The Pierre Auger Observatory

Studying the Highest Energy Cosmic rays

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Americas Research and Education Networks: Bringing the Universe to You!
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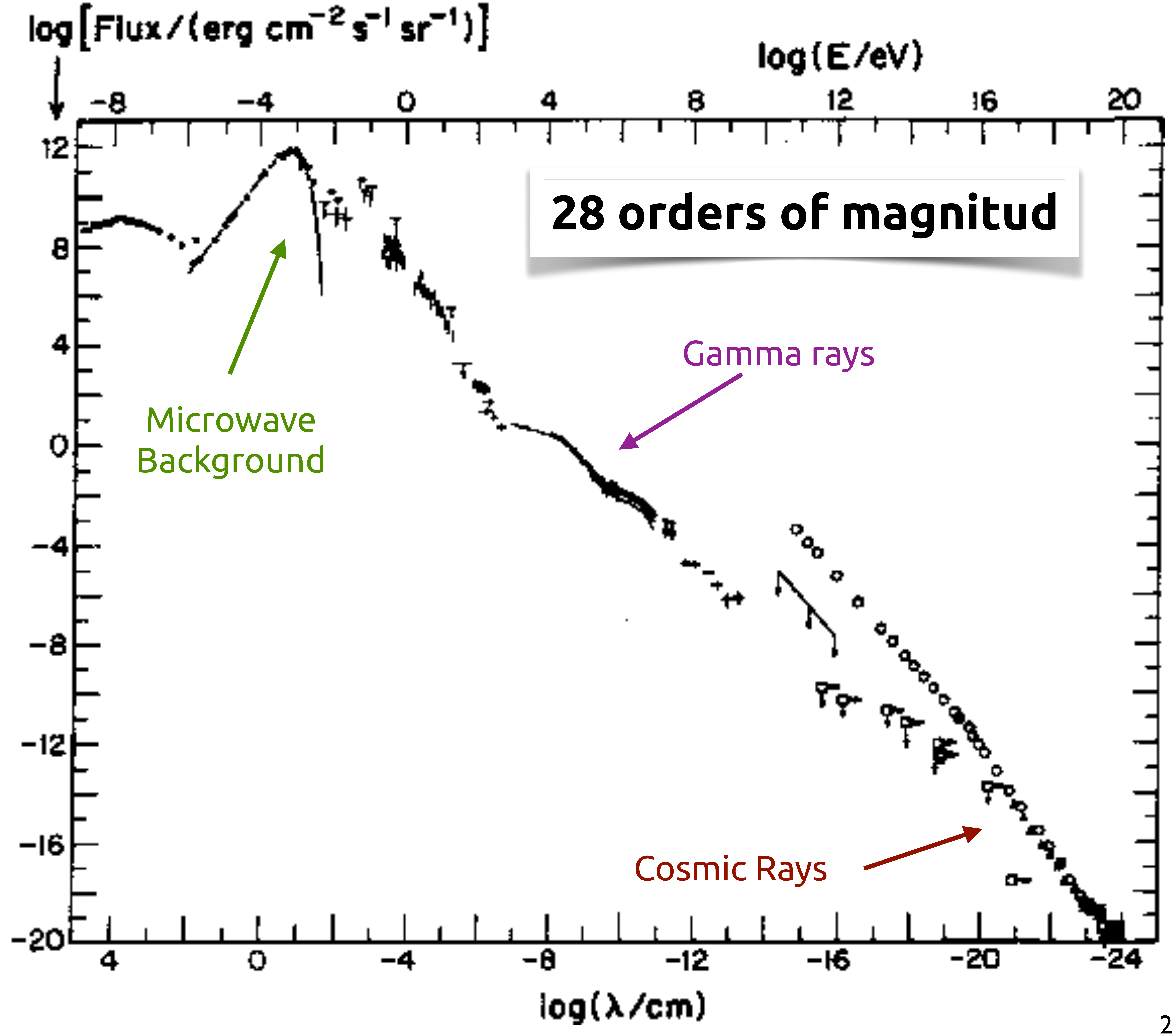
– Electromagnetic and particles –

- Cosmic rays are mostly charged particles
  - Electrons/positrons
  - Protons, nuclei
- Additionally (at the highest energies)
  - Neutrinos
  - Photons

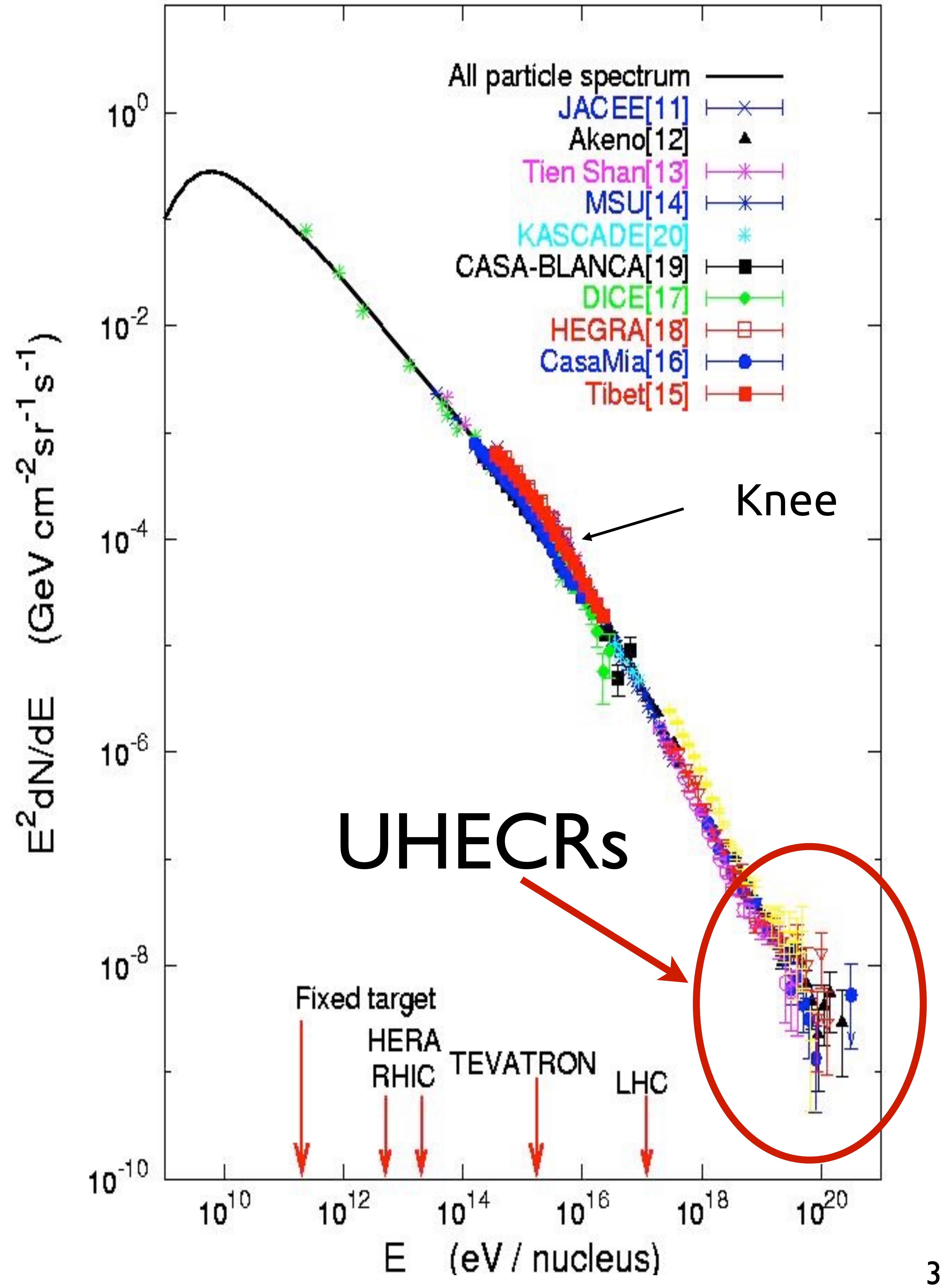


The spectrum of cosmic rays – looking for the highest energies

- spans 12 orders of magnitude
- Non-thermal, power-law

- Galactic origin up to 10^{16} eV

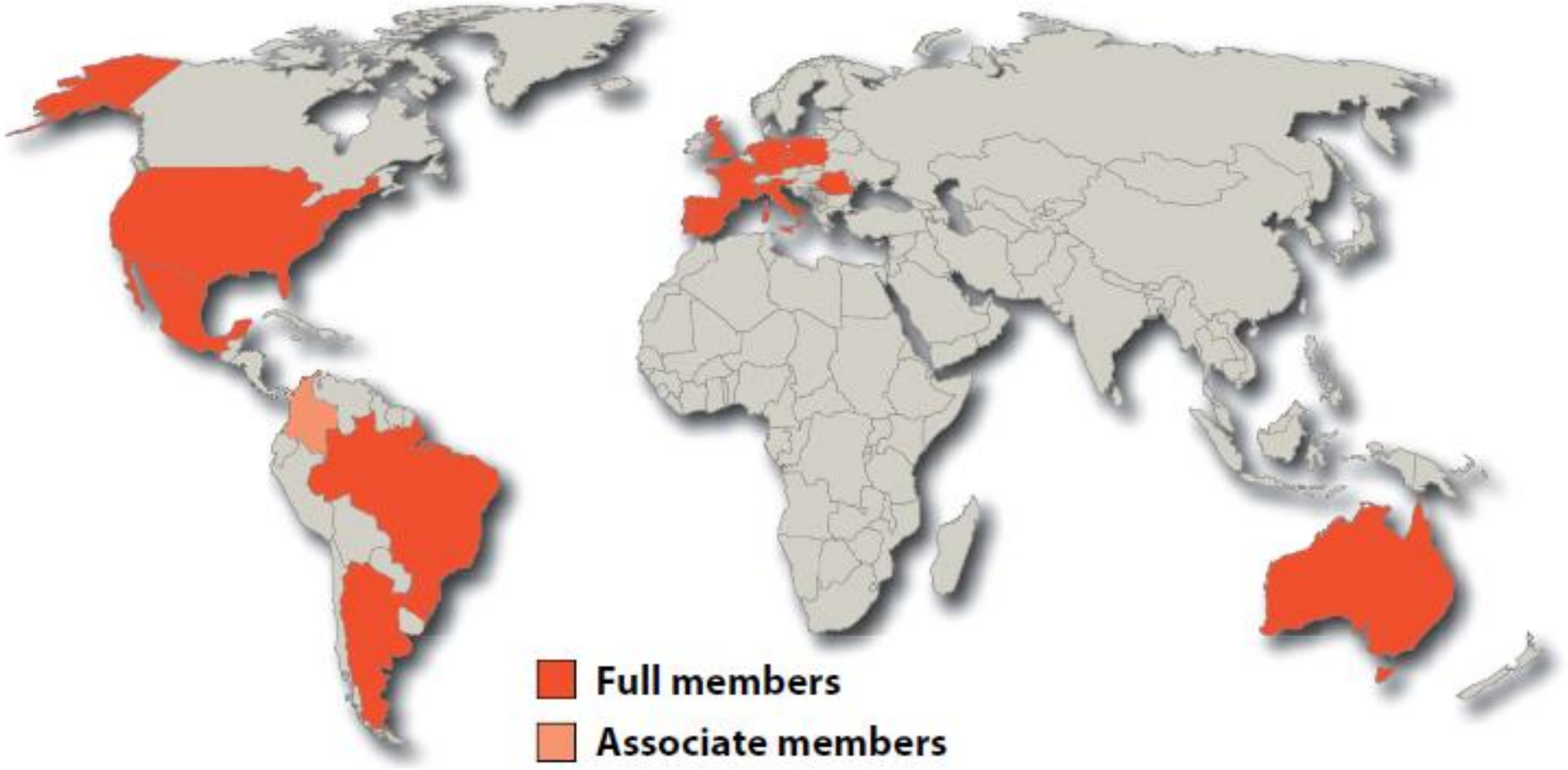
- Ultra High Energy Cosmic Rays: Energy above 10^{18} eV o 10^{19} eV
  - Extra-galactic origin
  - Very low flux



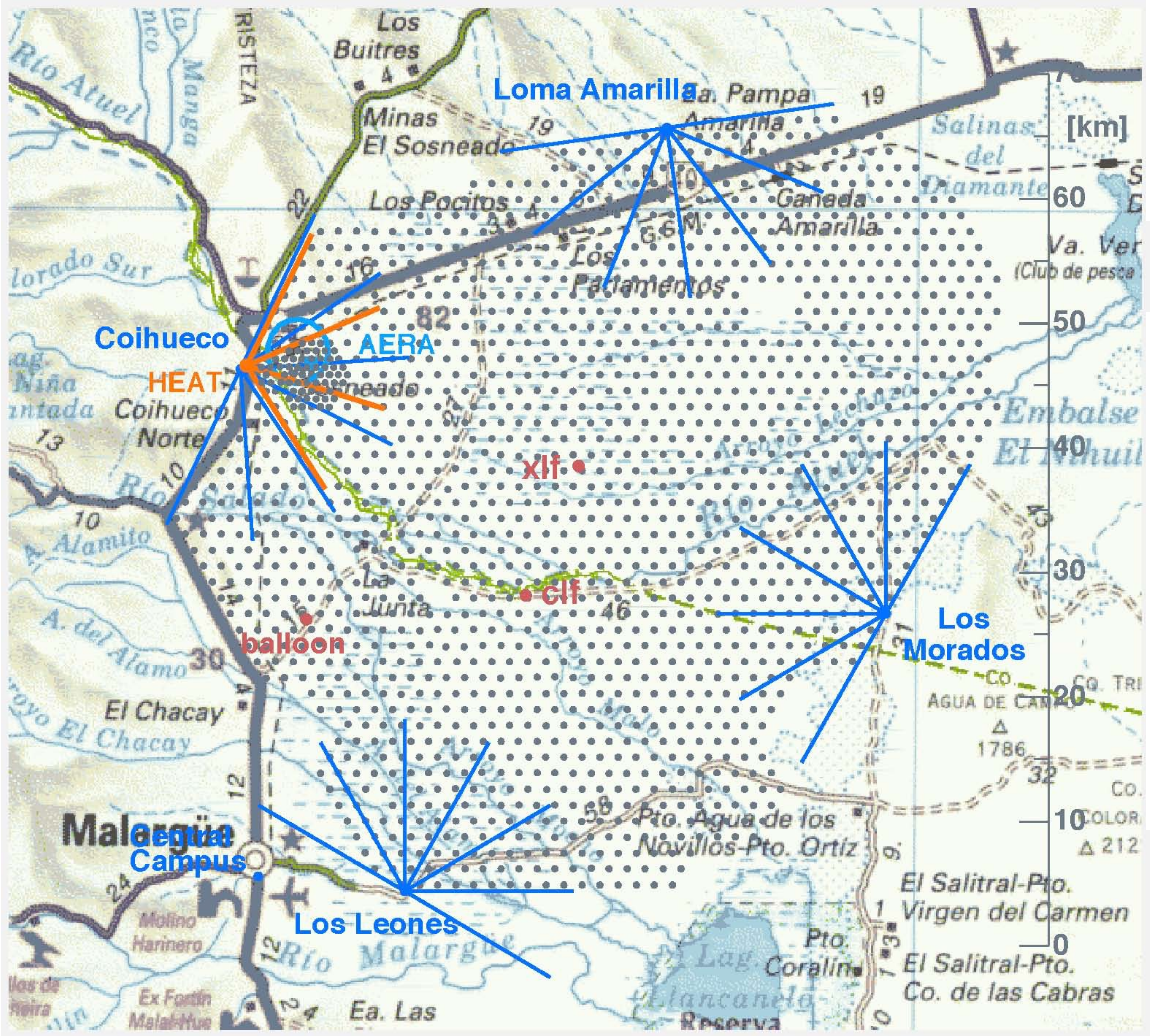
The Pierre Auger Collaboration

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

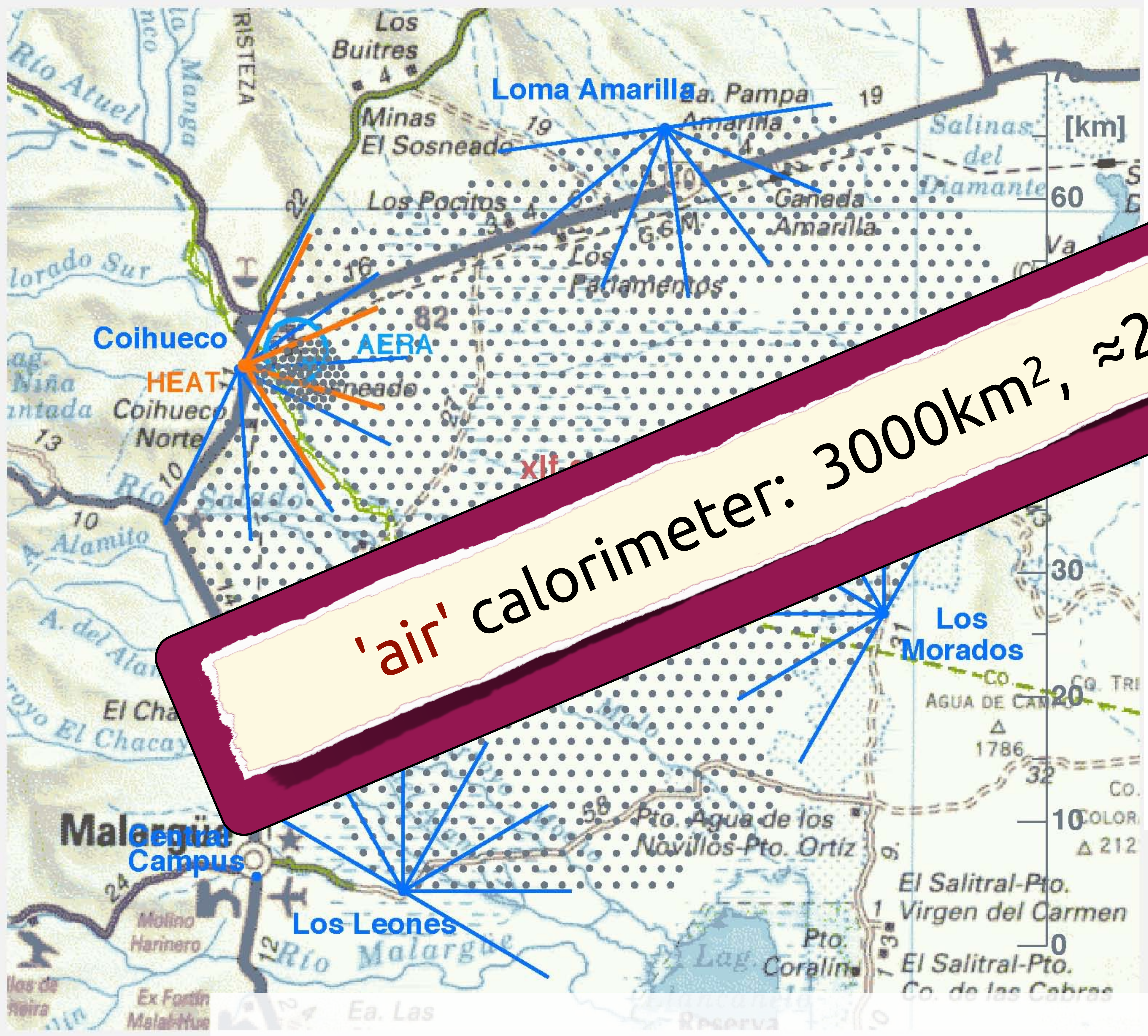
Infill: 750m spacing
+ buried μ detectors

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: 3000km^2, ≈2.5·10^{10} T

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Infill: 750m

+ bu

ce detector sites

telescopes each

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✱ 27 telescopes in total

✱ Full coverage of the surface array

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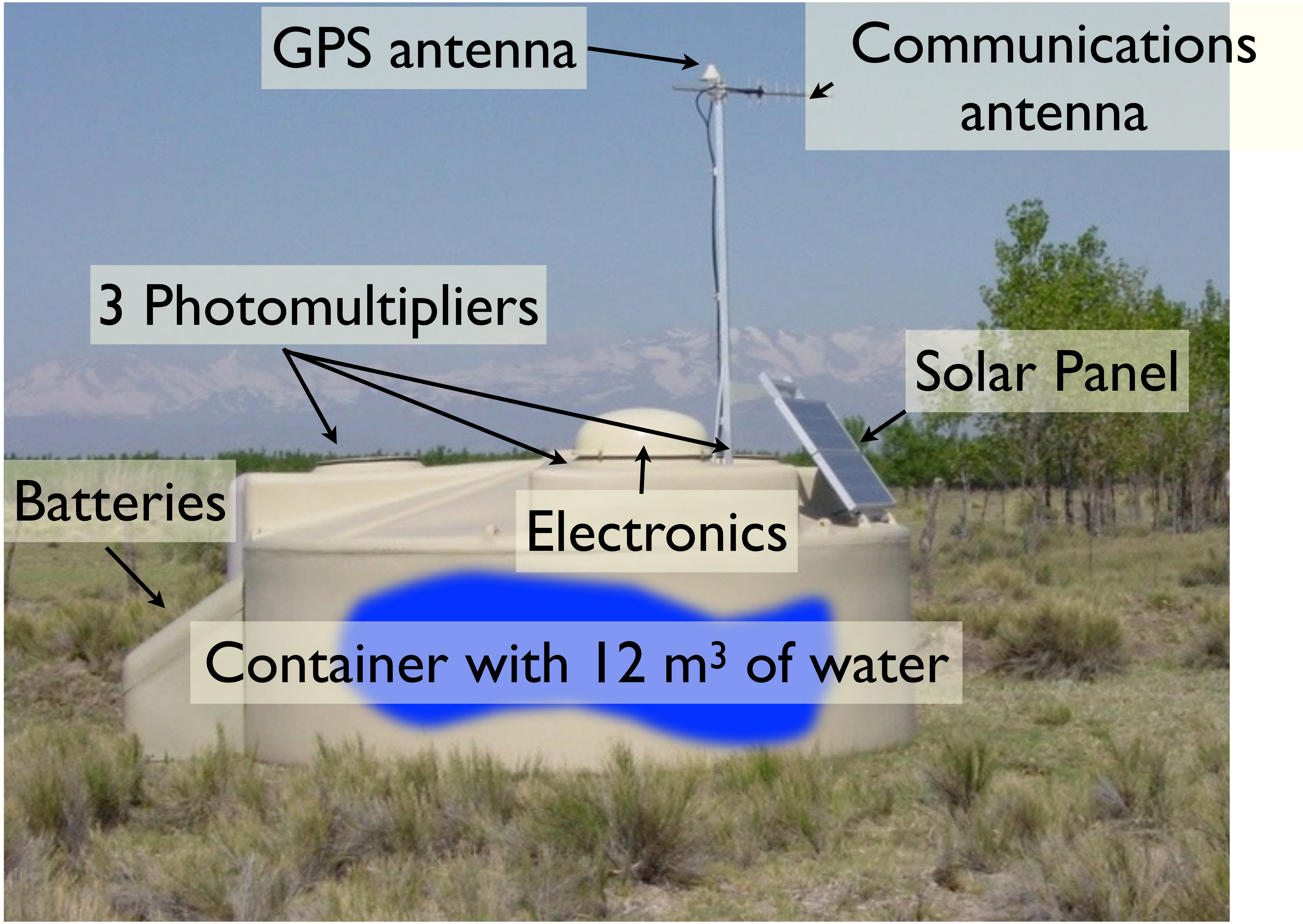
Low Energy Extensions

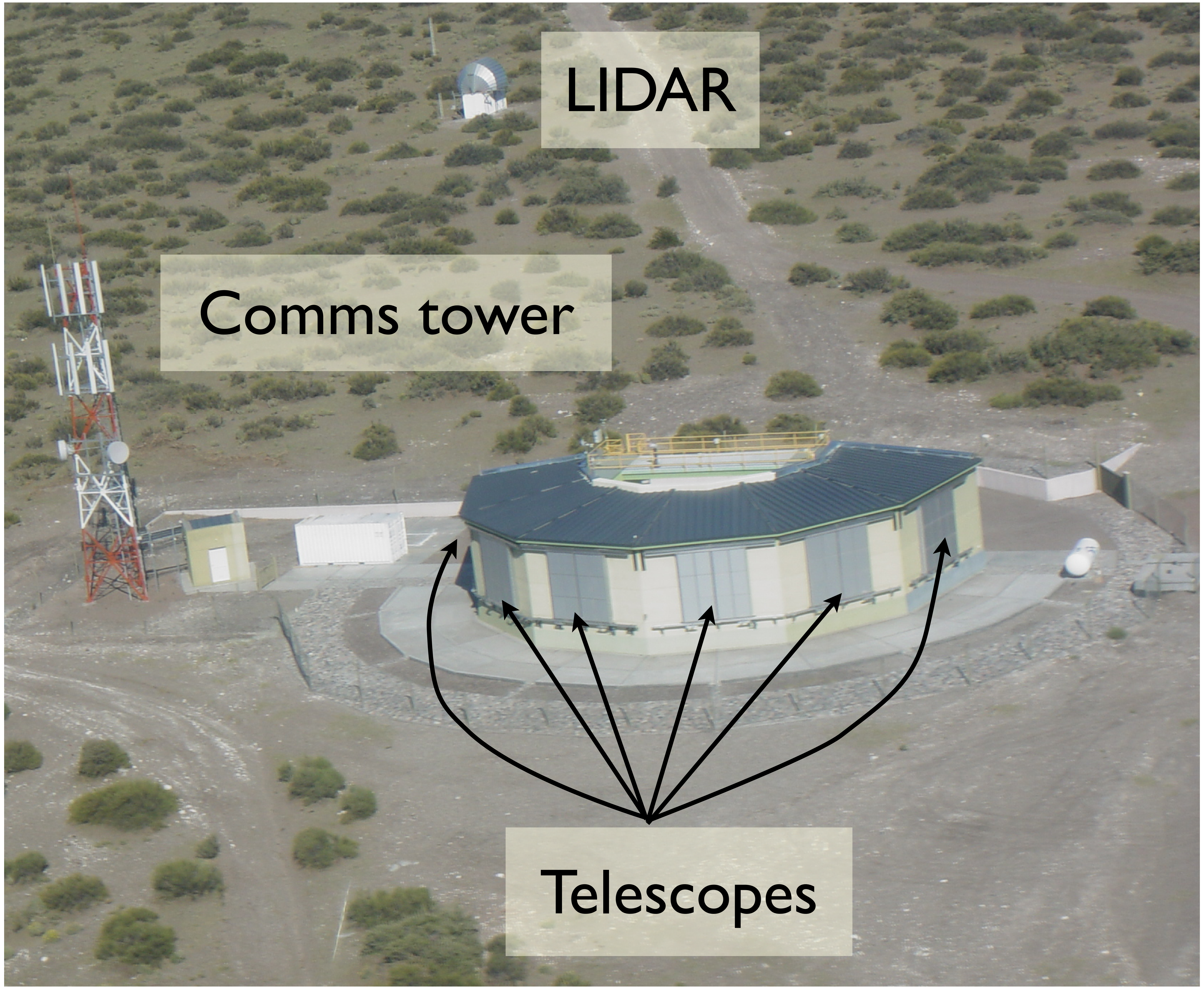
Radio Detectors

A surface detector station

A surface detector station



A Fluorescence Detector Site



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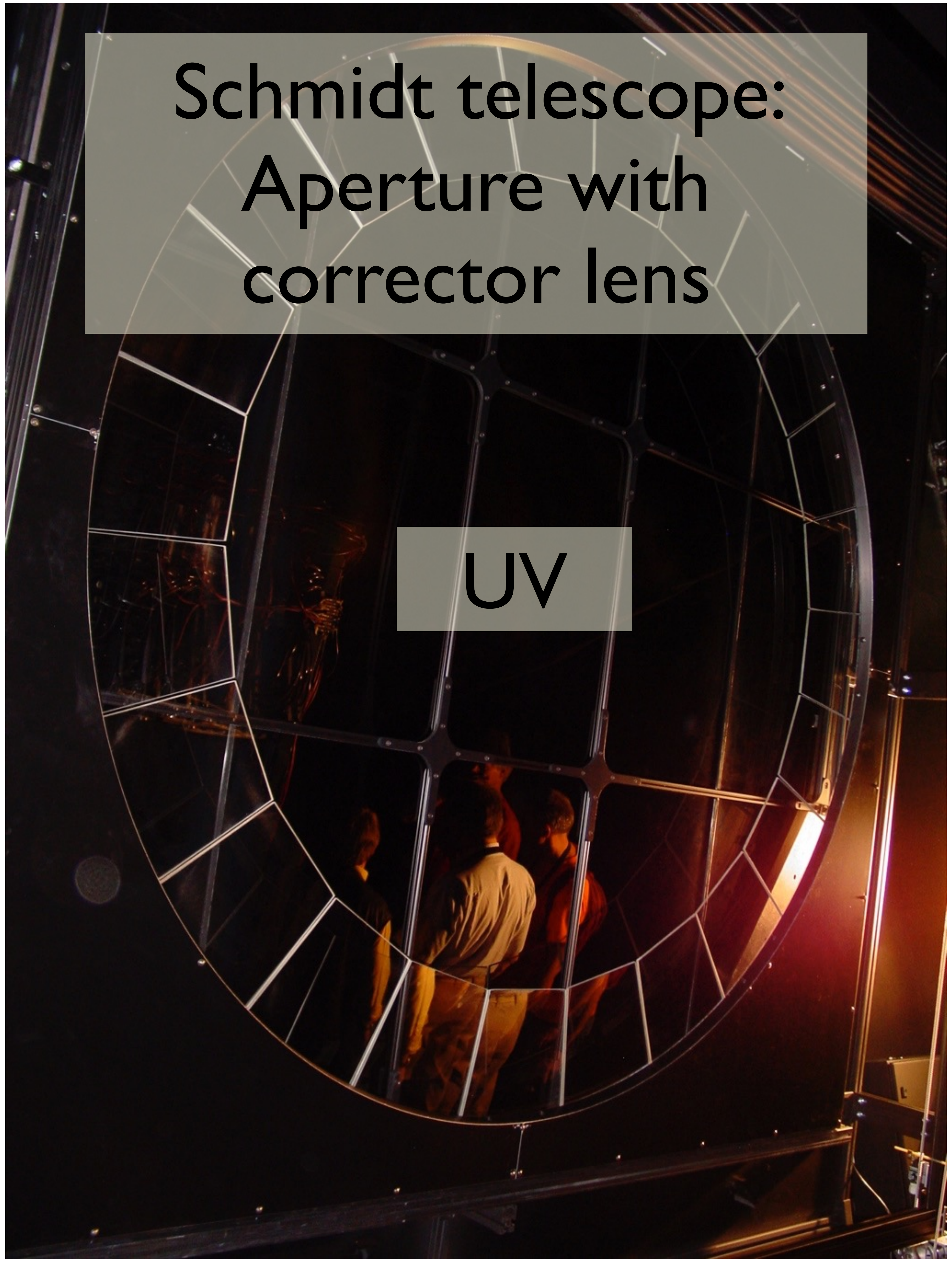

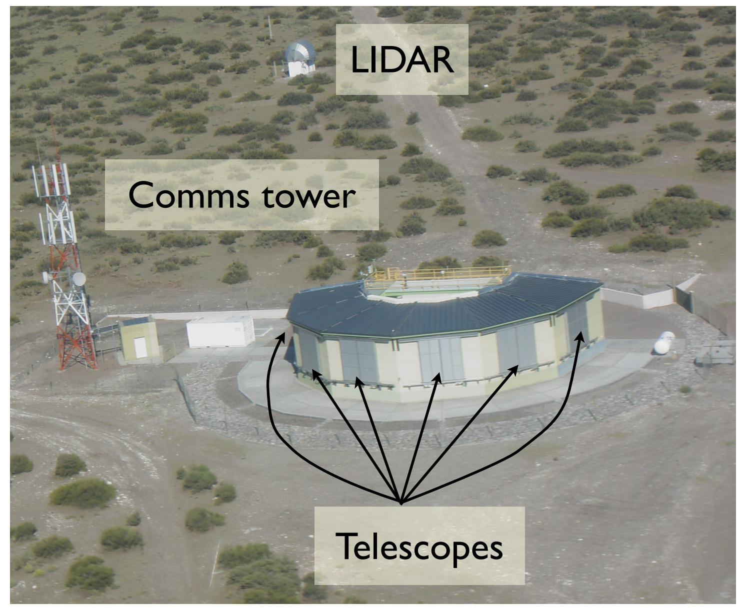

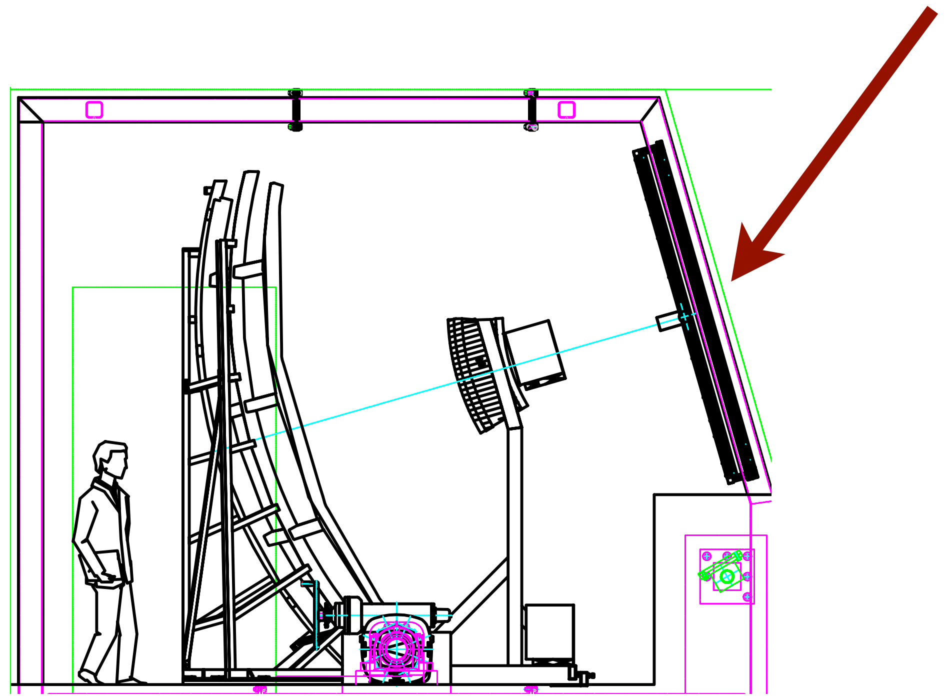

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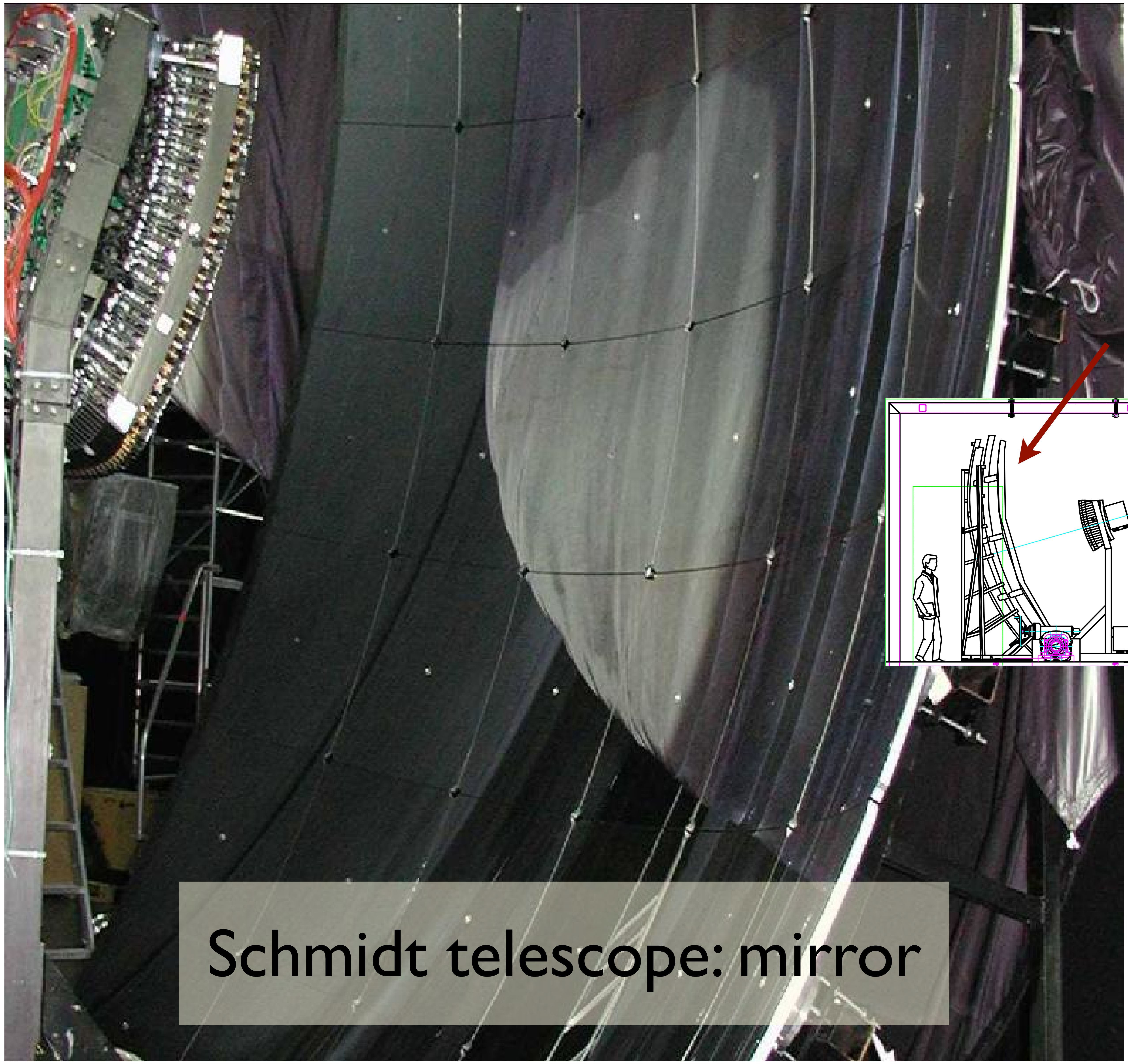

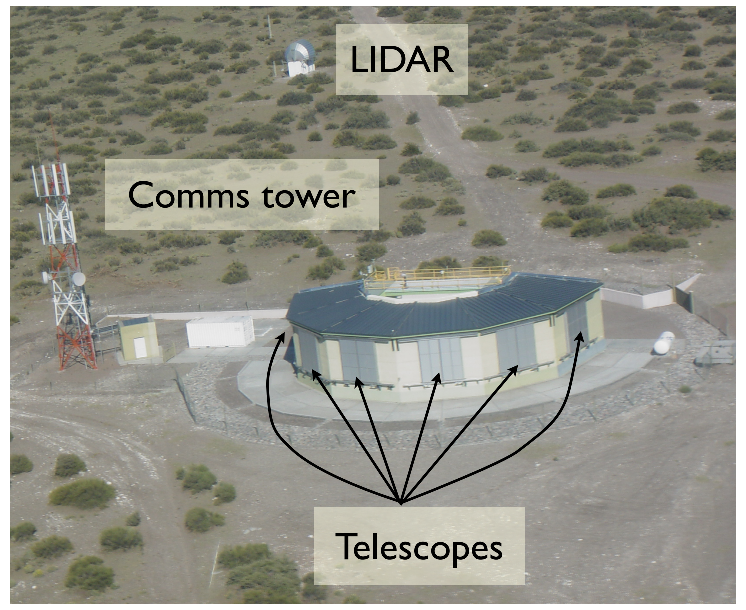

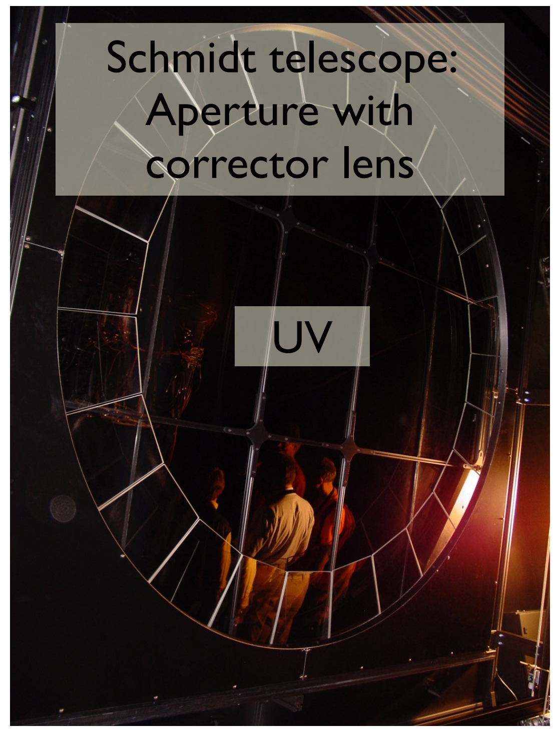

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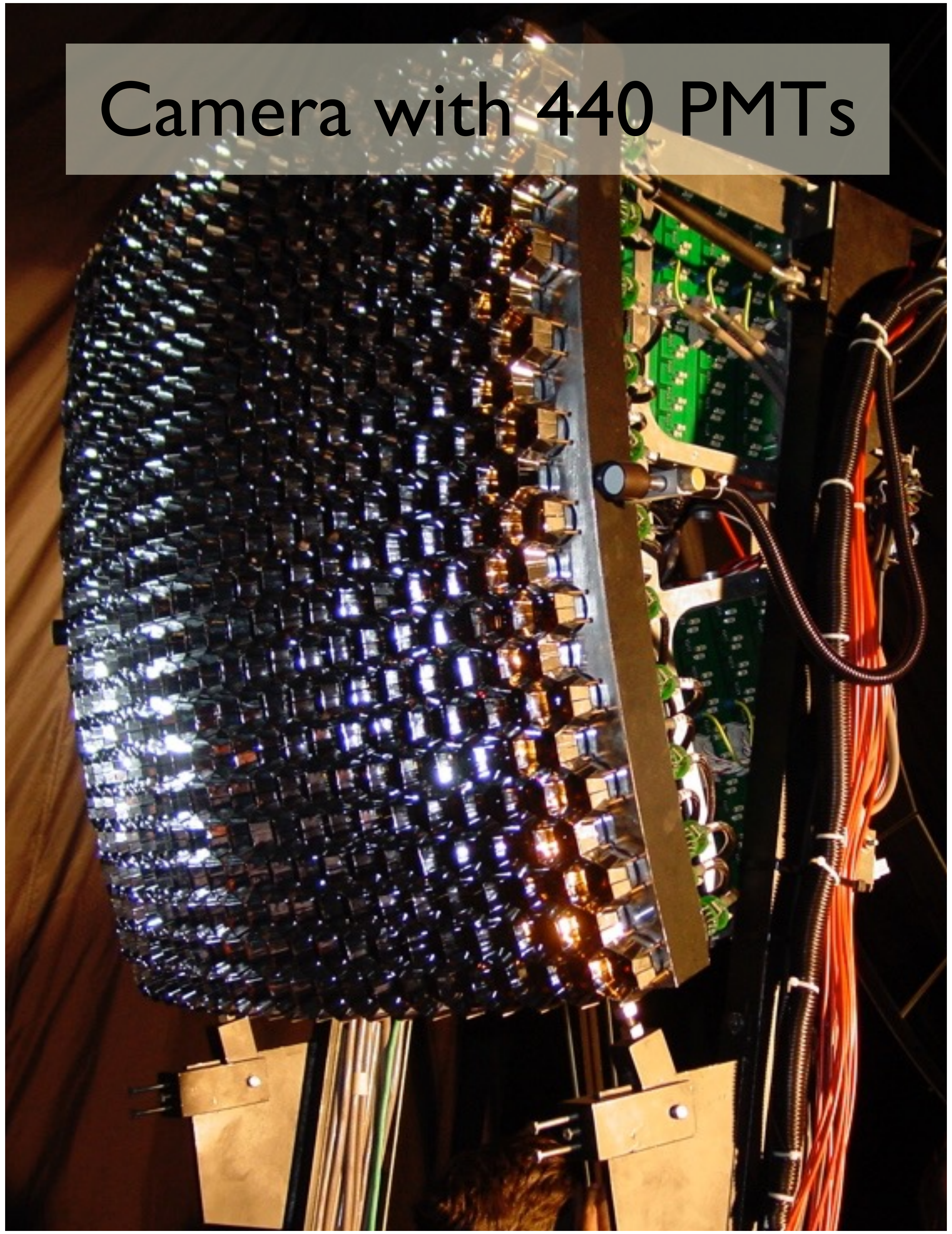
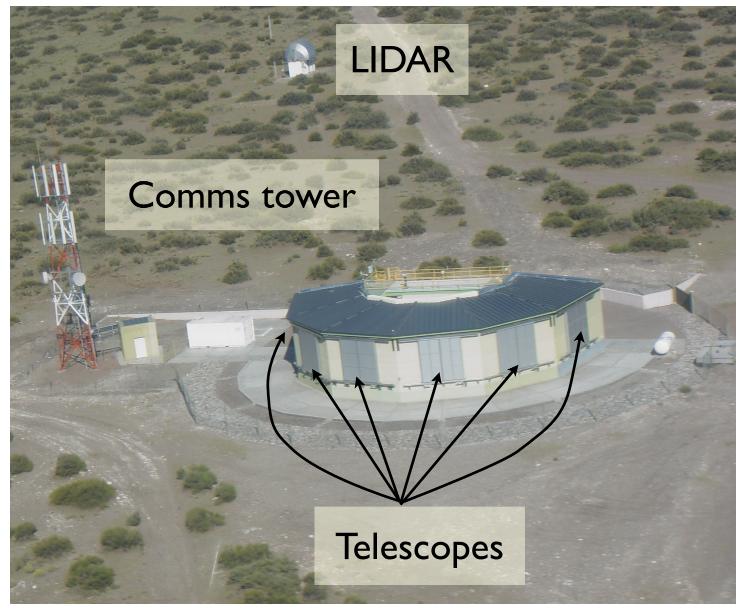
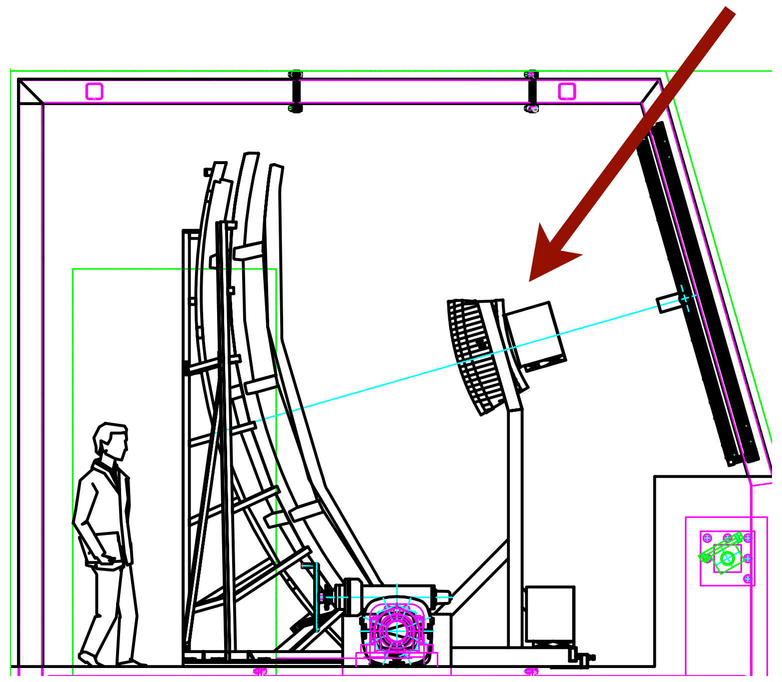
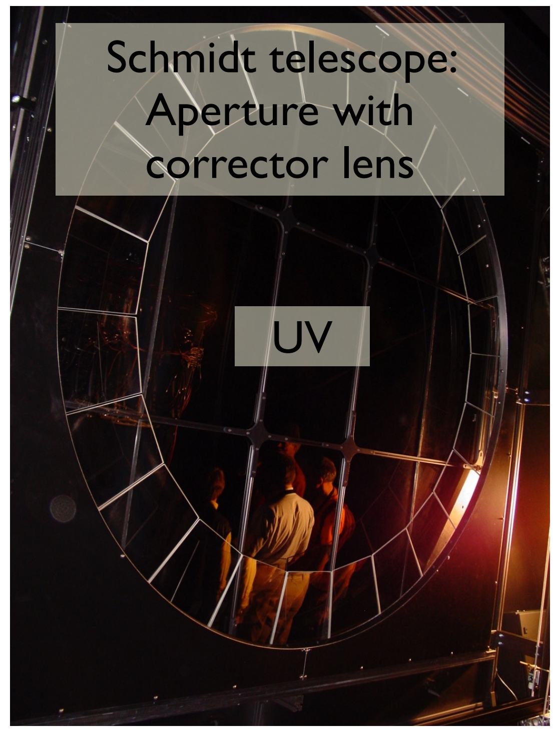
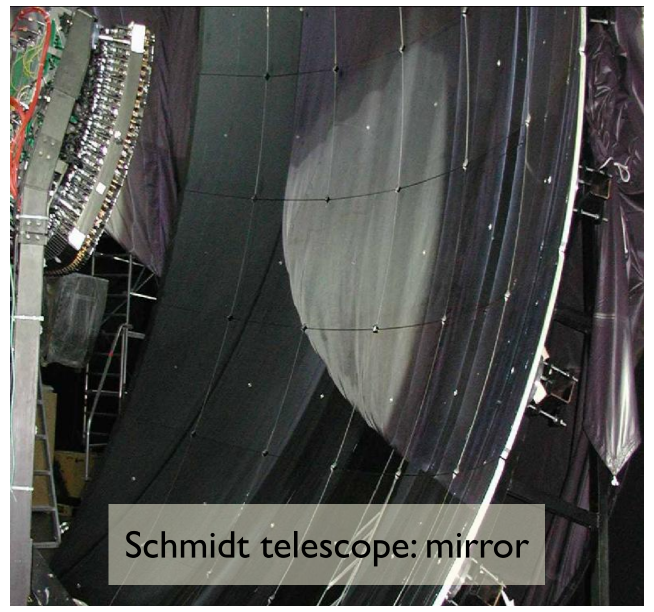


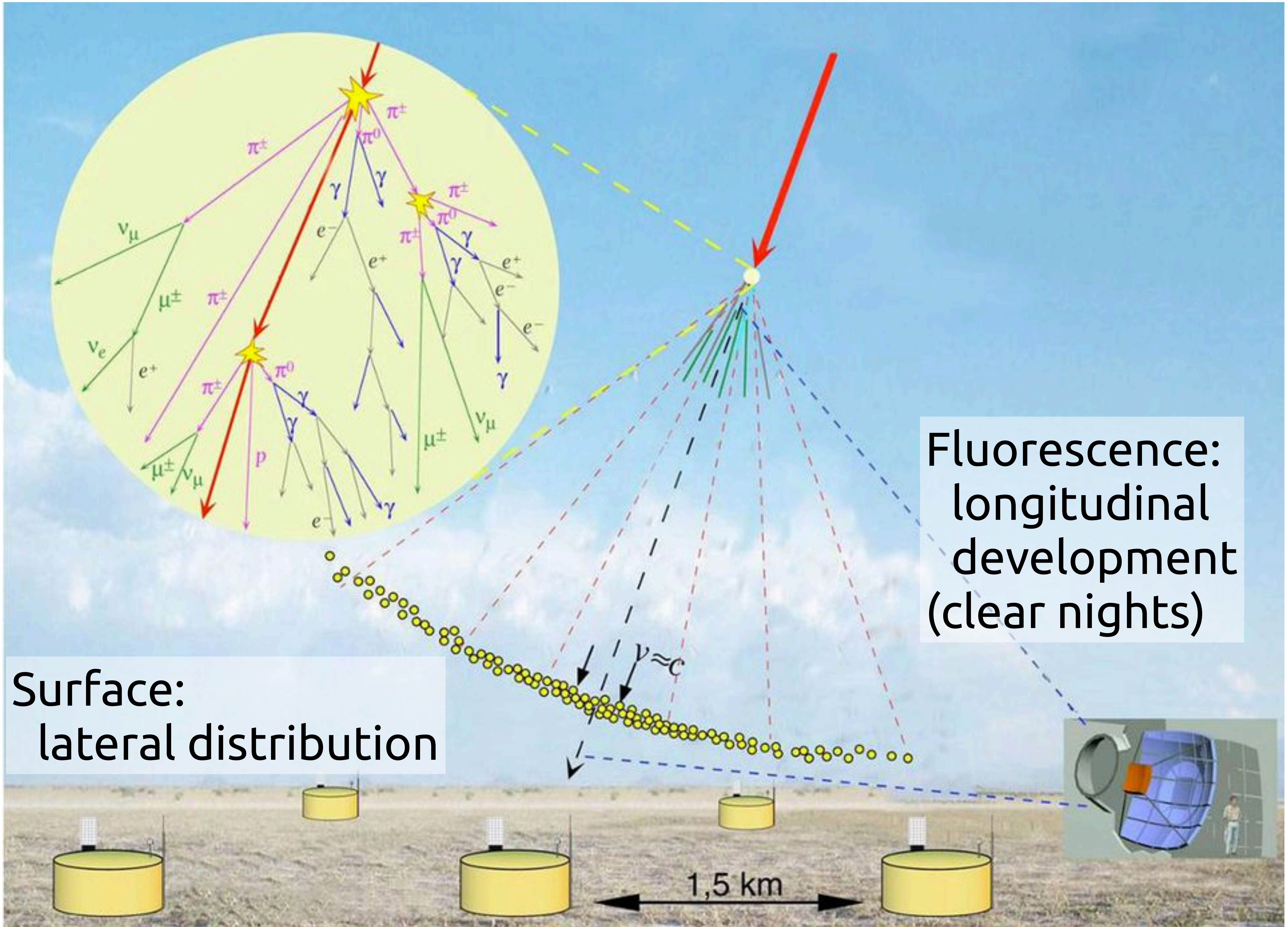








Air shower detection

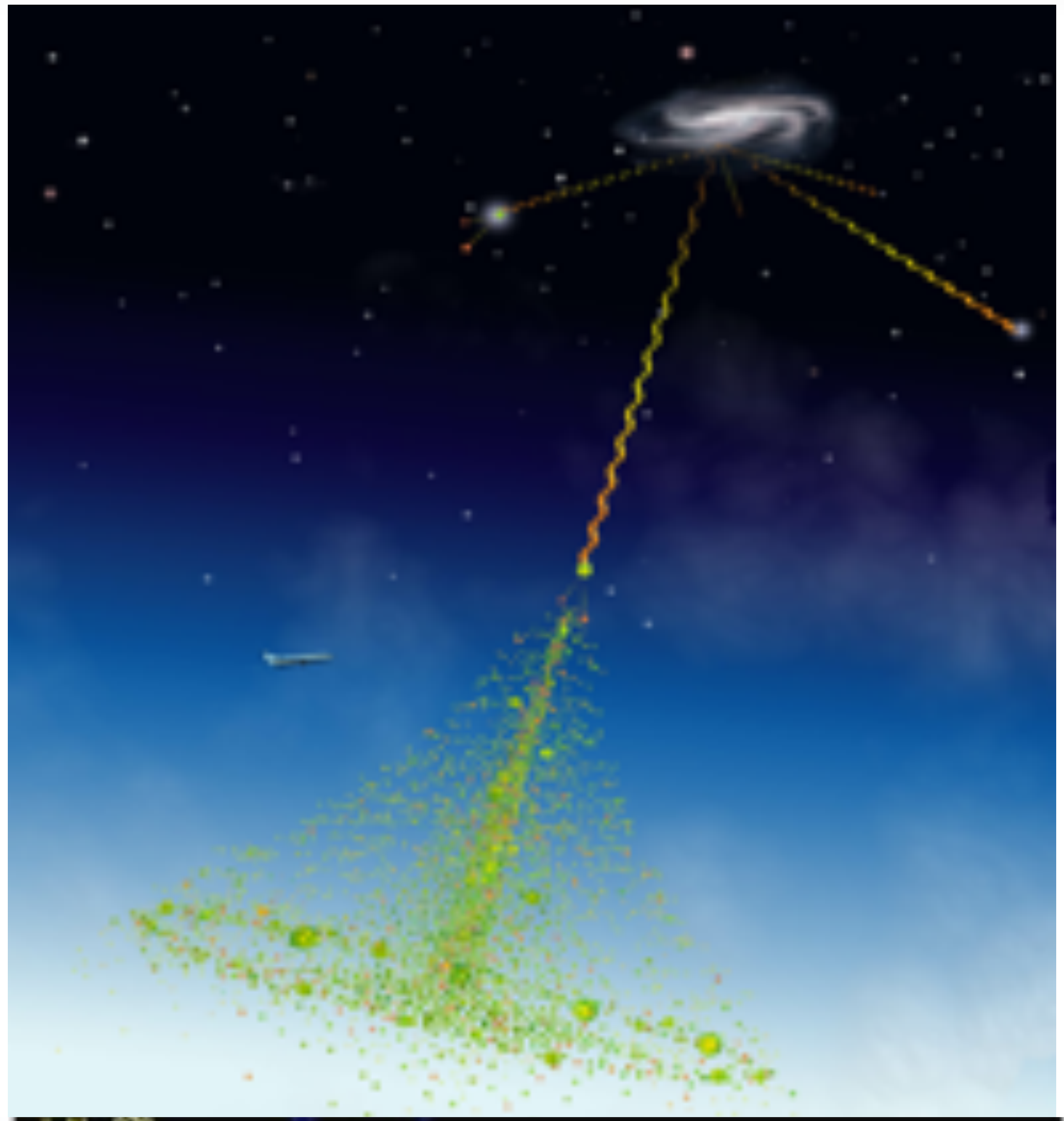


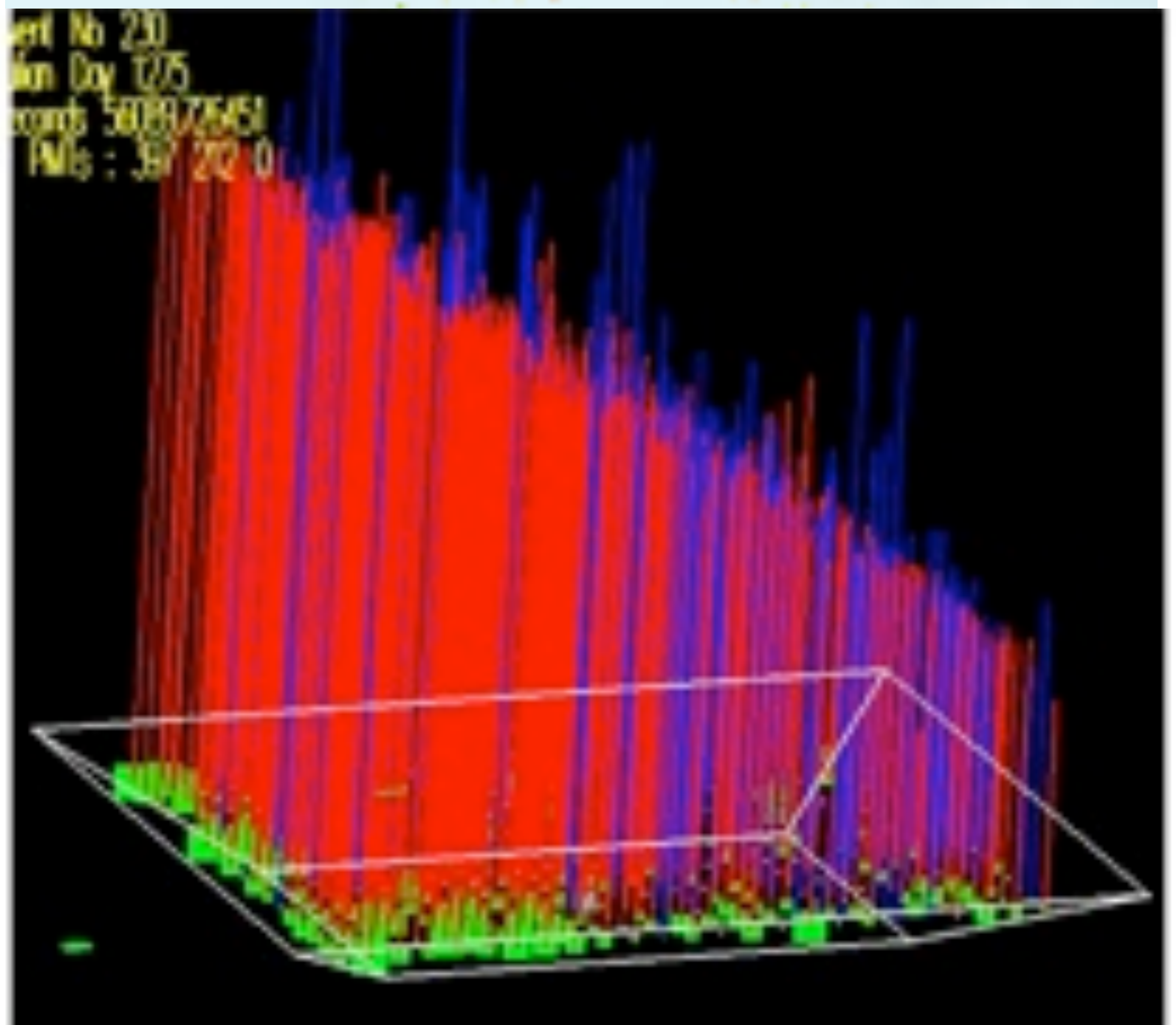
Time ⇨ Direction

- Velocity and time
  ⇒ distance

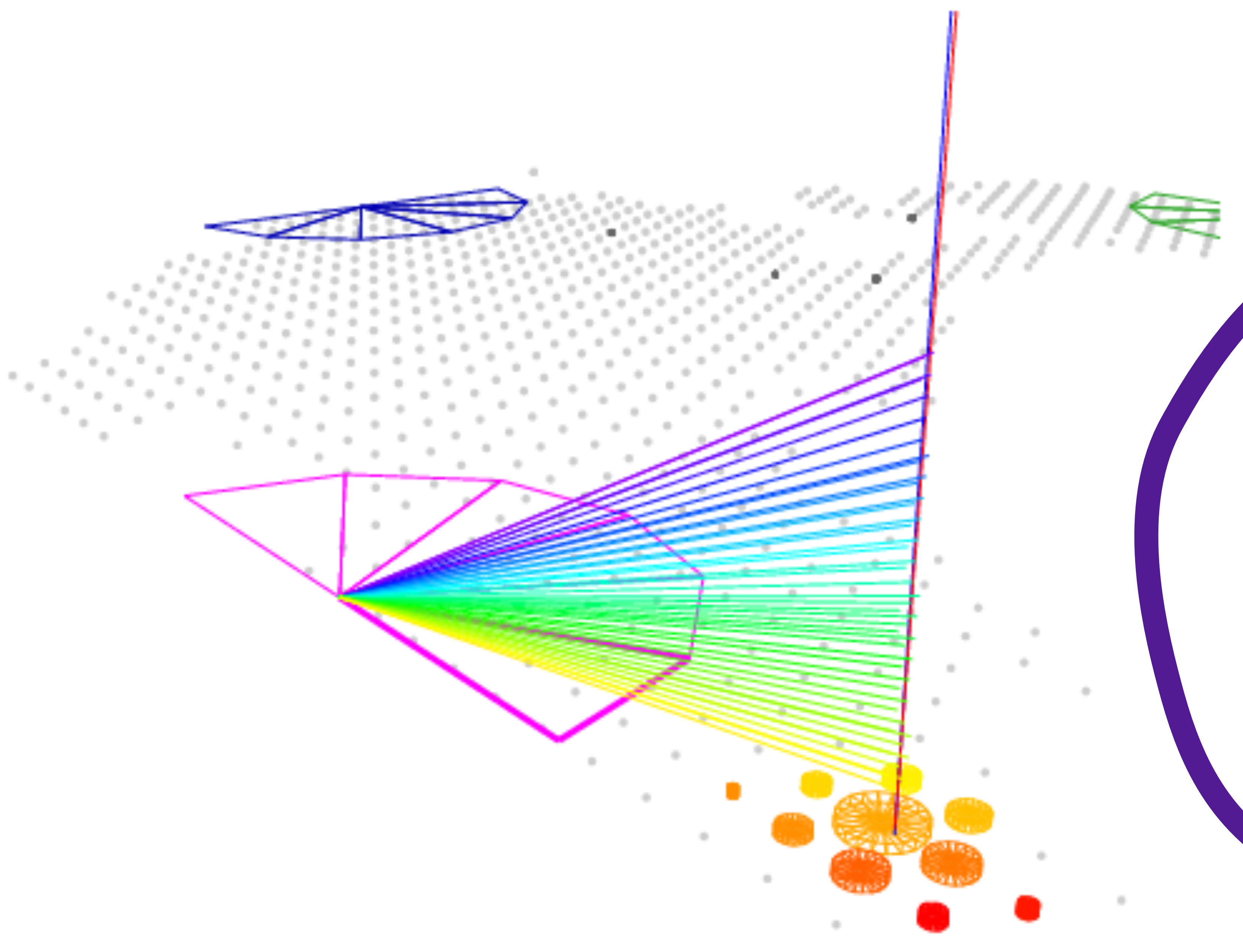
$$d = ct$$

- Perpendicular plane
  ⇒ direction

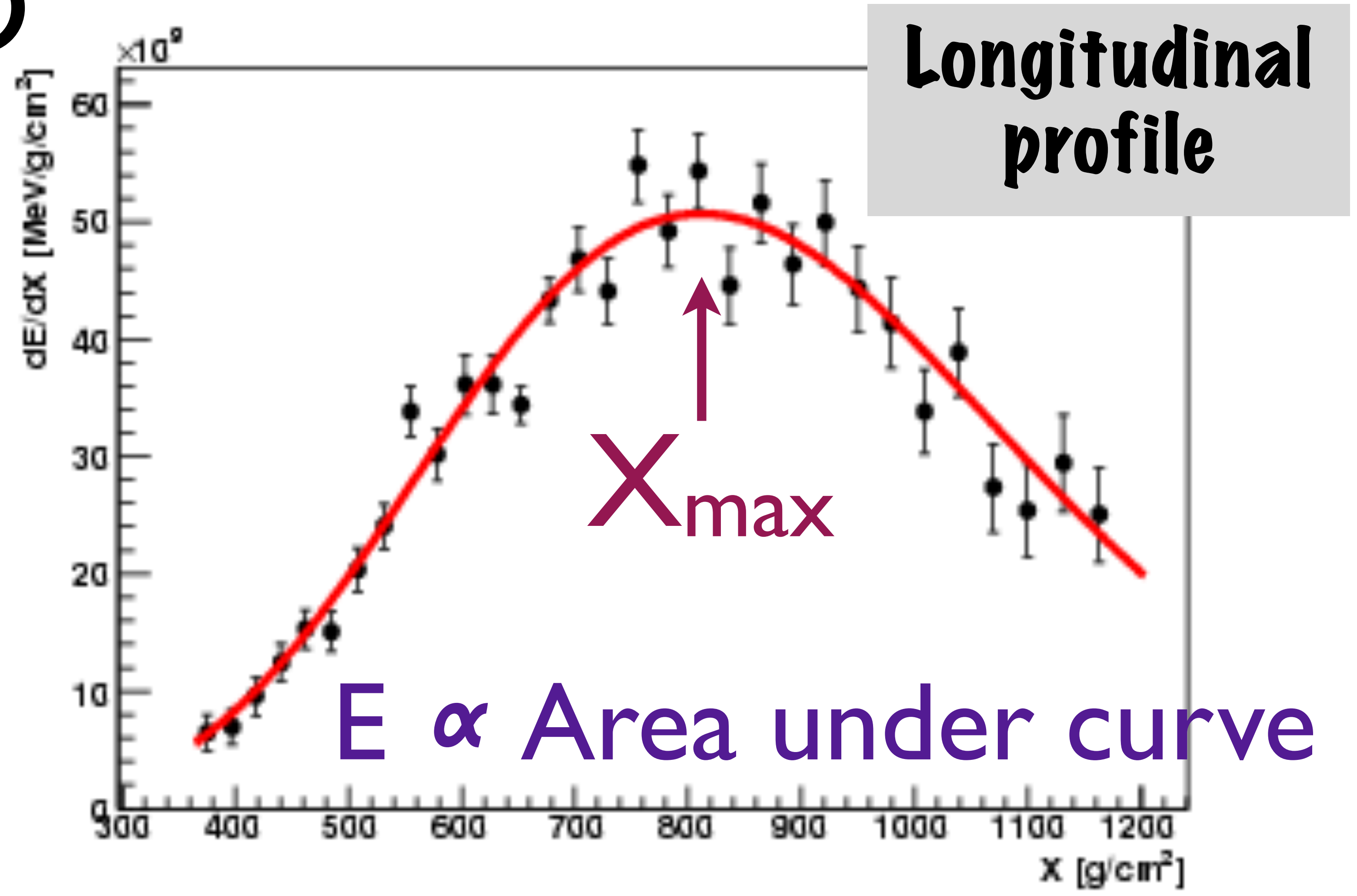




Surface detector Energy Determination



FD



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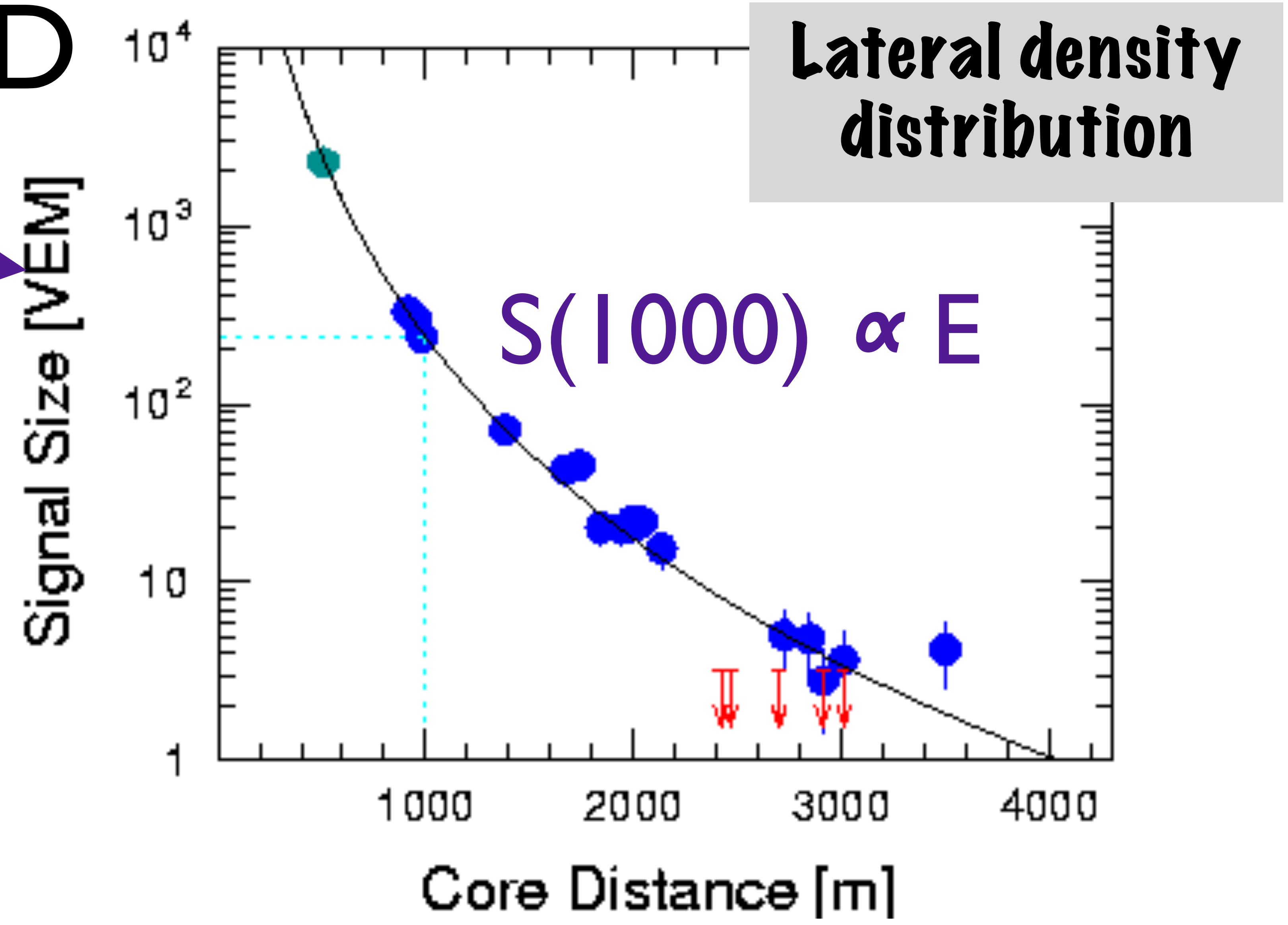
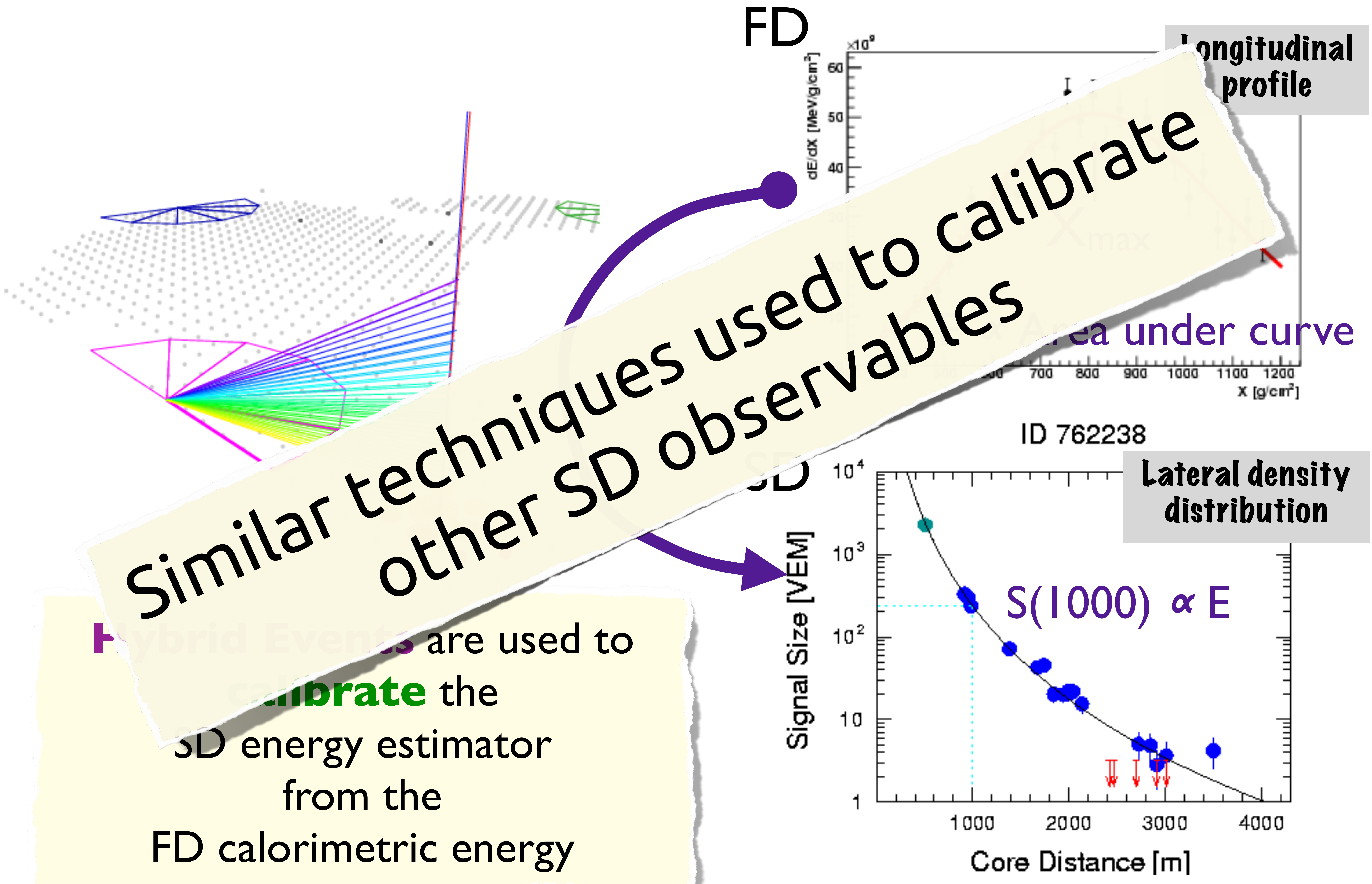
SD



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

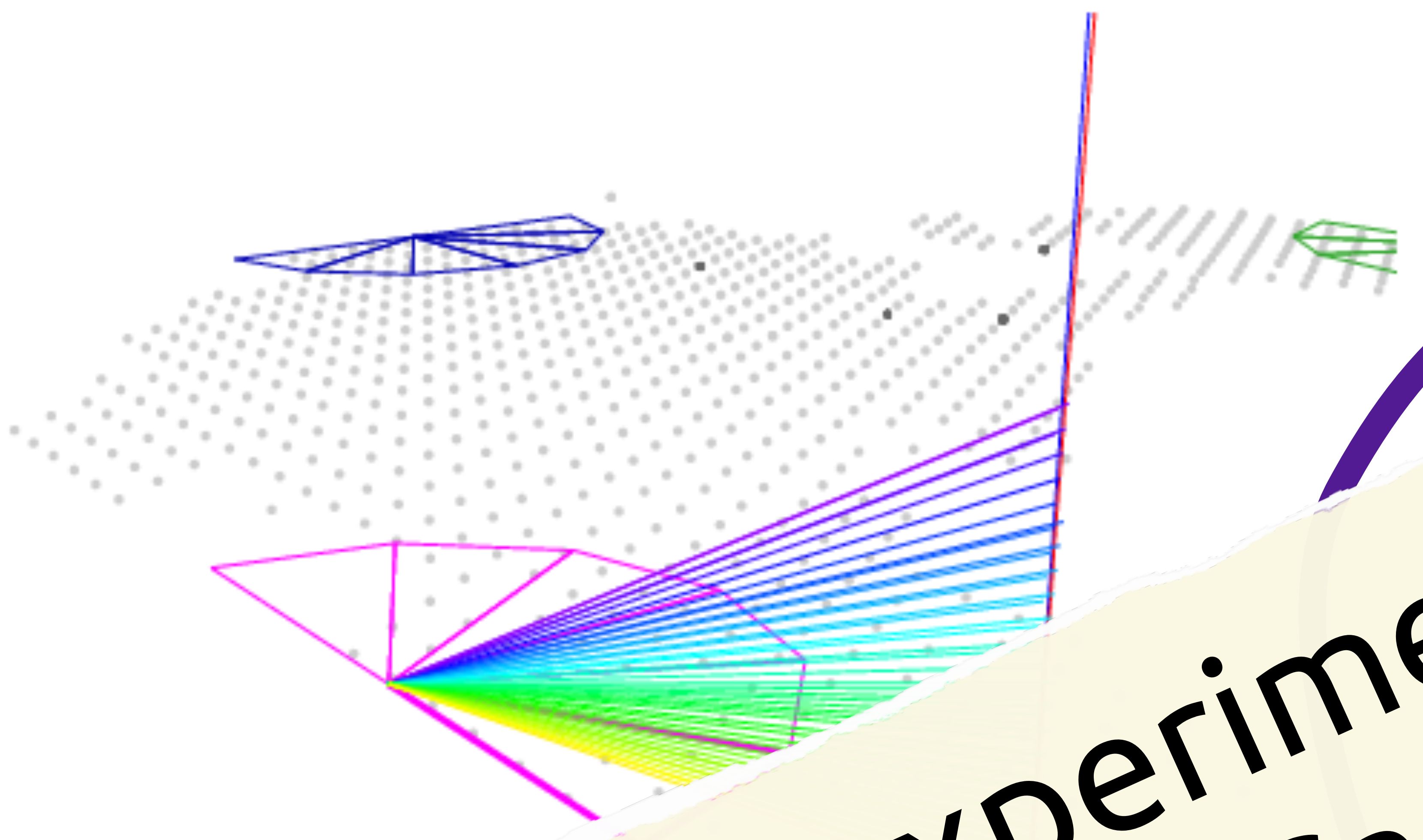
Surface detector Energy Determination

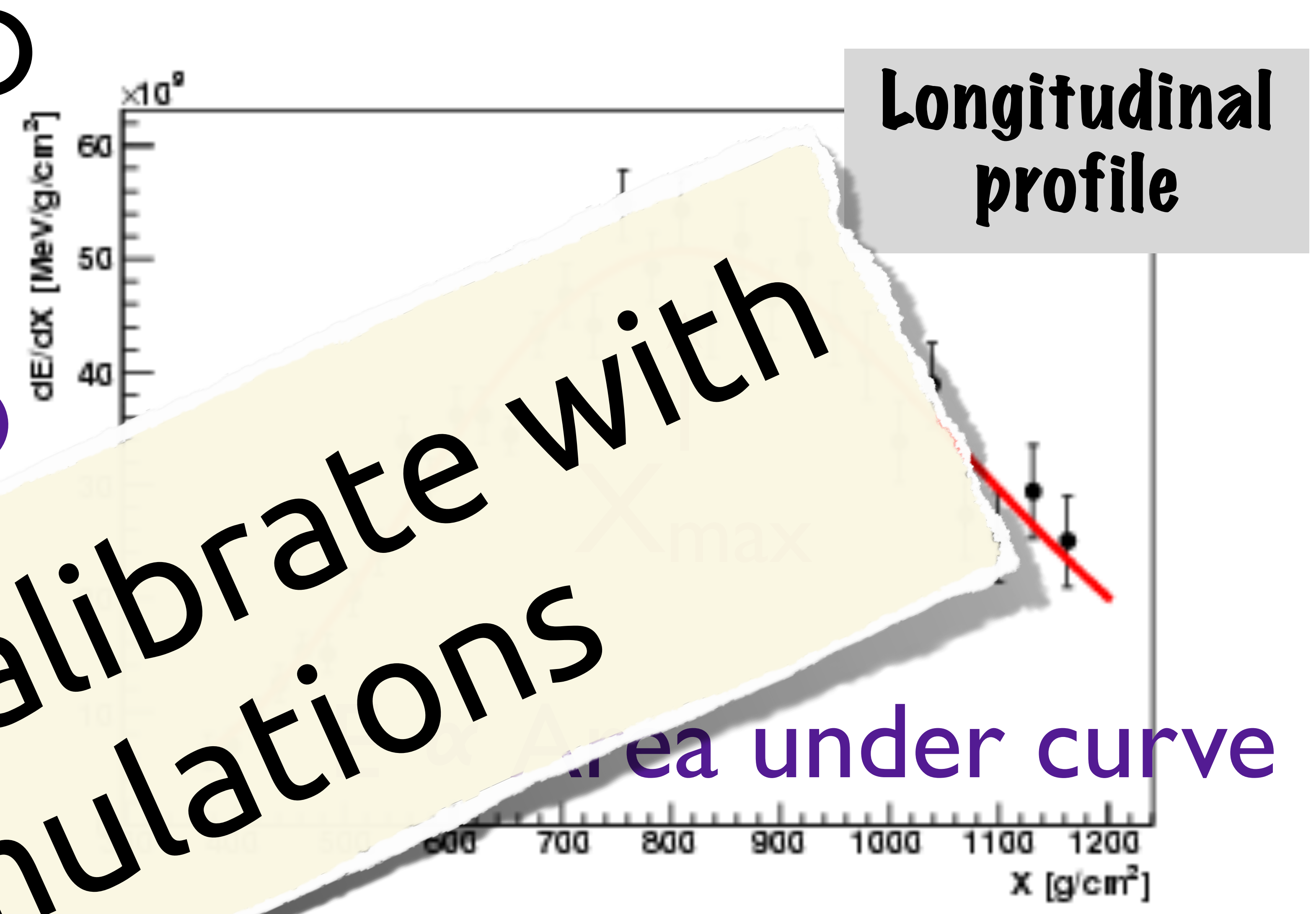


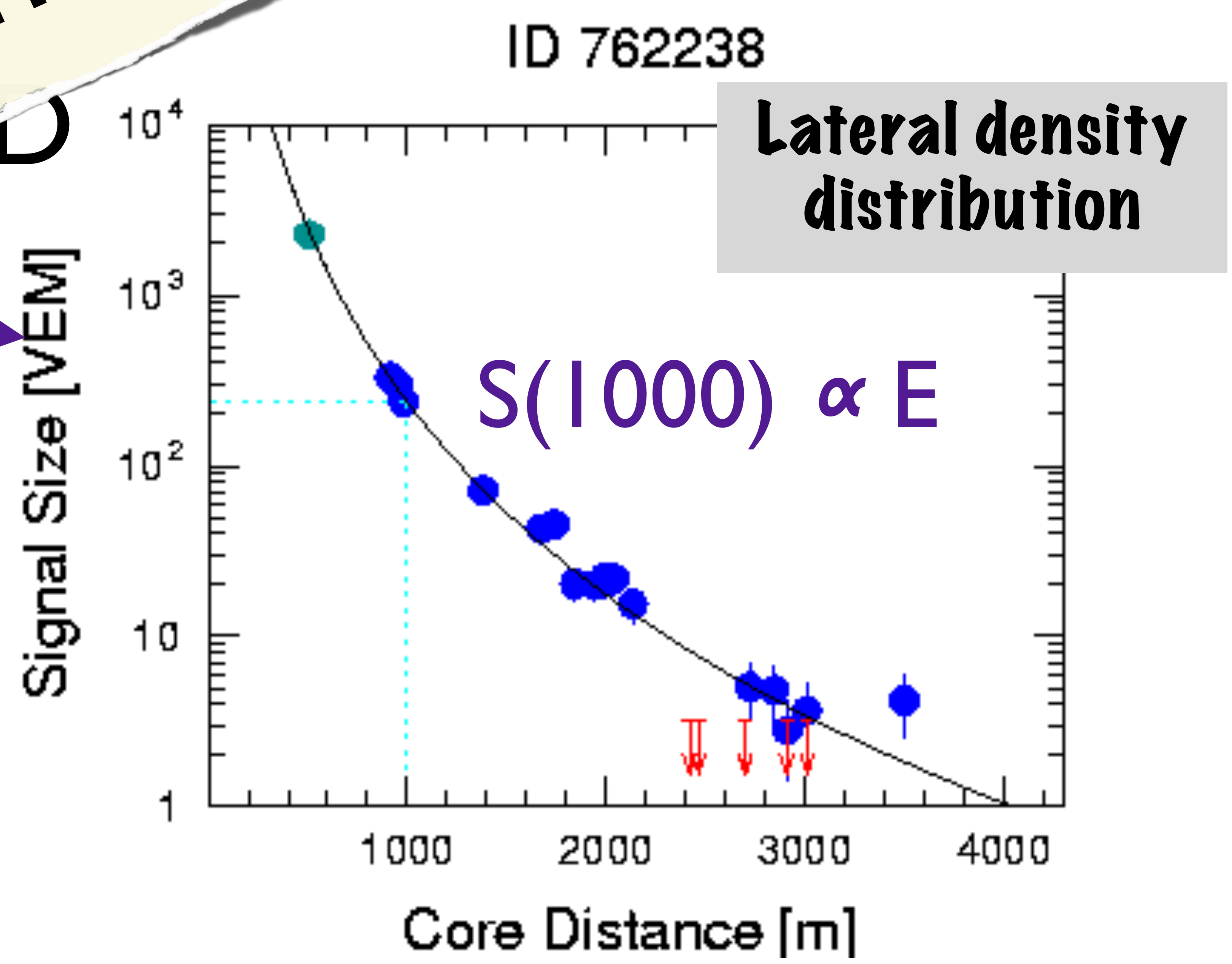
Similar techniques used to calibrate other SD observables

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

Surface detector Energy Determination







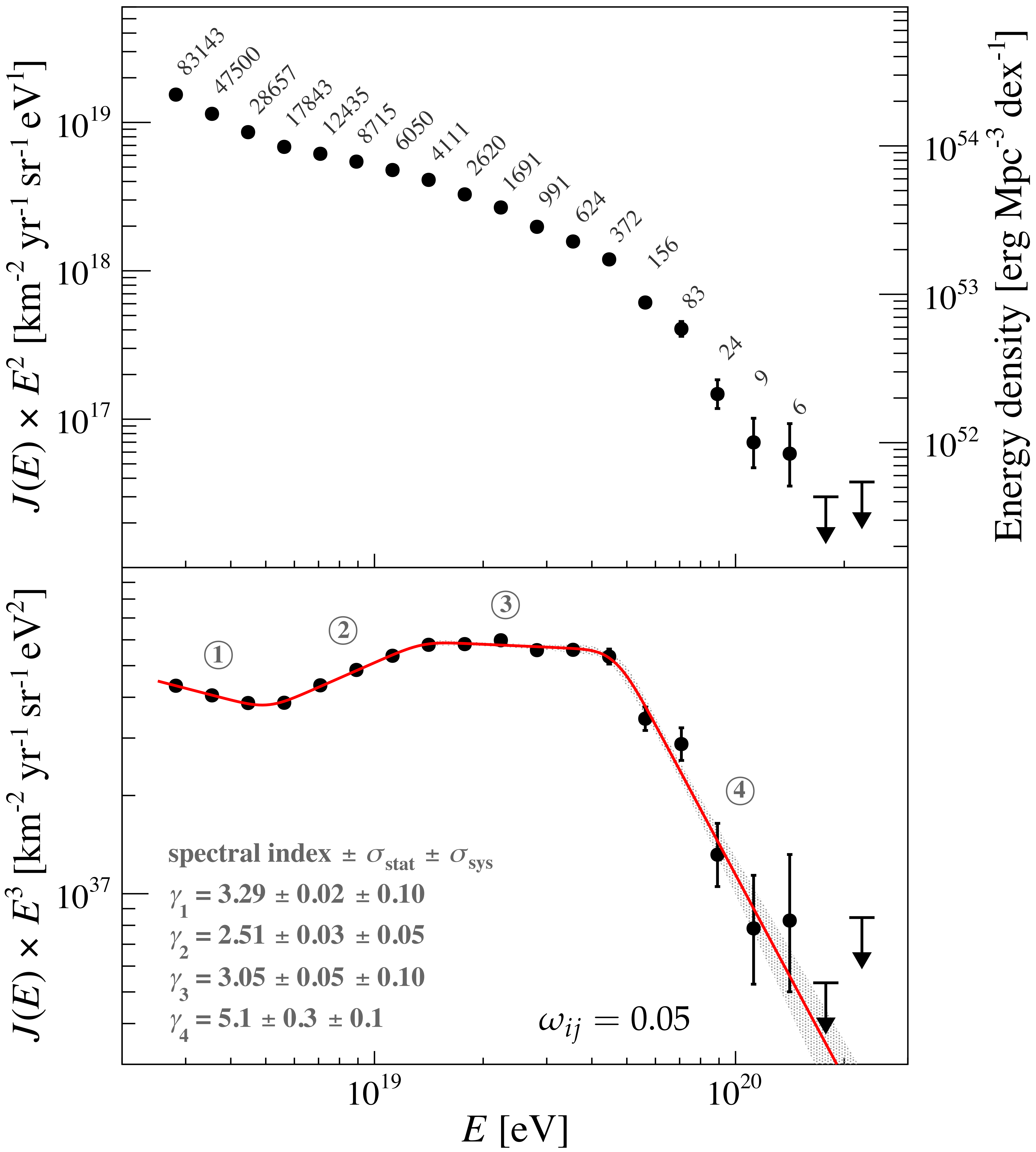
Other experiments calibrate with Monte Carlo simulations

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

Combined spectrum

- Combine results from different techniques and detectors

$$J(E) = J_0 \left(\frac{E}{10^{18.5}\,\mathrm{eV}}\right)^{-\gamma_1} \times \prod_{i=1}^{3}\left[1+\left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i-\gamma_j)\omega_{ij}}$$



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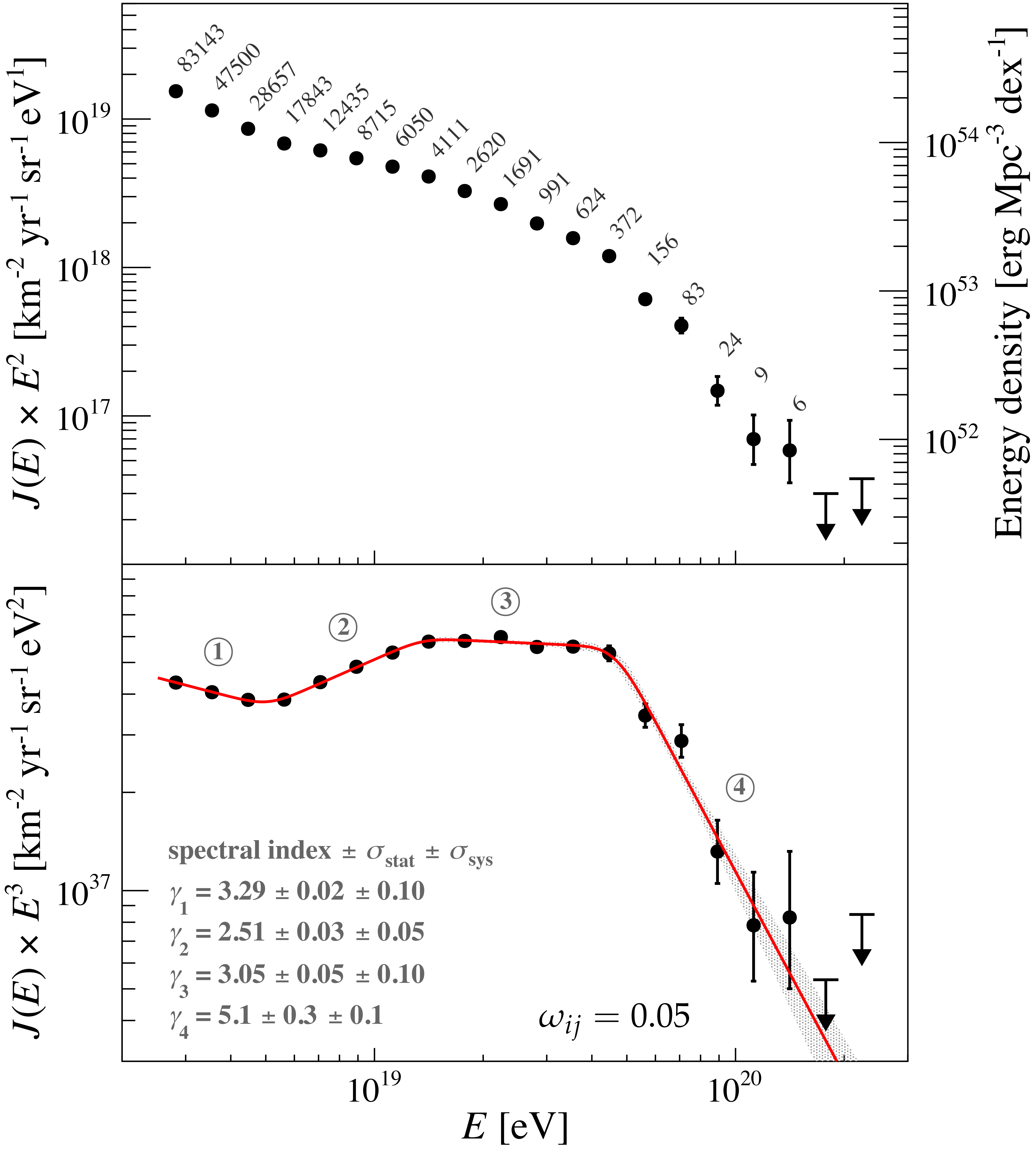
Spectral parameters:

E_{12} = 5 ± 0.1 ± 0.8 EeV

E_{23} = 13 ± 1 ± 2 EeV

E_{34} = 46 ± 3 ± 6 EeV



Anisotropy: Rayleigh analysis in right ascension

- Harmonic analysis in Right Ascension α

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

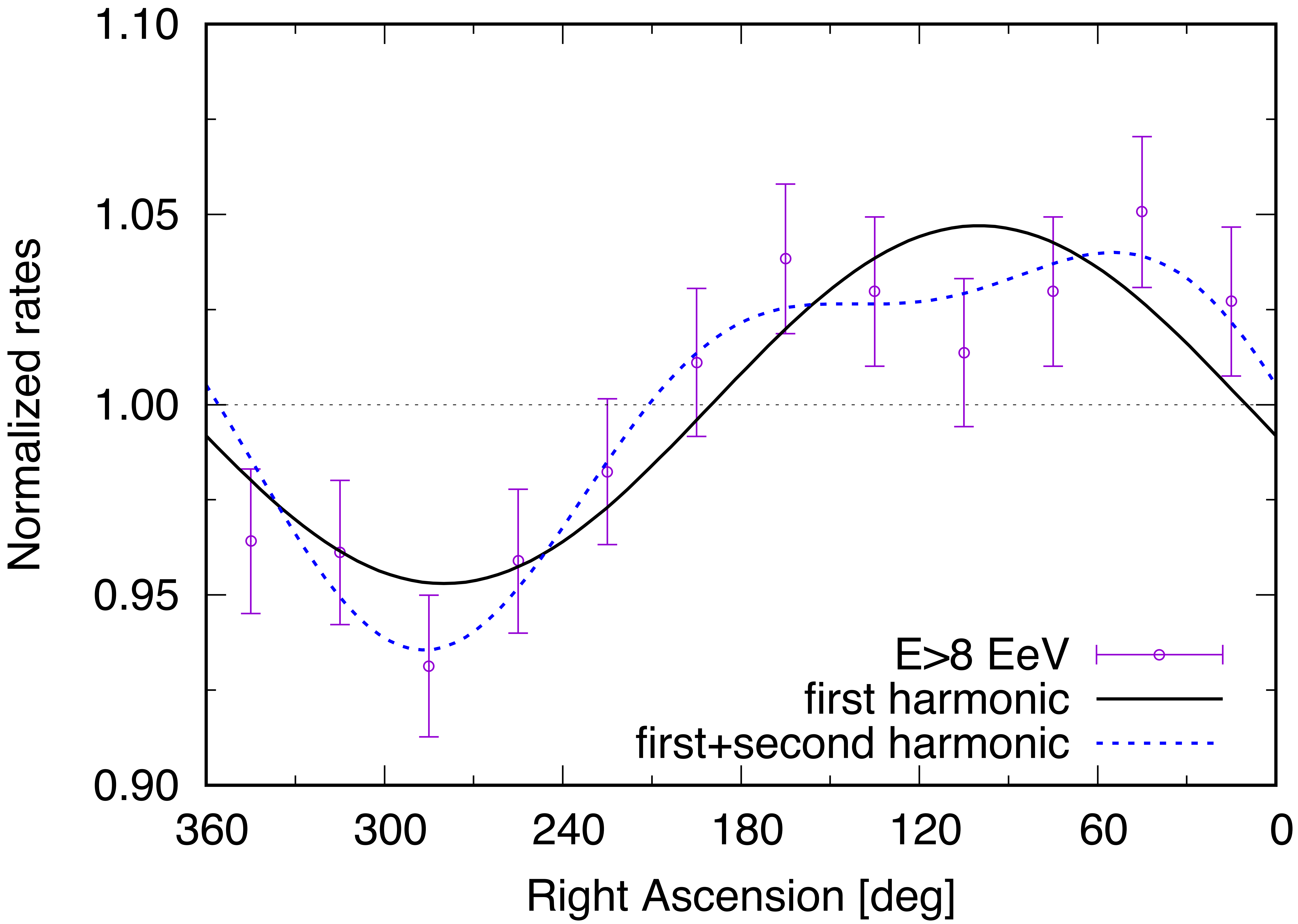
- Weights account for small non-uniformities

- Obtain: amplitude and phase of 1st harmonic

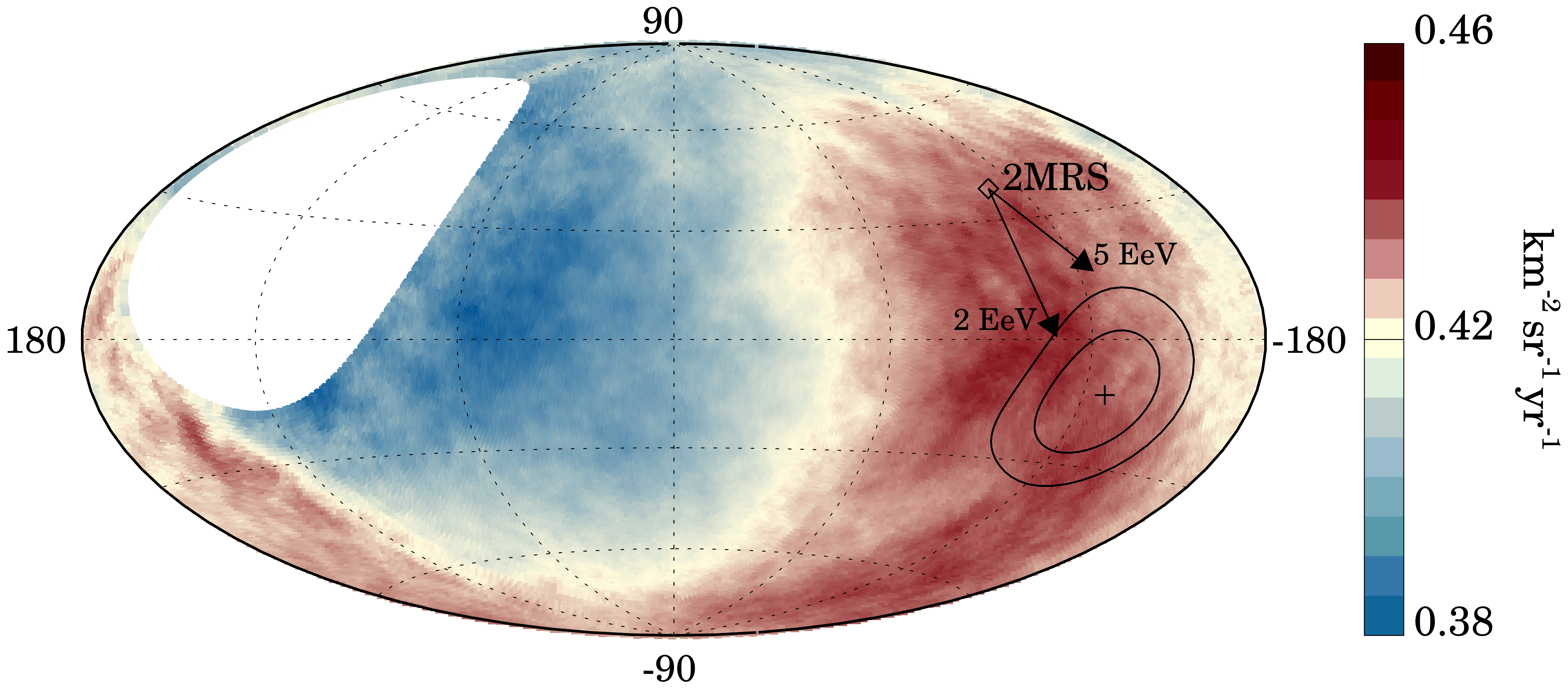
$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}, \qquad \tan \phi_\alpha = \frac{b_\alpha}{a_\alpha}$$

- 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

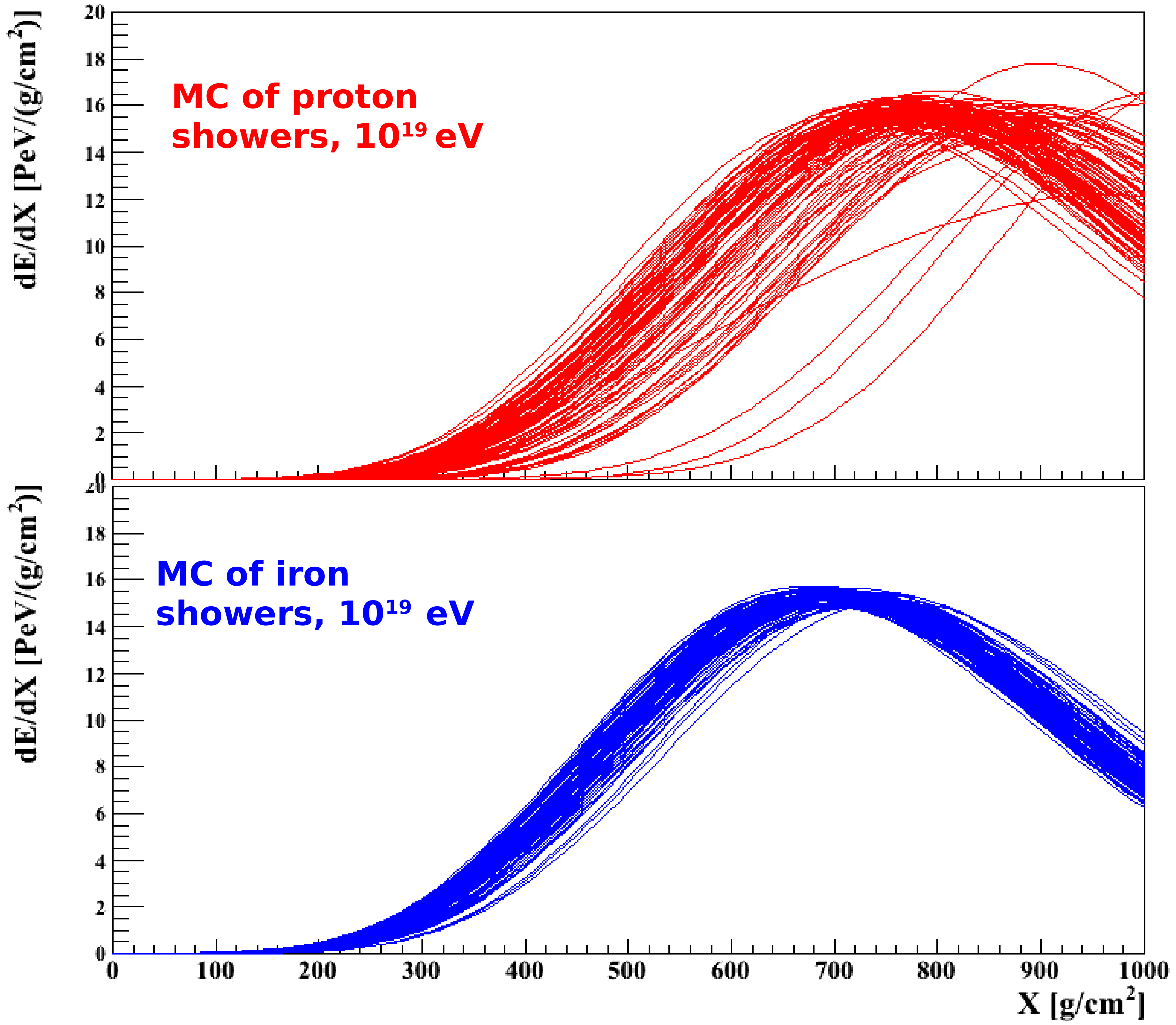


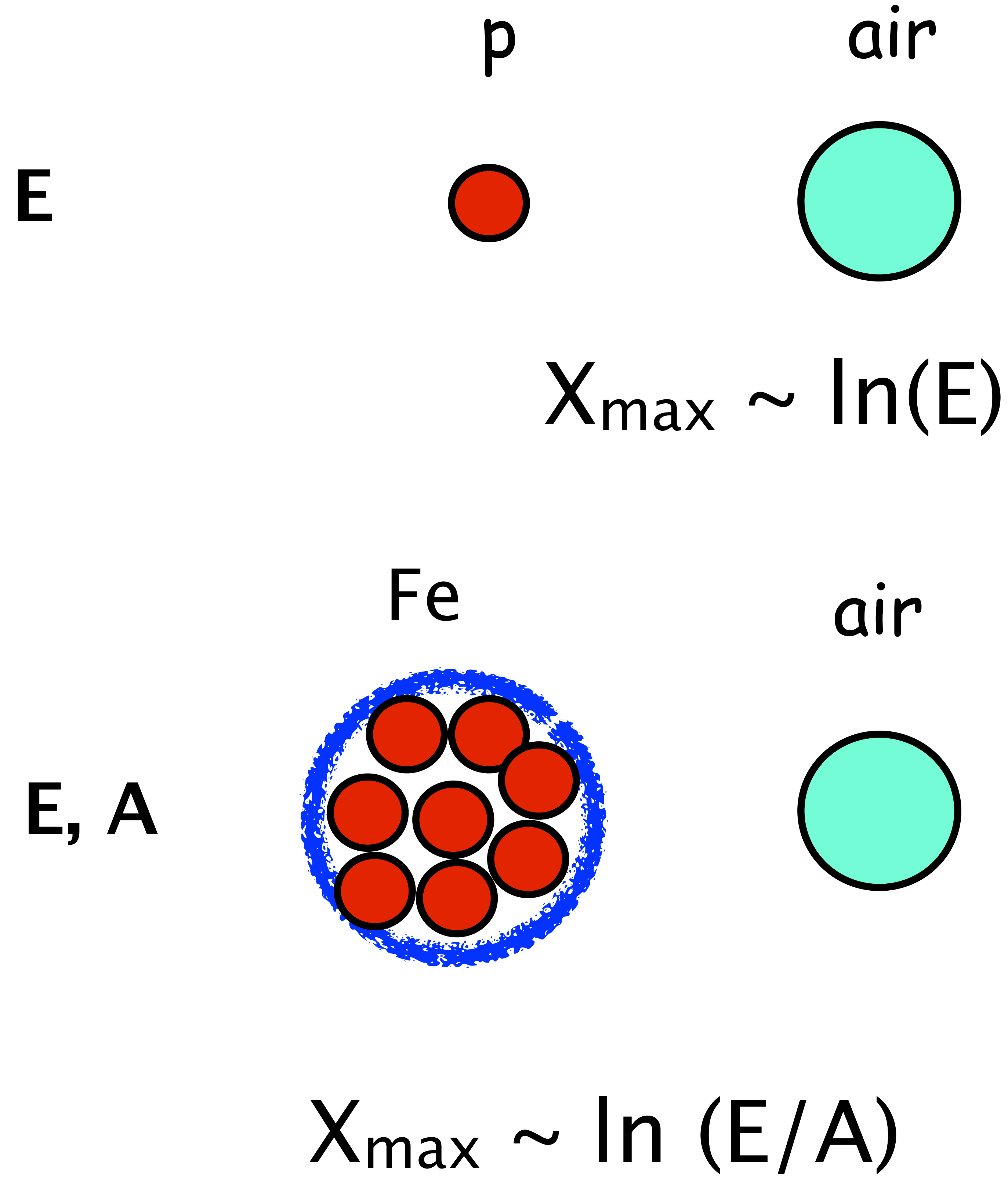
CR dipole vs 2MRS dipole



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

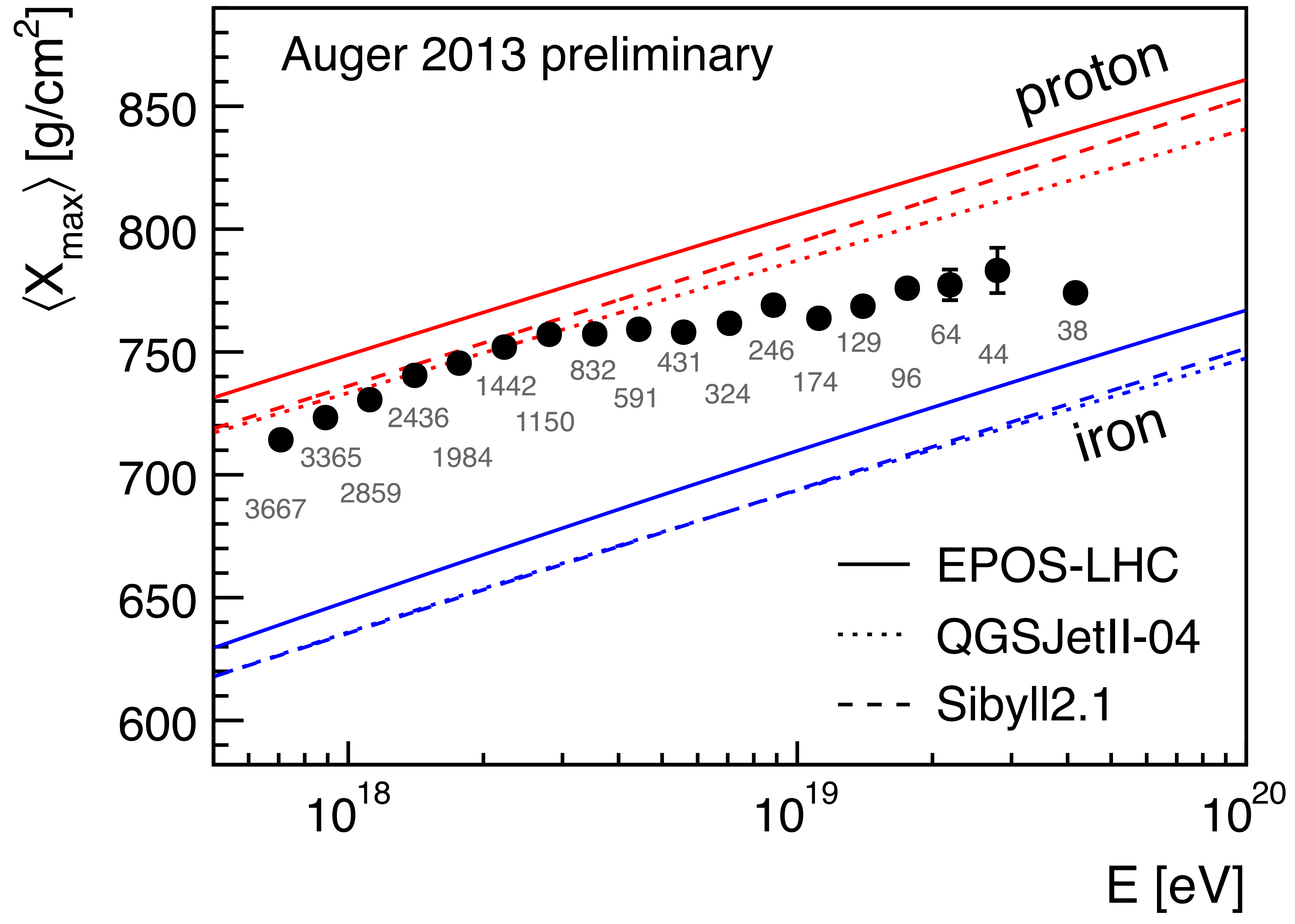
Composition and X_{max}

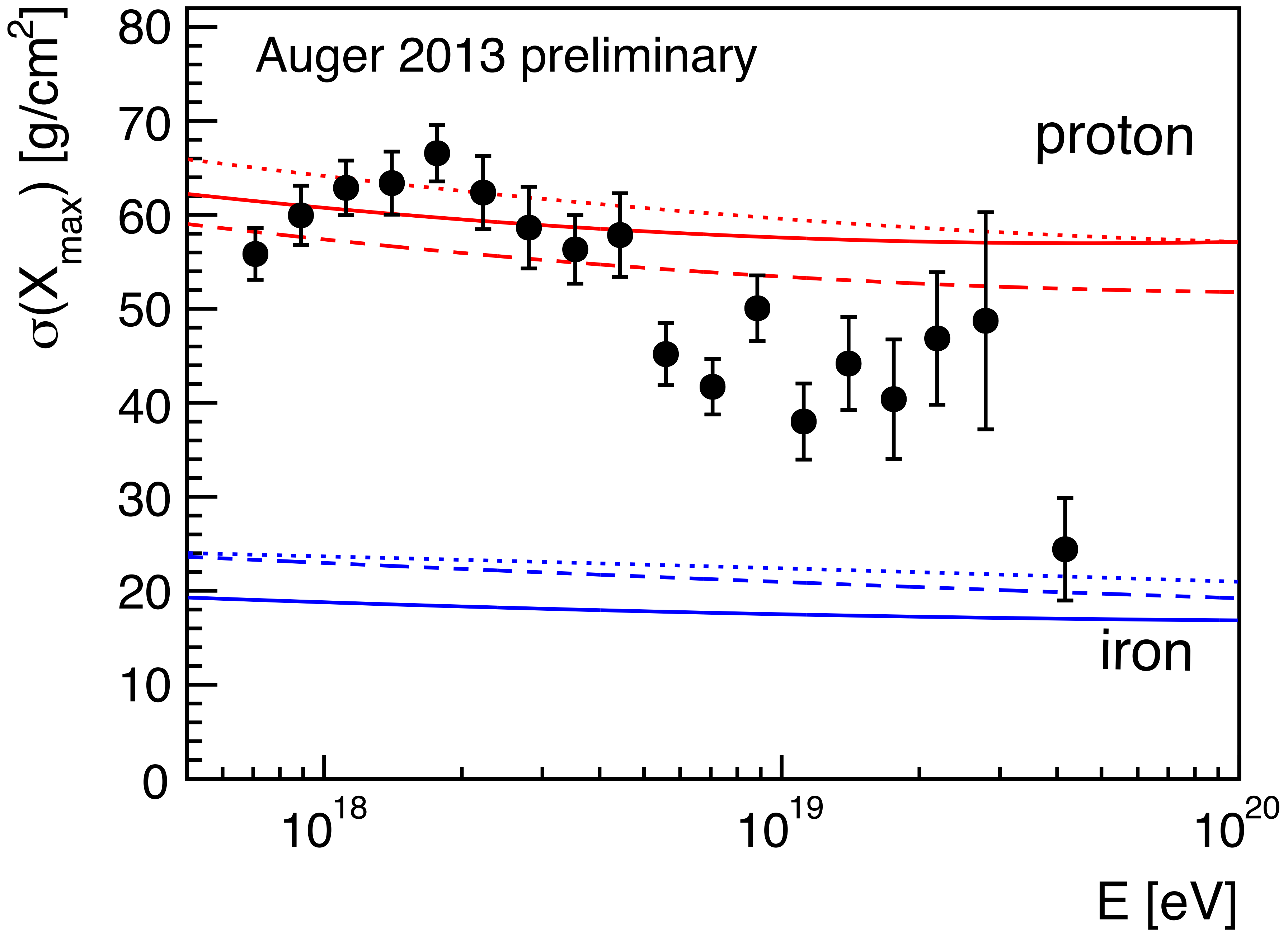




- Both X_{max} and RMS(X_{max}) depend on
  - Energy: Number of generations in air shower
  - Cross-section, i.e., type of primary: σ(Fe-Air) > σ(p-Air)

Composition



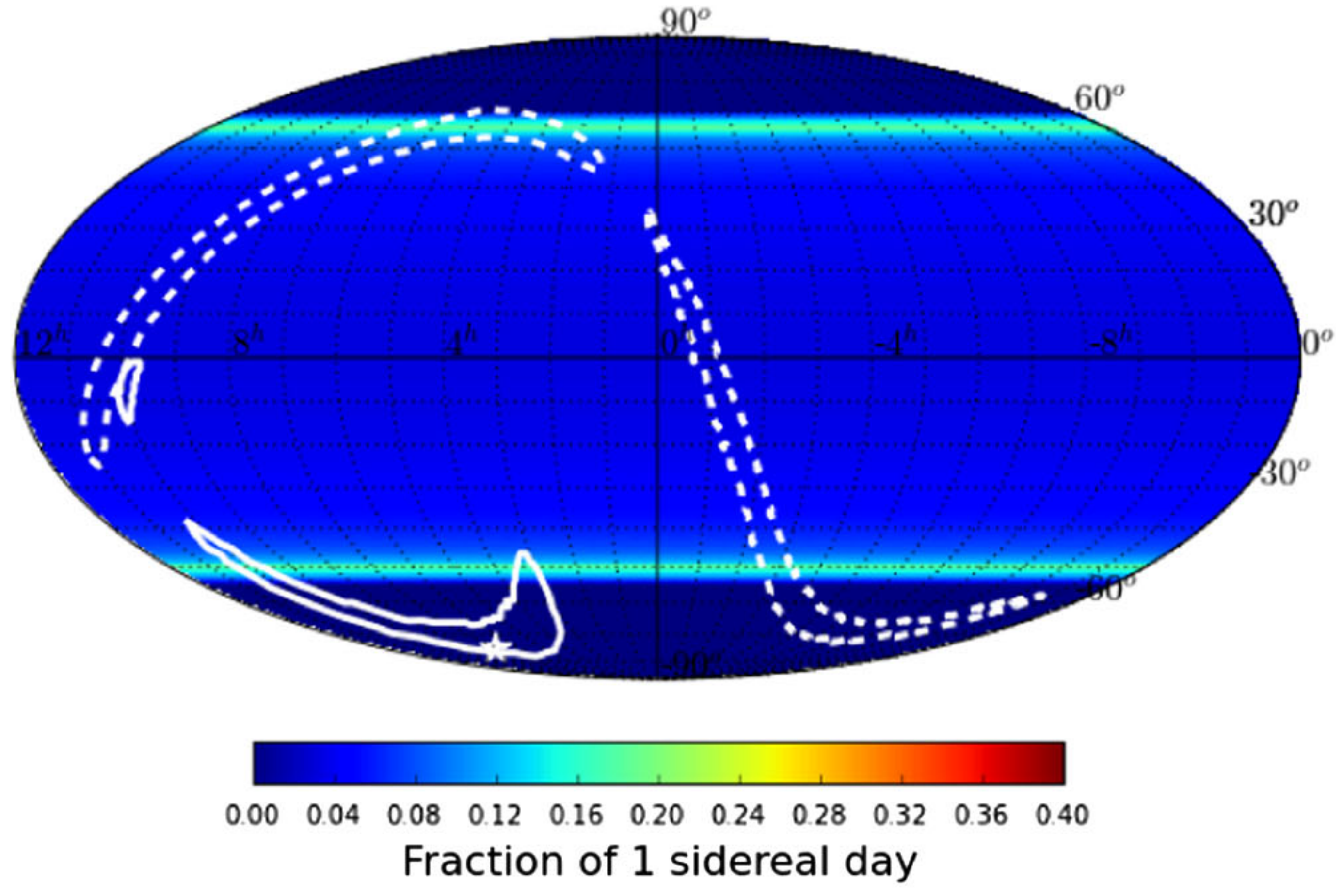


- ◉ Indication of a change from light to heavy as energy increases
- ◉ Interpretation requires models
- ◉ Observation not compatible with all models

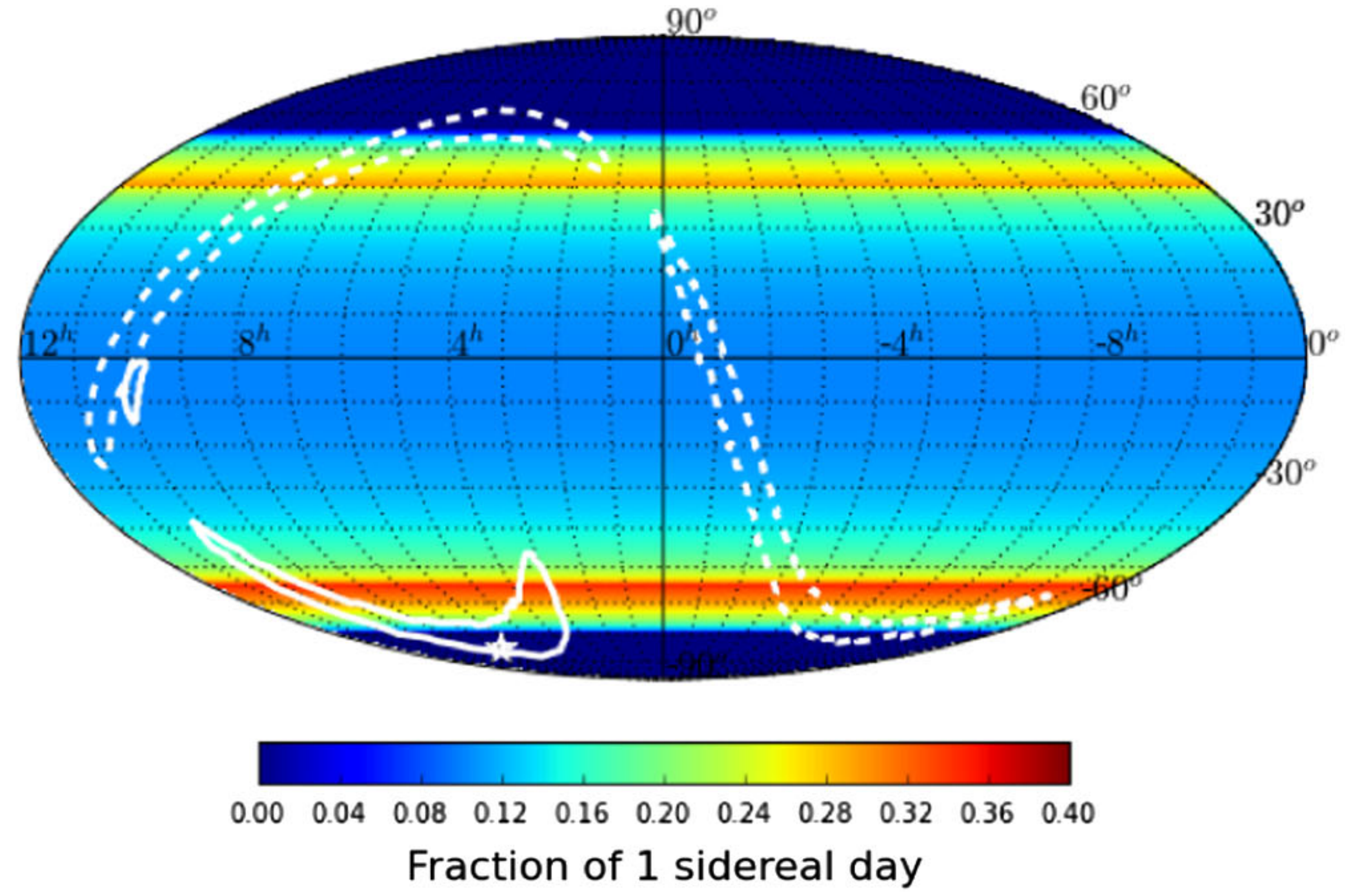
Neutrino followup of Gravitational Wave events

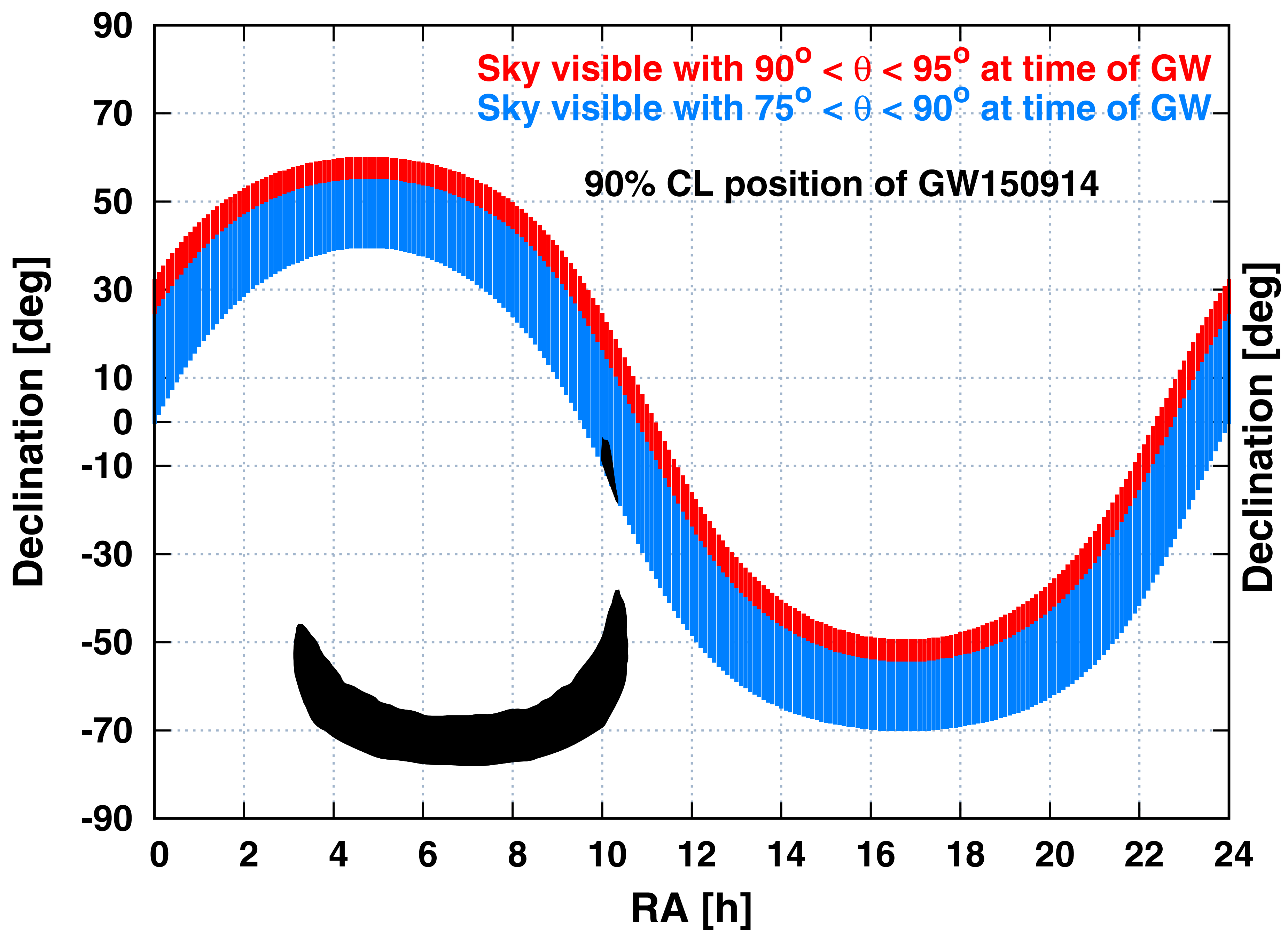
Sensitivity

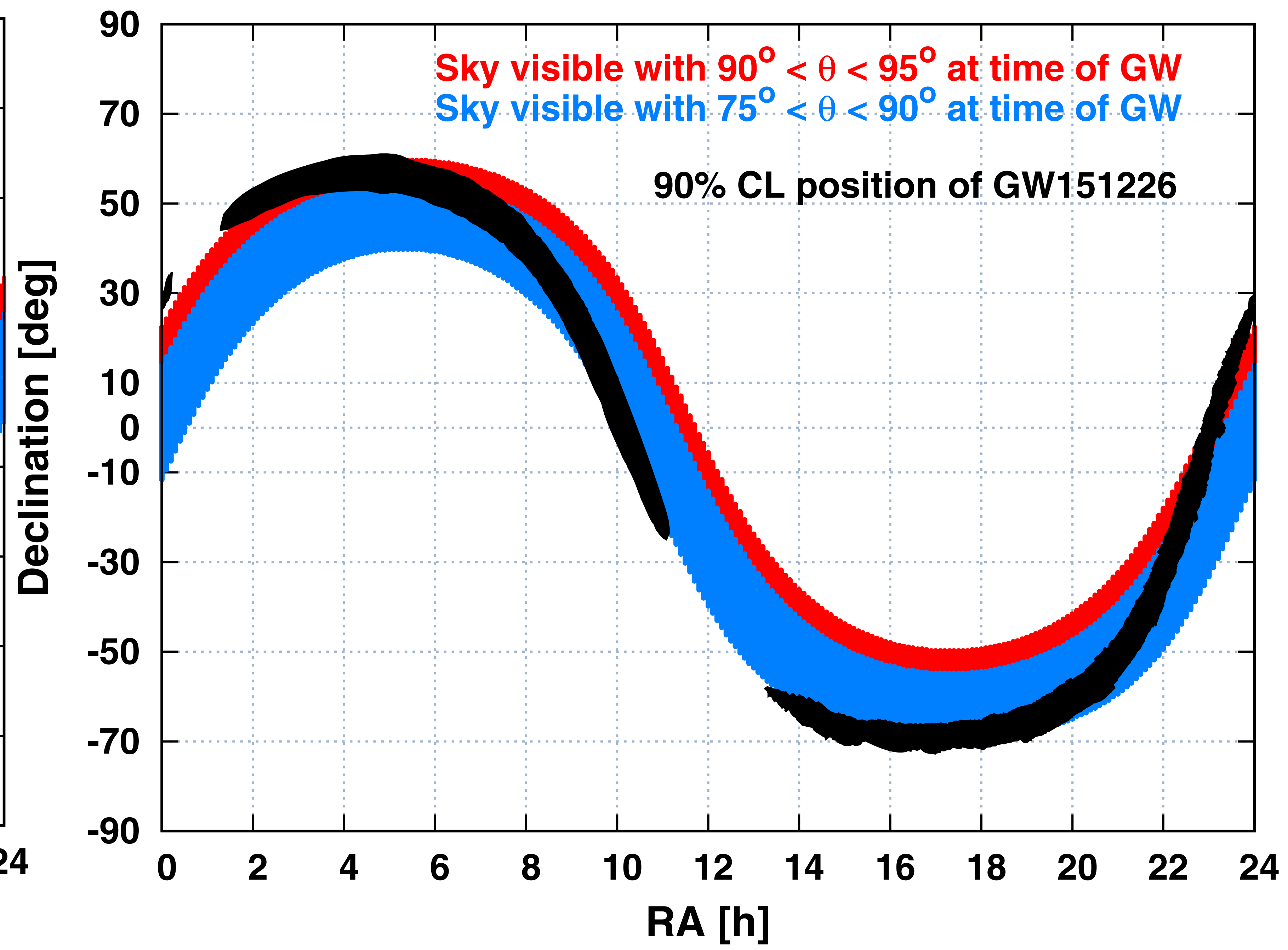
90° ≤ θ ≤ 95°



75° ≤ θ ≤ 90°

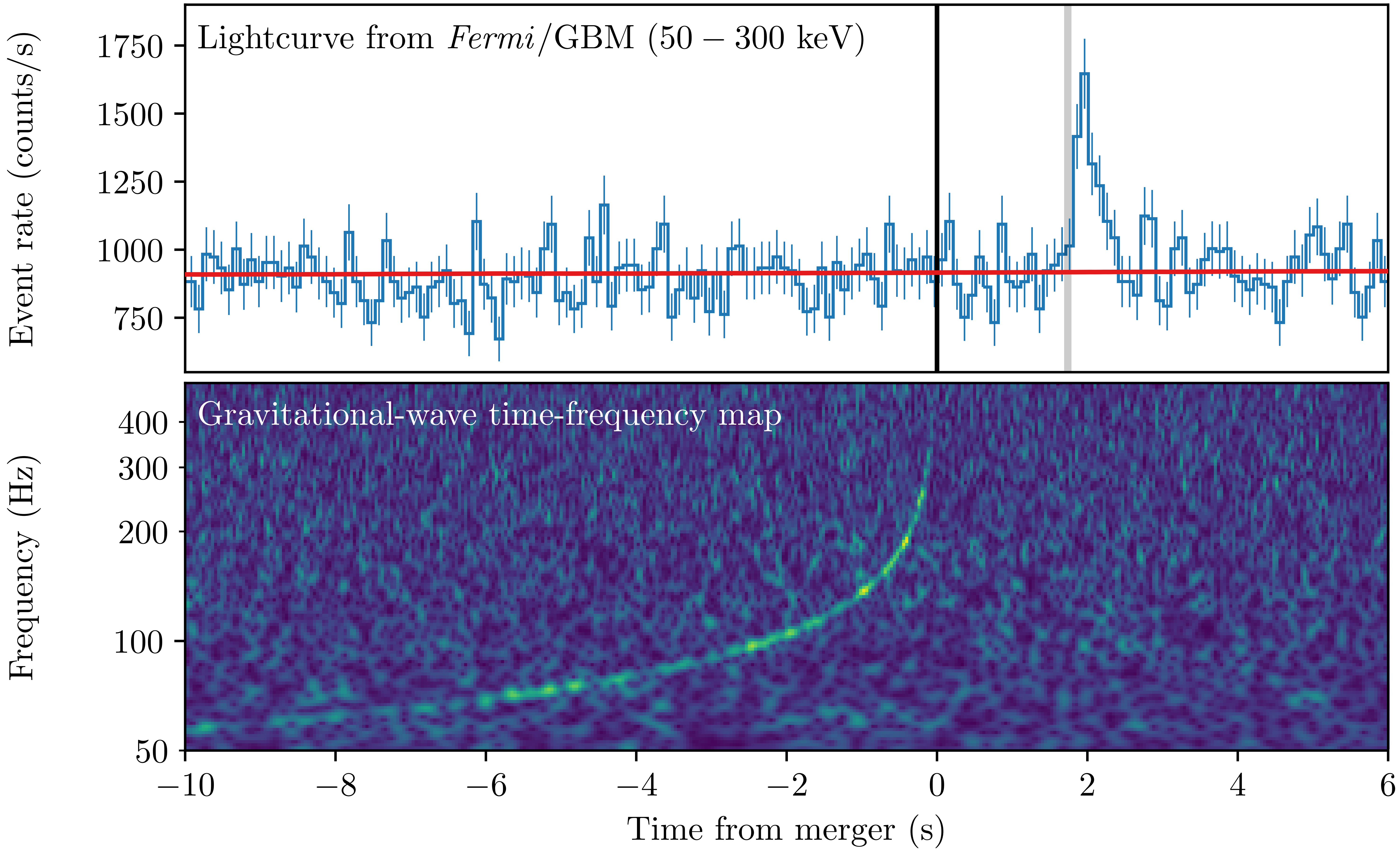




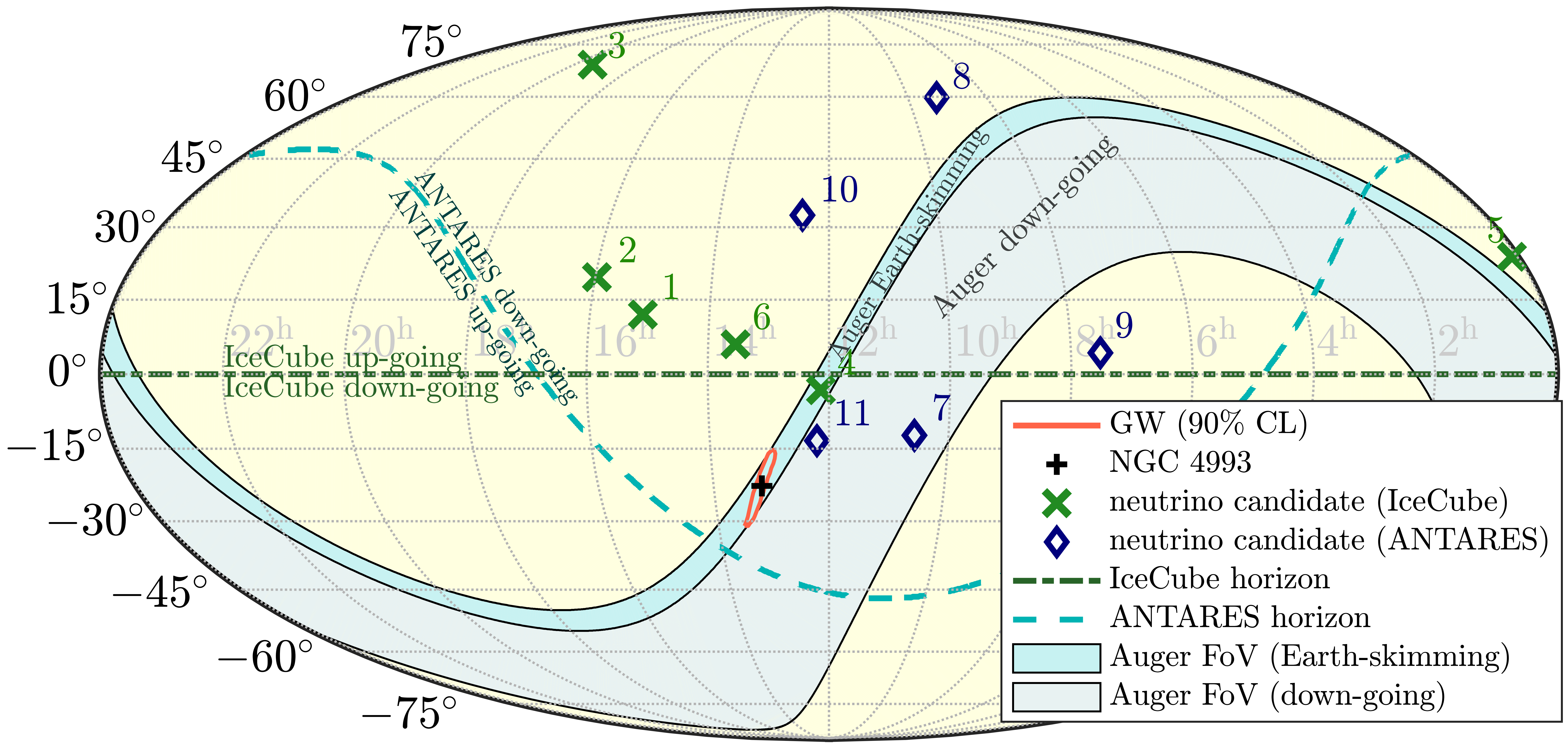


GW170817 / GRB170817A: NS-NS merger

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



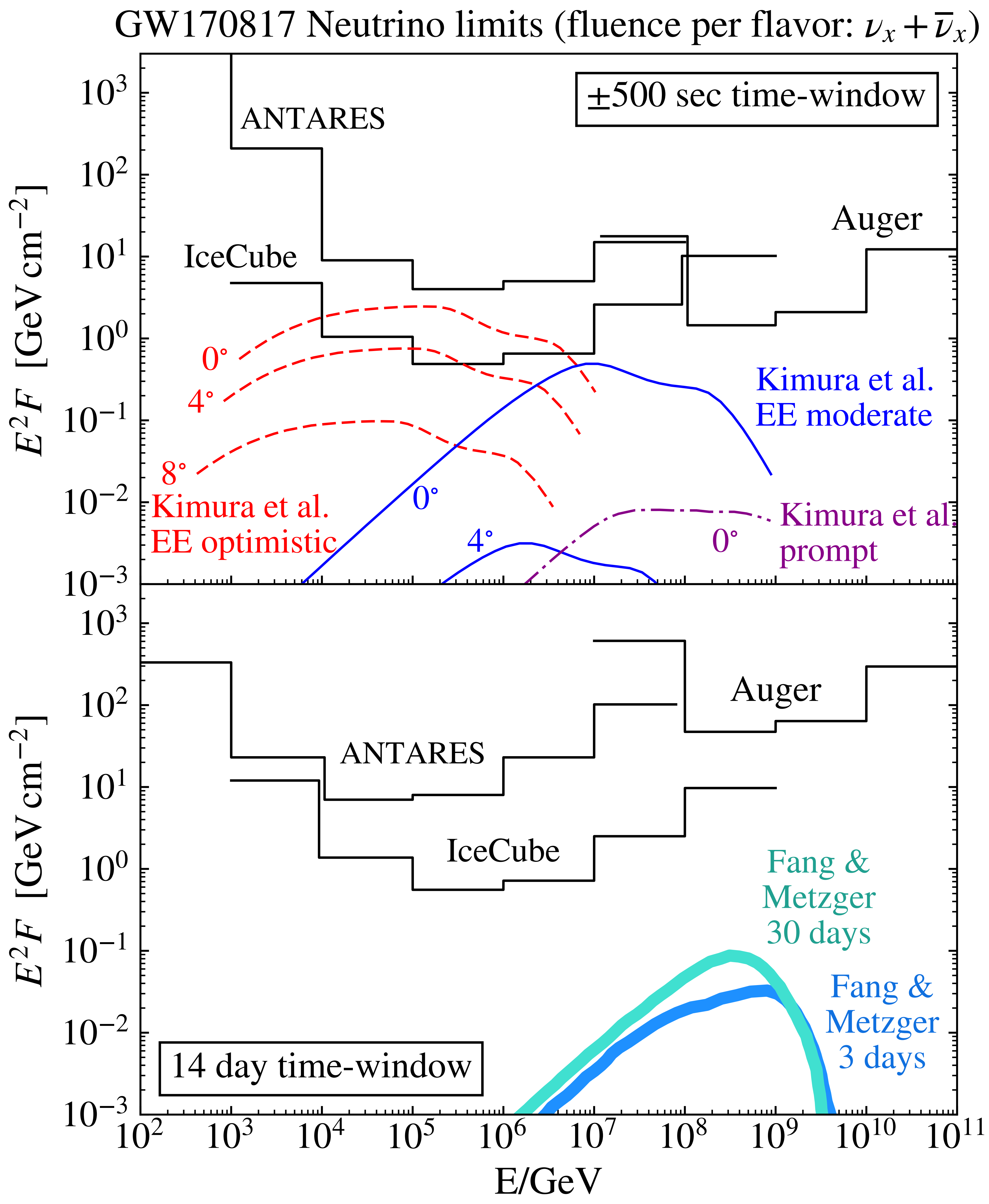
Neutrino Followup: IceCube, Antares, Pierre Auger Observatory



- 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



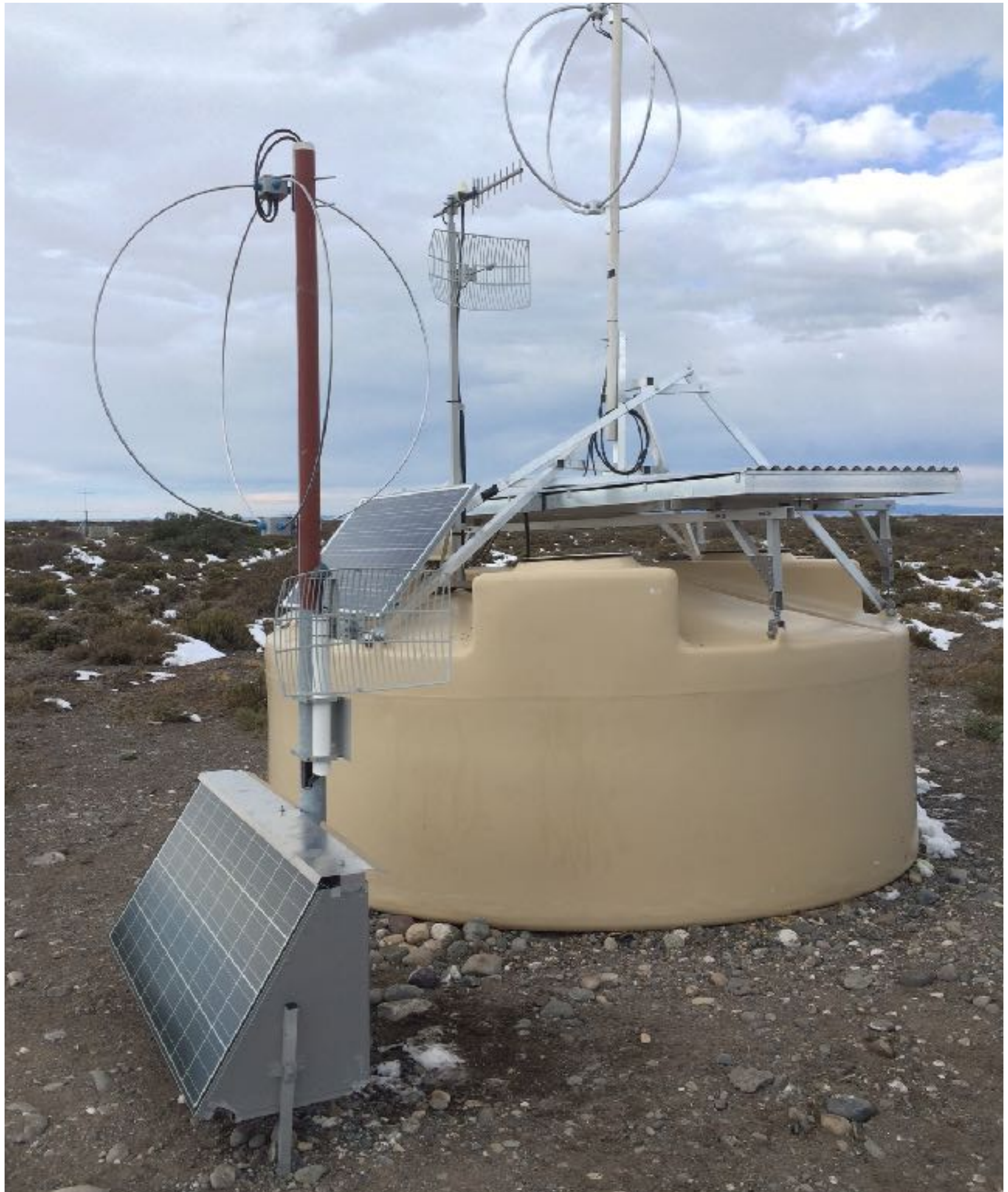
Auger Upgrade

- 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

Upgraded Station



- Scintillator counter on top of tank
- New, faster electronics
- Horizontal air showers: Electro-magnetic component
- Funded
- Prototype in the field

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 in progress
  - Extend science reach

Related experiments and spinoff

- HAWC Observatory in México: Gamma Ray Astronomy
  - Planning southern hemisphere counterpart SWGO
- LHC experiments: ALICE
- Driving HPC infrastructure
- Data intense science: current storage 7PB
  - Network demands