Recent results and future perspectives on the Ultra-High Energy Cosmic Rays

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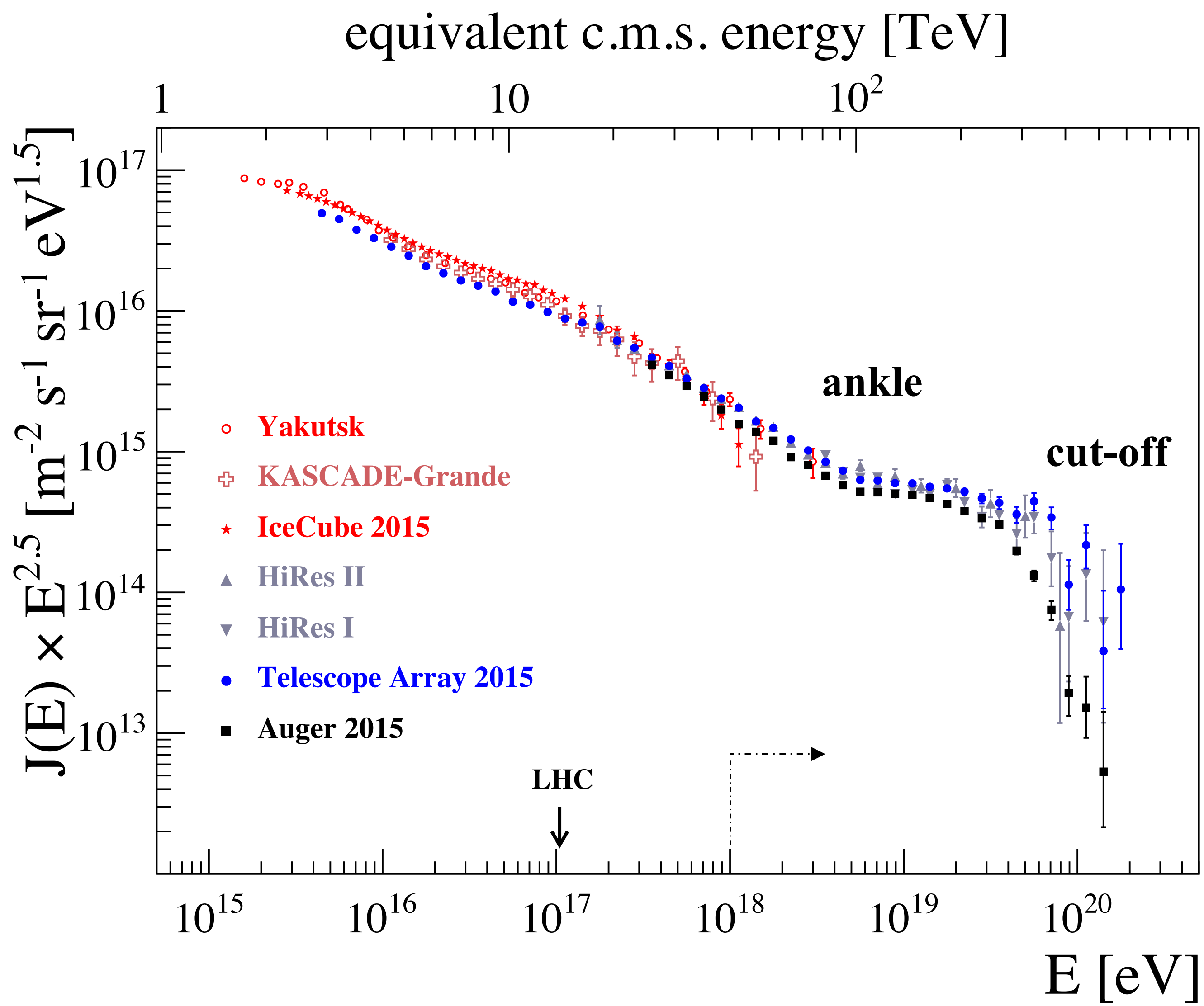
ENERGY SPECTRUM



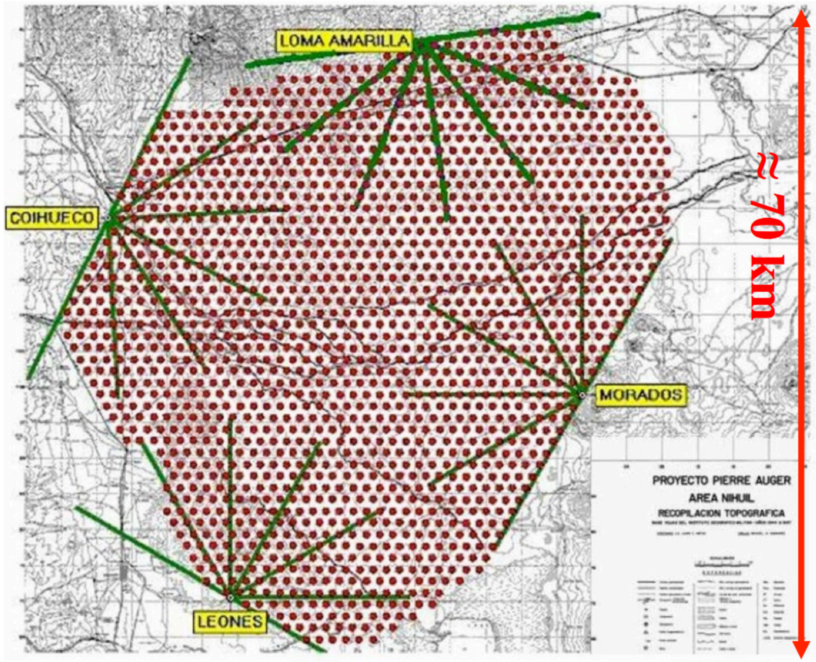
interactions with CMB
GZK horizon
~100 Mpc

minimal deflection in galactic and intergalactic magnetic fields

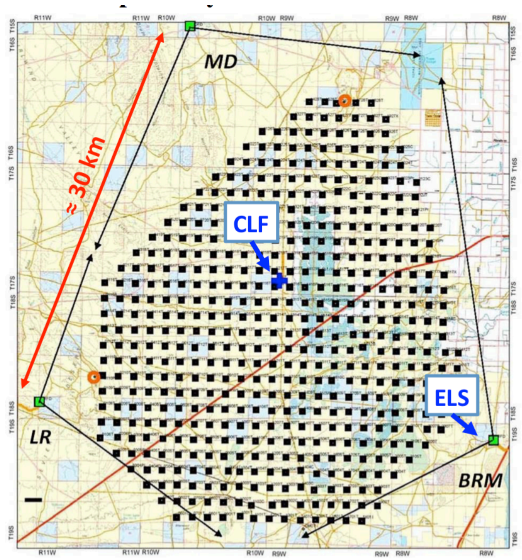
UHECR HYBRID OBSERVATORIES

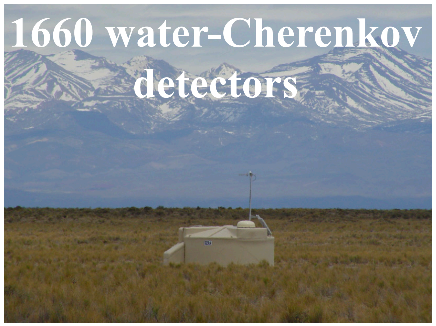
PIERRE AUGER OBSERVATORY
Malargüe – Mendoza (Argentina)
35^0 S latitude   3000 km^2

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



1400
m a.s.l.





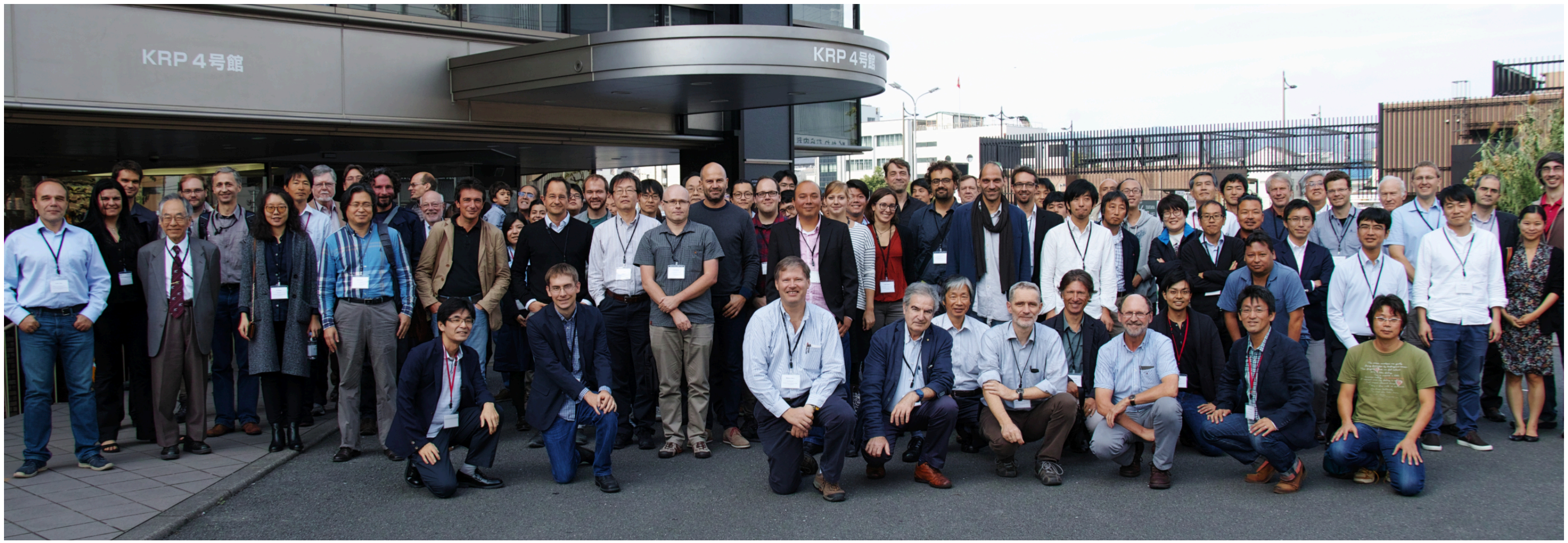
UHECR WORKING GROUPS

Telescope Array + Auger + IceCube

Spectrum, Anisotropy, Composition, Hadronic interactions, Multi-Messenger

Dedicated conferences:

- Nagoya (Japan) December 2010
- CERN February 2012
- Utah (USA) October 2014
- Kyoto (Japan) October 2016



HYBRID DETECTION TECHNIQUE

Surface Detector array (SD)

(+) duty cycle ~ 100%

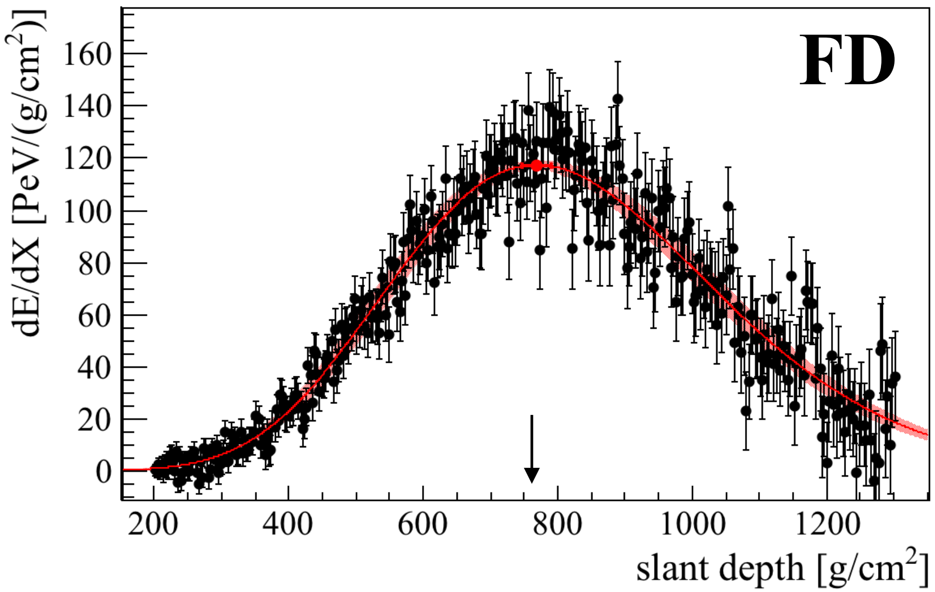
(-) shower size at ground ∝ E (systematics)

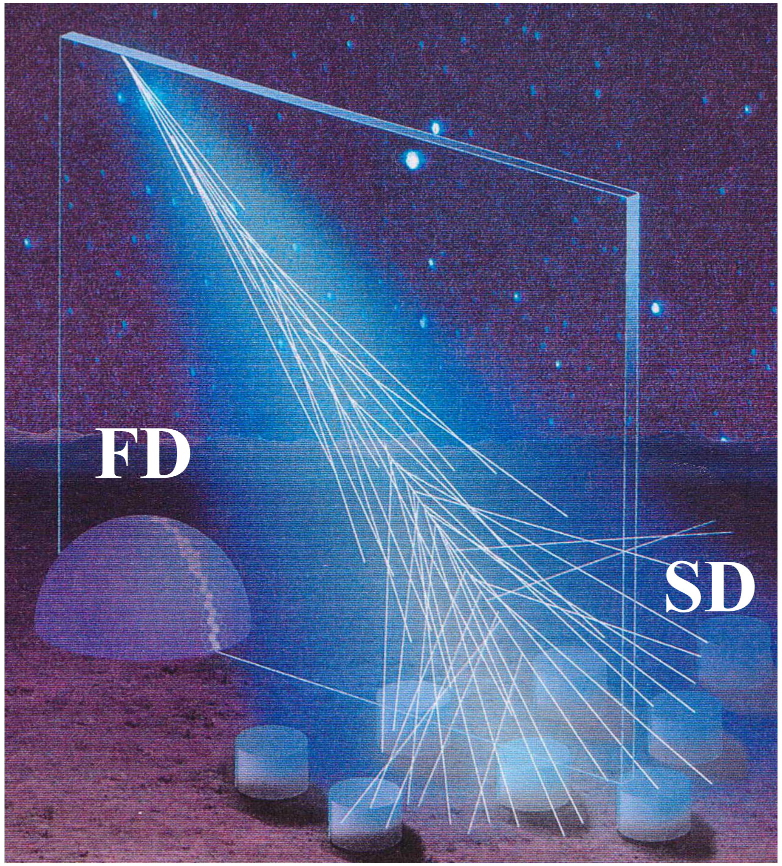
Fluorescence Detector (FD)

(-) duty cycle ~ 13%

(+) calorimetric measurement of E

Calibrate SD signal against FD energies



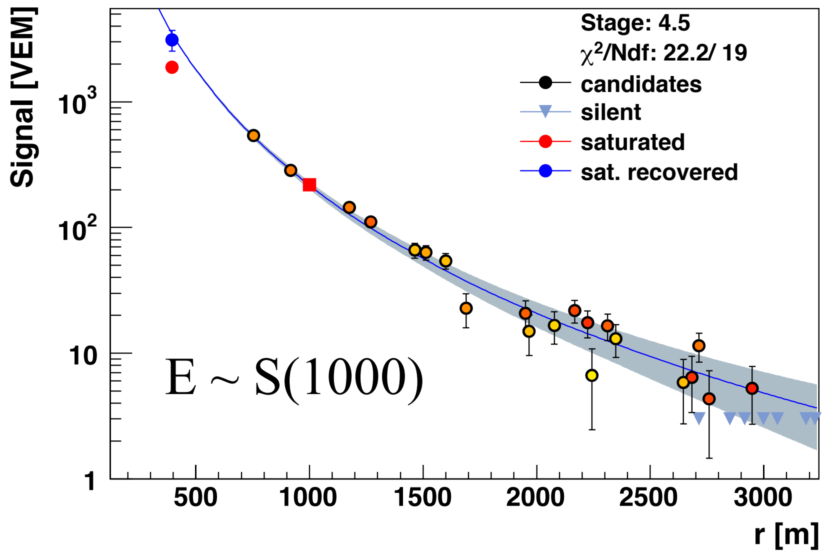


$$E_{cal} = \int \frac{dE}{dX} dX$$

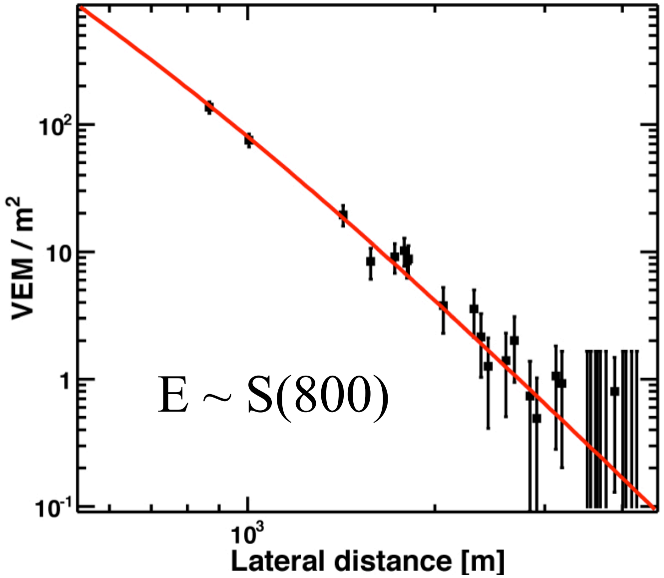
$$X_{max} \sim \ln\left(\frac{E}{A}\right)$$

SD EVENTS

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

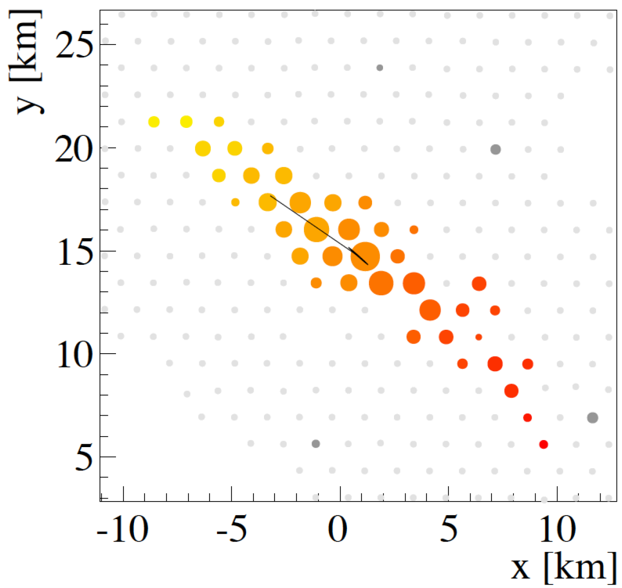


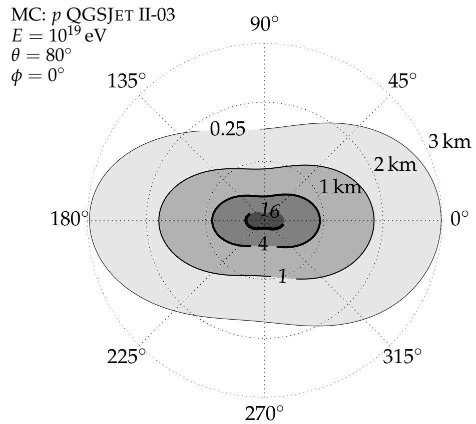
TA SD - $\theta < 45^0$



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

signal dominated by muons





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

$$E \sim N_{19}$$

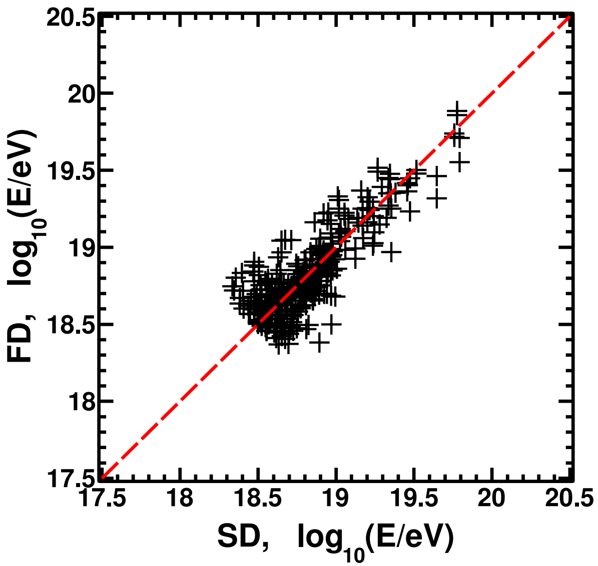
HYBRID EVENTS

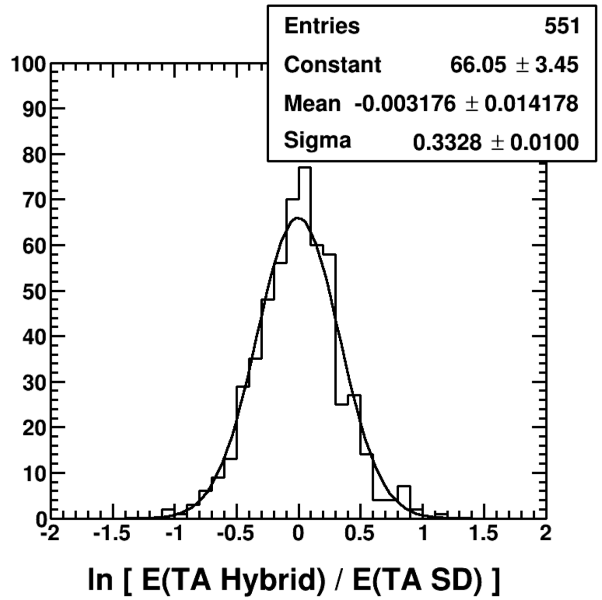
estimate of SD resolution

TA

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

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



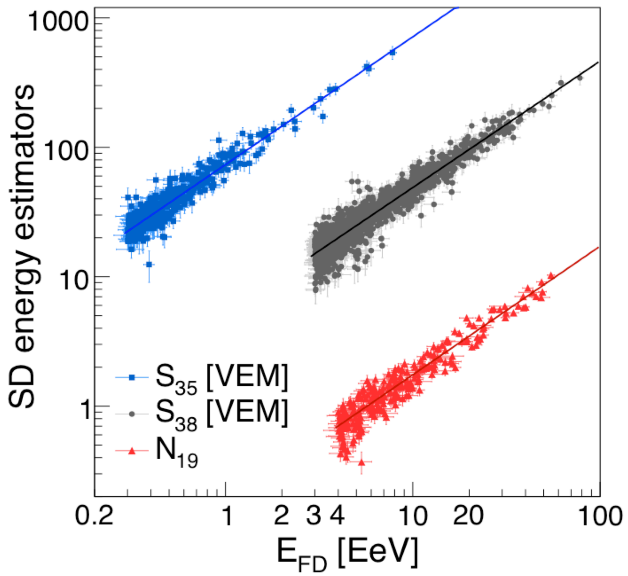


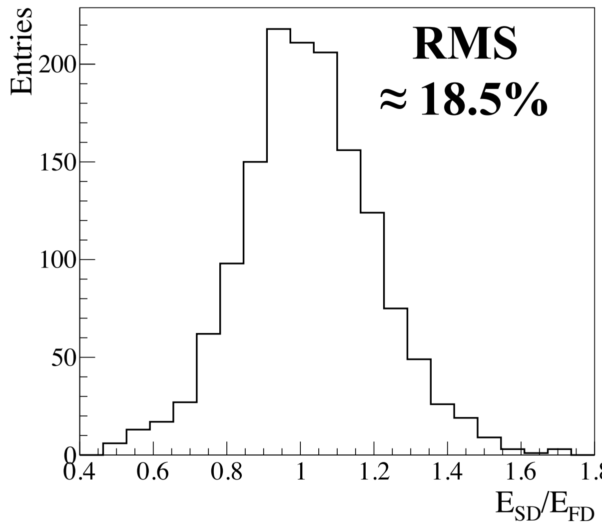
AUGER

CIC method to remove zenith angle dependence

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

$$B \approx 1$$



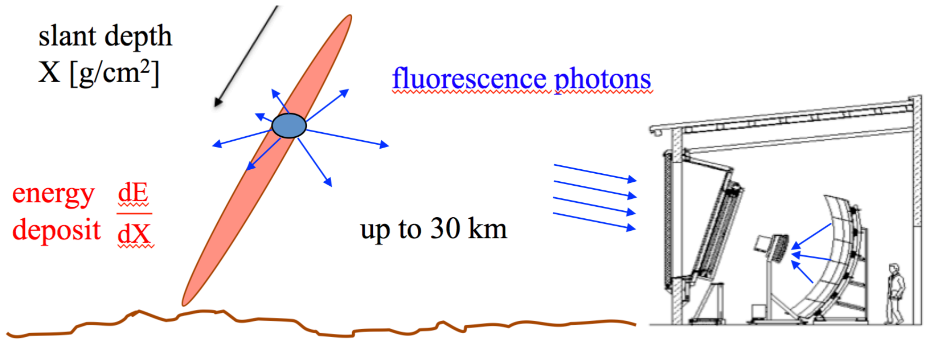


ENERGY SCALE

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	

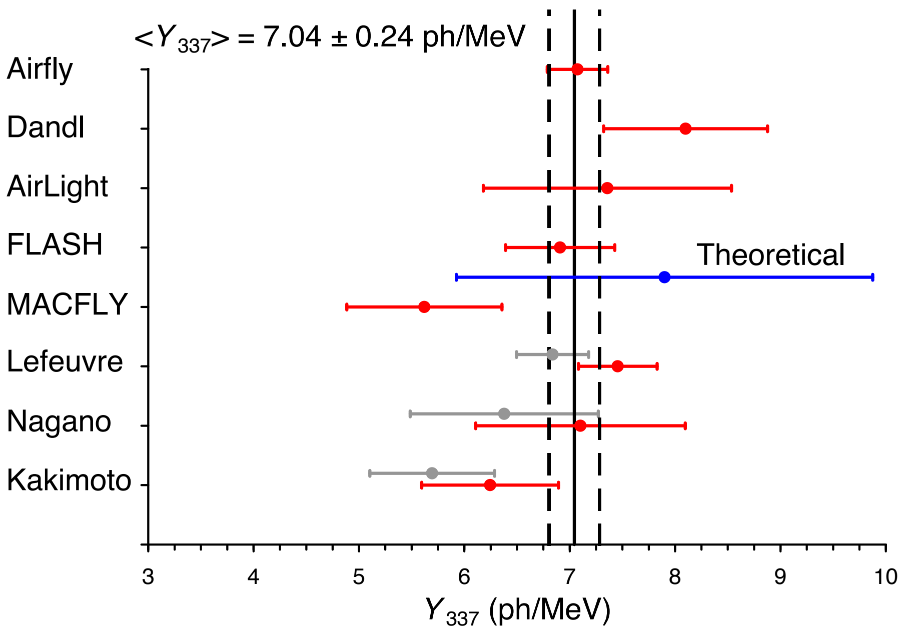
ENERGY SCALE

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

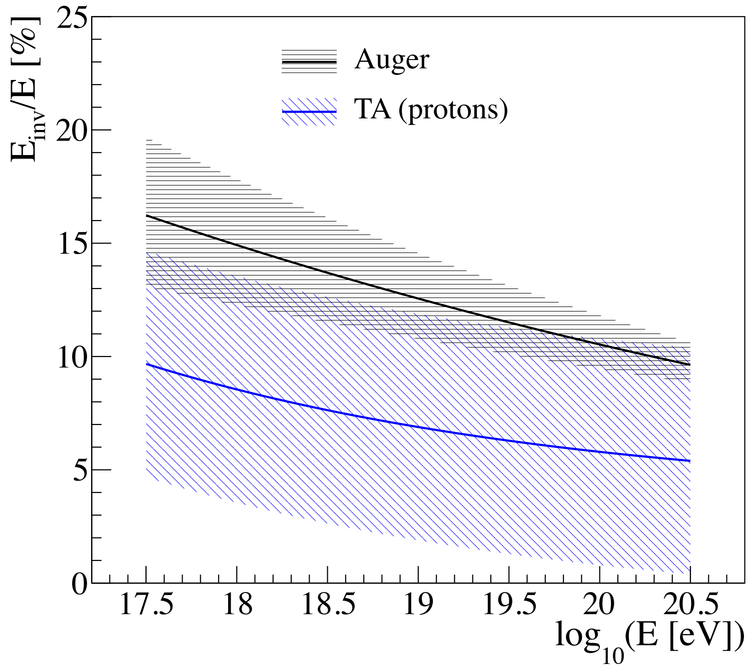
$$E = E_{cal} + E_{inv}$$

Fluorescence yield
Auger uses Airfly
TA uses Kakimoto+FLASH

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



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



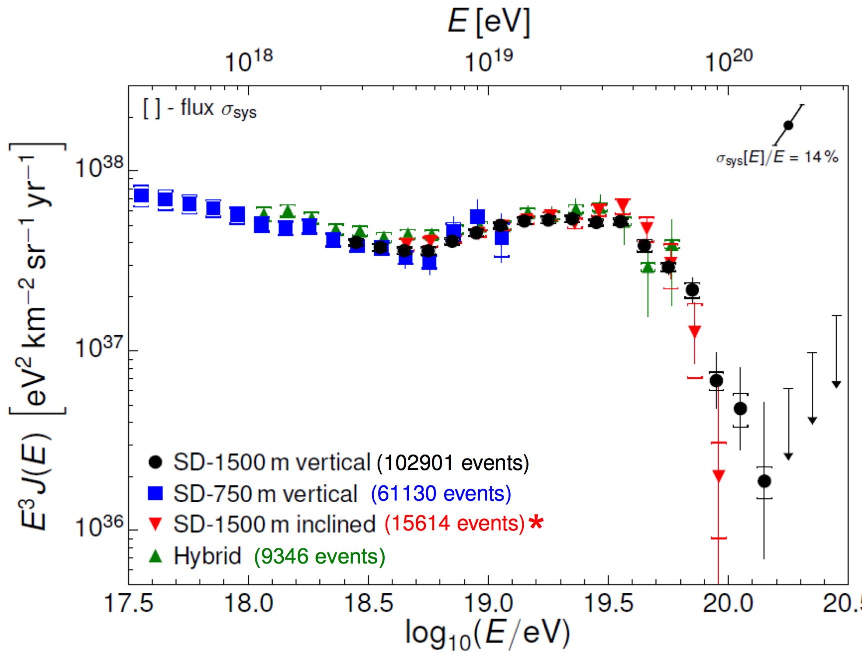
note: combined effect: 5%-10% relative shift between TA and Auger energy scales

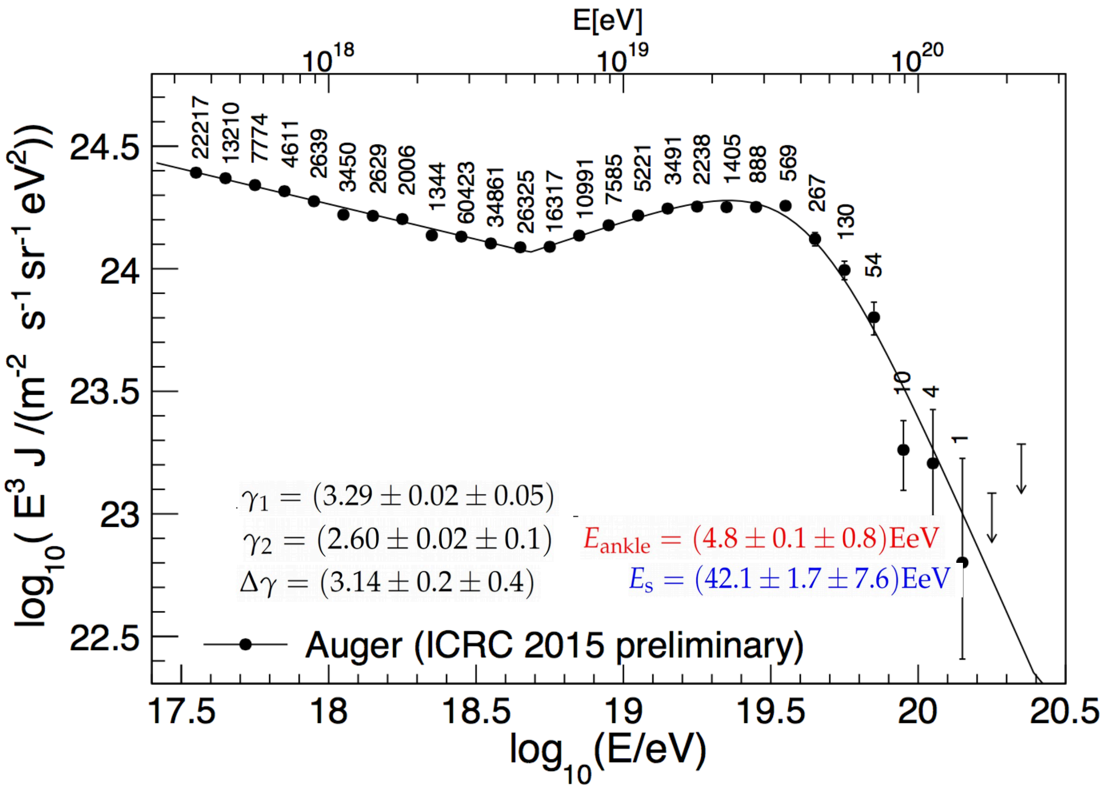
AUGER ENERGY SPECTRUM

I. Valino (Auger) Pos (ICRC15) 271

P. Ghia, Auger highligh ICRC15

unprecedented precision with eposure > 50000 km^2 sr yr

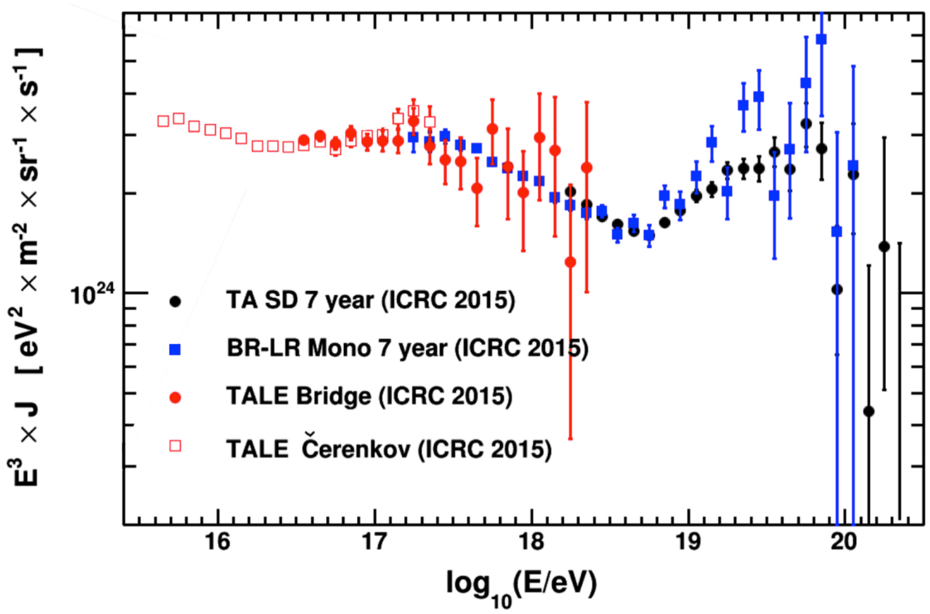


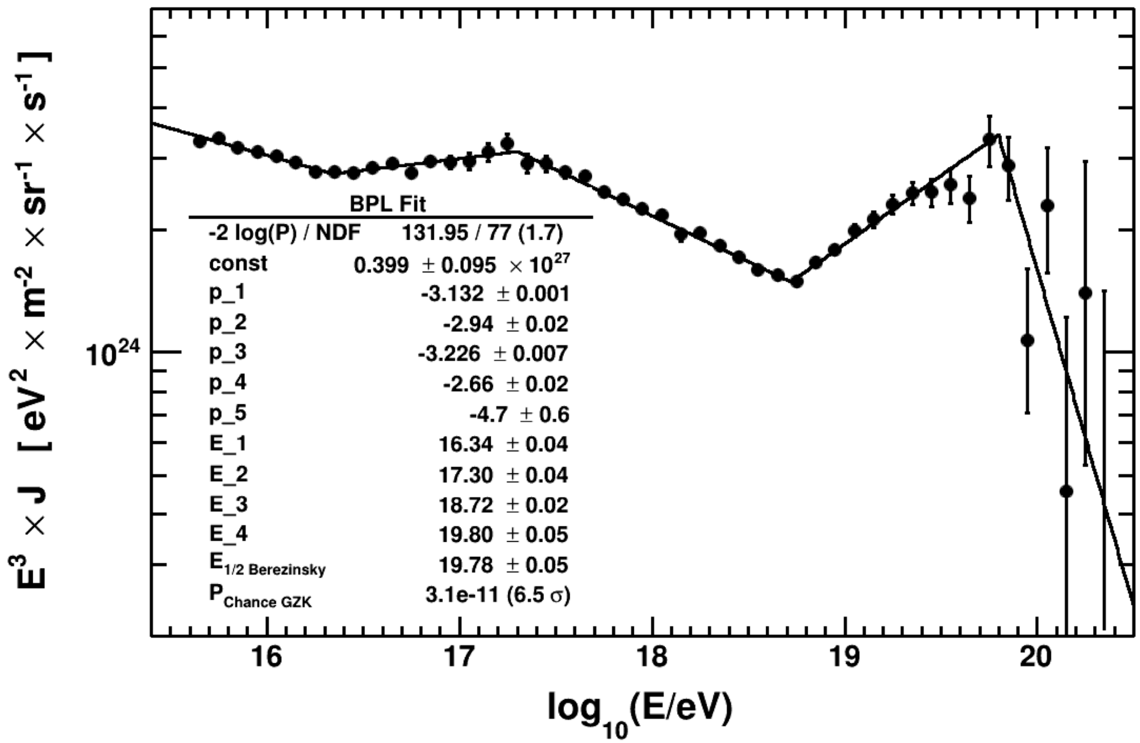


- consistency between different measurements
- common FD energy scale

TA ENERGY SPECTRUM

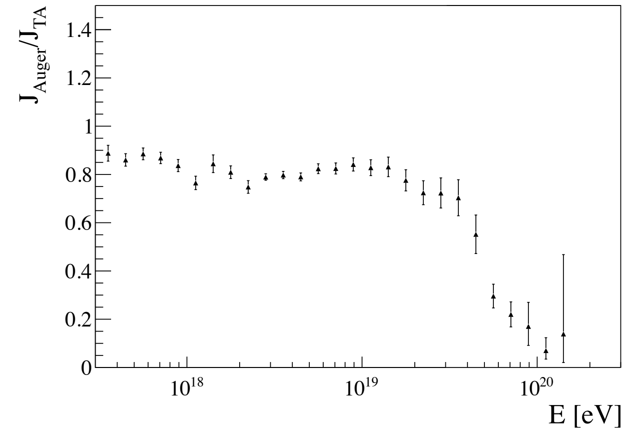
D. Ivanov (TA) Pos (ICRC15) 349





- consistency between different measurements
- common FD energy scale

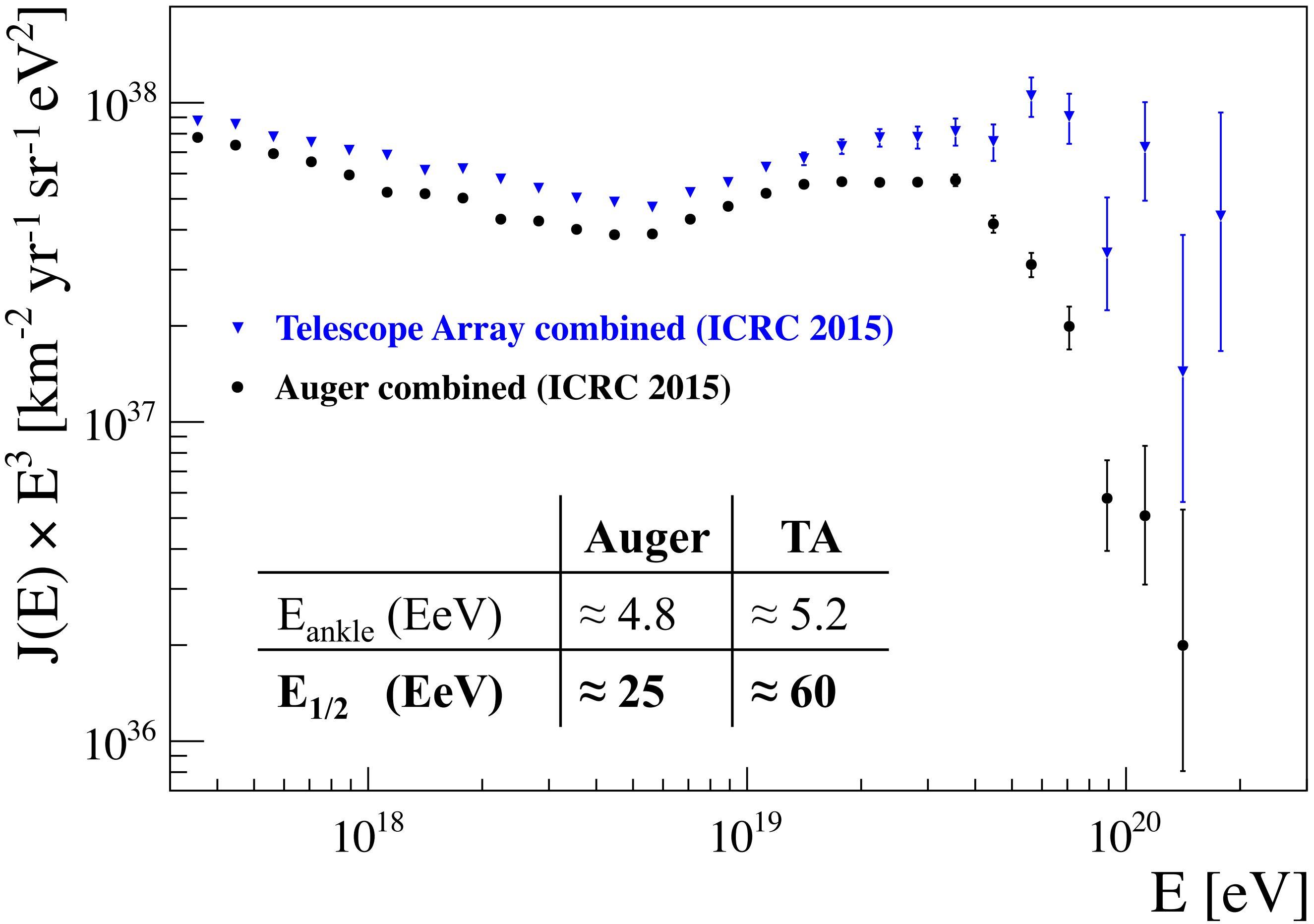
TA vs Auger



consistency up to 3×10^{19} eV

~10% energy shift is enough and expected from the different fluor. yield and E_{inv}

inconsistency above



	Auger	**TA**
E_{ankle} (EeV)	≈ 4.8	≈ 5.2
$E_{1/2}$ (EeV)	**≈ 25**	**≈ 60**

Is the difference at the highest energies due to experimental effects or to anisotropy signals?

ANISOTROPIES ABOVE 5×10^{19}eV

TA Hot Spot

P. Tinyakov (TA) PoS (ICRC2015) 326

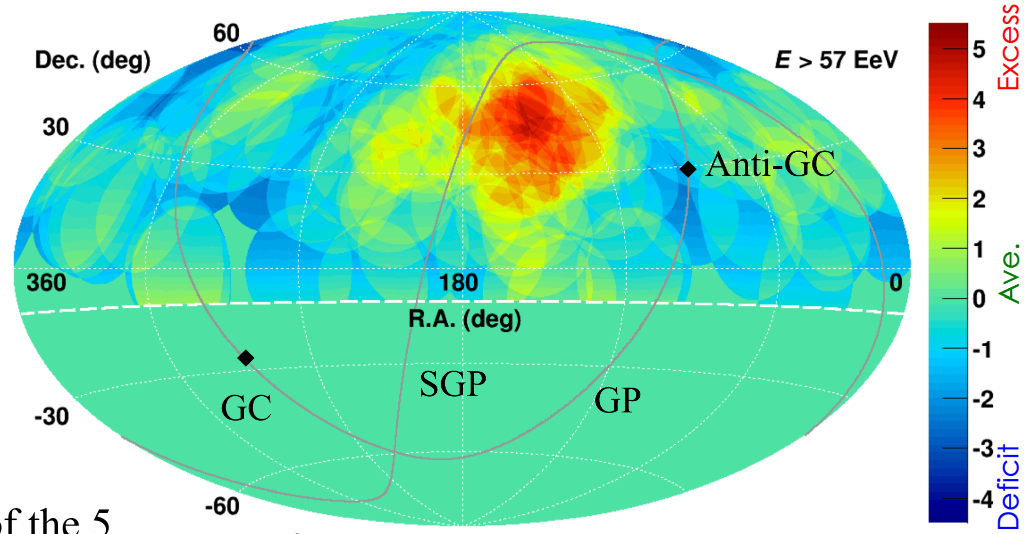
20^0 around RA=148.4^0 Dec=44.5^0

7 year data sample
over 109 events with E > 57 EeV
Hot Spot: 24 events with $N_{bkg} = 6.88$

3.4 σ post-trial

the same of the 5 year data sample

equat. coord.



20^0 oversampling radius

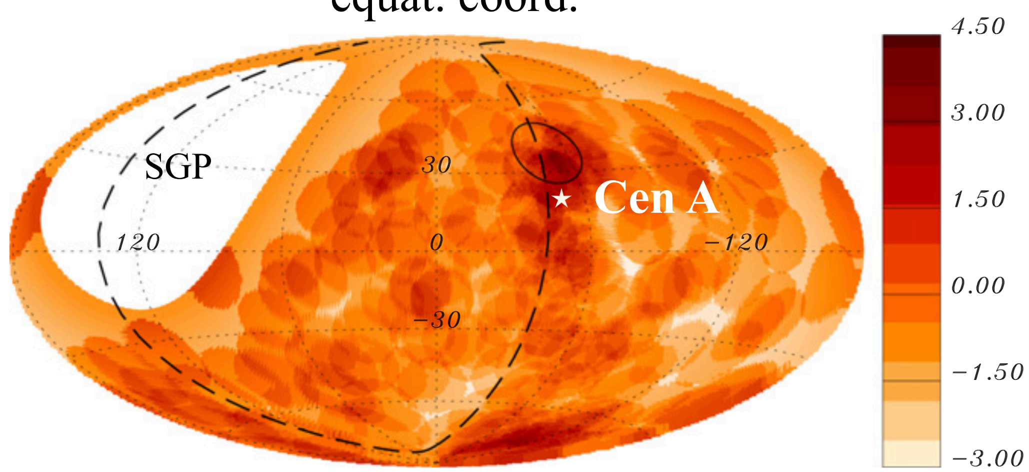
Auger 'warm' Spot

Auger , Astrophys. J. 804 (2015) 15

most significant excess: E > 54 EeV
RA=198^0 Dec=-25^0
14 events with $N_{bkg} = 3.23$

69% post-trial to be bkg

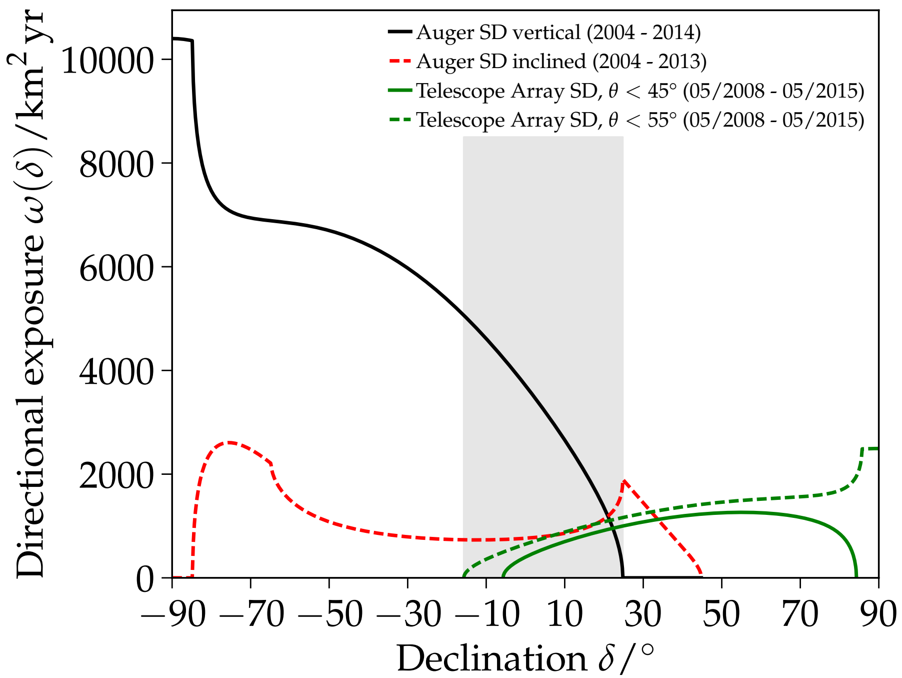
equat. coord.



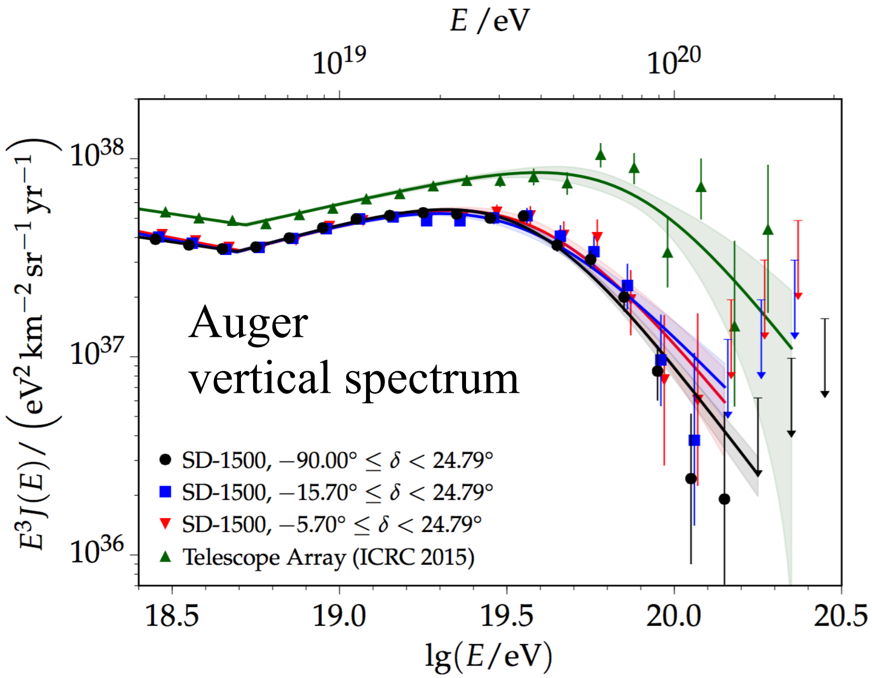
Li-Ma significances in 12^0 windows

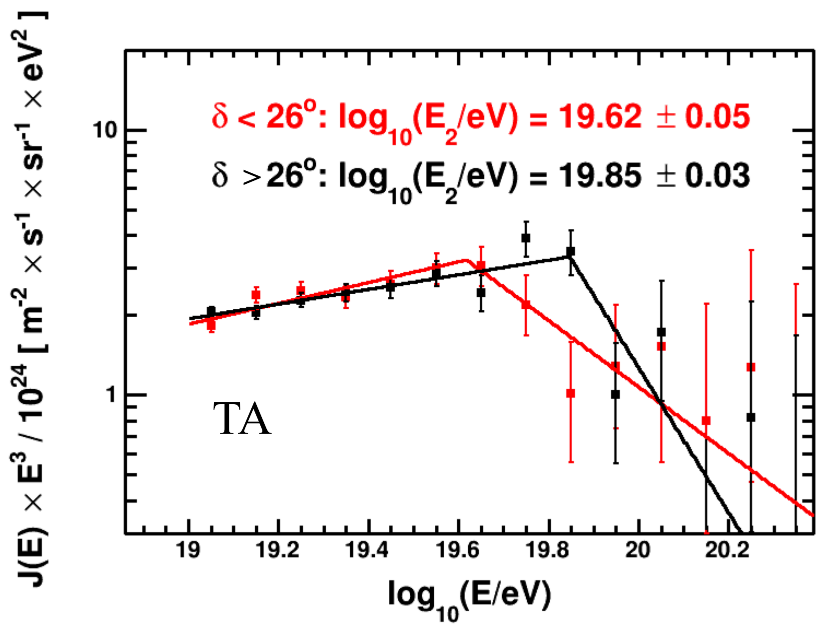
Compare the spectra in the same declination band

Auger TA WG



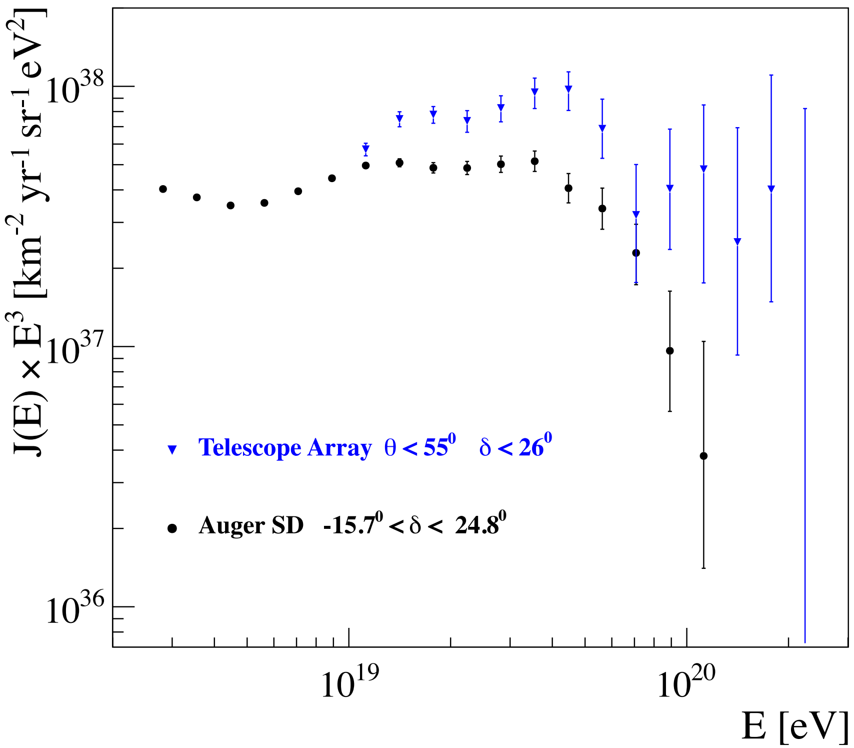
Hot Spot ($\delta = 44.5^0$) outside the common declination band

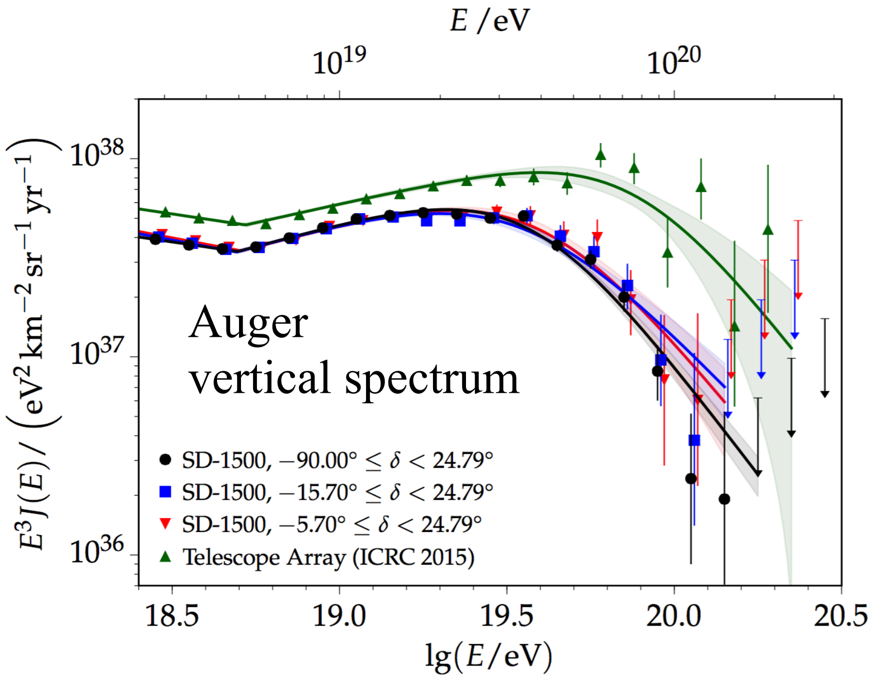


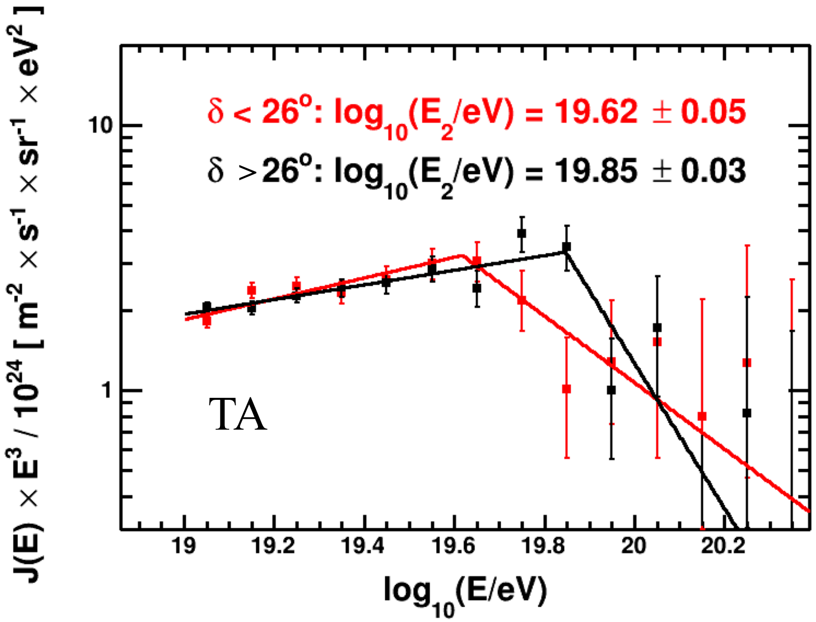


Compare the spectra in the same declination band

Auger TA WG







<u>work in progress to do quantify the differences</u>

EVIDENCE OF LARGE SCALE ANISOTROPY ABOVE 8×10^{18}eV

Auger

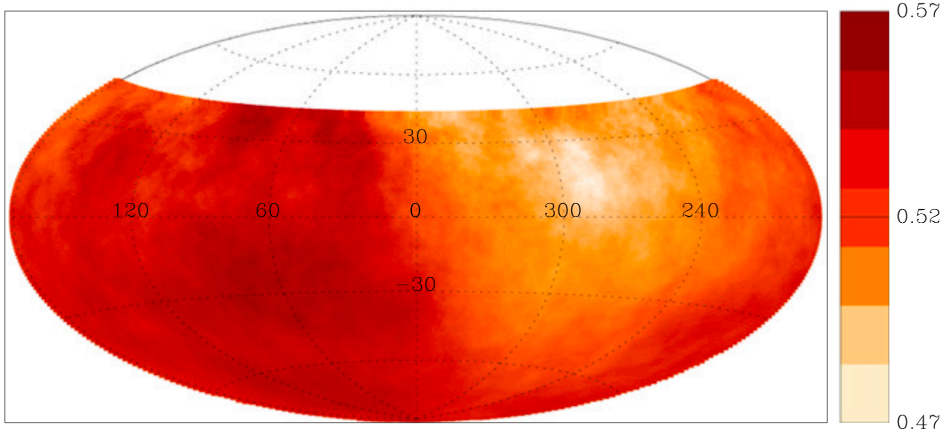
harmonic analysis in right ascension and azimuth - **vertical+inclined** events

- **isotropy between 4 and 8 EeV**
- **dipole amplitude above 8 EeV**

$7.3 \pm 1.5\%$ ($p=6.4 \times 10^{-5}$)
point. at $(\alpha, \delta) = (95^0 \pm 13^0, -39^0 \pm 13^0)$

➔**Extragalactic origin?**

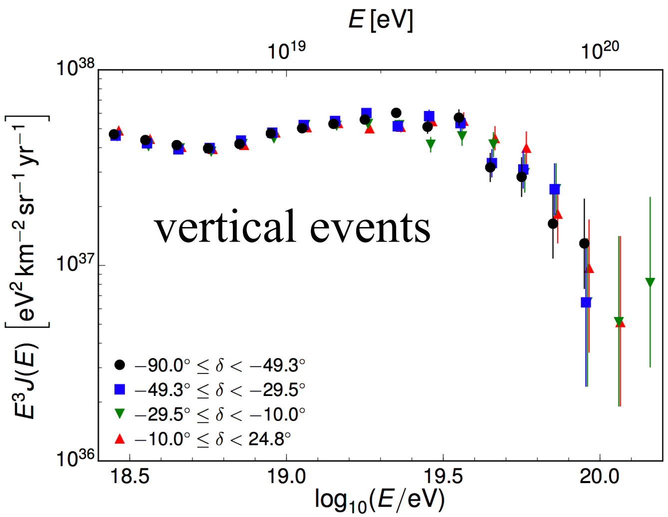
Equatorial coordinates - 45^0 smoothing

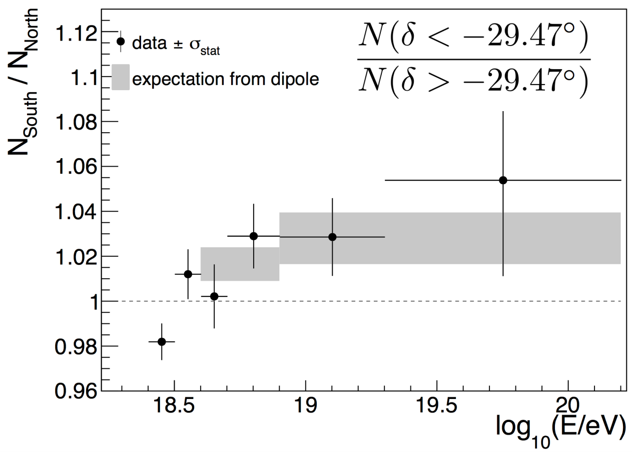


Auger, ApJ 802 (2015) 111

See also O. Deligny (Auger & TA) PoS (ICRC2015) 395 → full sky coverage

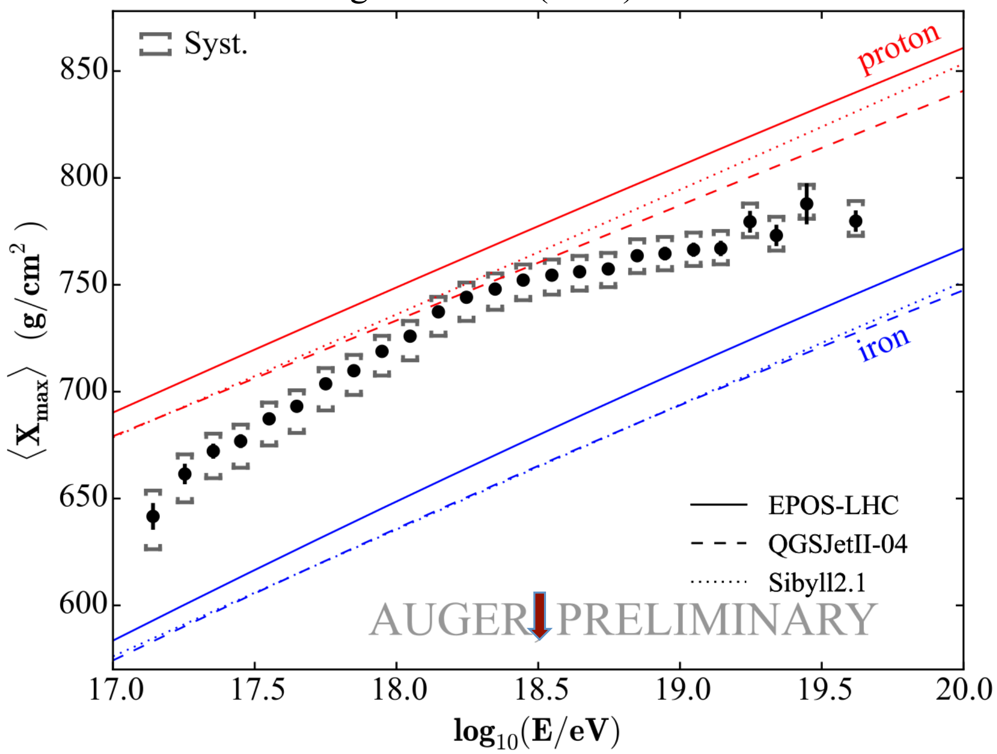
I. Valino (Auger)
Pos (ICRC15) 271



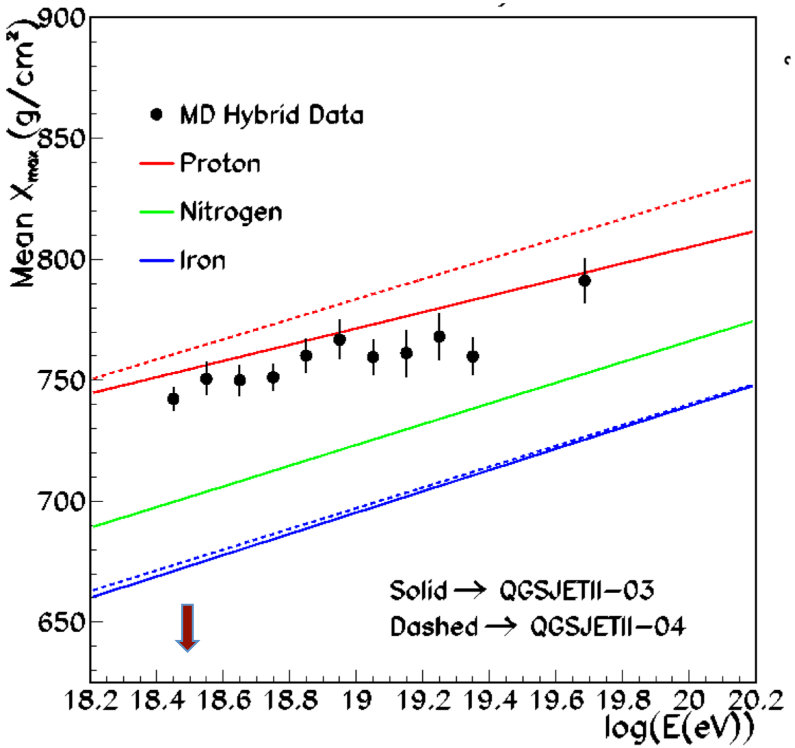


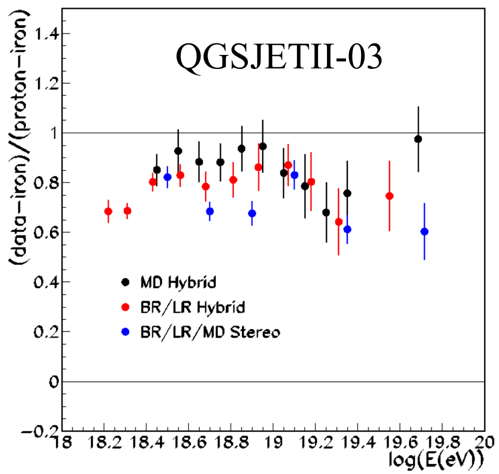
COMPOSITION

Porcelli (Auger) PoS (ICRC2015) 420
Auger PRD 90 (2014) 122005



C.Jui, highligh TA talk at ICRC15



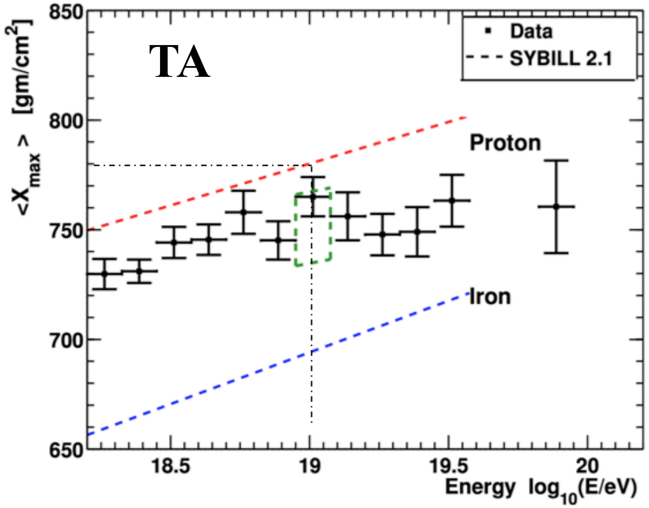


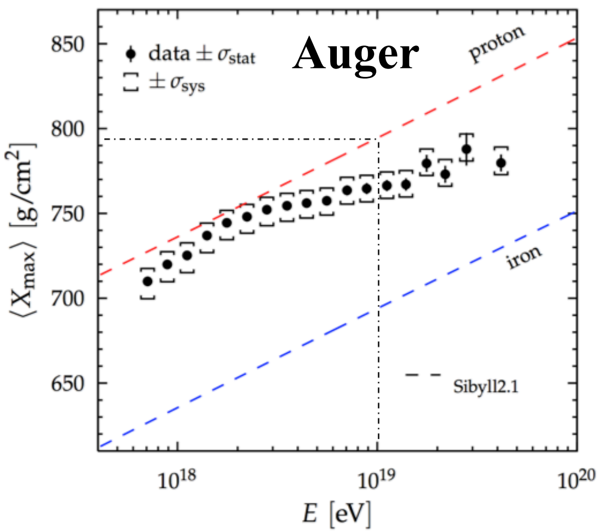
- break in the elongation rate
- composition interpretation is model dependent
- are the two measurements ?

COMPOSITION – TA vs AUGER

different ways to present the data:

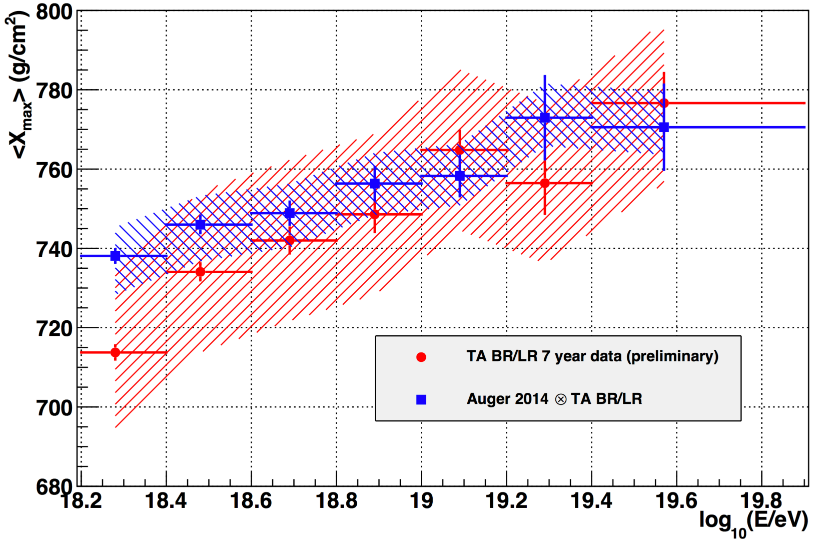
- TA folded with det./rec. effets
- Auger unbiased

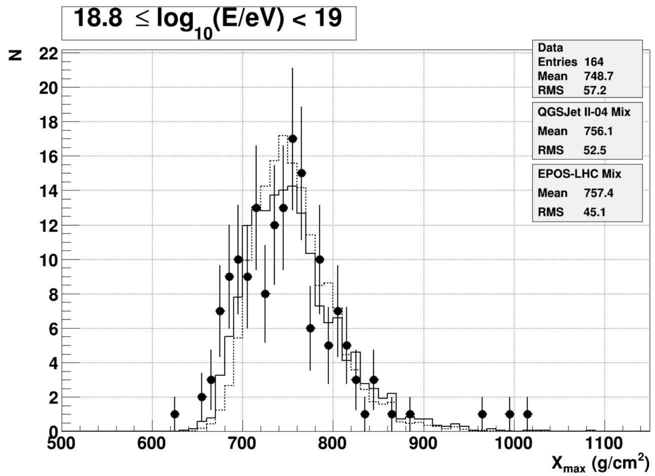




Auger TA WG

- **simulate TA events according to the auger X_{max} measurements**
- **reconstruct them and compare with data**





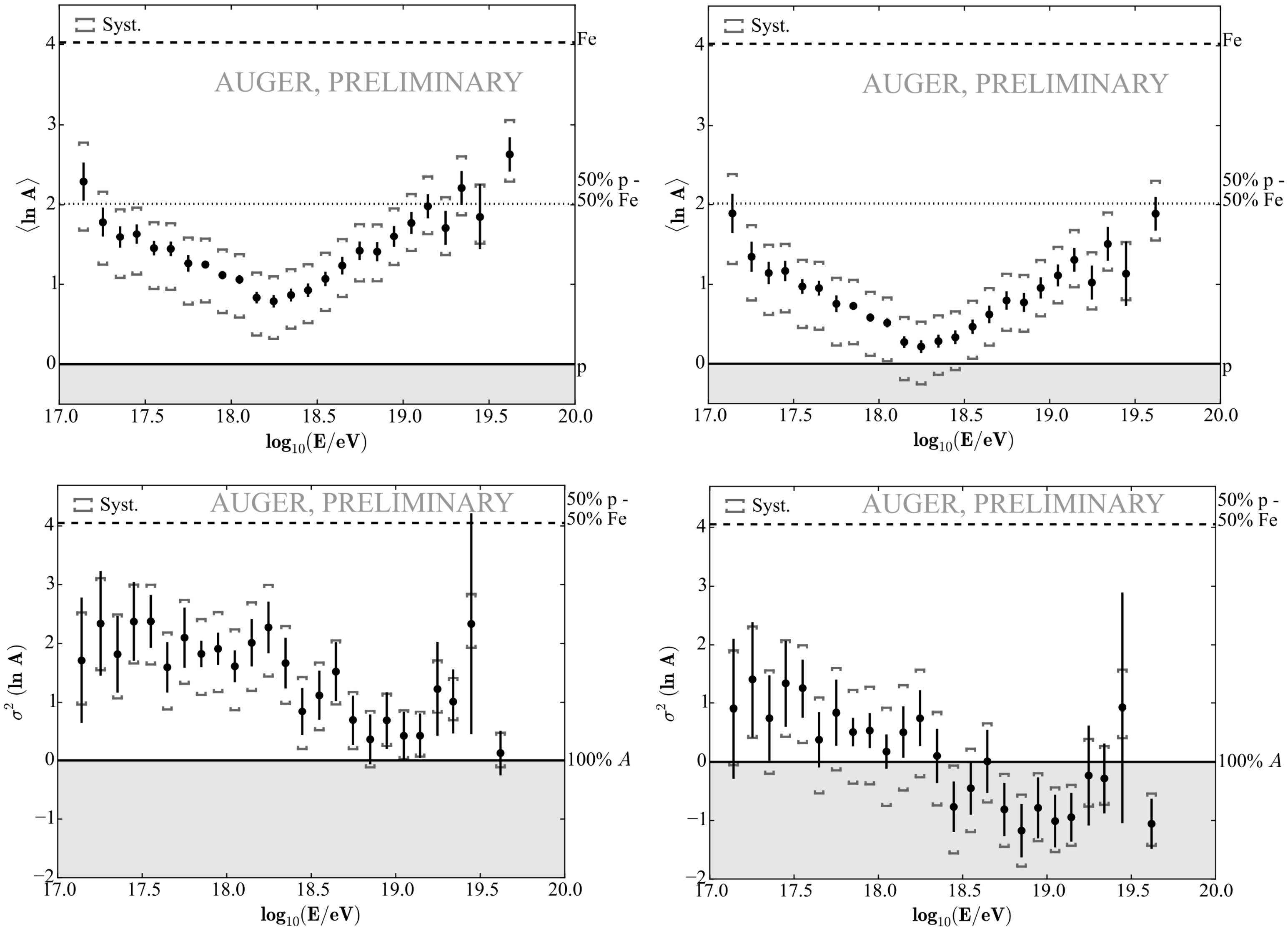
consistency within the systematics

COMPOSITION - AUGER

post-LHC models

Porcelli (Auger) PoS (ICRC2015) 420
Auger PRD 90 (2014) 122005

EPOS LHC **QGSJETII-04**



SPECTRUM INTERPRETATION

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

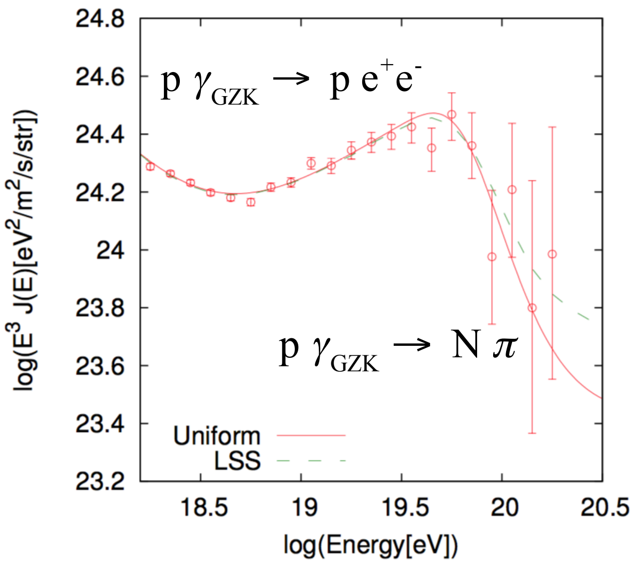
TA

E. Kido (TA) PoS (ICRC15) 258

- **assume a pure p composition**

fit (γ,m) at sources $\Phi \propto E^{-\gamma}(1+z)^{3+m}$

➢ **spectral features due to propagation effects**
(requires a strong evolution of the sources)



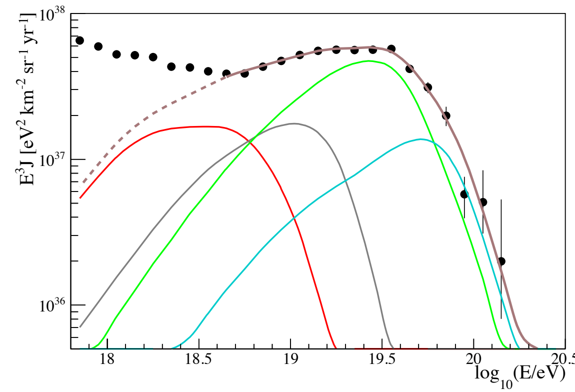
Auger

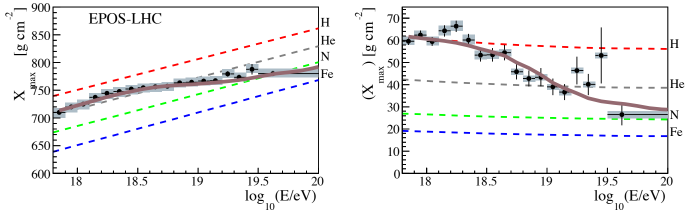
JCAP04 (2017) 038

- **predict also the X_{max} distributions**

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

➢ **scenario favored: observed cut-off due to low maximum injection energies**

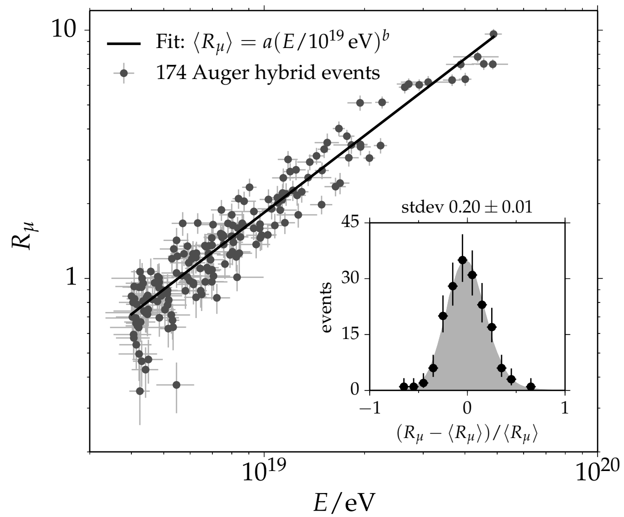


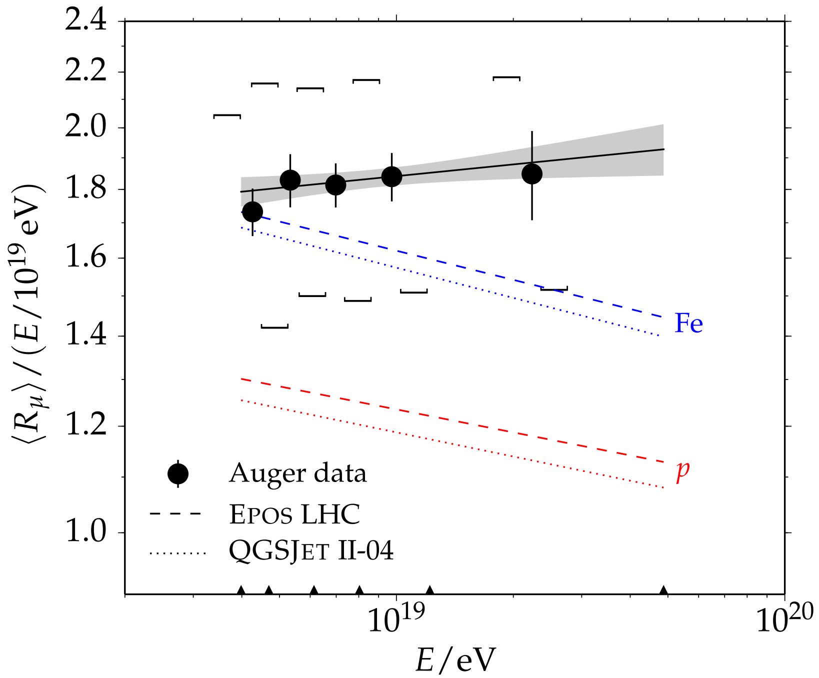


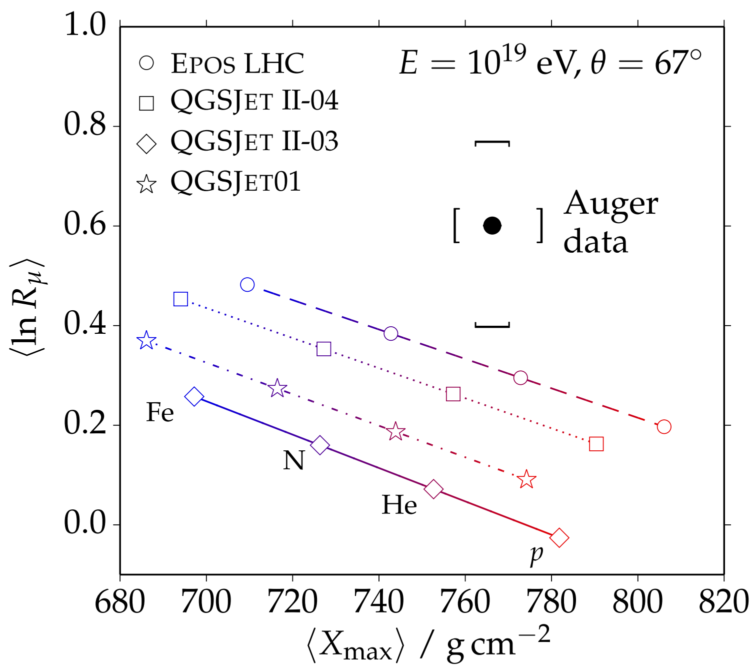
HADRONIC INTERACTIONS

Auger, PRD 91 (2015) 032003

hybrid showers inclined at large zenith angle







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

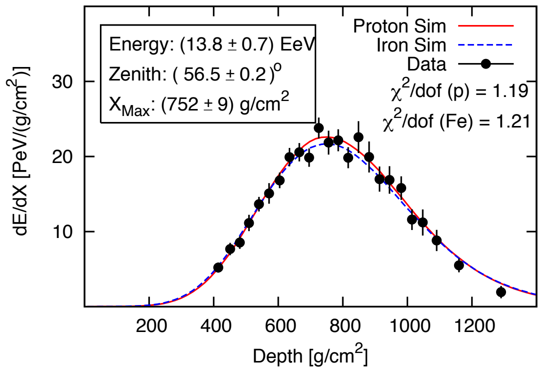
HADRONIC INTERACTIONS

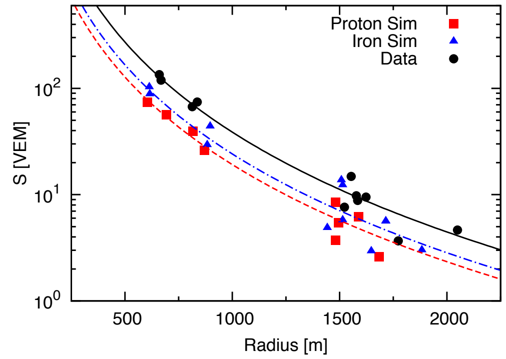
Auger, PRL 117 (2017) 192001

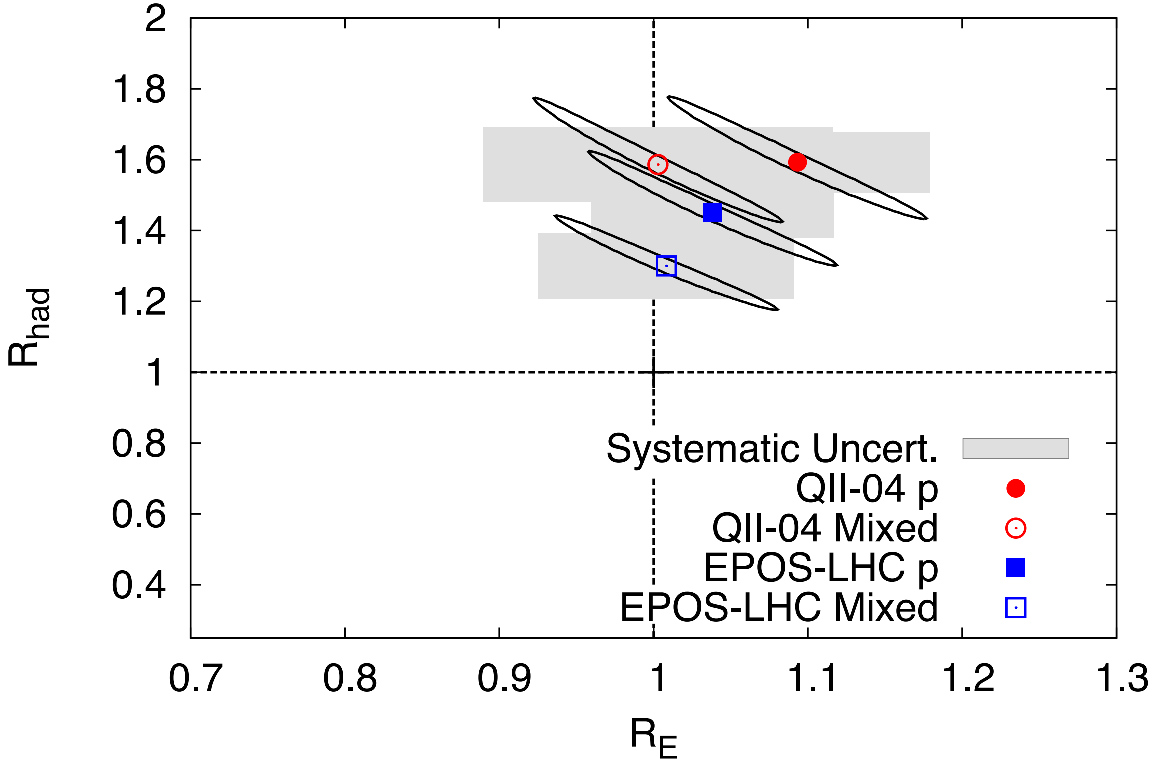
Auger hybrid events

$E \sim 10^{19}$ 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

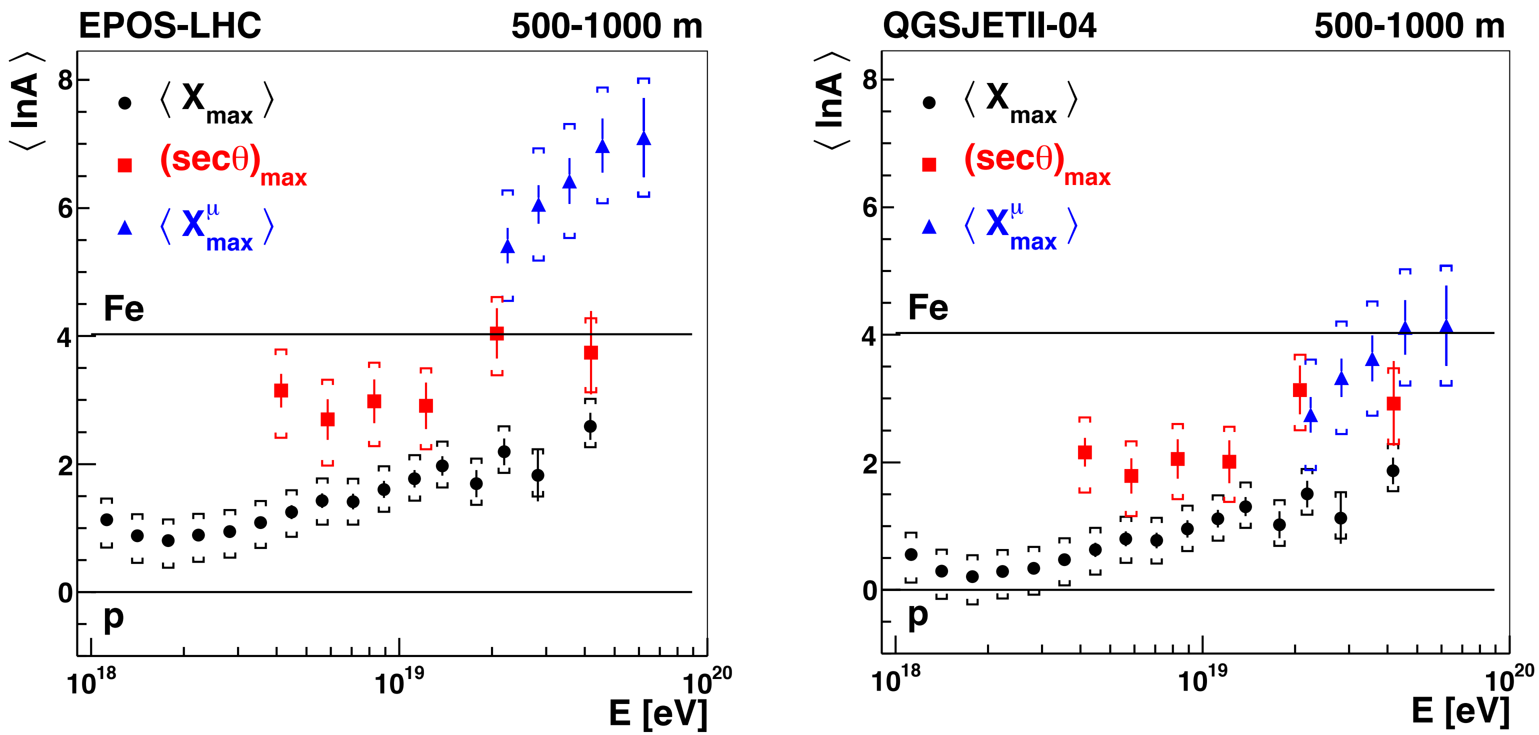
<u>evidence of muon excess not sensitive to energy scale uncertainty</u>

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



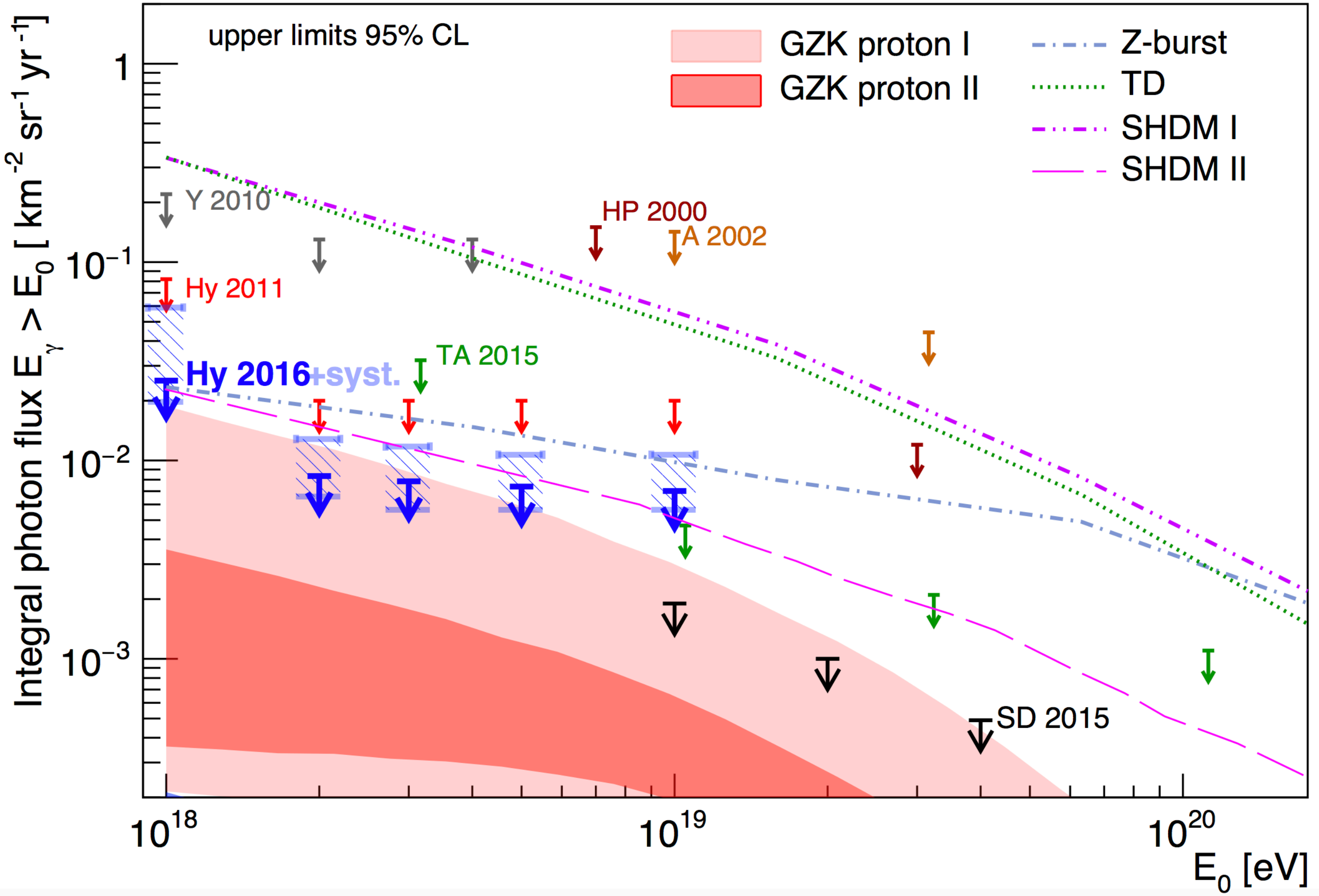
FD: X_{max} - 'e.m.'

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



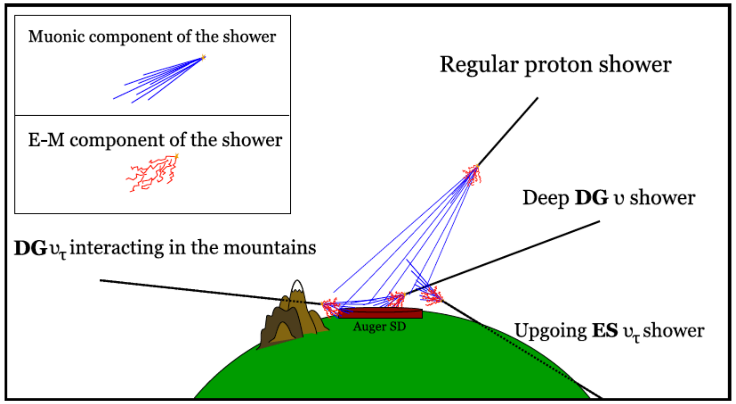
Auger, JCAP 04 (2017) 009

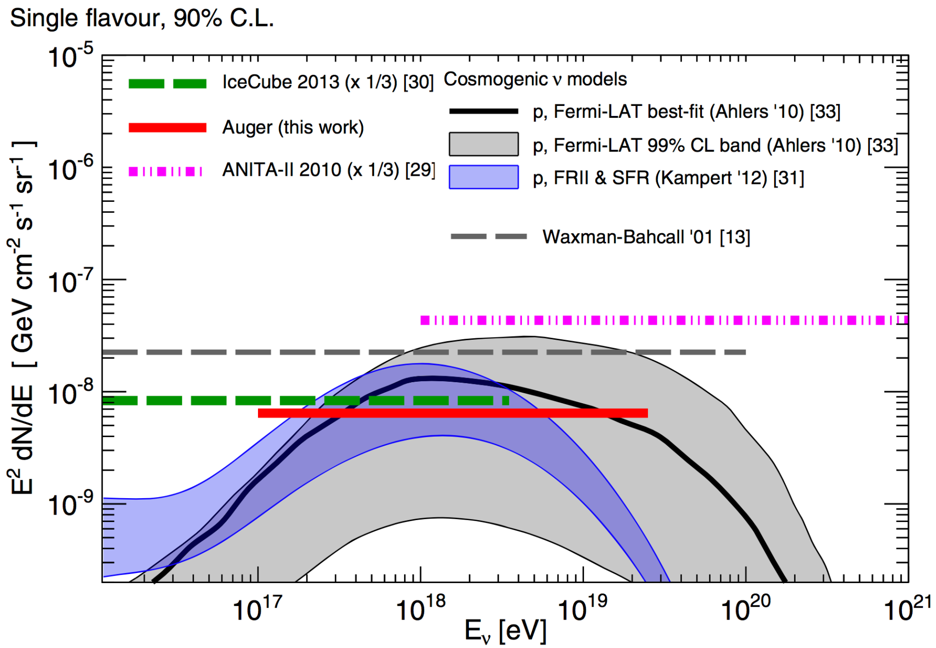
combine FD (X_{max}) and SD (steeper LDF for γ) data

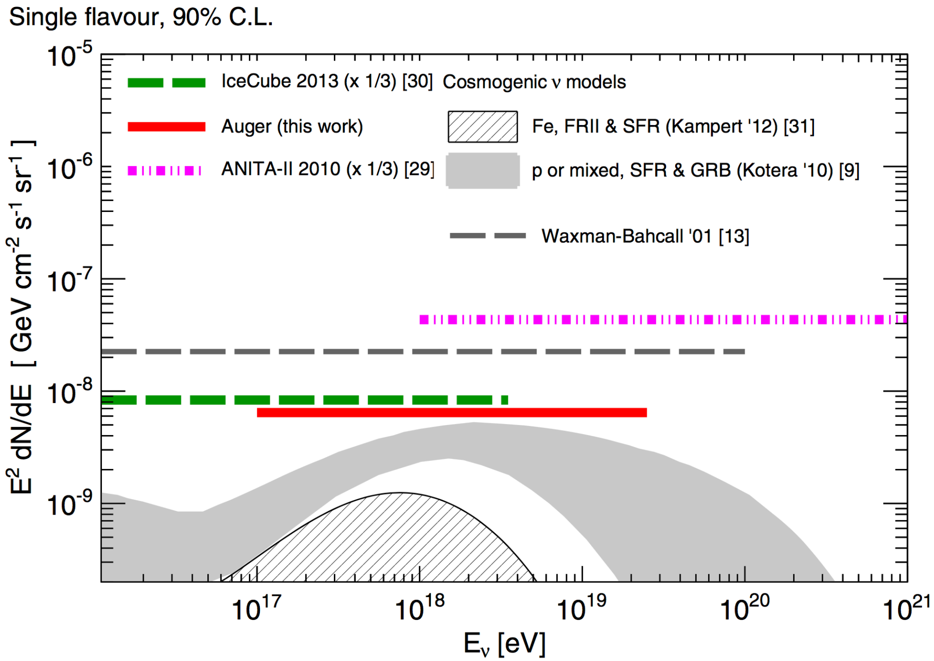
most of top-down models ruled-out

AUGER NEUTRINO LIMITS

Auger, Phys. Rev. D 91 (2015) 092008



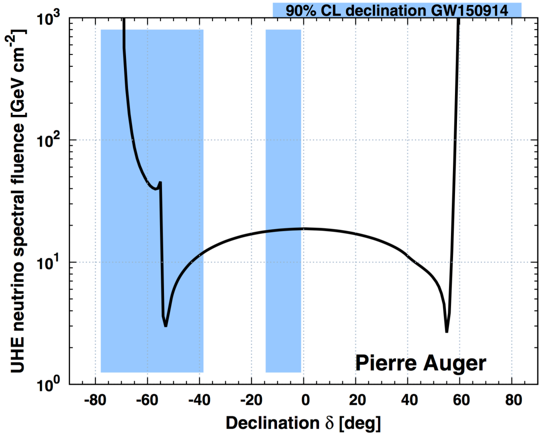




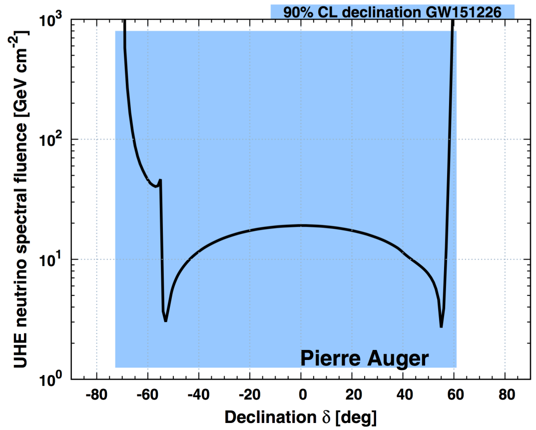
NO NEUTRINOS (E>100 PeV) IN COINCIDENCE WITH GW IN AUGER SD DATA

Auger, PRD 94 (2016) 122007

GW150914

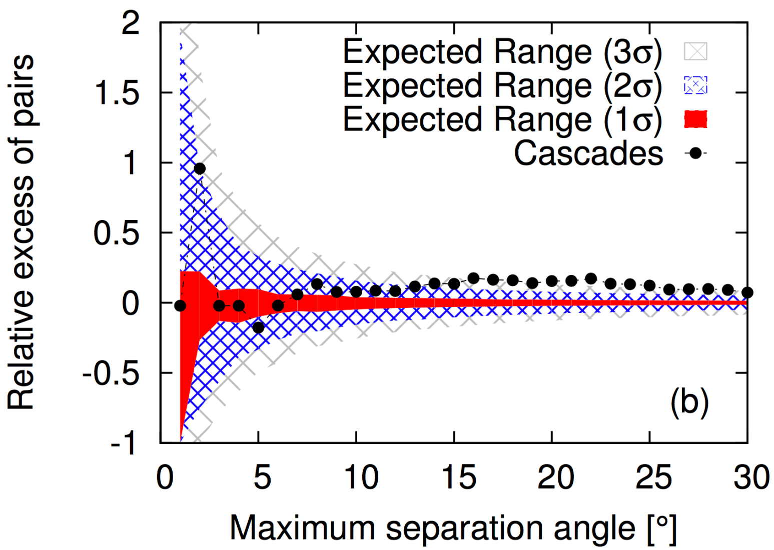


GW151226



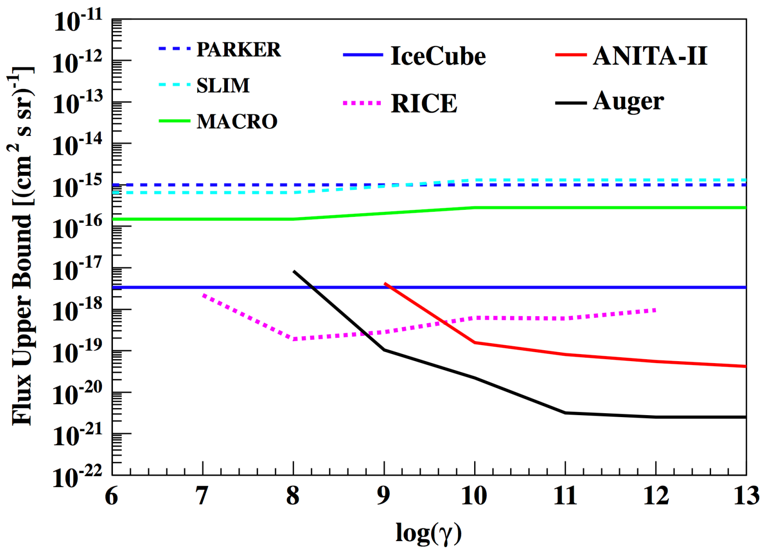
CORRELATIONS AMONG IceCube NEUTRINOS AND TA+AUGER CRs

IceCube, Auger & TA JCAP01 (2016) 037



NO ULTRARELATIVISTIC MONOPOLES IN AUGER FD DATA

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

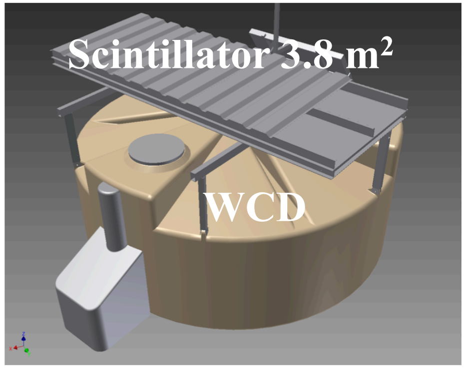


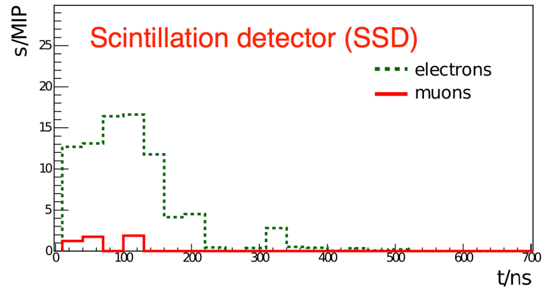
AUGER IN THE NEXT DECADE

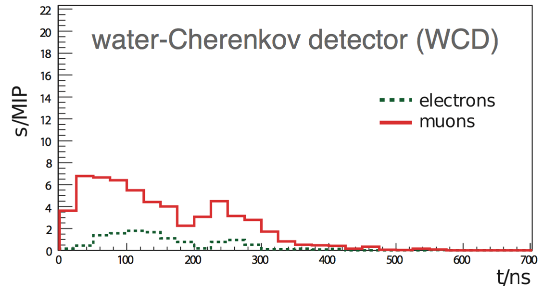
arXiv:1604.03637

AugerPrime
the upgrade of Auger

scintillator
faster electronic (120 MHz)
…



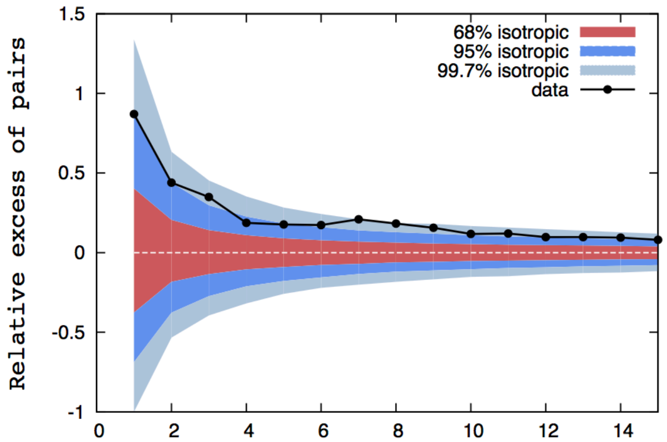


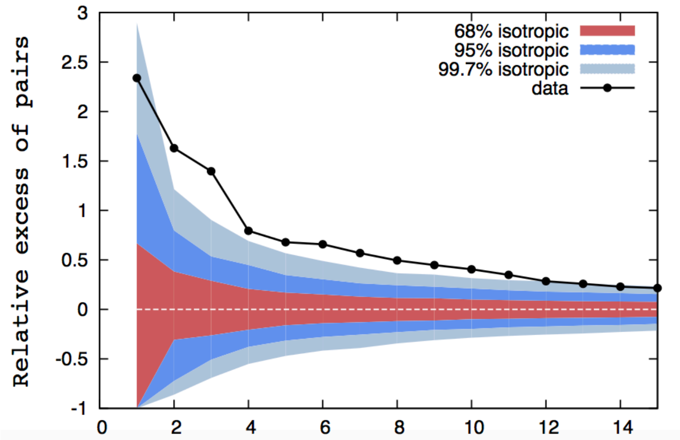


$$S_{\mu,\mathrm{WCD}} = a\, S_{\mathrm{WCD}} + b\, S_{\mathrm{SSD}}$$

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

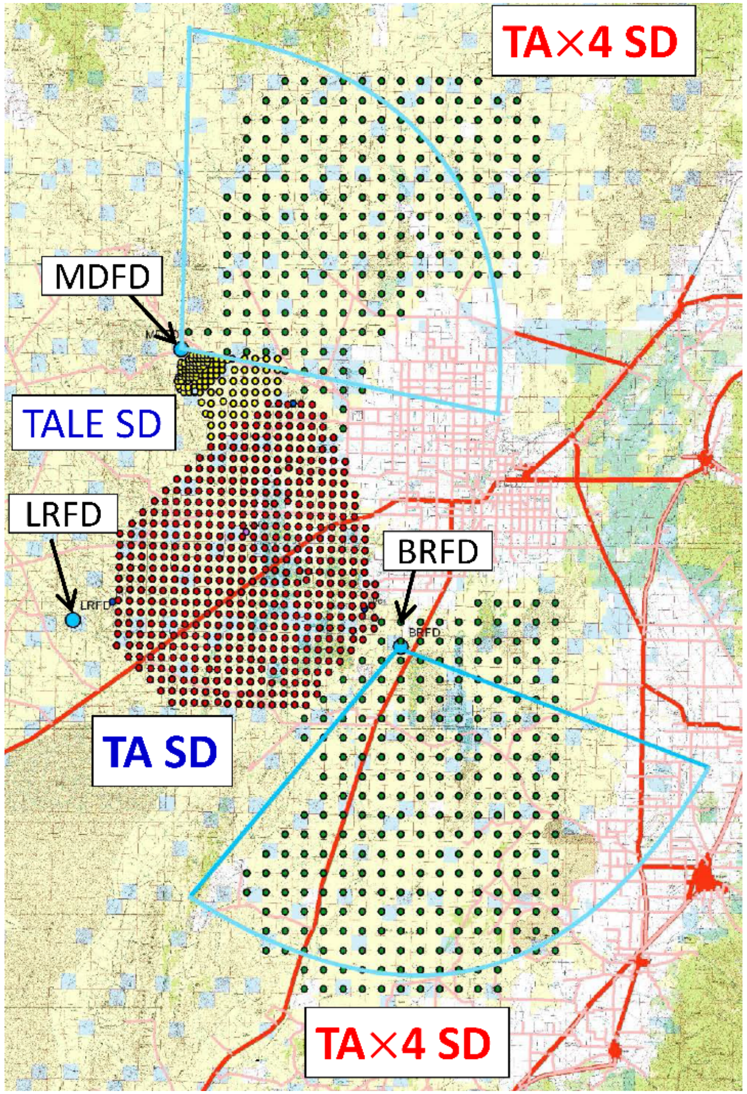
e.g. anisotropies for
light primaries





TA IN THE NEXT DECADE

H.Sagawa (TA), PoS (ICRC15) 657

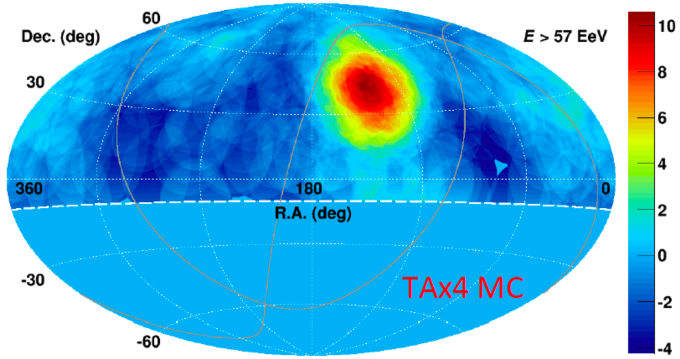


TAx4 ~3000 km^2

SD: 507 scintillators
1.2 km - 700 km^2

new 500 SD stations
2.08 km spacing

2 additional FDs in MD and BR



OUTLOOK

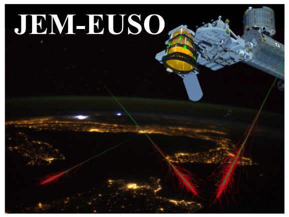
- **successful implementation of the hybrid technique (FD+SD) but still many open issues**
    - ankle and cut-off interpretation? Sources? Composition at the highest energies? Hadronic interaction models?

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

➢ **new LHC data**

excess of ρ^0 production by NA61/Shine - A.E.Hervé, PoS (ICRC15) 330
e.g.: R.Engel ICRC15, T.Pierog UHECR16 (Kyoto)

➢ **next generation experiments**
- new detection techniques (radio …)
- fluorescence detection from space



THANKS