Status and future perspectives on Ultra-High Energy Cosmic Rays

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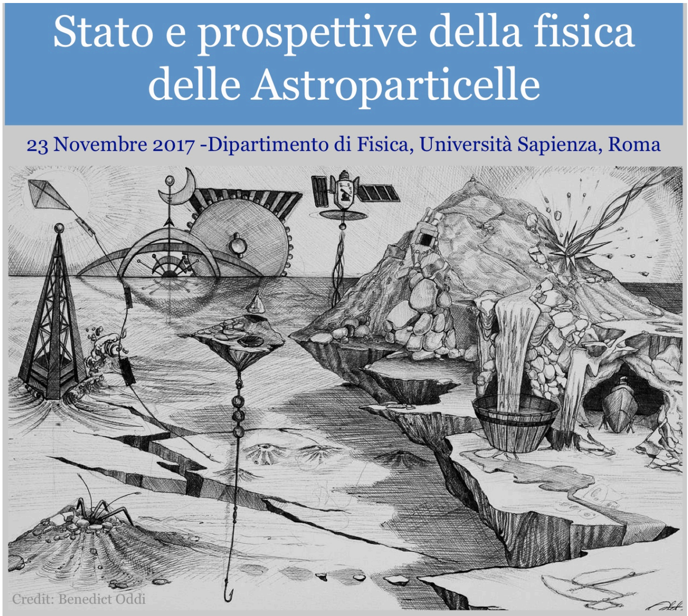

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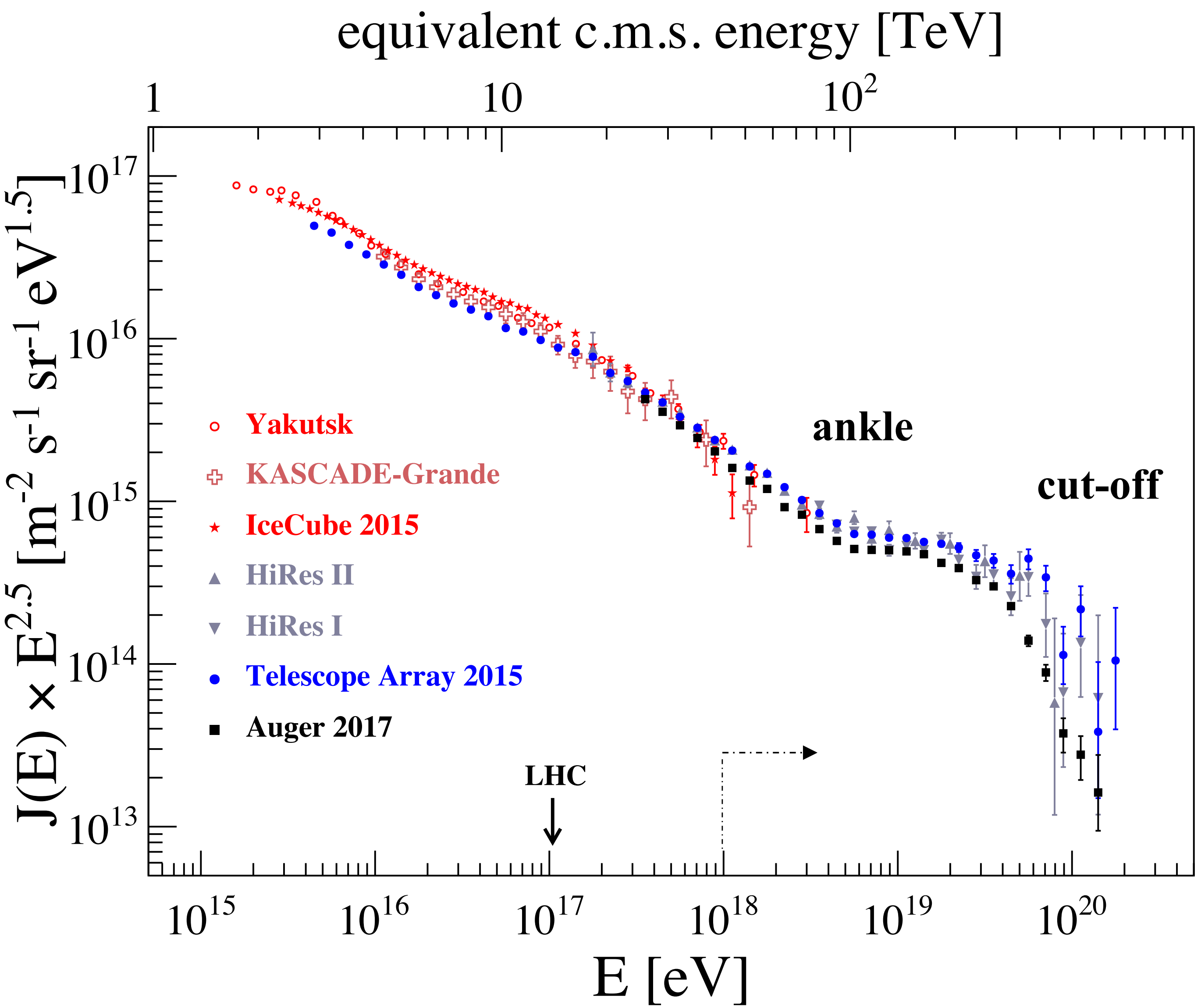
SAPIENZA UNIVERSITÀ DI ROMA
ARAP Associazione Romana per le Astro-Particelle
ROMA TRE UNIVERSITÀ DEGLI STUDI DIPARTIMENTO DI FISICA
UNIVERSITA' degli STUDI di ROMA TOR VERGATA
IFSC

ENERGY SPECTRUM



$\sqrt{s} \cong \sqrt{2 m_p E / A}$

at 10^{20} eV
~ 400 TeV

$$\frac{dN}{dE} \sim \frac{1}{E^3}$$

at 10^{20} eV
~ 1 part./km^2/century

note: at 10^{15} eV
~ 1 part./m^2/year

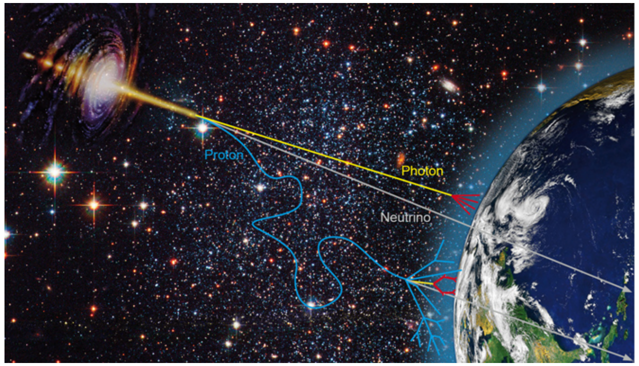
UHECR = Ultra-High Energy Cosmic Rays

SOURCES IDENTIFICATION

- nuclei (from p to Fe) likely of extragalactic origin

$$r_L[\text{kpc}] \sim \frac{E[\text{EeV}]}{Z\ \ B[\mu G]} \qquad B = 2 - 3\ \mu G$$

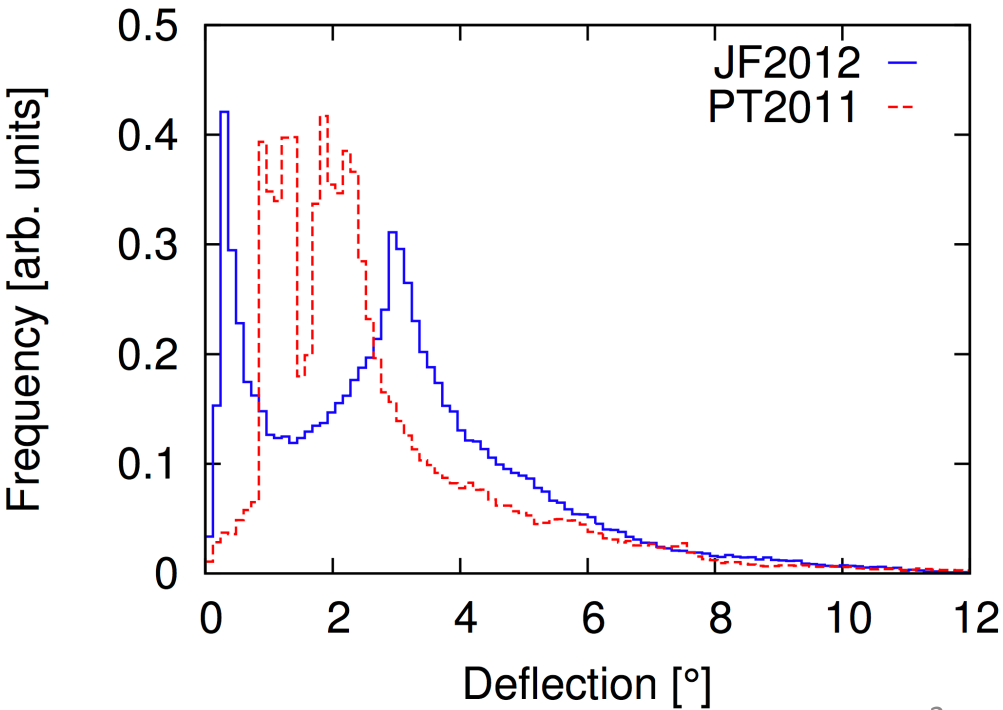
thickness of galactic disk ~ 300 pc



- sources identification possible if deflections in galactic and inter-galactic magnetic fields are small

IceCube Auger Telescope Array
JCAP 01 (2016) 037
and references therein

Galactic B E/Z = 100 EeV



- mass composition is crucial

PROPAGATION

interaction with the CMB

GZK effect $\quad p\,\gamma_{CMB} \rightarrow N\,\pi \qquad E_{th} \approx \frac{m_p m_\pi}{2\,\varepsilon_{CMB}} \approx 10^{20}\,eV$

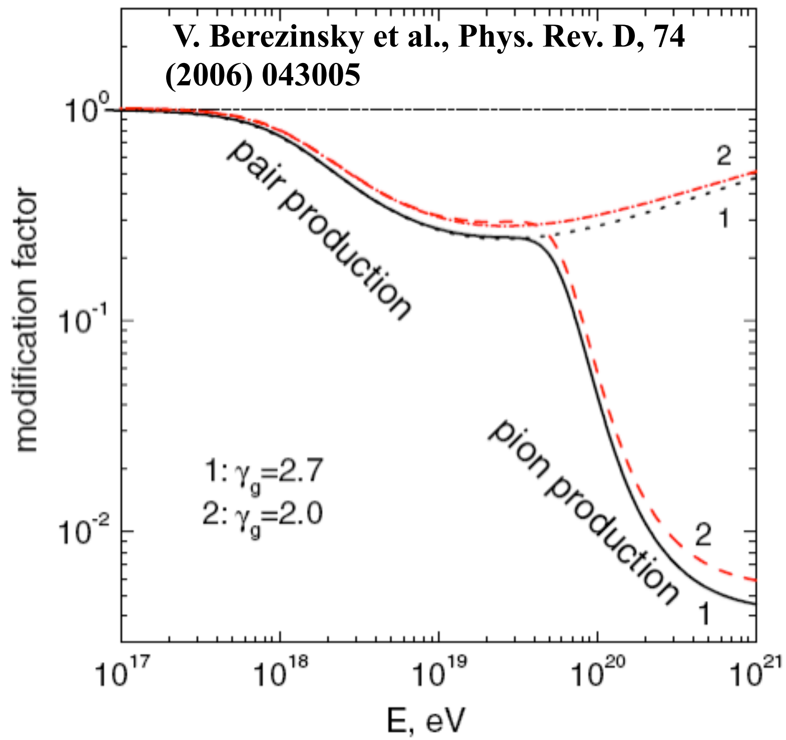
K. Greisen, Phys. Rev. Lett., 16 (1966) 748
G.T. Zatsepin and V.A. Kuz'min, Sov. Phys. JETP Lett., 4 (1966) 114

abrupt suppression consistent with the GZK cut-off

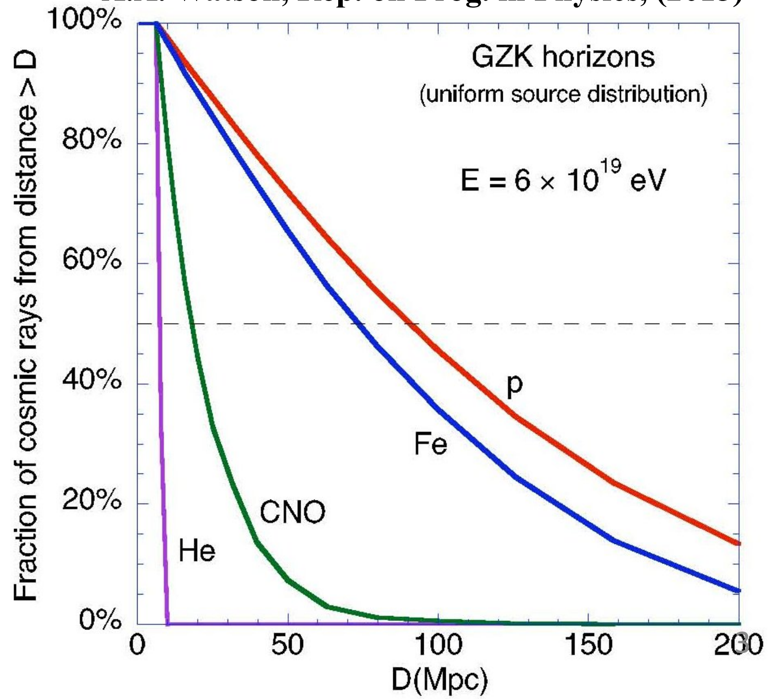
ankle consistent with
$p\,\gamma_{CMB} \rightarrow p\,e^+e^-$

- GZK horizon depends on primary mass
- mass composition at Earth ≠ from the one at the sources

$A\,\gamma_{CMB} \rightarrow A\text{-}1\;N$



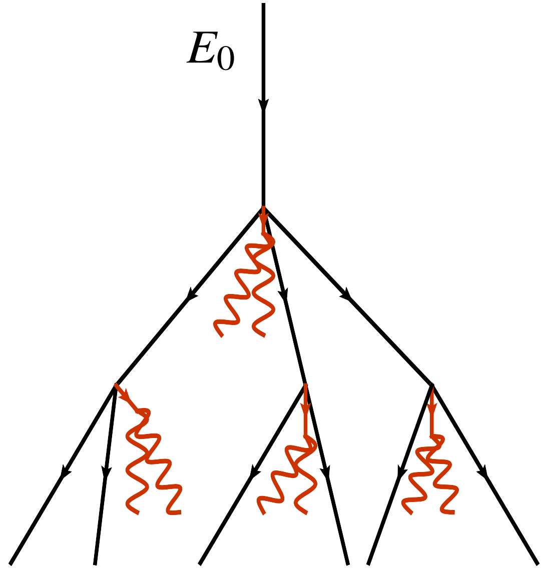
A.A. Watson, Rep. on Prog. in Physics, (2015)



ATMOSPHERIC SHOWERS

J. Matthews, Astropart. Phys. 22 (2005) 387

R. Engel ICRC 2015



$\pi^+\pi^-$ Hadronic energy

$\frac{2}{3}E_0$

$\frac{2}{3}\left(\frac{2}{3}E_0\right)$

⋮

$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0$$

$\pi^\pm \to \mu\nu_\mu$

Electromagnetic energy $\pi^0 \to \gamma\gamma$

$\frac{1}{3}E_0$

$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$

⋮

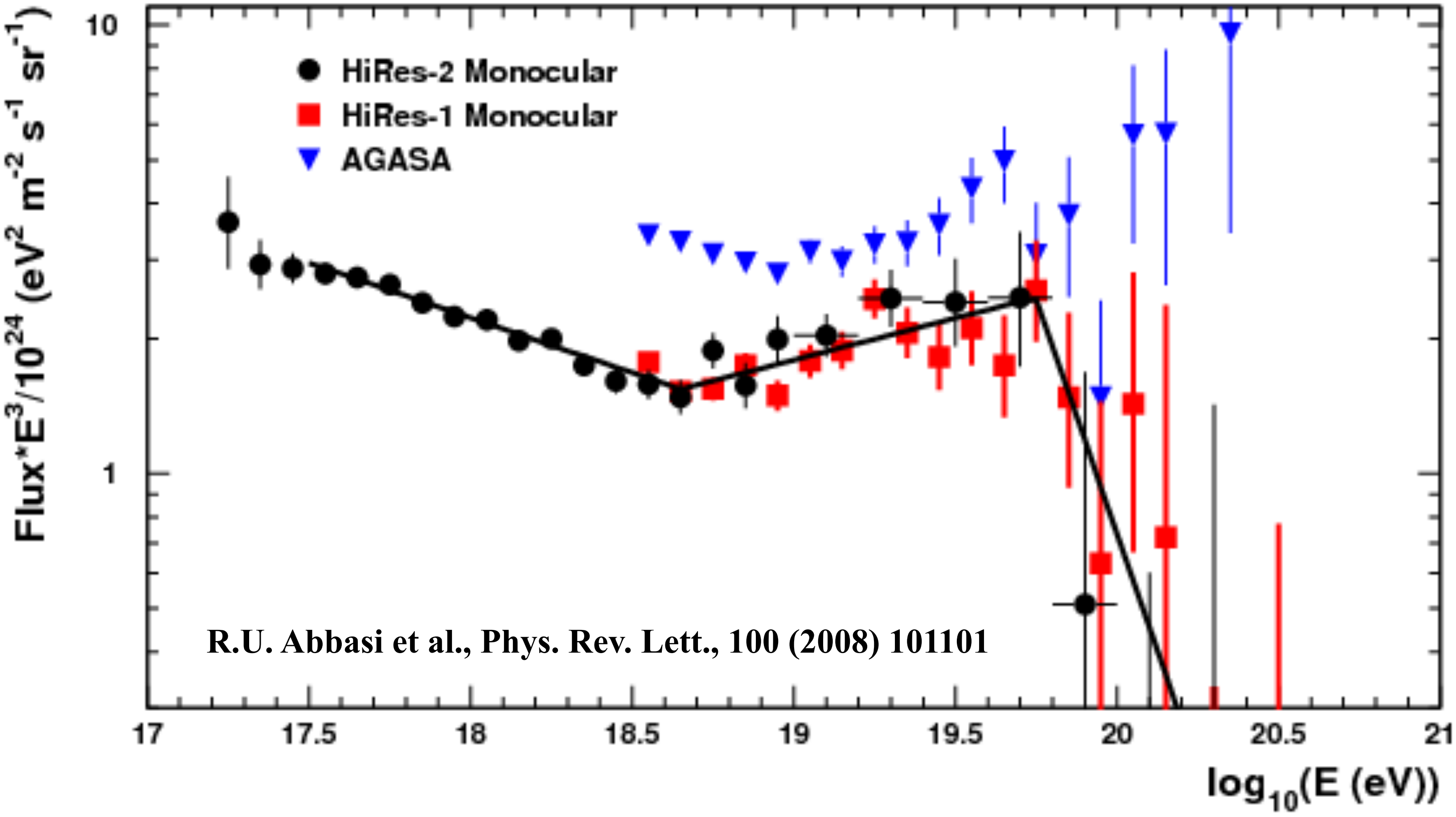
$$E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

After n generations ...

$n = 5,\ \ E_{\text{had}} \sim 12\%$
$n = 6,\ \ E_{\text{had}} \sim 8\%$

- most of the energy transferred to the em component
- shower development and signal at ground sensitive to the hadronic interactions

The importance to take under control the systematic uncertainties



AGASA: 100 km^2 array of scintillators
Hires: fluorescence detector

$$\frac{\Delta J}{J} \sim (\gamma - 1) \times \frac{\Delta E}{E}$$

DETECTION TECHNIQUES

Surface Detector array (SD)
detection of the shower front at ground

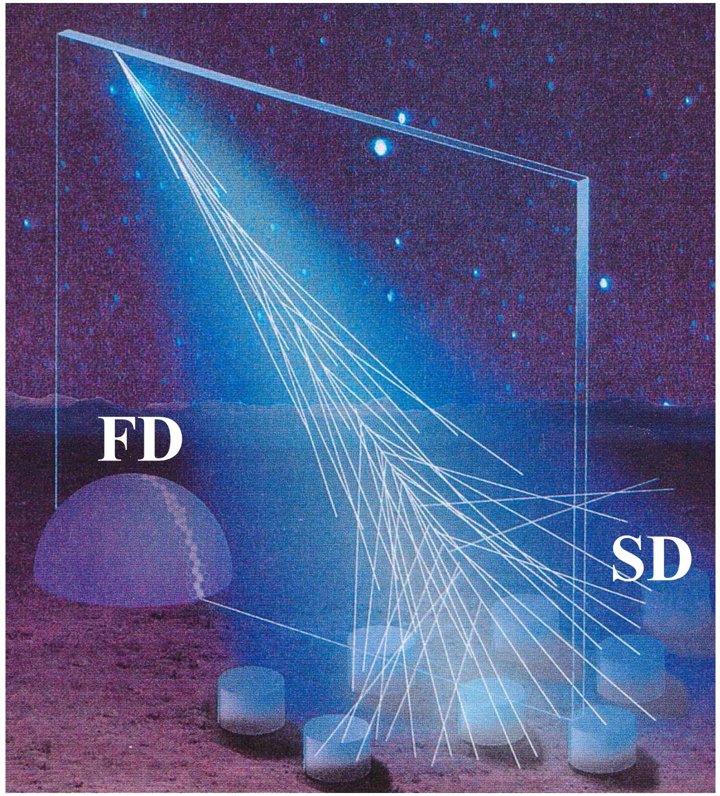
(+) duty cycle ~ 100%
(-) shower size at ground ∝ E (systematics)

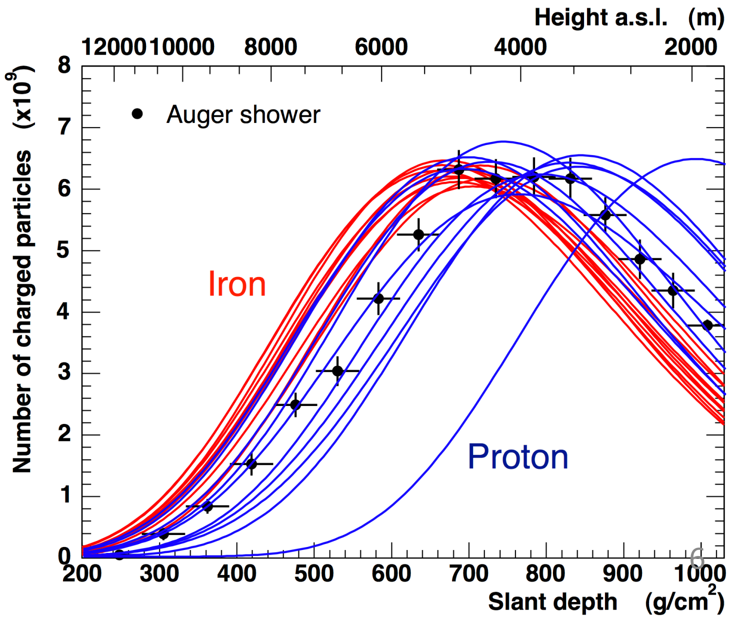
Fluorescence Detector (FD)
longitudinal shower development from fluorescence light from the N_2 de-excitation

(-) duty cycle ~ 13%
(+) calorimetric measurement of E

Hybrid detector (SD+FD)
calibrate the SD signals against FD energies

note: from FD $X_{max} \sim \ln\left(\frac{E}{A}\right)$

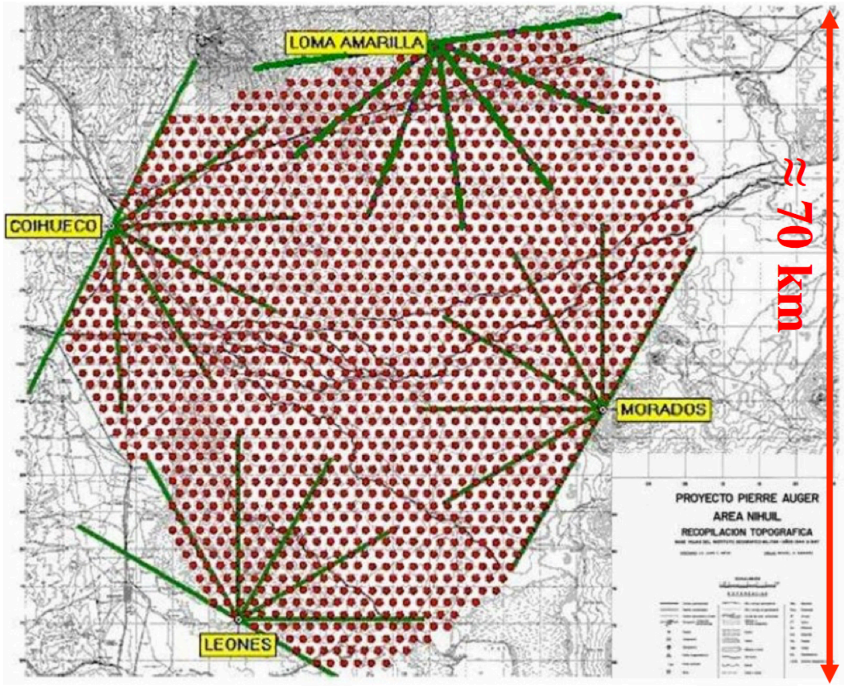




UHECR HYBRID OBSERVATORIES

PIERRE AUGER OBSERVATORY
Malargüe – Mendoza (Argentina)
35^0 S latitude   3000 km^2

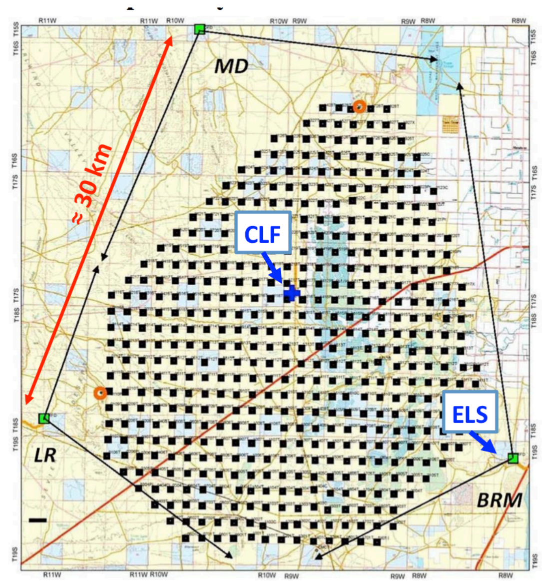
The Pierre Auger Collaboration, NIM A 798 (2015) 172-213

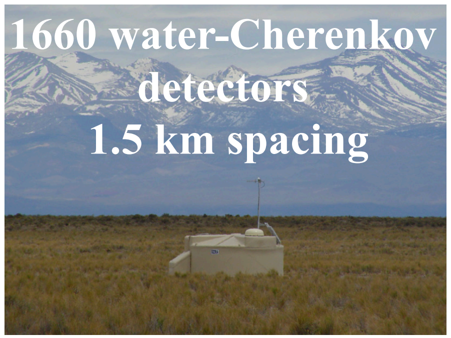


TELESCOPE ARRAY
Millard County, Utah (USA)
39^0 N latitude   700 km^2

M. Fukushima et al., Prog. Theor. Phys. Suppl. 151 (2003) 206

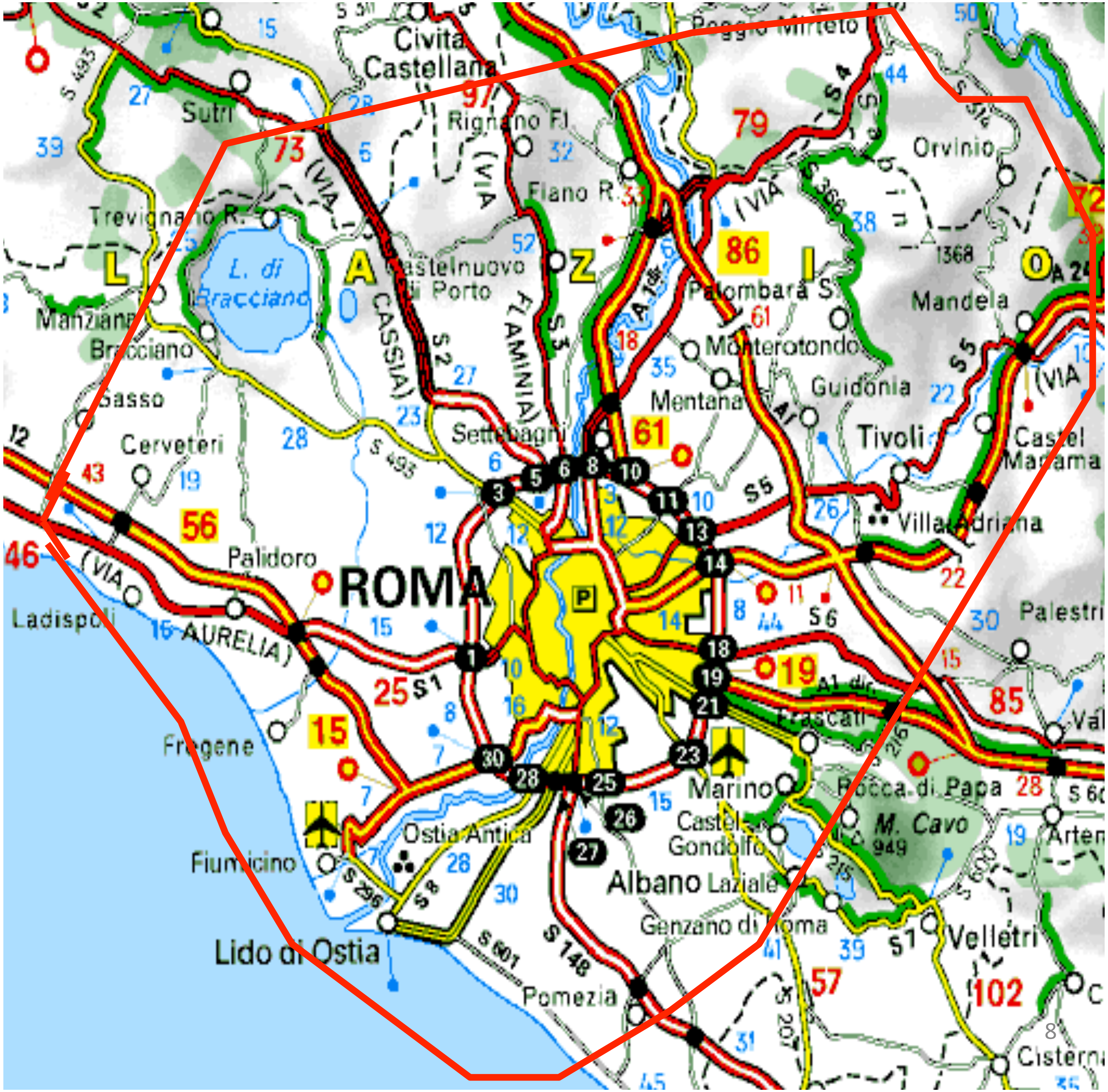
1400
m a.s.l.





fully operative since 2008

AUGER
vs
ROMA



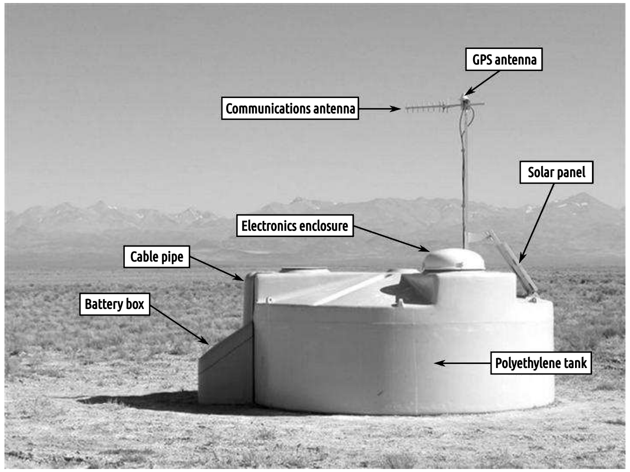
3000 km²

rate ≈ 1/km²/sr/century

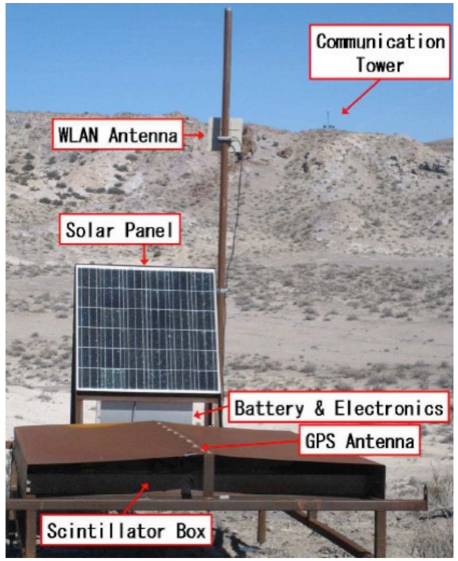
TA smaller by a factor 4

- autonomous units
- FADC at 40/50 MHz
- water cherenkov vs scintillators
  → sensitive to showers inclined at large zenith angle
  →more sensitive to μs

Auger

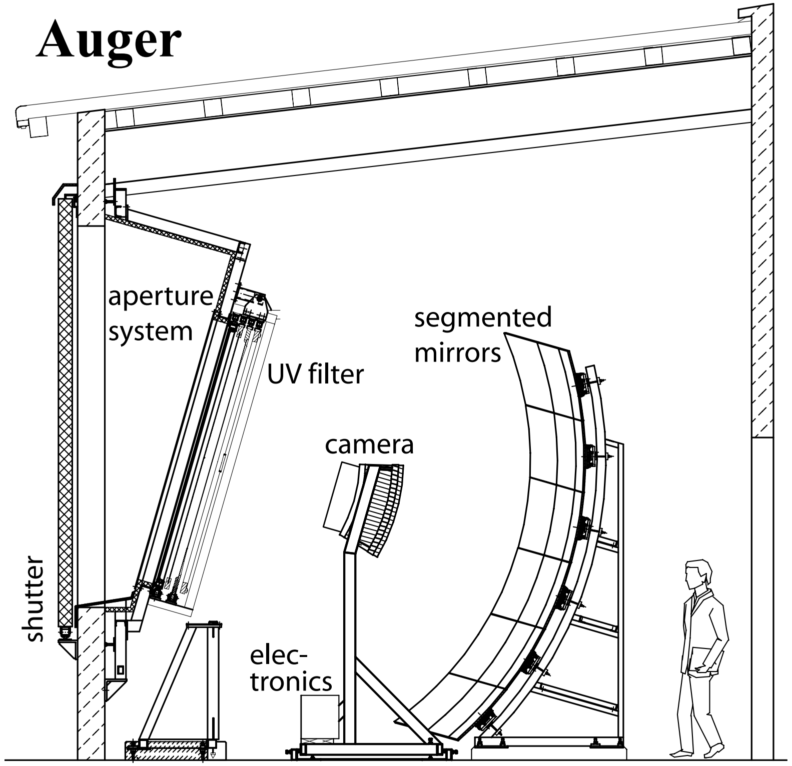


TA

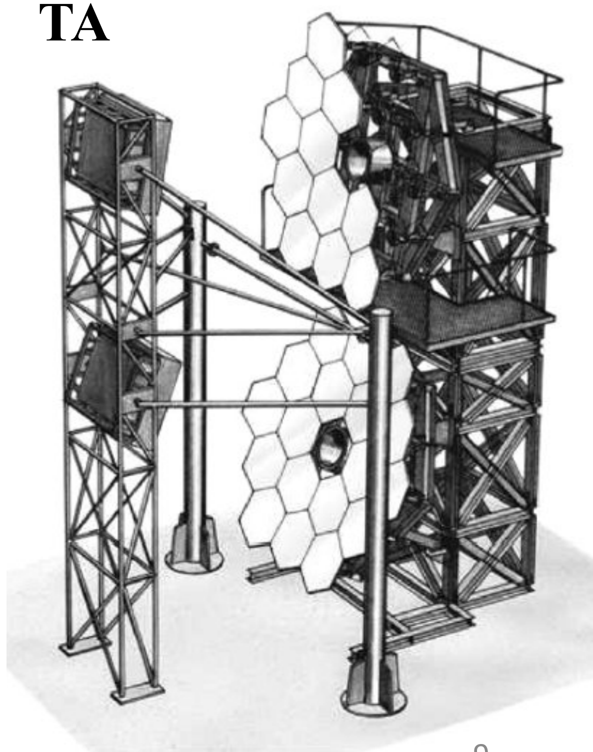


- large spherical mirrors
- camera in the focal surface covered by pmts
- FADC at 10/40 MHz
- similar f.o.v. (elevation ~ $0^0 - 30^0$)

Auger



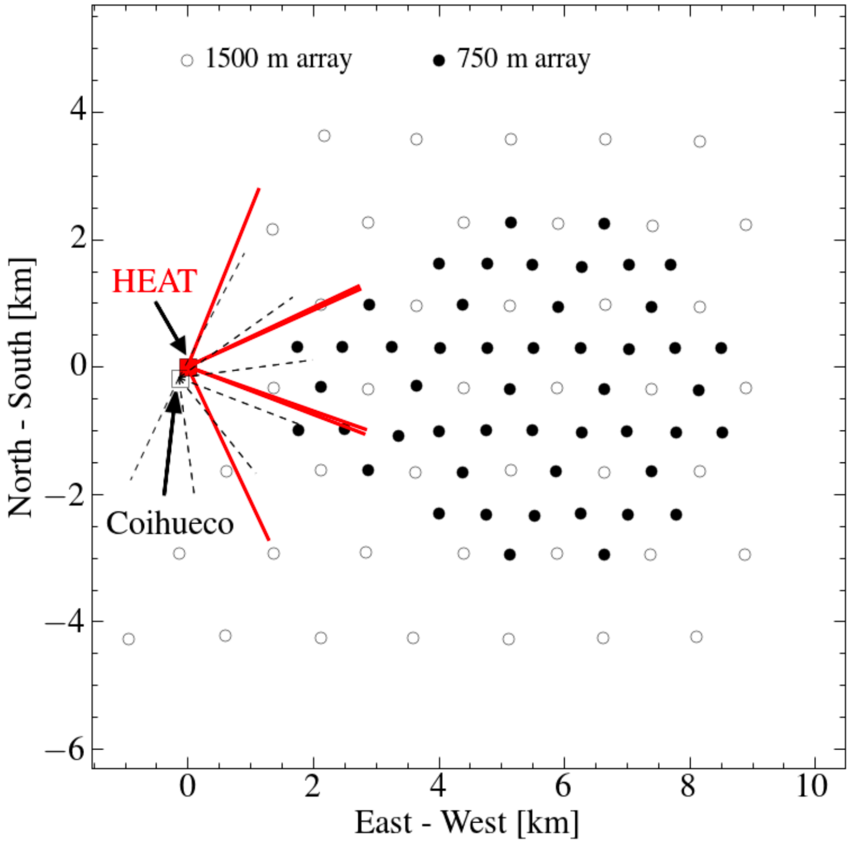
TA

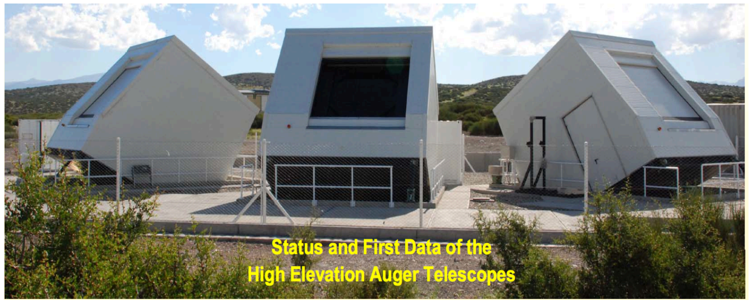


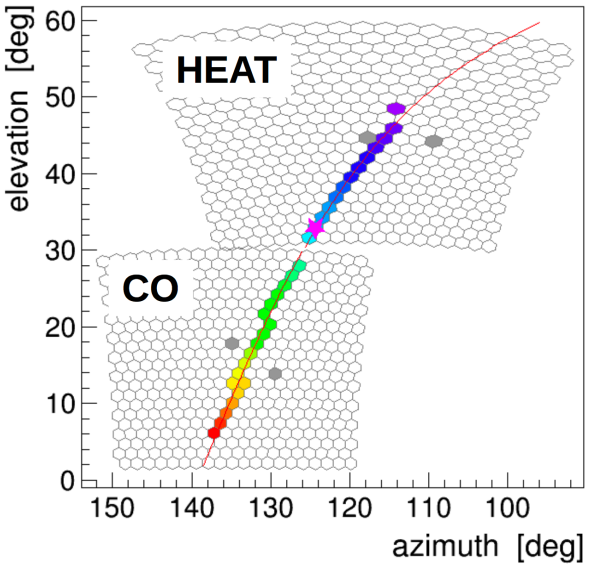
LOW ENERGY EXTENSION

Low energy extension

- **denser array**
- **high elevation FD telescopes (~ $30^0 - 60^0$)**

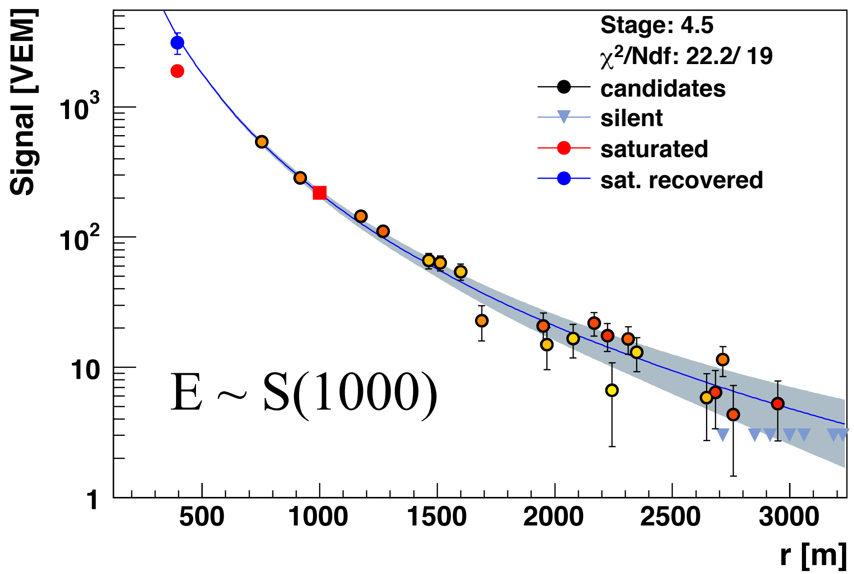




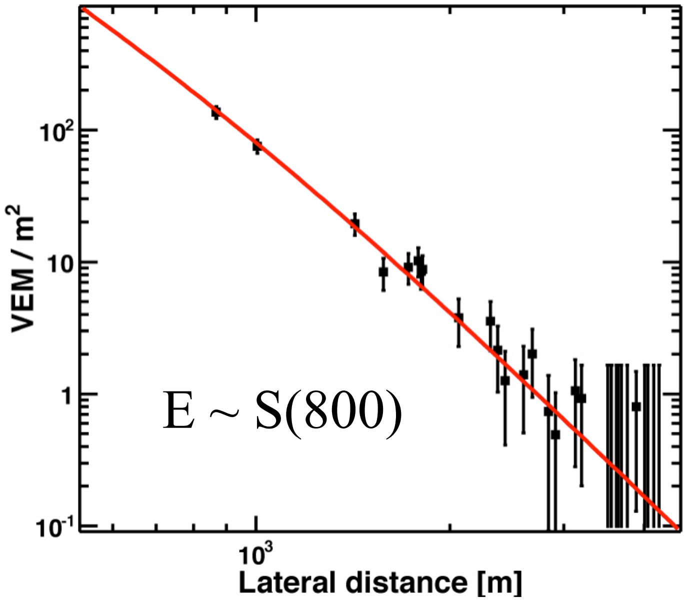


SD EVENTS

AUGER SD - $\theta < 60^0$ 'vertical'

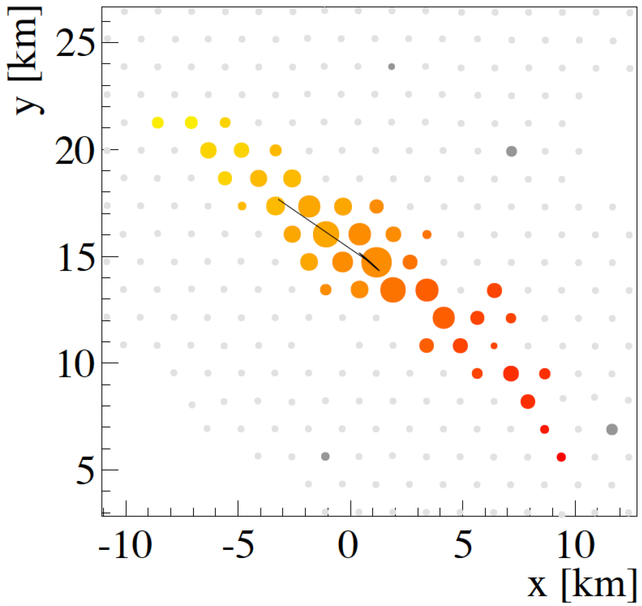


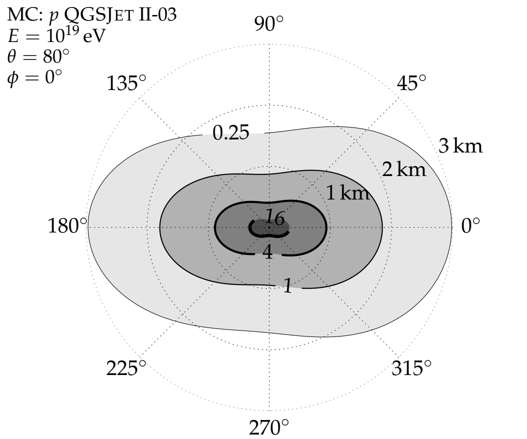
TA SD - $\theta < 45^0$



AUGER SD
$\theta > 60^0$ 'inclined'

signal dominated by muons
(em part absorbed in the atmosphere)



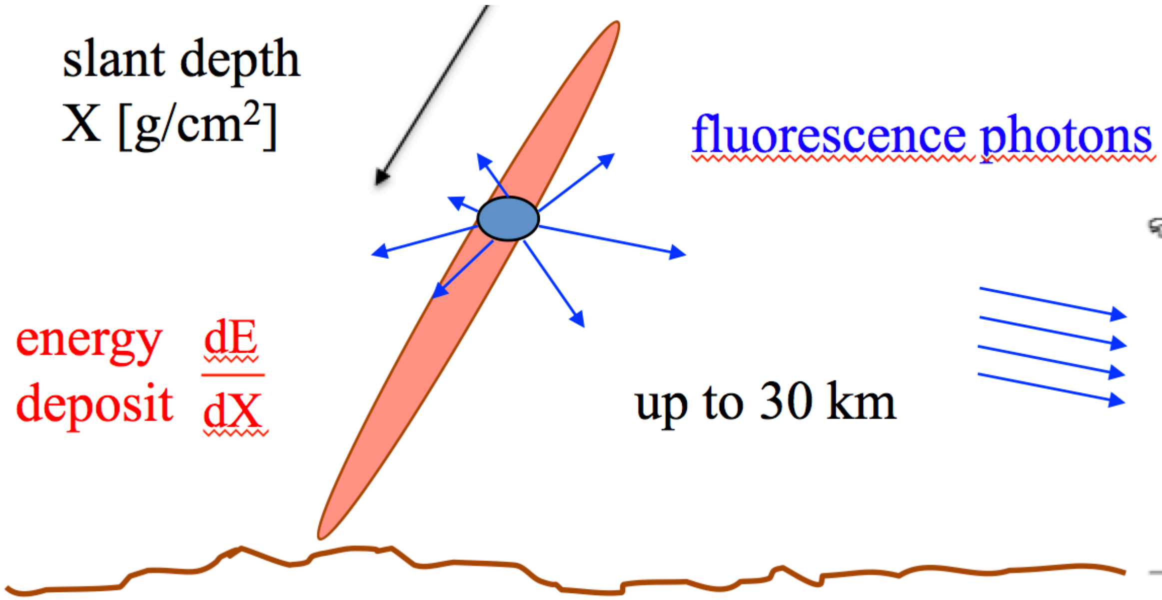


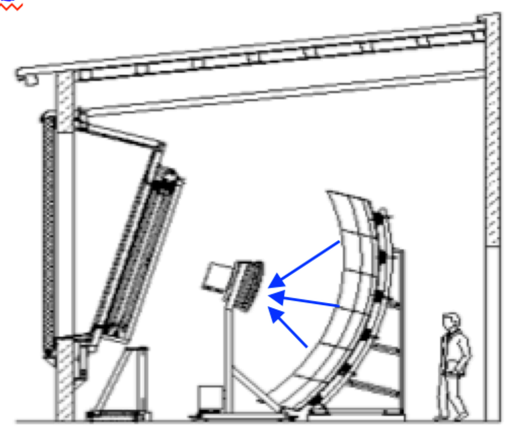
$$\rho_\mu = N_{19}\ \rho_{\mu,19}(r,\theta,\phi)$$

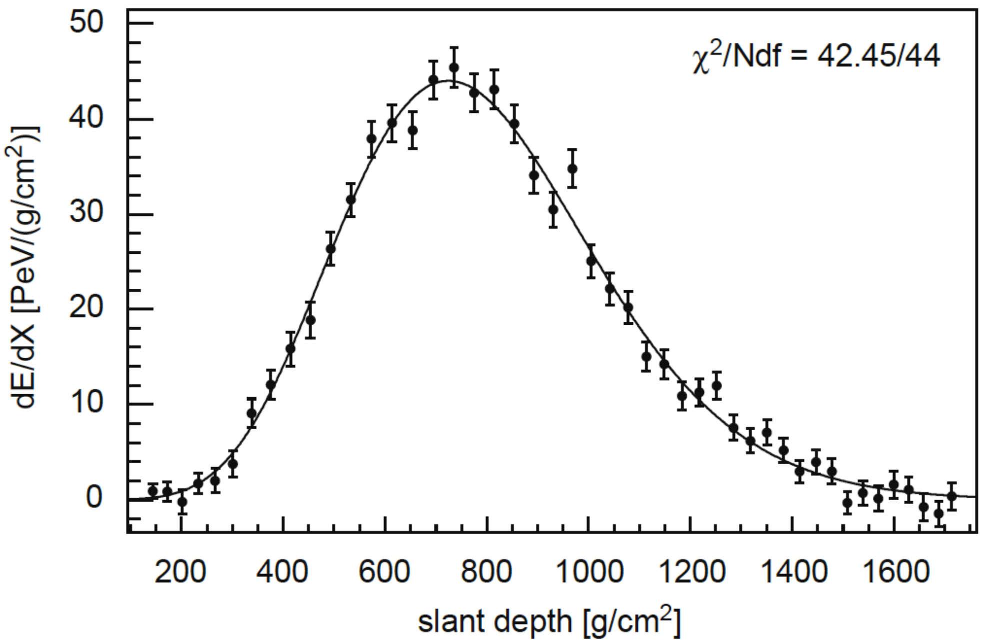
E ~ N_{19}

FD ENERGY SCALE

$$n_{ADC} \sim \frac{dE}{dX} Y_{flu}\ T_{atm} C_{calib}$$







Fluorescence yield

Atmosphere

FD calibration

dE/dX reconst. $\Rightarrow E_{cal} = \int \frac{dE}{dX} dX$

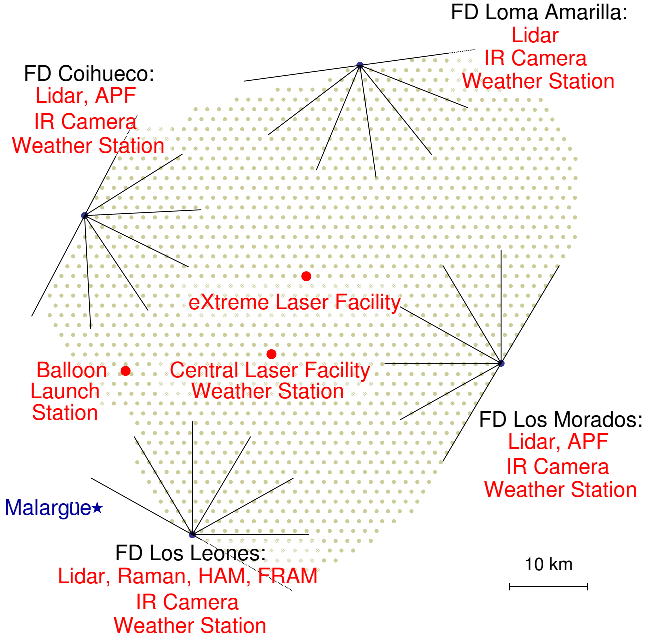
Invisible energy (ν, μ, ..) $\Rightarrow E_{inv}$

$$E = E_{cal} + E_{inv}$$

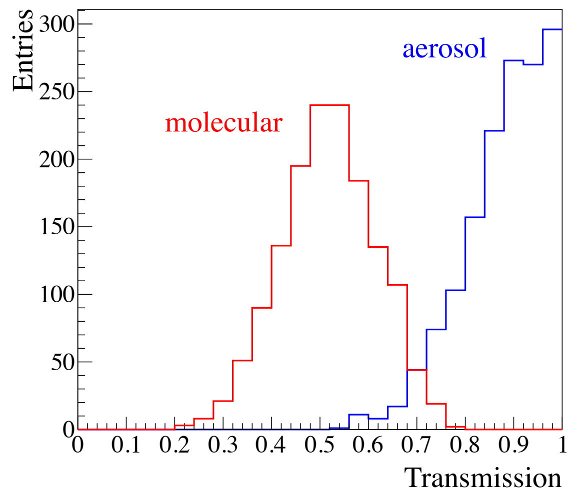
CHALLENGING EXPERIMENTS

- **complex atmospheric monitoring (aerosols, clouds, …)**

Auger, Astrop. Phys. 33 (2010) 108

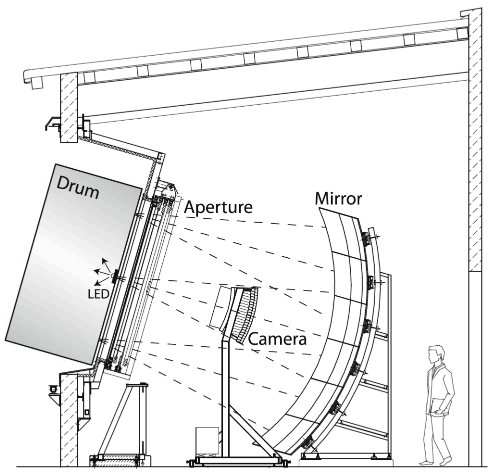


light transmission



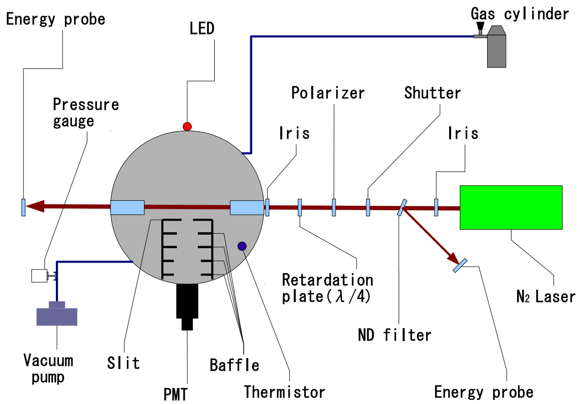
- **FD absolute calibration**

Auger Drum



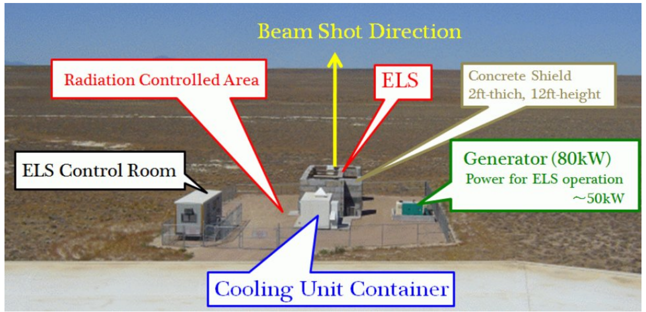
J. T. Brack et al.,
JINST 8 (2013) P05014

TA CRAYS



S. Kawana et al.,
Nucl. Instrum. Meth. A 681 (2012) 68

TA ELS
(linac accelerator)



B. Shin et al., PoS (ICRC2015) 640

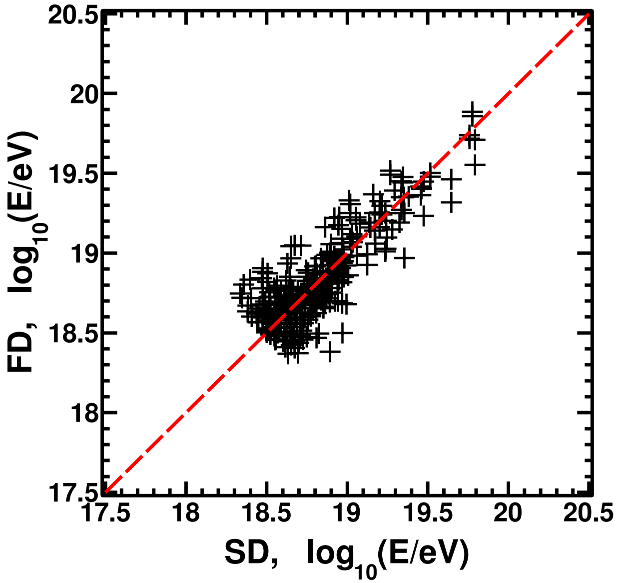
HYBRID EVENTS

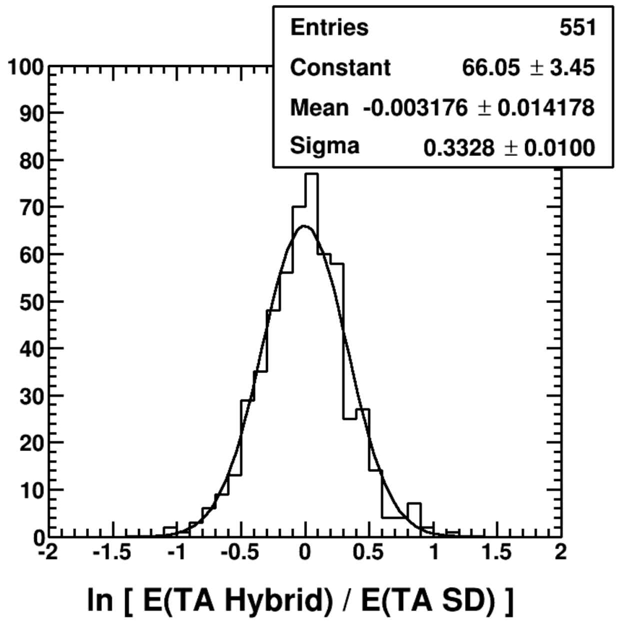
estimate of SD resolution

TA

MC simulations to covert S(800) into shower energy (E_{TBL})

$$E = \frac{E_{TBL}}{1.27}$$



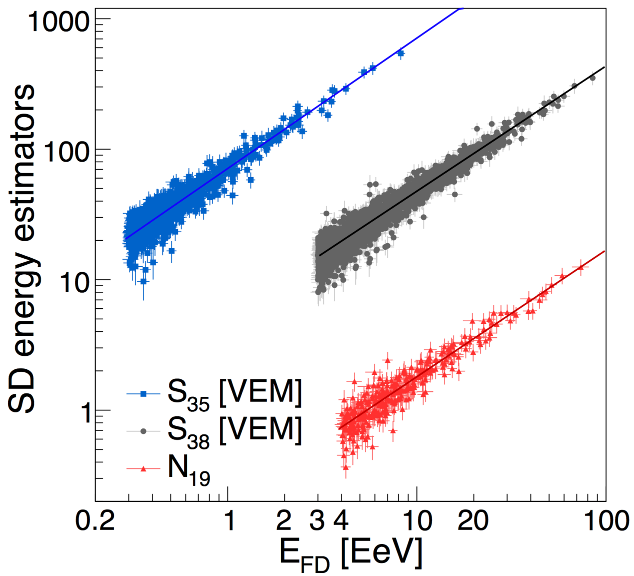


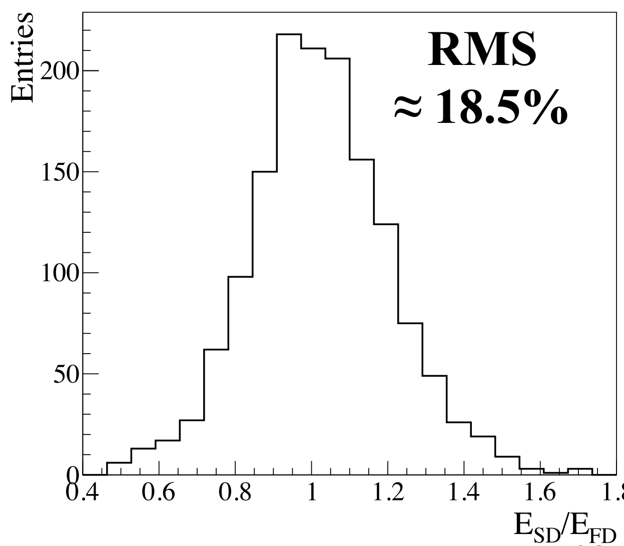
AUGER

CIC method to remove zenith angle dependence

$$E = A\ S^{B}$$

$$B \approx 1$$



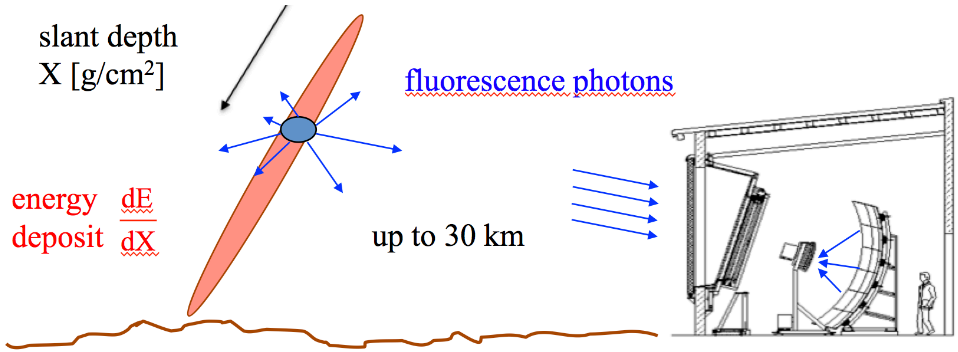


ENERGY SCALE

AUGER

ICRC13 arXiv:1307.5059

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**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.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**



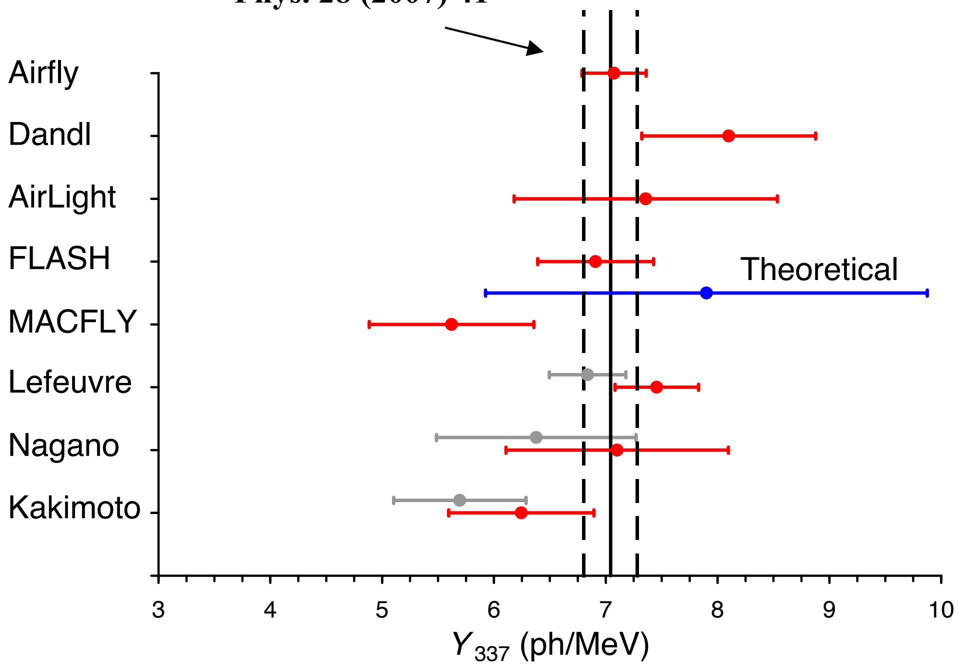
TA

Astropart.Phys. 61 (2015) 93-101

Item	Error (%)	Contributions
Detector sensitivity	10	PMT (8%), mirror (4%), aging (3%), filter (1%)
Atmospheric collection	11	aerosol (10%), Rayleigh (5%)
Fluorescence yield	11	model (10%), humidity (4%), atmosphere (3%)
Reconstruction	10	model (9%) missing energy (5%)
Sum in quadrature	21	

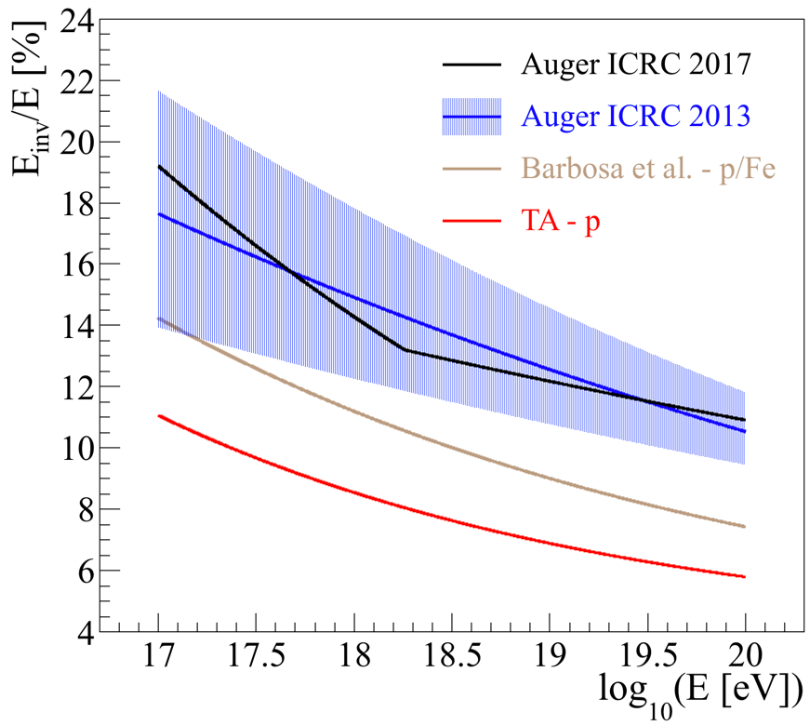
ENERGY SCALE

Fluorescence yield
Auger uses Airfly
TA uses Kakimoto + FLASH



J. Rosado et al., Astropart. Phys. 55 (2014) 51

Invisible energy (ν, μ, ..)
Auger: estimated from data exploiting the muon sensitivity of the SD signals



note: combined effect: 5%-10% relative shift between TA and Auger energy scales

TA ENERGY SPECTRUM

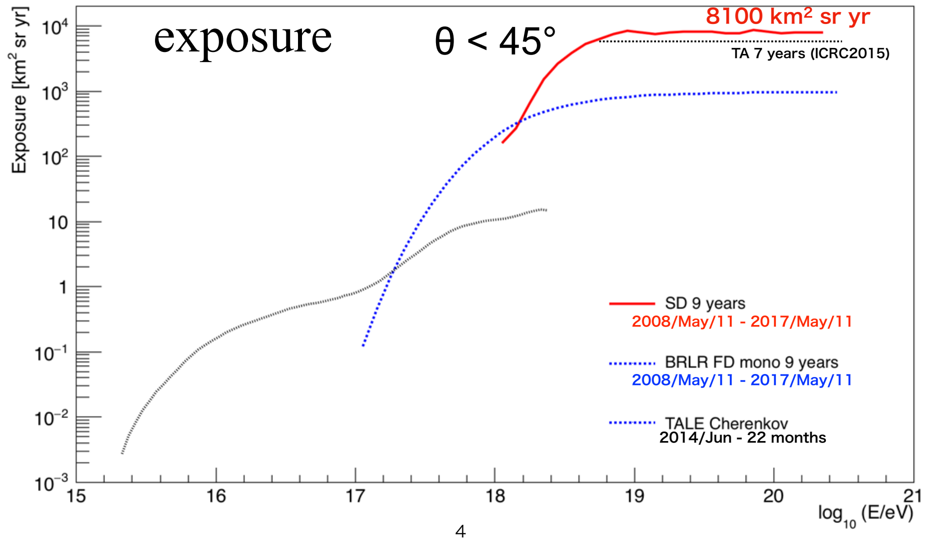
remarkable extension up to the knee

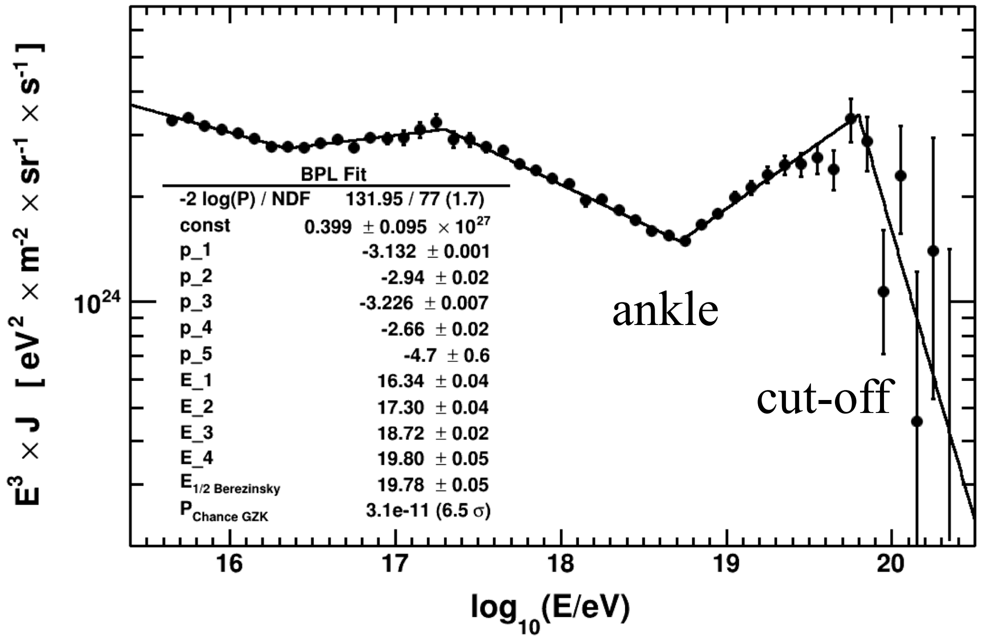
common energy scale

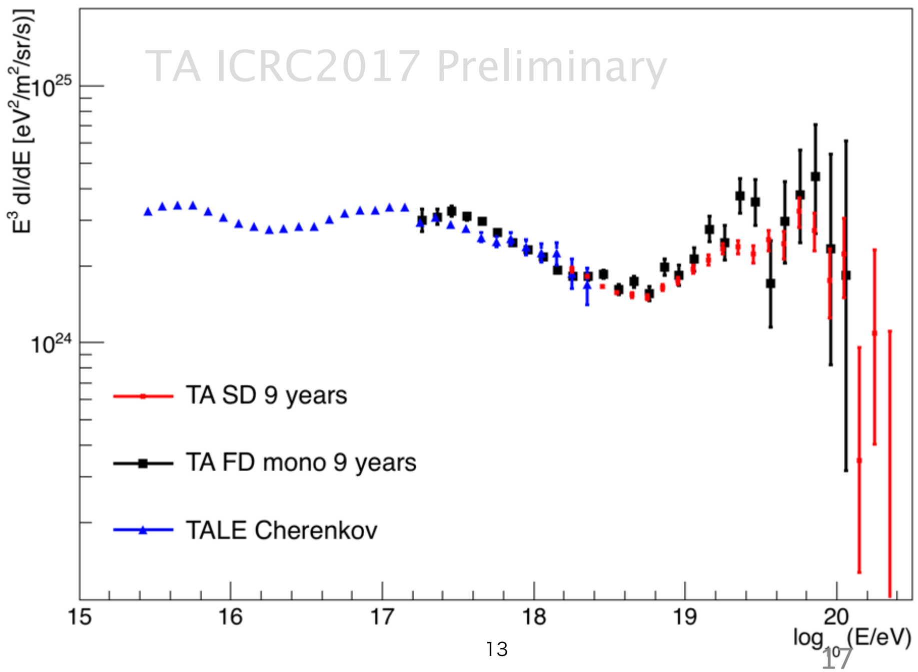
Y. Tsunesada et al., PoS (ICRC2017) 535

Tareq AbuZayyad , PoS (ICRC2017) 534

D. Ivanov, PoS (ICRC2015) 349







AUGER ENERGY SPECTRUM

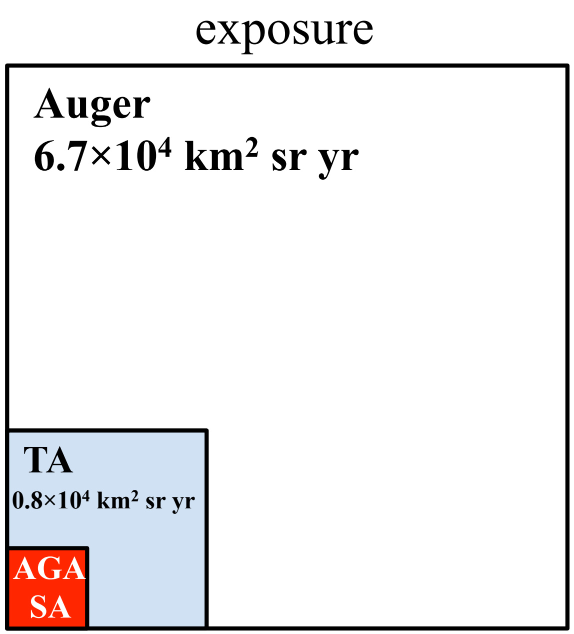
unprecedented statistics

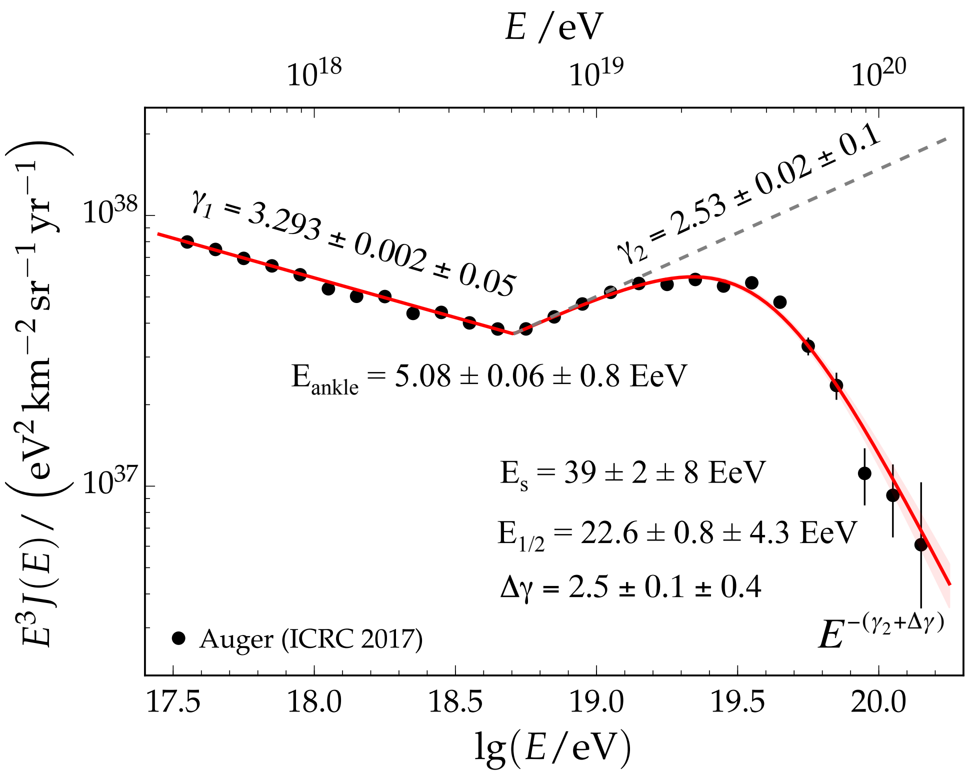
SD spectra only above full efficiency energy threshold

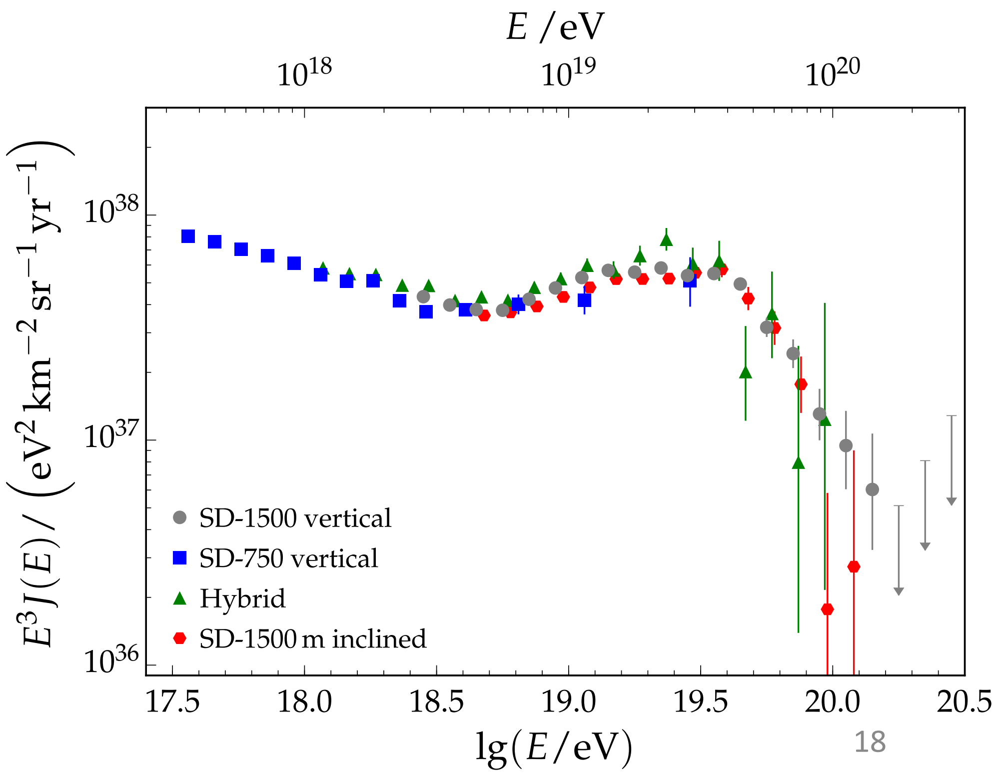
consistency between different measurements

common energy scale

Auger ICRC17 arXiv:1708.06592





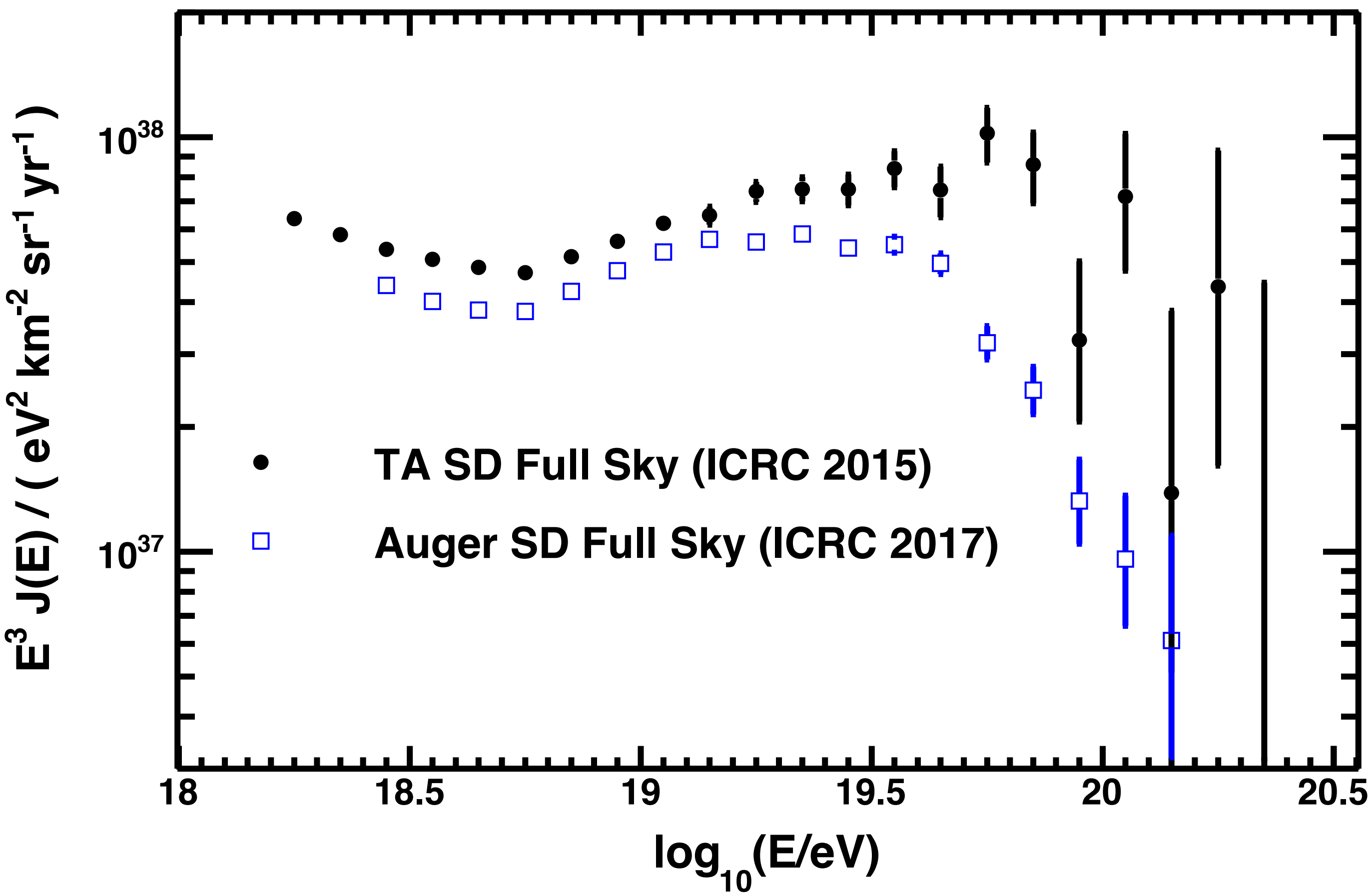


ENERGY SPECTRUM: AUGER vs TA

- consistency in the ankle position
- inconsistency in the cut-off position

	Auger	TA
E_{ankle} (EeV)	5.08	5.2
$E_{1/2}$ (EeV)	**22.6**	**60**

Auger + TA   Proceedings of UHECR2016   PoS (ICRC2017) 498

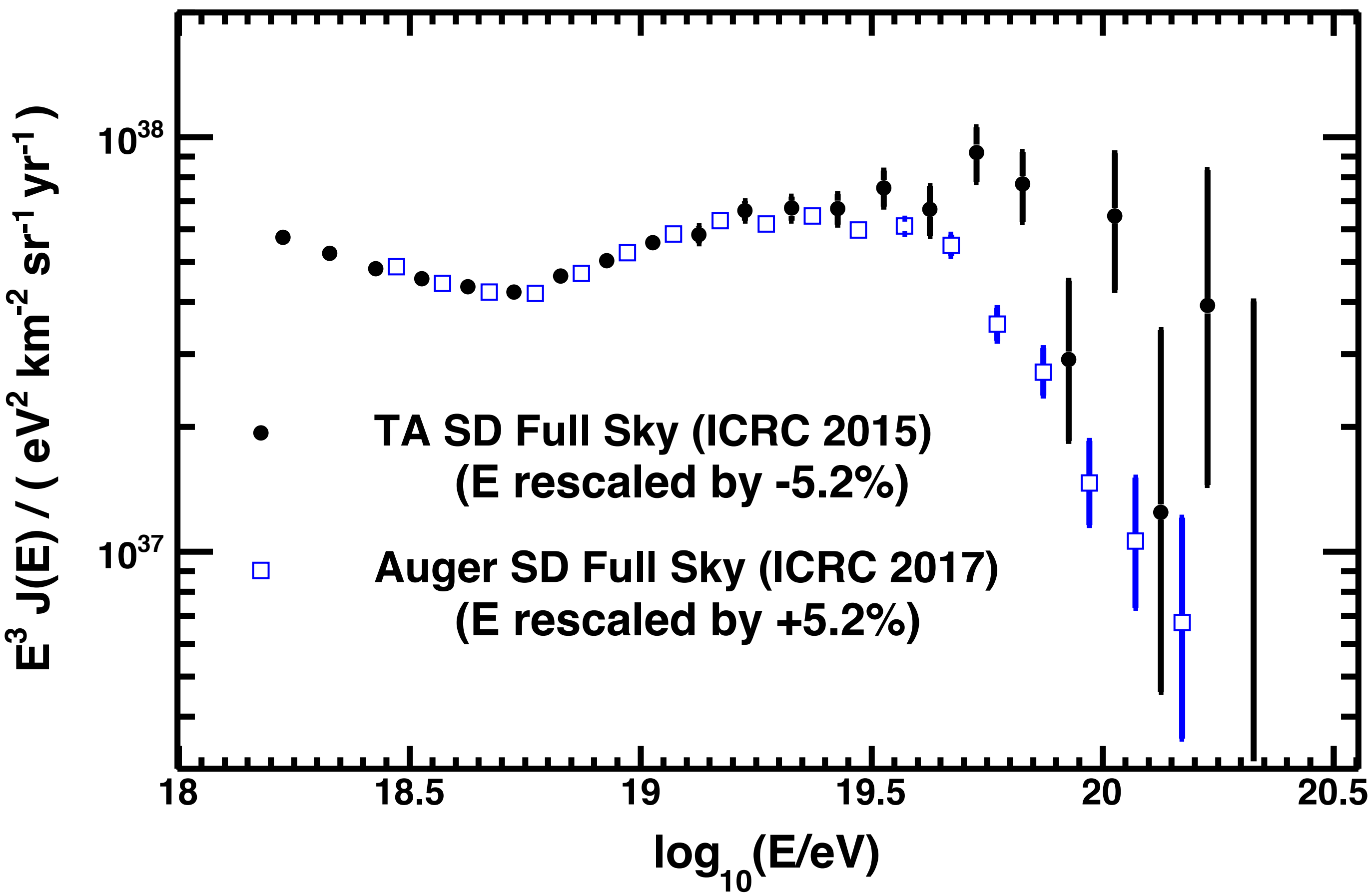


ENERGY SPECTRUM: AUGER vs TA

- a 10.4% rescaling factor is fully consistent with the different fluor. yield and E_{inv} (if TA uses Auger fluol. yeld & E_{inv} → $\Delta E/E \approx -9\%$)

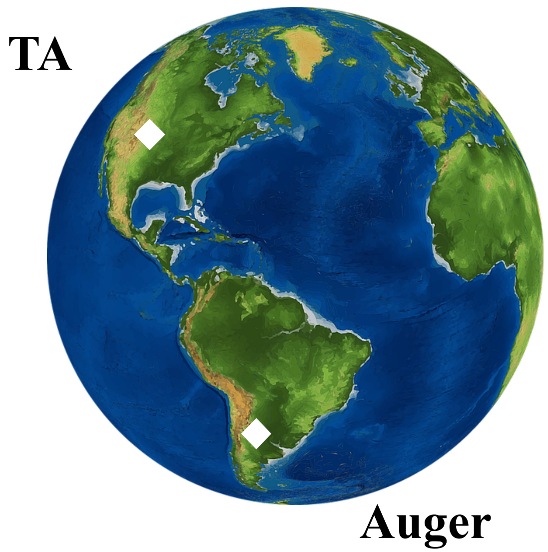
- why the spectra are so different at the cut-off?
  - astrophysics?
  - and/or experimental effects?

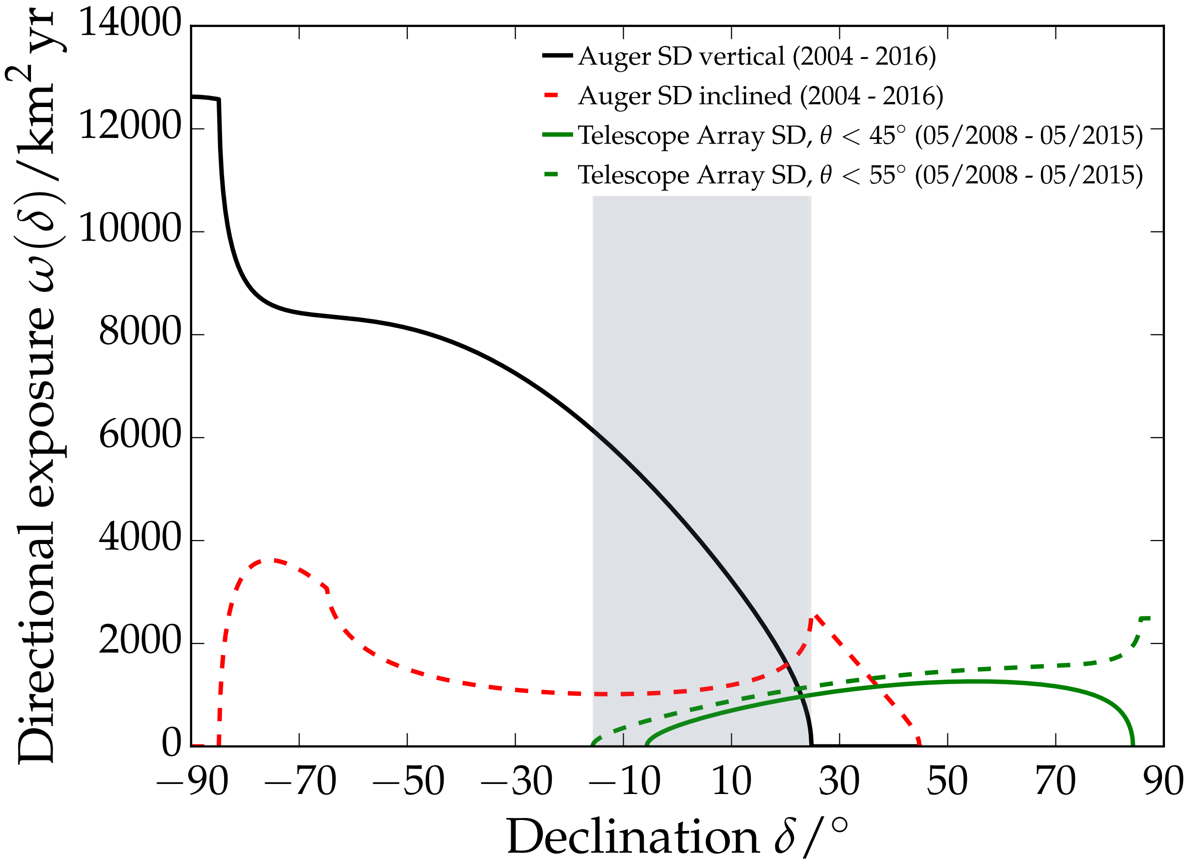
Auger + TA Proceedings of UHECR2016 PoS (ICRC2017) 498



Telescope Array & Auger

- common declination band → inter calibration, systematics, …, comparison of the energy spectra
- main goal: anisotropy with full sky coverage





Dedicated conferences:

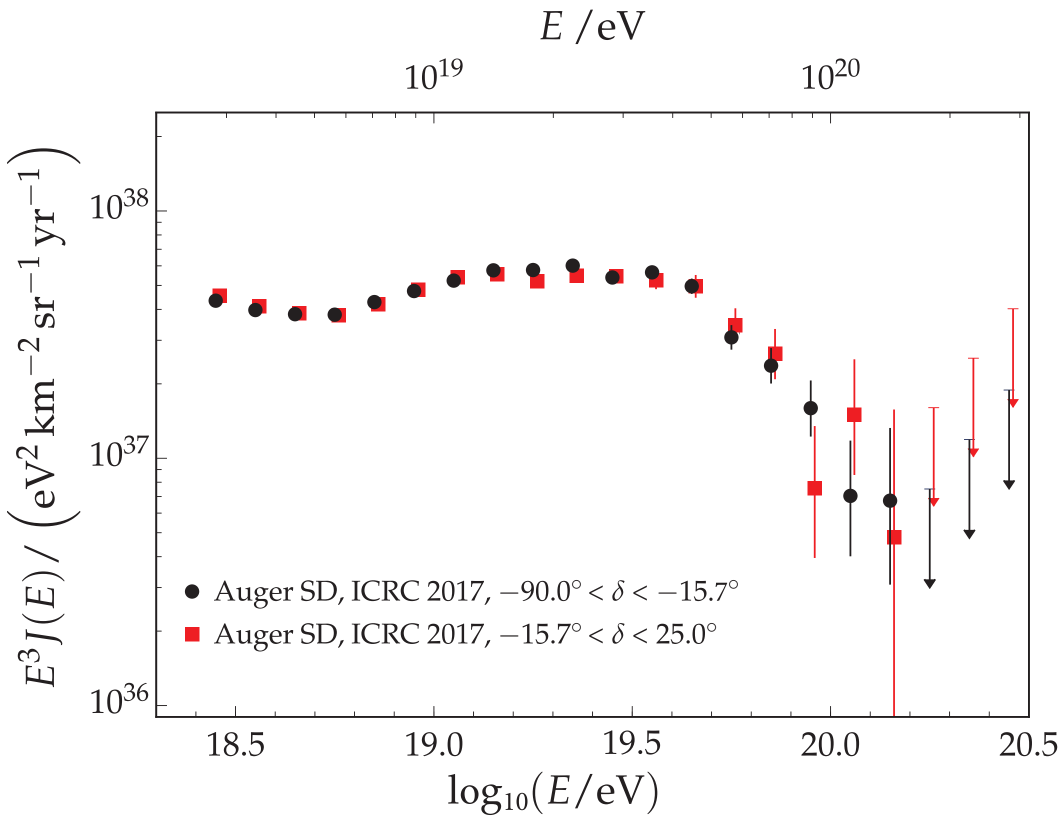
1) Nagoya (Japan) Dec 2010
2) CERN Feb 2012
3) Utah (USA) Oct 2014
4) Kyoto (Japan) Oct 2016

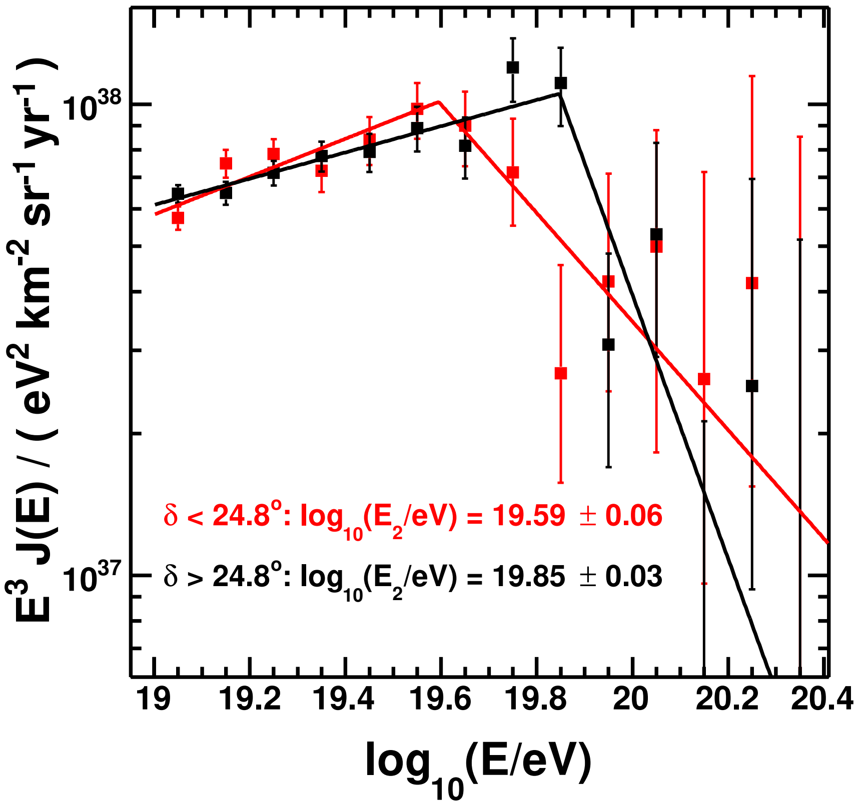
next: Oct 2018

DECLINATION DEPENDENCE OF THE ENERGY SPECTRA

Auger + TA   Proceedings of UHECR2016   PoS (ICRC2017) 498

- common declination band $-15.7^0 < \delta < 25^0$
- Auger has not a declination dependence
- TA: cut-off position in the common declination band closer to the Auger one (*)





(*) common decl. band $\log_{10}(E_2)$ = 19.59 e 19.56 for TA and Auger, respectively

Anisotropies at intermediate scale

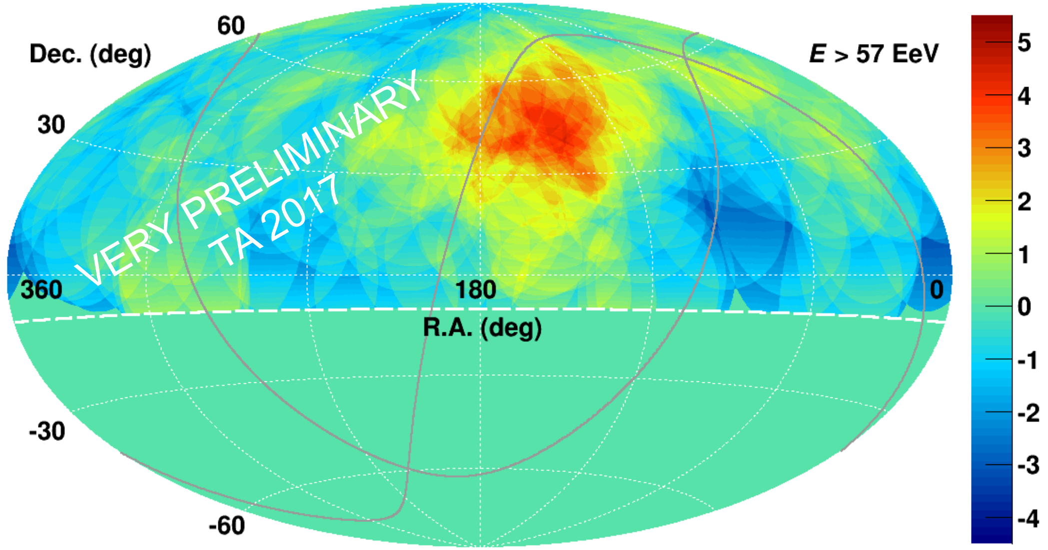
TA 'hot spot'

S. Troitsky
PoS (ICRC2017) 548

25^0 around $(\alpha,\delta) = (144.3^0, 40.3^0)$
143 events E > 57 EeV
$N_{obs} = 34$ $N_{exp} = 13.5$

~ 3σ post-trial

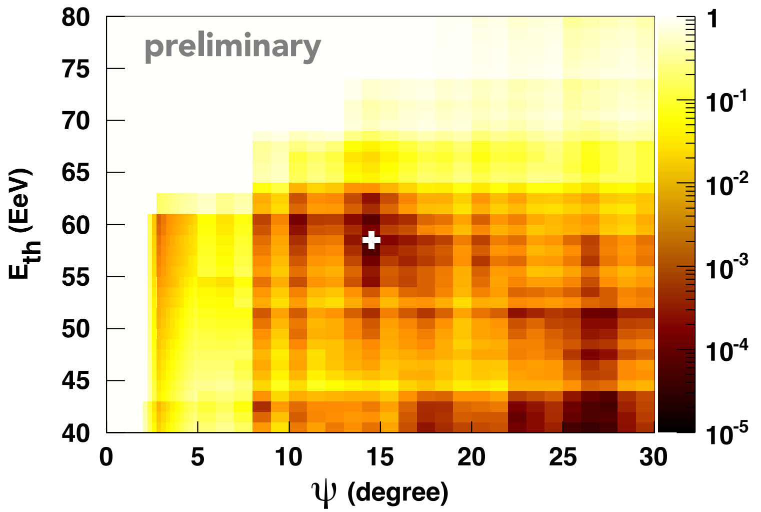
note: 'hot spot' outside the common declination band $-15.7^0 < \delta < 25^0$



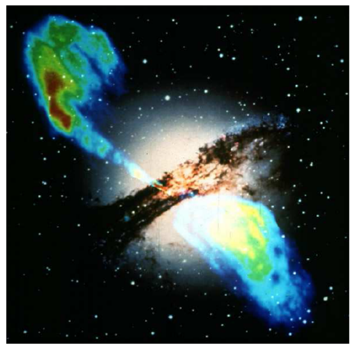
Auger

U. Cacciari
PoS (ICRC2017) 484

19 events
E > 58 EeV
$N_{obs} = 19$ $N_{exp} = 6$
~ 3σ post-trial



Centaurus A



AGN at only 3.4 Mpc

Anisotropies at intermediate scale - Auger

U. Cacciari,
PoS (ICRC2017) 484

UHECR produced in gamma-ray sources

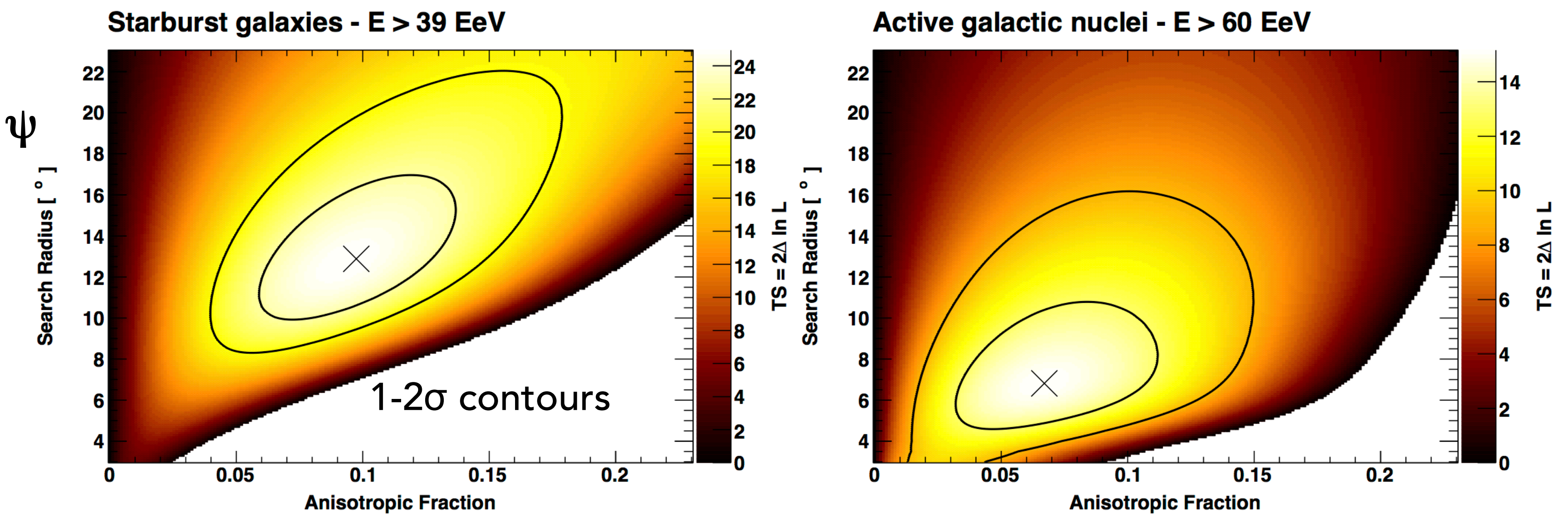
Active Galactic Nuclei
- 17 AGNs from 2FHL Catalog (Fermi-LAT) with E > 50 GeV
- Φ(> 50 GeV) proxy of UHECR flux

Star-forming or Starburst Galaxies
- 23 objects with Φ(> 1.4 GHz) from Fermi-LAT search list
- Φ(> 1.4 GHz) proxy of UHECR flux

Likelihood ratio $TS = 2\ln\left(\frac{H_1}{H_0}\right)$

$H_0 : isotropy$

$H_1 : (1-f)\times isotropy + f \times FluxMap(\psi)$

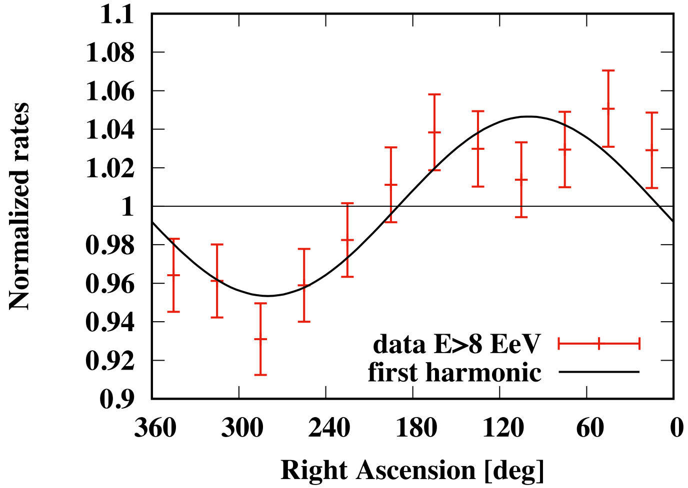


3.9 σ **post-trial significances** **2.7 σ**

OBSERVATION OF A LARGE SCALE ANISOTROPY

Auger, Science 57 (2017) 1266-1270

harmonic analysis in right ascension

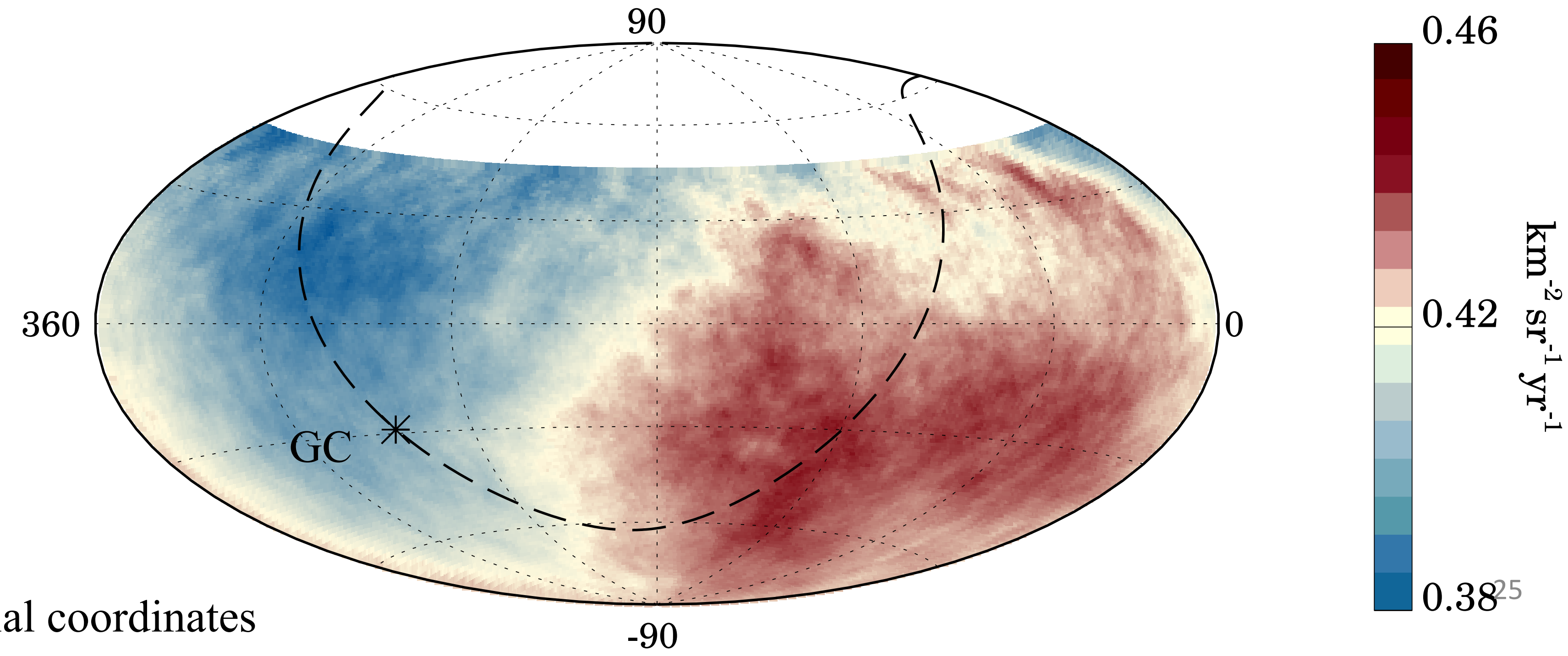


Energy (EeV)	Number of events	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	$0.005\ ^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	$0.047\ ^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

modulation > 8 EeV at 5.2 σ

first time!

with a similar analysis on azimuth angle:
3d dipole > 8 EeV $d = 6.5^{+1.3}_{-0.9}\%$ $(\alpha_d, \delta_d) = (100^0, -24^0)$

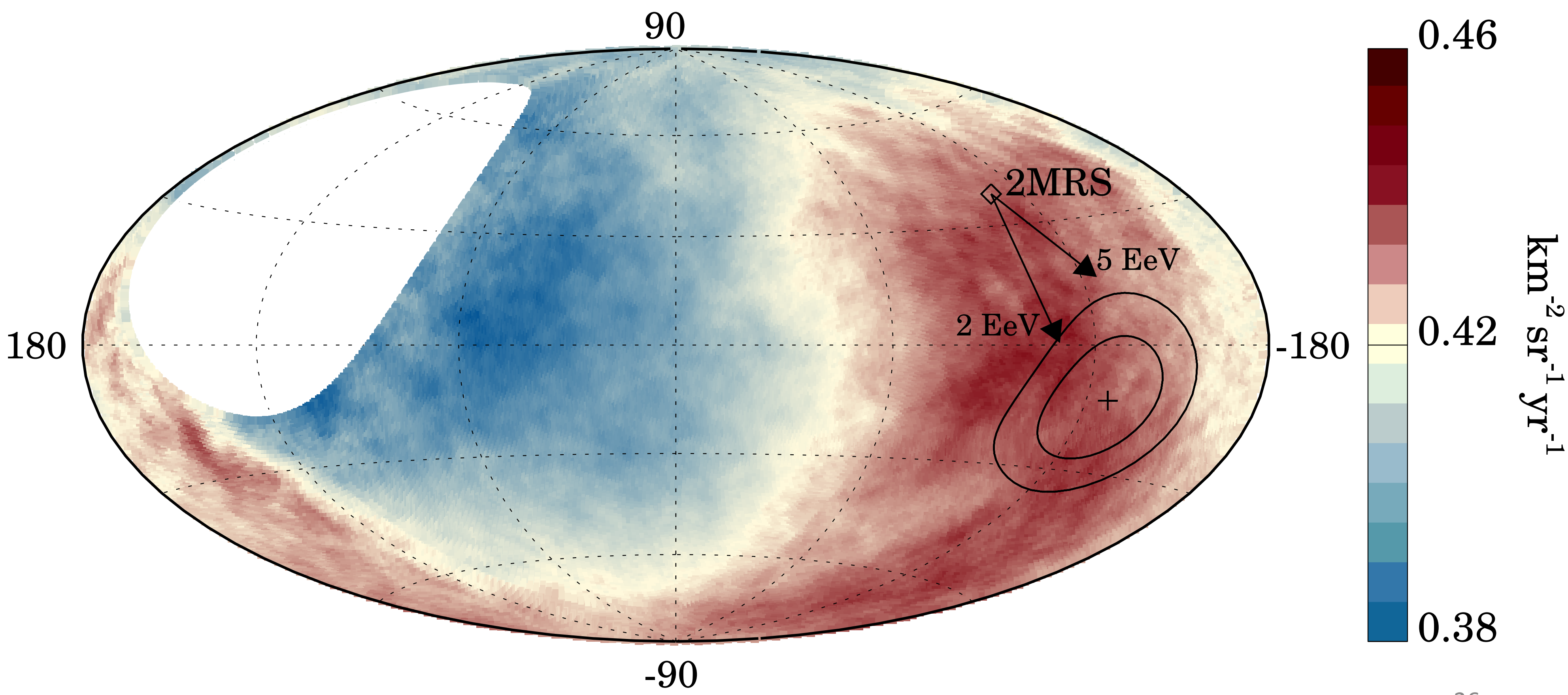


equatorial coordinates

EVIDENCE OF EXTRAGALACTIC ORIGIN OF UHECRs

Auger, Science 57 (2017) 1266-1270

- observed dipole lies ~125^0 from GC
- infrared-detected galaxies in 2MRS catalog
  - dipole lies ~ 55^0 from the expected one
  - better agreement when the Galactic B is taken into account



galactic coordinates

note: Z ~ 1.7 – 5 at 10 EeV

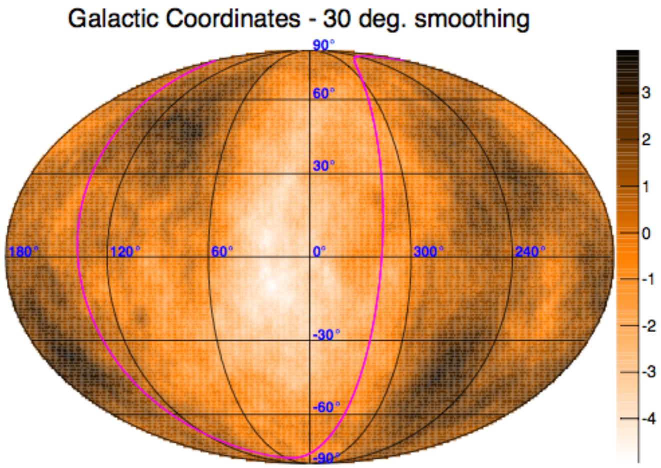
ANISOTROPIES WITH FULL SKY COVERAGE

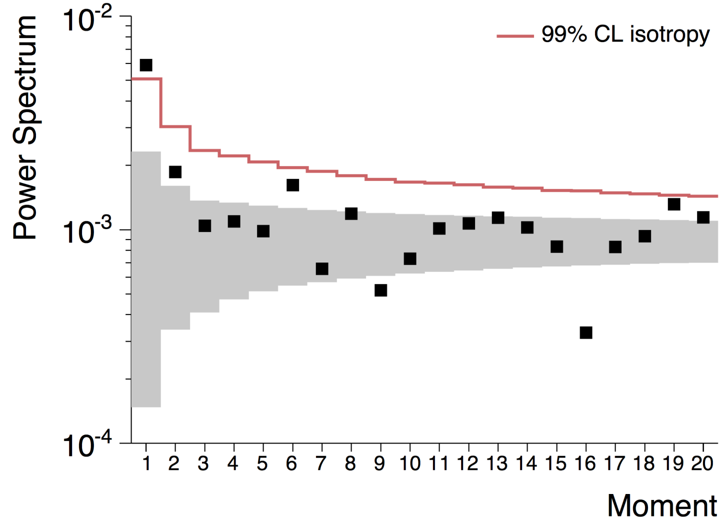
Higher order multipoles $\Phi(\mathbf{n}) = \sum_{\ell=0}^{+\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\mathbf{n})$ anisotropy at ~1/l radians

Auger + TA

O. Deligny
PoS (ICRC2015) 395

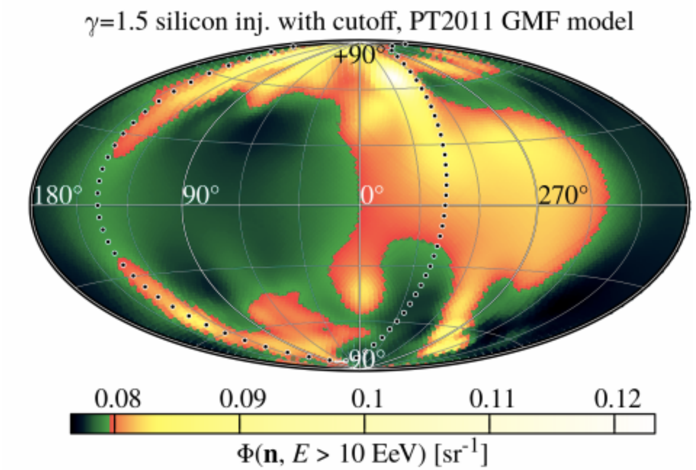
$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

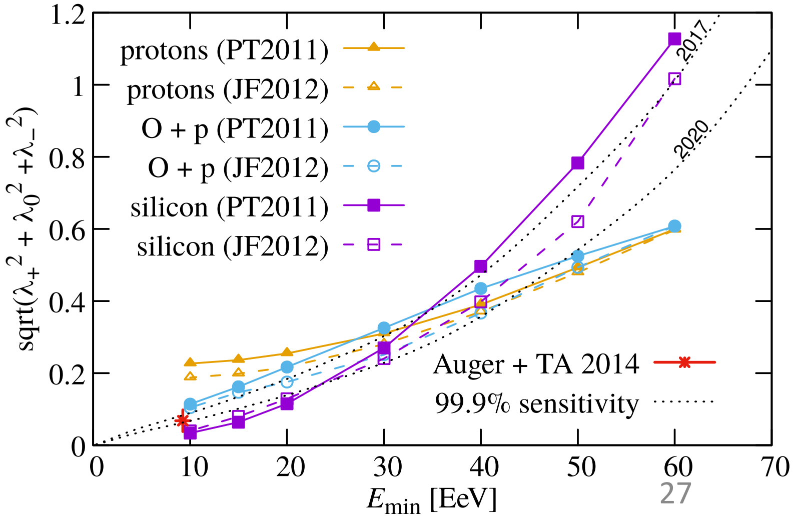




constraint on models?

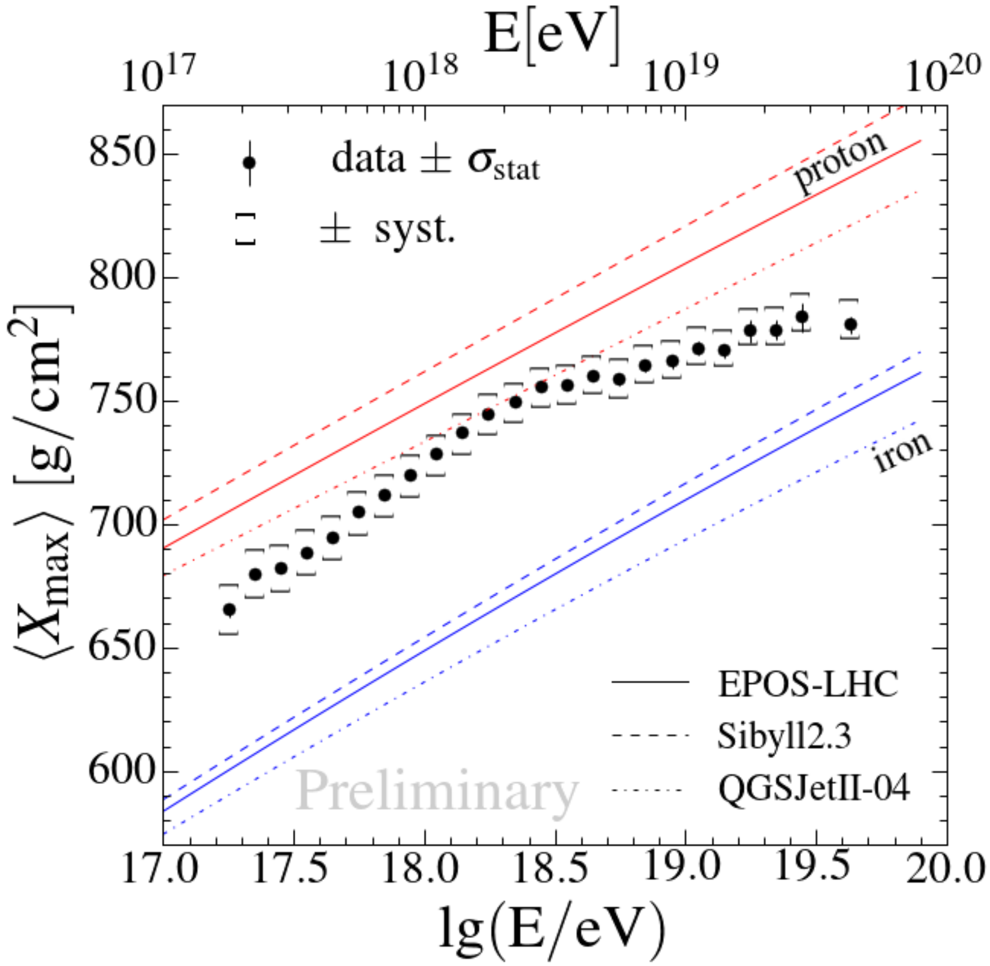
Di Matteo & Tyniakov
arXiv:1706.02534

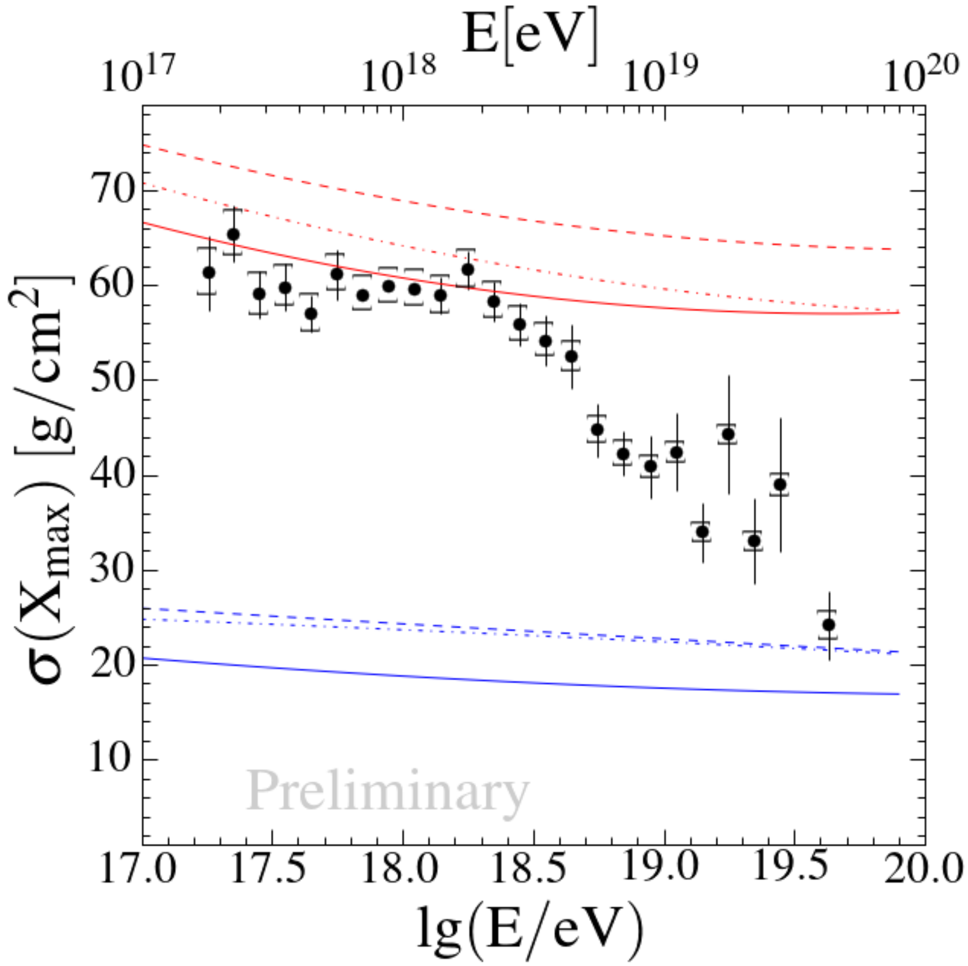




MASS COMPOSITION - AUGER

J. Bellido, PoS (ICRC2017) 522



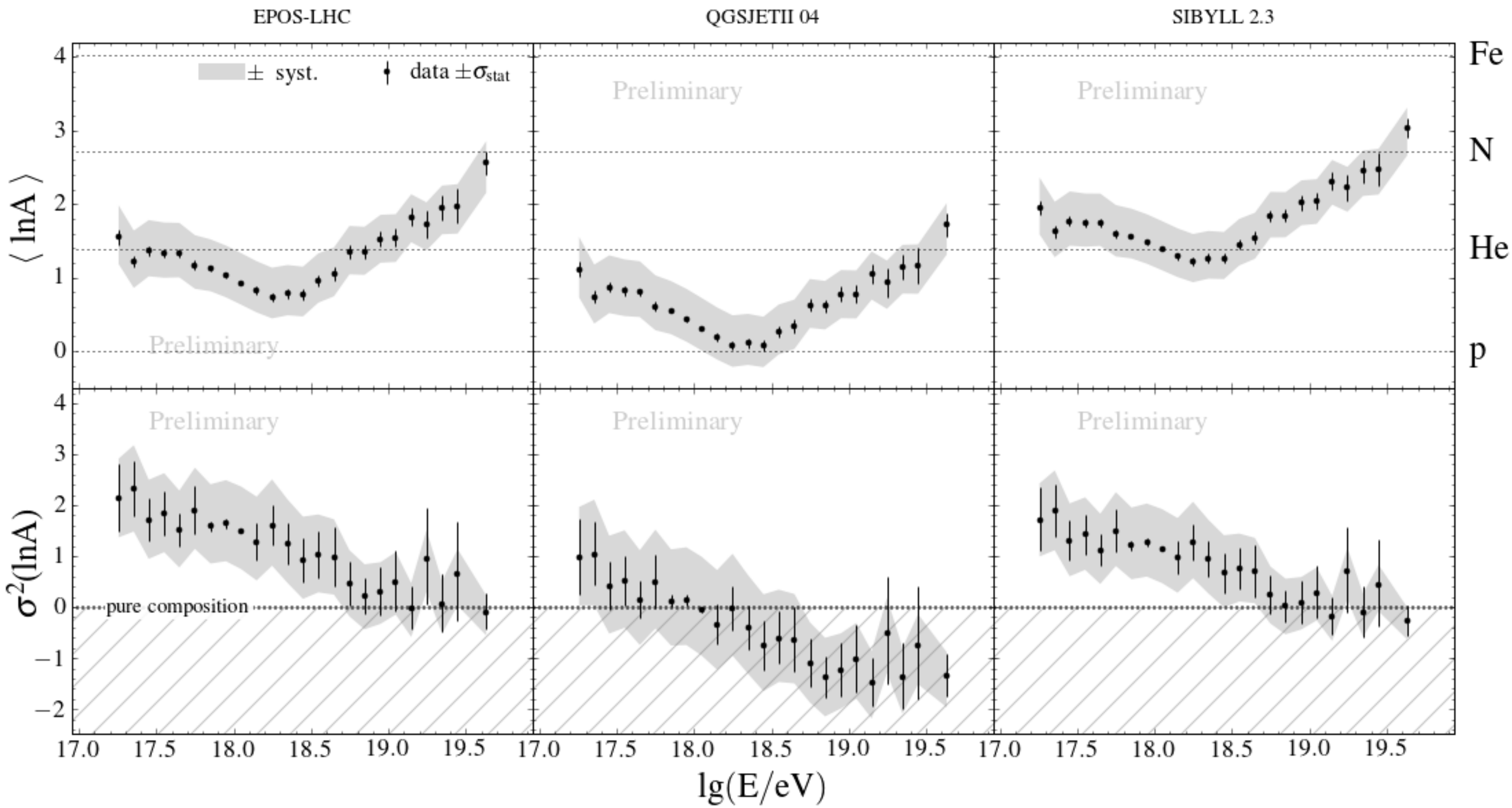


lightest composition at ~ 2×10^{18} eV
heavier composition at lower and at higher energies
narrower $\sigma(X_{max})$ above ~ 2×10^{18} eV

MASS COMPOSITION - AUGER

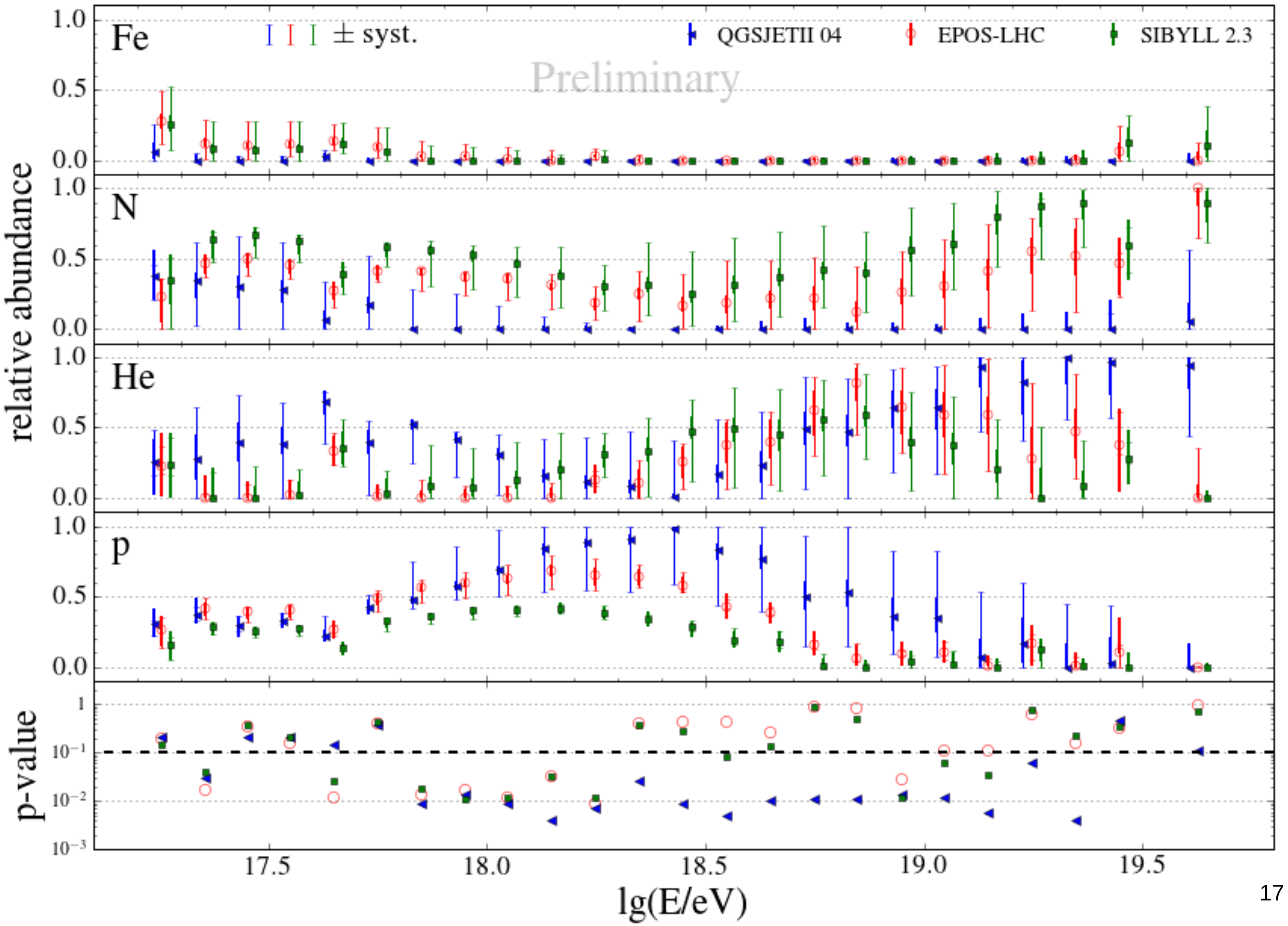
J. Bellido, PoS (ICRC2017) 522

mass composition from X_{max} distributions



MASS COMPOSITION - AUGER

J. Bellido, PoS (ICRC2017) 522

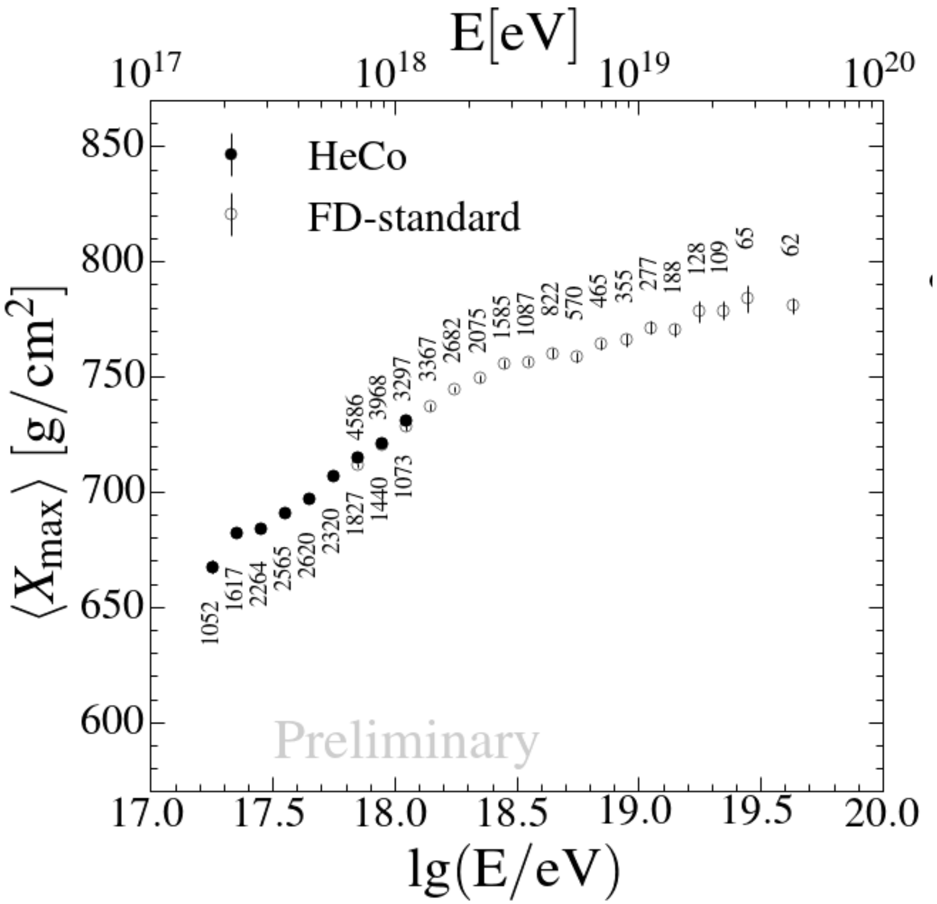


- largest proton fractions at $\approx 10^{18.3}$ eV
- above $10^{18.3}$ eV increasing fraction of He and N
- no Fe at almost all energies

X_{max} data

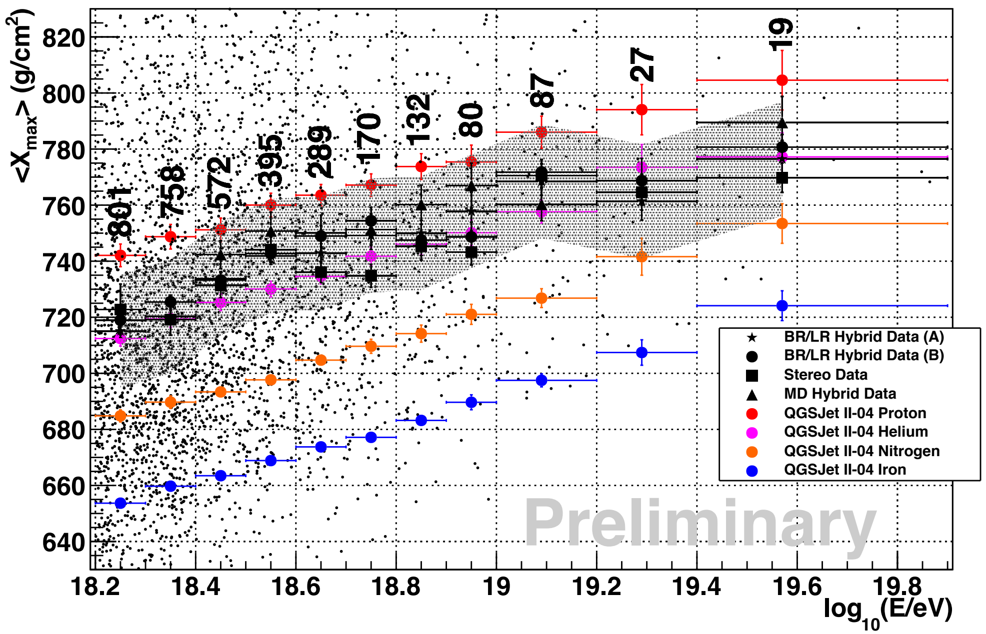
Auger

J. Bellido, PoS (ICRC2017) 522



TA

W. Hanlon, PoS (ICRC2017) 536



are the two measurements in agreement?

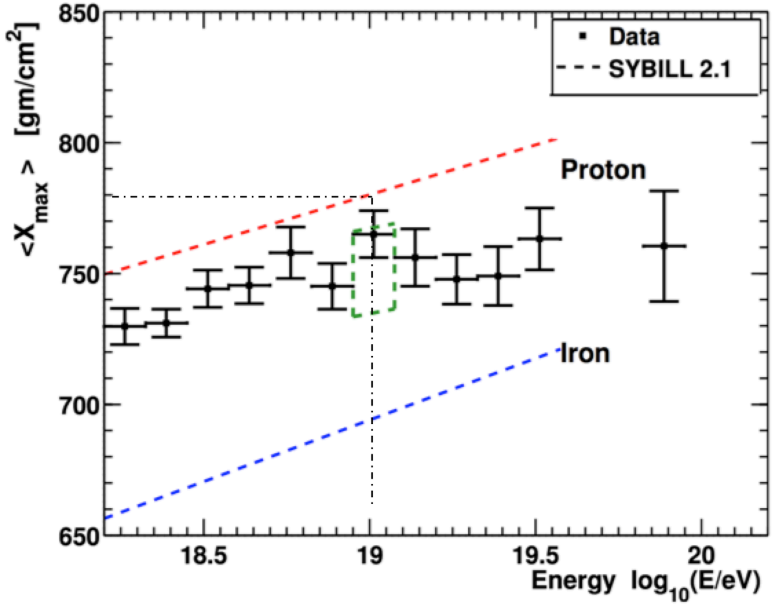
Auger vs TA

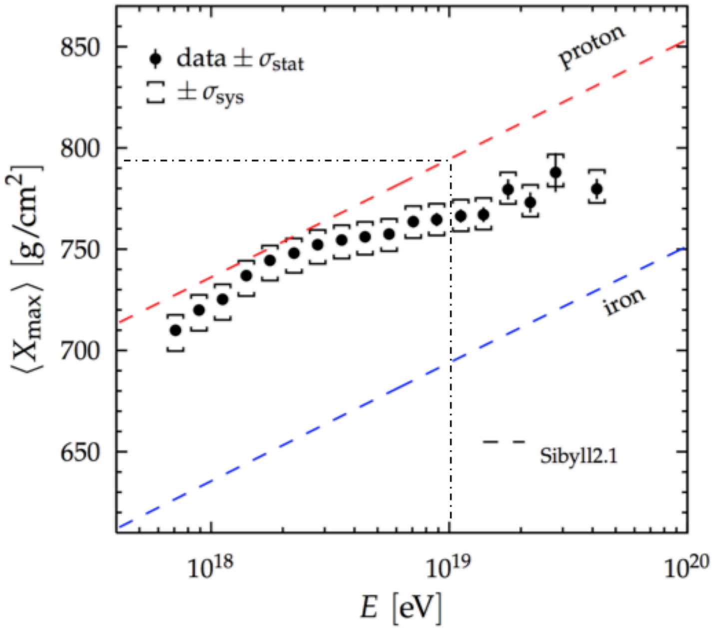
TA: X_{max} distributions folded with detector effects (maximize the statistics)

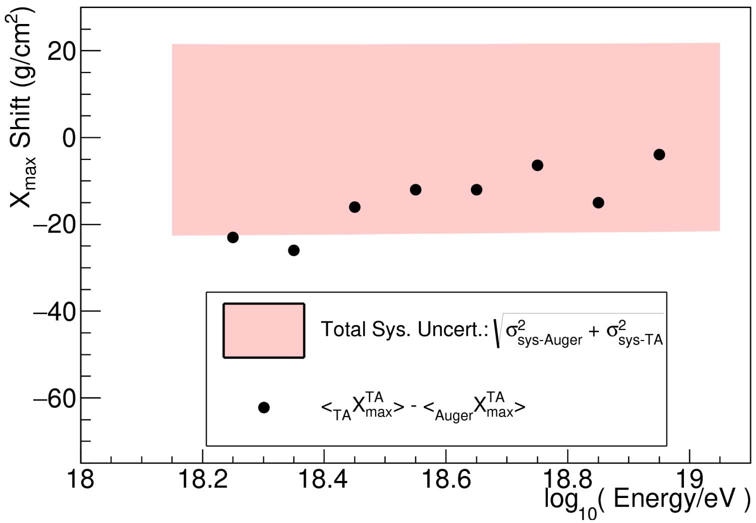
Auger: unbiased X_{max} distributions

M. Unger PoS (ICRC2015) 307

they can't be compared







1) simulate TA events according to the Auger composition
2) compare TA X_{max} distributions: data vs simulations

consistency within the systematics

V. De Souza PoS (ICRC2017) 522

SPECTRUM INTERPRETATION

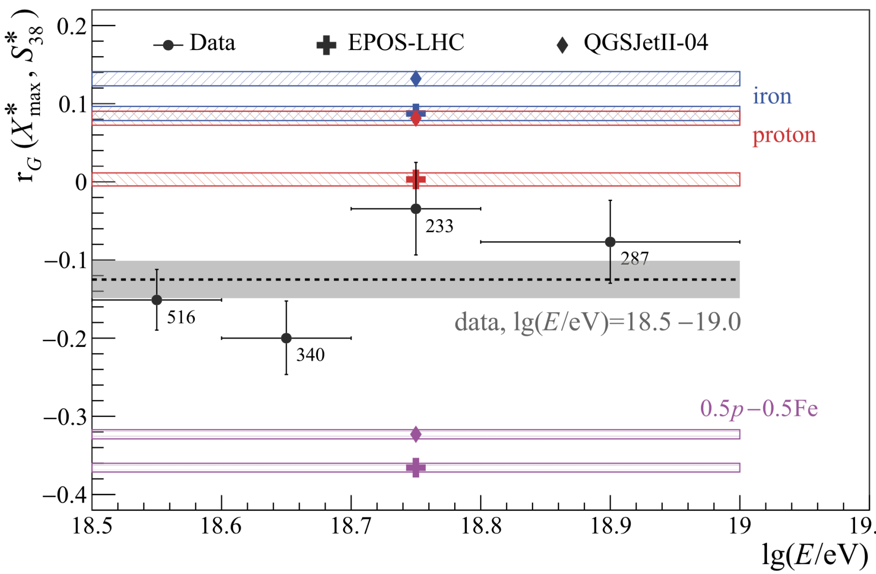
ankle 5×10^{18} eV

"dip" scenario requires extragal. protons (>85%)

BUT

correlation X_{max} vs S(1000)

evidence of a mixed composition at the ankle



Auger, Phys Lett. B 762 (2016) 288

cut-off

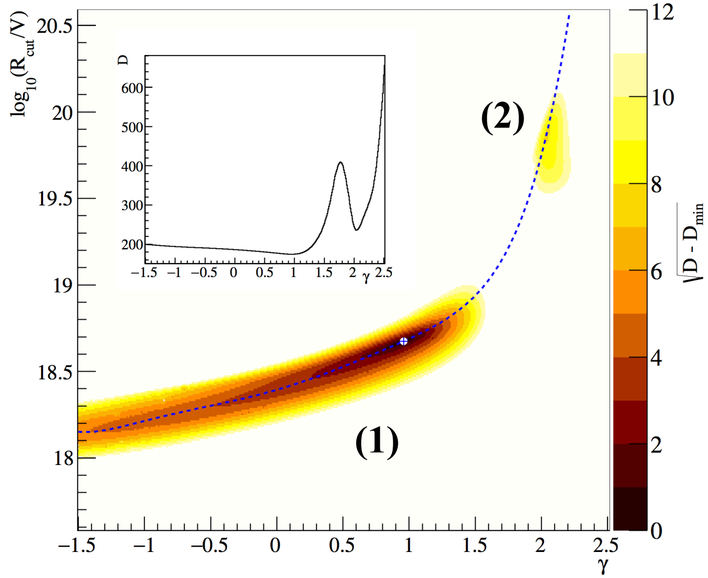
end of the spectrum due to propagation effects?

BUT

combined fit spectrum and composition

$$\Phi_A \propto f_A E^{-\gamma} f_{cut}(E, Z_A, R_{cut})$$

maximum rigidity (1) favored over photo-disintegration (2)



Auger, JCAP04 (2017) 038

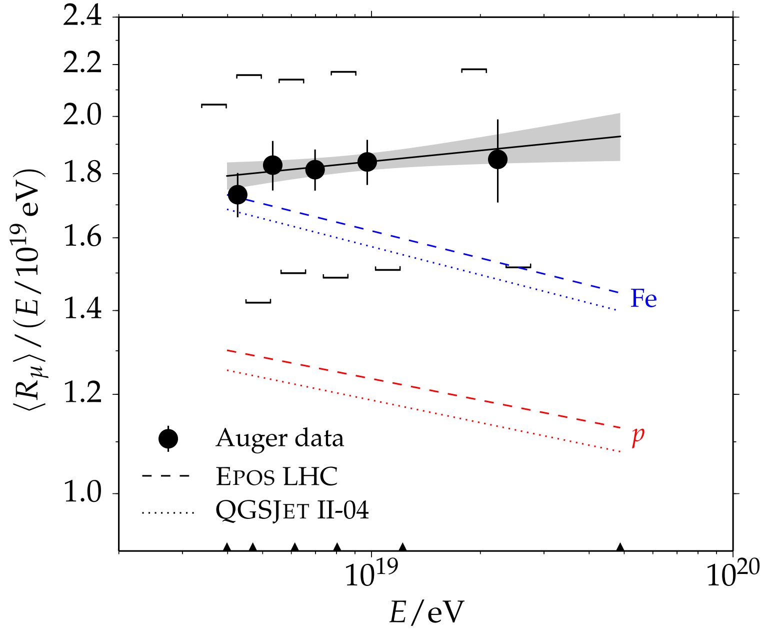
others: **R. Aloisio &V. Berezinsky arXiv1703.08671** **G.Farrar & M.Unger , PoS (ICRC2015) 336513**

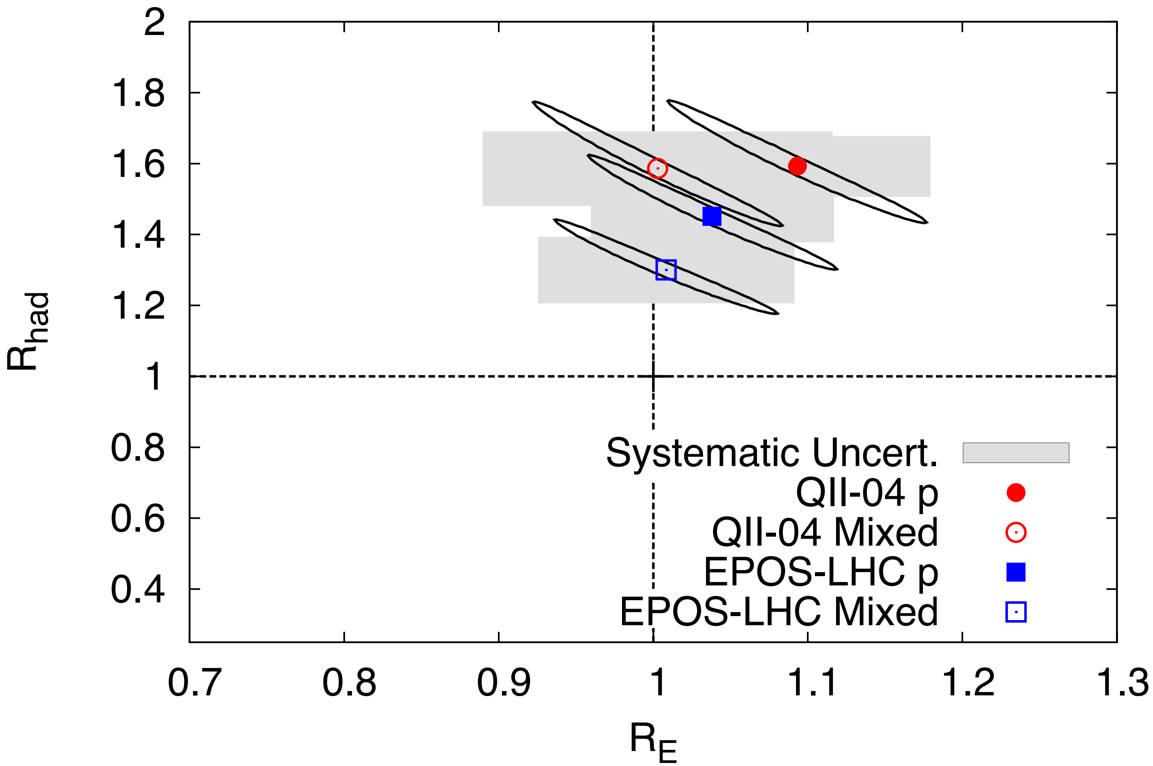
HADRONIC INTERACTIONS

Auger, PRD 91 (2015) 032003

showers inclined at large zenith angle

muon excess ~ 30%-80% for mass composition from X_{max}





Auger, PRL 117 (2017) 192001

$$S = R_E S_{EM} + R_{had} R_E^{\alpha} S_{had}$$

rescaling factors to match the SD and FD signals (hybrid data)

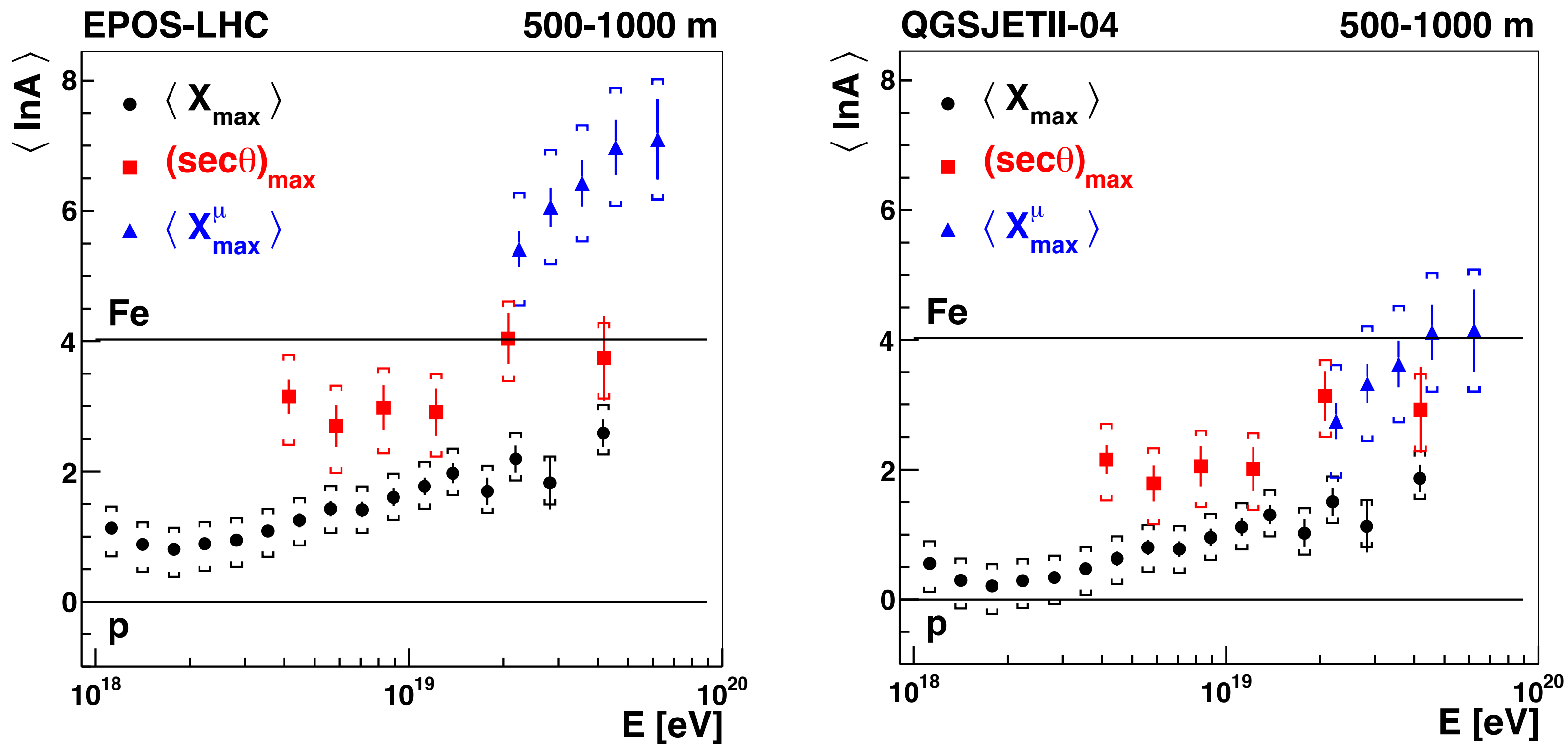
evidence of muon excess not sensitive to energy scale uncertainty

OTHER OBSERVABLES SENSITIVE TO MASS COMPOSITION

Auger, PRD 90 (2014) 122005
L.Collica (Auger) PoS (ICRC2015) 336

Auger, PRD 92 (2015) 019903

Auger, PRD 93 (2016) 072006



FD: X_{max} - 'e.m.'

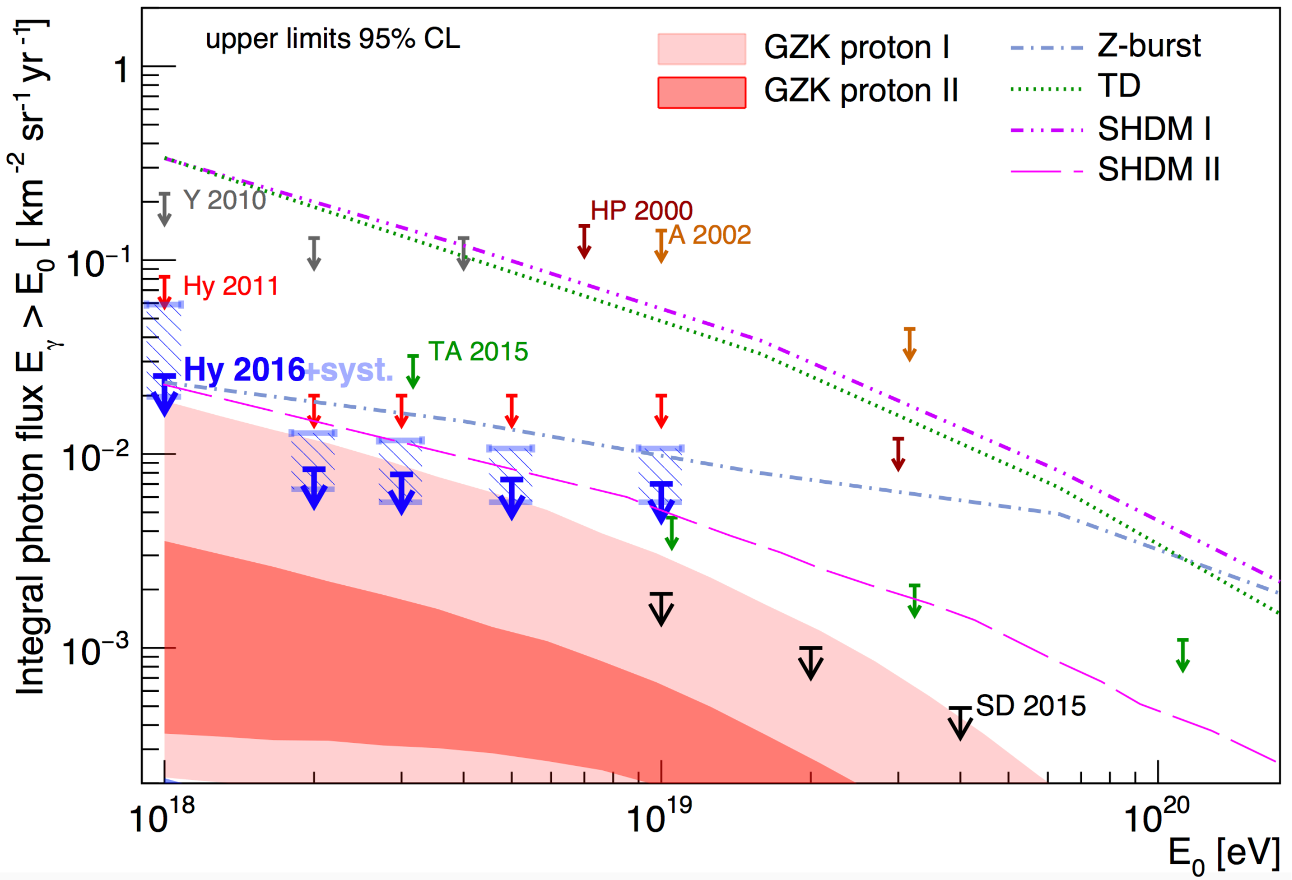
SD: $(\sec\theta)_{max}$ azimuthal asymmetry of rise time - 'e.m. + muons'

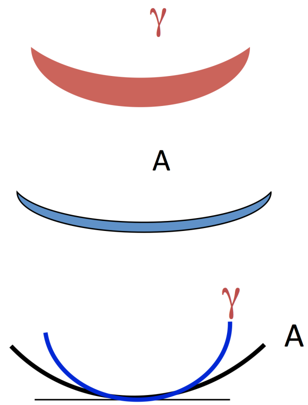
SD: X^{μ}_{max} muons production depth - 'muons'

Hadronic interaction models fail to provide consistent interpretations of different observables

PHOTON LIMITS

FD: X_{max}
SD: time spread, shower front curvature





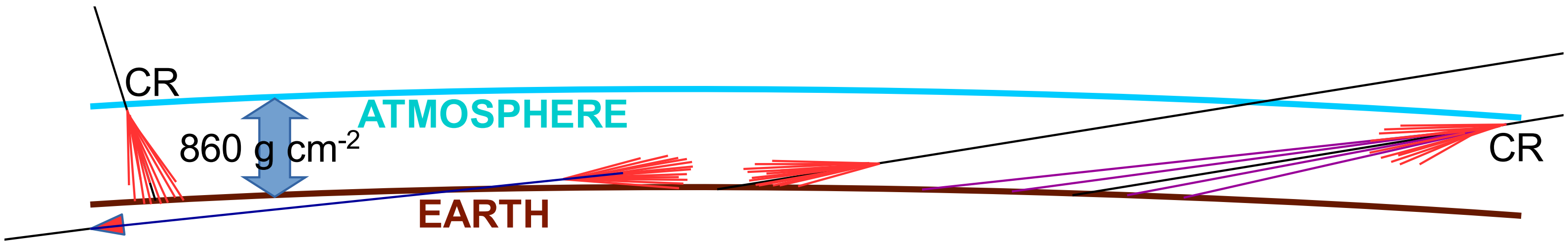
Auger, JCAP 04 (2017) 009 and references therein

most of top-down models ruled-out

start to constraint GZK photons

$p\ \gamma_{GZK} \rightarrow p\ \pi^0$

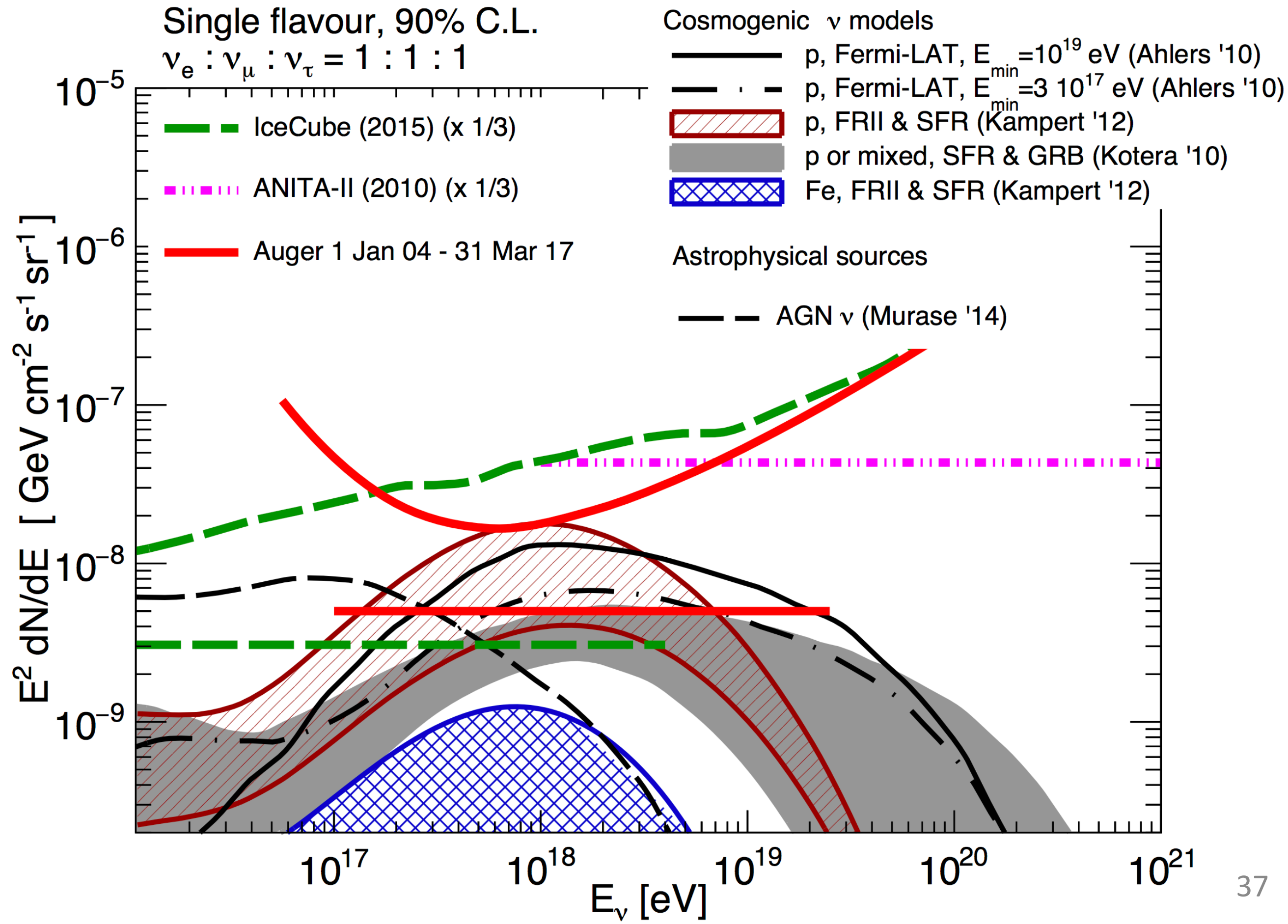
NEUTRINO LIMITS



Auger well suited for detecting cosmological neutrinos

E. Zas PoS (ICRC2017) 972

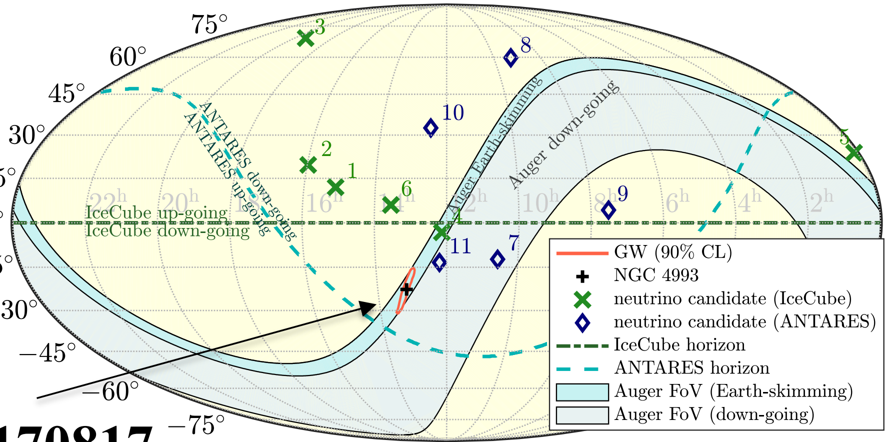
J. Alvarez-Muñiz PoS (ICRC2017) 1111



NO NEUTRINOS (E>100 PeV) IN COINCIDENCE WITH GW IN AUGER SD DATA

Auger Antares IceCube arXiv:1710.05839

E. Zas PoS (ICRC2017) 972 **Auger, Phys. Rev. D 94, 122007 (2016)**

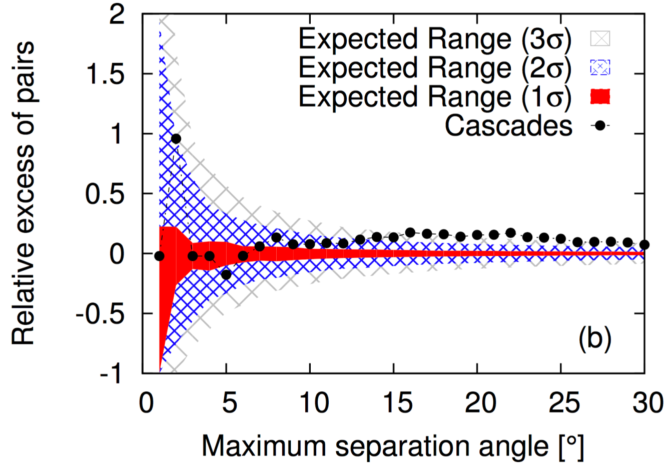


GW170817

ApJL, 848:L12, 2017

CORRELATIONS AMONG IceCube NEUTRINOS AND TA+AUGER CRs

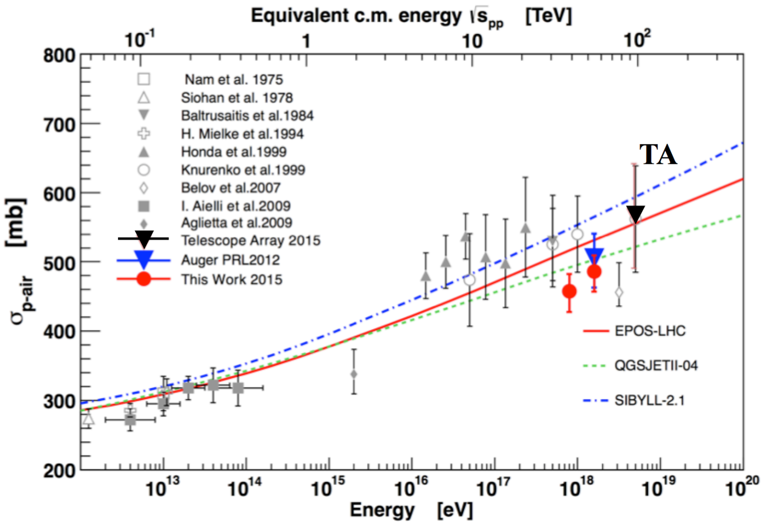
IceCube, Auger & TA JCAP01 (2016) 037



$\sigma_{p\text{-}air}$ FROM FD

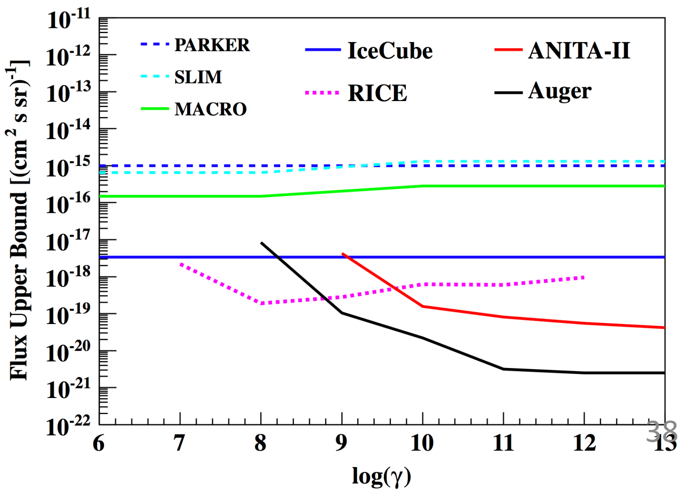
R. Ulrich PoS (ICRC2015) 401

R. Abbasi PoS (ICRC2015) 402



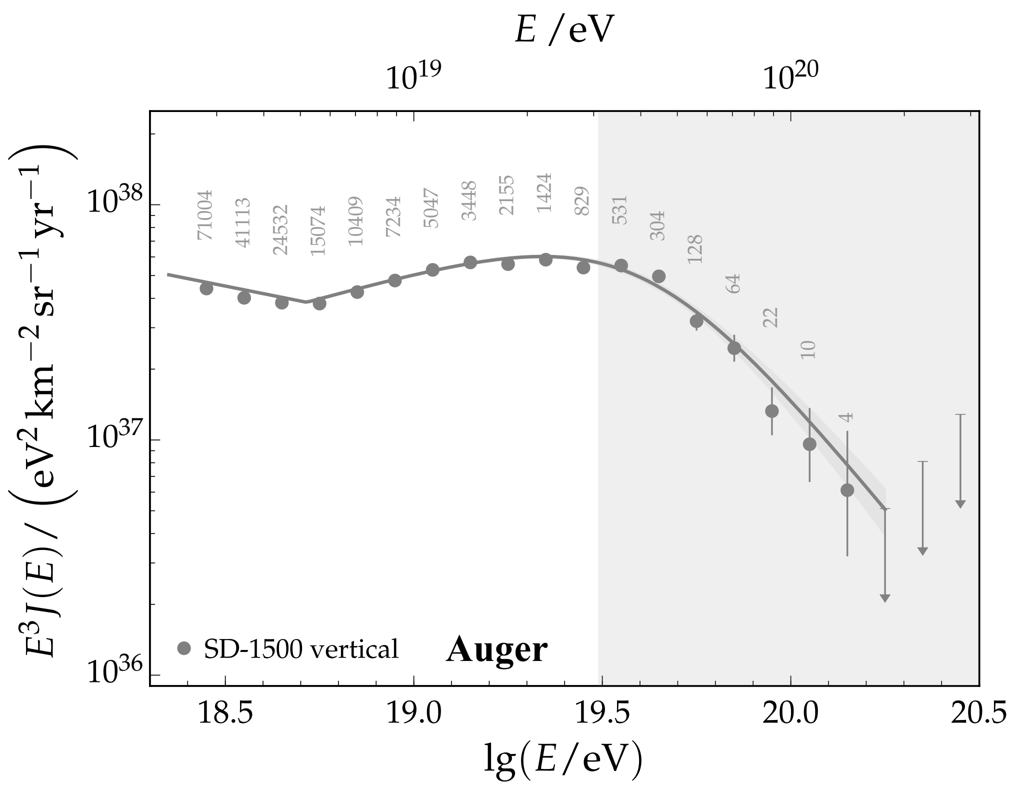
NO ULTRARELATIVISTIC MONOPOLES IN AUGER FD DATA

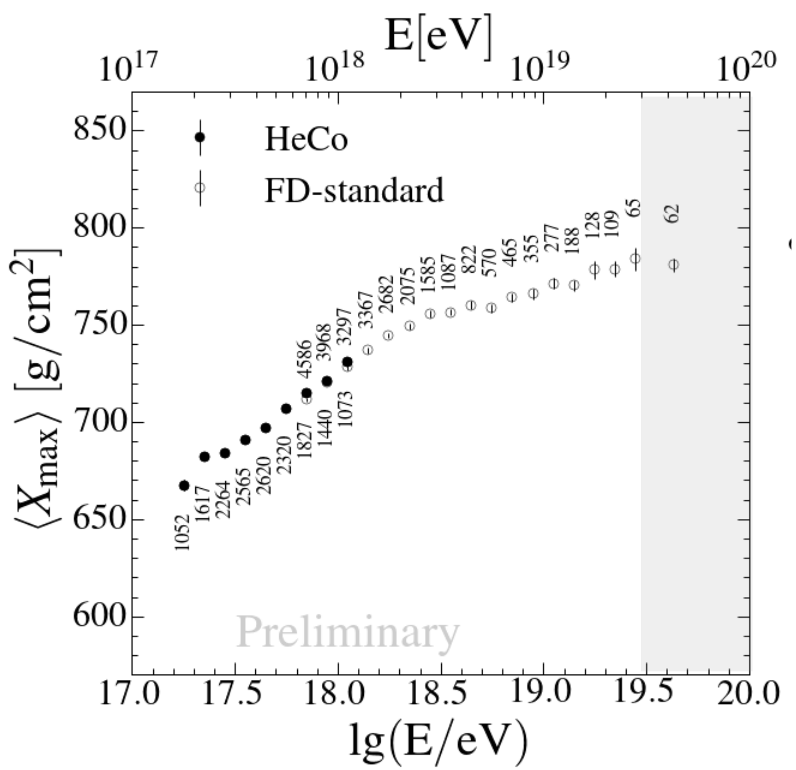
Auger, Phys. Rev. D 94 (2016) 082002



FUTURE

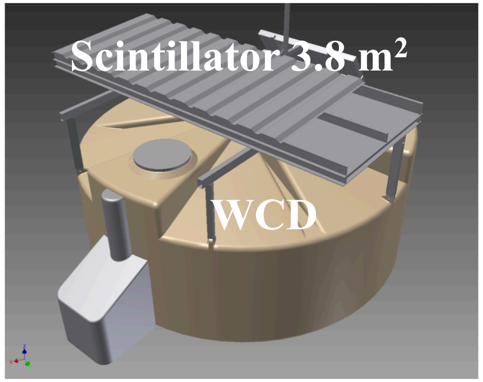
- accumulate exposure
- mass composition at the highest energies ?
- how to overcome the problem of the limited FD duty cycle ?

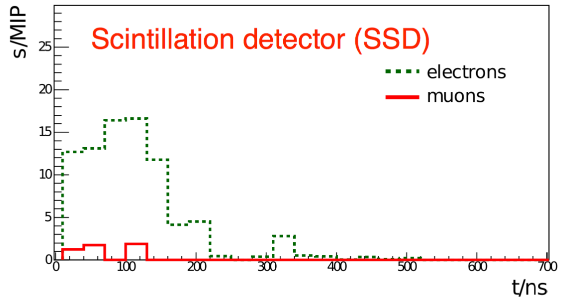


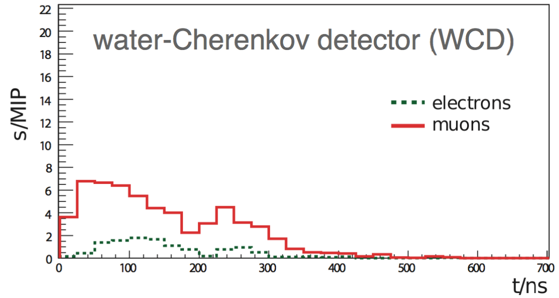


Auger upgrade

scintillator
faster electronic (120 MHz)
…



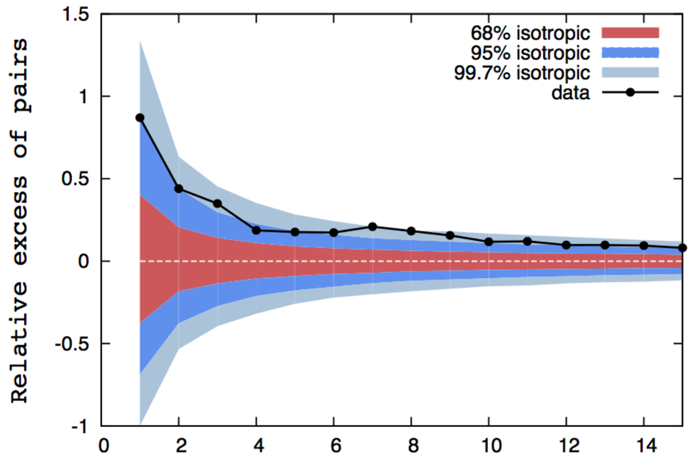


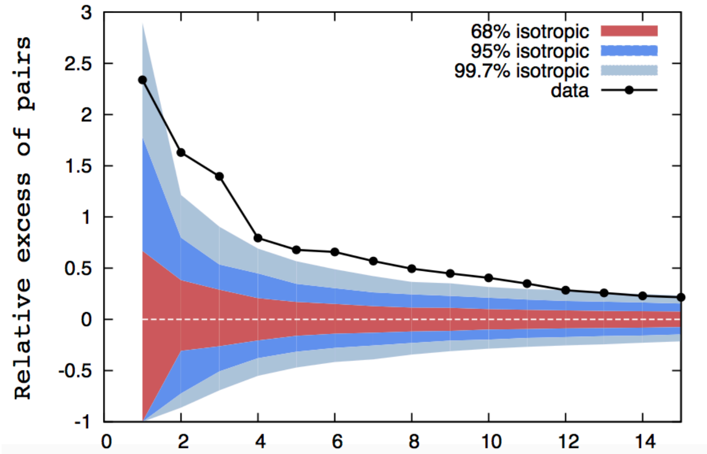


- discriminate e.m. and muonic components
- **mass sensitivity above the cut-off (no sensitivity from FD)**

$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$

e.g. anisotropies for light primaries



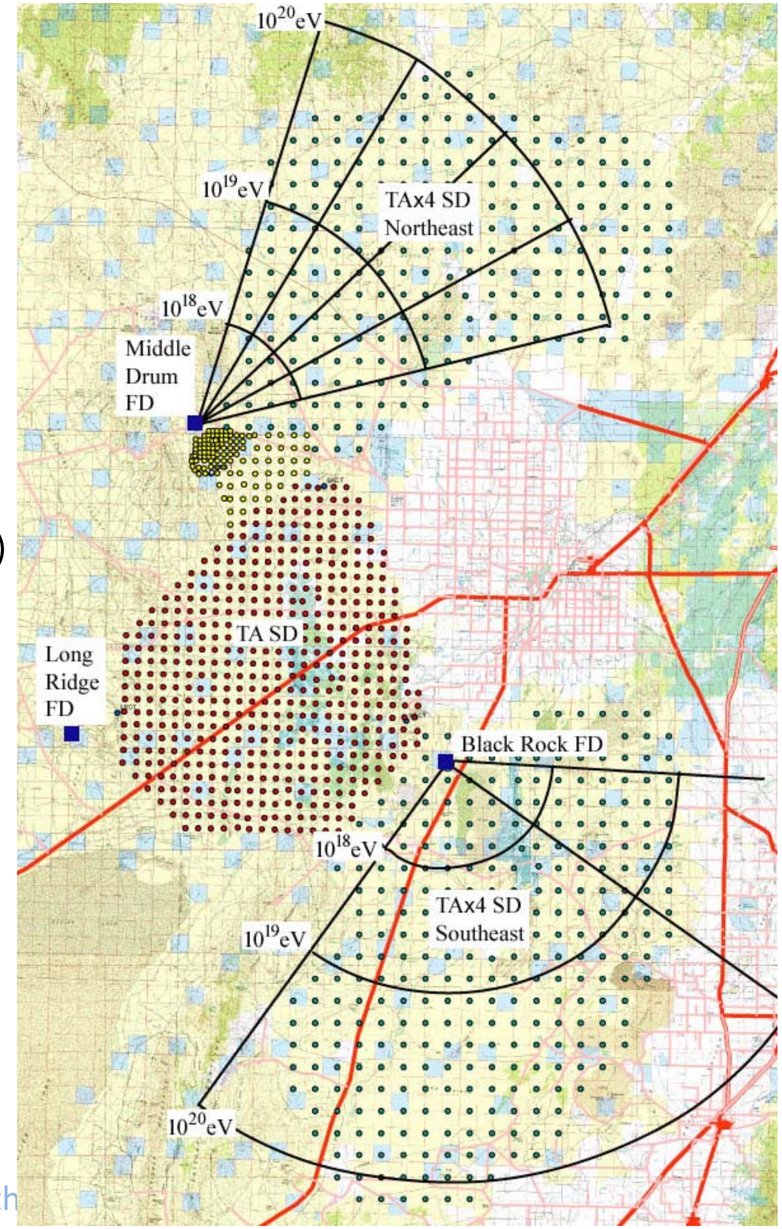


arXiv:1604.03637

D. Martello, PoS (ICRC17) 383

TA IN THE NEXT DECADE

J. Matthews, PoS (ICRC17) 1096

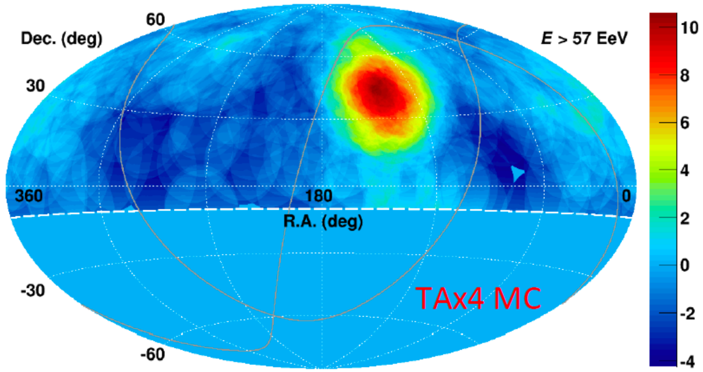


TAx4 ~3000 km^2

SD: 507 scintillators
1.2 km - 700 km^2

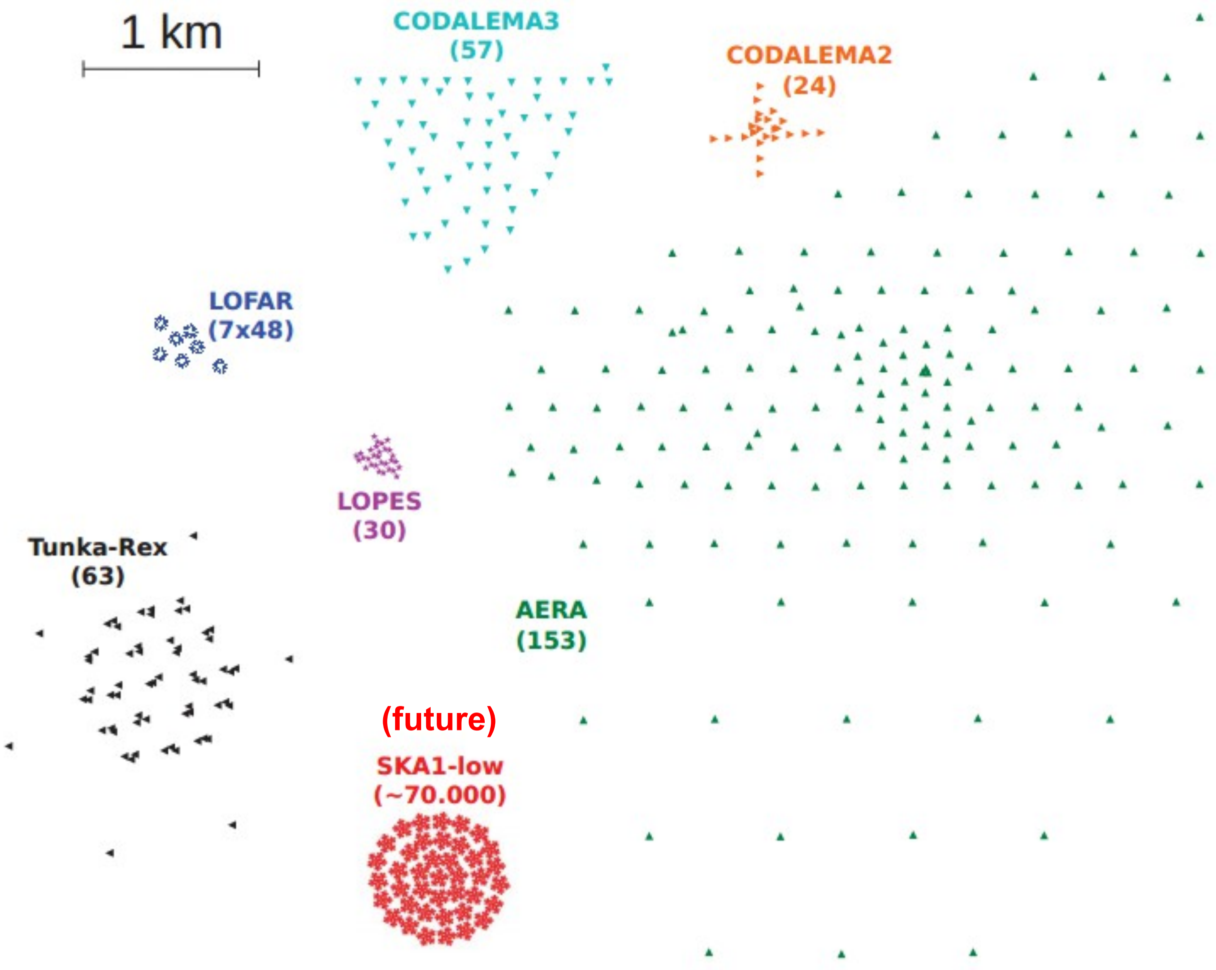
new 500 SD stations
2.08 km spacing

2 additional FDs in MD and BR

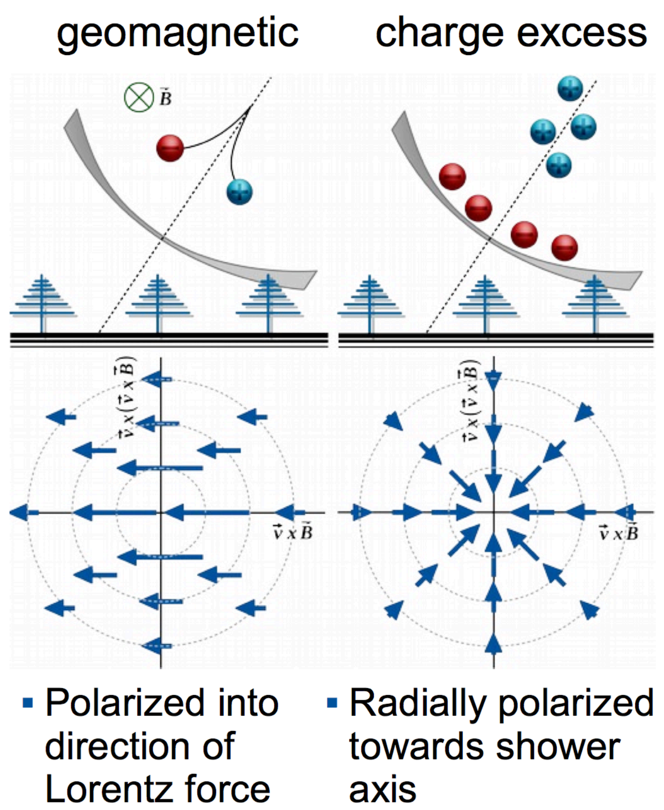


Radio detection of EAS

T. Heuge
Phys. Rep. 620, 1-52 (2016)



~ 100 MHz

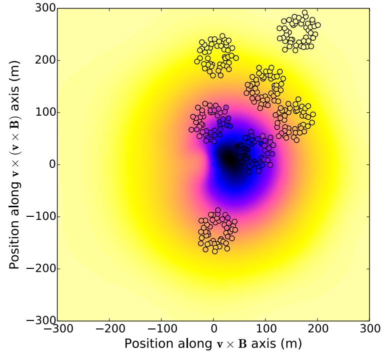


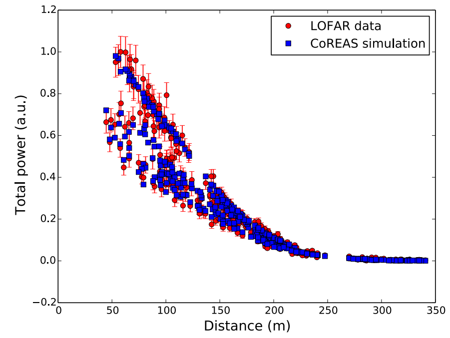
radio signals related to the em of the shower
100% duty cycle
no atmospheric attenuation, ...

Askaryan effect
25% of e^- over e^+

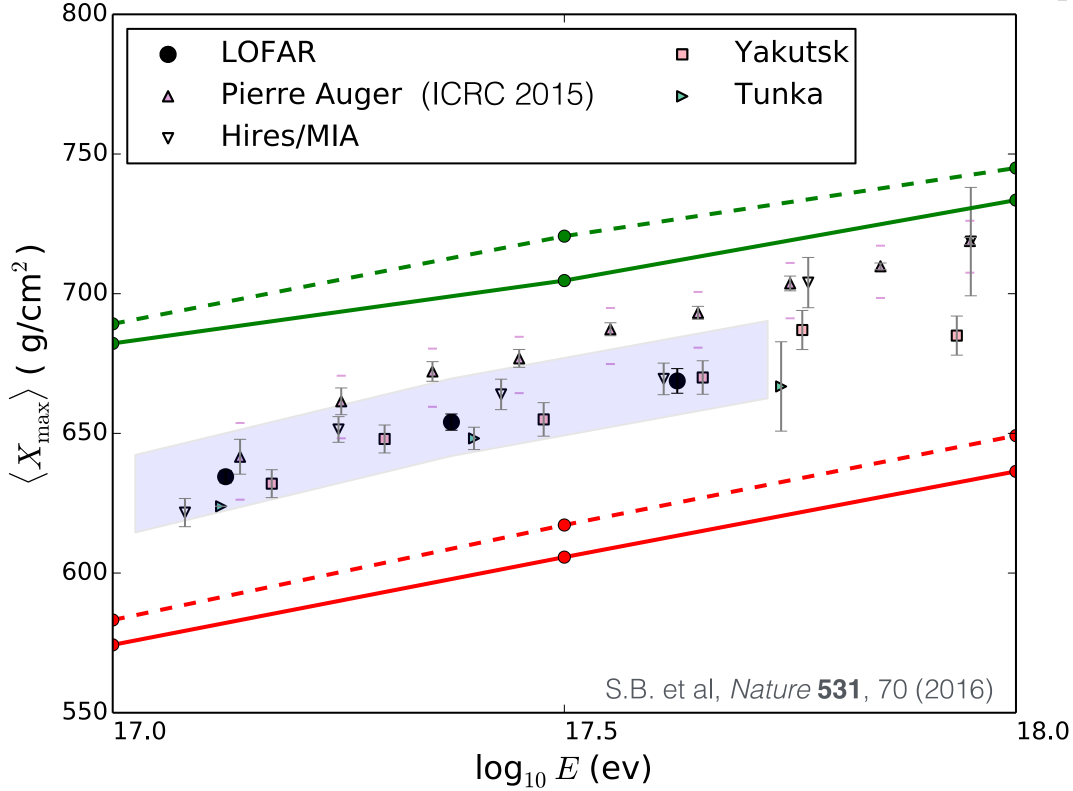
G. Askar´yan,
Soviet Phys. JETP 14, 441 (1962)

Radio detection of EAS

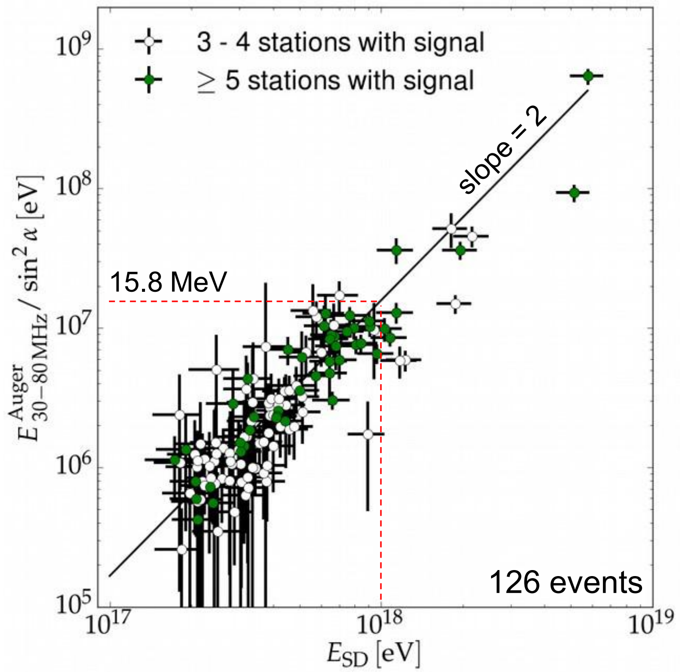




LOFAR



AERA (Auger)



many progresses and CR physics feasible

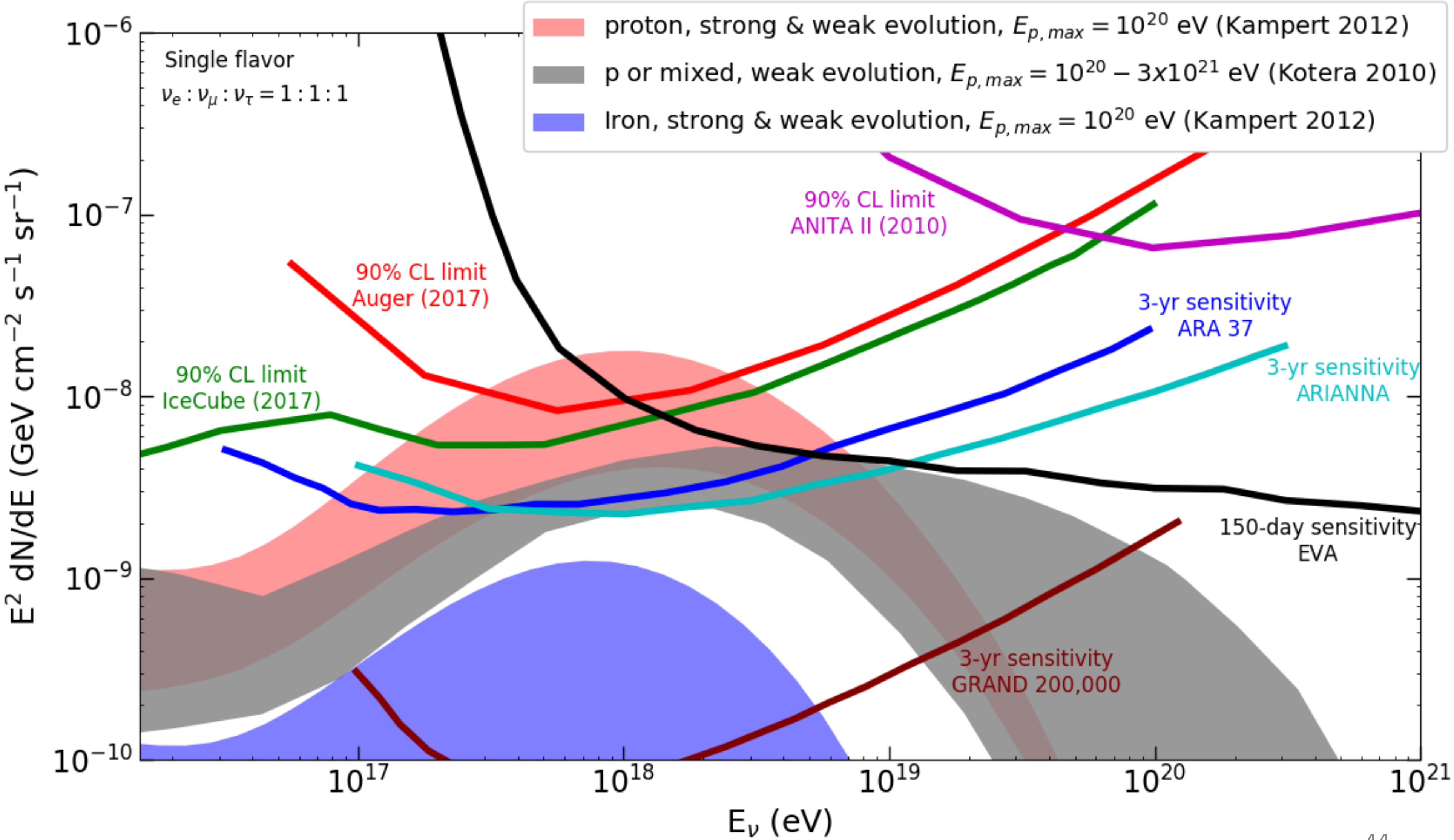
- X_{max} from LOFAR
- energy estimation from AERA (Auger)

main limitation:

- small footprint at ground → requires dense array of antennas

Neutrino with radio detectors

J. Alvarez-Muñiz PoS (ICRC2017) 1111



Fluorescence radiation detection from space

JEM-EUSO Program

EUSO-TA (2013 -)

EUSO-Balloon (2014)

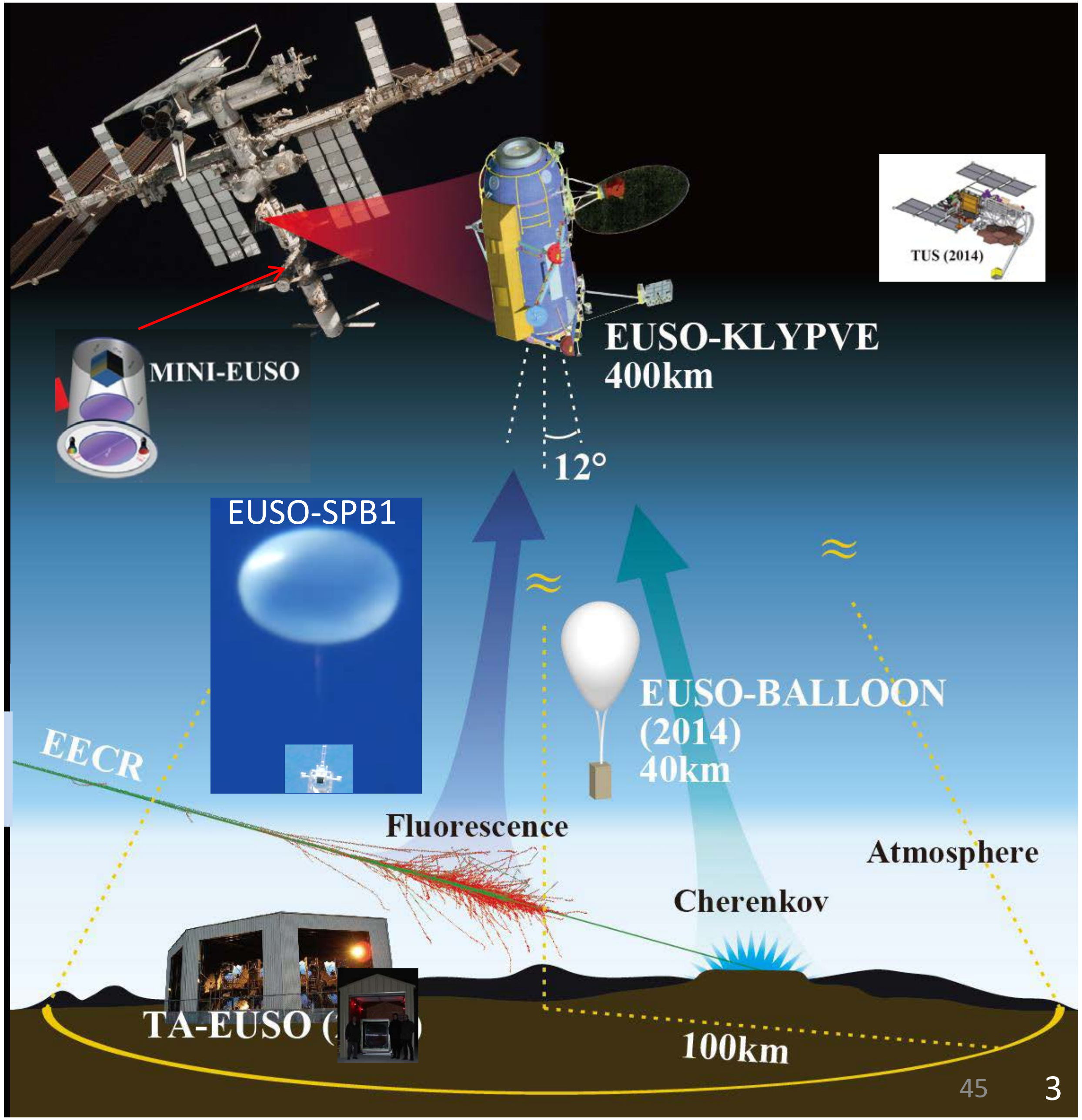
EUSO-SPB1 (2017)

MiniEUSO (2018)

EUSO-SPB2 (2021)

K-EUSO (2023)

also
POEMMA (2025 +)



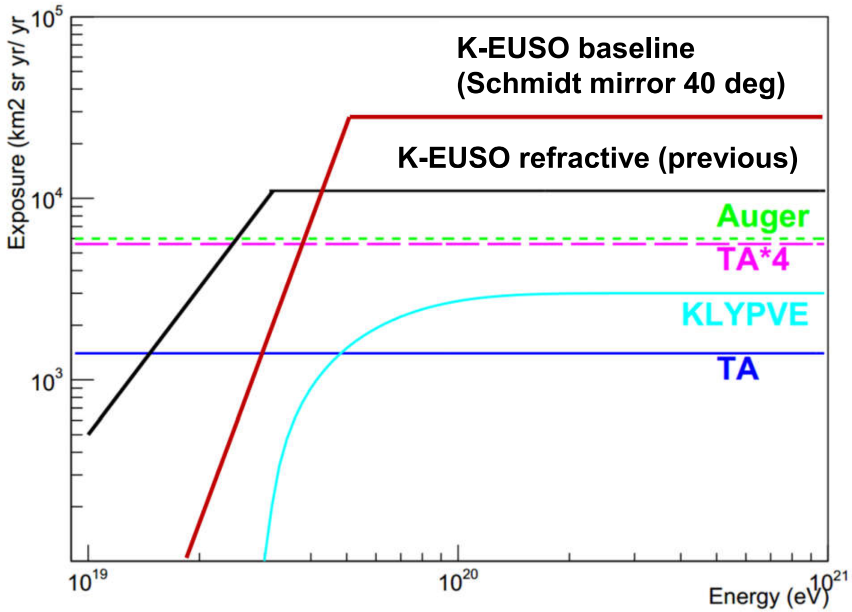
M. Casolino PoS (ICRC2017) 370

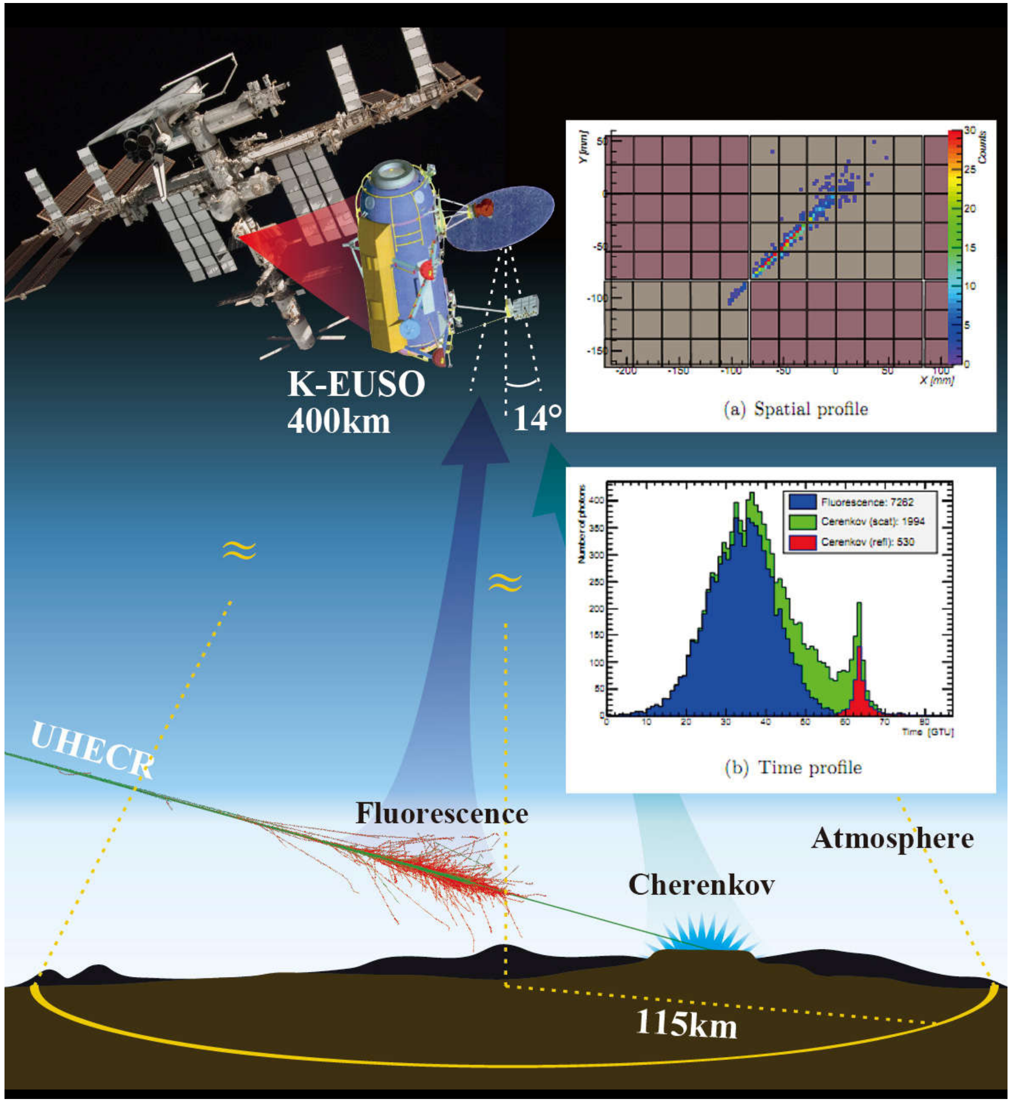
Fluorescence radiation detection from space

K-Euso - ISS

- approved by Russian Space Agency
- it is a concrete mission at a fraction of the cost of JEM- EUSO

uniform full sky coverage with large exposure





M. Casolino PoS (ICRC2017) 370

OUTLOOK

- **successful implementation of the hybrid technique (FD+SD) but still many open issues**
  - UHECRs are of extragalactic origin
  - there is some level of anisotropy but what are the sources?
  - UHECRs are not only protons. What is the mass composition at the cut-off? ankle and cut-off interpretation?
  - hadronic interaction models?

➢ **Auger and TA will take data in the next decade**
  - 6000 km^2 with full sky coverage
  - mass sensitivity at the highest energies

➢ **next generation experiments**
  - fluorescence detection from space
  - current UHECRs observatories are the ideal place where to develop new detection techniques (radio …)

➢ **new LHC data**

PIERRE AUGER OBSERVATORY

TELESCOPE ARRAY PROJECT

AugerNext R&D studies ASPERA

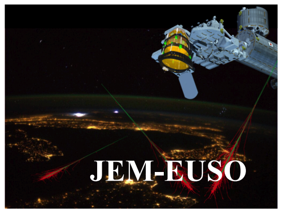
FAST Fluorescence detector Array of Single-pixel Telescopes

AERA Auger Engineering Radio Array

TOTEM

LHCf

SHINE NA61



LOFAR

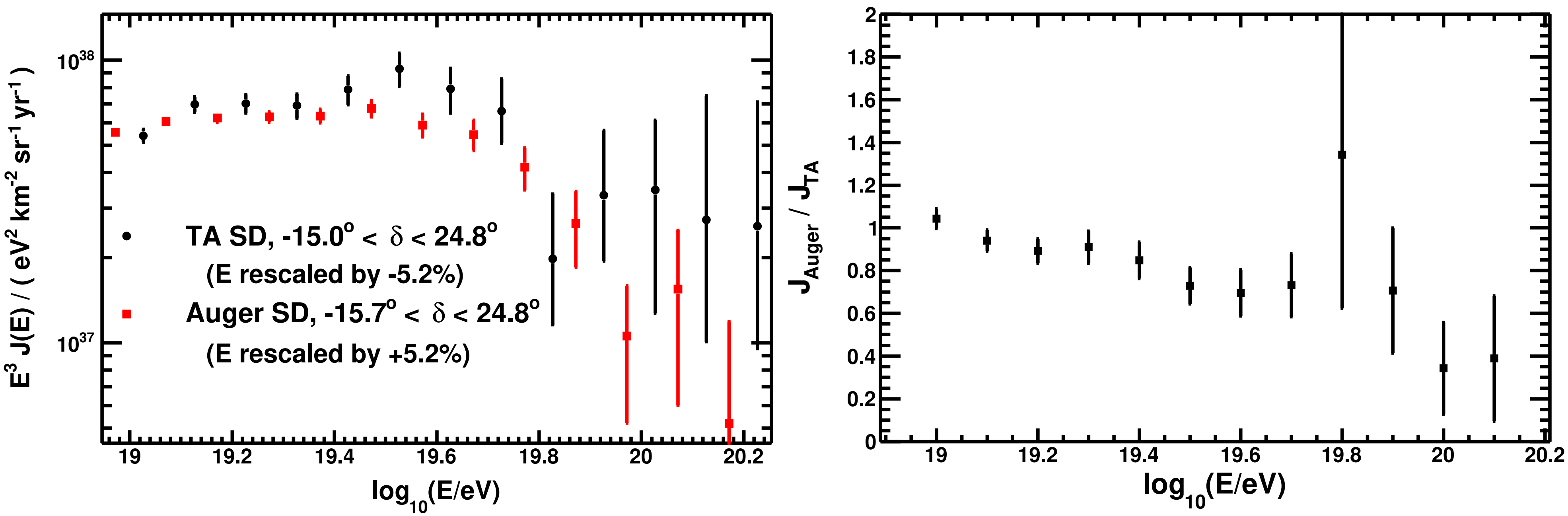
THANKS

COMPARISON OF THE ENERGY SPECTRA IN THE COMMON DECLINATION BAND

- common declination band $-15.7^0 < \delta < 25^0$
- account for the different shapes of the directional exposure

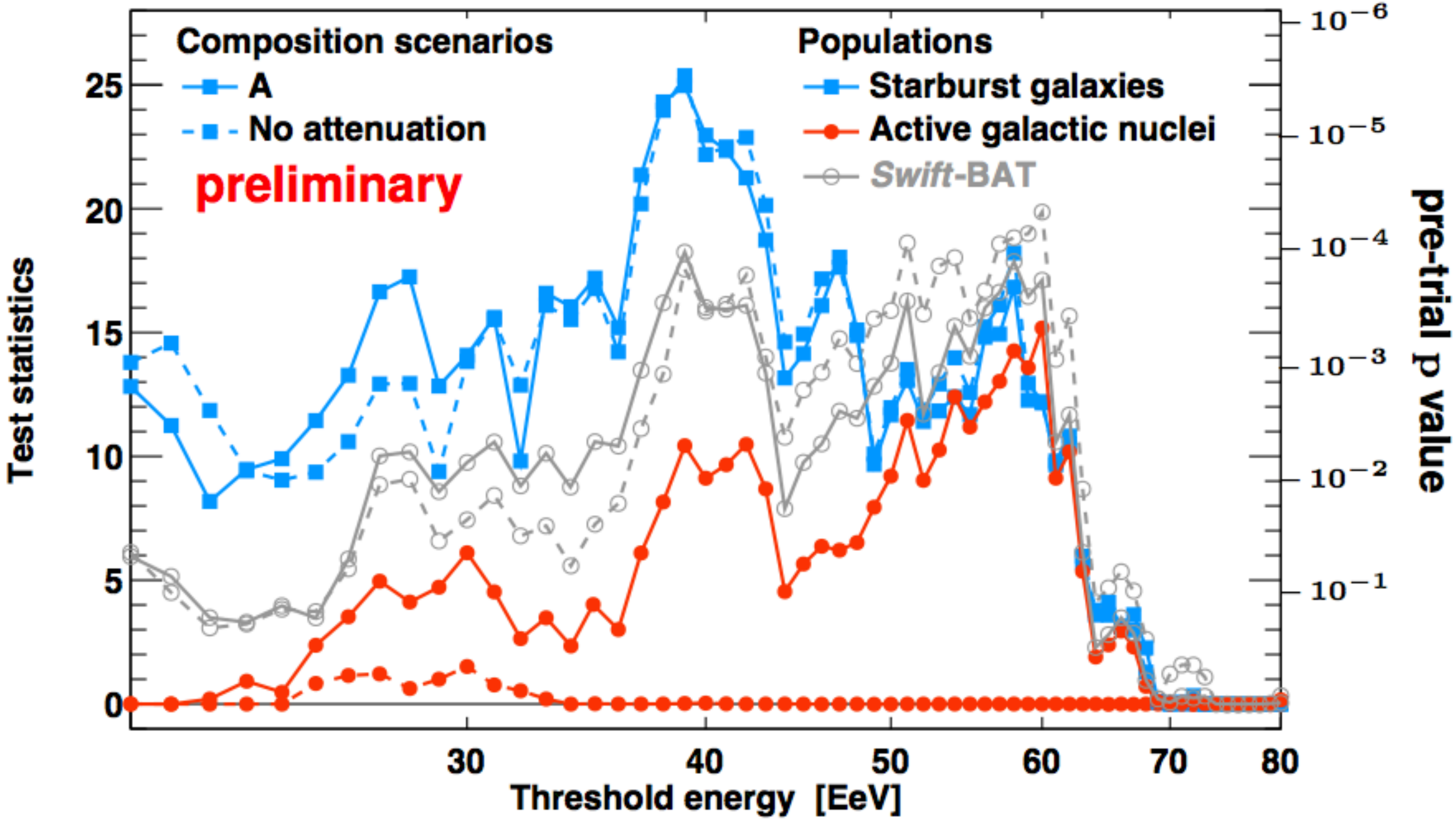
→ better agreement than in the full declination band
→ still some discrepancy that has to be due to experimental effects

Auger + TA Proceedings of UHECR2016 PoS (ICRC2017) 498



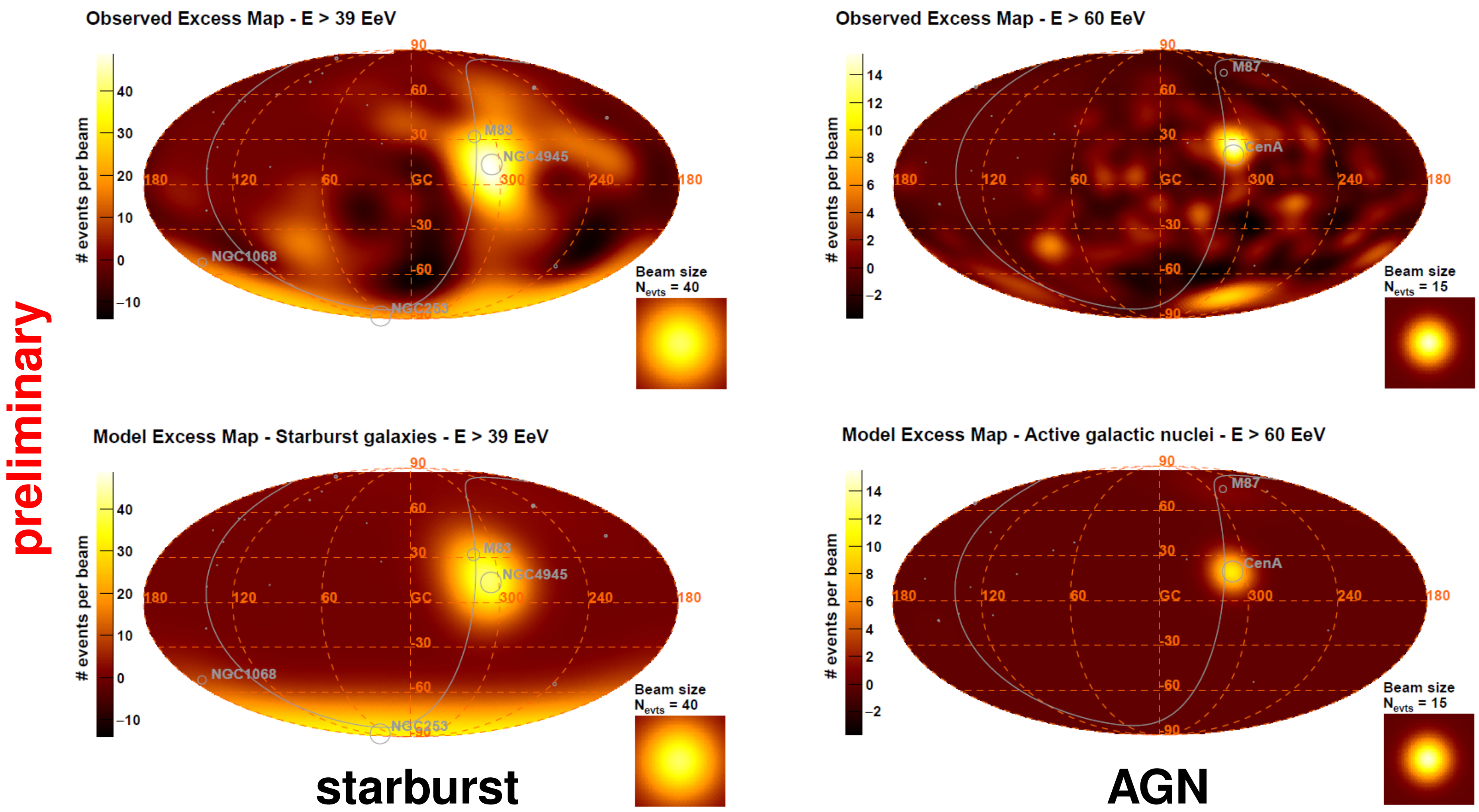
Anisotropies at intermediate scale - Auger

U. Cacciari, PoS (ICRC2017) 484



Anisotropies at intermediate scale - Auger

U. Cacciari,
PoS (ICRC2017) 484



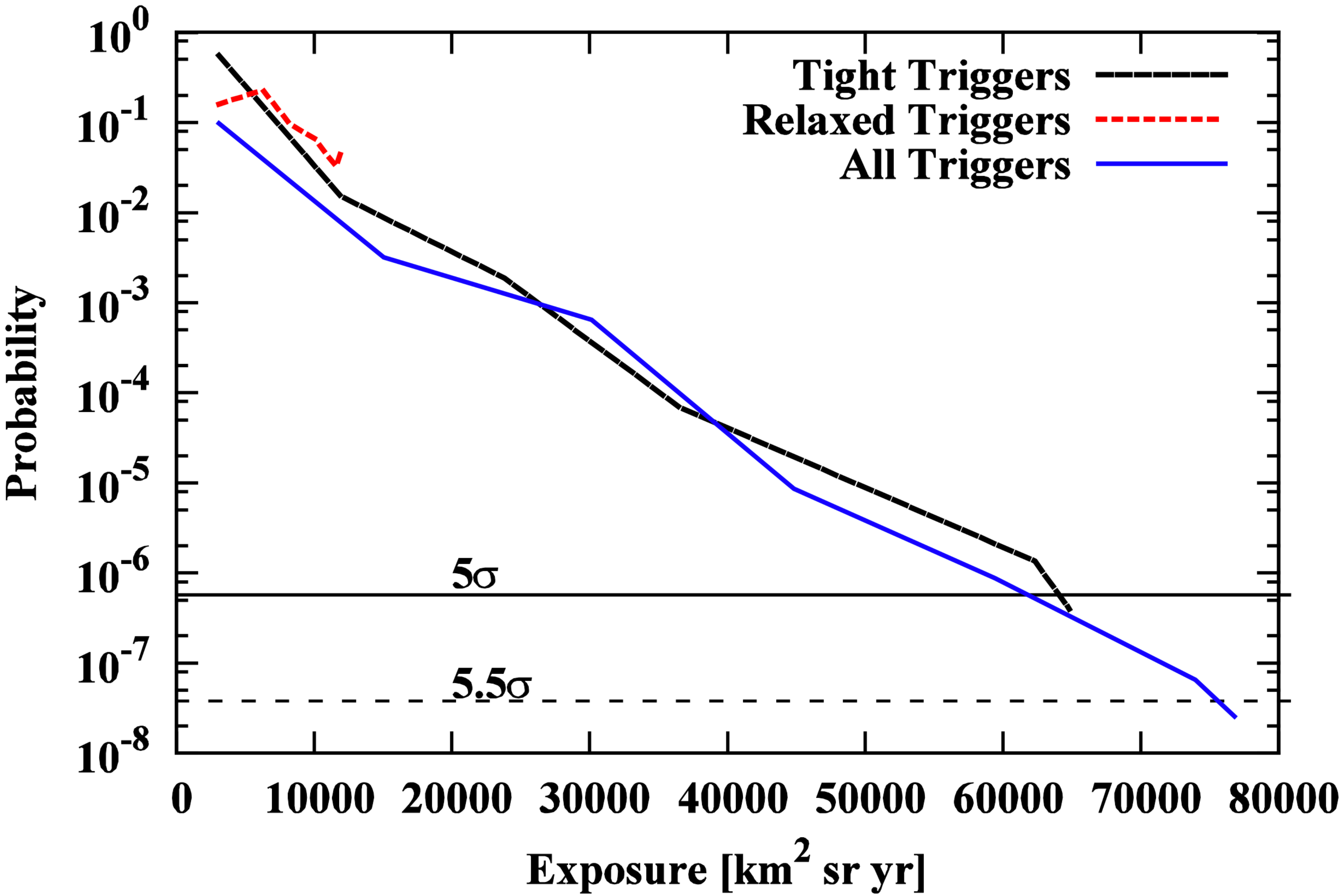
3.9 σ

post-trial significances
(energy scan)

2.7 σ

OBSERVATION OF A LARGE SCALE ANISOTROPY

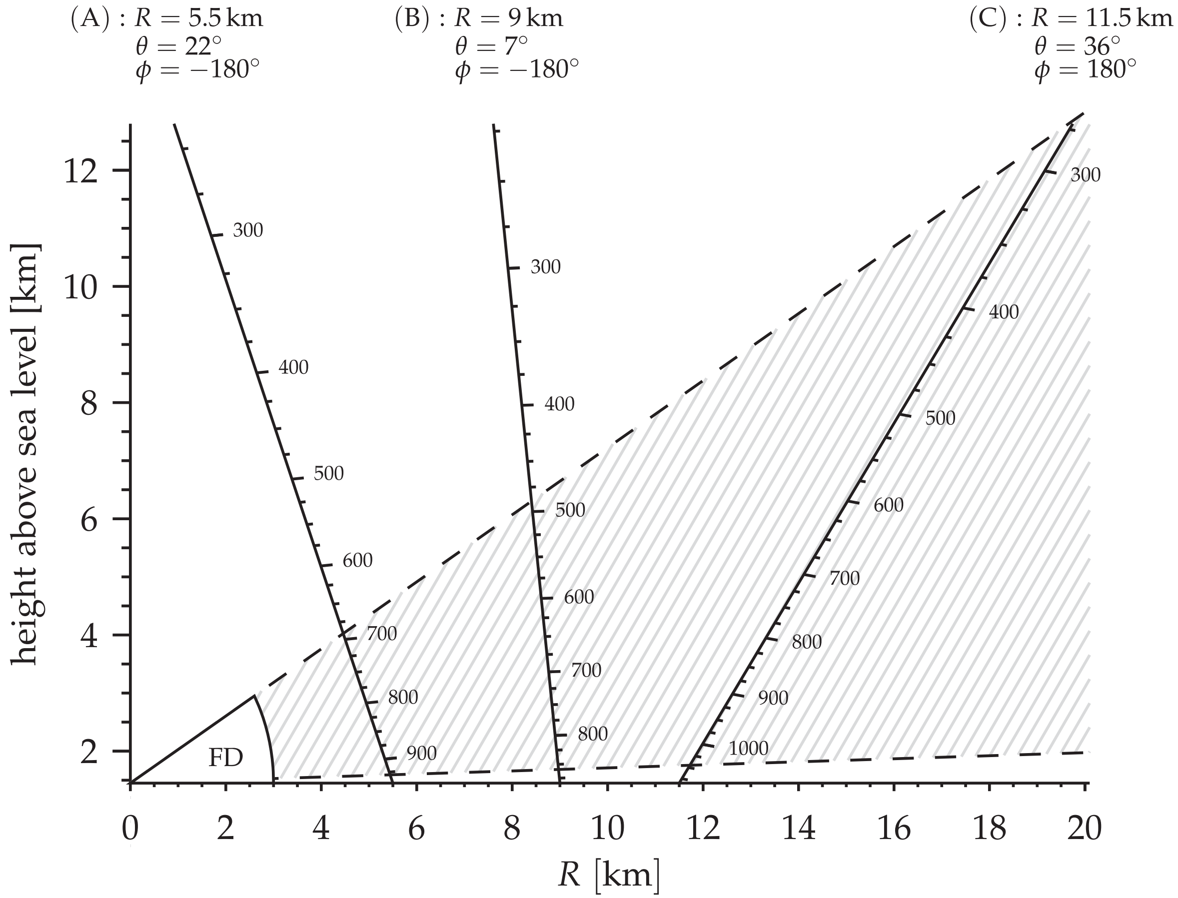
Auger, Science 57 (2017) 1266-1270

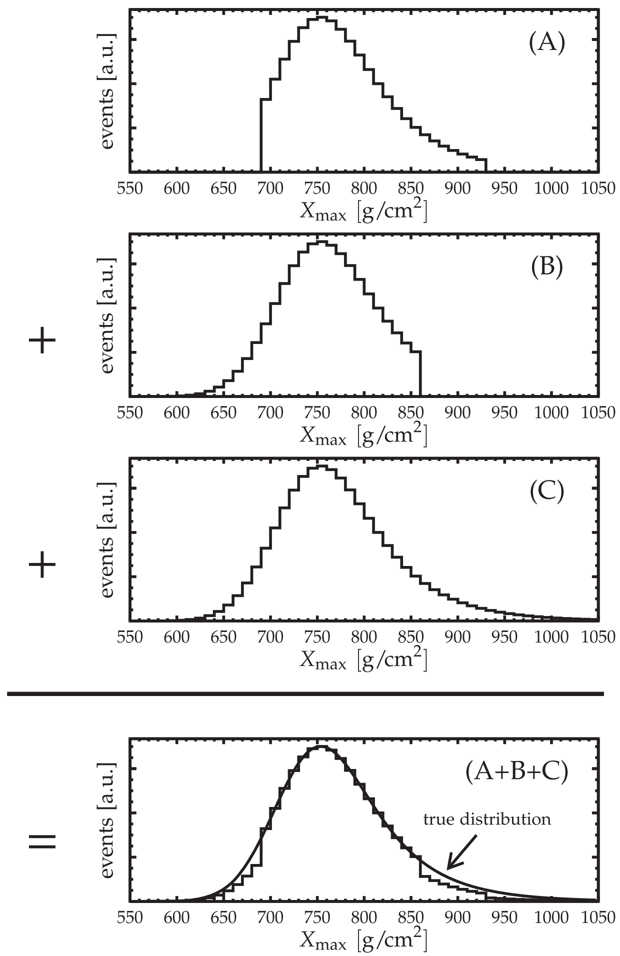


X_{max}: Auger vs TA

X_{max} distributions distorted by the FD field of view

- Auger: cuts to obtain unbiased X_{max} distributions
- TA: X_{max} distributions folded with detector effects (maximize the statistics)





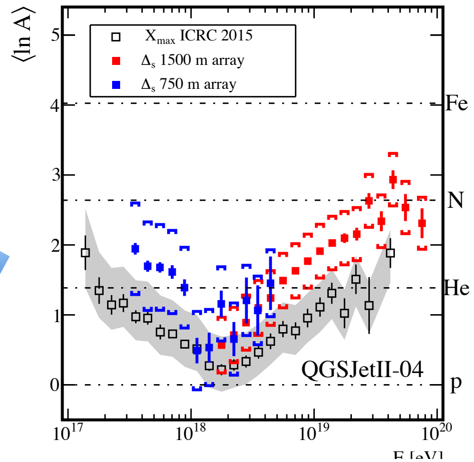
Calibrate SD mass estimator againts X_{max} from FD

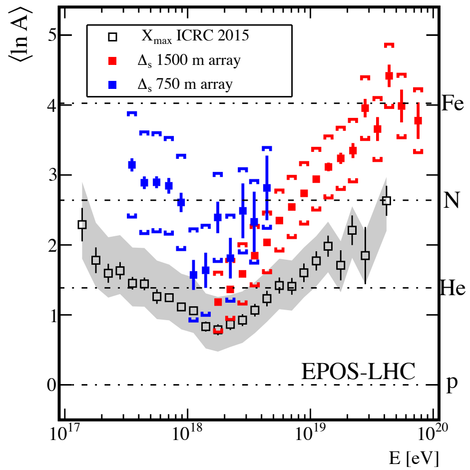
Auger arXiv:1710.07249

rise time in SD signals sensitive to mass composition

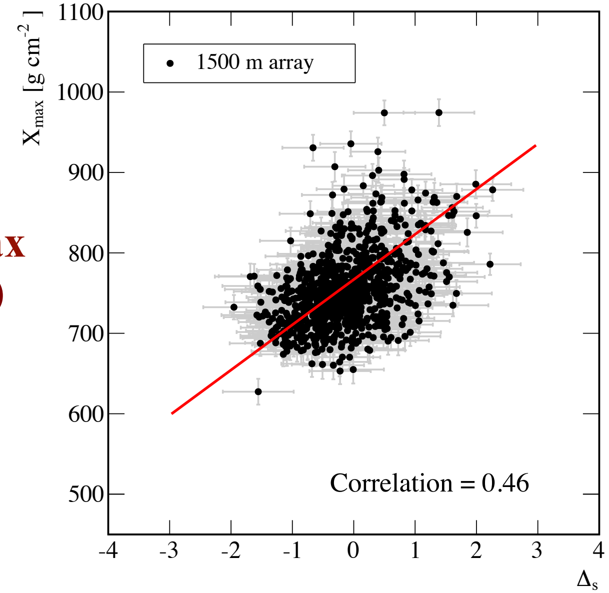
but its interpretation is not consistent with the one from X_{max}

calibrate it against X_{max} from FD

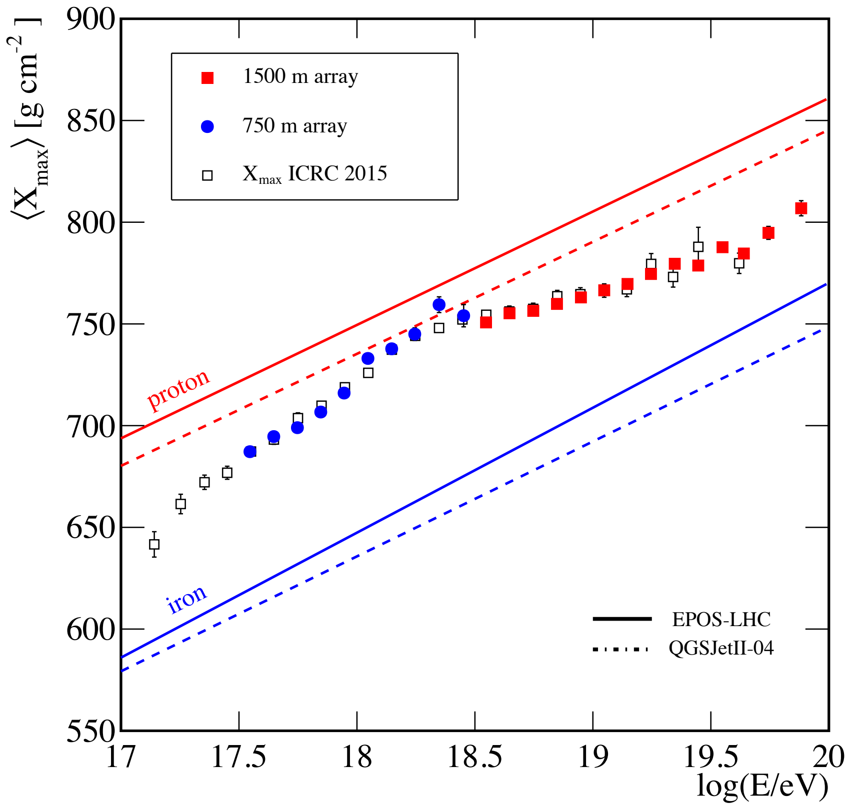




X_{max} FD

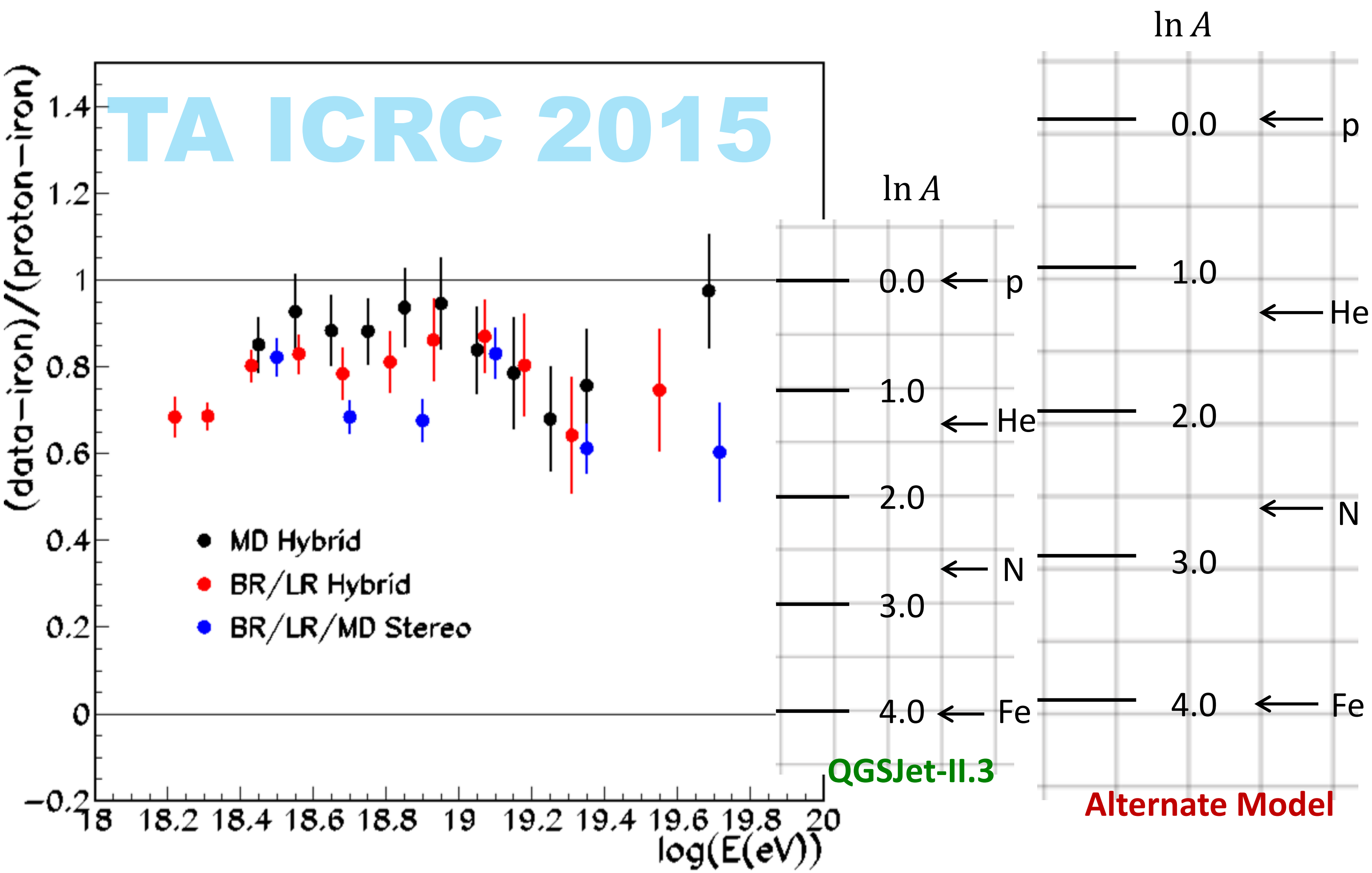


Δ_s SD



rise of mass composition > 50 EeV seems to stop

TA data compared to QGSJet-II.3

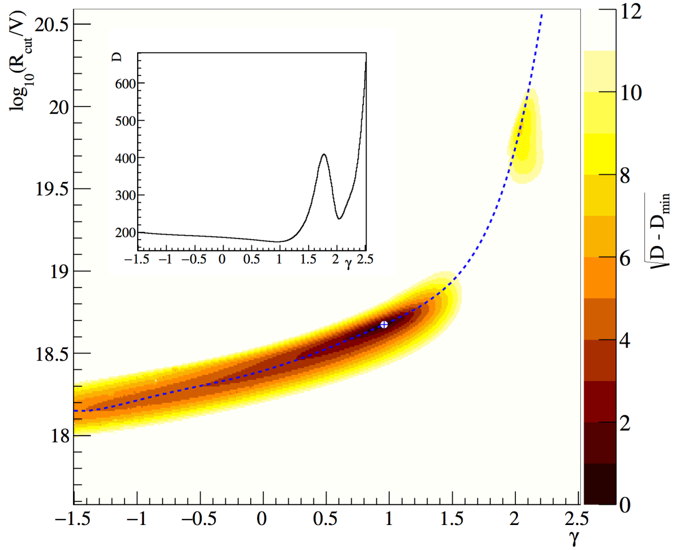


SPECTRUM INTERPRETATION

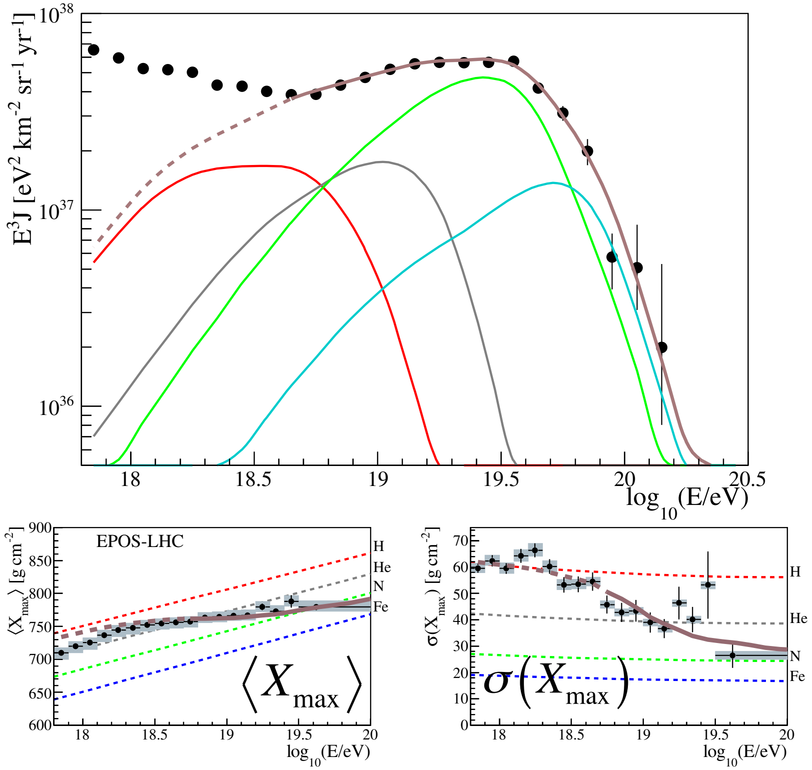
Auger, JCAP04 (2017) 038

predict the energy spectrum at Earth assuming that CRs are of extragalactic origin

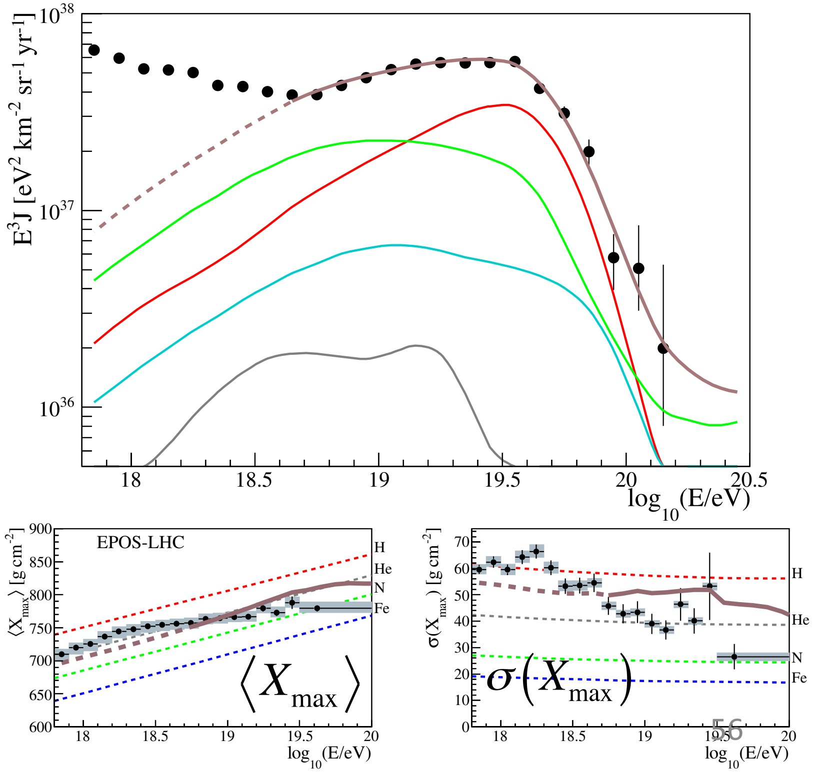
fit (f_A,γ,R_{cut}) at sources $\Phi_A \propto f_A E^{-\gamma} f_{cut}(E, Z_A, R_{cut})$



do we observe the cut-off at the sources?



^{1}H
^{4}He
^{14}N
^{56}Fe



HADRONIC INTERACTIONS

T. Pierog PoS (ICRC2017) 1100

predictions	**pre LHC**	**post LHC**
$\langle X_{max} \rangle$	~ 70 g/cm^2	~ 40 g/cm^2
elongation rate	different	similar

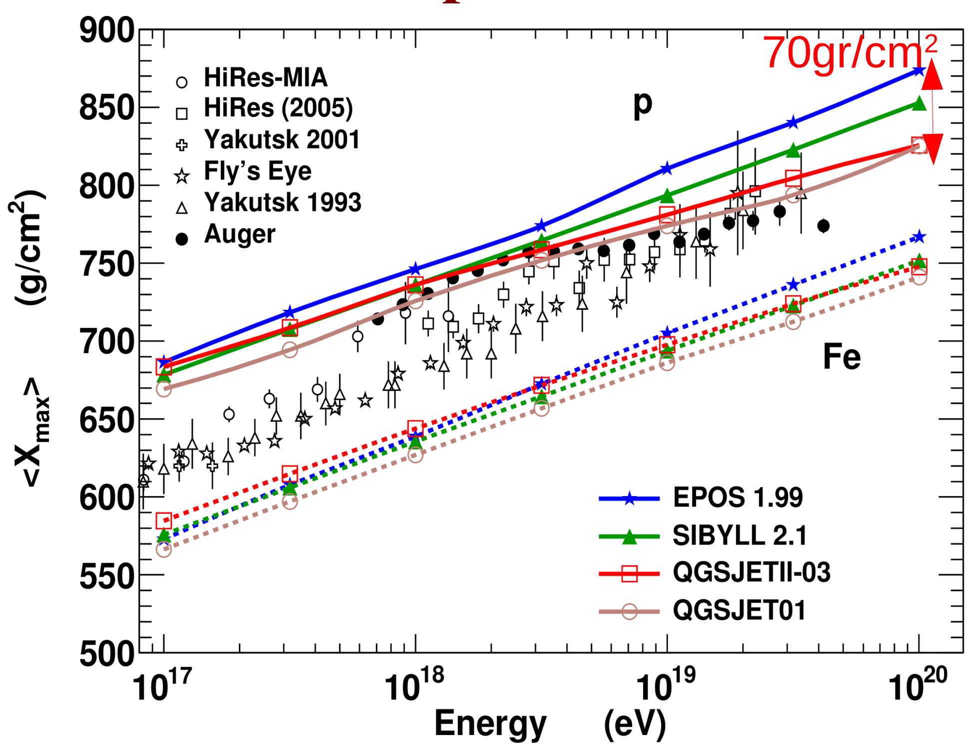
generalized Heitler model

J. Matthews, Astropart. Phys. 22 (2005) 387

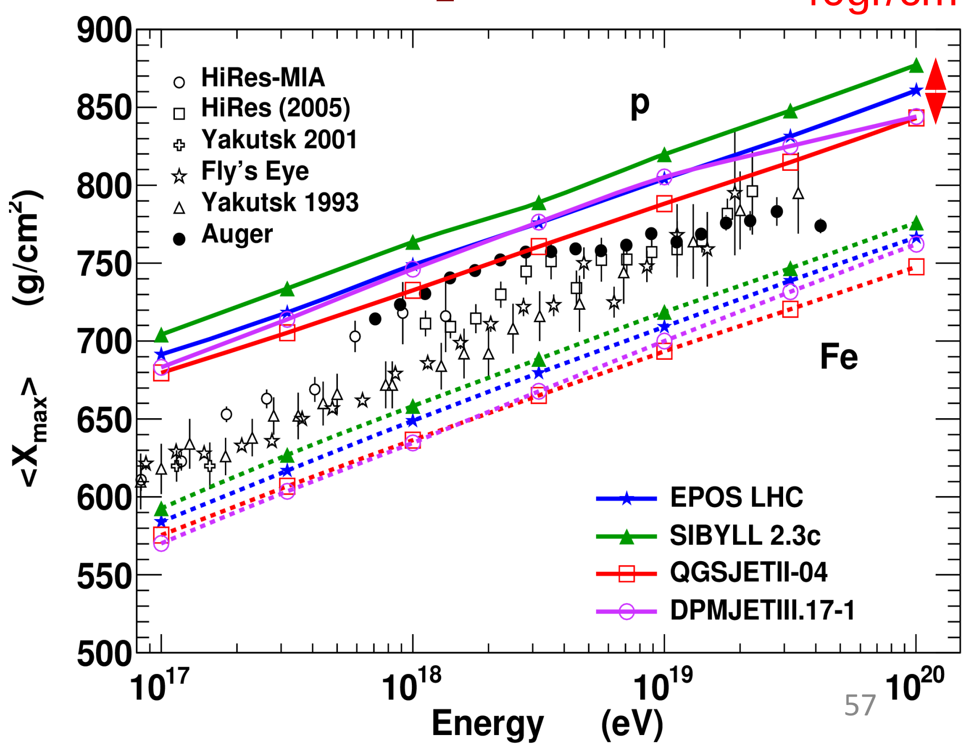
$$X_{\max} \sim \lambda_e \ln\left(\frac{(1-k)}{2\, n_{tot}} \times \frac{E}{A}\right) + \lambda_{ine}$$

elasticity (k), cross section (λ_{ine}), multiplicity (n_{tot})

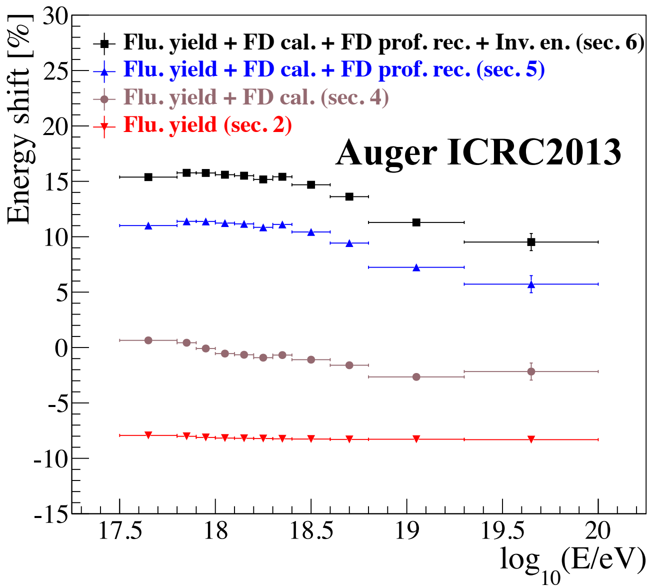
pre LHC



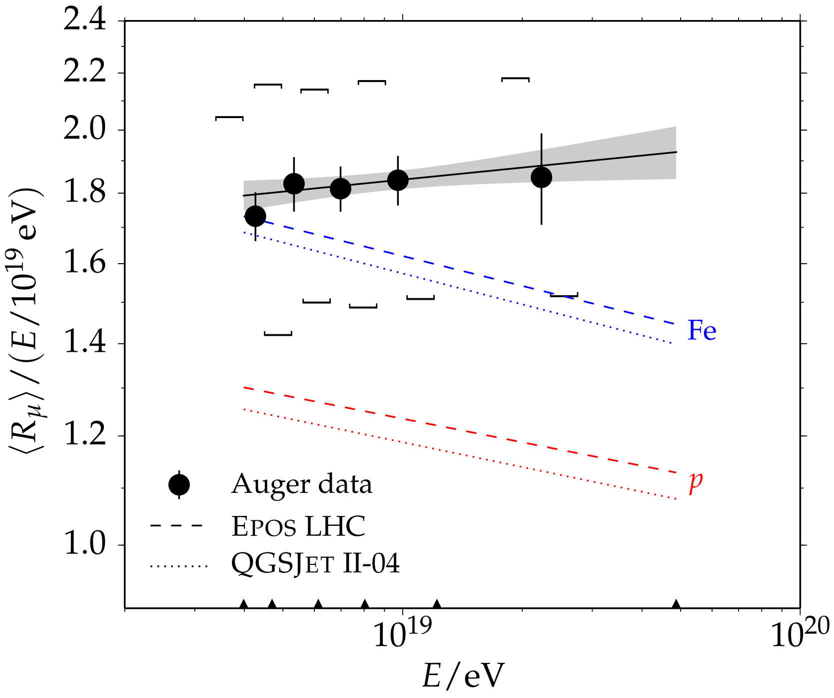
post LHC



HADRONIC INTERACTIONS

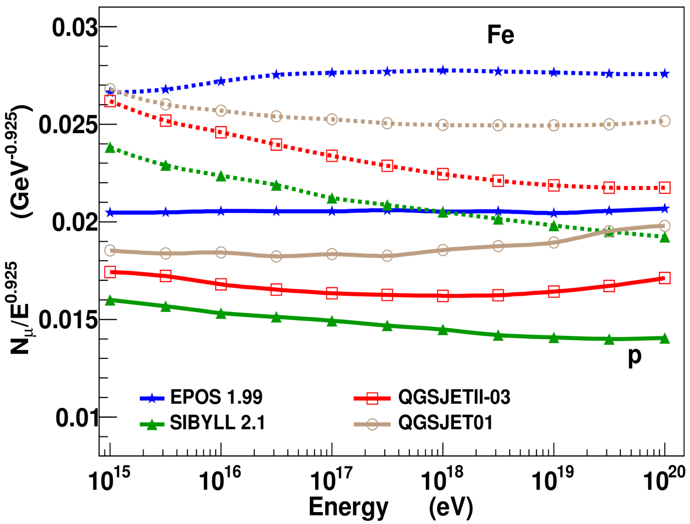


better energy estimation

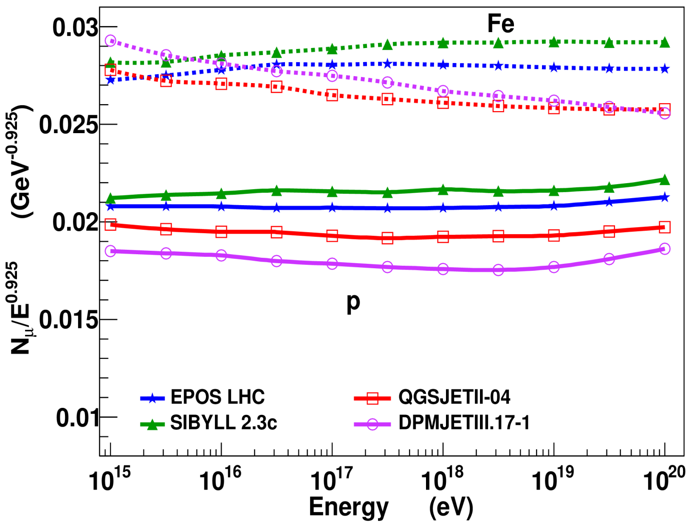


better prediction of N_μ

pre LHC



post LHC



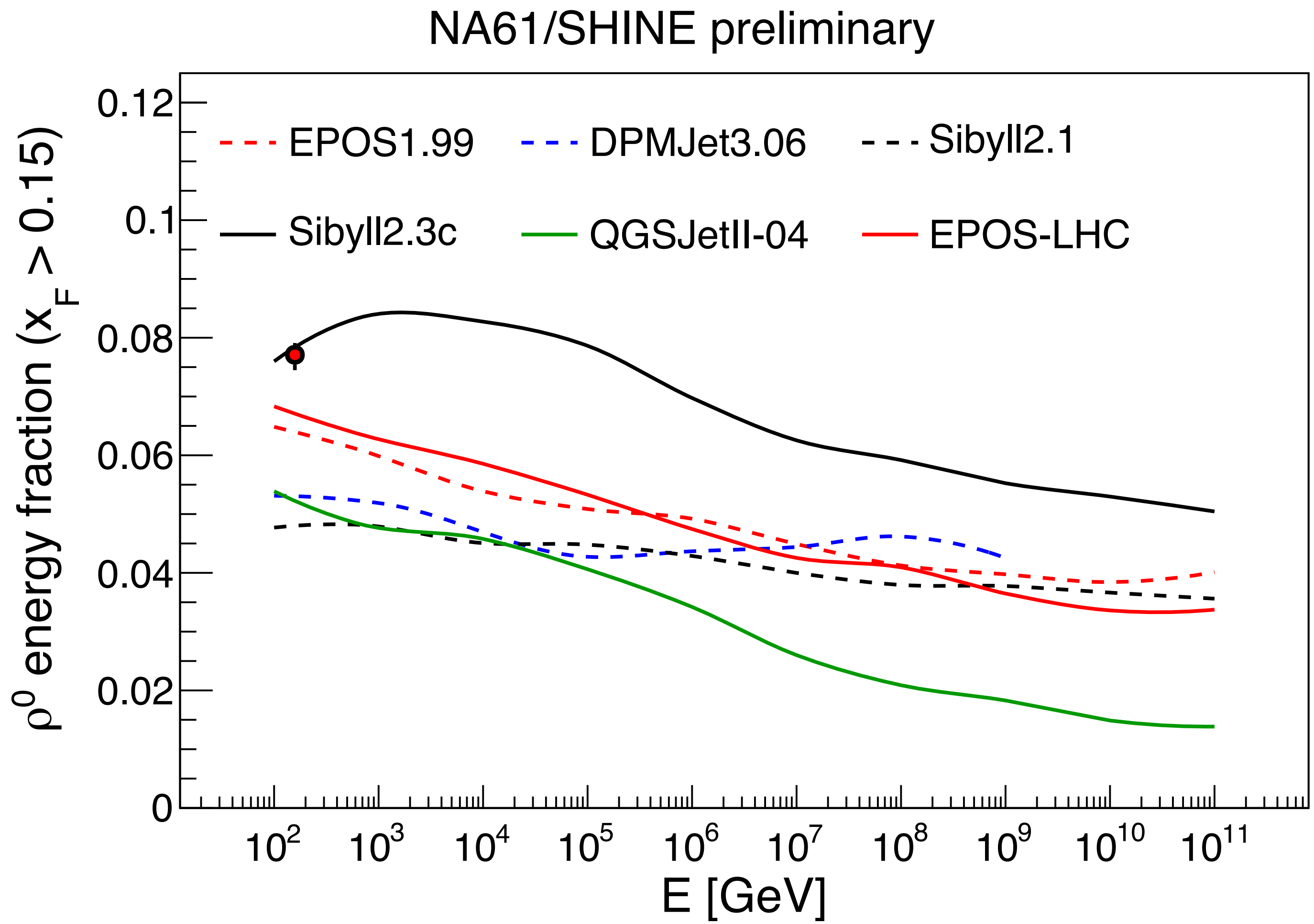
T. Pierog PoS (ICRC2017) 1100

R. Prado PoS (ICRC2017) 315

$\rho^0 \rightarrow \pi^+\pi^-$

$\pi^0 \rightarrow \gamma\gamma$

$\pi^\pm \rightarrow \mu\nu_\mu$

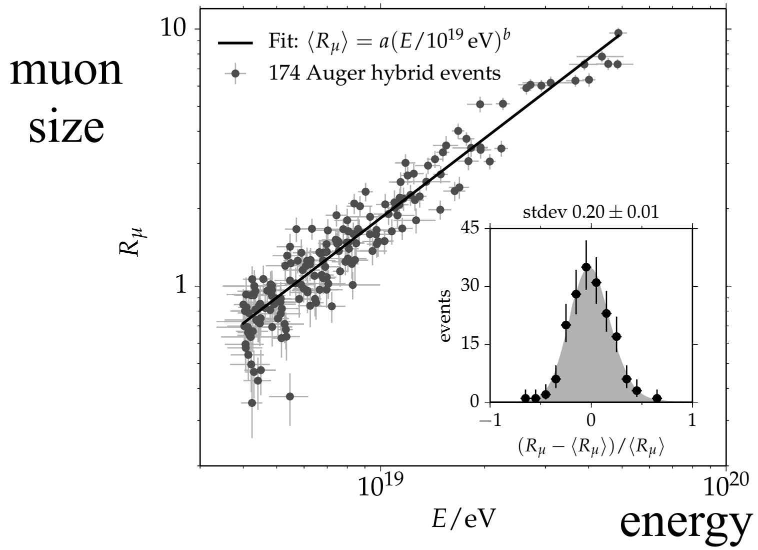


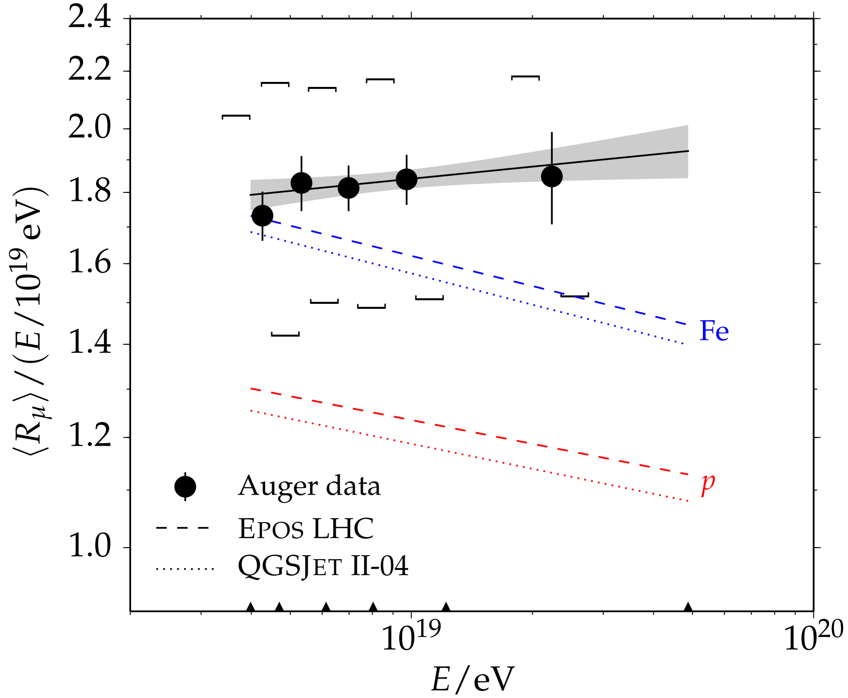
ρ^0 energy fraction in π^-+C

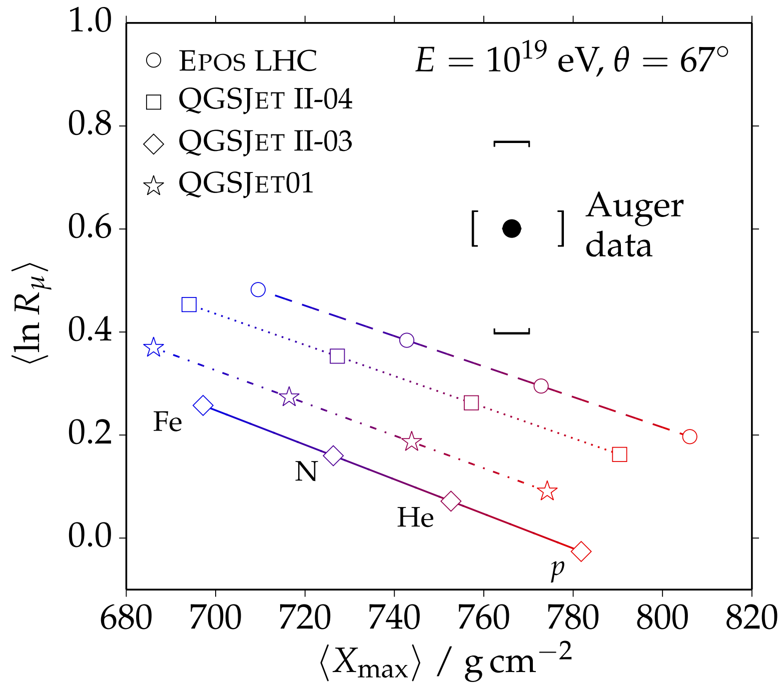
HADRONIC INTERACTIONS

Auger, PRD 91 (2015) 032003

hybrid showers inclined at large zenith angle







muon excess ~ 30%-80% for mass composition from X_{max}

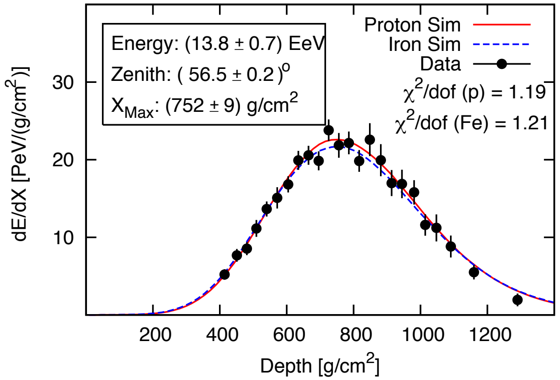
HADRONIC INTERACTIONS

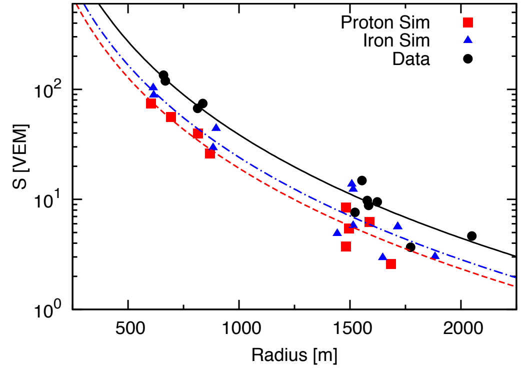
Auger, PRL 117 (2017) 192001

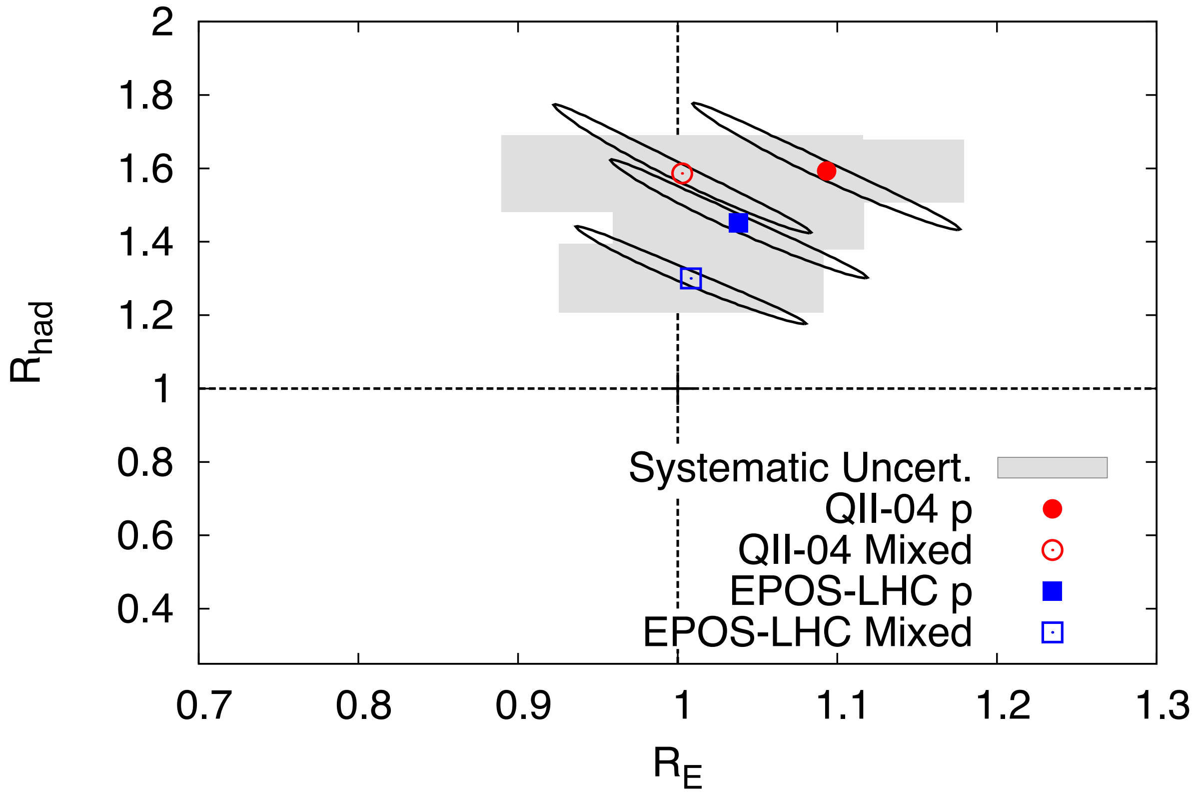
Auger hybrid events

$E \sim 10^{19}$ eV $\quad \theta < 60^0$

- simulate showers matching FD data
- compare simulated signal at ground with SD data







$$S = R_E S_{EM} + R_{had} R_E^{\alpha} S_{had}$$

rescaling factors to match the data

evidence of muon excess not sensitive to energy scale uncertainty

Expected cosmogenic νs with the Auger exposure

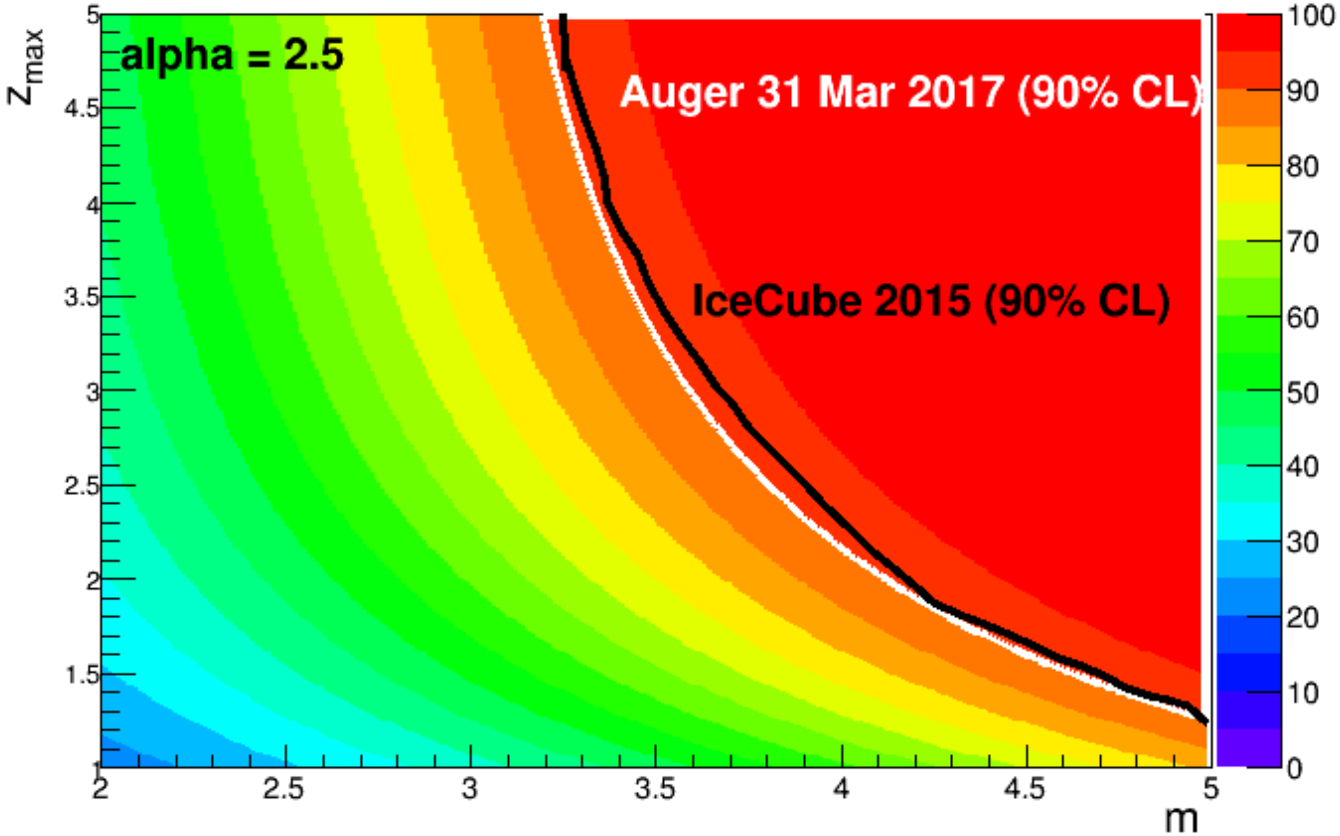
E. Zas PoS (ICRC2017) 972

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

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

Constraints on Cosmogenic neutrinos from proton-dominated sources

maximum source distance

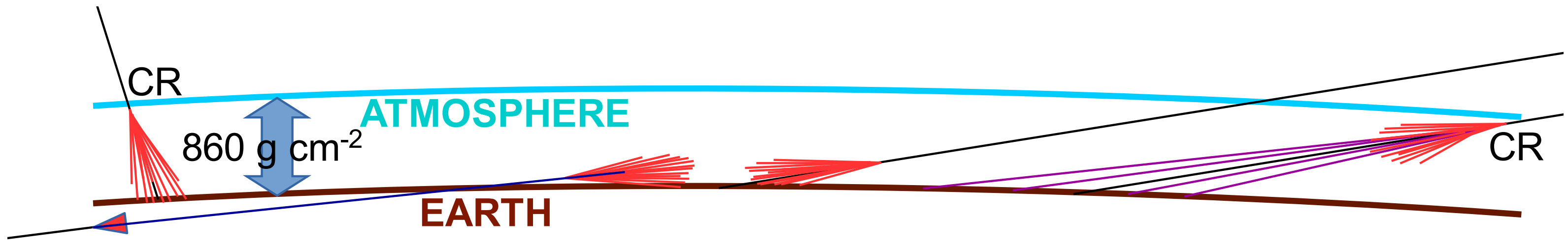


source evolution ~ $(1+z)^m$

Injection spectra $dN/dE \sim E^{-\alpha}$

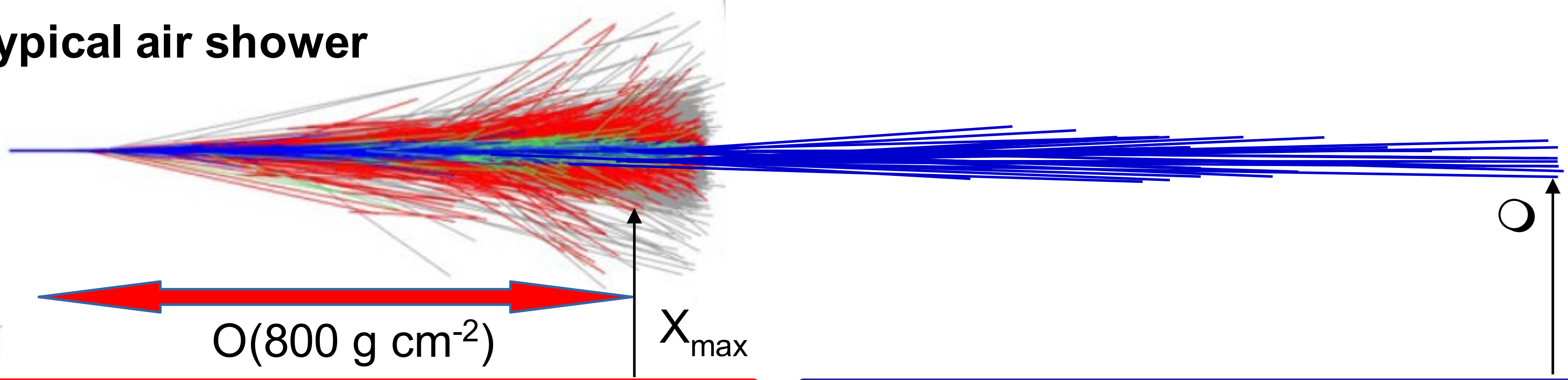
Unanbiguos identification of νs - Auger

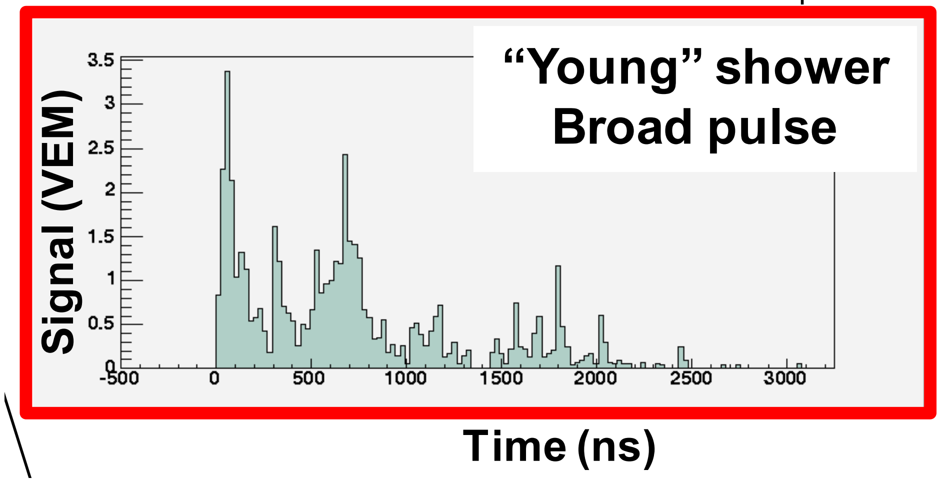
E. Zas PoS (ICRC2017) 972

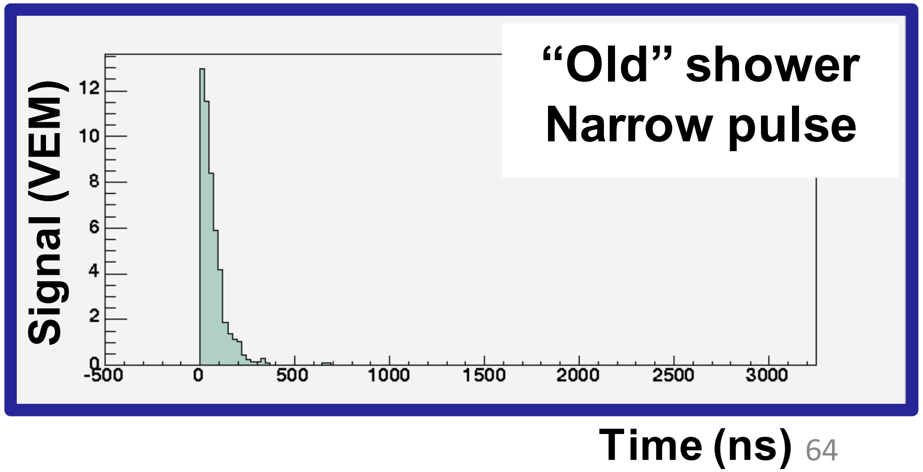


Neutrino: Inclined air shower with broad component

Typical air shower







X_{max} measured by LOFAR

fit of the asymmetric l.d.f.

200-450 antennas/event

118 showers

$\delta X_{max} \sim 15$ g/cm^2
$\delta E \sim 27\%$ (LORA)