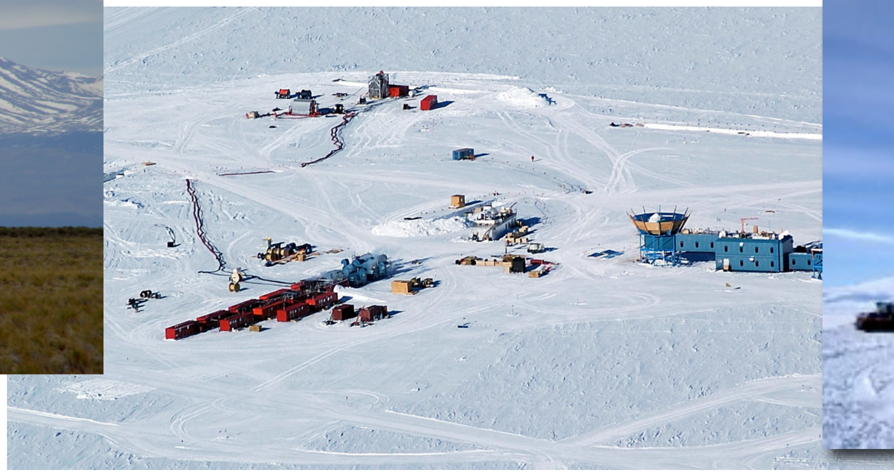
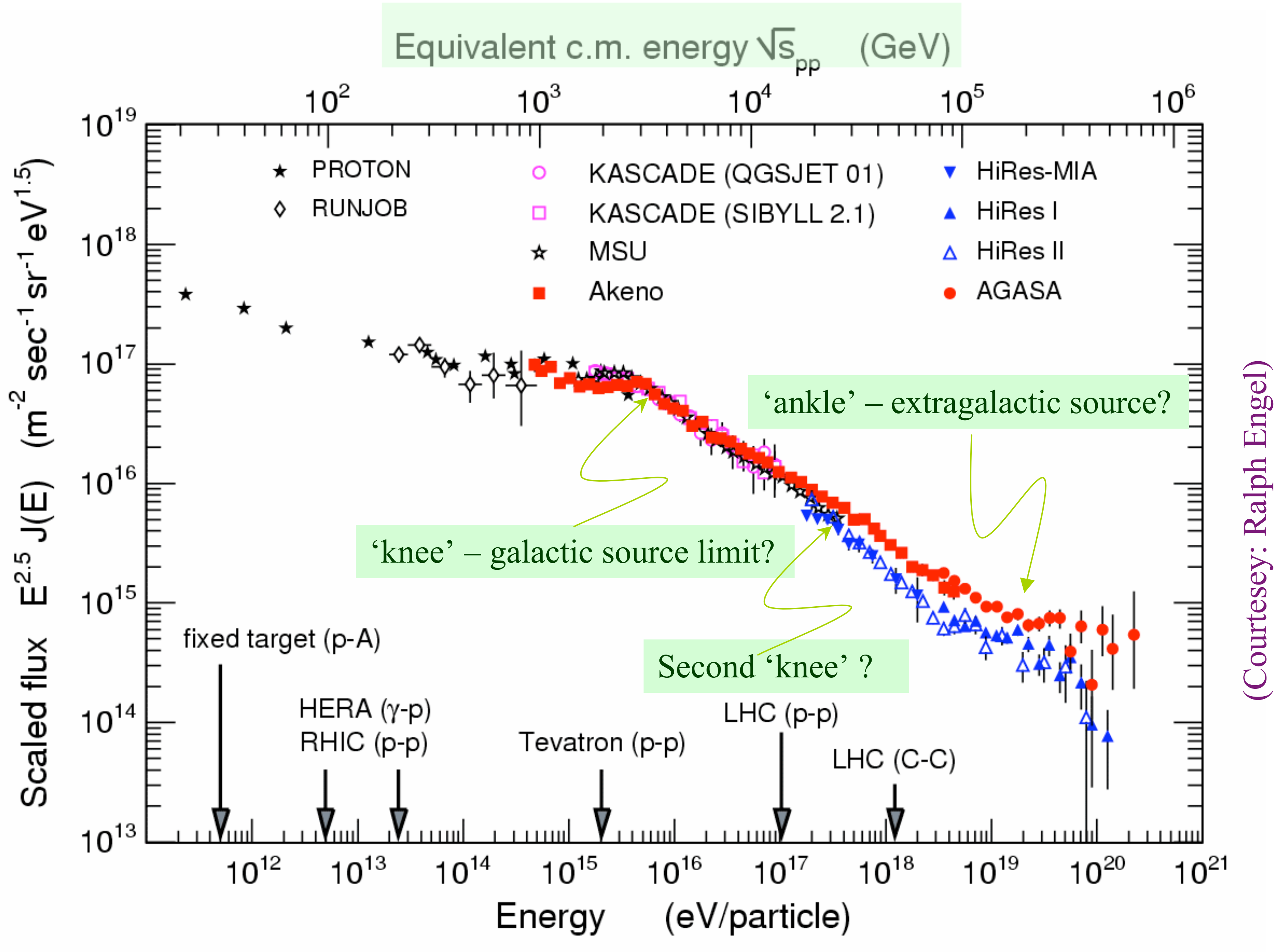
Implications of recent cosmic ray results for ultrahigh energy neutrinos


Subir Sarkar

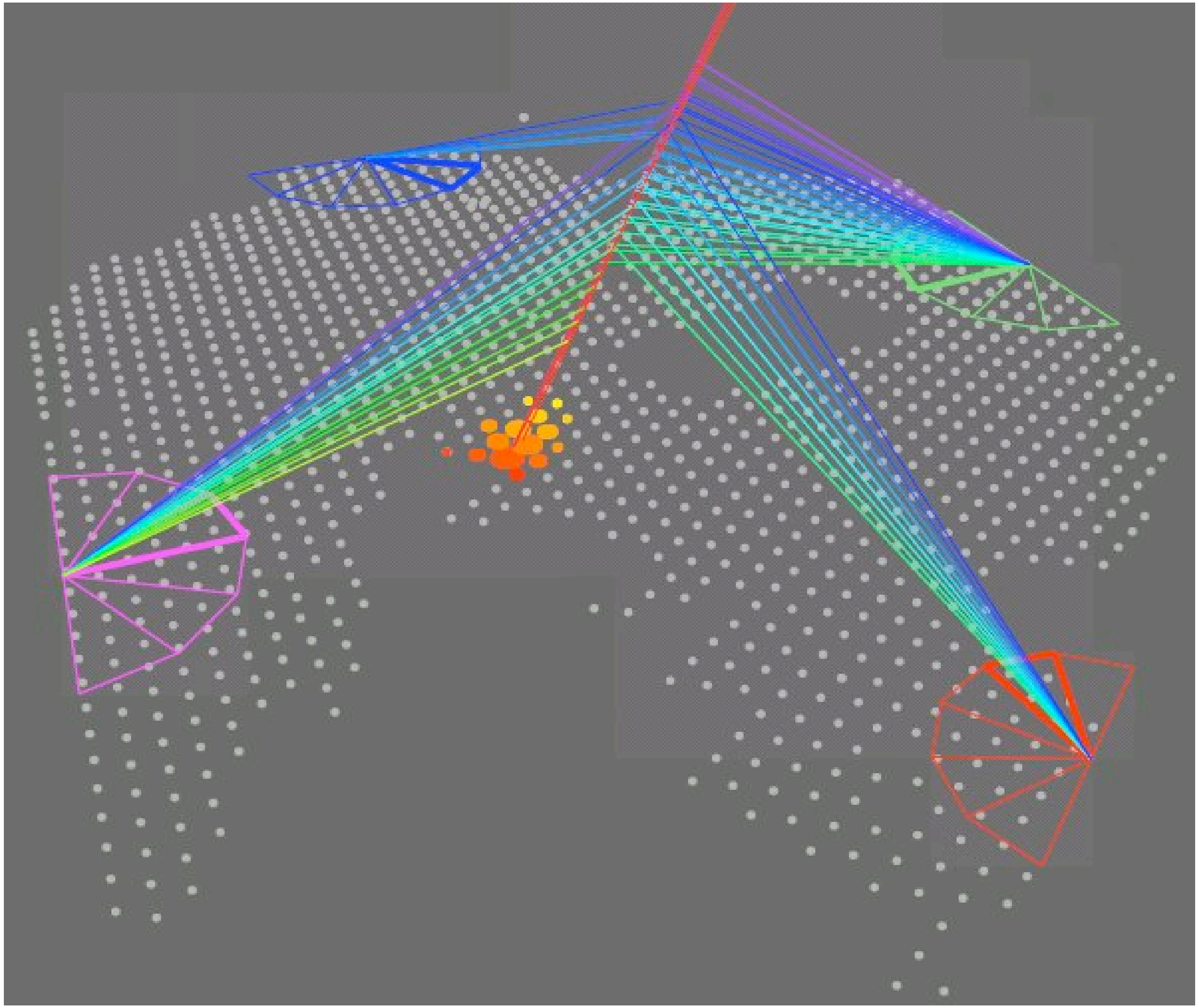

Neutrino 2008, Christchurch
31 May 2008


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

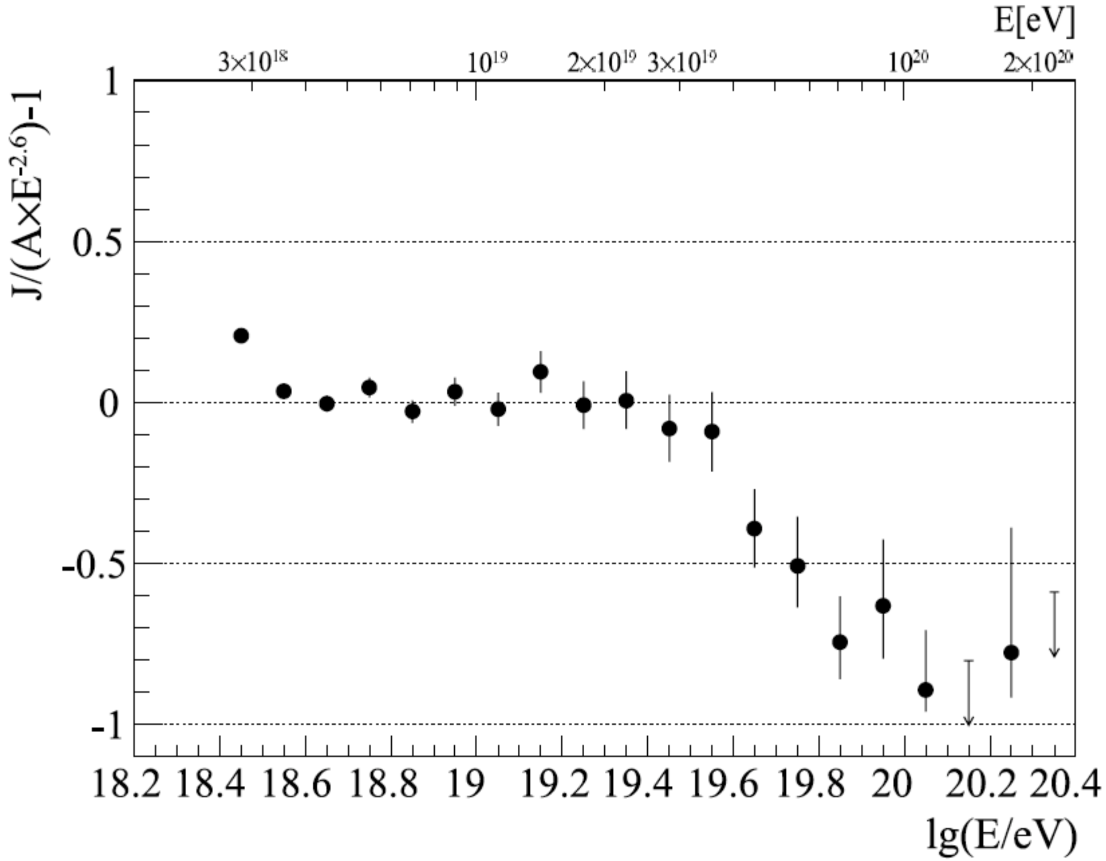


I will focus on the Auger results alone since its *hybrid* detection ability enables reliable determination of *both* the energy and the acceptance



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

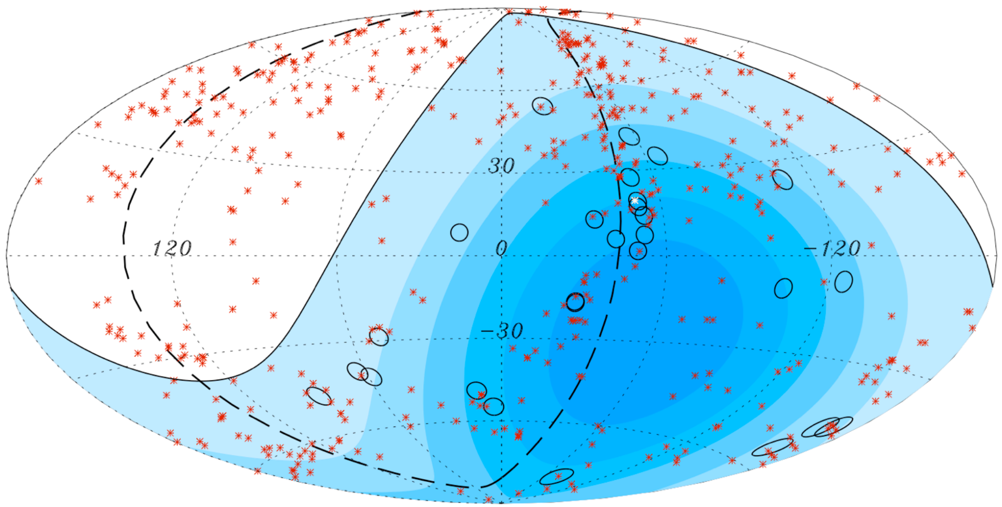
Recent cosmic ray results



The flux *is* suppressed beyond $\sim E_{GZK}$ [arXiv:0706.2096]

… but is it due to the GZK effect?

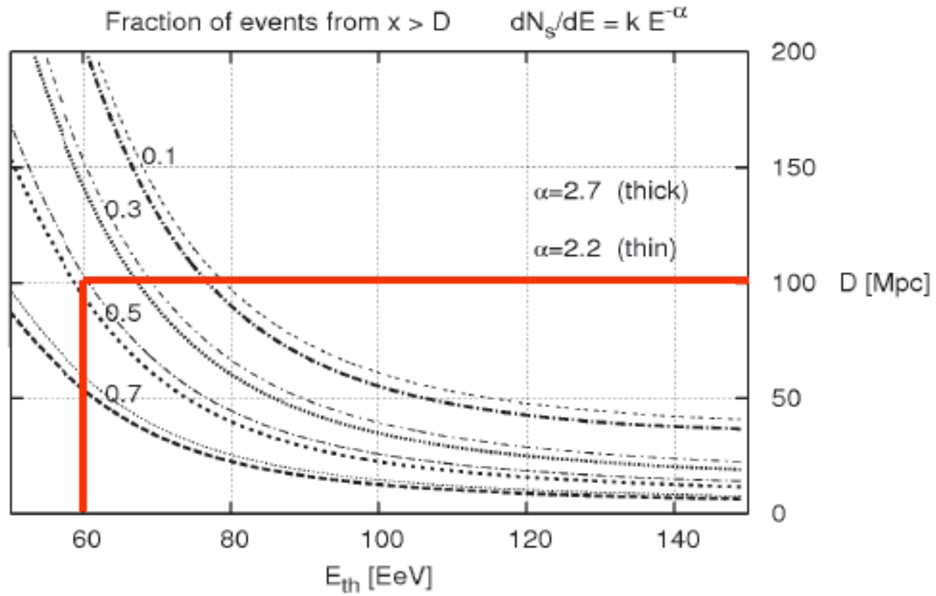
$$P + \gamma_{2.7\,K} \rightarrow \Delta^{+}_{1232} \rightarrow p + \pi^{0}$$



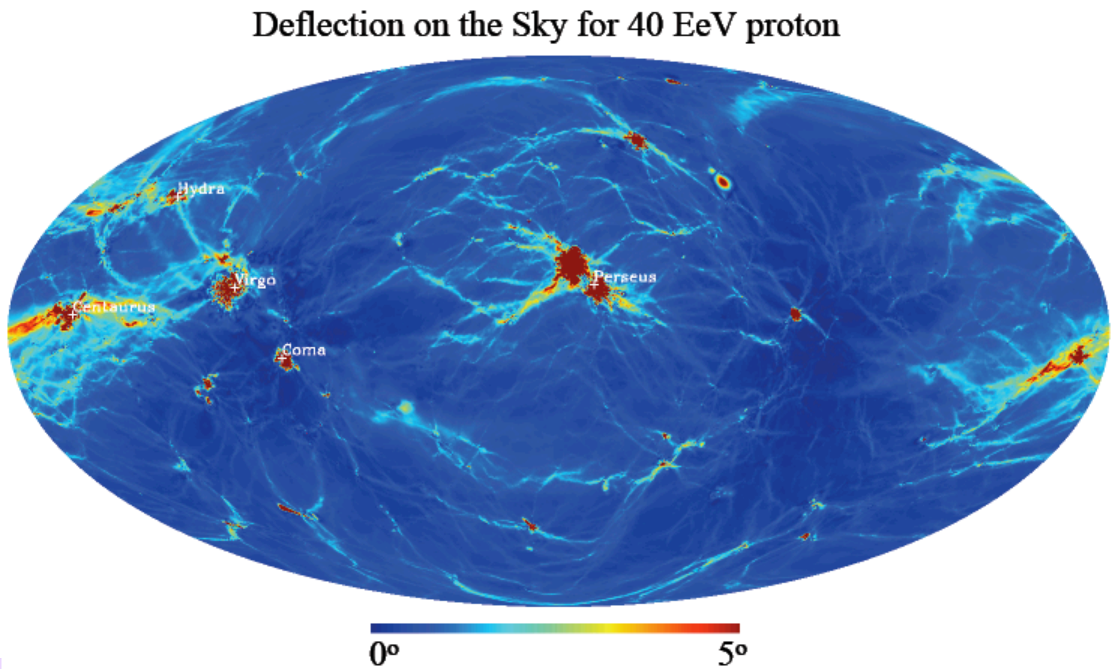
The arrival directions correlate with nearby AGN [arXiv:0711.2256]

… but are AGN really the sources?

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



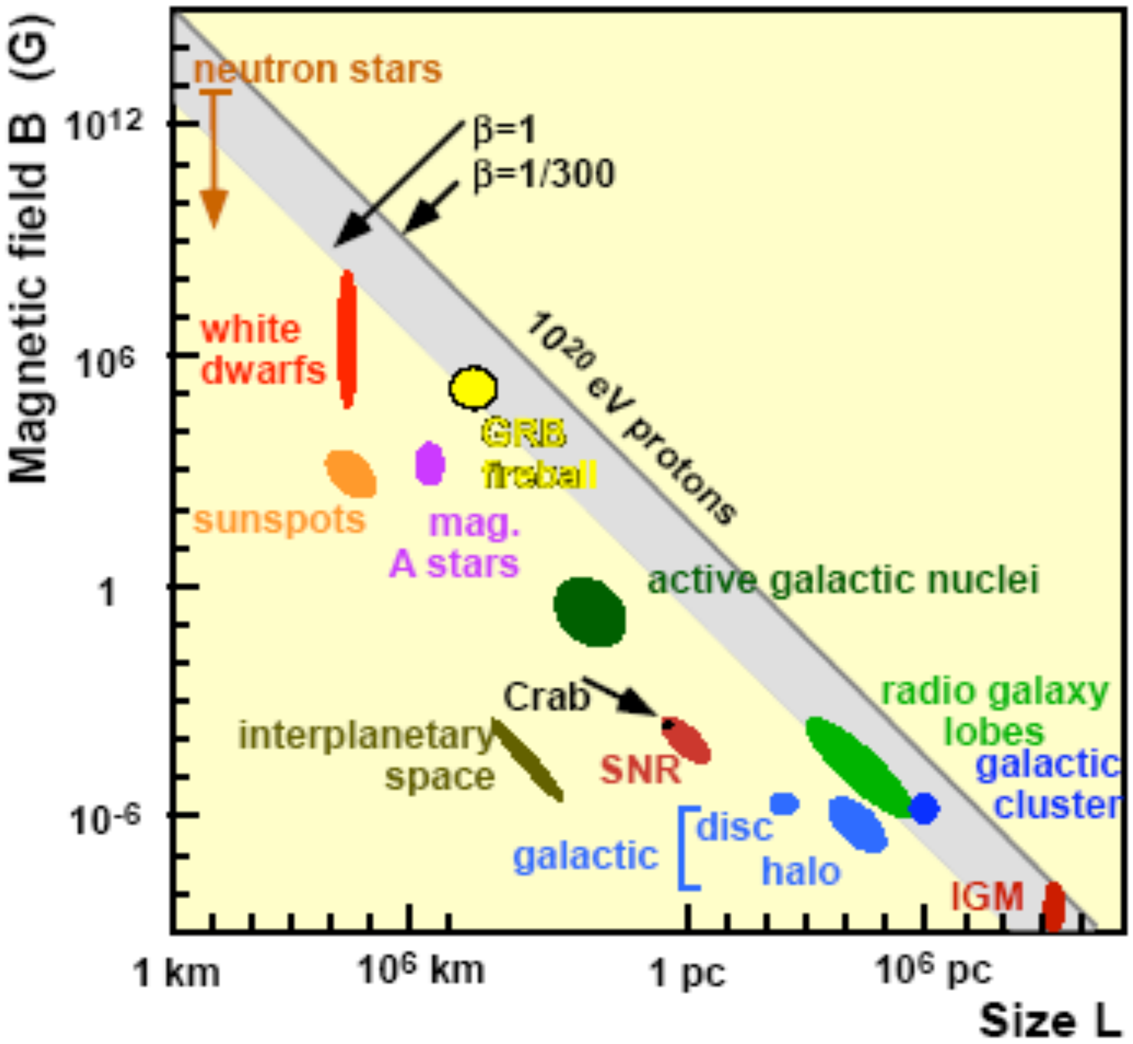
Harari, Mollerach & Roulet (2006)



Dolag, Grasso, Springel & Tkachev (2003)

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

Are there any plausible cosmic accelerators for such enormous energies?



A.M. Hillas 1984

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

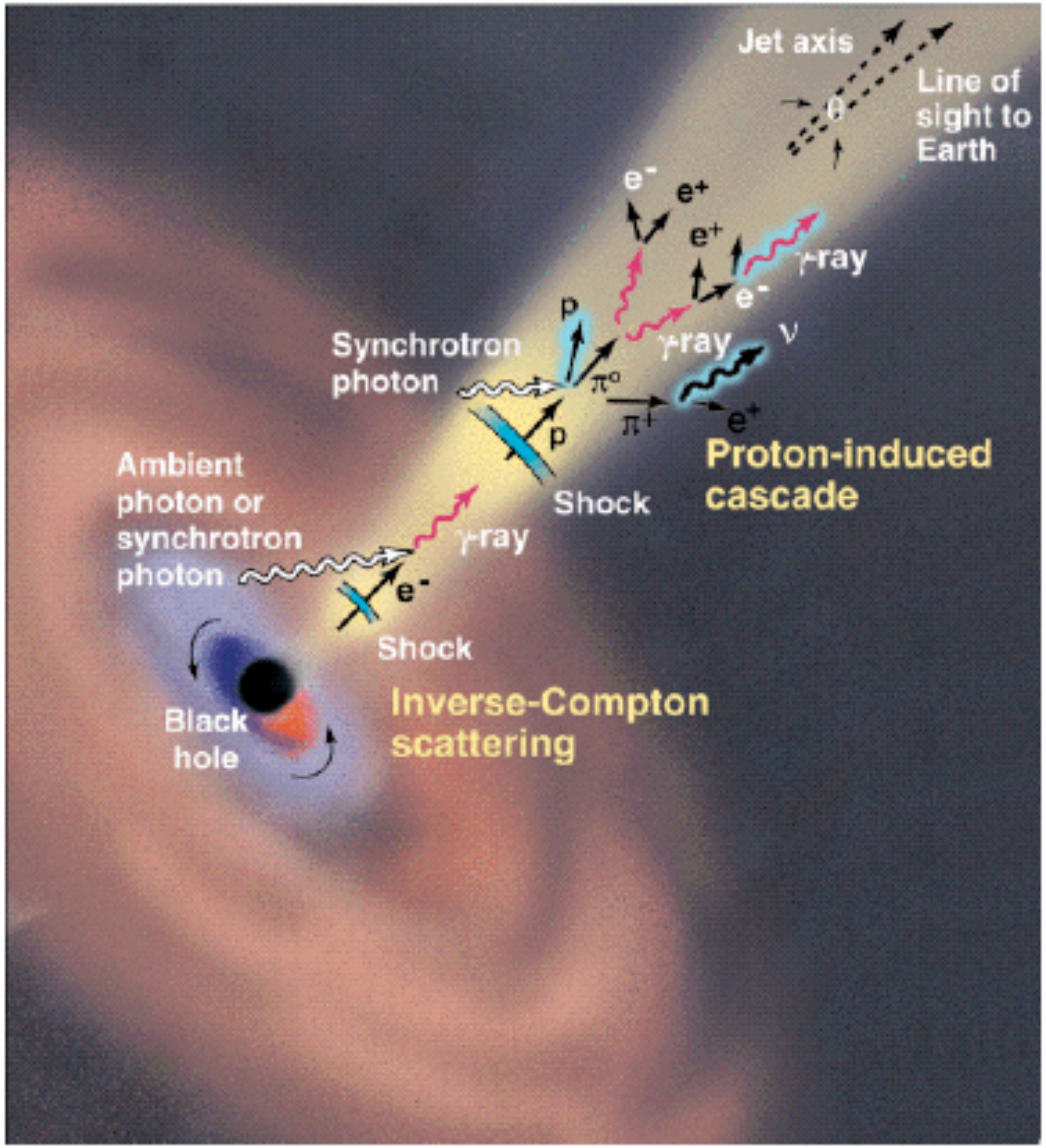
$B_{\mu G} \times L_{kpc} > 2\ (c/v)\ E_{EeV} / Z$

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.

Easier to accelerate heavy nuclei

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



Active galactic nuclei

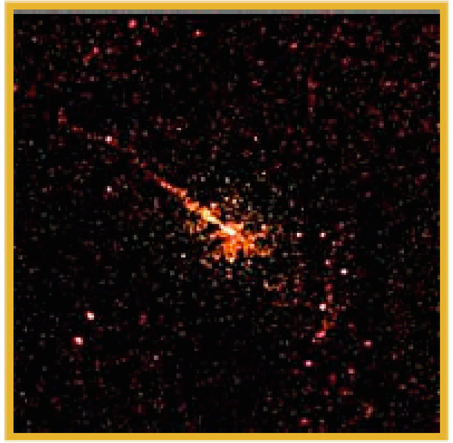
- Current paradigm:
  - **Synchrotron Self Compton**
  - External Compton
  - Proton Induced Cascades
  - Proton Synchrotron
- Energetics, mechanism for jet formation and collimation, nature of the plasma, and particle acceleration mechanisms are still poorly understood.

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

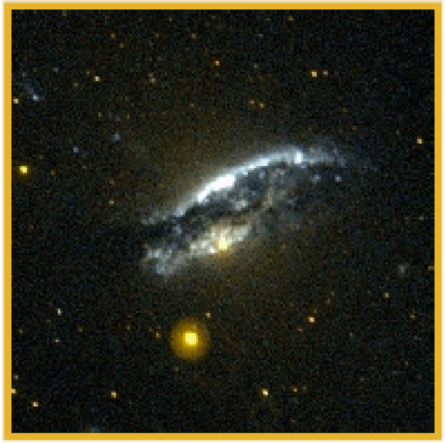
… renewed interest triggered by possible correlations with UHECRs - e.g. 2 Auger events within 3^0 of Cen A

Centaurus A – Peculiar Galaxy

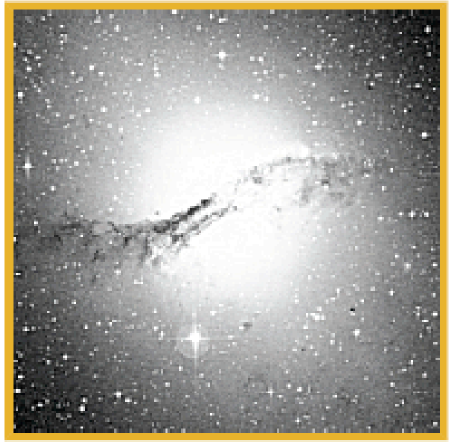
Distance: 11,000,000 ly light-years (3.4 Mpc) Image Size = 15 x 14 arcmin Visual Magnitude = 7.0



X-Ray: Chandra

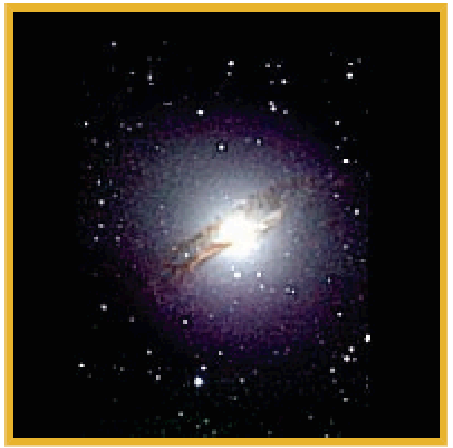


Ultraviolet: GALEX



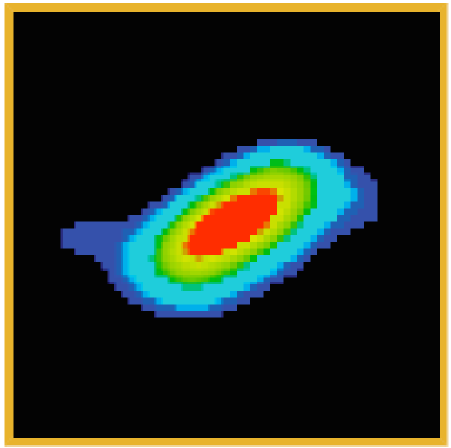
Visible: DSS

Visible: Color ©AAO

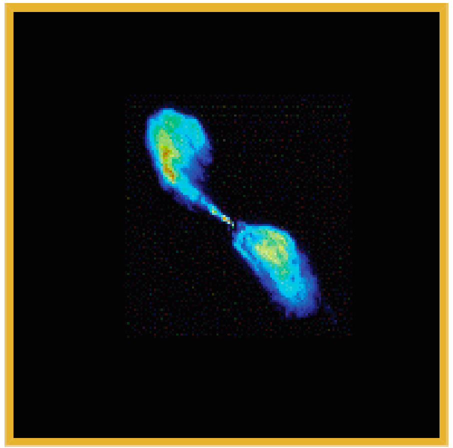


Near-Infrared: 2MASS

Mid-Infrared: Spitzer



Far-Infrared: IRAS



Radio: VLA

Estimate of ν flux from *p-p*:

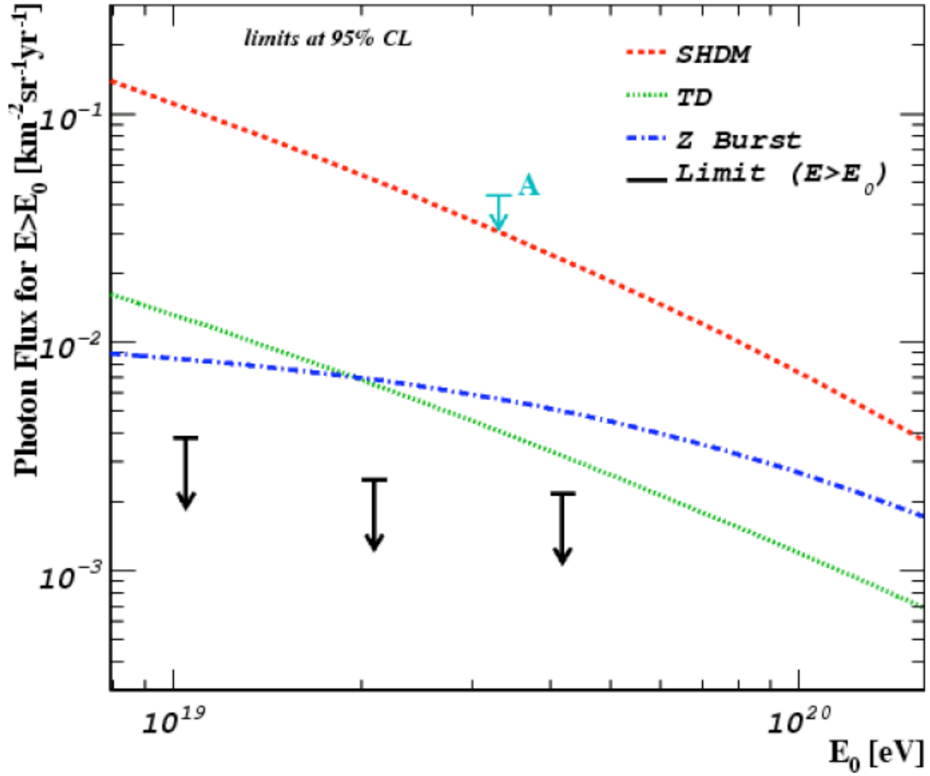
$$\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-2} \text{TeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}$$

⇒0.02-0.8 events/km^2 yr

Halzen & Murchadha [arXiv:0802.0887]

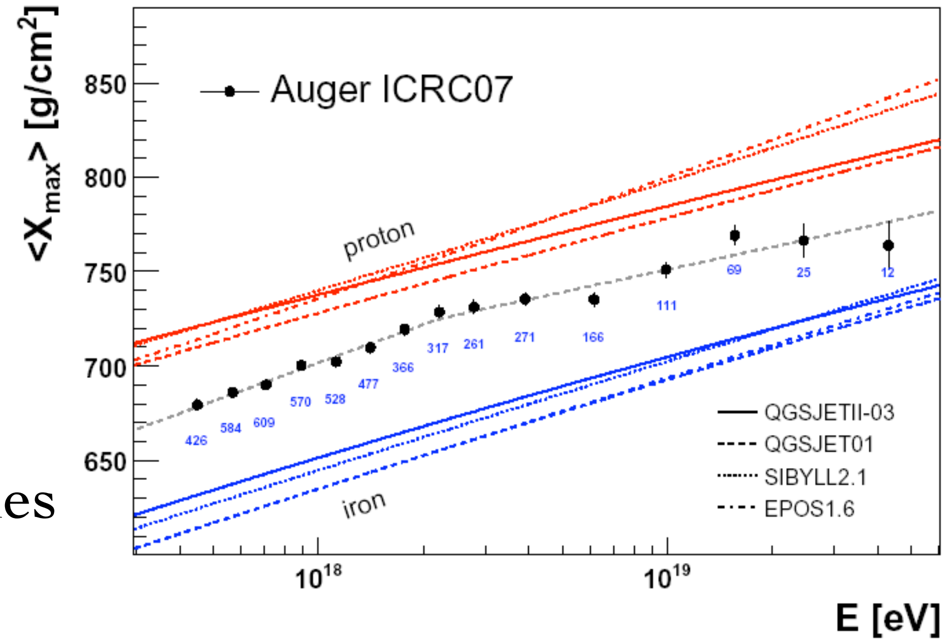
Recent cosmic ray results

The primaries are *not* photons
[arXiv:0712.1147]



… as predicted by 'top-down' models

… but may be heavy nuclei
[arXiv:0706.1495]



… easier to accelerate to such energies

What are the expectations for the *diffuse* neutrino background?

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 as is suggested by Auger data)

UHECR candidate accelerators (AGN, GRBs, …)

("Waxman-Bahcall flux" - normalised to extragalactic UHECR flux … sensitive to 'cross-over energy' above which they dominate, also to composition)

'Top down' sources (superheavy dark matter, topological defects)

(motivated by AGASA events - predicts that photons dominate over nucleons … all such models are now ruled out by new photon limit from Auger)

It was proposed that UHECRs are produced *locally* in the Galactic halo from the decays of metastable supermassive dark matter particles

These can be produced at the end of inflation by the changing gravitational field

→ **energy spectrum** determined by QCD fragmentation
→ **composition** dominated by photons rather than nucleons
→ **anisotropy** due to our off-centre position

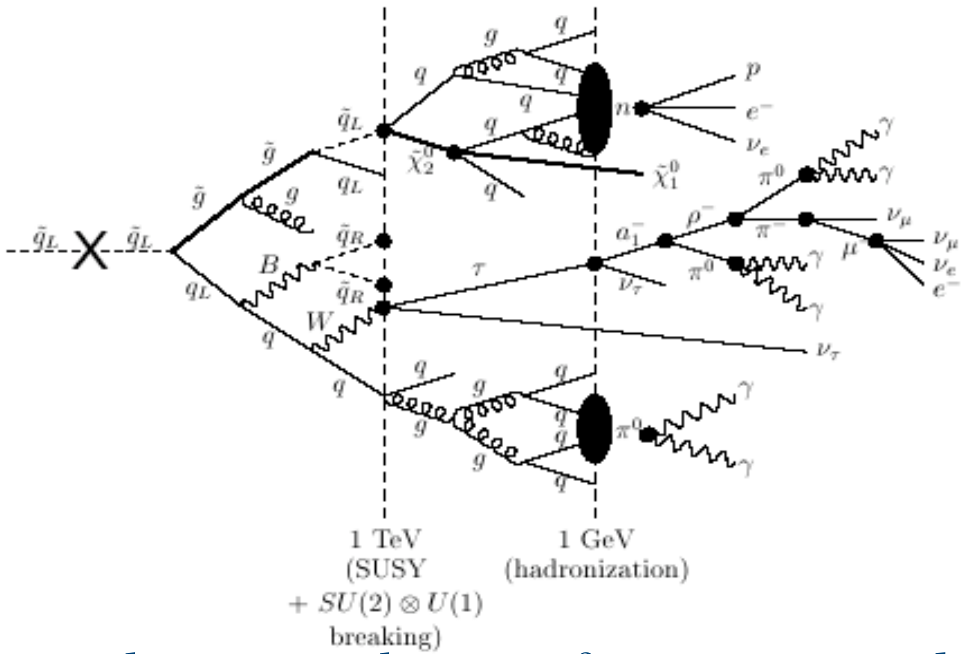
Simulation of galaxy halo (Stoehr *et al* 2003)

(Berezinsky, Kachelreiss & Vilenkin 1997; Birkel & S.S. 1998)

Modelling SHDM (or TD) decay

Most of the energy is released as neutrinos with some photons and a few nucleons …

X → partons → jets (→ ~90% ν, 8% γ + 2% p+n)



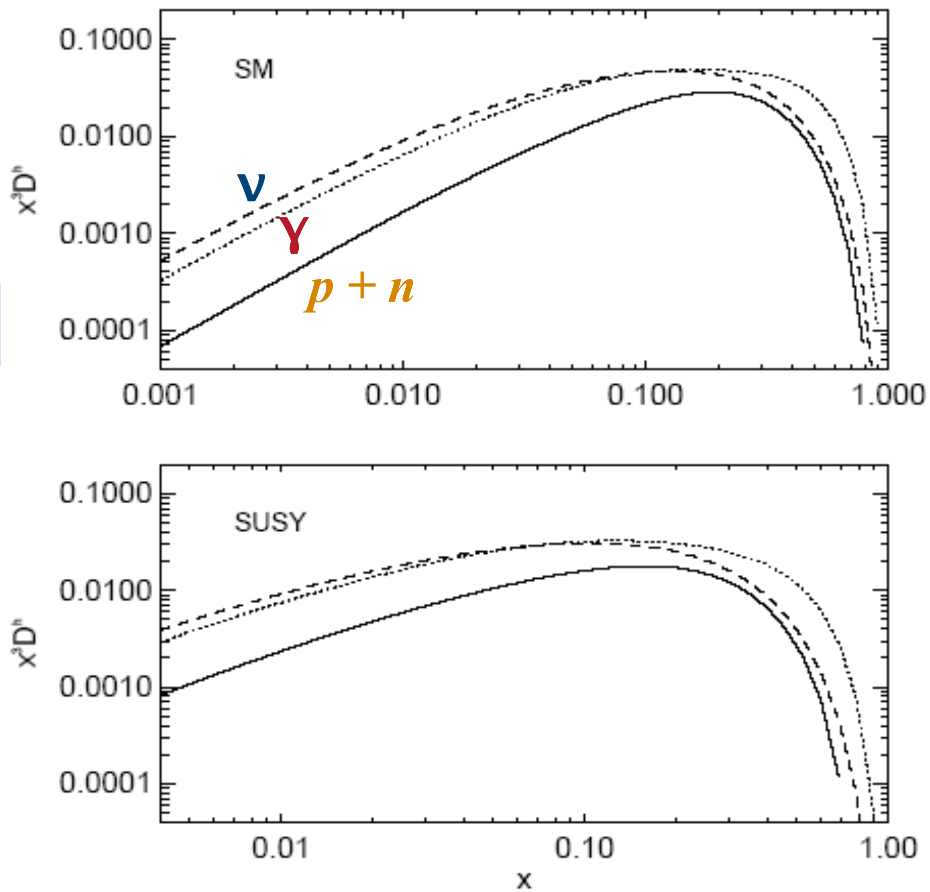


FIG. 6. Fragmentation functions for baryons (solid lines), photons (dotted lines) and neutrinos (dashed lines) evolved from M_Z up to $M_X = 10^{12}$ GeV for the SM (top panel) and for SUSY with $M_{\rm SUSY} = 400$ GeV (bottom panel).

Perturbative evolution of parton cascade tracked using (SUSY) DGLAP equation … fragmentation modelled semi-empirically

The fragmentation spectrum shape *matches* the AGASA data at trans-GZK energies … but *bad* fit to Auger

(Toldra & S.S. 2002; Barbot & Drees 2003; Aloisio, Berezinsky & Kachelreiss 2004)

Such models are *falsifiable* … and now ruled out by photon limit from Auger!

The "guaranteed" cosmogenic neutrino flux

<u>GZK mechanism :</u>

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

- $n \rightarrow p + e^- + \bar{\nu}_e$
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

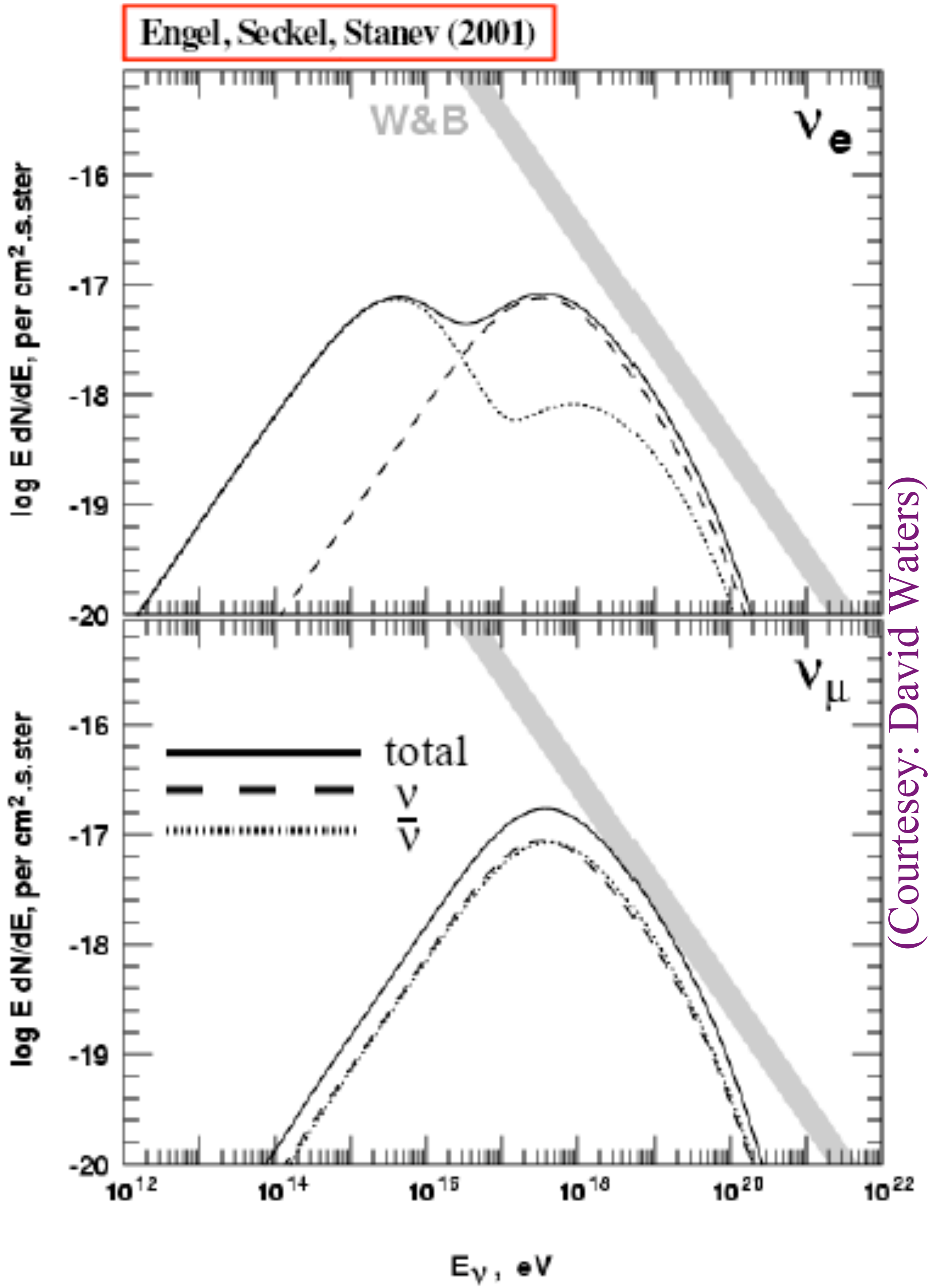
$E_{THRESH.} \sim 6 \times 10^{19}$ eV

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

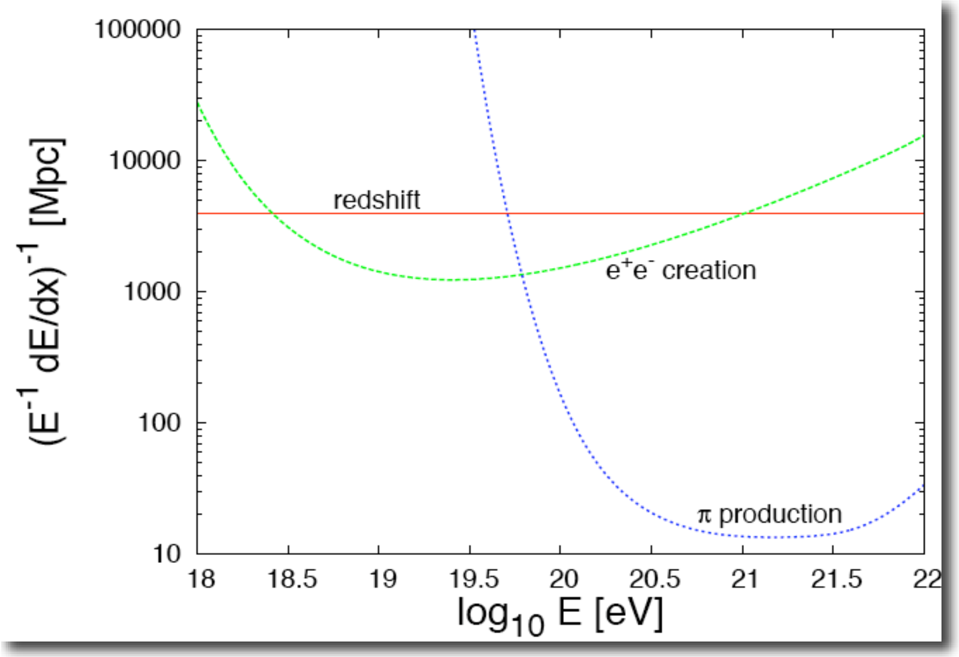
➡But what if the primaries are heavy nuclei?

… boosts ν_e flux but can suppress the ν_μ flux

Hooper, Taylor, S.S. (2004); Ave *et al* (2004)



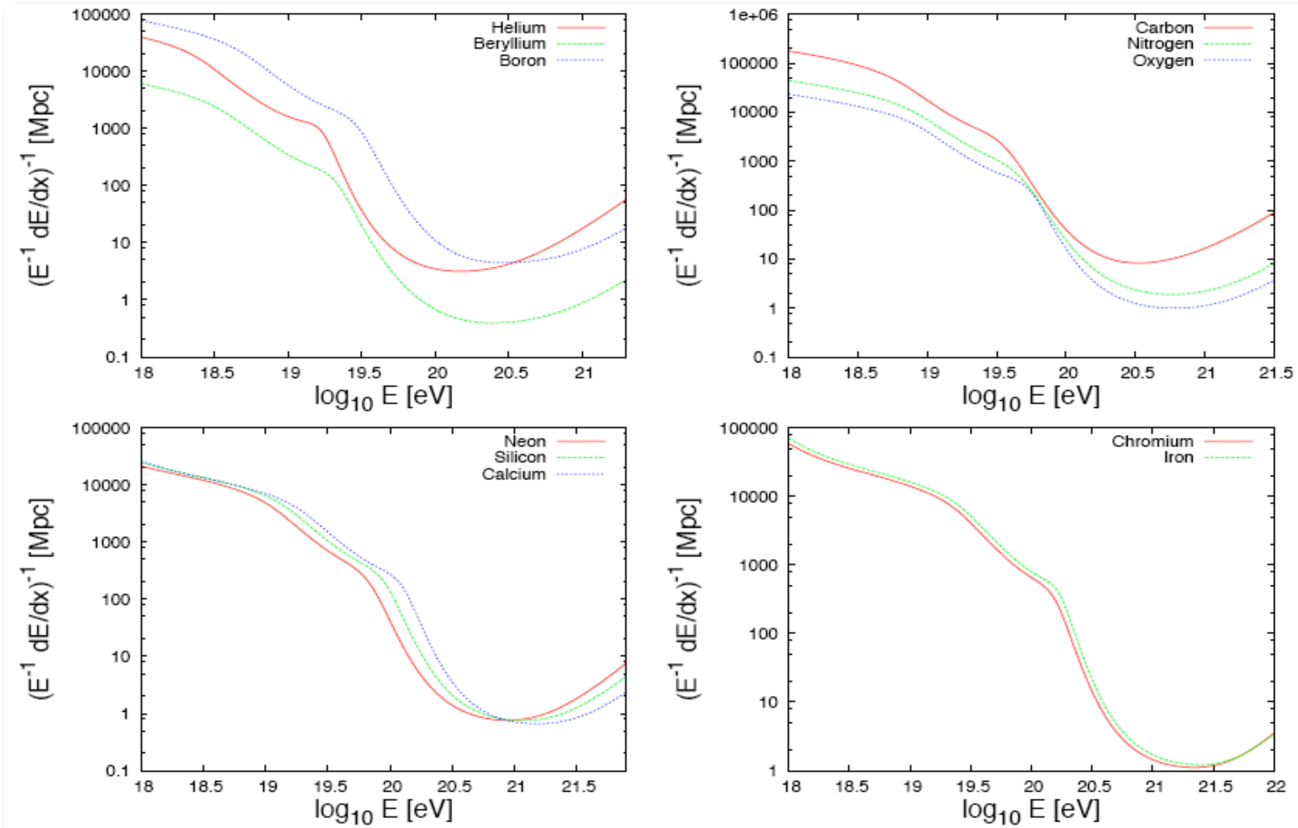
(Courtesey: David Waters)

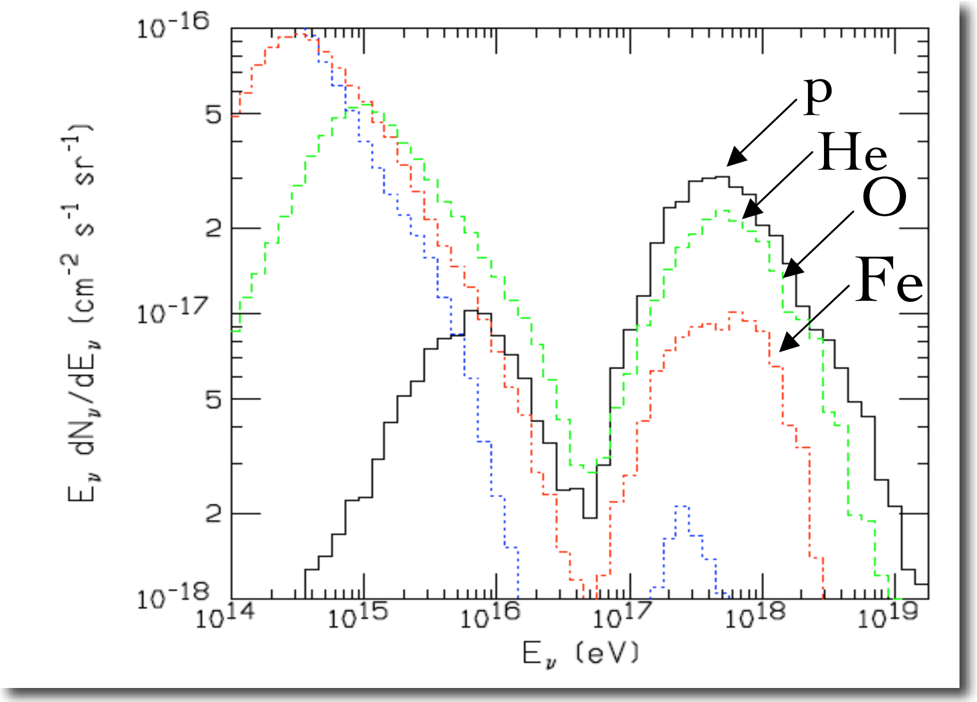


UHE protons lose energy mainly on the cosmic microwave background (CMB) … but UHE nuclei lose energy mainly on the cosmic infrared background (CIB) (now well-constrained by γ-ray data)

Hooper, S.S. & Taylor [astro-ph/0608085]

Small uncertainty due to unknowns in evolution of CIB and of source density with cosmic redshift … note that all *observed* cosmic rays come from z < 1



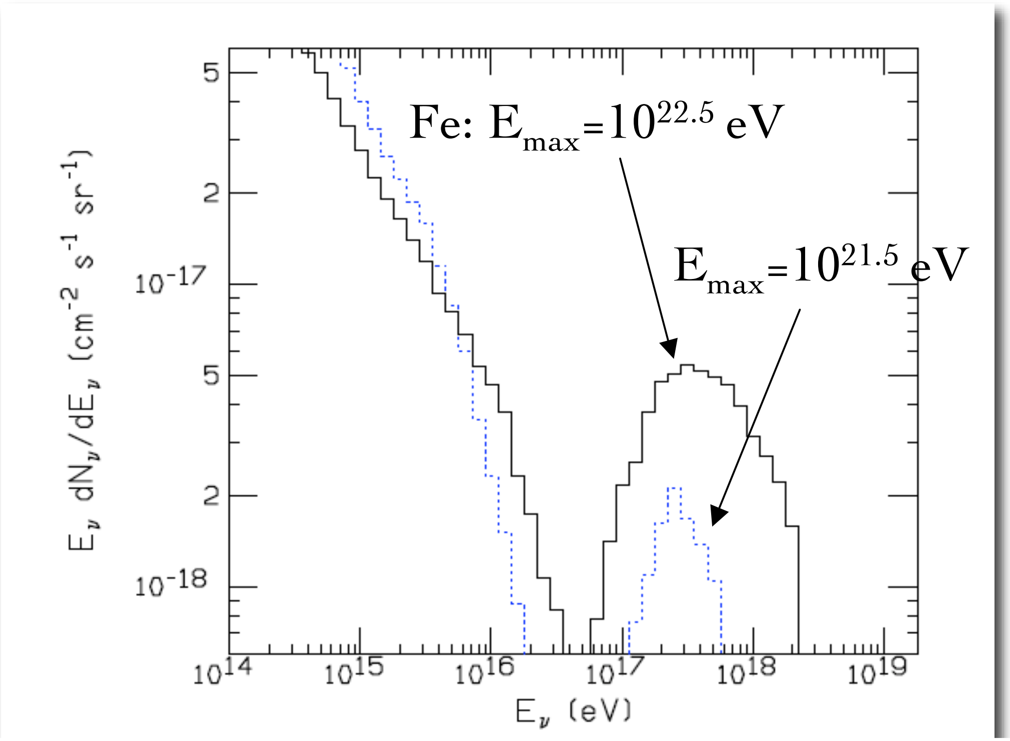


In order to contribute to the cosmogenic neutrino flux, the photo-disassociated protons must exceed the GZK cutoff in energy, hence the original nuclei must have energies > E_{GZK} x A

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

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

…



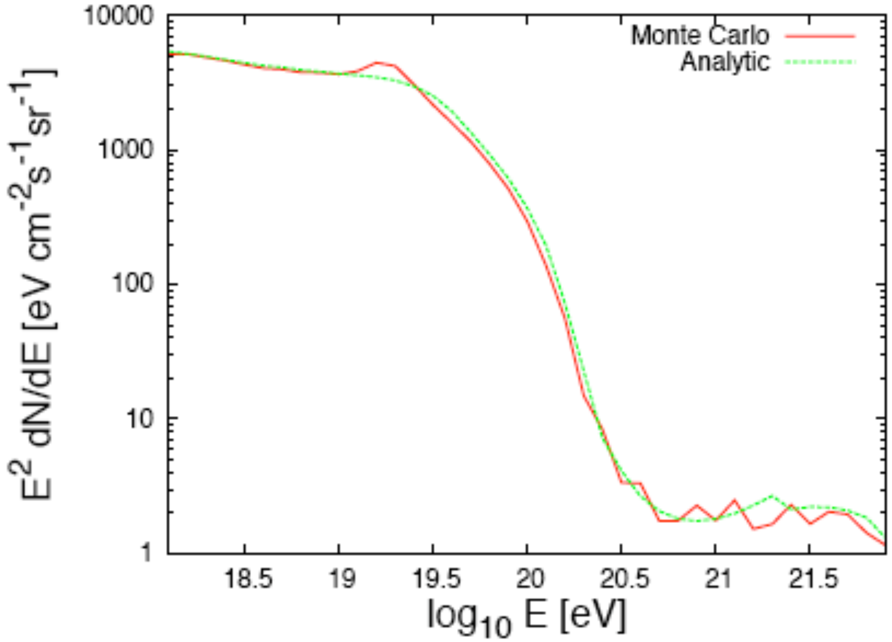
Hence the (lower energy) ν_e flux is boosted but the (higher energy) ν_μ flux is suppressed ⇒ **overall reduction in event rate** (but very sensitive to E_{max}!)

Analytic solution to photodisintegration of heavy cosmic ray nuclei on the CIB

$$\frac{\mathrm{d}N_1(E)}{\mathrm{d}L} = \frac{N_n(L,E_n)}{L_n(E_n)} + \frac{N_{n-1}(L,E_{n-1})}{L_{n-1}(E_{n-1})} + \ldots \frac{N_2(L,E_2)}{L_2(E_2)} \quad \Rightarrow \quad N_1(L',E_1) = \int_0^{L'} \mathrm{d}L \sum_{m=2}^{n} \frac{N_m(L,E_m)}{L_m(E_m)}$$

Obtain solution in *excellent* agreement with Monte Carlo simulations …

$$\frac{N_q(L,E_q)}{N_n(0,E)} = \sum_{m=q}^{n} L_q(E_q) L_m(E_m)^{n-q-1} \exp\left(\frac{-L}{L_m(E_m)}\right) \prod_{p=q(\neq m)}^{n} \frac{1}{L_m(E_m) - L_p(E_p)}$$



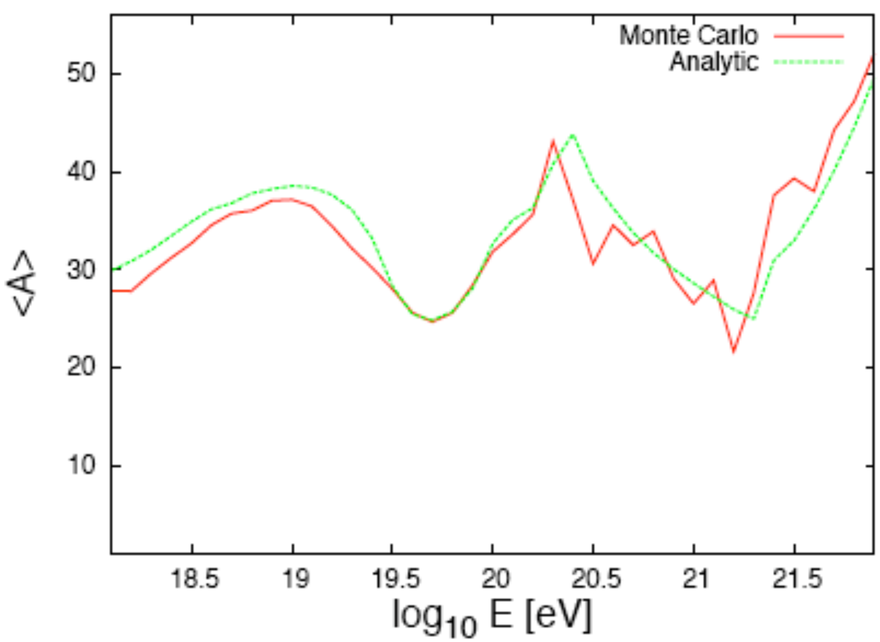
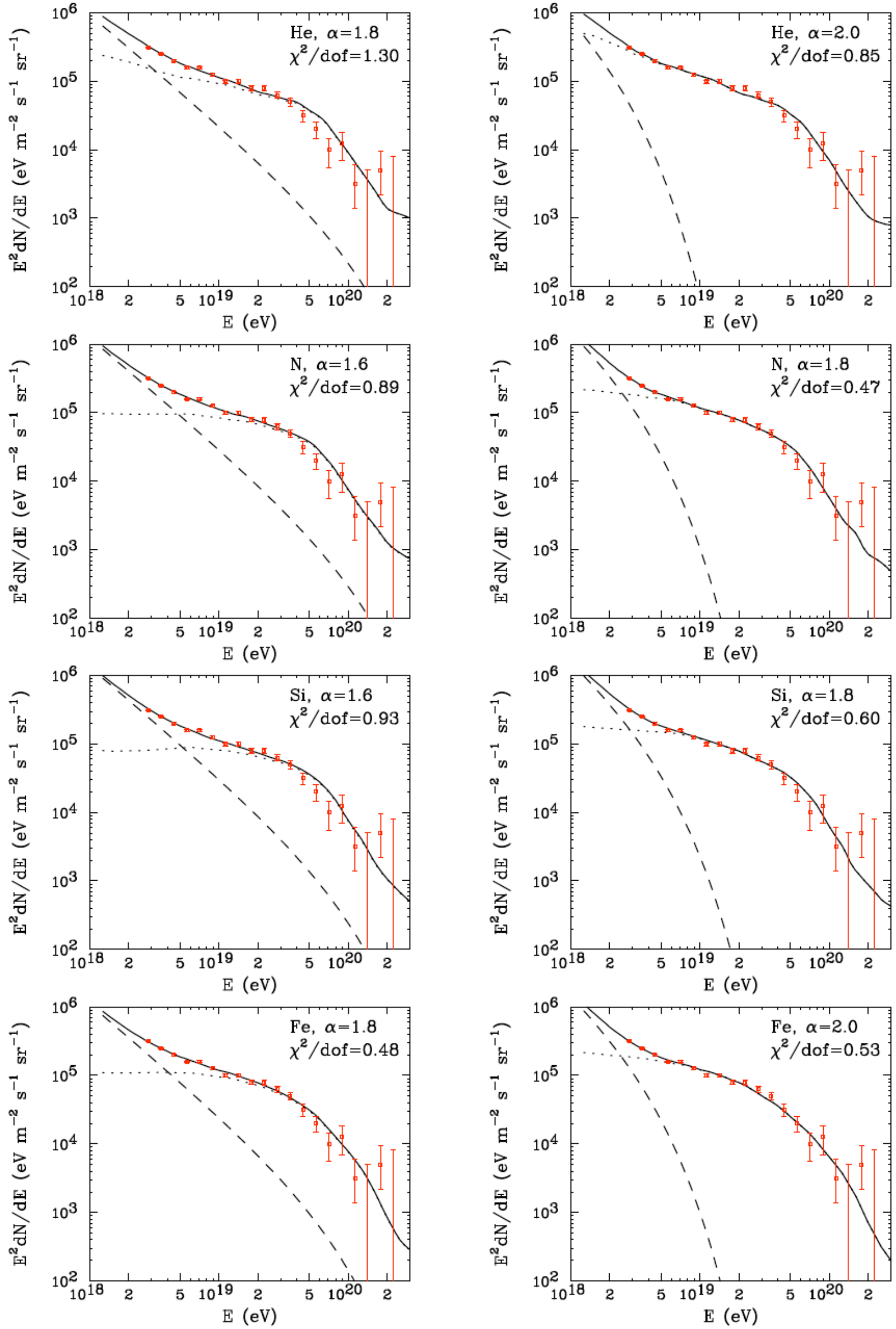
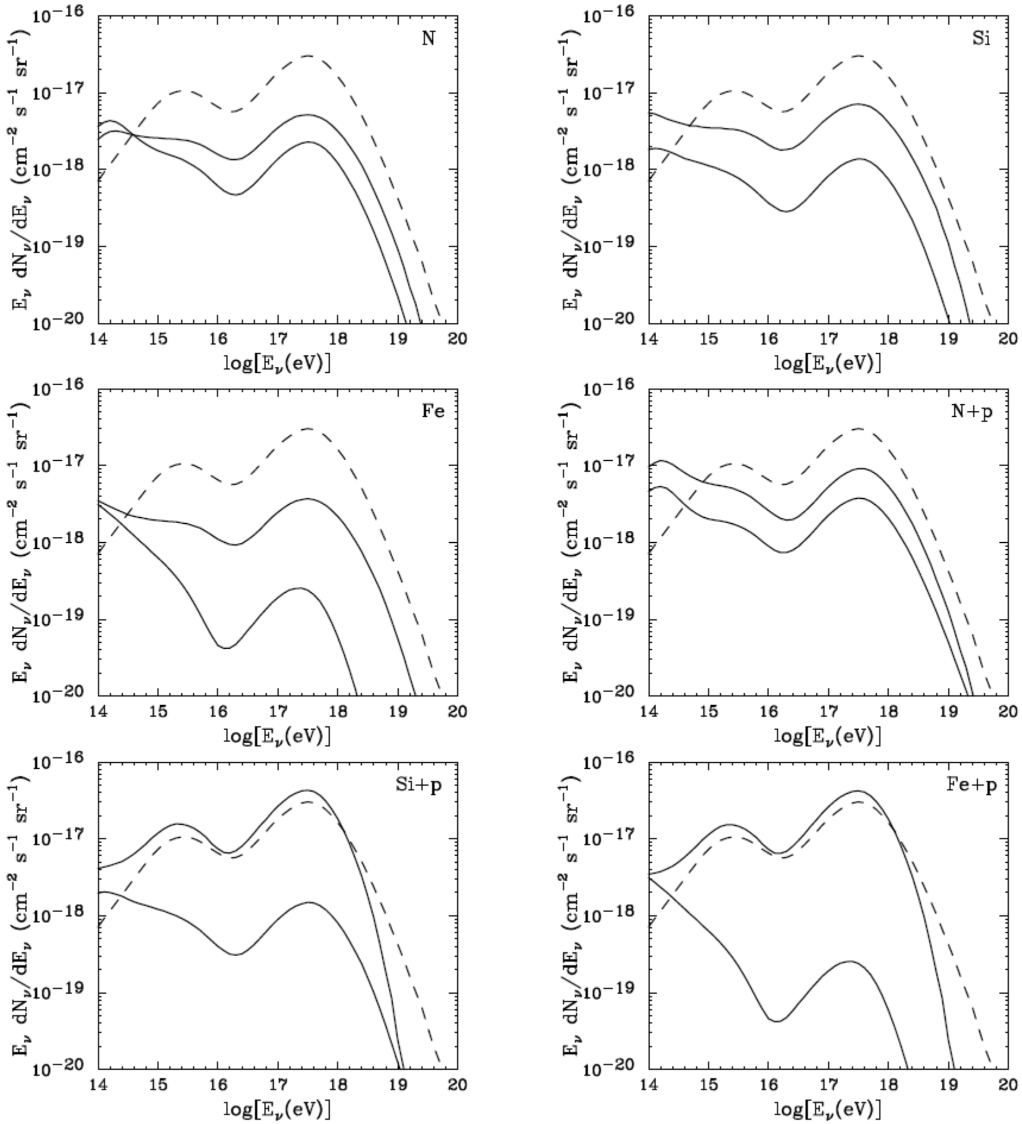


FIG. 4: The ultra-high energy cosmic ray spectrum (left) and average composition (right) calculated using both analytic and Monte Carlo techniques. These results are for the case of iron nuclei injected from a homogeneous distribution of sources with a spectrum of $\mathrm{d}N/\mathrm{d}N \propto E^{-2}$ up to a maximum energy of 5×10^{21} eV.

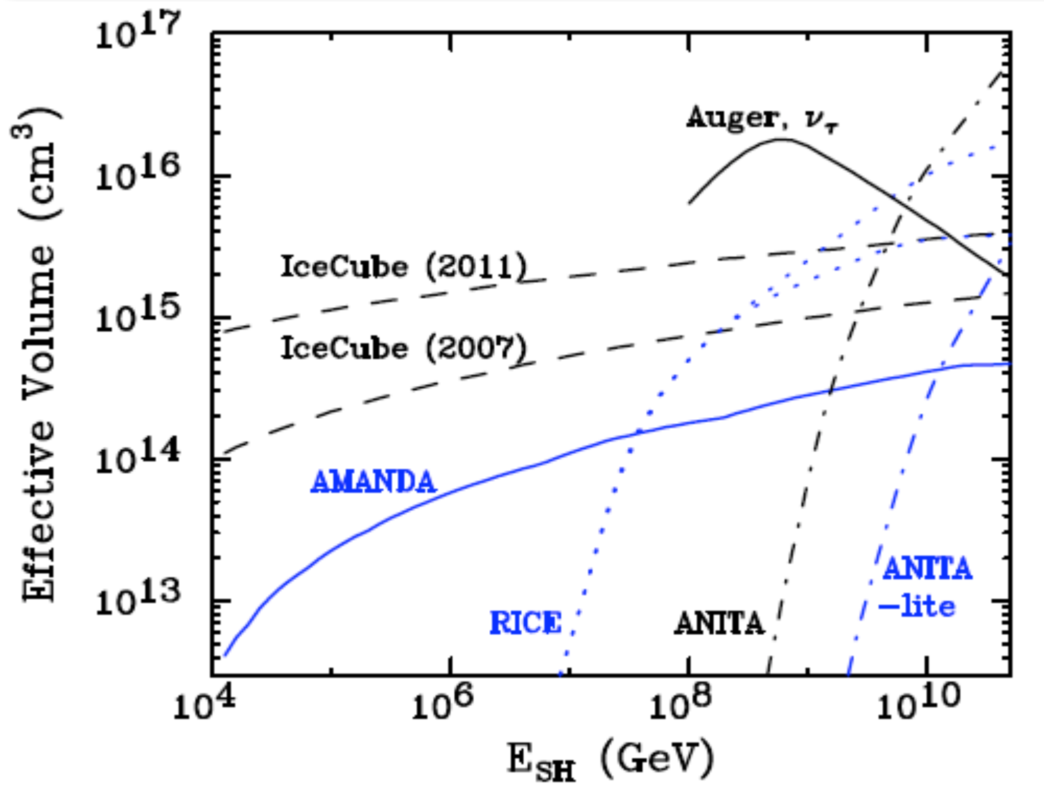
Hooper, S.S. & Taylor (2008)

Heavy nuclei as primaries are *consistent* with the observed energy spectrum and composition … but predict a *smaller* cosmogenic flux





Anchordoqui, Hooper, S.S. & Taylor [arXiv: 0709.0734]



Hence these estimated (cosmogenic ν) rates should now be considered as **upper limits**

	Event Rate	Current Exposure	2008 Exposure	2011 Exposure
AMANDA (300 hits)	0.044 yr^{-1}	3.3 yrs, 0.17 events	NA	NA
IceCube, 2007 (300 hits equiv.)	0.16 yr^{-1}	NA	0.4 events	NA
IceCube, 2011 (300 hits equiv.)	0.49 yr^{-1}	NA	NA	1.2 events
RICE	$\sim$ 0.07 yr^{-1}	2.3 yrs, 0.1-0.2 events	0.2-0.3 events	0.3-0.4 events
ANITA-lite	0.009 per flight [15]	1 flight, 0.009 events	NA	NA
ANITA	$\sim$ 1 per flight	NA	1 flight, $\sim$ 1 event	3 flights, $\sim$ 3 events
Pierre Auger Observatory	1.3 yr^{-1} [19]	NA	$\sim$ 2 events	$\sim$ 5 events

Halzen and Hooper [astro-ph/0605103]

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 :

$$[E_\nu^2 \Phi_\nu]_{\rm WB} \approx (3/8)\, \xi_Z\, \epsilon_\pi\, t_{\rm H}\, \frac{c}{4\pi}\, E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$$

Fraction of CR primary energy converted to neutrinos

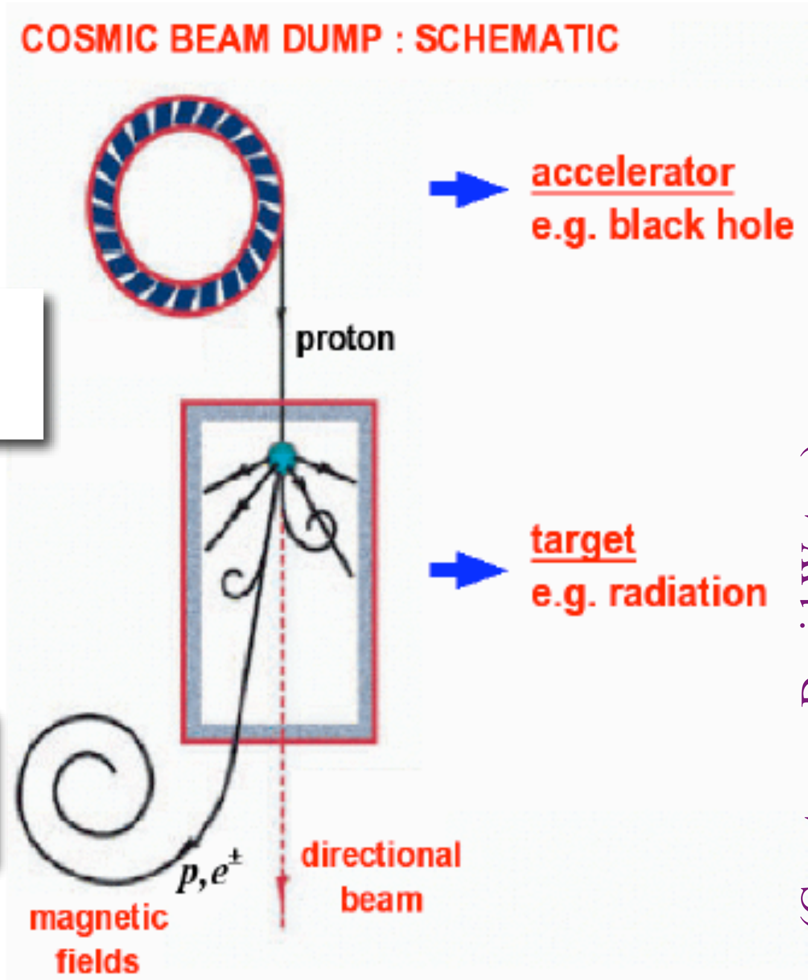
Hubble time

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

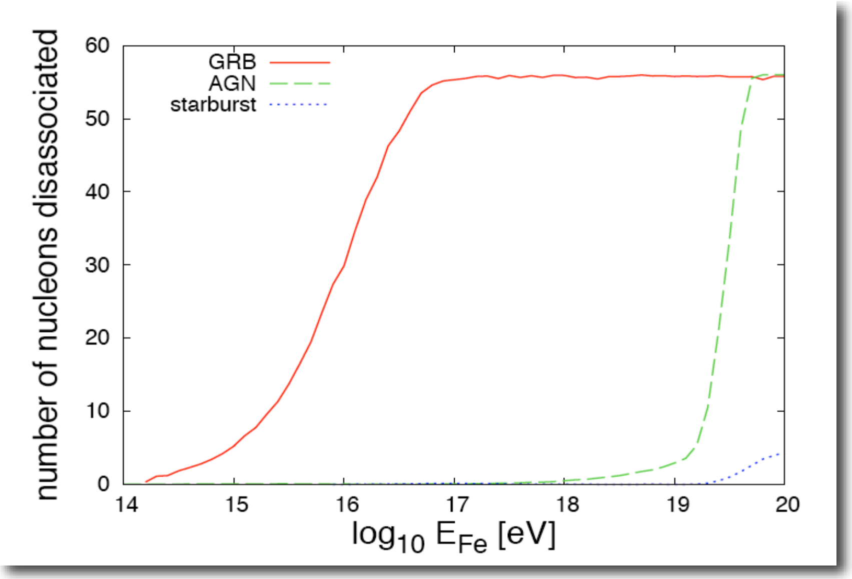
$$\approx 2.3 \times 10^{-8}\, \epsilon_\pi\, \xi_Z\, \mathrm{GeV\, cm^{-2}\, s^{-1}\, sr^{-1}}$$

➡Making a reasonable assumption about ϵ_π allows this to be converted into a flux prediction

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



(Courtesey: David Waters)

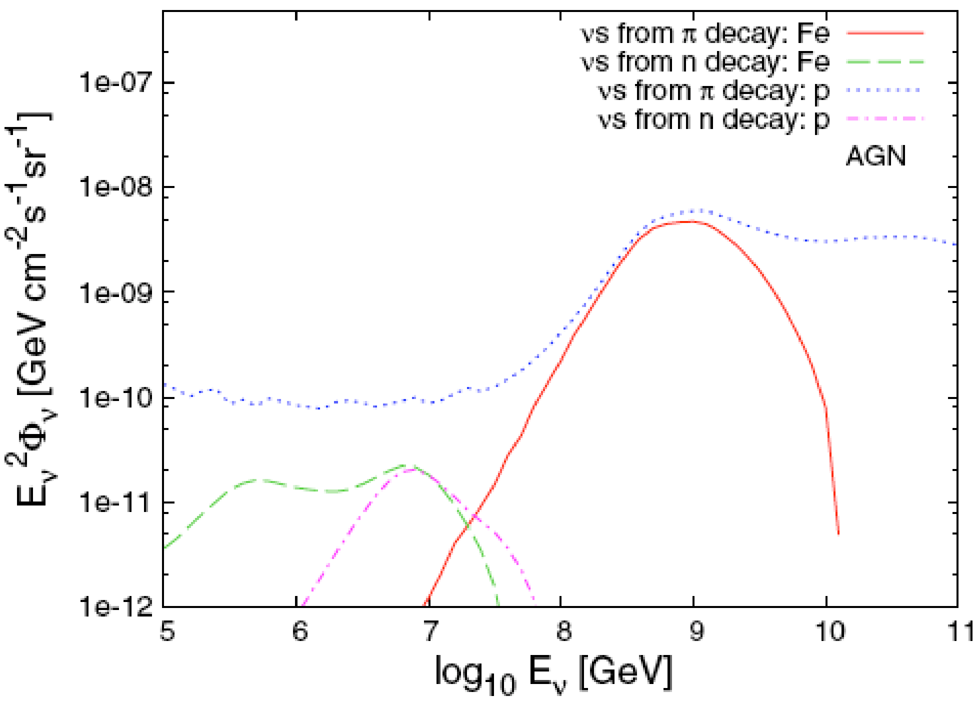


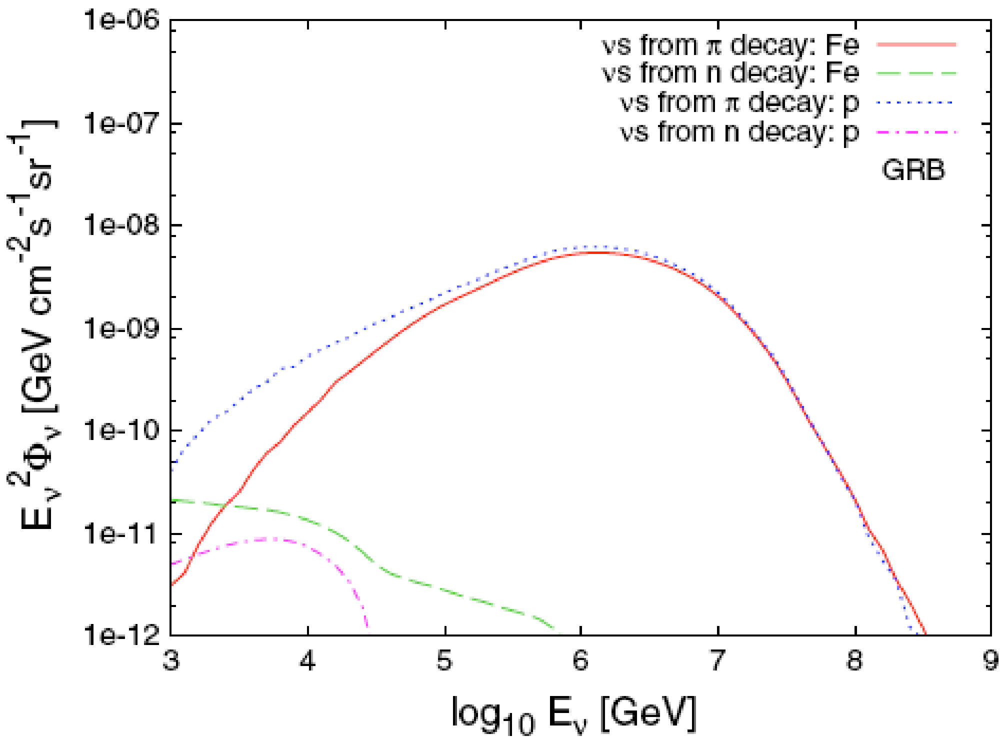
We have studied whether high energy nuclei can survive photodisintegration by the (known or estimated) photon fields in suggested extragalactic sources of cosmic rays … the answer is **no** for GRBs, **yes** for starburst galaxies, and **in between** (energy-dependent) for AGNS

Hence the effect on the expected WB flux depends on what the actual sources are … e.g. a bi-modal model would yield:

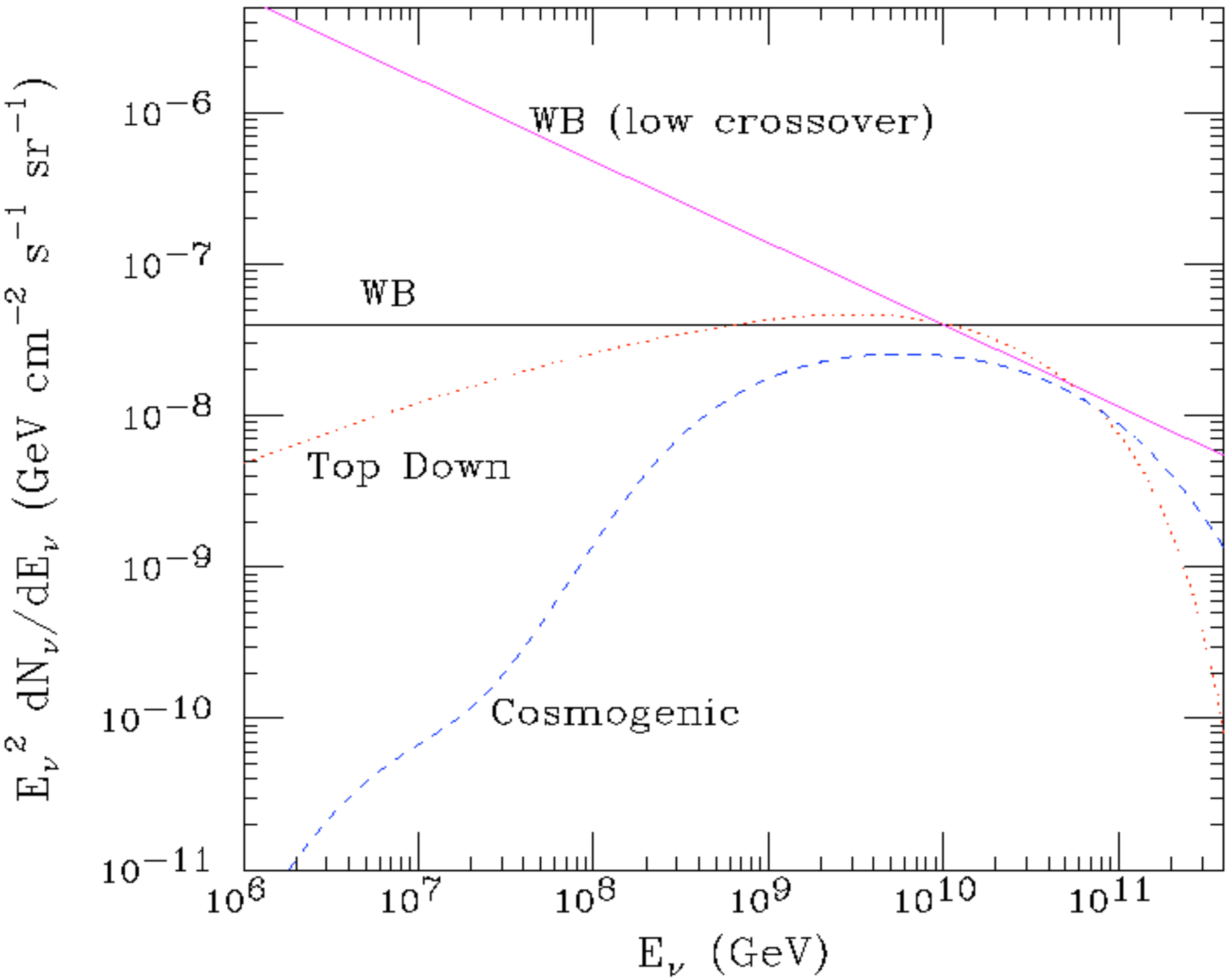
$$E^2 \varphi_\nu \sim 10^{-9} \text{ cm}^{-2} \text{ sec}^{-1} \text{ st}^{-1}$$

Anchordoqui, Hooper, SS & Taylor, astro-ph/0703001





Upper limits to UHE cosmic neutrino fluxes



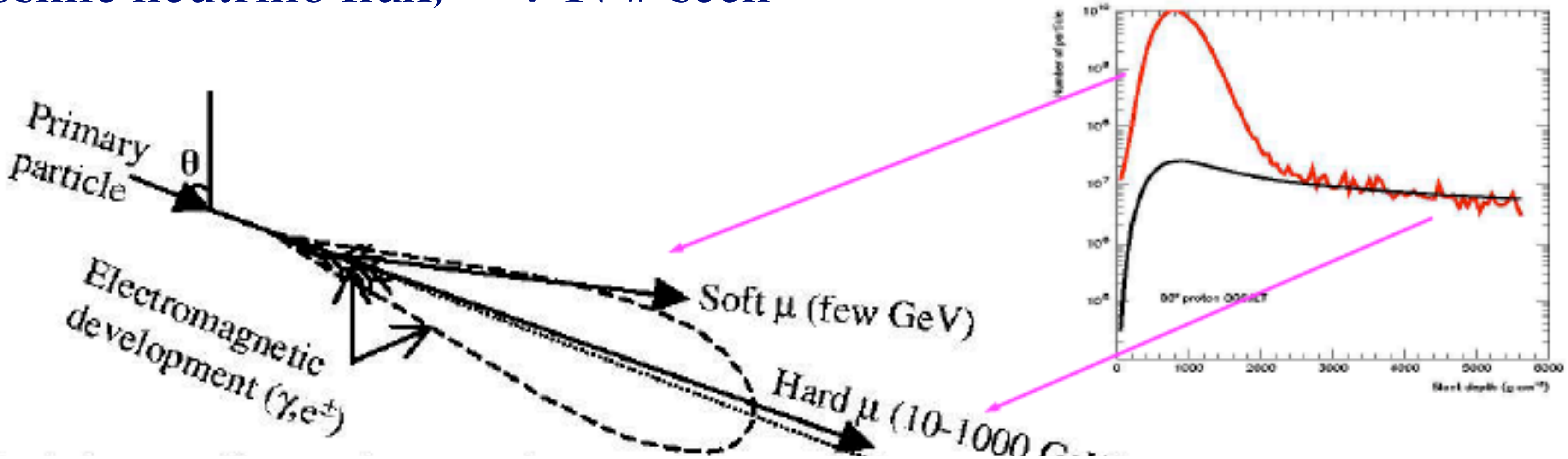
Limits from AMANDA/IceCube so far constrain the WB flux only in models where extragalactic sources are assumed to dominate from as low as ~10^{18} eV (Ahlers *et al* 2005)

To see the cosmogenic ν flux will require larger detection volume (ANITA, …)

An unexpected bonus – UHE neutrino detection with air shower arrays

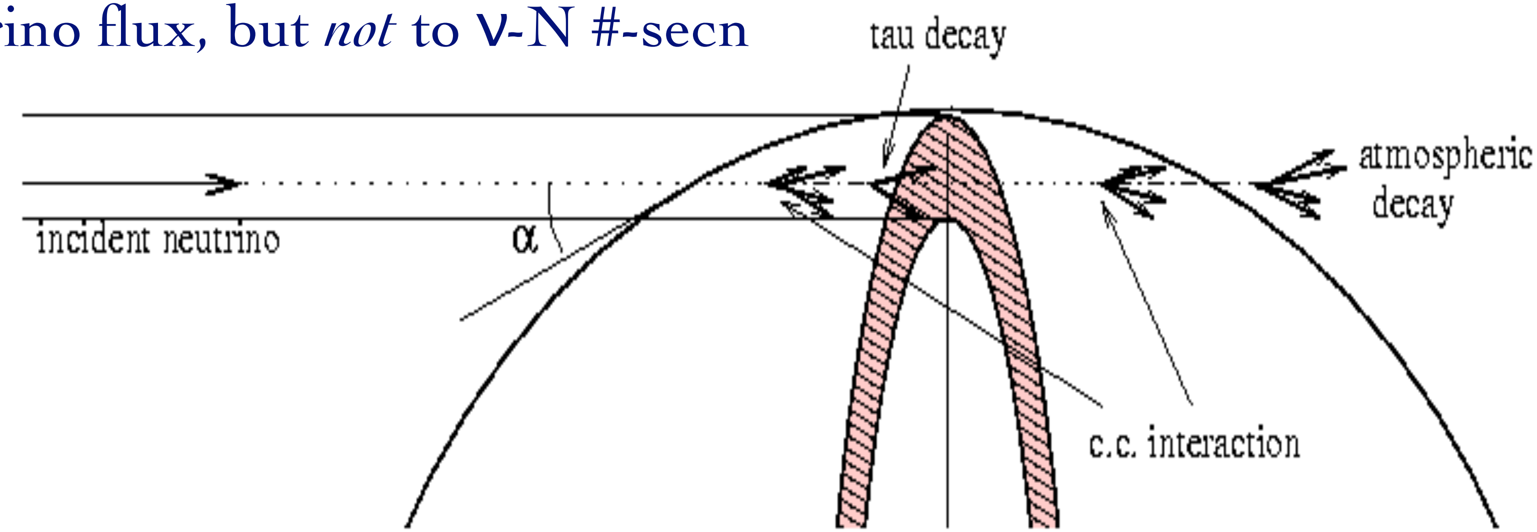
Auger can see ultra-high energy neutrinos as inclined deeply penetrating showers

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



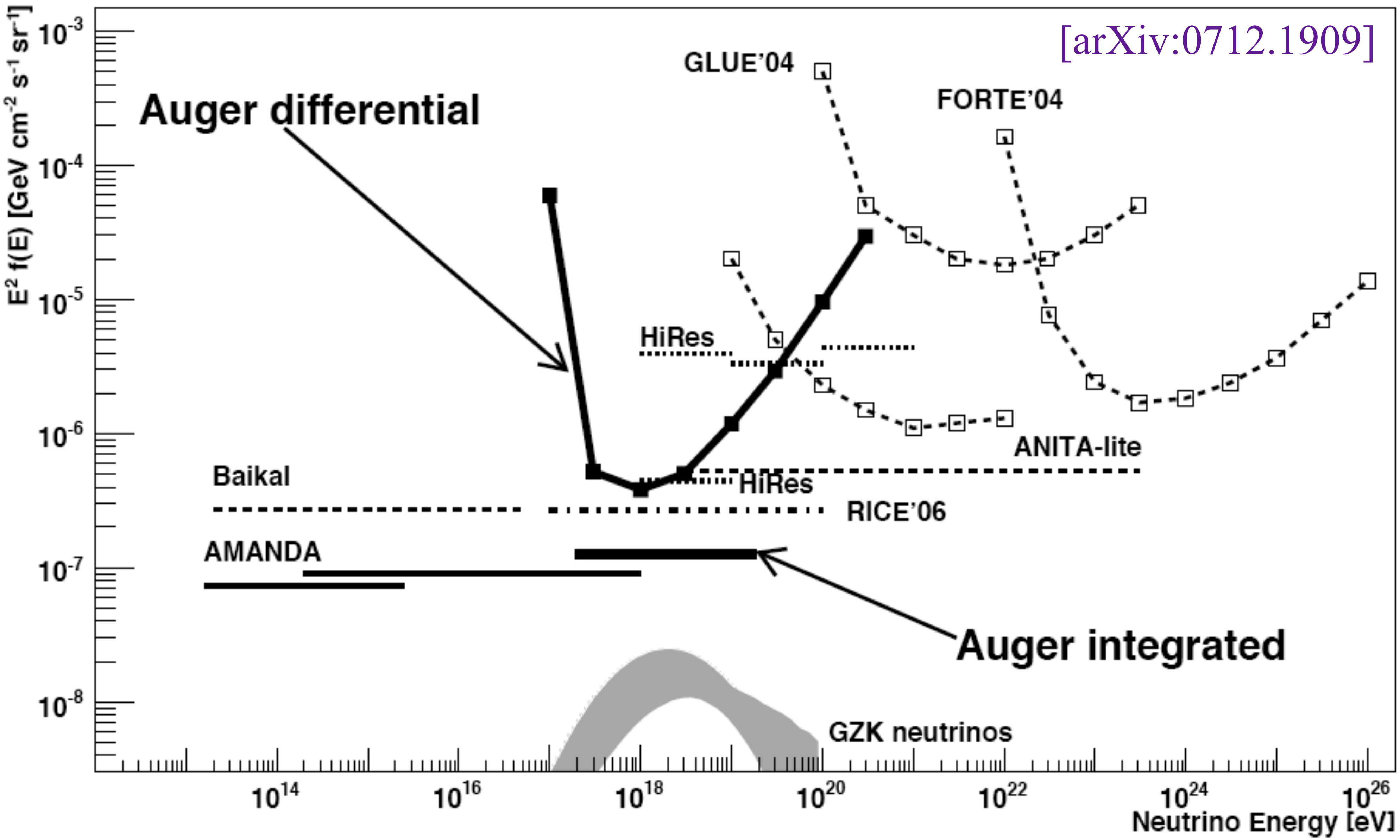
Auger can also see Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower

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



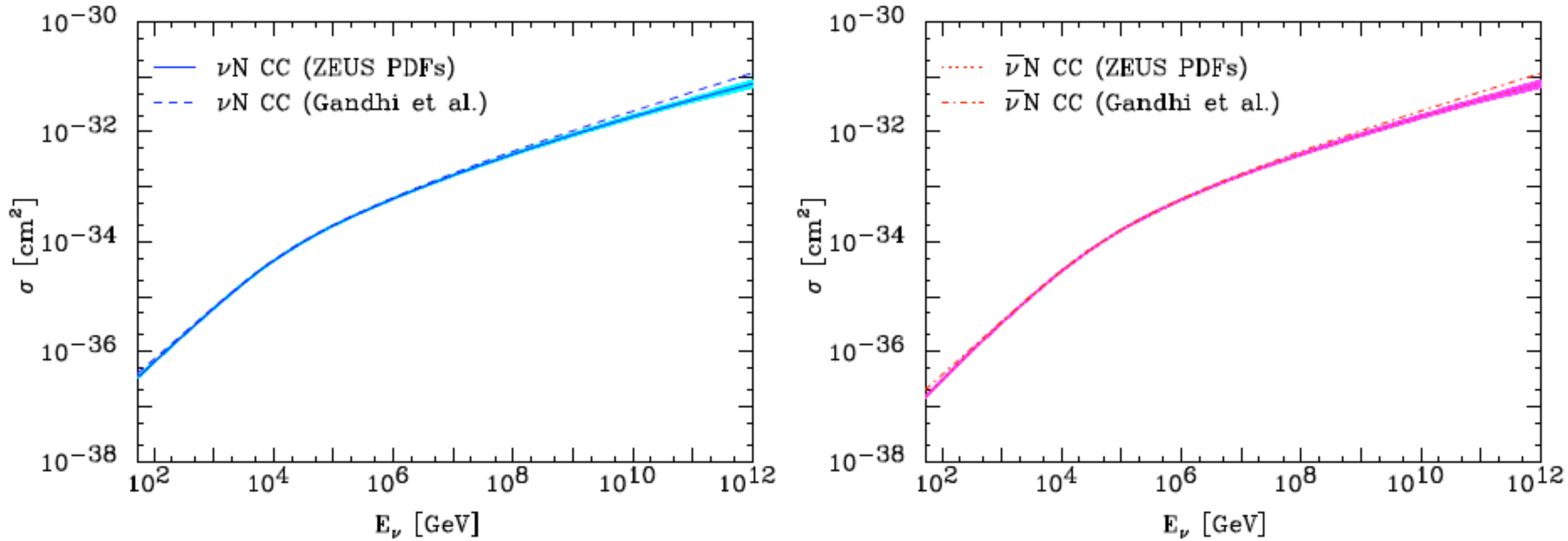
No neutrino events yet … but getting close to "guaranteed" cosmogenic flux

(NB: ~To do this we must know ν-N cross-section at ultrahigh energies)



Deep inelastic e-p scattering at HERA has probed the parton distribution functions down to very *low* $x_{Bjorken}$ and very *high* Q^2 … enables more reliable prediction of the UHE neutrino-nucleon cross-section (in the *perturbative* SM) using DGLAP evolution of the PDFs (at next-to-leading order, and including heavy quark corrections)

Cooper-Sarkar & S.S. [arXiv:0710.5303]

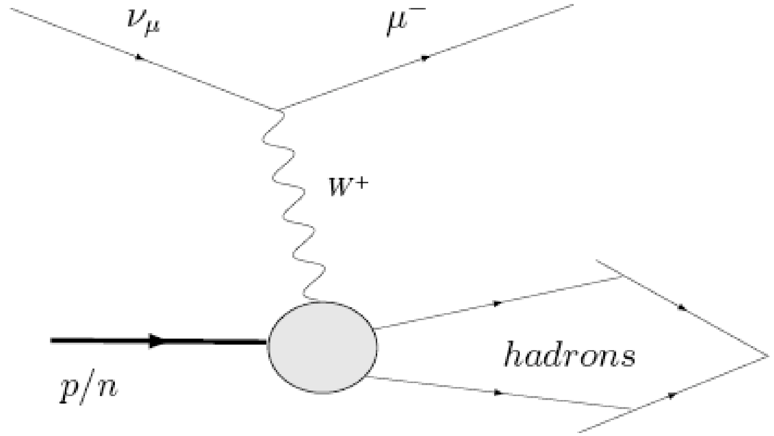


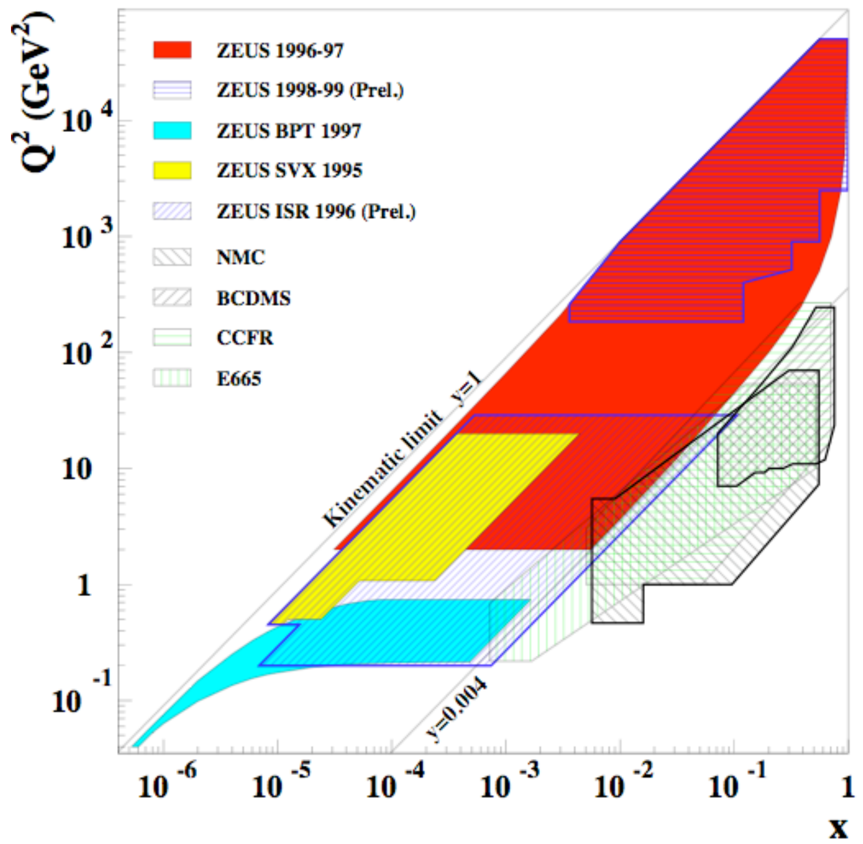
ν-N deep inelastic scattering

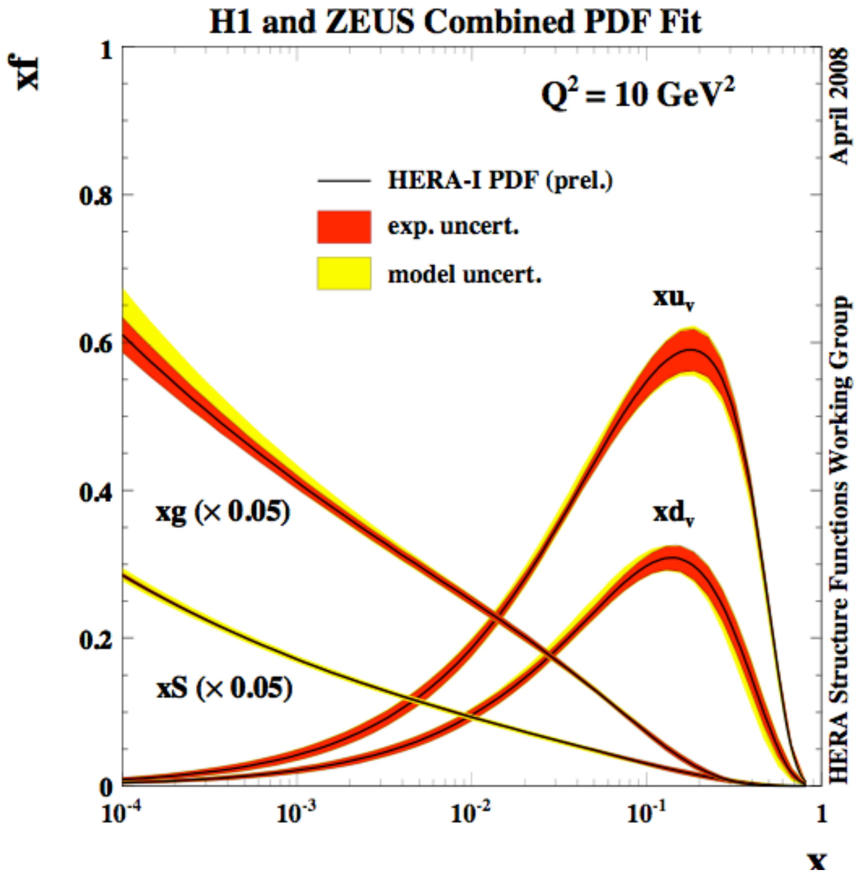
$$\frac{\partial^2 \sigma^{CC,NC}_{\nu,\bar{\nu}}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi} \left(\frac{M_i^2}{Q^2 + M_i^2} \right)$$

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

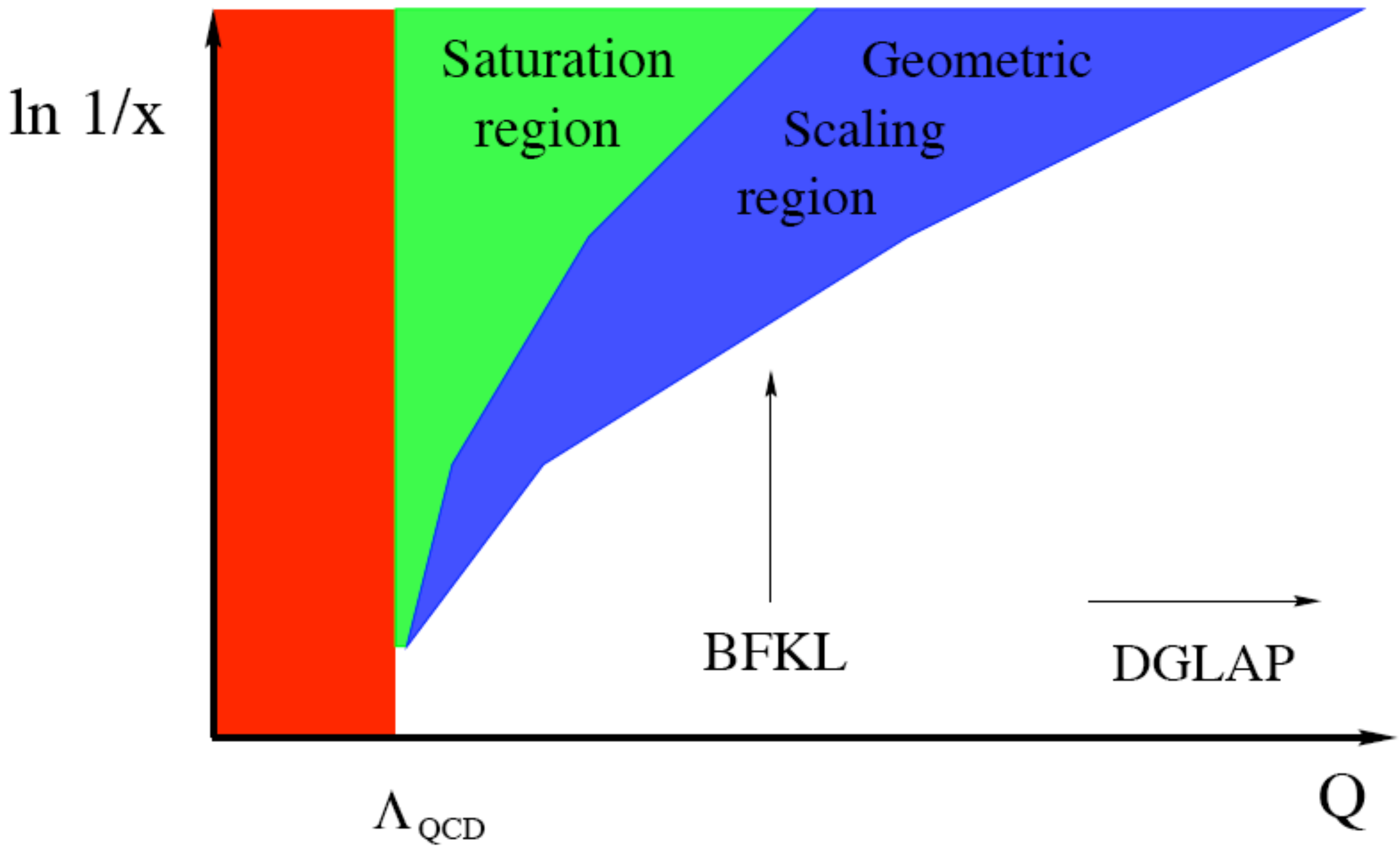
$$\left. \pm y \left(1 - \frac{y}{2}\right) x F_3^{CC,NC}(x, Q^2) \right]$$







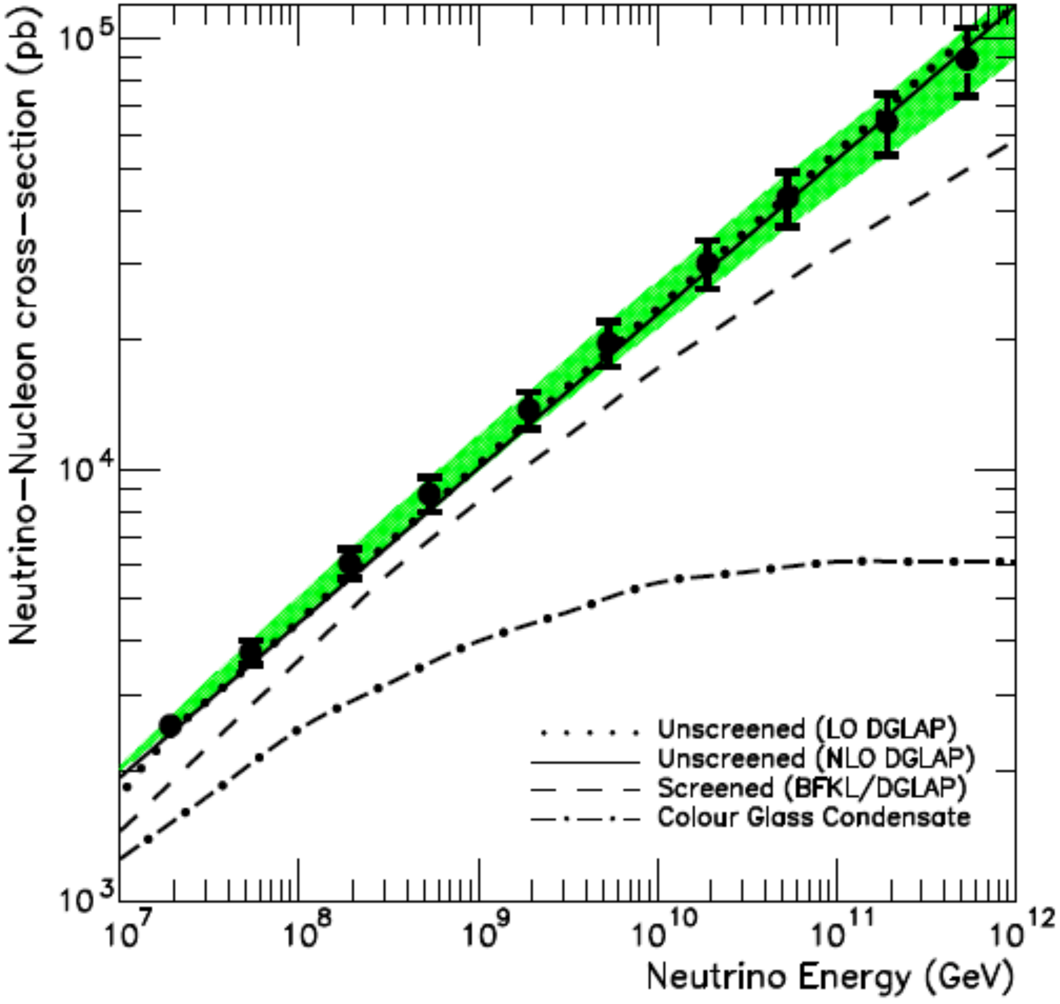
As the gluon density rises at low x, non-perturbative effects become important … a new phase of QCD - Colour Gluon Condensate - has been postulated to form

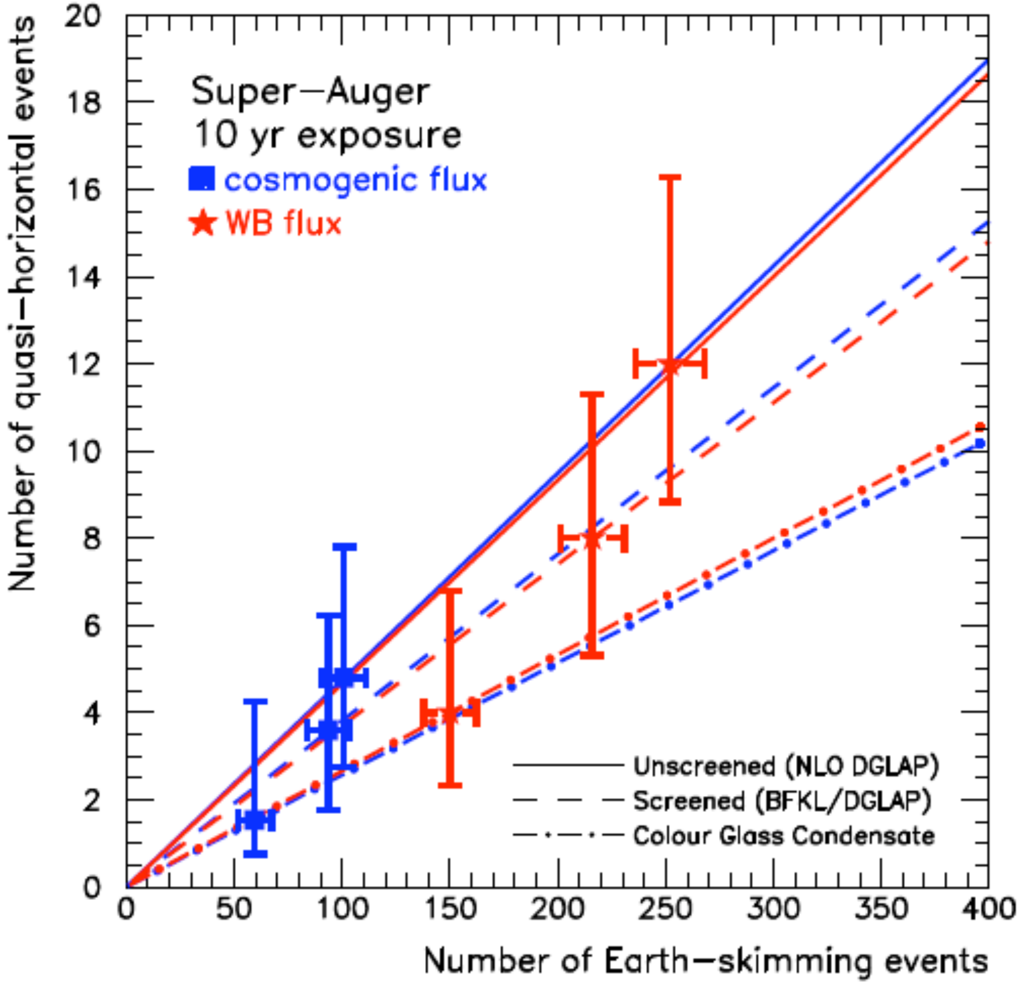


This would *suppress* the ν-N #-secn below its (unscreened) SM value

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

Anchordoqui, Cooper-Sarkar, Hooper, S.S. [hep-ph/0605086]





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 *measures* the cross-section

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
…but to do physics will likely require *multi*-km^3 detectors

Neutrino observatories will provide an unique laboratory for
new physics, both in and 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)