Results of the Telescope Array experiment

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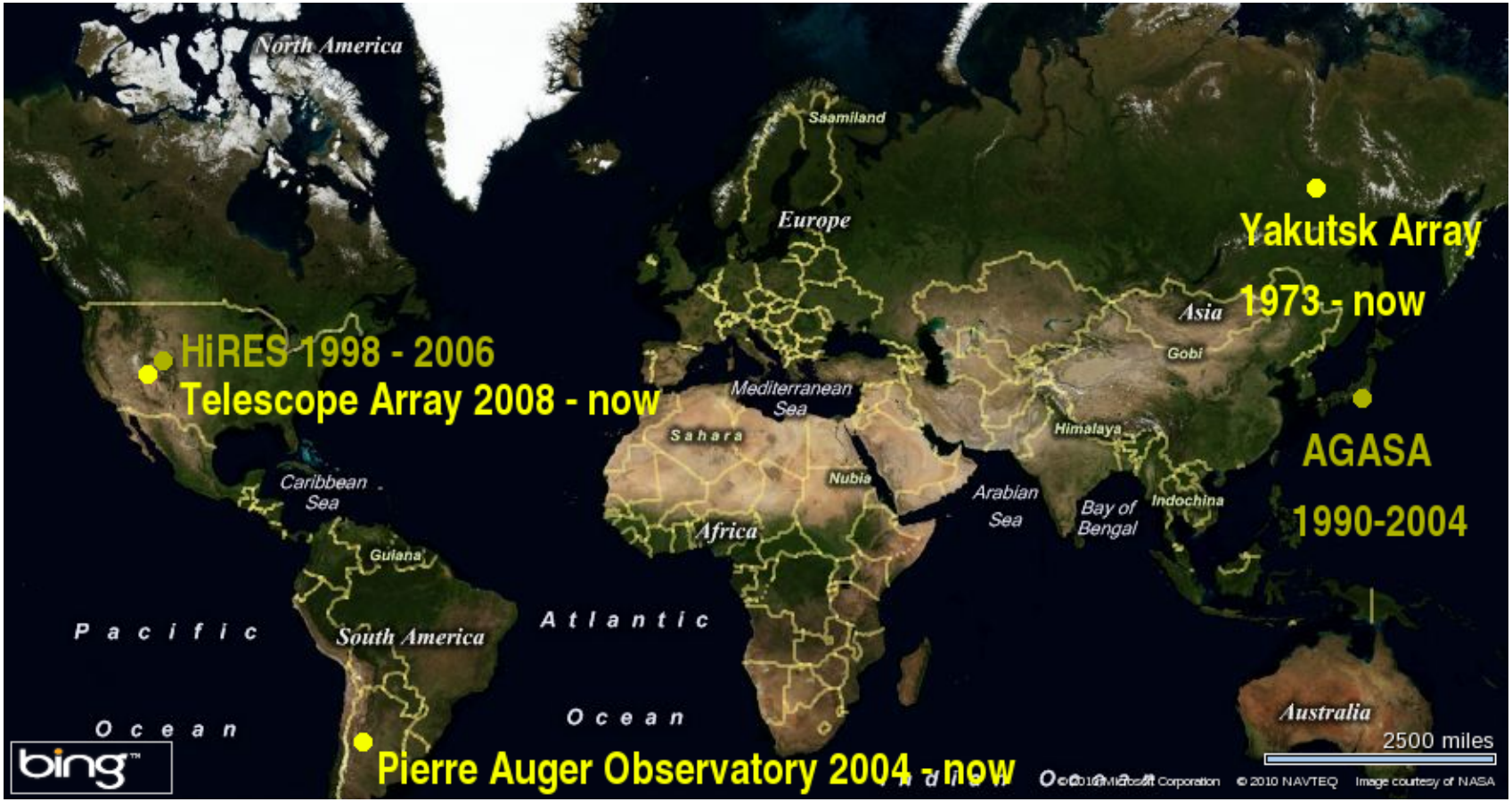
ULB Physique Théorique seminar
Bruxelles, February 4, 2011.

Outline

- Telescope Array experiment
- TA physics results on UHECRs
  - spectrum
  - chemical composition
  - search for sources
  - search for photons
- Conclusions

UHECR ground-based experiments, $E \gtrsim 10^{18}$ eV



Telescope Array Collaboration

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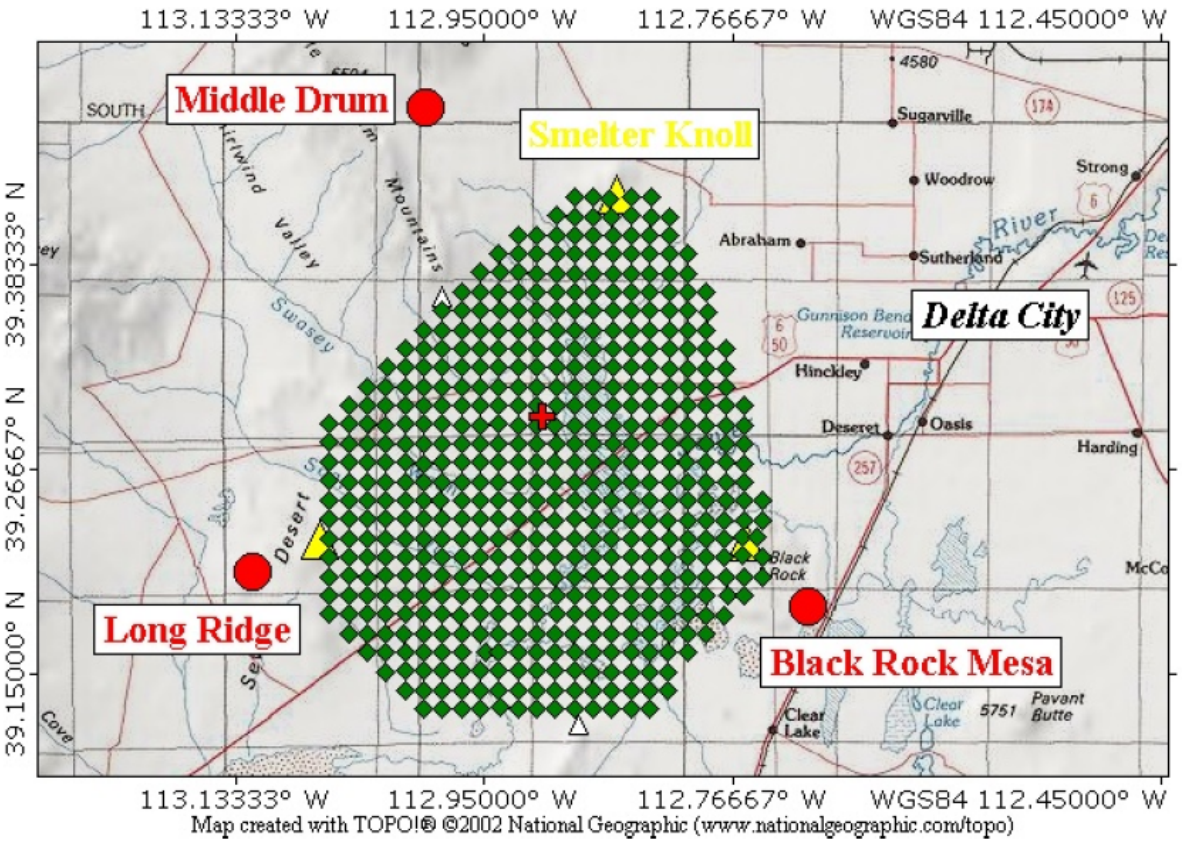
Telescope Array observatory



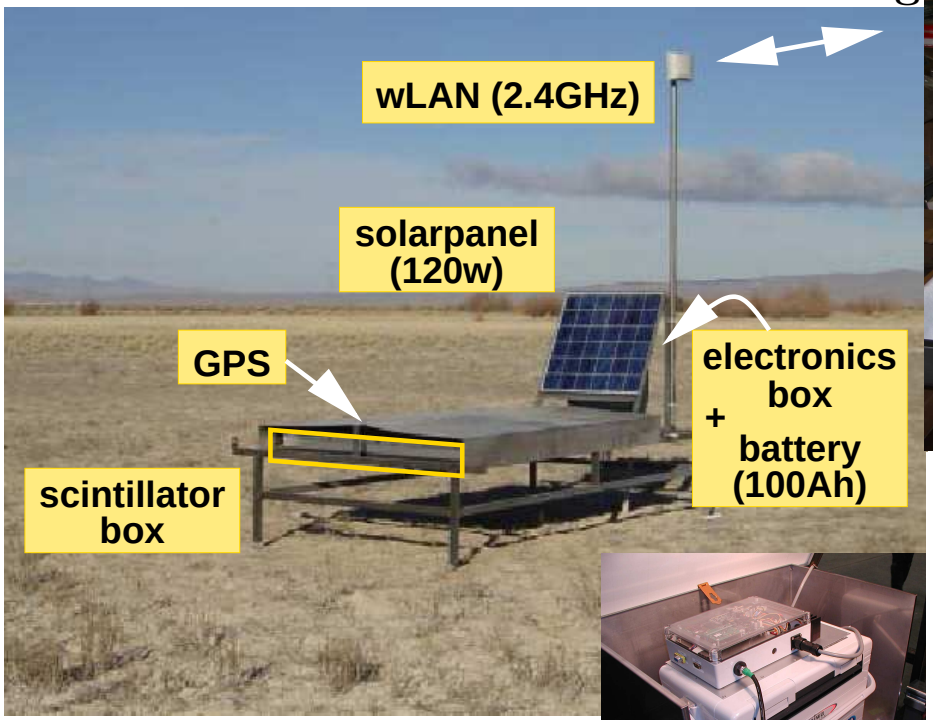
- 507 SD's, $S = 3m^2$
- 3 FD's
- CLF

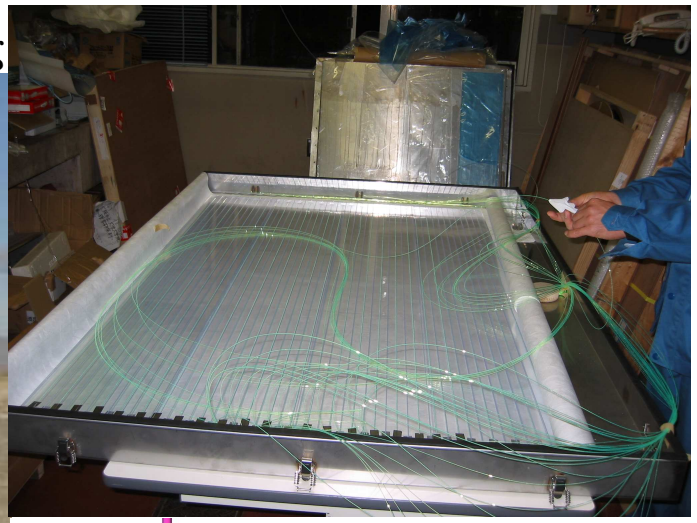
TA surface detector

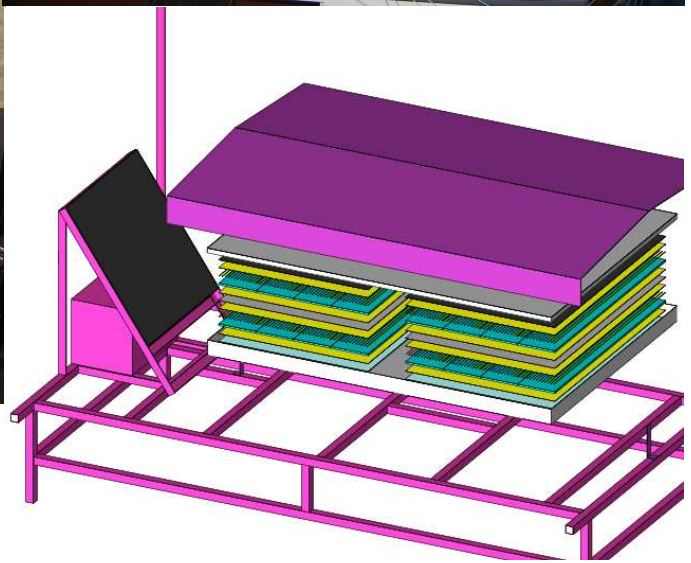
TA surface detector

< Surface Detector >

~200kg



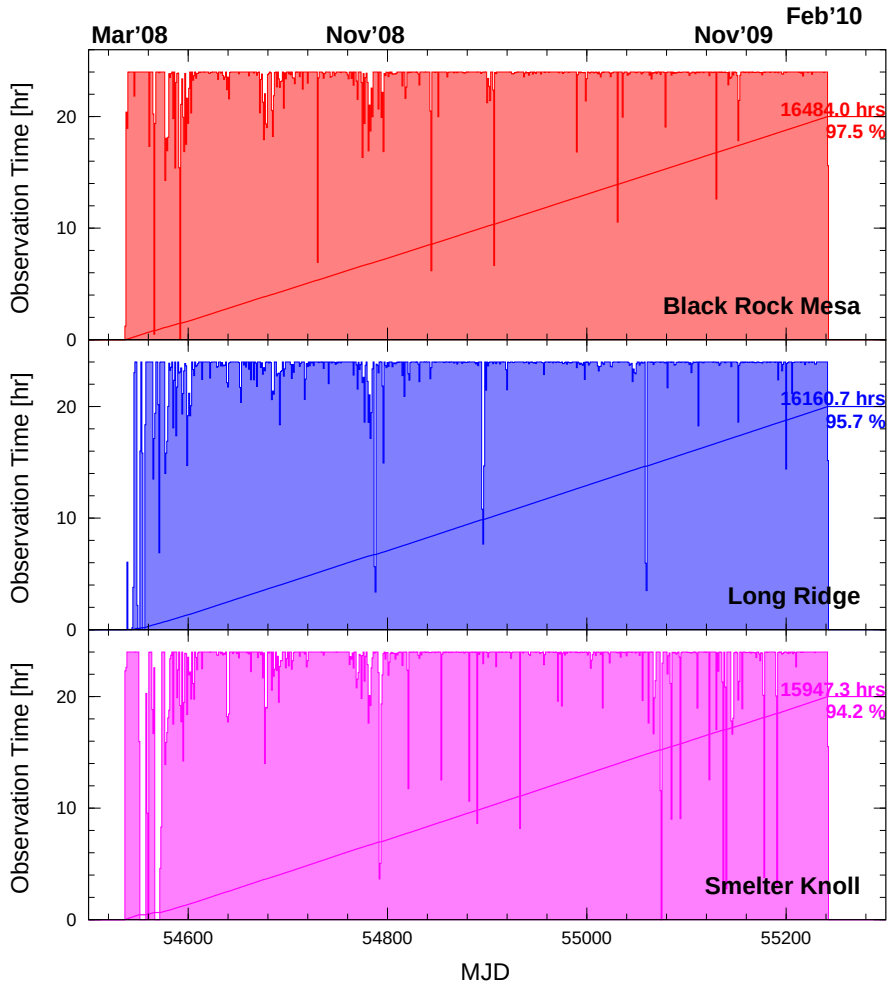




- **WLSF: 1.0mmϕ (2cm separation)**
- **PMTs: ET 9123SA $\times$ 2**
- **3m^2 (12mm $\times$ 2 layers)**

M. Takeda, JPS meeting, March 2010

< SD Observation Status >

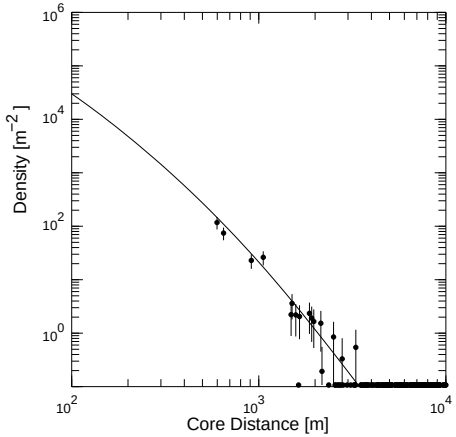


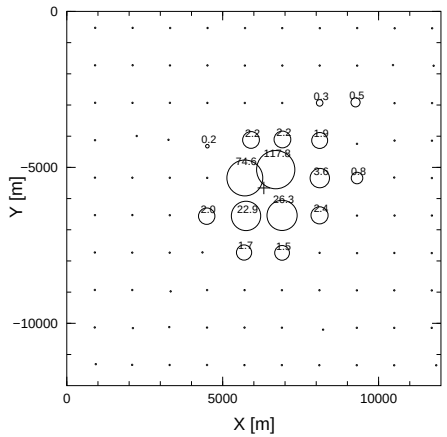
- operation in stable
  - $\gtrsim$ 95%
  - $\gtrsim$ 16k hours
- wLAN interference in early stage
- thunder storms in summer
- maintenance access in autumn
- low temperature & snow in winter

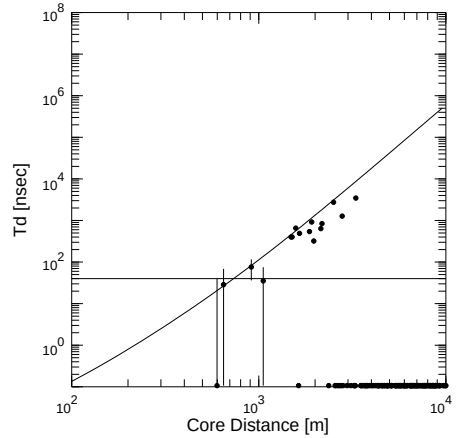
SD event example

M. Takeda, JPS meeting, March 2010

< SD Event Example >

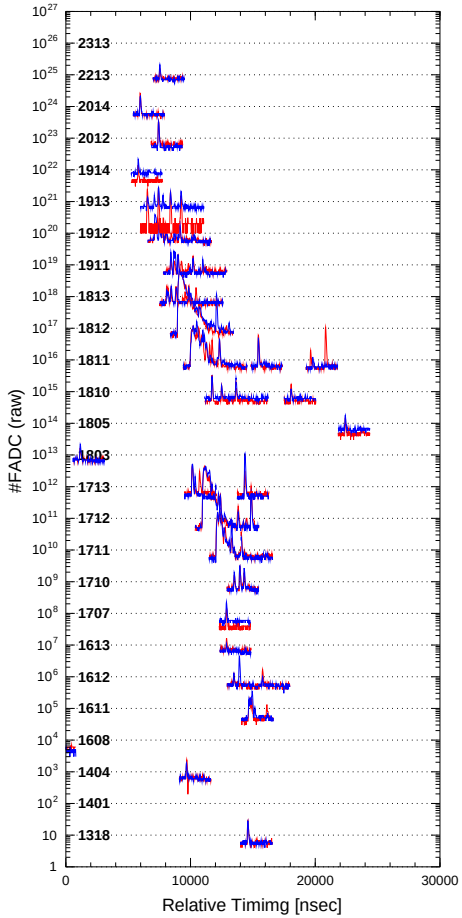






RUN(50141) **EVENT(2182)**

DATE(080531) **TIME(050737)**



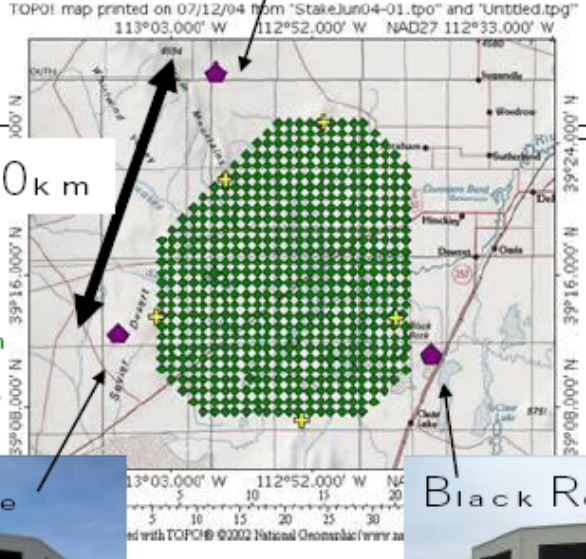
TA Fluorescence Detectors

Refurbished from HiRes

Observation started Dec. 2007

Middle Drum

14 cameras/station
256 PMTs/camera



~30km

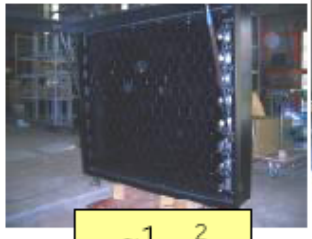
Observation started Nov. 2007

New FDs

256 PMTs/camera
HAMAMATSU R9508
FOV~15x18deg
12 cameras/station

Long Ridge

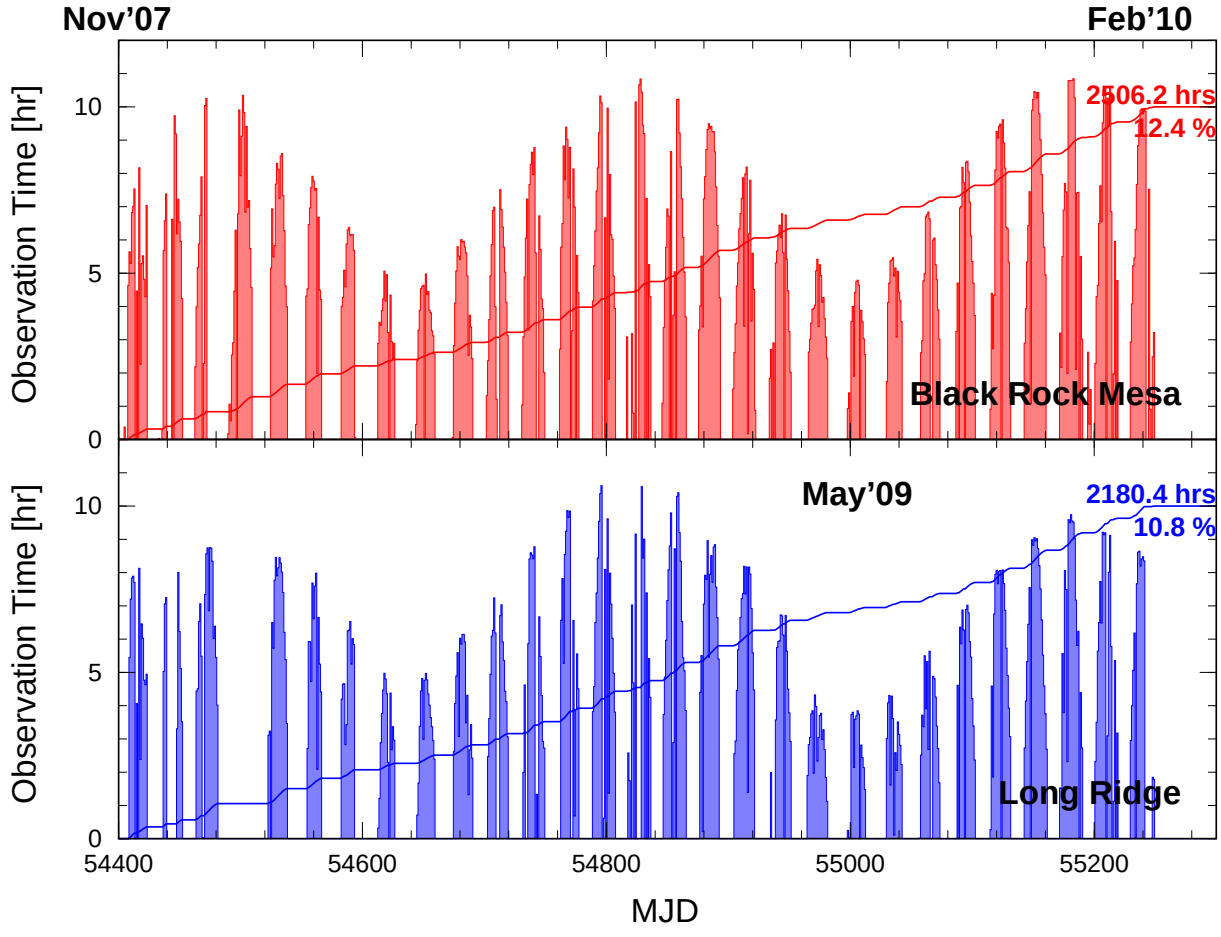
Black Rock Mesa



Observation started Jun. 2007

< FD Observation Status >

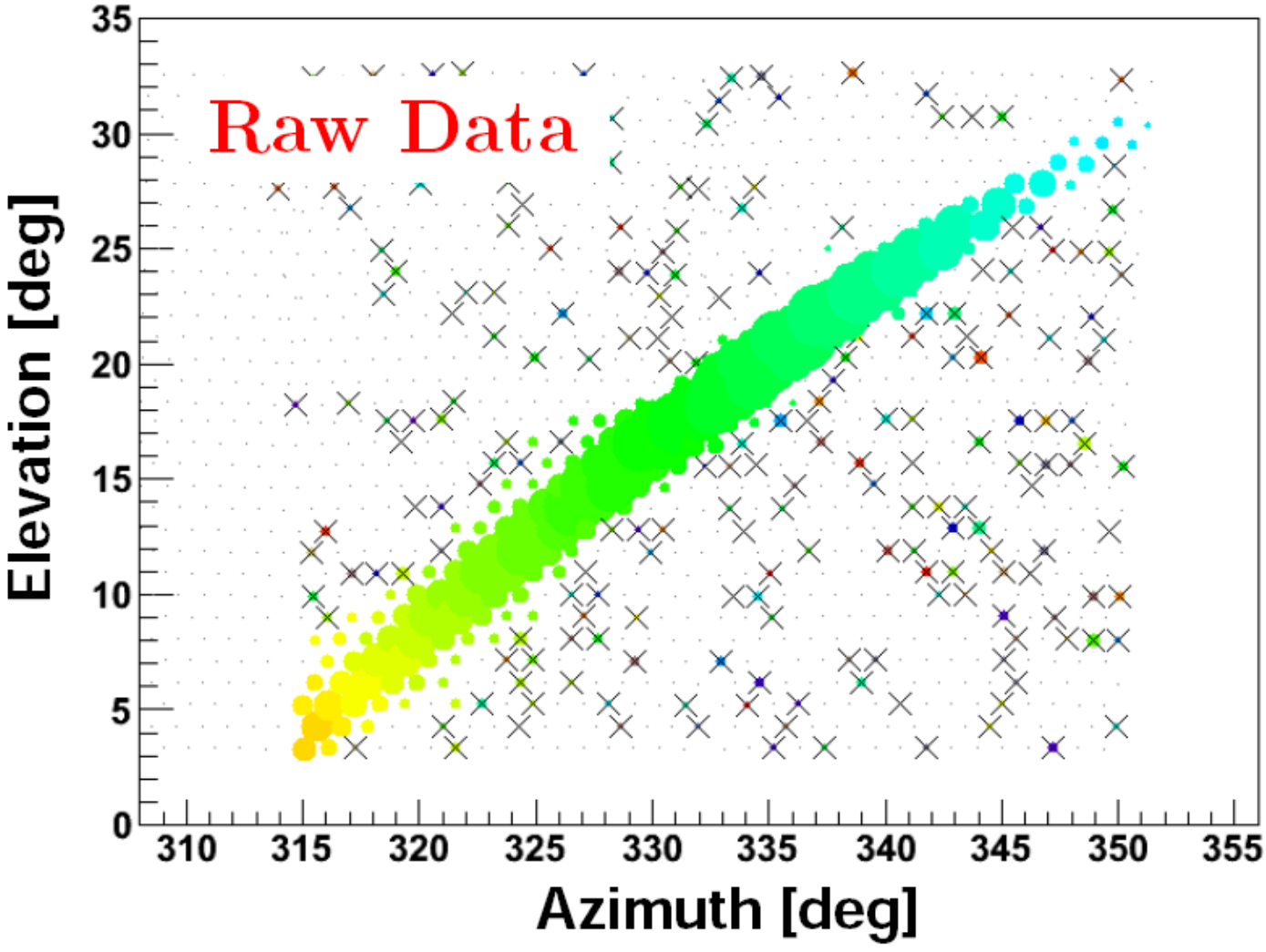
- **Full operation since Nov '07**



- $\gtrsim$ **2.5k hrs**
- $\gtrsim$ **2.1k hrs**
- **Long Ridge remote operation since May '09**

M. Takeda, JPS meeting, March 2010

FD event example



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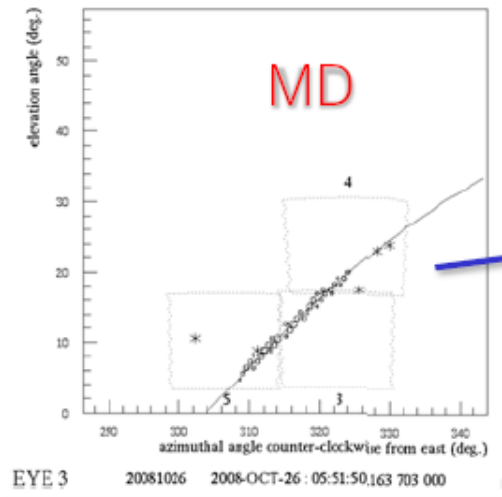
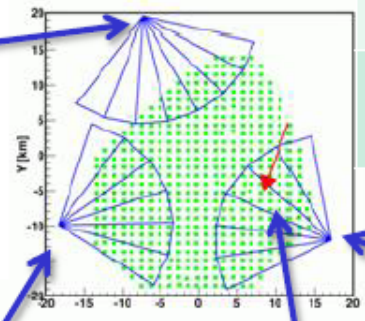
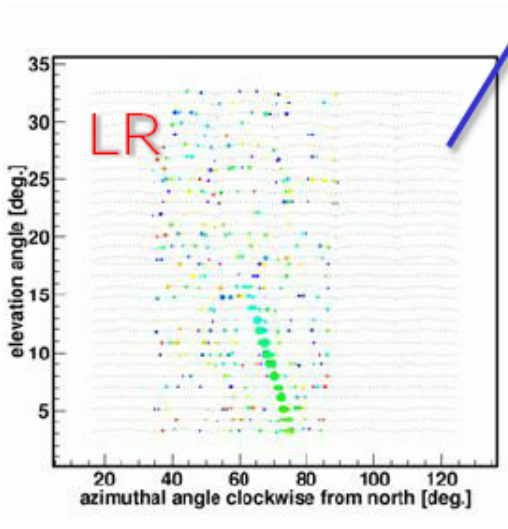
Hybrid event example

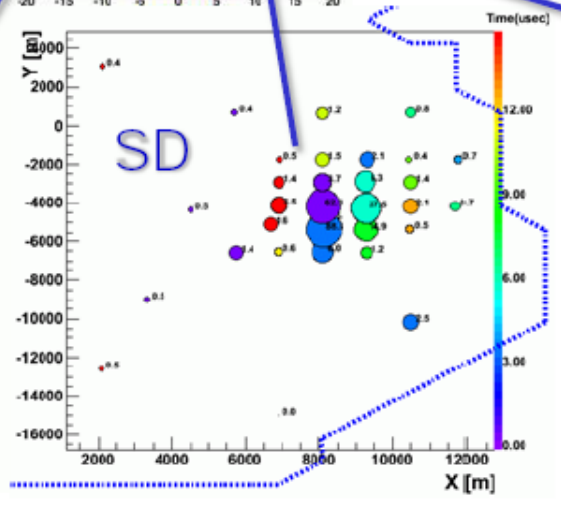
Triple FD Event (2008-10-26)

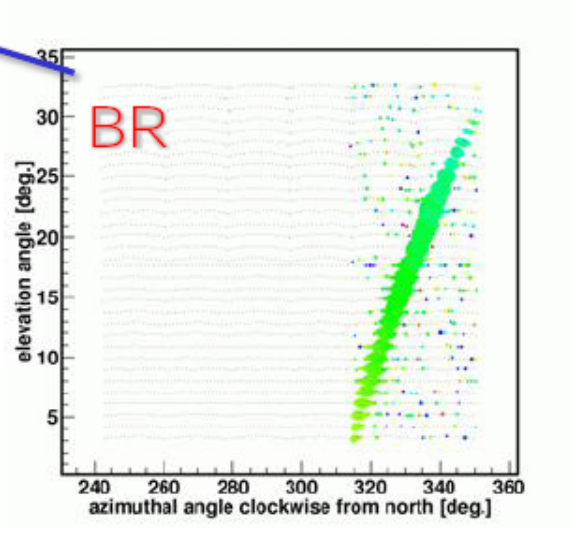
	θ[deg]	ϕ[deg]	X[km]	Y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88



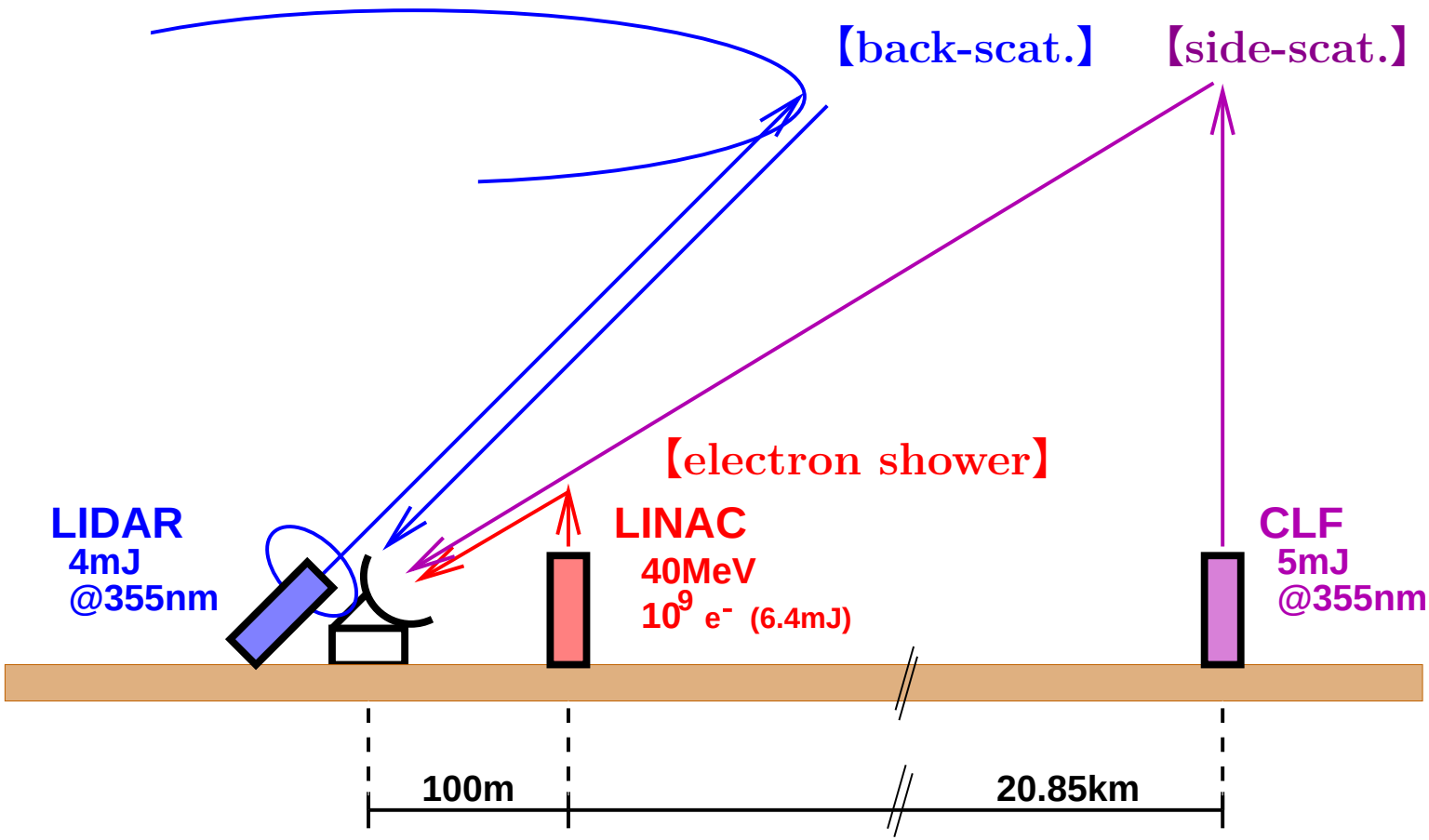






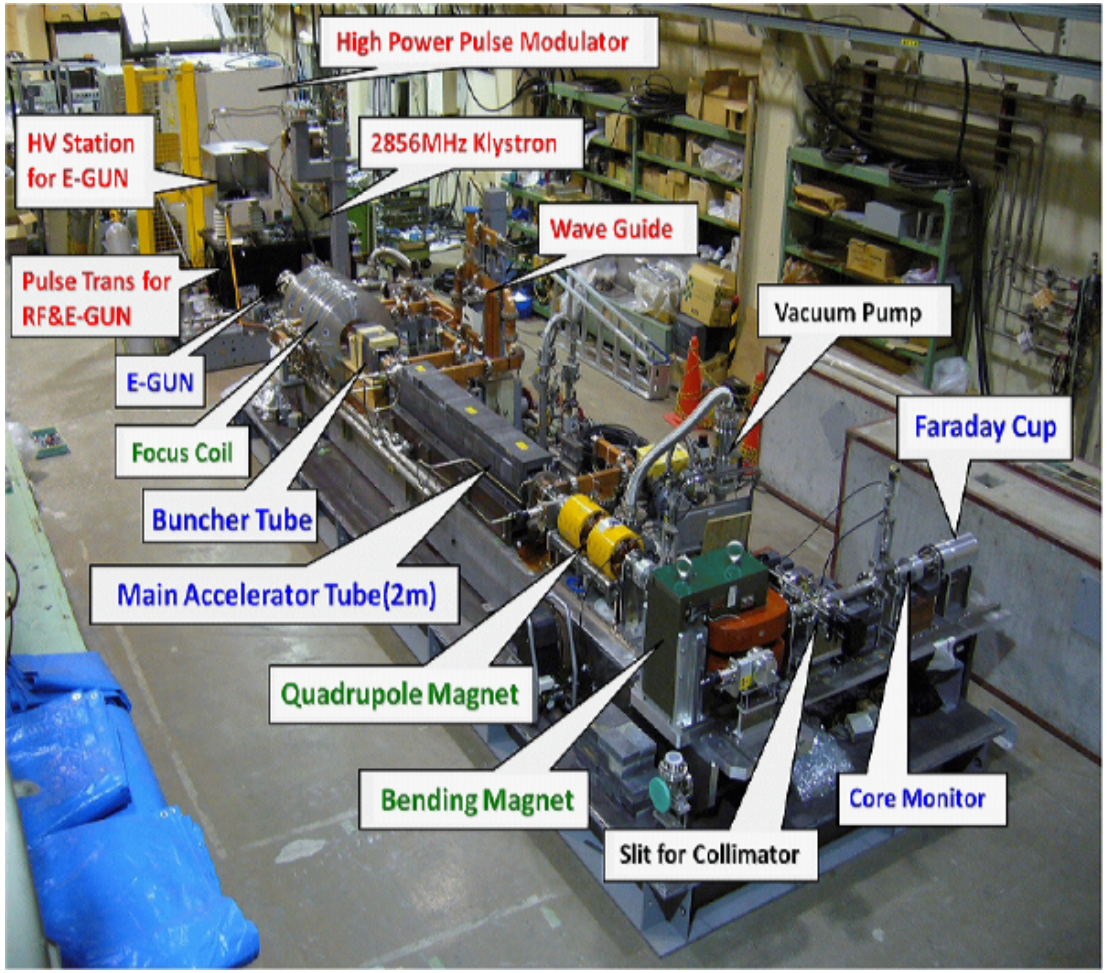


< Atmospheric Monitor (LIDAR, CLF) & LINAC >



TA-LINAC: Linear Accelerator @ TA

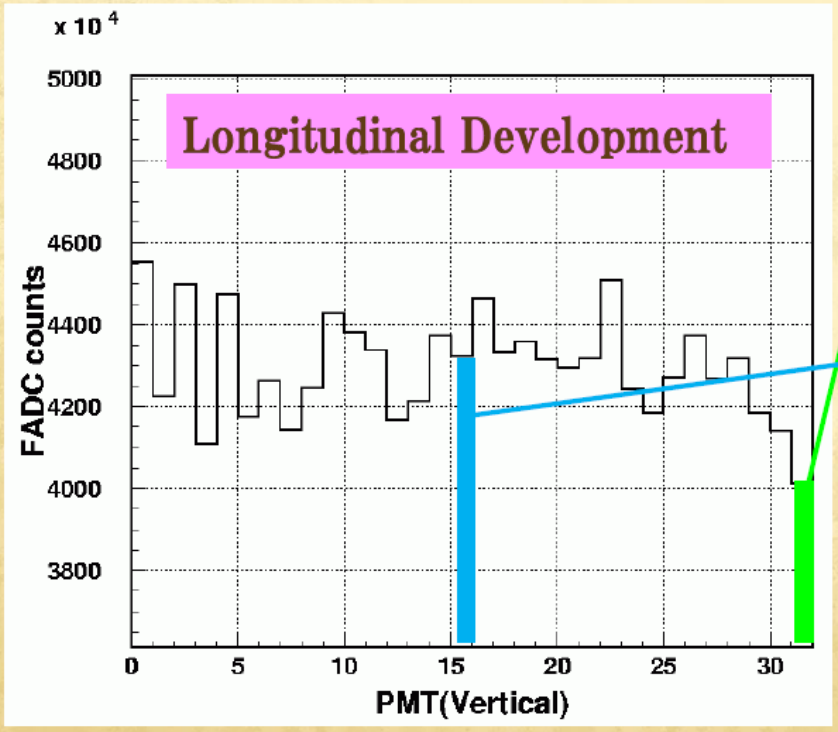
- Electron accelerator 100 m from TA FD
- Rate 0.5 Hz
- Energy $\sim$ 40 MeV
- Current $10 - 250$pC/pulse

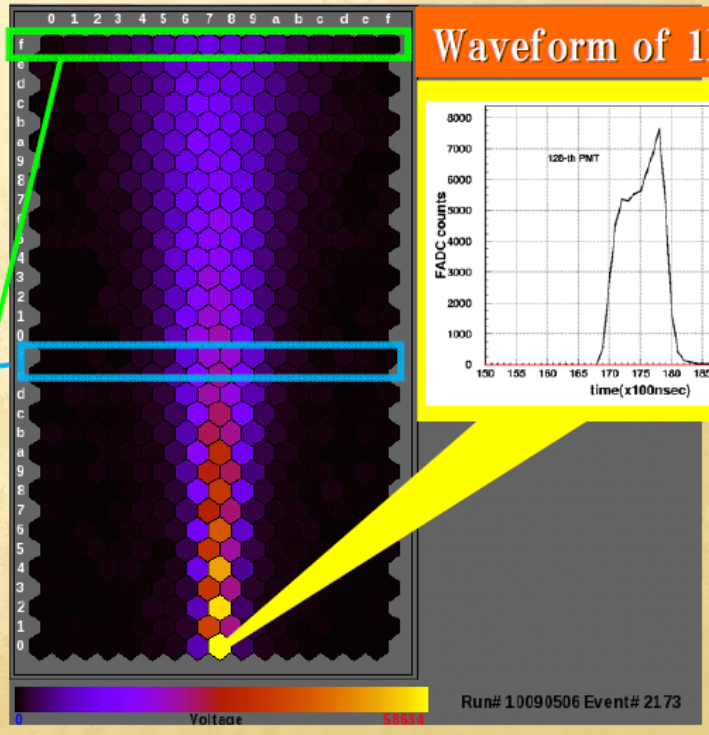


T.Shibata, UHECR-2010, Nagoya

Fist run: September 2010

Data set : Taken in Sep.5th (UTC)
checking now…

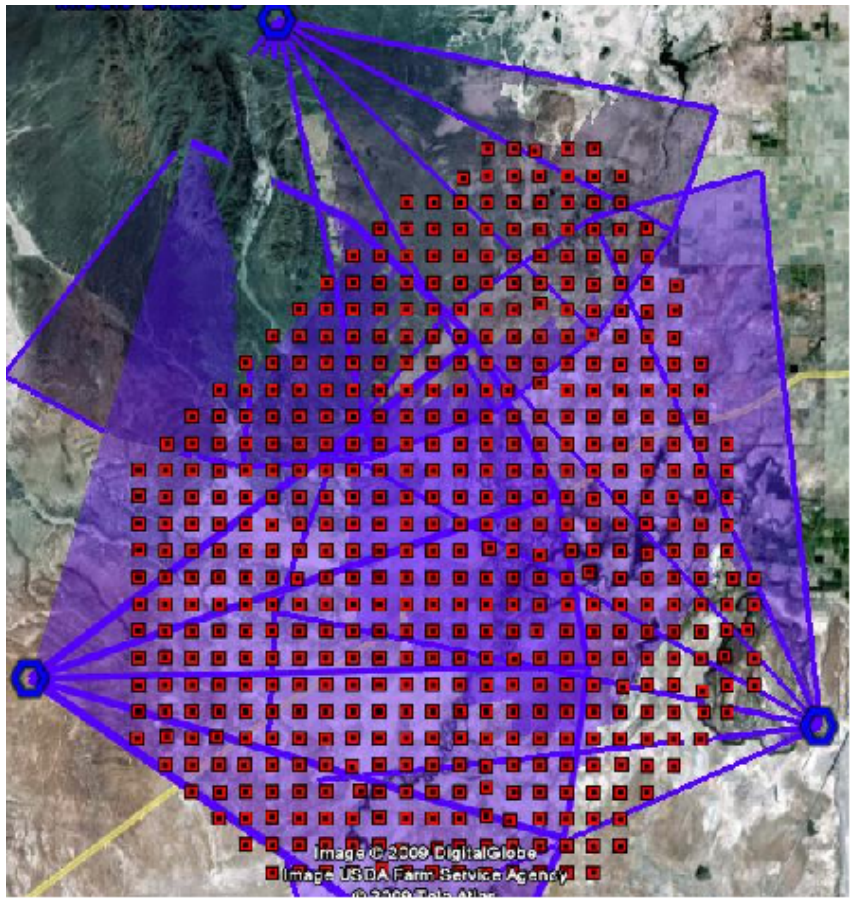




Telescope Array physics objectives

Study of UHECR E $\gtrsim 10^{18}$ eV

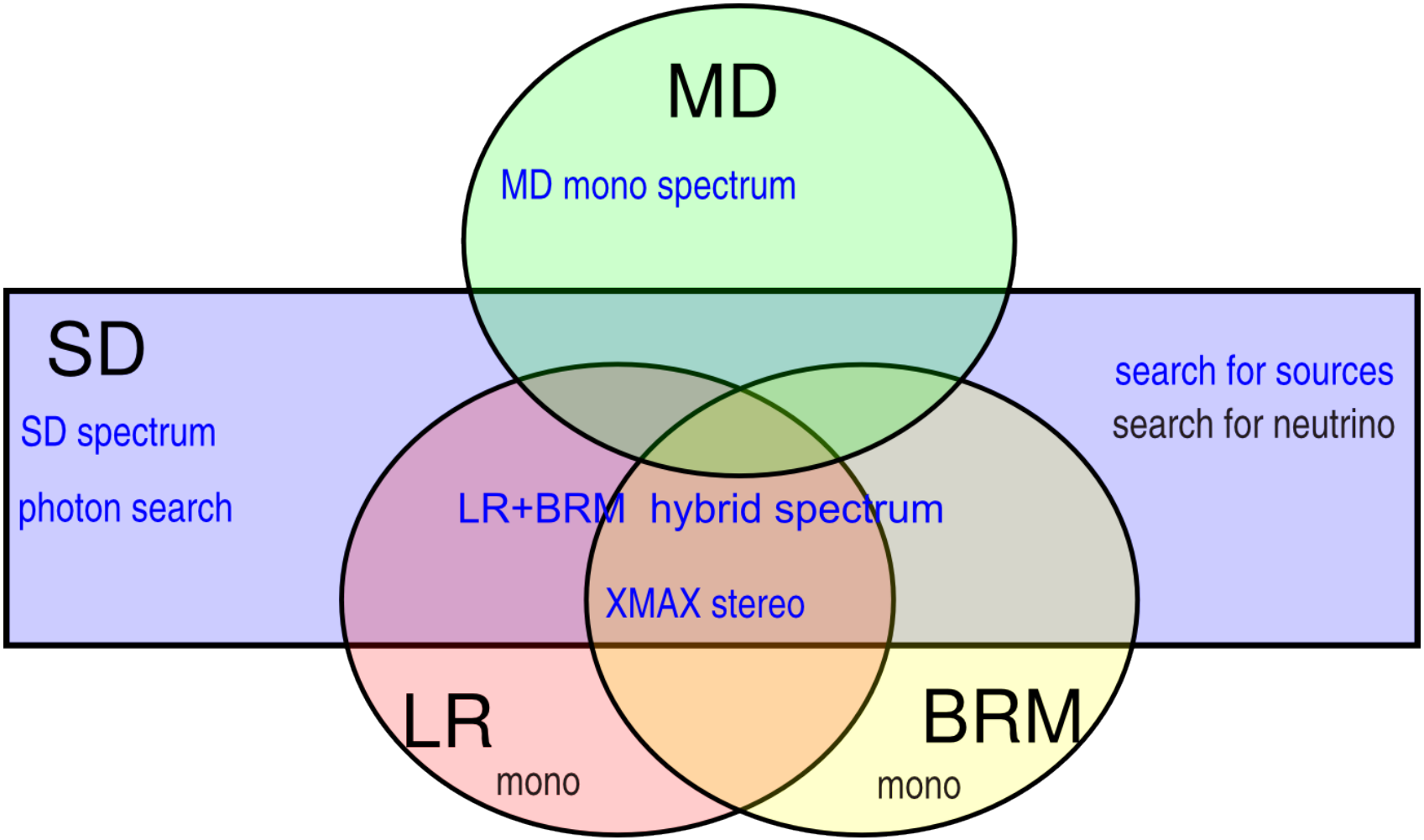
- Spectrum
- Chemical composition
- Search for sources
- Search for photons and neutrino
- Hadronic interactions properties



TA physics results

- I. UHECR spectrum
- II. Chemical composition by XMAX stereo
- III. Search for cosmic ray sources
- IV. Search for photons

TA physics results scheme



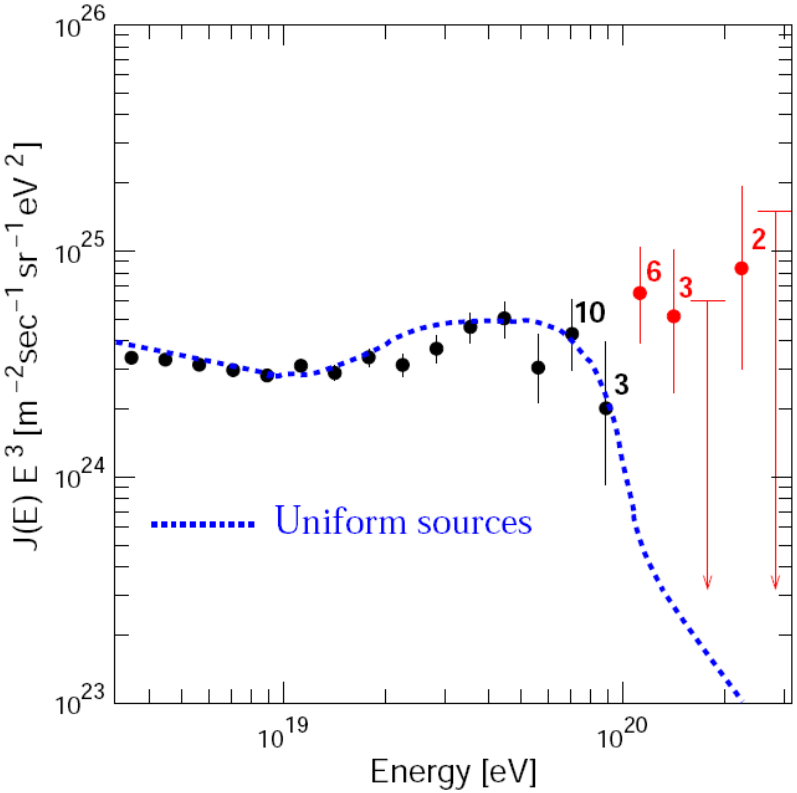
I. UHECR spectrum

GZK effect

Greisen, 1966; Zatsepin, Kuzmin, 1966

Cut-off predicted for $E \gtrsim 10^{19.7}$ eV.

$$p + \gamma_{2.7K} \rightarrow n + \pi^+$$
$$\rightarrow p + \pi^0$$

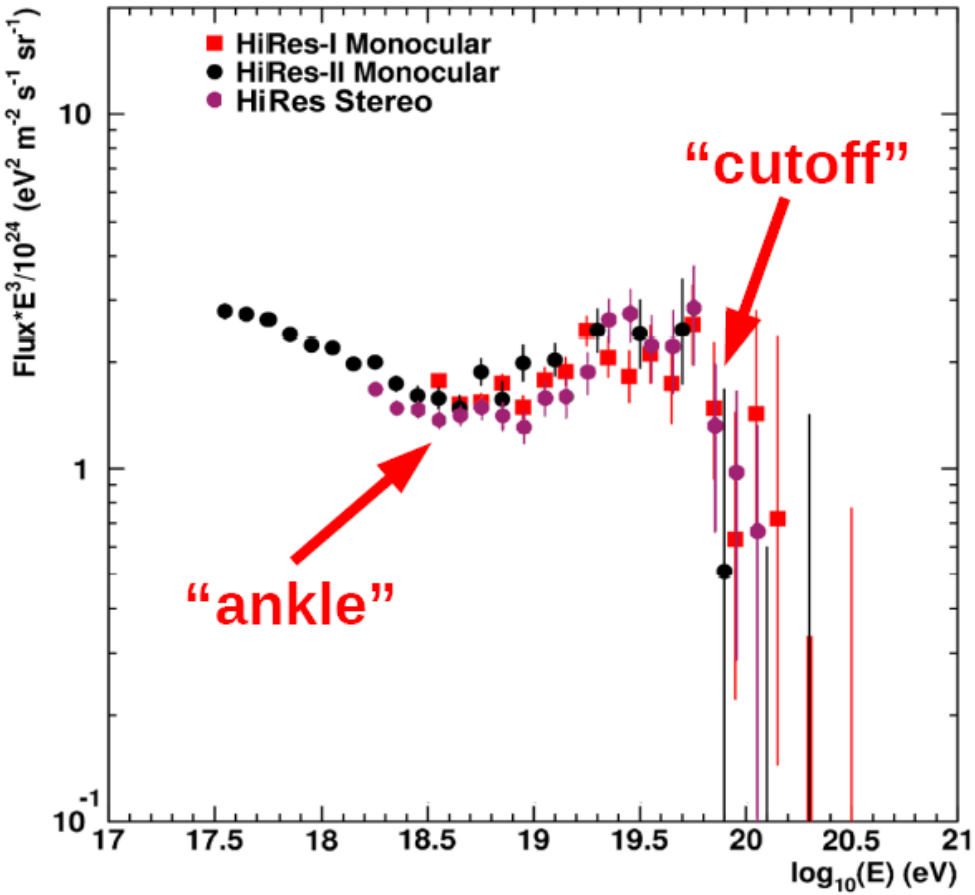


AGASA spectrum, 2003

Takeda, M. et al., Astropart. Phys 19(2003)

- Expected 1.9 event
- Observed 11 events above 10^{20} eV

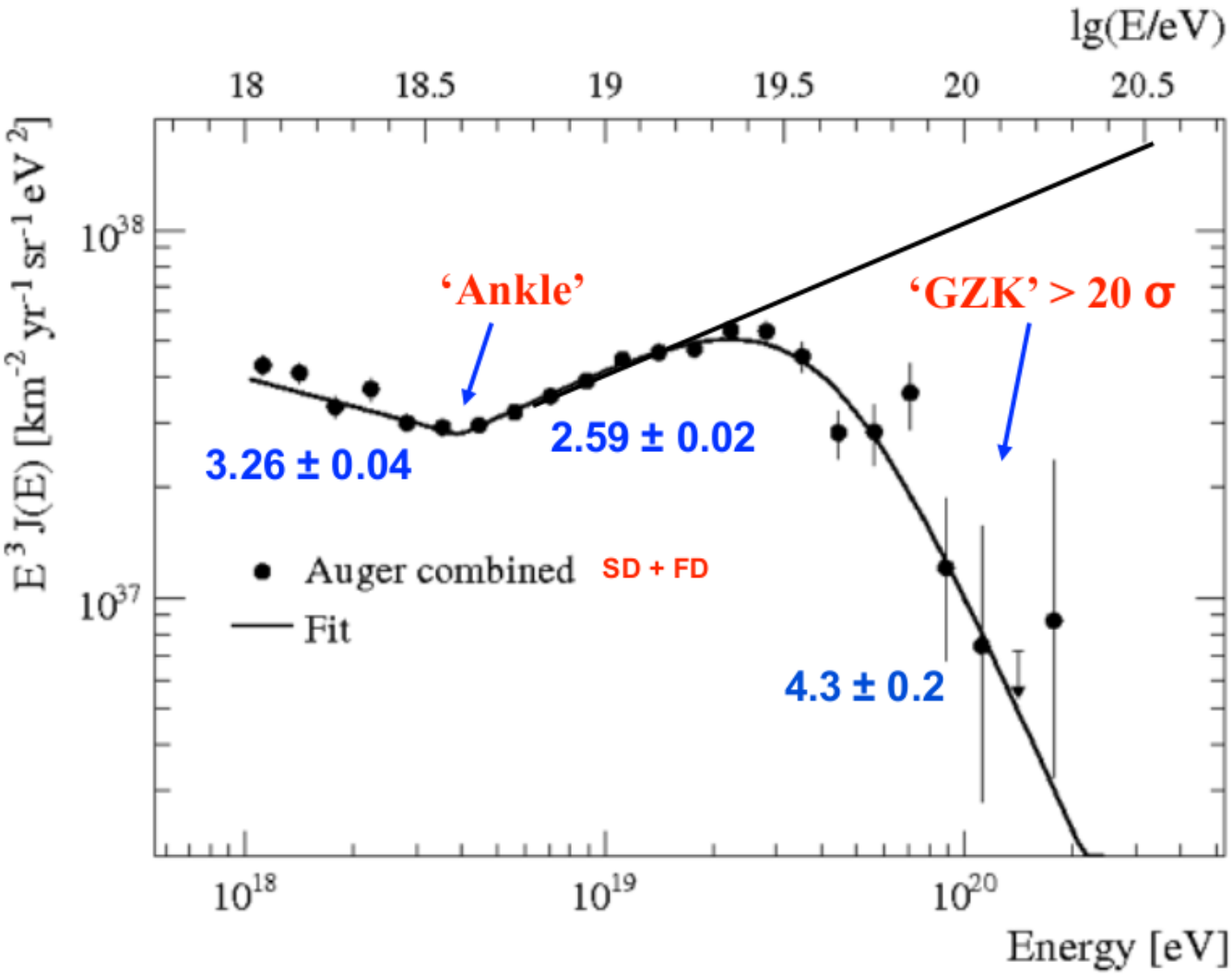
Cut-off observation by HiRES



Monocular: Quarks'06; PRL 100 (2008)

Stereo: Astropart. Phys. 32 (2010)

Pierre Auger spectrum



PRL 101 (2008) & Phys. Lett. B 685 (2010)

Telescope Array spectrum

TA measures spectrum by three techniques:

- Middle Drum fluorescence detector (FD) mono
- Surface detector (SD)
- Hybrid (SD+FD)

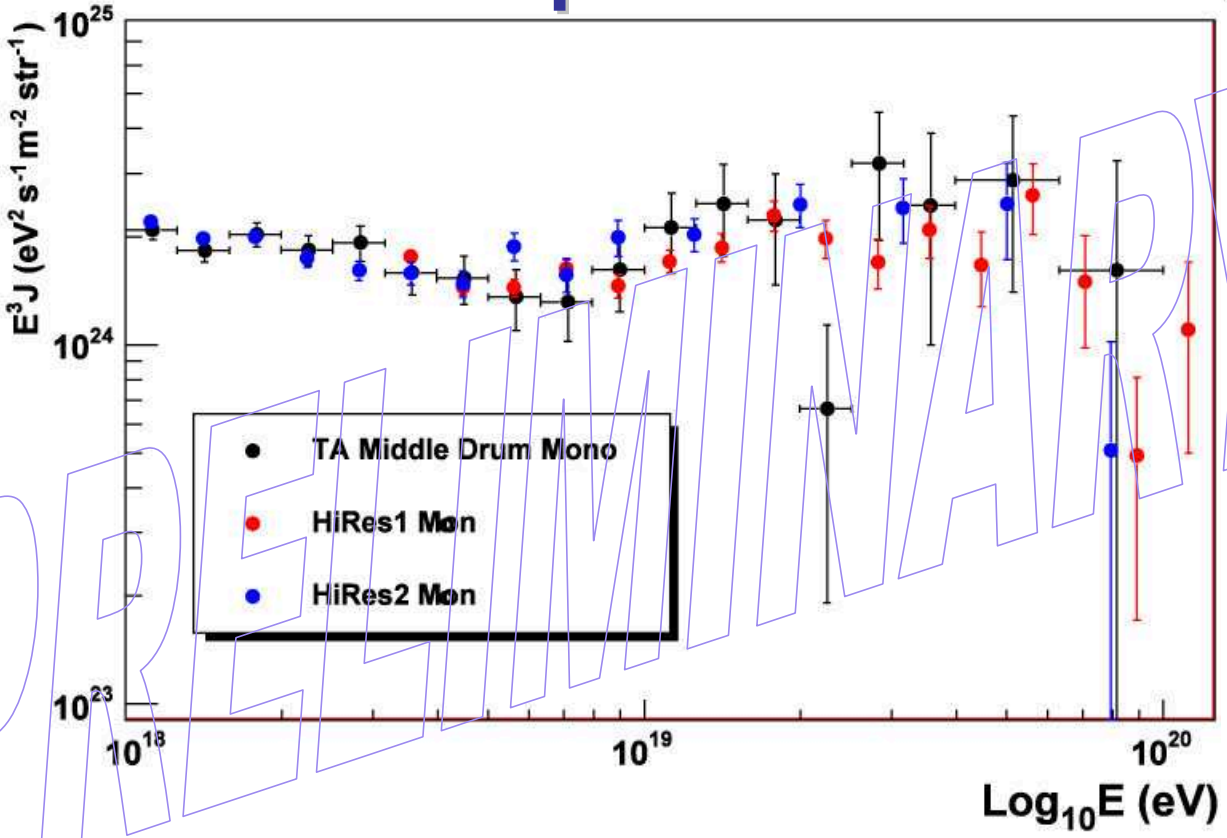
Monocular spectrum from Middle Drum (MD) detector

- MD uses 14 refurbish HiRes-1 telescopes.
- TAMD mono processing is identical to HiRes-1 monocular data analysis
  - same program set
  - same "average" atmospheric model
  - same event selection, cuts
  - Differences:
    - telescope location and pointing directions
    - Thresholds ($\sim$ 20% lower than HiRes-1)
- Exposure is calculated with Monte-Carlo

G.Thomson, ICHEP'10, Paris

Jui, ICRC 2009

MD Spectrum



Surface detector spectrum

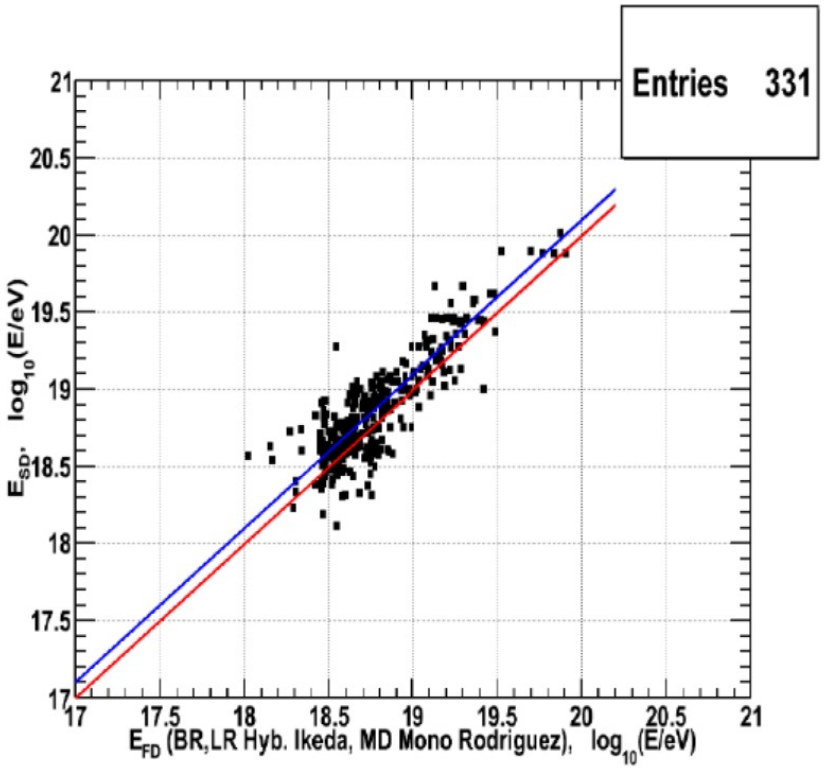
Dataset:

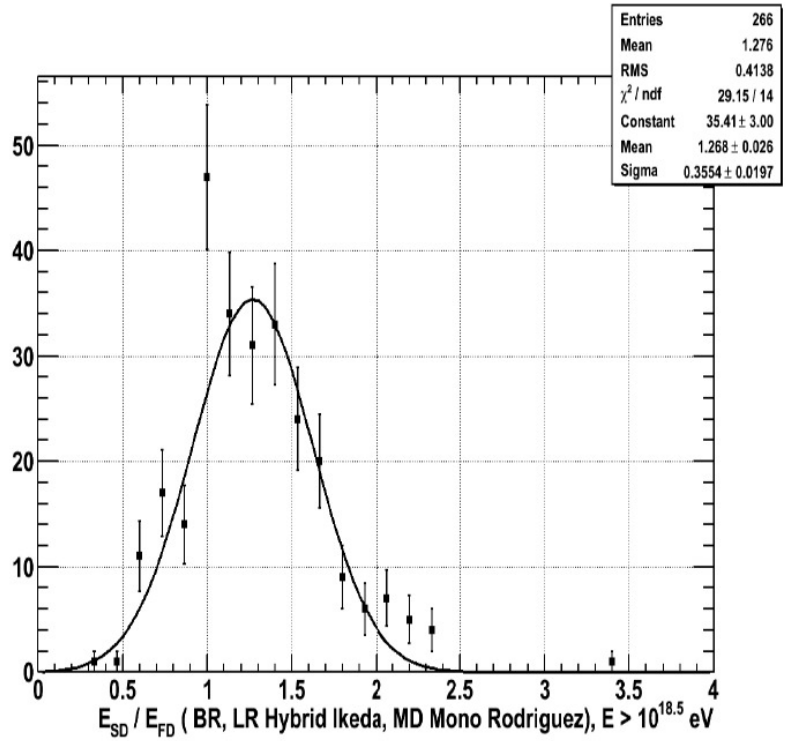
- Geometrical cuts:
  - $\theta < 45^\circ$
  - core inside the array, distance to border > 1200 m
- Cuts on reconstruction quality:
  - number of detectors hit $>= 4$
  - $\chi^2/\text{d.o.f} < 4.0$
  - pointing direction resolution $< 5^\circ$
  - fractional S_{800} uncertainty < 0.25

- 1.75 years, 6264 events after cuts

G.Thomson, ICHEP'10, Paris

Energy scale normalization

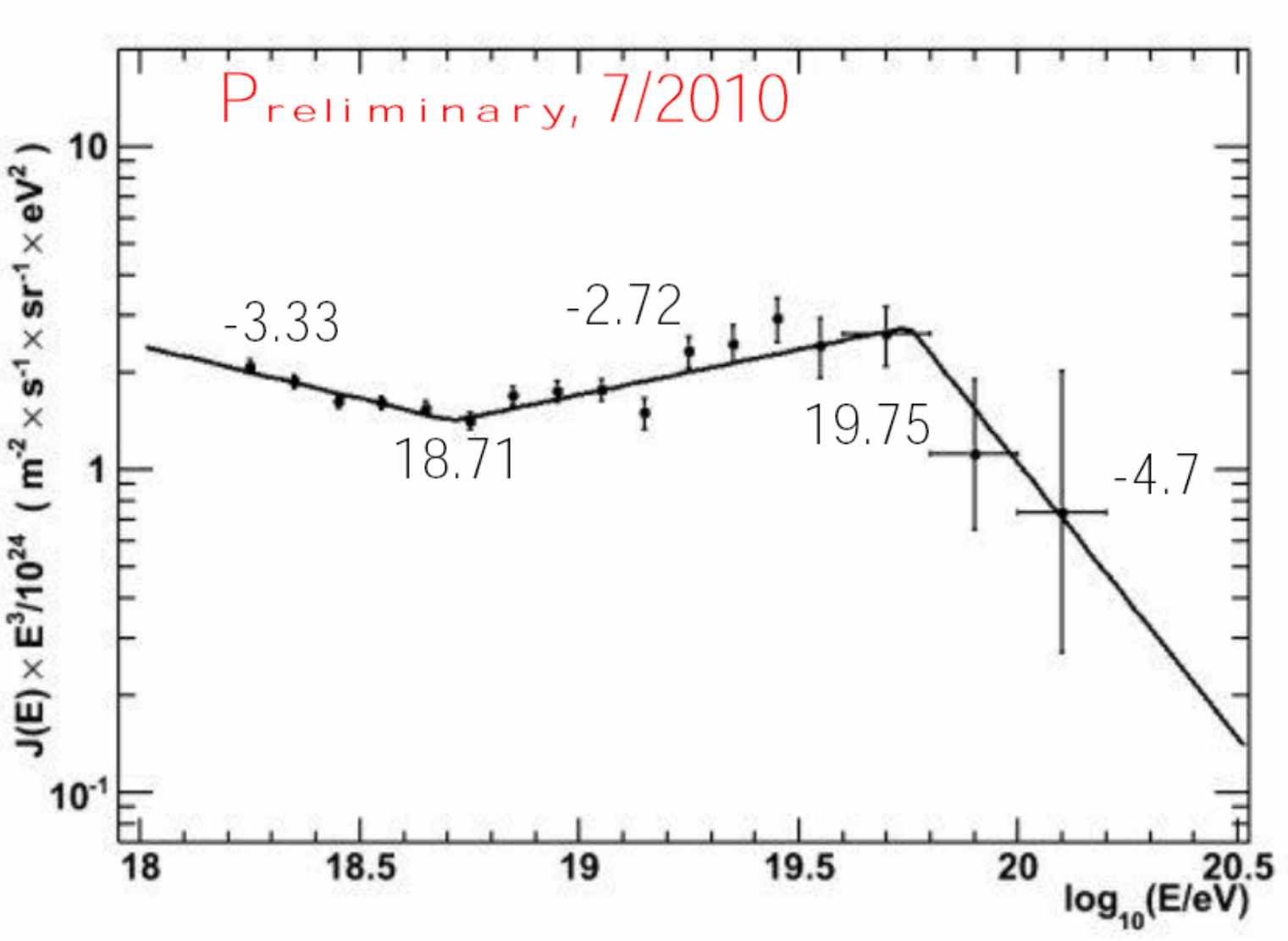




- SD energy: CORSIKA QGSJET-II full MC
- FD energy: MD mono, BRM, LR hybrid
- Result: $E = E_{SD}/1.27$

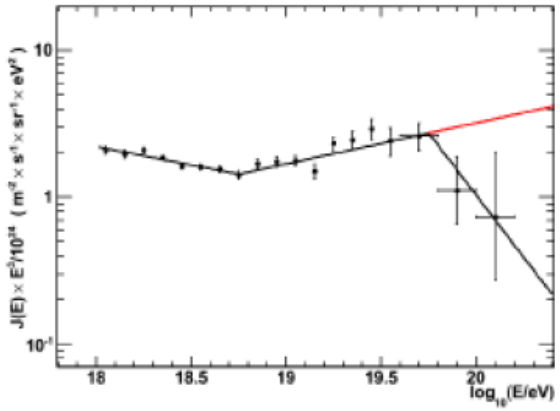
G.Thomson, ICHEP'10, Paris

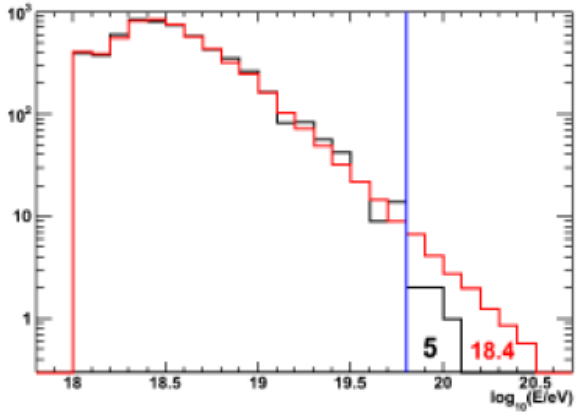
TA surface detector spectrum



G.Thomson, ICHEP'10, Paris

GZK cut-off statistical significance





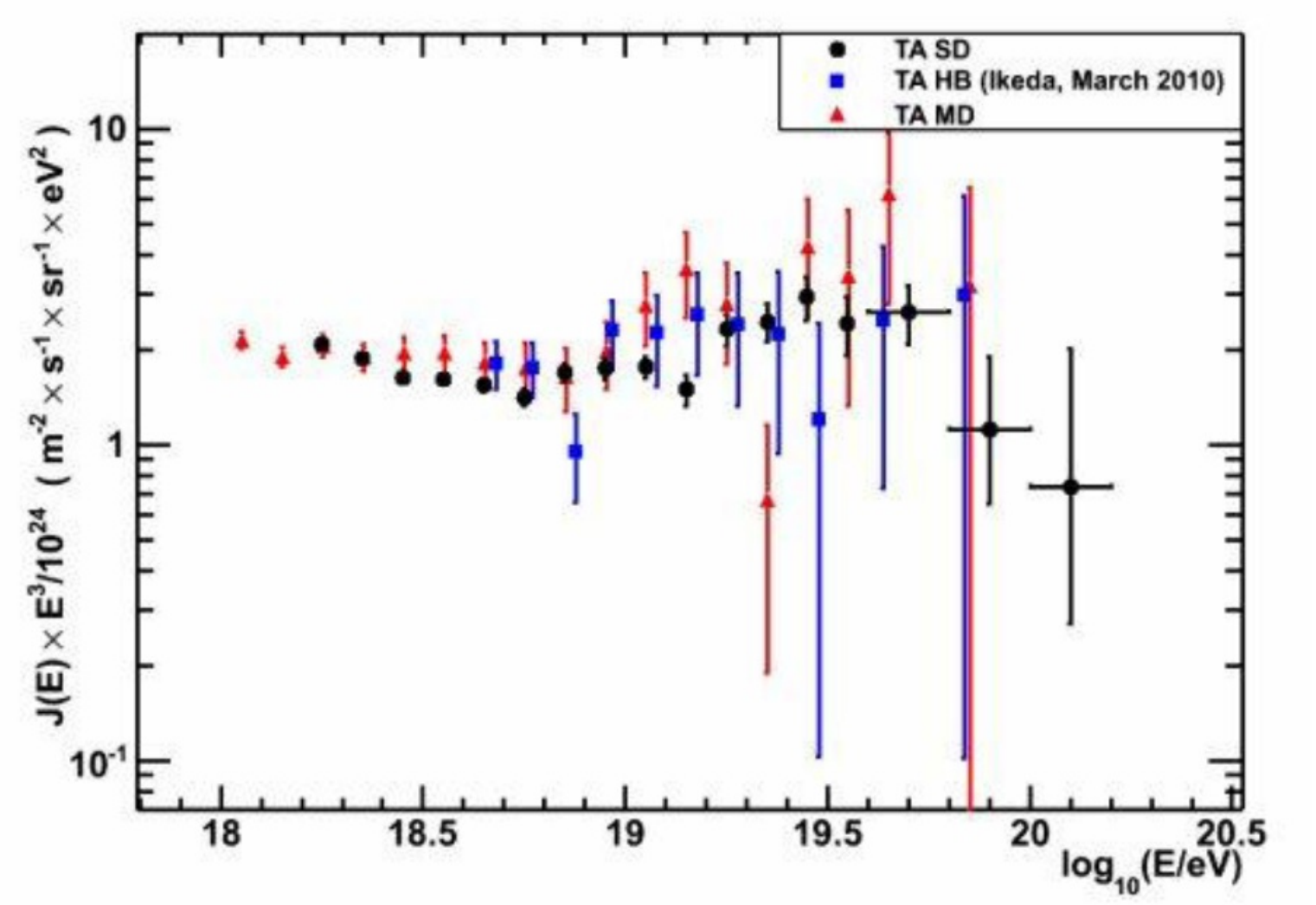
- Assume no GZK cutoff and extend the broken power law fit beyond the break
- Apply this extended flux formula to the actual TASD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10}$E bins after $10^{19.8}$eV bin:
  - $N_{EXPECT} = 18.4$
  - $N_{OBSERVE} = 5$

$$\text{PROB} = \sum_{i=0}^{5} Poisson(\mu = 18.4; i) = 2.41 \times 10^{-4}$$

(3.5σ)

G.Thomson, ICHEP'10, Paris

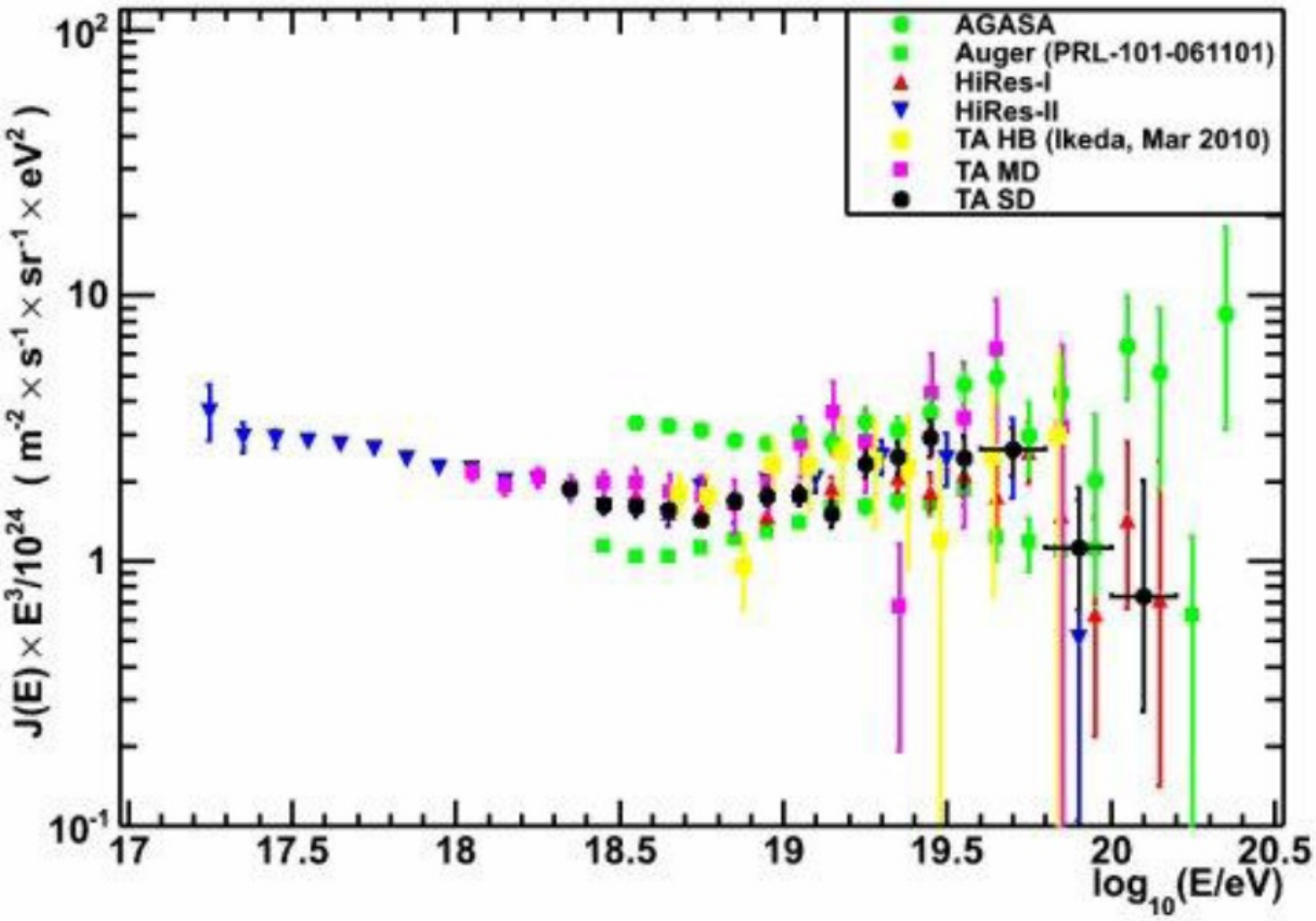
Surface detector, MD mono and hybrid spectra



Note: SD energy normalized by 27%

G.Thomson, ICHEP'10, Paris

Comparison with AGASA, HiRes, Auger



G.Thomson, ICHEP'10, Paris

Spectrum summary

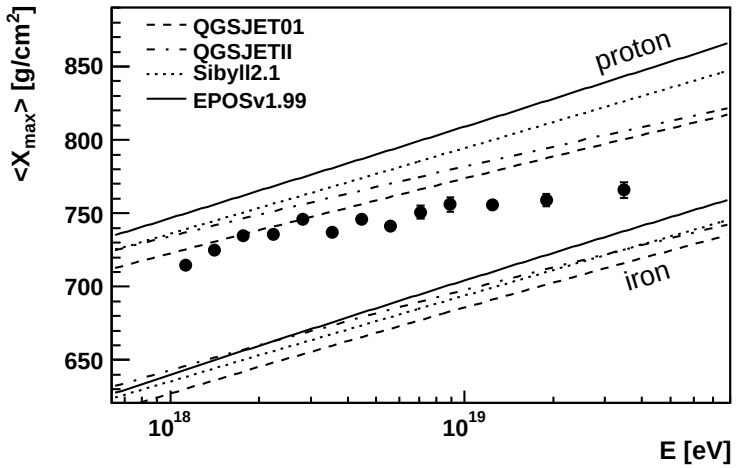
- Cut-off is observed by HiRES and confirmed by Pierre Auger and Telescope Array experiments
- GZK process in not questioned, but it's contribution to cut-off is unknown due to unknown spectrum and composition at the sources
- One may probe $E > 10^{20}$ eV physics by looking at GZK secondaries: photons and neutrinos

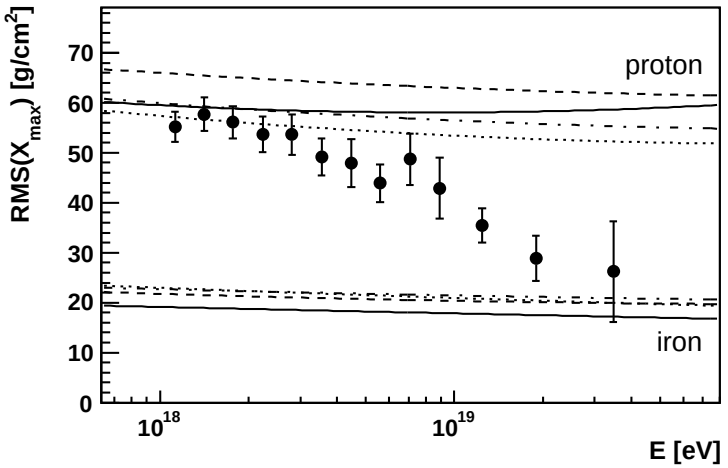
II. Chemical composition by XMAX stereo

Auger/HiRES XMAX results

Auger

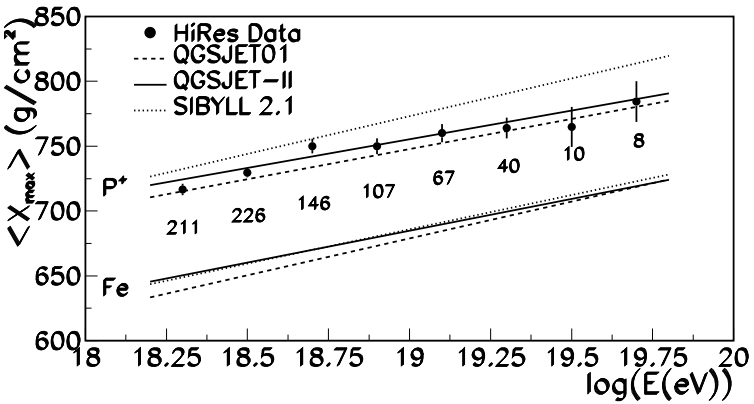
Phys.Rev.Lett.104.091101

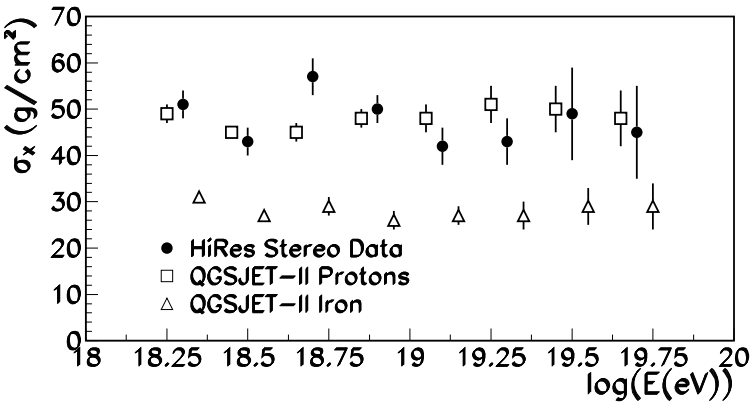




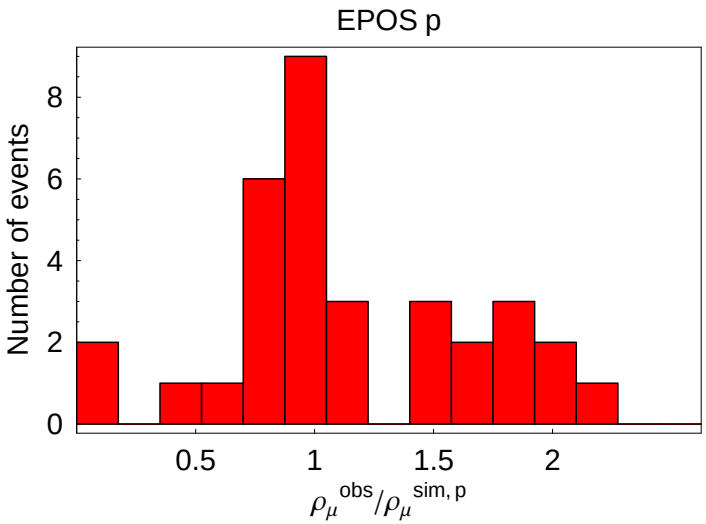
HiRES

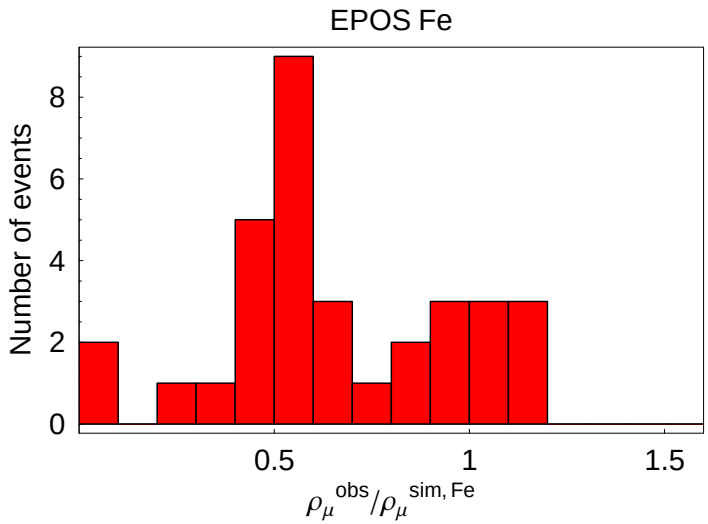
Phys.Rev.Lett.104.161101





Yakutsk array result on chemical composition





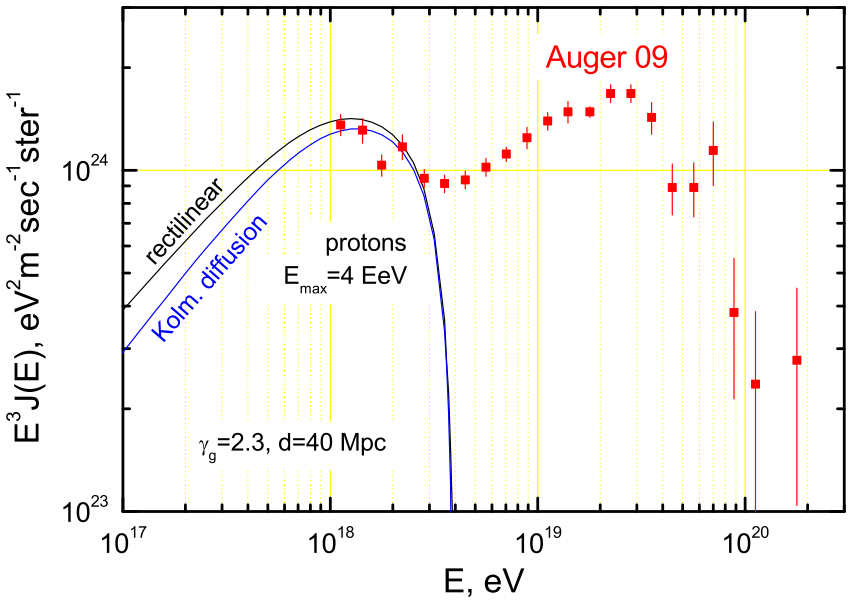
$$0.29 \leq \epsilon_{\mathrm{Fe}} \leq 0.68 \quad (95\%\mathrm{CL}), \qquad \mathrm{E} > 10^{19}\ \mathrm{eV}$$

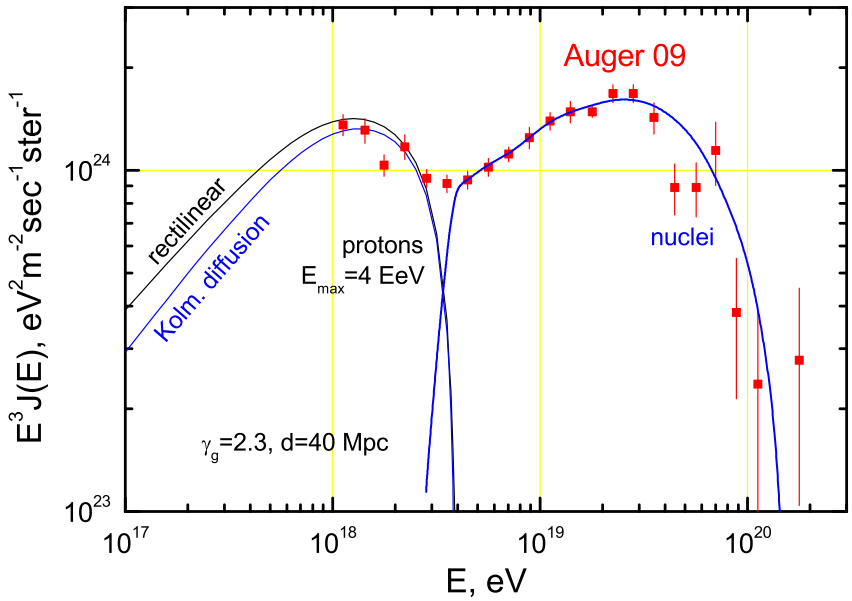
Glushkov et al,

JETP Letters 87:190-194,2008

Possible interpretation of Auger result

'The disappointing model'



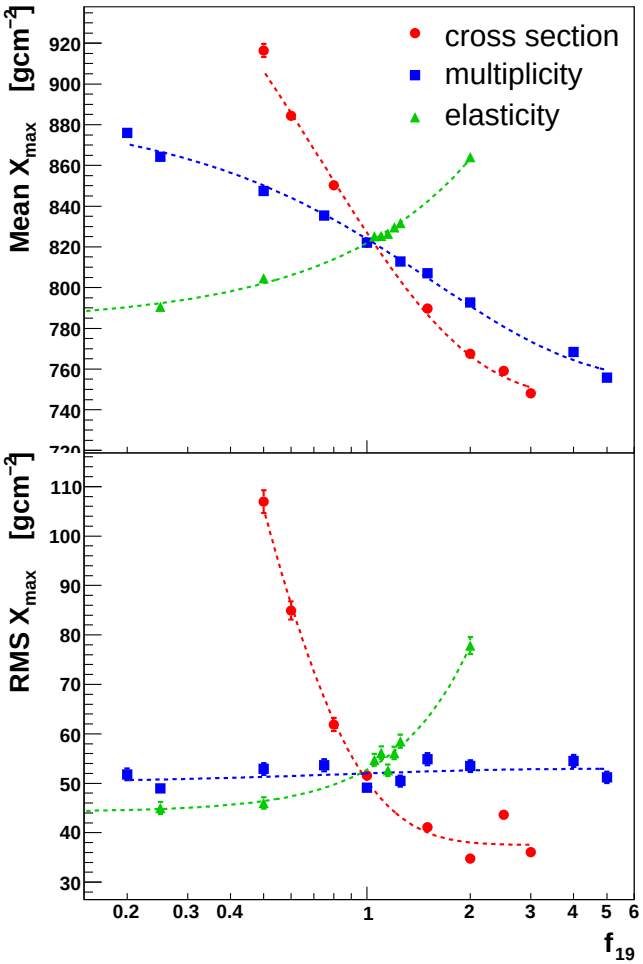


R. Aloisio, V. Berezinsky, A. Gazizov arXiv:0907.5194v1

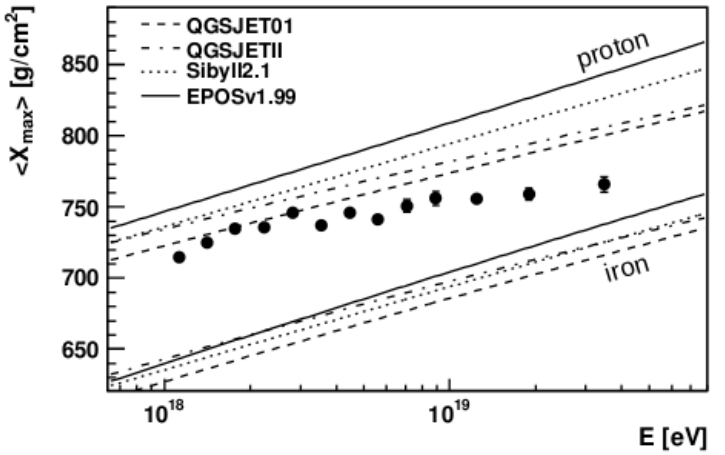
- No GZK-photons, no GZK-neutrino
- Will not see the sources

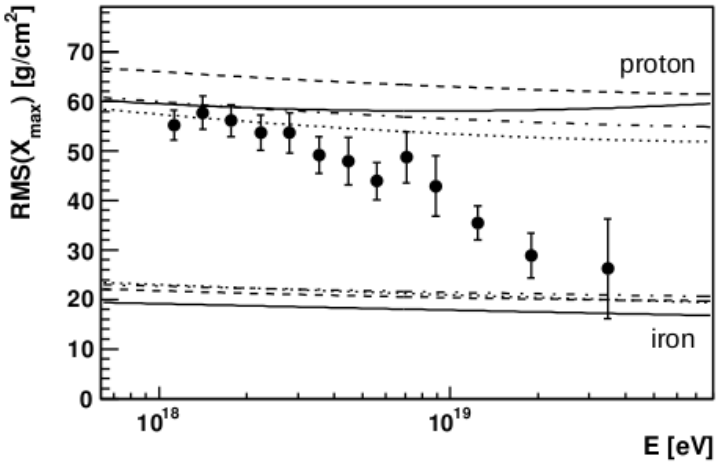
Another interpretation of Auger result

R. Engel, 31th ICRC, arXiv:0906.0418v1



Auger, Phys.Rev.Lett.104.091101





Protons with cross-section growth at high energies

Auger/HiRES XMAX results

Auger:

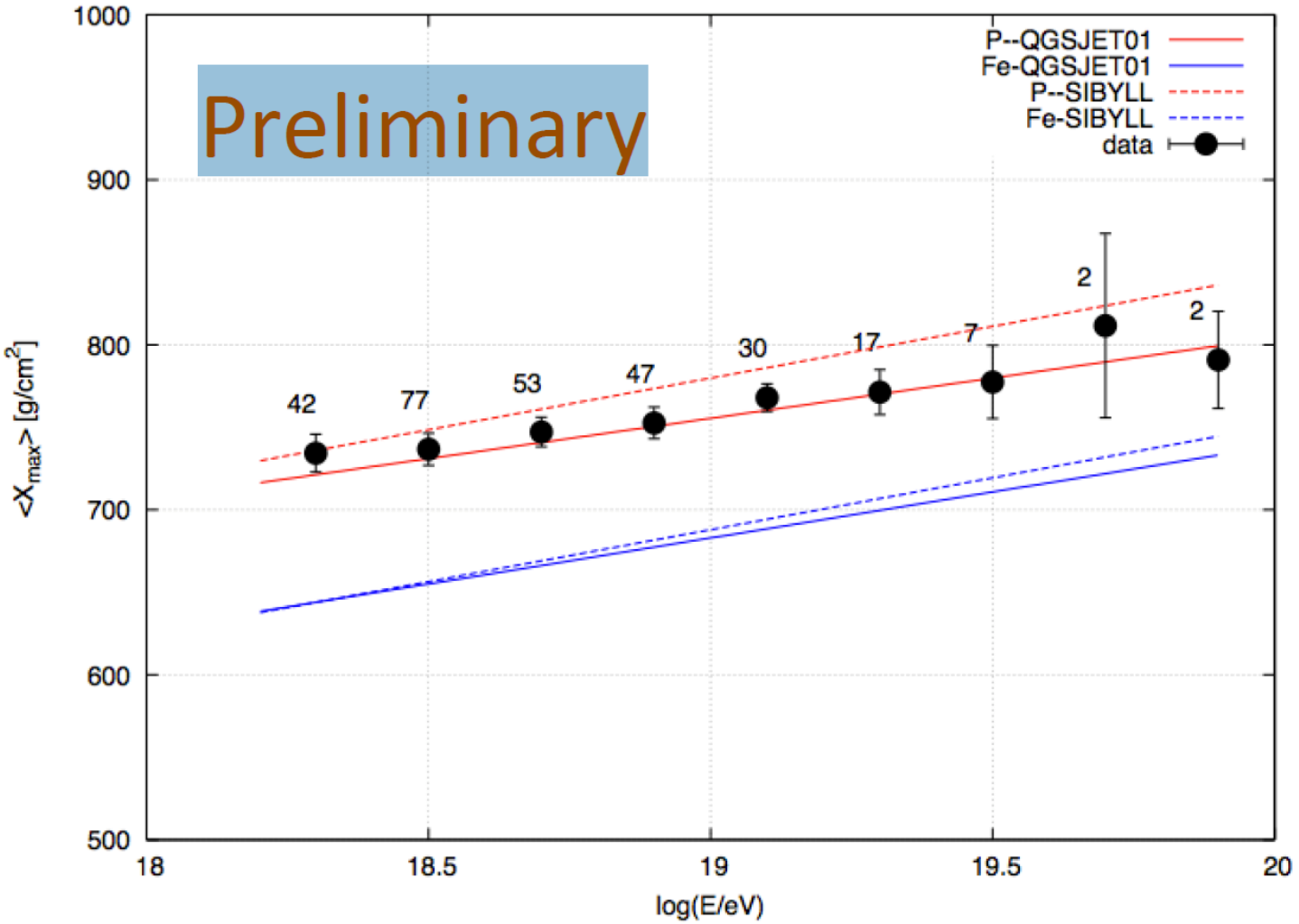
- Southern hemisphere
- Heavy nuclei or cross-section growth

HiRES:

- Northern hemisphere
- Protons dominate

?

Telescope Array stereo result

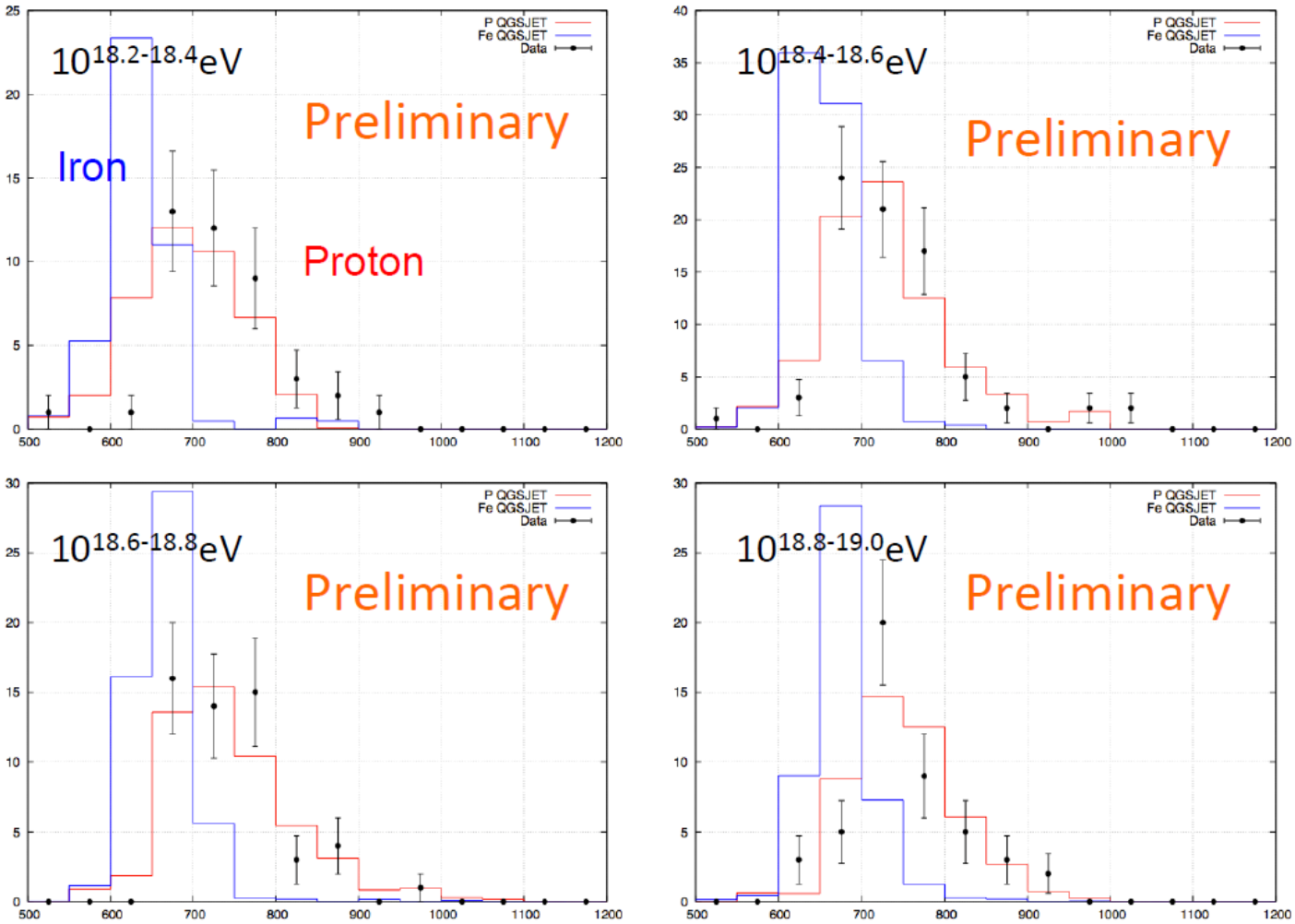


TA data favor protons

data collection is in progress

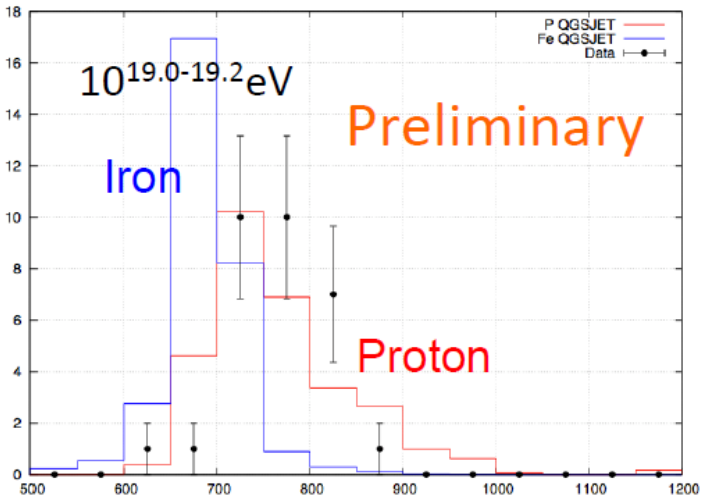
Y. Tameda, UHECR-2010, Nagoya

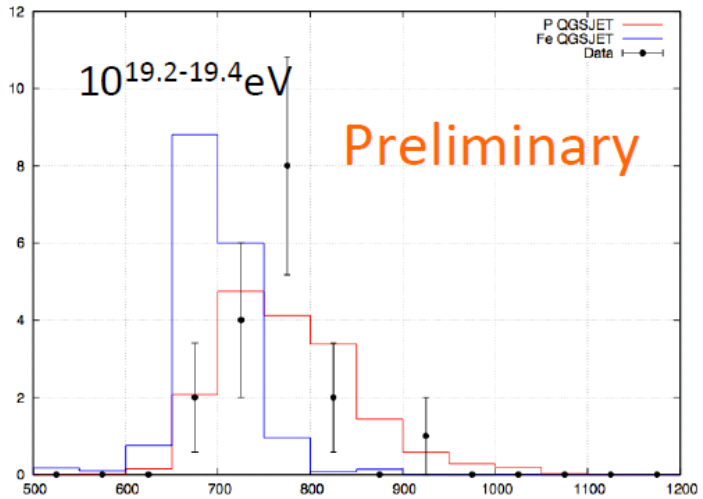
Xmax Distribution (QGSJET01)

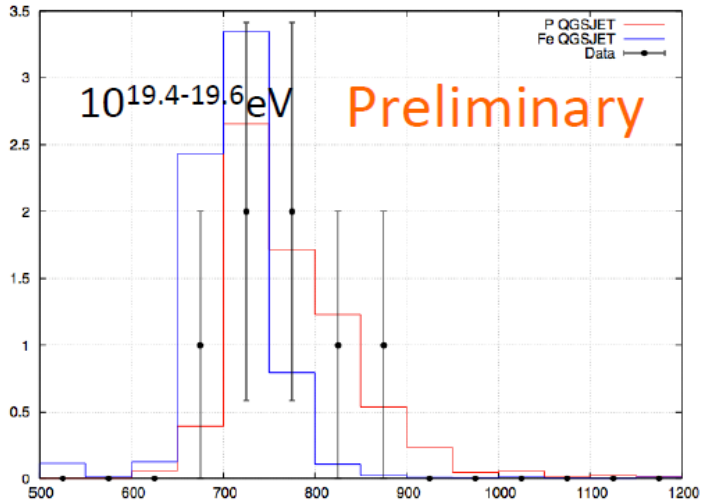


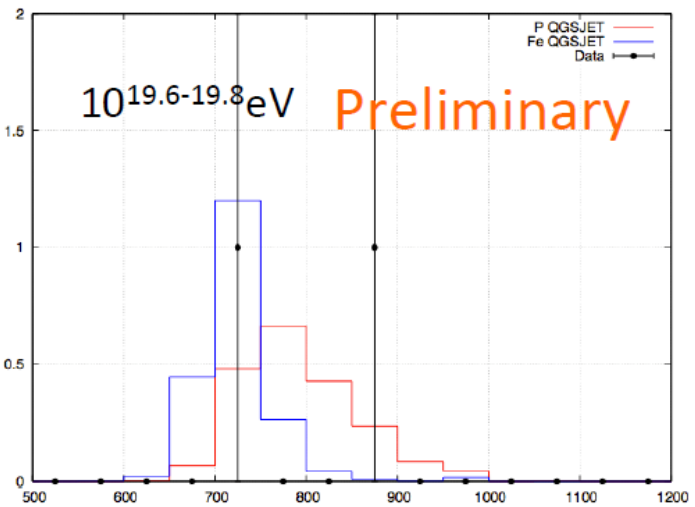
Y. Tameda, UHECR-2010, Nagoya

Xmax Distribution (QGSJET01)









Y. Tameda, UHECR-2010, Nagoya

III. Search for cosmic ray sources

Pierre Auger AGN claim

November 9, 2007

"Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects"

Anisotropy of the UHECR sky

AGN < 71 Mpc (VC catalogue)

Shading level: exposure

Cen A

30

0

−30

120

−120

Super Galactic Plane

Prob. chance correlation =21%

circles of 3.1° radius centered at UHECR arrival direction

27 events E> $5.7 \cdot 10^{19}$ eV

Angular resolution < 1°

Auger claim discussion

- HiRES doesn't see correlations with AGN (2 of 13, bg: 3)

  Astropart.Phys.30,2008

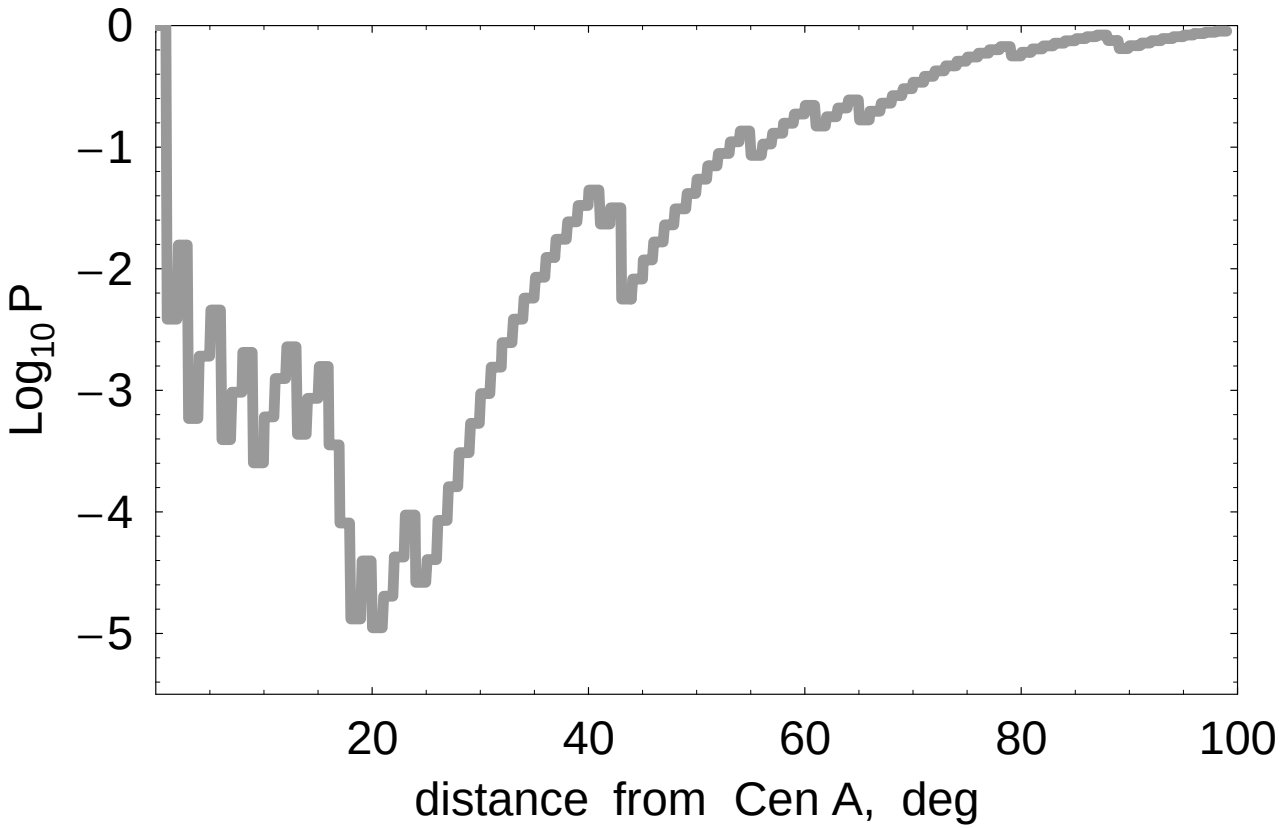
- Comment by Gorbunov,Tinyakov,Tkachev,Troitsky

  JETP Lett.87,2008

  - Events do not follow prediction of AGN hypothesis. E.g. nothing comes from Virgo, while it contains significant fraction of nearby AGNs
  - Cen A may be a single source with correlation angle about 20°

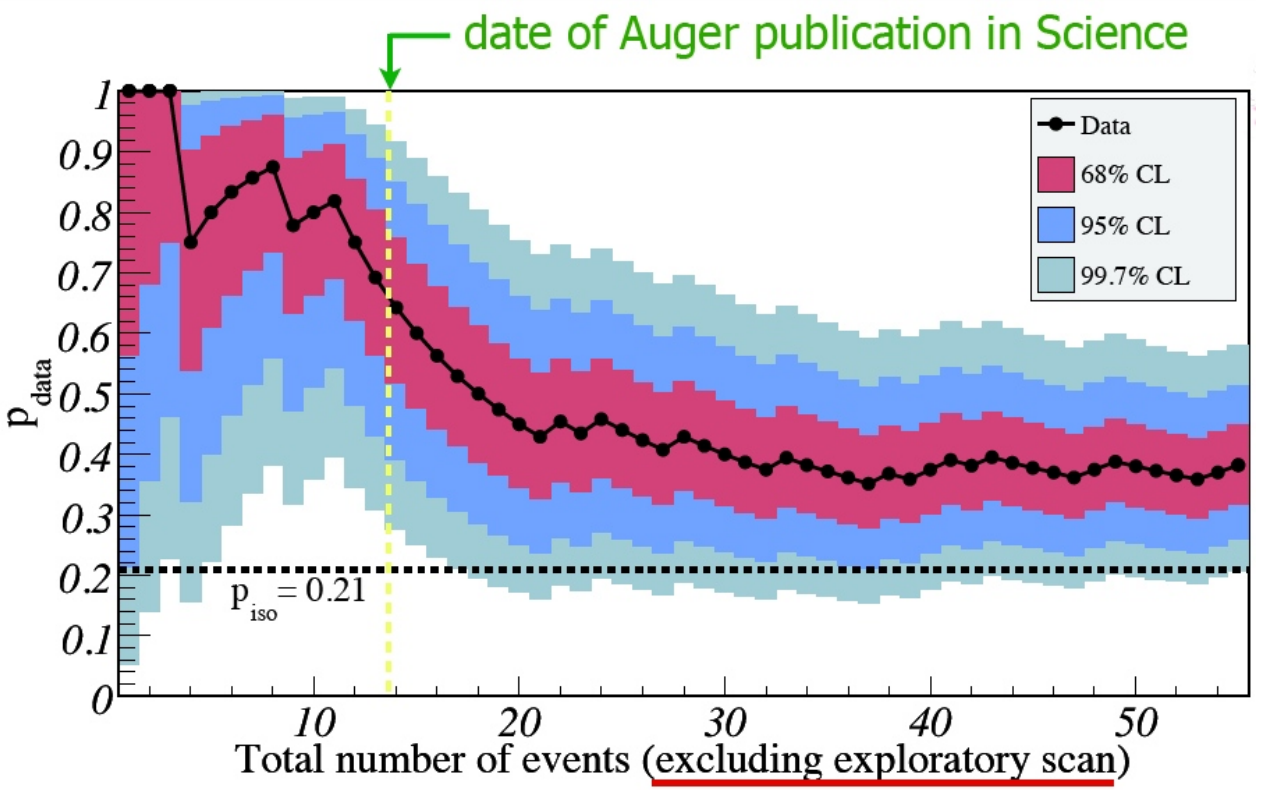
- AGN correlation requires proton primaries; contradicts with Auger composition results due to large deflection of nuclei in Galactic magnetic field

Pierre Auger claim discussion: Cen A



The Monte-Carlo probability P to have the observed number of events in a circle of a given radius around Cen A on the celestial sphere, out of the 27 events of the Auger sample. Gorbunov,Tinyakov,Tkachev,Troitsky, arXiv:0804.1088

Auger AGN correlation update

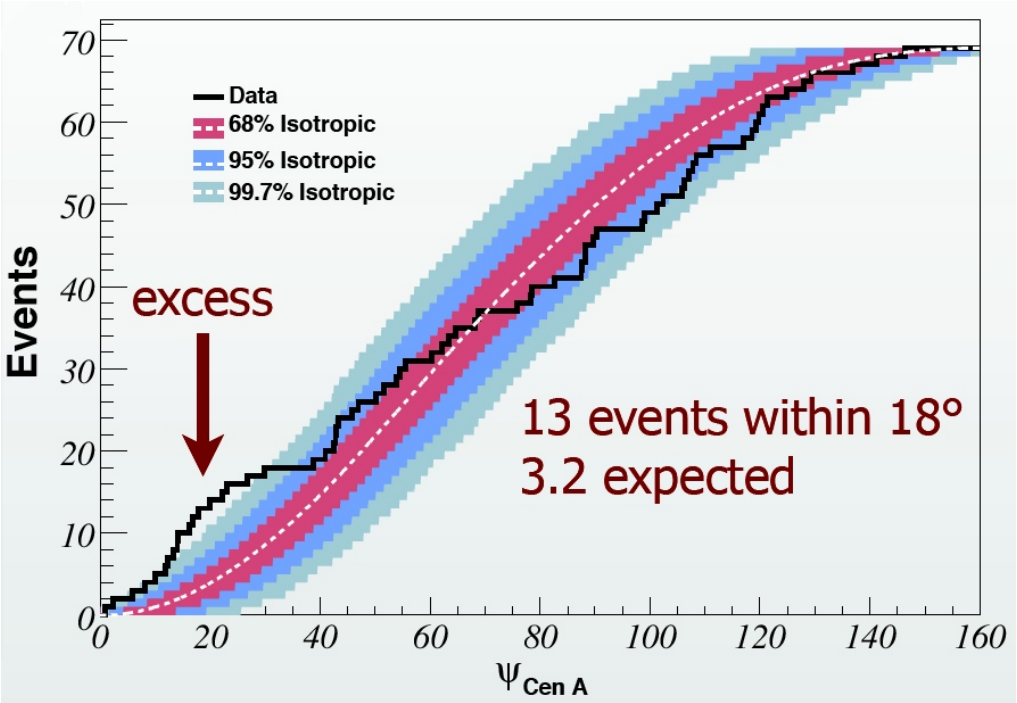


Pierre Auger collaboration, Astropart. Phys. 34 (2010)

Before publication date: $9/13$ correlate. Background: 2.7 ± 1.6

After publication date: $12/42$ correlate. Background: 8.9 ± 3.0

Auger Centaurus A update

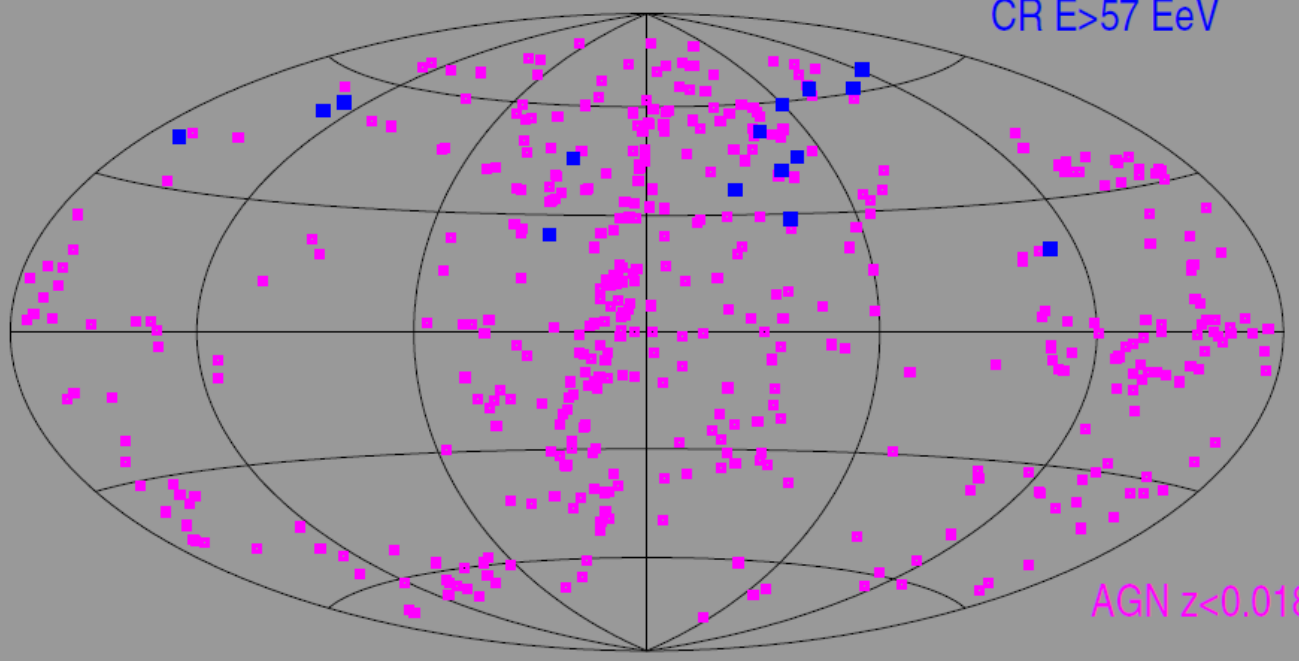


Pierre Auger collaboration, Astropart. Phys. 34 (2010)

- Cen A may be a source
- Unfortunately out of field of view of HiRES and TA

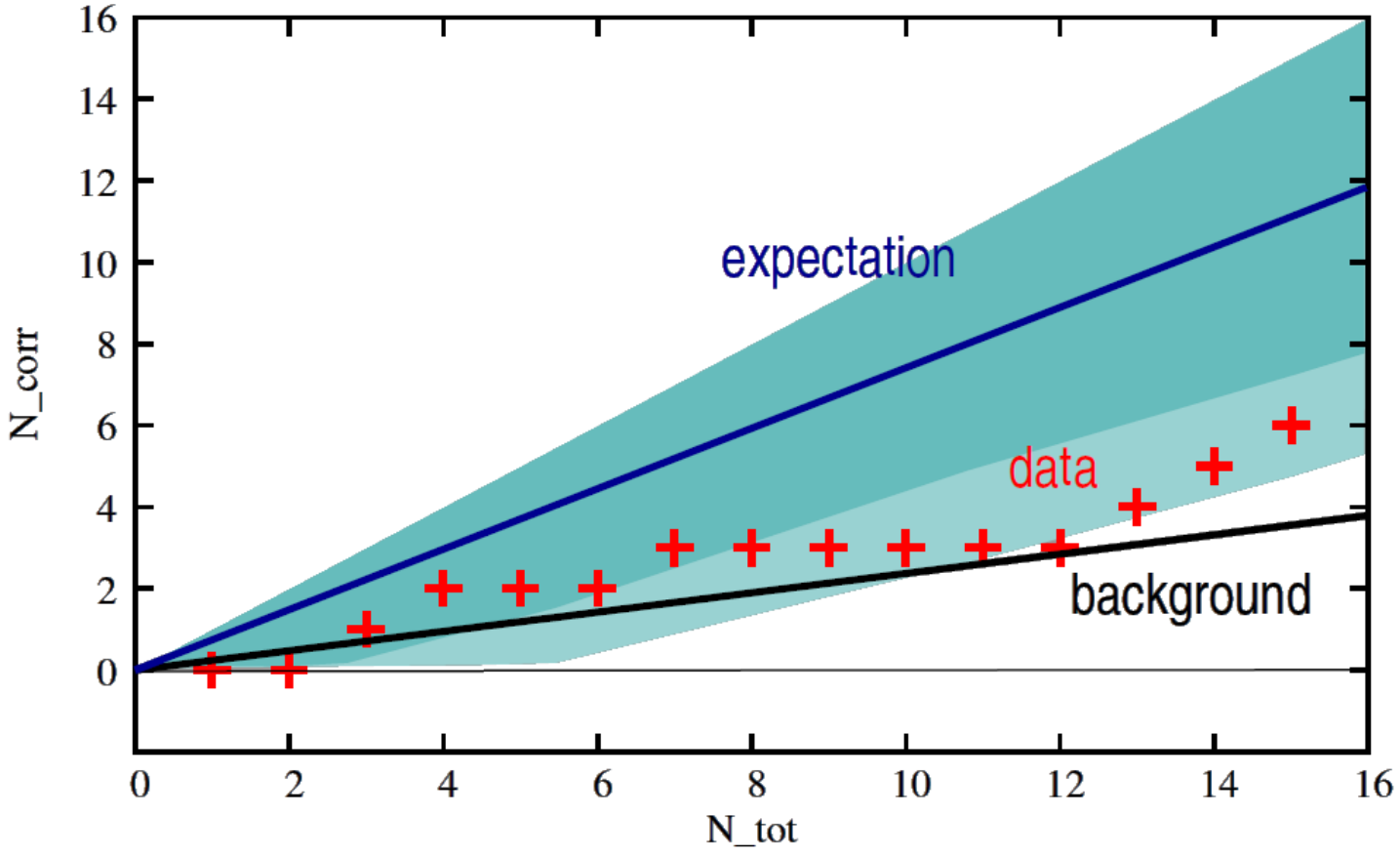
TA result on AGN correlation

- 472 AGN from 2006 Veron catalog with $z < 0.018$ ($D < 75$ Mpc)
- separation angle 3.1°



Equatorial coordinates

TA result on AGN correlation

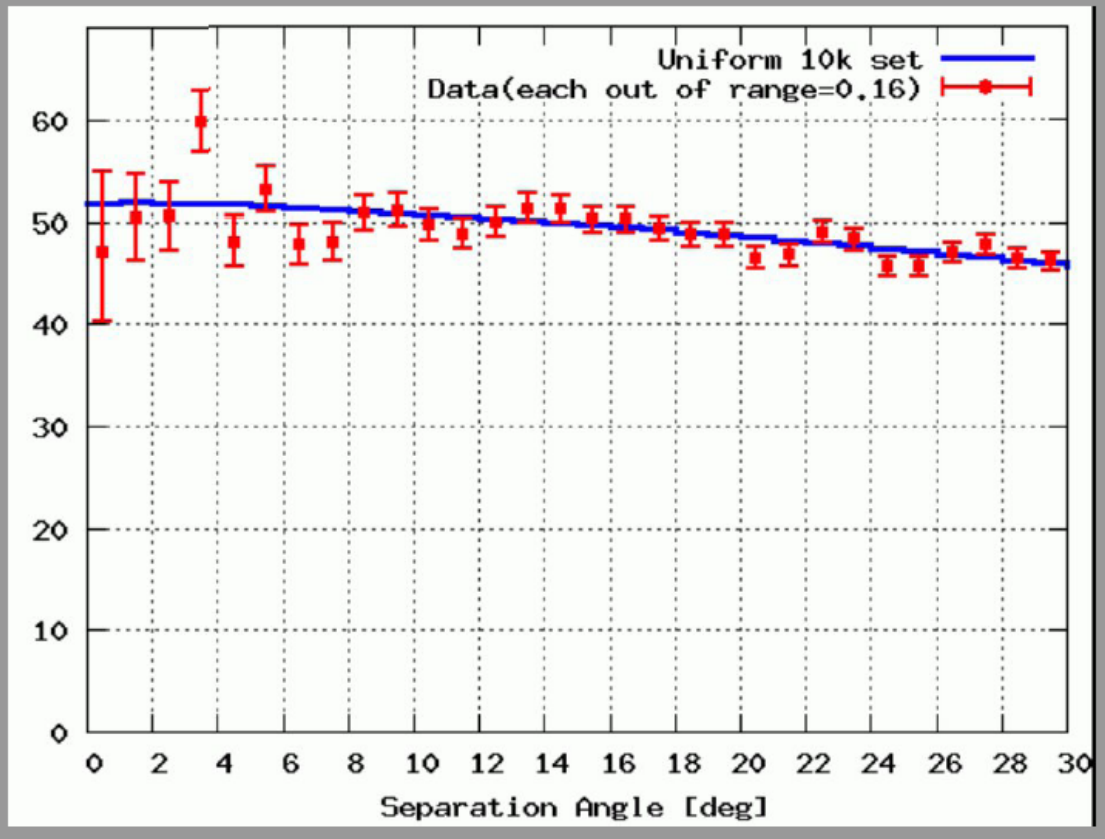


correlate: 6 of 15, bg: 3.6

P.Tinyakov, UHECR-2010, Nagoya

TA Autocorrelation analysis

$E > 10$ EeV

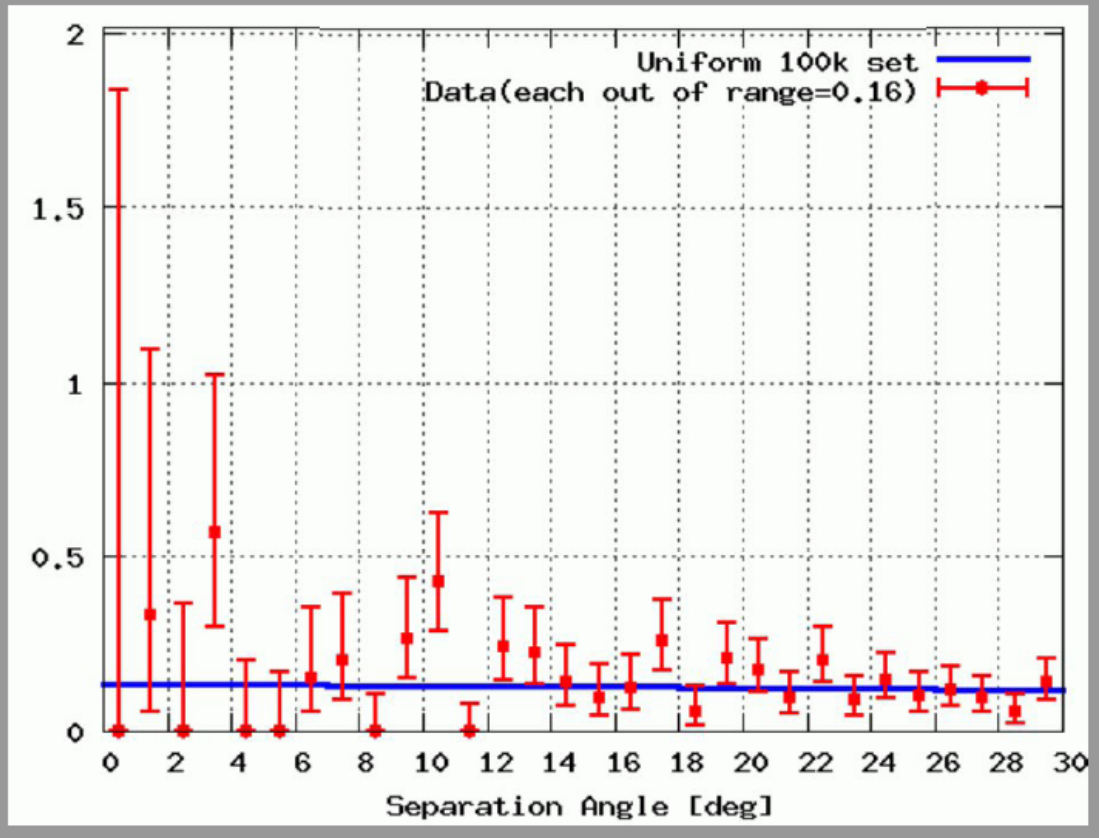


$\Longrightarrow$ no excess over background

P.Tinyakov, UHECR-2010, Nagoya

TA Autocorrelation analysis

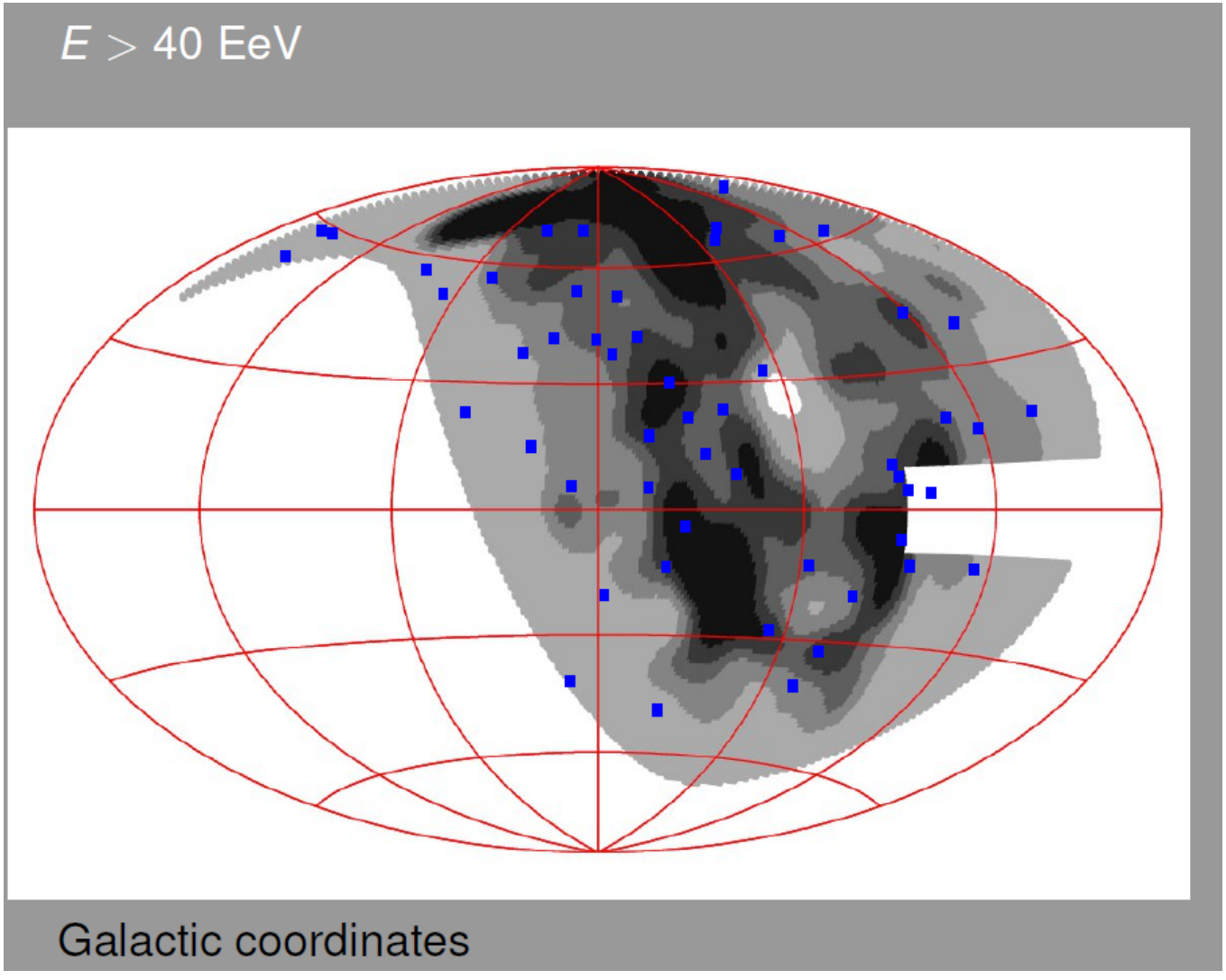
$E > 40$ EeV



$\Longrightarrow$ no excess over background

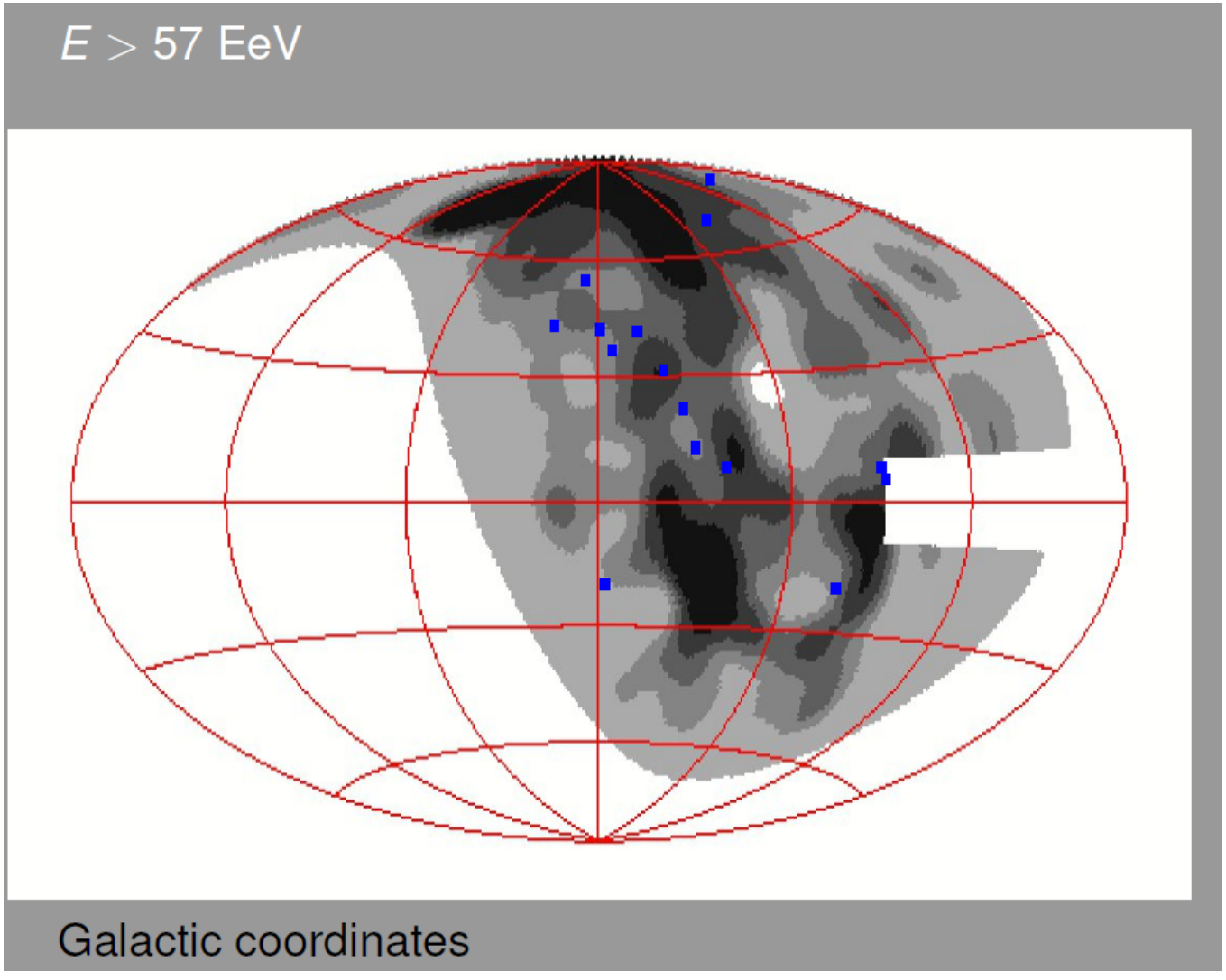
P.Tinyakov, UHECR-2010, Nagoya

TA correlations with LSS



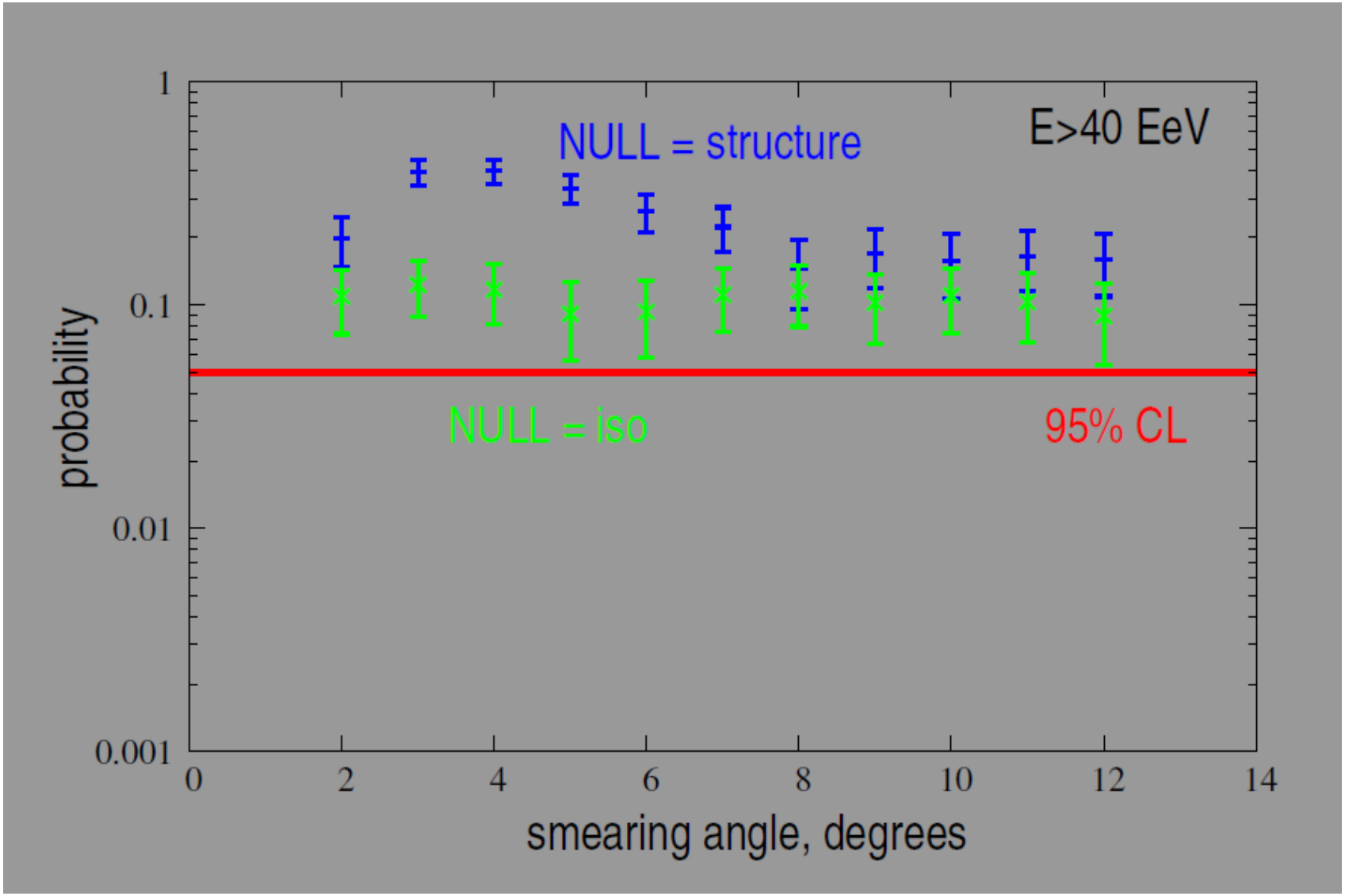
P.Tinyakov, UHECR-2010, Nagoya

TA correlations with LSS



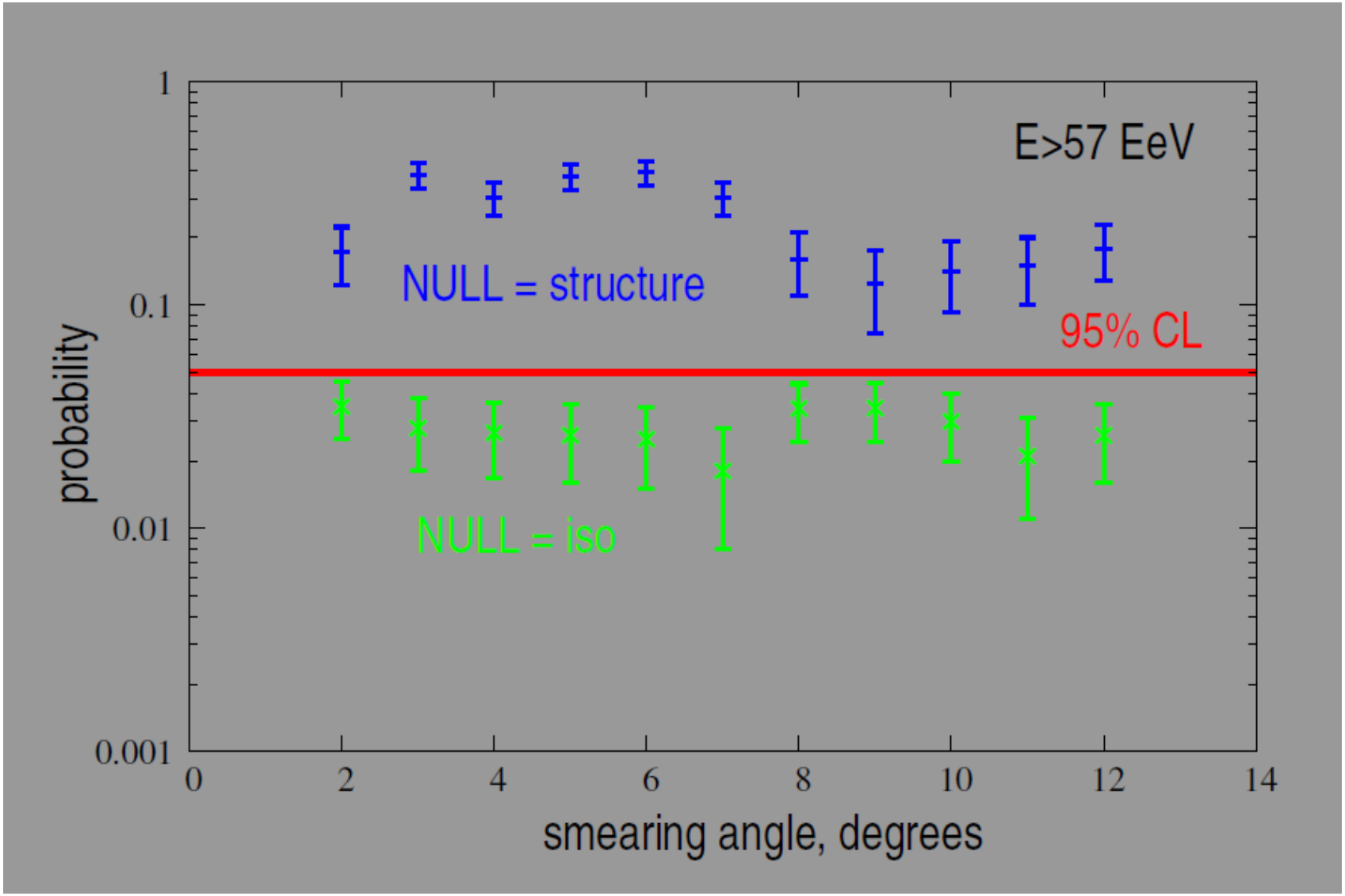
P.Tinyakov, UHECR-2010, Nagoya

TA LSS: result of the statistical tests



P.Tinyakov, UHECR-2010, Nagoya

TA LSS: result of the statistical tests



P.Tinyakov, UHECR-2010, Nagoya

Sources summary

- Correlations with AGN: 6/15 correlate; compatible with background;
- No significant clustering at E $>$ 10 EeV and E $>$ 40 EeV;
- Data with E $>$ 40 EeV are compatible both with structure and isotropy;
- Data with E $>$ 57 EeV are compatible with structure and incompatible with isotropy at 95% CL;

IV. Search for photons

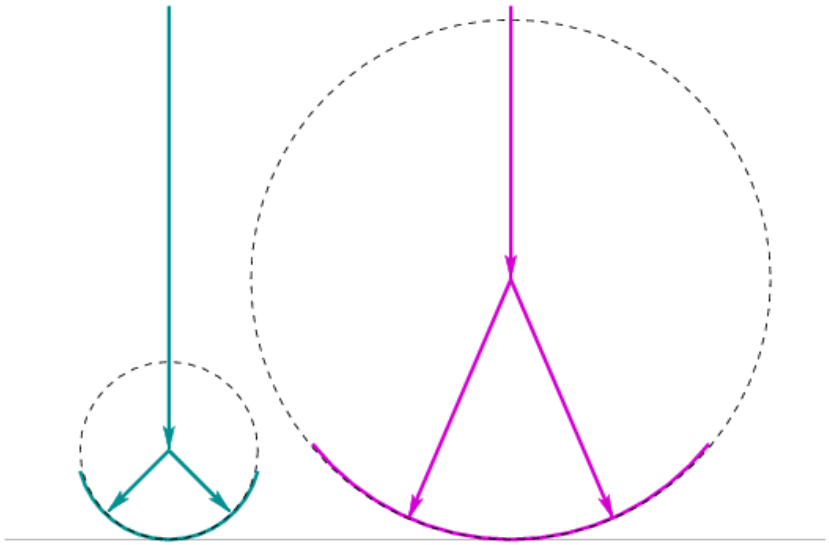
Photon search techniques

Photon-sensitive parameter:

AGASA, Yakutsk	muon density (strongest discrimination)
Pierre Auger SD	shower front curvature and thinkness
Pierre Auger hybrid	XMAX
Telescope Array SD	shower front curvature

Shower front curvature

deep shower maximum = curved front



- We use Linsley's shower front curvature parameter "a" as a composition sensitive parameter

TA SD photon search

Dataset:

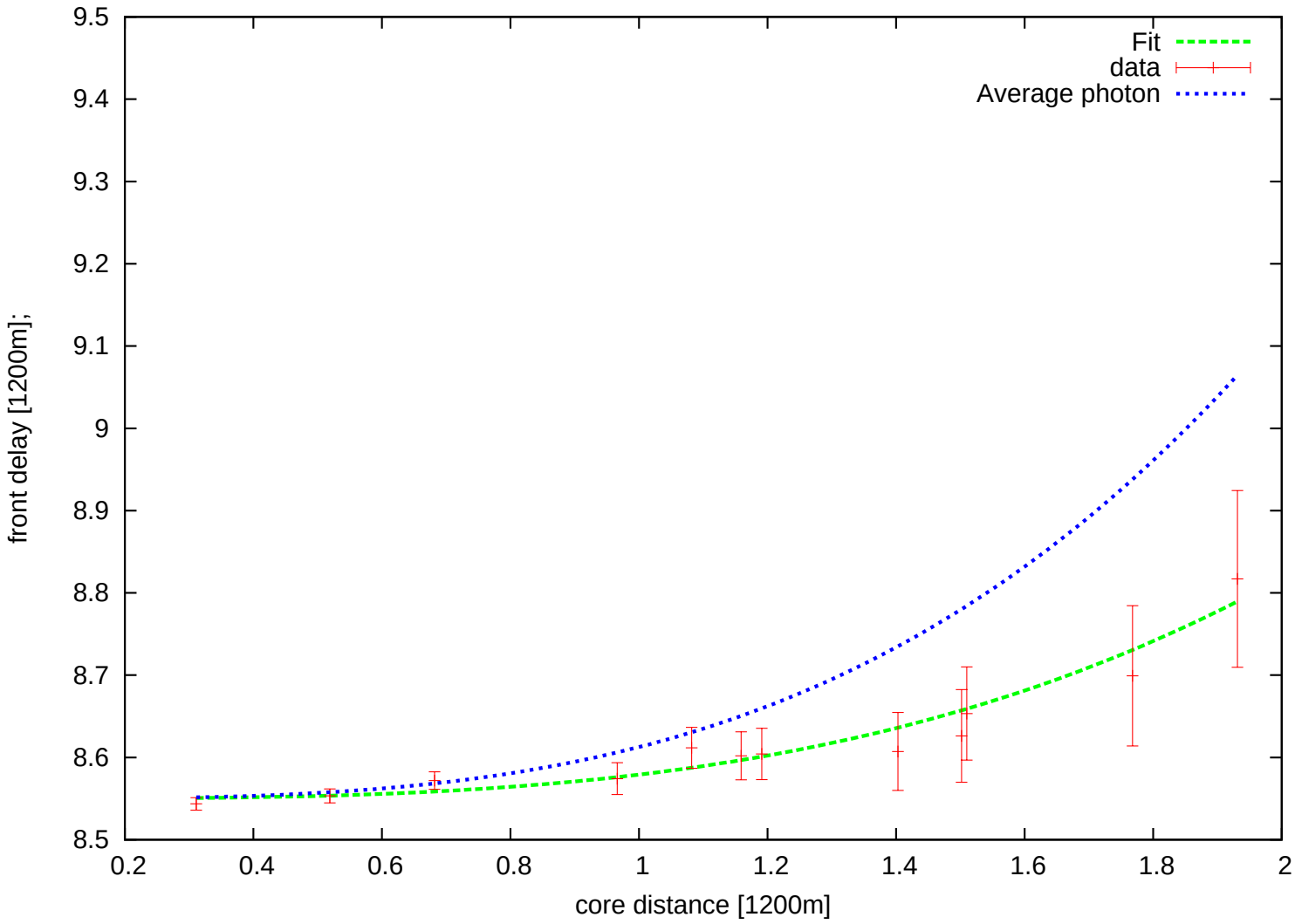
- Data collected by SD from 2008-05-11 to 2009-10-08
- Geometrical exposure for $\theta \in [\theta_1, \theta_2]$:

$$A_{geom} = 2346 \times (\sin^2\theta_2 - \sin^2\theta_1)\ \mathrm{km}^2\ \mathrm{sr\ yr}$$

Cuts for photon search:

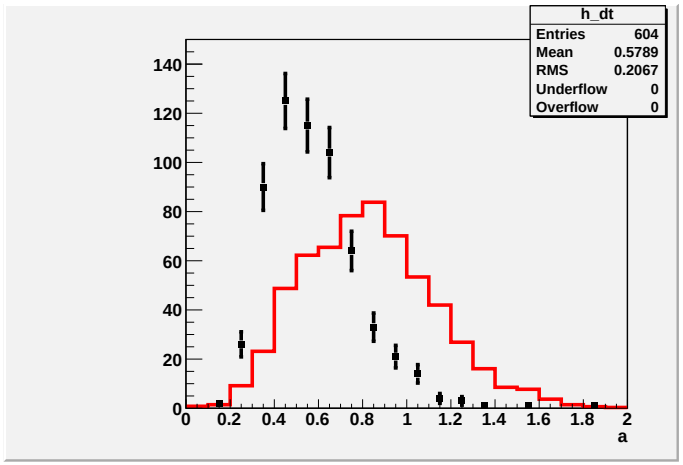
- Number of detectors triggered is 7 or more
- Shower core distance to array boundary is larger than 1 separation unit (1200 m)
- $\chi^2/\mathrm{d.o.f.} < 5$

Front curvature example

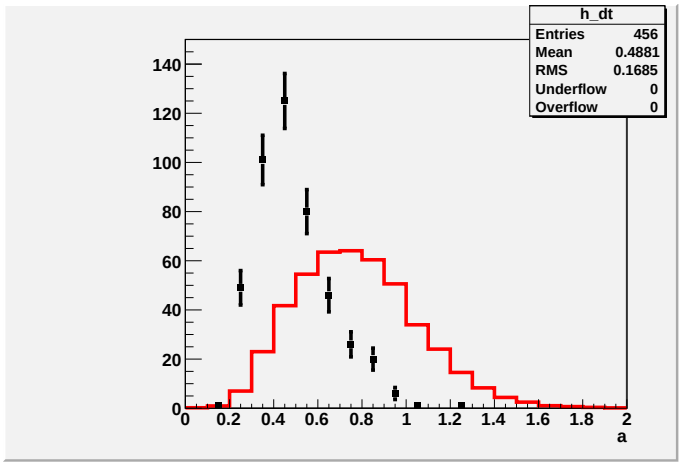


Linsley curvature "a": data vs photon MC

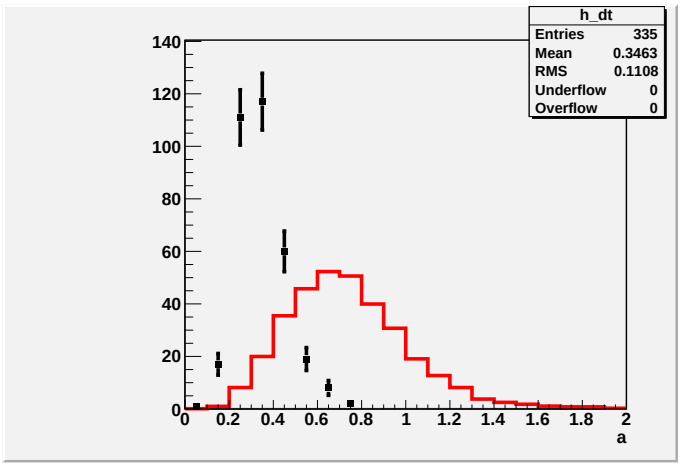
$0° - 30°$



$30° - 45°$



$45° - 60°$



$E_\gamma > 10^{19}$ eV

data

photon MC, E^{-2} spectrum

Event-by-event method

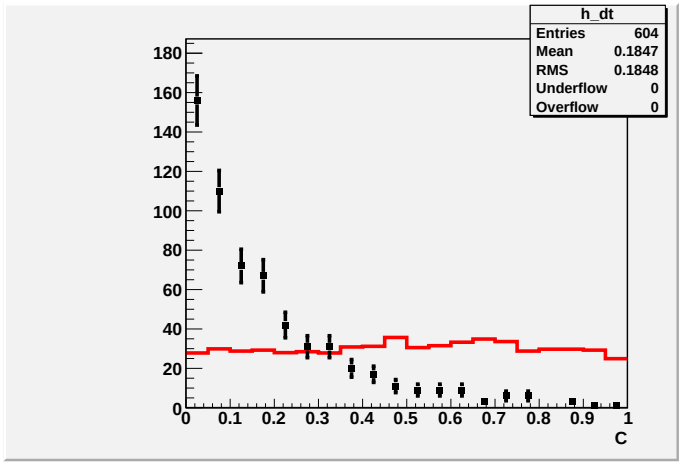
- For each event with curvature a_{obs} we select photon MC events compatible by arrival direction and S_{800}.
- We calculate curvature distribution function $f_\gamma(a)$ for MC photons
- Let's define

$$\mathcal{C} = \int_{-\infty}^{a_{obs}} f_\gamma(a)da$$

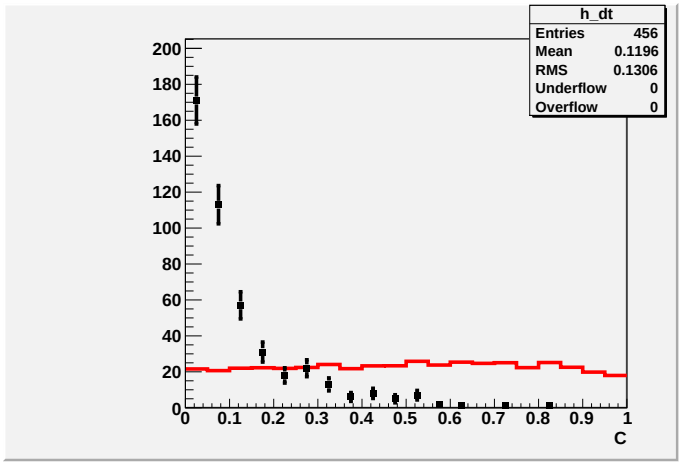
- $\mathcal{C}$ is defined event-by-event
- For gamma events, $\mathcal{C}$ is uniformly distributed between 0 and 1 (independently of the photon primary spectrum).

$\mathcal{C}$: data vs photon MC

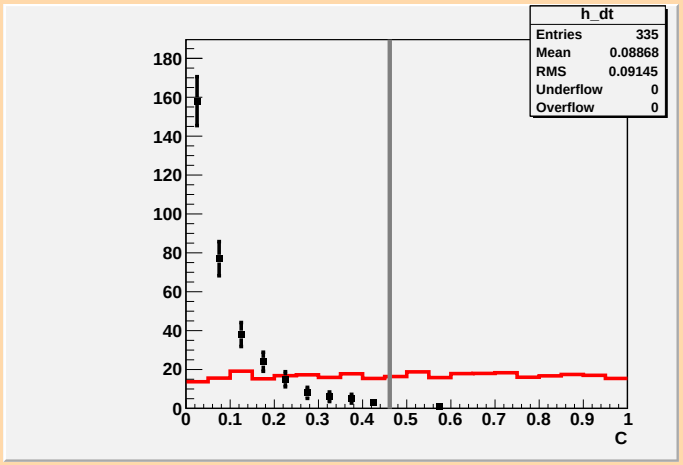
$0° - 30°$



$30° - 45°$



$45° - 60°$



$E_\gamma > 10^{19}$ eV

data

photon MC, E^{-2} spectrum

Calculations

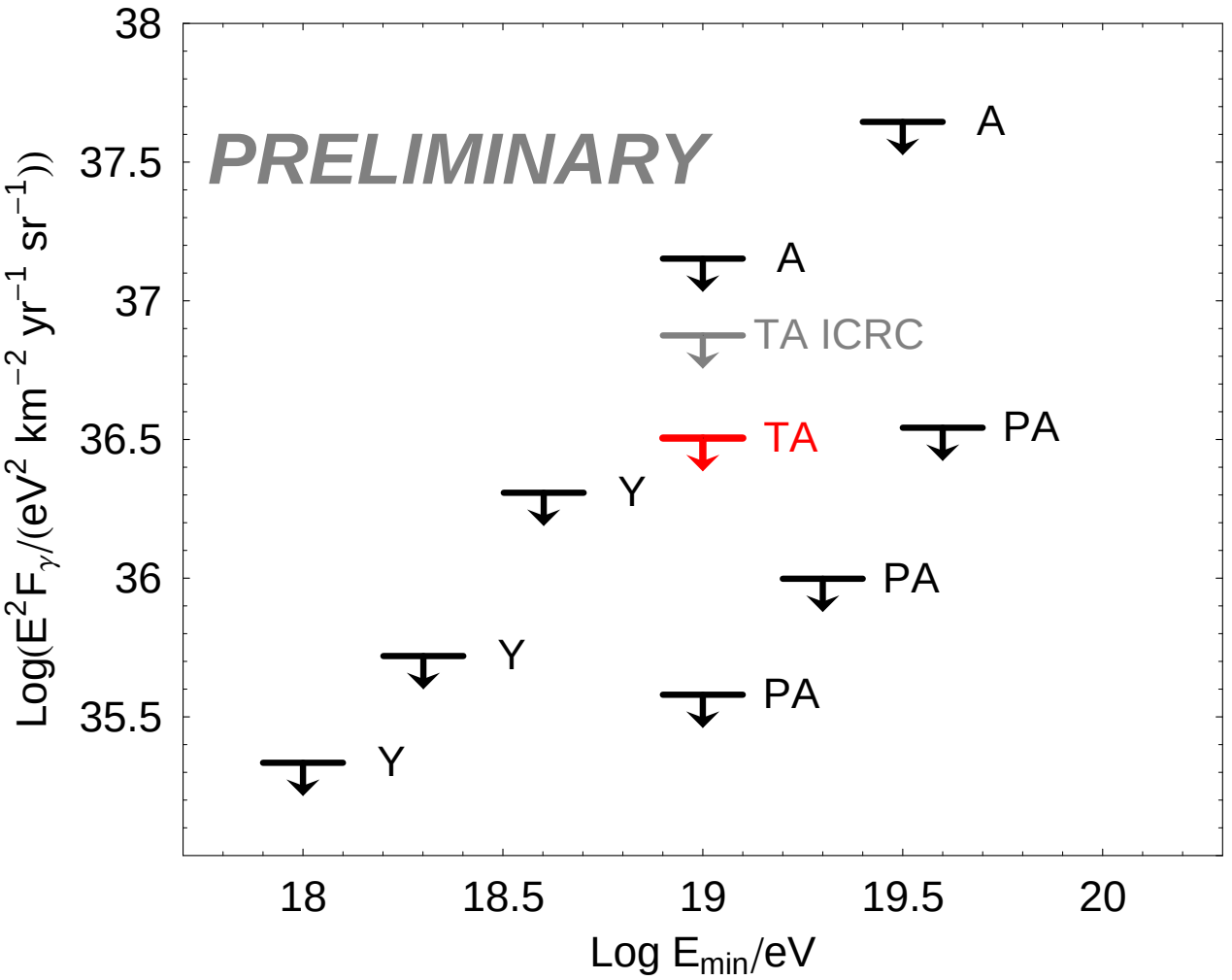
Search region:

- $E_{gamma} > 10^{19}$ eV — 1395 events
- $45^\circ < \theta < 60^\circ$ — 335 events
- $\mathcal{C} > 0.5$ — 1 event
- Poisson 95% upper limit: — ≤ 5.14 events

- Total exposure: $A_{total} = 158$ km^2 sr yr

- $F_\gamma < 3.3 \cdot 10^{-2}$ km^{-2}sr^{-1}yr^{-1} (95% CL)
  /PRELIMINARY/

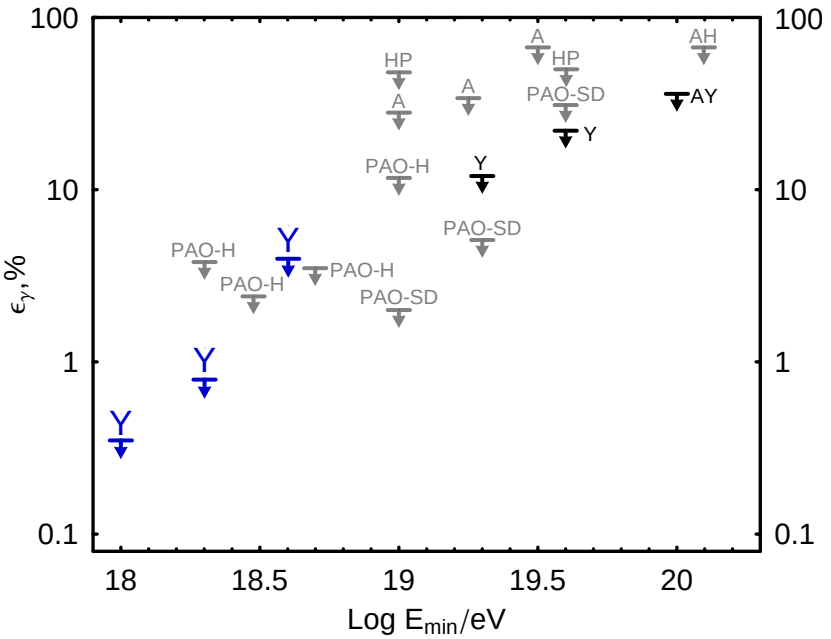
Photon flux limits



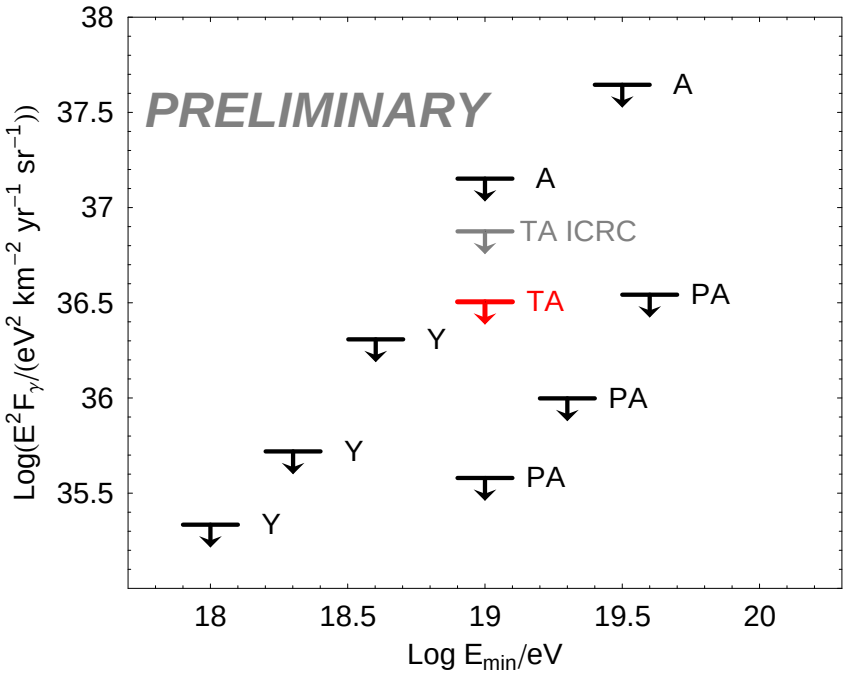
G.Rubtsov, JPS March 2010; Quarks'10

Photon fraction and flux limits

Fraction limits



Flux limits

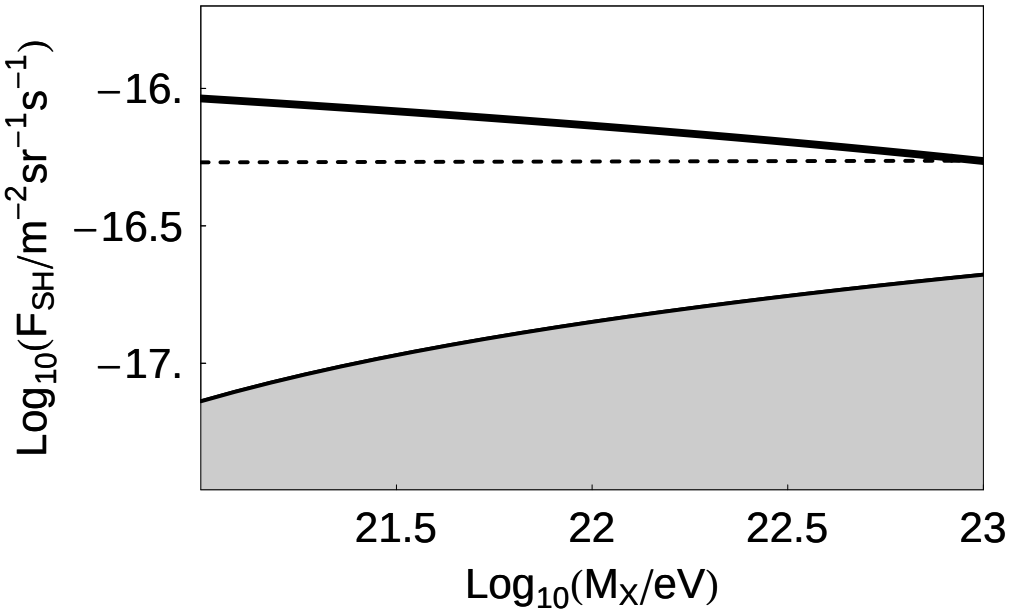


- GZK prediction: $\epsilon_\gamma < 1\%$ for $E > 10^{19}$ eV

  Gelmini,Kalashev,Semikoz, JCAP 0711 (2007)

- Photons may be detected in the near future (depends on astrophysics parameters)

Constraints on parameters of Superheavy dark matter



F_{SH} – flux of SHDM-produced cosmic rays $E > 10^{20}$ eV
above thick line – excluded by spectral fits
shaded area – allowed by spectrum and γ limits
$\Rightarrow$ SHDM decay may not be the source of all UHECRs

Kalashev, Rubtsov, Troitsky, Phys.Rev.D80,2009

Lorentz invariance violation tests 1/2

- LIV is proposed by Coleman & Glashow to suppress GZK process Phys.Rev.D59,1999
- If LI is broken, threshold of GZK reaction may be upshifted $p + \gamma_{2.7K} \rightarrow \Delta(1232)$
- If we can prove that GZK reaction takes place, we have a constraint on LIV parameters
- One approach to confirm GZK reaction is to observe secondary photons
- These tests are strongest due to huge Lorentz factors.

Lorentz invariance violation tests 2/2

- If LI is broken for photons in form

$$\omega^2 = \mathrm{k}^2 + \xi_\mathrm{n}\mathrm{k}^2(\mathrm{k}/\mathrm{M_{Pl}})^\mathrm{n}$$

pair production on CMB

$$\gamma + \gamma_\mathrm{CMB} \rightarrow \mathrm{e}^+ + \mathrm{e}^-$$

may be suppressed by kinematics and photons will propagate through large distances.

- Observed photon flux will contradict existing photon limits if $|\xi_1| \gtrsim 10^{-14}$ or $\xi_2 \lesssim -10^{-6}$.

Galaverni, Sigl, Phys.Rev.Lett.100, 2008

- Drawback: conclusion depends on the primary composition

Conclusions

- TA is a large scale detector operating in the northern hemisphere
- Results on spectrum, composition and anisotropy are presented
- UHECR sources are not yet discovered
- Good chance to detect GZK photons in the midrange future (3 - 5 years)
- Photon discovery will highlight the highest energy processes

Thank you!