PIERRE AUGER OBSERVATORY

# Multimessenger astrophysics: the ultrahigh-energy picture with the Pierre Auger Observatory

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PennState

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# Outline

- UHE Cosmic Rays:
- Questions:
  - What are the messengers?
  - What are the sources?
  - Acceleration? Maximum energy?
  - Highest-energy physics?

Observables:

Composition (Ze, $\nu$, $\gamma$)

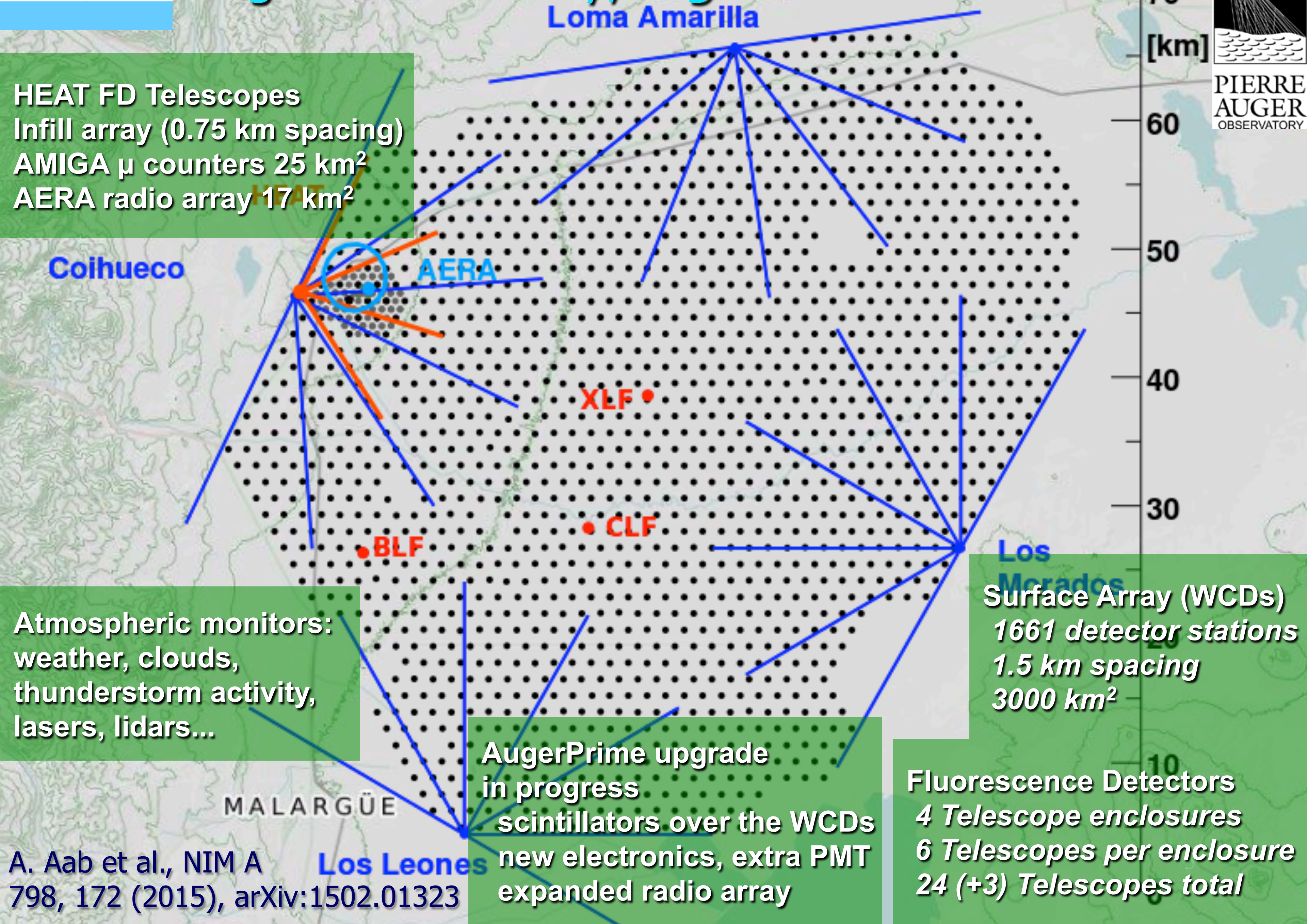
Arrival directions

Energy spectrum

Air shower properties

- Auger:
  - Many new results with >67,000 km$^2$ sr yr exposure;
    (2017 ICRC, Busan, South Korea)
  - First signs of anisotropy;
  - Hadronic interactions results and puzzles;
  - New era of multimessenger astrophysics.

# Auger Observatory, *Argentina*




**HEAT FD Telescopes**
**Infill array (0.75 km spacing)**
**AMIGA μ counters 25 km$^2$**
**AERA radio array 17 km$^2$**

**Atmospheric monitors:**
**weather, clouds, thunderstorm activity, lasers, lidars...**

**AugerPrime upgrade in progress**
- **scintillators over the WCDs**
- **new electronics, extra PMT**
- **expanded radio array**

**Surface Array (WCDs)**
- ***1661 detector stations***
- ***1.5 km spacing***
- ***3000 km$^2$***

**Fluorescence Detectors**
- ***4 Telescope enclosures***
- ***6 Telescopes per enclosure***
- ***24 (+3) Telescopes total***

A. Aab et al., NIM A 798, 172 (2015), arXiv:1502.01323

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# Hybrid design

~500 collaborators;
16 countries;
86 institutions;
> 67,000 – 89,000 km$^2$ sr yr

A multi-component
hybrid Observatory;
study of UHECRs >$10^{17}$ eV.

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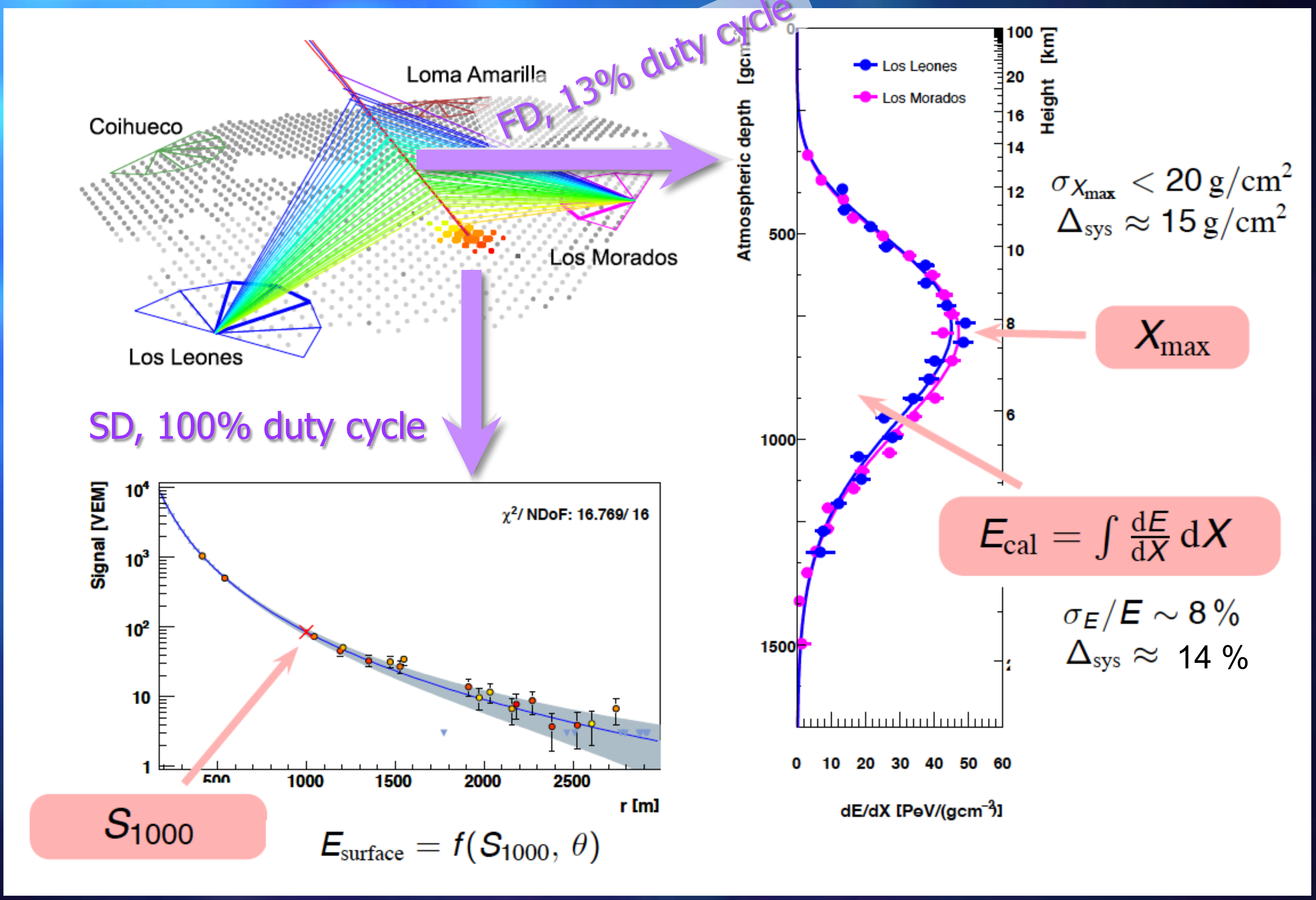
# Event reconstruction

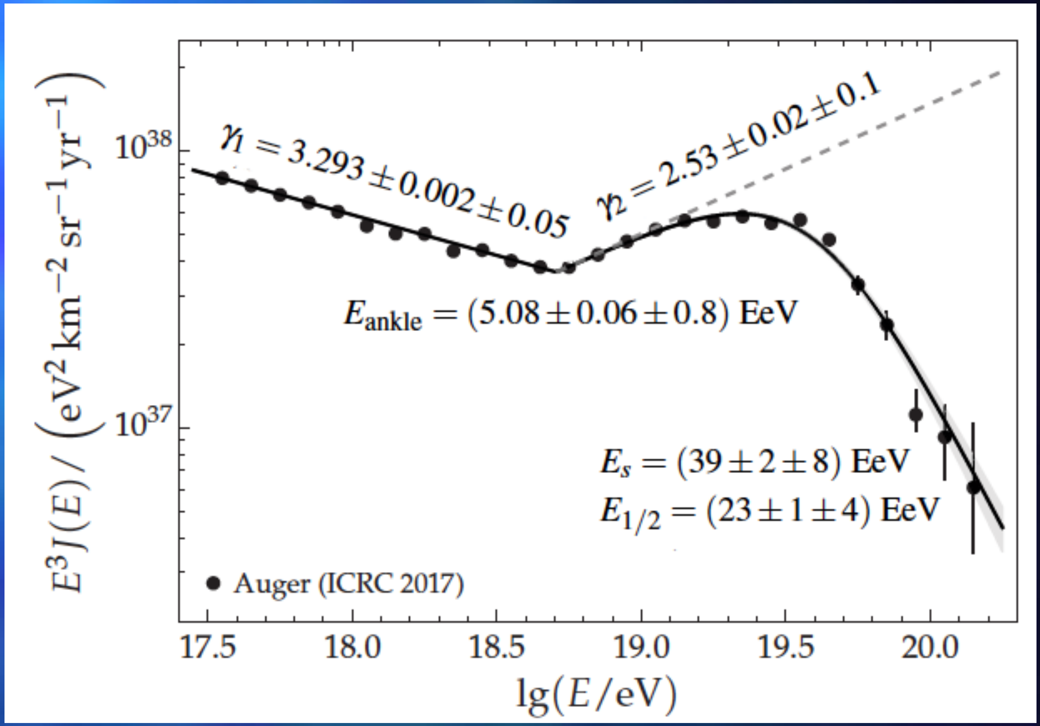


# Energy spectrum

F. Fenu et al., Proc. of 35th ICRC, Busan (2017)

- Updated, combined Auger spectrum:
- 203,000 SD (>3 EeV) + 87,000 infill (>0.3 EeV) + 12,000 hybrid events (>1 EeV);
- Exposure = 67,000 km$^2$ sr yr .

Smooth suppression definitely seen (>20σ)




$$J_{\text{unf}}(E) = \begin{cases} J_0 \left(\frac{E}{E_{\text{ankle}}}\right)^{-\gamma_1} & ; E \leq E_{\text{ankle}} \\ J_0 \left(\frac{E}{E_{\text{ankle}}}\right)^{-\gamma_2} \left[1 + \left(\frac{E_{\text{ankle}}}{E_s}\right)^{\Delta\gamma}\right] \left[1 + \left(\frac{E}{E_s}\right)^{\Delta\gamma}\right]^{-1} & ; E > E_{\text{ankle}} \end{cases}$$

# Energy spectrum

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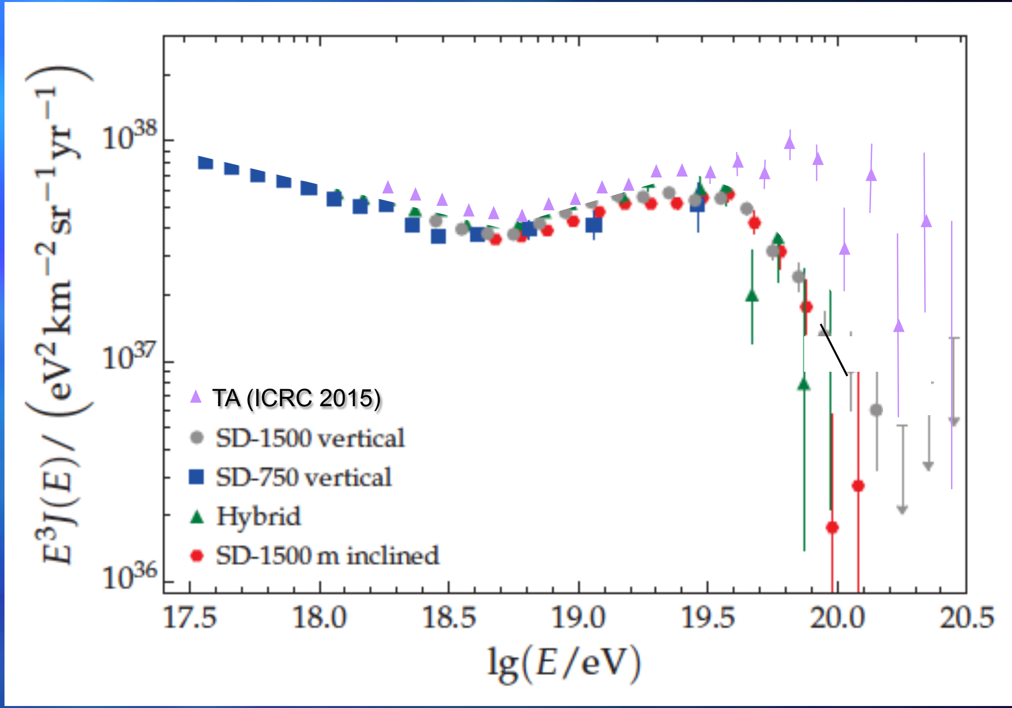


C. Jui et al., Proc. of 34th ICRC, The Hague (2015)
R.U. Abbasi et al., Astropart. Phys. 68, 27 (2015)

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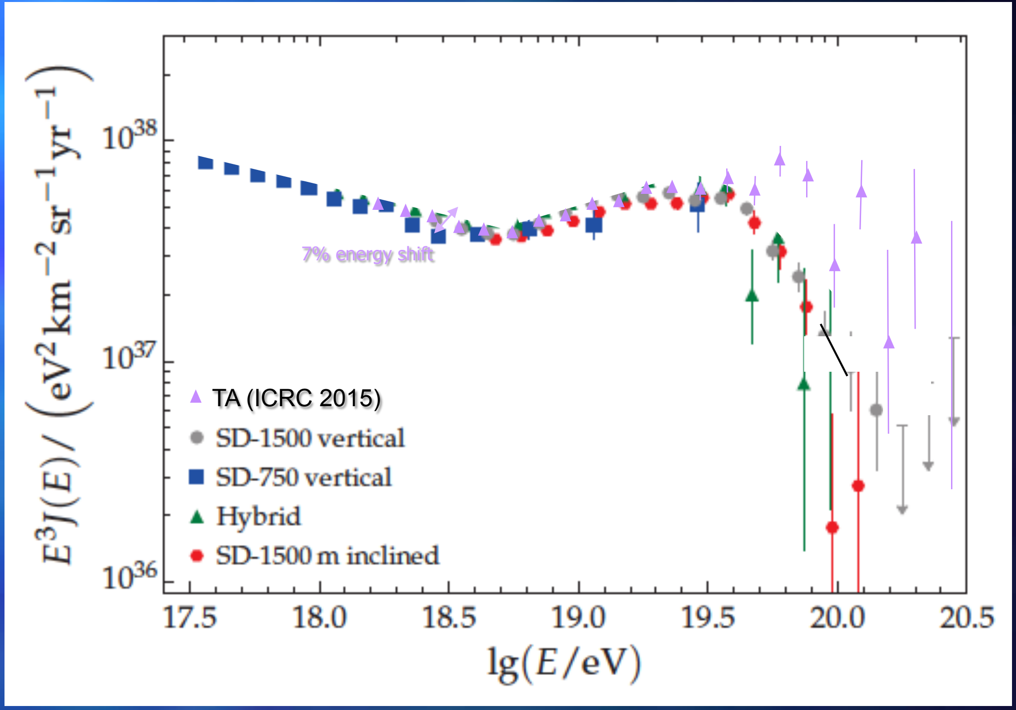
**Smooth suppression definitely seen (>20σ)**

Differences between Auger and TA can be (mostly) accommodated within a systematic energy shift...

... but not easily at the highest energies.

F. Fenu et al., Proc. of 35th ICRC, Busan (2017)




C. Jui et al., Proc. of 34th ICRC, The Hague (2015)
R.U. Abbasi et al., Astropart. Phys. 68, 27 (2015)

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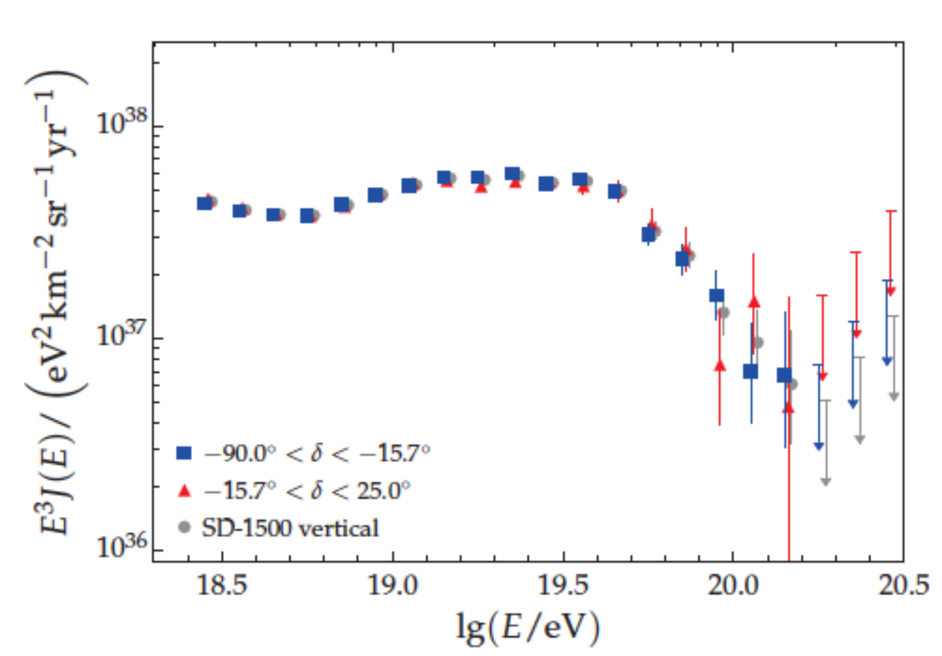
# A North/South difference?

F. Fenu et al., Proc. of 35th ICRC, Busan (2017)




Auger spectrum divided into 2 separate declination bands covering >70% of the sky;

No evidence for spectral dependence on source location.

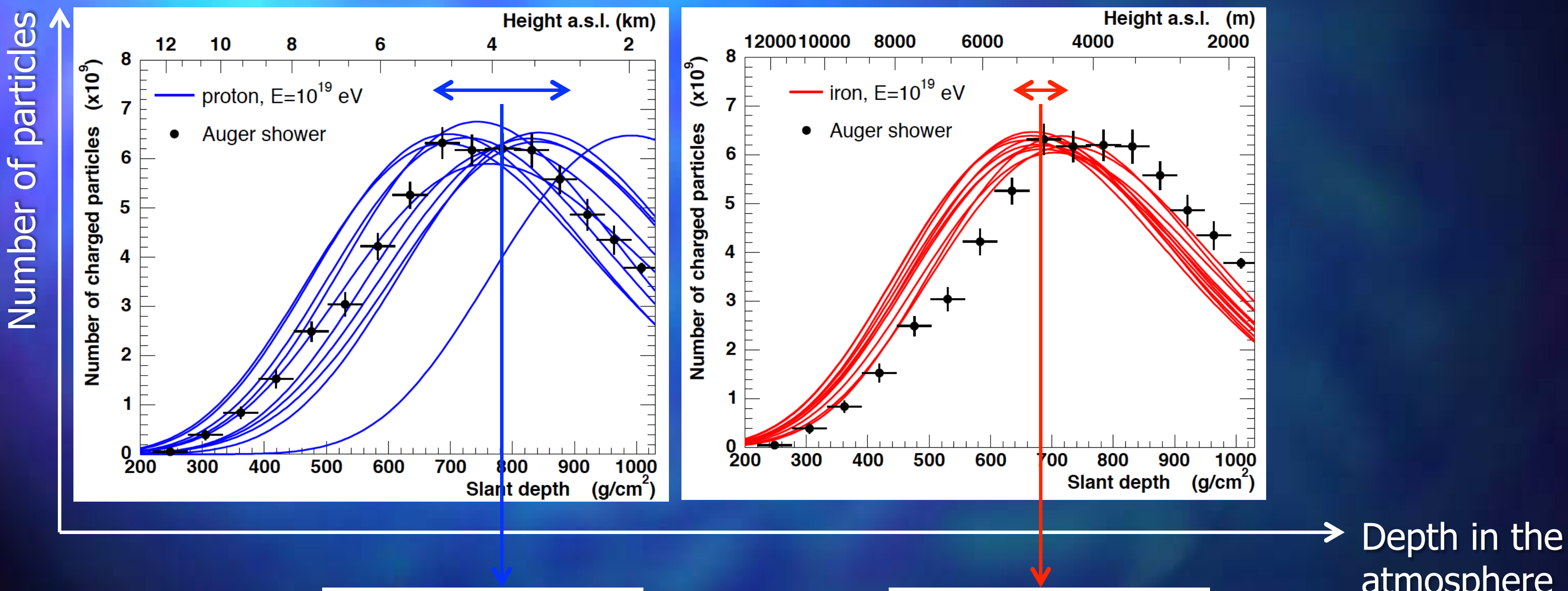
What is the nature of the spectral suppression?

- GZK propagation effects (attenuation due to CMB interactions)?
- Intrinsic difficulty of producing $10^{20}$ eV particles in astrophysical sources?

1) Study mass composition and air shower development (UHE physics);
2) look for sources in arrival direction distribution.

# Nature of UHECRs

Hybrid measurements are sensitive to mass composition




$X_{max}$ ~ 780 g/cm$^2$

$X_{max}$ ~ 680 g/cm$^2$

p-induced showers develop deeper than Fe-induced ones

and have greater fluctuations

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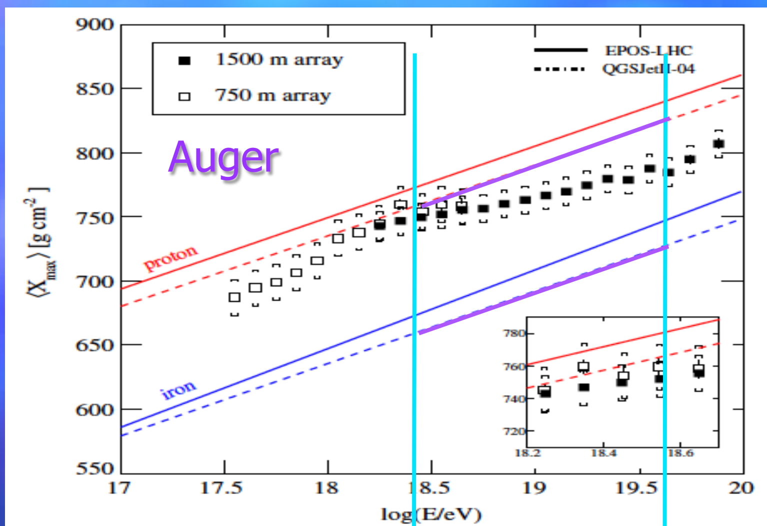
# Mass composition

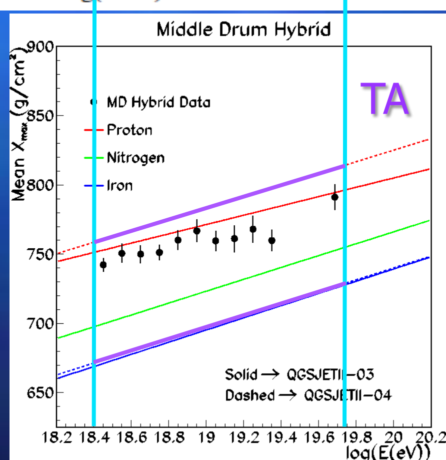
A. Aab et al., PRD 96, 122003 (2017)



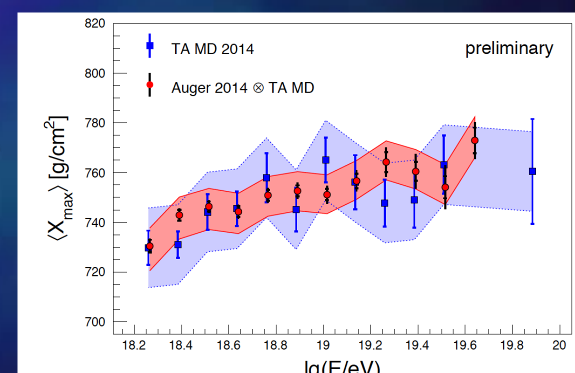

Clean hybrid events (strong anti-bias cuts); detector-independent measurements.

Hadronic interaction MCs tuned to 7 TeV LHC data.

TA distribution is *not* detector independent; instrumental effects folded into MC.




Fold Auger $X_{max}$ distribution into TA MC algorithm... excellent agreement!




M. Unger et al., Proc. of 34th ICRC, The Hague (2015)

J.P. Lundquist et al., Proc. of 34th ICRC, The Hague (2015)

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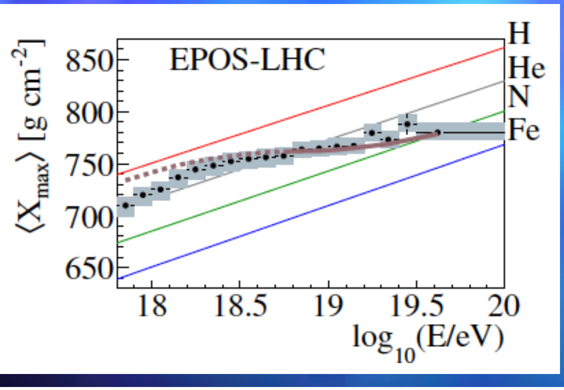
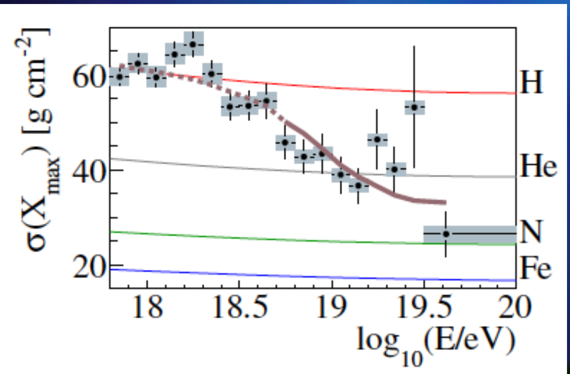
# Combining $X_{max}$ and spectrum

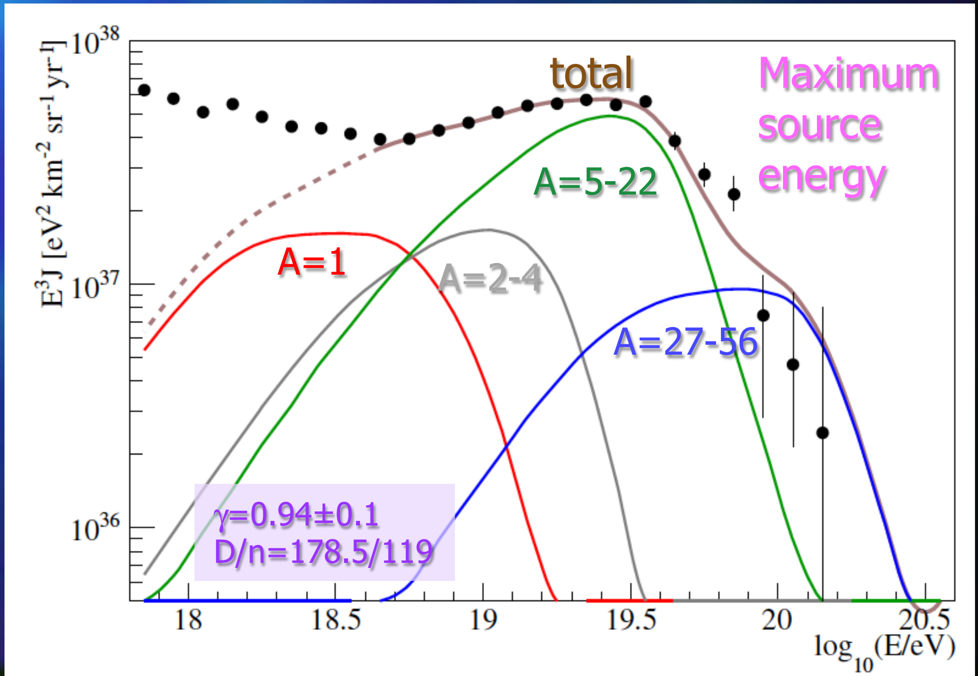
Homogeneous distribution of identical sources of p, He, N and Fe nuclei;
125 data points, 6 fit parameters: injection flux norm. and spec. index $\gamma$, cutoff rigidity $R_{cut}$, p/He/N/Fe fractions;
best fit with very hard injection spectra ($\gamma \leq 1$).

Rich phenomenology !
(but needs enhanced composition sensitivity)

A. Aab et al., JCAP 04, 038 (2017)



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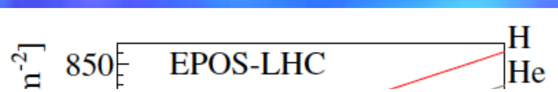
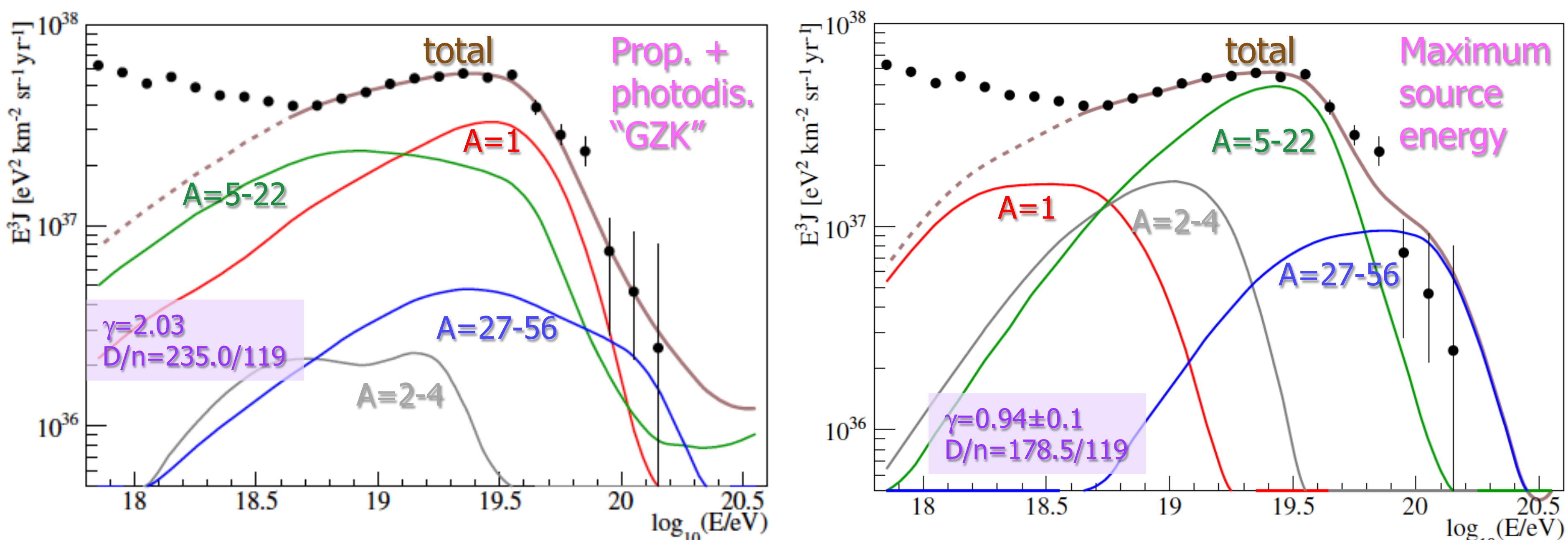



A. Aab et al., JCAP 04, 038 (2017)



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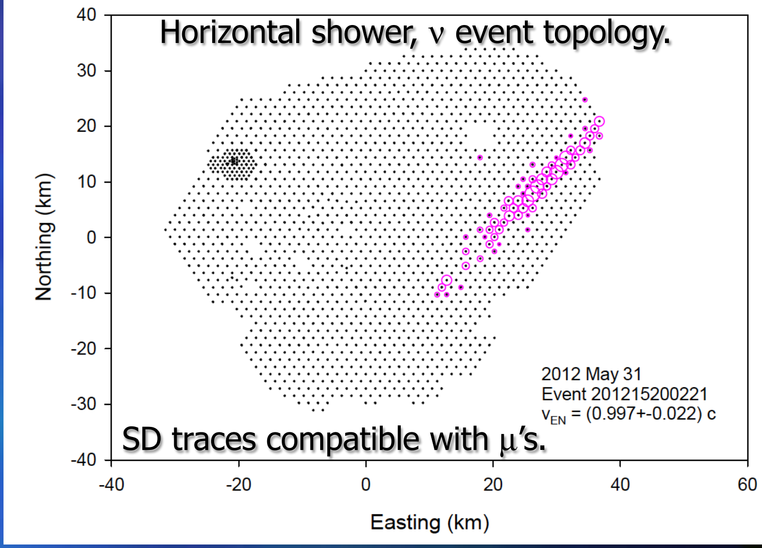
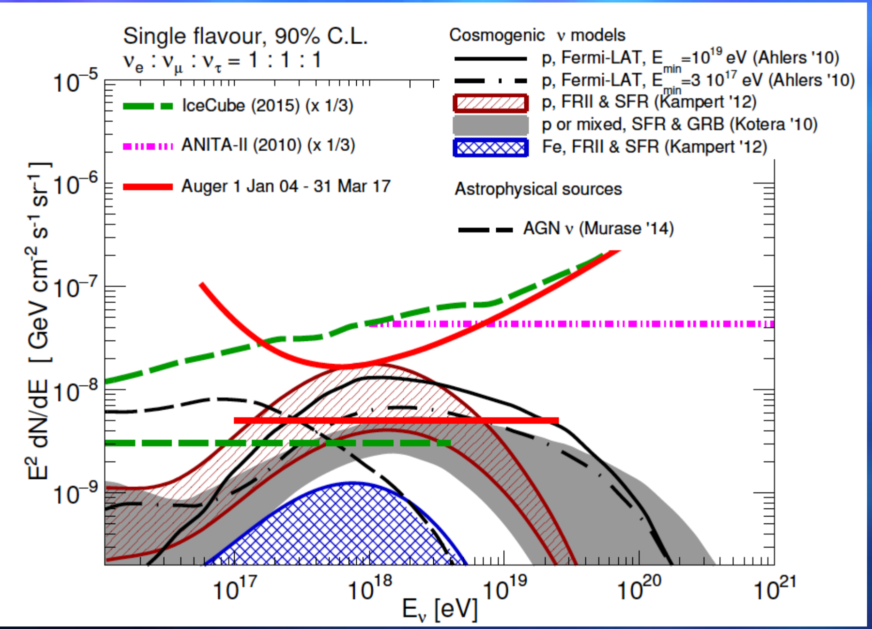
None seen so far.

# Neutral UHECRs?

- Neutrinos? Horizontal showers with EM activity; shape of footprint, SD time structure.
- Photons? Deep showers with low μ content; shape of LDF, SD time structure.

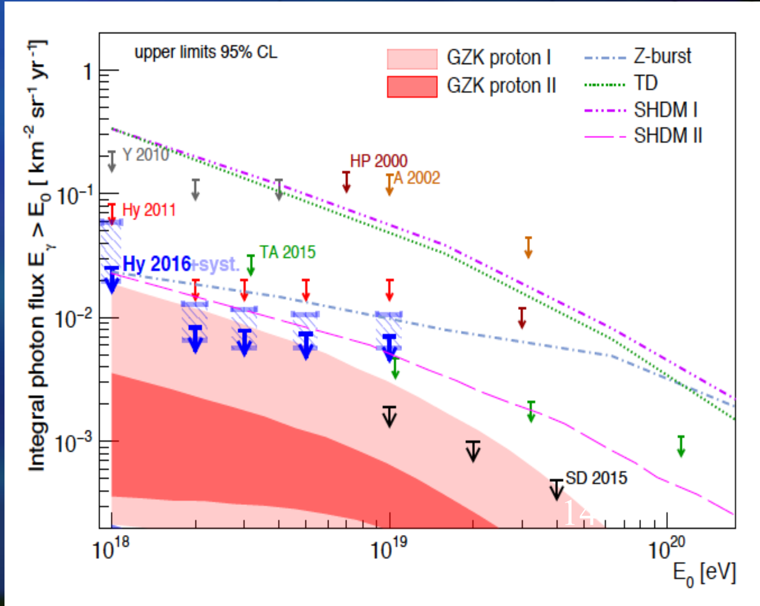



ν: A. Aab et al., PRD 91, 092008 (2015)
γ: A. Aab et al., ApJ 789, 160 (2014)
A. Aab et al., ApJL 837, L25 (2017)




E. Zas et al., Proc. of 35th ICRC, Busan (2017)

M. Niechciol et al., Proc. of 35th ICRC, Busan (2017)




Top-down models strongly disfavored

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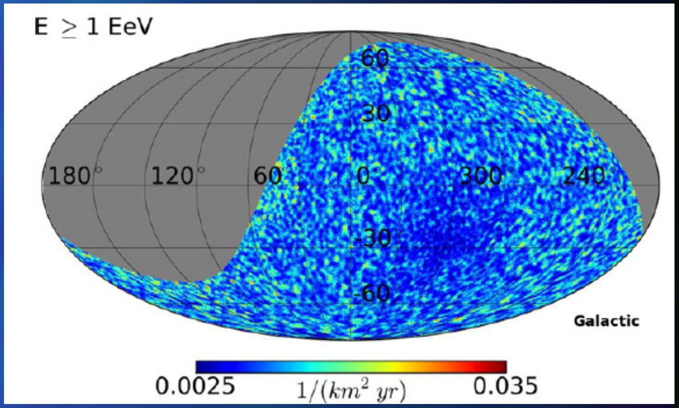
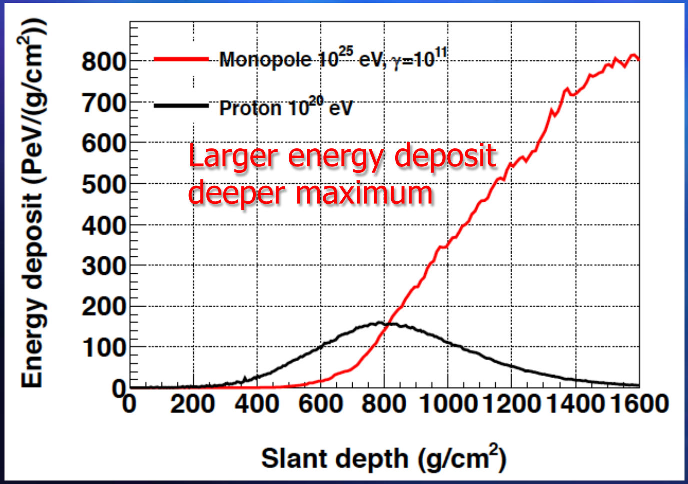
# Other types of UHECRs?

n: P. Abreu et al., ApJ 760, 148 (2012)
A. Aab et al., ApJ 789, L34 (2014)

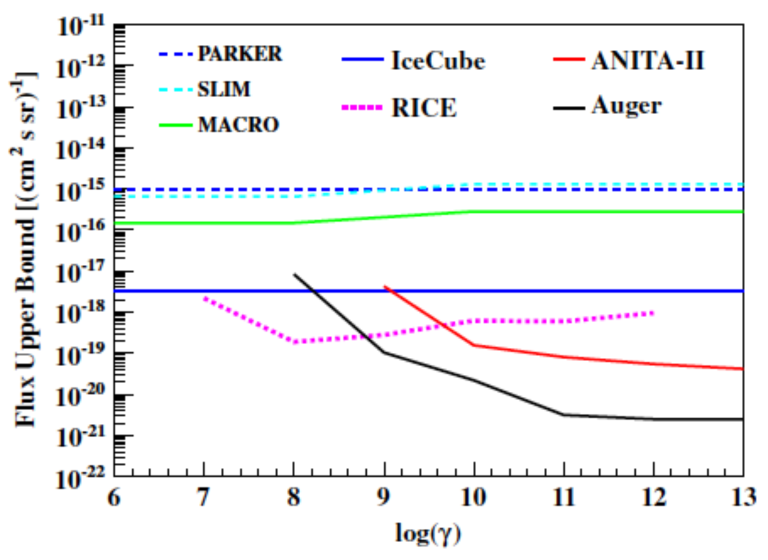



- Neutrons? ~EeV air showers showing Galactic anisotropies; n decay length ~(9.2E) kpc, about Sun's Galactic radius; no significant excess in blind search or stacked search; n flux limits are below the detected TeV gamma ray fluxes.

- Magnetic monopoles? Ultra-relativistic monopoles (masses $10^{11} - 10^{20}$ eV/c²) deposit a comparable dE/dx in air to UHECRs (pair production, photonuclear interactions).




No candidate; first limit from EAS experiment; lowest limit for $\gamma > 10^9$.




A. Aab et al., PRD 94, 082002 (2016)

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# Large scale anisotropy

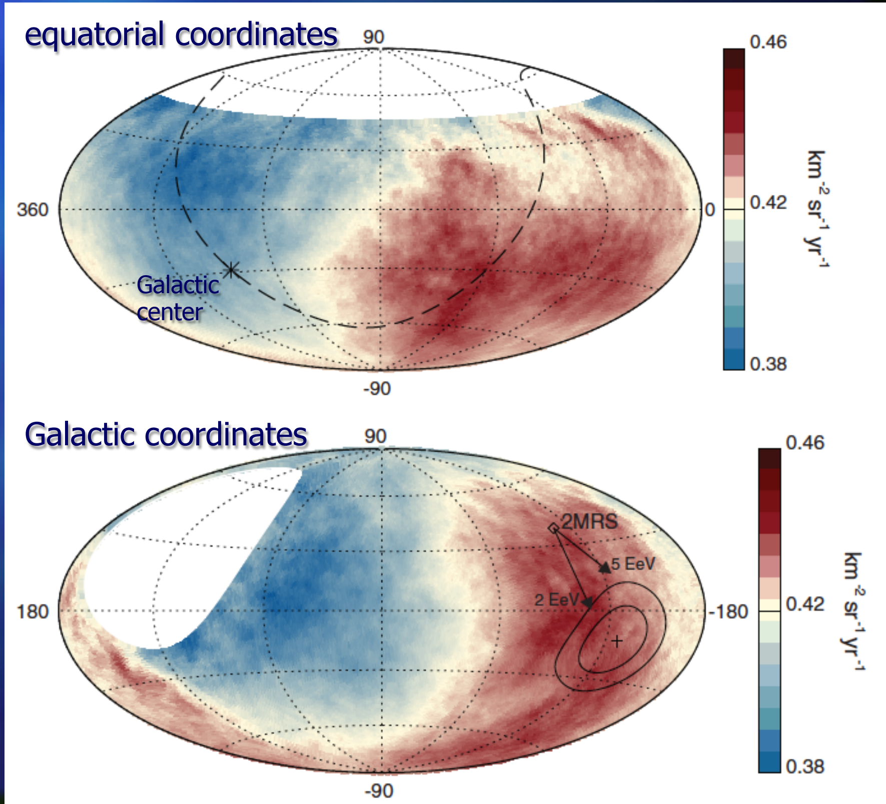
Largest data set: 76,800 km$^2$ sr yr since 2004;
85% sky coverage;

Auger Rayleigh analyses:

- 80,000 events at 4 – 8 EeV;
- distribution compatible with isotropy;

- 30,000 events > 8 EeV;
- dipole of amplitude (6.5+1.3-0.9)% (5.2σ), pointing to (a,d) = (100°±10°, -24°+12°-13°).

A. Aab et al., Science 357, 1266 (2017)
45° top-hat smoothing




Challenges expectation of isotropy at these "low" energies. Magnetic deflections important.

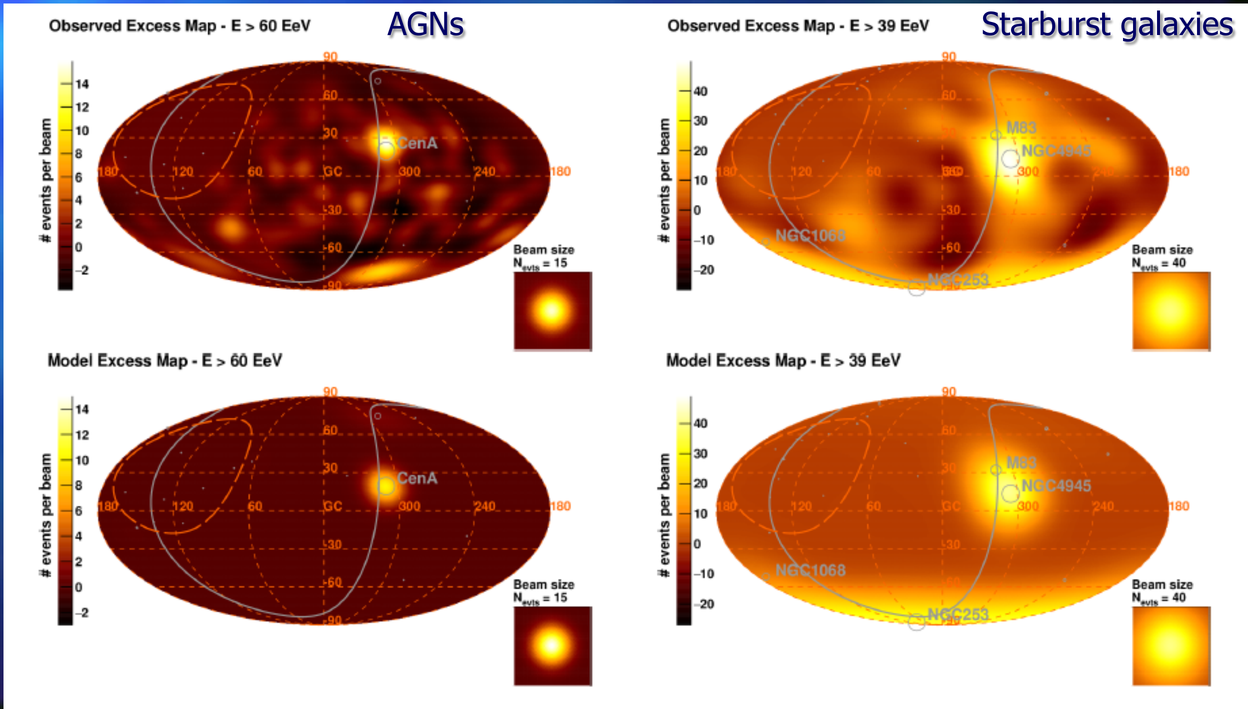
# Intermediate scale anisotropy

Anisotropy tests with astrophysical structures: 2FHL catalog (hard Fermi-LAT sources) and starburst galaxies within 250 Mpc;

Auger: 89,720 km$^2$ sr yr since 2004; 5514 events above 20 EeV; optimize threshold energy and scan over search radius and anisotropic fraction.

Best significance: 4.0σ for E>39 EeV
10% SBG + isotropic background;
13° search window.

A. Aab et al., ApJL 853, L29 (2018)



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# Auger in multimessenger era

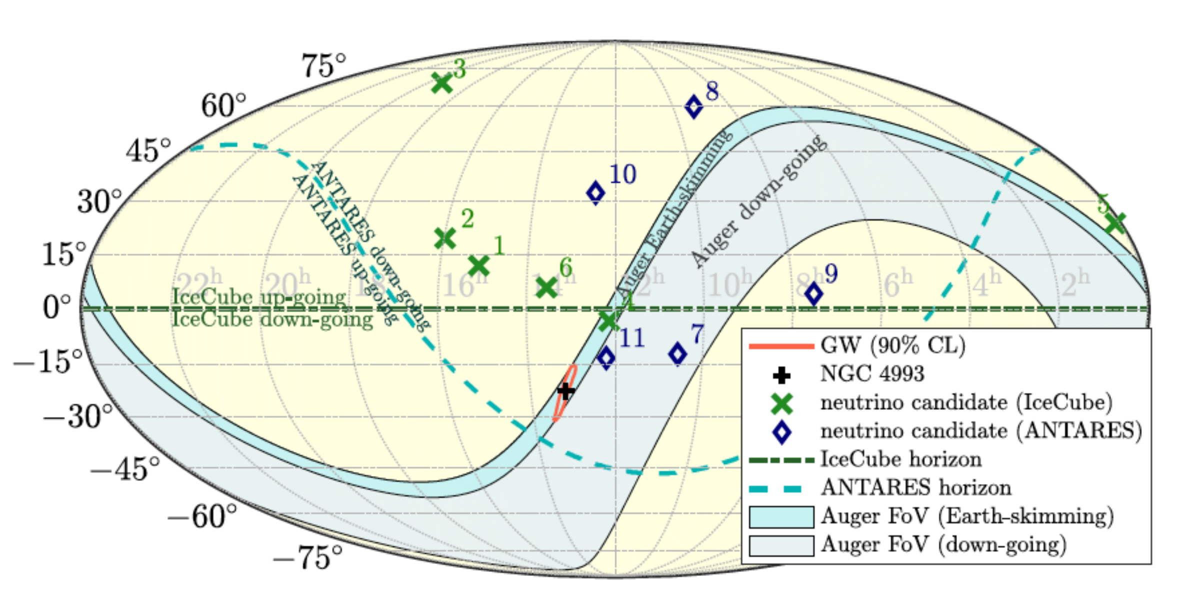
Auger search for UHE (>100 PeV) neutrinos associated with GW150914 or GW151226; none seen within ±500s of the events or within 1 day afterwards. A. Aab et al., PRD94, 122007 (2016)

August 2017: LIGO/Virgo GW170817 + GRB seen by Fermi and INTEGRAL + EM follow up ➔ NGC 4993

No neutrino candidates from IceCube, ANTARES or Auger within ±500s of the event or within 14 days afterwards.

A. Albert et al., ApJL 850, L35 (2017) ANTARES+Auger+IceCube

Typical short GRB viewed off axis, absence of neutrinos not unexpected.



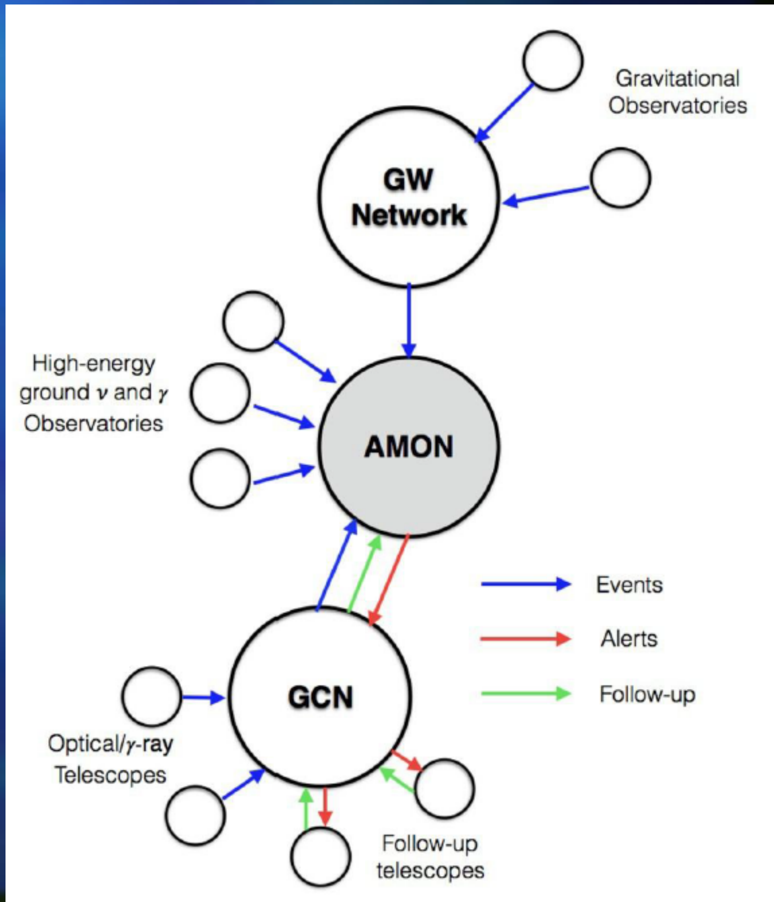
AMON

Astrophysical Multimessenger Observatory Network

http://amon.gravity.psu.edu

- Combine subthreshold signals from multiple participating observatories;
- similar to previous efforts:
  - neutrino (SNEWS),
  - gamma-ray bursts (GCN),
  - GW observatories,
- but now with all messengers.

- Triggering observatories [Swift, Fermi, LIGO, IceCube, Auger, HAWC, ANTARES];
- Follow up observatories [FACT (Canary), LMT (Mexico), LCOGT (8 telescopes), MASTER (9 telescopes), PTF (CA), VERITAS];
- data sharing begun:
  - archival searches;
  - real-time alerts for EM follow up.



# AMON searches

SEARCH FOR BLAZAR FLUX-CORRELATED TEV NEUTRINOS IN ICECUBE 40-STRING DATA

C. F. Turley[1,3,5], D. B. Fox[2,3,4], K. Murase[1,2,3,4], A. Falcone[2,3], M. Barnaba[2], S. Coutu[1,3], D. F. Cowen[1,2,3], G. Filippatos[1,3], C. Hanna[1,2,3], A. Keivani[1,3], C. Messick[1,3], P. Mészáros[1,2,3,4], M. Mostafá[1,2,3], F. Oikonomou[1,3], I. Shoemaker[1,3], M. Toomey[1,3], G. Tešić[1,3]
(The AMON Core Team)

ApJ 833, 117 (2016)
VERITAS+IceCube

ApJL 832, L1 (2016)
Swift-BAT+Parkes

DISCOVERY OF A TRANSIENT GAMMA-RAY COUNTERPART TO FRB 131104

J. J. DeLaunay[1,3], D. B. Fox[2,3,4], K. Murase[1,2,3,4], P. Mészáros[1,2,3,4], A. Keivani[1,3], C. Messick[1,3], M. A. Mostafá[1,3], F. Oikonomou[1,3], G. Tešić[1,3], and C. F. Turley[1,3]

**Multiwavelength follow-up of a rare IceCube neutrino multiplet**

IceCube: M. G. Aartsen[2], M. Ackermann[116], J. Adams[28], J. A. Aguilar[16], M. Ahlers[67], M. Ahrens[101], I. Al Samarai[43], D. Altmann[40], K. Andeen[69],

The Astrophysical Multimessenger Observatory Network: D. B. Fox[109,111,112], J. J. DeLaunay[110,111], C. F. Turley[110,111], S. D. Barthelmy[47], A. Y. Lien[47], P. Mészáros[110,109,111,112], K. Murase[110,109,111,112]

A&A 607, A115 (2017)
IceCube + ASAS-SN, AMON, Fermi, HAWC, LCO, MASTER, Swift, VERITAS

**Four *Swift* searches for transient sources of high-energy neutrinos**

A. Keivani et al., PoS(ICRC2017)1015
IceCube+Swift-BAT

In progress:
- IceCube+Fermi-LAT
- Fermi-LAT+ANTARES

Of course:

**Multi-messenger Observations of a Binary Neutron Star Merger***

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration,

ApJL 848, L12 (2017)
LIGO + everybody

# Example: Auger + IceCube

IceCube streams:

- HESE (high-energy starting events) public / private;
- EHE (extremely high-energy) public / private;
- Singlets (low-energy) private;
- Sent in real time (~40 s).

Auger streams:

- Single event stream private;
  - $E > 3$ EeV;
  - quality cuts (e.g., $\theta<60°$);
- Archival data from 2004;
- Sent in real time (~10 min).

Here use public IC59 data (May 2009 – May 2010);
George Fillipatos (PSU Schreyer Scholar).

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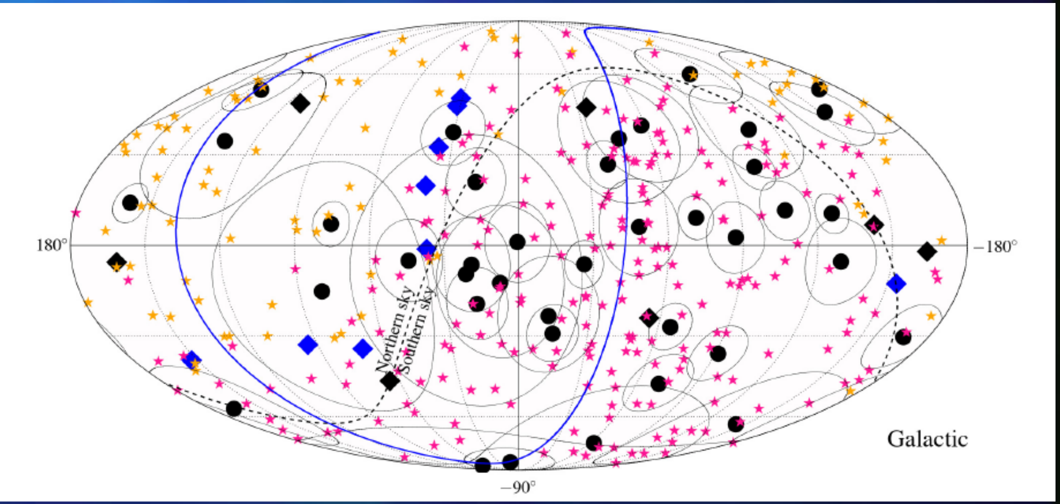
# Published Auger/TA/IceCube analysis

- High-energy $E_{CR}$>57 EeV;
- Spatial correlations only;
- Plot shows:
    - Auger (pink);
    - TA (orange);
    - IceCube (blue/black);

- No indications of sources at discovery level.

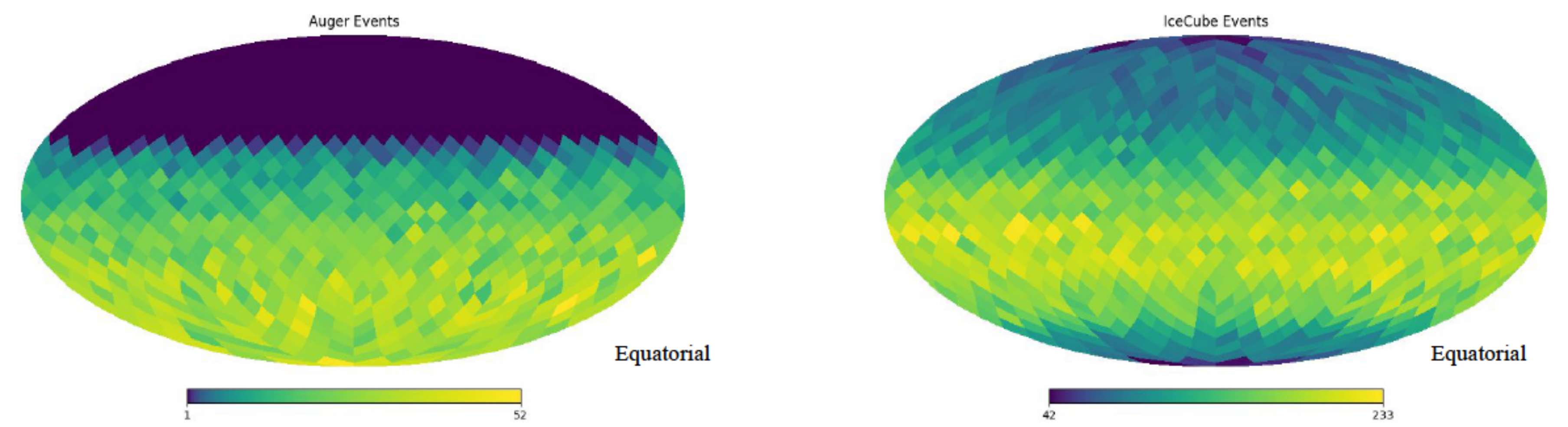
JCAP 01, 037 (2016)
IceCube+Auger+TA



# Subthreshold data: May '09 – May '10

- Auger;
  - AMON events;
  - E>3 EeV;
  - θ<60°;
  - ~11,000 events.

- IceCube;
  - IC59 public events;
  - ~100,000 events;
  - ~1 year of data.



# Correlation analysis

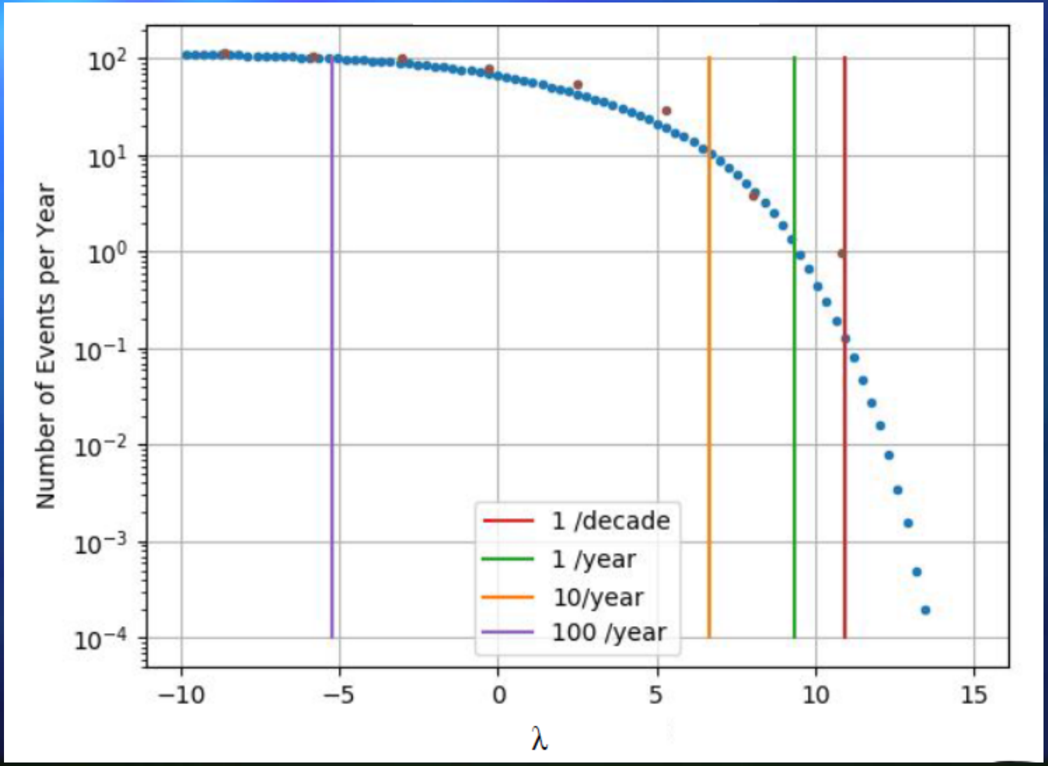
- Look for neutrinos within 5° and 1000s of a cosmic-ray event;
- Allow for multiple neutrinos;
- Calculate test statistic λ:
  - based on temporal and spatial correlation;
  - take into account declination-specific background;
- Null hypothesis: scramble arrival directions and randomize times;
- Compare simulated (scrambled) to actual λ distributions.

$$\lambda = \ln\left(N! \prod_{i=1}^{N} \frac{P_{t_i} P_{S_i}}{B_i(\delta)}\right)$$

- $N$ = number of particles in the multiplet
- $P_S$ = spatial probability of particle $i$
  calculated based on best fit position
- $P_t$ = Temporal probability of particle $i$
  falling exponential in time
- $B(\delta)$ = background at declination $\delta$
  calculated from exposure of each detector
- optimization is performed

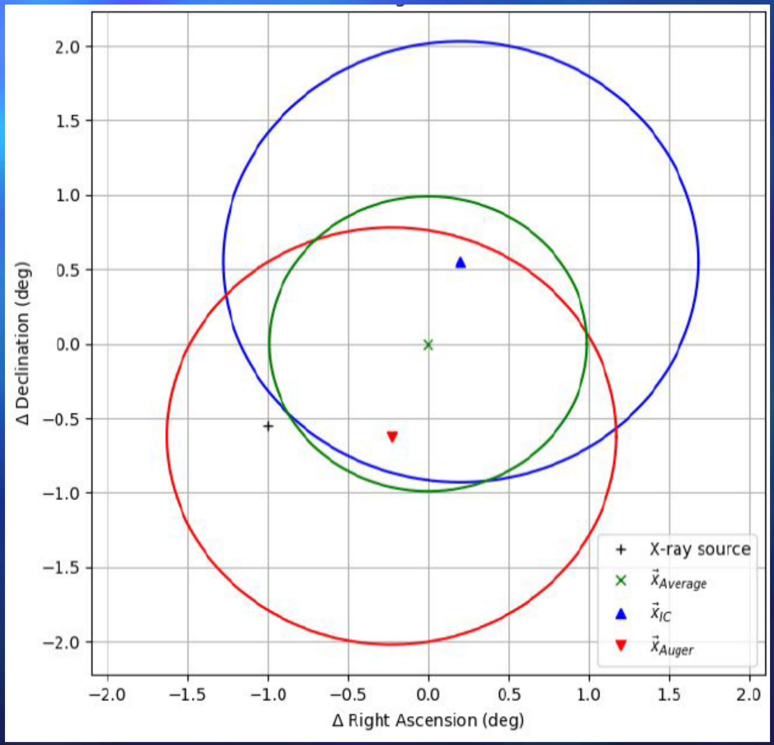
# Results

- One event above the 1/year threshold;
  - expected once per 9 years;
  - ~12% chance probability;
- Real distribution compatible with the scrambled data.



# Highest λ event

- Auger/IceCube events separated by 27s and 1°;
- Outside the Galactic plane;
- Near AGN NGC 7743.



# Potential for real-time analysis

- Both detectors sending data to AMON;
- Ranked alerts could be sent to follow up observatories;
  - Standard AMON analyses distribute events that exceed 1/month false alarm rate
- Possible streams:
  - Auger/HESE;
  - Auger/IceCube singlets.

- Ongoing work:
  - Expand to IceCube data from 2010 to present;
  - Develop a real-time alert stream for EM follow up observations.

In USA, thanks to

# Conclusions

- Flux suppression above ~40 EeV; GZK effect? source exhaustion?
- UHE sources do appear to be extragalactic;
- Large-scale dipole in arrival distribution above 8 EeV;
- Intriguing correlations above 39 EeV with starburst galaxies, particle astronomy is *hard* !
- Magnetic fields (Galactic, extragalactic) play a huge role;
- $X_{max}$ (and its RMS) evolution with energy suggest mass becomes heavier at the highest energies;
- Important limits to fluxes of neutrinos, photons, neutrons, magnetic monopoles;
- Highest-energy physics: reasonable $\sigma_{p\text{-}air}$ cross-section, but inconsistency in muon data;
- Hadronic interaction issues?
- Improved knowledge of mass composition is needed (AugerPrime, radio technique);

New era of multimessenger astrophysics!


Merci !