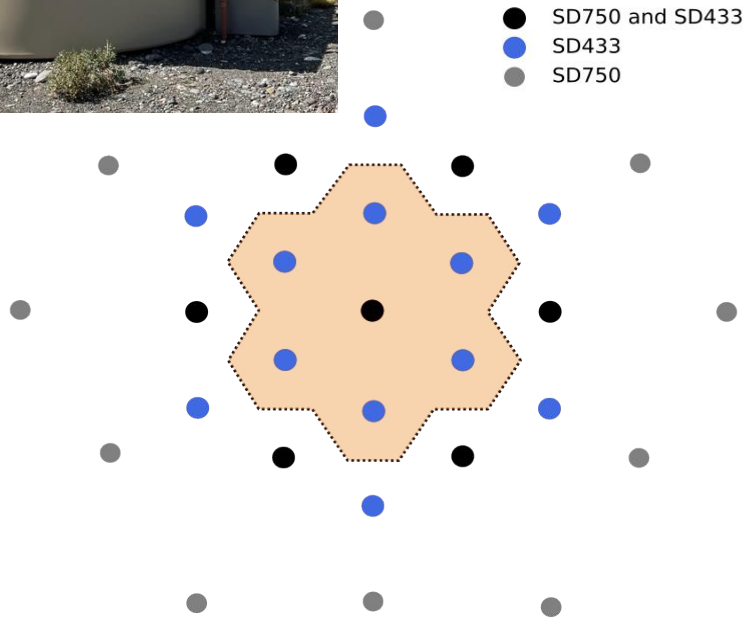
SD433 Spectrum

Gabriel Brichetto Orquera
gabriel.brichetto@iteda.cnea.gov.ar

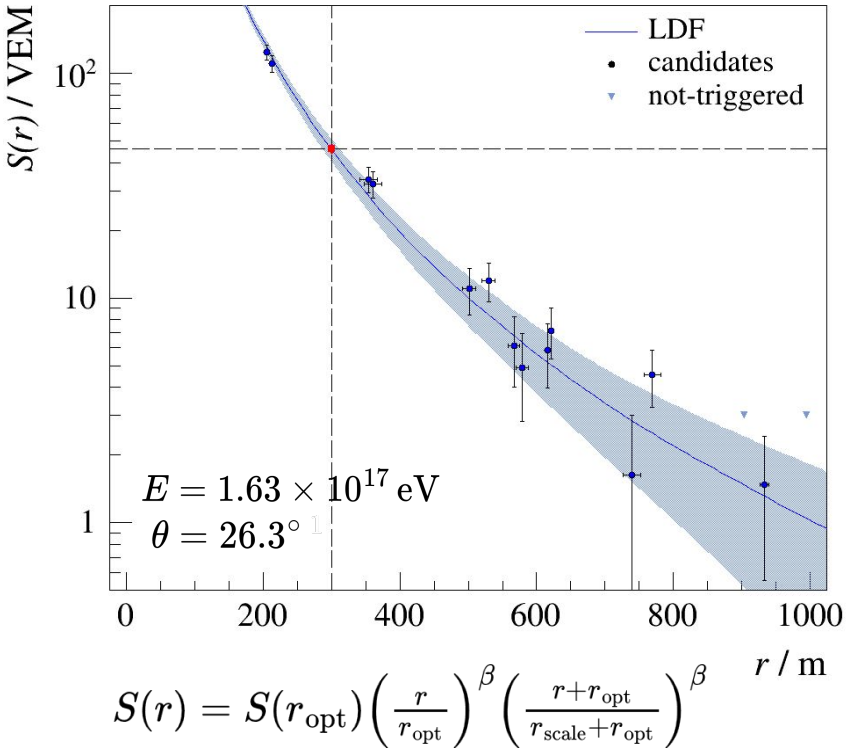
Auger Youngsters Meeting
Sep 5th 2024 - Siegen

The SD433

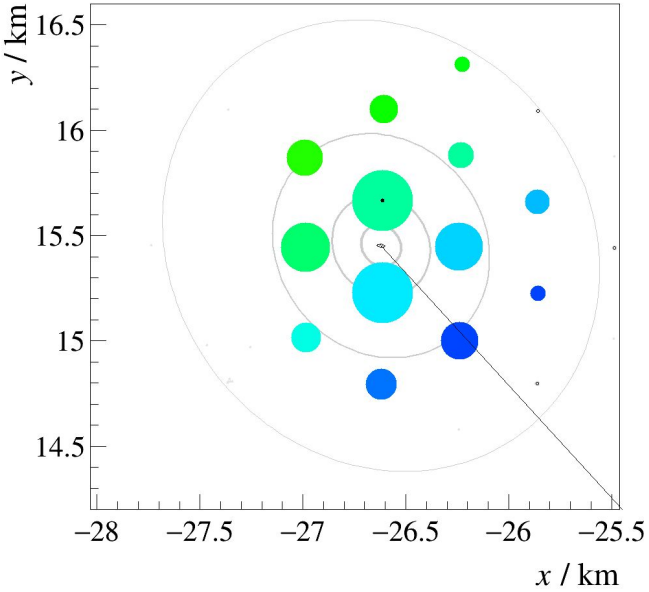
- 19 Water-Cherenkov detectors with 433 m separation
- Denser array to lower the energy threshold of the Spectrum
- Two hexagons around a central station with 1.1 km^2 of effective surface
- Spectrum reported from 63 PeV for zenith angle lower than 45°



SD433 event reconstruction

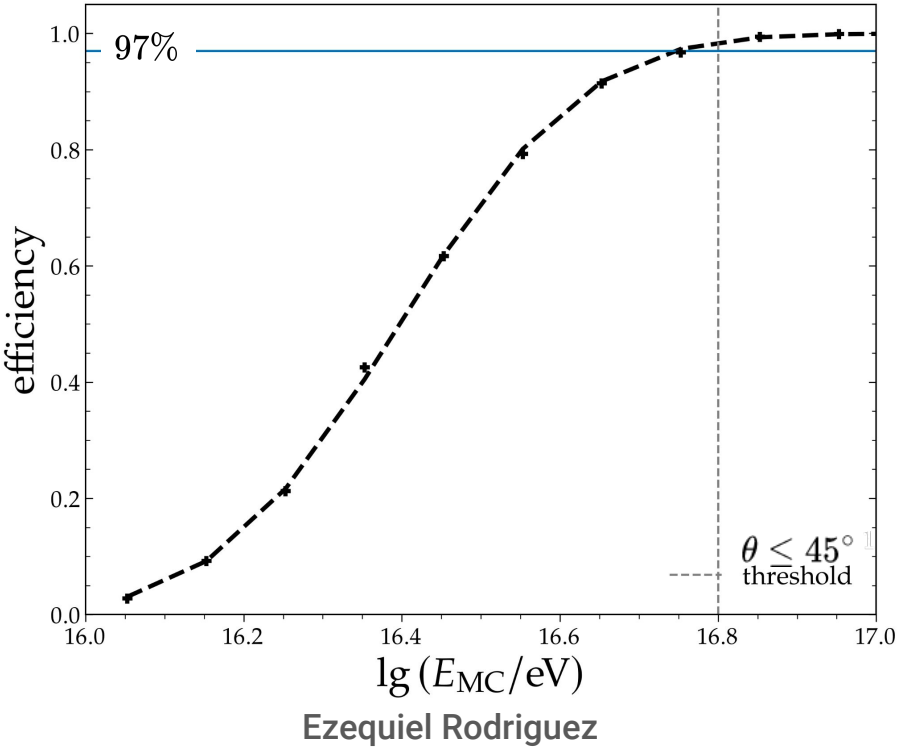


$$S(r) = S(r_{\text{opt}}) \left(\frac{r}{r_{\text{opt}}} \right)^{\beta} \left(\frac{r + r_{\text{opt}}}{r_{\text{scale}} + r_{\text{opt}}} \right)^{\beta}$$

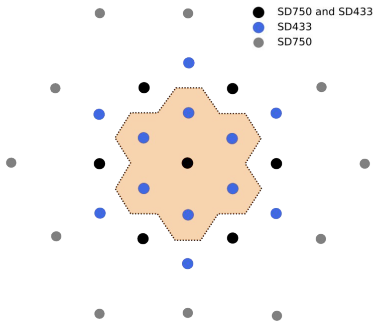


- Fall-off of the WCD signal with a LDF
- Modified Nishimura-Kamata-Greisen function used
- Shower size estimated at 300 m from the core where systematics are minimized

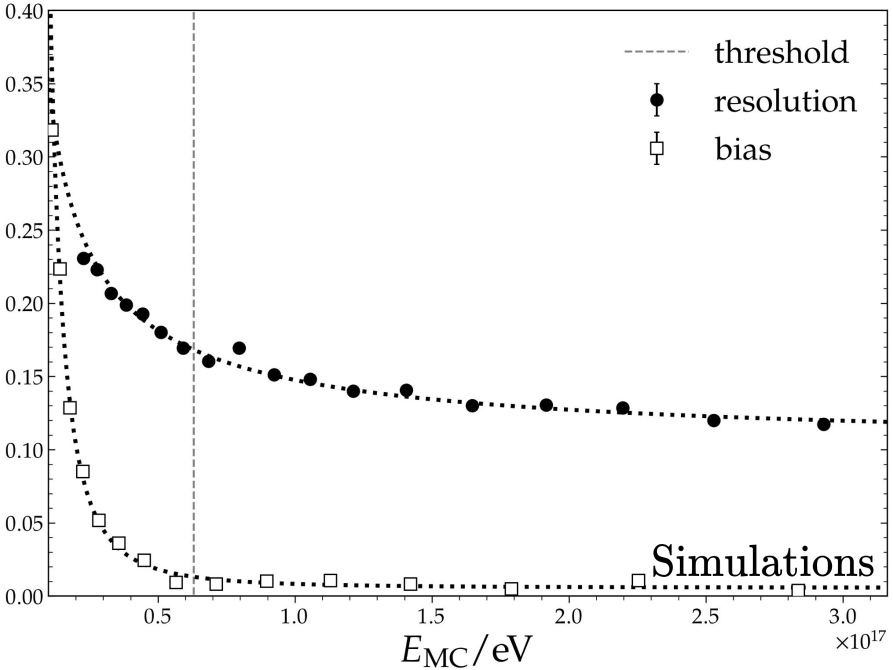
Efficiency and exposure



- 97% efficiency at 6.3 x 10^{16} eV from simulations
- Geometrical exposure calculation
- Exposure: **3.87 km² sr yr** (Jan 2018 - Dec 2021)
- Mixed Composition from Global Spline Fit (Dembinski et al. ICRC 2017)



Energy resolution and bias



Ezequiel Rodriguez

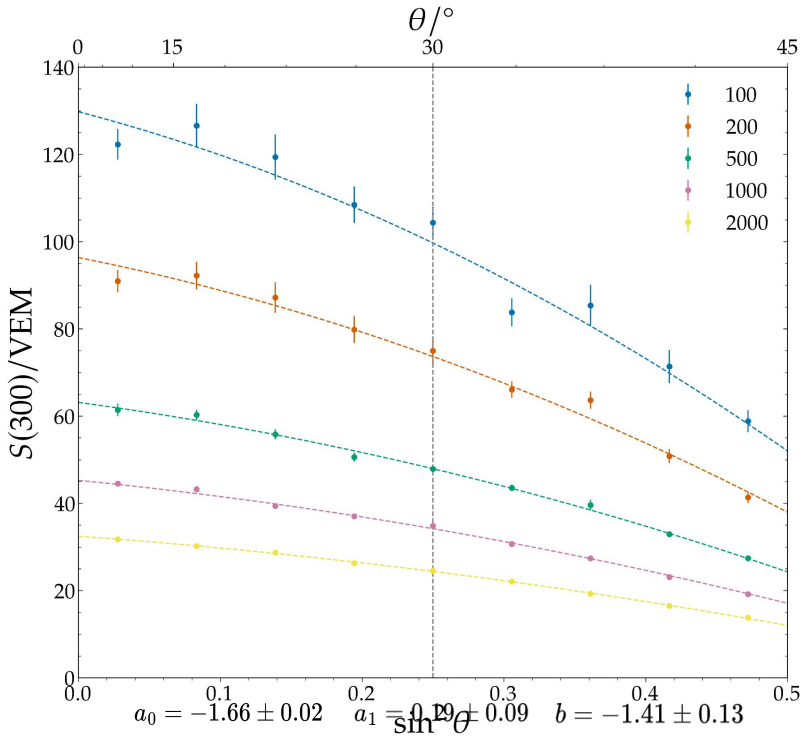
- Resolution and bias for calibration and spectrum unfolding
- Two component resolution model:

$$R^2_{433} = R^2_{sh} + \frac{R^2_0 E_0}{E}$$

$$R_0 = (12 \pm 1)\% \quad R_{sh} = (9 \pm 1)\% \quad E_0 = 10^{17}\,\text{eV}$$

- ~17% resolution at energy threshold
- <2% bias below the full efficiency threshold

Attenuation

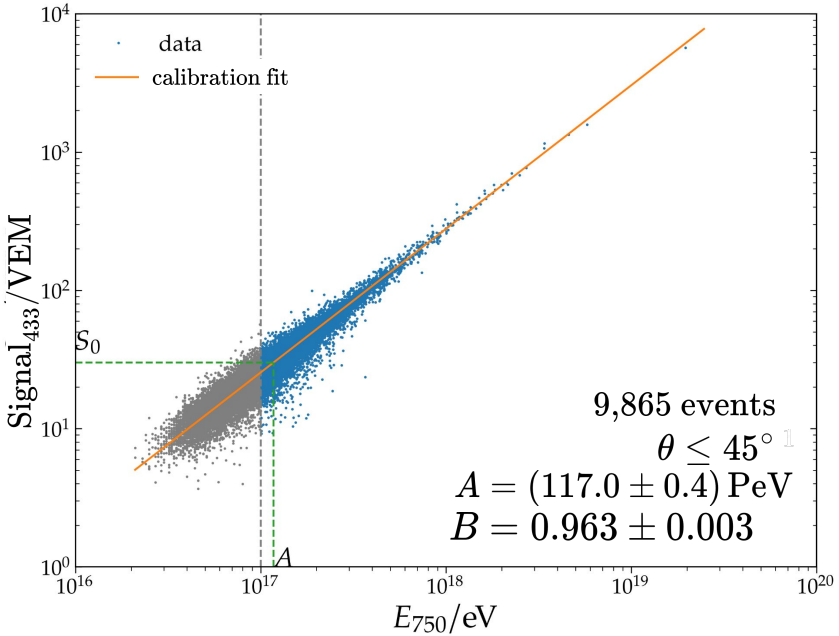


- Shower size attenuates with zenith angle
- Data driven correction with constant-intensity cut method
- Energy dependent attenuation

$$S(300) = S_{30}\left[1 + a(S_{30})\,x + b\,x^2\right]$$

$$a_0 + a_1 \lg\left(\frac{S_{30}}{30\ \mathrm{VEM}}\right) \qquad \sin^2(\theta) - \sin^2(30^\circ)$$

Energy Calibration



- Different calibration from the other SD arrays
- SD433 is below the energy threshold of the Fluorescence Detector
- SD433 is calibrated against the 750-metre array
- Energy scale set indirectly by the FD
- Likelihood fit considering energy resolutions and spectrum shape

$$E_{433} = A\left(\frac{S_{30}}{30\ \mathrm{VEM}}\right)^{B}$$

Forward Folding

Model is folded with the response matrix.

v_i are included in the Poisson likelihood with data.

Minimization of the likelihood to get the spectrum parameters

$$R_{ij} = \int_{\Delta E_i} dE_j \kappa(E_i|E_j)\epsilon(E_j)$$

$$J(E|s)$$

$$\downarrow$$

$$\mu_j = \frac{1}{\varepsilon} \int_{\Delta E_j} J(E|s)$$

$$\downarrow \quad R_{ij}$$

$$\boldsymbol{\nu_i}$$

$$\downarrow$$

$$D = 2\sum_i \left(\nu_i(s) - N_i + N_i \ln\left(\frac{N_i}{\nu_i(s)}\right)\right)$$

Spectrum Systematic sources

Sources:

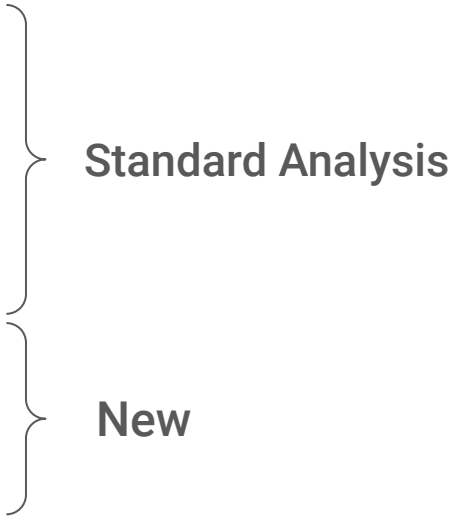
FD Energy scale

Unfolding

Exposure

Energy calibration

Transition width



Assess the impact in the 2nd knee energy and the spectral indexes

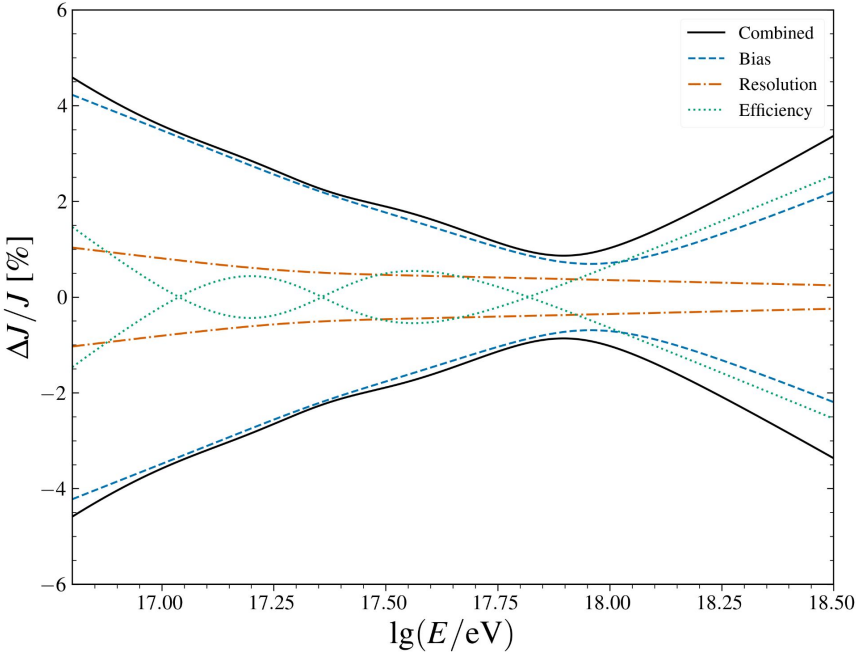
Detector response systematic

Detector systematic sources:

- Efficiency: Pure Proton / Iron
- Bias: Pure Proton / Iron
- Resolution $\pm\sigma$

Sum in quadrature of the flux component leads to less than 5% systematic in the flux

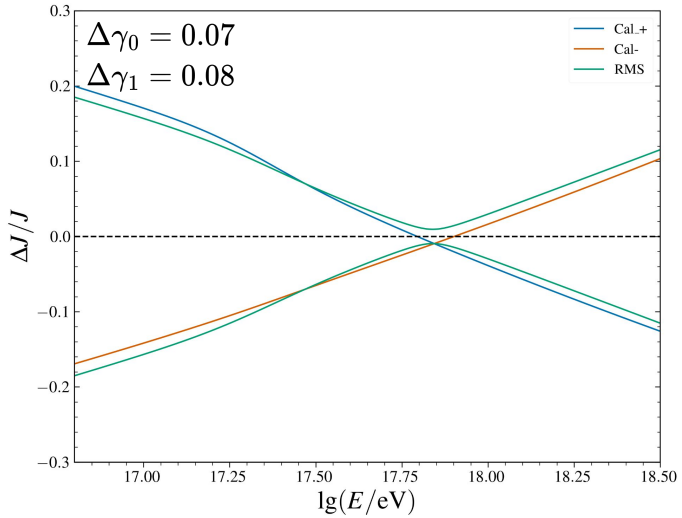
Negligible contribution to the spectral indexes (<0.5%)

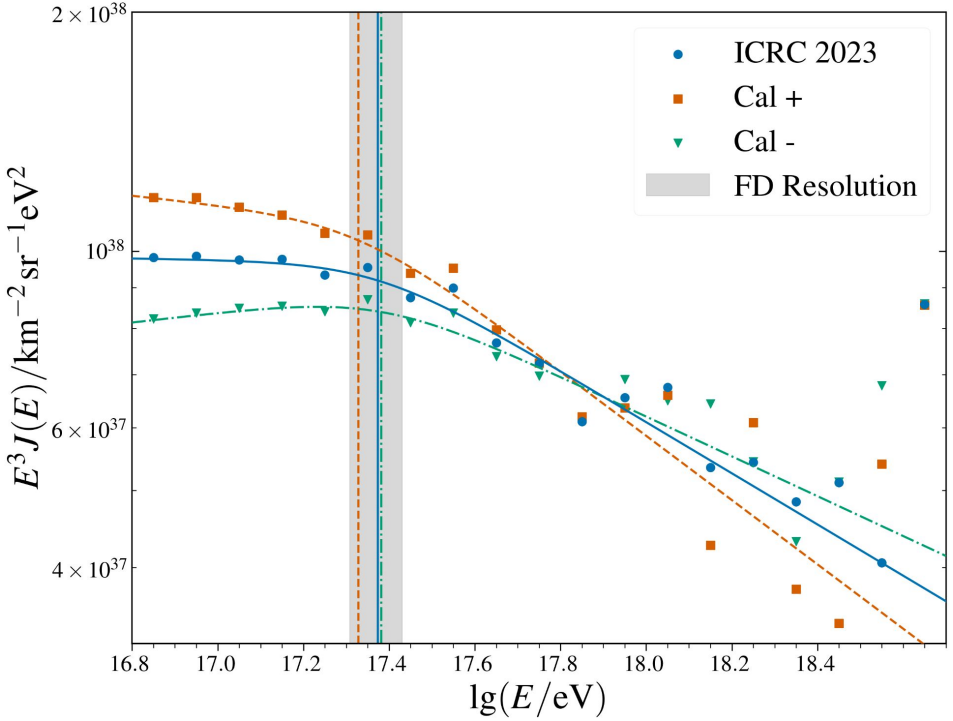


Energy Calibration Systematic

High slope leads to change in the 2nd knee

Difference of ~20% in flux at lowest energies





SD433 Spectrum Systematics

Exposure systematic: 4% in flux, energy independent

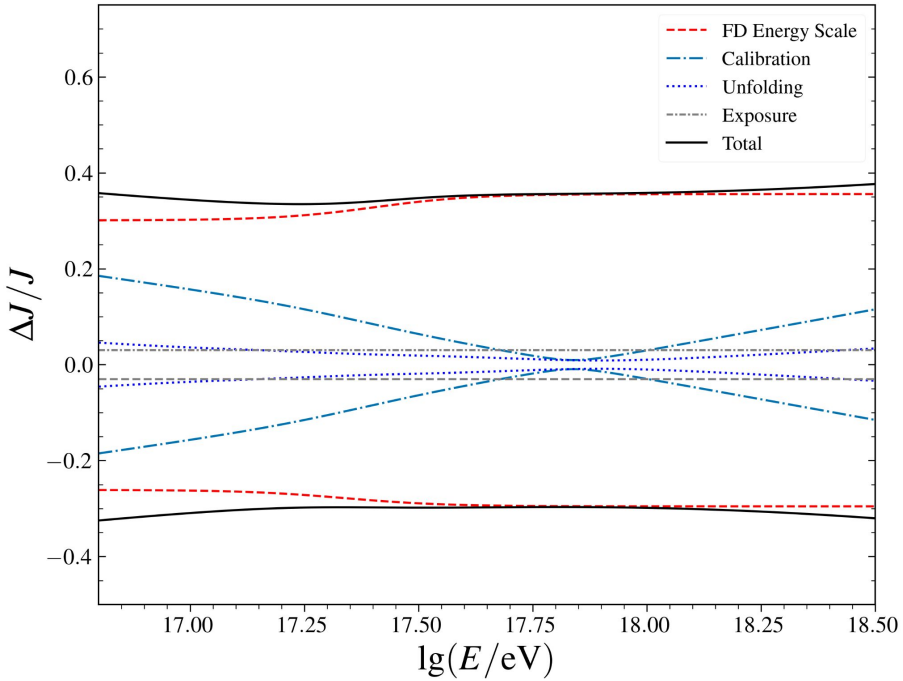
Total contribution in flux is almost constant +37% -30%

Total flux systematic at 10^{17} eV = 34% (J_0)

Total E_{01} systematic = 42 PeV

Total γ_0 systematic = 0.11

Total γ_1 systematic = 0.11



Spectrum Systematics Update

Measurement of the spectrum with updated Systematics:

$$J(E) = J_0 \left(\frac{E}{10^{17}\,\mathrm{eV}}\right)^{-\gamma_0} \left[1 + \left(\frac{E}{E_{01}}\right)^{\frac{1}{\omega_{01}}}\right]^{(\gamma_0-\gamma_1)\omega_{01}}$$

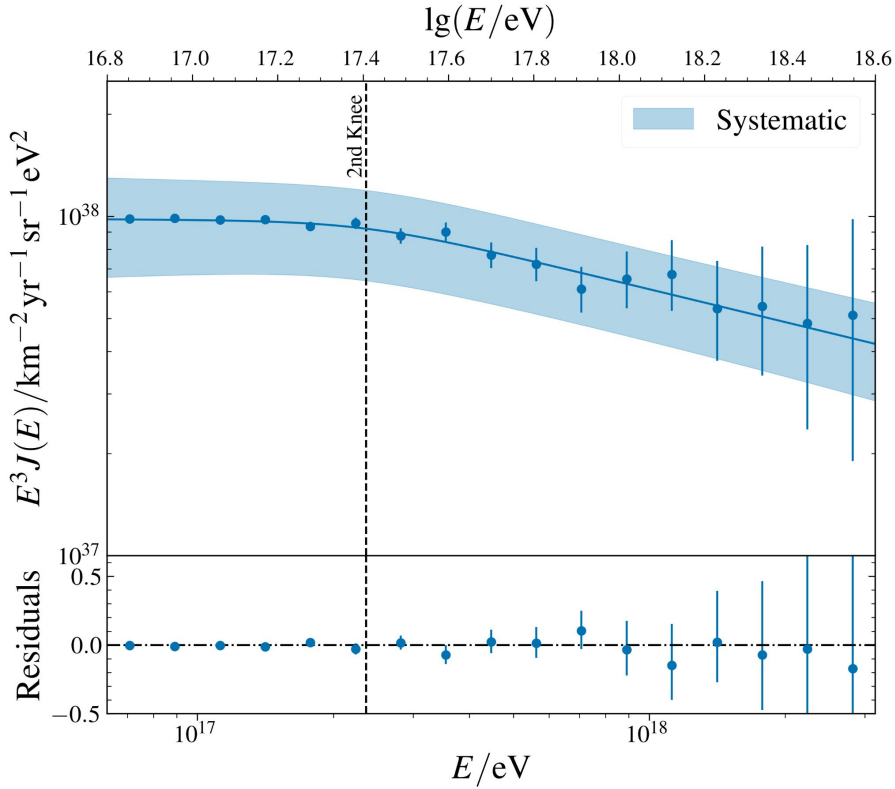
$$J_0 = (0.97 \pm 0.02\,\mathrm{stat} \pm 0.33\,\mathrm{syst}) \times 10^{-13}\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{eV}^2$$

$$E_{01} = (230 \pm 50\,\mathrm{stat} \pm 42\,\mathrm{syst})\,\mathrm{PeV}$$

$$\gamma_0 = 3.00 \pm 0.05\,\mathrm{stat} \pm 0.11\,\mathrm{syst}$$

$$\gamma_1 = 3.32 \pm 0.08\,\mathrm{stat} \pm 0.11\,\mathrm{syst}$$

$$\omega_{01} = 0.25\ (\mathrm{fixed})$$



SD433 and SD750 Combined Spectrum

$$\mathcal{L}_{\text{combined}} = \mathcal{L}_{\text{SD433}} \times \mathcal{L}_{\text{SD433}} \times \mathcal{L}_{\delta\varepsilon_{SD433}}$$

$$\mathcal{L}_{\text{SD433}} = \text{Poiss}(\nu|\text{n})$$

$$\mathcal{L}_{\text{SD750}} = \text{Poiss}(\nu|\text{n})$$

$$\mathcal{L}_{\delta\varepsilon_{\text{SD433}}} = \text{Gauss}(\delta\varepsilon_{\text{SD433}}|\sigma_{\varepsilon_{\text{SD433}}})$$

$$J_i^{\text{comb}} = \frac{c_i^{\text{SD750}} N_i^{\text{SD750}} + c_i^{\text{SD433}} N_i^{\text{SD433}}}{\varepsilon_i^{\text{eff}} \Delta E_i}$$

$J_0/(\text{km}^2\,\text{yr}\,\text{sr}\,\text{eV})$	$(1.09 \pm 0.04 \pm 0.28) \times 10^{-13}$
ω_{01}	$0.49 \pm 0.07 \pm 0.34$
γ_1	$3.34 \pm 0.02 \pm 0.09$
E_{12}/eV	$(3.9 \pm 0.8 \pm 1.1) \times 10^{18}$
γ_2	$2.6 \pm 0.2 \pm 0.1$
γ_0	2.64 – fixed
E_{01}/eV	1.24×10^{17} – fixed
ω_{12}	0.05 – fixed

SD750 Paper

$J_0 = (0.97 \pm 0.02\,\text{stat} \pm 0.33\,\text{syst}) \times 10^{-13}$

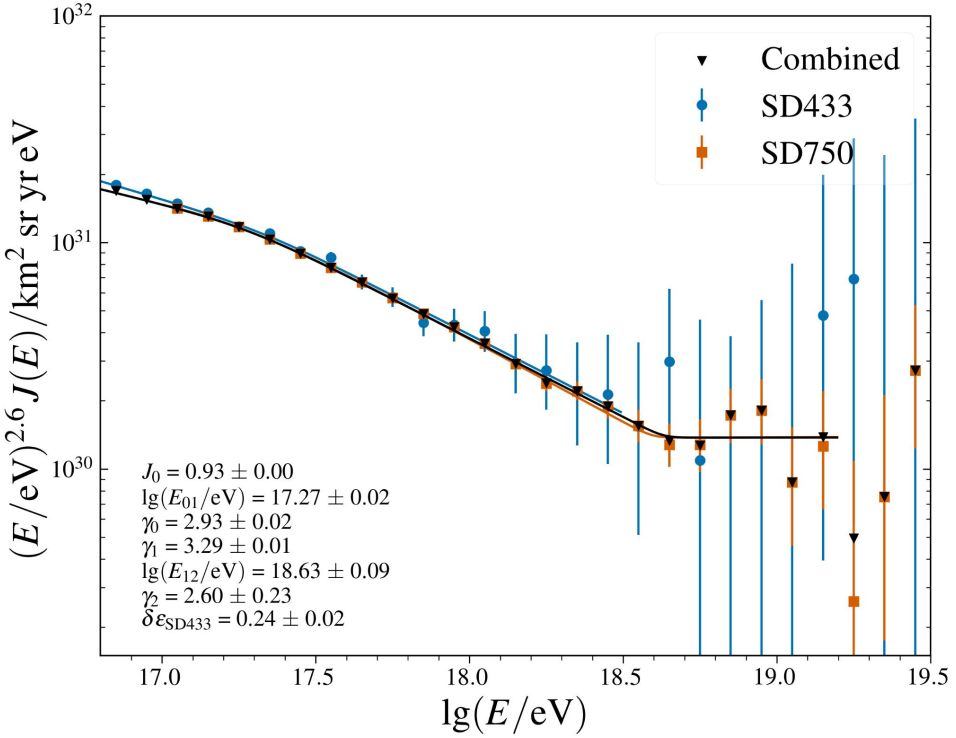
$E_{01} = (230 \pm 50\,\text{stat} \pm 42\,\text{syst})\,\text{PeV}$

$\gamma_0 = 3.00 \pm 0.05\,\text{stat} \pm 0.11\,\text{syst}$

$\gamma_1 = 3.32 \pm 0.08\,\text{stat} \pm 0.11\,\text{syst}$

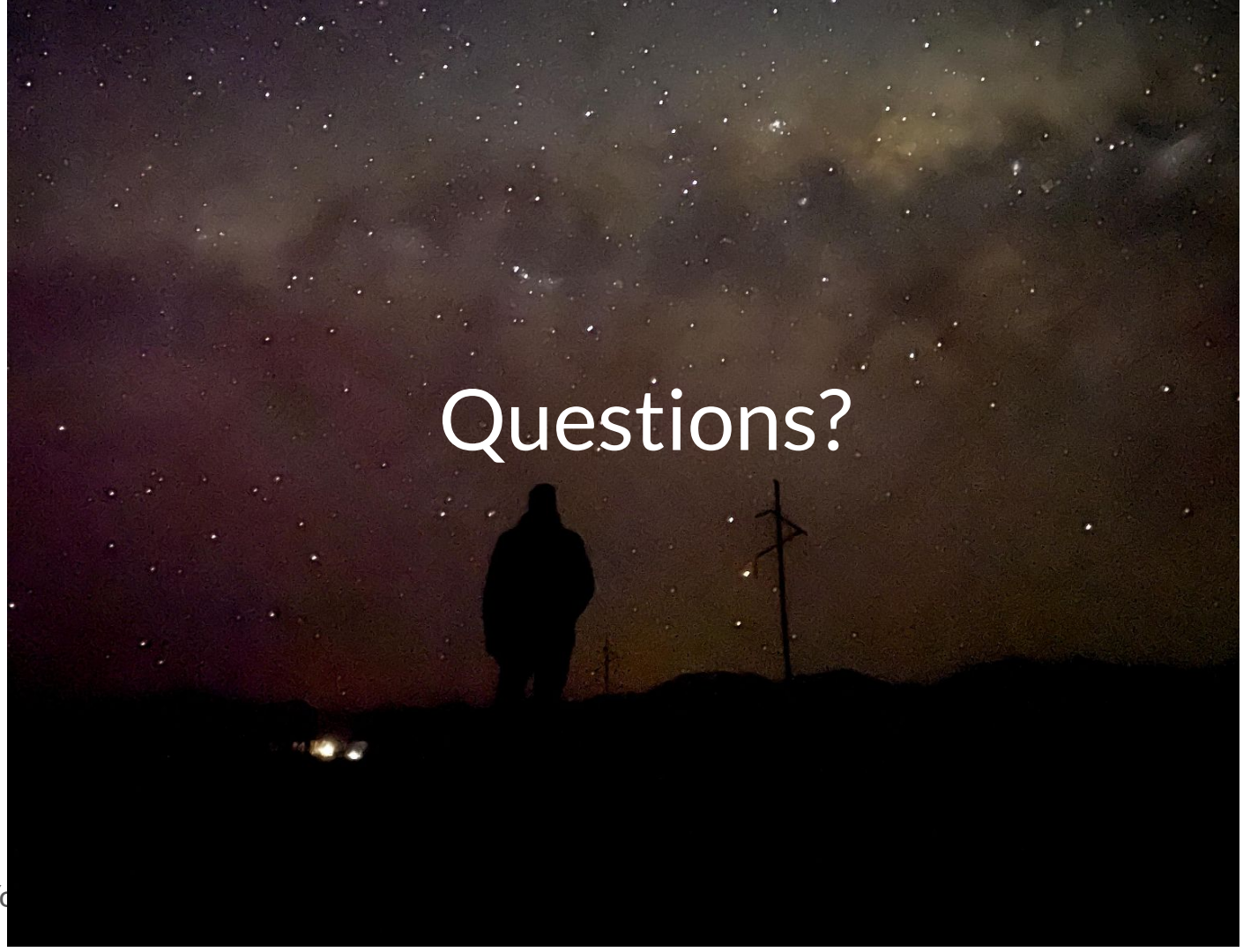
$\omega_{01} = 0.25$ (fixed)

SD433



Summary

- **Energy spectrum measurement with the SD433**
- **First measurement of the second knee with a FD calibrated detector**
- **Combined SD433 and SD750 spectrum**
- **Measurement of the second knee in accordance to the SD433 only spectrum**


Questions?