News from the Pierre Auger Observatory

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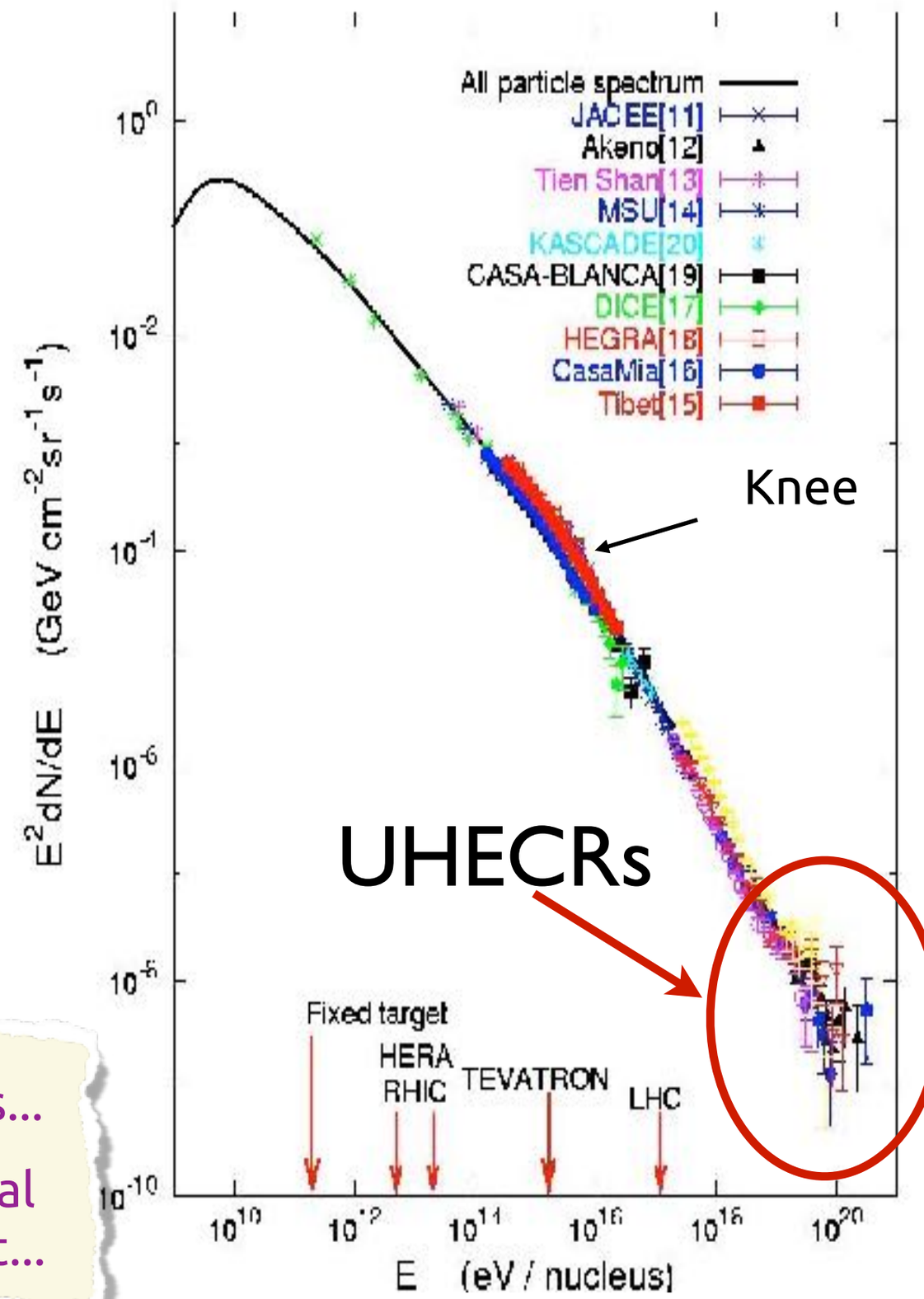
Ultra-High Energy Cosmic Rays

- Energies above 10^{18} eV or 10^{19} eV
- Center of mass energies larger than that of the LHC ☞ Particle Physics
- Low flux: 1 per 100 - 1000 km^2 per year
- Acceleration mechanism not known
- Sources not known

Have hints...

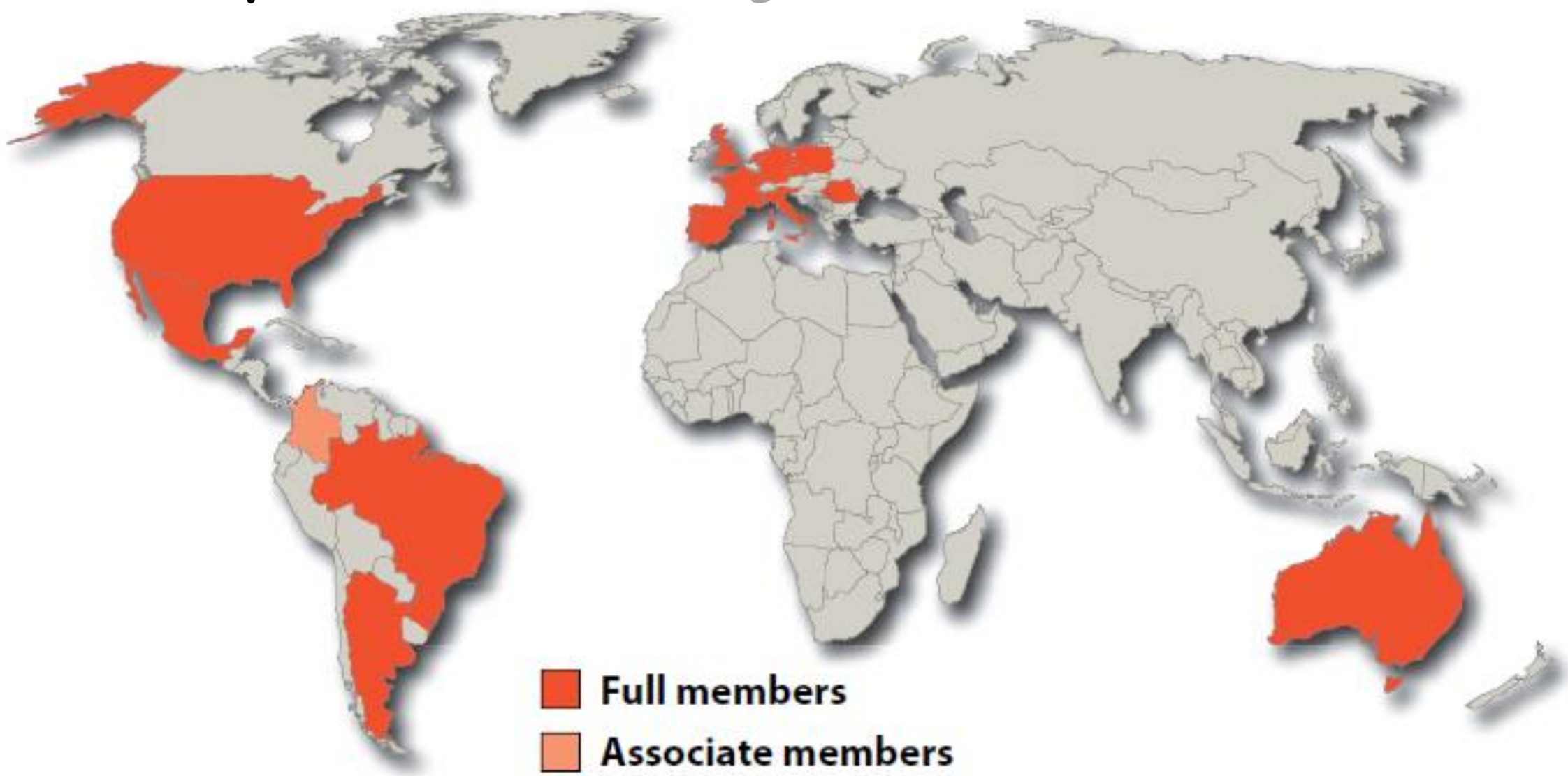
Theoretical ideas exist...



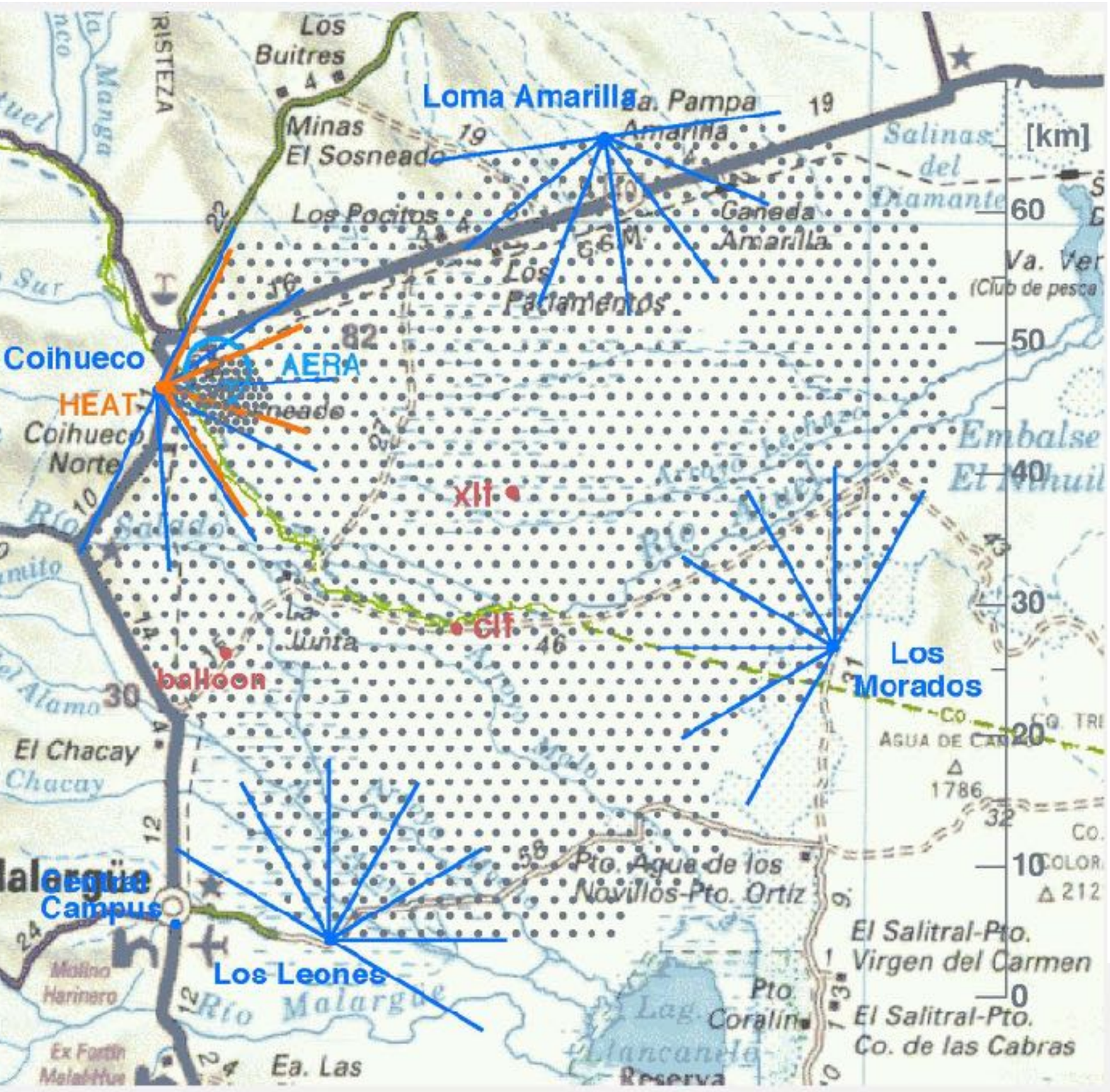
The Pierre Auger Collaboration

17 countries , ≈460 collaborators

Argentina – Australia – Bolivia – Brazil – Colombia – Czech Republic – France – Germany – Italy – Mexico – Netherlands – Poland – Portugal – Romania – Slovenia – Spain – ~~United Kingdom~~ – United States



The Auger Site



1660 surface detector stations, 1.5 km spacing

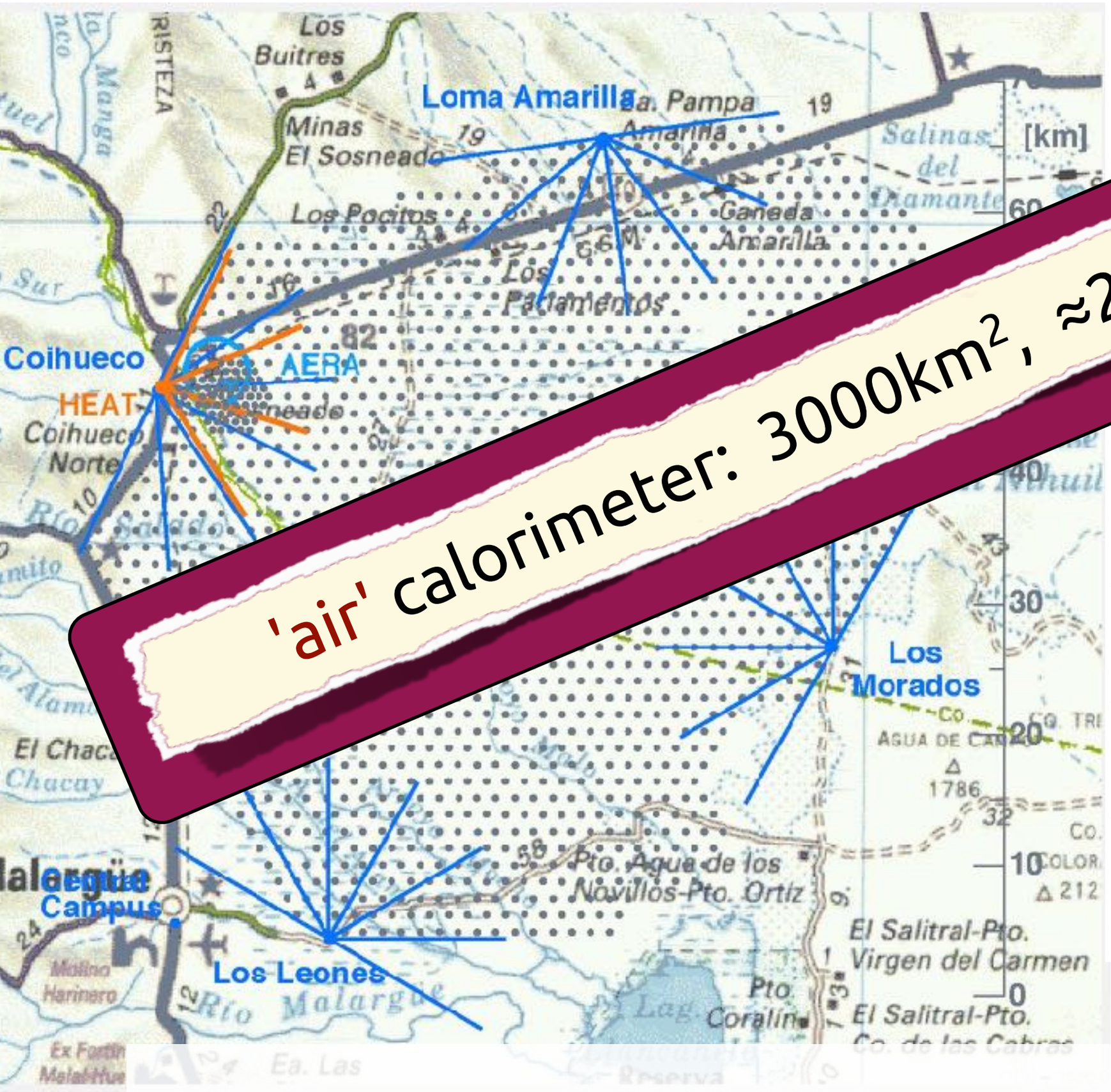
- 1638 with water
- 1635 with electronics

4 Fluorescence detector sites

- 6 telescopes each
- 24 telescopes in total
- Full coverage of the surface array
- Capability to detect stereo events
- Quadruple events seen

Low Energy Extensions
Radio Detectors

The Auger Site



'air' calorimeter: 3000km^2, ≈2.5·10^{10} T

1660 surface detector stations, 1.5 [illegible] cing

* [illegible]
* [illegible] cs
* [illegible] cence detector [illegible] es
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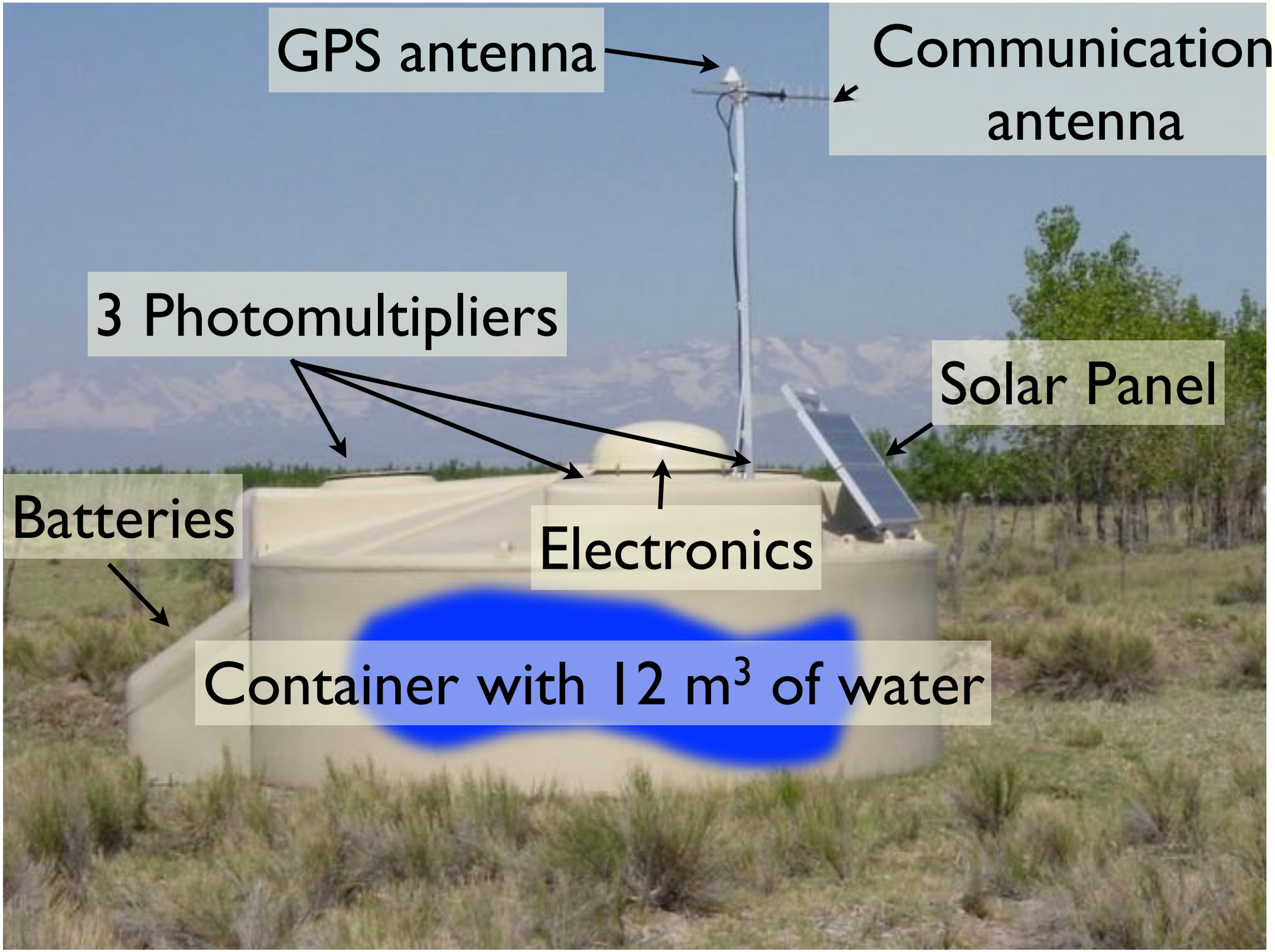
Low Energy Extensions

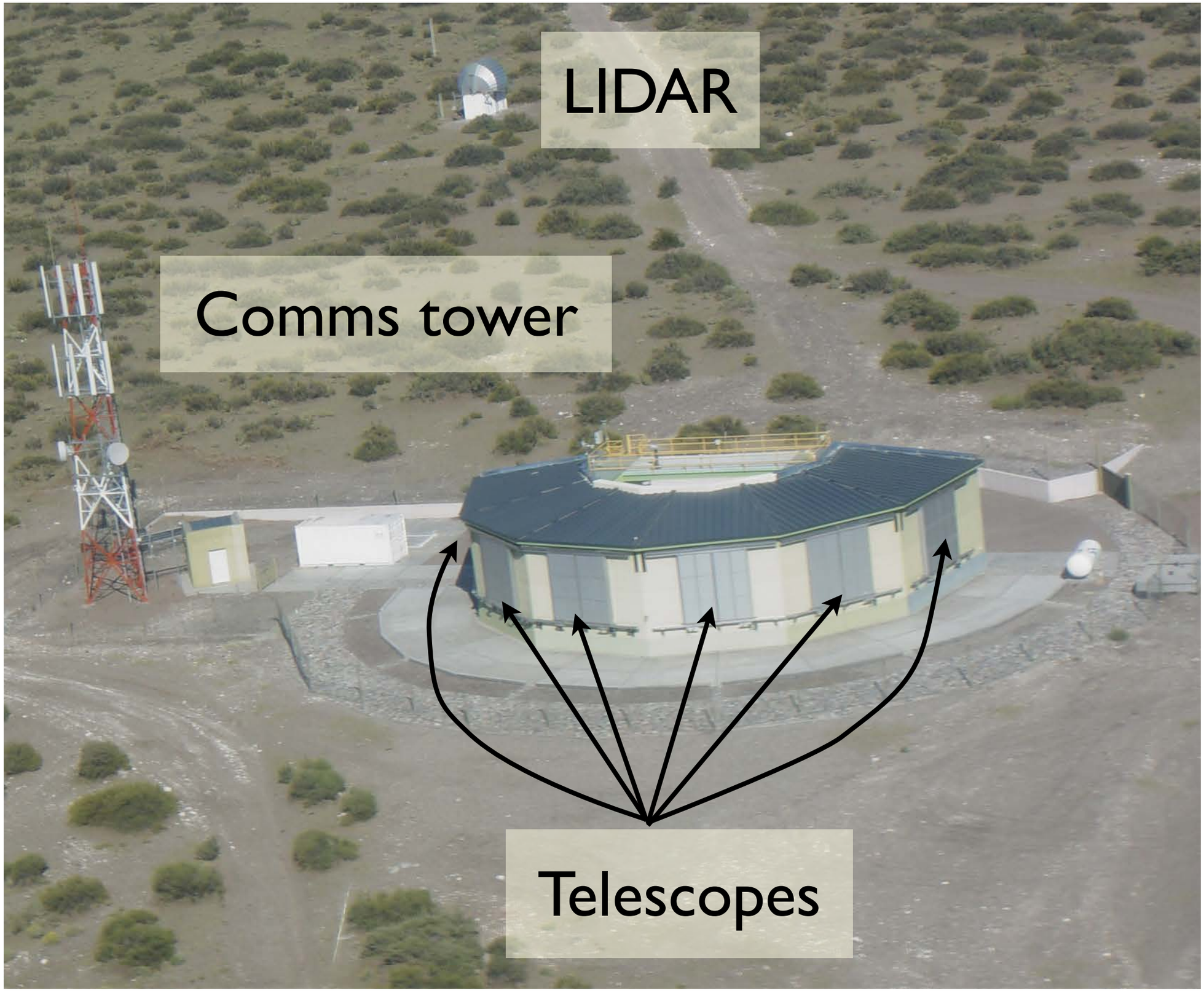
Radio Detectors

A surface detector station

A surface detector station



A Fluorescence Detector Site



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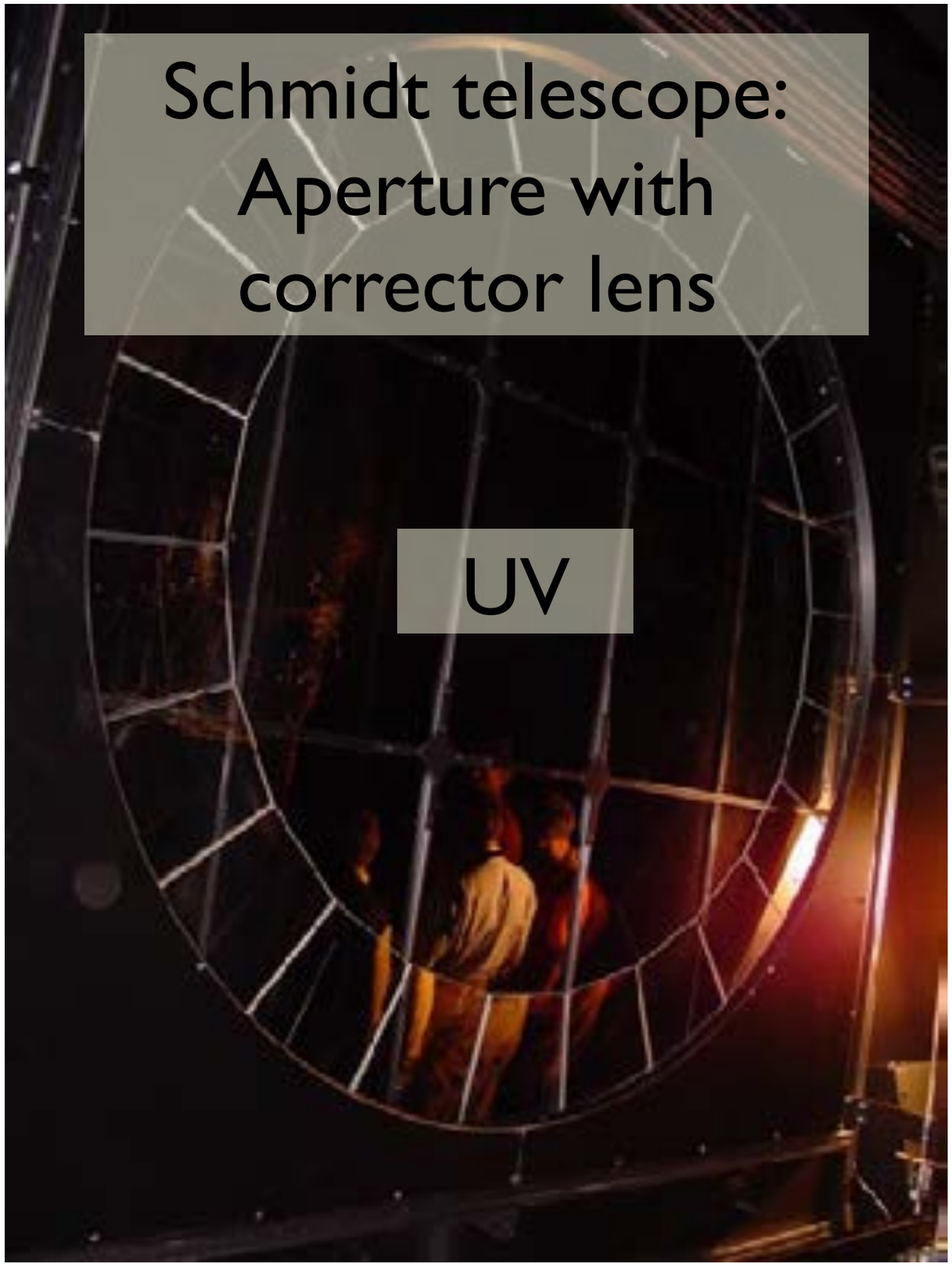

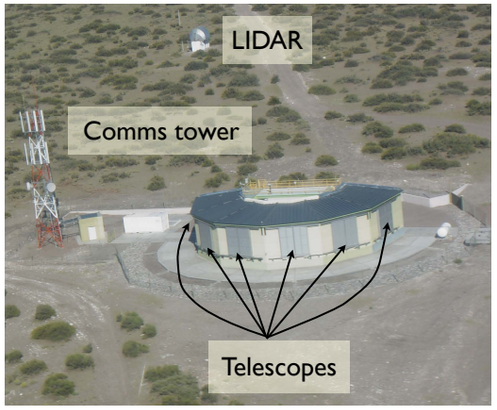

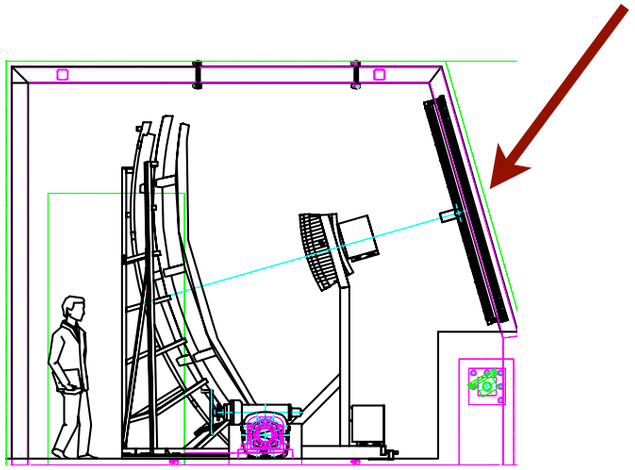

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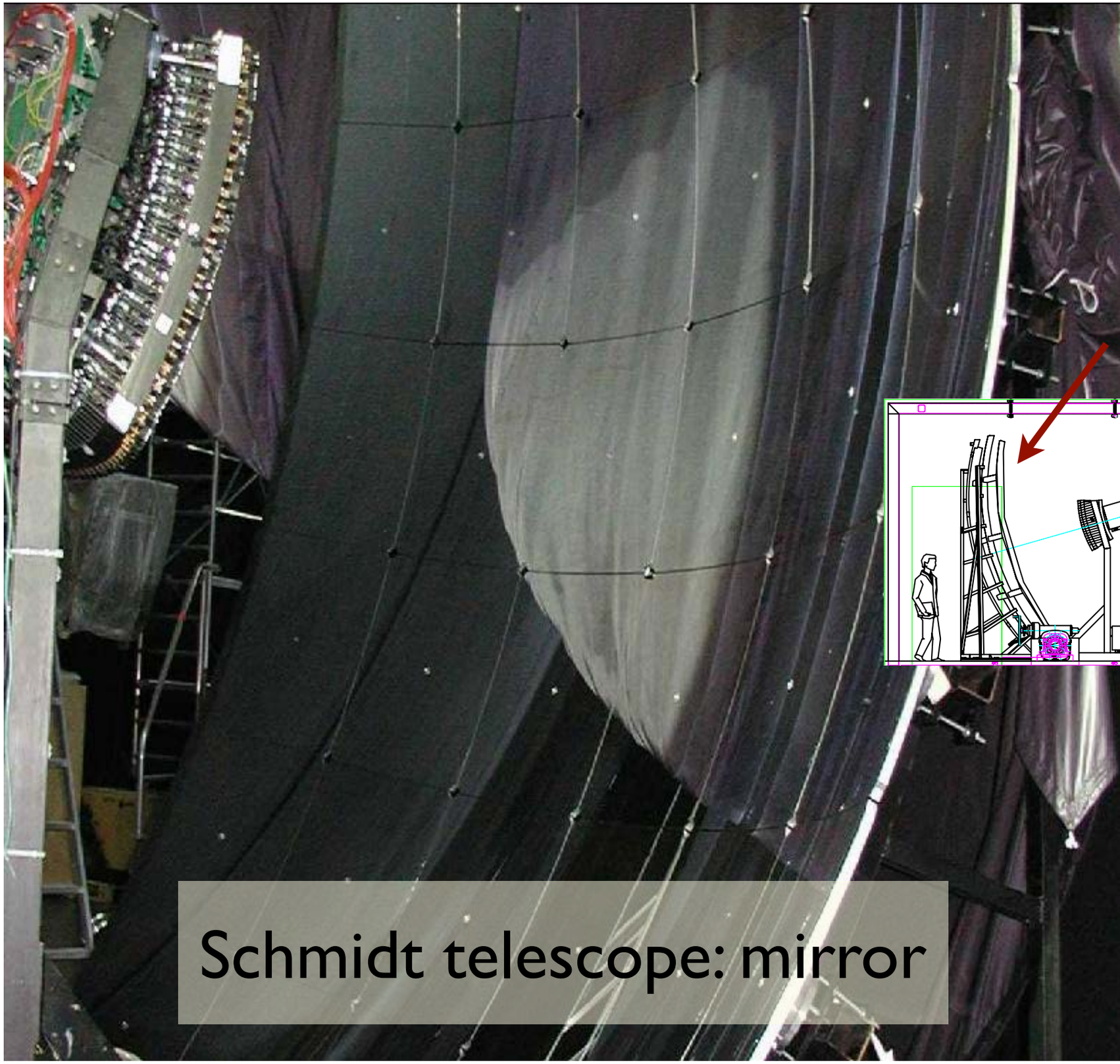

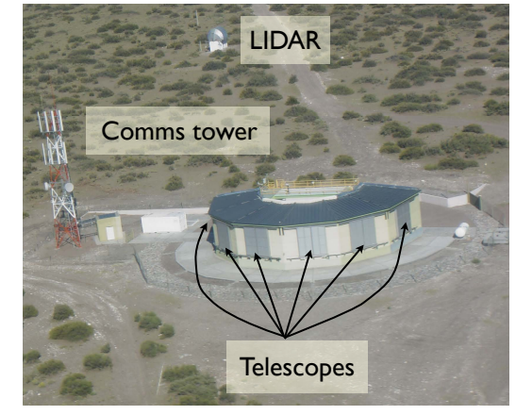

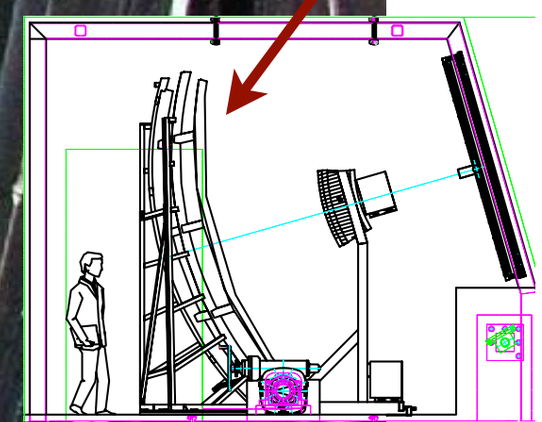

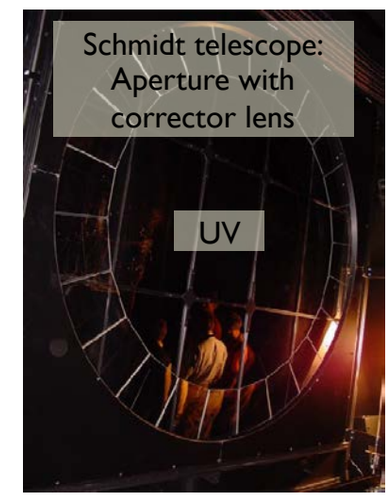

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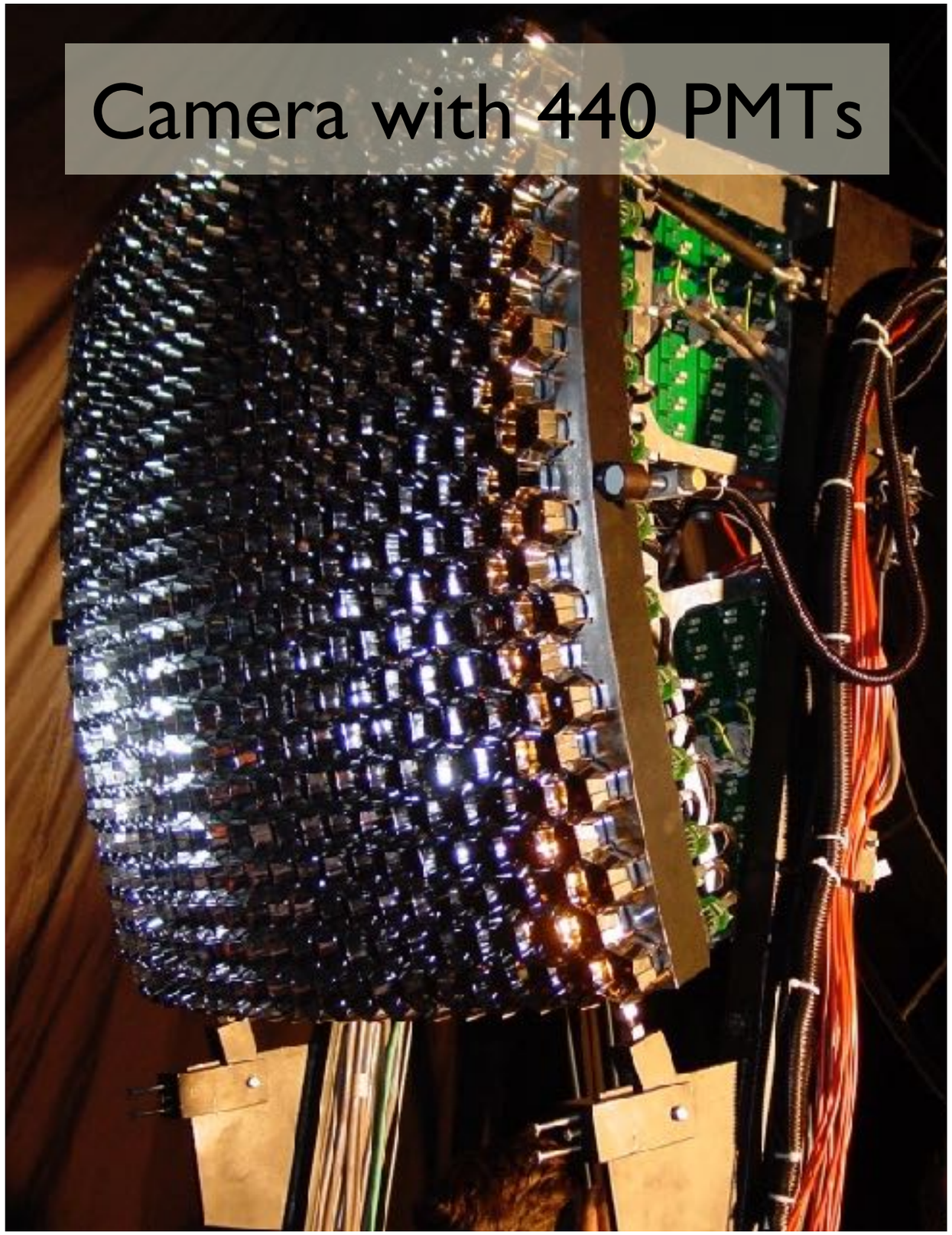
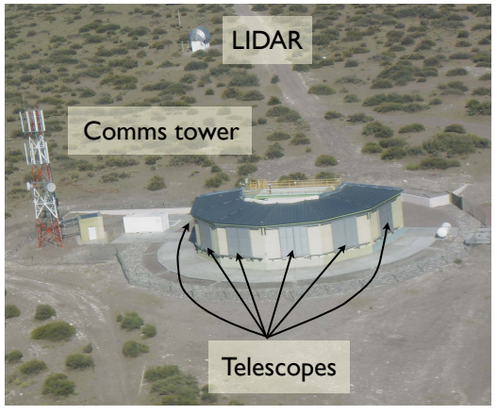
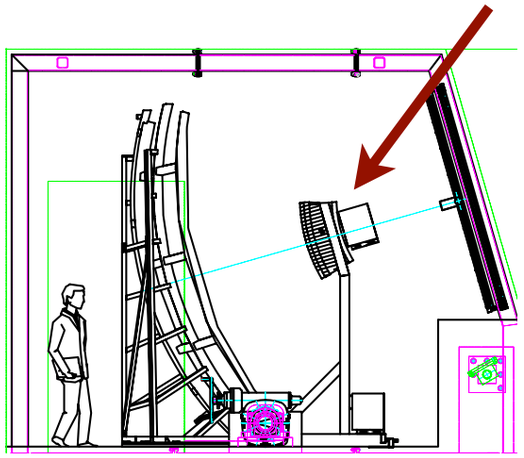
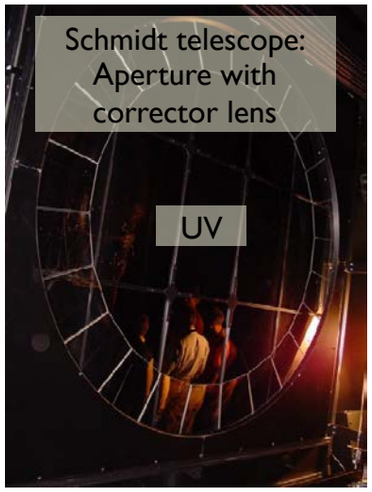
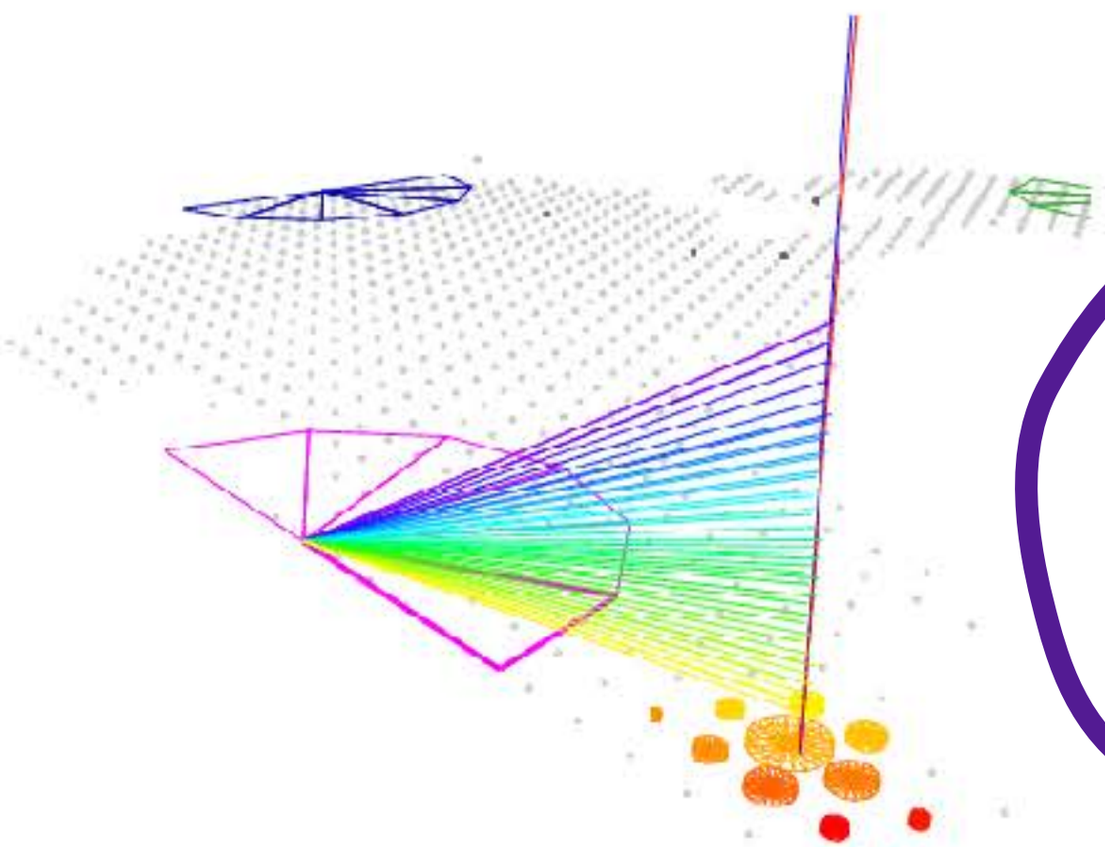




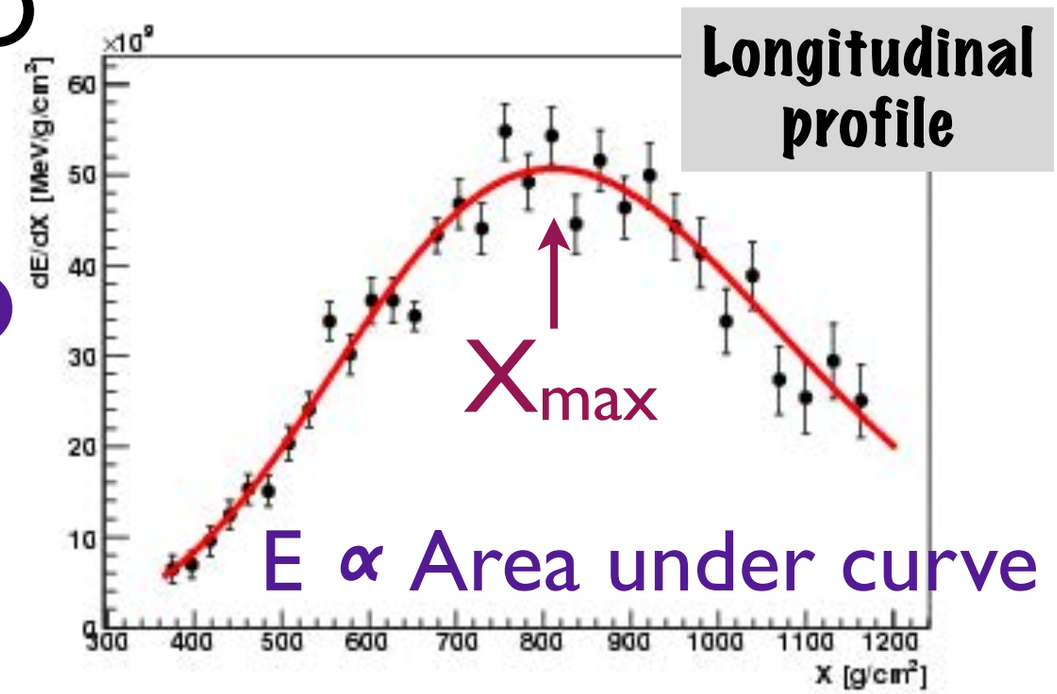




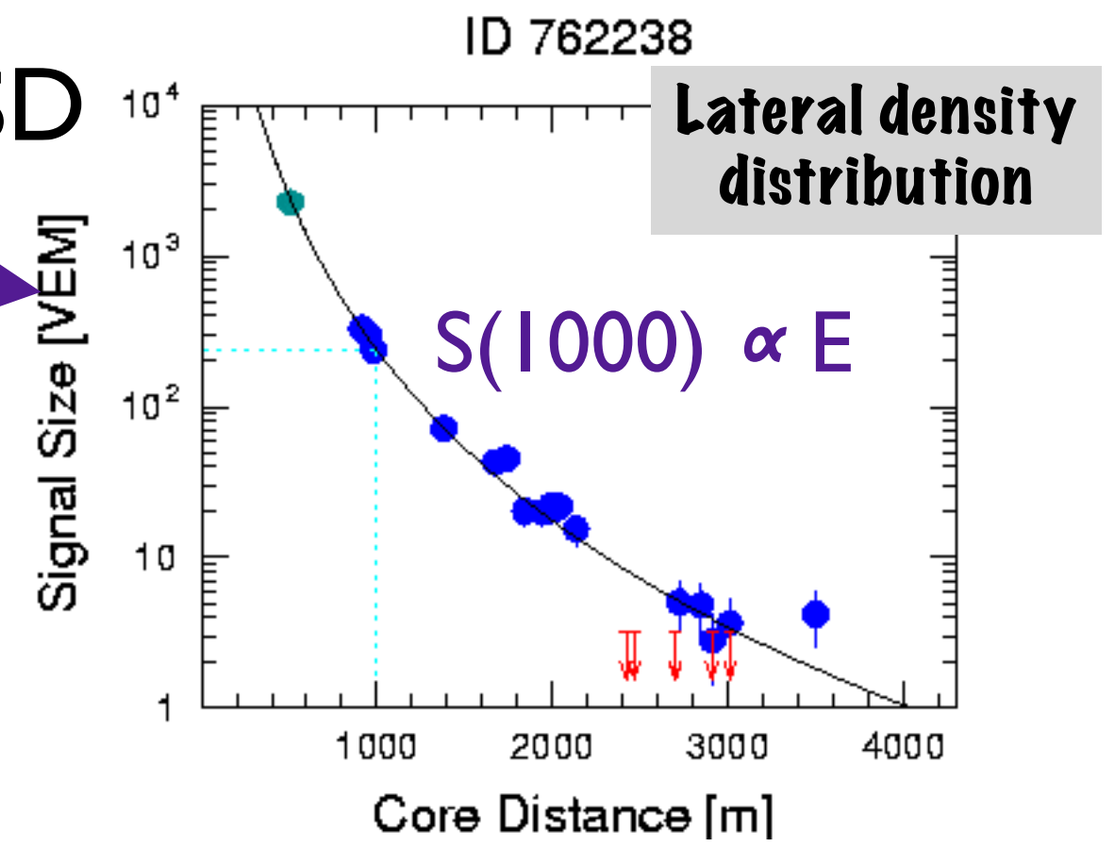
Energy Determination



FD



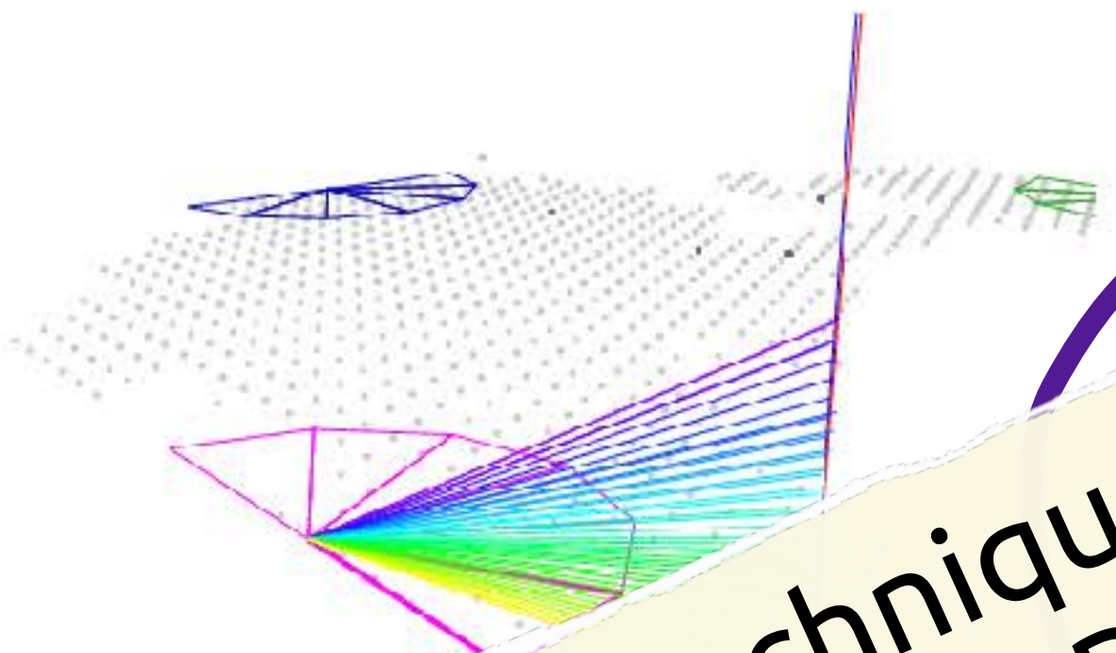
SD

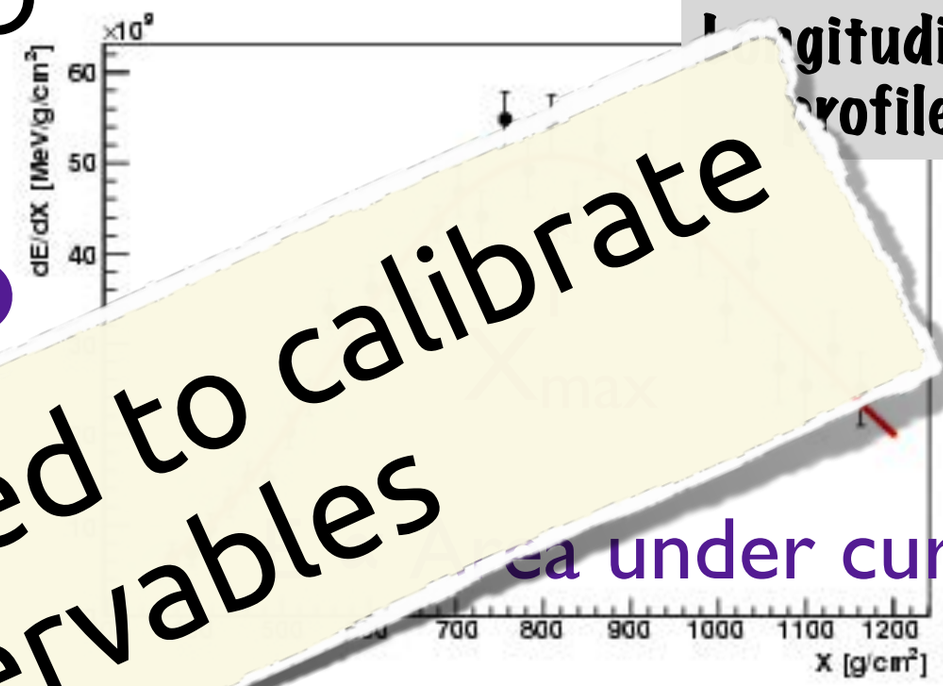


Hybrid Events are used to **calibrate** the SD energy estimator from the FD calorimetric energy

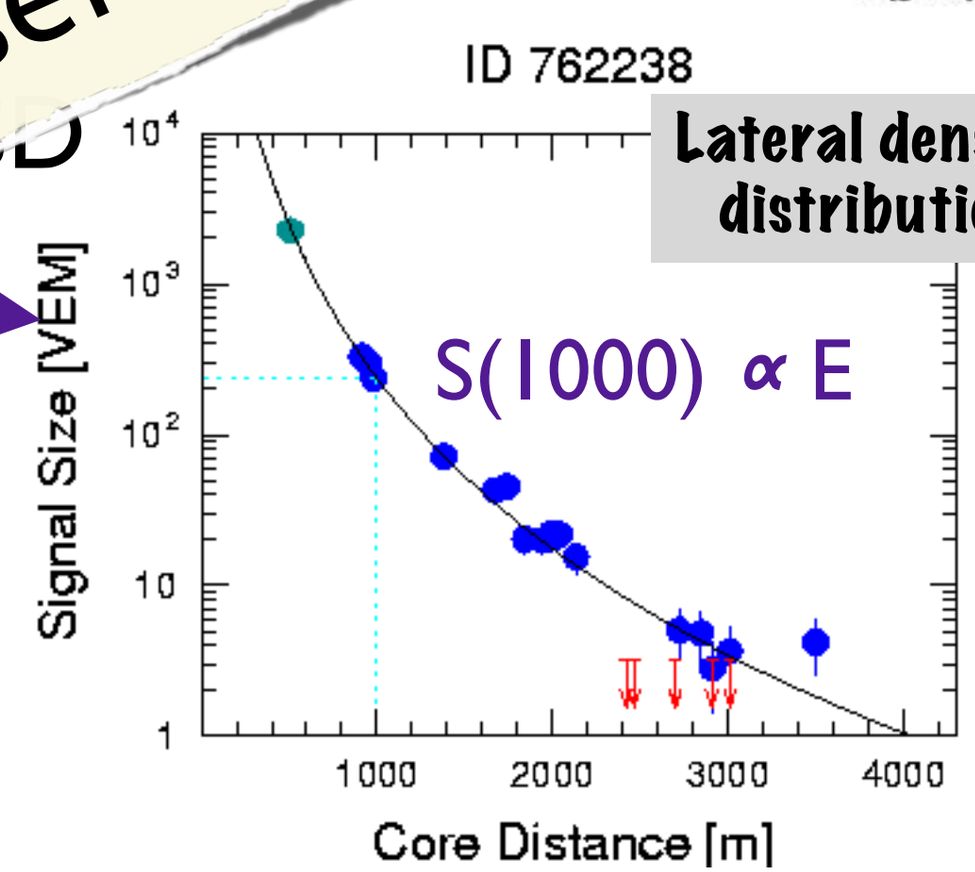
Energy Determination

FD





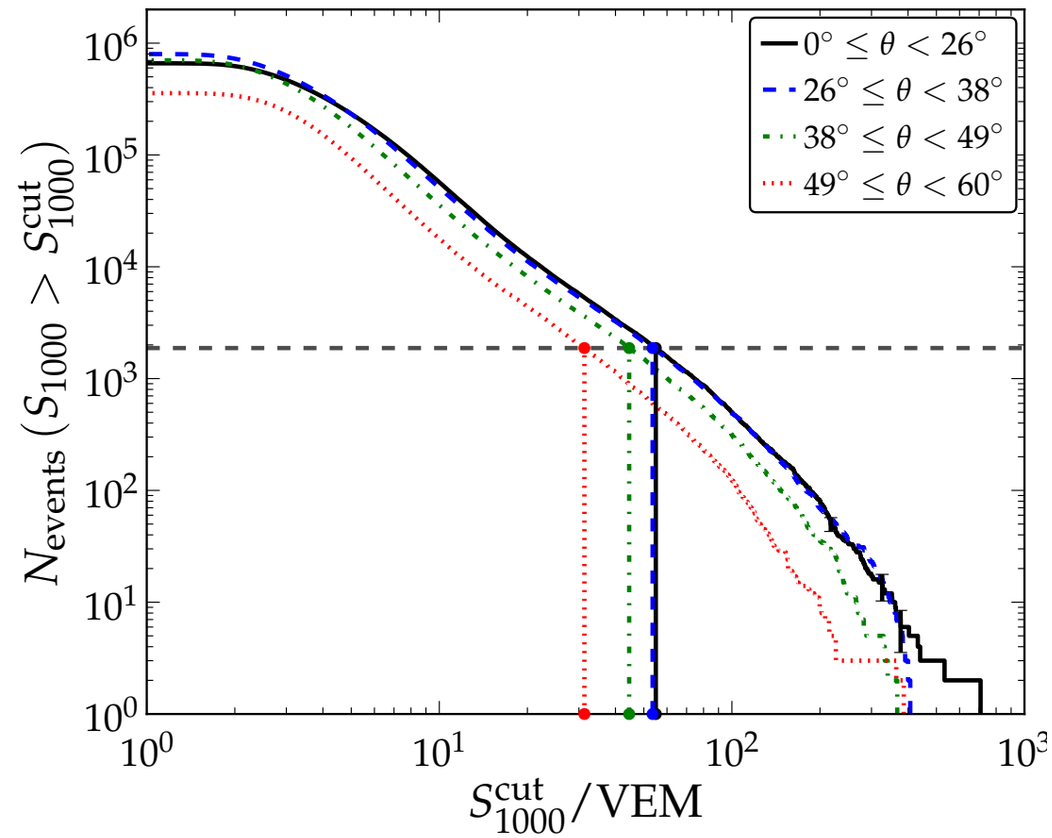
Similar techniques used to calibrate other SD observables



Hybrid Events are used to calibrate the SD energy estimator from the FD calorimetric energy

Constant Intensity Cut

- Energy estimator depends on zenith
- Isotropy of Cosmic Rays
  ⇨ Integrated constant Intensity
- Constant Intensity
  ⇨ Constant Energy



- S_{38} = S(1000) / CIC(sec(θ)) (signal at 38°)
  - 38° is the average zenith angle of events

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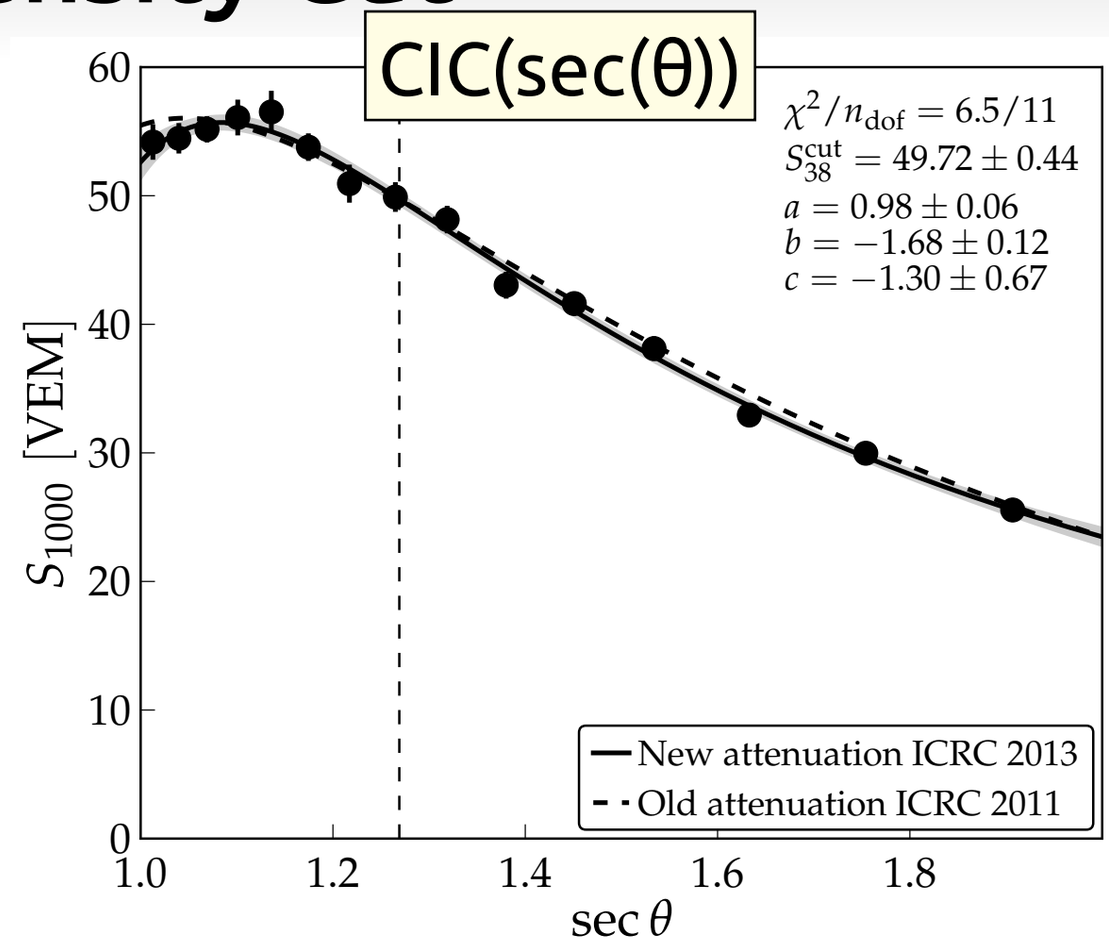
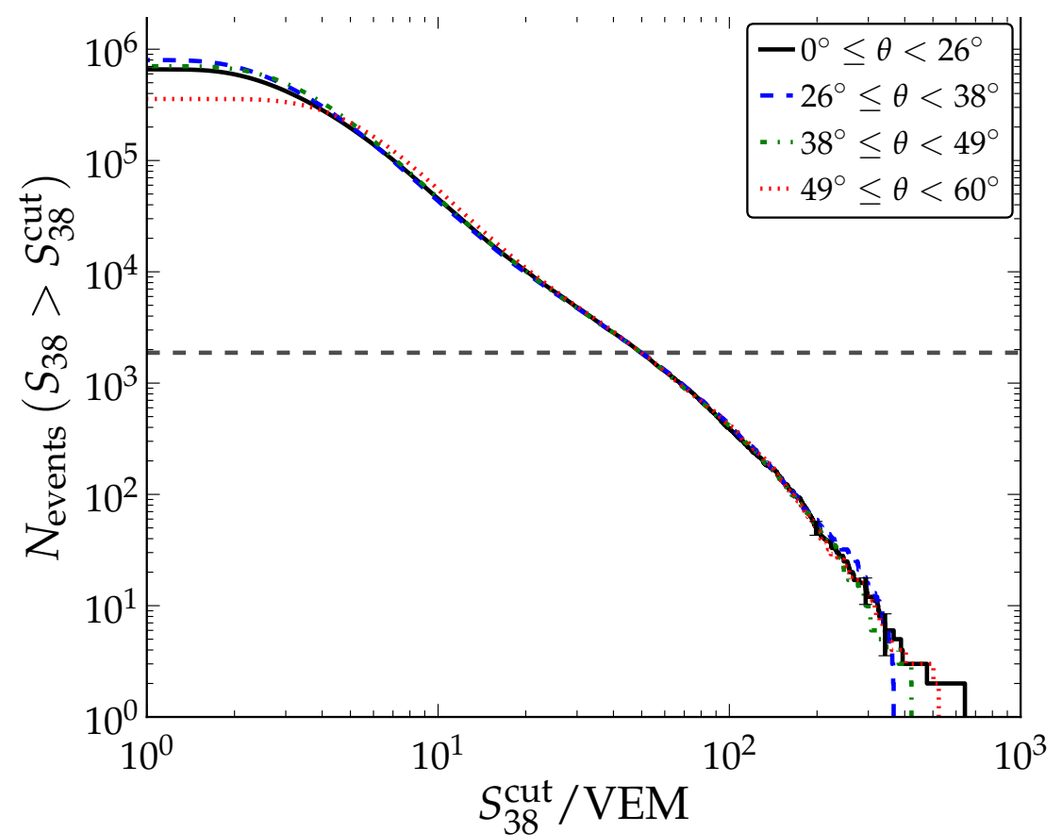
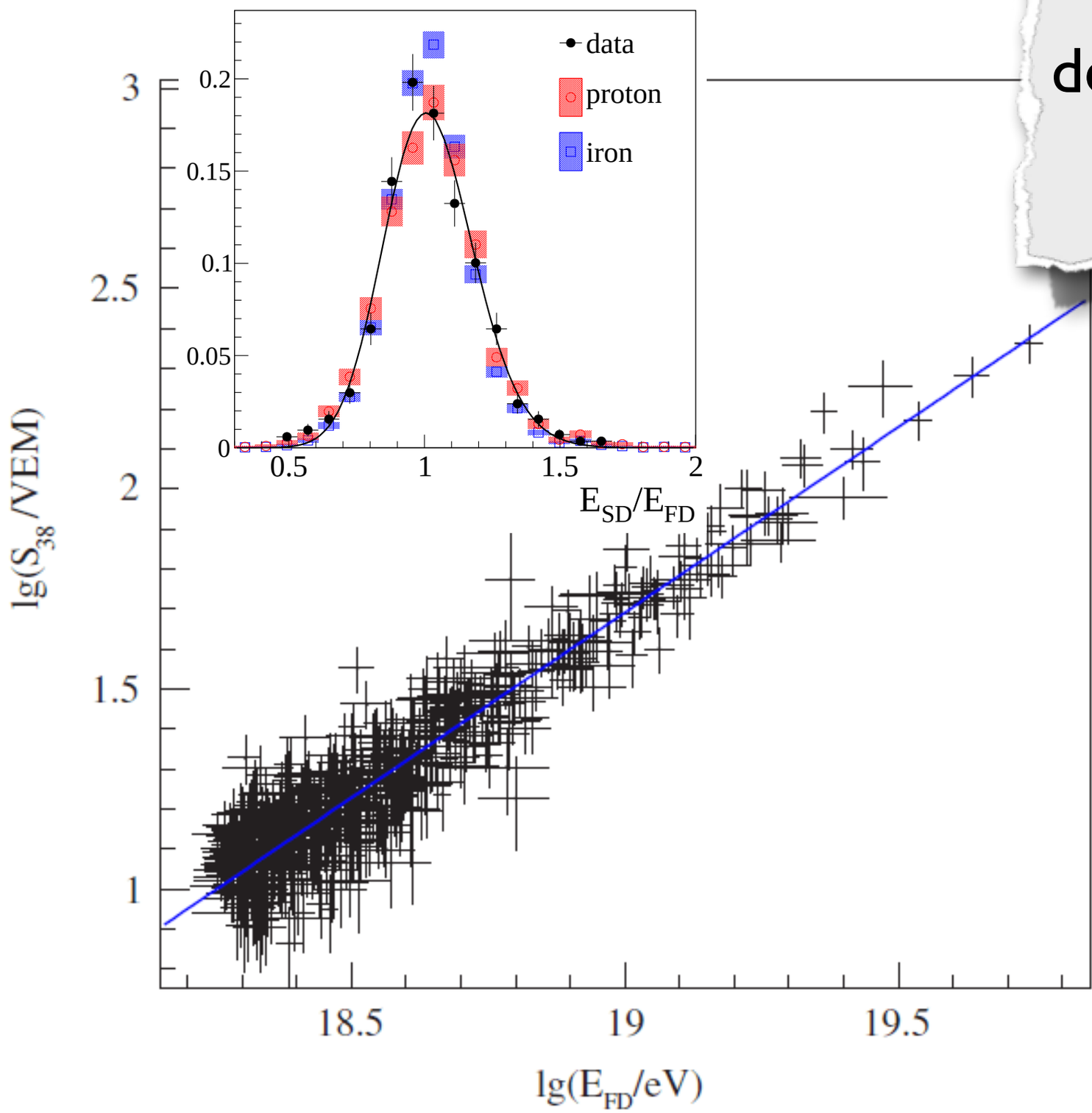




Calibration curve



Both S_{38} and E_{FD} are determined experimentally

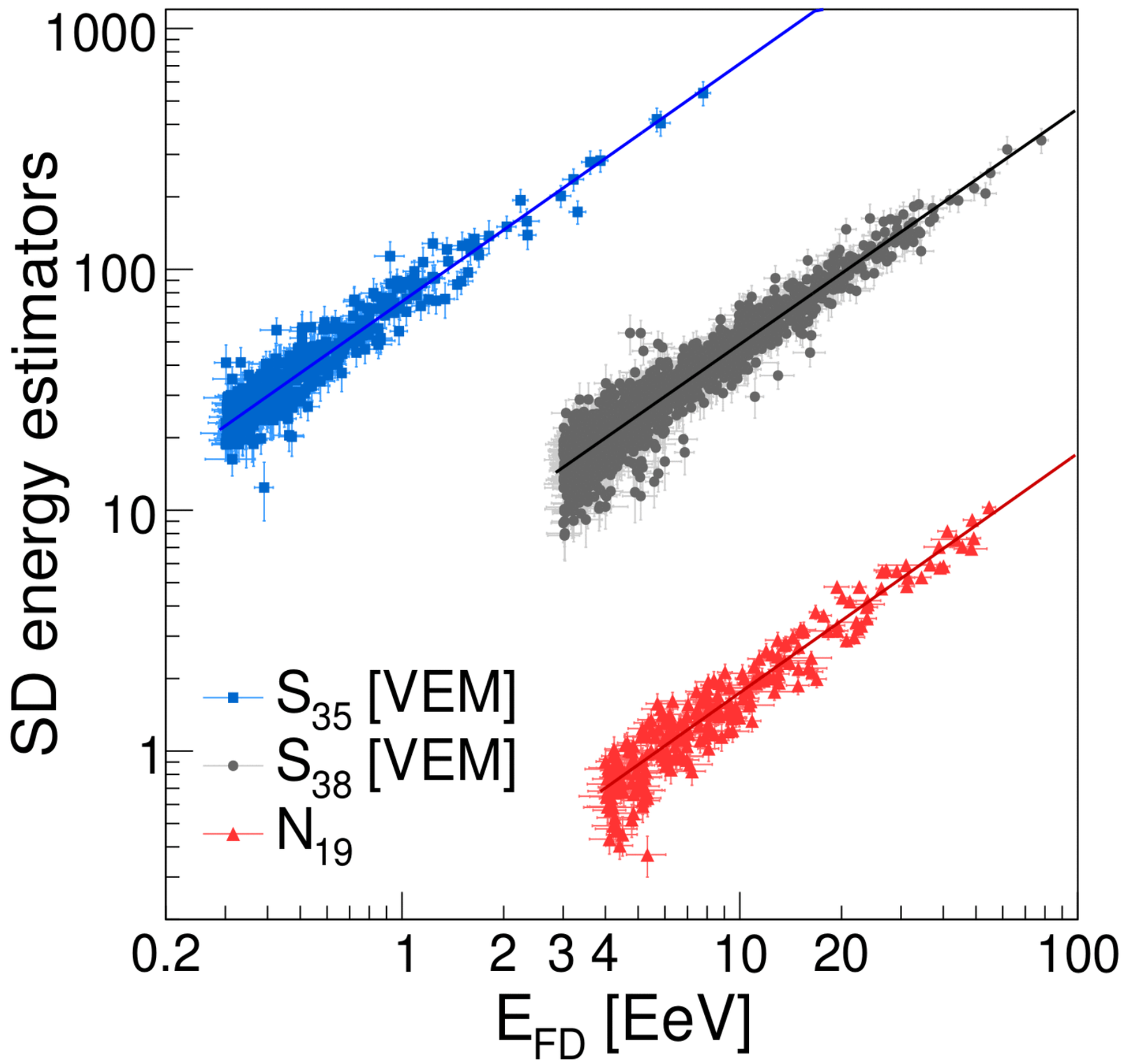
☛ No dependence on simulations

Energy calibration improves with statistics

Not dependent on primary particle

≈18% uncertainty

Calibration of different E estimators



Different Energy estimators

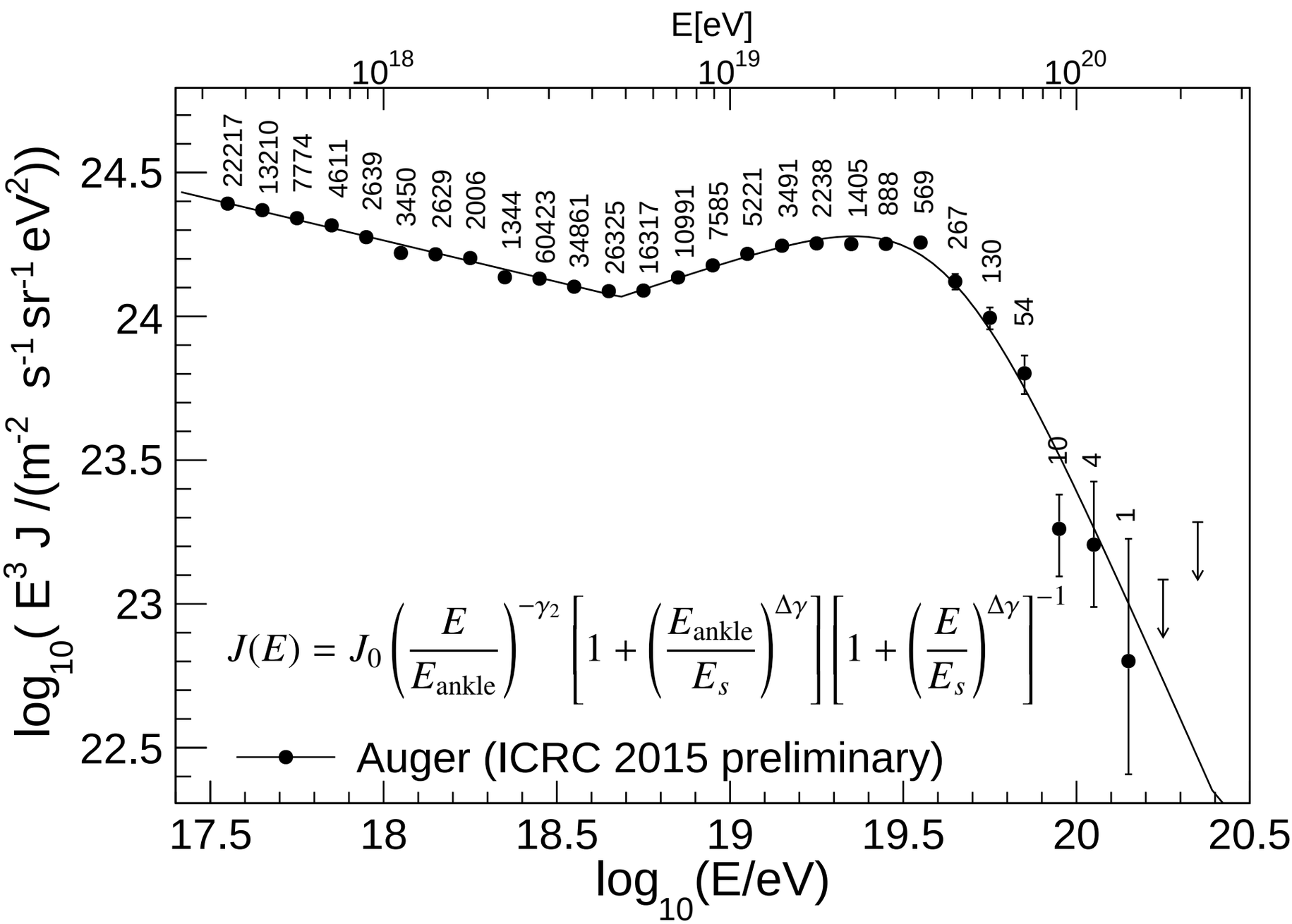
S_{38}: 1500m array
$0 \leq \theta \leq 60°$

S_{35}: 750m array
$0 \leq \theta \leq 55°$

N_{19}: Inclined showers

Combined spectrum

- Combine results from different techniques and detectors



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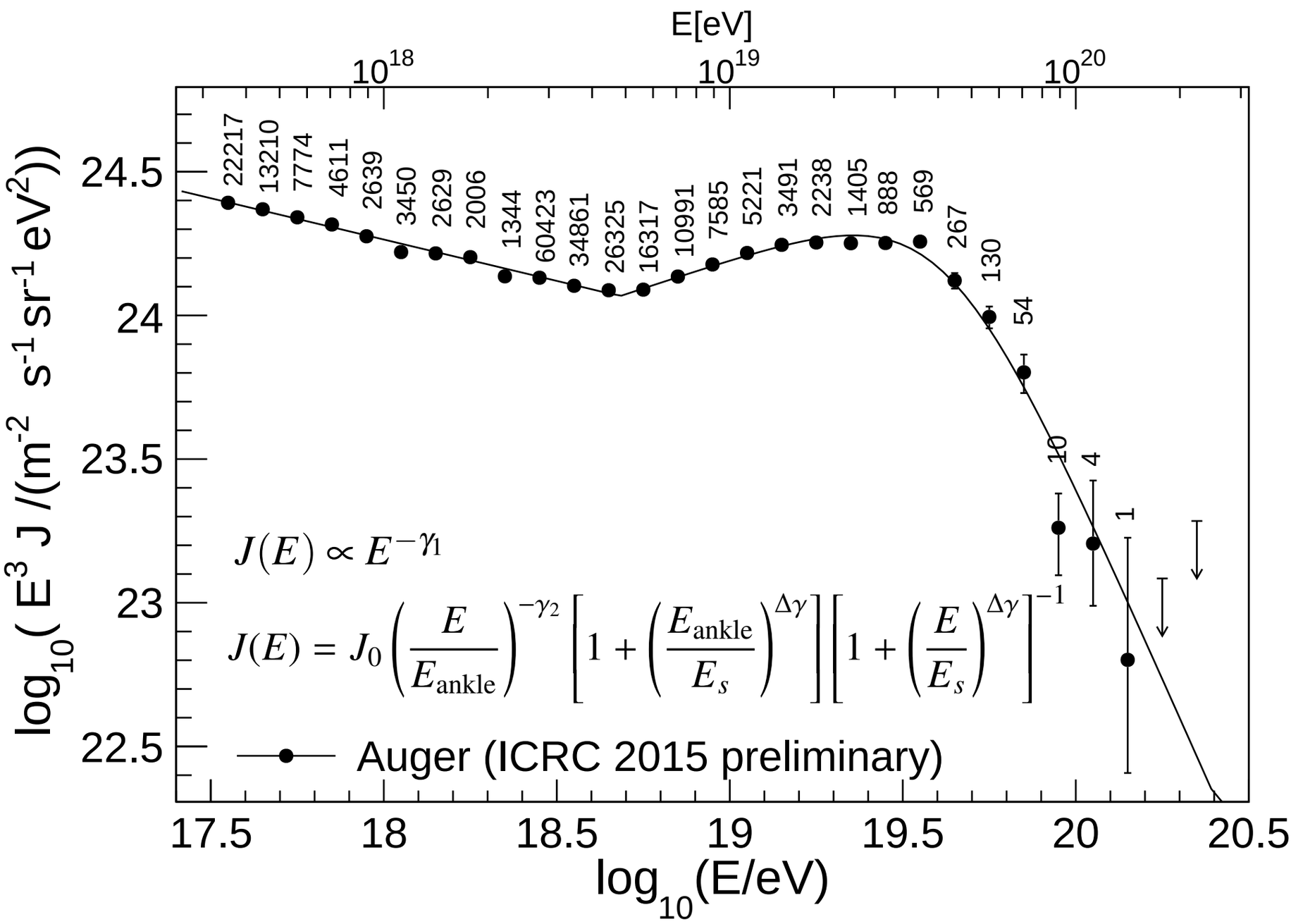


Spectral parameters:

E_{ankle} = 4.82 ± 0.07 ± 0.8 EeV

E_s = 42.1 ± 1.7 ± 7.6 EeV

γ_1 = 3.29 ± 0.02

γ_2 = 2.60 ± 0.02

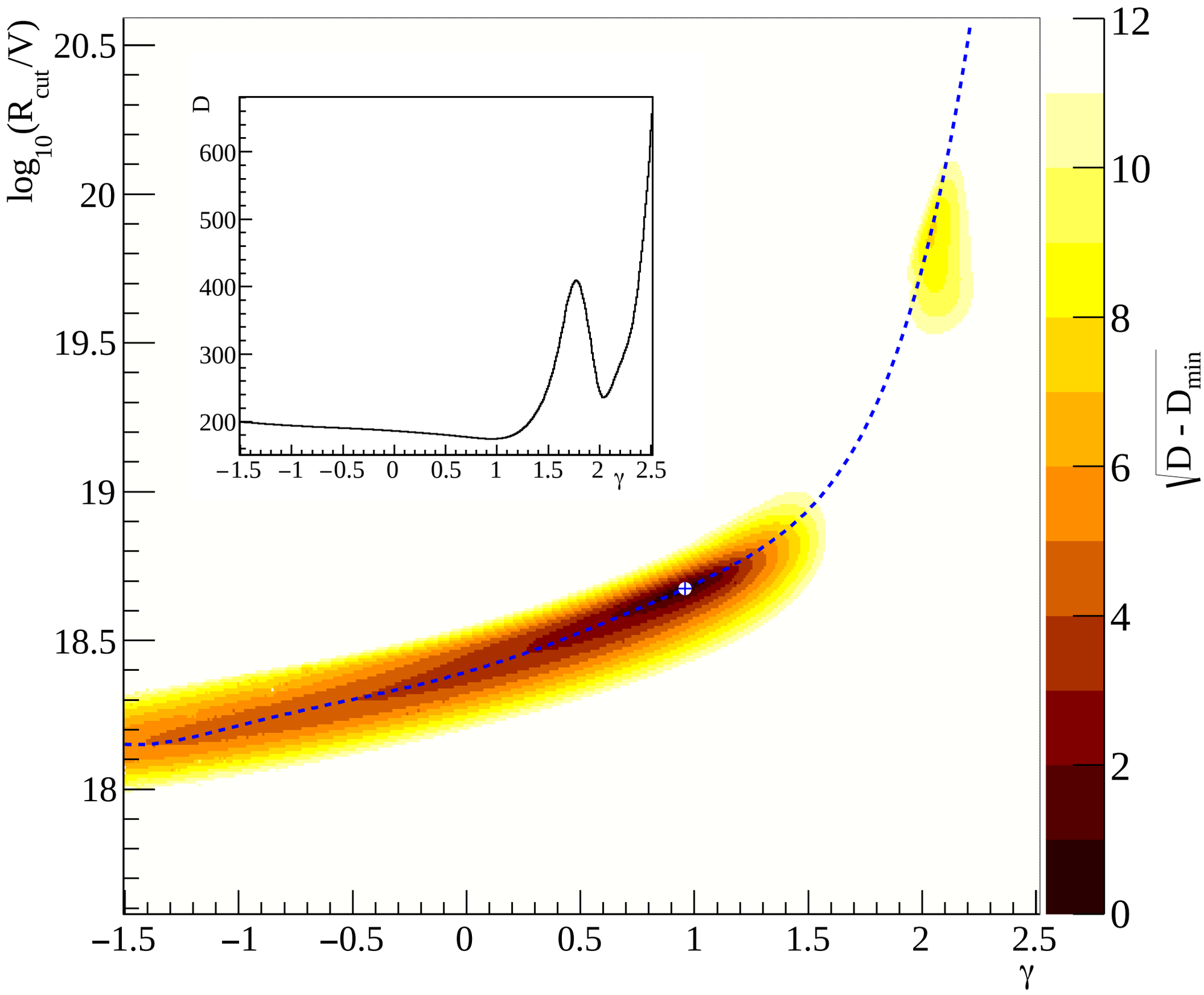
$\Delta\gamma$ = 3.14 ± 0.02

Combined fit

- Fit spectrum and X_{max}
- Uniform source model
- Free parameters:
  - Injection **spectral index** γ
  - **Cutoff rigidity R_{cut}**
  - Spectrum **normalization J_0**
  - Mass **fractions f_A** (4 independent)
    H, He, N, Si, Fe
- Propagation
  - Photon interaction: CMB, EBL
  - Pair production
  - Photodisintegration

} **Different models**

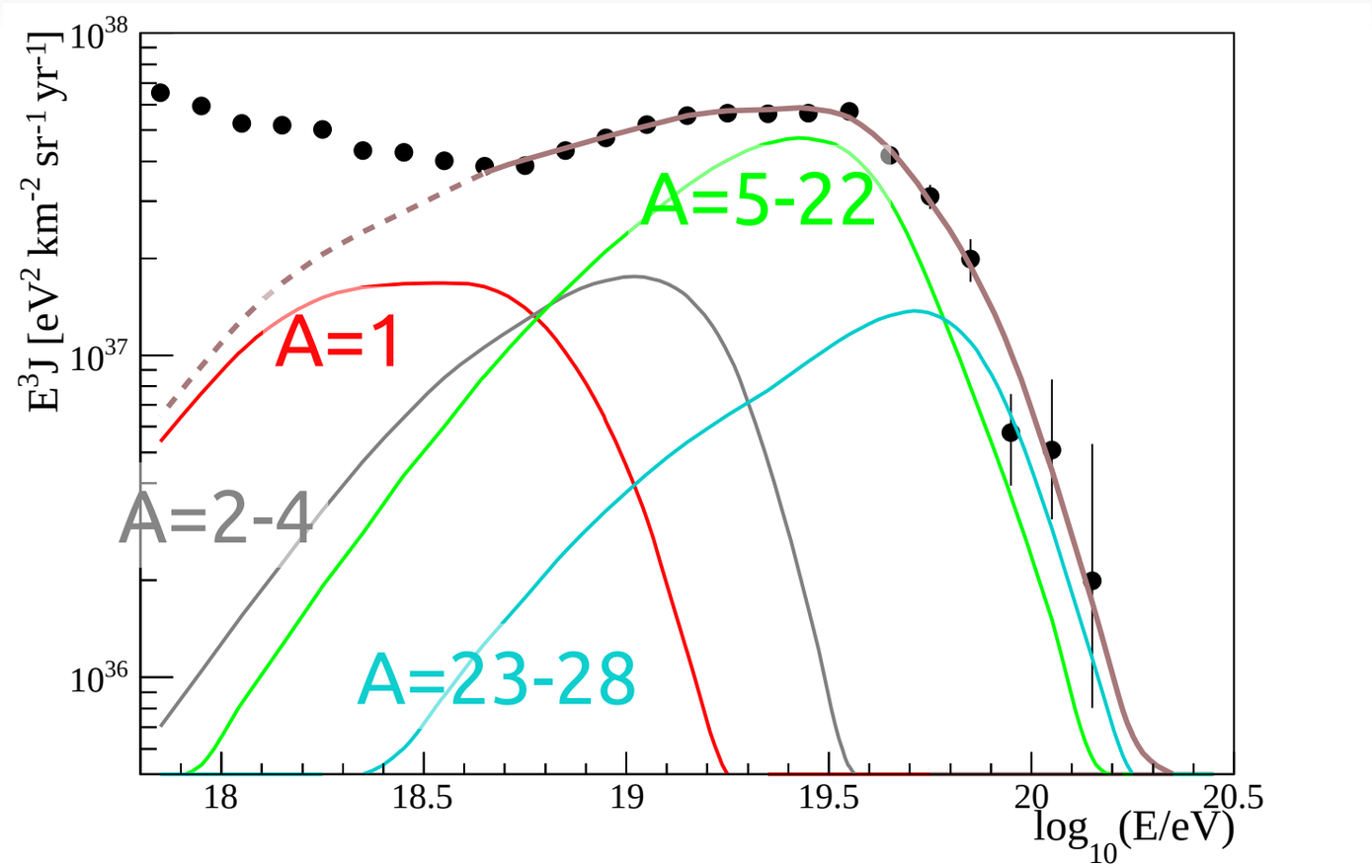
Fit result

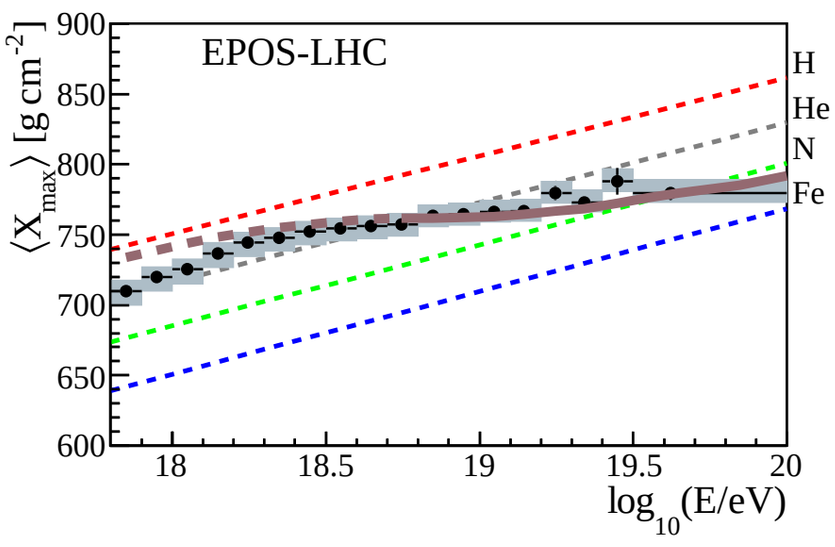


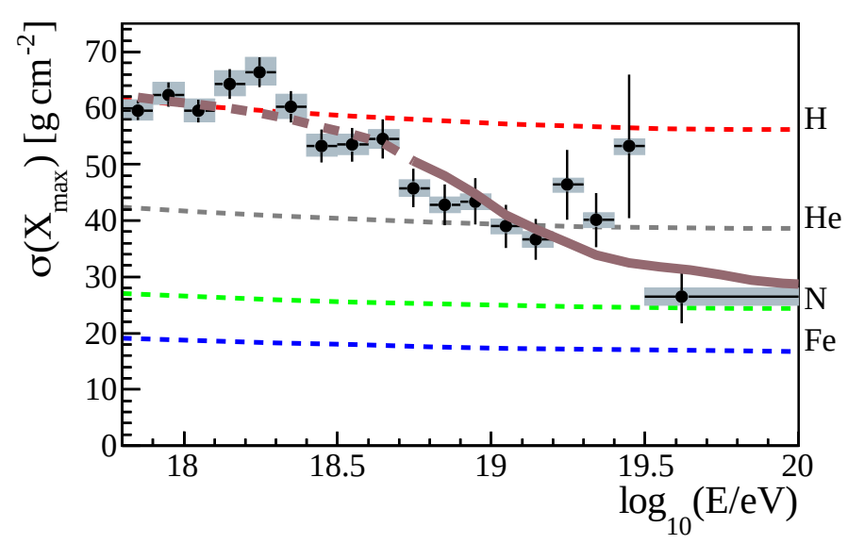
2 minima

Extended 1st min

1st minimum

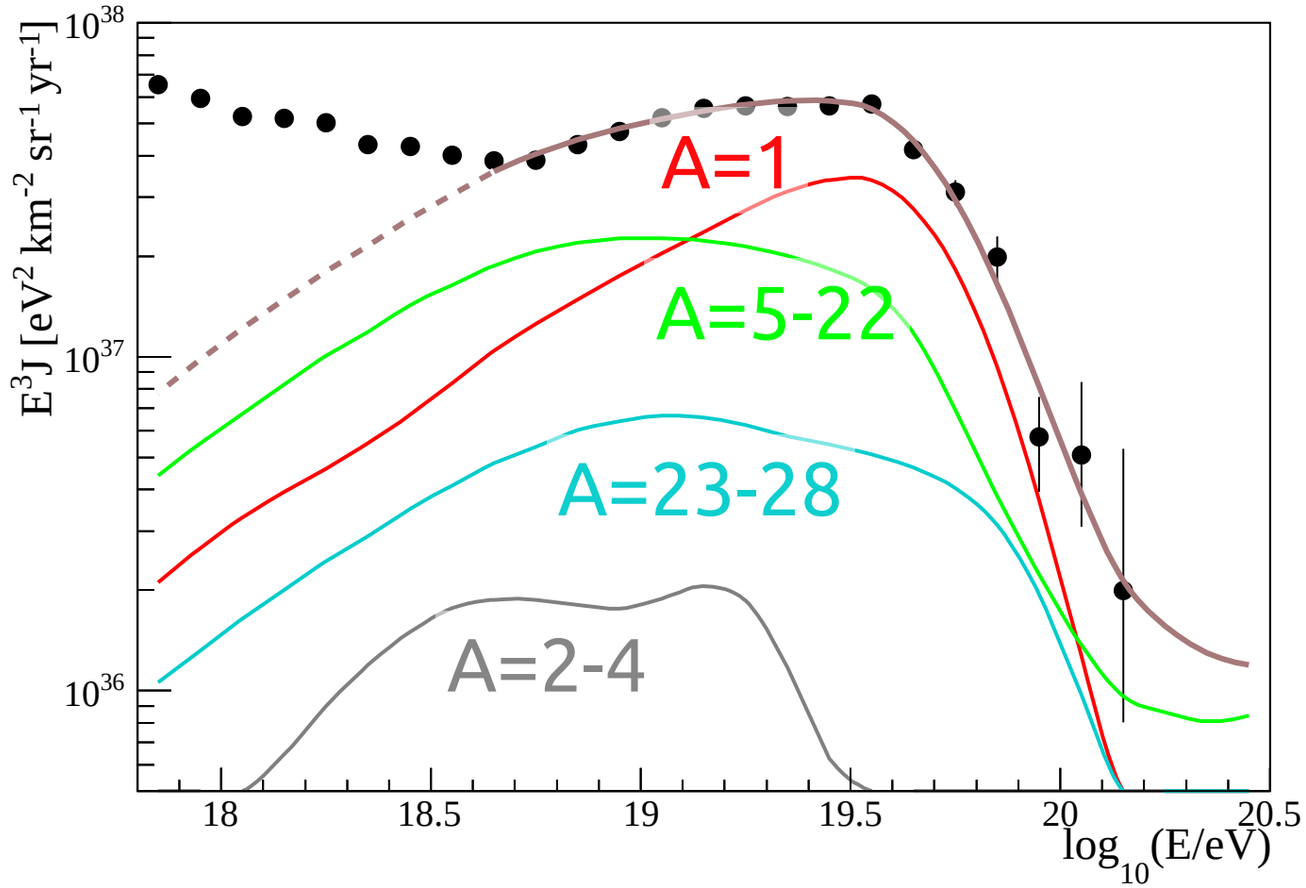


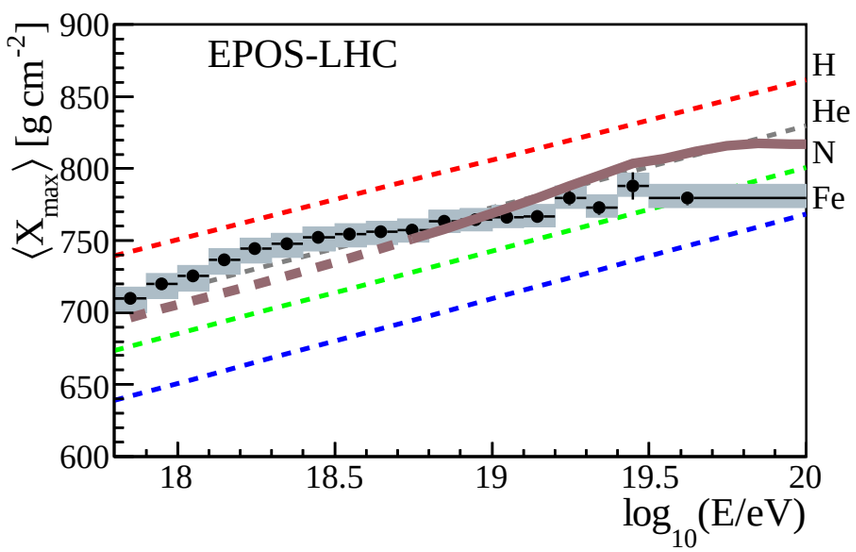


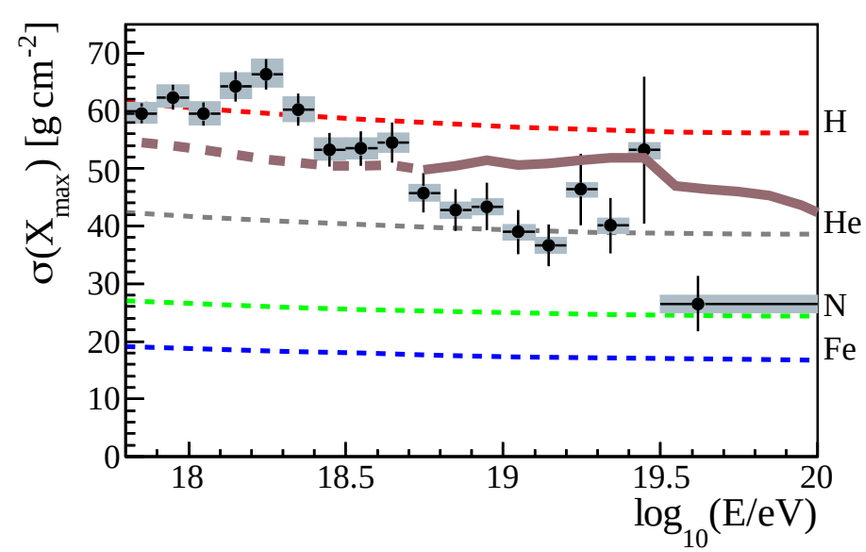


◉ Absence of Fe?

2nd minimum


E^3J [eV^2 km^{-2} sr^{-1} yr^{-1}]
10^{38}
10^{37}
10^{36}
A=1
A=5-22
A=23-28
A=2-4
18
18.5
19
19.5
20
20.5
$\log_{10}(E/eV)$


EPOS-LHC
$\langle X_{max} \rangle$ [g cm^{-2}]
900
850
800
750
700
650
600
H
He
N
Fe
18
18.5
19
19.5
20
$\log_{10}(E/eV)$


$\sigma(X_{max})$ [g cm^{-2}]
70
60
50
40
30
20
10
0
H
He
N
Fe
18
18.5
19
19.5
20
$\log_{10}(E/eV)$

Combined fit interpretation

- 1st minimum extended: hard to fix values
- 2nd minimum well reproduced
  Too many protons
- Preferred low Rcut:
  Cutoff in spectrum combined effect of propagation (GZK) and source cutoff
- Mixed composition: conflicts with pure proton, electron dip model

Anisotropy: Angular power spectrum

- Expand anisotropy: moments beyond monopole
- C_l: Spectral coefficients

$$\Delta(\mathbf{n}) = \sum_{\ell>0} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{n}),$$

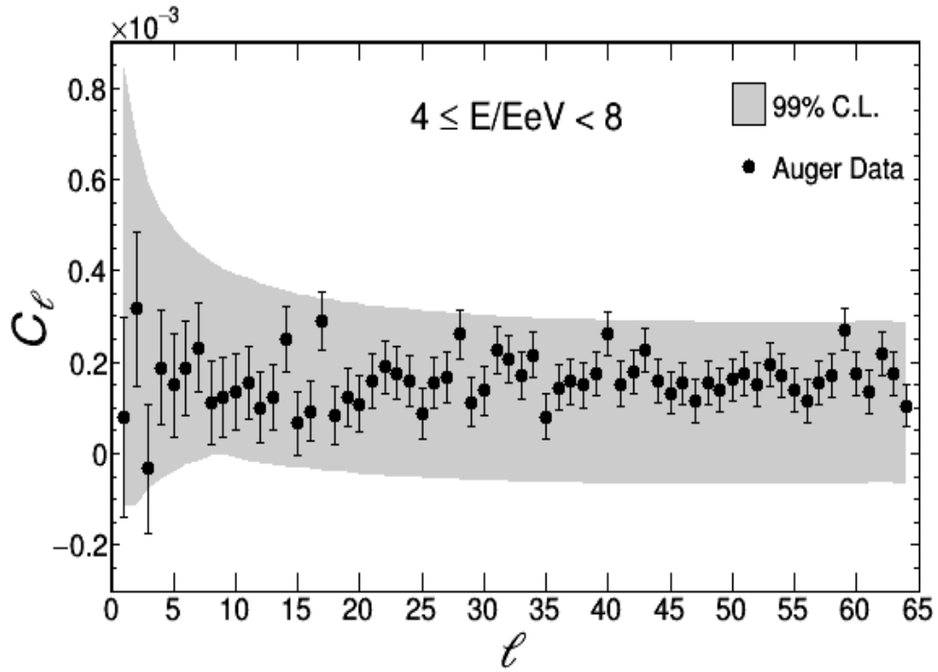
$$C_\ell = \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2/(2\ell+1)$$

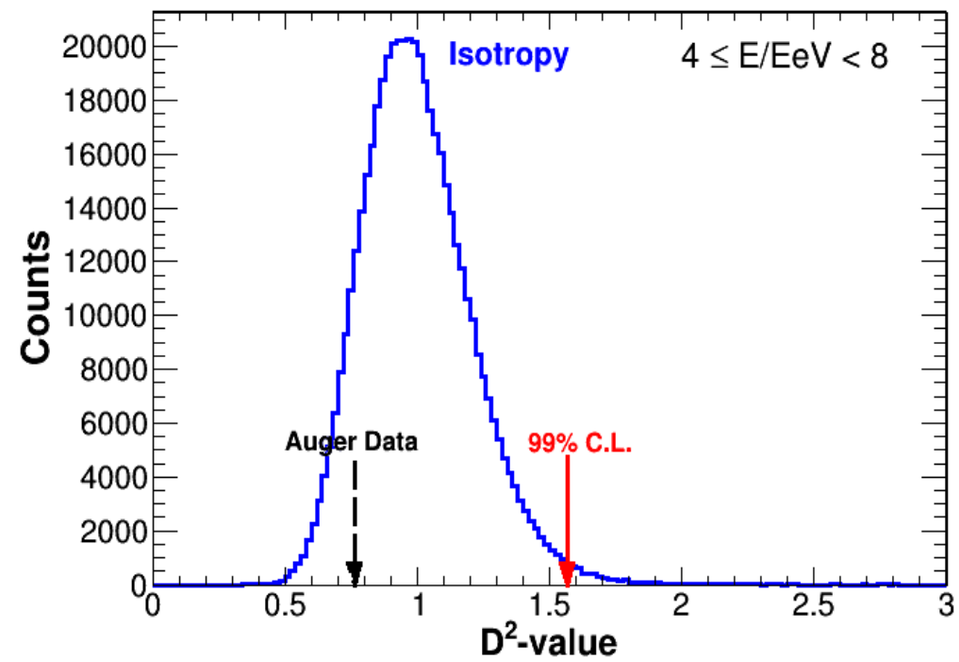
- Combined, global anisotropy estimator

$$D^2 = \frac{1}{\ell_{\max}} \sum_{\ell=1}^{\ell_{\max}} \left(\frac{C_{\ell,\mathrm{data}} - \langle C_{\ell,\mathrm{iso}} \rangle}{\sigma_{\ell,\mathrm{iso}}} \right)^2$$

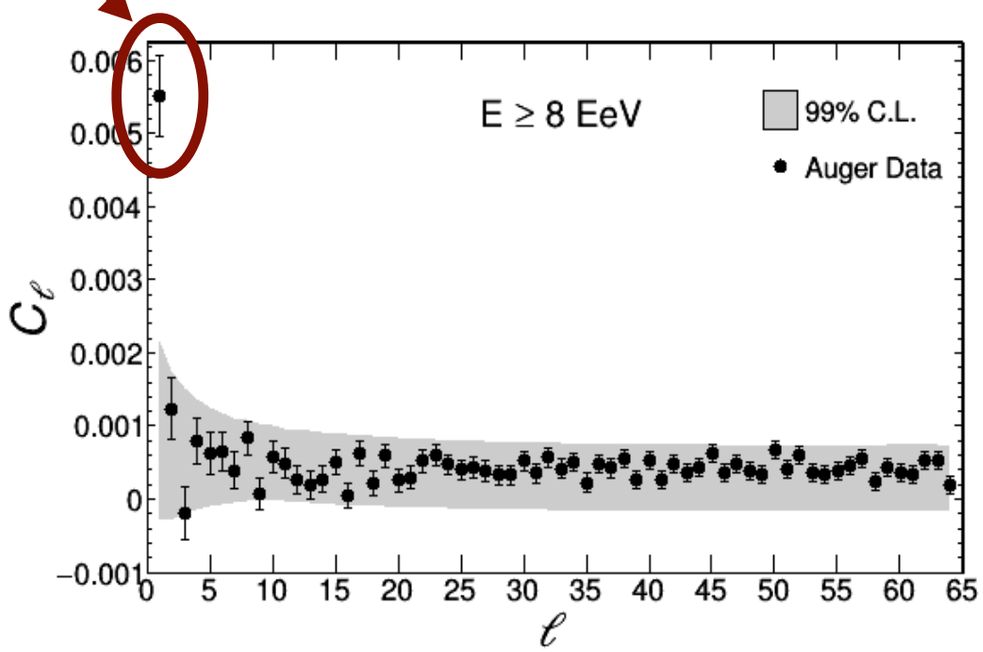
Deviation from isotropy

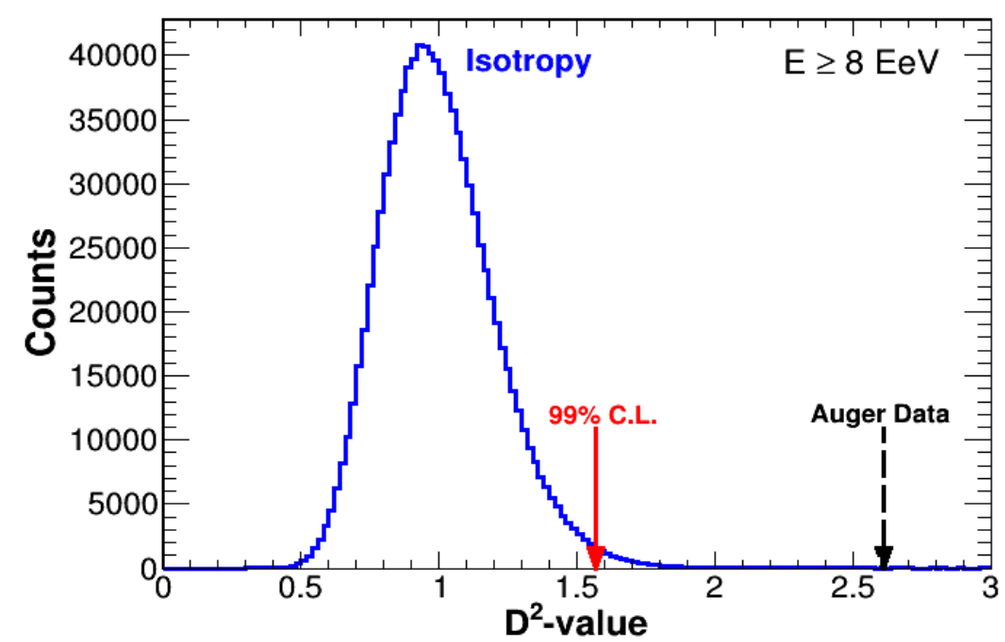
Angular power spectrum





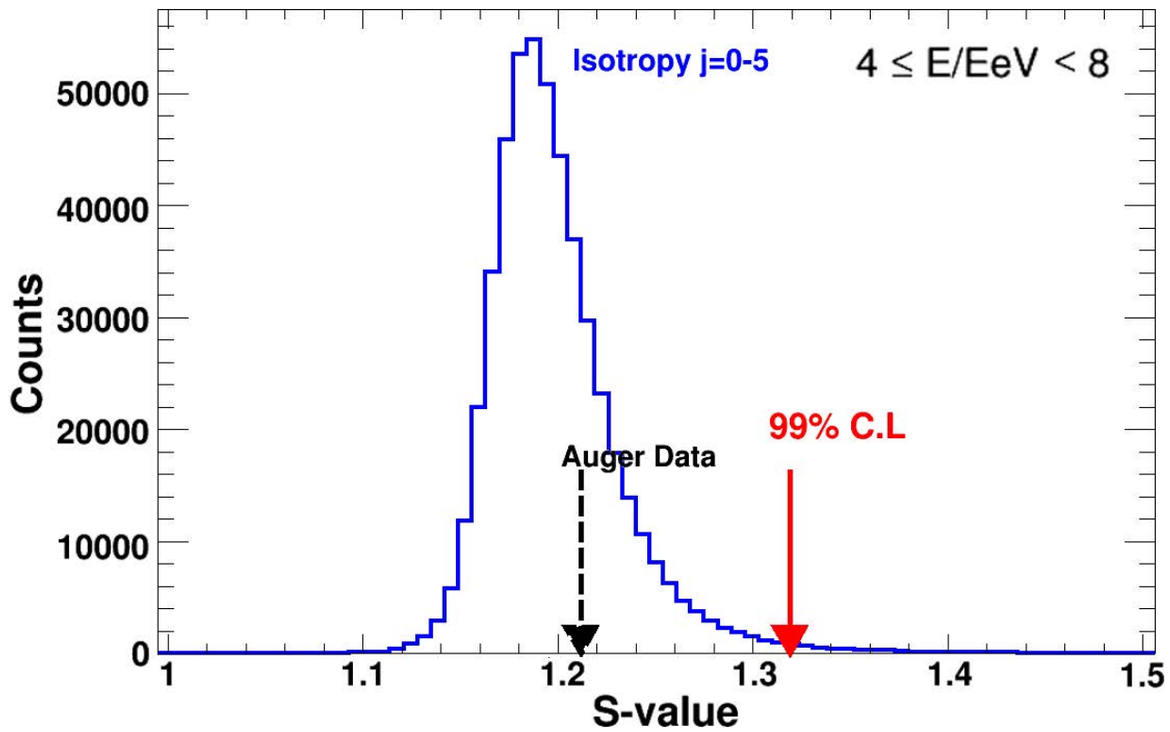
Dipole

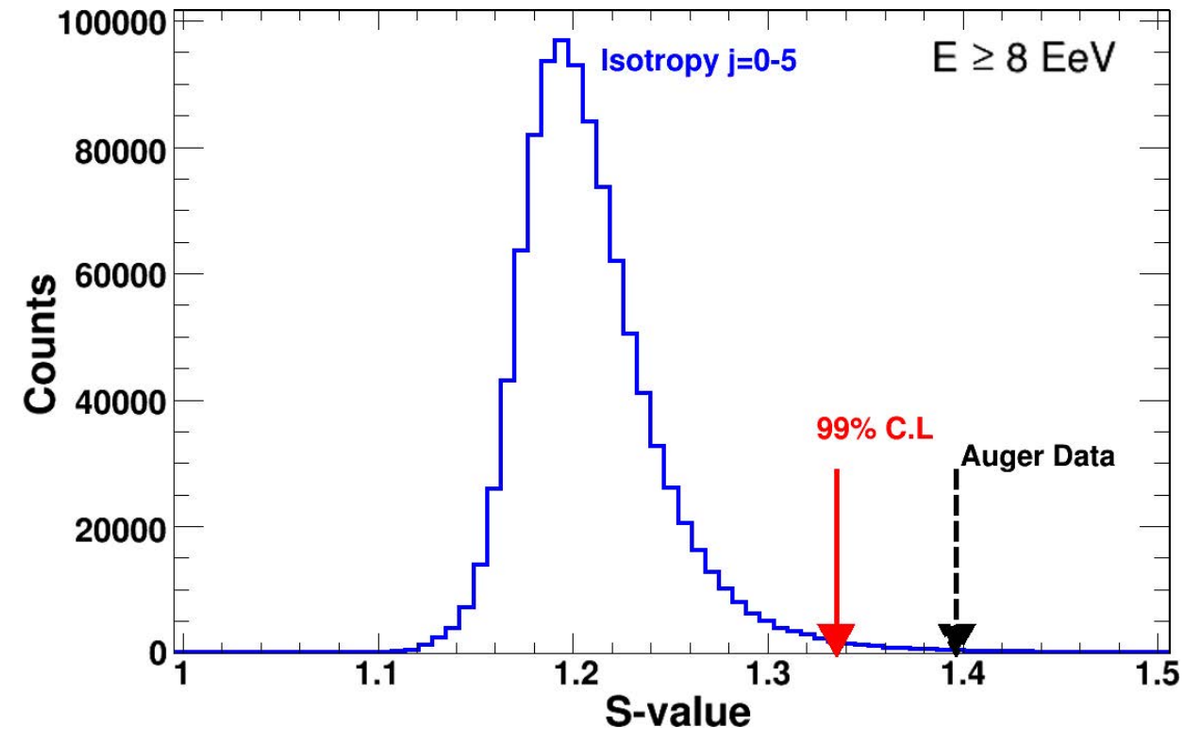




◉ Clear deviation from isotropy for E > 8 EeV

Needlet analysis



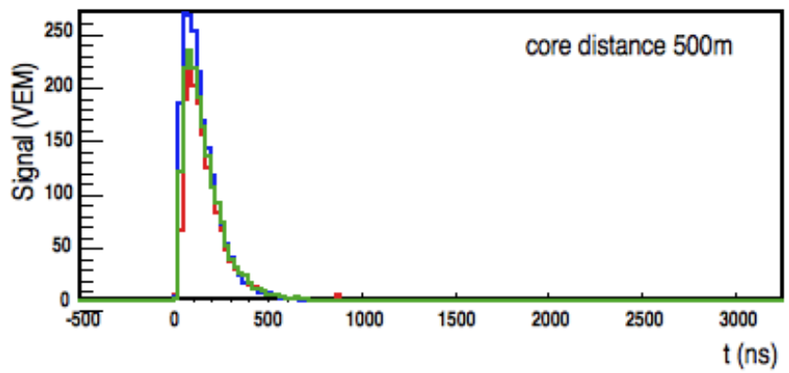


- Needlet: localized wavelet on sphere
- Reproduces: deviation from isotropy for E > 8 EeV

Neutrino detection: Geometry of air showers

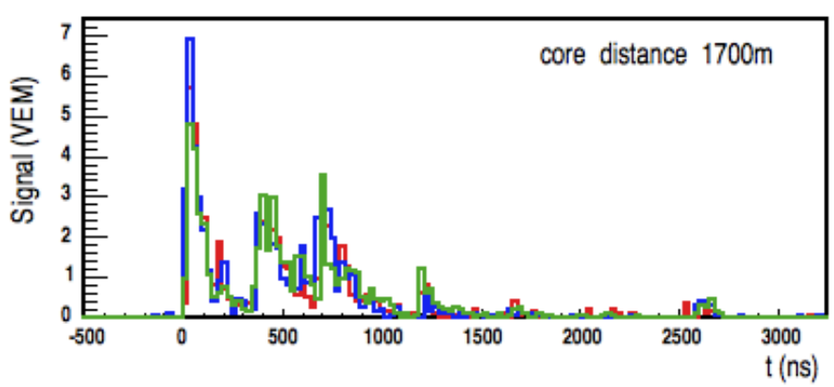
Younger Shower
- Thick front
- Large curvature

Close to core

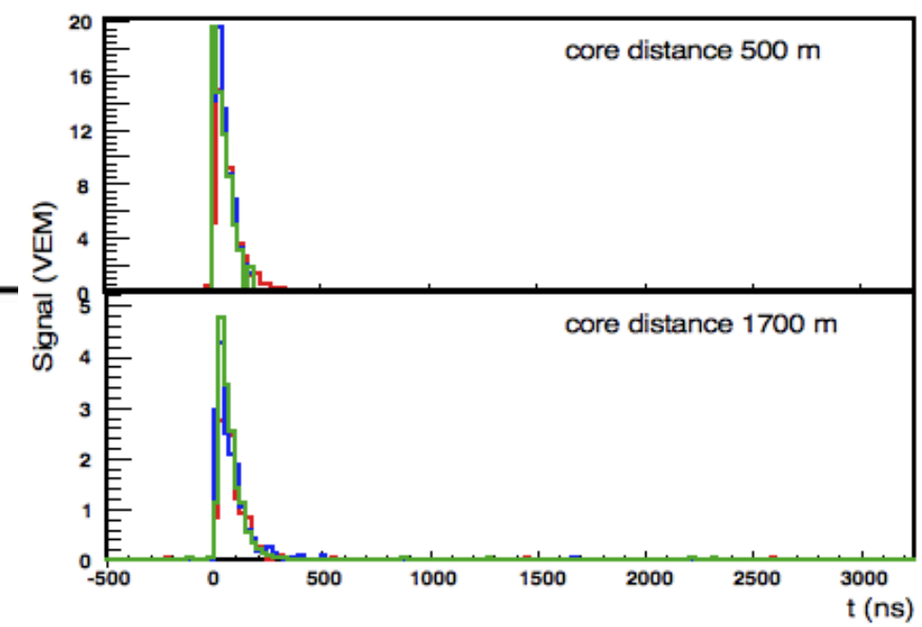


most active region

Far from core

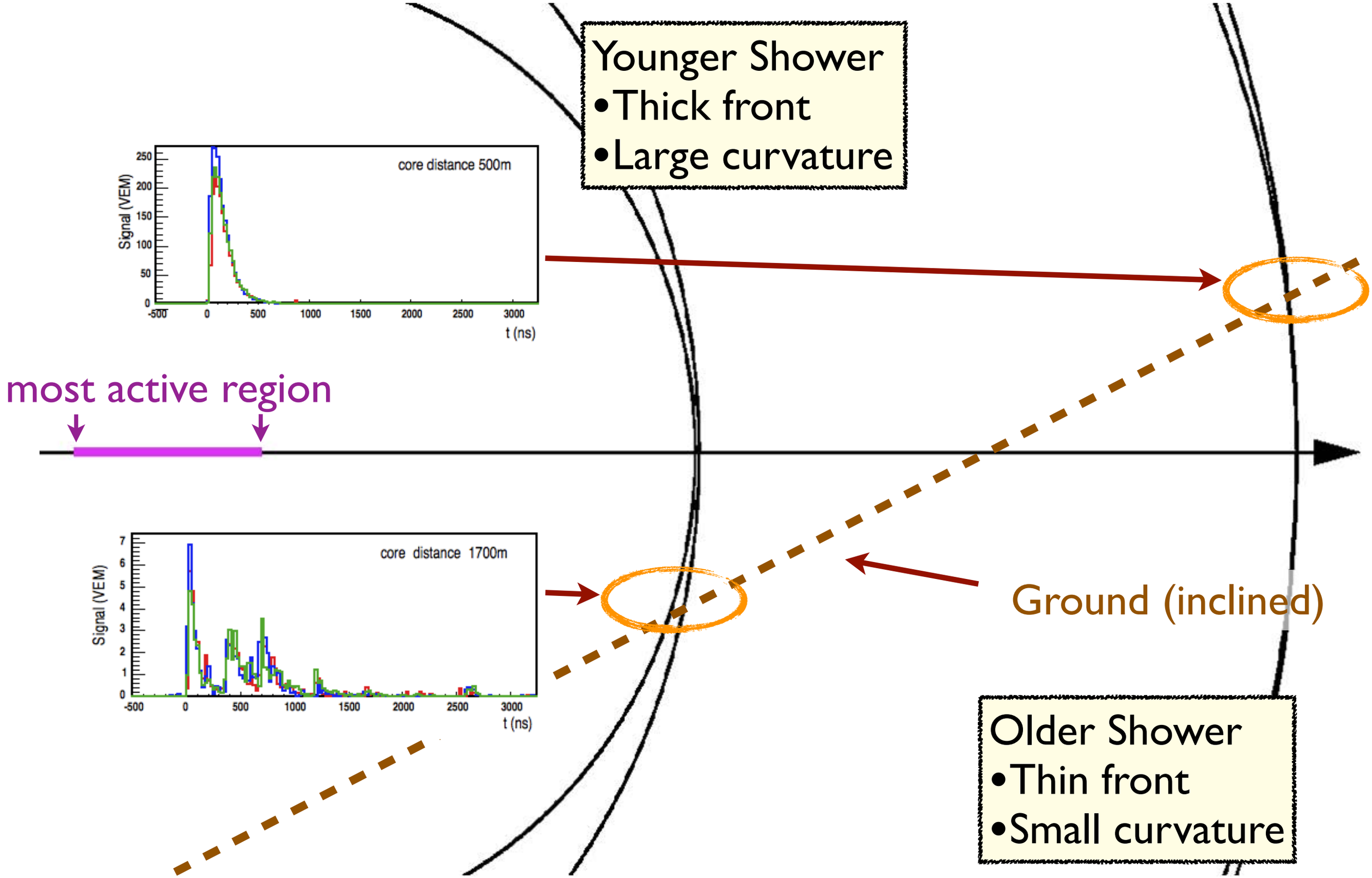


At any distance

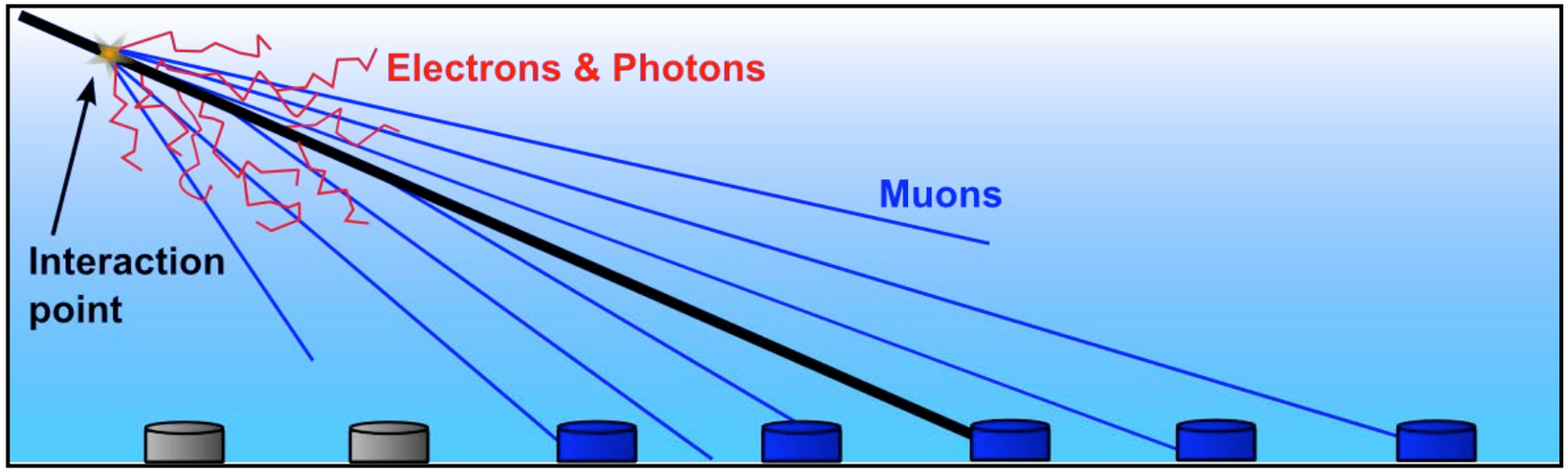


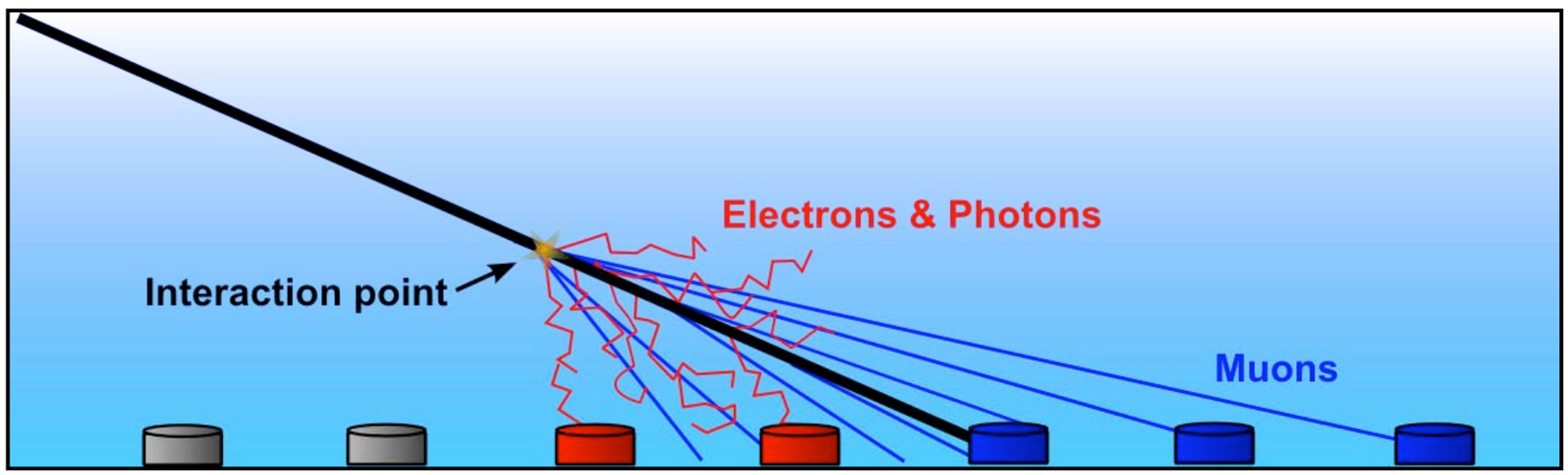
Older Shower
- Thin front
- Small curvature

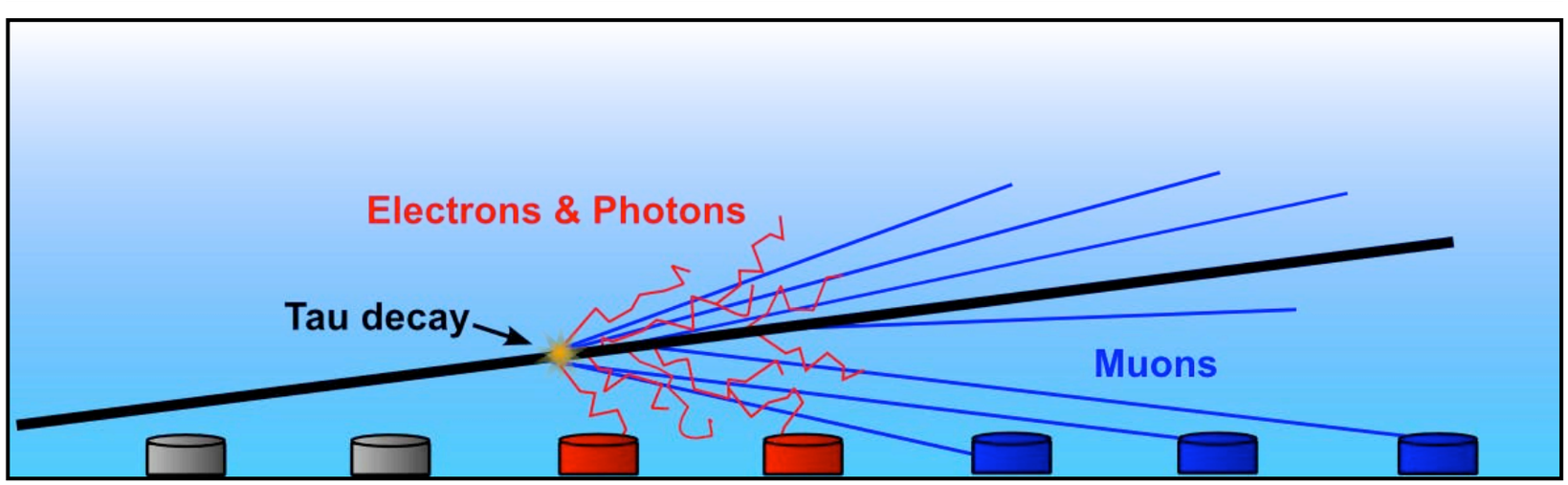
Neutrino detection: Geometry of air showers



Inclined showers





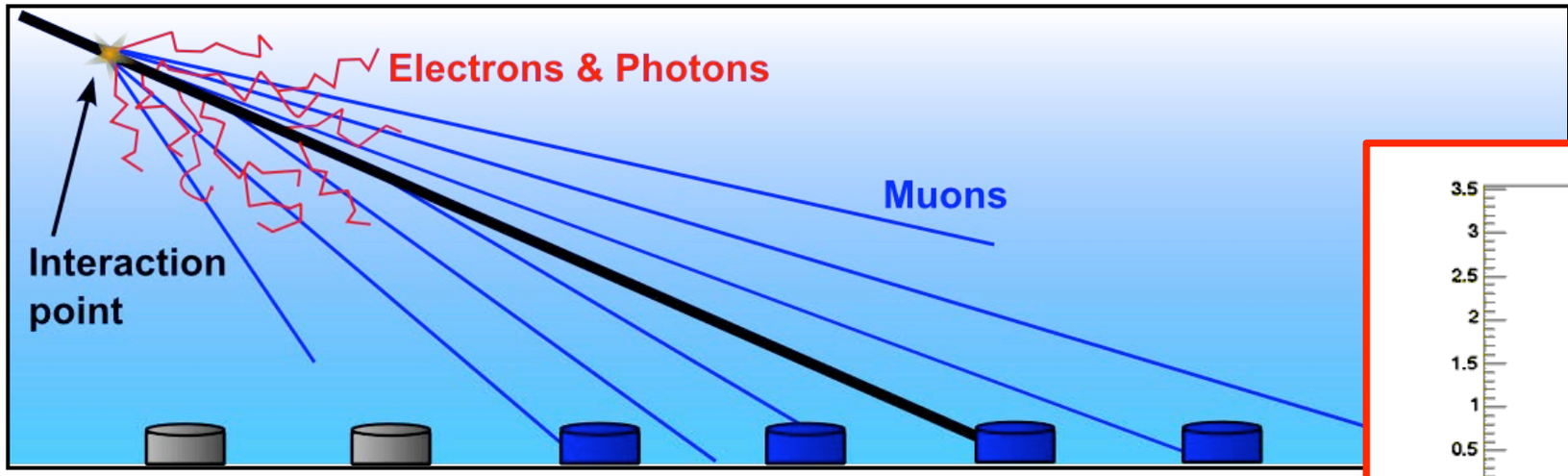


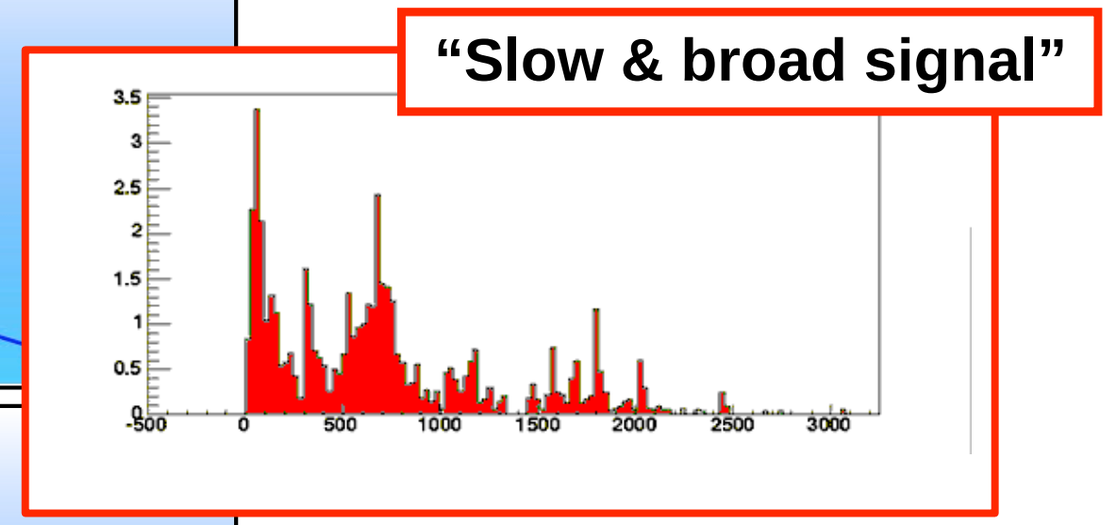
Hadronic shower:
Old, develops far from the detector

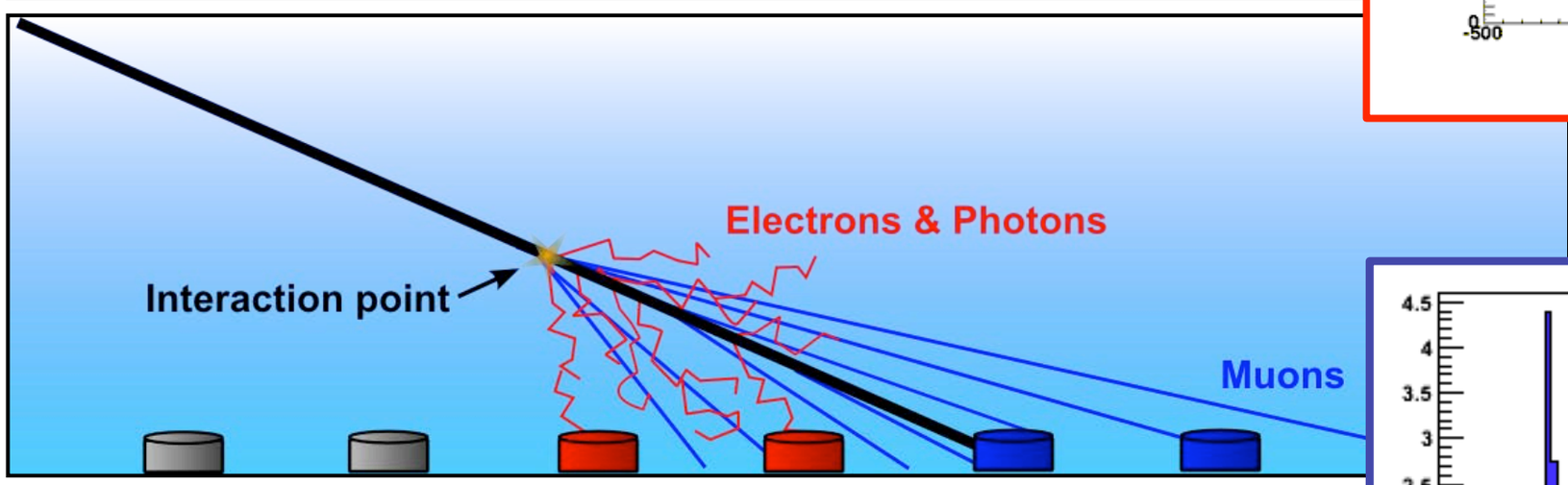
Neutrino shower:
Early region: young
Late region: old

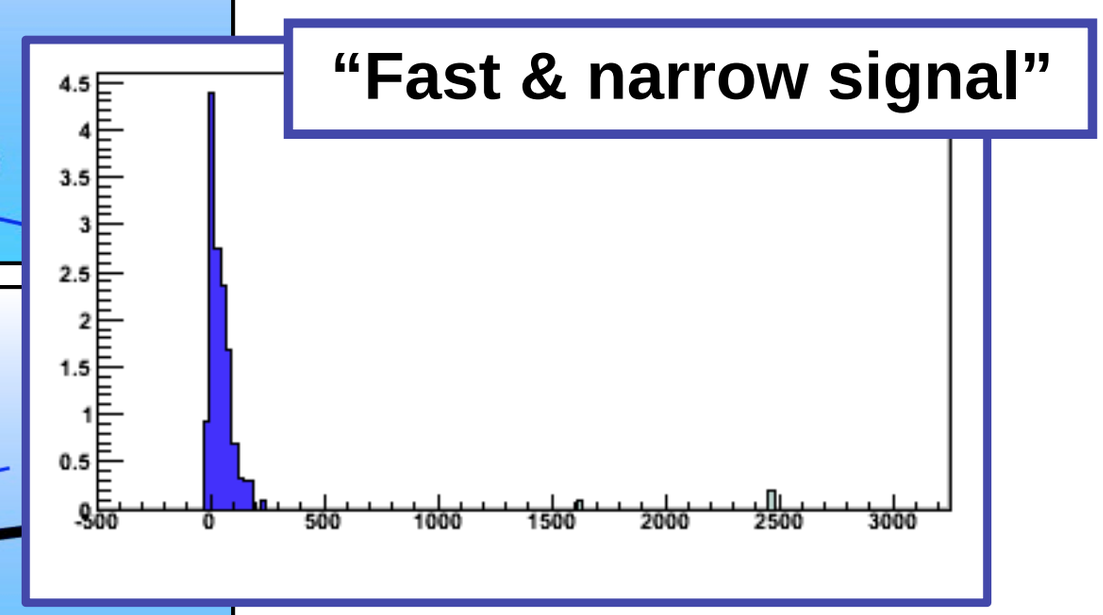
Note:
1000g/cm^2 are
$\approx$ 10km at 90°
$\therefore$ Showers age along footprint

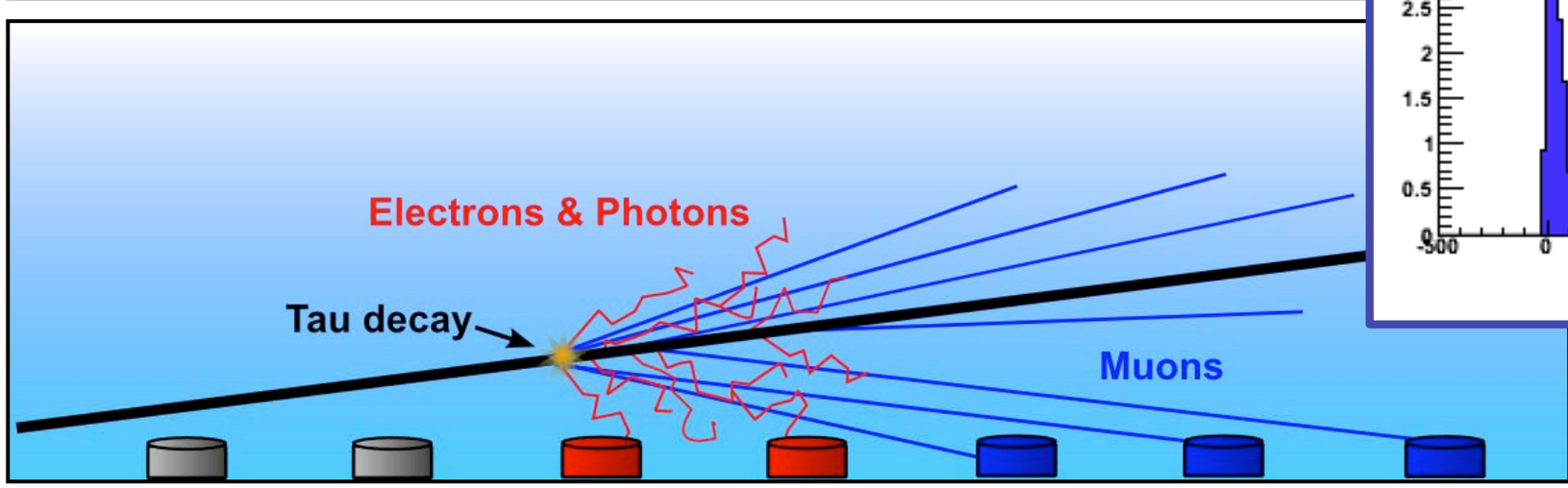
Inclined showers



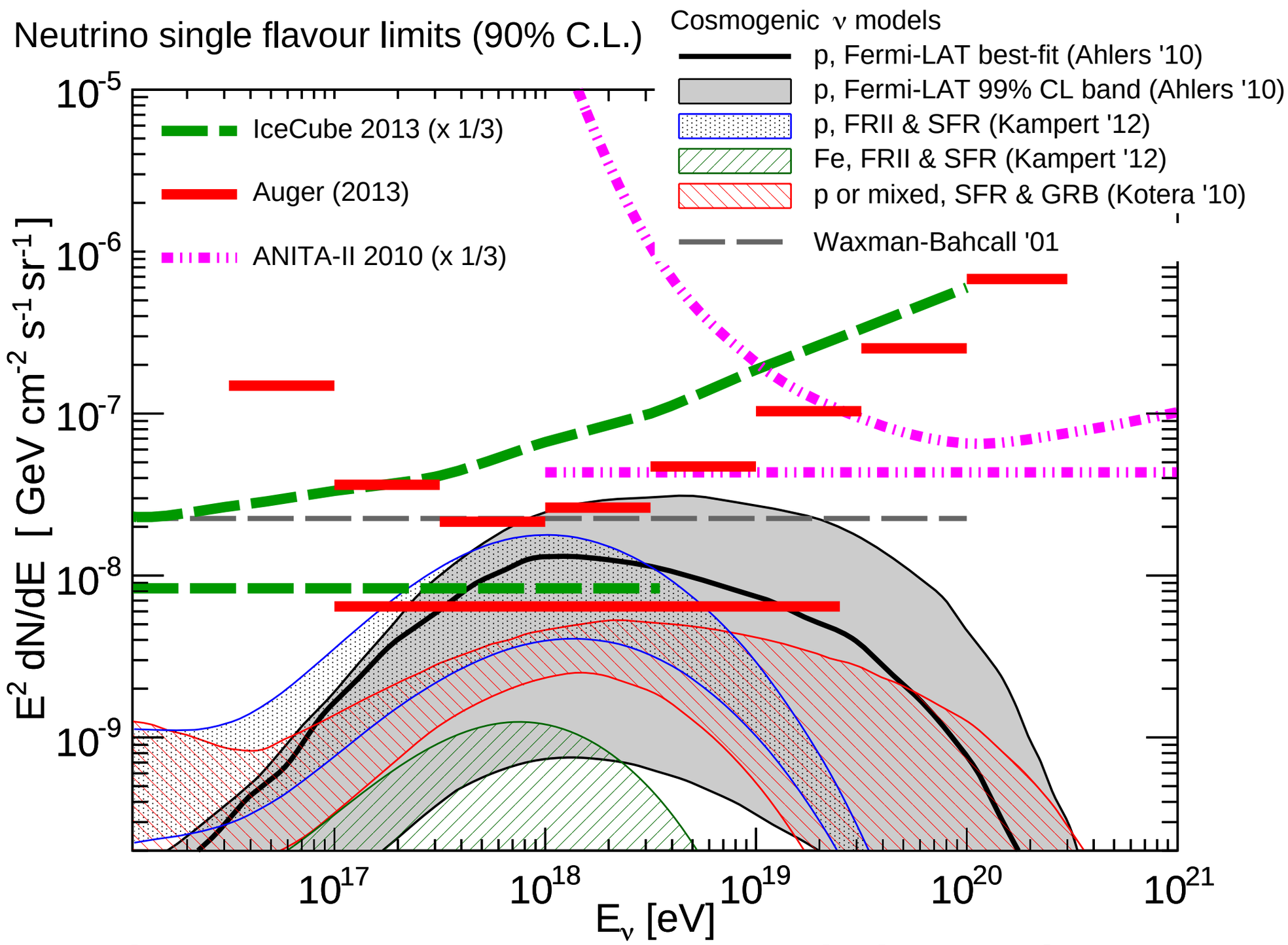






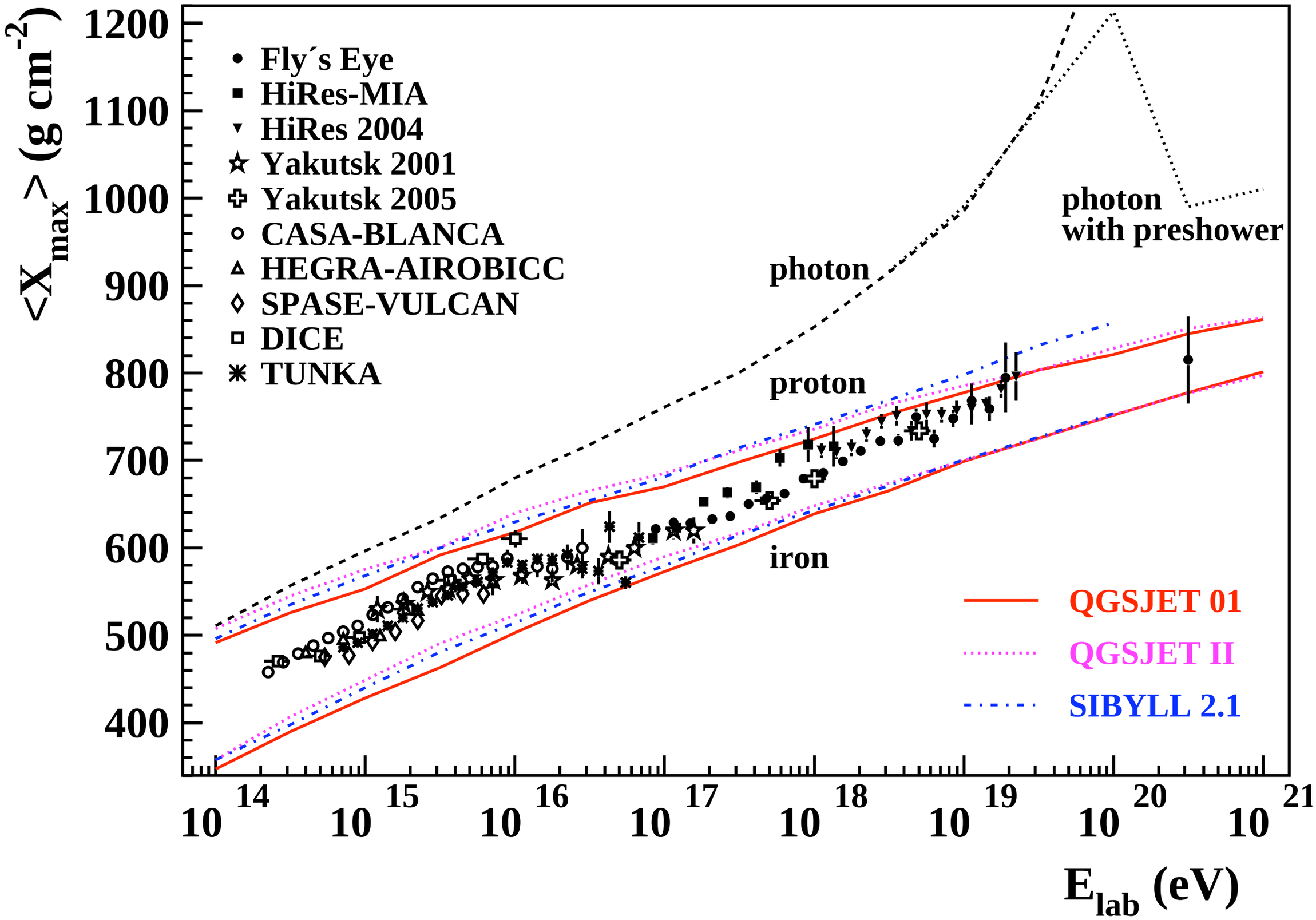


Neutrino limits



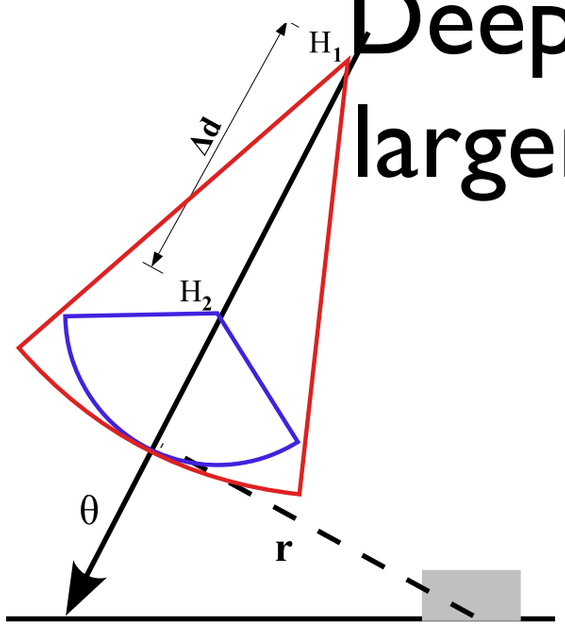
Starts to limit some source models and approach cosmogenic flux predictions

FD photon discrimination

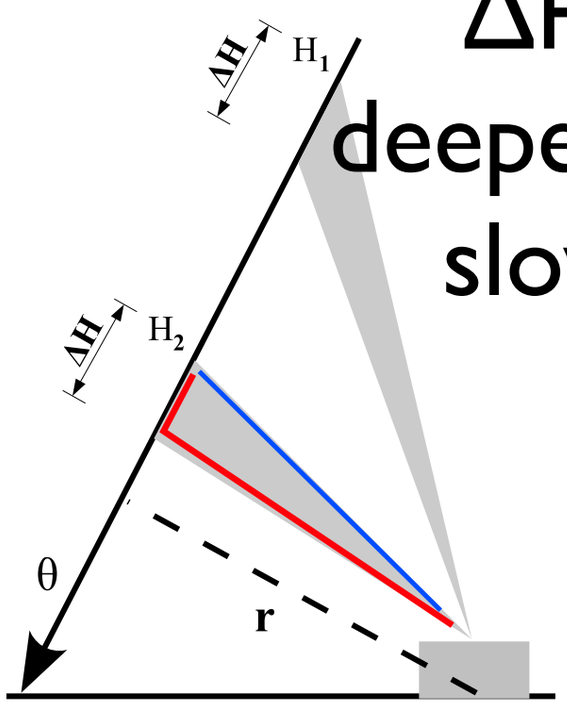


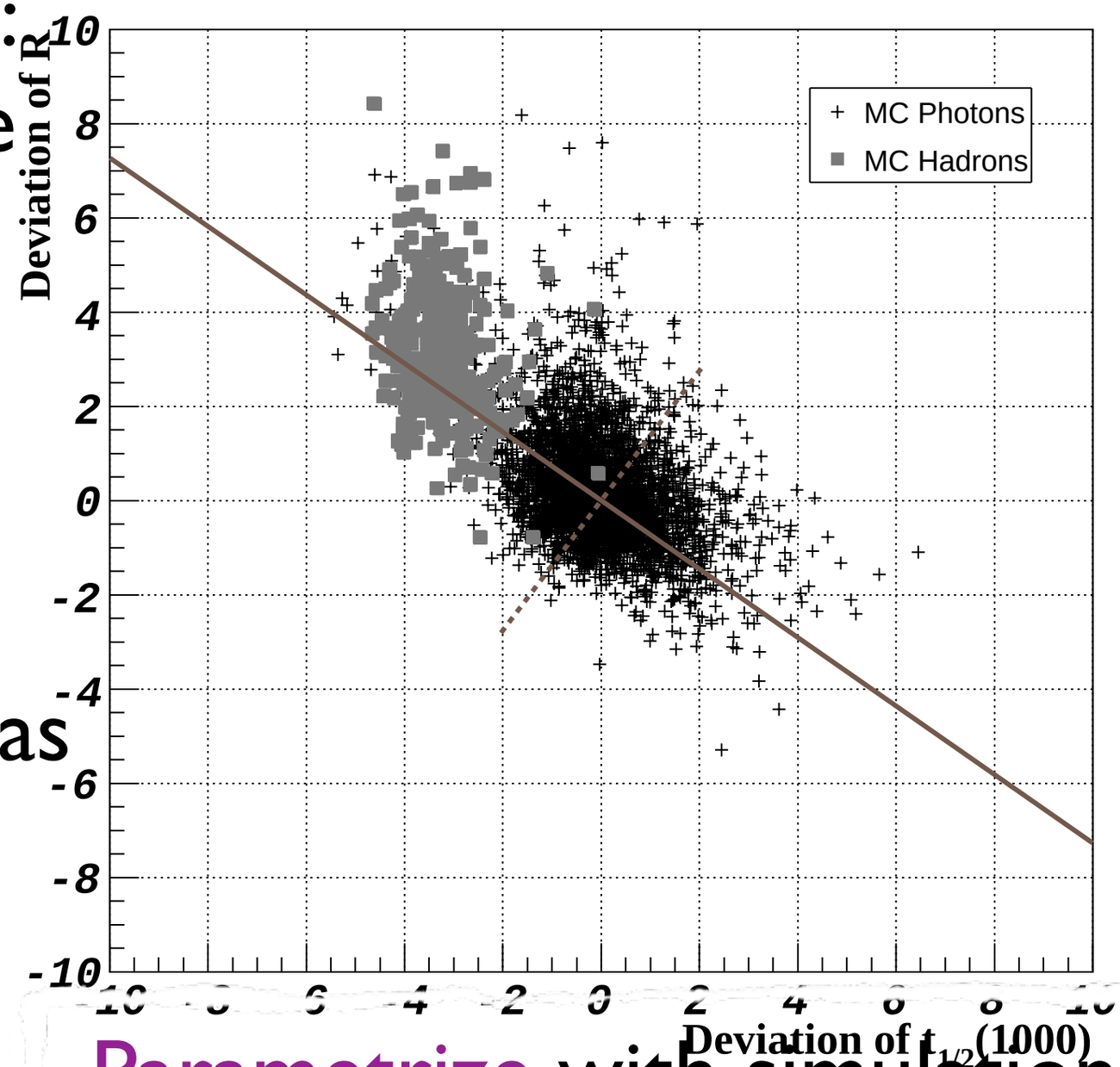
SD photon discrimination

Deeper shower: larger curvature



ΔH gives Δt: deeper shower has slower signals

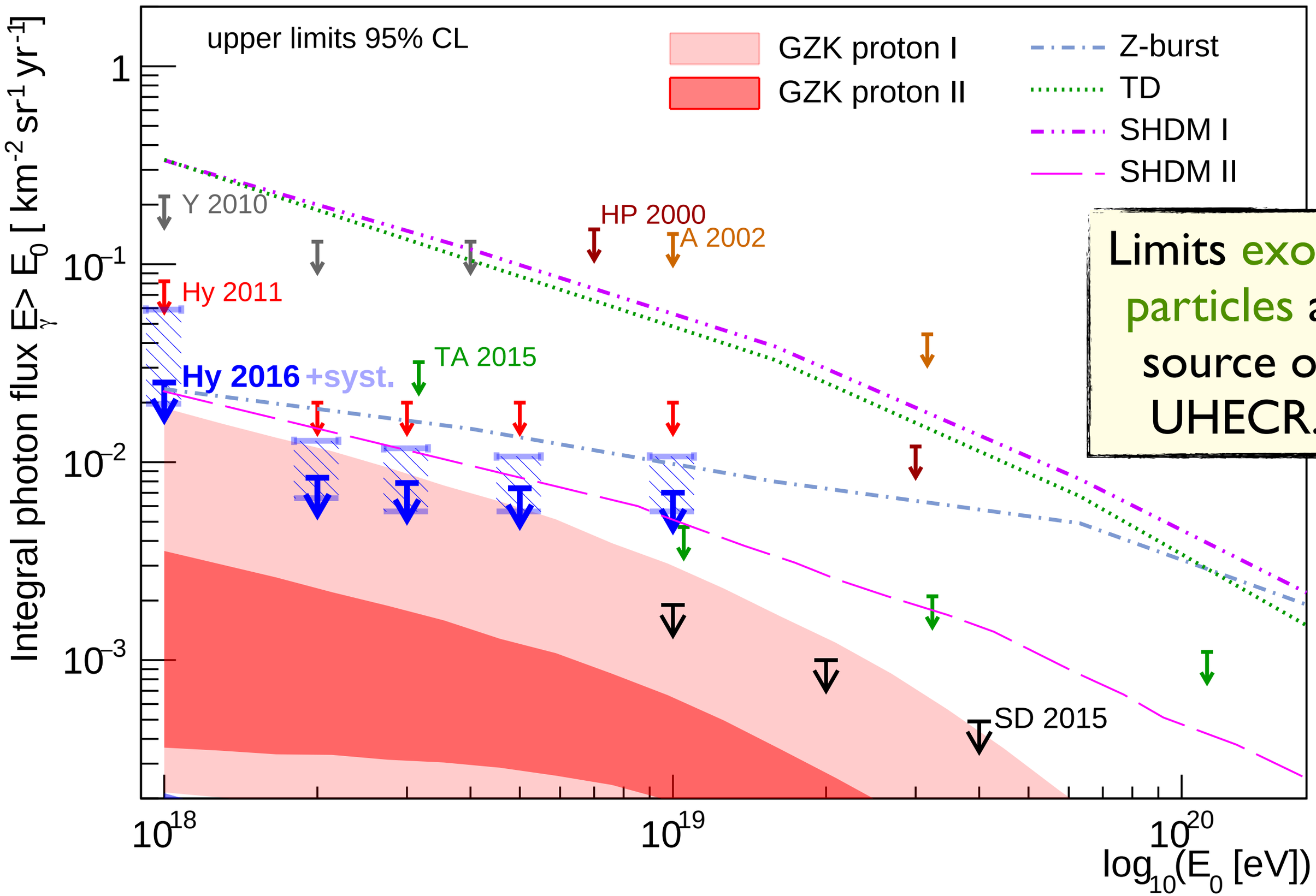




Parametrize with simulations

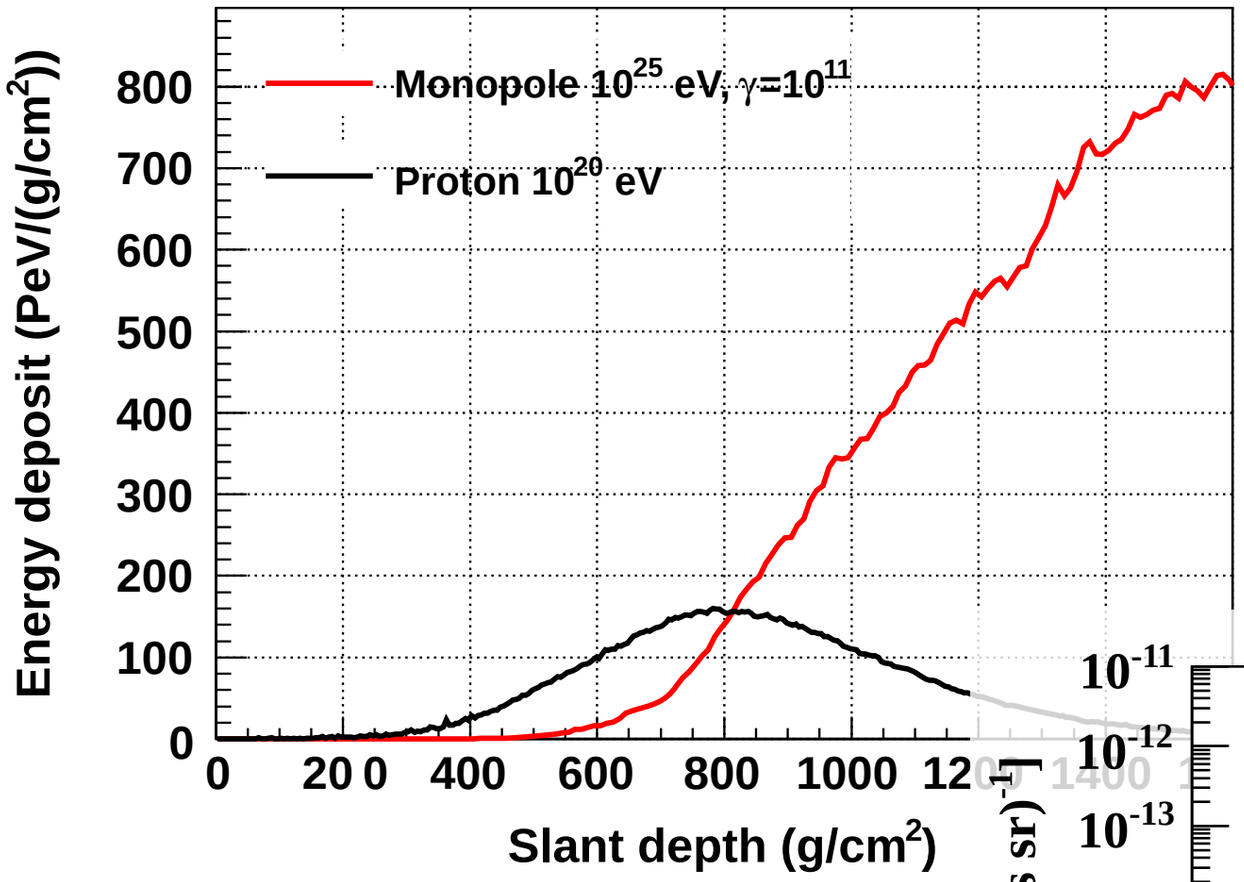
Principal component analysis on deviation

Photon limit



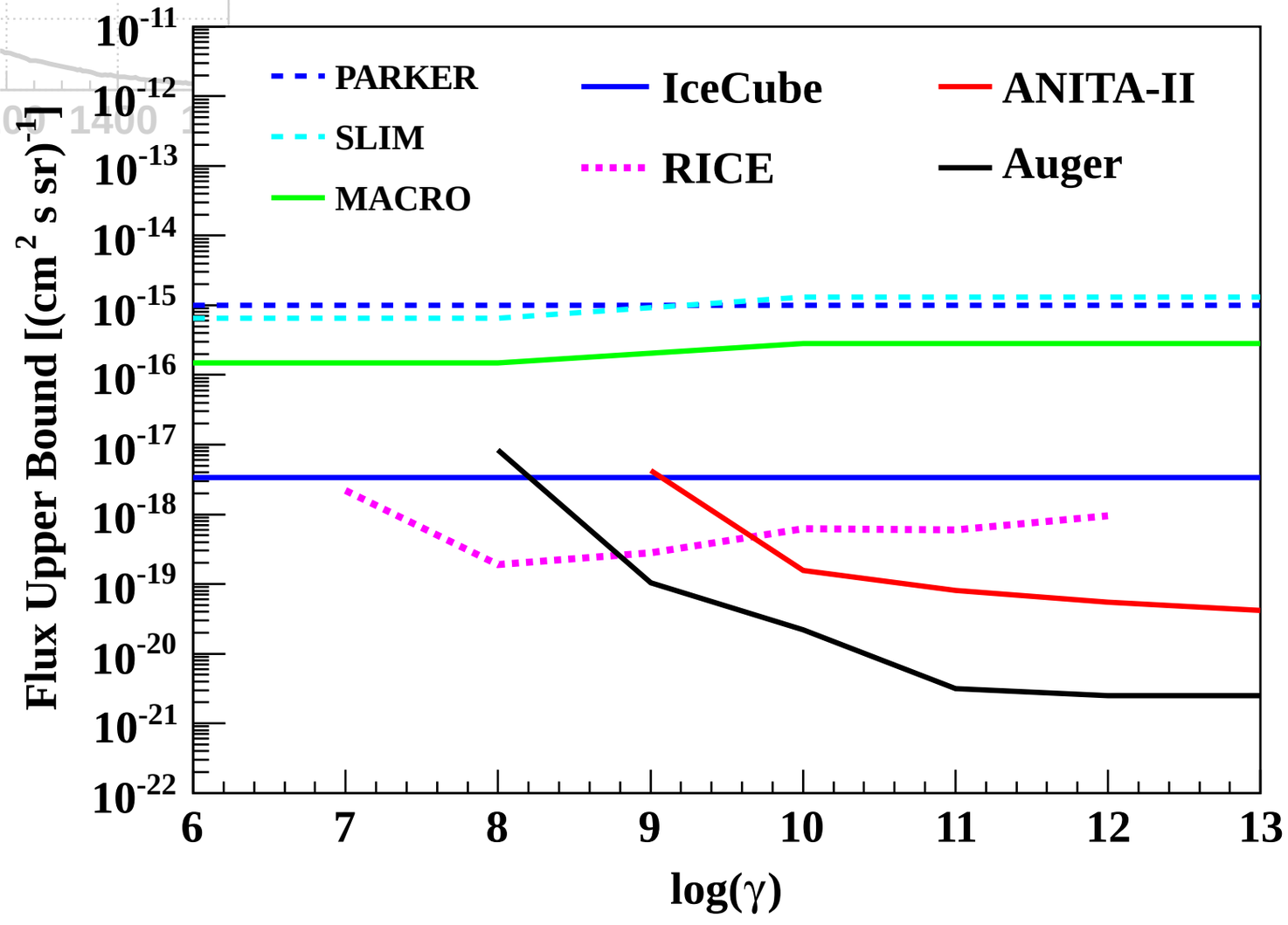
Limits exotic particles as source of UHECR.

Search for magnetic monopoles

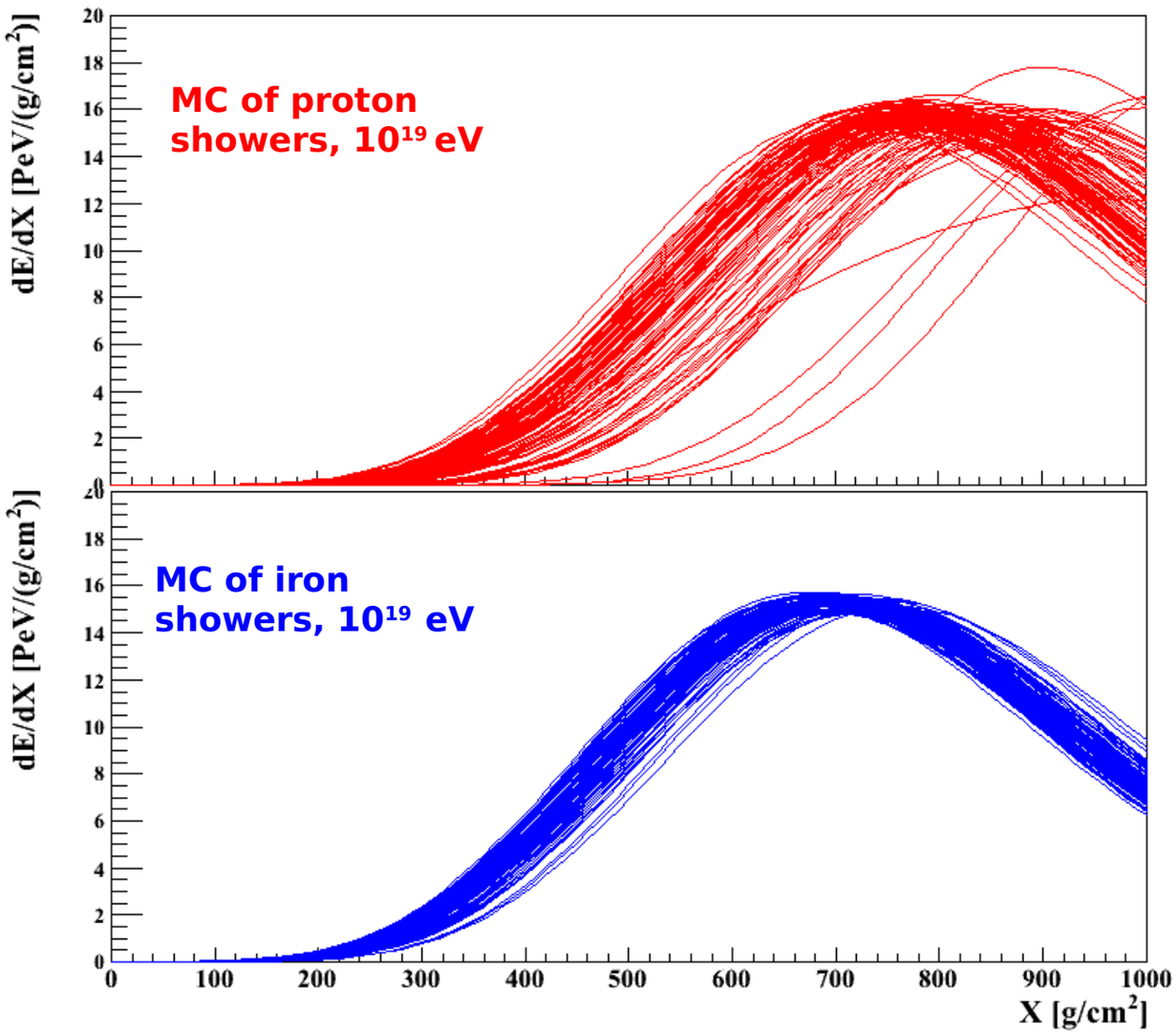


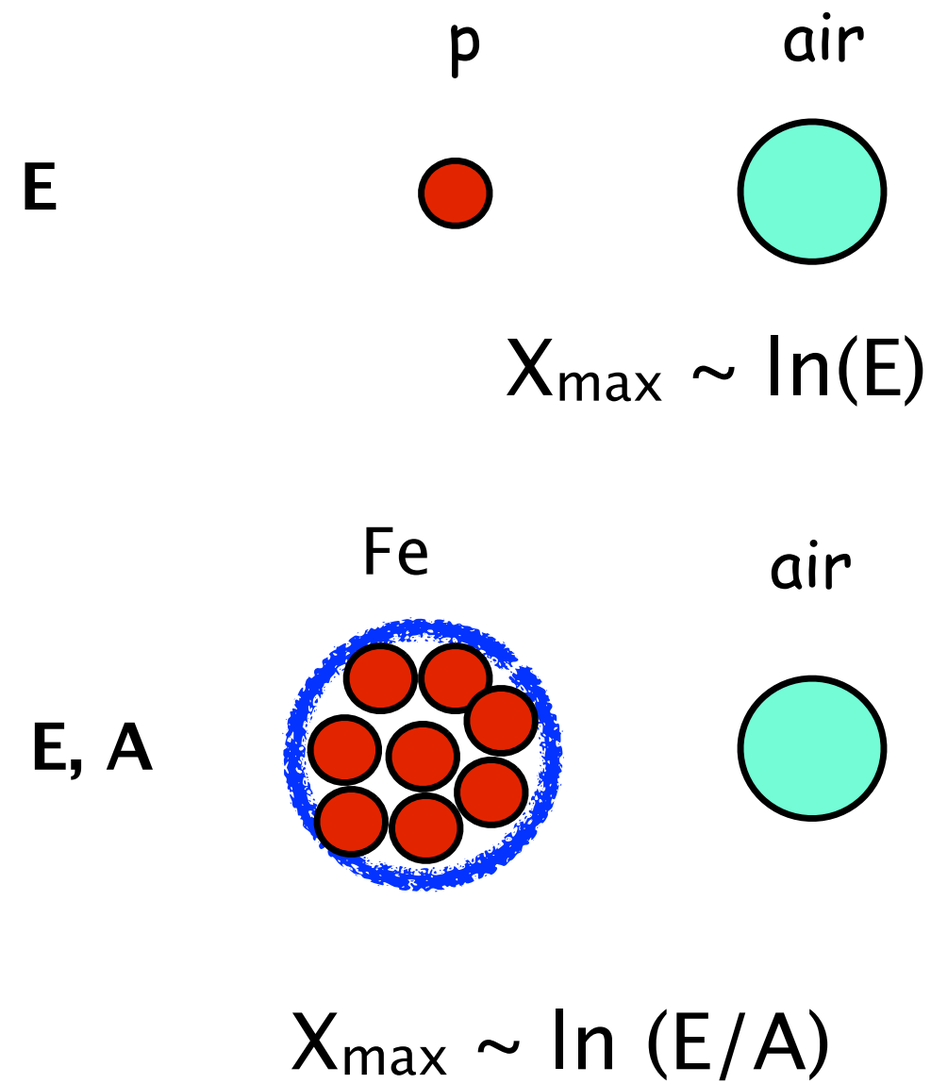
Energy deposit different from hadronic shower

Auger: strongest limits at high E



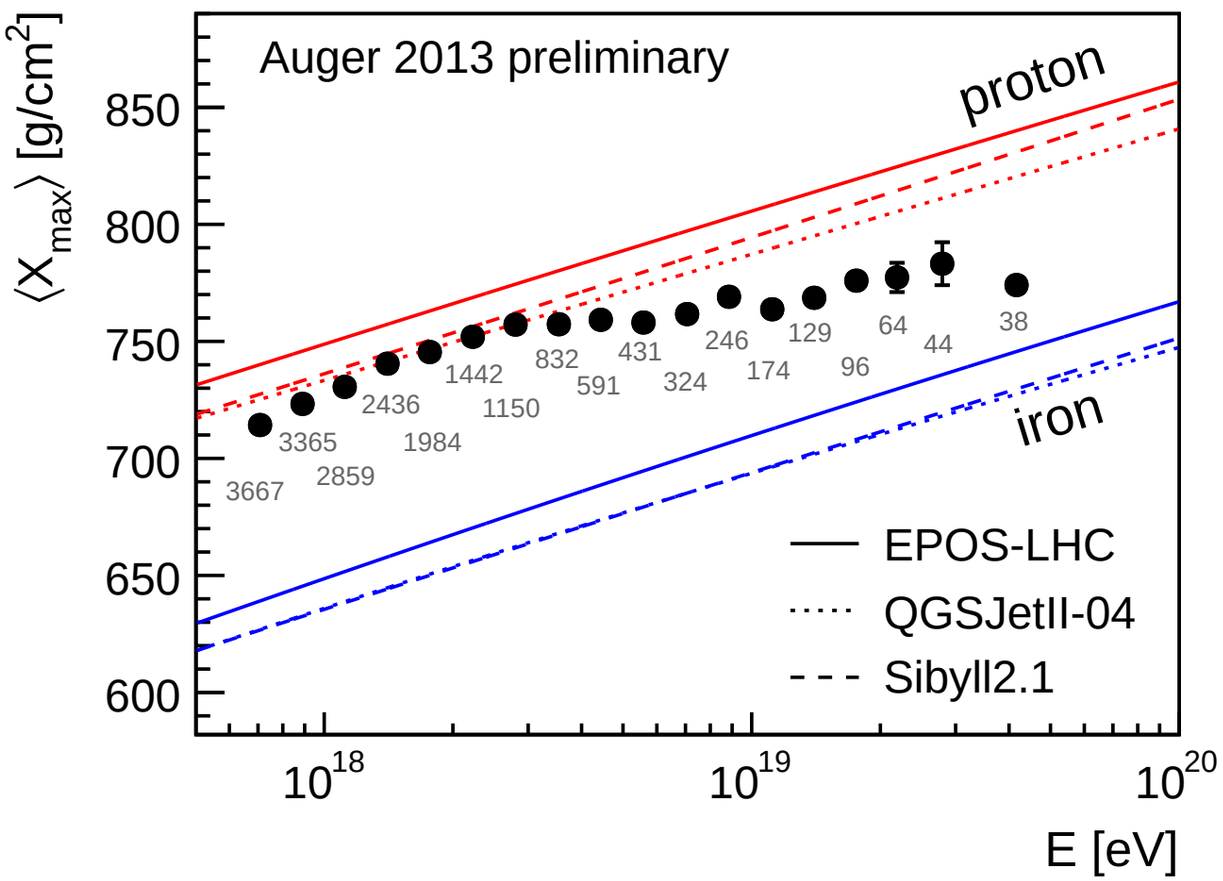
Composition and X_{max}

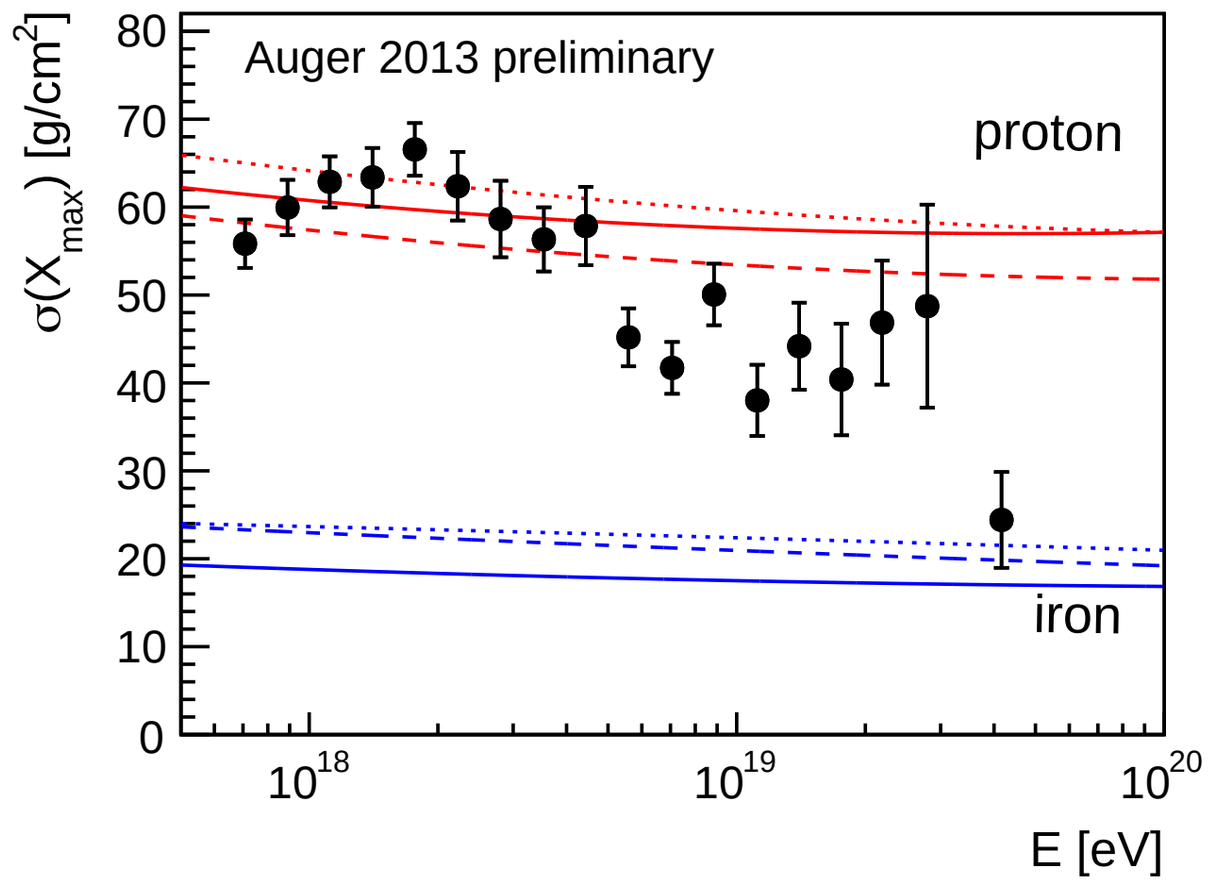




- Both **X_{max}** and **RMS(X_{max})** depend on
  - Energy: Number of generations in air shower
  - Cross-section, i.e., type of primary:
    σ(Fe-Air) > σ(p-Air)

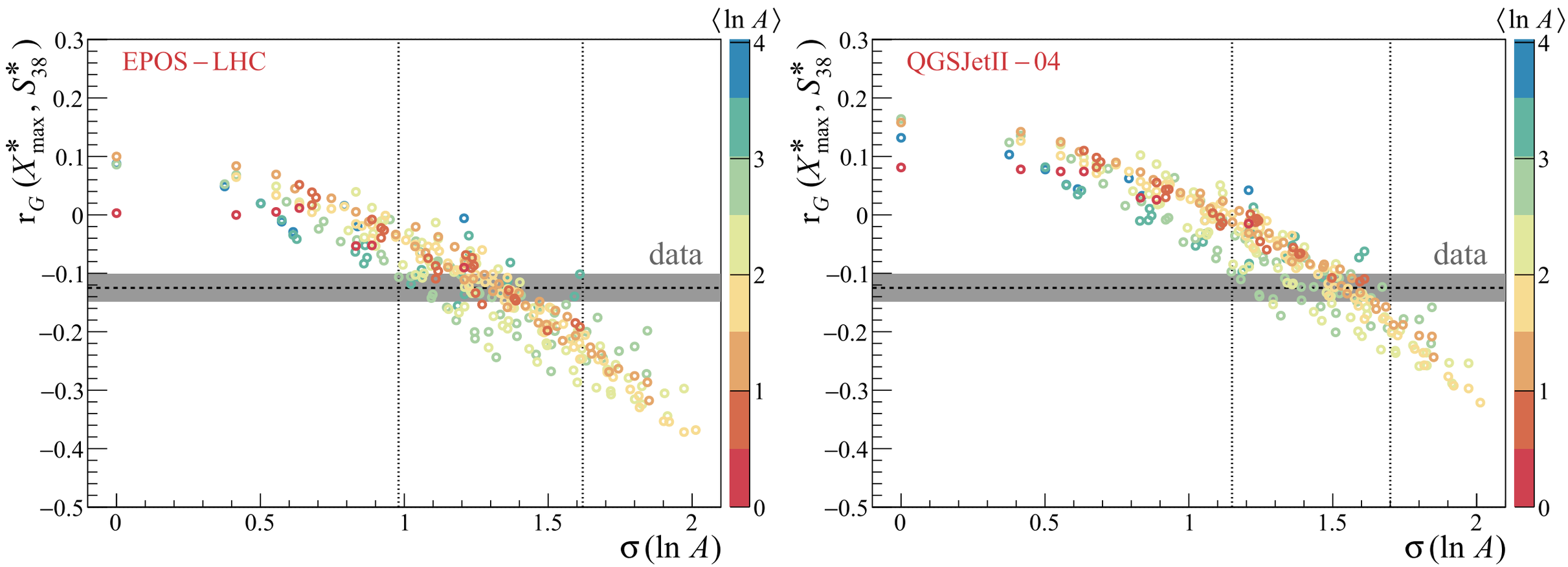
Composition





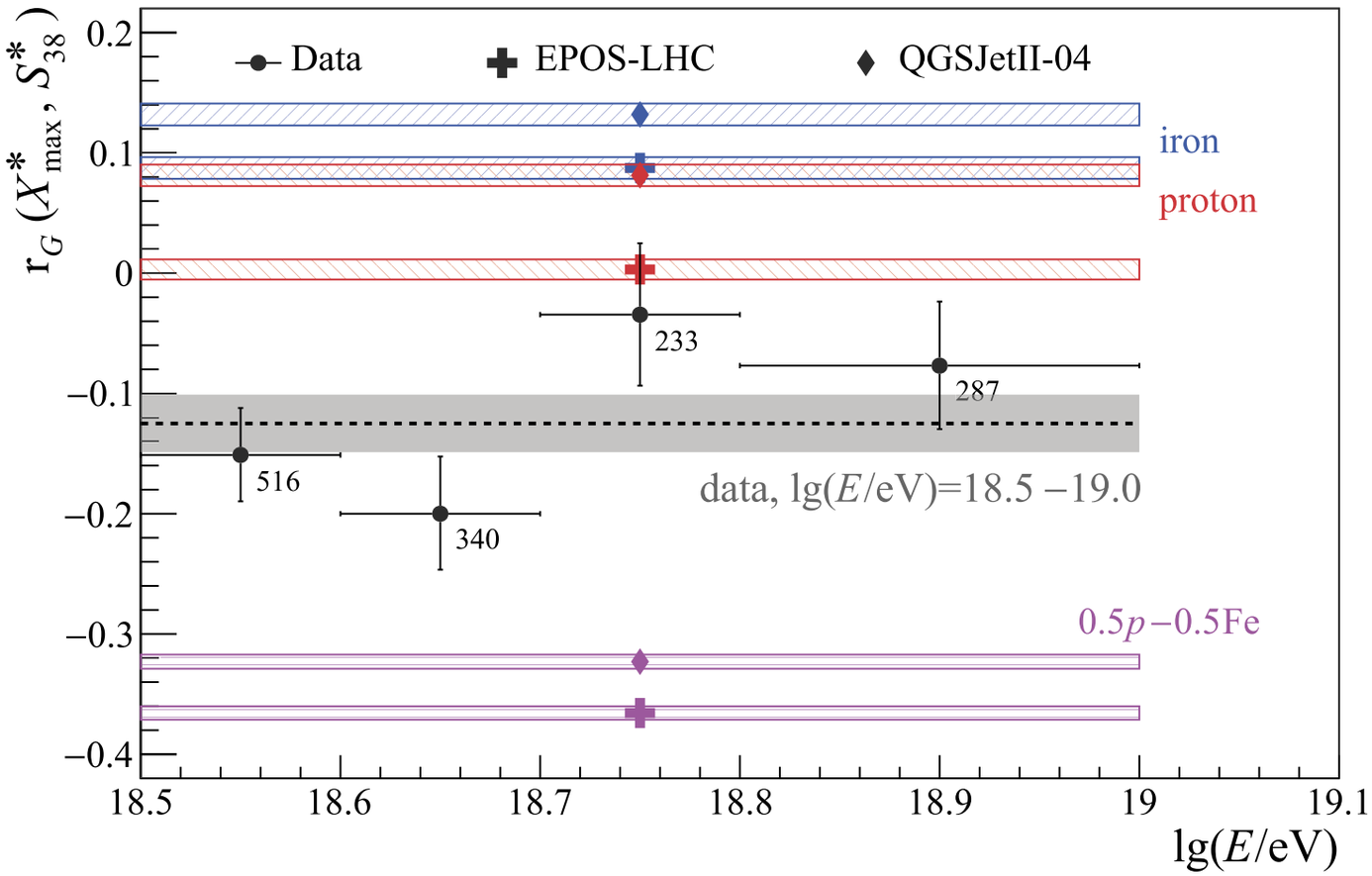
- Indication of a change from light to heavy as energy increases
- Interpretation requires models
- Observation not compatible with all models

Mixed composition at ankle: Spread of X_{max}



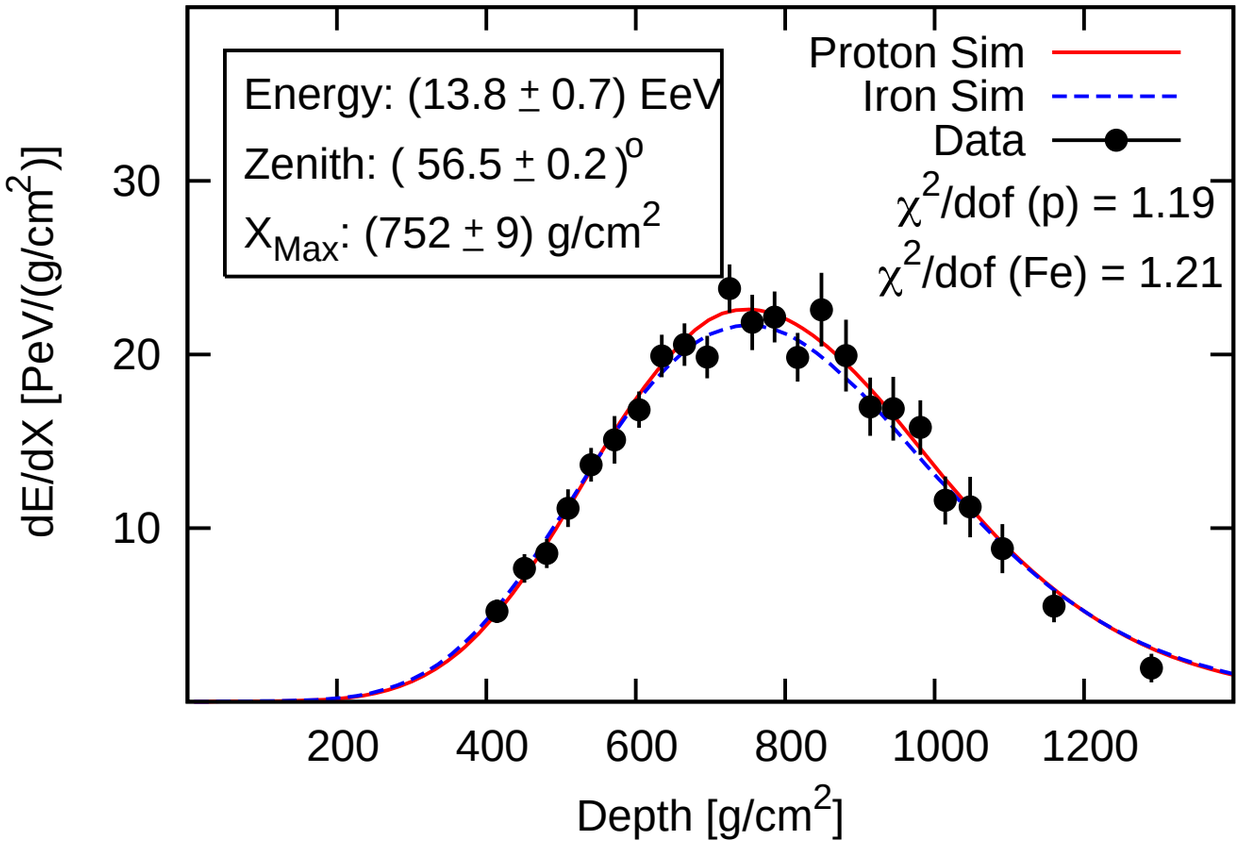
- Correlation Xmax-Signal cannot be fitted using pure composition (σ(ln A) = 0)

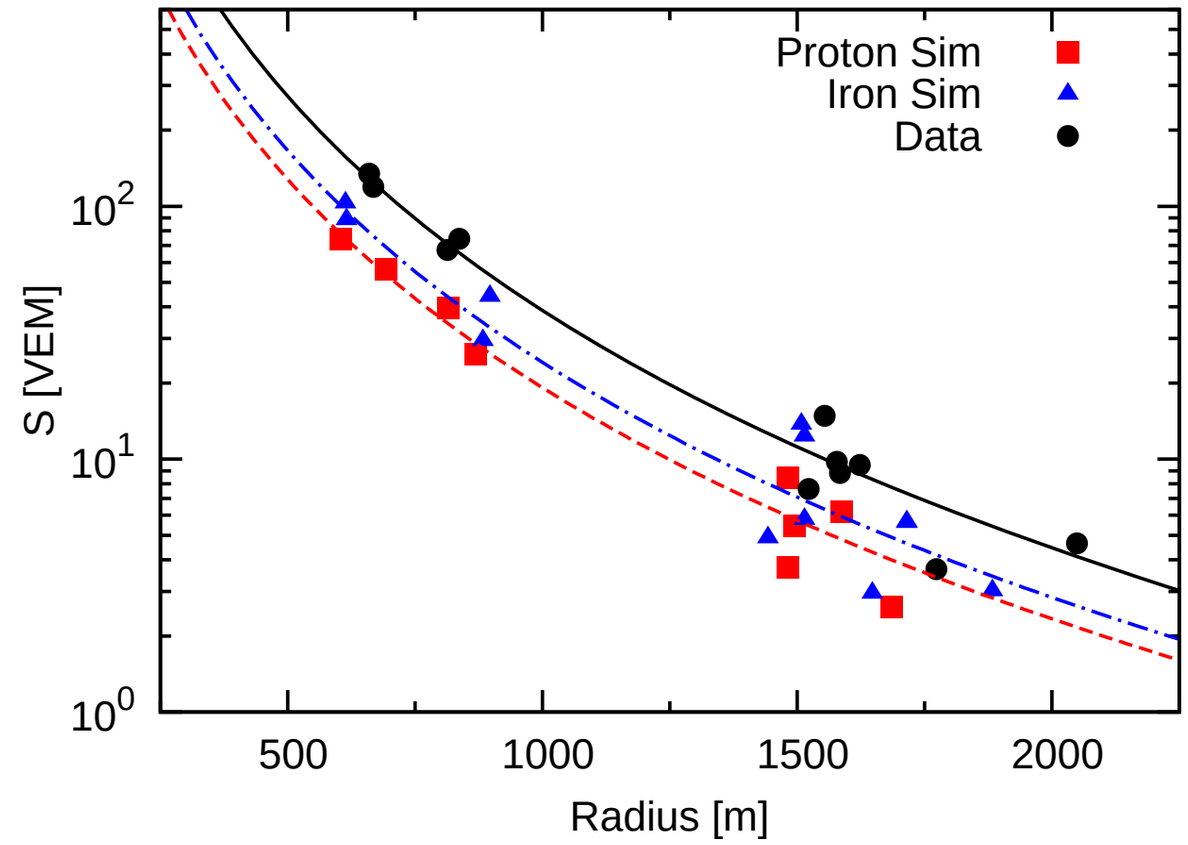
Mixed composition at ankle: Spread of X_{max}



- Correlation Xmax-Signal cannot be fitted using pure composition (σ(ln A) = 0)

Muon fraction



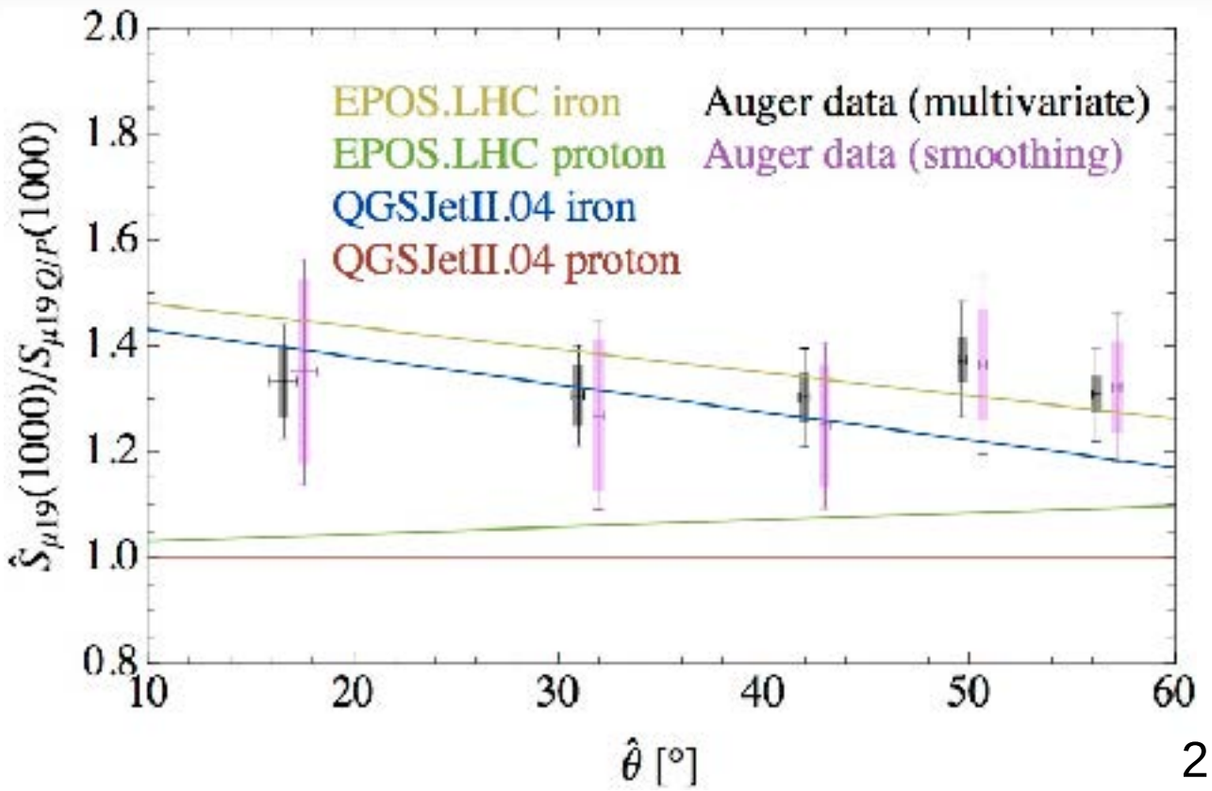


FD: em signal
Good fit

SD: em + μ signal
Data above sim

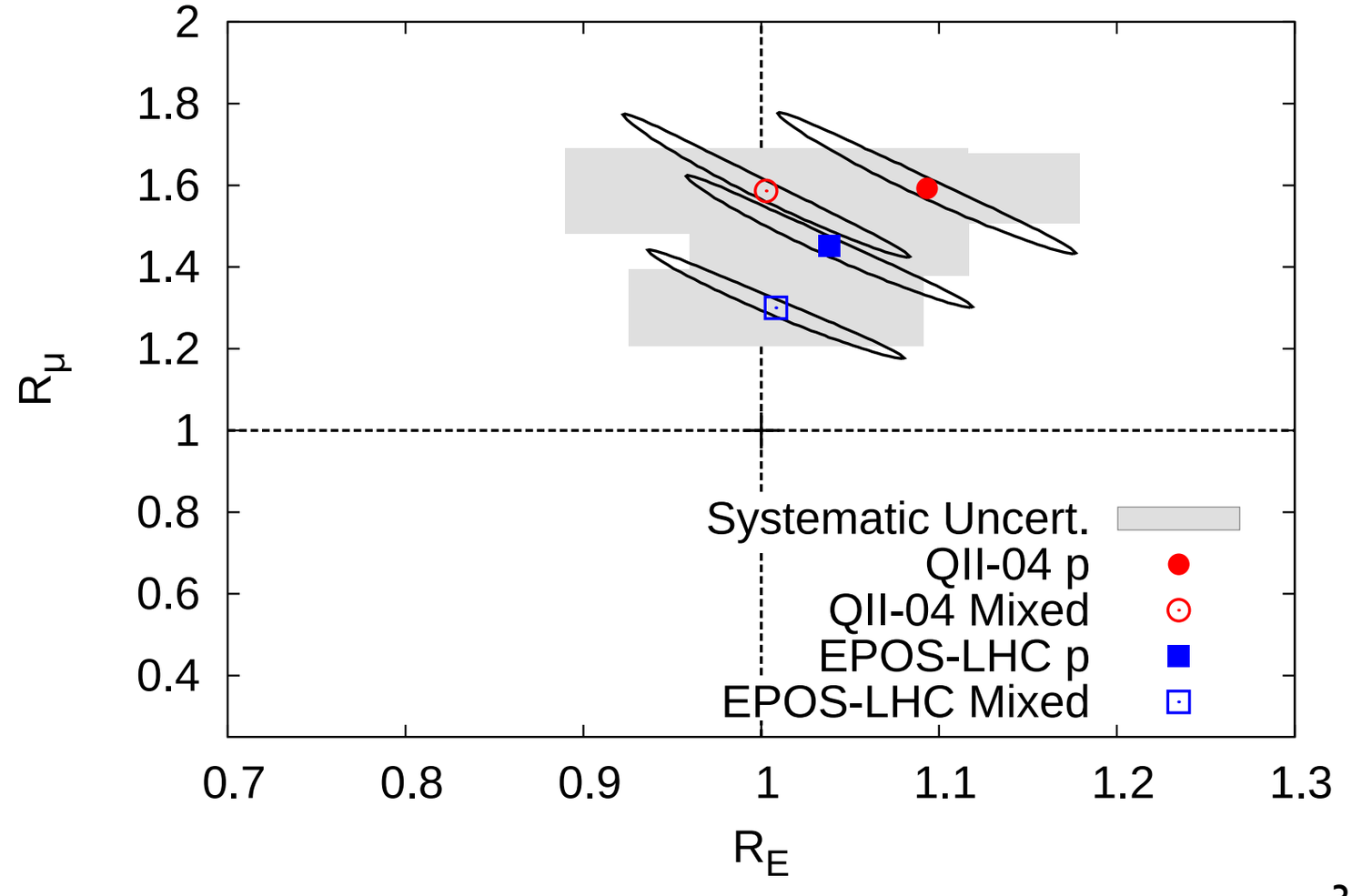
- Extracted fraction of muons and models disagree ⇒ rescale

Muon rescaling

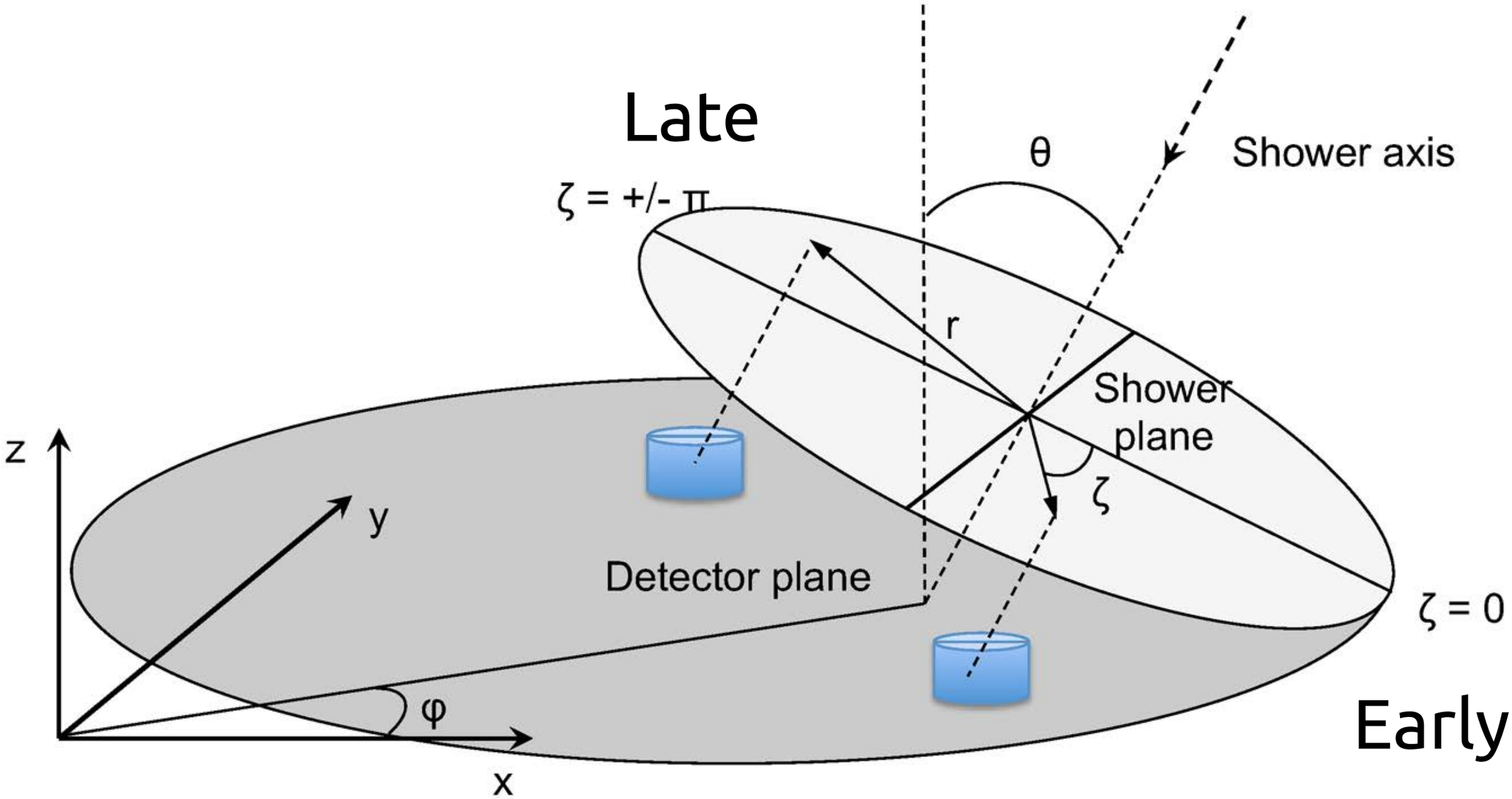


Rescaling, using QGSJetII.04 proton as a baseline

Best fit muon and EM rescaling for different models and compositions

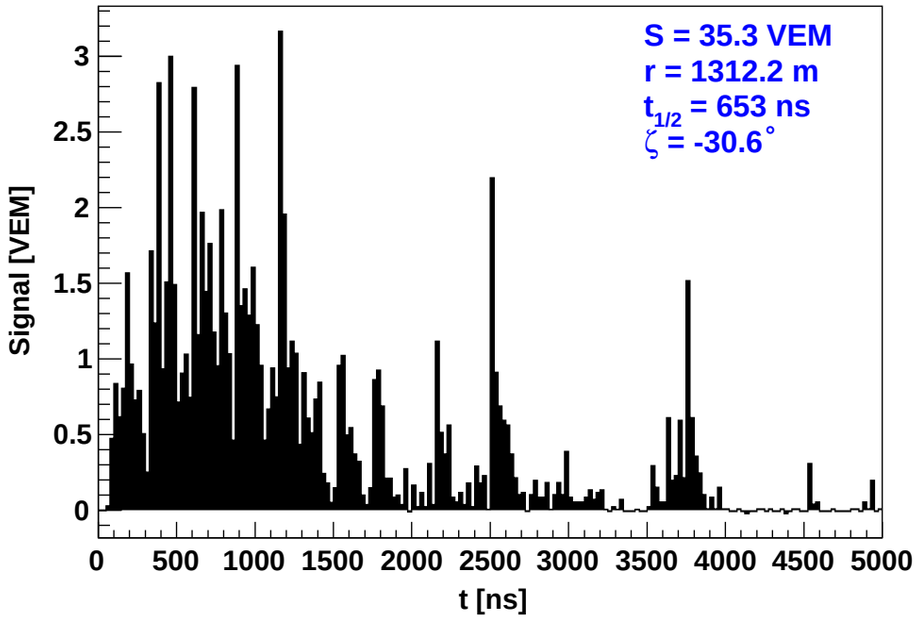


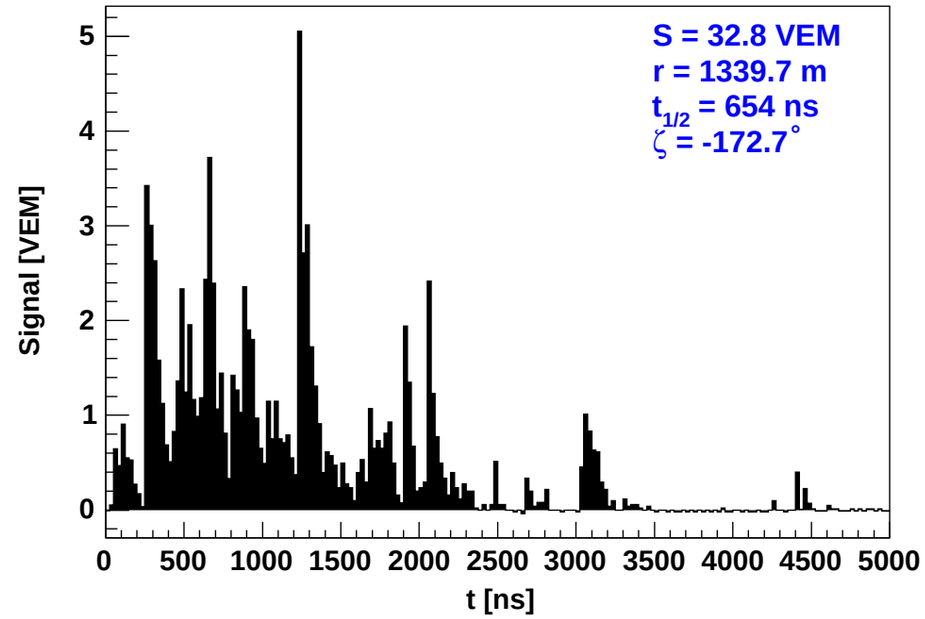
Risetime asymmetry



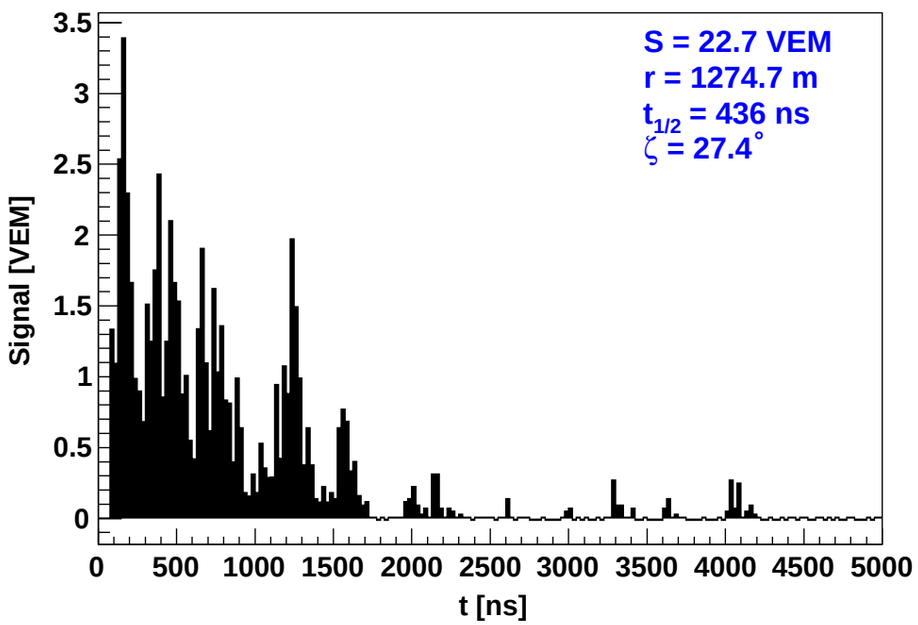
- Early vs late shower
  - Additional propagation for late part

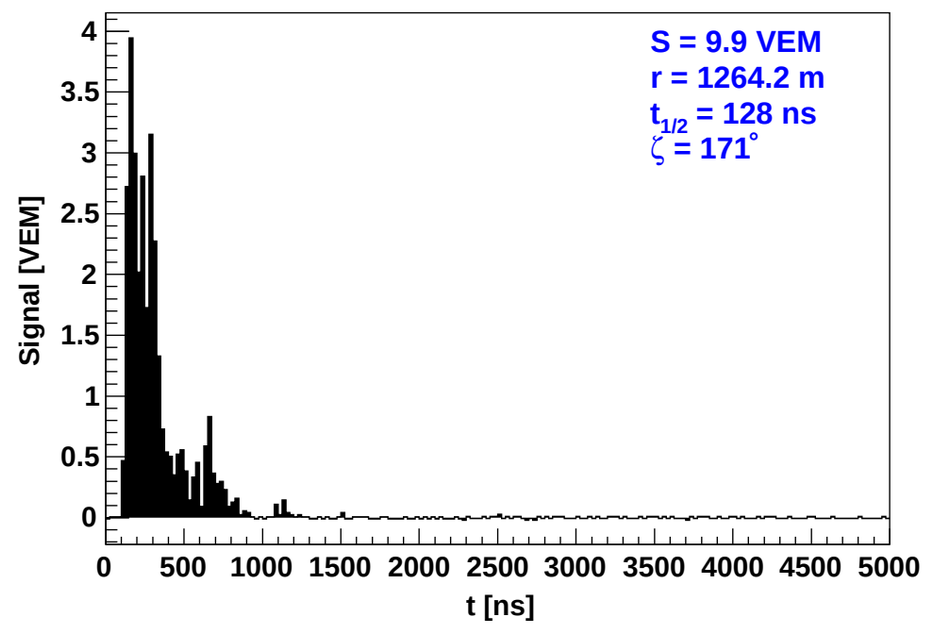
Asymmetry example





E = 16.9 EeV
θ = 15.7°



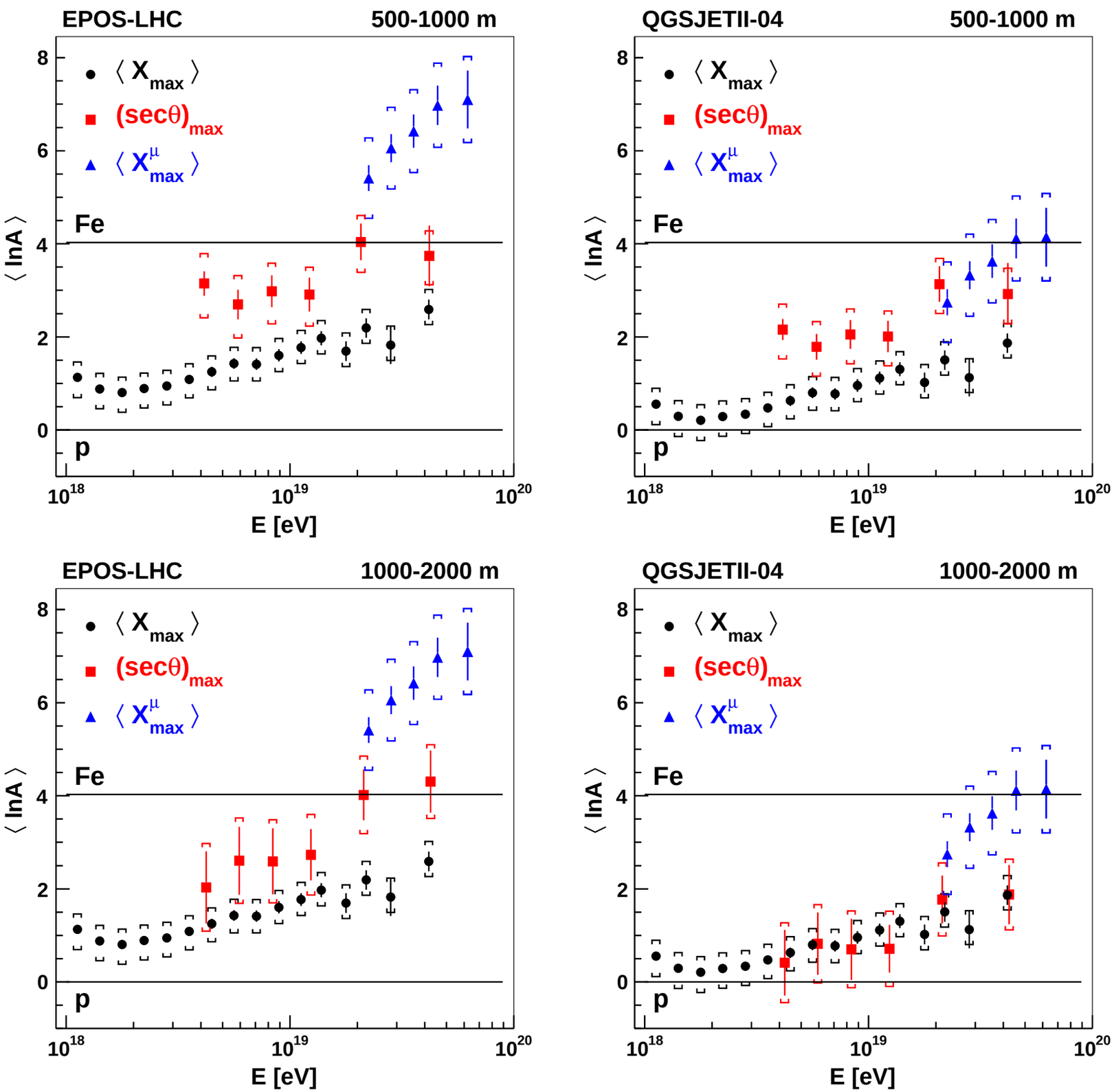


E = 7.7 EeV
θ = 52°
more asym.

Early

Late

Models: lack of ability to fit



Neither model fits all data:

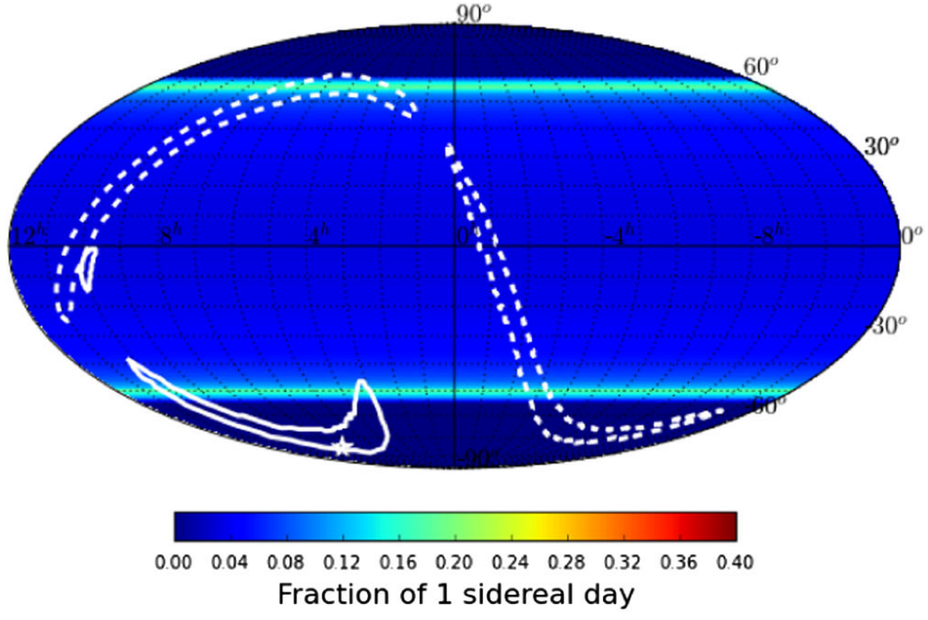
EPOS-LHC: fails X^{μ}_{max}

QGSJETII: inconsistent $(\sec\theta)_{max}$ for different distances

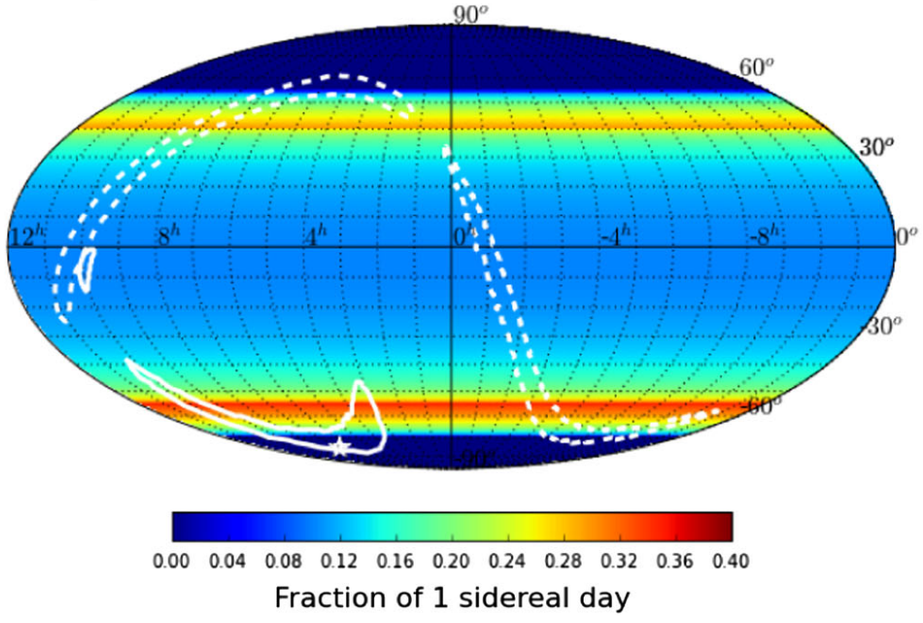
Neutrino followup of Gravitational Wave events

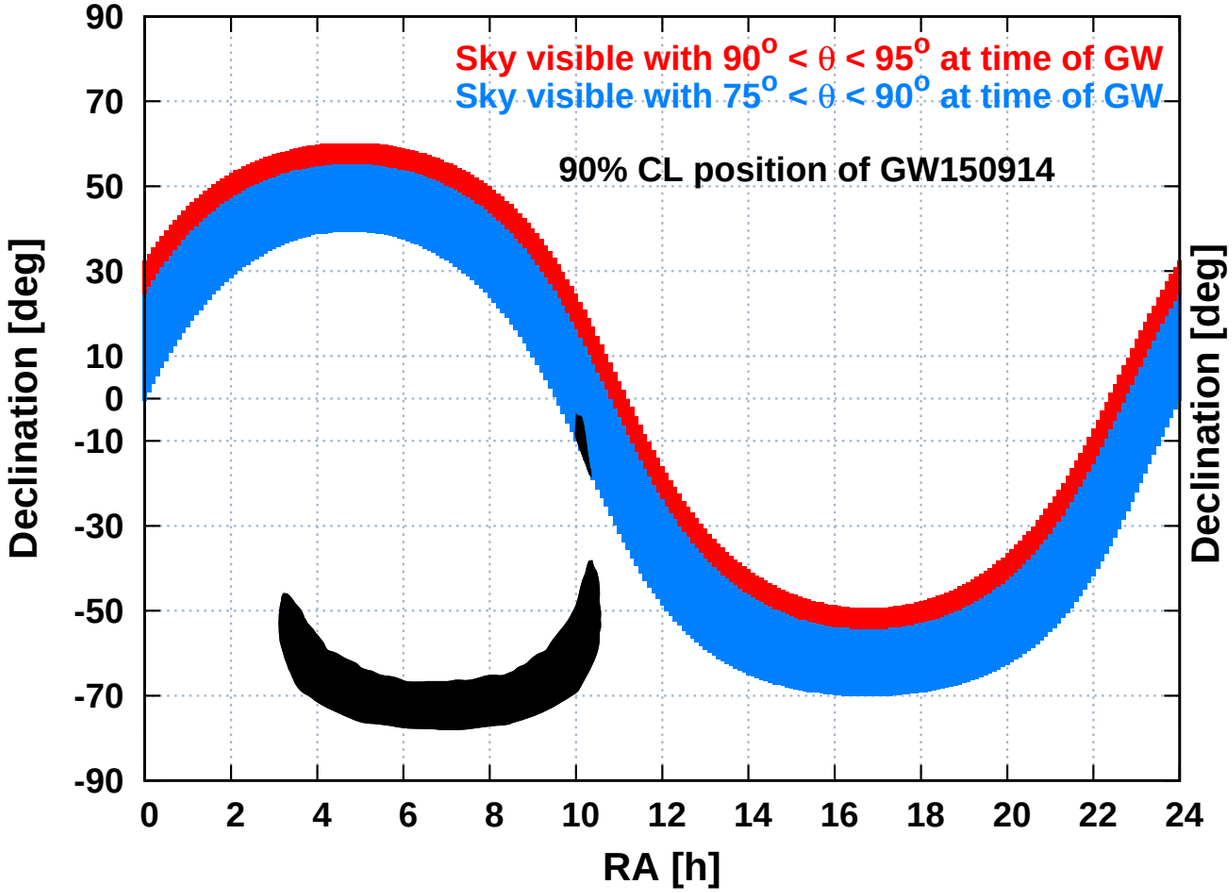
Sensitivity

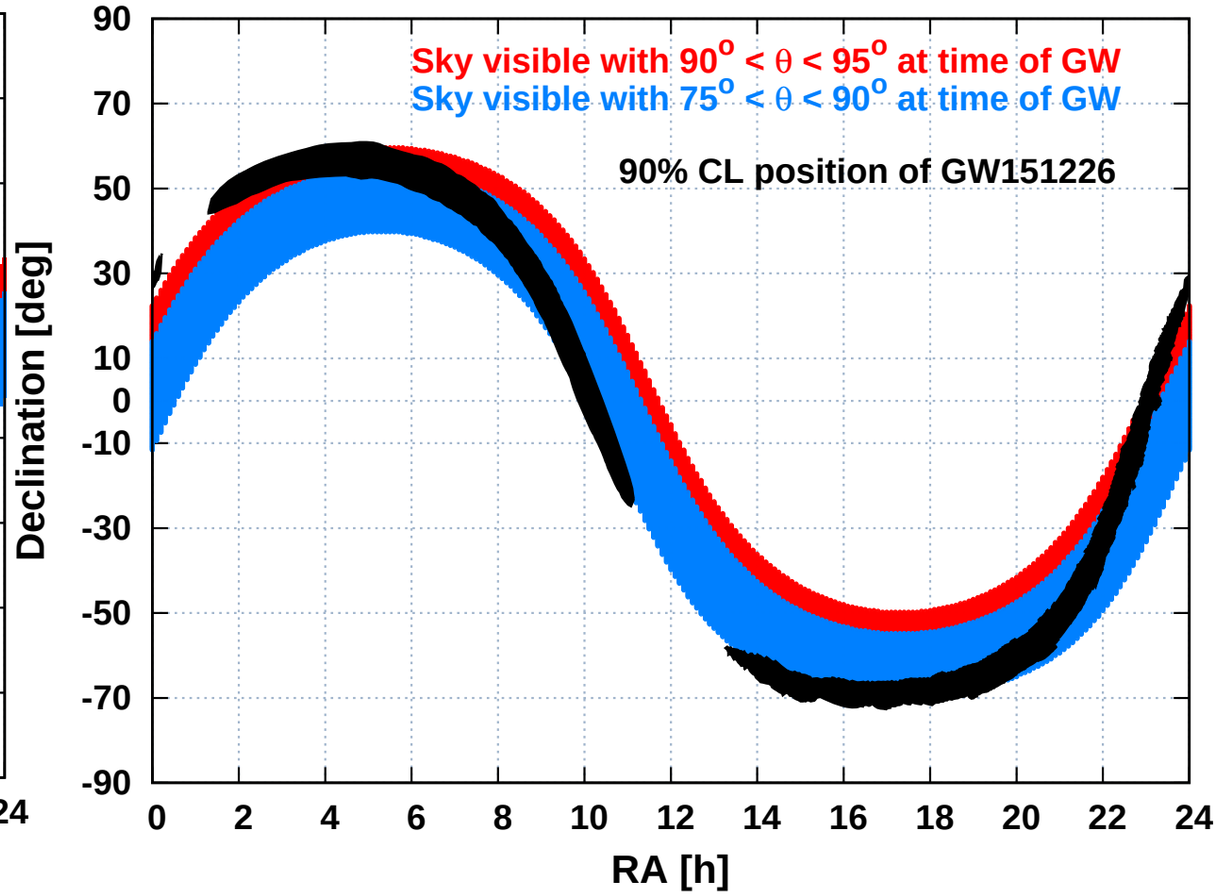
$90° \leq \theta \leq 95°$



$75° \leq \theta \leq 90°$

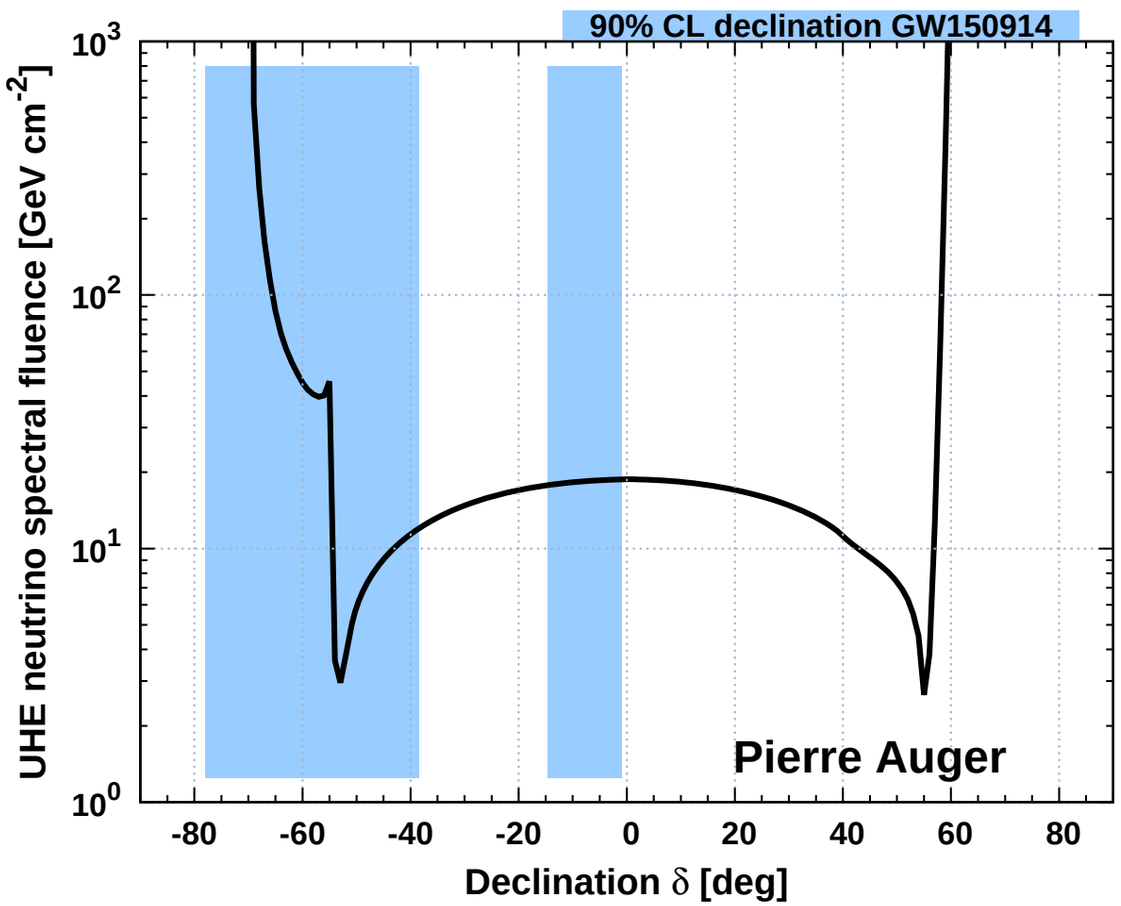


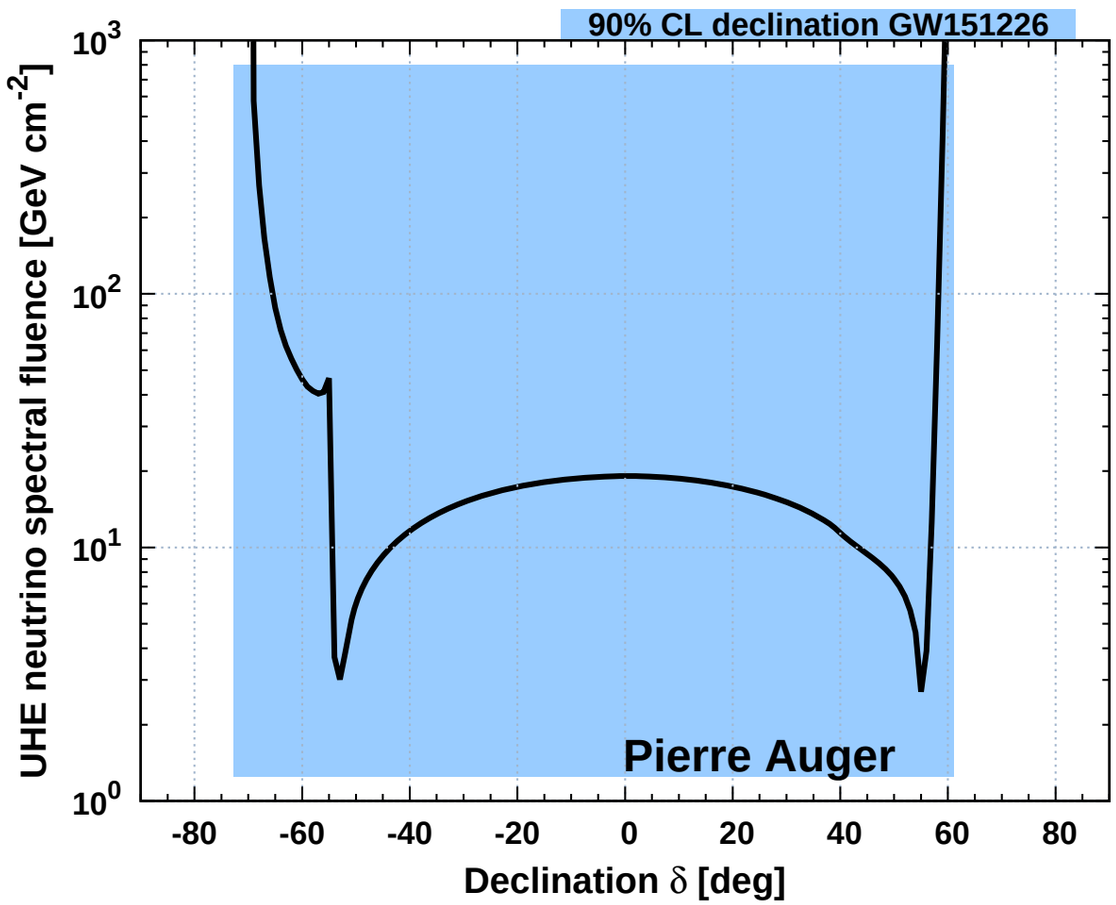




GW neutrino flux limits

- No neutrino candidates seen correlated with GW events





Auger Upgrade

- Lack of knowledge of composition limits the interpretation of results
- Separate determination of muonic and electro-magnetic signal is important

Goal:

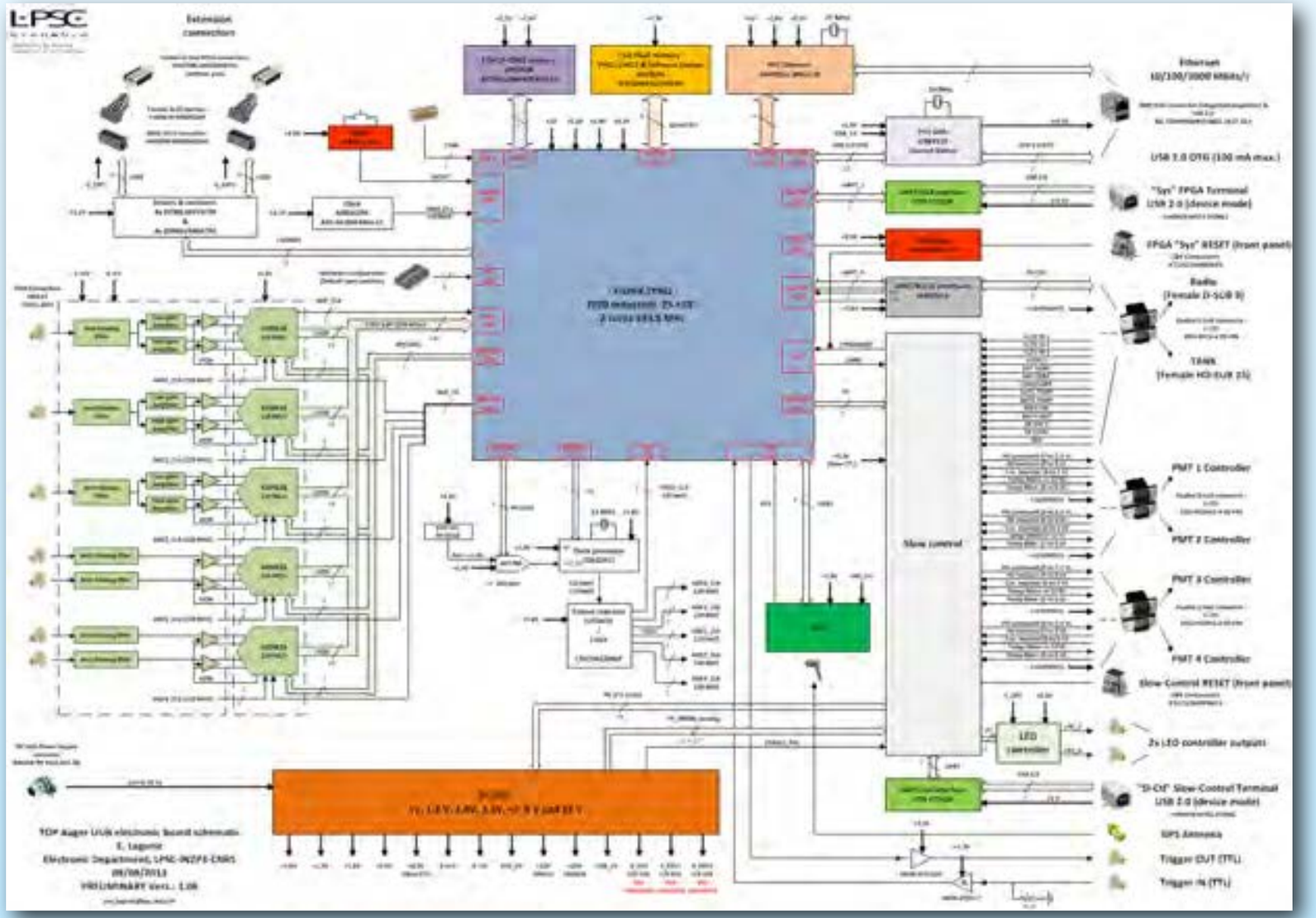
- Determine origin of flux suppression: GZK or maximum energy of sources
- Search for proton component at the highest energies (➤ astronomy)
- Study air showers and particle production at $E_{cms} > 70\text{TeV}$

1) New SD-Electronics

Purpose:

- facilitate the readout of new electronic channels (PMTs)
- faster sampling (40➔120 MHz) for better timing and μ-identification
- enhanced dynamic range (by adding a small PMT)
- faster data processing and more sophisticated triggers
- better data monitoring

- design is ready
- prototypes are now being produced



2b) Enhanced Muon Counting: ASCII

ASCII: Auger Scintillator for Composition II

Conclusions

- Auger operating since 2004, complete since 2008
- Robust, stable detector. Results:
  - Spectrum: ankle, suppression
  - Anisotropy: Evidence for dipole
  - Competitive neutrino limits
  - Photon limits rule out some models
  - Exotics: Monopoles, Lorentz violation
  - Muon counting, asymmetries: discrepancy with interaction models
  - LIGO/VIRGO GW neutrino followup (MoU)
  - Measured p-Air cross-section at 57 TeV
  - Non-cosmic ray science
- Upgrade planed
  - Extend science reach


Thank
you!