Highlights from Telescope Array

Yoshiki TSUNESADA

Tokyo Institute of Technology

on behalf of the Telescope Array Collaboration

第３２回宇宙線国際会議、北京、中国

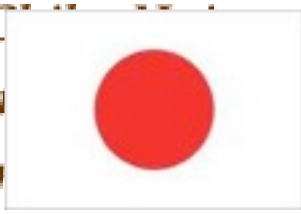
32nd International Cosmic Ray Conference, Aug 13 2011, Beijing, China

Telescope Array Collaboration

T Abu-Zayyad[1], R Aida[2], M Allen[1], R Azuma[3], E Barcikowski[1], JW Belz[1], T Benno[4], DR Bergman[1], SA Blake[1], O Brusova[1], R Cady[1], BG Cheon[6], J Chiba[7], M Chikawa[4], EJ Cho[6], LS Cho[8], WR Cho[8], F Cohen[9], K Doura[4], C Ebeling[1], H Fujii[10], T Fujii[11], T Fukuda[3], M Fukushima[9,22], D Gorbunov[12], W Hanlon[1], K Hayashi[3], Y Hayashi[11], N Hayashida[9], K Hibino[13], K Hiyama[9], K Honda[2], G Hughes[5], T Iguchi[3], D Ikeda[9], K Ikuta[2], SJJ Innemee[5], N Inoue[14], T Ishii[2], R Ishimori[3], D Ivanov[5], S Iwamoto[2], CCH Jui[1], K Kadota[15], F Kakimoto[3], O Kalashev[12], T Kanbe[2], H Kang[16], K Kasahara[17], H Kawai[18], S Kawakami[11], S Kawana[14], E Kido[9], BG Kim[19], HB Kim[6], JH Kim[6], JH Kim[20], A Kitsugi[9], K Kobayashi[7], H Koers[21], Y Kondo[9], V Kuzmin[12], YJ Kwon[8], JH Lim[16], SI Lim[19], S Machida[3], K Martens[22], J Martineau[1], T Matsuda[10], T Matsuyama[11], JN Matthews[1], M Minamino[11], K Miyata[7], H Miyauchi[11], Y Murano[3], T Nakamura[23], SW Nam[19], T Nonaka[9], S Ogio[11], M Ohnishi[9], H Ohoka[9], T Okuda[11], A Oshima[11], S Ozawa[17], IH Park[19], D Rodriguez[1], SY Roh[20], G Rubtsov[12], D Ryu[20], H Sagawa[9], N Sakurai[9], LM Scott[5], PD Shah[1], T Shibata[9], H Shimodaira[9], BK Shin[6], JD Smith[1], P Sokolsky[1], TJ Sonley[1], RW Springer[1], BT Stokes[5], SR Stratton[5], S Suzuki[10], Y Takahashi[9], M Takeda[9], A Taketa[9], M Takita[9], Y Tameda[3], H Tanaka[11], K Tanaka[24], M Tanaka[10], JR Thomas[1], SB Thomas[1], GB Thomson[1], P Tinyakov[12,21], I Tkachev[12], H Tokuno[9], T Tomida[2], R Torii[9], S Troitsky[12], Y Tsunesada[3], Y Tsuyuguchi[2], Y Uchihori[25], S Udo[13], H Ukai[2], B Van Klaveren[1], Y Wada[14], M Wood[1], T Yamakawa[9], Y Yamakawa[9], H Yamaoka[10], J Yang[19], S Yoshida[18], H Yoshii[26], Z Zundel[1]

[1]University of Utah, [2]... nology, [4]Kinki University,
[5]Rutgers Universit... nce, [8]Yonsei University,
[9]Institute for Cosmic Ray ... icle and Nuclear Studies, KEK,
[11]Osaka City Unive... an Academy of Sciences,
[13]Kanagawa University ... Pusan National University,
[17]W... sity, [18]C... ity [19]E... University ... n Natio... ty,
[21]U... re de Br... versity ... Kochi Unive... shima ... ty,
[25]Natio... of Radi... nce, Japan, ... ersity

~140 collaborators,
26 institutions

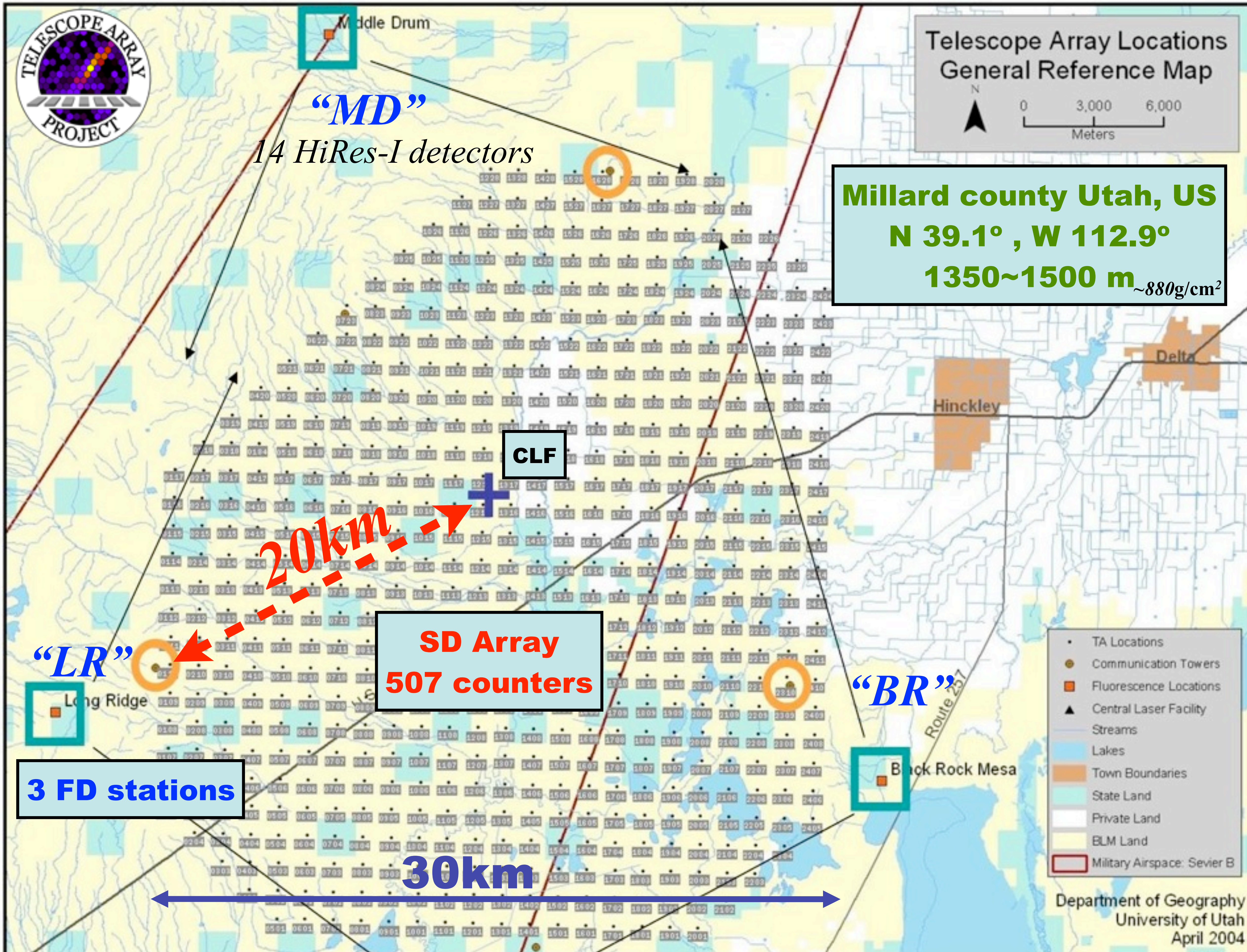




Outline

- **TA Detectors & Commissioning**
- **TA results updated**
  - Energy Spectrum
  - <X_{max}> : UHECR Mass Composition
  - Anisotropy
- **Stepping further**
  - ELS: Electron Lights Source
  - Bistatic Radar at TA
  - TA: TA Low Energy Extension

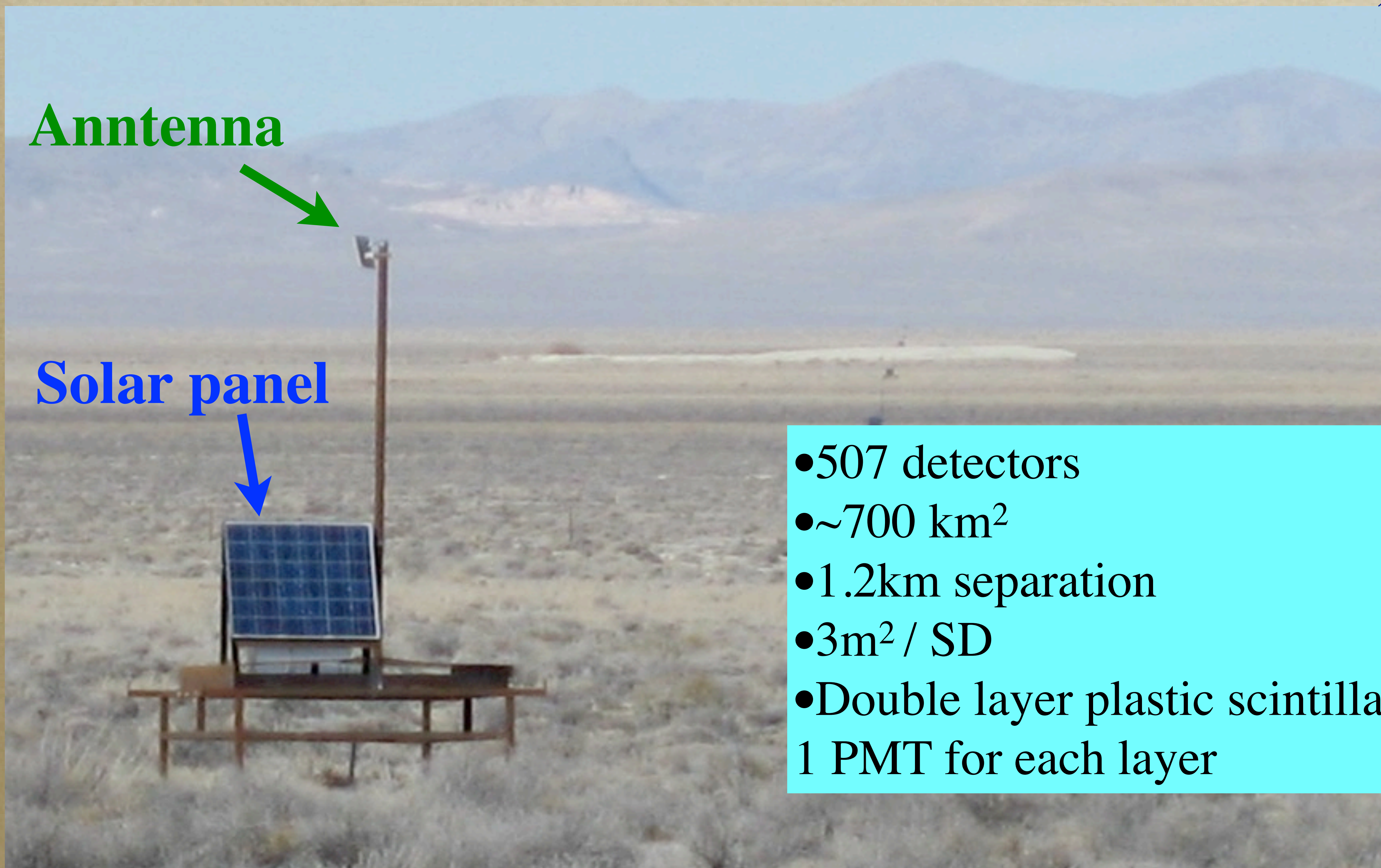
Telescope Array

- A follow-up to HiRes and AGASA
- Millard county, Utah, US
- 507 scintillation counters in ~700km^2
- 12 + 12 + 14 fluorescence detectors
- Full operation since May 2008


TELESCOPE ARRAY PROJECT
Middle Drum
"MD"
14 HiRes-I detectors
Telescope Array Locations
General Reference Map
N
0 3,000 6,000
Meters
Millard county Utah, US
N 39.1° , W 112.9°
1350~1500 m ~880g/cm²
Delta
Hinckley
CLF
20km
"LR"
Long Ridge
SD Array
507 counters
"BR"
Route 257
Black Rock Mesa
3 FD stations
30km
TA Locations
Communication Towers
Fluorescence Locations
Central Laser Facility
Streams
Lakes
Town Boundaries
State Land
Private Land
BLM Land
Military Airspace: Sevier B
Department of Geography
University of Utah
April 2004

TA Surface Detectors (SD)

T.Nonaka *et al.*, Poster 0984



- 507 detectors
- ~700 km^2
- 1.2km separation
- 3m^2 / SD
- Double layer plastic scintillators, 1 PMT for each layer

TA Fluorescence Detectors (FDs)

S.Ogio *et al.*, Poster 1308

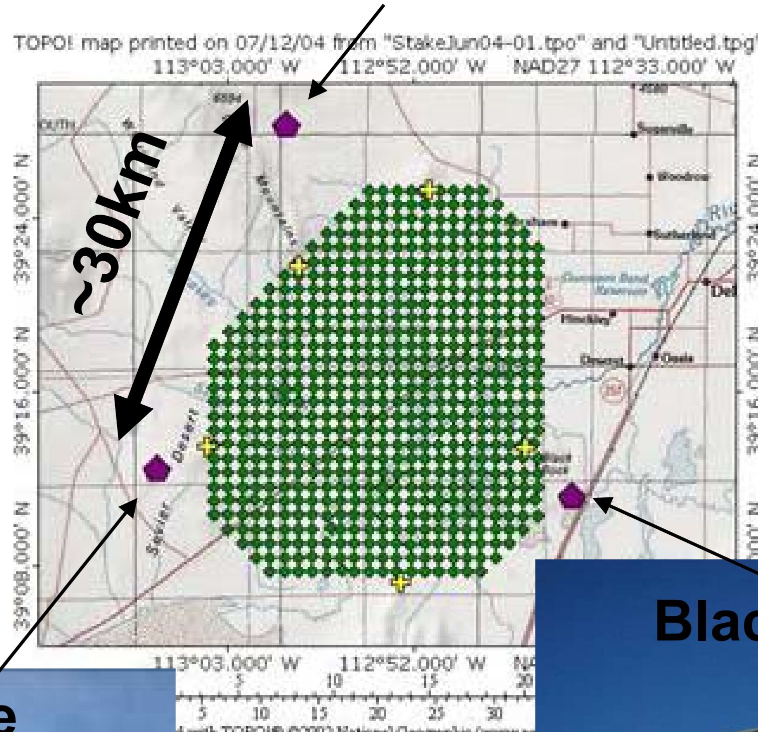
Refurbished from HiRes-I

Observations since ~10/2007

14 telescopes@station
256 PMTs/camera

5.2 m^2

Middle Drum



New FDs

Observation since ~11/2007

12 telescopes/station
FOV~15x18deg /ea

Long Ridge

Observation since ~6/2007

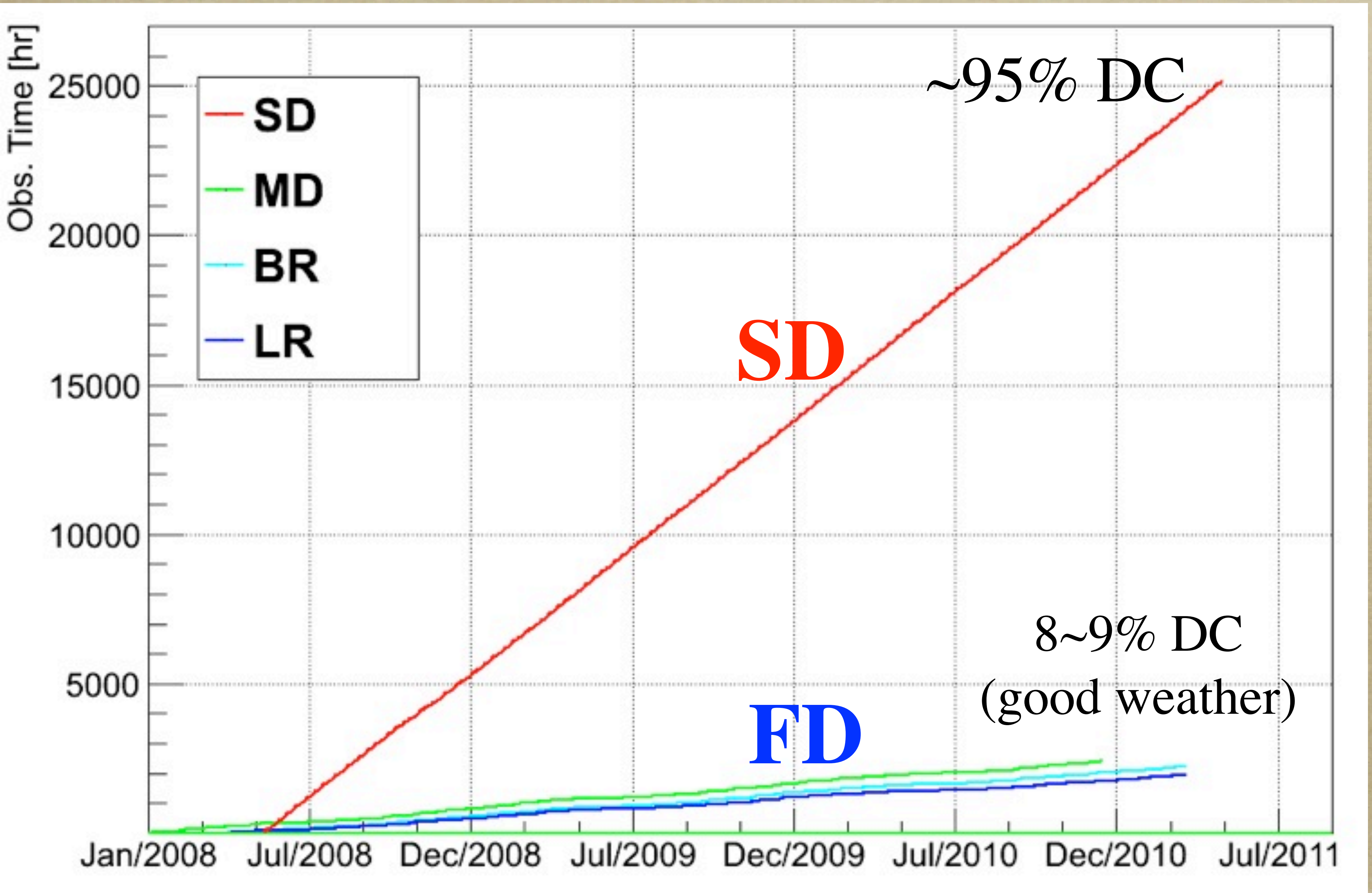
Black Rock Mesa

~1 m^2

6.8 m^2

TA Commissioning

SD&FD Full operation since May 2008



Exposure:

- SD: ~1.7 AGASA (0.x Auger)
- FD: ~1/3 HiRes-I

TA Shower Analyses

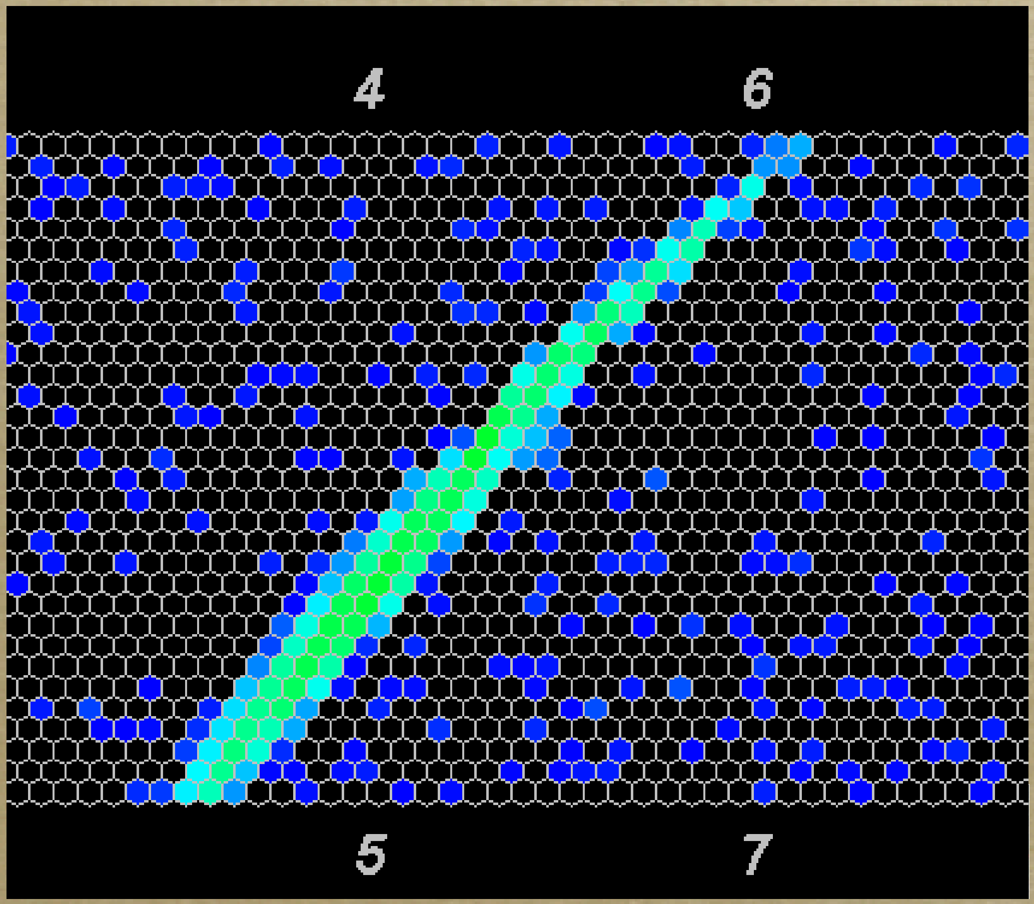
- D.Ikeda: Oral 1264 (Aug12)
- D.Rodriguez: Poster 1303
- D.Bergman: Poster 1300
- S.Stratton: Poster 1299
- T.Abu-Zayyad: Poster 1312
- M.Allen: Poster 0699
- D.Ivanov/B.Stokes: Oral 1297 (Aug12)
- B.Stokes: Poster 1288

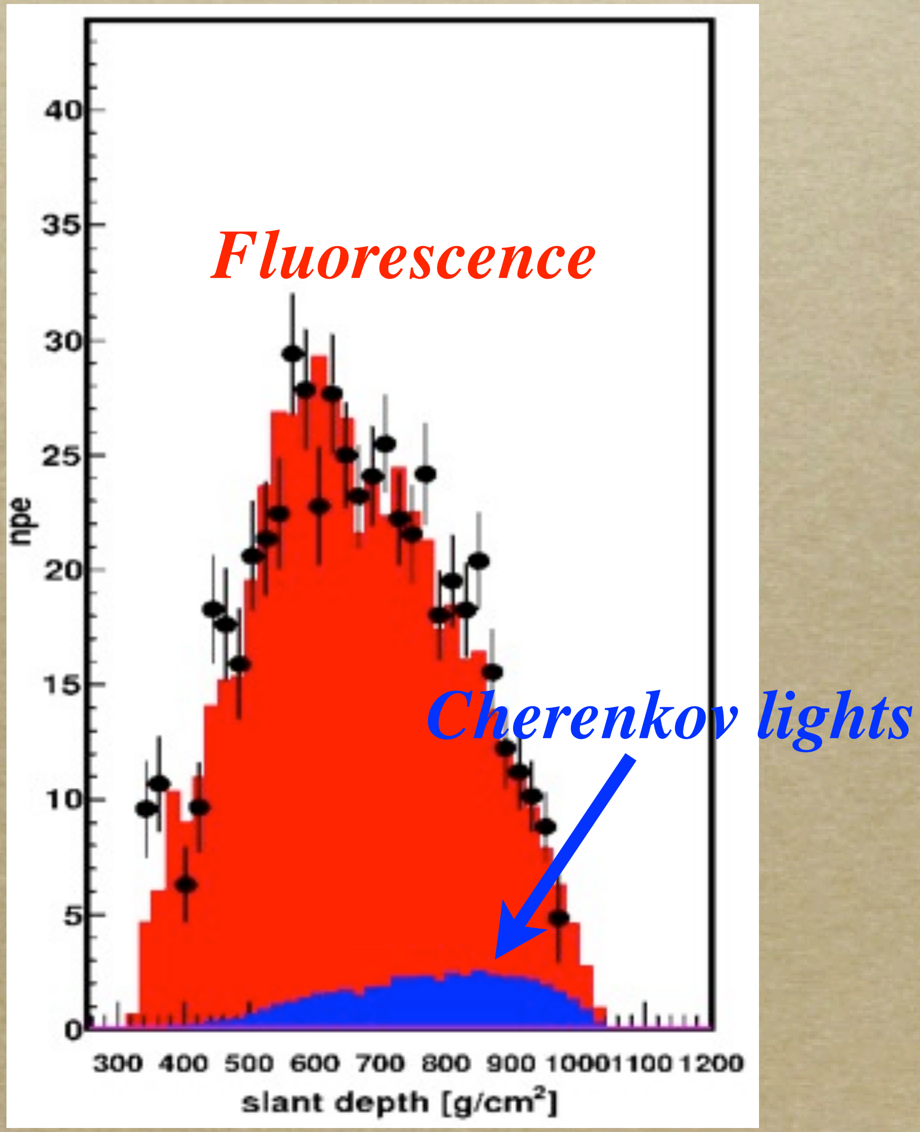
- **FD**: **Longitudinal shower profile** -> Calorimetric measurement

TA Shower Analyses

- •D.Ikeda: Oral 1264 (Aug12)
- •D.Rodriguez: Poster 1303
- •D.Bergman: Poster 1300
- •S.Stratton: Poster 1299
- •T.Abu-Zayyad: Poster 1312
- •M.Allen: Poster 0699
- •D.Ivanov/B.Stokes: Oral 1297 (Aug12)
- •B.Stokes: Poster 1288

- **FD**: **Longitudinal shower profile** -> Calorimetric measurement

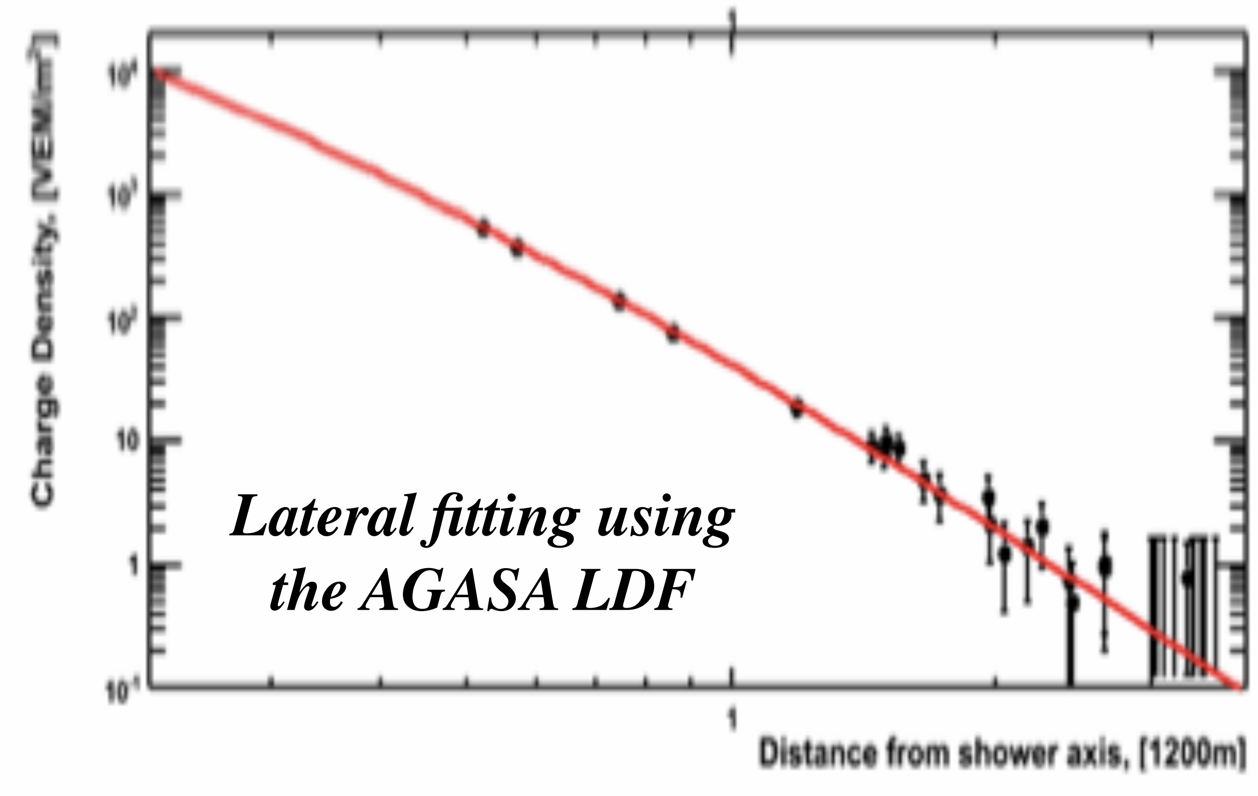




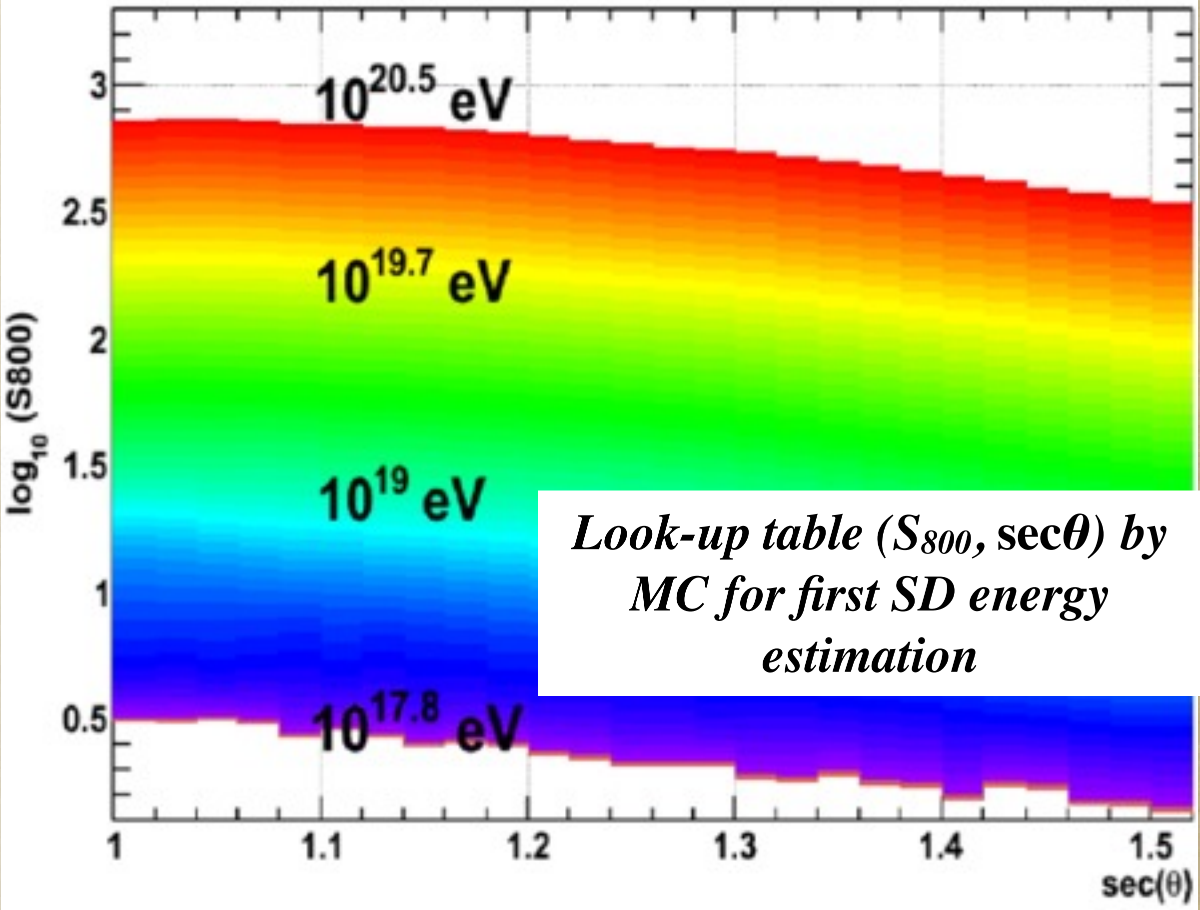
TA Shower Analyses

- D.Ikeda: Oral 1264 (Aug12)
- D.Rodriguez: Poster 1303
- D.Bergman: Poster 1300
- S.Stratton: Poster 1299
- T.Abu-Zayyad: Poster 1312
- M.Allen: Poster 0699
- D.Ivanov/B.Stokes: Oral 1297 (Aug12)
- B.Stokes: Poster 1288

- **FD**: **Longitudinal shower profile** -> Calorimetric measurement
- **SD**: Lateral distribution of particles at the ground
  - Energy estimator: "S_{800}"



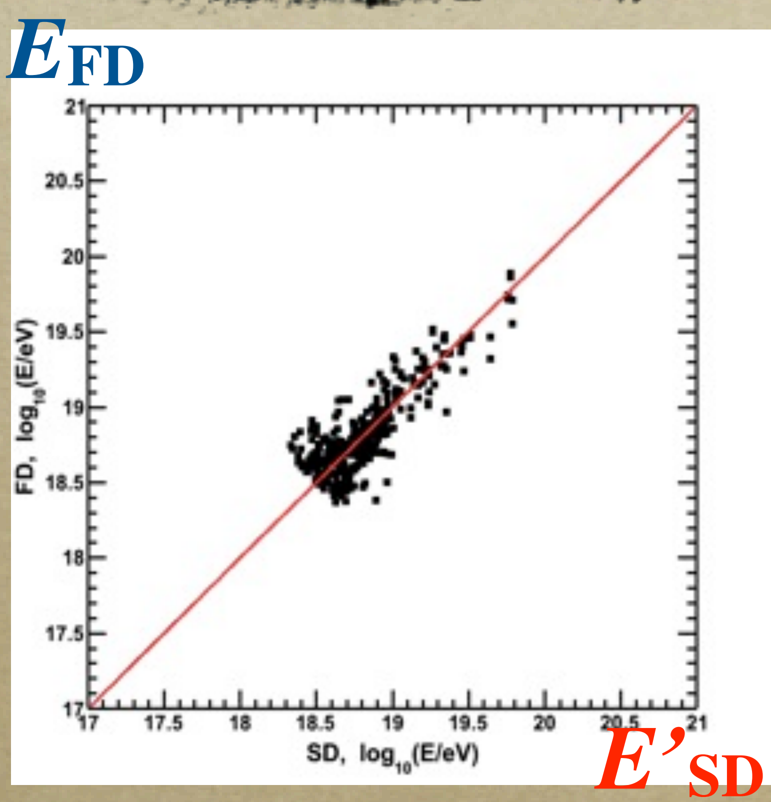
Lateral fitting using the AGASA LDF

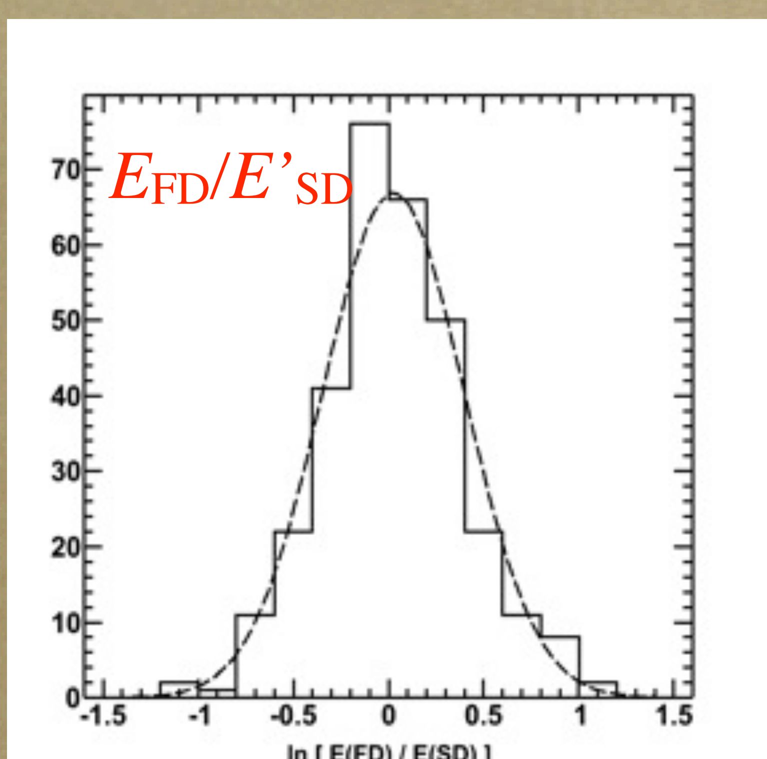


Look-up table (S_{800}, secθ) by MC for first SD energy estimation

TA Energy Scale

- D.Ivanov/B.Stokes: Oral 1297
- B.Stokes: Poster 1288
- Y.Tsunesada: Poster 1270





- Use E_{FD} as reference: calorimetrically determined energy
- E_{FD} - E'_{SD} plot for hybrid events

$$\left\langle \frac{E'_{\mathrm{SD}}}{E_{\mathrm{FD}}} \right\rangle_{\mathrm{hyb}} = 1.27$$

- Rescale the SD energy:

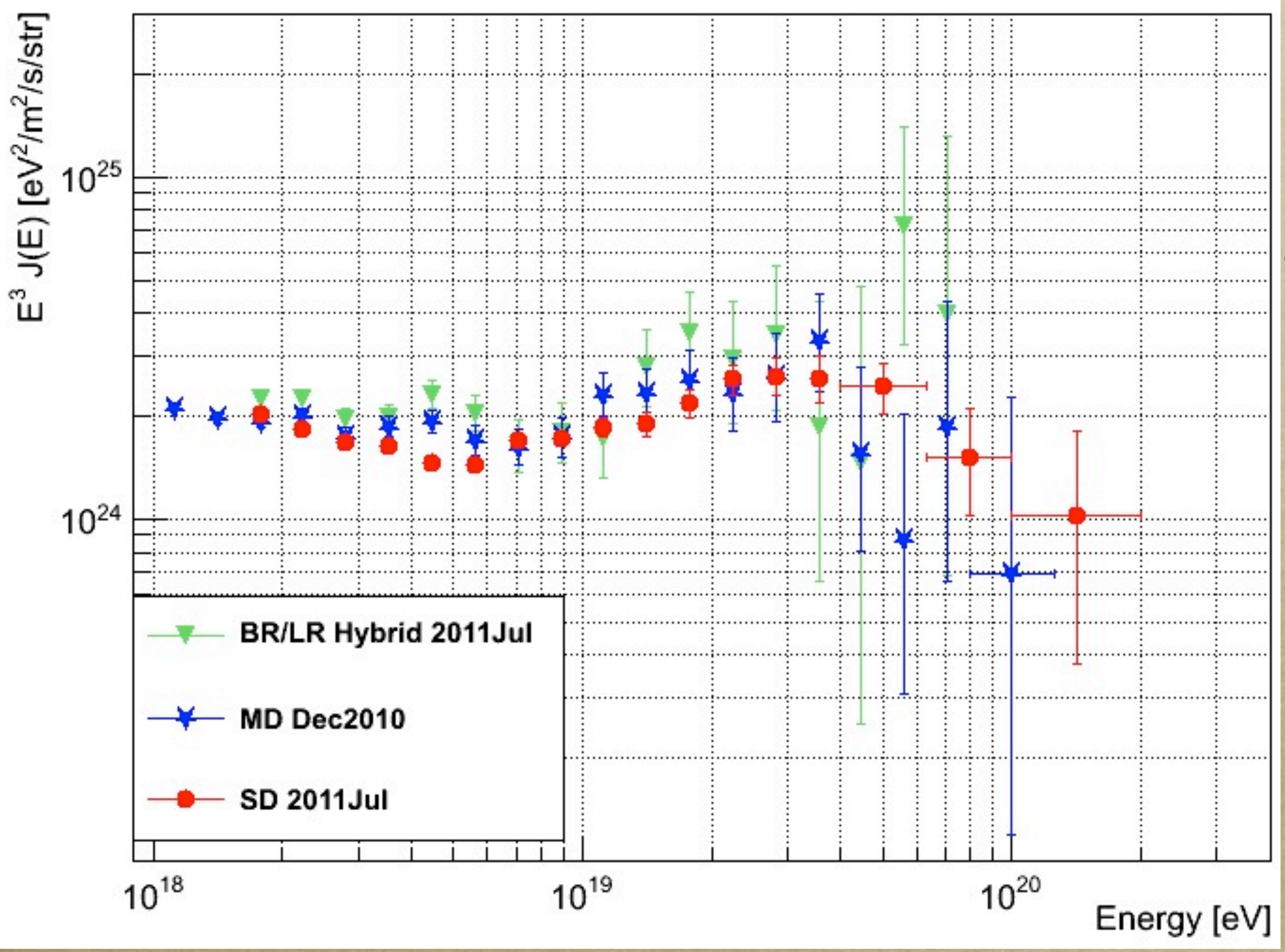
$$E_{\mathrm{SD}} = \frac{1}{\left\langle \frac{E'_{\mathrm{SD}}}{E_{\mathrm{FD}}} \right\rangle_{\mathrm{hyb}}} E'_{\mathrm{SD}}$$

FD energy uncertainty

Source	ΔE/E
Fluorescence yield	11%
Detector	10%
Atmosphere	11%
Reconstruction	10%
Total	21%

Energy Spectrum

TA Spectra: MD, BR/LR Hybrid, SD



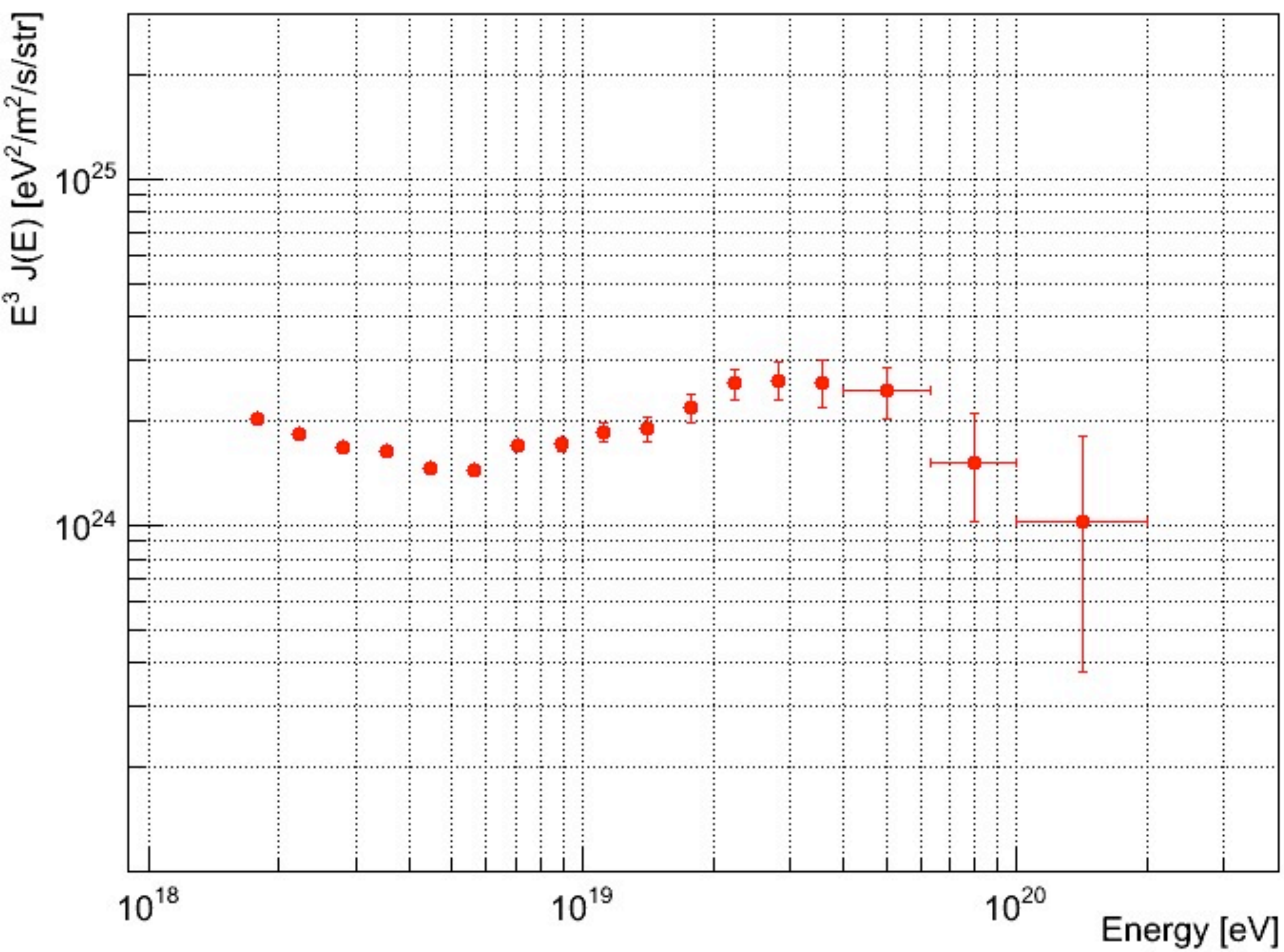
- "MD": FD mono
- "Hybrid": BR/LR mono + 1-SD timing
- "SD": SD self-trigger events

- All are consistent within a few % level.
- Consistent with HiRes.

- **D.Rodriguez, Poster1303**
- **D.Ikeda, Oral 1264**
- **B.Stokes/D. Ivanov, Oral 1297**

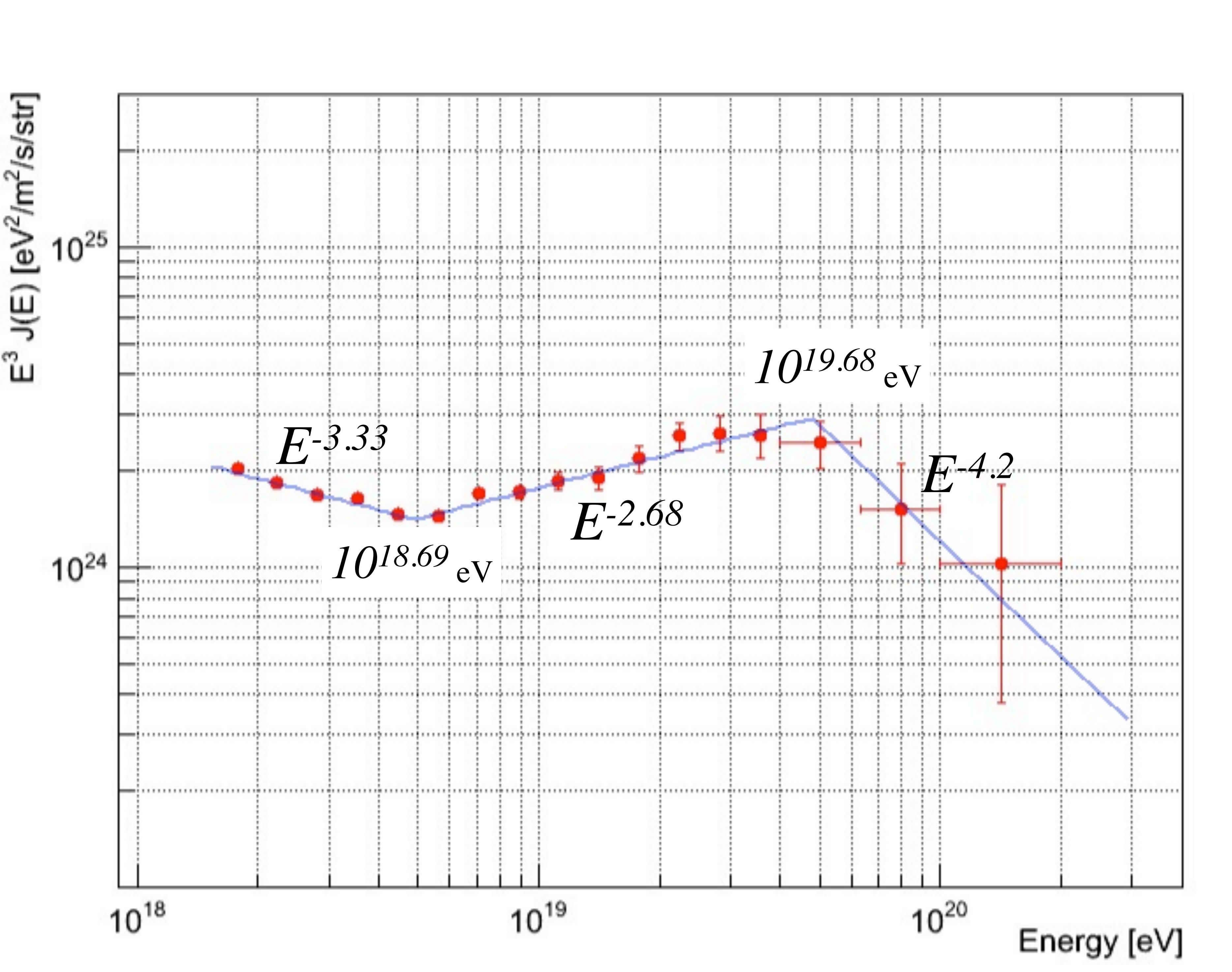
TA-SD Spectrum

B.Stokes/D. Ivanov, Oral 1297



TA-SD Spectrum

B.Stokes/D. Ivanov, Oral 1297



- Broken power-law fit

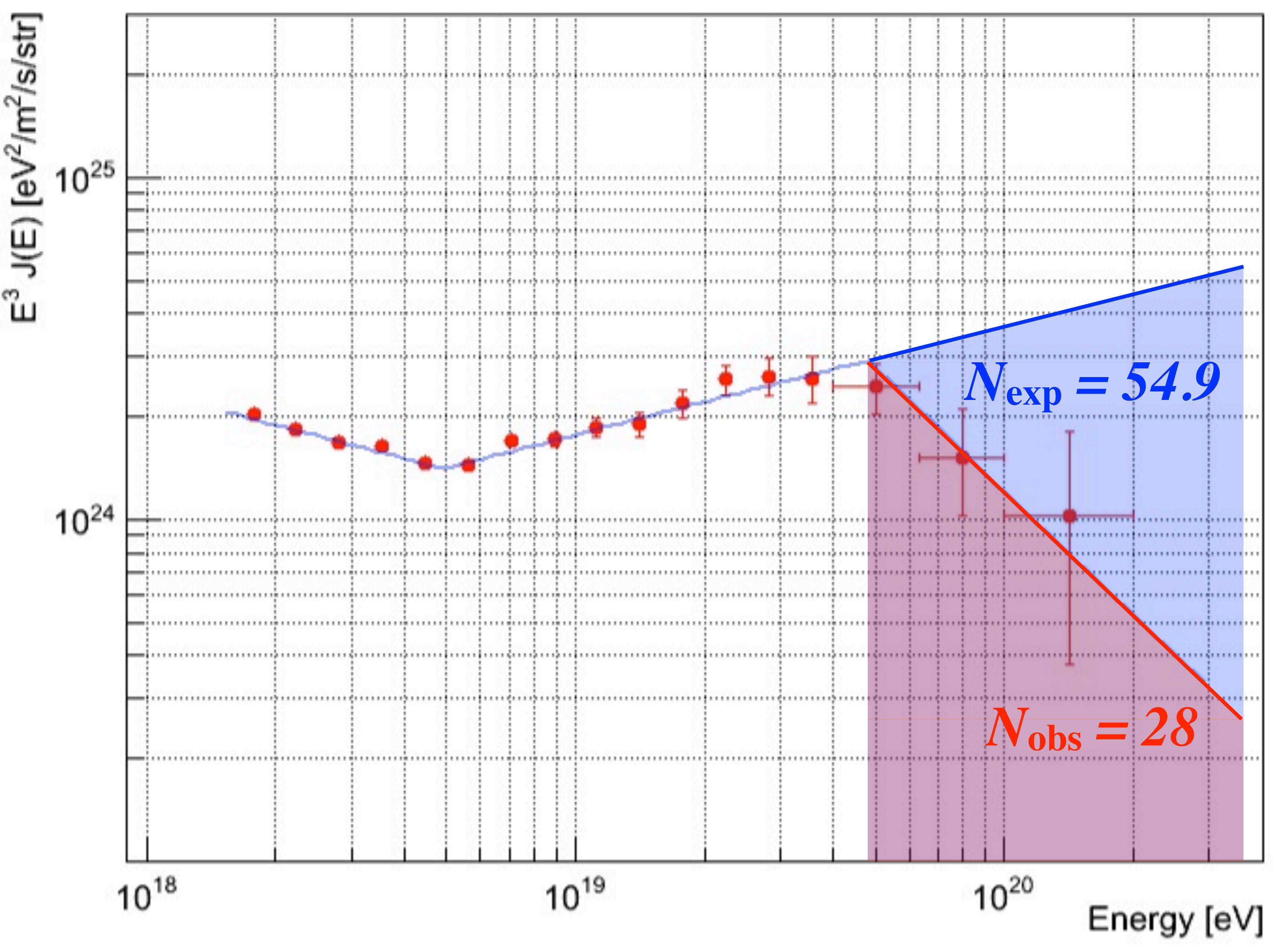
  $E_{\rm ank} = 10^{18.69}$ eV

  $E_{\rm cut} = 10^{19.68}$ eV

  ($E_{1/2} = 10^{19.69}$ eV)

TA-SD Spectrum

B.Stokes/D. Ivanov, Oral 1297



- Broken power-law fit

$E_{ank} = 10^{18.69}$ eV

$E_{cut} = 10^{19.68}$ eV

($E_{1/2} = 10^{19.69}$ eV)

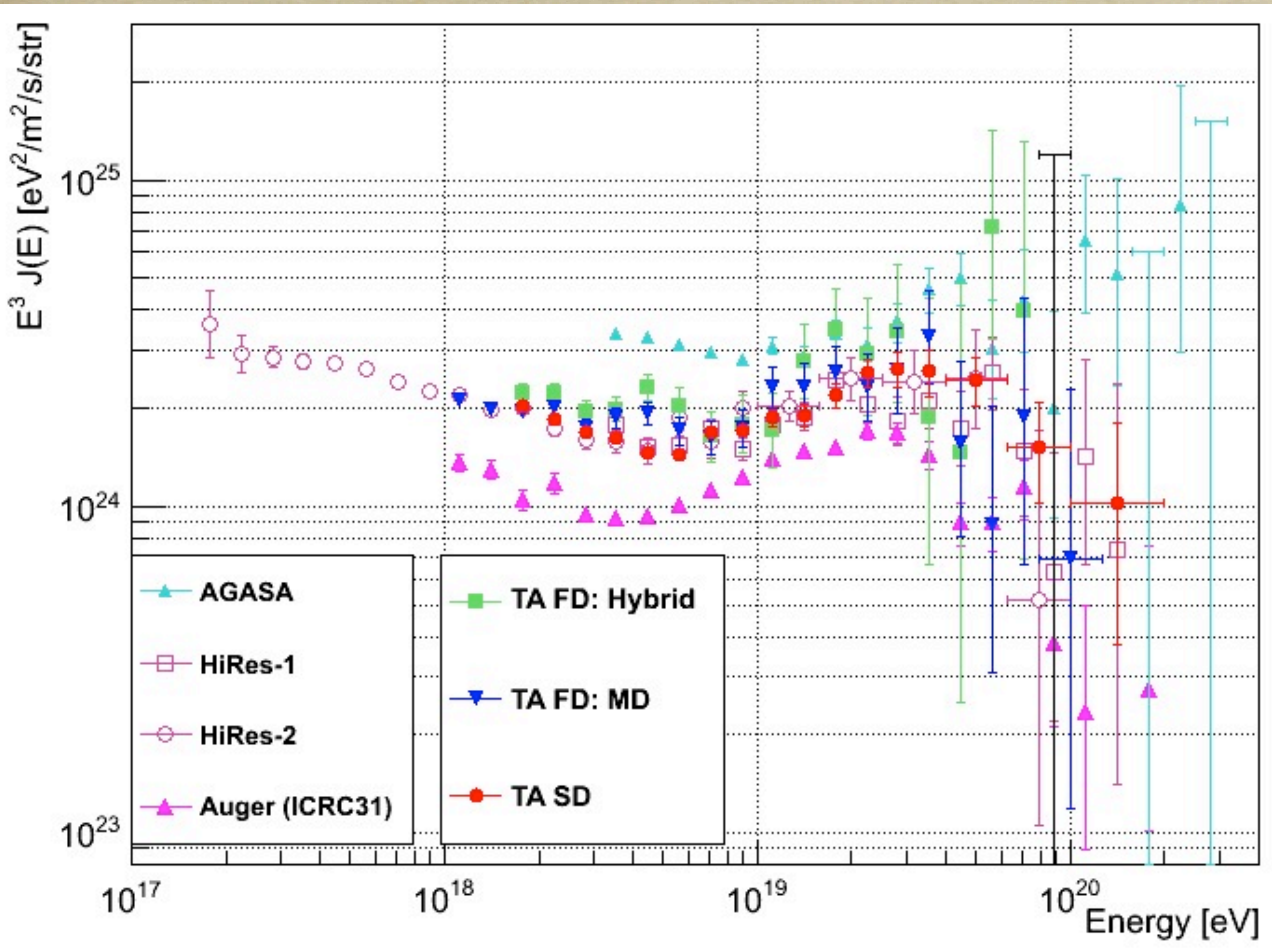
- Significance of the event deficit

$$\sum_{i=0}^{28} \text{Poisson}(i; \mu = 54.9)$$

$$= 4.75 \times 10^{-5}$$

3.9σ

AGASA, HiRes, Auger, TA



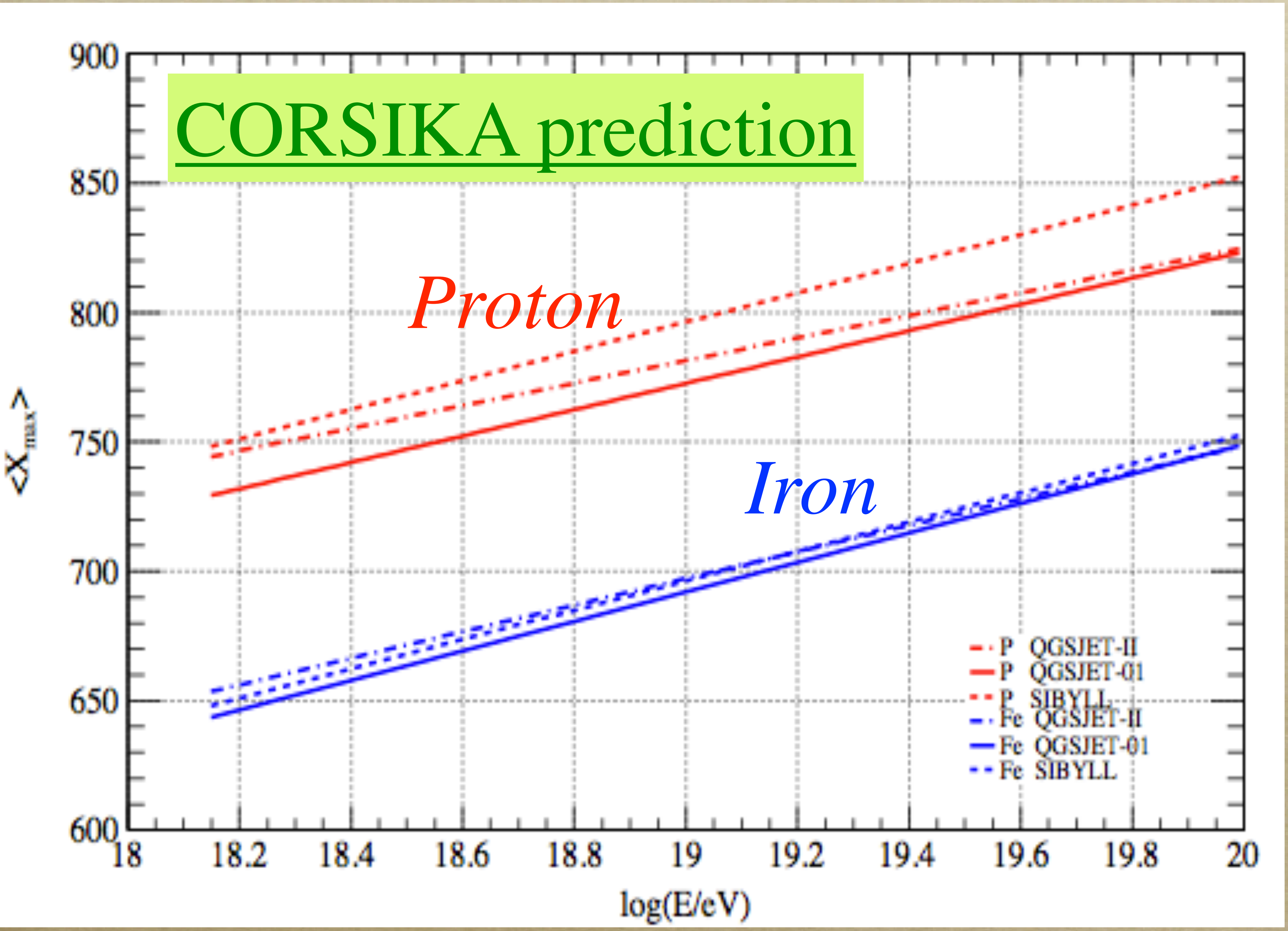
- TA spectra are consistent with HiRes.
- -20% AGASA
- +20% Auger

- 9% difference from the FLY model (Kakimoto et al. in TA/ Nagano et al./AirFly : Tsunesada Poster 1279)
- ~22% total systematic uncertainty in both TA & Auger

Towards UHECR Mass Composition

<X_{max}> Analysis

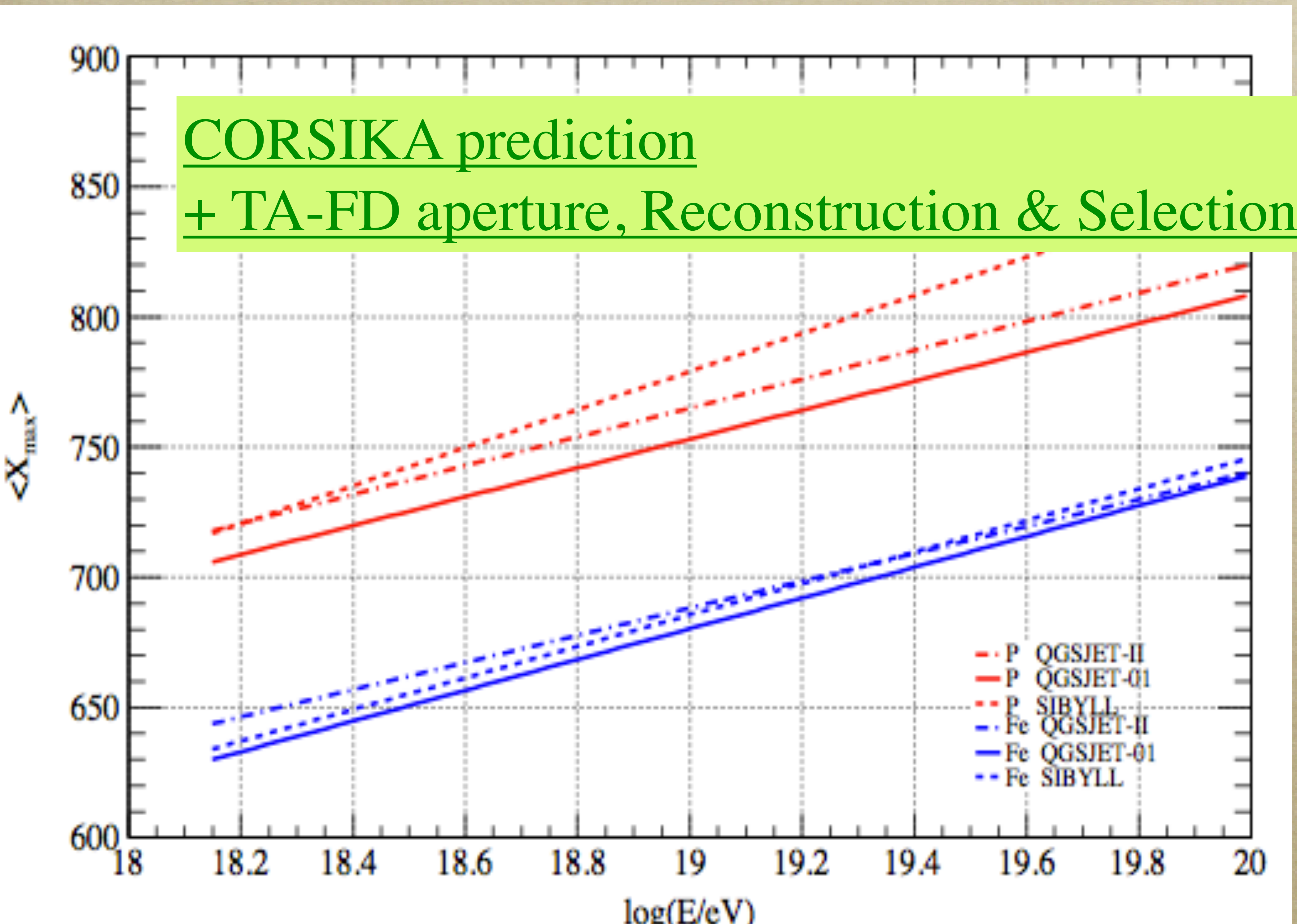
Y.Tameda, Oral 1268



- Compare model prediction and data : should be bias-free

<X_{max}> Analysis

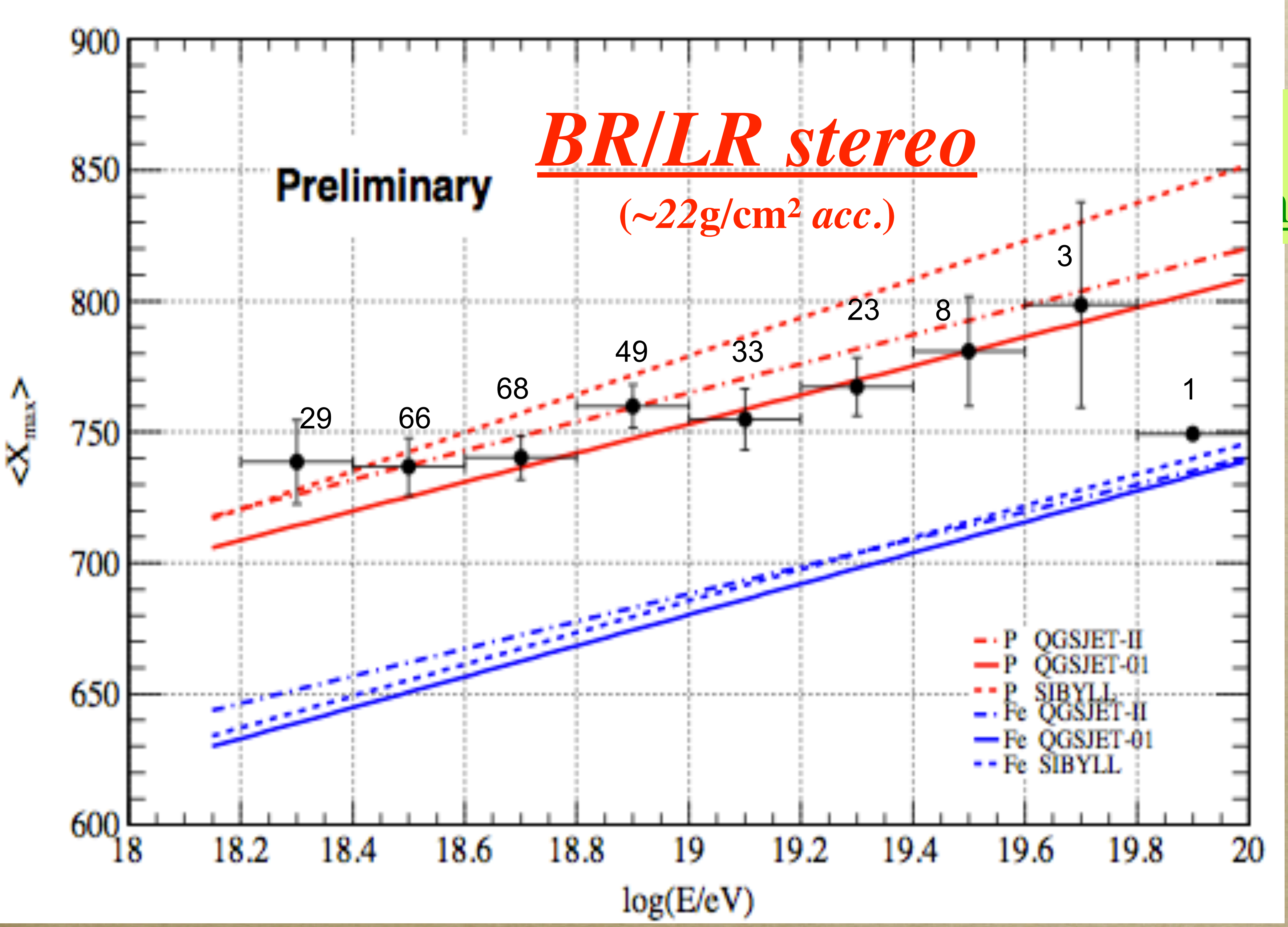
Y.Tameda, Oral 1268



- Compare model prediction and data : should be bias-free
- Compare “biased” model prediction and “biased” data

<X_{max}> Analysis

Y.Tameda, Oral 1268

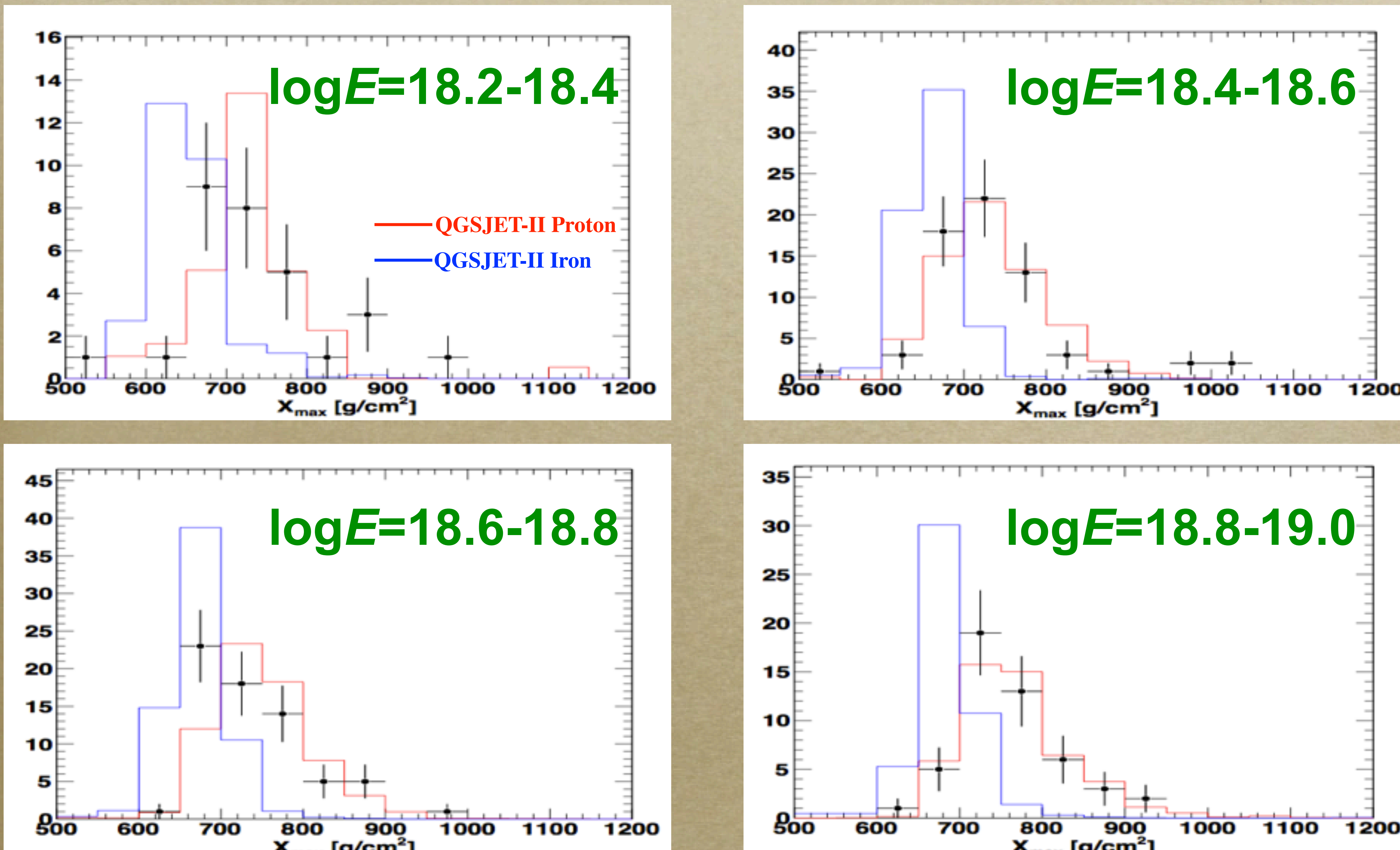


•Compare model prediction and data : should be bias-free

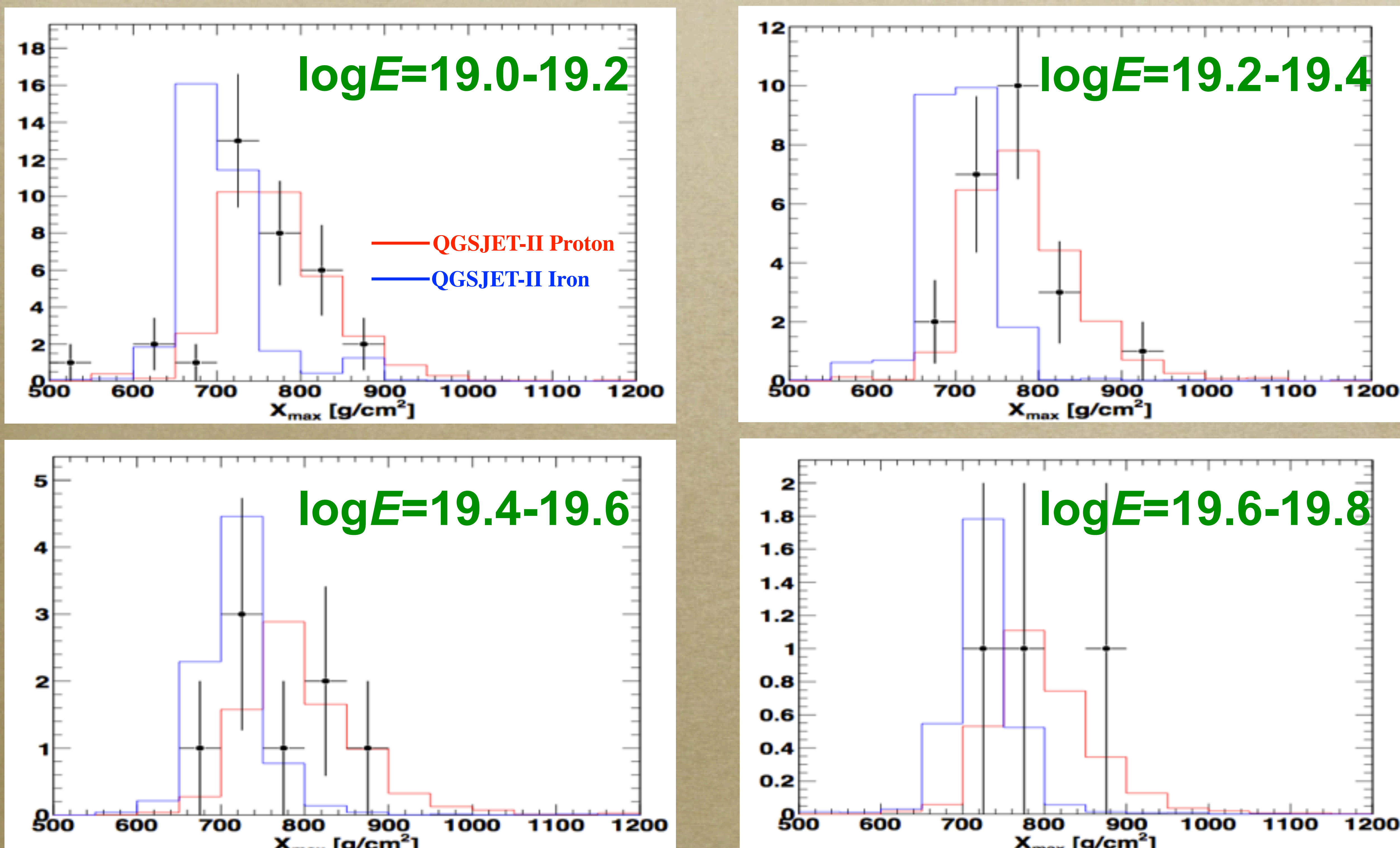
•Compare "biased" model prediction and "biased" data

•BR/LR stereo events
•Consistent with proton-dominated composition

X_{max} Distribution: log$E$=18.2 ~ 19.0



X_{max} Distribution: log$E$=19.0 ~ 19.8



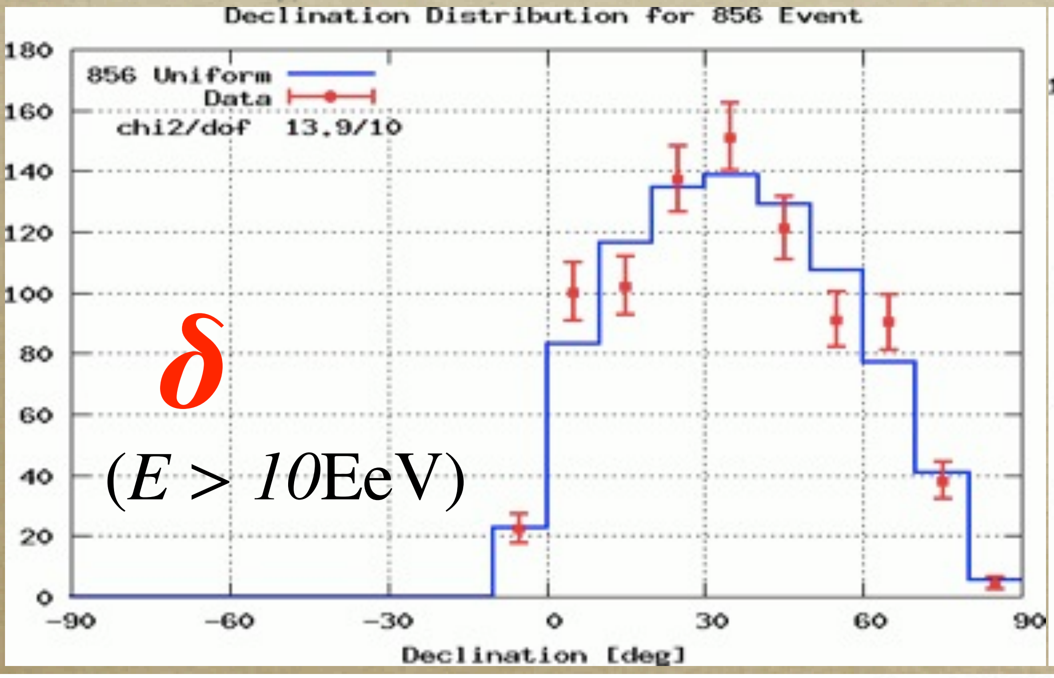
Anisotropy

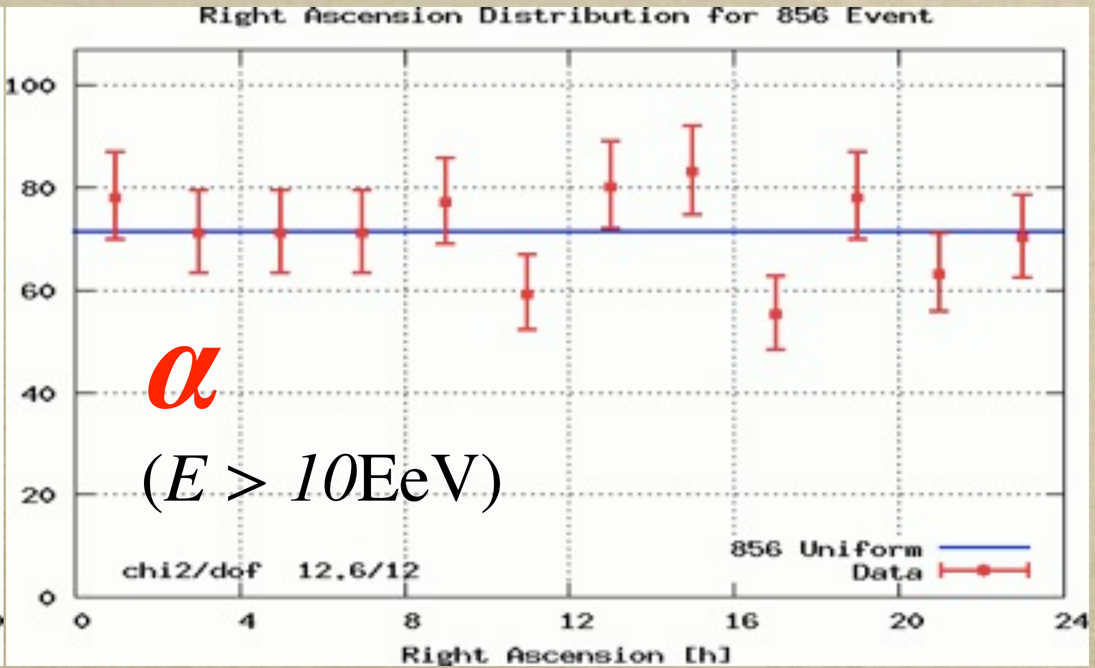
Anisotropy Analyses

- Use SD events (1.27 scaled)
- 2008/05/11 - 2011/05/01: 1086 days
- Zenith angle < 45deg
- Array boundary cut
- Angular resolution: 1.5^{o} ($E > 10^{19}$ eV)
- Number of events:
  - $E >$ 10 EeV: 854
  - $E >$ 40 EeV: 49
  - $E >$ 57 EeV: 20

TA Event Map

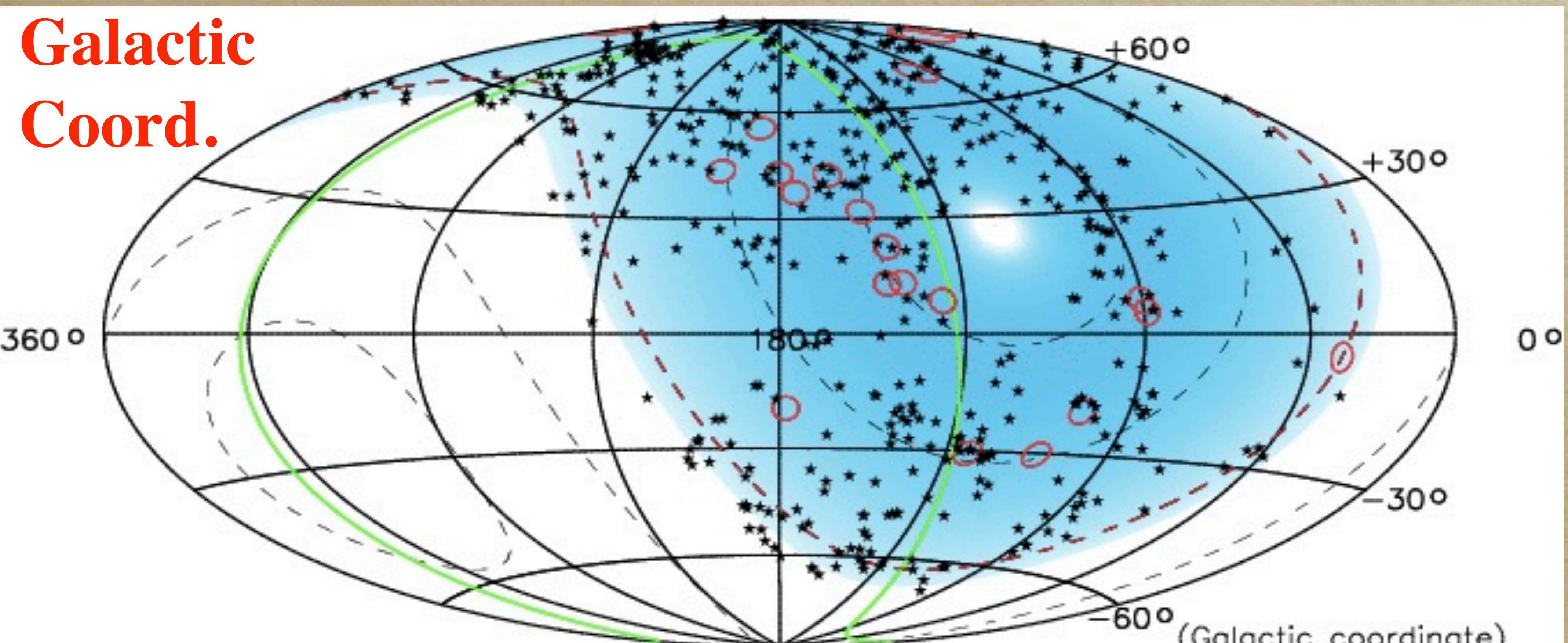
Okuda/Tkachev
Oral 1311





- *Looks isotropic in* (α, δ)
  $(E > 10\text{EeV})$

Galactic Coord.



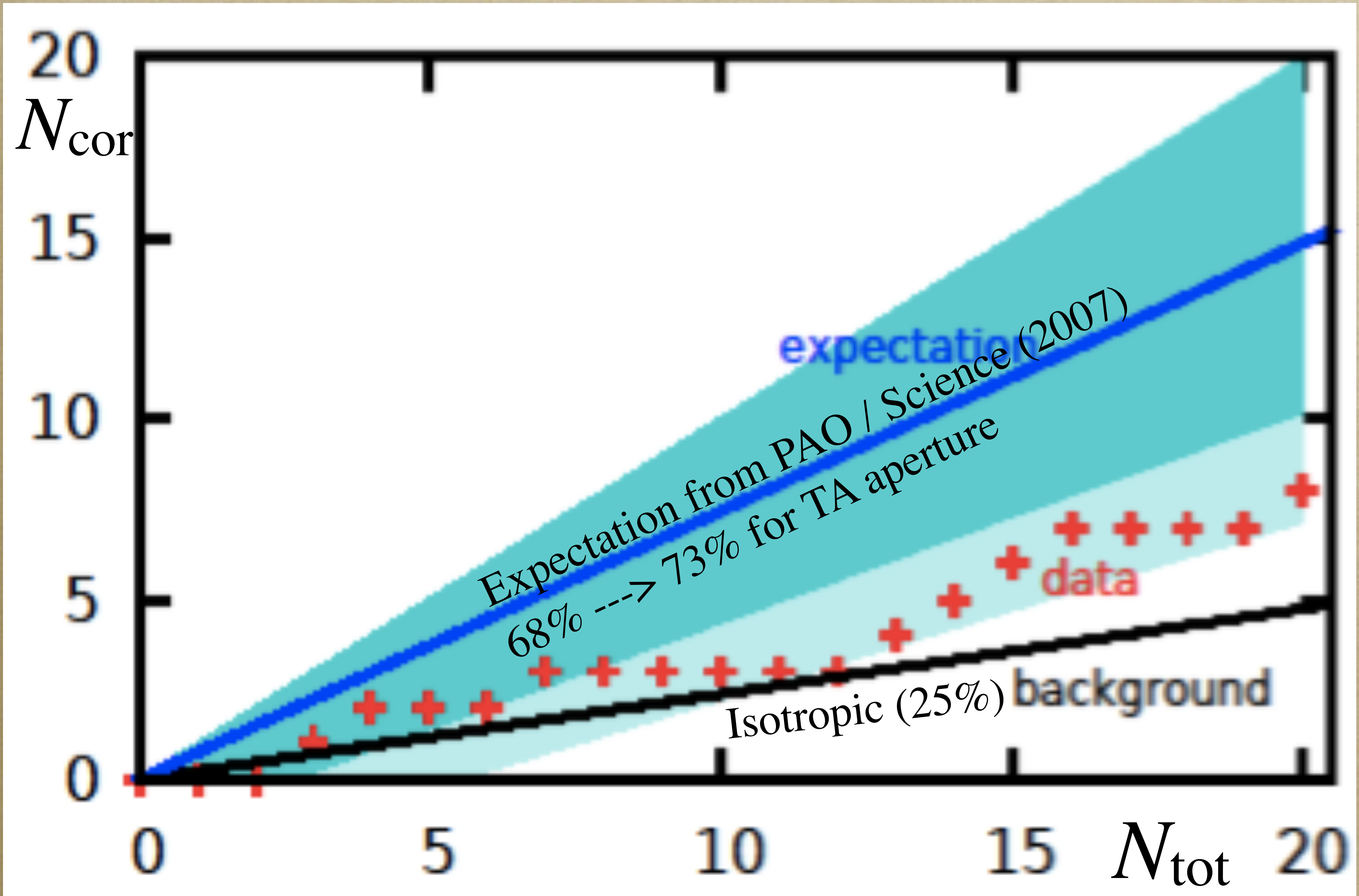
★ AGN

○ SD event, > 57EeV (3.1° radii)

Correlation with the VCV Catalog Objects ?

Okuda/Tkachev Oral 1311

Binominal Correlation of event energy > 57EeV, with Veron AGN 12th. Zmax=0.018 (472AGN), Within 3.1deg.

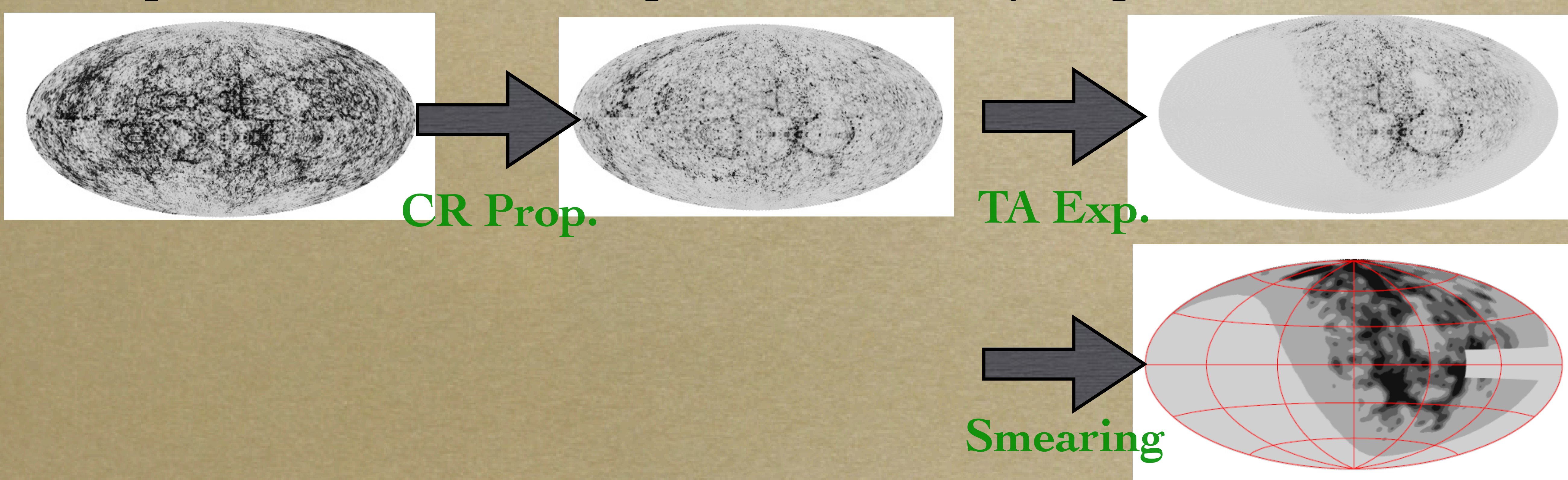


- 8 of 20 correlated
  - *4.8 for isotropic*
- *(Auger result has been updated: 68% ---> 38%)*
- Compatible with both isotropy and AGN correlation hypothesis.

Search for Large-Scale Anisotropy

Tinyakov/Kido Oral 1317

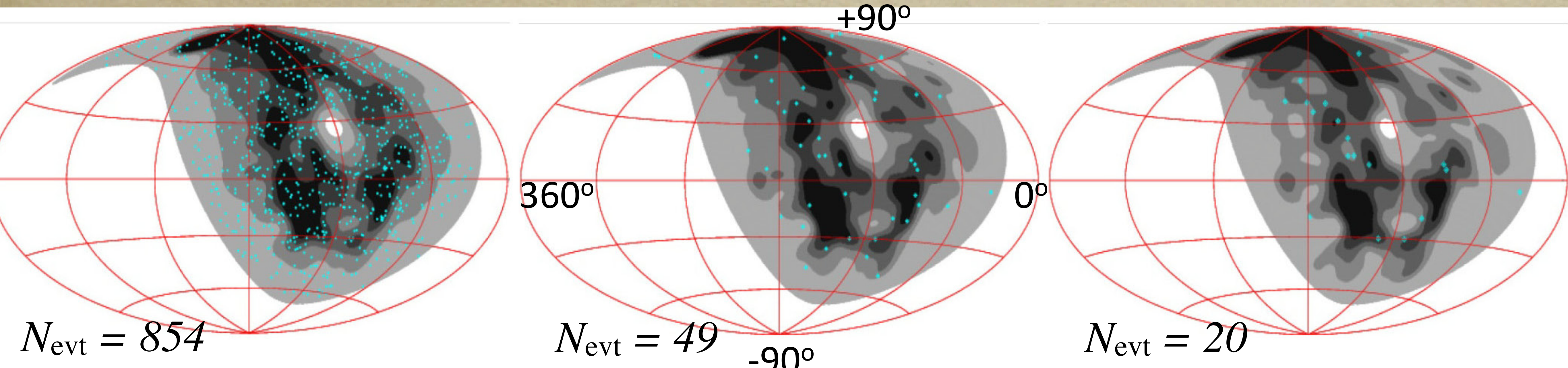
- 2MASS galaxy redshift catalog (XSCz), 5Mpc ~ 250Mpc
  - Uniform intensity beyond 250Mpc
- Proton primary, injection spectrum $E^{-2.2}$
- Interactions/redshift TA exposure taken into account
- Smearing angle parameter: ~20^{o} (Magnetic deflection, angular resolution etc.)
- GC region excluded ($|b| < 10^{o}$, $| l | < 90^{o}$)
- Compare TA data and the expected CR density map



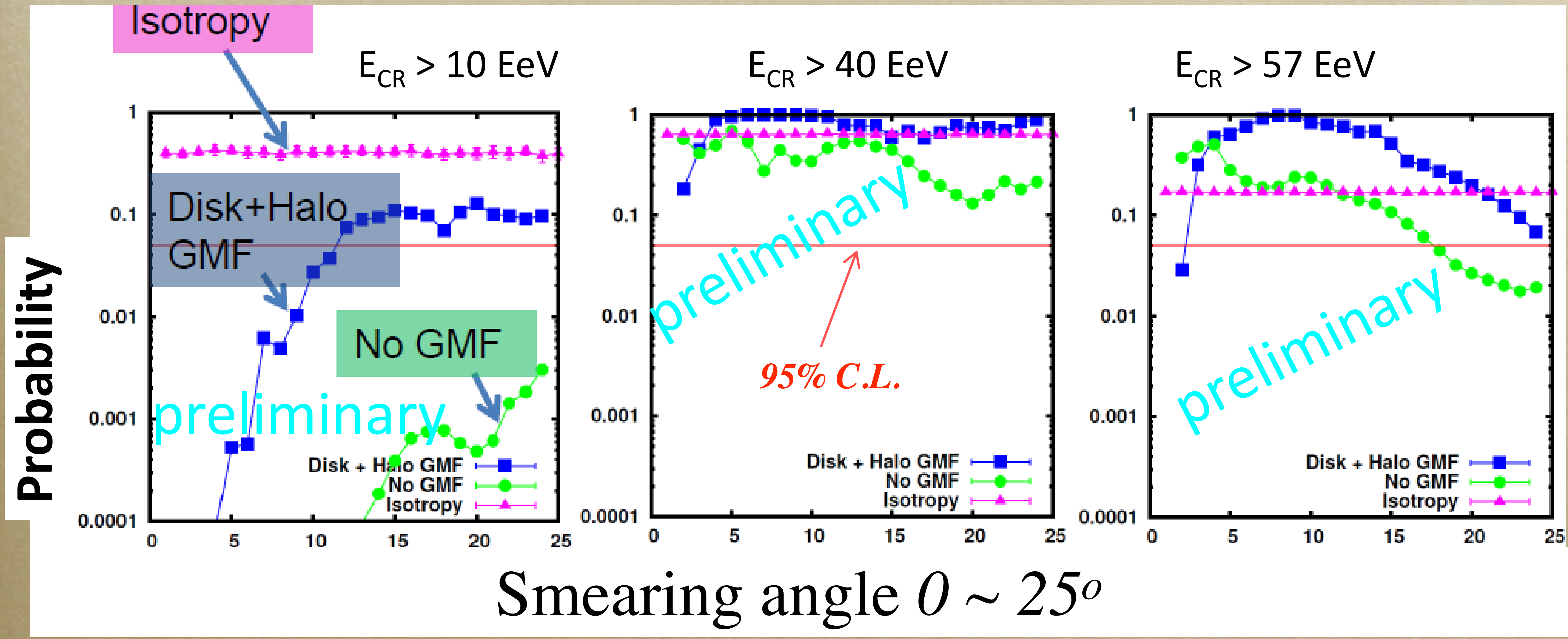
Search for Large-Scale Anisotropy

Tinyakov/Kido Oral 1317

***E* > *10*EeV** ***E* > *40*EeV** ***E* > *57*EeV**



TA Events & LSS: KS Test

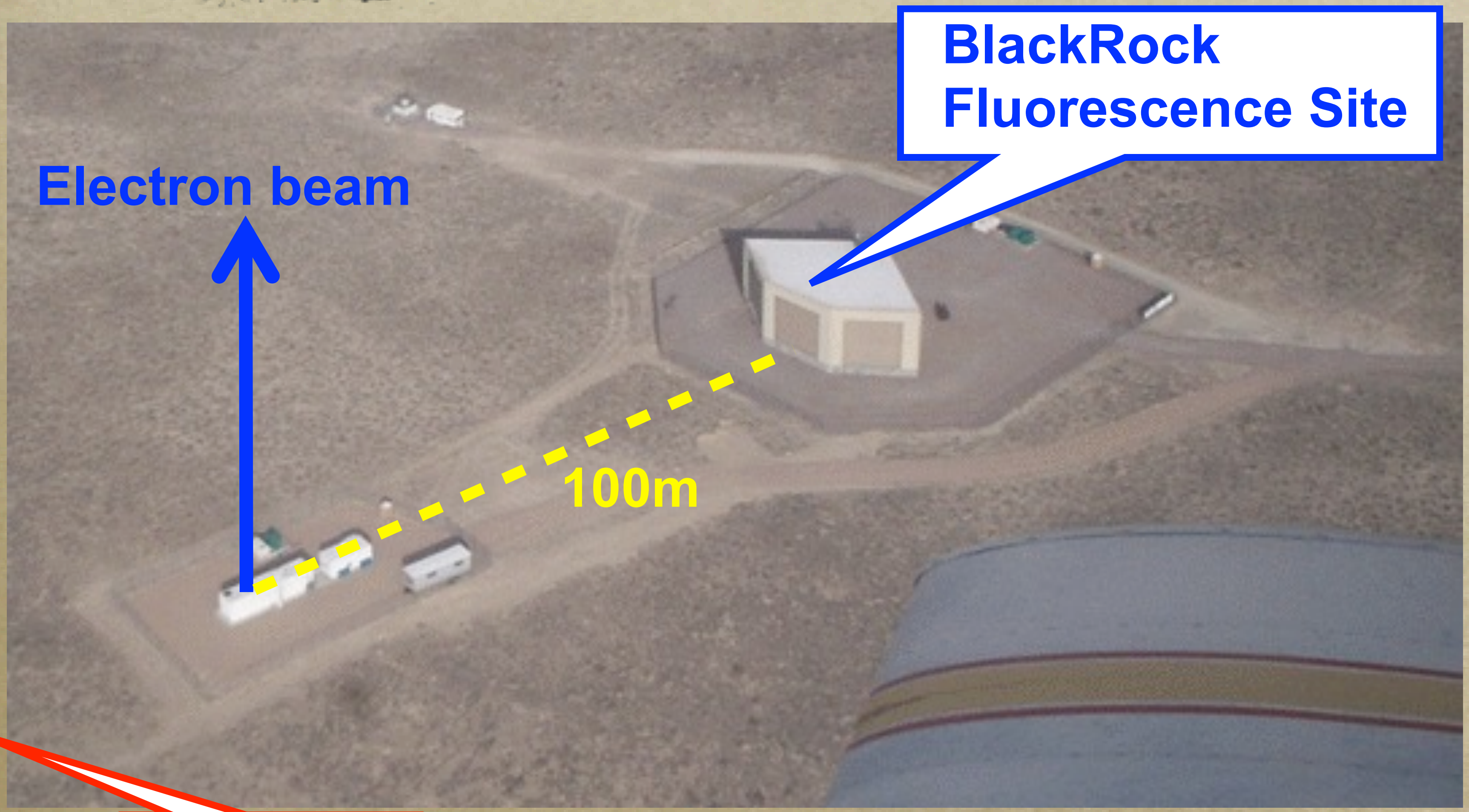


- Compatible with isotropy for all energy regions
- Also compatible with the structure hypothesis at *40/57* EeV w/ or w/o GMF
- Not compatible with LSS for *E > 10*EeV, without strong/extended halo field

We also presented...

- **UHE Photon limit**: G. Rubtsov, Oral Talk 1266
- **Anisotropy: autocorrelation**: T. Okuda, Oral Talk 1311
- **MD hybrid analysis:** M.Allen, Poster 0699
- **Shower MC with GPU:** T.AbuZayyad, Poster 1329
- **Detailed Shower MC: CORSIKA & COSMOS:** J.Kim, Poster 0812
- **Hybrid triggering system:** H.Tokuno, Poster 1275
- **FD cross-calibration:** T.Stroman, Poster 1301
- **Atmospheric monitoring:** LIDAR: T.Tomida, Poster 1279
- **Atmospheric monitoring:** CLF-LIDAR: D.Oku, Poster 1278
- **Atmospheric monitoring:** IR camera: F. Shibata, Poster 1277

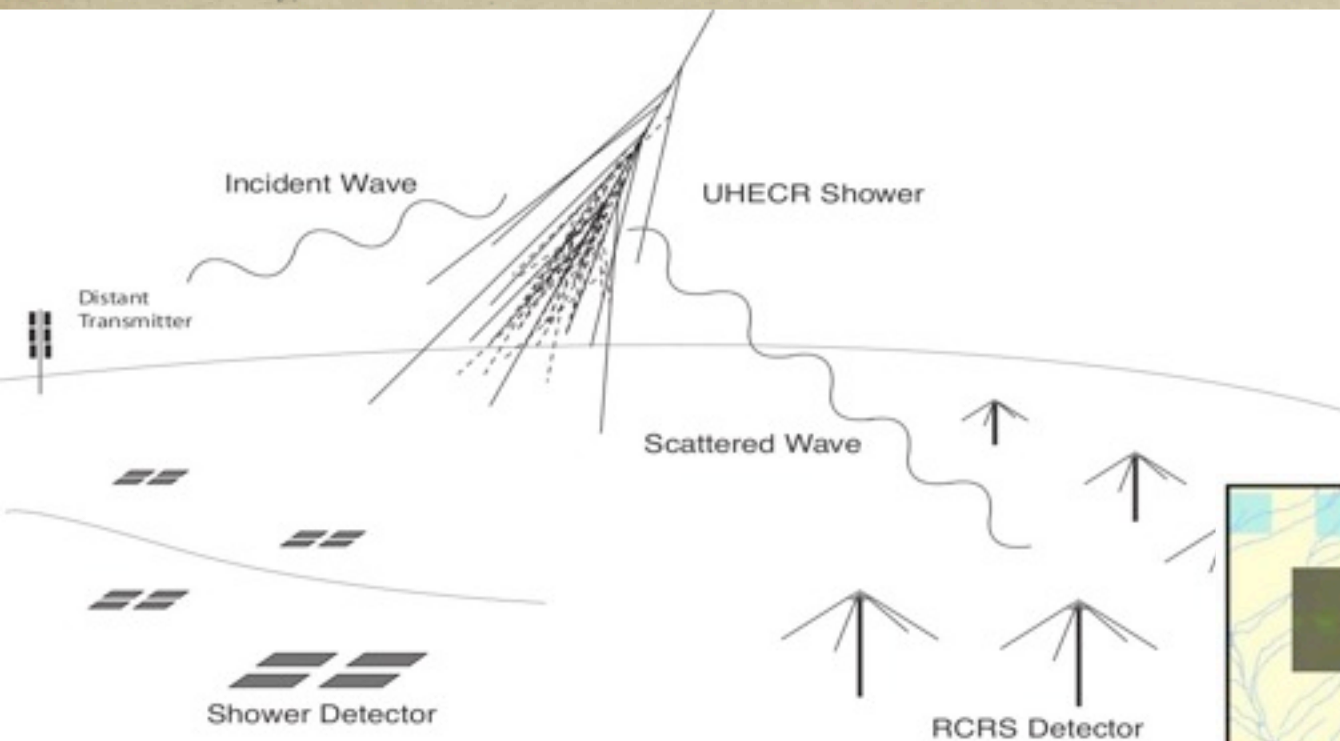
ELS: Electron Accelerator



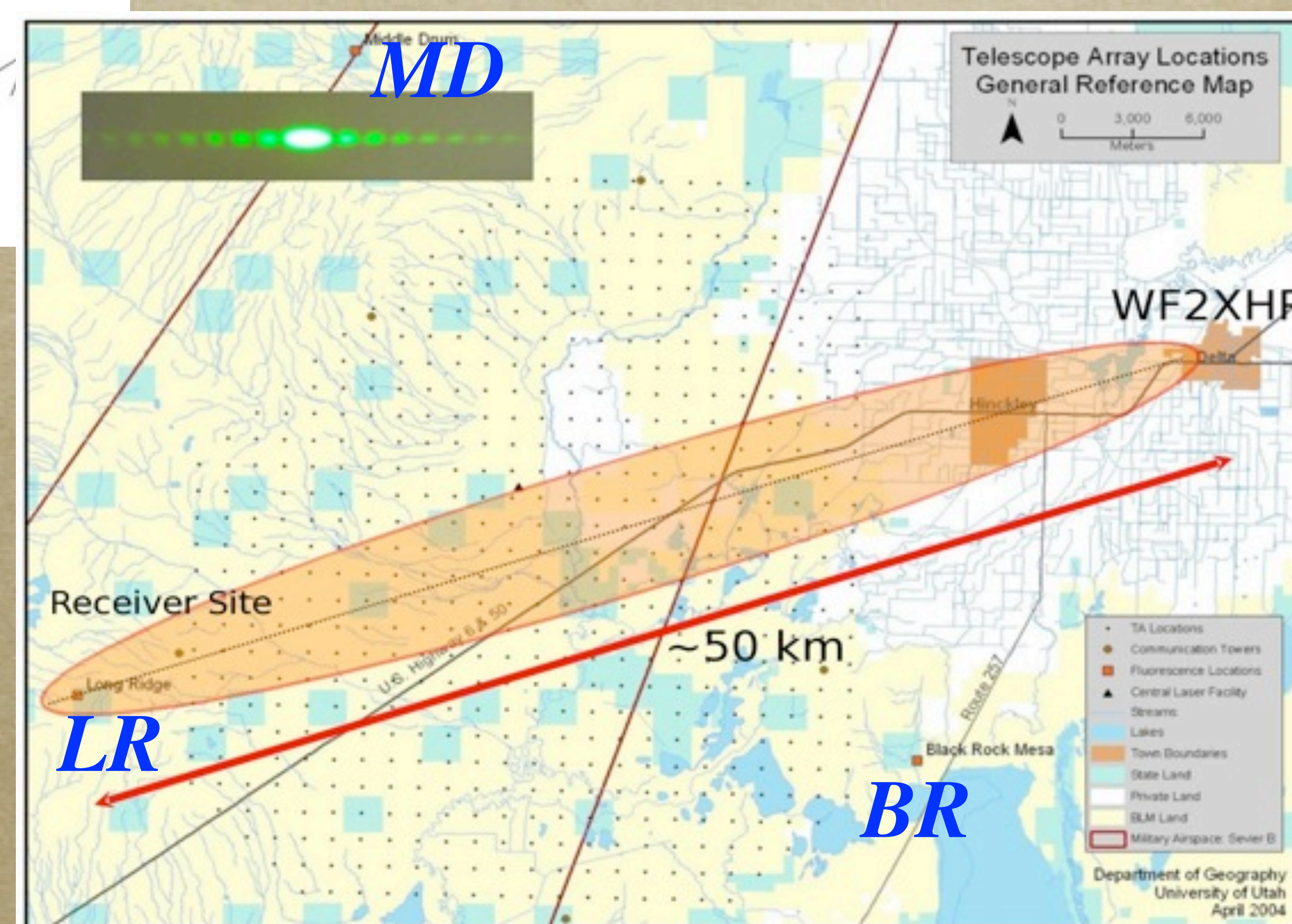
T.Shibata
Oral 1252 (Aug 17)

- *40*MeV, 10^9 electrons
- E2E calibration of FD energies
- First shot in Sep.2010
- Analysis ongoing

Bistatic Radar at TA



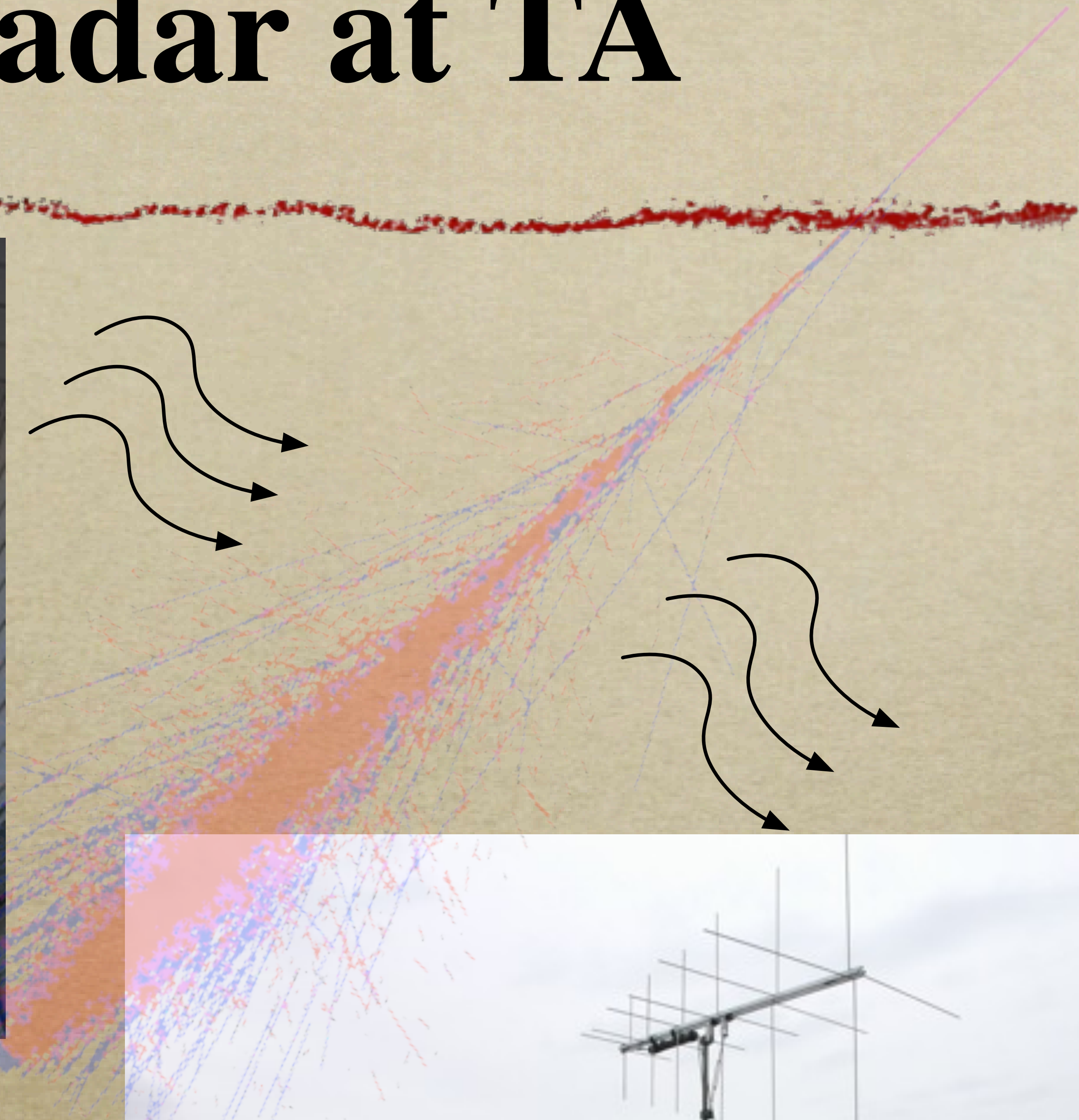
J.Belz: Oral 1314
J.Belz *et al*.: Poster 1315



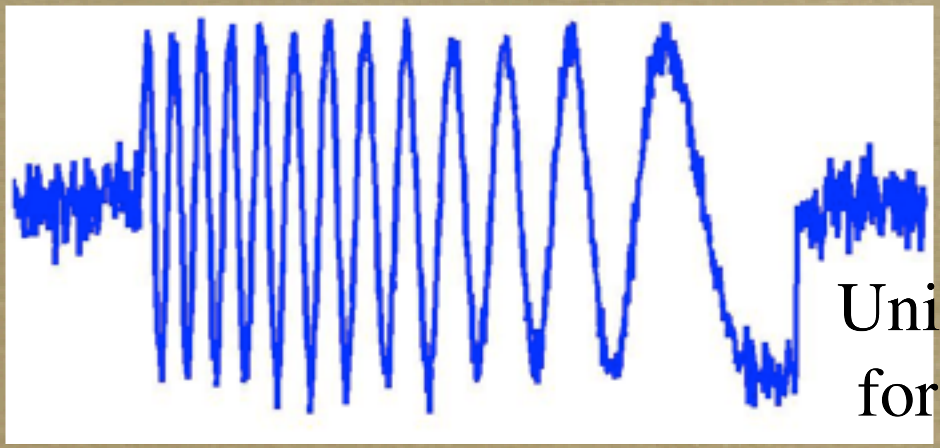
- Air shower plasma should reflect low-VHF (~50 MHz) radiation (Blackett and Lovell, 1940).
- Low-cost remote sensing technique

Bistatic Radar at TA

2kW Transmitter
2011 Jan.
To be updated to 40kW



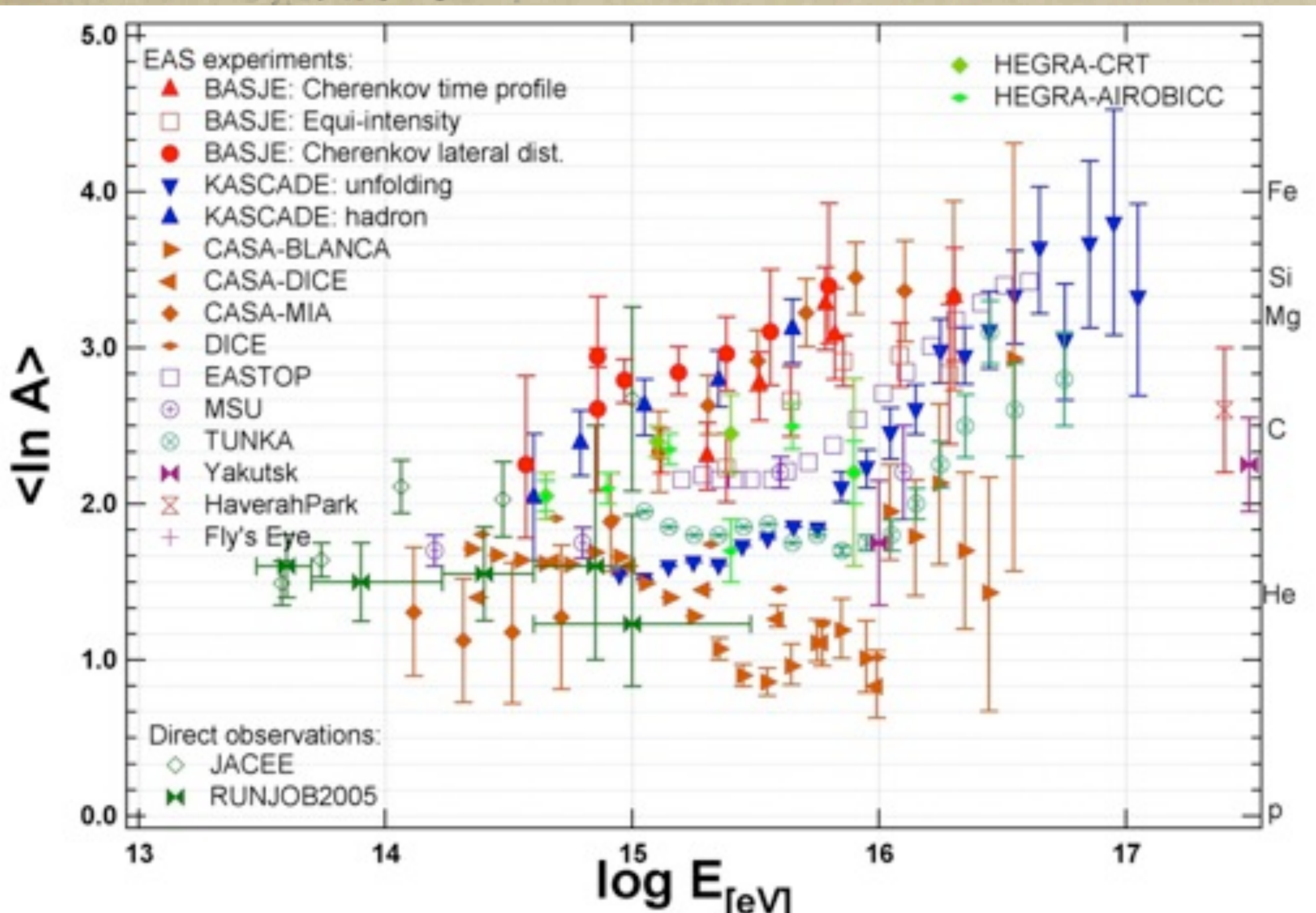
Receiver at the TA site



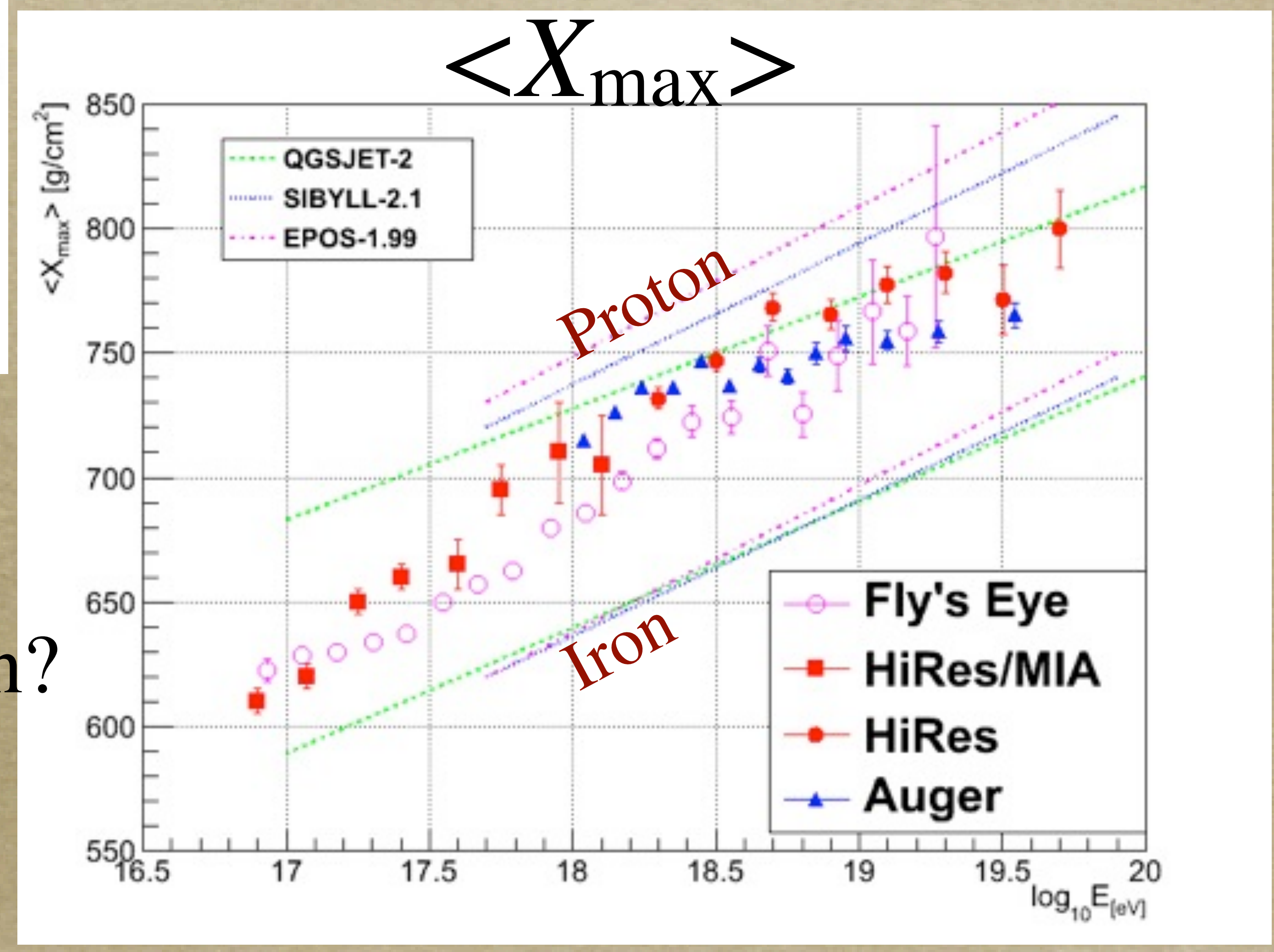
Unique signature
for EAS echoes

TALE: TA Low-Energy Extension

G.Thomson *et al.*: Poster 1307



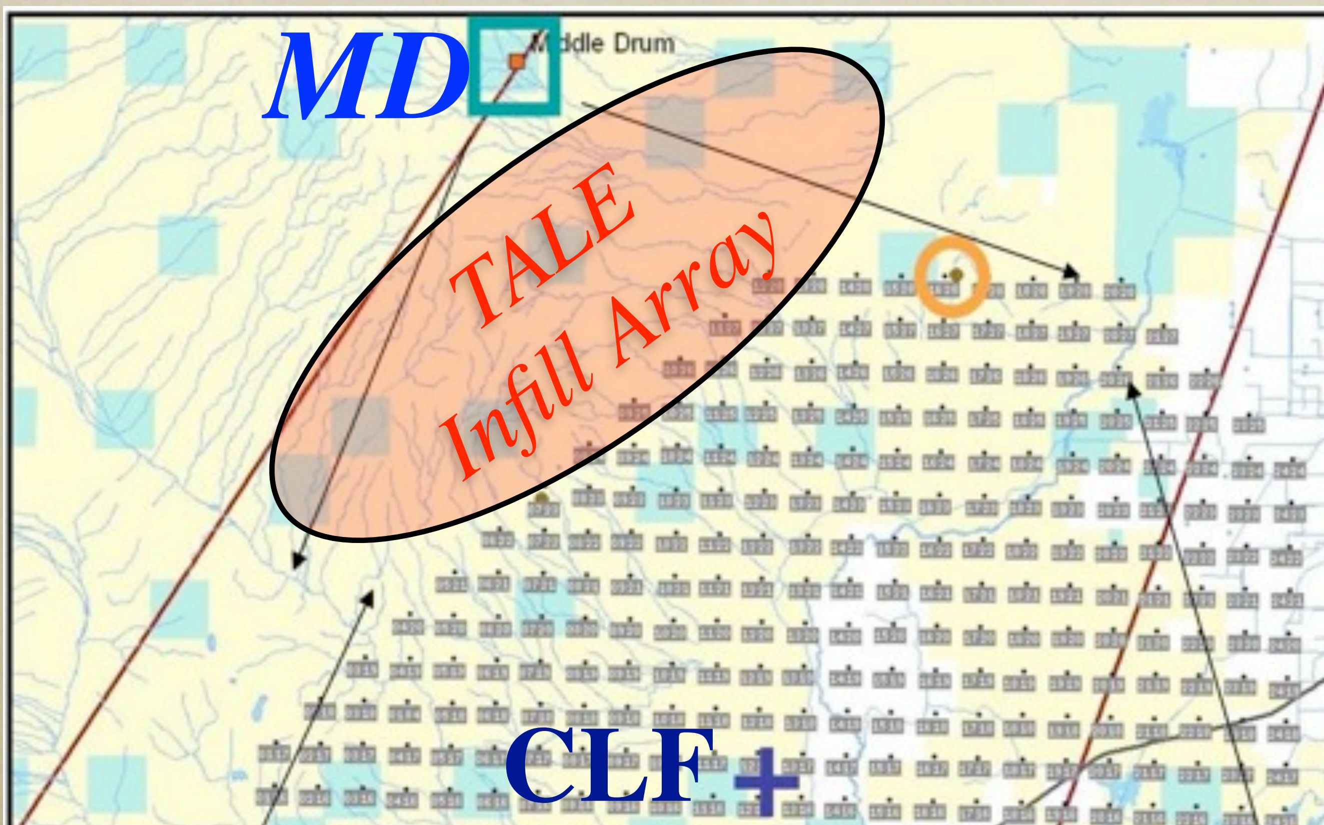
Importance of $10^{16\sim18}$eV

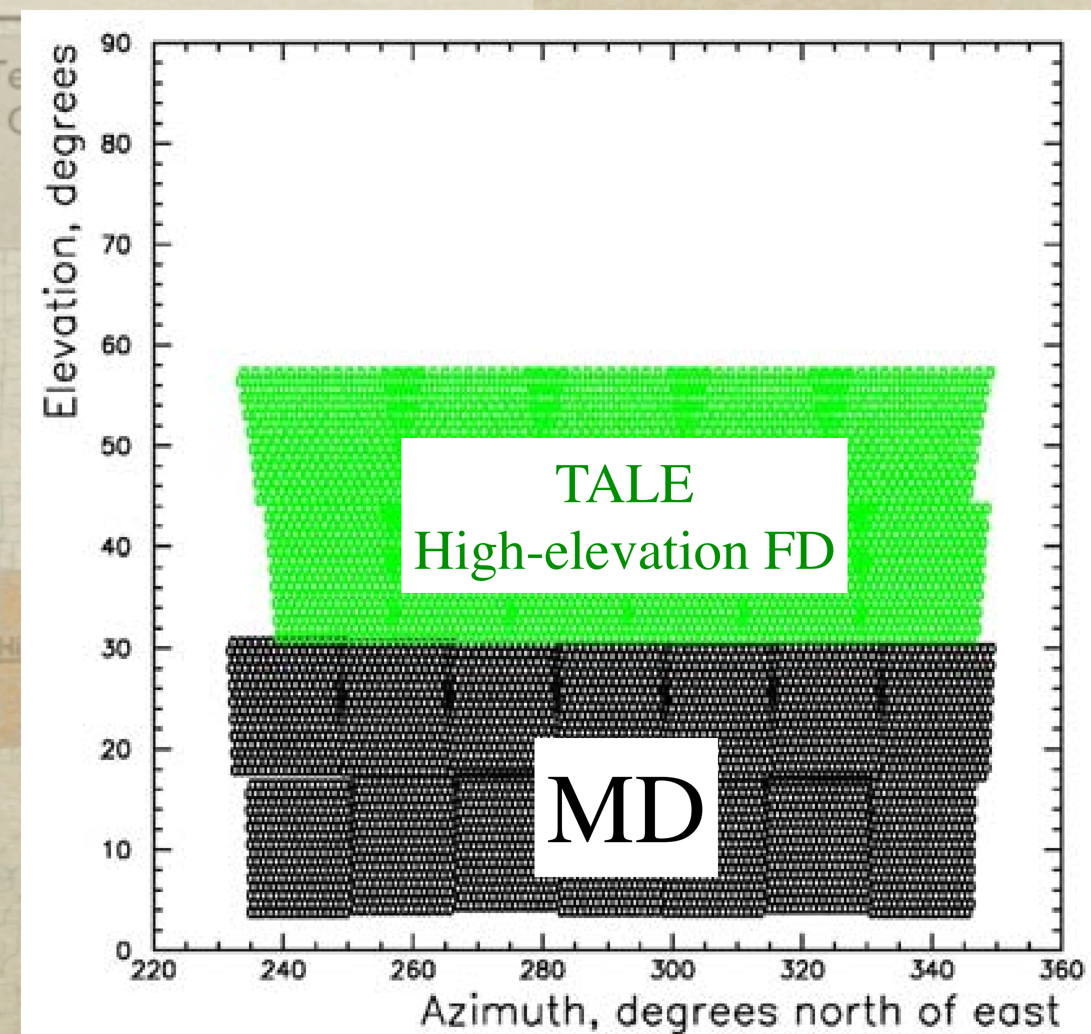


- Drastic change of composition at $\sim 10^{17}$eV?
- Galactic-to-extra-galactic transition?
- Second knee?
- LHC $\sqrt{s}$!

TALE: TA Low-Energy Extension

G.Thomson *et al.*: Poster 1307





- **SD: Infill array near MD**
  - 400/600m separation
  - >10% efficiency for $E > 10^{16.5}$eV
- **FD: High-elevation telescopes**
  - Up to 59°
  - HiRes-II

Conclusion

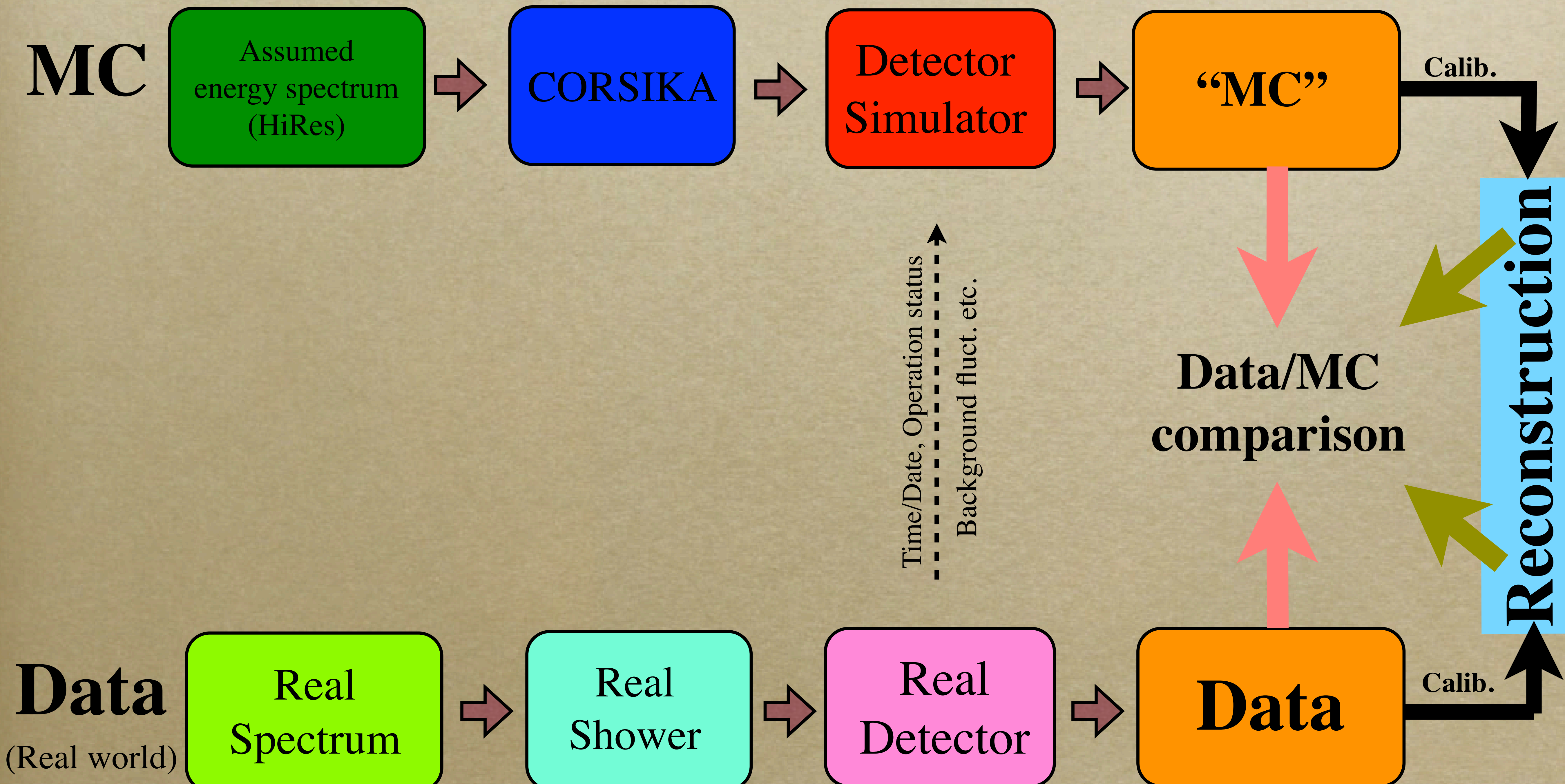
- 3 years TA full operation
- Energy Spectrum:
  - Consistent with HiRes
    - SD/FD energy scale difference
  - Ankle at $10^{18.69}$ eV
  - Cut-off at $10^{19.68}$ eV: Deficit: 3.9σ
- Proton dominant composition up to the cut-off energy
- Anisotropy: Need more statistics!
  - Compatible with both isotropy and AGN/LSS correlation hypothesis

Conclusion

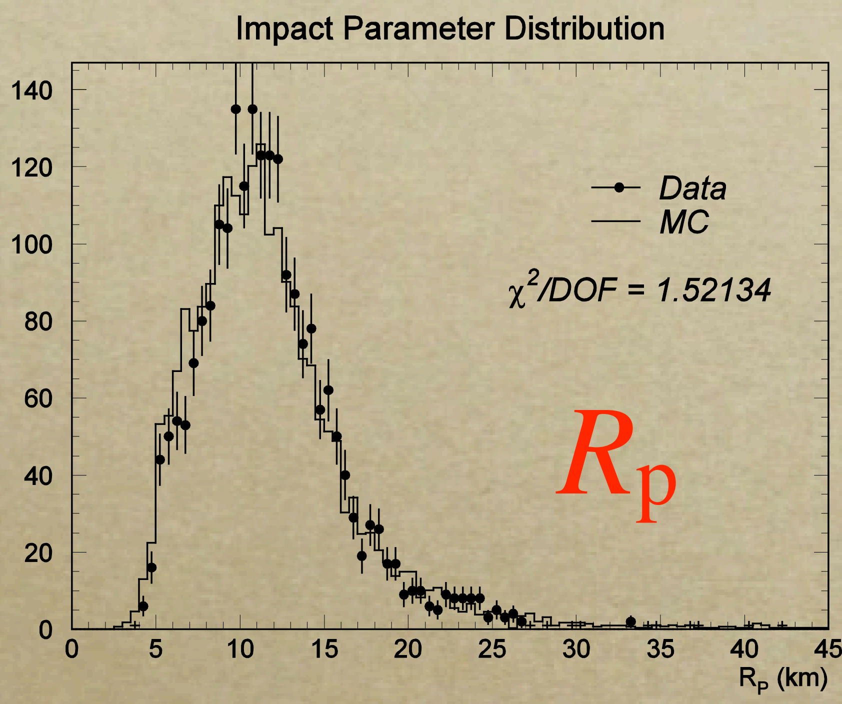
- 3 years TA full operation
- Energy Spectrum:
  - Consistent with HiRes
    - SD/FD energy scale difference
  - Ankle at $10^{18.69}$ eV
  - Cut-off at $10^{19.68}$ eV: Deficit: 3.9σ
- Proton dominant composition up to the cut-off energy
- Anisotropy: Need more statistics!
  - Compatible with both isotropy and AGN/LSS correlation hypothesis
- Question: Have we seen the GZK cut-off?
  - *Consistency between composition and the position of E_{cut} ?*
  - *Anisotropy: CR horizon? z_{max} dep.? B-field? Spectral shape around E_{cut}?*

Backup

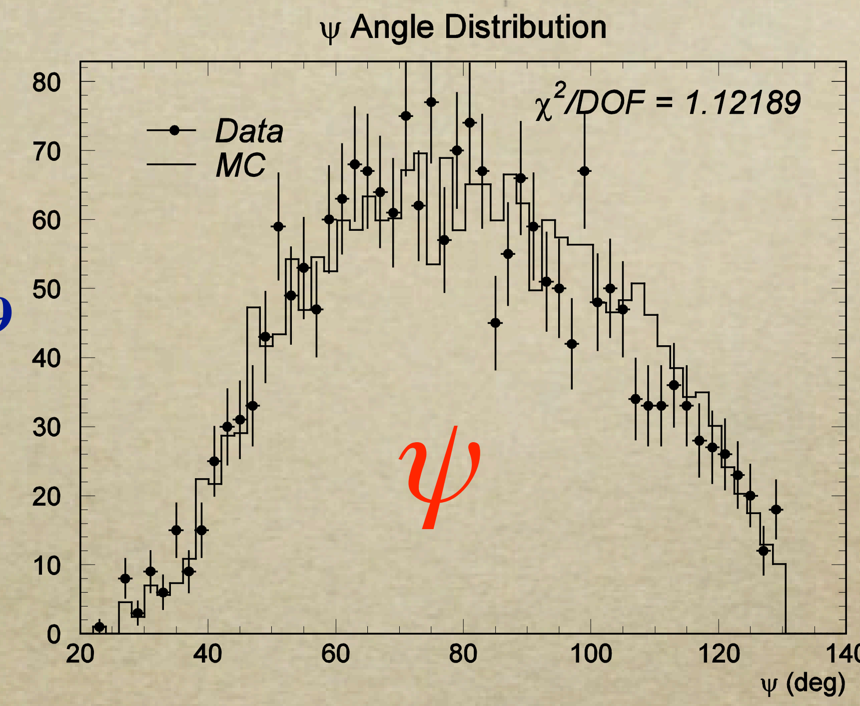
Understanding Our Detectors

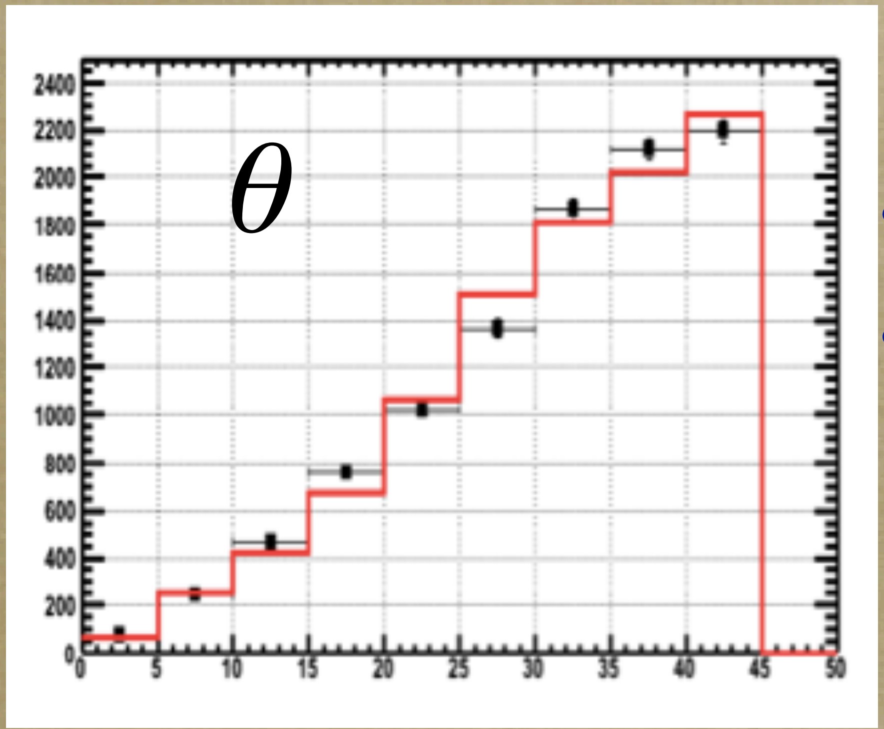


Understanding Our Detectors

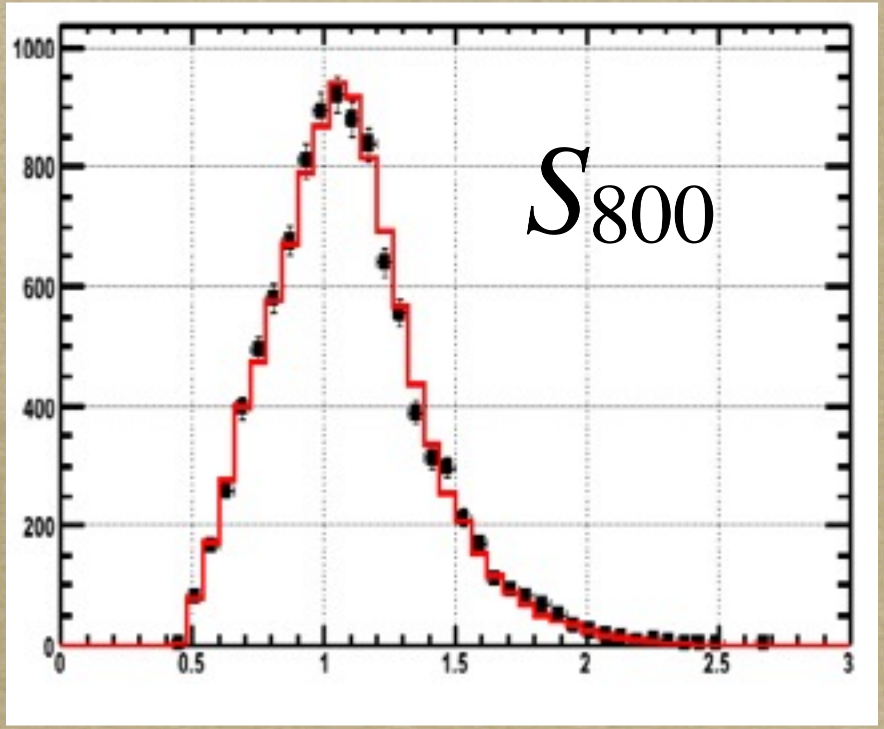


•S.Stratton: Poster 1299





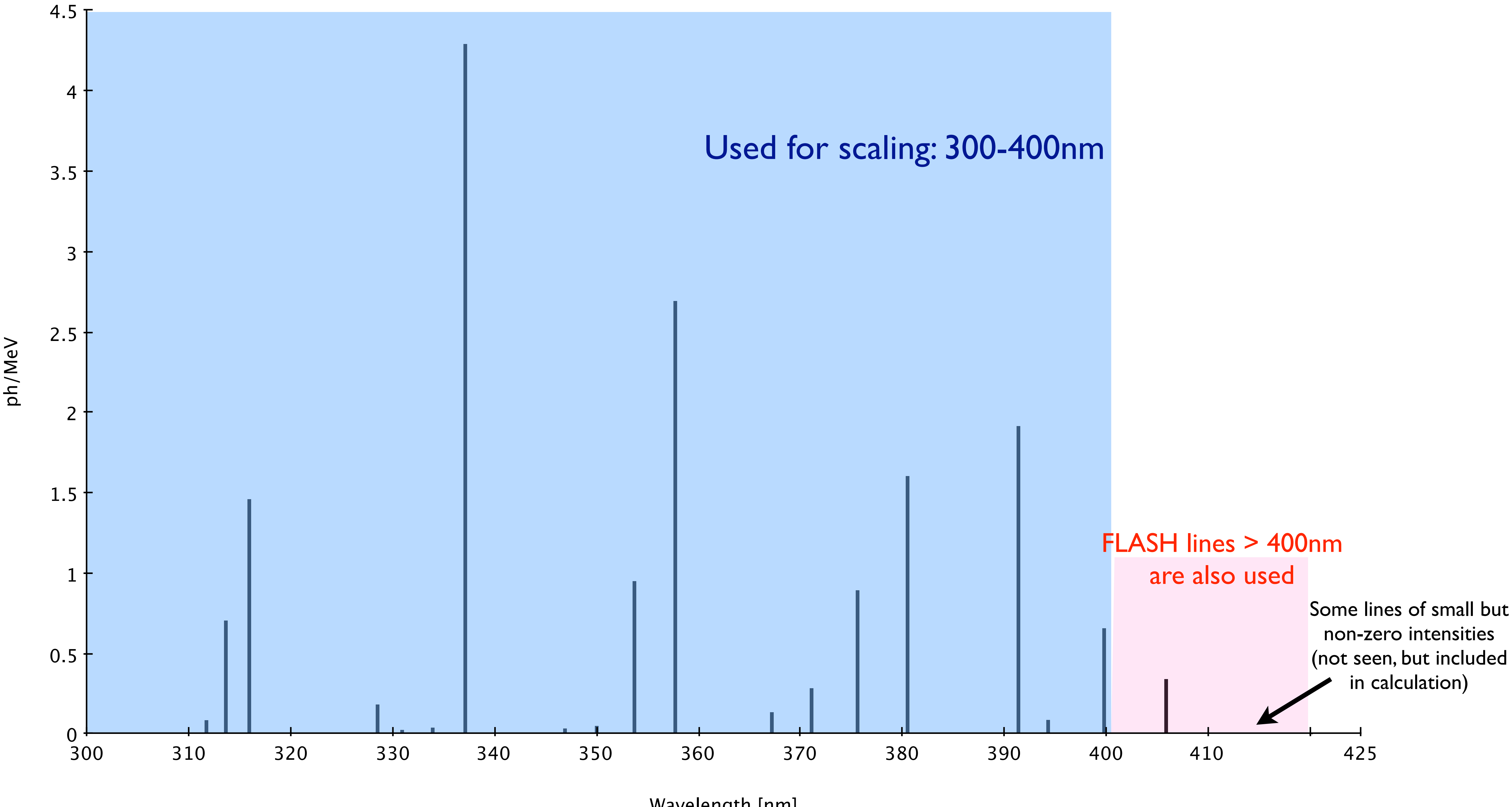
•D.Ivanov/B.Stokes:
Oral 1297 (Aug12)
•B.Stokes: Poster 1288



TA FLY Model

2011/Mar/04 Y.Tsunesada, K. Hayashi (TokyoTech)

- Spectral lines and their relative intensities are from Abbasi *et al. Astropart. Phys.*, **29** 77-86 (2008)
    - Defined in 300-420nm
- Scaled to the Kakimoto's yield in 300-400nm, Kakimoto *et al. NIM A*, **372** 527-533 (1996)
    - (The total yield of the TA FLY model in 300-420nm is slightly larger than Kakimoto's.)



- Spectral lines and relative intensities are from FLASH:

$$\int_{300}^{420} f_{\mathrm{FLASH}}(\lambda) d\lambda = 1$$

Abbasi *et al. Astropart. Phys.*, **29** 77-86 (2008) Figure 9.

- $FLY_{\mathrm{TA}}(\lambda)$ ([ph/MeV] or [ph/m]) **is defined by scaling** $f_{\mathrm{FLASH}}(\lambda)$

$$FLY_{\mathrm{TA}}(\lambda)\ [\mathrm{ph/MeV}] \equiv \alpha f_{\mathrm{FLASH}}(\lambda)$$

- The scaling factor α is obtained as

$$\alpha \int_{300}^{400} f_{\mathrm{FLASH}}(\lambda) d\lambda = K = \mathrm{Kakimoto's}$$ @ 1013hPa/293K

- Therefore

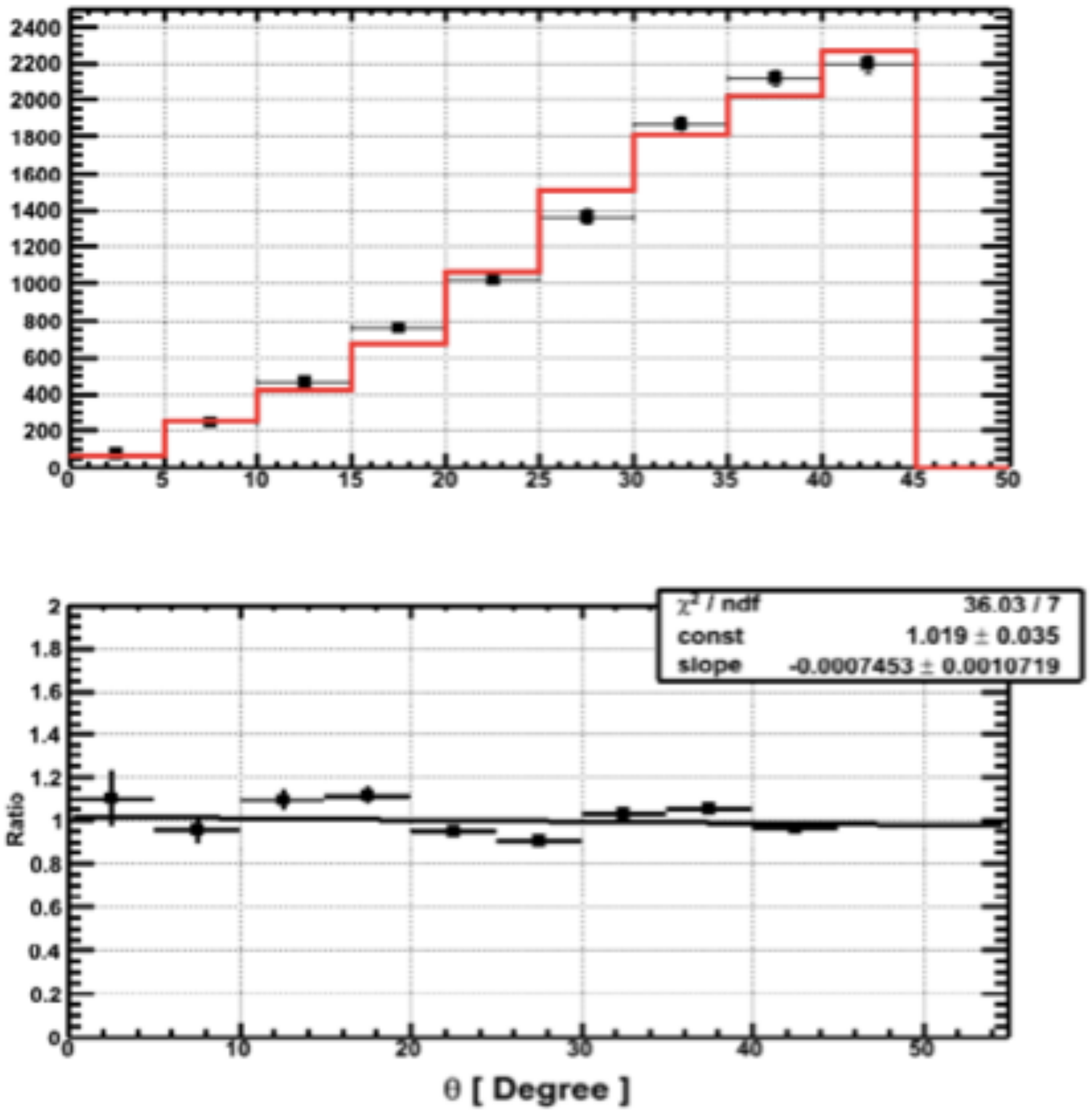
$$FLY_{\mathrm{TA}}(\lambda) \equiv \frac{K}{\int_{300}^{400} f_{\mathrm{FLASH}}(\lambda) d\lambda} f_{\mathrm{FLASH}}(\lambda)$$

Note that $\int_{300}^{420} FLY_{\mathrm{TA}}(\lambda) d\lambda > K$

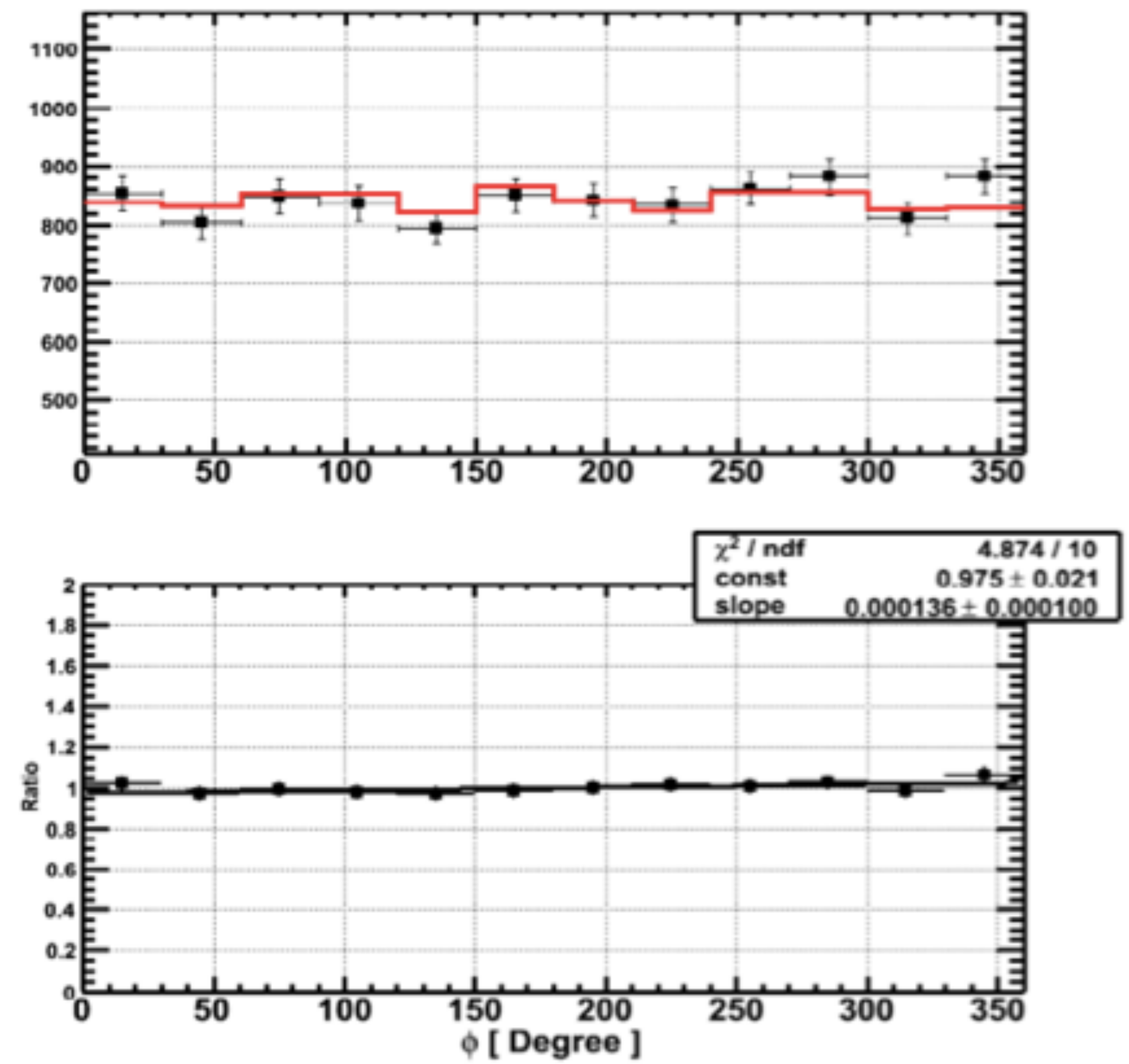
SD Analysis: Data Quality Cuts

- Good data fits:
  - χ^2/d.o.f.: > 4.0
  - Pointing direction resolution: < 5^o
  - Fractional S800 uncertainty: < 25%
- Good shower geometry:
  - Border Cut > 1200m
  - Zenith Angle Cut: < 45^o
- **3 years, 10,997 events**

SD Analysis: Data/MC Comparisons

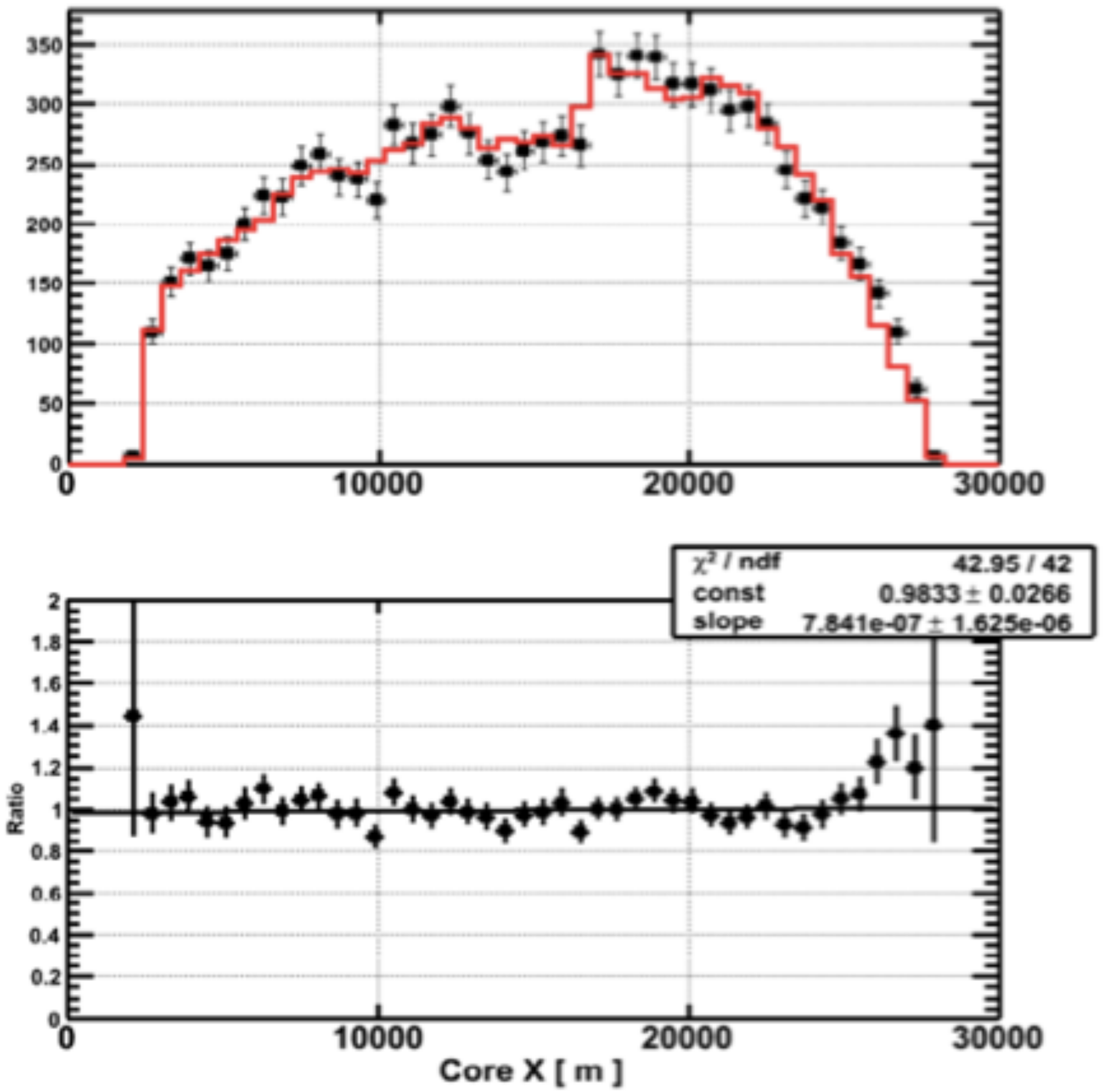


Zenith angle

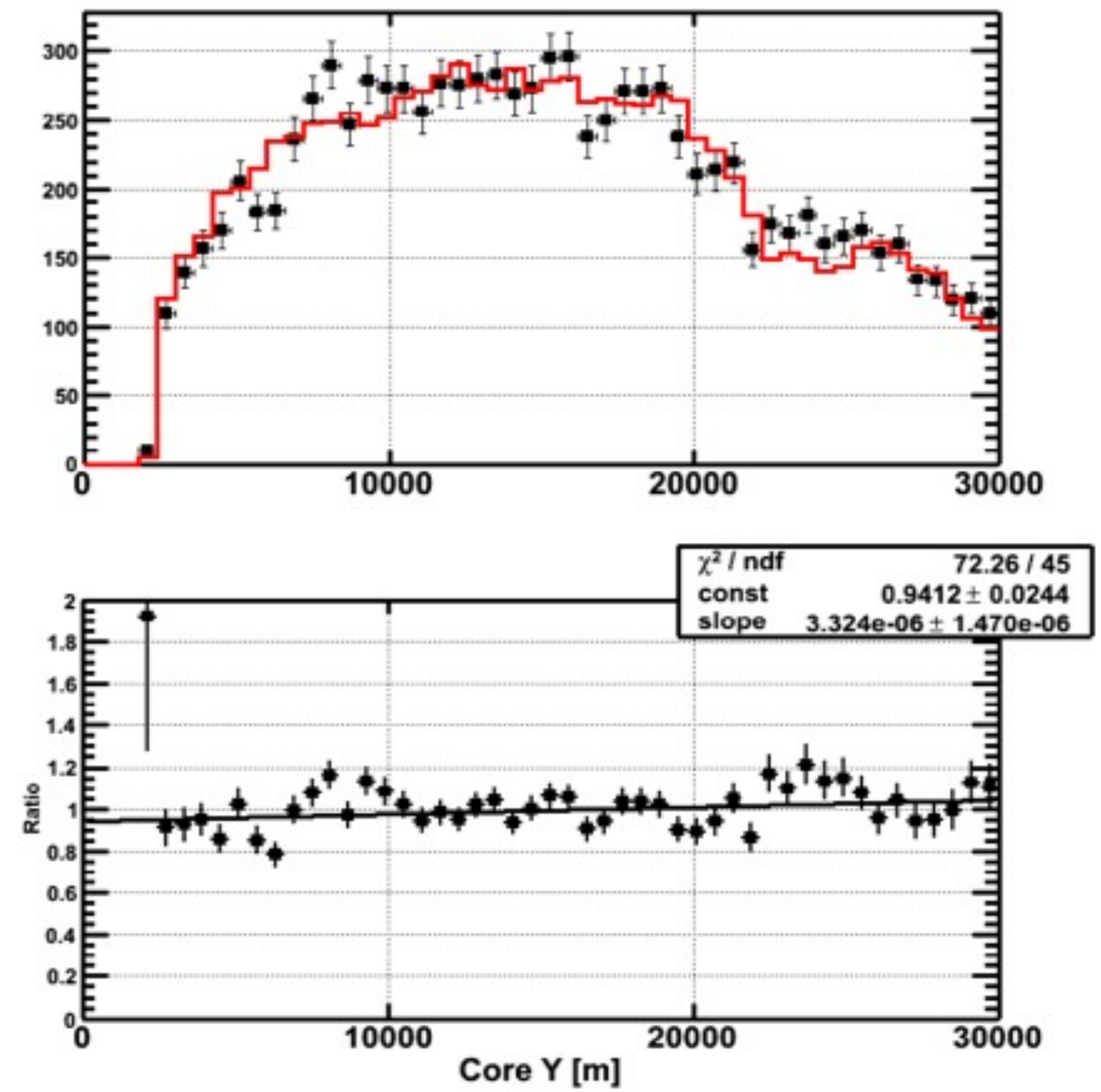


Azimuthal angle

SD Analysis: Data/MC Comparisons



Core Position (E-W)

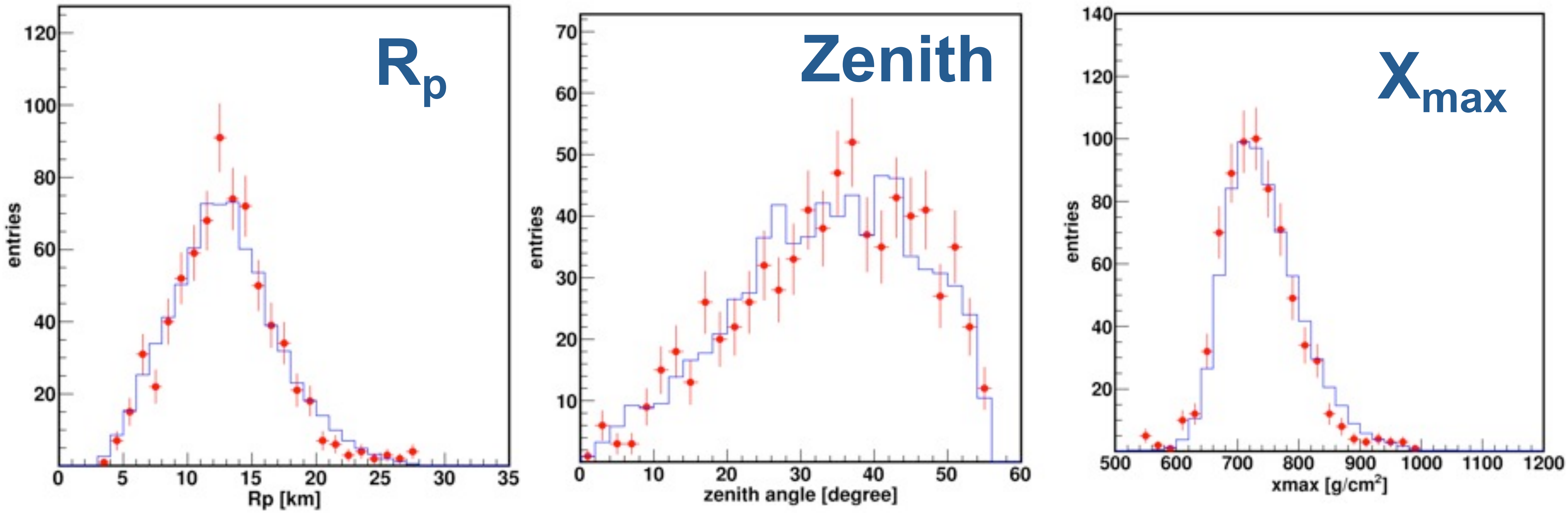


Core Position (N-S)

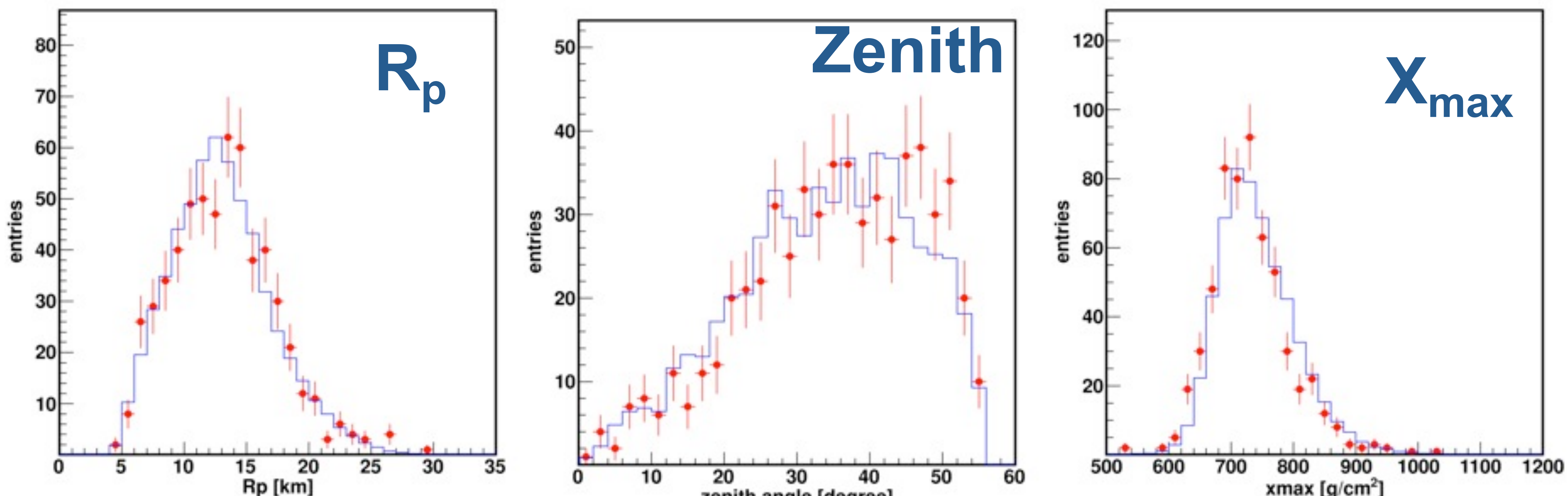
Data / MC comparison

Red points: Data, Blue histograms : MC

BR

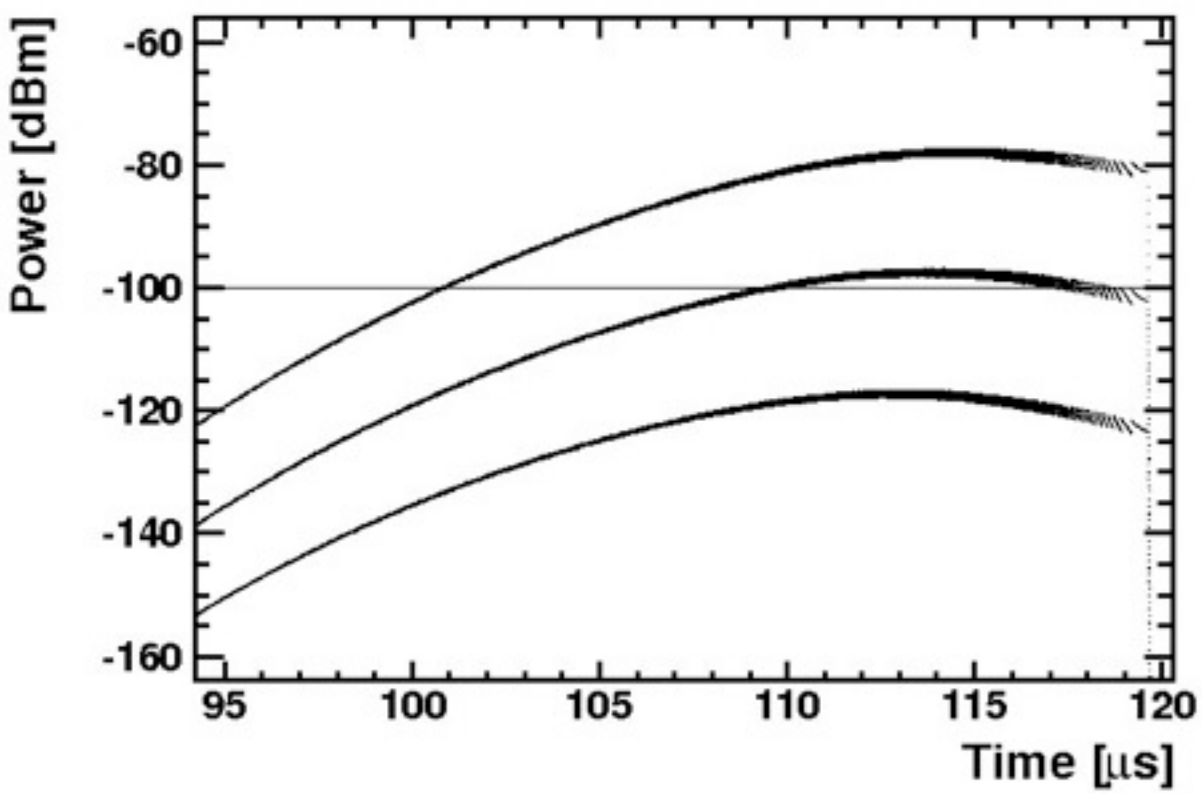


LR



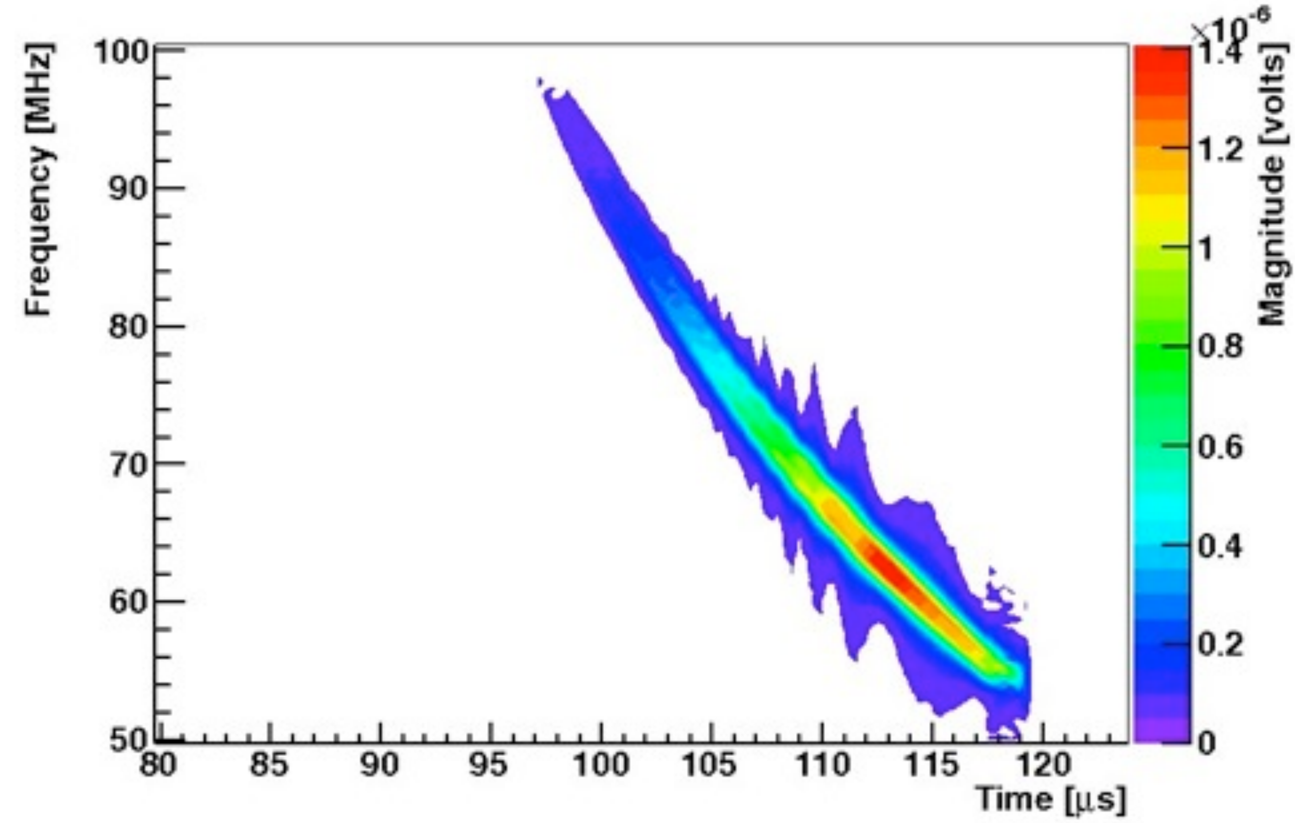
Signal Characteristics

Signal-to-Noise



- Assume 20 kW transmitter
- Prediction for received power for 10^{18}, 10^{19}, 10^{20} eV showers, 30° from zenith, typical TA distances and antenna gain.
- Horizontal line: Galactic noise floor (4 MHz B.W.)

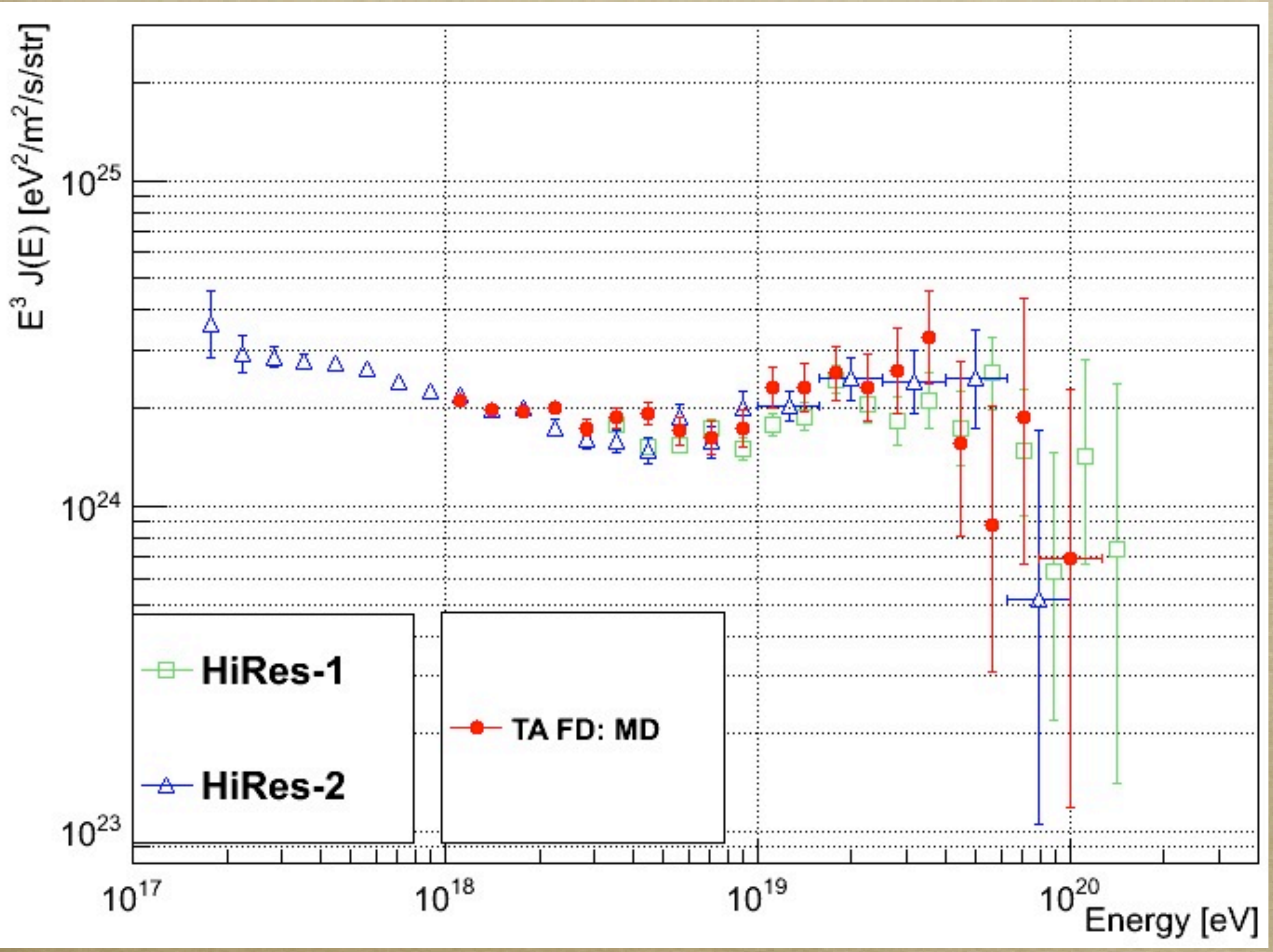
Phase Modulation



- Predicted signal for 10^{19} eV shower, 30° from zenith; frequency vs time.
- Rapid movement of "target" produces Doppler-like frequency shift.
- Unique signature for air shower echoes!

TA-MD & HiRes Spectra

D.Rodriguez *et al.*, Poster 1303



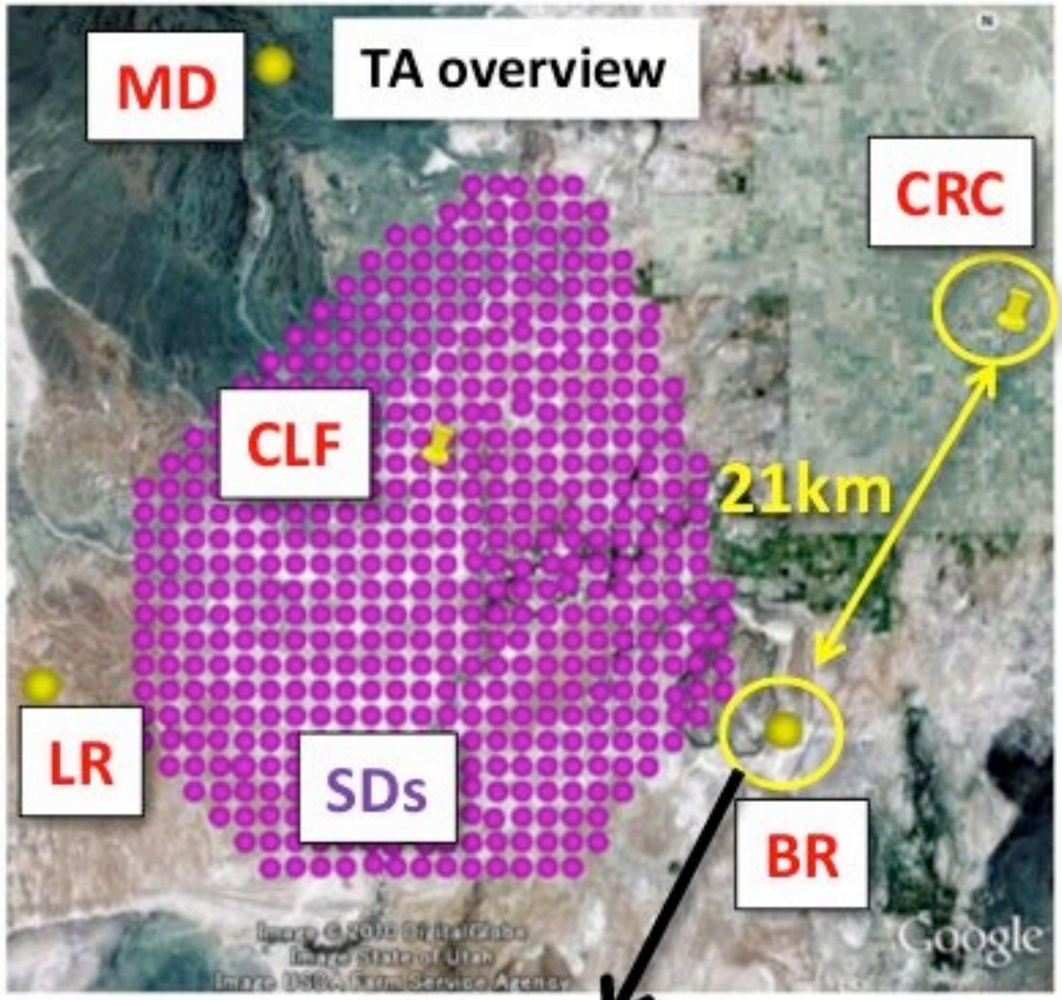
- Three years data of TA-MD, refurbished HiRes-I detector
  - ~1/3 HiRes-I exposure

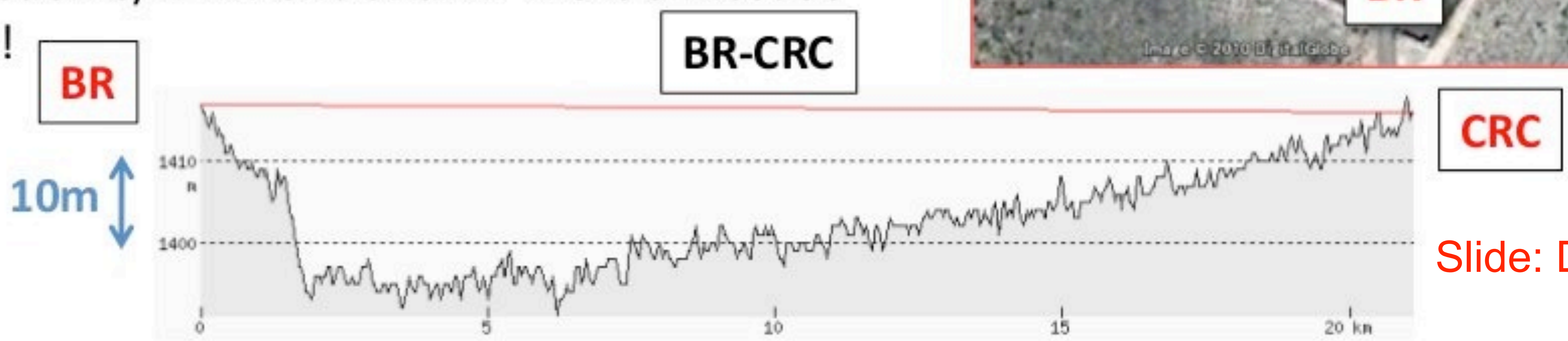
- Excellent agreement between HiRes and MD: HiRes is still alive!

ELS observation

Observation for the reflected radio from ELS shower to confirm the method

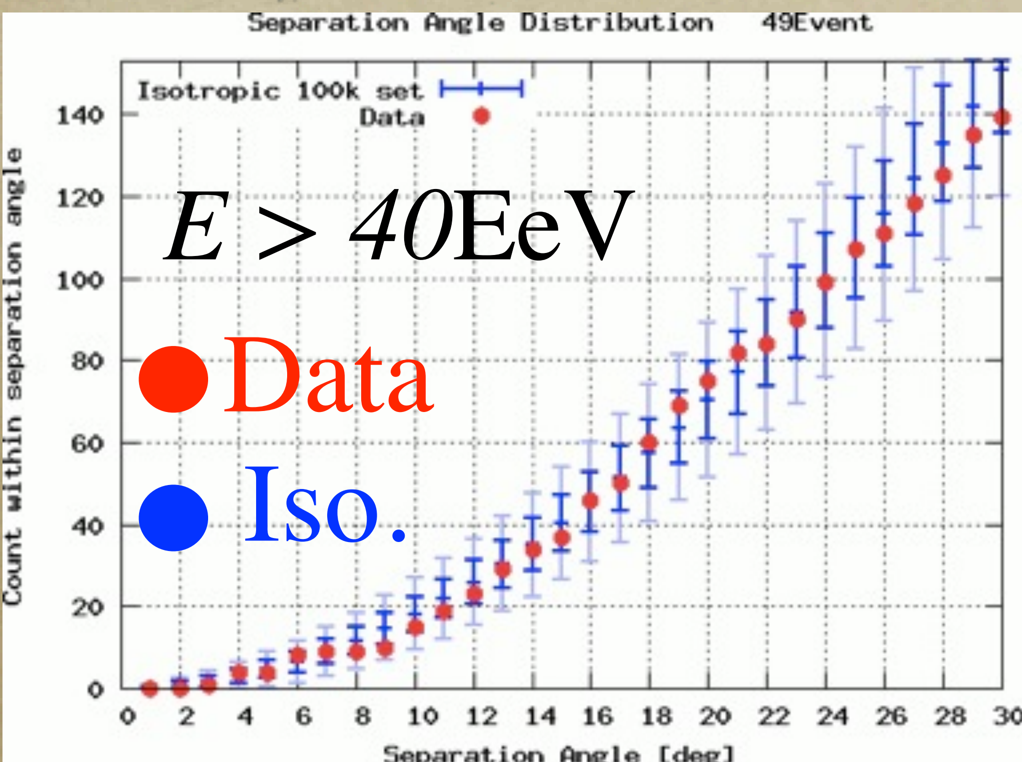
- Set the observer to the roof of BR station
- Radio path: CRC - ELS - BR
- Receiver : Five-element Yagi antenna
    - Design is fixed (see other file)
- Also we can measure the cross-section
    - Distance: CRC-BR >> ELS-BR
    - Can measure the power of coming radio from CRC by seeing to CRC
    - Cross-section is obtained by the ratio of detected power: seeing to ELS / seeing to CRC
- For this test, E-Plane of trans. wave should be vertical.
- Geometry b/w BR and CRC is better for radio transmission.
- The direction b/w BR-CRC and BR-ELS is almost 90 degrees !!

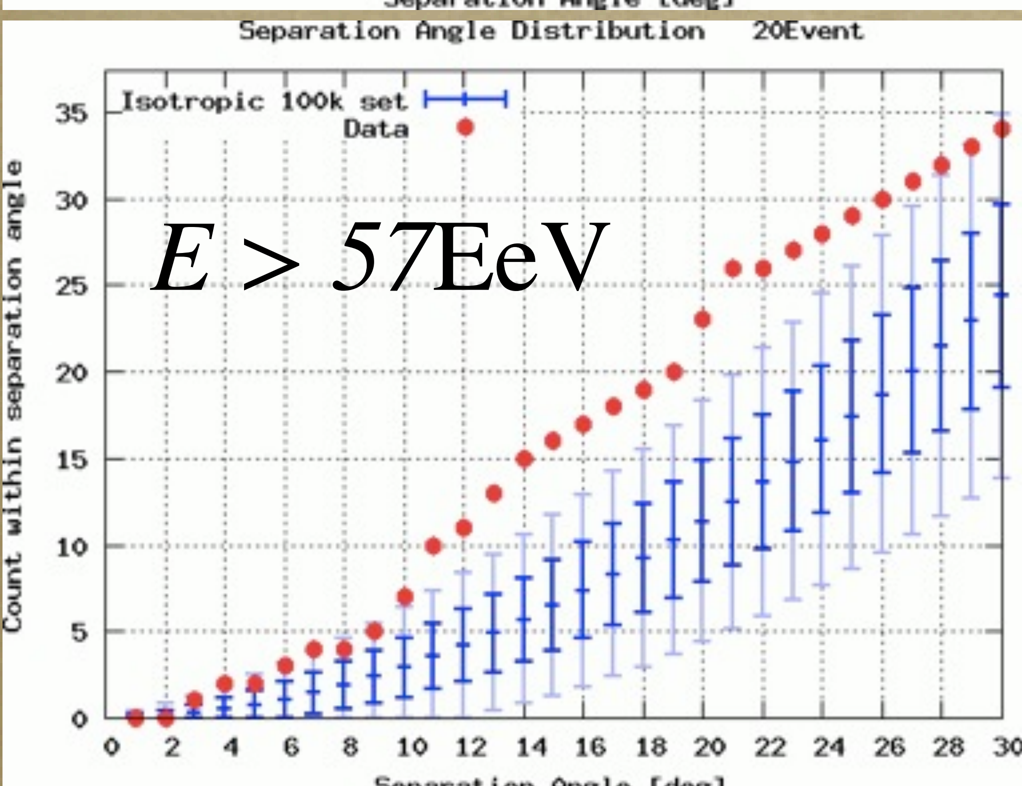




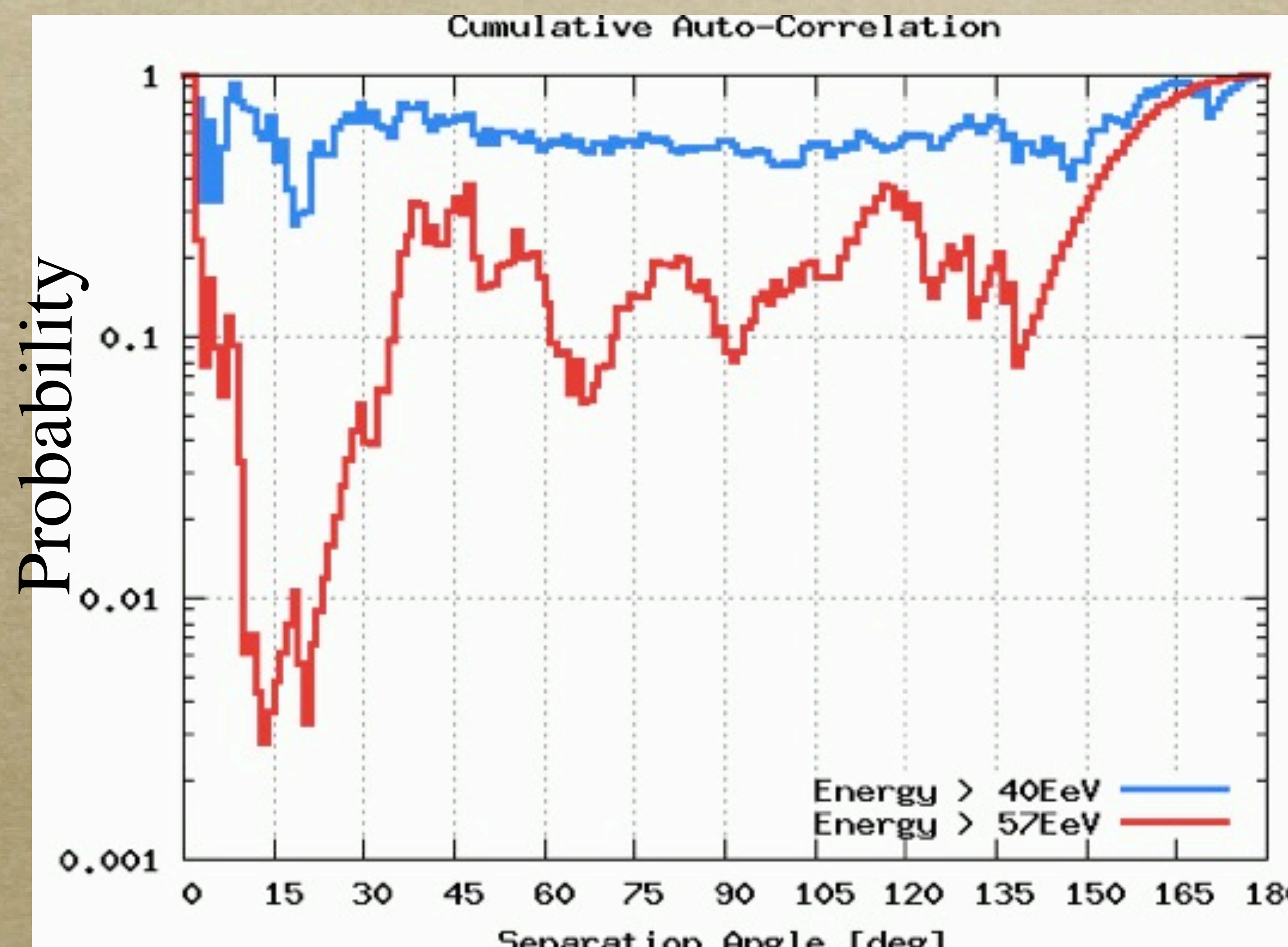
Slide: D. Ikeda

Auto-correlation: Event Clustering?

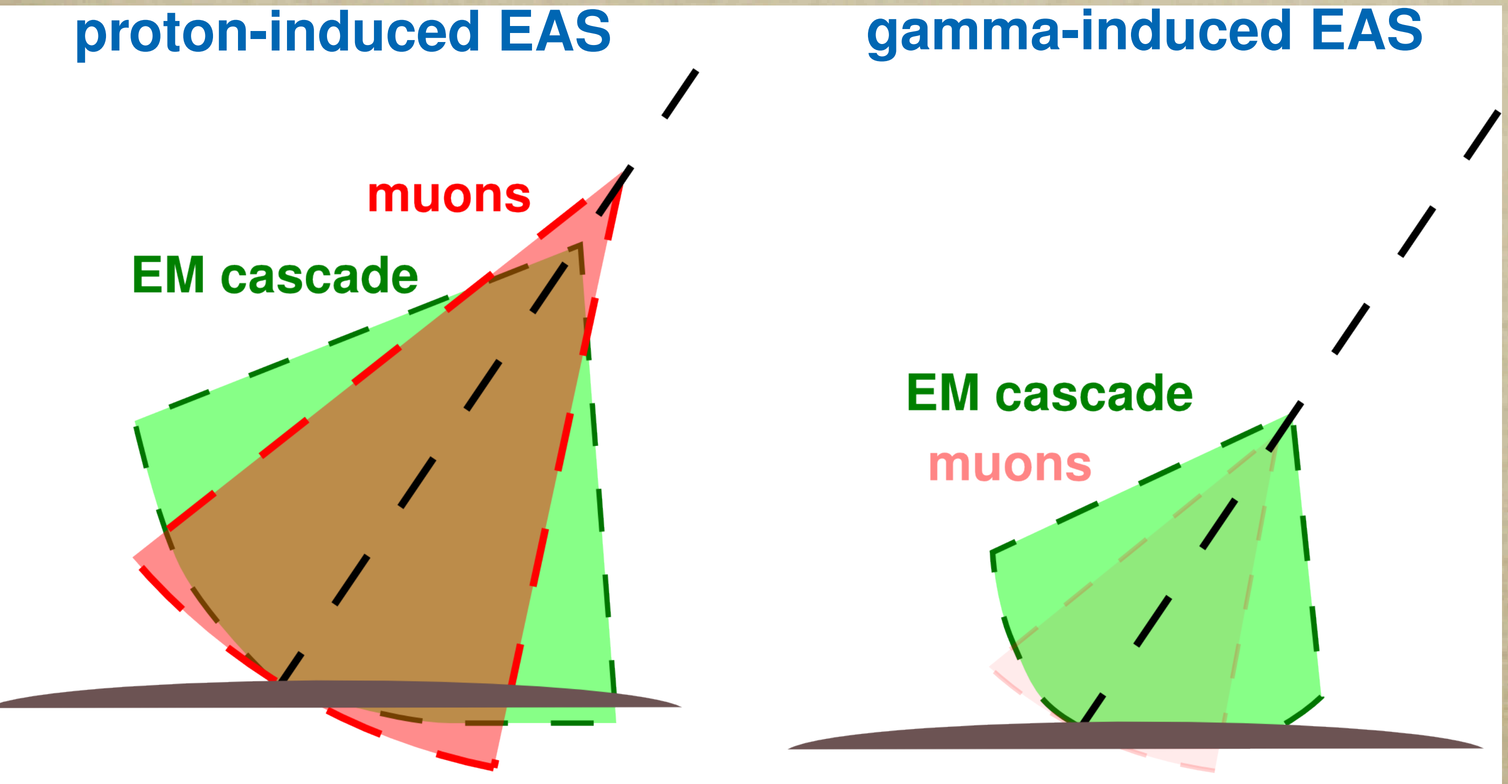




- Event counting as a function of angular distances
- No significant clustering found
- Clustering at 57EeV in 10~20^o ? $< 3\sigma$



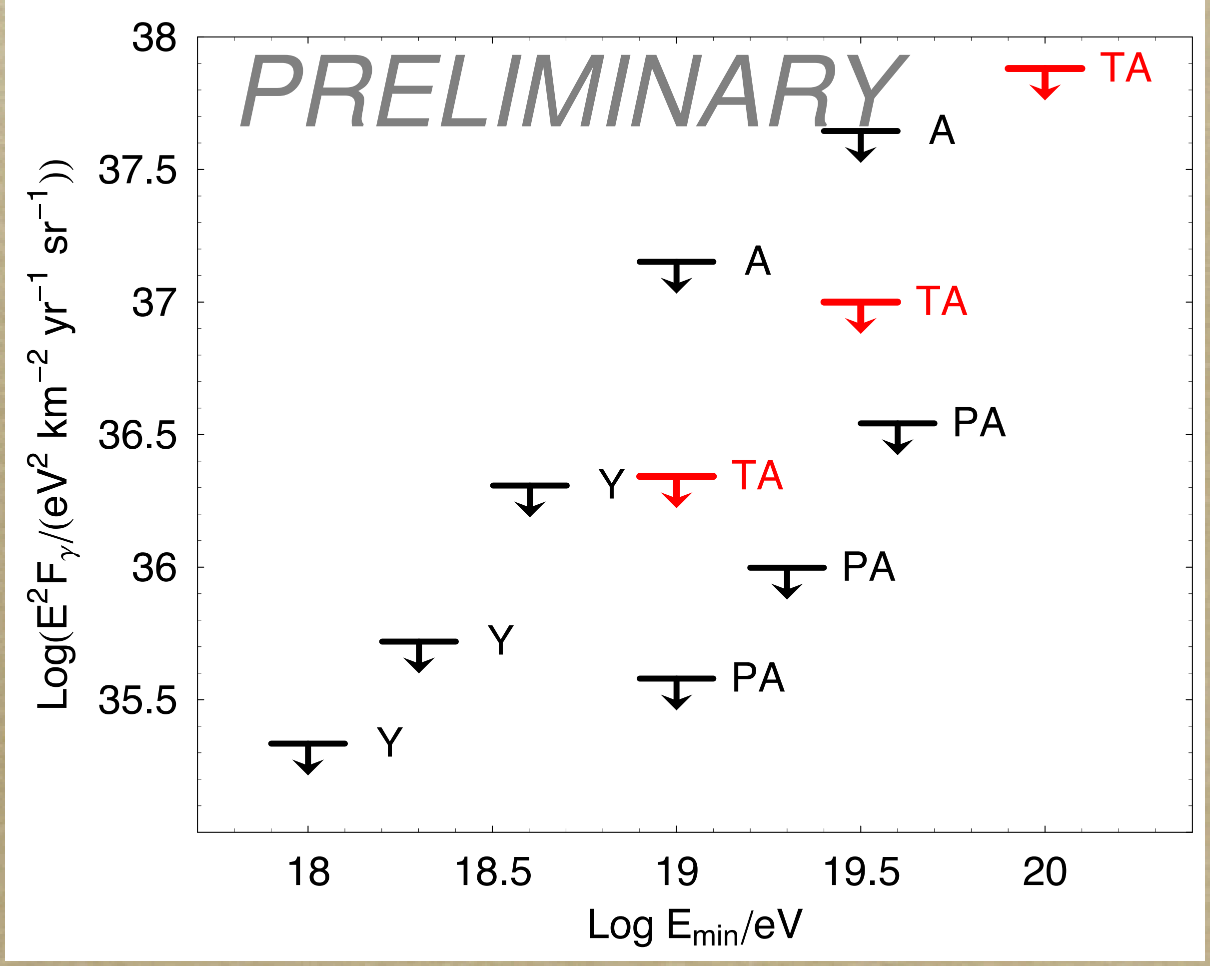
UHE Photon Limit by SD



Deep shower maximum and shortage of muons ⇒ curved front

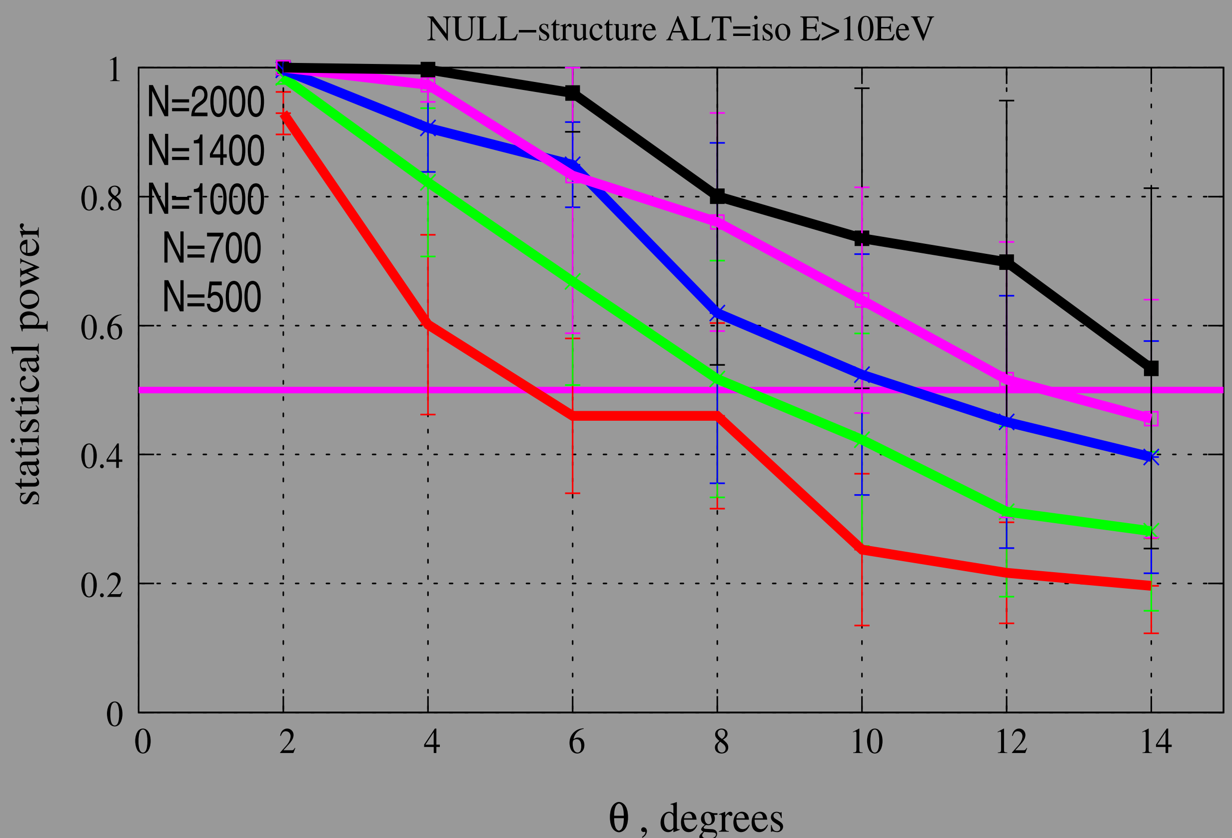
G.Rubtsov, Oral 1266

- Gamma-showers have curved front.
- Use SD 3 years data

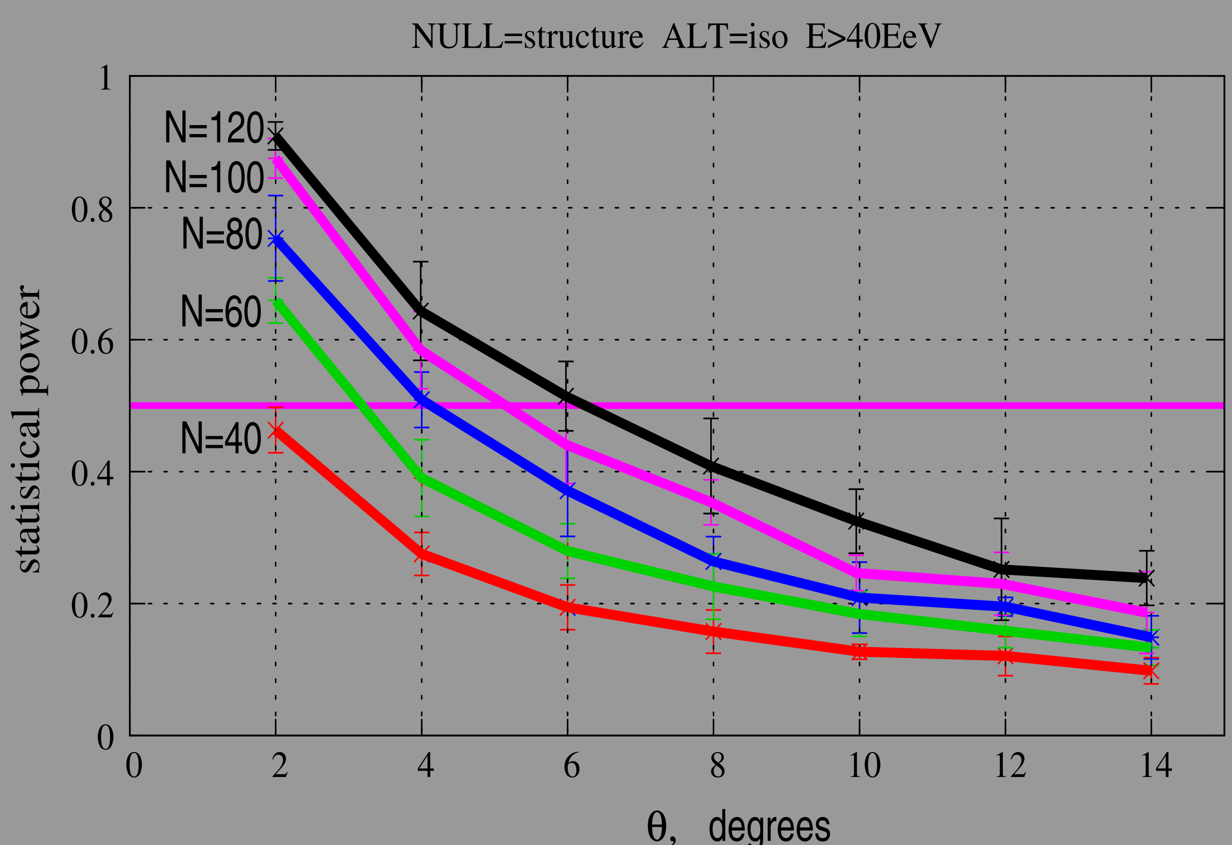


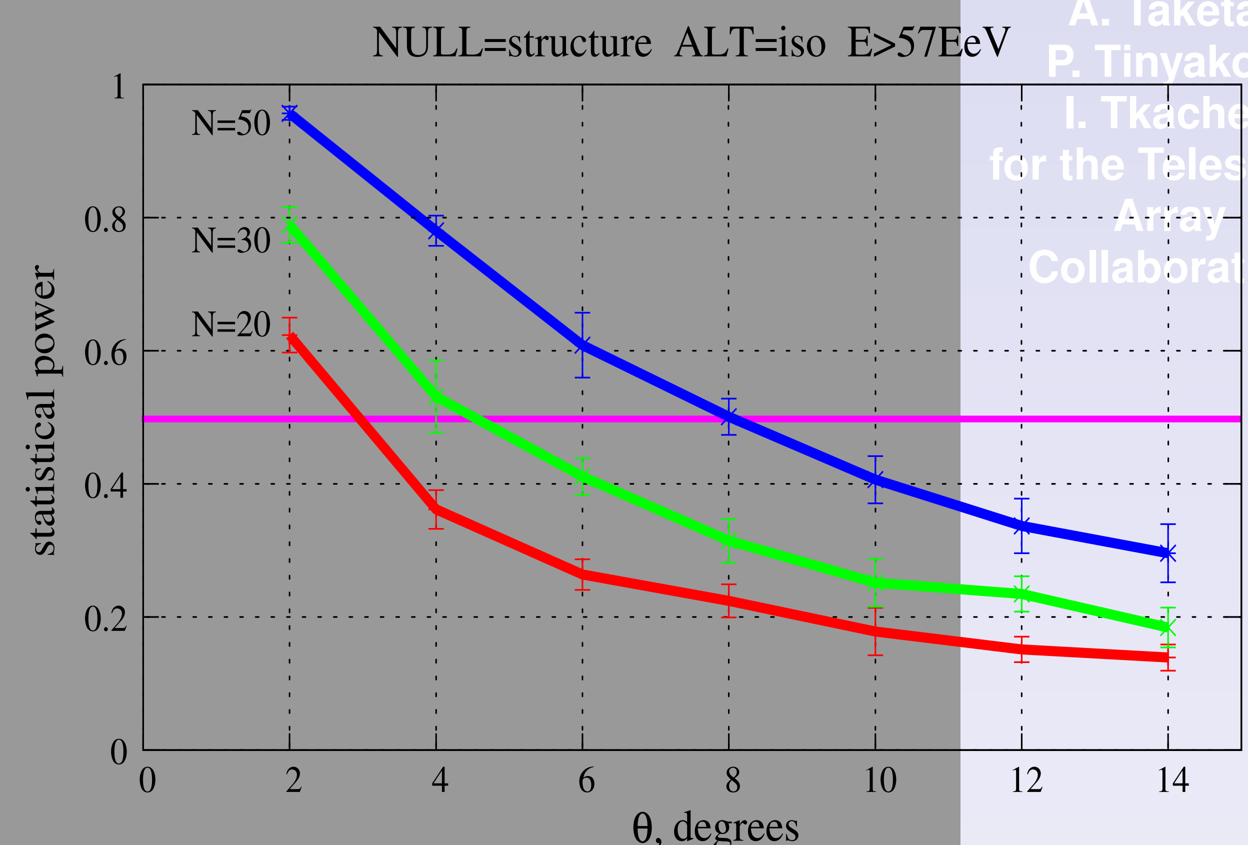
- Flux/Photon fraction limits obtained (95% CL) (Rubtsov 1266 Aug12)

STATISTICAL POWER



- Statistical power to tell isotropy from structure at different energy and number of events





SEARCH FOR LARGE-SCALE ANISOTROPY OF UHECR WITH TELESCOPE ARRAY

M. Fukushima,
E. Kido,
T. Nonaka,
T. Okuda,
M. Pshirkov,
G. Rubtsov,
H. Sagawa,
A. Taketa,
P. Tinyakov,
I. Tkachev
for the Telescope Array Collaboration