WG Review of UHE Spectrum Data

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Energy Spectrum Working Group

Auger: B.R. Dawson, I.C. Mariş, M. Roth, F. Salamida,
Yakutsk: M. Pravdin, A. Sabourov
HiRes/TA: T. AbuZayyad, D. Ikeda, D. Ivanov, YT

What we are?

- **UHECR2010 Nagoya meeting**

  "... Recent progress of ultra-high-energy cosmic-ray observation will be reviewed. We plan to discuss such topics as energy spectrum, arrival direction distribution, composition, energy scale, interaction models, and future directions..."

- **Recent progress**
  - Unprecedented statistics
  - High quality measurements and reconstruction: Hybrid approach

- **Current situation**
  - Basically happy,
  - Not fully satisfied
  - Good experiments enhance differences from others

- **Future directions**
  - Order of magnitude physics ---> Precision science
  - Astronomy by charged particle probes
  - Actions to be done, as community

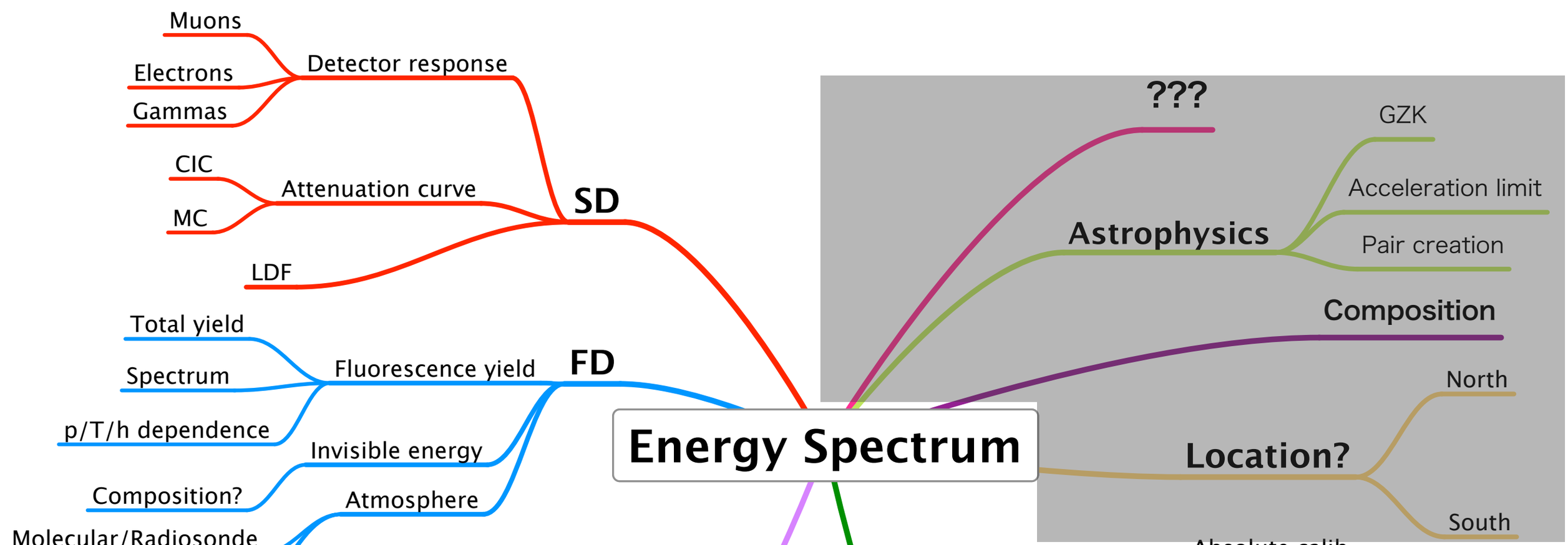
What we are?

- **Five Working Groups**
  - Energy spectrum
  - Composition
  - Anisotropy
  - Modeling and description or air showers
  - Multi-messenger data
- 1~4 people from each group (HiRes/Yakutsk/Auger/TA)
- Discussion in advance
- Give a joint talk at UHECR2012

Energy Spectrum WG

- 10Dec: B.Dawson and YT started initial discussion
- 11Dec: WG wiki opened
    - Share information/data
    - Exchanged questions in analyses (Auger <---> TA)
- 16Jan: The 1st meeting (Skype)
    - Agreed having weekly meeting, regardless of participants' convenience or progress
- Four times meetings (16Jan, 23Jan, 30Jan, 06Feb)

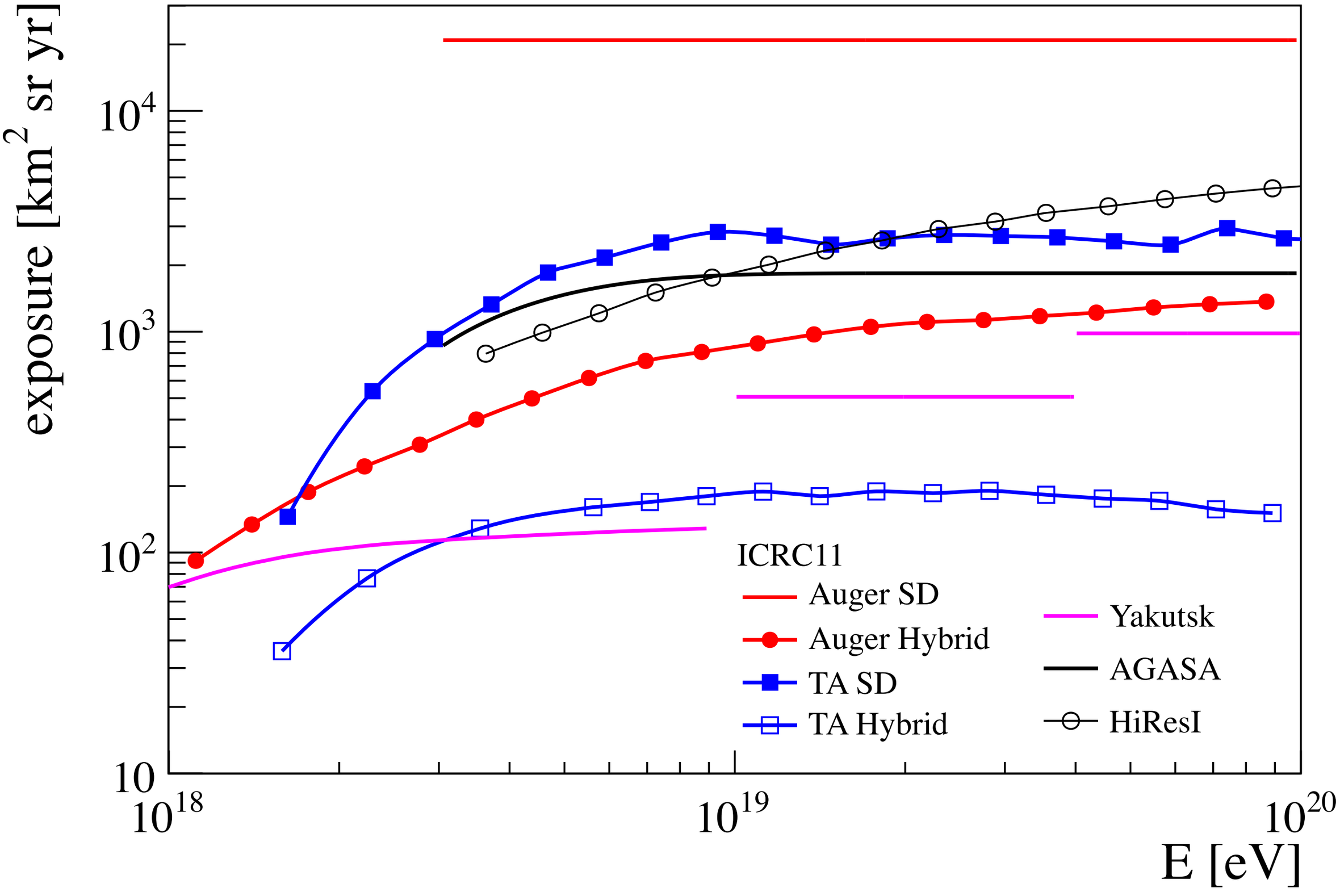
Scope of the WG



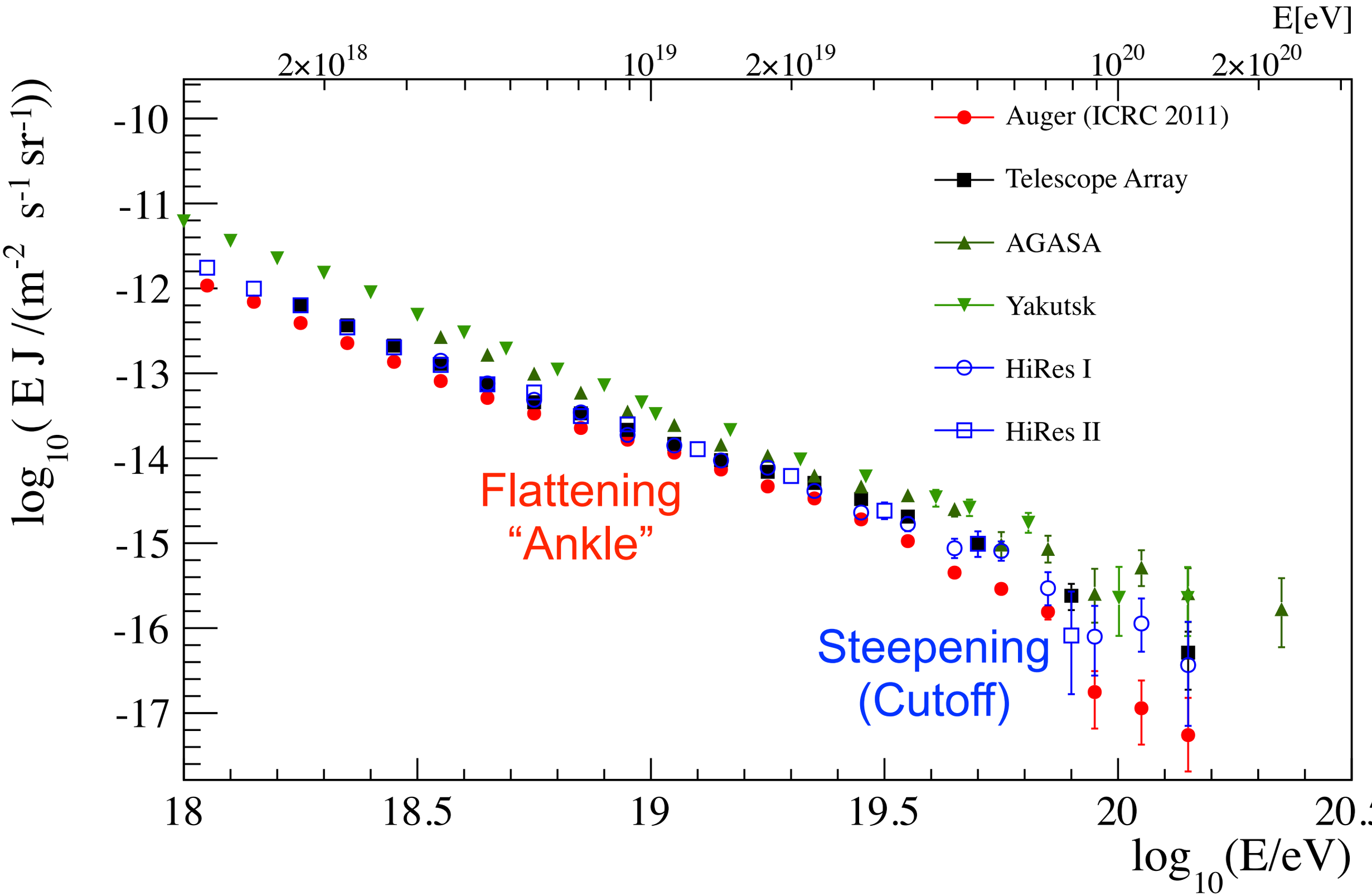
- To know the current situation
  - Agreement and differences
- Technical details in the analyses
- Future directions

Exposures: ~ICRC2011

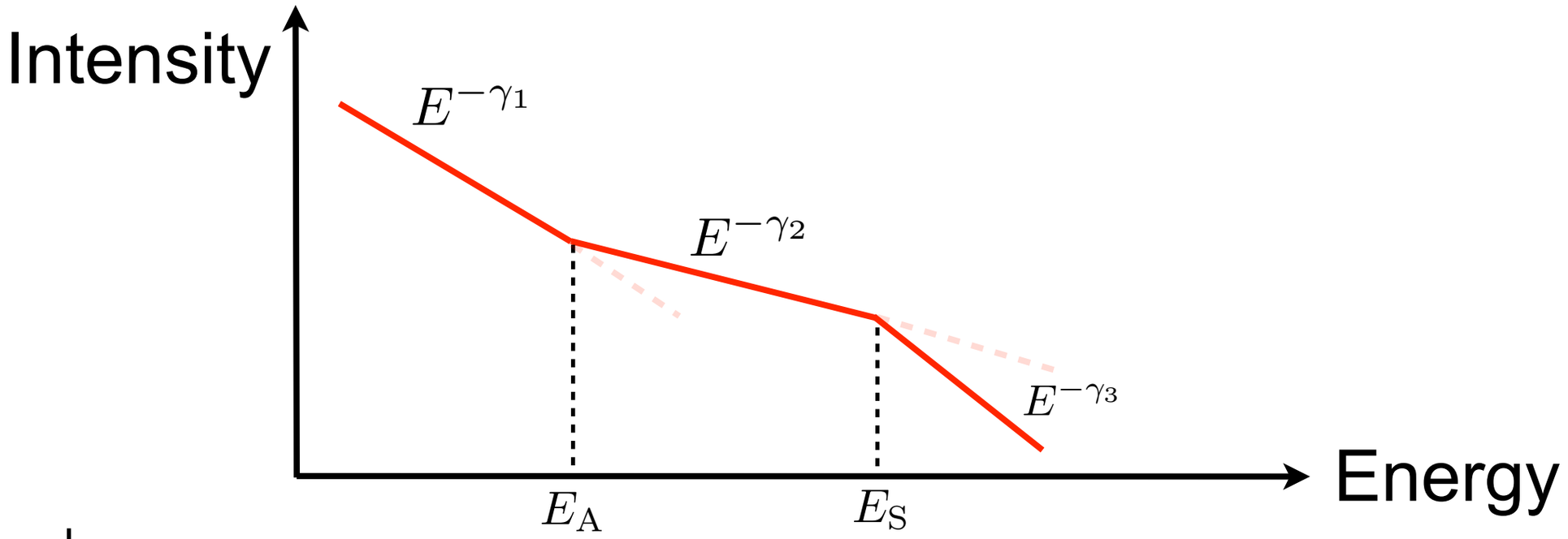
(M.Unger, KIT)



UHECR Energy Spectrum



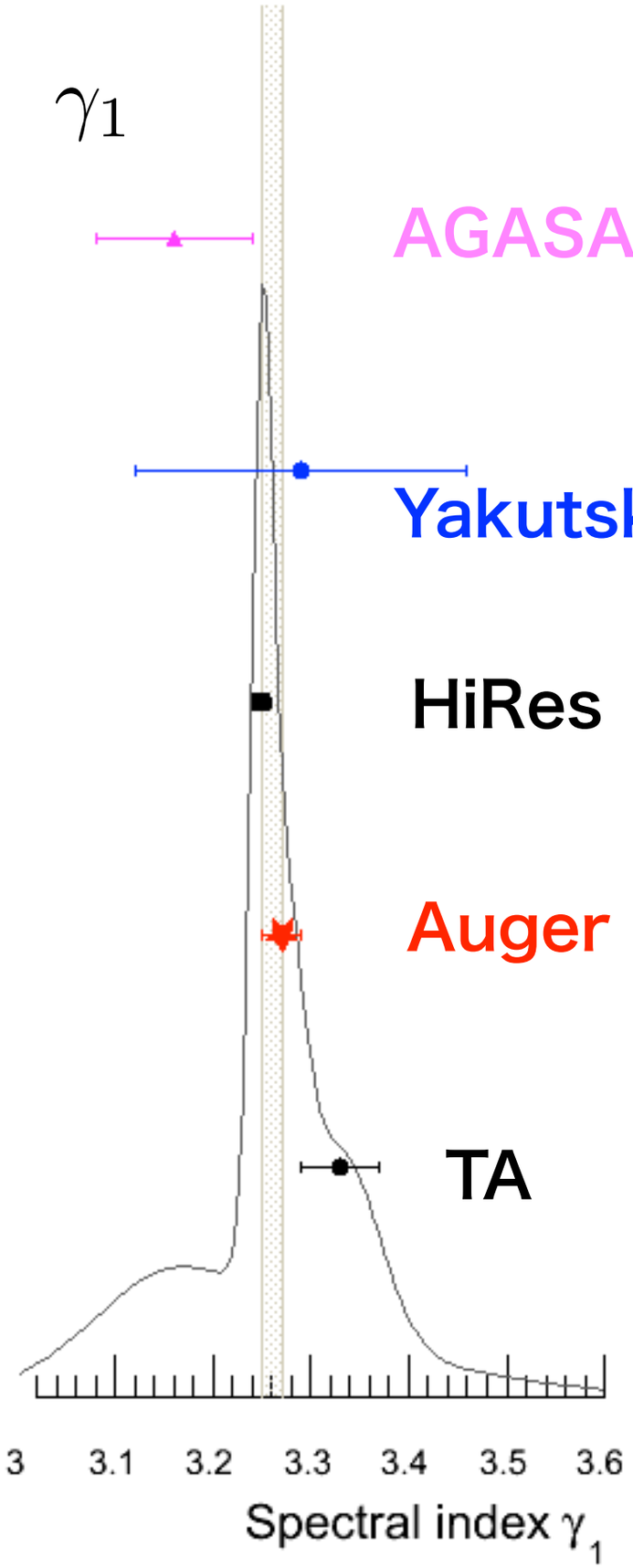
Three Power-law fit

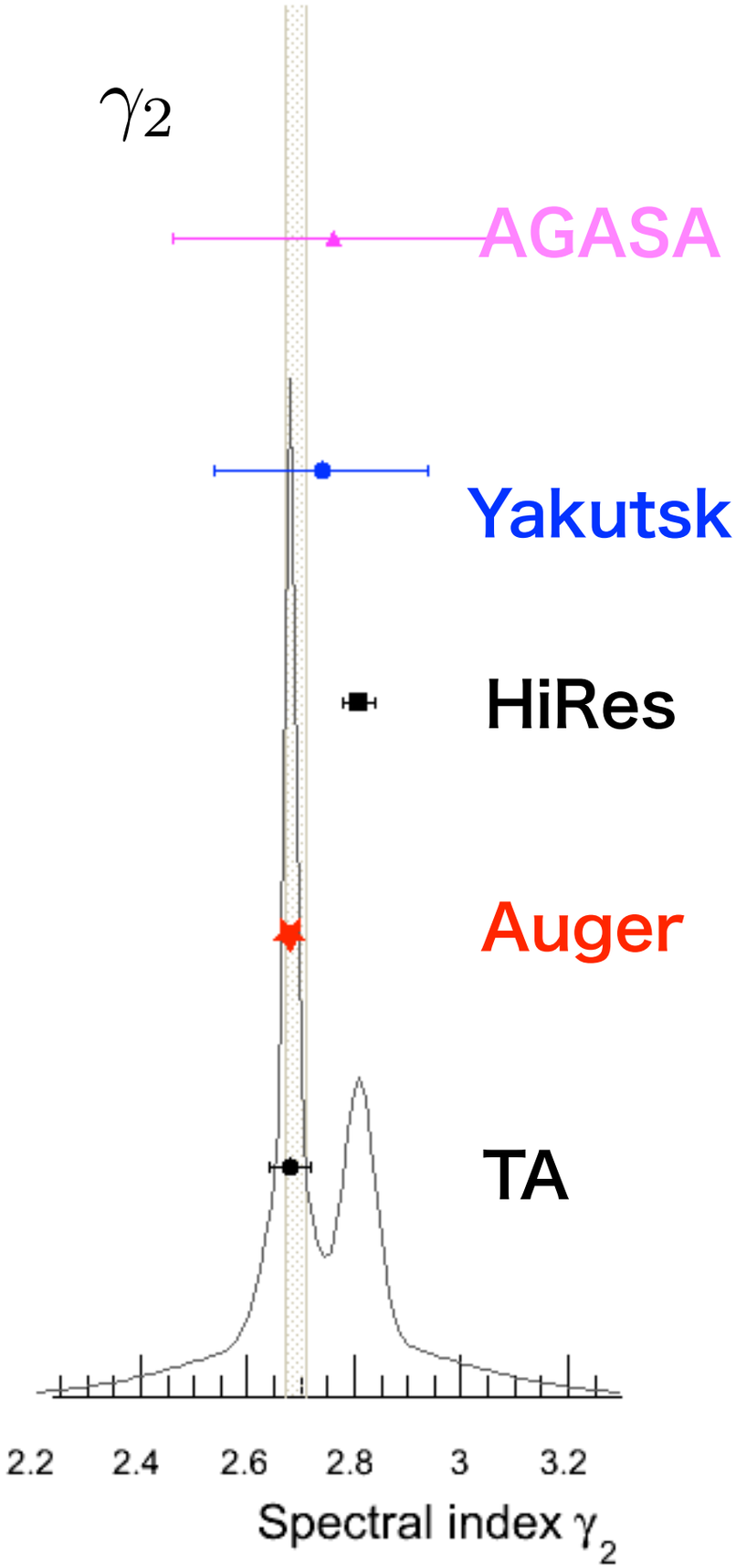


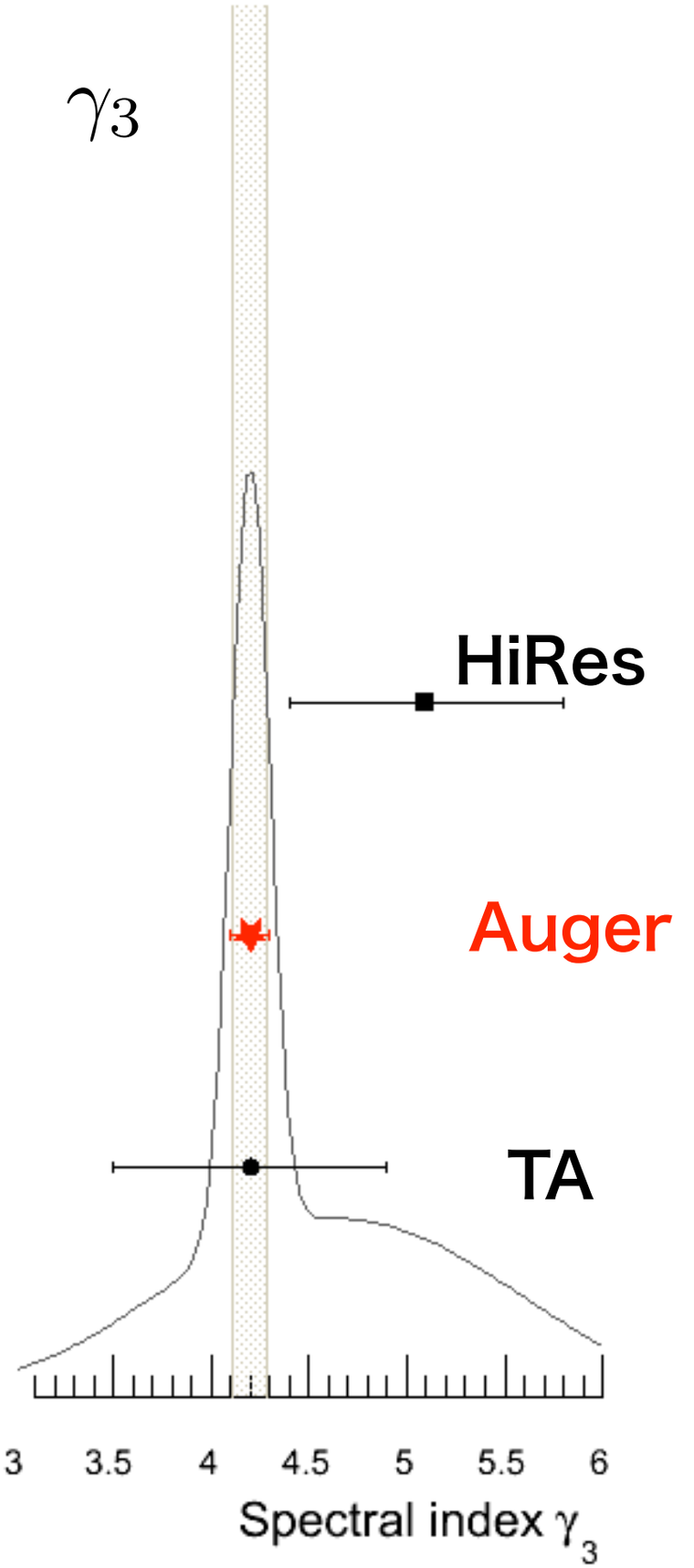
	γ_1	γ_2	γ_3	$\log E_{\rm A}$	$\log E_{\rm S}$
AGASA	3.16 (0.08)	2.78 (0.3)	-	19.01	
Yakutsk	3.29 (0.17)	2.74 (0.20)	-	19.01 (0.01)	-
HiRes	3.25 (0.01)	2.81 (0.03)	5.1 (0.7)	18.65 (0.05)	19.75 (0.04)
Auger	3.27 (0.02)	2.68 (0.01)	4.2 (0.1)	18.61 (0.01)	19.41 (0.02)
TA	3.33 (0.04)	2.68 (0.04)	4.2 (0.7)	18.69 (0.03)	19.68 (0.09)

- AGASA: Takeda *et al.*, *PRL*, **81**, 1163 (1998)
- Yakutsk: Fit by the WG
- HiRes: Abbasi *et al.*, *PRL*, **100**, 101101 (2008)
- Auger: ICRC2011 (F.Salamida icrc893)
- TA: ICRC2011 (B.Stokes/D.Ivanov icrc1297)

Comparison of the parameters: $E^{-\gamma}$







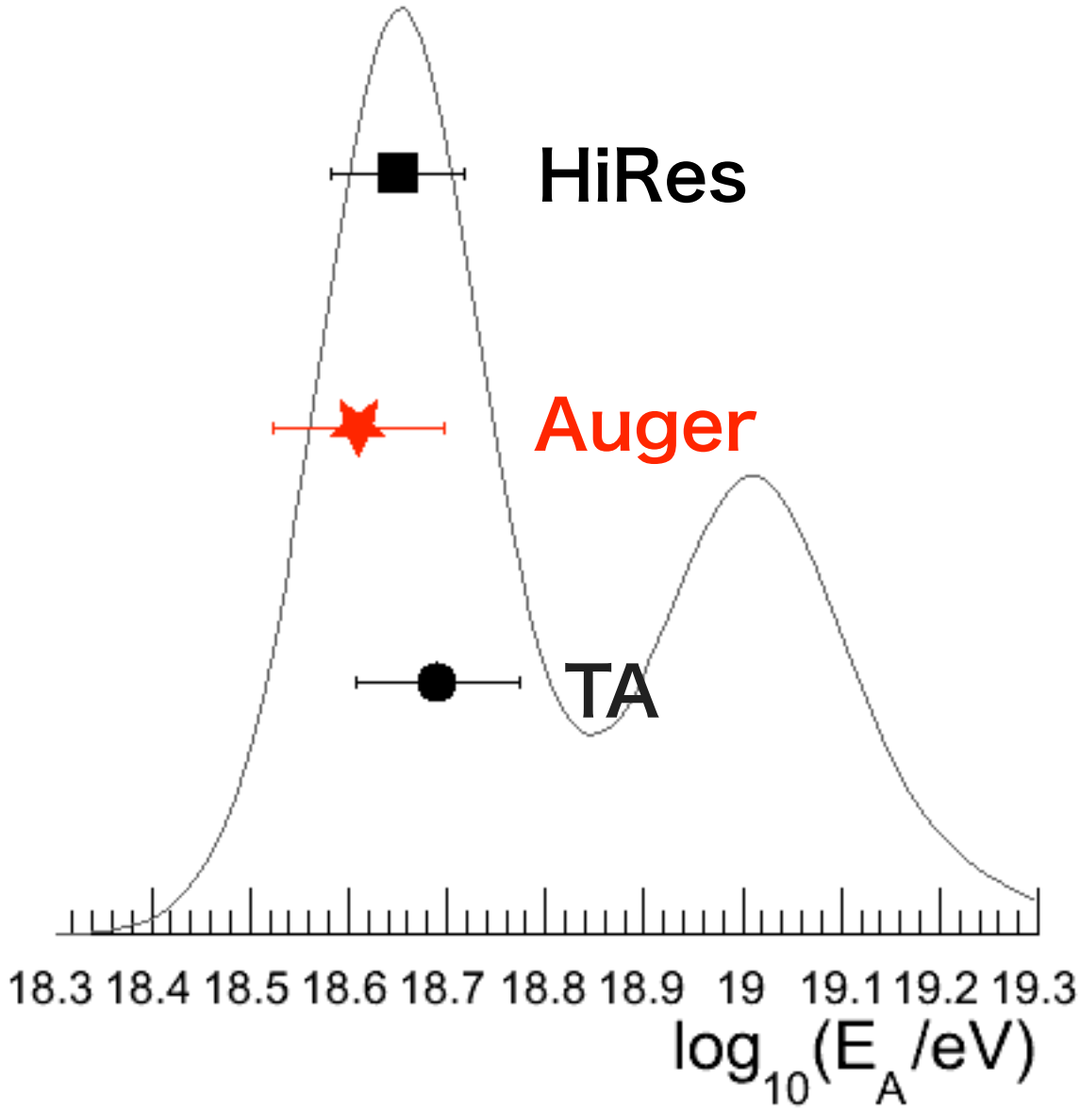
Ankle/Steepening Positions

Error bars:
systematic uncertainties
+ statistical errors

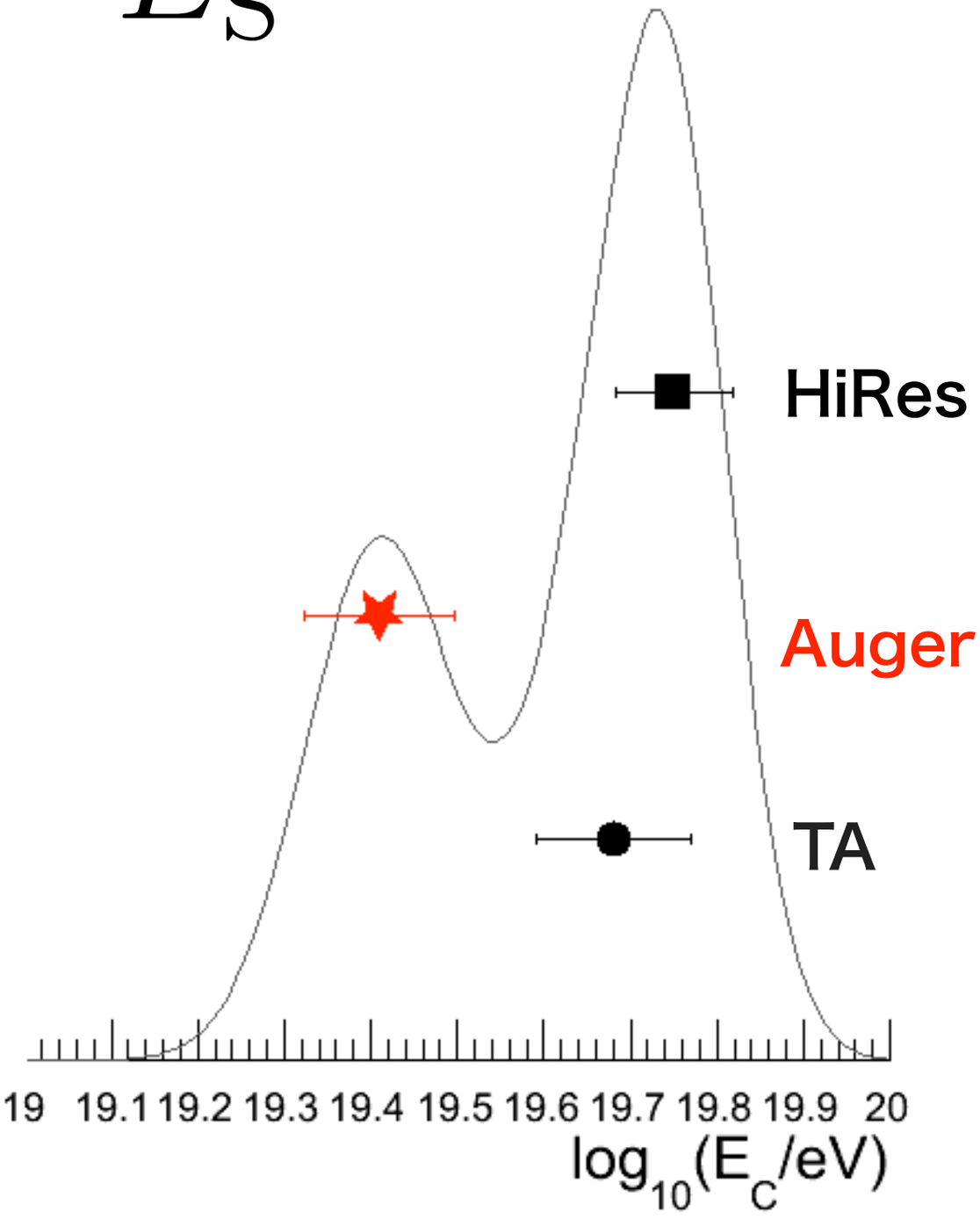
$E_{\rm A}$

AGASA

Yakutsk



$E_{\rm S}$



Energy Uncertainty Budget

AGASA

Detector (gain, linearity, response)	9%
Shower phenomenology (LDF, Shower front etc.)	11%
Energy estimator S600 (interaction, composition, reconstruction, etc.)	12%
Total	18%

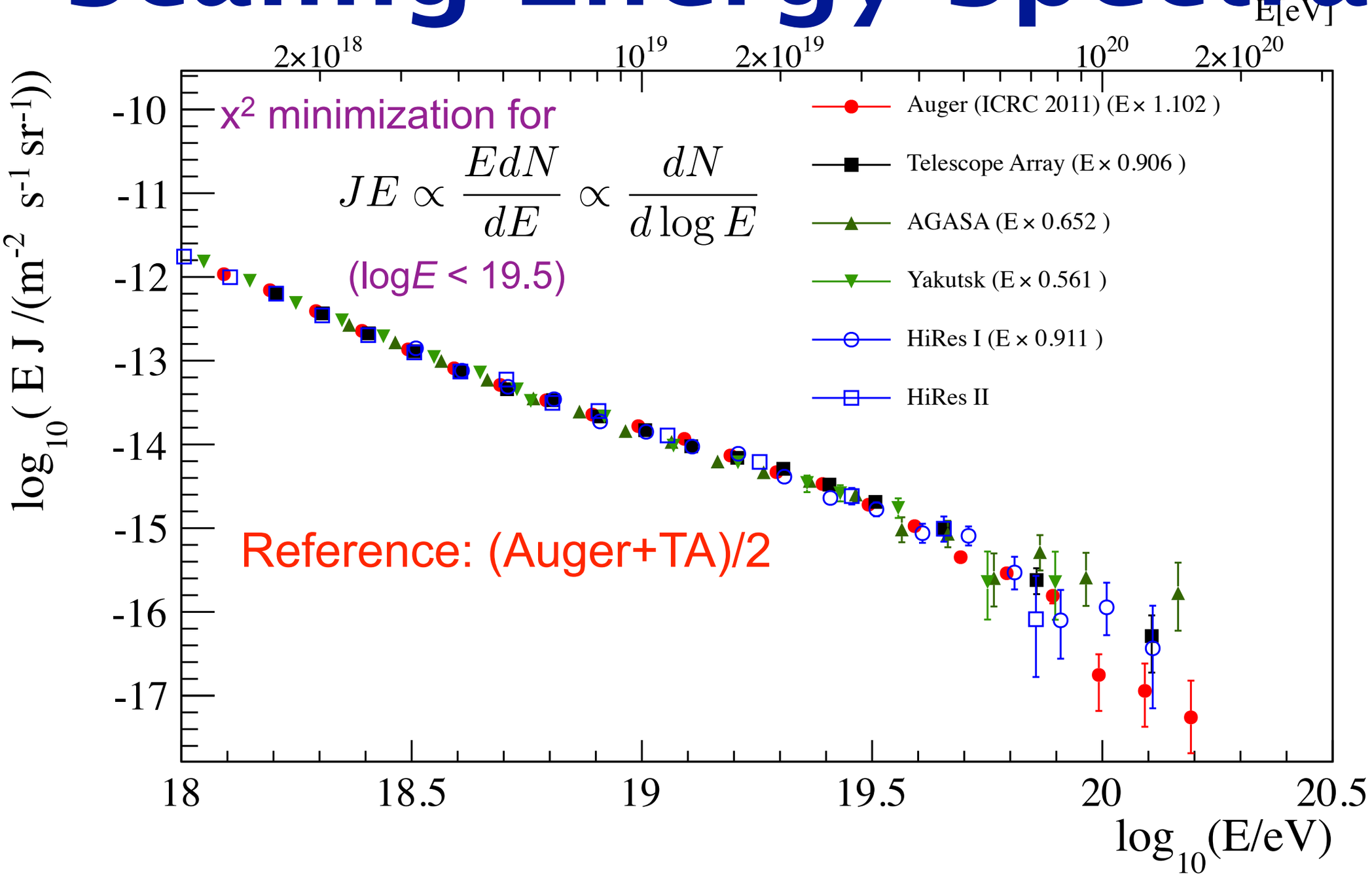
M.Takeda et al., Astropart. Phys., 19, 447 (2003)

Energy Uncertainty Budget

	HiRes	Auger	TA
Calibration	10%	9.5%	10%
Fluorescence yield	6%	14%	11%
Atmosphere	5%	8%	11%
Reconstruction	15%	10%	10%
Invisible energy	5%	4%	(included above)
Total	**17%**	**22%**	**21%**

- HiRes: Abbasi et al., PRL 100 101101 (2008)
- Auger: ICRC2011
- TA: ICRC2011

Scaling Energy Spectra



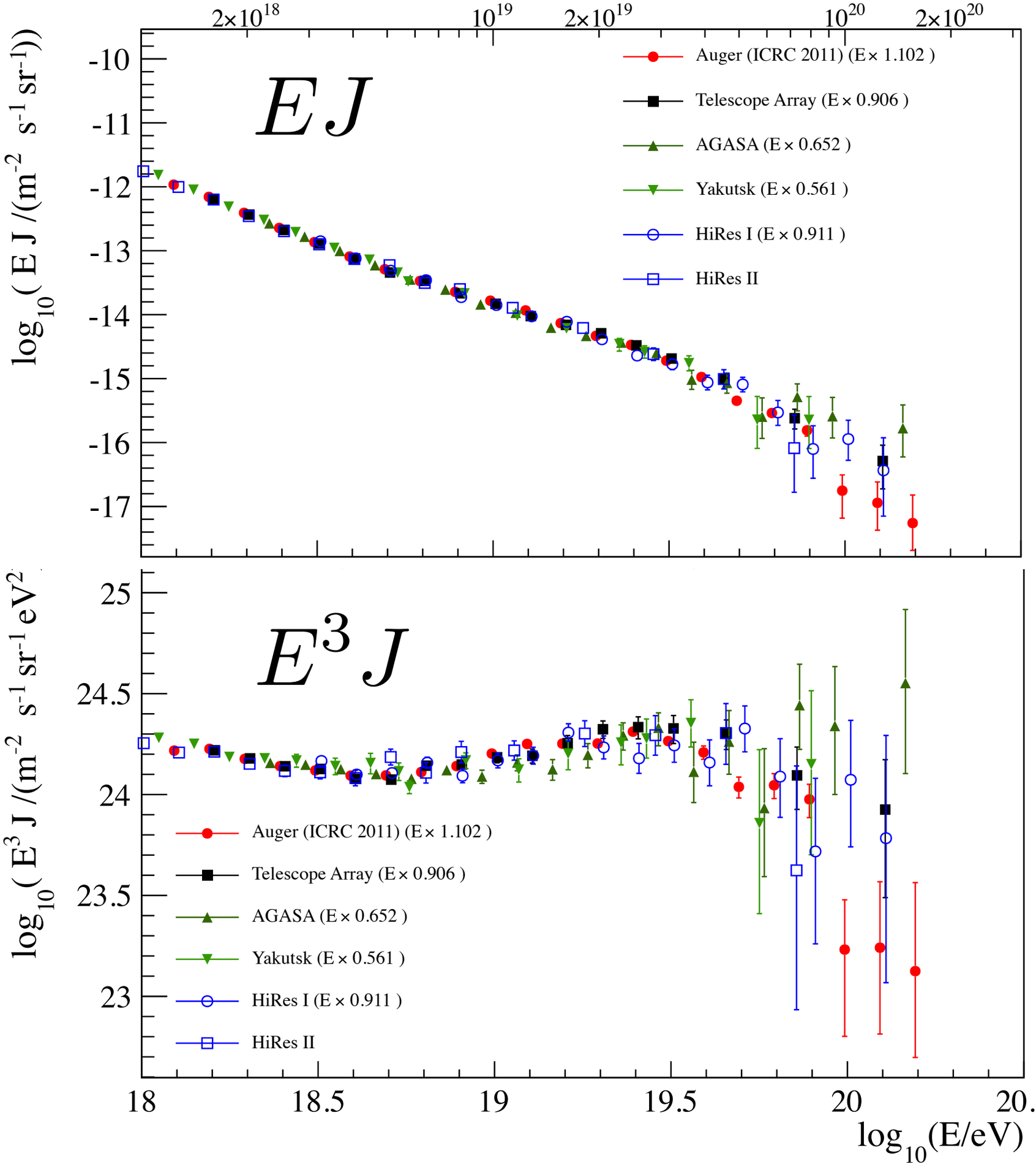
	Auger	TA	HiRes	AGASA	Yakutsk
$\log_{10}\alpha$ Relative to (Auger+TA)/2	-0.042 (0.003)	+0.042 (0.003)	+0.041 (0.005)	+0.19 ( )	+0.26 (0.004)

Energy Spectra

(after the scaling)

- We can find scaling factors to match the spectra: shape are similar (below log*E*=19.5)

- Auger/HiRes/TA are in agreement well within the systematic uncertainties

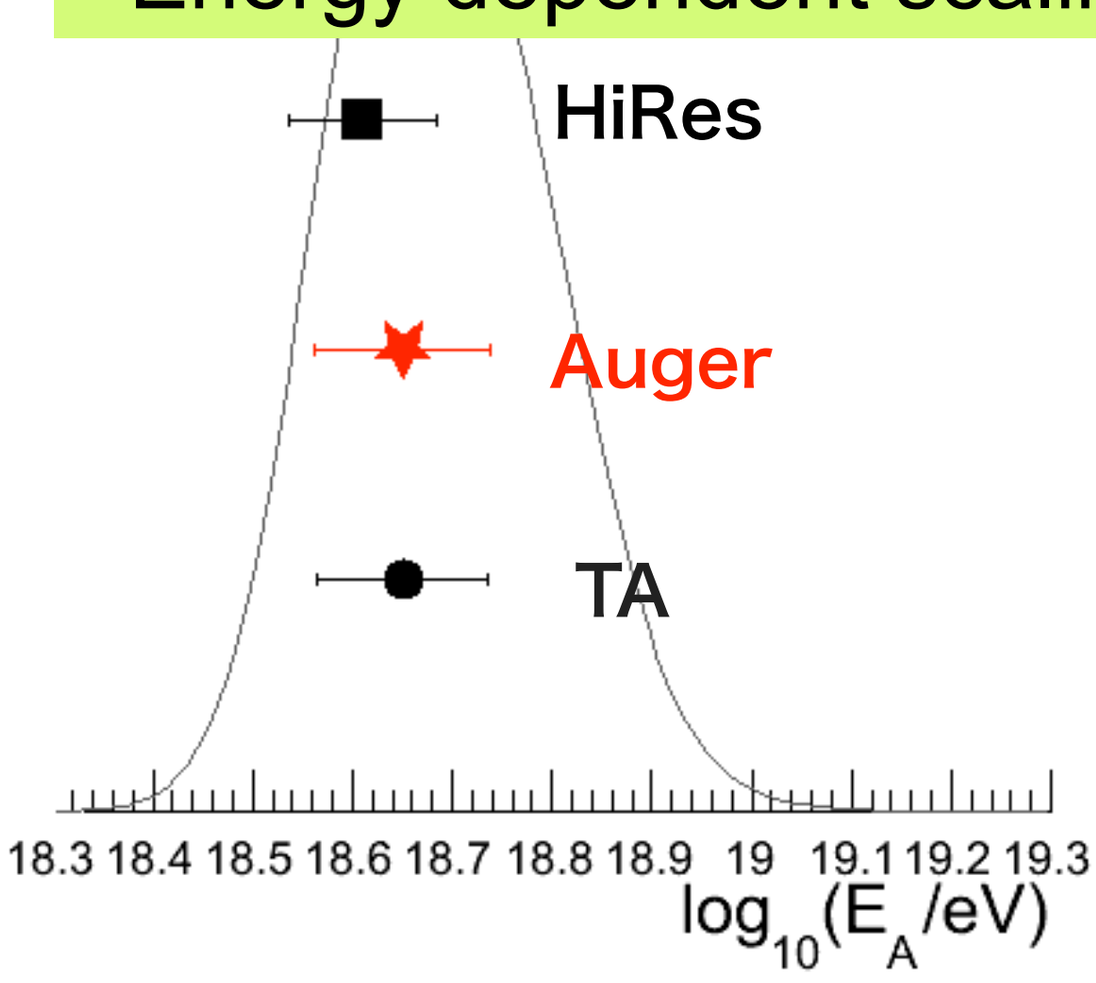


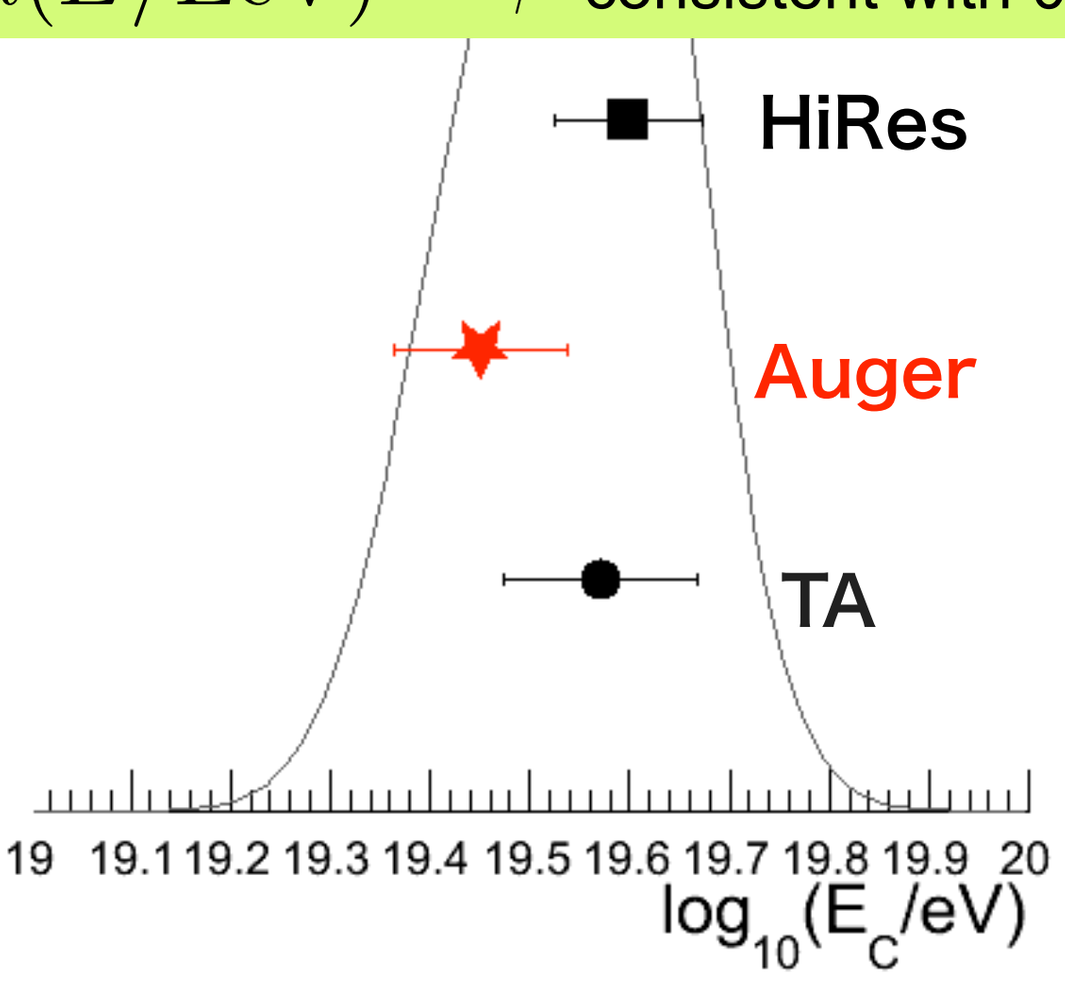
Ankle/Steepening Positions

(After the energy scaling)

Error bars:
systematic uncertainties
+ statistical errors

- Agreement of the spectra within the systematic uncertainties.
- Similar shape: The ankle/steepening energies are consistent after the energy shift (by x^2 minimization).
- Energy dependent scaling? $\alpha(E/\mathrm{EeV})^{\beta}$ β consistent with 0





What are the sources?

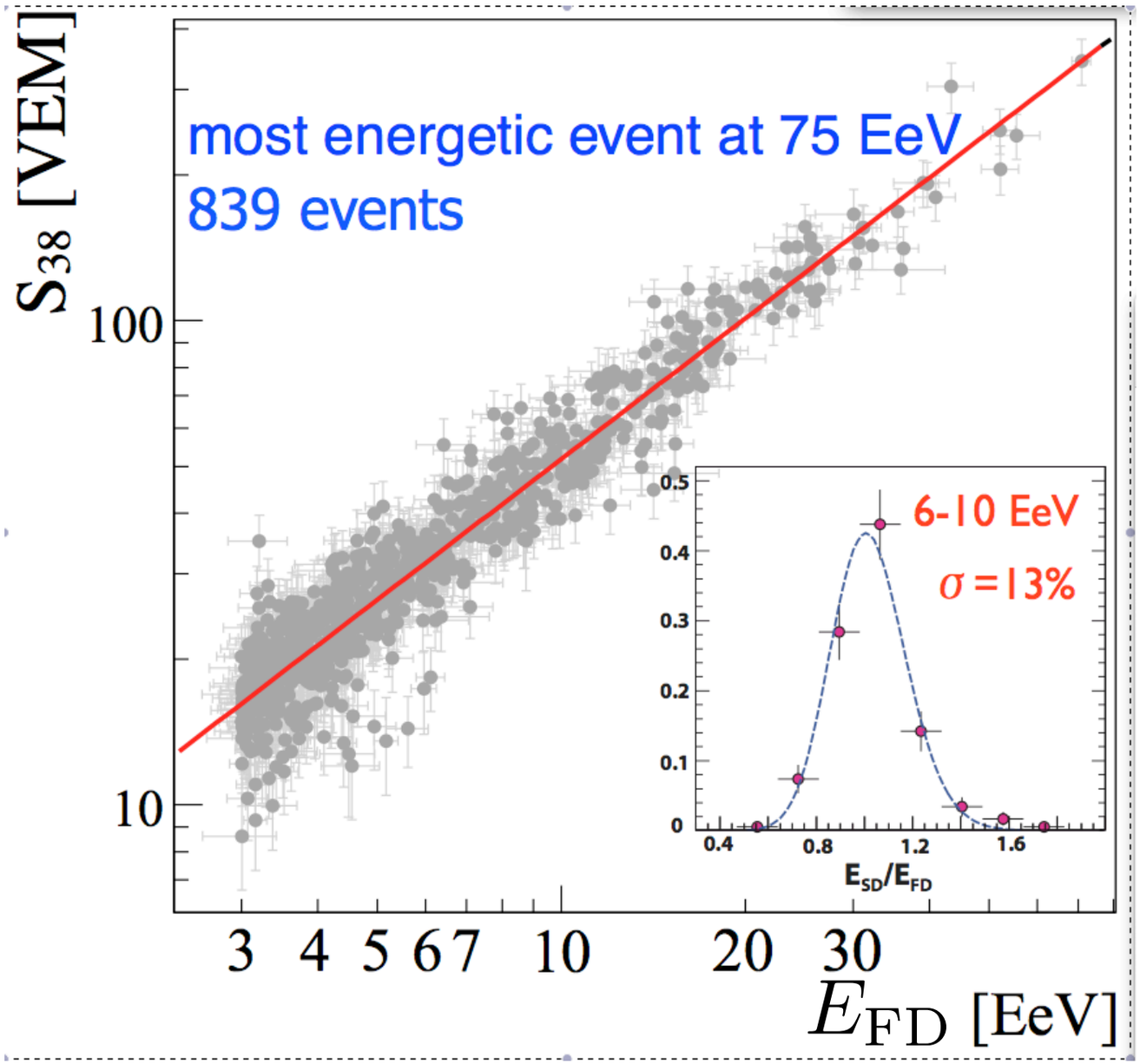
Energy Determination Methods

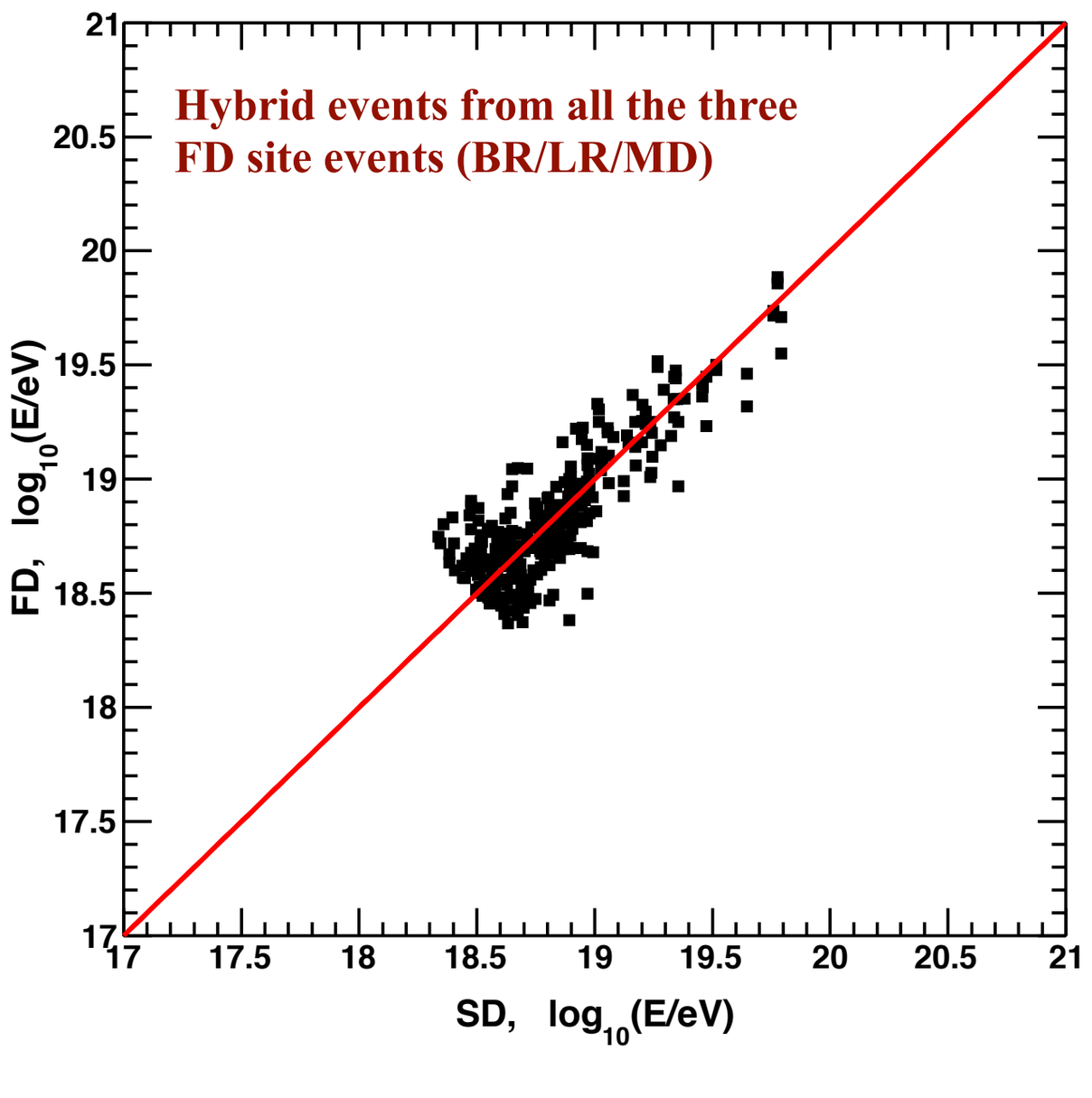
Experiment	Energy Estimator	Formula
HiRes/ Auger/TA FD	$E_{\rm cal}^{\rm FLY}$	$E = E_{\rm MC}(E_{\rm cal}^{\rm FLY})$ "missing energy correction"
AGASA	$S_\theta(600)$	$E = E_{\rm MC}(S_0^{\rm CIC})$
Yakutsk	$S_\theta(600), Q(400), \mu$	$E = E_{\rm EMP}(S_0^{\rm CIC})$
Auger SD	$S_\theta(1000)$	$E = E_{\rm FD}(S_{38}^{\rm CIC})$
TA SD	$S_\theta(800)$	$E = E_{\rm FD}\,(E_{\rm MC}(S_\theta))$

SD Energy: Scaled to FD energy, measured by means of calorimetry

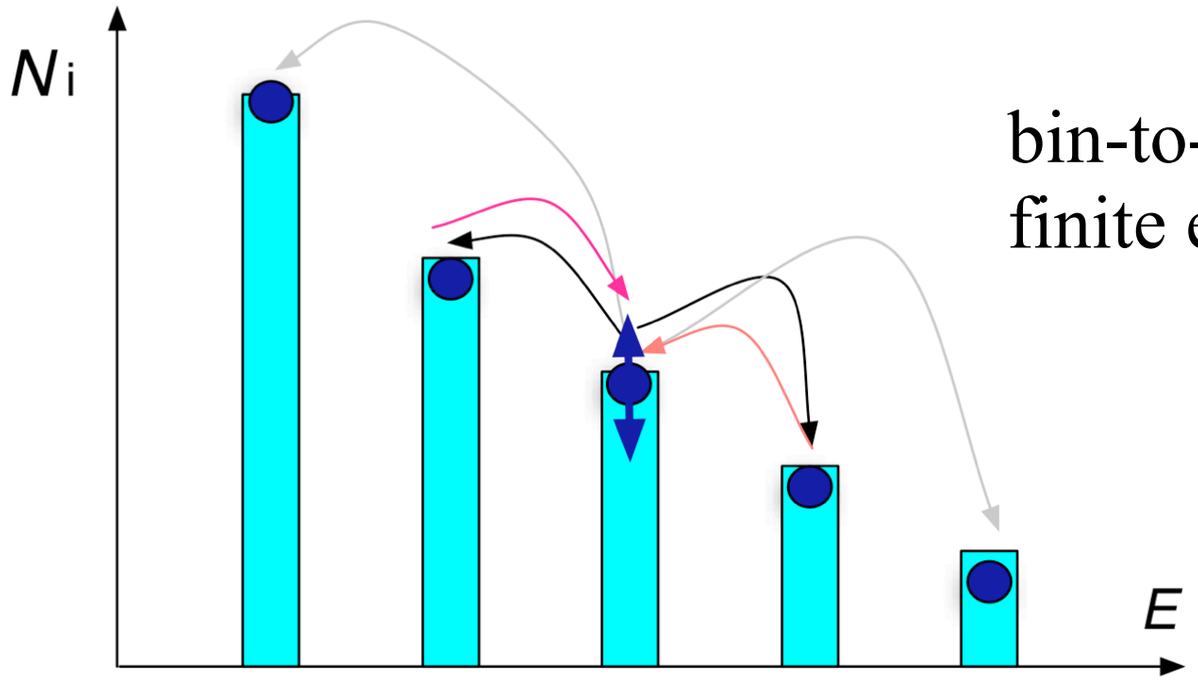
$$E = E_{\rm FD}(S_{38}^{\rm CIC}) = a_{\rm h} S_{38}^{b_{\rm h}}$$

$$E = E_{\rm FD}(E_{\rm MC}(S_\theta)) = \frac{1}{\left\langle \frac{E_{\rm SD}}{E_{\rm FD}} \right\rangle_{\rm h}} E_{\rm MC}(S_\theta)$$





Spectrum Unfolding



bin-to-bin migration due to finite energy resolution

- **Auger**
  - Forward folding approach:
    - Migration matrix by MC
    - Preparing a paper for the details

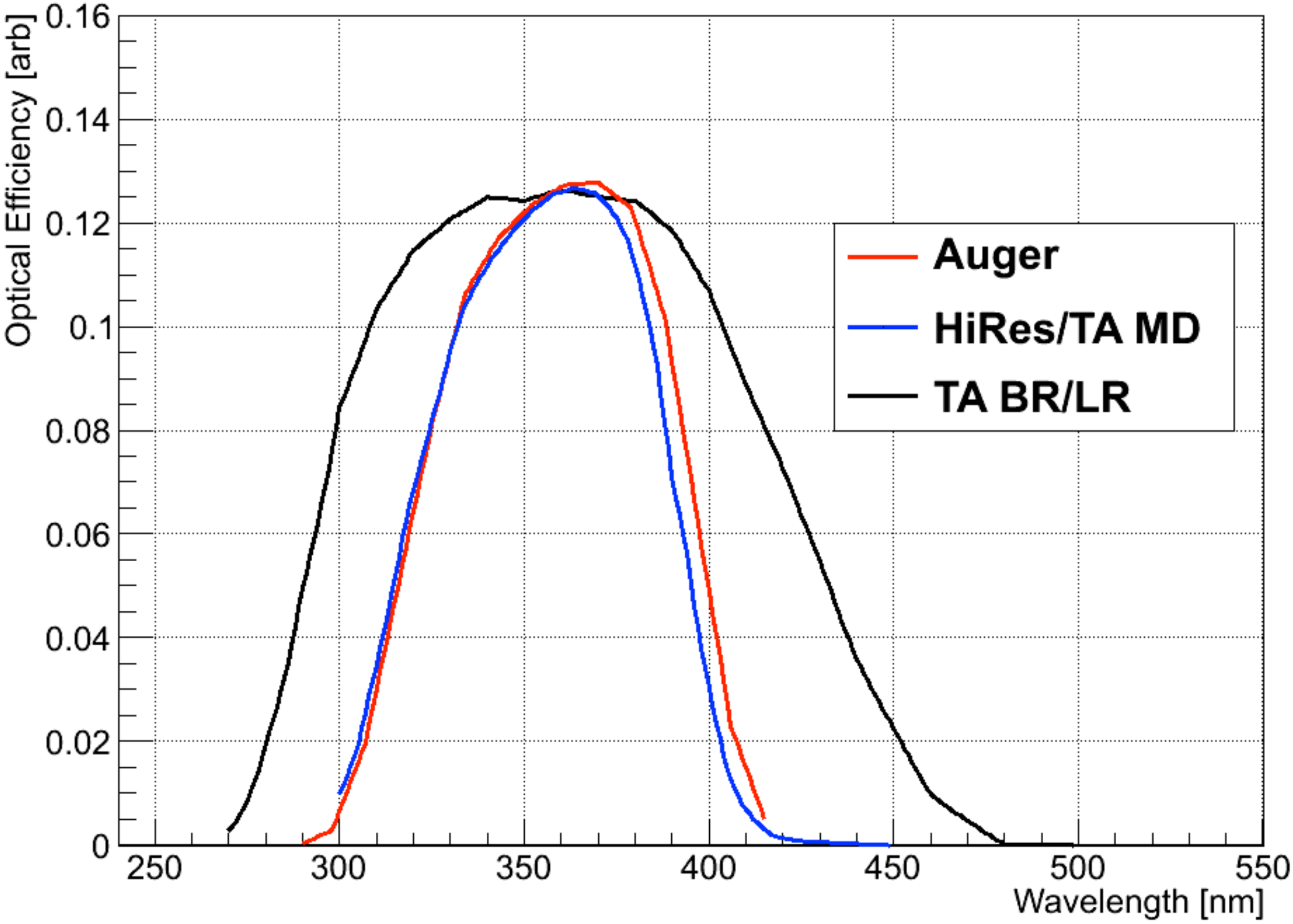
- **HiRes/TA**

$$A^i = A_0 \frac{N_d^i}{N_{\rm thr}^i}$$

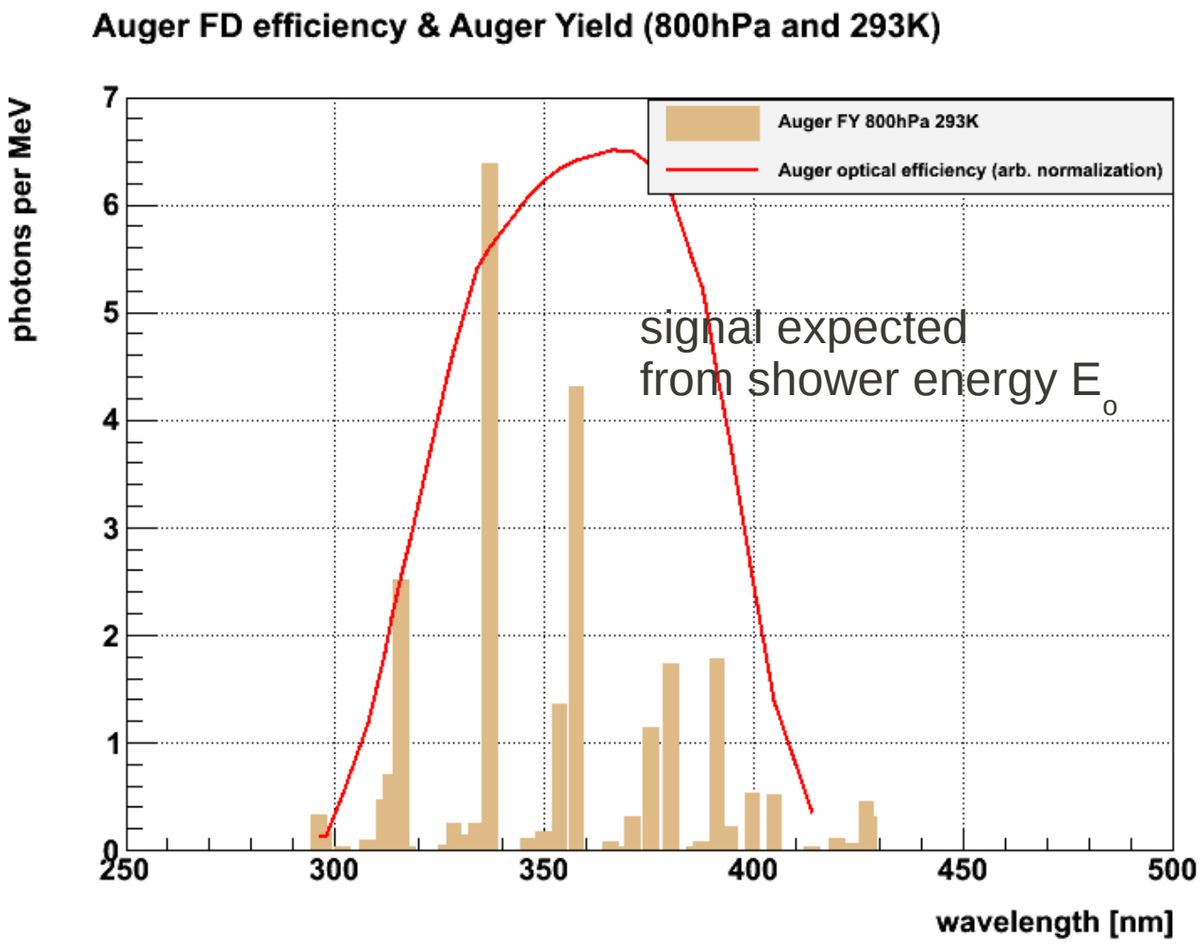
$$J^i = \frac{N_{\rm obs}^i N_{\rm thr}^i}{A_0 T N_{\rm d}^i}$$

Fluorescence Yield

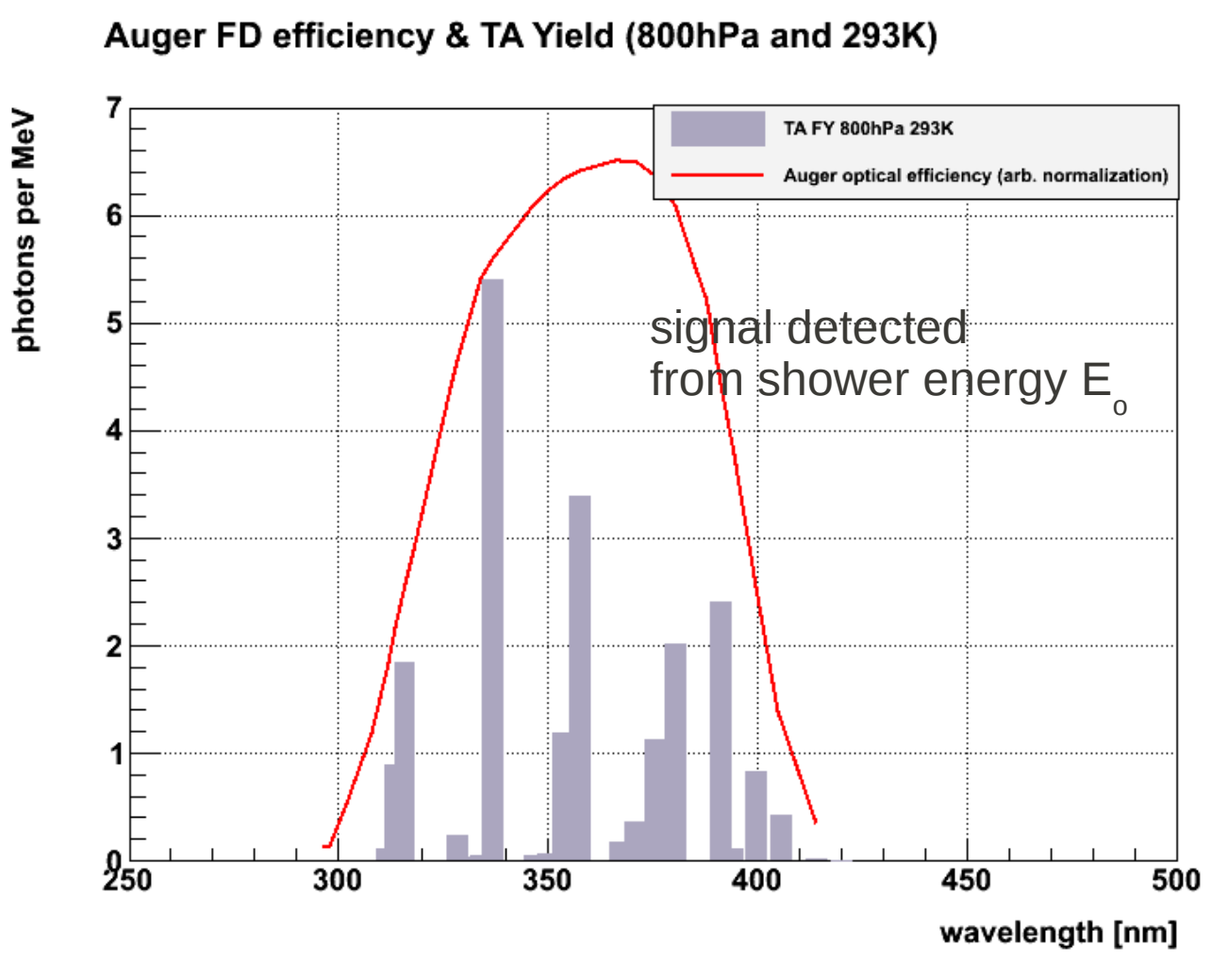
	Spectrum	Total Yield	p, T	Humidity
HiRes/TA	FLASH	Kakimoto et al.	Kakimoto et al.	-
Auger	AirFly	Nagano et al.	AirFly	AirFly


Optical Efficiency [arb]
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
250
300
350
400
450
500
550
Wavelength [nm]
Auger
HiRes/TA MD
TA BR/LR

Impact of FLY and Optical Eff.



signal = 18.1



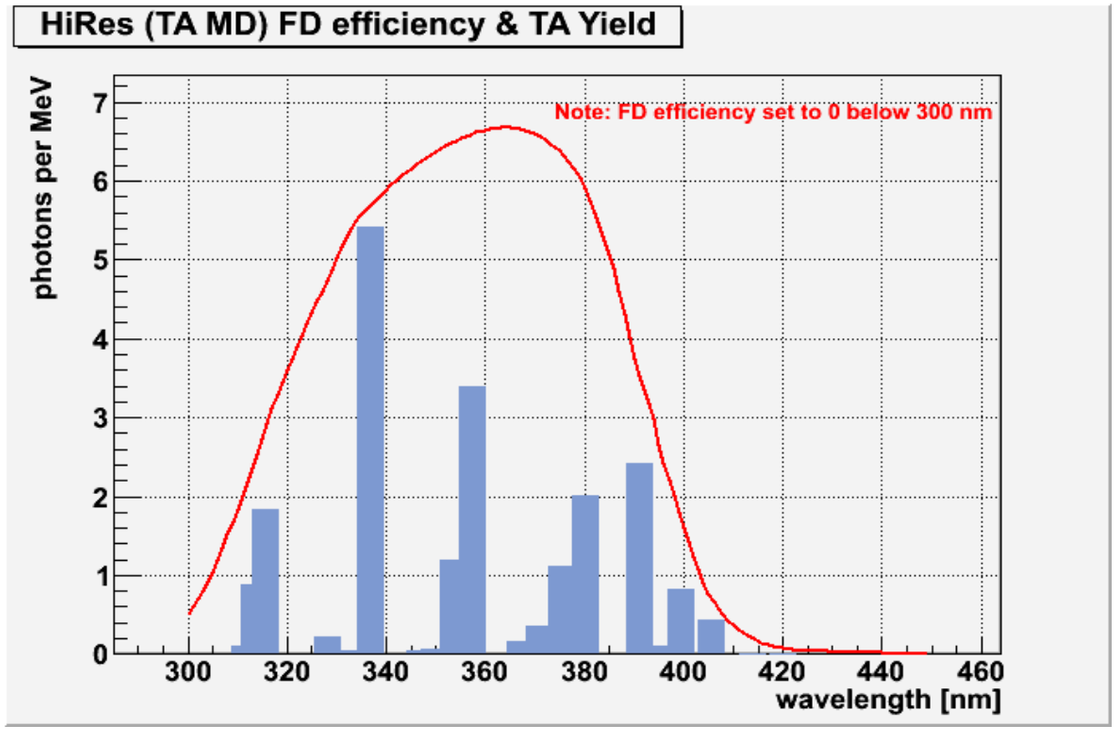
signal = 16.1

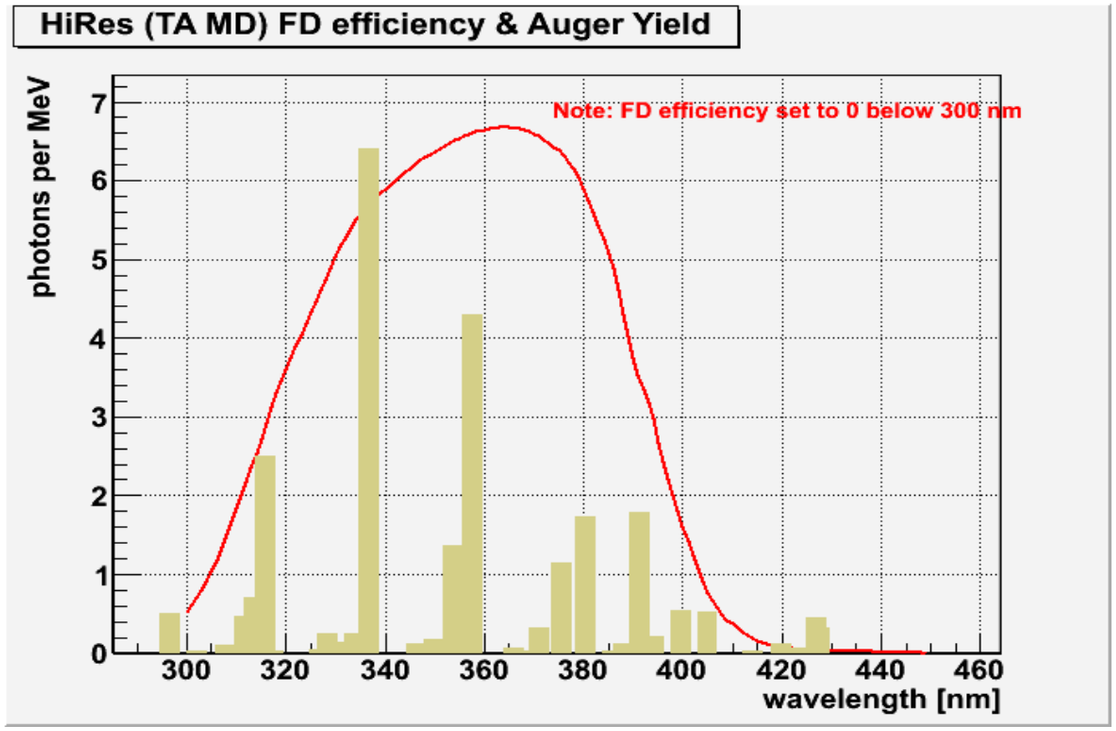
Assume “true” yield is the TA one. Auger assumes Auger yield. So Auger sees a signal of 16.1 but expects a signal of 18.1 for an energy of E_0. So Auger will reconstruct an energy which is too low by 1-(16.1/18.1) = 11%

This becomes even smaller if we consider atmospheric effects (e.g. humidity quenching).

Impact of FLY and Optical Eff.

Multiply FY spectrum with optical efficiency (normalized to 1 at 375nm), then integrate.





signal = 16.27

signal = 18.55

- Following Bruce's argument: Assume “true” yield is the Auger one. TA(MD) assumes TA yield. So TA(MD) sees a signal of 18.55 but expects a signal of 16.27 for an energy of E0.
- So TA will reconstruct an energy which is too high by (18.55/16.27)-1 = 14%

Atmospheric Modeling/Monitoring

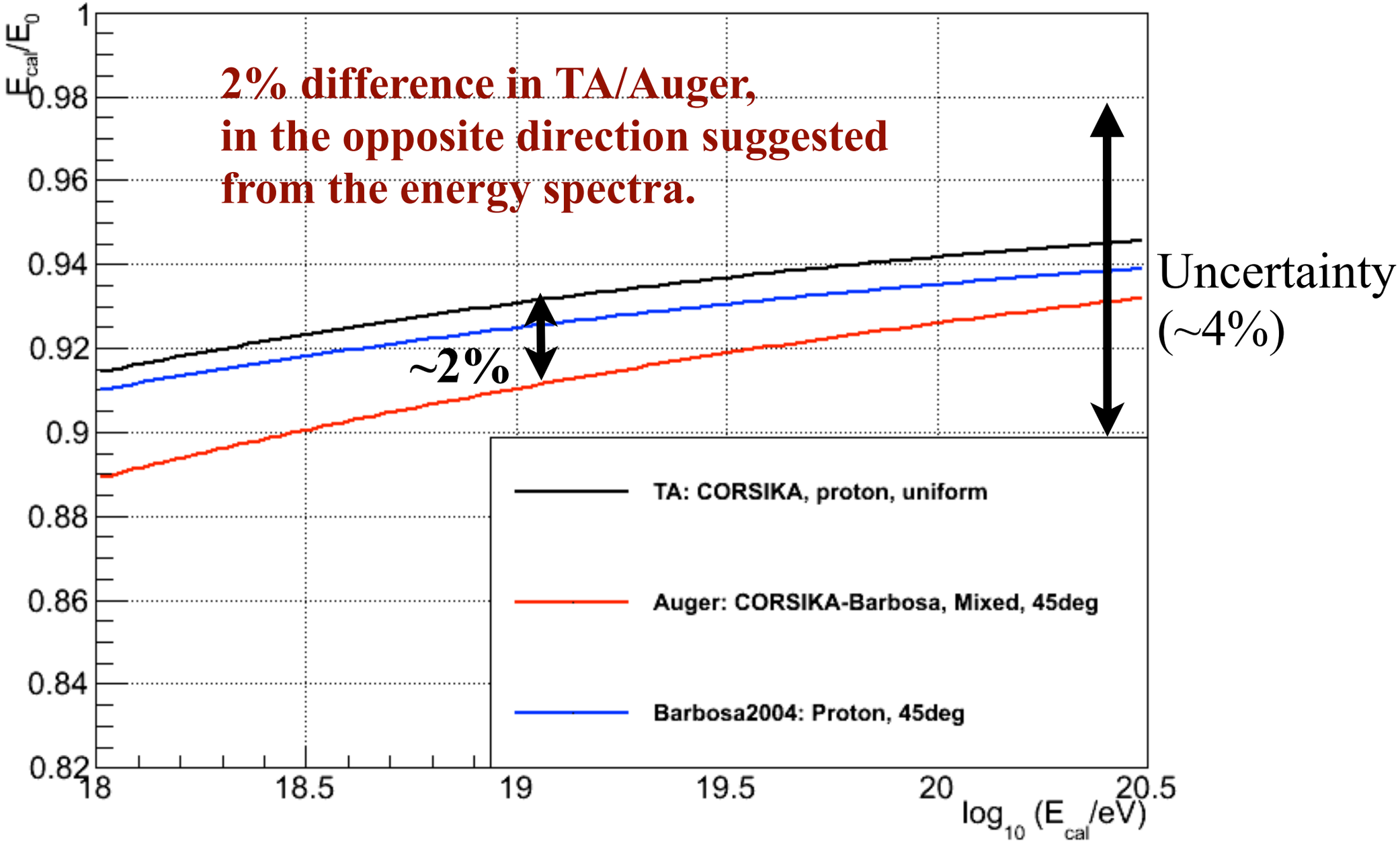
	Radiosonde	LIDAR	CLF	IR camera	Other
HiRes ~5%	· (stereo) **Public data** (Salt Lake City and Elko, ~200km from the site) · (mono) used US 1976 standard atmosphere.	NA	· (stereo) Hourly · (mono) used average aerosols	NA	
Auger ~8%	Monthly models derived from **own radiosonde data**. Now replaced by GDAS data *, with 3 hourly updates	**4 sites**, **hourly**. Cloud cover and height, cross-check of VAOD	2 sites, CLF & XLF. Hourly measure of VAOD, **used in analysis**	**4 sites**, **5 minute scans** of telescope FoV. Data selection currently via LIDAR cloud fraction.	2 aerosol phase function monitors; HAM (wavelength dependence of aerosol scatter)
TA ~11%	**Public data** (Salt Lake City and Elko, ~200km from the site)	**1 site (BR)**, **twice in a day**, use a static model in reconstruction (averaged VAOD, HAL, scale height)	Hourly, analysis ongoing	**1 site, Hourly monitoring**, Used for date selection	

* "Description of Atmospheric Conditions at the Pierre Auger Observatory using the Global Data Assimilation System (GDAS)", Auger Collab, Astropart. Phys. (in press) (2012)

Correction of Invisible Energy

$$\frac{E_{\rm cal}}{E_0} = A - B\left(\frac{E_{\rm cal}}{\rm EeV}\right)^{-C}$$

- Auger: Barbosa *et al, Astropart. Phys.* **22** 159 (2004)
  - p 50% + Fe 50%
  - @ 45degrees
  - A = 0.967, B = 0.078, C = 0.140
- TA MEC function is derived from its own CORSIKA simulation
  - p 100%
  - Uniform arrival directions
  - A = 0.963, B = 0.049, C = 0.181



Future Directions

Each experiment will

- Keep taking data
    - Spectra of different declination band, sky patches
    - *“Be patient” (P. Privitera)*

- Strive to reduce systematic uncertainties in energy calibration, attenuation curves, and reconstruction issues

- Continue to employ cross-checks to validate these methods

    - Laser checks of photometric calibration, hybrid data checks of SD attenuation, etc.)

- Continue to improve atmospheric monitoring and correction

- Scintillators at Malargue

Future Directions

As a community:

- Should use a world-wide fluorescence yield model, including the total yield, spectral intensities, humidity/ pressure/temperature dependence. (B. Keilhauer)

- Use a common set of procedures as much as possible.
  - If some procedure is not the preferred one for a particular experiment, it should be at least be cross-checked.
  - E.g.: CIC for TA, an MC attenuation curve in Auger.

- Should attempt to compare method of atmospheric characterization

Future Directions

As a community:

- Should attempt to cross-check the TA-Auger FD photometric calibration
  - using an absolutely-calibrated octocopter (*optocopter*)
  - using a standard close-by laser
  - *CRAYS*, a laser in N_2 chamber for some Auger PMTs

- Must maintain contacts between experiments.
  - Need a high-level organization to encourage this.
  - More than a yearly meeting?

Conclusions (1)

- All of the spectra are in agreement within the systematic energy uncertainties.
  - Spectral shapes are very similar: positions of the first bend is in agreement, and marginally consistent for the second bend after the energy scaling.
- Status of the spectral structures
  - Ankle: CONFIRMED
  - *Suppression*
    - AGASA: not compatible
    - Yakutsk: “Deficit”, no sign of an extended spectrum
    - HiRes/Auger/TA: Confirmed with good statistical significance
    - HiRes claimed the GZK cutoff
      - Protonic composition
      - Position of the steepening is consistent with theoretical expectation
    - Composition and anisotropy (UHECR horizon?)

Conclusions (2)

- There are many differences in methods, but these are equivalent in principle.
- The 20% difference has not been fully explained.
- Need comparison in more low level.
- Need high level contact.
- Now we have a channel.
  - TA: AGASA + HiRes
    - Reported by Japanese press as “呉越同舟”
    - Successful collaboration
  - Yakutsk, Auger and TA!

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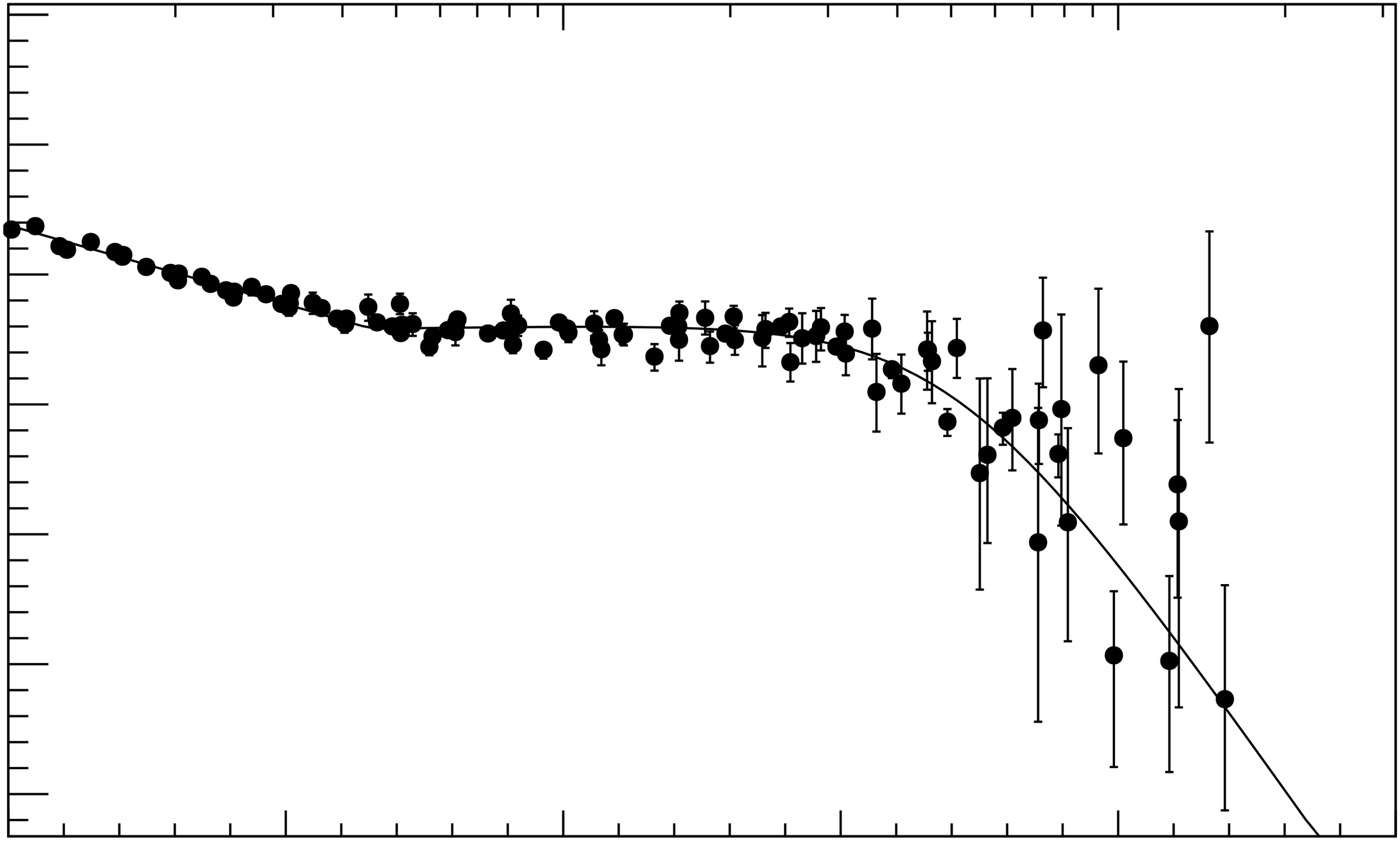

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