News from the Pierre Auger Observatory

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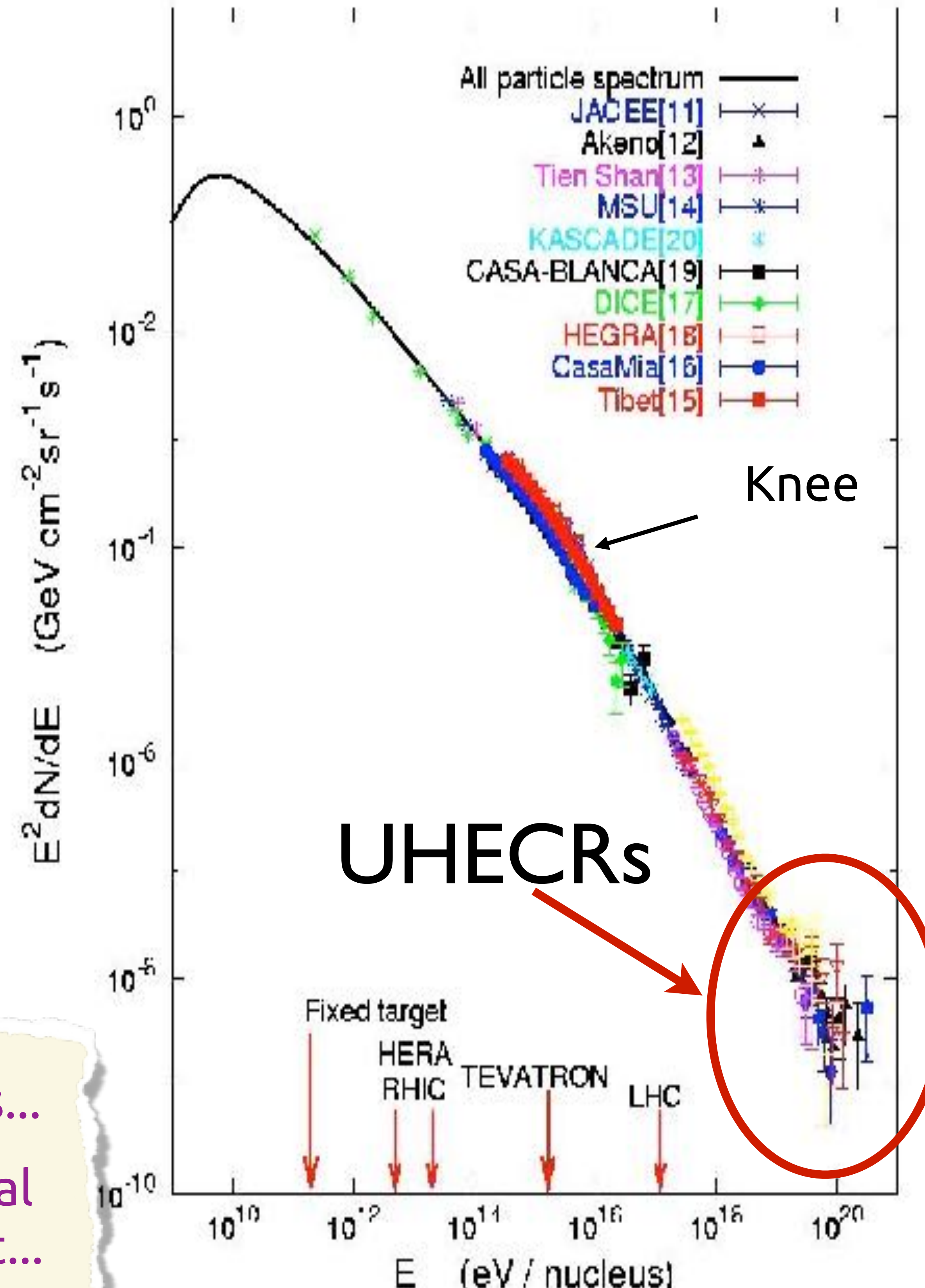
Ultra-High Energy Cosmic Rays

- 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 km² per year
- Acceleration mechanism not known
- Sources not known

Have hints…

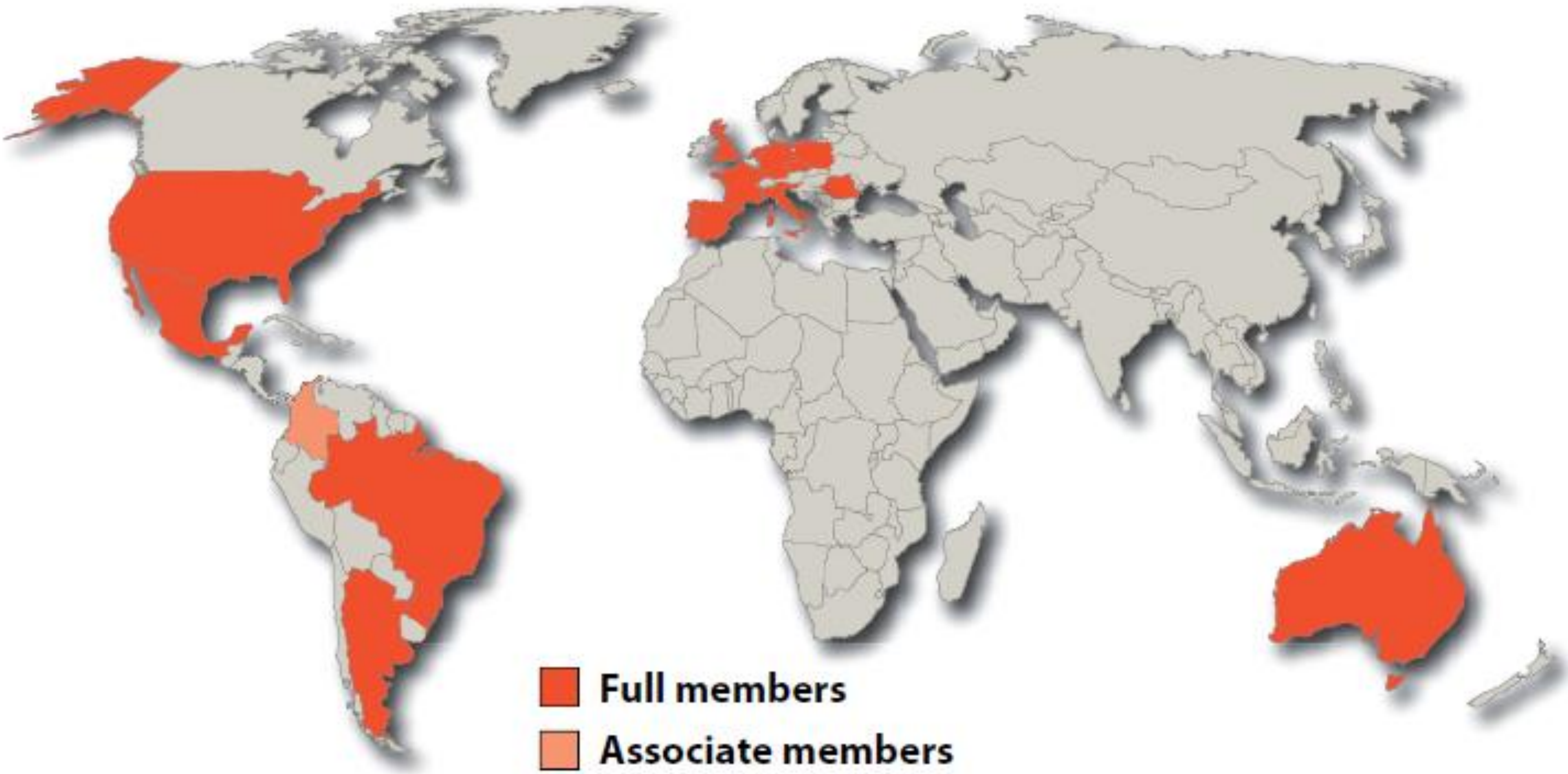
Theoretical ideas exist…



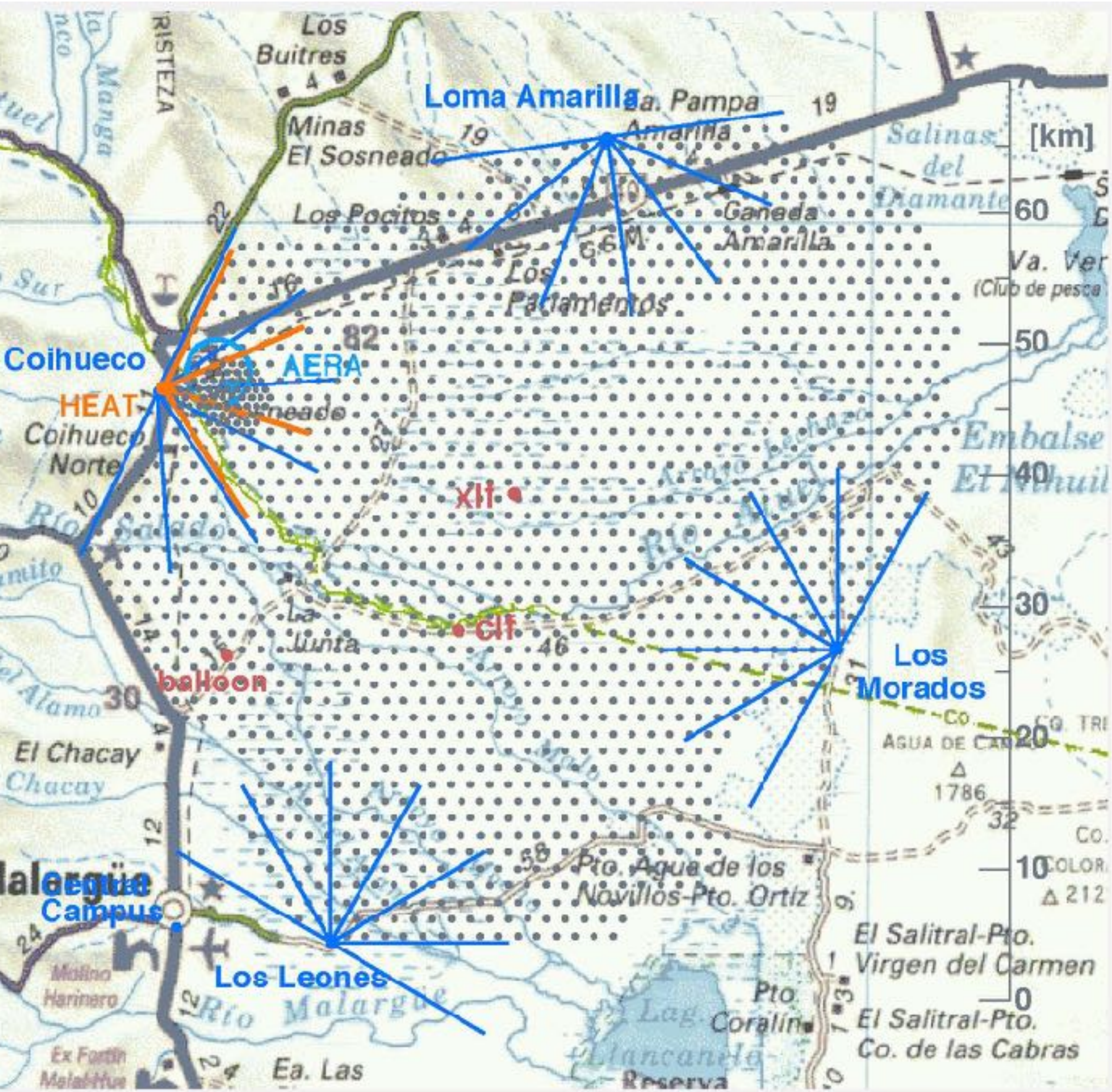
The Pierre Auger Collaboration

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

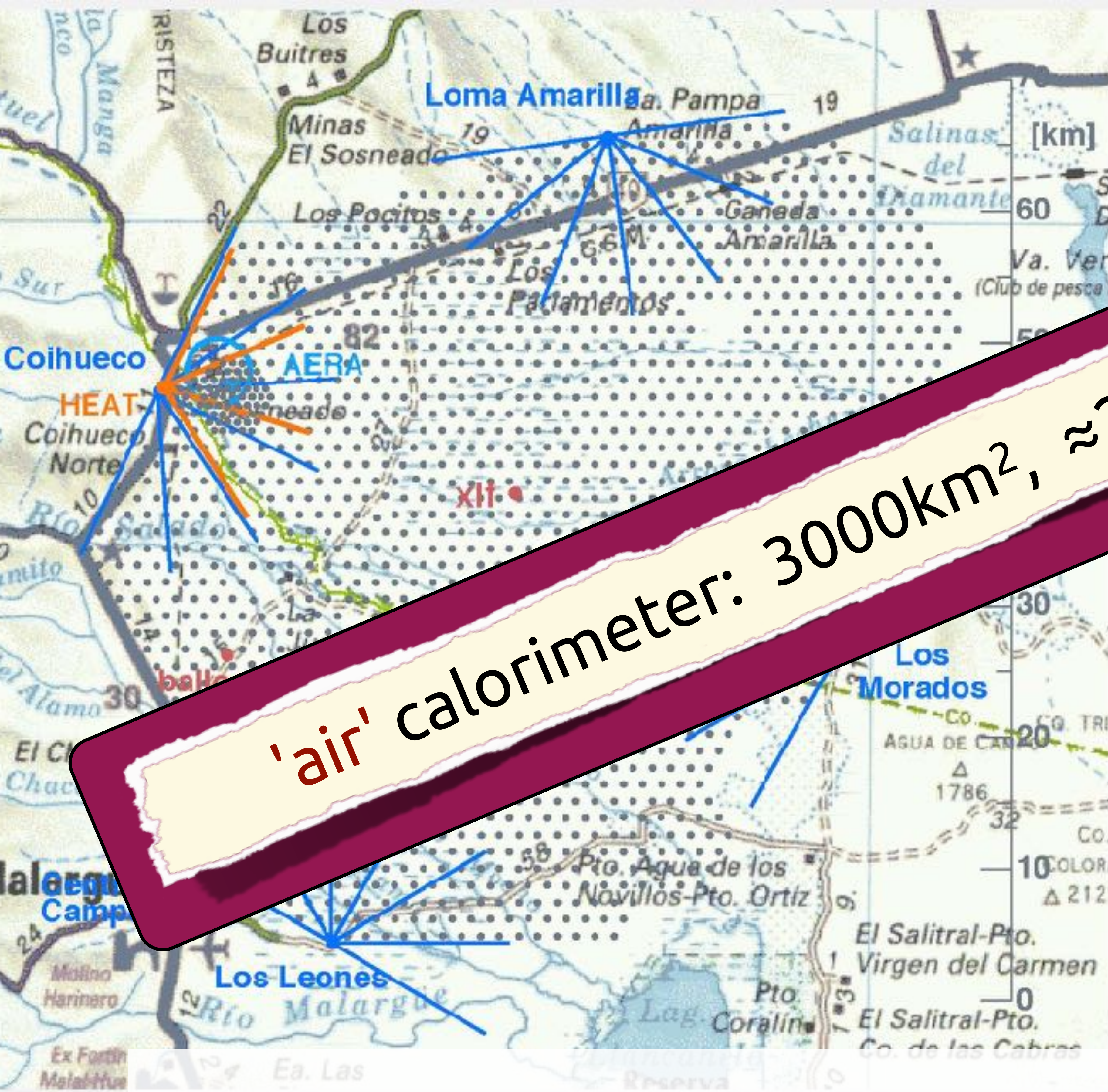
Infill: 750m spacing

4 Fluorescence detector sites

- 6 telescopes each
  - +3 elevated
- 27 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: $3000 km^2$, $\approx 2.5 \cdot 10^{10}$ T

1660 surface detector stations, 1.5 km spacing

Infill: 750m spa…

4 Fl… …tor

… each

… elevated

27 telescopes in total

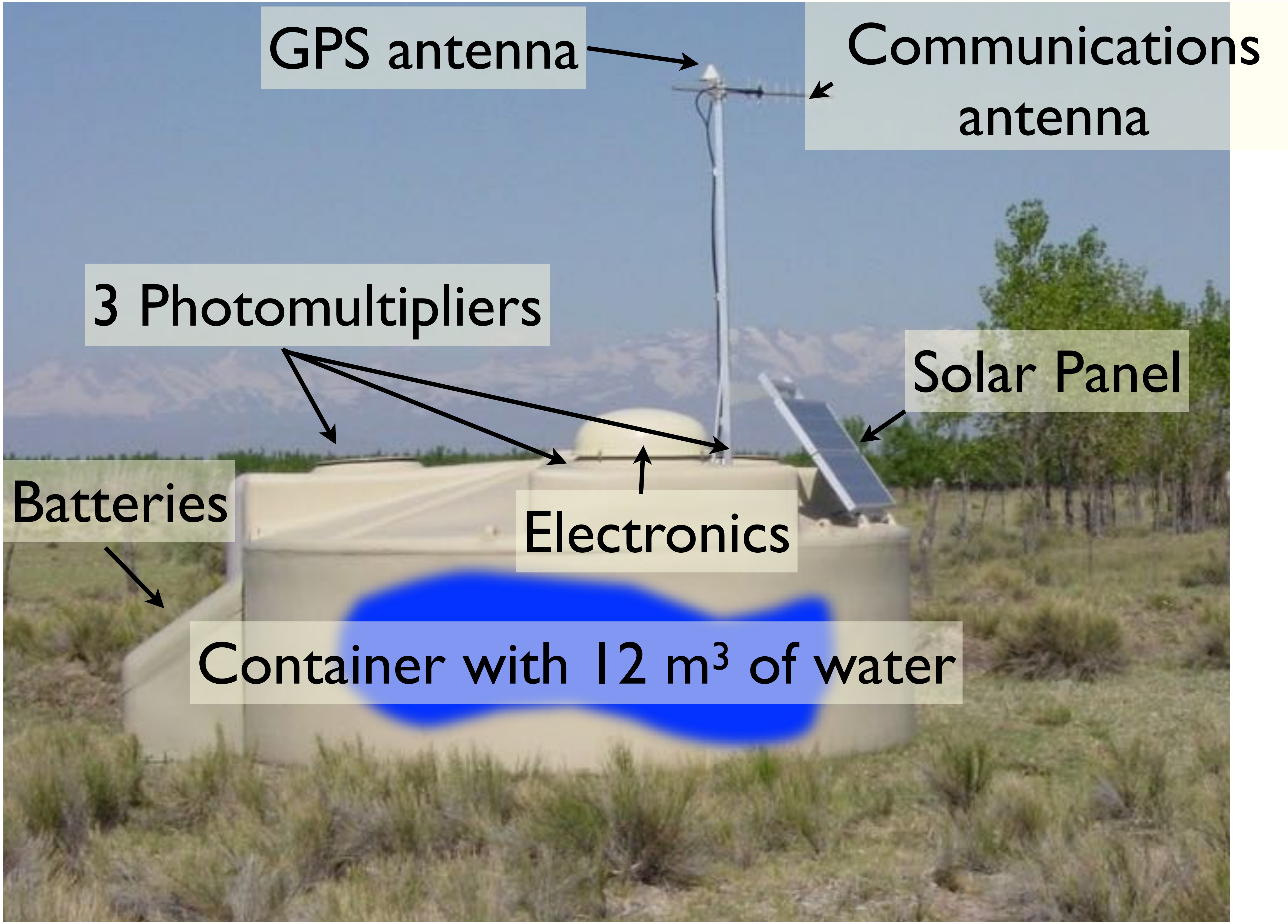
- Full coverage of the surface array
- Capability to detect stereo events
- Quadruple events seen

Low Energy Extensions

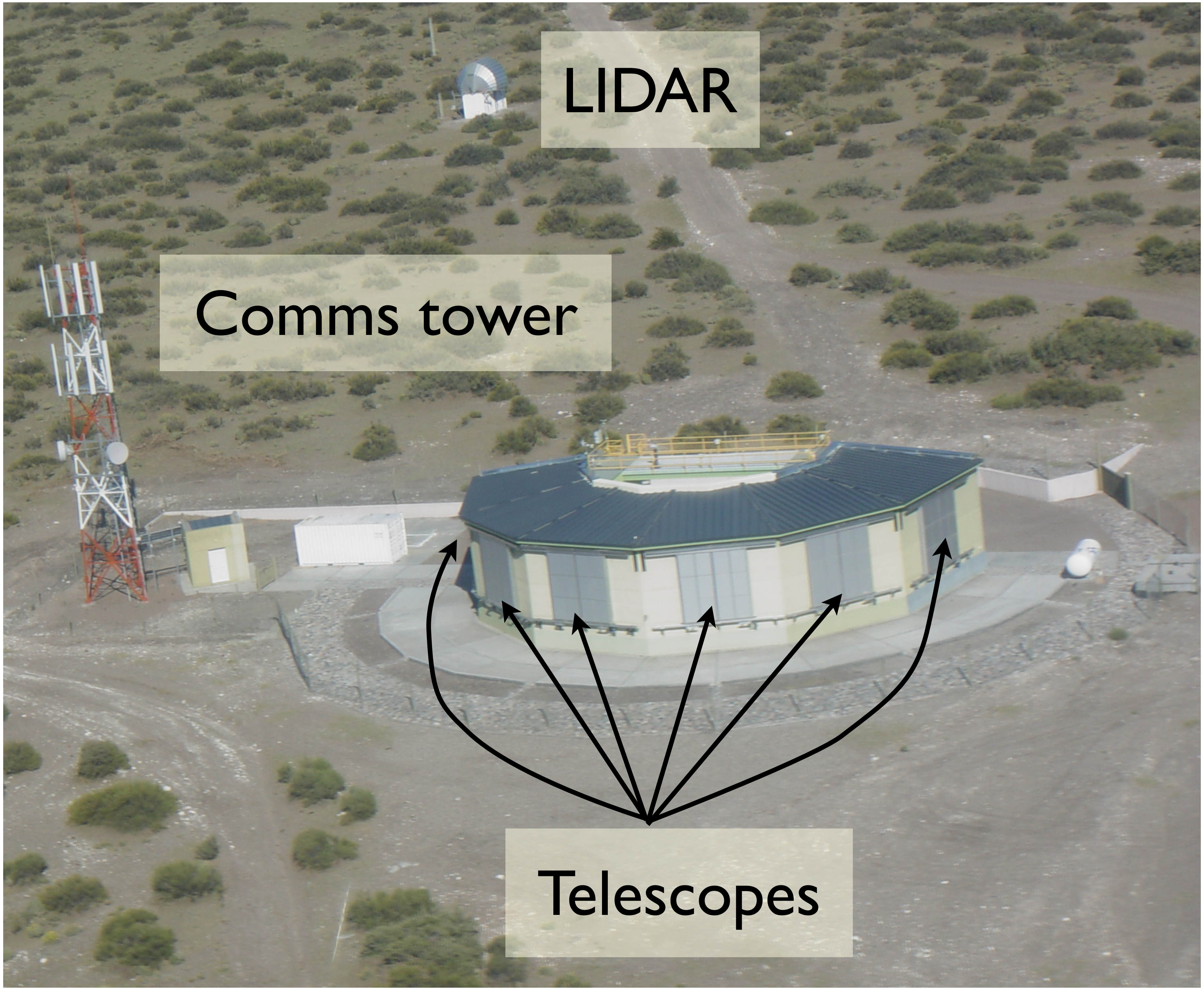
Radio Detectors

A surface detector station

A surface detector station



A Fluorescence Detector Site



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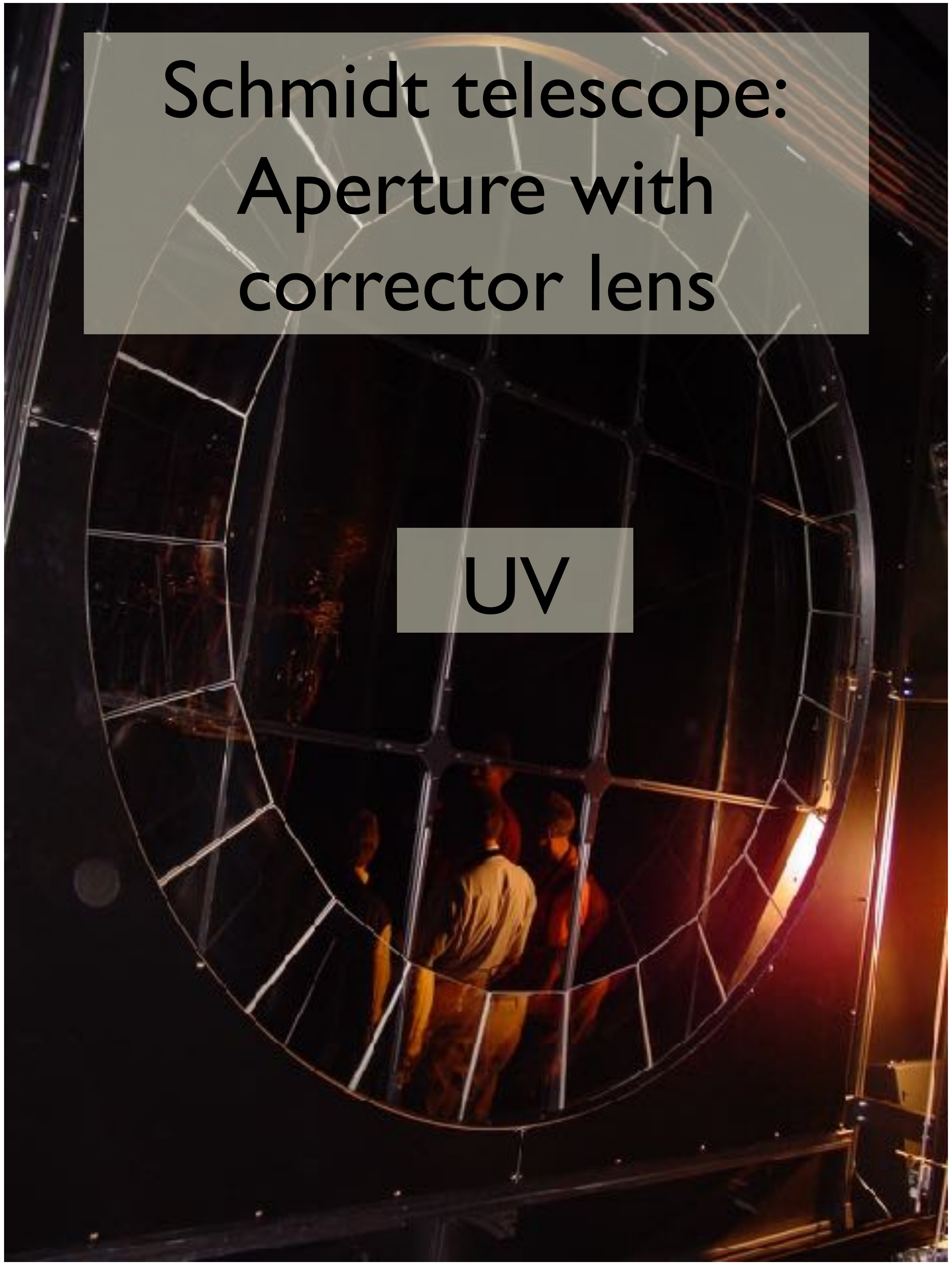
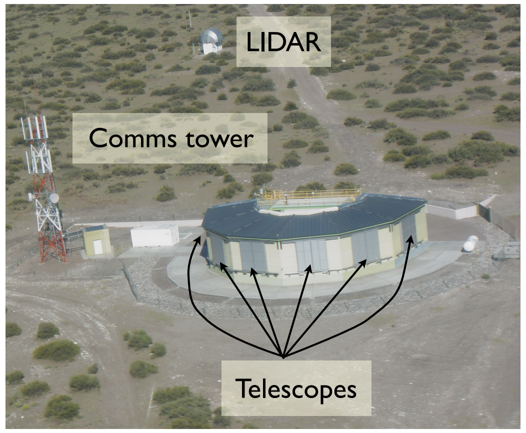
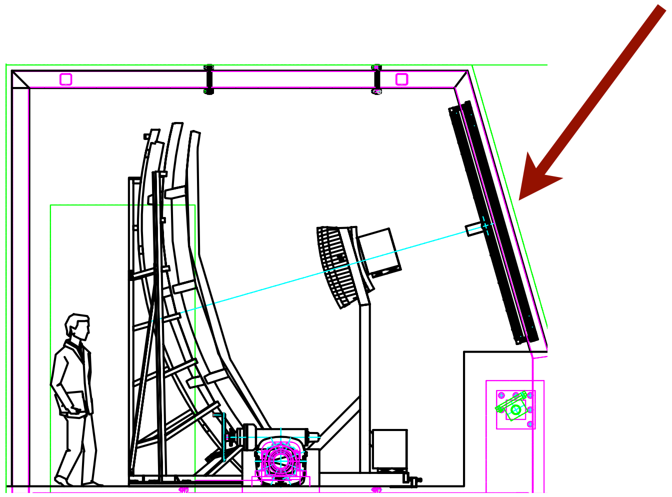
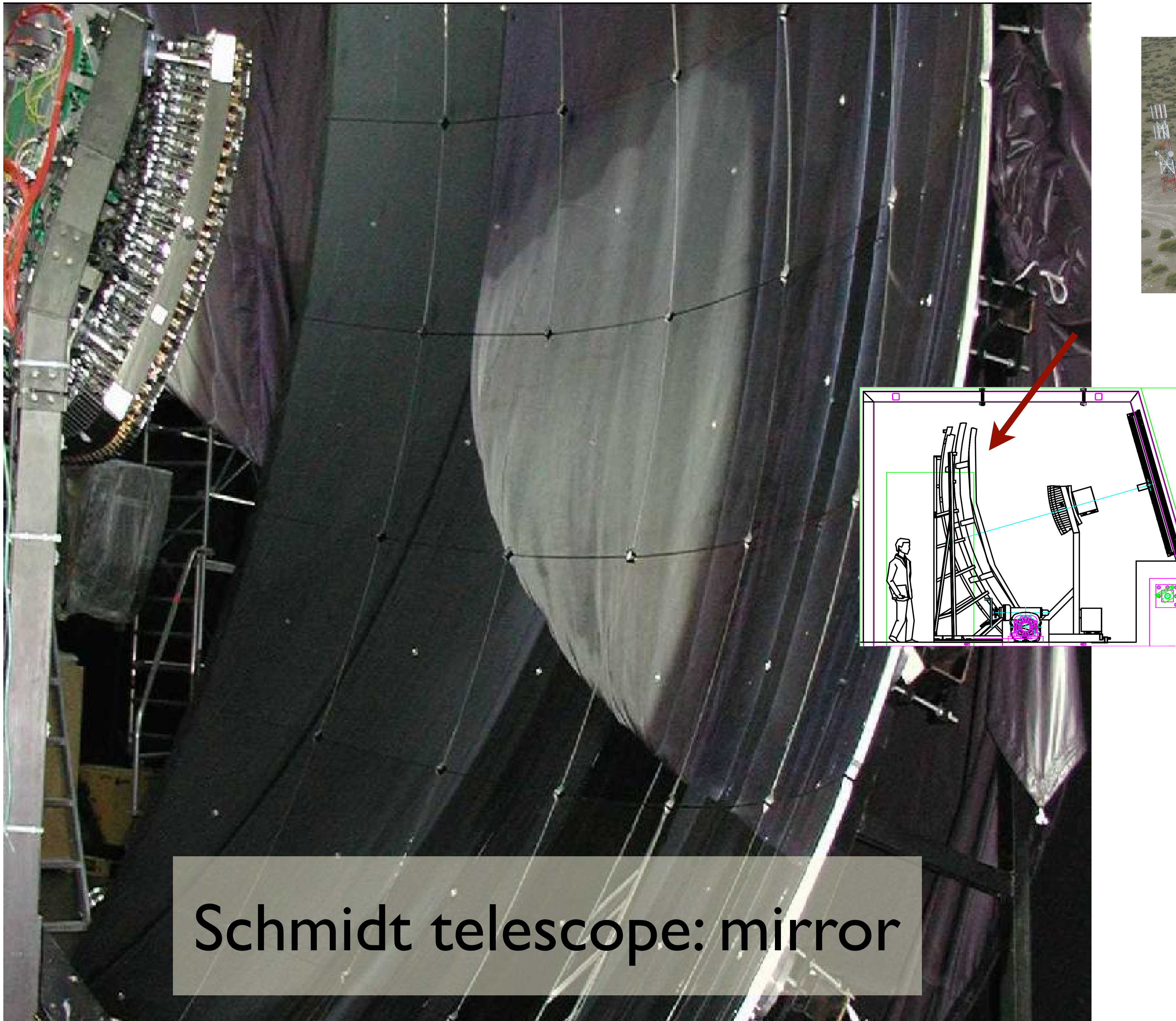
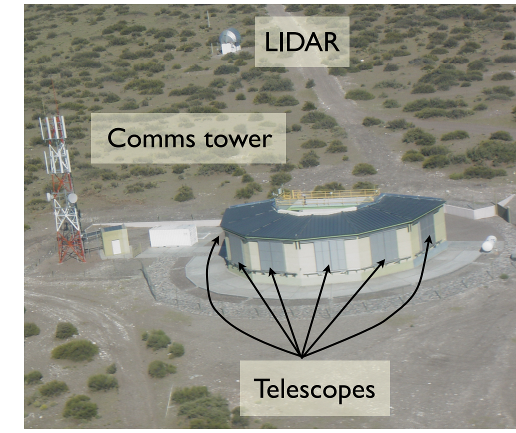


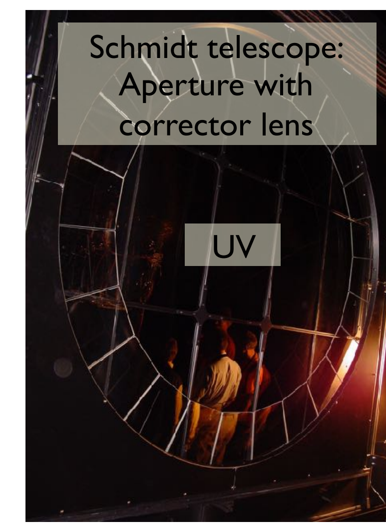




A Fluorescence Detector Site







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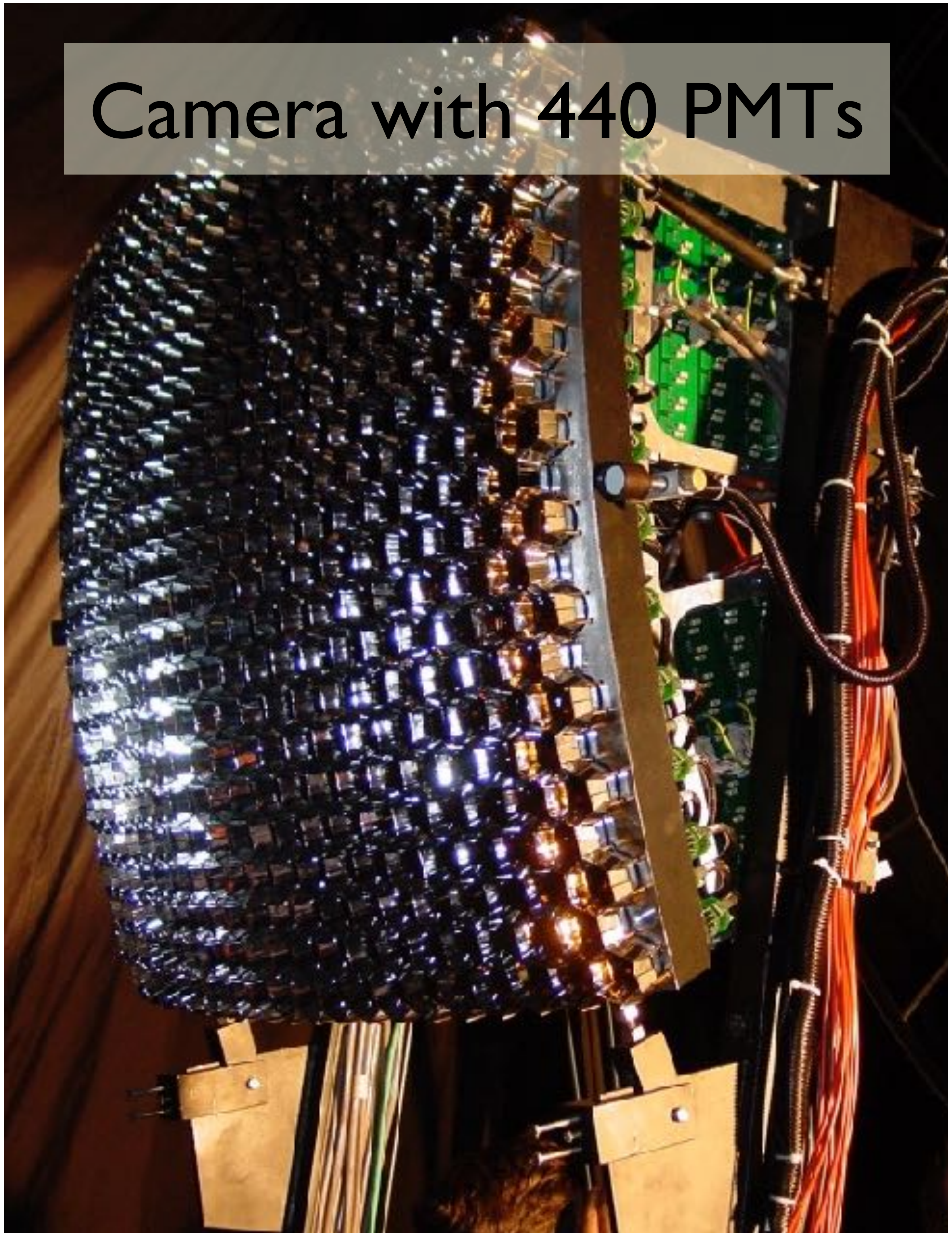
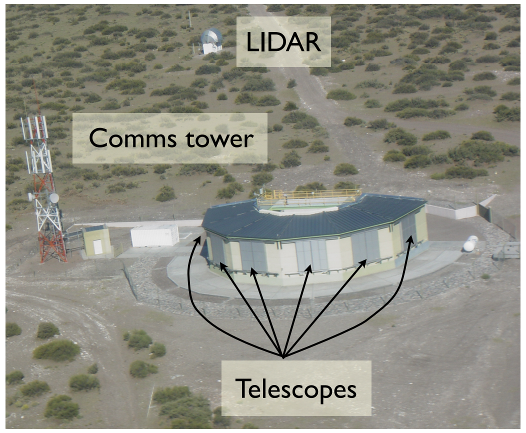
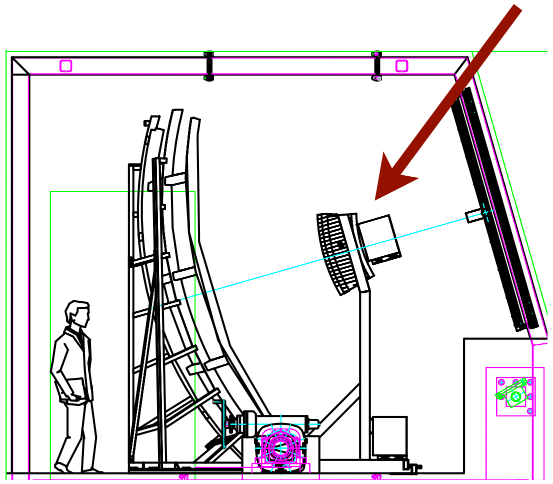
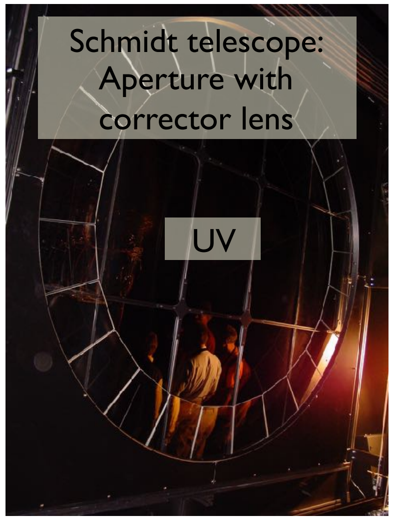
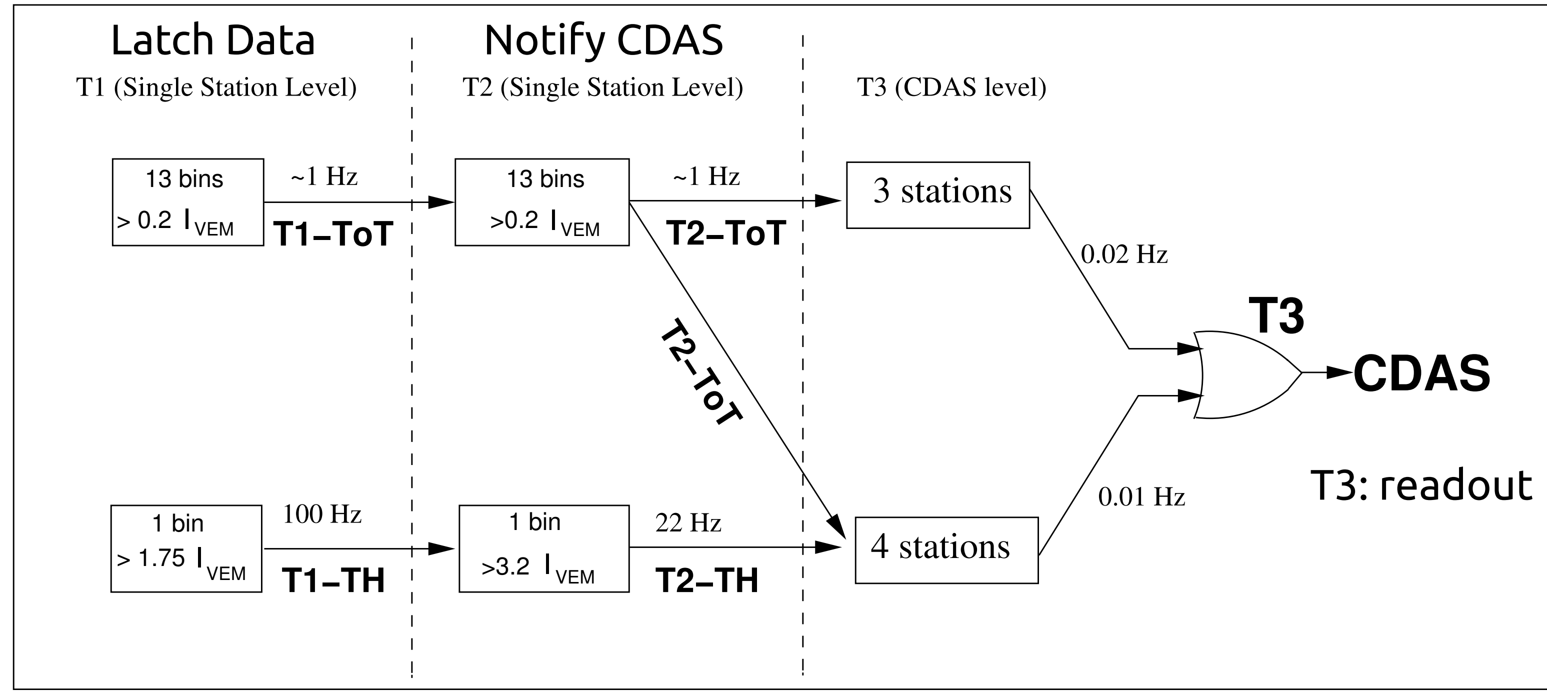




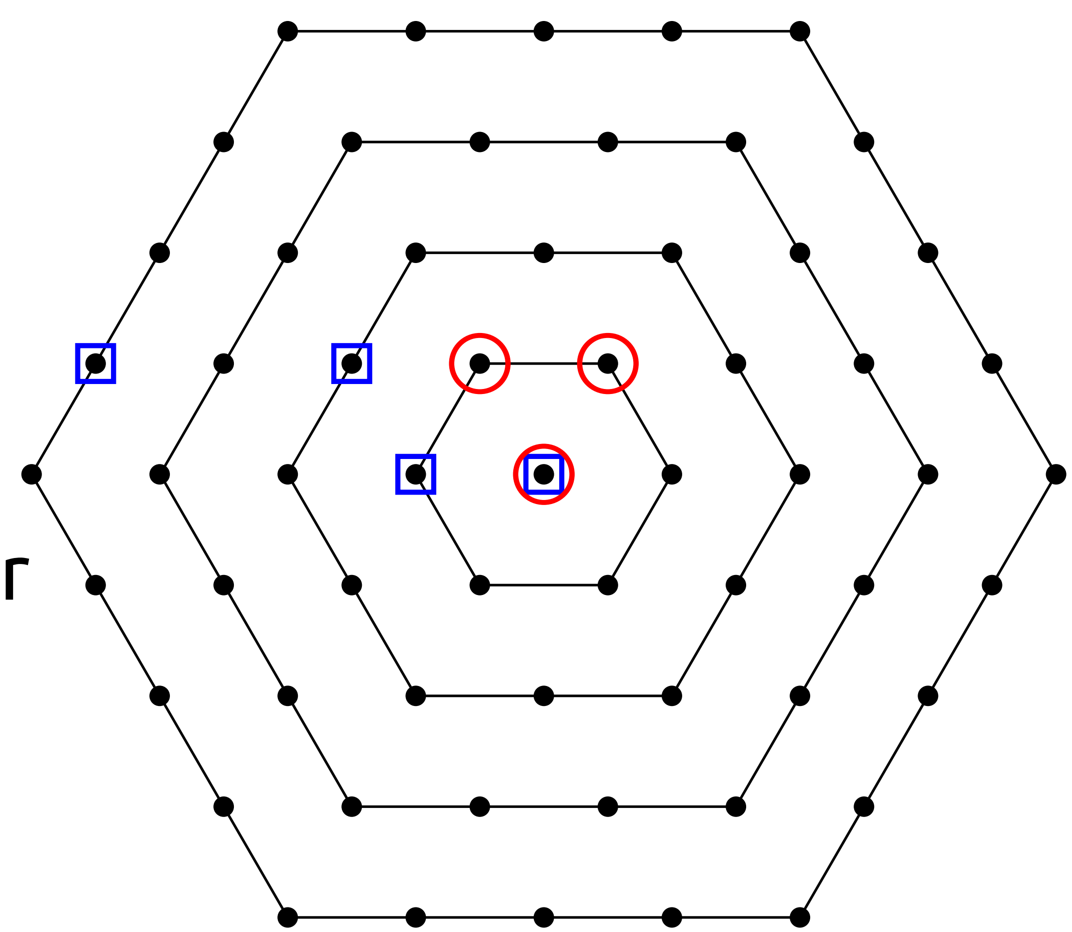




Triggering the Pierre Auger Observatory - SD

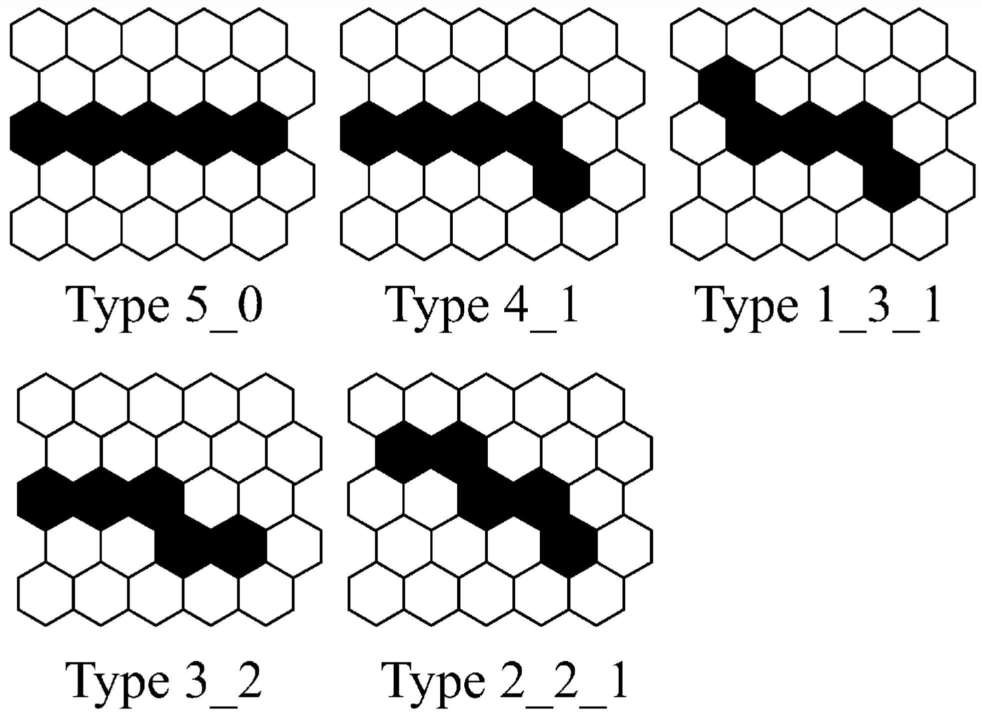


- SD station trigger
  - Threshold
    - Threshold deconvolved
  - Time over threshold
    - Multiplicity of positive steps: count positive steps, fixed range
  - Variants: lower E threshold
    - Thanks to reduced muons in trigger
- Central Trigger (T3)
  - Space-time coincidence of station T2



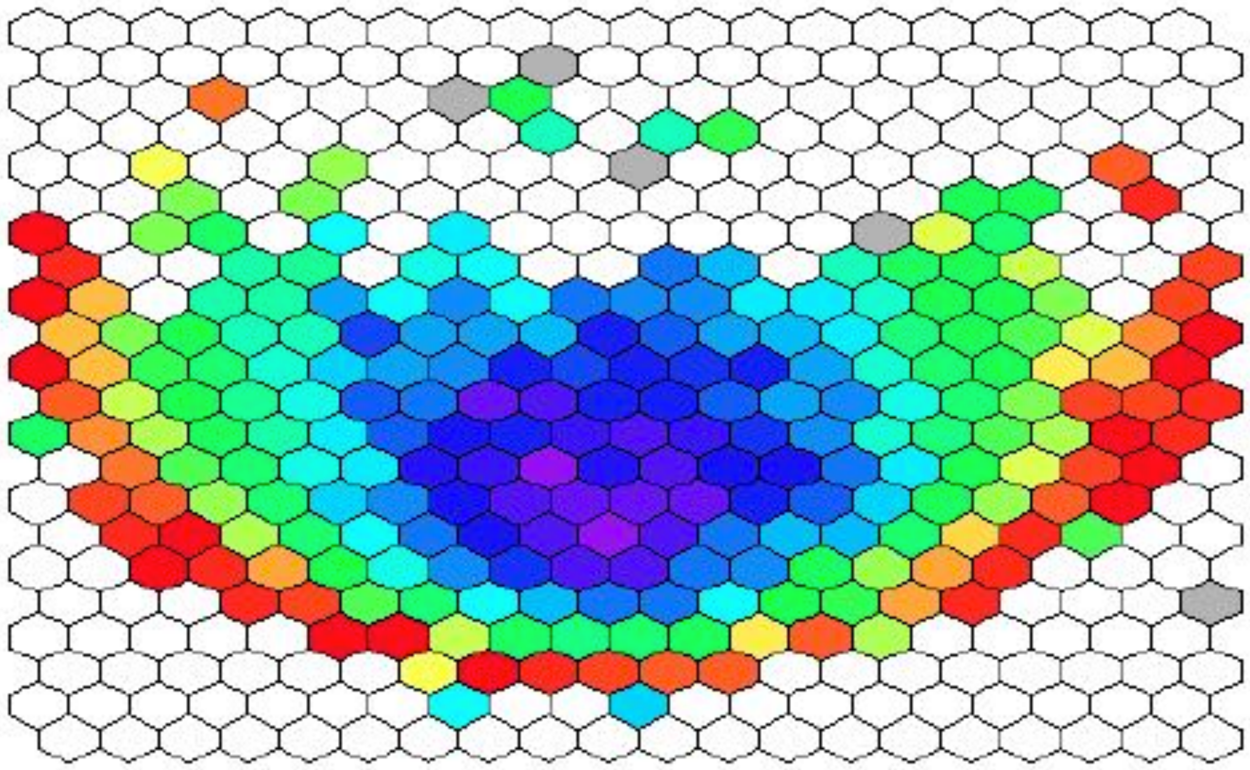
Triggering the Pierre Auger Observatory - FD

- First level trigger: pixel threshold
- Second level trigger: track fragments

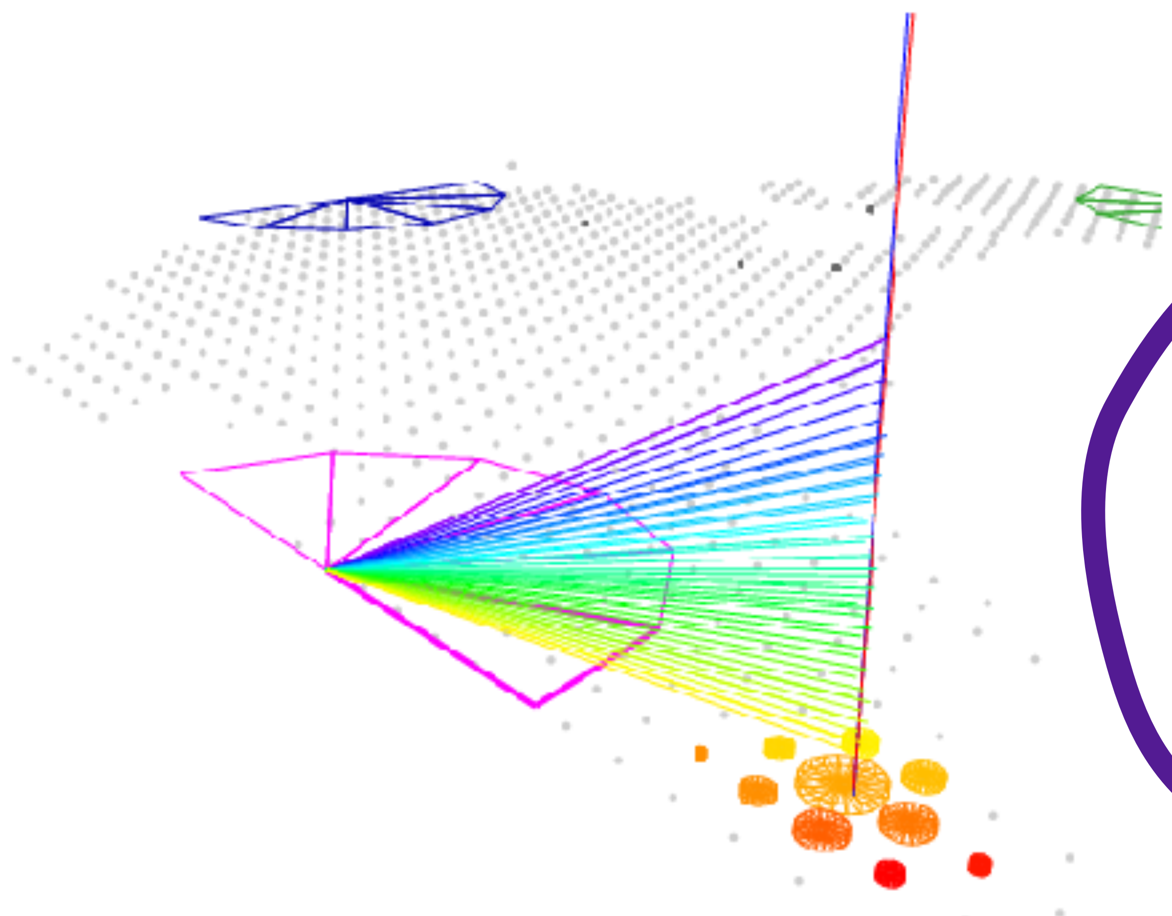


- Quick analysis and reconstruction: Request SD readout (T3 to CDAS)

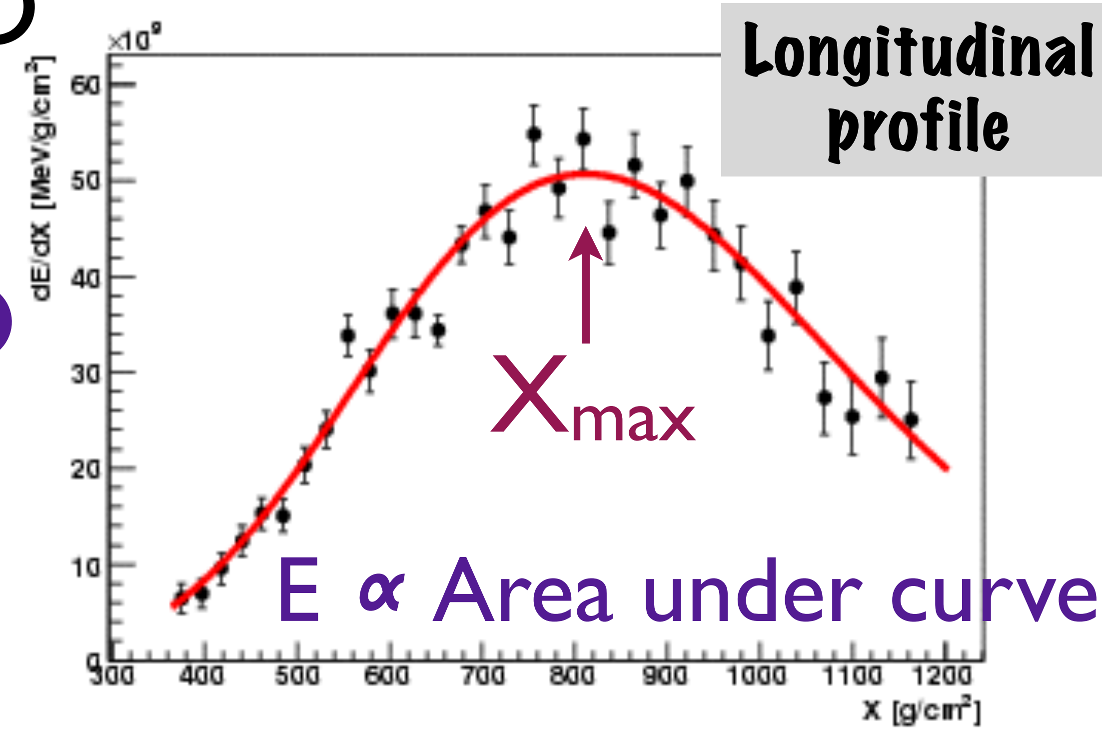
- New: modified 3rd level readout: Detection of ELVES (lightning)



Energy Determination

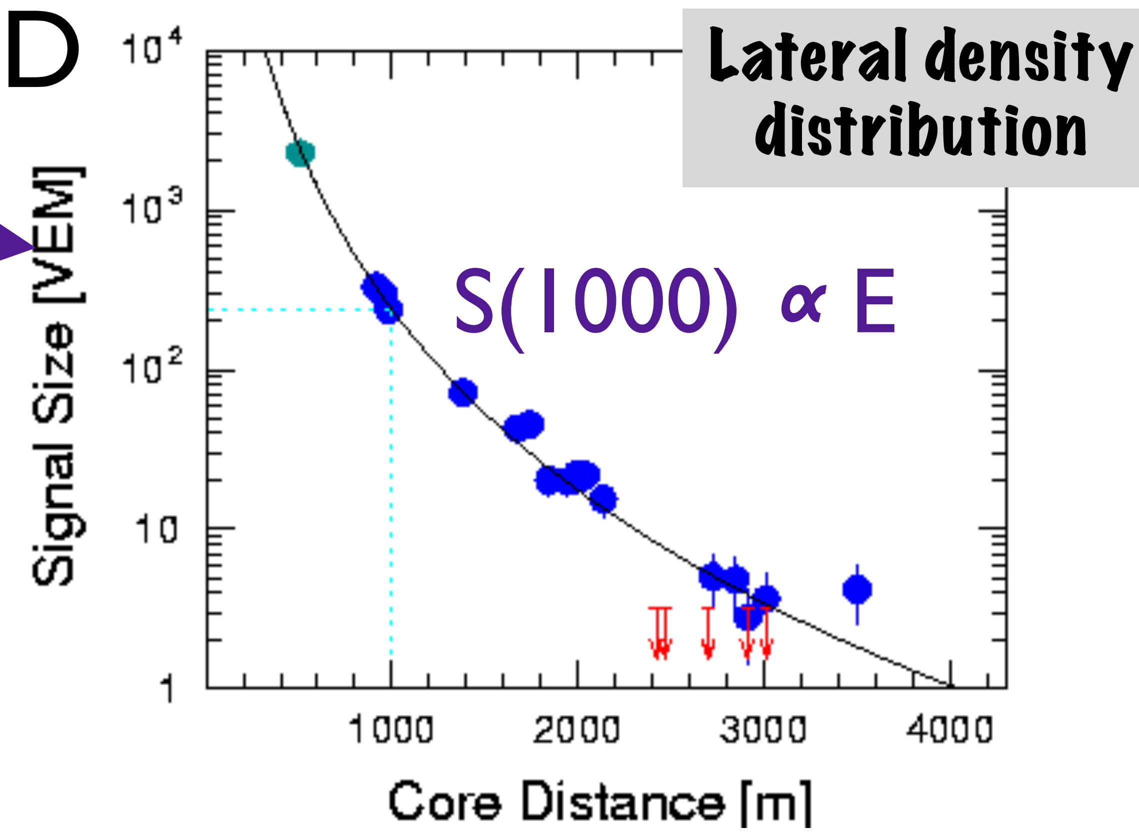


FD



ID 762238

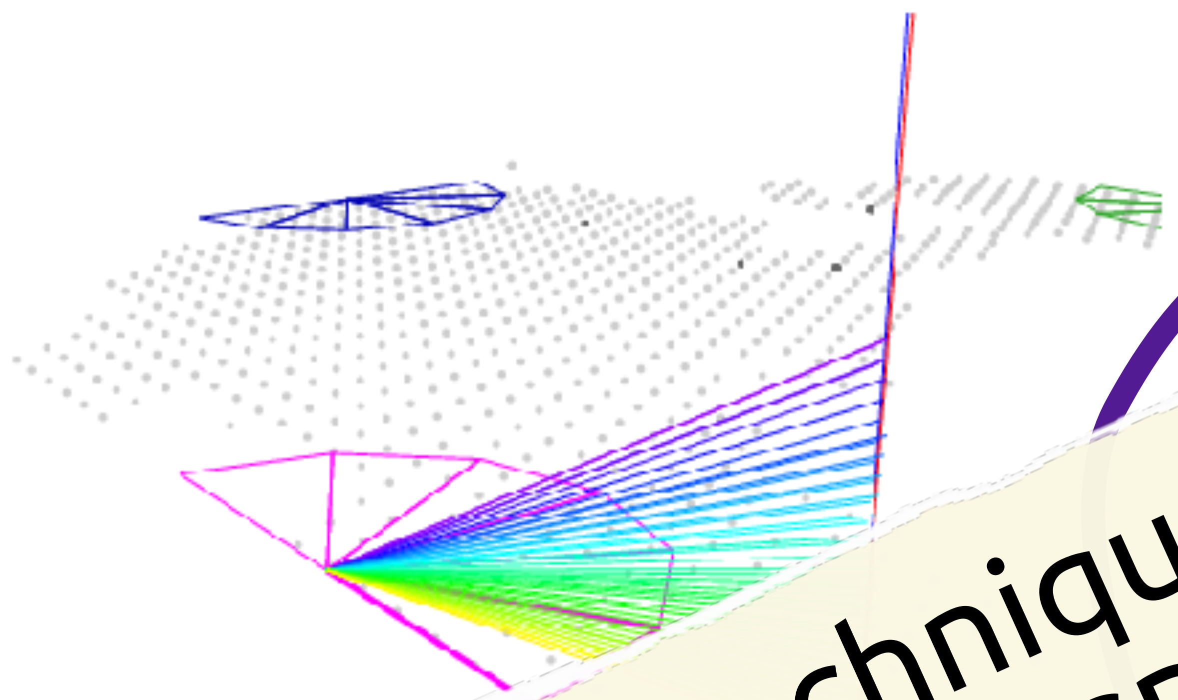
SD

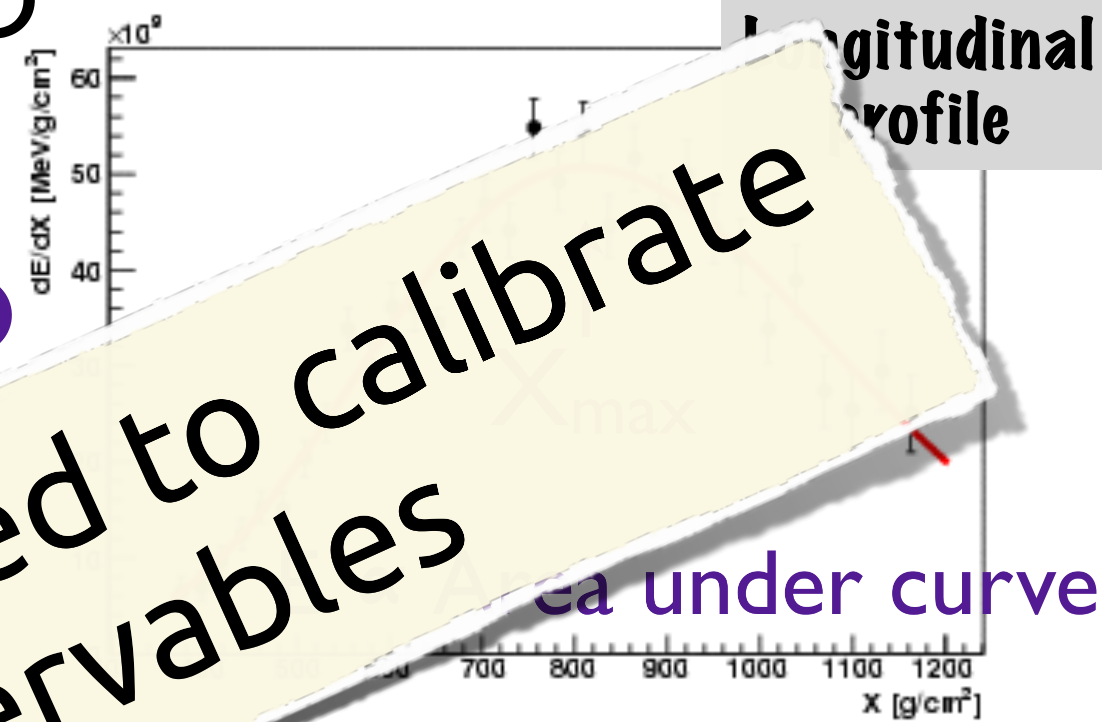


Hybrid Events are used to **calibrate** the
SD energy estimator
from the
FD calorimetric energy

Energy Determination

FD





Similar techniques used to calibrate other SD observables

SD

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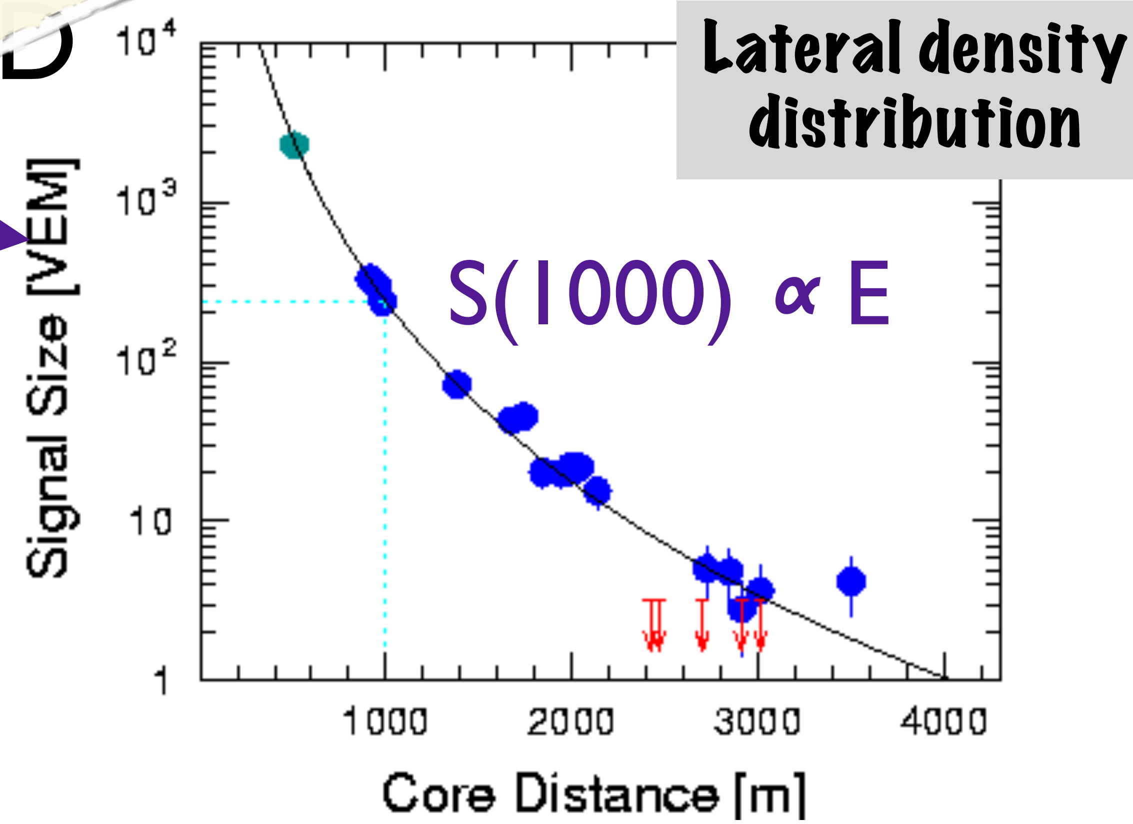
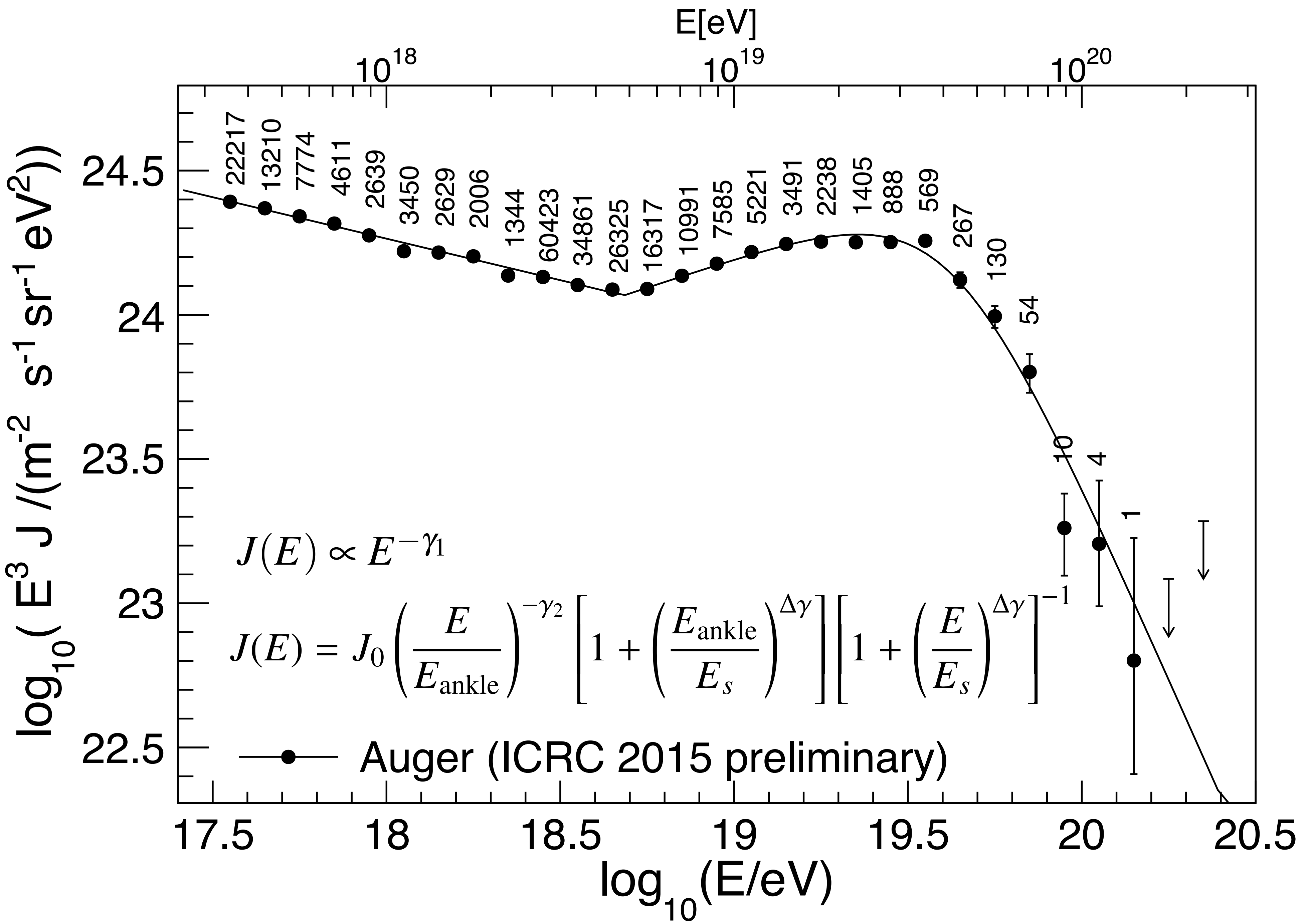


Hybrid Events are used to **calibrate** the SD energy estimator from the FD calorimetric energy

Combined spectrum

- Combine results from different techniques and detectors



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

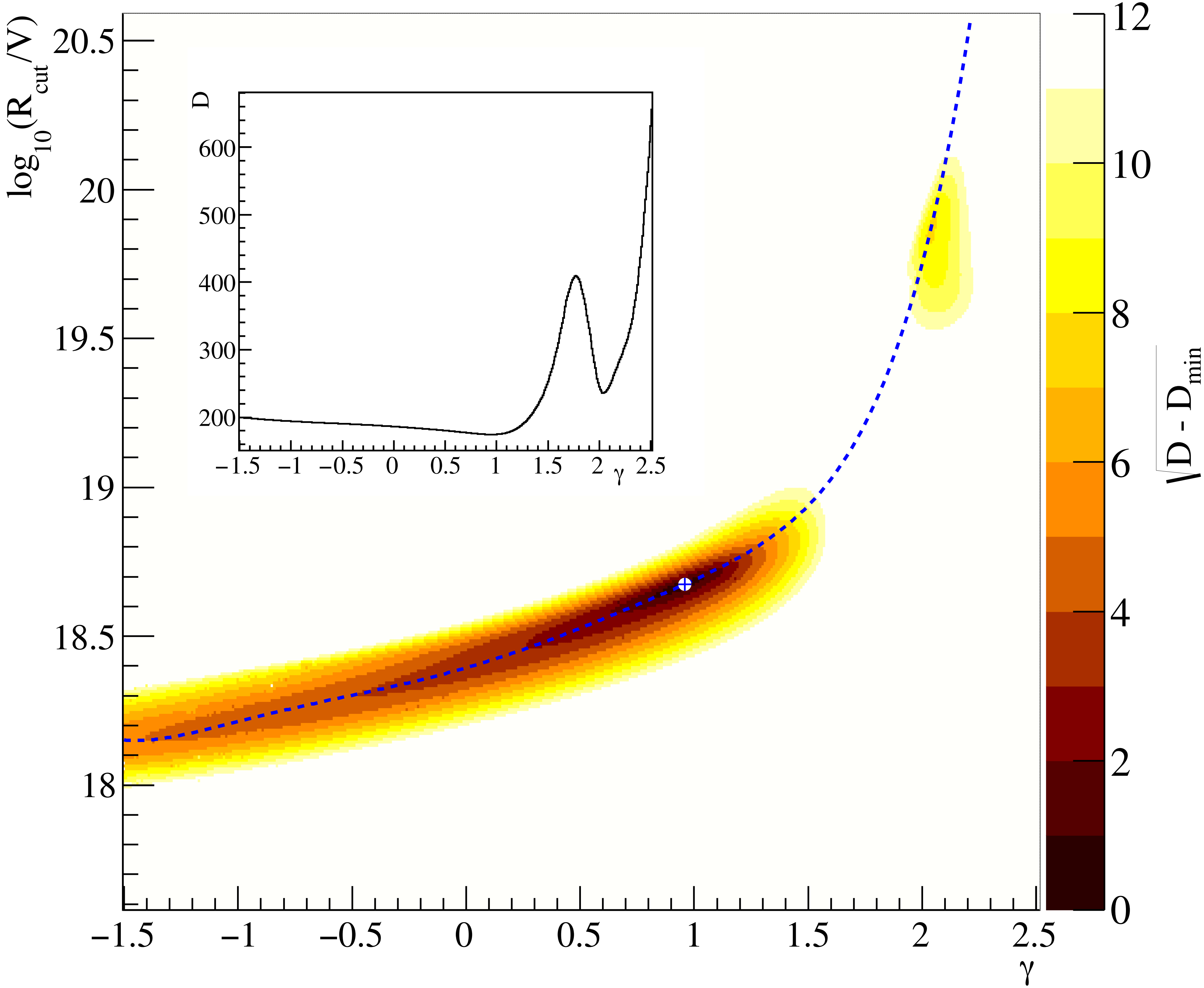
$\Delta\gamma$ = 3.14 ± 0.02

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**

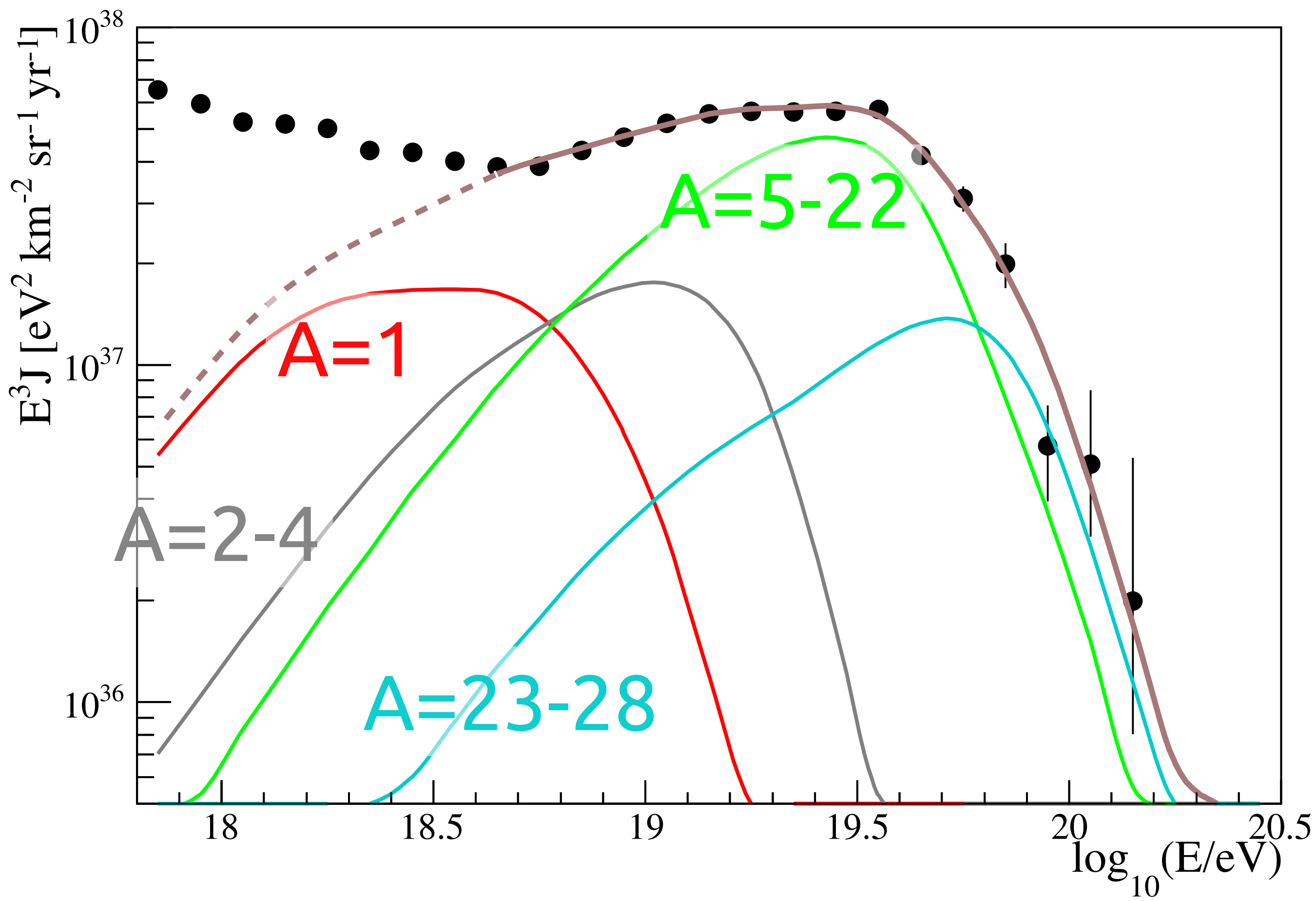
Fit result

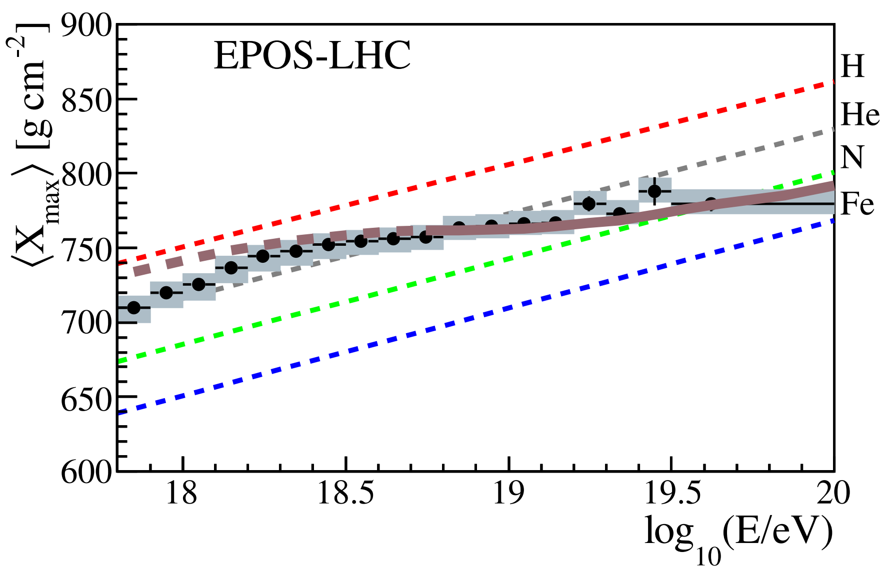


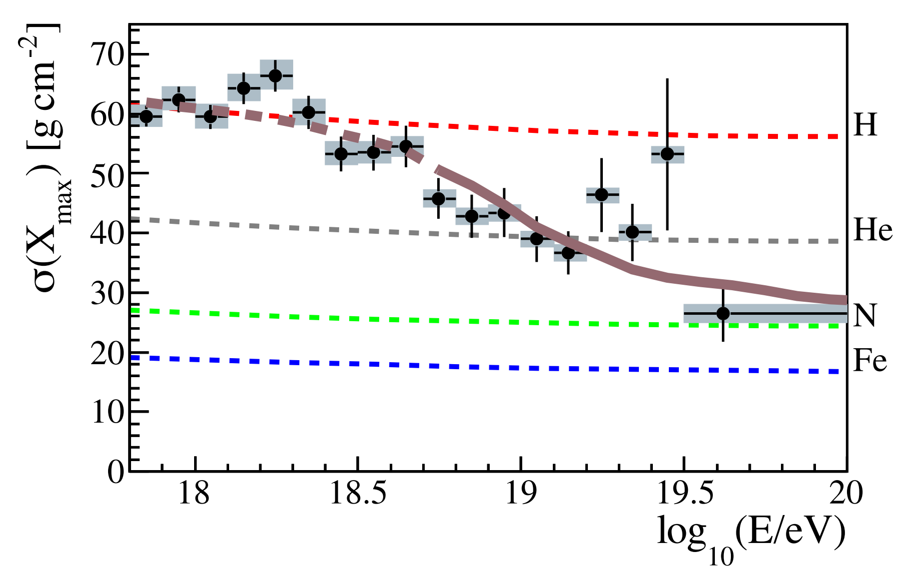
2 minima

Extended 1st min

1st minimum

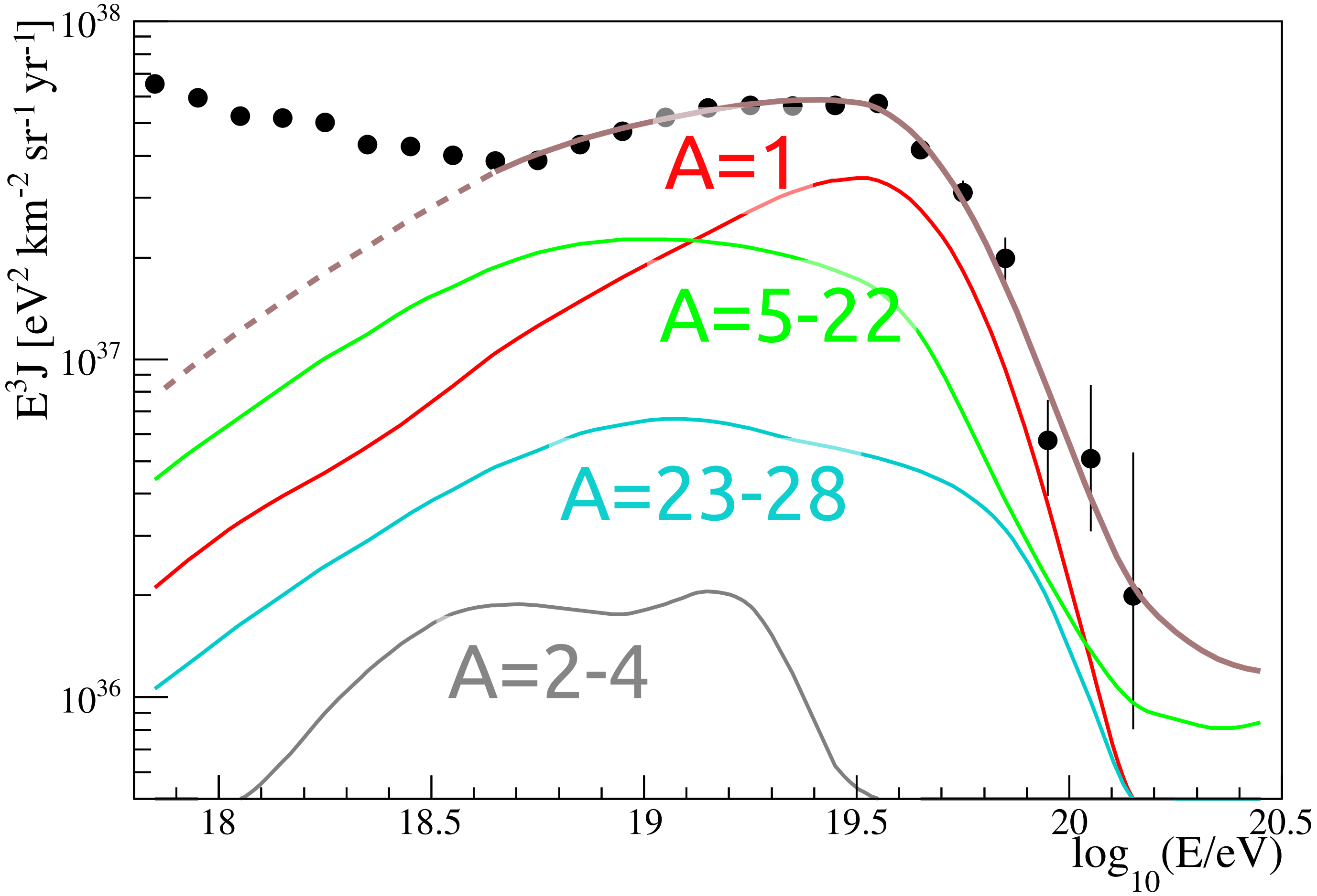




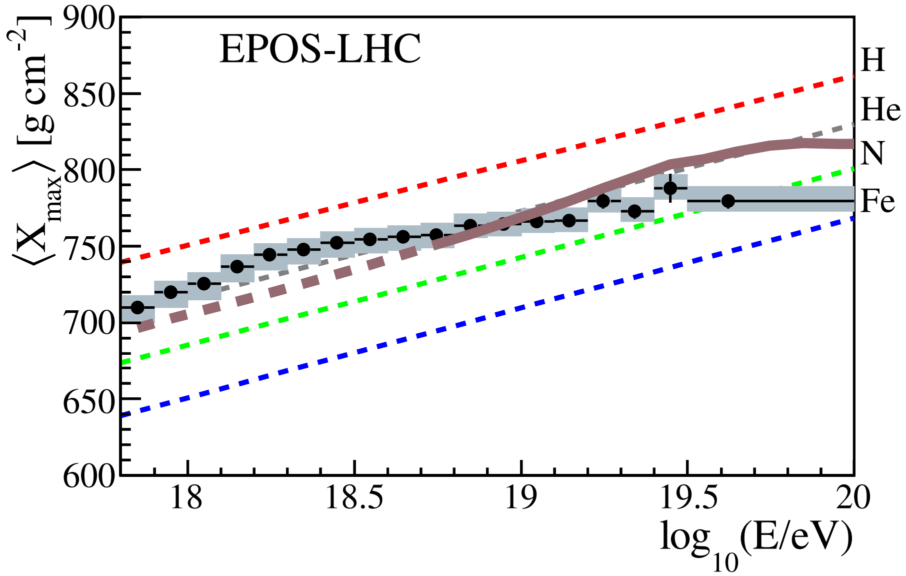


- Absence of Fe?

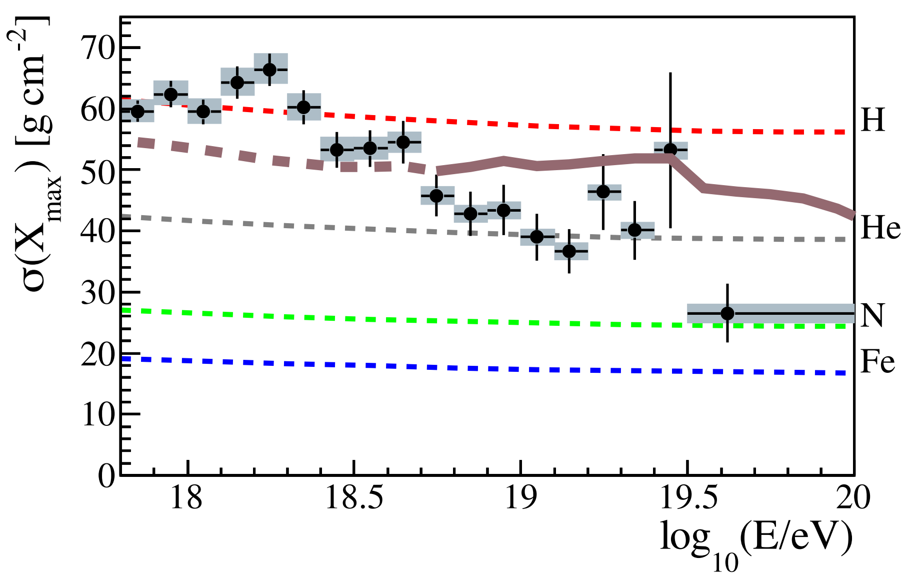
2nd minimum



$E^3 J$ [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: Rayleigh analysis in right ascension

- Harmonic analysis in Right Ascension α

$$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos\alpha_i, \qquad b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin\alpha_i$$

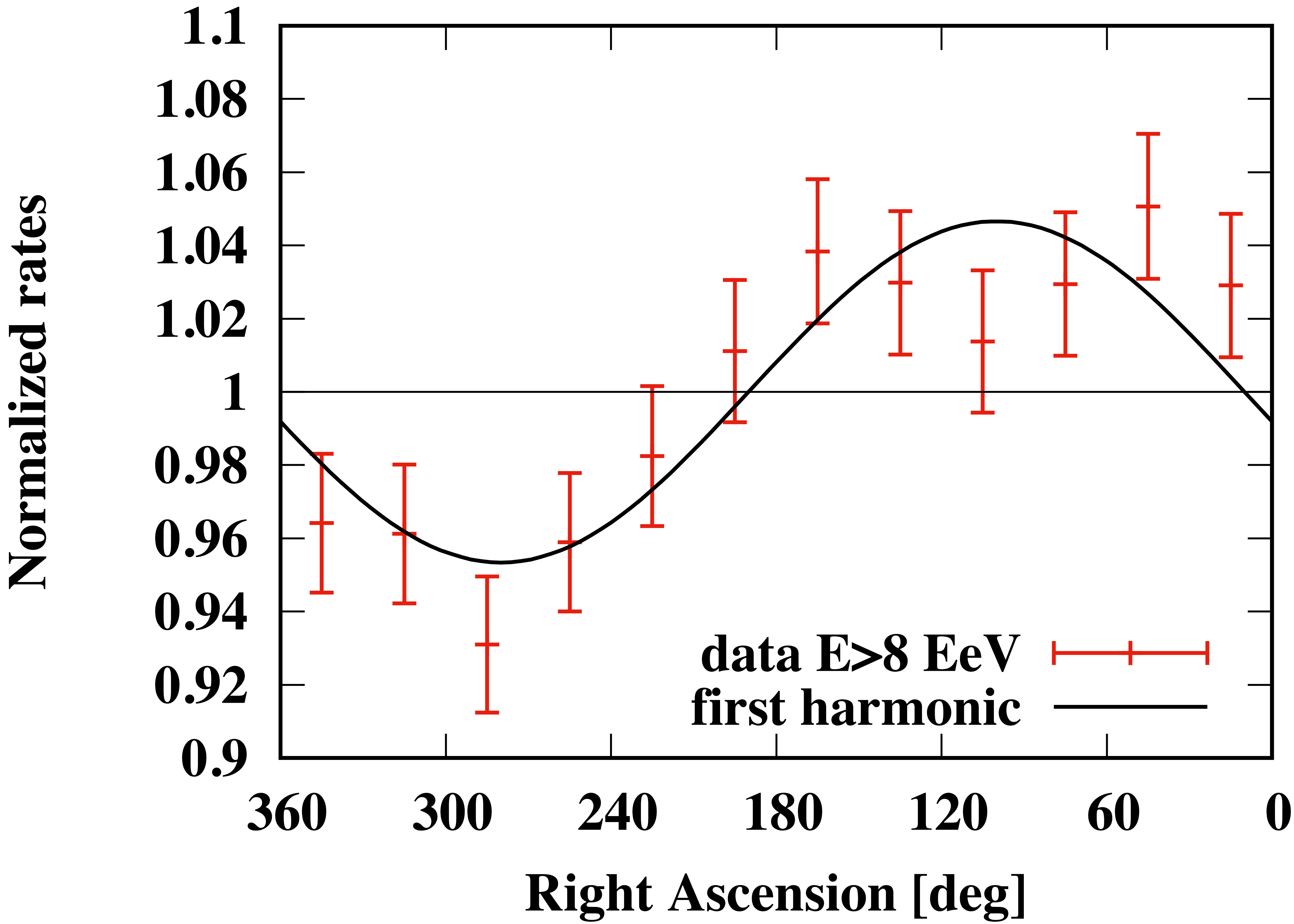
- Weights account for small non-uniformities

- Obtain: amplitude and phase of 1st harmonic

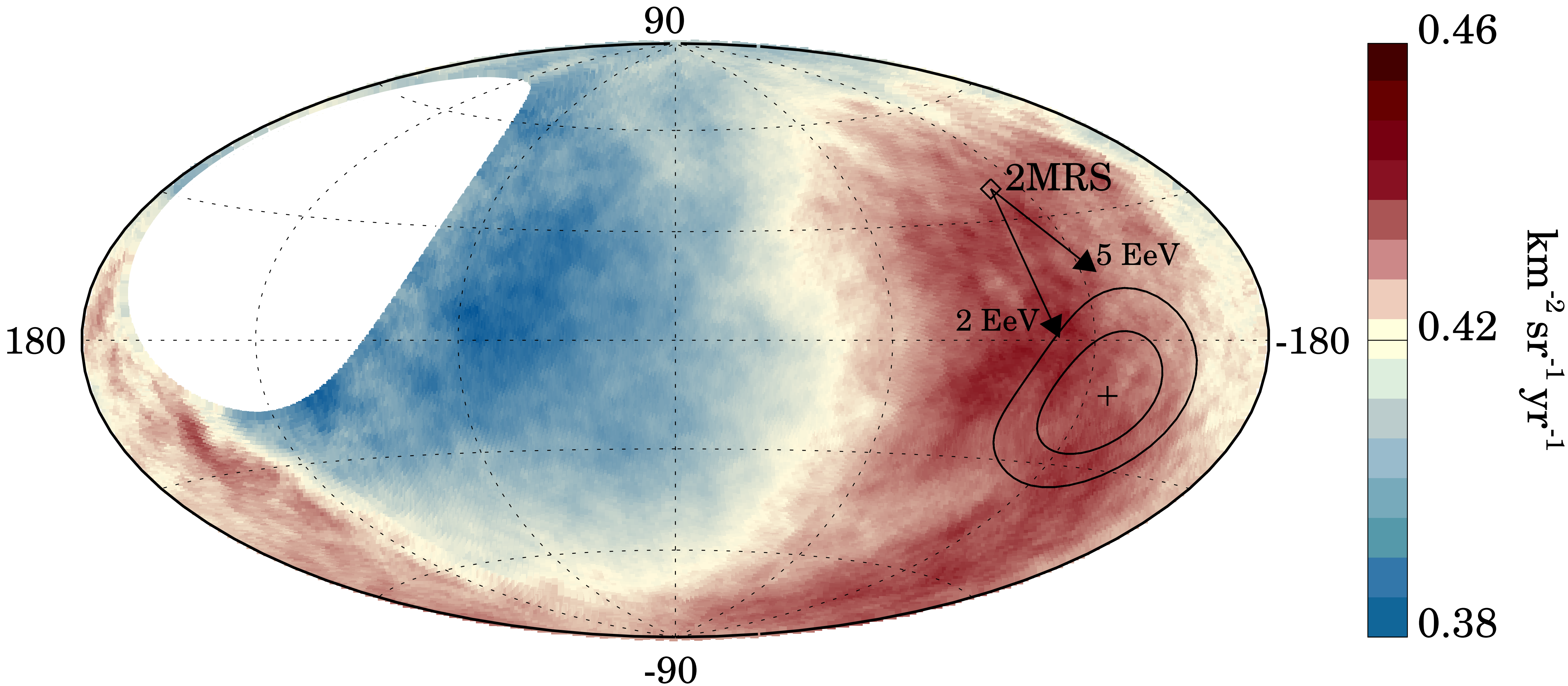
$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}, \qquad \tan\phi_\alpha = \frac{b_\alpha}{a_\alpha}$$

- For events above 8 EeV
  - Amplitude $4.7^{+0.8}_{-0.7}\%$
  - Chance probability 2.6×10^{-8}
  - After penalization: 5.2σ

Event rate vs Right Ascension

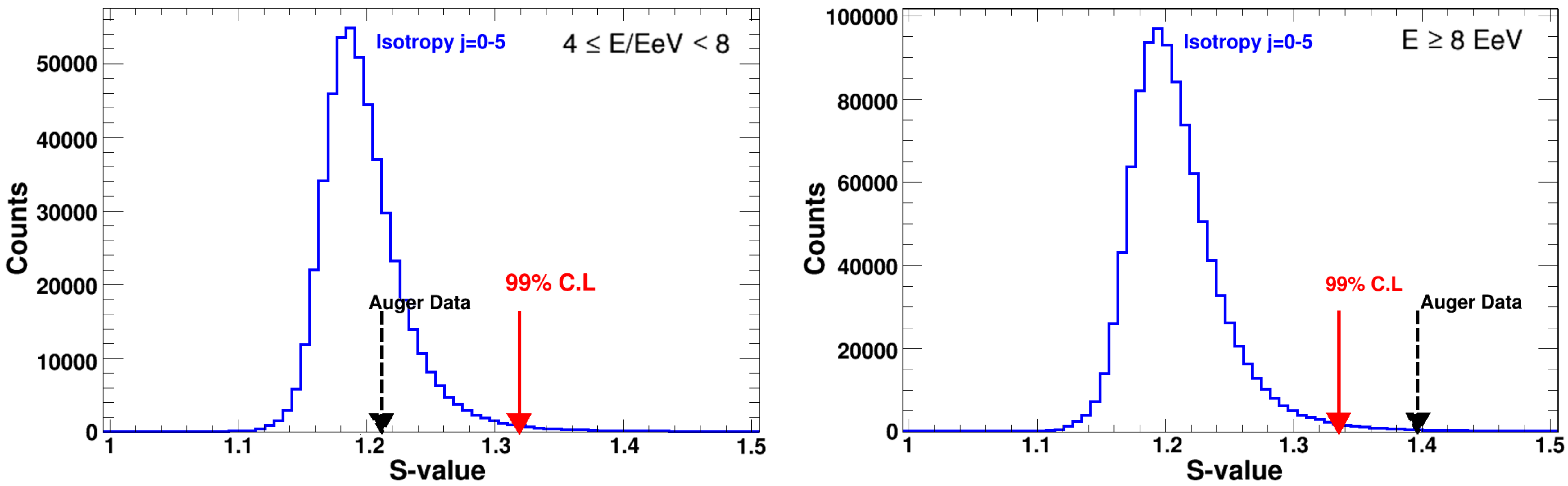


CR dipole vs 2MRS dipole



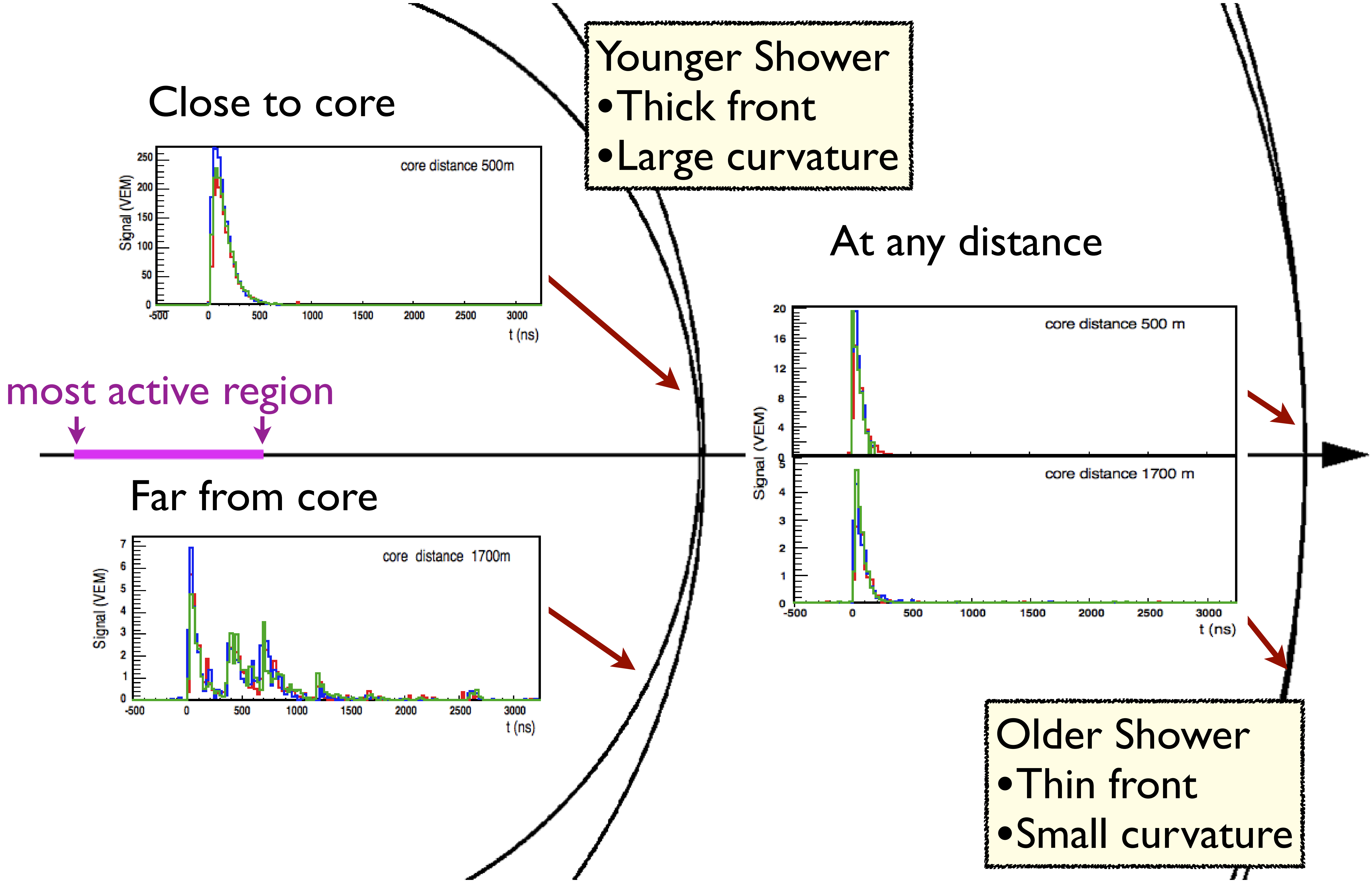
- Cross indicates CR dipole, Diamond 2MRS dipole
- Expected deflection shown for specific model for magnetic fields

Needlet analysis



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

Neutrino detection: Geometry of air showers



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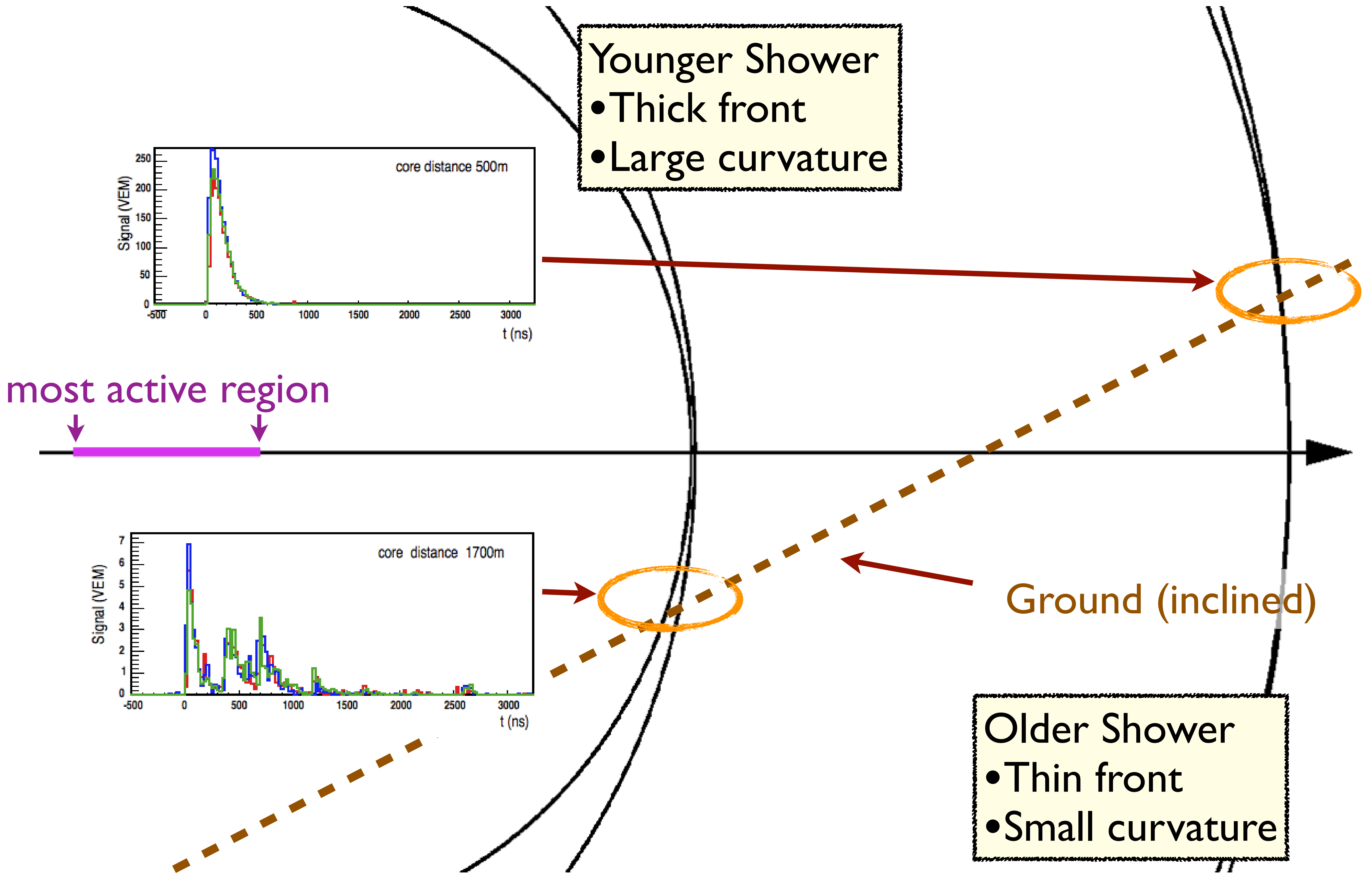
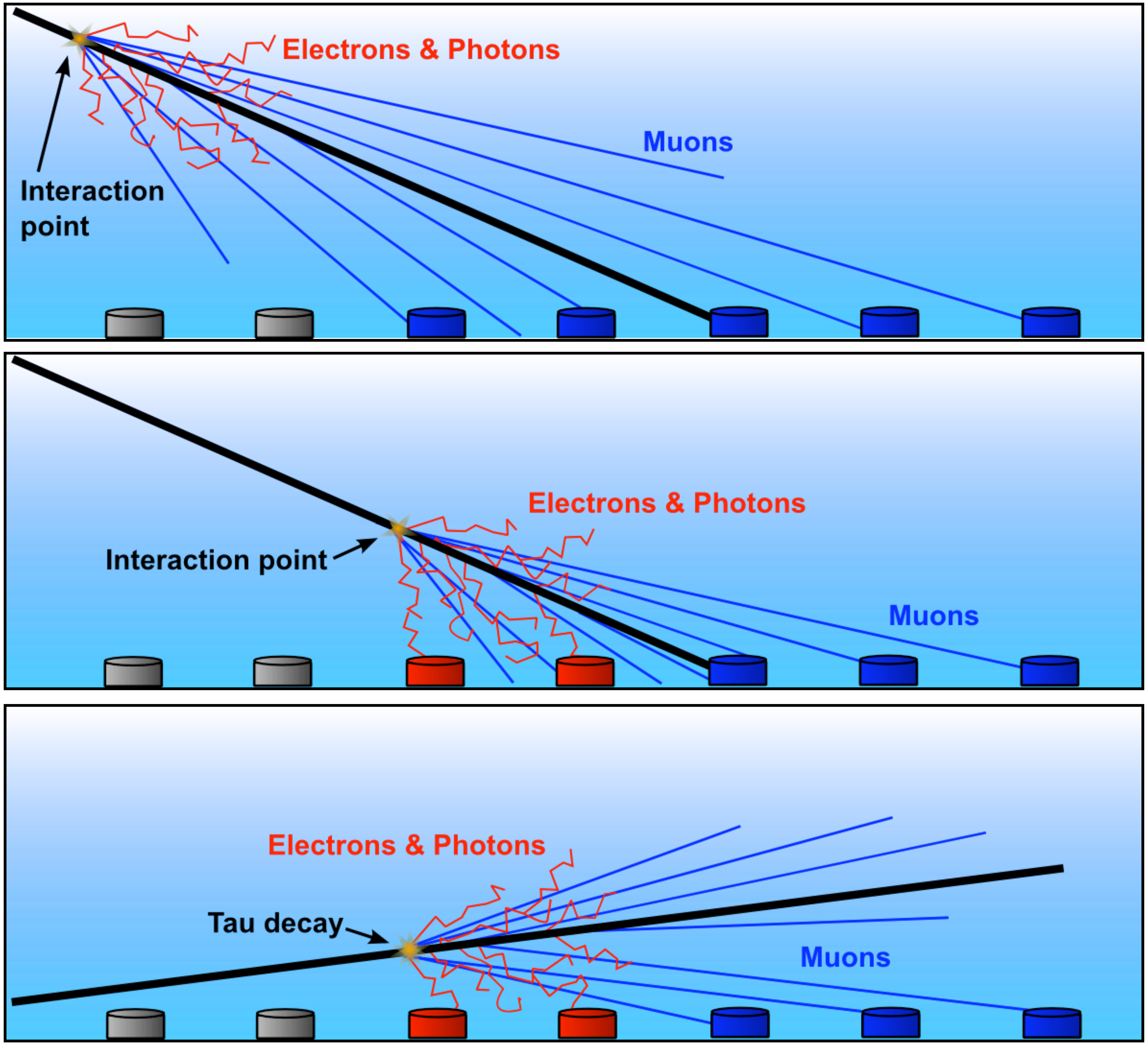


Inclined showers

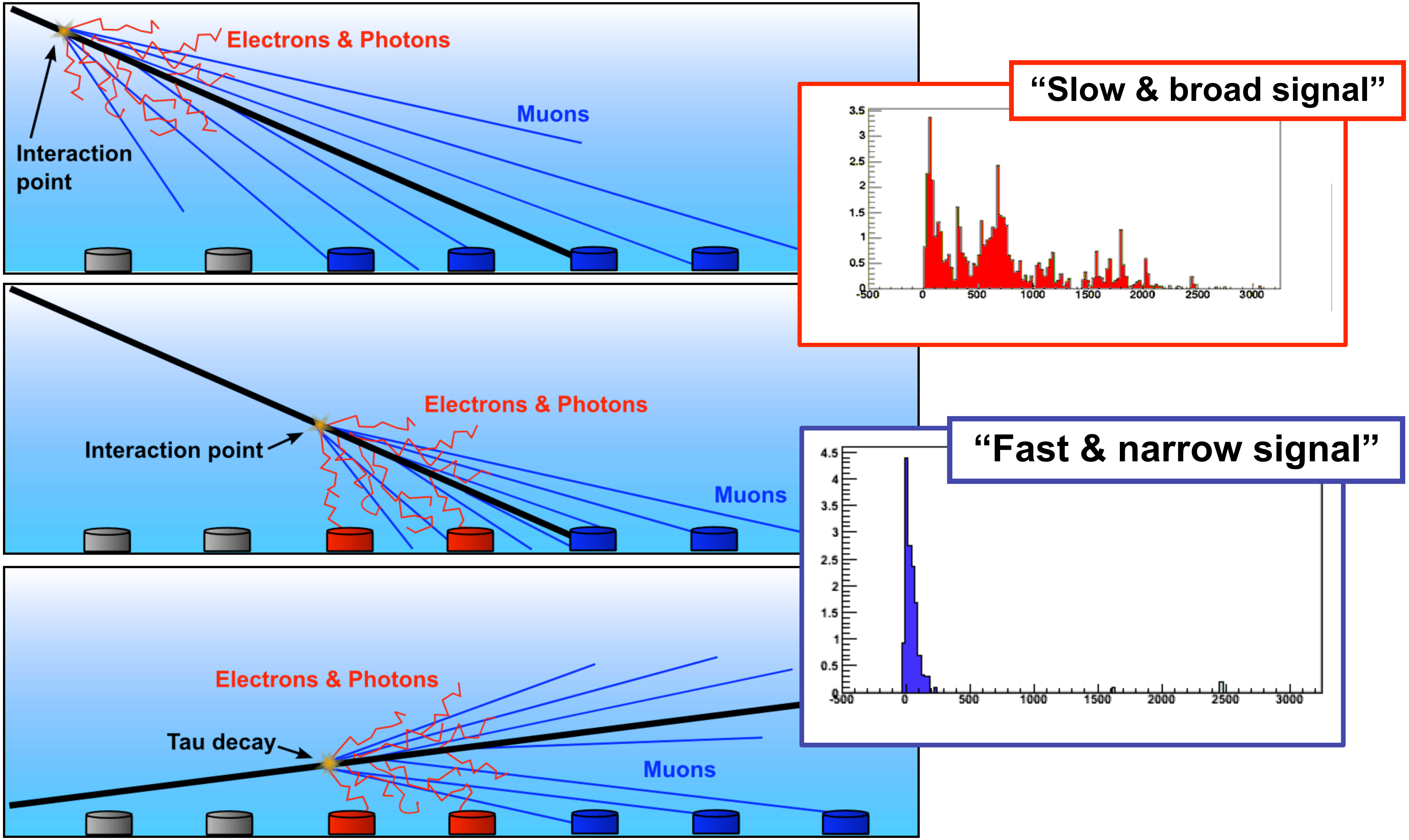


Hadronic shower:
Old, develops far from the detector

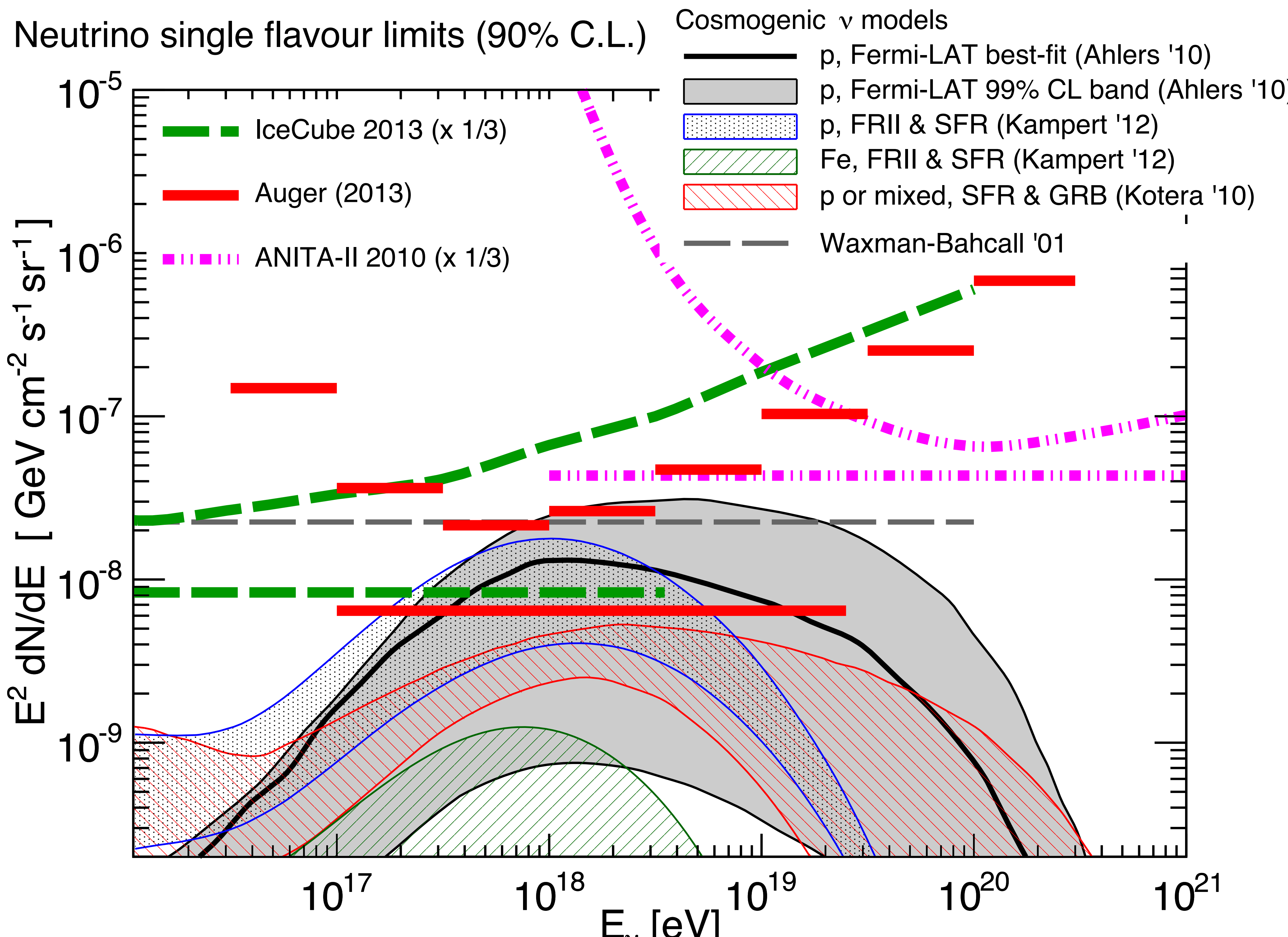
Neutrino shower:
Early region: young
Late region: old

Note:
$1000 g/cm^2$ are ≈ 10km at 90°
∴ Showers age along footprint

Inclined showers

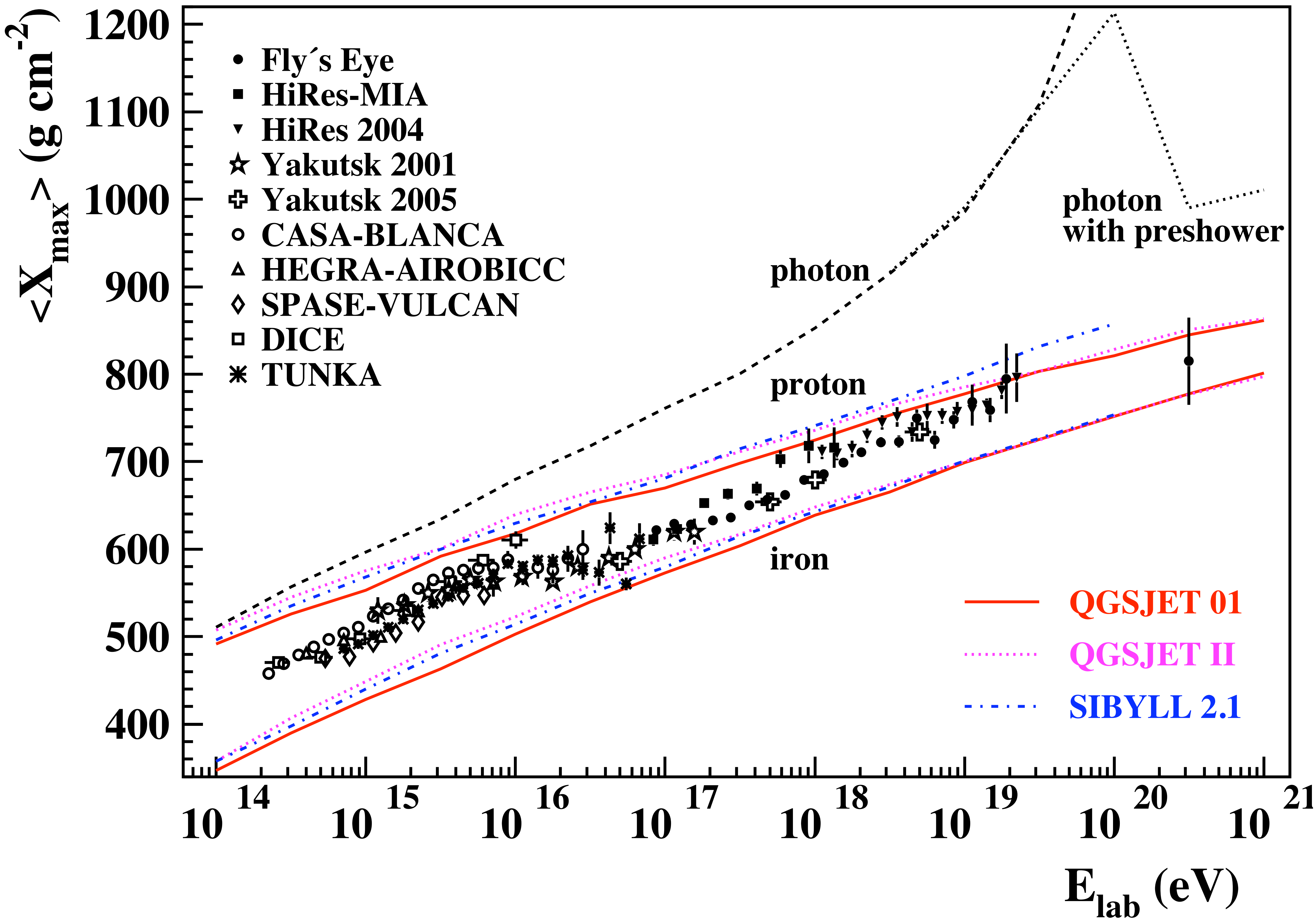


Neutrino limits

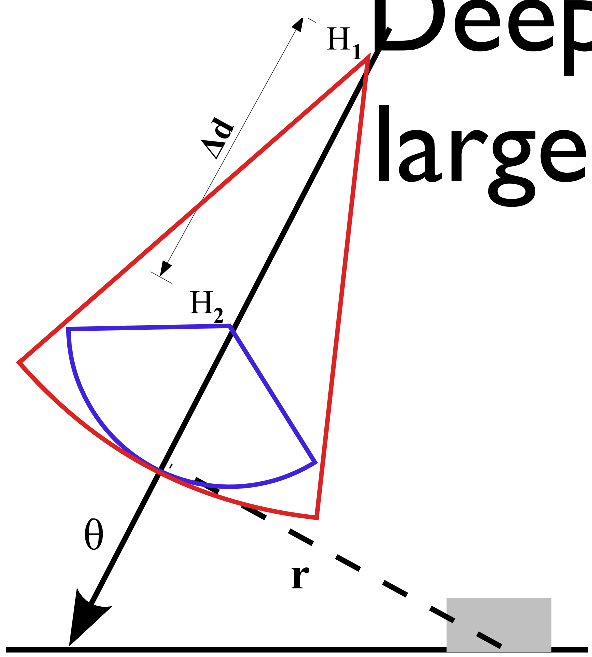


Starts to limit some source models and approach cosmogenic flux predictions

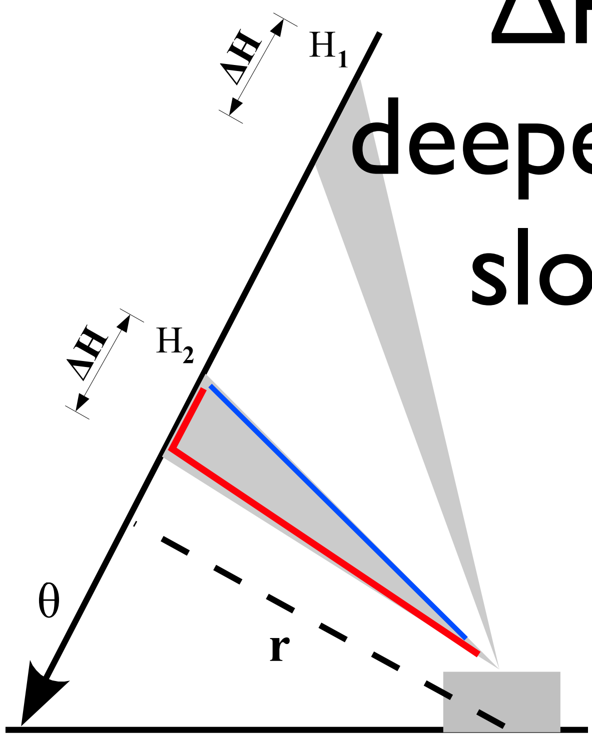
FD photon discrimination



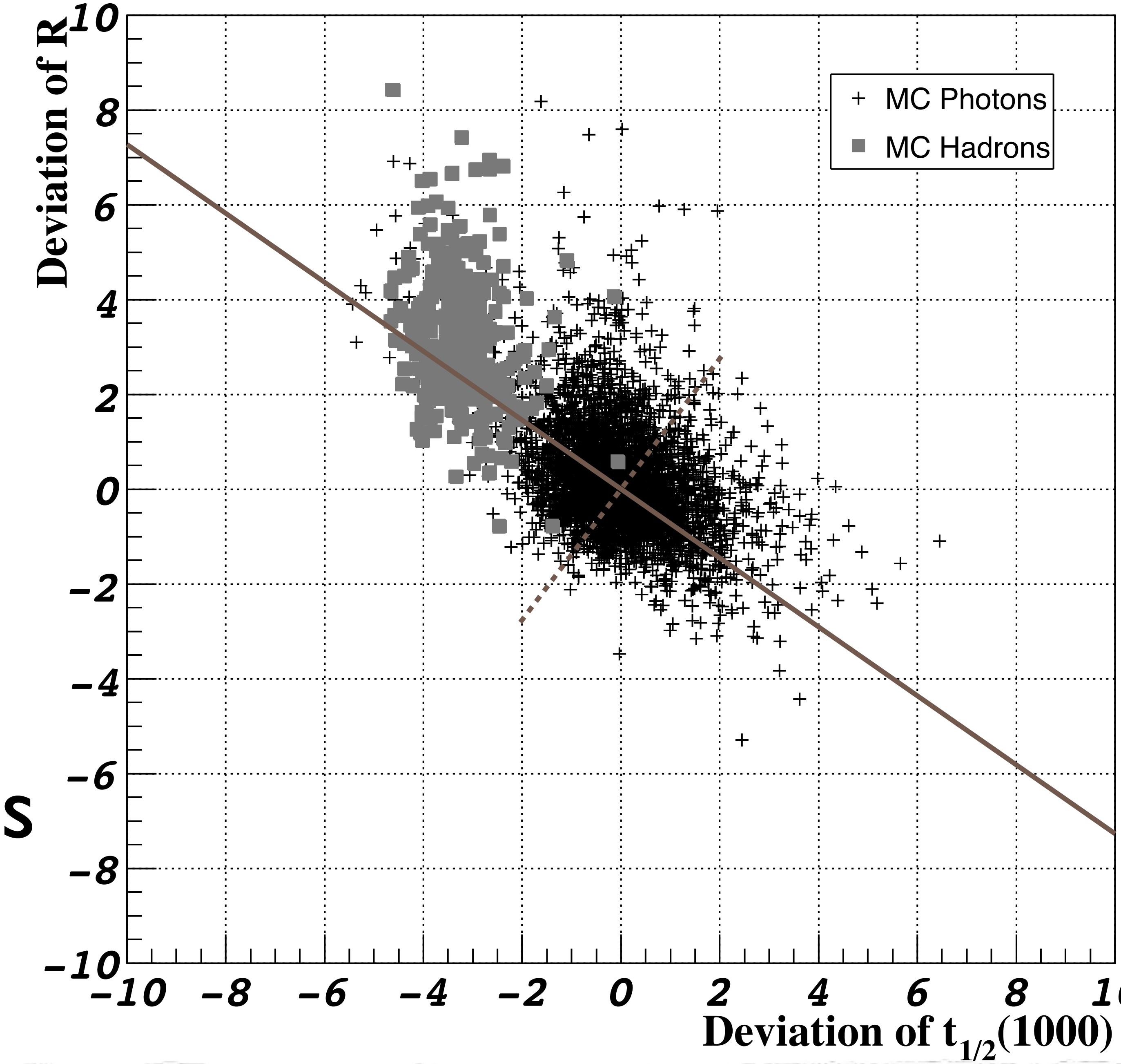
SD photon discrimination



Deeper shower: larger curvature

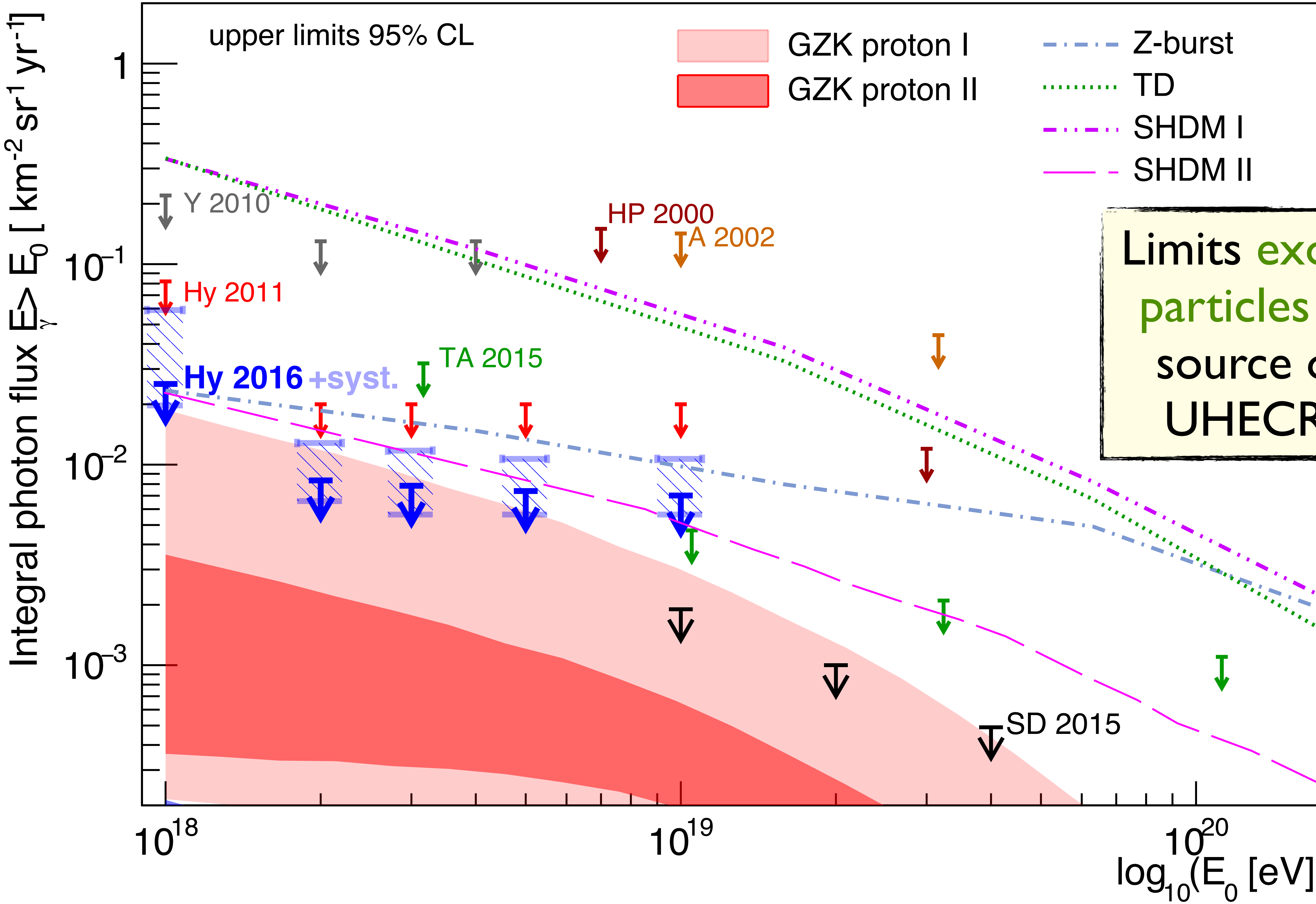


ΔH gives Δt: deeper shower has slower signals



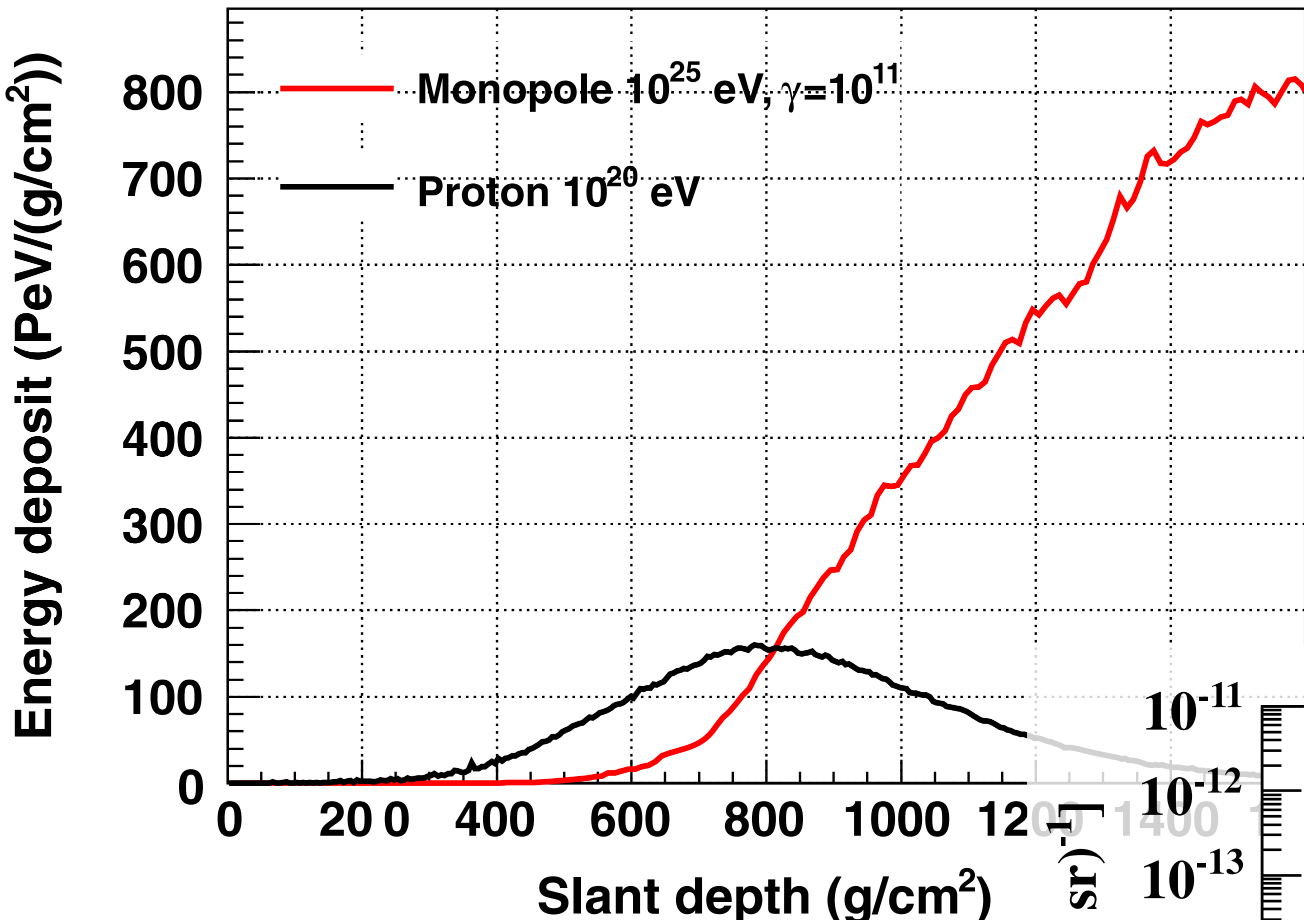
Parametrize with simulations
Principal component analysis on deviation

Photon limit



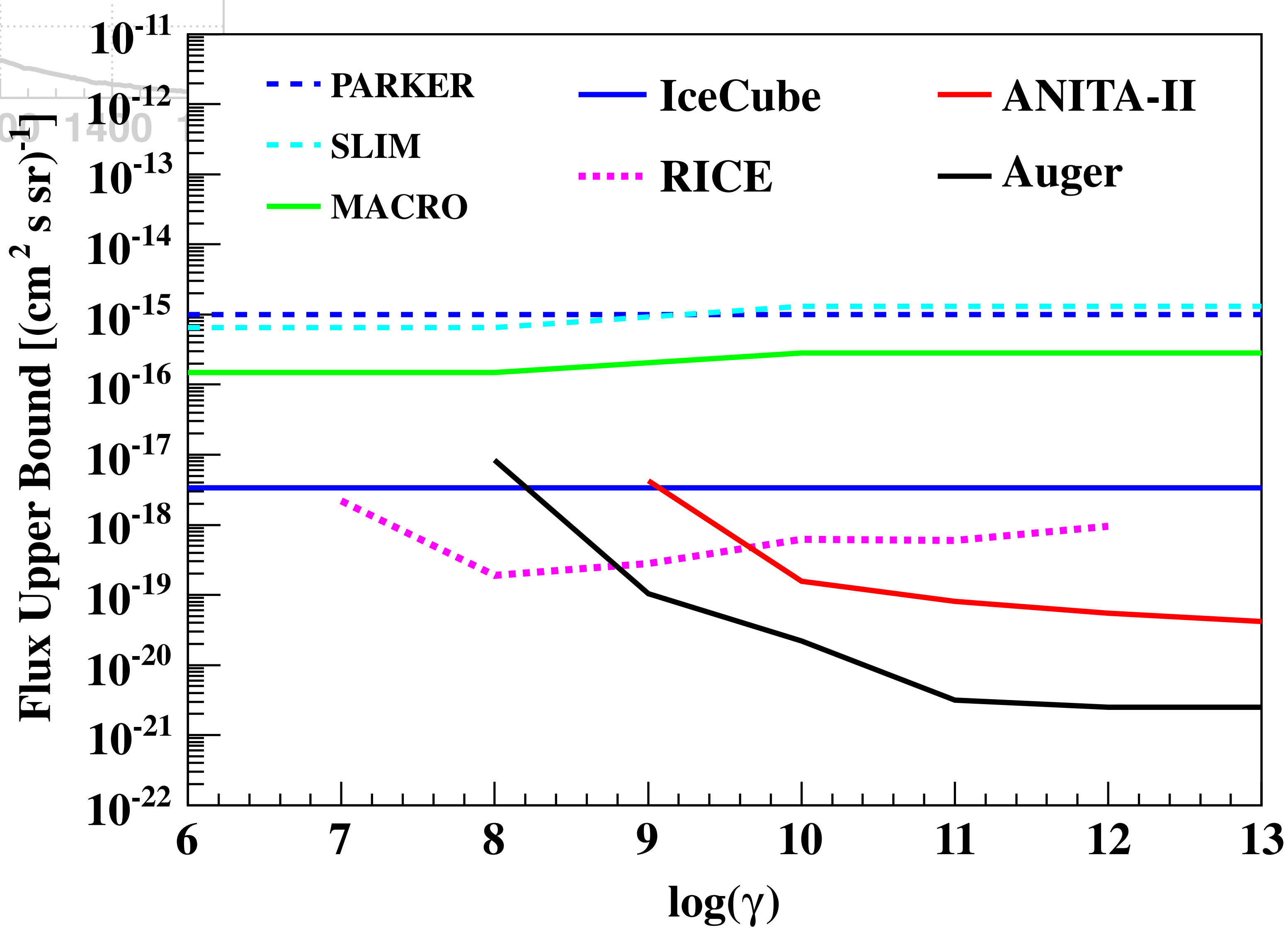
Limits exotic particles as source of UHECR.

Search for magnetic monopoles

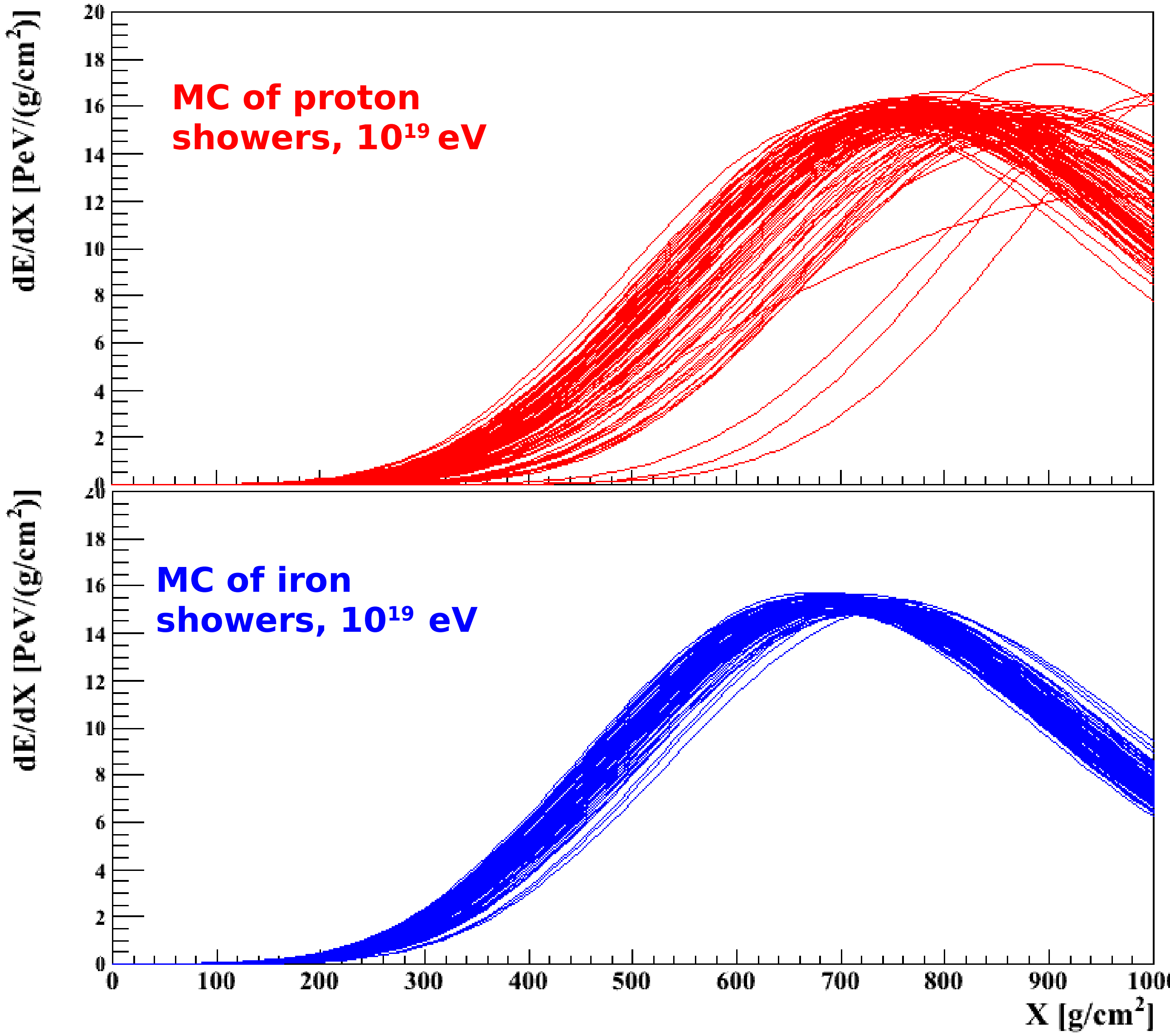


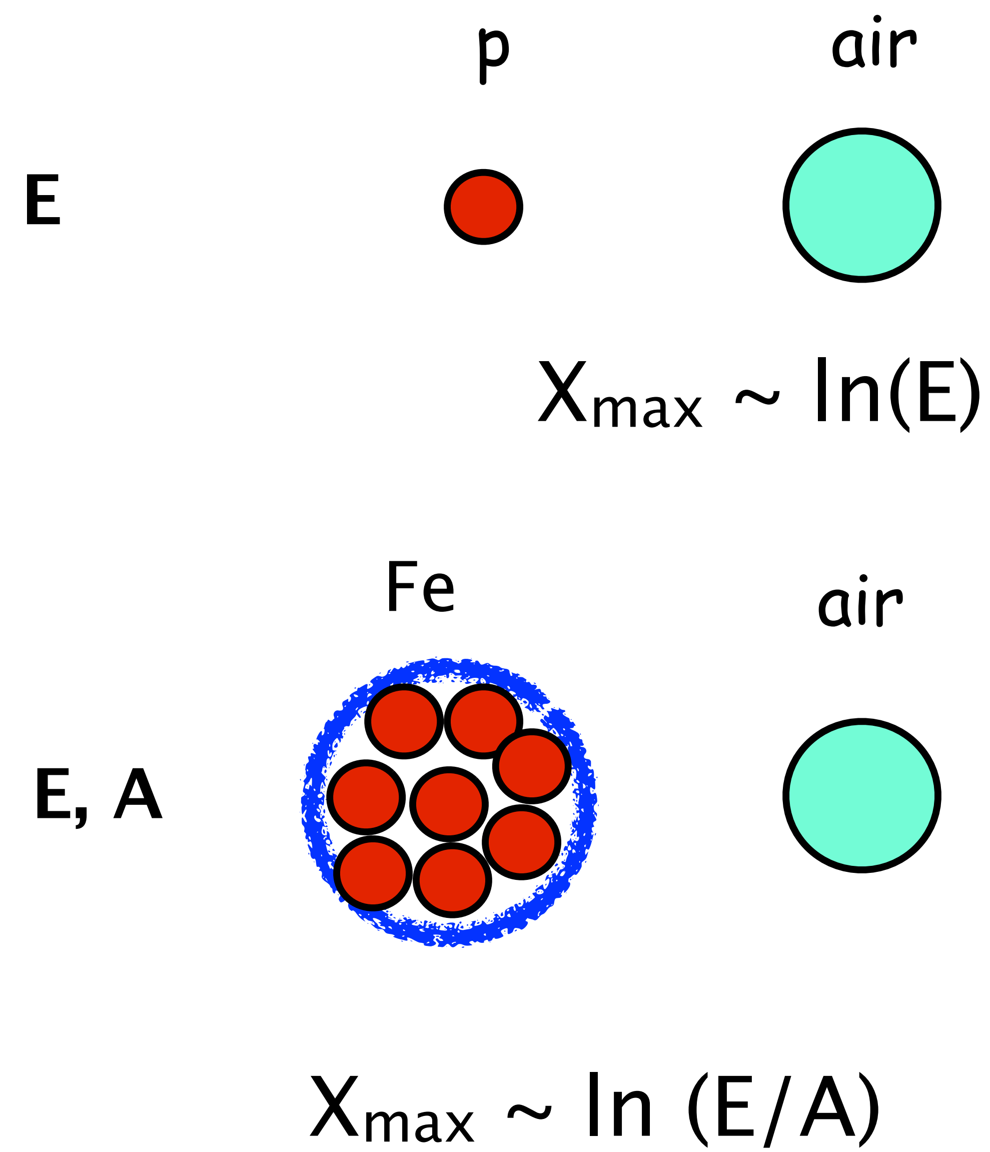
Energy deposit different from hadronic shower

Auger: strongest limits at high E



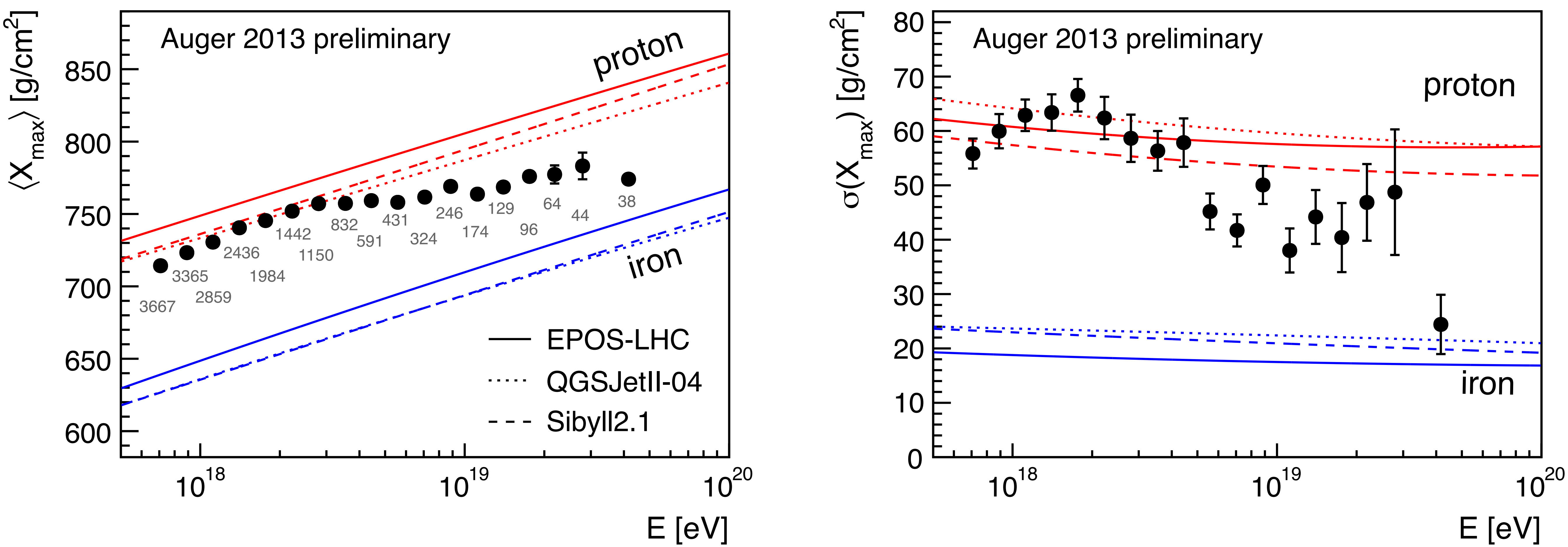
Composition and X_{max}





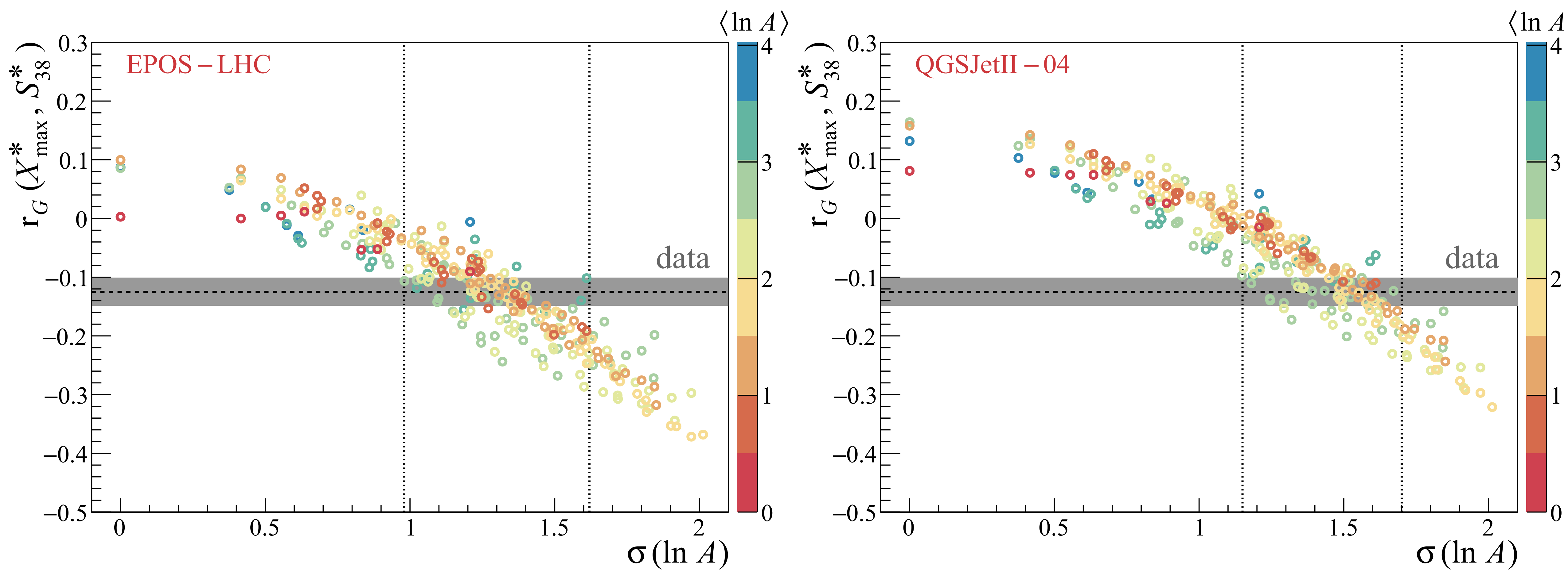
- Both X_{max} and RMS(X_{max}) depend on
  - Energy: Number of generations in air shower
  - Cross-section, i.e., type of primary: σ(Fe-Air) > σ(p-Air)

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 (A const, i.e., σ(ln A) = 0)
  - r_G: Measure for correlation

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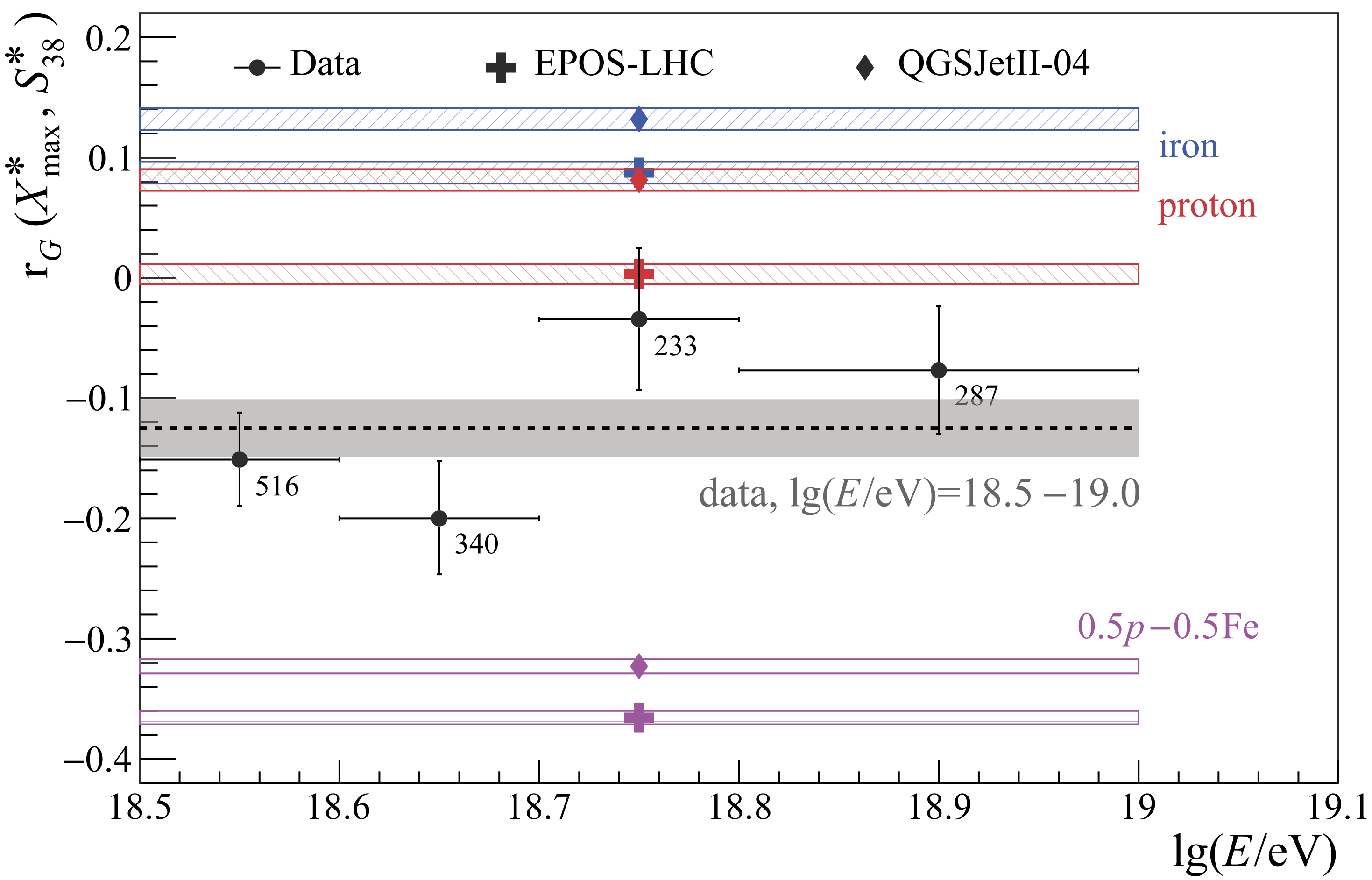

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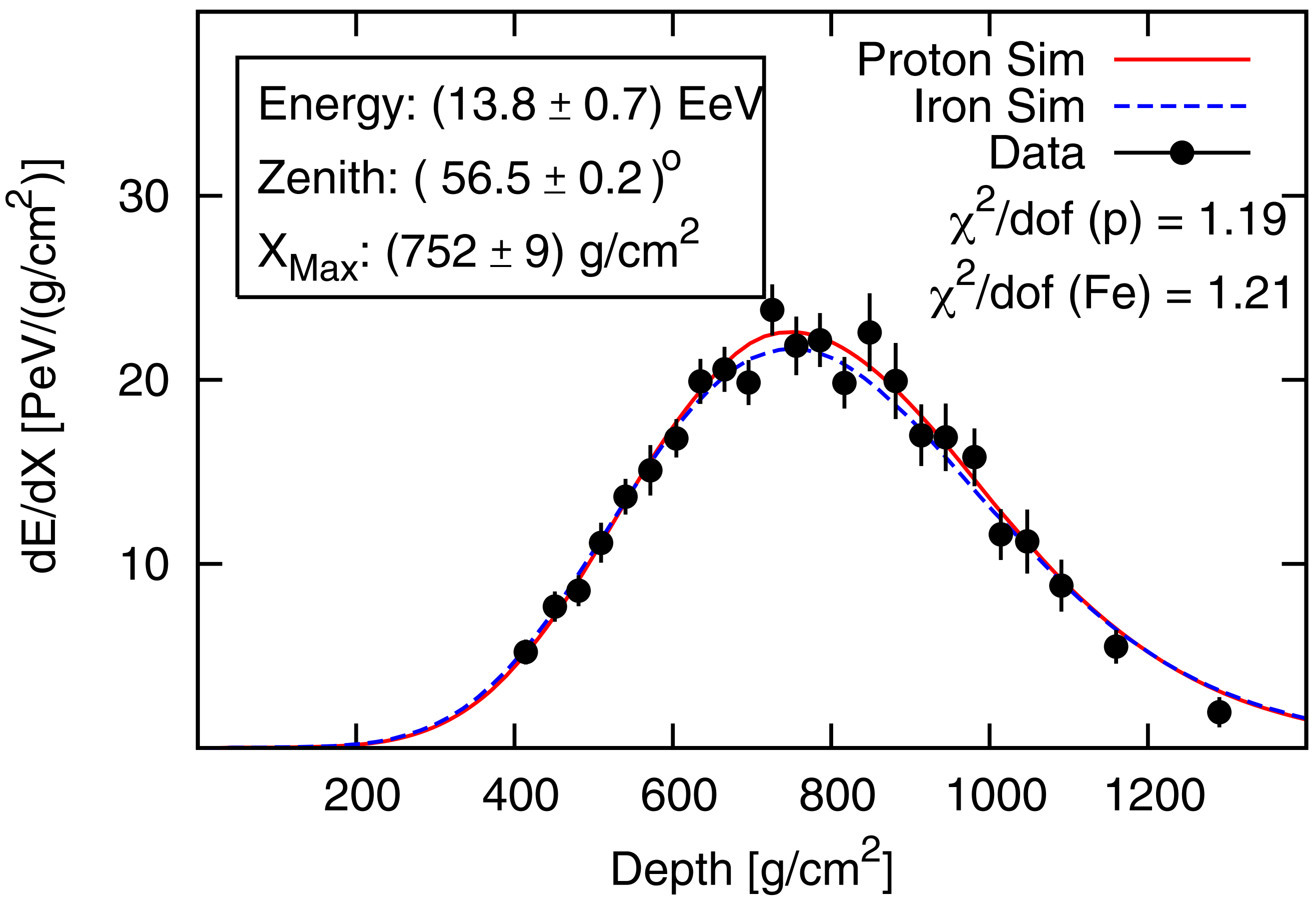
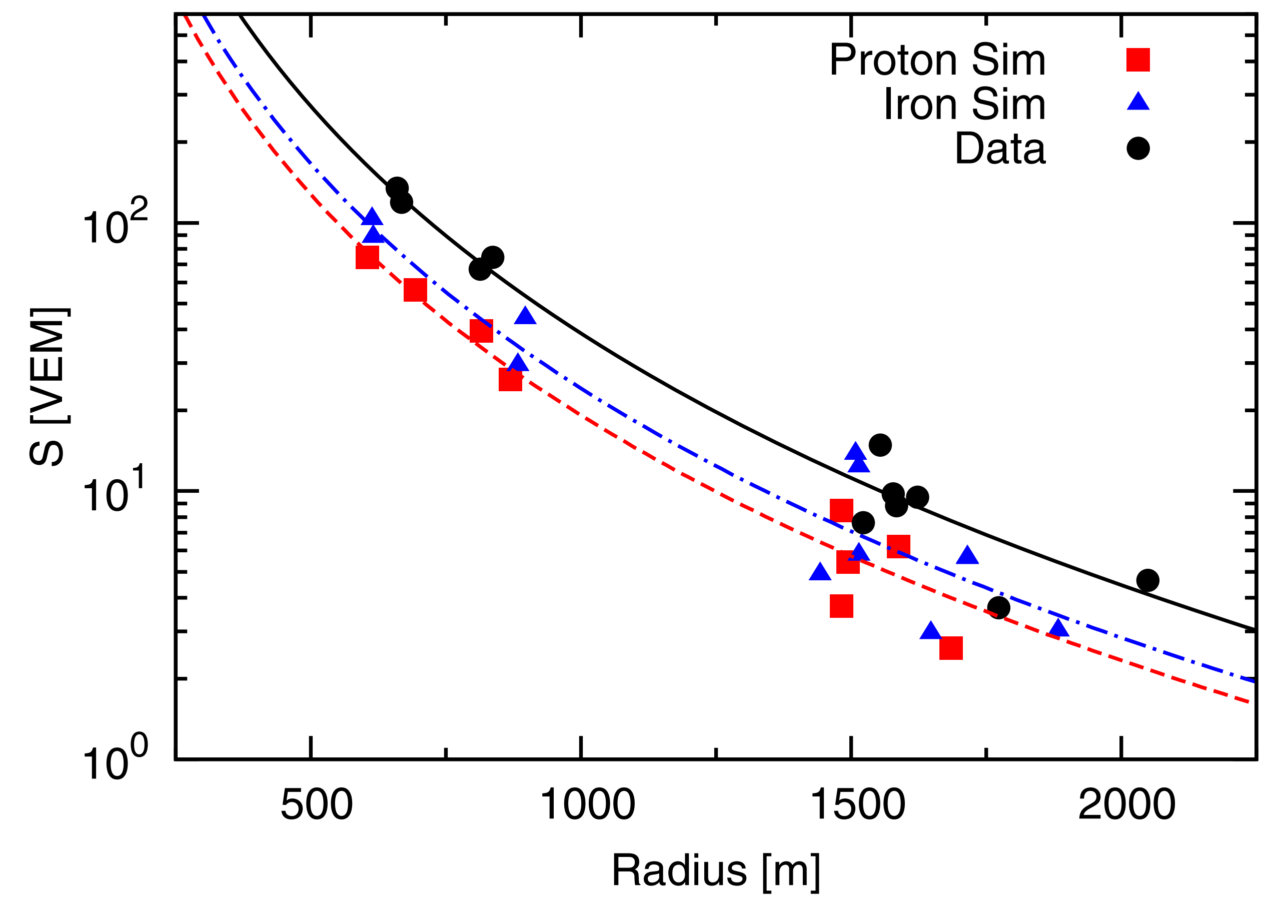
Muon fraction



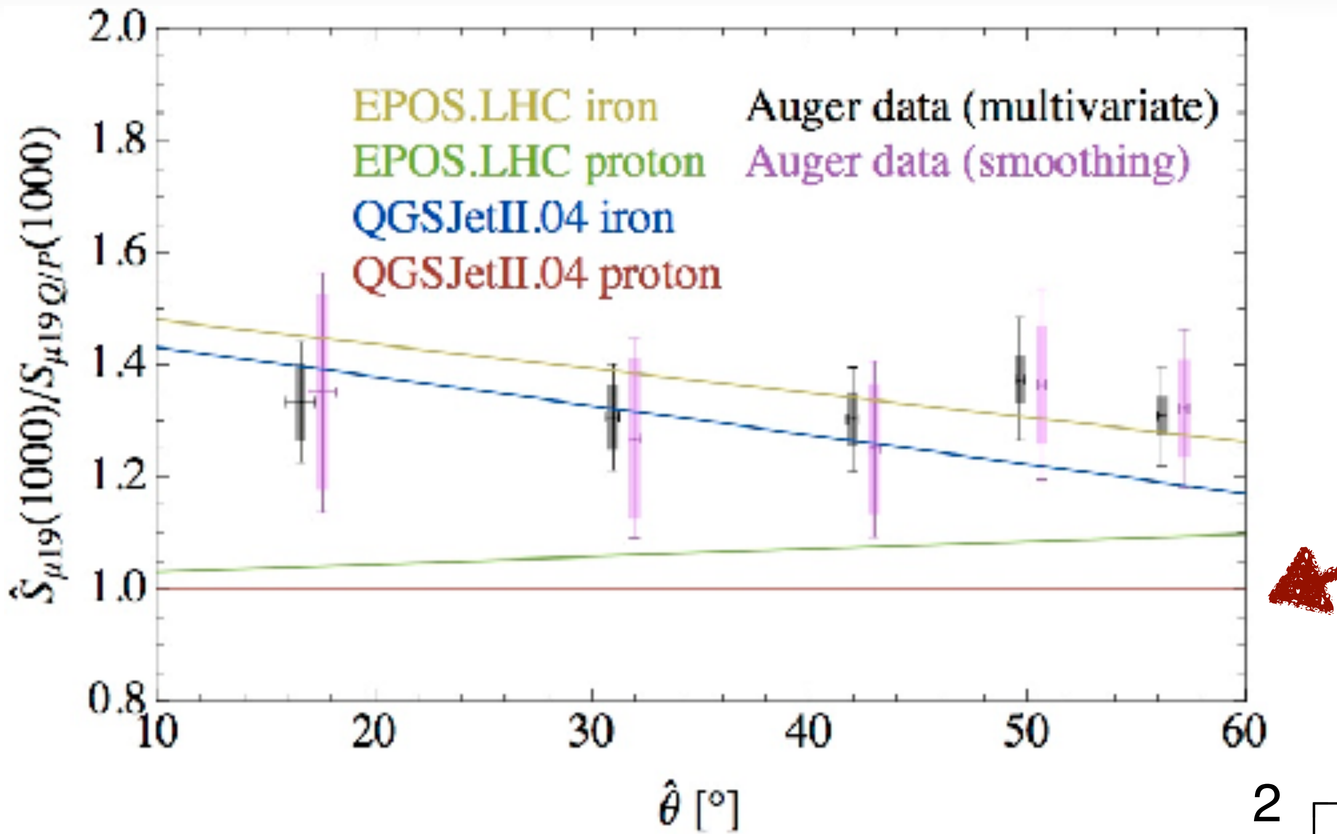


FD: em signal
Good fit

SD: em + μ signal
Data above sim

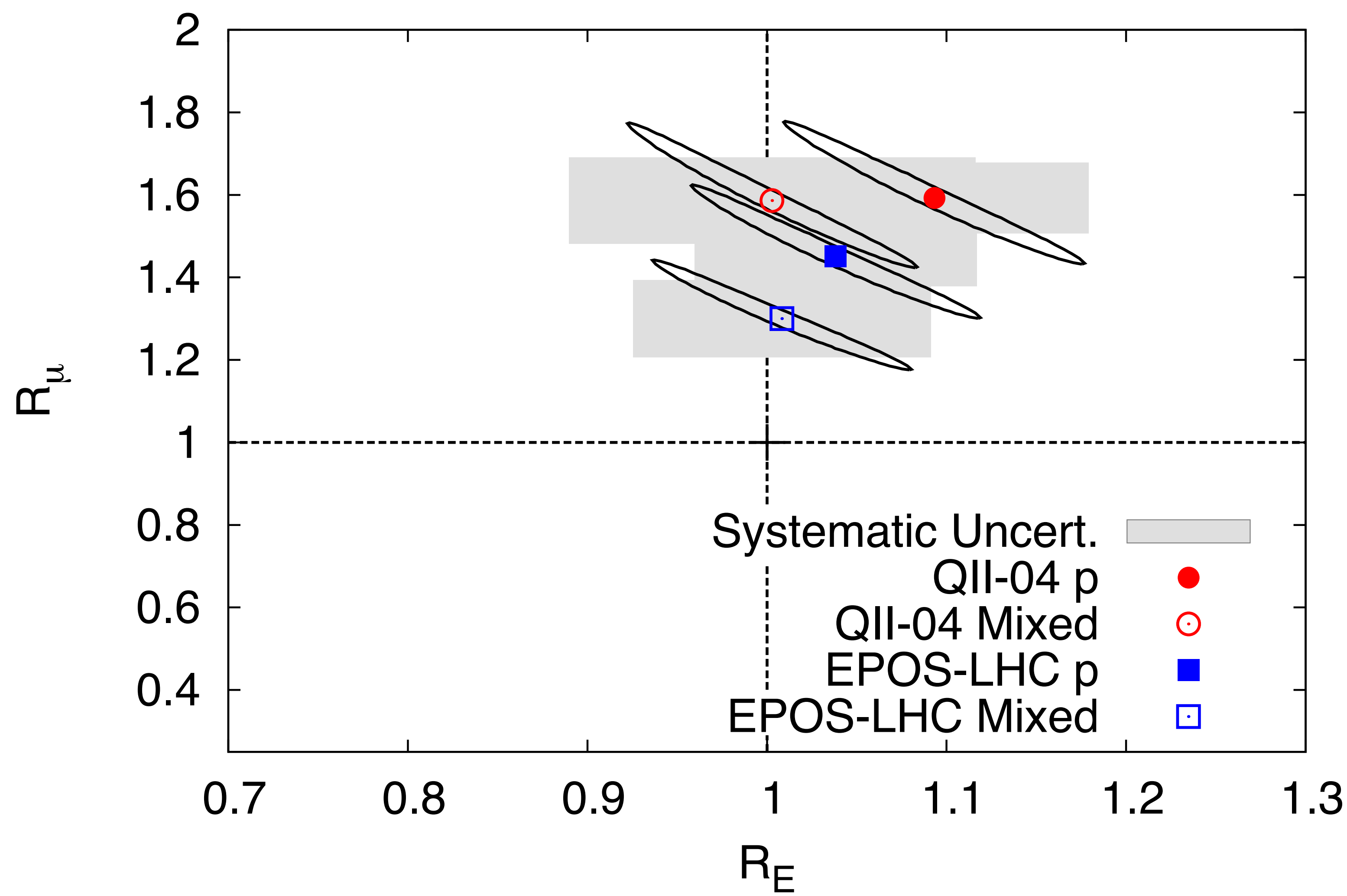
- Extracted fraction of muons and models disagree ⇒ rescale

Muon rescaling

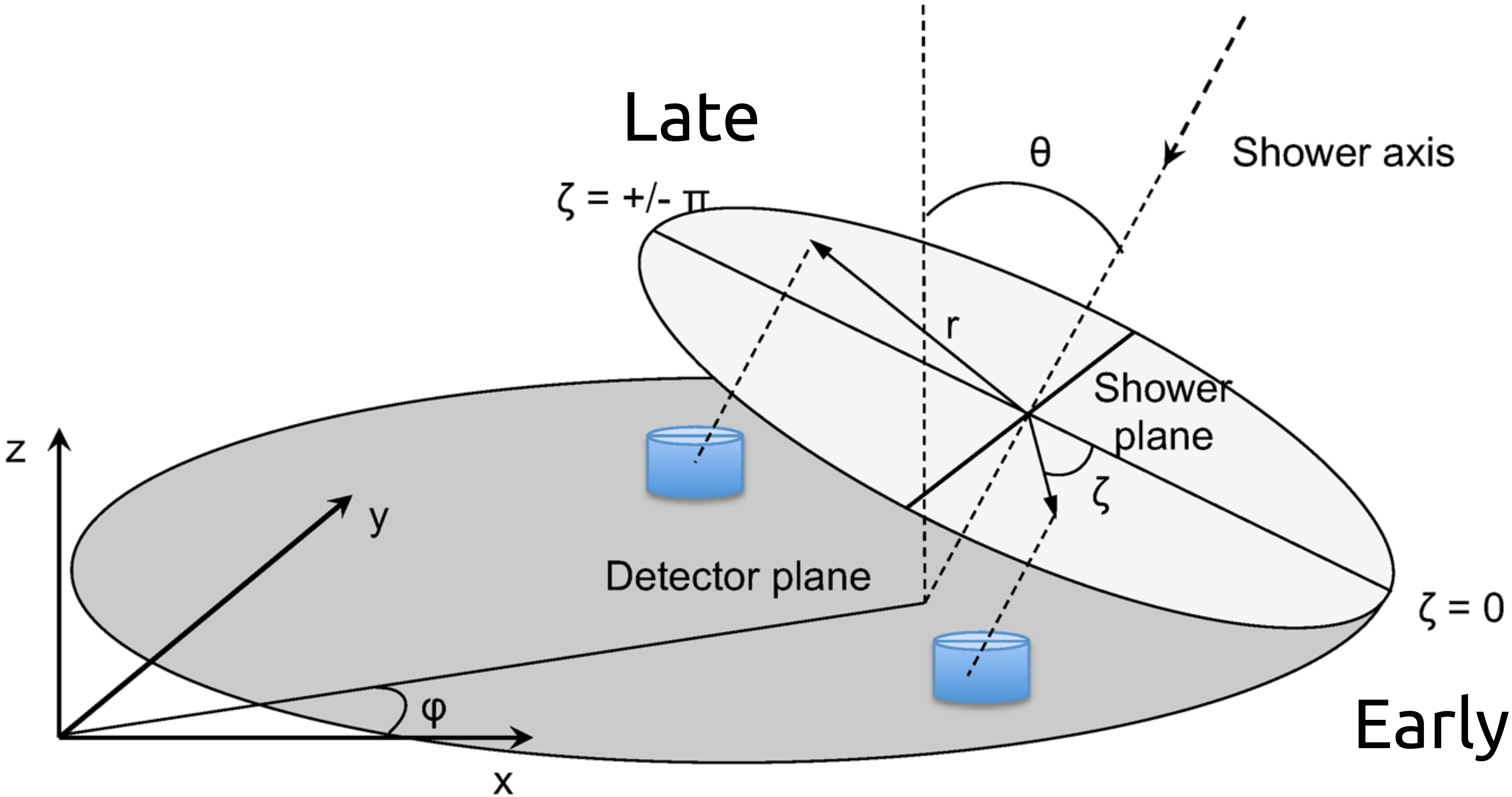


Rescaling, using QGSJetII.04 proton as a baseline

Best fit muon and EM rescaling for different models and compositions

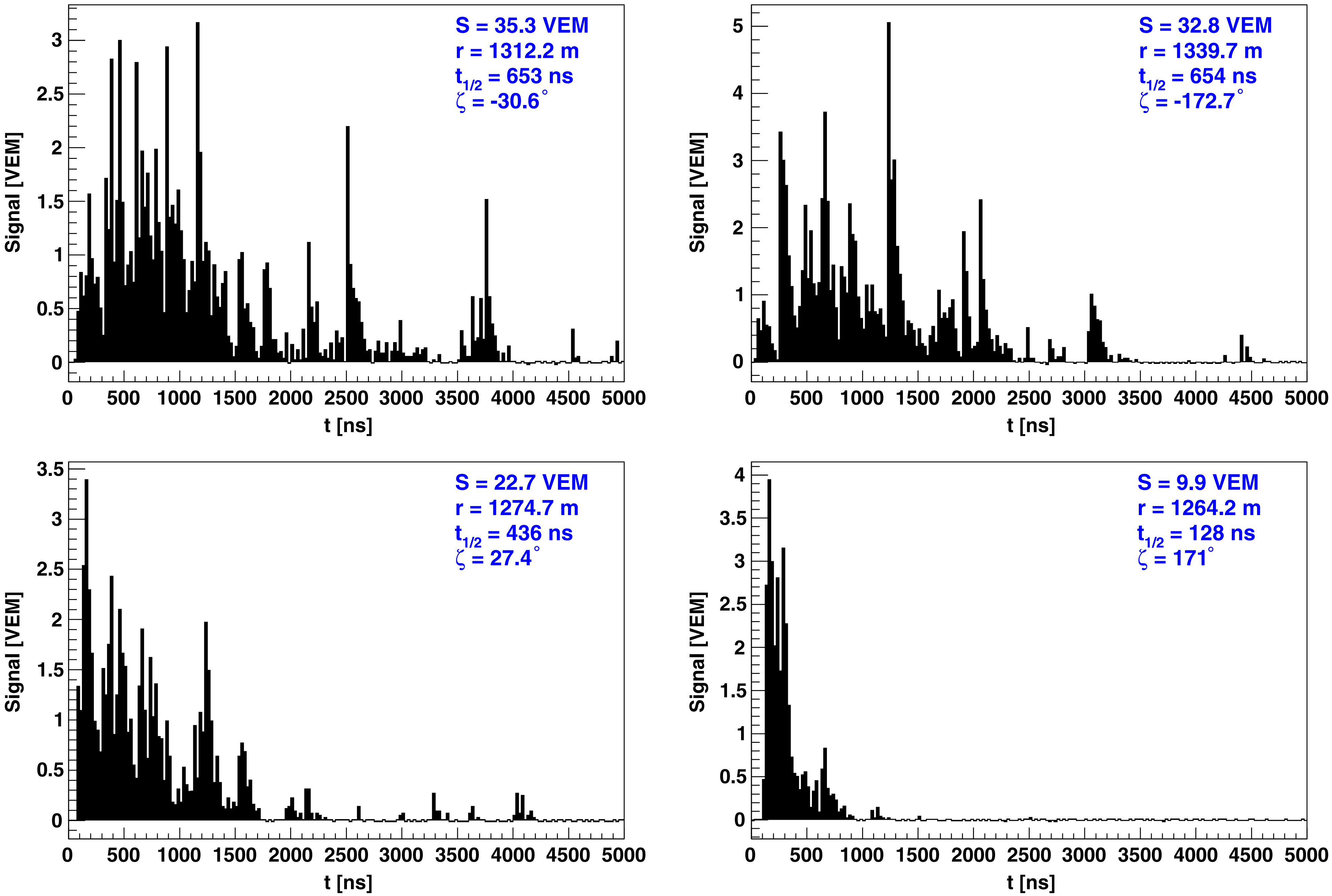


Risetime asymmetry



- Early vs late shower
  - Additional propagation for late part
- Composition dependent

Asymmetry example (data)

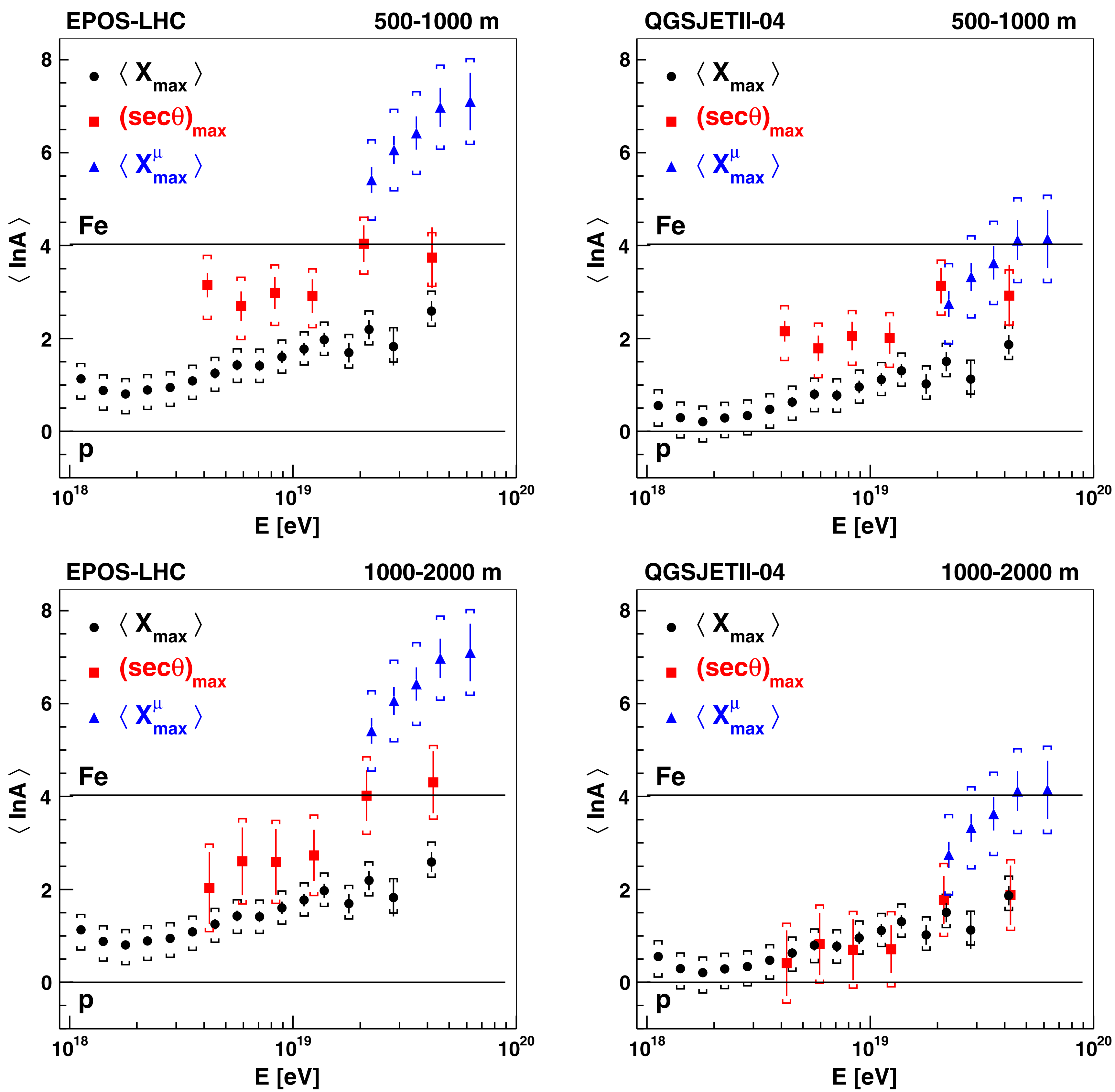


E = 16.9 EeV
θ = 15.7°

E = 7.7 EeV
θ = 52°
more asym.

Early Late

Models: lack of ability to fit

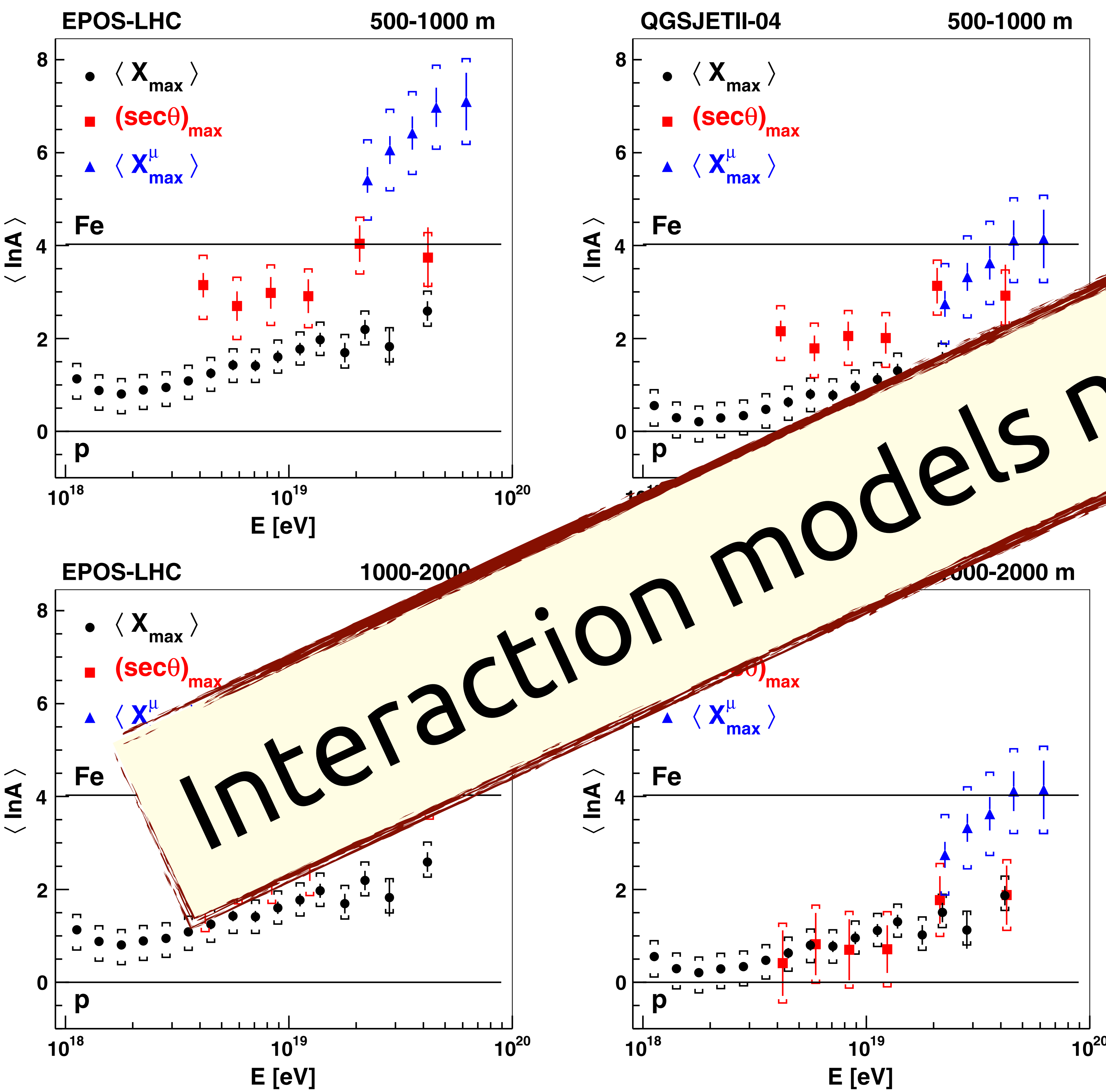


Neither model fits all data:

EPOS-LHC: fails X^{μ}_{max}

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

Models: lack of ability to fit



Interaction models need work

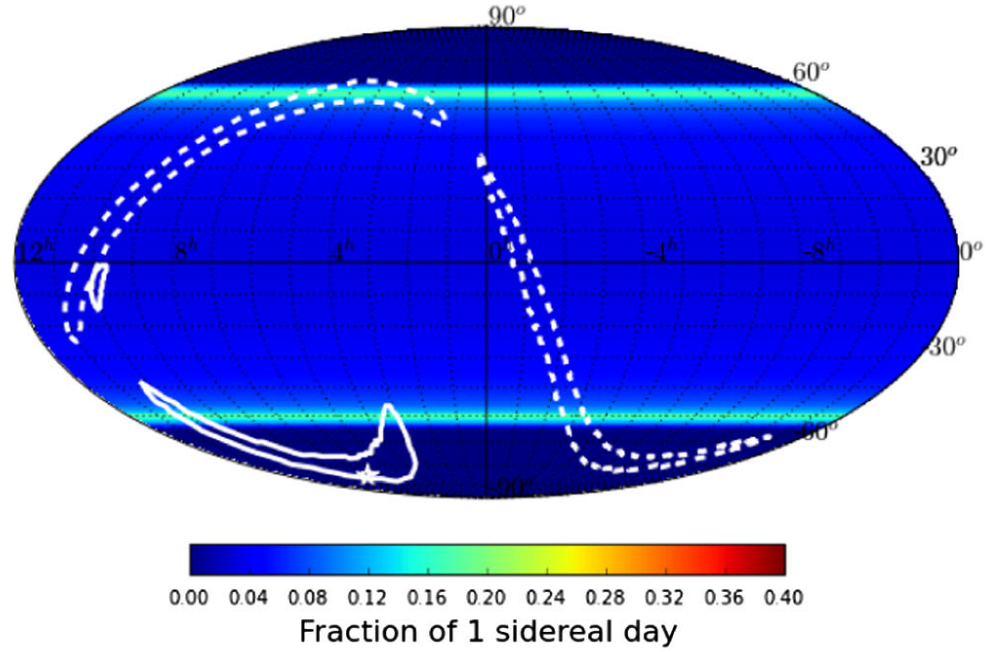
Neither model fit

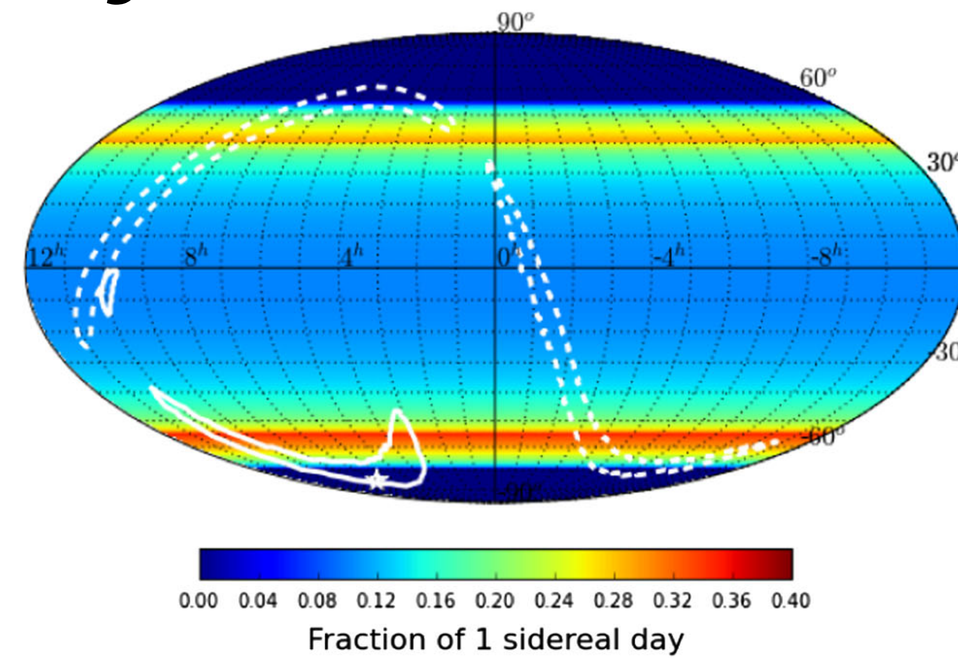
EPOS-LHC: fails X^{μ}_{max}

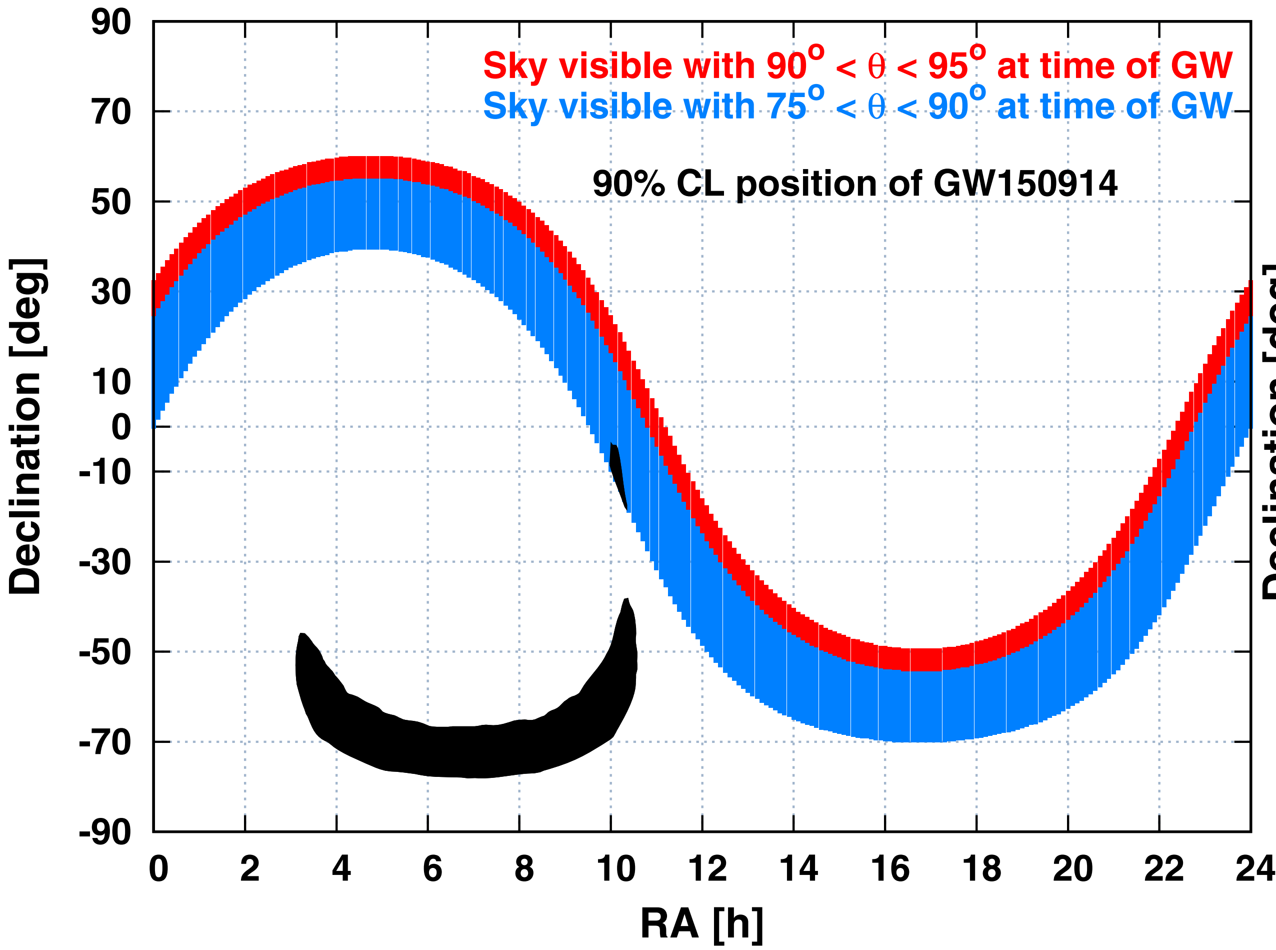
QGSJETII: inconsistent $(\sec\theta)_{max}$ for different distances

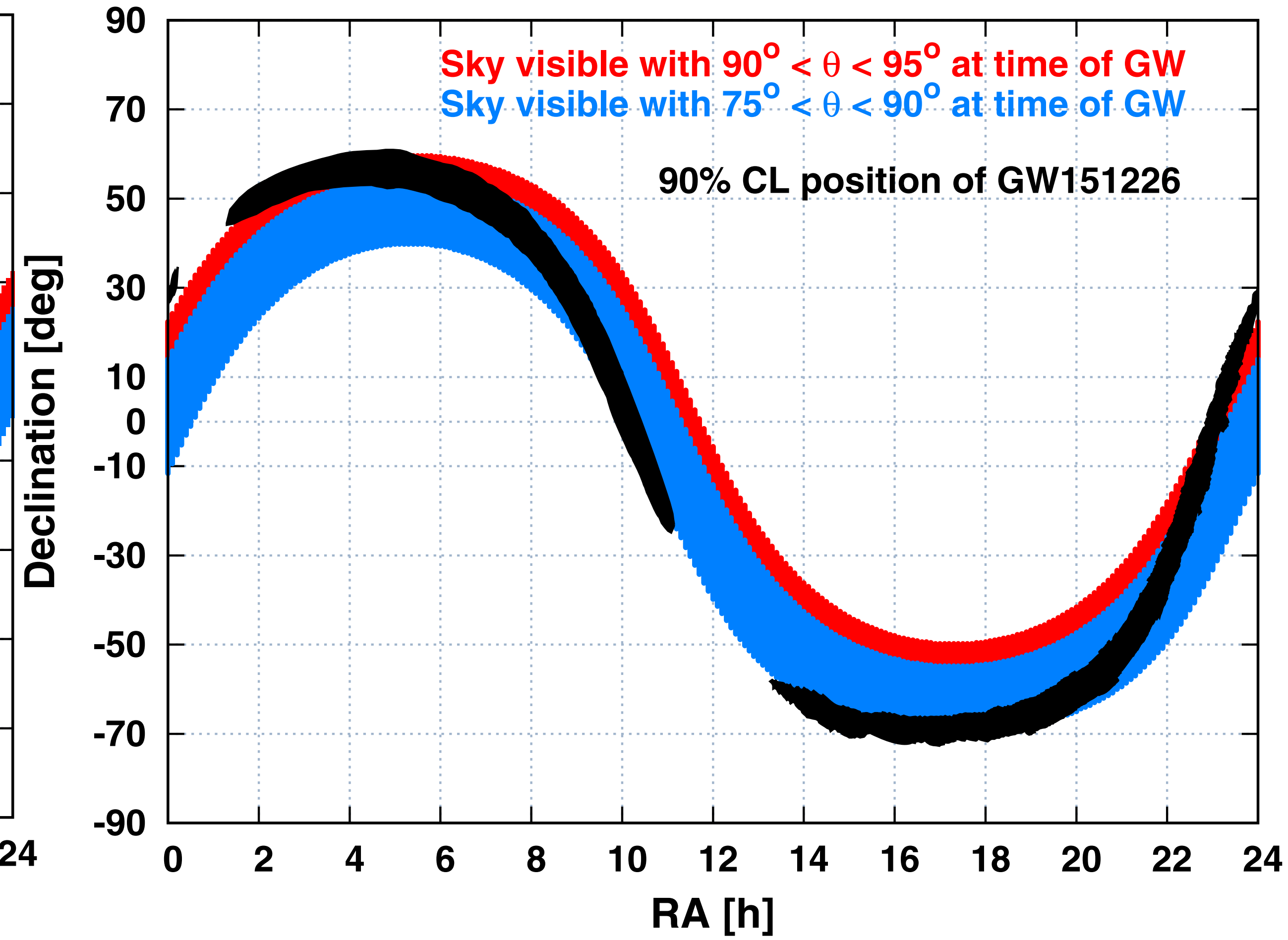
Neutrino followup of Gravitational Wave events

$90° \leq \theta \leq 95°$ Sensitivity $75° \leq \theta \leq 90°$



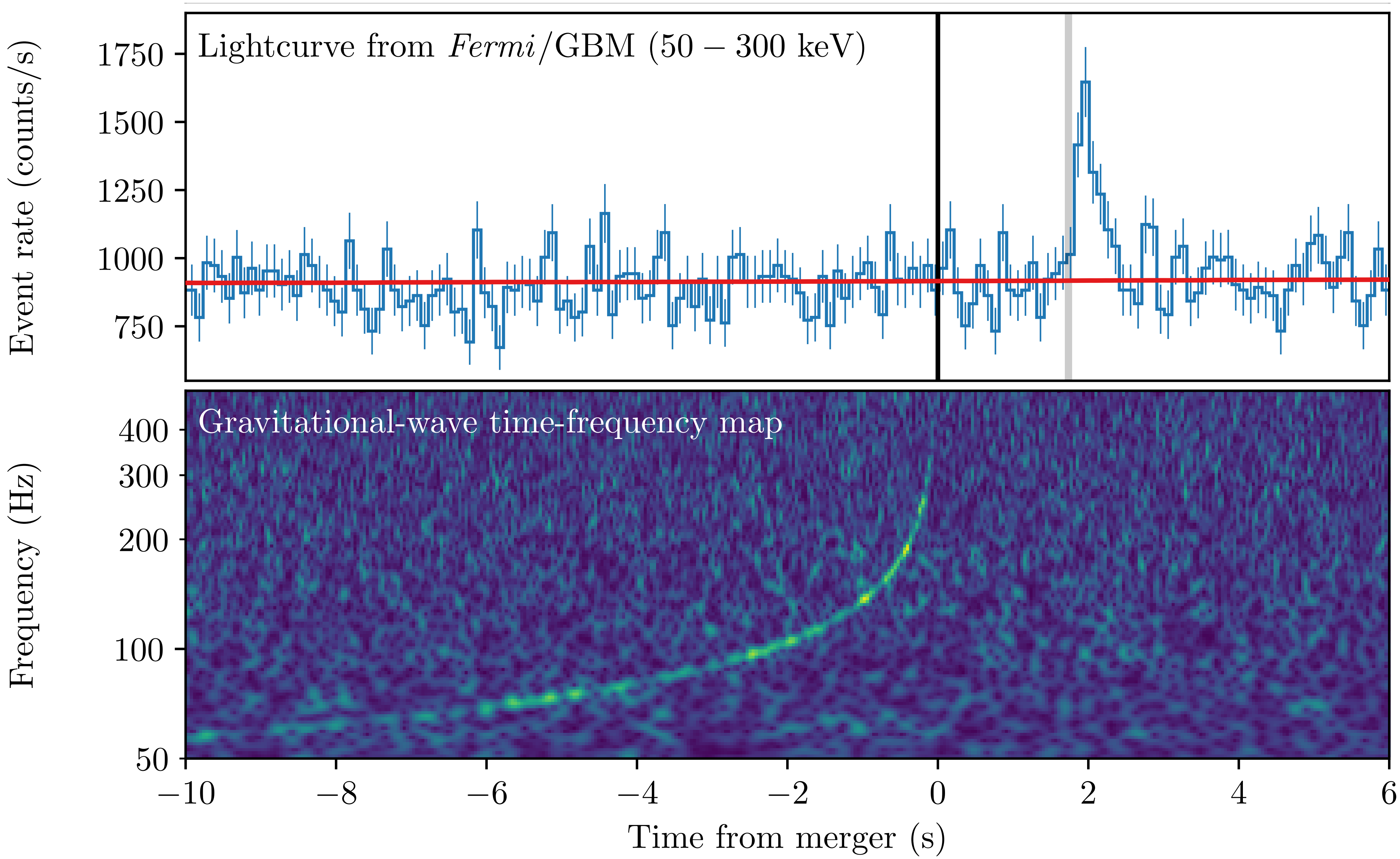




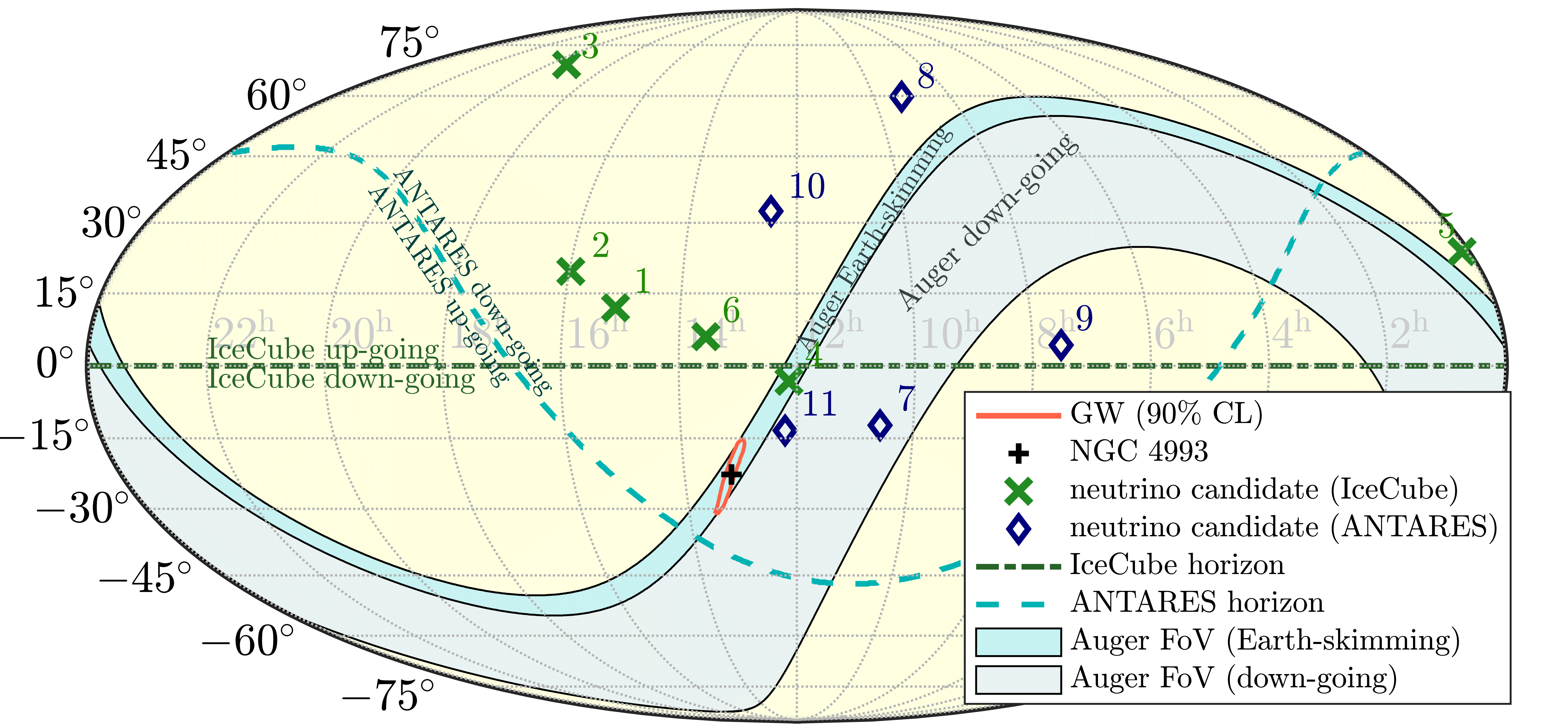


GW170817 / GRB170817A: NS-NS merger

- NS-NS merger seen in Gravitational Waves
- Confirmed as short GRB (Fermi GBM, Integral)
  - Fermi LAT, H.E.S.S., HAWC observe region much later



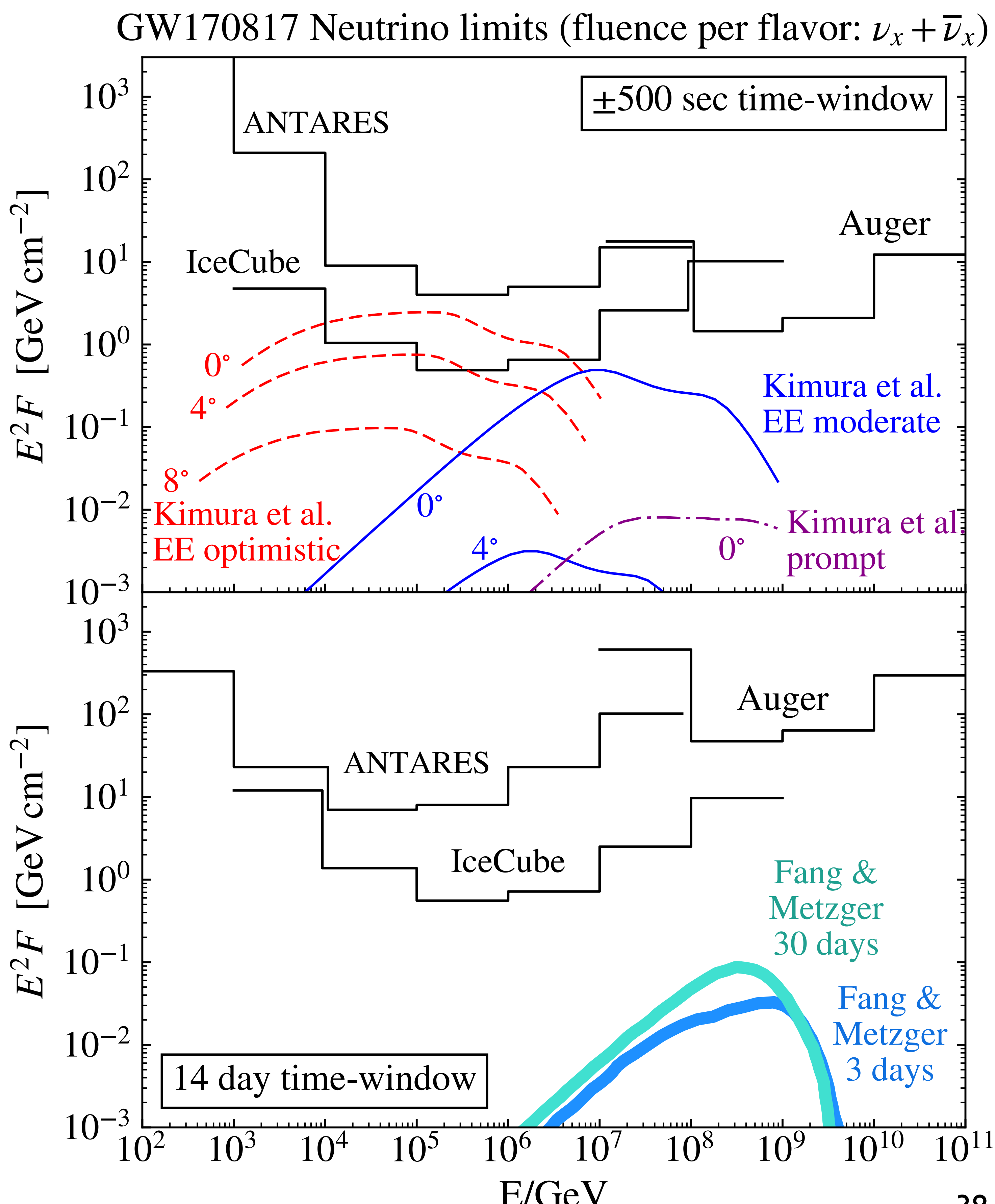
Neutrino Followup: IceCube, Antares, Pierre Auger Observatory



- At time of GW trigger:
  Event in region of maximum sensitivity for Auger

GW170817 Neutrino Limits

- Time windows: 500 sec, 14 days
- Only optimistic model constraint by observations
- Consistent with
  - GRB observed off-axis
  - Low luminosity GRB



Auger Upgrade

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

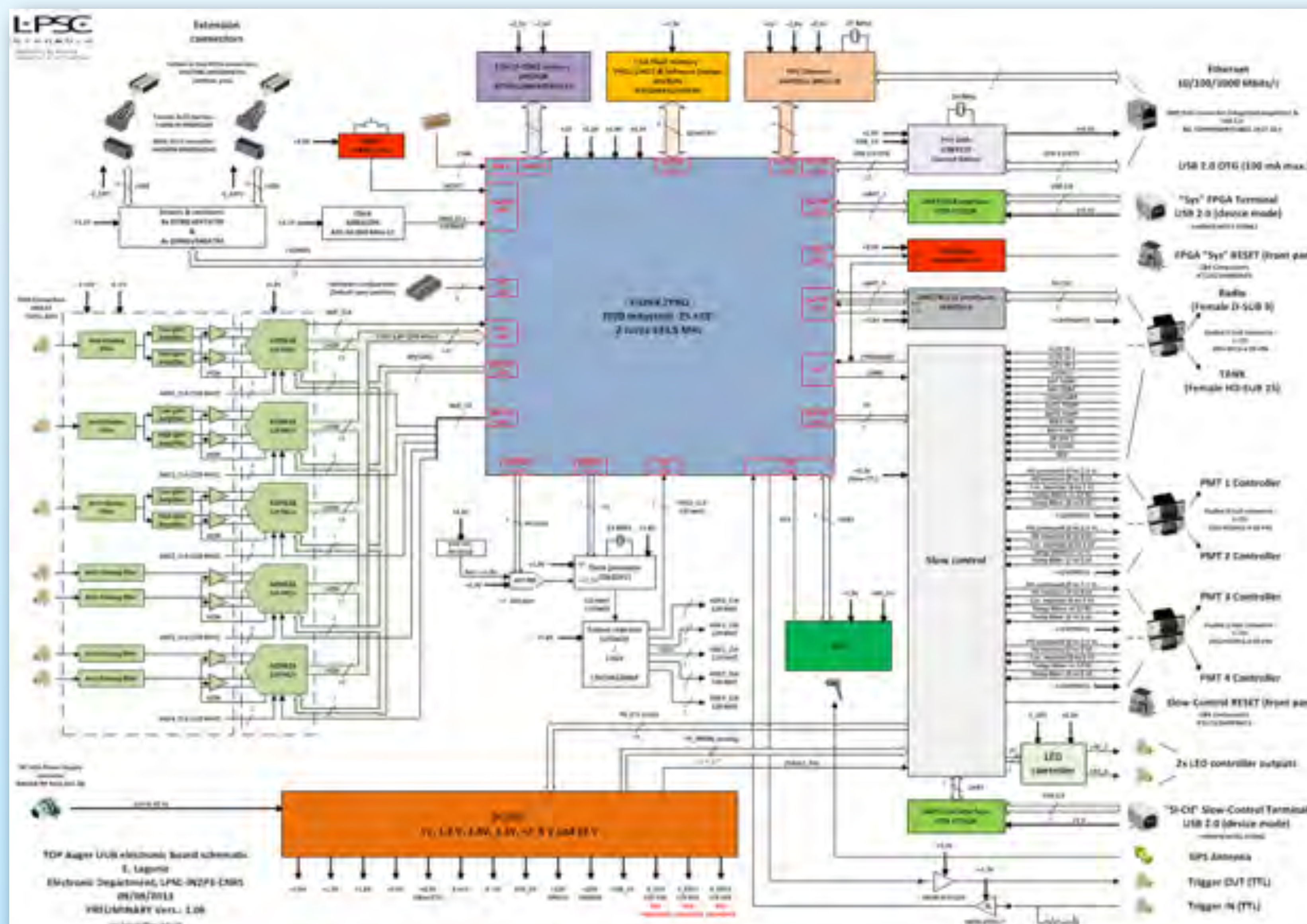
Goal:

- 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} > 70TeV

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!