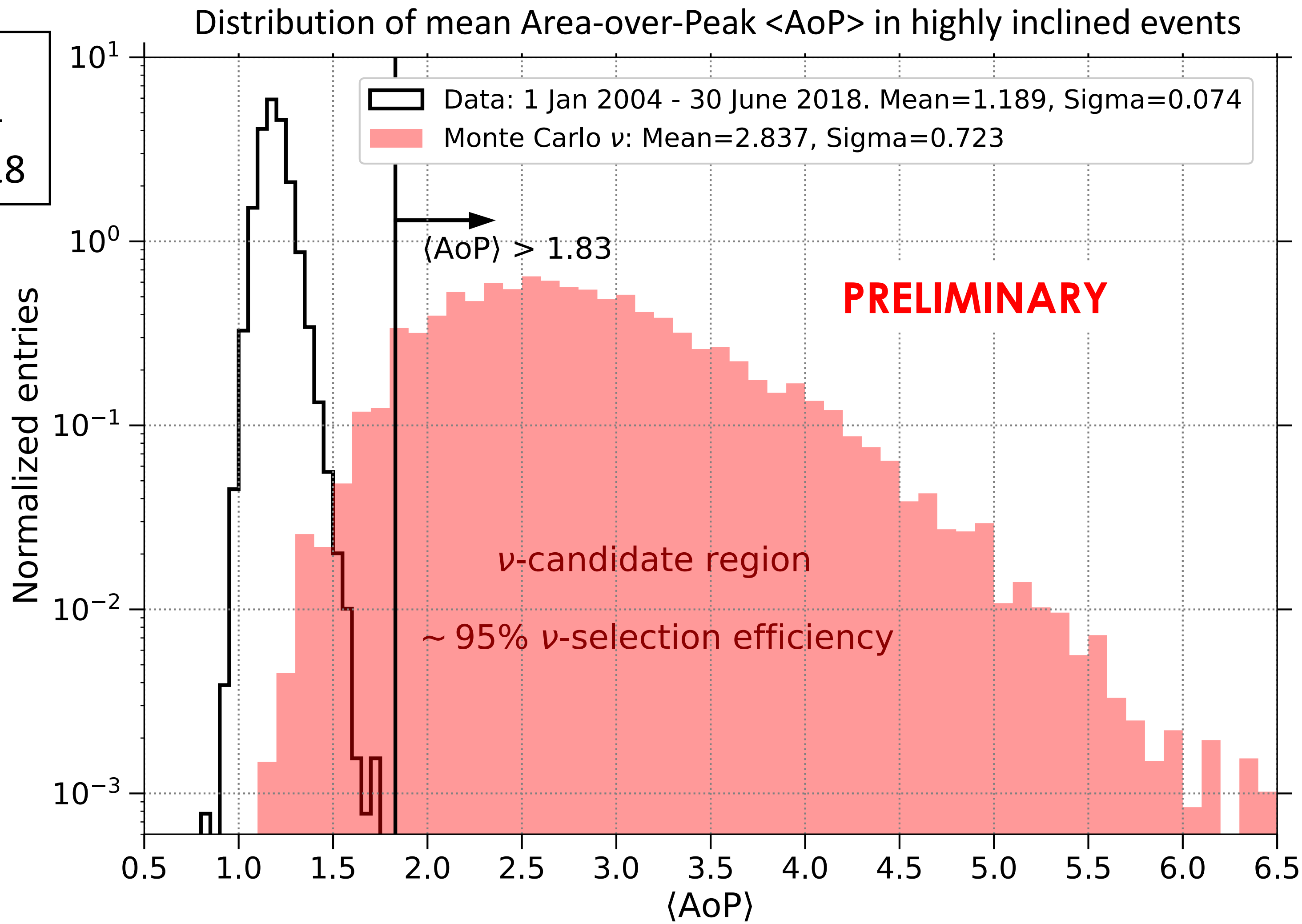


- Inclined air showers at EeV illuminate large ground areas of several km^2 growing with zenith angle
- Measurable with sparse radio-antenna arrays with grid sizes of a km or more => cost-effective instrumentation of the large areas needed for UHECR detection
- Radio has a ~ 100% duty cycle. Can provide shower energy & depth of shower max.

Pierre Auger Collab. JCAP **10** (2018) 026

Data unblinding: Earth-Skimming channel

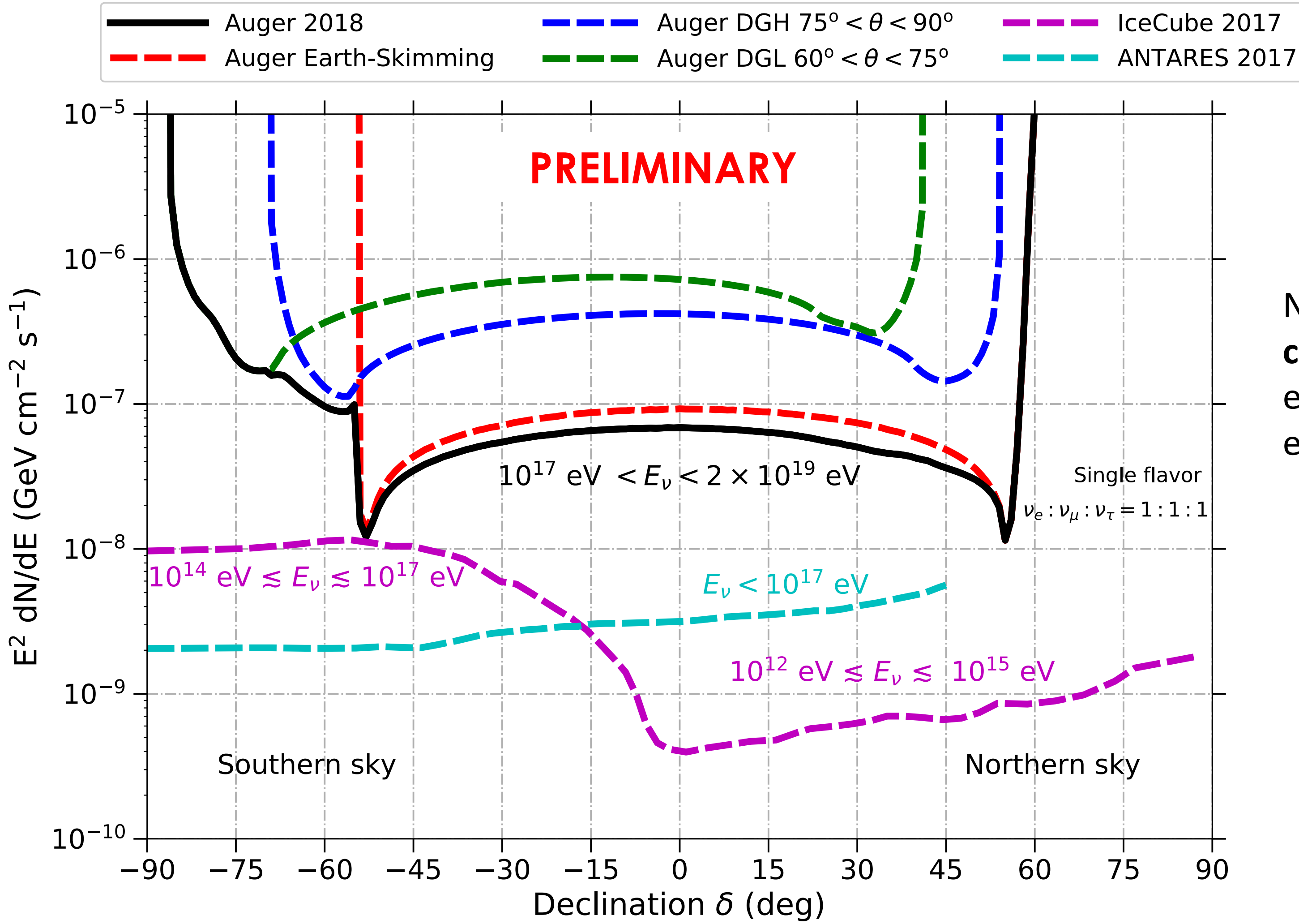
Auger data:
1 Jan 2004 -
30 June 2018



No neutrino candidates in the Earth-Skimming channel
Large ν-selection efficiency => sensitivity dominated by exposure, NOT by background

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°

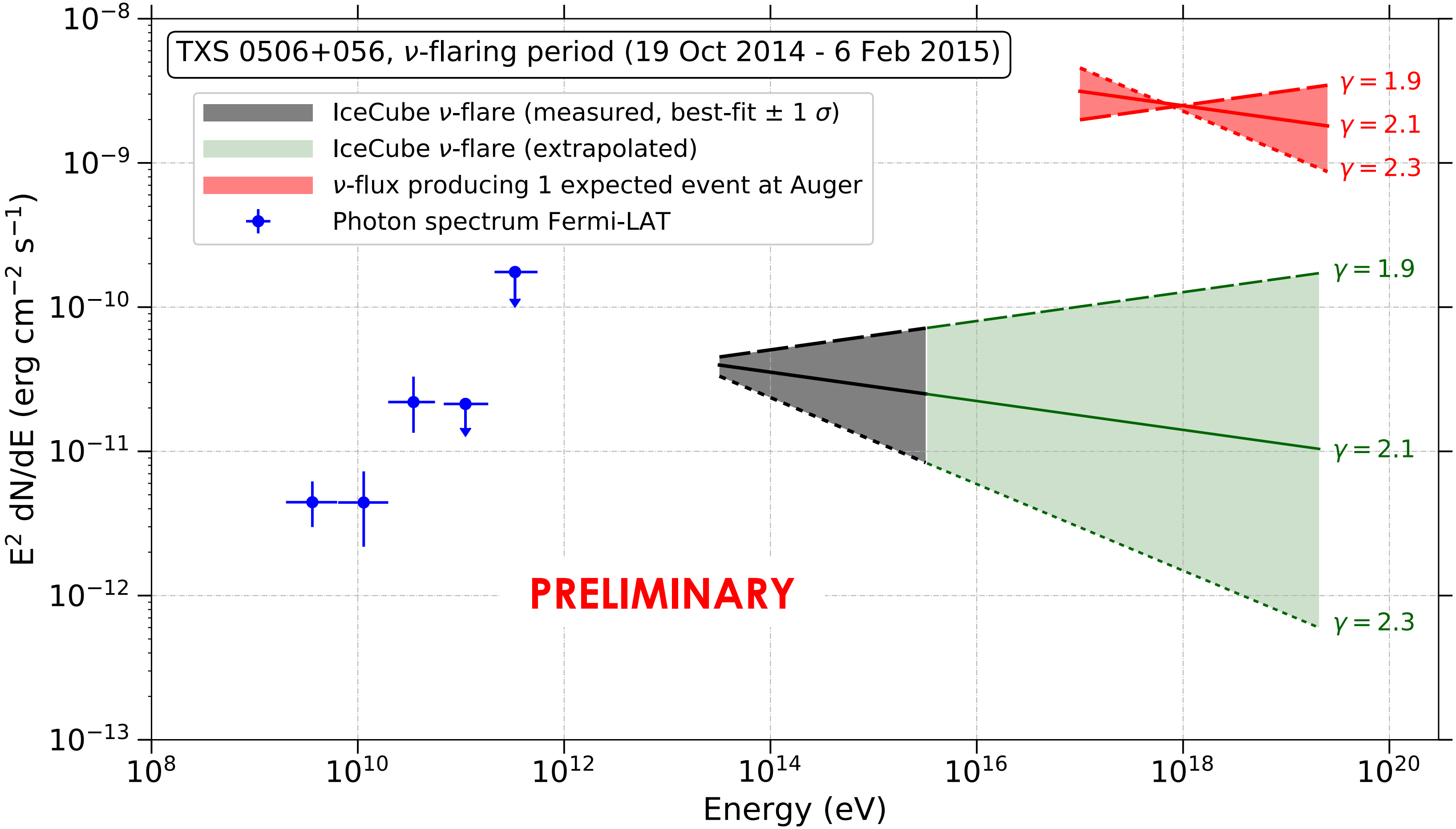


NOTE **complementary** energy ranges of experiments

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

ν flux/limits from Blazar TXS 0506 + 056 (dec ~ 5.7°)

TXS 0506+056 in the (Gaussian) time window of 110 days
(19 Oct 2014 – 6 Feb 2015) when IceCube neutrino excess was observed

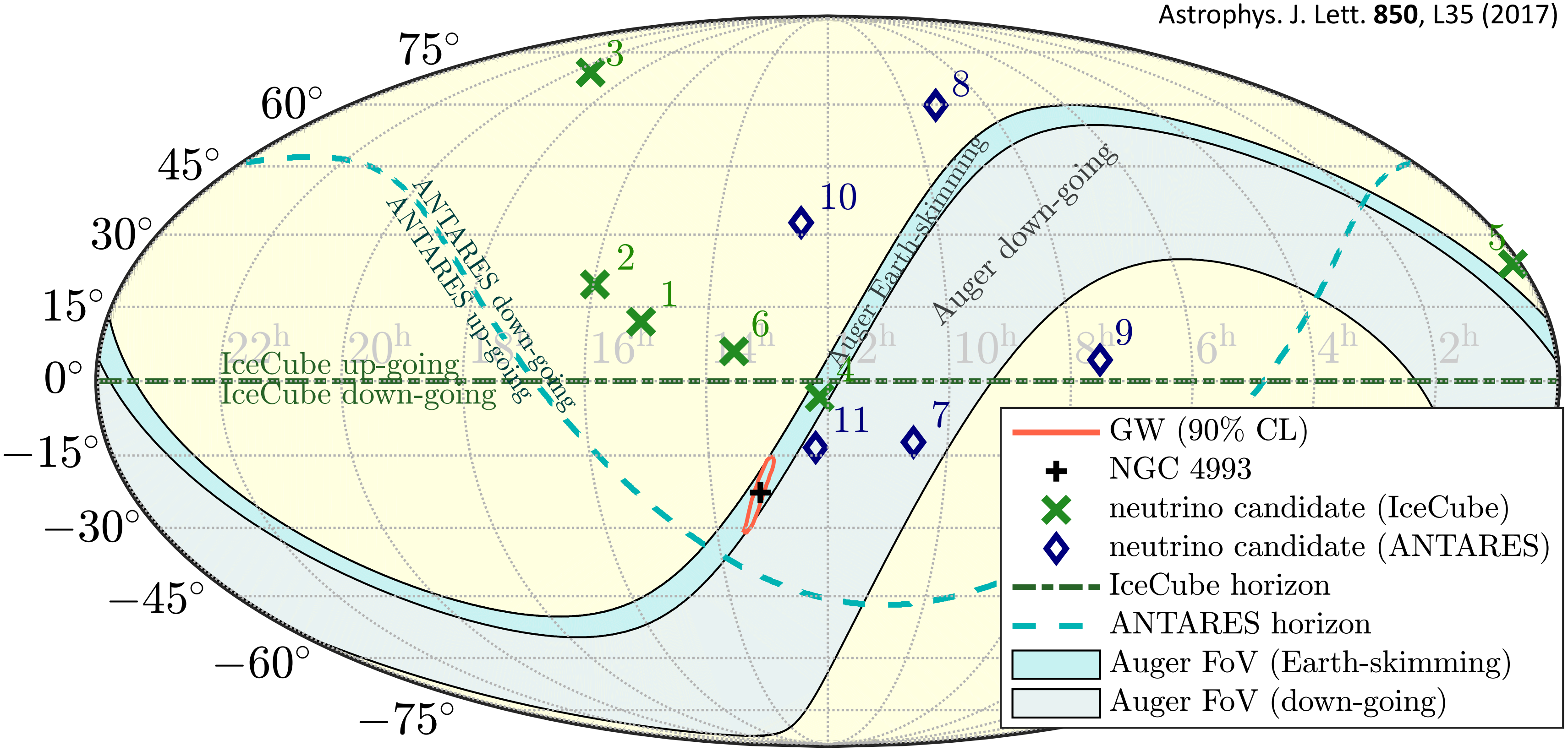


First upper limits to the neutrino flux from TXS 0506+056 at EeV energies

IceCube, Science **361**, 147 (2018). P. Padovani et al. MNRAS **480**, 192 (2018)

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

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

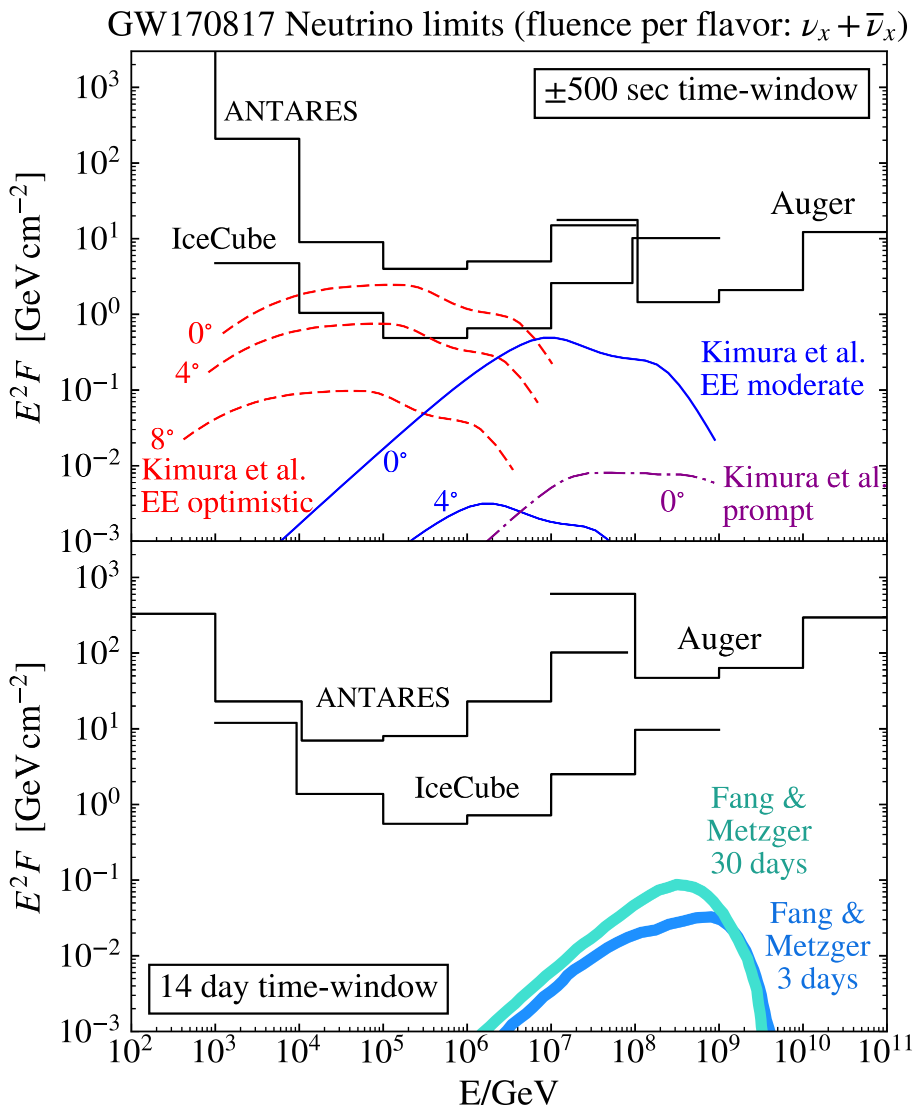


The NS-NS merger was in an **optimal position** for the detection of UHE tau neutrinos from Auger at the instant of emission of GW170817

Limits to ν from Binary NS-NS event GW170817: ANTARES, Auger & IceCube

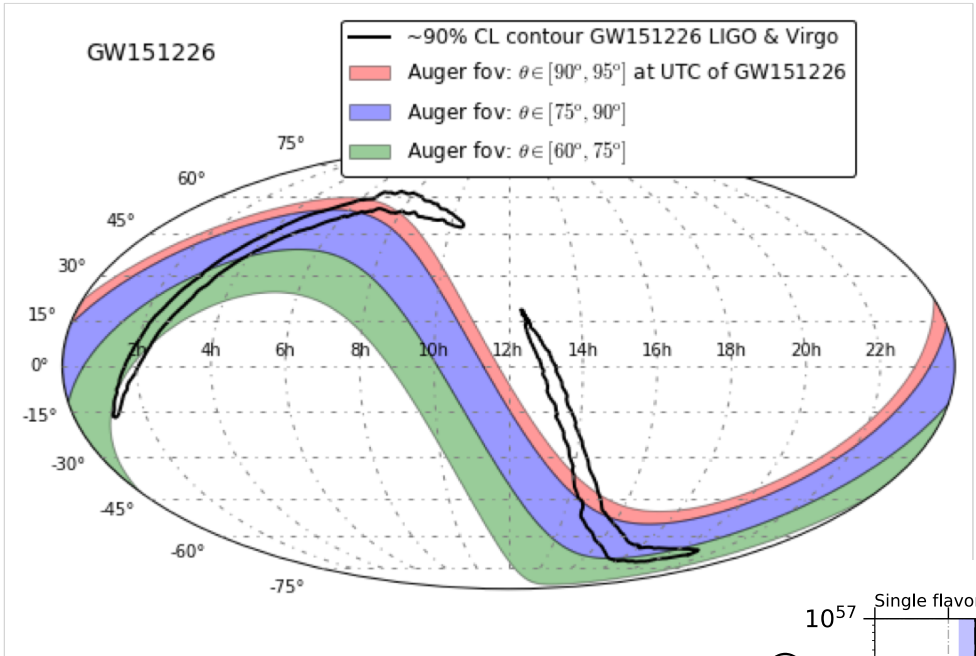
- Neutrino limits based on non-observation in ± 500 sec & +14 days-time windows

- Lack of neutrino detection consistent with expectations from a short GRB viewed at a large off-axis angle ≳ 20° (in agreement with LIGO/Virgo & GRB observations)



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

Limits to Binary Black Hole mergers: GW151226



Skymap (equatorial coords.):

- Localization of GW151226
- field-of-view of Auger in inclined directions at instant GW151226 occurred

Pierre Auger , PRD **94**, 122007 (2016)

Limits to energy emitted in the form of UHEν from non-observation of ν candidates in Auger 1 day after GW151226:

- Less than a few solar masses in the form of neutrinos.
- Compatible with expectations of absence of ν production in "naked" BH-BH mergers.