Observation of EHE Cosmic Rays with the Telescope Array experiment

Masahiro TAKEDA (ICRR)

ICNFP2018 (Greece), 2018/07/12(Thu)

< The Telescope Array (TA) Collaboration

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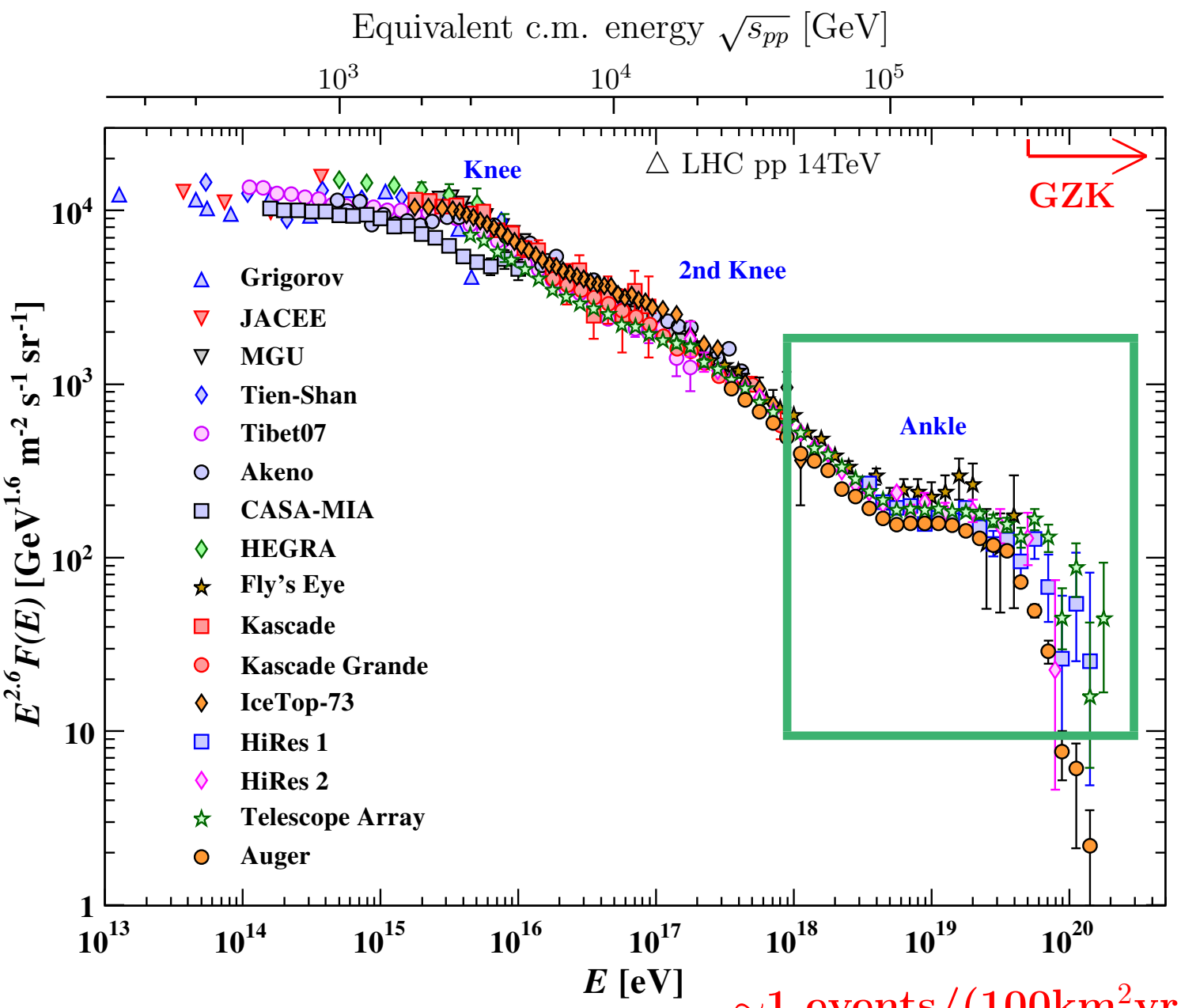
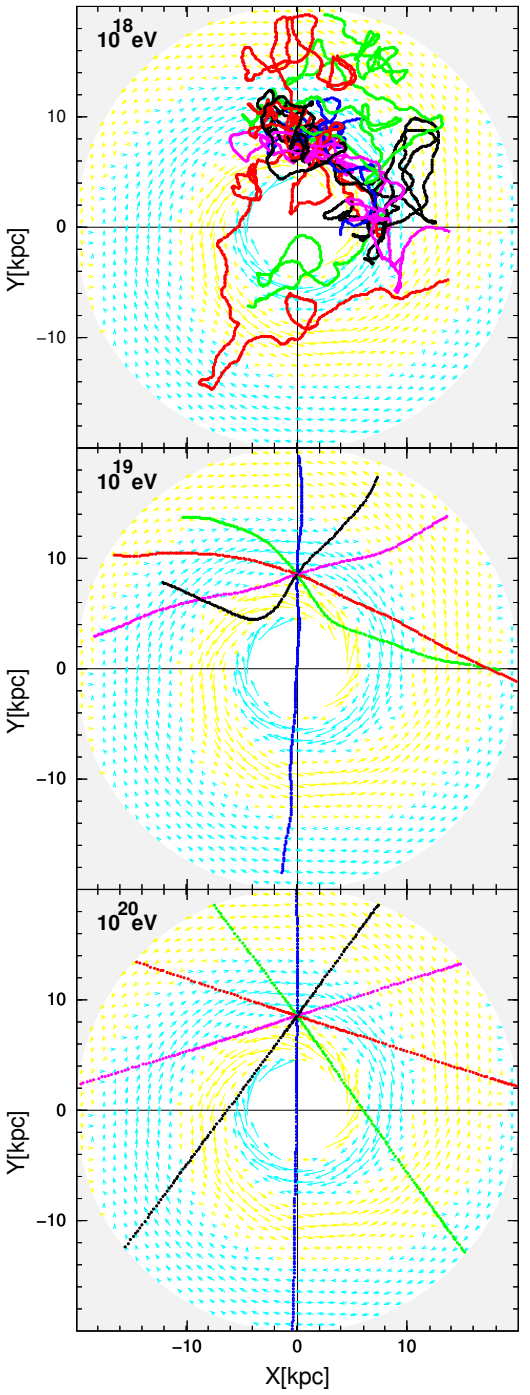
(126, 30)

< Ultra High Energy Cosmic Rays >

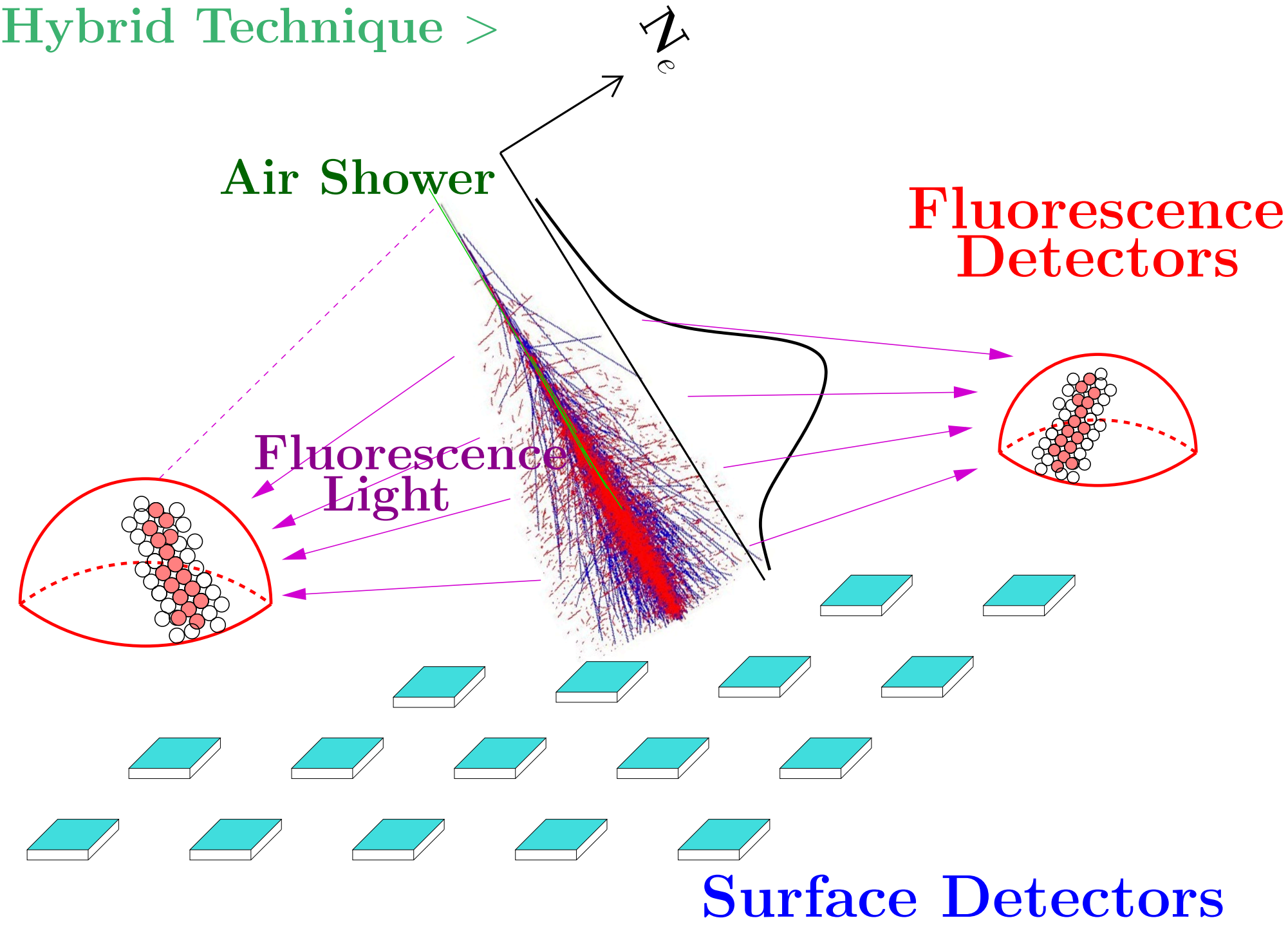




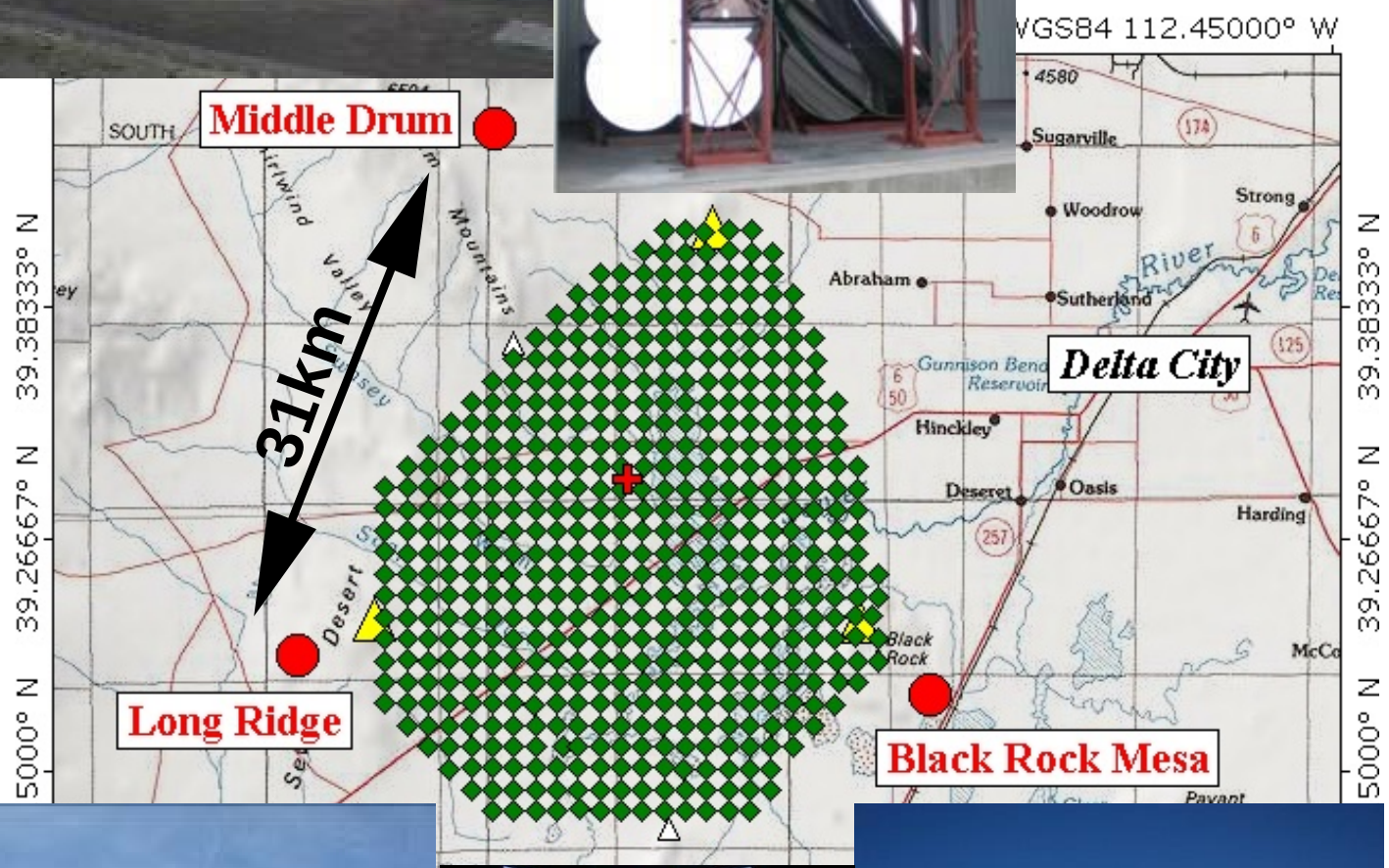
~1 events/(100km^{2}yr)
@ 10^{20}eV

PDG2016

< Hybrid Technique >



< Telescope Array Experiment >



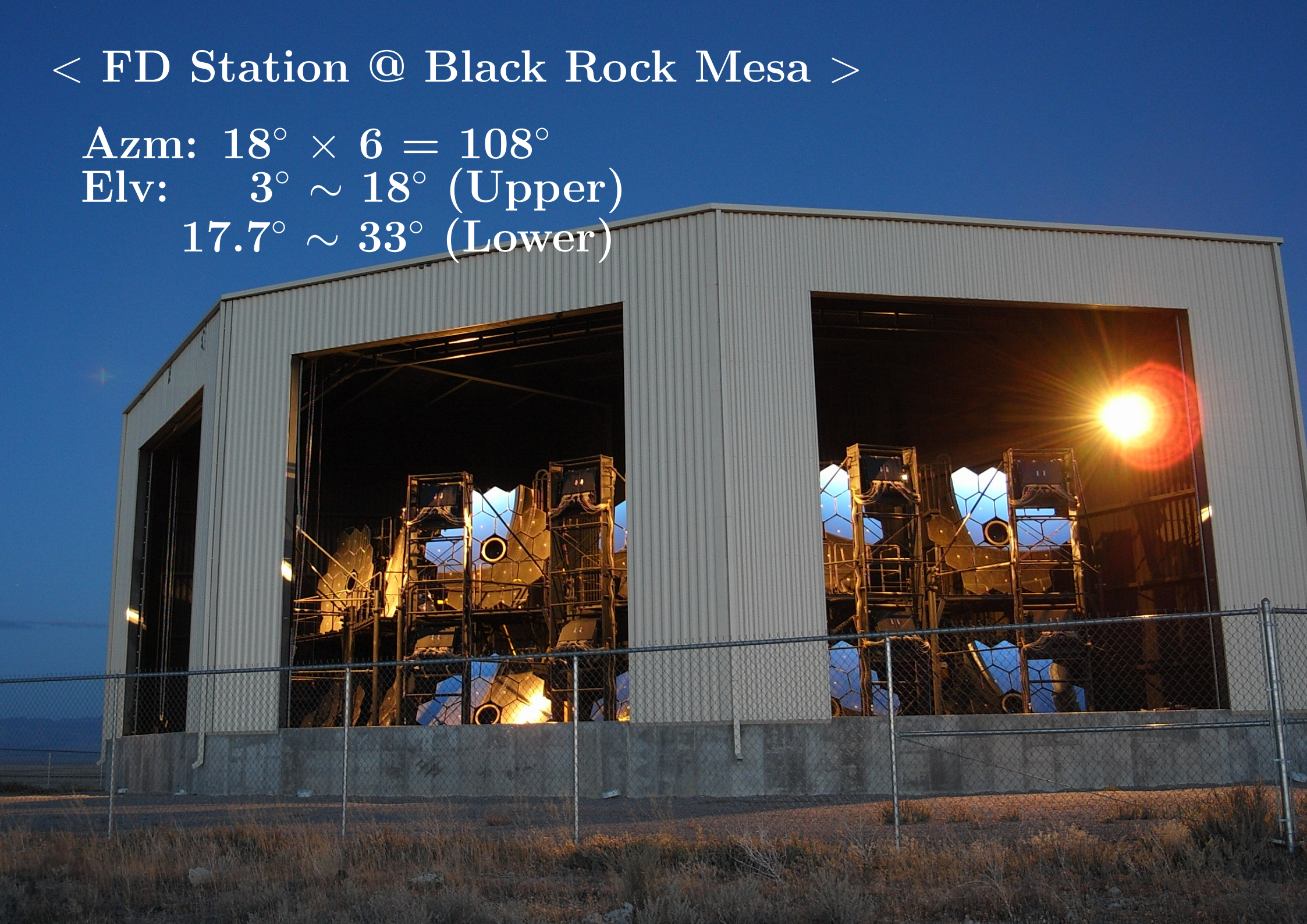
- MD FD
  14 telescopes
  - $5.2m^2$
  - 256 PMTs
  - 1° pixel

- SD array
  507 detectors
  - 1.2km grid
  - $3.0m^2$
  - wireless comm
  - solar panel

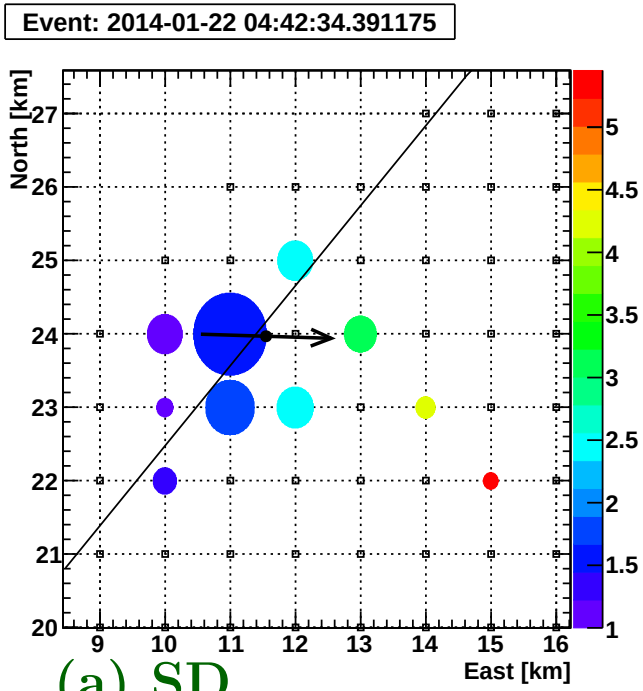
- BRM / LR FD
  12 telescopes
  - $6.8m^2$
  - 256 PMTs
  - 1° pixel

< FD Station @ Black Rock Mesa >

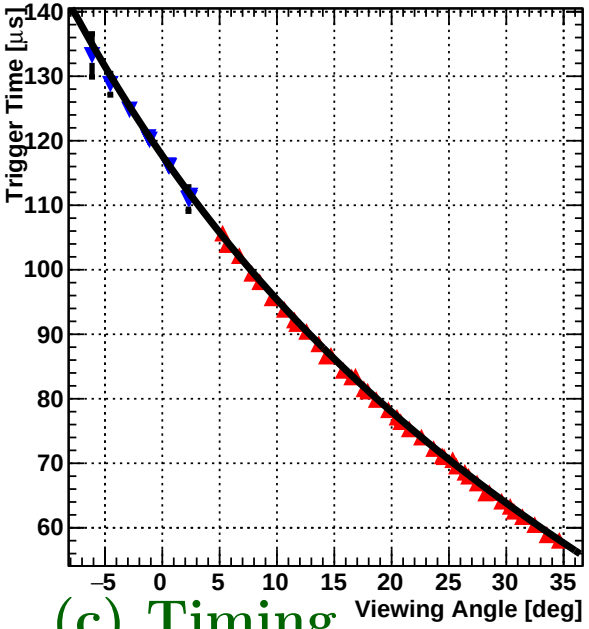
Azm: $18^\circ \times 6 = 108^\circ$
Elv: $3^\circ \sim 18^\circ$ (Upper)
$17.7^\circ \sim 33^\circ$ (Lower)



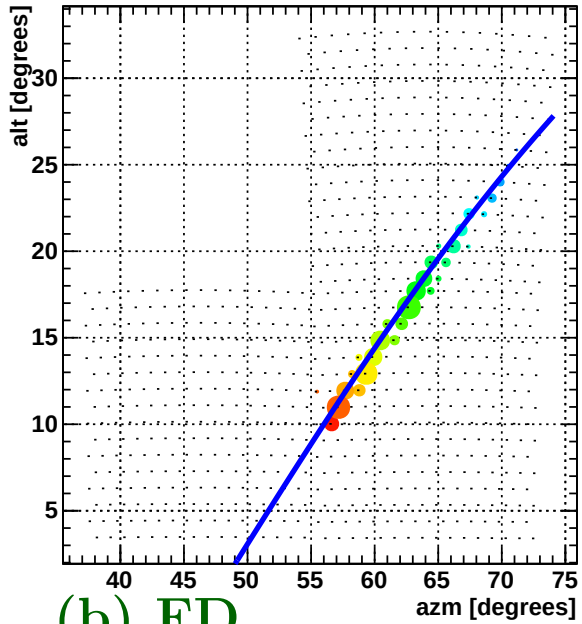
< FD (hybrid) Event Example >



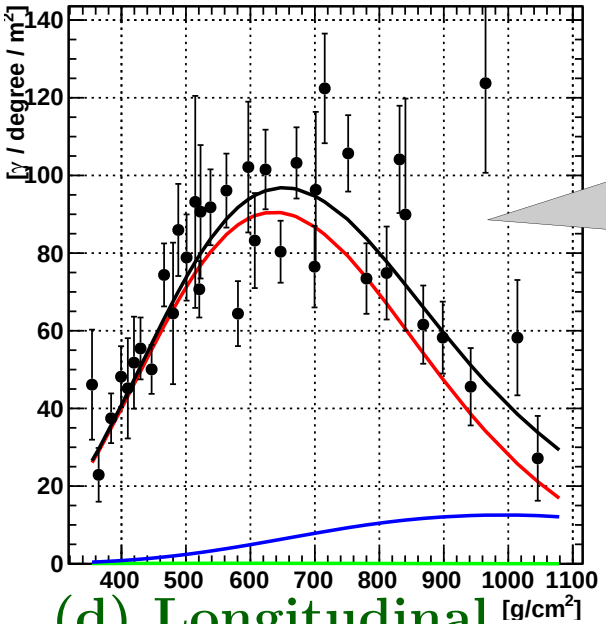
(a) SD



(c) Timing



(b) FD

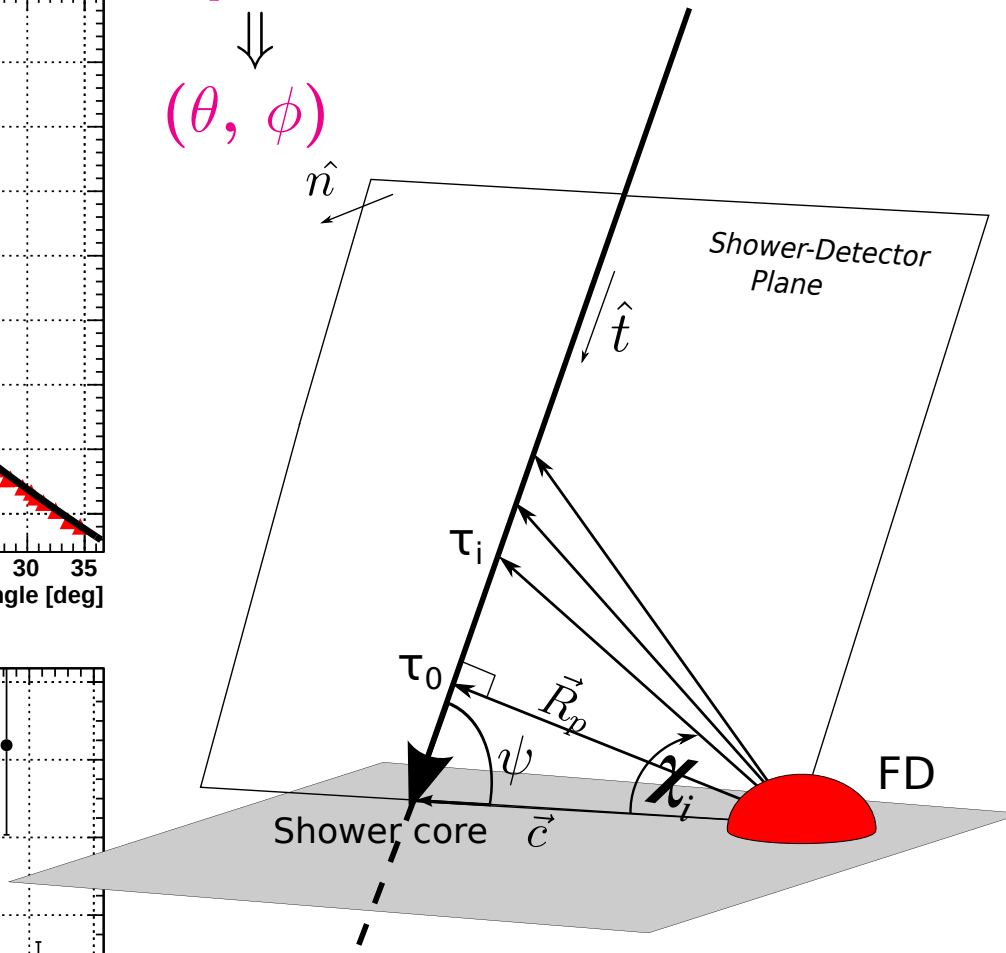


(d) Longitudinal

$(\mathbf{R}_p, \psi)$

$\Downarrow$

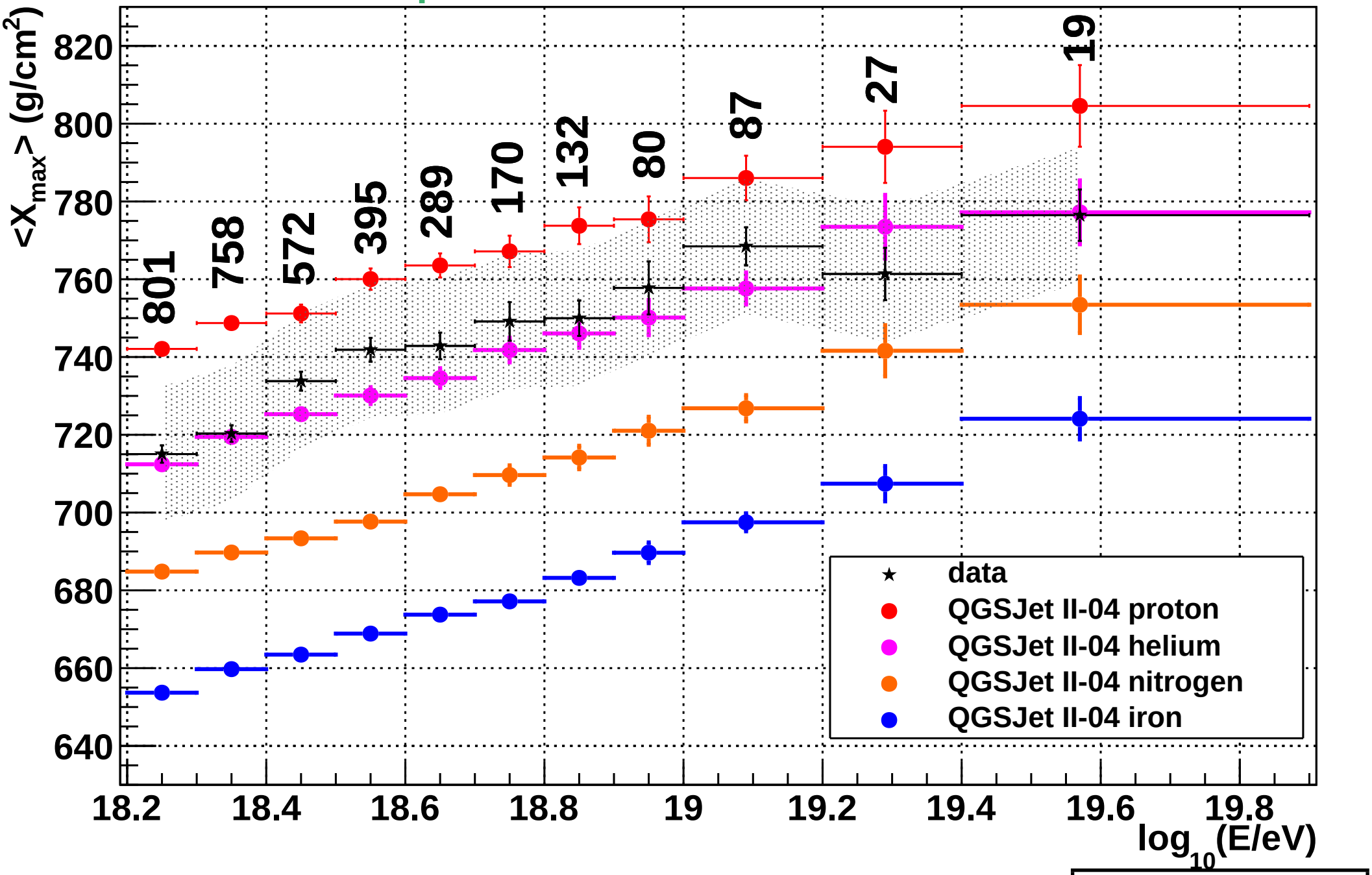
(θ, ϕ)



(E, Xmax)

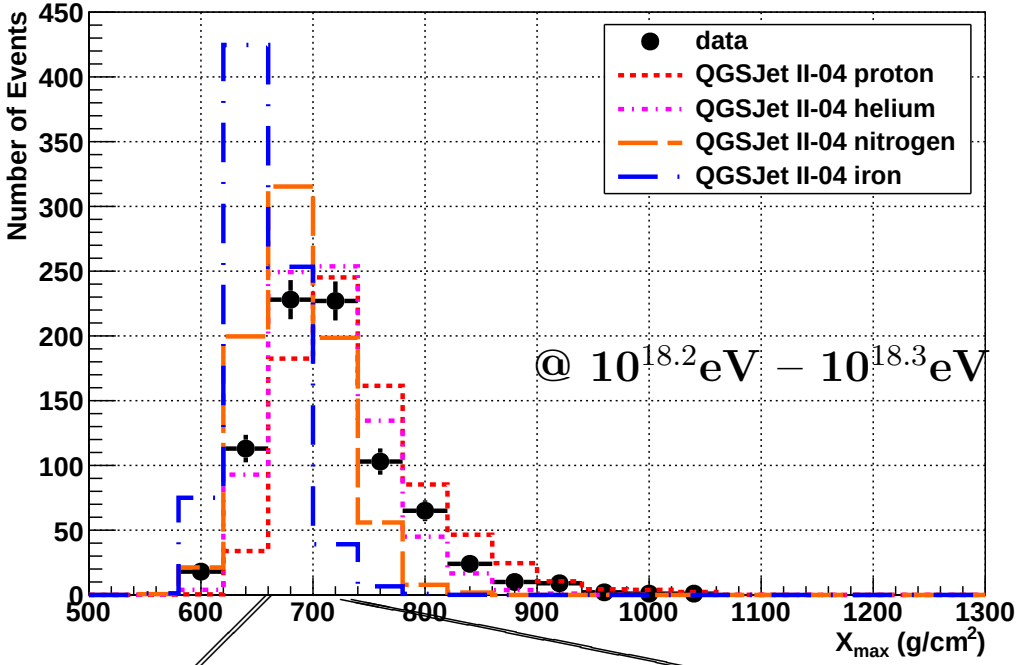
ApJ 858(2018)76

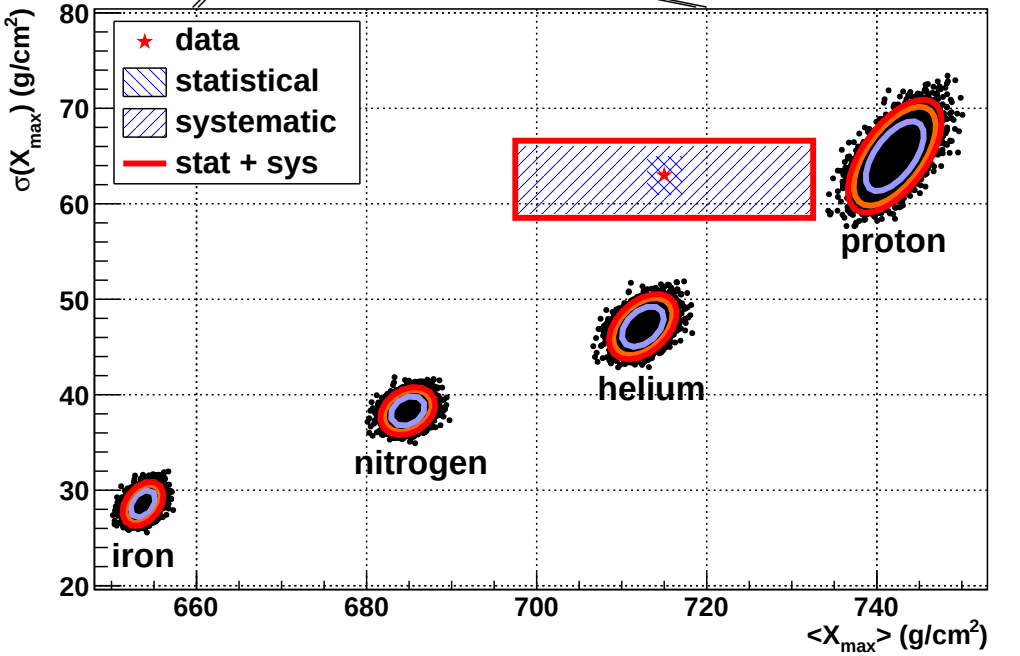
< Mean Xmax -plot >

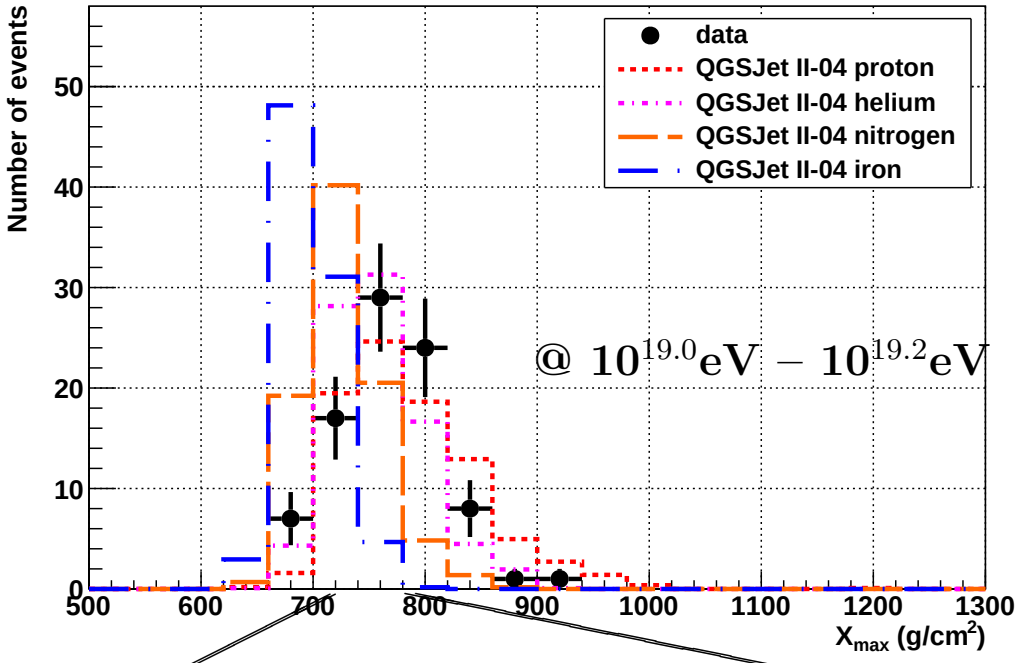


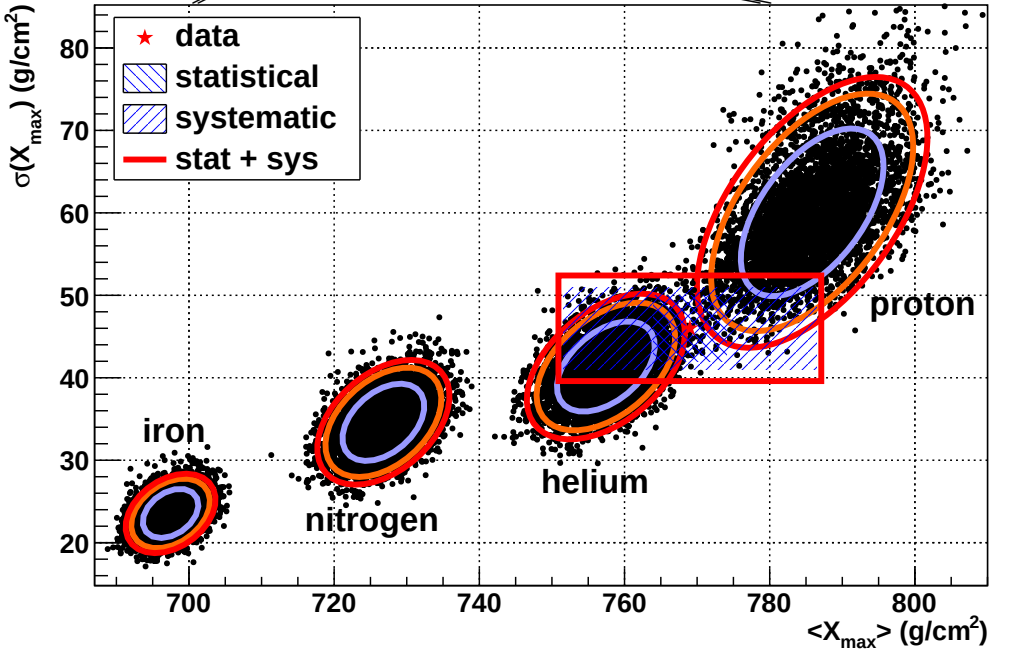
ApJ 858(2018)76

< Xmax distribution >



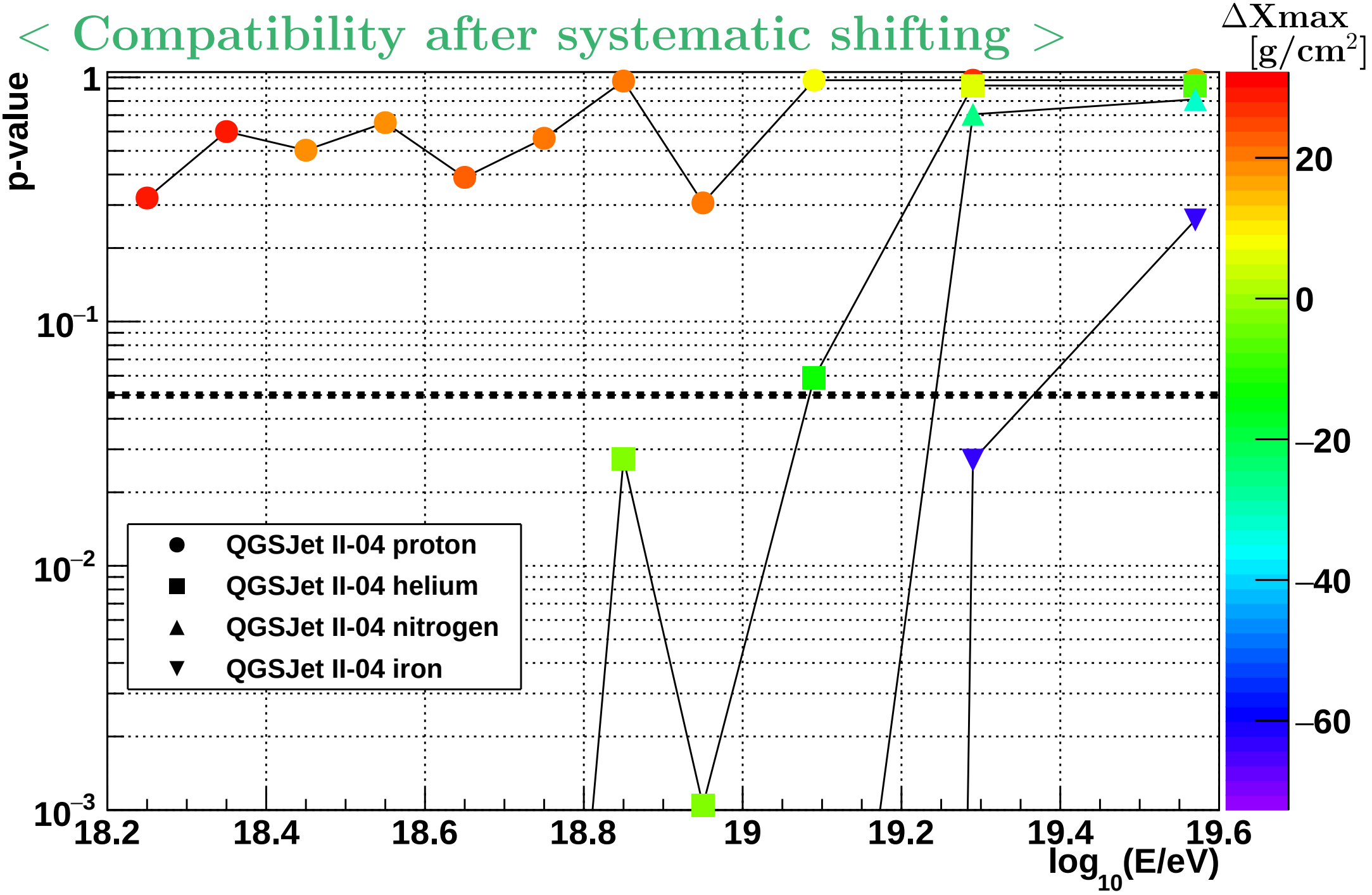






ApJ 858(2018)76

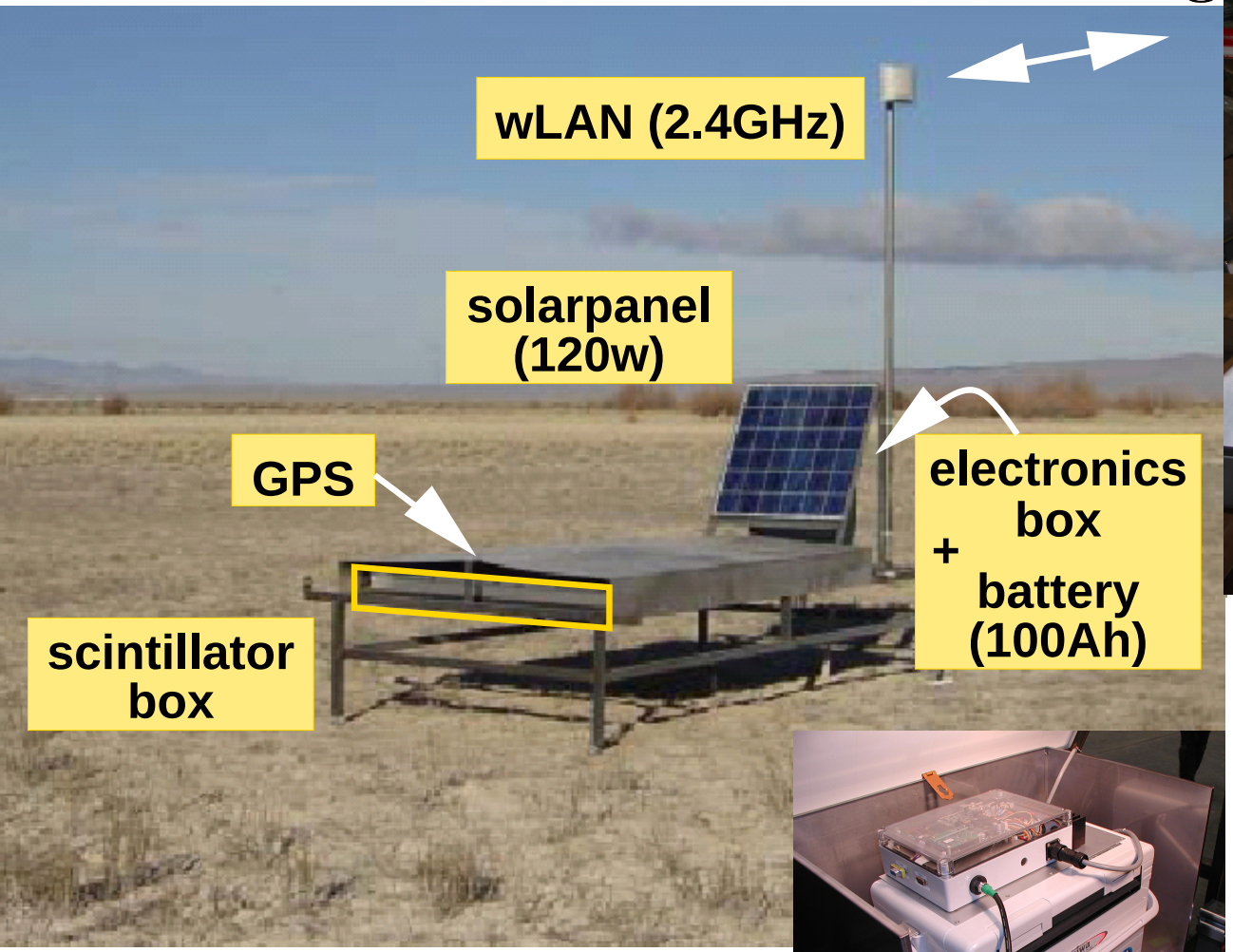
< Compatibility after systematic shifting >

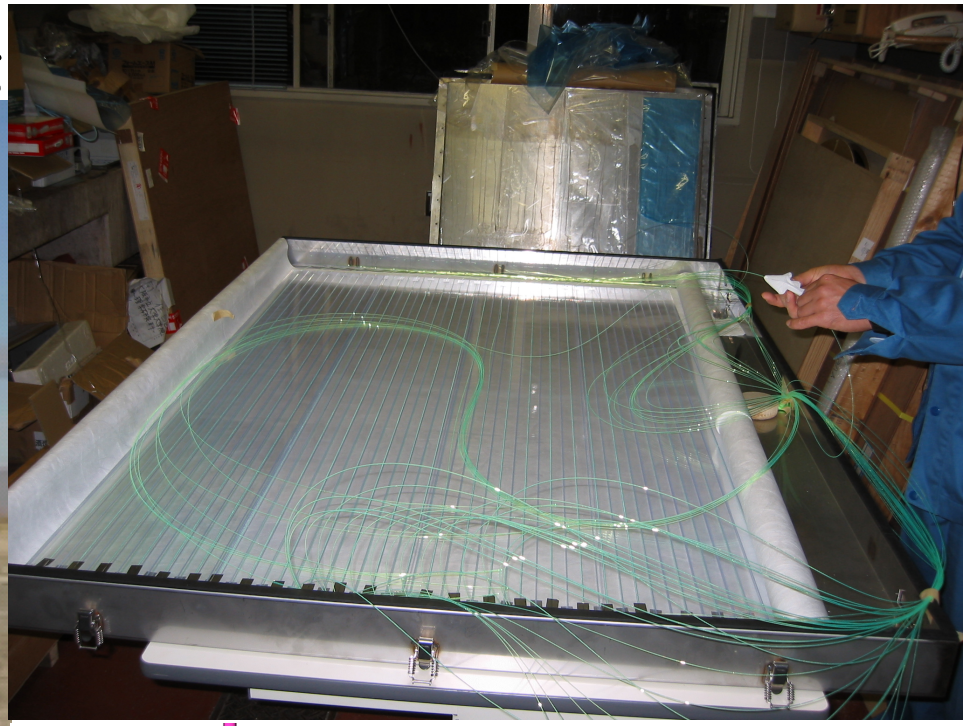


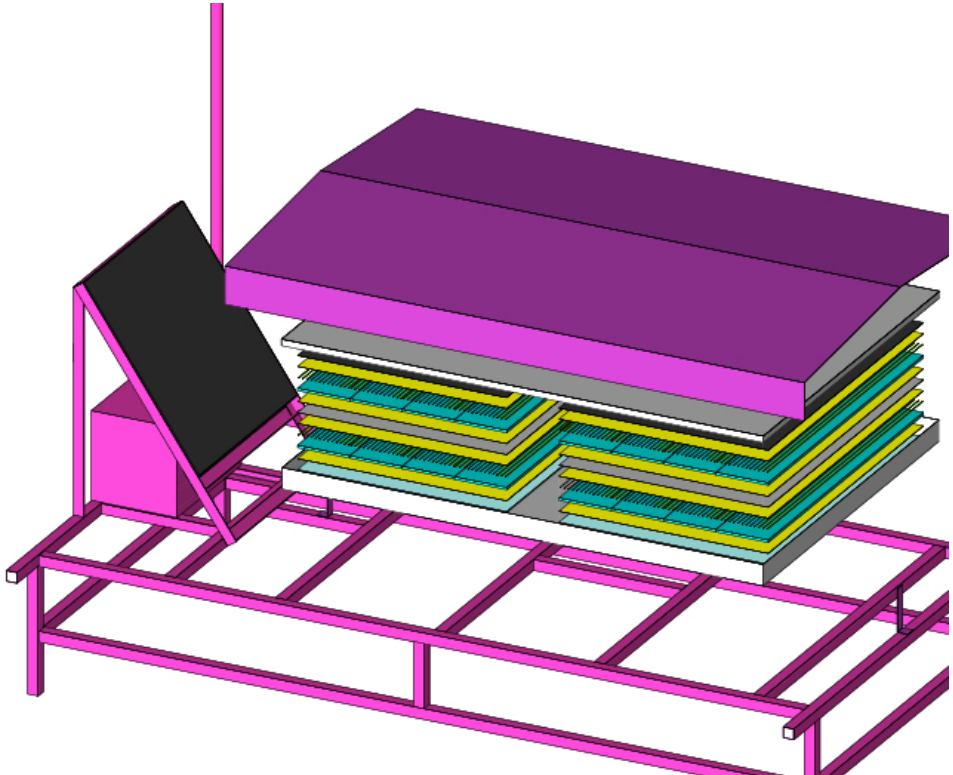
ApJ 858(2018)76

< Surface Detector >

~200kg

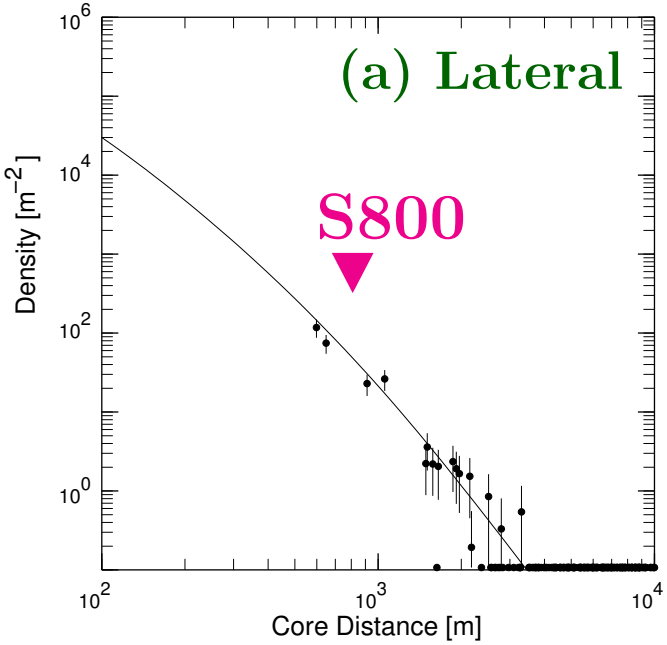


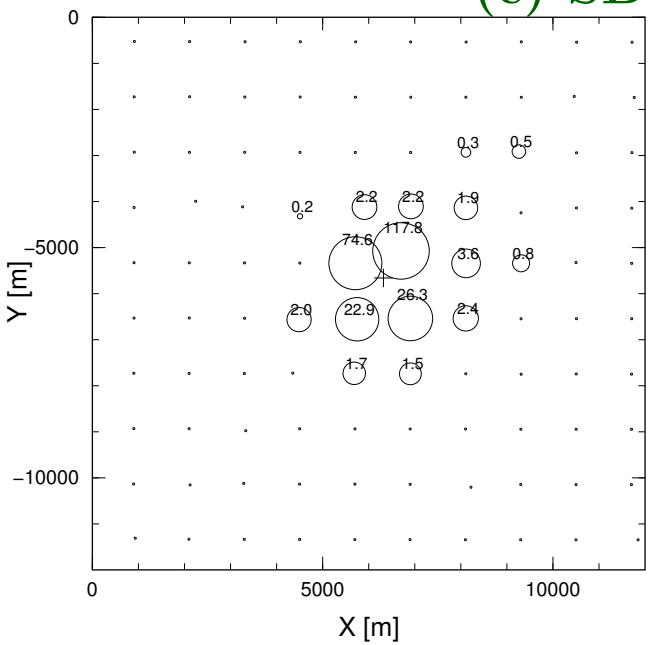


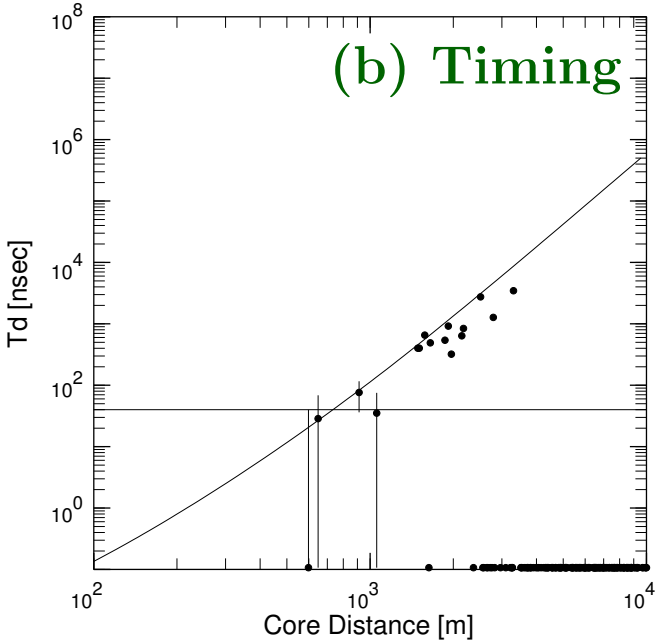


- WLSF: 1.0mmϕ (2cm separation)
- PMTs: ET 9123SA $\times$ 2
- 3m^2 (12mm $\times$ 2 layers)

< SD Event Example >



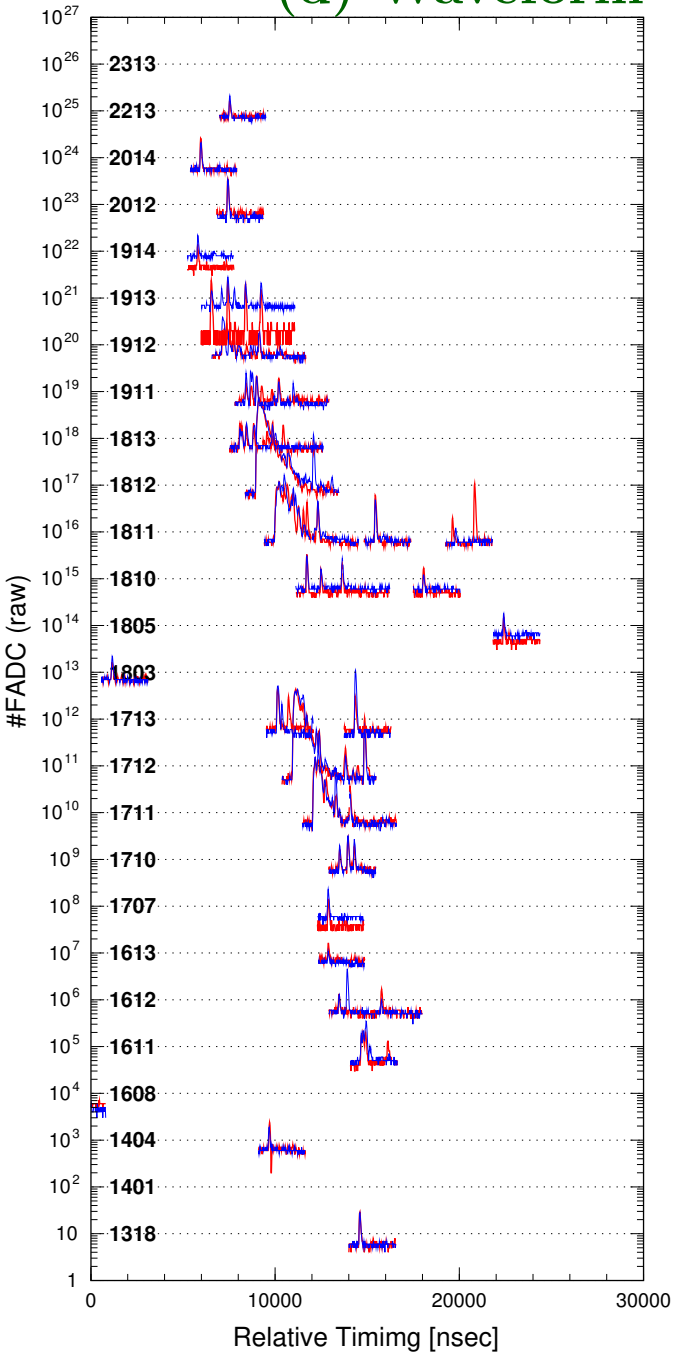




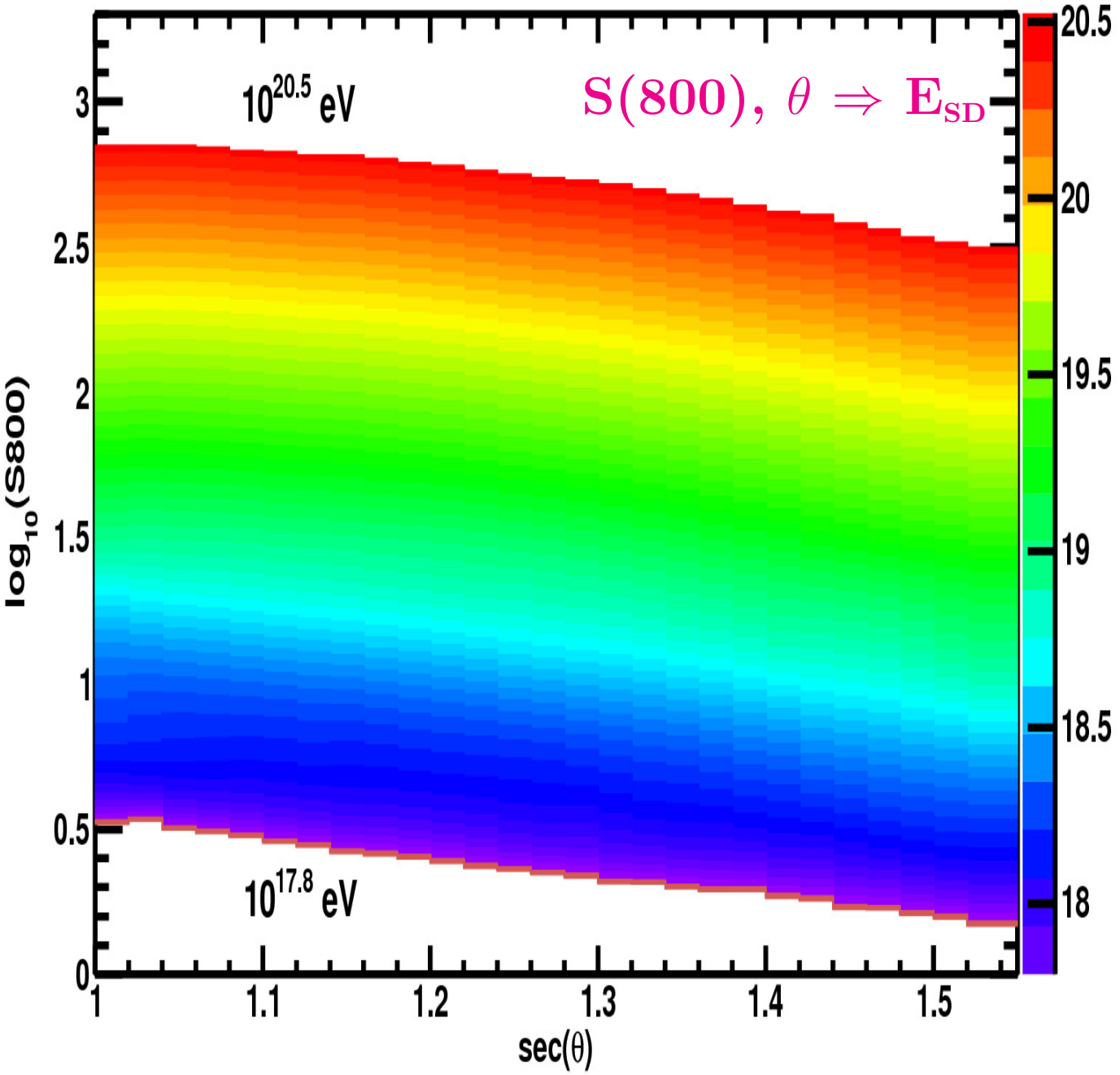
RUN(50141) **EVENT(2182)**

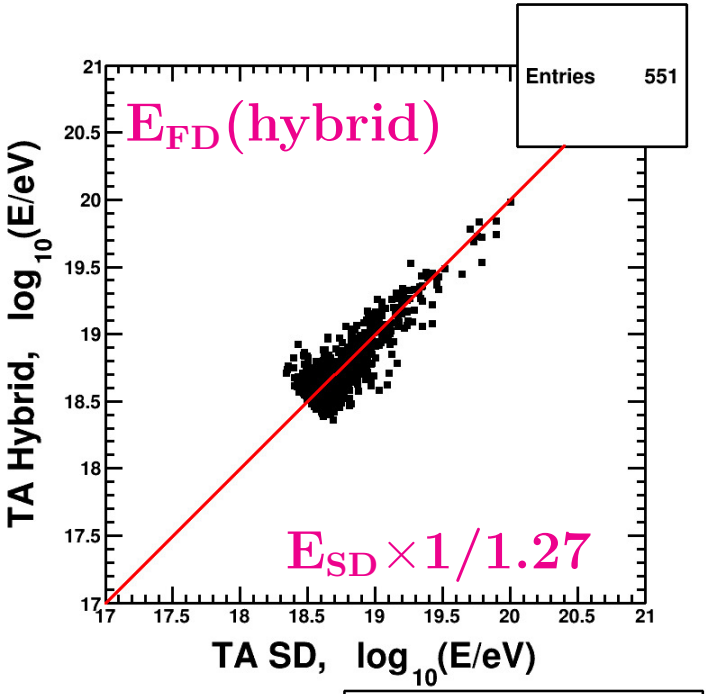
DATE(080531) **TIME(050737)**

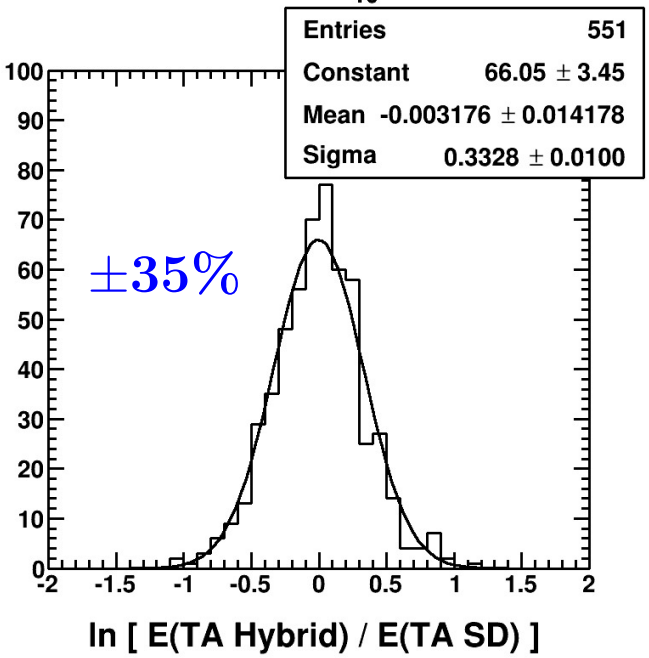
(θ, ϕ)



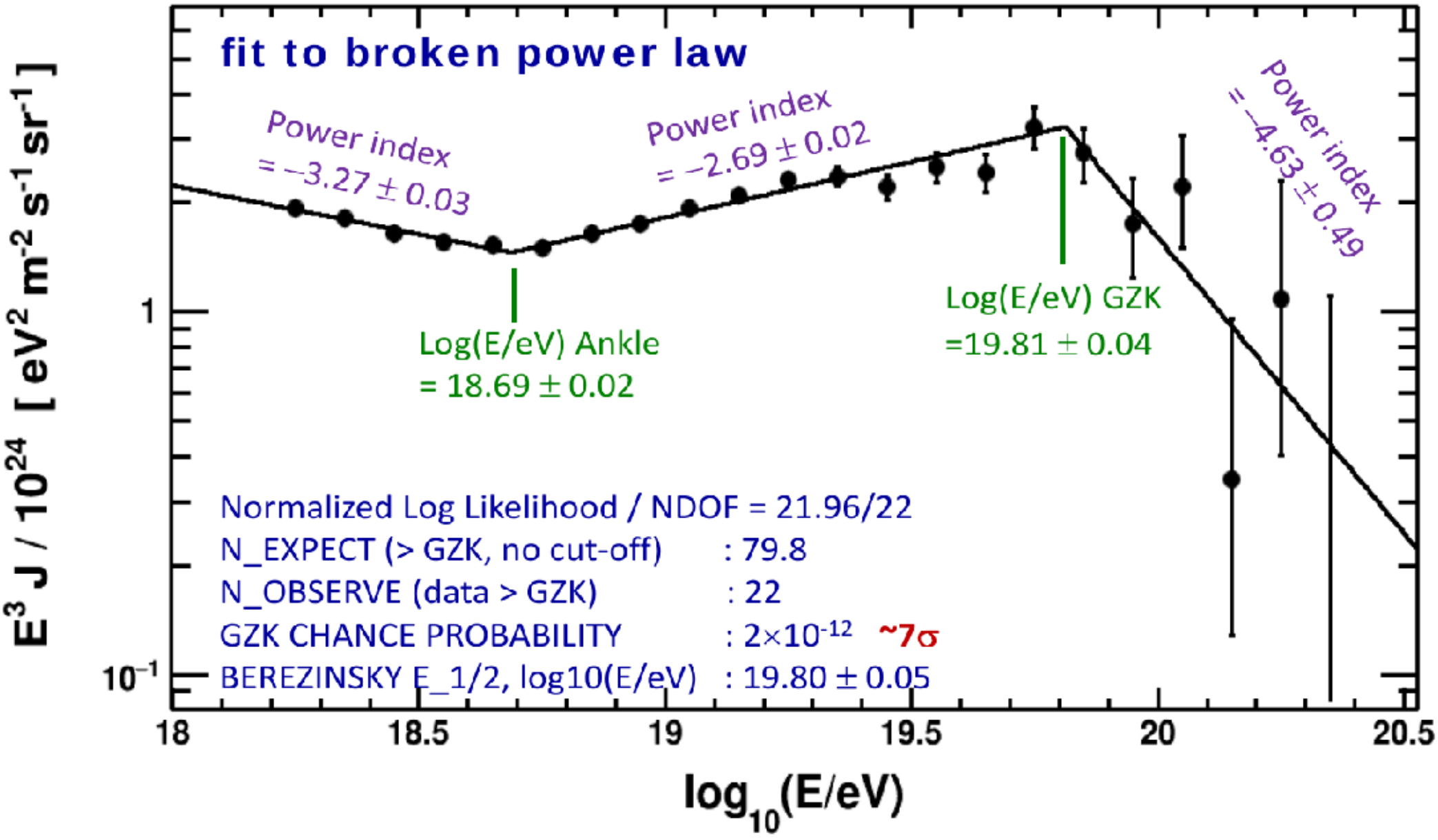
< TA Energy Estimation >





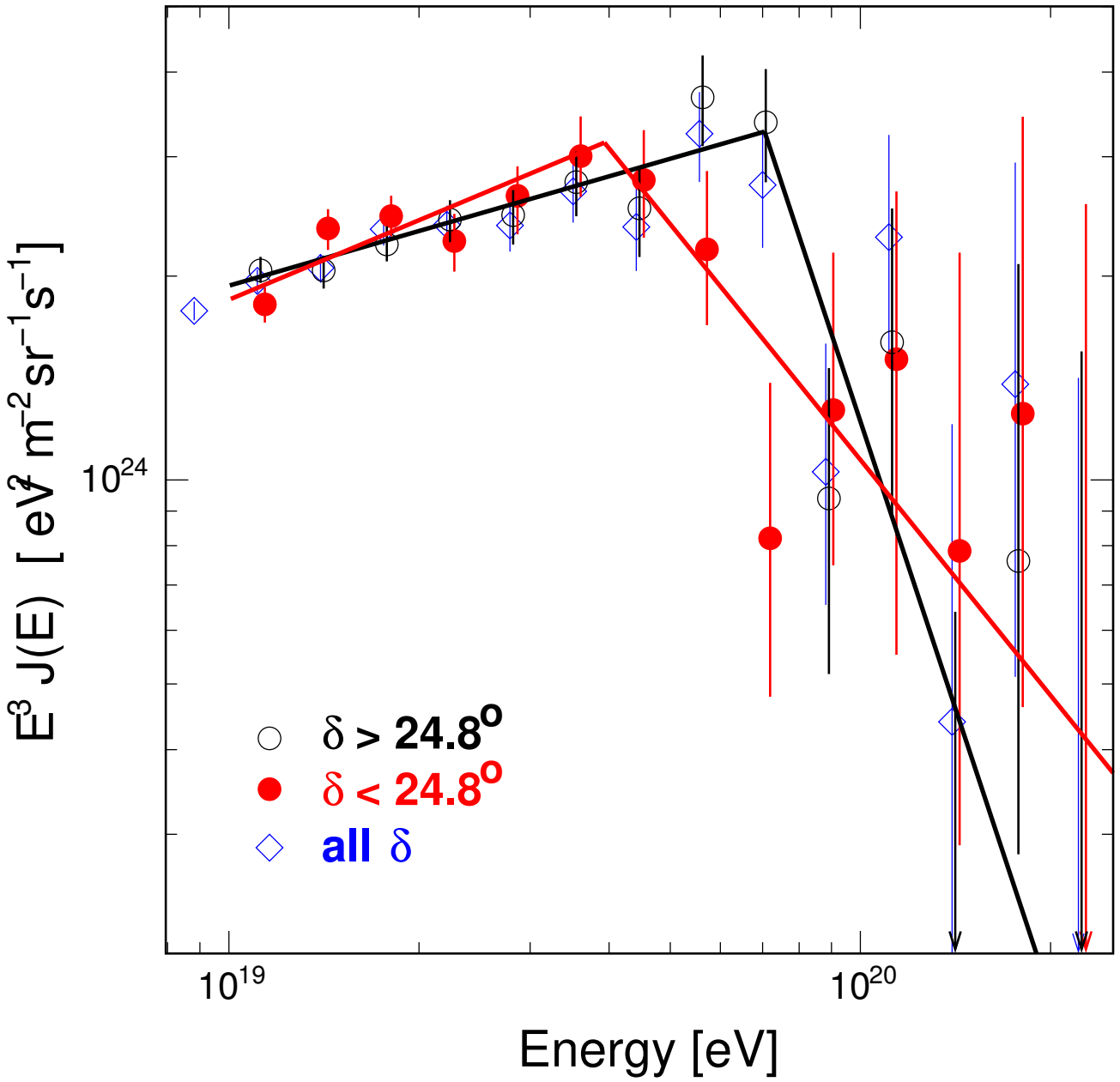


< Energy Spectrum (TA-SD: 9yrs) >



ICRC2017 CRI172

< Declination Dependence >



E_2[eV]: Cutoff Energy

◇ **all δ**

$\log(E_2[\mathrm{eV}]) = 19.78^{\pm 0.06}$

• $\delta > 24.8^\circ$ **(North)**

$\log(E_2[\mathrm{eV}]) = 19.85^{\pm 0.03}$

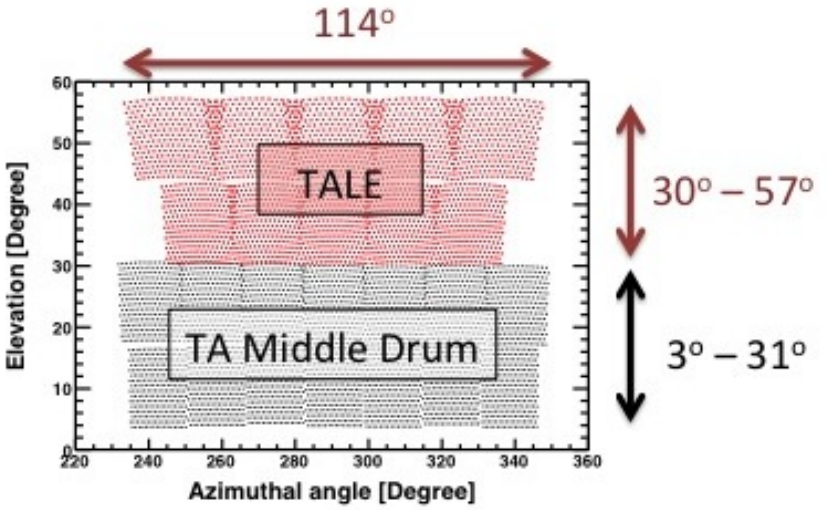
⇕ **3.5σ difference**

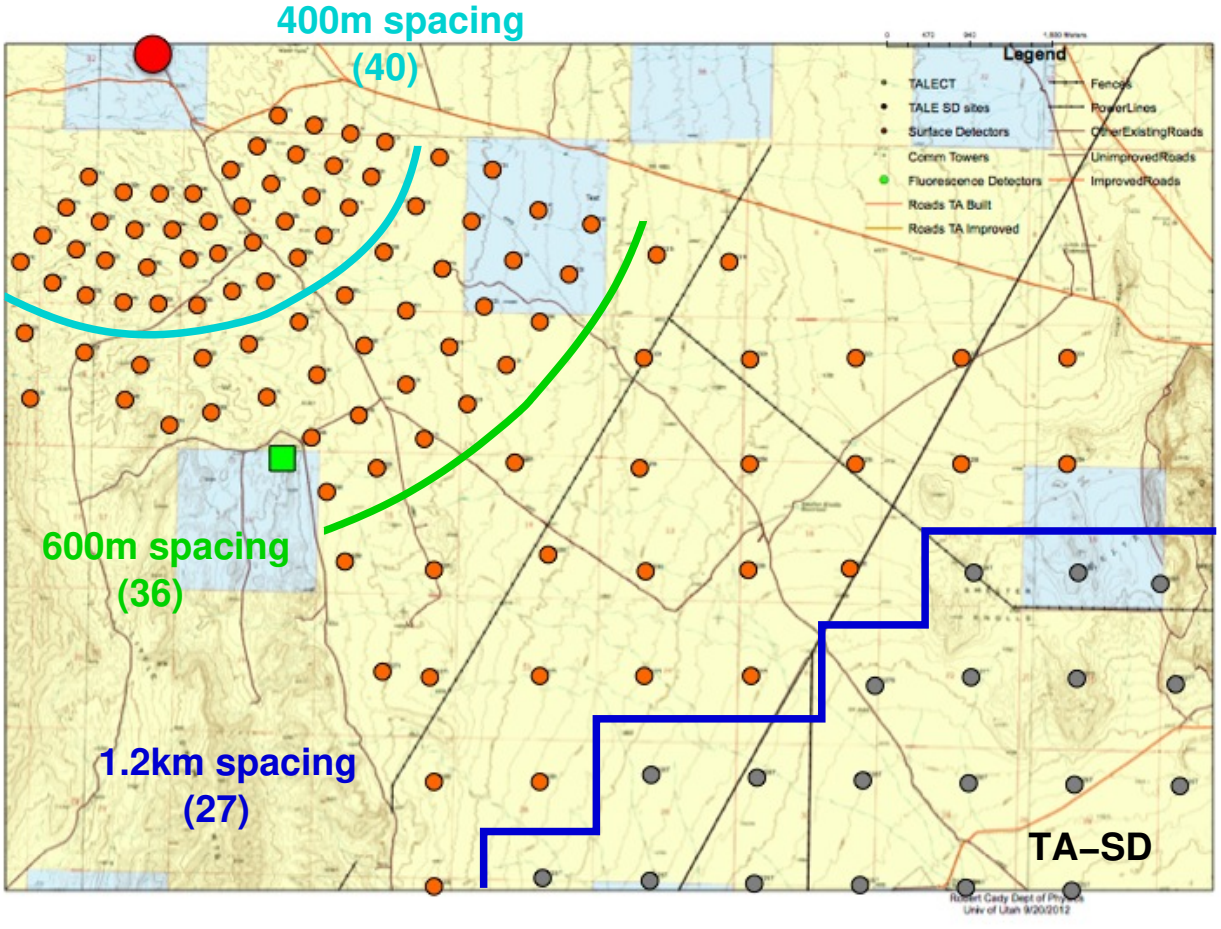
◦ $\delta < 24.8^\circ$ **(South)**

$\log(E_2[\mathrm{eV}]) = 19.59^{+0.05}_{-0.07}$

arXiv:0181.07820

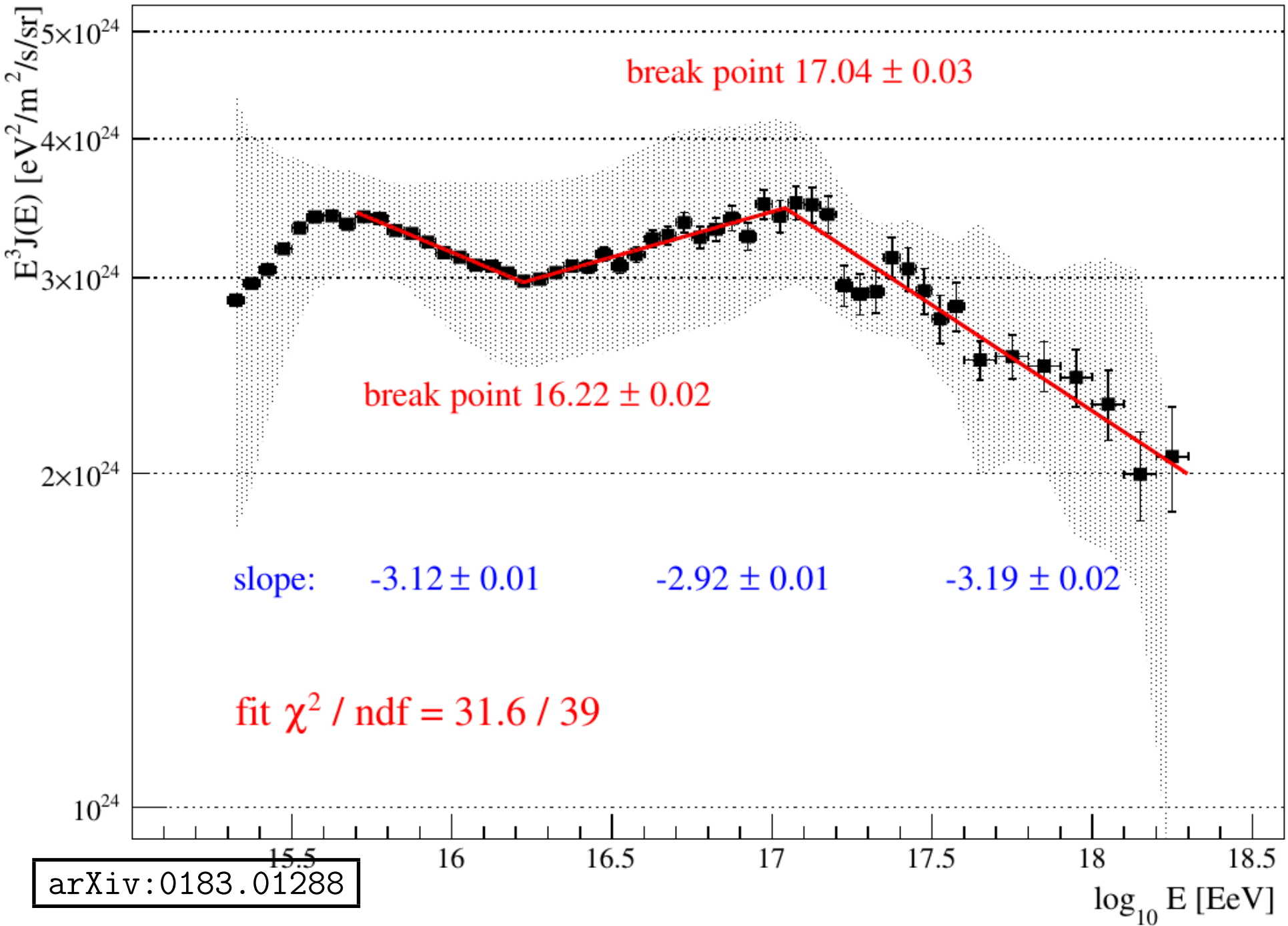
< TALE (TA Low-energy Extension) >





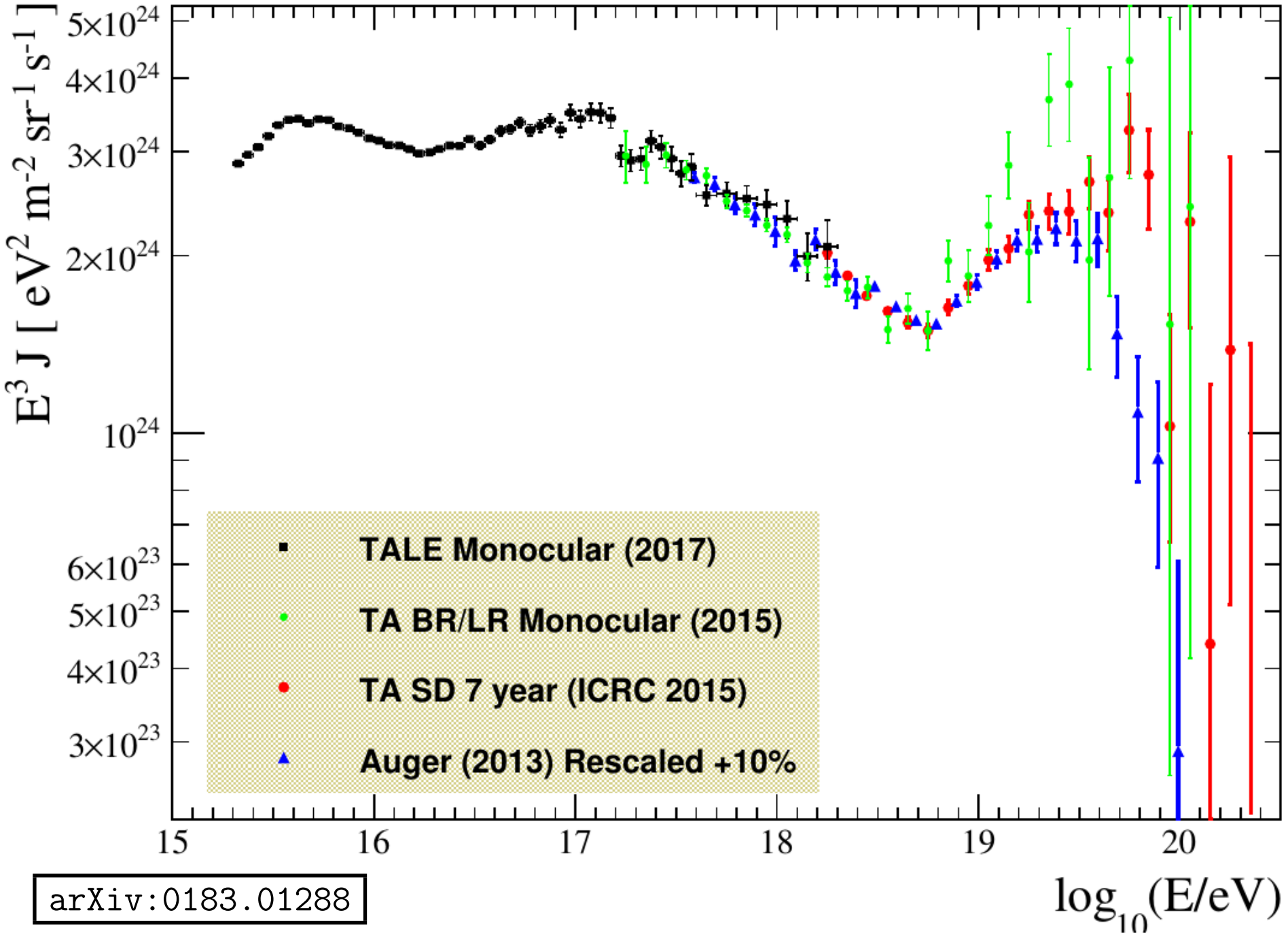
- Hybrid = FD + SD
- 10^{16}eV–$10^{18.5}$eV

< Energy Spectrum (TALE-FD: 2yrs) >



arXiv:0183.01288

< Energy Spectrum (TA-SD, TA-FD, TALE-FD) >



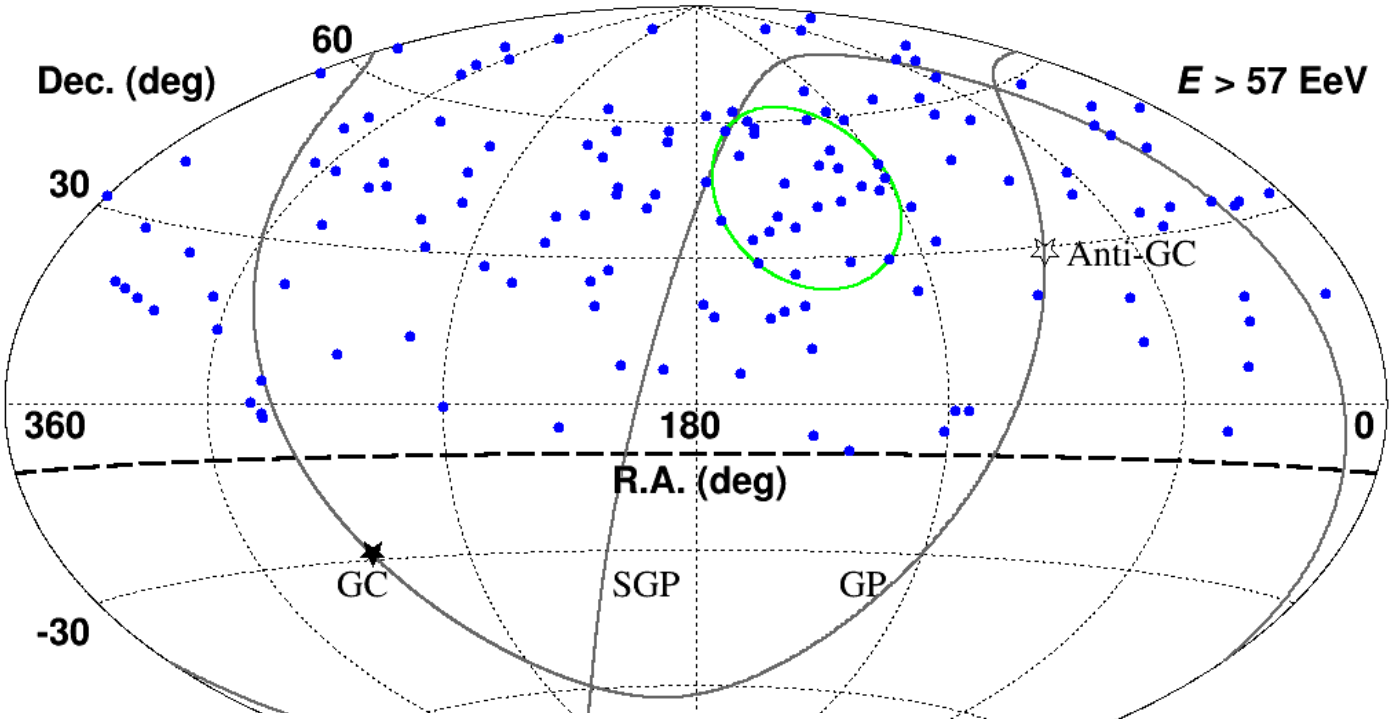
arXiv:0183.01288

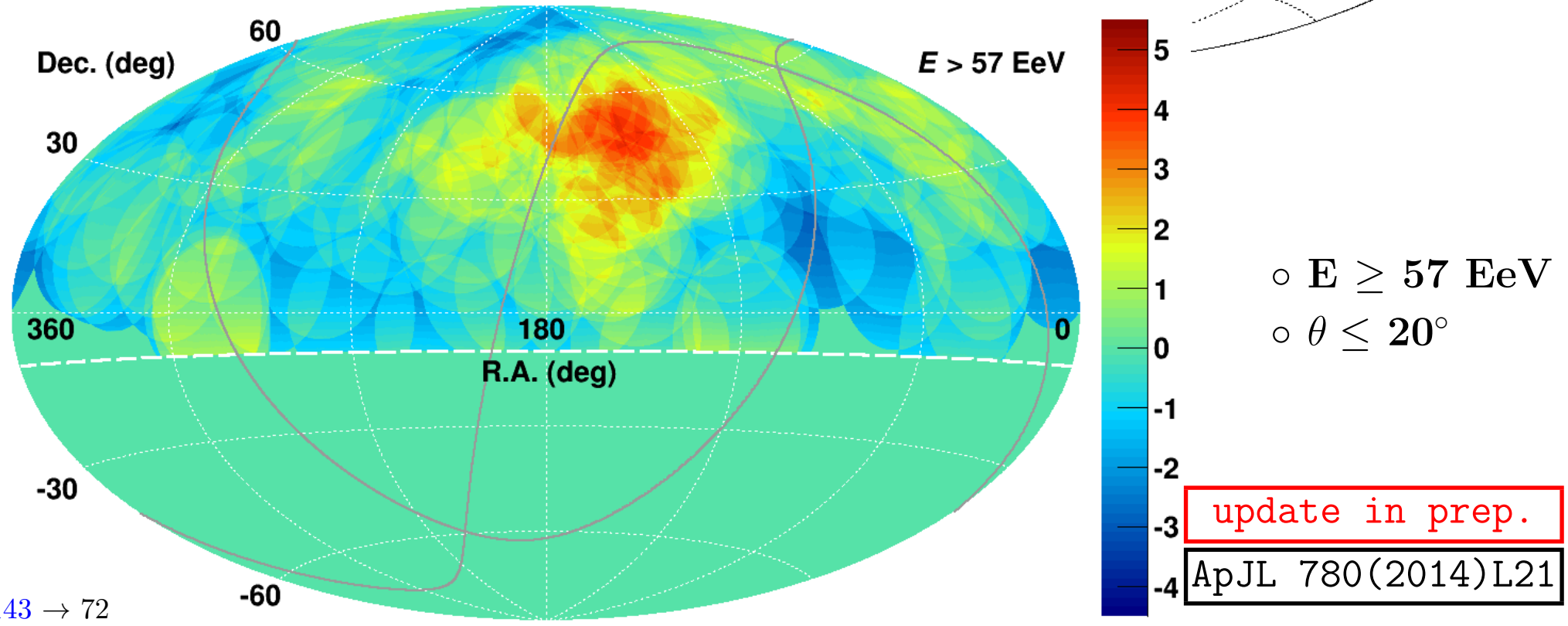
< Hot Spot >

- 9yrs data
  4.5σ (Nobs=26/Nexp=9.32)

$\Uparrow$

- 5yrs data in ApJL
  5.1σ (Nobs=19/Nexp=4.49)





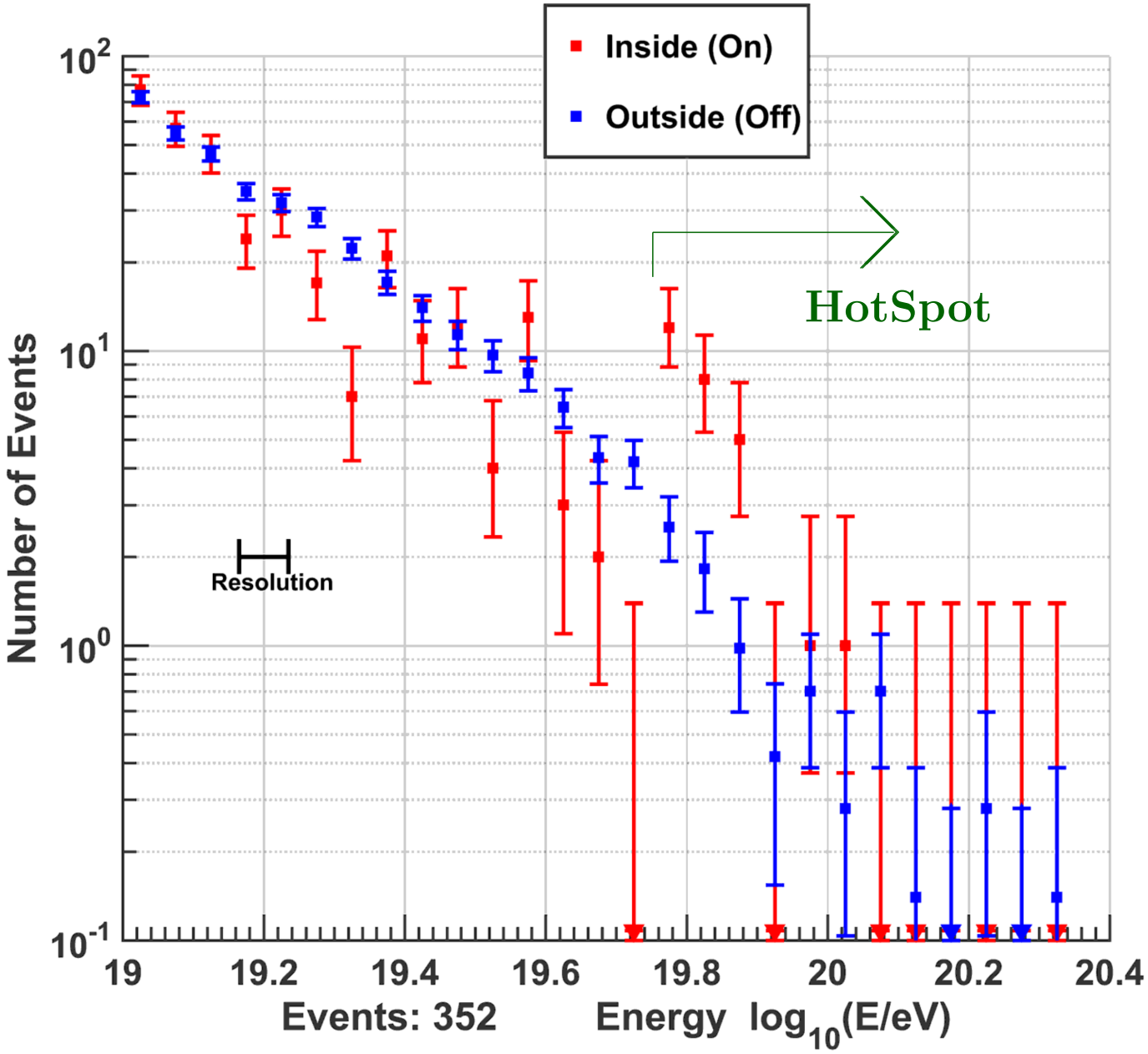
- $E \geq 57$ EeV
- $\theta \leq 20^\circ$

update in prep.

ApJL 780(2014)L21

Ntot=143 $\rightarrow$ 72

< Hot / Cold Spot (Energy Distribution) >



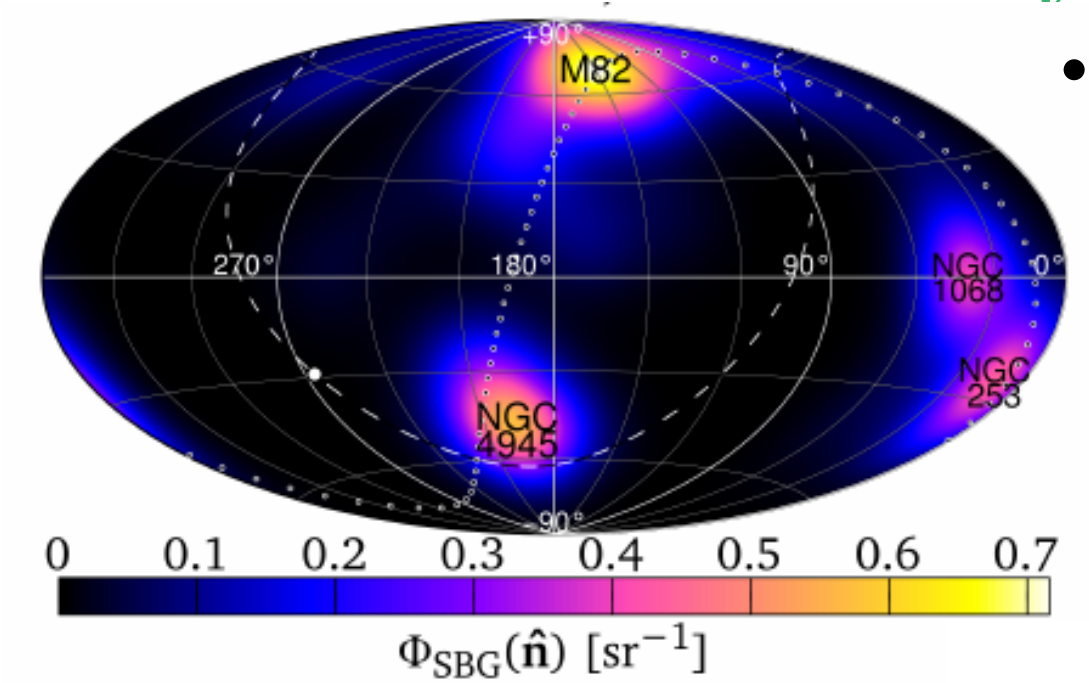
@ $(9^h16^m, 45^\circ)$

- Inside ($\theta \leq 28.43^\circ$)
- Outside ($\theta > 28.43^\circ$)

arXiv:1802.05003

$6.17\sigma(\text{local}) \rightarrow 3.74\sigma(\text{global})$

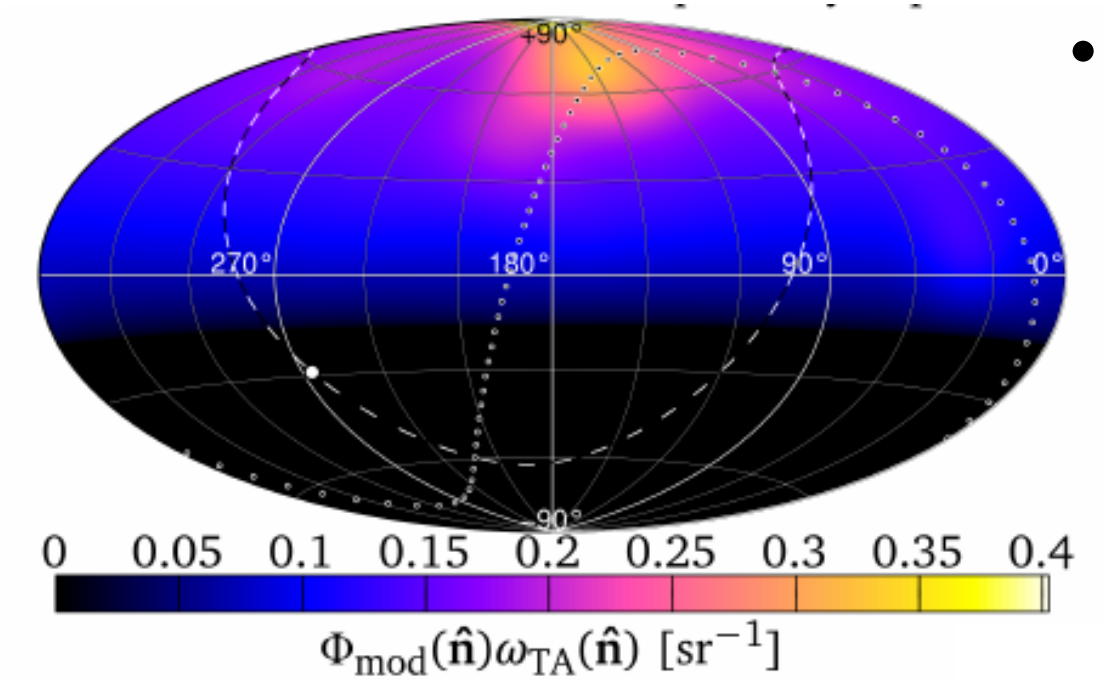
< Flux Pattern from Nearby Starburst Galaxies >



- **SBG model flux w/ $\theta = 12.9^\circ$**

$$\Phi_{mod} = f_{SBG}\,\Phi_{SBG} + (1 - f_{SBG})\Phi_{ISO}$$

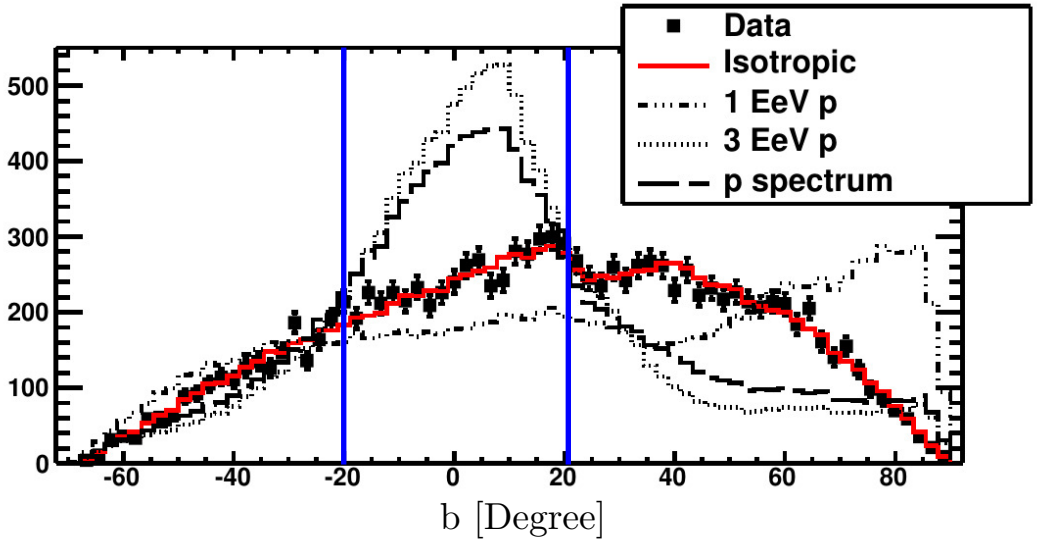
  - f_{SBG}: **SBG fraction (top: $f_{SBG} = 0$)**
  - Φ_{ISO}: **Isotropic flux**
  - Φ_{SBG}: **weighted sum of von Mises-Fisher distributions ($\sim$ spherical 2D Gaussian)**
  - θ: **RMS deviation ($\sim$ smearing)**



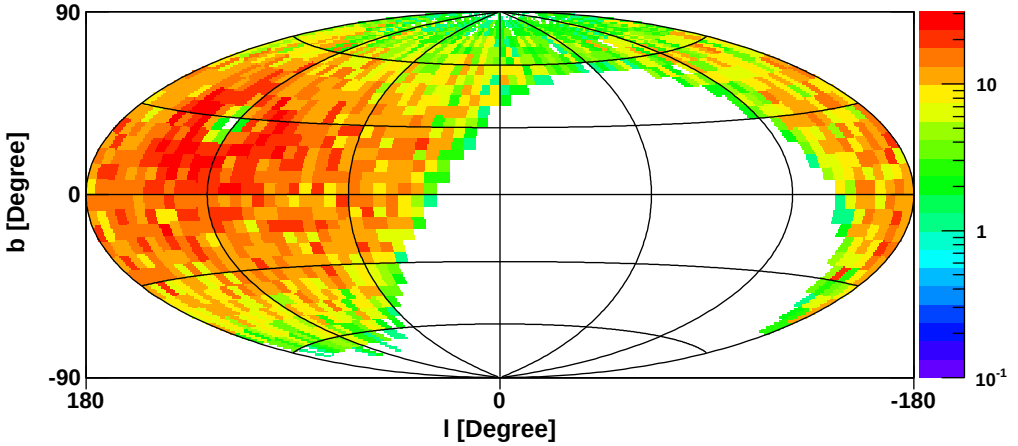
- **SBG model flux w/ TA exposure**
  - $\theta = 12.9^\circ$
  - $f_{SBG} = 9.7\%$

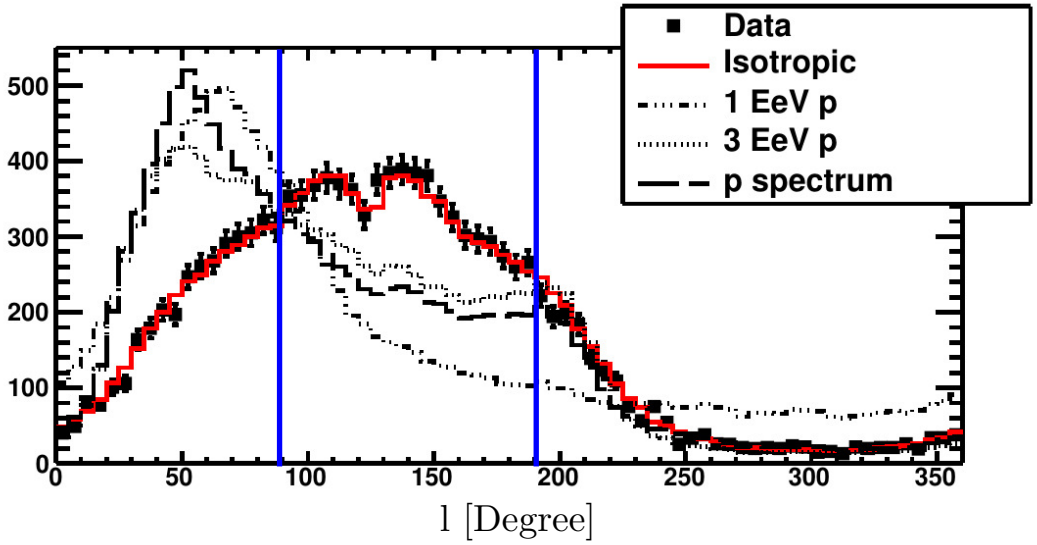
in preparation

< Anisotropy around 1EeV @ TA >

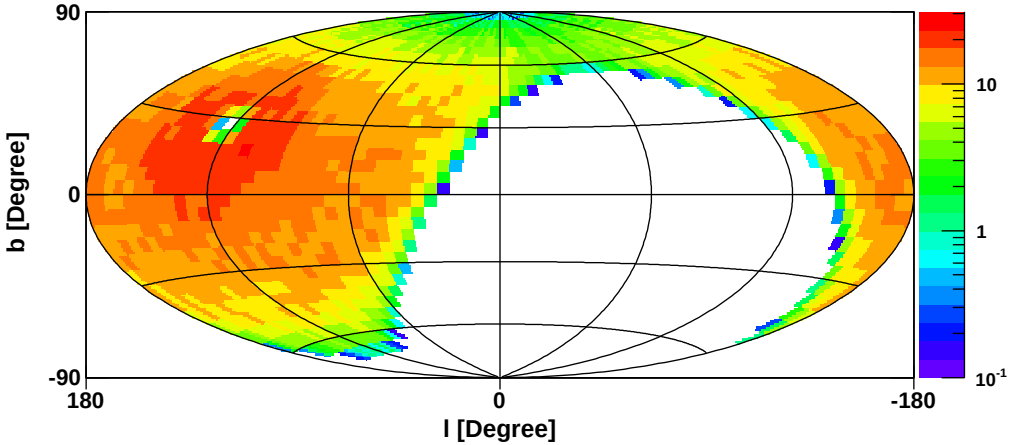


- Data @ $10^{18.0}$eV–$10^{18.5}$eV





- MC w/ 0.9% Galactic Protons



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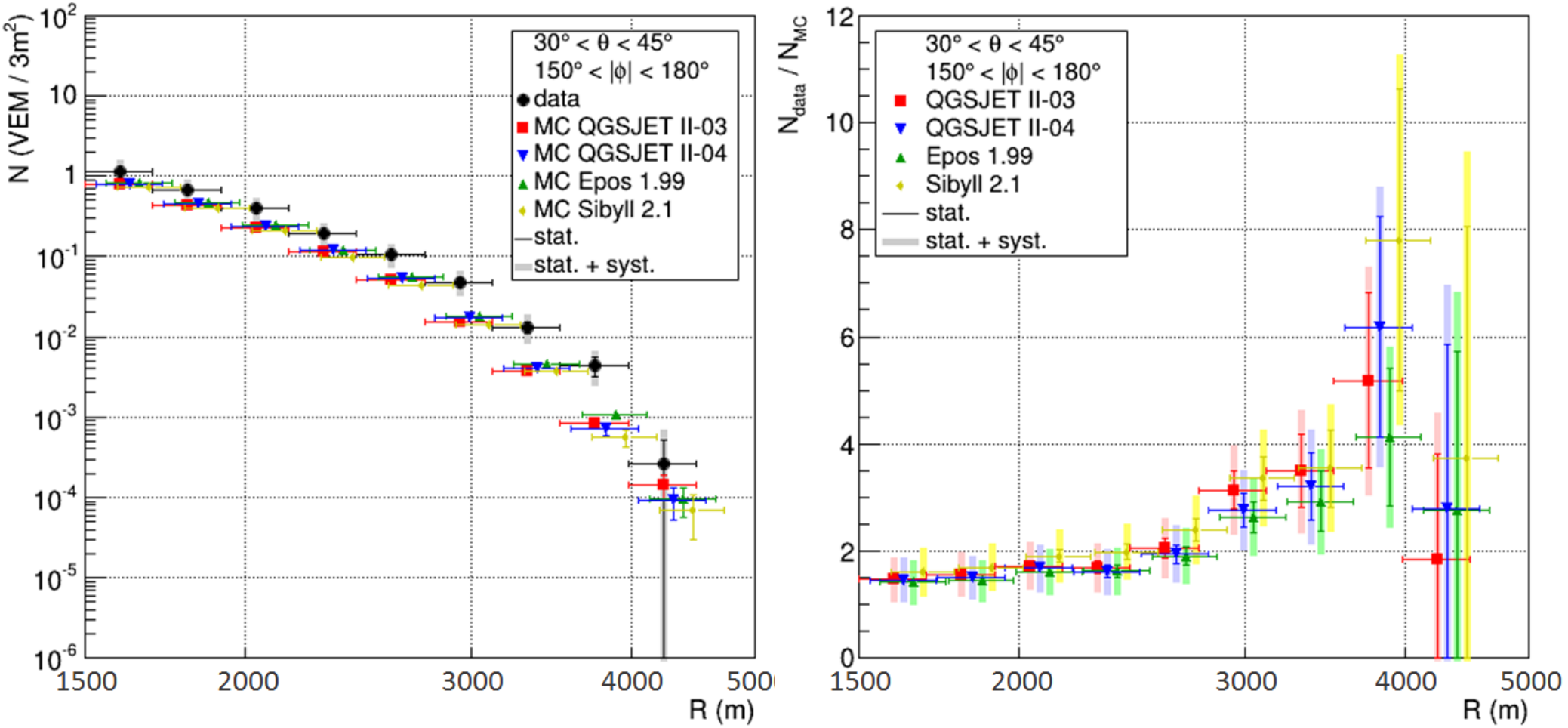
PSRs 0.3% in l, 1.3% in b

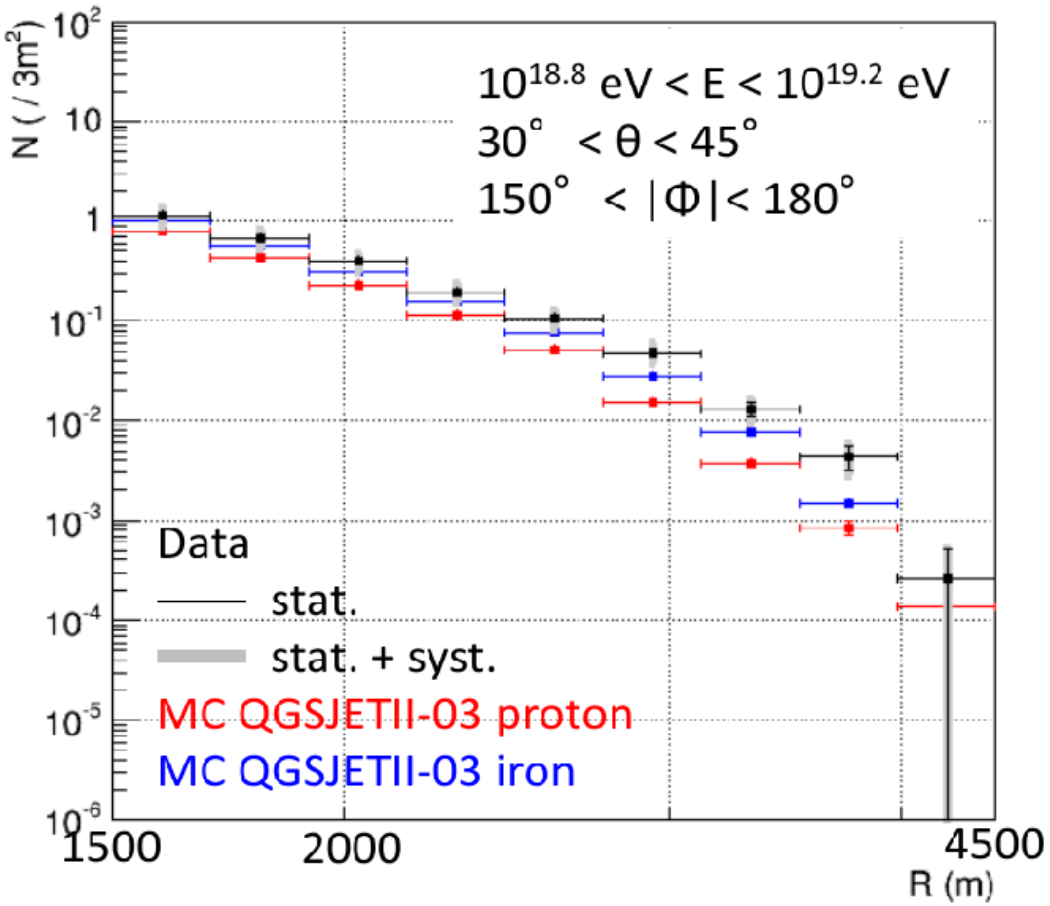
< Muon Excess in MC Comparison >

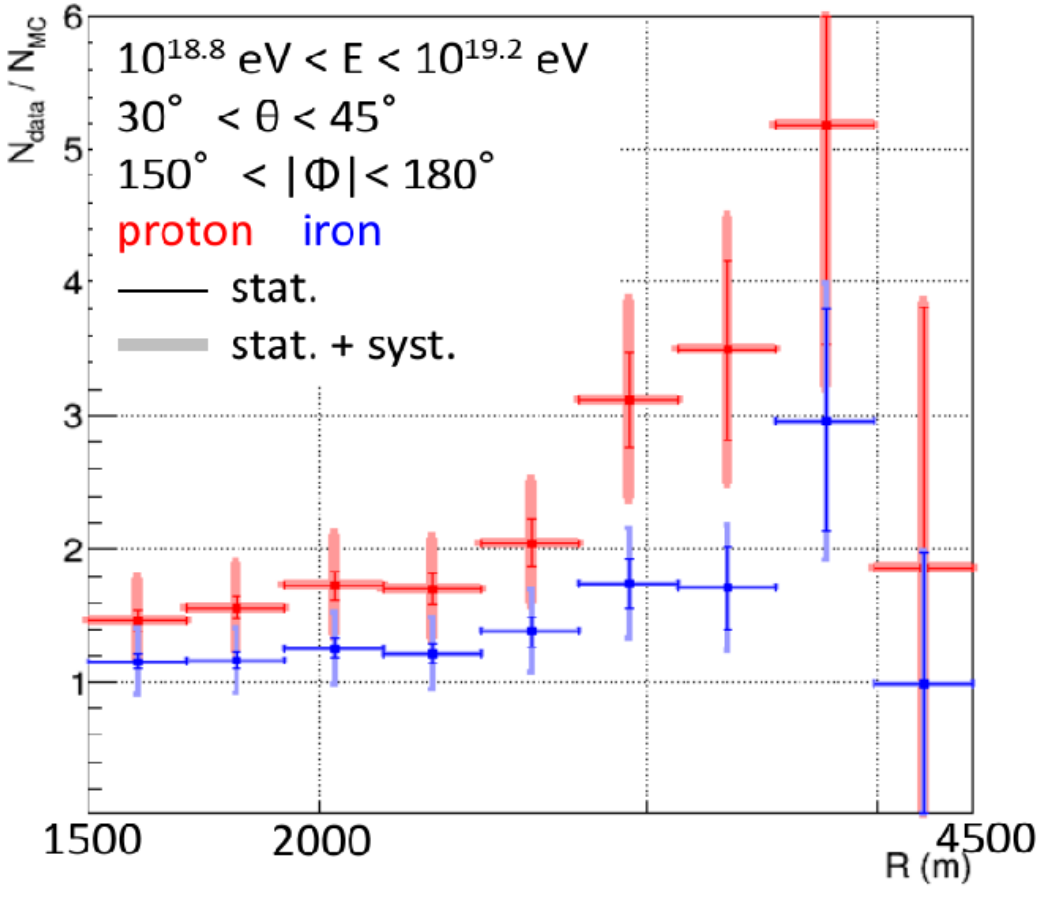


- **Lateral distribution with various hadronic models;**
  QGSJET II-03 , **QGSJET II-04** , **EPOS 1.99** , **Sibyll 2.1**
- **Data is larger than MC for all considered models.**

arXiv:1804.03877

< Muon Excess in p/Fe Comparison >



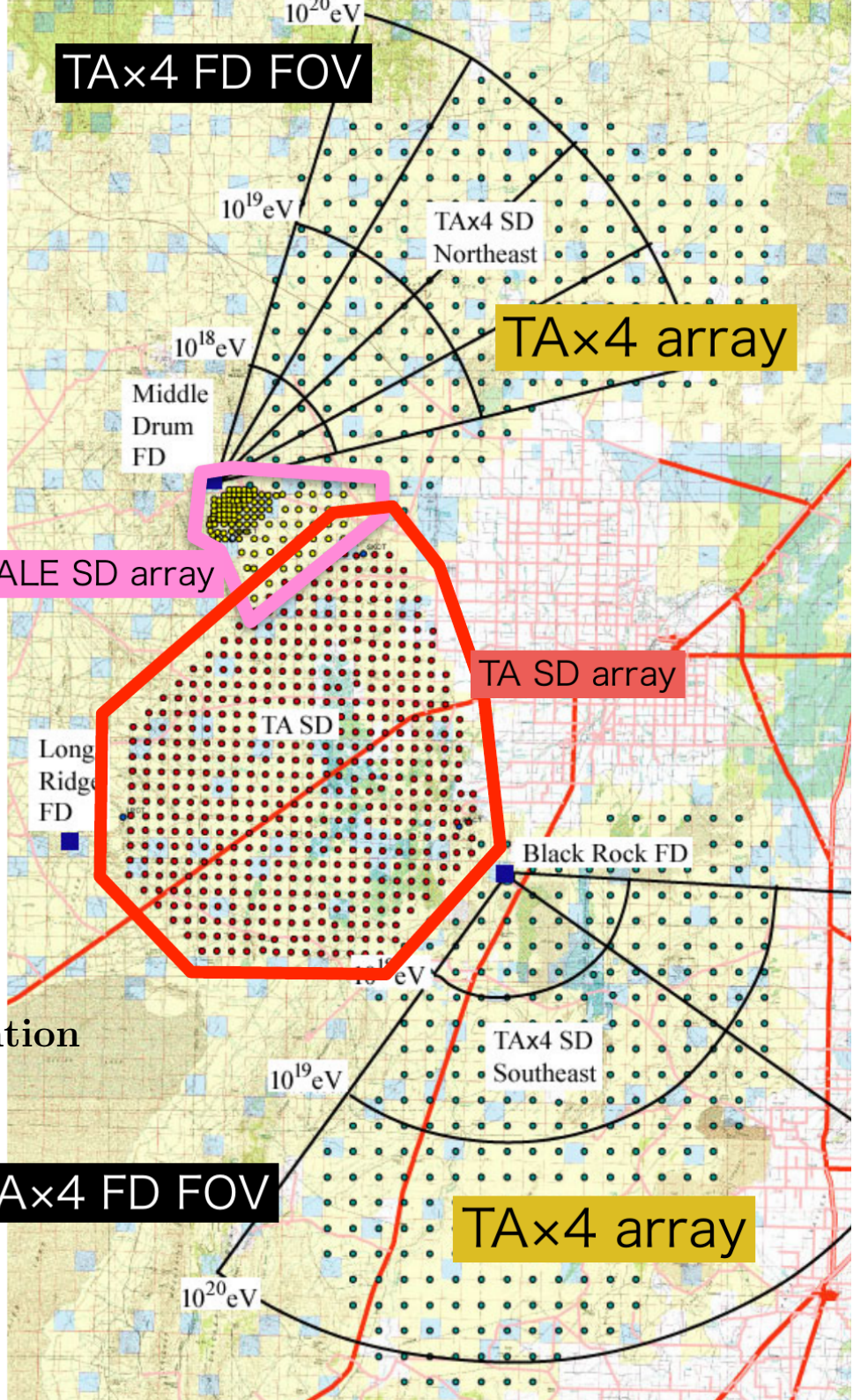


R (m)	Data/MC proton	Data/MC iron
[1910, 2160]	1.72±0.10(stat.)±0.40(syst.)	1.26±0.07(stat.)±0.29(syst.)
[2760, 3120]	3.14±0.36(stat.)±0.72(syst.)	1.74±0.19(stat.)±0.40(syst.)

arXiv:1804.03877

< TAx4 Experiment >

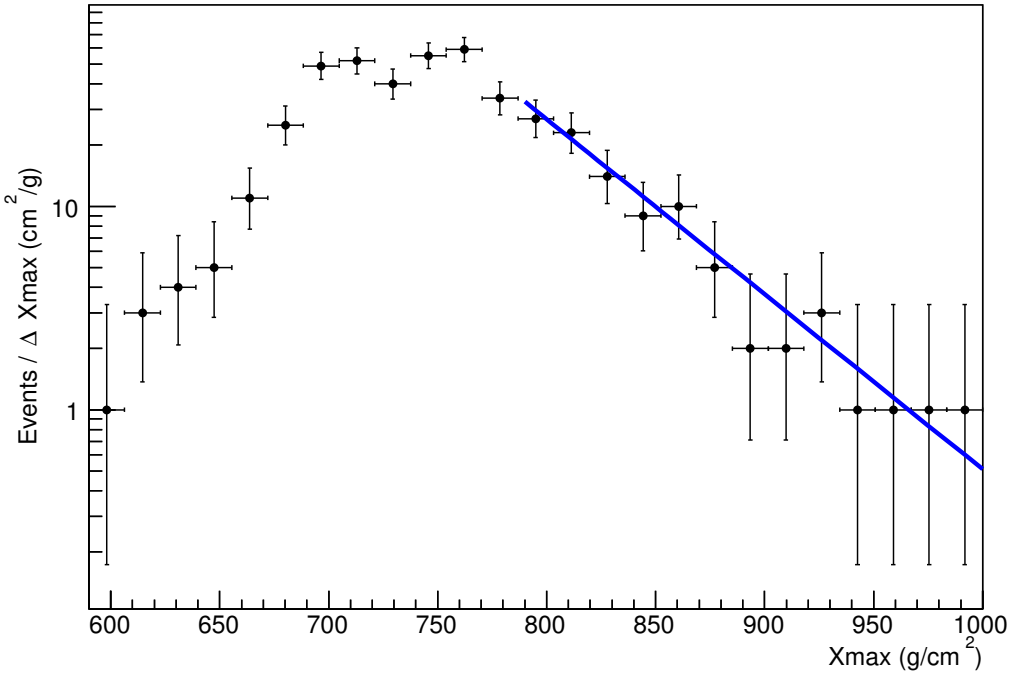
- **~3000km^2 SD array (Quadruple area)**
  - Approved by Japanese government 2015
  - 500 scintillator SDs
  - 2.08km spaceing
  - 3yrs construction
  - first 180 SDs have arrived in Utah.
  - Next 60 SDs to be prepared at ICRR and SKKU in 2018 summer and shipped to Utah
- **2 FD stations (12 HiRes-II telescopes)**
  - Approved by US NSF 2016
  - Telescopes/electronics being prepared at Univ. of Utah
  - first light at the northern station
  - Site construction underway at the southern station
- **by 2020,**
  - Get 19 TA-equiv years of SD data
  - Get 16.3 (current) TA years of hybrid data



< Summary >

- Telescope Array is UHECR observatory in the northern hemisphere.
- Hybrid = Fluorescence Detectors + 700 km^2 Surface Detector array
- TA hybrid Xmax measurements
  - Below $10^{18.8}$eV, allowing 10-20g/cm^2 shifts, data points looks like "proton".
  - Above $10^{18.8}$eV, data points looks like heavier primary than "proton",
  - There are significant overlaps between plots of different primaries because of small statistics.
- Energy spectrum from 9 year observations by TA SD array
  - Auger-TA discrepancy above $10^{19.4}$eV
  - Indication of the declination dependence
- TA Low-energy Extension (TALE) FD have measured energy spectrum.
  - TA and TALE covered $10^{15.3}$eV to 10^{20}eV and observed spectral features.
- We have reported a hot spot in the direction of Ursa Major. It now appears larger(extended) than we originally thought.
- We need much more data at high energy end. – TAx4 comes soon.
- Full TALE SD is now on-line !
  - Hybrid measurement has extended the energy reach below $\sim 10^{16}$eV.

$< \sigma^{\rm inel}_{\rm p-air}$ from Xmax Distribution $>$

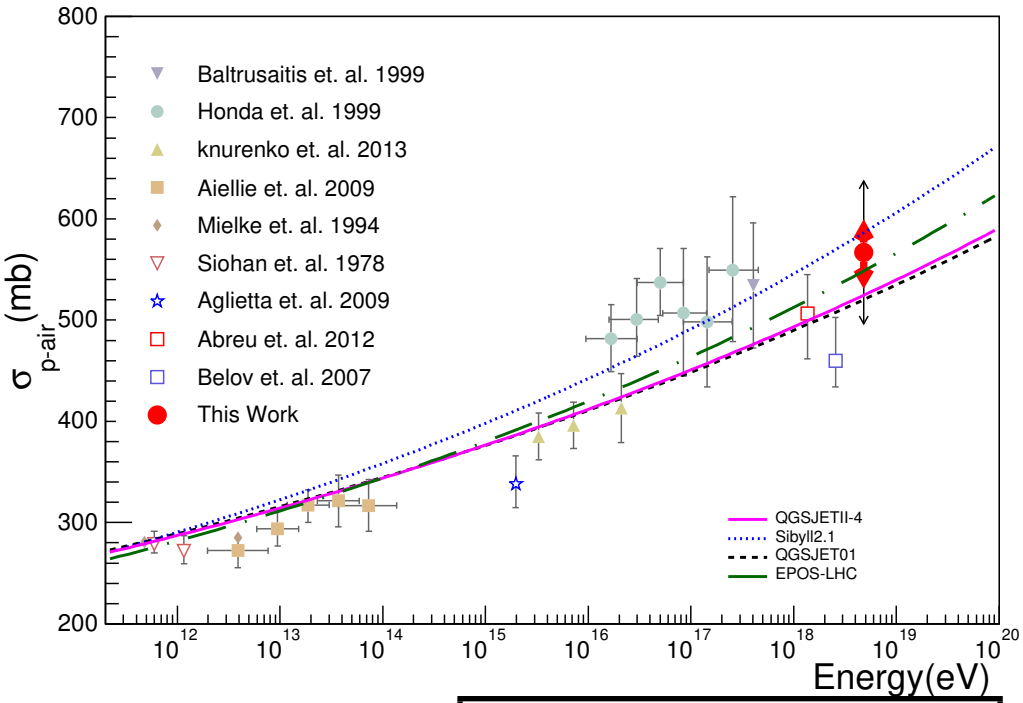


$$\Lambda_{\rm m} = 50.47 \pm 6.26 \ ({\rm stat}) \ [{\rm g/cm^2}]$$
$$\text{in } 10^{18.3}{\rm eV} - 10^{19.3}{\rm eV}$$

$$\sigma^{\rm inel}_{\rm p-air} = {\rm K} \times 24{,}160 \ / \ \Lambda_{\rm m} \ [{\rm mb}]$$
$$= 567.0 \pm 70.5 \ ({\rm stat}) \ [{\rm mb}]$$

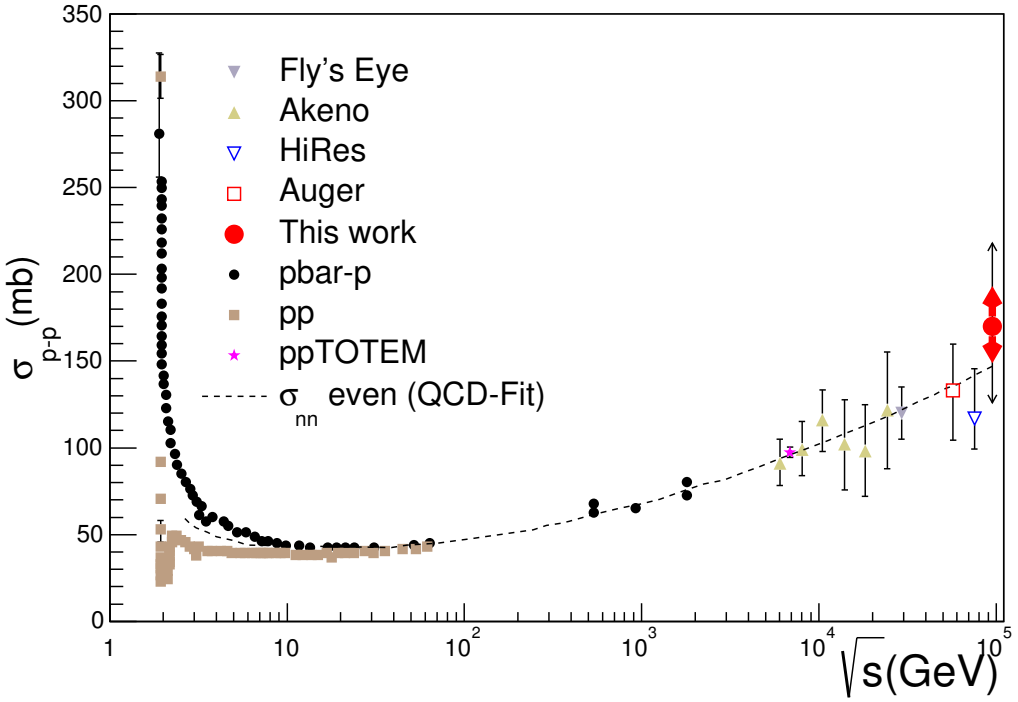
$$\left(\Lambda_{\rm m} = {\rm K} \ \lambda_{\rm p-air} = {\rm K} \ \frac{14.45 m_p}{\sigma^{\rm inel}_{\rm p-air}} \right)$$

※ K has ~3% model uncertainty

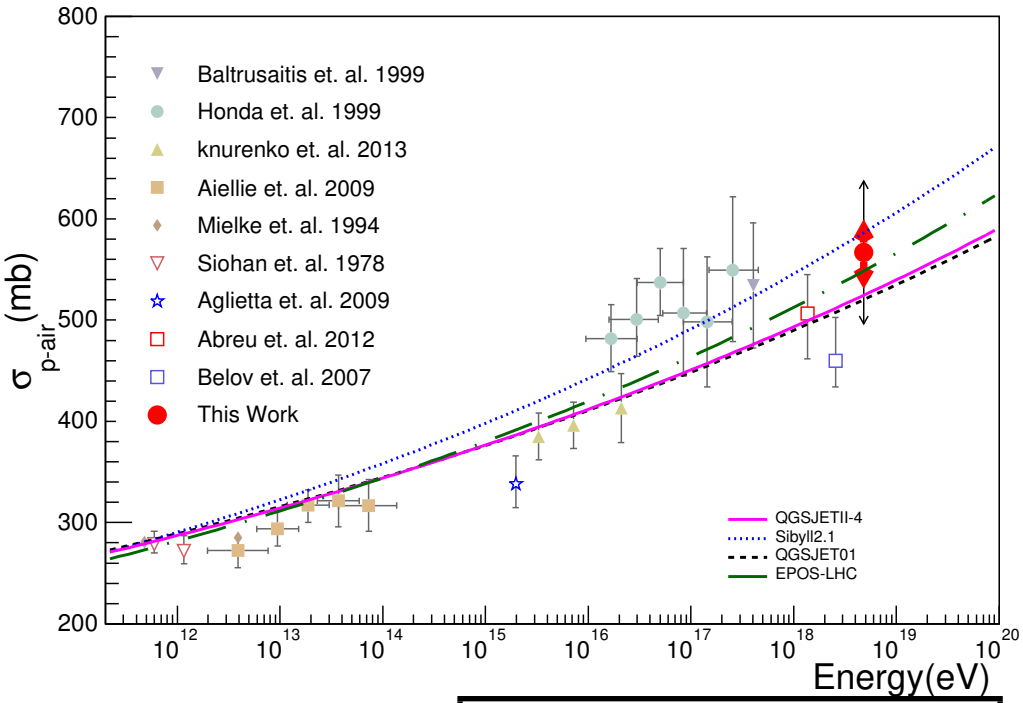


PRD 92(2015)032007

$< \sigma^{\rm total}_{\rm p-p}$ from Xmax Distribution $>$



$$\sigma^{\rm total}_{\rm p-p} = 170\ ^{+48}_{-44}({\rm stat})\ ^{+19}_{-17}({\rm sys})\ [{\rm mb}]$$
$$\text{at } \sqrt{s}{=}95^{+5}_{-8}\ [{\rm TeV}]$$



$$\sigma^{\rm inel}_{\rm p-air} = 567.0 \pm 70.5\ ({\rm stat})\ [{\rm mb}]$$

Model dependence :	± 17 [mb]
Helium (10%,20%,50%) :	-9,-18,-42 [mb]
Gamma :	$+23$ [mb]
Summary (20% He) :	(-25,+29) [mb]

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