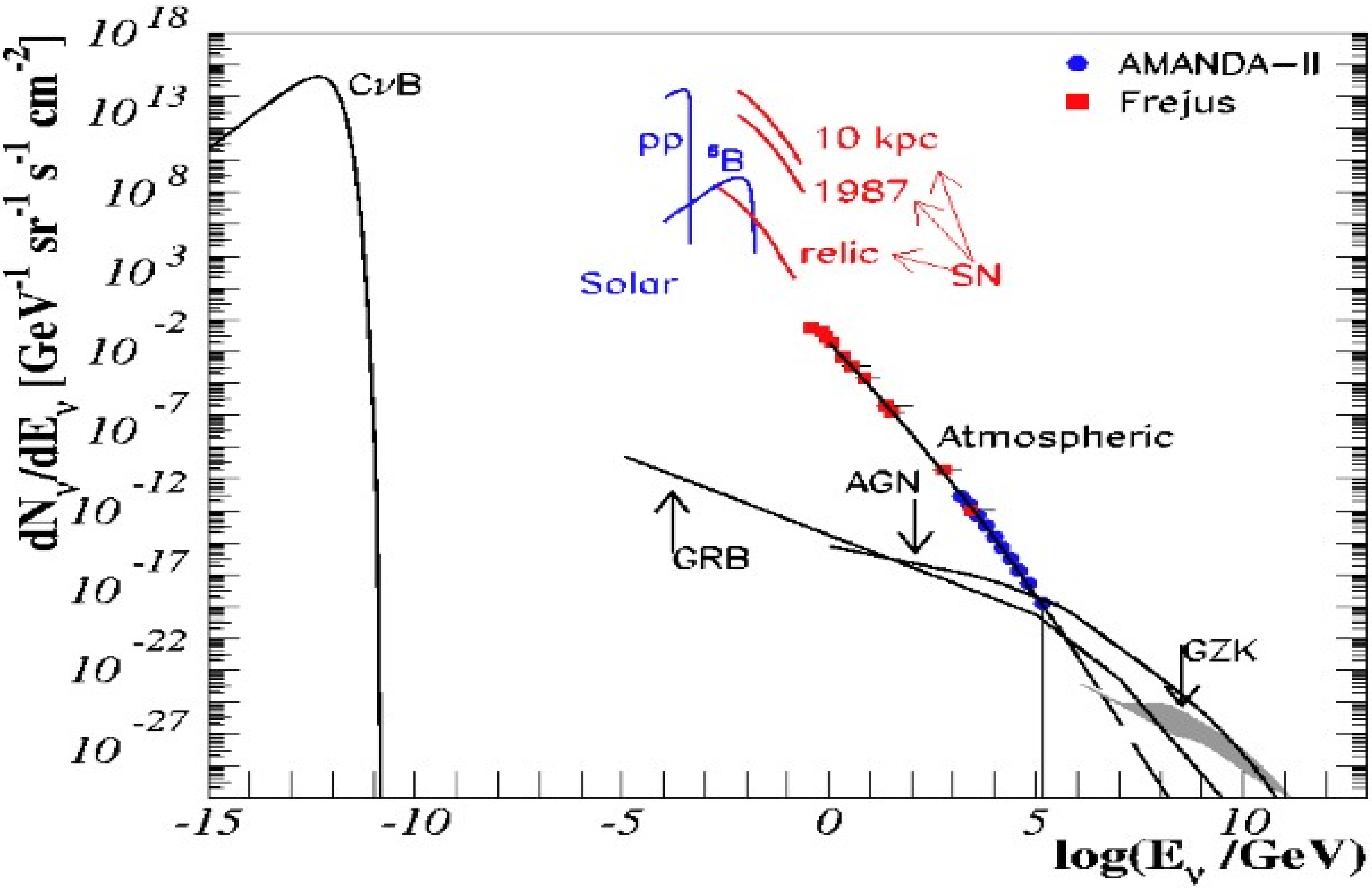
SEARCHES OF VERY HIGH ENERGY NEUTRINOS

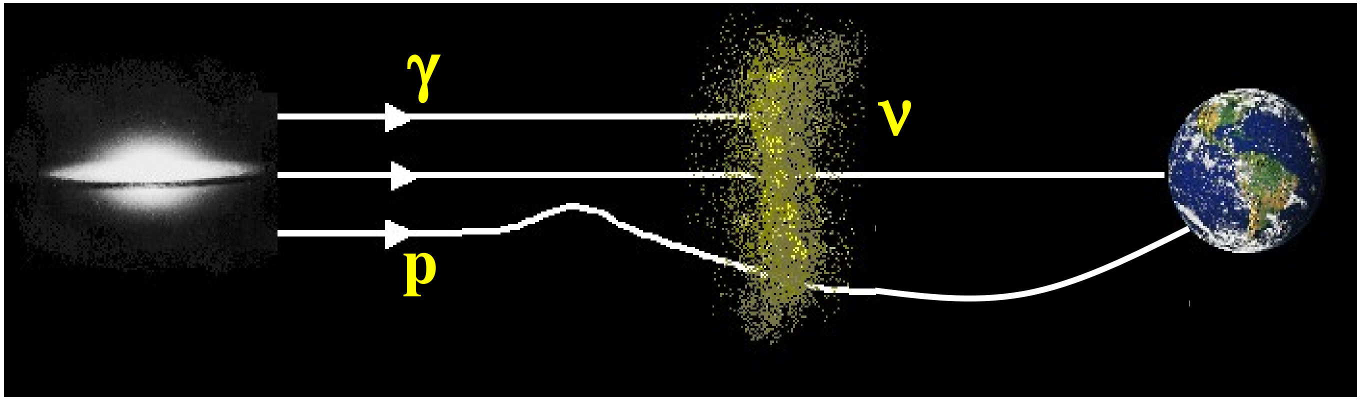
Esteban Roulet
CONICET, Centro Atómico Bariloche

THE NEUTRINO SKY

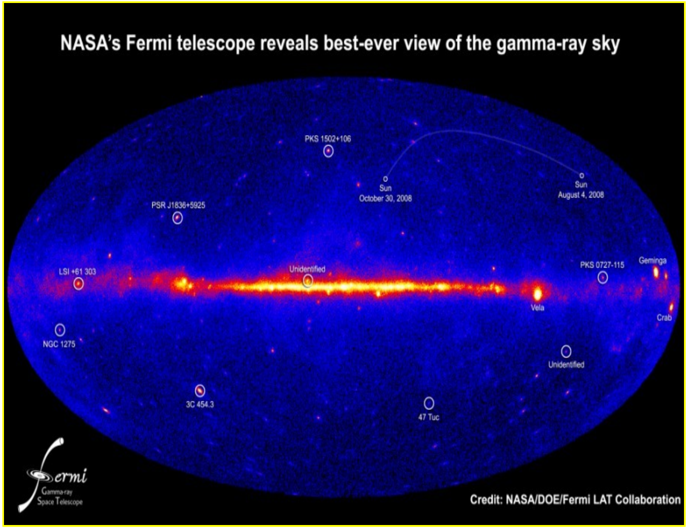


THE ENERGETIC UNIVERSE

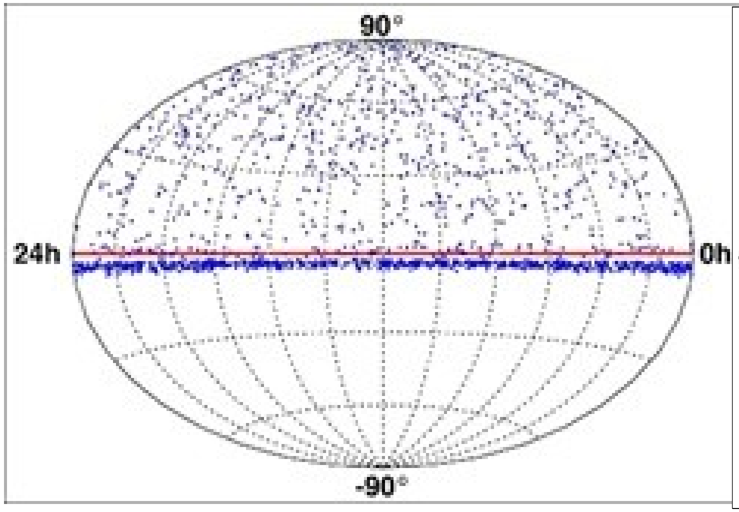
multimessenger astronomy



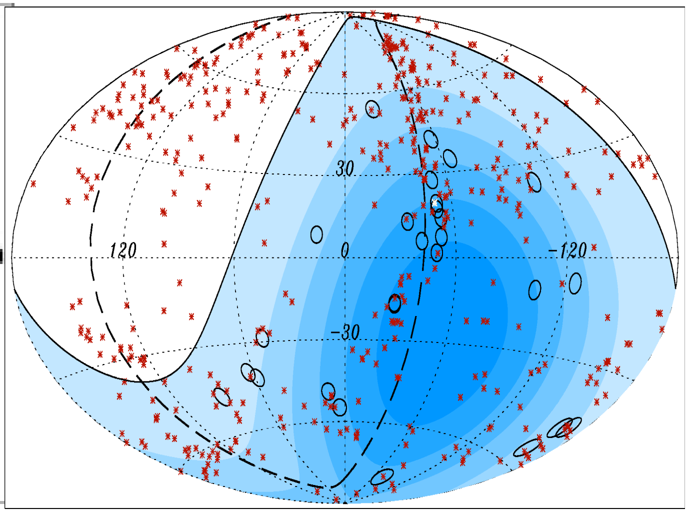
γ rays (Fermi)



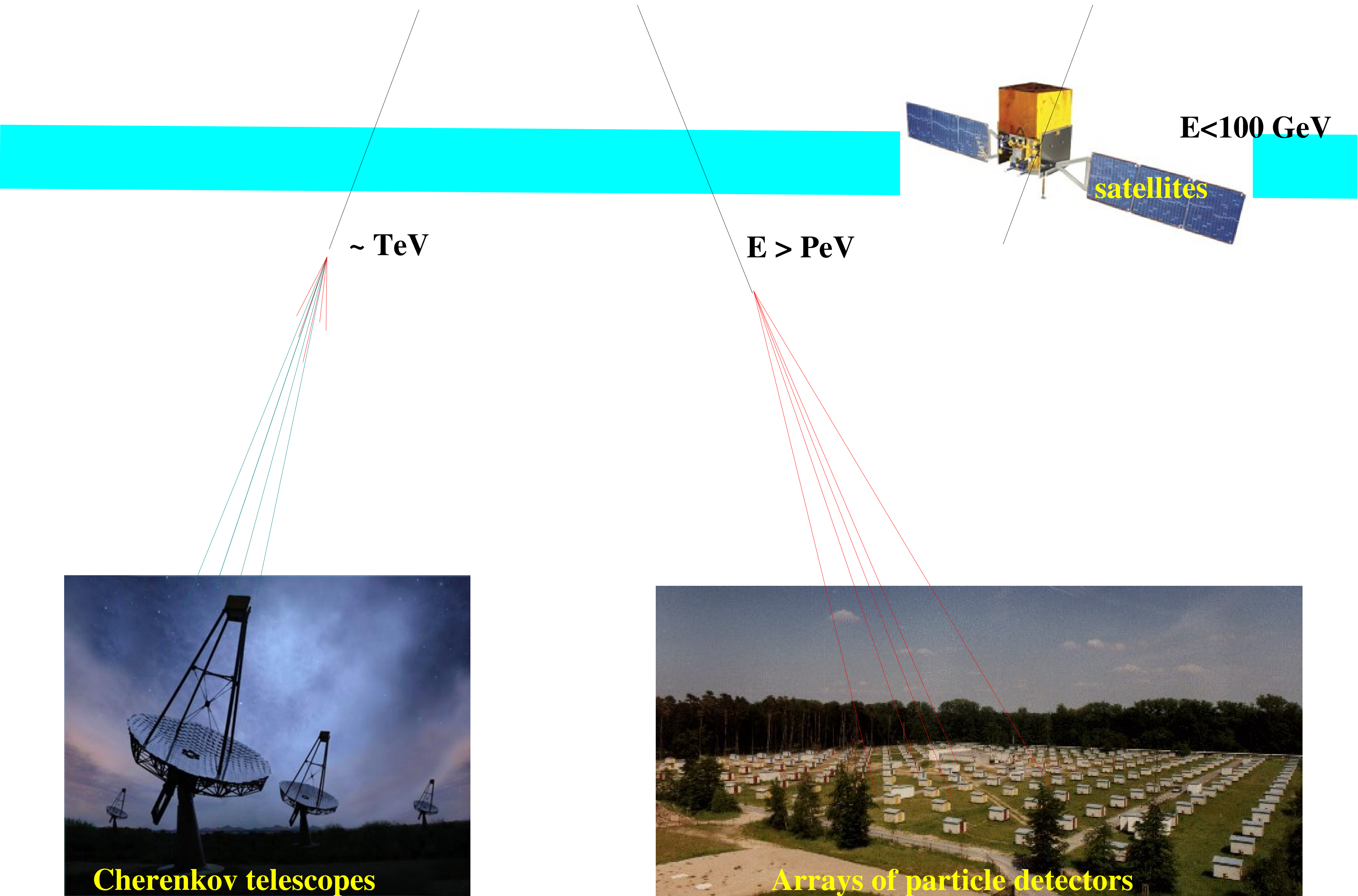
ν (Amanda)



UHE Cosmic rays (Auger)

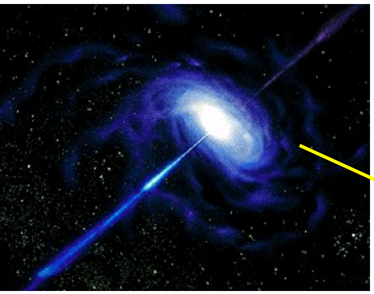


TYPES OF COSMIC RAY DETECTORS

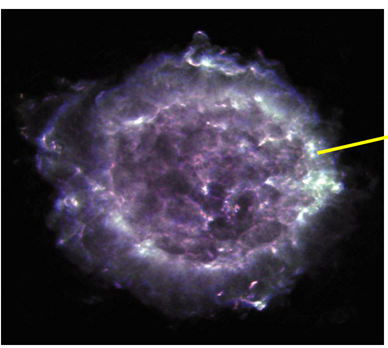


Examples of powerful astrophysical Objects/potential CR accelerators

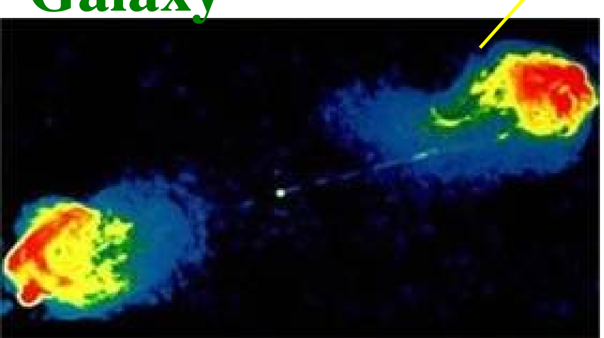
AGN

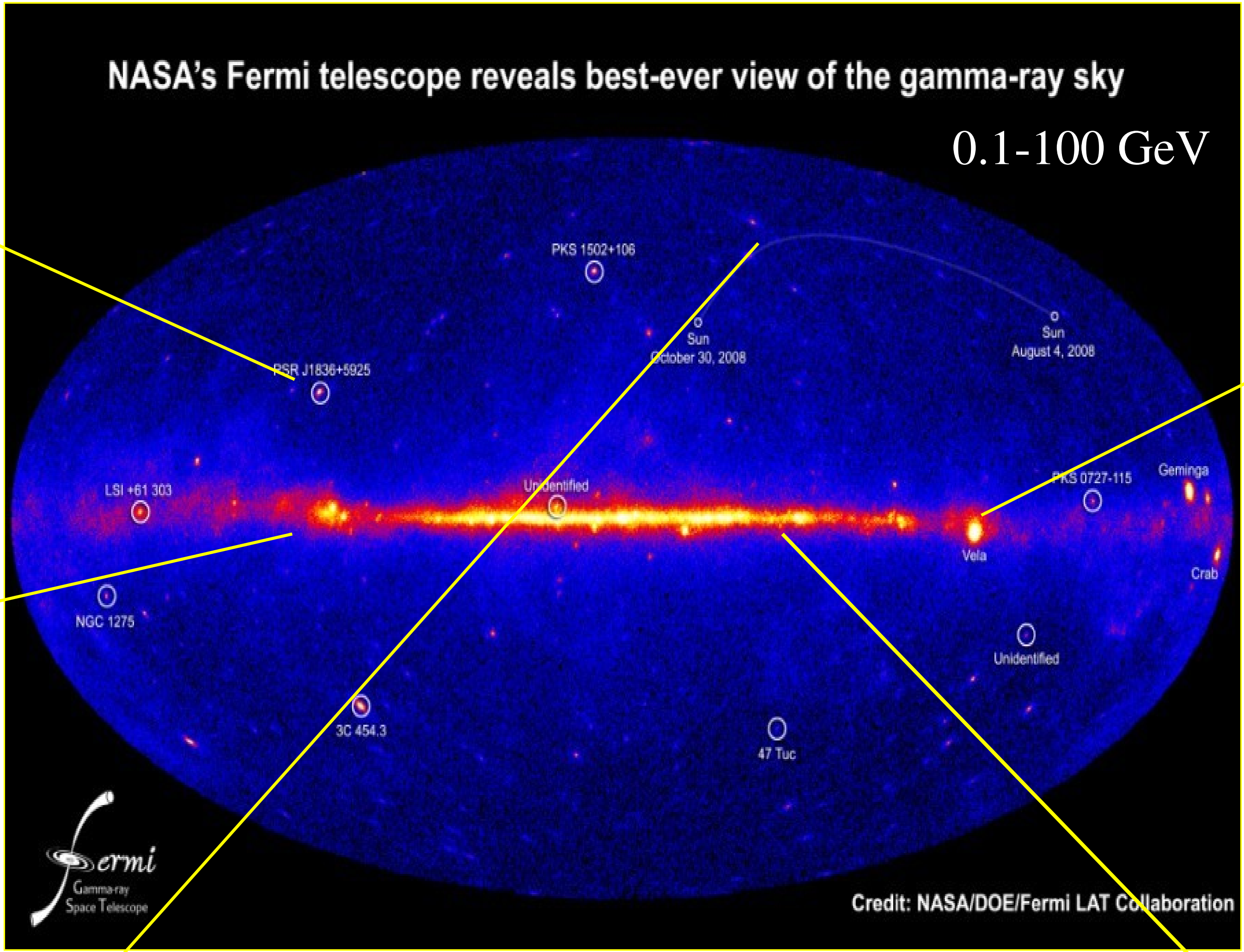


SNR



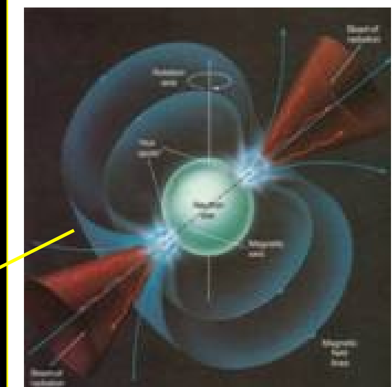
Radio Galaxy



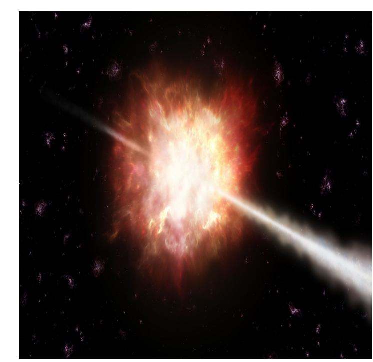


Colliding galaxies

Pulsar



GRB



Diffuse emission

Discriminating leptonic vs. hadronic scenarios

(a way to know if protons are indeed accelerated in SNR)

Brems: $e + gas \rightarrow \gamma + \ldots$ **Synch:** $e + Bfield \rightarrow e + Xray$ **IC:** $e + Xray \rightarrow \gamma + e$

Hadronic: $CR + \gamma\,(p) \rightarrow \pi + X$ $\pi^0 \rightarrow \gamma\gamma\ ,\ \pi^- \rightarrow e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$

e.g. CasA γ spectrum

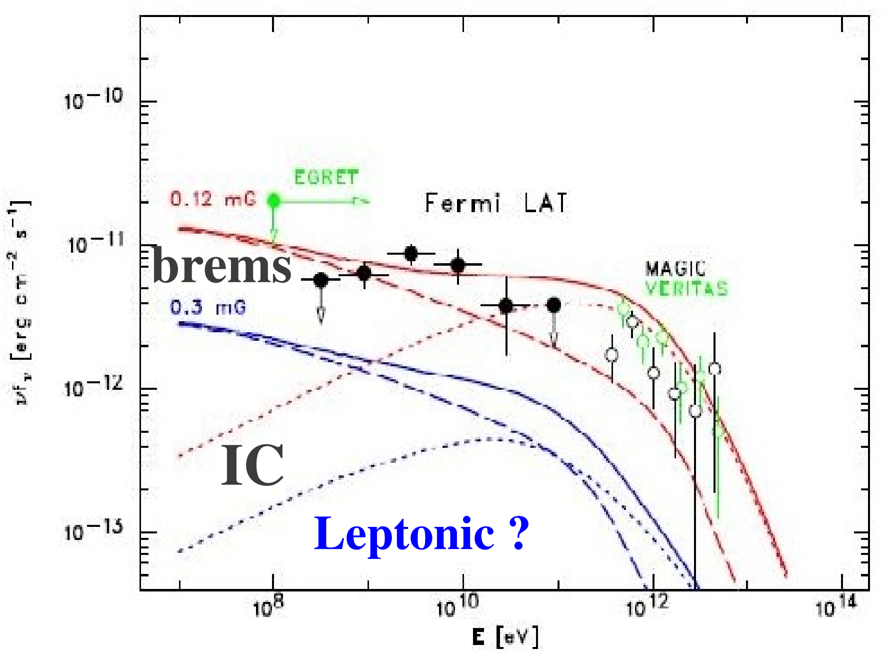


Fig. 3.— Energy spectrum of Cas A in a leptonic emission model. Shown is the *Ferr* detected emission (filled circles) in comparison to the energy spectra detected by M (black open circles; Albert et al. 2007) and VERITAS (green open circles; Humensky

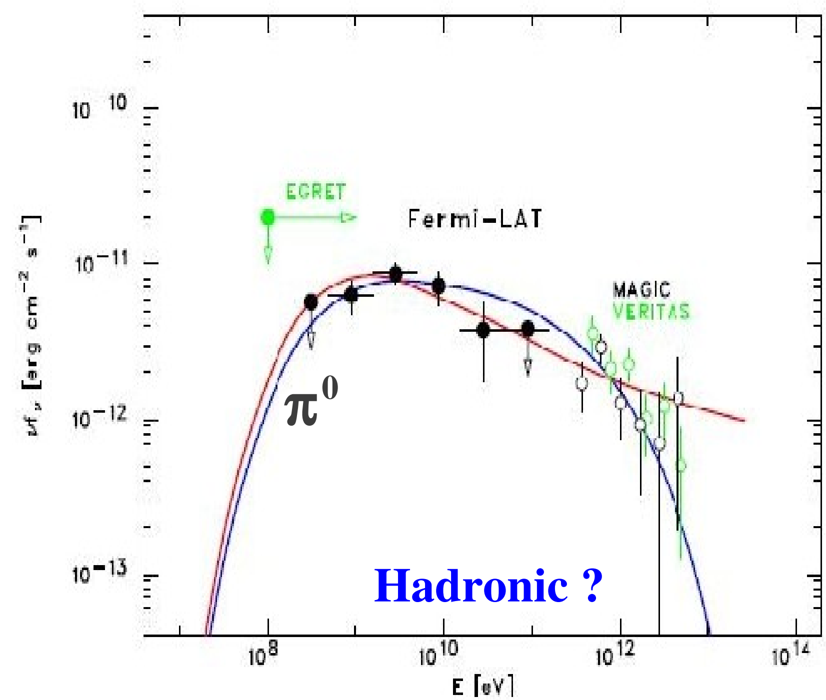
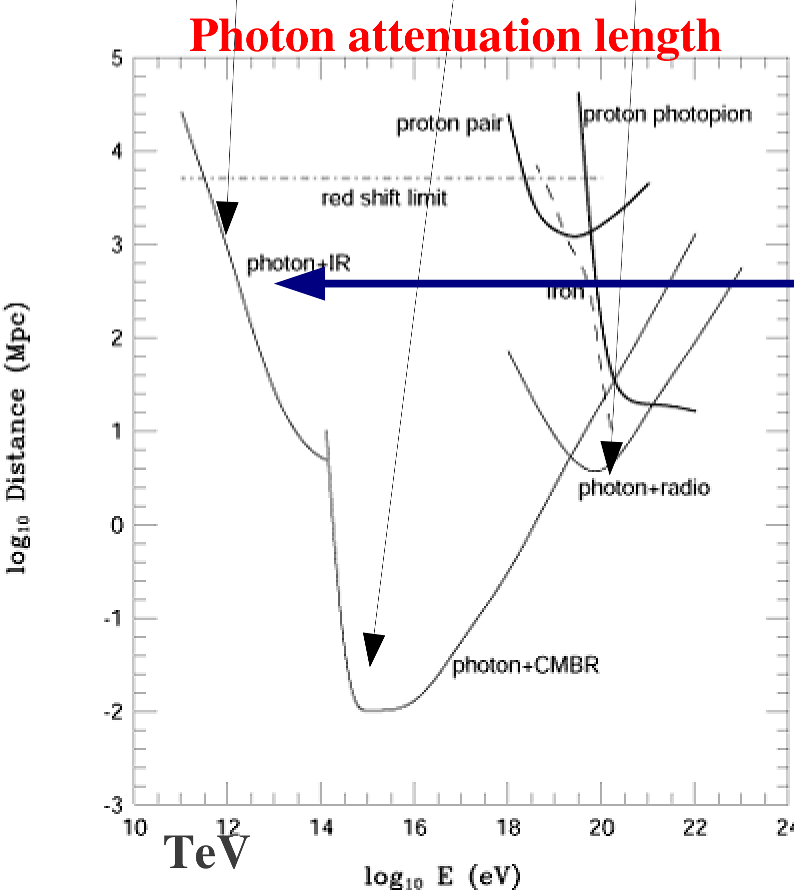


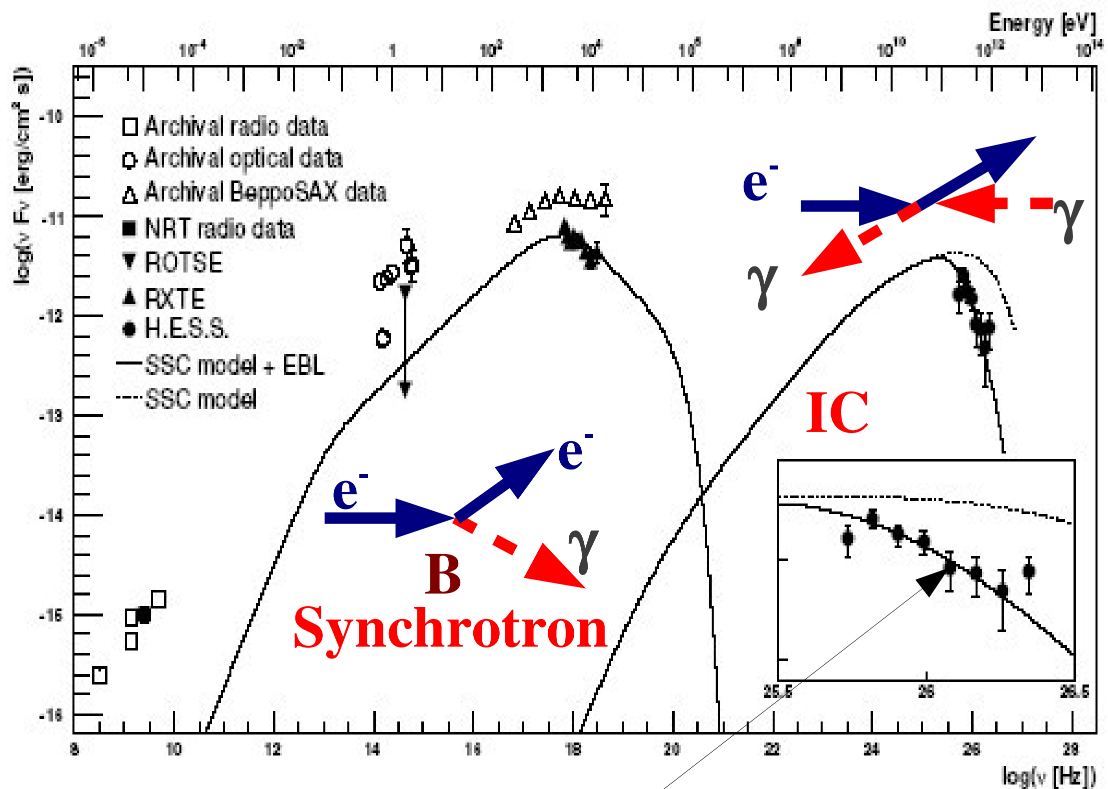
Fig. 4.— Same as Fig. 3 but in a hadronic emission model. Shown are π^0-decay spectra for

Still inconclusive, observation of neutrinos would be unambiguous!

But distant γ sources strongly attenuated by background photons (starlight, CMB, radio, ...): $\gamma\gamma \rightarrow e^{+}e^{-}$



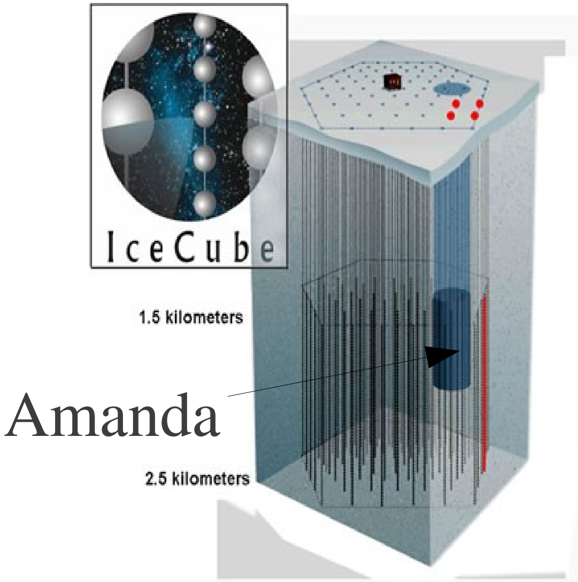
z=0.165 BLLac (H2356-309)



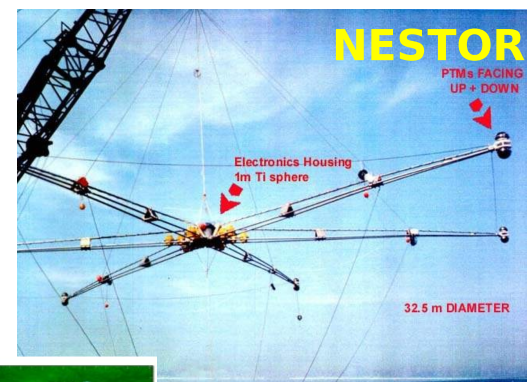
Can measure IR background from observed attenuation

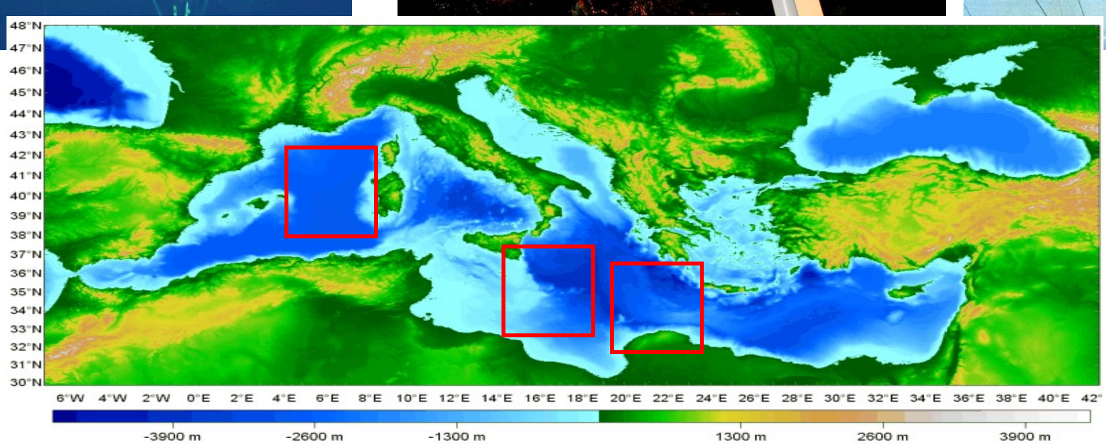
beyond few TeV, high redshift Universe is unobservable with photons

NEUTRINO TELESCOPES (10 GeV to PeV and beyond)



km^3 detector at South Pole,
completed by 2011,
looking at northern ν sky
(and to southern sky above PeV)





km^3 detector at Mediterranean
looking at southern neutrino
sky (proposed km3NET
& GVD in Baikal)

Deep inelastic Neutrino nucleon interactions

$$\frac{d^2\sigma_{CC}^{DIS}}{dx\,dy} = 2\frac{G_F^2}{\pi} m_N E_\nu \frac{M_W^4}{(Q^2+M_W^2)^2}\left[xq(x,Q^2)+x(1-y)^2\bar{q}(x,Q^2)\right]$$

E > GeV

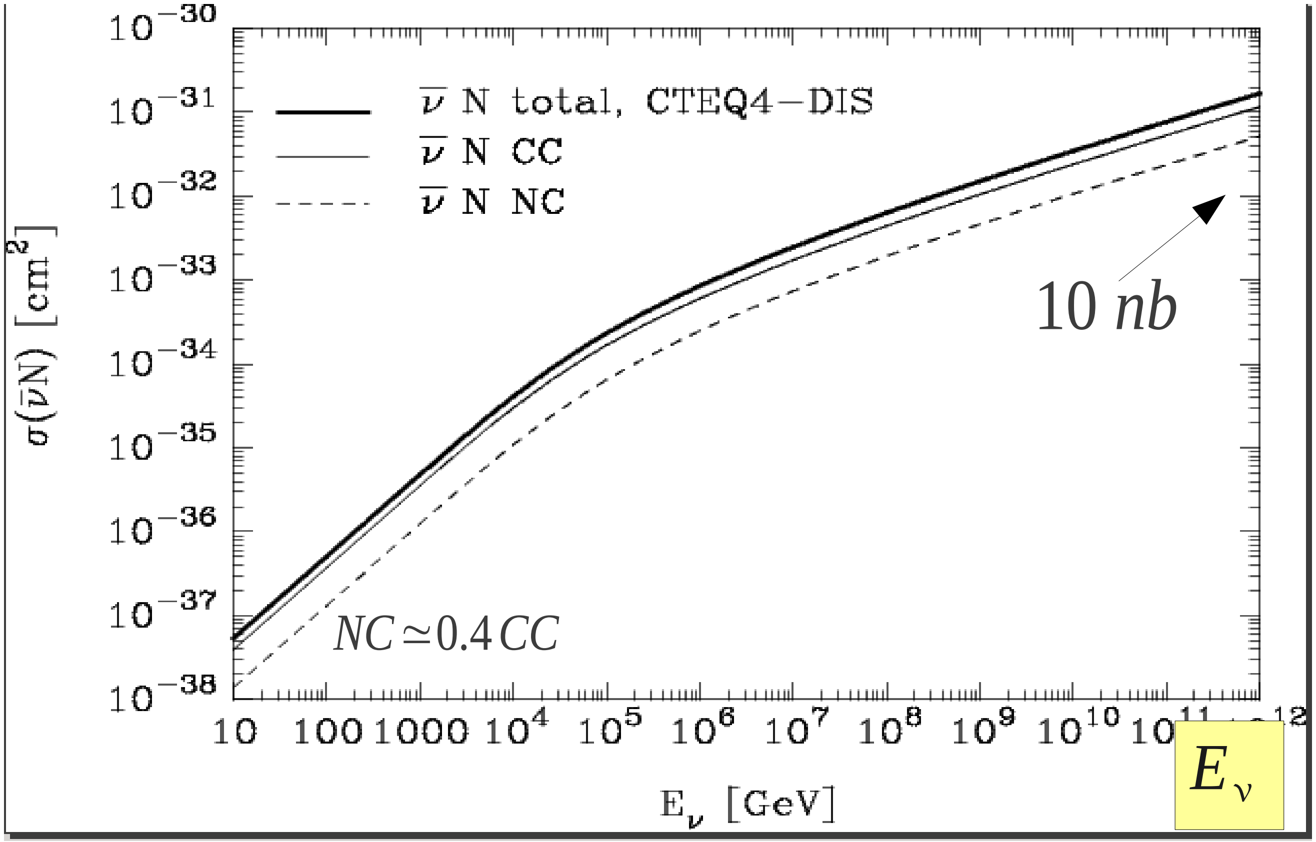
$$Q^2 \equiv -(p_\nu - p_l)^2 \ , \ x \equiv Q^2/2m_N(E_\nu - E_l) \ , \ y \equiv (E_\nu - E_l)/E_\nu$$

$$E_\nu < M_W^2/2m_N \approx 3\,TeV$$

$$\sigma^{DIS} \propto E_\nu$$

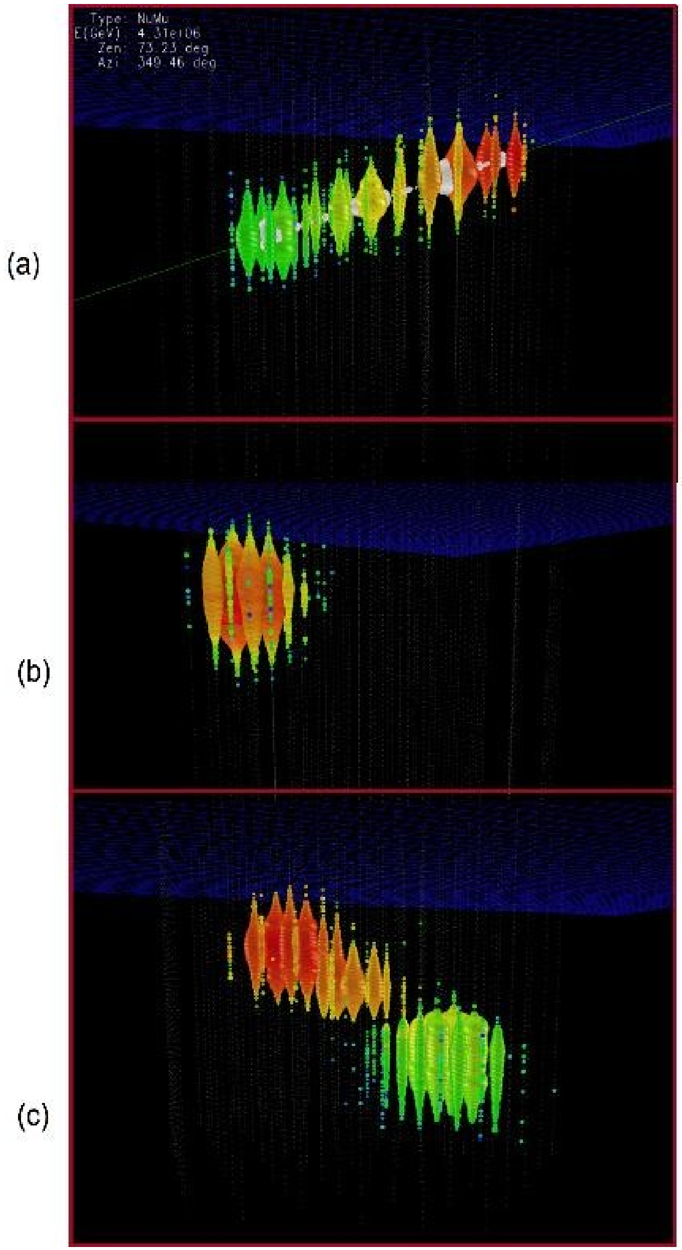
$$E_\nu \gg 3\,TeV$$

$$\sigma^{DIS} \propto E_\nu^{0.363}$$



Earth opaque for E>40 TeV→ Need to look above horizon

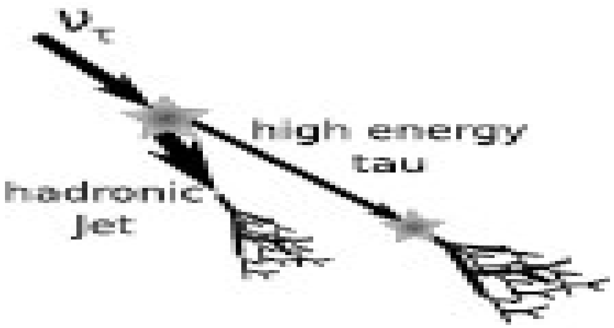
One may even distinguish neutrino flavors



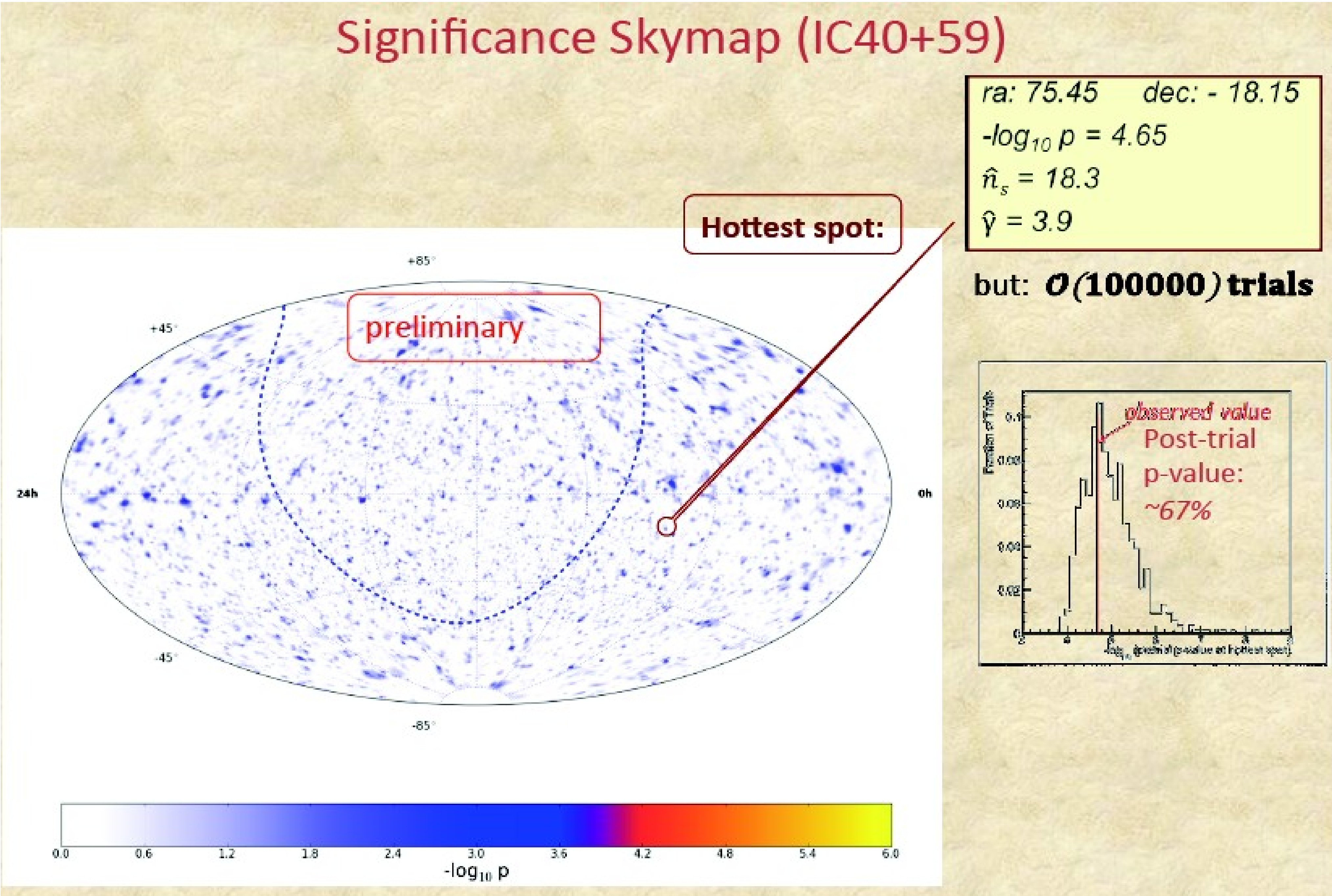
muon neutrino (track)

electron neutrino (cascade, also from NC)

tau neutrino (double bang)

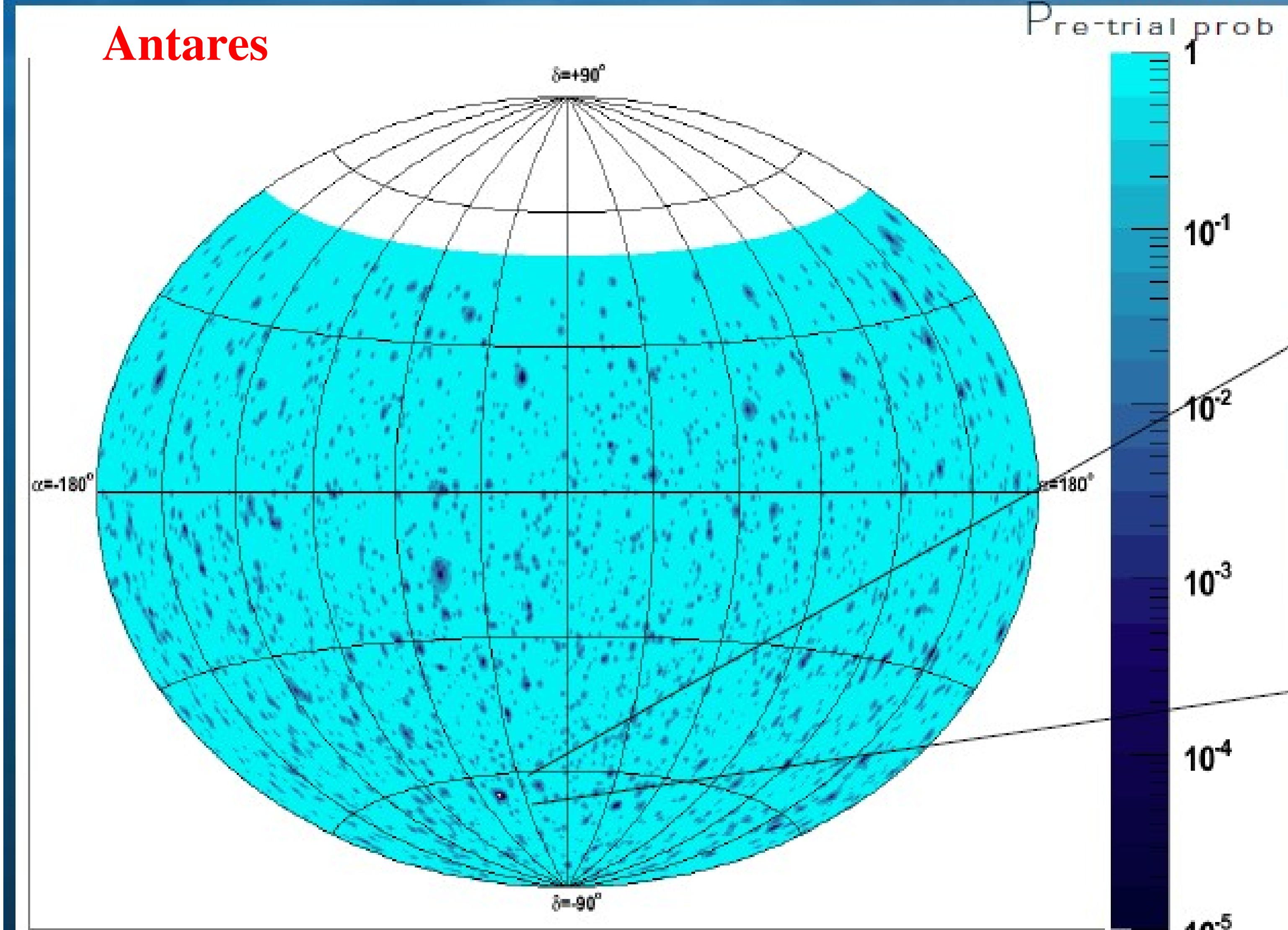


No point sources observed by Icecube nor Antares



Full-Sky Search (2007-2010)

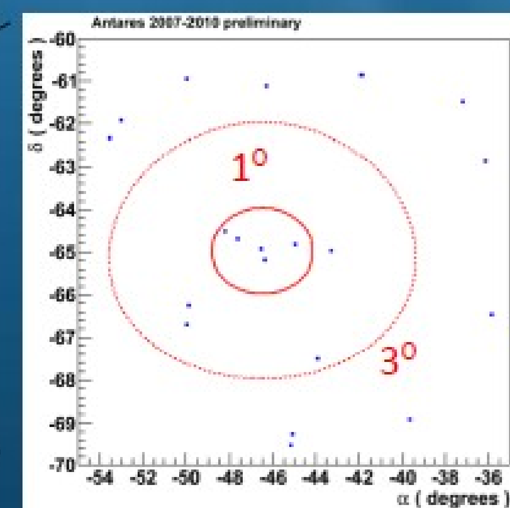
Sky map in equatorial coordinates (3058 candidates)



Most significant cluster at:

RA= −46.5°,

δ= −65.0°



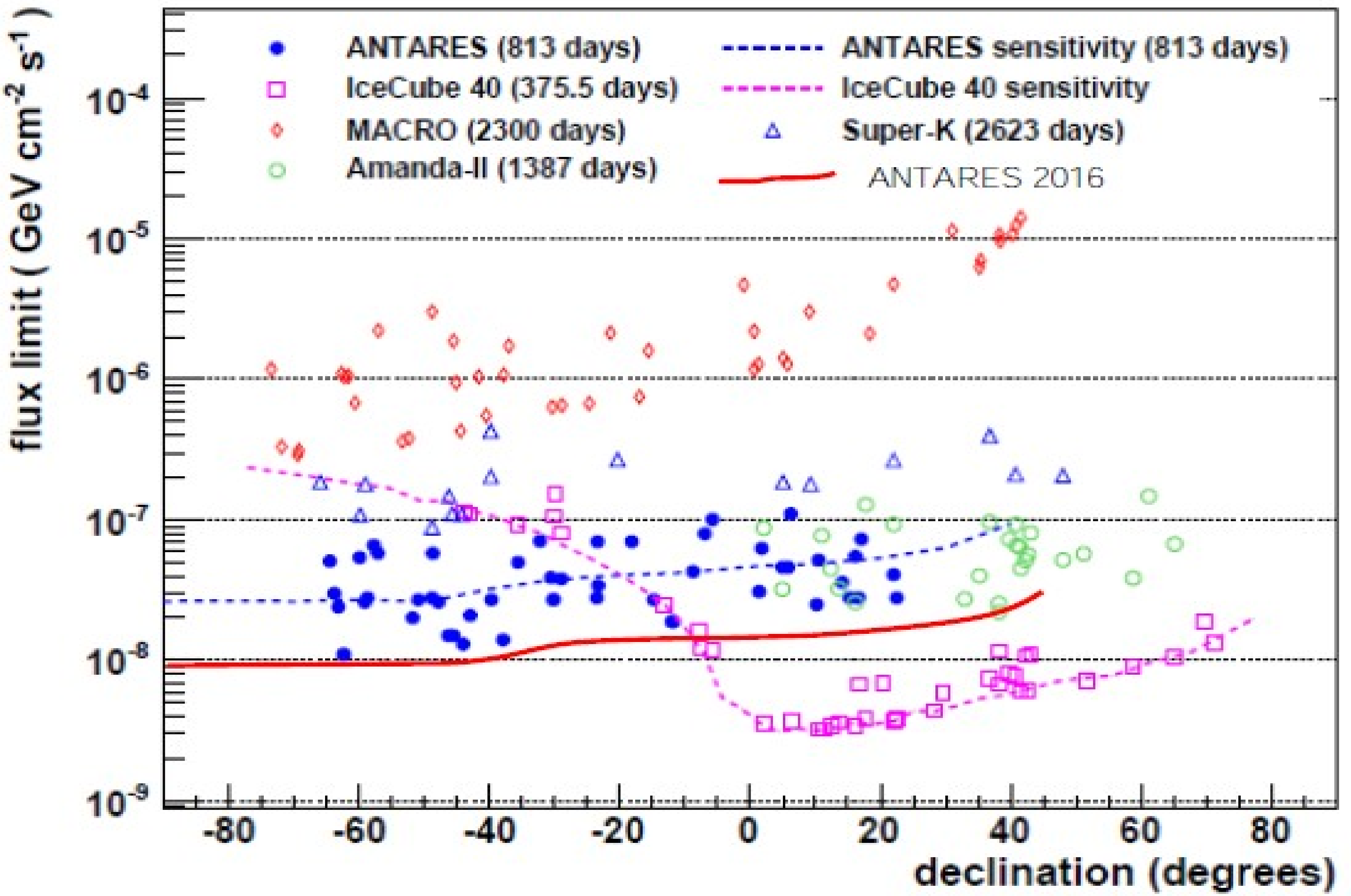
N_{sig} = 5

p-value=0.026 (post-trial)

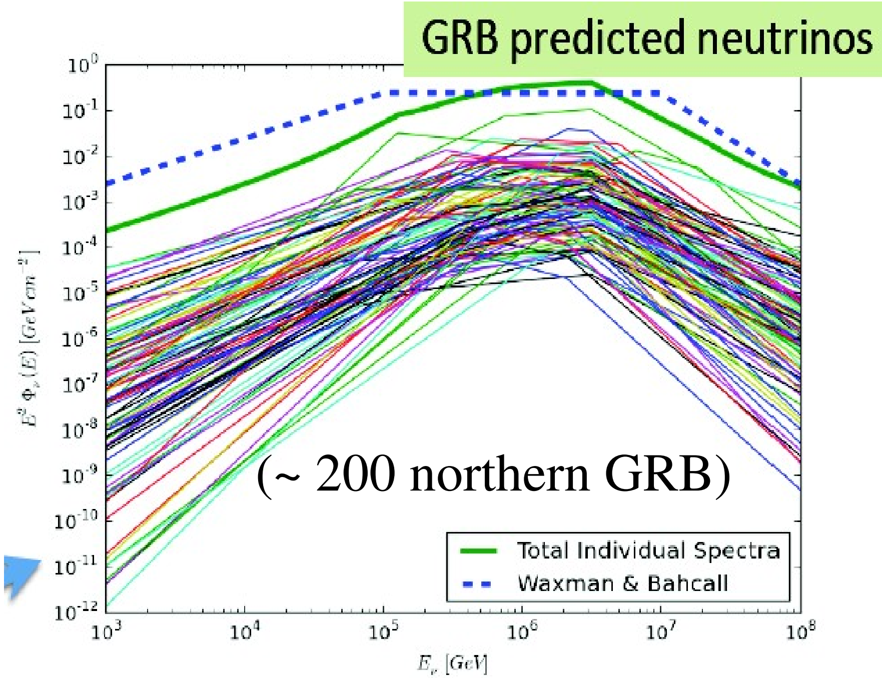
Significance = 2.2 σ

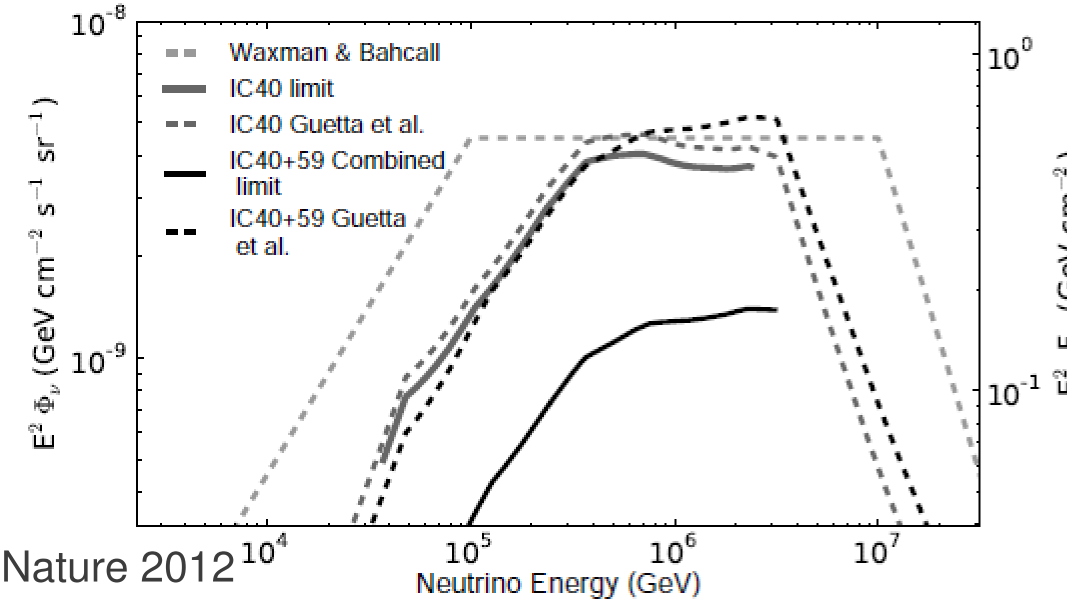
Results compatible with the background hypothesis

Targeted searches (galactic and extra-galactic candidates): SNR, AGN,...



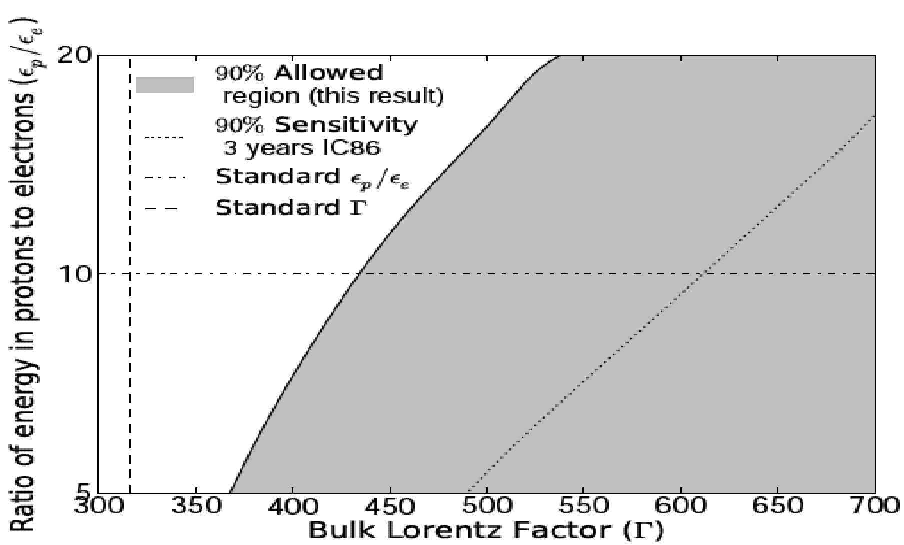
ICECUBE stacked search for neutrinos coincident with observed GRB 2008/2010

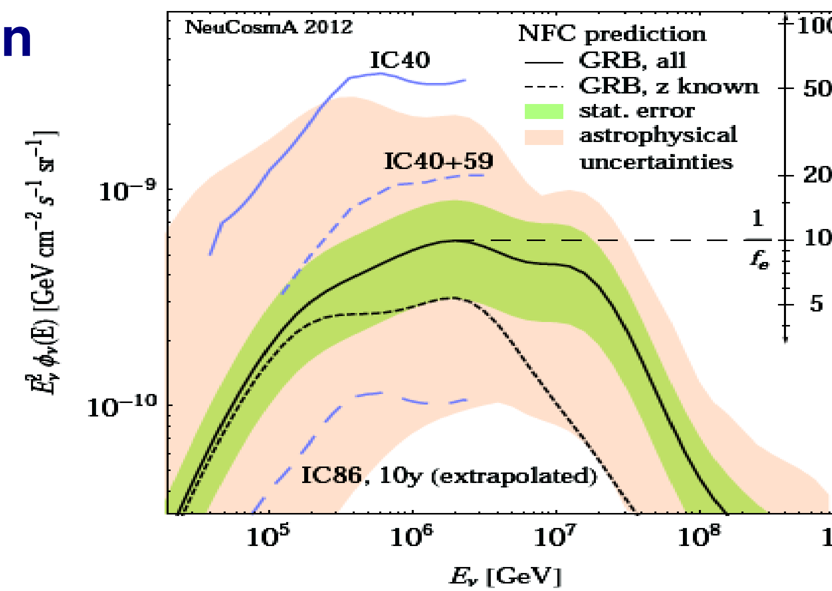




Nature 2012

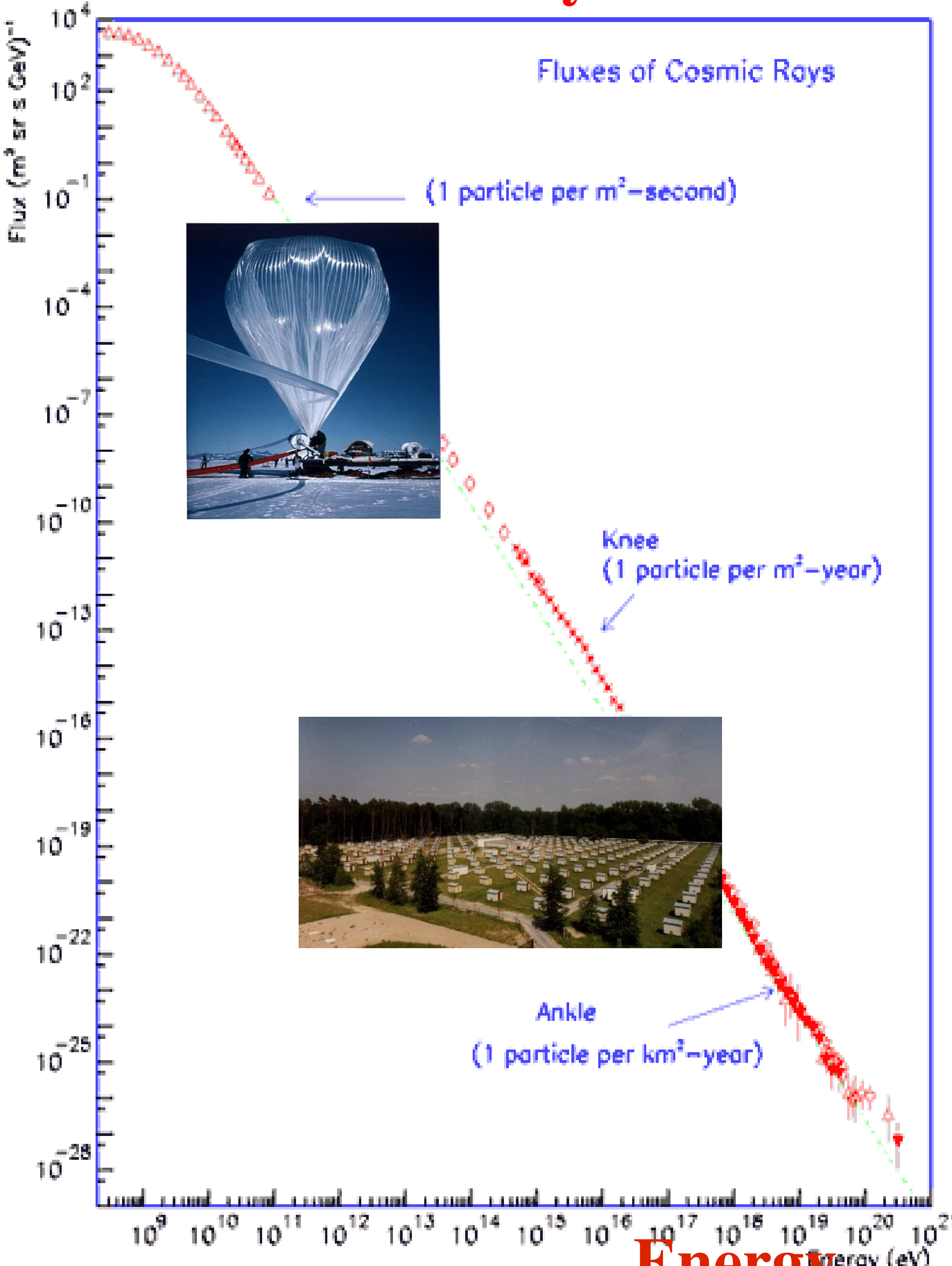
Bound factor 4 below standard predictions → GRB are not main source of UHECRs or production models need revision





Revised model: (Baerwald et al.)

Cosmic ray flux



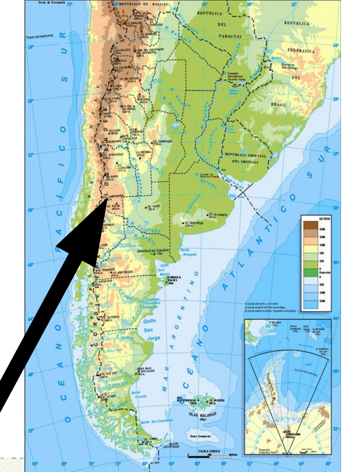
Energy

Power law flux ~ E^{-3}

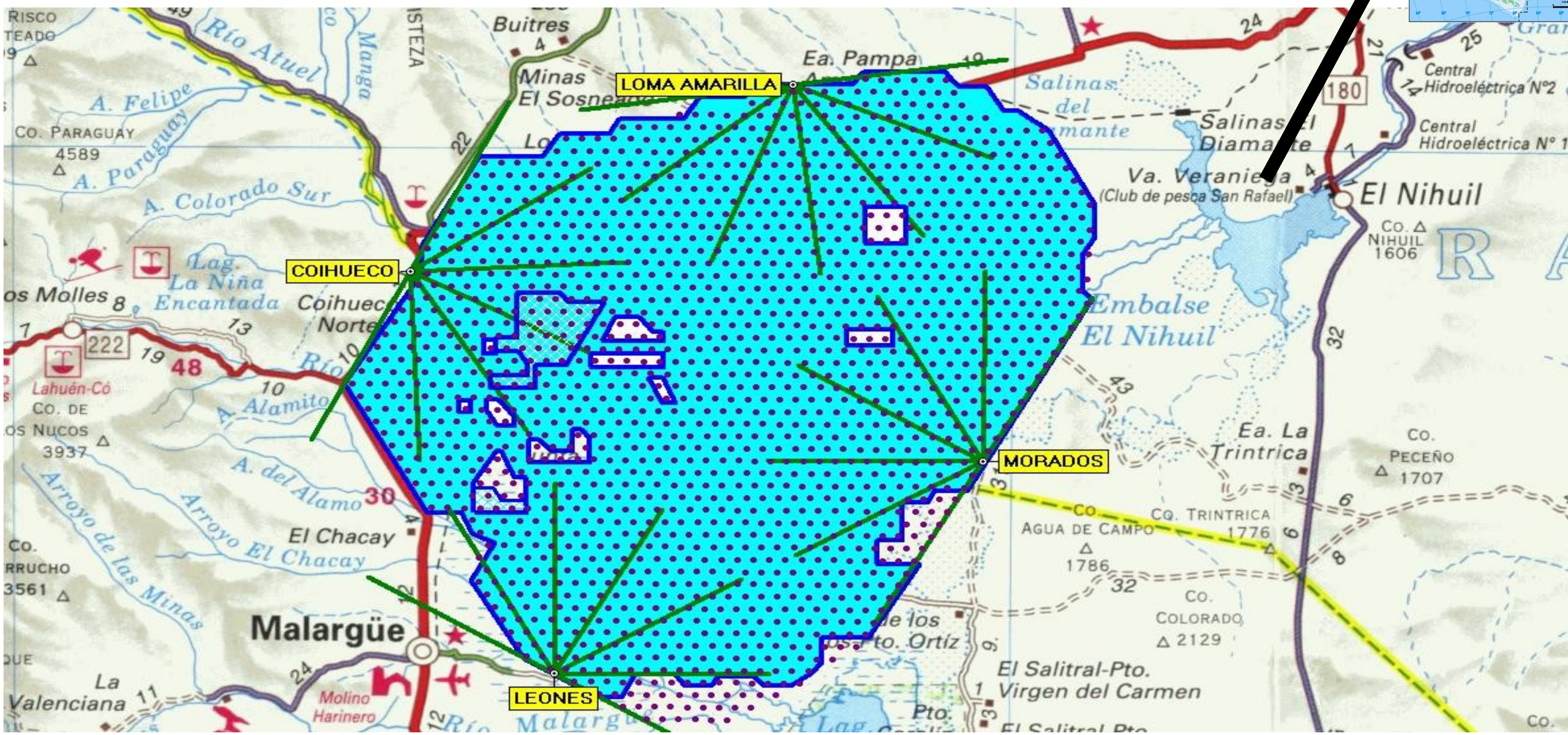
higher E → larger detector required

at the highest energies, only few cosmic rays (CR) arrive per km^2 per century !

to see some, a huge detector is required:



THE PIERRE AUGER OBSERVATORY



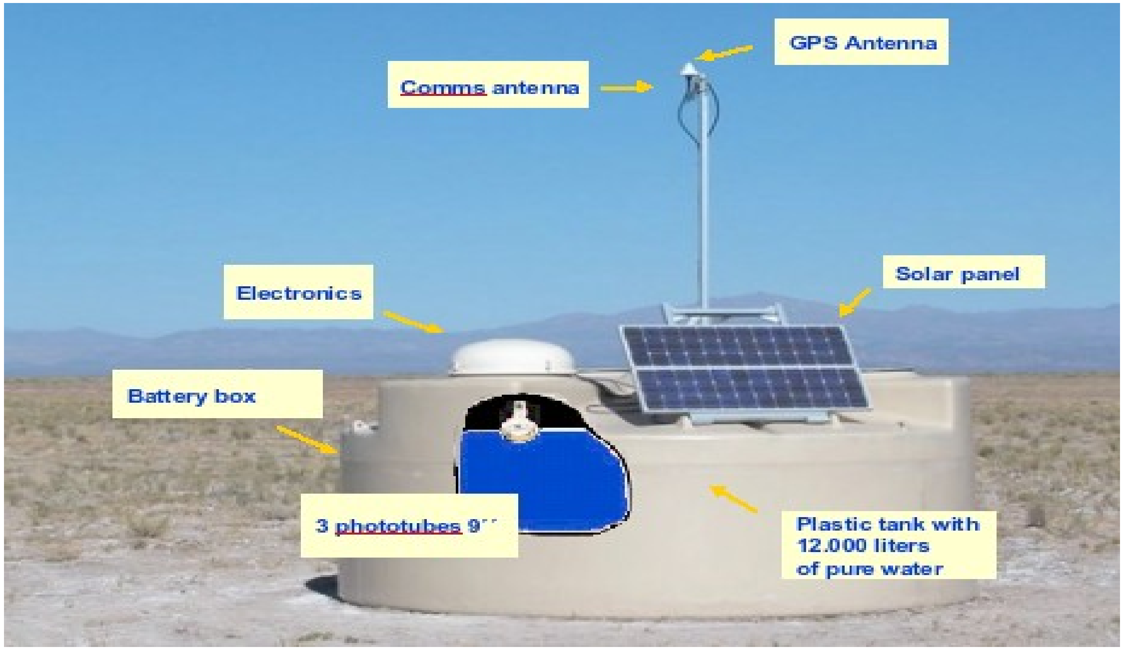
1660 detectors instrumenting 3000 km^2 and 27 telescopes

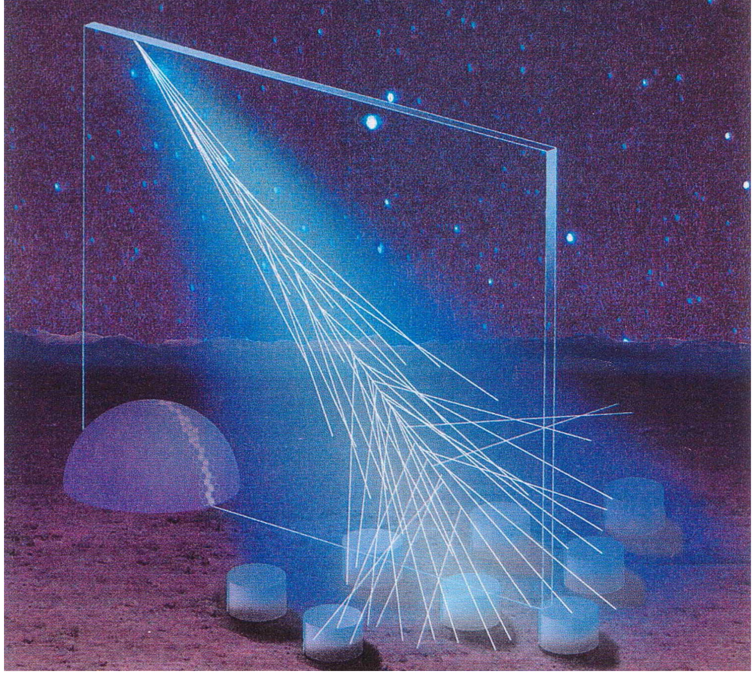
the Auger Collaboration: 17 countries, ~ 400 scientists

Telescope Array (~ 760 km^2 in Utah)

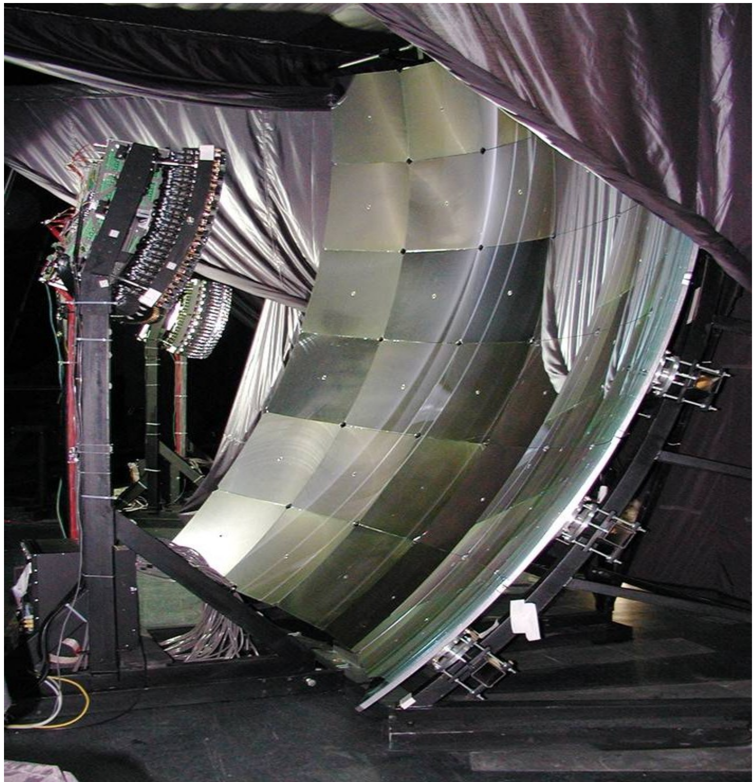
Previous experiments: AGASA, Fly's Eye/HiRes, Haverah Park, Volcano Ranch

surface detector

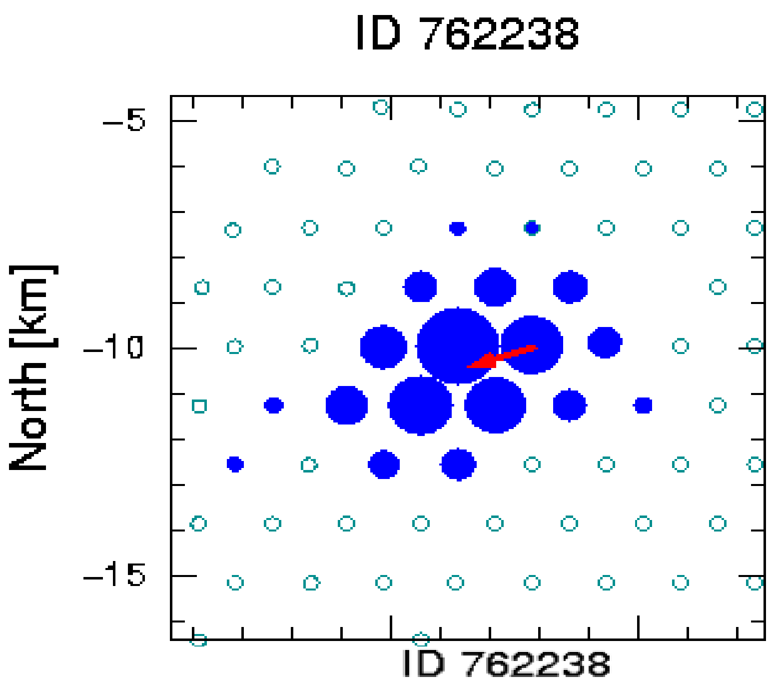


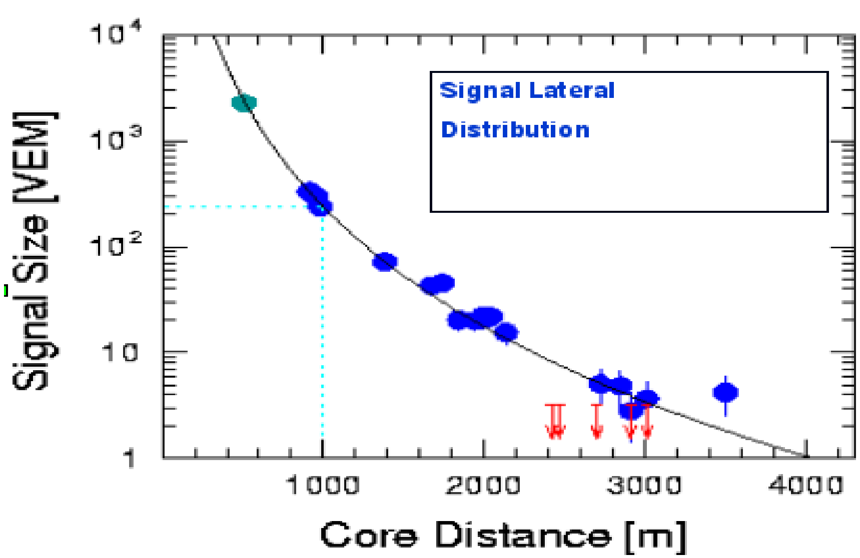


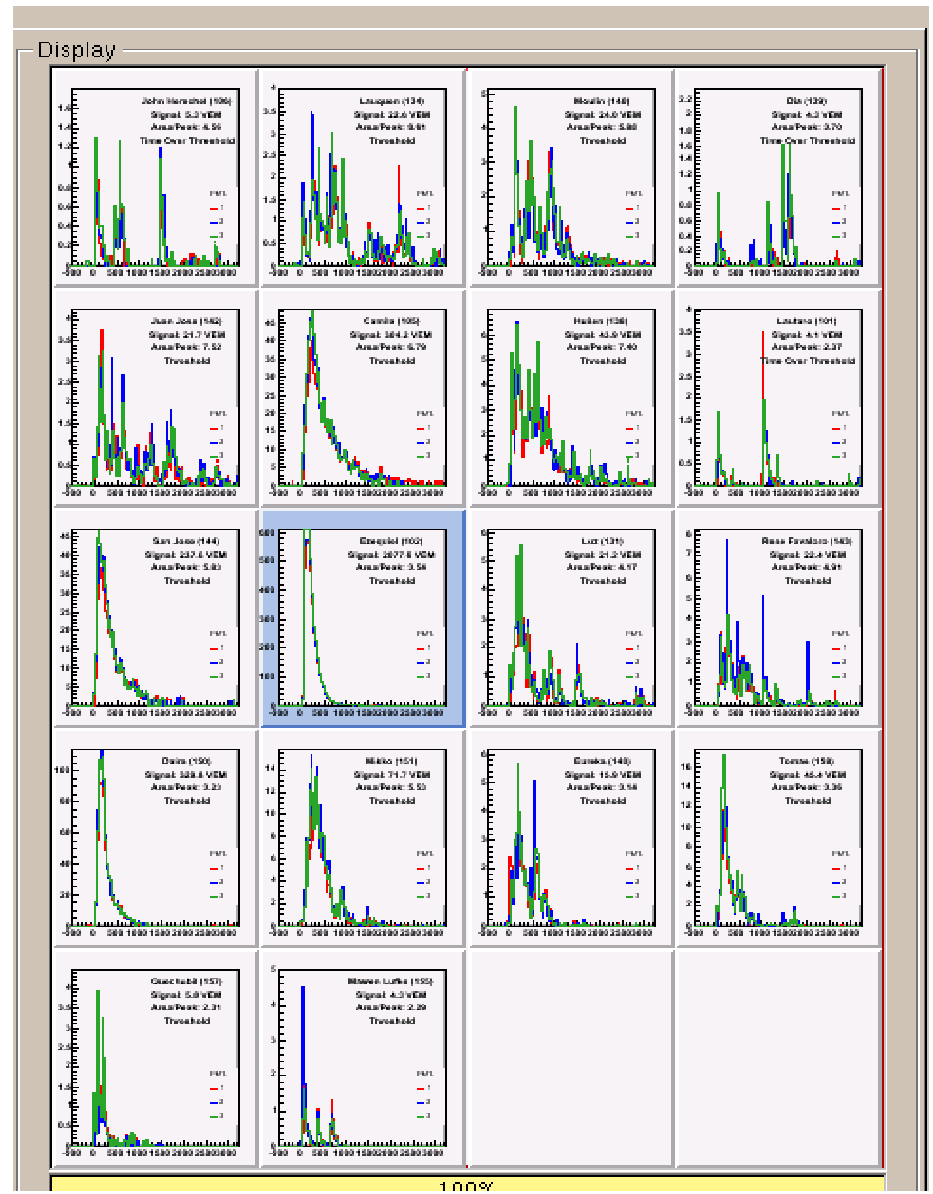
fluorescence detector



event reconstruction with the surface detector

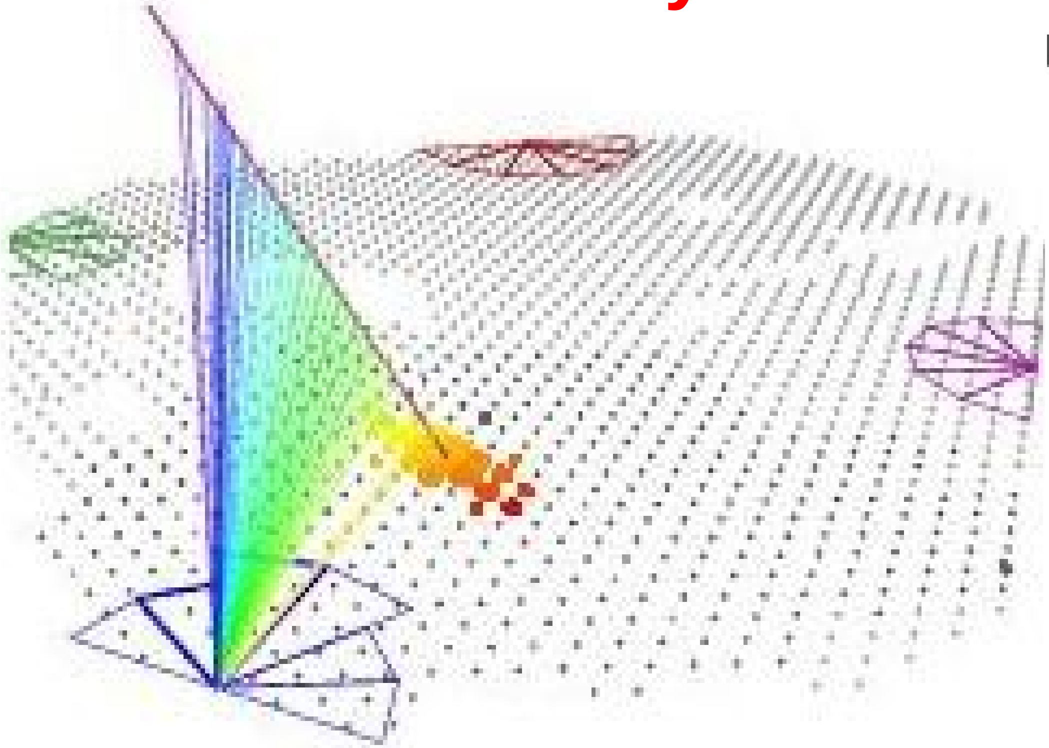


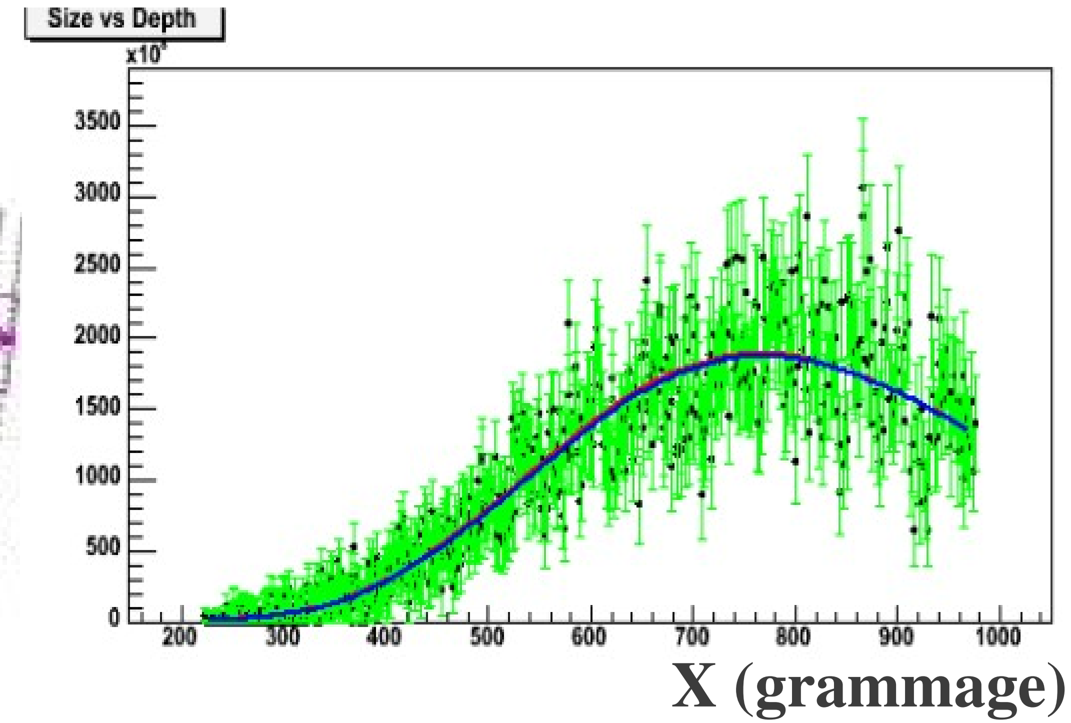


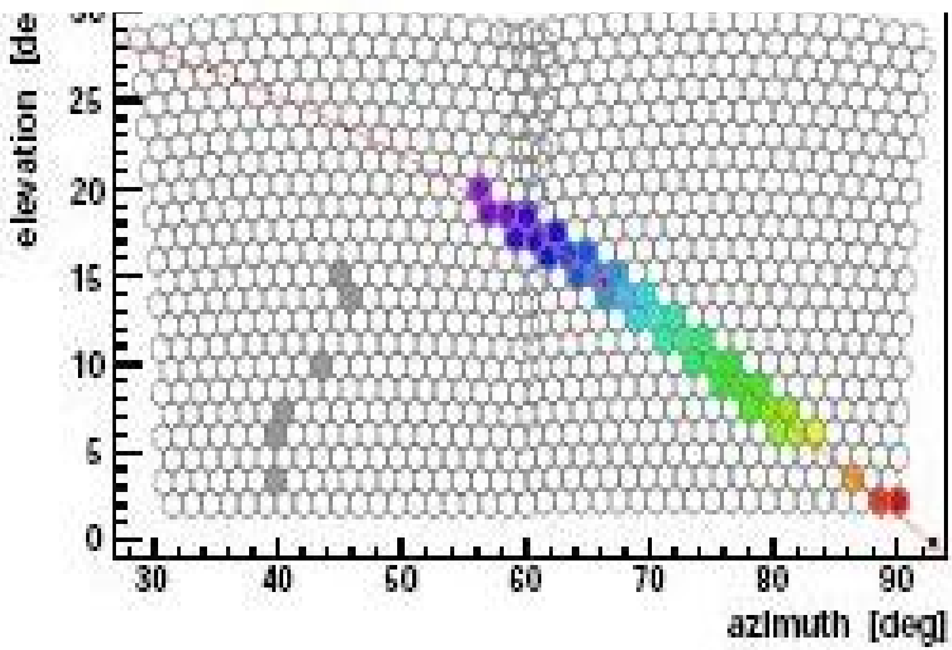


Event with θ ~ 48º, E ~ 70 EeV (1 EeV = 10^{18} eV)

a hybrid event







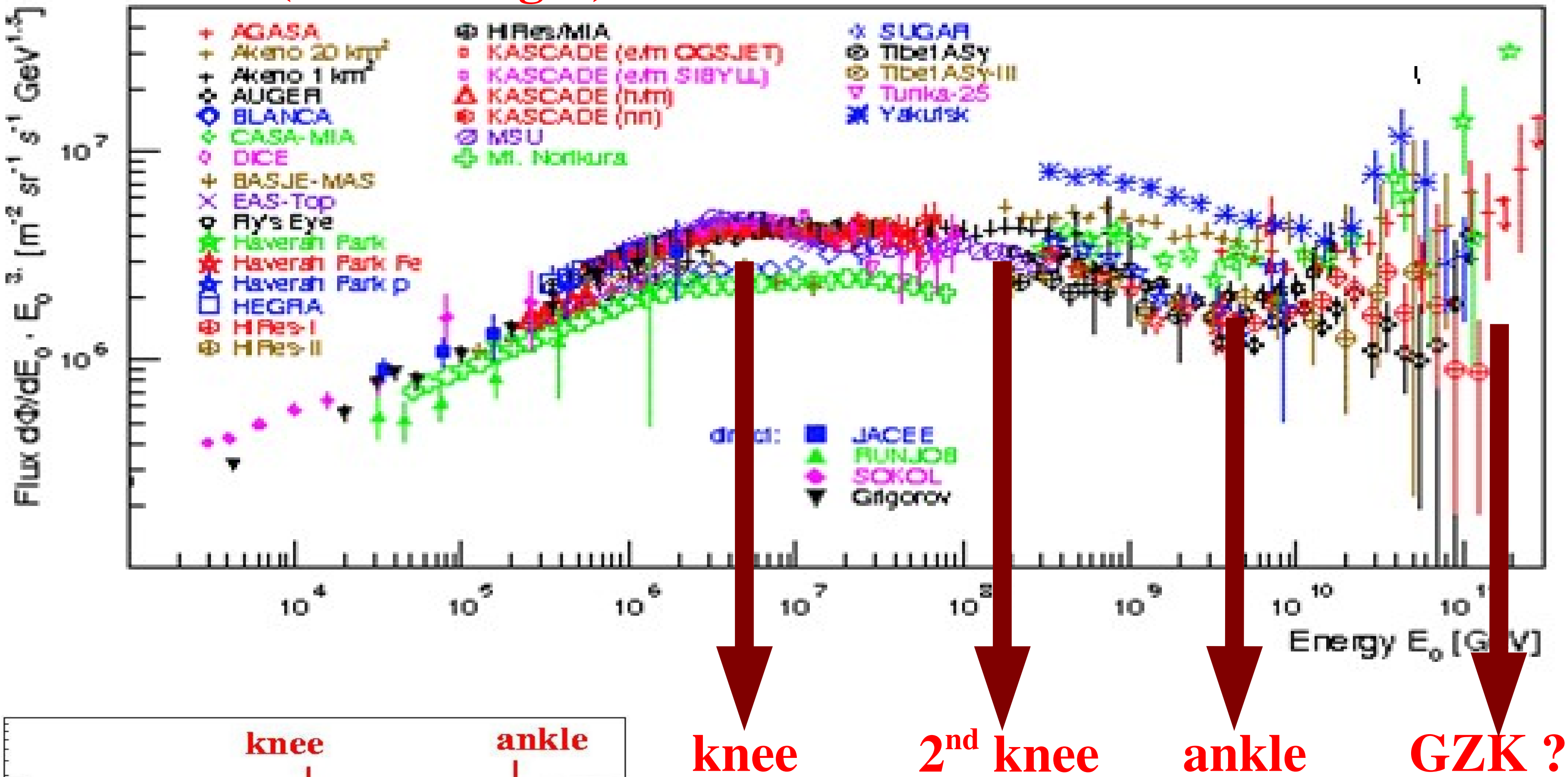
Measure X_{max}

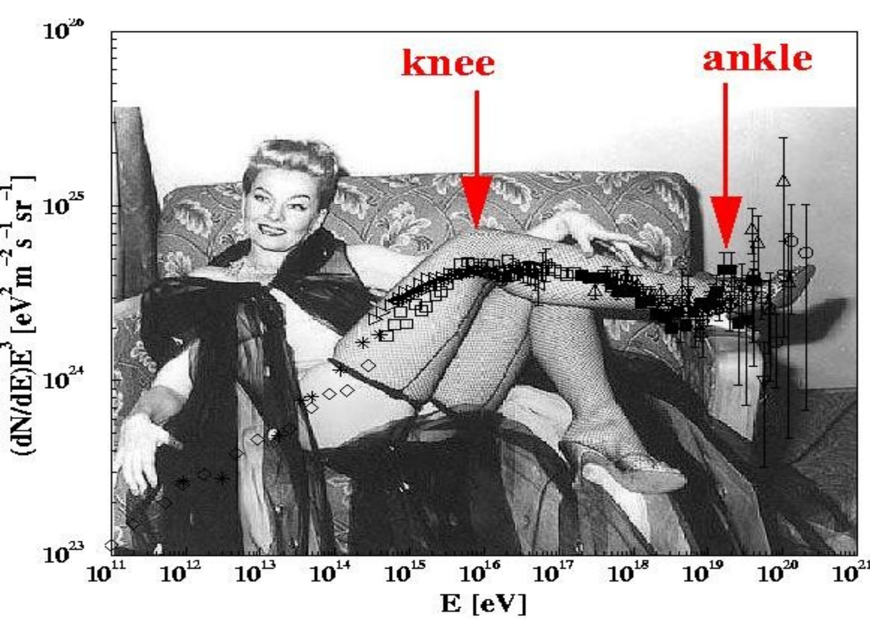
Energy calibration

angular resolution studies ...

(but duty cycle ~15%)

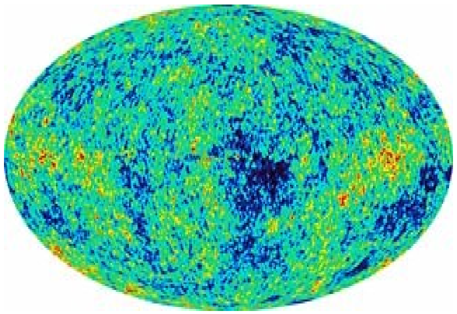
E^3 x FLUX (before Auger)

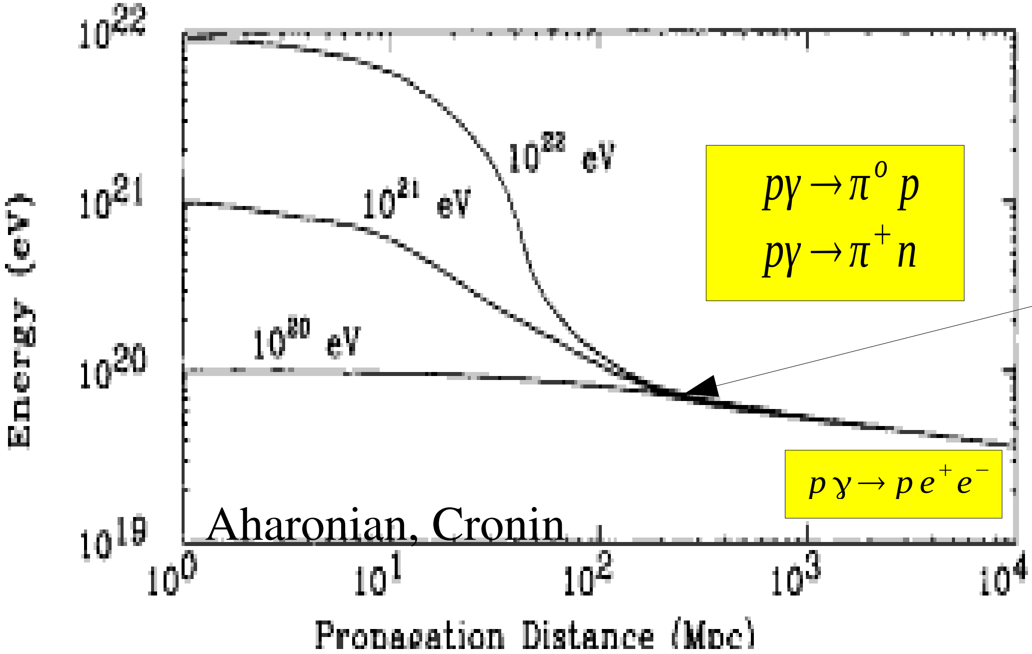




the Greisen-Zatsepin-Kuzmin effect (1966)

AT THE HIGHEST ENERGIES, PROTONS LOOSE ENERGY BY INTERACTIONS WITH THE CMB BACKGROUND



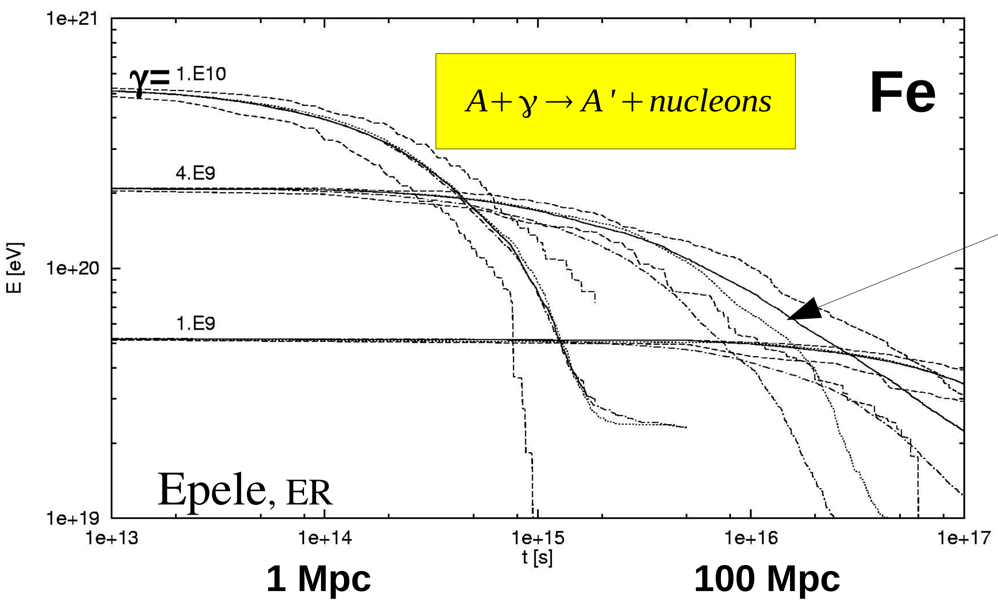


PROTONS CAN NOT ARRIVE WITH $E > 6x10^{19}$ eV FROM D > 200 Mpc

(π^0 produce GZK photons)

($\pi^{\pm}$ produce cosmogenic neutrinos)

(Berezinsky & Zatsepin 69)



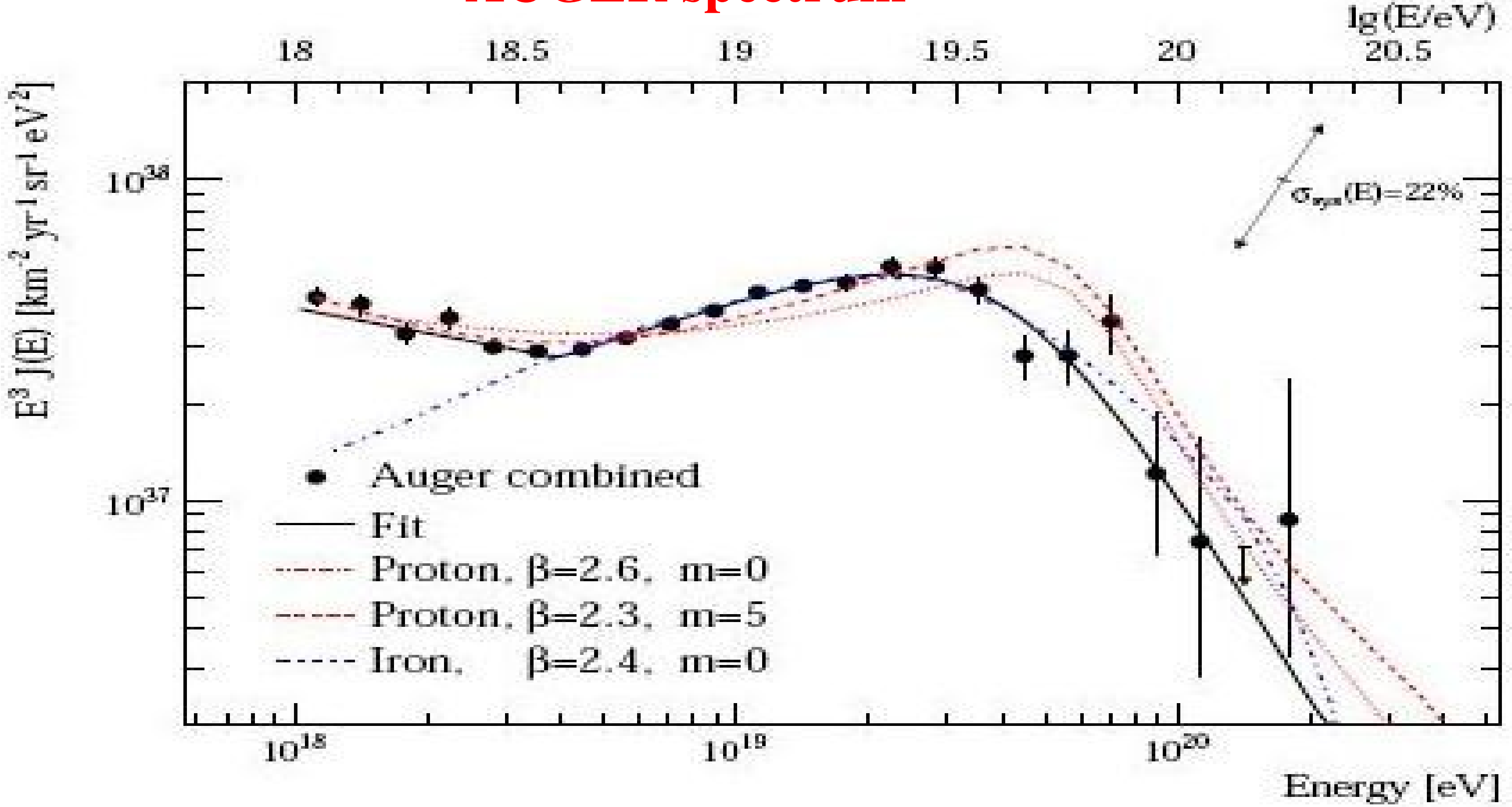
For Fe nuclei: after ~ 200 Mpc the leading fragment has $E < 6x10^{19}$ eV

ligther nuclei get disintegrated on shorter distances

(fewer neutrinos produced)

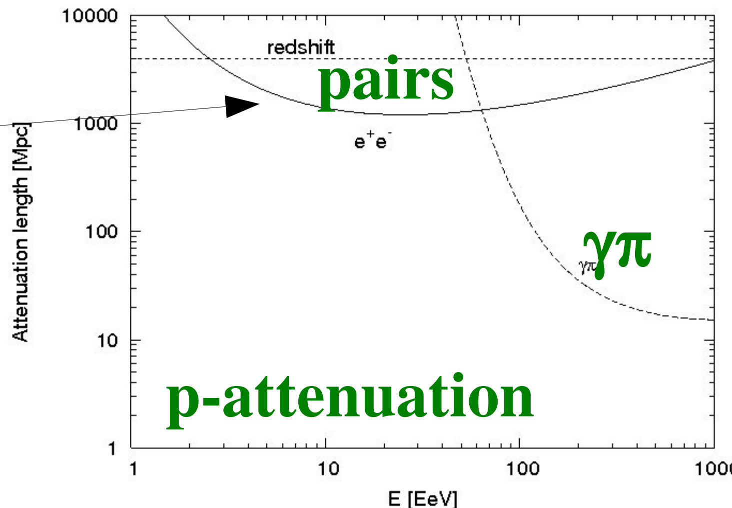
(ICRC09)

AUGER spectrum



Ankle: **Galactic – extragalactic transition**

or e^+e^- dip in Xgal protons ?

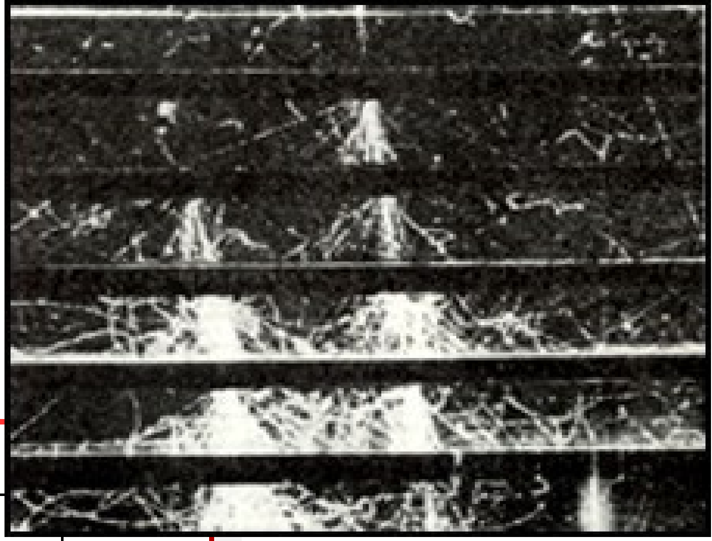


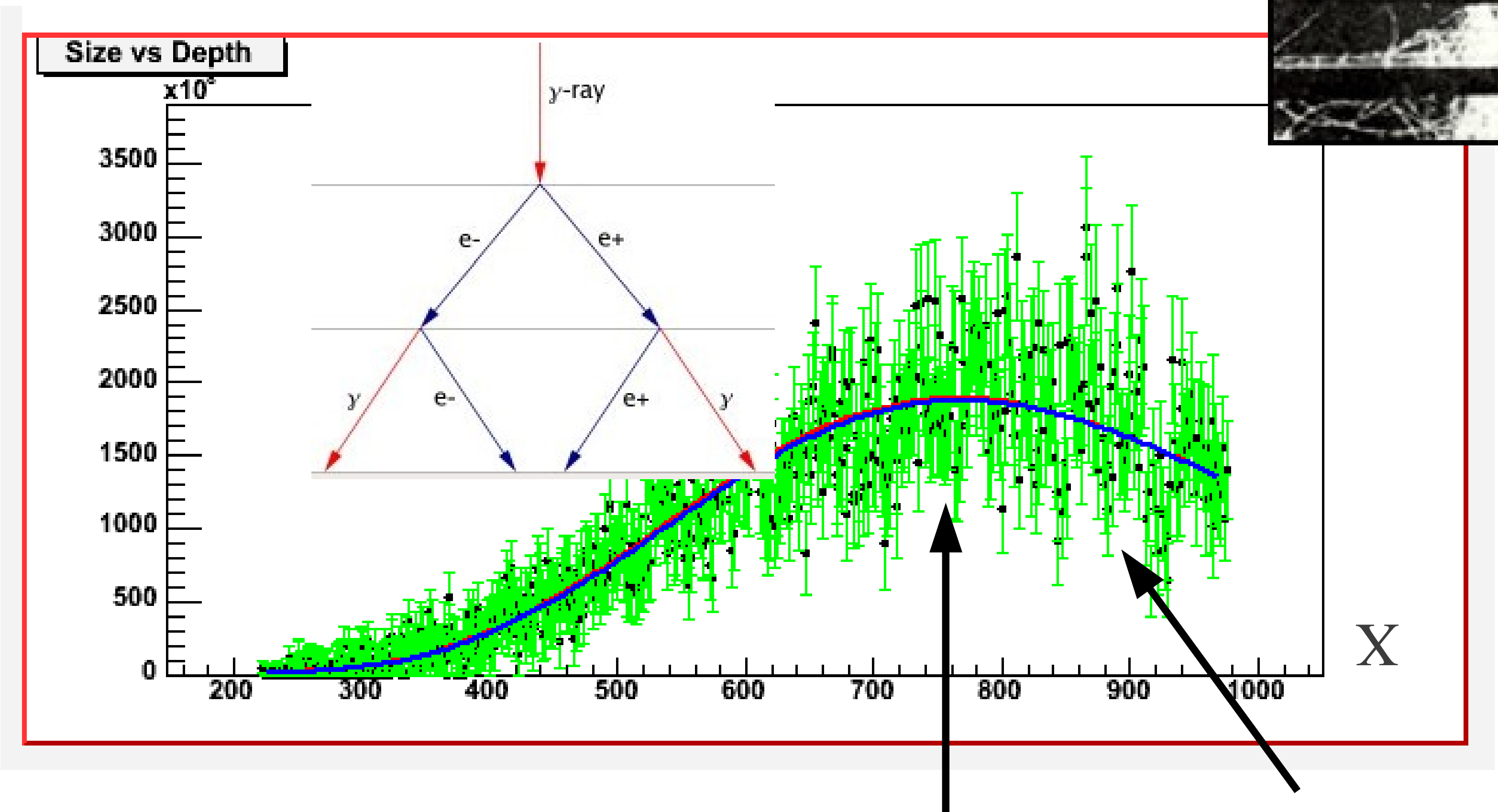
GZK: **proton or Fe suppression ?**

(and/or exhaustion of sources?)

Some basics on air showers:

ELECTROMAGNETIC SHOWERS (e^+ , e^- , γ)





N grows exponentially

Ionisation losses dominate

$$X_{max} \propto \ln(E_0)$$

$$N_{max} \simeq 10^{11} \frac{E_0}{10^{19} eV}$$

HADRONIC SHOWERS

each interaction produces n_{tot} **pions (multiplicity)**

$n_{neut} = n_{tot}/3 \;\; (\pi^0 \rightarrow 2\gamma)$ **em component**

$n_{ch} = 2\, n_{tot}/3 \;\; (\pi^{\pm})$ **reinteract until** $E < E_{dec} \; (\pi \rightarrow \mu\nu\nu) \sim 10\, GeV$

Typically number of pion generations = 5 - 6 $(E_{EM} \simeq 0.9\, E_{tot})$

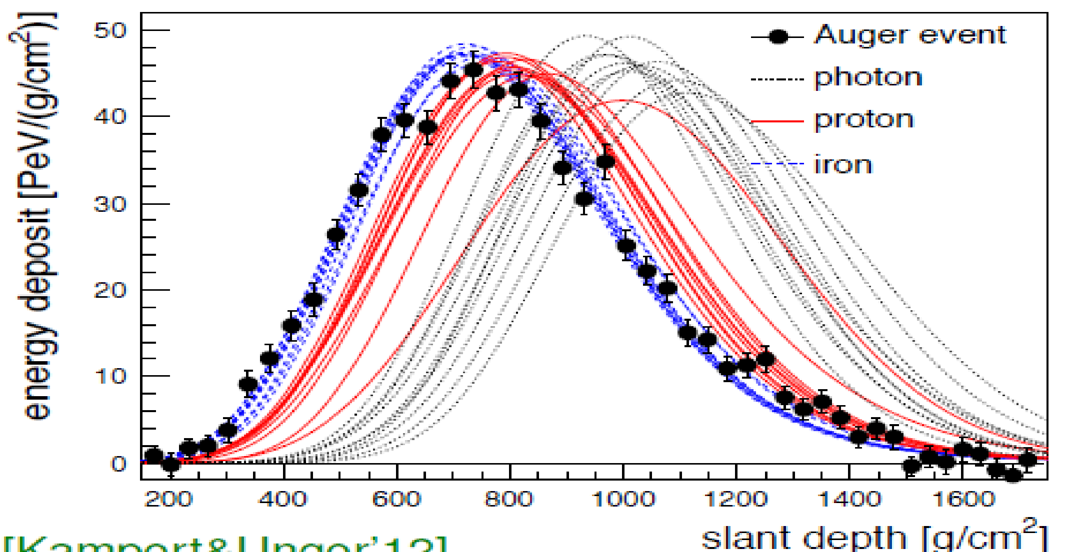
Estimating X_{max} **as the maximum of the first generation** π^0 **s:**

$$X_{max} = \lambda_I + X_R \ln\left(\frac{E_0/n_{tot}}{E_c}\right)$$

depends on $\lambda_I \sim \sigma^{-1}_{p-air}$ **and** n_{tot}

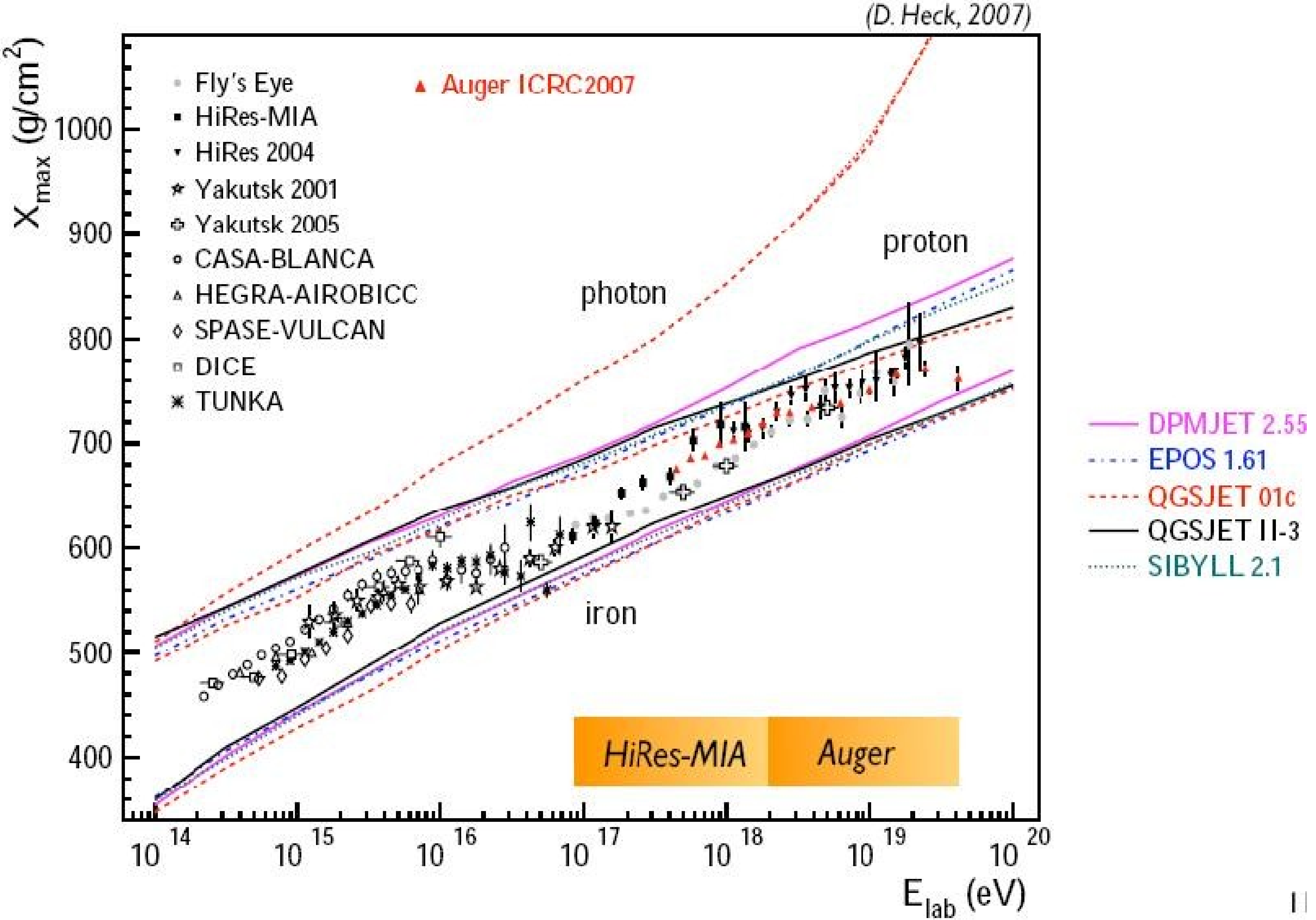
For nuclei: behave as

A **nucleons with** $E_n = E_0/A$



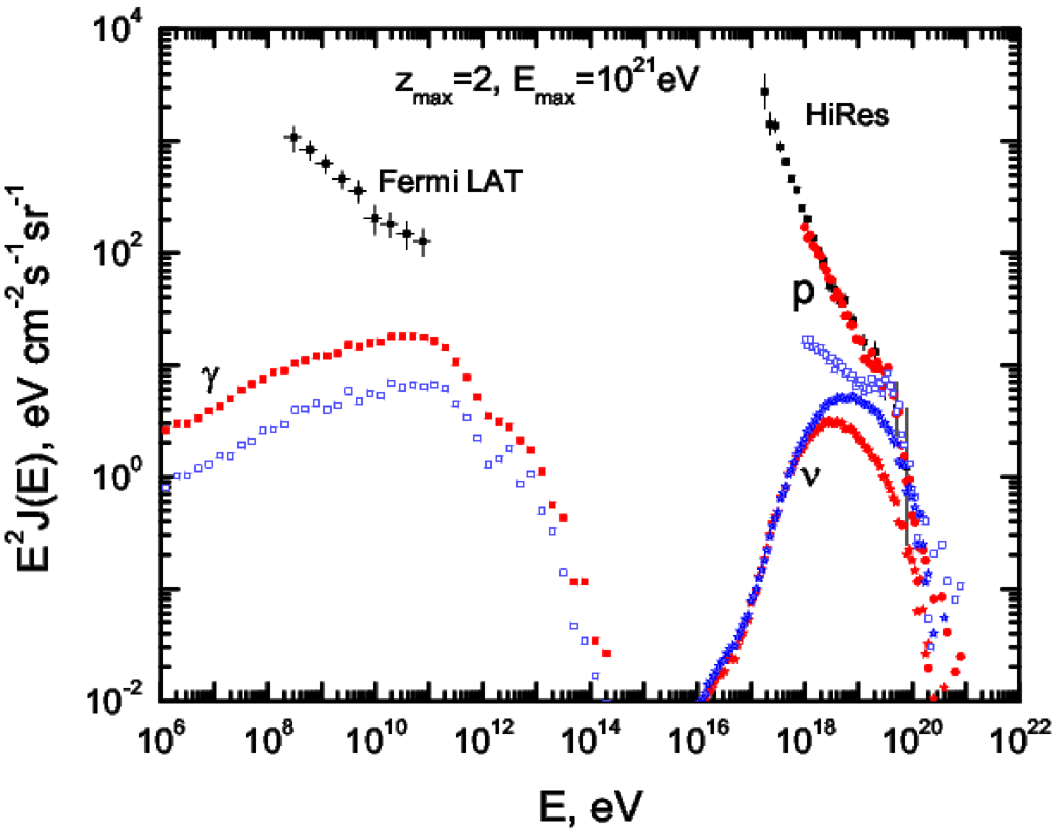
[Kampert&Unger'12]

COMPOSITION FROM X_{max}

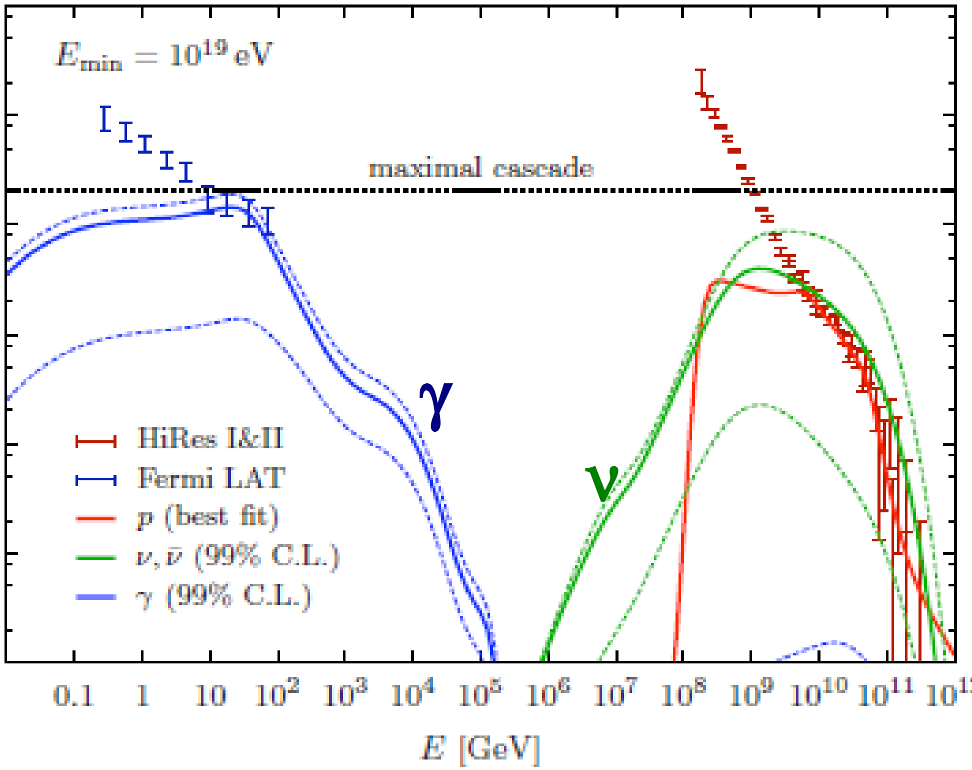


COSMOGENIC NEUTRINO FLUXES:

Berezinsky et al., arXiv:1003.1496



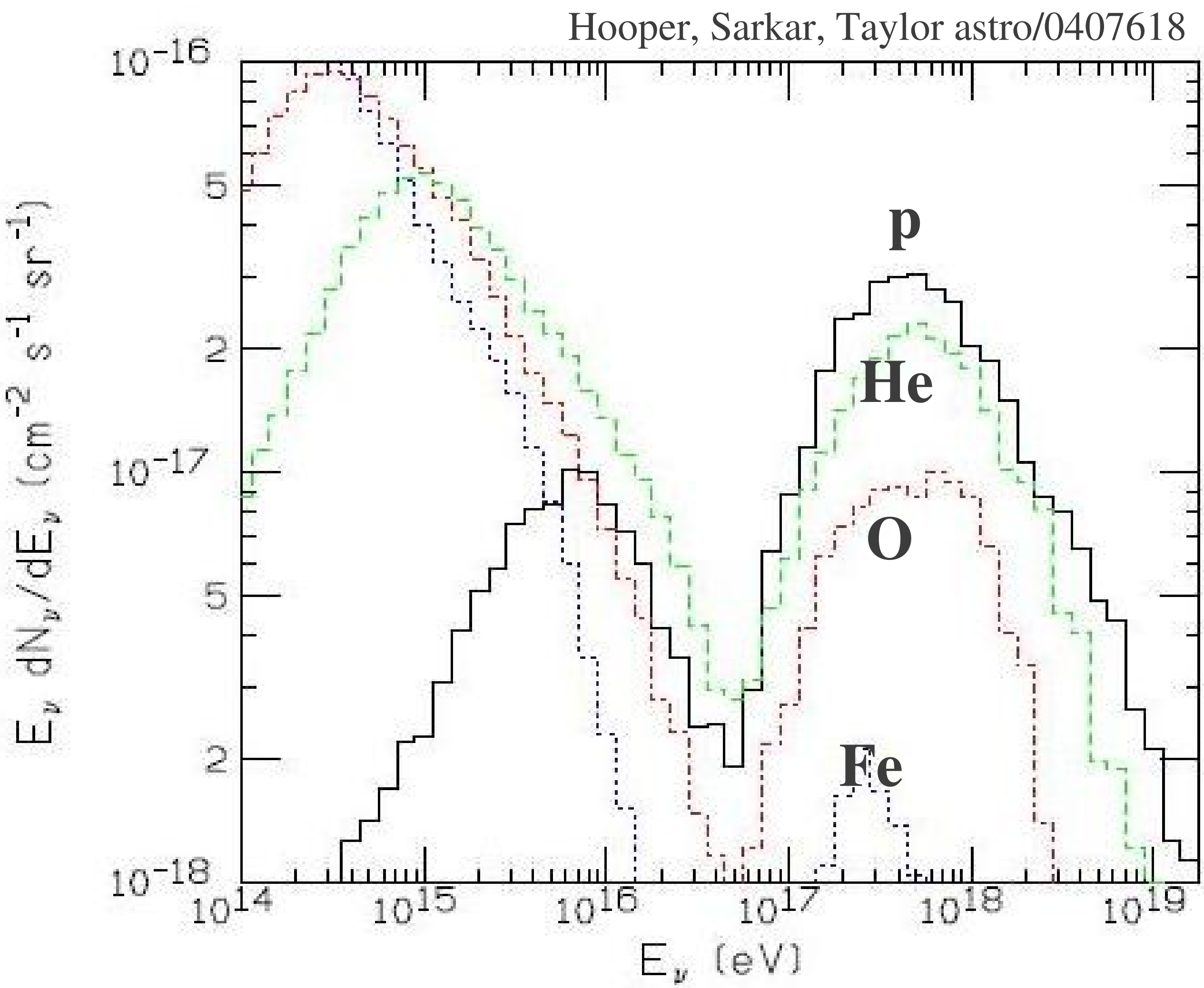
Ahlers et al., arXiv:1005.2620



- ankle models (harder fluxes) lead to larger cosmogenic neutrino fluxes than dip models

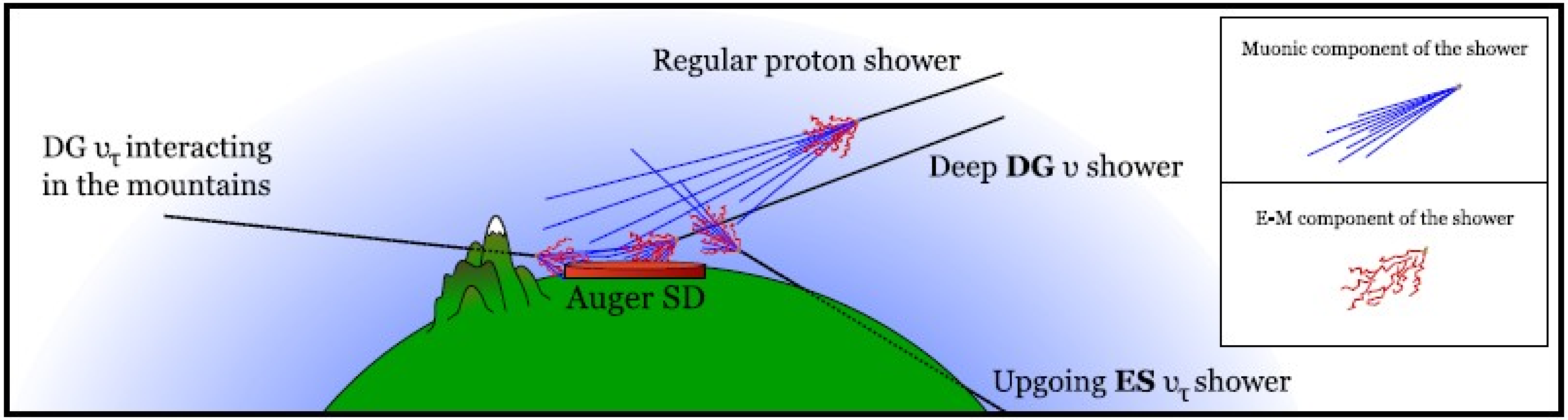
- fluxes at EeV comparable to CR fluxes, but cross section tiny (~ 10 nb) → probability of Interacting in atmosphere small (~10^{-5} for vertical)

If GZK neutrinos were observed,
it would be a strong hint favoring a light composition,
And could confirm that spectrum attenuation is due to GZK effect

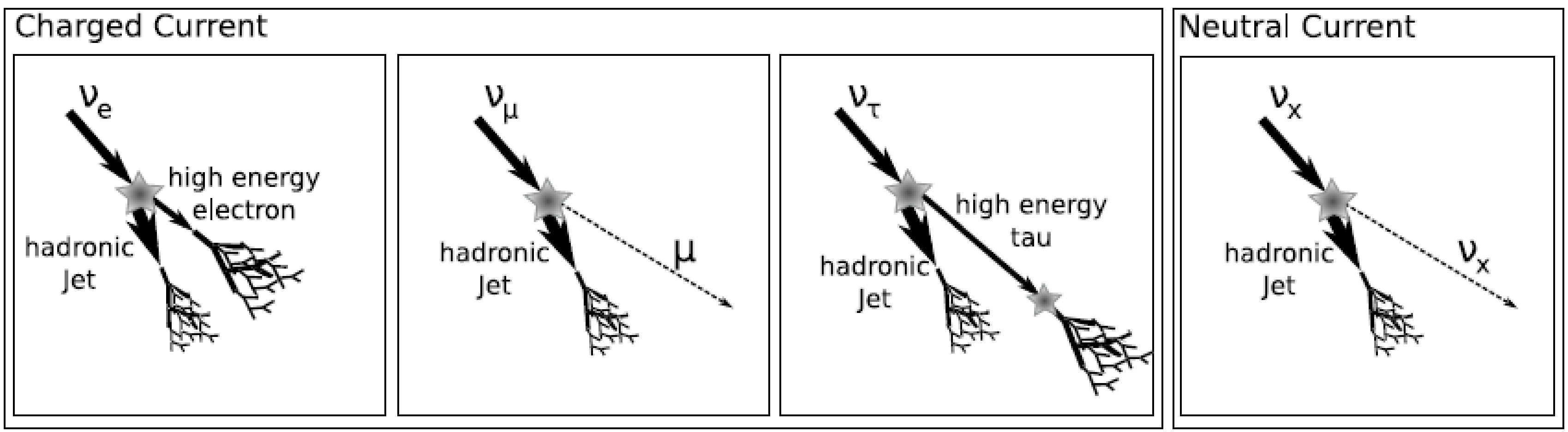


Flux not so much 'guaranteed'

Neutrino detection in AUGER



Only neutrinos can produce young horizontal showers



For downgoing showers: (assuming 1:1:1 flavor ratios)

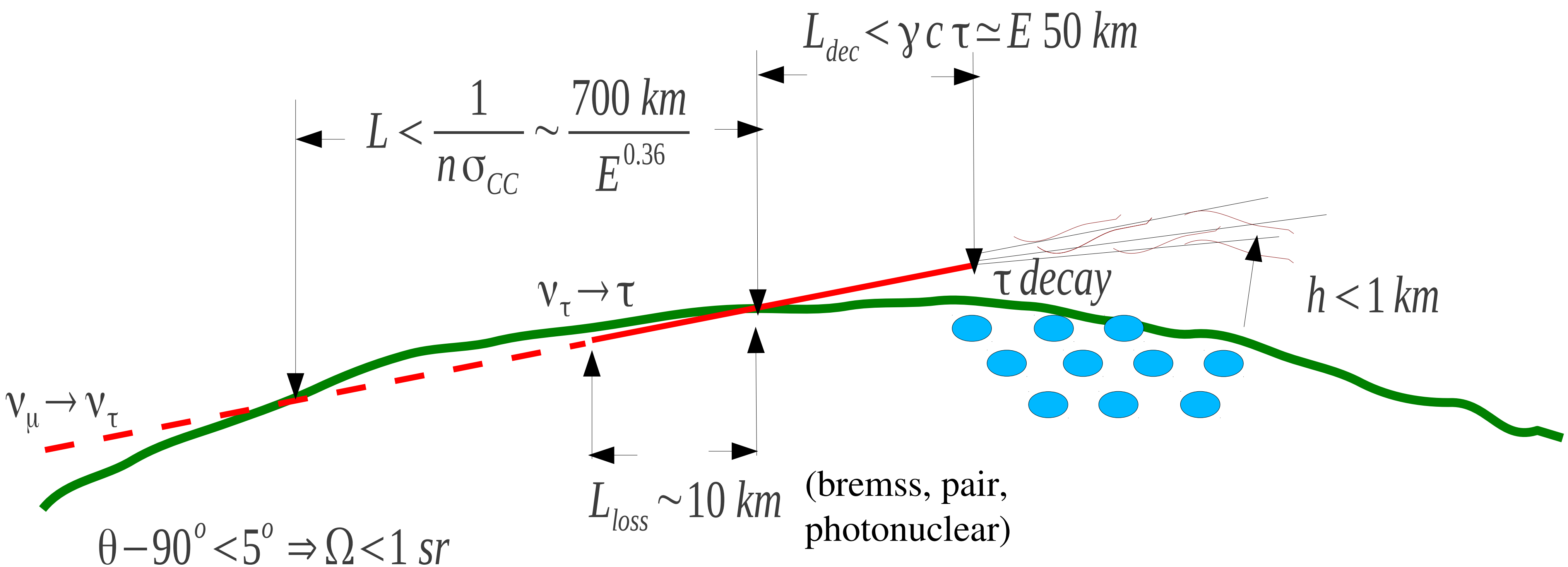
38% from ν_e, 18% from ν_μ, 29% from ν_τ – air, 15% from ν_τ – mountain

but Earth-skimming ν_τ searches are more sensitive

Fargion 2000,
Bertou et al '01
Feng et al. '02

Up-going Earth-skimming ν_τ showers

$$\sigma_{CC} \simeq 10^{-32}\, cm^2\, E^{0.36} \qquad (E\,[EeV])$$

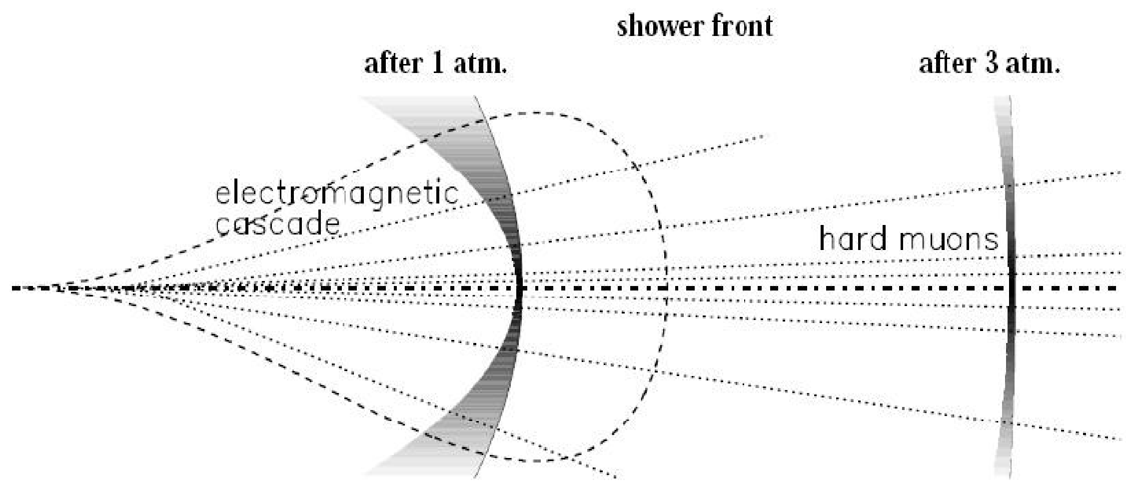


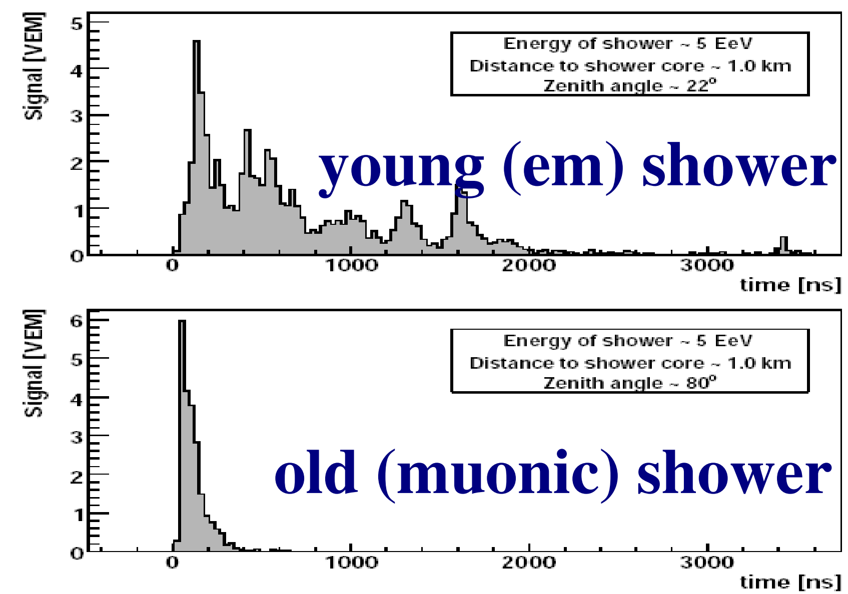
Probability of interacting
in the last 10 km ~ 0.01

→ Effective exposure ~ 0.1 km^2 sr
(c.f. ~ 10^4 km^2 sr for UHECR)

AUGER BOUNDS ON DIFFUSE NEUTRINO FLUX

unlike hadronic CRs, neutrinos can produce young horizontal showers above the detector, and upcoming near horizontal tau lepton induced showers



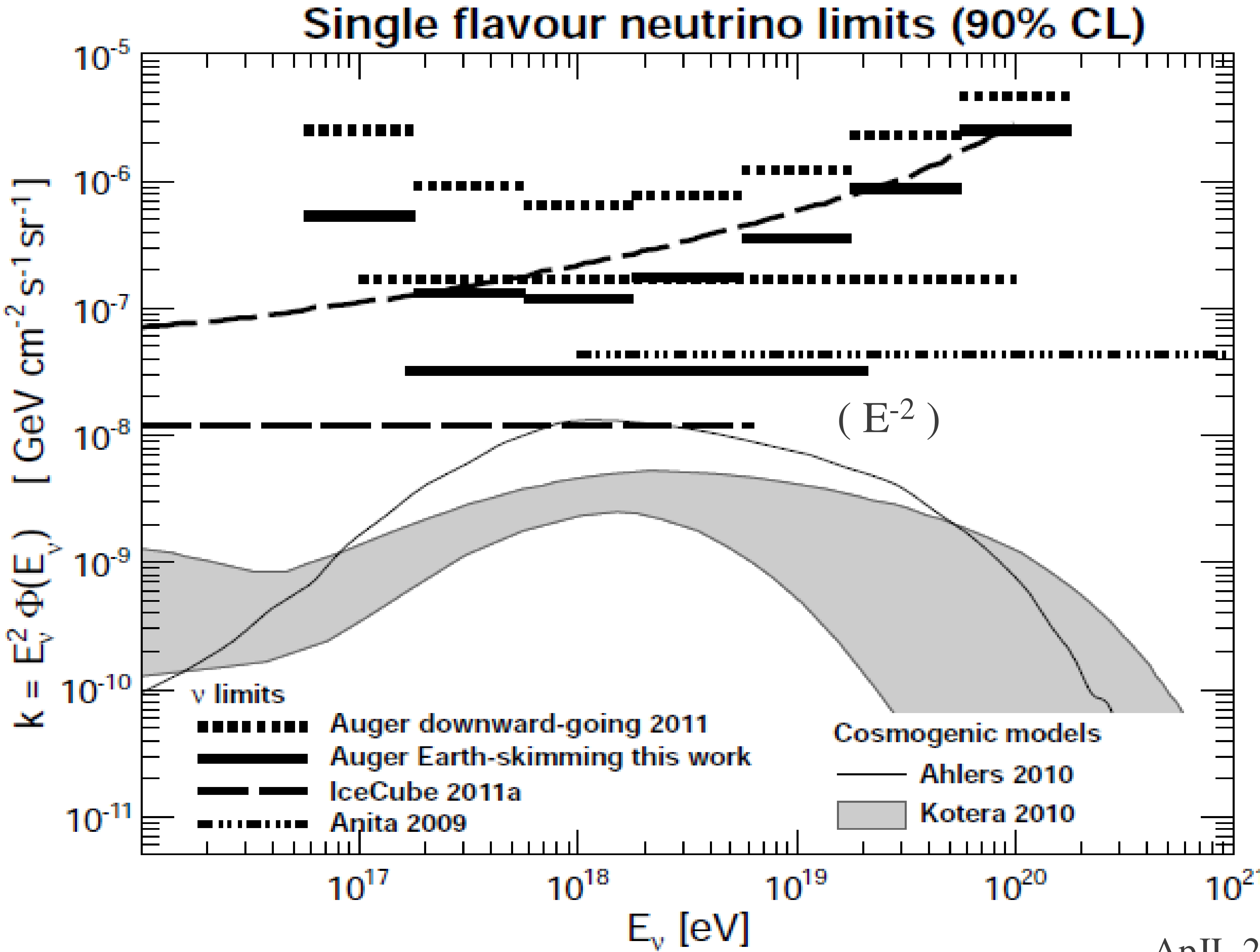


Horizontal young showers?

tank signals with large Area / peak

Elongated tracks, Propagation with v ~ c

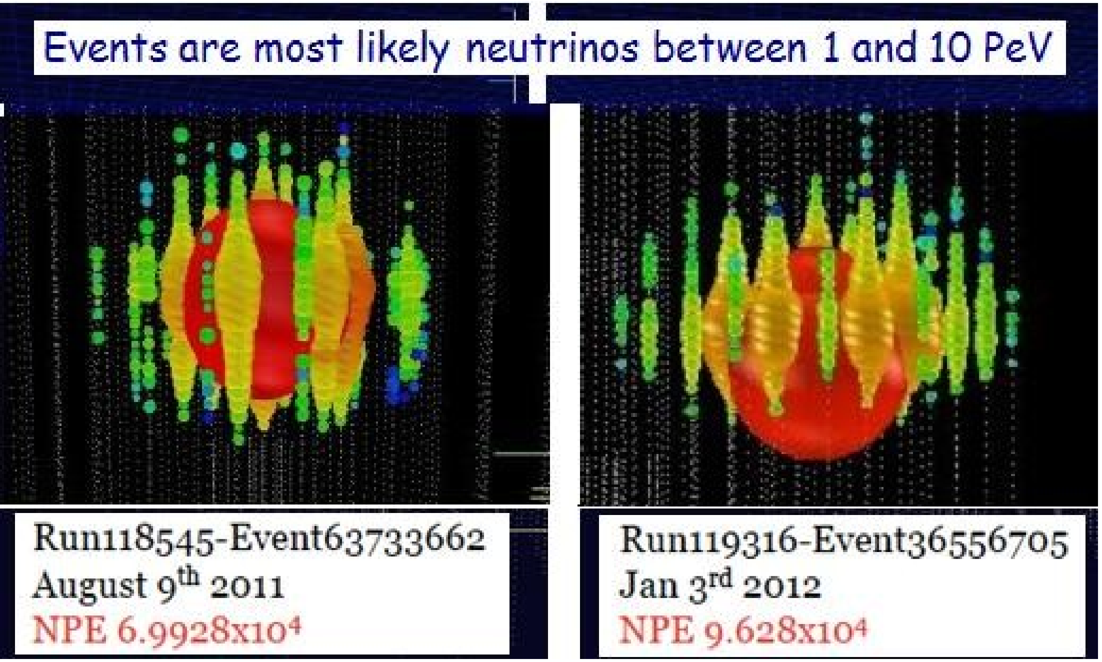
ZERO CANDIDATES



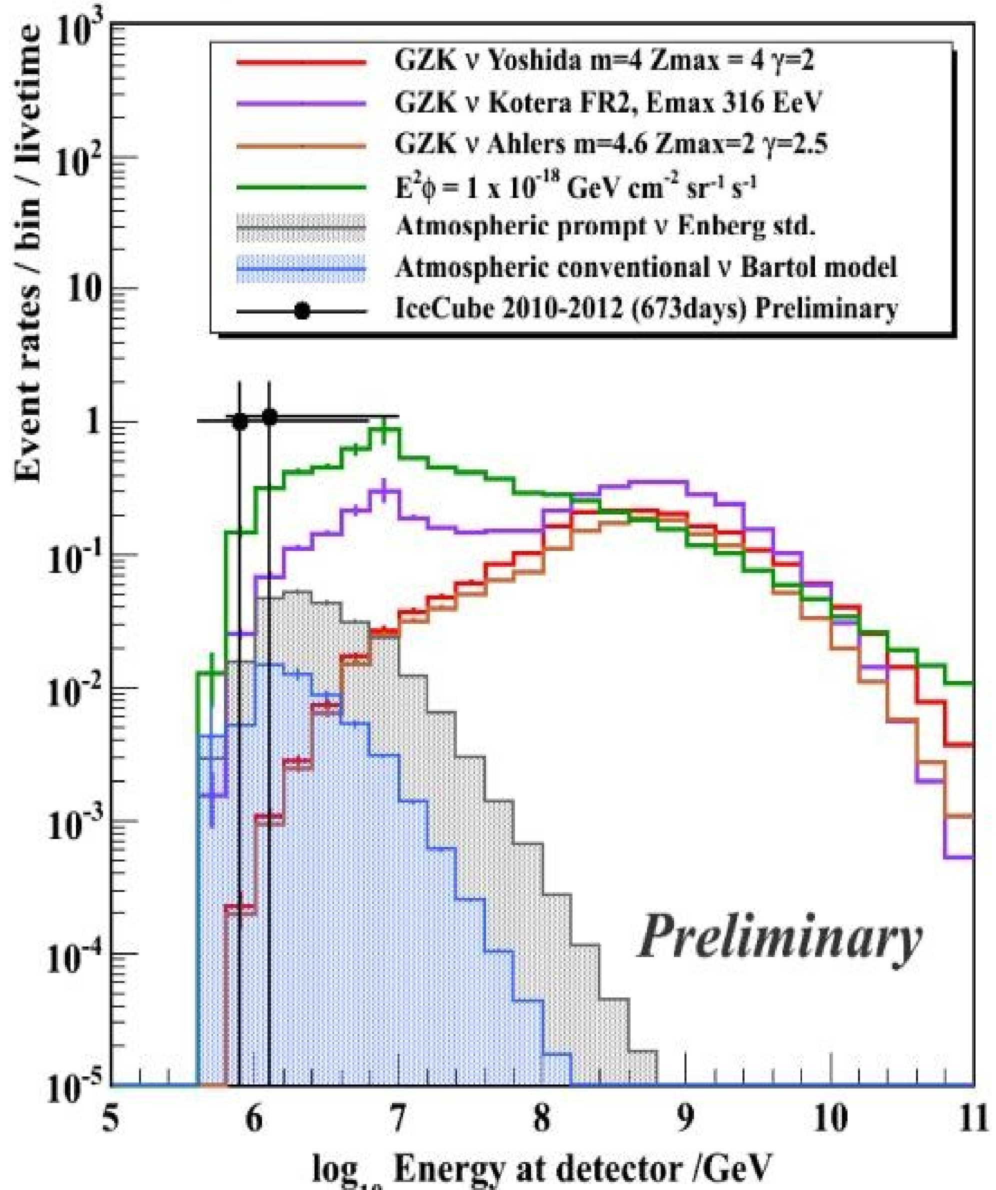
ApJL 2012

0 events observed → bounds scale linearly with exposure

The two highest energy neutrino events observed by ICECUBE



Energy Distributions 2010-12



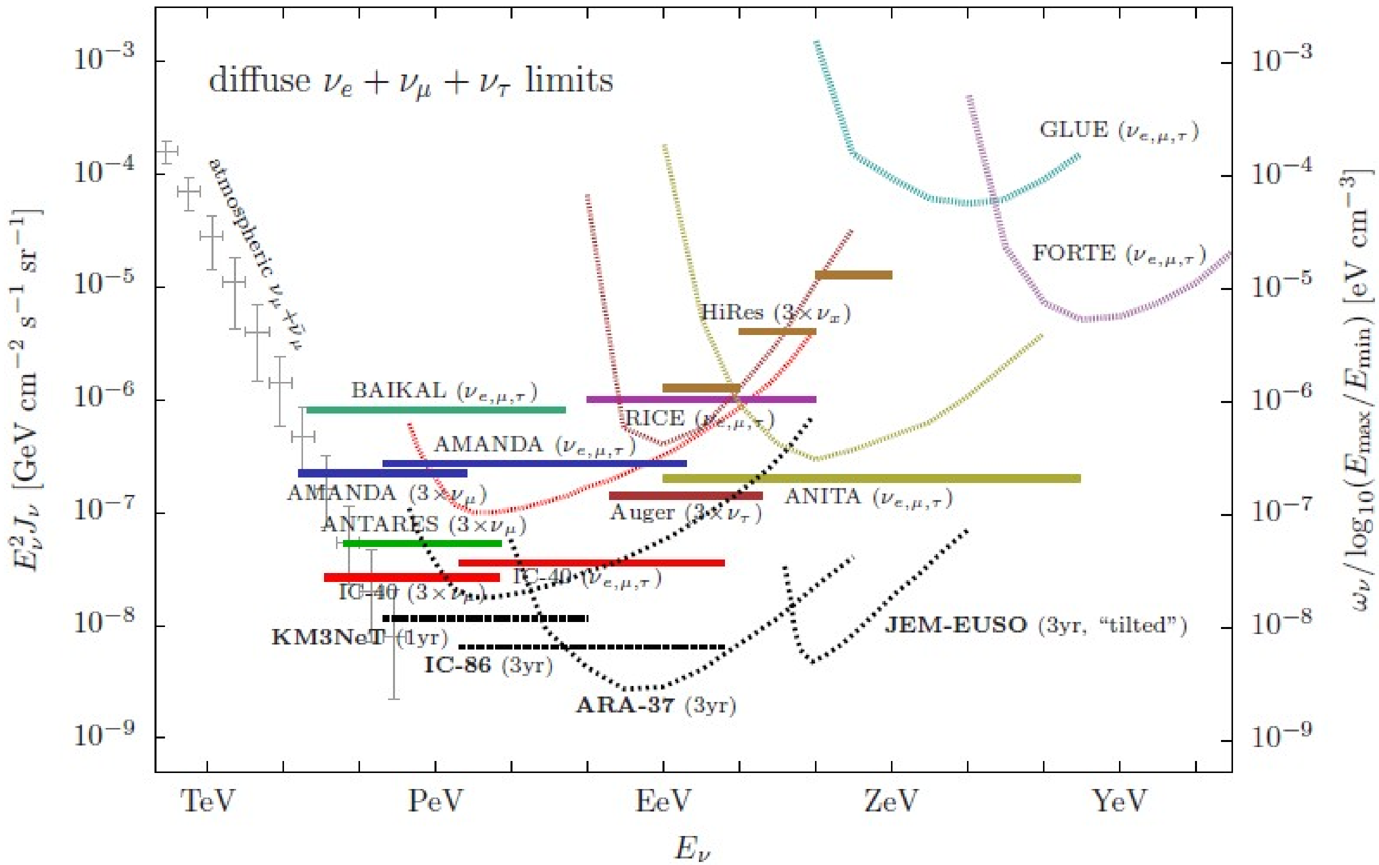
Possibility of the origin includes

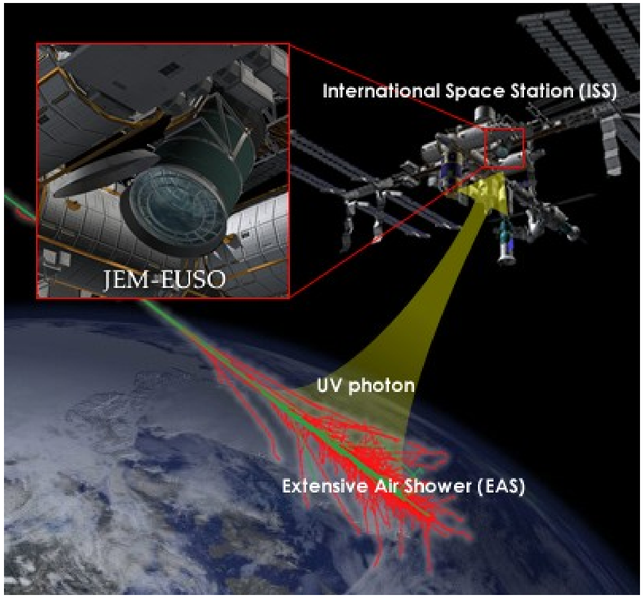
- cosmogenic ν
- on-site ν production from the cosmic-ray accelerators
- atmospheric prompt ν
- atmospheric conventional ν

LOOKING TO ν FROM THE SKY

ANITA looked for up-going neutrino showers on ice producing radio coherent emission (Askaryan effect)
~ 1 month balloon flights in Antarctica
→ next generation: EVA ? (x 100 better)

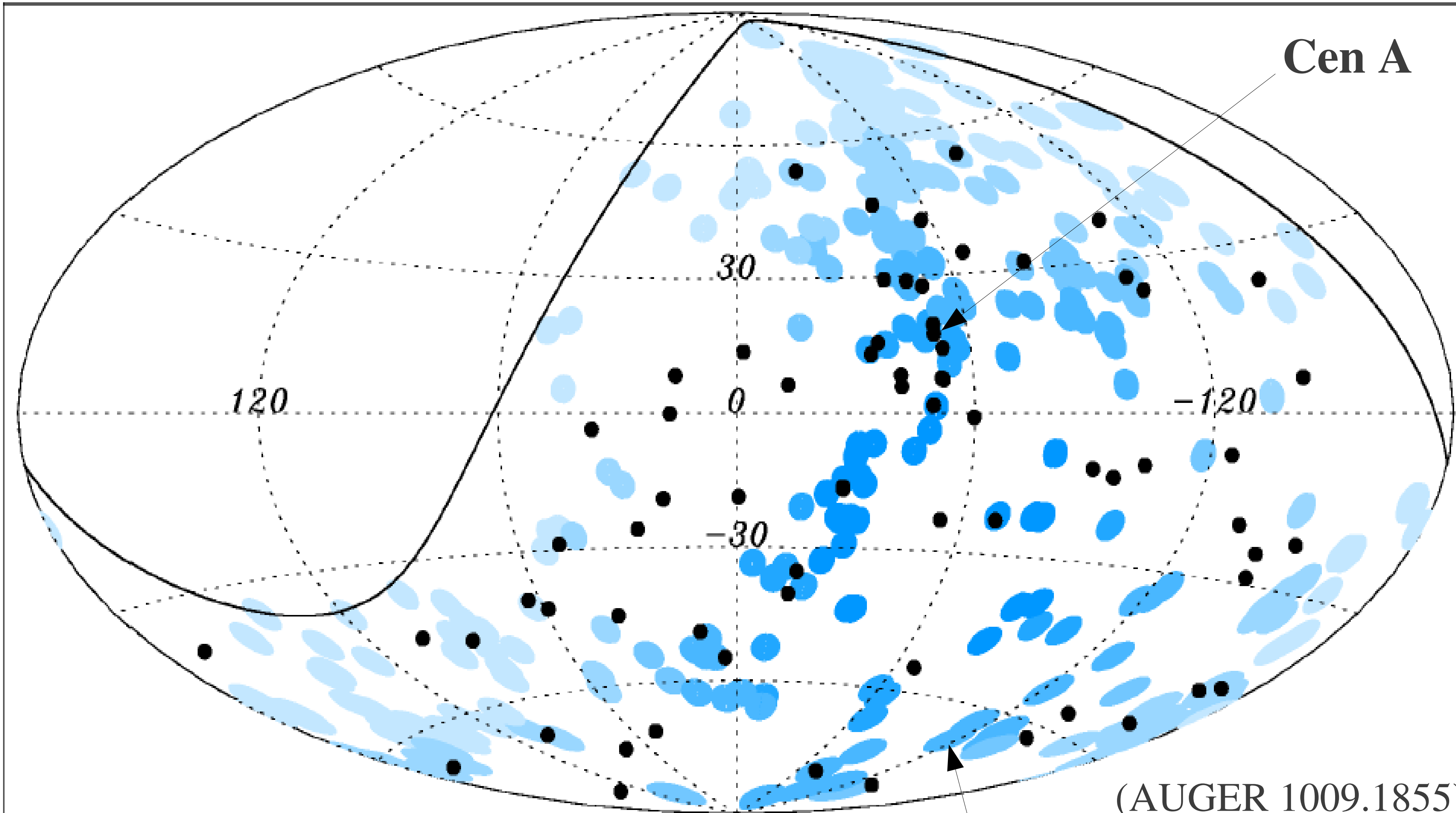
ARA: Askaryan Radio Array
(prototipe deployment in 2011)





Or from the space station?
→ JEM-EUSO

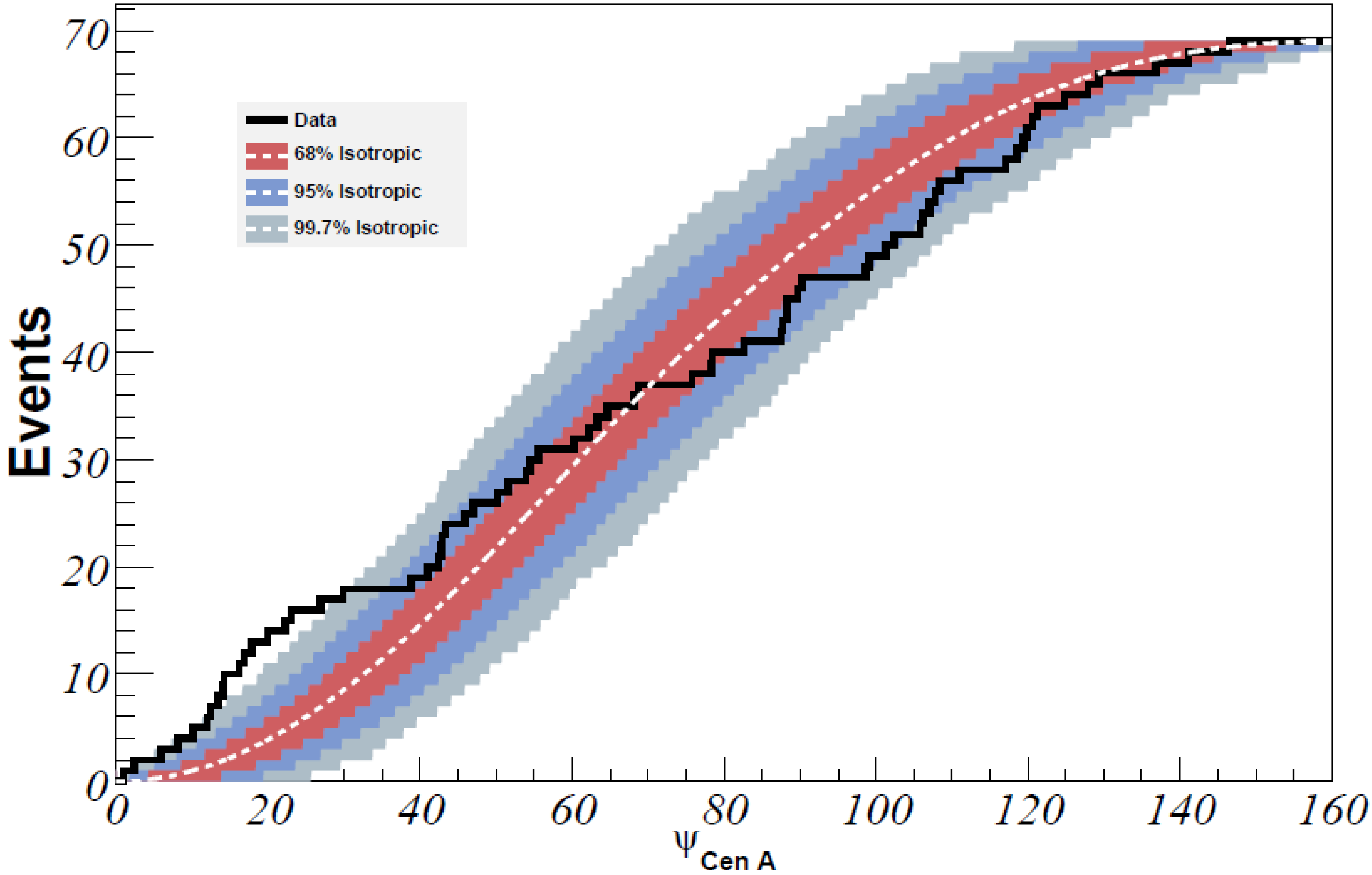
AUGER sky map above 55 EeV



69 events with E > 55 EeV

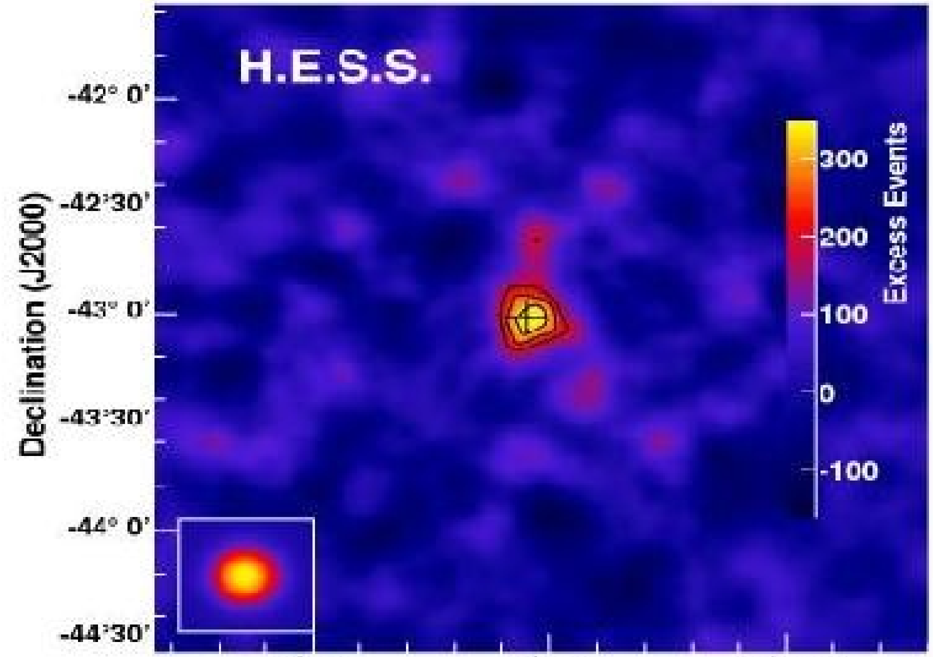
Nearby AGN at < 75 Mpc

Excess around Centaurus A: closest AGN



13 events within 18 deg of CenA, while 3.2 expected for isotropy

HESS observation of Centaurus A (0.1 – 10 TeV gammas)



Discovery of very high energy γ-ray emission from Centaurus A 3

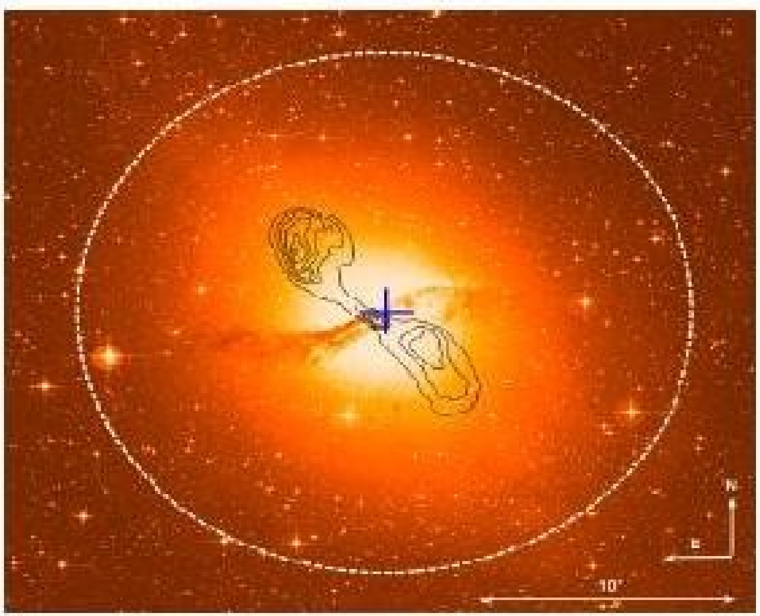


FIG. 2.— Optical image of Cen A (UK 48-inch Schmidt) overlaid with radio contours (black, VLA, Condon et al. 1996). VHE best fit position with 1 σ

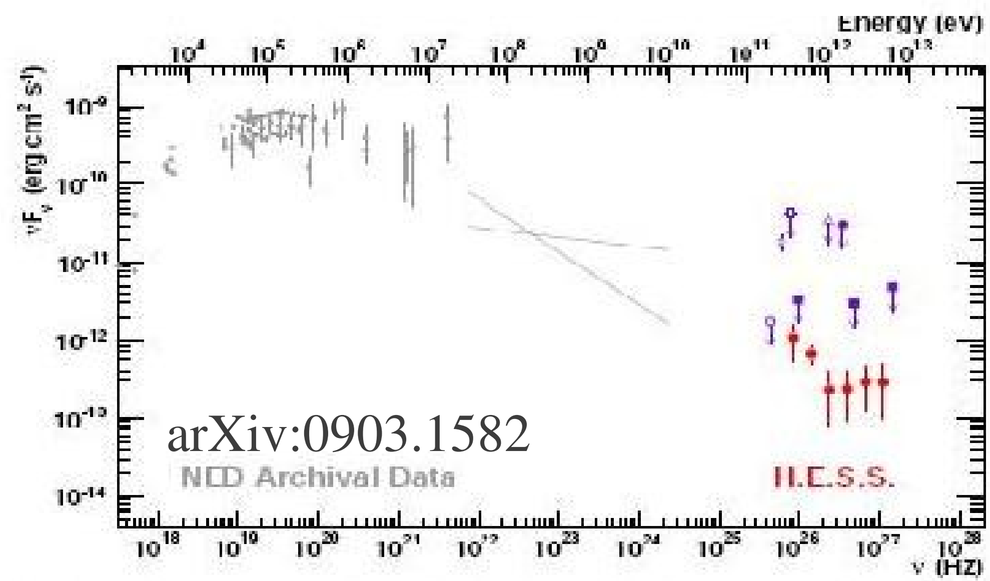
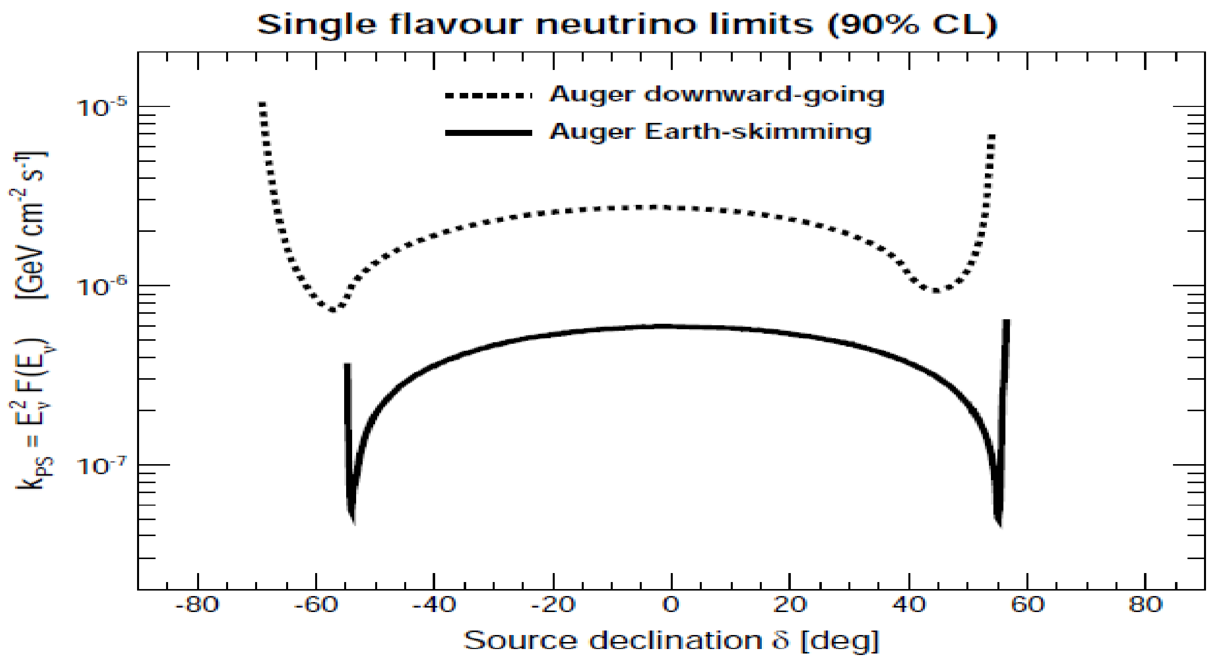


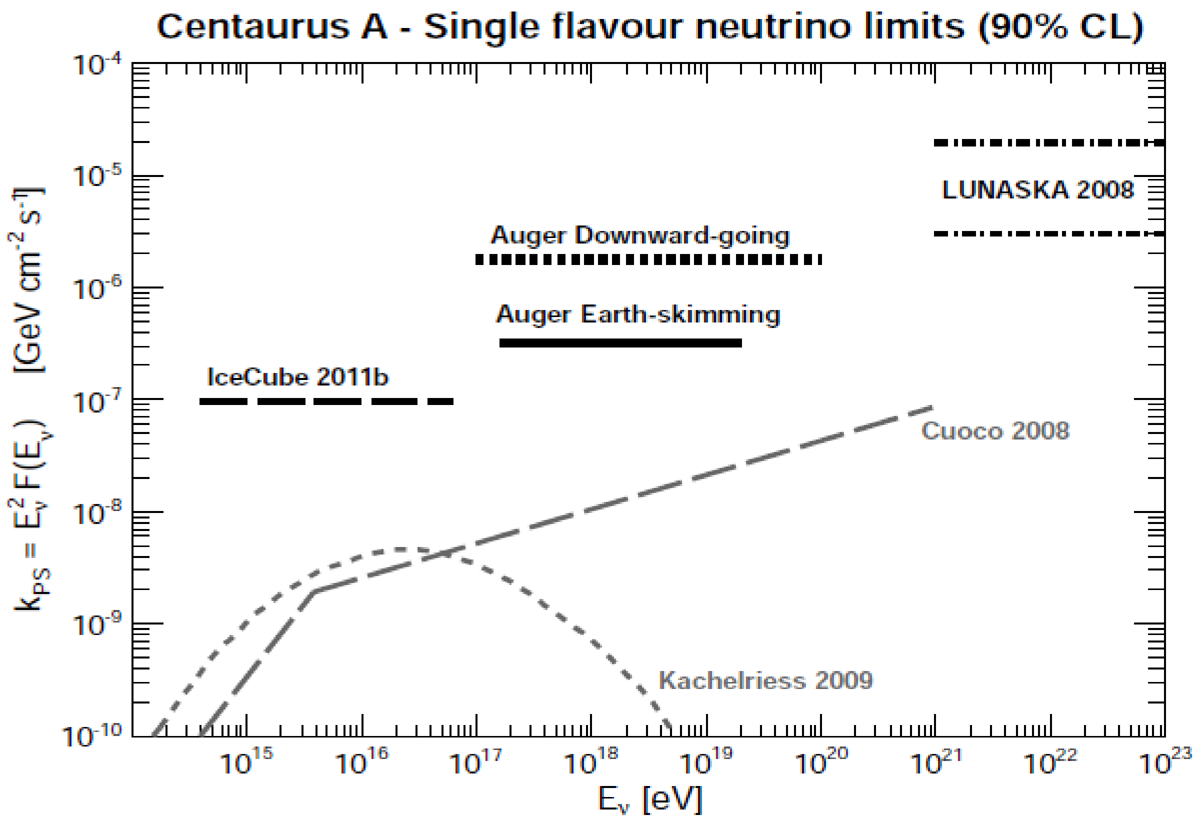
FIG. 4.— Spectral energy distribution of Cen A. Shown are the VHE spectrum as measured by H.E.S.S. (red filled circles), previous upper limits and tentative detections in the VHE regime (purple markers: Grindlay et al. 1975

If γ are hadronic → neutrinos from CenA may be observed at ICECUBE/ Auger?

(but predictions ~ 0.01 – 1 per year)

Auger observed no neutrinos (in particular none from Cen A)





CONCLUSIONS

breakthroughs expected to come from very high energy neutrinos:

TeV NEUTRINO SEARCHES (km^3 detectors) → identify CR accelerators

EeV COSMOGENIC NEUTRINOS → CR propagation, GZK effect, CR composition

EXOTIC SOURCES? TOPOLOGICAL DEFECTS, SUPER HEAVY DECAYS, ...

POSITIVE DETECTIONS HOPEFULLY NOT VERY FAR AWAY, STAY TUNED