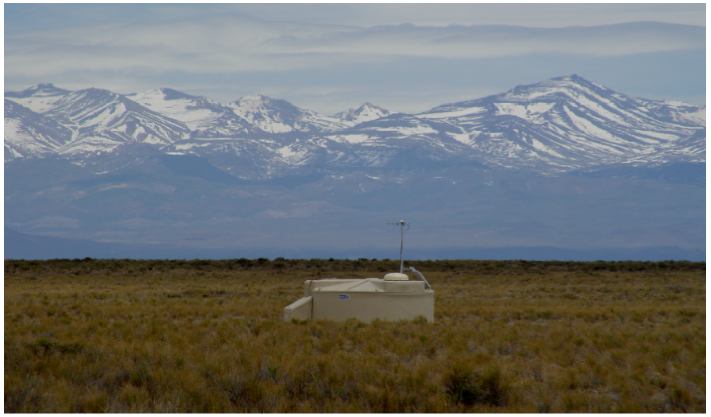
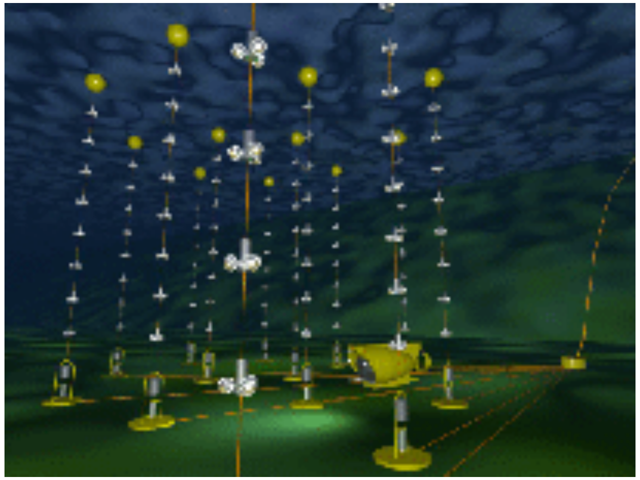
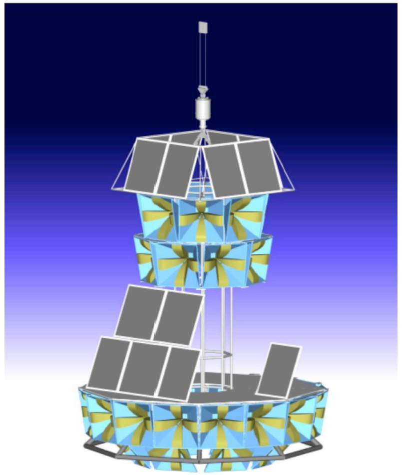






# *Probing new physics with ultrahigh energy cosmic neutrinos*

**Subir Sarkar**
University of Oxford

*Neutrino Horizons in the 21st Century,*
Cosener's House, Abingdon, 18 April 2008

# Colliders and Cosmic Rays

The LHC will achieve ~14 TeV cms if all goes well …

But 1 EeV ($10^{18}$ eV) cosmic ray initiating giant air shower
$\Rightarrow$ 50 TeV cms (rate ~ 10/day in 3000 $km^2$ array)

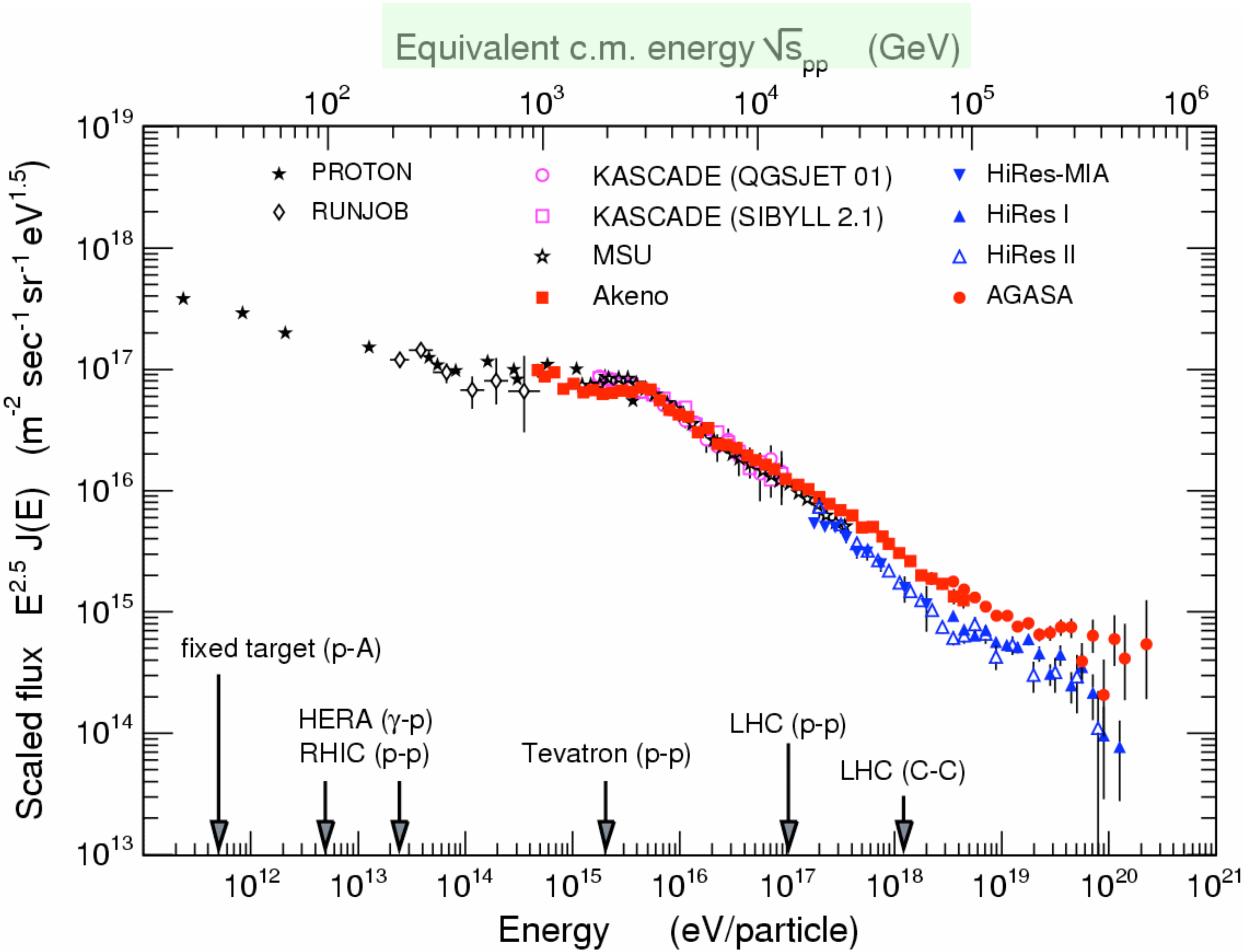
New physics would be hard to see in hadron-initiated showers

(#-secn $TeV^{-2}$ vs $GeV^{-2}$)

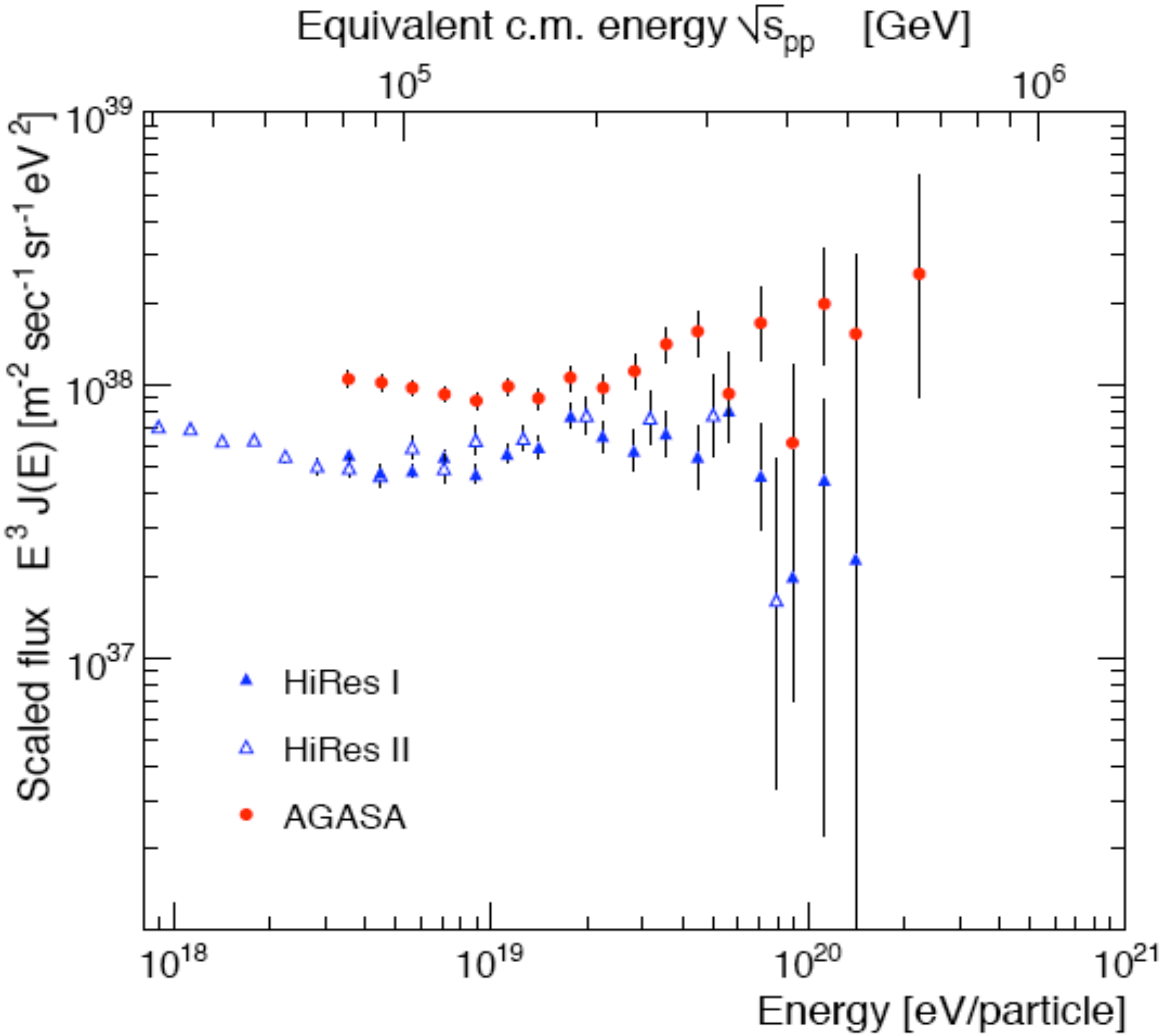
**... but may have a dramatic impact on *neutrino* interactions**

$\rightarrow$ may be able to probe physics **beyond the Standard Model** by observing **ultra-high energy cosmic neutrinos**

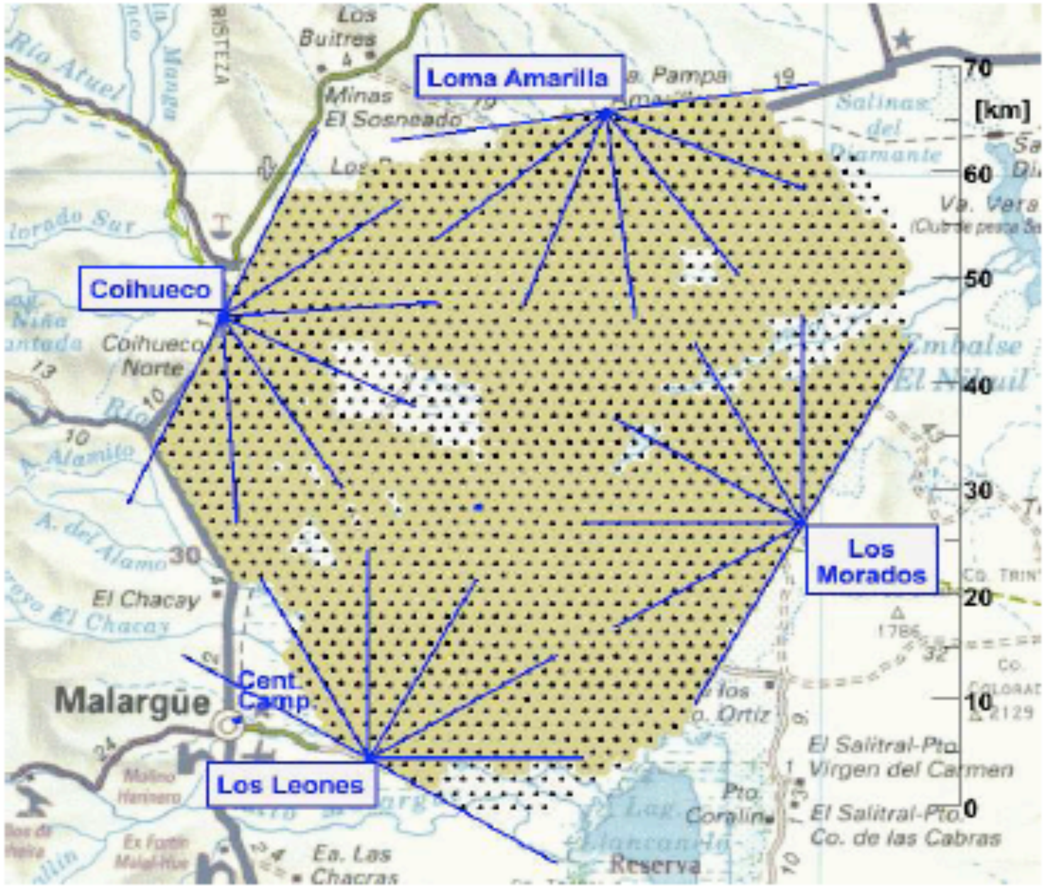
# Cosmic rays have energies upto ~$10^{11}$ GeV … and so *must* cosmic neutrinos

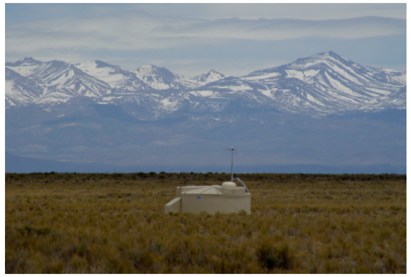


# Is there a 'GZK cutoff' in the cosmic ray spectrum?
## … conflicting results from surface array vs fluorescence detectors



# The Pierre Auger Observatory



- 1600 water-cherenkov detectors ($\approx$ 1535 active)
- Aperture $>$ $7000\ \mathrm{km}^2\ \mathrm{sr\ yr} \equiv 7000\ \mathrm{Linsley}$
- $4 \times 6$ telescopes

## Auger Energy Determination: Step 1

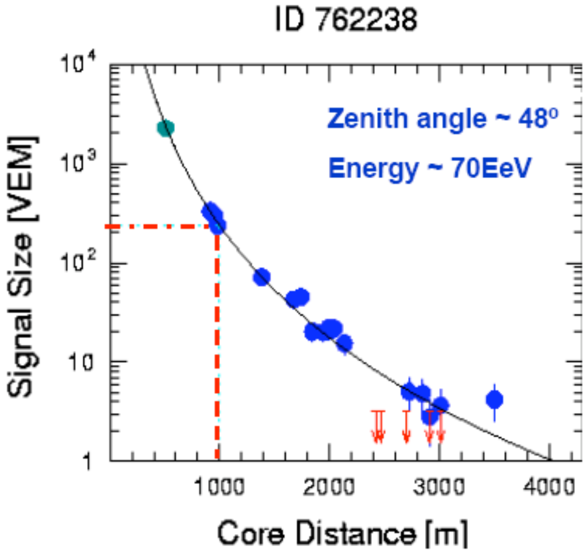
***The energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.***

The detector signal at 1000 m from the shower core

– called the ground parameter or S(1000)

- is determined for each surface detector event using the lateral density function.

**S(1000)** is **proportional to the primary energy.**




For the surface array, the acceptance is simple to calculate and there are lots of events but the energy calibration depends on semi-empirical simulations

For the fluorescence detectors, the acceptance is harder to estimate and the event statistics are low but the energy determination is essentially calorimetric …

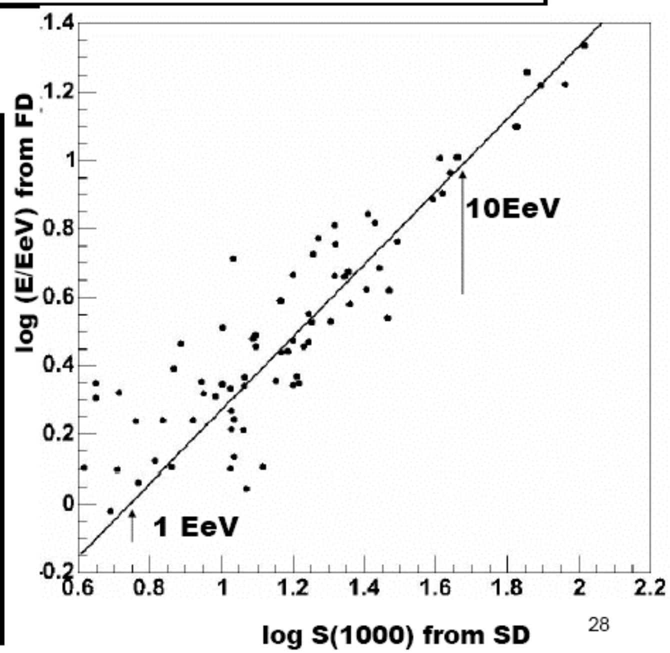
## Auger Energy Determination: step 2

**Hybrid Events with STRICT event selection:**

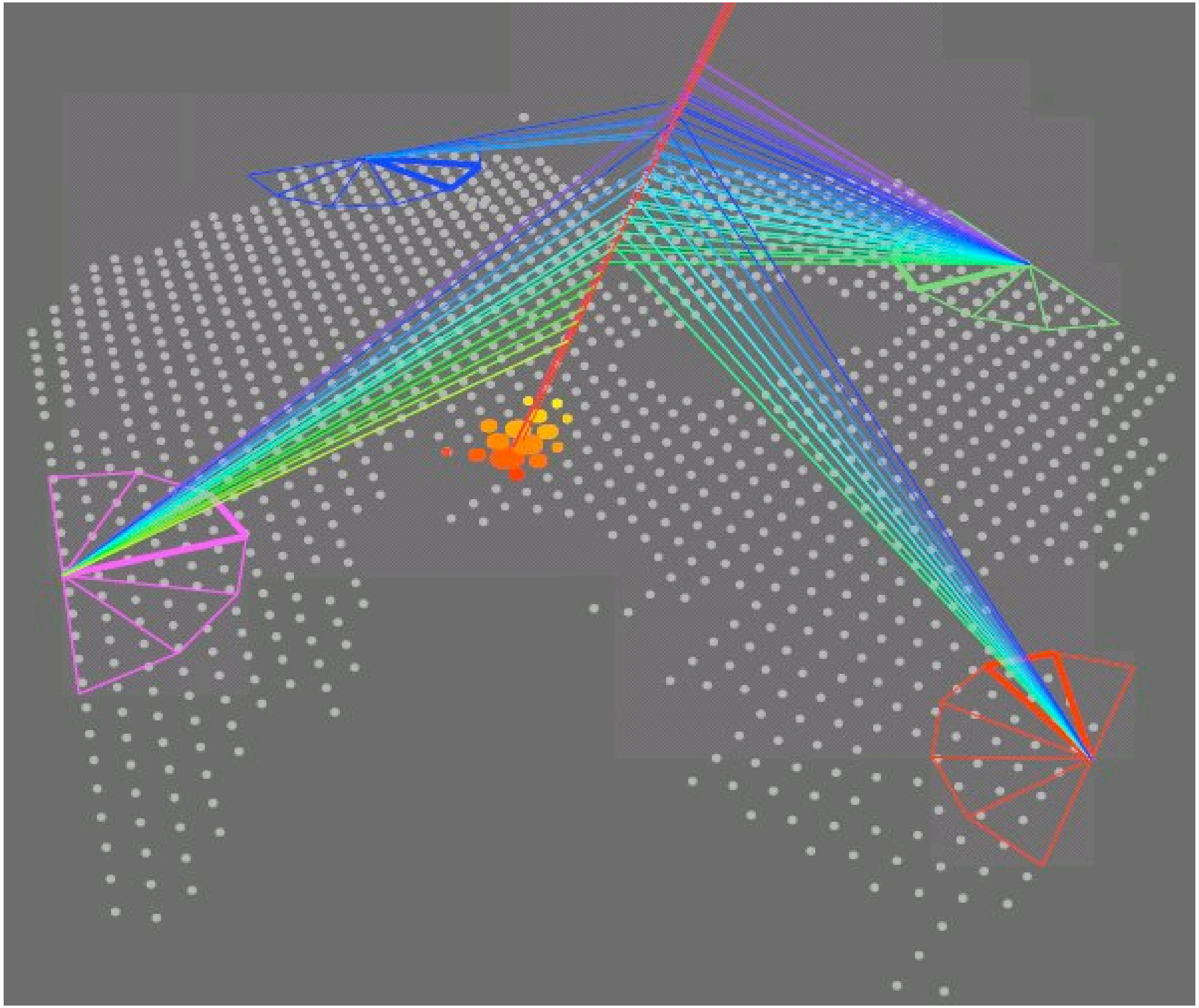
**aerosol content measured**

**track length > 350 g cm$^{-2}$**

**Cherenkov contamination <10%**

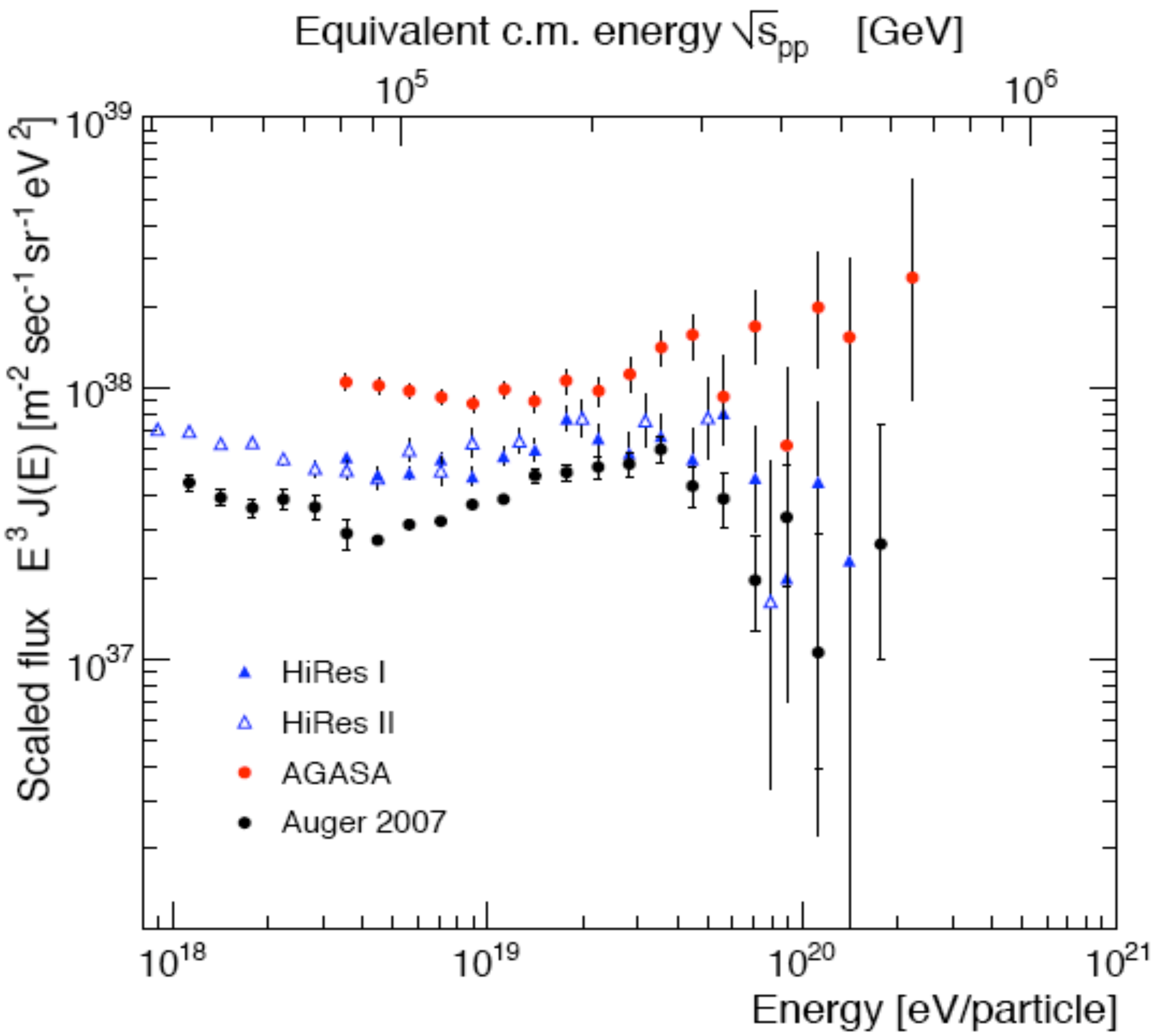


Auger is a *hybrid* detector, combining the advantages of both techniques

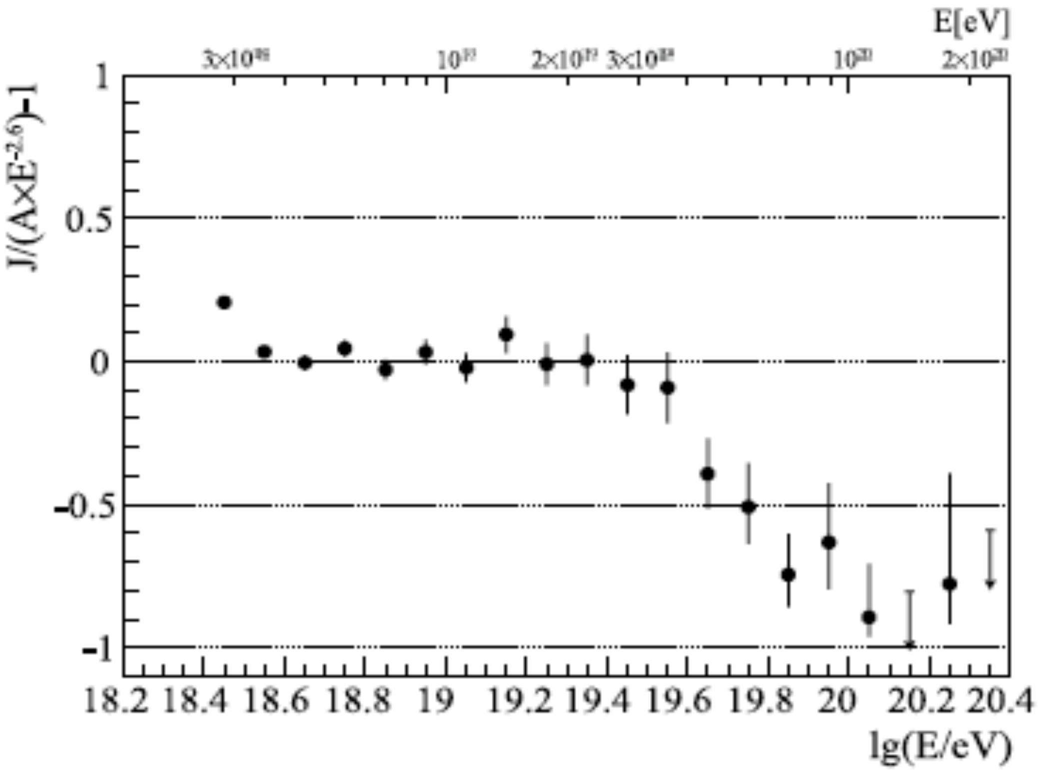


10 May 2007, E ~ $10^{10}$ GeV

# Auger has resolved the puzzle… the flux *is* suppressed beyond $E_{GZK}$



## Need more statistics to establish that this *is* the GZK cutoff




### flux suppression

- clear $6\sigma$ effect
- $E_{\mathrm{cut}}$ corresponding to predicted GZK-cutoff

$$p + \gamma_{2.7\mathrm{K}} \longrightarrow \Delta^+(1232) \longrightarrow p + \pi^0$$

# The "guaranteed" cosmogenic neutrino flux

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

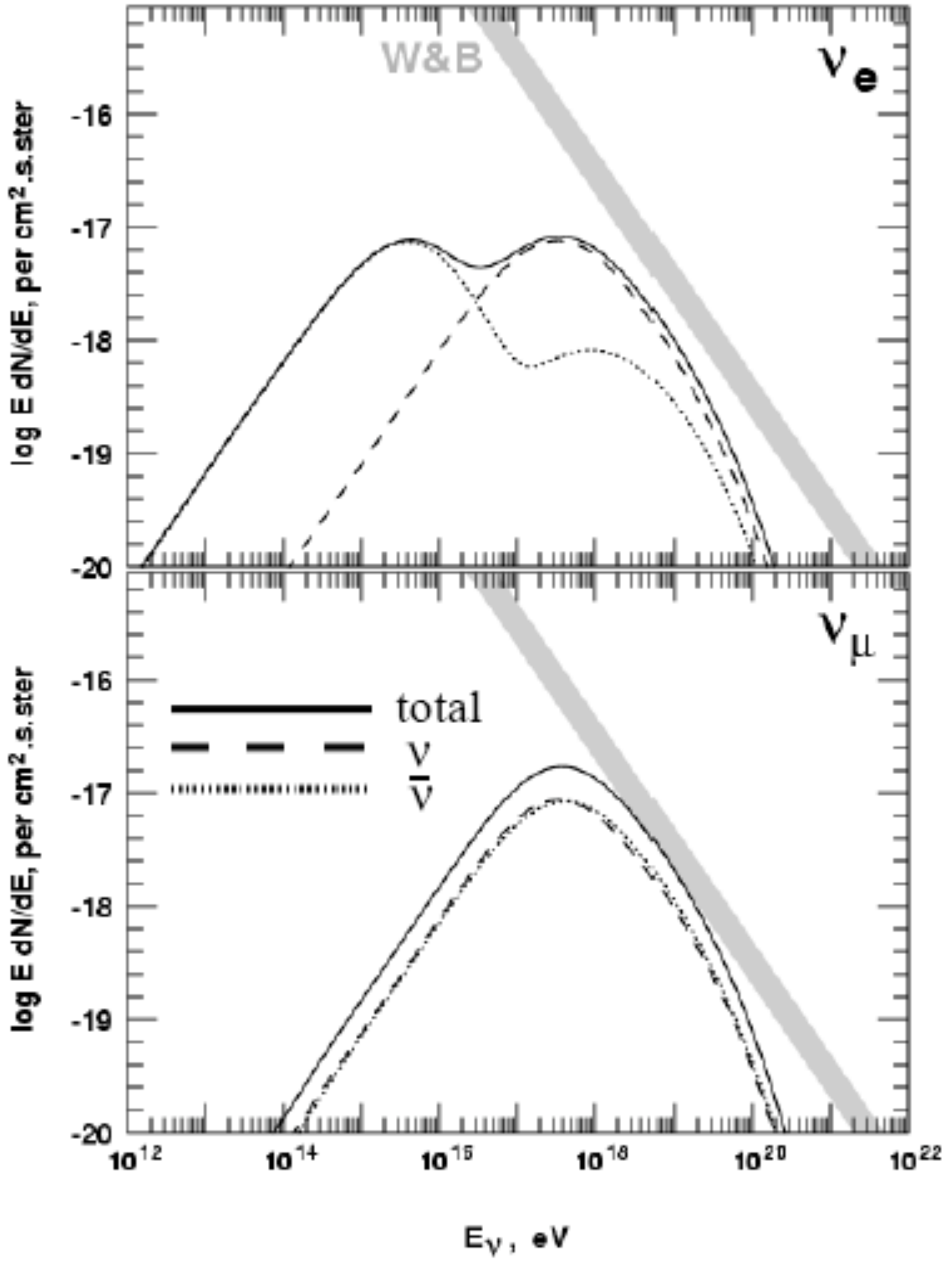
- Uncertainties in flux calculations :
  - UHECR luminosity; $\rho_{CR}(\text{local}) \neq \langle\rho_{CR}\rangle$
  - injection spectrum
  - cosmological evolution of sources
  - IRB & optical density of sources

➡But what if the primaries are heavy nuclei?

… boosts $\nu_e$ flux but can suppress the $\nu_\mu$ flux

Hooper *et al* (2004); Anchordoqui *et al* (2007)

Engel, Seckel, Stanev (2001)



# The sources of cosmic rays *must* also be neutrino sources

Waxman-Bahcall Bound :

- $1/E^2$ 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

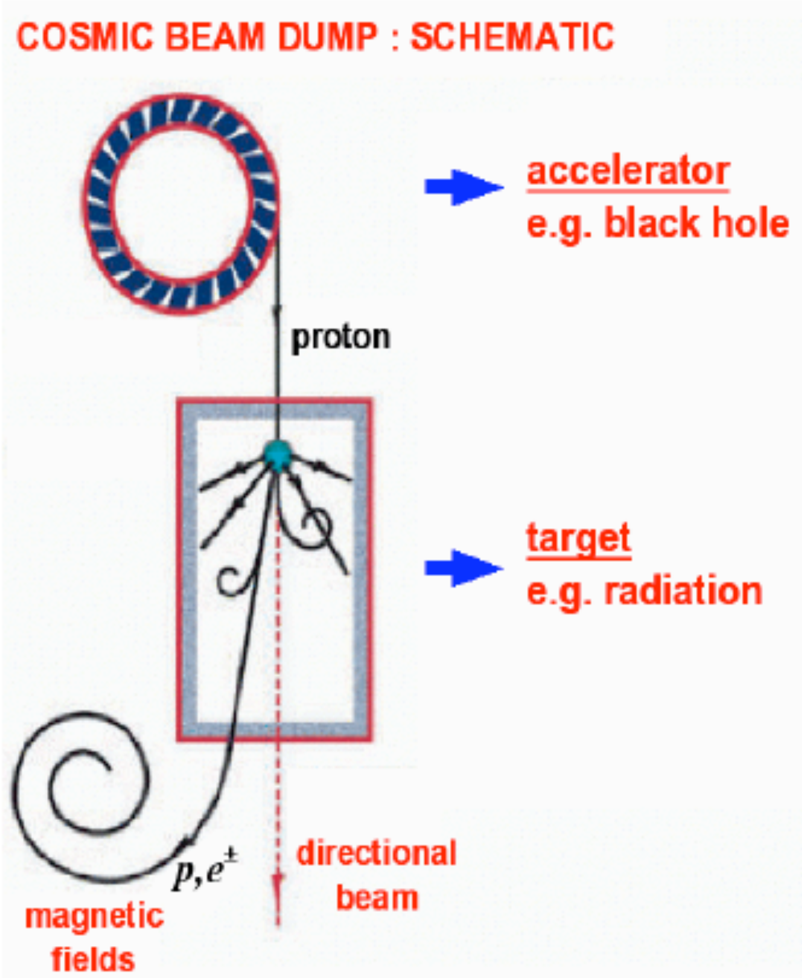
Hubble time

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

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

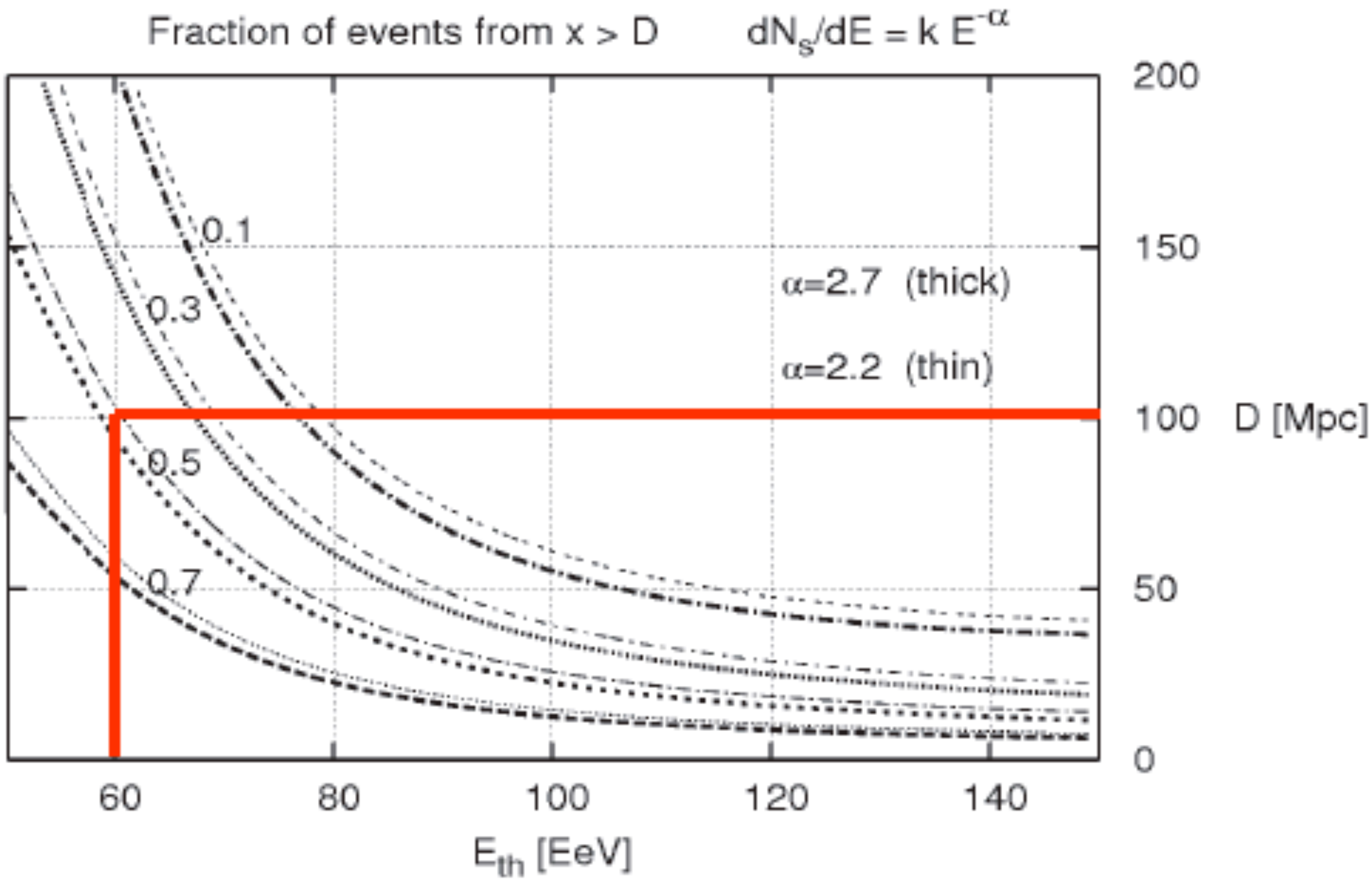
➡Making a reasonable assumption about ϵ allows this to be coverted into a flux prediction

(would be higher if extragalactic cosmic rays become dominant at energies below the 'ankle' )

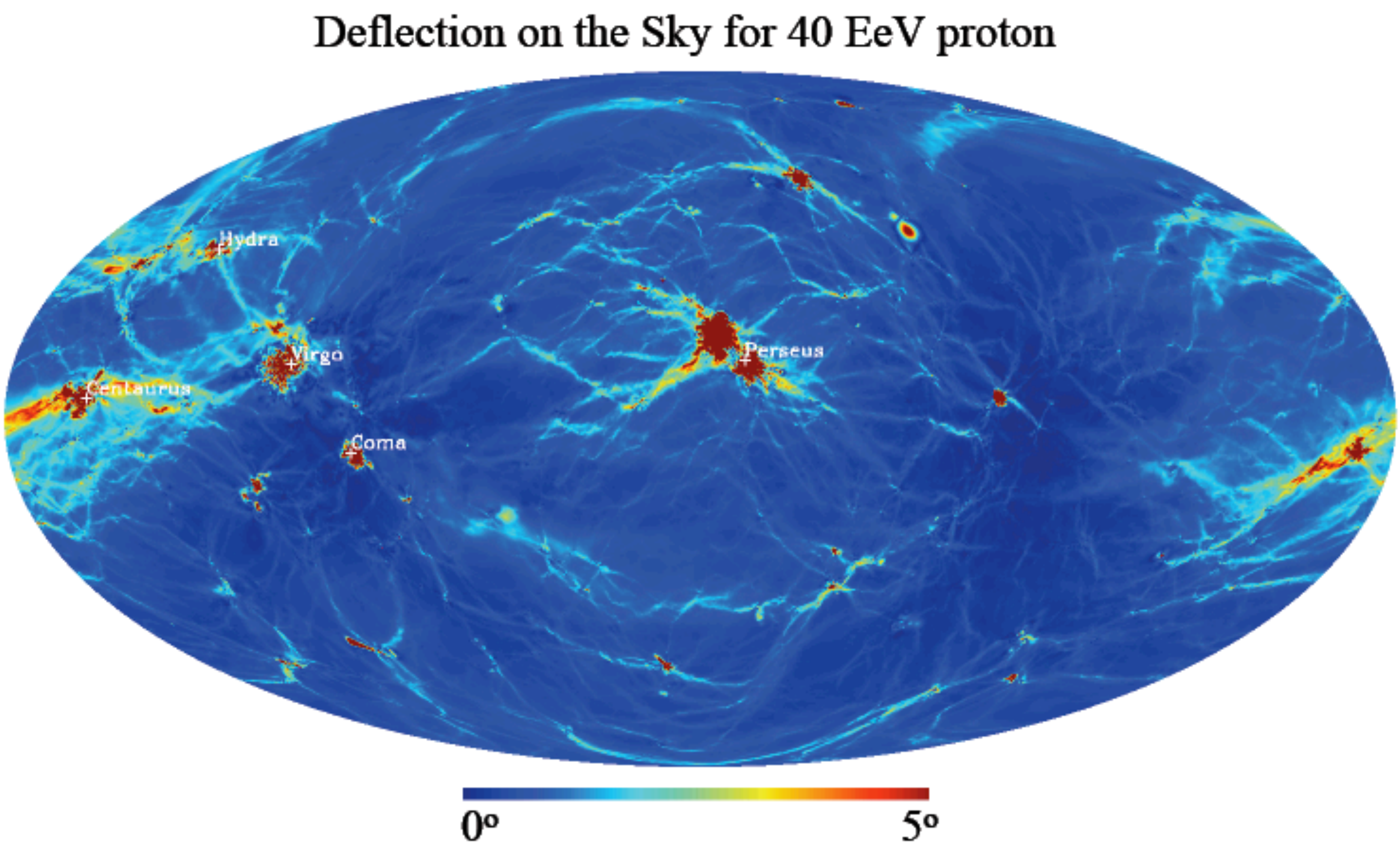



(courtesey: Dave Waters)

At these high energies the sources must be *nearby* … within the 'GZK horizon'



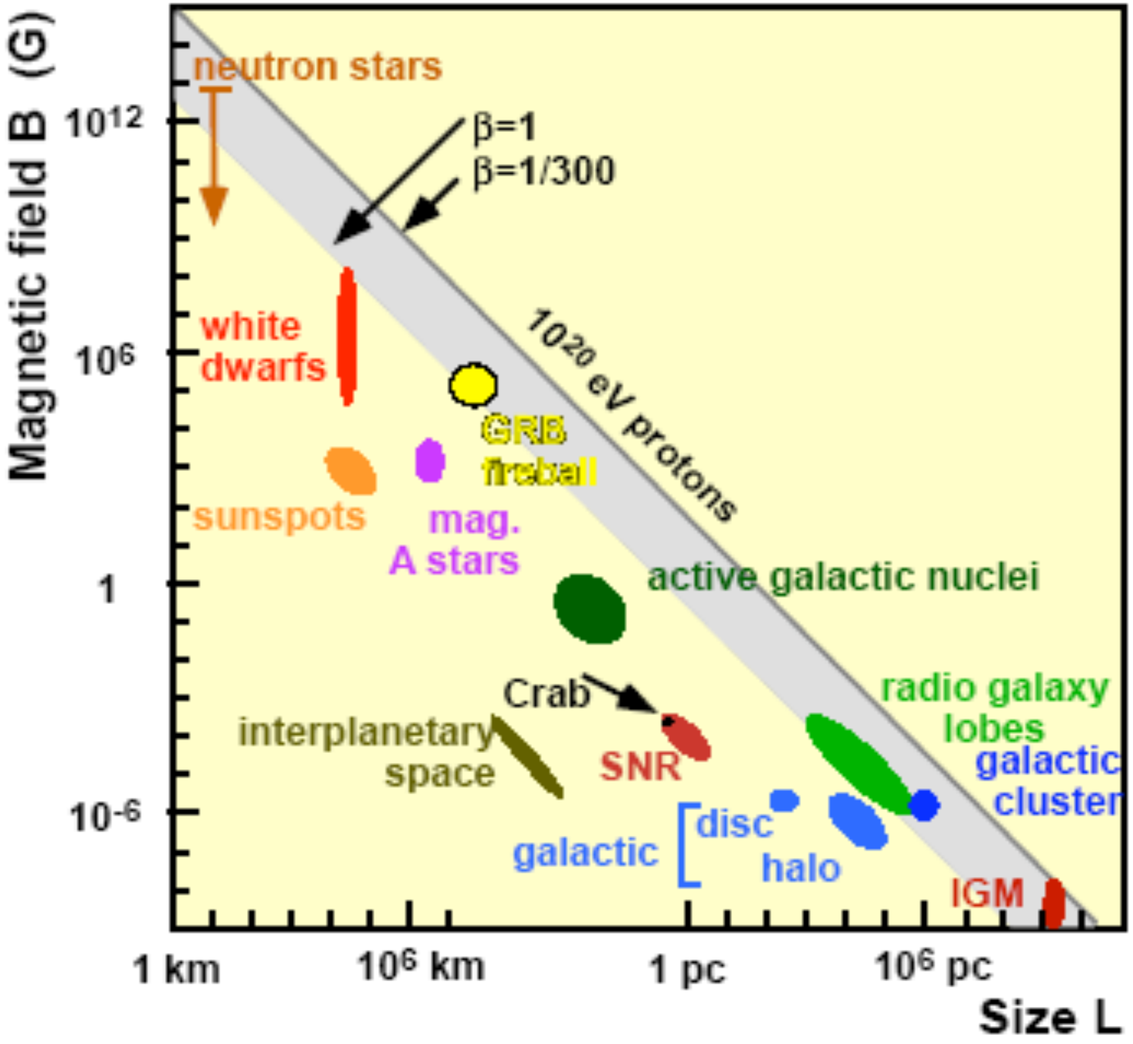
# … and the observed UHECRs should point back to the sources




‘Constrained’ simulation of local large-scale structure including magnetic fields shows that deflections are small, except in the cores of rich galaxy clusters

Dolag, Grasso, Springel & Tkachev (2003)

## Are there any plausible cosmic accelerators for such enormous energies?




A.M. Hillas 1984

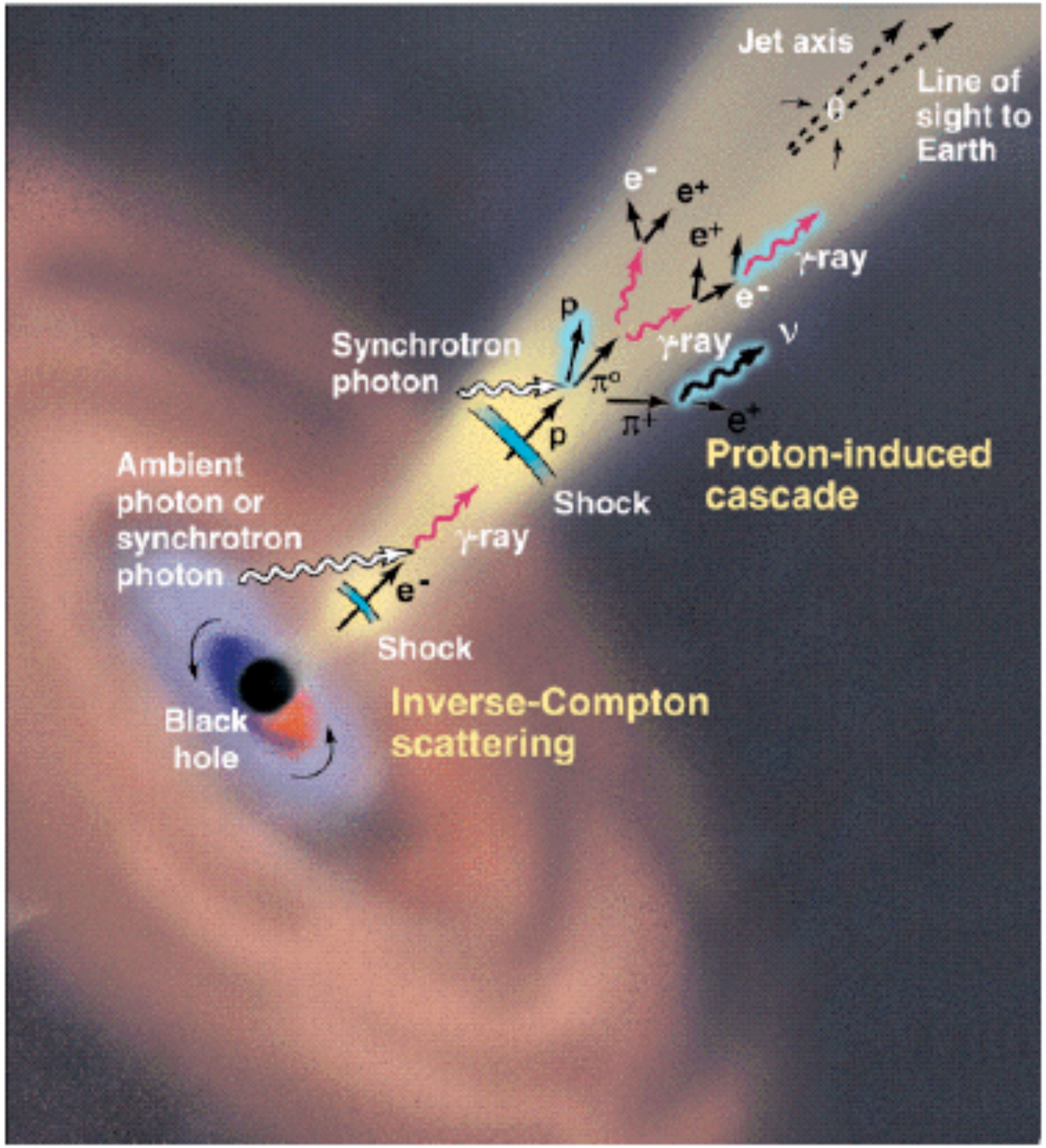
$B_{\mu G} \times L_{kpc} > 2\, E_{EeV} / Z$

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

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.

**Whatever they are, the observed UHECRs should point back to them …**




# 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.

**TeV γ-rays seen from AGN , however no direct evidence so far that *protons* are actually accelerated in such objects**

► No UHECRs pointed back to nearby active galaxies like M87 or Cen A

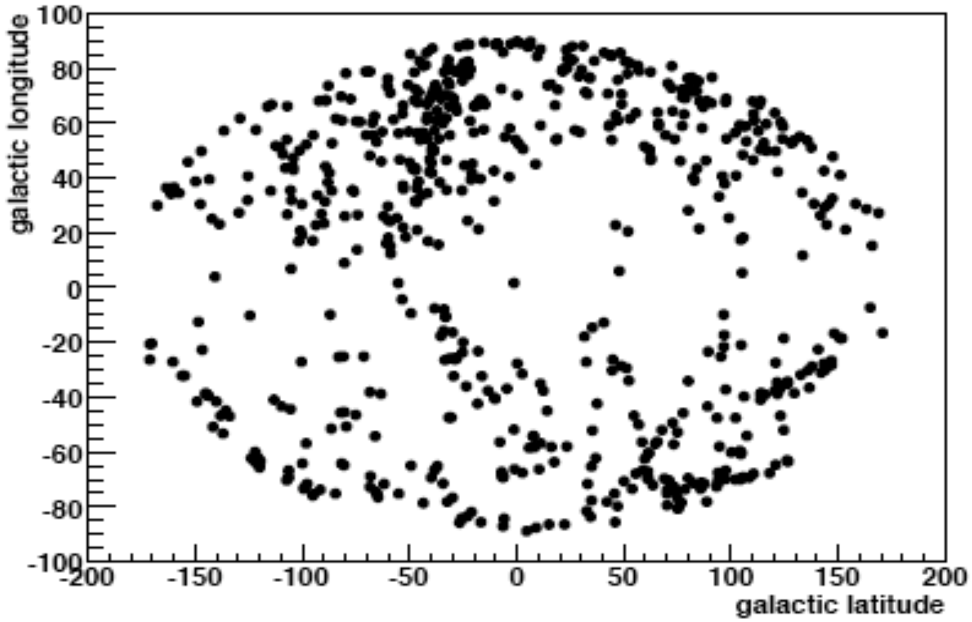
► Neutrinos not detected from AGN (during 'orphan flare' in 1ES1959+650?)

# AGN catalogue

Véron-Cetty / Véron, 12th Edition, 2006

assumption: catalogue is complete and homogenous at small distances ($R < 100\ \mathrm{Mpc}$) and outside the galactic plane

AGNs $z \leq 0.024 \quad \longrightarrow \quad$ 694 AGN; 472 in Auger-FOV



# searching the UHECR sources

## basic ideas + assumptions

- search correlation between UHECR arrival directions and source catalogue
- GZK flux suppression $\longrightarrow$ only nearby sources can contribute at highest energies
- magnetic deflection small at highest energies

---

## technique

- Auger events + Véron-Cetty / Véron AGN catalogue
- scan max. source distance $z$
- scan min. UHECR energy $E_{\mathrm{thr}}$
- scan max. angular window around sources $\Delta_{\Omega}$

## Statistics

### chance probability $P_{\rm iso}$

- probability for UHECR from isotropic sources to *correlate* with AGN

- larger source distance $\rightarrow$ more sources $\rightarrow$ higher $P_{\rm iso}$
- larger $\Delta_\Omega$ $\rightarrow$ larger sky coverage $\rightarrow$ higher $P_{\rm iso}$
- Auger sky coverage not uniform

- $P_{\rm iso}(z = 0.018, \Delta_\Omega = 3.1^\circ) \approx 21\%$

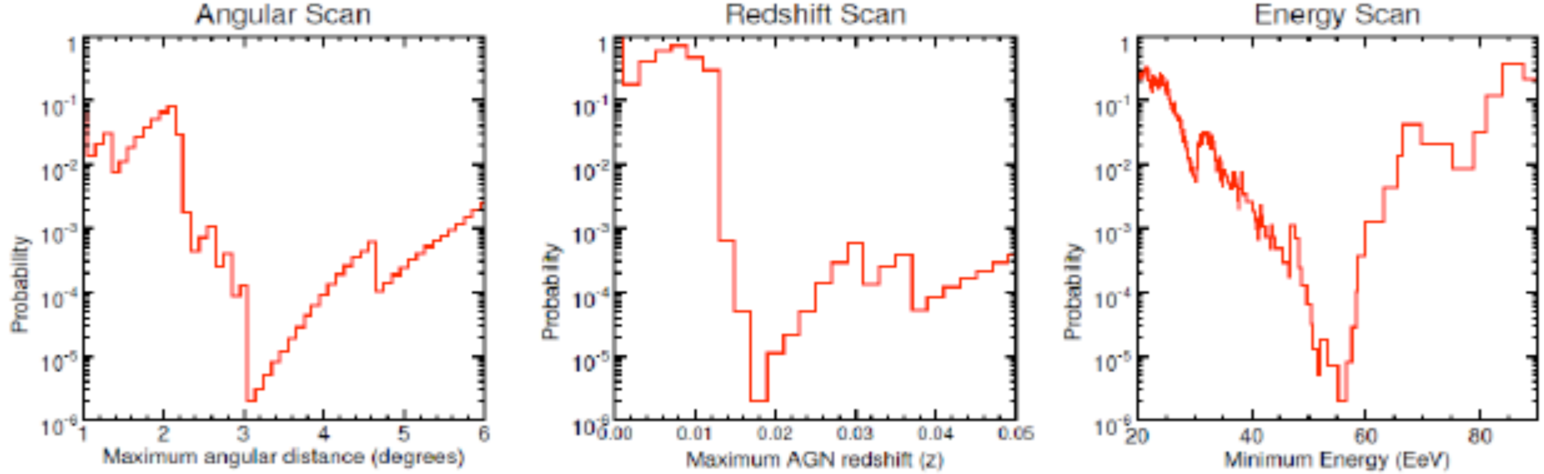
---

### Binomial probability to have $N_{\rm cor}$ or more correlating events given an isotropic distribution of $N_{\rm sel}$ events

$$P(N_{\rm cor}|N_{\rm sel}, P_{\rm iso}) = \sum_{n=N_{\rm cor}}^{N_{\rm sel}} \binom{N_{\rm sel}}{n} \cdot P_{\rm iso}^n \cdot (1 - P_{\rm iso})^{N_{\rm sel}-n}$$

# UHECR:AGN correlation scan

## internal Auger note 06/2006 $\longrightarrow$ prescription




## Prescription parameters

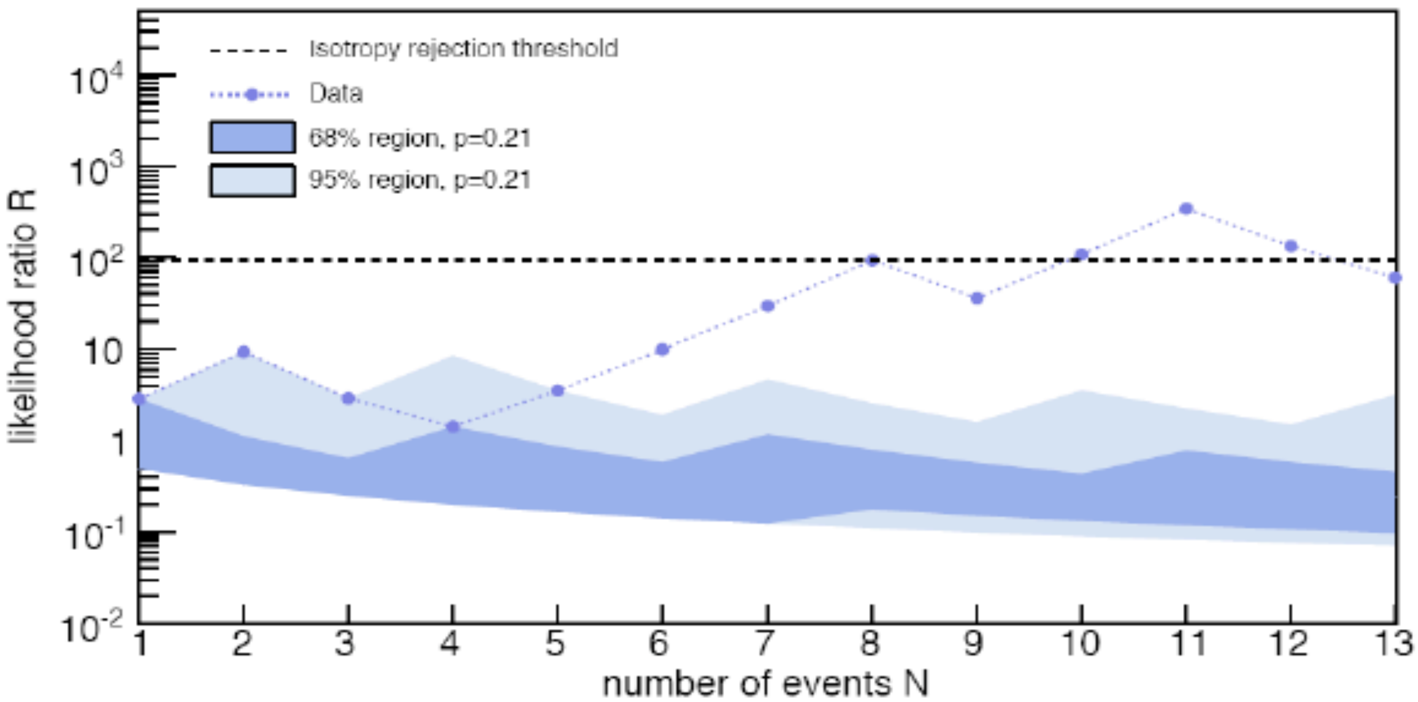
- CDAS v4r4 reconstructed energy $\geq 56\ \mathrm{EeV}$
- CDAS v4r4 reconstructed zenith $\leq 60^\circ$
- ICRC-2005-T5

- Veron/Veron-Cetty AGN catalogue (12th edition)
- $\mathrm{z} \leq 0.018$
- $\Delta_\Omega(\mathrm{CR} : \mathrm{AGN}) \leq 3.1^\circ$

# Signal confirmation

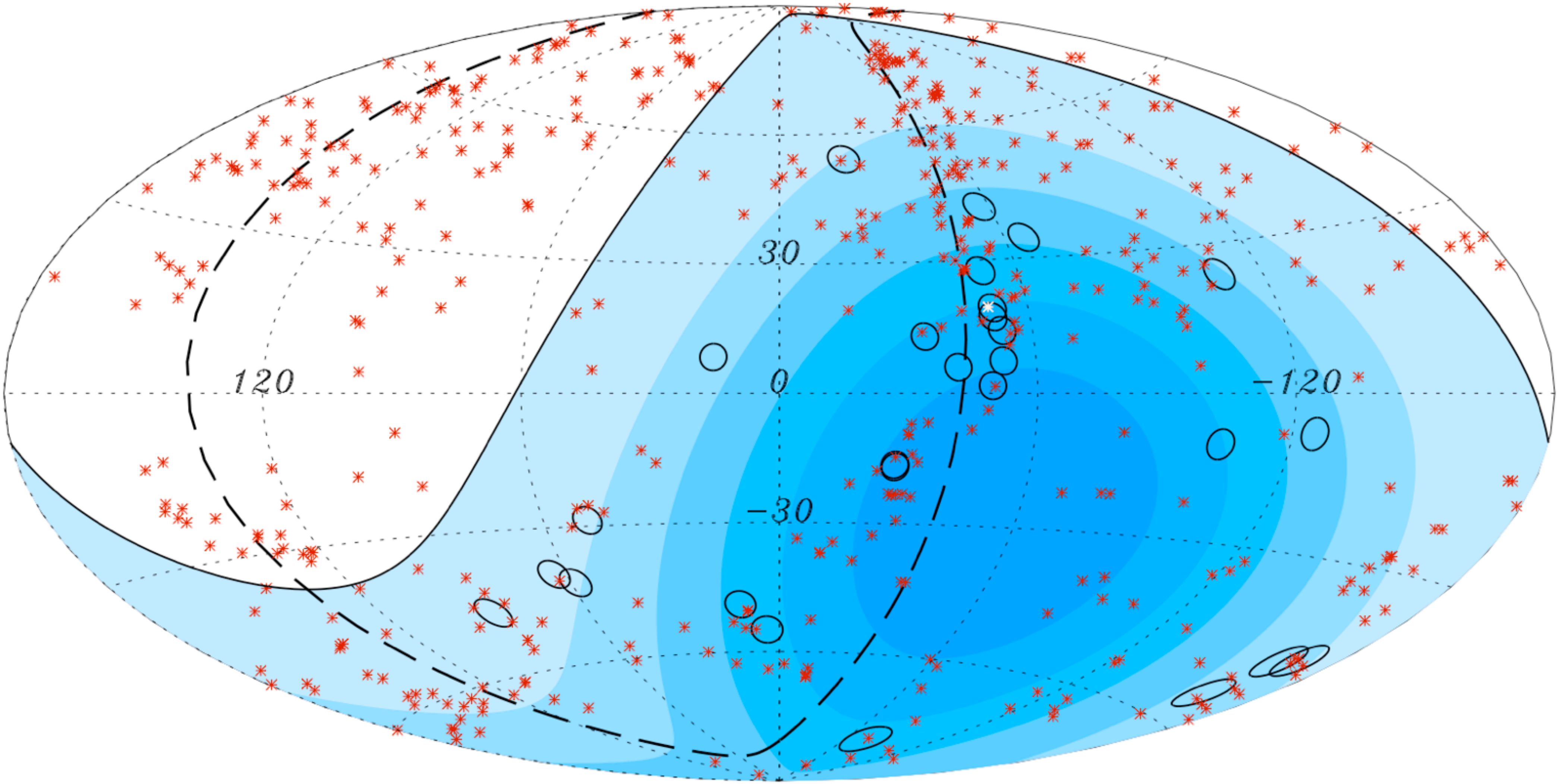
## new dataset

- 06/2006 - 08/2007 (additional ≈ 500.000 events)
- prescribed confidence level 99%
- 8 out of 13 events correlate (2.7 expected)




Chance probability for an isotropic distribution = $1.7 \times 10^{-3}$

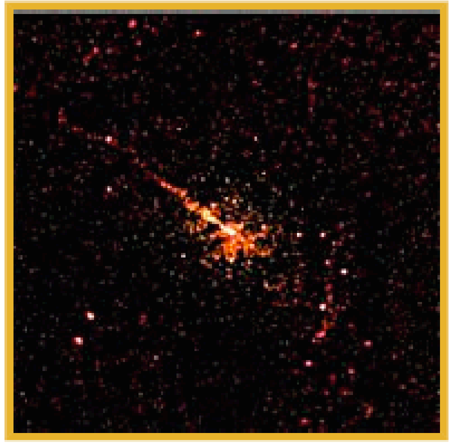
# We are beginning to glimpse a new sky - the universe at ultrahigh energies



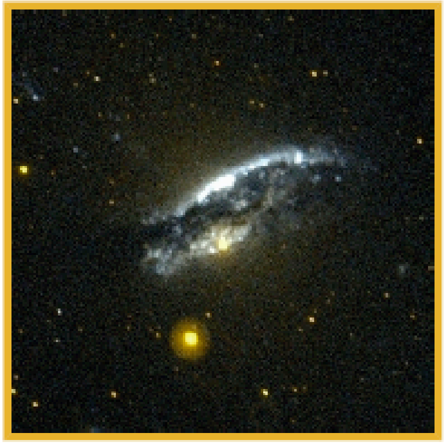

Auger is ~doubling statistics every year - we will soon know the sources of UHE νs

# Centaurus A – Peculiar Galaxy

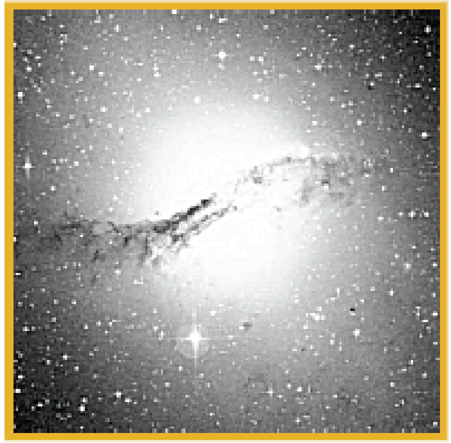
Distance: 11,000,000 ly light-years (3.4 Mpc) | Image Size = 15 x 14 arcmin | Visual Magnitude = 7.0



X-Ray: Chandra

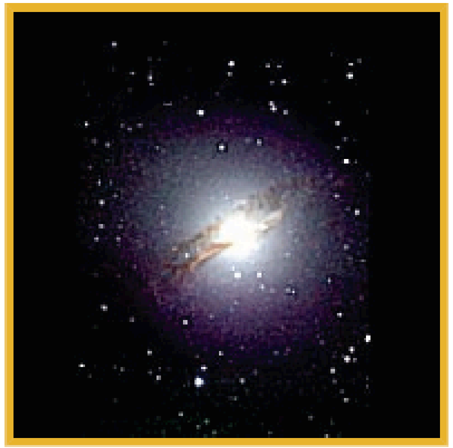


Ultraviolet: GALEX



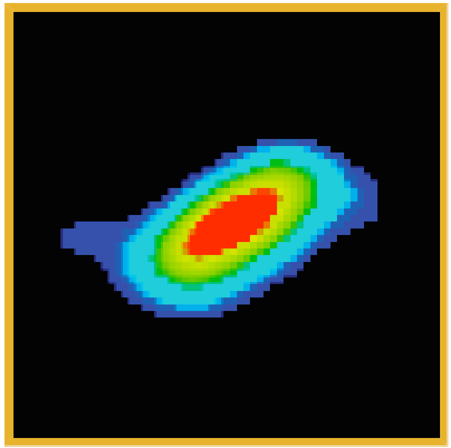
Visible: DSS

Visible: Color ©AAO

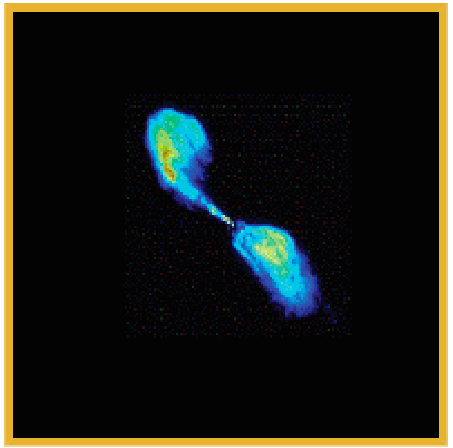


Near-Infrared: 2MASS

Mid-Infrared: Spitzer



Far-Infrared: IRAS



Radio: VLA

*"The only real voyage consists not in seeking new landscapes, but in having new eyes"*

Marcel Proust

# Where there are high energy cosmic rays, there *must* also be neutrinos …

**GZK interactions of extragalactic UHECRs on the CMB**

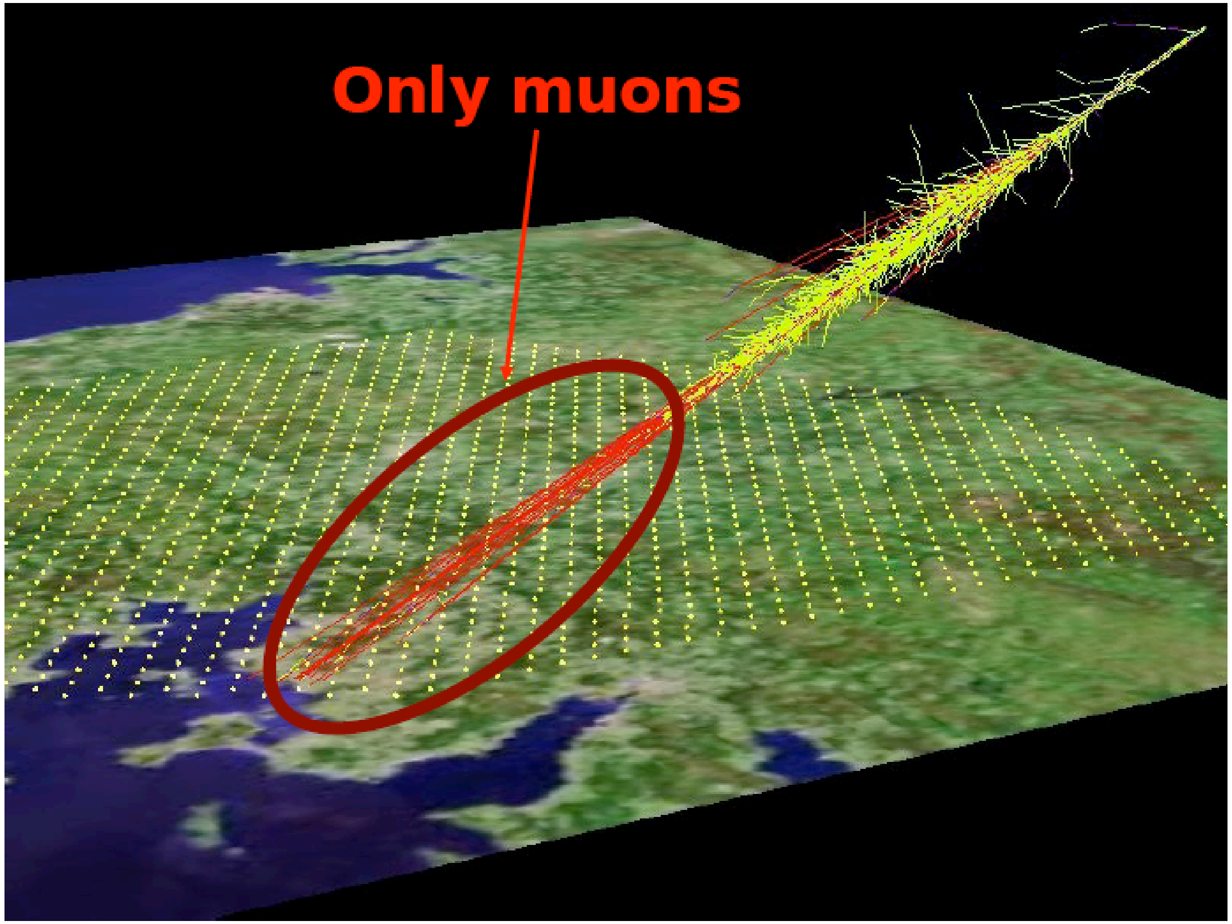
(“guaranteed” cosmogenic neutrino flux … but may be altered significantly if the primaries are heavy nuclei rather than protons)

**UHECR candidate accelerators (γ-ray bursts, active galactic nuclei, micro-quasars, …)**

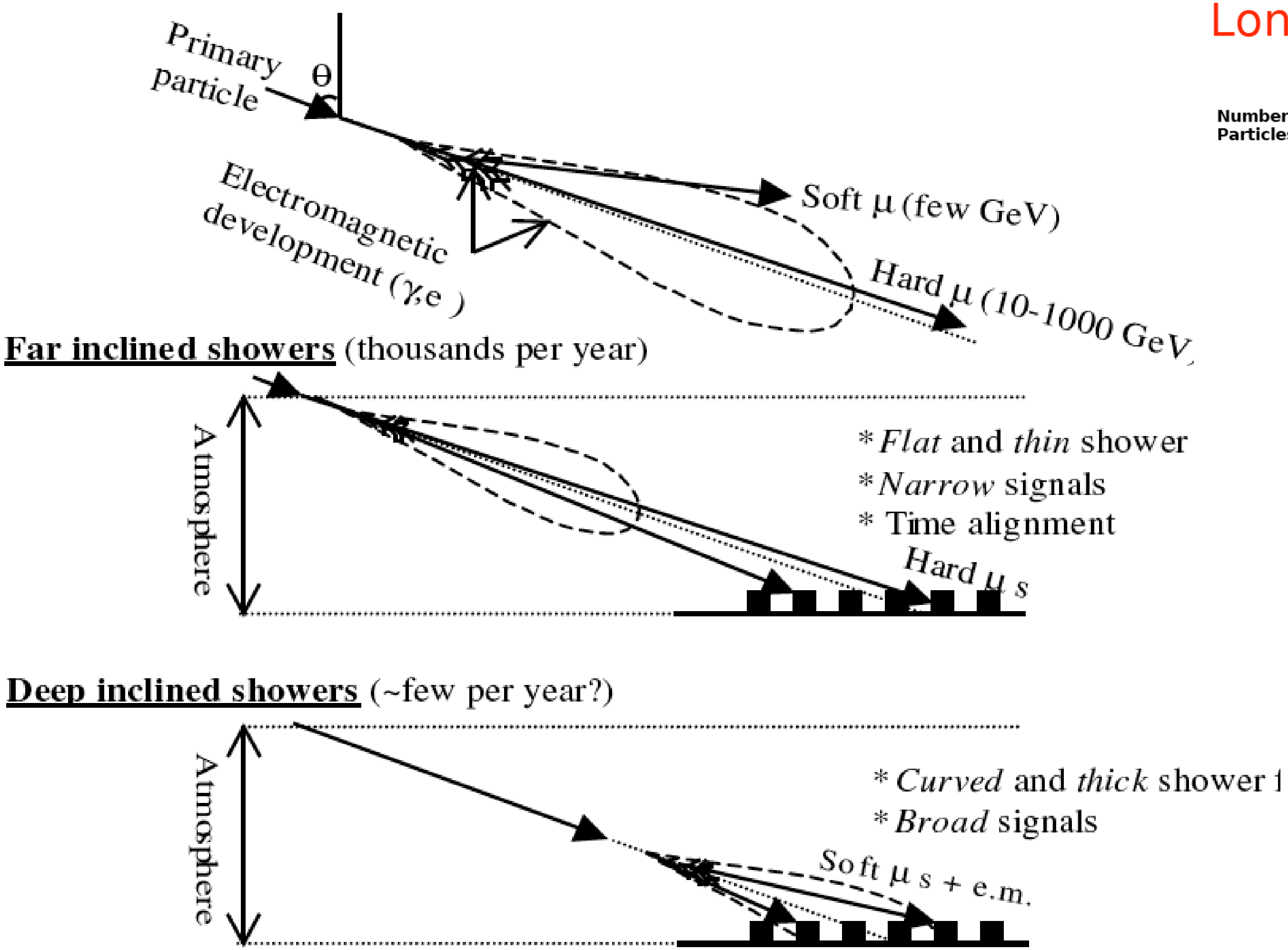
(“Waxman-Bahcall flux” - normalised to extragalactic UHECR flux … sensitive to ‘cross-over energy’ above which they dominate)

## Need *multi*-km$^3$ detectors for physics studies

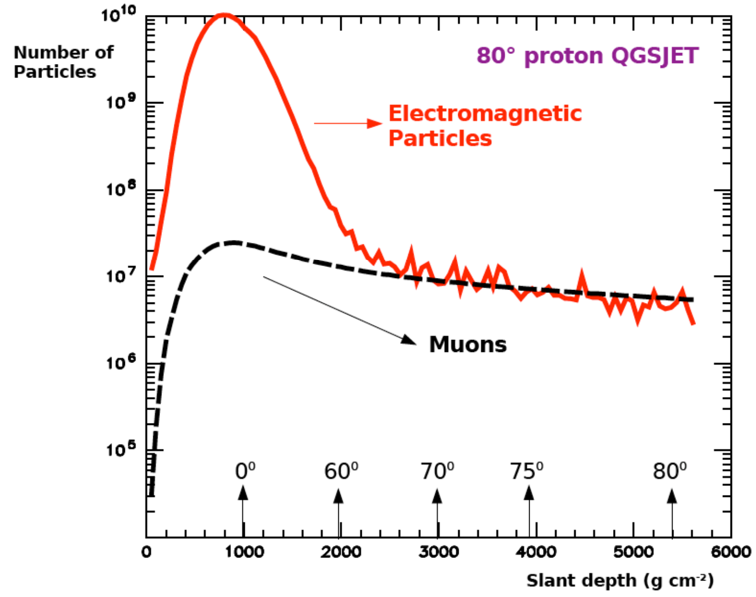
# Can UHE neutrinos be detected with air shower arrays?

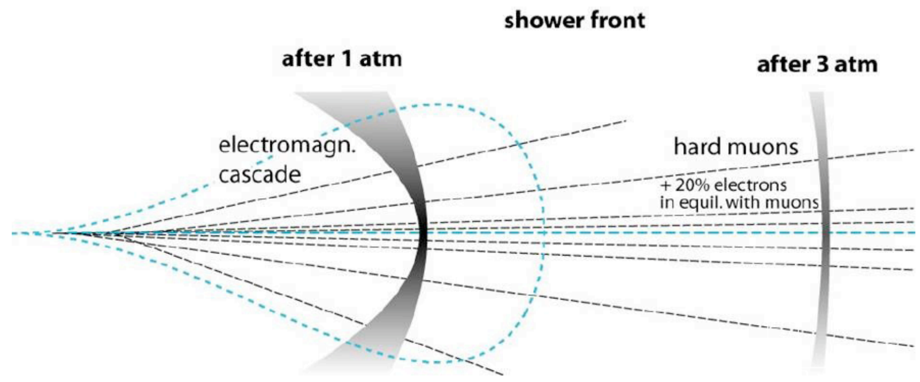



In ‘horizontal’ air showers, only muons can survive absorption by the atmosphere
***… if an em component is seen, the primary particle must be a neutrino***




## Longitudinal Shower development



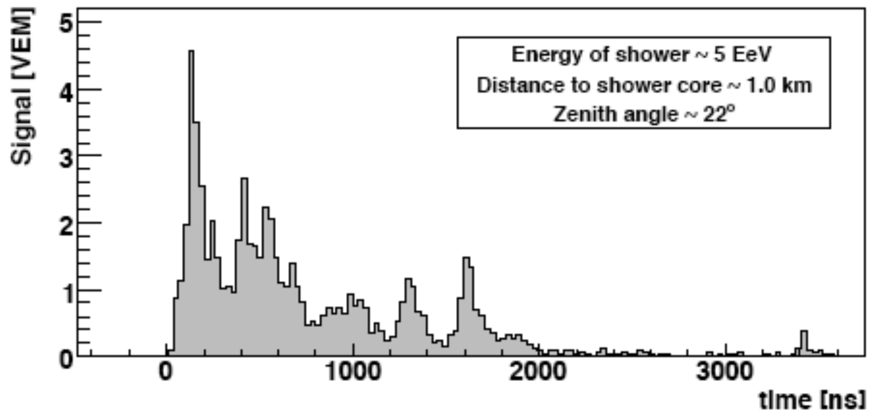




- Wide time distribution
- Strong curvature
- Steep lateral distribution

- Narrow time distribution
- Weak curvature
- Flat lateral distribution

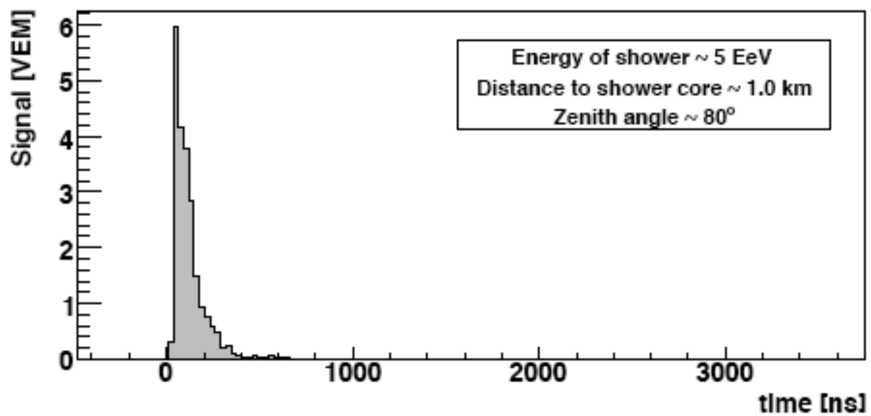
**We see many ‘young’ vertical showers and quite a few ‘old’ horizontal showers … if we see a ‘young’ horizontal shower it can *only be due to a neutrino***

# FADC traces at 1 km from the shower core for $5x10^{18}$ eV showers



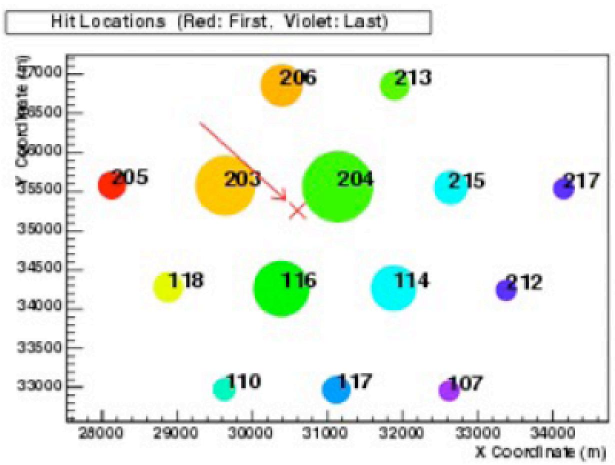

***Vertical shower***

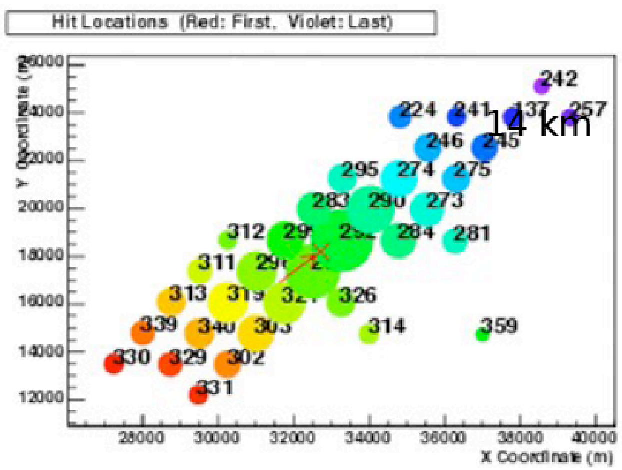
**EM component**



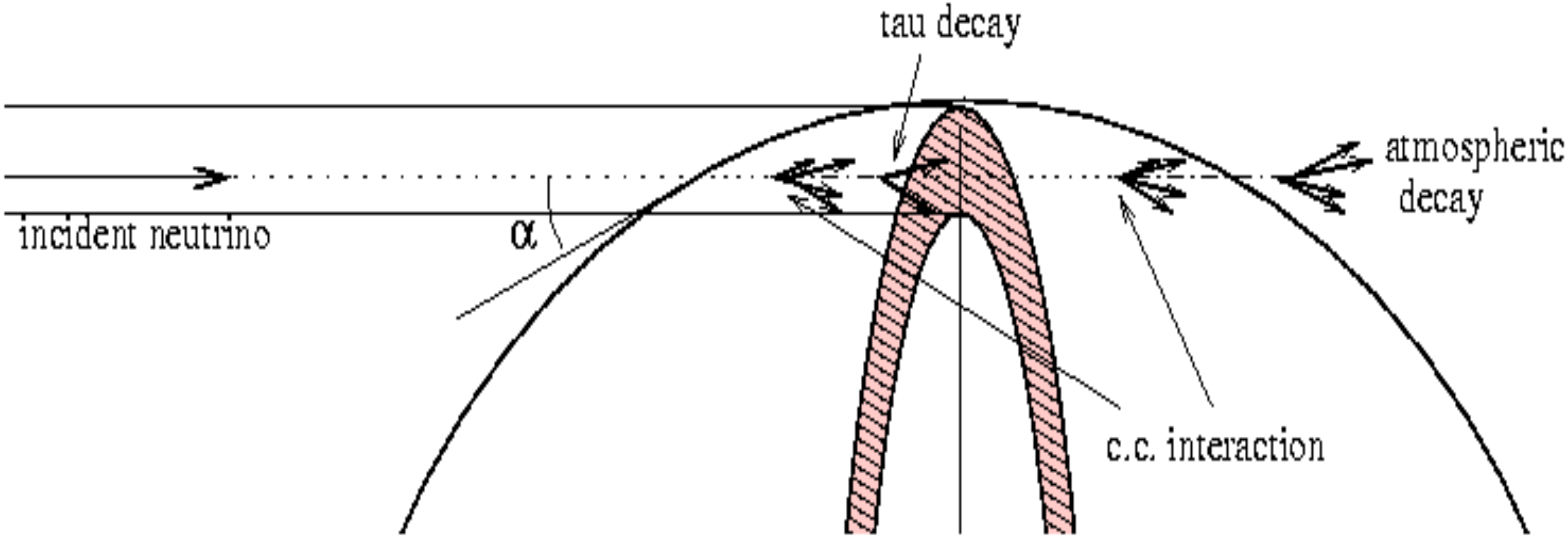

***Horizontal shower***

**Only muon signal**



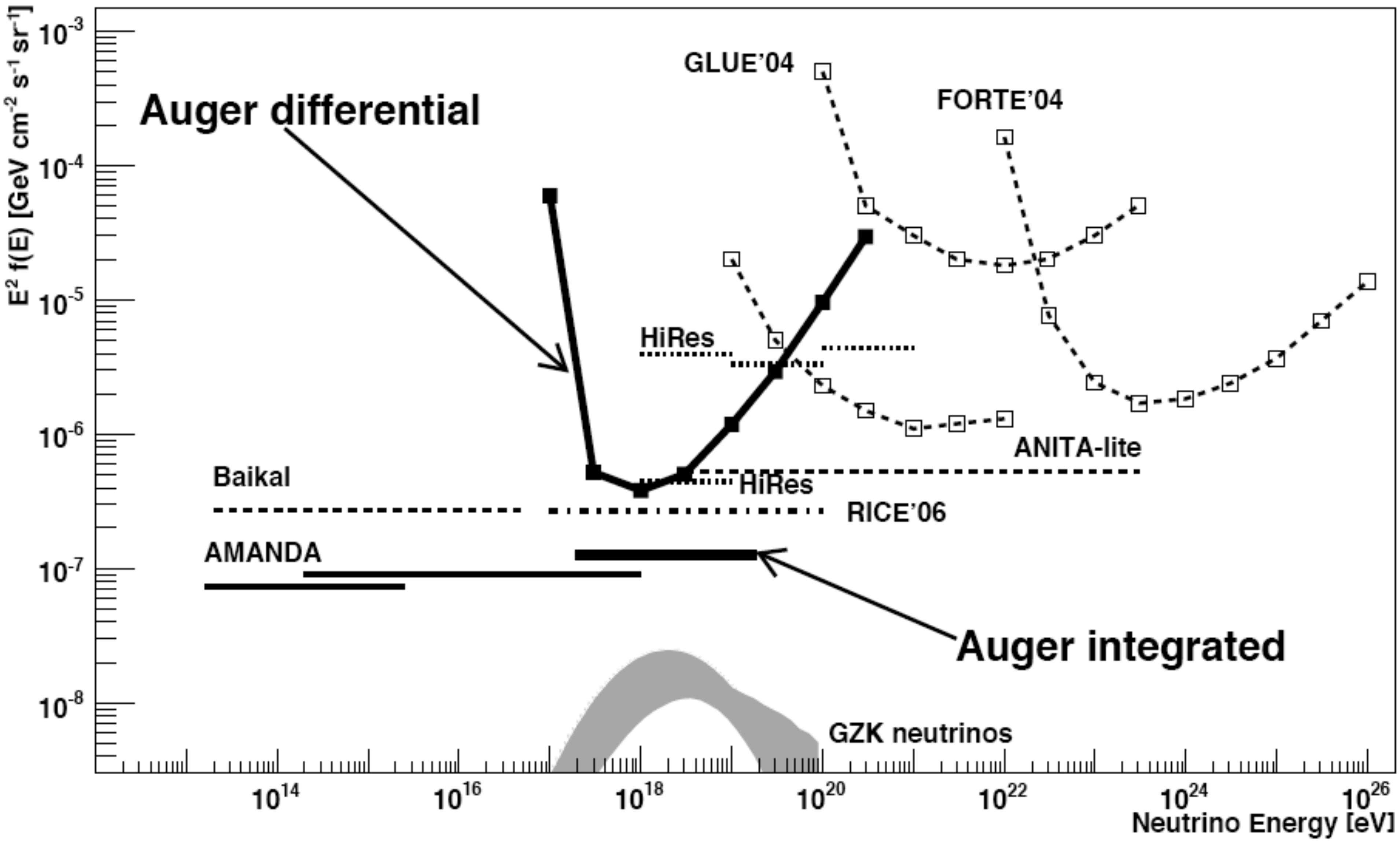



Auger can also see Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower




The rate of quasi-horizontal events is proportional to the cosmic neutrino flux *and* to the ν-N #-secn

The rate of Earth-skimming events is also proportional to the cosmic neutrino flux but *not* proportional to the ν-N #-secn




No neutrino events yet … but getting close to "guaranteed" cosmogenic flux

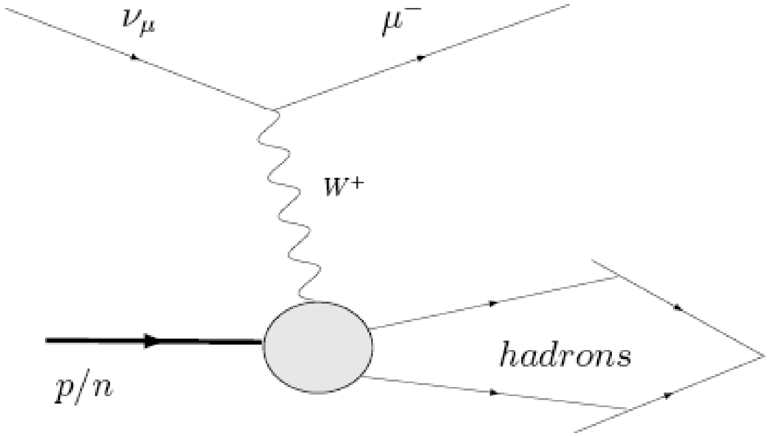
(NB: Must know ν-N cross-section at ultrahigh energies)

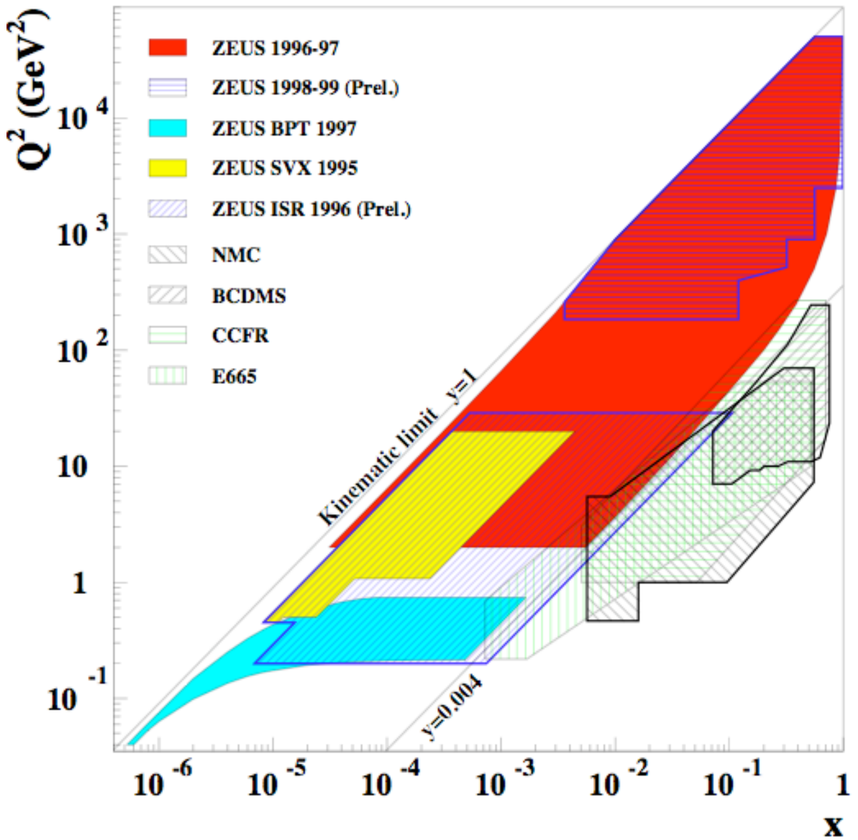
# ν-N deep inelastic scattering

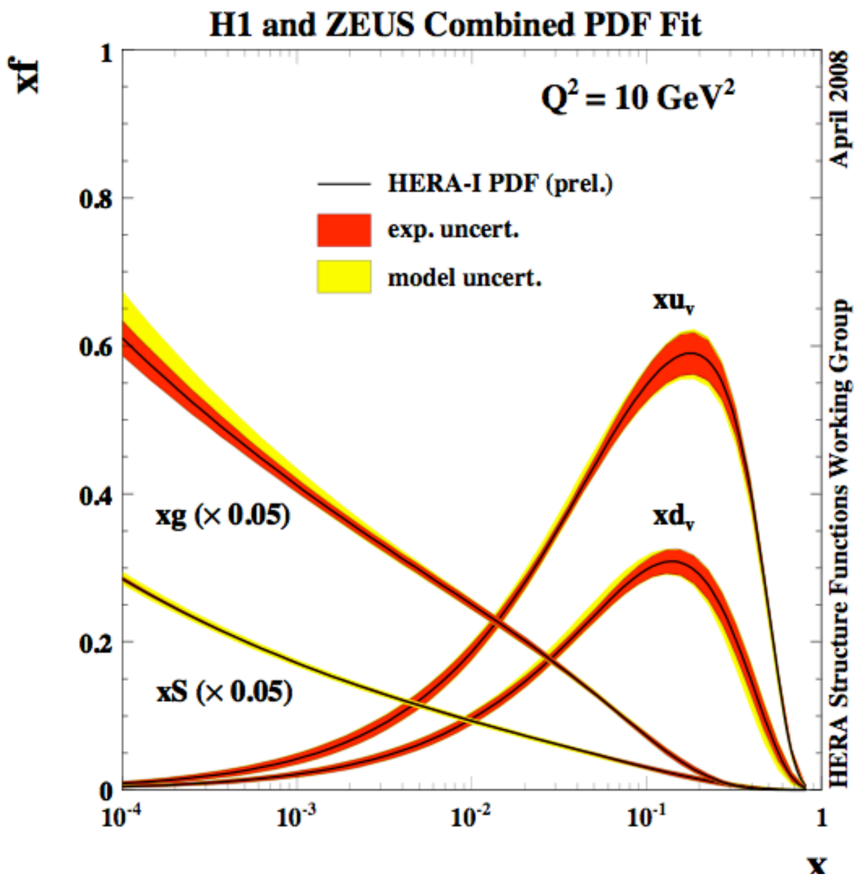
$$\frac{\partial^2 \sigma^{CC,NC}_{\nu,\bar{\nu}}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi} \left( \frac{M_i^2}{Q^2 + M_i^2} \right)$$

$$\left[\frac{1 + (1-y)^2}{2} F_2^{CC,NC}(x, Q^2) - \frac{y^2}{2} F_L^{CC,NC}(x, Q^2)\right.$$

$$\left. \pm y \left(1 - \frac{y}{2}\right) x F_3^{CC,NC}(x, Q^2)\right]$$

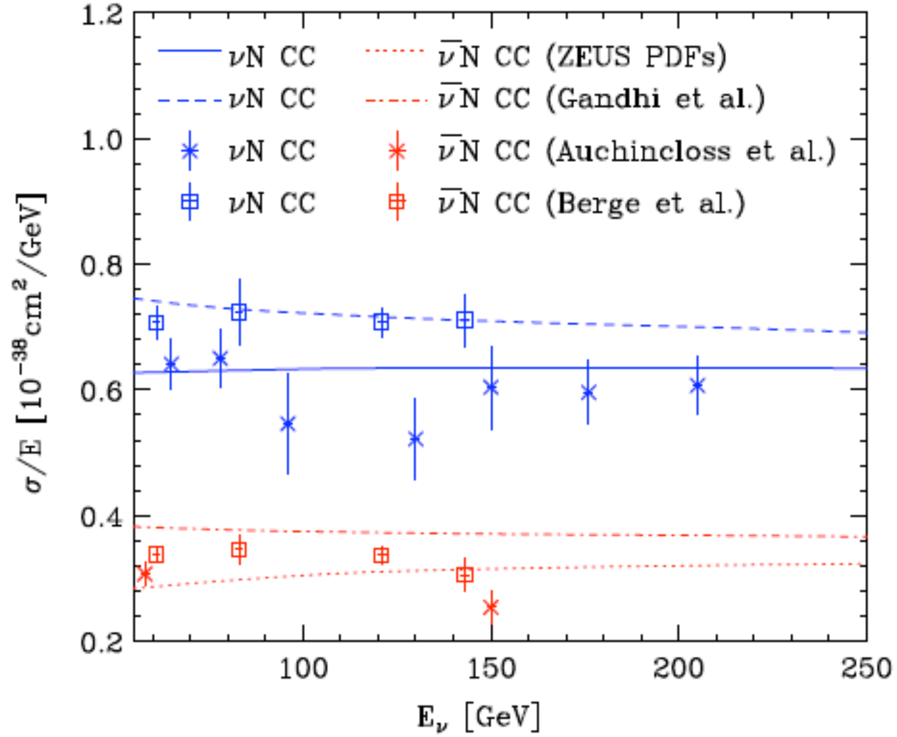


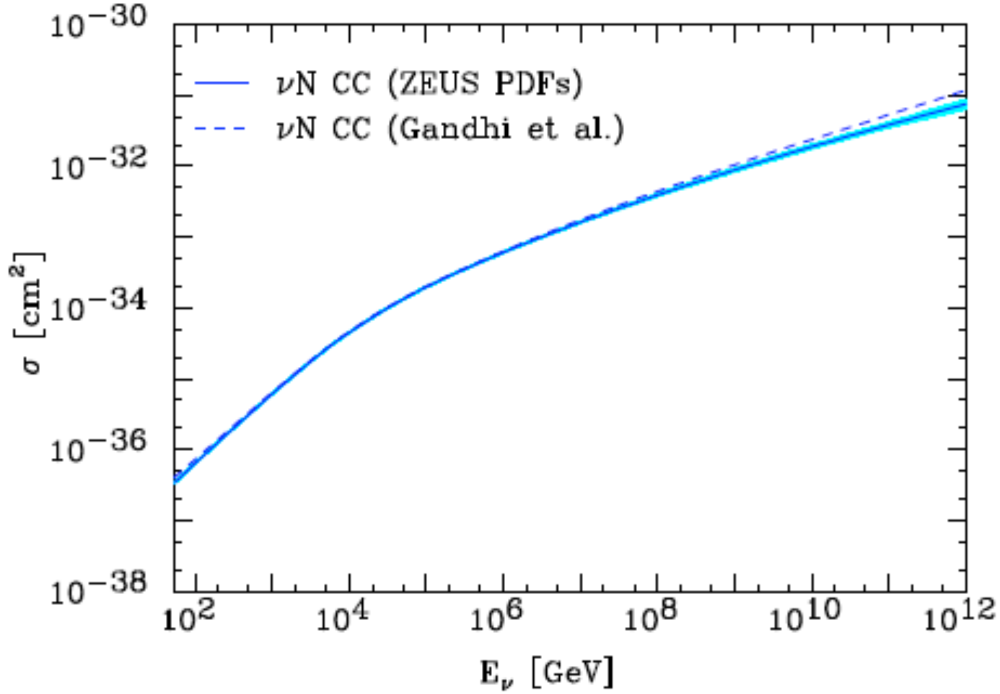



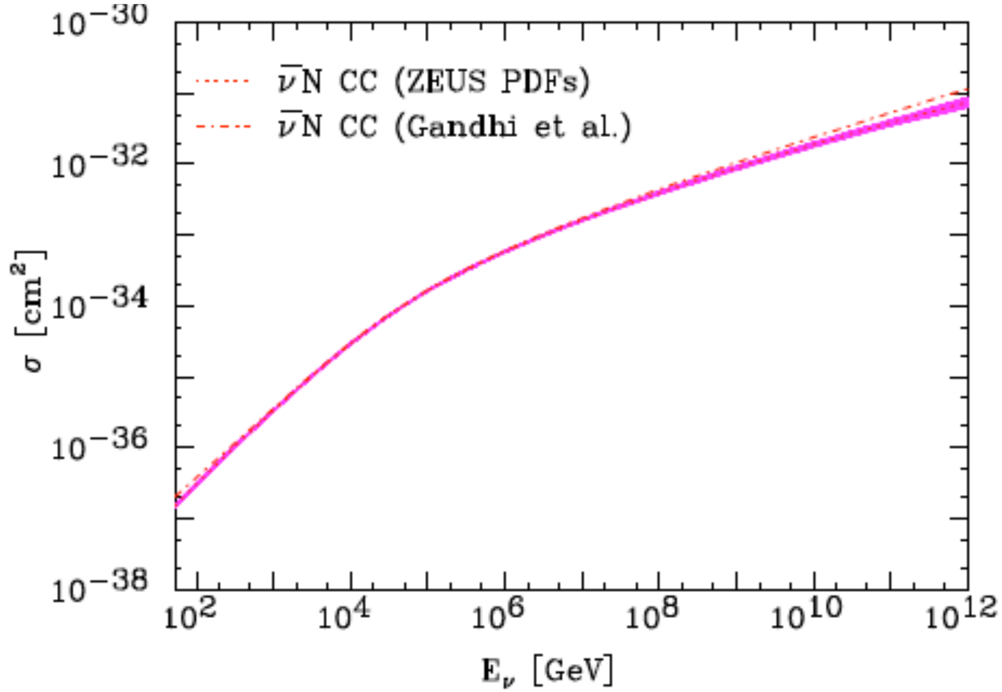



Deep inelastic e-p scattering has probed down to very low $x_{Bjorken}$ and very high $Q^2$ … necessary for predicting the UHE neutrino cross-section (in the SM) using DGLAP evolution of the PDFs @NLO

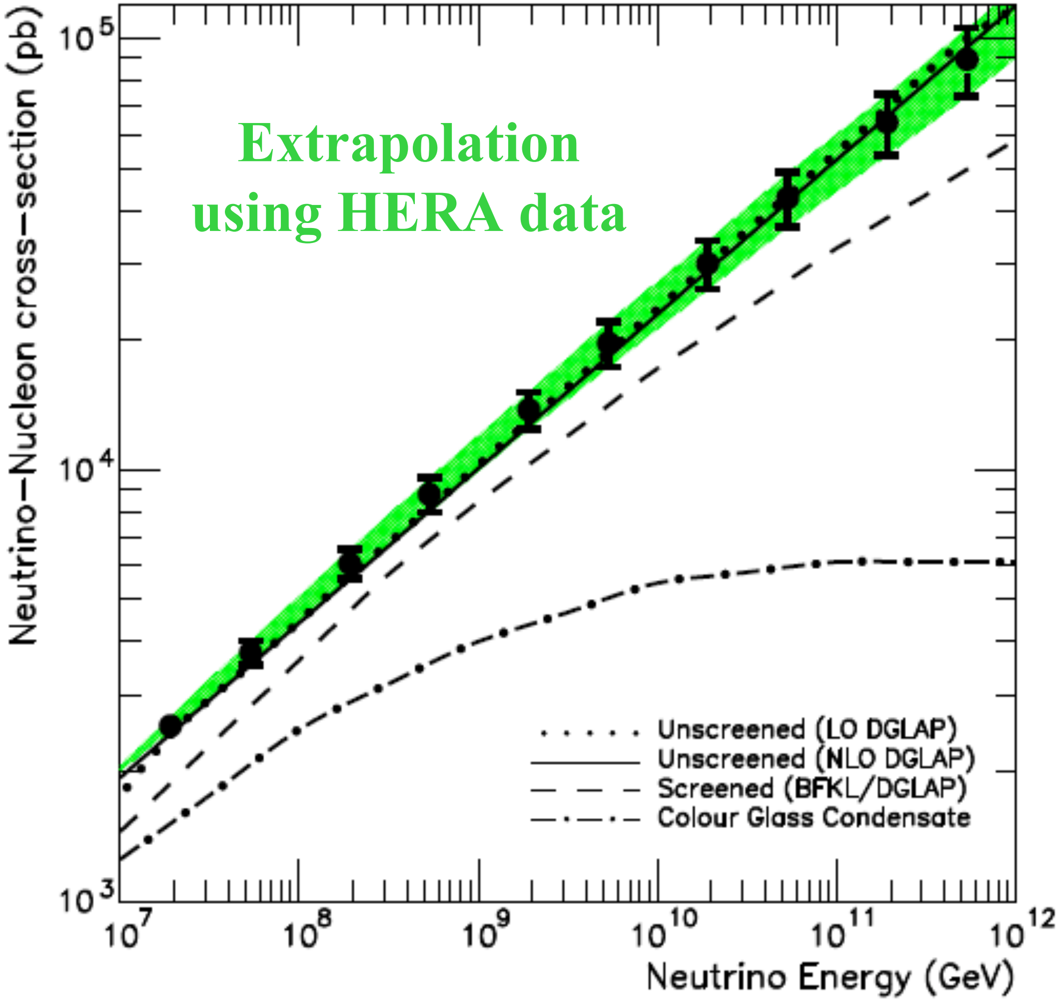
Cooper-Sarkar & Sarkar (2008)



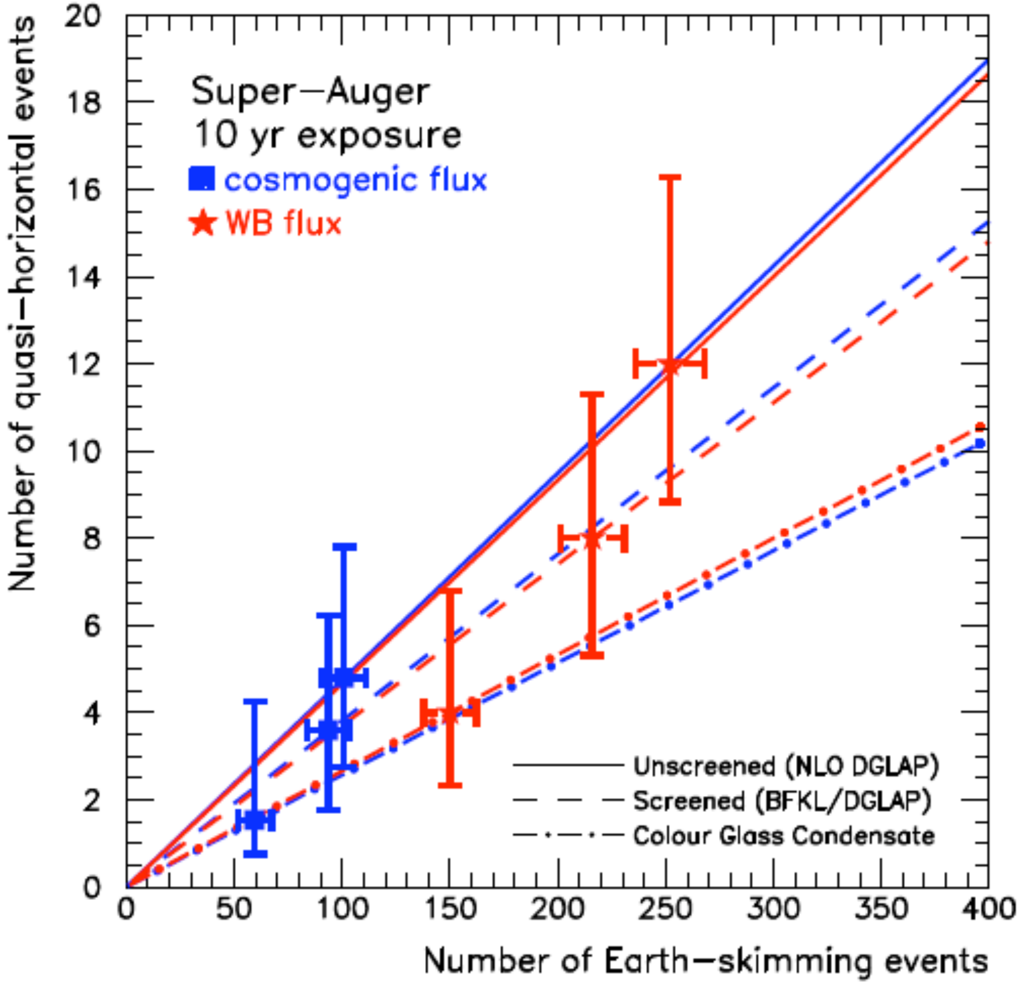



# Beyond HERA: probing low-x QCD with DIS of cosmic neutrinos




Anchordoqui, Cooper-Sarkar, Hooper, Sarkar (2006)



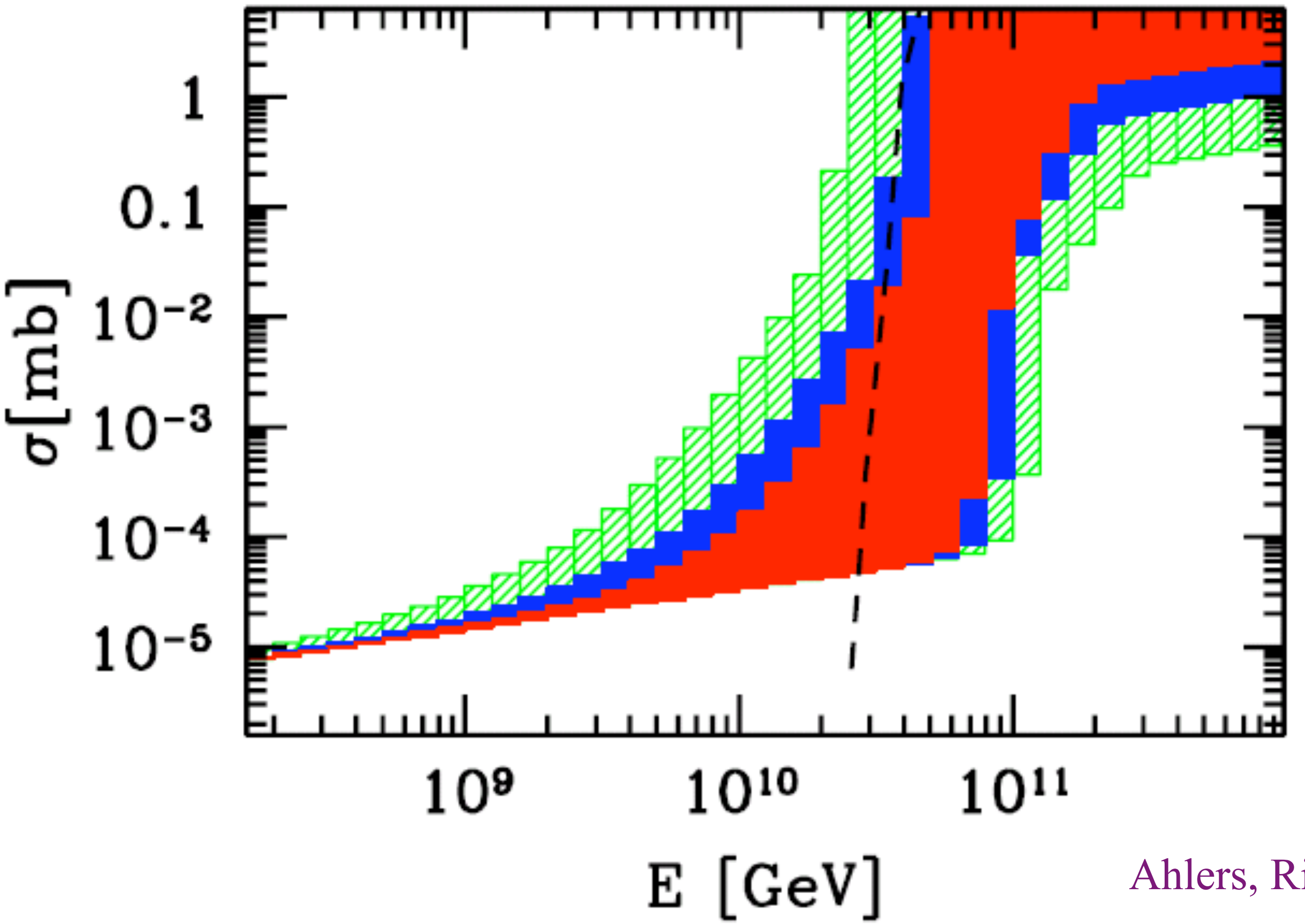

The steep rise of the gluon density at low-$x$ *must* saturate (unitarity!)
**⇒suppression of the UHE ν-N #-secn**

The ratio of quasi-horizontal (all flavour) and Earth-skimming ($\nu_\tau$) events *measures* the cross-section

# Electroweak instanton-induced interactions in the SM

Non-perturbative transitions between degenerate SM vacuua (with different B+L #) are exponentially suppressed below the "sphaleron" mass: $\pi\, M_W/\alpha_W \sim 8$ TeV

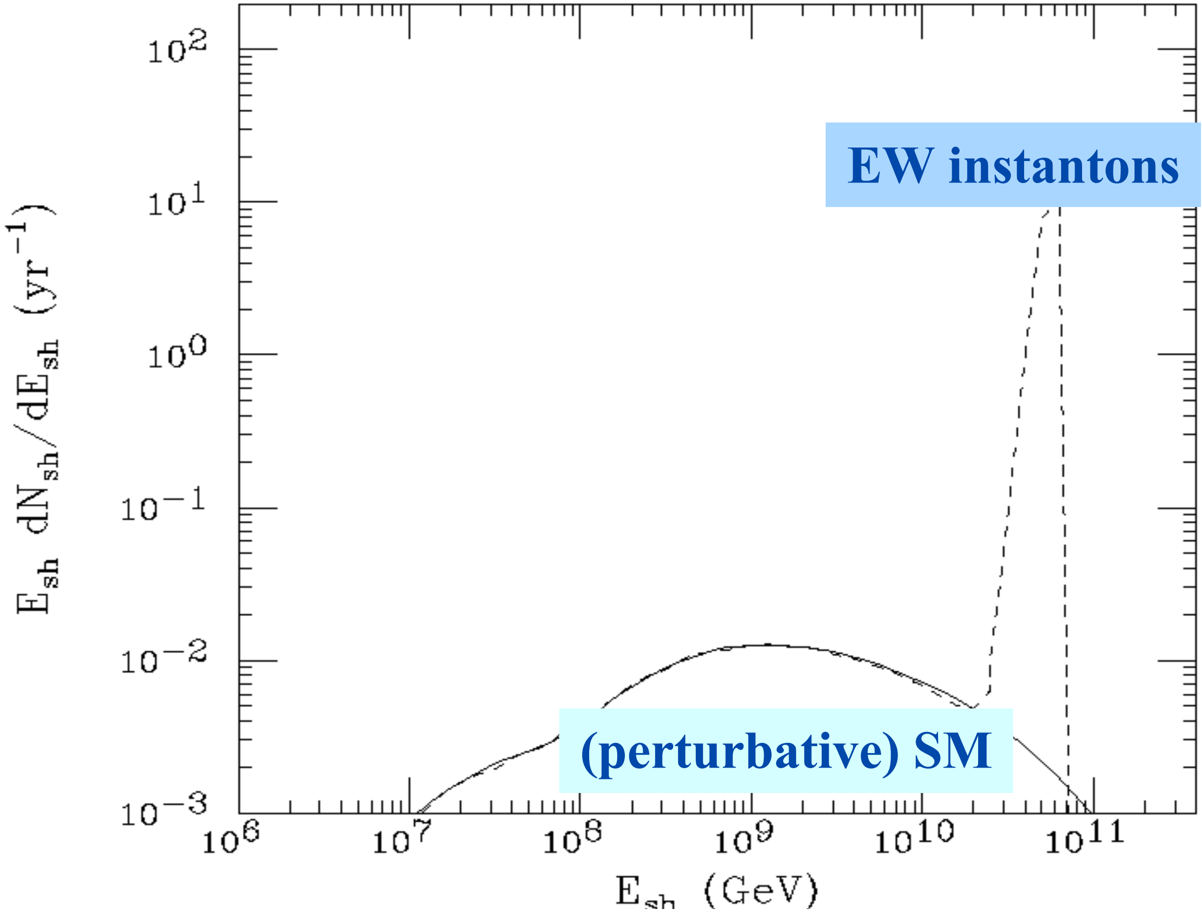
… but *huge* cross-sections are predicted for $\nu$-N scattering at higher cms energies (would enable neutrinos to generate apparently hadronic super-GZK air showers)




Ahlers, Ringwald & Tu (2005)

# Electroweak instantons at Auger

**Quasi-horizontal ν showers (assuming cosmogenic flux)**



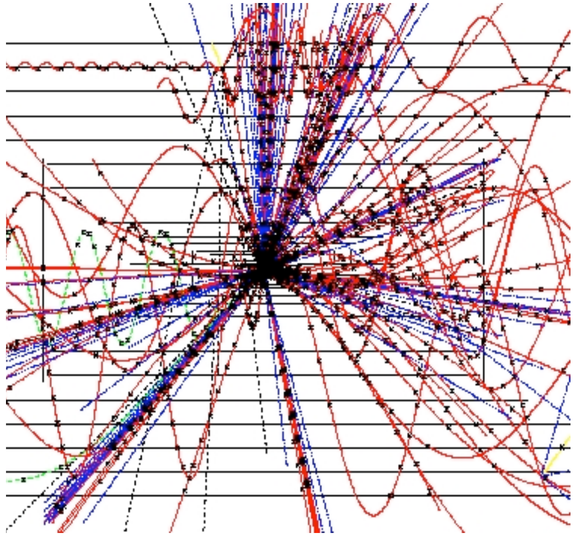

***Large* deviations from perturbative SM expected above $10^{10}$ GeV**

**predict 4.3 QH showers/yr ⇒ have not seen any so far!**

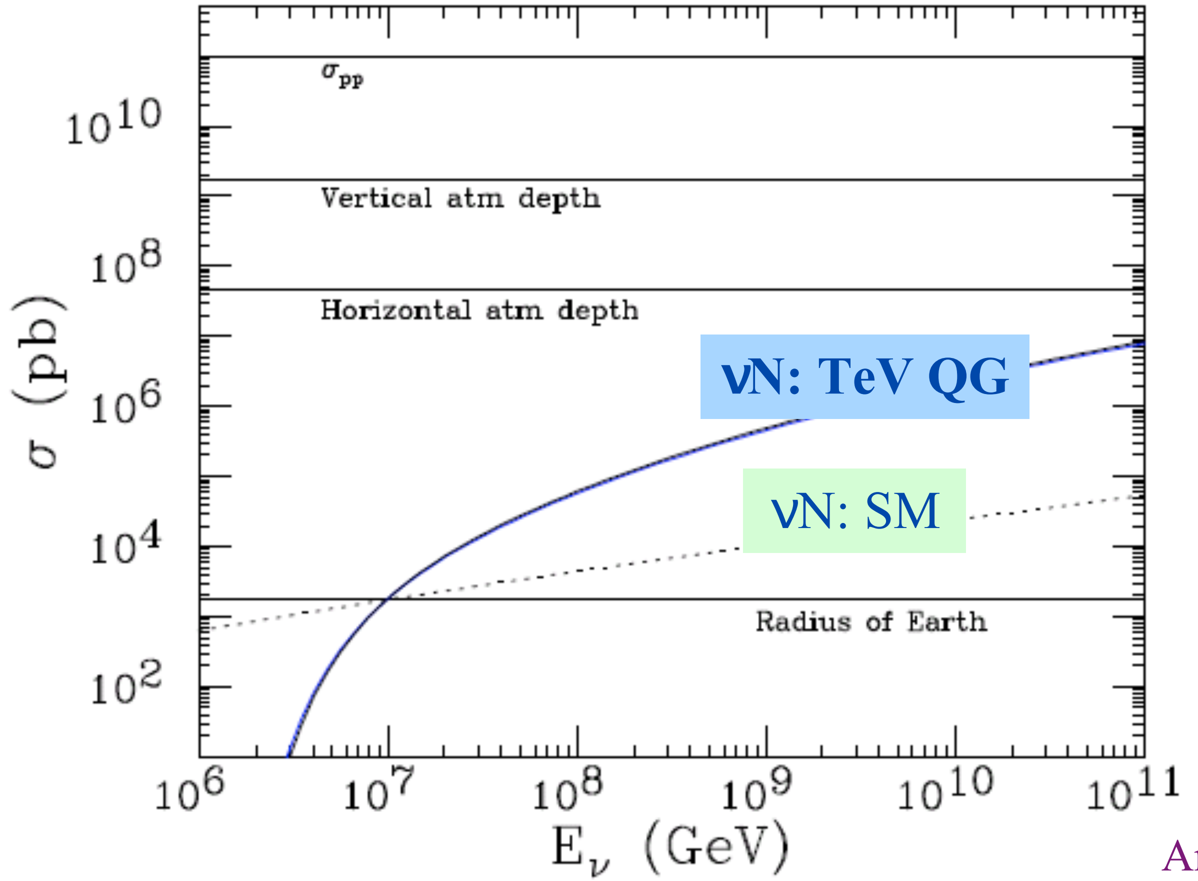
Anchordoqui, Han, Hooper, Sarkar (2005)

# TeV scale quantum gravity?

If gravity becomes strong at the TeV scale (as in some brane-world models) then at cms energies well *above* this scale, **black holes** will form with $M \sim \sqrt{\hat{s}}$ and $\sigma \sim \pi R^2_{\text{Schwarzschild}}$



De Rocek (2002)

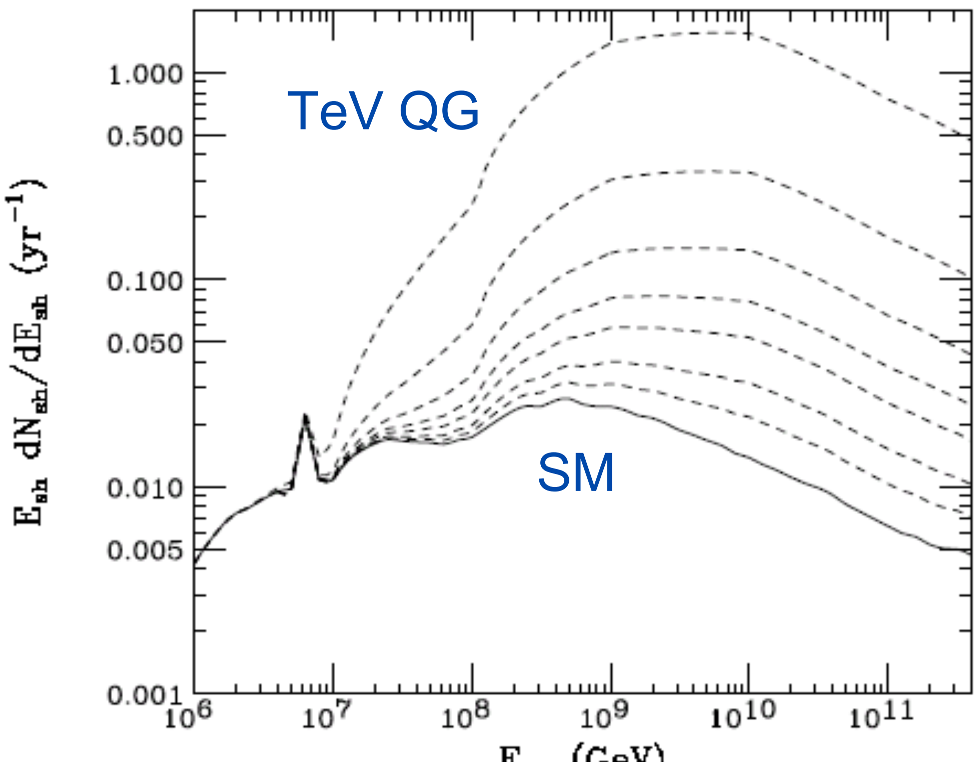



… and then rapidly evaporate by Hawking radiation (+ gravitational waves?)

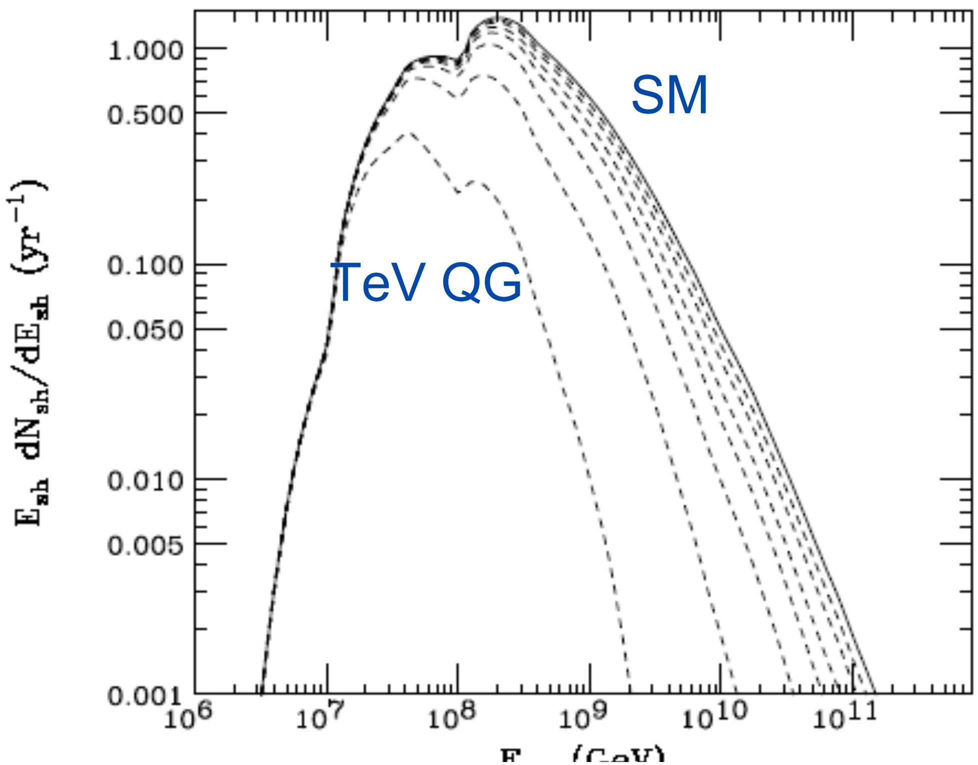
Anchordoqui, Feng, Goldberg, Shapere (2002)

# Testing TeV scale quantum gravity (assuming WB flux)

## Quasi-horizontal ν showers




## Earth-skimming $\nu_\tau$ showers




Auger is well suited for probing microscopic black hole production

# QH/# ES= 0.04 for SM, but 10 for Planck scale @ 1 TeV!

Anchordoqui, Han, Hooper, Sarkar (2005)

# Many other probes of new physics at neutrino telescopes …

- Neutrinos from annihilations of trapped dark matter in Sun
  - complementary to direct laboratory searches

- Non-standard neutrino oscillations (over *very* long baselines)
  - e.g. test of decoherence due to quantum gravity vacuum

- New long-lived charged particle (e.g. NLSP staus)
  - complementary to collider searches

- Other exotica - monopoles, nuclearites … the *unexpected*

# Summary

Cosmic ray astronomy has been born …

The sources of UHE cosmic rays *must* also emit neutrinos!

The detection of UHE cosmic neutrinos is eagerly anticipated … will identify the sources *unambiguously*

Neutrino observatories will provide an unique laboratory for tests of new physics beyond the Standard Model

> *"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)