Highlights from the Pierre Auger Observatory

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25th Anniversary of the Rencontres du Vietnam
Windows on the Universe 2018 (Quy Nhon, 07.08.2018)

Outline

- **Introduction**
  - Ultra-high-energy cosmic rays
  - Pierre Auger Observatory
- **Current results**
  - Energy spectrum
  - Composition
  - Anisotropy
- **Perspectives**
  - AugerPrime

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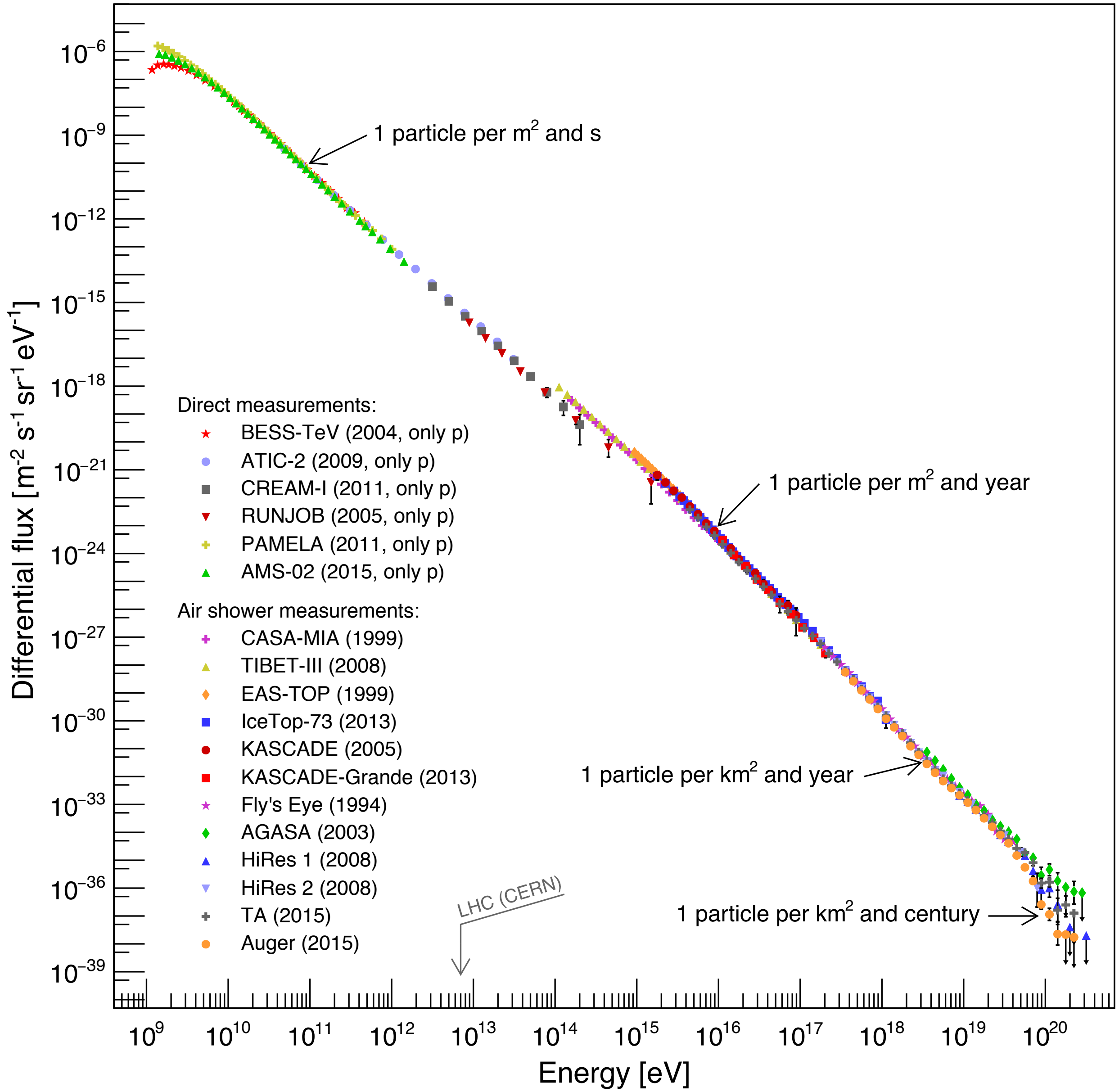
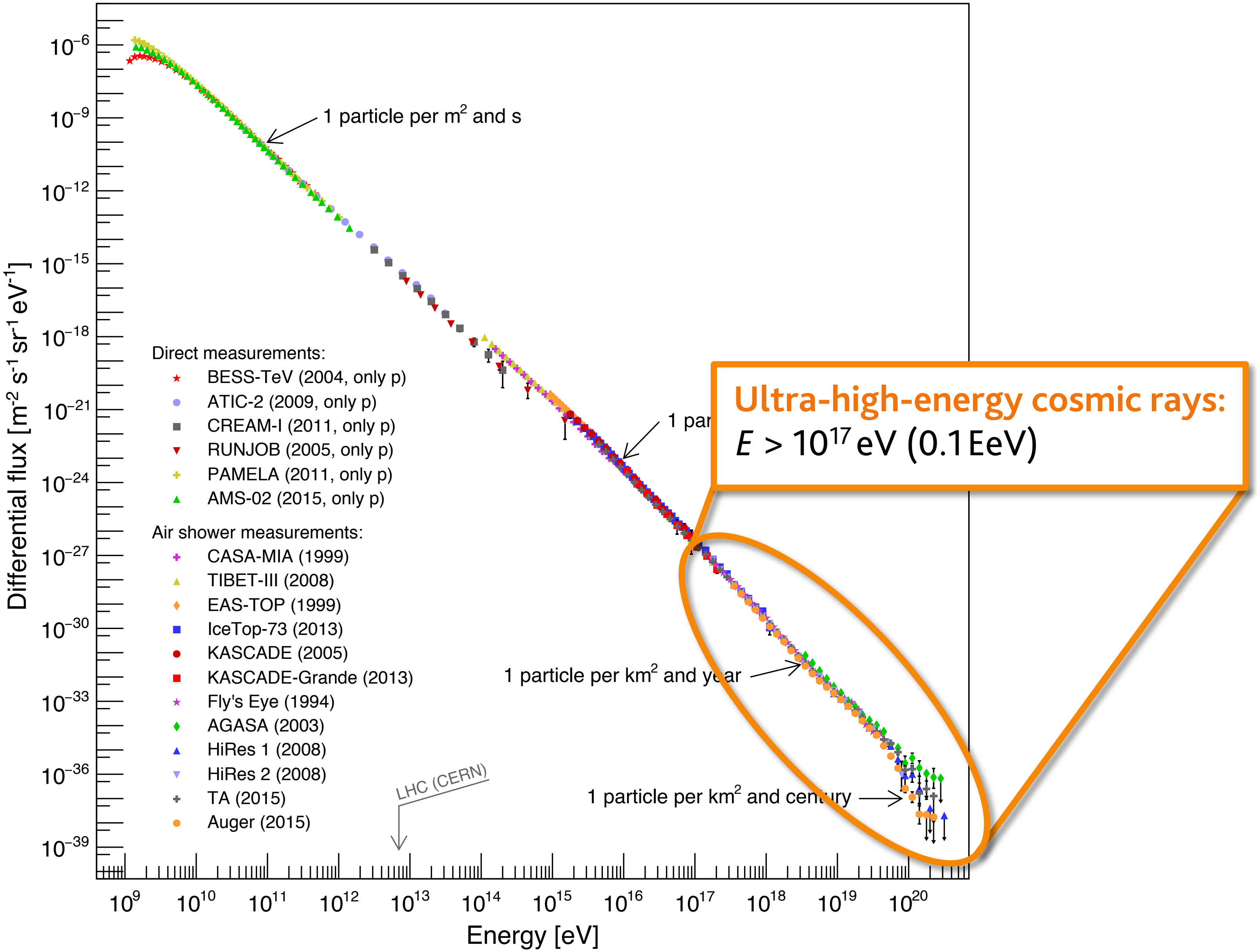
Cosmic rays



Differential flux [m^{-2} s^{-1} sr^{-1} eV^{-1}]
Energy [eV]
1 particle per m^2 and s
1 particle per m^2 and year
1 particle per km^2 and year
1 particle per km^2 and century
LHC (CERN)
Direct measurements:
BESS-TeV (2004, only p)
ATIC-2 (2009, only p)
CREAM-I (2011, only p)
RUNJOB (2005, only p)
PAMELA (2011, only p)
AMS-02 (2015, only p)
Air shower measurements:
CASA-MIA (1999)
TIBET-III (2008)
EAS-TOP (1999)
IceTop-73 (2013)
KASCADE (2005)
KASCADE-Grande (2013)
Fly's Eye (1994)
AGASA (2003)
HiRes 1 (2008)
HiRes 2 (2008)
TA (2015)
Auger (2015)

Cosmic rays



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Differential flux [m⁻² s⁻¹ sr⁻¹ eV⁻¹]
Energy [eV]
Ultra-high-energy cosmic rays:
E > 10¹⁷ eV (0.1 EeV)

Pierre Auger Observatory (I)

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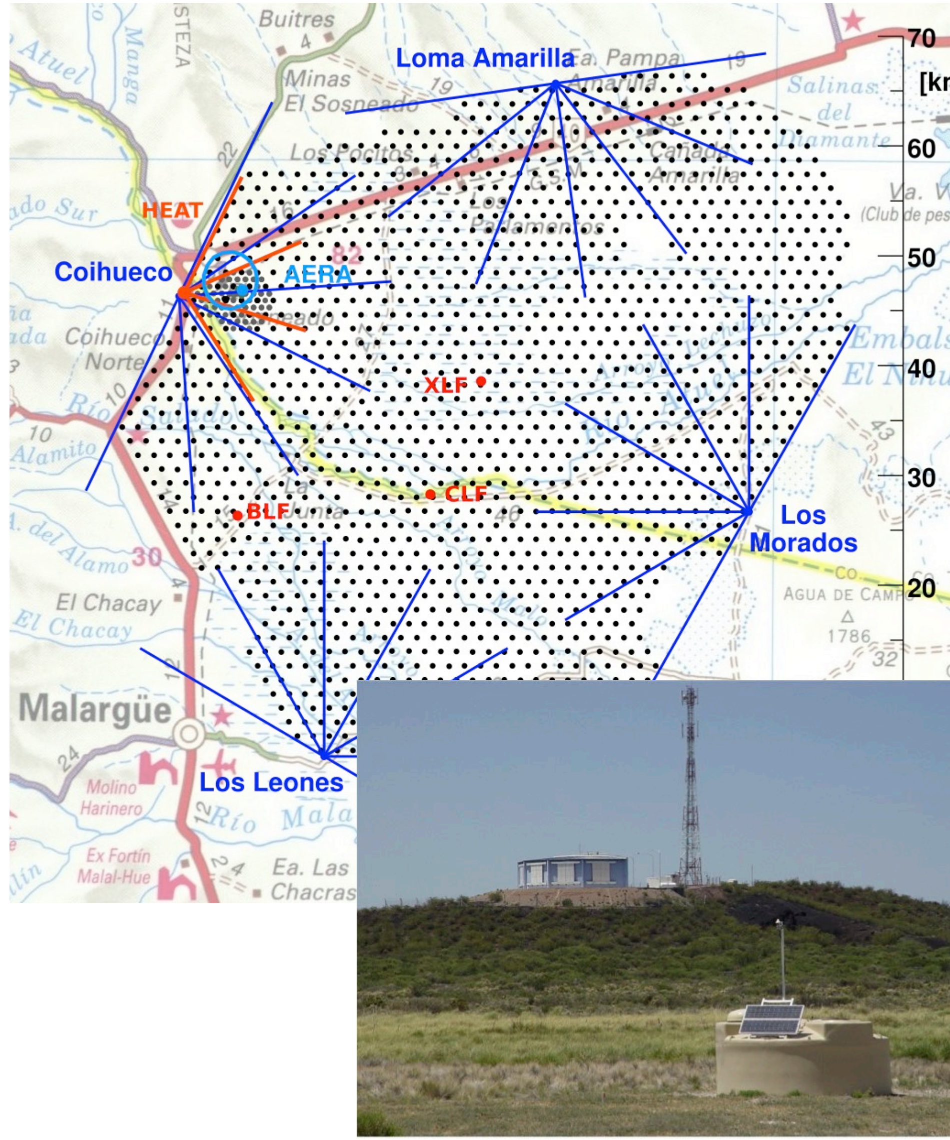
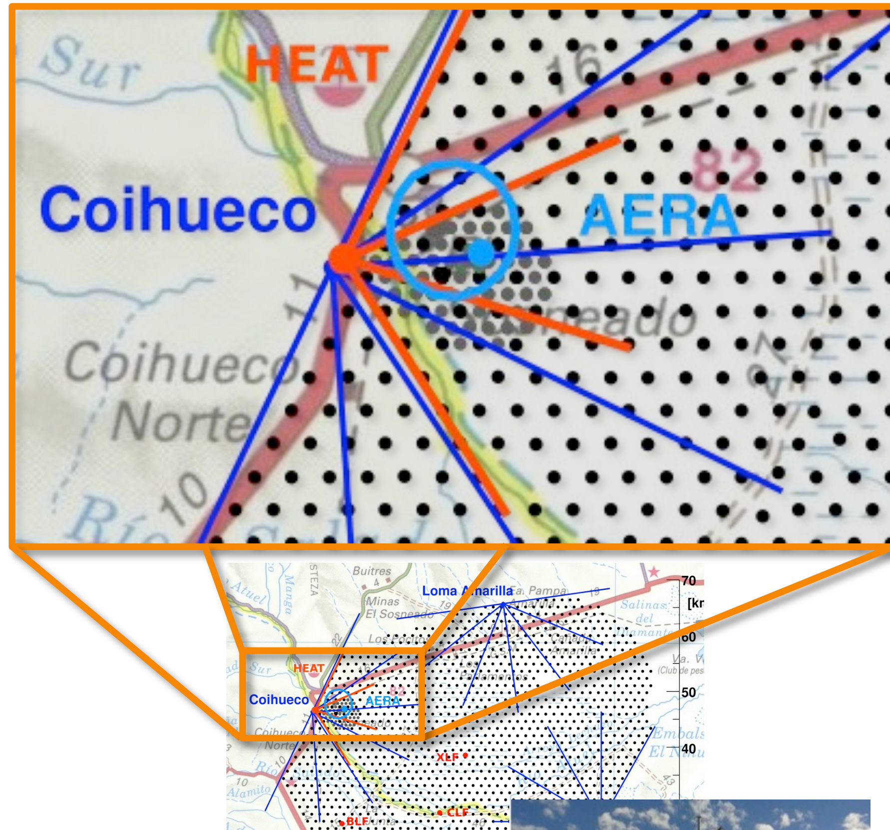
- **General**
  - Located near Malargüe, Argentina; latitude 35.2 °S, longitude 69.3 °W
  - Start of data taking: 2004
- **Surface detector (SD)**
  - 1600 water Cherenkov detectors
  - 1500 m distance, area: 3000 km^2
  - $E > 10^{18.5}$ eV
  - ~100 % duty cycle
- **Fluorescence detector (FD)**
  - 4 stations with 6 telescopes each
  - Field of view per telescope: 0-30° elevation, 30° azimuth
  - $E > 10^{18}$ eV
  - 13 % duty cycle



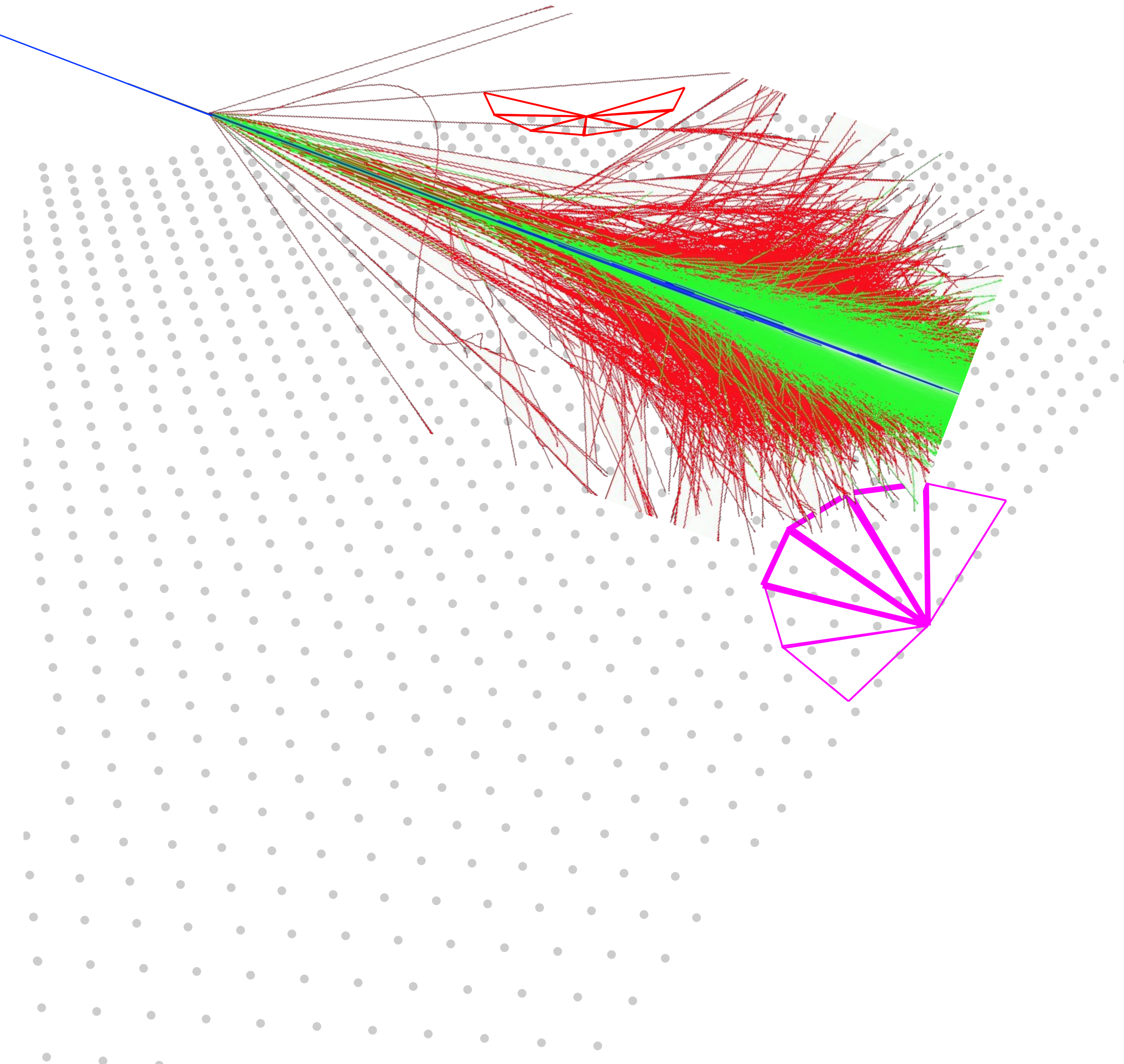
[The Pierre Auger Collaboration, NIM A 798 (2015) 172-213]

- **Infilled array**
  - 60 additional water Cherenkov detectors
  - 750 m distance, area: 24 km^2
  - $E > 10^{17.5}$ eV
- **HEAT**
  - 3 additional fluorescence telescopes
  - Tilted field of view: 30-60° elevation
  - $E > 10^{17}$ eV
- **AERA**
  - 124 radio stations
  - Different distances, area 17 km^2
  - Measurement of the radio signals emitted by air showers (frequencies 30-80 MHz)

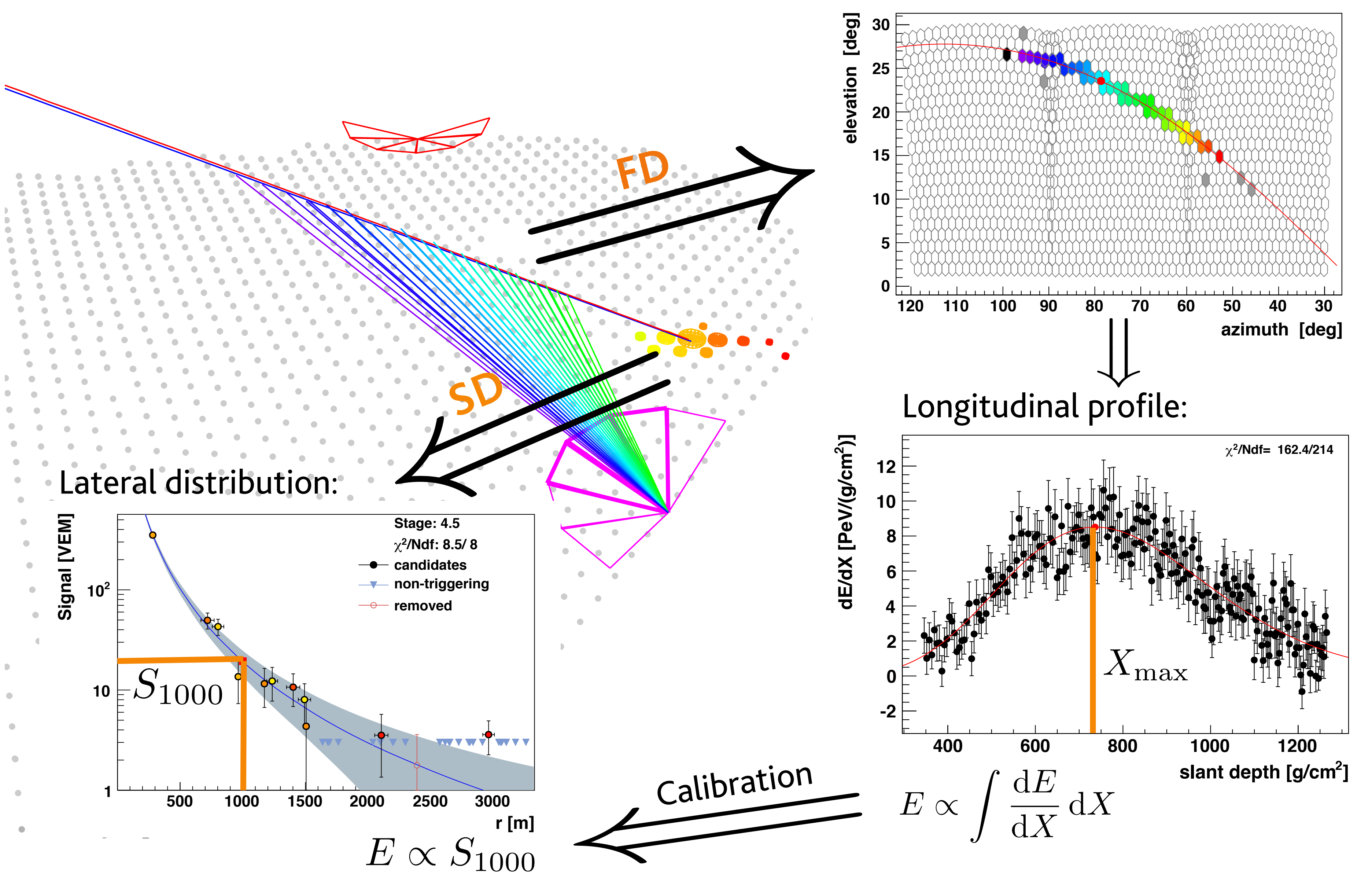


[The Pierre Auger Collaboration, NIM A 798 (2015) 172-213]

Hybrid concept (I)



Hybrid concept (II)



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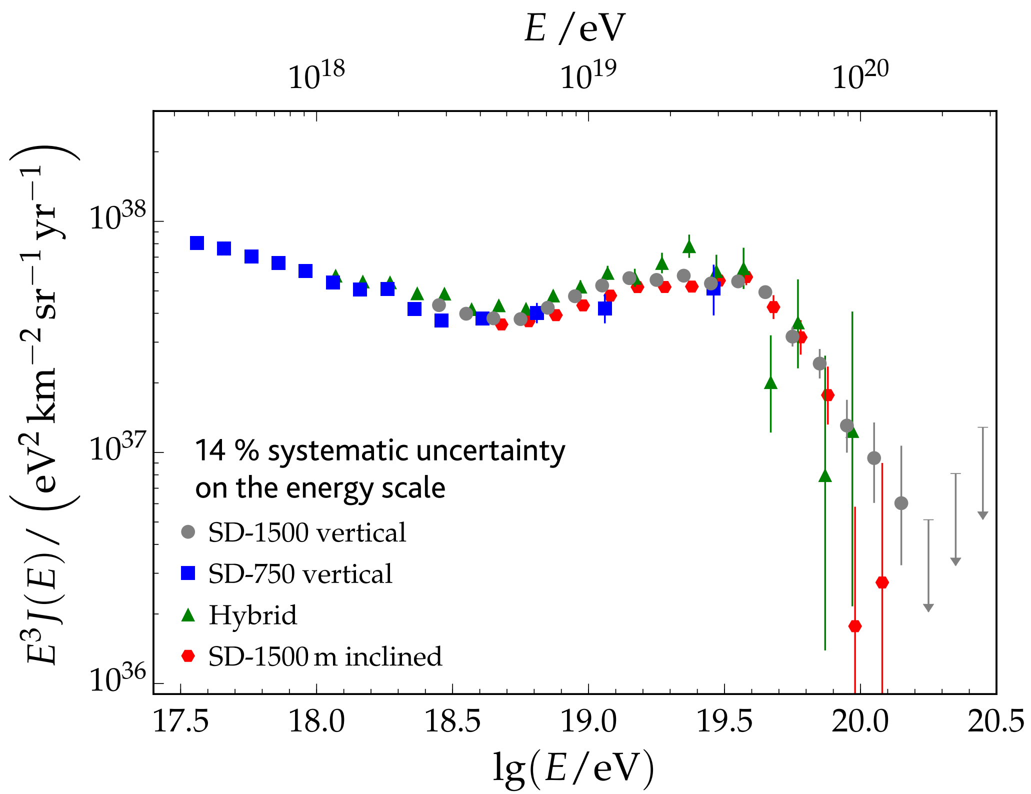
- **Precise reconstruction of the energy spectrum of UHECRs** over three decades in energy
  - **4 datasets**: FD (Hybrid), SD 750 m, SD 1500 m (0-60°), SD 1500 m (60-80°)
  - ~300.000 events, ~70.000 km^2 sr yr exposure, -90°…+45° covered in δ

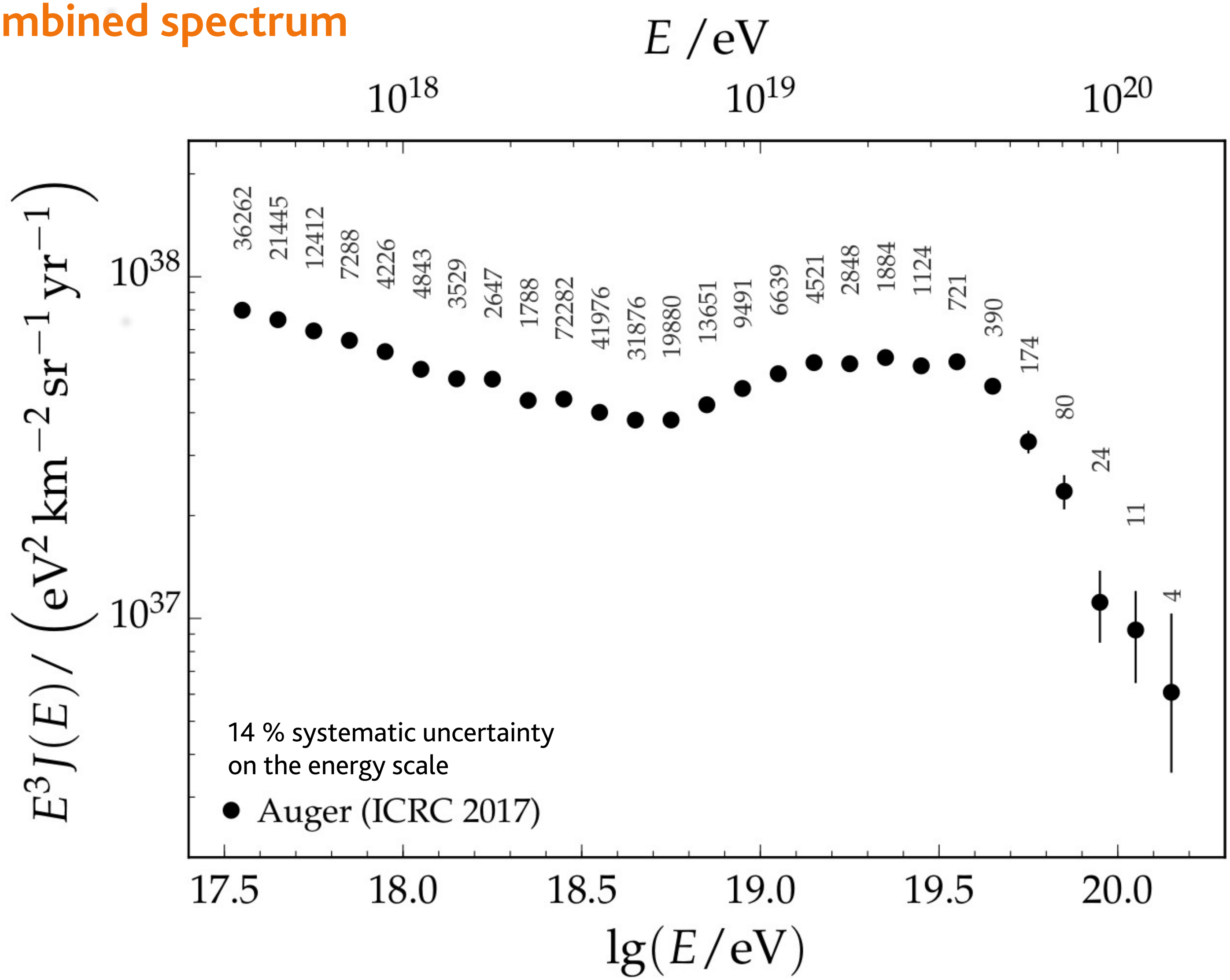


  - Good agreement of the individual spectra within the uncertainties: $\longrightarrow$ **Combined spectrum**

[F. Fenu for the Pierre Auger Collaboration, PoS(ICRC2017)486]

Energy spectrum (II)

- **Combined spectrum**



[F. Fenu for the Pierre Auger Collaboration, PoS(ICRC2017)486]

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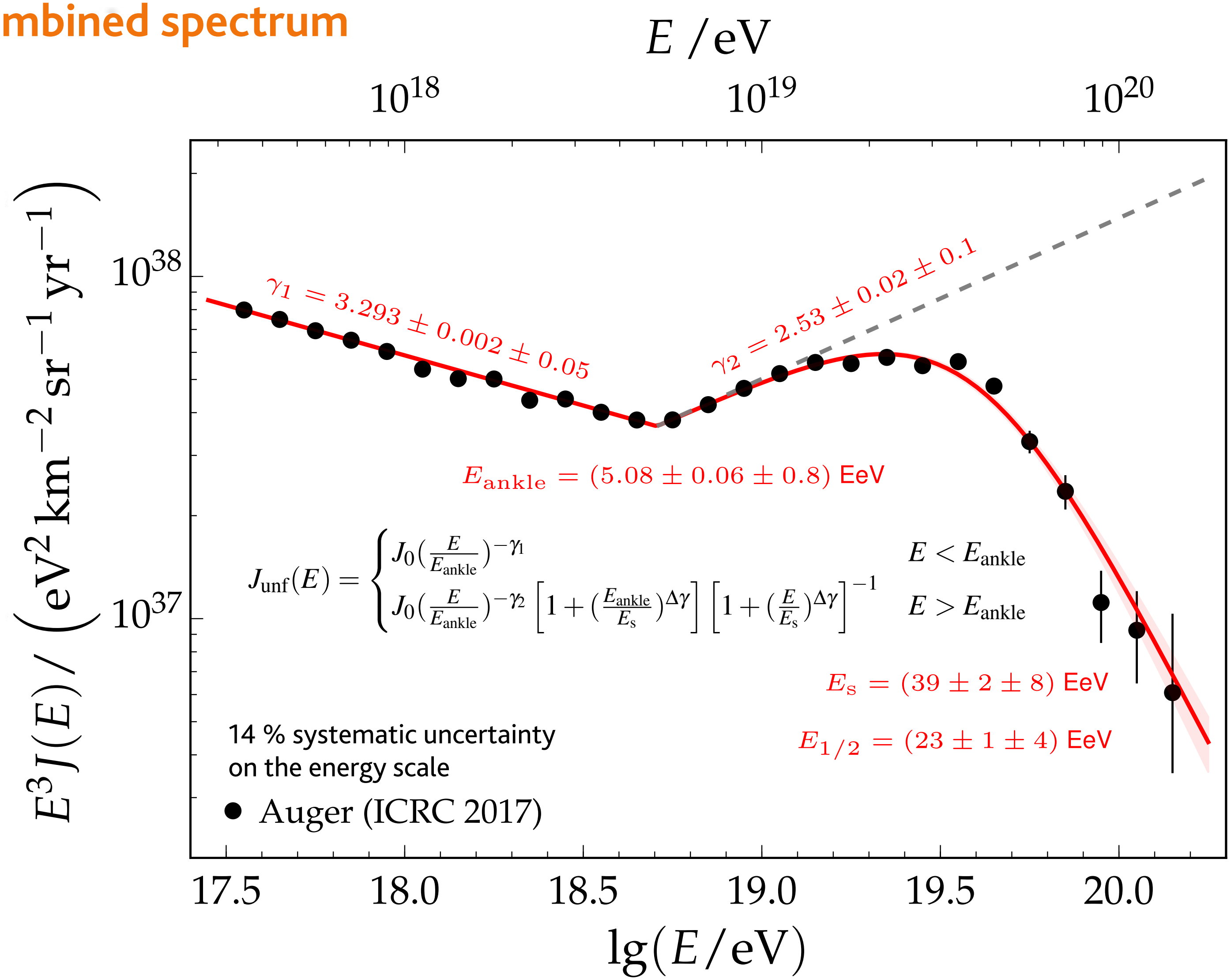
- **Combined spectrum**



[F. Fenu for the Pierre Auger Collaboration, PoS(ICRC2017)486]

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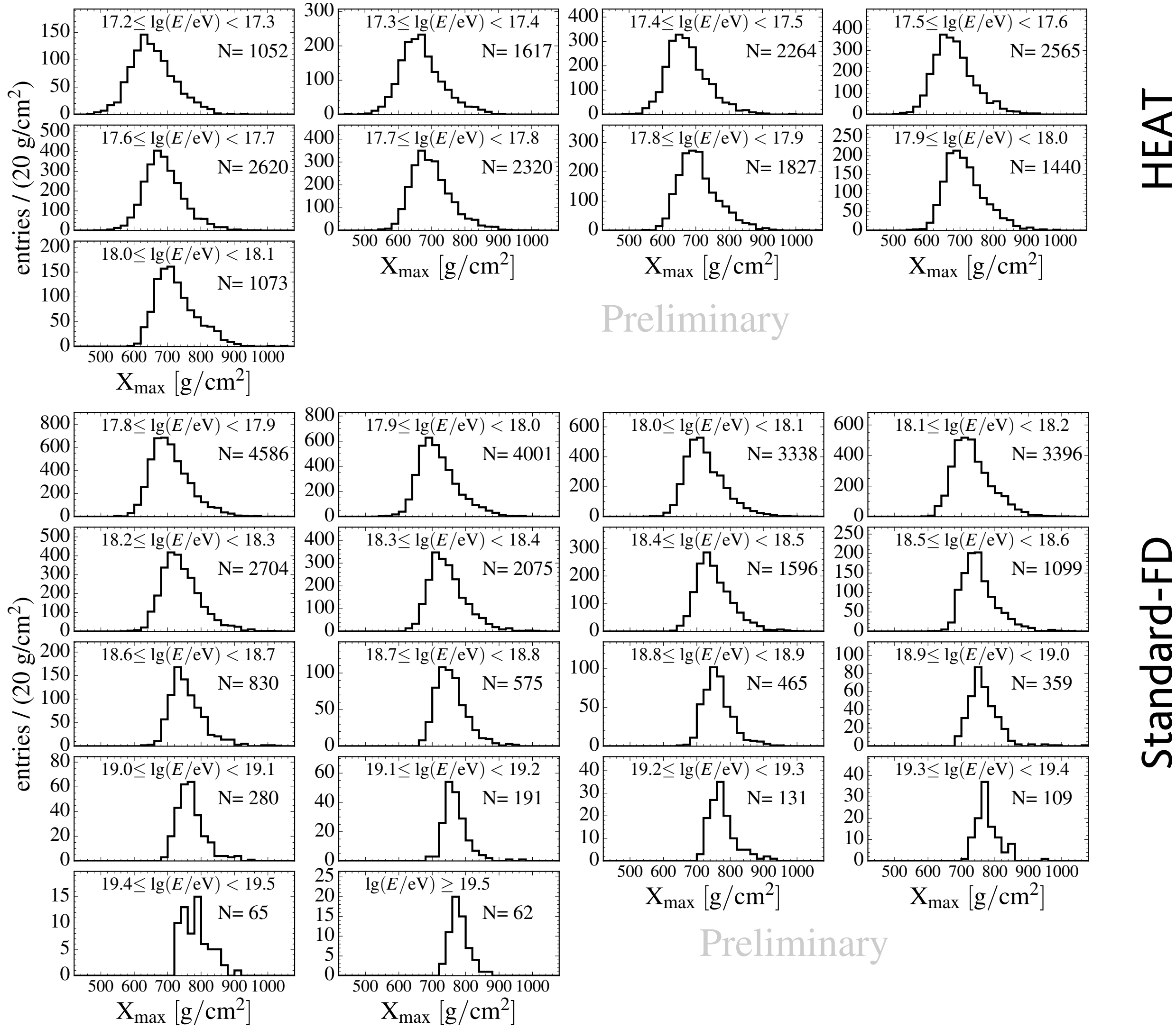
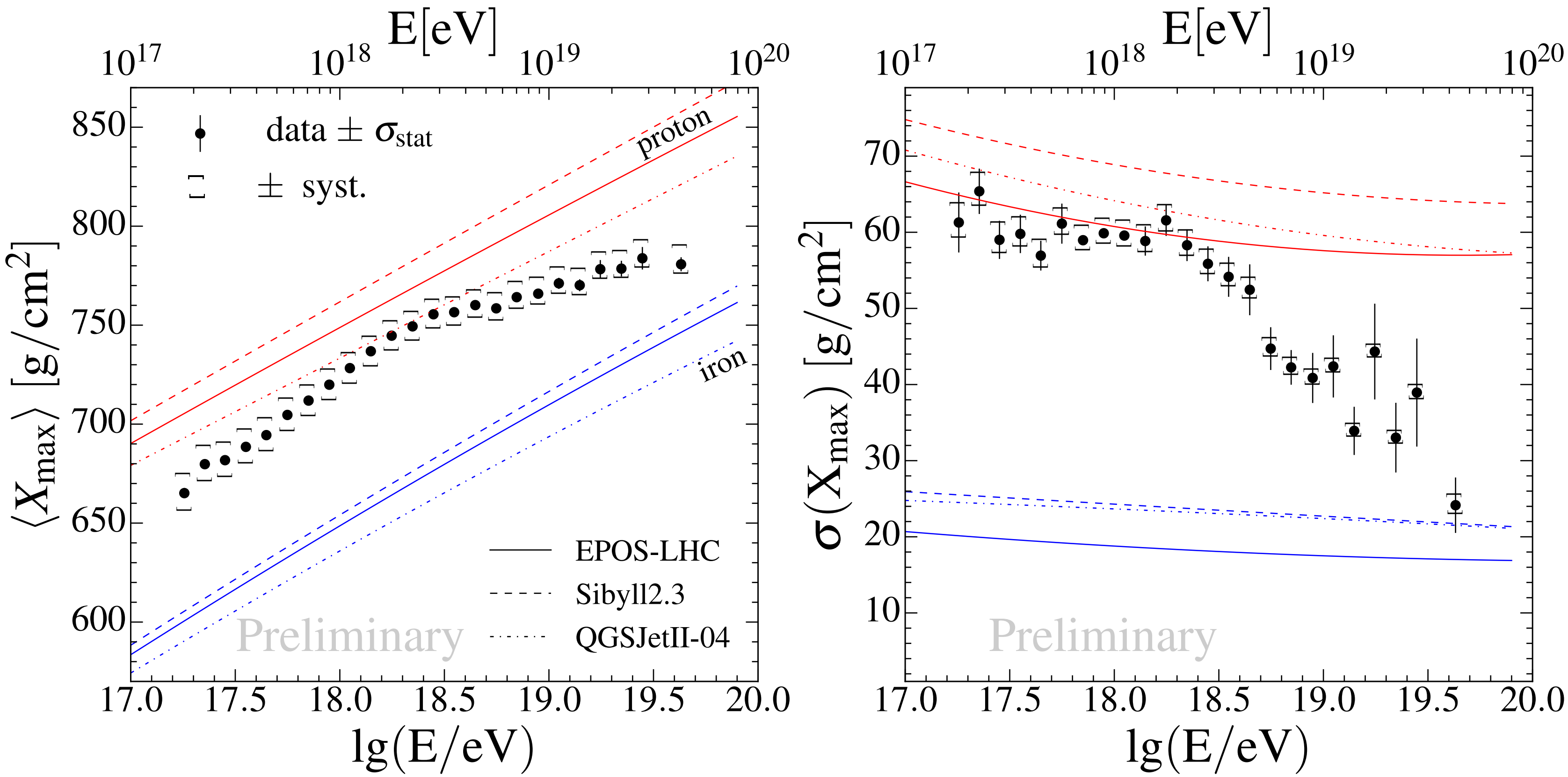
- Combine Standard-FD and HEAT to obtain **unbiased X_{max} distributions**



[J. Bellido for the Pierre Auger Collaboration, PoS(ICRC2017)506]

Composition: $\langle X_{max} \rangle$ and $\sigma(X_{max})$

- Determine **$\langle X_{max} \rangle$ and $\sigma(X_{max})$** from the unbiased distributions



- **Elongation rate** (79 ± 1) g cm^{-2} decade^{-1} below ~$10^{18.3}$ eV, (26 ± 2) g cm^{-2} decade^{-1} above
  - ~60 g cm^{-2} decade^{-1} expected for constant composition

[J. Bellido for the Pierre Auger Collaboration, PoS(ICRC2017)506]

Composition: $\langle \ln A \rangle$ and $\sigma^2(\ln A)$

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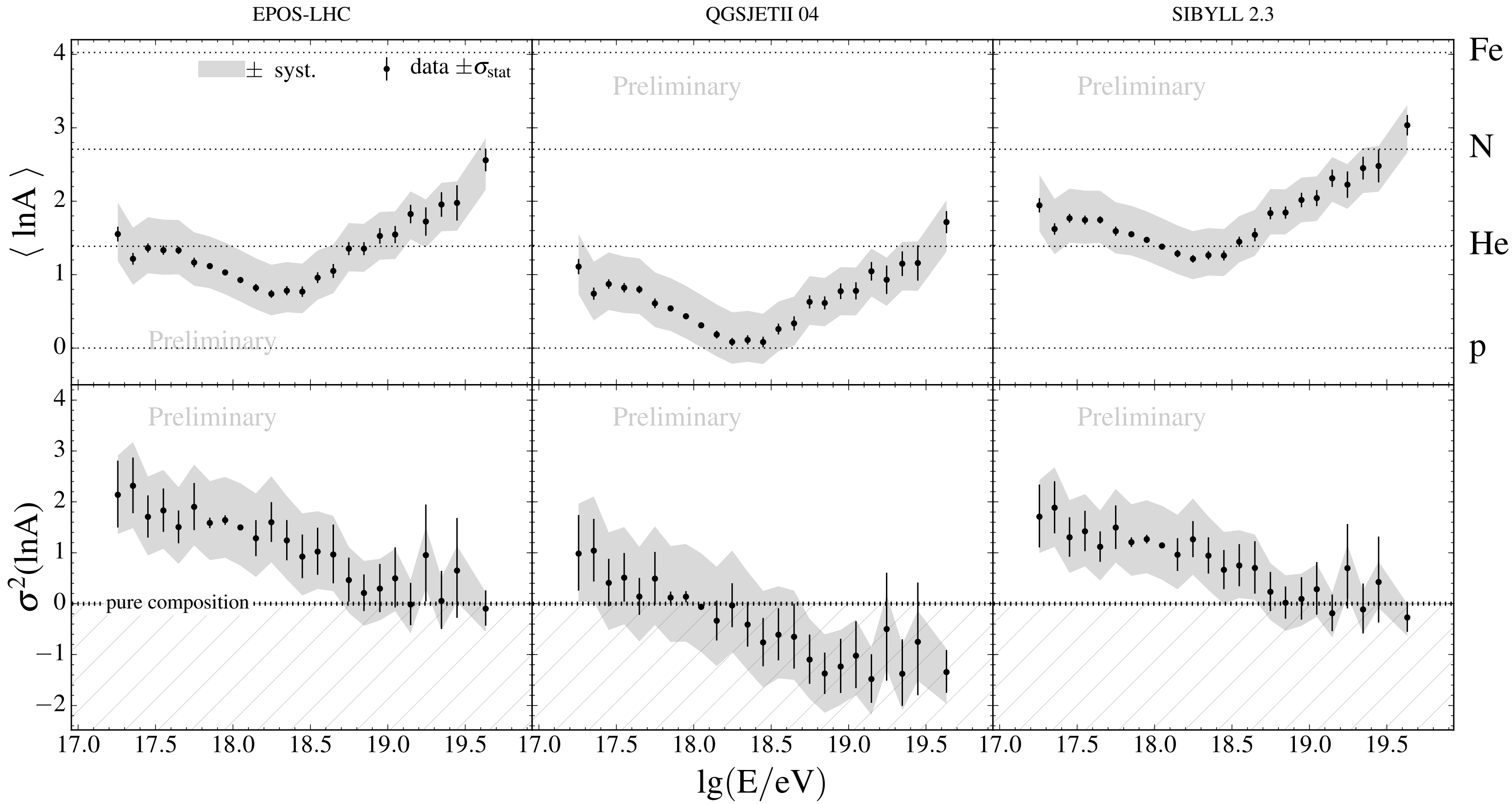
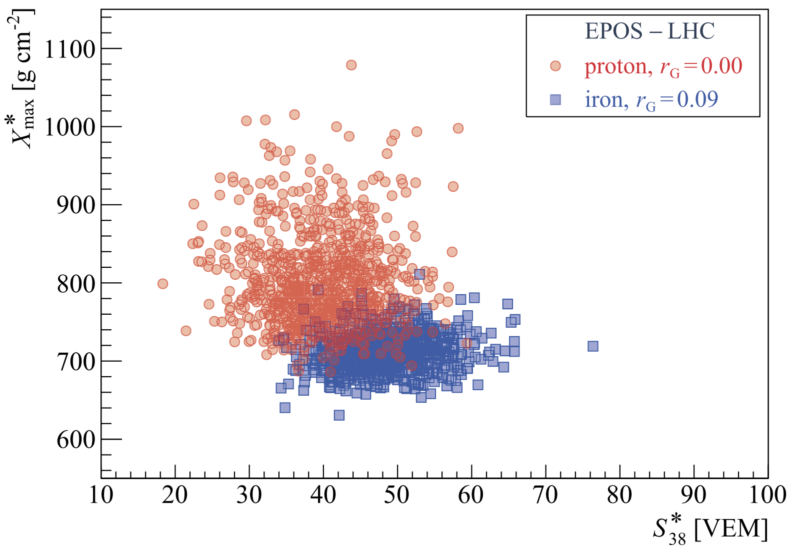
- Calculate **$\langle \ln A \rangle$ and $\sigma^2(\ln A)$** from $\langle X_{max} \rangle$ and $\sigma(X_{max})$ **using current hadronic interaction models**
  - **Same trend for all models:** composition gets lighter until ~$10^{18.3}$ eV, then heavier again

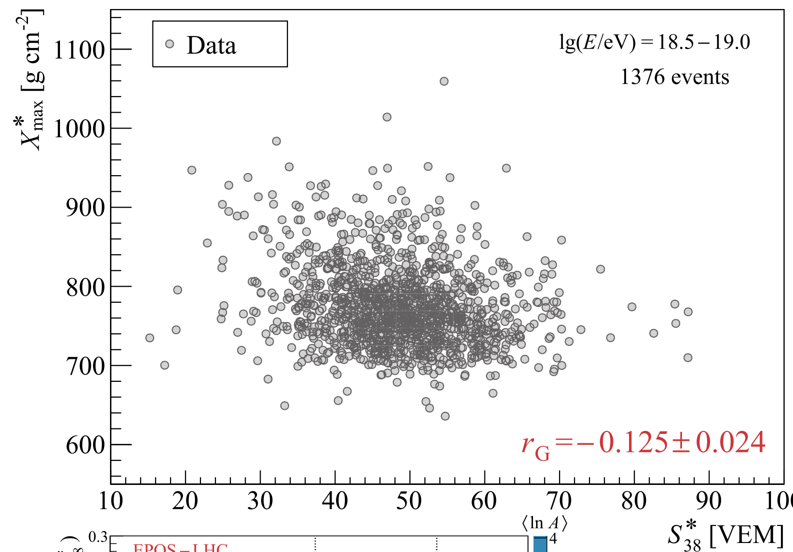


- Results also serve as a **test of the hadronic interaction models**

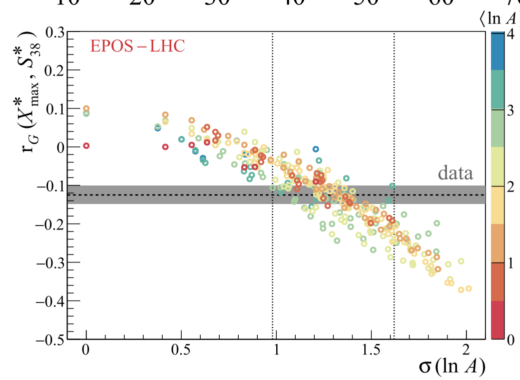
[J. Bellido for the Pierre Auger Collaboration, PoS(ICRC2017)506]

- Study the **correlation between X_{max} and S_{1000}** for $18.5 < \log_{10}(E\,[\mathrm{eV}]) < 19.0$
  - Correlation coefficient ~0: "pure" composition (e.g. 100 % p or 100% Fe)
  - Correlation coefficient < 0: mixed composition
  - Expectation **robust against uncertainties** in the hadronic interaction models





- **Data:** significantly negative correlation $\longrightarrow$ **mixed composition**
- Mixture of only protons and Helium **not sufficient** to explain the data, also **heavier nuclei** are necessary



[The Pierre Auger Collaboration, Phys. Lett. B 762 (2016) 288-295]

Search for UHE photons

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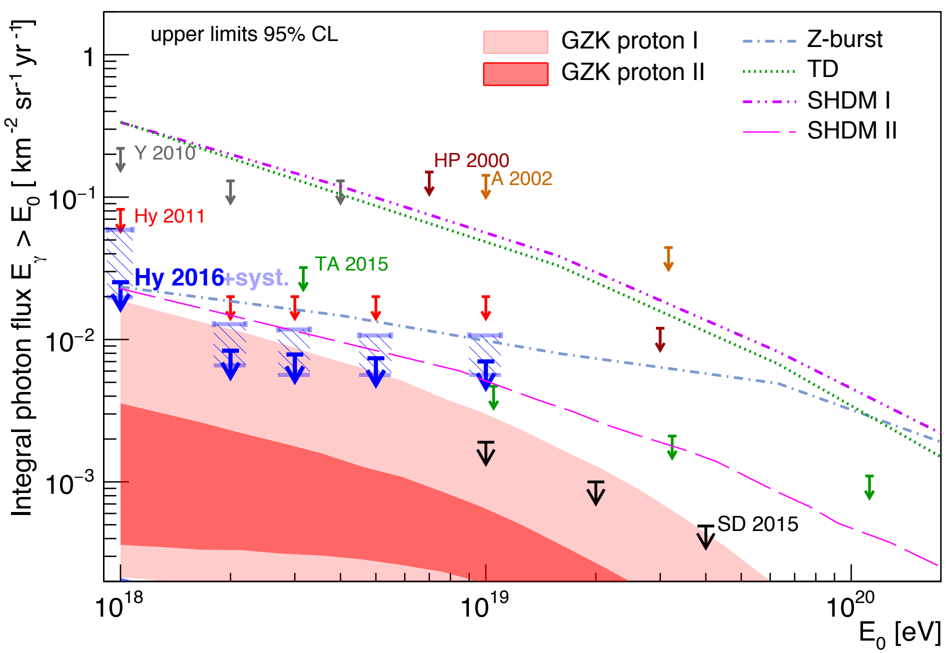
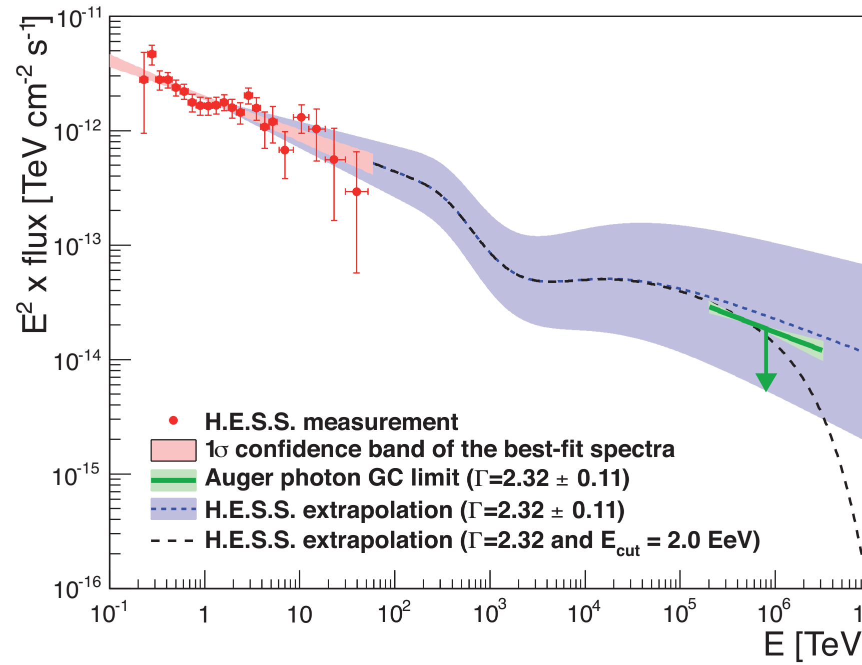
- **Stringent limits** on the diffuse flux of UHE photons
  - **Exotic models** strongly constrained
  - Predictions of some **cosmogenic models** are within reach
- **Targeted search** for sources of UHE photons
  - **No evidence for EeV photon emitters** in any of the studied source classes (e.g. pulsars, X-ray binaries…)
  - Connection to H.E.S.S. measurements of the **Galactic Center** in the TeV regime

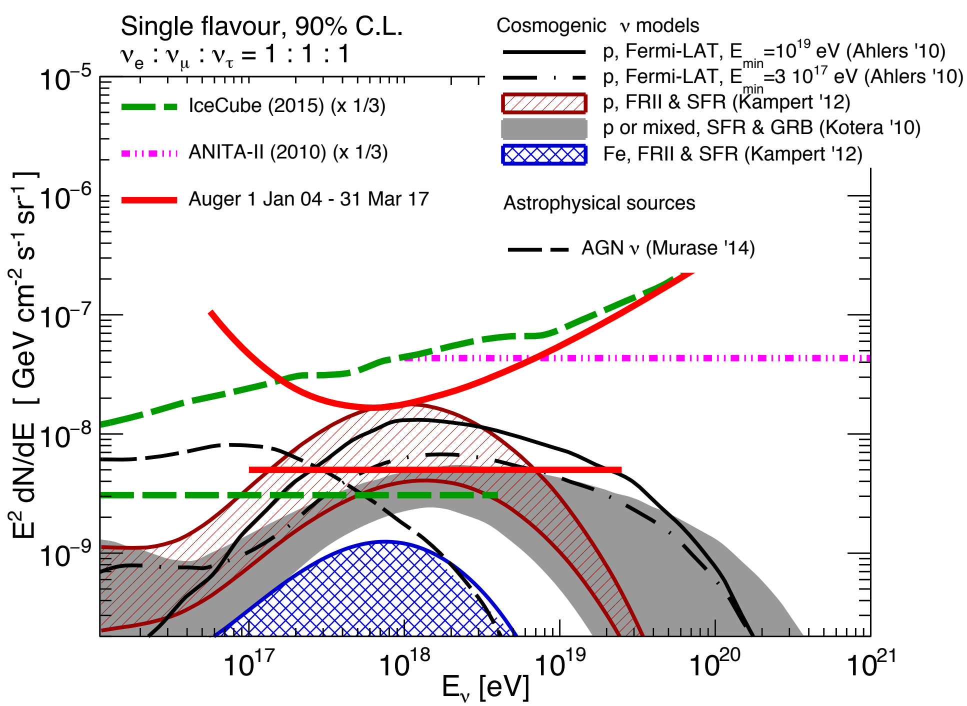




[The Pierre Auger Collaboration, JCAP 04 (2017) 009]
[The Pierre Auger Collaboration, ApJ 837 (2017) L25]

Search for UHE neutrinos

- Limits on the diffuse flux of UHE neutrinos allow for **constraints on cosmogenic neutrino source models**
  - Pure-proton models with strong source evolution are **excluded**

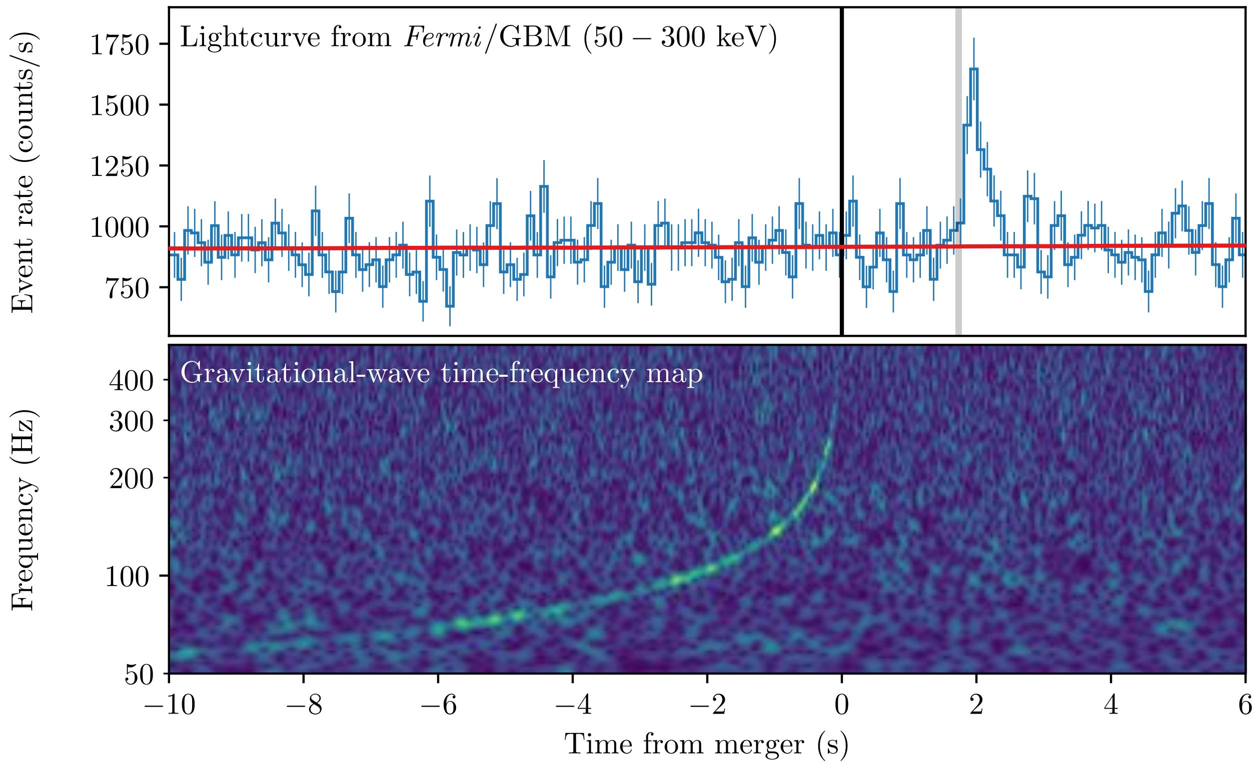


Diffuse flux neutrino model	Expected events (1 Jan 04 - 31 Mar 17)
Cosmogenic - proton - strong source evolution	
Cosmogenic - proton, FRII evol. (Kampert 2012)	$\sim$ 5.2
Cosmogenic - proton, FRII evol. (Kotera 2010)	$\sim$ 9.2
Cosmogenic - proton - moderate source evolution	
Cosmogenic - proton, SFR evol (Aloisio 2015)	$\sim$ 2.0
Cosmogenic - proton, SFR evol, $E_{\max} = 10^{21}$ eV (Kotera 2010)	$\sim$ 1.8
Cosmogenic - proton, SFR evol. (Kampert 2012)	$\sim$ 1.2
Cosmogenic - proton, GRB evol. (Kotera 2010)	$\sim$ 1.5
Cosmogenic - proton - normalized to Fermi-LAT GeV γ-rays	
Cosmogenic - proton, Fermi-LAT, $E_{\min} = 10^{19}$ eV (Ahlers 2010)	$\sim$ 4.0
Cosmogenic - proton, Fermi-LAT, $E_{\min} = 10^{17.5}$ eV (Ahlers 2010)	$\sim$ 2.1
Cosmogenic - mixed and iron	
Cosmogenic - mixed (Galactic) UHECR composition (Kotera 2010)	$\sim$ 0.7
Cosmogenic - iron, FRII (Kampert 2012)	$\sim$ 0.35
Astrophysical sources	
Astrophysical - radio-loud AGN (Murase 2014)	$\sim$ 2.6
Astrophysical - Pulsars - SFR evol. (Fang 2014)	$\sim$ 1.3

EXCLUDED (> 90% CL), **DISFAVORED** (85% < CL < 90%), **ALLOWED**

[E. Zas for the Pierre Auger Collaboration, PoS(ICRC2017)972]

- **Searches for neutrinos** in association with **gravitational wave events** detected by LIGO and Virgo
  - Discussed here: **GW170817** (binary neutron star merger)
  - 2 s later detection of a **gamma-ray burst** (GRB170817A) by Fermi GBM and INTEGRAL
  - **Follow-up observations** by many observatories and instruments; searches for associated neutrinos by **IceCube, Antares and Auger**



[Ligo Scientific and Virgo Collaborations, Fermi GBM, INTEGRAL, ApJL 848 (2017) L13]

Multimessenger astronomy (II)

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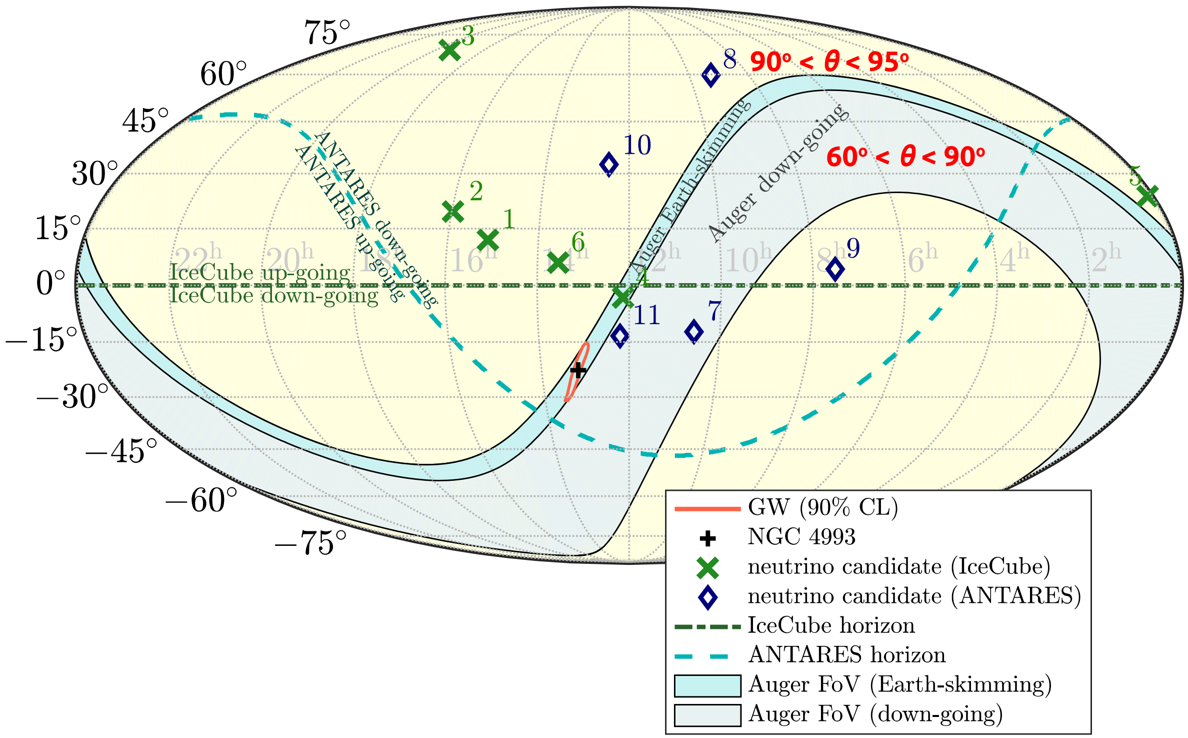
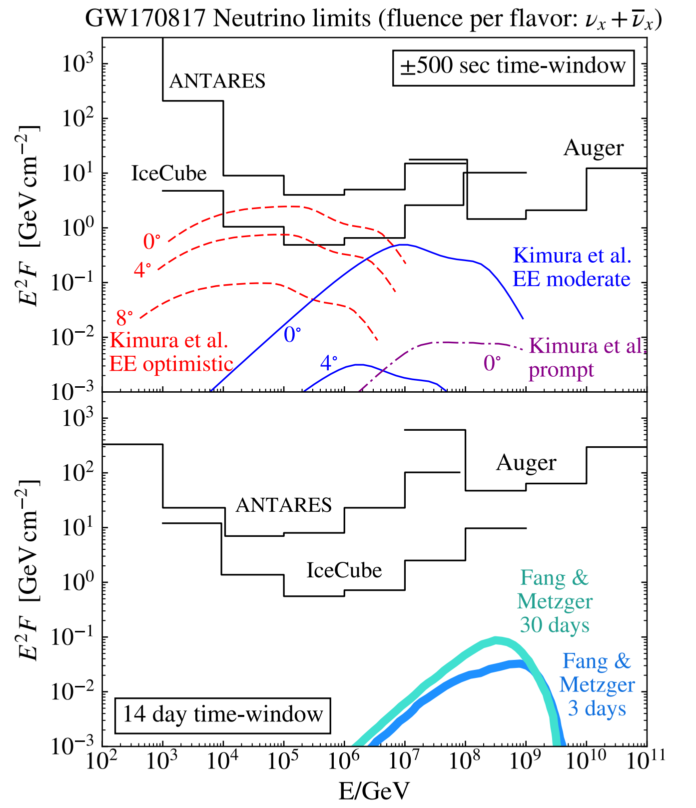
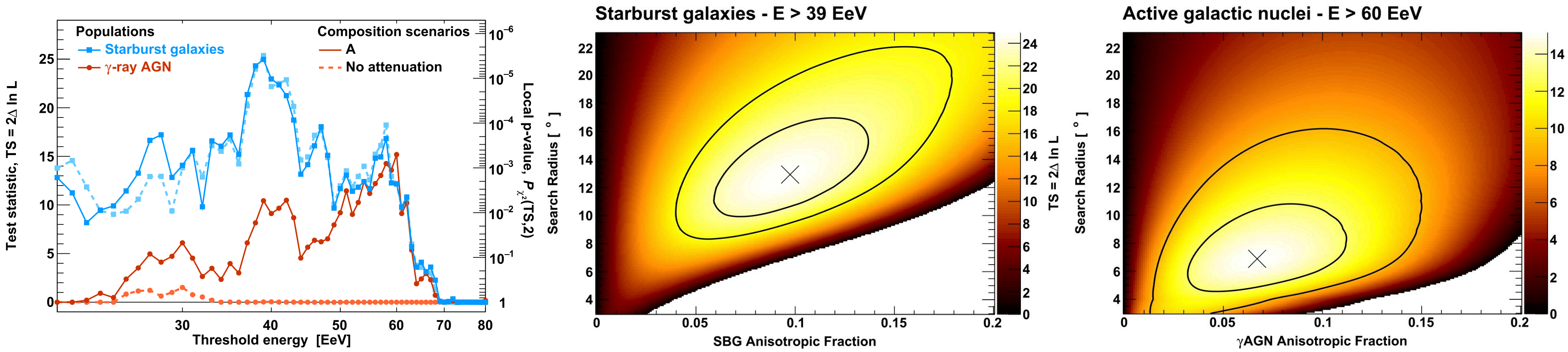




[Antares, IceCube, Pierre Auger, Ligo Scientific and Virgo Collaborations, ApJL 850 (2017) L35]

Intermediate-scale anisotropy (I)

- Compare the **arrival directions of UHECRs** with the expected flux pattern from two catalogs of extragalactic γ-ray emitters
  - γ-ray-detected **Active Galactic Nuclei (γAGN)** from the 2FHL catalog, 17 radio-loud objects within 250 Mpc (mainly BL-Lac-type blazars and FR-I-type radio galaxies), use $\Phi(>50\,\mathrm{GeV})$ as proxy for the UHECR flux
  - **Starburst Galaxies (SBG)** from a Fermi-LAT search list, select the 23 brightest objects within 250 Mpc, use $\Phi(>1.4\,\mathrm{GHz})$ as proxy for the UHECR flux
- **Likelihood ratio analysis** as test statistics for deviation from isotropy
  - **2 free parameters**: search radius ψ, anisotropic fraction f
  - **Null hypothesis**: isotropy; **hypothesis** under test: $(1\text{-}f) \times$ isotropy $+ f \times$ flux map from catalog



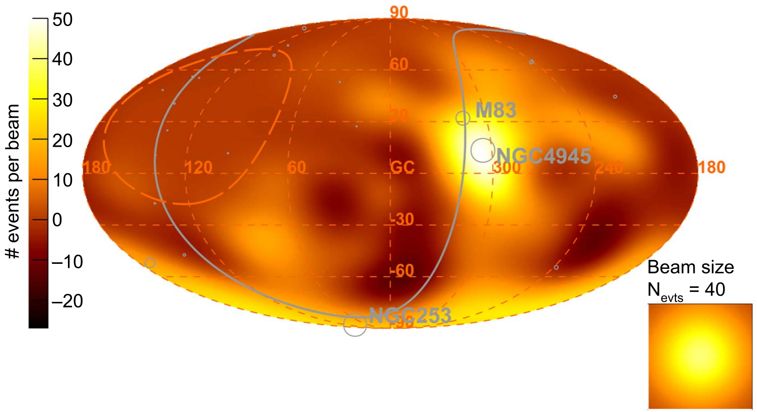
Post-trial probability (SBG): 3.6×10^{-5} (4.0σ)

Post-trial probability (γAGN): 3.1×10^{-3} (2.7σ)

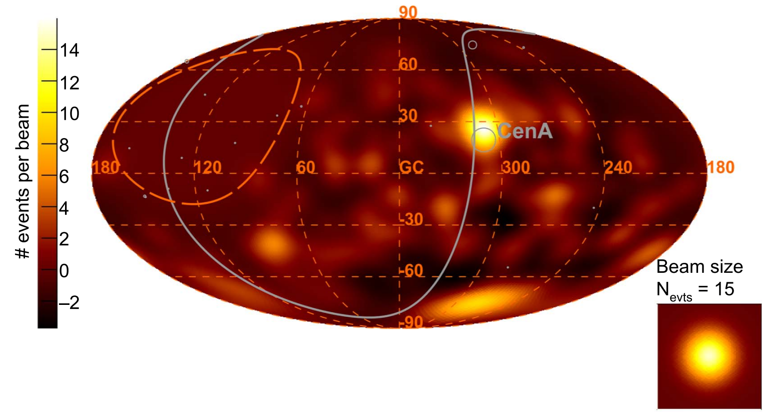
Intermediate-scale anisotropy (II)

- Isotropy at intermediate angular scales **disfavored** at the 4σ level for the comparison with the SBG catalog
- Results indicative of an excess of events from **strong, nearby sources**

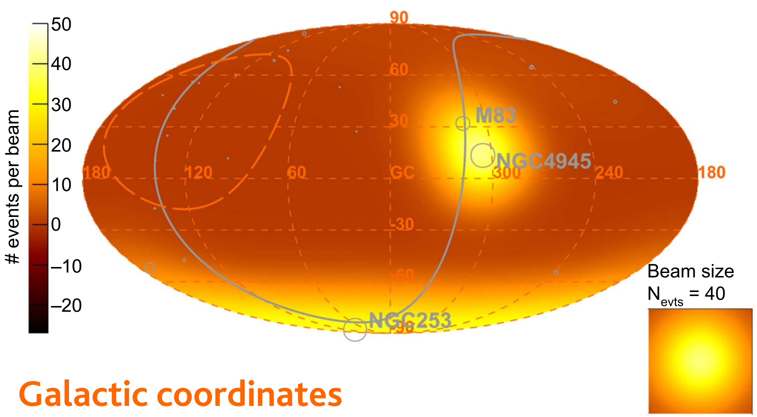
Observed Excess Map - E > 39 Eev



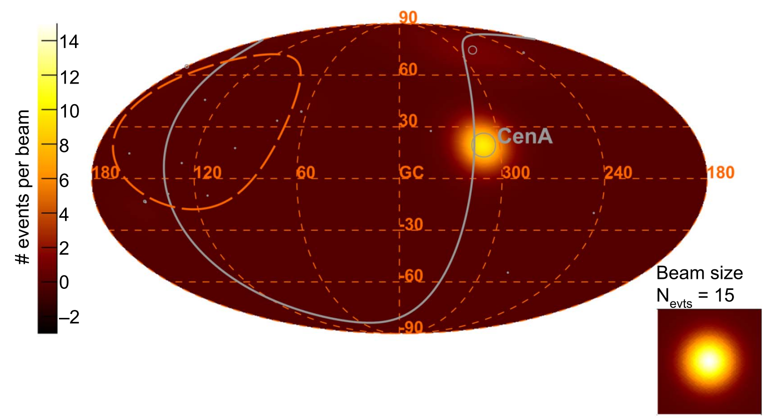
Observed Excess Map - E > 60 Eev



Model Excess Map - Starburst galaxies - E > 39 EeV



Model Excess Map - Active galactic nuclei - E > 60 EeV



Galactic coordinates

Large-scale anisotropy (I)

- Rayleigh analysis of the first harmonic in right ascension α
  - ~114,000 events with $E > 4$ EeV and $\theta < 80°$, declination range $-90° < \delta < 45°$ (85 % sky coverage); 2 energy bins (4-8 EeV, > 8 EeV)

$$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos \alpha_i$$

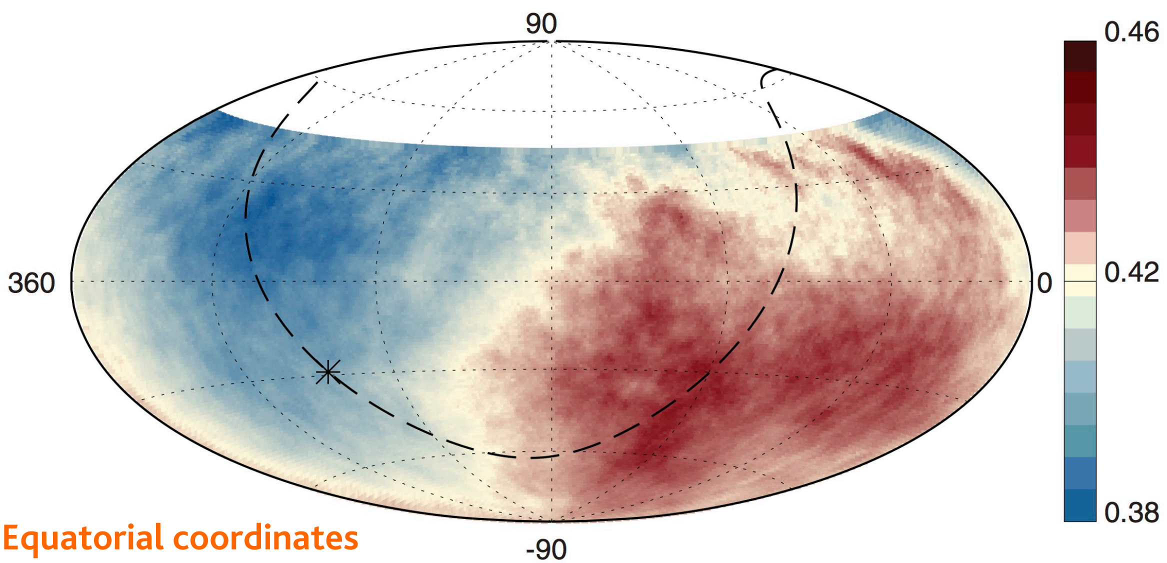
$$b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin \alpha_i$$

Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

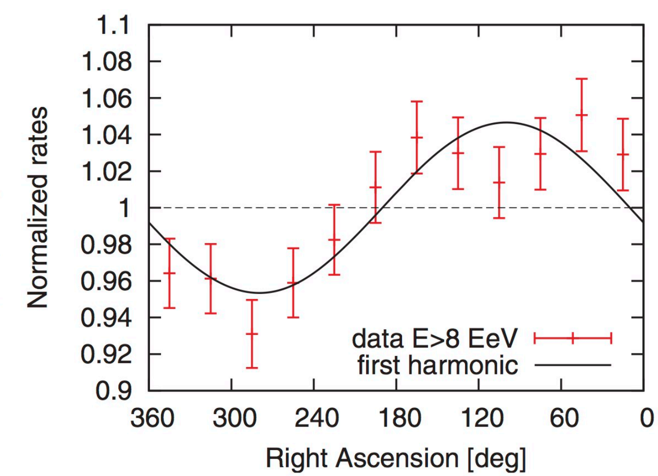
$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}$$

$$\tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$

  - Above 8 EeV: significant modulation at a level of 5.2σ (5.6σ before penalization)



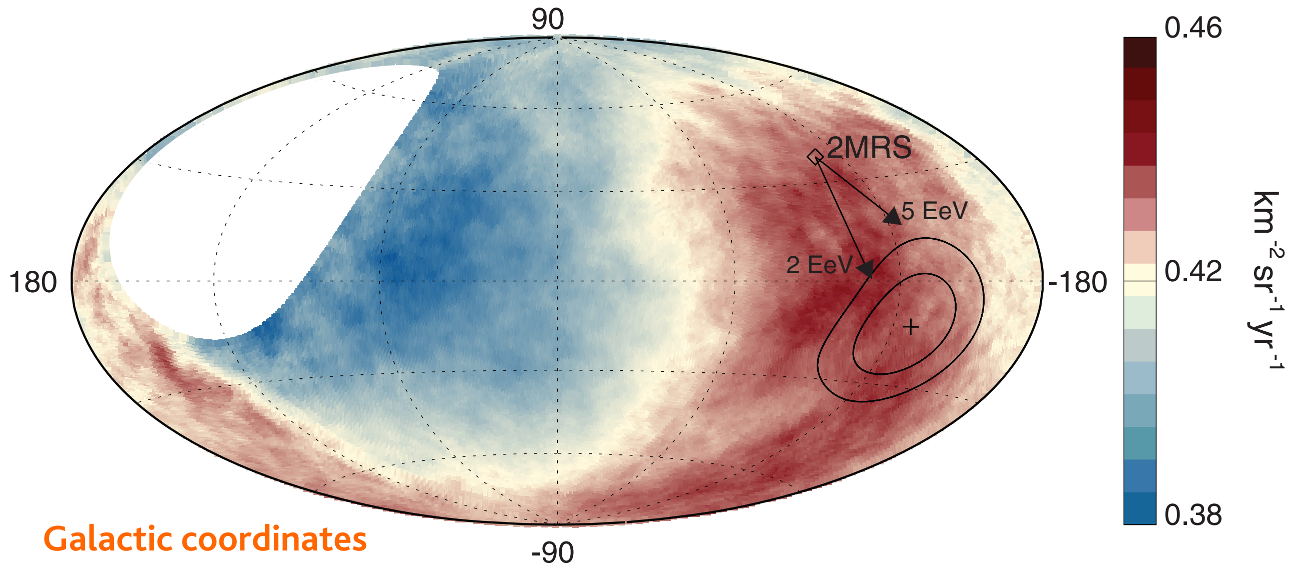
Equatorial coordinates



[The Pierre Auger Collaboration, Science 357 (2017) 1266]

- Reconstruction of the **dipole structure:**

Energy (EeV)	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d (°)	Dipole right ascension α_d (°)
≥8	−0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10



Galactic coordinates

- Dipole structure is **expected** if cosmic rays diffuse to the Galaxy from sources distributed similar to **nearby galaxies** (take e.g. the **2MRS catalog**)
  - Deflection of the dipole pattern due to the **Galactic magnetic field**
- Strong indication for an **extragalactic origin** of UHECR above 8 EeV

[The Pierre Auger Collaboration, Science 357 (2017) 1266]

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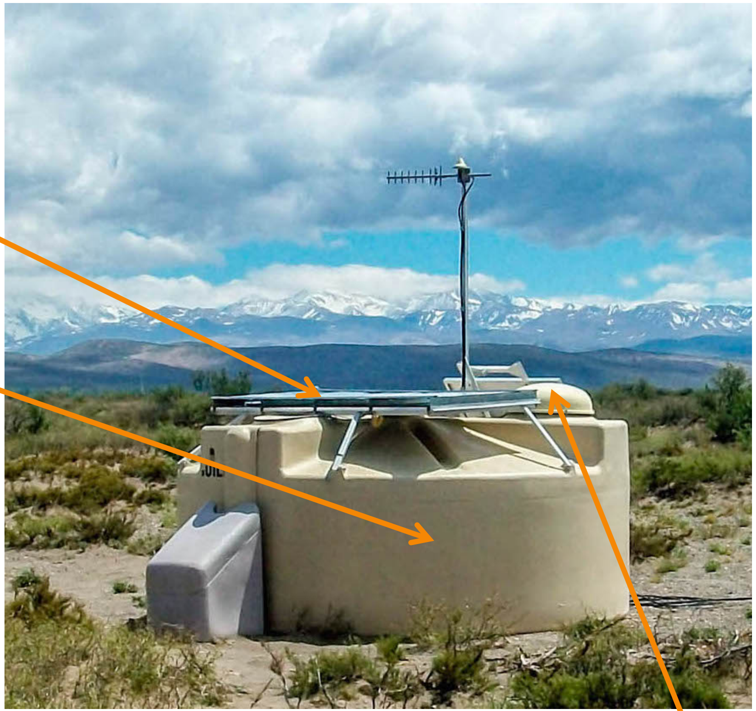
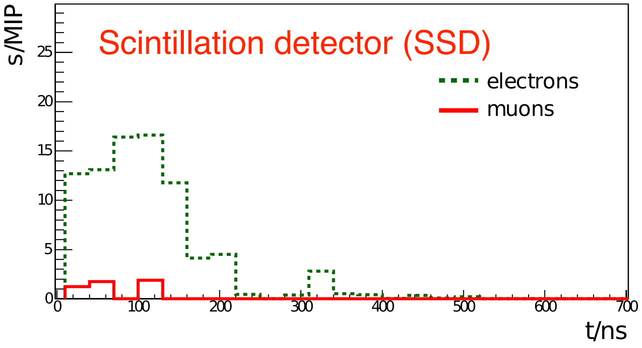
Motivation for AugerPrime

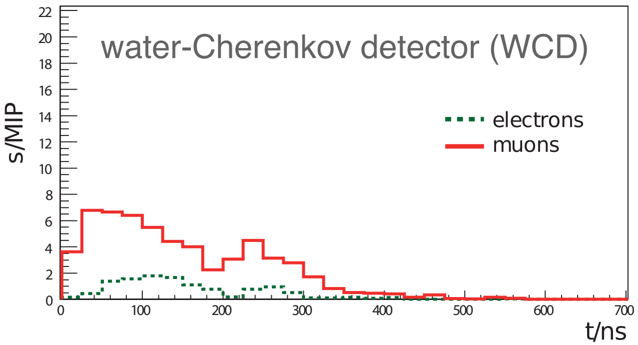
- **Complex and unexpected picture of UHECR** is emerging from the data
  - **Suppression of the flux** of cosmic rays at the highest energies firmly established, …**but** the origin of the suppression **not yet clear** (propagation effect? maximum energy at the source? both?)
  - $\langle X_{max} \rangle$ data indicate a **light (and mixed) composition** around the ankle and a **heavier composition** towards the highest energies, …**but** the detailed interpretation of the data is currently limited by uncertainties in the **hadronic interaction models**
  - We start seeing **anisotropies in the arrival directions** (observation of a large-scale dipole structure, indications for anisotropy at intermediate scales) ...**but** is there a **rigidity-dependence**?

- **Open questions** cannot be answered with only more statistics
  - An **upgraded detector** is needed, in particular an improved measurement of the muonic shower component to increase the **composition sensitivity**, with a duty cycle of ~100 % $\longrightarrow$ **AugerPrime**

- **Main part** of the upgrade: equip every water Cherenkov detector (WCD) with an **additional scintillation counter** (Scintillation Surface Detector, SSD)
    - Exploit the **different response** of the two detectors to the electromagnetic and muonic shower components to **disentangle** the components







- **Moreover:**
    - Extension of the **FD duty cycle**
    - Dedicated (buried) **muon counters** in the 750 m array for cross-checks (AMIGA)

[The Pierre Auger Collaboration, arXiv:1604.03637]

AugerPrime (II)

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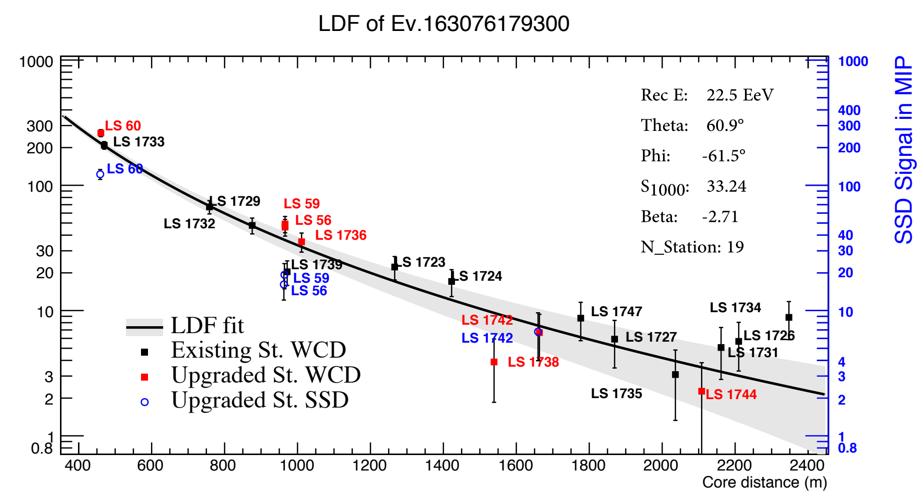
- September 2016: deployment of an **SSD Engineering Array** (12 stations)
  - Since then **data taking and first data analysis**
- 2018: **Design finalized and tested**, large-scale production of SSDs started
  - Deployment of the SSDs in the full SD array in 2018-2019
- **Data taking** until 2025 (exposure ~40.000 km^2 sr yr)

Deployment of 5-10 SSDs per day



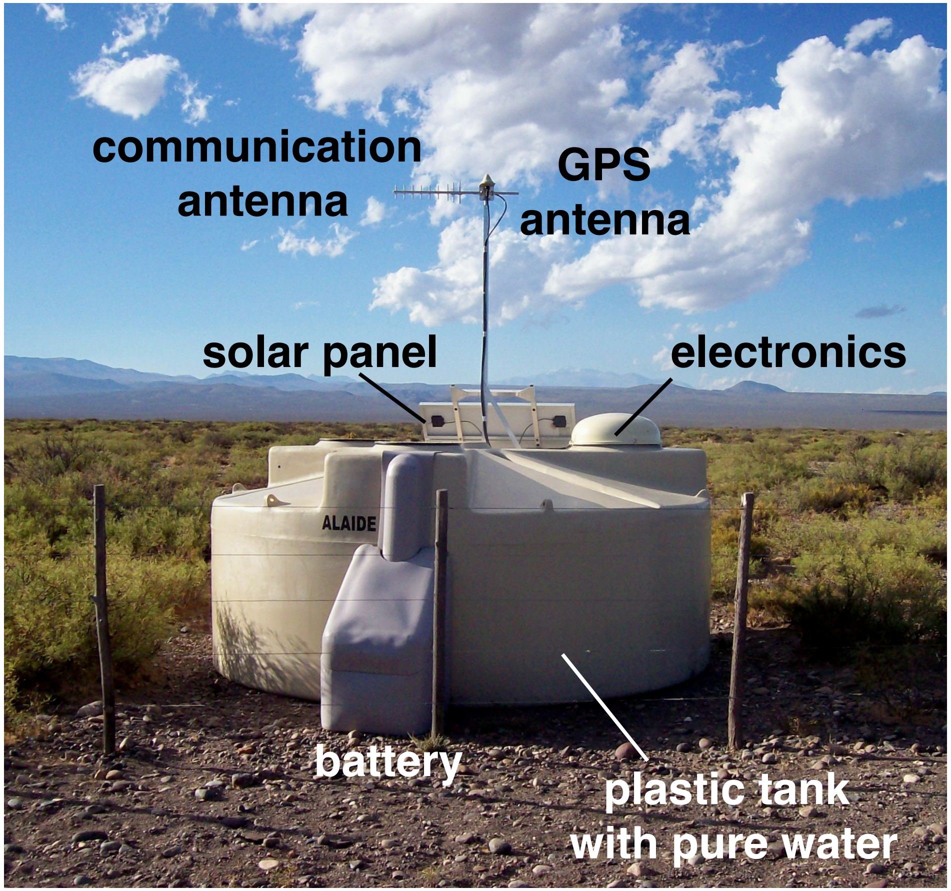
[The Pierre Auger Collaboration, arXiv:1604.03637]

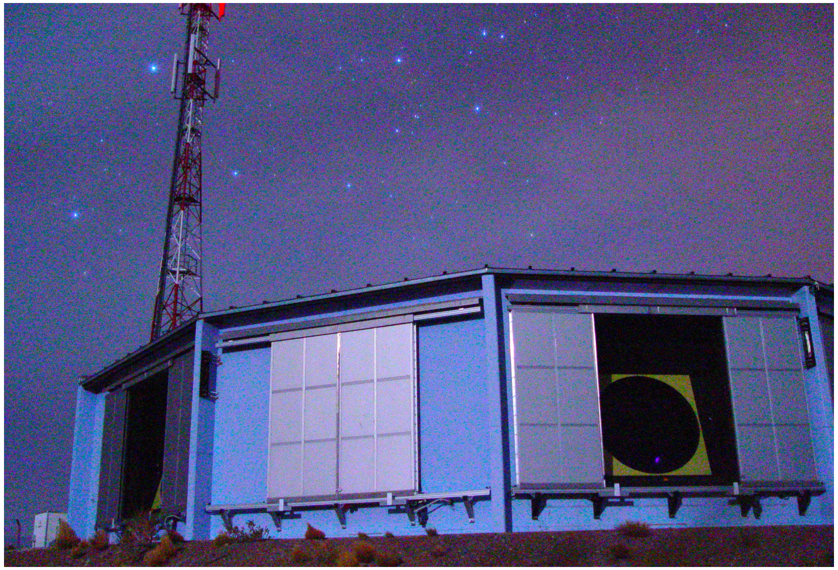
Summary

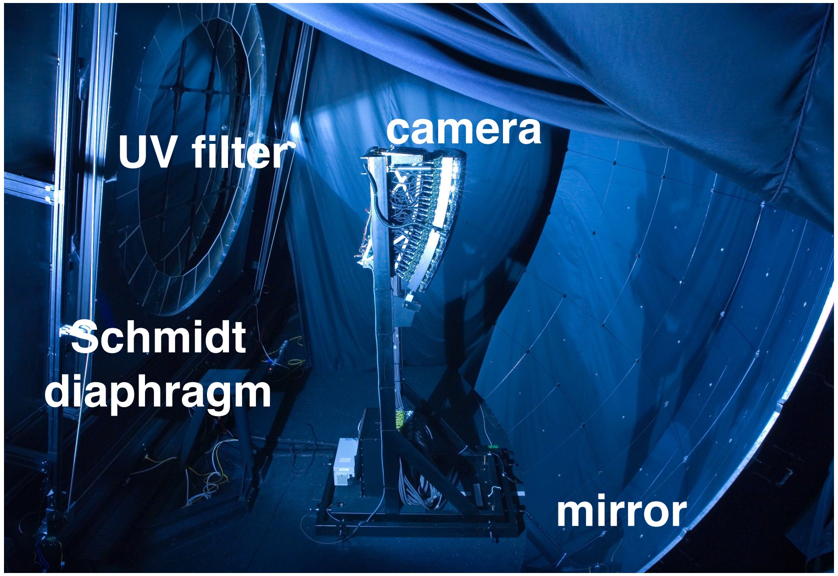
- The **Pierre Auger Observatory** has been successfully taking data since **almost 15 years**
- **Key results**
  - Precise measurement of the **energy spectrum** above ~10^{17} eV: flux suppression above 40 EeV firmly established
  - Composition: **measurements of $\langle X_{max} \rangle$** over 3 orders of magnitude in energy; evidence for a **mixed composition** around the ankle
  - Anisotropy: observation of a **dipole structure** above 8 EeV, indications of an **intermediate-scale anisotropy**
  - ….and **a lot more**!
- Results led to **new (and unexpected) questions** about UHECR
  - To answer them, an **extensive upgrade program (AugerPrime)** has been started
  - **Exciting times ahead!**

Backup

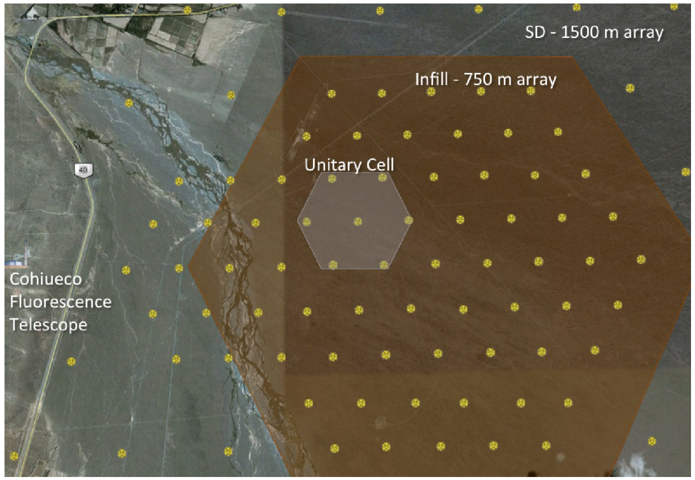
SD and FD

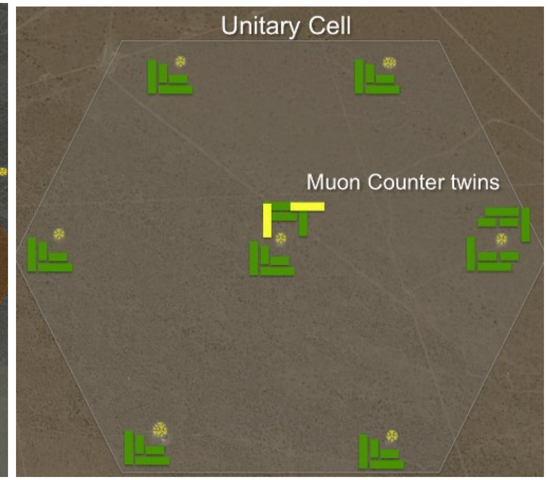


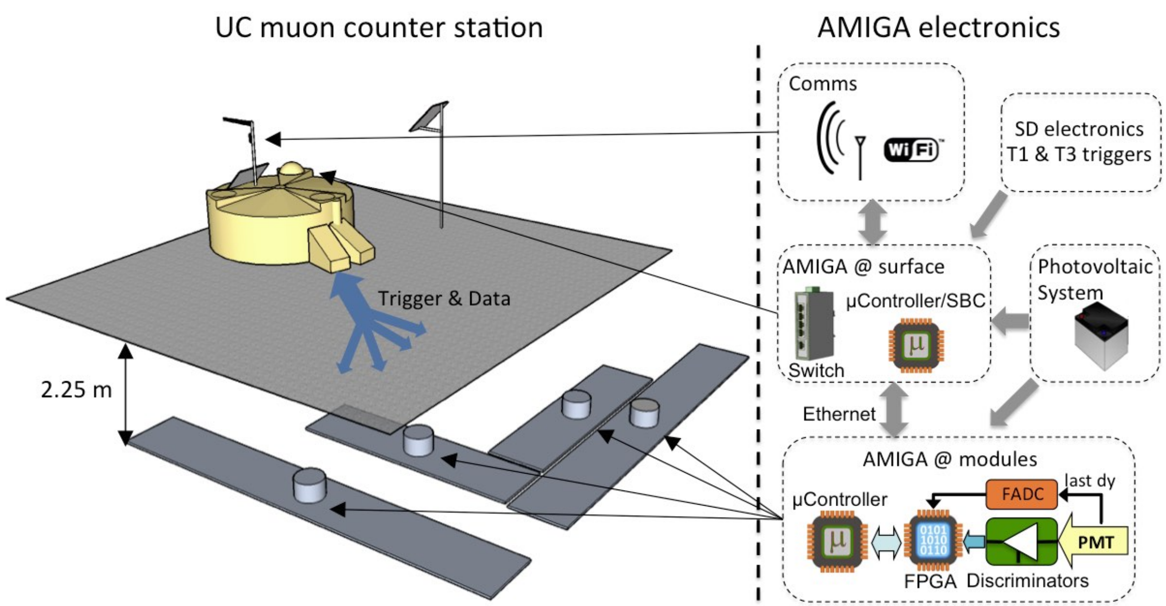




[C. Peters]







[The Pierre Auger Collaboration, JINST 11 (2016) P02012]

Atmospheric monitoring

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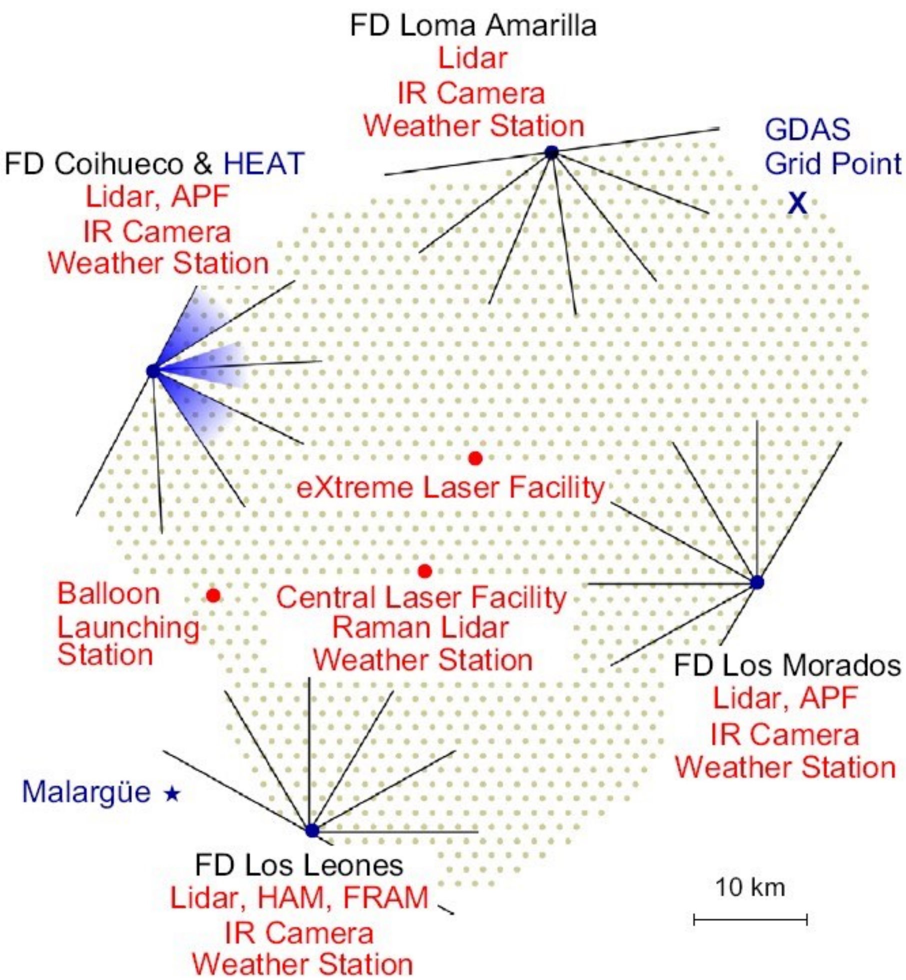
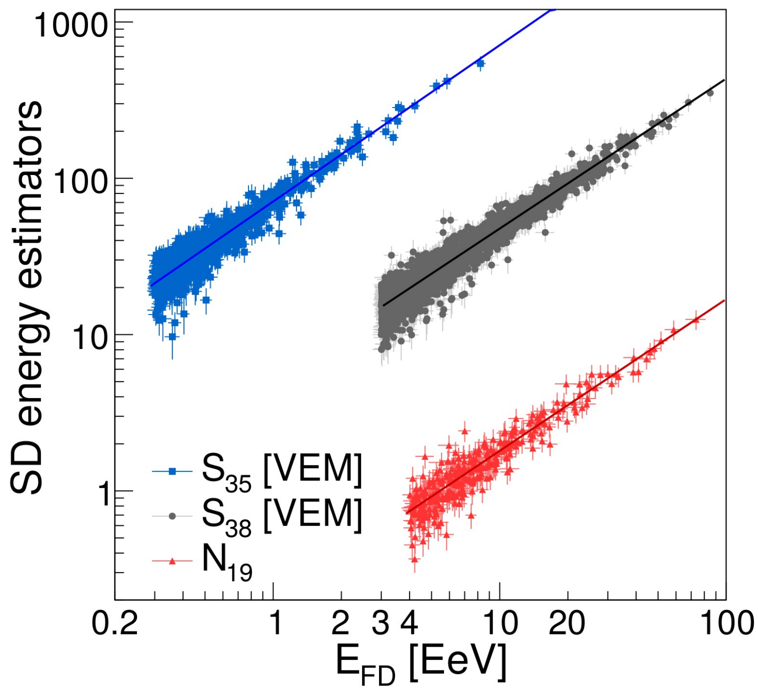


[C. Peters]

Energy calibration

	SD 1500 < 60°	SD 1500 > 60°	SD 750	Hybrid
Data taking period	Jan. 2004 – Dec. 2016	Jan. 2004 – Dec. 2016	Aug. 2008 – Dec. 2016	Jan. 2007 – Dec 2015
Exposure [km^2 sr yr]	51,588	15,121	228	1946 @10^{19} eV
Number of events	183,332	19,602	87,402	11,680
Zenith angle range [deg.]	0–60	60–80	0–55	0–60
Energy threshold [eV]	3×10^{18}	4×10^{18}	3×10^{17}	10^{18}
Calibration parameters				
Number of events	2661	312	1276	
A [eV]	$(1.78 \pm 0.03) \times 10^{17}$	$(5.45 \pm 0.08) \times 10^{18}$	$(1.4 \pm 0.04) \times 10^{16}$	
B	1.042 ± 0.005	1.030 ± 0.018	1.000 ± 0.008	
Energy resolution [%]	15	17	13	



$$E_{FD} = A\,\hat{S}^B$$

$$\hat{S} = S_{38}, S_{35}, N_{19}$$

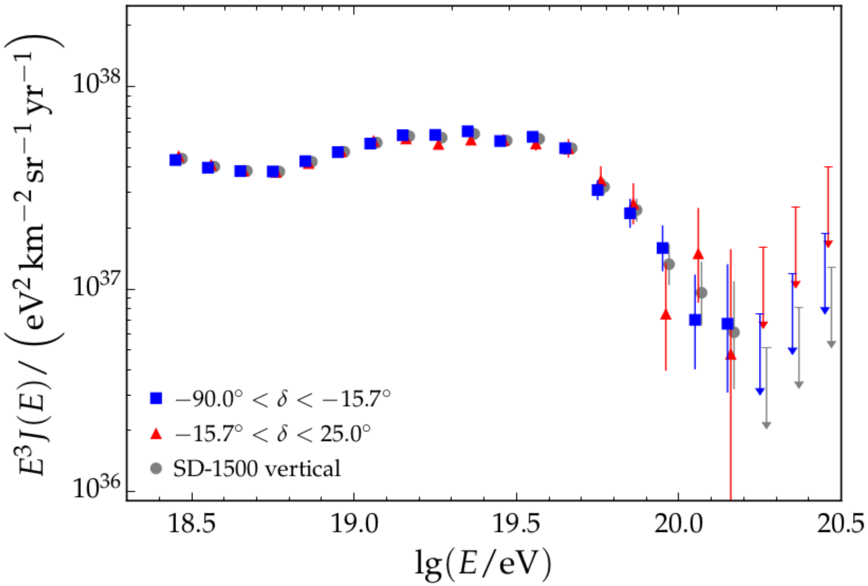
[F. Fenu for the Pierre Auger Collaboration, PoS(ICRC2017)486]

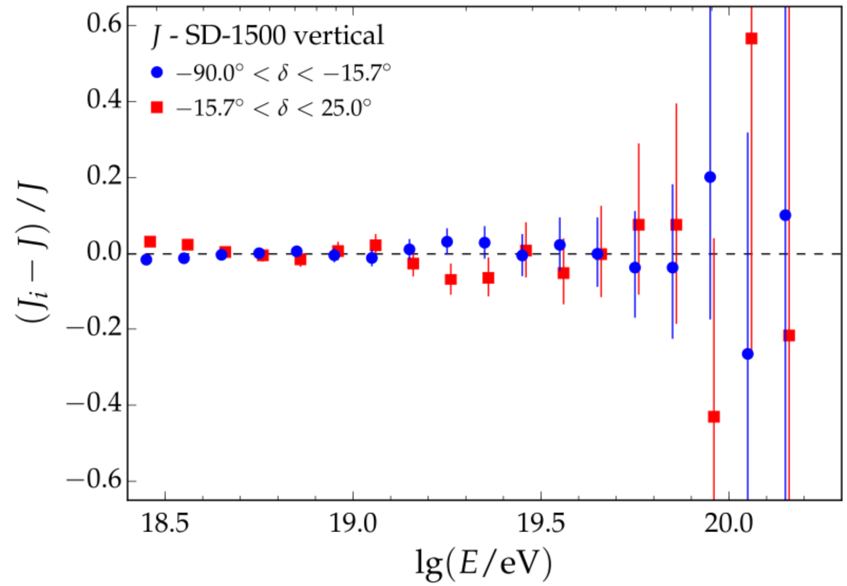
Energy scale uncertainties

Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere - sec. 3)	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration - sec. 4)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec. - sec. 5)	**6.5% ÷5.6%**
Invisible energy (sec. 6)	**3%÷1.5%**
Stat. error of the SD calib. fit (sec. 7)	**0.7%÷1.8%**
Stability of the energy scale (sec. 7)	**5%**
Total	**14%**

[V. Verzi for the Pierre Auger Collaboration, ICRC 2013]

Declination dependence





[F. Fenu for the Pierre Auger Collaboration, PoS(ICRC2017)486]

X_{max} resolution and systematics

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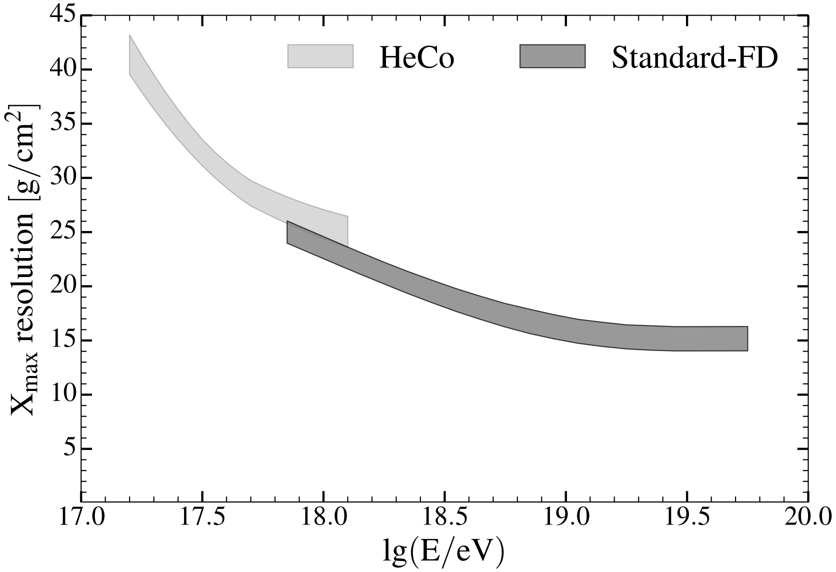
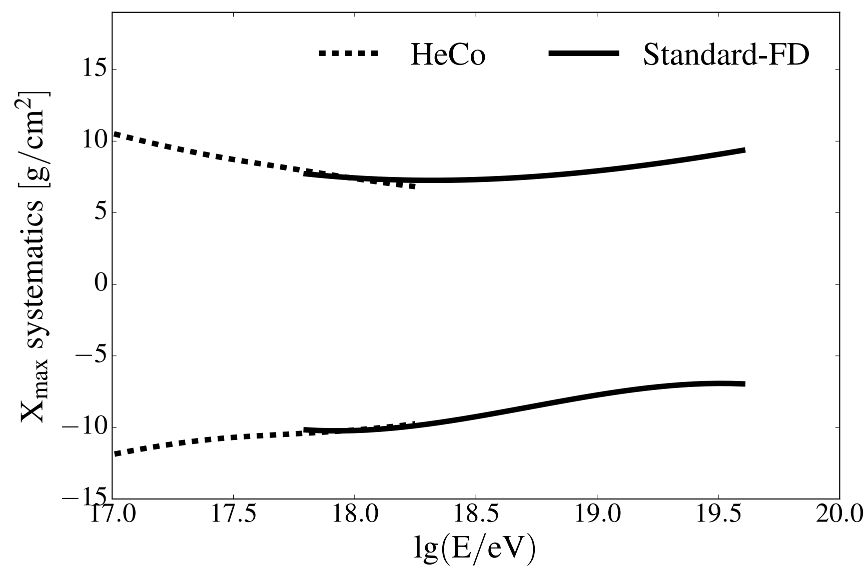
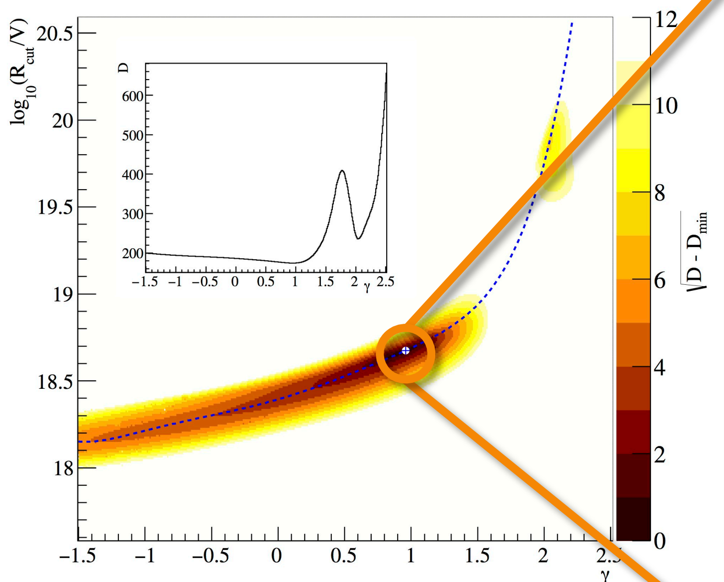




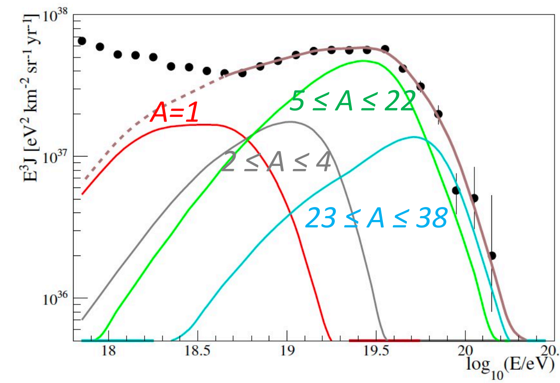
[J. Bellido for the Pierre Auger Collaboration, PoS(ICRC2017)506]

Combined fit

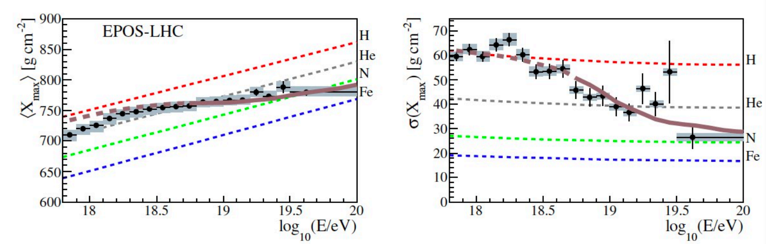
- **Simultaneous fit** of a simplified scenario to the spectrum and X_{max} data
  - **One-dimensional propagation**, homogeneous distribution of **identical sources** of protons, Helium, Nitrogen, Silicon and Iron
  - Injection spectrum at the source: **power law with cut-off in rigidity**
  - **Model dependence:** propagation code, cross-sections, EBL models…
  - **Reference model:** SimProp, PSB cross-sections, Gilmore 2012 EBL, EPOS LHC
  - **Scan** in the spectral index γ and the cut-off rigidity R_{cut} for the reference model



γ	$0.96^{+0.08}_{-0.13}$
$\log_{10}(R_{cut}/V)$	$18.68^{+0.02}_{-0.04}$
$f_H(\%)$	0.0
$f_{He}(\%)$	67.3
$f_N(\%)$	28.1
$f_{Si}(\%)$	4.6
$f_{Fe}(\%)$	0.0



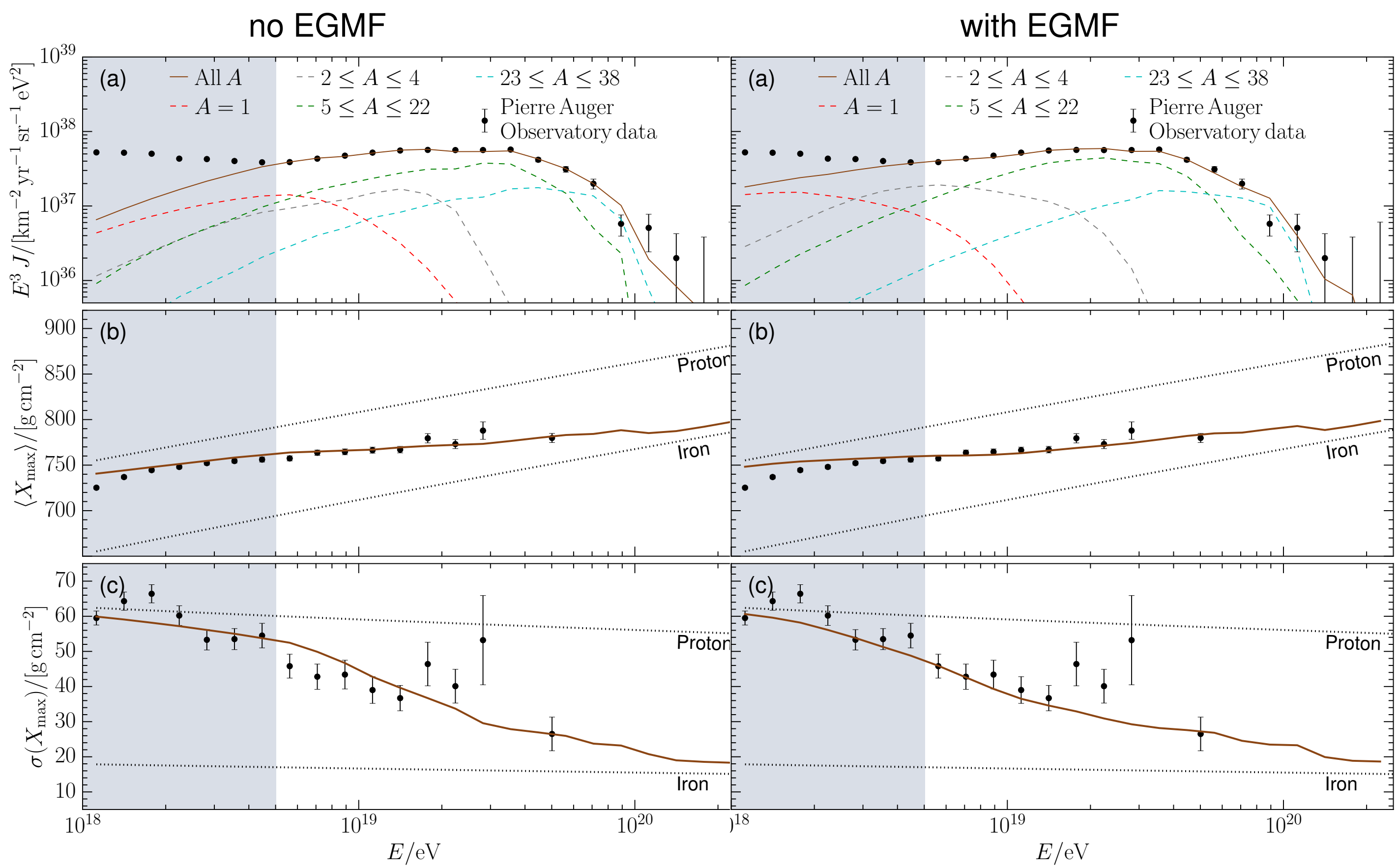
Best fit scenario



[The Pierre Auger Collaboration, JCAP 04 (2017) 038]

Combined fit: EGMF (I)

- Include the **extragalactic magnetic field** in the combined fit
  - **4D propagation** using CRPropa3 instead of SimProp 1D
  - Use **large-scale structure** following Dolag 2012 for the source distribution
  - Results for a **single model** (CRPropa3, TALYS cross sections, Gilmore 2012 EBL, EPOS LHC)



[D. Wittkowski for the Pierre Auger Collaboration, PoS(ICRC2017)563]

Combined fit: EGMF (II)

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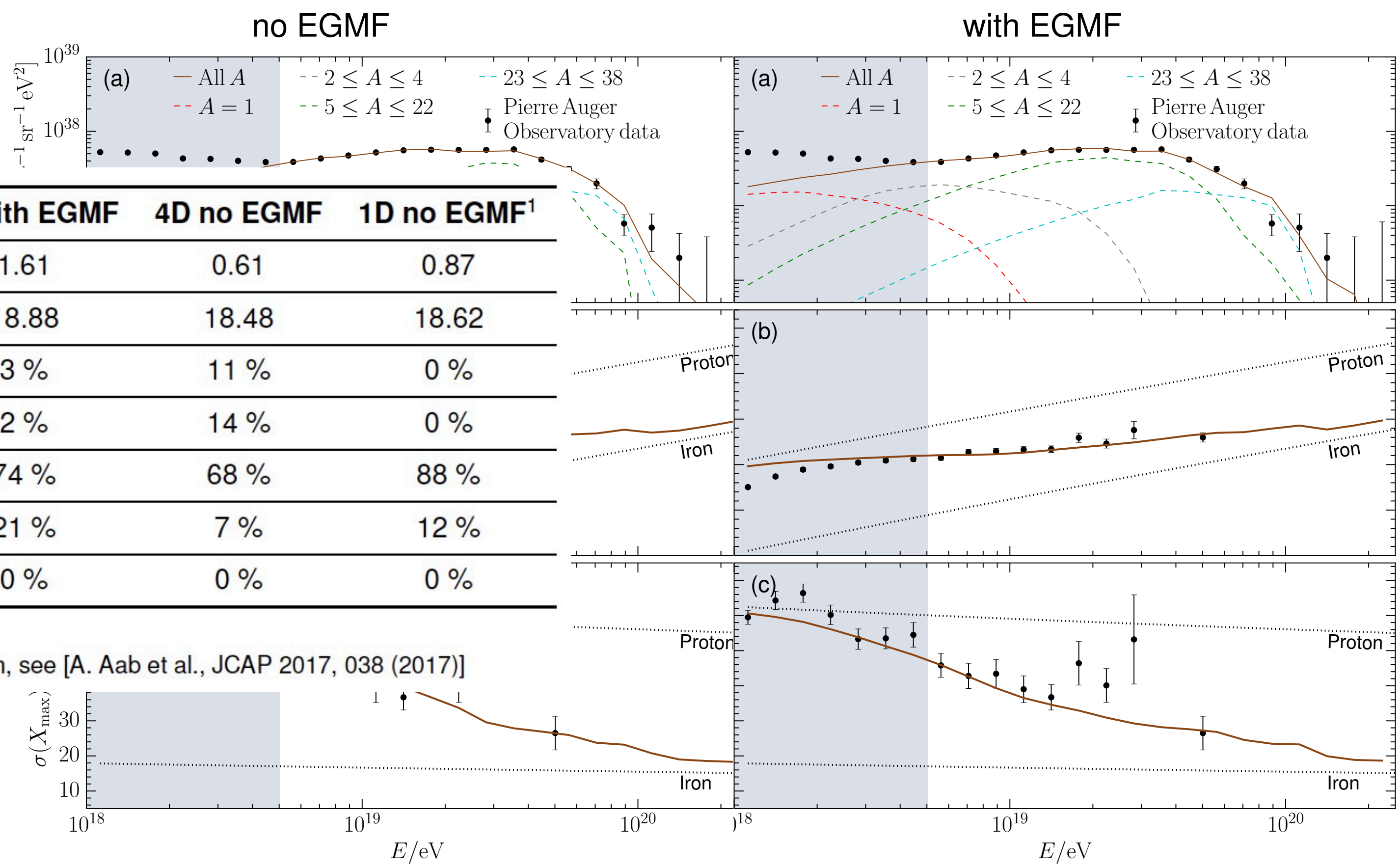
- Include the **extragalactic magnetic field** in the combined fit
  - **4D propagation** using CRPropa3 instead of SimProp 1D
  - Use **large-scale structure** following Dolag 2012 for the source distribution
  - Results for a **single model** (CRPropa3, TALYS cross sections, Gilmore 2012 EBL, EPOS LHC)



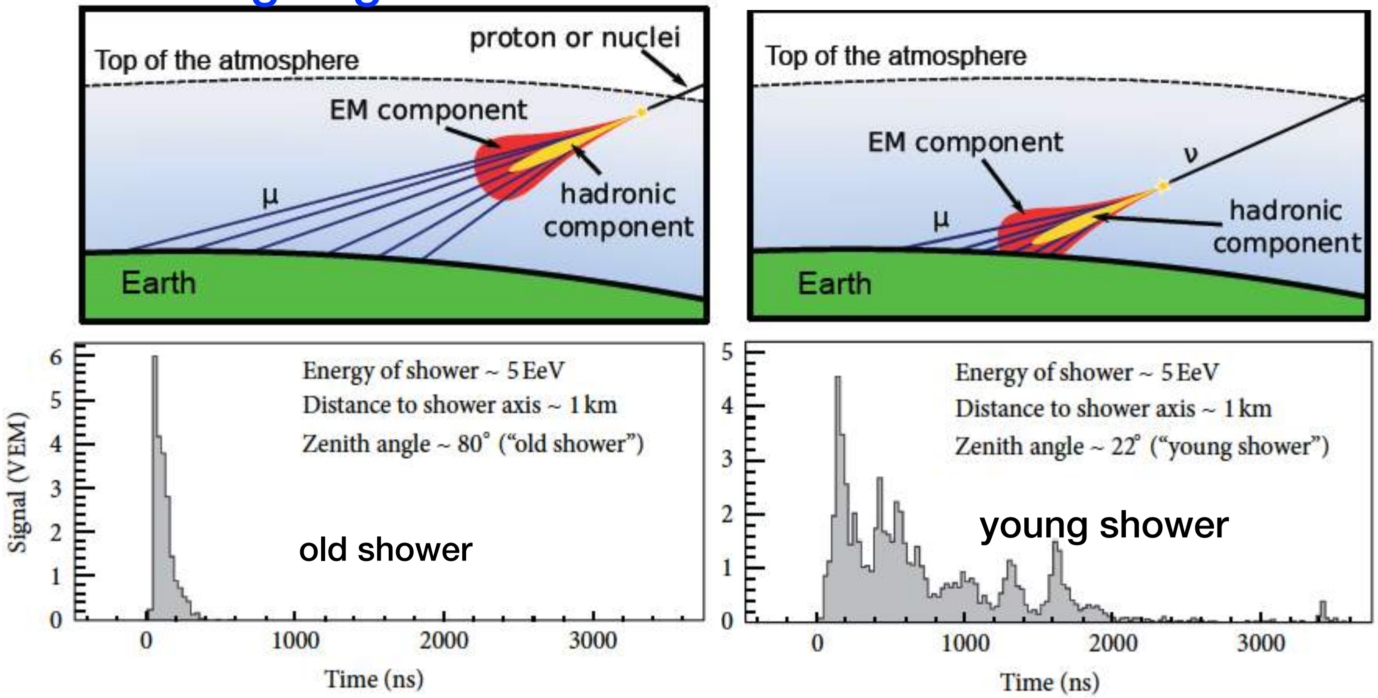
Source properties	4D with EGMF	4D no EGMF	1D no EGMF[1]
γ	1.61	0.61	0.87
$\log_{10}(R_{cut}/\mathrm{eV})$	18.88	18.48	18.62
f_H	3 %	11 %	0 %
f_{He}	2 %	14 %	0 %
f_N	74 %	68 %	88 %
f_{Si}	21 %	7 %	12 %
f_{Fe}	0 %	0 %	0 %

[1] Homogeneous source distribution, see [A. Aab et al., JCAP 2017, 038 (2017)]

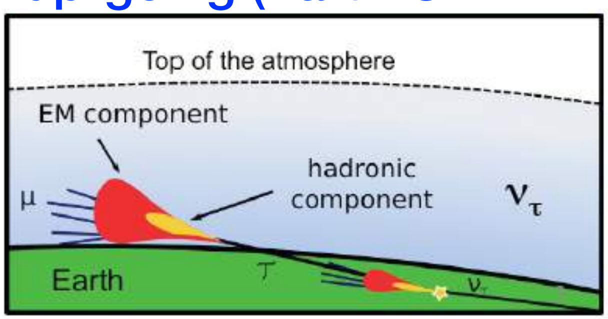
[D. Wittkowski for the Pierre Auger Collaboration, PoS(ICRC2017)563]

Search for UHE neutrinos

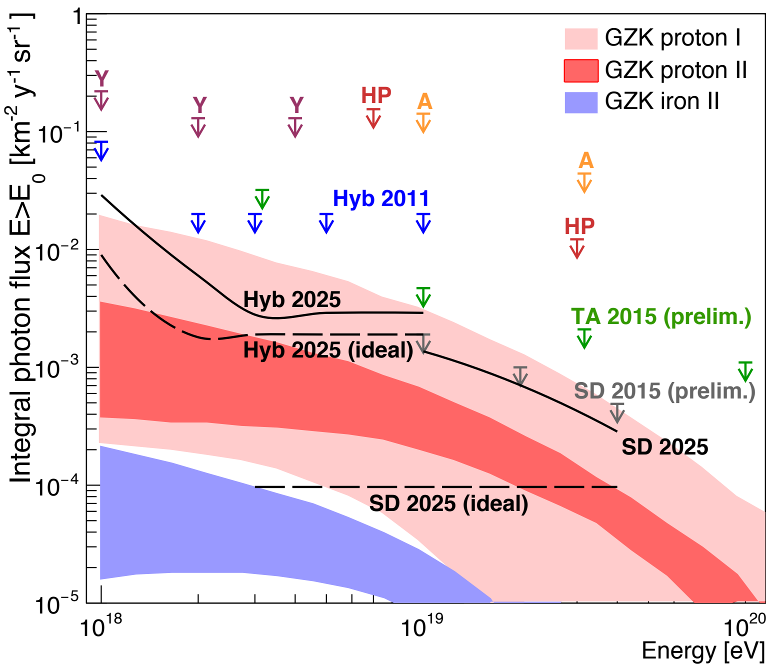
- down-going

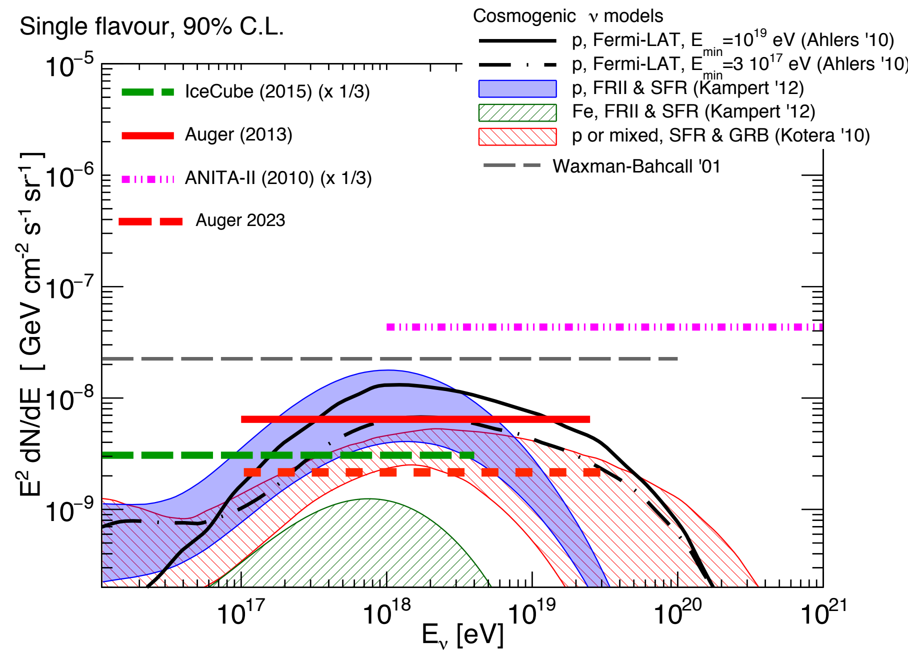


- up-going (Earth-Skimming)



AugerPrime: sensitivity to γ/ν





[The Pierre Auger Collaboration, arXiv:1604.03637]