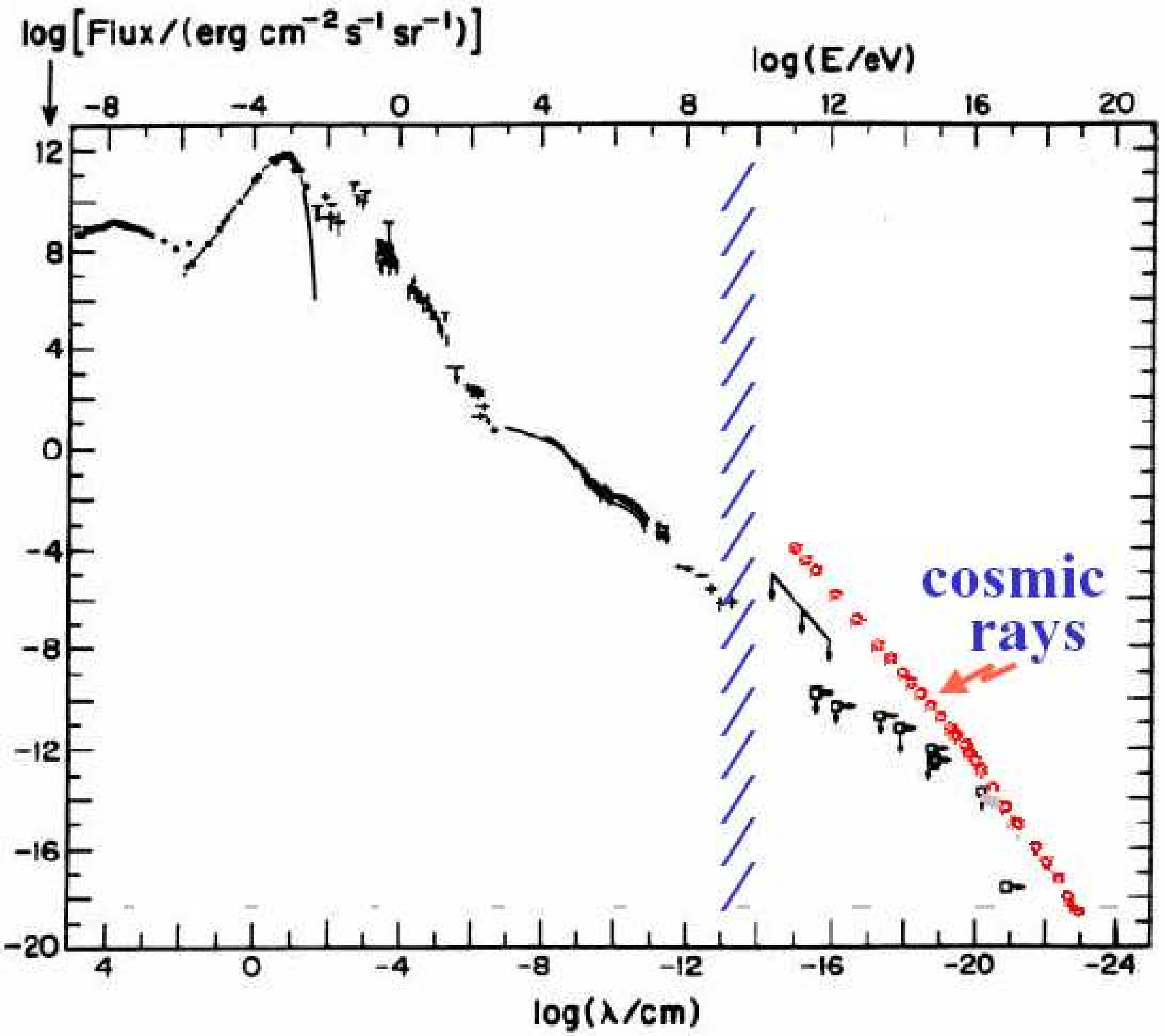
Probing the high energy universe with cosmic rays and neutrinos

Subir Sarkar
University of Oxford

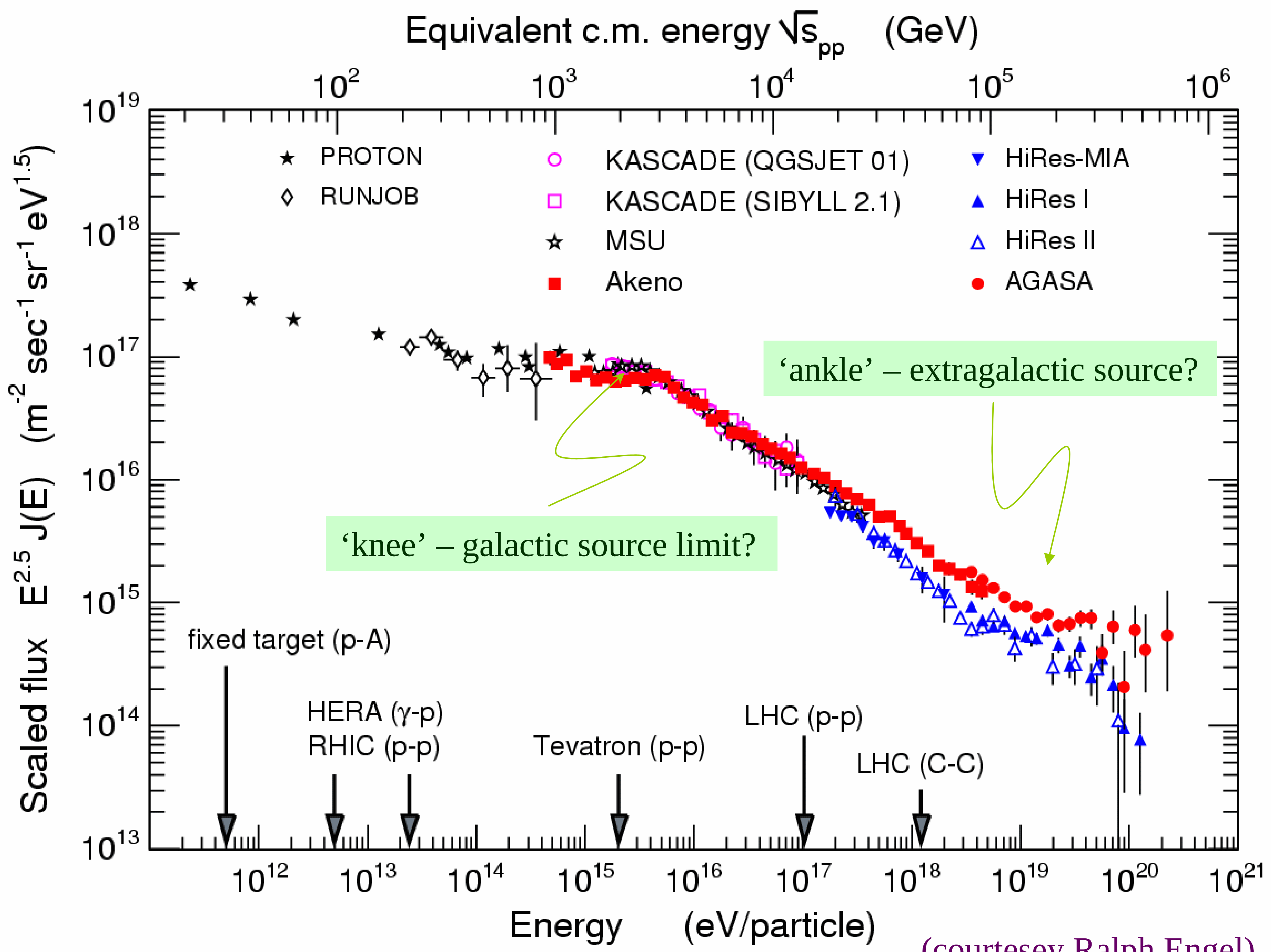
COSMO'05, Bonn, 28 August 2005

In cosmology (as in particle physics), we cannot yet 'see' the universe at energies > few TeV since photons are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on the cosmic infrared & microwave radiation



But using cosmic rays we should be able to see up to energies of order 10^{11} GeV before they get attenuated through photopion interactions on the CMB

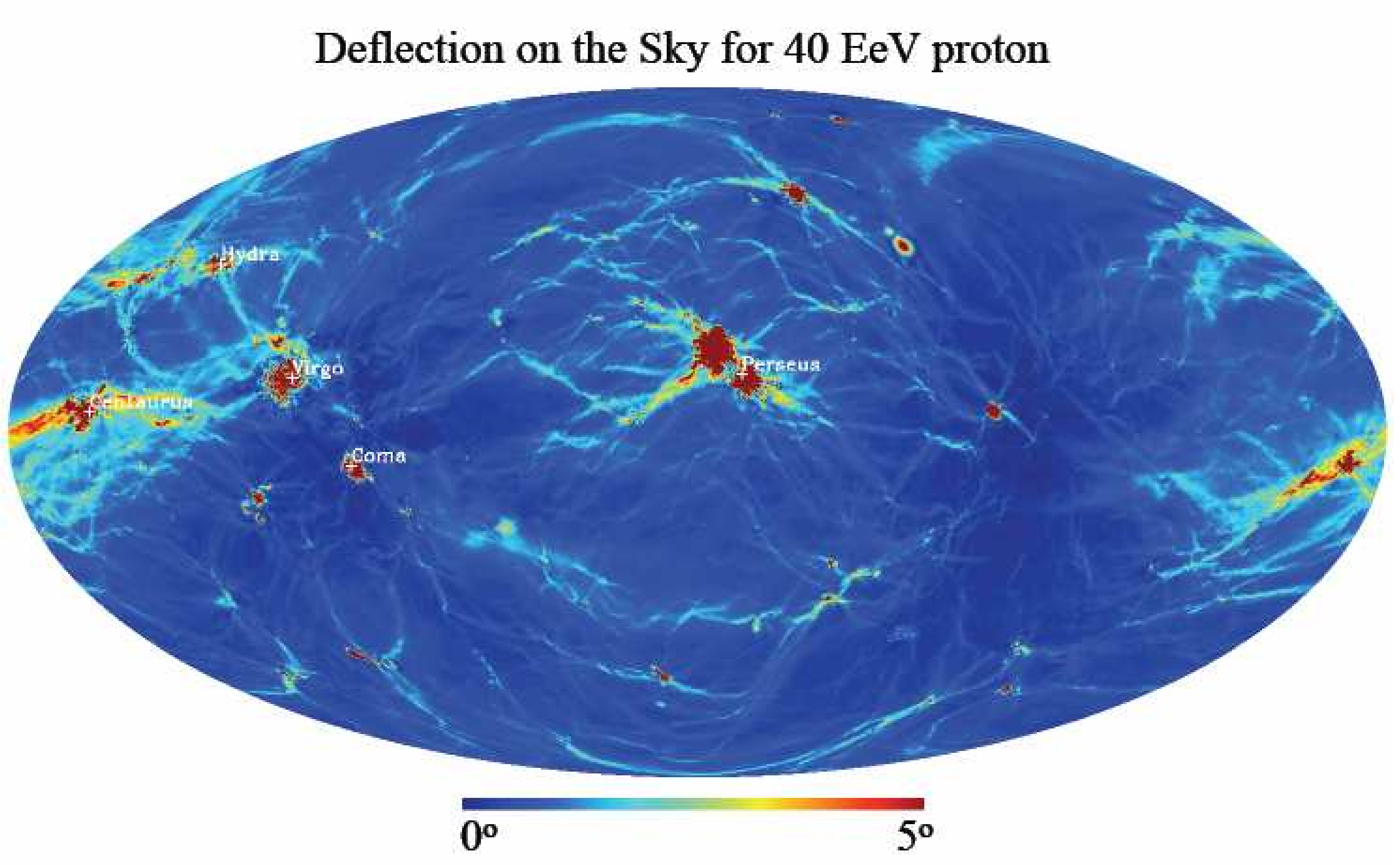
Moreover by studying cosmic ray interactions we can probe new physics beyond the reach of terrestrial accelerators …



(courtesey Ralph Engel)

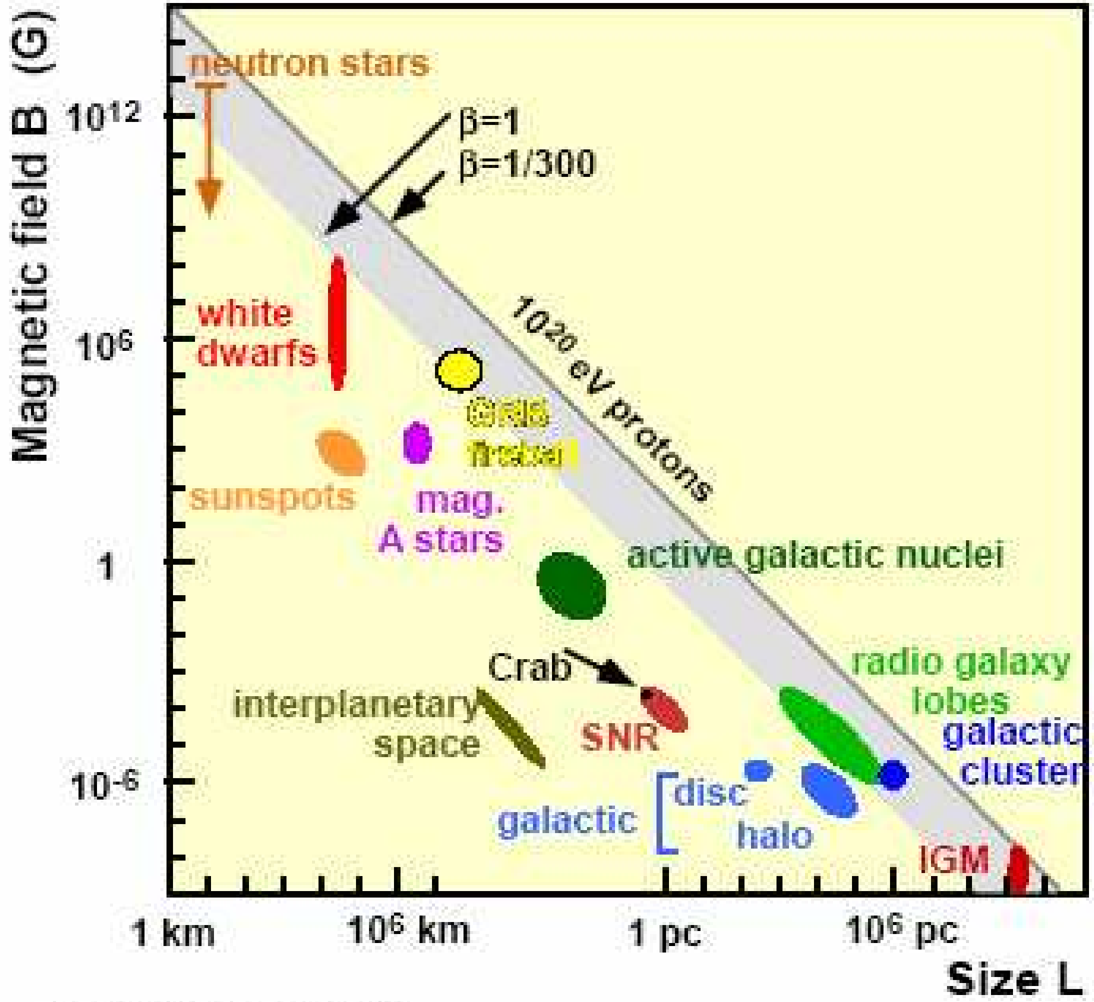
‘Constrained’ simulation of local large-scale structure including magnetic fields

Dolag, Grasso, Springel & Tkachev (2003)



So charged particle astronomy should be possible at energies above ~$4\text{x}10^{10}$ GeV

What are the cosmic accelerators which achieve such enormous energies?



A.M. Hillas 1984

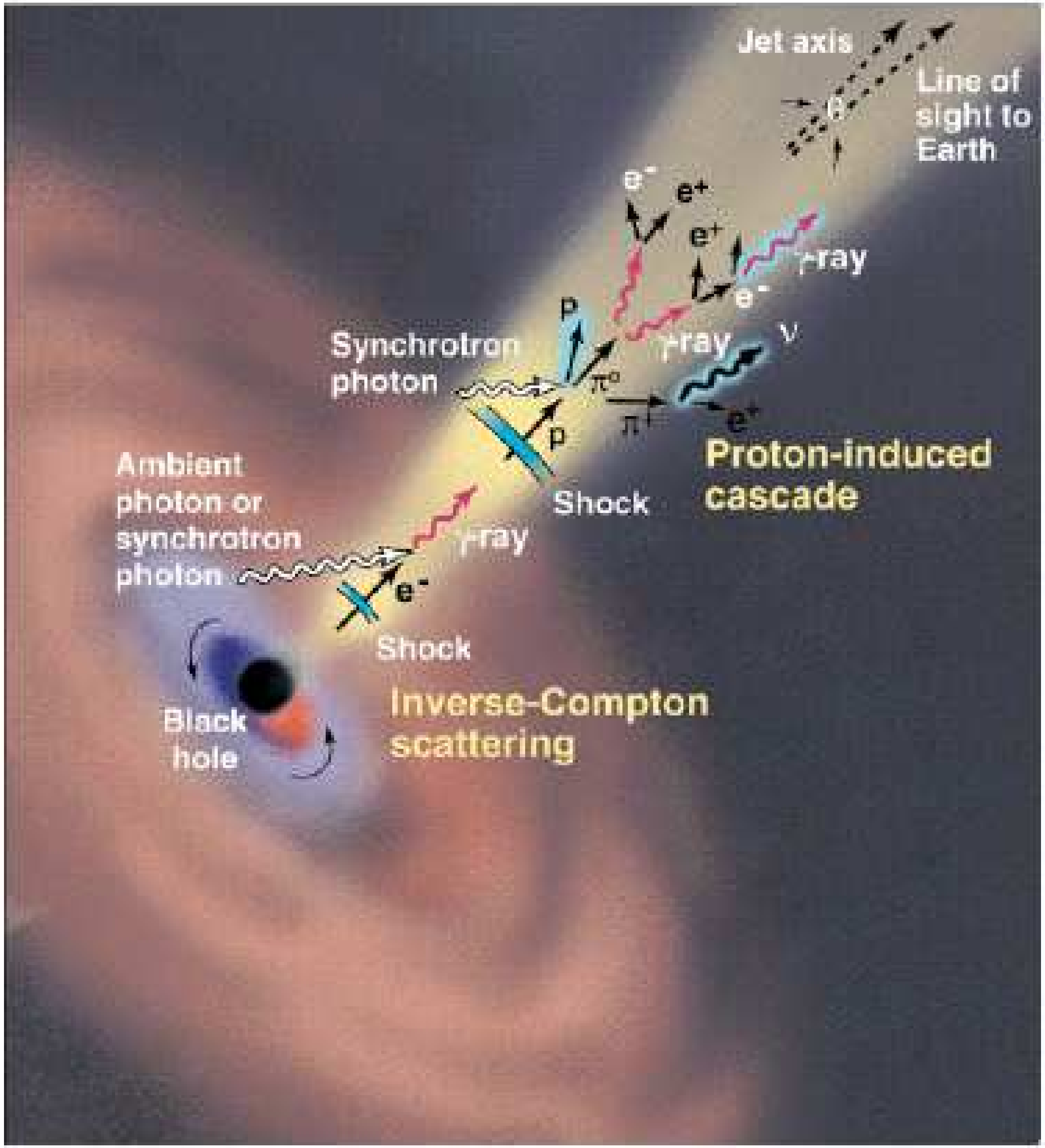
$B_{\mu G} \times L_{kpc} > 2\, E_{EeV} / Z$

$B_{\mu G} \times L_{kpc} > 2\, (c/v)\, E_{EeV} / Z$

to fit gyro radius within L and to allow particle to wander during energy gain

But also:
gain should be more rapid than losses due to magnetic field (synchrotron radiation) and photo-reactions.

- ►If they are nearby, then observed UHECRs should point back to them
- ►If they are far away then the spectrum should exhibit the ‘GZK cutoff’



Active galactic nuclei

- Current paradigm:
  - **Synchrotron Self Compton**
  - External Compton
  - Proton Induced Cascades
  - Proton Synchrotron
- Energetics, mechanism for jet formation and collimation, nature of the plasma, and particle acceleration mechanisms are still poorly understood.

So far, no conclusive evidence that protons are accelerated in such objects … no cosmic ray events point back to nearby active galaxies like M87 or CenA

Where is the GZK cutoff?

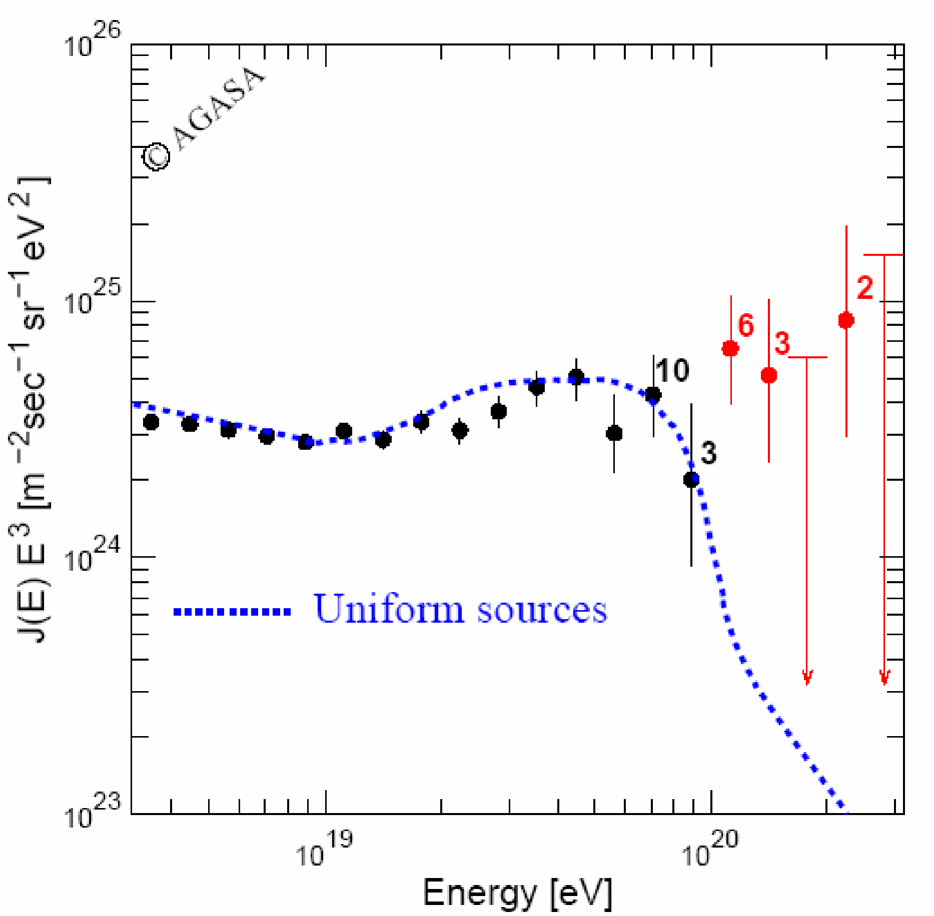
$$p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$$

$$n \to p + e^- + \bar{\nu}_e$$

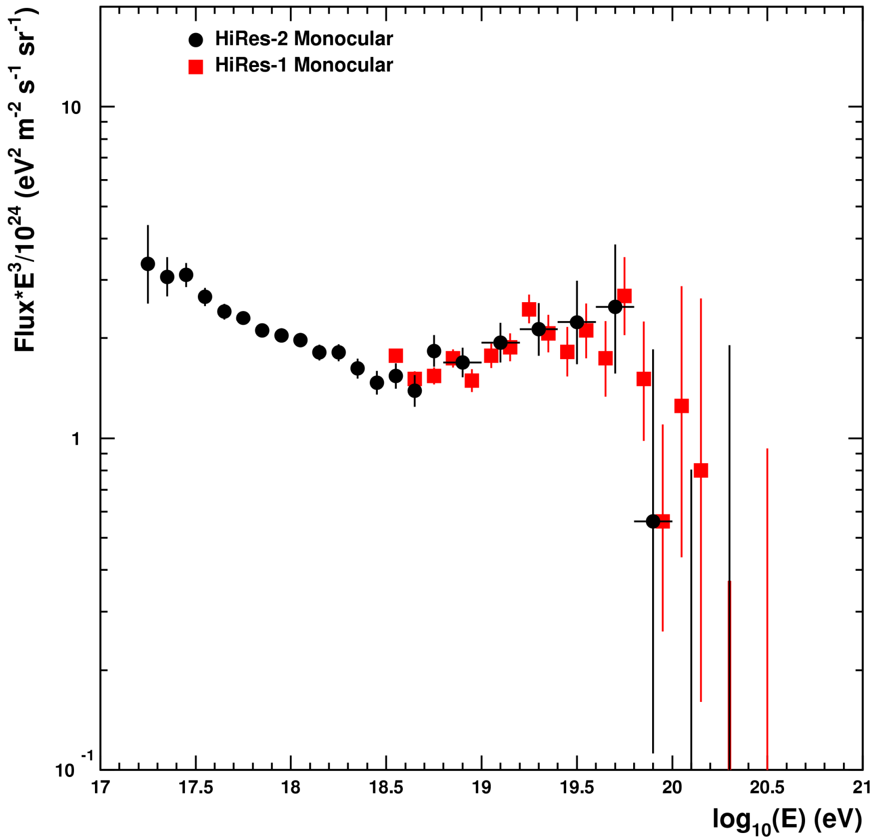
$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

AGASA spectrum continues smoothly!



… but HiRes sees expected suppression



Is there a ~25% energy calibration mismatch between air shower and air fluorescence detectors?

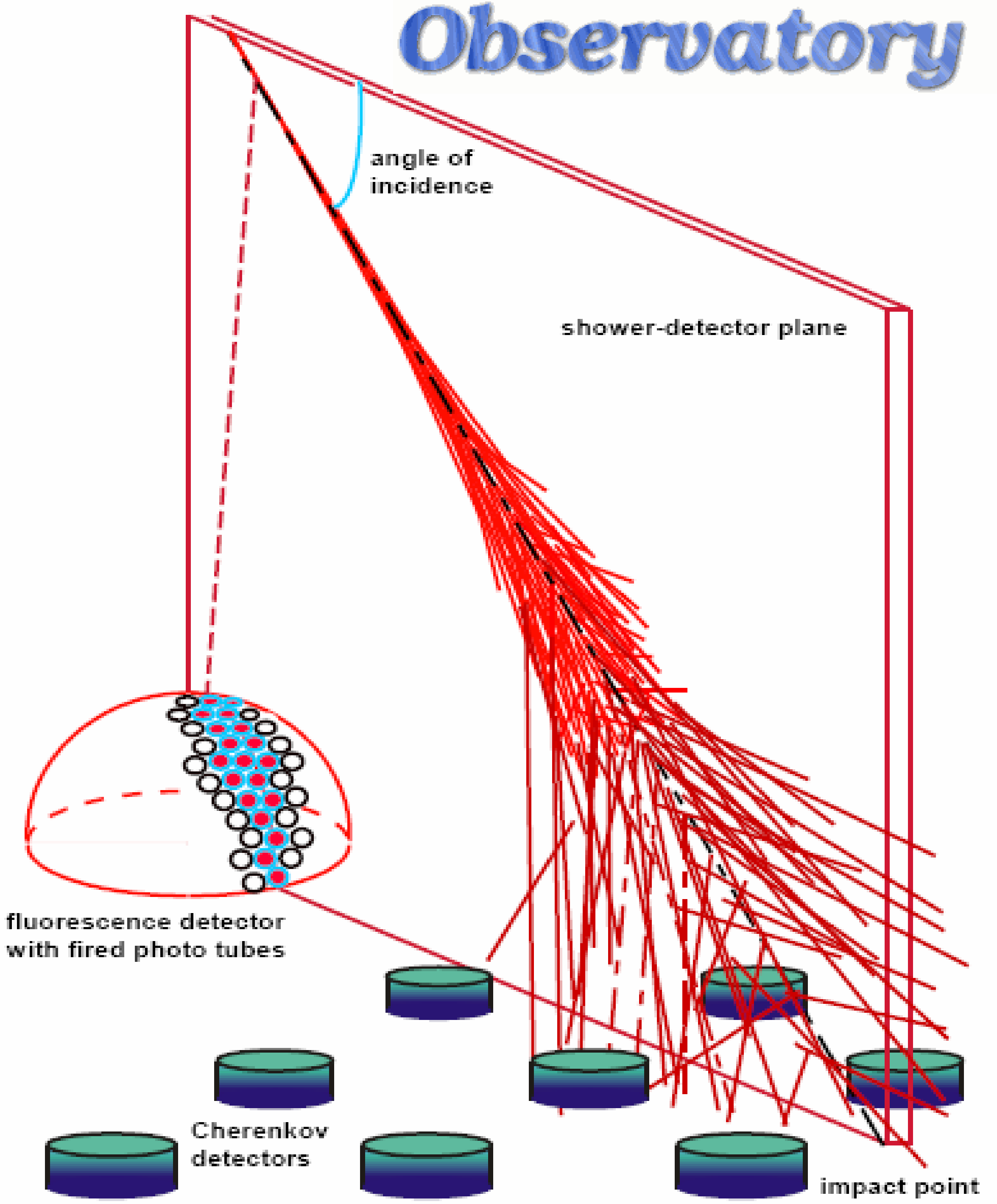
Pierre Auger Observatory

Hybrid Detector

allows cross-calibration of energy scale
control of systematics

FD: calorimetric energy measurement
X_{max} directly measured,
stereo imaging, good geometry,
low energy threshold (~10^{18} eV)

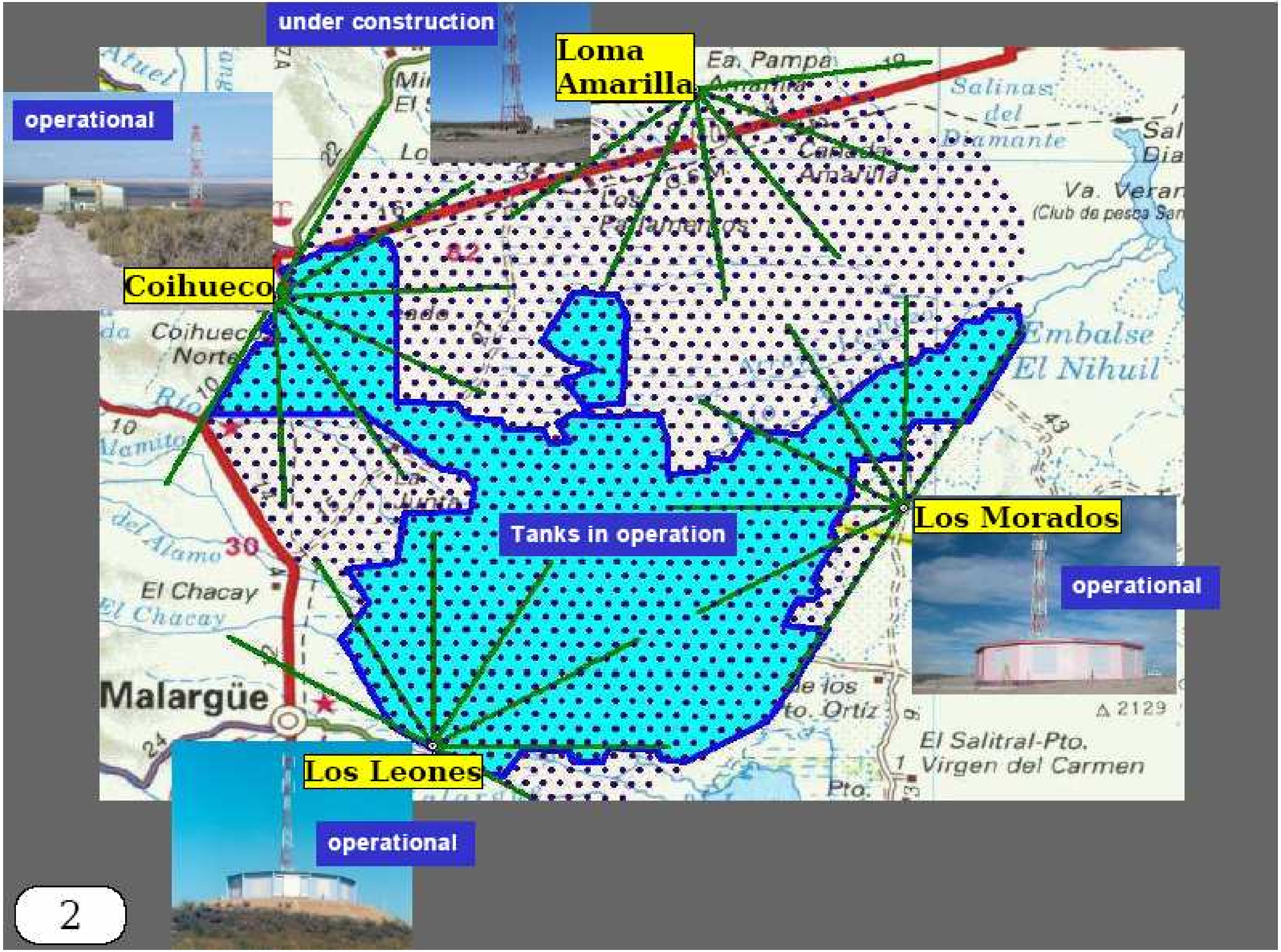
SD: 100% duty cycle, high statistics,
(rel.) simple detectors, cheap,
easy to calculate aperture



24 fluorescence telescopes (30° x 30°)

1600 water Cherenkov detectors
on 3000 km^2
arranged in hexagonal grid
with 1.5 km grid spacing

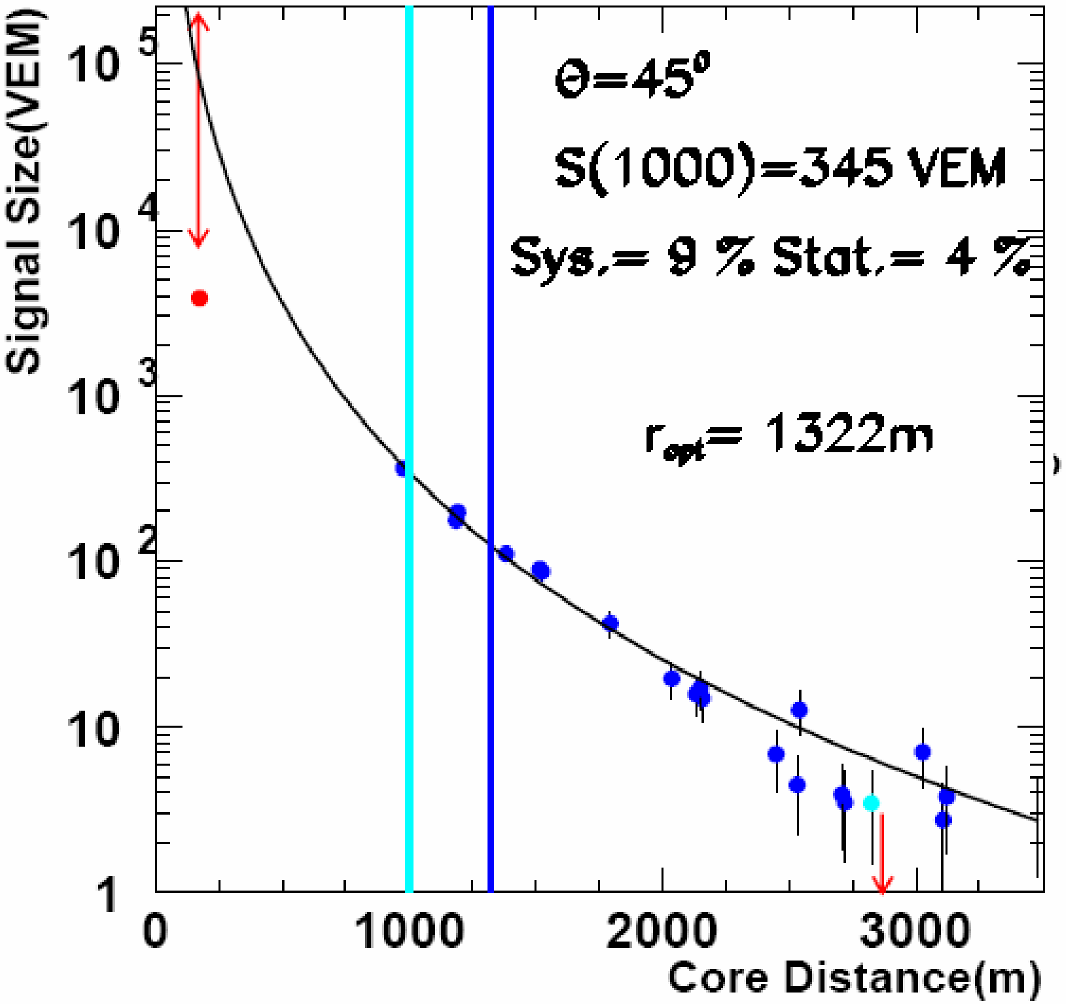
Currently ~1/2 the array is in place … expected to be complete by 2006

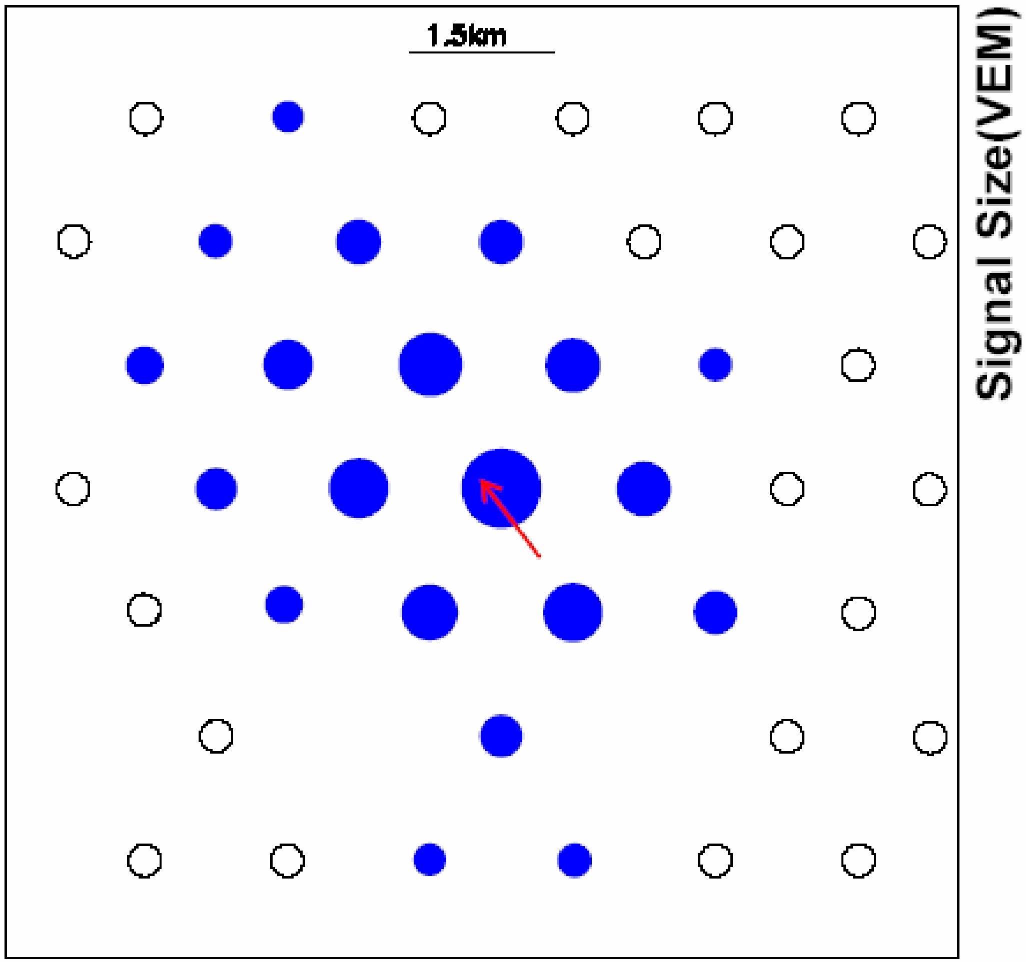


(Juan Bellido, ICRC 2005)

Lateral Distribution Function

Highest Energy Event – 86 EeV





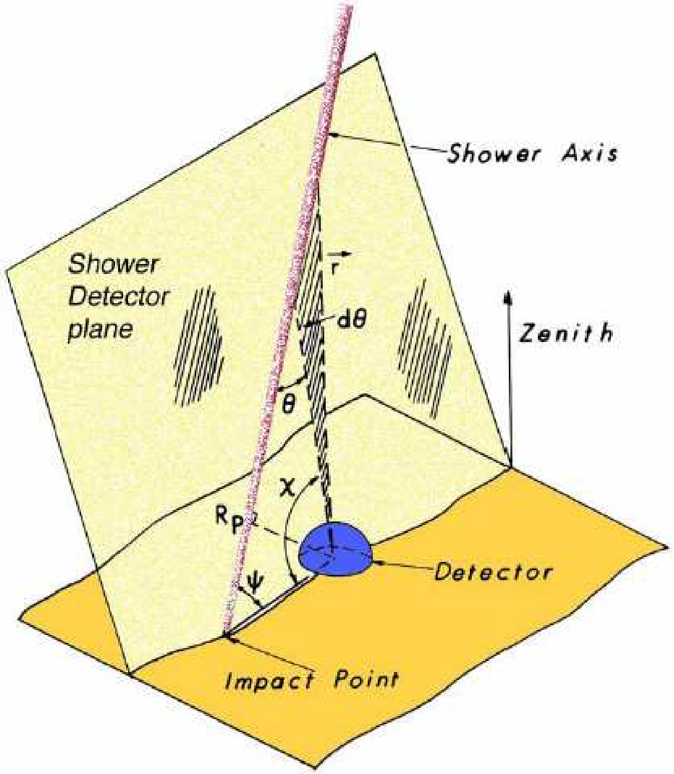
$$S(r) = A\, x^{-\beta} (1 + x)^{-\beta}$$

where:

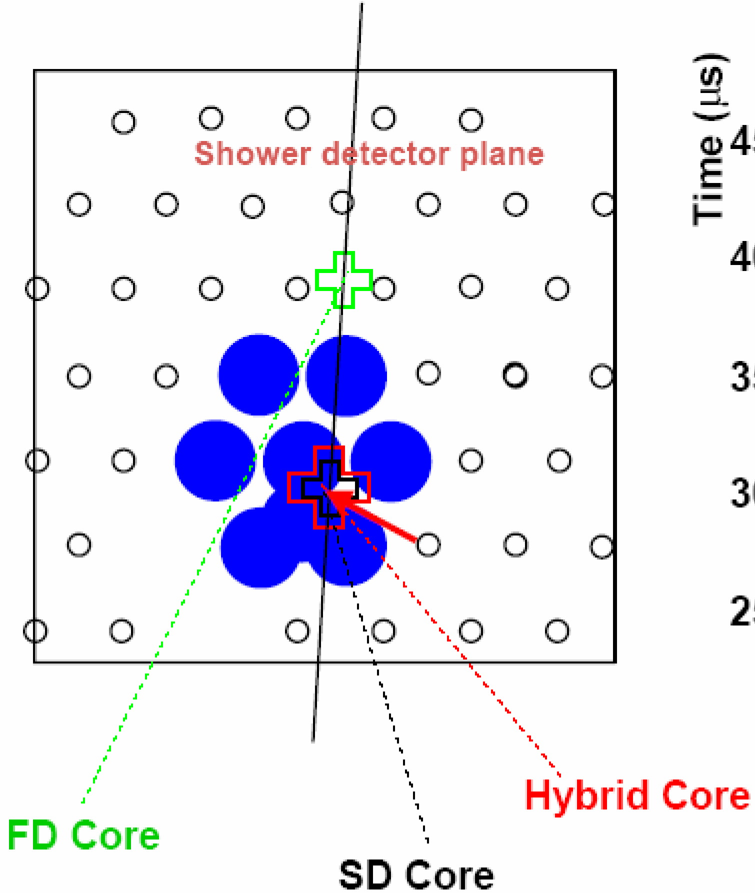
$X = r/r_s$ $\quad r_s = 700$ m *(scale factor)*

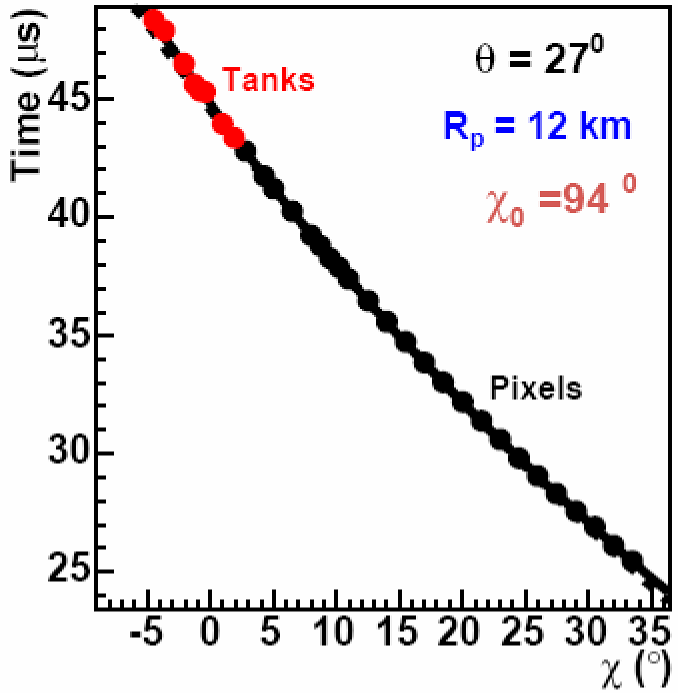
S(1000) is related to primary energy

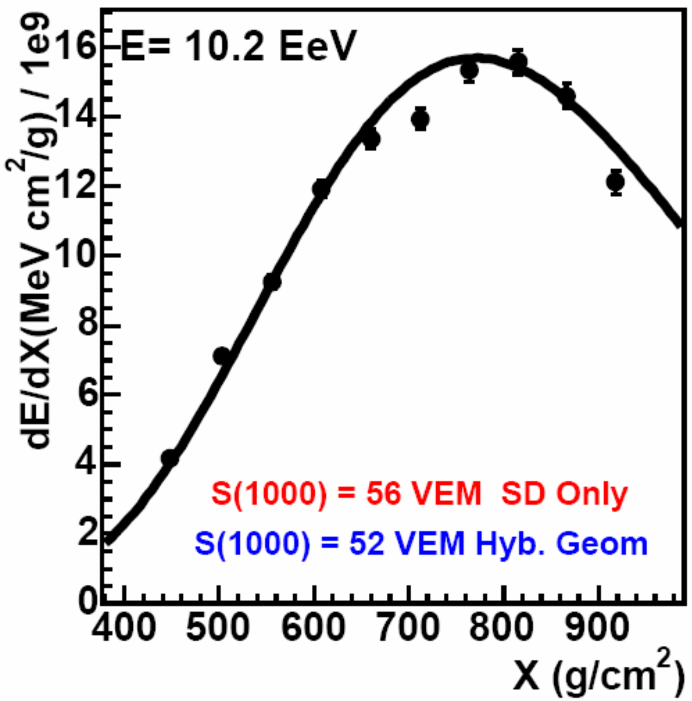
(Jim Mathews, ICRC 2005)



10.2 EeV Hybrid event







(Jim Mathews, ICRC 2005)

First spectrum from Auger

1 Jan 2004 – 5 June 2005

Array size ~1500 km^2

Trigger: SD with highest signal has ≥ 5 working full efficiency nearest neighbors

Zenith angle range ~0-60^0

Exposure ~1750 km^2 sr yr

3525 events above 10$^{18.5}$ eV

Energy calibration using FD

… no shower models used!

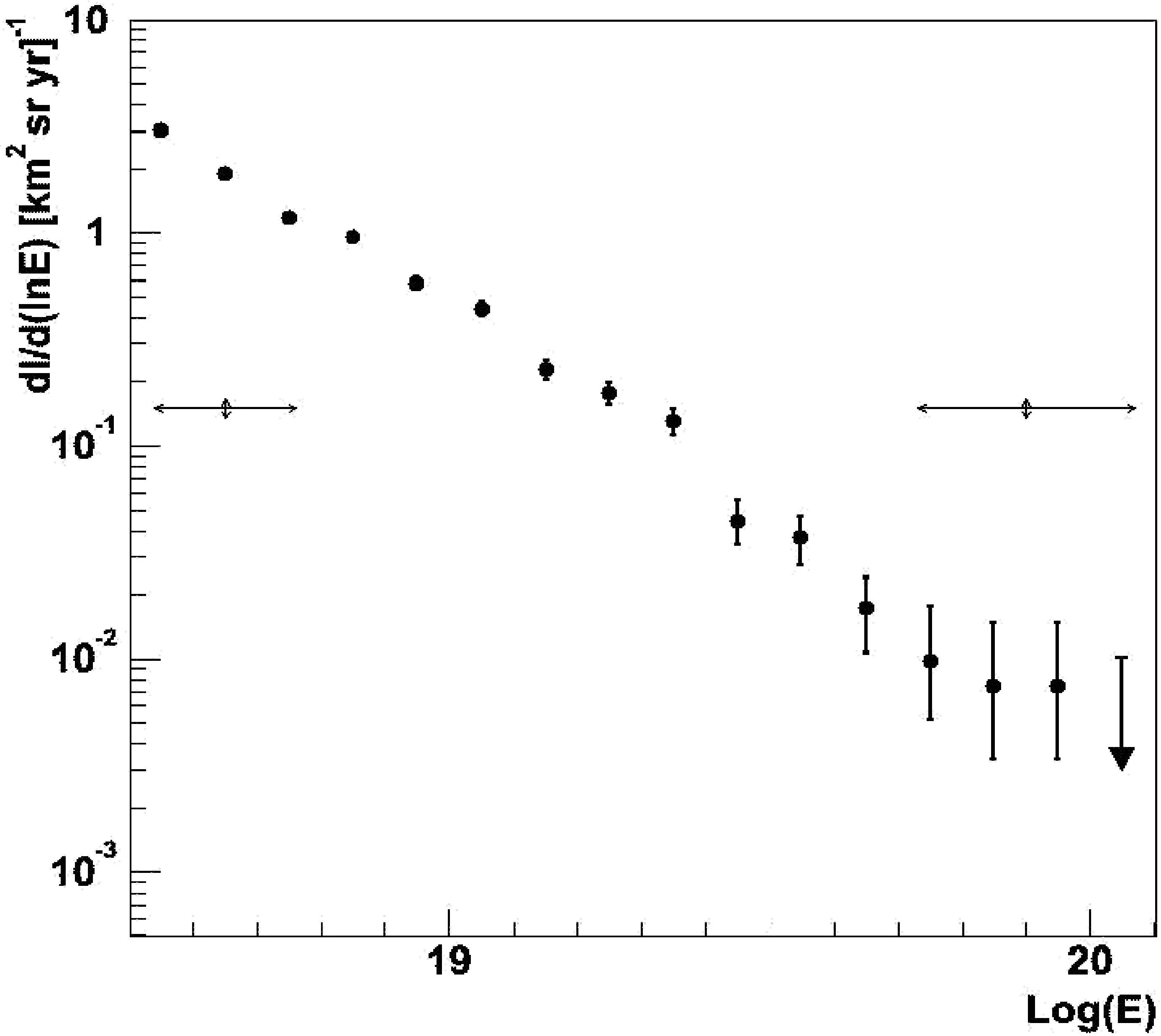
Horizontal: Systematic ΔE

~30% E @ 10$^{9.5}$ GeV

~50% E @ 10^{11} GeV

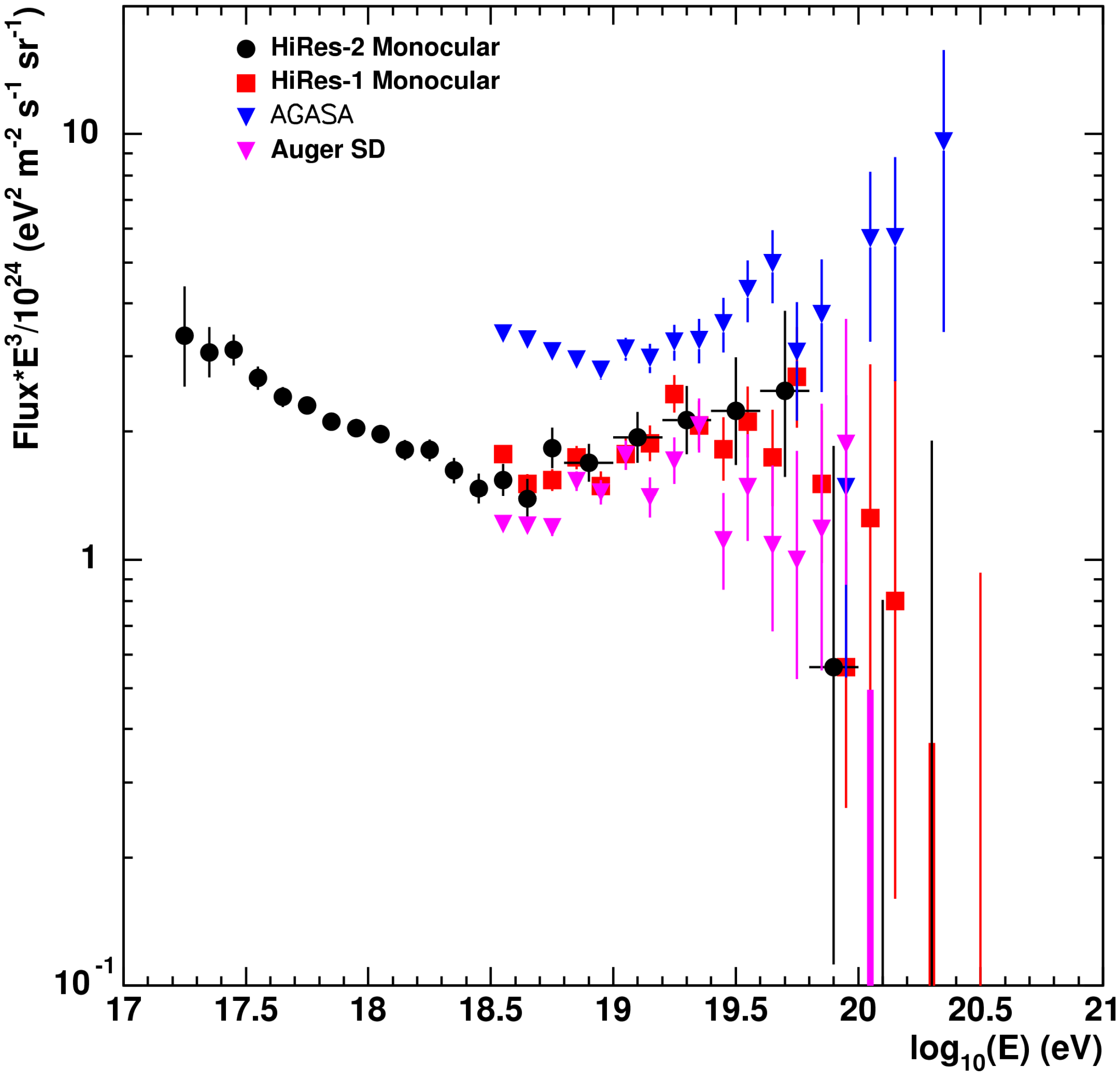
Vertical: Exposure uncertainty

~10%



(Paul Sommers, ICRC 2005)

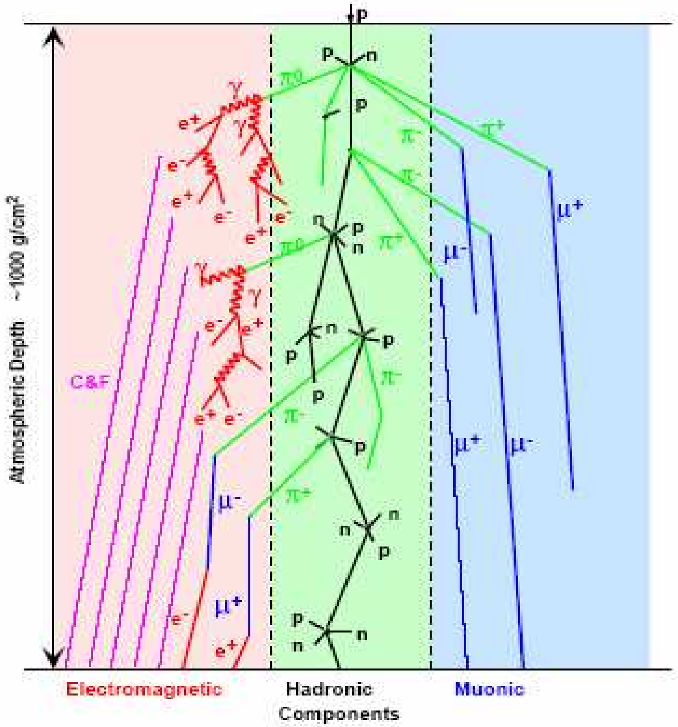
Perhaps you'd like to see how the Auger data compare with AGASA and HiRes …



But need to be cautious … these are early days! (Shigeru Yoshida, ICRC 2005)

Shower Development

(courtesey Johannes Knapp & Ralph Engel)



Fluorescence & (isotropic)
Cherenkov-Light (forward peaked)

p, n, π : near shower axis
μ, e, γ : widely spread

e, γ : from π^0, μ decays ~ 10 MeV
μ : from $\pi^\pm$, K, ... decays ~ 1 GeV

$N_{e,\gamma} : N_\mu$ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

Details depend on:
- interaction cross-sections,
- hadronic and el.mag. particle production,
- decays, transport, ...

at energies well above man-made accelerators

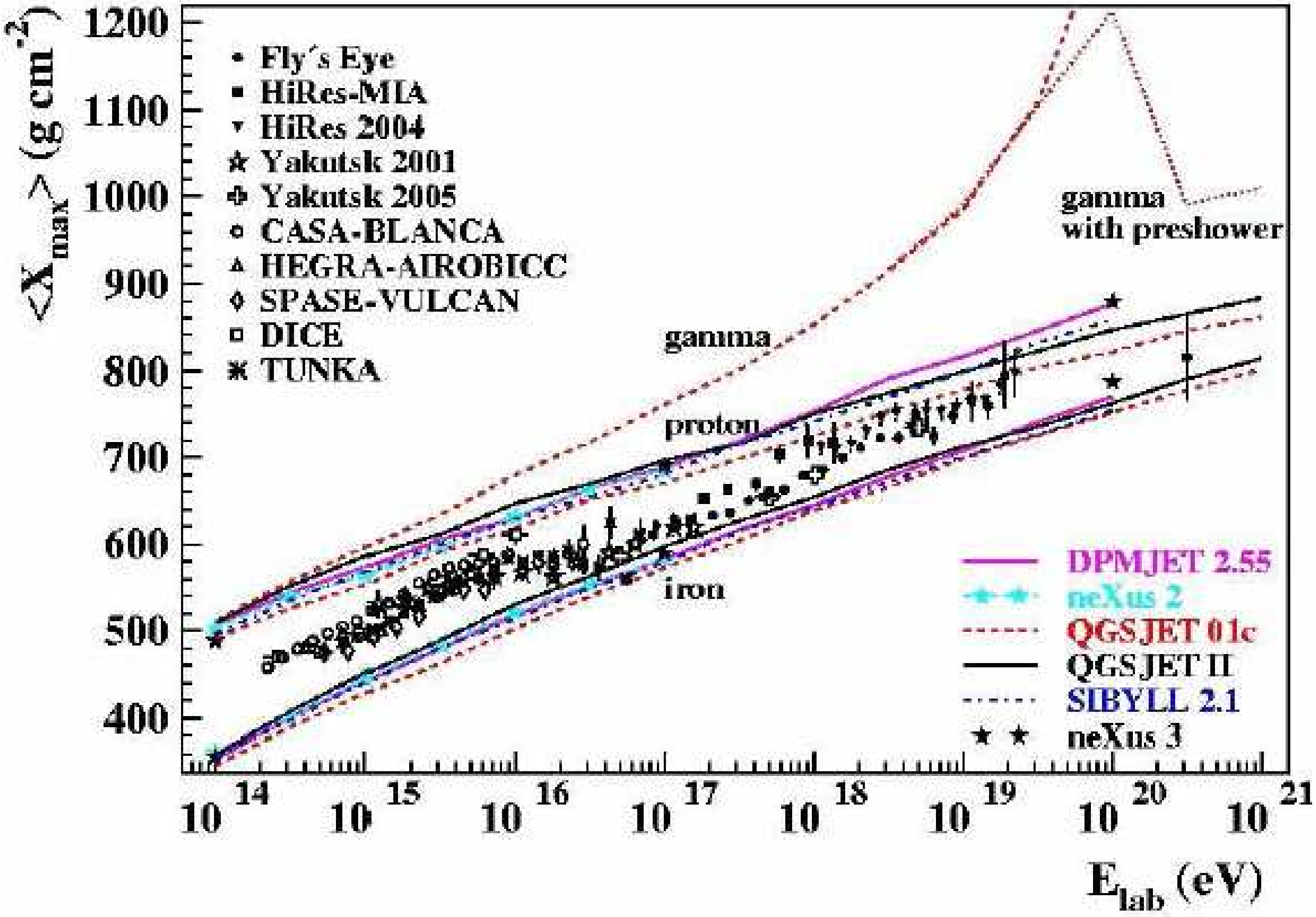
Complex interplay with many correlations
requires MC simulations

Main sources of uncertainty

- Minijet cross-section (parton densities, range of applicability)
- Transverse profile function (total #-secn, multiplicity distribution)
- Energy dependence of leading particle production
- Role of nuclear effects (saturation, stopping power, QGP)

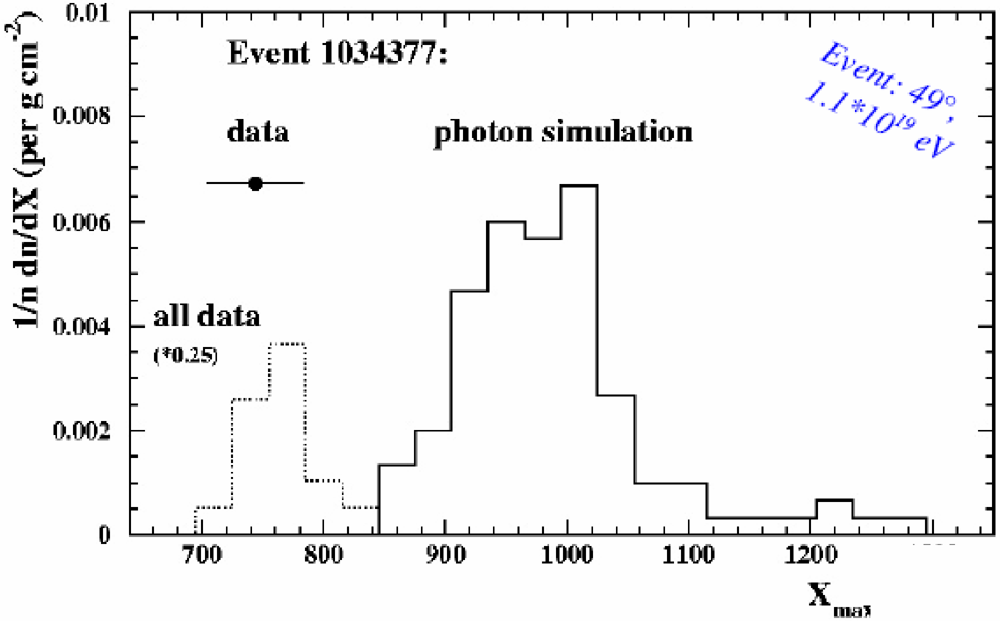
Expect significant input from forthcoming LHC experiments CASTOR, TOTEM …)

Photon discrimination with X_{max}



→ at 10^{19} eV: $\Delta<X_{max}>$ (photon, hadron) > 200 g cm^{-2}

Example



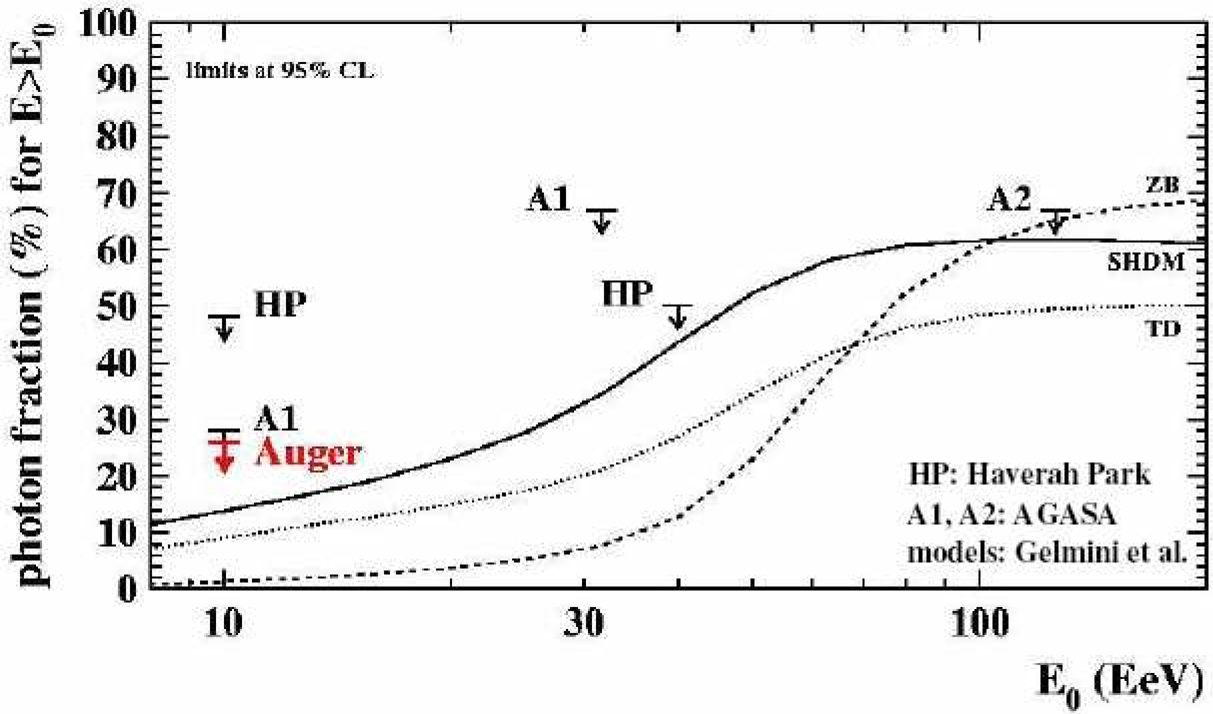
- event: $X_{max} = 744 \pm 40$ g cm^{-2}
- photons: $<X_{max}> = 1020$ g cm^{-2} , rms = 80 g cm

→ observed X_{max} well below photon expectation

Constrains (but does not yet rule out) 'top-down' models of UHECR origin

… the highest energy particles seem to be protons, not photons

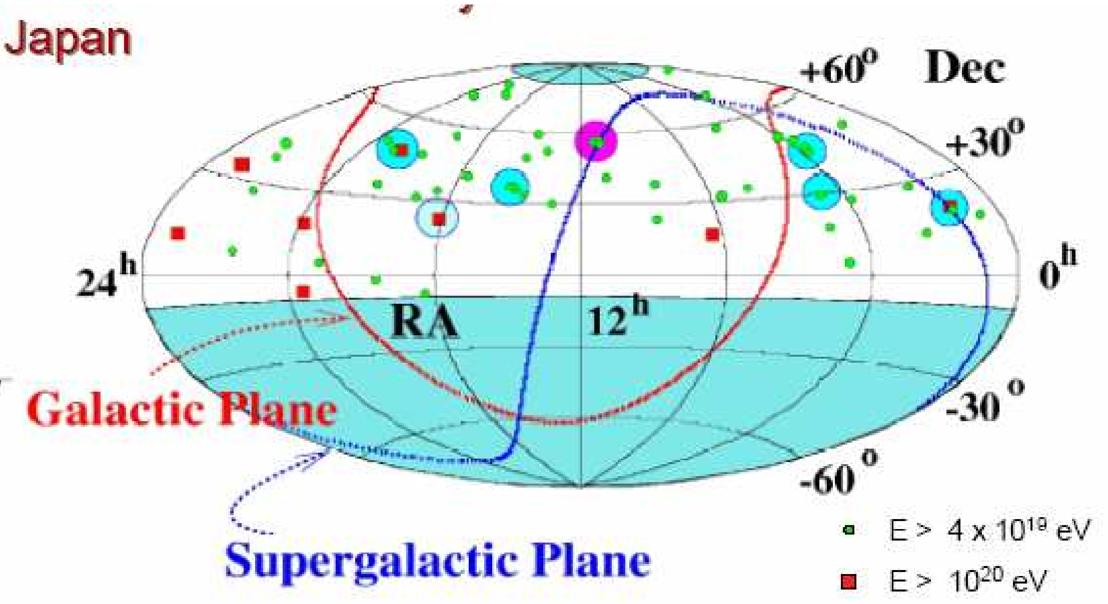
New upper limit

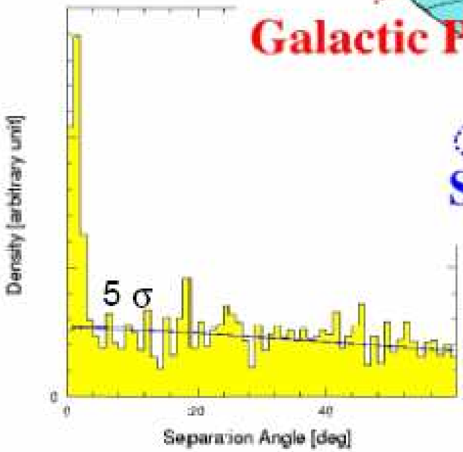


(Markus Risse, ICRC 2005)

- **26% upper limit** (95% CL) on cosmic-ray photon fraction

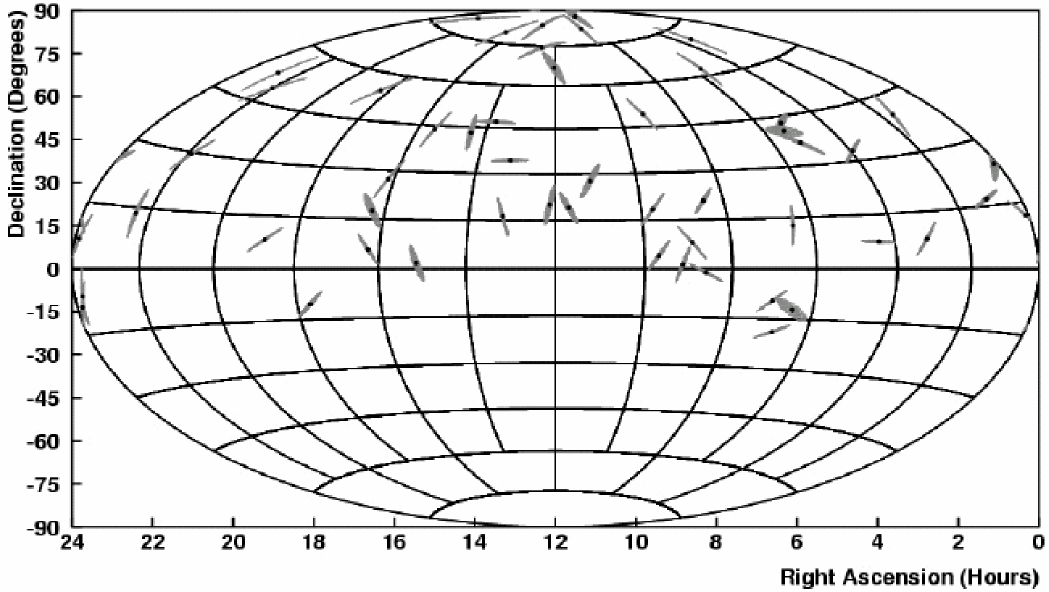
AGASA, Japan





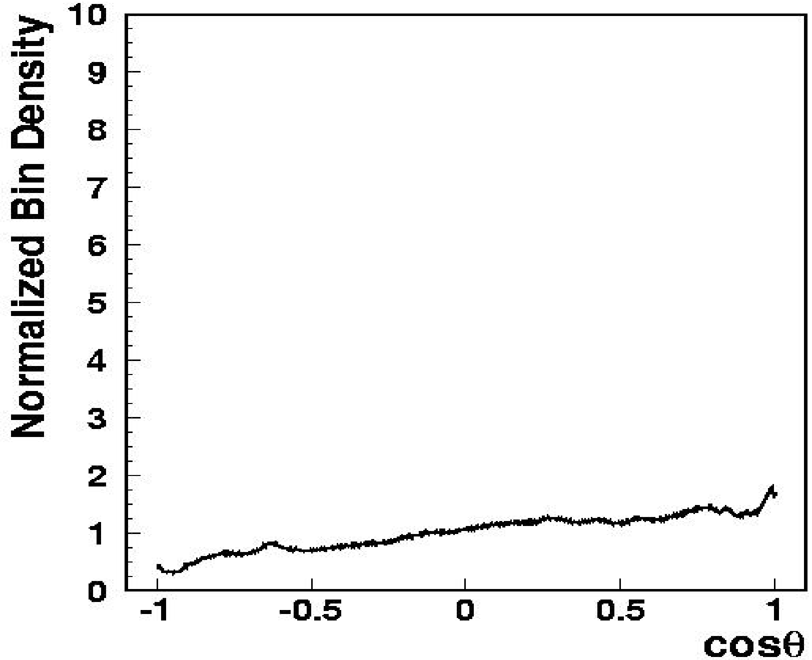
No obvious correlation with nearby matter
(supergalactic plane, quasars, ...).

6 doublets and one triplet
Isotropy or indication of point sources?



Stokes *et al* (2004)

By contrast, HiRes (with superior angular resolution) sees no evidence for any small-angle clustering



But HiRes does see correlations with BL Lacs

… active galaxies ('blazars') in which the jet from the BH points directly towards us

Veron 11th Catalogue:

178 objects with magnitude < 18

Claim: excess number of BL Lacs seen near HiRes events > 10^{10} GeV, consistent with the HiRes angular resolution of ~ 0.6°

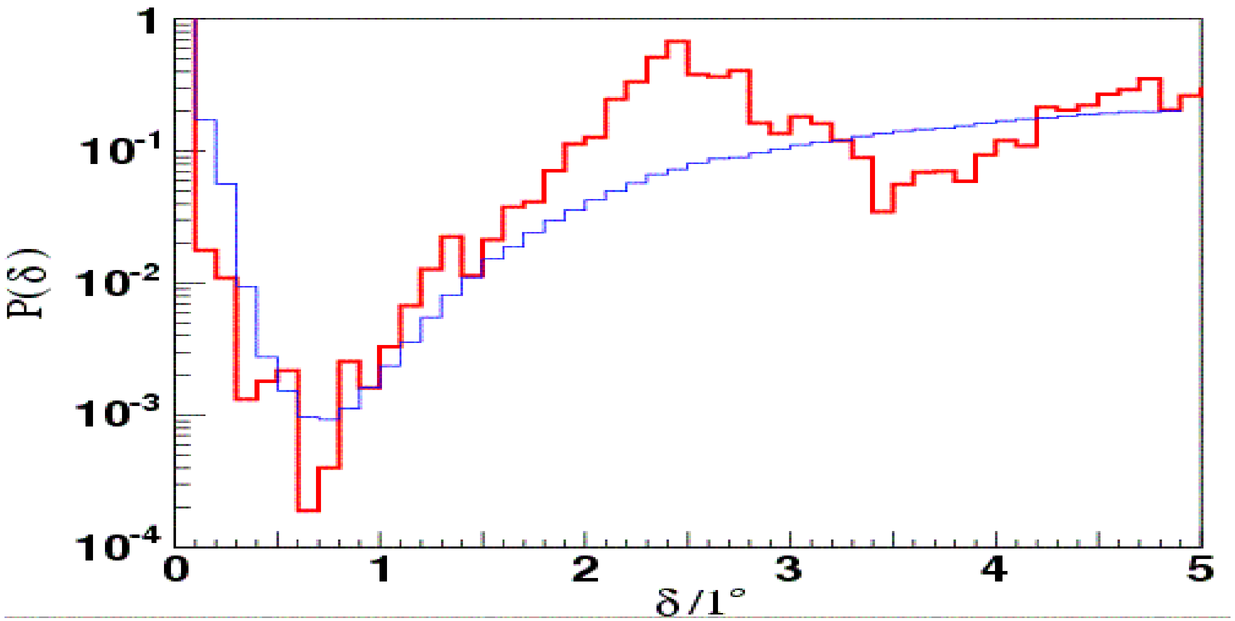
see 11 pairs < 0.8° and expect ~ 3,

$\Rightarrow$ probability ~ 5×10^{-4}

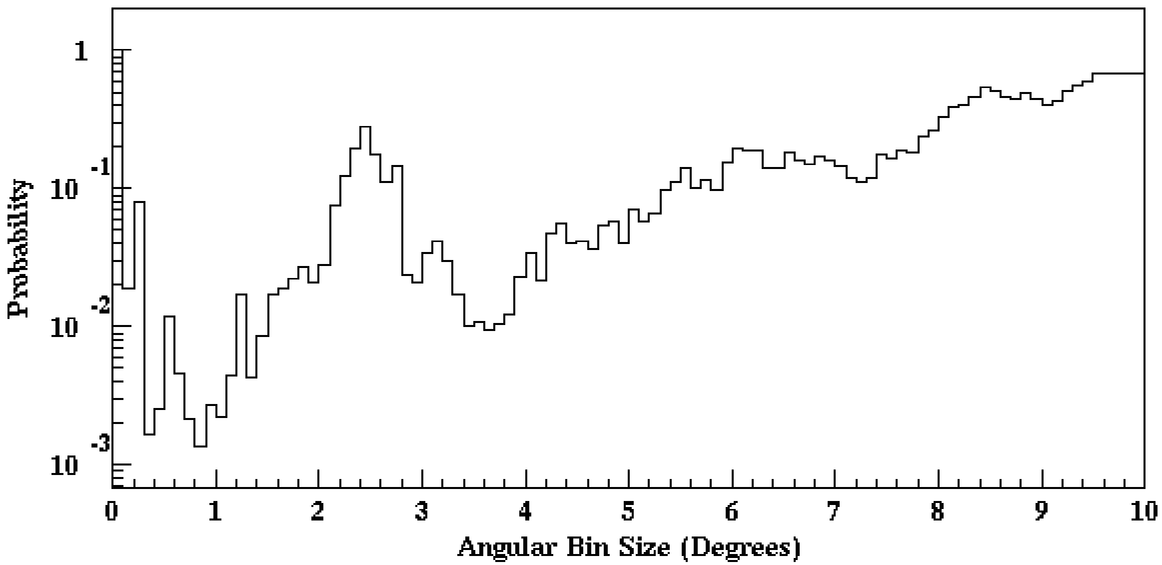
But these BL Lacs are hundreds of Mpc distant!

Few % of primaries must be *neutral* @ 10^{10} GeV

(charged particles would have been deflected by galactic and extragalactic magnetic fields)



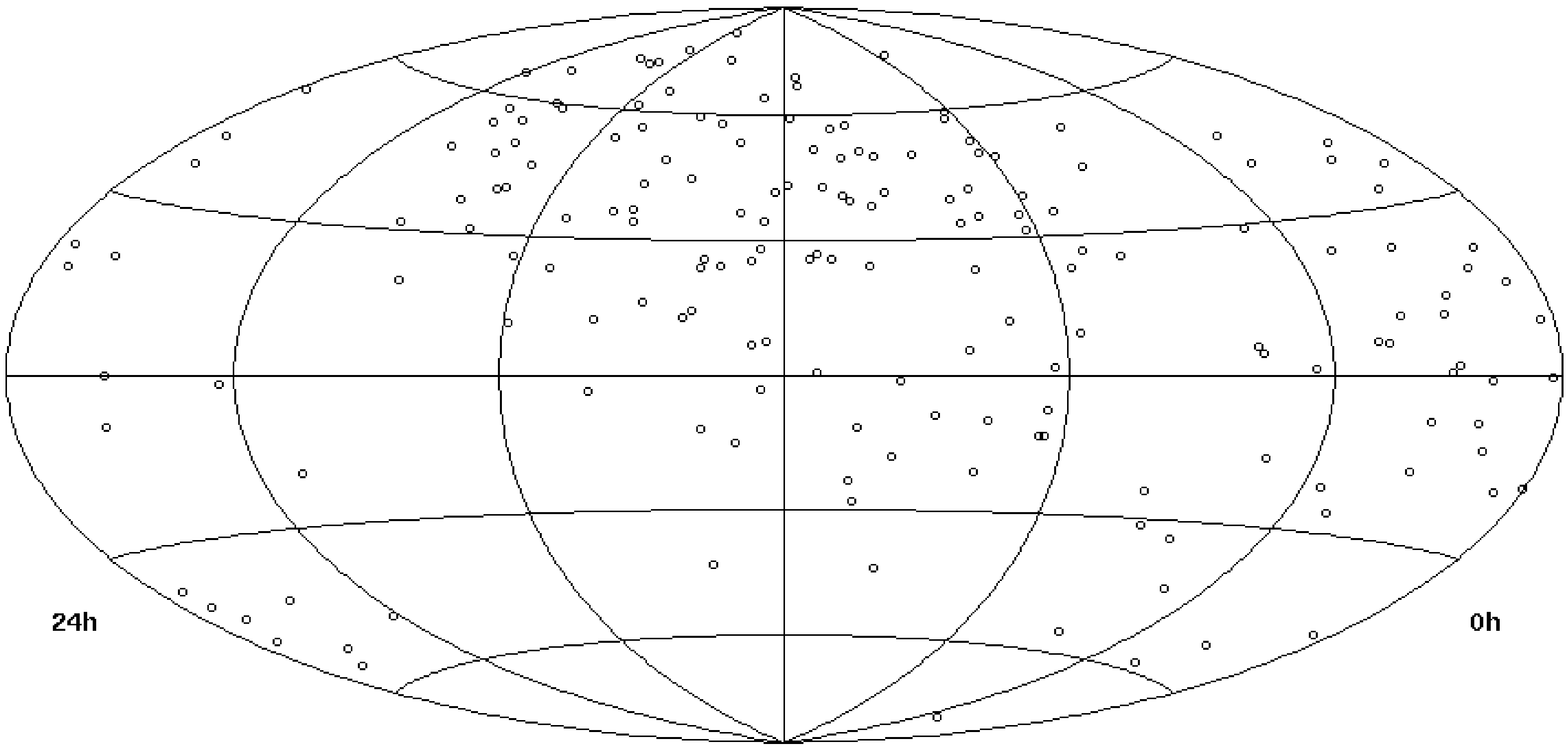
Gorbunov *et al* (2004)



Westerhoff *et al* (2005)

The BL Lac hypothesis is testable with a few years of HiRes data

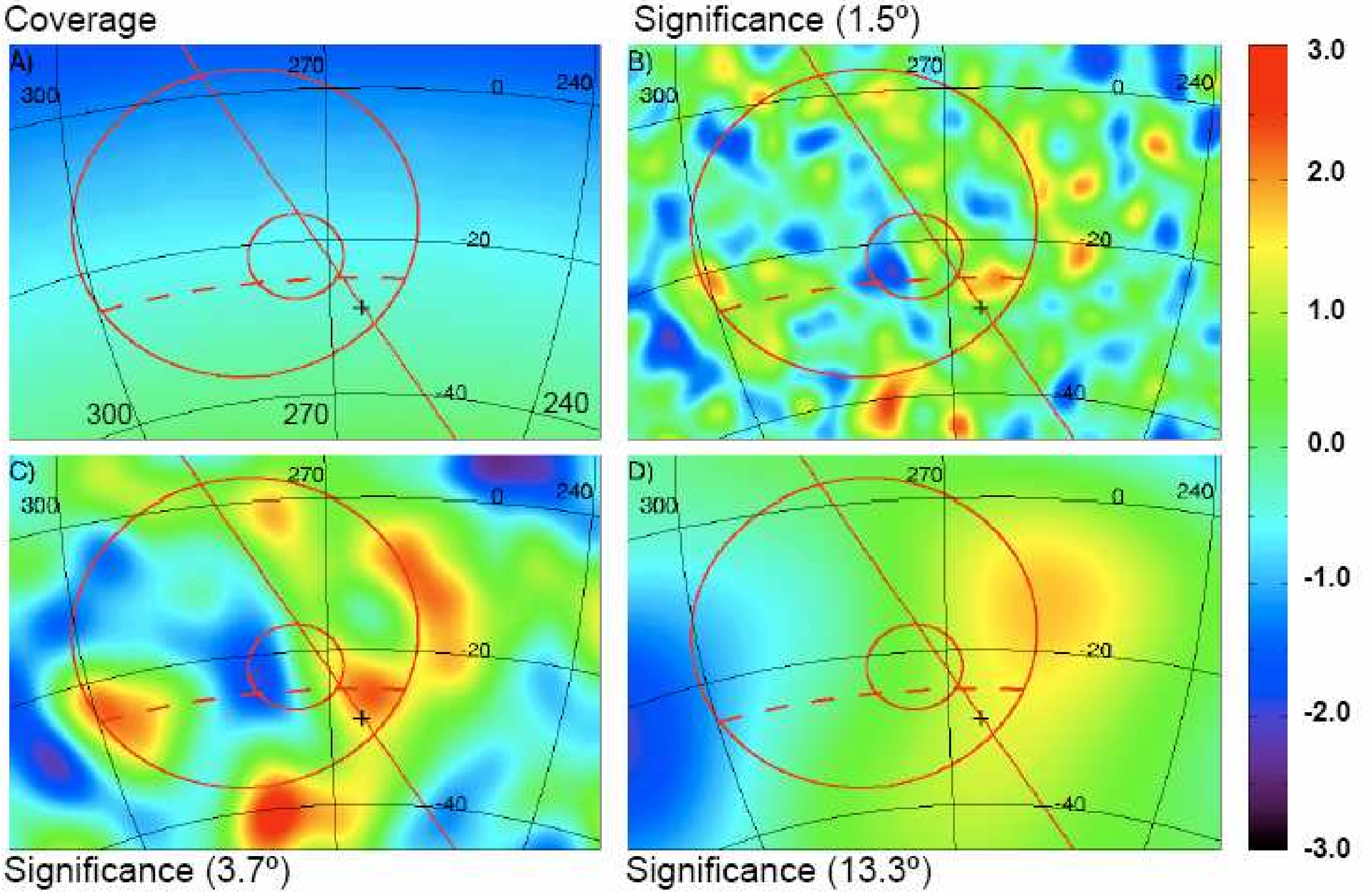
Note this is a new hypothesis – *not* the earlier claim of correlations with AGASA and Yakutsk (Tinyakov & Tkachev (2001, 2002) which was discredited by Evans, Ferrer & Sarkar (2003)



HiRes sees most of the selected BL Lacs, Auger (South) does not …

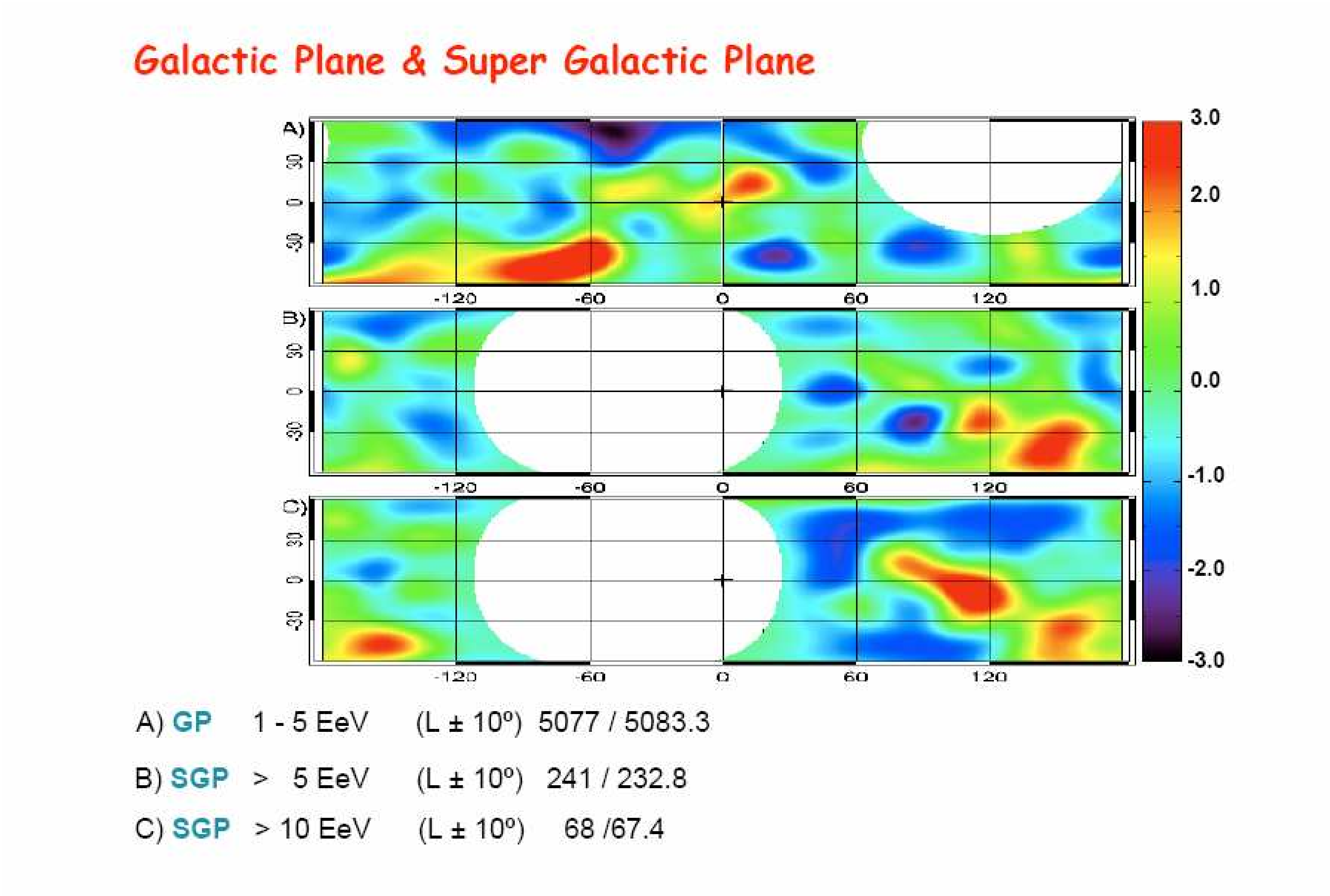
(Pierre Sokolsky 2005)

Auger sees *no* excess towards the Galactic Centre (contrary to claims by AGASA and SUGAR)



(Antoine Letessier-Selvon, ICRC 2005)

Auger sees *no* concentration of events along the Galactic or Super-Galactic planes

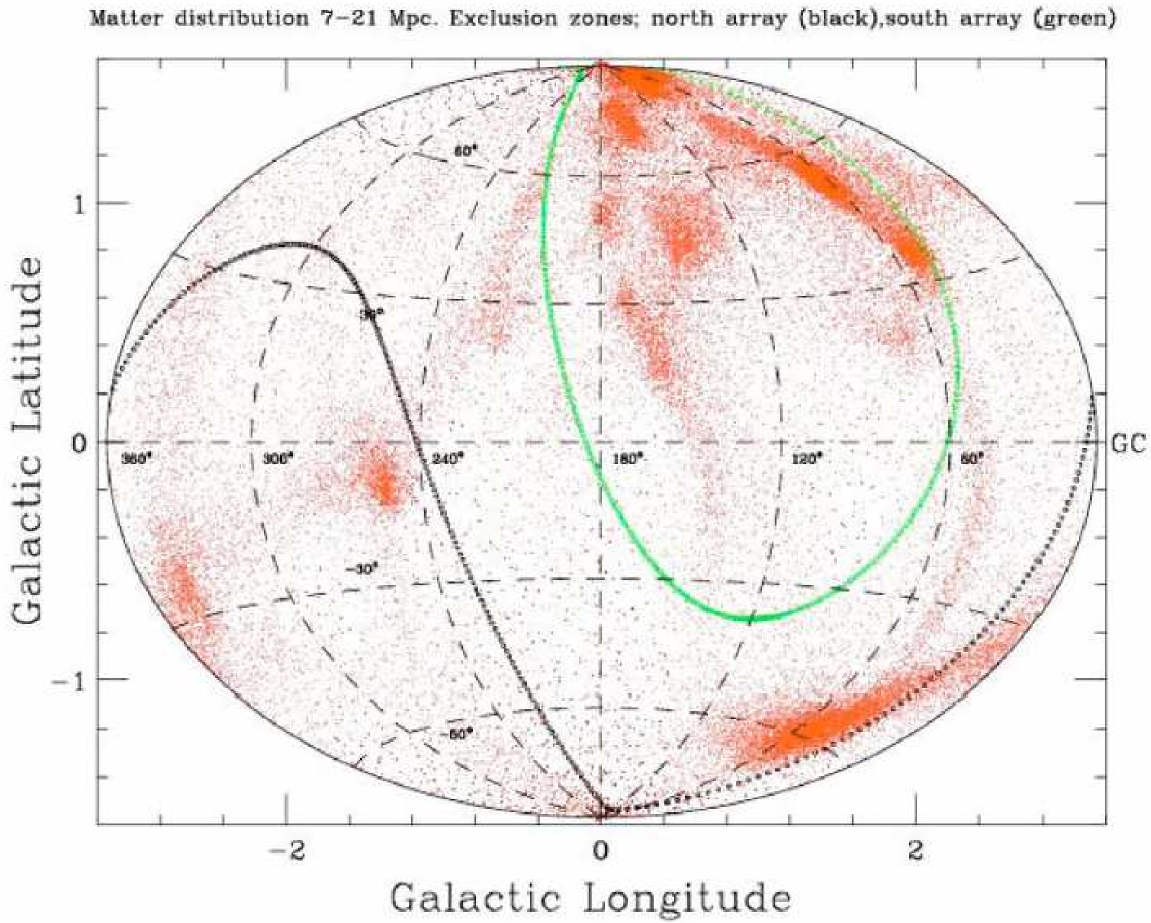


(Antoine Letessier-Selvon, ICRC 2005)

Need to wait for increased statistics and better understanding of systematics before coming to firm conclusions about energy spectrum or anisotropies

If correlations with astrophysical objects are established then essential to also have an observatory in the Northern hemisphere …

Northern and Southern matter distributions...



The sources of cosmic rays *must* also be sources of neutrinos

<u>Waxman-Bahcall Bound :</u>

- $1/E^2$ injection spectrum (Fermi shock).
- Neutrinos from photo-meson interactions in the source.
- Energy in ν's related to energy in CR's :

$$E_\nu^2 \mathrm{d}N_\nu/\mathrm{d}E_\nu \sim 0.25 \times \epsilon \times t_H \times E_{CR}^2 \mathrm{d}\dot{N}_{CR}/\mathrm{d}E_{CR}$$

Fraction of CR primary energy converted to neutrinos

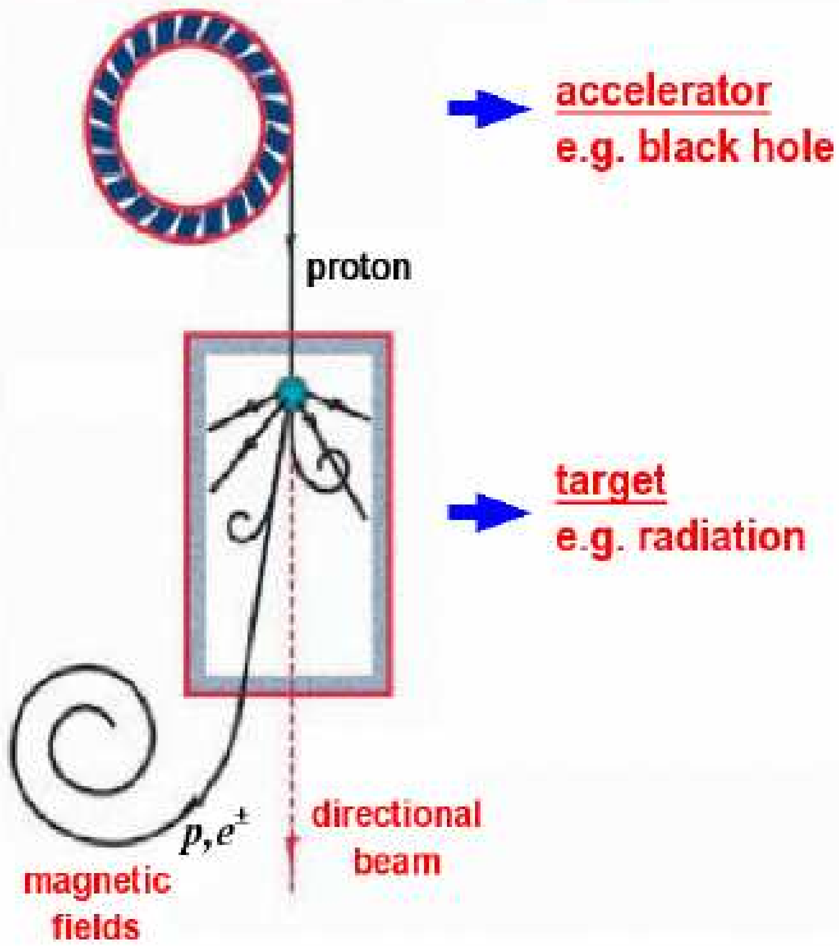
Hubble time

From rate of UHE CR's (10^{19}-10^{21} eV)

$$\Rightarrow \quad E_\nu^2 \Phi_\nu \lesssim 5 \times 10^{-8} \ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

- *Many* qualifications and caveats.
- Can be **evaded** if :
  - sources are optically thick
  - neutrinos from other sources ("top-down")

COSMIC BEAM DUMP : SCHEMATIC



(courtesey Dave Waters)

Cosmogenic neutrinos – the "guaranteed signal"

GZK mechanism :

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

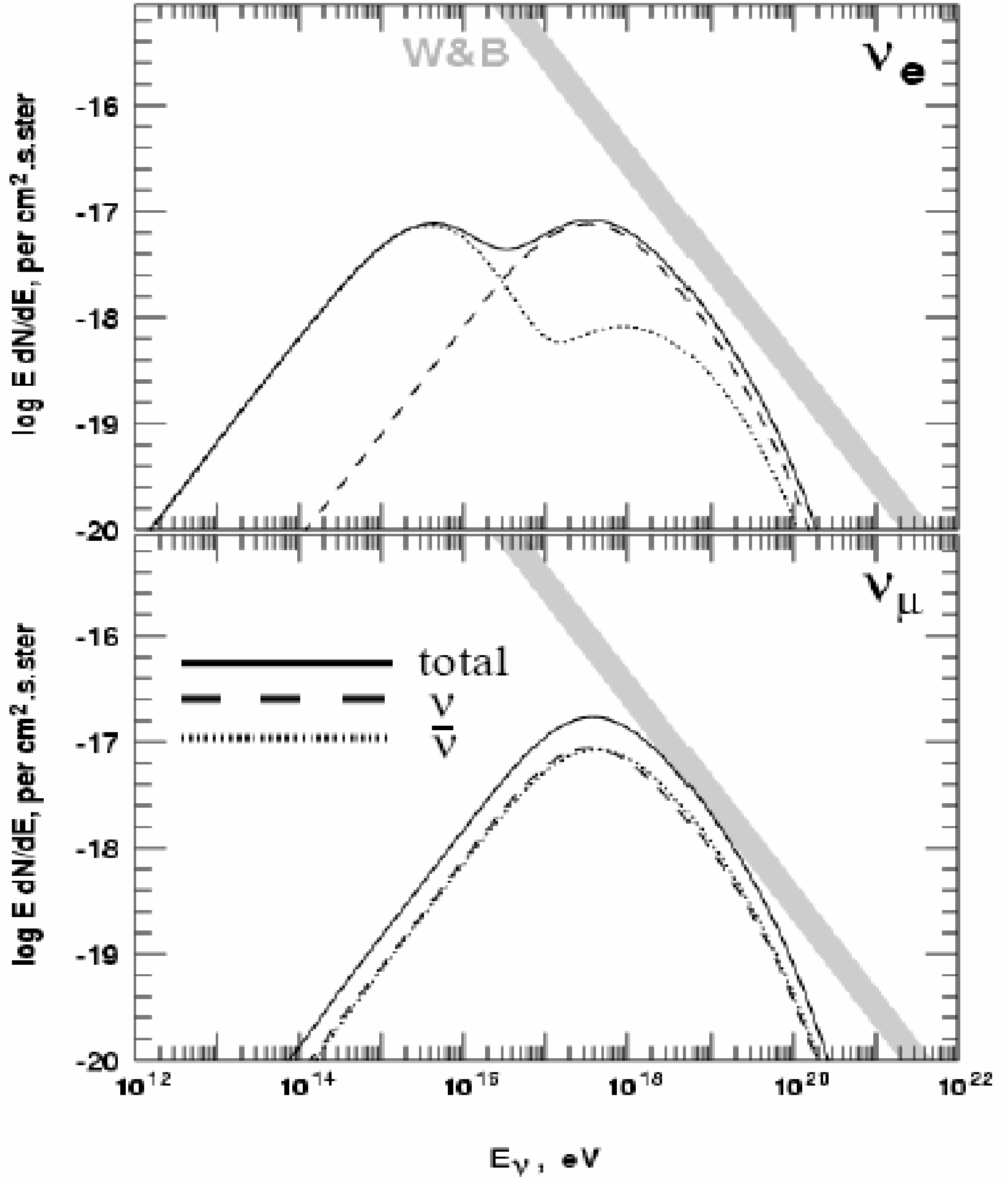
$E_{THRESH.} \sim 6 \times 10^{19}$ eV

- Uncertainties in flux calculations :
  - UHECR luminosity; ρ_{CR}(local) $\neq \langle\rho_{CR}\rangle$
  - injection spectrum
  - cosmological evolution of sources
  - IRB & optical density of sources

The nature of the primaries is crucial – if Fe (not p) then would photodissociate rather than produce π's so 'guaranteed' ν flux may be substantially reduced

Hooper, Sarkar & Taylor (2004),
Ave, Busca, Olinto, Watson, Yamamoto (2004)

Engel, Seckel, Stanev (2001)



(courtesey Dave Waters)

No-lose argument for detectable UHE ν flux – whether UHECRs exhibit the GZK cutoff or not!

Primary CR spectrum exhibits GZK cut-off ?

YES

Confirms basis of GZK neutrino flux calculation.

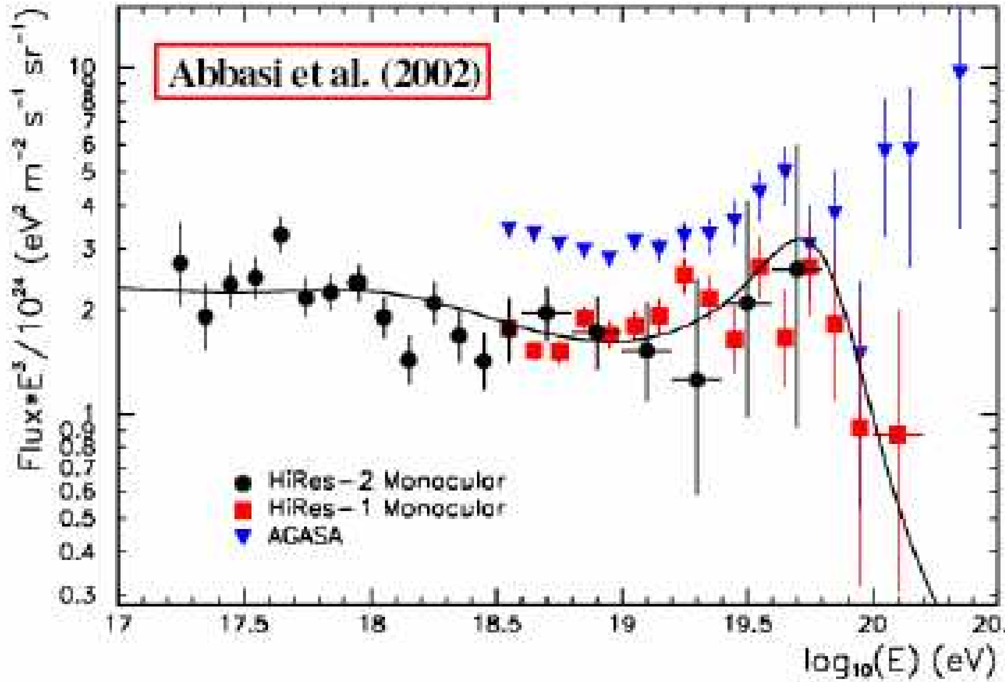
NO

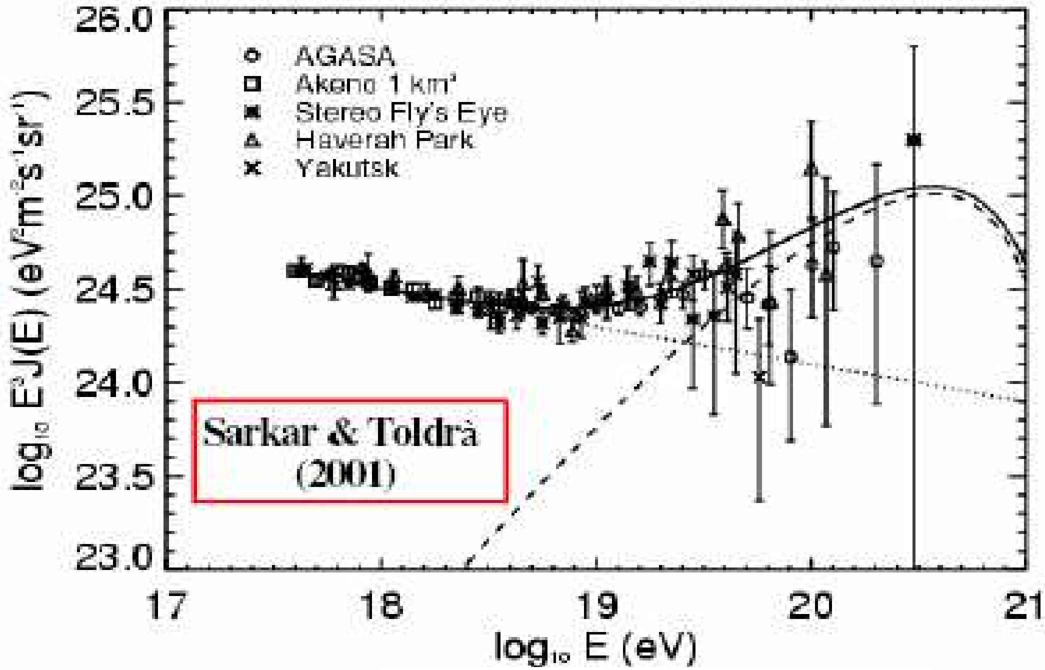
Local source of UHE cosmic rays :

$$X\,(10^{12}\,\mathrm{GeV}) \rightarrow h + X$$

Model dependent, but generally give neutrino fluxes ≥ GZK flux.

Auger will settle this definitively

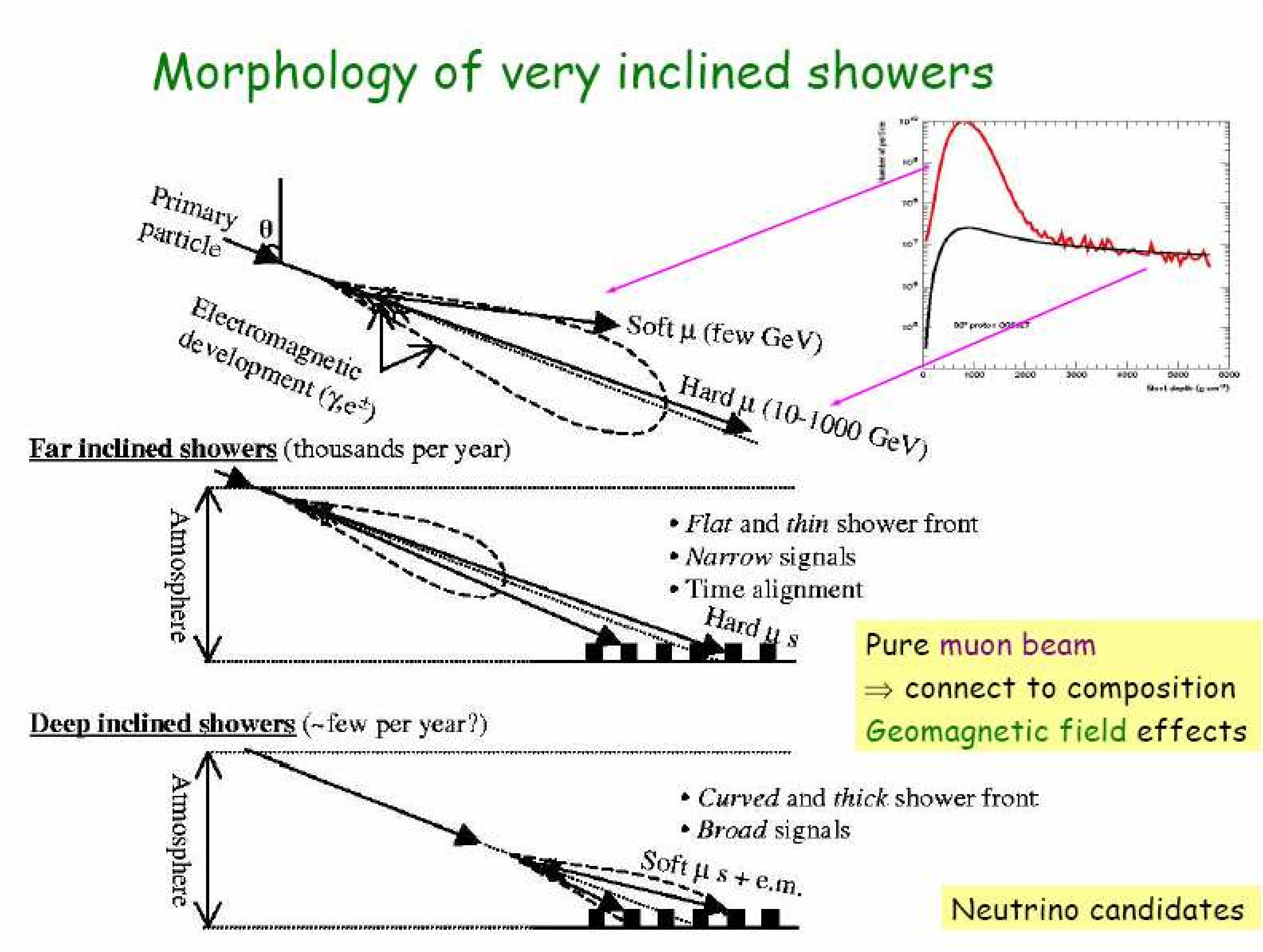




(courtesey Dave Waters)

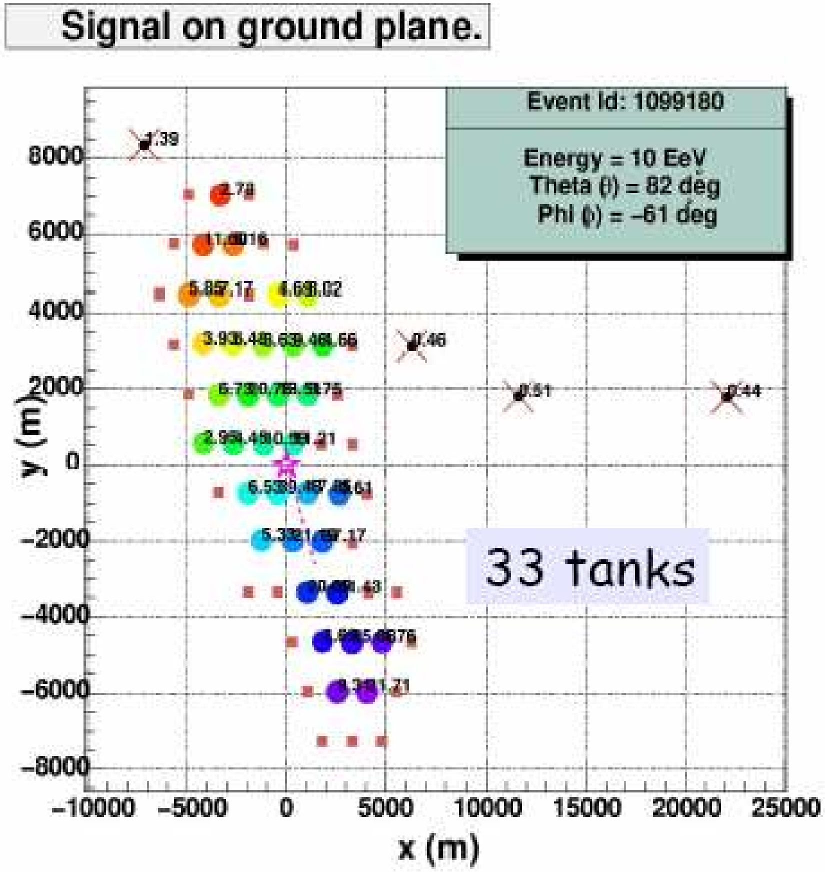
Auger can detect ultrahigh energy neutrinos as ~horizontal, deeply penetrating showers

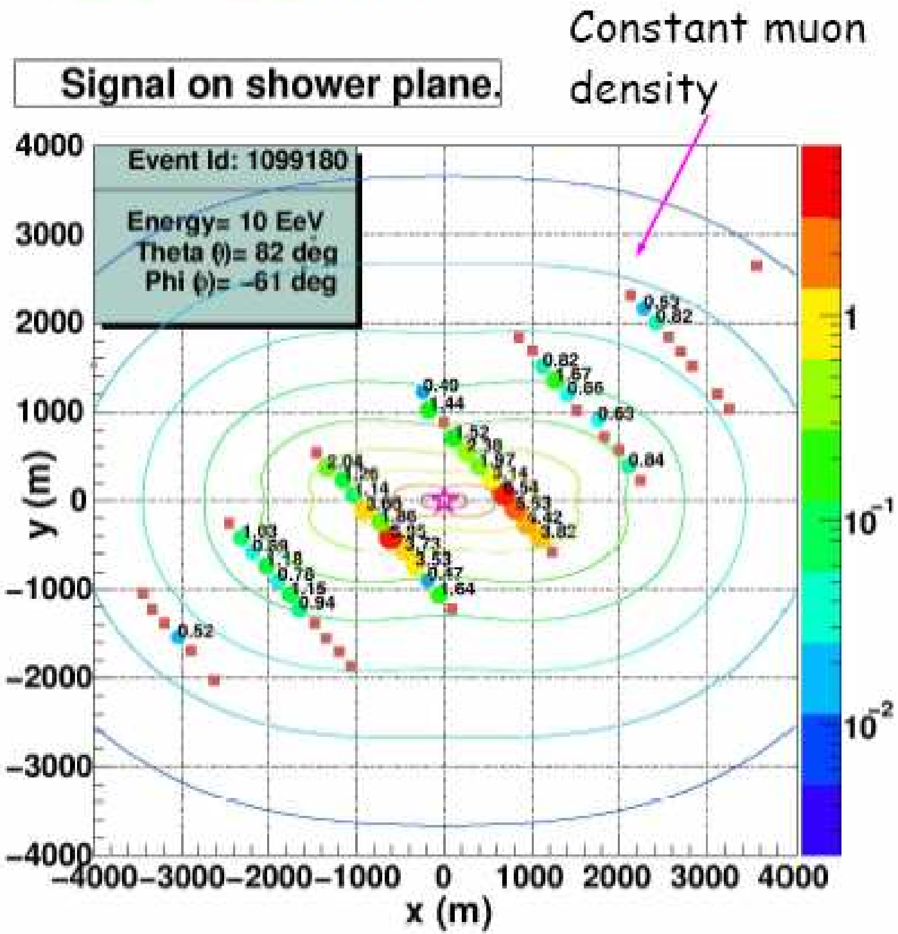
Capelle, Cronin, Parente & Zas (1998)



(Lukas Nellen, ICRC 2005)

A very inclined event: ≈82° zenith





Inclined showers have extended footprint and high multiplicities

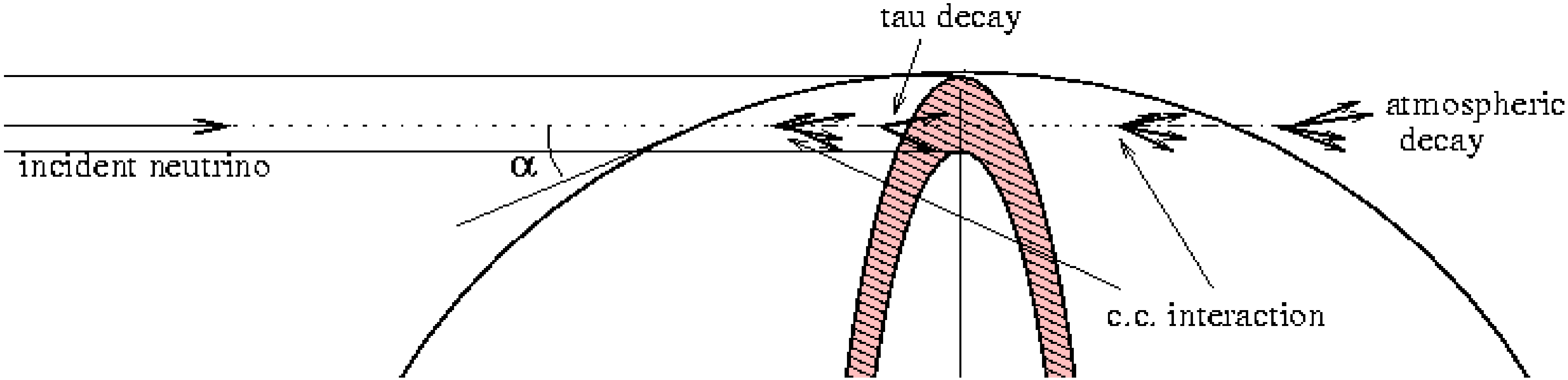
Positive and negative muons get separated by the geomagnetic field

But no confirmed neutrino events yet …

(Lukas Nellen, ICRC 2005)

Auger will also detect Earth-skimming $\nu_\tau \to \tau$ generates upgoing hadronic shower

Bertou, Billoir, Deligny, Lachaud & Letessier-Selvon (2002); Feng, Fisher, Wilczek & Yu (2002)

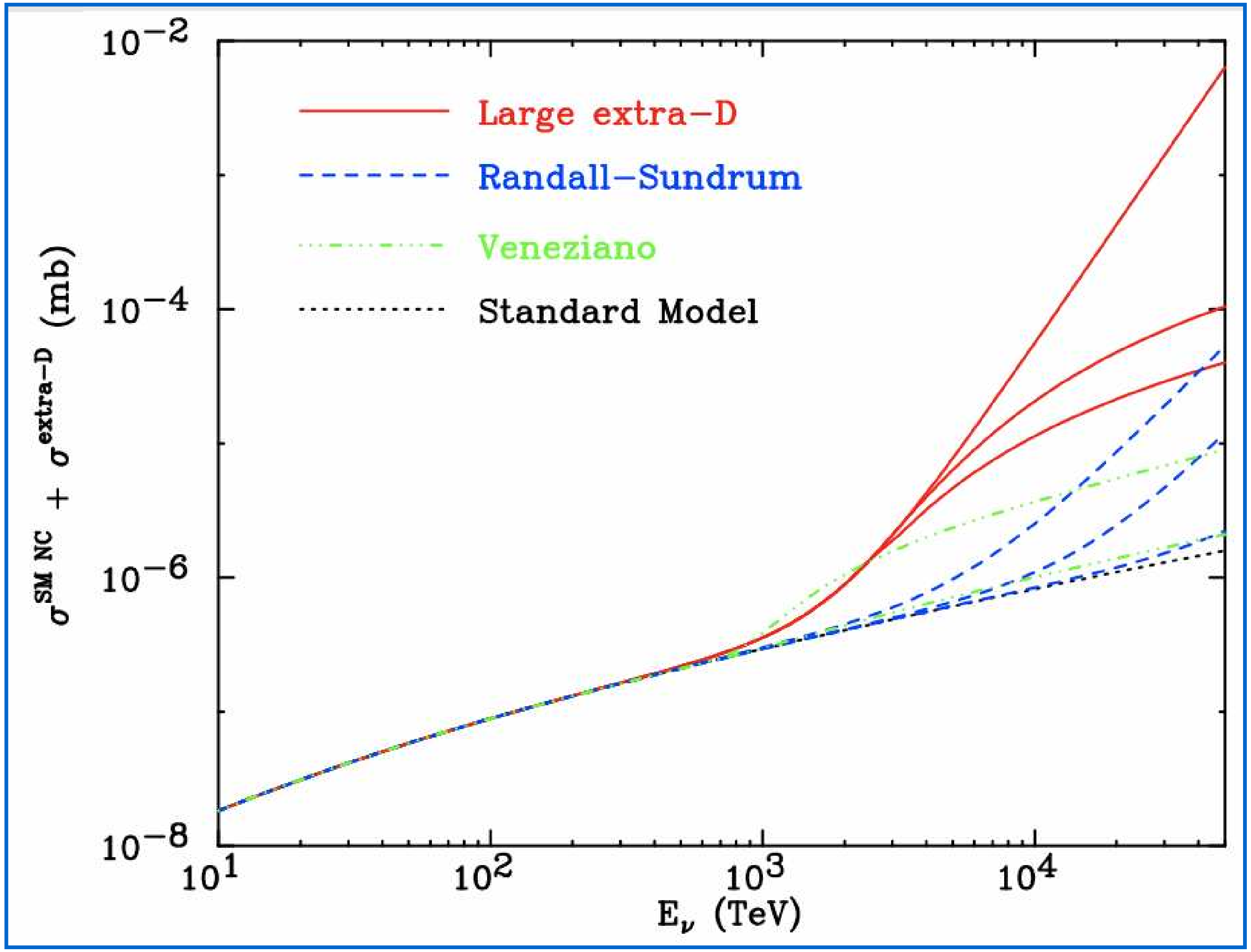


Any increase in ν-secn above SM value will enhance quasi-horizontal showers but suppress Earth-skimmers, so observed ratio of rates can test for new physics

Anchordoqui, Han, Hooper & Sarkar (2005)

ν-N cross-sections for TeV scale gravity with extra dimensions

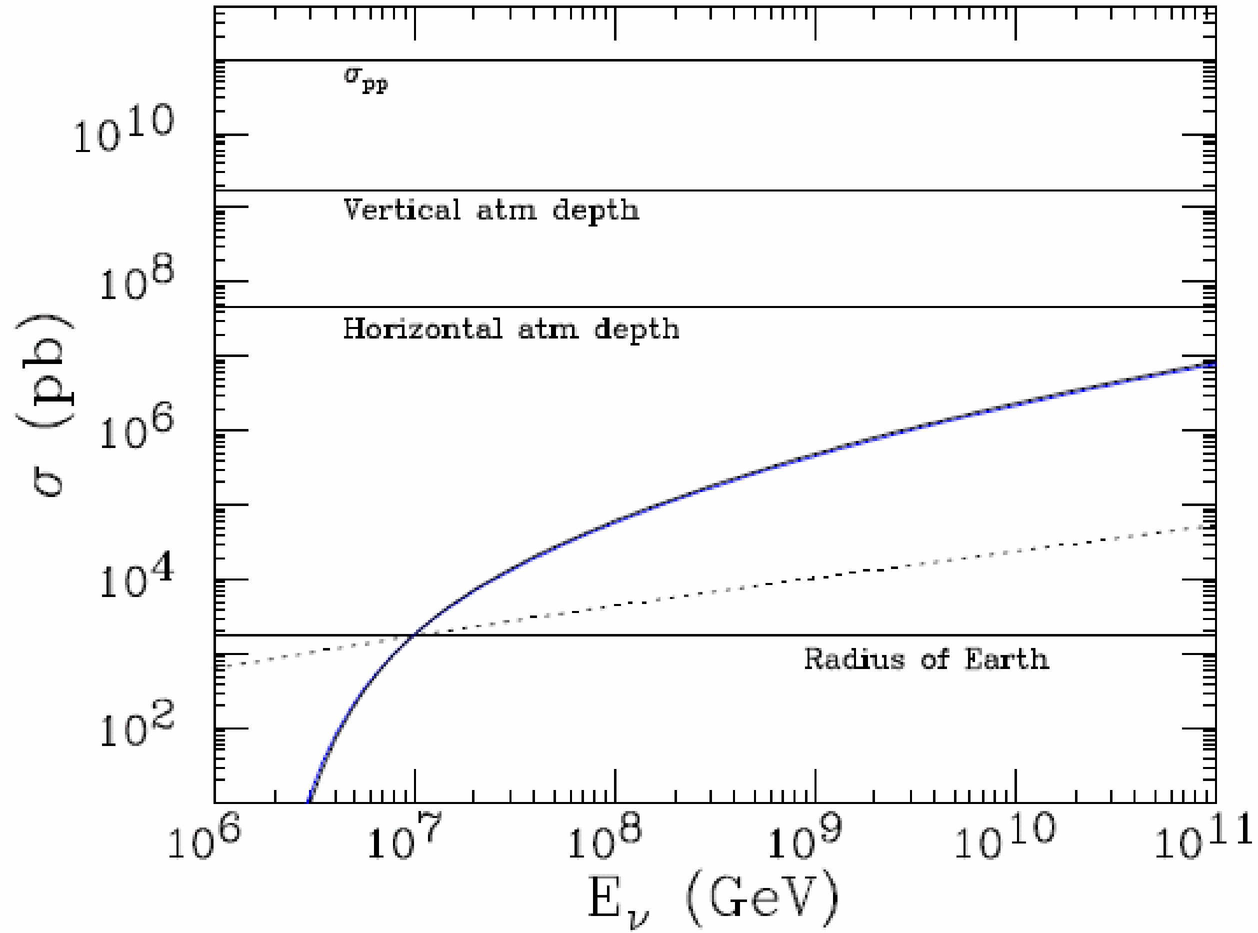
KK graviton excahnge … valid at cm energies below fundamental Planck scale



Alvarez, Halzen, Han & Hooper (2001)

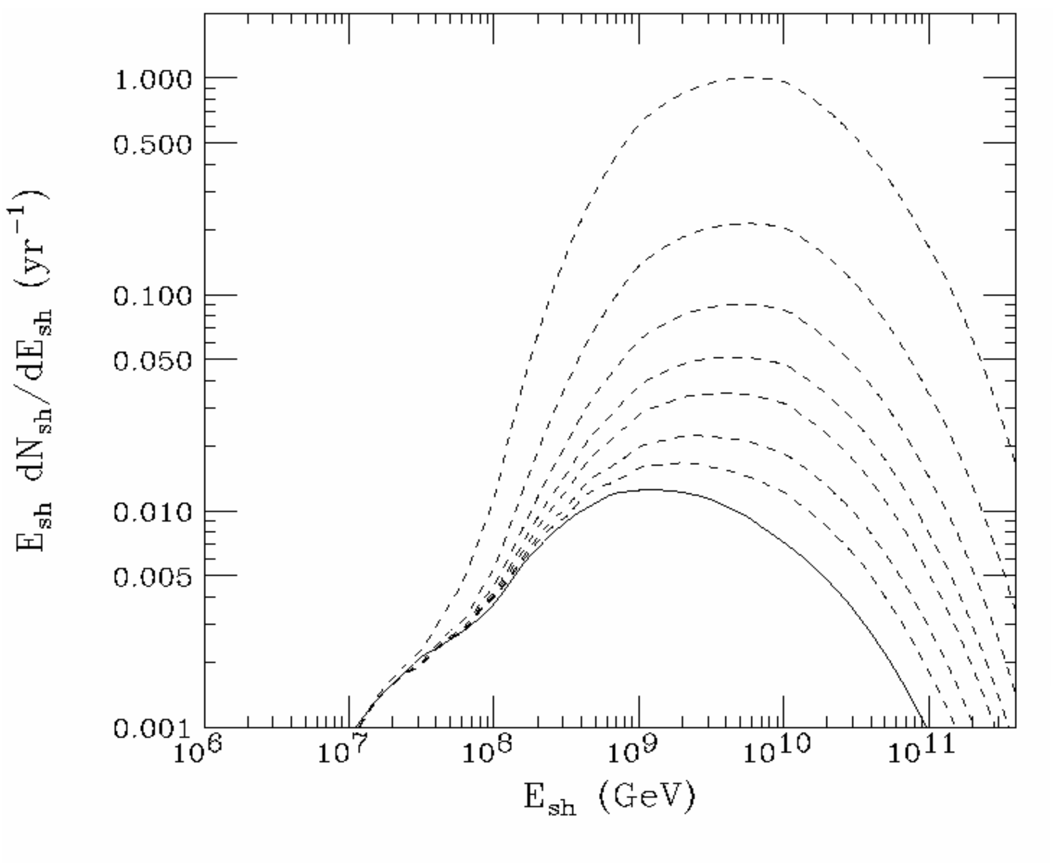
Microscopic Black Hole Production

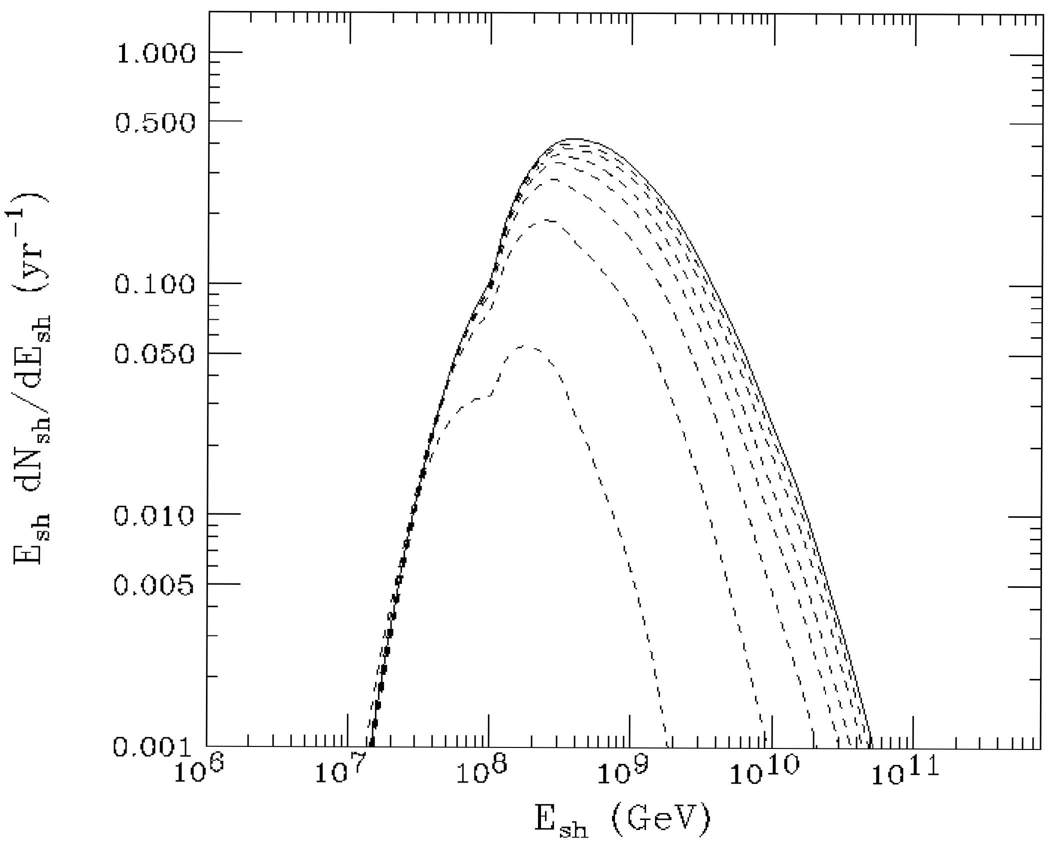
At cm energies above fundamental Planck scale, black holes formed with $\sigma \sim \pi R^2_{sch}$ … rapidly evaporate by Hawking radiation (gravitational waves?)



Anchordoqui *et al* (2004)

Testing TeV scale gravity at Auger





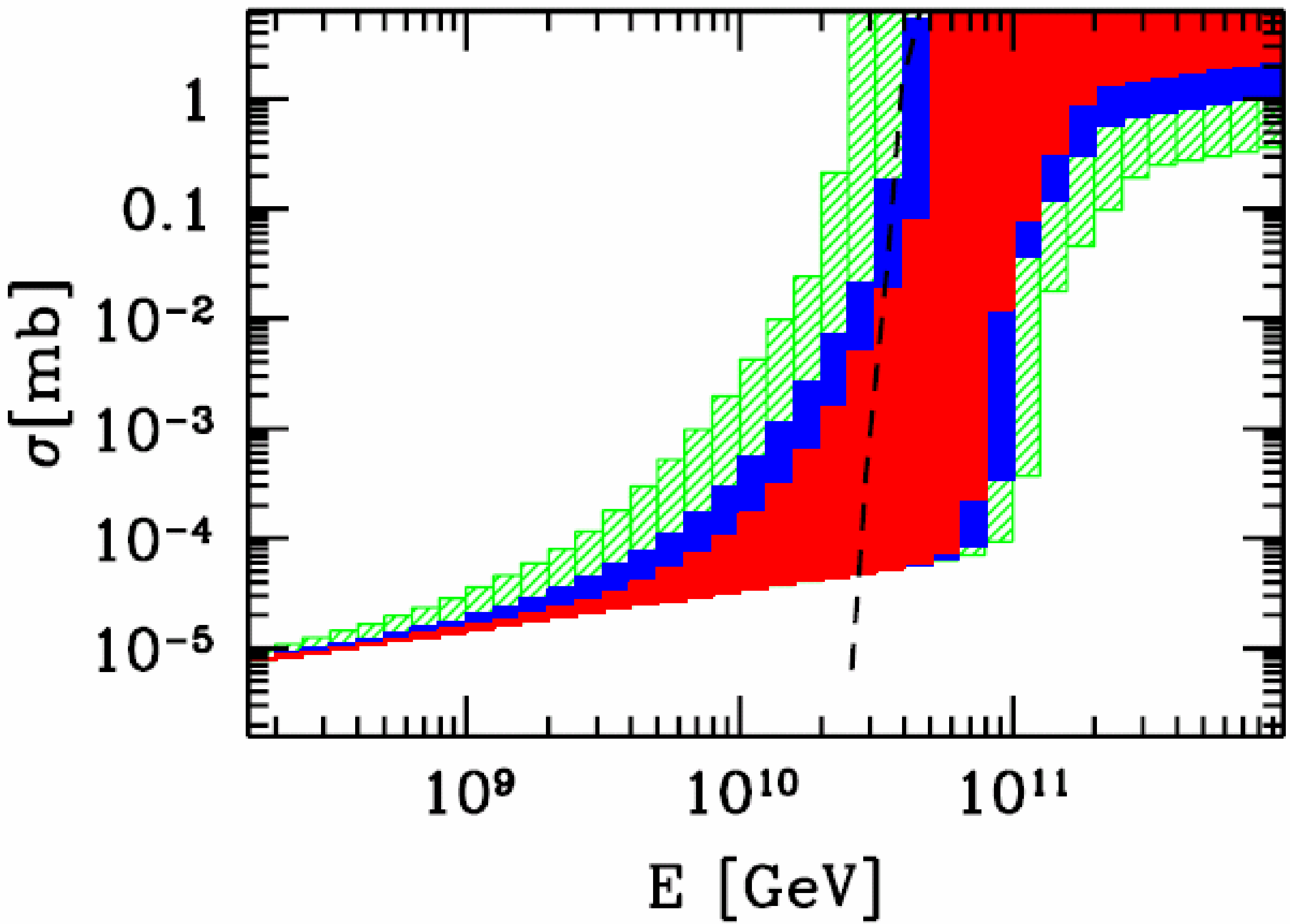
Auger is well suited for probing microscopic black hole production

\# QH/# ES= 0.05 for SM but 36 for 1 TeV Planck scale!

Anchordoqui, Han, Hooper & Sarkar (2005)

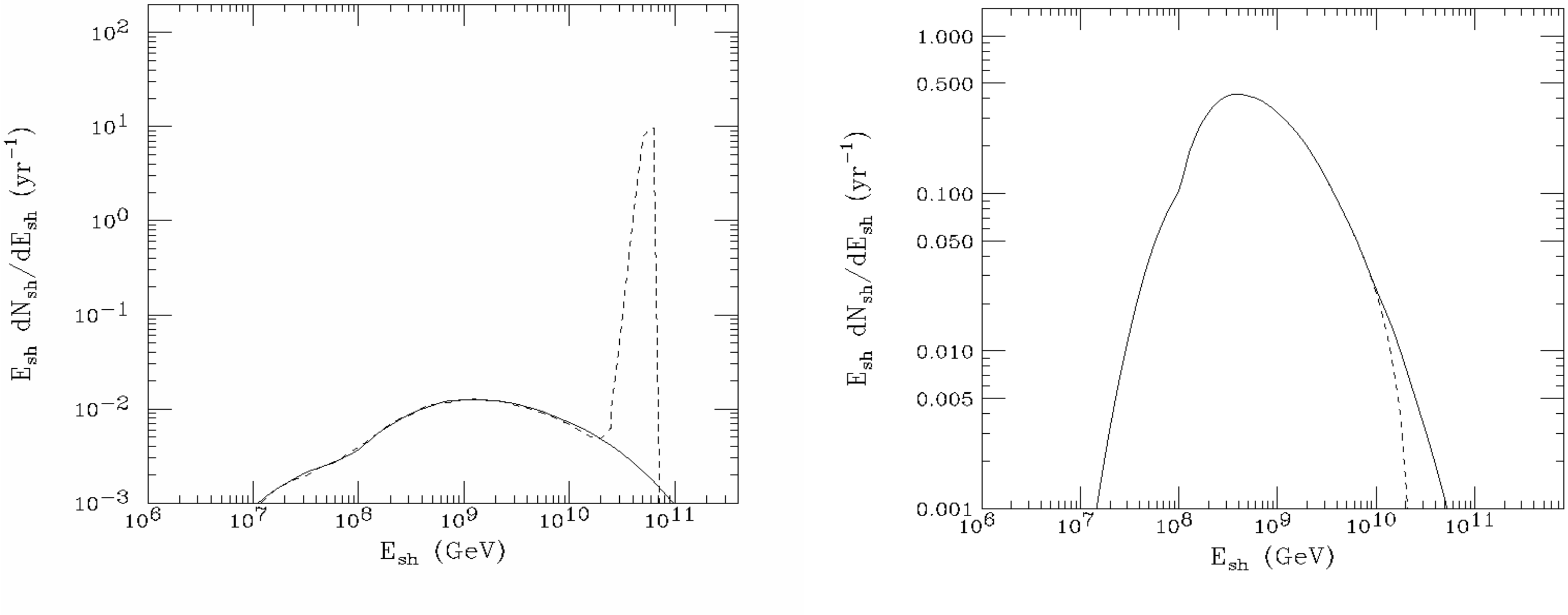
SM electroweak instanton induced interactions

Non-perturbative transitions between degenerate vacuua (with different B+L) are exponentially suppressed below "sphaleron" mass, $\pi M_W/\alpha_W \sim 8$ TeV … but huge cross-sections predicted for ν-N scattering at higher cm energies



Ringwald (1990)

EW instantons at Auger



Large deviations from perturbative SM expected above 10^{10} GeV …

~4 QH showers/yr predicted $\Rightarrow$ 30 times more than for CC/NC alone

Anchordoqui, Han, Hooper and Sarkar (2005)

Summary

Auger has presented first results … expected to soon answer crucial questions about the nature and origin of ultrahigh energy cosmic rays

The detection of cosmic ultrahigh energy neutrinos is eagerly anticipated – will provide complementary information and identify the sources

Cosmic ray and neutrino observatories provide an unique laboratory for tests of new physics

"The existence of these high energy rays is a puzzle, the solution of which will be the discovery of new fundamental physics or astrophysics"

Jim Cronin (1998)