Seeing the high energy universe

cosmic rays, gamma-rays & neutrinos

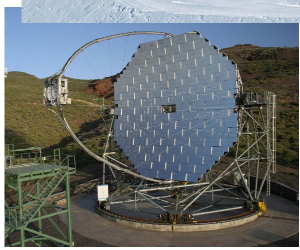
Subir Sarkar







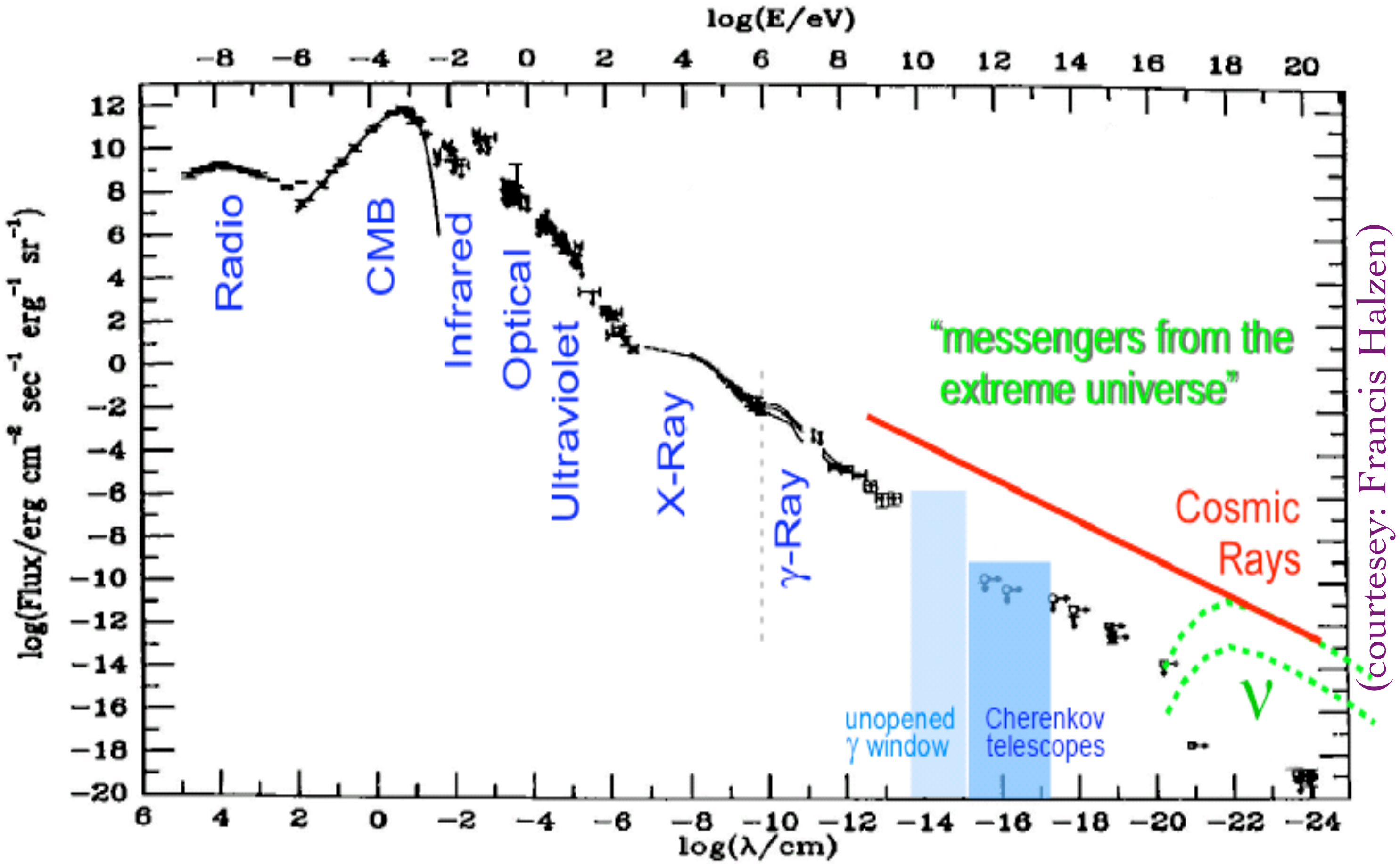




CORSIKA School, Cosmic Ray Laboratory, Ooty, 17th December 2010

We can *see* the universe with **photons** up to a few TeV (up to ~50 TeV nearby)

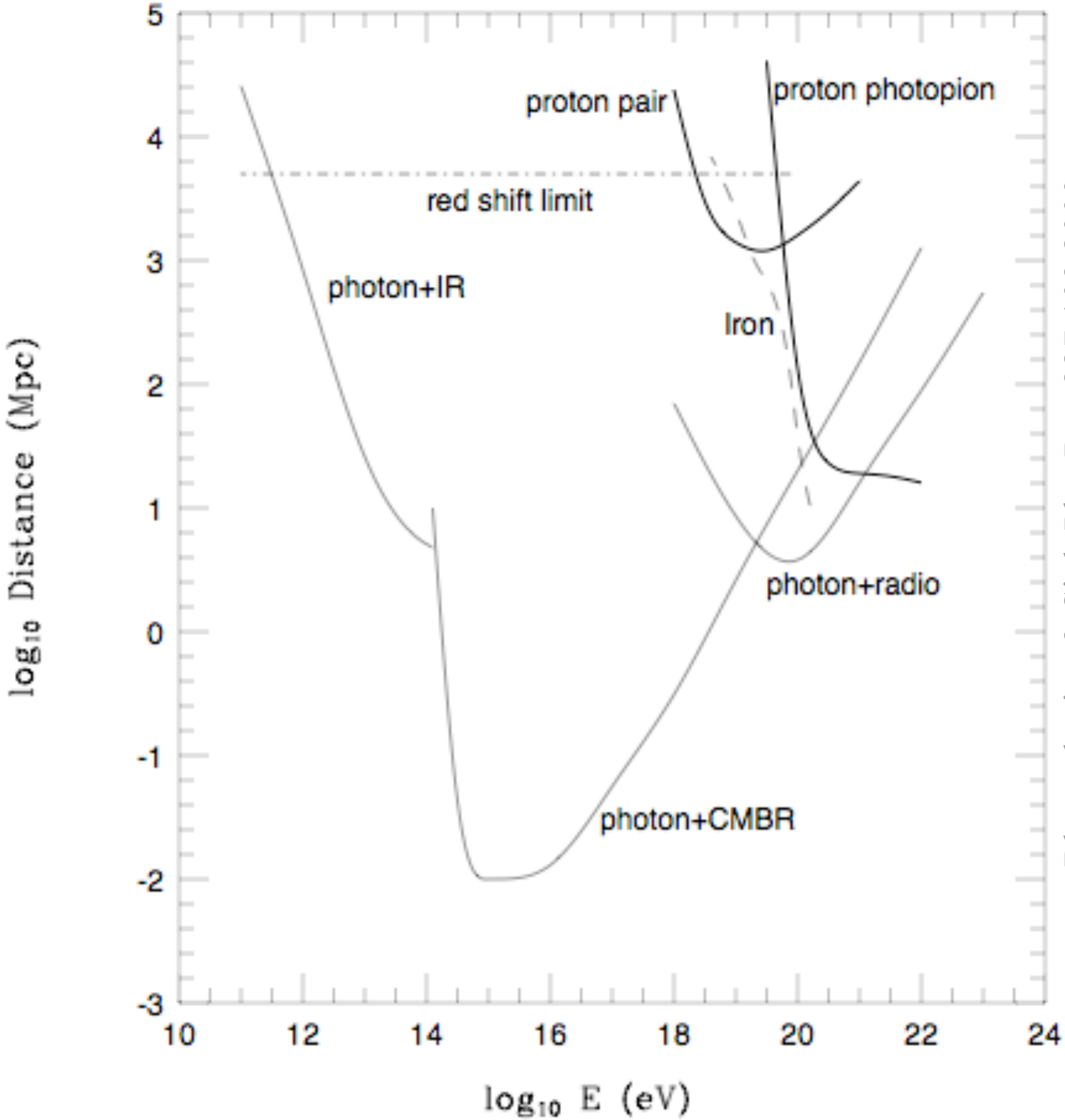
… beyond this energy they are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on the CIB/CMB



Using **cosmic rays** we should be able to 'see' up to ~ 6 x10^{10} GeV
(before they get attenuated by $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+, p\pi^0$, on the CMB)

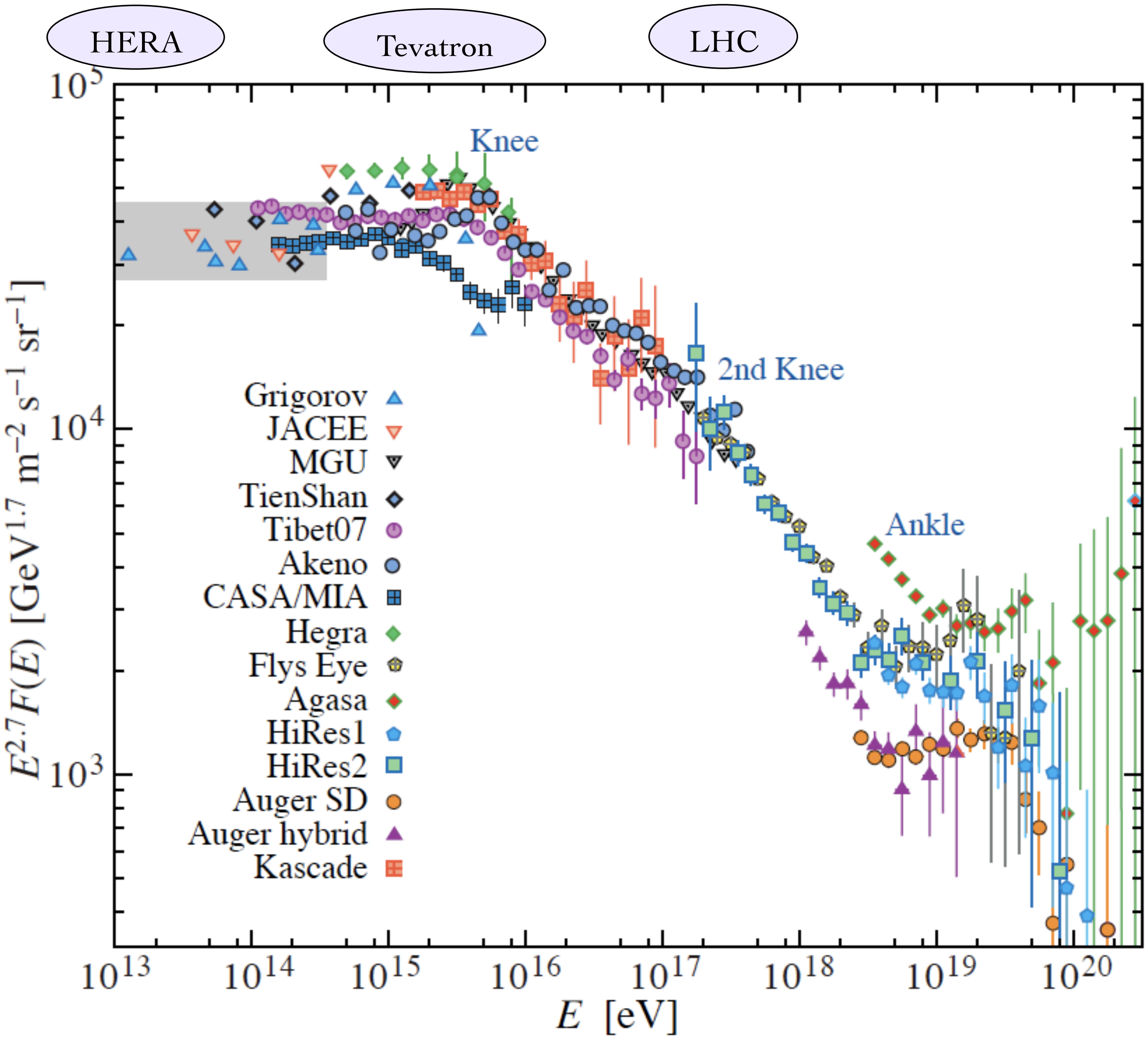
… and the universe is transparent to **neutrinos** at nearly *all* energies

Attenuation of cosmic messengers

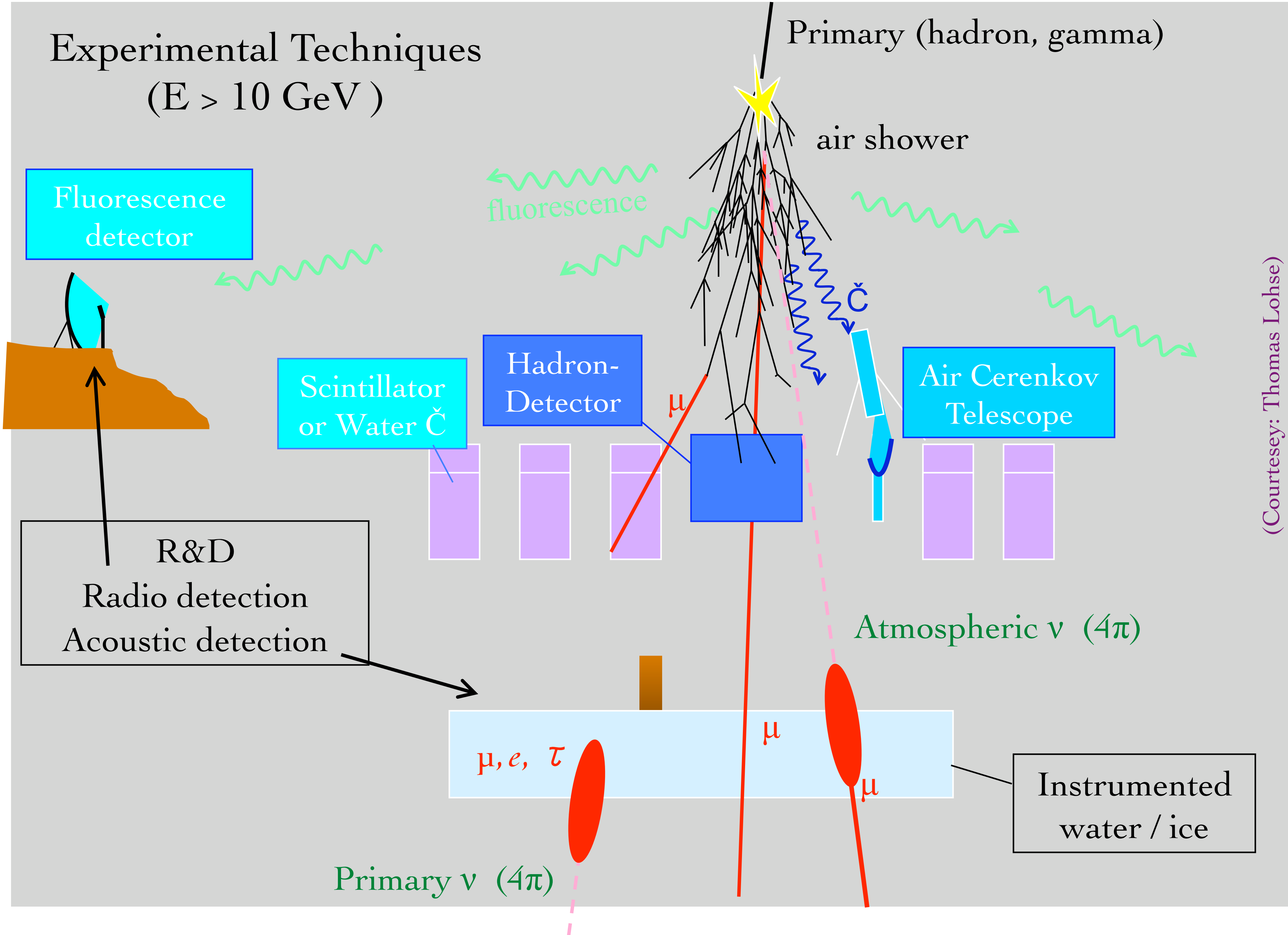


Bhattacharjee & Sigl, PhysRep 327:109,2000

By studying cosmic ray (p, γ, ν) interactions we can also 'see' into the *microscopic universe,* well beyond the reach of terrestrial accelerators



(Gaisser & Stanev, *Reviews of Particle Properties* 2010)


Experimental Techniques
(E > 10 GeV)
Primary (hadron, gamma)
air shower
Fluorescence detector
fluorescence
Č
Hadron-Detector
Scintillator or Water Č
μ
Air Cerenkov Telescope
(Courtesey: Thomas Lohse)
R&D
Radio detection
Acoustic detection
Atmospheric ν (4π)
μ, e, τ
μ
μ
Instrumented water / ice
Primary ν (4π)

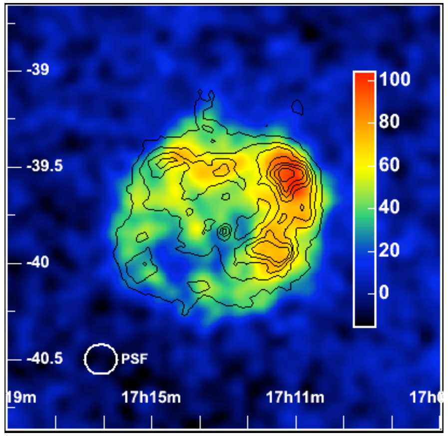
We are witnessing great advances in γ-ray astronomy

→ the sources of low energy cosmic rays may soon be known – **SNRs**?

➢ Do the observed γ-rays arise from hadronic interactions (π^0 decays) , or from inverse-Compton scattering by (radio synchrotron emitting) electrons ?

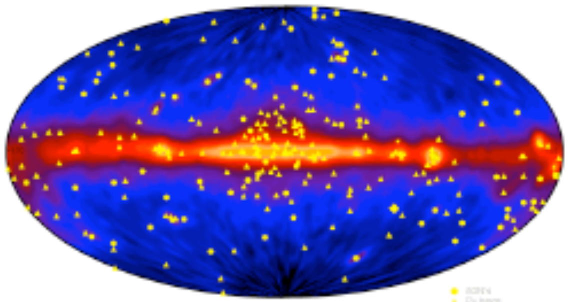
➢ Can 1st-order Fermi acceleration at SNR shocks explain the spectrum (injection, magnetic field amplification, diffusion losses vs anisotropy) ?

➢ What are the 'unidentified' γ-ray sources in the Milky Way – are there new source classes (micro-quasars, PWNs, binaries …), acceleration mechanisms ?

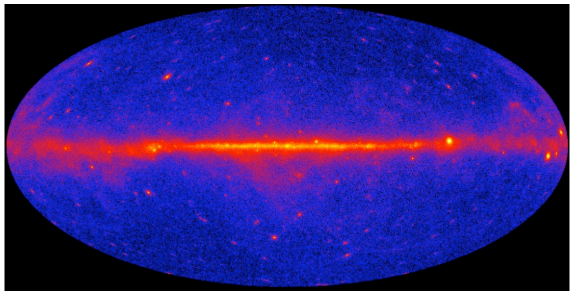


RXJ1713.7-3946 (HESS, 2004)

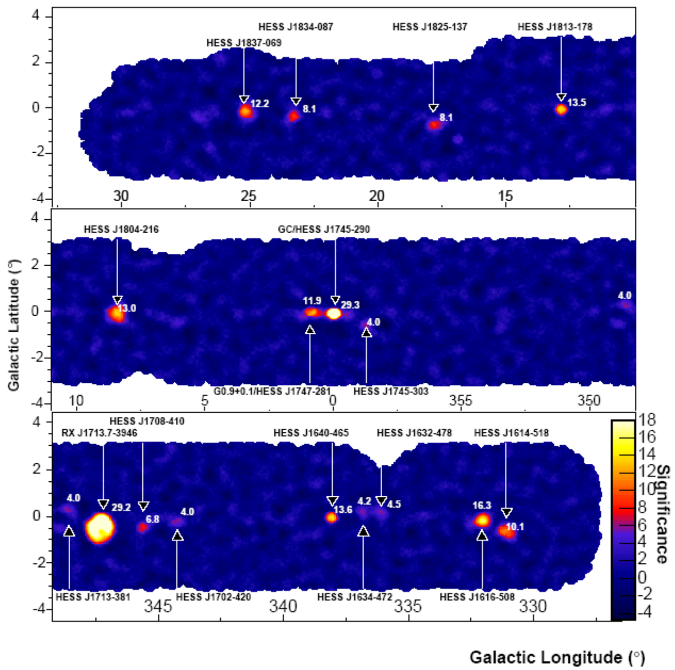
EGRET 1991 - 2000



Fermi (GLAST) 2009 -

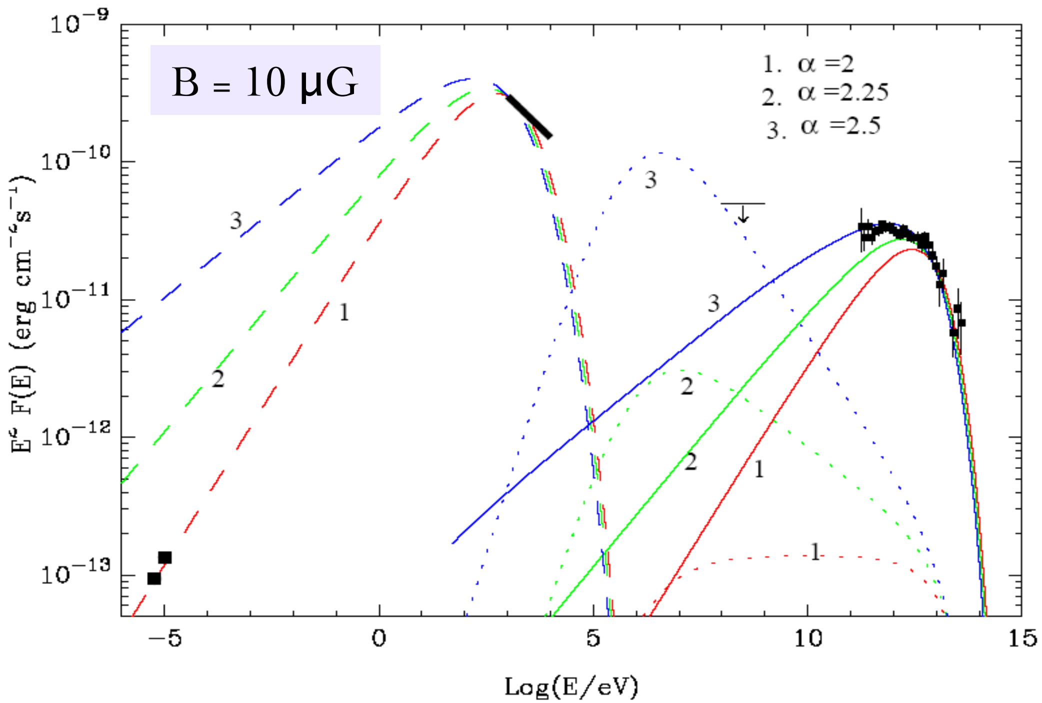


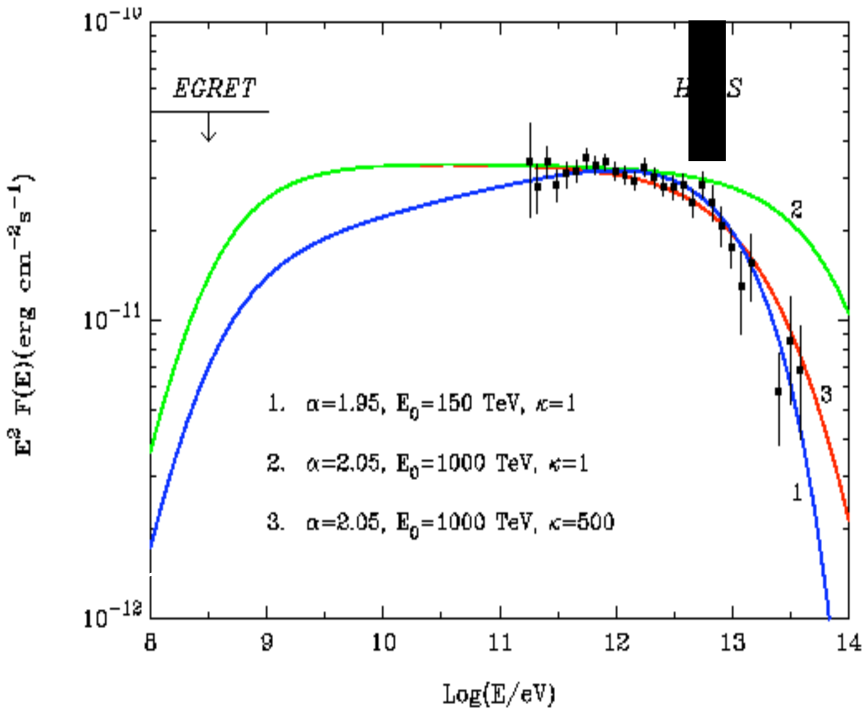
HESS Southern Plane Survey 2005



Much progress has been made but these questions are *not* fully answered … to *unambiguously* identify the cosmic ray sources, we need to observe **TeV neutrinos** - also **ultra high energy cosmic rays** point back to sources …

Primary population in ***RXJ1713.7-3946***: *e* or *p*?



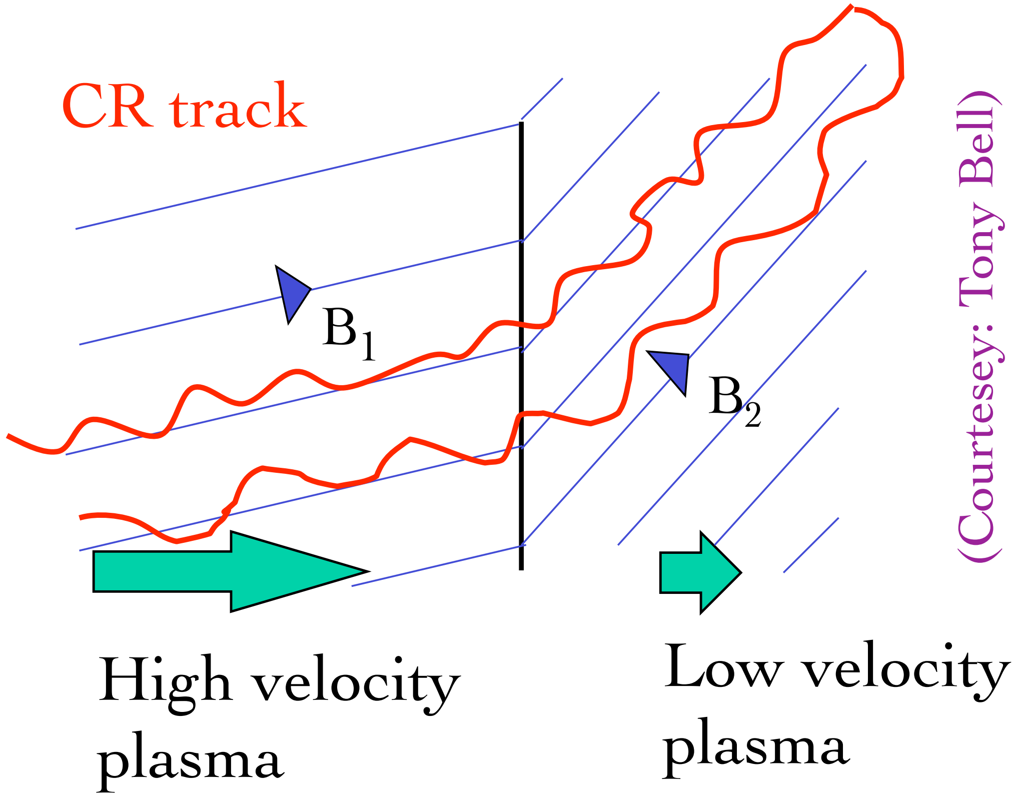


(HESS collaboration, 2006)

γ-ray emission well fitted by IC scattering of ~10^2 TeV electrons on CMB/starlight
… alternatively γ-rays may be from decays of π^0s produced by ~10^3 TeV protons

There is no *definite* evidence yet that SNRs accelerate *protons* to high energies..

First-order Fermi acceleration at SNR shocks



Shock velocity v_s: $\beta = v_s/c$

Simple diffusion theory: prob. of CR crossing shock $\geq m$ times is $(1-\beta)^m$

Average fractional energy gained at each crossing is: $\Delta\varepsilon/\varepsilon = \beta$

$\Rightarrow$ differential spectrum: $n(\varepsilon) \propto \varepsilon^{-2}$

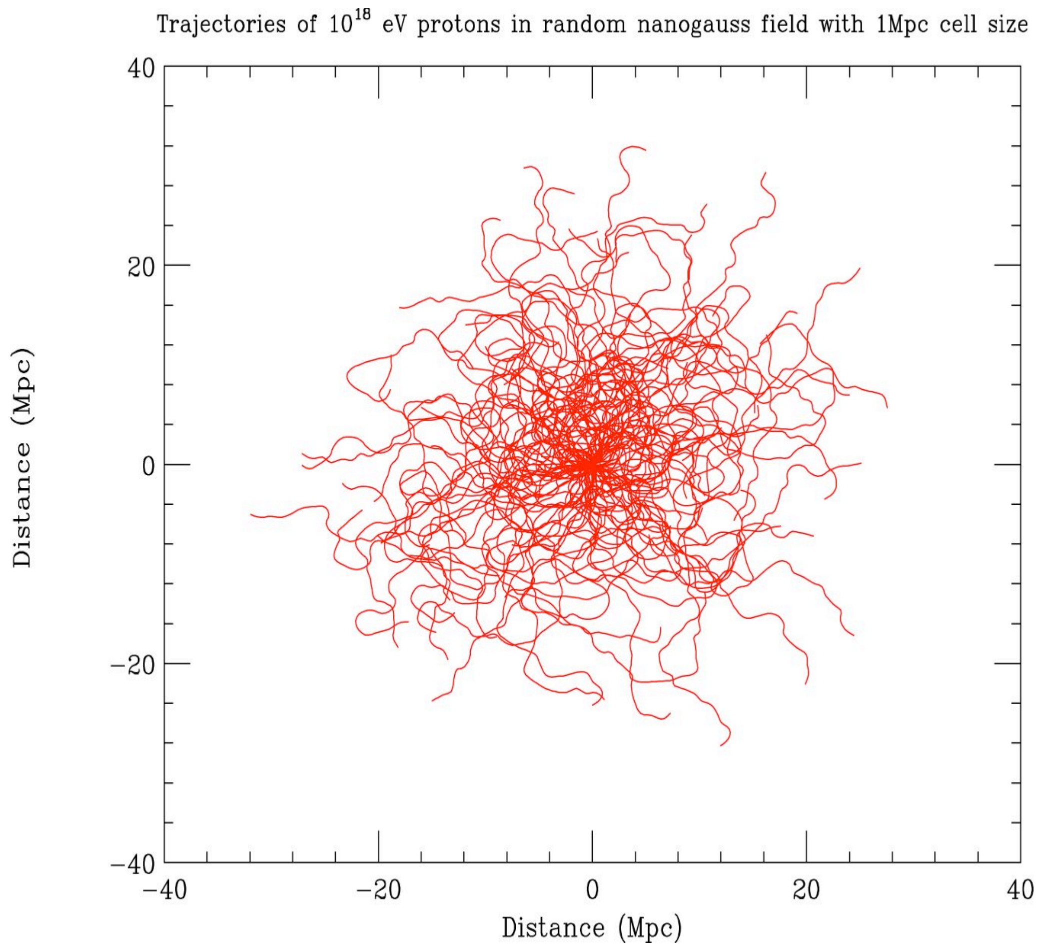
Invoking diffusion loss time-scale $\propto \varepsilon^{-0.7}$ can *match* the observed spectrum $\propto \varepsilon^{-2.7}$

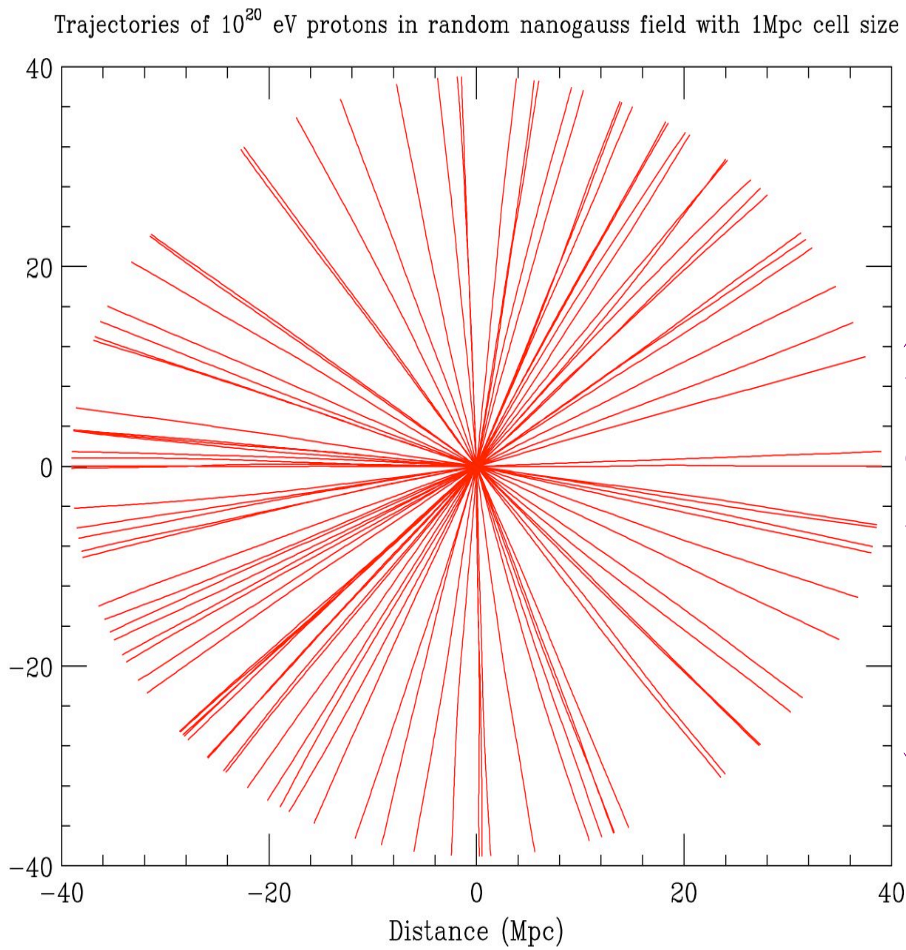
Due to scattering on magnetic field irregularities, cosmic ray crosses shock many times, gaining energy each time, so *can* yield the required ~10-15% conversion of the shock wave K.E. into particles

But this model *cannot* easily account for:

- ►why cosmic ray anisotropy does *not* increase $\propto \varepsilon^{0.7}$
- ►smooth continuation of the spectrum beyond the 'knee'
- ►absence of (π^0 decay) γ-rays from *most* SNRs
- ► High efficiency ⇨ *concave* spectra *cf.* observed *convexity*..

The trajectories of cosmic rays are randomised by cosmic magnetic fields … so need to go to ultrahigh energies to do cosmic ray astronomy





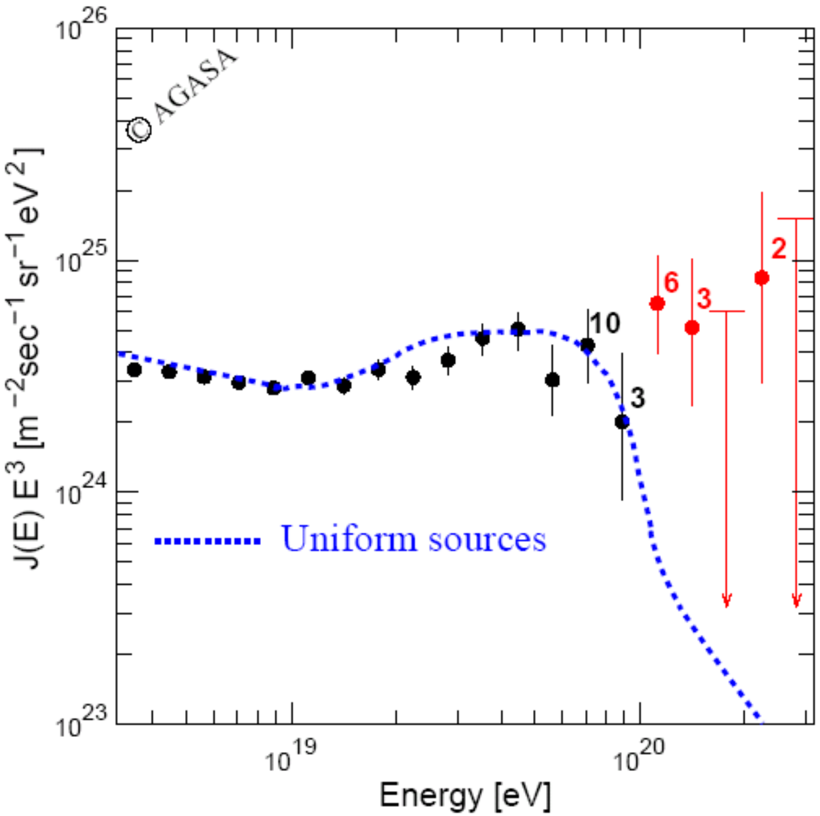
(courtesey: Jim Cronin)

Estimates of cosmic magnetic fields are rather uncertain … however general consensus that much beyond the 'knee' (~10^{18} eV) cosmic rays can no longer be deflected significantly by magnetic fields and must correlate with their sources

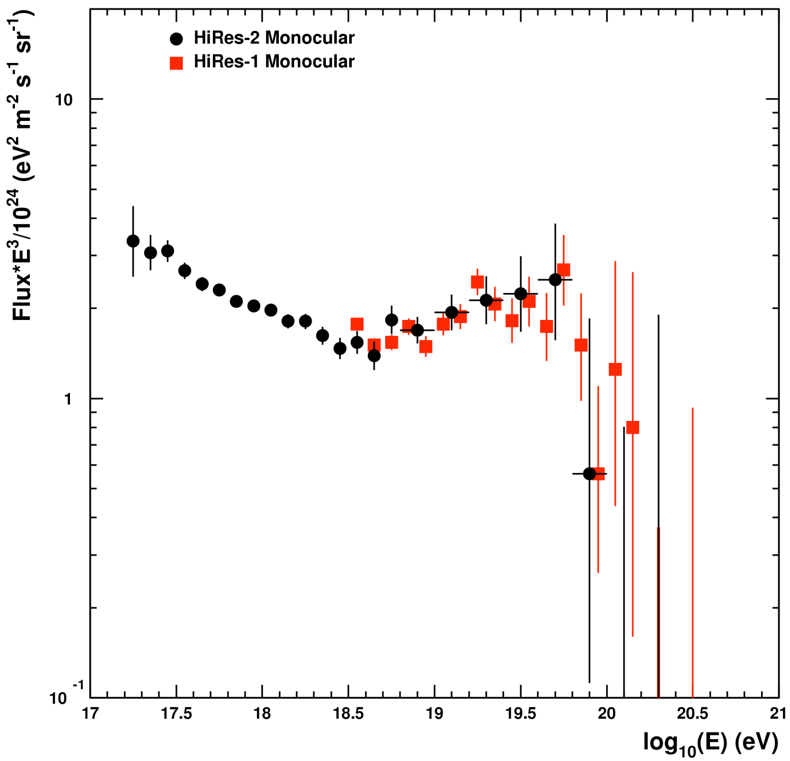
Where is the GZK cutoff?

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$
$$n \hookrightarrow p + e^{-} + \bar{\nu}_{e}$$
$$\pi^{+} \hookrightarrow \mu^{+} + \nu_{\mu}$$
$$\mu^{+} \hookrightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

AGASA spectrum continues smoothly!



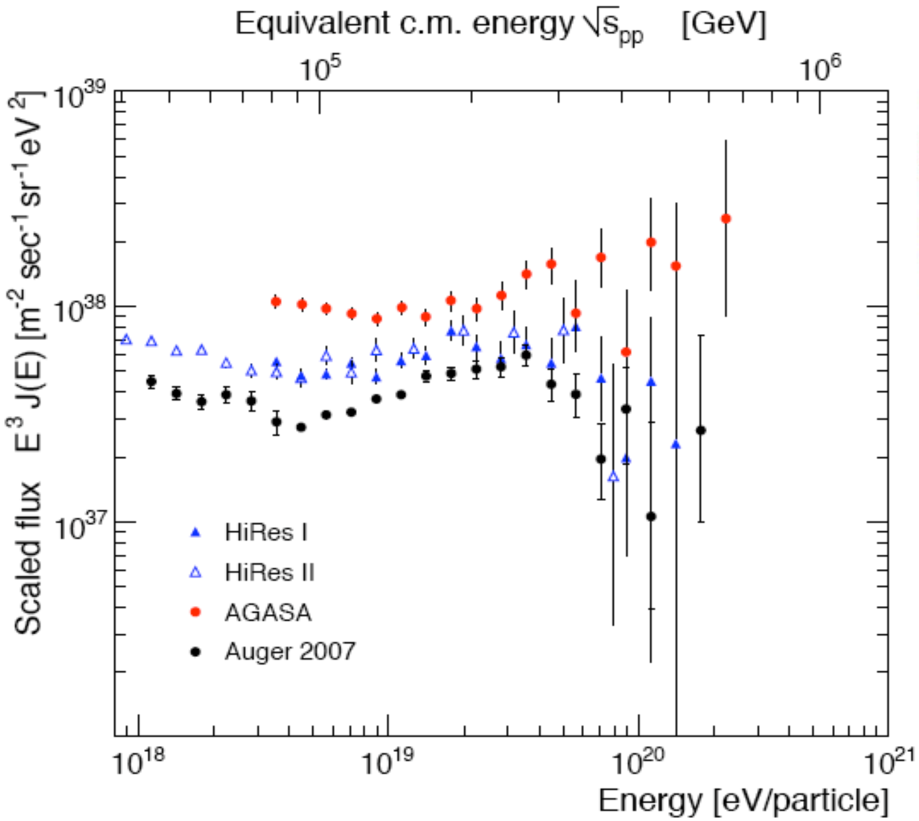
… but HiRes sees expected suppression

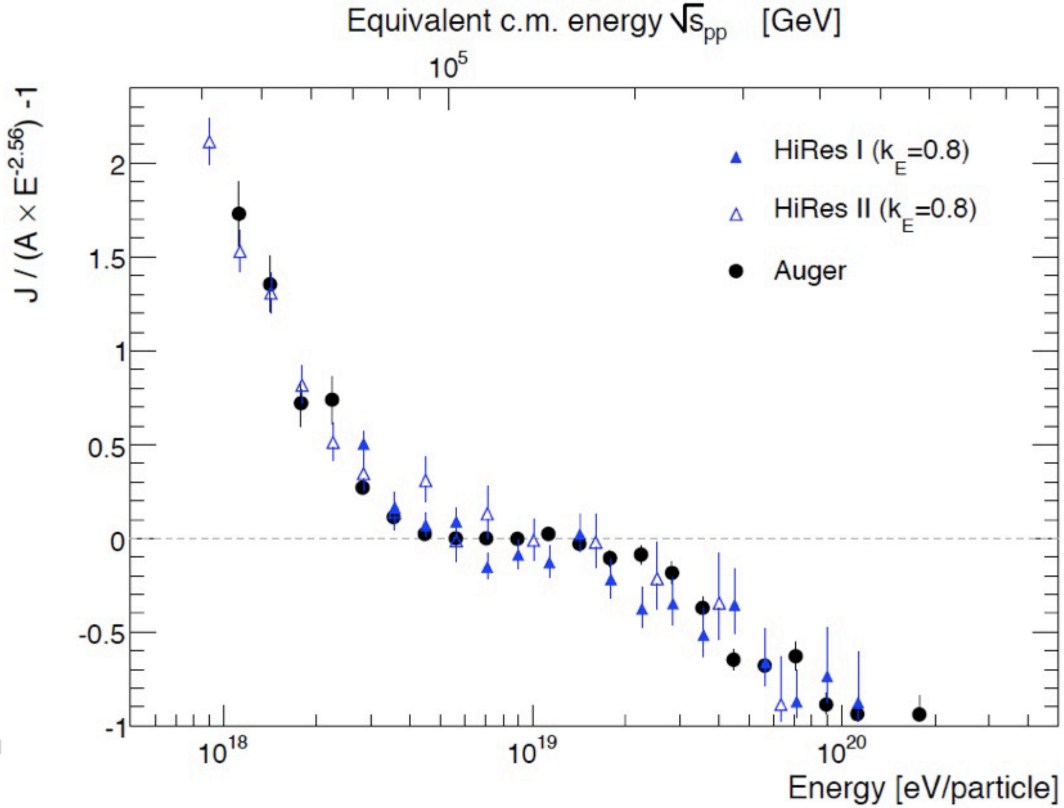


Is there a ~25% energy calibration mismatch between surface arrays and air fluorescence detectors?

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

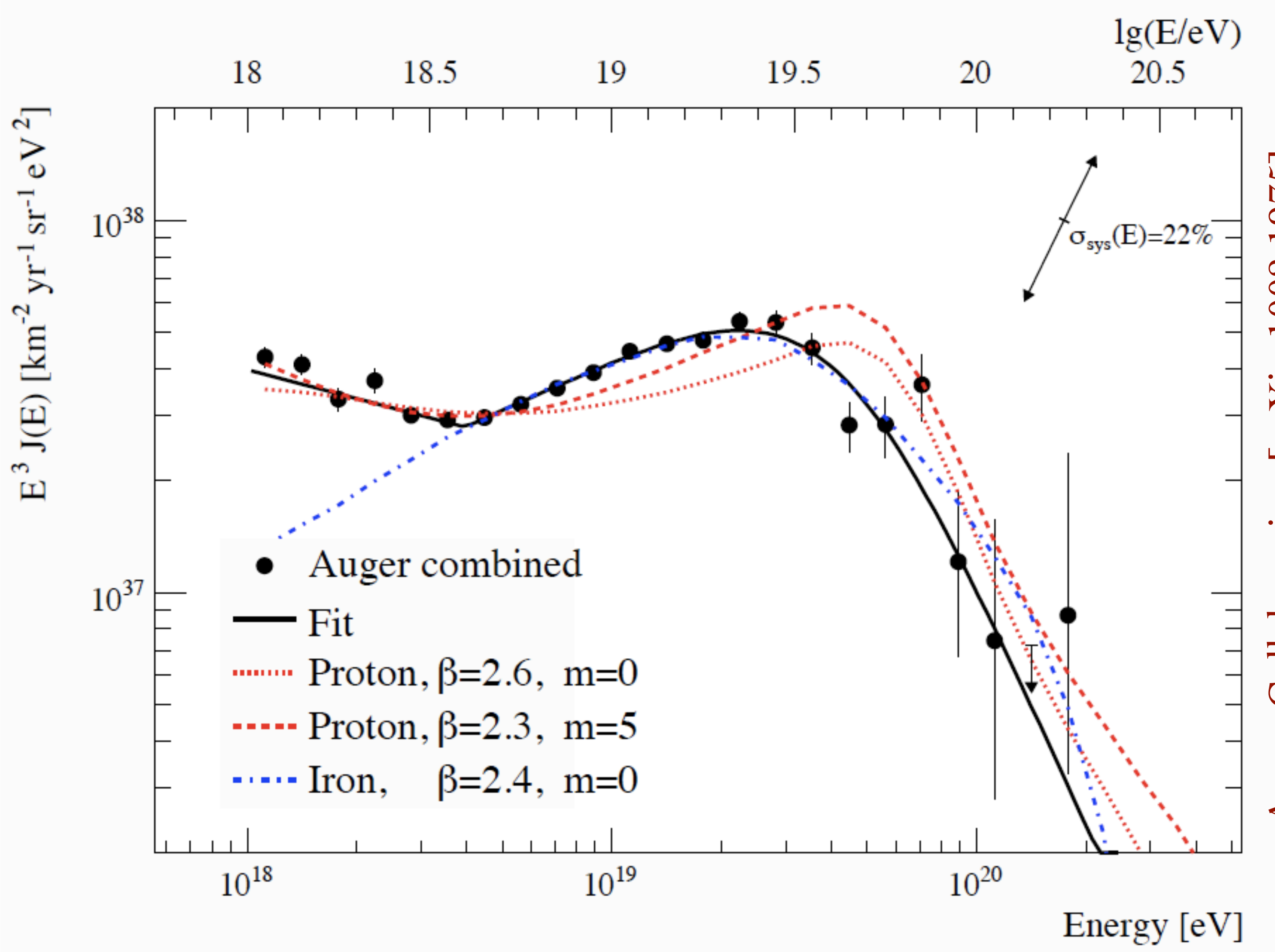
Hence the sources of ultra high energy cosmic rays must be extragalactic





Precise measurement of the shape of the cut-off can, with sufficient statistics, establish whether this is indeed the 'GZK suppression' (or whether e.g. the sources are just running out of power)

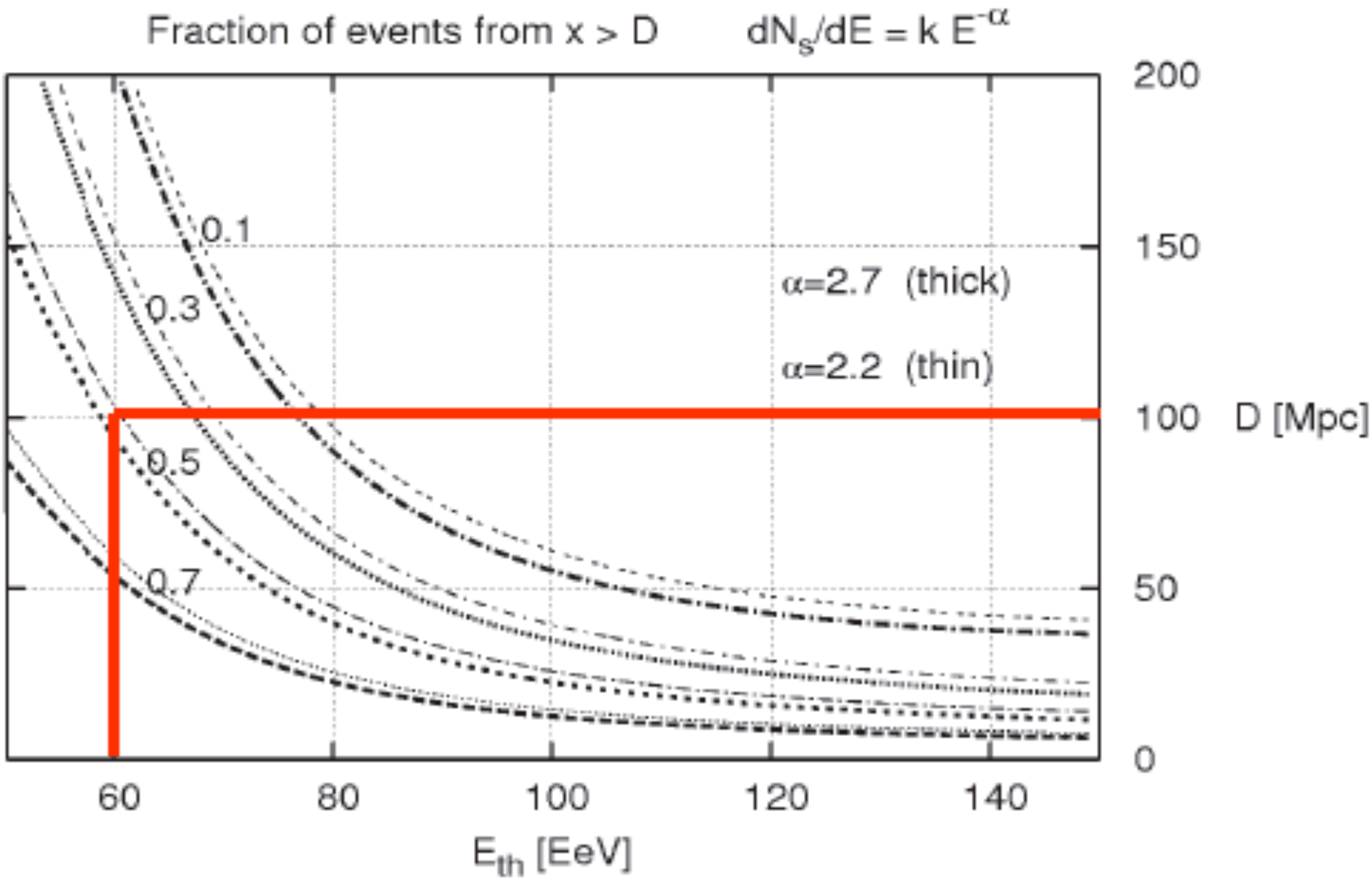
Present data on the energy spectrum *cannot* distinguish between primary protons (with source density evolving with redshift as $(1+z)^5$) and nuclei (no evolution)



Auger Collaboration [arXiv:1002.1975]

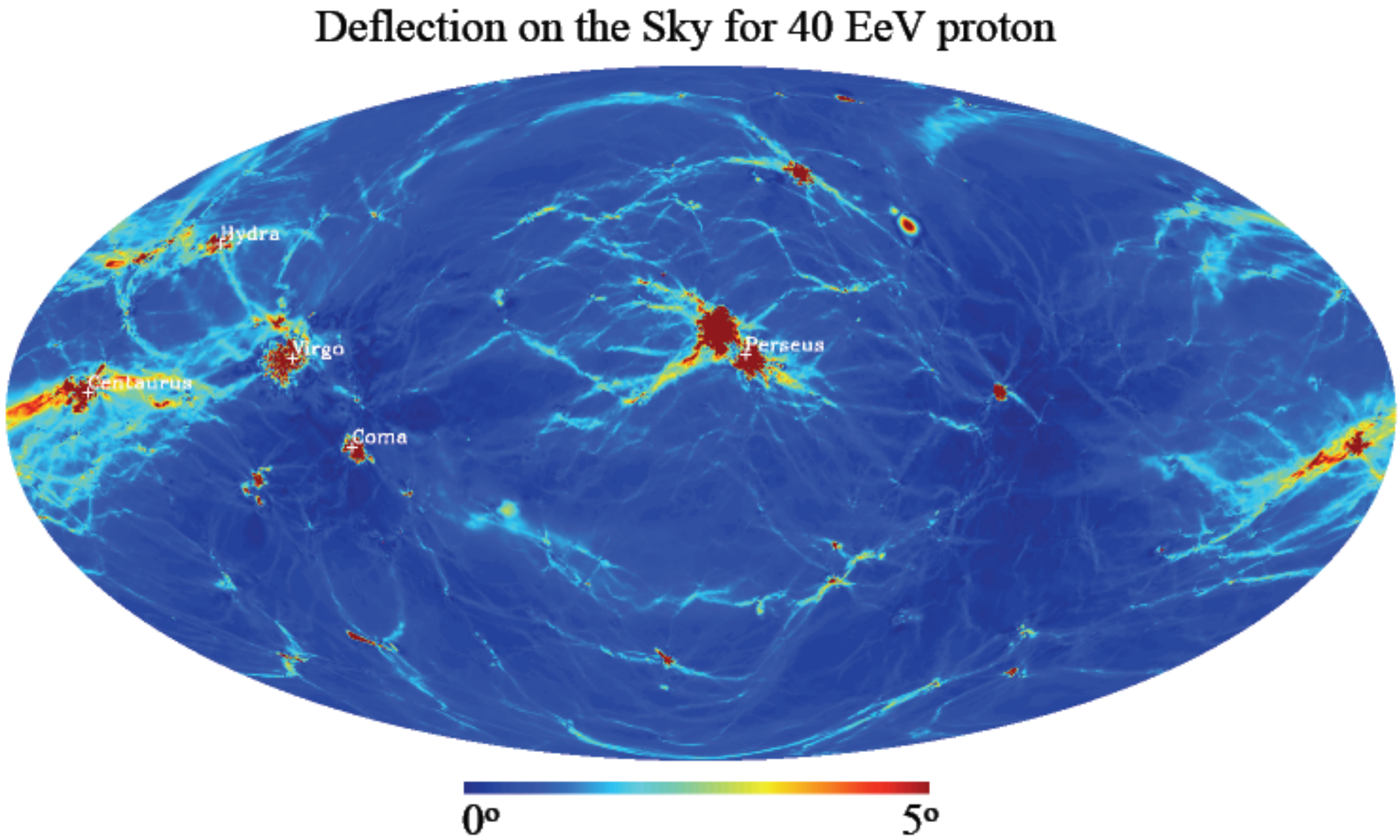
… the 'cosmogenic' neutrino flux is however quite different in the two cases so can in principle be used as a discriminant

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



This is true whether the primaries are protons or heavy nuclei …

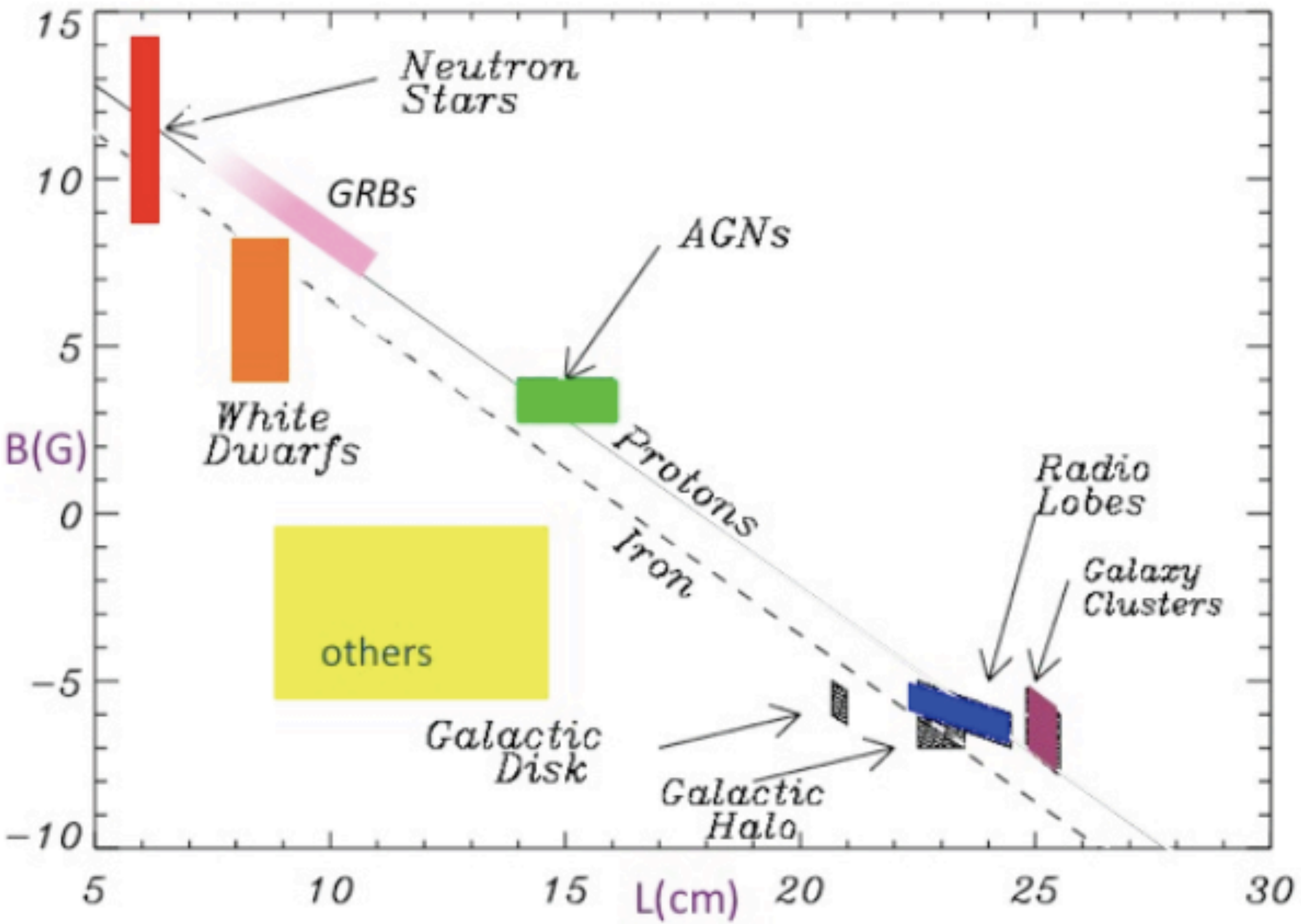
So we should be able to see which objects the UHECRs *point back* to …



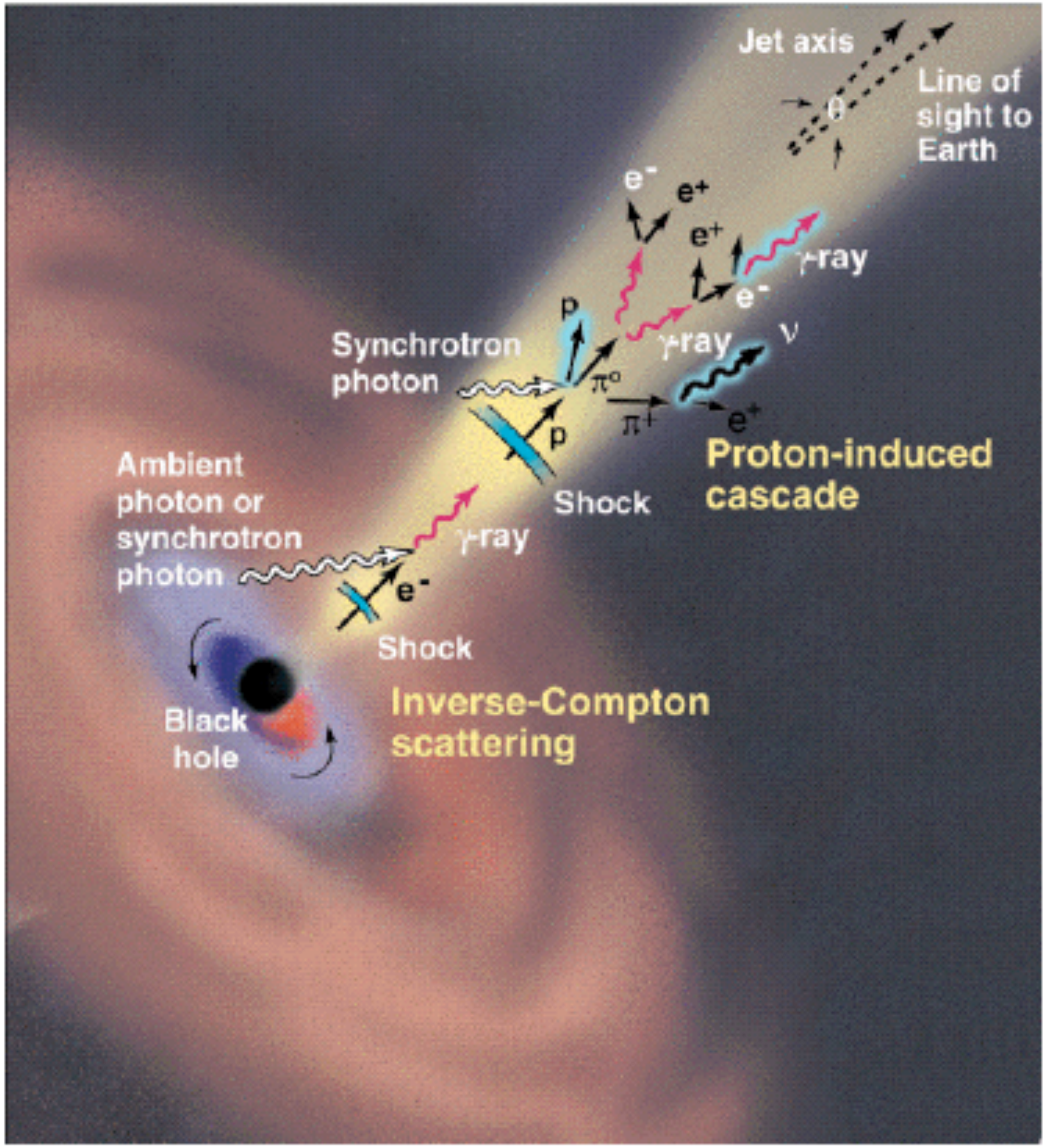
'Constrained' simulation of local large-scale structure including magnetic fields suggests that deflections are small, except in the cores of rich galaxy clusters

Dolag, Grasso, Springel & Tkachev, JCAP 0501:009,2005

Are there any plausible cosmic accelerators for such enormous energies?



Whatever their sources (within the GZK 'horizon' of ~100 Mpc), the observed UHECRs should point back to them, *if* magnetic deflections are not too large



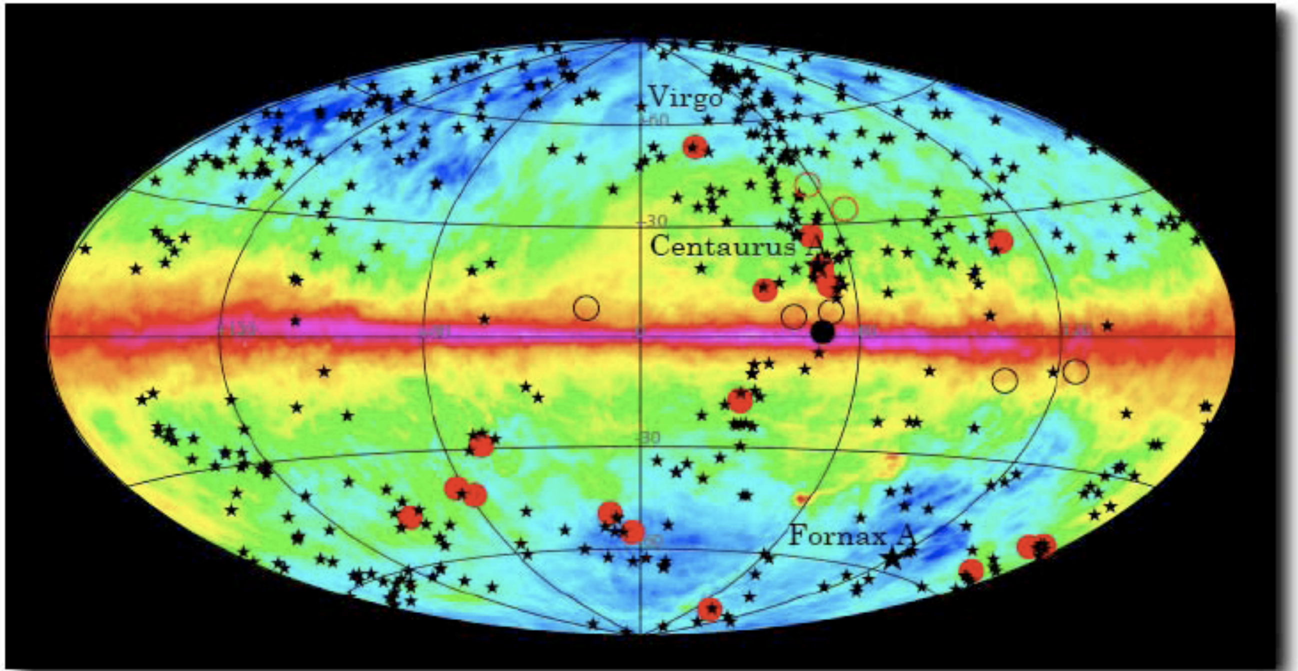
Active galactic nuclei

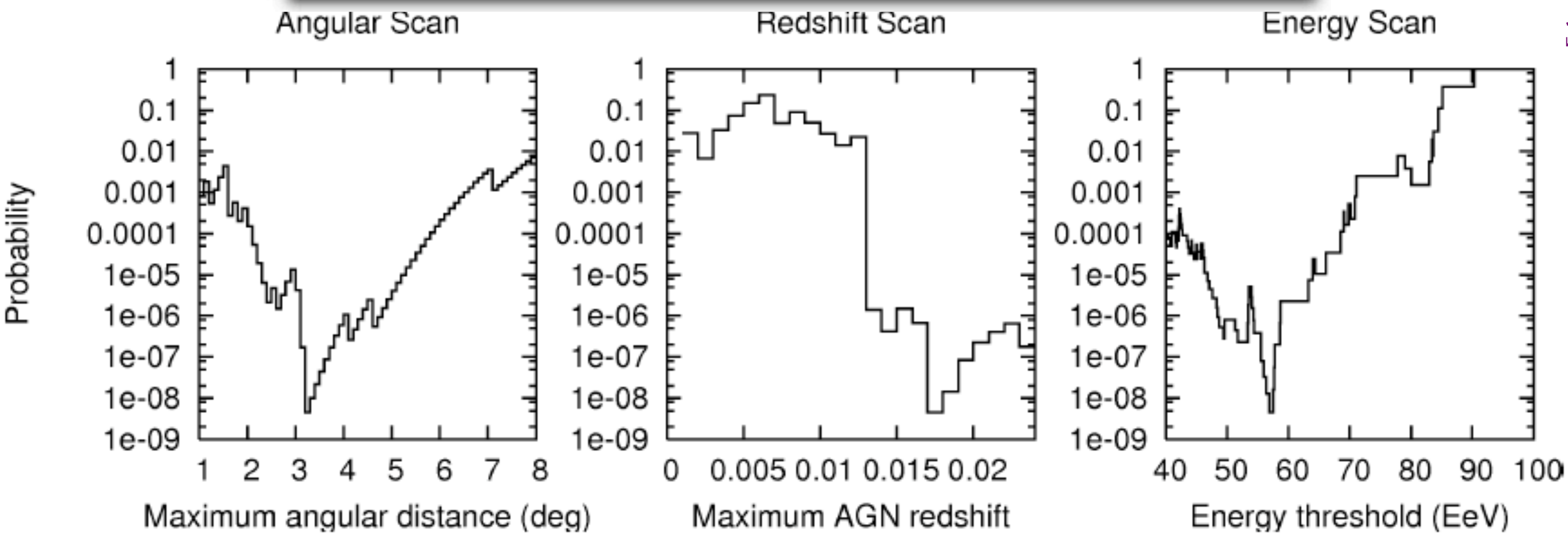
- Current paradigm:
  - **Synchrotron Self Compton**
  - External Compton
  - Proton Induced Cascades
  - Proton Synchrotron
- Energetics, mechanism for jet formation and collimation, nature of the plasma, and particle acceleration mechanisms are still poorly understood.

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

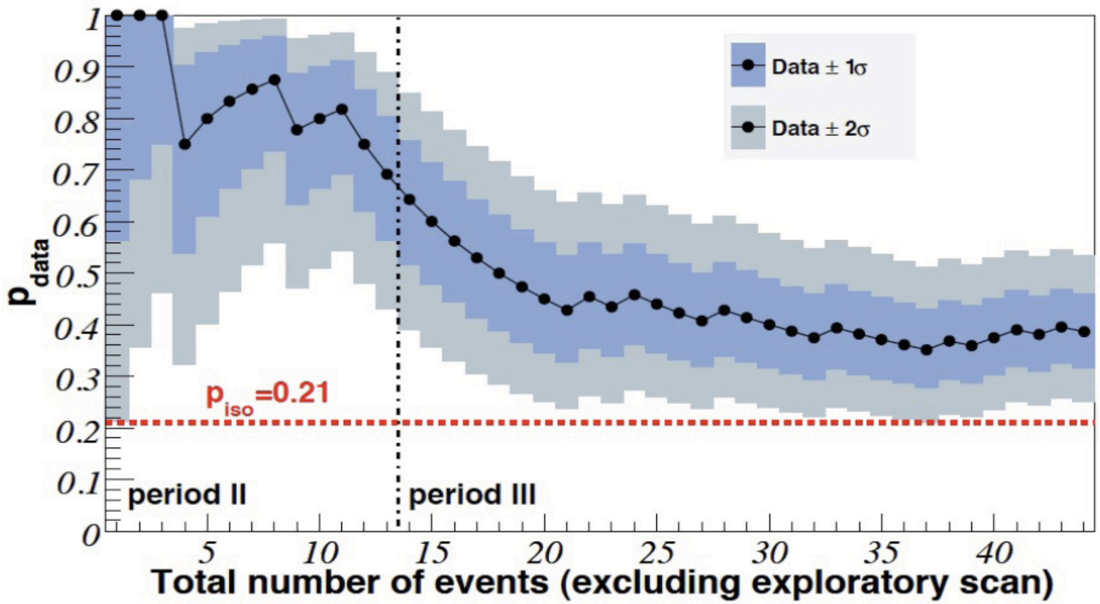
… renewed interest triggered by possible correlations with UHECRs - e.g. 2 Auger events within 3^0 of Cen A

The UHECR arrival directions do correlate with a catalogue of nearby AGN





[Auger Collaboration, arXiv:0711.2256]

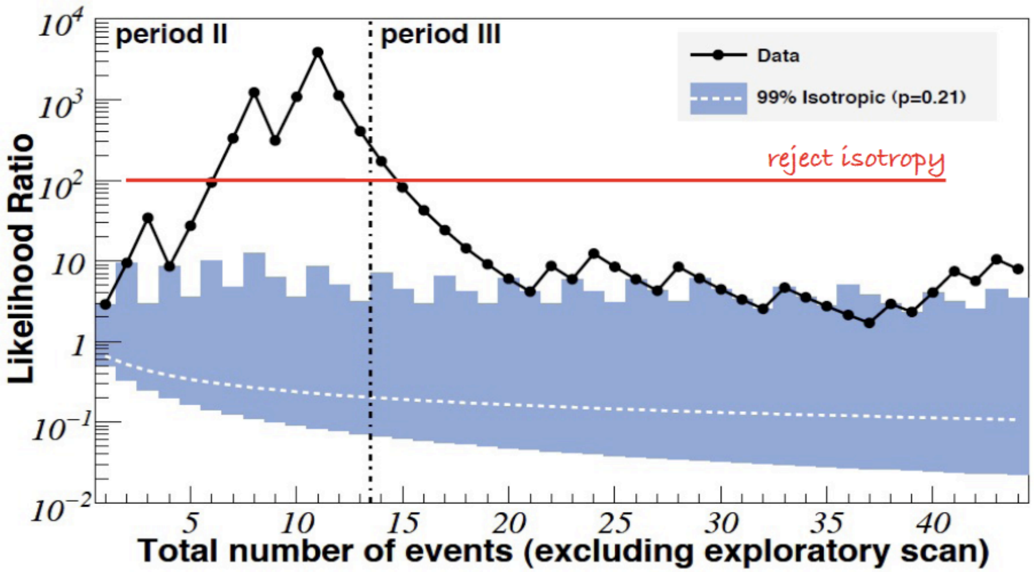


But subsequently the strength of the correlations has not increased

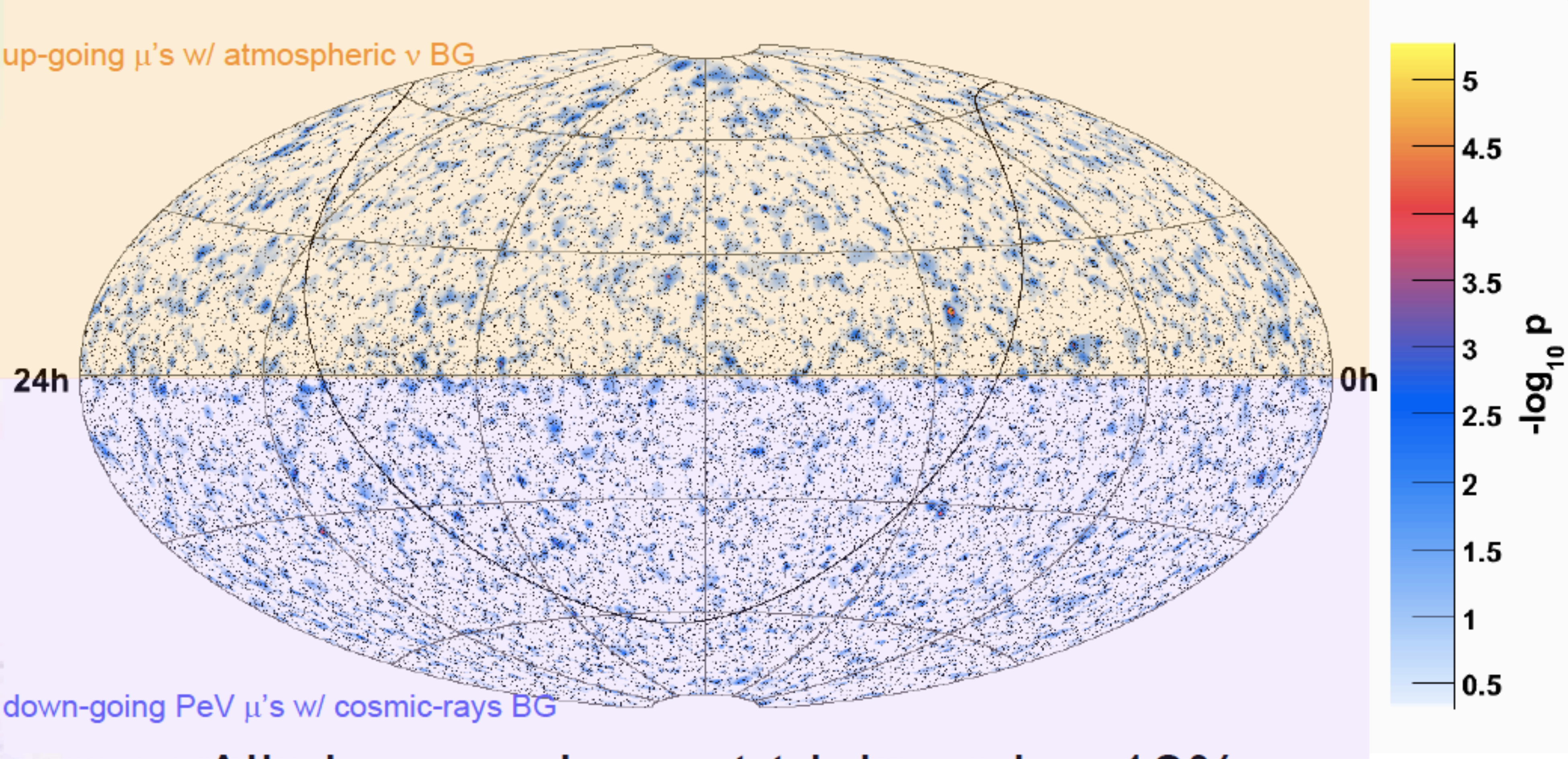
… although 17 out of 44 post-scan events still correlate – so the sky distribution is still *anisotropic*

$$R = \frac{\int_{p_{\rm iso}}^{1} p^k (1-p)^{N-k} \, dp}{p_{\rm iso}{}^k (1-p_{\rm iso})^{N-k+1}}$$

The argument for proton primaries, based on the observed correlations (within 3 degrees), is thus less compelling …



... no sources so far either on ν skymap



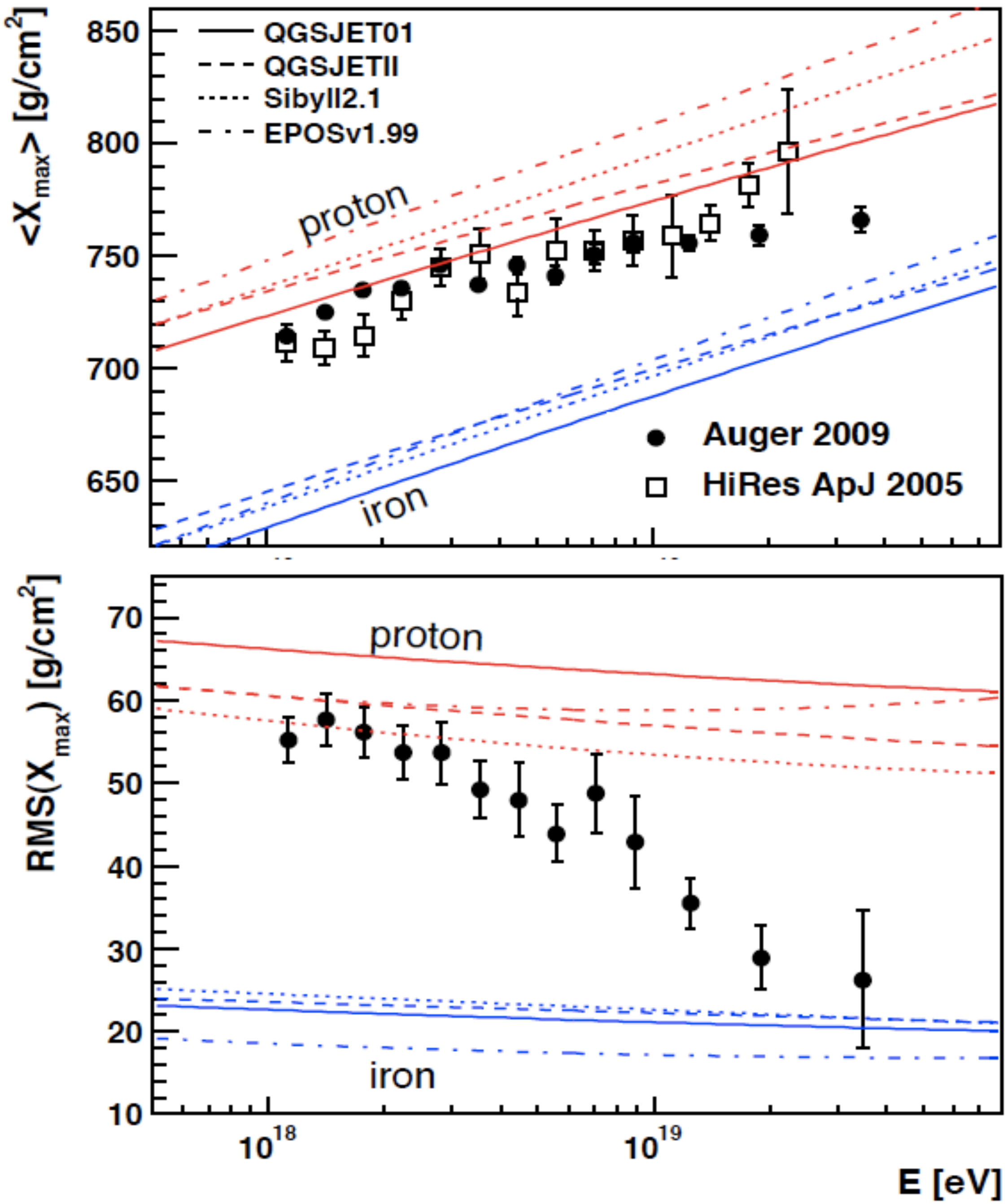
All sky search: post-trial p-value 18%

Hottest spot: RA 113.75 Dec 15.15 -log(p)=5.28

New data on the *fluctuations* of X_{max} shows this to be decreasing with energy, strengthening the evidence for a transition to a heavy composition above 10 EeV

… however an *increase* of the *p*-air #-secn over the usual extrapolation may partially fake this apparent change

Interesting astrophysics and possible new particle physics are closely coupled … to distinguish between these possibilities will require more data and a better understanding of high energy interactions (incl. from LHC)



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

GZK interactions of extragalactic UHECRs on the CMB

"guaranteed" cosmogenic neutrino flux

➔ may be altered *significantly* if the primaries are not protons but heavy nuclei

UHECR candidate accelerators (AGN, GRBs, …)

"Waxman-Bahcall flux" … normalised to observed UHECR flux

➔ sensitive to 'cross-over' energy above which they dominate, also to composition

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

motivated by trans-GZK events observed by AGASA

➔ all such models are now *ruled out* by new Auger limit on primary photons

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

… produced at the end of inflation by the rapidly changing gravitational field

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

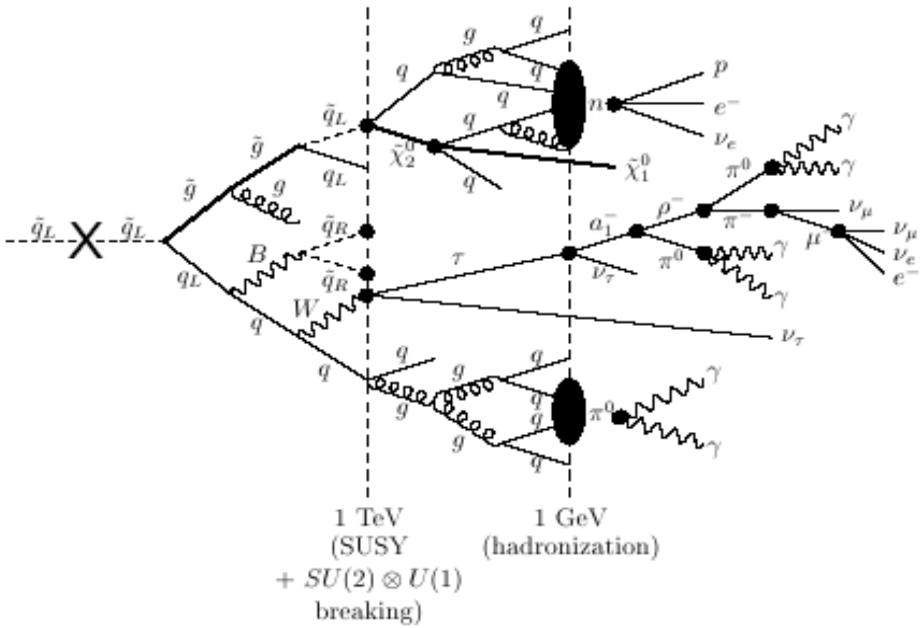
Simulation of galaxy halo (Stoehr *et al* 2003)

(Berezinsky, Kachelreiss & Vilenkin 1997; Birkel & Sarkar 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*)



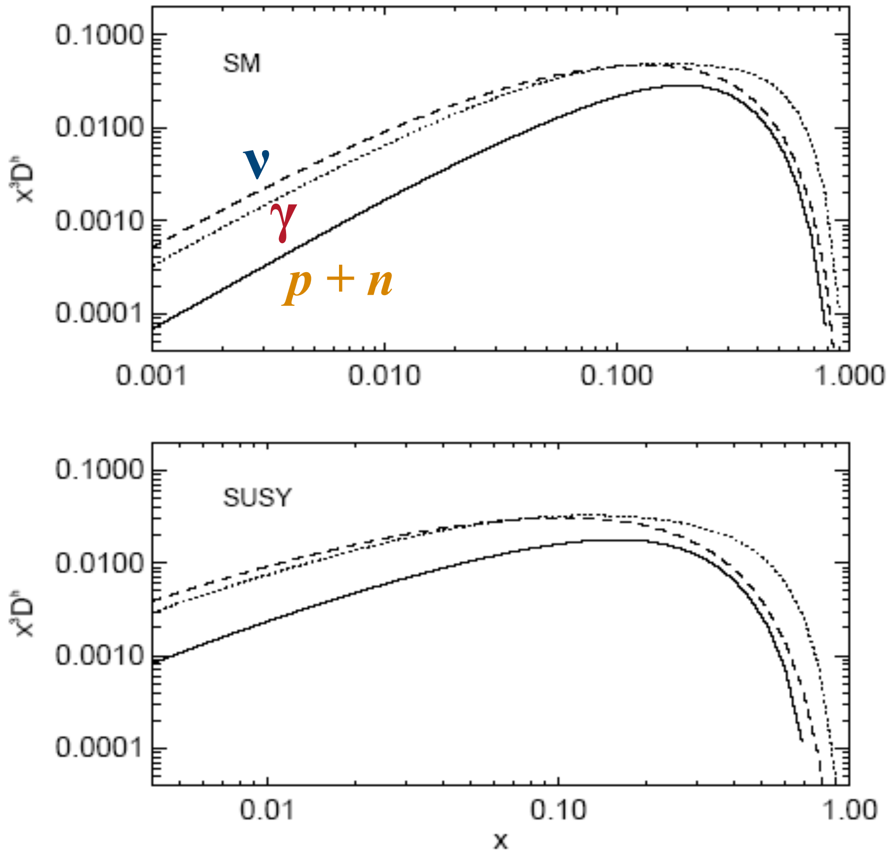


FIG. 6. Fragmentation functions for baryons (solid lines), photons (dotted lines) and neutrinos (dashed lines) evolved from M_Z up to $M_X = 10^{12}$ GeV for the SM (top panel) and for SUSY with $M_{\rm SUSY} = 400$ GeV (bottom panel).

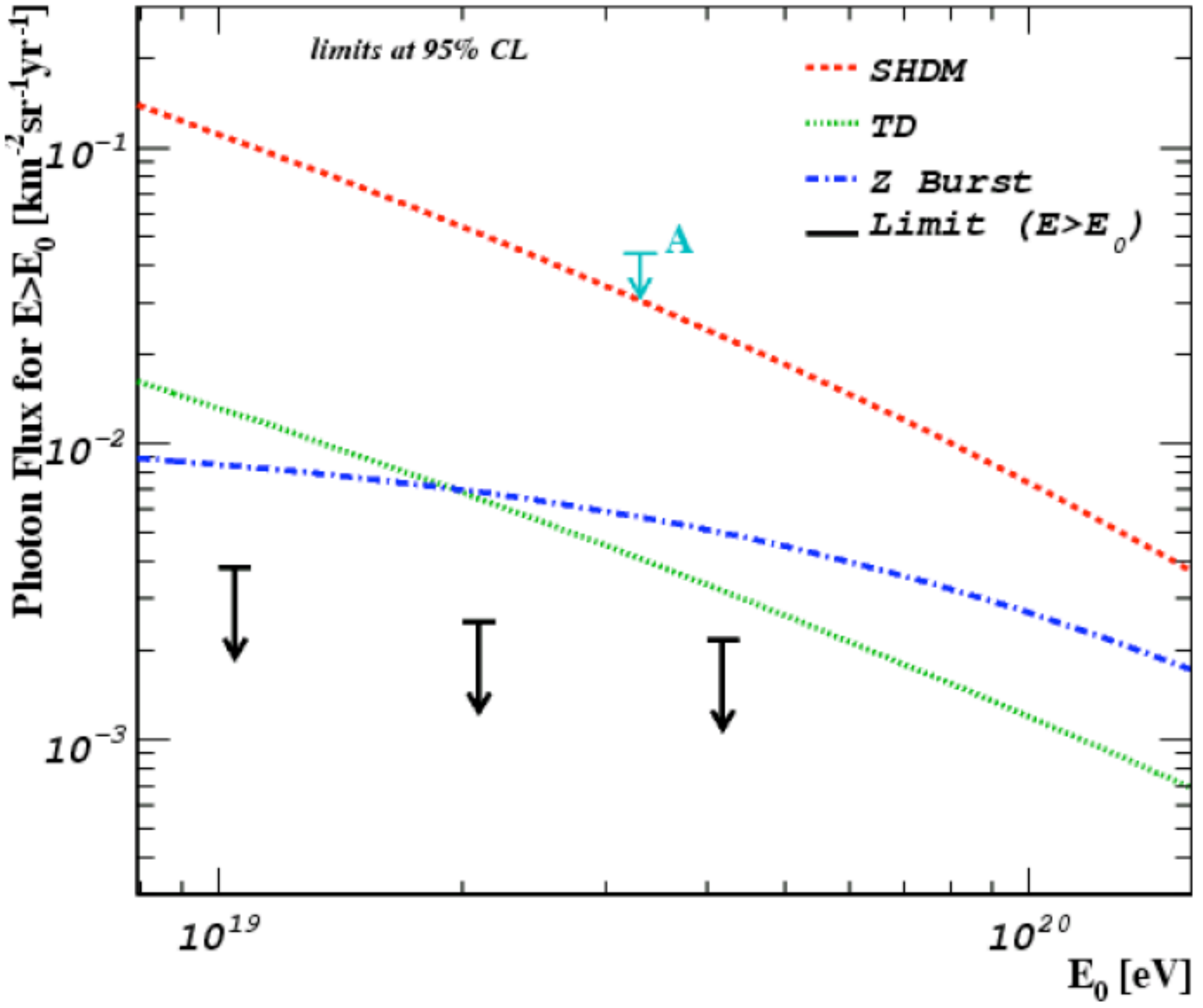
Perturbative evolution of parton cascade tracked using (SUSY) DGLAP equation … fragmentation modelled semi-empirically

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

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

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

UHECRs are *not* photons - rules out 'top down' models of their origin



[Auger collaboration, arXiv:0712.1147]

The "guaranteed" cosmogenic neutrino flux

GZK mechanism :

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

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

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

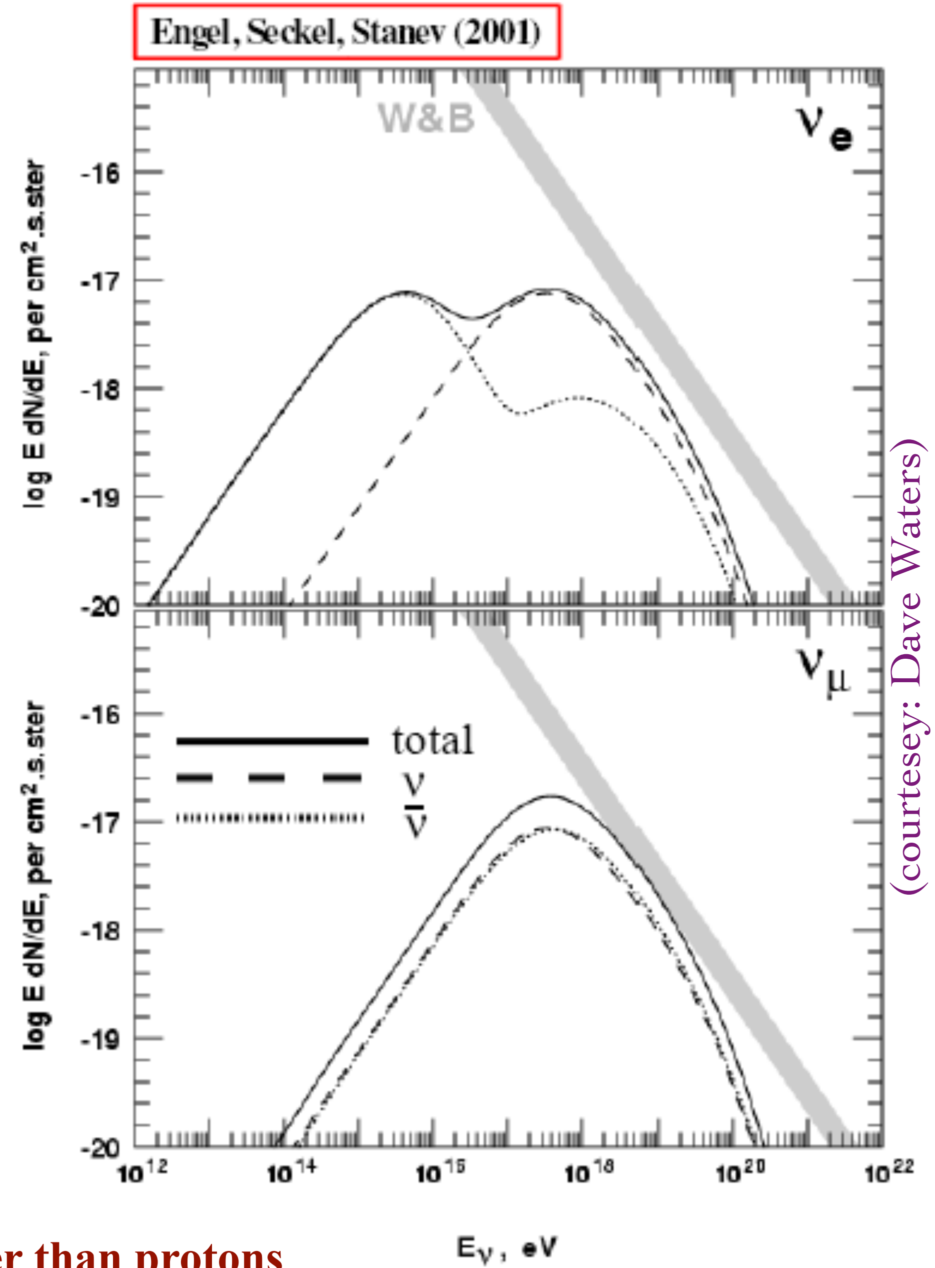
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

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

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

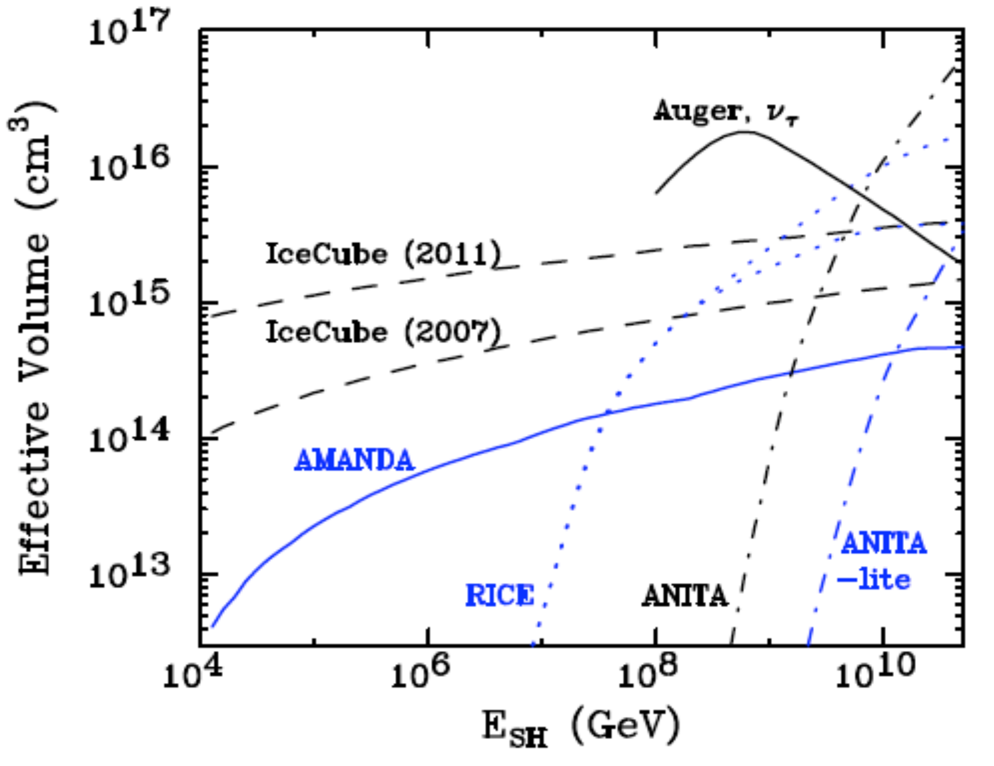
factors of ~2 uncertainty each;
factor of ~4 overall (?)

… would be smaller if primaries are heavy nuclei rather than protons



(courtesey: Dave Waters)

Estimated (cosmogenic ν) rates in running/near future experiments



Halzen & Hooper, PRL 97:099901,2006

	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

Fermi bound on diffuse γ-ray bkgd. constrains cosmogenic flux too [Ahlers *et al*, arXiv:1005.2620]

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

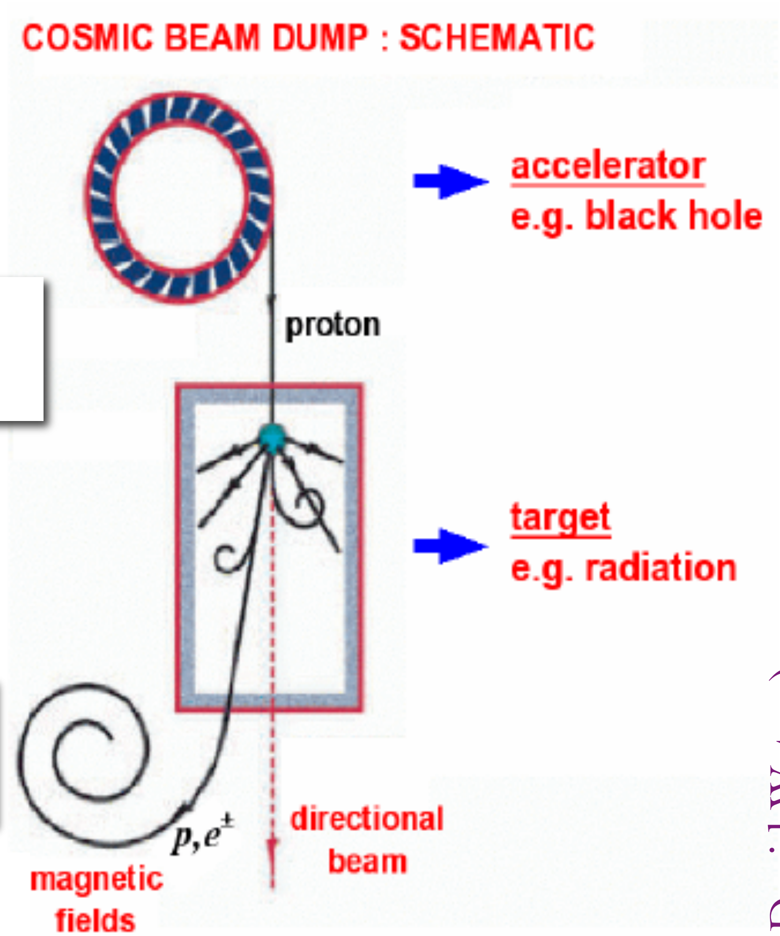
Hubble time

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

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

➡Making a reasonable estimate for ε_π etc allows this to be converted into a flux prediction

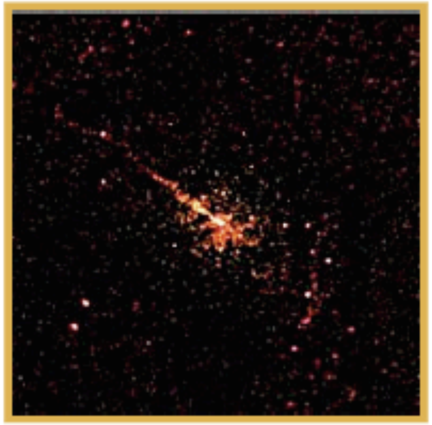
(would be higher if extragalactic cosmic rays become dominant at energies below the ‘ankle’)



(Courtesey: David Waters)

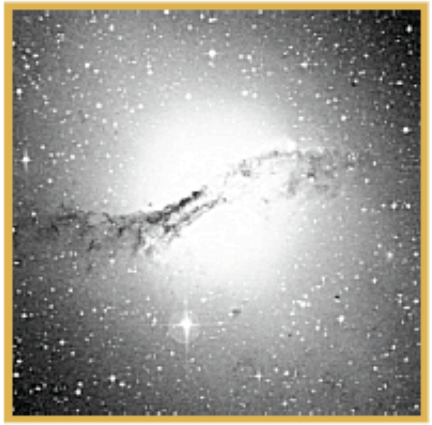
Centaurus A – Peculiar Galaxy

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

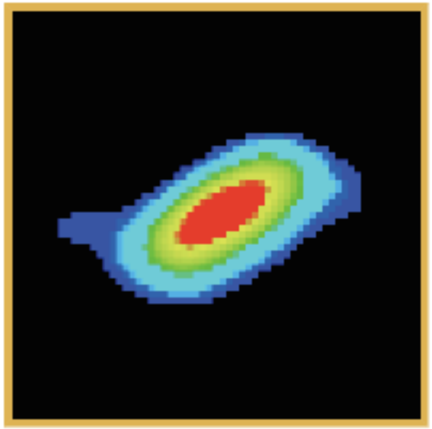


Visible: DSS

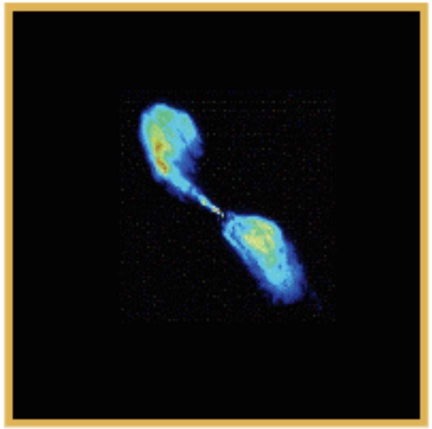
Visible: Color ©AAO

Near-Infrared: 2MASS

Mid-Infrared: Spitzer



Far-Infrared: IRAS



Radio: VLA

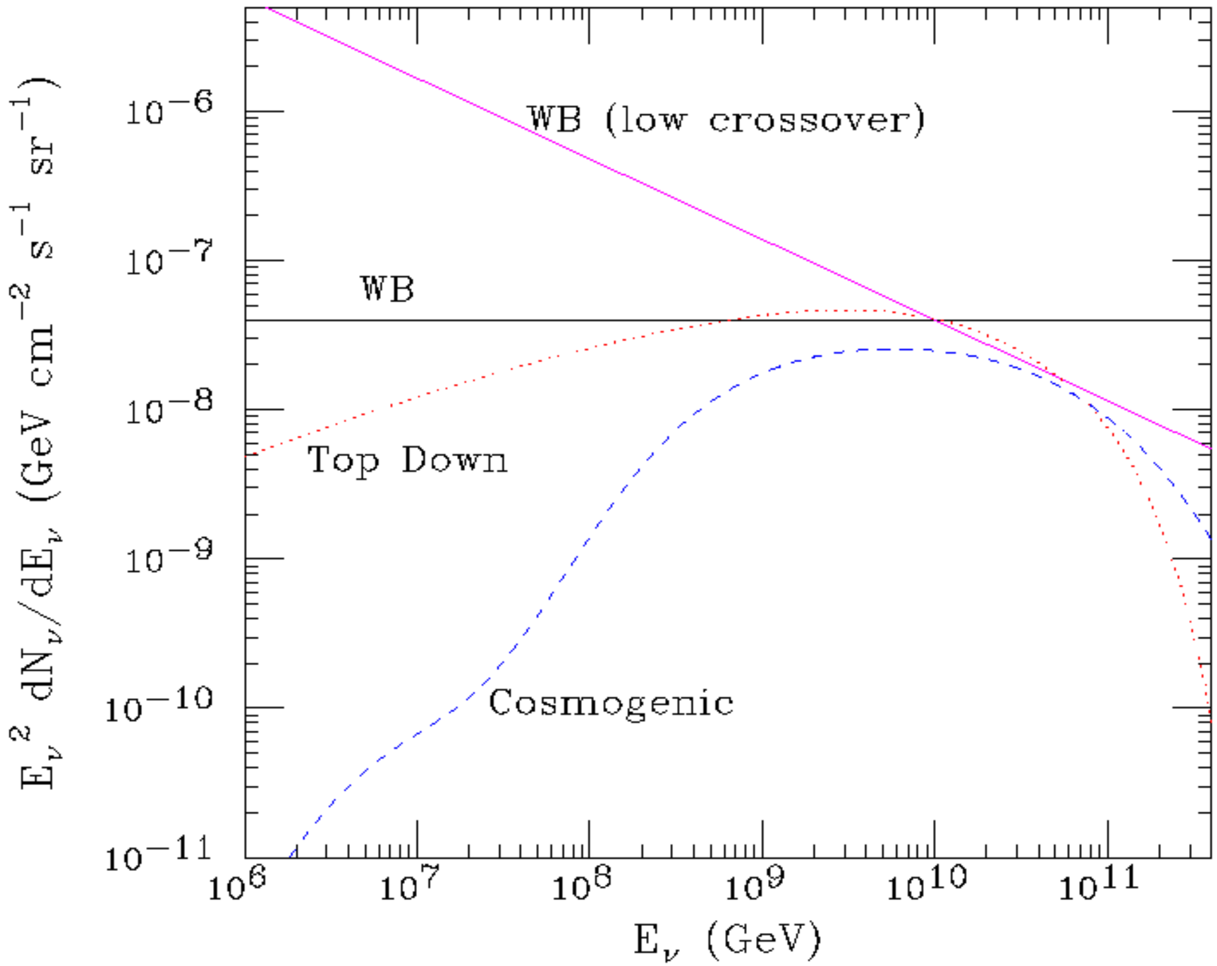
Estimate of ν flux from *p-p*:

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

~ 0.02-0.8 events/km^2 yr

Halzen & Murchadha [arXiv:0802.0887]

Plausible (optimistic) UHE cosmic neutrino fluxes



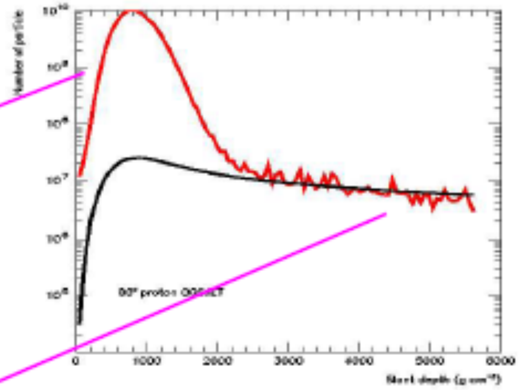
Anchordoqui, Han, Hooper & Sarkar, AP 25:14,2006

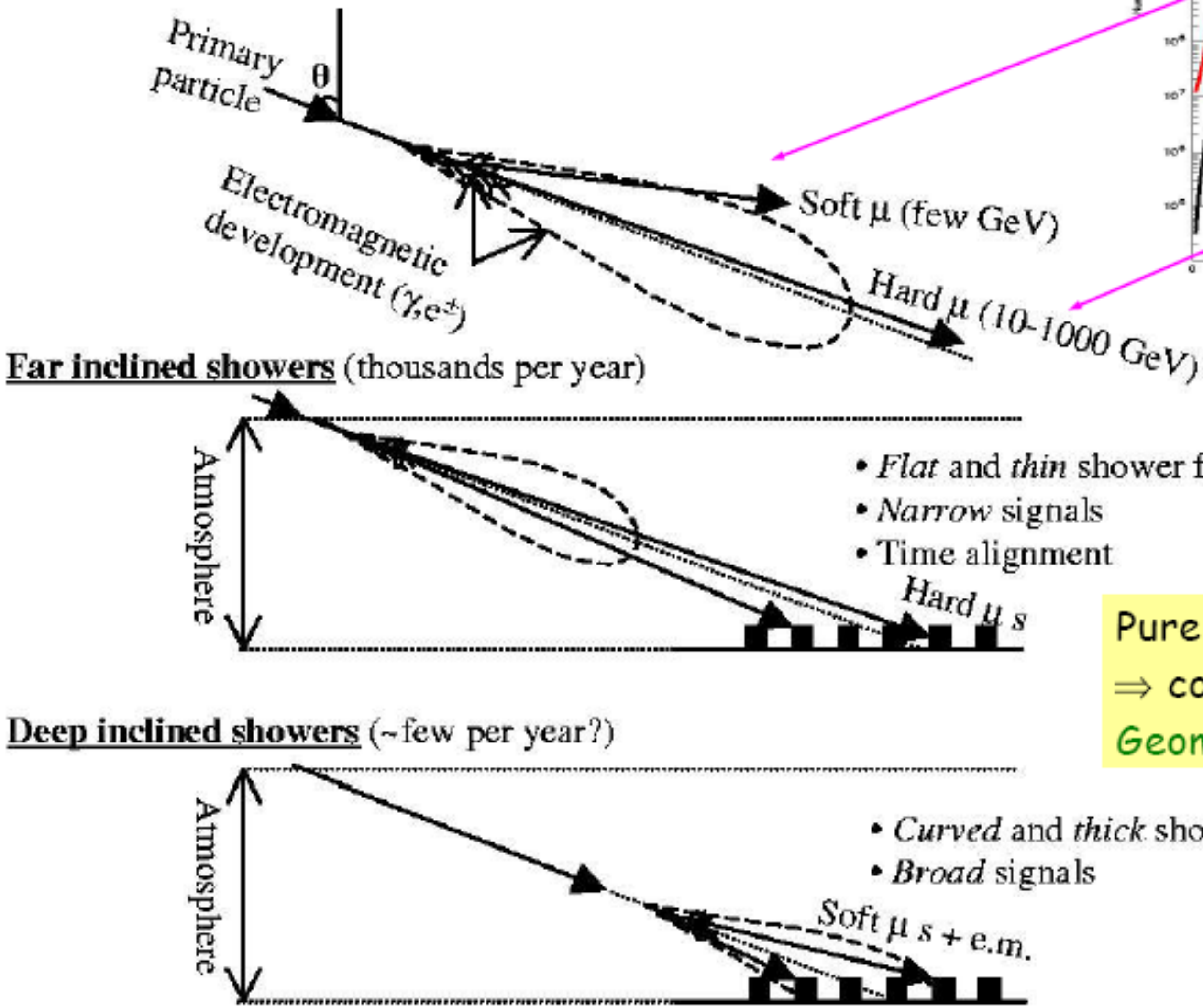
WB flux is enhanced in models where extragalactic sources are assumed to dominate from ~10^{18} eV … close to being ruled out (Ahlers, Anchordoqui & Sarkar, PRD79:083009,2009)

To see cosmic νs may require >100 km^3 detection volume (ANITA, IceRay, ARA …)

An unexpected bonus – UHE neutrino detection with air shower arrays

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



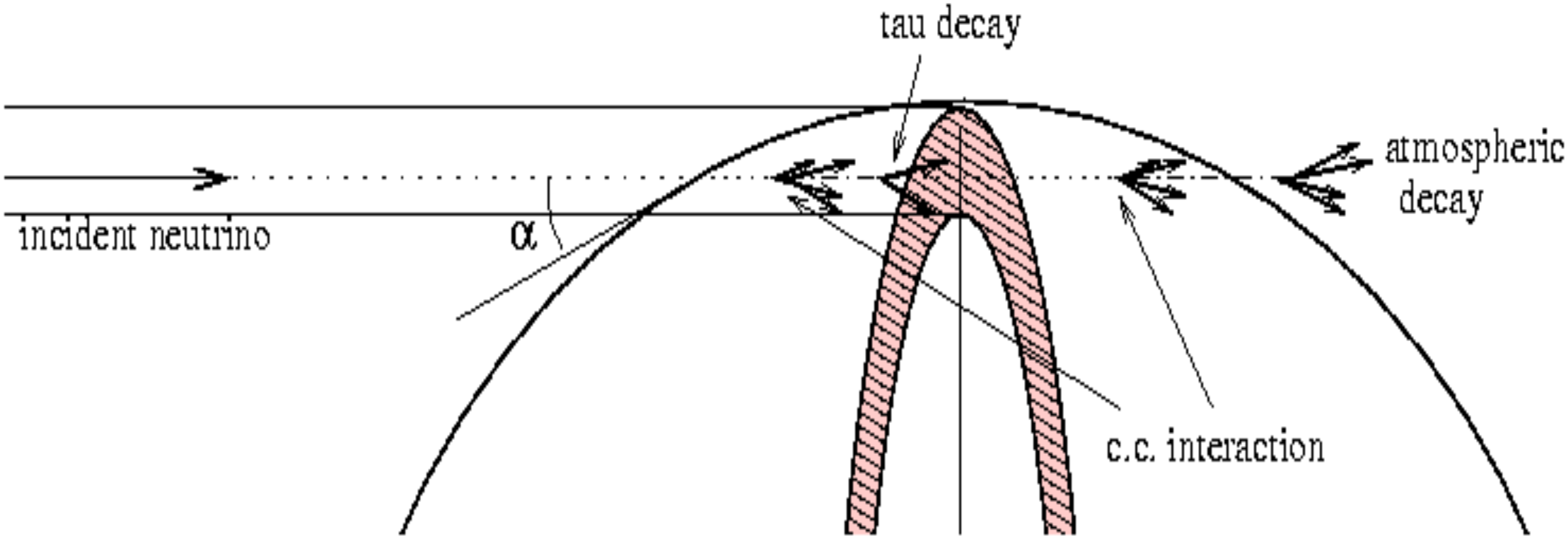


Pure muon beam
⇒ connect to composition
Geomagnetic field effects

Neutrino candidates

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

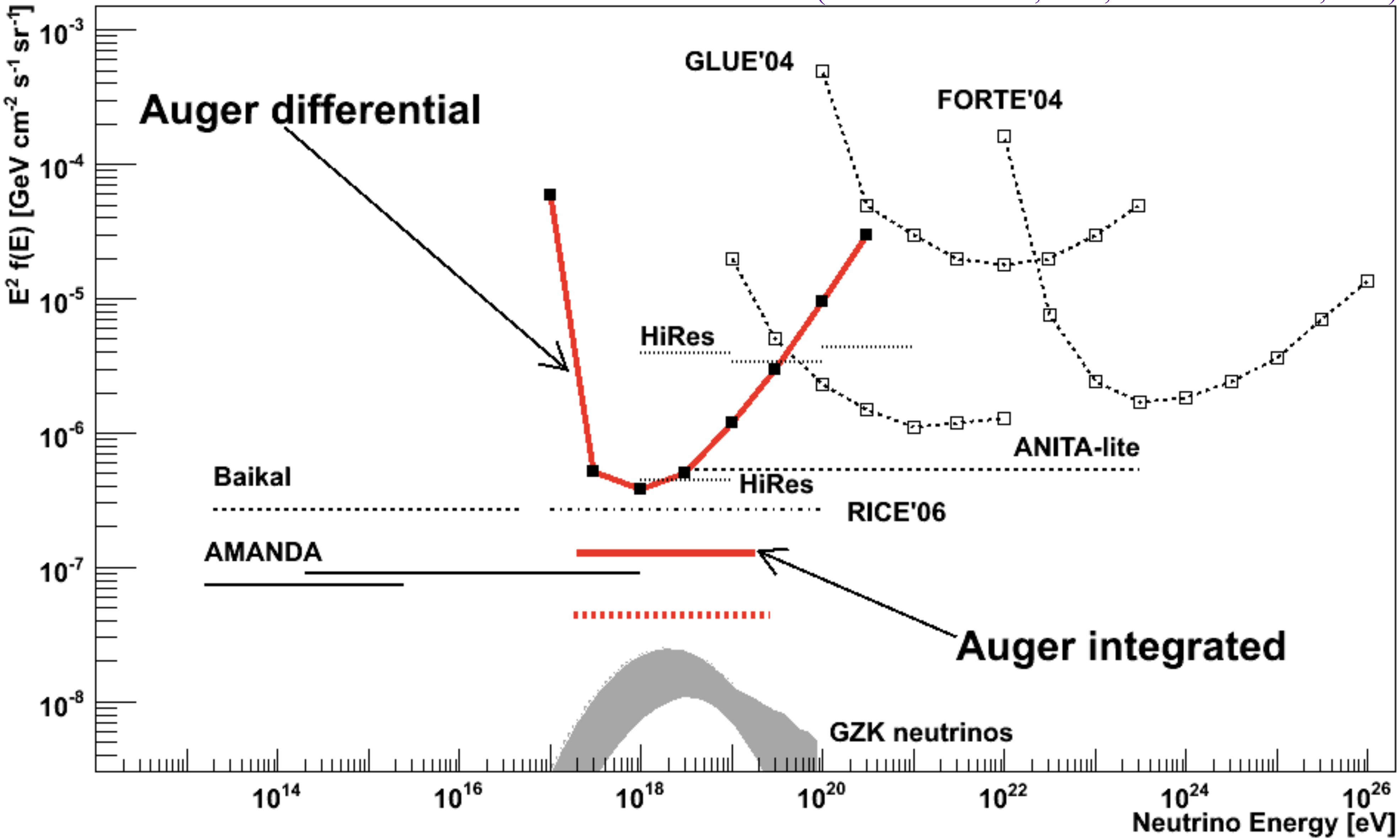
Rate ~ cosmic neutrino flux, but *not* to ν-N #-secn



… so if we can detect both quasi-horizontal and Earth-skimming events, then can get handle on ν-N #-secn *independently* of absolute flux!

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

(PRL 100:211101,2008; PR D79:102001,2009)



(NB: To do this we need to know *ν-N* cross-section at ultrahigh energies)

Colliders & Cosmic rays

The LHC will soon achieve ~14 TeV cms …

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

→ can probe new physics both **in and beyond the Standard Model** by observing **ultra-high energy cosmic neutrinos**

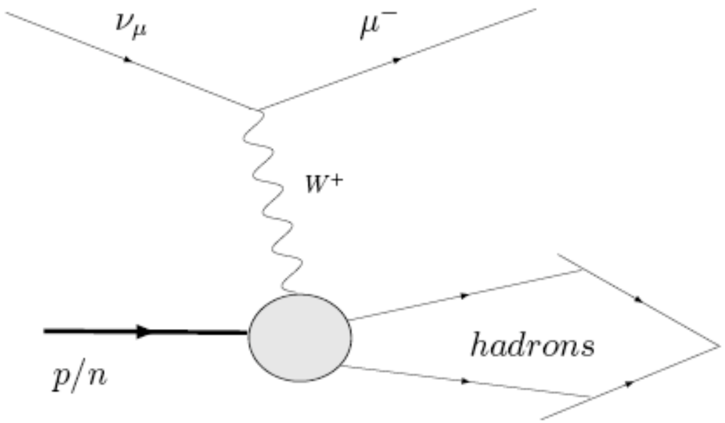
ν-N deep inelastic scattering

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

Q^2 ↑ propagator ↓

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

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



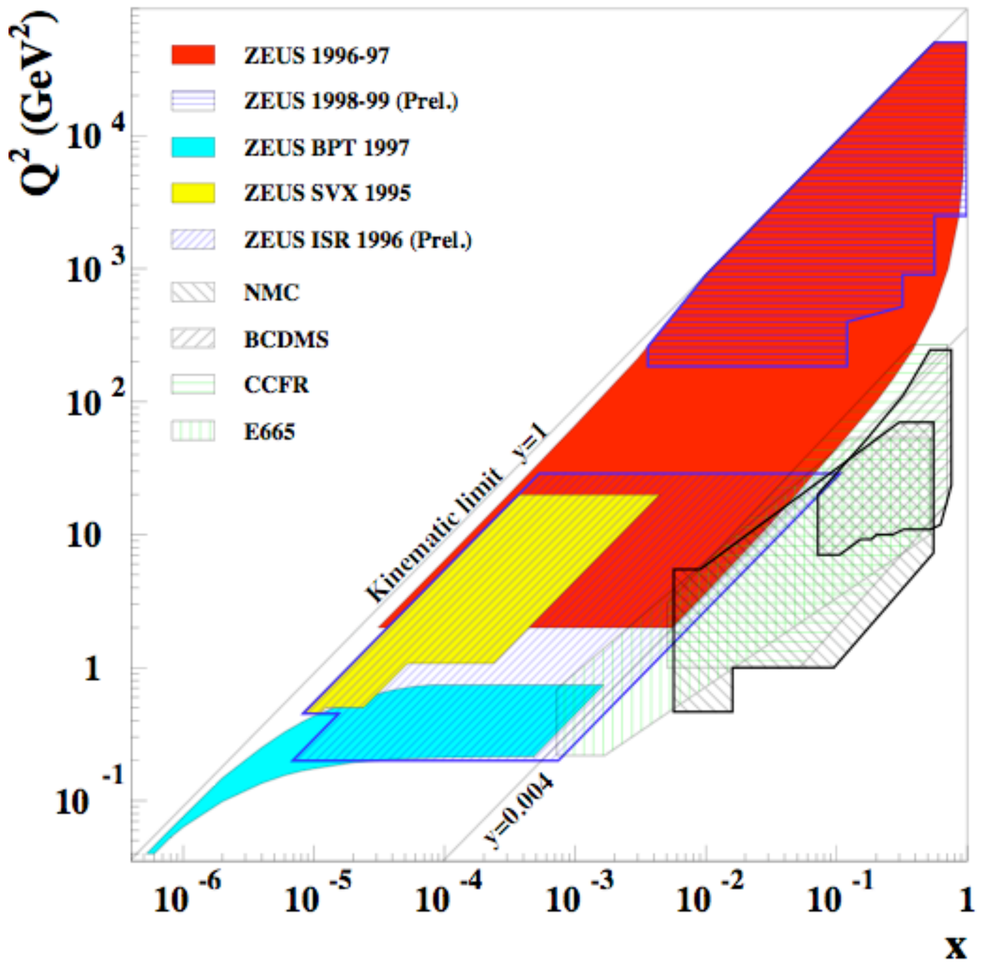
Q^2 ↑ parton distrib. fns ↓

Most of the contribution to σ-secn comes from: $Q^2 \sim M_W^2$ *and* $x \sim \frac{M_W^2}{M_N E_\nu}$

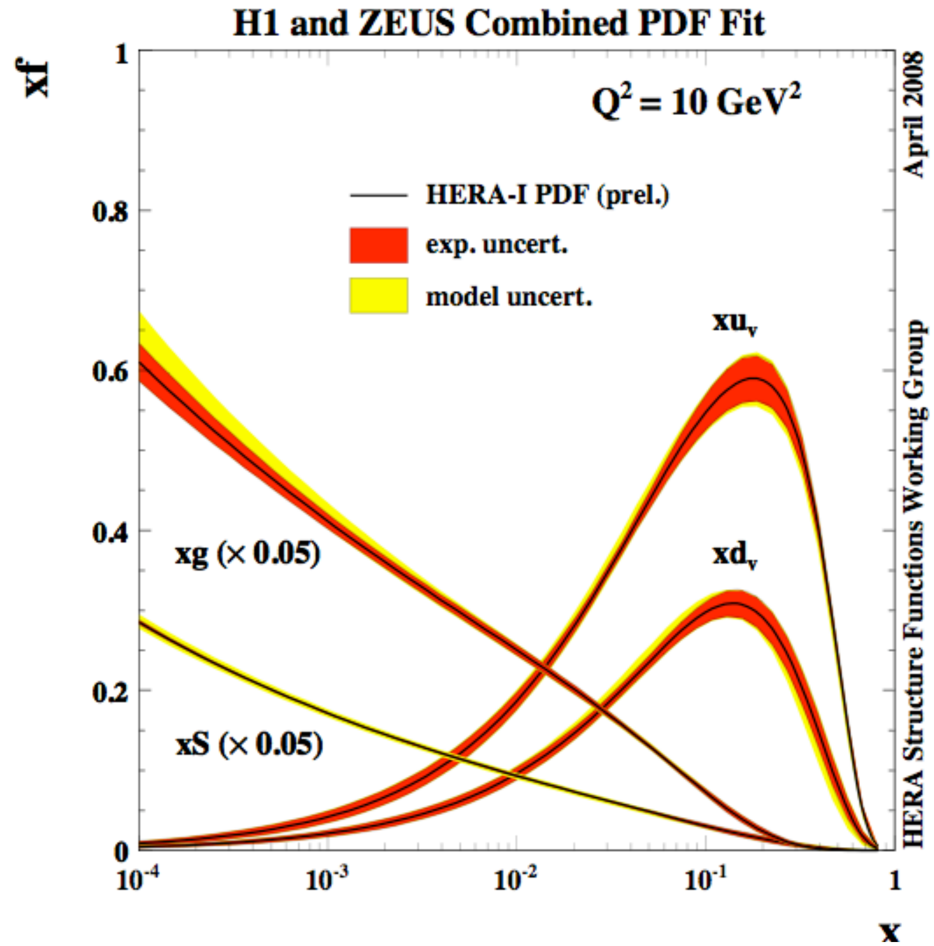
At leading order (LO) : $F_L = 0$, $\quad F_2 = x(u_v + d_v + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c})$,

$$xF_3 = x(u_v + d_v + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_v + d_v + 2s + 2b - 2\bar{c})$$

At NLO in α_s, it gets more complicated … but is still calculable



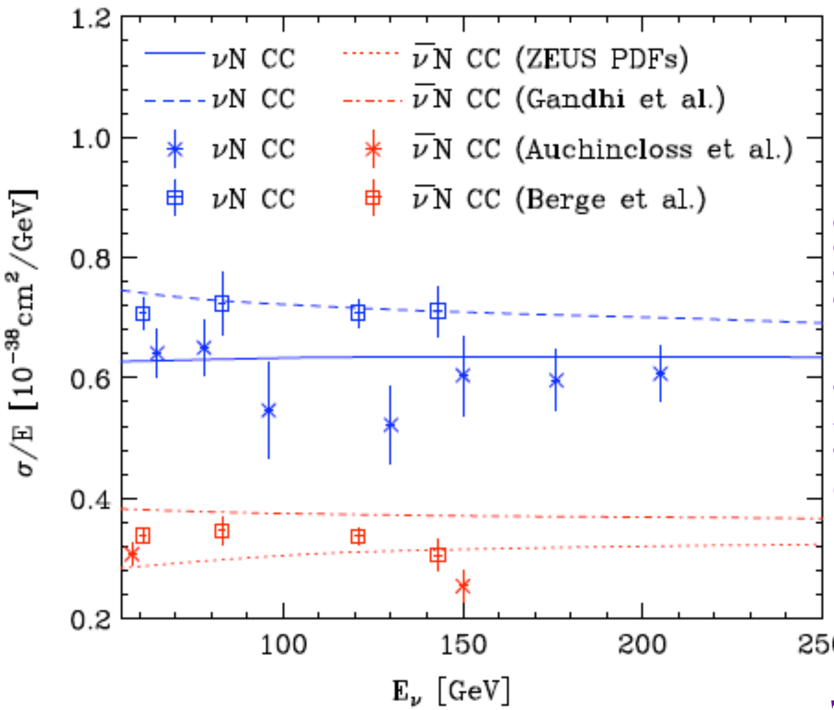
The H1 and ZEUS experiments at HERA have made great progress by probing a much deeper kinematic region



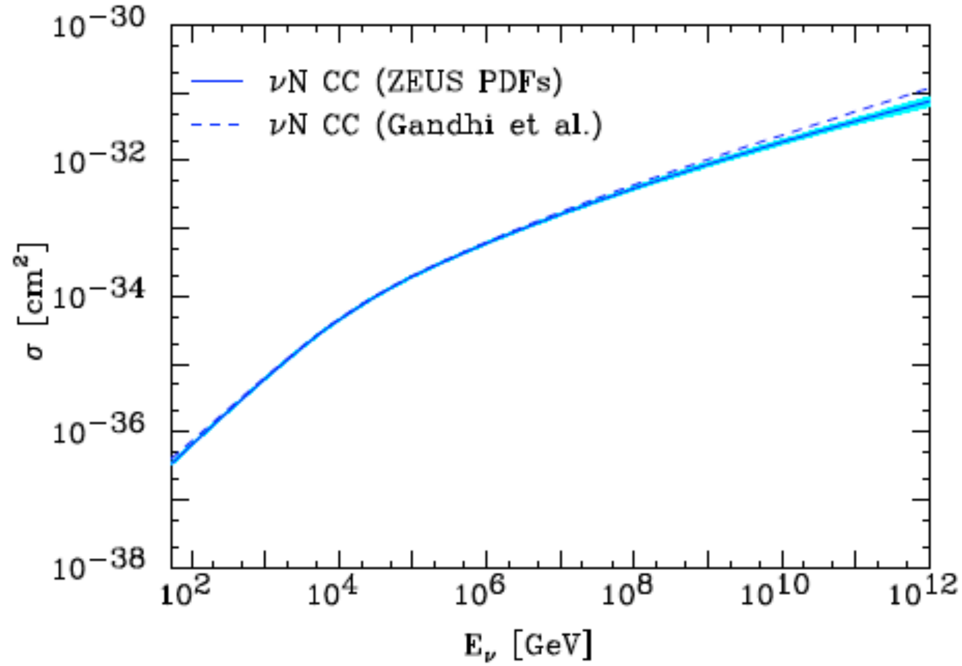
Most surprising result is the steep rise of the gluon structure function at low Bjorken x ➔ significant impact on ν scattering

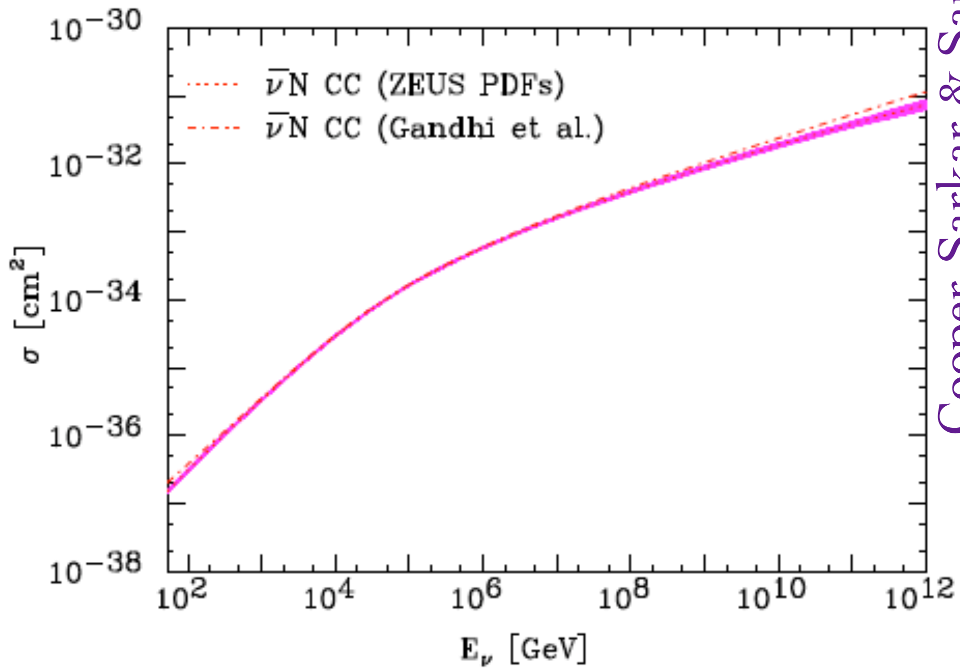
The #-section is up to 40% *below* the widely used calculation by Gandhi *et al* (1996) … more importantly the (perturbative SM) *uncertainty* has now been calculated

Being used by Auger, IceCube etc … to be incorporated in ANIS MC

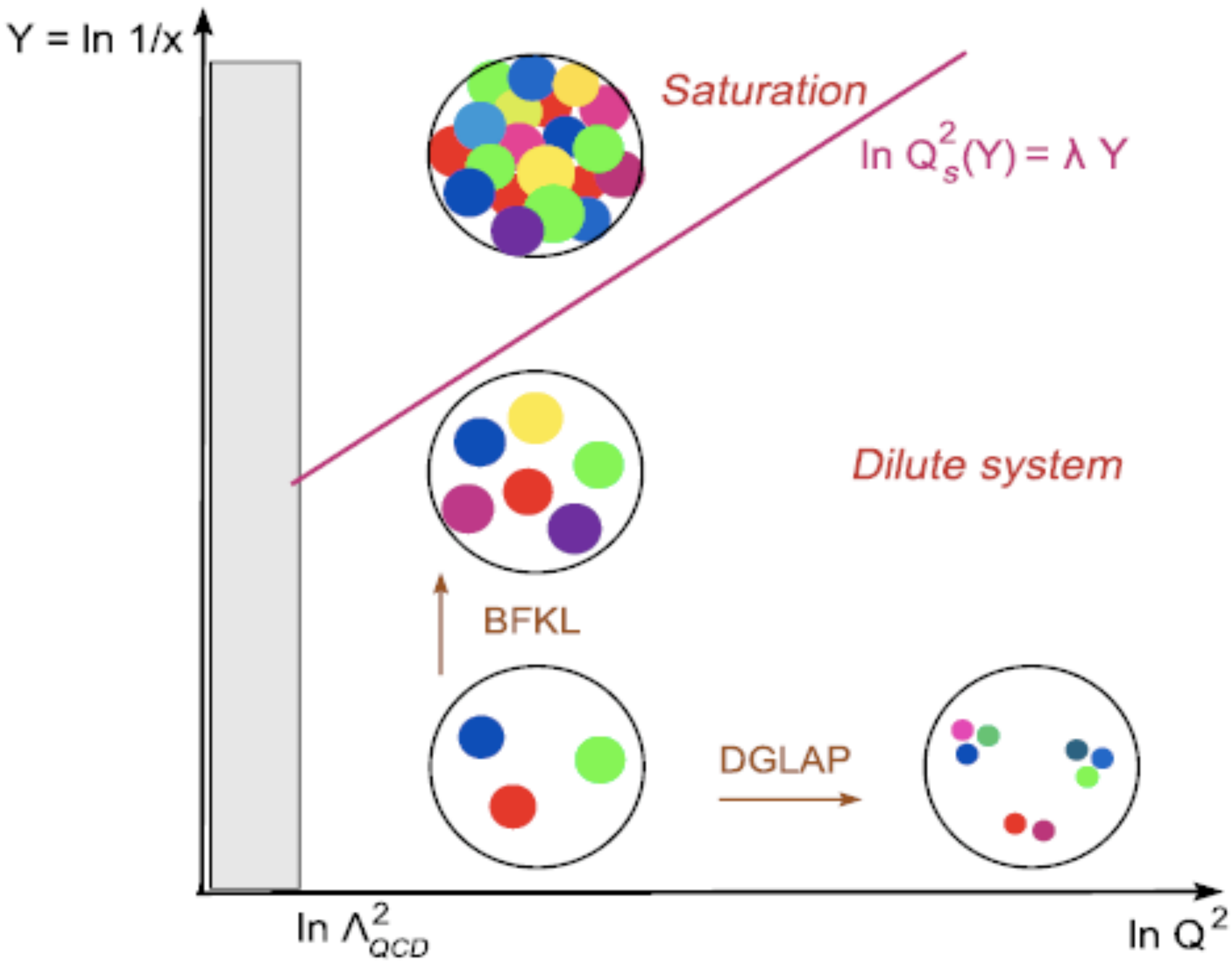


Cooper-Sarkar & Sarkar, JHEP 01:075,2008





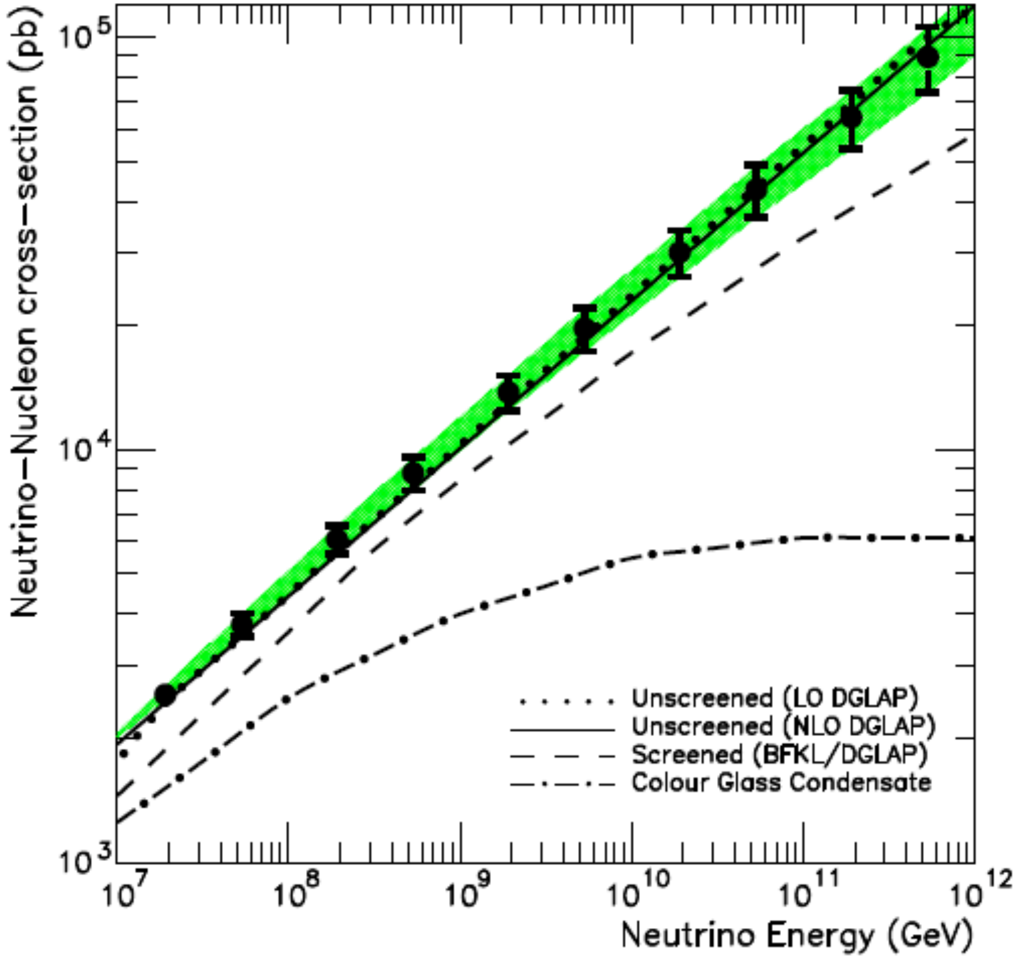
As the gluon density rises at low x, non-perturbative effects become important … a new phase of QCD - Colour Gluon Condensate - has been postulated to form

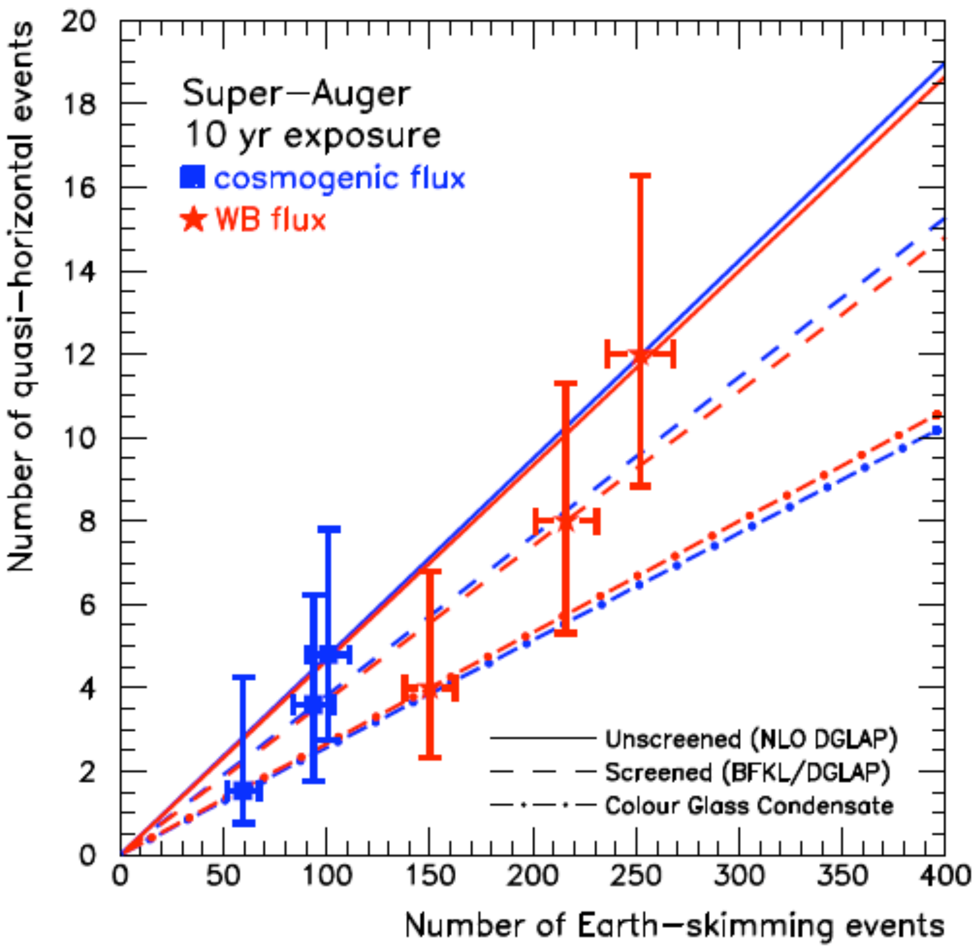


This would *suppress* the ν-*N* #-secn below its (unscreened) SM value

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

Anchordoqui, Cooper-Sarkar, Hooper & Sarkar, PRD74:043008,2006



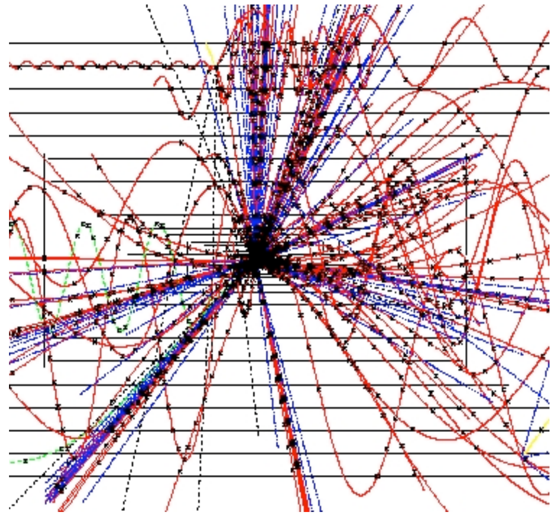


The steep rise of the gluon density at low-x must saturate (unitarity!) ➔ suppression of the ν-N #-secn

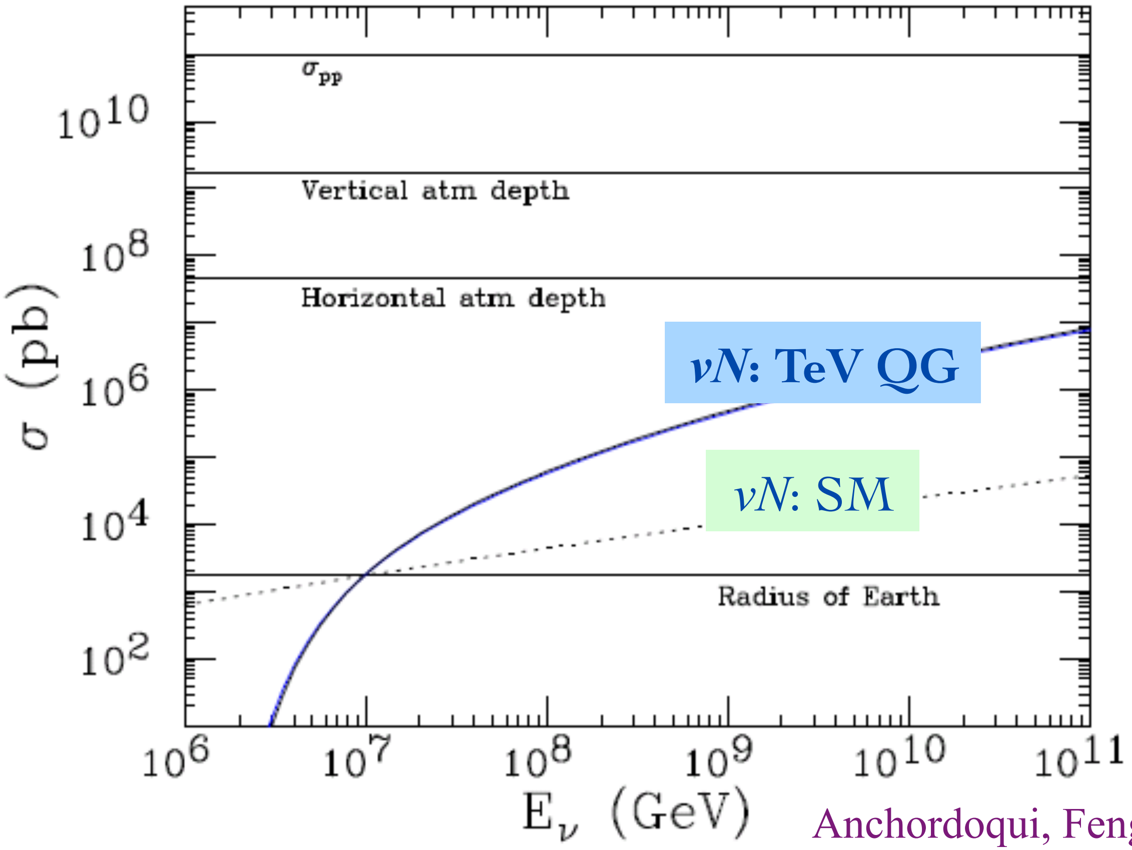
The ratio of quasi-horizontal (all flavour) and Earth-skimming (ν_τ) events *measures* the cross-section

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 $A \sim \pi R^2_{Schwarzschild}$



(courtesey: Albert De Rocek)

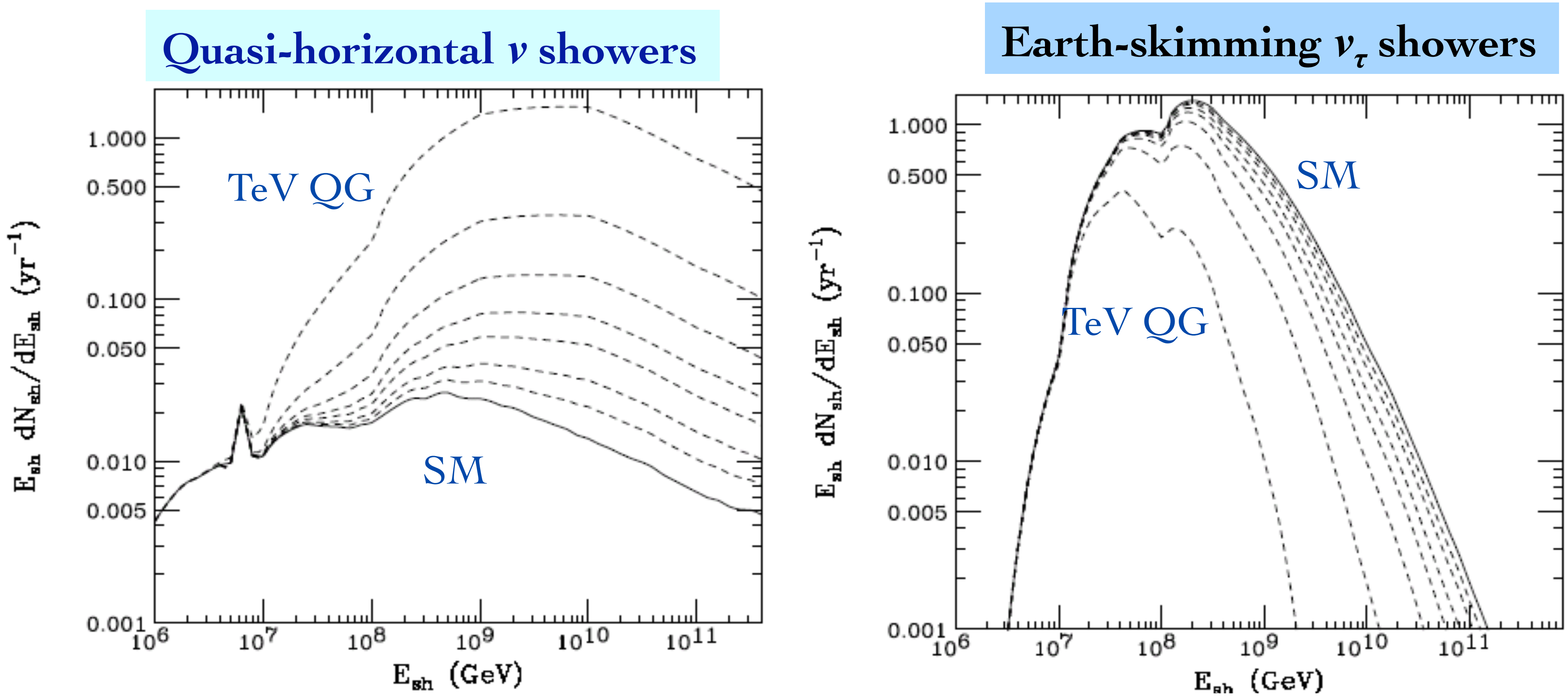


… and then evaporate rapidly by Hawking radiation (+ gravitational waves?)

This will enhance the neutrino scattering #-secn significantly

Anchordoqui, Feng, Goldberg & Shapere, PRD68:104025,2003

Testing TeV scale quantum gravity (assuming W-B flux)



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, AP 25:14,2006;
Anchordoqui *et al*, PRD82:043001,2010

<u>Summary</u>

Prospects are good for identifying the sources of medium energy cosmic rays by γ-ray telescopes (*CTA, HAWC*) … more work needed on theory

Auger and *Telescope Array* are addressing crucial questions about the energy spectrum, composition and anisotropies of ultra-high energy cosmic rays … the theoretical situation is even more challenging

The detection of UHE cosmic neutrinos by *IceCube* is eagerly awaited – will provide complementary information and identify the sources

Cosmic ray and neutrino observatories 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)