The "guaranteed" cosmogenic neutrino flux

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In this world nothing is certain but death and taxes.

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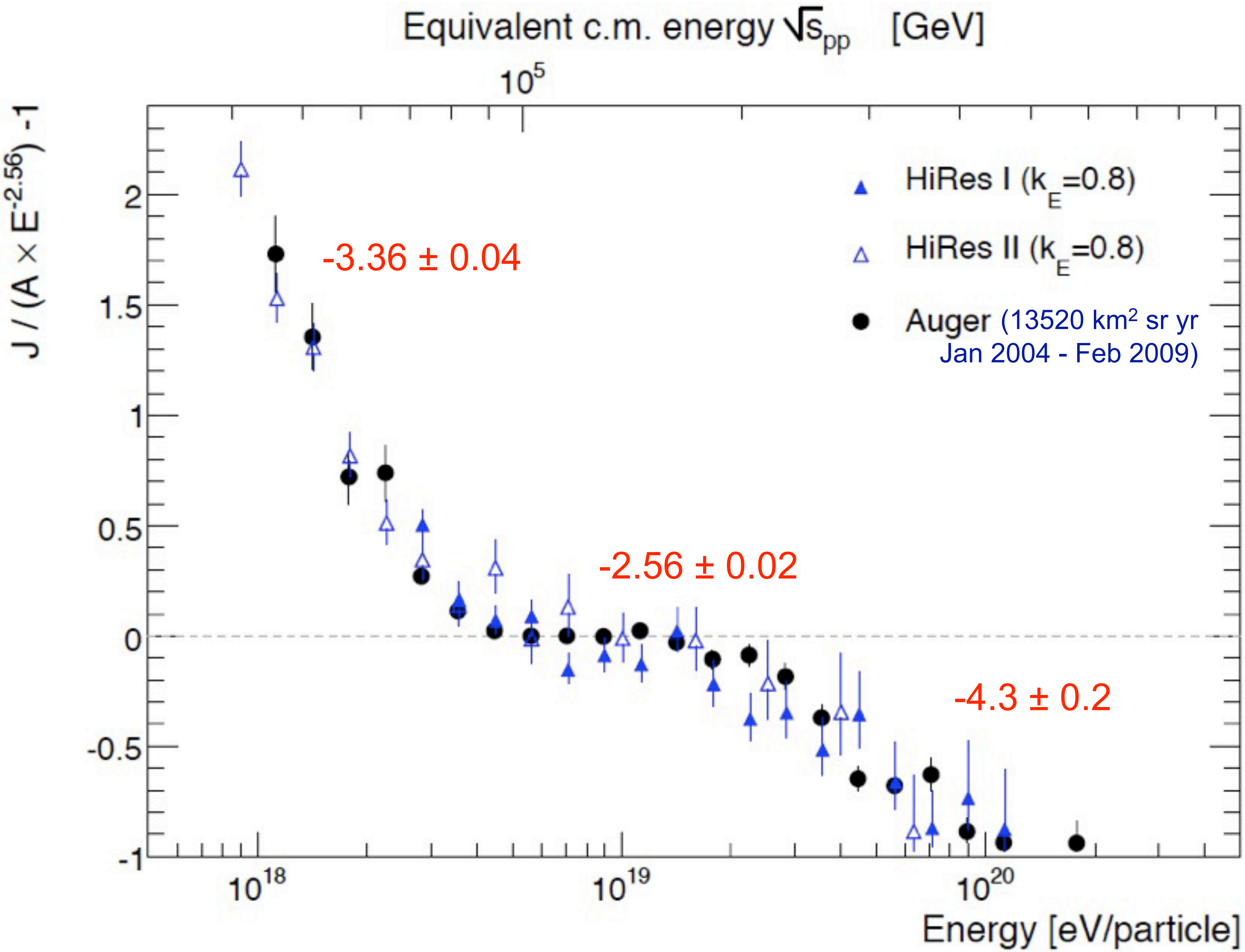
The GZK cutoff has supposedly been seen … *if* the primaries are protons *and* the sources accelerate them to energies > 10^{20} eV *and* are homogeneously distributed



… *if* so, we then have the "guaranteed" cosmogenic neutrino flux

GZK mechanism :

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

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

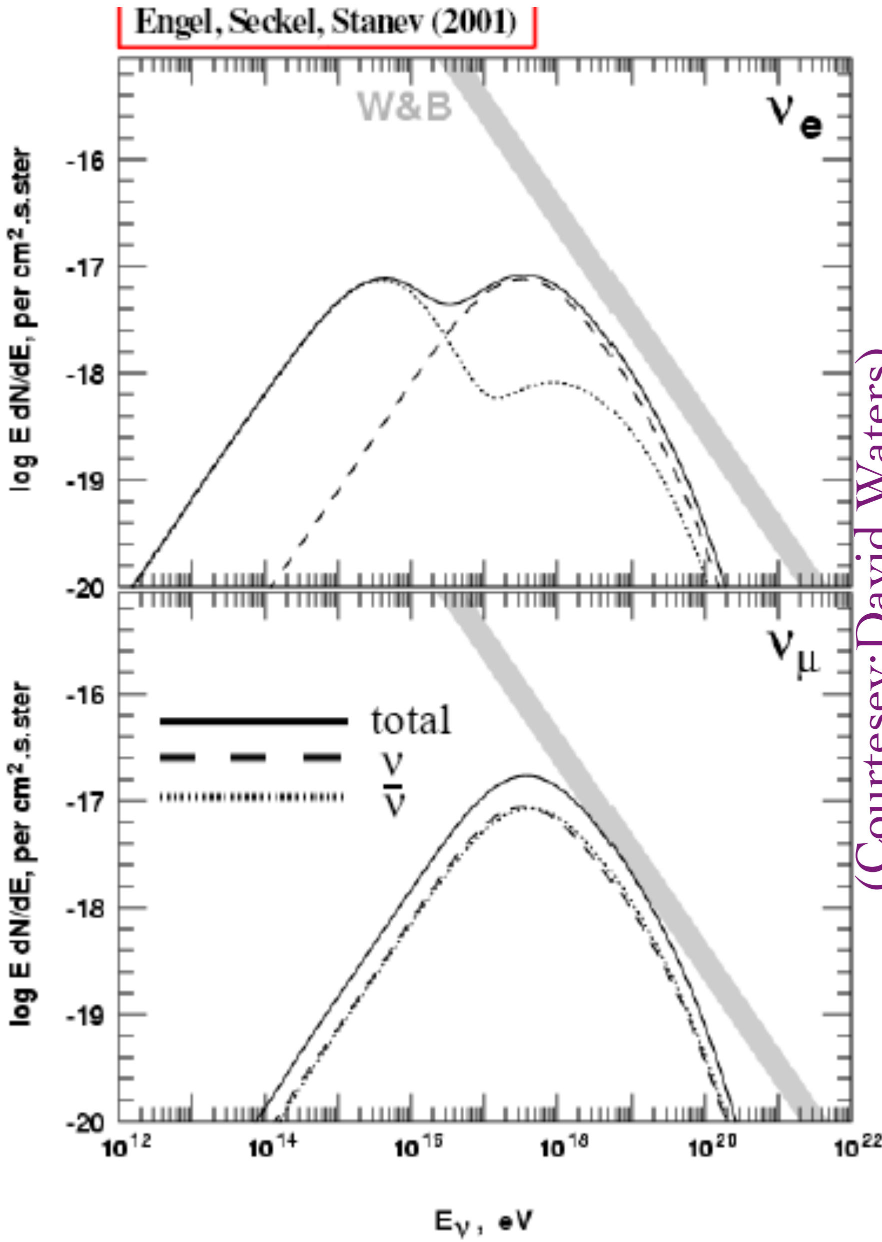
$$\pi^+ \rightarrow \mu^+ +\nu_\mu$$

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

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

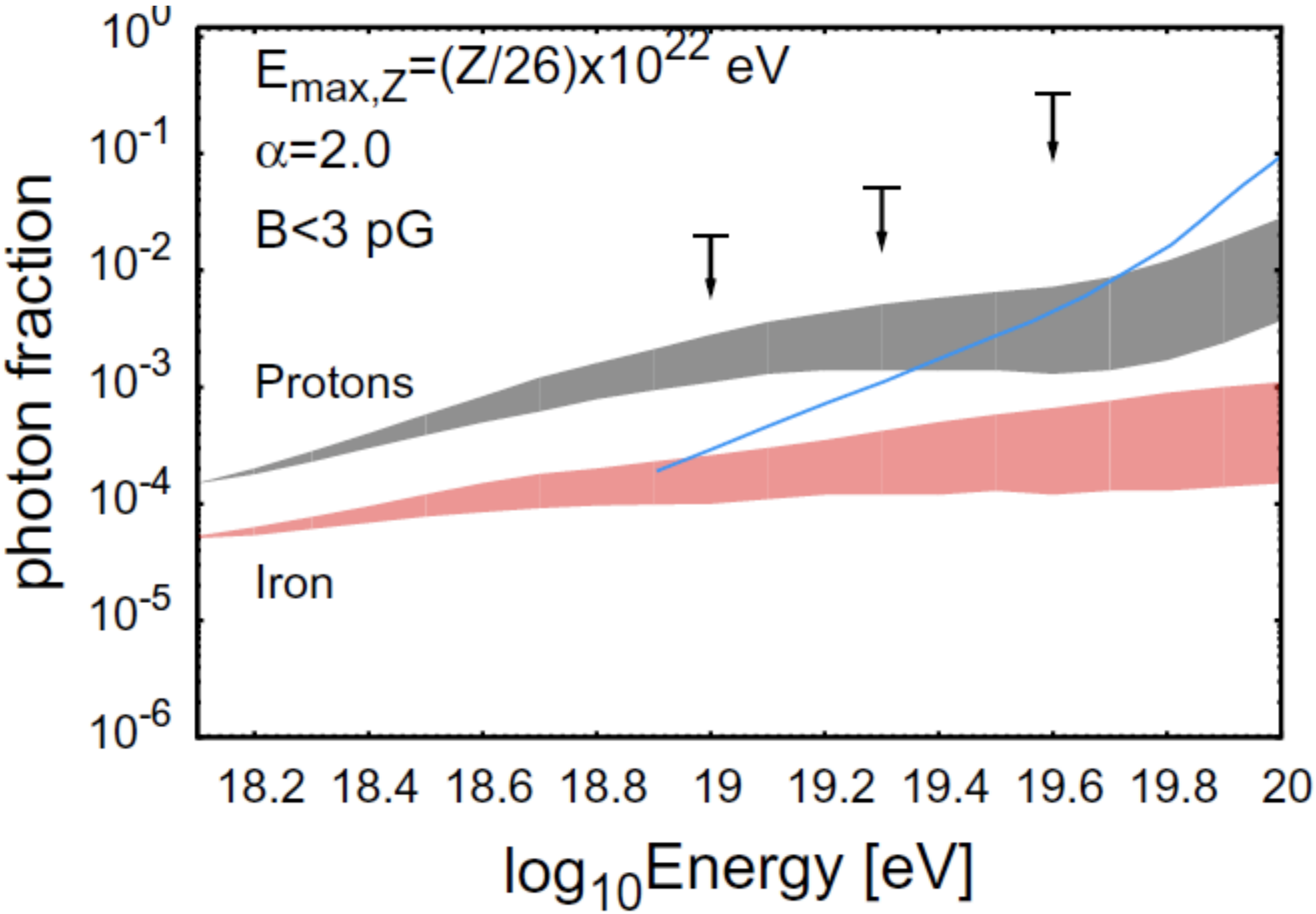
factors of ~2 uncertainty each;
factor of ~4 overall (?)



(Courtesey:David Waters)

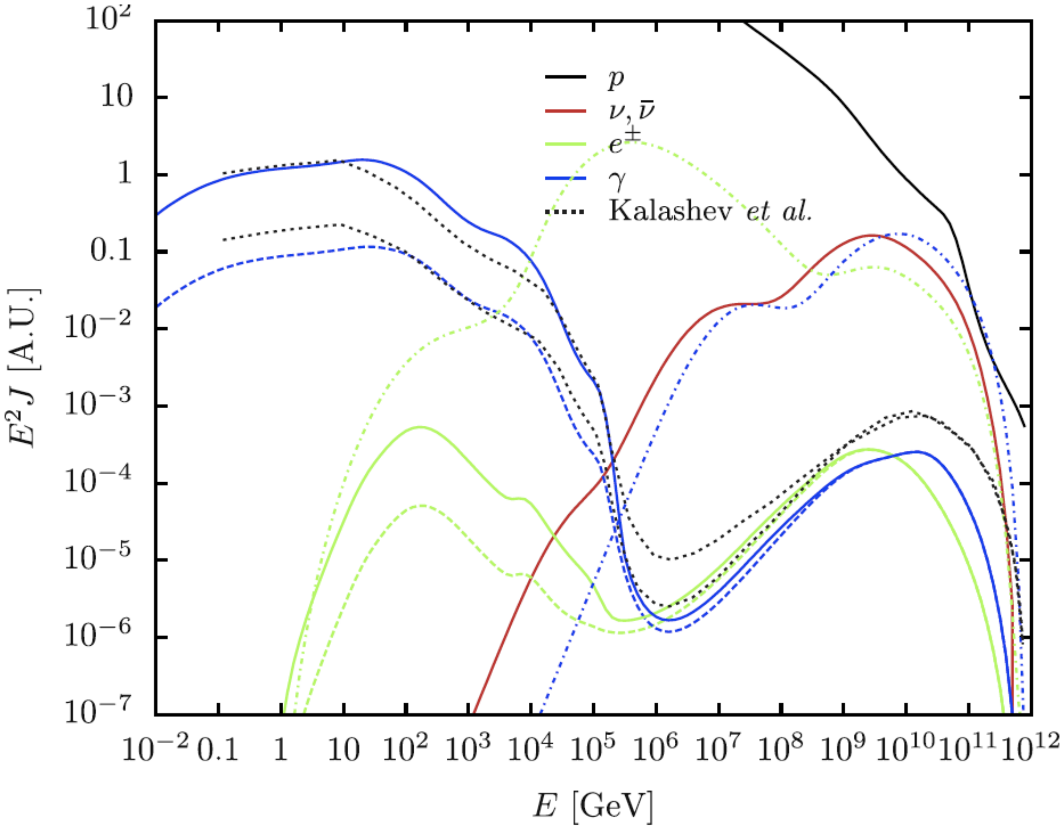
➡ Also what if the primaries are heavy nuclei (as is indicated by air shower measurements)? will boost ν_e flux but suppress the ν_μ flux (Hooper *et al* 04, Ave *et al* 04, Anchordoqui *et al* 07)

There is also a GZK **photon** flux from π^0 decay, pair production etc …
a challenging target for air shower arrays (Gelmini, Kalashev & Semikoz, 2007)

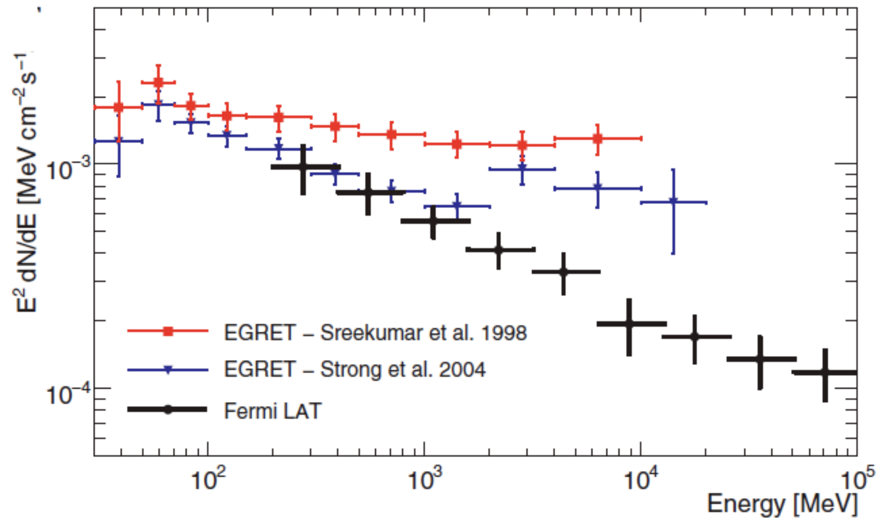


Auger has set stringent limits and may ultimately have the sensitivity to detect this flux (blue line above) … alternatively can wait for the photons to be degraded to lower energies and then detect them

The GZK photons will cascade on intergalactic radiation backgrounds and magnetic fields to generate a diffuse background at GeV-TeV energies

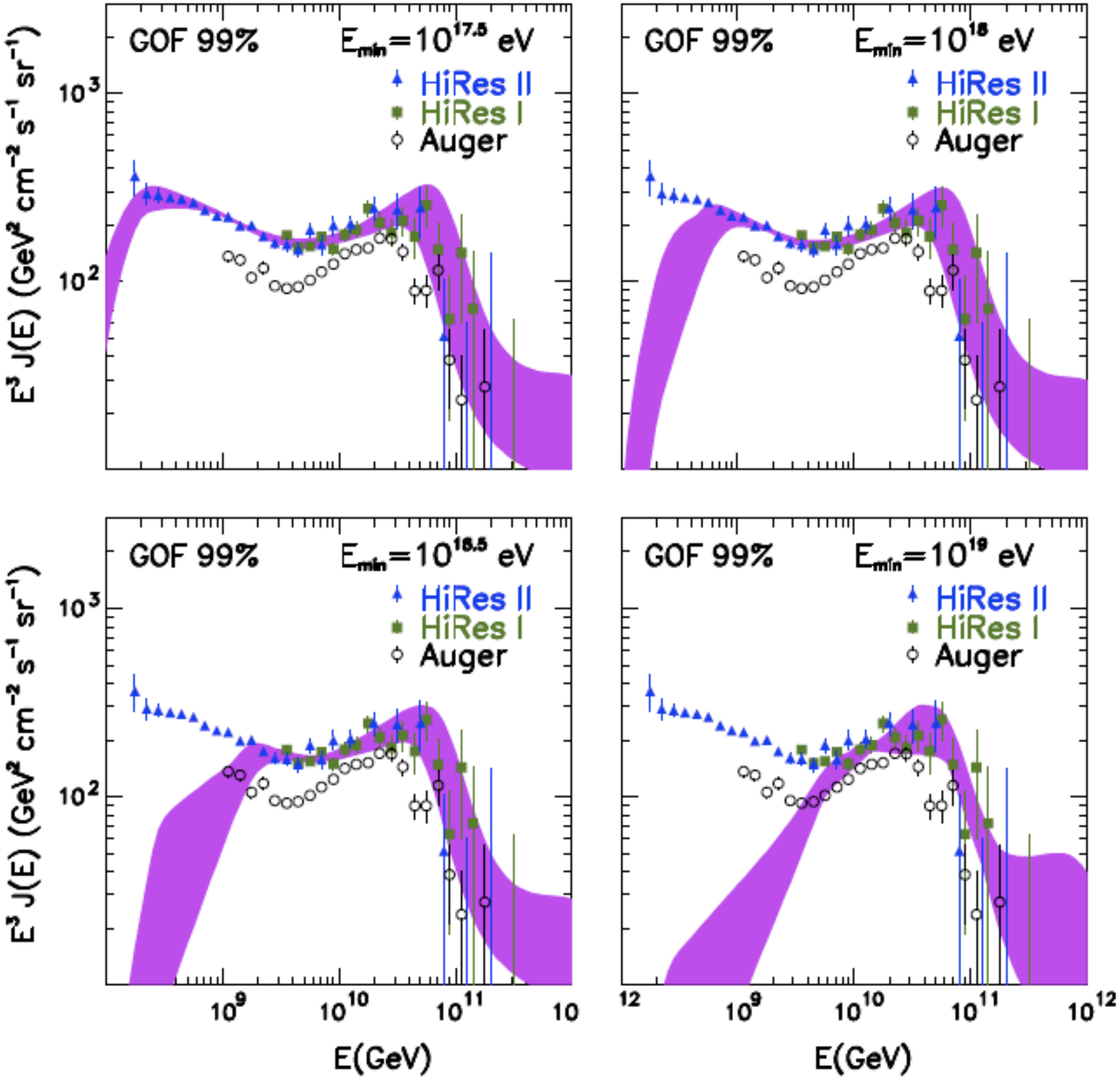


This is now constrained by the measurement by Fermi-LAT of the extragalactic γ-ray backgd.



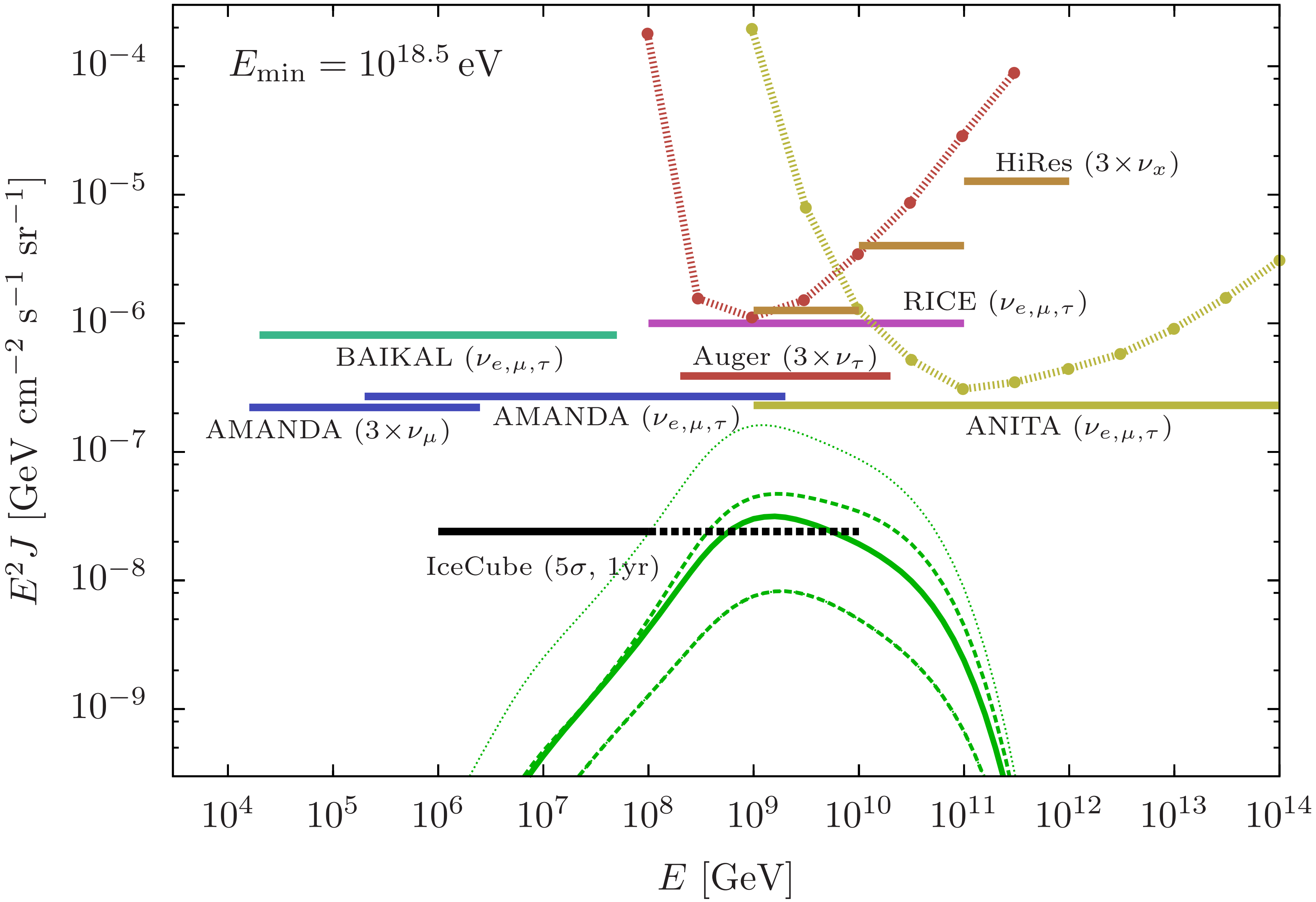
Ahlers, Anchordoqui, Gonzalez-Garcia, Halzen & S.S., AP 34:106,2010

We can fit the observed spectrum for various combinations of injection spectral index, maximum energy *etc* as well as the 'cross-over' energy at which the extragalactic cosmic rays begin to dominate over the galactic component



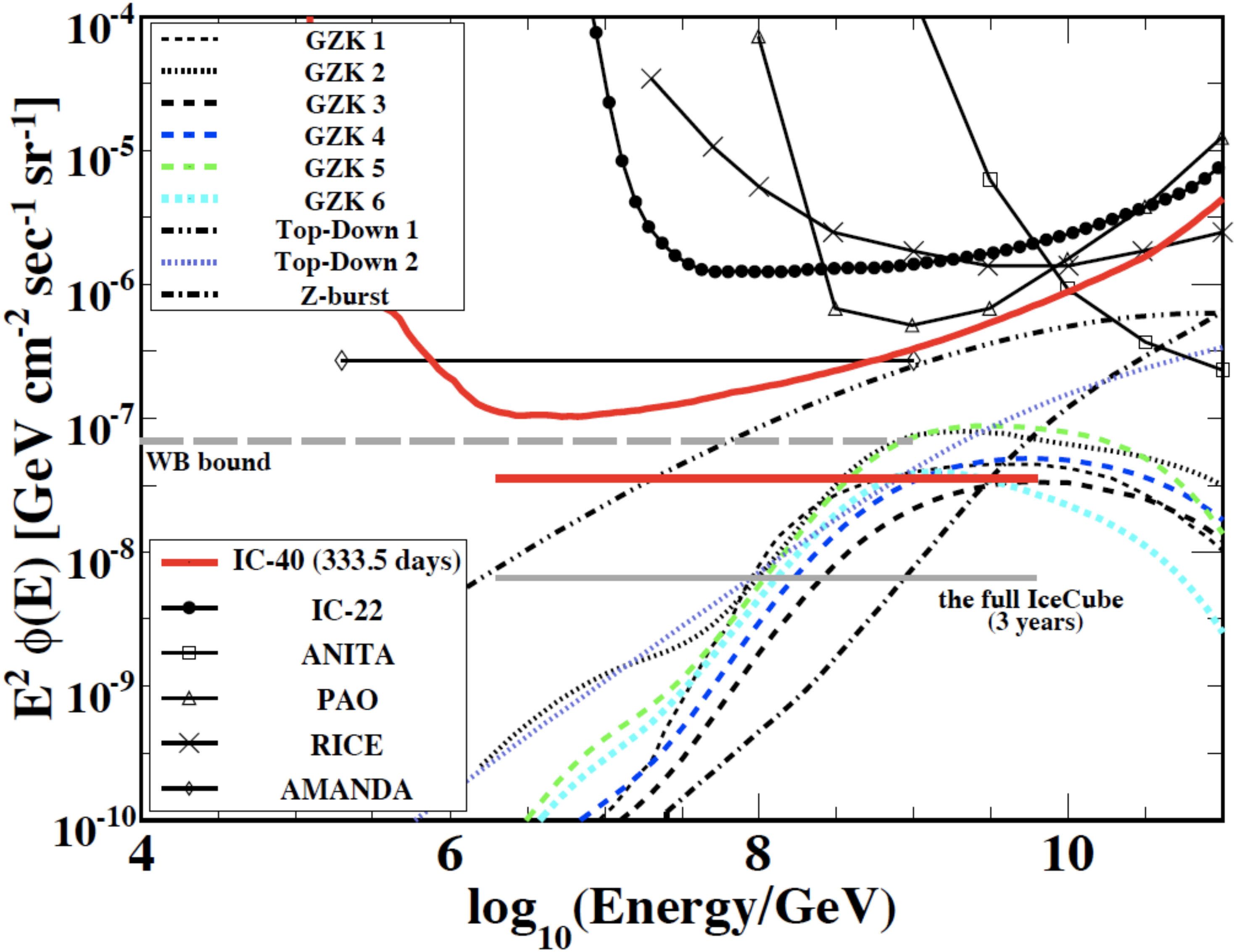
Ahlers, Anchordoqui, Gonzalez-Garcia, Halzen & S.S., AP 34:106,2010

The corresponding cosmogenic flux can then be calculated … but when the Fermi-LAT constraint is imposed, its maximum value is *restricted* (dashed lines)



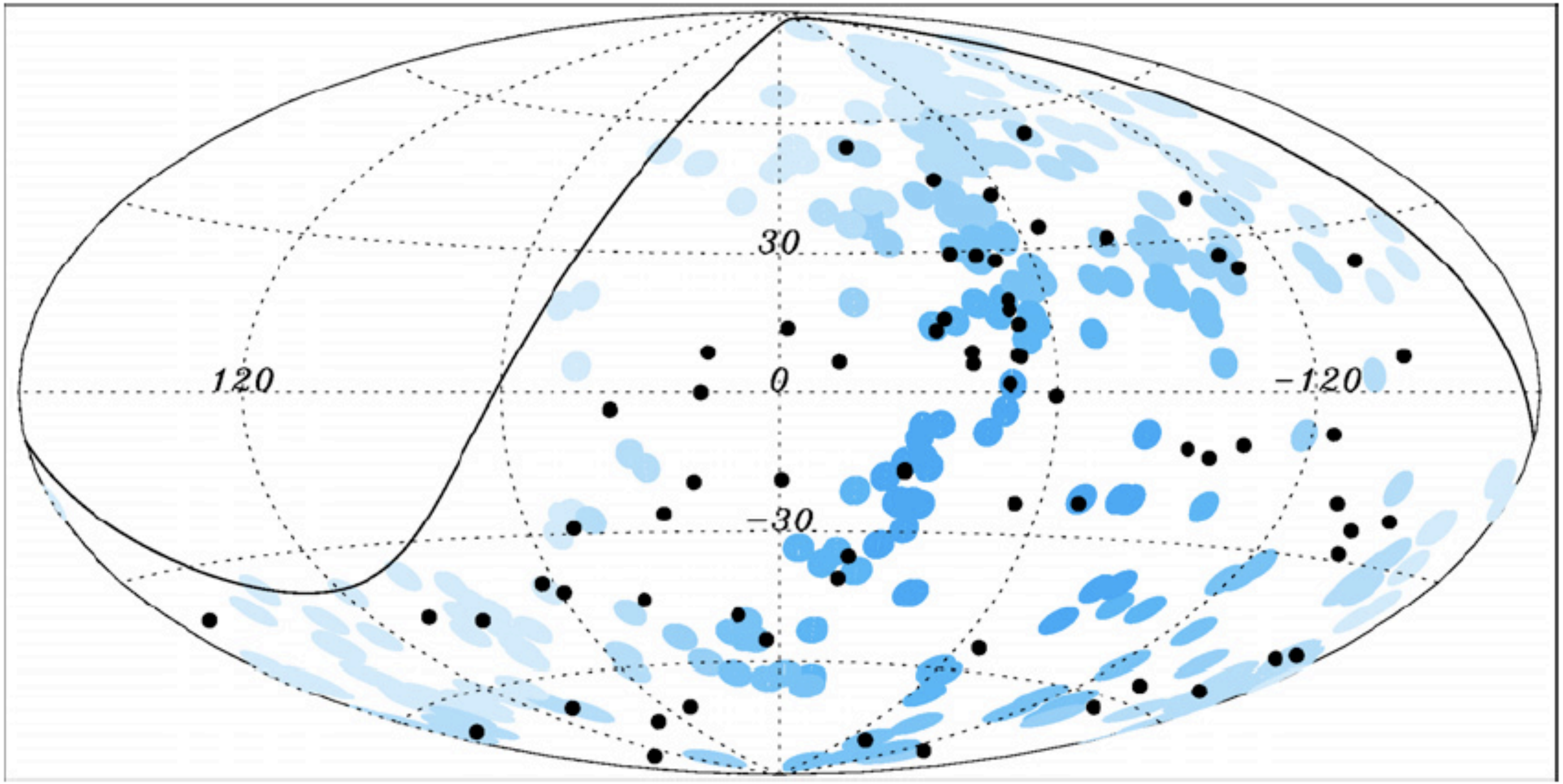
Ahlers, Anchordoqui, Gonzalez-Garcia, Halzen & S.S., AP 34:106,2010

The best-fit (with the Fermi-LAT constraint) is shown below as "GZK 6"
… the current best limit (IC-40 preliminary) is still a factor of ~8 too high



But what if even the full IceCube (or ANITA or Auger) fails to see the expected flux?

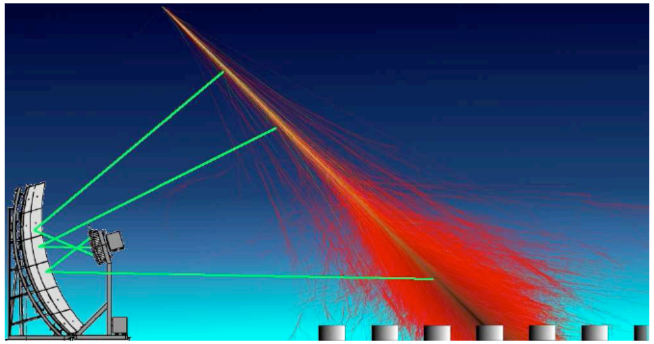
Primary protons are *consistent* with the Auger observation of the correlation of arrival directions with nearby AGNs

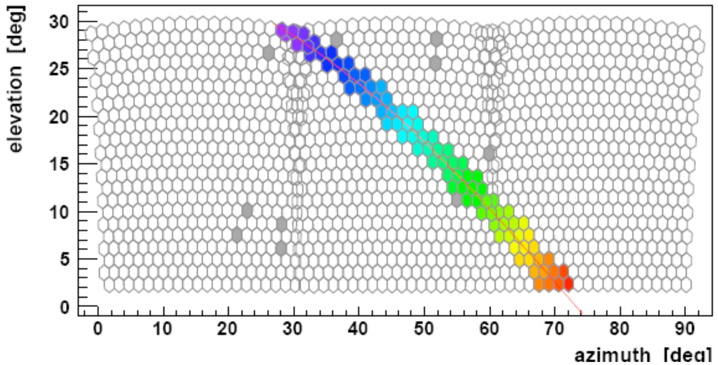


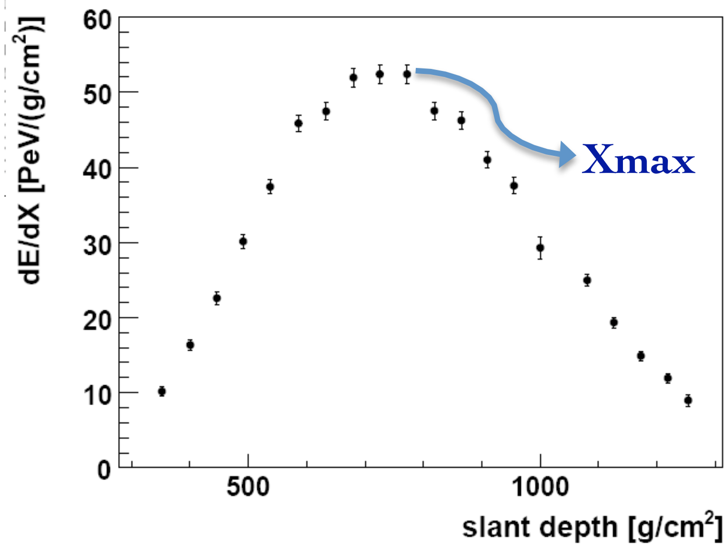
Astropart. Phys. 34:314,2010

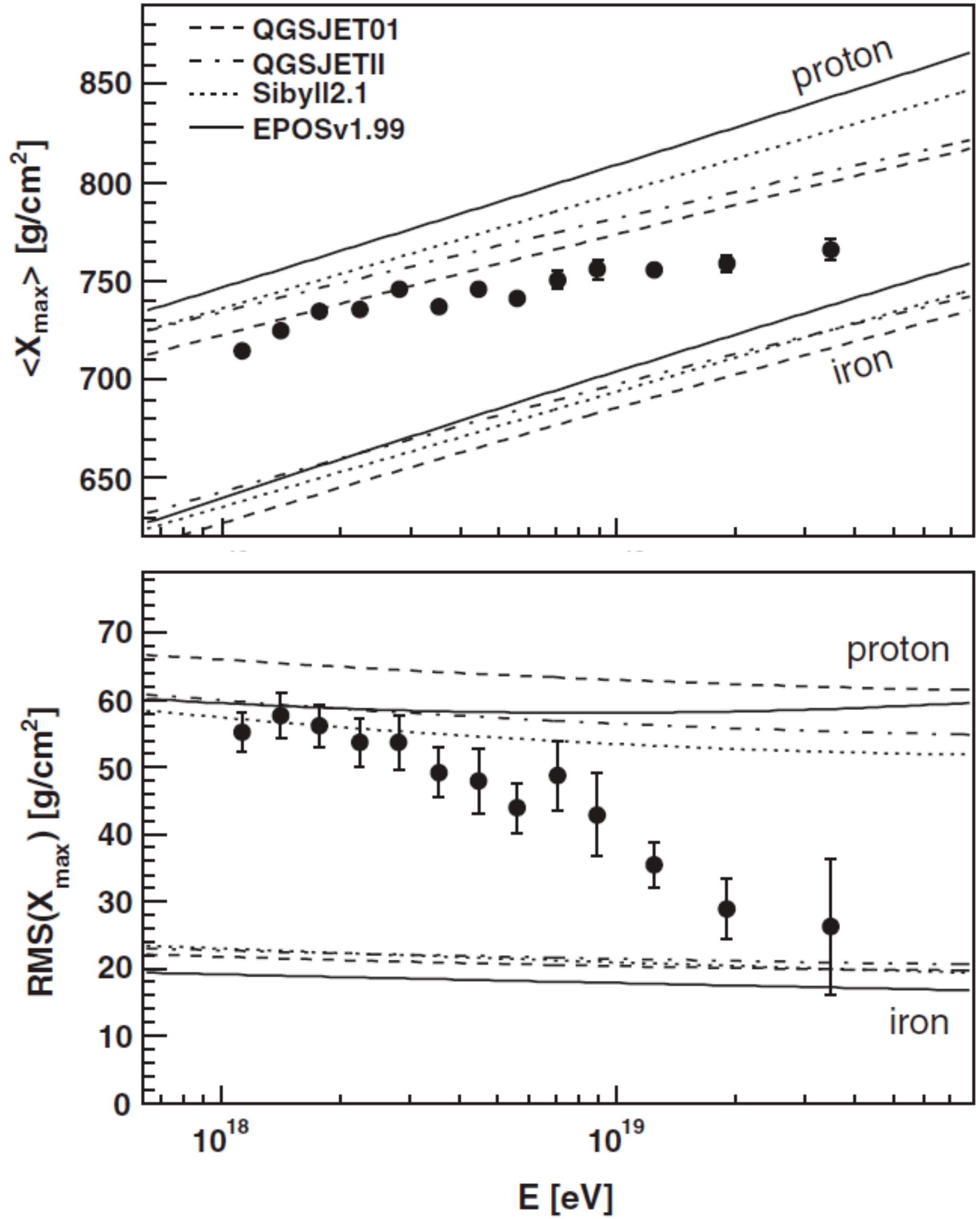
… but given our imprecise understanding of intervening magnetic fields, this argument cannot yet be reversed to require that the primaries *are* protons

Observations at Auger of the depth of maximum and its fluctuations indicate an increasingly *heavier* composition at E > 10 EeV





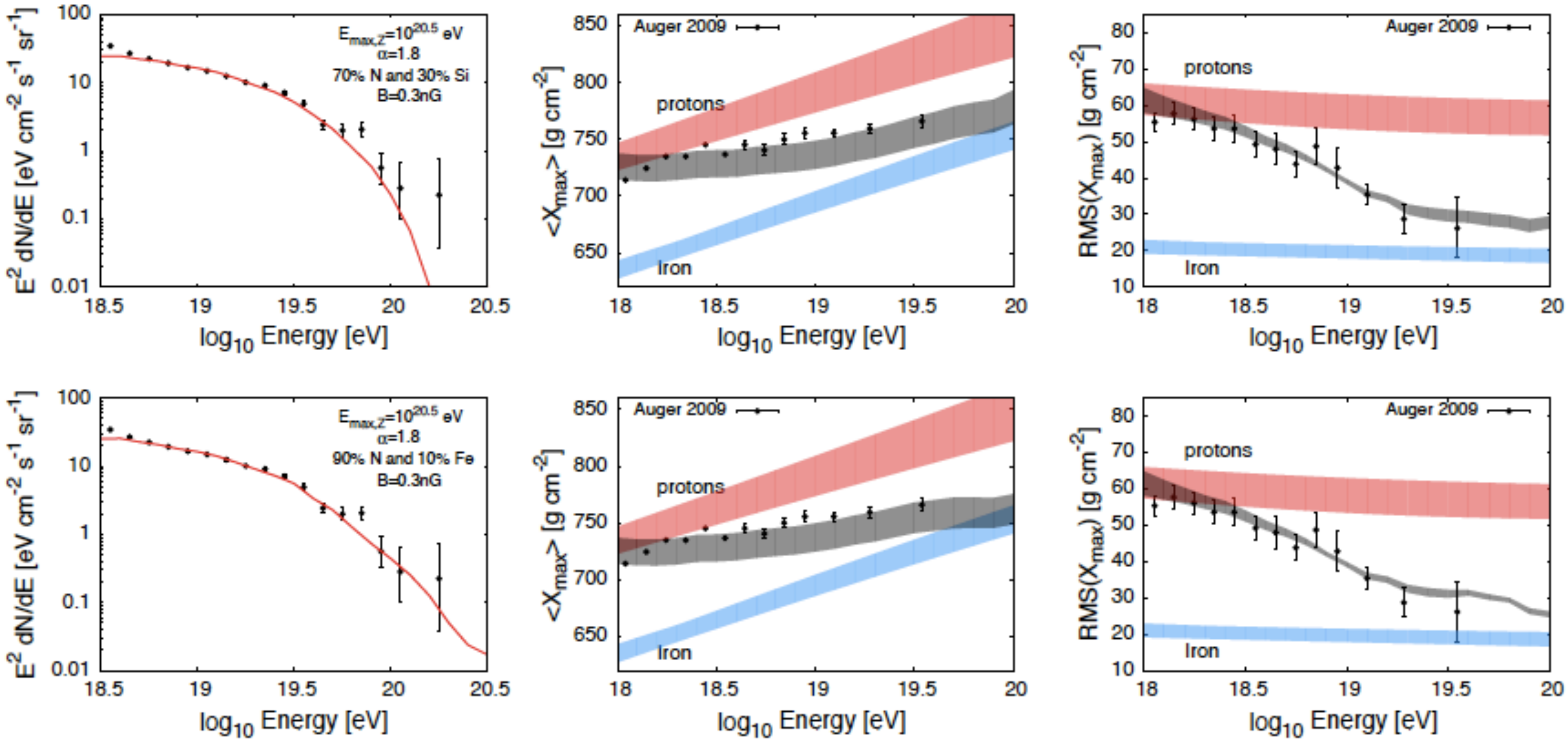




PRL 104:091101, 2010

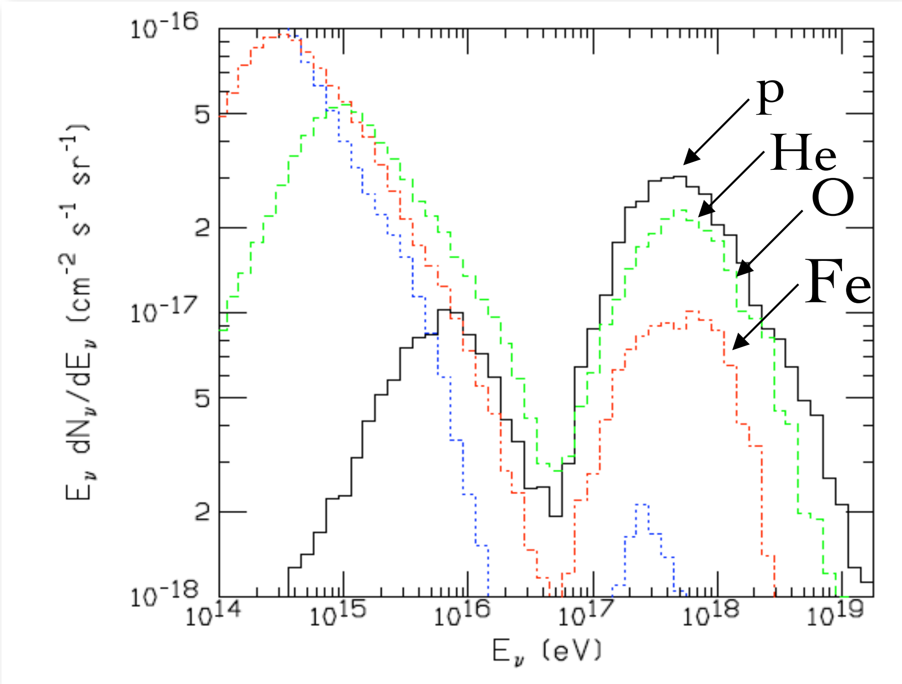
Can fit the data reasonably well if the primaries are heavy nuclei

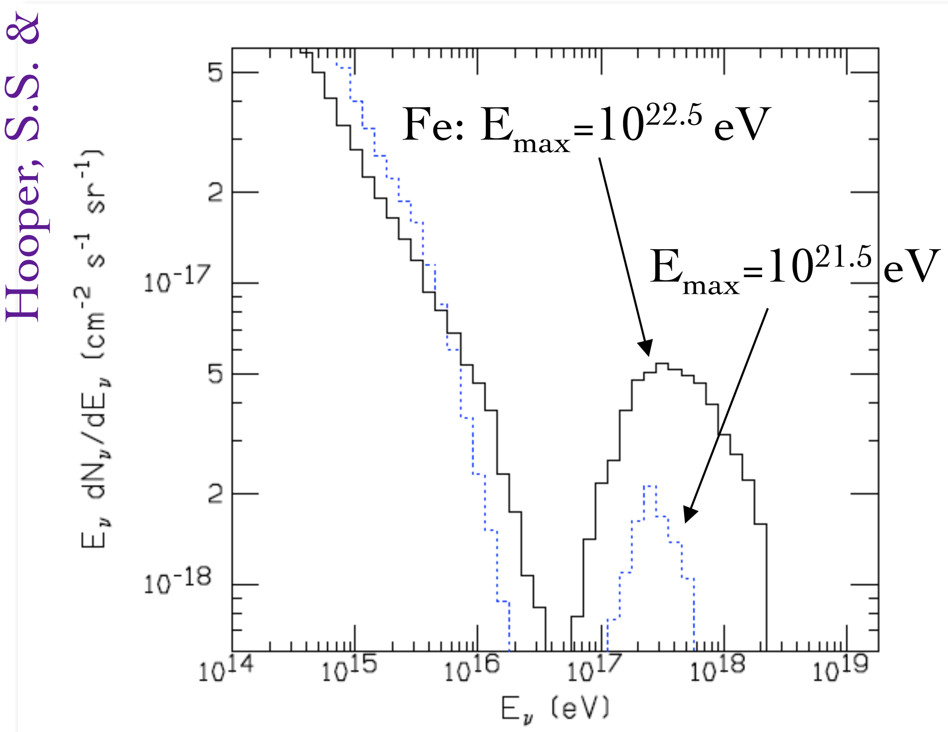
(Note that when propagated through intergalactic radiation fields, photodisintegration results in a *mixed* composition at Earth)



Hooper & Taylor, Astropart.Phys. 33:151,2010

This is *not* the GZK cutoff, so pion production and the neutrino flux will be *suppressed*





Hooper, S.S. & Taylor, AP 23:11,2005

In order to contribute to the cosmogenic ν flux, the photo-disassociated protons must exceed the GZK cutoff in energy, hence the original nuclei must have energies > E_{GZK} x A

$$^{56}\mathrm{Fe} + \gamma_{CMB/CIB} \rightarrow\ ^{55}\mathrm{Mn} + p,$$

$$^{55}\mathrm{Mn} + \gamma_{CMB/CIB} \rightarrow\ ^{54}\mathrm{Mn} + n,$$

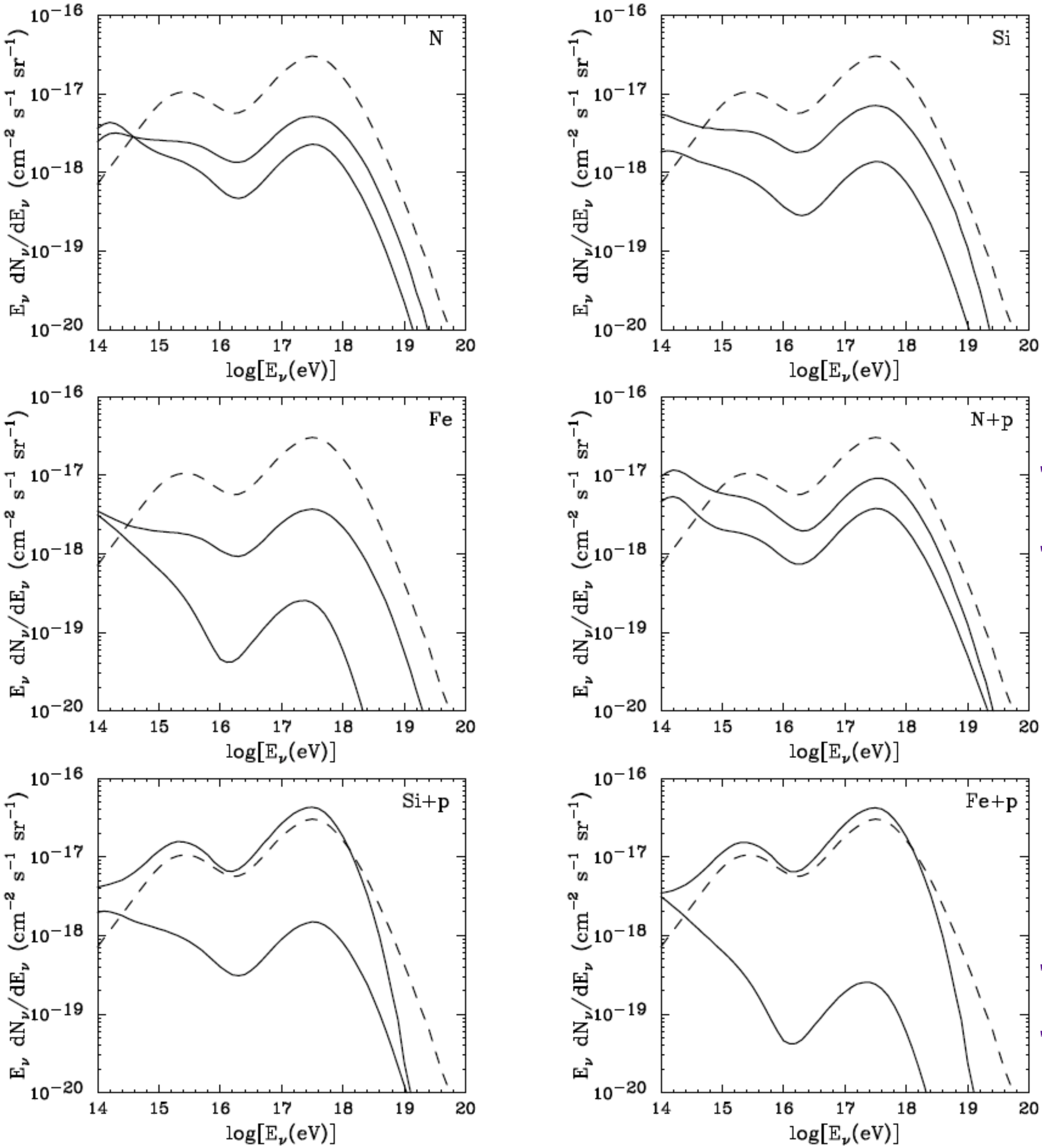
...

Hence the (lower energy) ν_e flux is boosted but the (higher energy) ν_μ flux is *suppressed* ➔ **overall reduction in event rate** (but rather sensitive to E_{max}!)

The cosmogenic ν_μ flux may then be suppressed *further* relative to that for proton primaries (dashed lines)

To detect this might require a ~100 km^3 volume … as might be possible using radio detection (ARIANNA, ARA)

Is it worth it just to confirm that there is a cosmogenic flux?



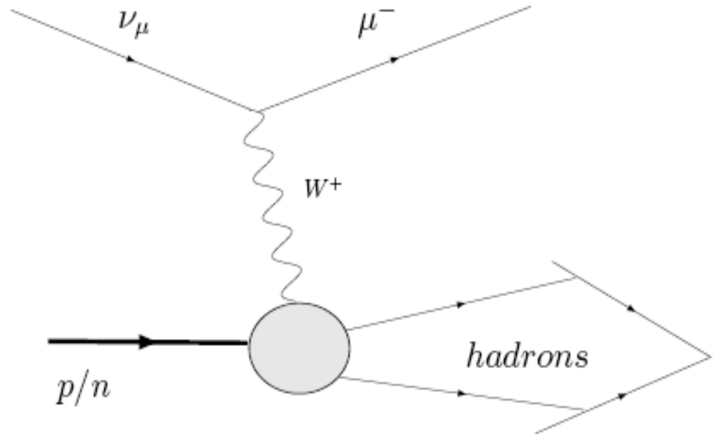
Anchordoqui, Hooper, S.S. & Taylor Phys.Rev.D76:123008,2007

ν-N deep inelastic scattering

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

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

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

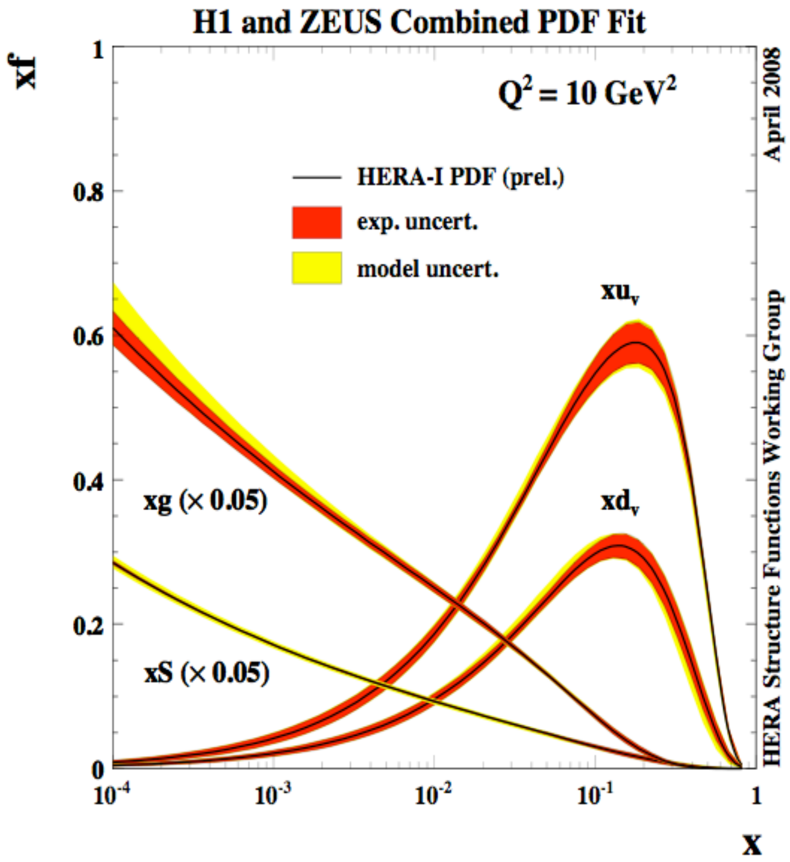


Most of the contrib. to the #-secn is from:

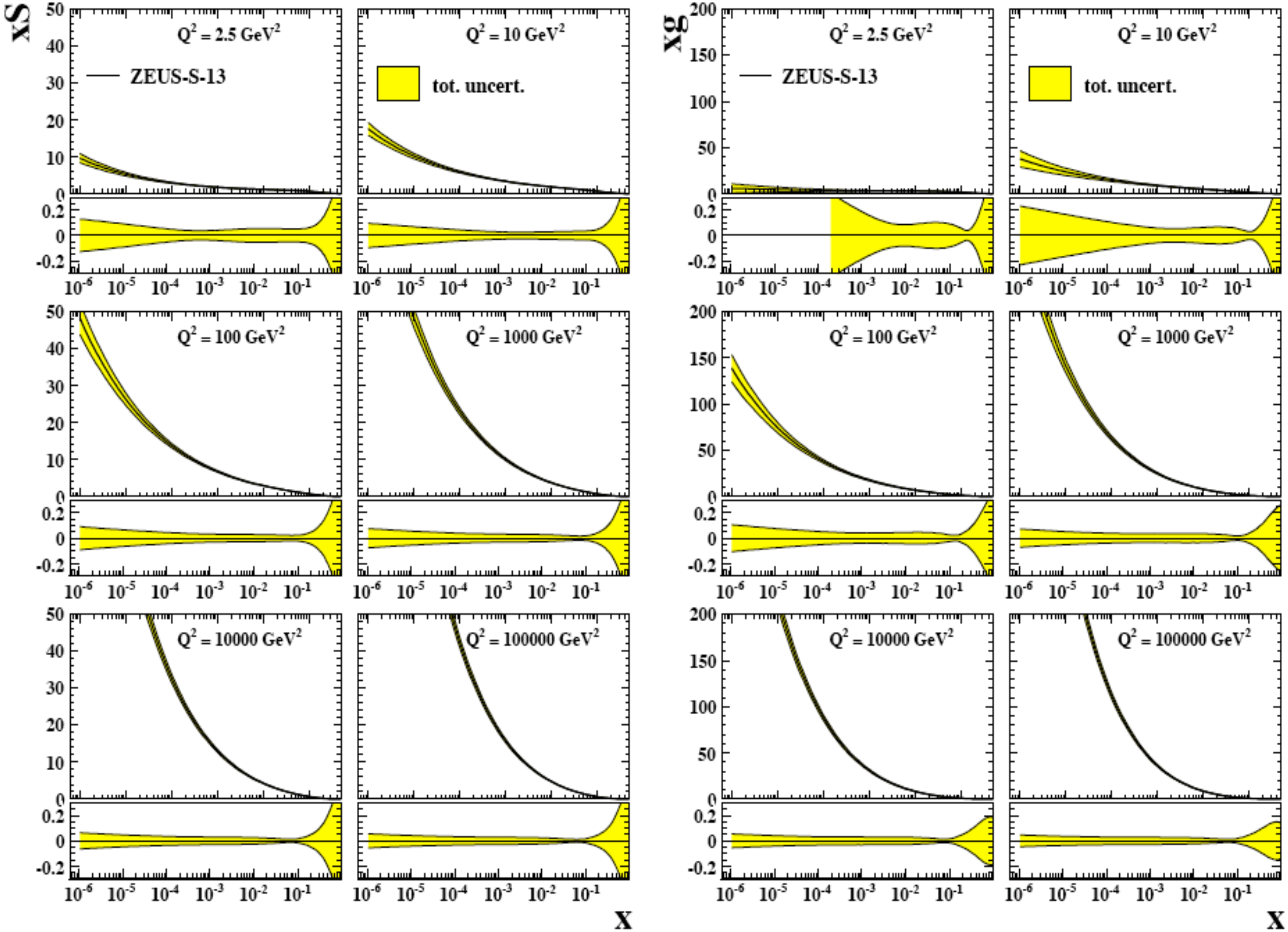
$$Q^2 \sim M_W^2 \ and \ x \sim \frac{M_W^2}{M_N E_\nu}$$

So for cosmogenic νs with E ~ 10^{10} GeV, a new kinematic region of x ~ 10^{-6} is being probed

The HERA experiments showed that the gluon structure function rises steeply at low x but it *cannot* keep rising indefinitely … saturation/screening must set in - but there is no theoretical concensus as to exactly what happens (colour glass condensate?)



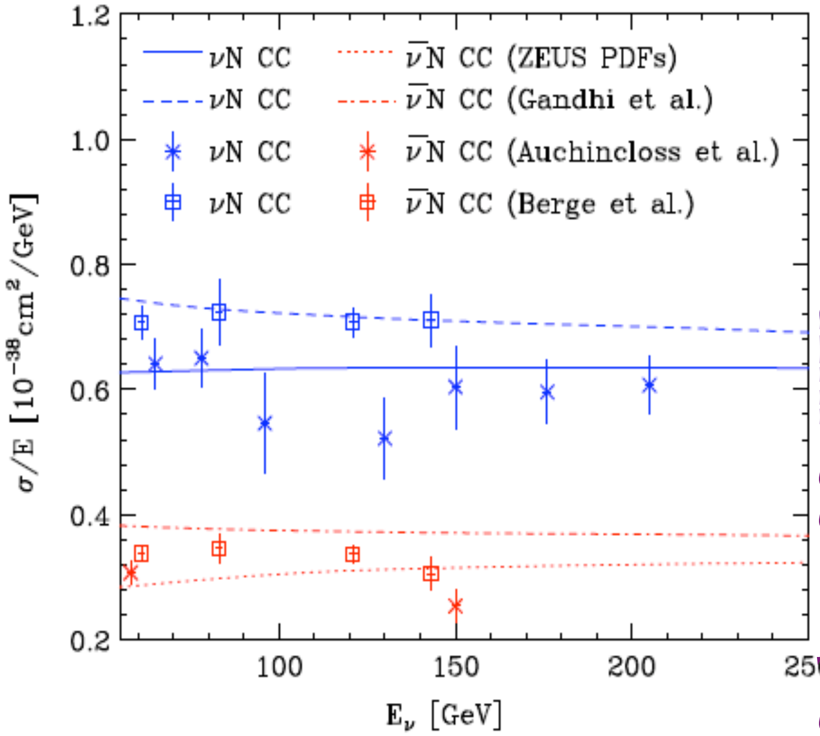
Parton distribution functions from the ZEUS-S global data analysis



Cooper-Sarkar & S.S. JHEP 01:275,2008

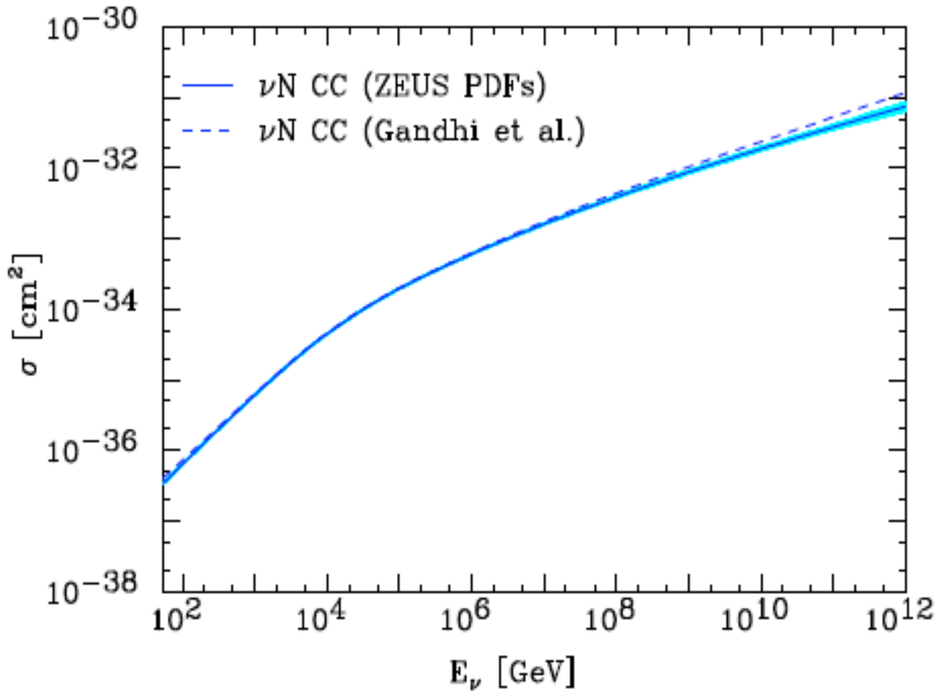
using DGLAP evolution of the PDFs (at NLO, incl. heavy quark corrections)

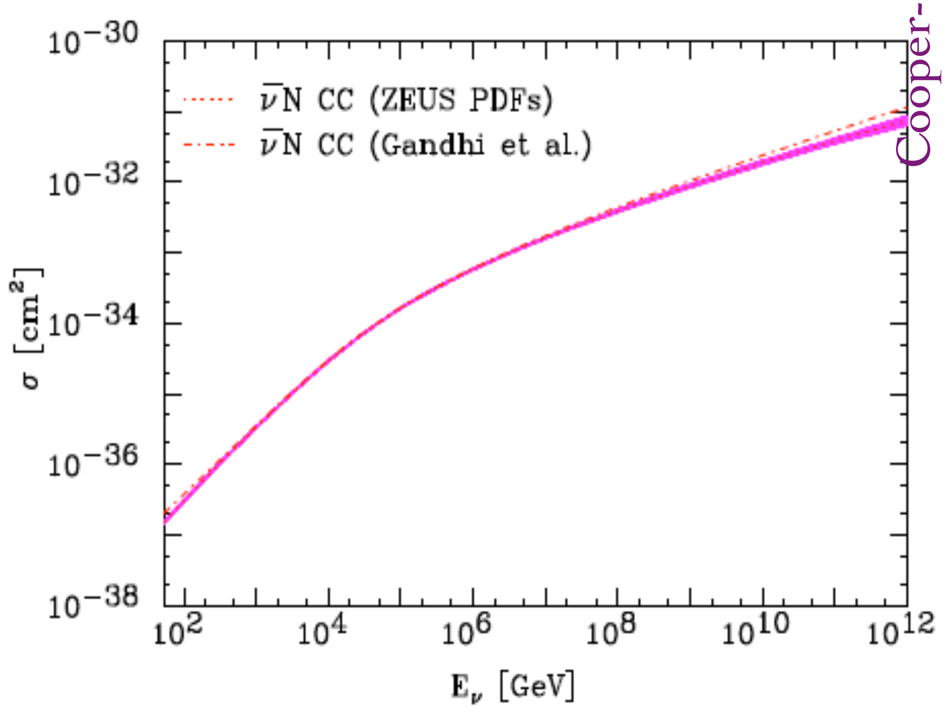
Deep inelastic e-p scattering has probed down to very low x and very high Q^2 values relevant for predicting the UHE neutrino cross-section in the SM … (using DGLAP evolution of PDFs at NLO, incl. heavy quark corrections)



The #-section is up to ~40% *below* the previous 'standard' calculation … more importantly the (perturbative SM) *uncertainty* is now calculated

Cooper-Sarkar & S.S. JHEP 01:275,2008

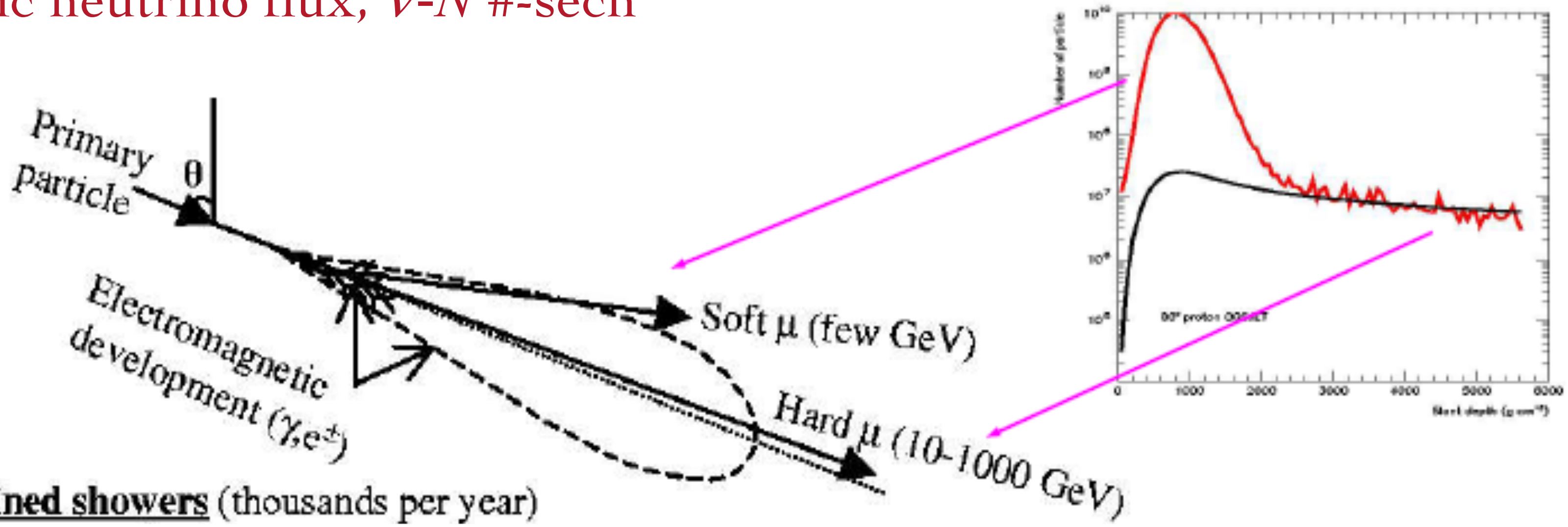




An unexpected bonus – UHE neutrino detection with air shower arrays

Auger can see ultra-high energy neutrinos as inclined deeply penetrating showers

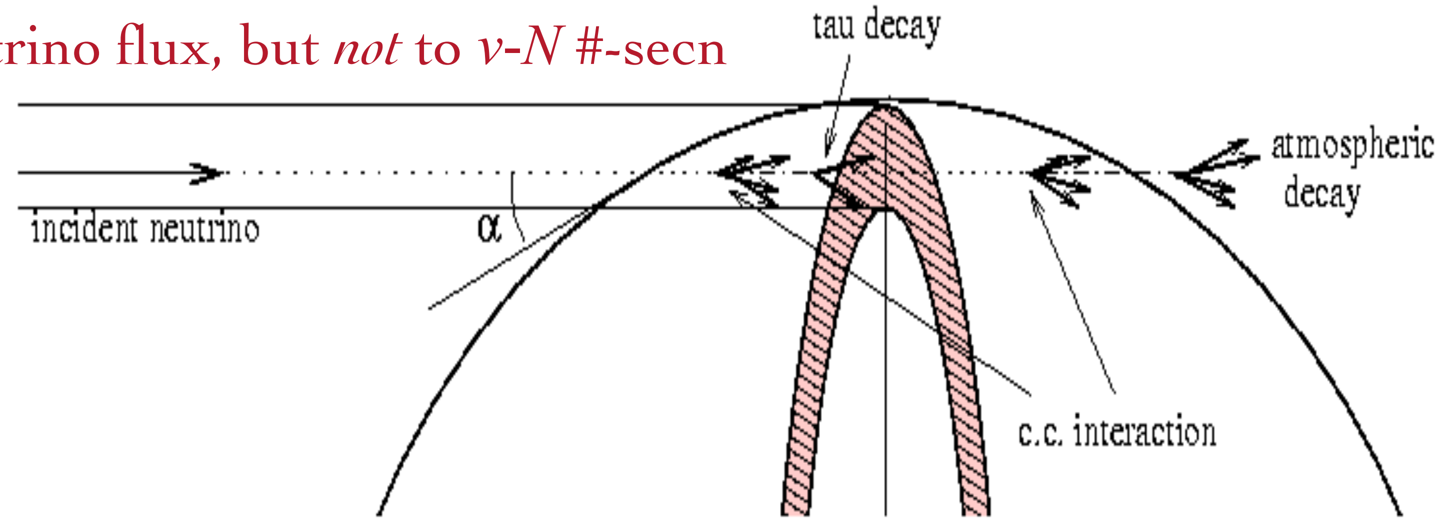
Rate ∞ cosmic neutrino flux, ν-N #-secn



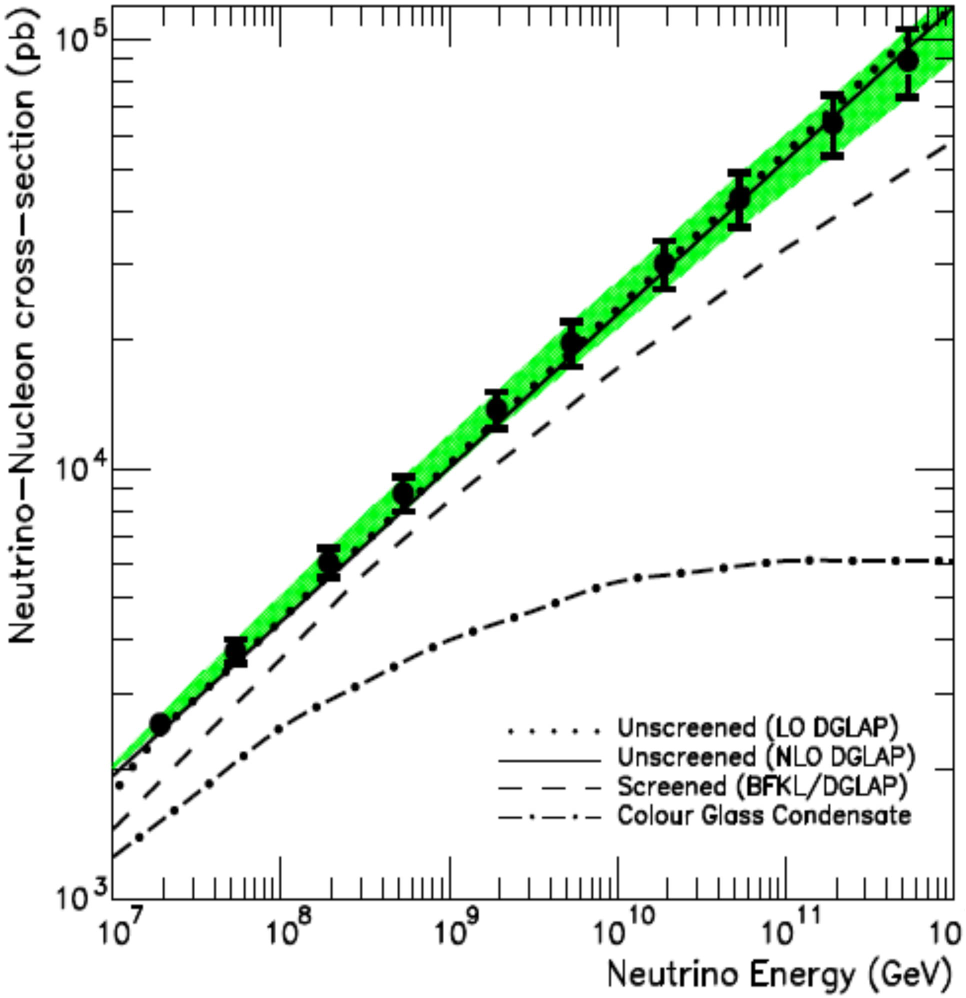
Far inclined showers (thousands per year)

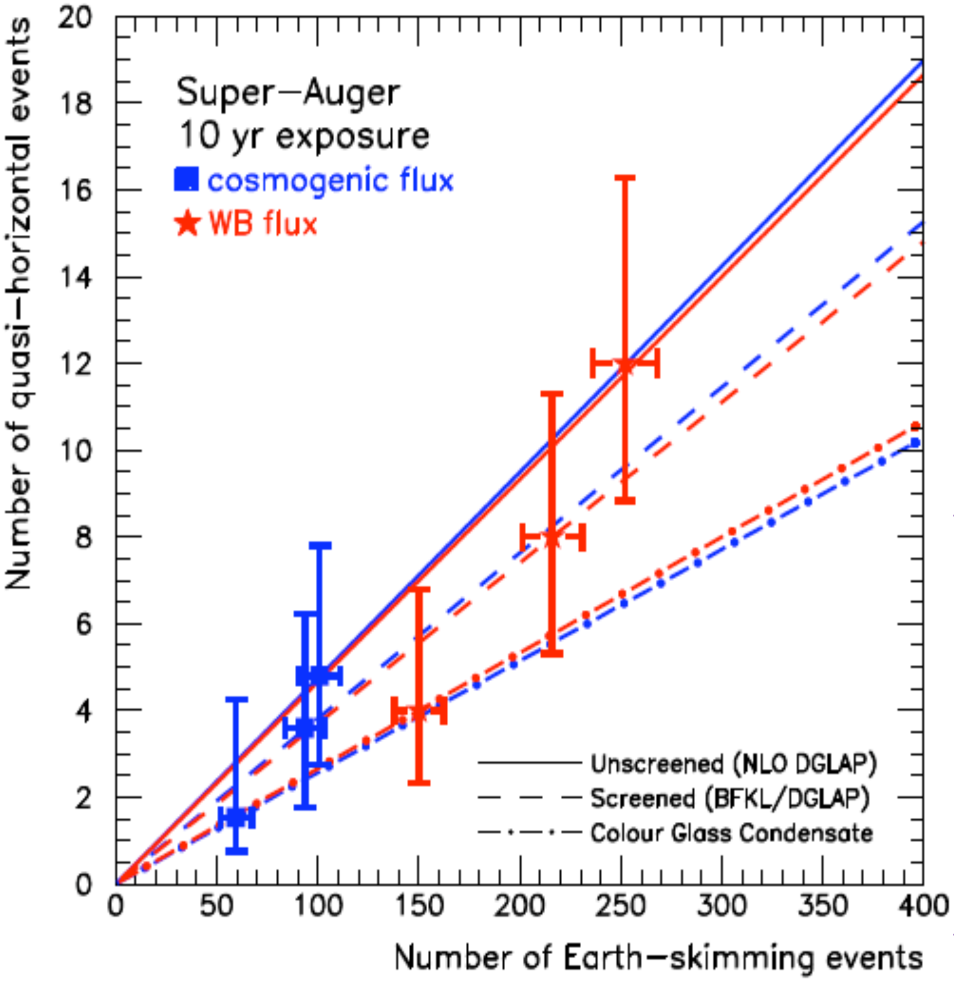
Auger also sees Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower

Rate ∞ cosmic neutrino flux, but *not* to ν-N #-secn



Beyond HERA: probing low-x QCD with cosmic UHE neutrinos





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

The ratio of quasi-horizontal (all flavour) and Earth-skimming (ν_τ) events is sensitive to the #-section

nchordoqui, Cooper-Sarkar, Hooper & S.S. Phys.Rev.D74:043008,2006

Summary

If you want to detect the "guaranteed" cosmogenic flux and learn interesting astrophysics + possible new physics, then

think BIG