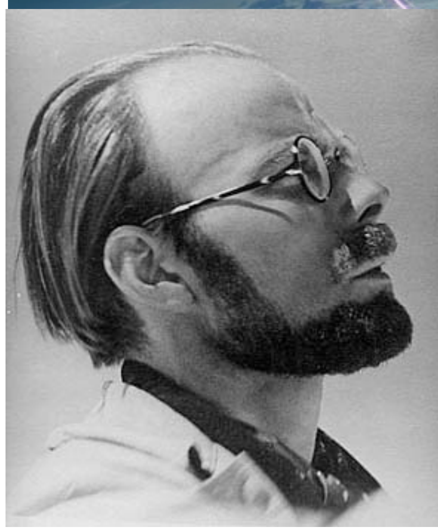

Auger Spectrum and its implications

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PIERRE AUGER OBSERVATORY

5th Workshop on Air Shower Detection at High Altitude
26-28 May, 2014, Paris

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

The Pierre Auger Observatory

Ultra High Energy Cosmic Ray (UHECR) detector located in Argentina, Mendoza province, Malargüe

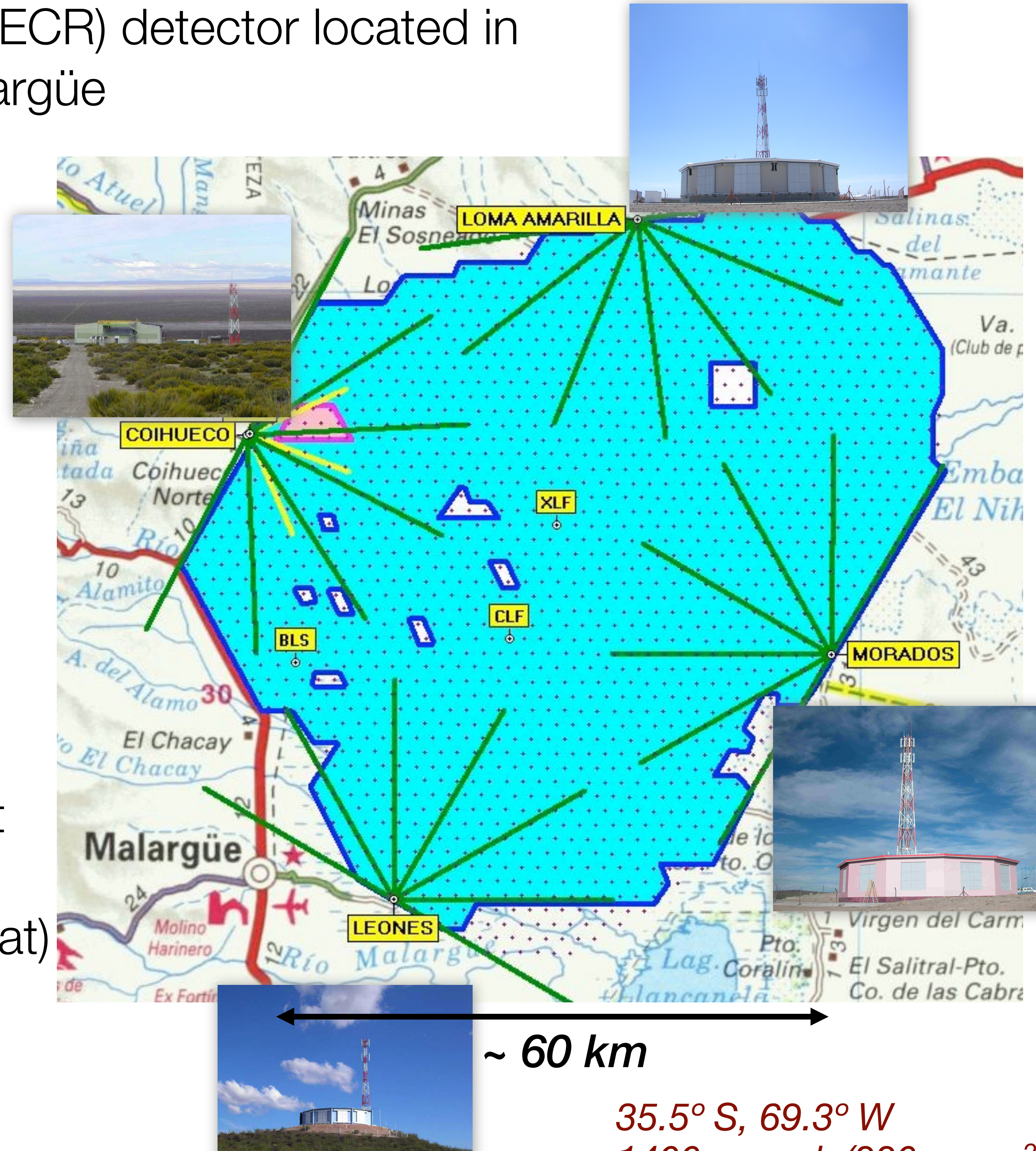
Total area 3000 km^2

Surface Detector array (SD):

- water Cherenkov detectors
- 1660 in 1.5 km grid
- 61 in 0.75 km grid (infill low energies ~3 x 10^{17}eV)
- ~100% duty cycle

Fluorescence Detector (FD):

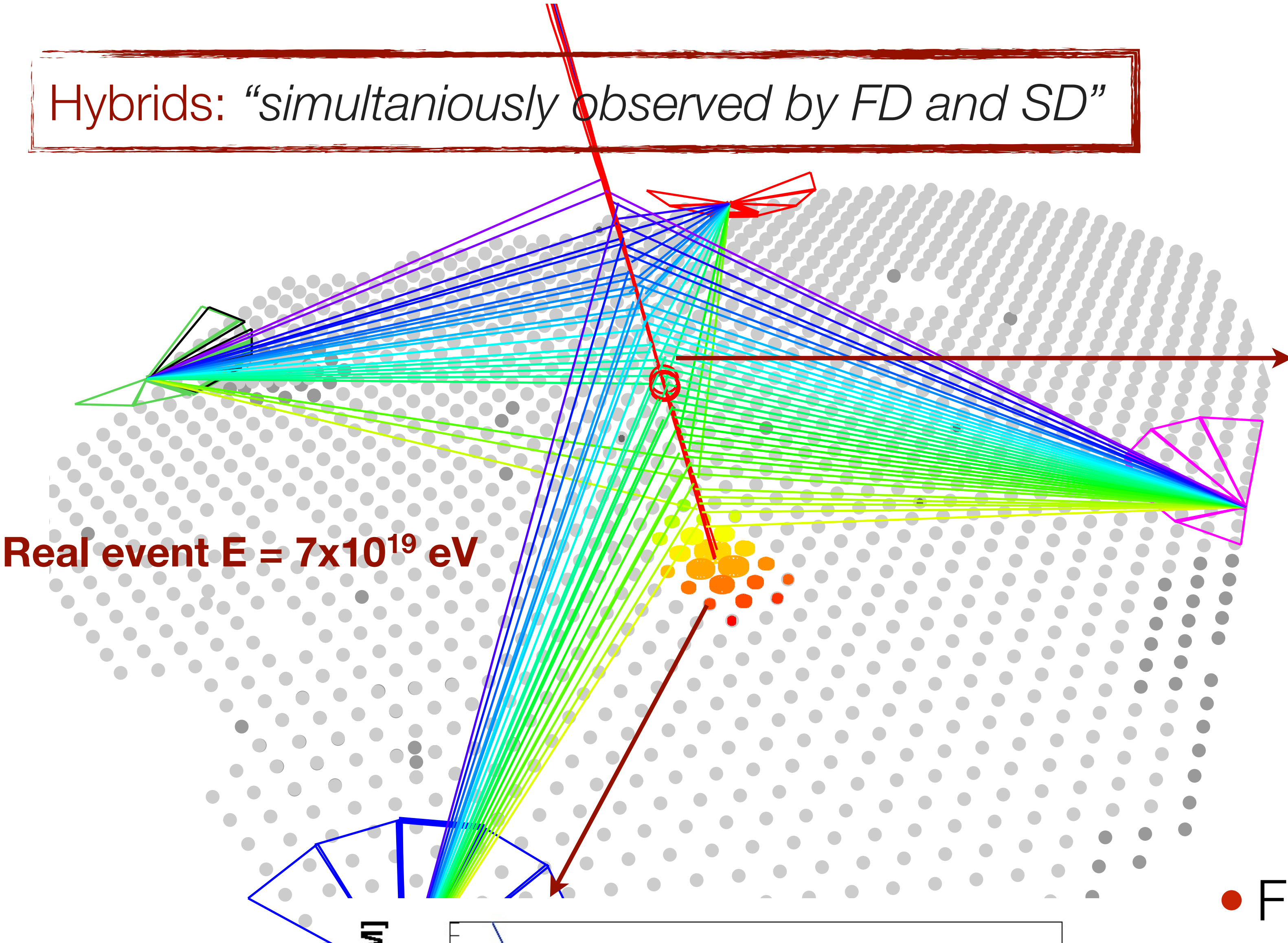
- 4 Fluorescence sites + 1 (Heat low energies ~10^{17}eV)
- 6 telescopes per site (3 for Heat)
- ~14% duty cycle (moonless nights)

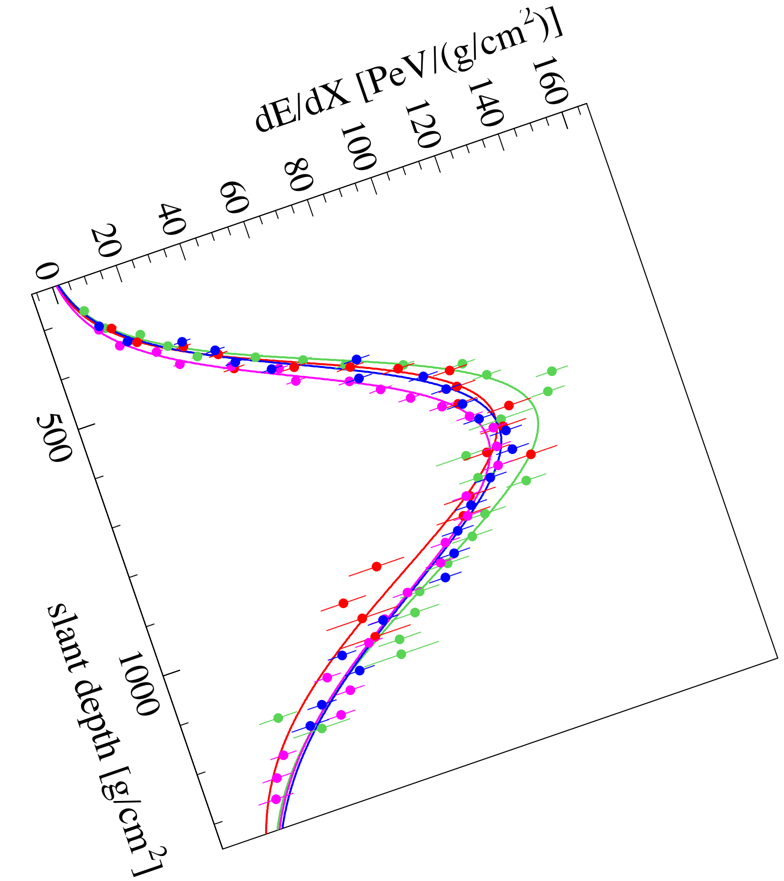


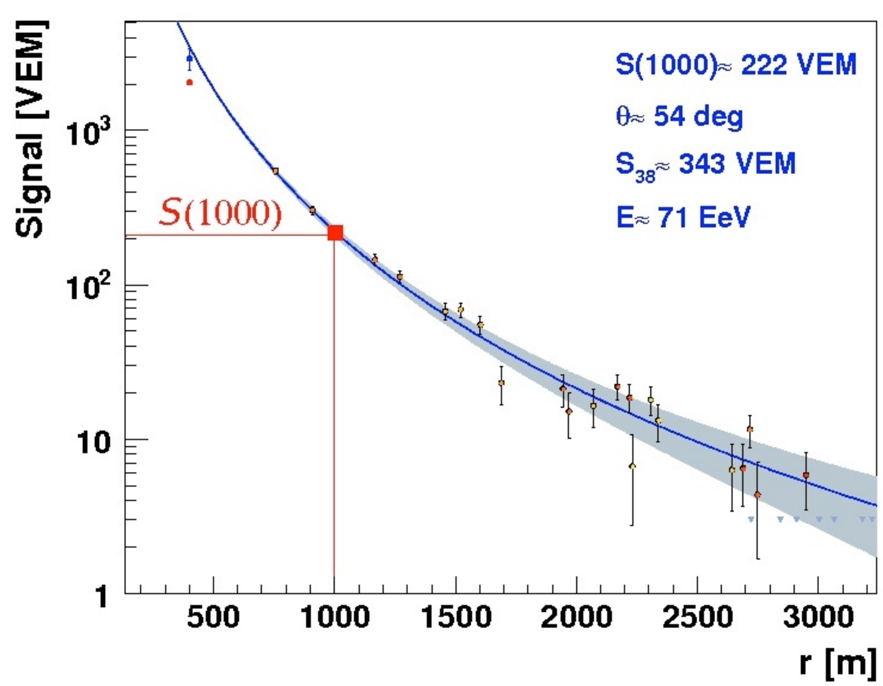
35.5° S, 69.3° W
1400 m a.s.l. (880 g cm^{-2})

Air shower reconstruction

Hybrids: *"simultaniously observed by FD and SD"*







- FD energy given by the integral of the longitudinal profile
- The position of the shower maximum (Xmax) gives information on the primary mass
- SD energy: proportional to signal at 1 km from the shower core

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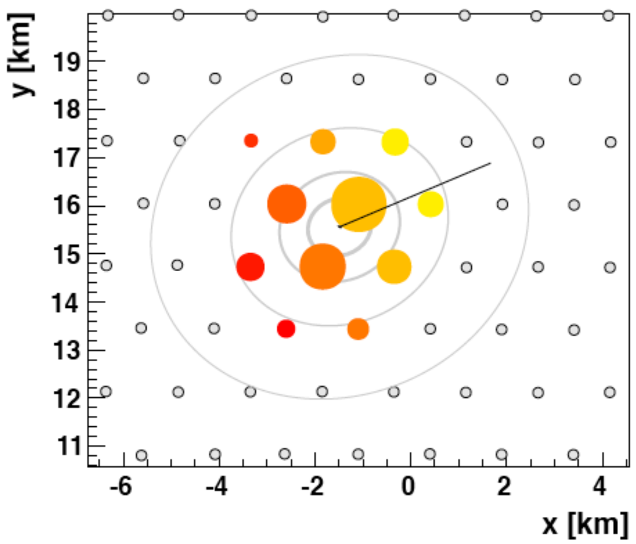
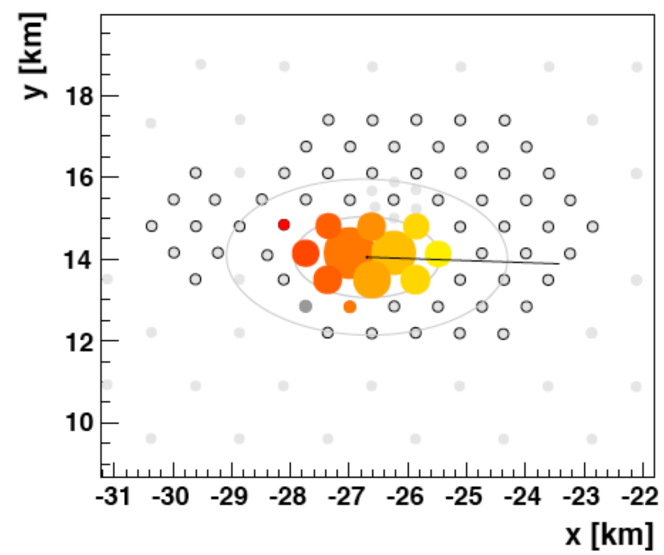
The Auger Zoo

SD 1500 m, $\theta < 60°$



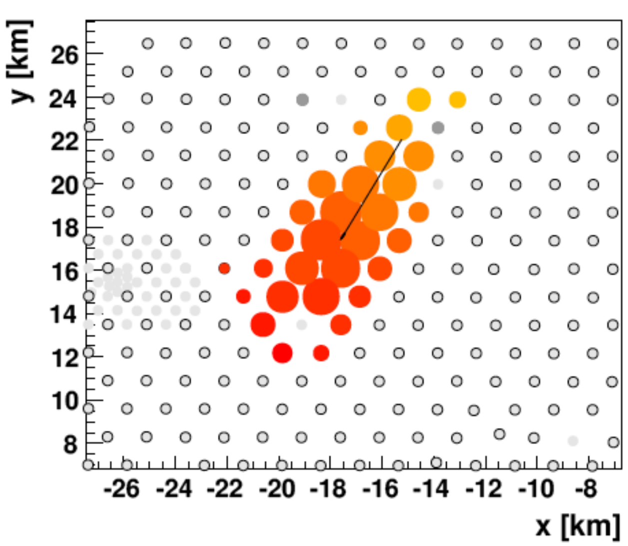
Vertical events
fully efficient:
E > 3 EeV
energy estimator:
S38

SD 750 m, $\theta < 55°$



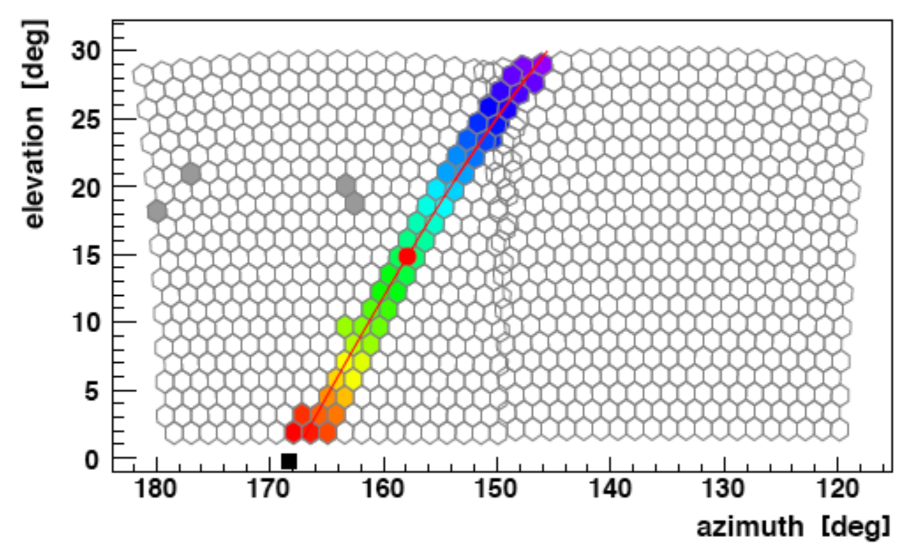
750m events
fully efficient:
E > 0.3 EeV
energy estimator:
S35

SD 1500 m, $62° < \theta < 80°$



Inclined events
fully efficient:
E > 4 EeV
energy estimator:
N19

Hybrid(FD + 1 SD), $\theta < 60°$



Hybrid events
fully efficient:
E 1 EeV
energy meas.

Combined measurement allows to cover 3 decades in energy

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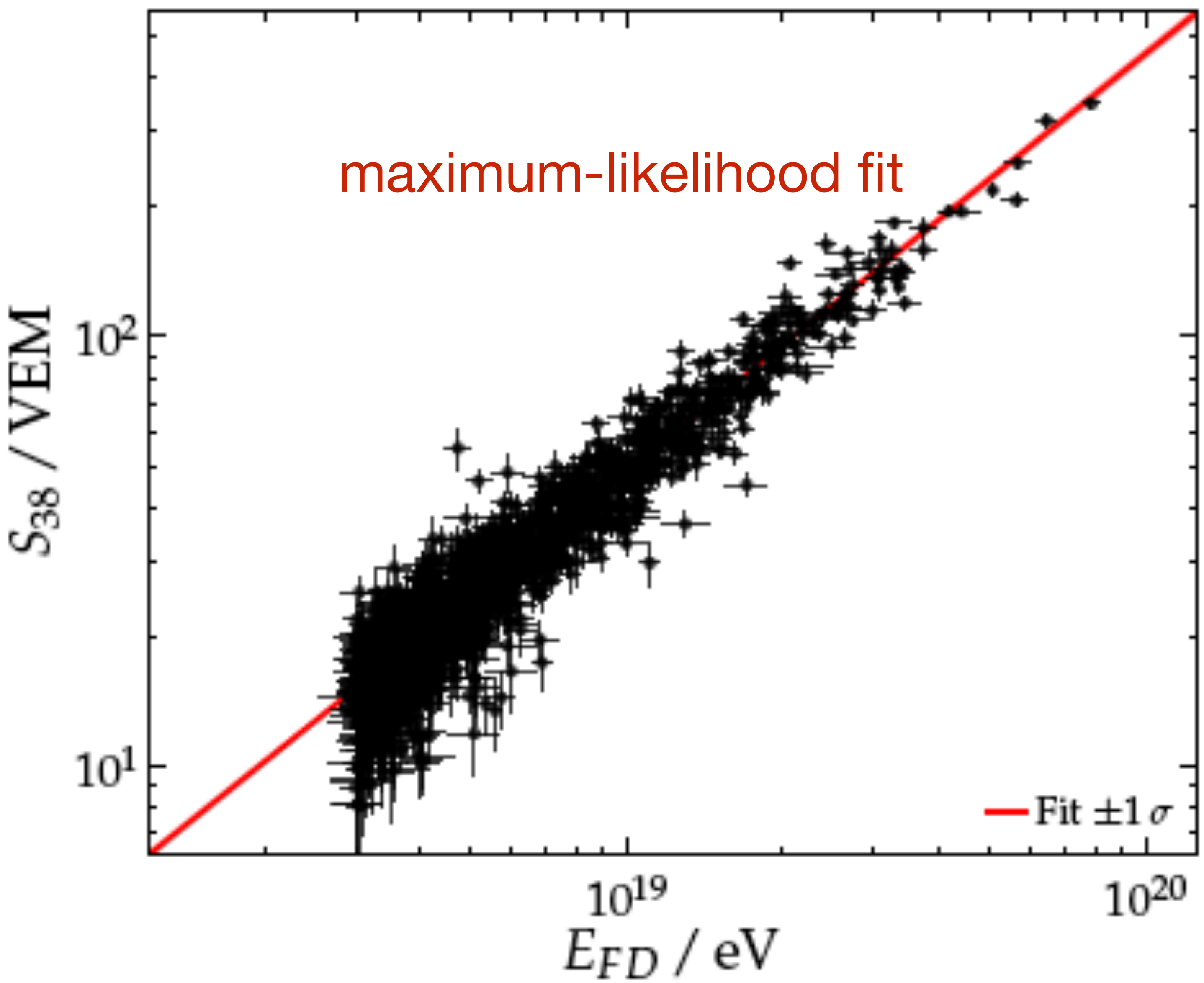
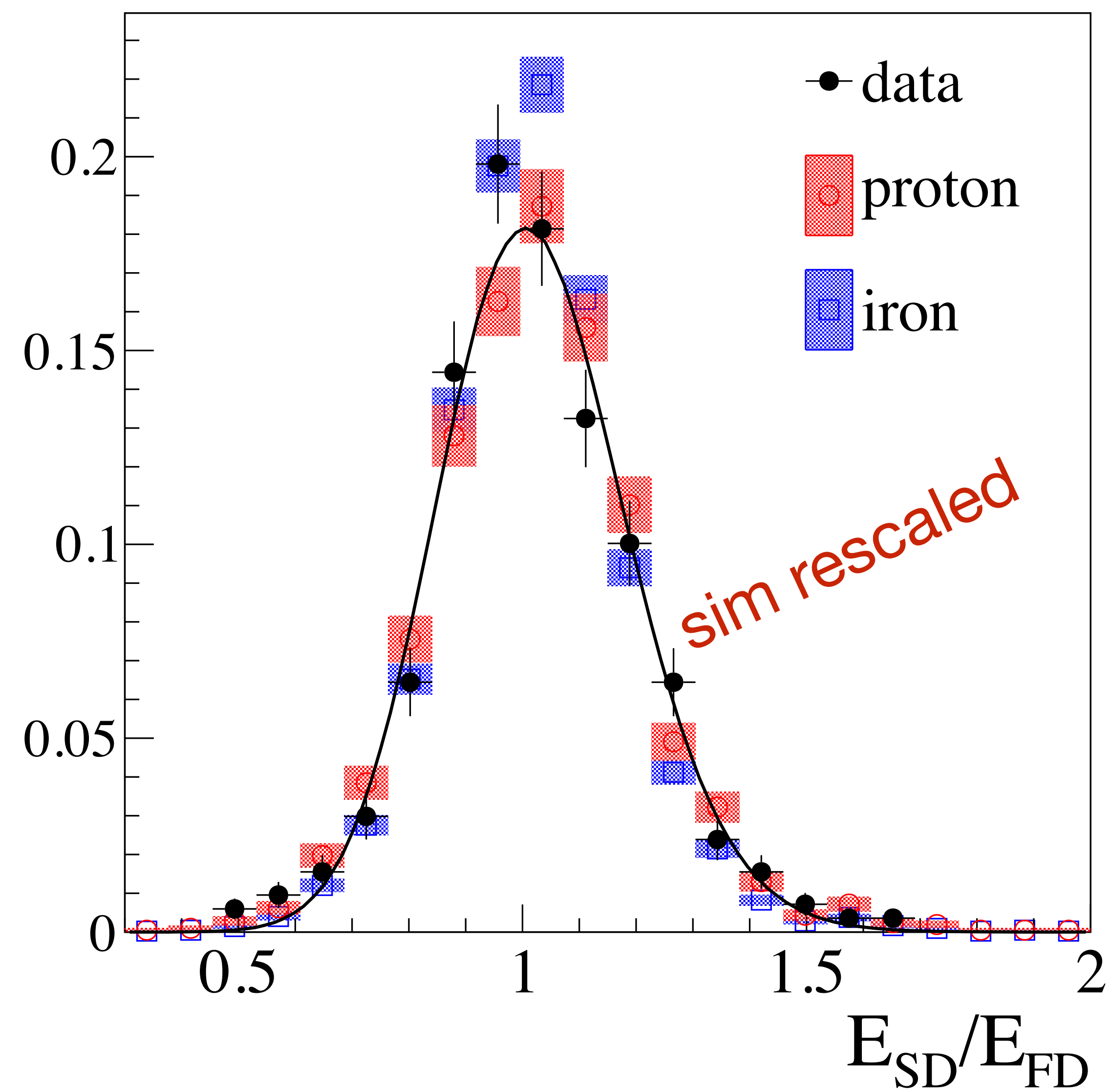
SD Calibration

- high quality events triggered and reconstructed independently form SD and FD
- SD energy resolution 15% (< 12%), E < 6EeV (E > 10EeV)
- shower to shower fluctuation is the major contribution at highest energies (~12%)
- resolutions compared to Monte Carlo simulations (SD sim rescaled by 24%)





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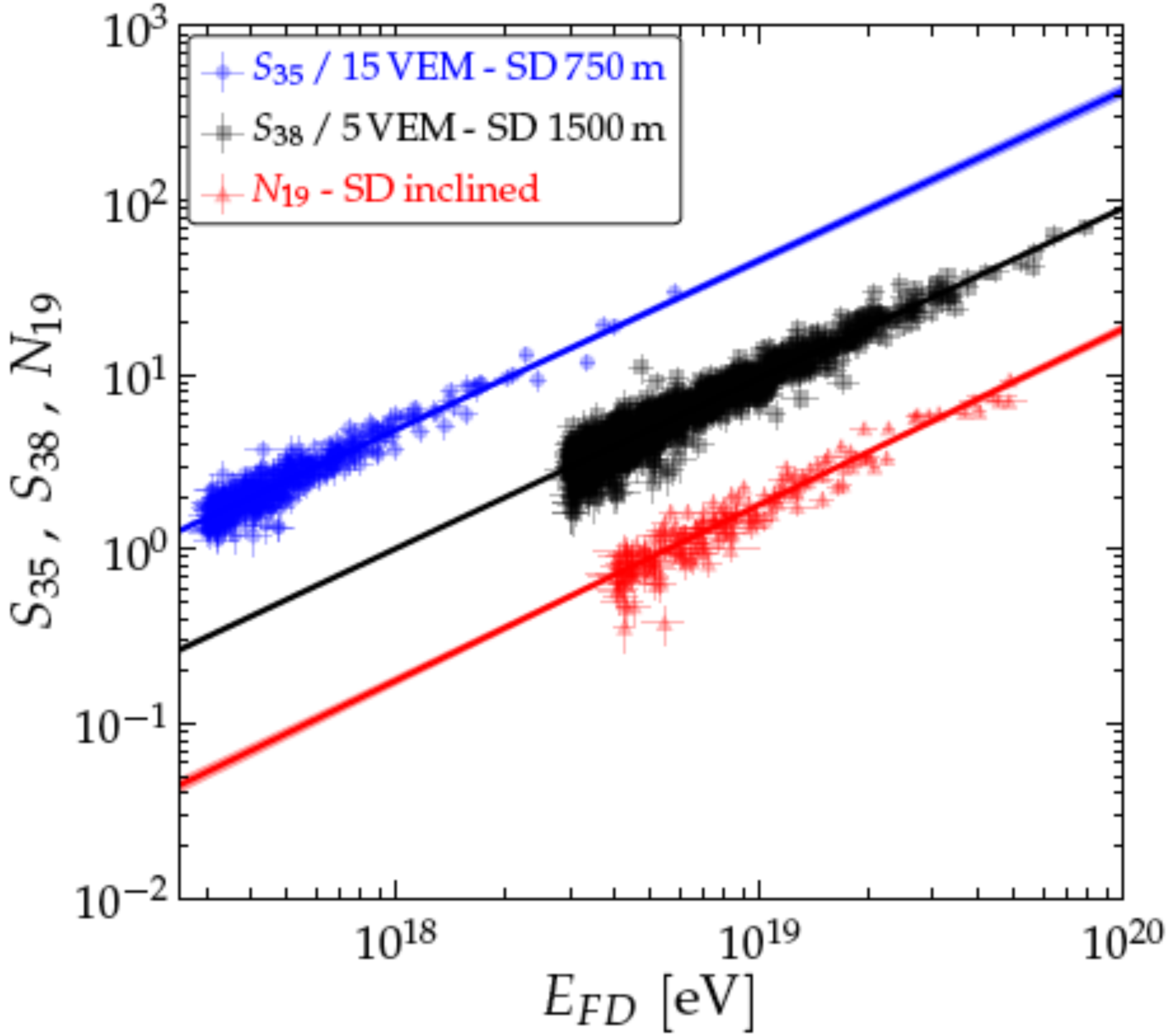
Calibrations



Calibration functions:

$E = A \cdot S^B$

SD 1500 m
A = (0.190 ± 0.005) EeV
B = 1.025 ± 0.007

SD inclined
A = (5.61 ± 0.1) EeV
B = 0.985 ± 0.02

SD 750m
A = (12.1 ± 0.7) PeV
B = 1.03 ± 0.02

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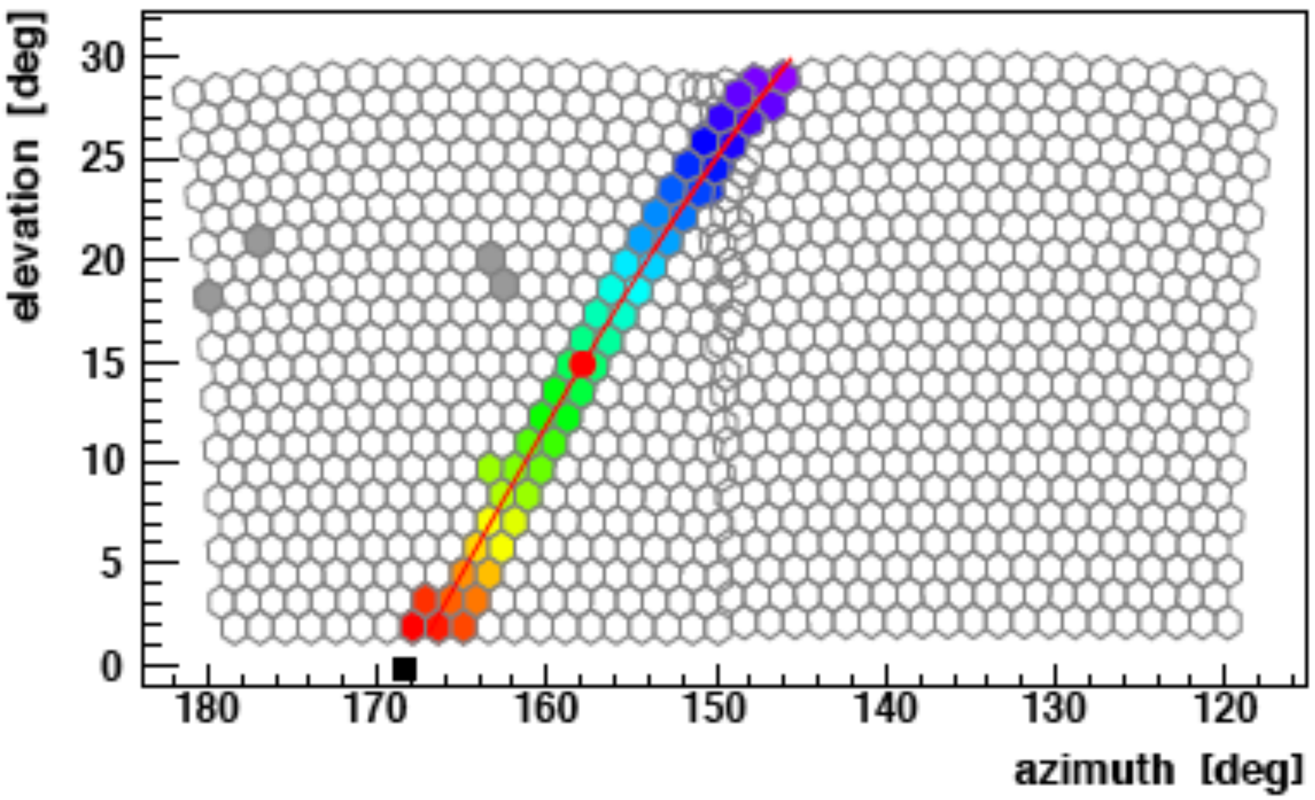
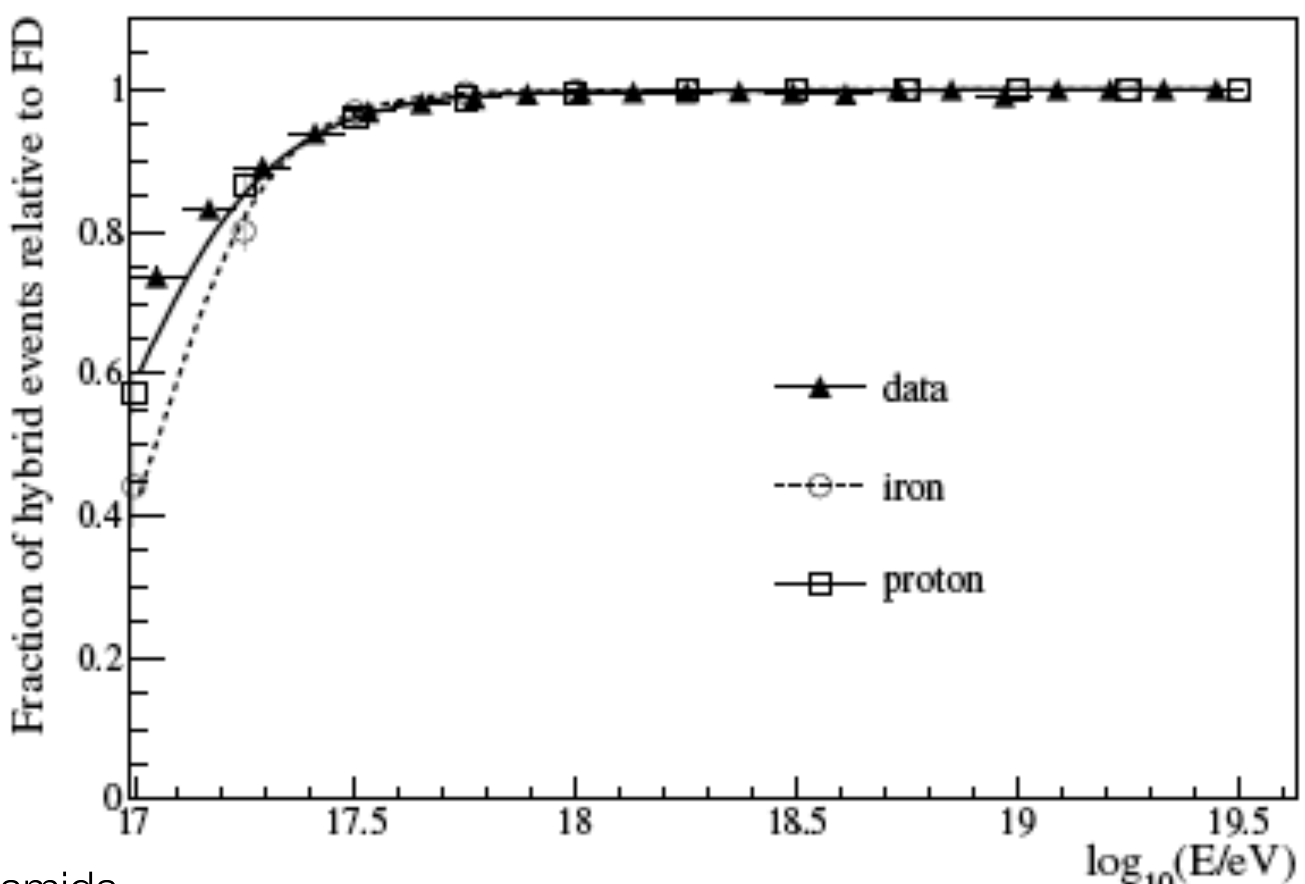
Hybrids



FD + at least one SD station
Geometrical reconstruction:
angular resolution < 1°
Energy reconstruction:
resolution 8%



Detector fully efficient above
$E = 10^{17.8}$ eV

exposure calculation,via Monte-Carlo, includes efficiencies of all involved components

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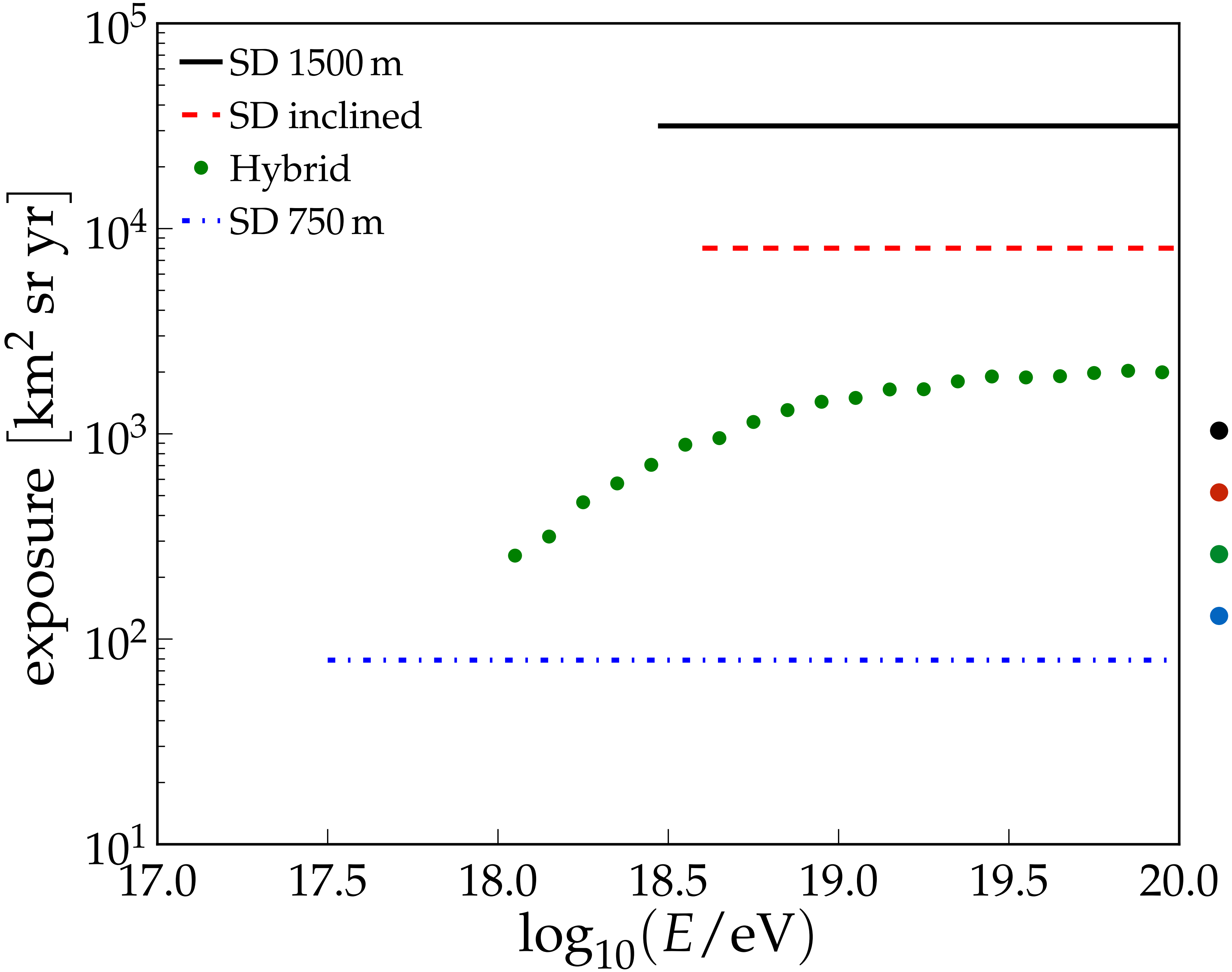
Exposure



Exposures at 10 EeV
[km2 sr yr]

- SD vertical: 31645 ± 950
- SD inclined: 8027 ± 240
- Hybrid: 1496 ± 25
- SD 750 m: 79 ± 4

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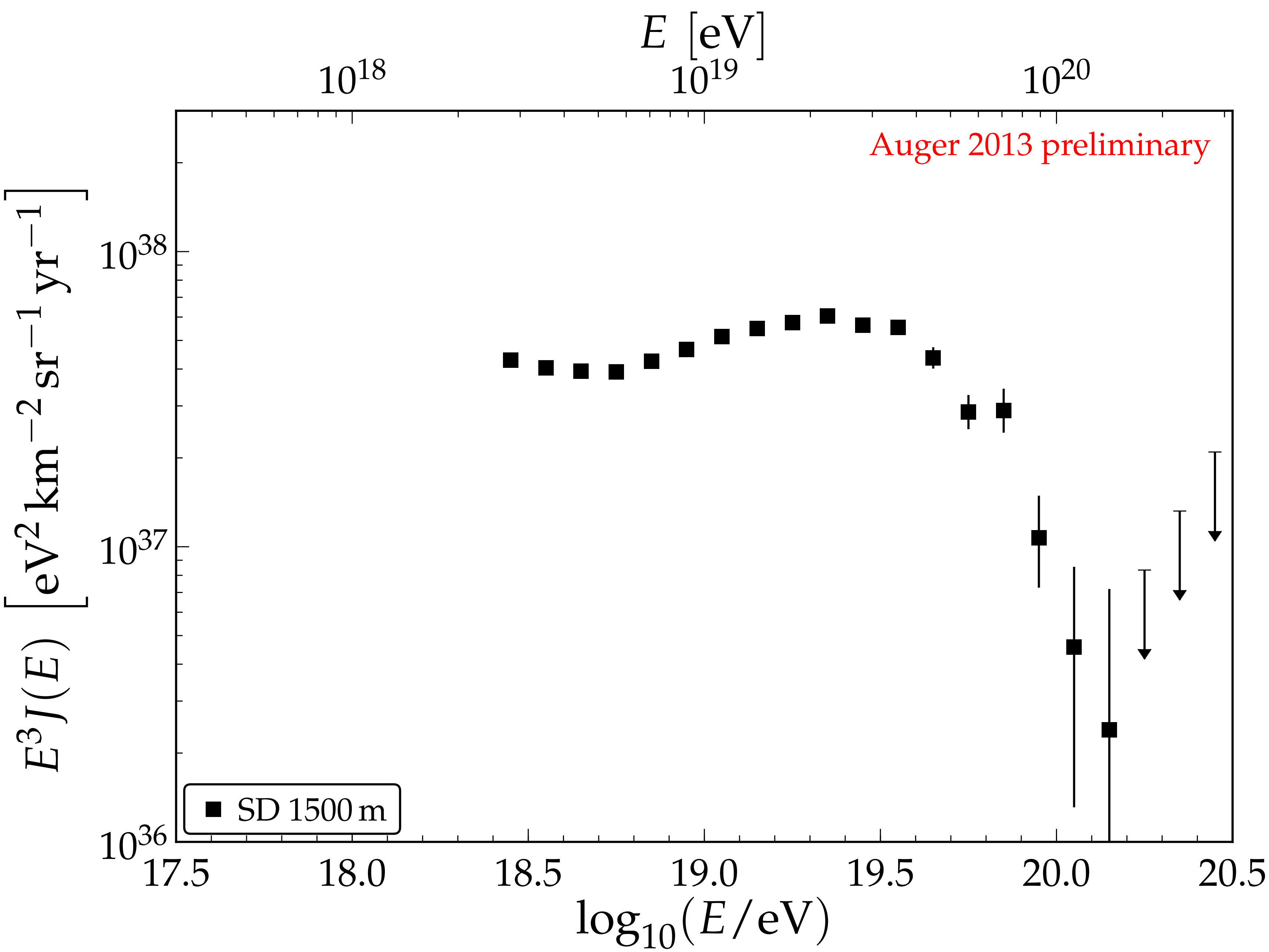
Energy Spectra

Forward-folding: correction for bin-to-bin migrations due to the detector resolution and steepness of spectrum, 17% (5%) at 3 EeV (10 EeV).

SD vertical spectrum: 82318 events above 3 EeV



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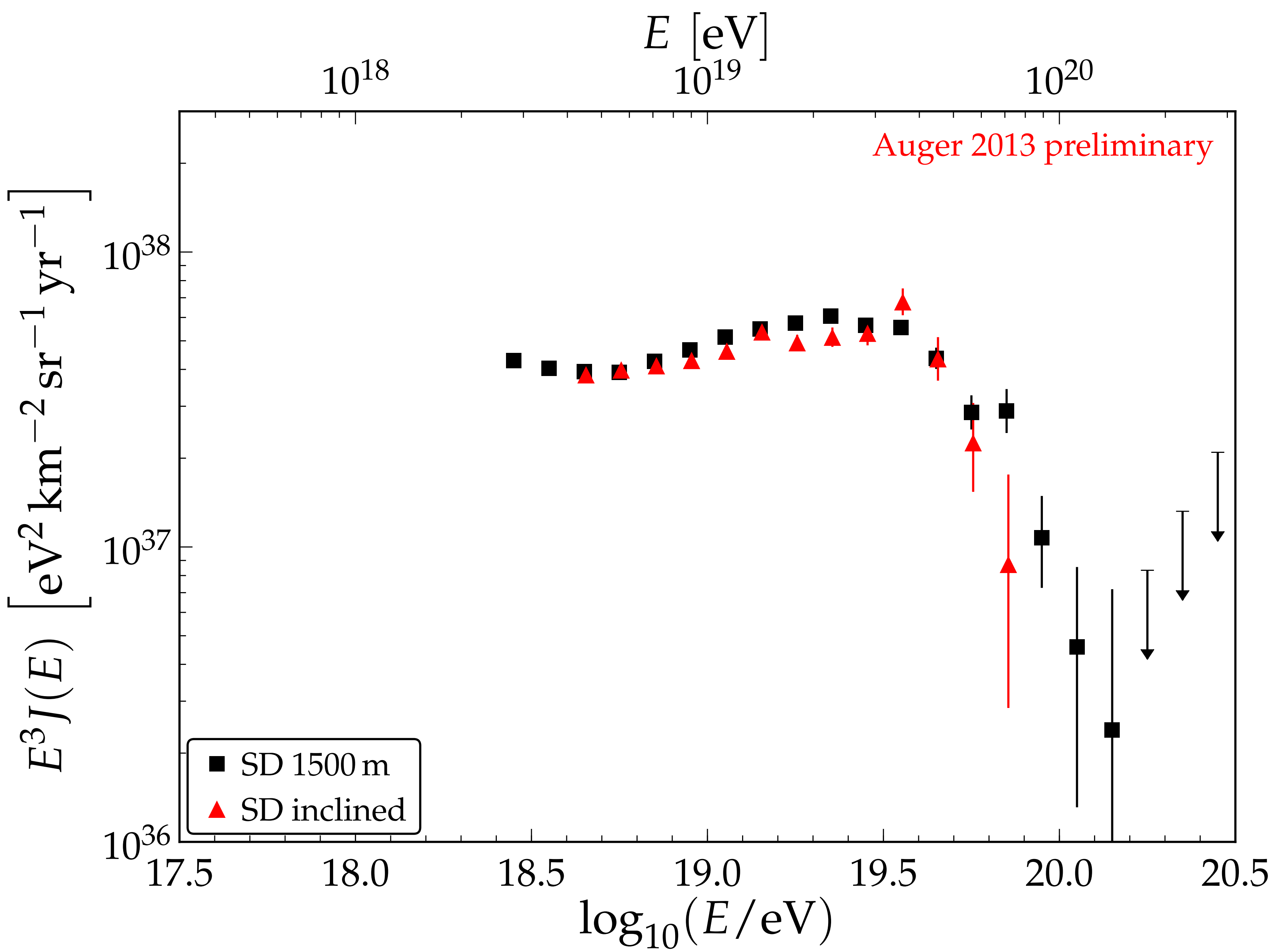
Energy Spectra

Forward-folding: correction for bin-to-bin migrations due to the detector resolution and steepness of spectrum, 12% (5%) at 4 EeV (10 EeV).

SD inclined spectrum: 11074 events above 4 EeV



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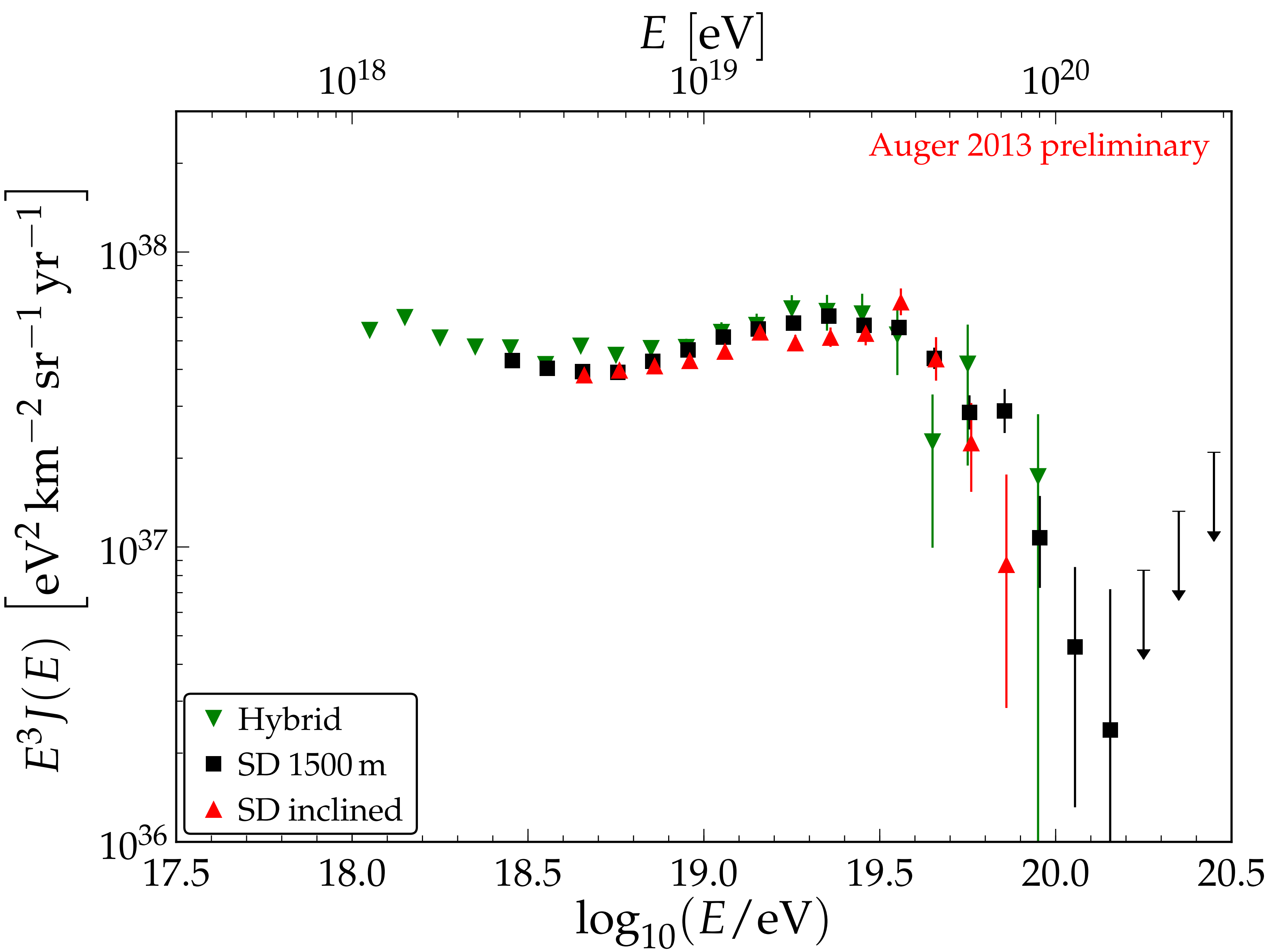
Energy Spectra

Forward-folding: correction for bin-to-bin migrations due to the detector resolution and steepness of spectrum, < 3%

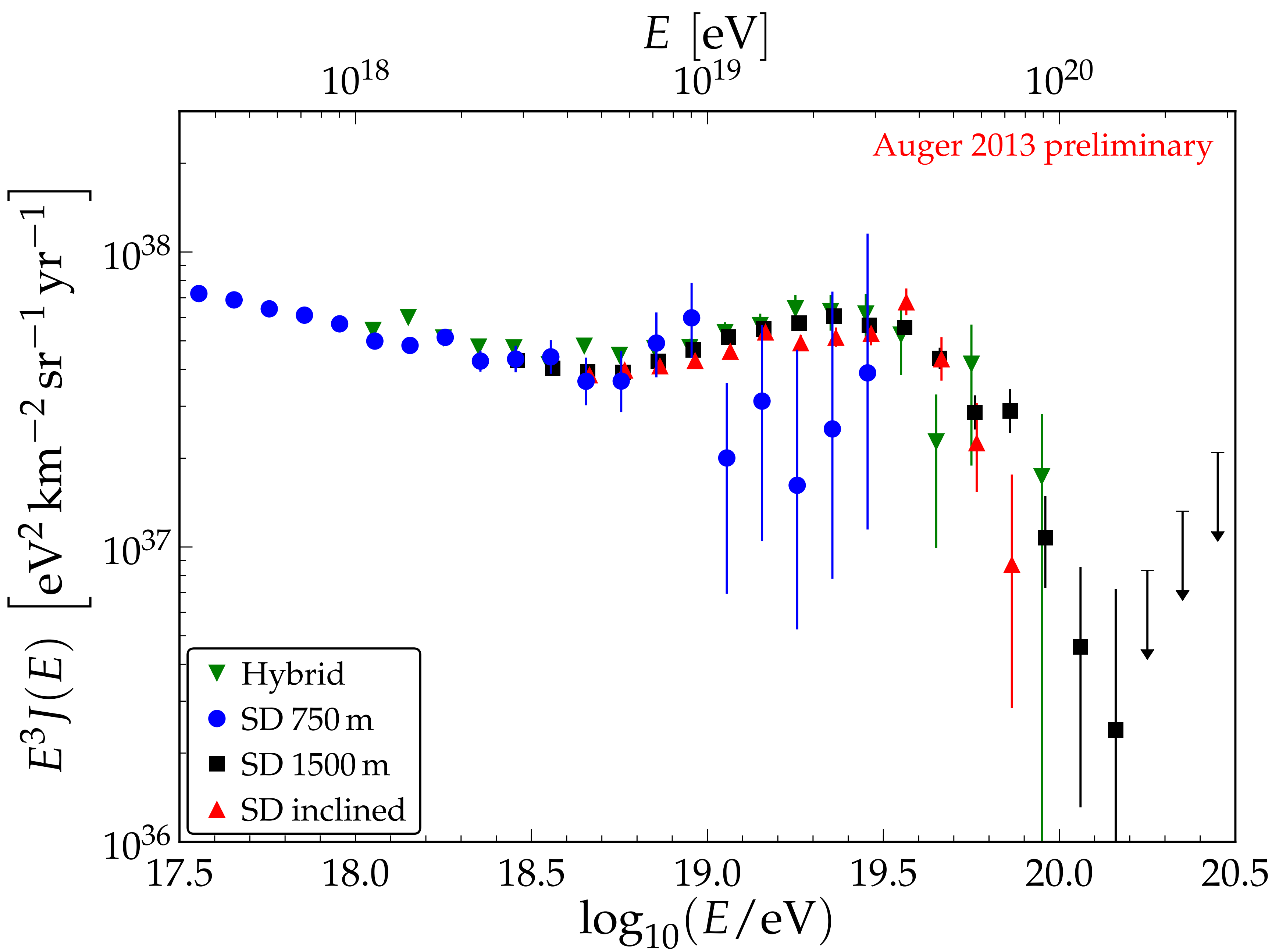
FD hybrid spectrum: 11155 events above 1 EeV



Energy Spectra

Forward-folding: correction for bin-to-bin migrations due to the detector resolution and steepness of spectrum, 10% (5%) at 0.3 EeV (3 EeV).

SD 750 m spectrum: 29585 events above 4 EeV



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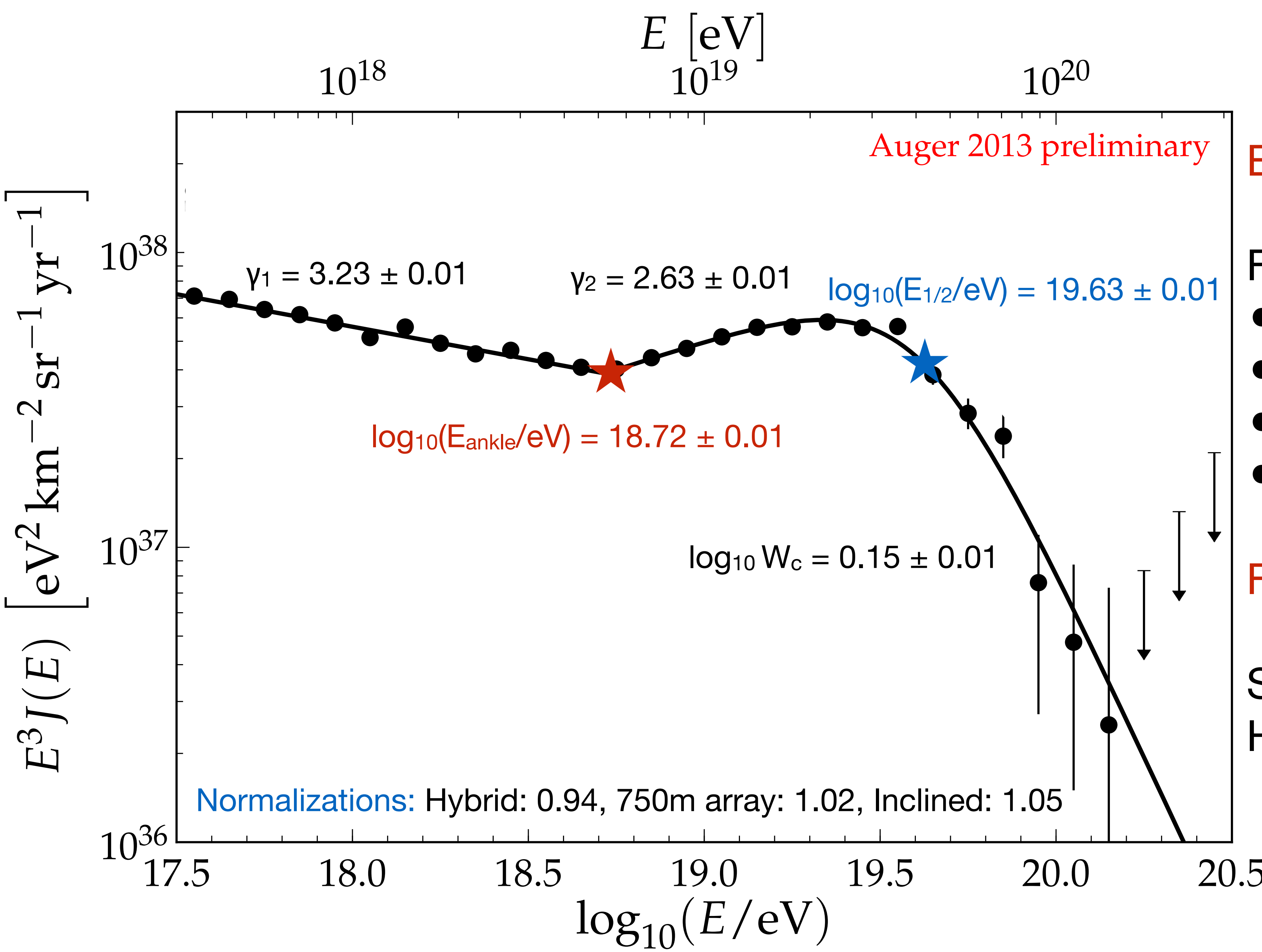
Combined Energy Spectrum

Combined maximum-likelihood fit, the normalisations of the different spectra are allowed to vary within the corresponding uncertainties

Fit function ➡ $J(E; E > E_a) \propto E^{-\gamma_2} \left[1 + \exp\left(\frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1}$



Energy systematic uncertainties

FD energy scale: 14%

- Absolute calibration: 9%
- Fluorescence yield: 4%
- Shower reconstruction: 6%
- Atmospheric conditions: 3-6%

Flux systematic uncertainties

SD vertical: 6%

Hybrid: 10% (6%) 1 EeV (10 EeV)

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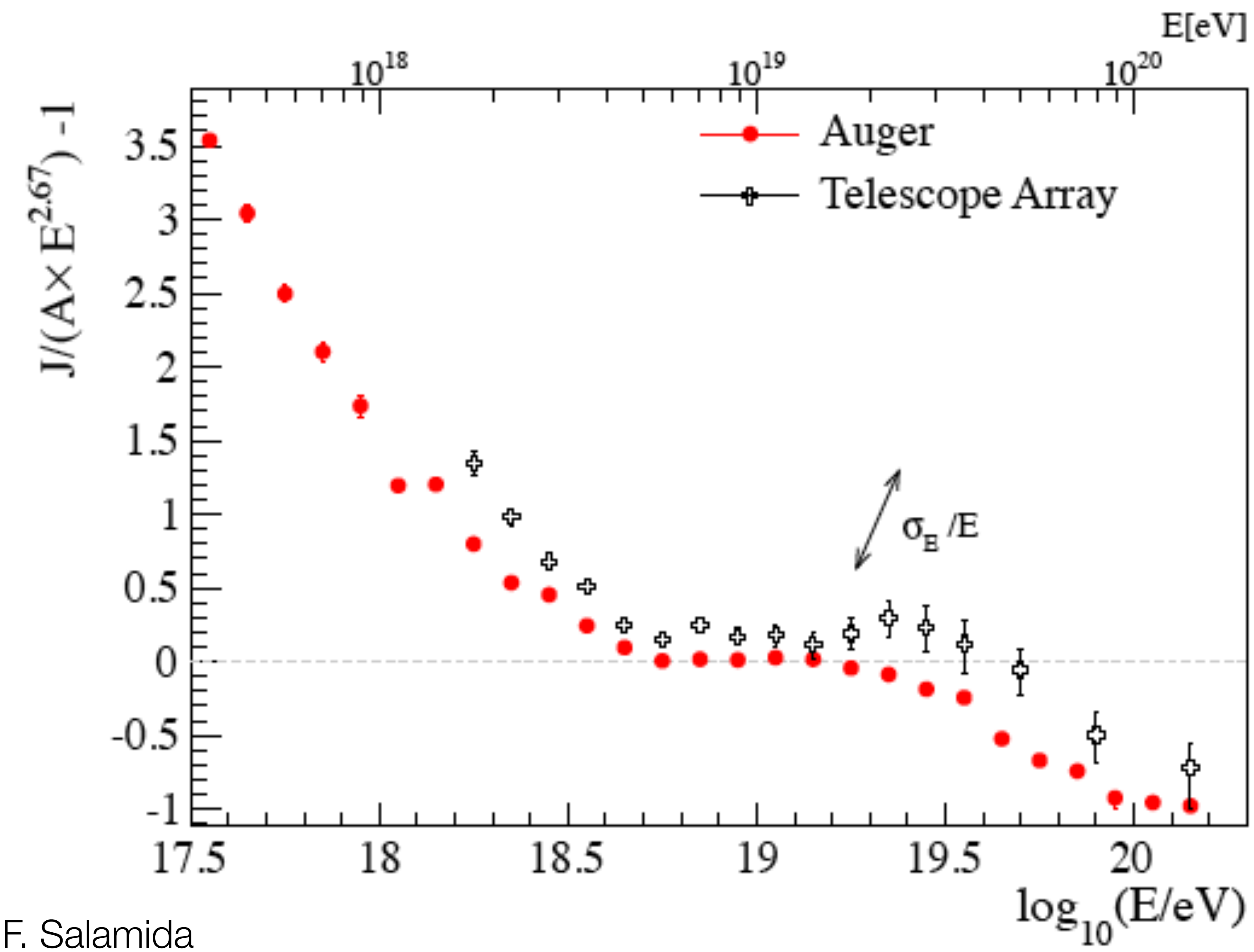
Auger/TA comparison

	Auger	Telescope Array
Location	Southern hemisphere	Northern hemisphere
Area [km	~ 3000	~ 700
Events per year above 10	~ 56000	~ 3500
Energy scale uncertainty	14%	20%
Detector type	Water Cerenkov	Plastic scintillator



Spectral features

Auger	Telescope Array
$\gamma_1 = 3.23 \pm 0.01$	$\gamma_1 = 3.28 \pm 0.03$
$\log_{10}(E_{ankle}/eV) = 18.72 \pm 0.01$	$\log_{10}(E_{ankle}/eV) = 18.7 \pm 0.02$
$\gamma_2 = 2.63 \pm 0.01$	$\gamma_2 = 2.68 \pm 0.03$
$\log_{10}(E_{1/2}/eV) = 19.63 \pm 0.01$	$\log_{10}(E_{1/2}/eV) = 19.74 \pm 0.08$

The results are compatible within the energy scale uncertainties

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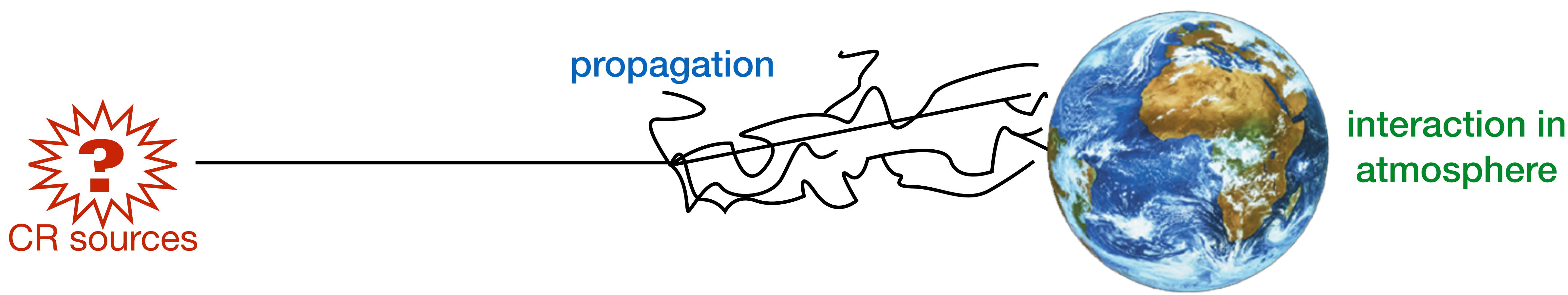
CR propagation

Propagation through the astrophysical background gives the link between measurements and the possible scenarios

- CRs above 10^{18} eV are probably extragalactic
- Not enough energy in the Galaxy (SNRs) to accelerate light elements (TA +Auger mass composition results) Aloisio, Berezinsky, Blasi arXiv:1312.7459



- Photon background:
  - ✓*CMB* - Cosmic Microwave Background
  - ✓*EBL* - Extragalactic Background Light (mainly IR)
- Cosmological distances of sources:
  - ✓*adiabatic energy losses* (i.e cooling of Universe due to expansion)
  - ✓*cosmological evolution* of sources
- Interaction in atmosphere
  - ✓hadronic interaction models
  - ✓extrapolation from *LHC data*

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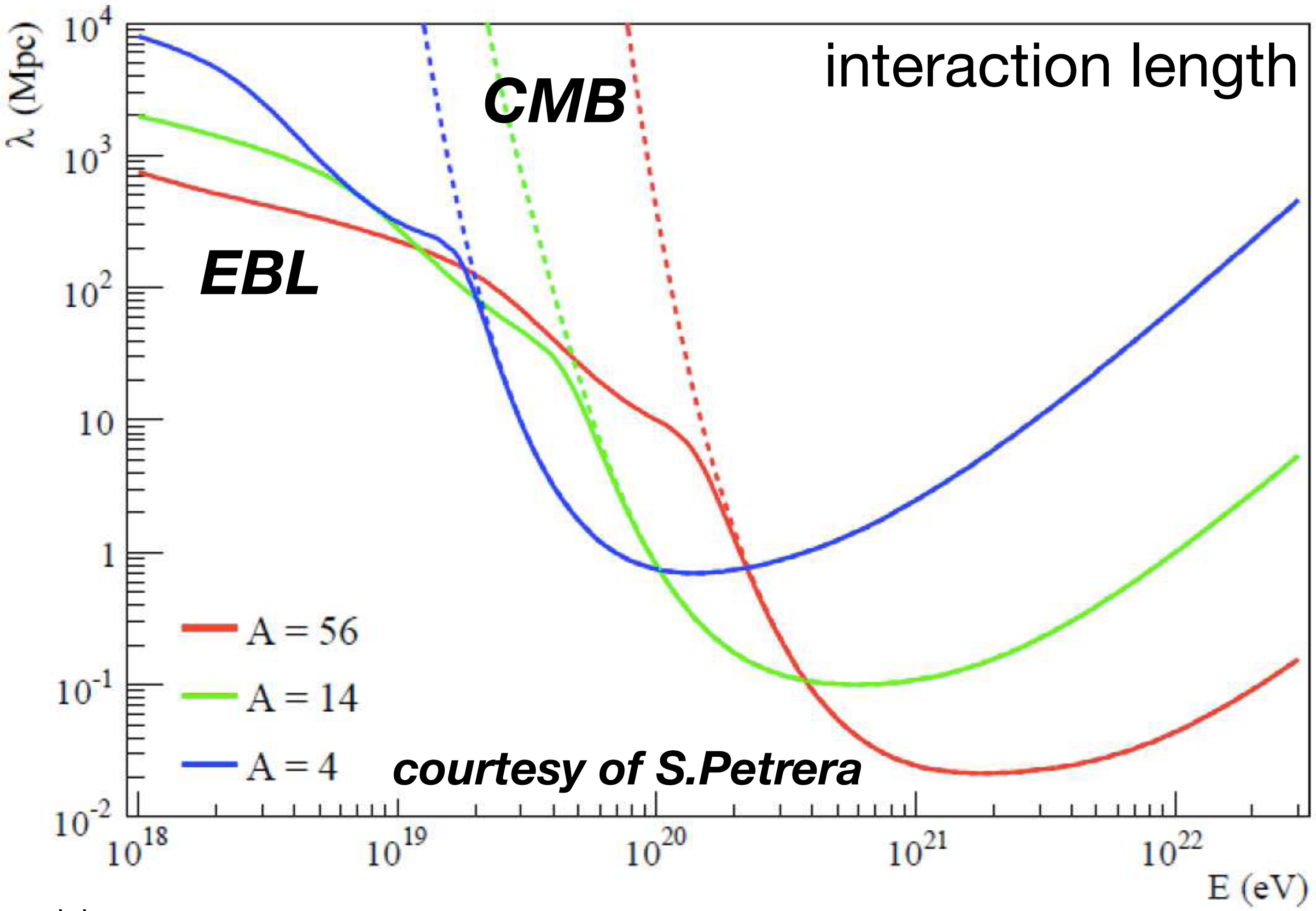
CR propagation

- protons:
  1. pair production $p + \gamma_{CMB} \rightarrow p + e^+ + e^-$ ankle interpreted as "dip": Berezinsky
  2. pion production $p + \gamma_{CMB} \rightarrow p + \pi^0, \quad p + \gamma_{CMB} \rightarrow n + \pi^+$ above 5×10^{19} eV GZK cut-off
- nuclei:
  3. photo-disintegration

$$(A, Z) + \gamma_{CMB,EBL} \rightarrow (A - i, Z) + i \cdot n$$
$$(A, Z) + \gamma_{CMB,EBL} \rightarrow (A - i, Z - i) + i \cdot p$$

dominated by the *Giant Dipole Resonance*



EBL (IR) includes the *cosmological evolution* of sources

adiabatic energy loss

$$\left(\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right)^{ad} = -H(z)$$

$$H(z) = H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$$

WMAP data

Processes are known with sufficient accuracy

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CR propagation

In Auger we use two different public codes to test the different scenarios:

- CRPropa *(Alves Batista et al.)* arXiv:1307.2643
- SimProp *(Aloisio et al.)* arXiv:1204.2970

For a given scenario

- distribution of sources
- primary composition
- maximum energy
- injection spectrum

⇨ Spectrum and composition at Earth

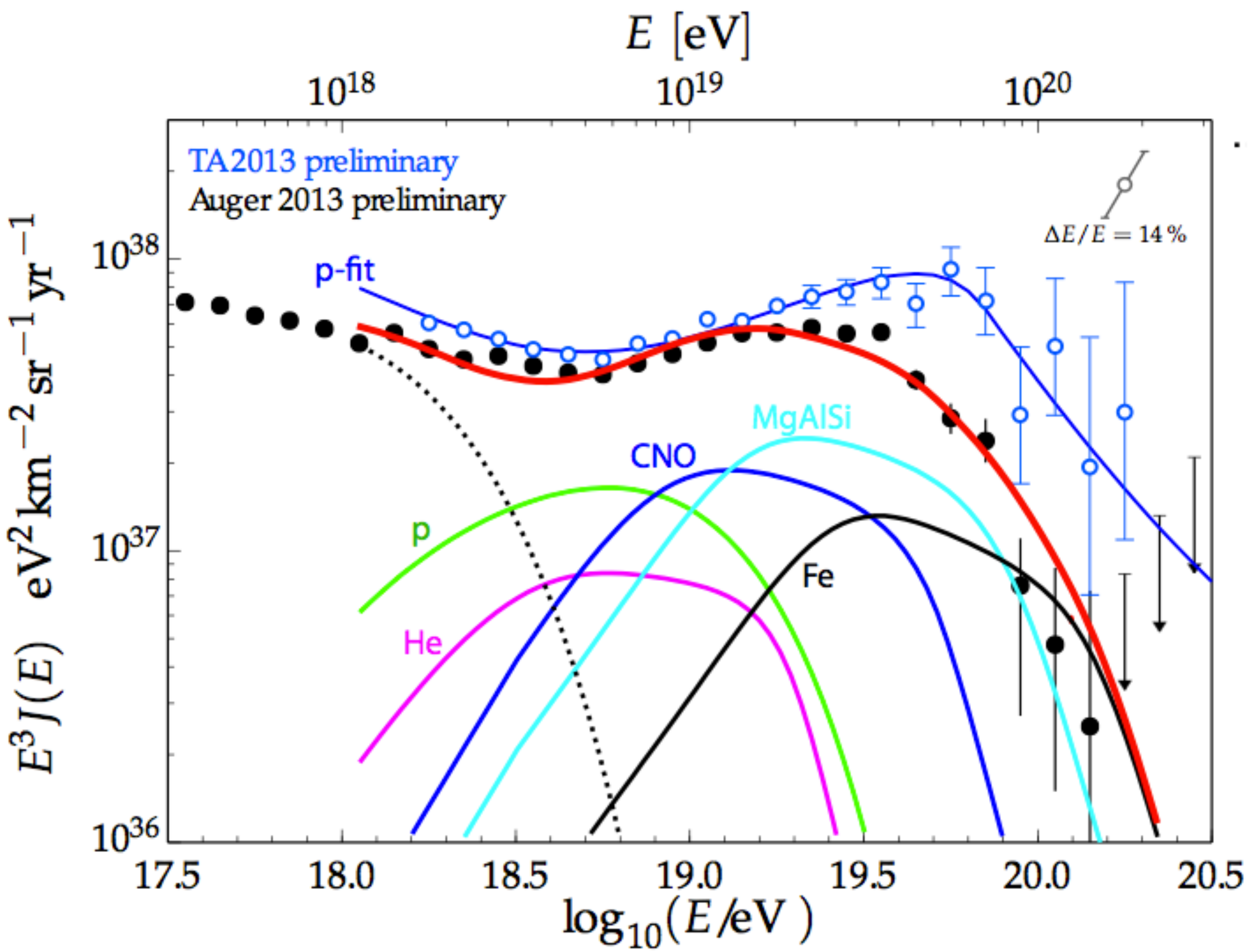
The major scenarios we can test are:

- proton dominated
- mixed composition

Proton-dominated

- source distribution ~ $(1+z)^{4.4}$
- proton primaries at source
- spectral index at injection $\gamma = 2.4$

- Ankle from pair production
- GZK form pion production
- protons at Earth



Experimental facts

- TA data well described by this scenario
- incompatible with Auger mass composition
- need of anisotropy (not evident in TA/Auger)

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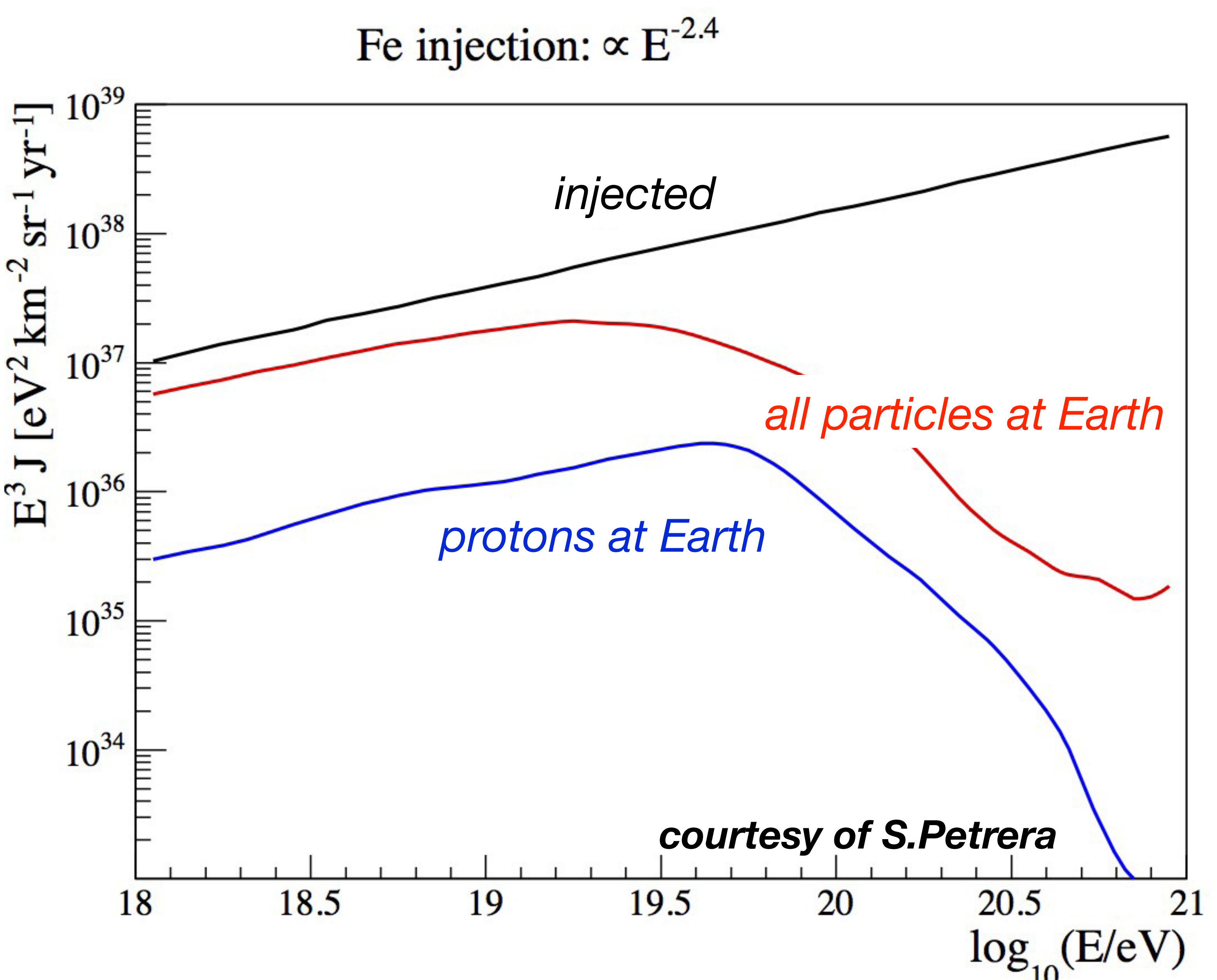
Mixed-composition

- CRs sources accelerate nuclei
- the most relevant process is the photo-disintegration
- during propagation both mass and energy decrease
- secondary flux of protons $E_{max}(p) = E_{max}(Fe)/26$ eV



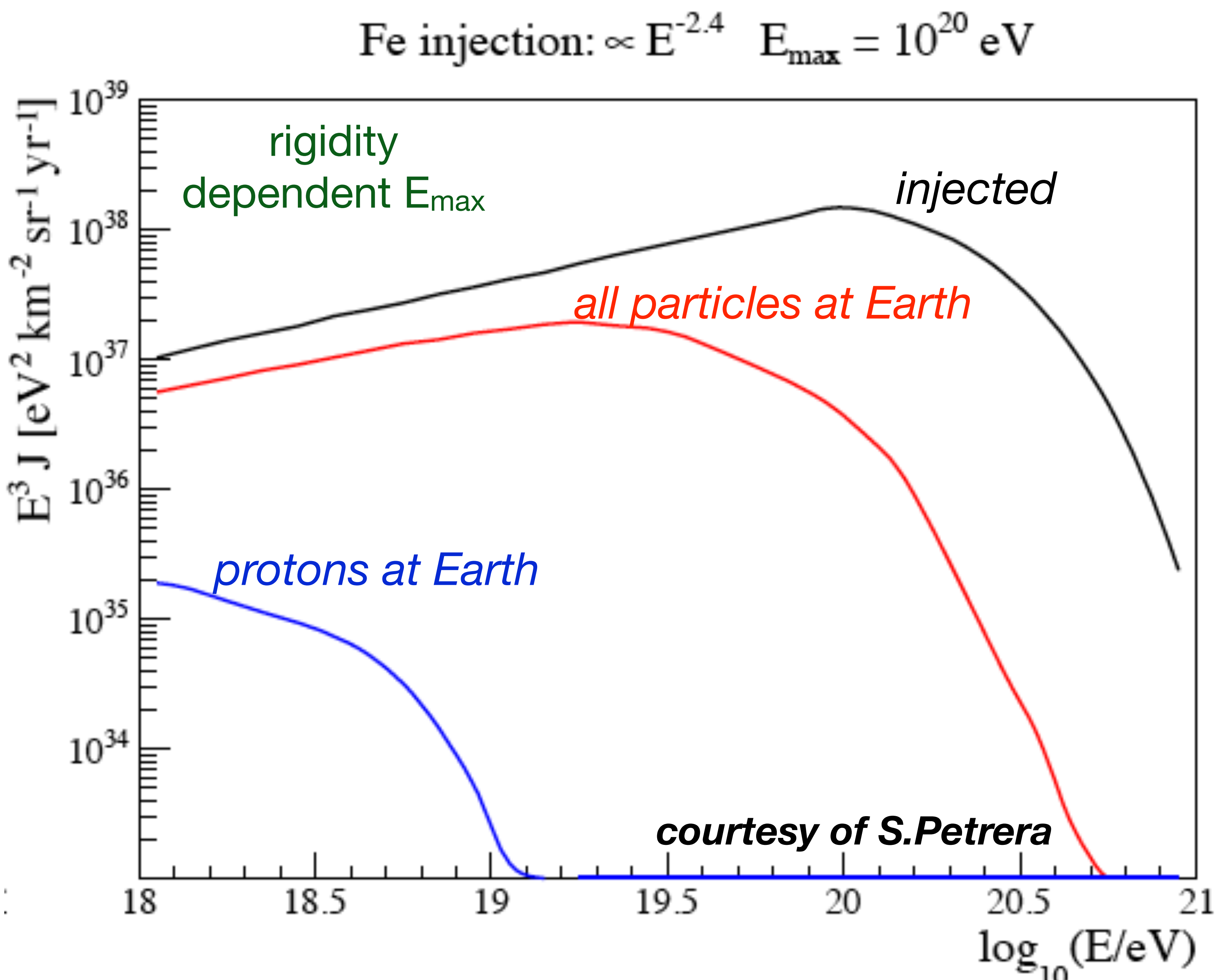
Depending on the model parameters can be produced a cut-off at highest energies similar to the GZK

Cut-off directly related to the propagation

Protons at the highest energies

Mixed-composition

- CRs sources accelerate nuclei
- the most relevant process is the photo-disintegration
- during propagation both mass and energy decrease
- secondary flux of protons $E_{max}(p) = E_{max}(Fe)/26$ eV



Depending on the model parameters can be produced a cut-off at highest energies similar to the GZK

Cut-off related to the maximum energy of the sources

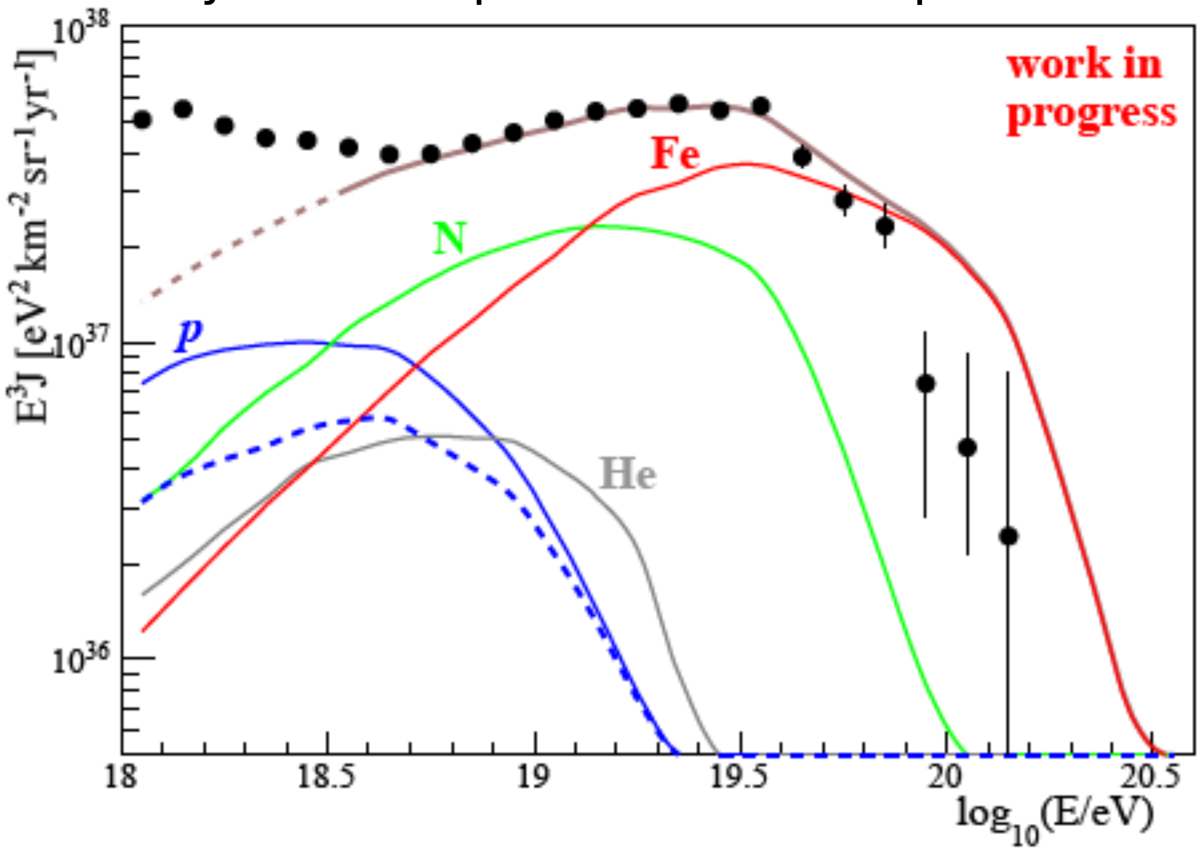
NO protons at the highest energies

Mixed-composition

Allard type (gal. like composition)

$E_{max}(Fe) = 10^{20.1}$ eV

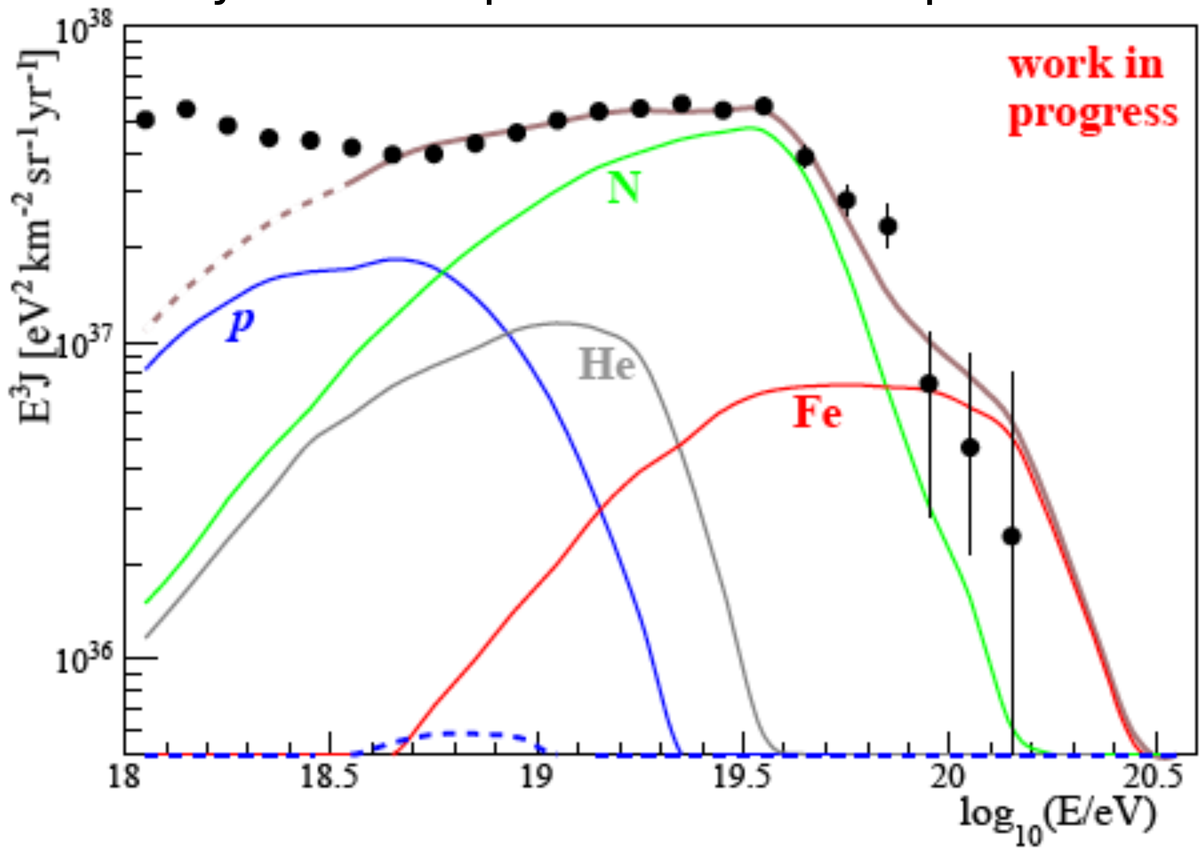
injection spectral index $\gamma = 1.7$



Hooper-Taylor type

$E_{max}(Fe) = 10^{20.2}$ eV

injection spectral index $\gamma = 1.15$



- Good agreement with Auger spectrum
- Good agreement with Auger mass composition
- the highest energy cut-off determined by the CRs sources maximum energy
- Another component is necessary to explain the ankle at $10^{18.7}$ eV

Mixed-composition

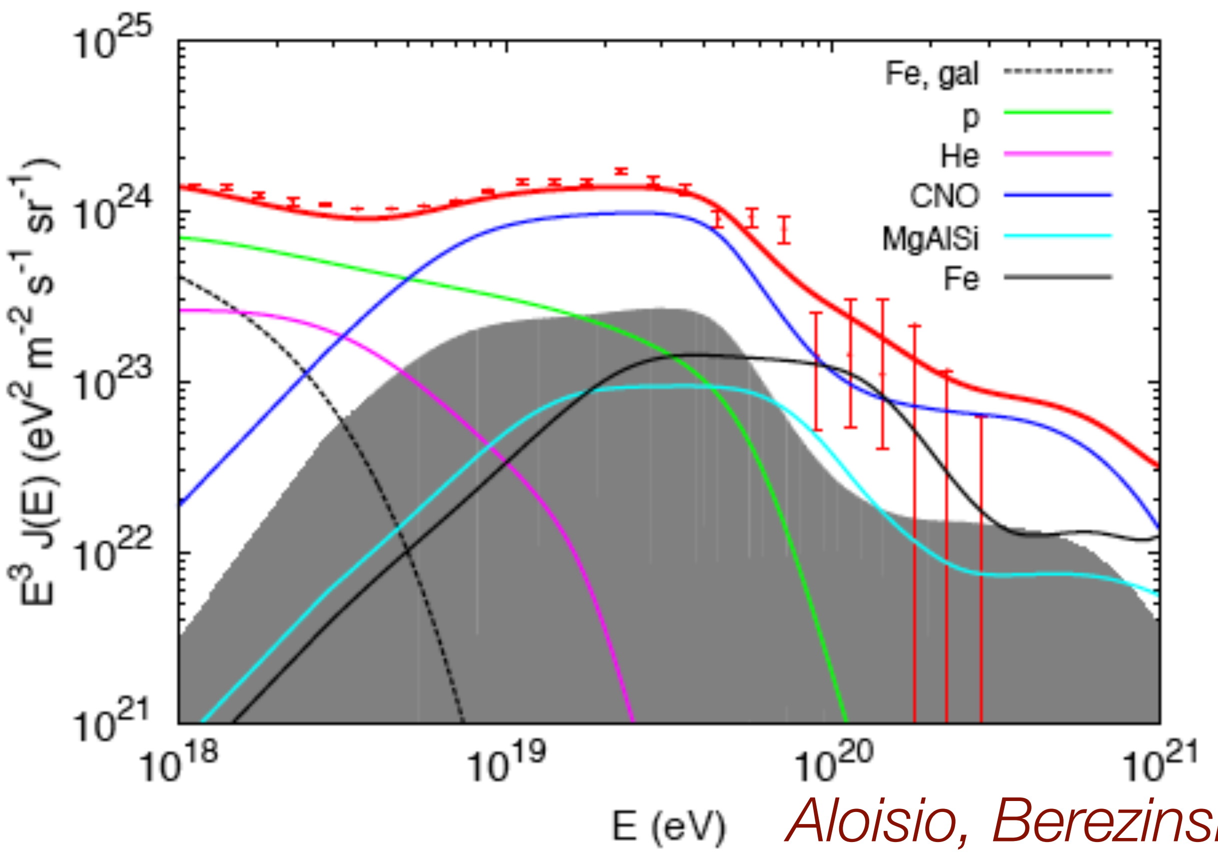
Above $5 \cdot 10^{18}$ eV

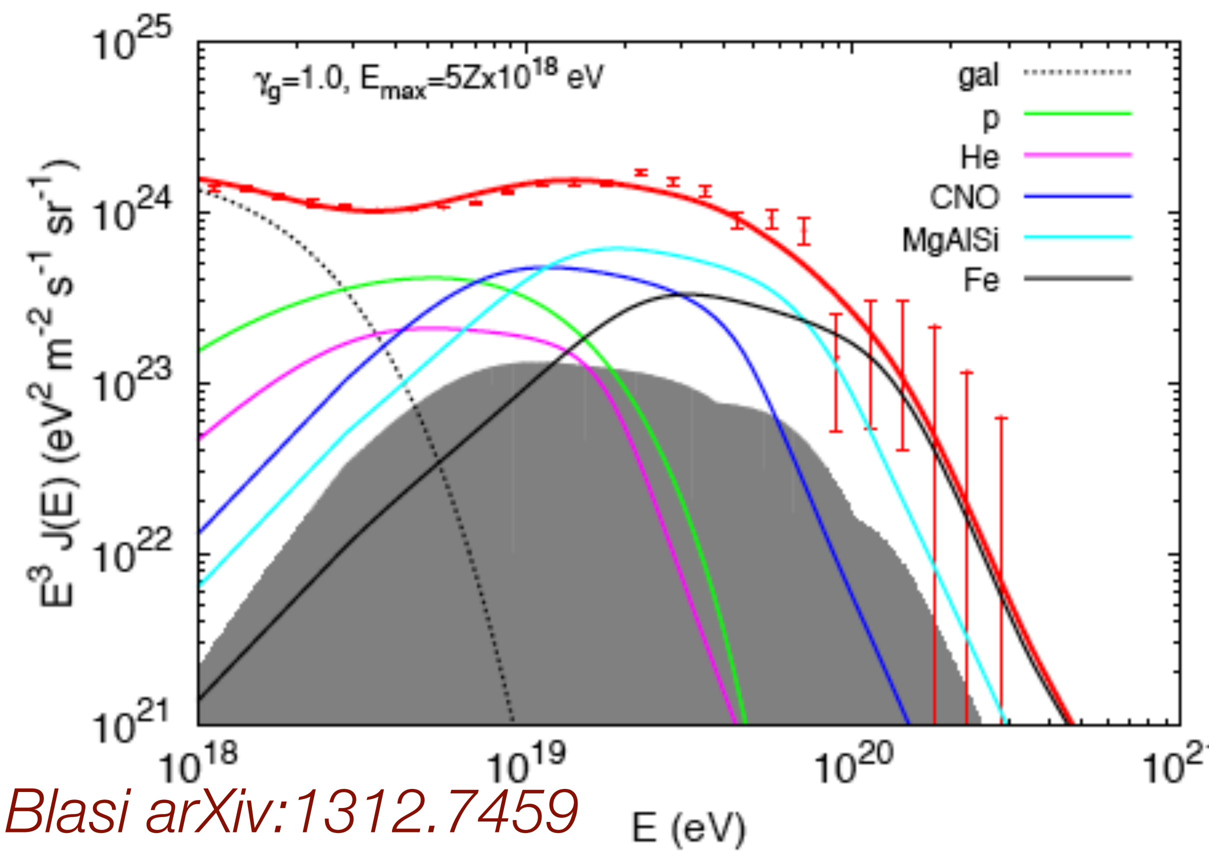
- injection spectral index $\gamma \leq 1.5$-1.6
- suggests acceleration in the magnetosphere of rotating neutron stars
- composition related to the metal enriched surface of neutron stars

Below $5 \cdot 10^{18}$ eV

- Additional class of extragalactic sources (proton + helium with $\gamma = 2.7$)
- Fe galactic CRs
- unappealing scenario

- Galactic CRs above 10^{18} eV
- Fe disfavoured by mass composition res.
- p/He difficult to be accelerated by SN at 10^{18} eV





Aloisio, Berezinsky, Blasi arXiv:1312.7459

Conclusions

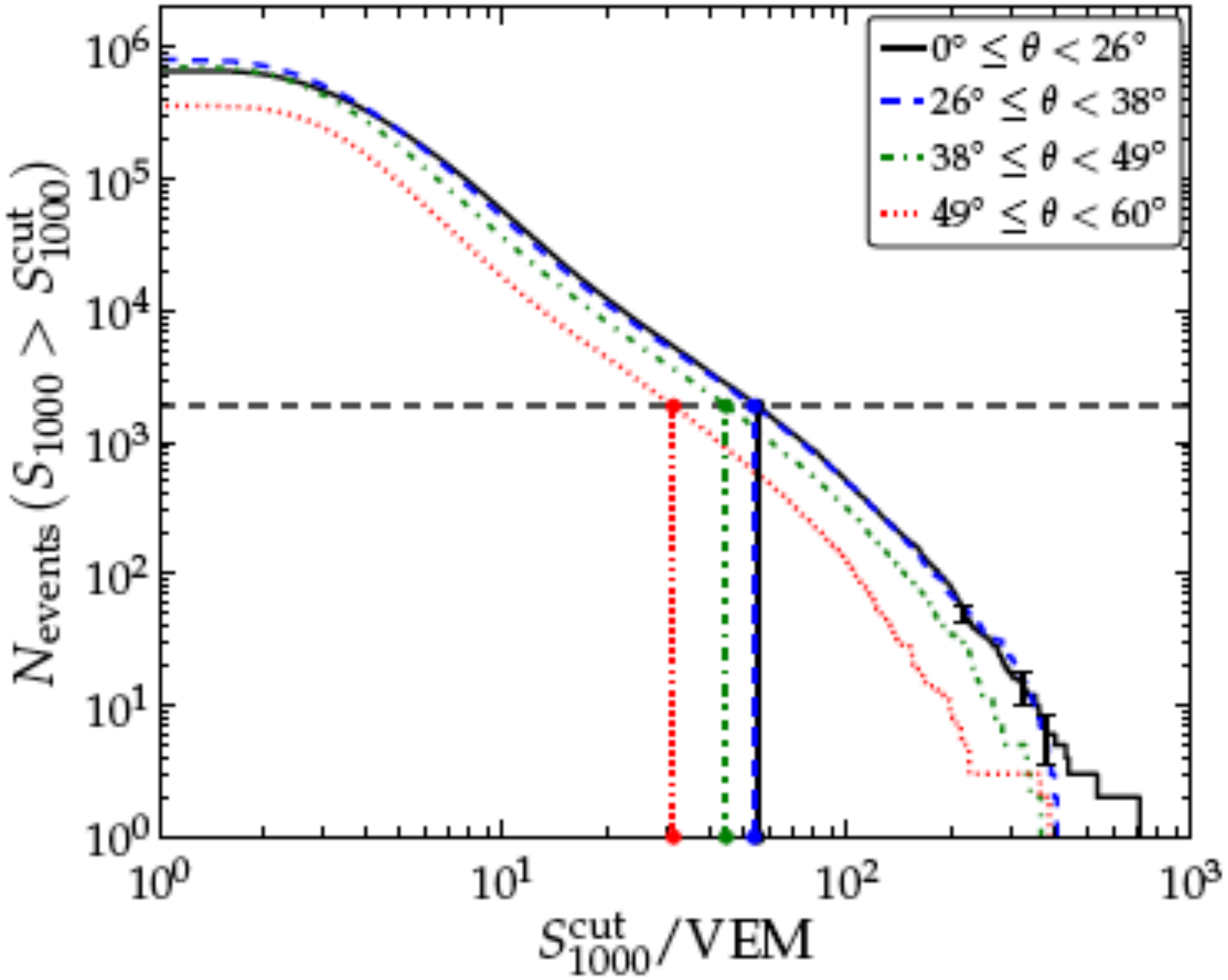
- Pierre Auger combined Spectrum has been presented
- The ankle at $10^{18.7}$ eV and the cut-off at the highest energies measured
- Interpretation needs to simultaneously use the information from spectrum, mass composition and anisotropy
- The maximum energy of sources is good candidate to explain the highest energies cut-off, but …

… open points

- spectral index
- maximum energy
- anisotropy
- sub-dominant proton component the highest energies
- nature of CR below the ankle, Gal./extra-Gal. transition

Backup Slides

Vertical SD events - Constant Intensity Cut



Attenuation in atmosphere

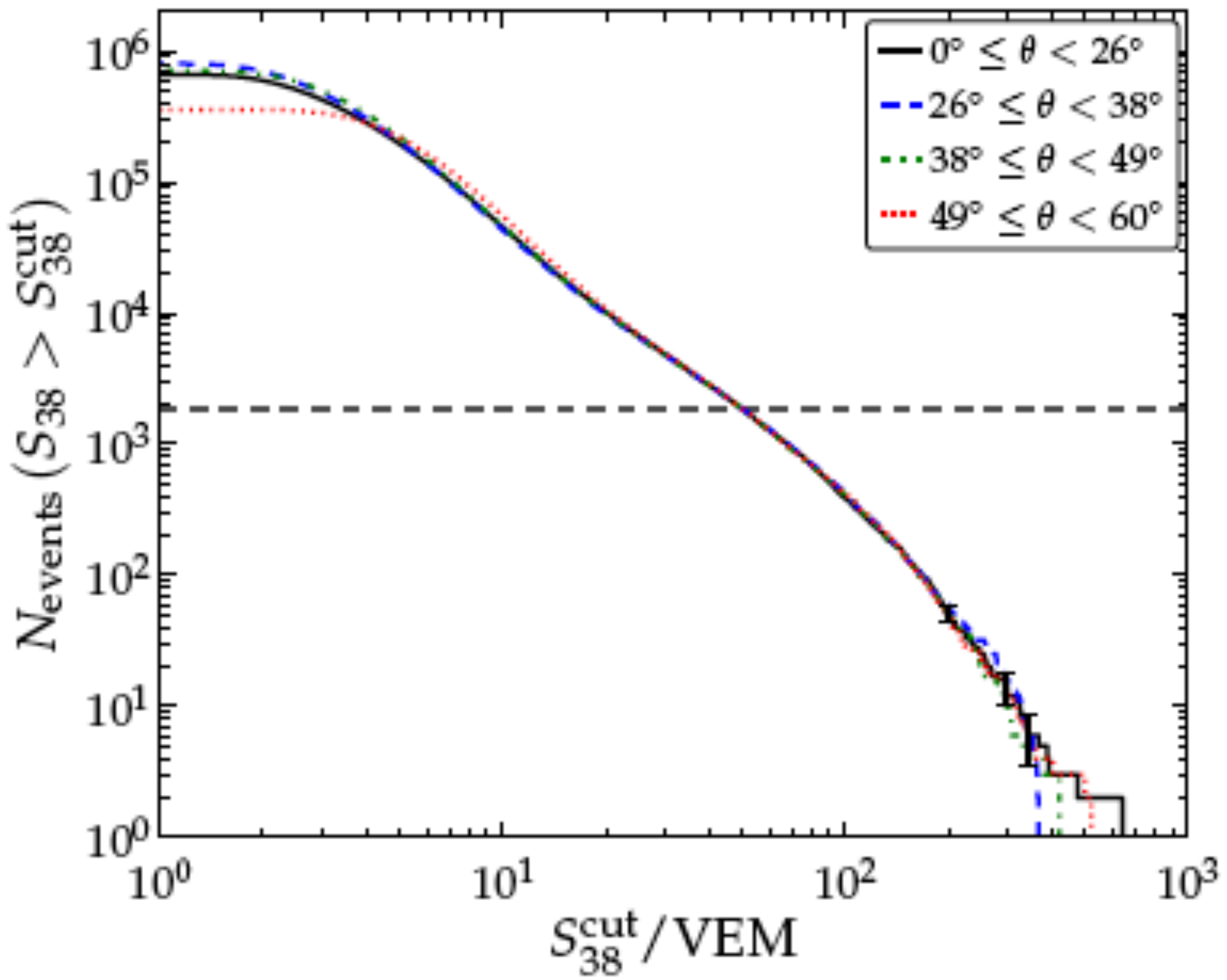
⇒ zenith angle dependent

energy estimator $S(1000)$

Exploit CIC hypothesis

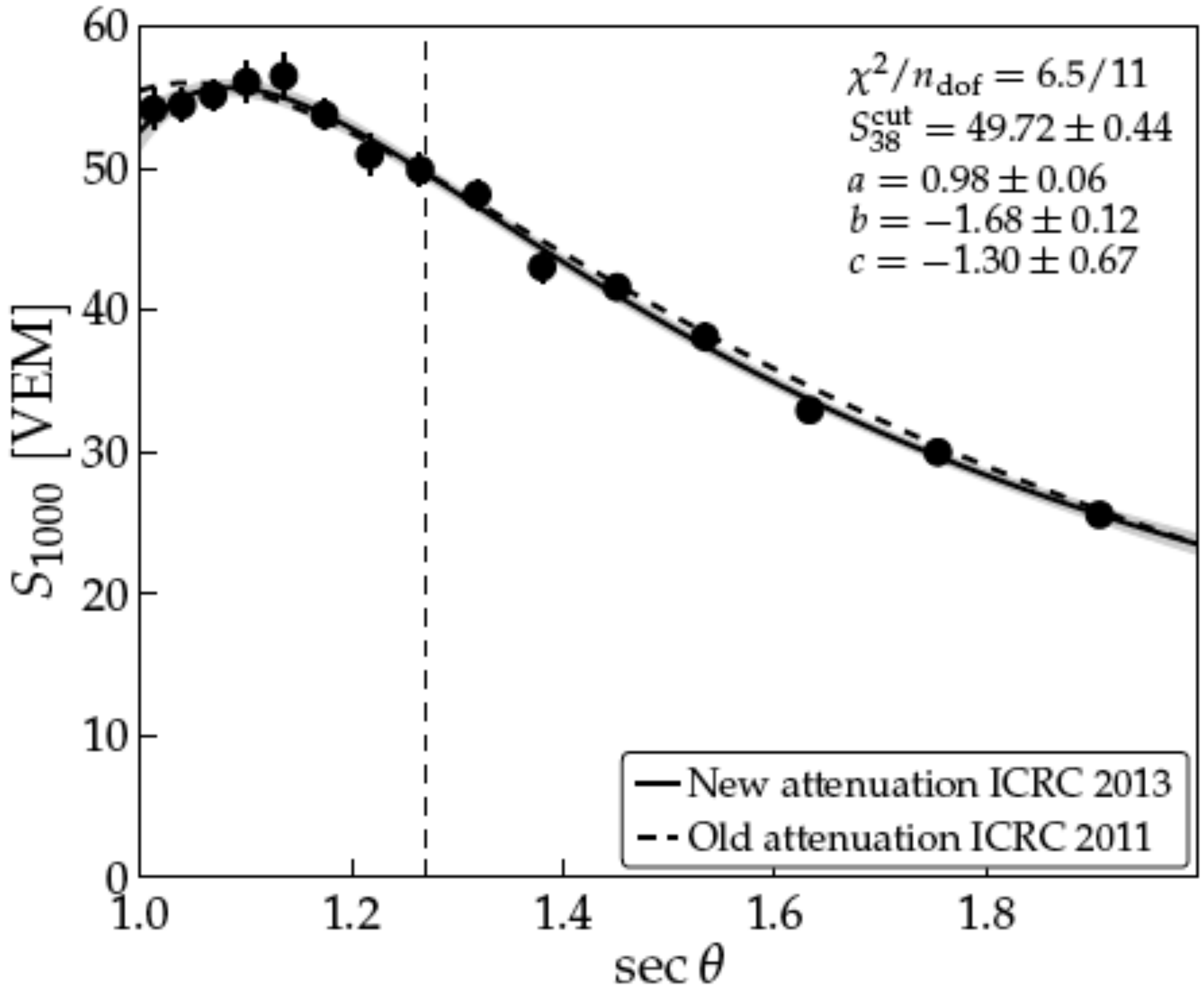
⇒ Correction completely determined from data,

No energy dependence above $\approx 20\,\mathrm{VEM} \approx 6\,\mathrm{EeV}$



$S(1000)$ attenuation function

- Empirical correction with 3rd deg. polynomial
  $\mathrm{CIC}(\theta) = 1 + ax + bx^2 + cx^3 \;\; (x = \cos^2\theta - \cos^2 38°)$
- Zenith angle independent energy estimator $S_{38} = S(1000)/\mathrm{CIC}(\theta)$



- In case of SD 750 m array: $S(450) \Rightarrow S_{35}$. Separate attenuation function.

CR propagation in a nutshell

Photon background

- protons:
  - pair production $p + \gamma_{CMB} \rightarrow p + e^+ + e^-$ — ankle interpreted as "dip": Berezinsky
  - pion production $p + \gamma_{CMB} \rightarrow p + \pi^0, \quad p + \gamma_{CMB} \rightarrow n + \pi^+$ — above 5×10^{19} eV GZK cut-off
- nuclei:
  - photo disintegration

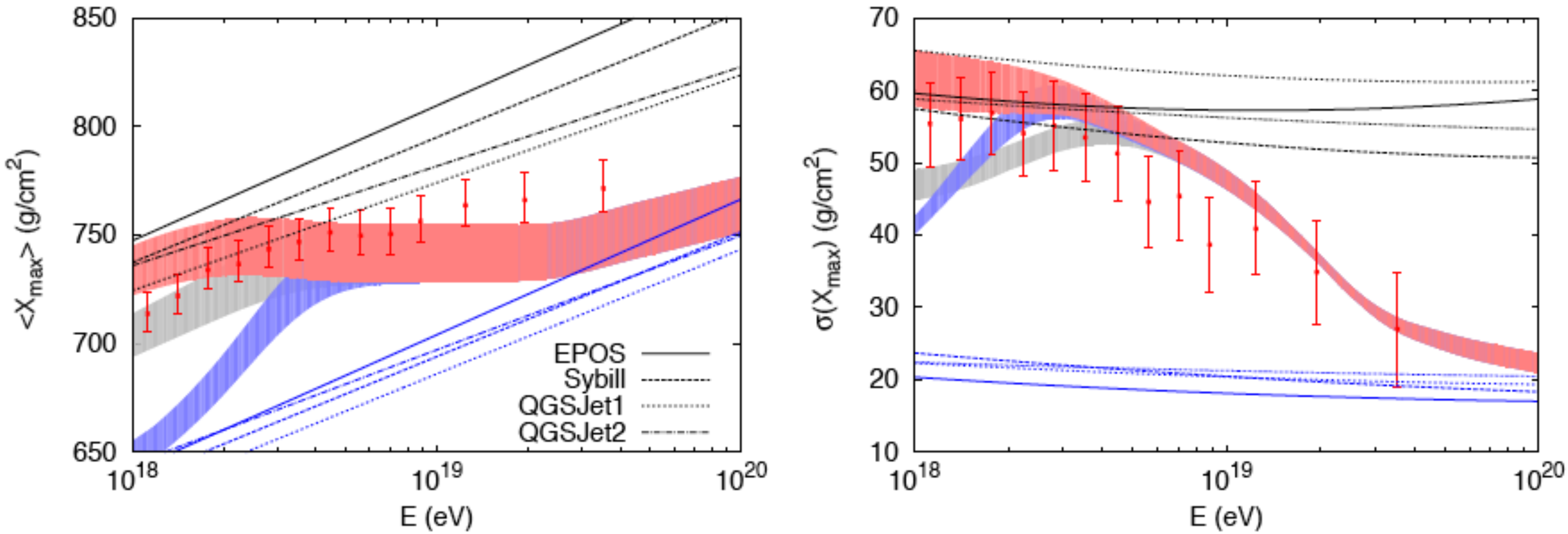
$$(A, Z) + \gamma_{CMB,EBL} \rightarrow (A-1, Z) + n$$
$$(A, Z) + \gamma_{CMB,EBL} \rightarrow (A-1, Z-1) + p$$

The CEL approximation consists in assuming that particles lose energy (i.e. change their Lorentz factor) continuously. In the propagation through astrophysical backgrounds the interactions of UHE particles are naturally affected by fluctuations, with a non-zero probability for a particle to travel without losing energy. In the CEL approximation such fluctuations are neglected.

The change in the Lorentz factor of the propagating particles is also linked to the cosmological evolution of the Universe. The expansion of the Universe causes an adiabatic energy loss to the propagating particles, that is (by definition) a continuous process common to protons and nuclei given by

$$\left(\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right)^{ad} = -H(z) \qquad (2.2)$$

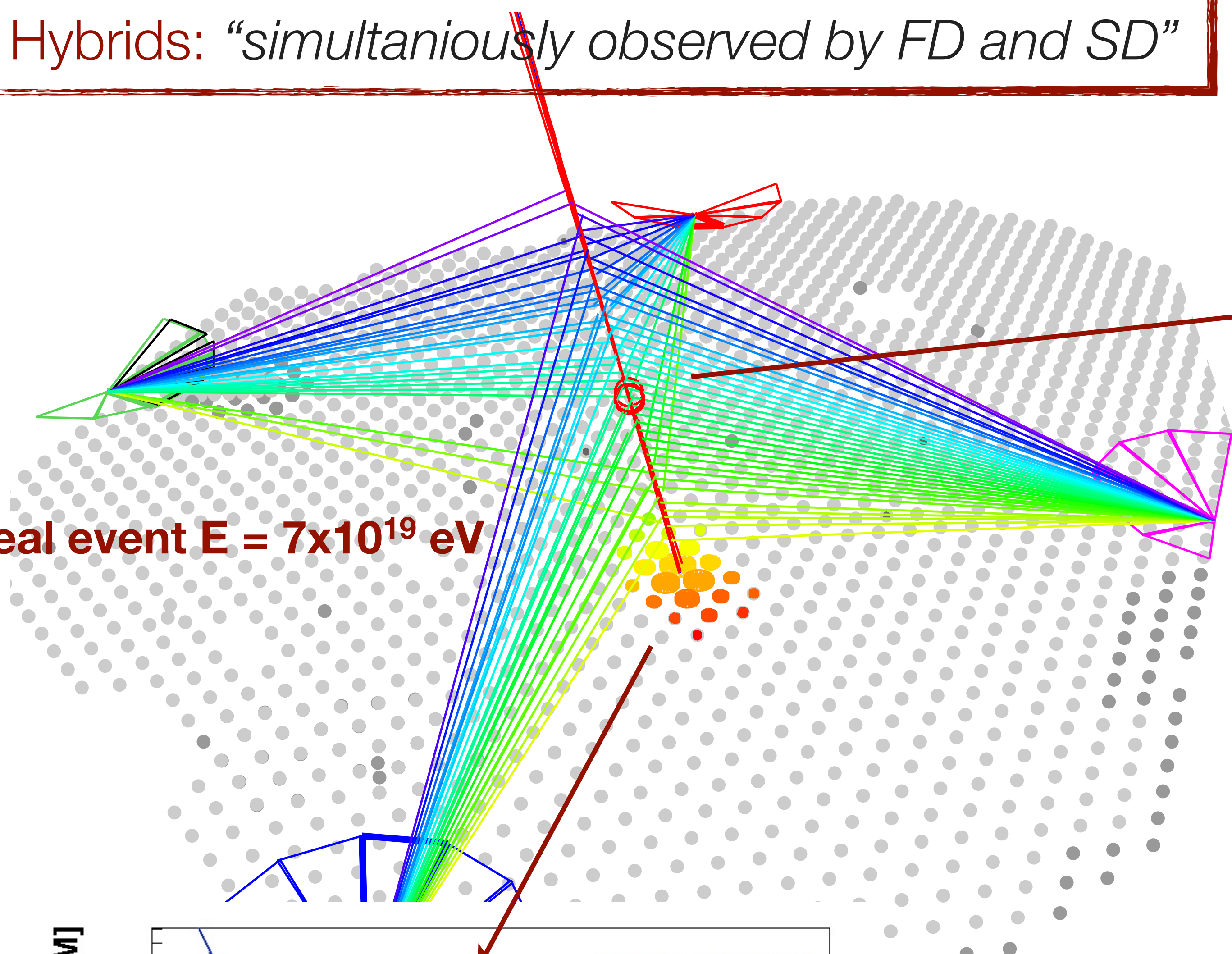
where $H(z) = H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$ is the Hubble parameter at redshift z in a standard cosmology with: $H_0 = 71$ km/s/Mpc, $\Omega_m = 0.24$ and $\Omega_\Lambda = 0.72$ according to WMAP data



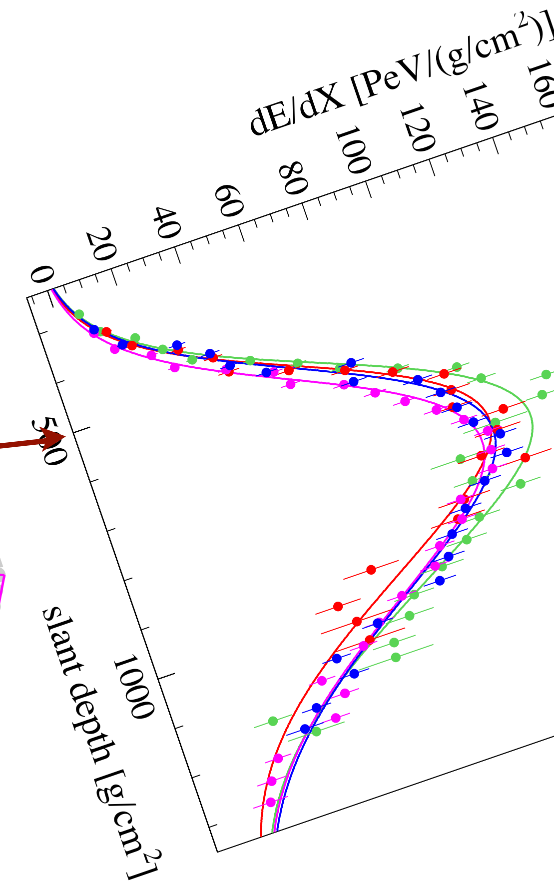
850
800
750
700
650
$<X_{max}>$ (g/cm^2)
10^{18}
10^{19}
10^{20}
E (eV)
EPOS
Sybill
QGSJet1
QGSJet2
70
60
50
40
30
20
10
$\sigma(X_{max})$ (g/cm^2)
10^{18}
10^{19}
10^{20}
E (eV)

Air shower reconstruction

Hybrids: *“simultaniously observed by FD and SD”*

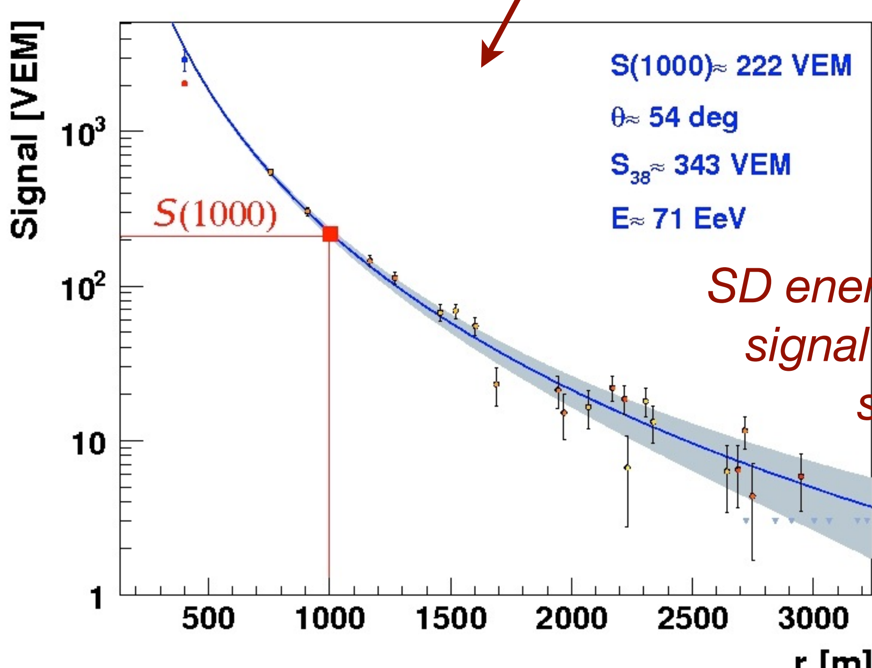


Real event E = 7x10^{19} eV



FD energy given by the integral of the longitudinal profile

The position of the shower maximum (Xmax) gives information on the primary mass



SD energy: proportional to signal at 1 km from the shower core

Why use hybrid events?

- Possible to separate iron-like events from proton-like using X_{max} (resolution < 40 g/cm^2)
- calorimetric measurement of the primary energy
- very good angular resolution < 1 deg
- calibration of the SD energy

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