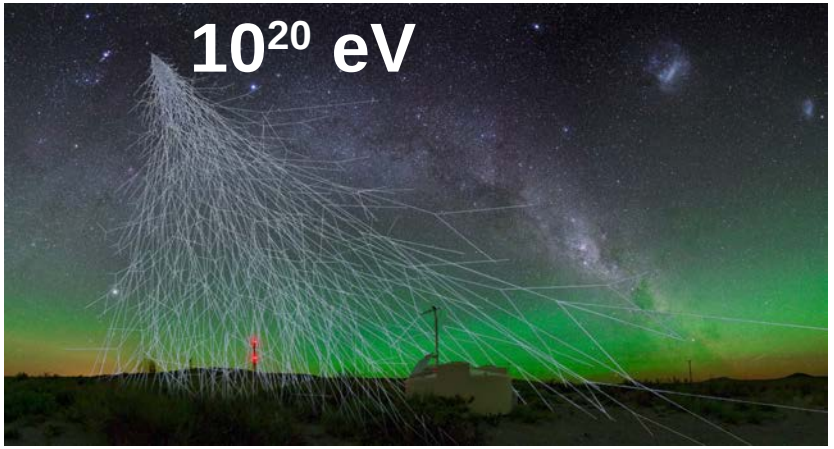


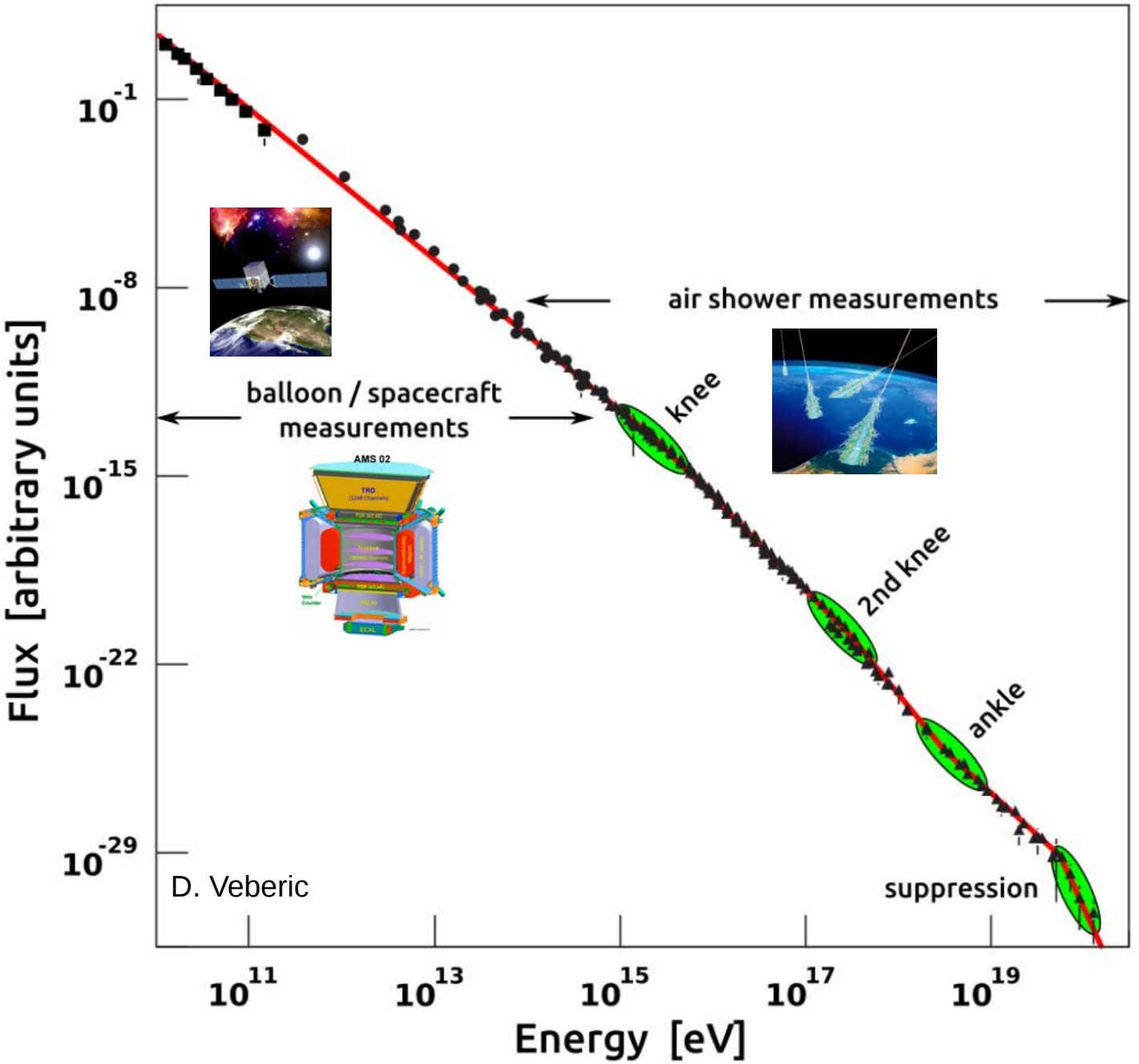
Probing the Universe at the Highest Energies with the Pierre Auger Observatory

Jakub Vícha (vicha@fzu.cz)

Institute of Physics of the Czech Academy of Sciences

on behalf of the Pierre Auger Collaboration

Cosmic-ray flux

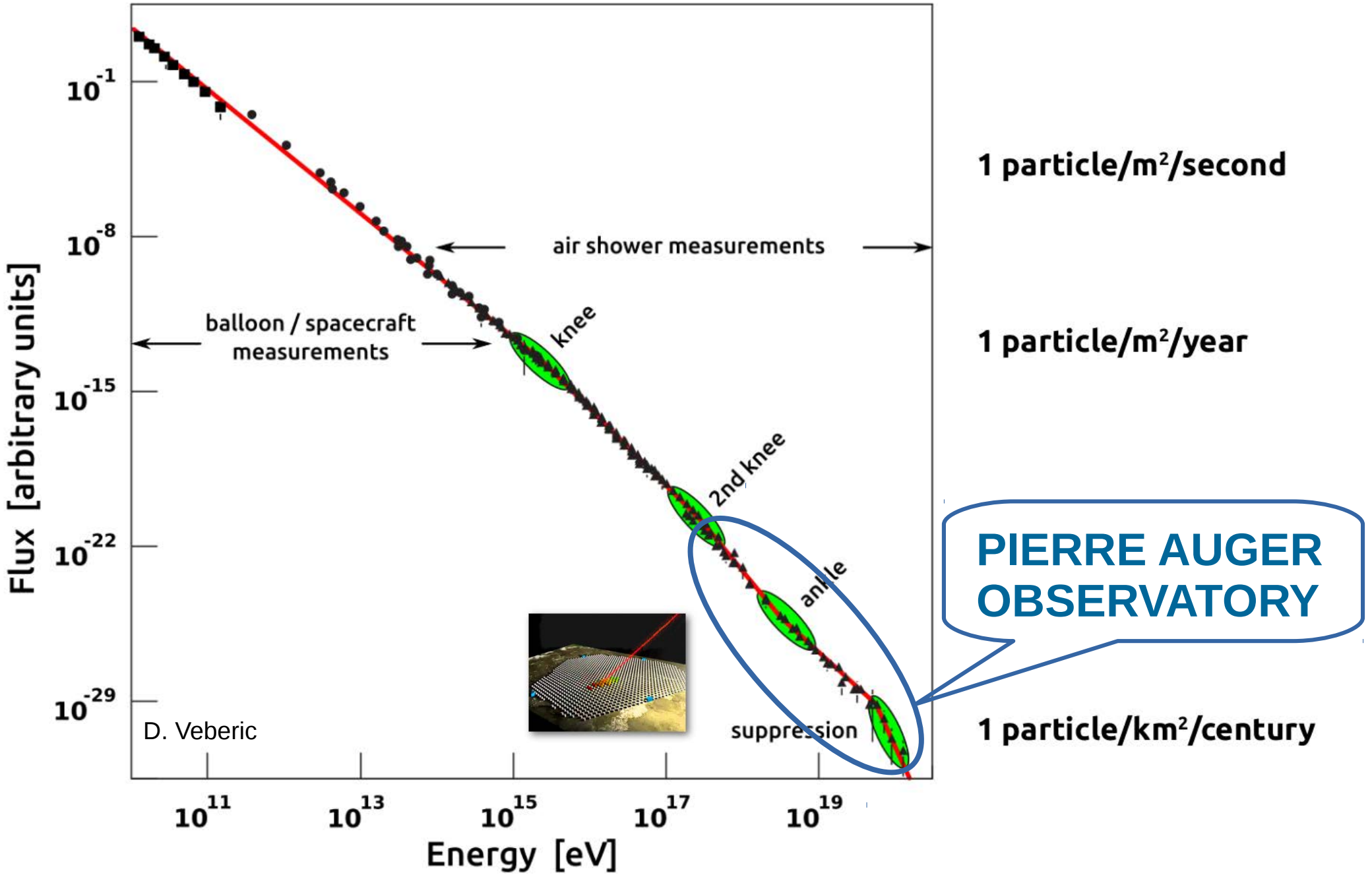


1 particle/m²/second

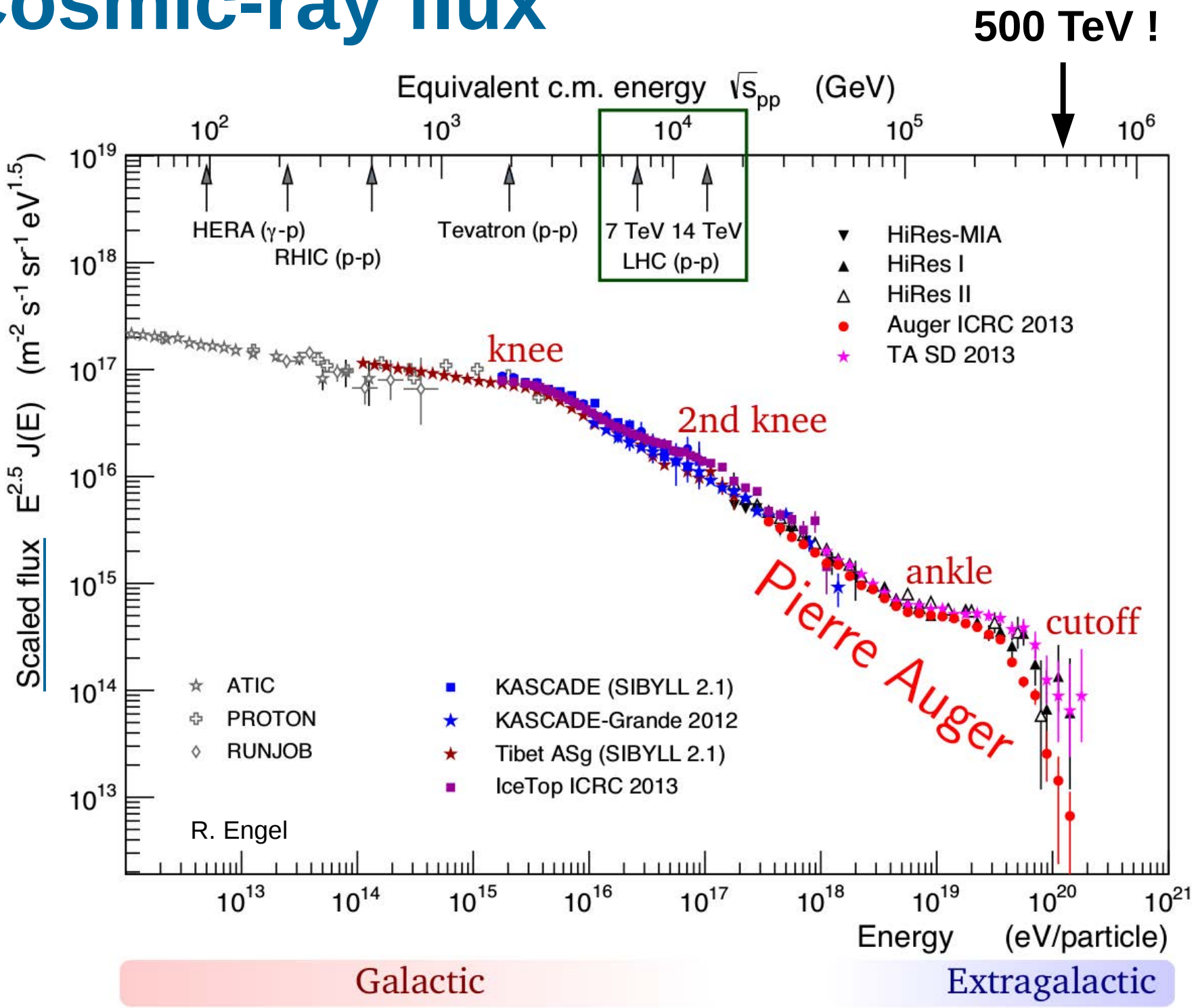
1 particle/m²/year

1 particle/km²/century

Cosmic-ray flux

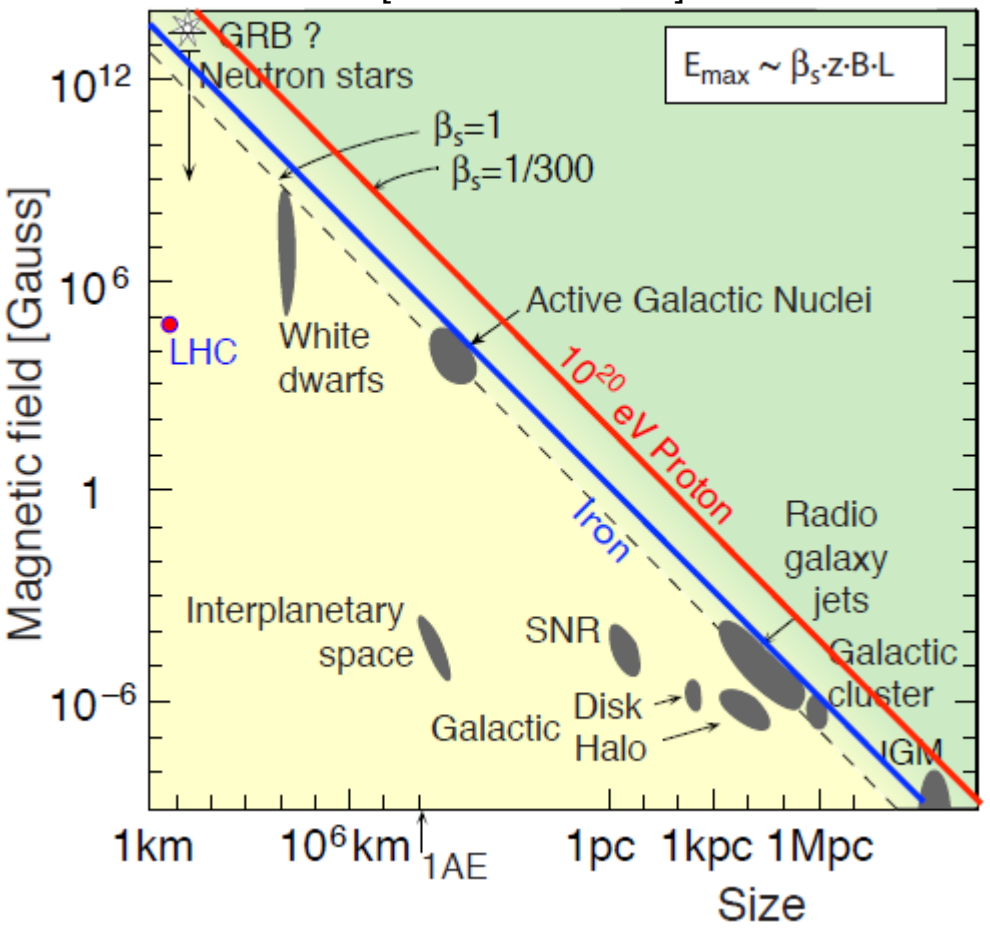


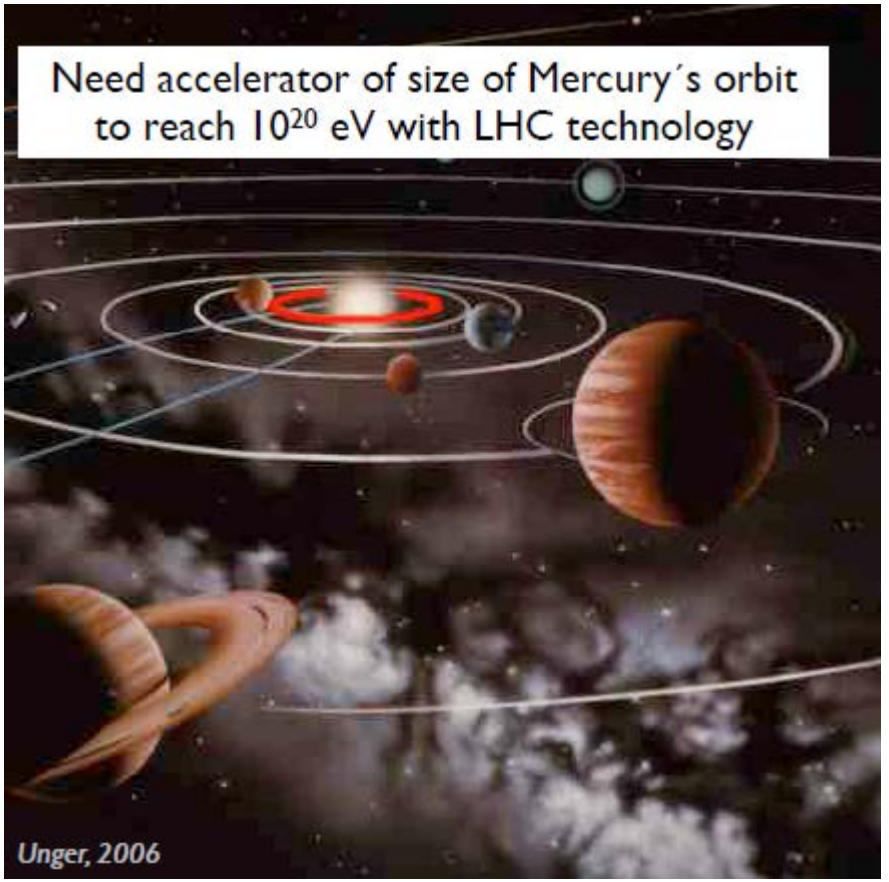
Cosmic-ray flux



Mysterious 10^{20} eV particles

[A. M. Hillas 1984]



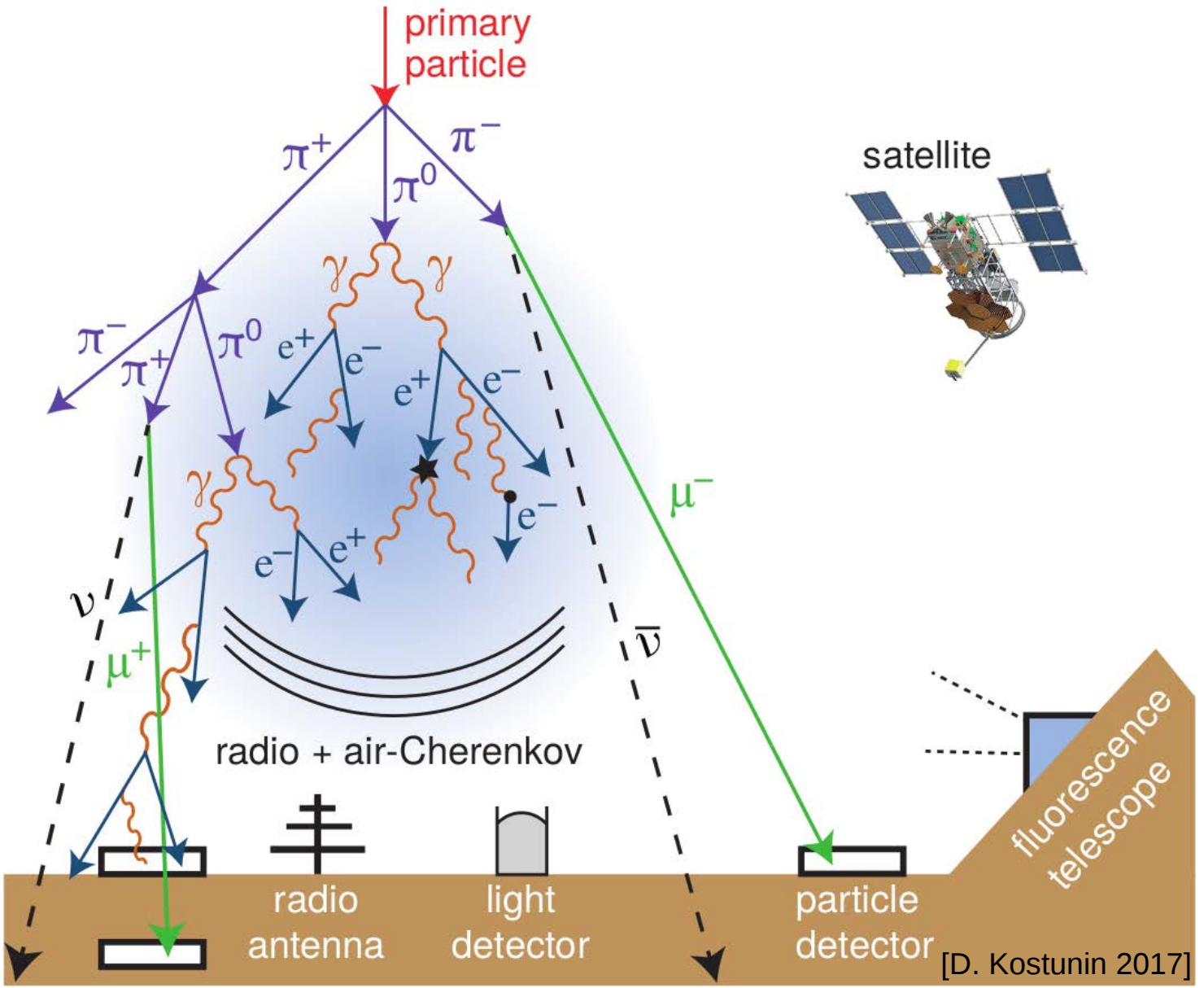


What are the sources???

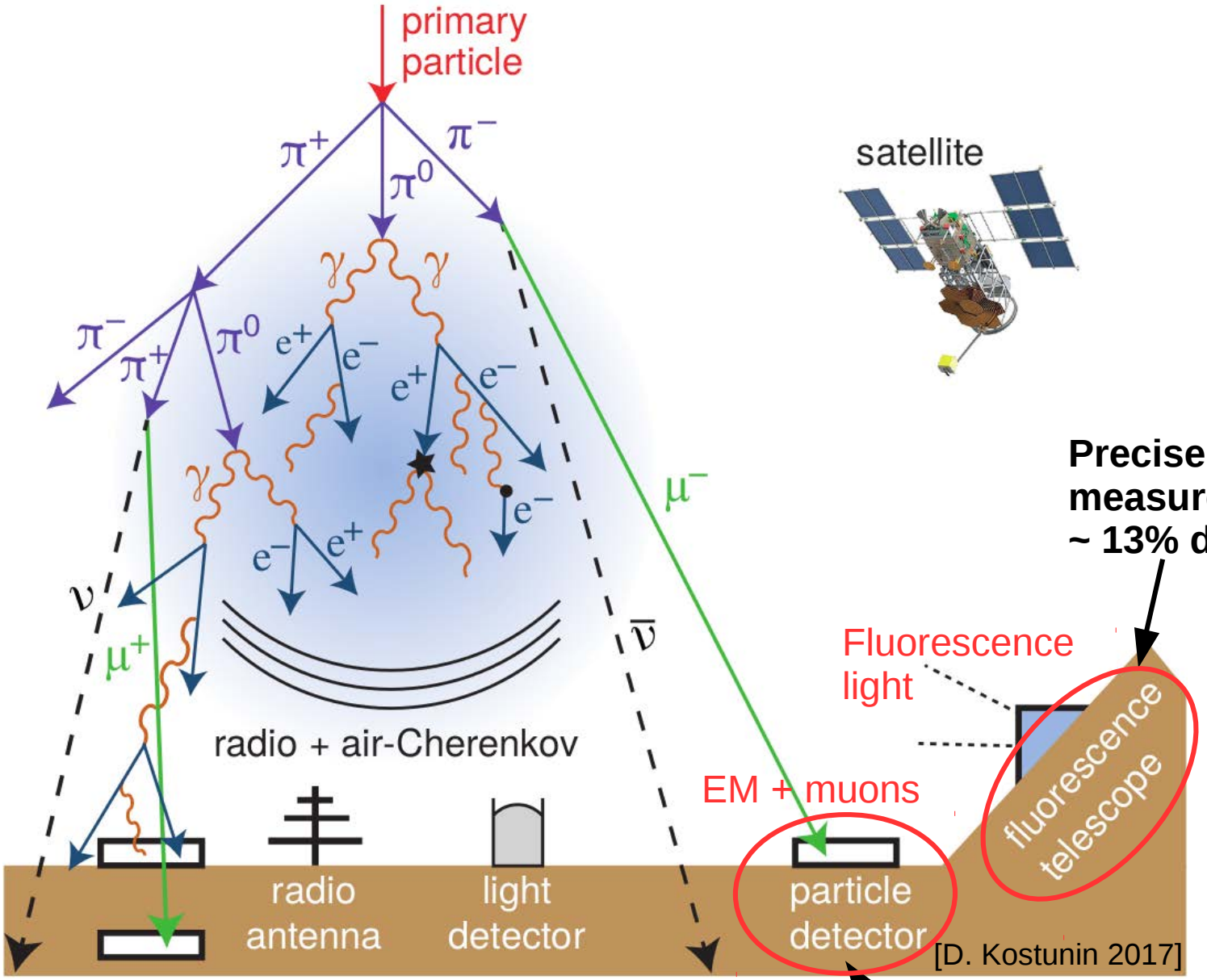
Indirect hints from:

- **energy spectrum**
- **mass composition**
- **anisotropy searches**

Detection of extensive air-showers



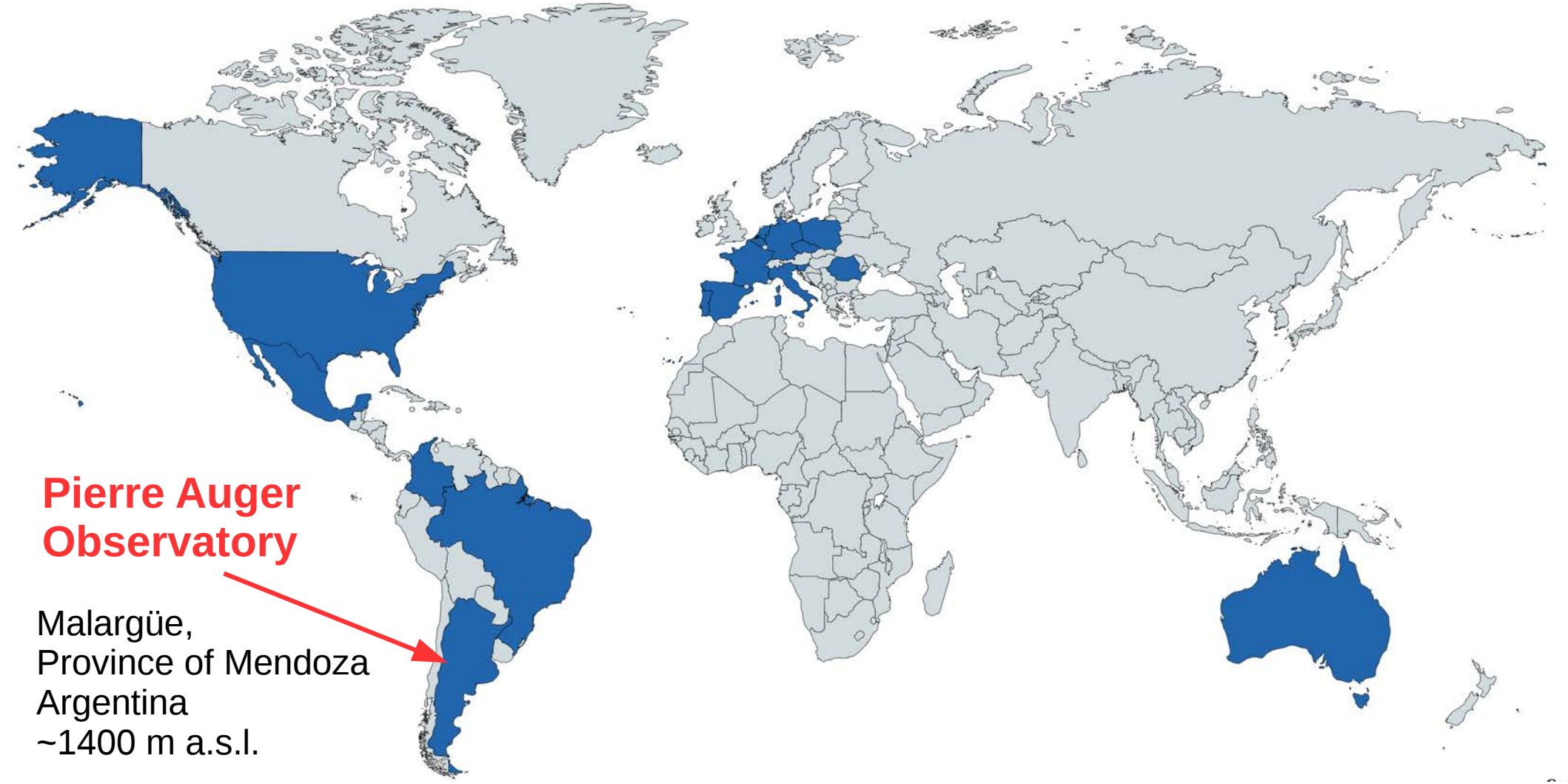
Detection of extensive air-showers

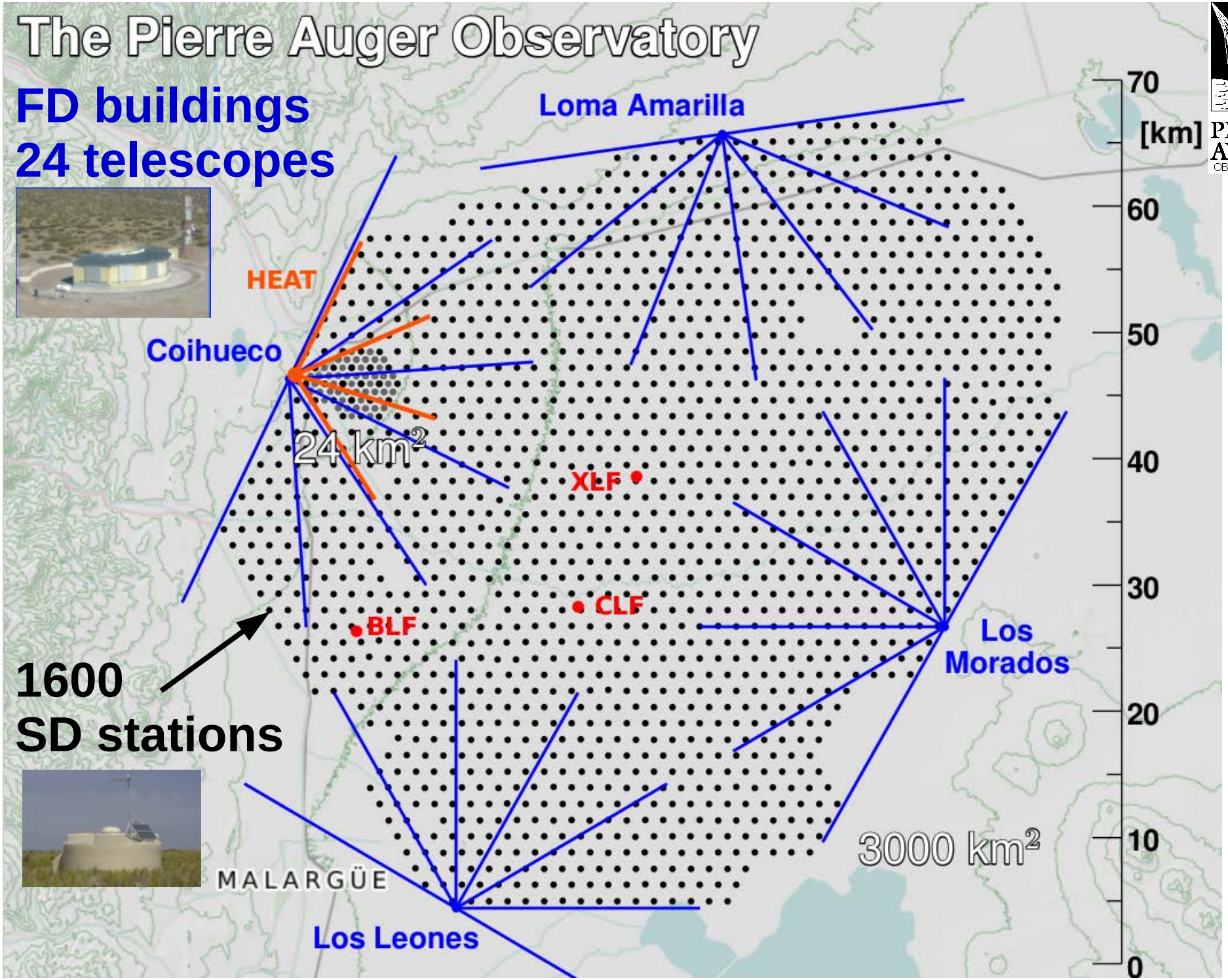


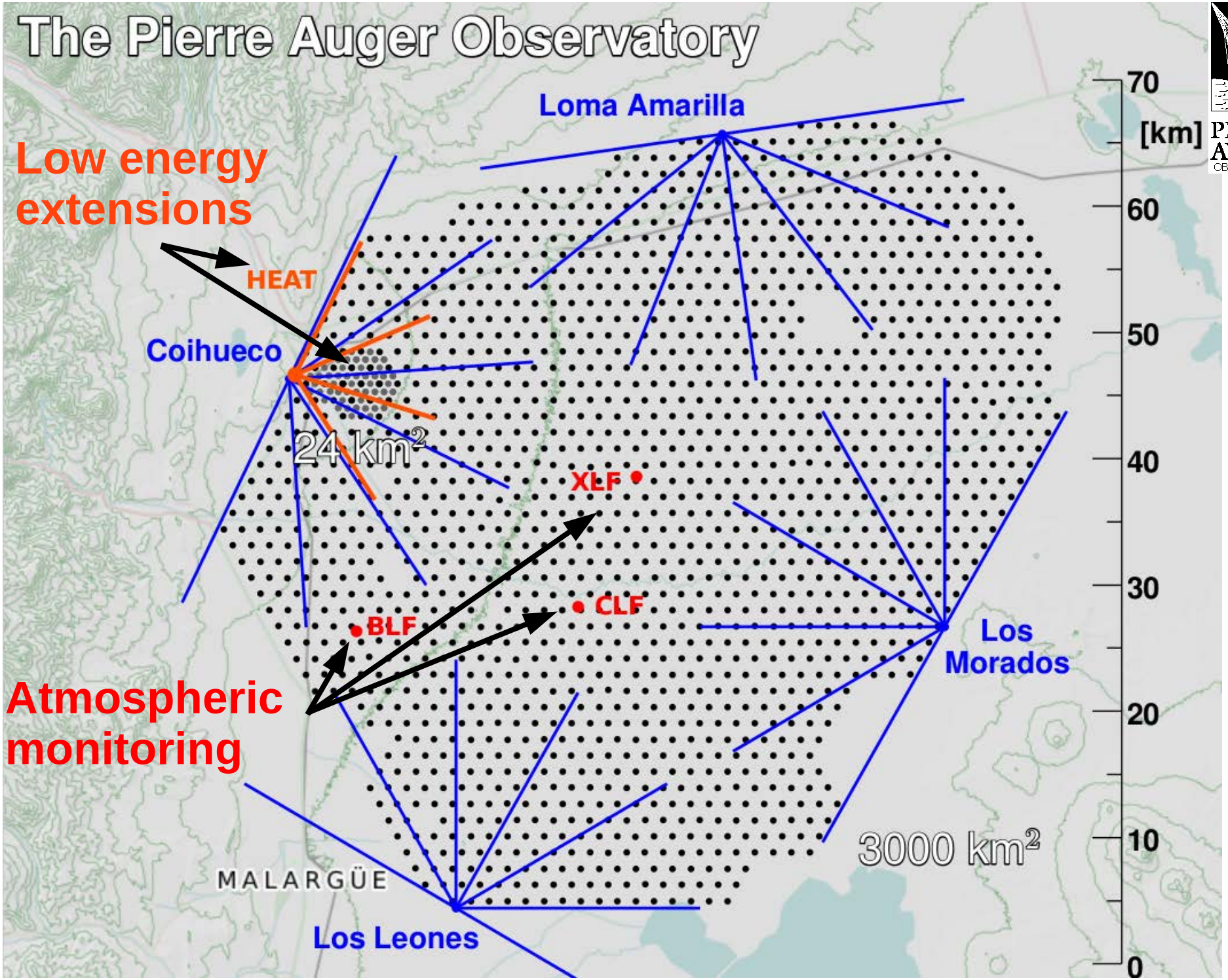
Precise measurement with ~ 13% duty cycle

Shower sampling at large area with ~ 100% duty cycle

Pierre Auger Collaboration
~ 450 scientists from 17 countries



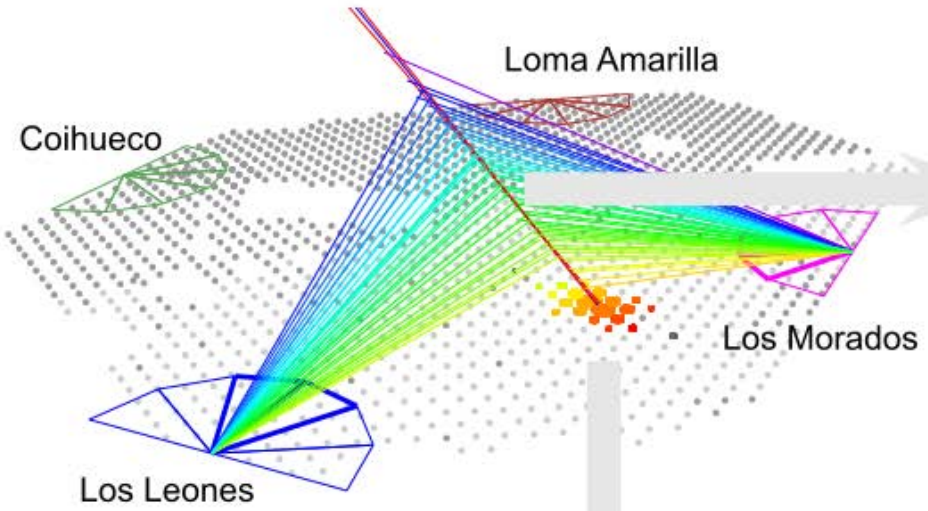

The Pierre Auger Observatory
FD buildings
24 telescopes
HEAT
Coihueco
24 km²
Loma Amarilla
XLF
CLF
BLF
Los Morados
1600
SD stations
MALARGÜE
Los Leones
3000 km²
70
[km]
60
50
40
30
20
10
0
PIERRE AUGER OBSERVATORY


The Pierre Auger Observatory
Low energy extensions
HEAT
Coihueco
24 km²
XLF
CLF
BLF
Atmospheric monitoring
Loma Amarilla
Los Morados
3000 km²
MALARGÜE
Los Leones
70
[km]
60
50
40
30
20
10
0
PIERRE AUGER OBSERVATORY

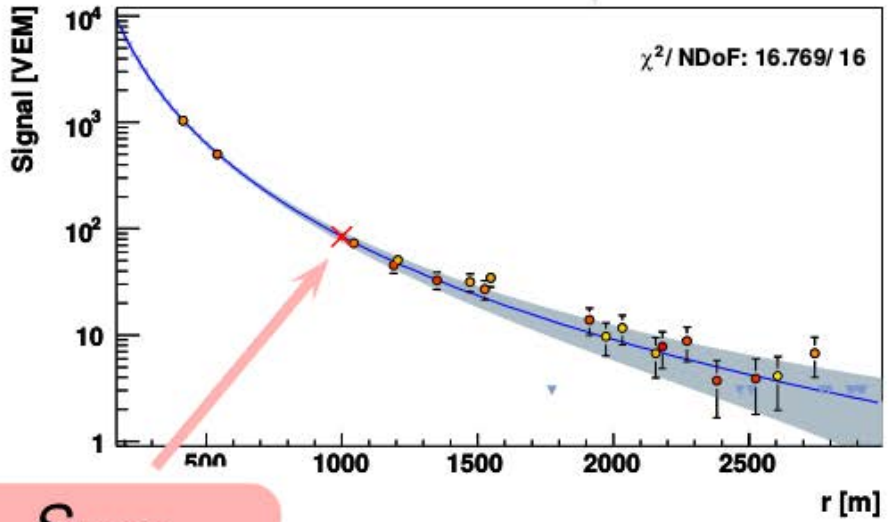
Pierre Auger Observatory

Scientific data since 2004, deployment completed in 2008, currently operating and upgrading

Hybrid detection of air-showers

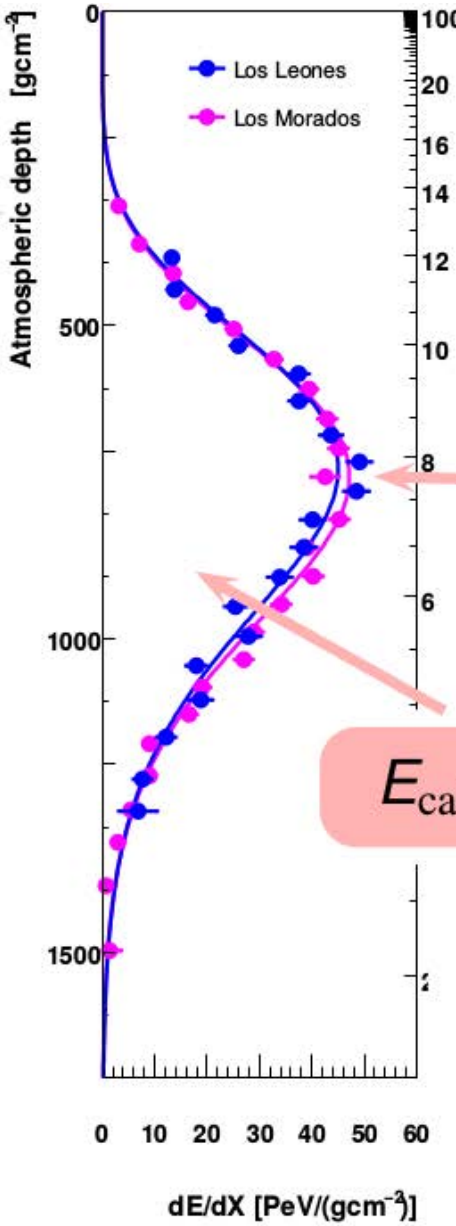


M. Unger



S_{1000}

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



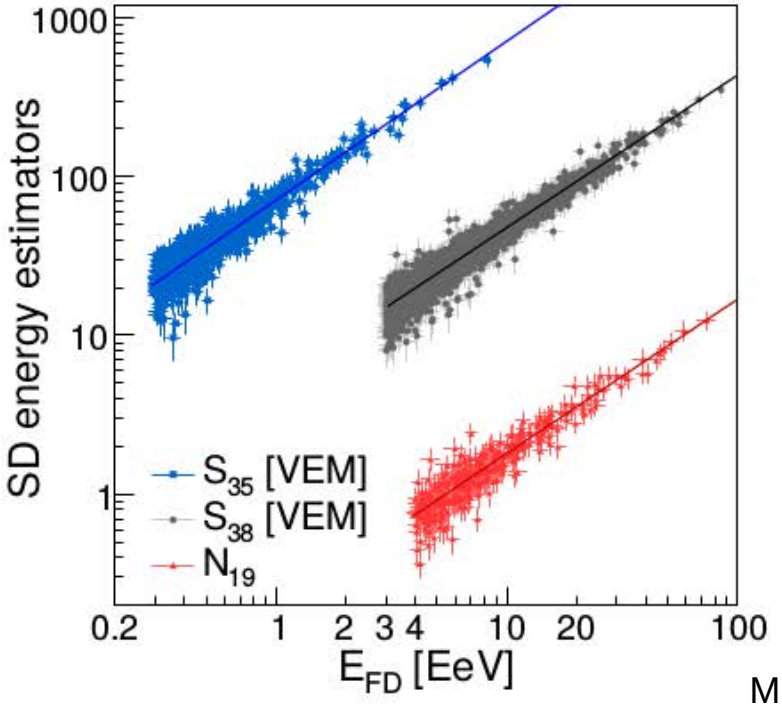
$\sigma_{X_{\max}} \leq 20\,\text{g/cm}^2$
$\Delta_{\text{sys}} \leq 10\,\text{g/cm}^2$

$X_{\max}$

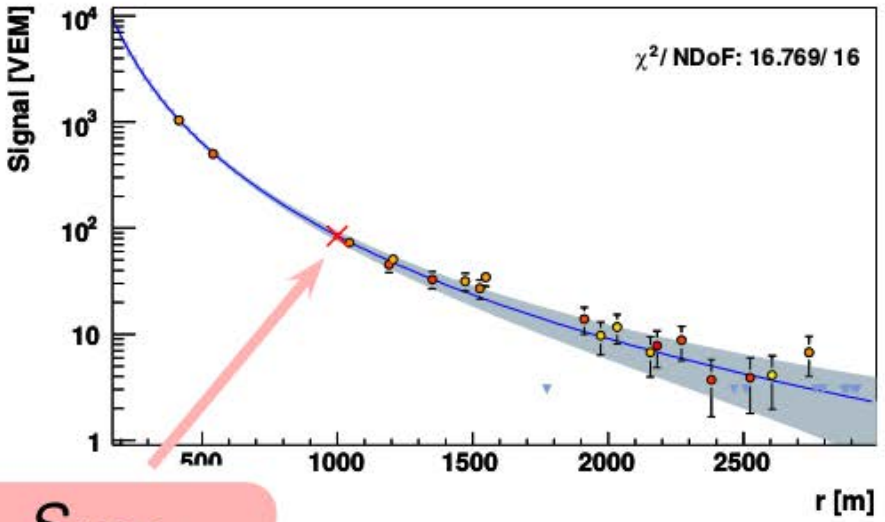
$E_{\text{cal}} = \int \frac{dE}{dX}\, dX$

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

Energy Calibration



M. Unger



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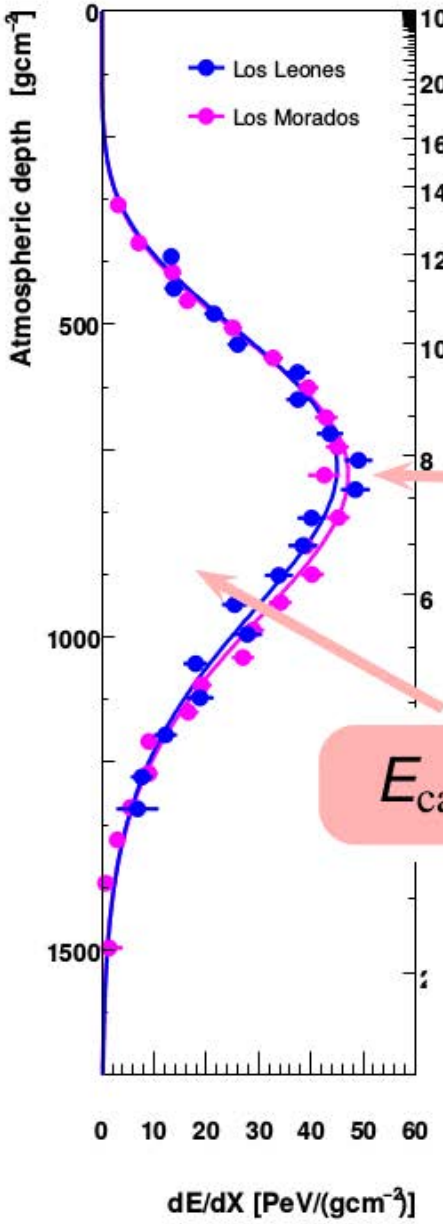

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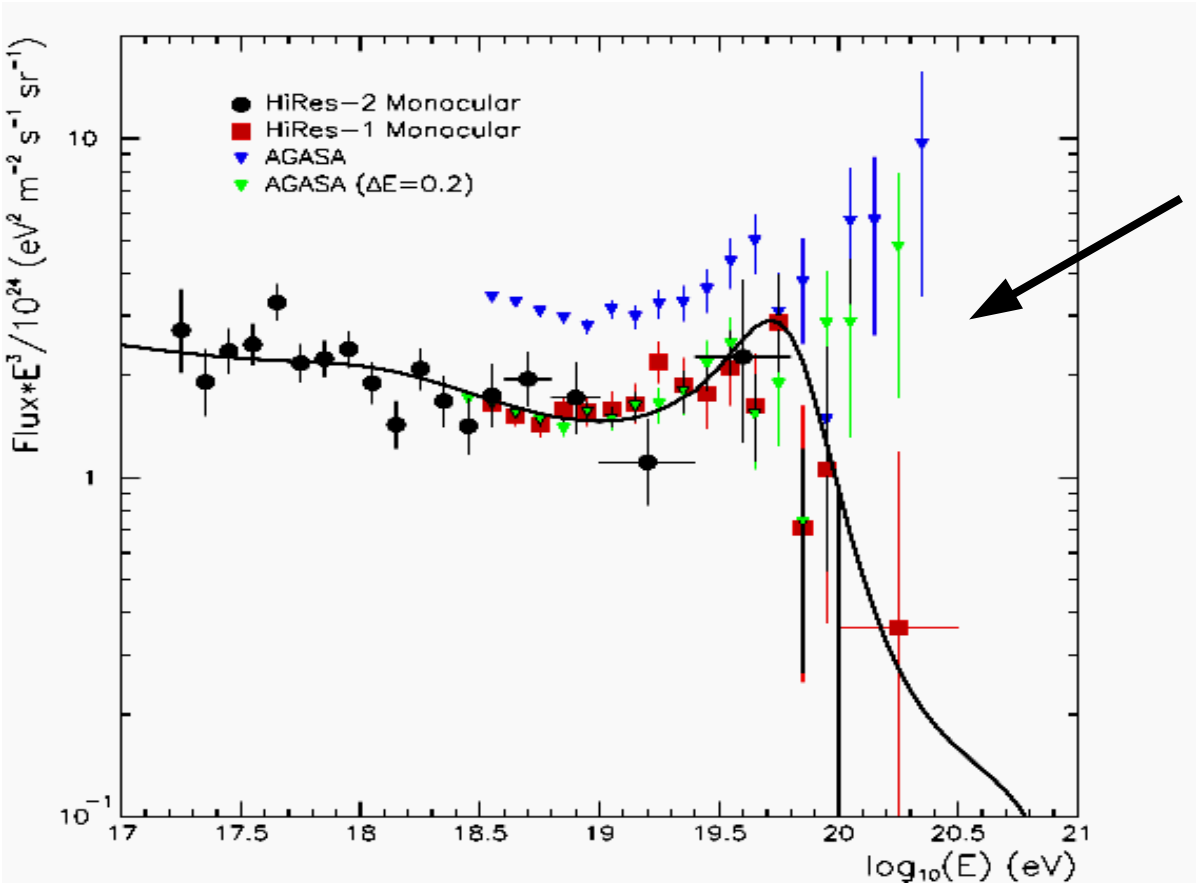
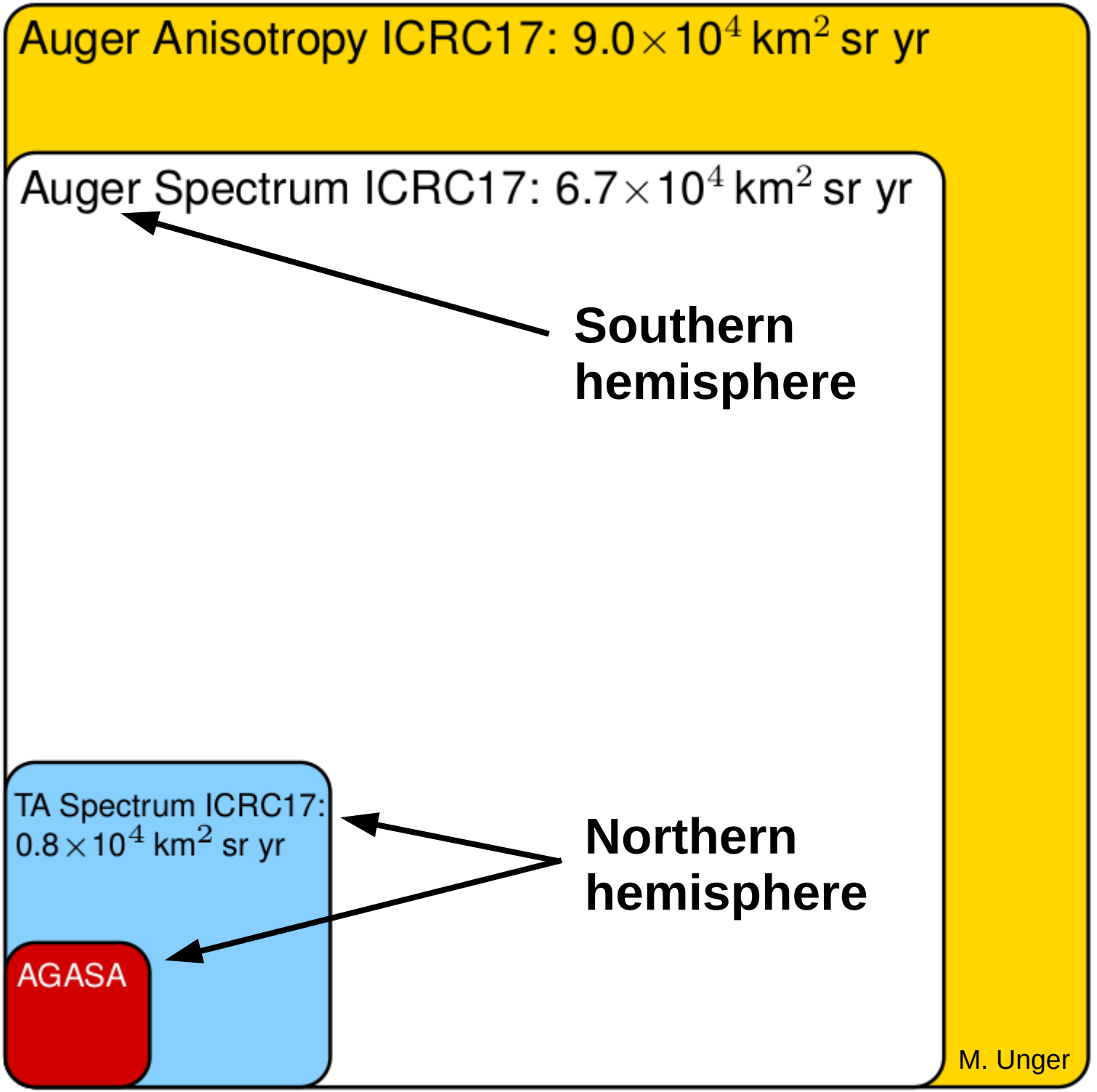
$\sigma_E/E \sim 8\,\%$

$\Delta_{\text{sys}} \approx 15\,\%$

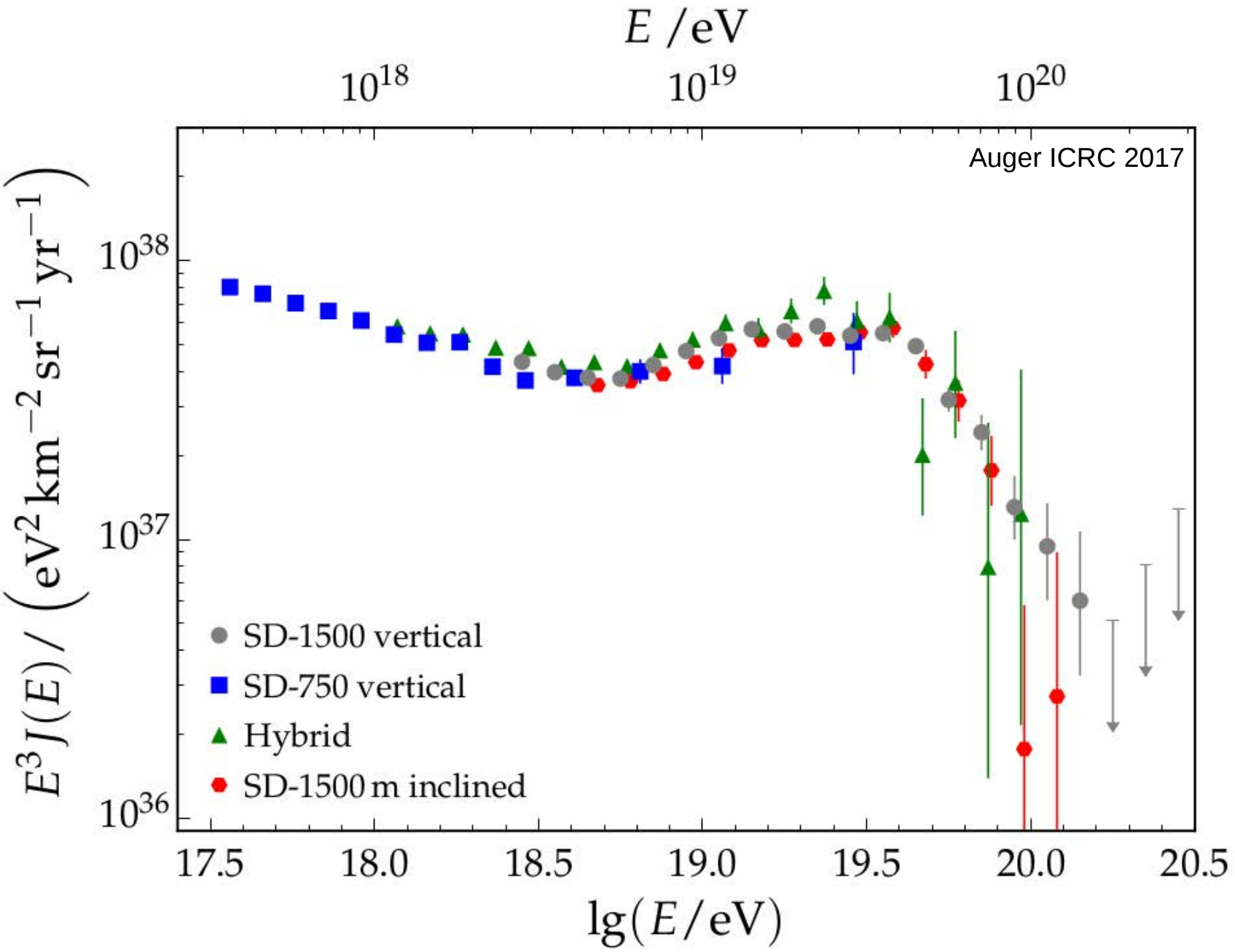
Energy Spectrum before the Pierre Auger Observatory



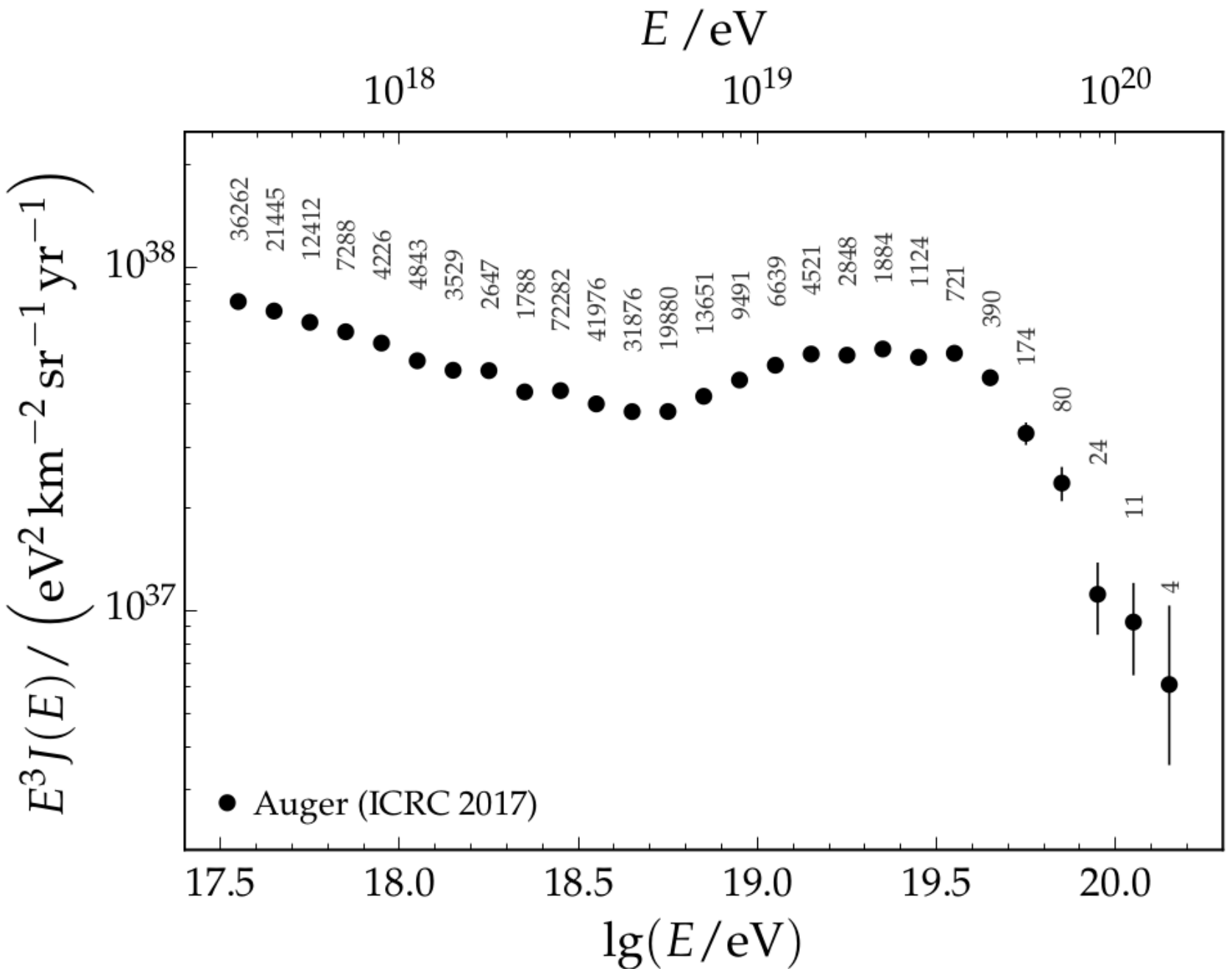
Steep decrease (proton horizon) or exotic source (decay of DM)?


Auger Anisotropy ICRC17: 9.0×10^4 km^2 sr yr
Auger Spectrum ICRC17: 6.7×10^4 km^2 sr yr
Southern hemisphere
TA Spectrum ICRC17: 0.8×10^4 km^2 sr yr
Northern hemisphere
AGASA
M. Unger

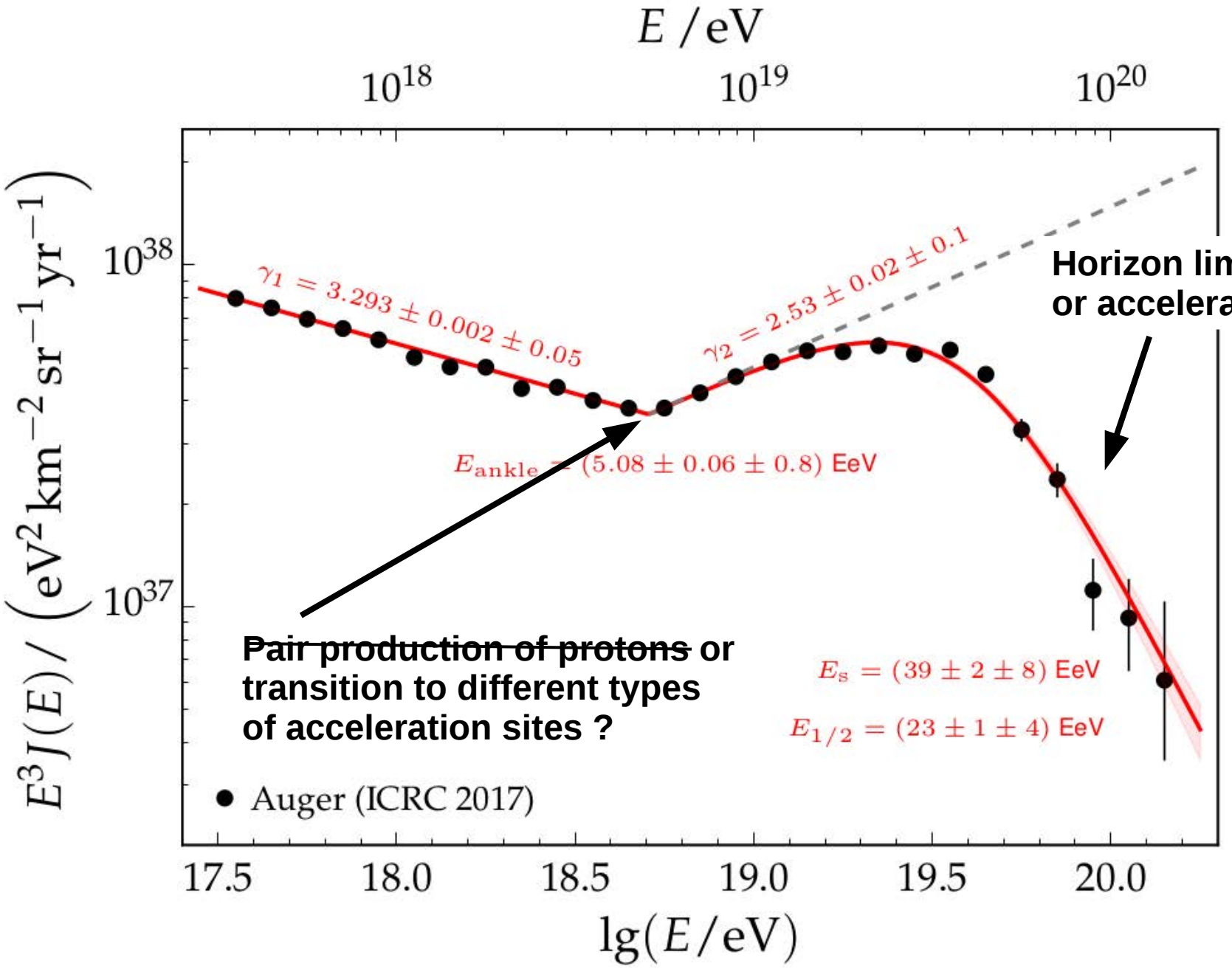
Energy Spectrum



Combined Energy Spectrum



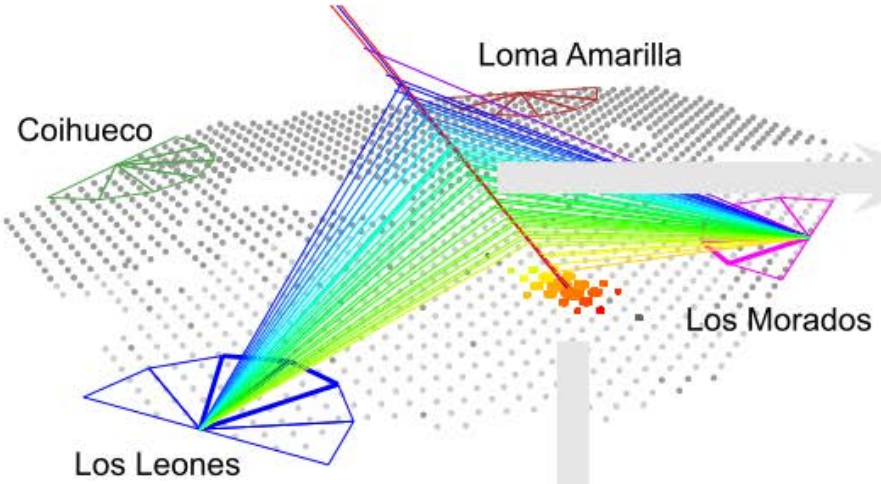
Spectral Features



Horizon limit or acceleration limit?

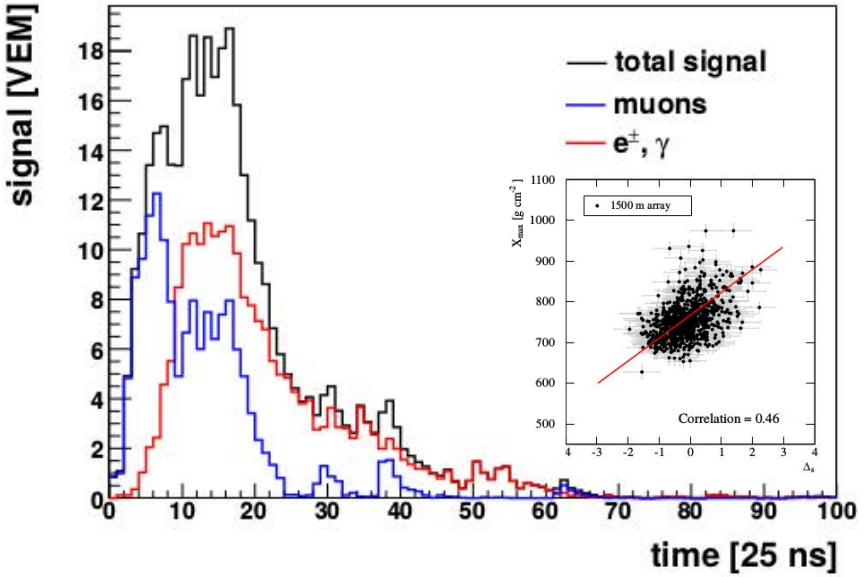
~~Pair production of protons~~ or transition to different types of acceleration sites ?

Mass Composition

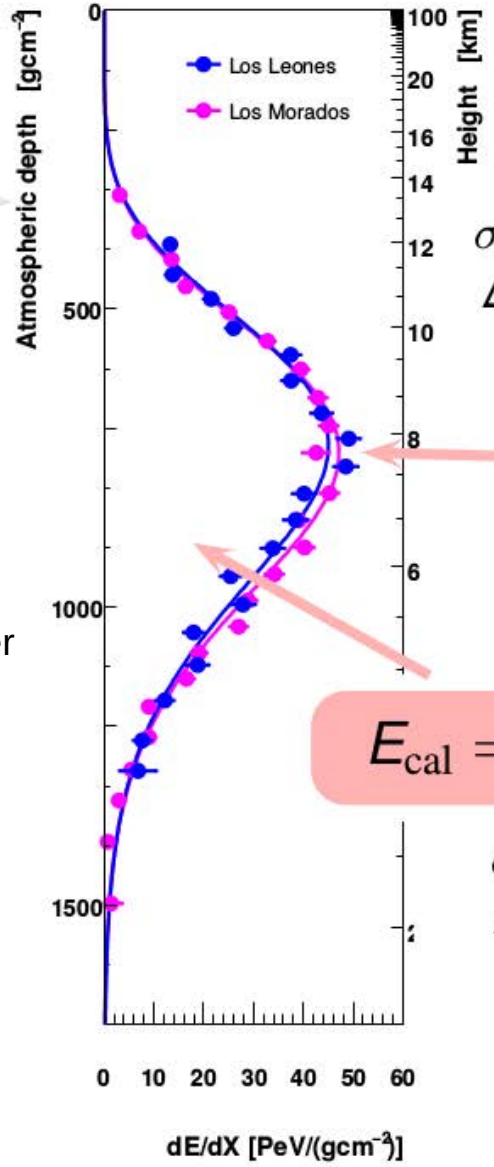


SD ~ 100% duty cycle

M. Unger



FD ~ 13% duty cycle



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$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

$X_{\max}$

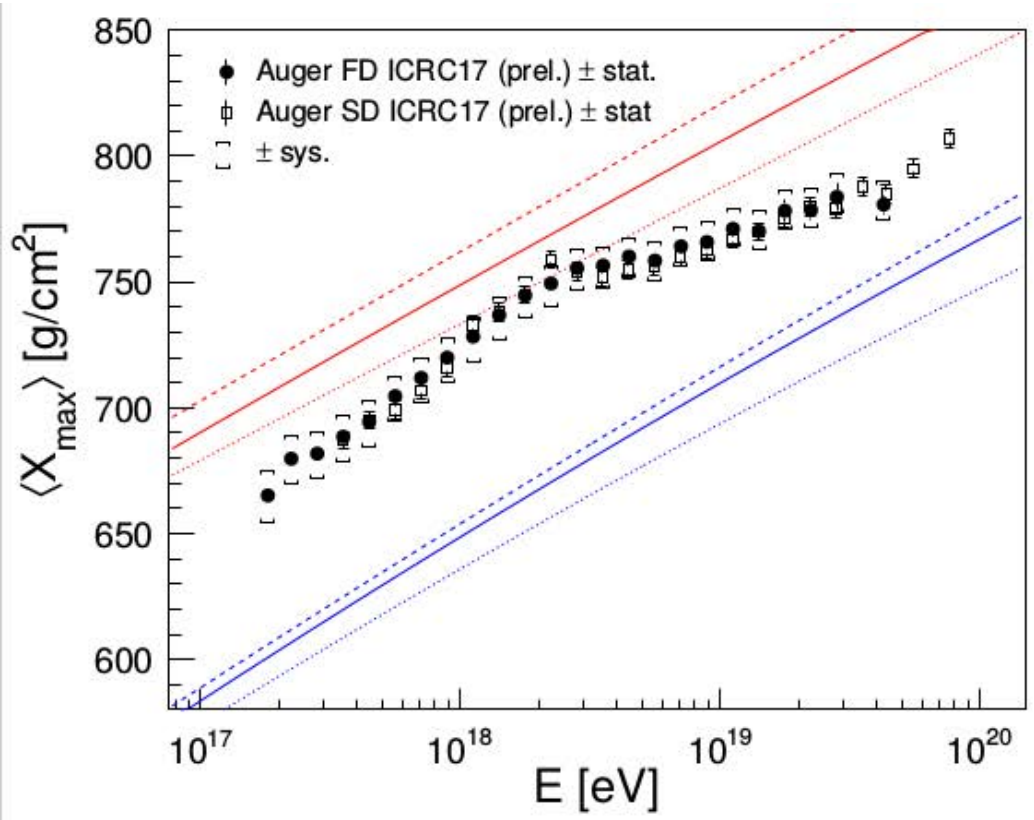
$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

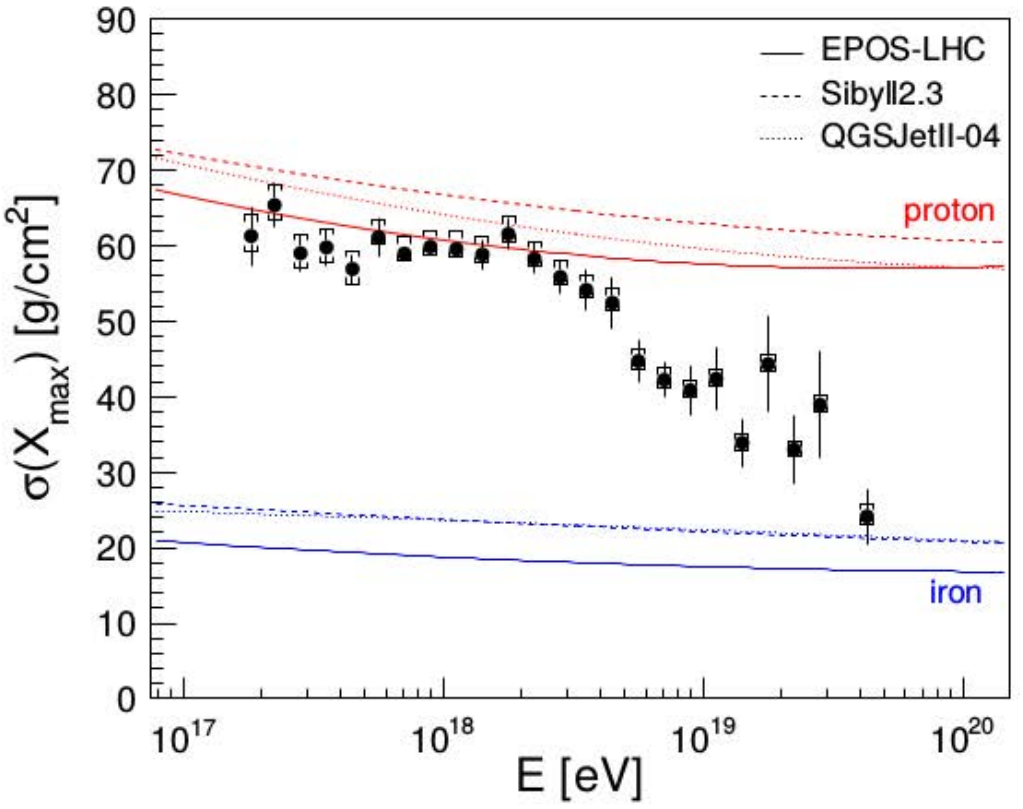
$\sigma_E/E \sim 8\,\%$

$\Delta_{\mathrm{sys}} \approx 15\,\%$

Energy Evolution of Mass Estimators

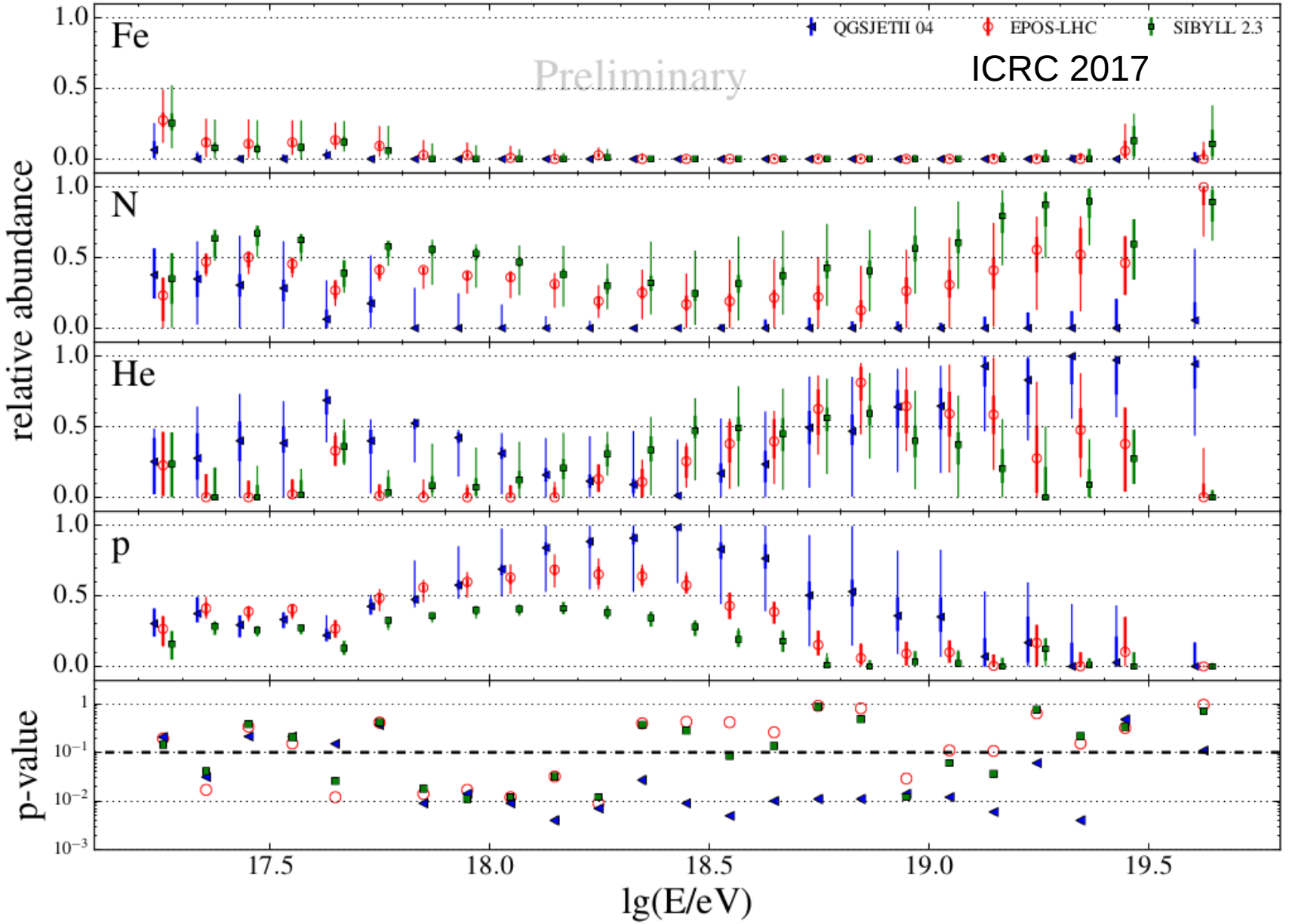
Increase of average mass with increasing energy





Models of hadronic interactions tuned to the LHC data (Run I)

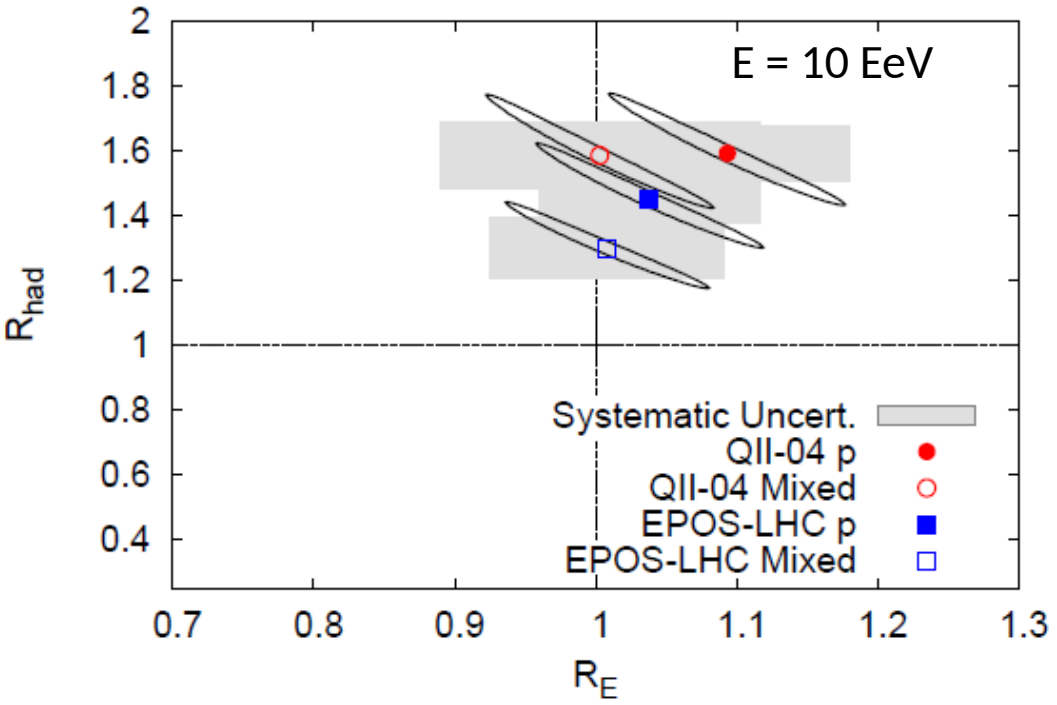
Primary Fractions from Xmax distribution fits



Excess of muons in measured data wrt. MC

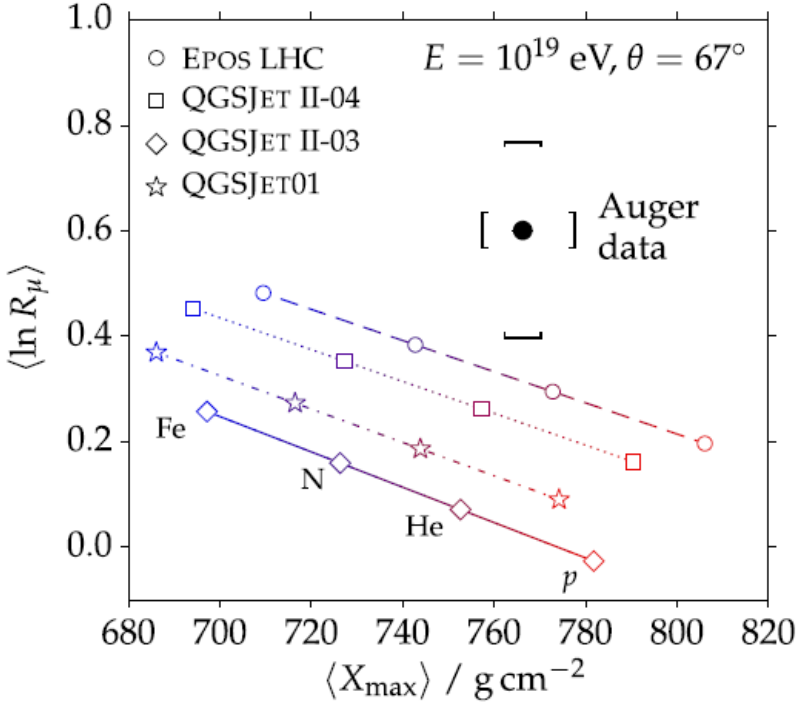
Zenith (0-60)deg

[Phys. Rev. Lett. 117 (2016) 192001]



Zenith (62-80)deg

[Phys. Rev. D 91 (2015) 032003]



EPOS-LHC needs 10-50% more muons

QGSJet II-04 needs 30-80% more muons

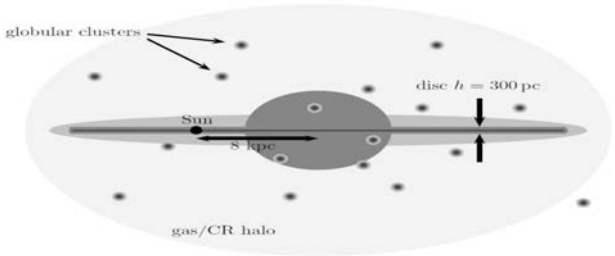
Distortions in magnetic fields

$$r_l[kpc] = \frac{E[10^{18}\,eV]}{Z \cdot B[\mu G]}$$

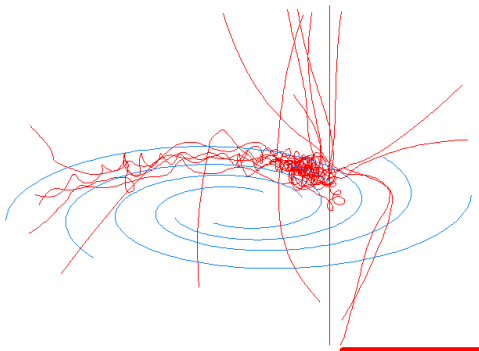
Galactic field

- $B_G \approx 3\mu G$
- Proton with E ~ 10^{18} eV

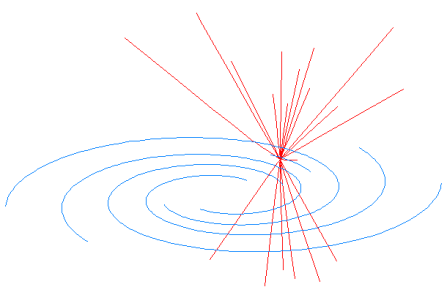
  => r_l = 0.3 kpc (disc thickness)



p 10^{18} eV

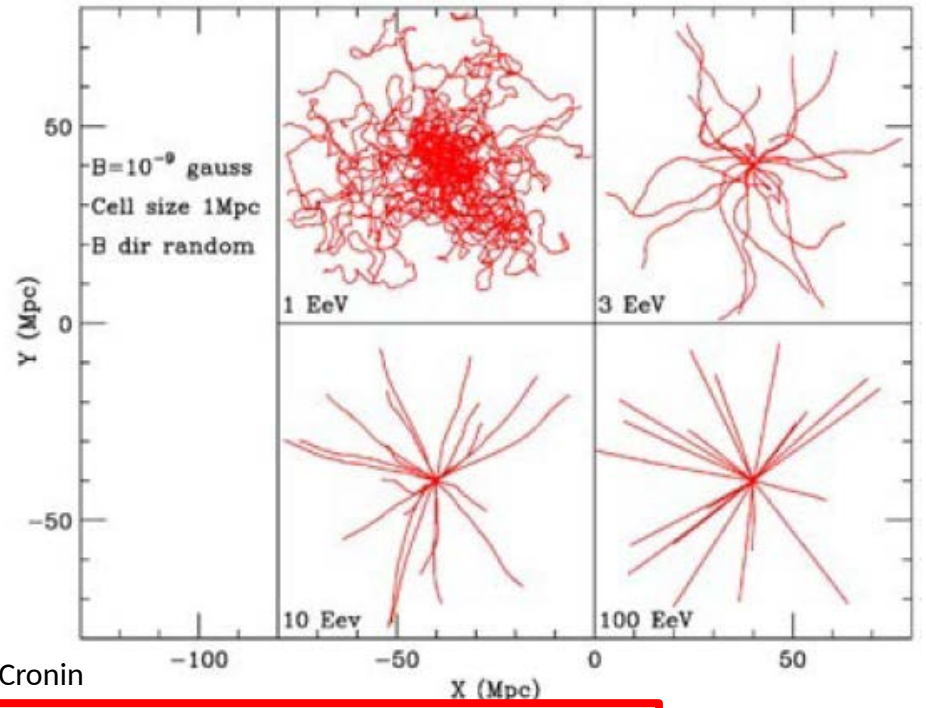


p 10^{20} eV



Extragalactic field

- Extragalactic field $B_{EG} \leq$ nG
- The closest AGN is Centaurus A (≈ 4 Mpc)

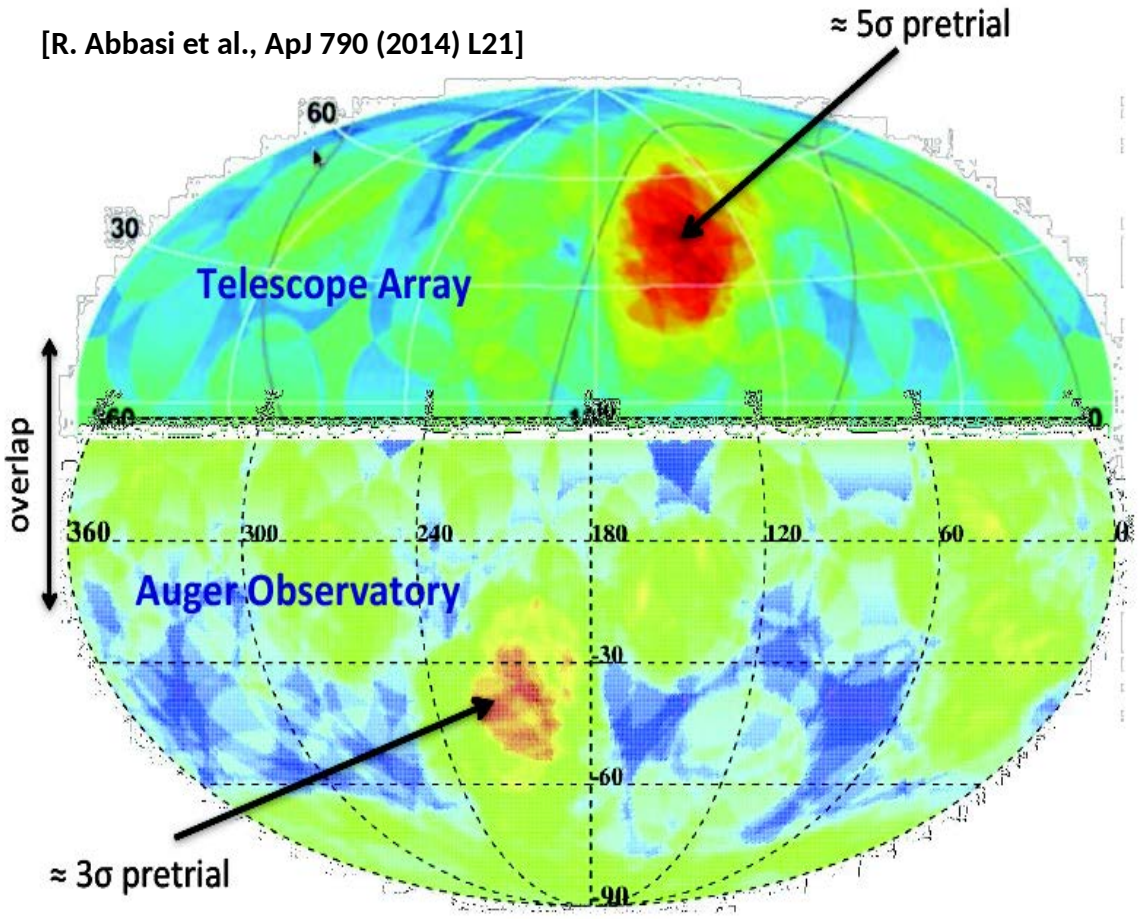


J. Cronin

few deg expected for 50 EeV protons

Anisotropies at the highest energies (above ~ 50 EeV)

[R. Abbasi et al., ApJ 790 (2014) L21]

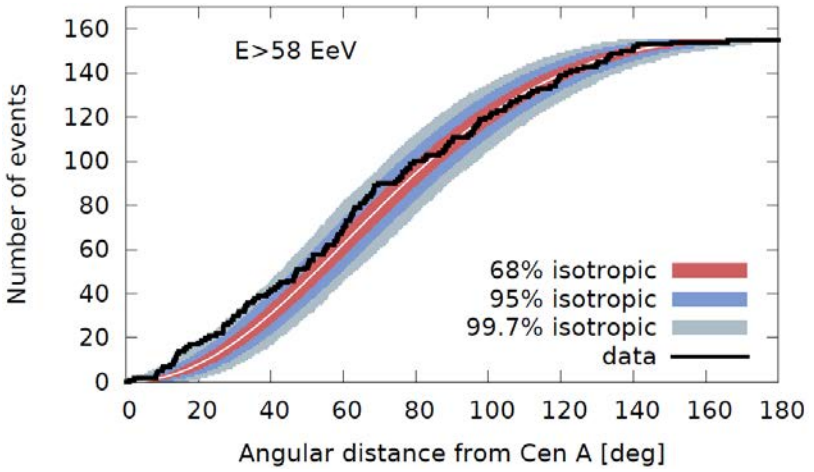


Equatorial coordinates [A. Aab et al., ApJ 804 (2015) 15]

~ 5-σ local significance
(no obvious source nearby)

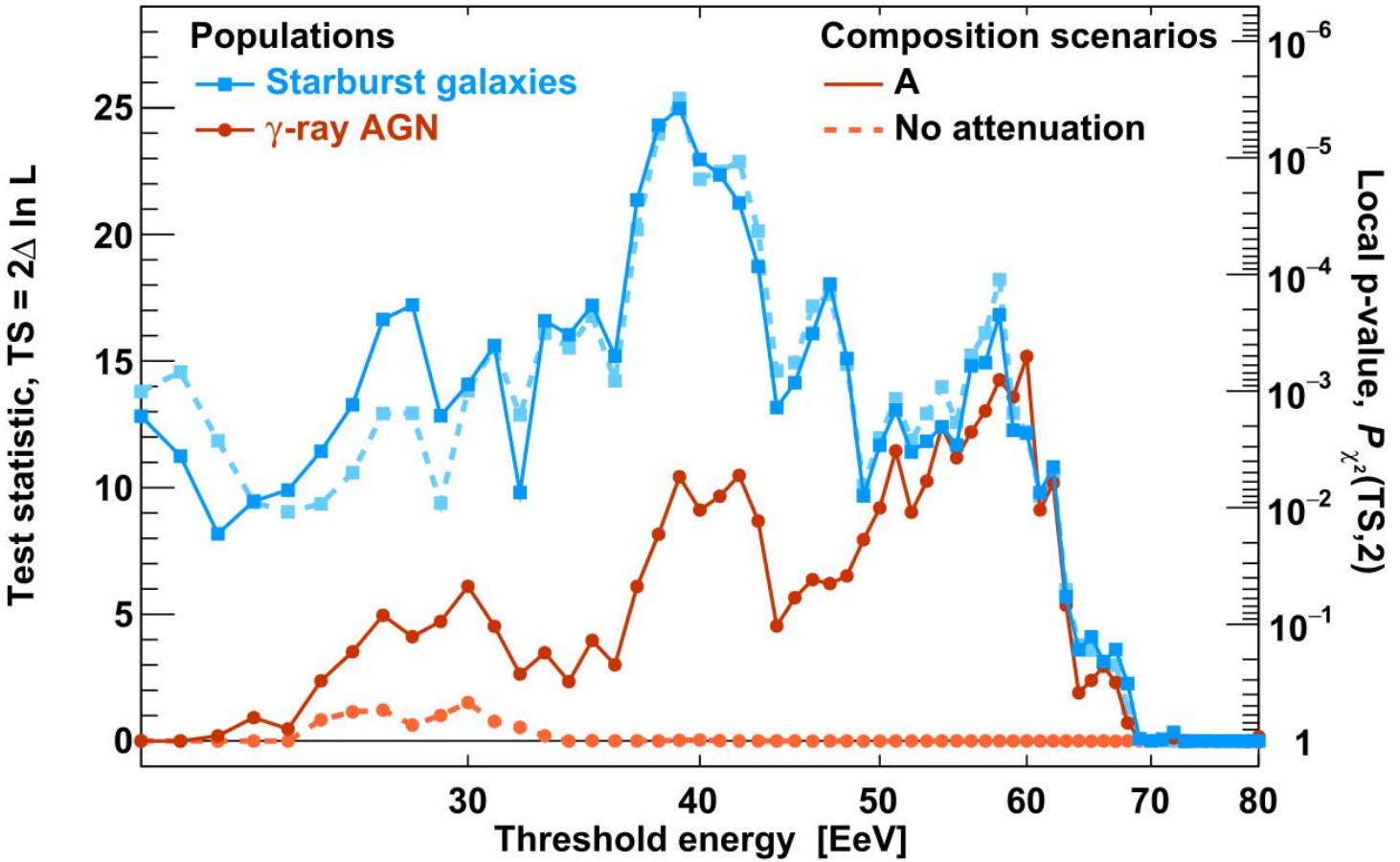
20 deg hot spots!

~ 3-σ local significance
(around Cen A – AGN 4 Mpc)



Intermediate Scale Anisotropy

[ApJ 853:L29, 2018]



← 4-σ

← 2.7-σ

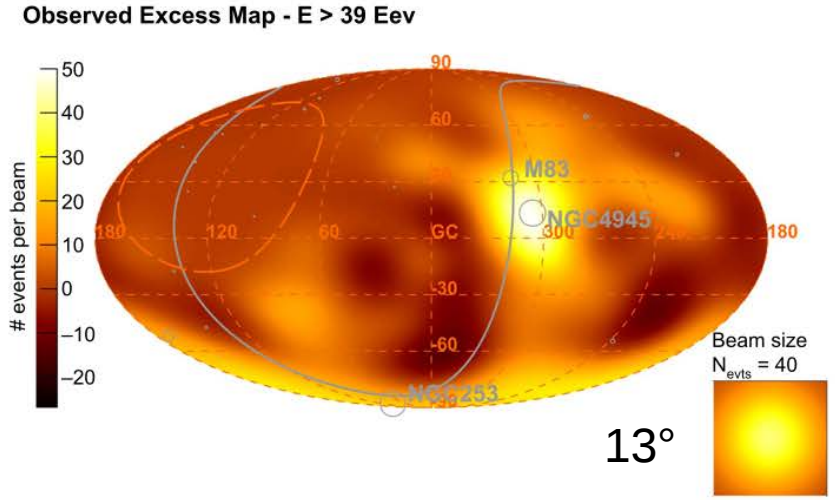
No penalization for catalogue scan!

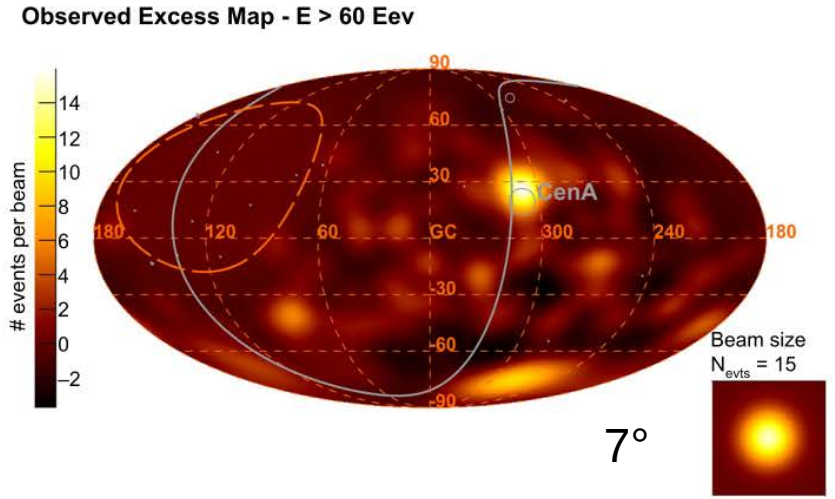
- 5514 events above 20 EeV
- 17 y-ray AGN
- 23 Starburst galaxies
- Flux-limited sources

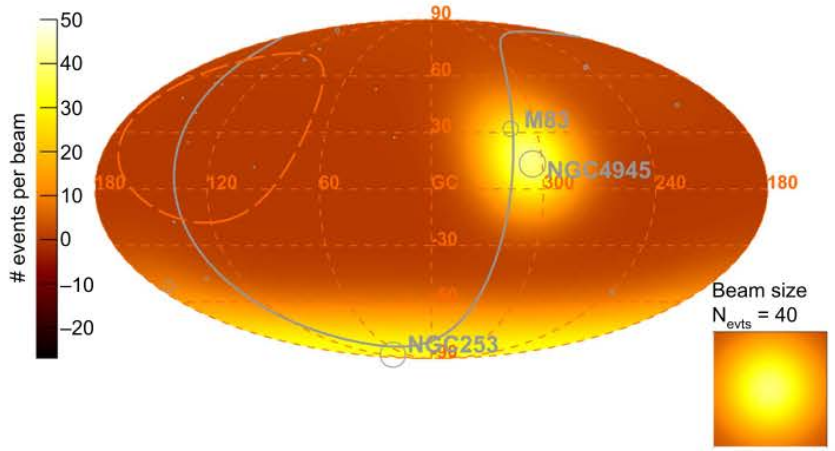
2FHL catalogue (Fermi-LAT within 250 Mpc)

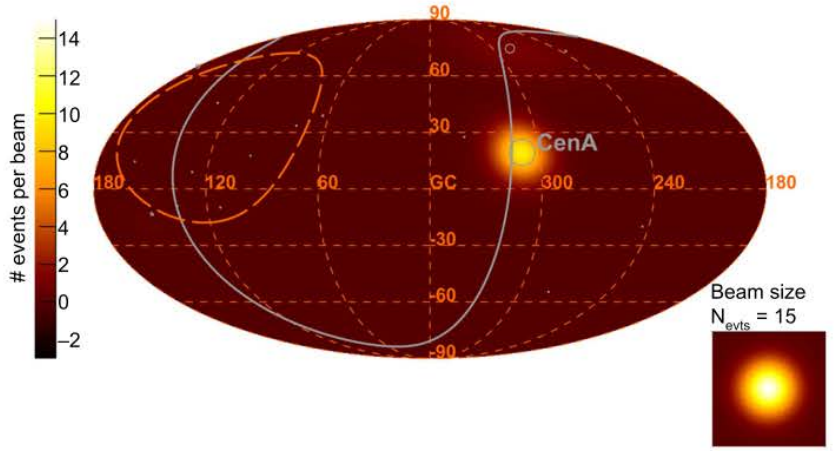
Intermediate Scale Anisotropy

[ApJ 853:L29, 2018]









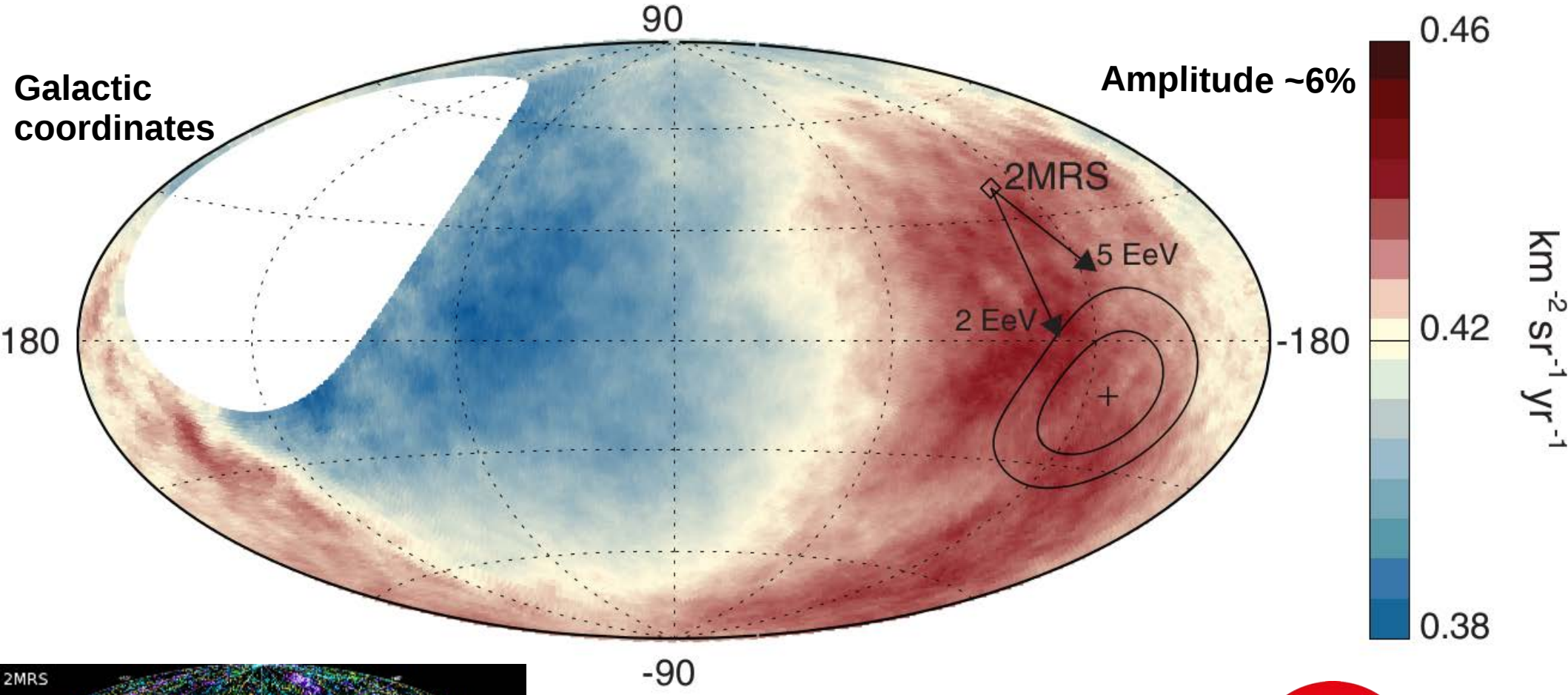
The pattern of arrival directions best matched by a model on which 10% of them arrive from the directions clustered around bright, nearby Starburst galaxies

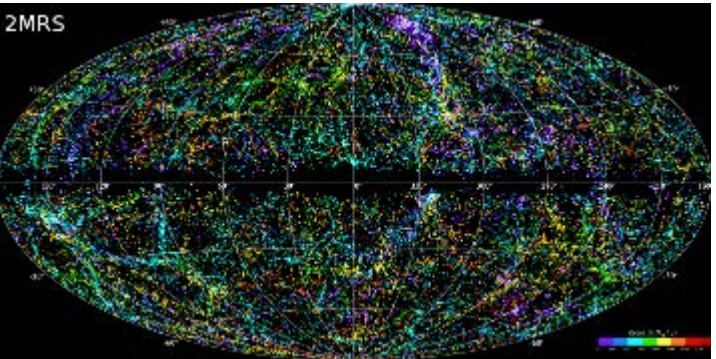
Large-scale Dipole - 5 σ discovery!

[Science 57 (2017) 1266-1270]

PIERRE AUGER OBSERVATORY

Energy above 8 EeV, 5.2 σ after all penalizations from more than 32 000 events





Extragalactic origin!

~125° from the Galactic Center

physicsworld TOP 10 BREAKTHROUGH 2017

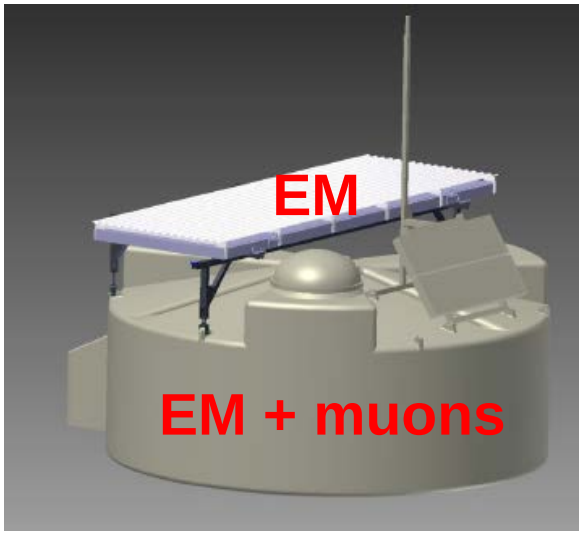
Remaining questions

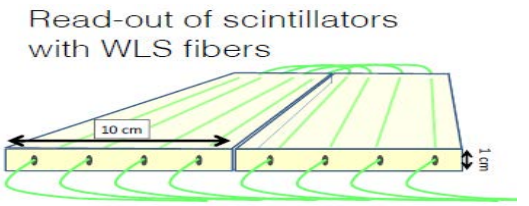
- What is the origin of the flux suppression?
- What is the proton fraction at the end of E spectrum?
- Is there a rigidity dependence of anisotropies?
- What about hadronic physics above $\sqrt{s}$ = 140 TeV?

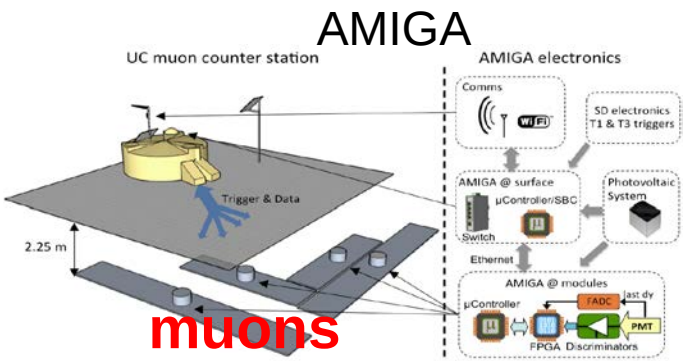
We need a large-exposure detector with good composition sensitivity!

AugerPrime – upgrade of the Pierre Auger Observatory

- Instalation of 1650 **scintillation detectors** (3.8 m^2, 1 cm thick, 3000 km^2)
- Instalation of **new electronics** (40 Mhz → 120 MHz all stations)
- Instalations of small **PMTs** (all stations saturation of SD signal from 500 m to 300 m from the shower core for log(E/eV)>19.5)
- **Cross check** with 61 **muon detectors** (30m^2 2.3m under ground - AMIGA, 750m spacing, 23.4 km^2)
- **Increase of FD exposure** by 50% at the highest energies decreasing HV on PMT







Interesting Era Ahead !

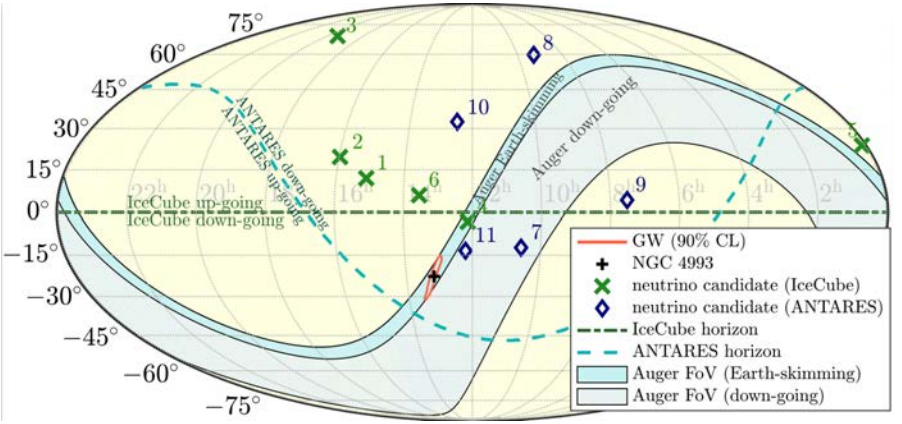
AugerPrime

PIERRE AUGER OBSERVATORY

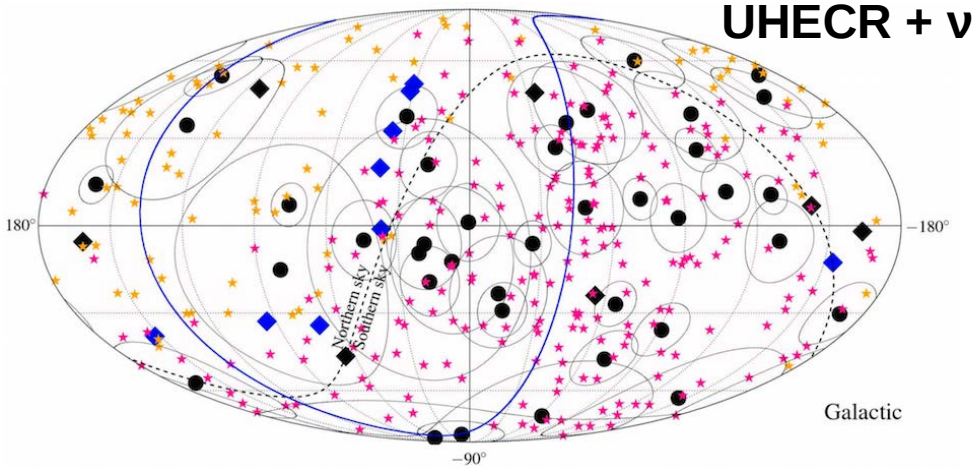
$\log_{10}(E/\mathrm{eV})$	$\mathrm{d}N/\mathrm{d}t\|_{\mathrm{infill}}$ [yr^{-1}]	$\mathrm{d}N/\mathrm{d}t\|_{\mathrm{SD}}$ [yr^{-1}]	$N\|_{\mathrm{infill}}$ [2018-2024]	$N\|_{\mathrm{SD}}$ [2018-2024]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	~1	100	7	700
19.8	-	9	-	60
20.0	-	~1	-	~9

Multi messenger astronomy

UHEν + GW

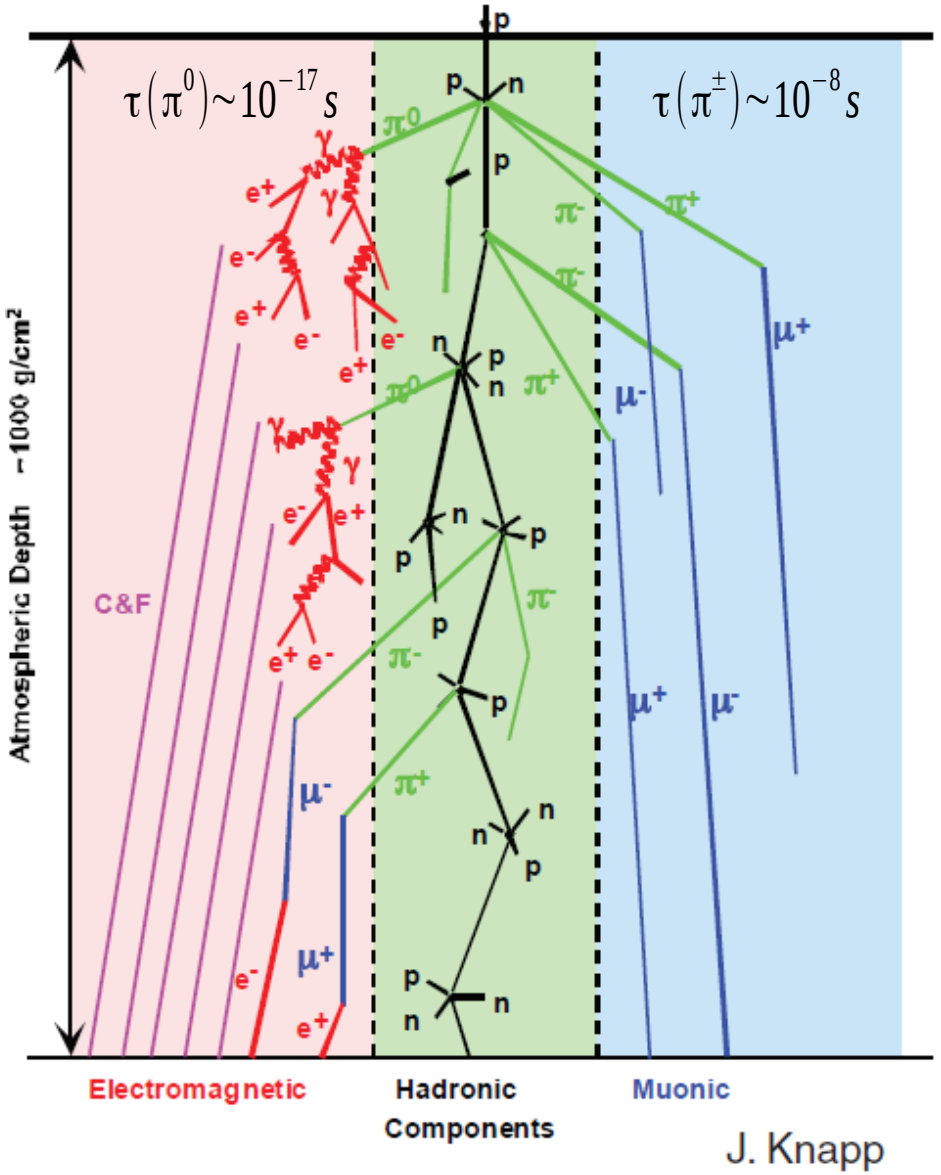


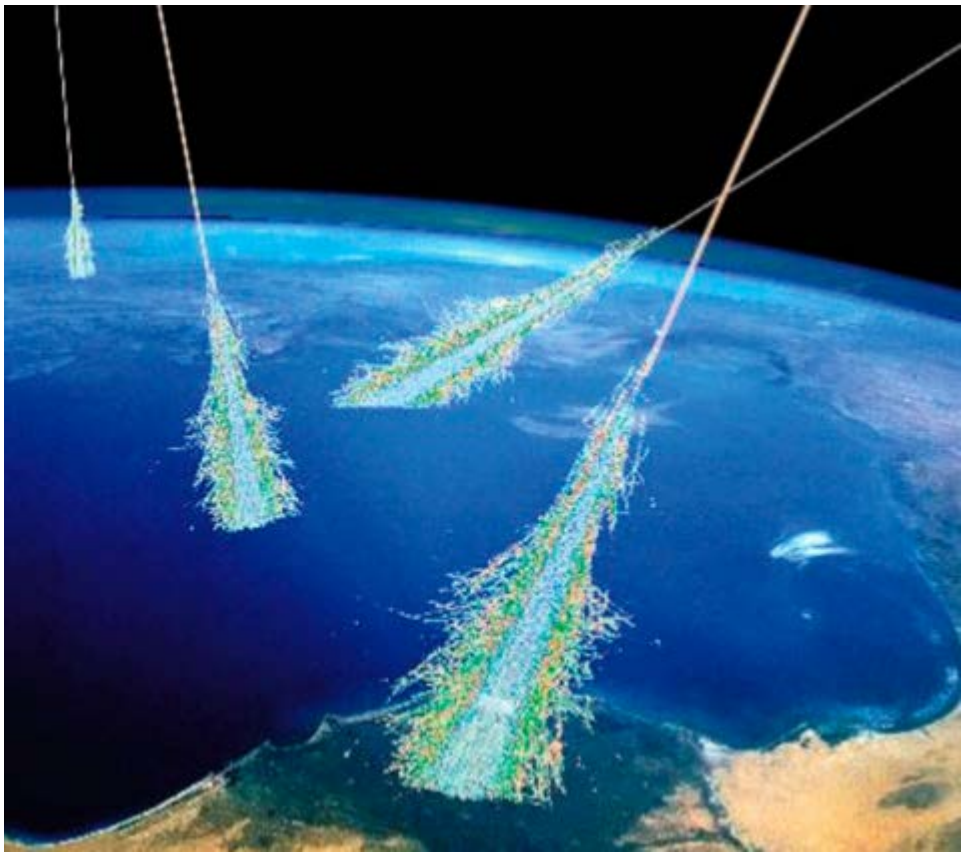
UHECR + ν



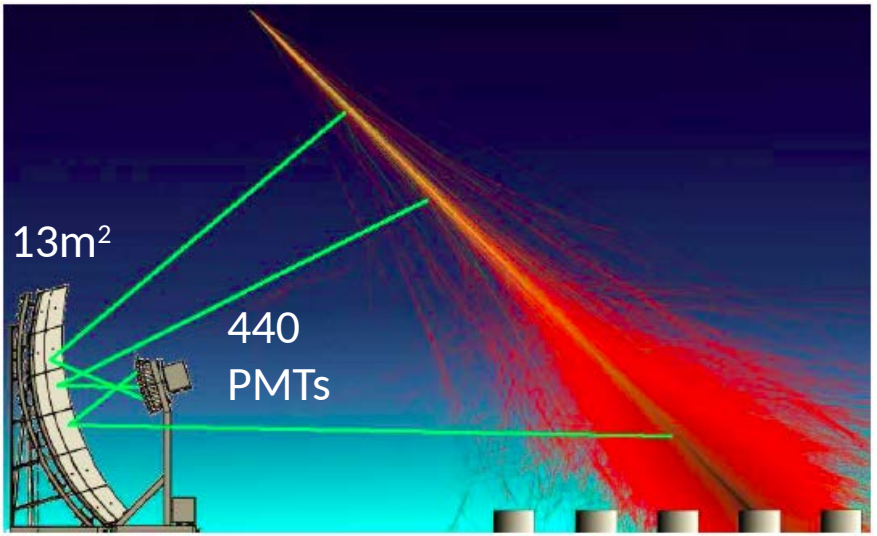
Backup slides

Extensive Air Showers

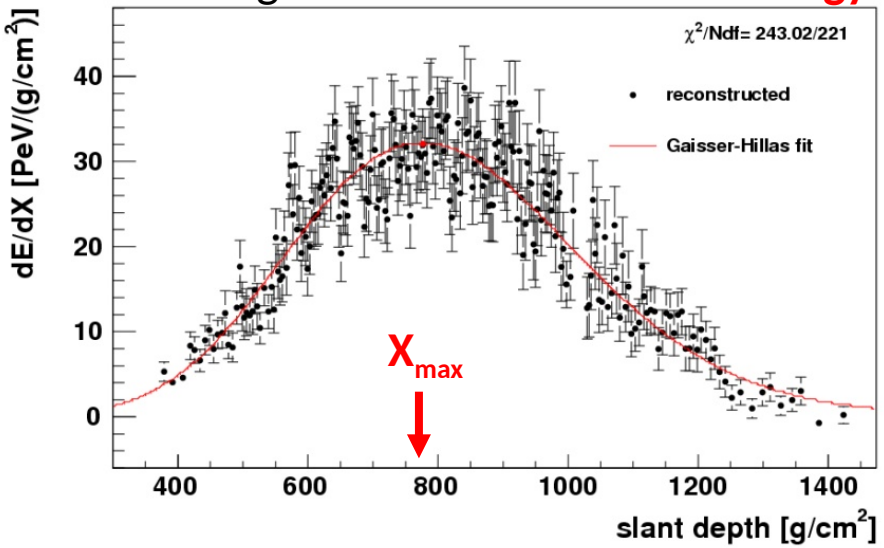




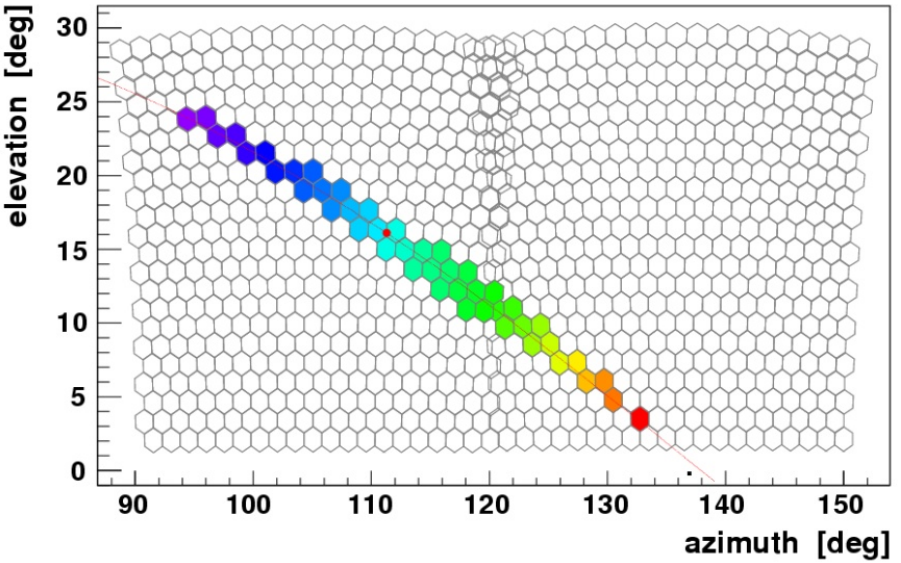
Fluorescence Detector



Integration of G.H. fit -> **cal. energy**

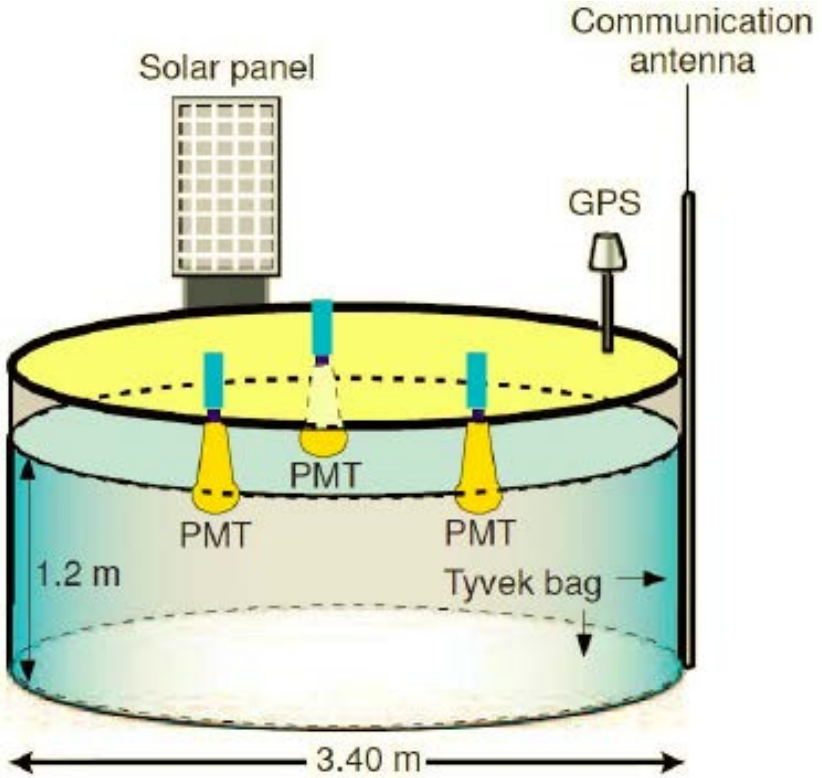


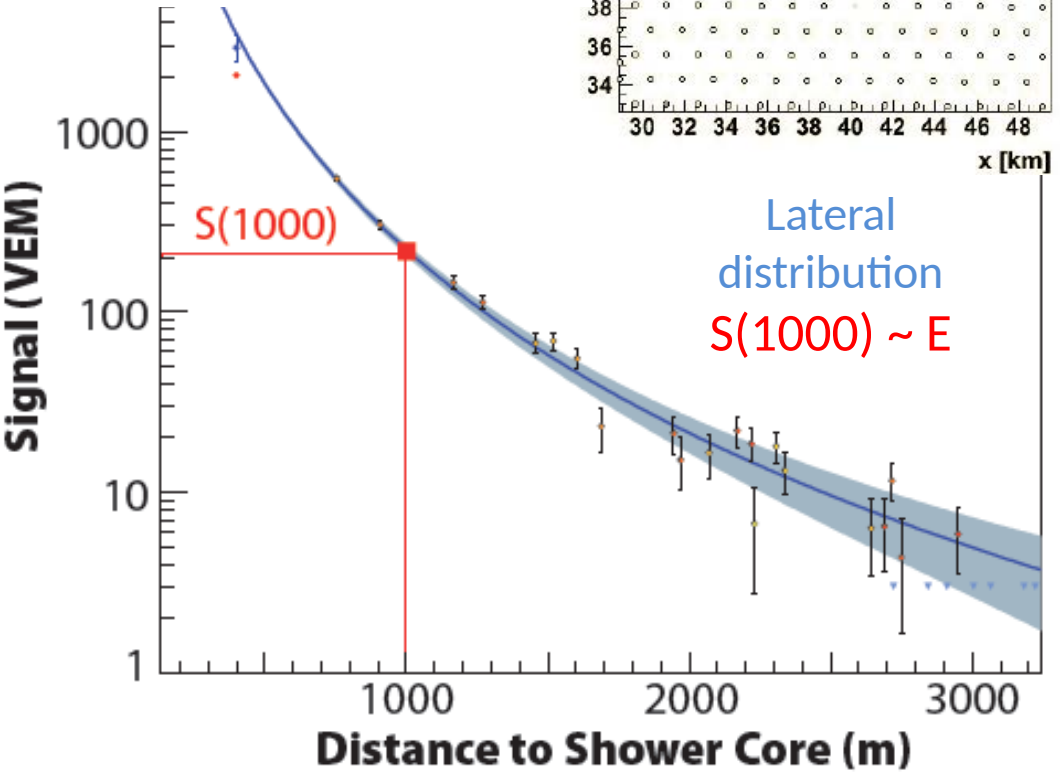
- **Calorimetric** measurement
  (+ correction for invisible energy)
- **13%** duty cycle
- Hybrid detection improves the precision of shower reconstruction

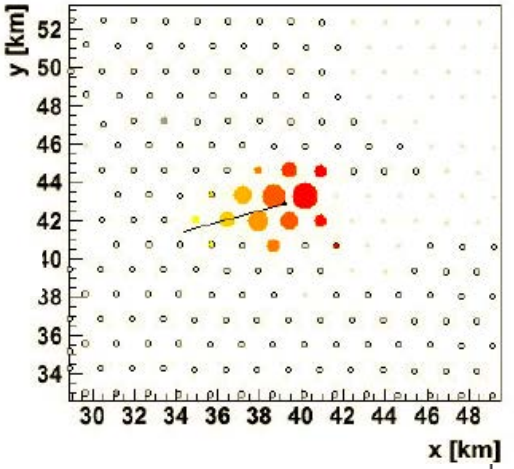


- Observation of X_{max} in FOV
- Energy resolution **7-8%**
- Sys. uncertainty decreased to **14%**

Surface Detector



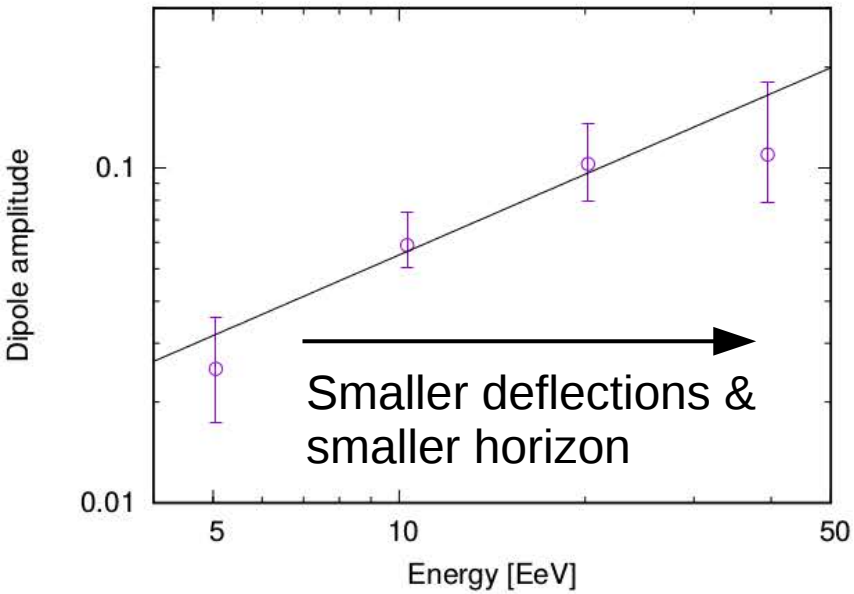


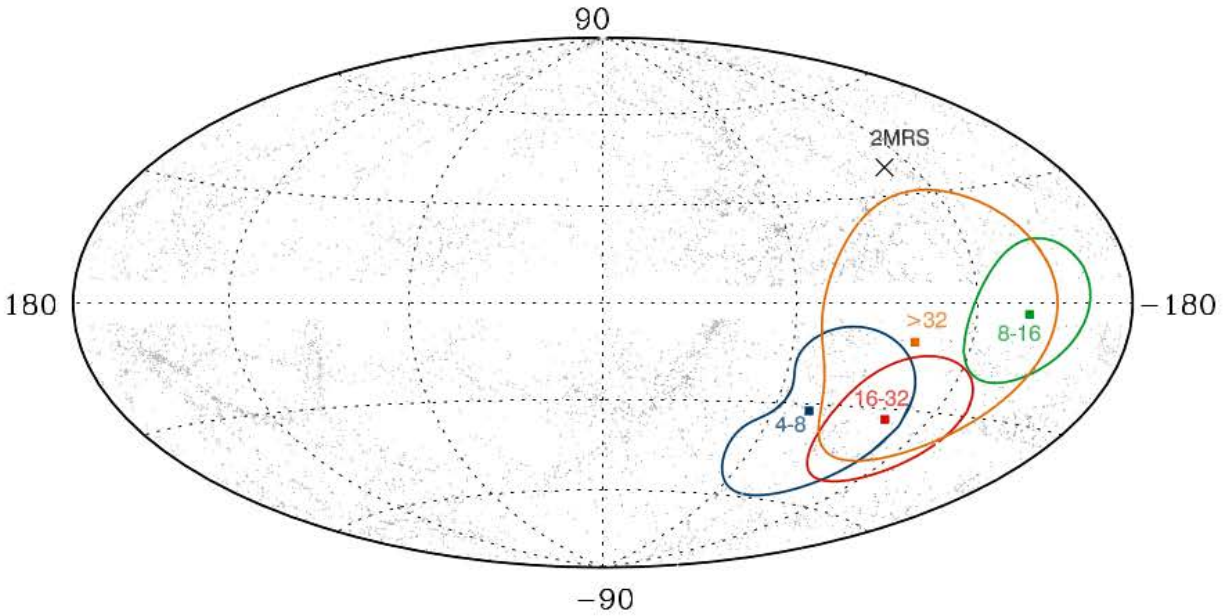


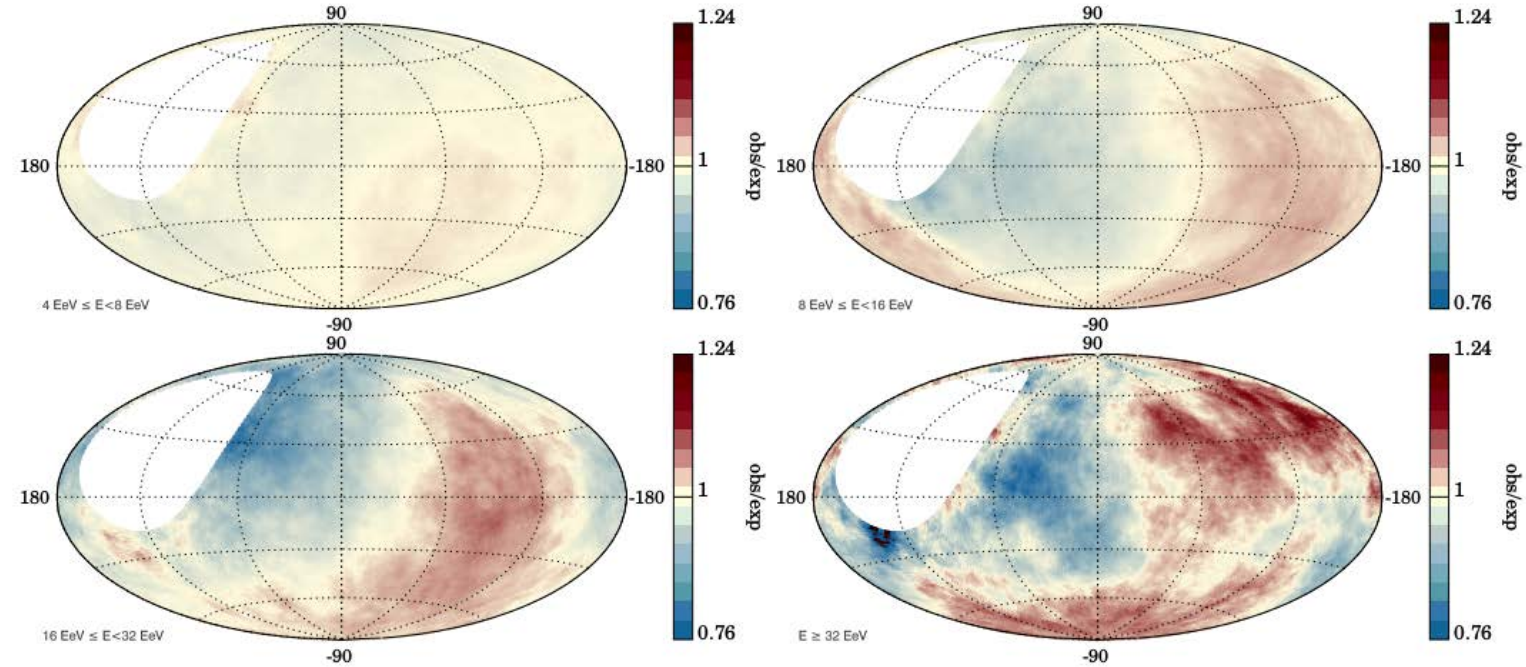
- Water Cherenkov tanks sensitive to **muons and EM** component
- **100% duty cycle**
- Signal attenuation corrected by the CIC method (data driven)
- Energy calibration using FD, resolution **17-12 %**, angular < 1° above 10 EeV
- For zenith angles **> 60°** SD signal dominantly from **muon** component

Energy dependence of dipole anisotropy

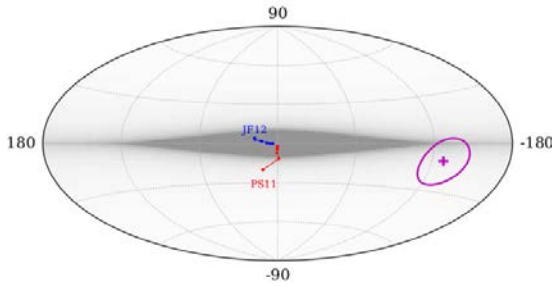
arXiv:1808.03579 [astro-ph.HE] To be submitted to ApJ





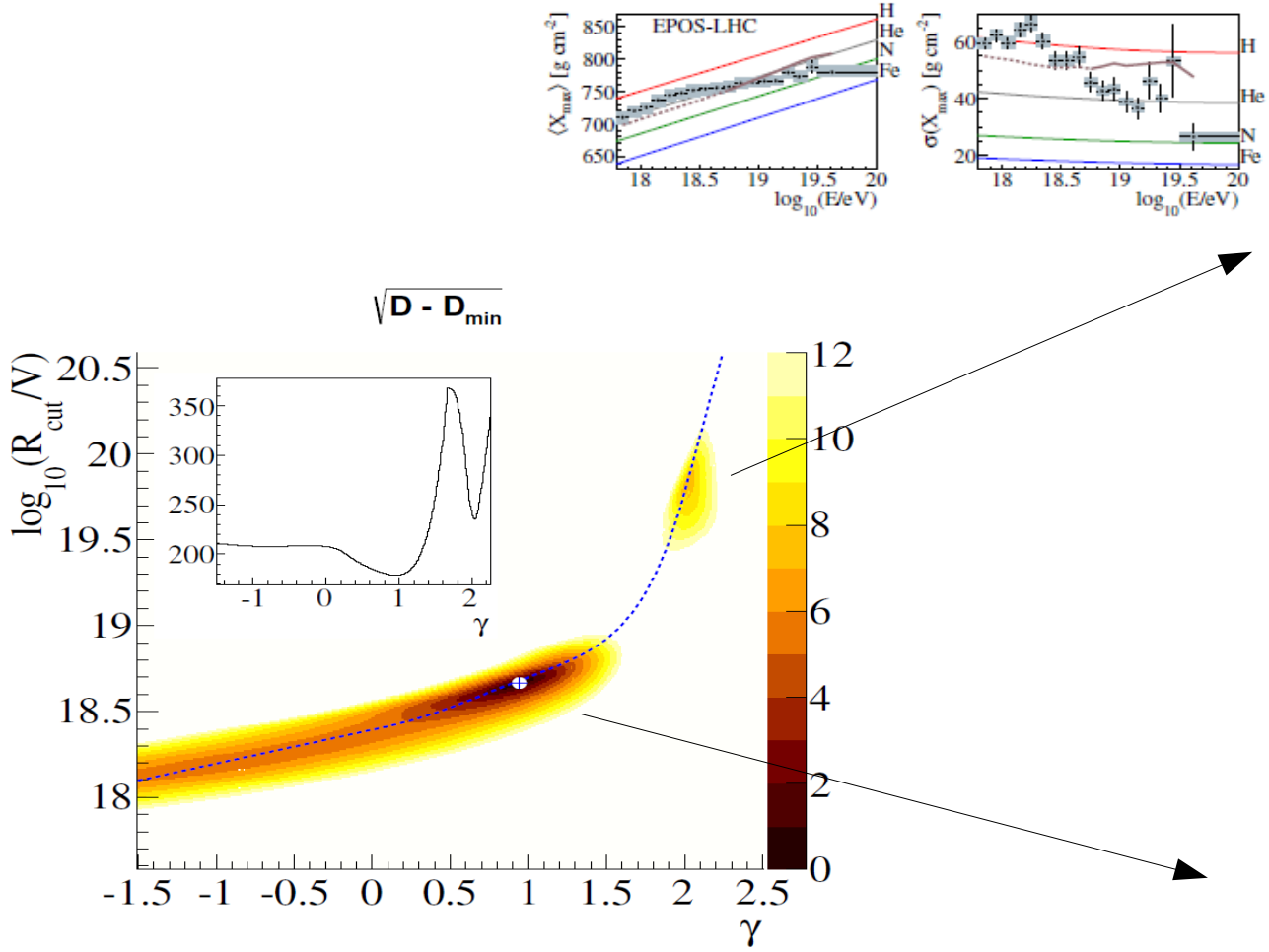


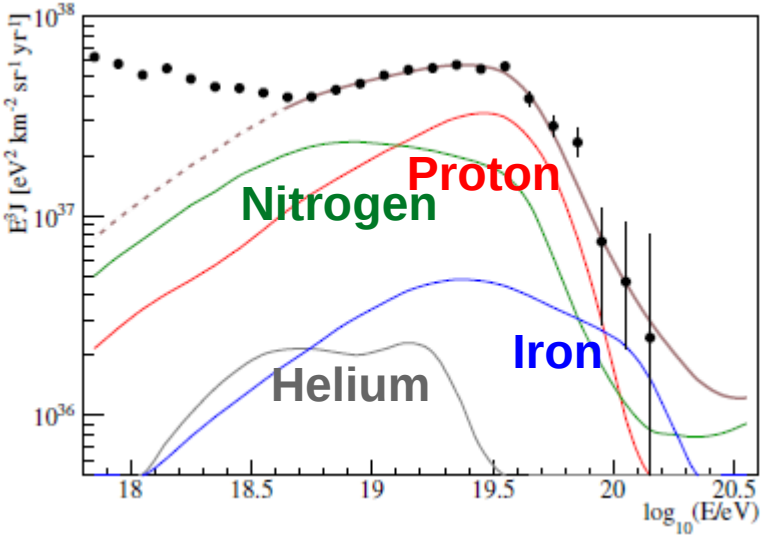
E > 8 EeV

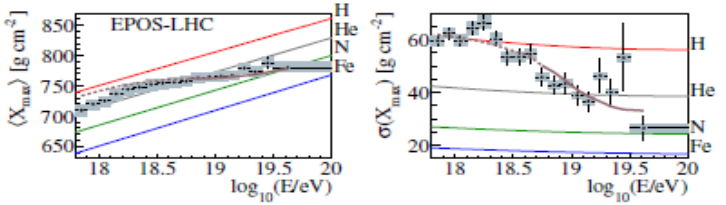


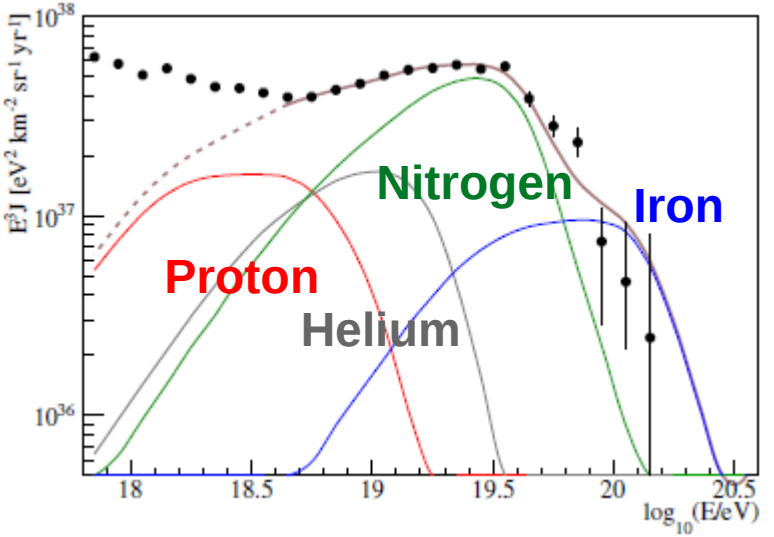
Fitting spectrum and composition

[JCAP 04 (2017) 038]



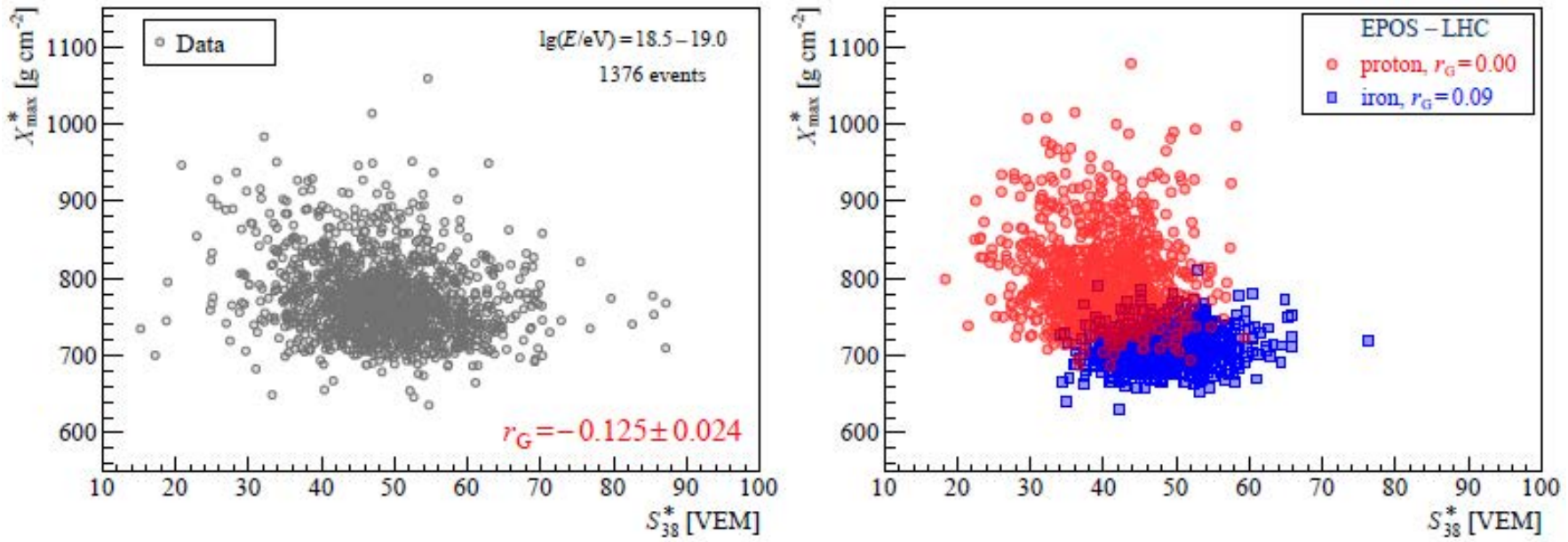






Correlation between Ground signal and X_{max}

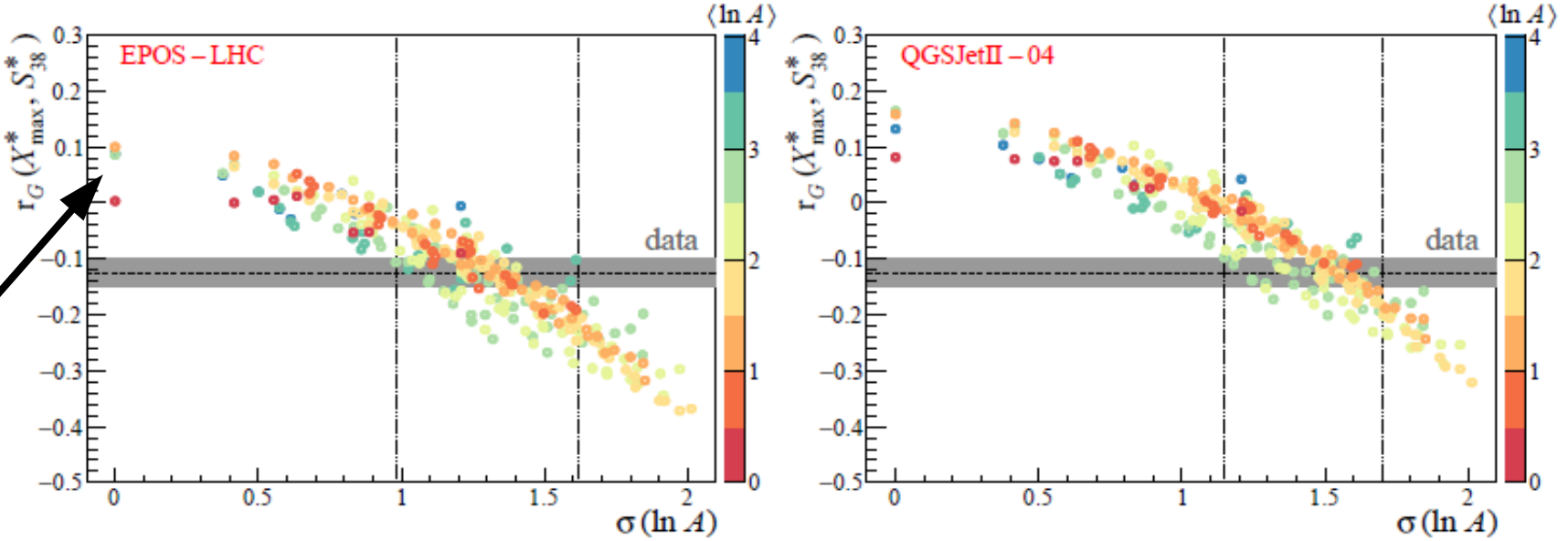
[A. Aab et al., Phys.Lett. B 762 (2016) 288-295]



Cosmic rays are of mixed composition in log(E/eV) = 18.5-19.0

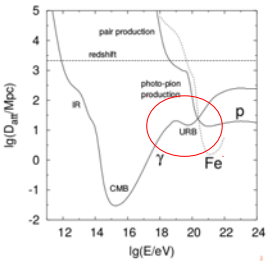
=> spectral ankle not caused by the pair production of protons!

Pure beams

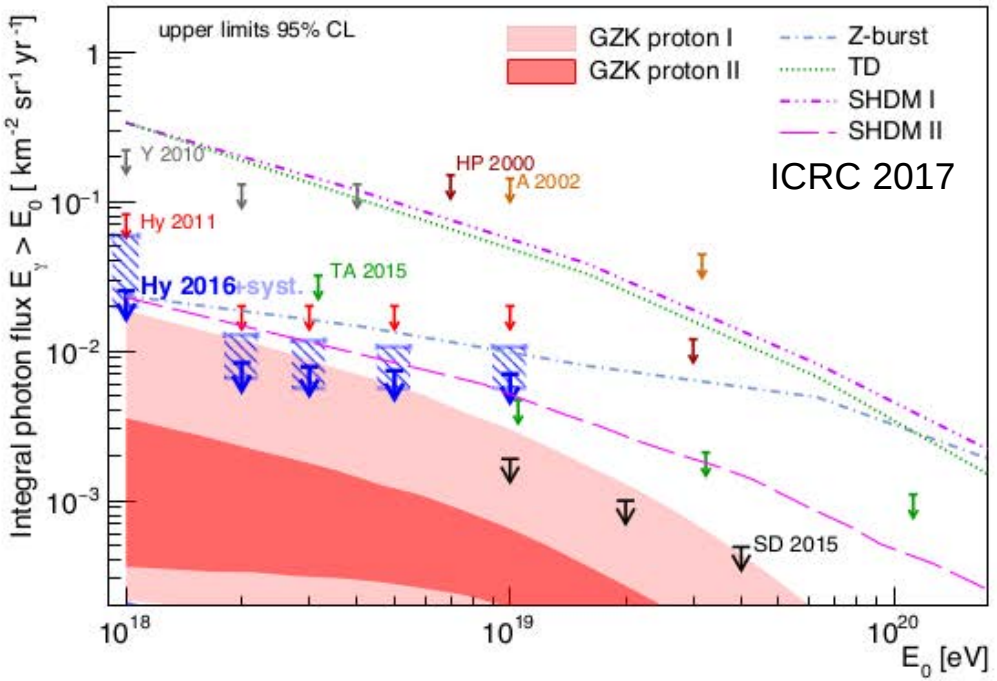


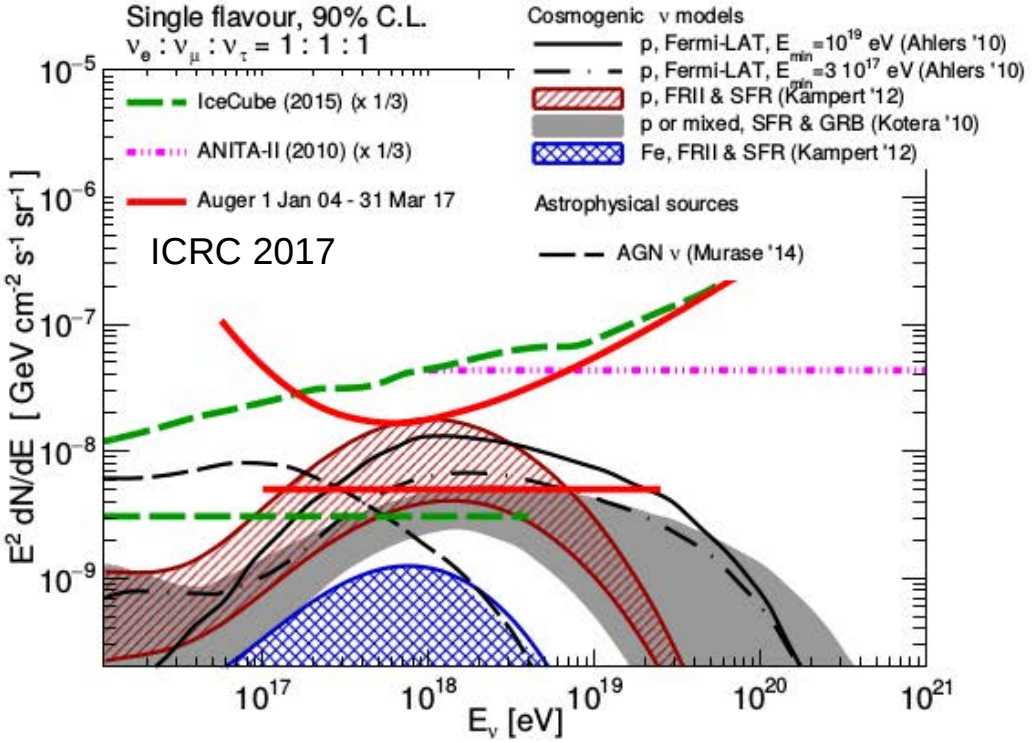
Photon and neutrino limits

$$p + \gamma_{CMB} \rightarrow p + \pi^0 \searrow \gamma\gamma$$



$$p + \gamma_{CMB} \rightarrow n + \pi^+ \searrow e^+ + 3\nu$$

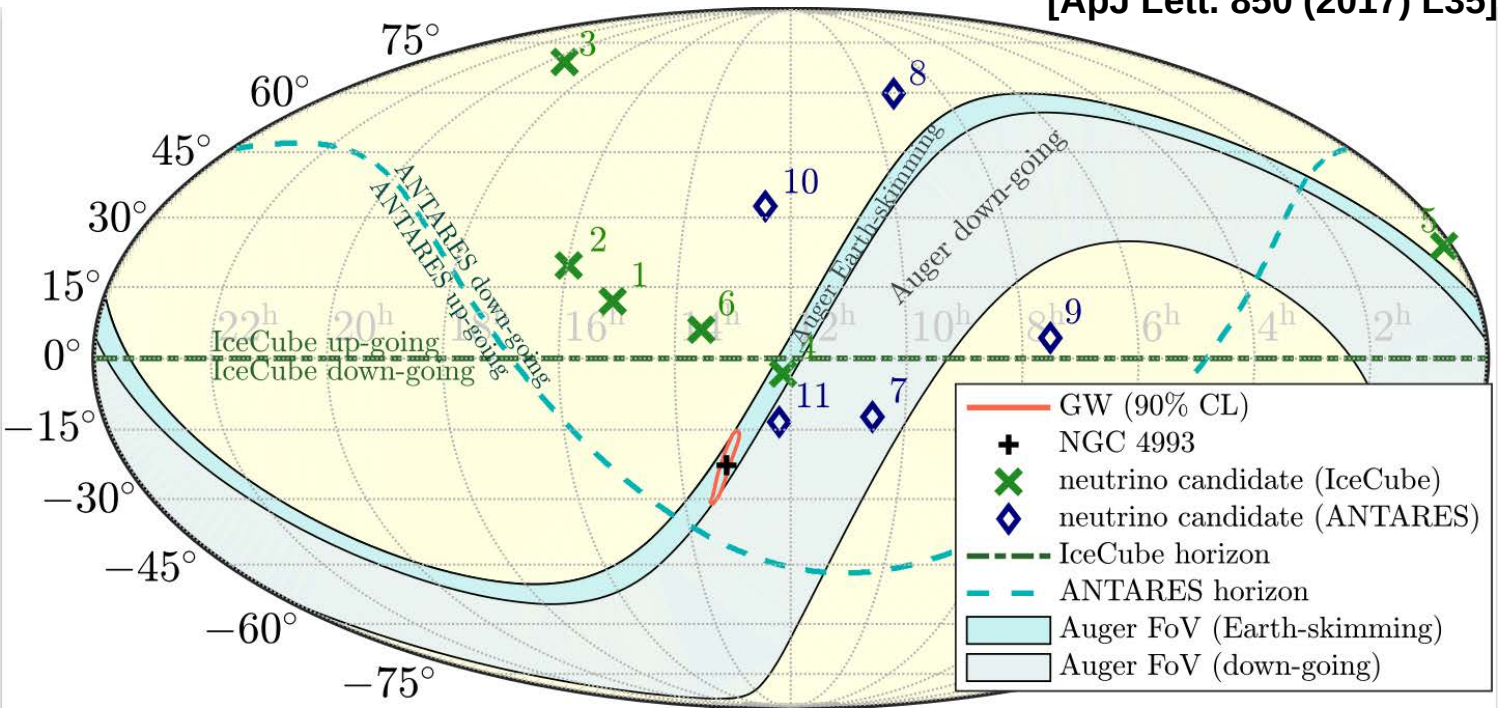


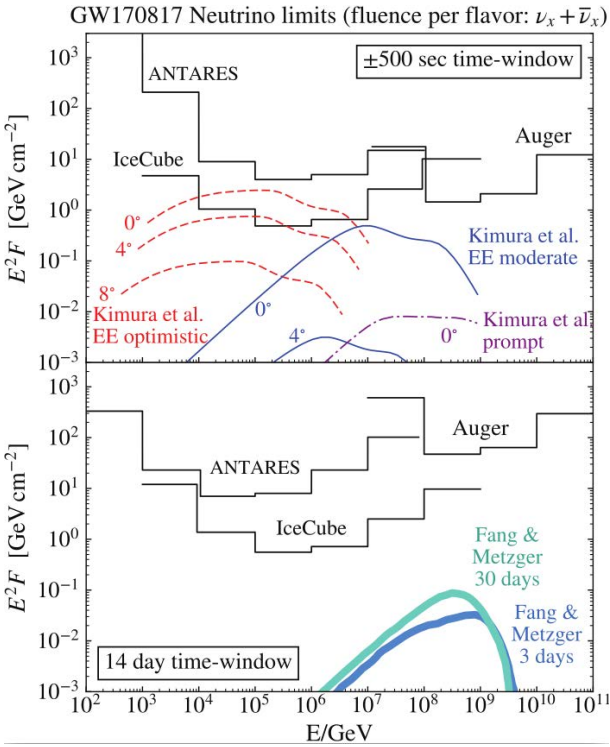


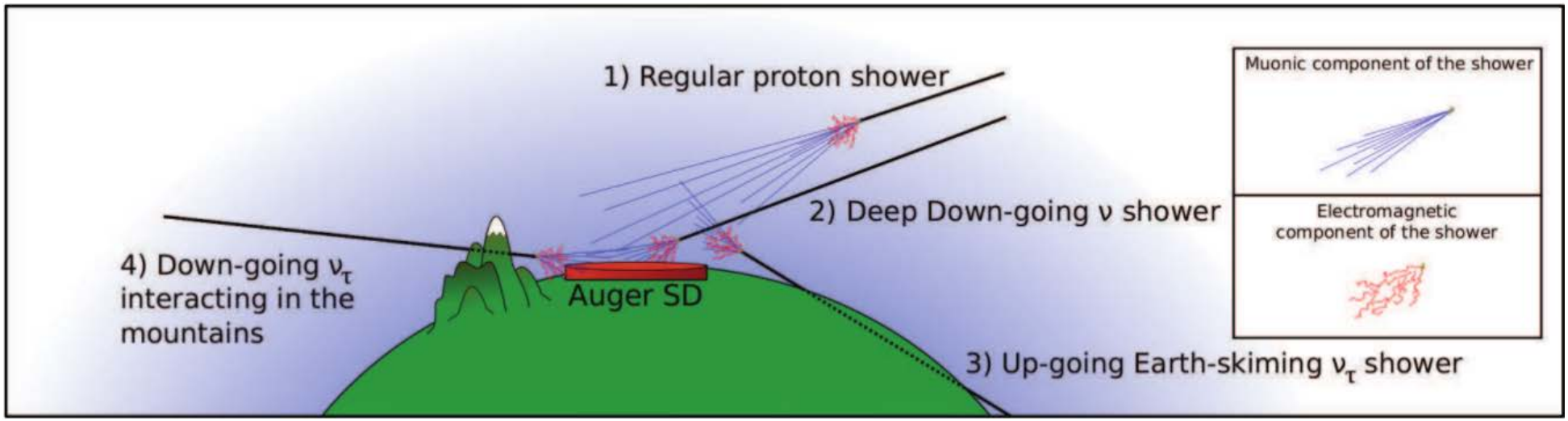
Exotic Top-down models ruled out to be dominant sources of UHECR

Auger neutrino follow-up of GW

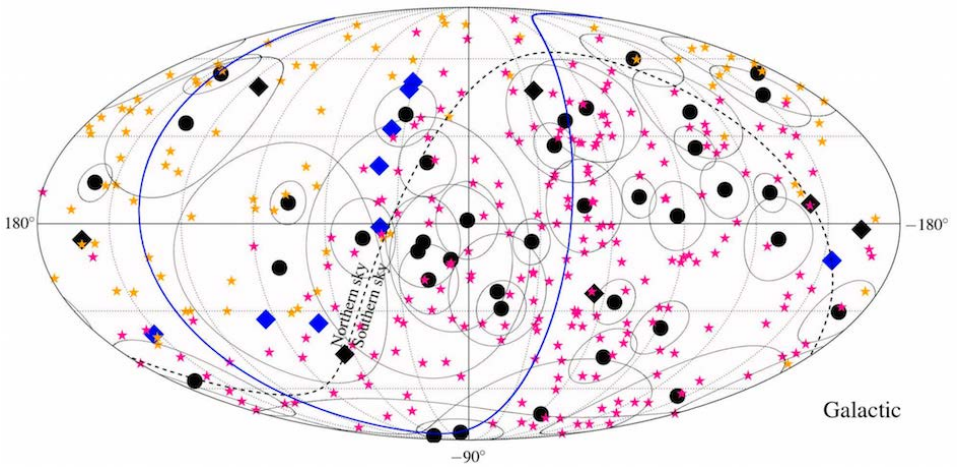
[ApJ Lett. 848 (2017) L12]
[ApJ Lett. 850 (2017) L35]





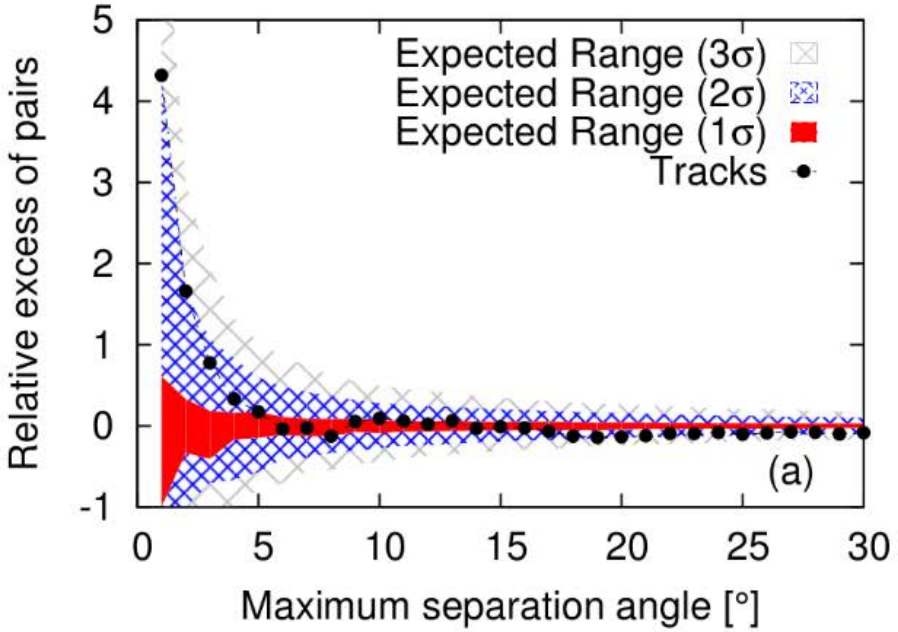


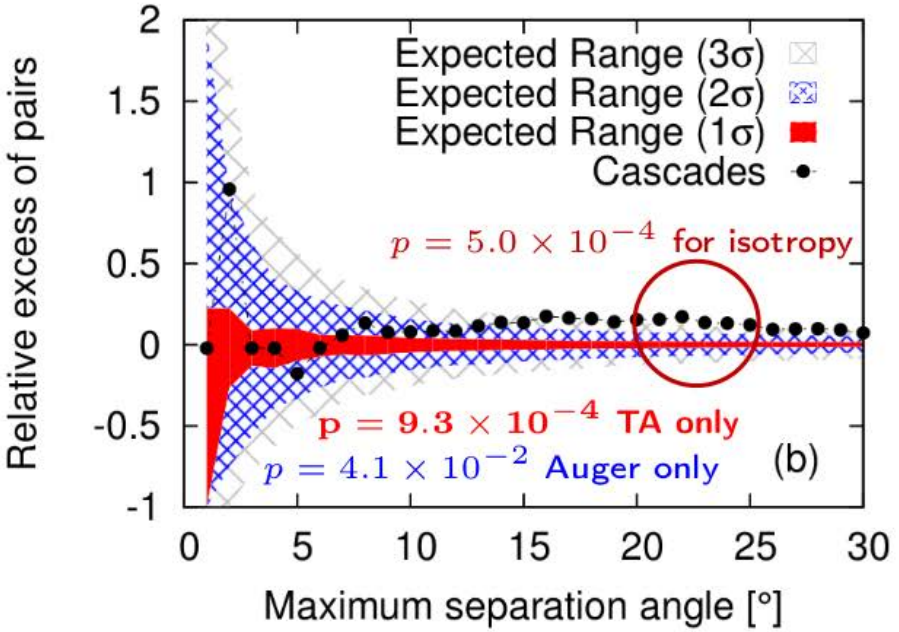
Cross-correlation of UHECR with neutrinos



- **IceCube high energy track-like and cascade events**

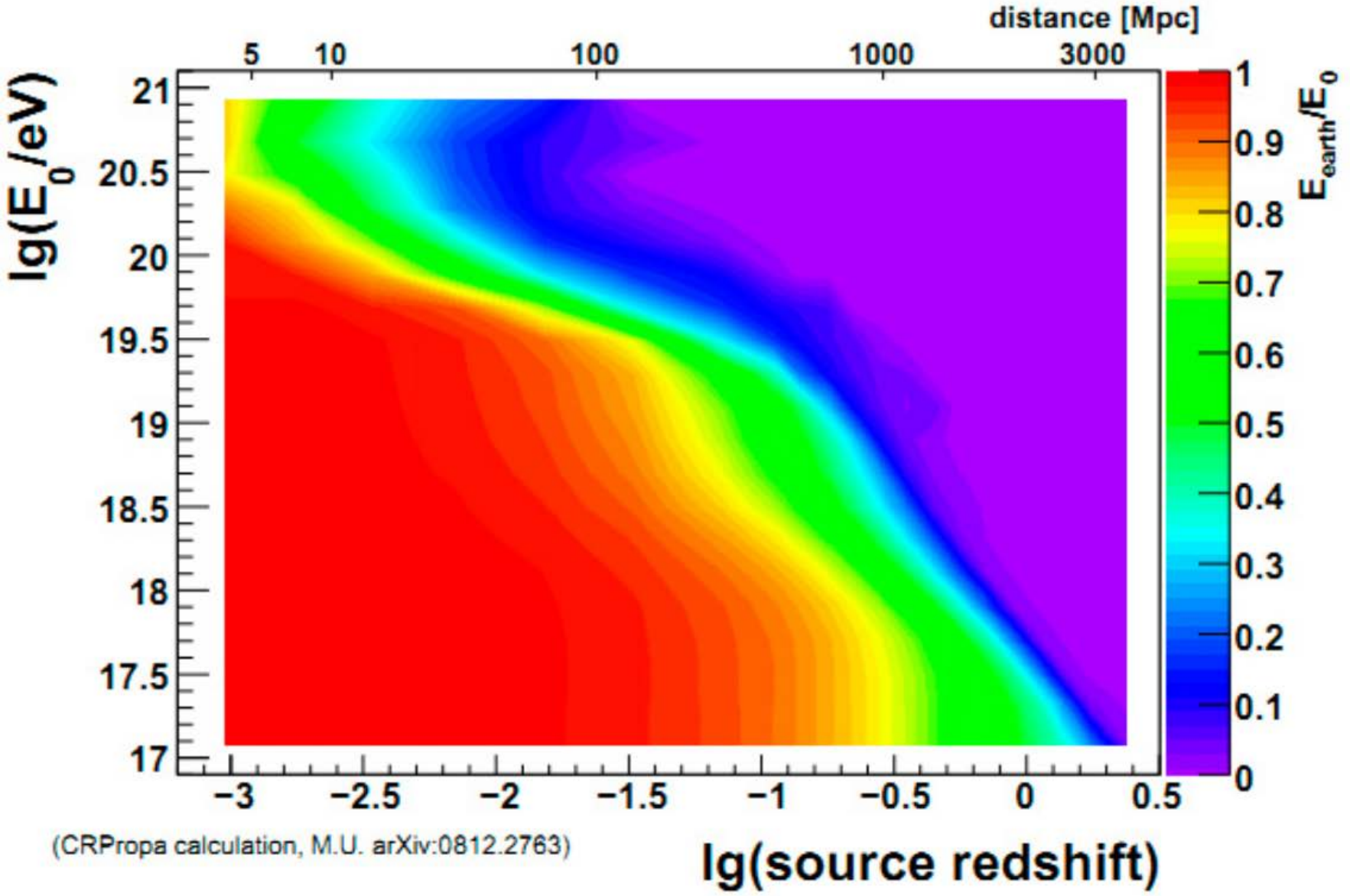
[JCAP 01 (2016) 037]



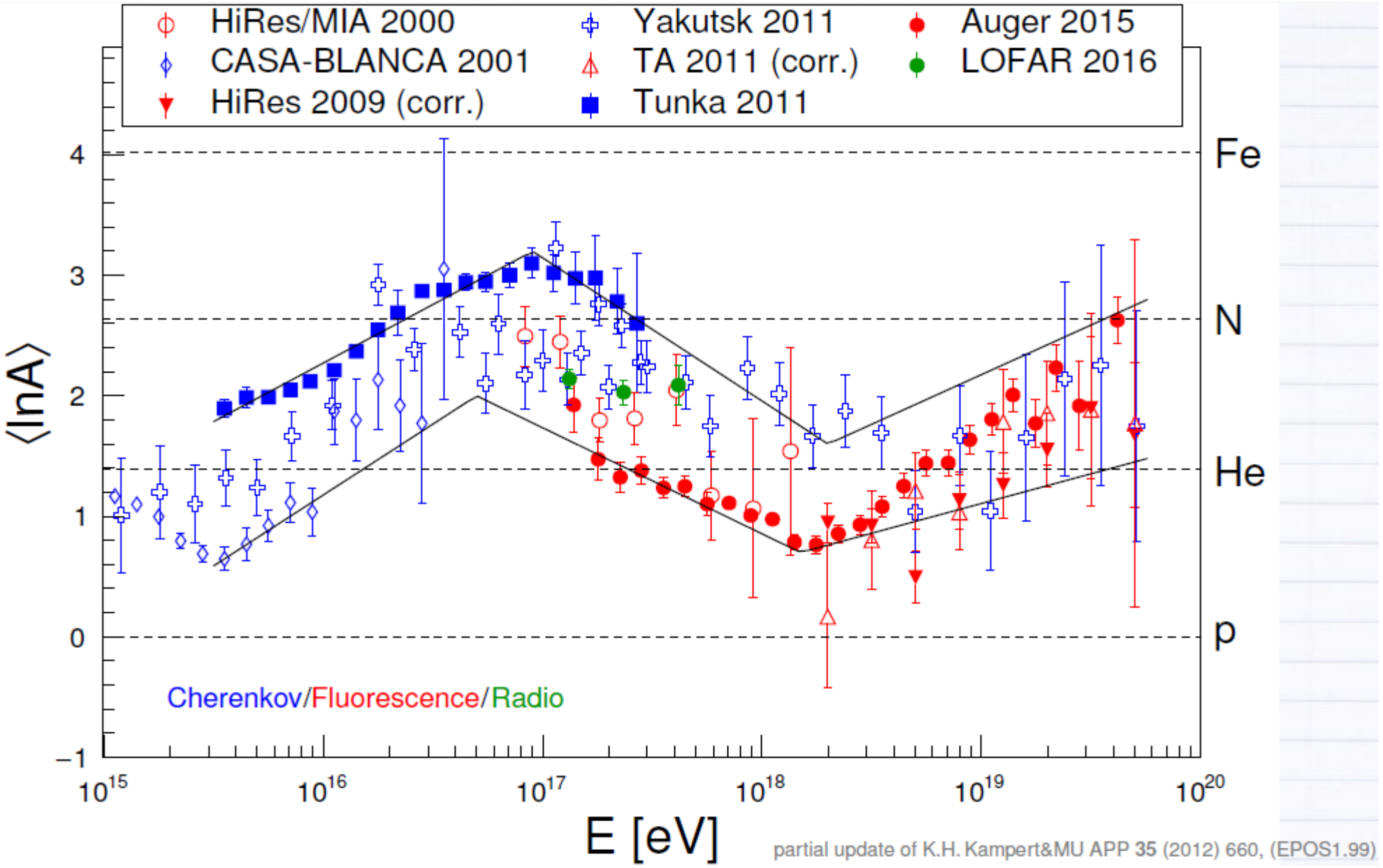


Propagation of extragalactic protons

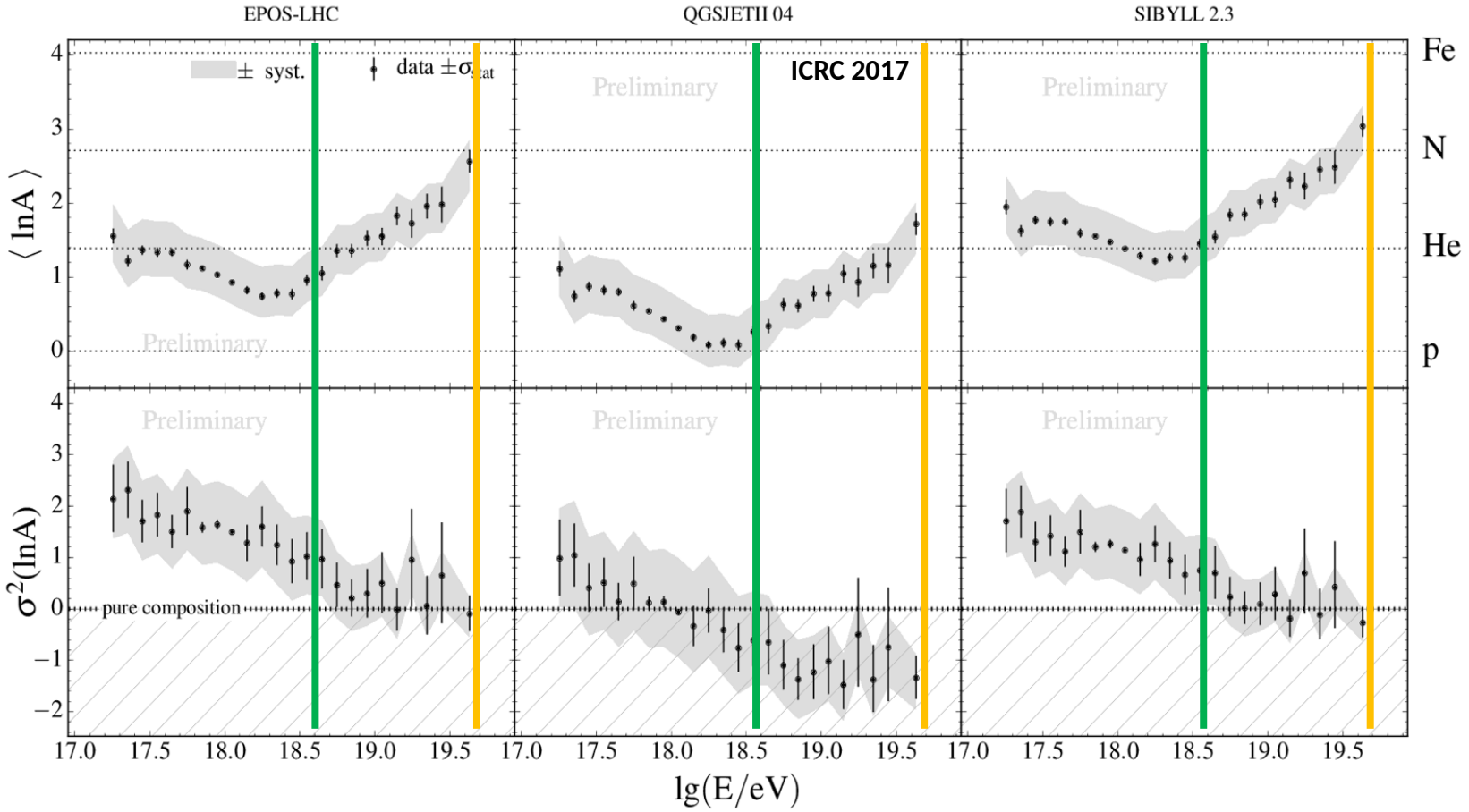
redshift + $p + \gamma_{CMB} \rightarrow p + e^+ + e^-$ + $p + \gamma_{CMB} \rightarrow p + \pi^0$



X_{max} measurements



Mass composition – X_{max} moments interpreted with ln A moments



Ankle

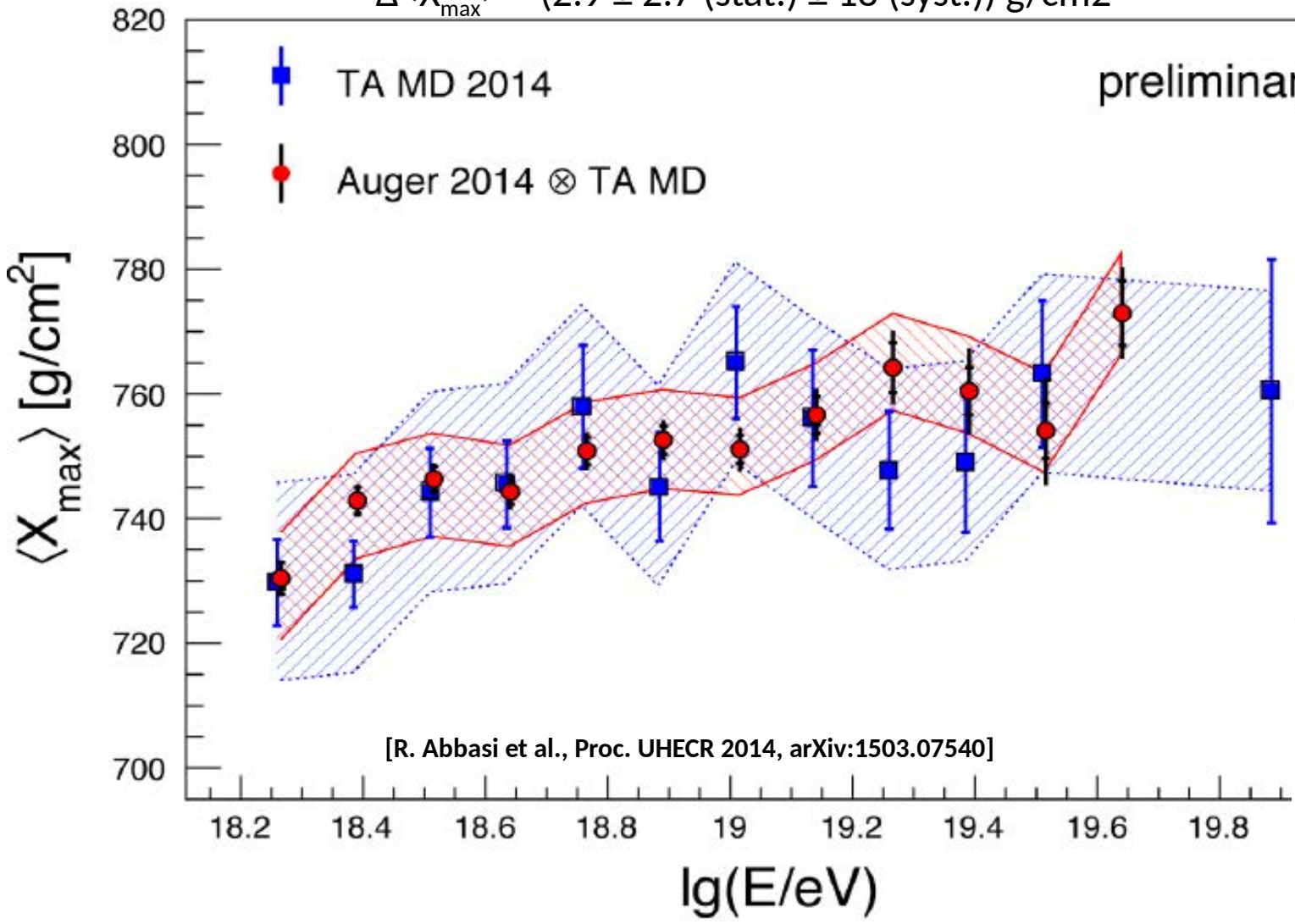
$$\langle \ln A \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{f_E}$$

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{\mathrm{sh}}(\langle \ln A \rangle)}{b\ \sigma_p^2 + f_E^2}$$

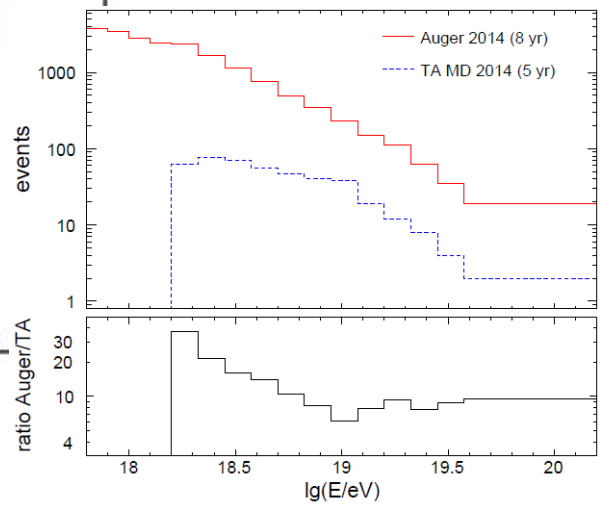
Beginning of Suppression

$\langle X_{max} \rangle$ measurements of the Pierre Auger Observatory and Telescope Array are in good agreement !

$\Delta\langle X_{max} \rangle$ = (2.9 ± 2.7 (stat.) ± 18 (syst.)) g/cm2



[R. Abbasi et al., Proc. UHECR 2014, arXiv:1503.07540]



Measurement of the Muon Production Depth at the Pierre Auger Observatory

[A. Aab et al., Phys. Rev. D 90, 012012 (2014)]