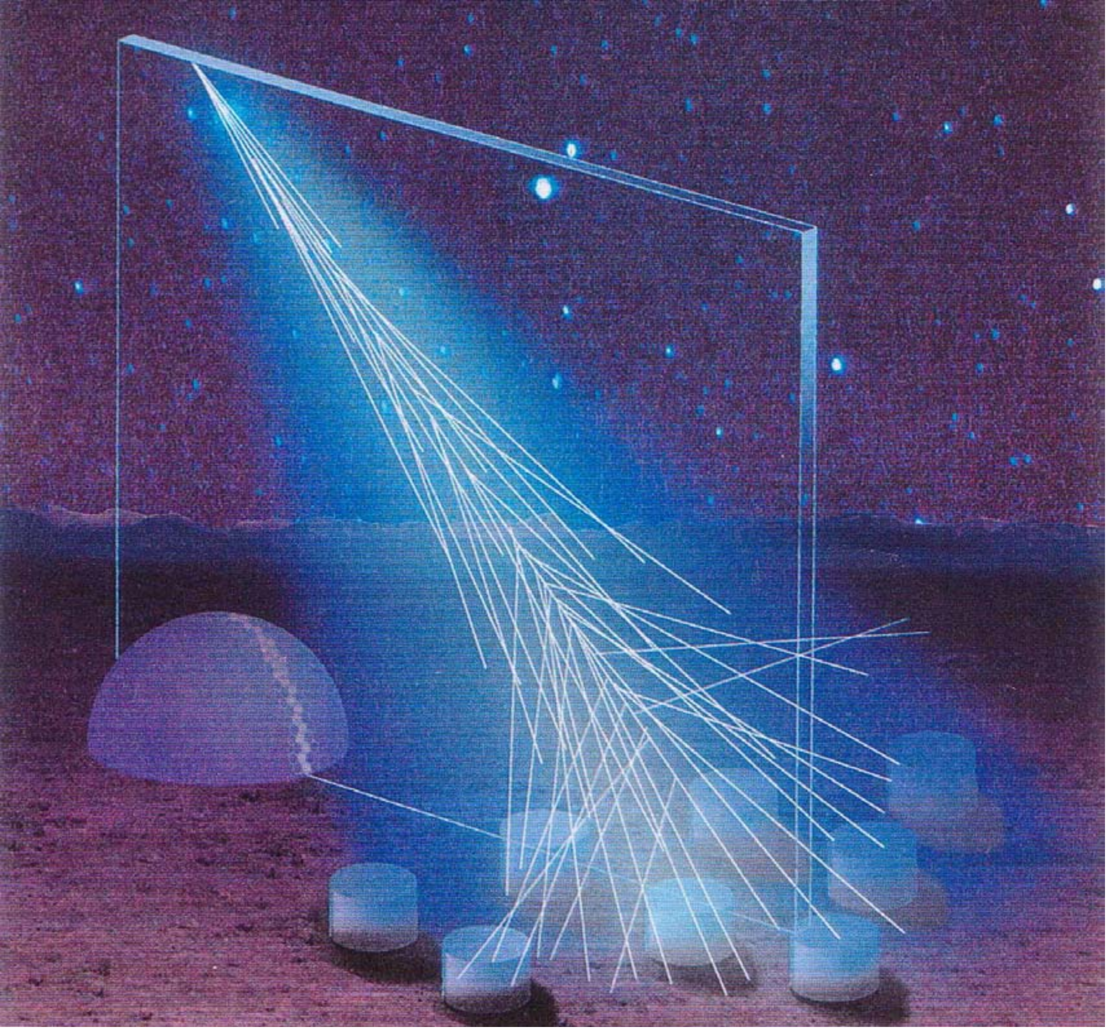


Ultra-High-Energy Cosmic Rays (UHECR)

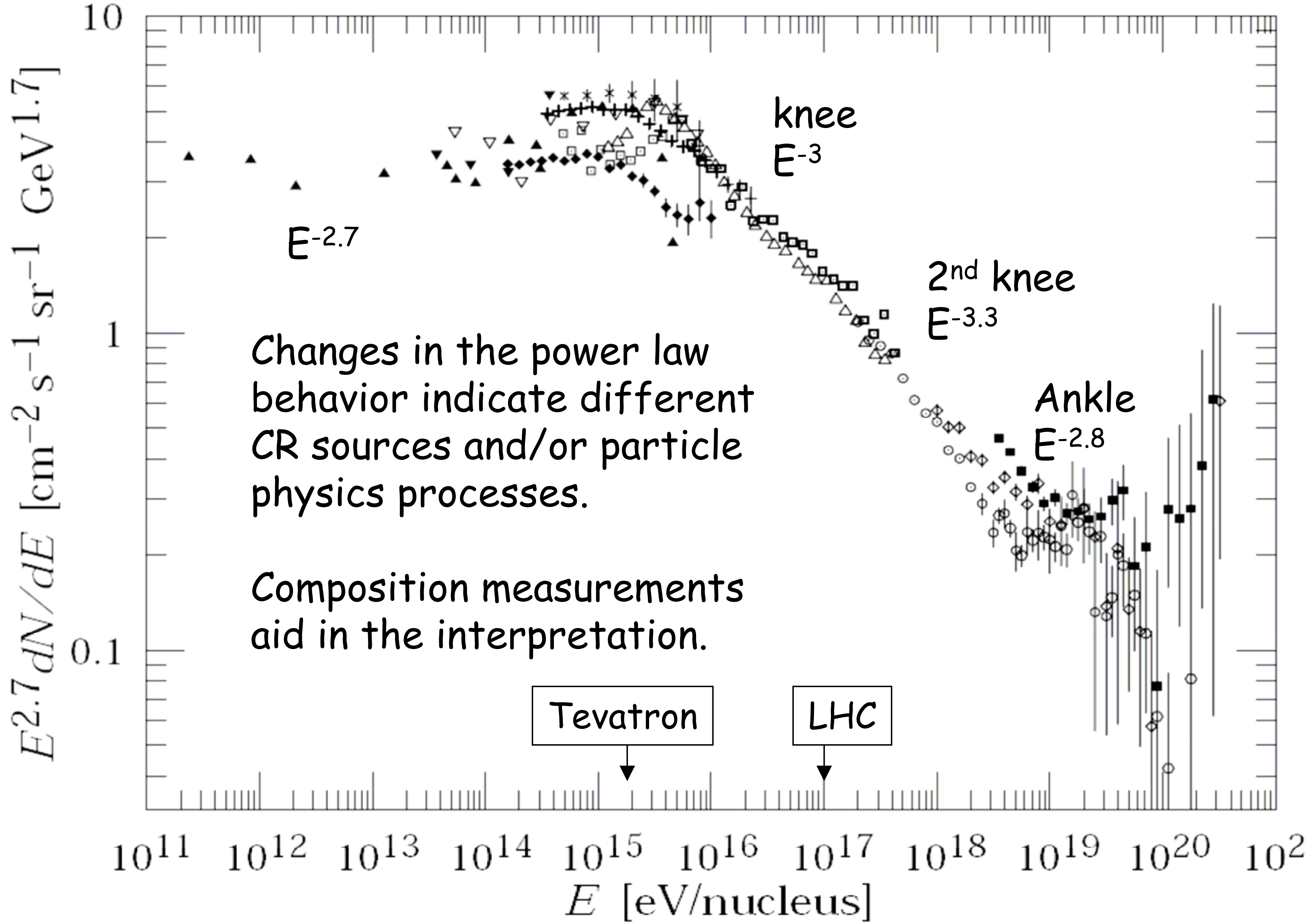
Aaron S. Chou
UTeV lecture
May 3, 2007

Note: this is **_not_** an Auger seminar. Instead, I cover a variety of topics necessary for understanding current experimental results

Some Useful Notation

- New energy unit: exa-electron-volt (EeV) = 10^{18} eV
- Megaparsec (Mpc) = 10^6 * 3.26 light years
- Primary cosmic ray = the first one that hits the atmosphere, as opposed to the particles produced in the air shower
- For air showers, use density-weighted distances: Depth[g/cm^2] = ρ[g/cm^3] * L[cm] to account for varying interaction rates at different atmospheric altitudes.
  - Density of air near ground ~ 100 g/cm^2/km
  - Total vertical depth of atmosphere ~ 1000 g/cm^2
  - Hadronic interaction length ~ 80 g/cm^2
  - dE/dX ionization loss ~ 2 MeV/(g/cm^2)

Cosmic ray all-particle spectrum (PDG2004)



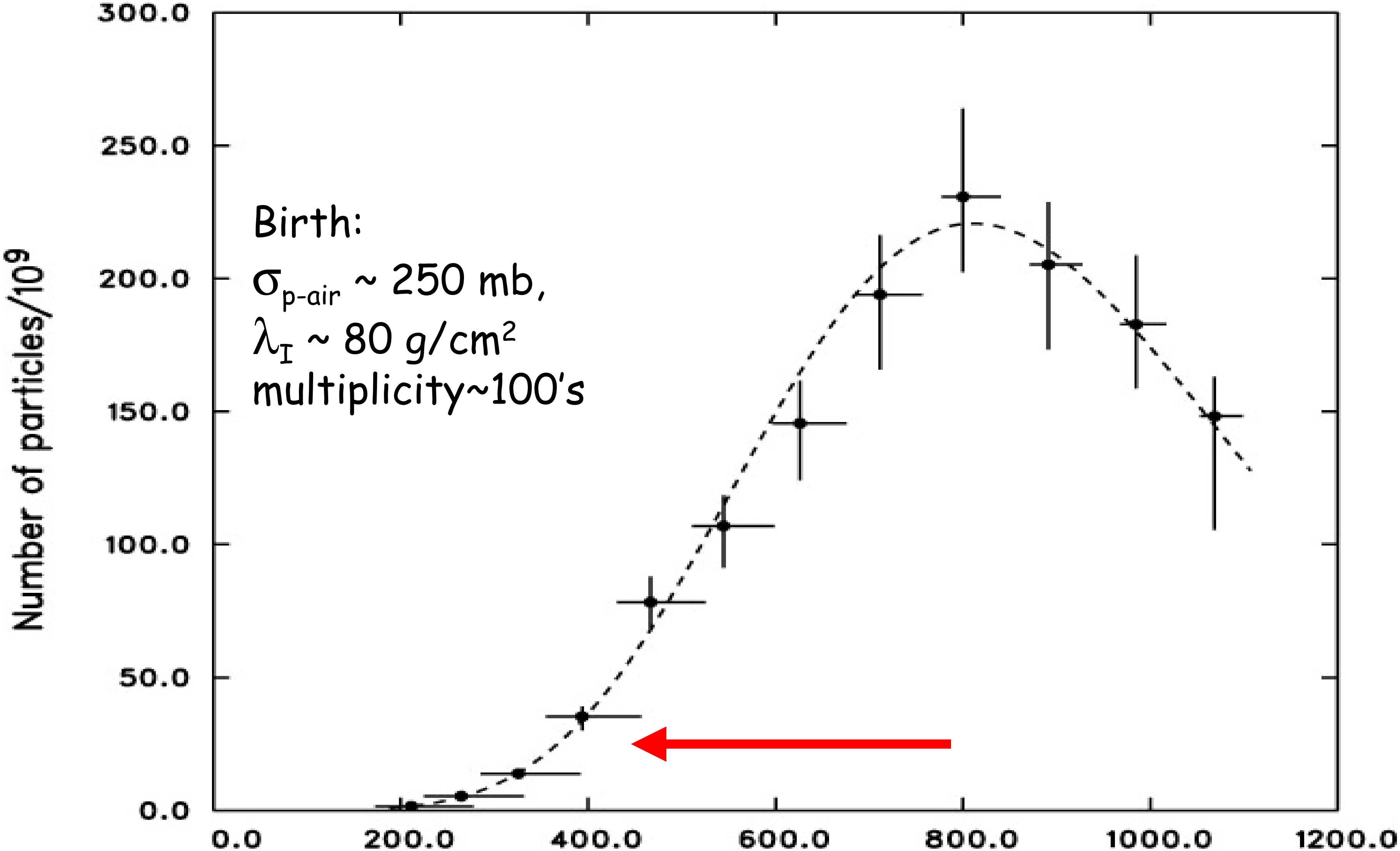
Changes in the power law behavior indicate different CR sources and/or particle physics processes.

Composition measurements aid in the interpretation.

Part 1: Air shower development

Important events in the life of a hadronic cosmic ray air shower

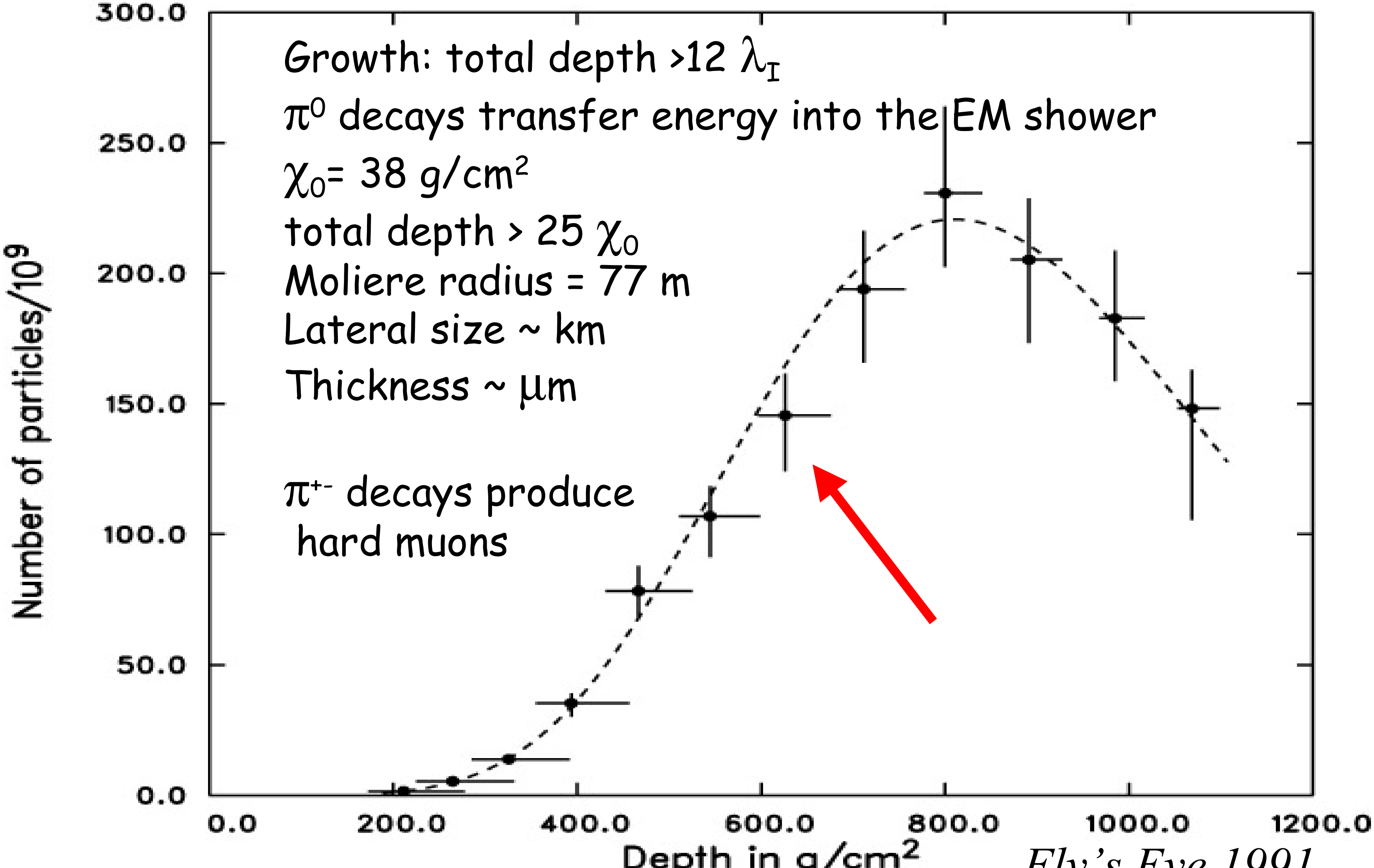
- $E = 3 \times 10^{20}$ eV



Fly's Eye 1991

Important events in the life of a hadronic cosmic ray air shower

- $E = 3 \times 10^{20}$ eV



Growth: total depth >12 λ_I

π^0 decays transfer energy into the EM shower

χ_0= 38 g/cm^2

total depth > 25 χ_0

Moliere radius = 77 m

Lateral size ~ km

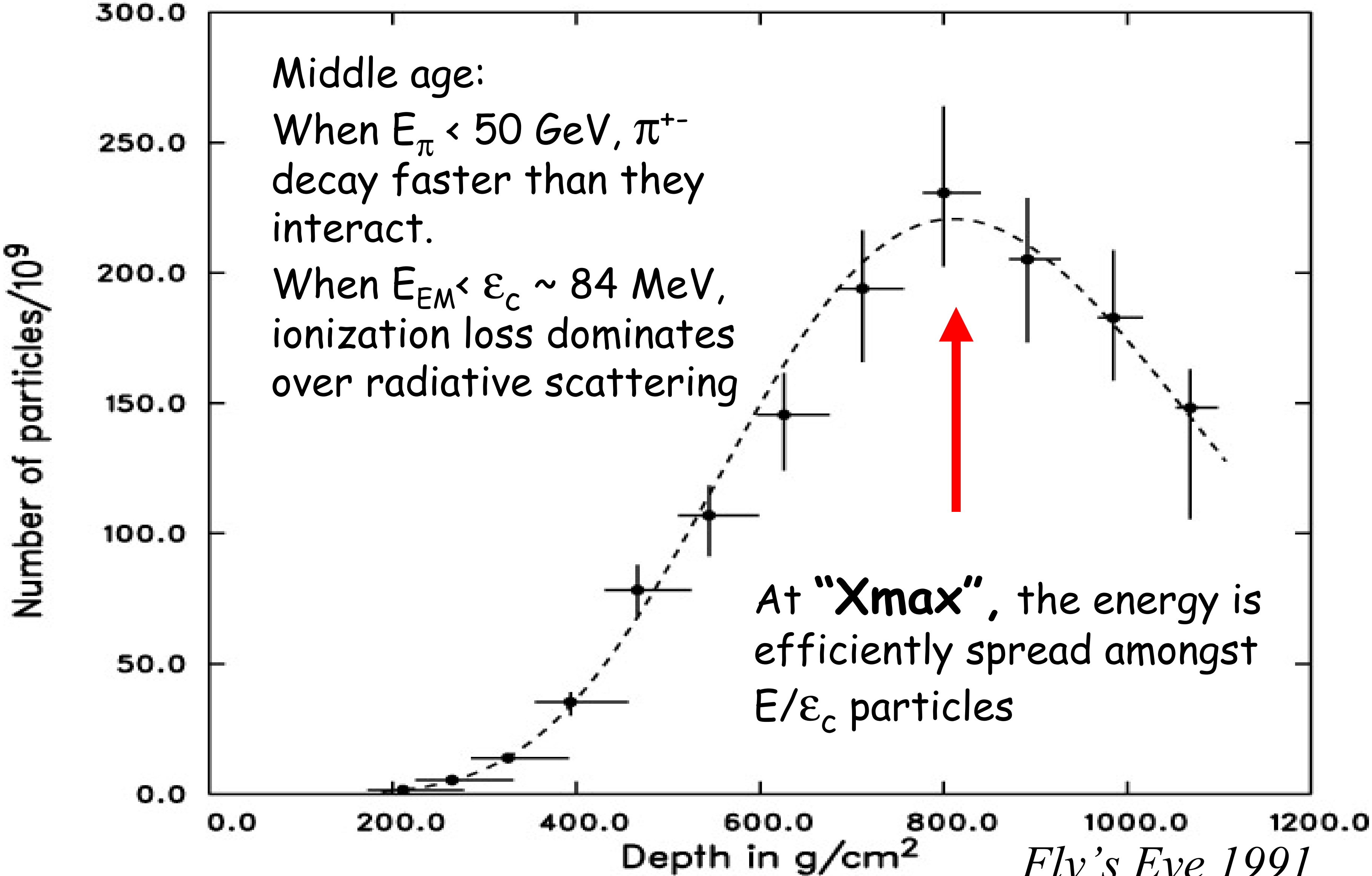
Thickness ~ µm

π^{+-} decays produce hard muons

Fly's Eye 1991

Important events in the life of a hadronic cosmic ray air shower

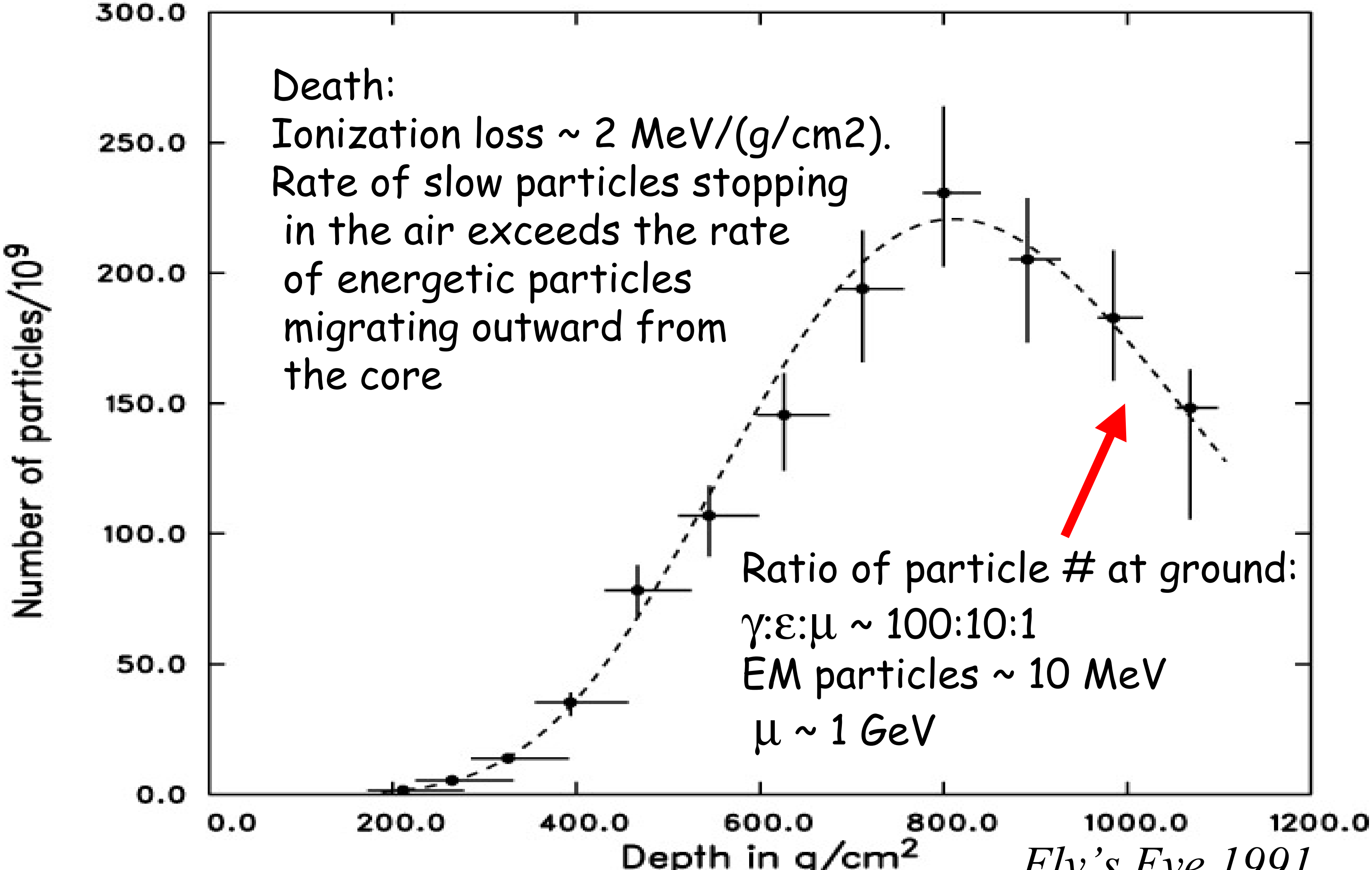
• $E = 3 \times 10^{20}$ eV



Fly's Eye 1991

Important events in the life of a hadronic cosmic ray air shower

- $E = 3 \times 10^{20}$ eV



Fly's Eye 1991

Part 2: Detection techniques

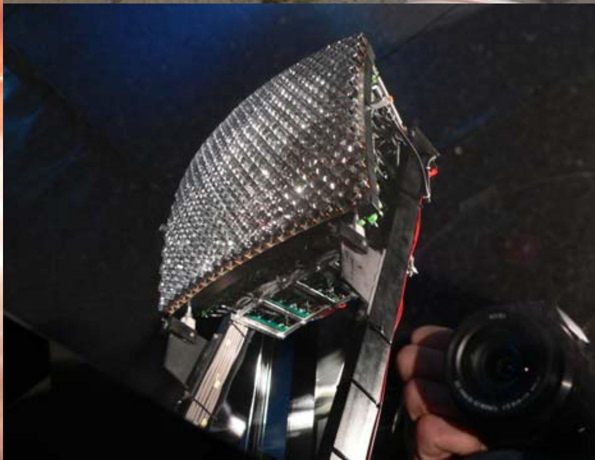
Calorimetry via air fluorescence

Fluorescence:
~4 photons/m/MIP in the UV.
(air shower ~ 100W light bulb)

Proportional to ionization loss.

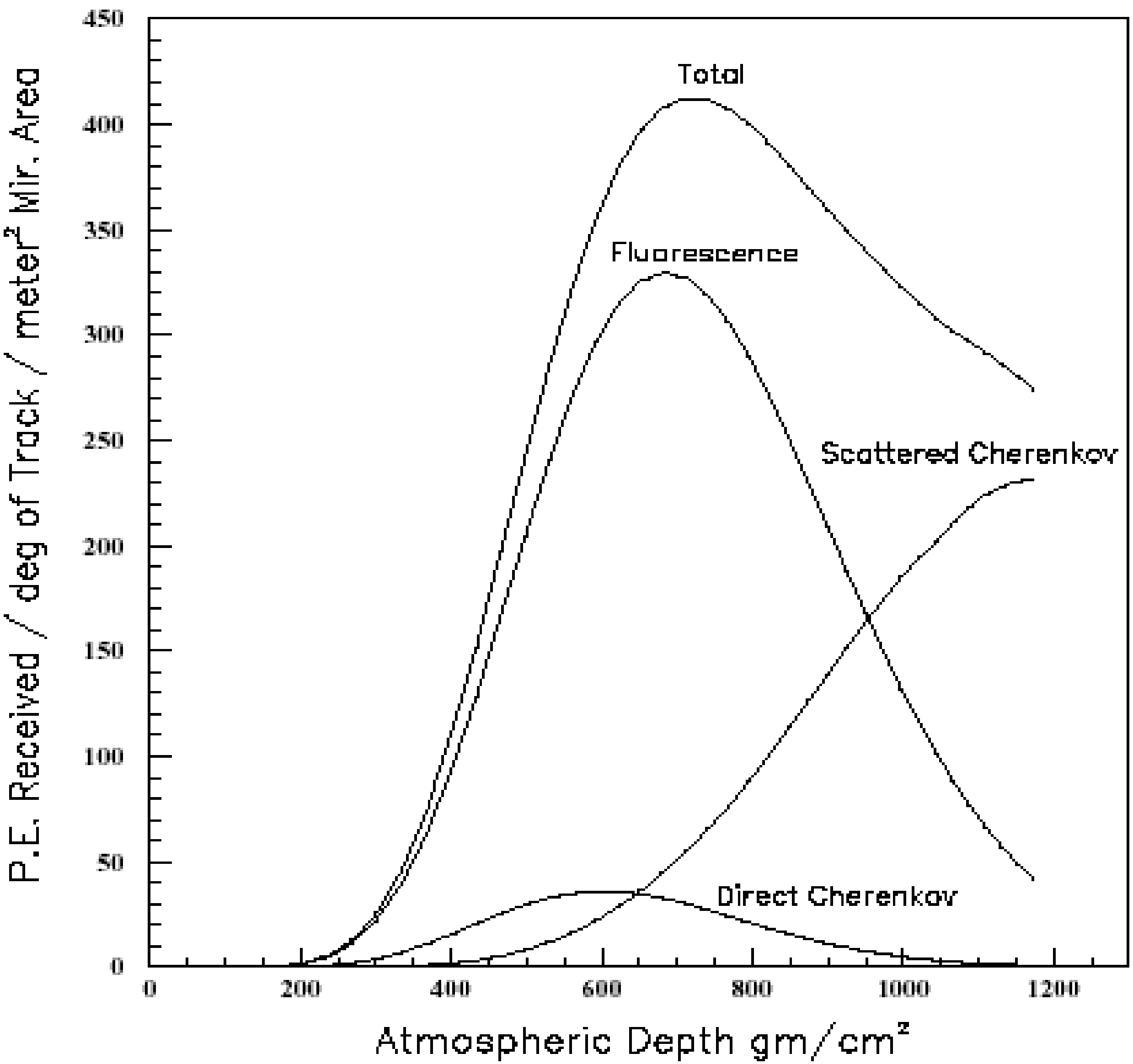
Image the UV photons onto a pixel detector, and convert the longitudinal signal profile into a dE/dX profile.

Integrate, and correct for invisible energy.



Expts:
Fly's Eye,
HiRes,
Auger,
Telescope Array

Converting photons received into MIPs is not easy

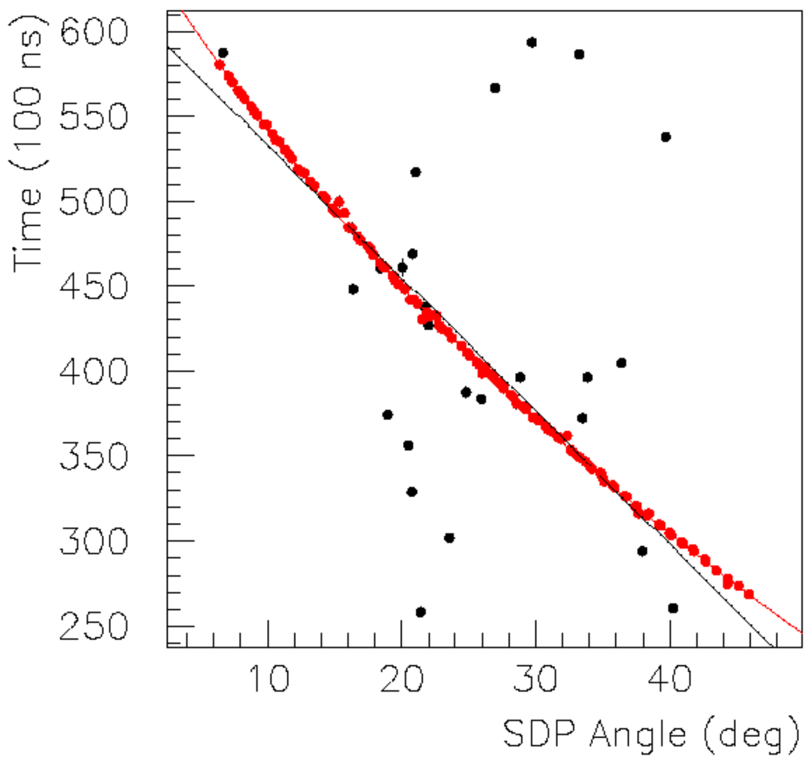


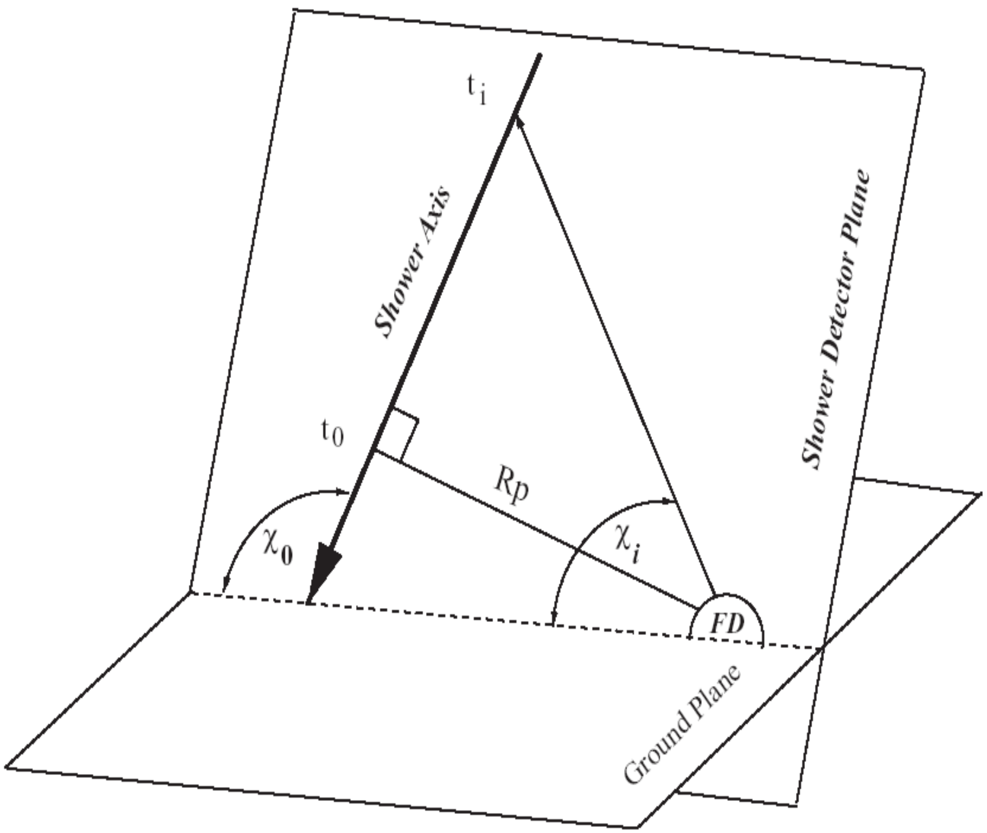
Need to correct for Rayleigh scattering and Mie scattering on the aerosols.

The Cherenkov light produces a large contamination.

Need to monitor the atmosphere with test beams, LIDAR, weather balloons, cloud cameras….

Fluorescence monocular geometric reconstruction

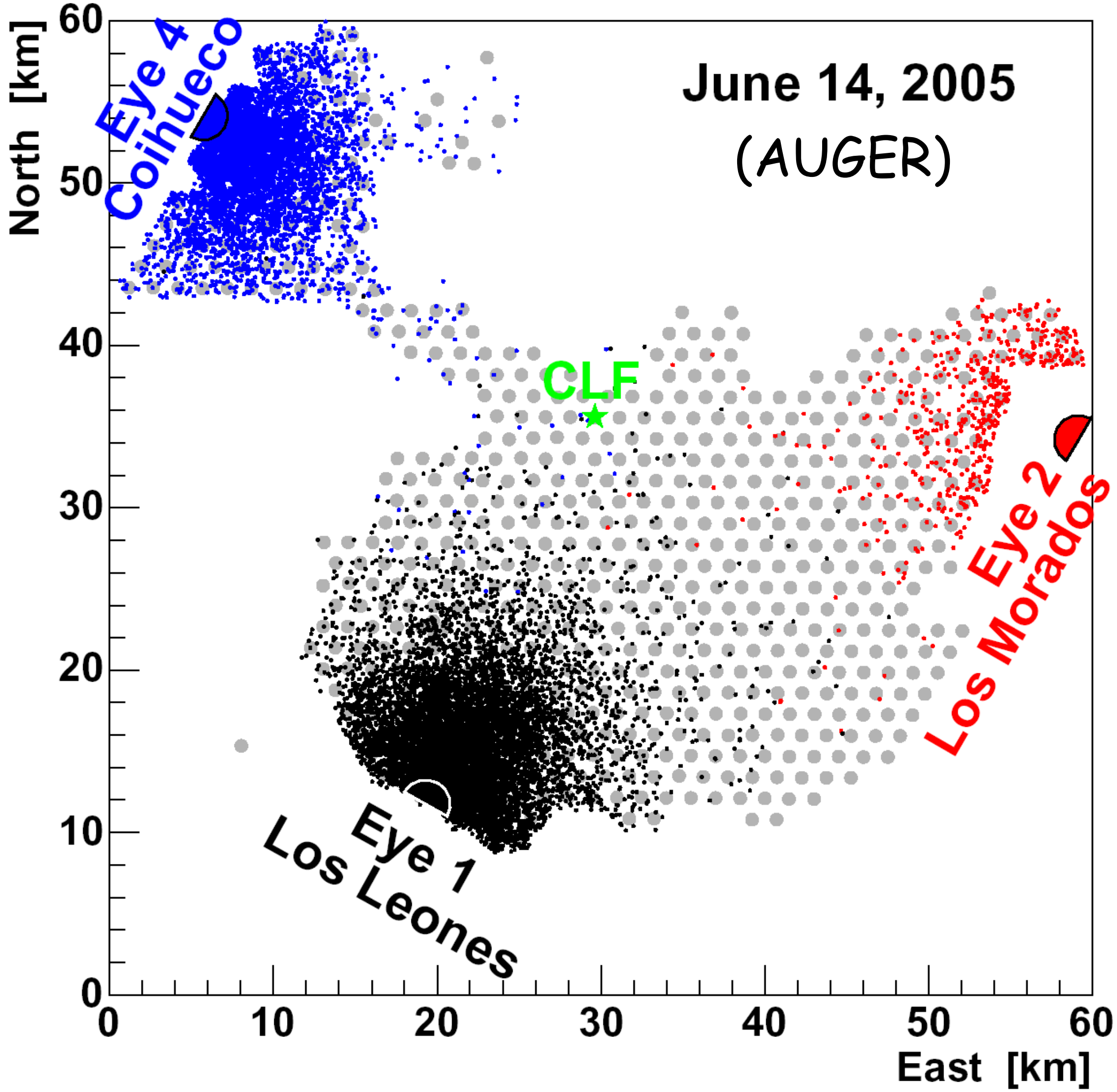




$$t_{i,\exp} = t_0 + R_p/c \tan[(\chi_0 - \chi_i)/2]$$

Very poor resolution (due to short tracks, poor timing resolution). Instead, HiRes1 must assume that the CRs have proton-like interaction lengths and constrain their geometries to produce proton-like dE/dX profiles.

How far away do you think you can really see?



Lower energy events are dimmer and can only be seen close to the telescopes. They suffer from larger Cherenkov contamination.

Higher energy events can be seen further away. The angular span of the viewed track is much smaller, and there is more atmospheric attenuation.

It is very difficult to estimate the energy-dependent Fluorescence aperture to produce an energy spectrum measurement.

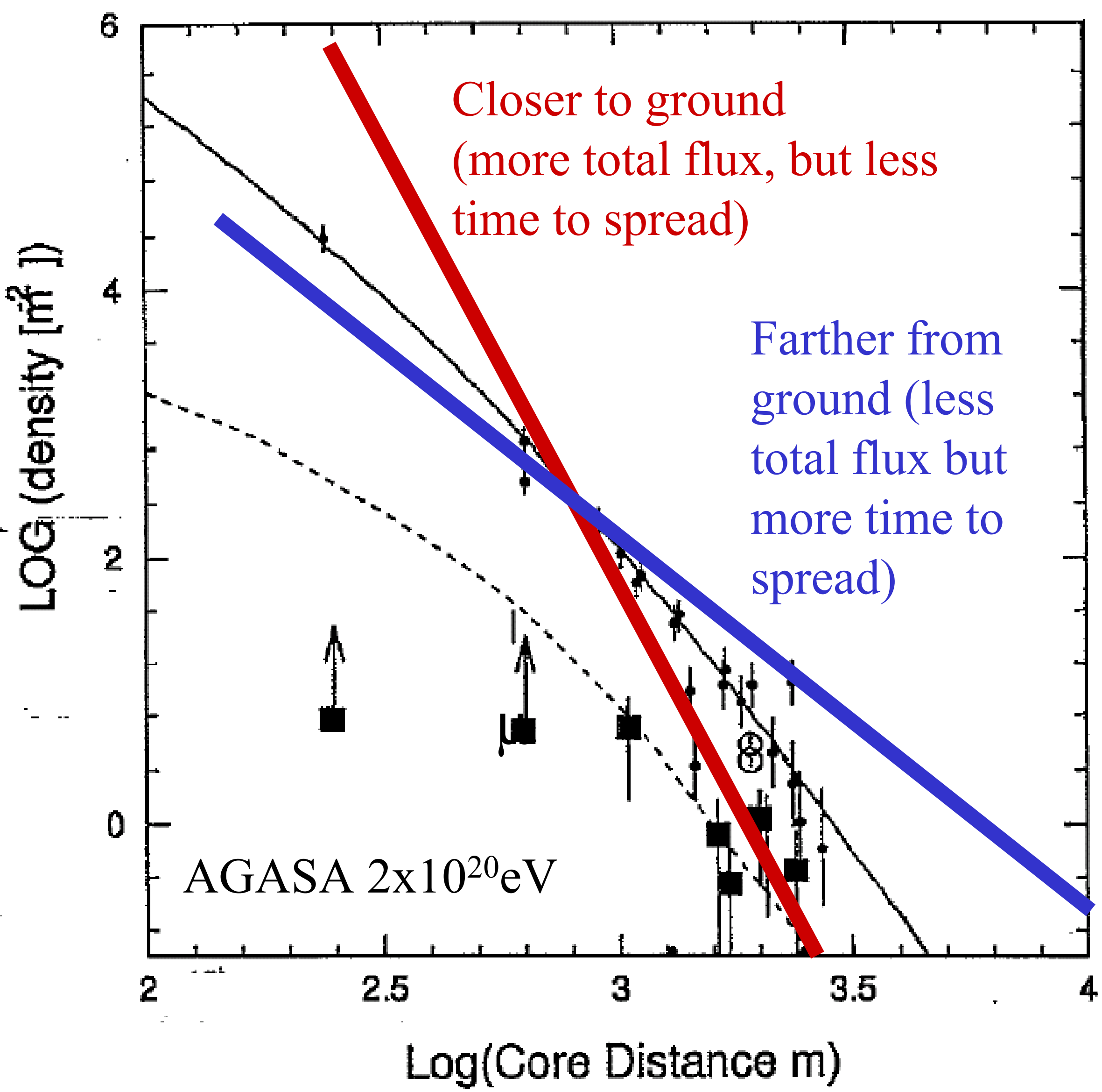
Surface detector arrays to measure the transverse profile at the ground plane

Water Cherenkov measures
EM + 25x muons

Unshielded scintillators
measure mainly EM.

Volcano Ranch, Yakutsk, Haverah Park, AGASA, SUGAR, Auger, Telescope Array

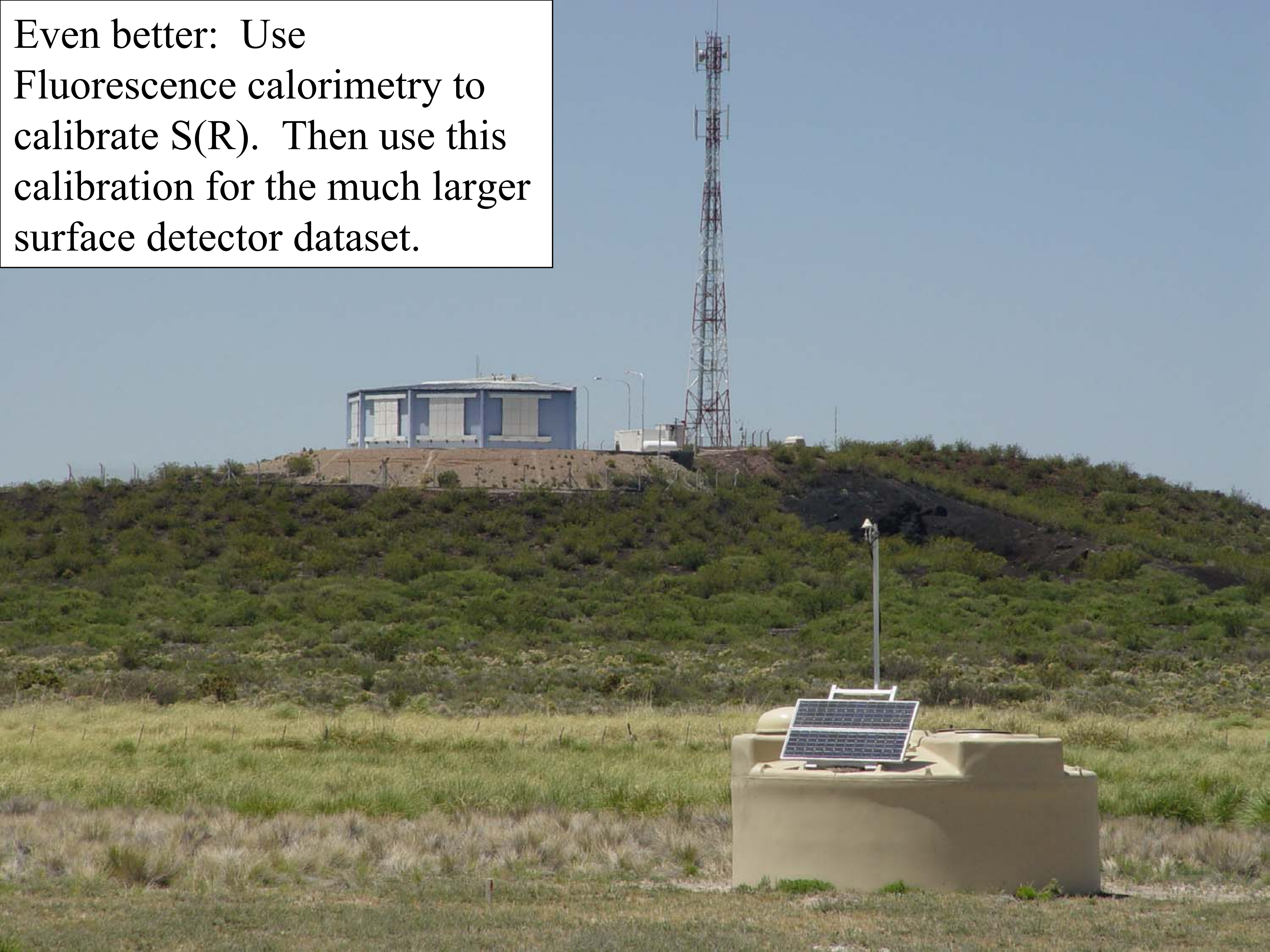
Plot Signal vs transverse core distance. The signal flux normalization is related to the CR energy



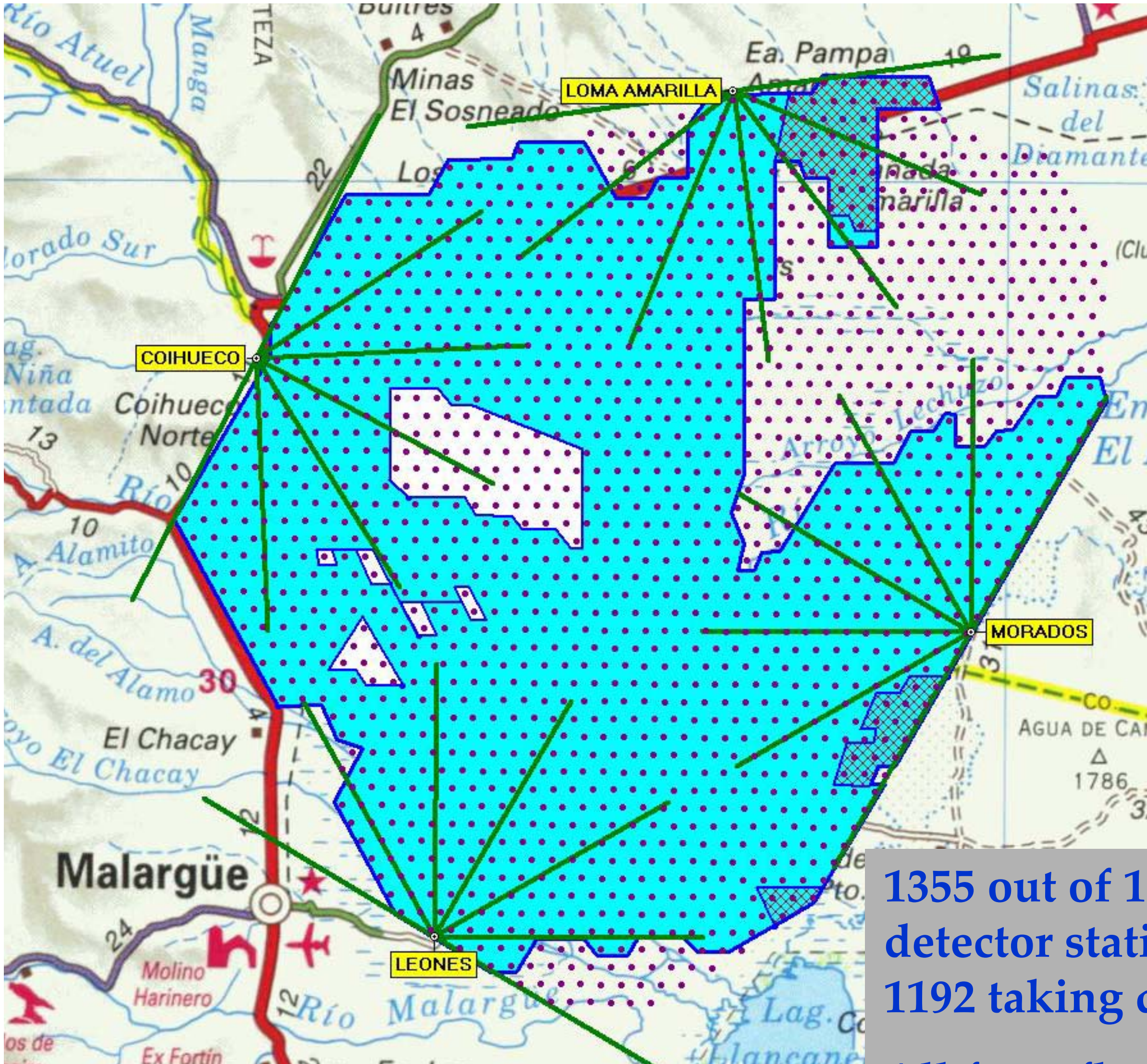
While the total integrated ground flux is exponentially sensitive to event-by-event fluctuations in the shower penetration depth, **an interpolated parameter S(R) at finite core distance is rather insensitive to this stochastic uncertainty.**

Use Monte Carlos to map S(R) onto CR energy.

Even better: Use Fluorescence calorimetry to calibrate S(R). Then use this calibration for the much larger surface detector dataset.



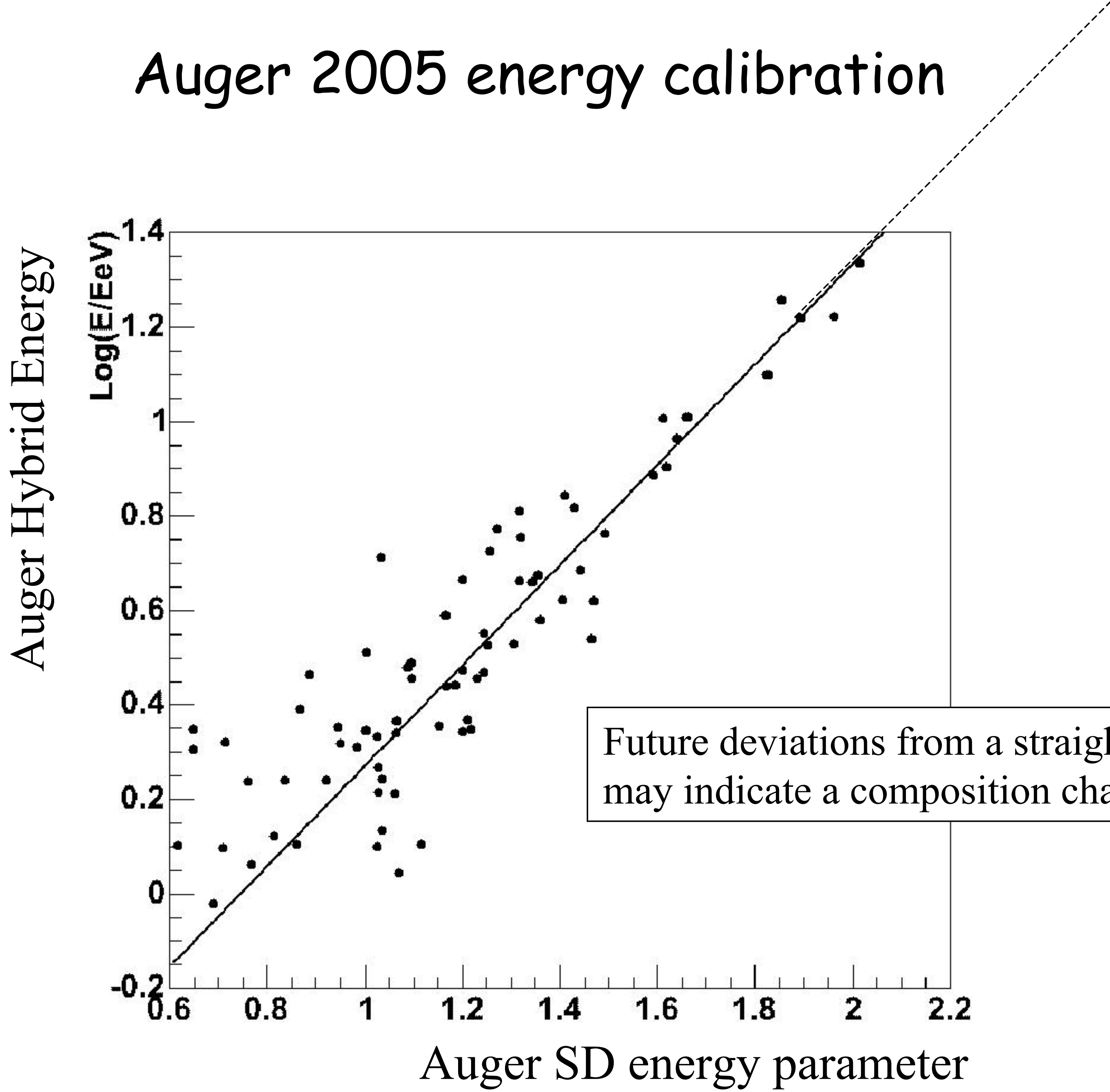
Auger Status



1355 out of 1600 surface detector stations deployed – 1192 taking data.

All four fluorescence buildings now operational

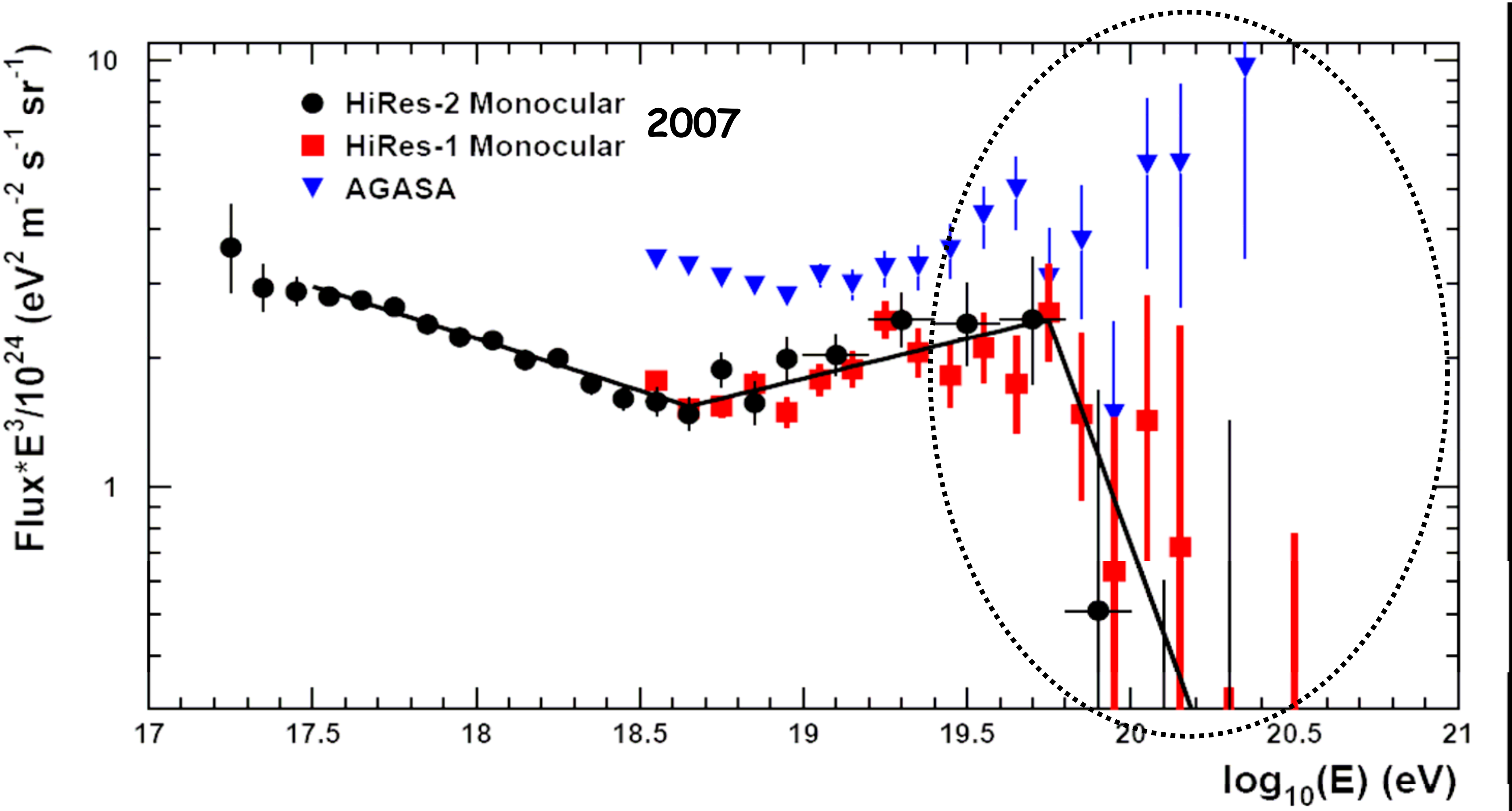
Auger 2005 energy calibration



Future deviations from a straight line may indicate a composition change

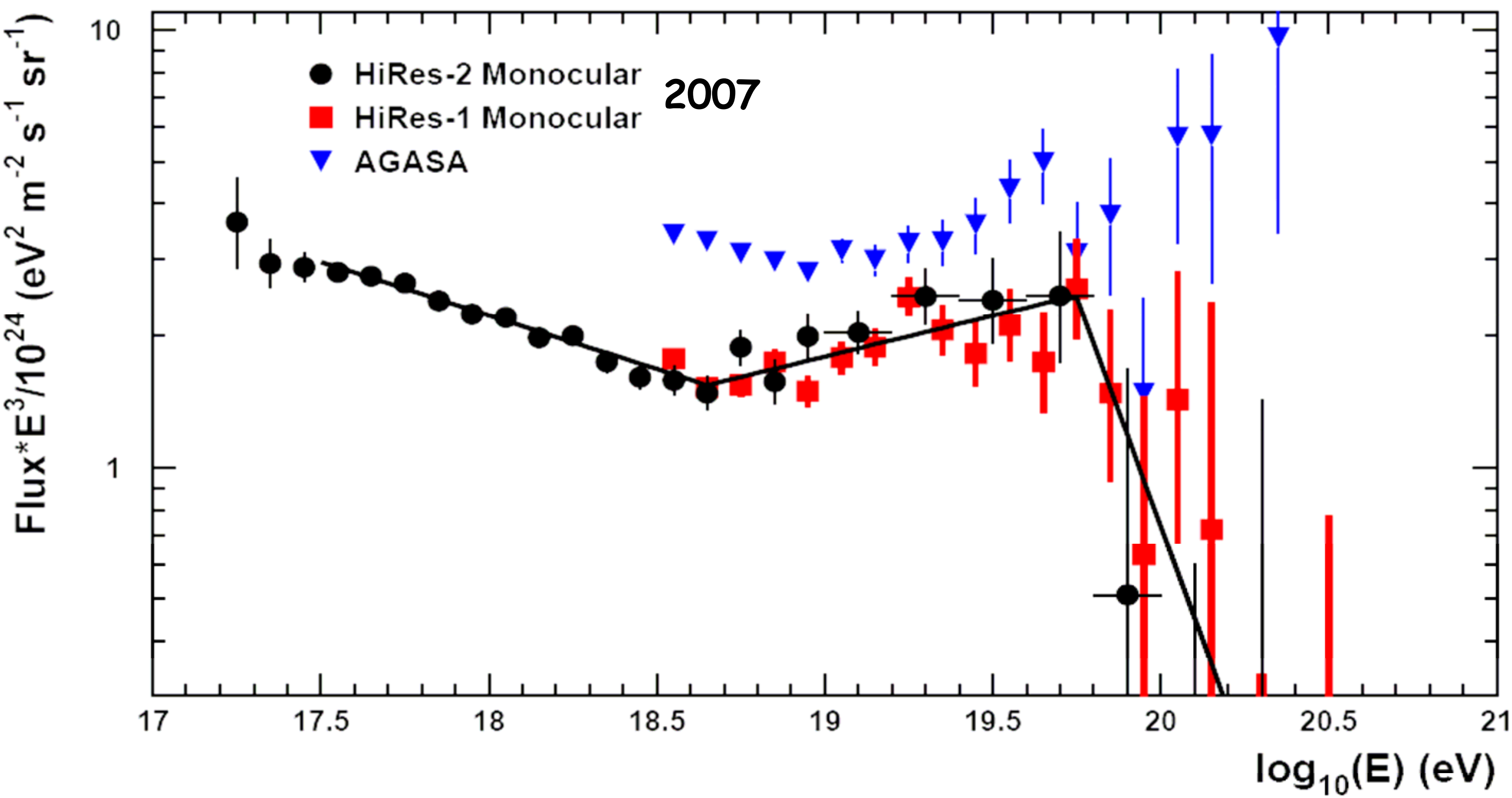
Part 3: Conventional Physics.
CR from astrophysical sources

At the highest energies



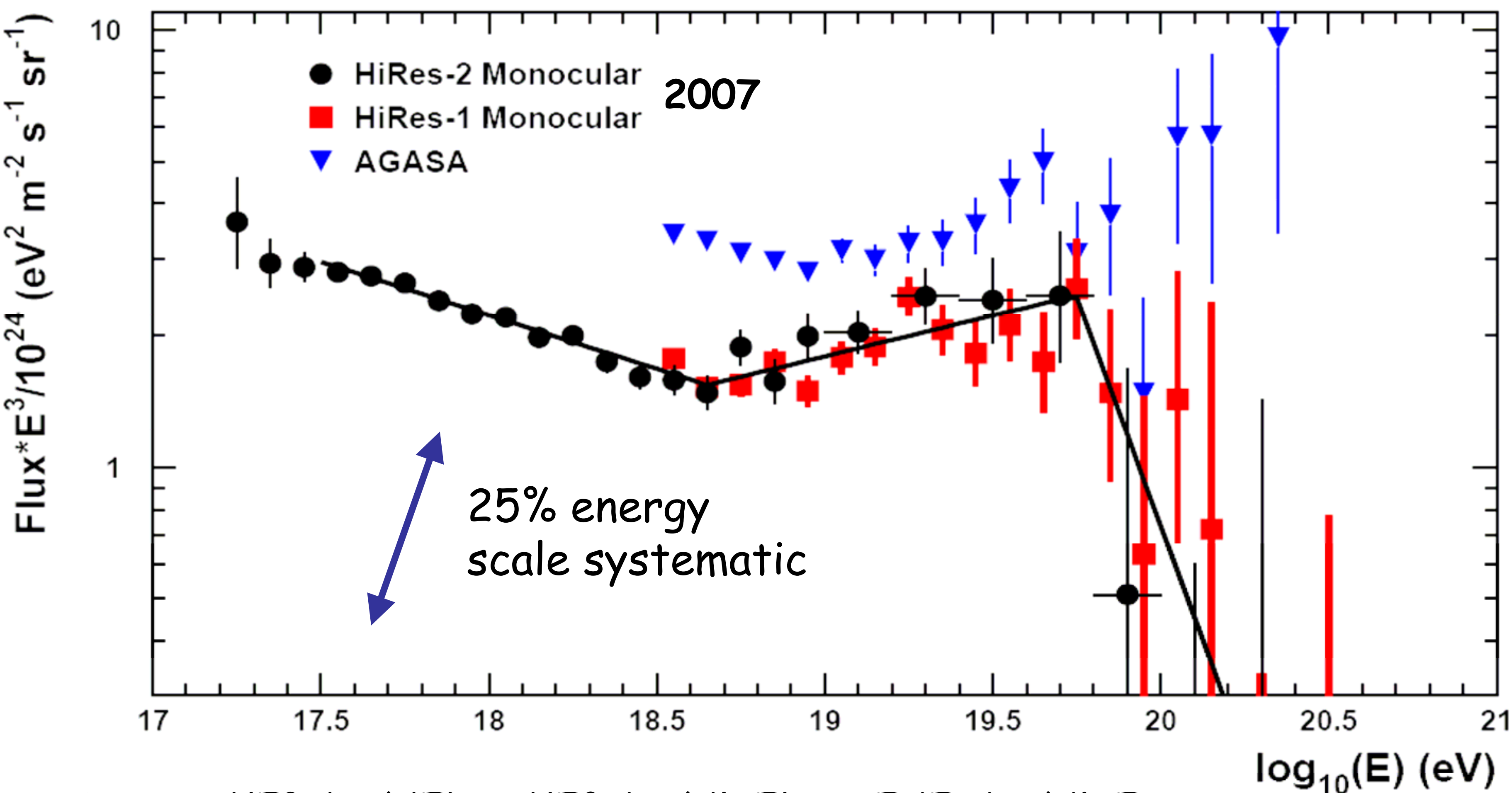
HiRes sees "GZK" suppression (4.8σ), AGASA does not.
(Auger sees a deficit, but is compatible with both.)

At the highest energies



Flux = energy histogram (binned in log E) / exposure
The vertical error bars include Poisson error and exposure errors (efficiency, geometric aperture, livetime).

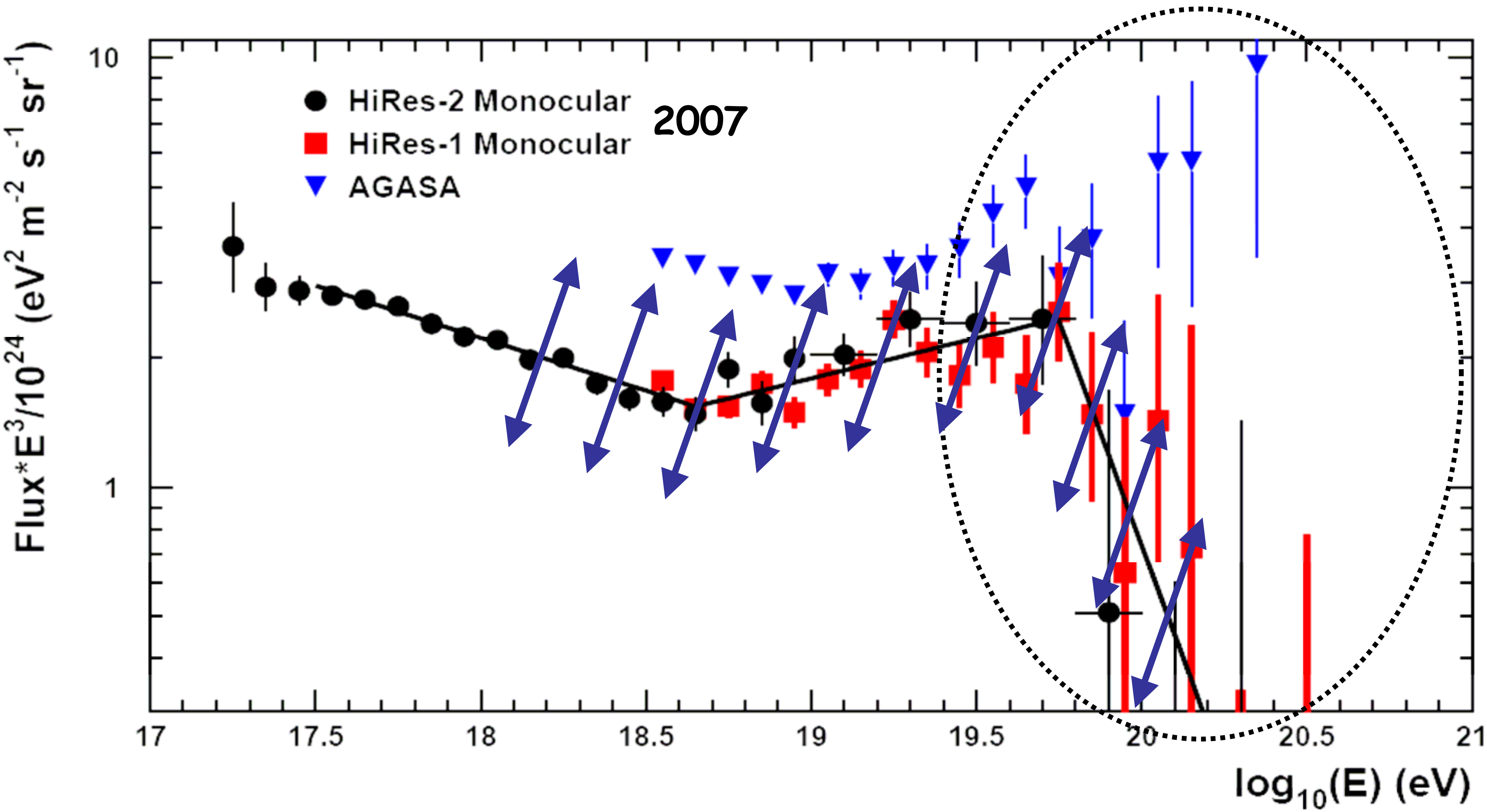
At the highest energies



Note: $d(E^3\, dN/dE) = d(E^2\, dN/d\ln E) = 2E dE\, dN/d\ln E$

→ $\Delta(E^3\, dN/dE)/(E^3\, dN/dE) = 2\, \Delta E/E = 2\, \Delta \ln E$ → Diagonal error bars!

At the highest energies



The discrepancy is still there, but is less significant than it appears after accounting for the simplest systematic error.

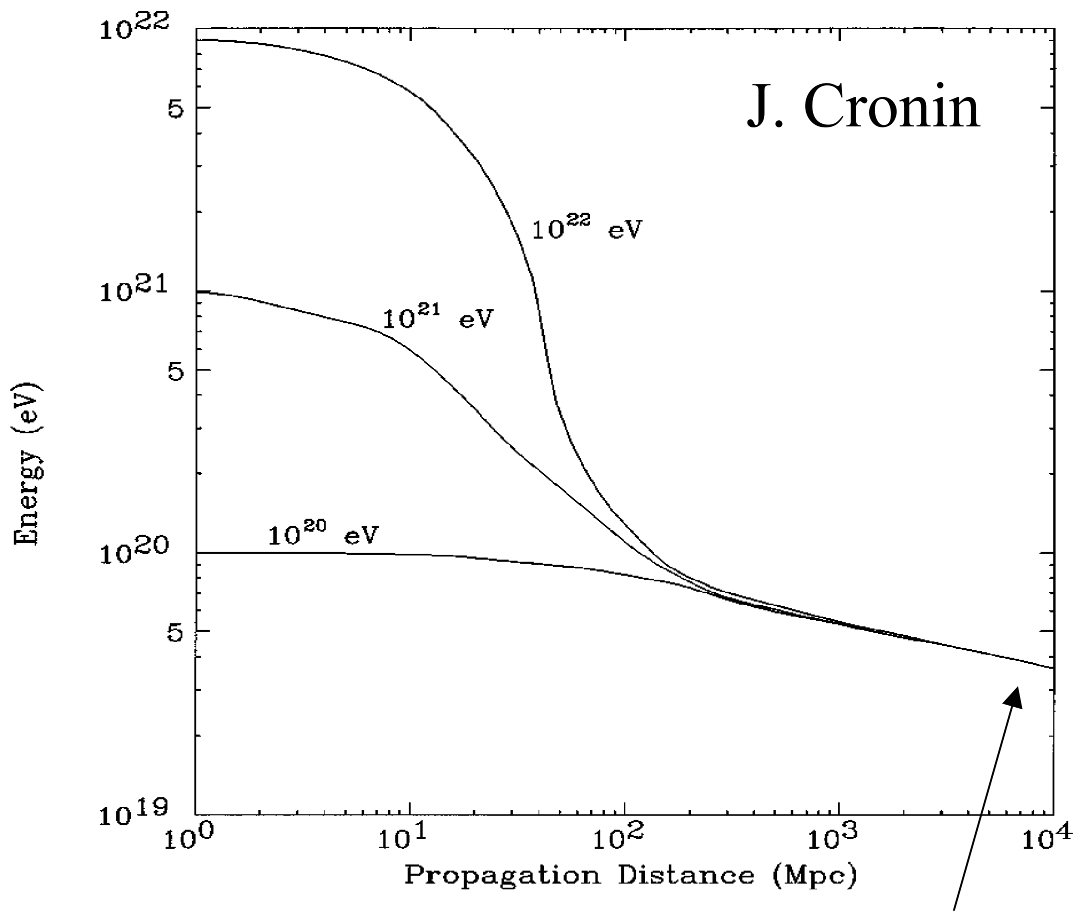
UHECR Interactions with the CMB

$$p + \gamma_{CMB} \rightarrow \Delta(1232) \rightarrow p + \pi^0 \rightarrow p\gamma\gamma$$
$$\rightarrow n + \pi^+ \rightarrow pe^-\bar{\nu}_e + e^+\nu_e\bar{\nu}_\mu\nu_\mu$$

$\lambda_I \sim 5$ kpc

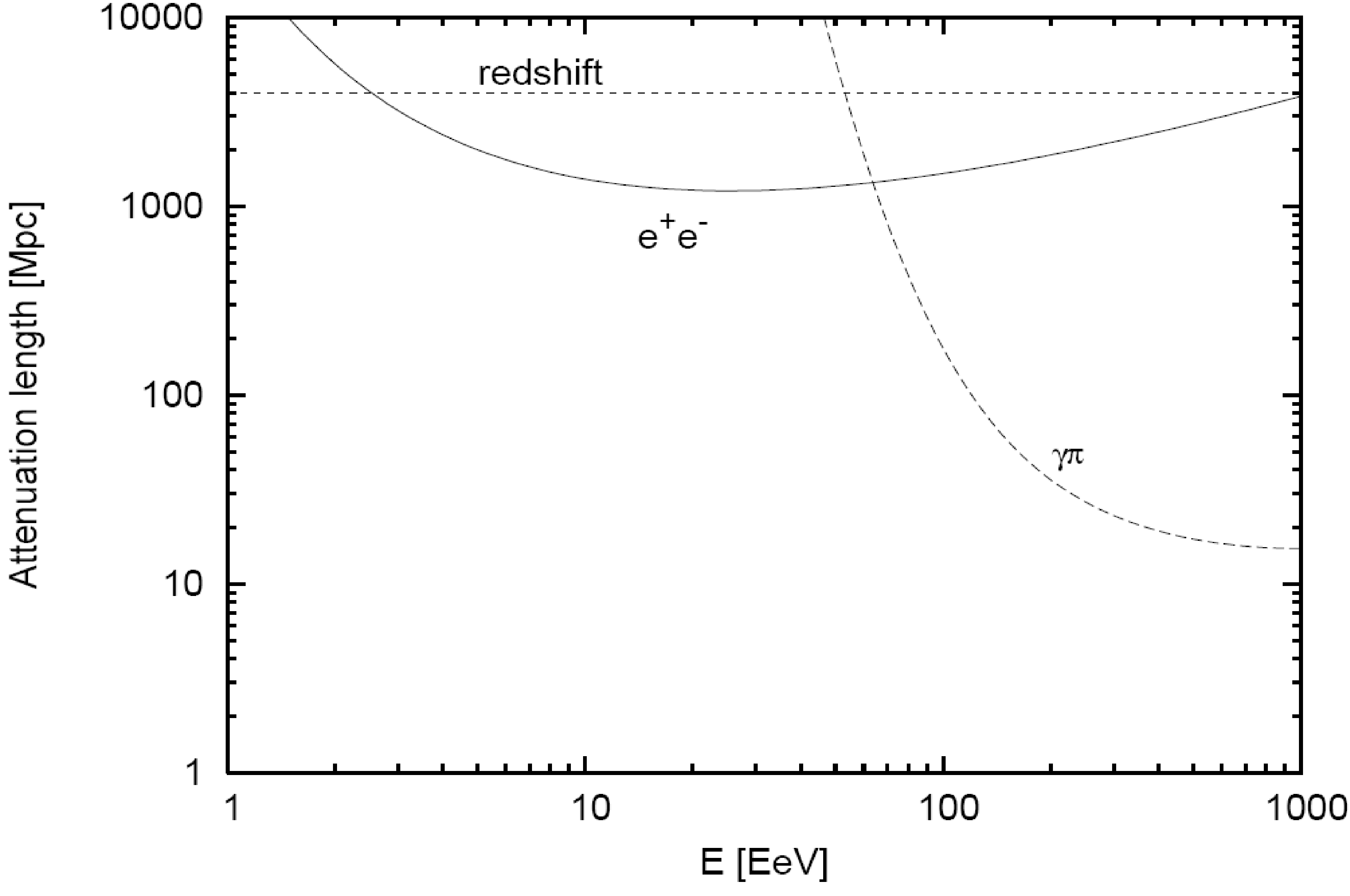
The AGASA super-GZK sources must be local (R<100Mpc) unless:

1. Lorentz invariance is broken or
2. $\sigma_{CR-\gamma}$ is suppressed (nuclei, shadrons, neutrinos, etc.)



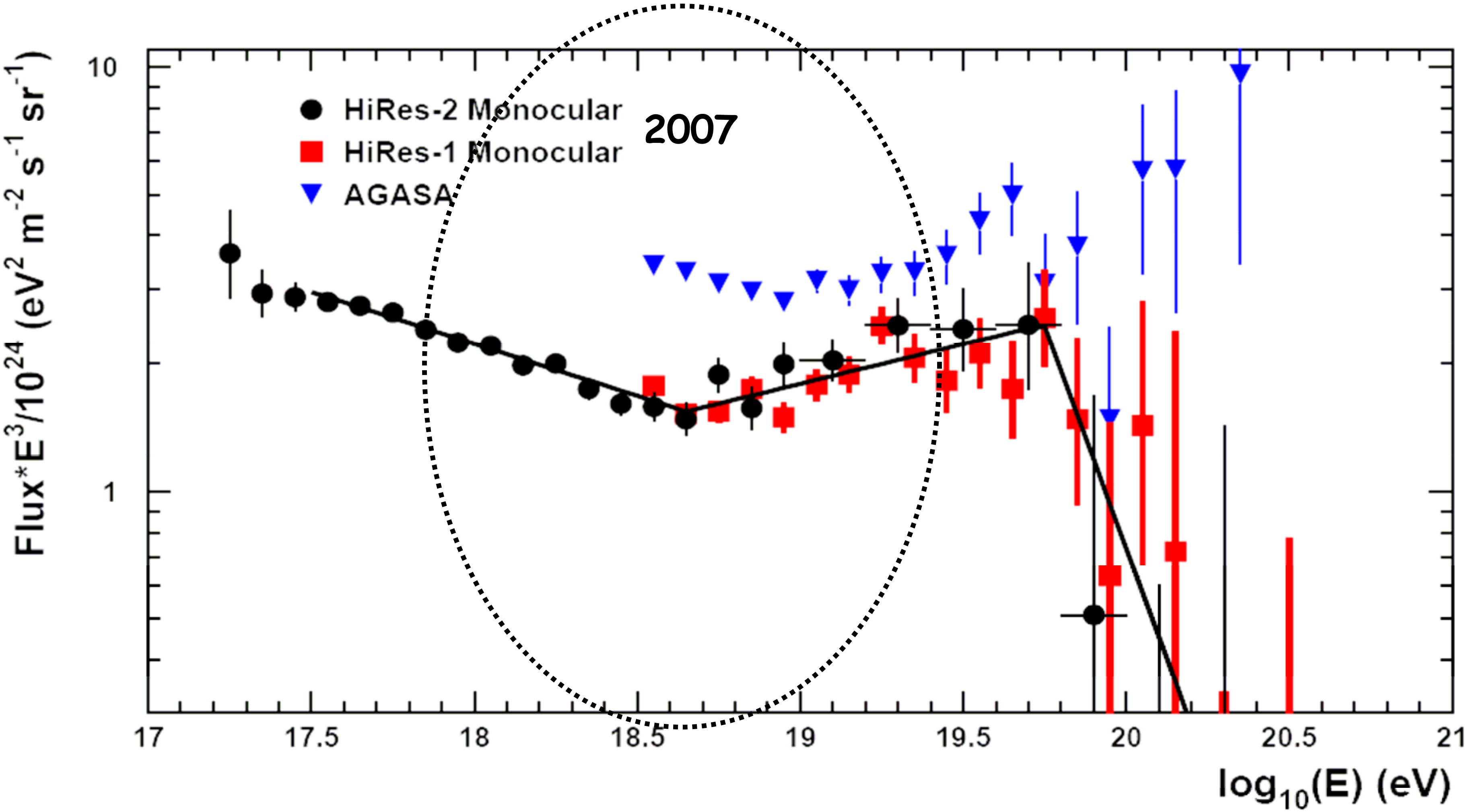
Asymptotic GZK (Greisen, Zatsepin, Kuzman) energy

Proton 1/e energy attenuation length



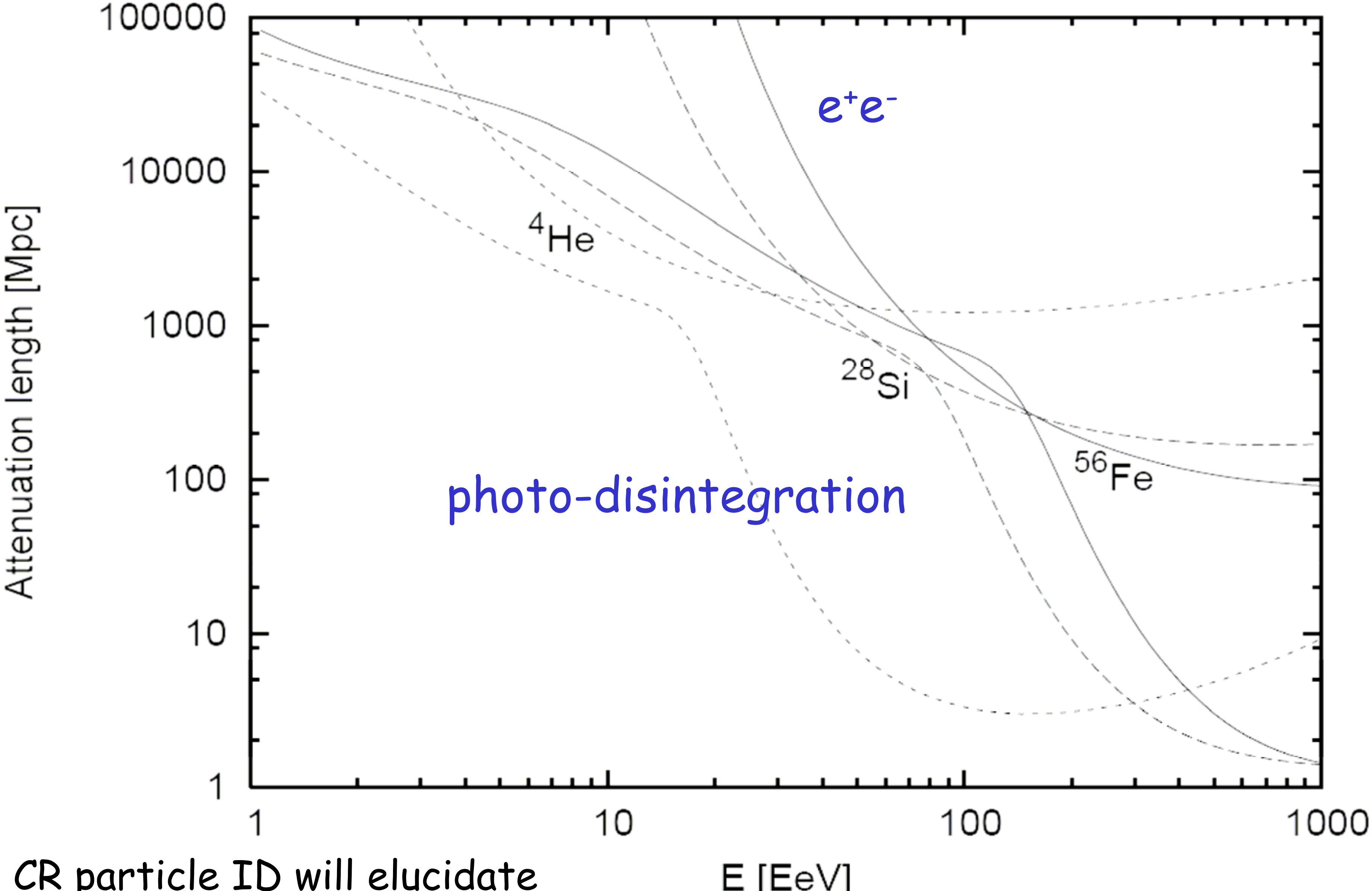
Harari, Mollerach, Roulet (2006)

Interpretations of the Ankle



The “Ankle” could be due to 1) energy loss in propagation due to pair production, or 2) an extra-galactic flux finally appearing above the magnetically confined galactic flux

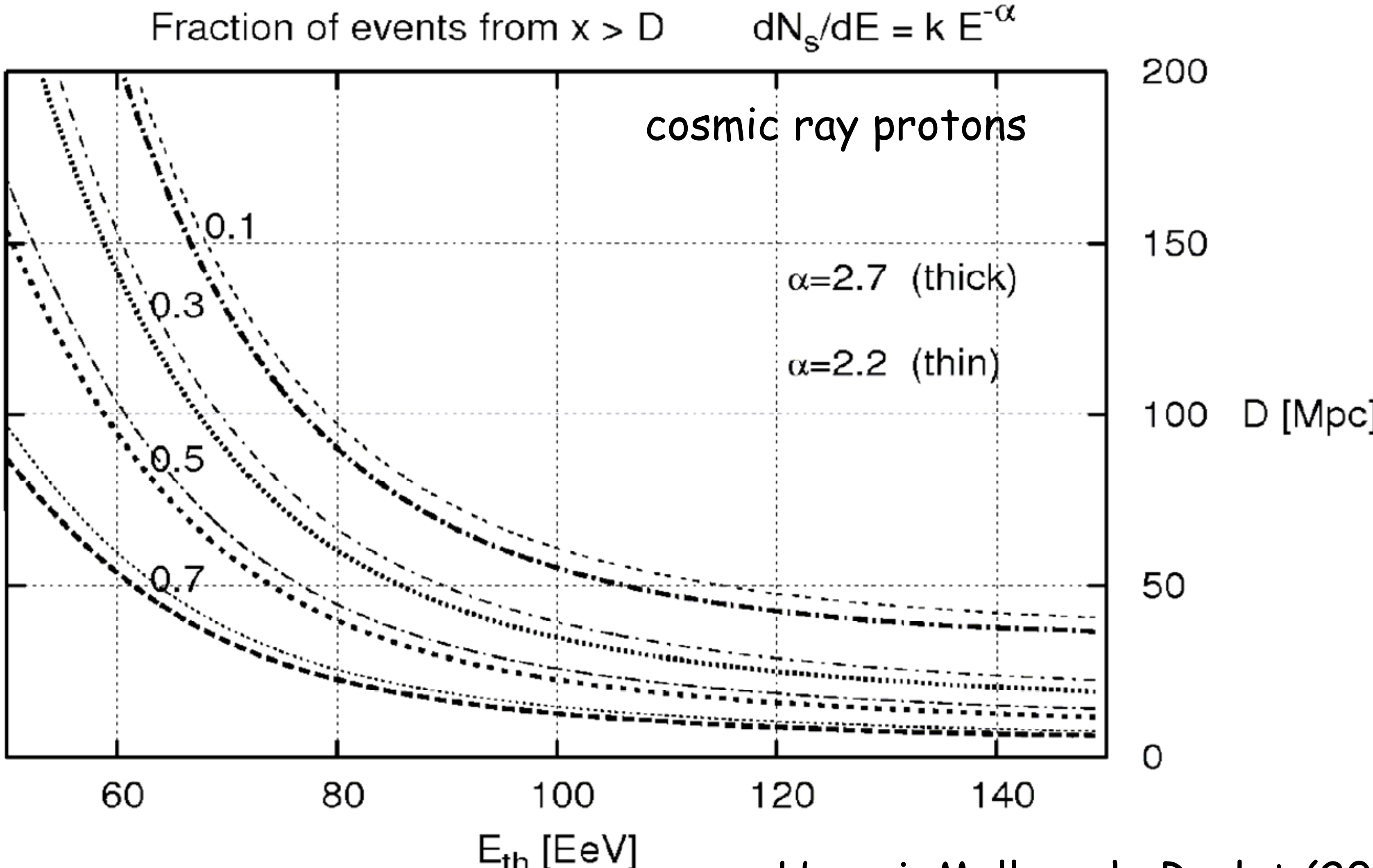
Attenuation lengths of CR nuclei



CR particle ID will elucidate the nature of the ankle

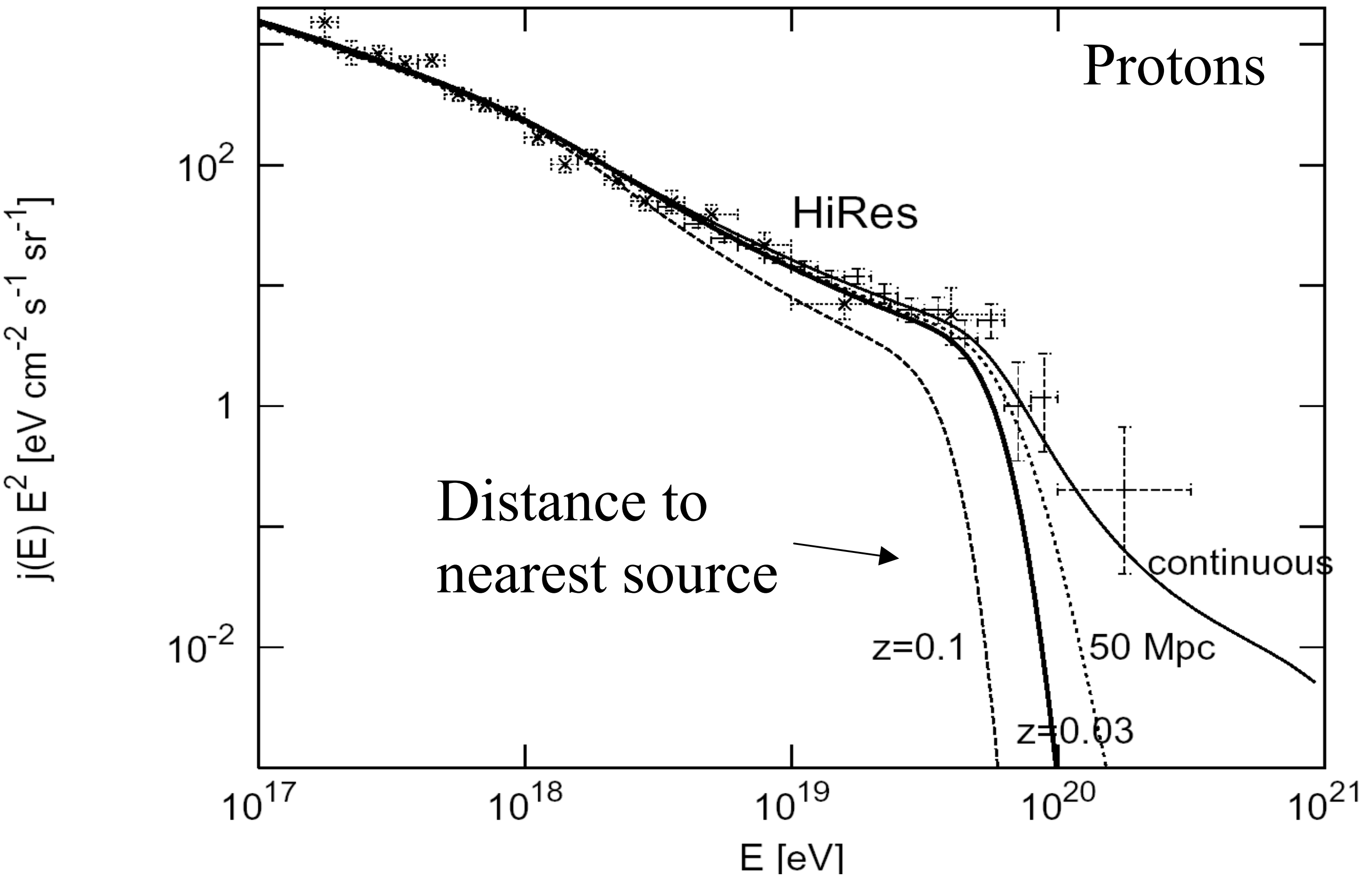
Harari, Mollerach, Roulet (2006)

Assuming GZK attenuation and that the true source spectrum continues beyond GZK energies, what are the typical distances to the sources?



Harari, Mollerach, Roulet (2006)

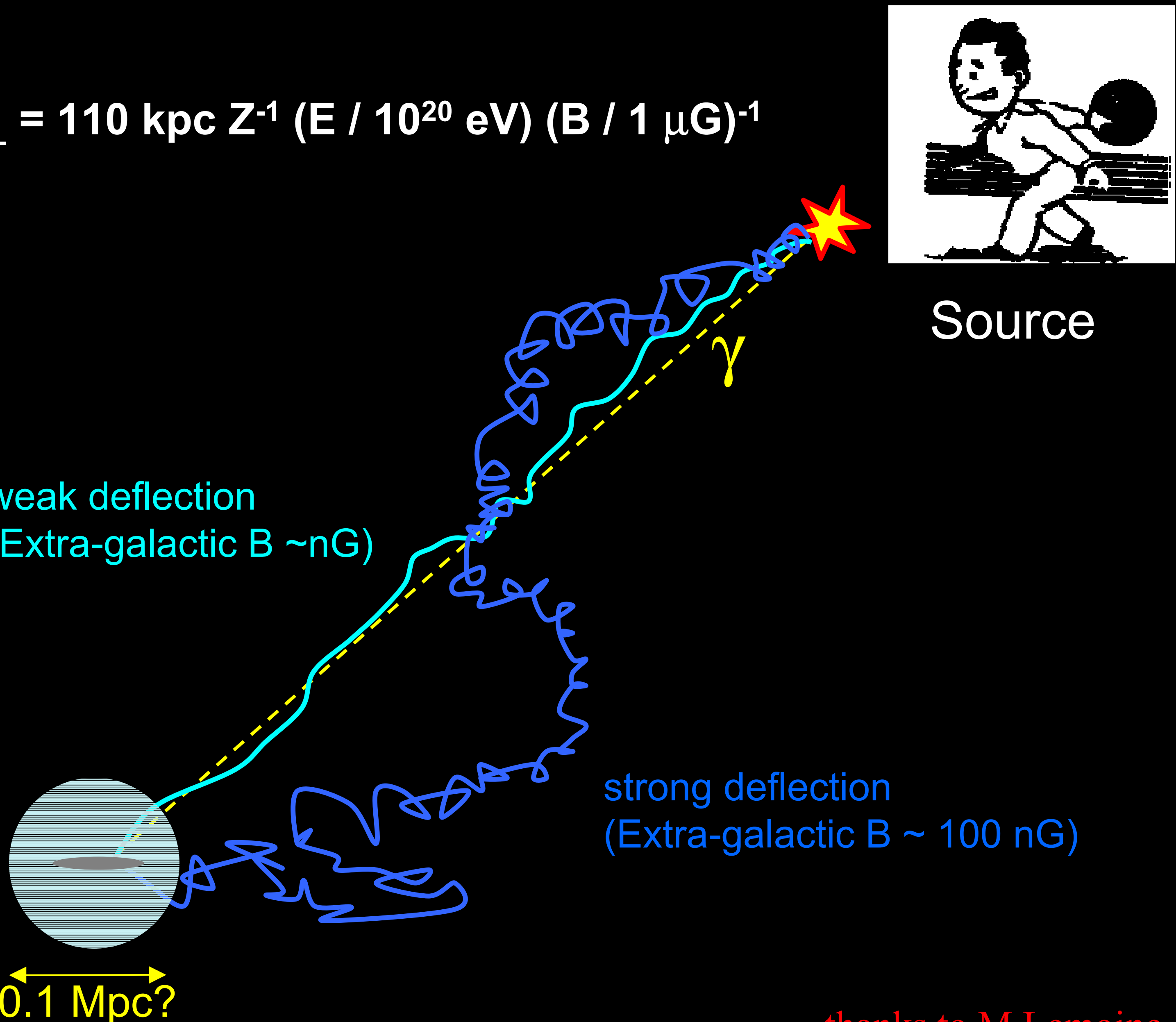
The GZK feature is not unique. Its shape depends on the local source distribution (and on magnetic fields)



Kachelrieß, Semikoz, Tortola (2003)

Influence of cosmic magnetic fields

Larmor radius: $\mathbf{r_L = 110\ kpc\ Z^{-1}\ (E\ /\ 10^{20}\ eV)\ (B\ /\ 1\ \mu G)^{-1}}$



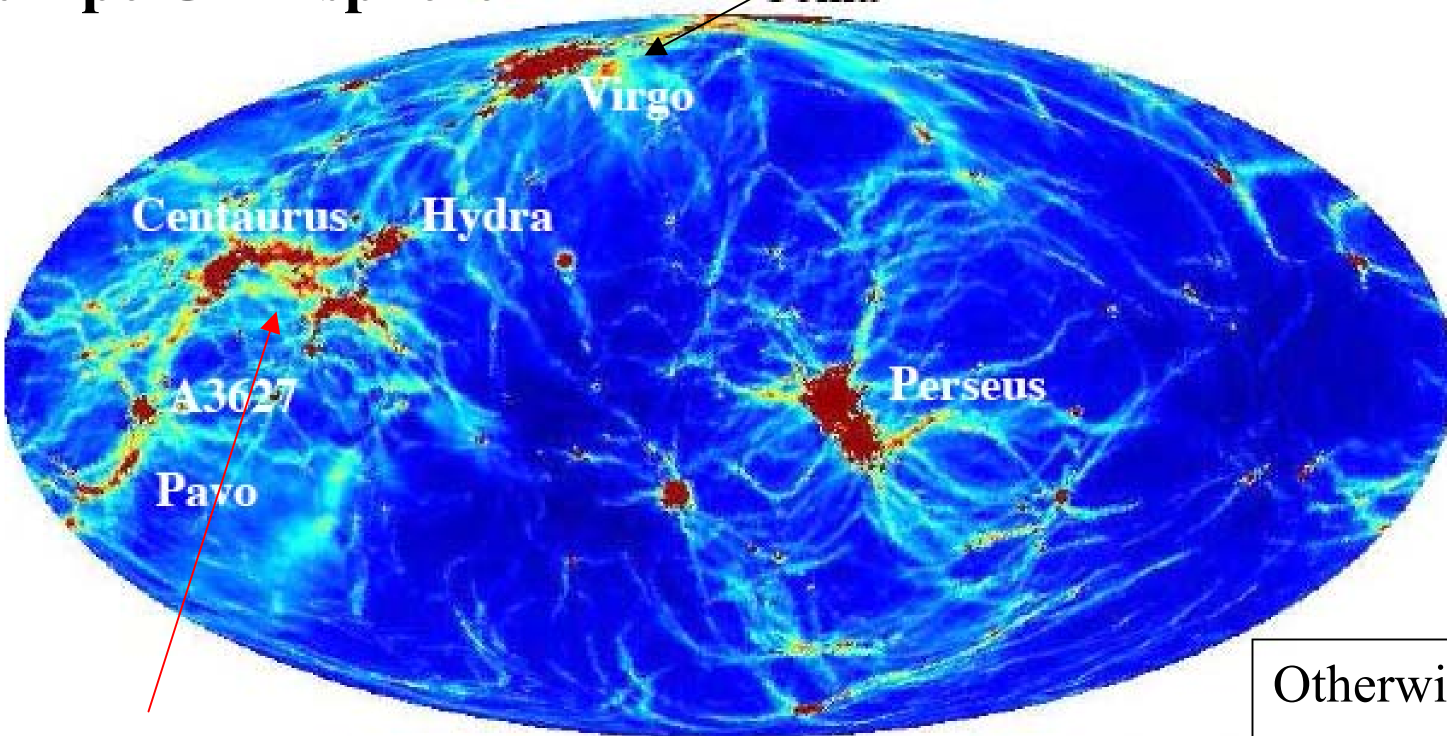
Halo B ~ μ**G**.
Confines $E<10^{18}$,
Distorts trans-
GZK spectrum?

thanks to M.Lemoine

SuperGZK cosmic rays point to their sources if B~nG!

M87 (~20Mpc)

110Mpc GZK sphere



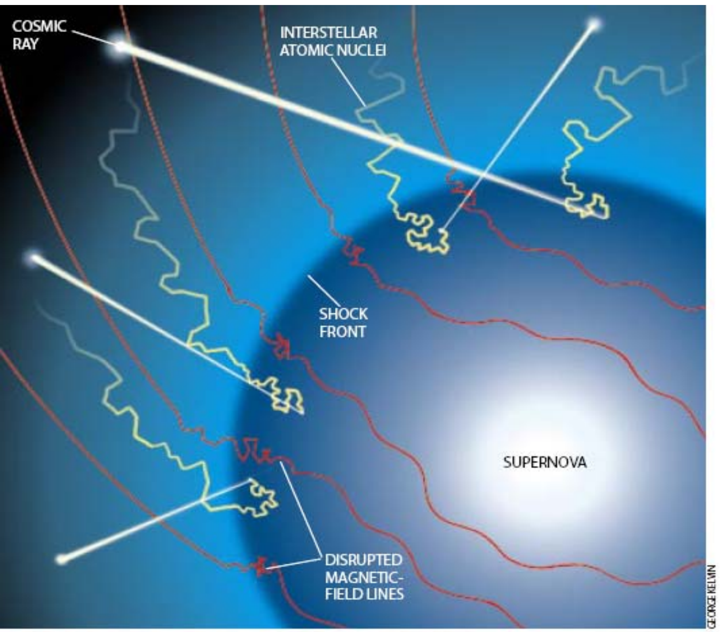
Cen A (~4Mpc)

Otherwise, AGN sources + strong B

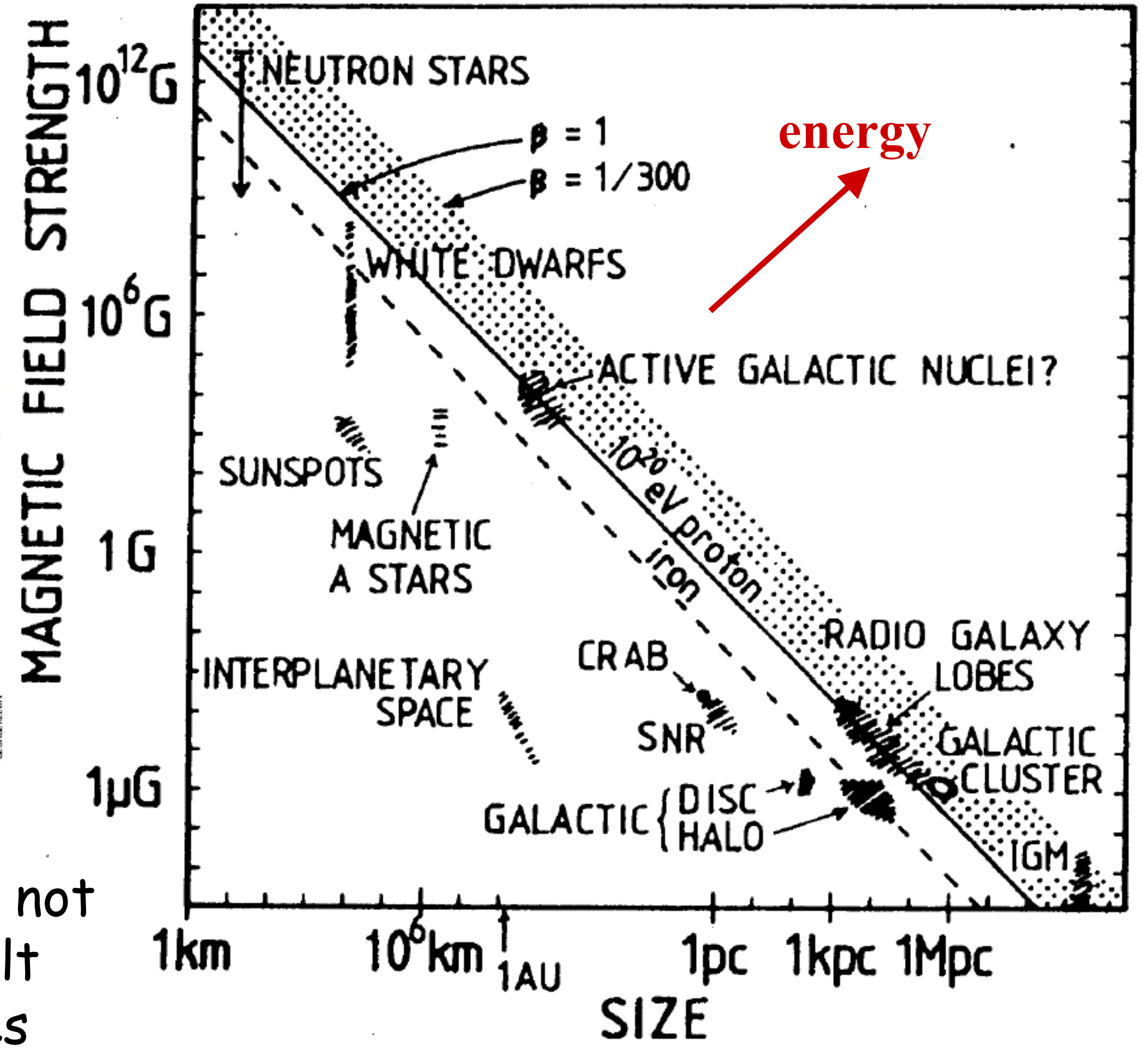
Simulated magnetic deflection angle for 10^20eV protons. Dolag, et.al, 2004

What are the GZK sources???

Zevatrons
via Fermi shock acceleration?



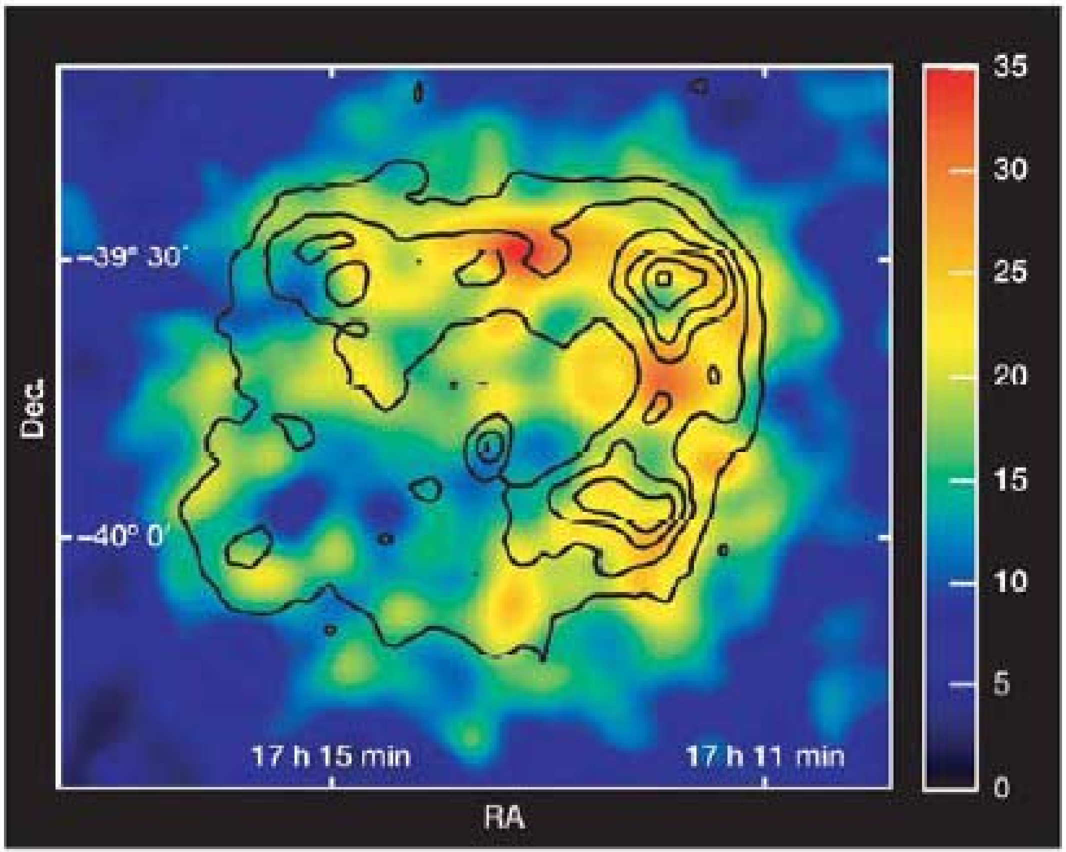
Hillas, 1984



Astrophysical sources are not forbidden, but are difficult to realize for EeV energies

Evidence for Pevatrons

Galactic supernova remnant RX J1713.7-3946.
(Aharonian, et.al. 2004)



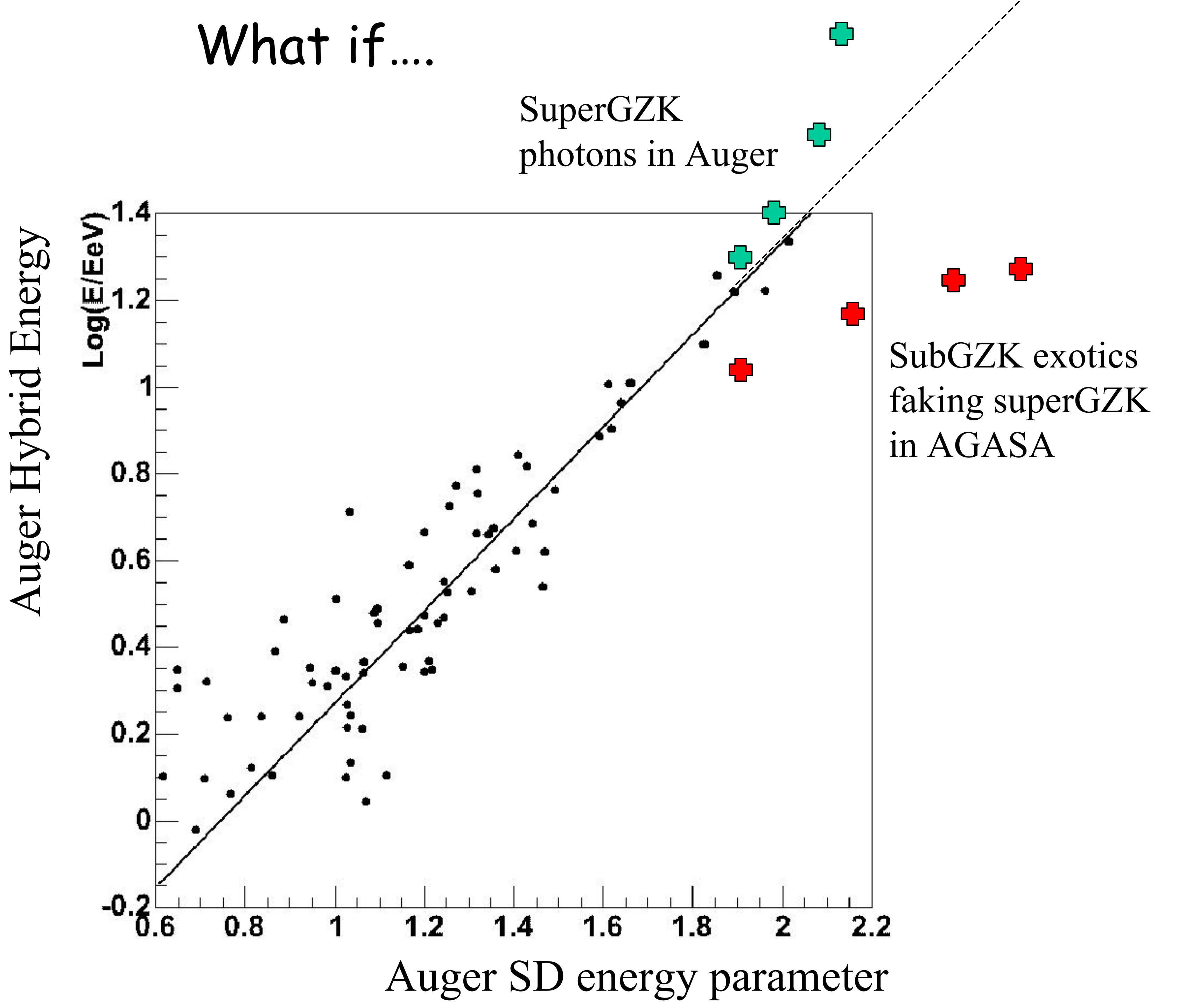
HESS TeV Gamma ray image with ACSA X-ray image overlaid.

TeV fluxes are consistent with the decay of π^0 from p-p interactions in the Pevatron.

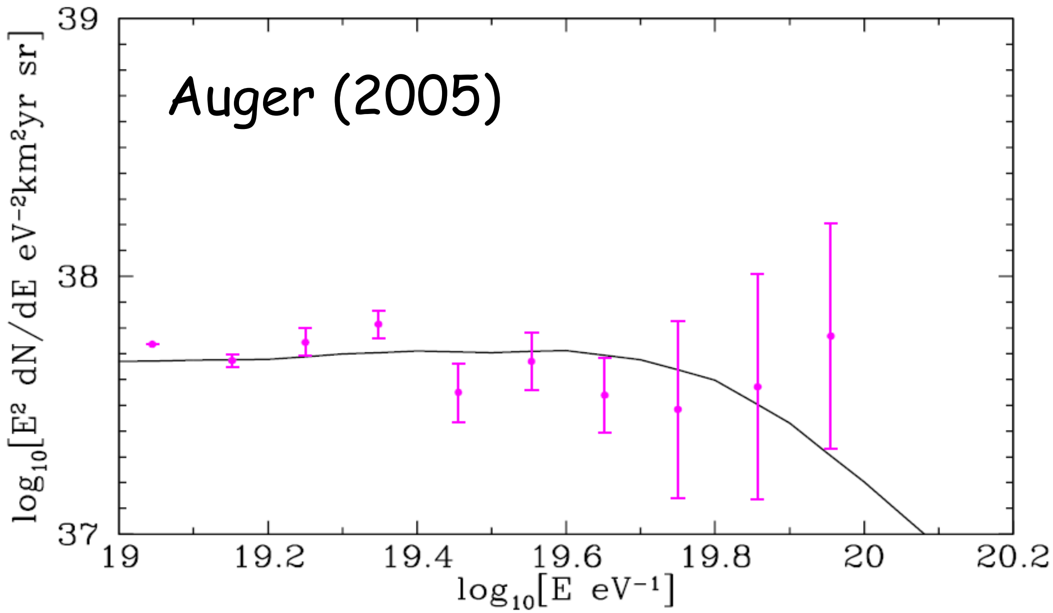
X-ray fluxes are consistent with synchrotron radiation.

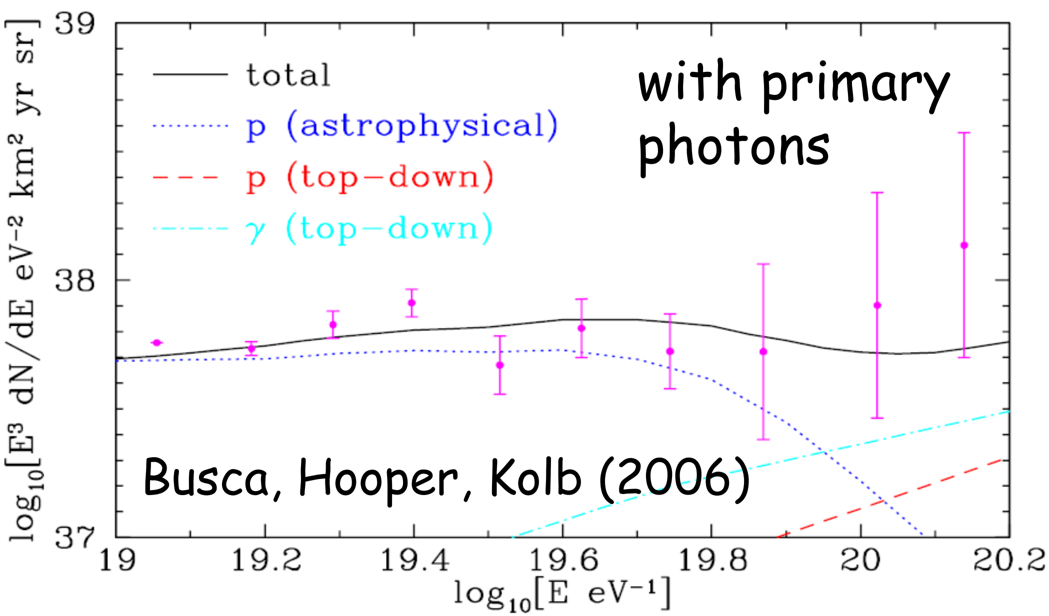
Exotic physics

What if….


SuperGZK
photons in Auger
SubGZK exotics
faking superGZK
in AGASA
Auger Hybrid Energy
Log(E/EeV)
Auger SD energy parameter
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2

The spectra all have composition systematics!





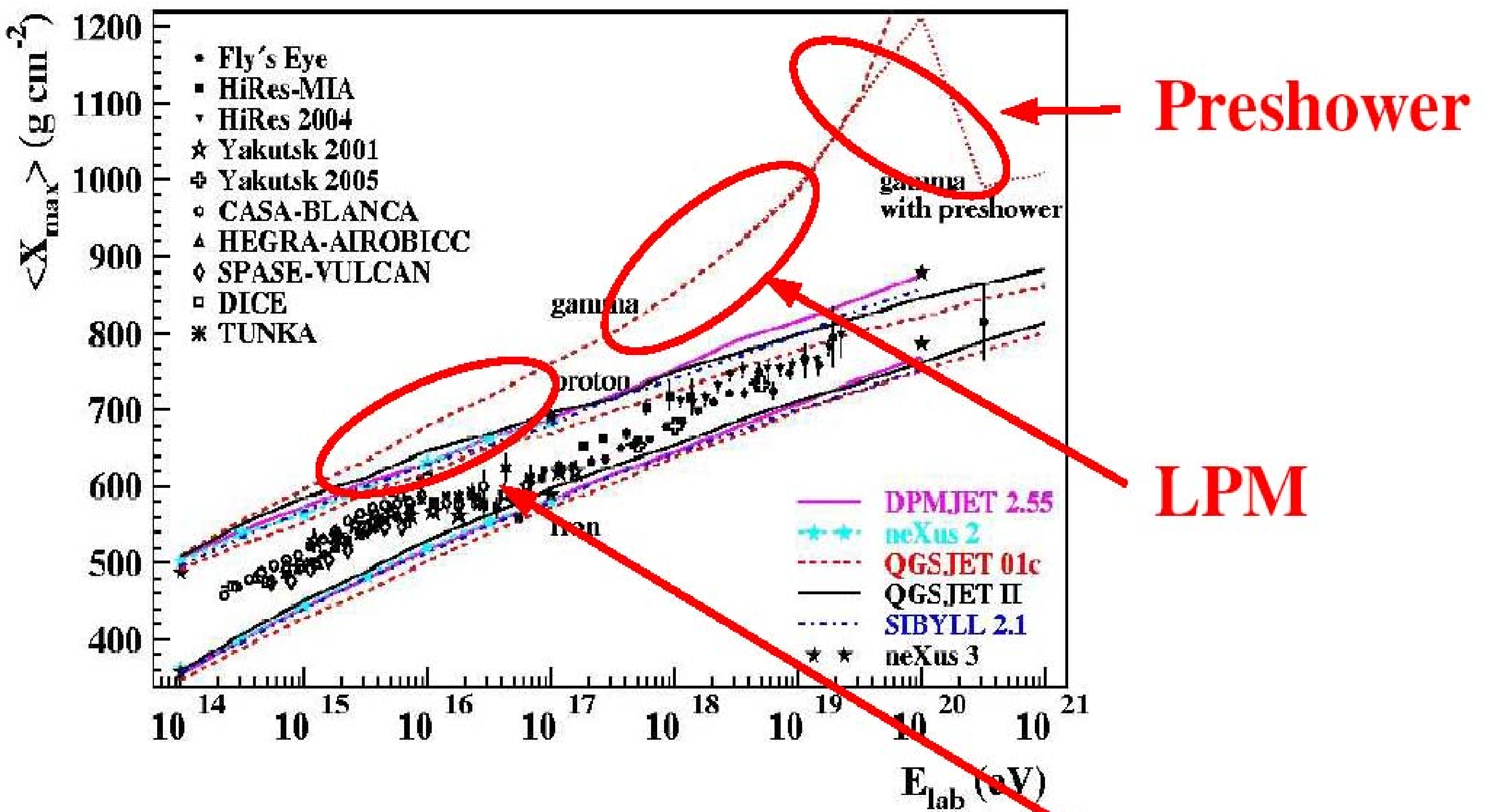
HiRes1 must assume that all particles are protons in order to reconstruct

AGASA must assume all particles are protons in order to assign MC energies

Auger must assume that all particles behave like the typical particle in order to assign calibrated energies.

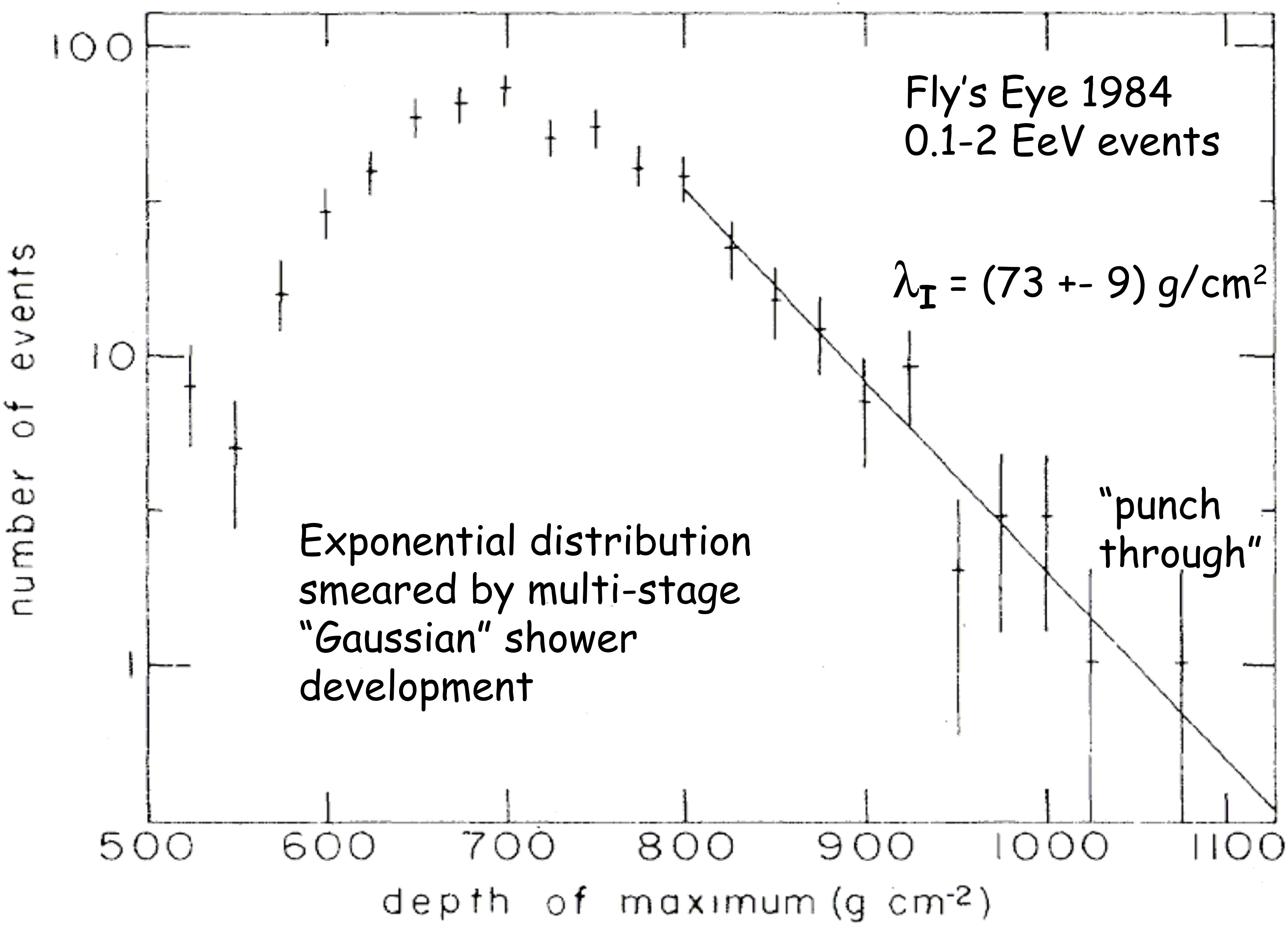
CR composition must be studied separately in dedicated analyses.

Use <Xmax>(E) to detect composition changes

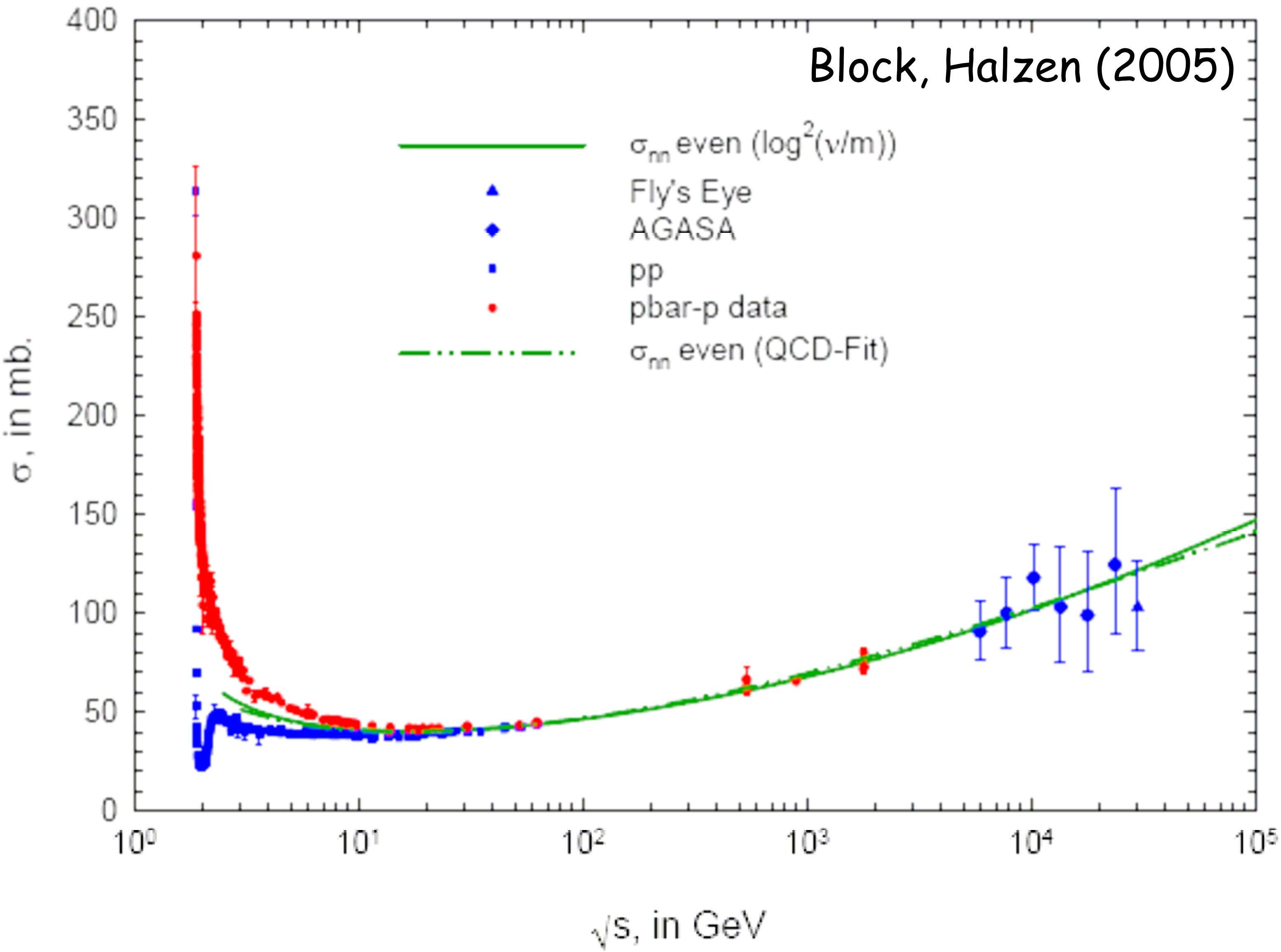


Contrary to intuition, the photon showers are deeper than hadron showers

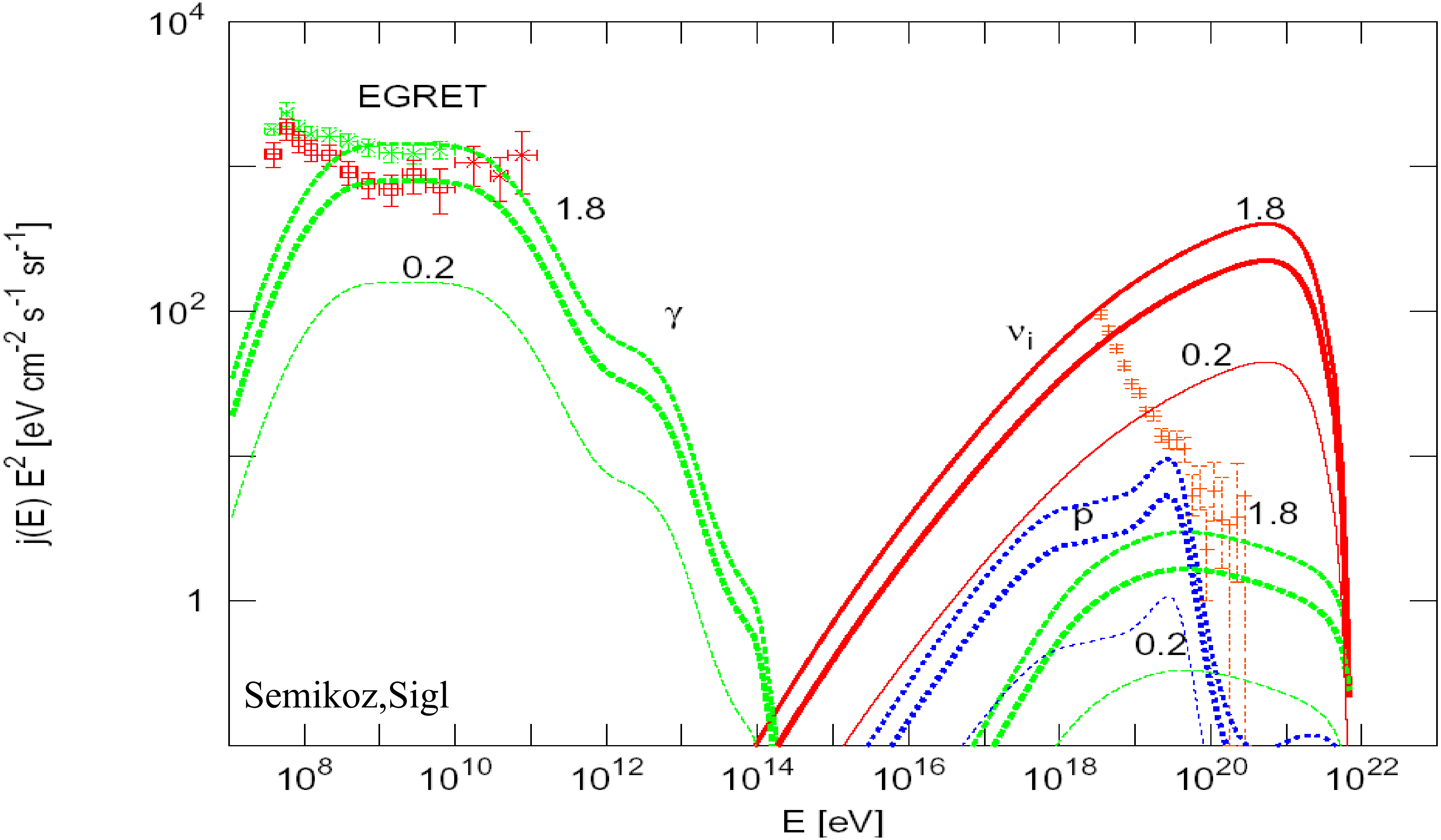
Measuring hadronic cross-sections via Xmax



The CR hadronic cross-sections saturate the Froissart Unitarity bound $\sigma^{max} \sim ((\log s)/m_p)^2$



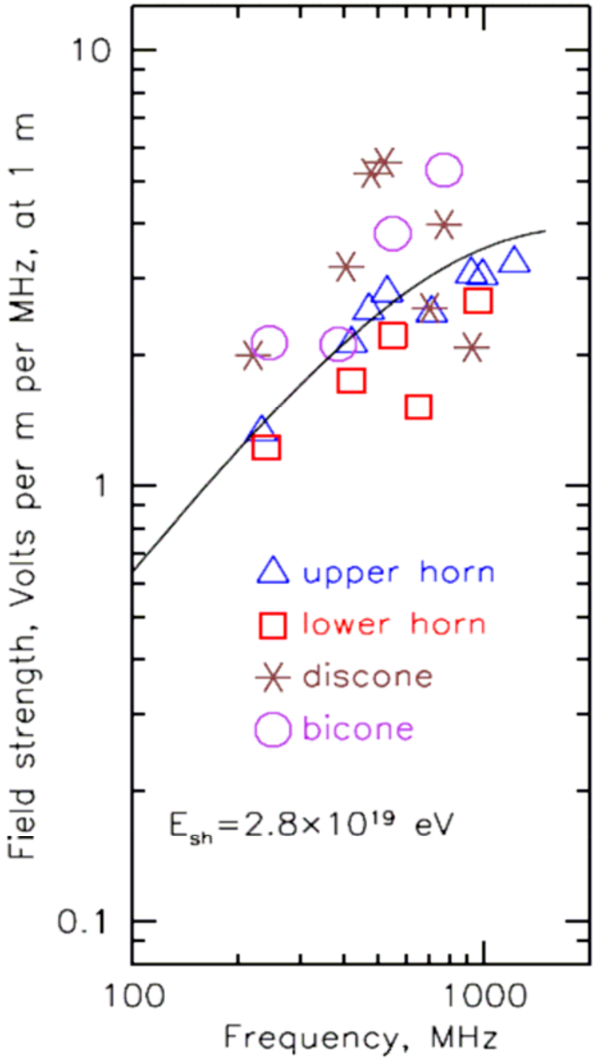
Models are constrained by the GeV photon flux

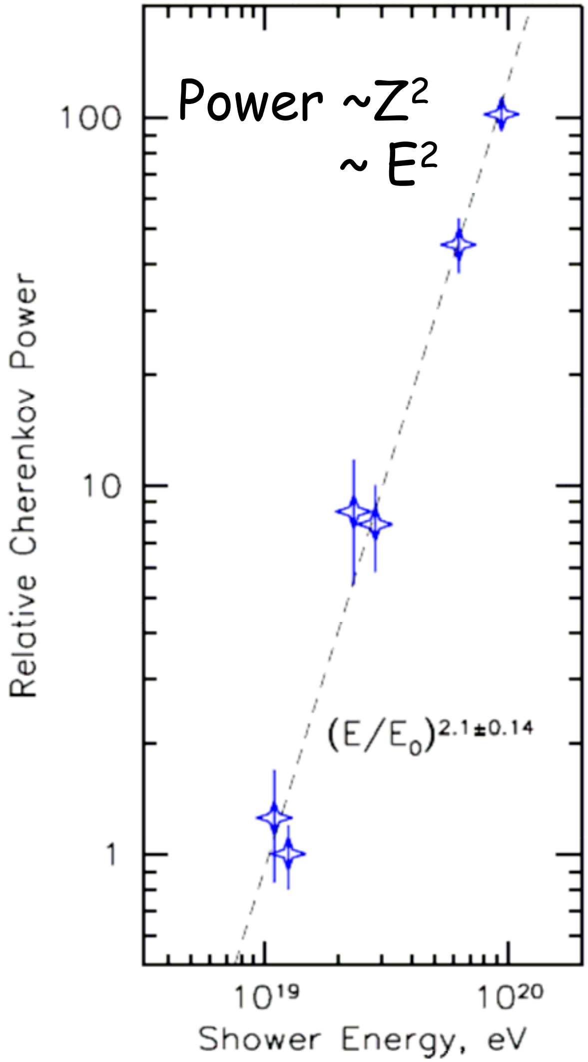


UHE processes produce π^0s which produce Mpc scale electromagnetic cascades due to scattering on the CMB and the diffuse infrared background. New GeV data soon from GLAST!

The UHE neutrinos may be observed via the Askaryan effect (coherent Cherenkov emission when Moliere Radius ~ 10cm in ice « Cherenkov wavelength)

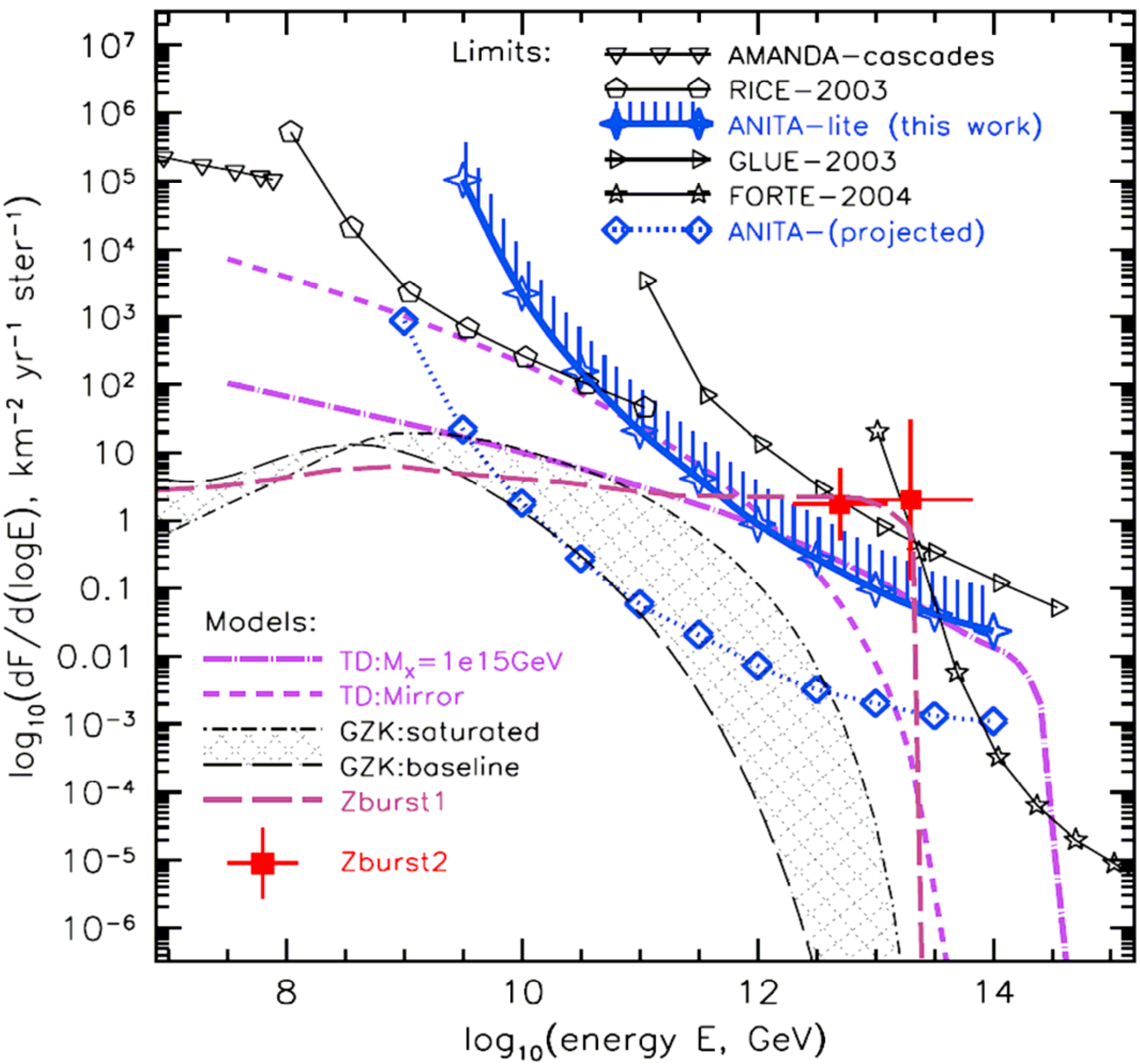
ANITA test at SLAC





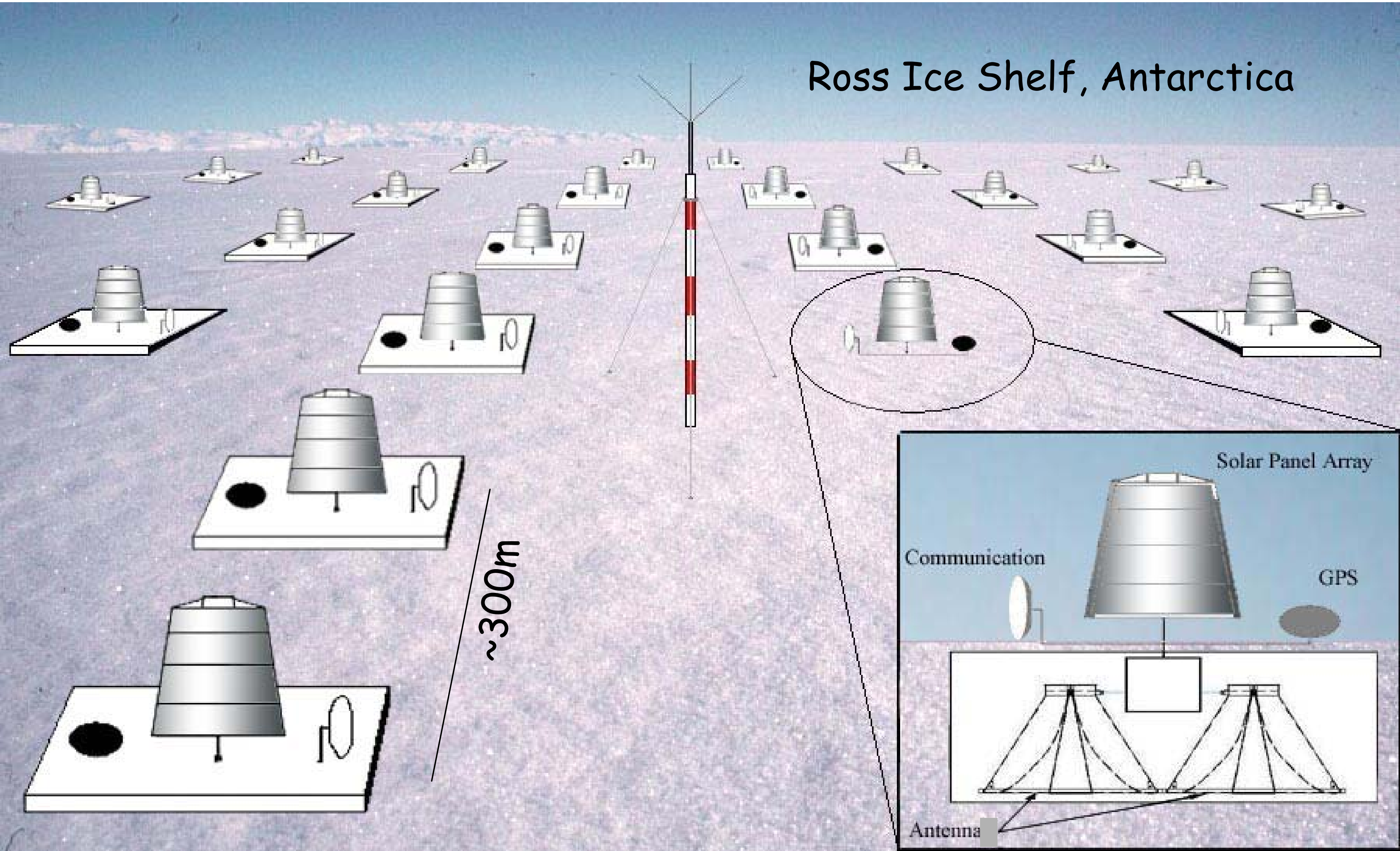
ANITA 12/2006-1/2007
~25 days of data enough to probe even the GZK neutrino flux

ANITA projected sensitivity (50 days)



ARIANNA Concept

100 x 100 station array, ~1/2 Teraton



Auger North planned for Lamar, CO

Get large aperture for CR source studies at the highest energies.
Measure Northern sky.