Measurement of air shower maxima and p-Air cross section with the Telescope Array

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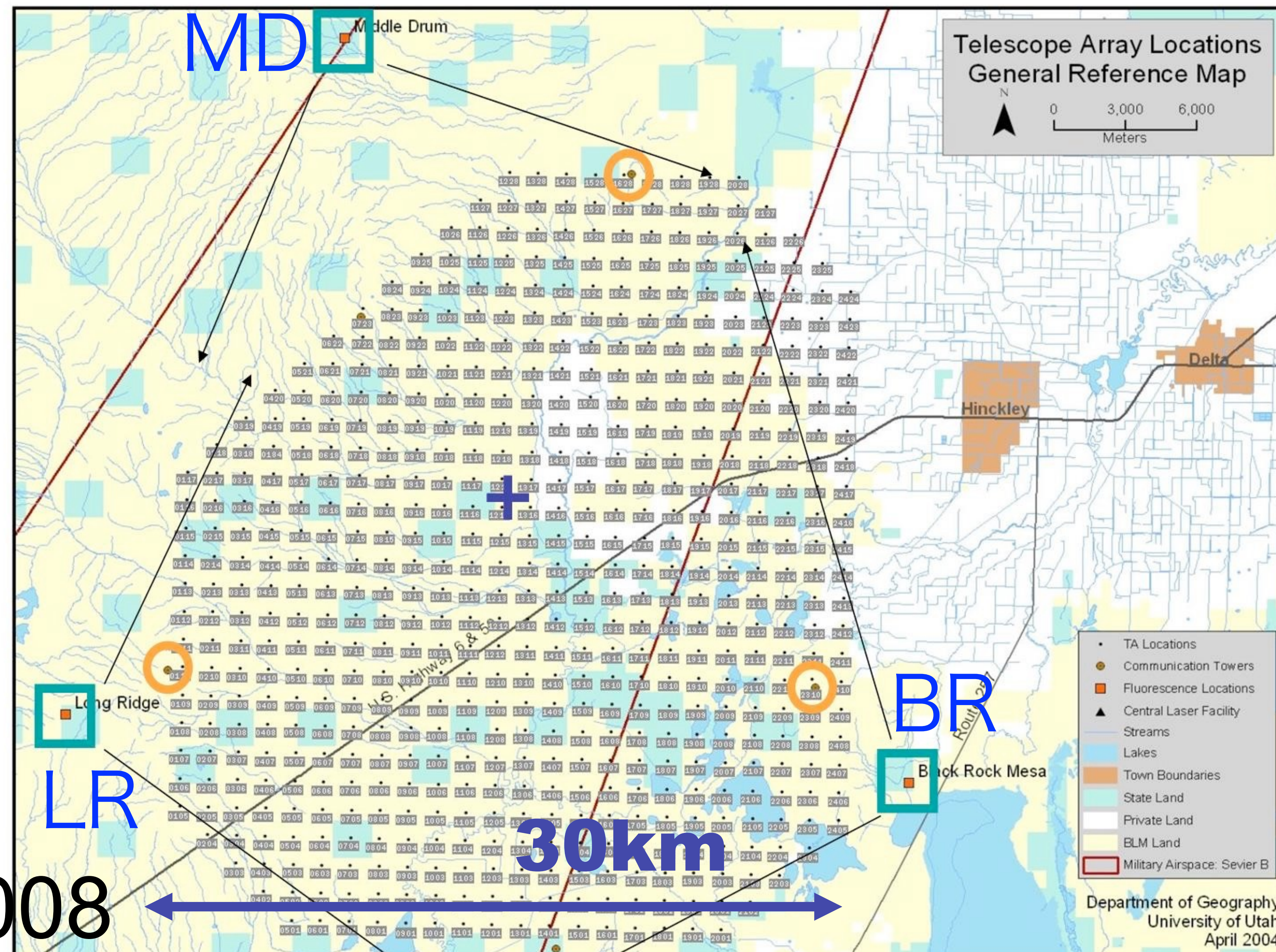
Telescope Array

- Cosmic ray observatory in Millard county, Utah, the US
  - US, Japan, Russia, Korea, and Belgium
- Surface detectors (SDs): 507 scintillation counters
- Fluorescence detectors (FDs): 38 telescopes in 3 stations
- 700km^2
- Operation since 2008



UHECR: Early Spectra

AGASA (~2004) and HiRes Fly's Eye (~2006) experiments

AGASA

JP: Surface detector array, 111 counters, ~100km^2

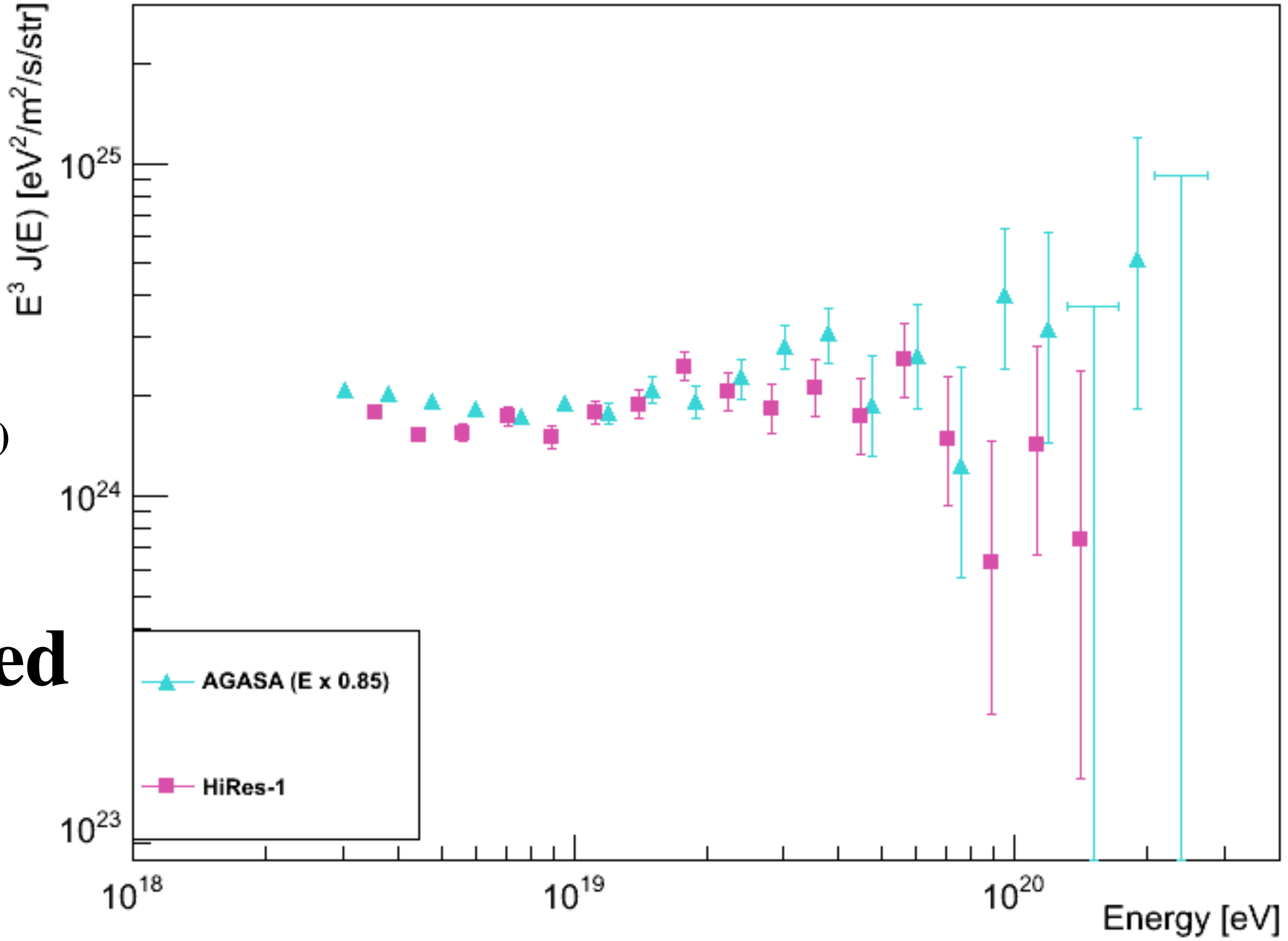
- Energy spectrum extends > 10^{20}eV without a cutoff **M.Takeda *et al.*, *Phys.Rev.Lett.*, 81, 63 (1998)**

HiRes

US: Fluorescence detectors

- There *exists* a cutoff

Phys. Rev. Lett. 100 101101 (2008)



Different techniques resulted in different conclusions?

UHECR: Early Spectra

AGASA (~2004) and HiRes Fly's Eye (~2006) experiments

AGASA

JP: Surface detector array, 111 counters, ~100km^2

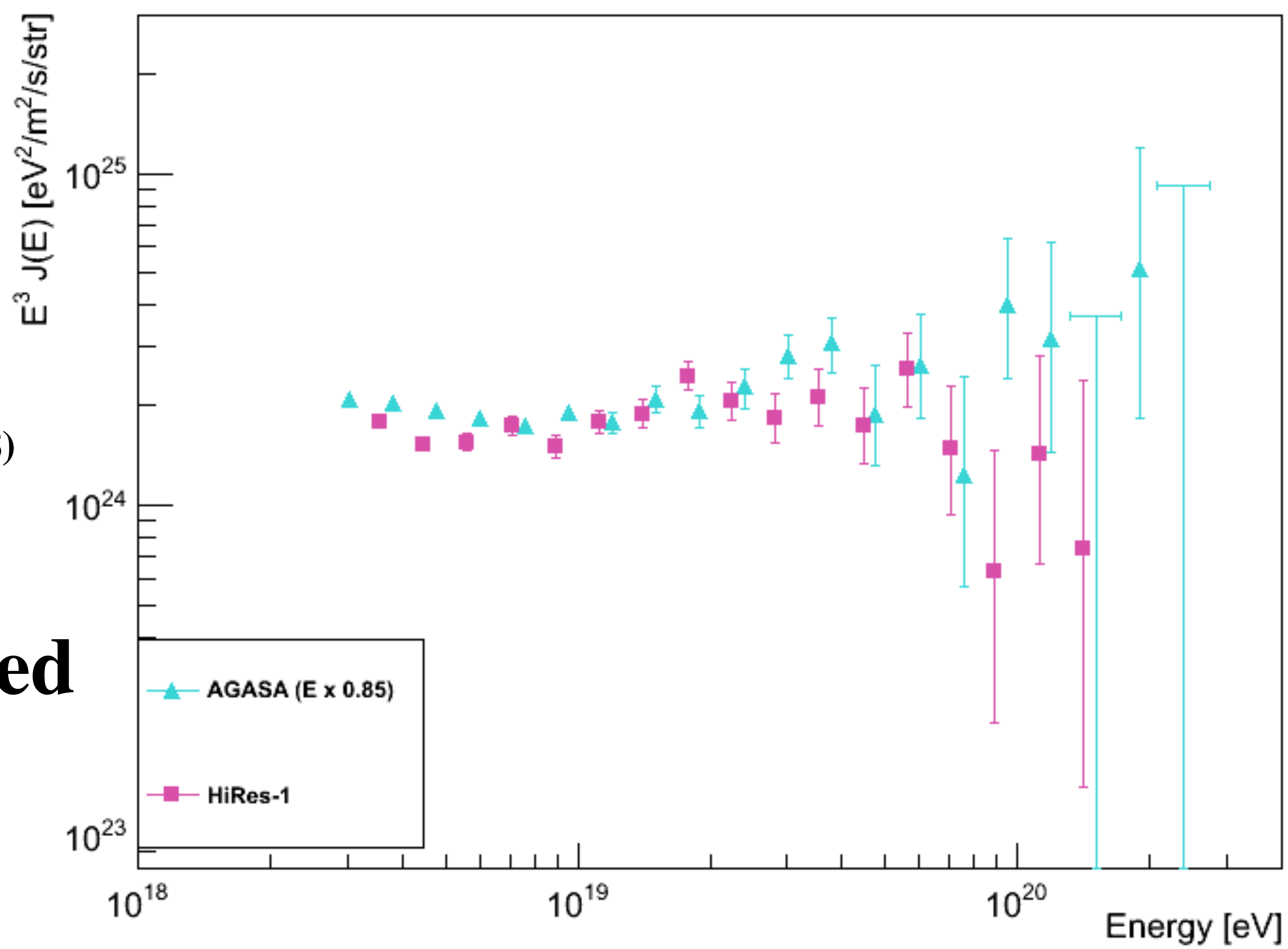
- Energy spectrum extends > 10^{20}eV without a cutoff **M.Takeda *et al., Phys.Rev.Lett.,* 81, 63 (1998)**
  - *How do we understand?*
    - *Violation of Lorentz invariance?*
    - *Topological defect?*
    - *New physics? So exciting!?*

HiRes

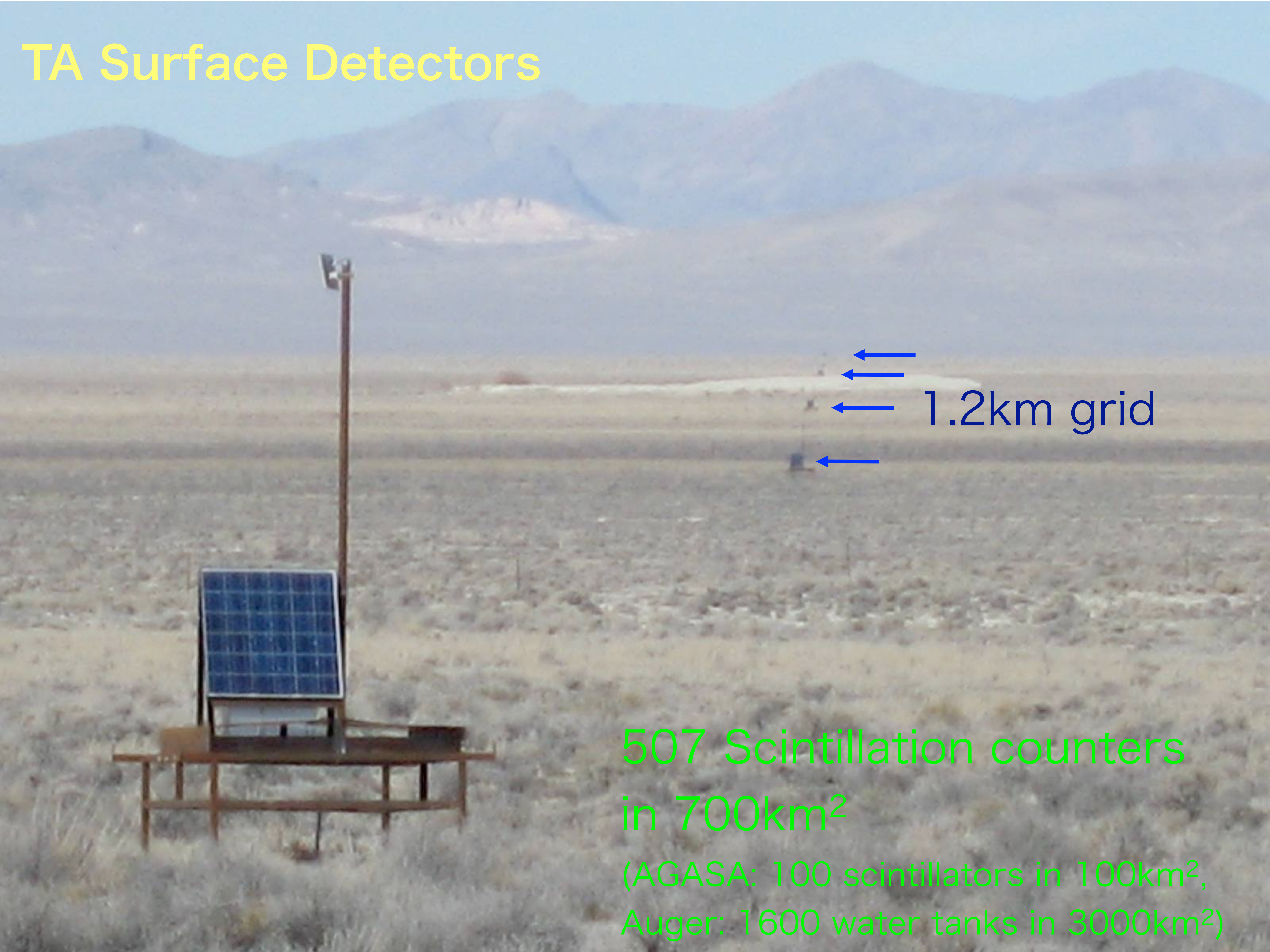
US: Fluorescence detectors

- There *exists* a cutoff

Phys. Rev. Lett. 100 101101 (2008)



Different techniques resulted in different conclusions?


TA Surface Detectors
1.2km grid
507 Scintillation counters in 700km²
(AGASA: 100 scintillators in 100km²,
Auger: 1600 water tanks in 3000km²)

TA Fluorescence Detectors

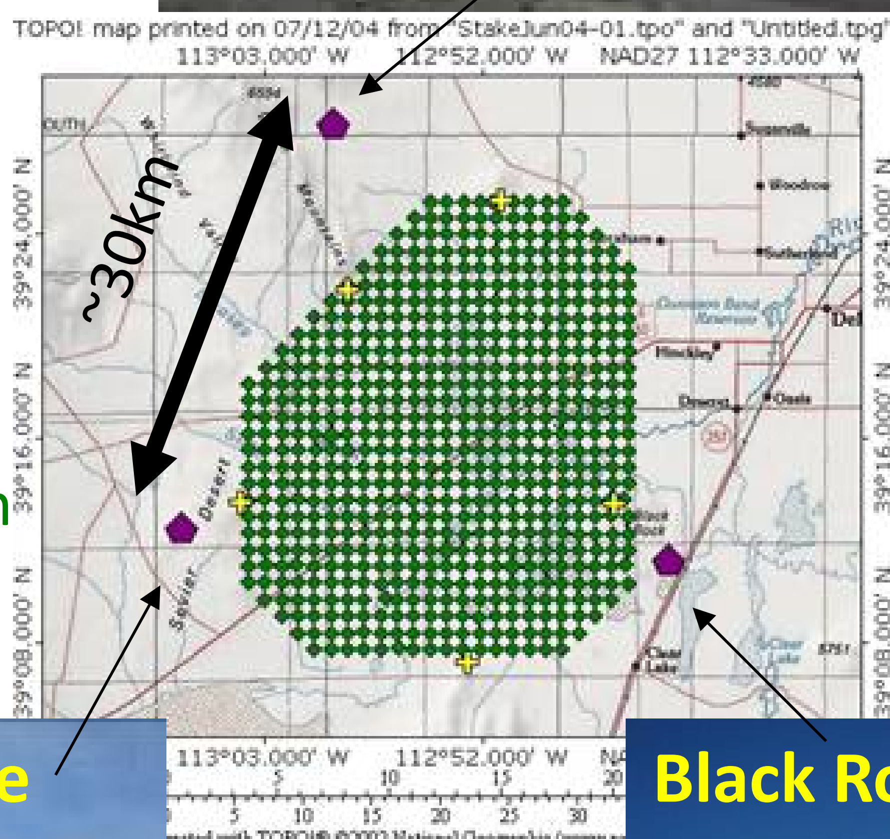
Refurbished from HiRes-I

Observations since ~10/2007

Middle Drum

14 telescopes@station
256 PMTs/camera

5.2 m^2

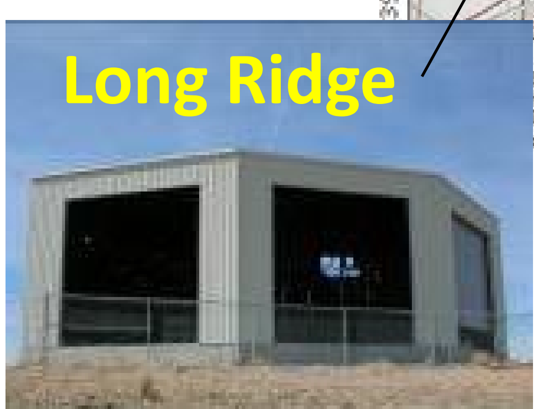


New FDs

Observation since ~11/2007

12 telescopes/station
256 PMTs/camera
Hamamatsu R9508
FOV~15x18deg

1° pixels

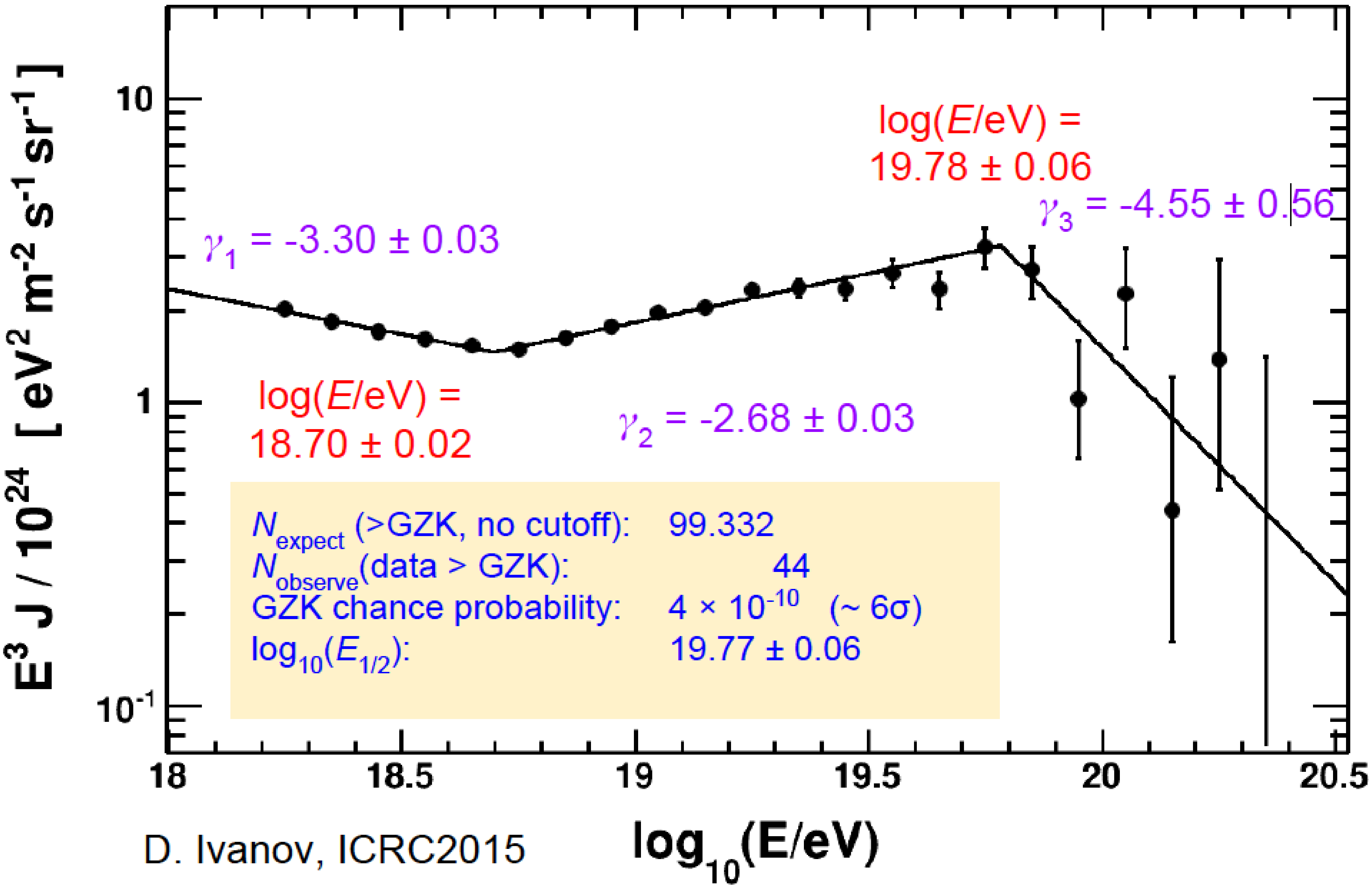


Observation since ~6/2007

~1 m^2

6.8 m^2

TA 7-Year Energy Spectrum

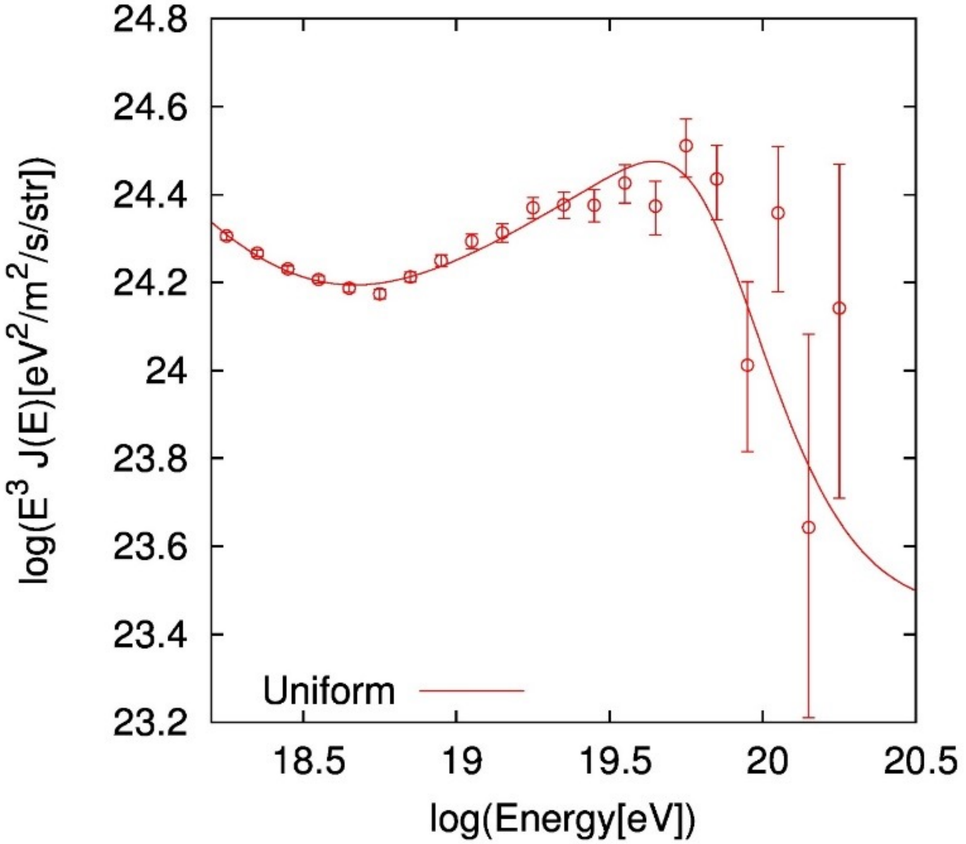


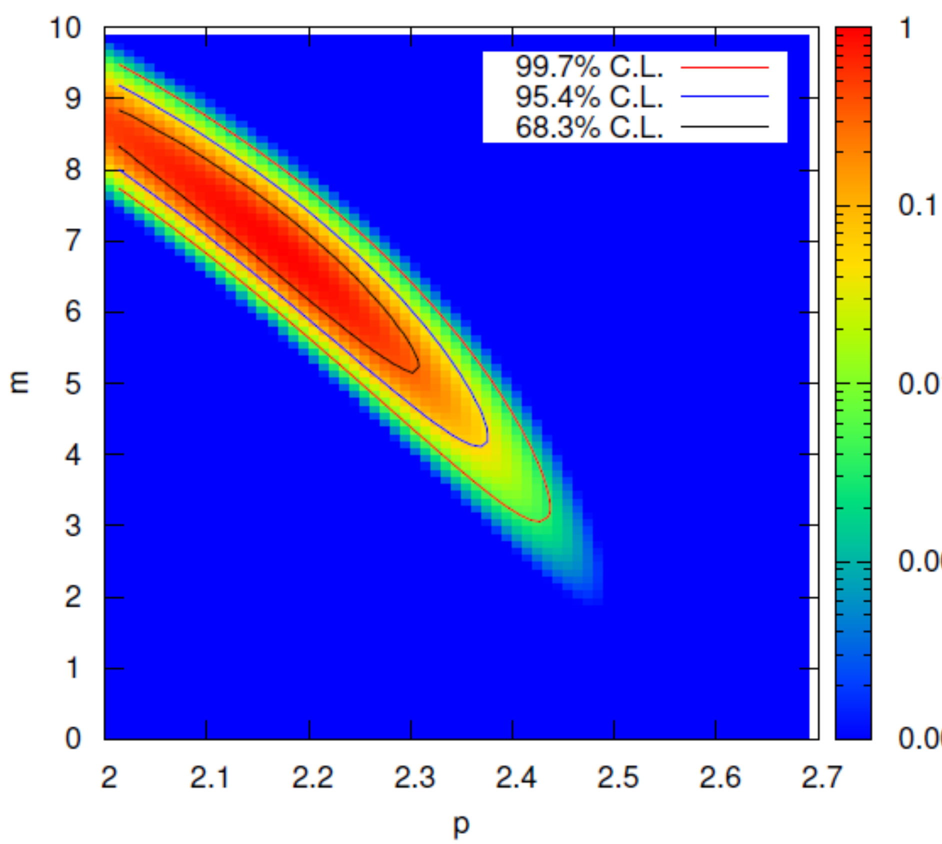
D. Ivanov, ICRC2015

Fitting the TA Spectrum to a "Minimal Cosmological Model"

- Physical processes:
  - Proton
  - Photo-pion production
  - e-pair production
  - Hubble expansion
  - Isotropic distribution of sources of equal intensities
- Fit parameters:
  - Power-law index at the sources E^{-p}
  - Cosmological evolution $(1+z)^m$

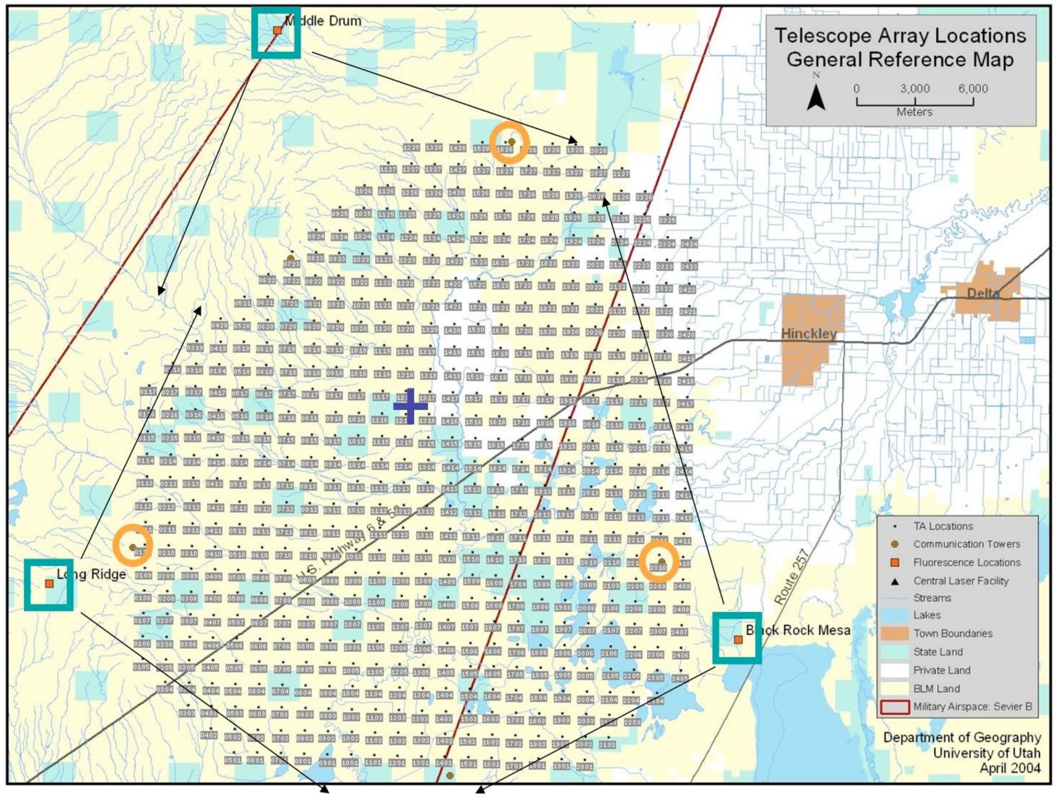
Based on the assumption of pure-proton CRs. What is the CR composition at the highest energies?





TA $\langle X_{max} \rangle$ Analyses

- Use fluorescence detectors
- Two analyses in parallel
  - MD(HiRes-I)
  - BR/LR
- Independent analyses by subgroups in the collaboration using the same data
  - Systematic check
- Xmax resolution and systematic uncertainty ~ 20 g/cm^2



FD Measures Xmax

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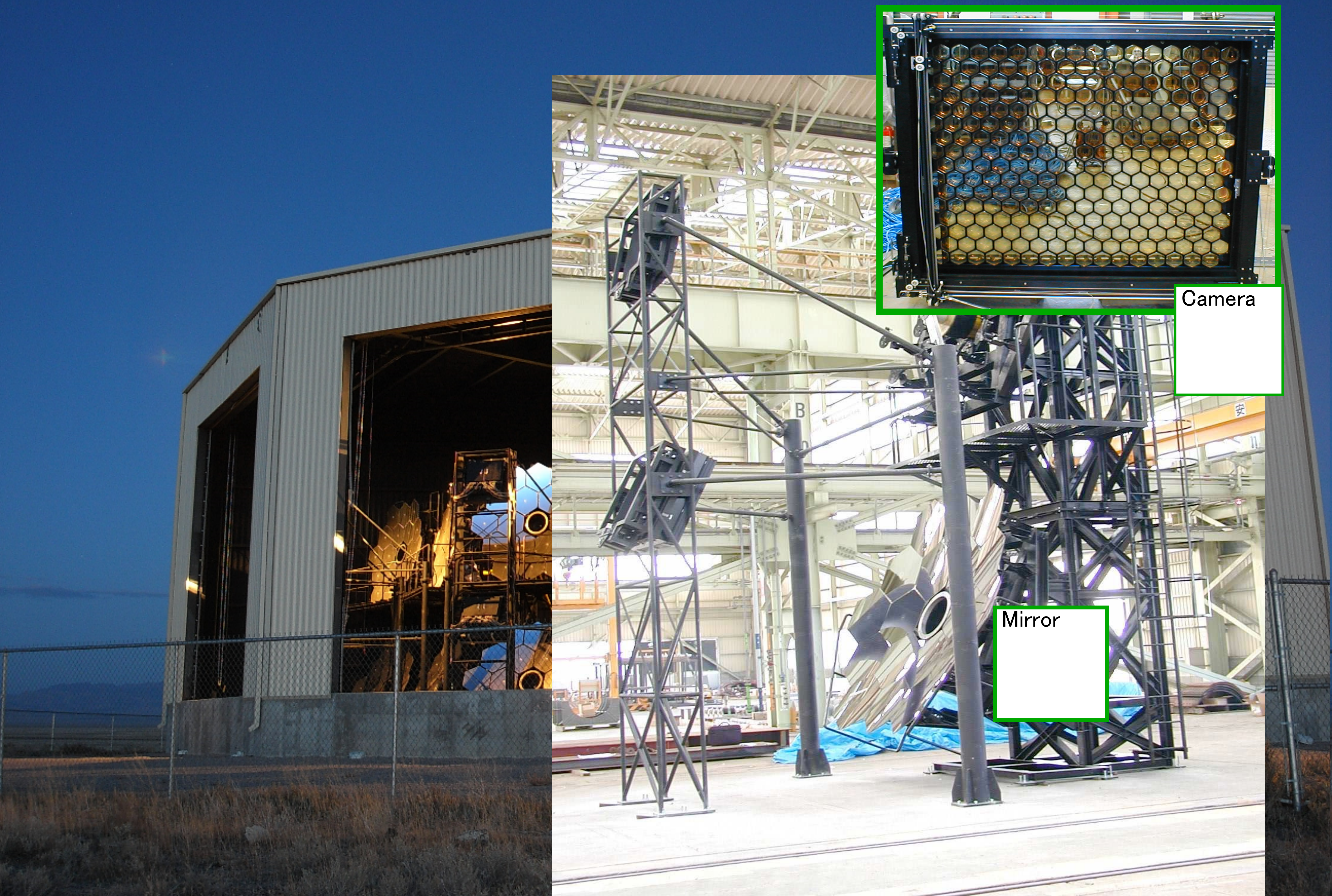
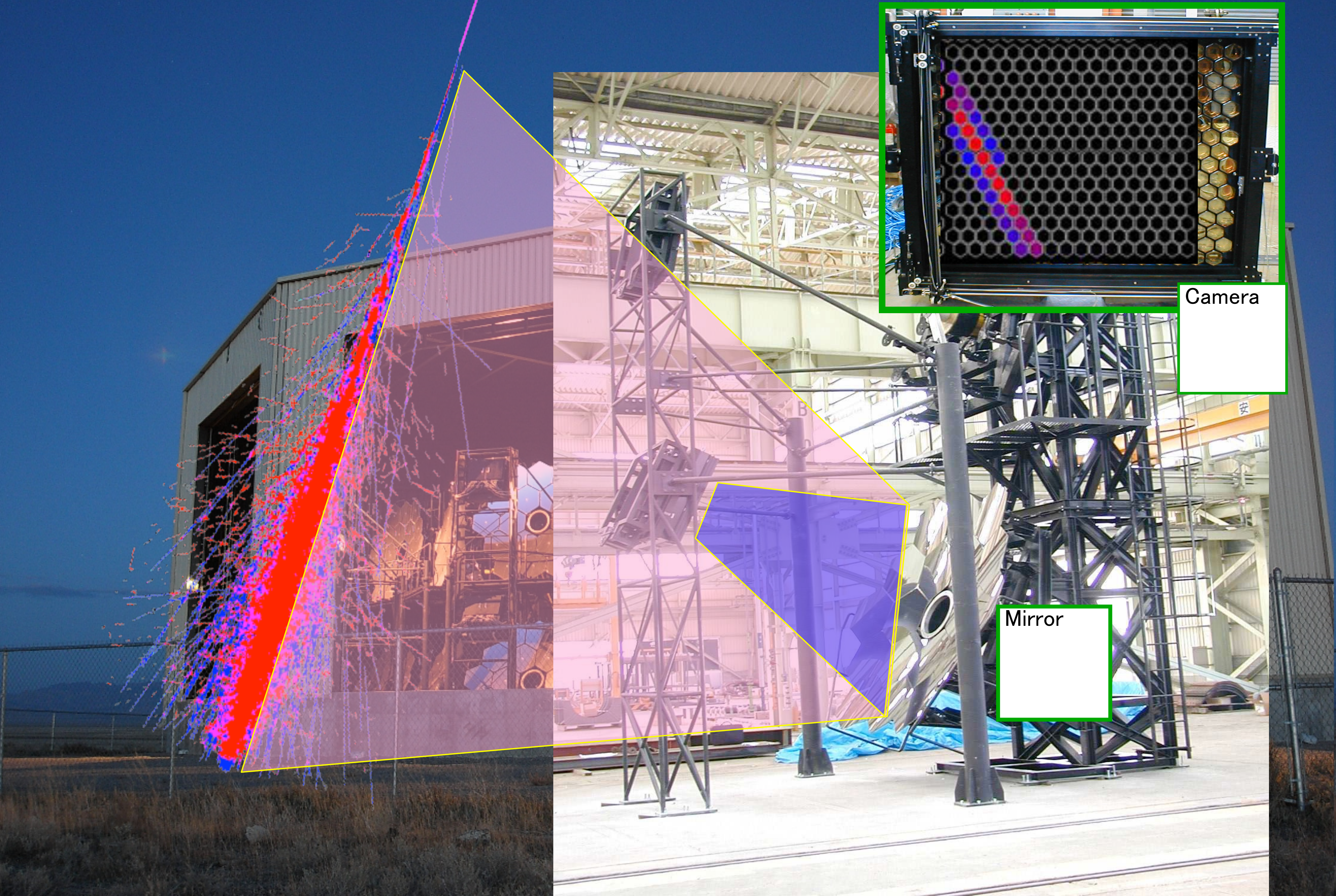
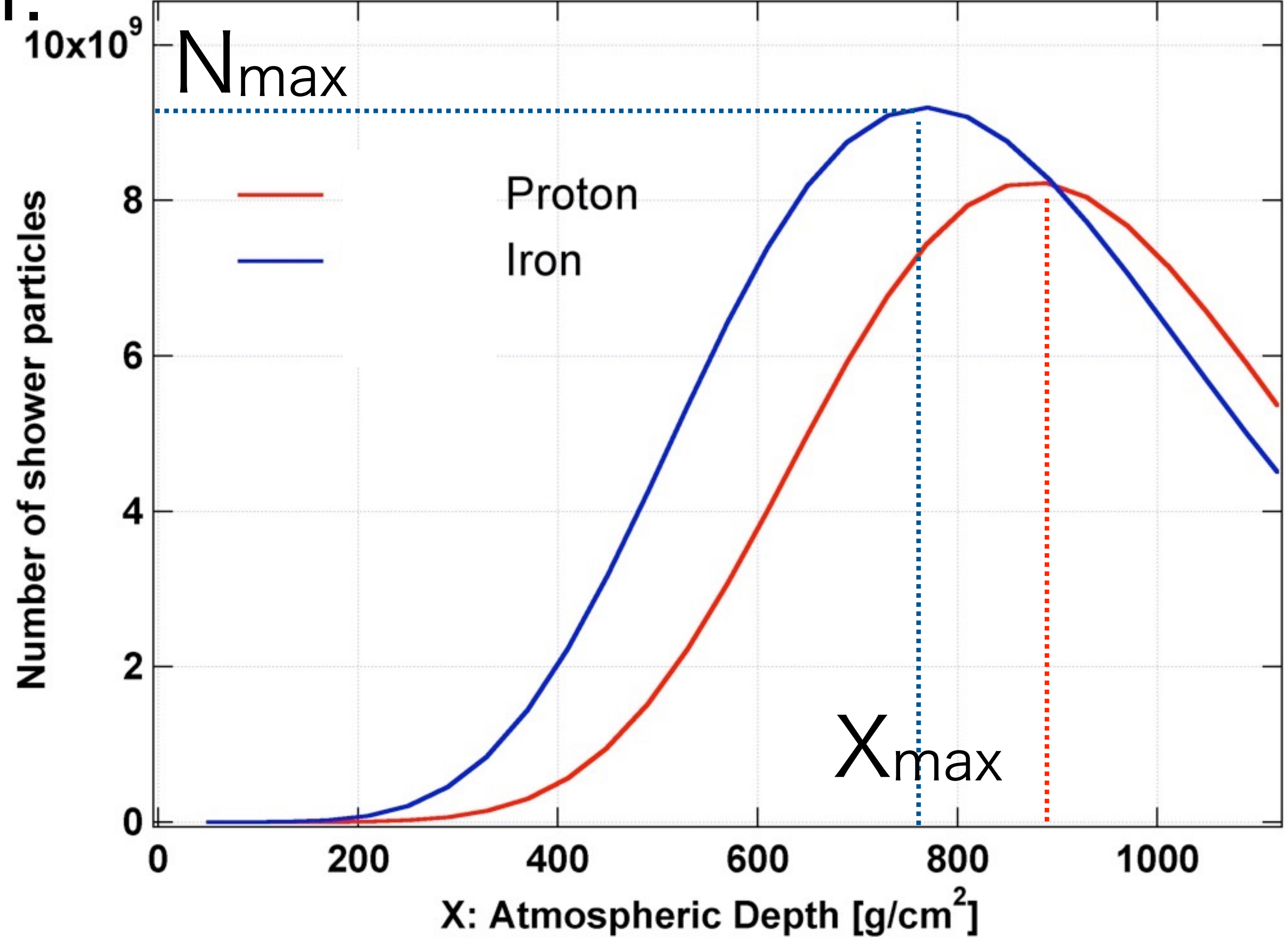


FD Measures Xmax



X_{max}

- Depth at the shower maximum
- Heavier nuclei:
  - Larger cross section
  - Smaller energy/nucleon
- A shower by heavier nuclei develops rapidly and therefore X_{max} gets smaller.

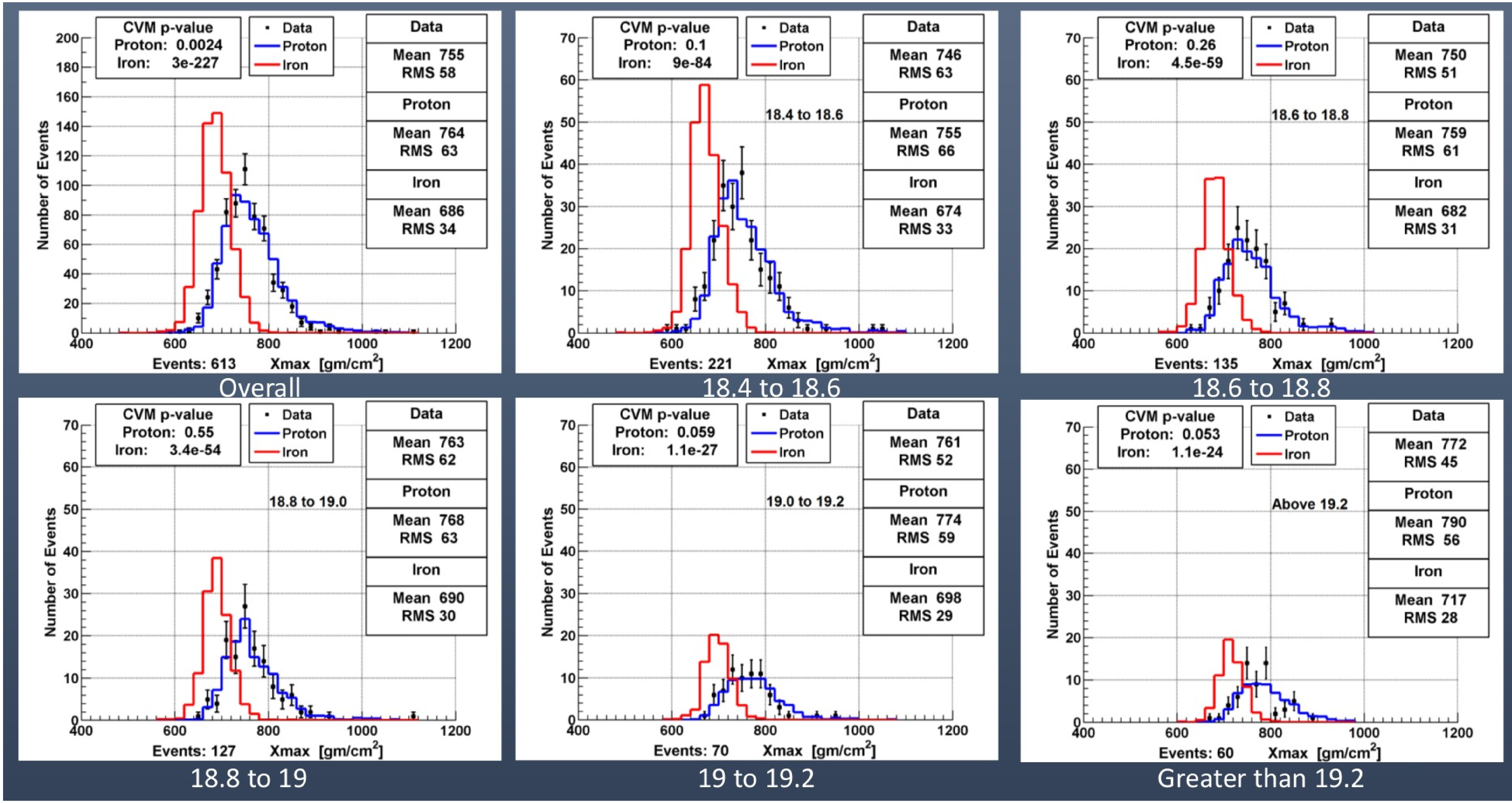


- Event-by-event fluctuation of X_{max} is also smaller:
  - Heavier nucleus shower is a "superposition" of proton showers - its X_{max} is an average of proton X_{max}s.

MD $\langle X_{max} \rangle$

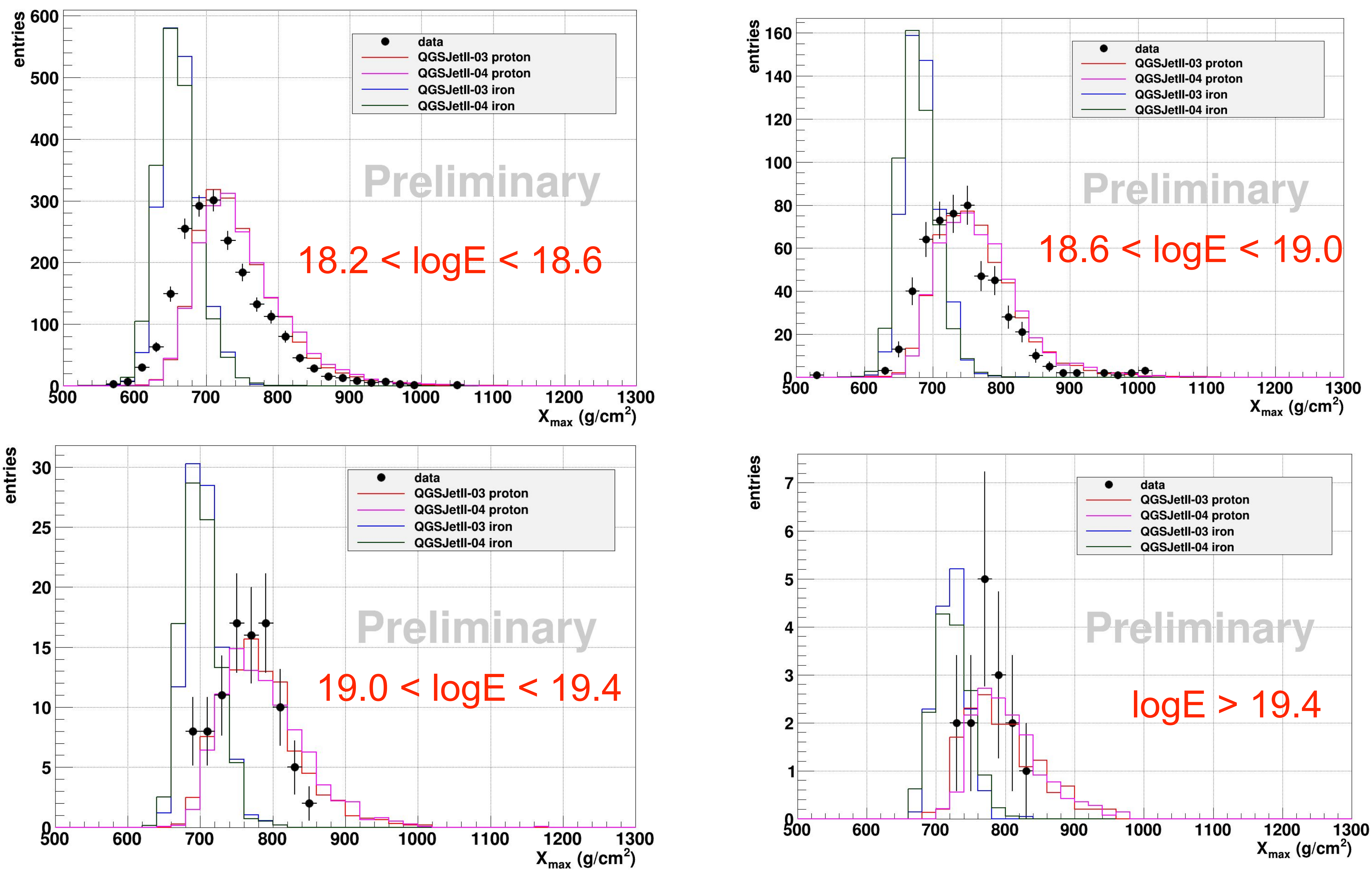
J.P. Lundquist ICRC2015
J. Belz ICRC2015
R. Abbasi *et al.*, *Astropart. Phys.*, **64**, 49 (2015)

TA MD + SD. MC: QGSJET-II-03

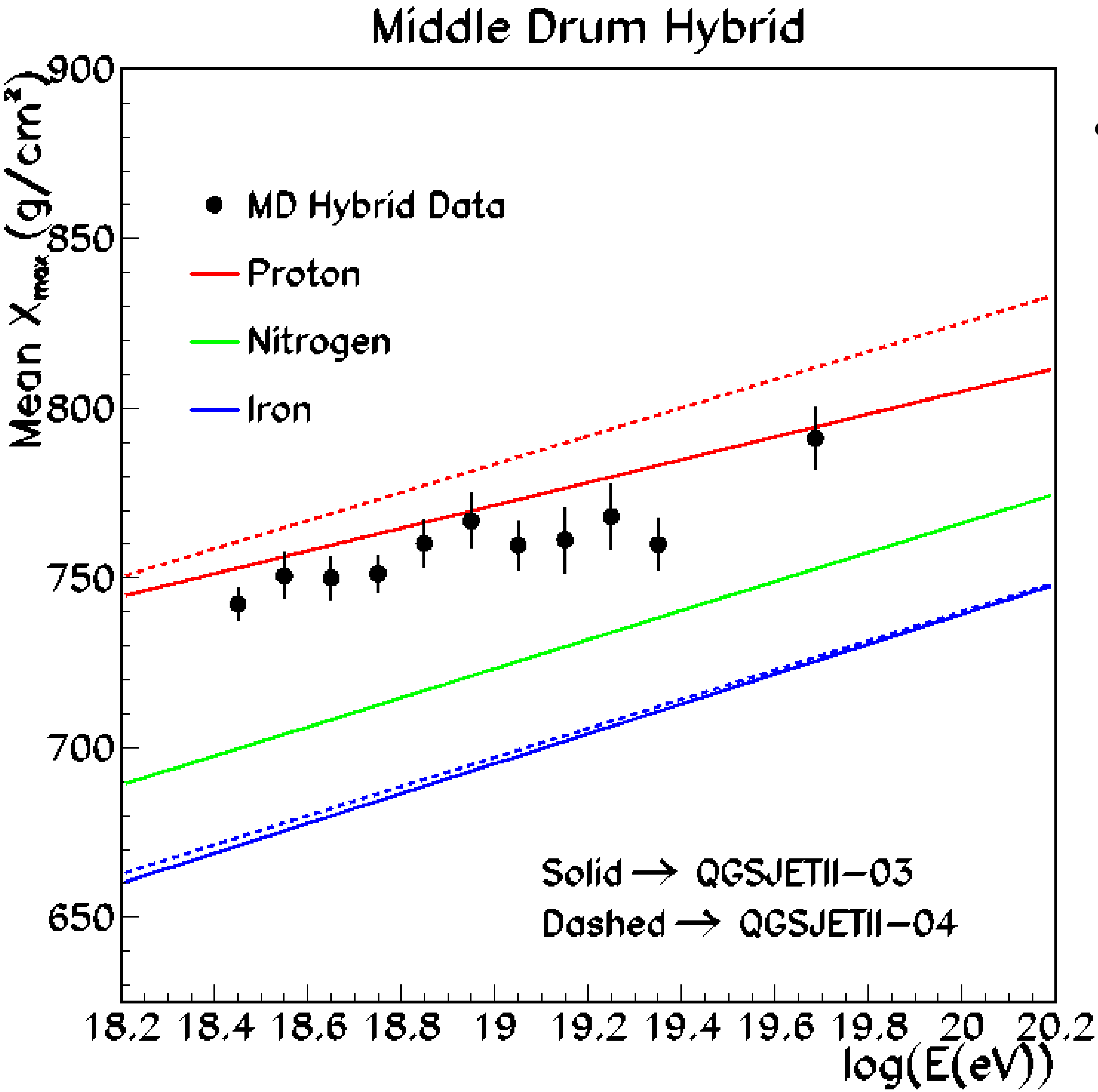


BR/LR Xmax Distributions

W. Hanlon, APS Meeting 2016



TA MD Elongation Rate



BR/LR Elongation Rate

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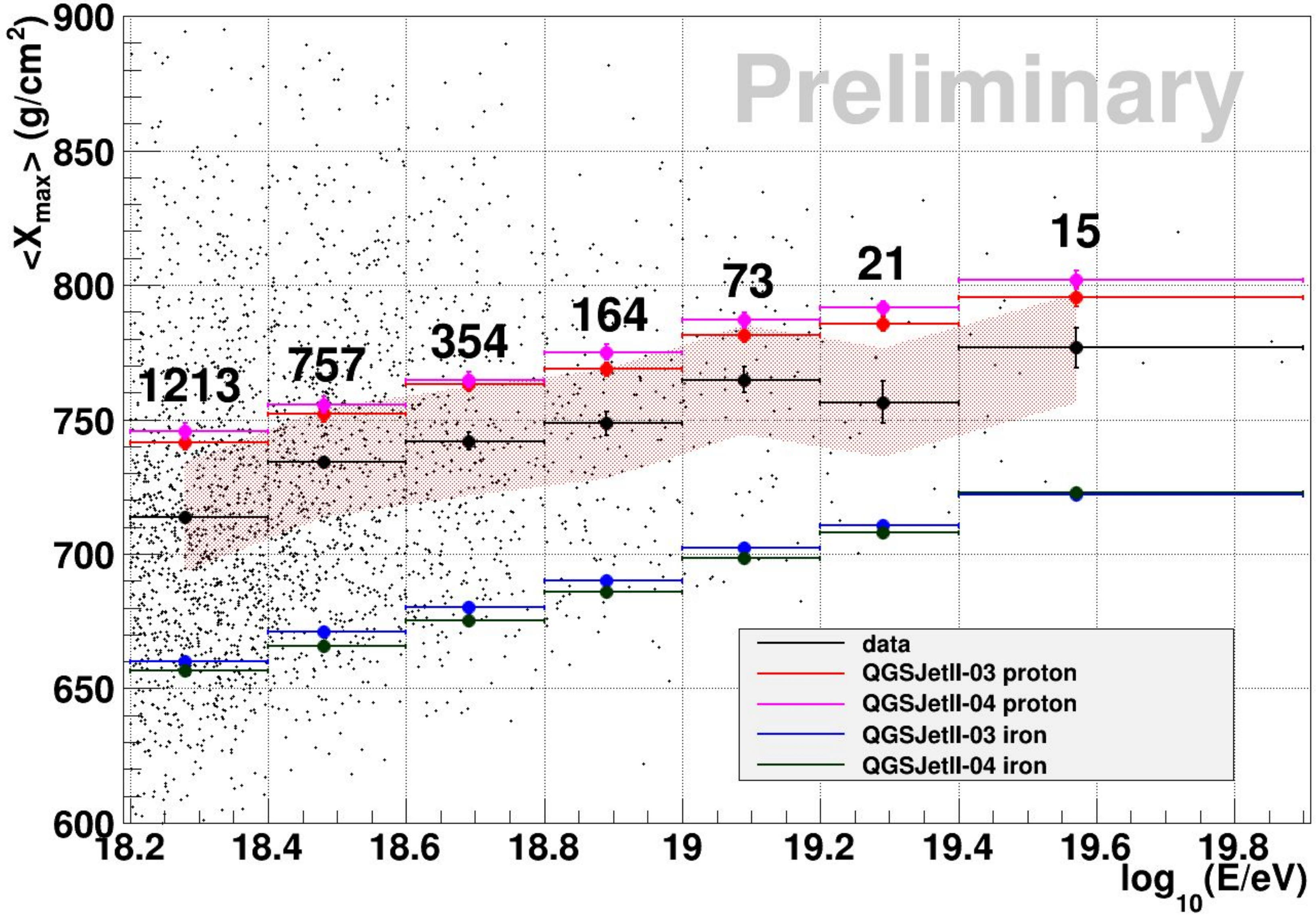


Mean X_{max} with systematic uncertainties:

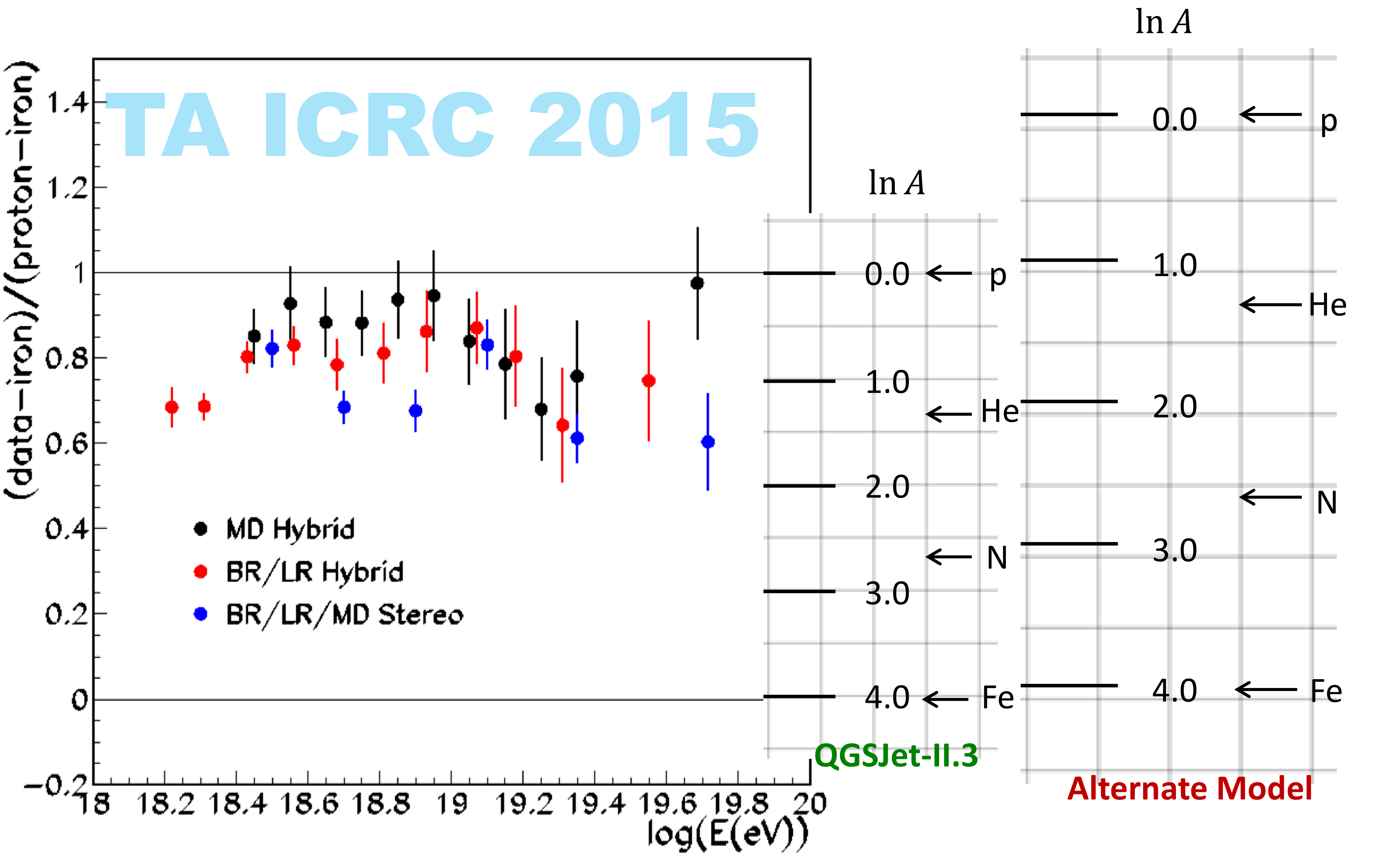
1) Reconstruction: 4.1 g/cm^2
2) Atmospherics: 10.9 g/cm^2
3) Detector geometry: 3.3 g/cm^2
4) Aerosols: 2 g/cm^2

Total systematic uncertainty: 20.3 g/cm^2

Means favor a light composition.

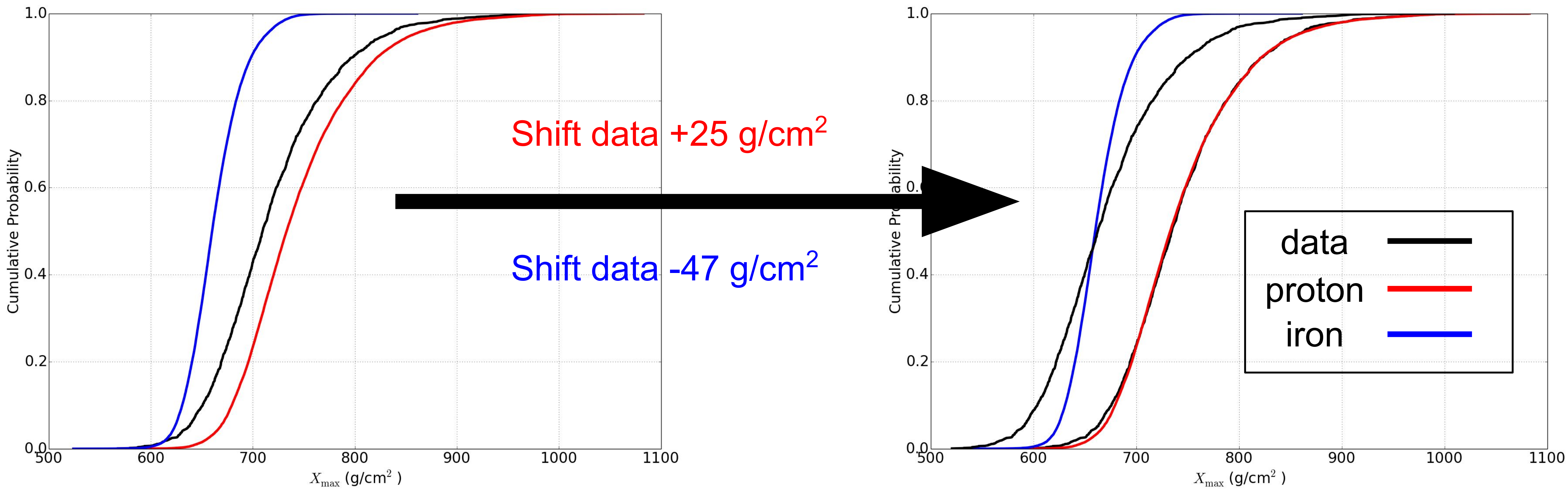
<lnA> Plot

Measures distance between the data and iron, normalize by (proton-iron), and scale in [ln 1, ln56] = [0, 4].



Comparing Data and MC: CvM Test

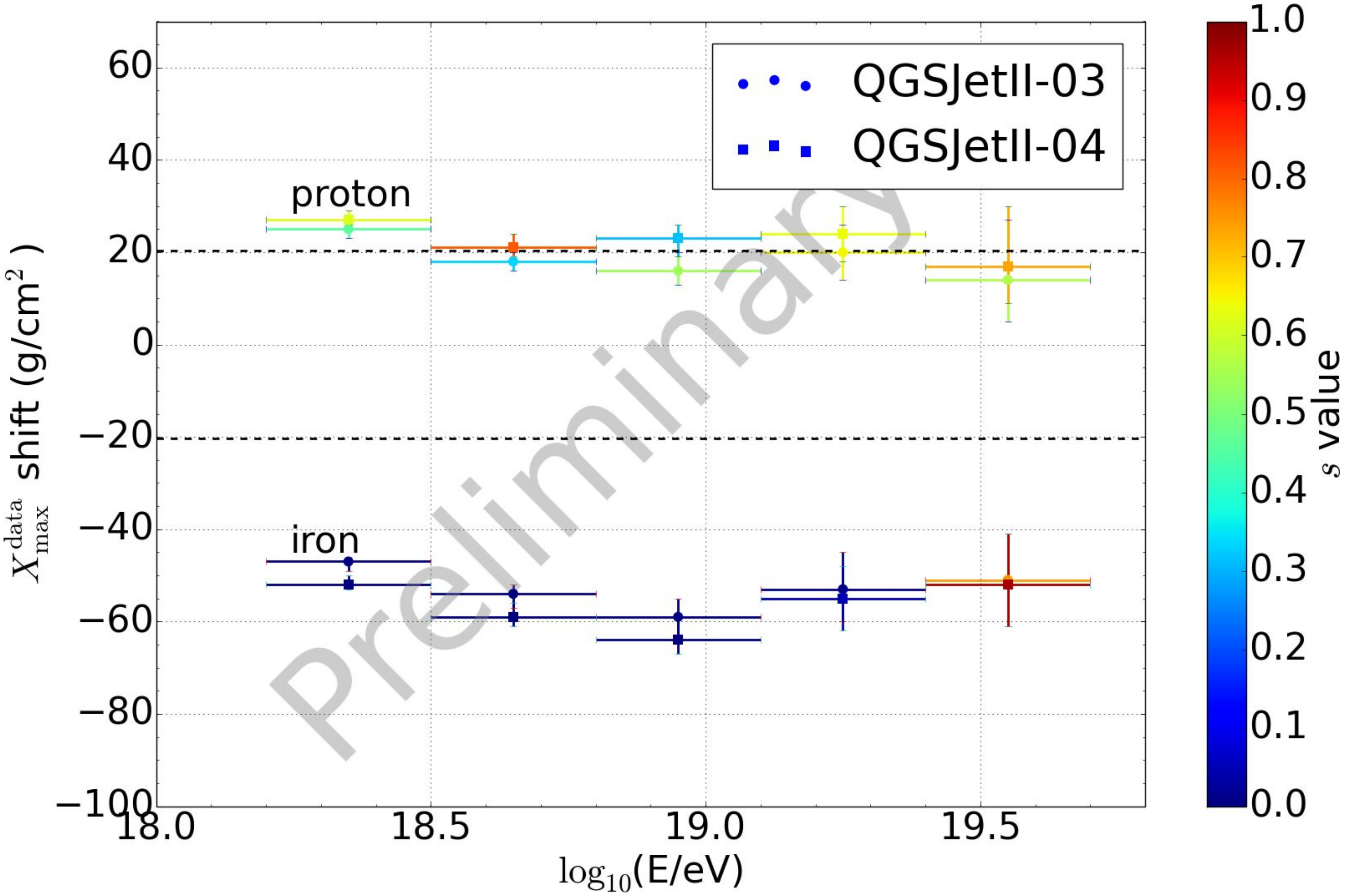
W. Hanlon, APS Meeting 2016



- Mean and RMS are heavily influenced by what happens in the tails → sampling bias.
- Utilize Cramér-von Mises (CvM) non-parametric goodness of fit test.
- Ask the question: how much does data need to be shifted to find agreement with CORSIKA models.
- Apply the CvM test to evaluate the agreement of the entire distribution without relying on the moments of the distribution.

Comparing Data and MC: CvM Test

W. Hanlon, APS Meeting 2016



Amount that data needs to be shifted to match CORSIKA models. Find the best value of the two-sample CvM test statistic.

s-value is the *p*-value under the assumption both samples were drawn from the same parent distribution *after shifting the data.*

To find agreement with heavy elements, large shifts are needed and the *s*-values are too small.

Light composition is favored.

X_{max} systematics: ± 20.3 g/cm^2

Cross Section of CR-Air interaction

p-Air Cross Section from Xmax Distribution

- Interaction length of CR proton in the air

$$\lambda_{\mathrm{p-Air}} = \frac{1}{A m_p \sigma_{\mathrm{p-Air}}}$$

- Depth of first int. distributes in exp. with the slope $\lambda_{\text{p-Air}}$

- Exp. slope of Xmax

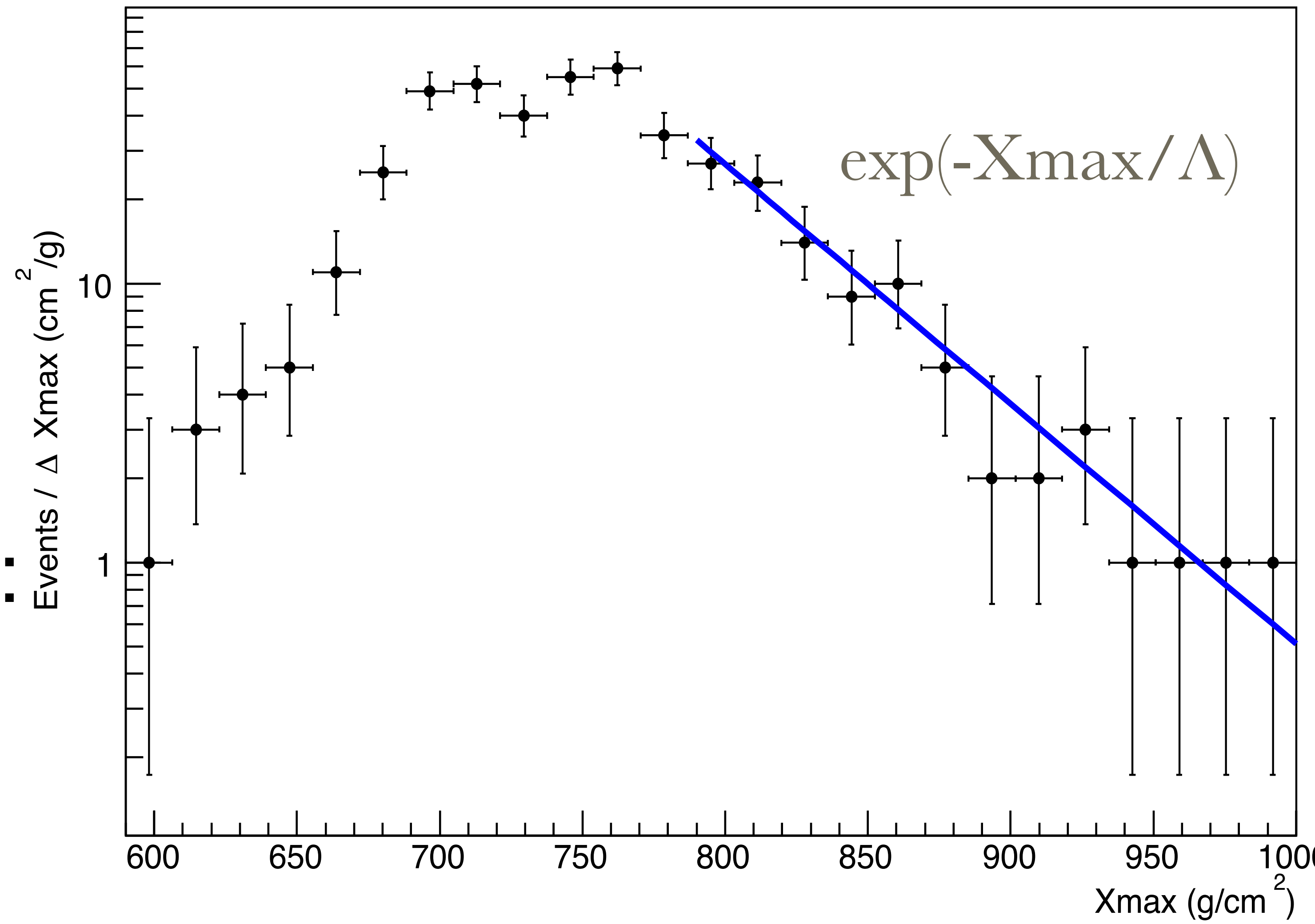
$$\Lambda_{\mathrm{p-Air}} = k \lambda_{\mathrm{p-Air}}$$

- TA MD data in $10^{18.3\text{-}19.3}$eV:

$$\Lambda_{\mathrm{p-Air}} = 50.5 \pm 6.3\,\mathrm{g/cm^2}$$

- Need *k* to obtain λ

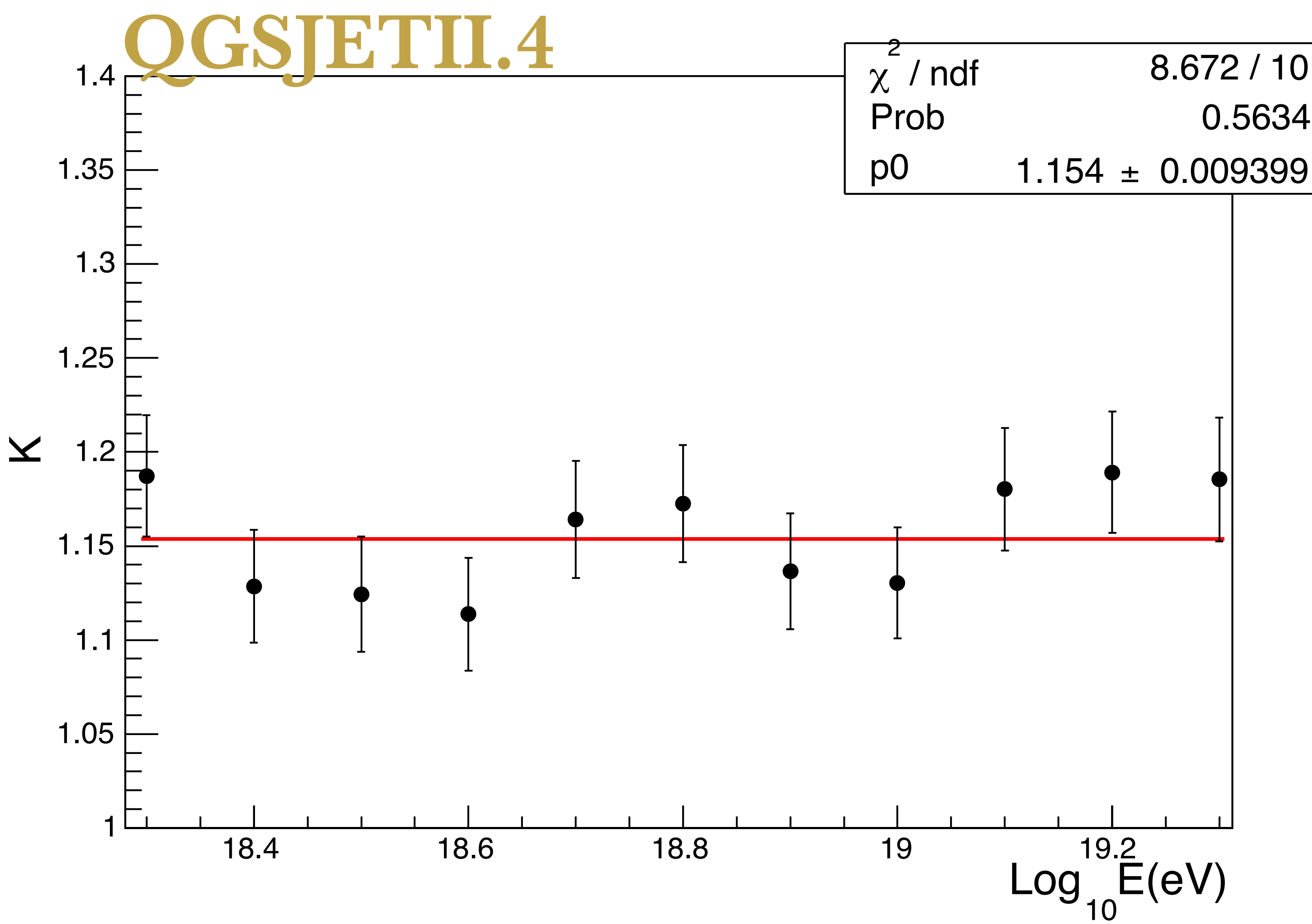
R. Abbasi ICRC2015,
R. Abbasi et al., Phys. Rev. D, 92, 032007 (2015)



Estimating k values

- 10^4 showers in each dlogE=0.1 step
- Calculate *k* from the slopes Λ of Xmax and λ of X1
- Acceptance bias negligible: k of MC-thrown showers and reconstructed showers are the same.

Model	*k* (Error = 0.01)
QGSJET-II-04	1.15
QGSJET-01	1.22
SIBYLL	1.18
EPOS-LHC	1.19



p–Air Cross Section

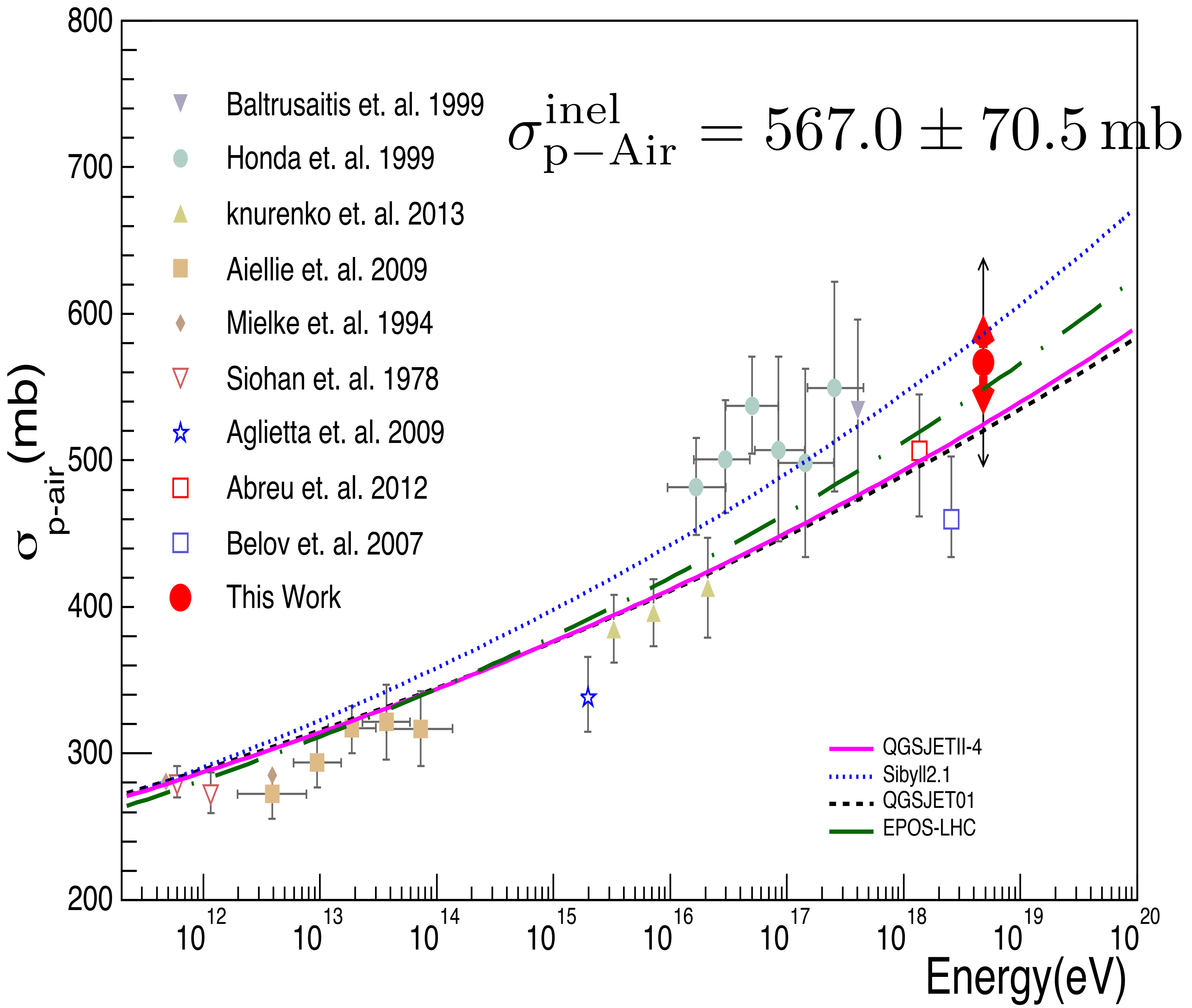
Model	$k = \Lambda/\lambda$ (Error = 0.01)	$\sigma_{\text{p-Air}}$ [mb]
QGSJET-II-04	1.15	550.3 ± 68.5
QGSJET-01	1.22	583.7 ± 72.6
SIBYLL	1.18	564.6 ± 70.2
EPOS-LHC	1.19	569.4 ± 70.8

$$\sigma^{\text{inel}}_{\text{p-Air}} = 567.0 \pm 70.5\,\text{mb} \qquad \sqrt{s} \sim 95\,\text{TeV}$$

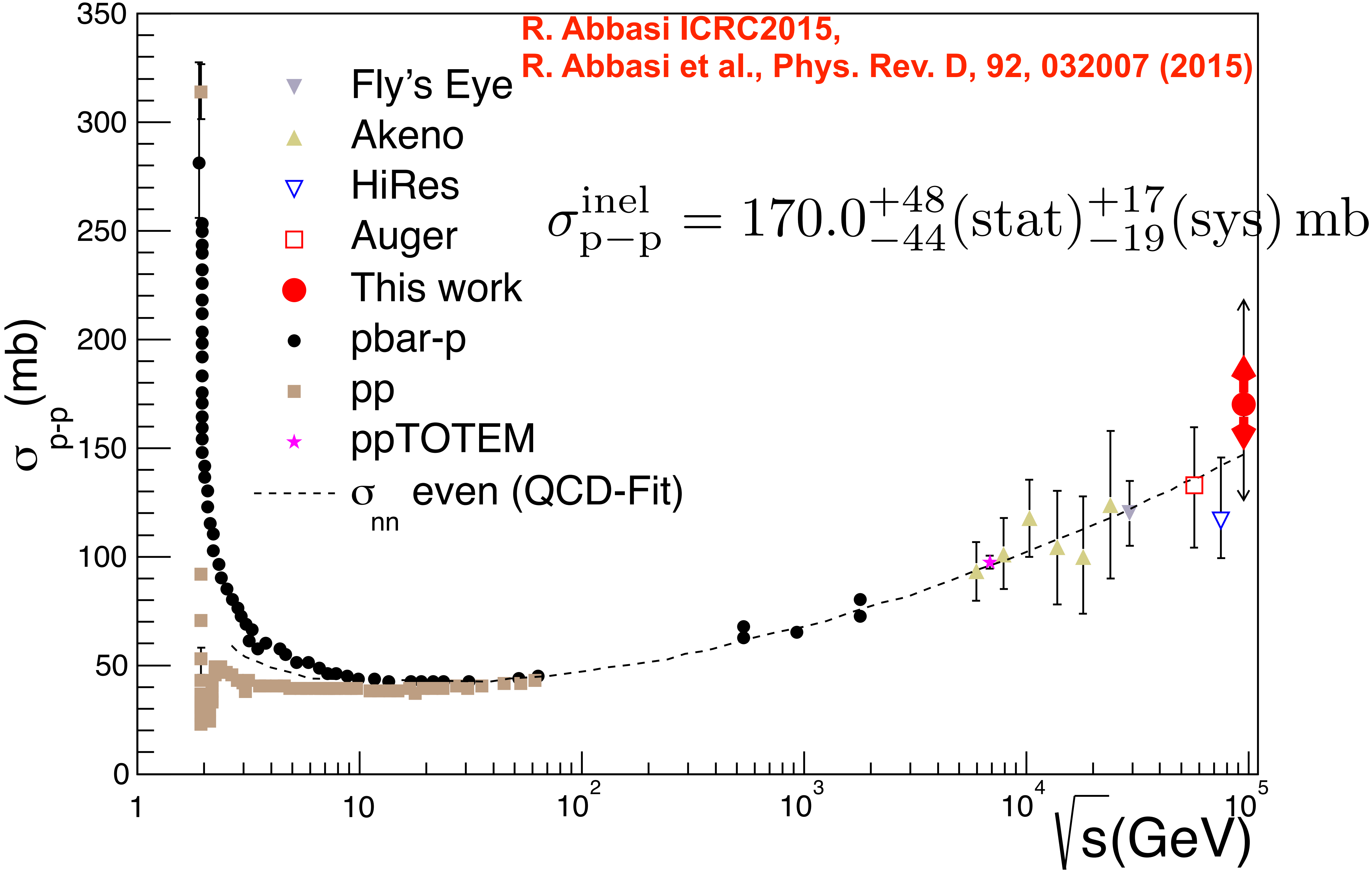
p–Air Cross Section and Systematic Uncertainty

R. Abbasi ICRC2015,
R. Abbasi et al., Phys. Rev. D, 92, 032007 (2015)

Systematic source	Systematic (mb)
Model Dependence	±17
10% Helium	+9
20% Helium	+18
50% Helium	+42
Gamma < 1%*	-23
Total (20% He)	(+25,-29)



p-p Cross Section by the Glauber Formalism



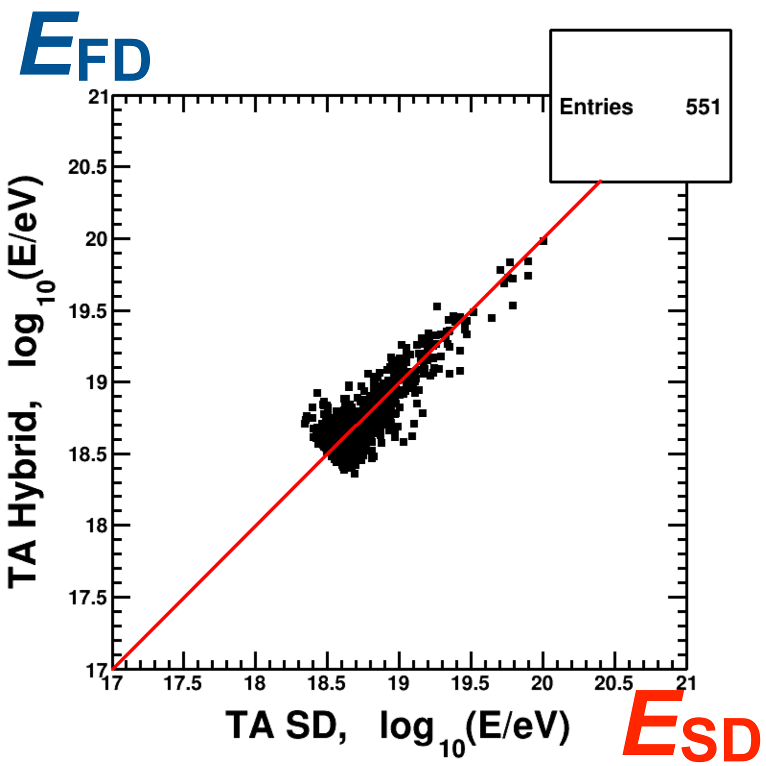
Summary

- 7-year TA data
- Xmaxs analysis
  - MD and BR/LR analysis
  - Agreement with “light” composition with systematic uncertainties
    - <Xmax> agrees with Auger
    - Xmax distributions support light composition
  - Statistics still limited in higher energies
- Cross section measurement
  - Λ, the slope of Xmax distribution
  - Use the “k” parameter to obtain λ ∝ 1/σ

$$\sigma^{\rm inel}_{\rm p-Air} = 567.0 \pm 70.5({\rm stat})^{+25}_{-29}({\rm sys})\,{\rm mb}$$

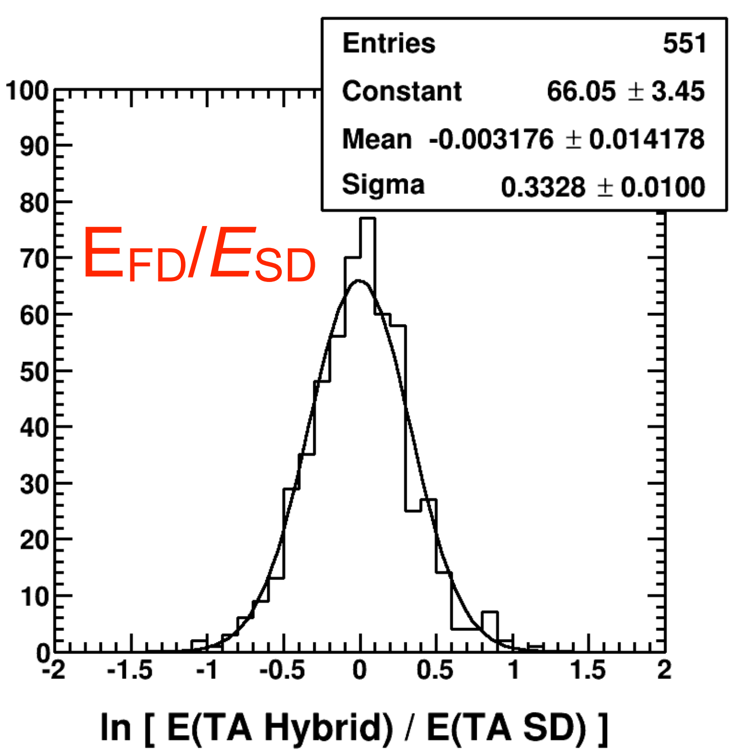
$$\sigma^{\rm inel}_{\rm p-p} = 170.0^{+48}_{-44}({\rm stat})^{+17}_{-19}({\rm sys})\,{\rm mb}$$

Energy Determination in TA



- Use *hybrid* events, and calculate E_{FD} and E'_{SD}.
- Use E_{FD} as reference: calorimetrically determined energy
- Calculate $E'_{\mathrm{SD}}/E_{\mathrm{FD}}$ ratio for the hybrid events

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

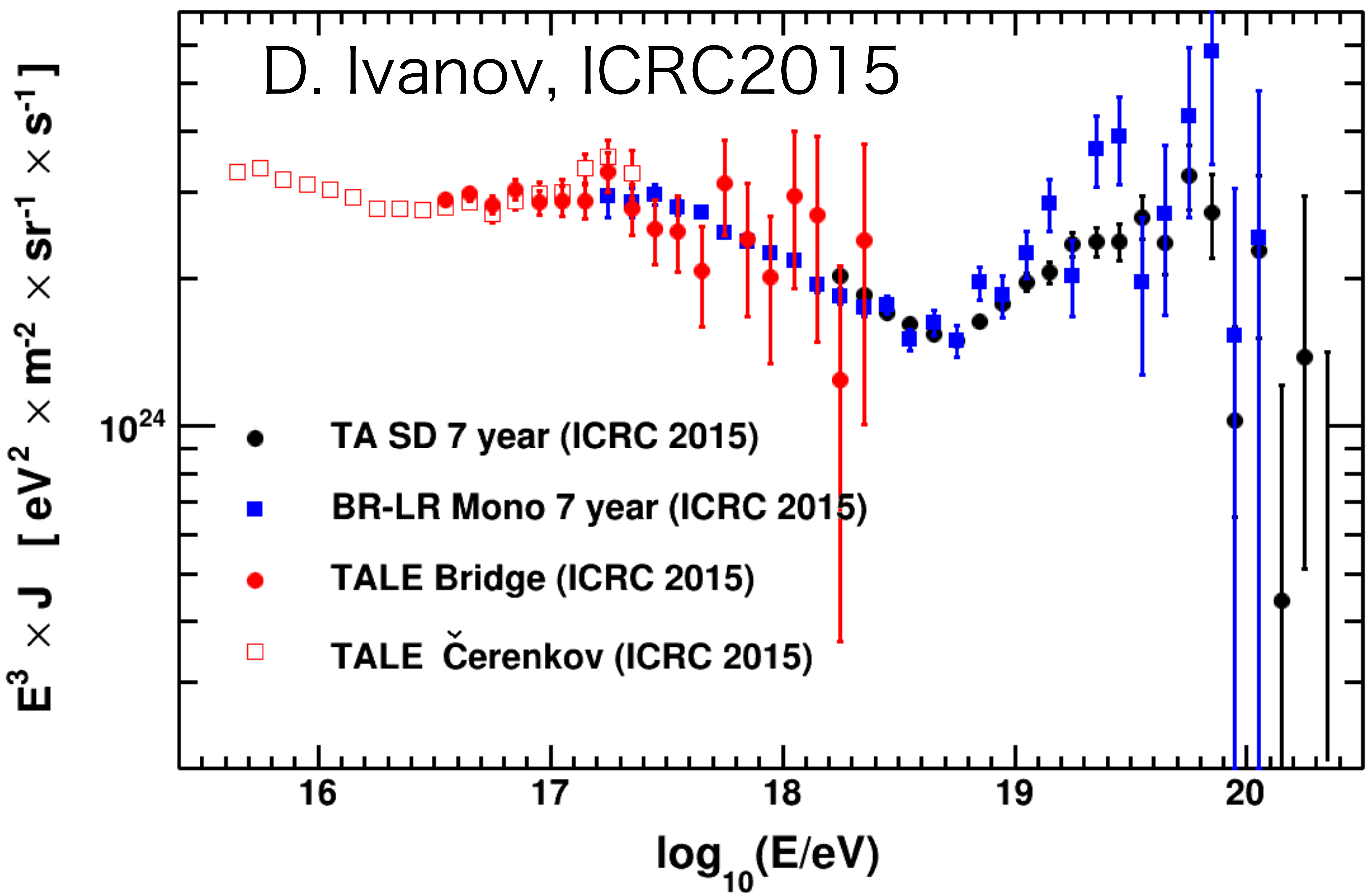


- Rescale the SD energy for all the SD events

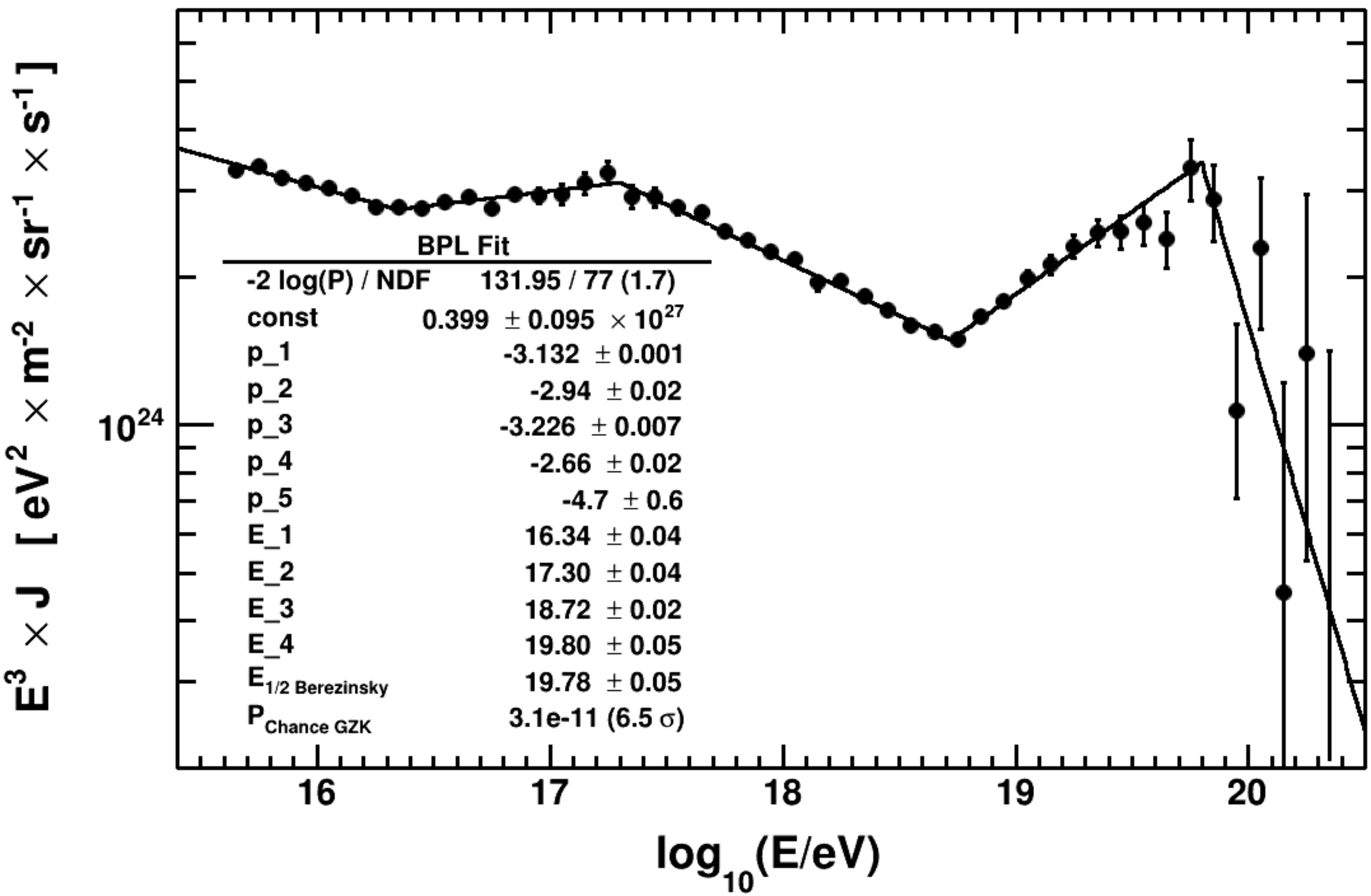
$$E_{\mathrm{SD}} = \frac{1}{\left\langle \frac{E'_{\mathrm{SD}}}{E_{\mathrm{FD}}} \right\rangle_{\mathrm{hyb}}} E'_{\mathrm{SD}}$$

TA 4.7-Decade Spectra

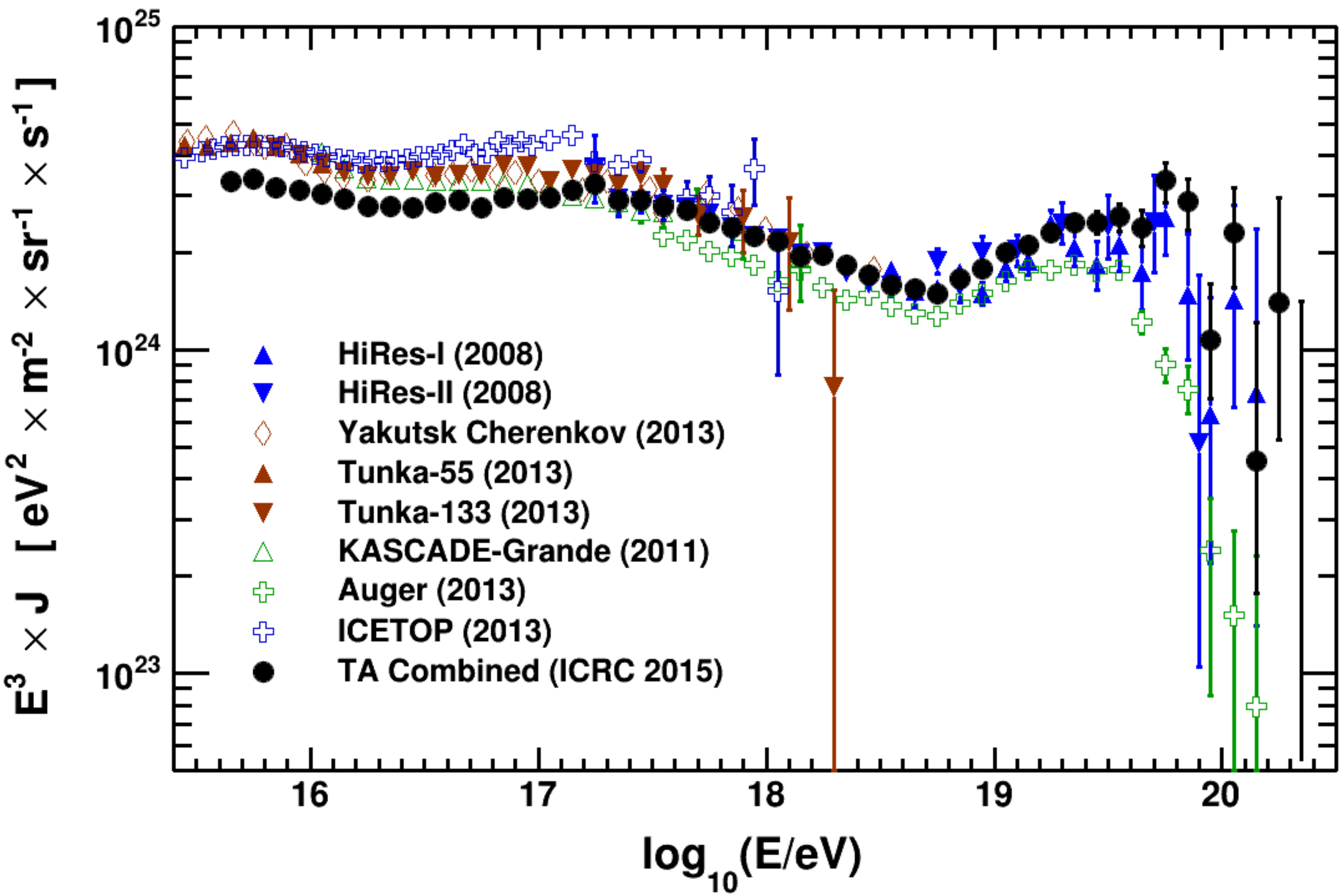
Energy systematic error: 22%



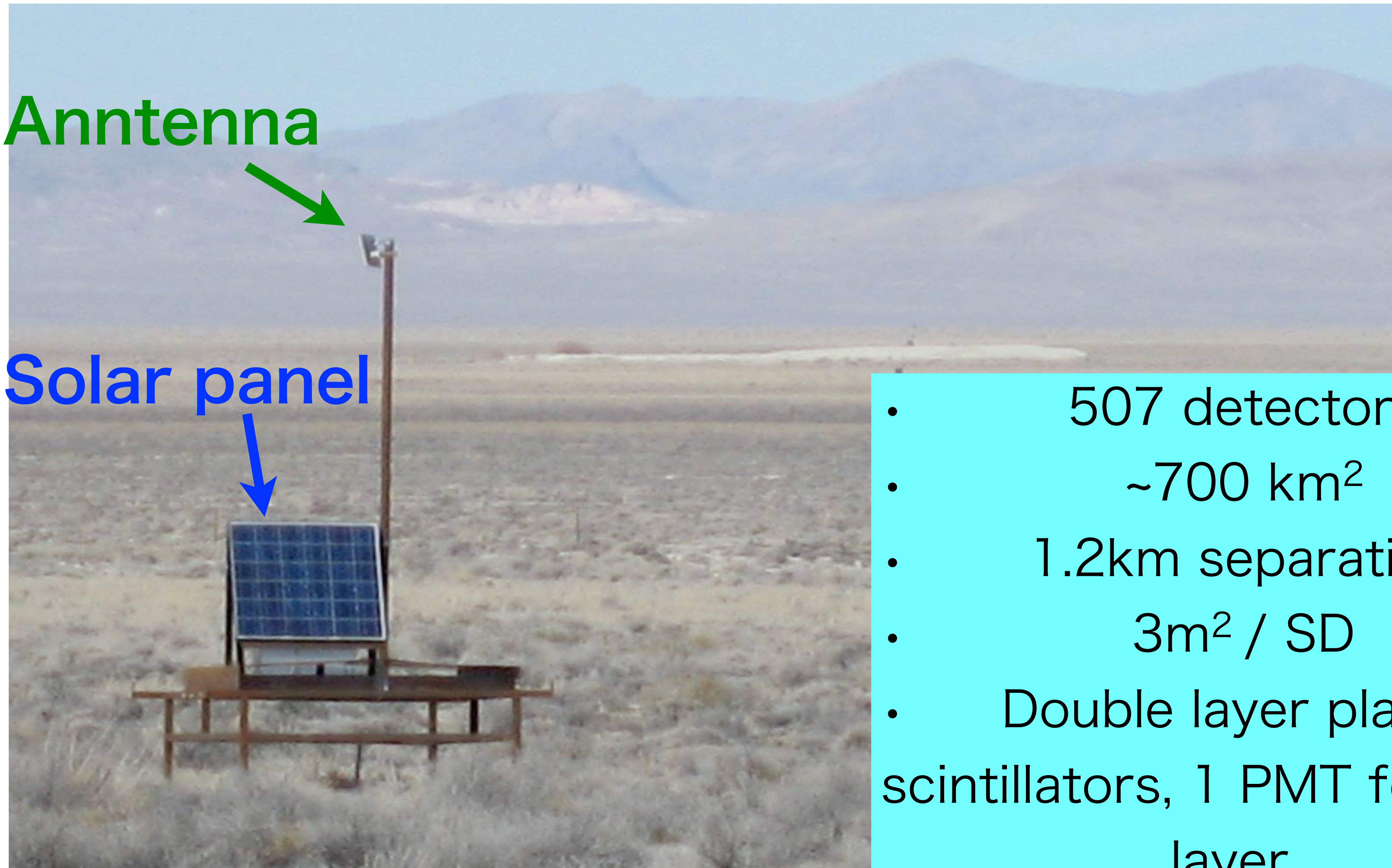
TA Combined Spectrum



TA Spectrum with Other Experimental Results



TA Surface Detectors (SD)



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

TA Fluorescence Detectors (FDs)

Refurbished from HiRes-I

Observations since ~10/2007

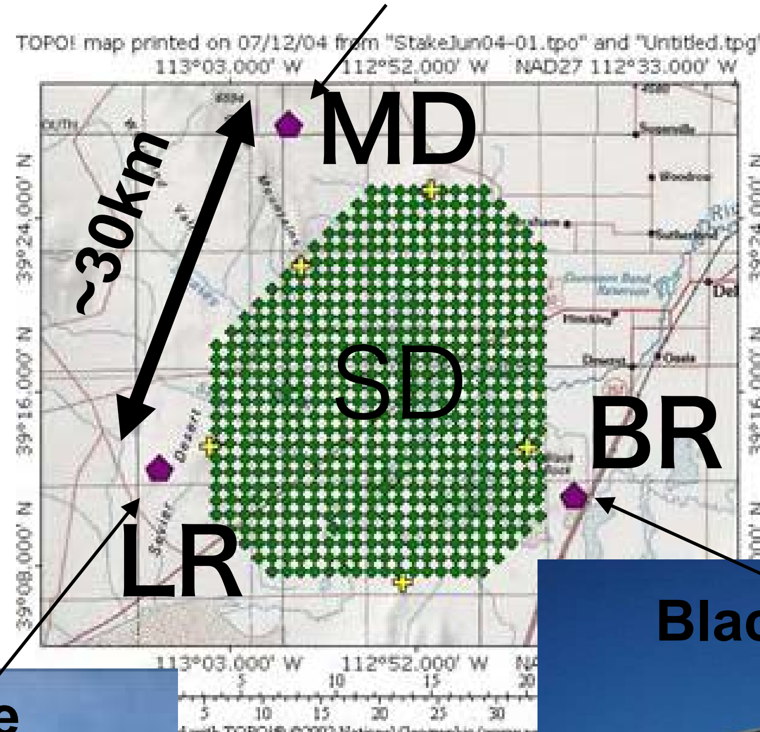
Middle Drum

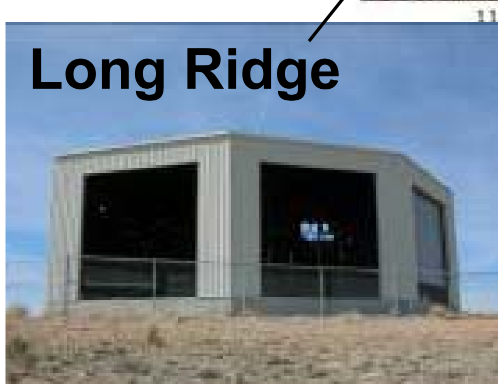
14 telescopes@station
256 PMTs/camera

5.2 m^2

New FDs

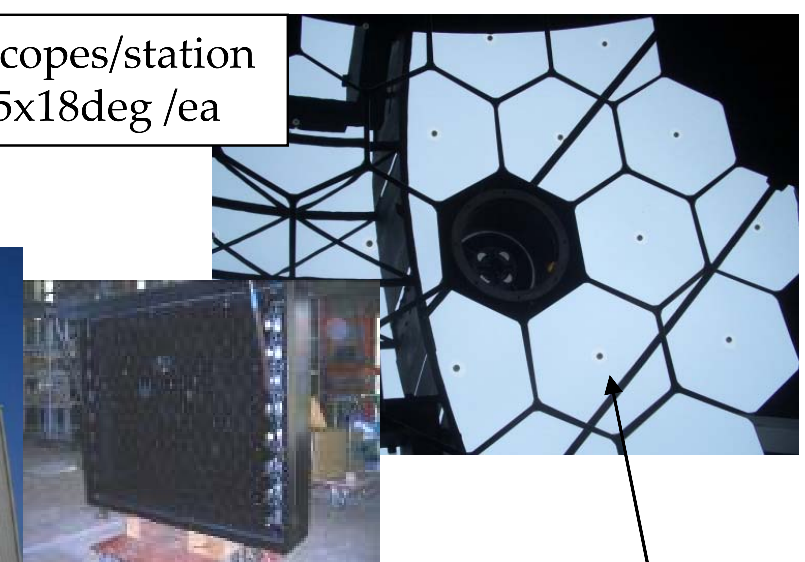
Observation since ~11/2007





Observation since ~6/2007

12 telescopes/station
FOV~15x18deg /ea

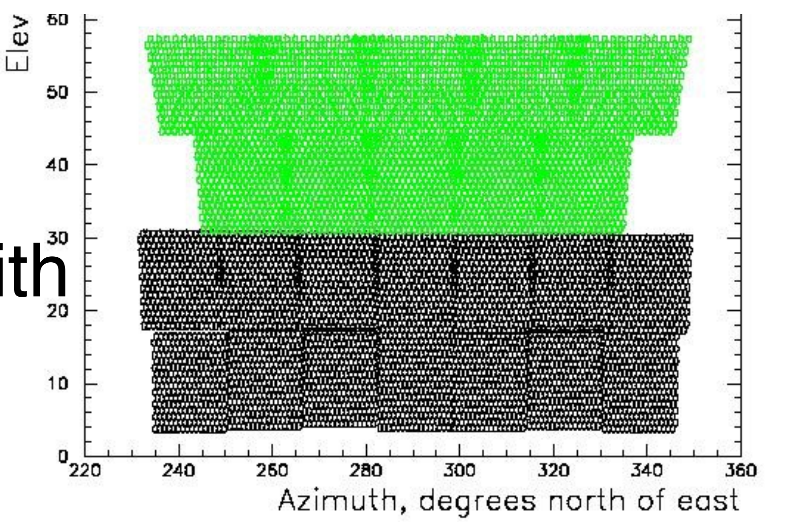


~1 m^2

6.8 m^2

TALE: TA Low-Energy Extension

TALE telescopes



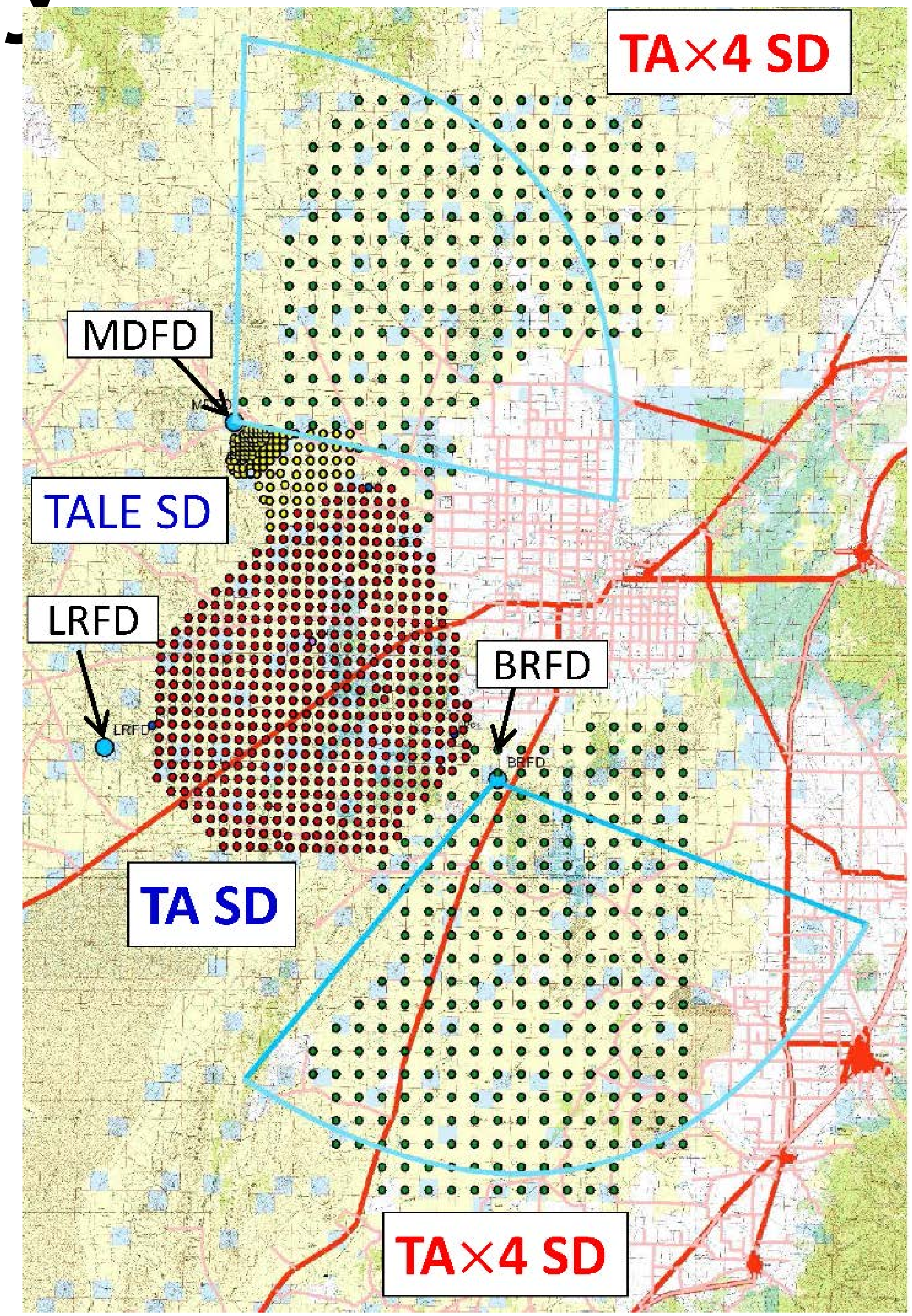
TA MD telescopes

- Study the 10^{16} and 10^{17} eV decades with a hybrid detector.
  - End of the rigidity-dependent cutoff that starts with the knee (at 3×10^{15} eV).
  - The second knee
  - The galactic-extragalactic transition
- High energy physics measurements:
  - σ(p-air) and σ(p-p) from LHC energy (10^{17}) to 10^{19} eV.
- Need to observe from 3×10^{16} eV to 3×10^{20} eV all in one experiment. That is TA and TALE.

TAx4: Enlarging the TA SD Array

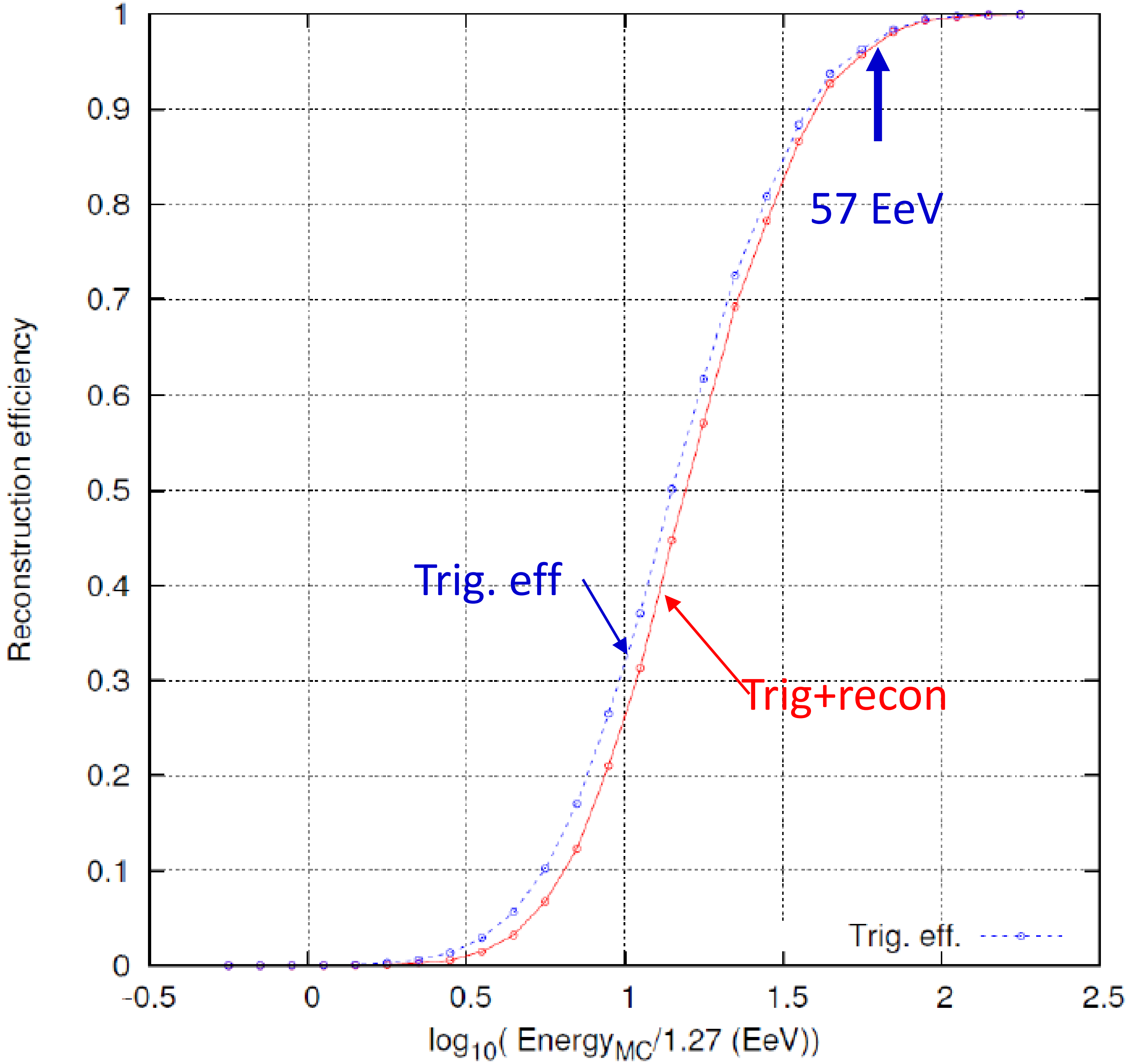
H. Sagawa, ICRC2015

- Quadrule TA SD (~3000 km^2)
  - 500 scintillator SDs
    2.08 km spacing
- 2 FD stations
- Proposals
  - SD: approved in Japan in April 2015
  - FD: submit in US in October 2015
- Get 19 TA years of SD data by 2010
- Get 16.3 TA years of hybrid data
  - 2.7-year construction
    - TA in operation
  - 2.3-year observation



TAx4 Detection Efficiencies

H. Sagawa, ICRC2015



Trigger condition
. 3 MIPS
. 3-fold SDs
. < 8x2.08/1.2usec

Reconstruction
. NSD≥ 4

TA SD reconstruction efficiency =100% for $E > 10^{19}$eV