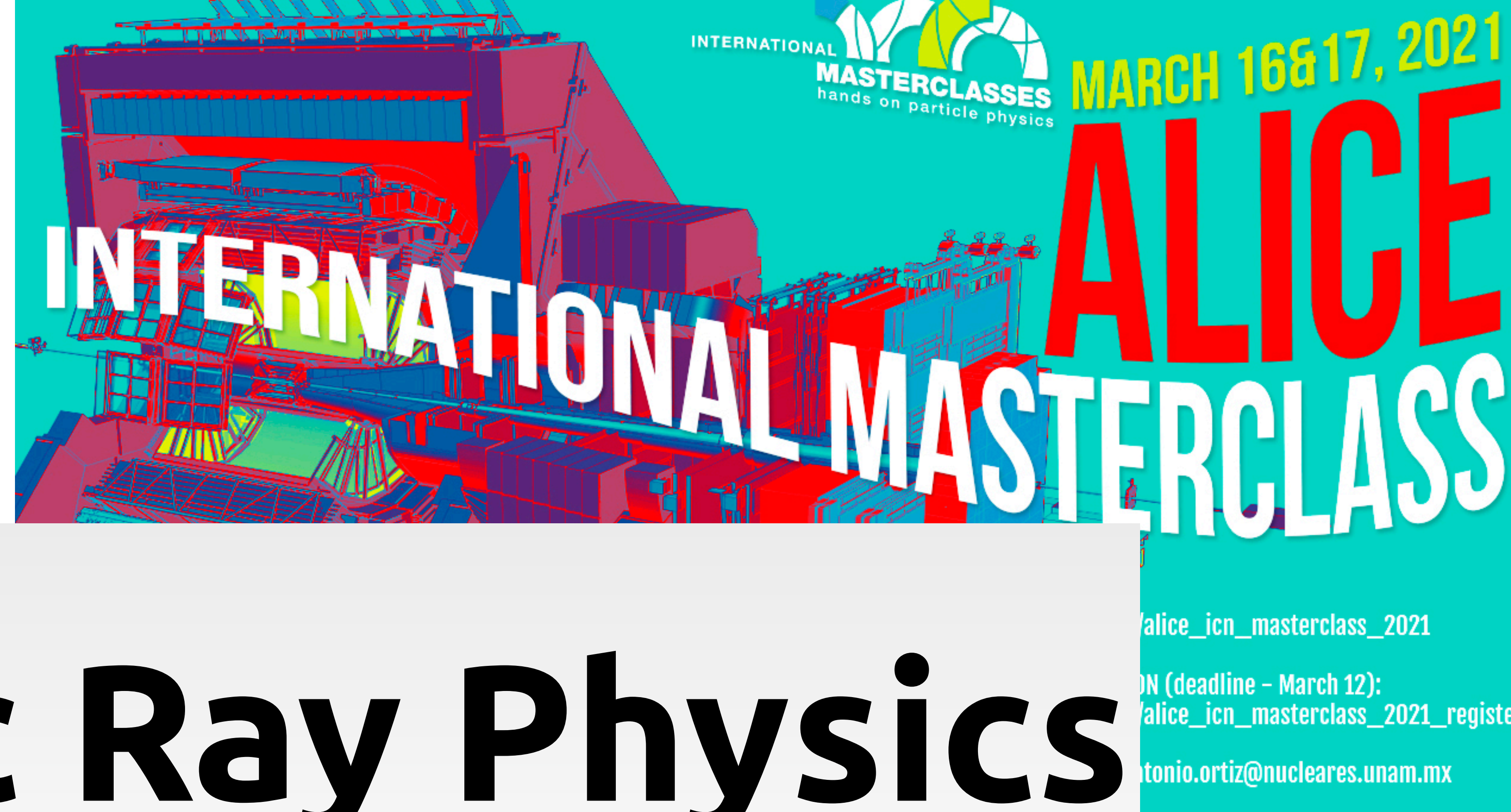

Cosmic Ray Physics
– Auger and HAWC –

Lukas Nellen
ICN-UNAM
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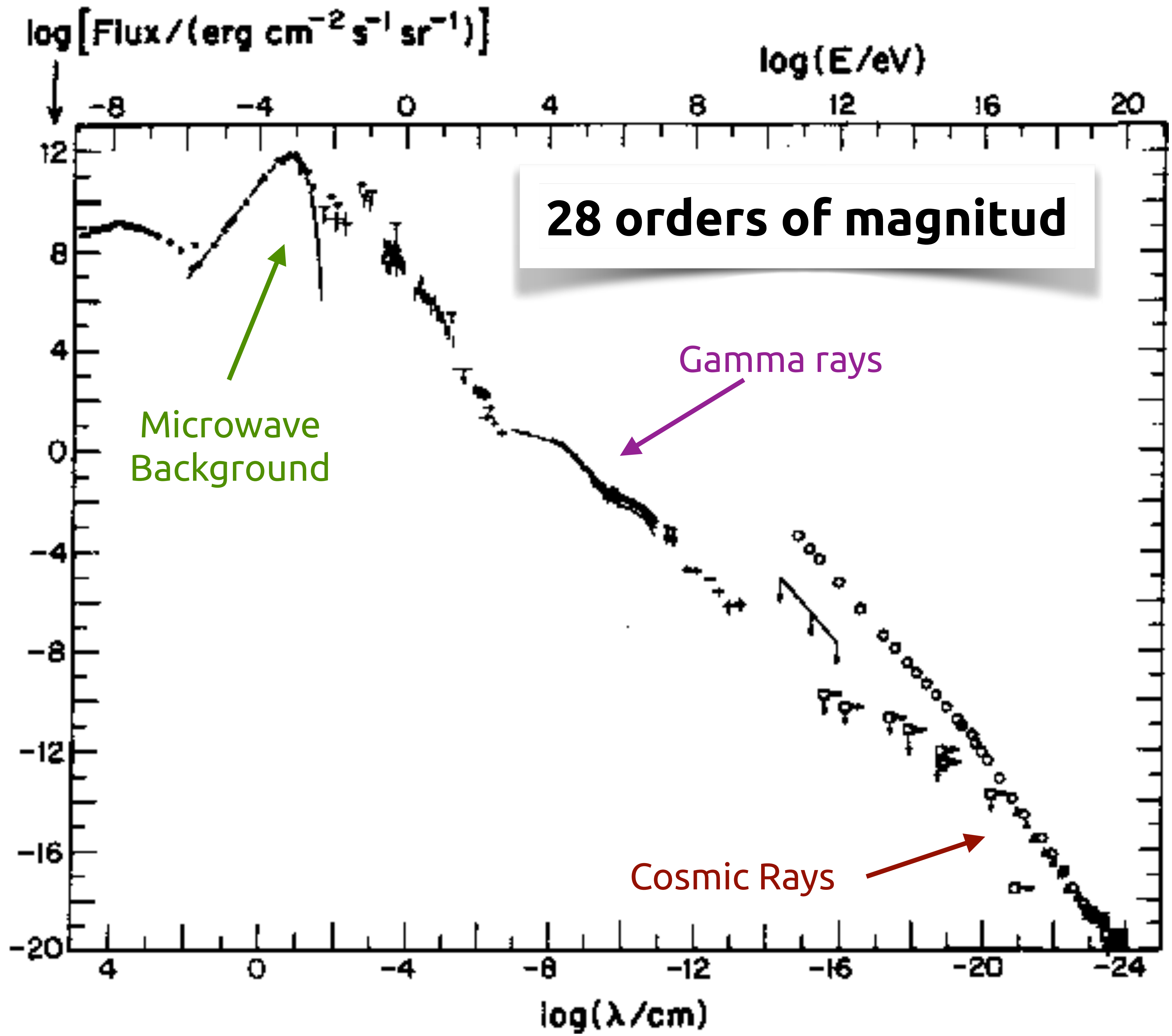
Summary

- History
- Astrophysics of cosmic rays
- Extended Air Showers
- Detection of Cosmic Rays
- The Pierre Auger Observatory
- The HAWC Observatory
- Auger Open Data

History

Radiation in the Universe

– Electromagnetic and particles –



Unkown ionizing radiation

Early 20th century:
The puzzle of the electroscopes

- Loss of charge without ionizing sources
  - Unknown ionizing radiation
  - What type of radiation?
  - Where does it come from?

Victor Hess, 1912

- Balloon flights
- Reached 5 km

- Scientific payload: 2 electroscopes

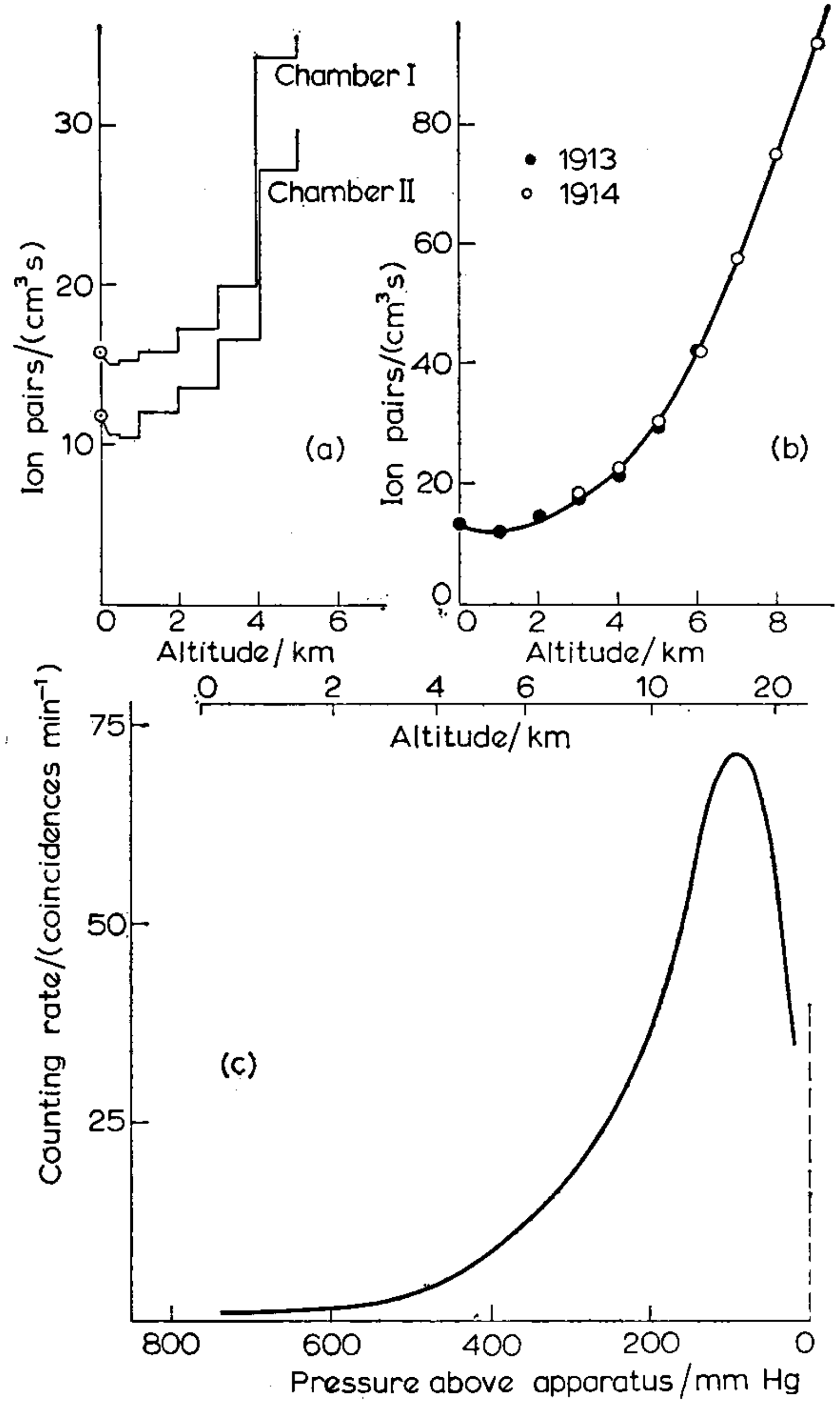
- Determine if radiation emitted by earth

Hess bei Ballonlandung (1912).

Radiation from space

- Measured: density of ion pairs
  - Increases with altitude

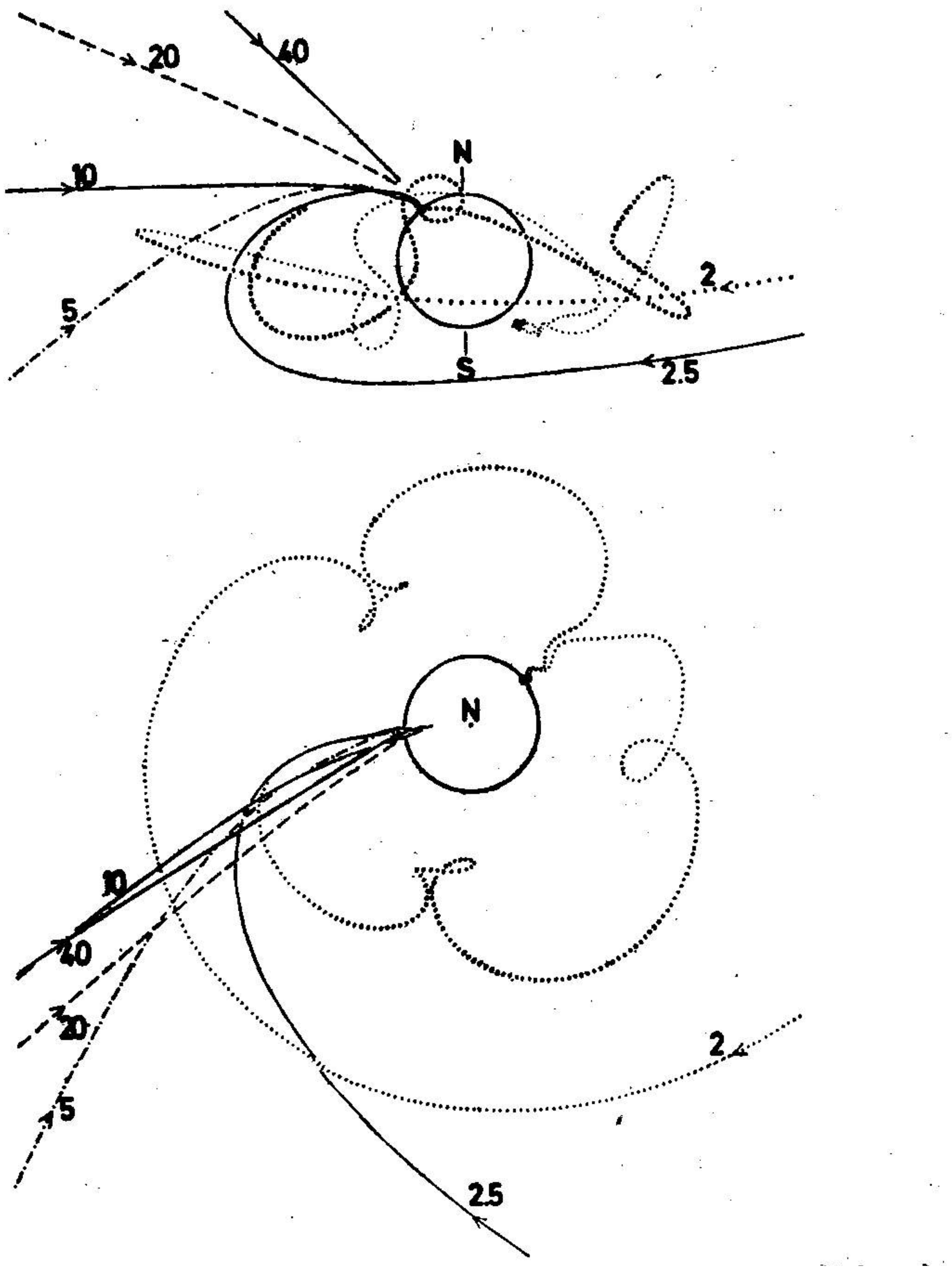
- Conclusio: **Extraterrestrial origin**
- Nature unknown
  - Gamma rays?
  - Charged radiation?
    - Sign of charge?



?. Altitude variation of ionization. (*a*) Balloon ascent by Hess (1912) carrying two ion chambers. (*b*) Ascents by Kolhörster (1913, 1914) using ion chambers. (*c*) Coincidence counter telescope flown by Pfotzer (1936).

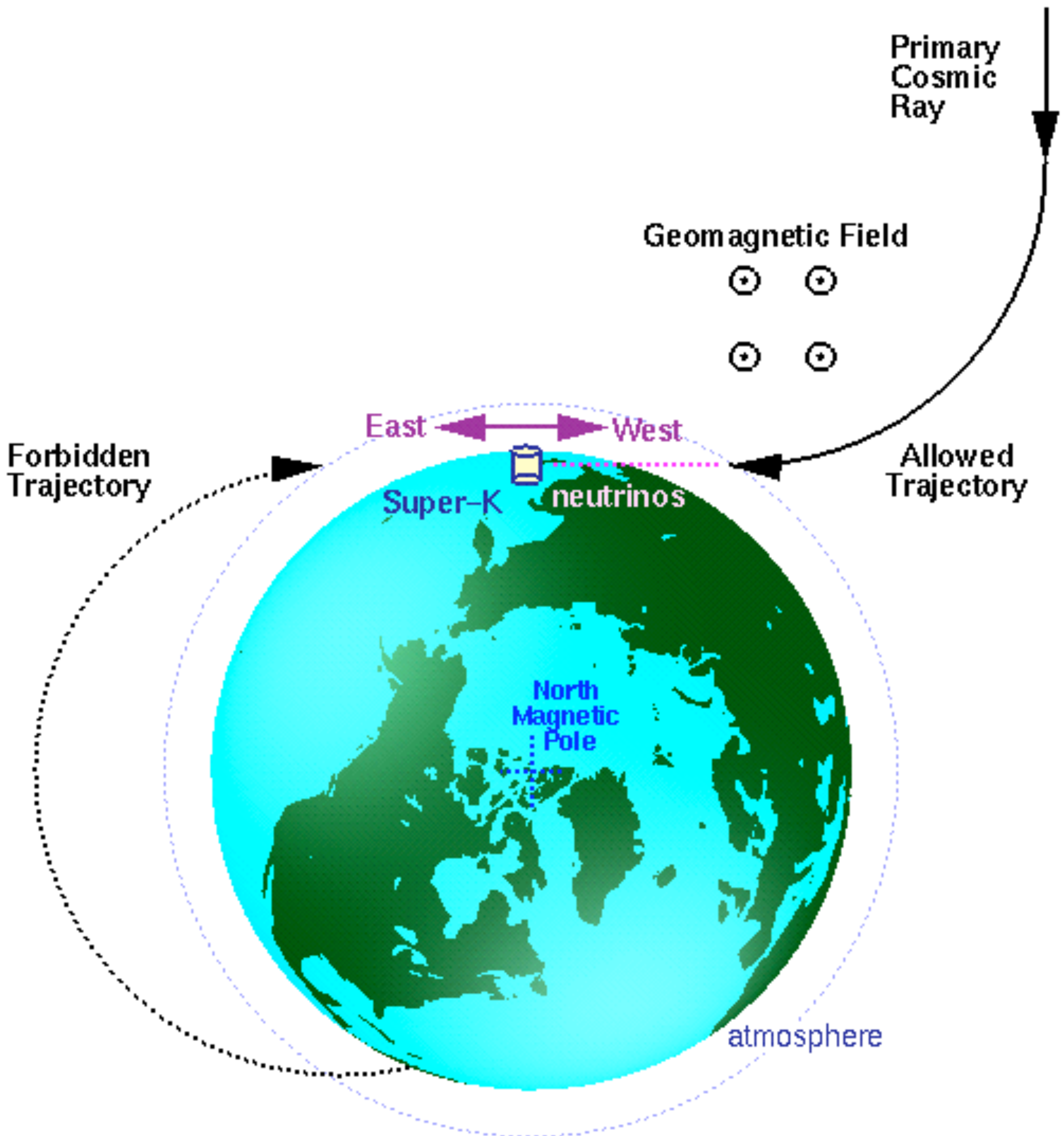
Charged particles in vicinity of the Earth

- Charged particles in the Earth magnetic field: Numerical simulation of trajectories
- Sandoval-Vallarta, 1932 (Princeton)

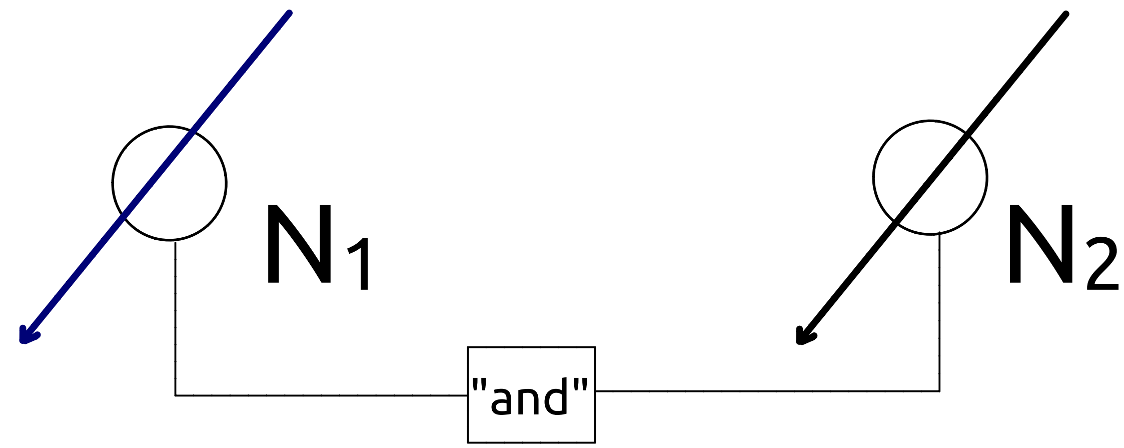


The East-West Effect

- First observed in Mexico City
  - Effect stronger closer to the equator
- Luis Alvaréz, 1932 (Then student of Compton)
- Proves: The cosmic radiation consists predominantly of **positively charged particles**



Extended Air Showers: Pierre Auger, 1938



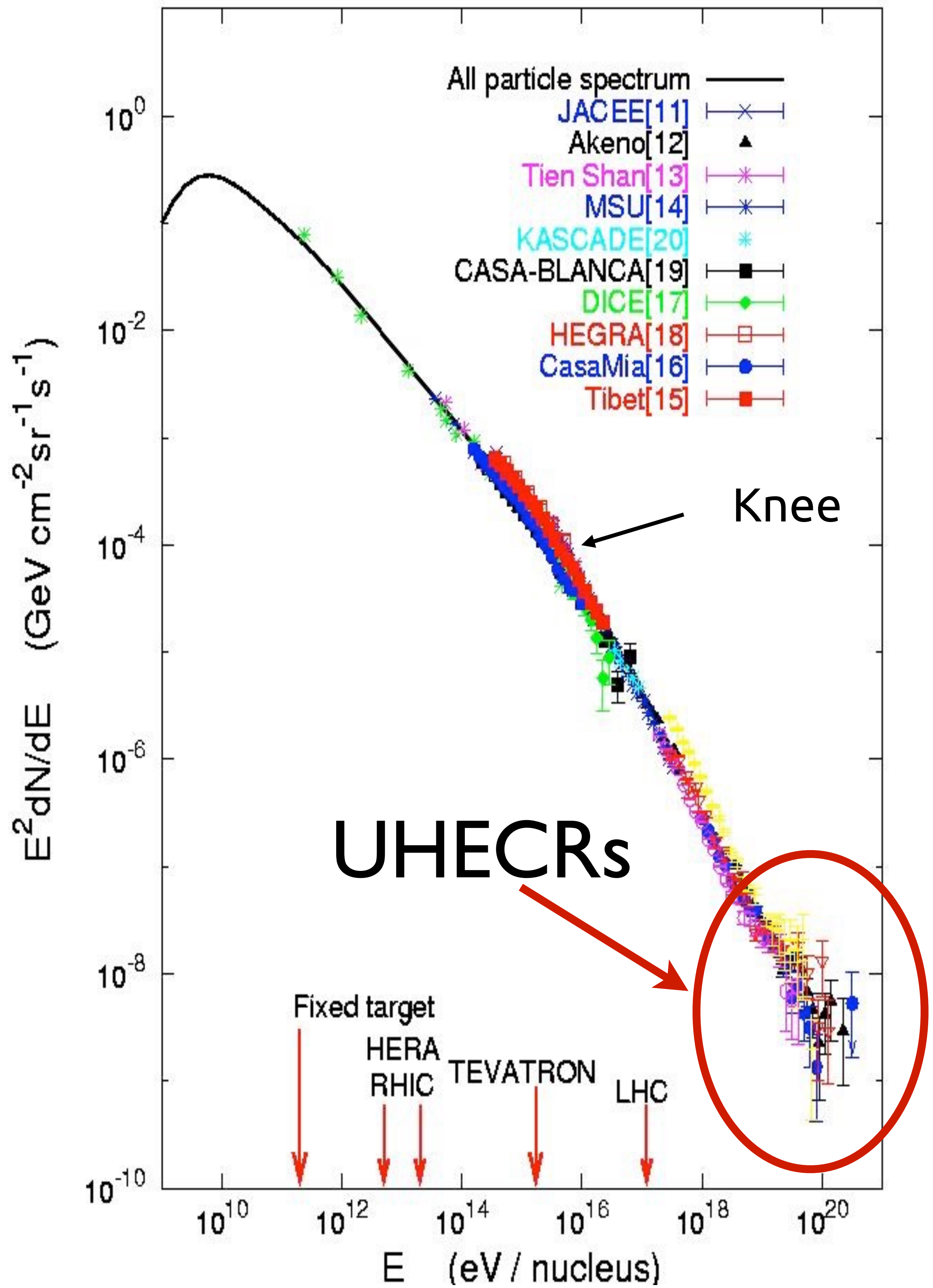
Random coincidence: $2N_1N_2\tau$

N_1, N_2: local rate, τ: coincidence window

- Detectors up to 300m apart
- Observed rate higher than predicted
  - Correlated, extended flux
- Estimated energy: **10^{15} eV = 1PeV**

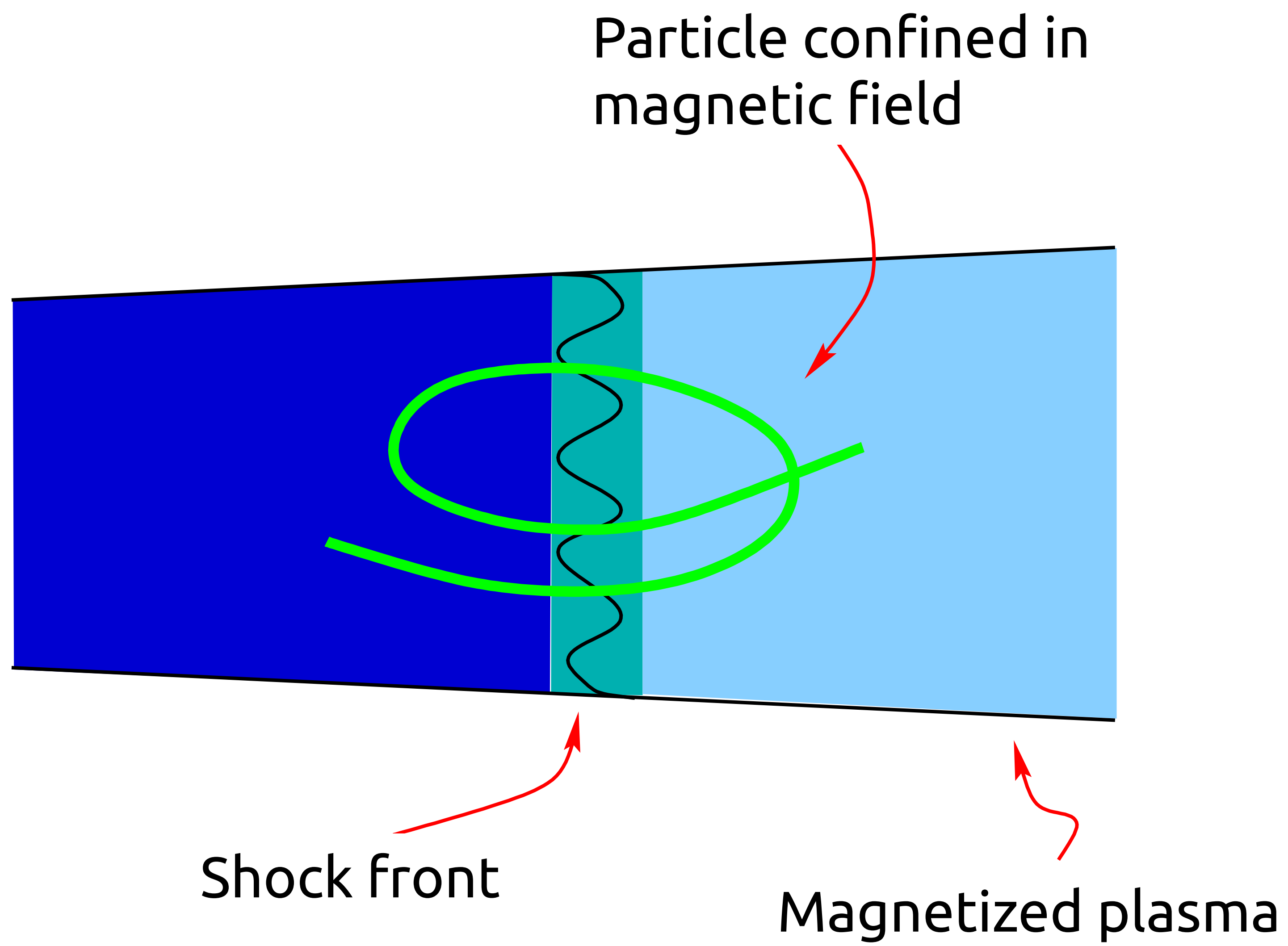
The spectrum of cosmic rays

- 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



Sources of Cosmic Rays

The Fermi Mechanism



- Cosmic Ping-Pong
- Particle confined in plasme
- Gains energy in each crossing of shock front
- Observed in interplanetary medium

Femi acceleration: spectrum

- Energy gain in crossing

$$\Delta E = \xi E$$

- Initial energy E_0, after n crossings:

$$E_n = E_0(1+\xi)^n$$

- Probability to escape source in one turn: P_{esc}. After n crossings:

$$P(n) = (1-P_{esc})^n$$

- Number of crossings needed to get to energy E:

$$n = \log(E/E_0)/\log(1+\xi)$$

- Fraction of particles with energy larger than E:

$$N(\geq E) \propto \sum_{m=n}^{\infty}(1-P_{esc})^m = \frac{(1-P_{esc})^n}{P_{esc}}$$

- Power law spectrum (non-thermal):

$$N(\geq E) \propto (P_{esc})^{-1}(E/E_0)^{-\gamma}$$

with

$$\gamma = -\log(1-P_{esc})/\log(1+\xi)$$
$$\approx P_{esc}/\xi = \xi^{-1}T_{cycle}/T_{esc}$$

for the integral spectrum

Properties of the Fermi mechanism

- Power-law spectrum

  $N(> E) \propto E^{-\gamma}$ (int.), $N(E) \propto E^{-\gamma-1}$ (dif.)

- Spectral index for thin shock: $\gamma \approx 1$

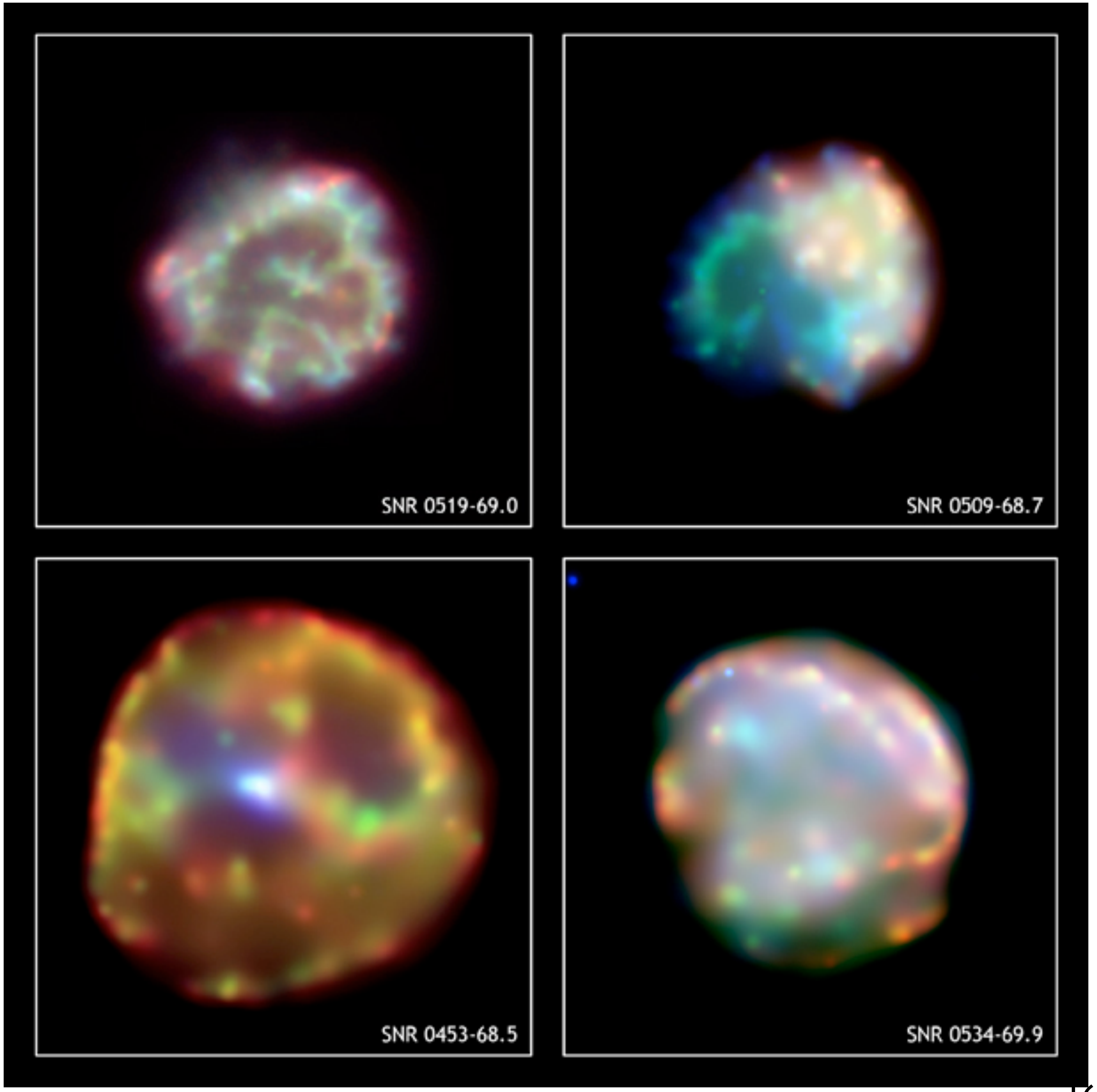
- Maximum energy depends on accelerator
  - size and magnetic field
  - Lifetime of the source

- Propagation changes spectral index

  ⇨ Source value not directly observable

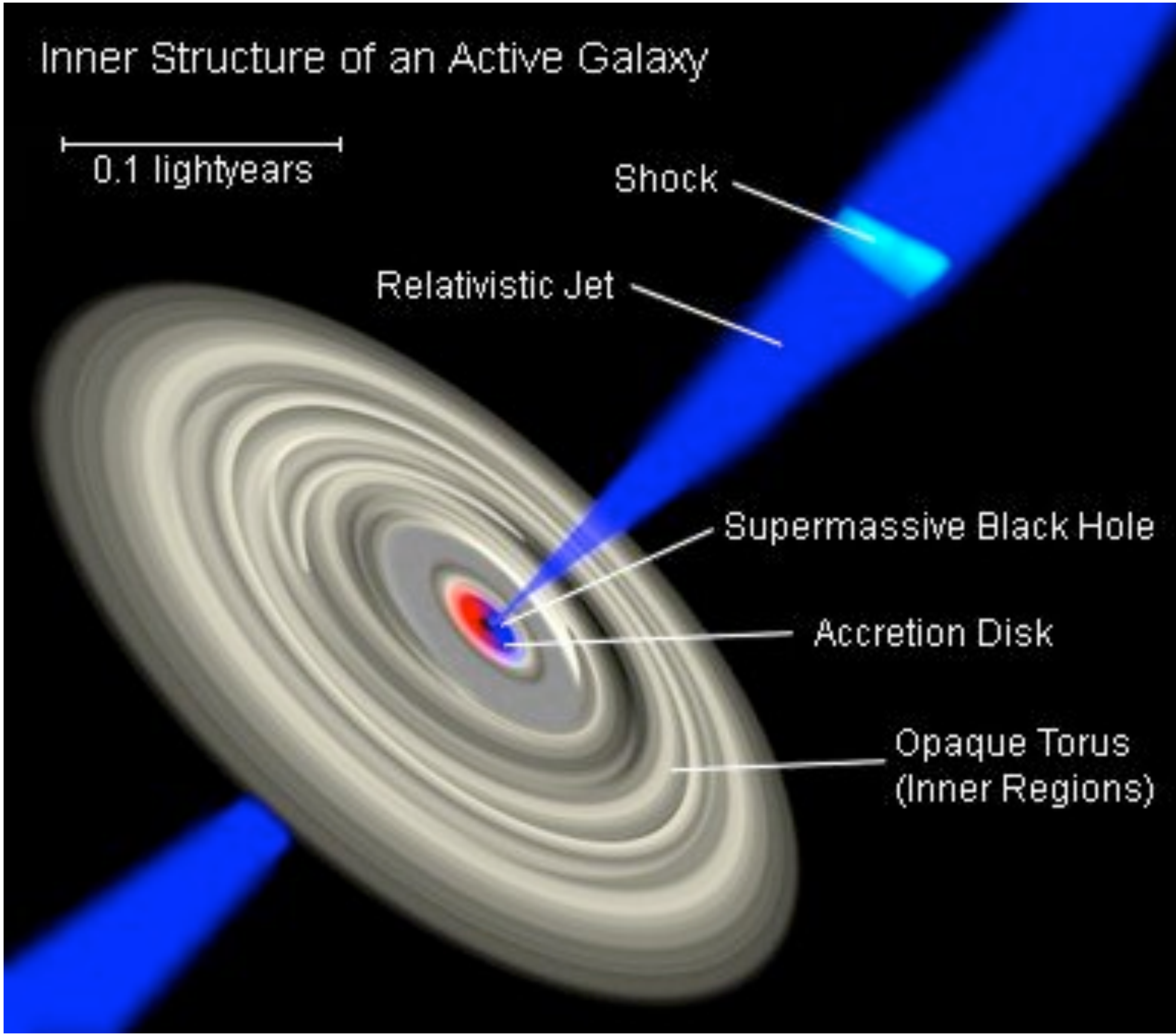
Supernovae

- Termination shock with interstellar medium

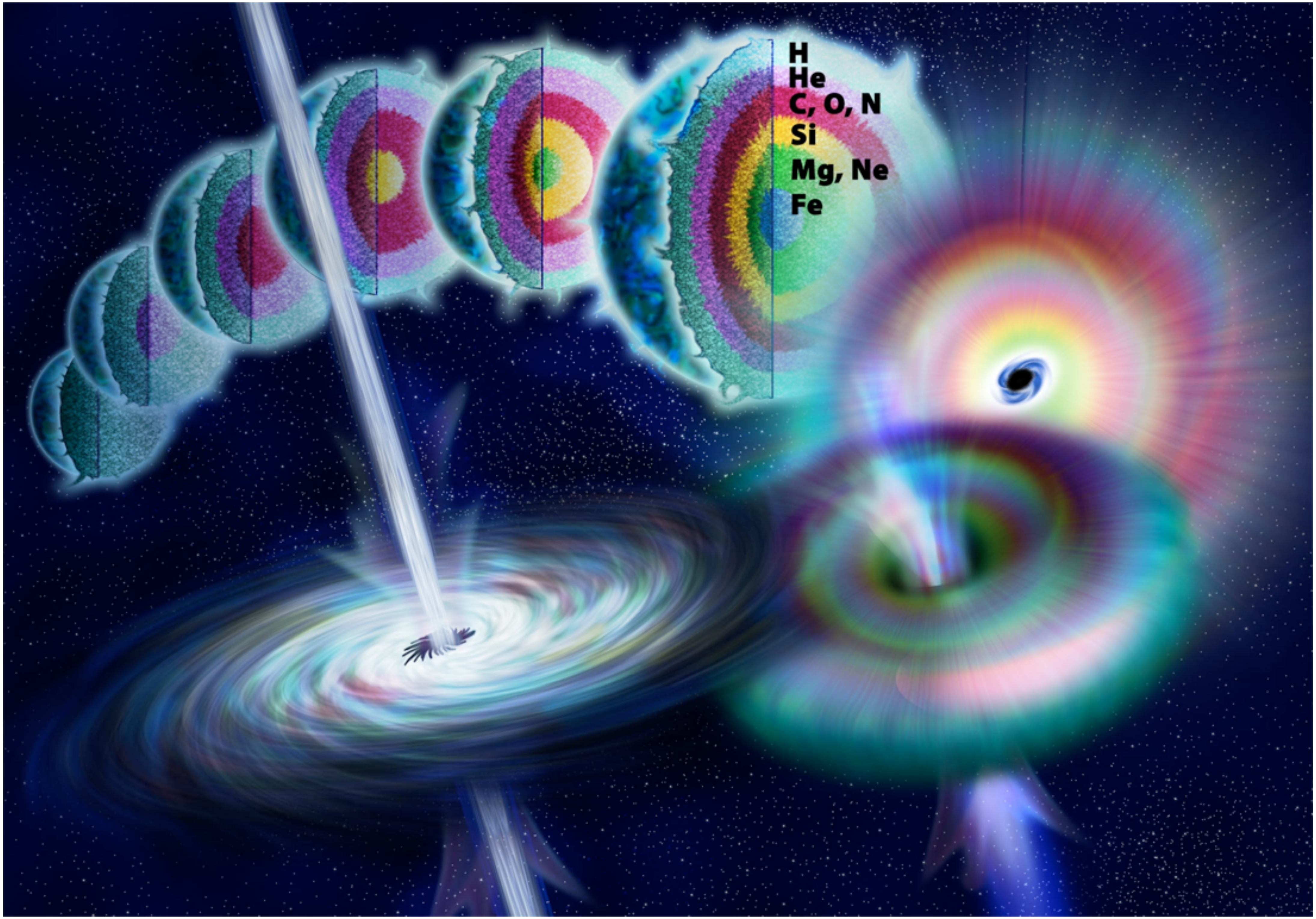


Active Galactic Nuclei

- Plasma jet with internal shocks
- Terminal shock of jet in intergalactic medium



Gamma Ray Bursts



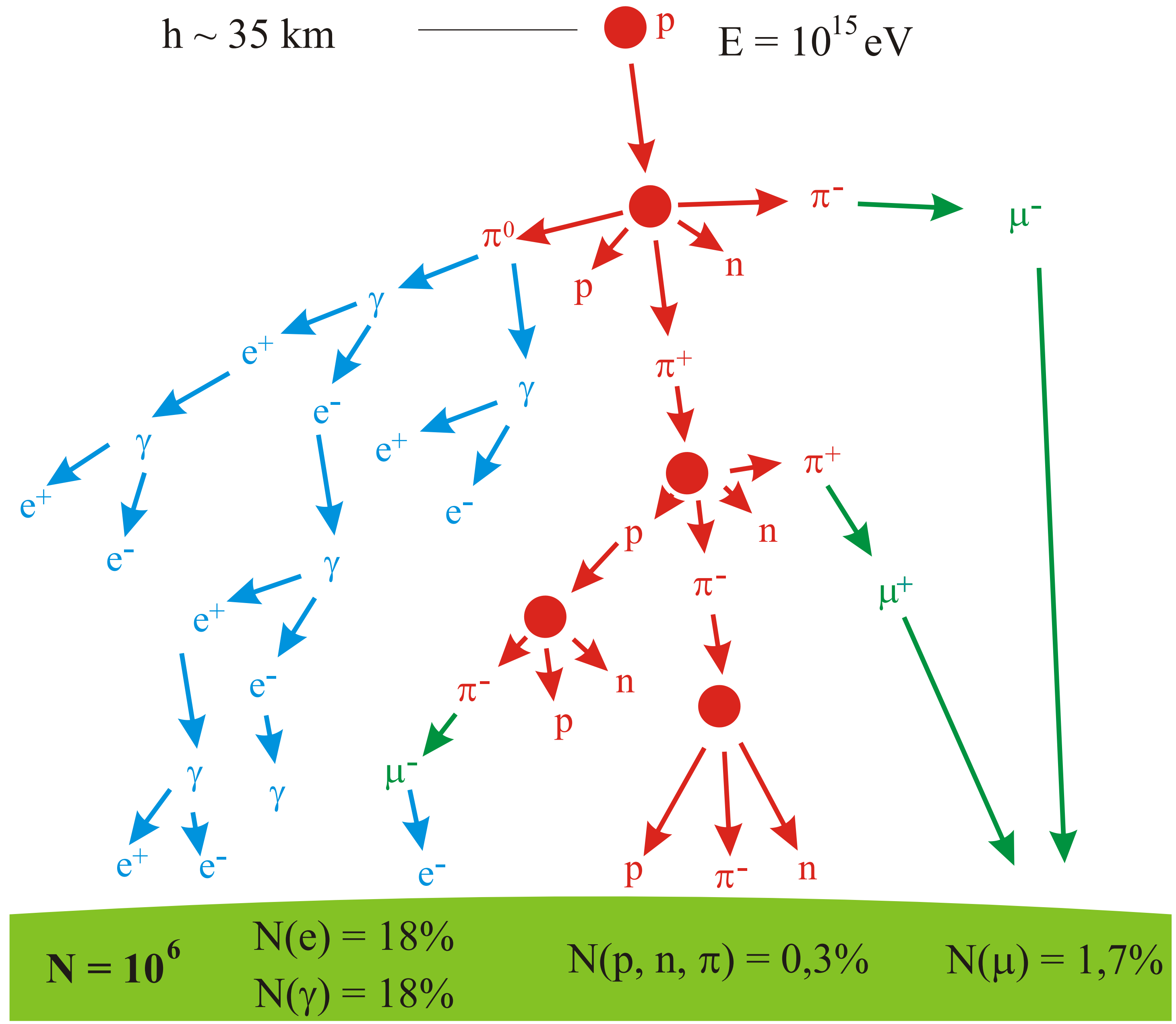
- Hypernovae
- Collision of neutron stars

Extended Air Showers

Extended Air Shower schematic

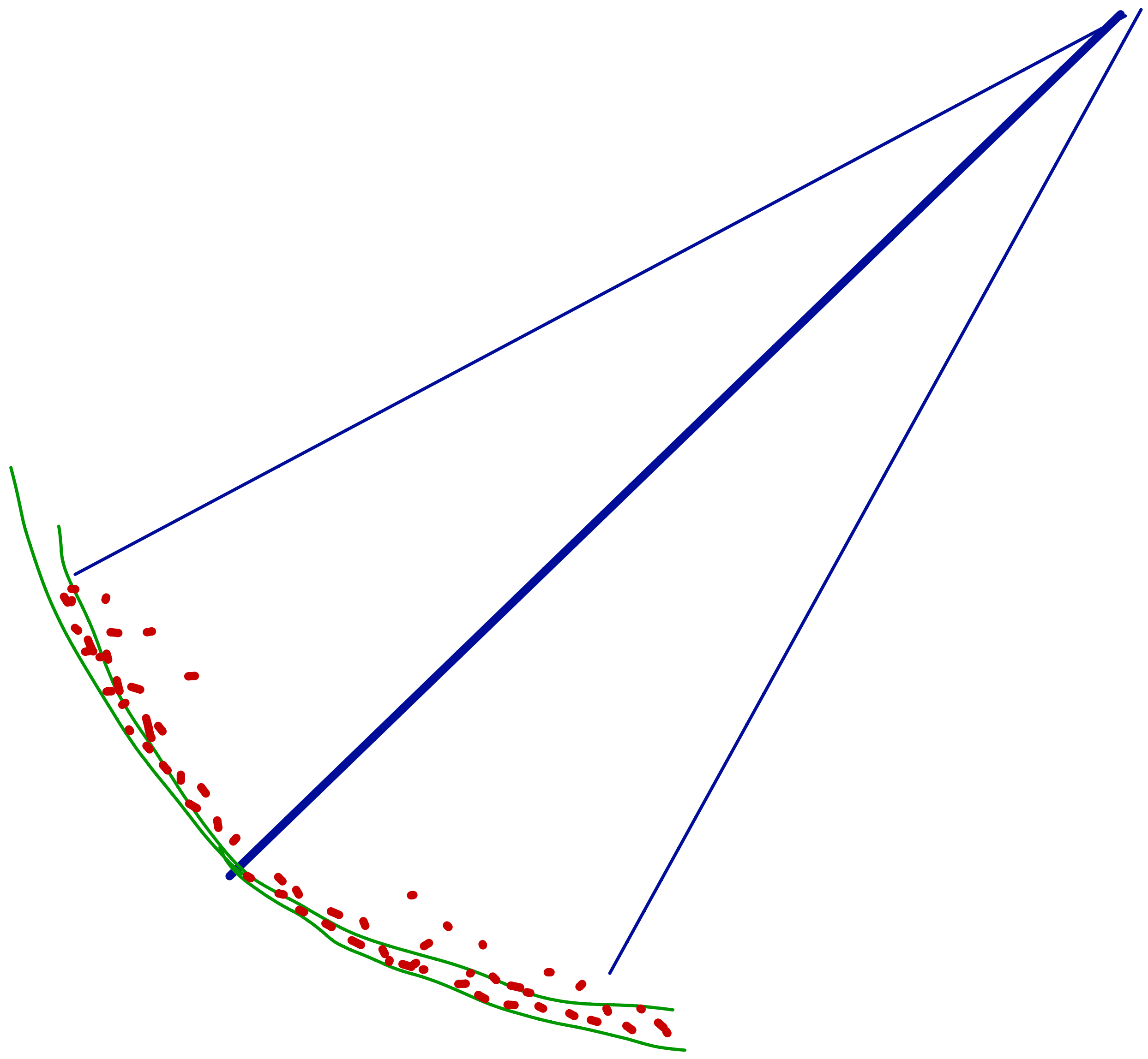
- Particle cascades in the atmosphere
  - Hadrons
  - Electro-magnetic EM: e^+, e^-, γ
  - Muons
    - Decays of $\pi^\pm$
  - neutrinos
    - invisible

- EM cascades without hadronic core



Air shower snapshot

- Shower front travels at the speed of light
- Curved because of distance to first interaction
- Delayed particles because of
  - Speed less than c
  - Geometry of path



A hadronic air shower in numbers

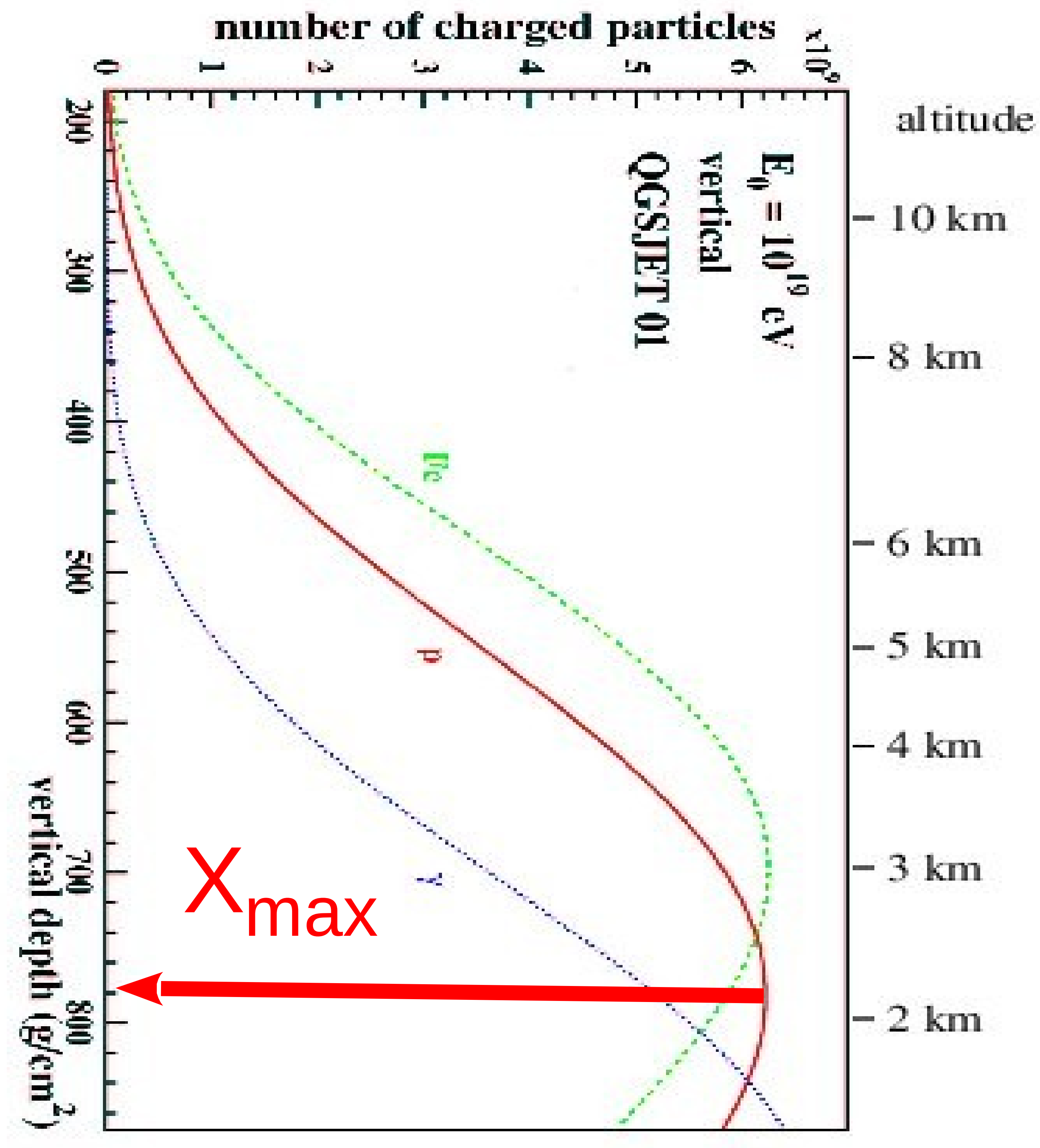
- Particles at the shower
  - 99.88% EM
  - 0.1% muons
  - 0.02% hadrons
- Energy
  - from 100% in hadrons
  - to 90% EM + 10% muons
- Converts energy to particles
  - We see $E=mc^2$ in action
  - Count particles to determine energy of primary

Observable: longitudinal development

- Number of particles as function of depth

  $X = \int_h^\infty dz \rho(z)$ $[g/cm^2]$

- Extract
  - depth of maximum X_{max}
  - Fluctuations $\langle X_{max} \rangle$

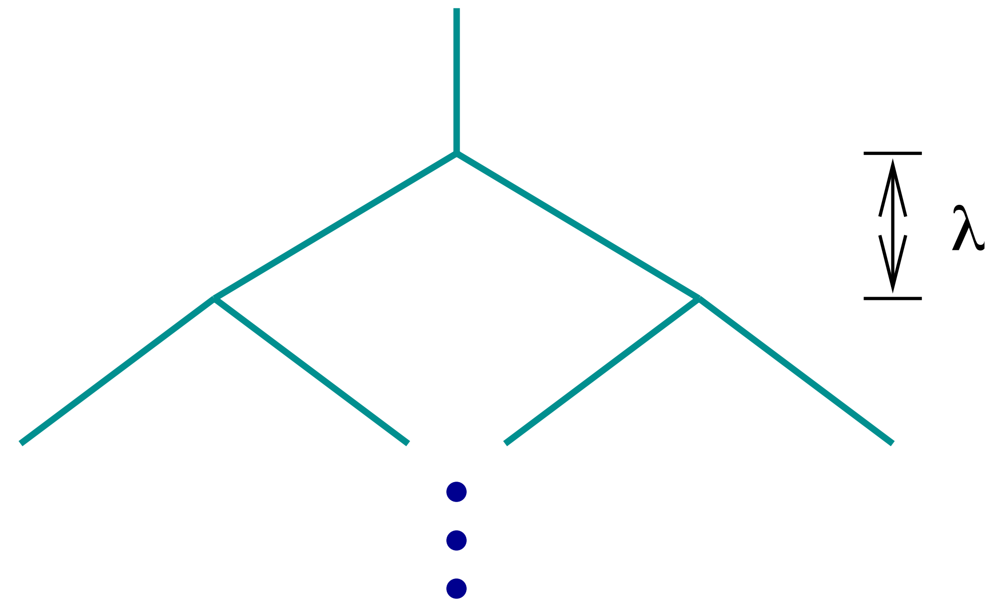


Electro-magnetic Heitler model

- In each interaction: particle generates 2
  - γ: pair production
  - e±: γ emission in bremsstrahlung
- Interaction length: λ
  - particle type
- Terminates when:

$$E(X) = E_c$$

- Attenuation for $E > E_c$



$$N(X) = 2^{X/\lambda}$$

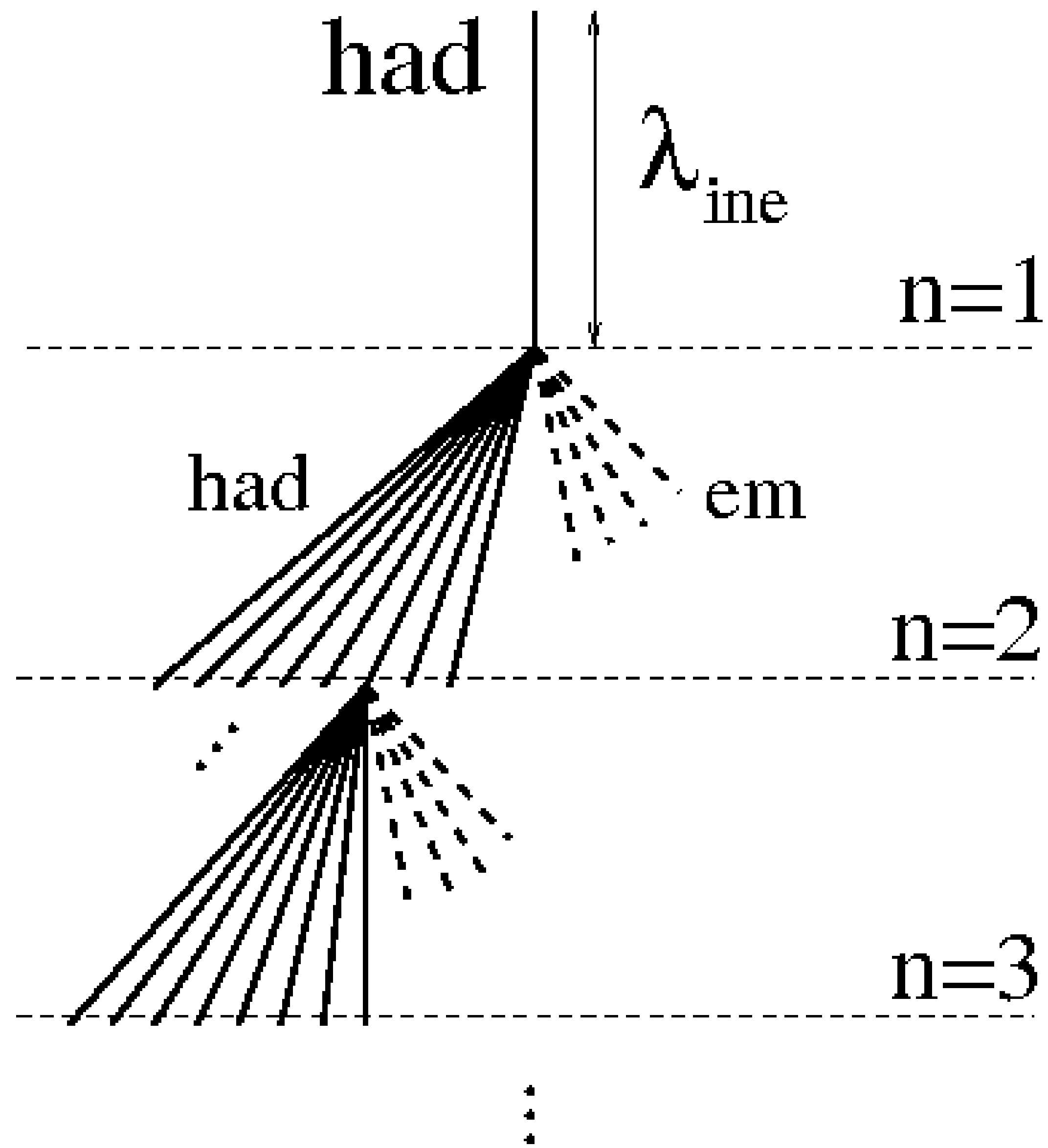
$$E(X) = E_0/N(X)$$

$$N(X_{max}) = E_0/E$$

$$X_{max} = \lambda \frac{\log(E_0/E)}{\log 2}$$

Extended Heitler model (J. Matthews)

- Hadronic primary
  - Fixed interaction length
  - Uniform energy re-distribution
  - Particle types:
    - hadrons
      including decay into muons
      when reaching E_{dec} ($\pi^{\pm}$)
    - Electro-magnetic
      (π^{0} decay)



$$N(n) = N_{had}^{n} \qquad E(n) = E_0 / N_{tot}^{n}$$

$$E_{dec} = E_0 / N_{tot}^{n_{max}} \qquad n_{max} = \frac{\ln(E_0/E_{dec})}{\ln(N_{tot})}$$

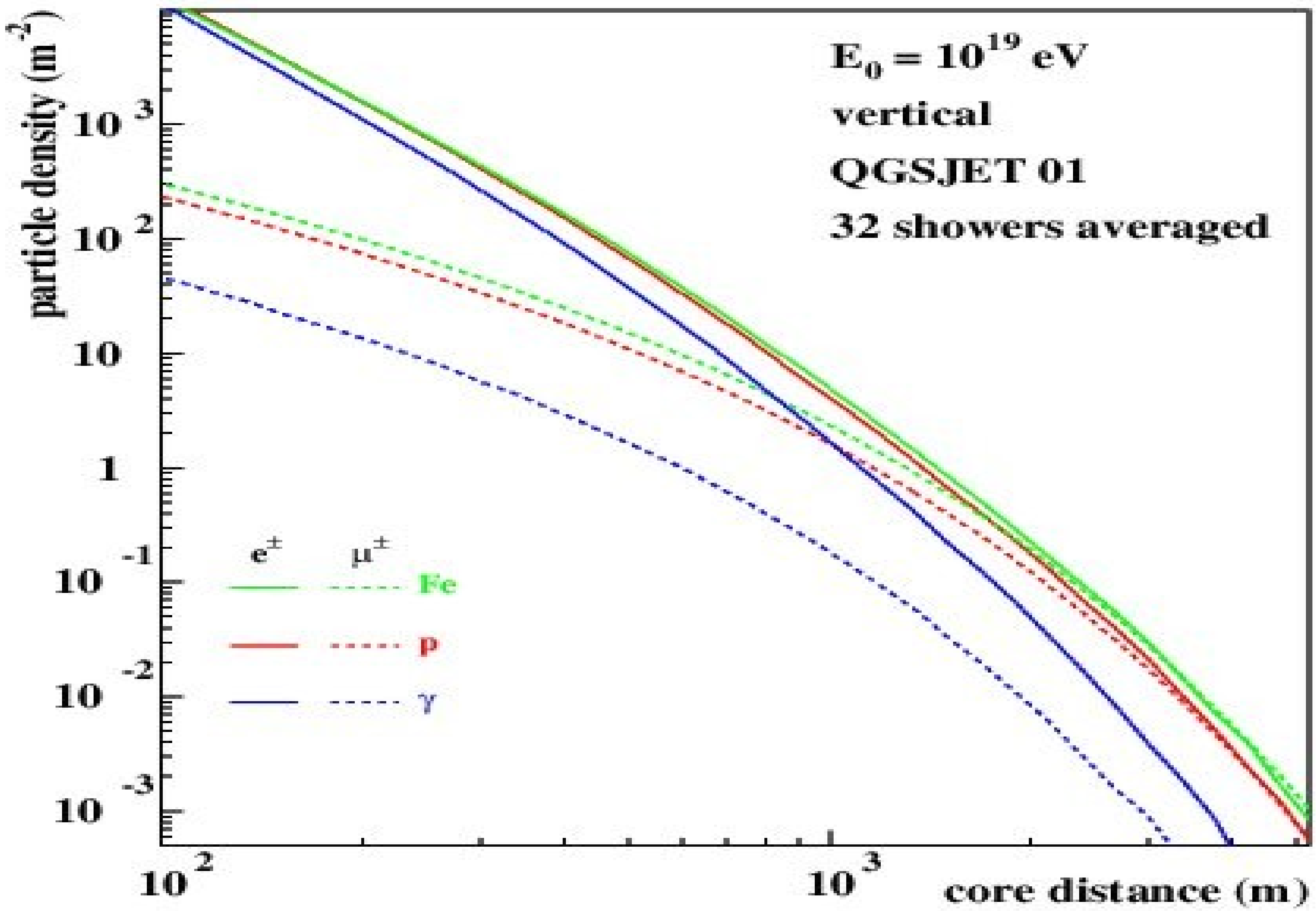
$$\ln(N_\mu) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

$$N_{tot} = N_{had} + N_{em}$$

$N_{tot} = 2$ for original Heitler model

doi.org/10.1016/j.astropartphys.2004.09.003

Observable: Lateral Distribution (LDF)



- Number of particles as function of distance from core

Superposition model

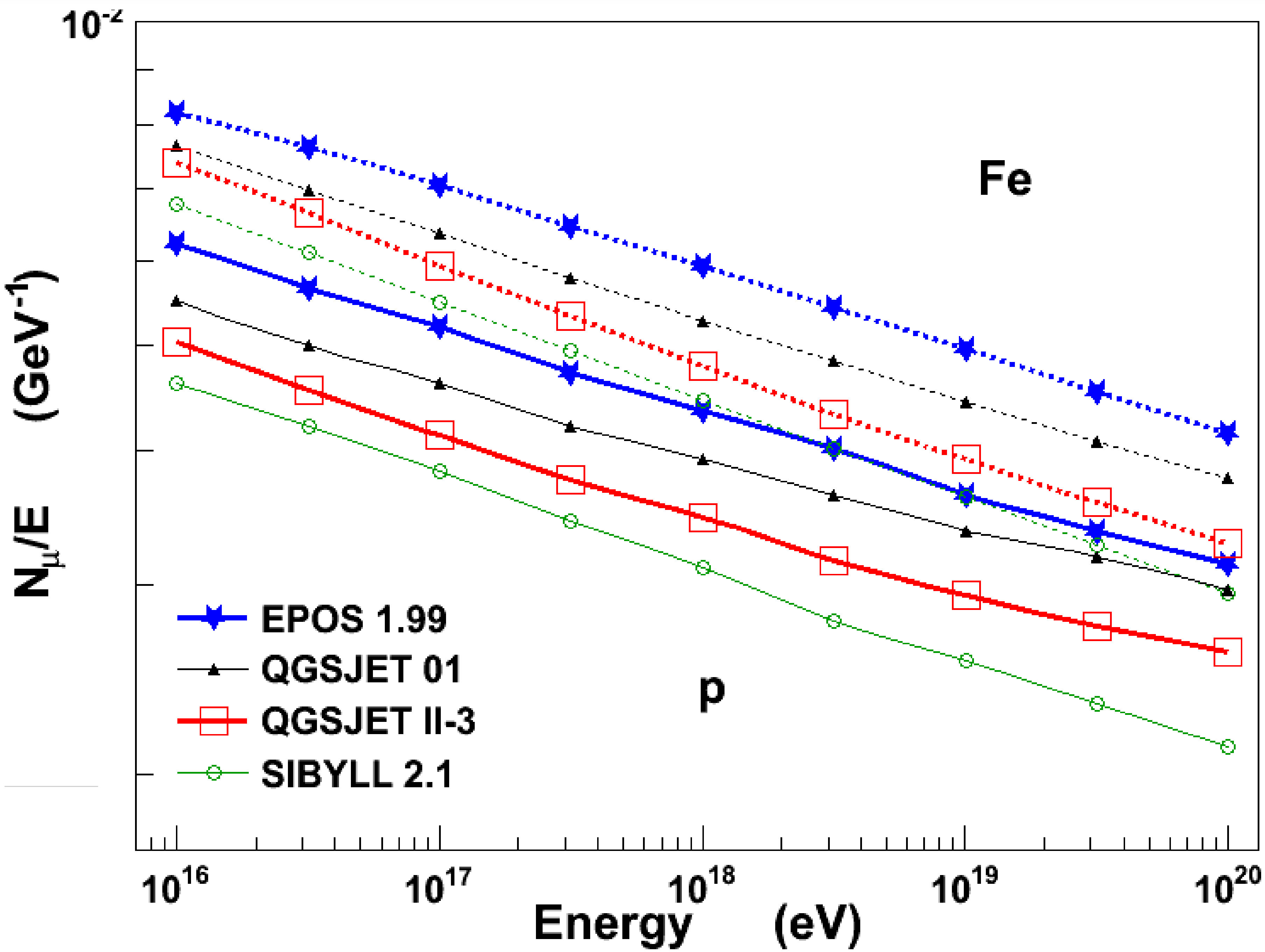
- Primary with mass A and energy E: equivalent to A proton showers with energy E/A

$$N_\mu(A) = A\left(\frac{E_0/A}{E_{dec}}\right)^\alpha \qquad \alpha \approx 0.925$$

- Nuclei generate more muons than pure protons

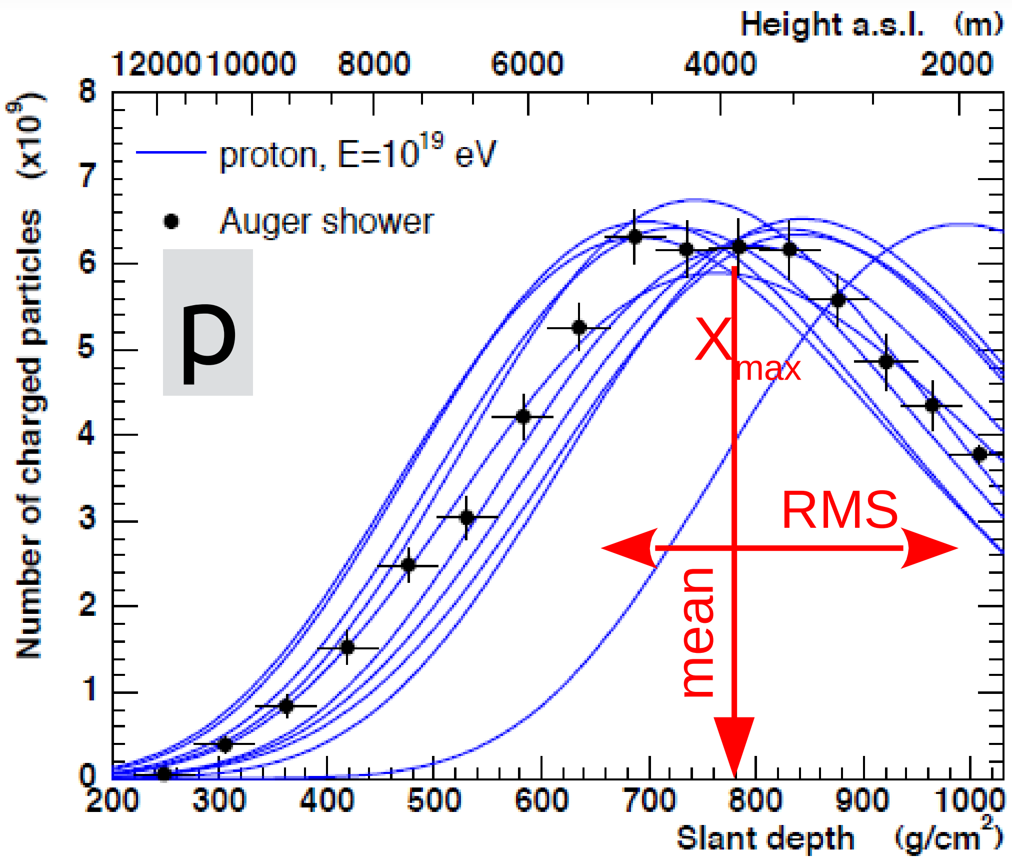
$$\boxed{N_\mu(A) = N_\mu(p)A^{1-\alpha}}$$

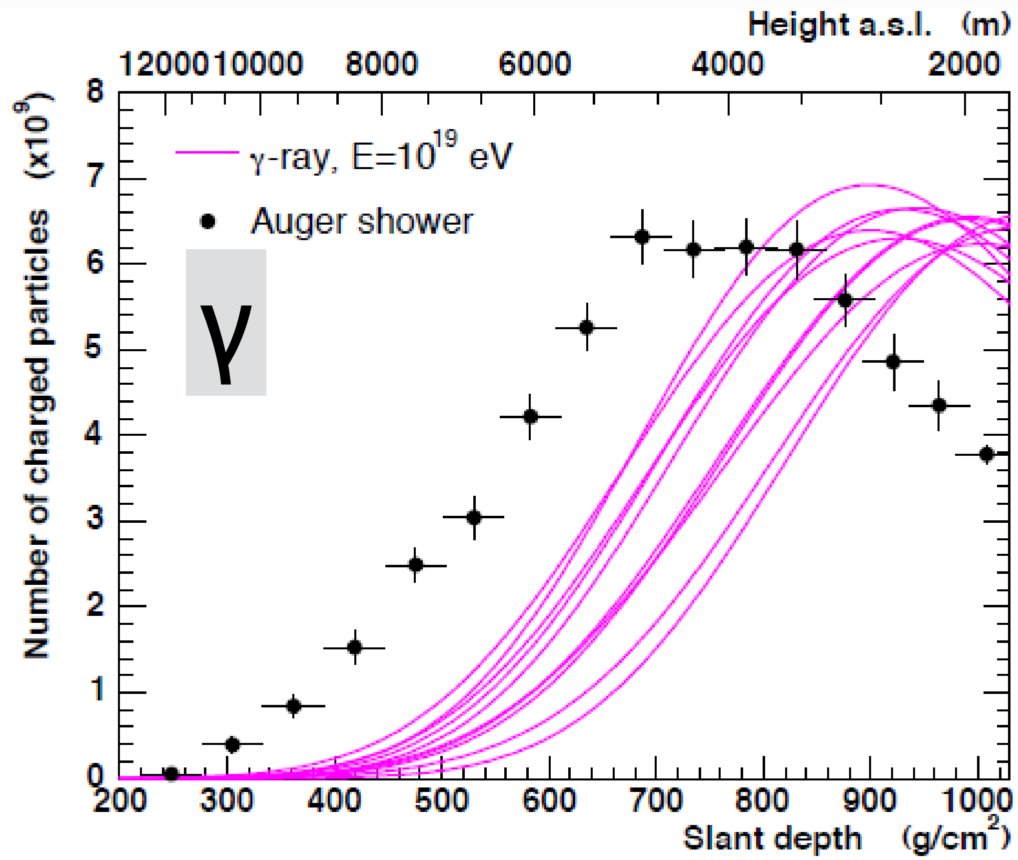
Number of muons in simulations



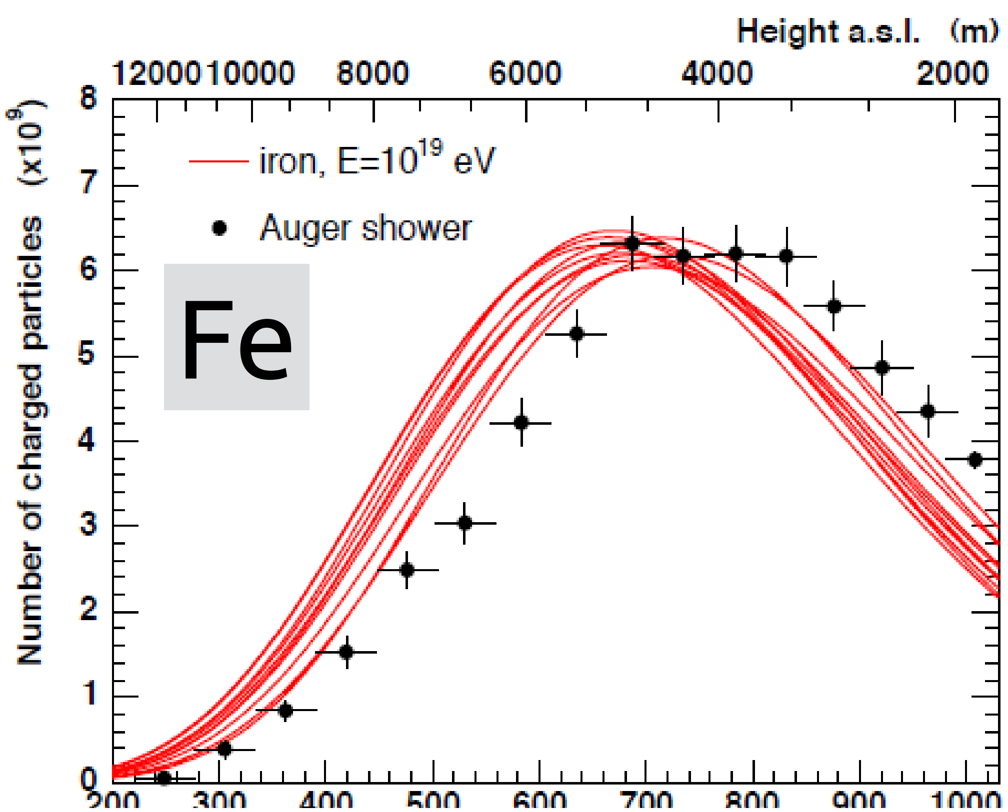
- Number of muons goes down with E:
  $\pi^\pm$ interact before decaying
- Fe produces more muons than p
- Differences between models: systematics in simulations

Longitudinal development





Example: event measured by Auger Collab. (ICRC 2003)



- Mean and fluctuations of X_{max} are important observables

Gold standard for simulations: CORSIKA

https://www.iap.kit.edu/corsika/

- Universally used
  - Replaced private codes used in collaborations
  - Comparison of results simplified
- Different interaction models
- Atmospheric profile configurable

- CONEX: semi-analytic code
  - MC for first interactions: fluctuations
  - analytic cascade equations (1d, 3d)
  - MC close to ground
  - Faster than full simulations
  - Lateral distribution complicated
- CORSIKA 8 under development
  re-write in C++

Interaction models in CORSIKA

(HDPM)

Old generation : SIBYLL 2.1 (QGSJET01 DPMJET 2.55 VENUS) (<2001)

All Glauber based

Engel et al.

But differences in hard, remnants, diffraction …

semi-hard

soft

NEXUS 3.97

Attempt to get everything described in a consistent way (energy sharing)

New generation : (QGSJET II-03)(DPMJET III) (EPOS 1.99) (2005-2012)

LHC tuned : QGSJET II-04 EPOS LHC (2013-)

Ostapchenko

Pierog & Werner

LHC inspired : SIBYLL 2.3 QGSJET III EPOS 3 (2015-)

Motivation :

- **update with latest LHC results in simple model**

Motivation :

- **Hard Pomeron-Pomeron connexion**

Motivation :

- **binary scaling in hard probes**

Interaction models in CORSIKA

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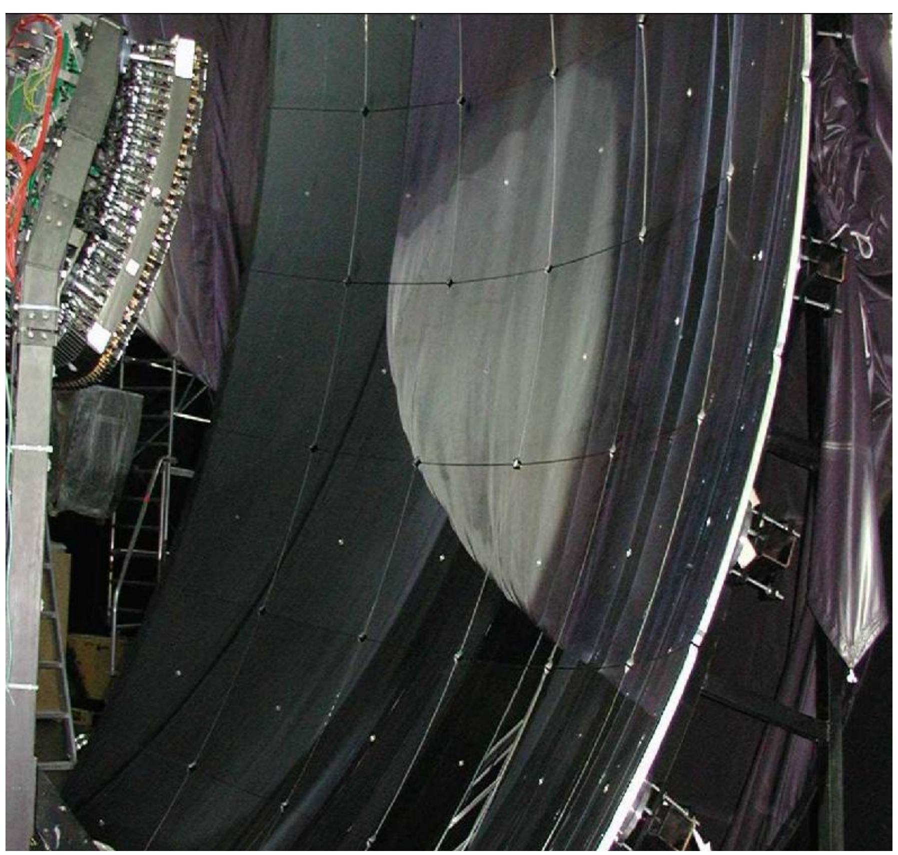
The Observatories

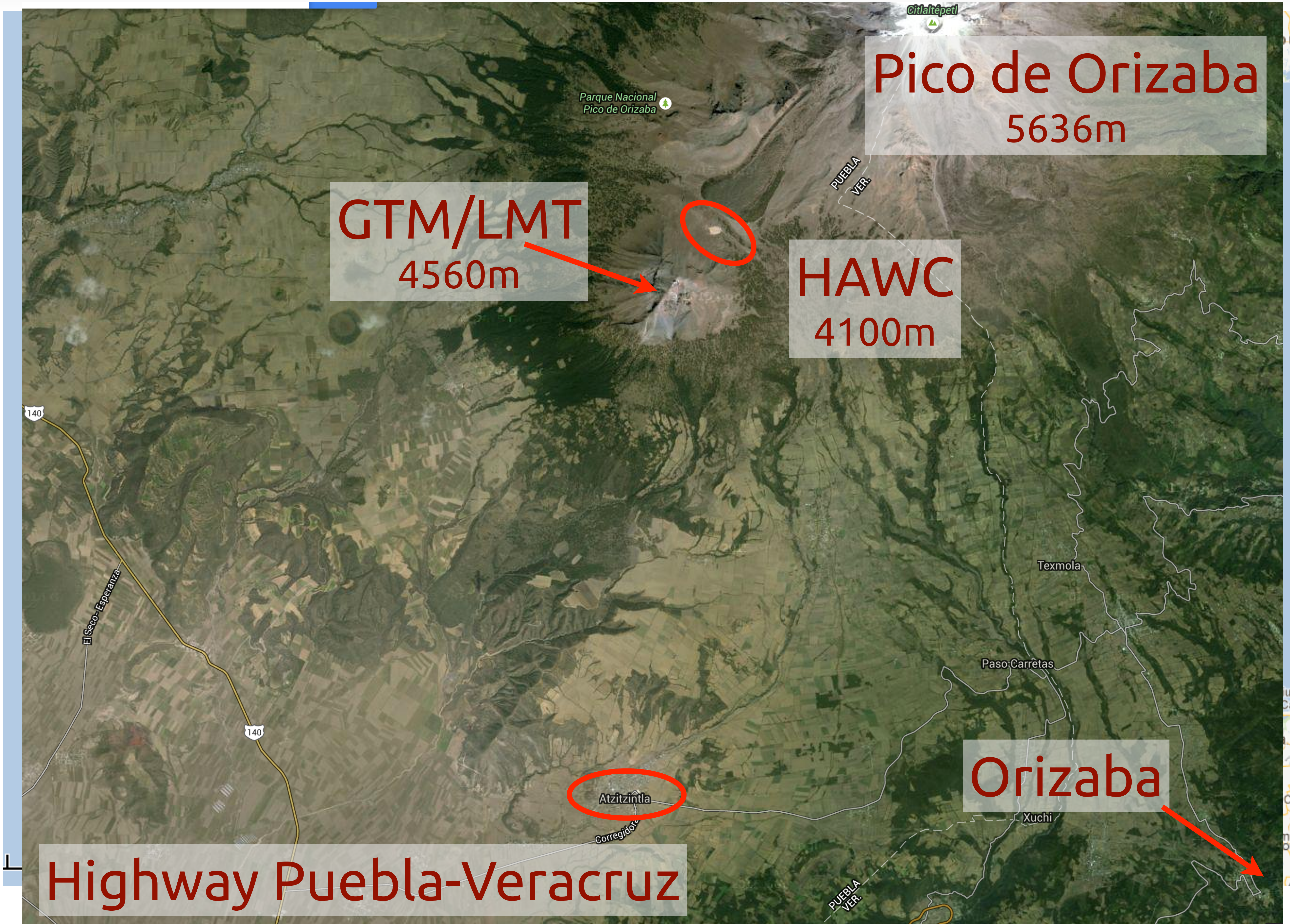
Our instruments at high energies

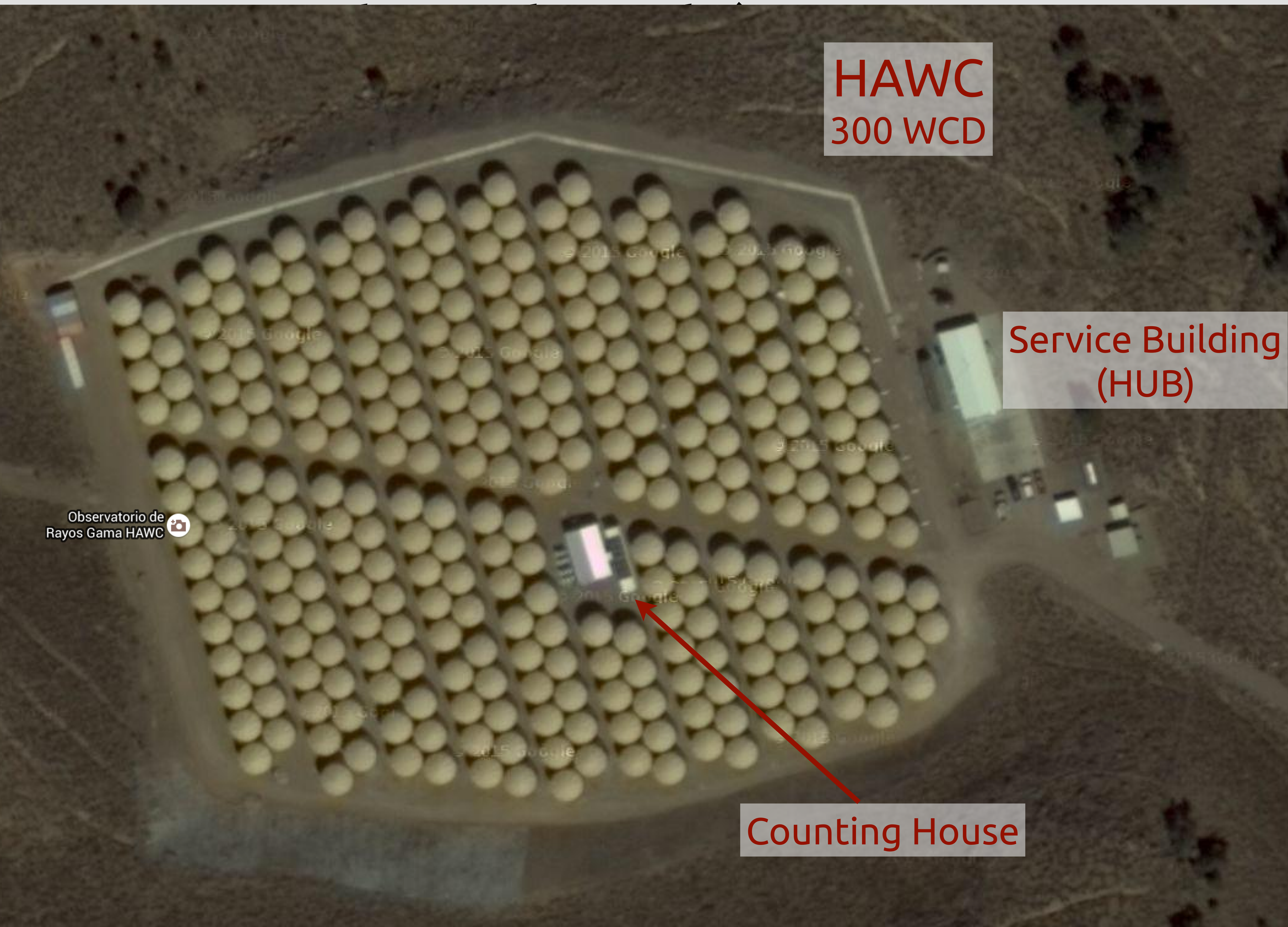


Pierre Auger
Observatory

HAWC located at Volcán Sierra Negra

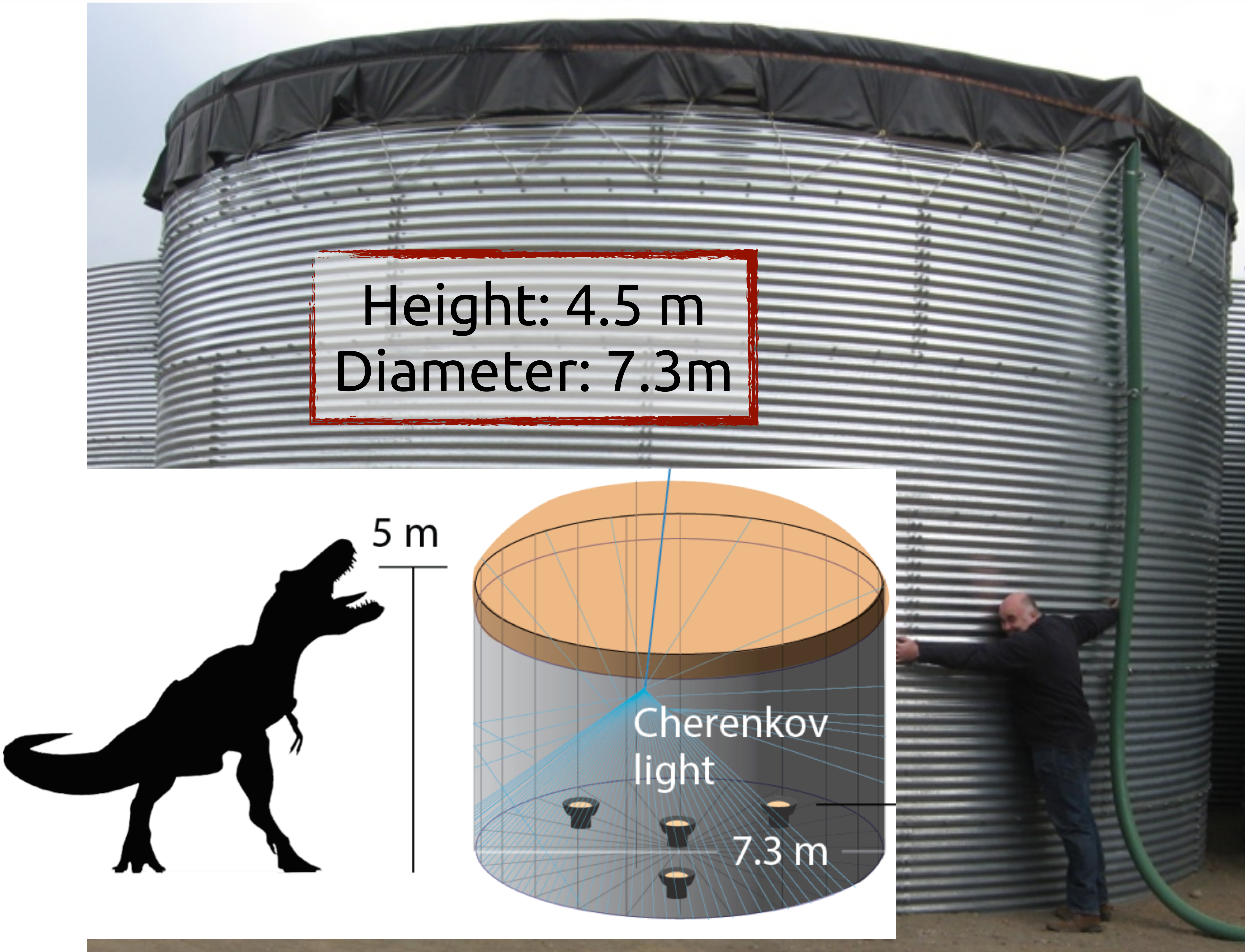
HAWC located at Volcán Sierra Negra



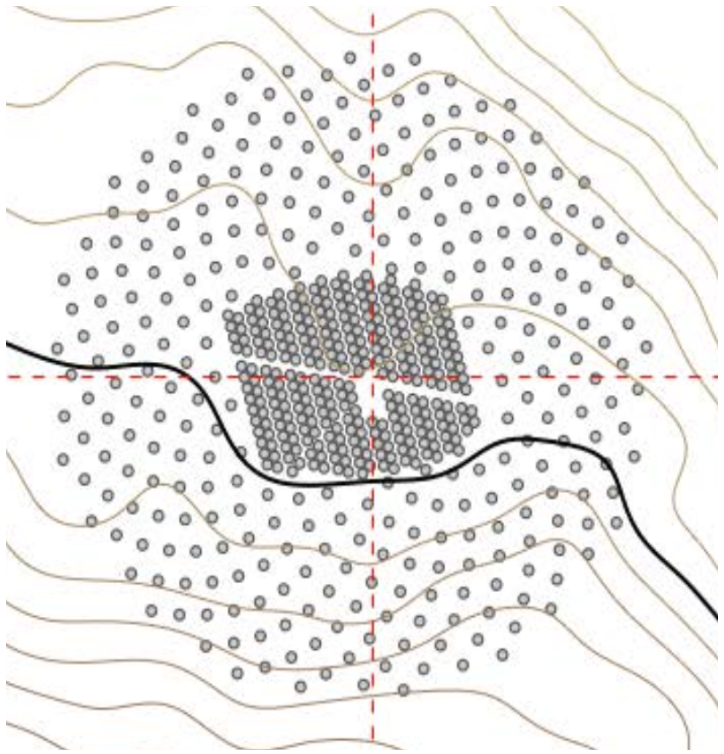

HAWC
300 WCD
Service Building
(HUB)
Observatorio de
Rayos Gama HAWC
Counting House

A big Cherenkov Detector

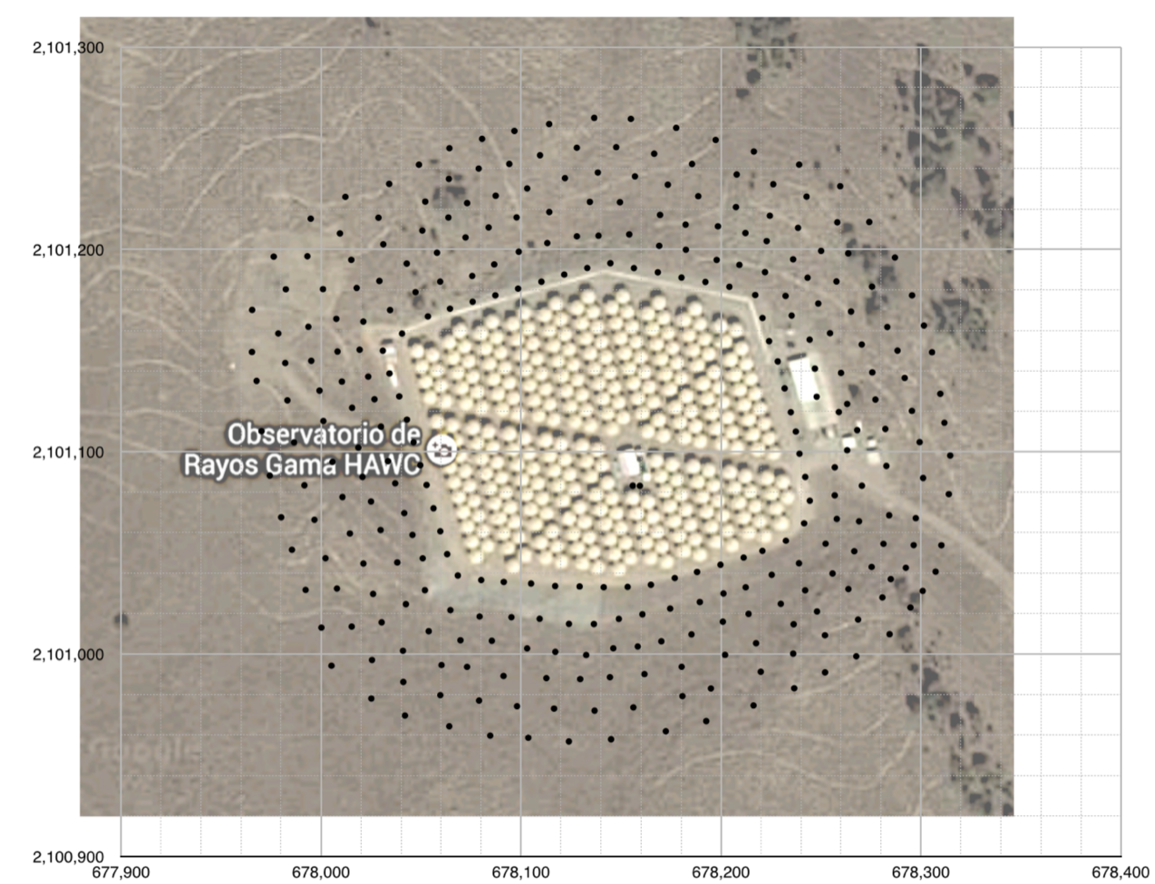
A big Cherenkov Detector



Expansion



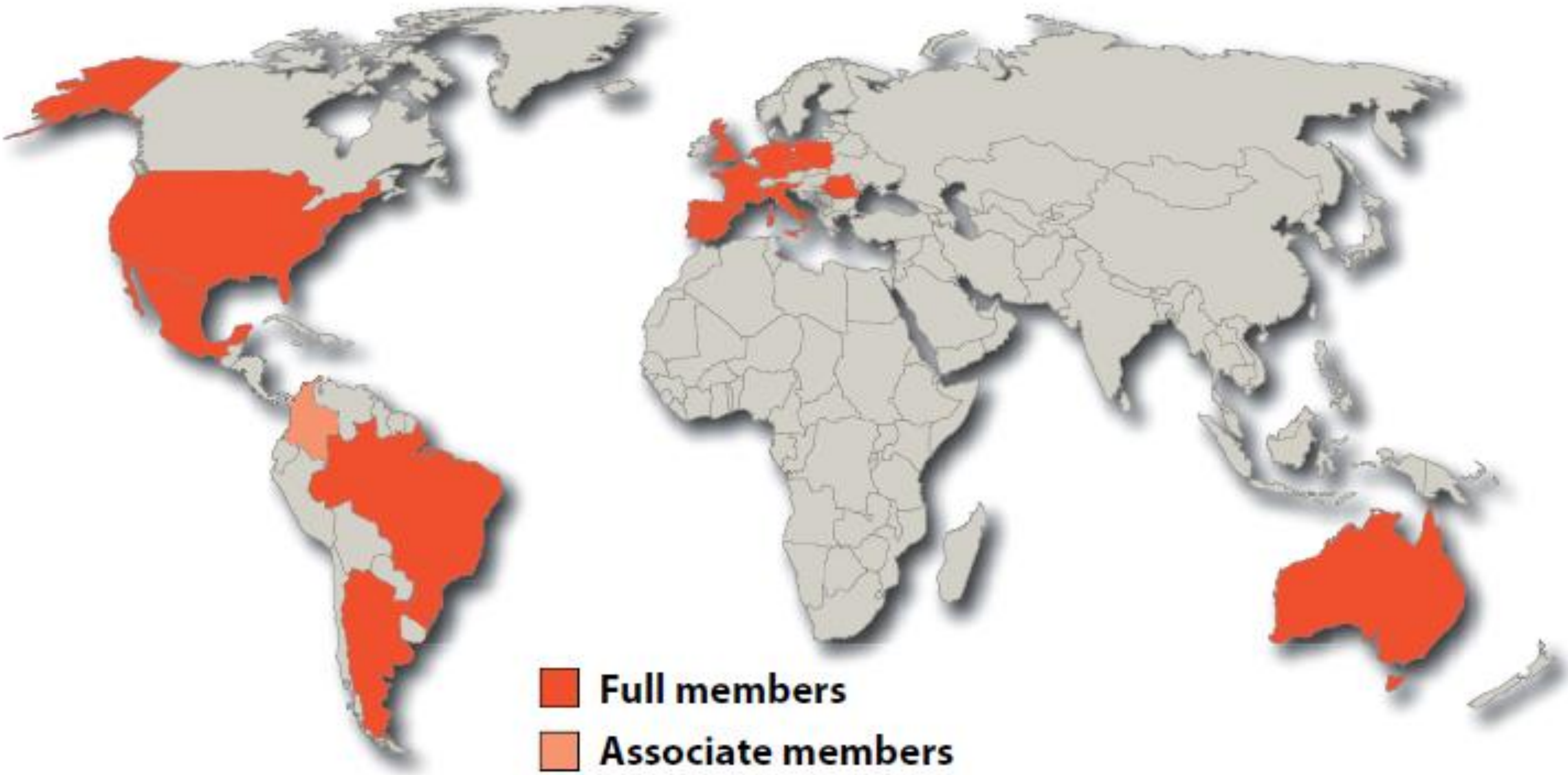
- Additional WCD (outriggers)
  - Smaller size
  - Expand area for high energy observations
  - Increase sensitivity above 10 TeV
- Detector of 2500l



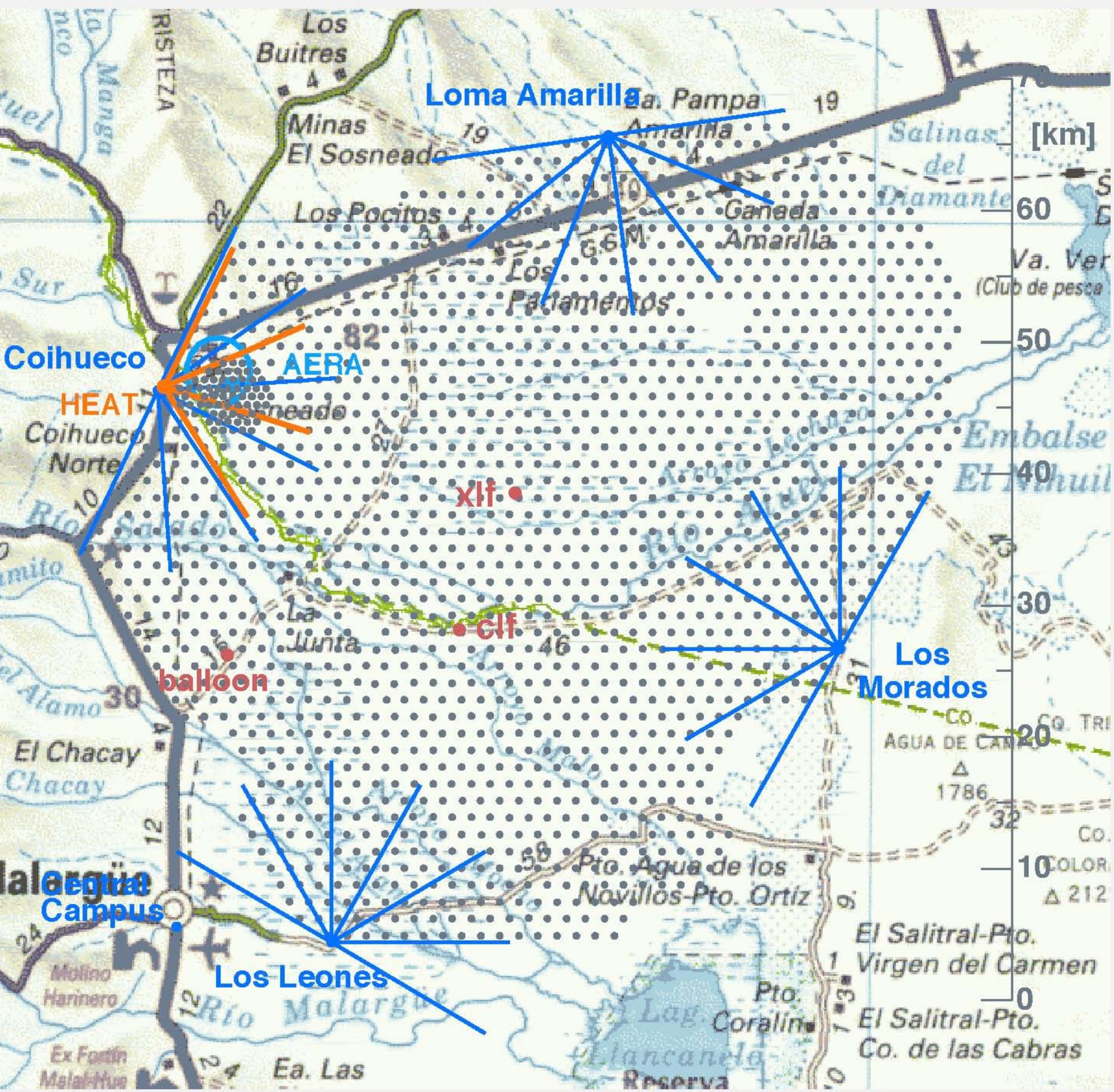
The Pierre Auger Collaboration

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

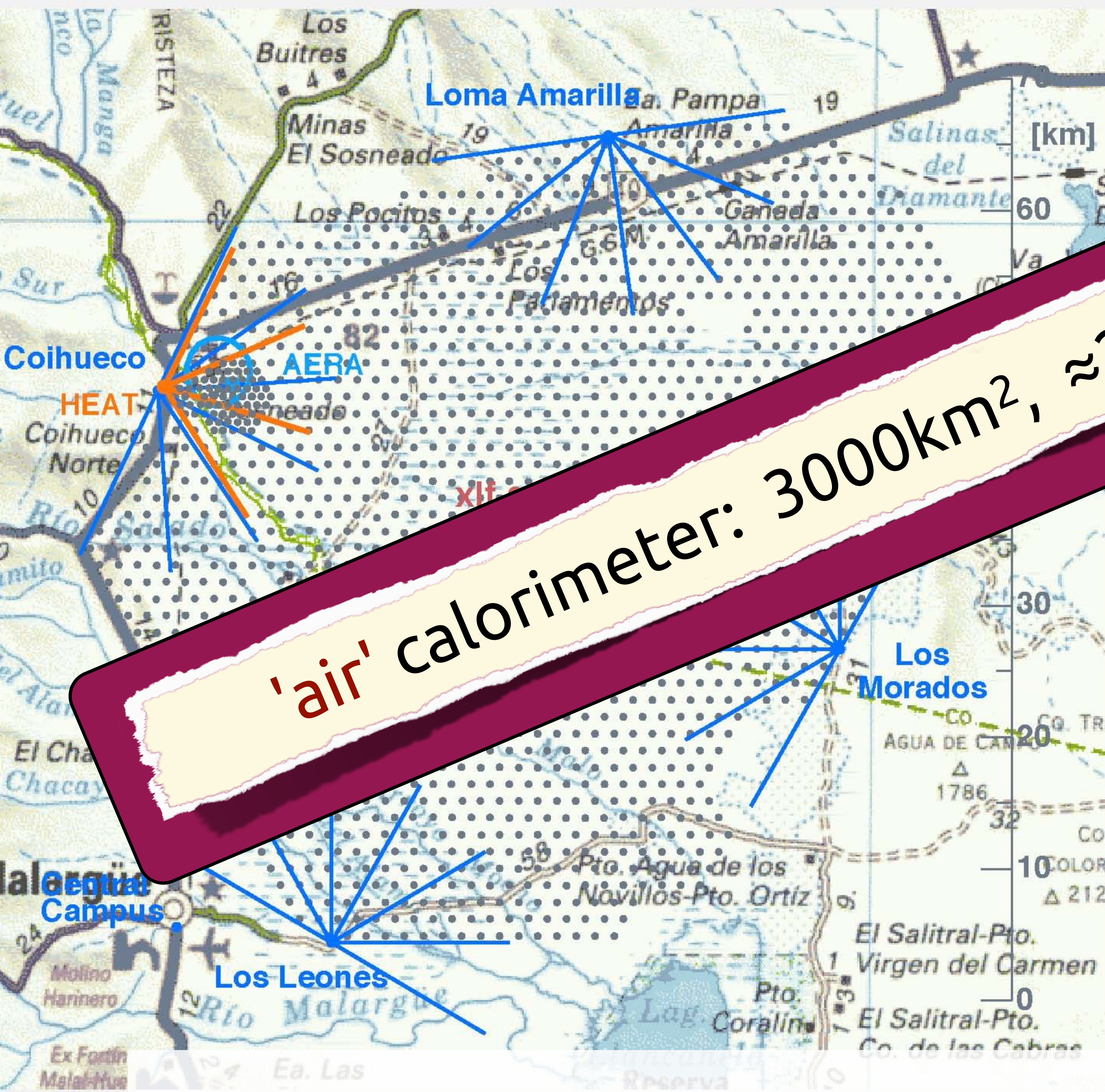
Infill: 750m spacing
+ buried μ detectors

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: 3000km², $\approx 2.5 \cdot 10^{10}$ T

1660 surface detector stations, 1.5 km spacing

Infill: 750m

+ bu

…ector

… telescopes each

- ✱ +3 elevated
- ✱ 27 telescopes in total
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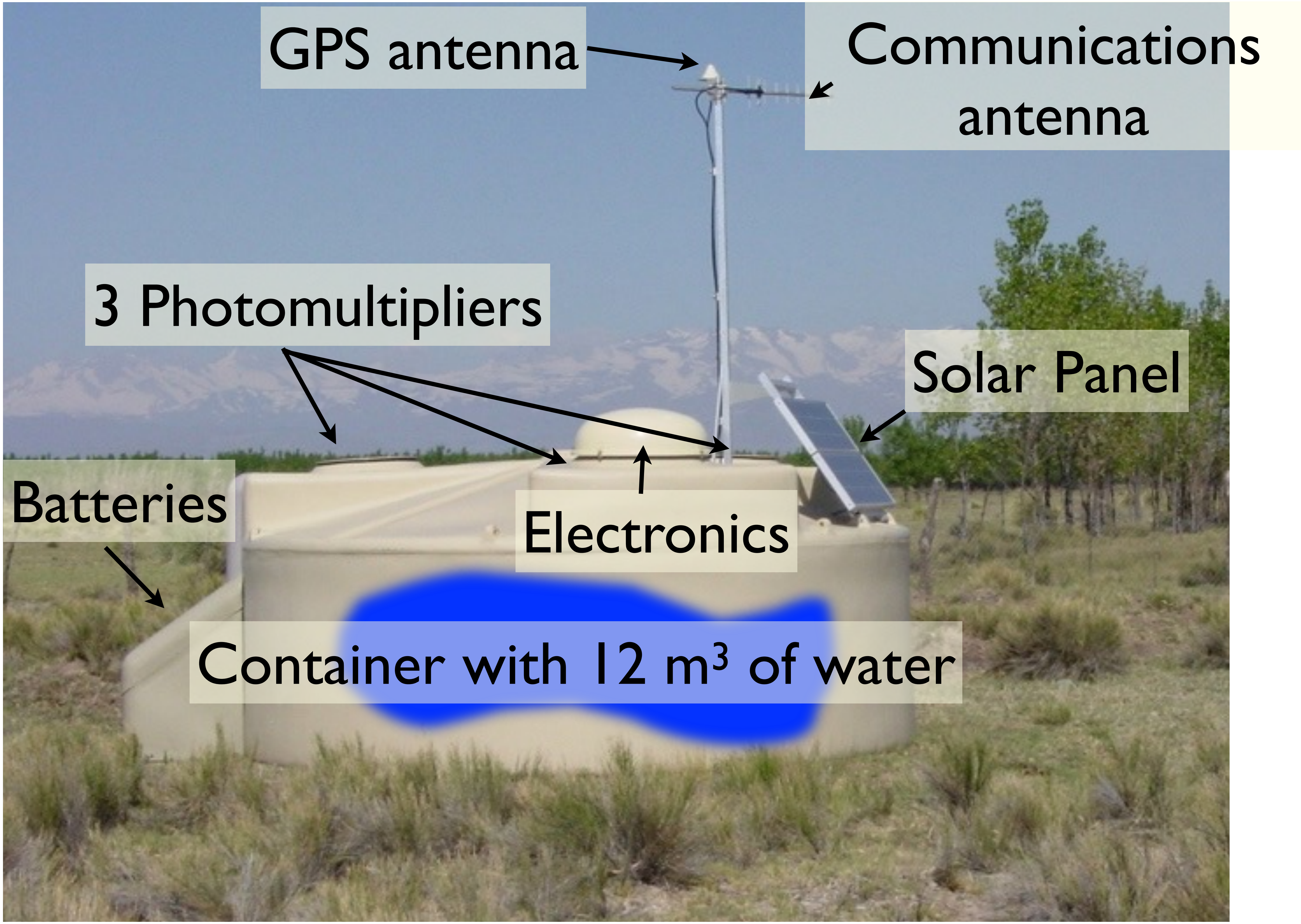
Low Energy Extensions

Radio Detectors

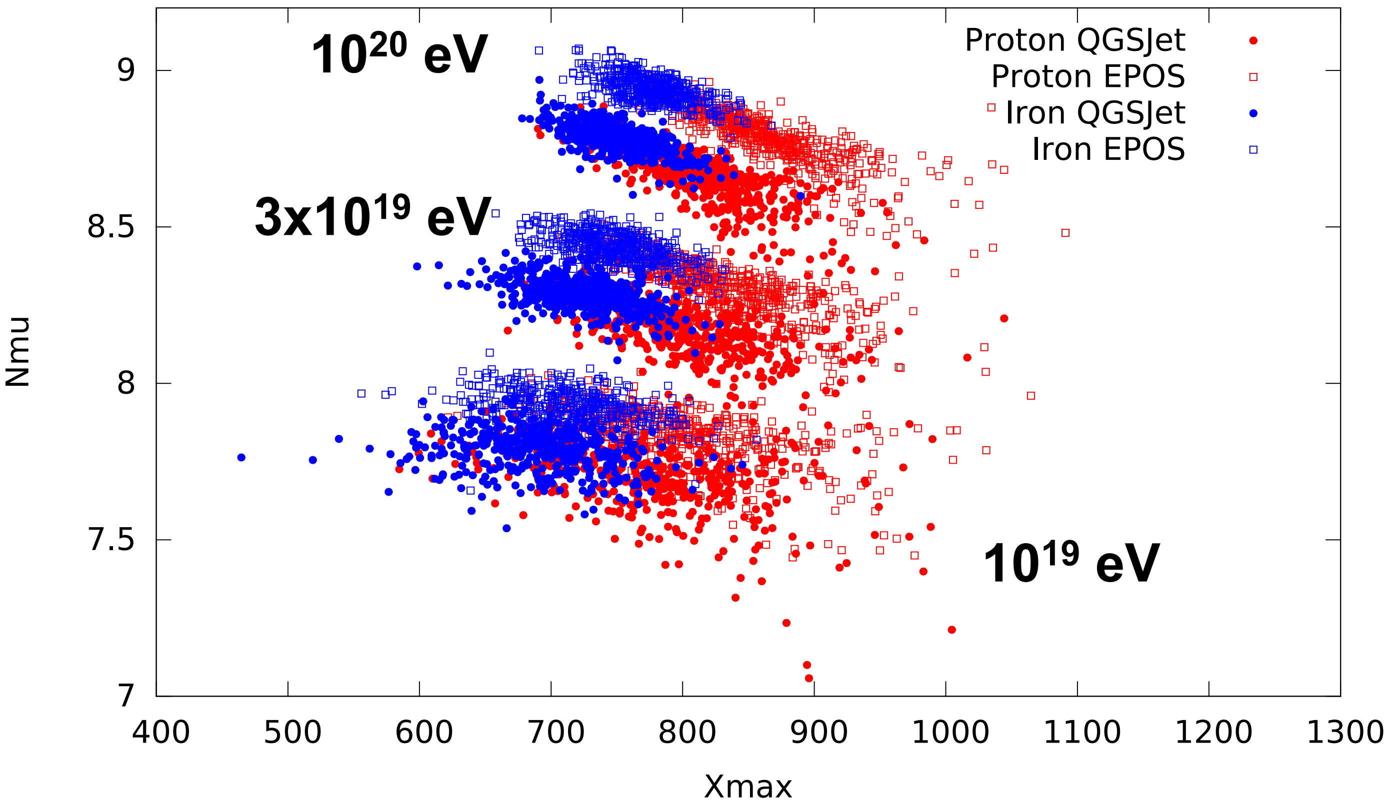
A surface detector station

A surface detector station



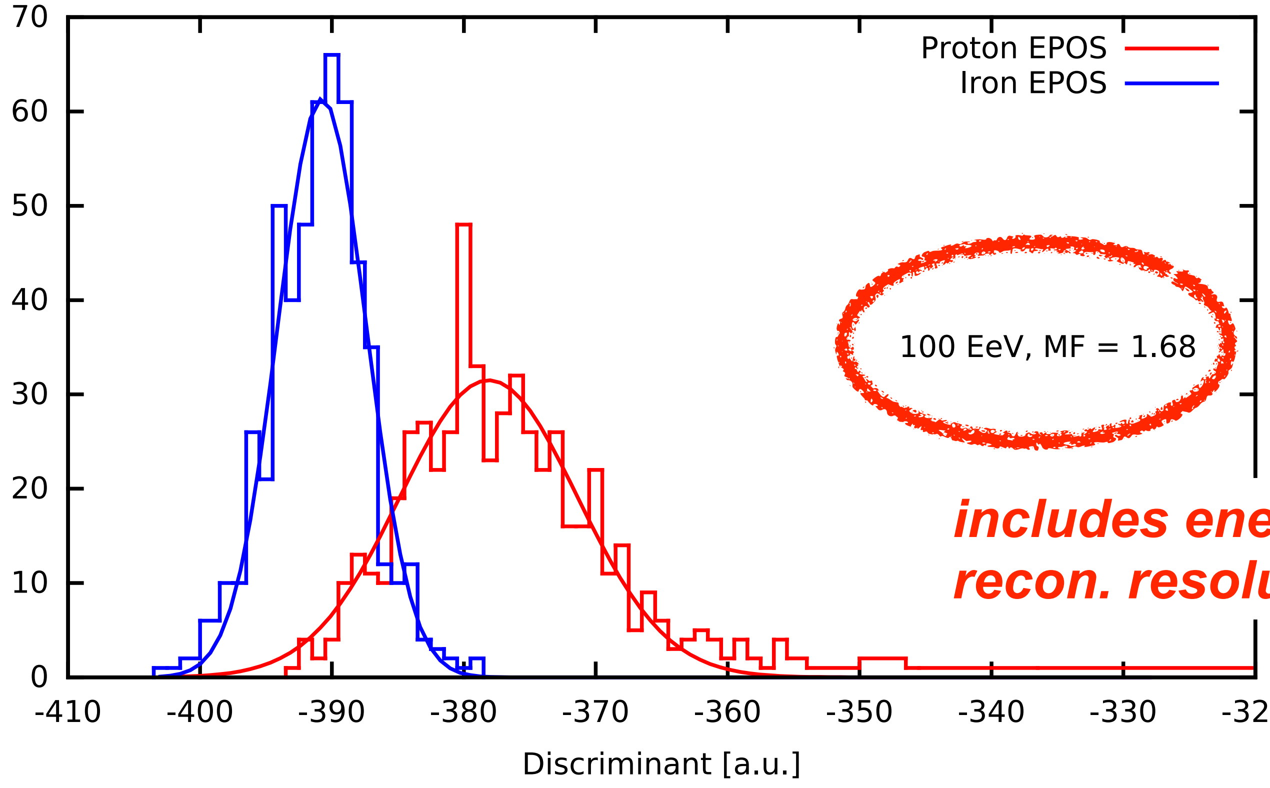
Auger upgrade: scintillators above each detector

Simulated configuration:
2 m² scintillator on top of tank



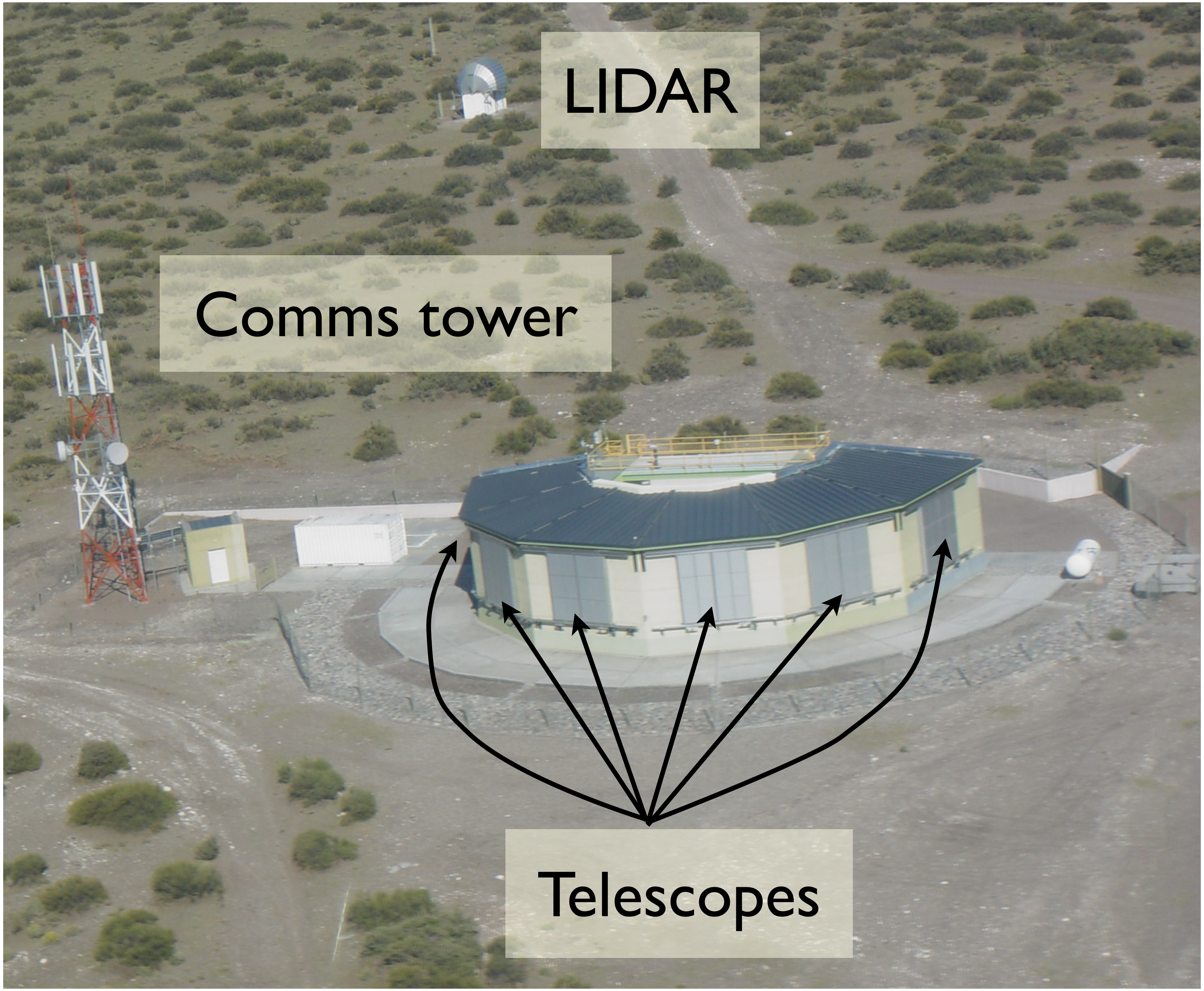
Merit factor
(discrimination power)

$$f_{\mathrm{p,Fe}} = \frac{|\langle S_{\mathrm{Fe}}\rangle - \langle S_{\mathrm{p}}\rangle|}{\sqrt{\sigma^2{}_{\mathrm{Fe}} + \sigma^2{}_{\mathrm{p}}}}$$



includes energy recon. resolution

A Fluorescence Detector Site



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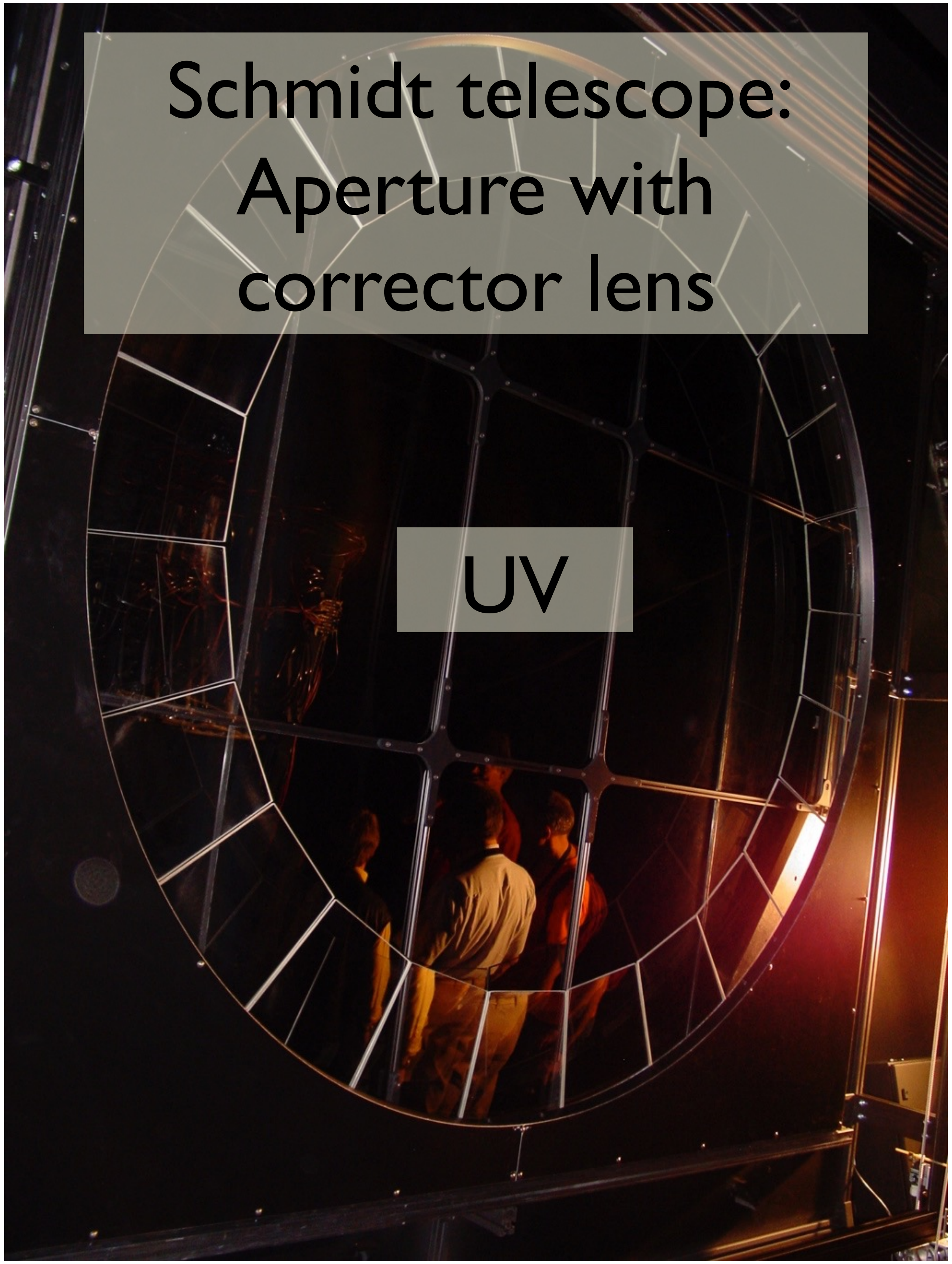

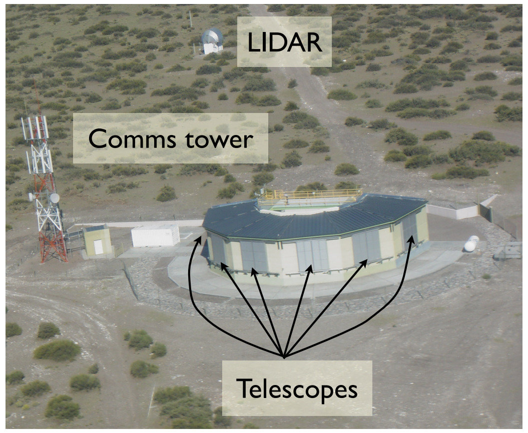

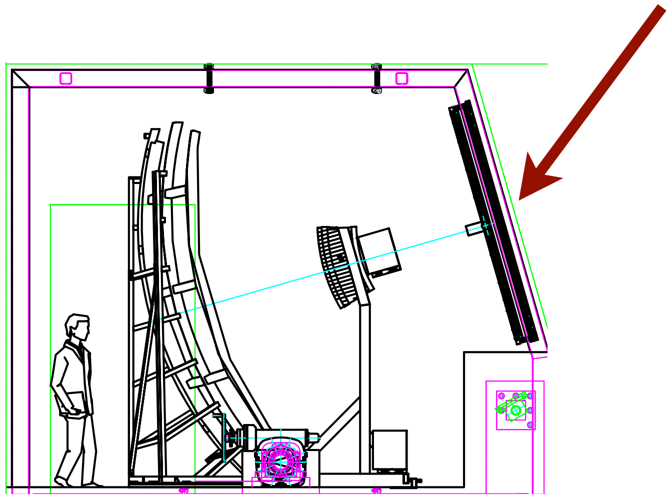

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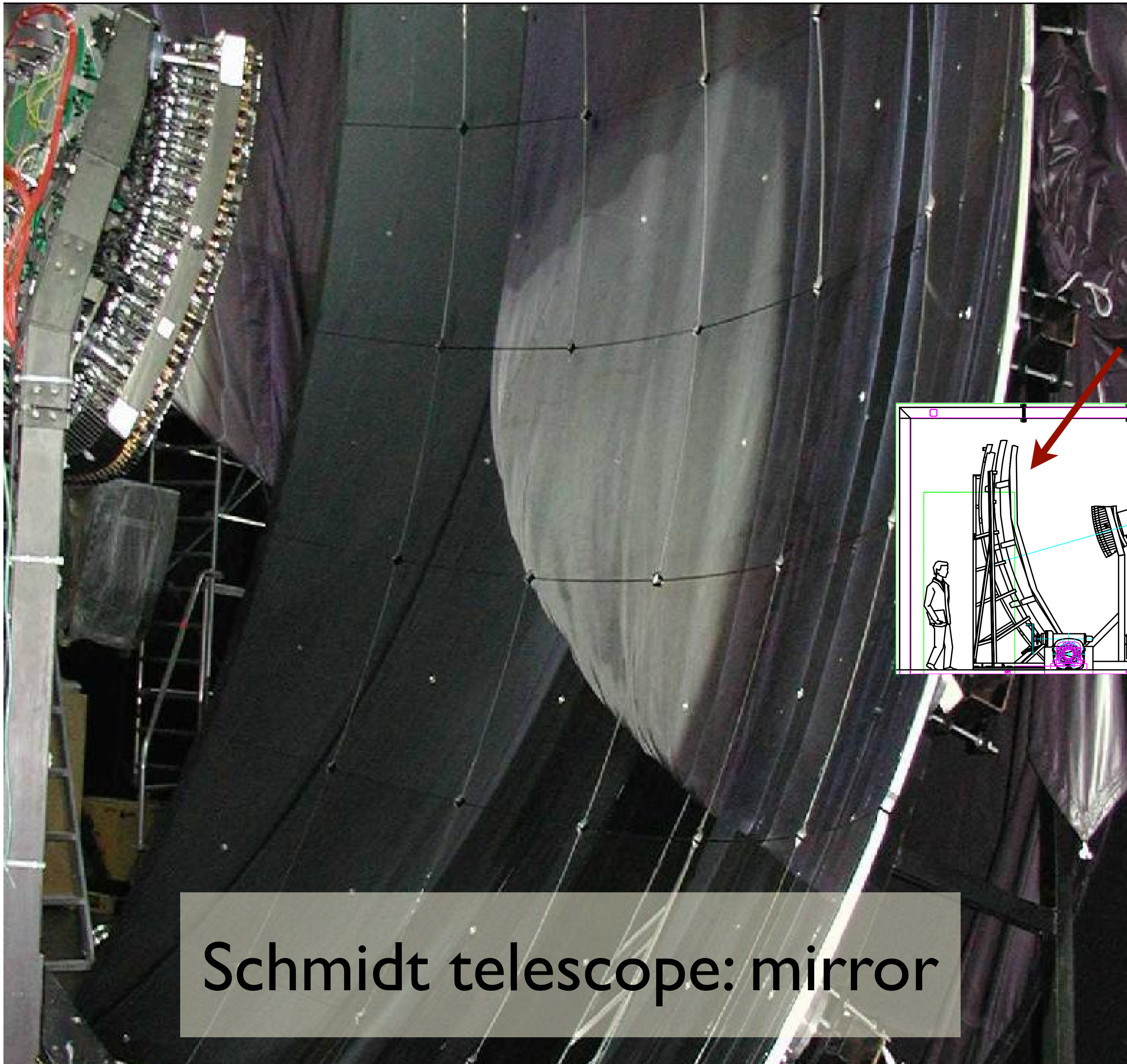

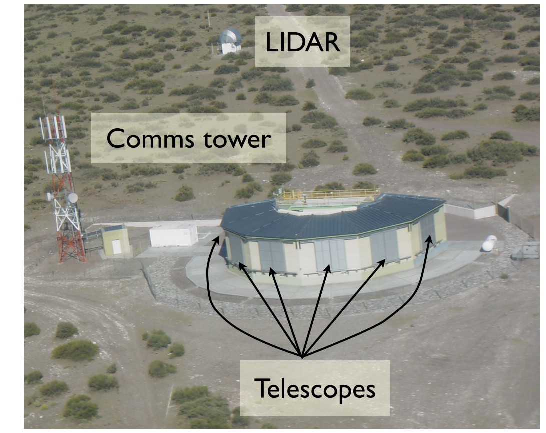

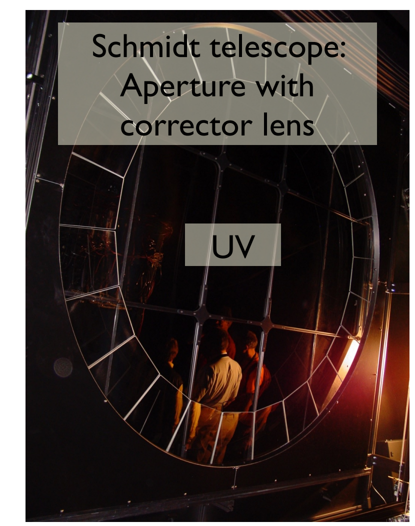

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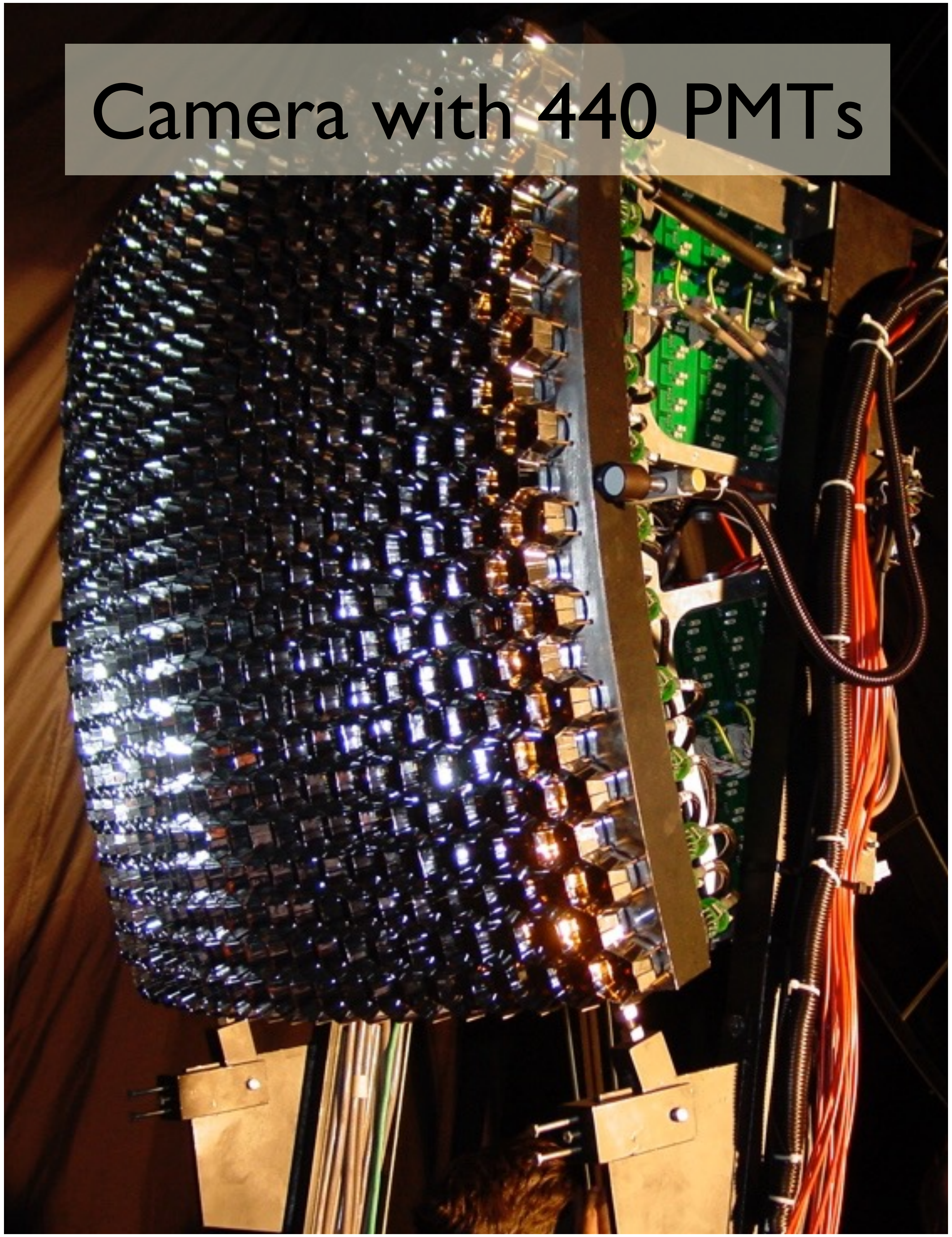
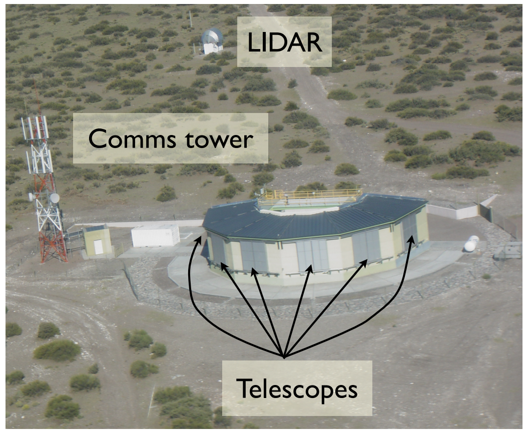
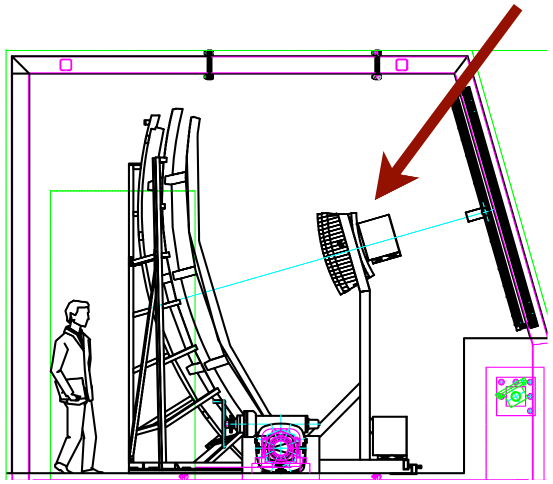
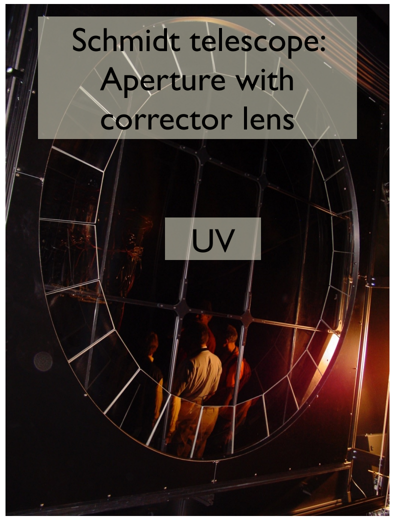
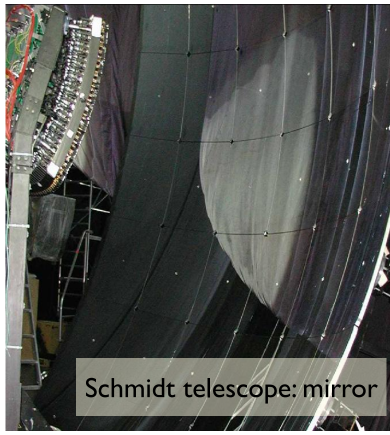




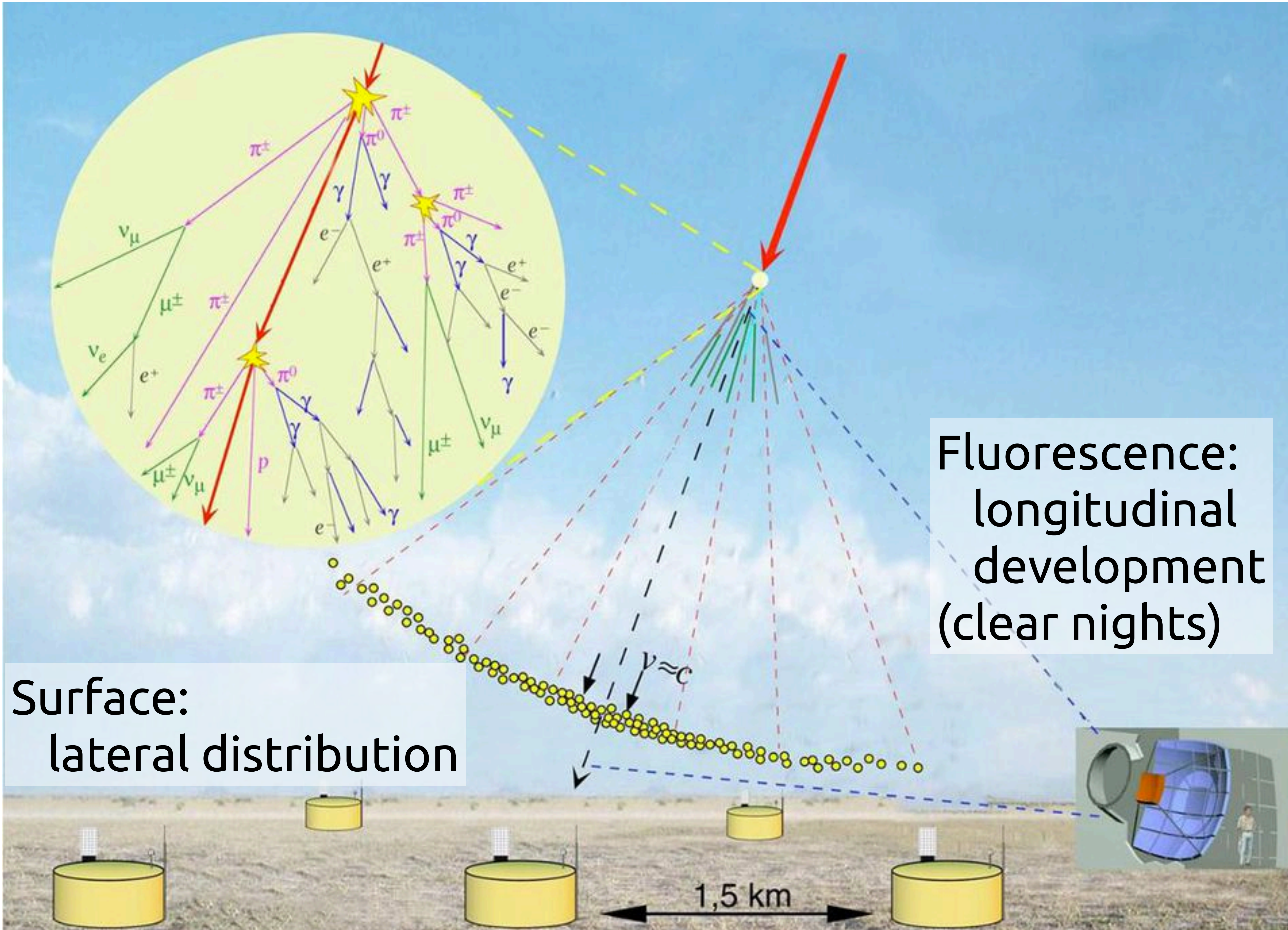




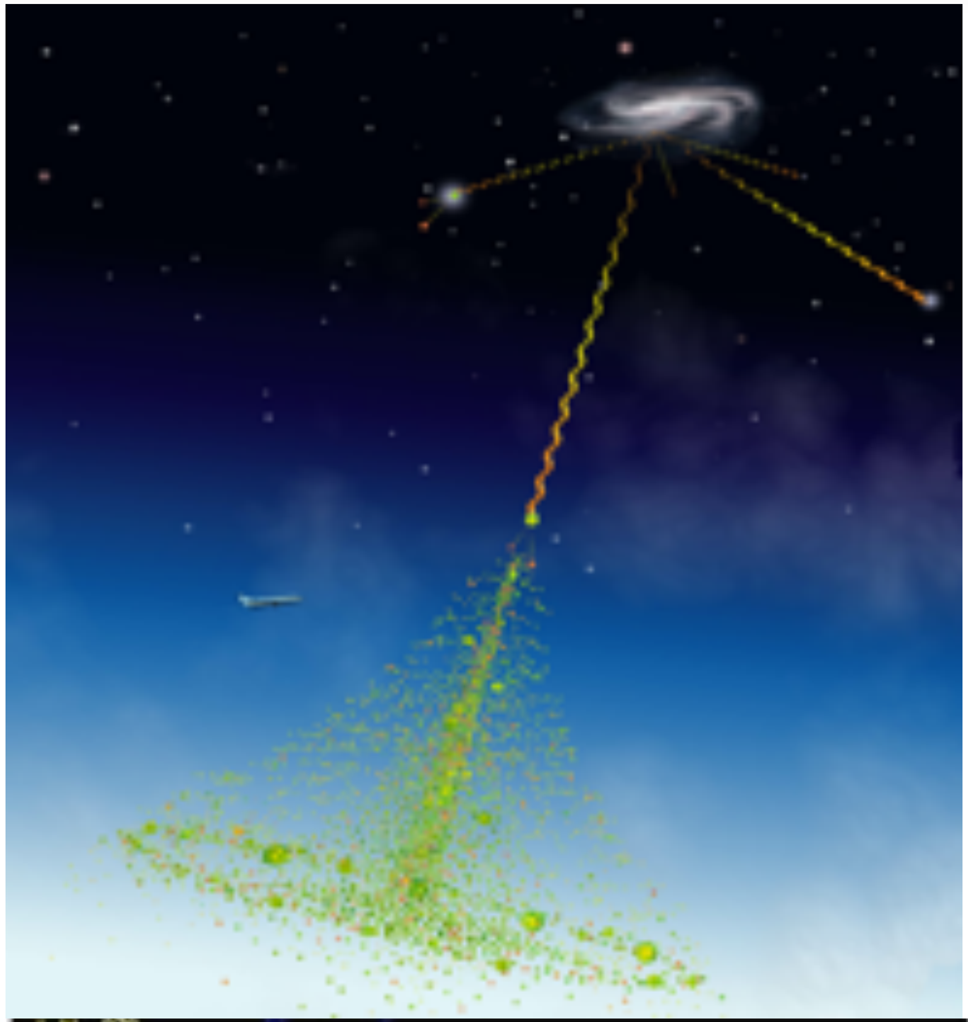


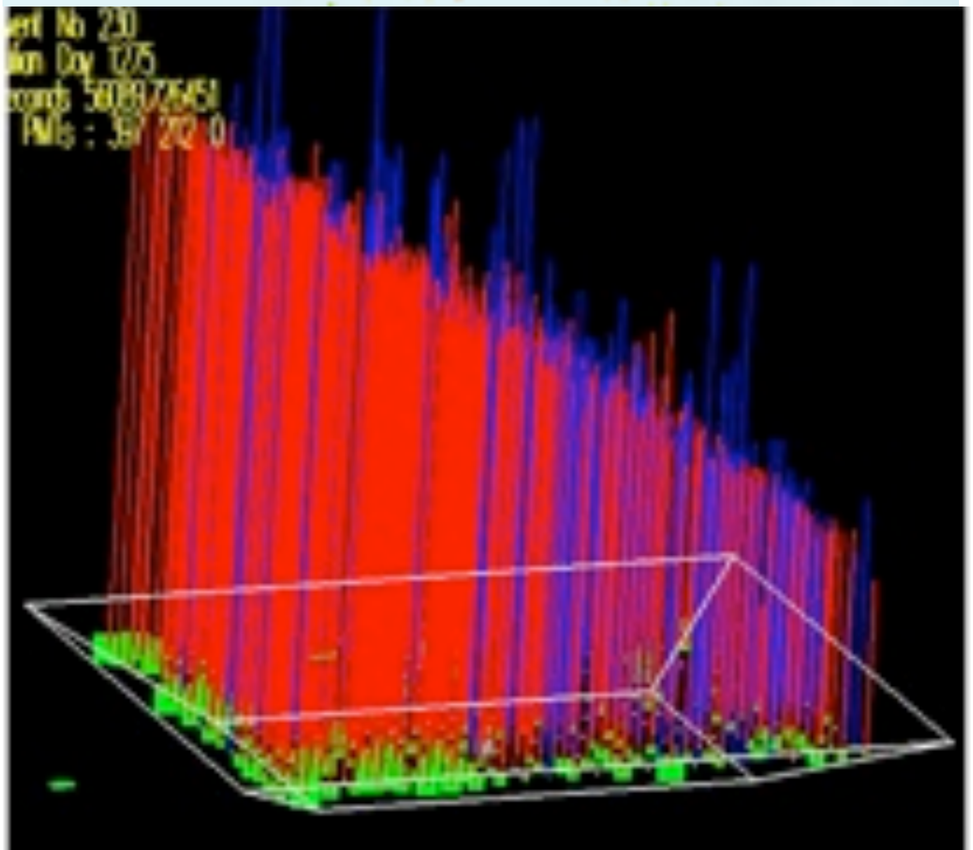
Reconstruction of basic quantities

Air shower detection



Time ⇨ Direction



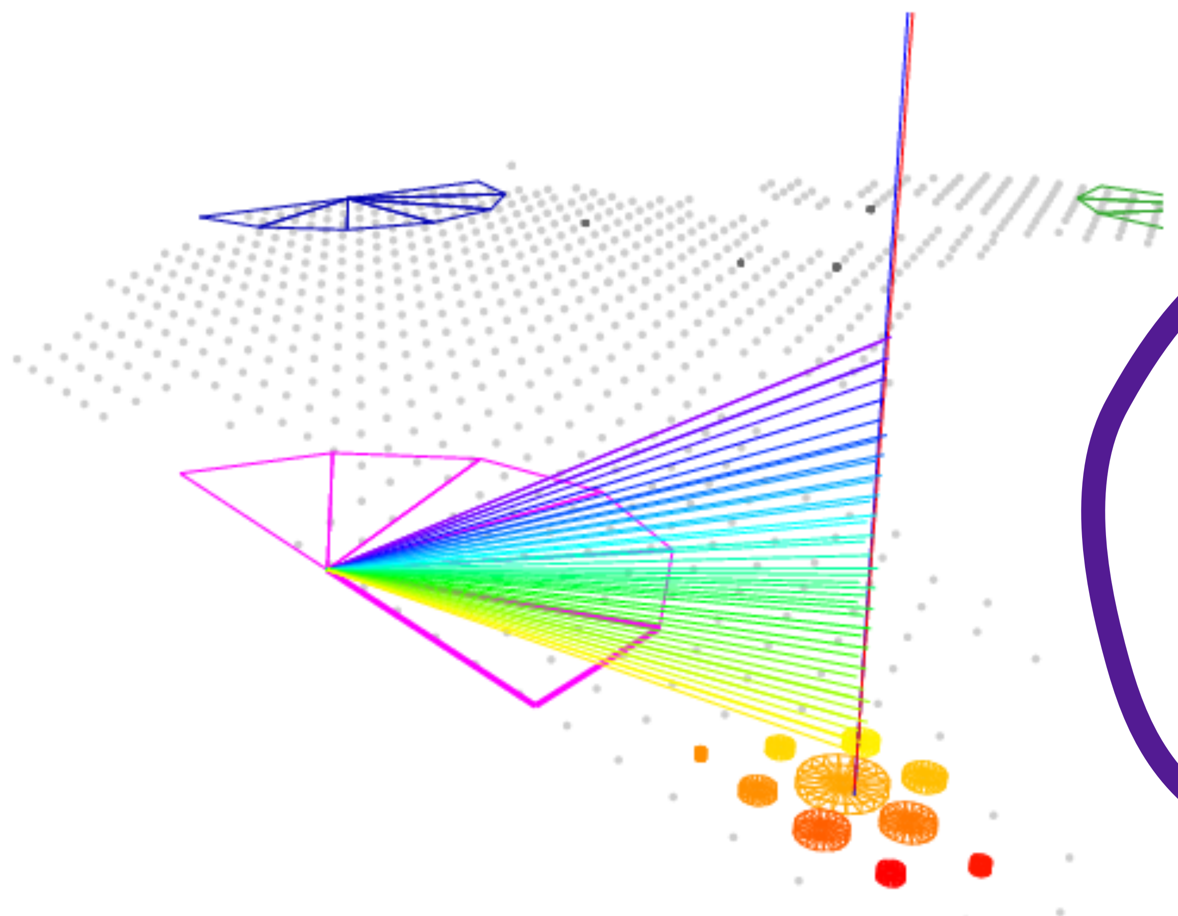


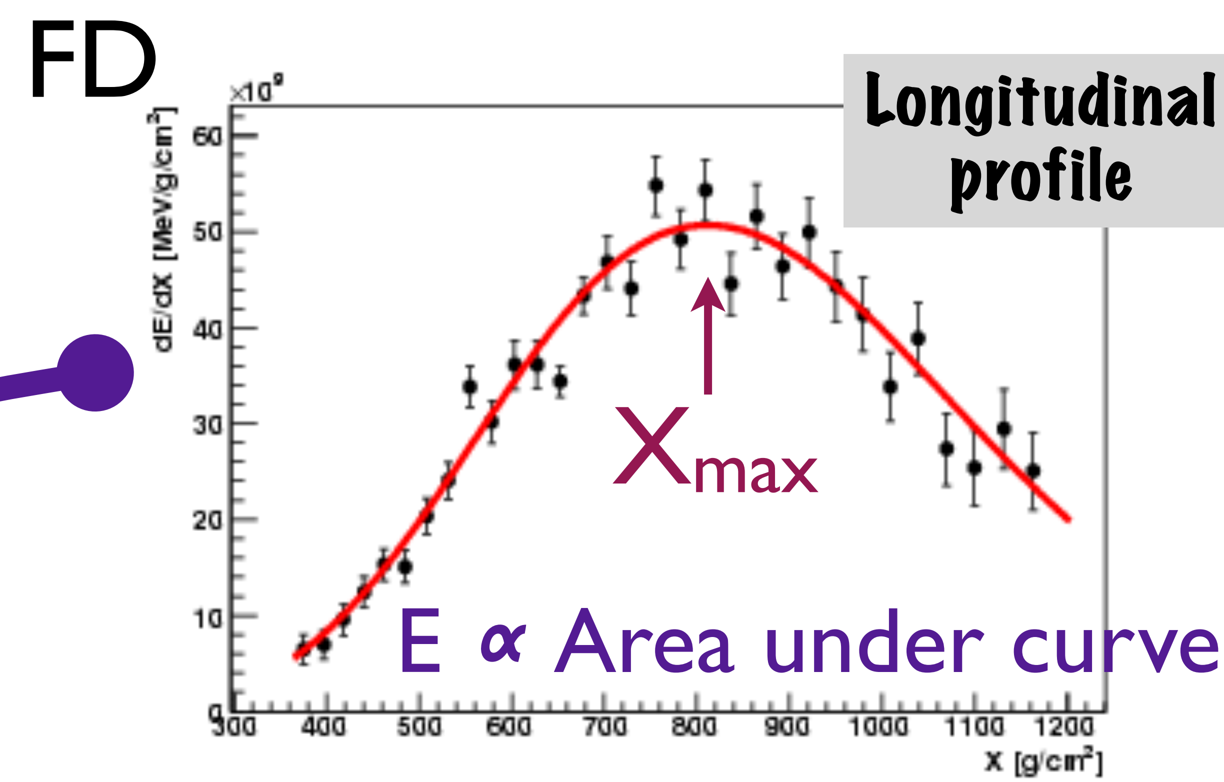
- ◉ Velocity and time
  ⇒ distance

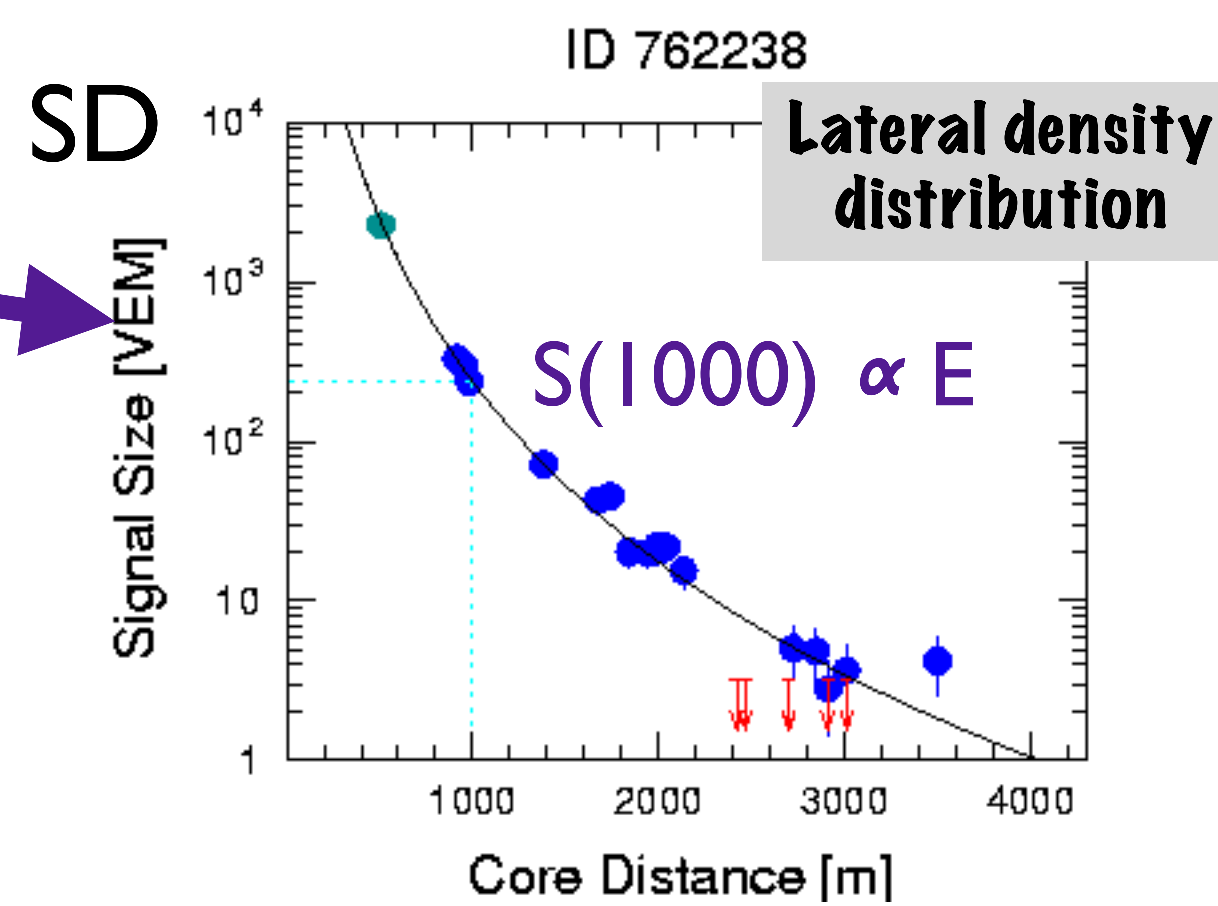
$$d = ct$$

- ◉ Perpendicular plane
  ⇒ direction

Surface detector Energy Determination

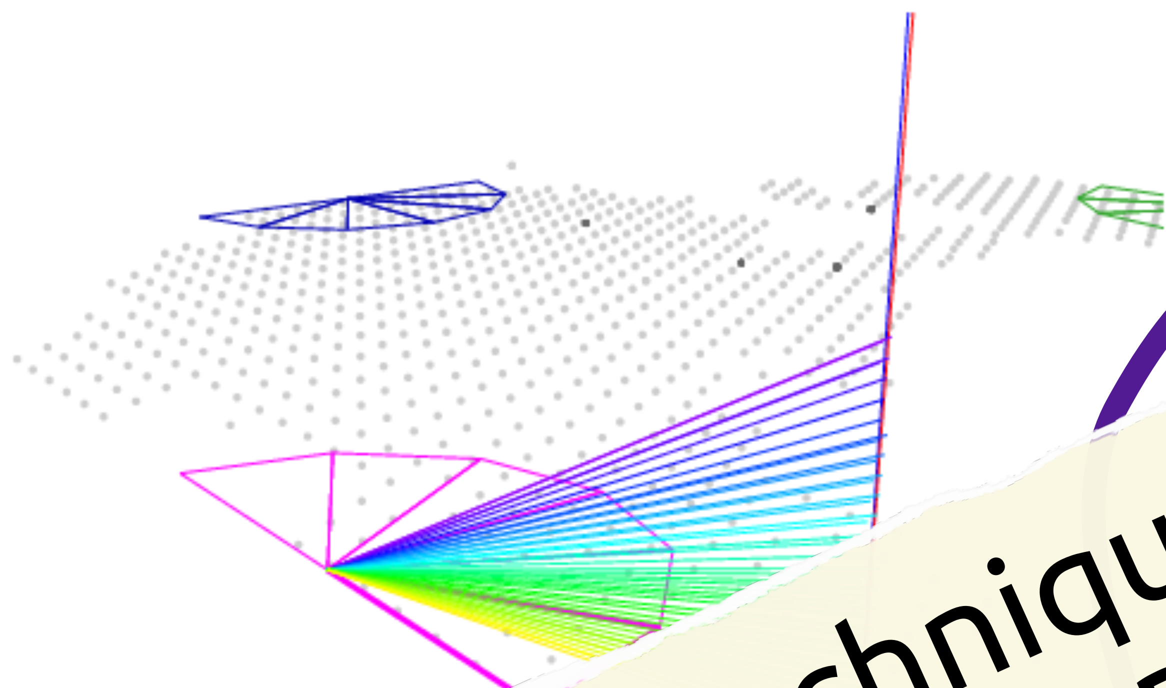




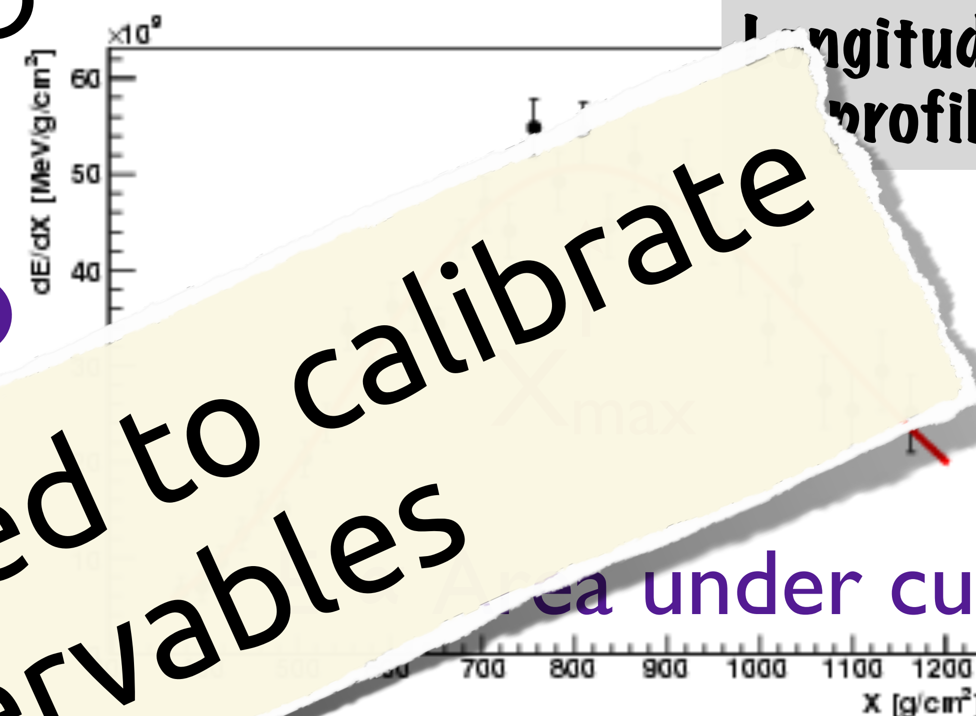


Hybrid Events are used to **calibrate** the SD energy estimator from the FD calorimetric energy

Surface detector Energy Determination



FD



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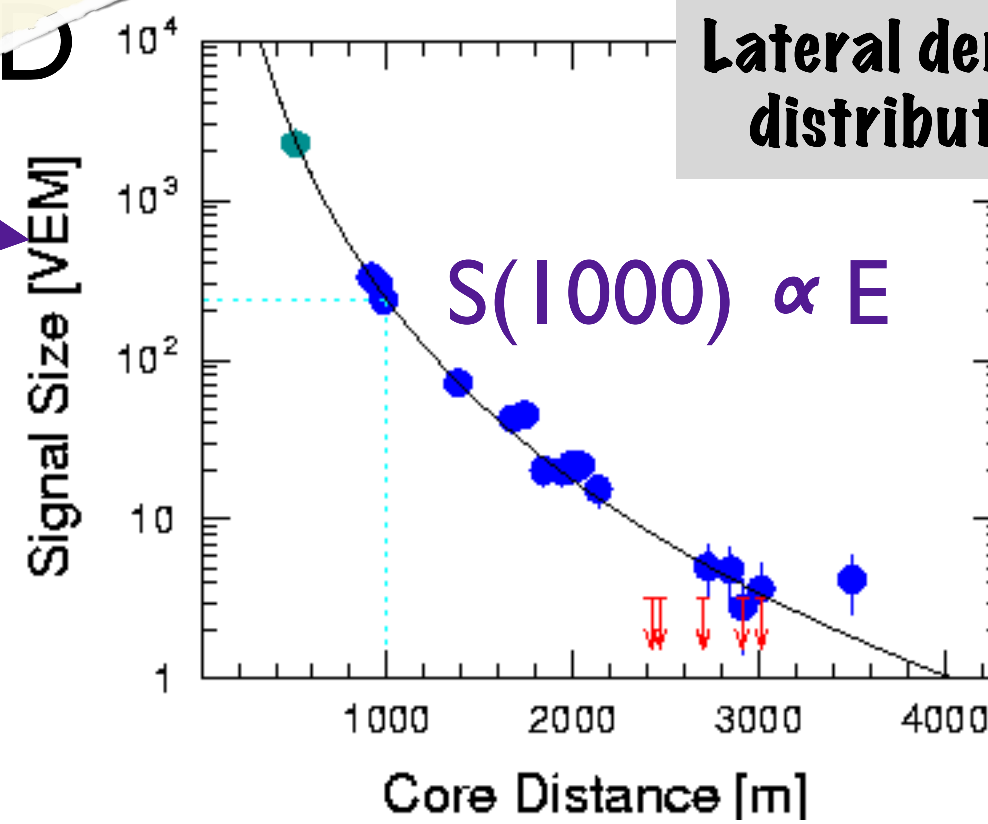
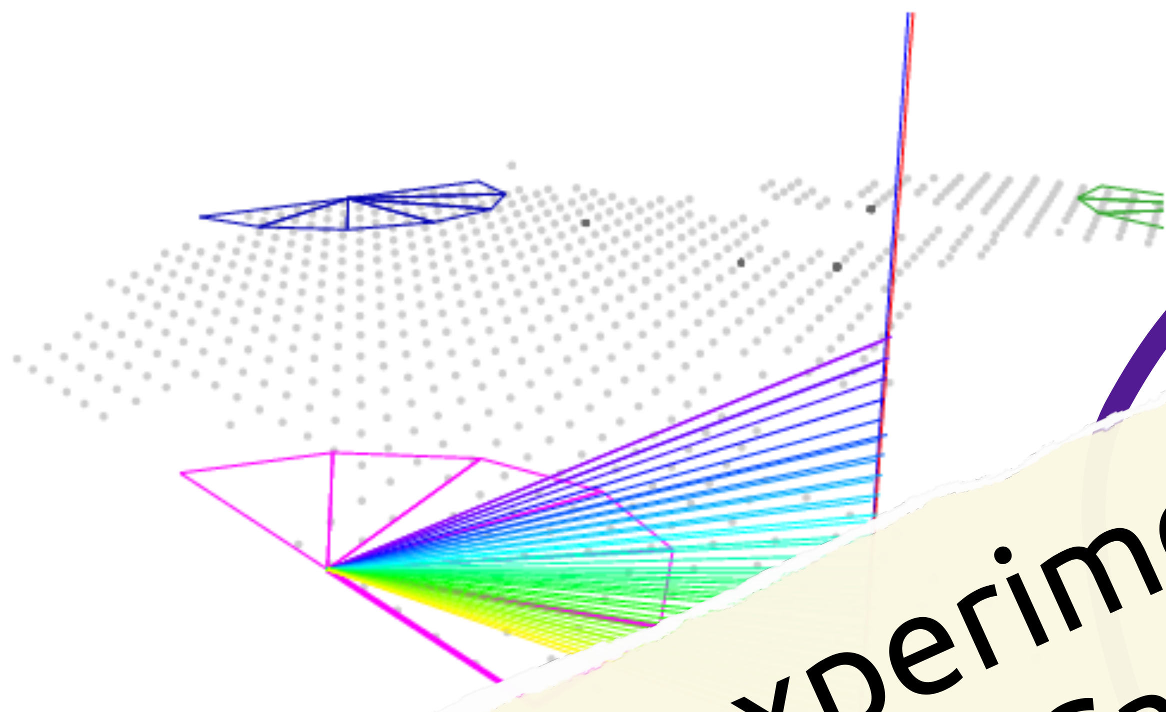


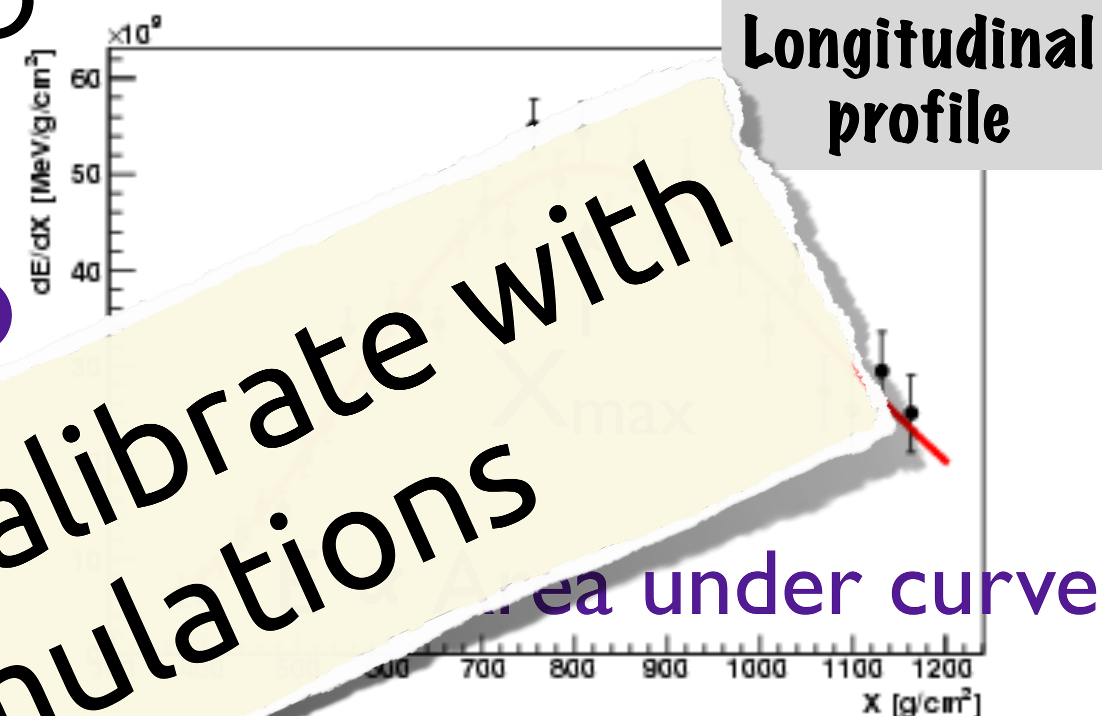
Similar techniques used to calibrate other SD observables

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

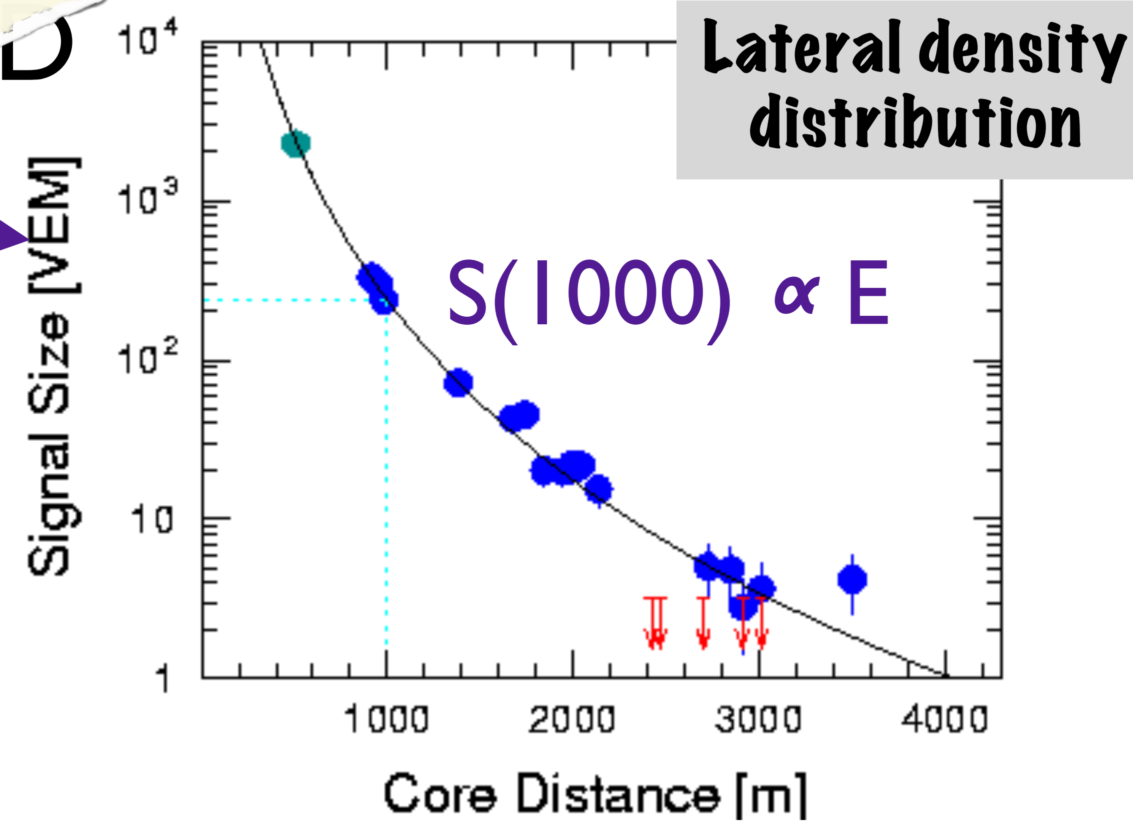
Surface detector Energy Determination



FD



SD



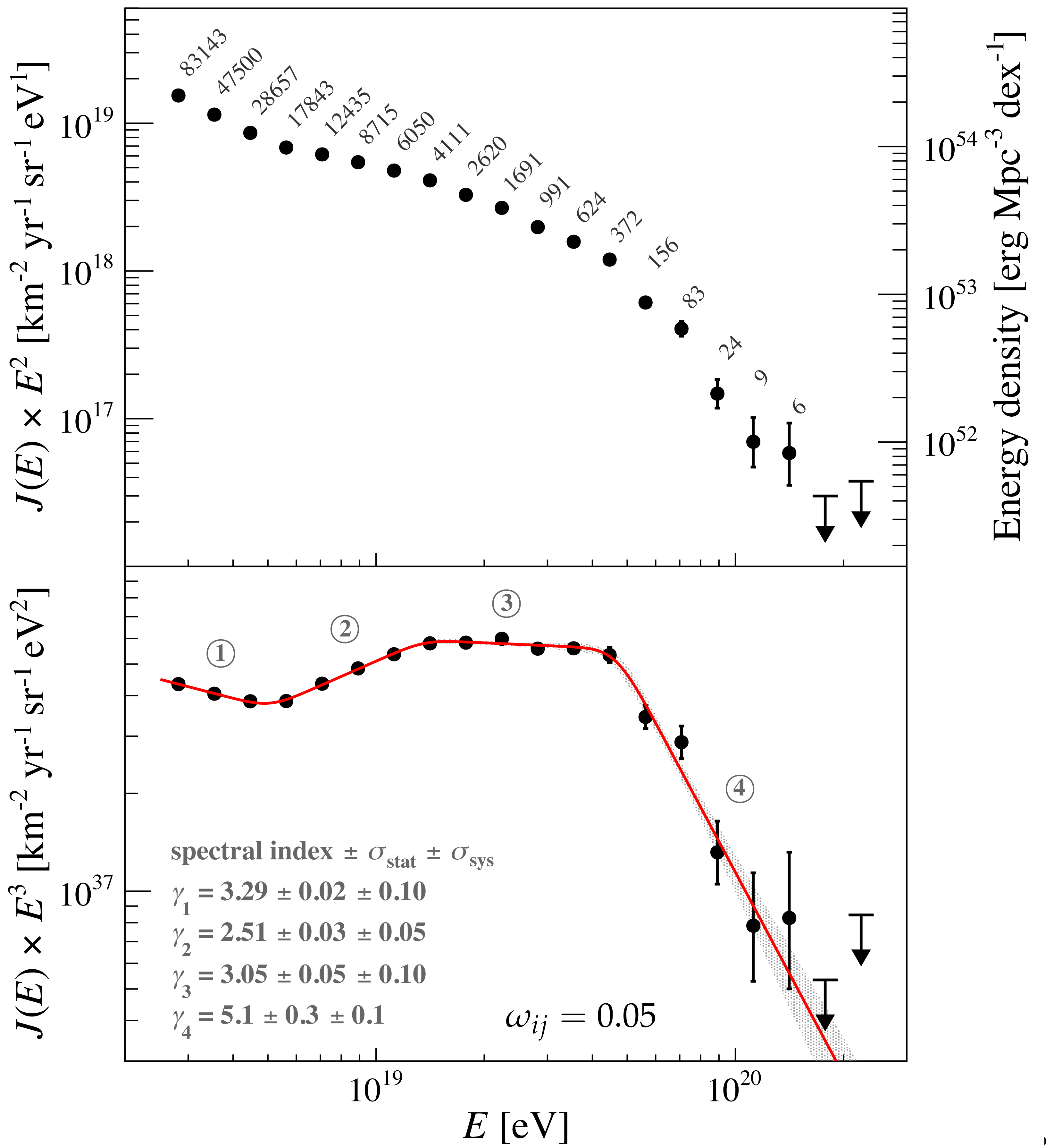
Hybrid Events are used to **calibrate** the SD energy estimator from the FD calorimetric energy

Other experiments calibrate with Monte Carlo simulations

Combined spectrum

- Combine results from different techniques and detectors

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



Combined spectrum

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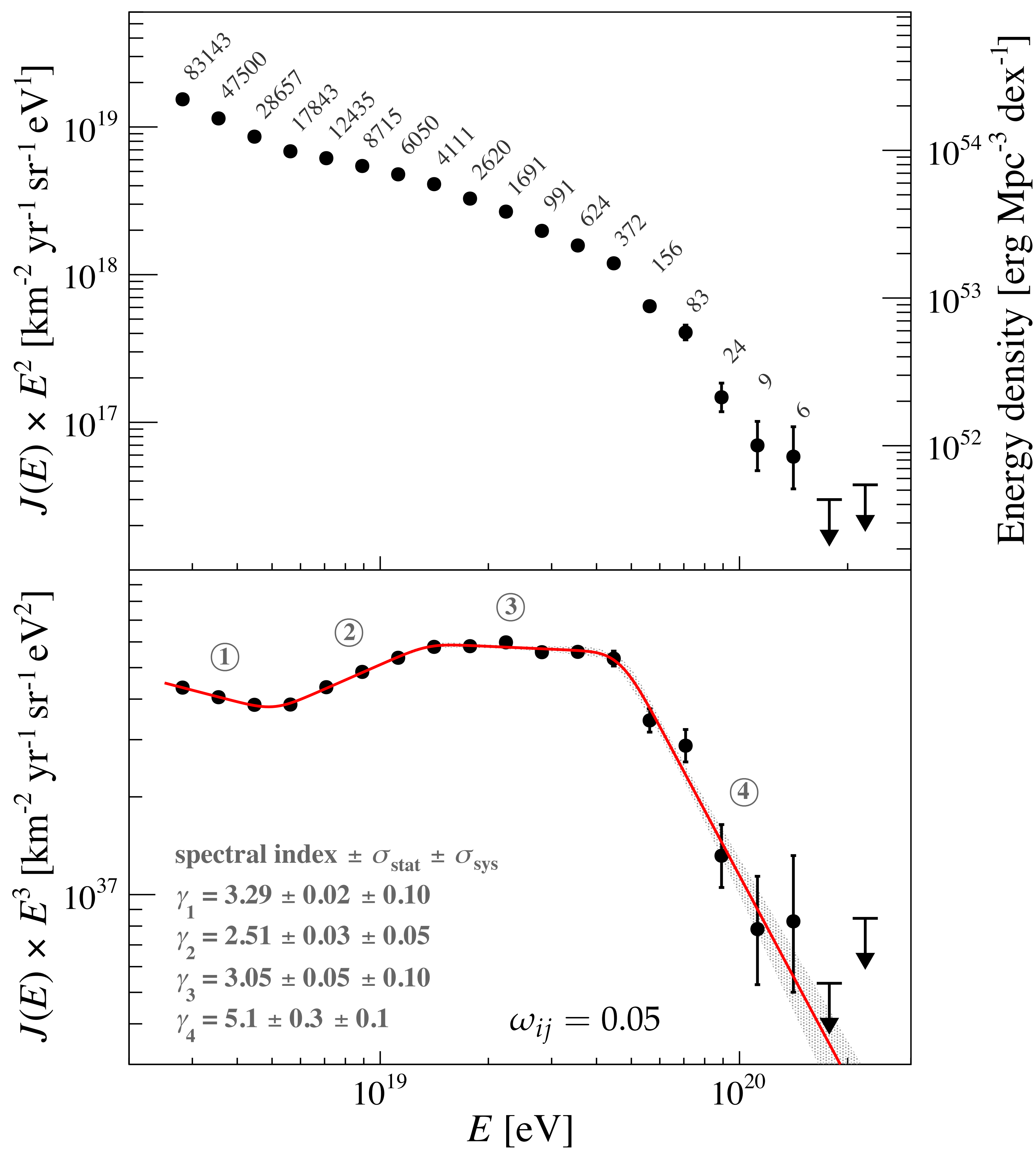
Spectral parameters:

E_{12} = 5 ± 0.1 ± 0.8 EeV

E_{23} = 13 ± 1 ± 2 EeV

E_{34} = 46 ± 3 ± 6 EeV



Photon Identification

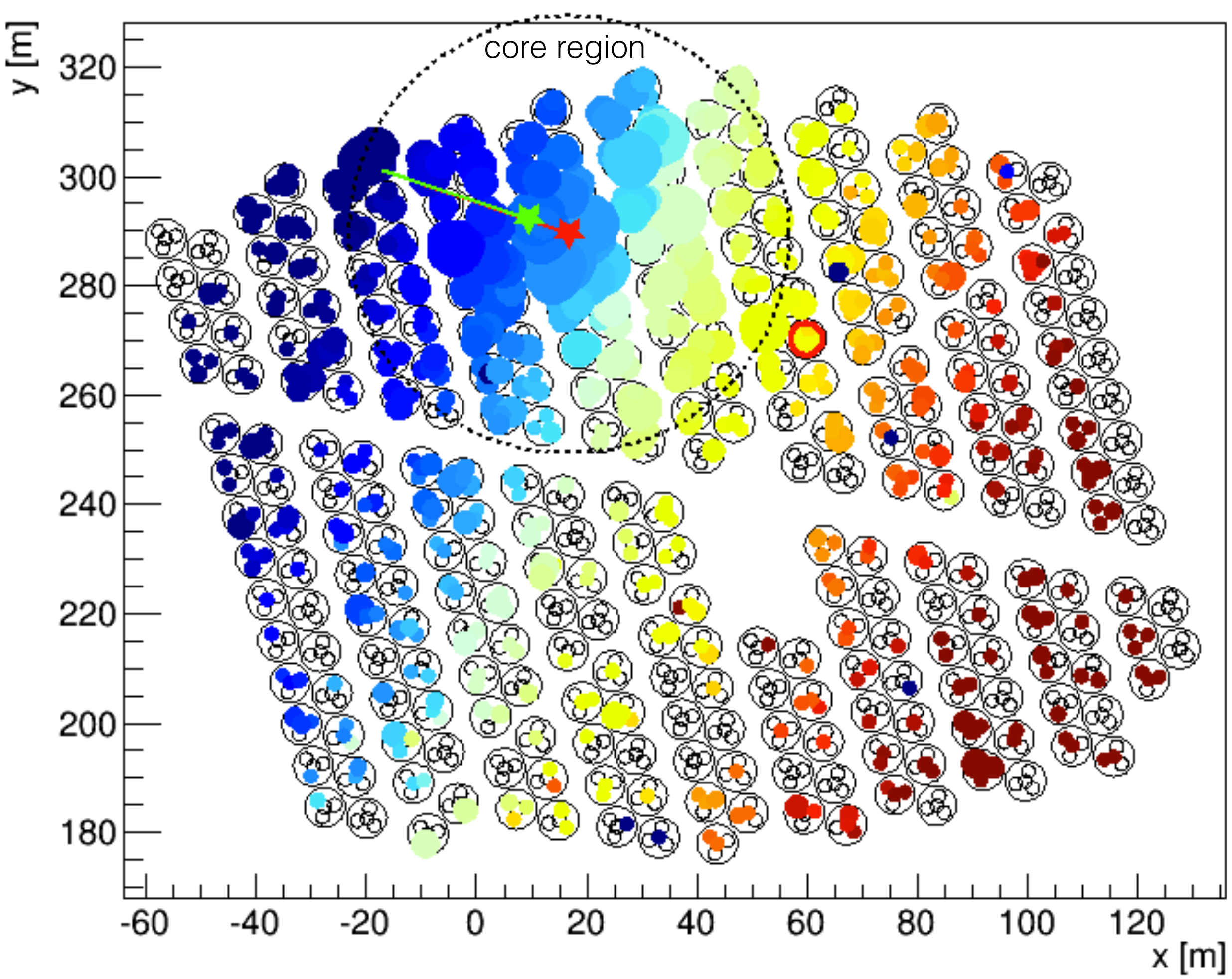
HAWC Gamma-Hadron separation

Machine Learning

Gamma: Smooth
Most signal in reference circle

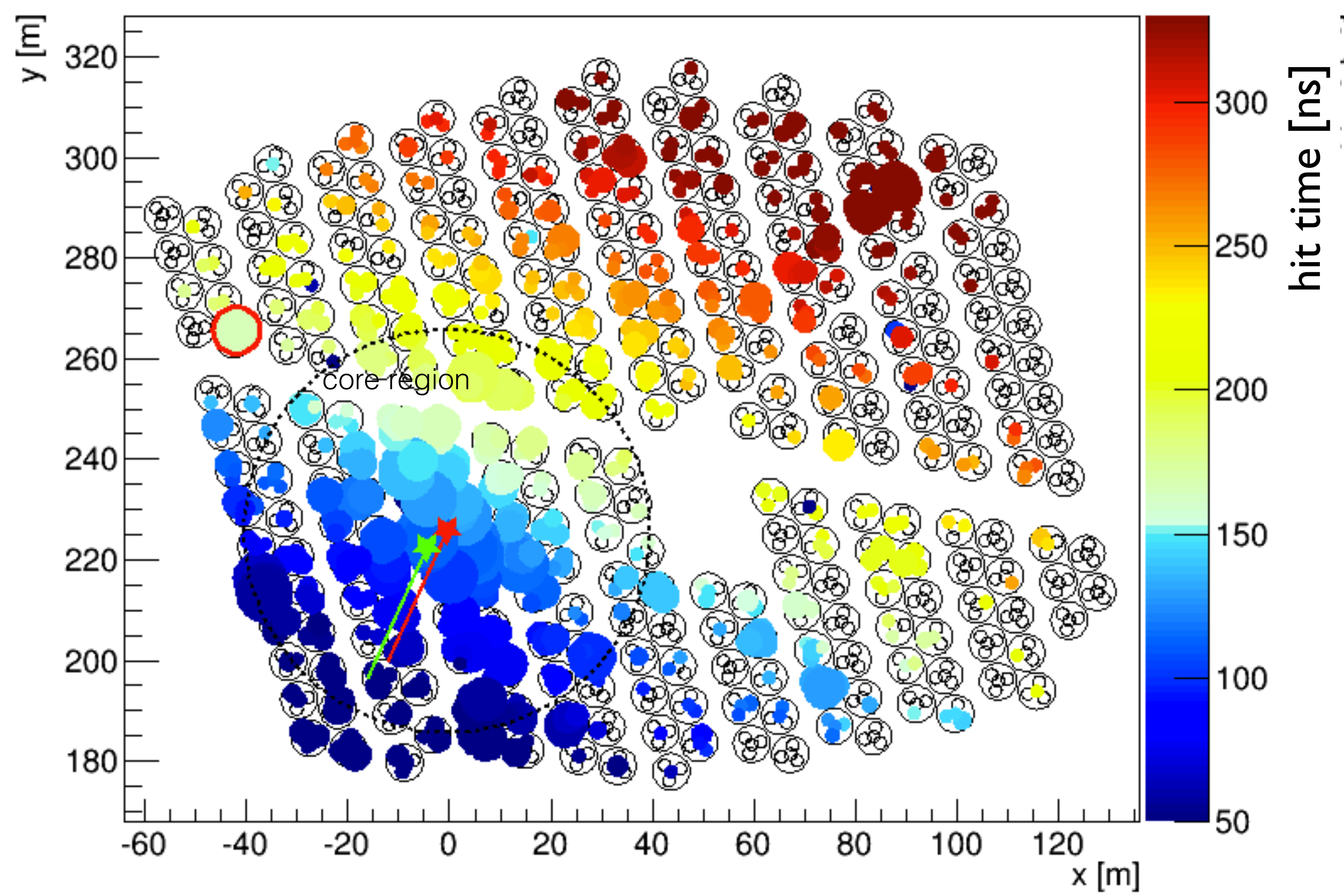
Protón: Rough front
Detector with large signal outside reference circle

7 TeV Gamma Shower



circle size = light collected
(measures local E)

47 TeV Hadron Shower



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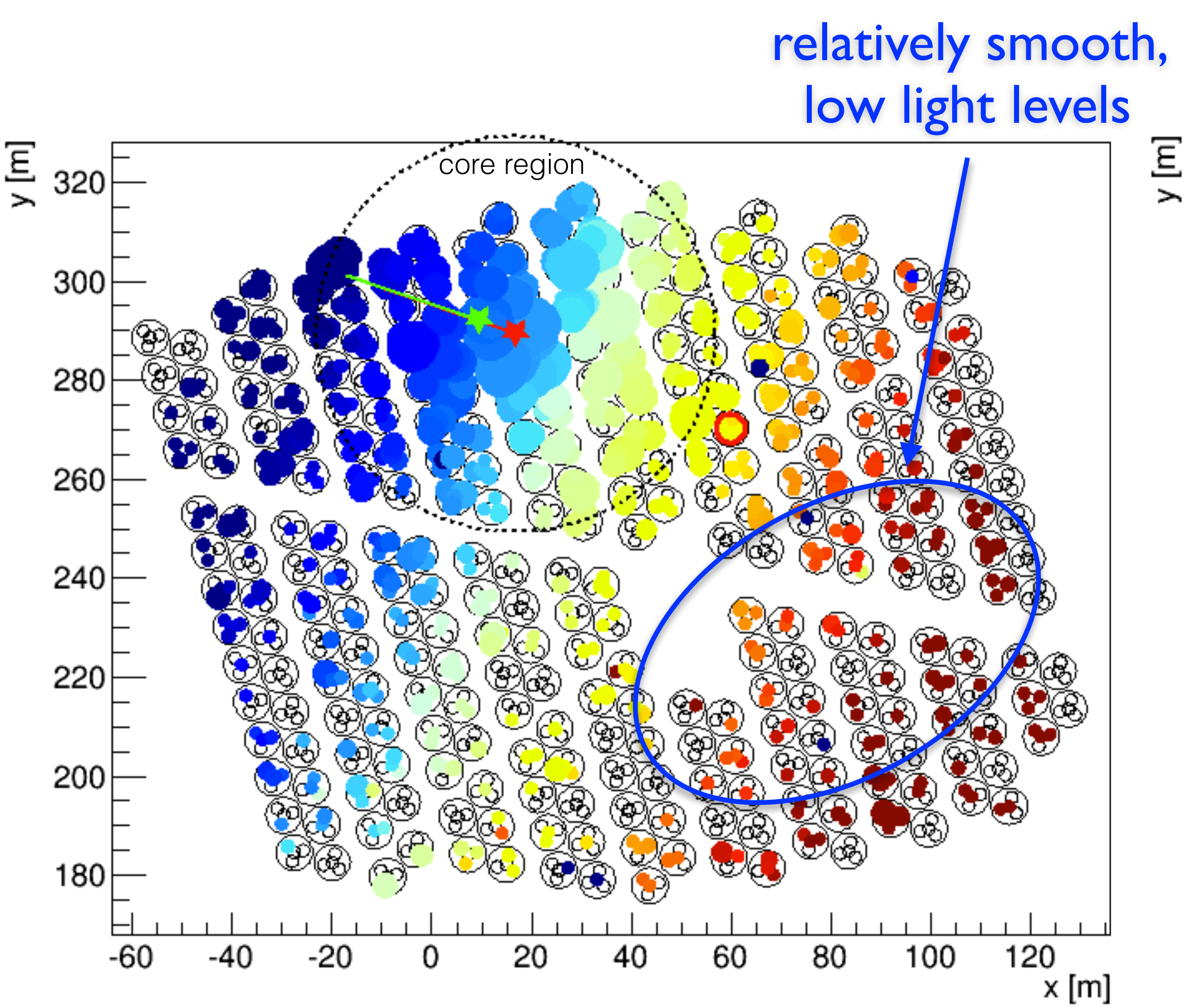

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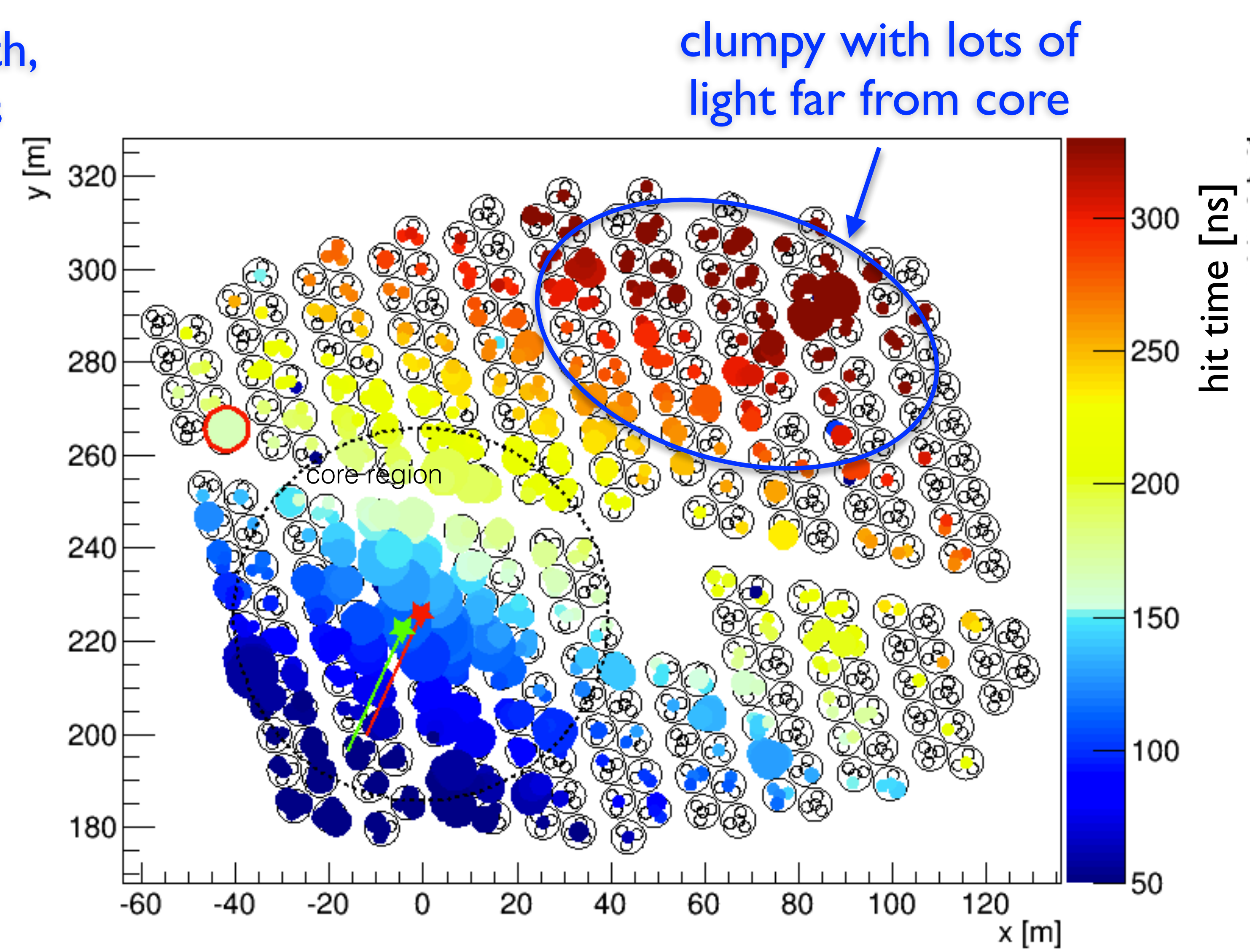
47 TeV Hadron Shower



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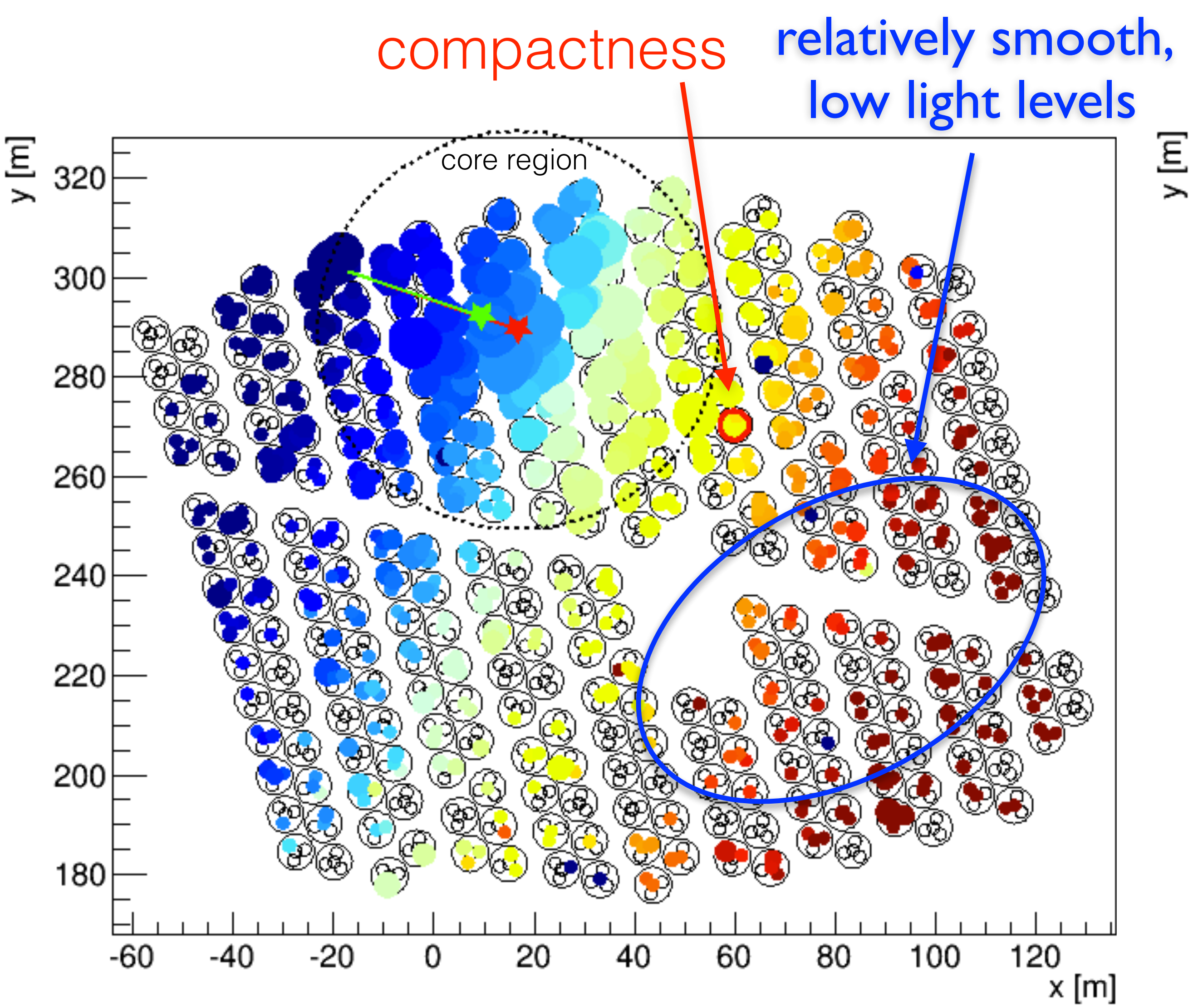

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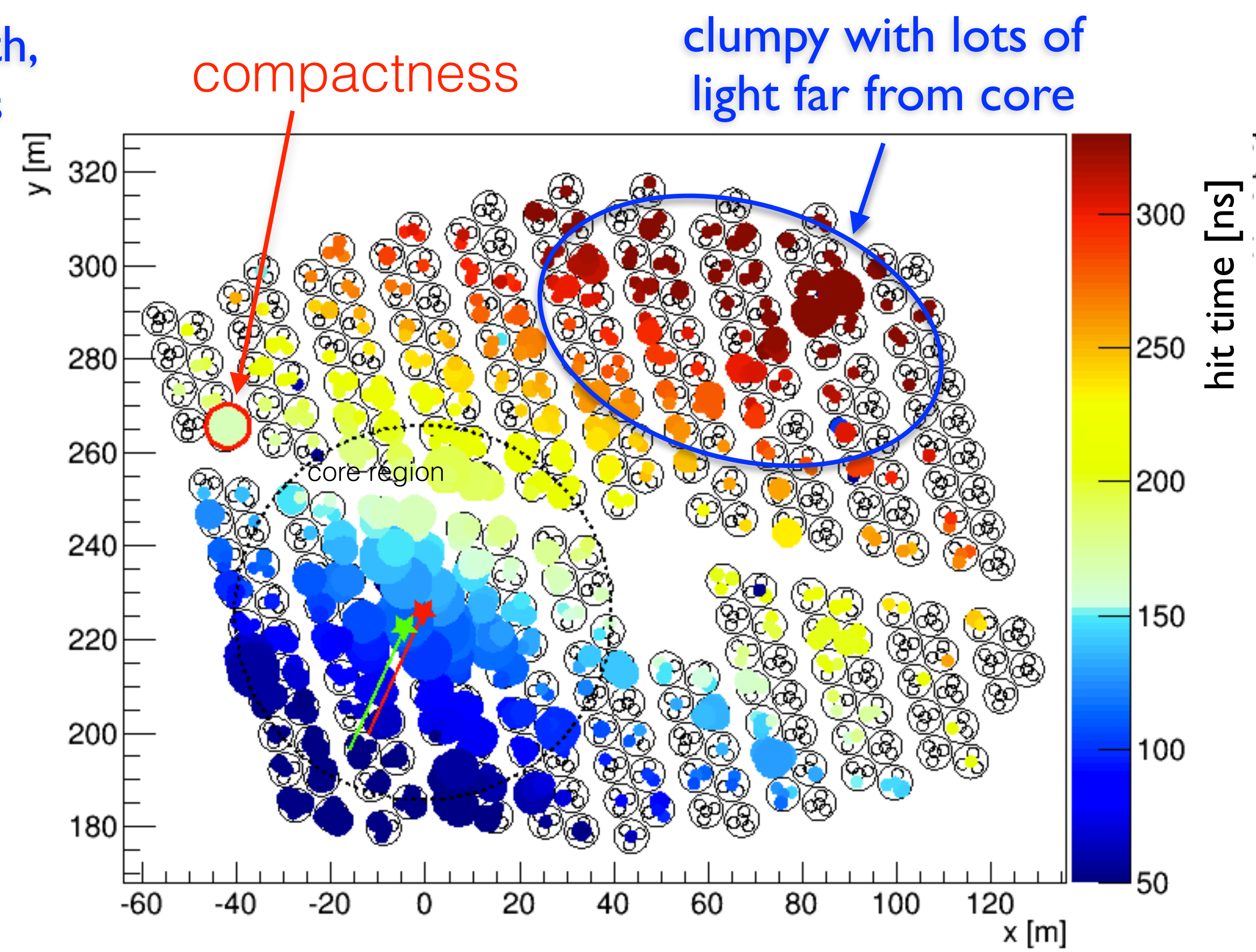

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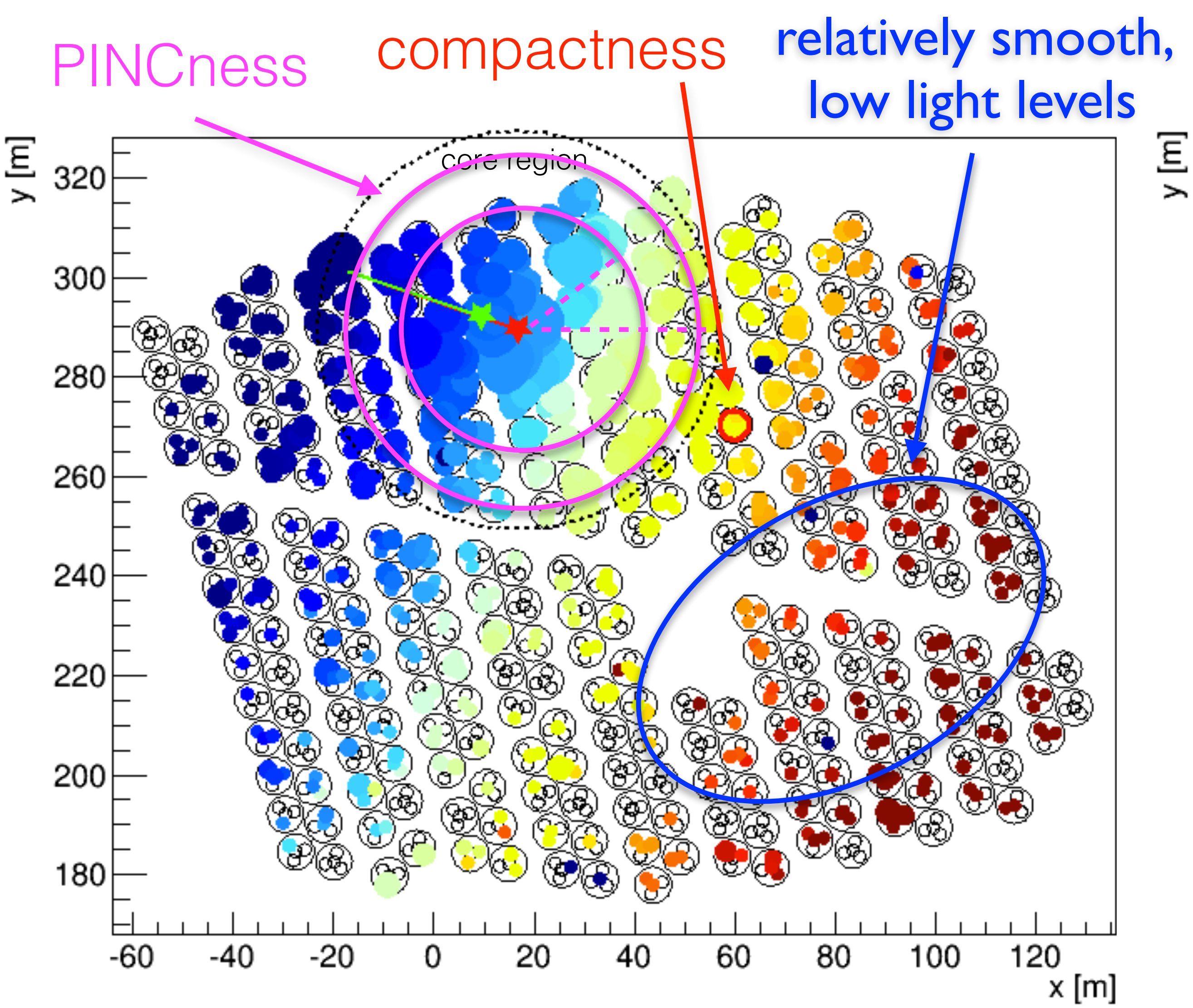

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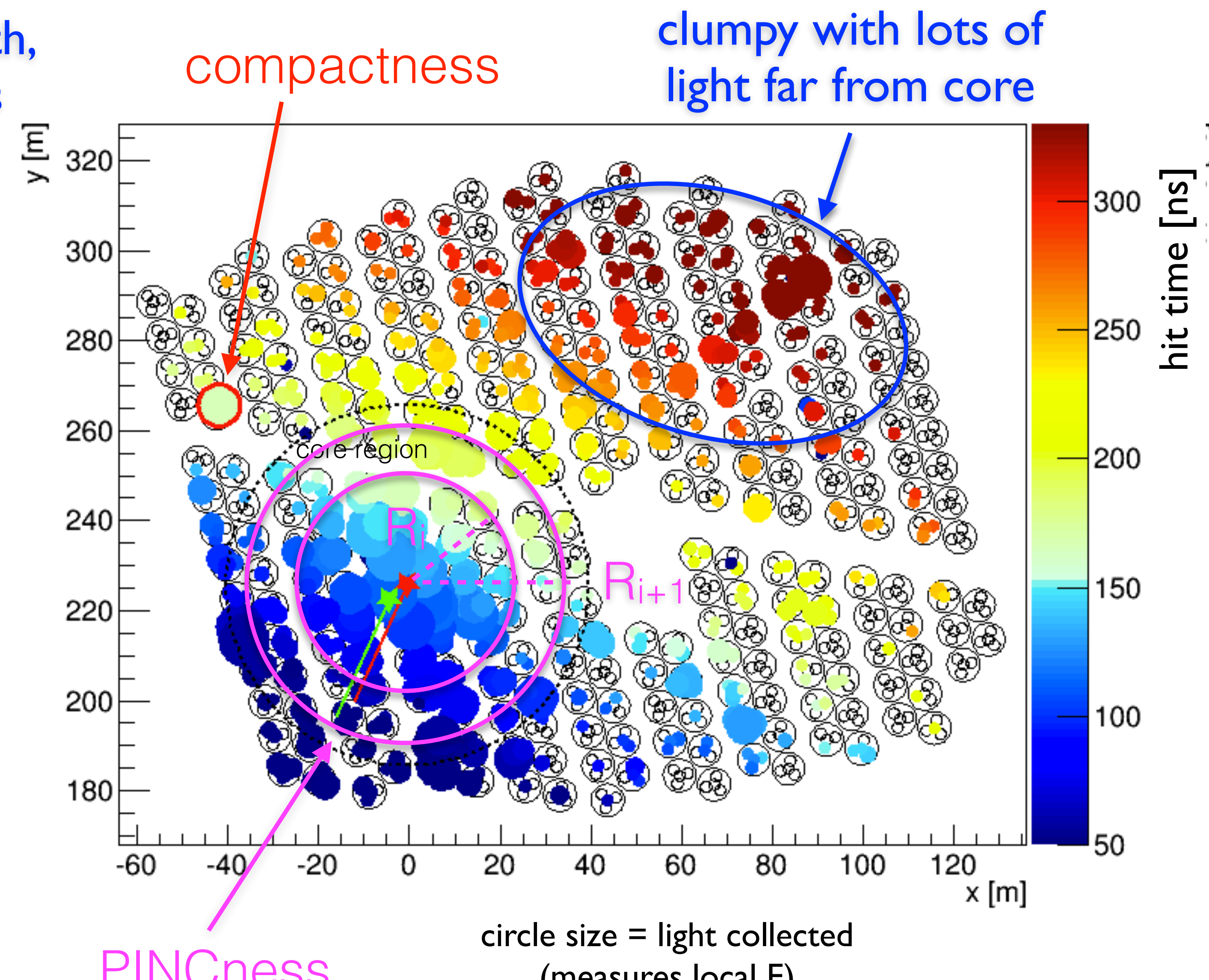
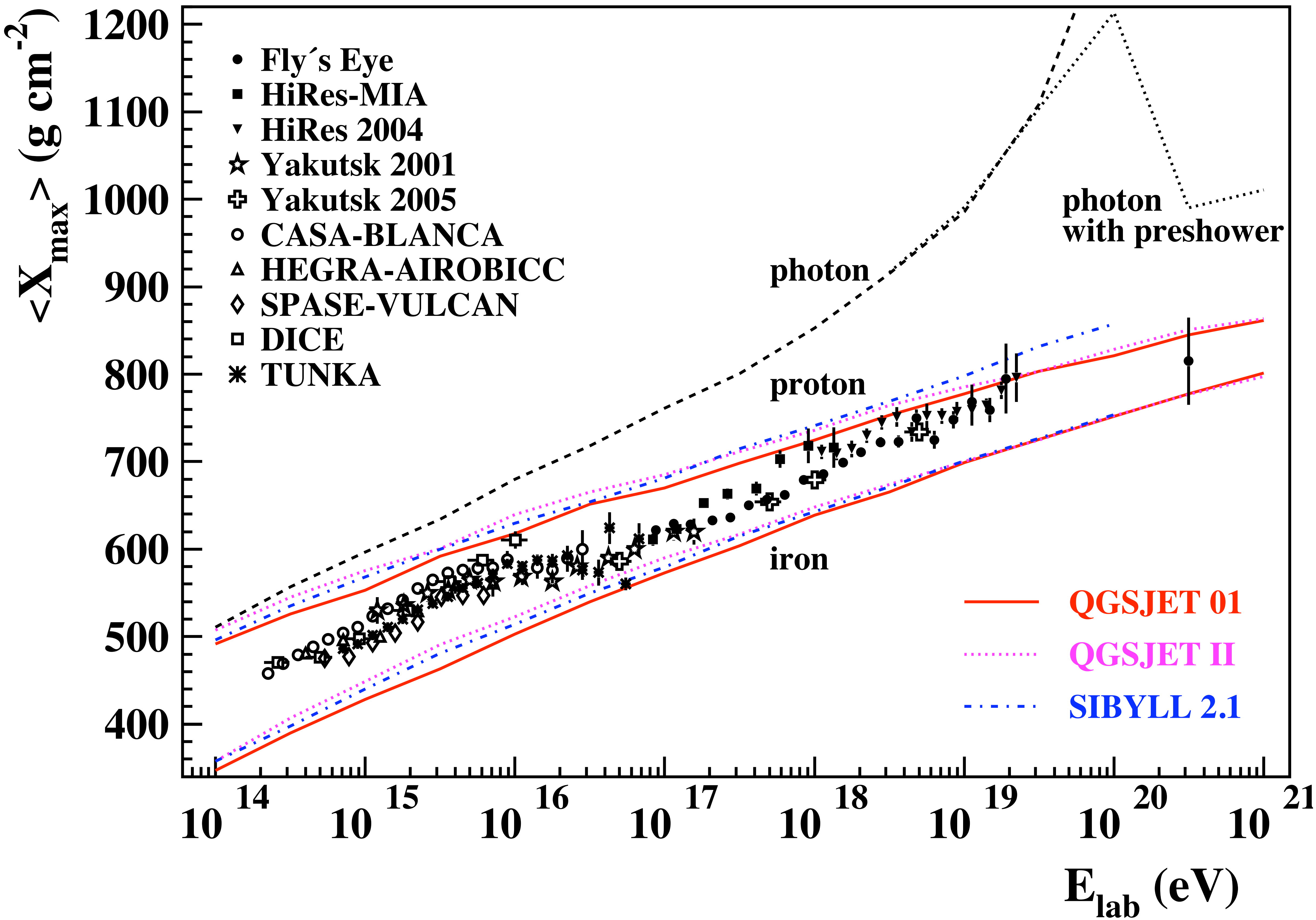
47 TeV Hadron Shower

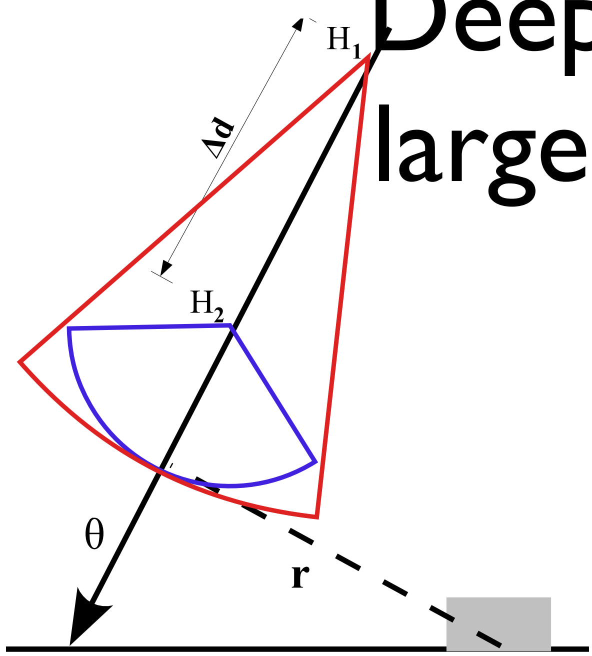


circle size = light collected
(measures local E)

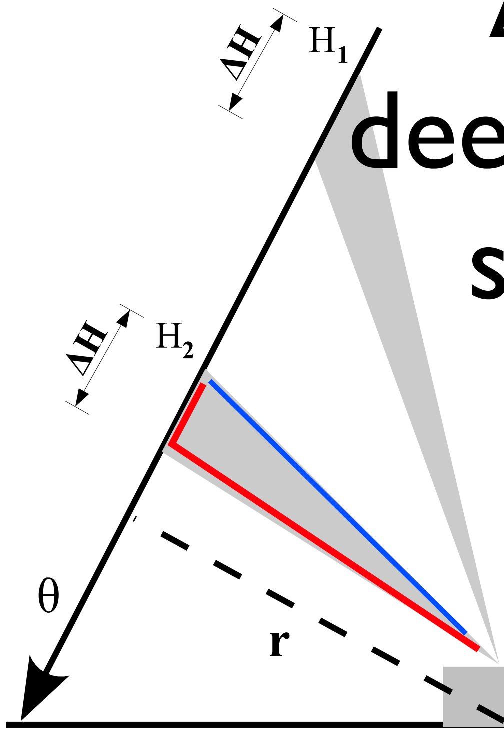
Auger FD photon discrimination



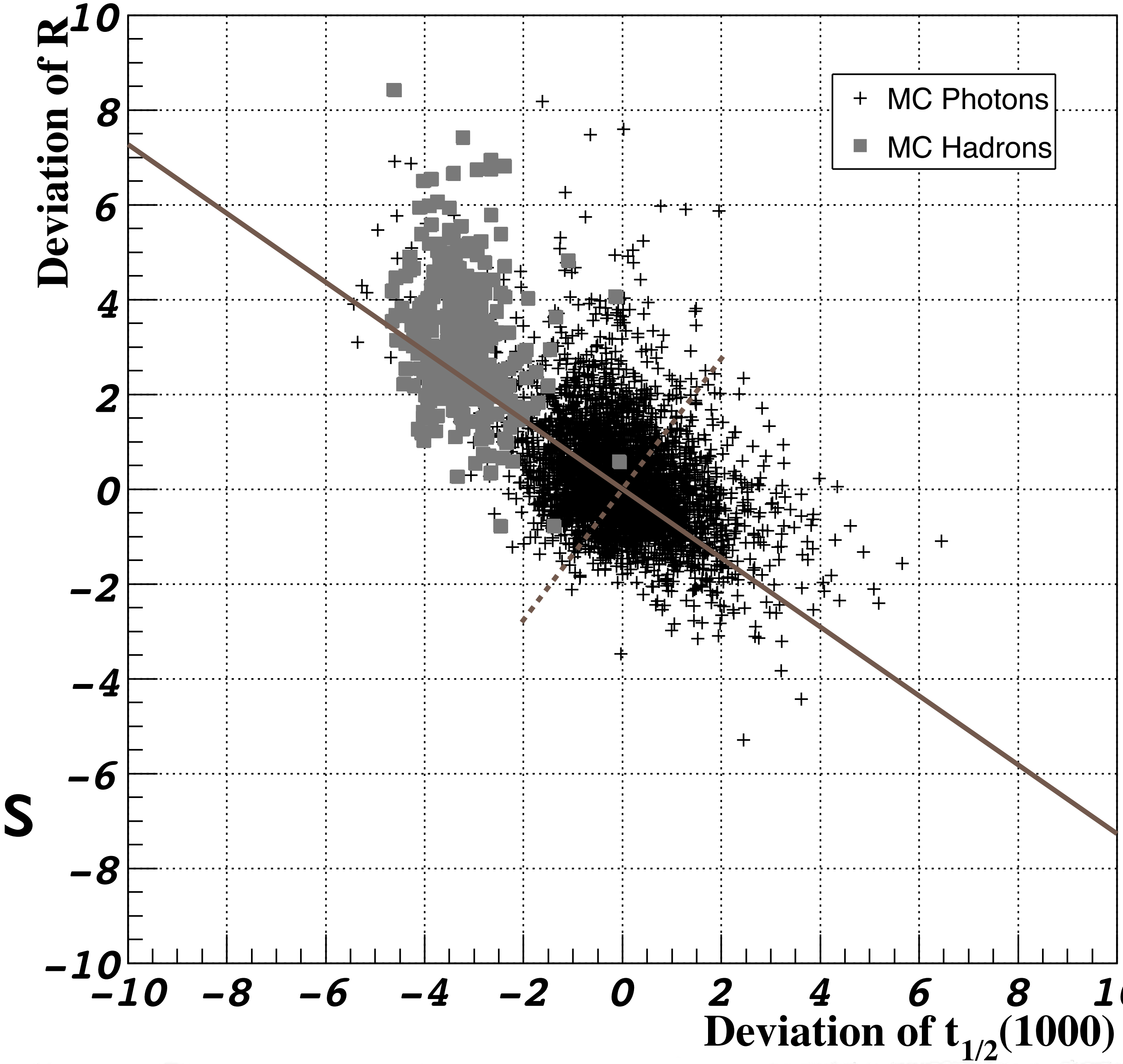
Auger SD photon discrimination



Deeper shower:
larger curvature

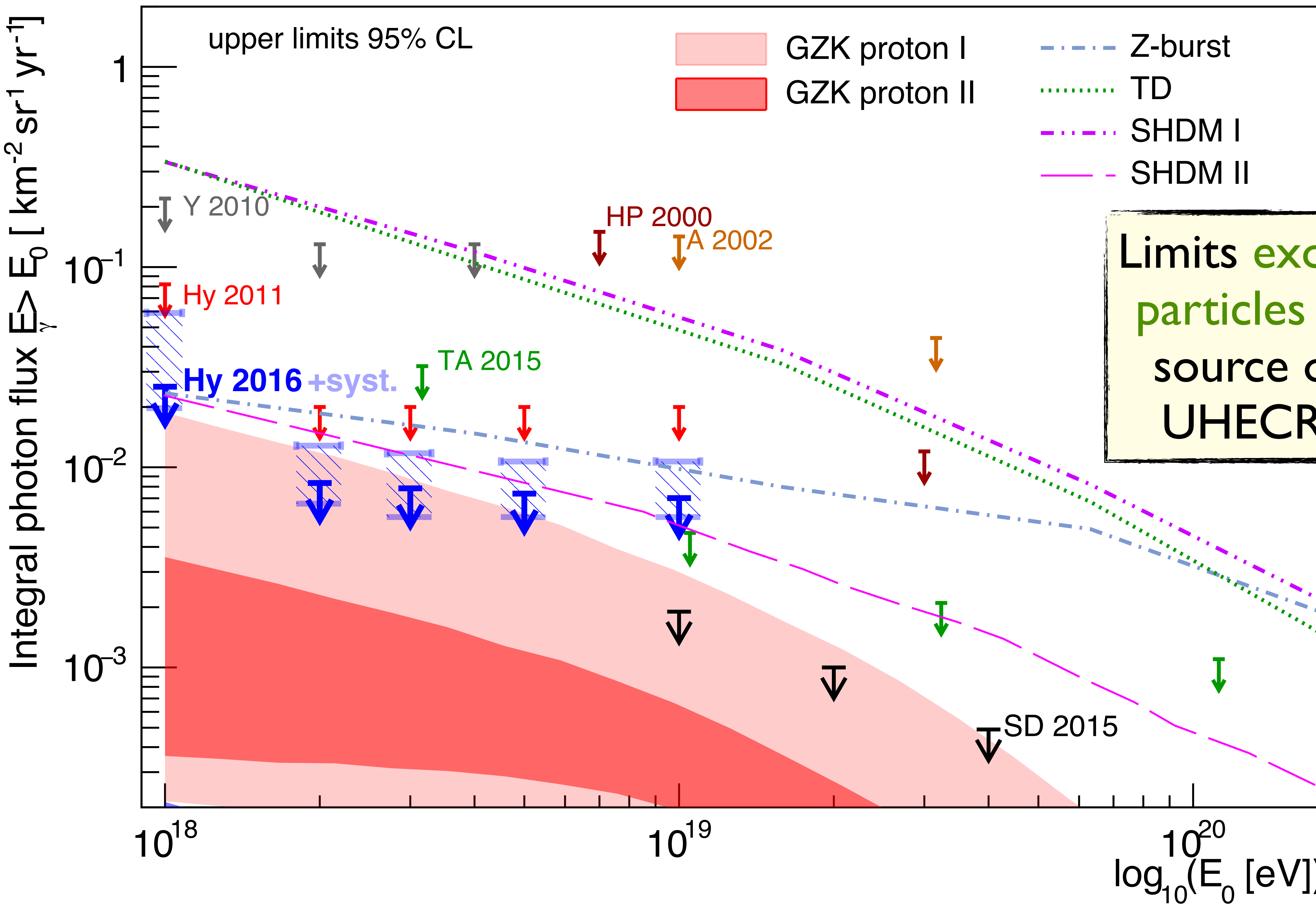


ΔH gives Δt:
deeper shower has
slower signals



Parametrize with simulations
Principal component analysis
on deviation

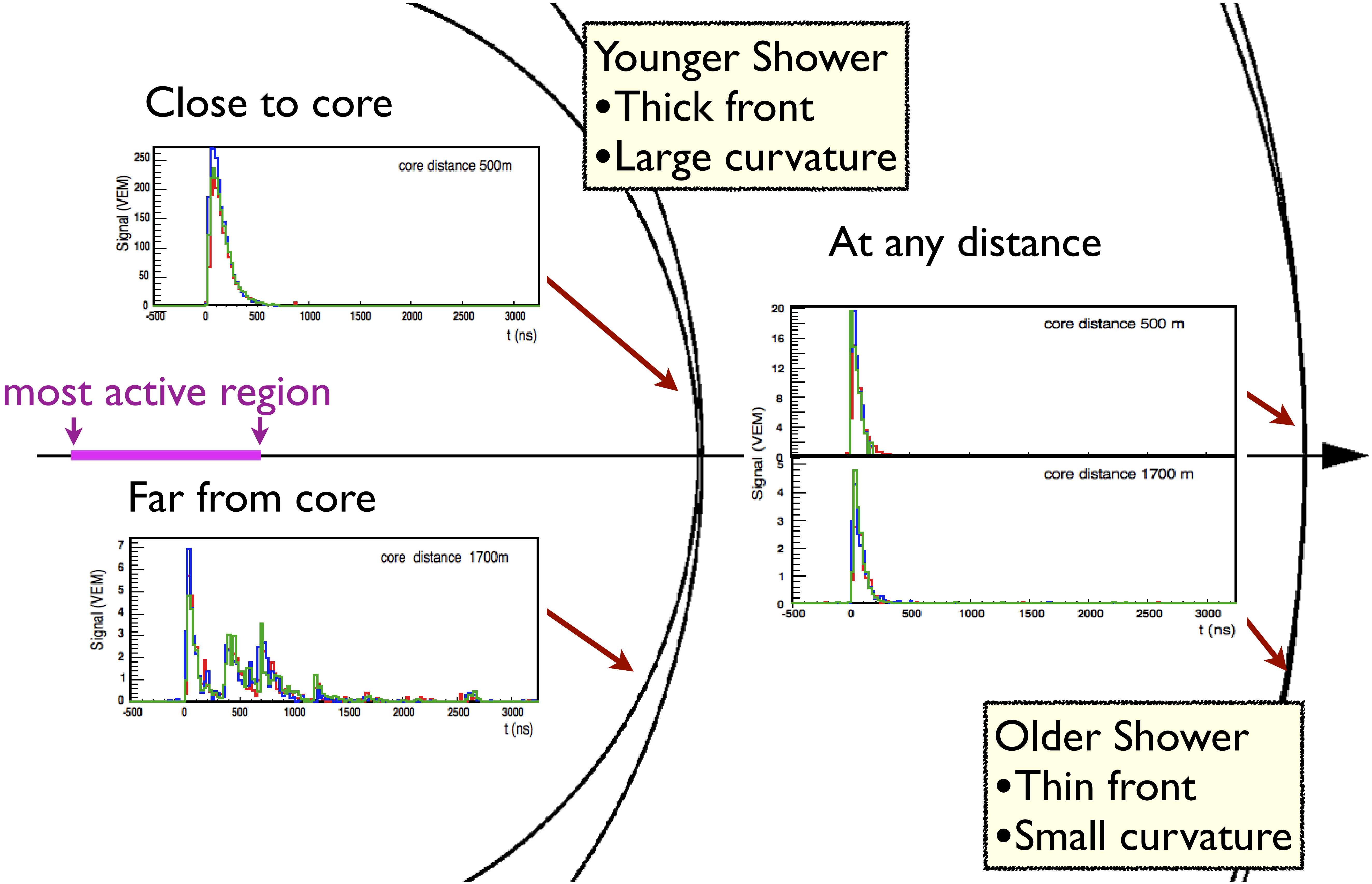
Auger Photon limit



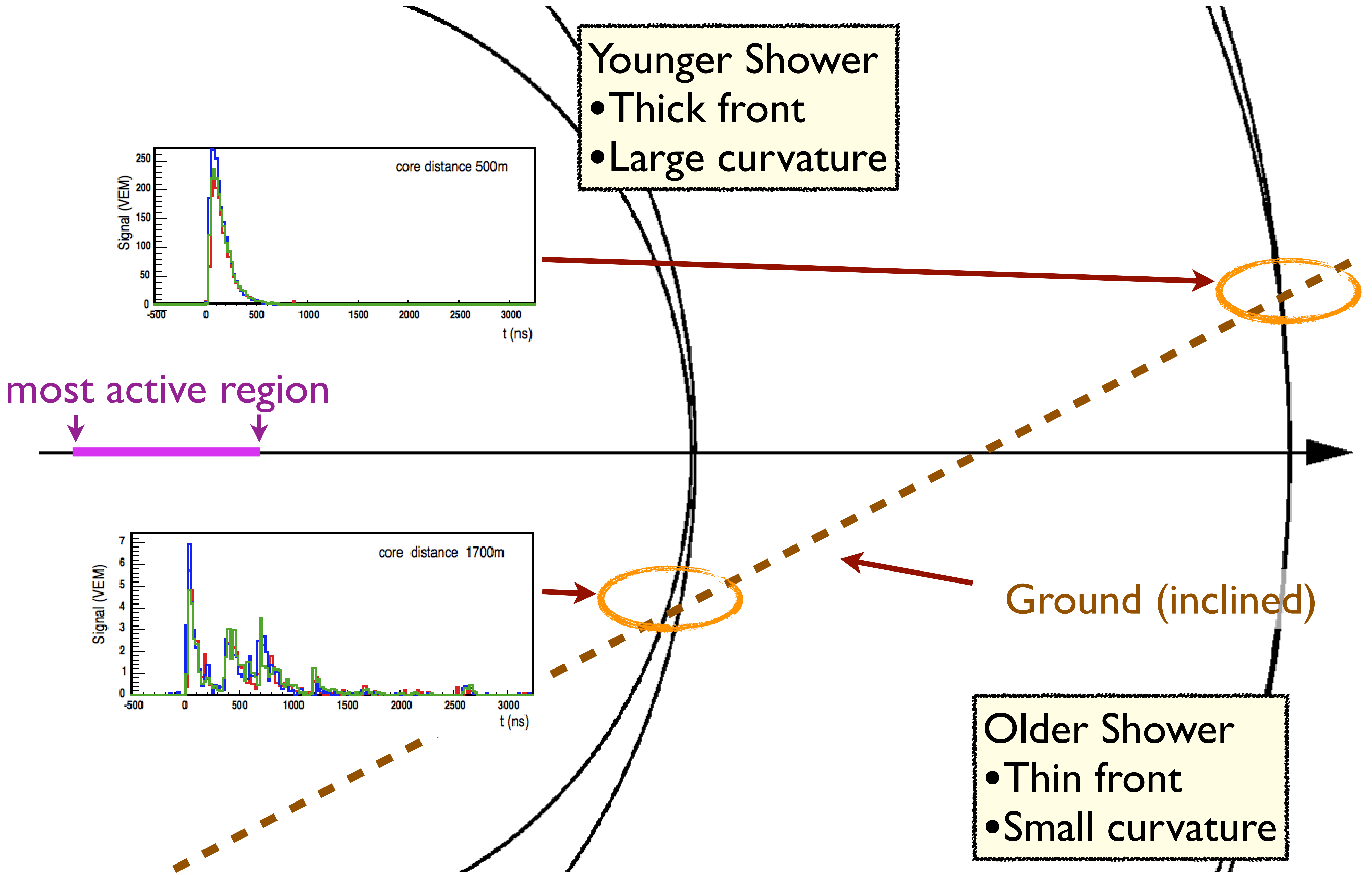
Limits **exotic particles** as source of UHECR.

Neutrinos

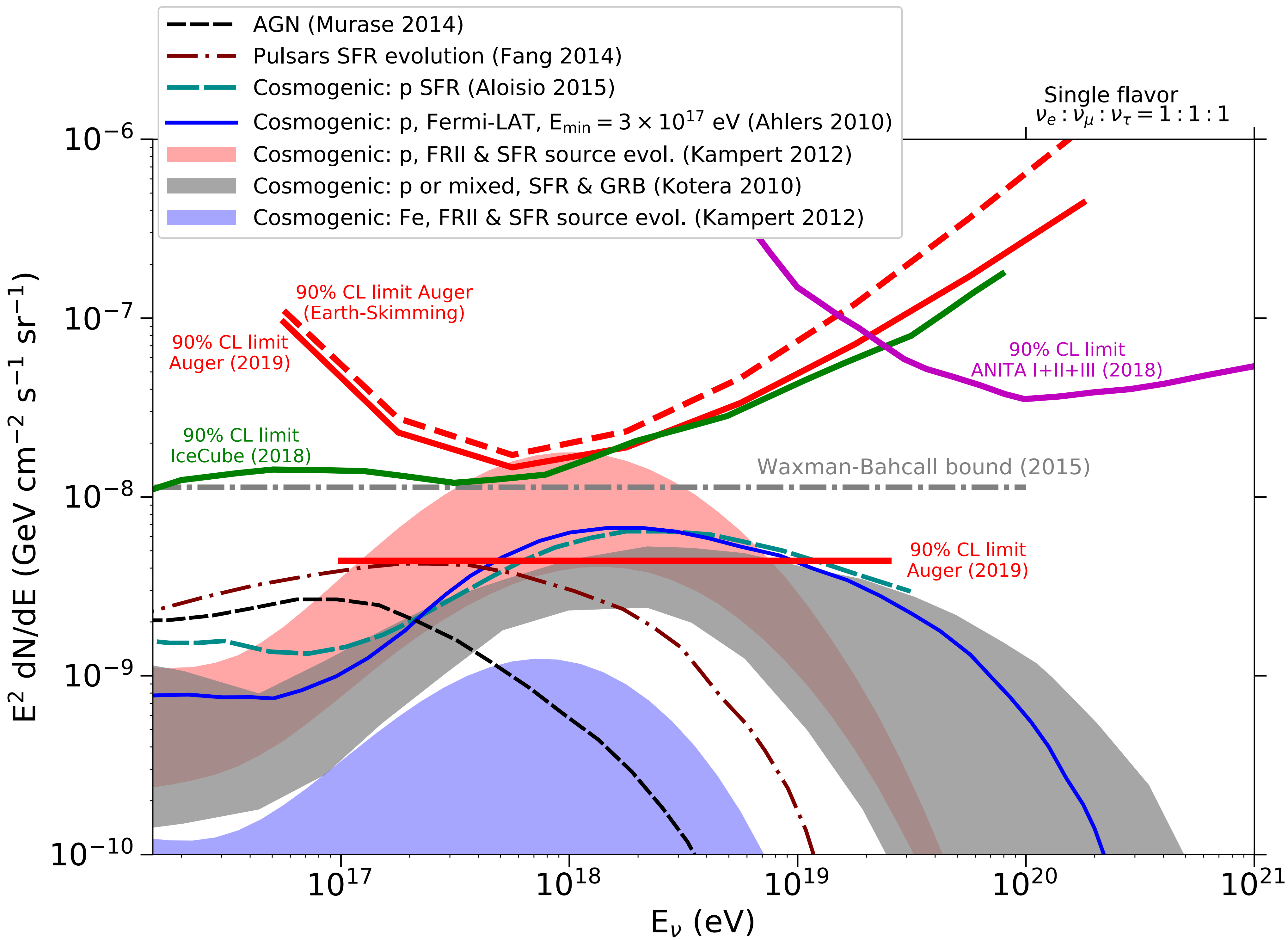
Neutrino detection: Geometry of air showers



Neutrino detection: Geometry of air showers



Neutrino limits

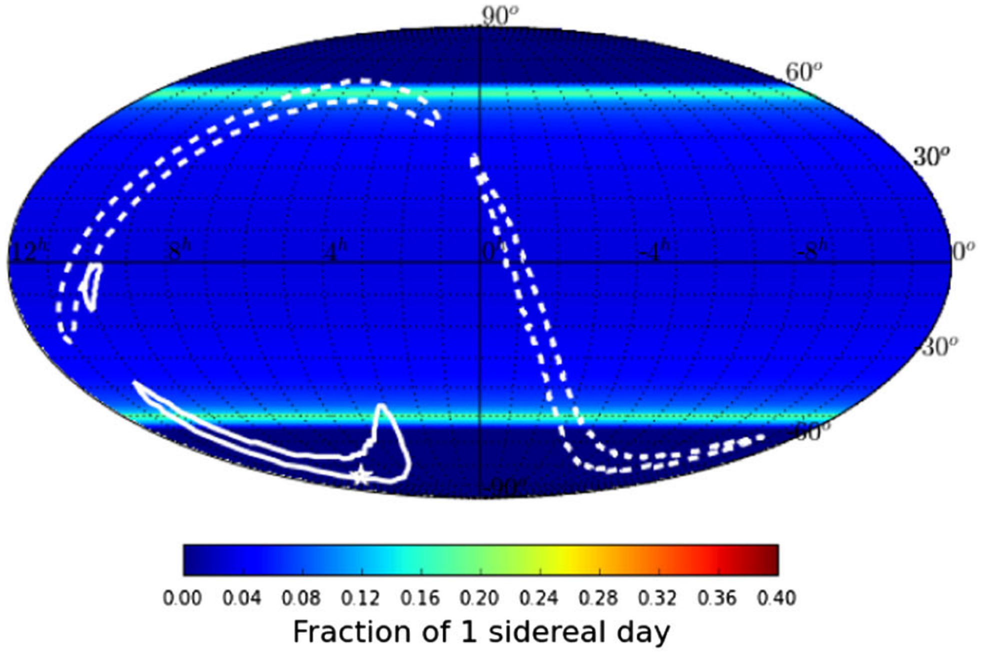


Starts to limit some source models and approach cosmogenic flux predictions

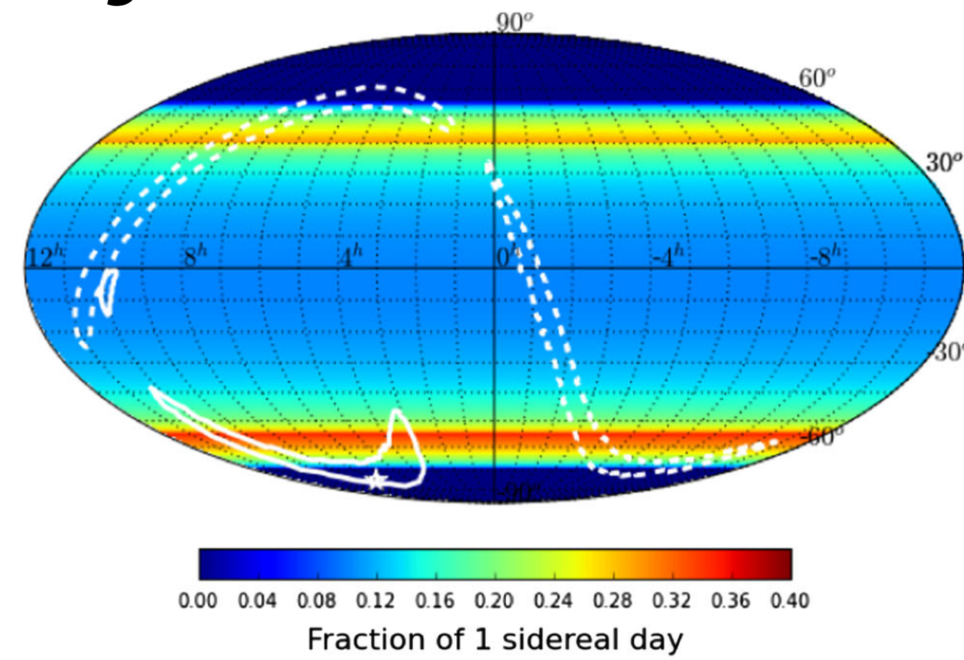
Neutrino followup of Gravitational Wave events

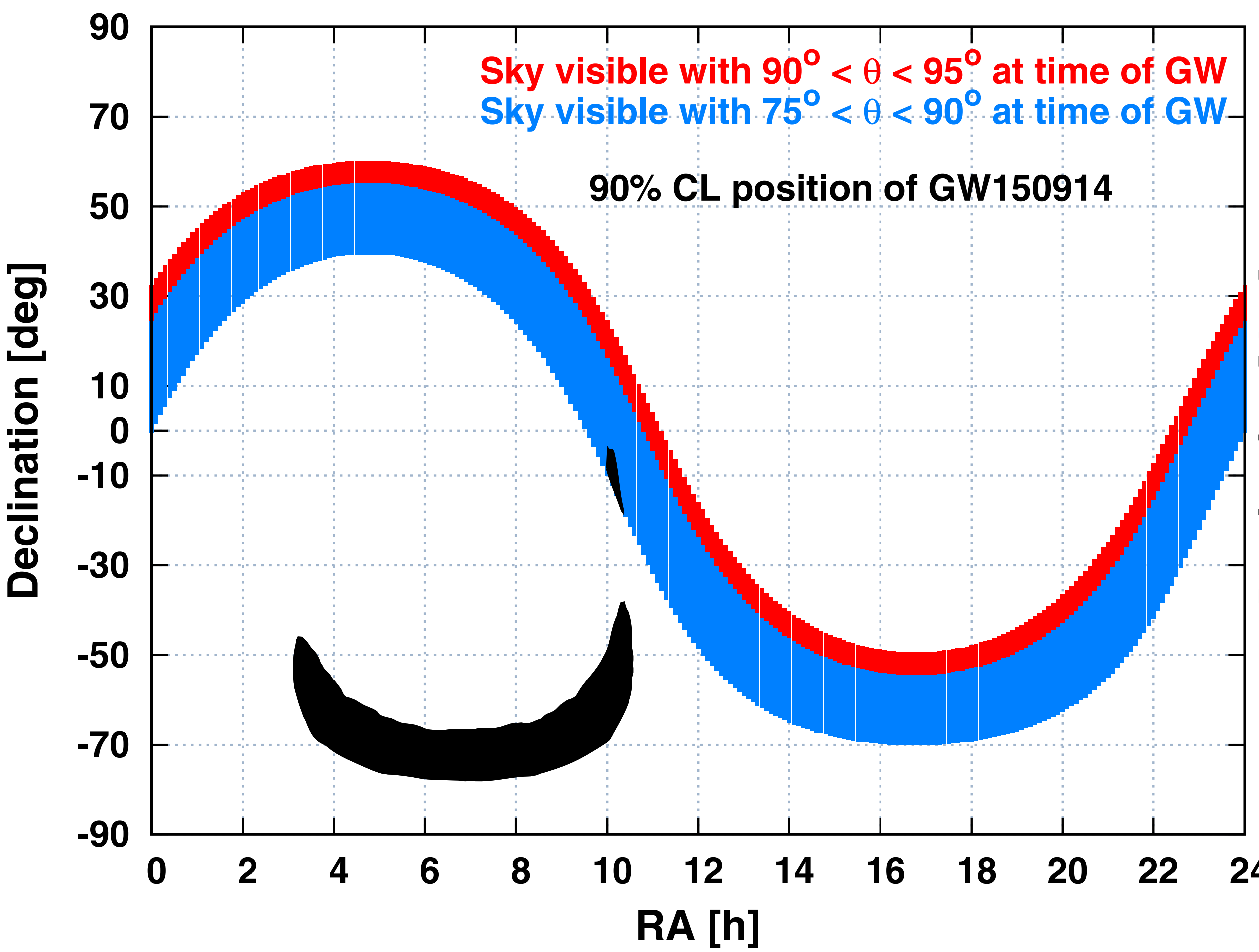
Sensitivity

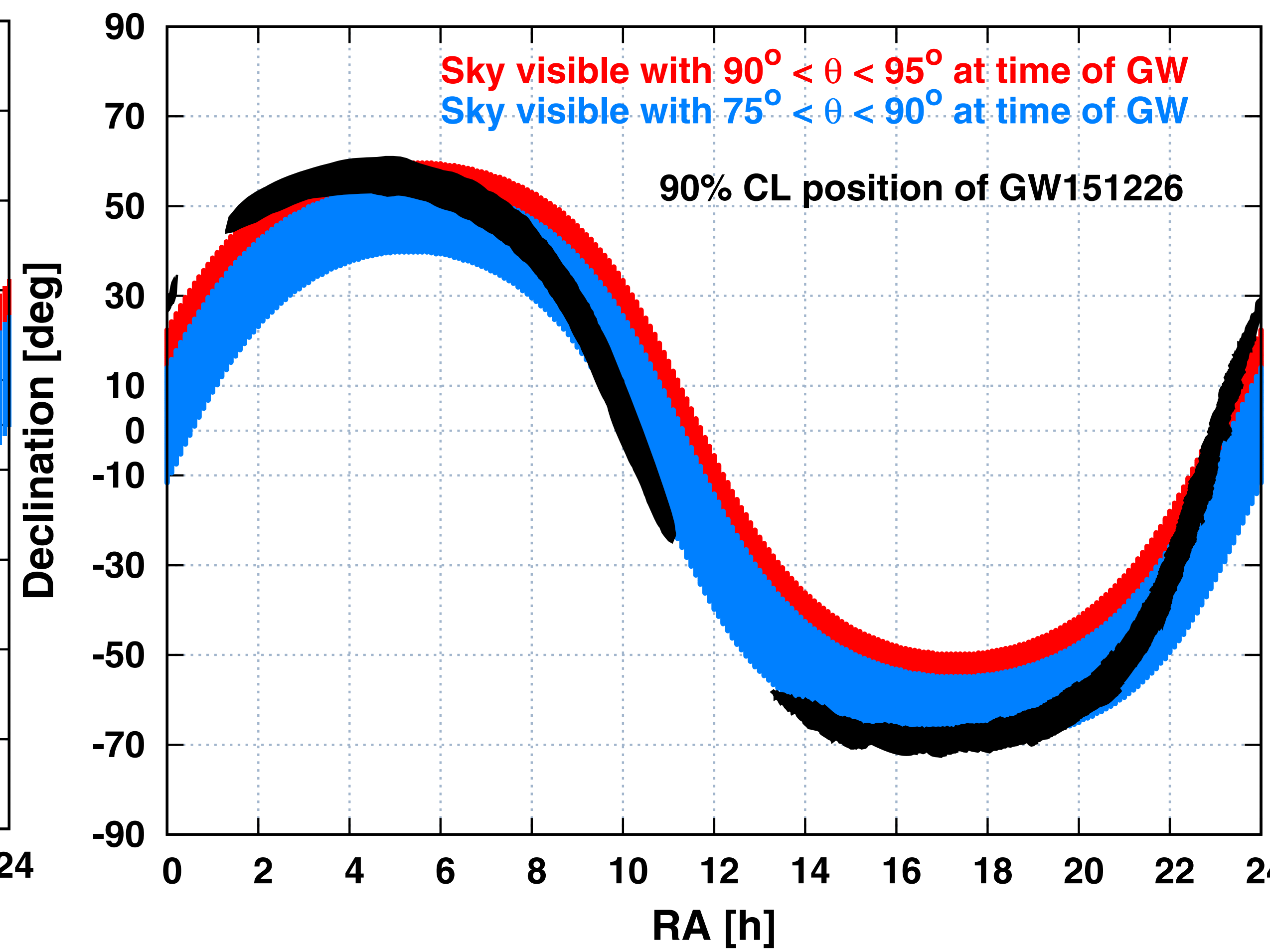
$90° \leq \theta \leq 95°$



$75° \leq \theta \leq 90°$

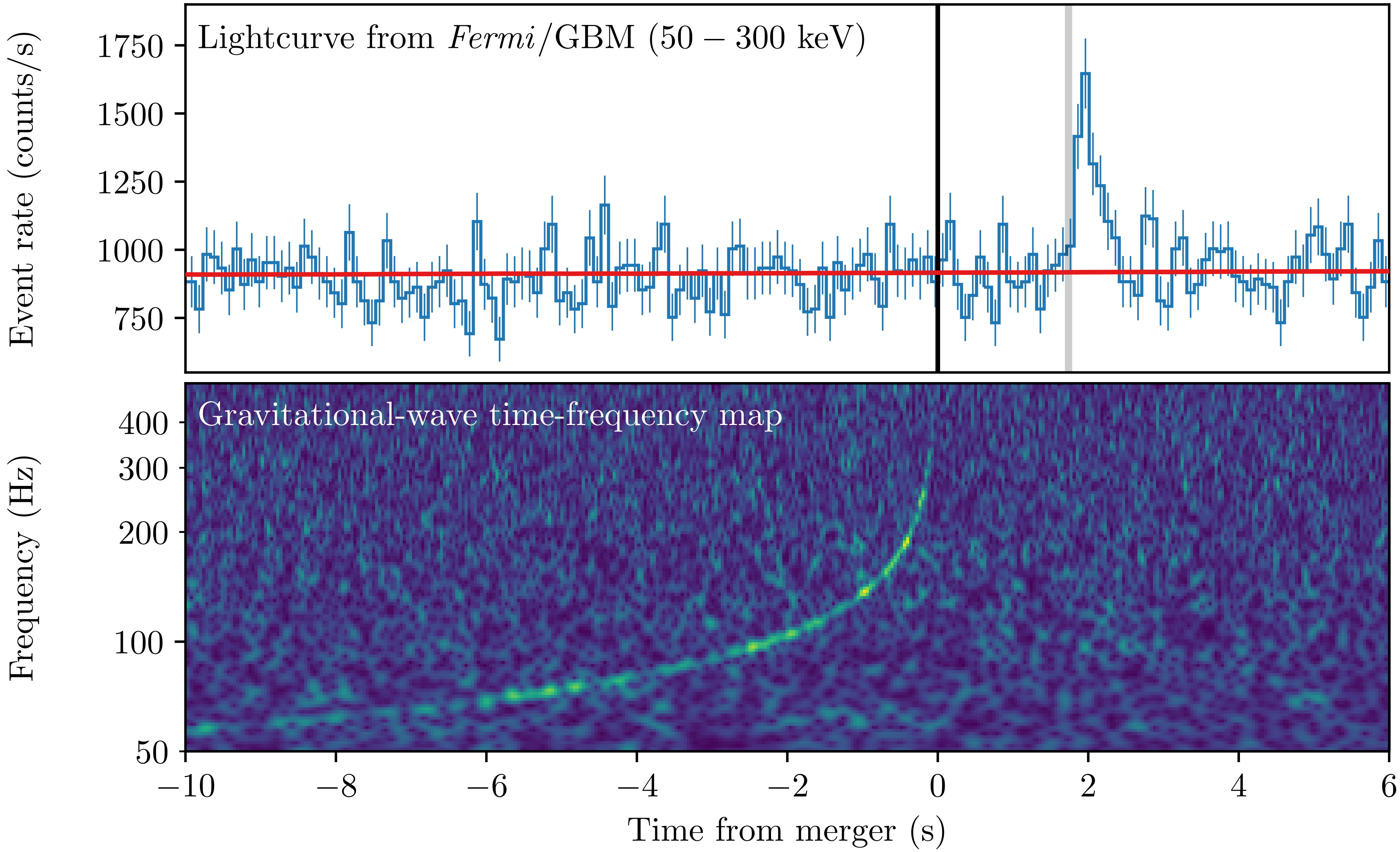




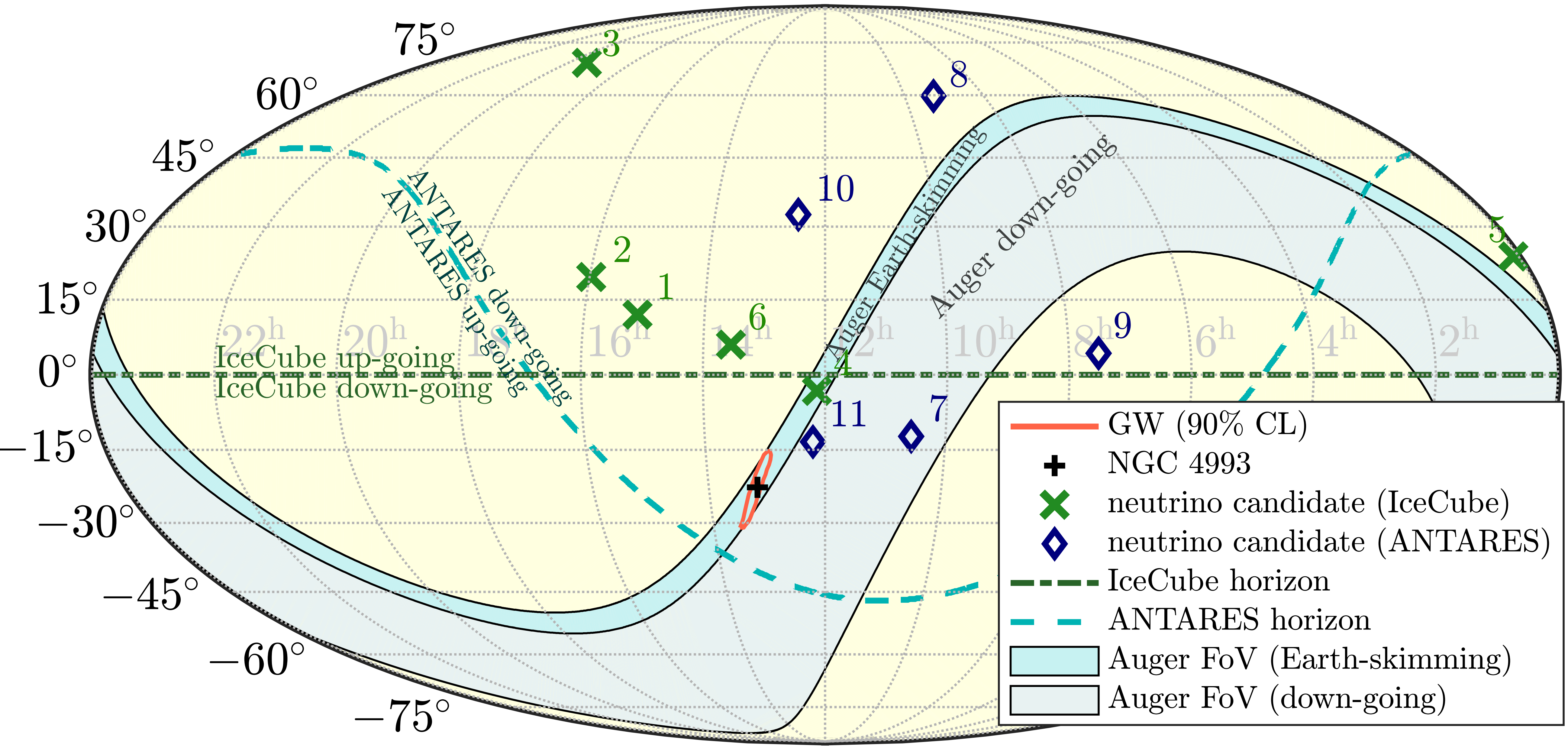


GW170817 / GRB170817A: NS-NS merger

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



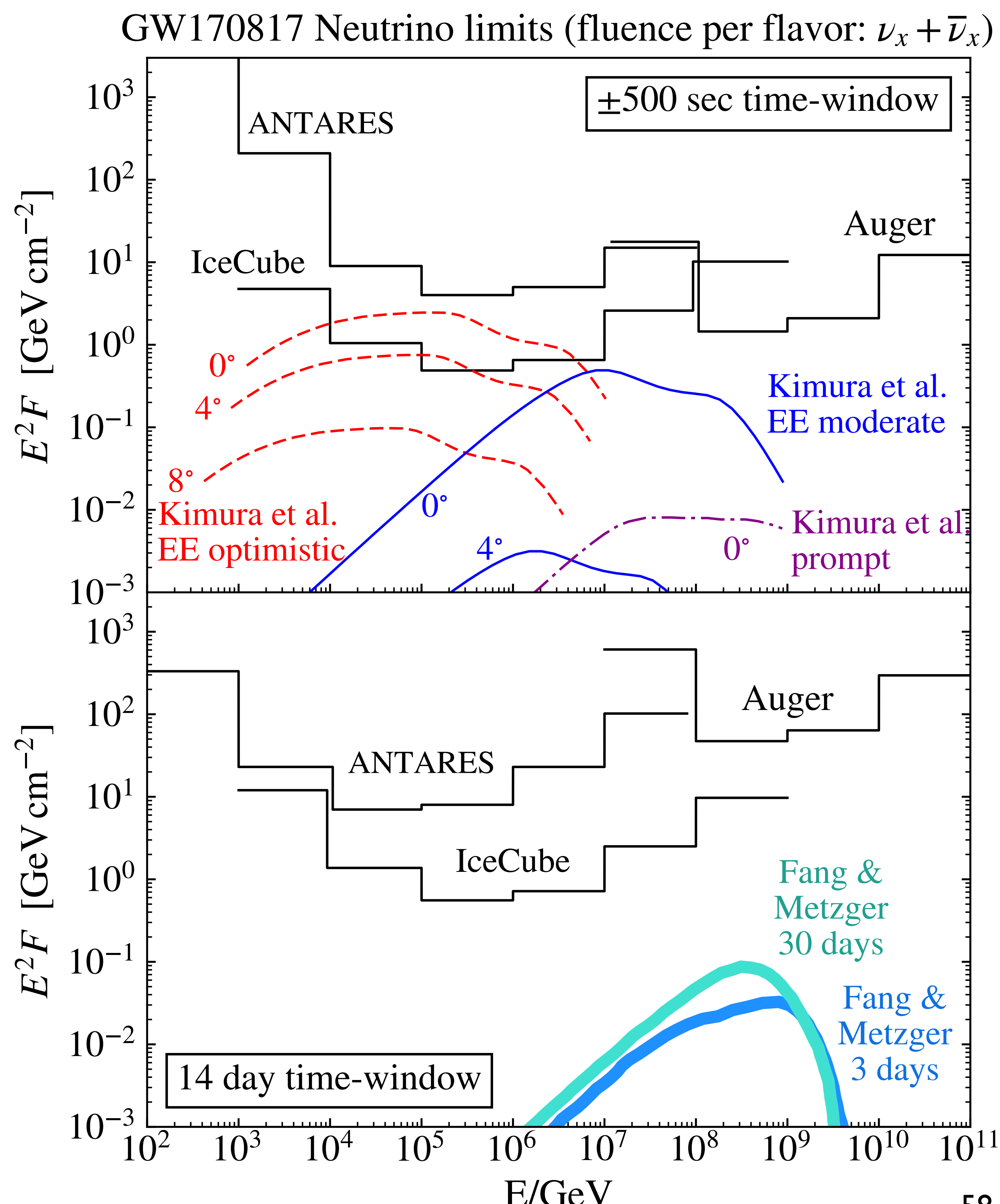
Neutrino Followup: IceCube, Antares, Pierre Auger Observatory

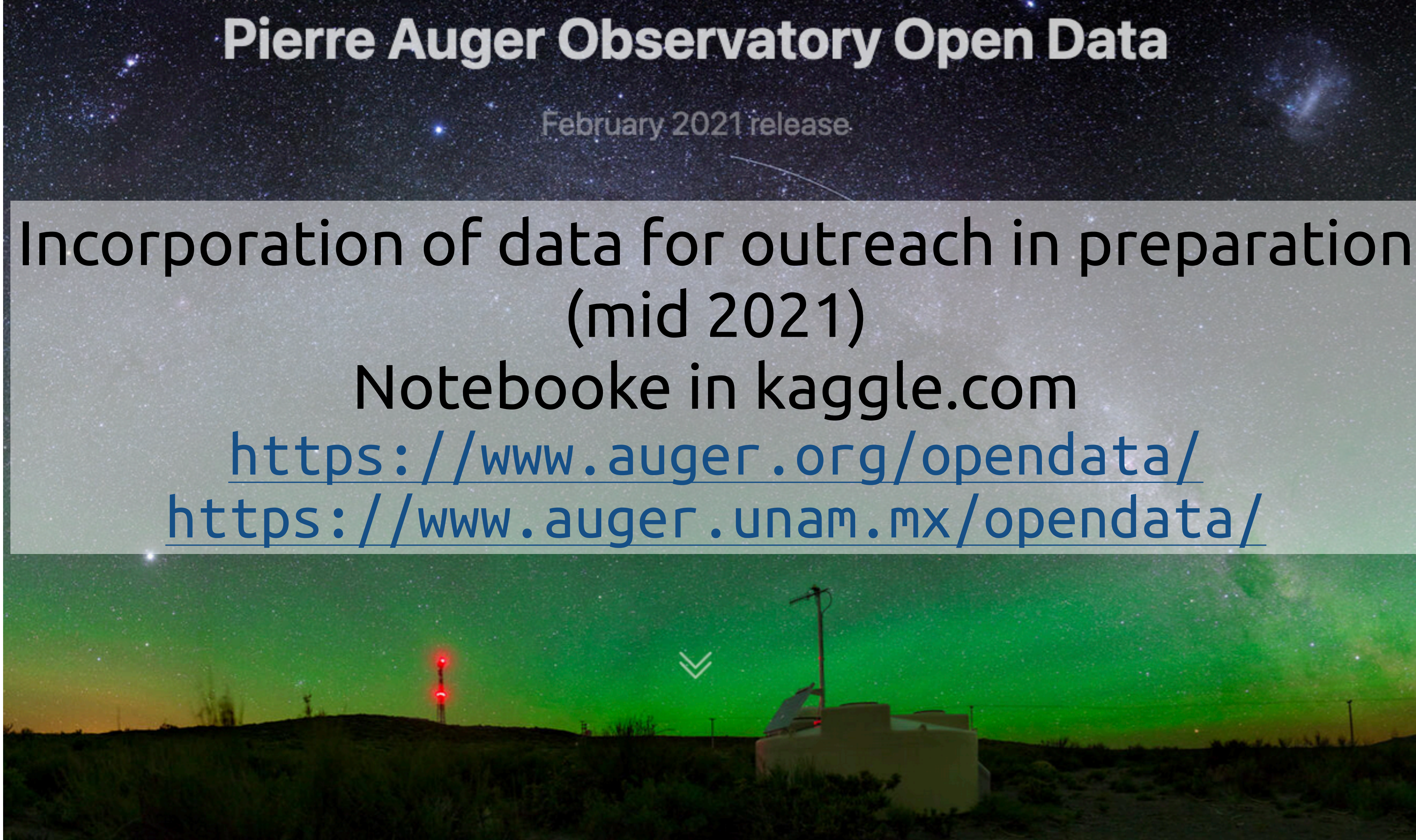


- At time of GW trigger:
  Event in region of maximum sensitivity for Auger

GW170817 Neutrino Limits

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





Incorporation of data for outreach in preparation (mid 2021)

Notebooke in kaggle.com

https://www.auger.org/opendata/

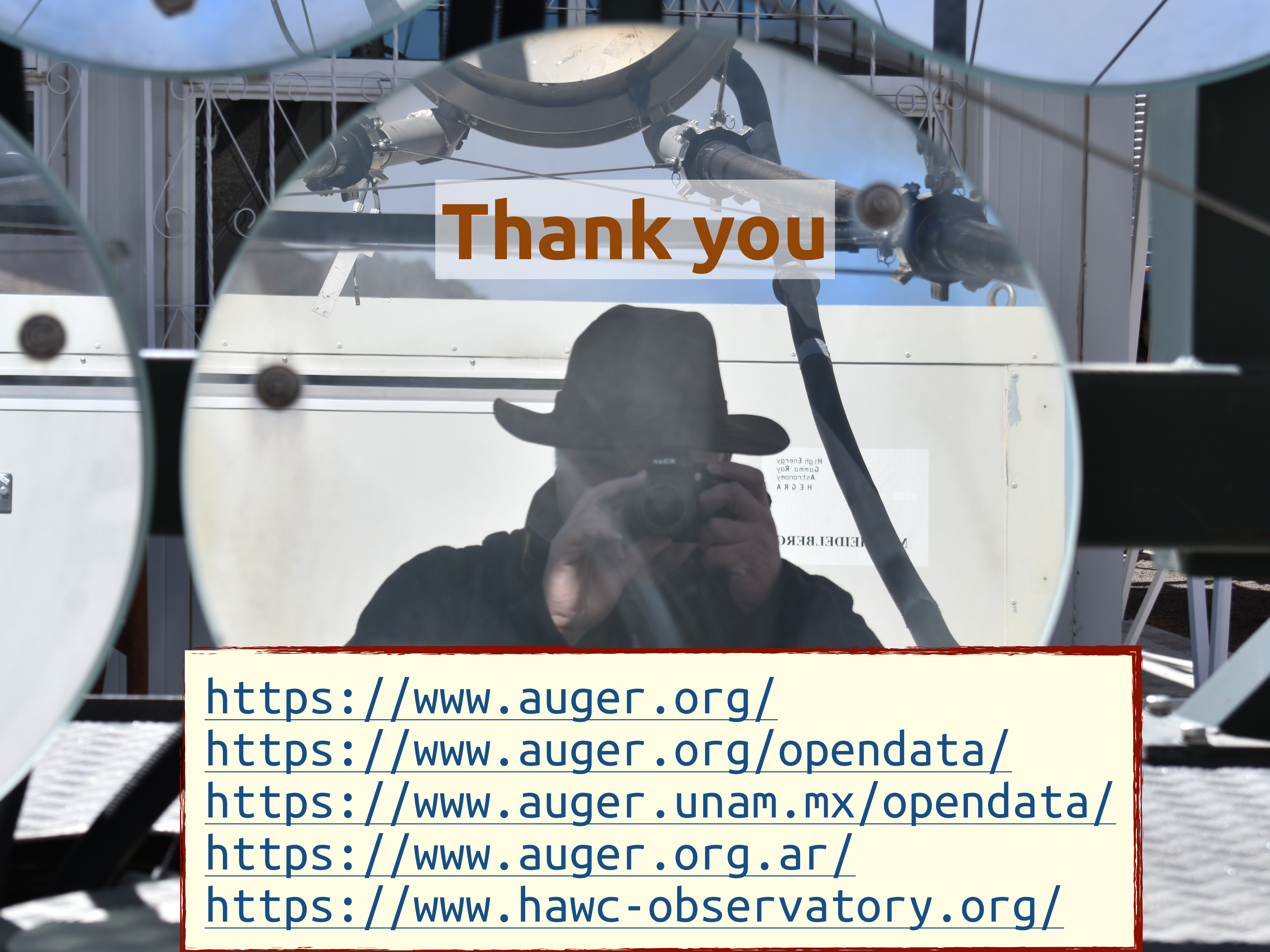
https://www.auger.unam.mx/opendata/

The Pierre Auger 2021 Open Data is the public release of 10% of the Pierre Auger Observatory data presented at the 36th International Cosmic Ray Conference held in 2019 in Madison, USA, following the Auger collaboration open data policy.

This website hosts the datasets for download. An online event display is available to explore the released events, and example analysis codes are provided. See below for a brief overview of the Pierre Auger Observatory and of the Auger Open Data.

Topics not mentioned

- More on Multi-Messenger studies
- Cosmic ray sources
- Cosmic magnetic fields
- Dark matter
- Fundamental physics
  - Lorenz Invarianz Violation (relativity!)
  - Magnetic monopoles
  - proton-Air cross section
  - models of hadronic interactions



Thank you

https://www.auger.org/
https://www.auger.org/opendata/
https://www.auger.unam.mx/opendata/
https://www.auger.org.ar/
https://www.hawc-observatory.org/