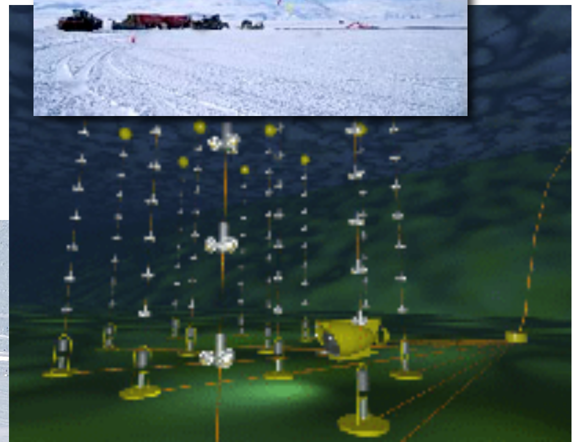
Seeing the high energy universe

iii) extragalactic cosmic rays & neutrinos

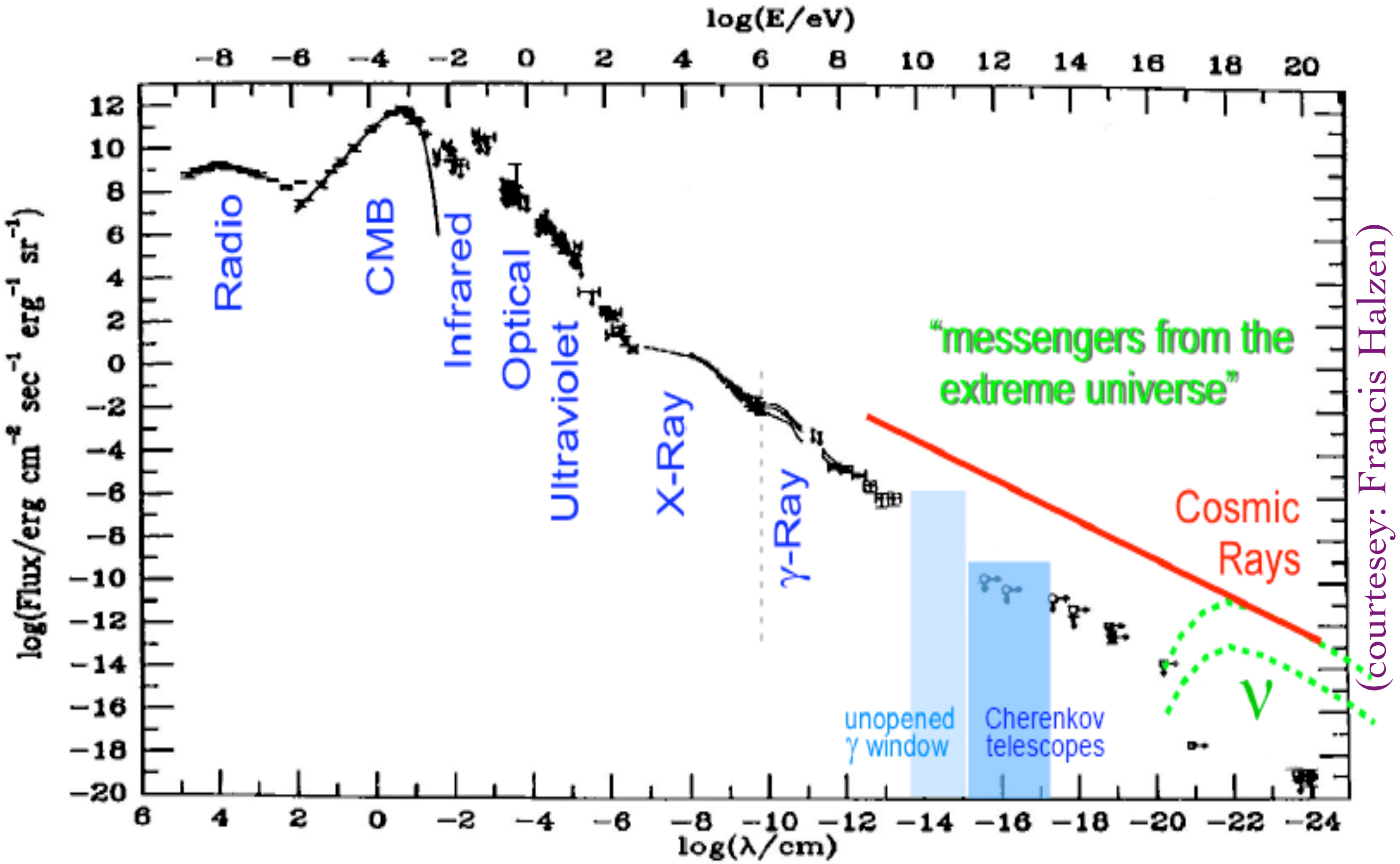
Subir Sarkar



Lecture 3, *Taller de Altas Energias*, Universitat de Barcelona, 9^{th} September 2010

We can *see* the universe directly with **photons** up to a few TeV

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

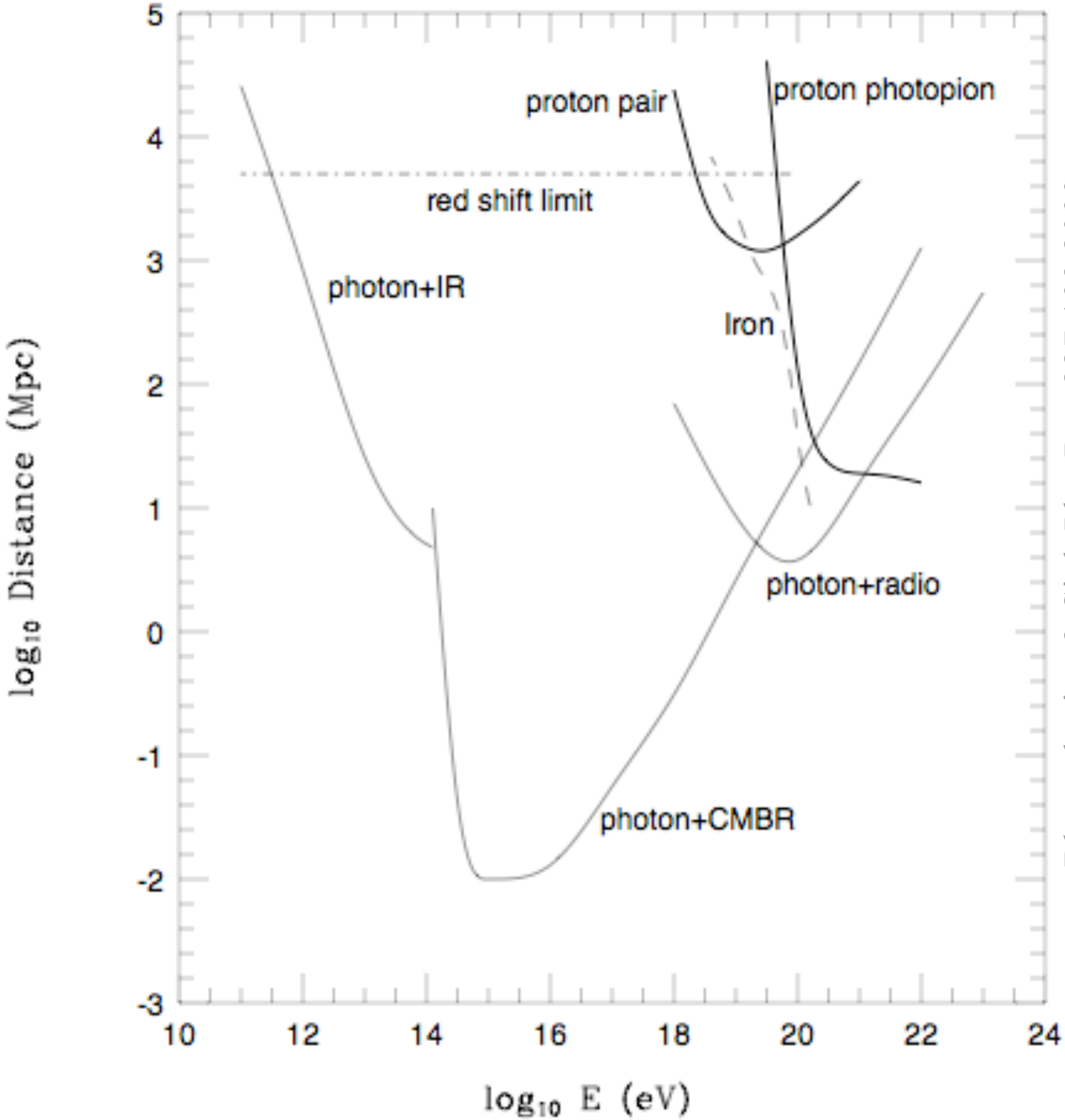


Using **cosmic rays** we should be able to 'see' up to ~ 6 x10^{10} GeV

(before they get attenuated by $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+, p\pi^0$, on the CMB)

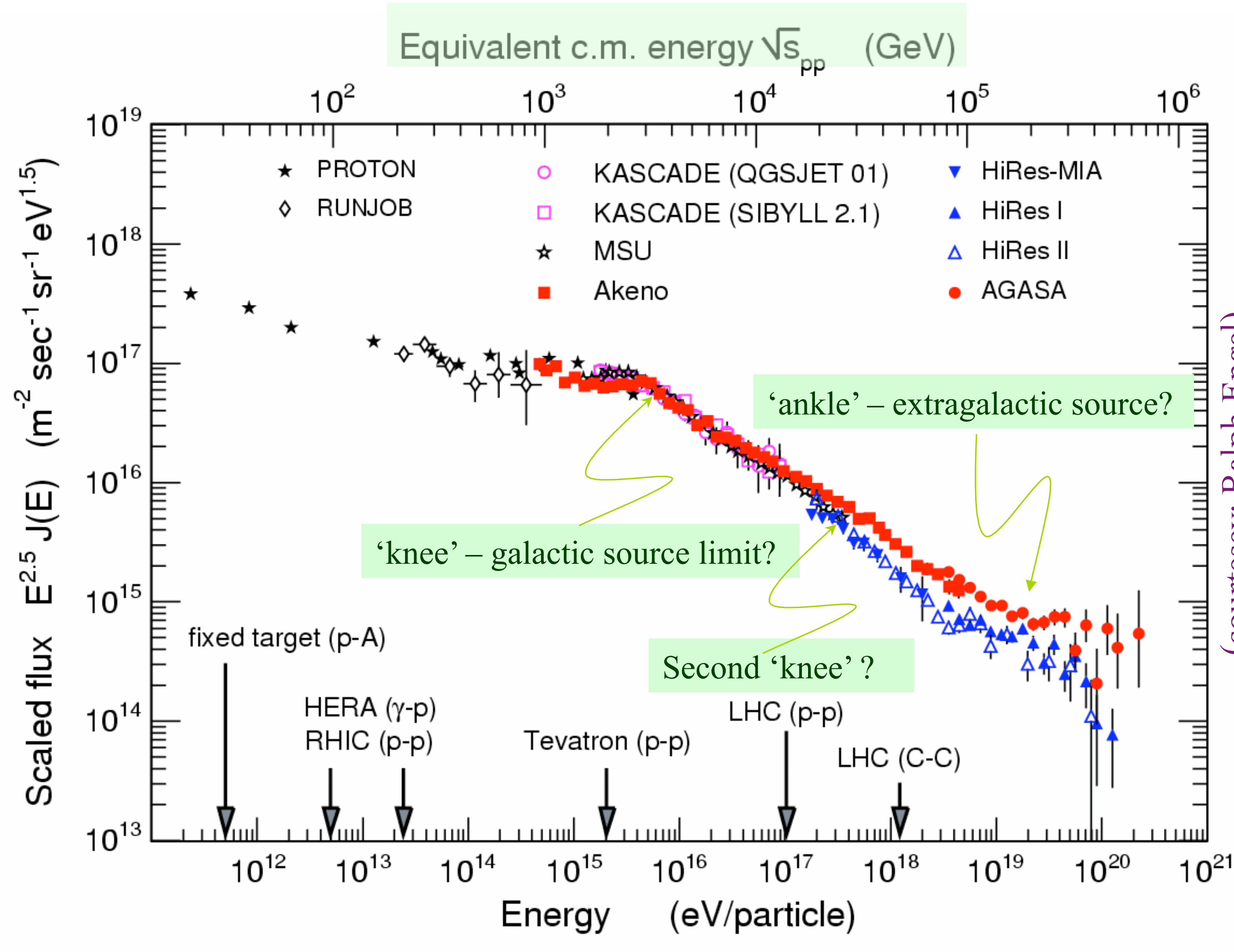
… and the universe is transparent to **neutrinos** at nearly *all* energies

Attenuation of cosmic messengers



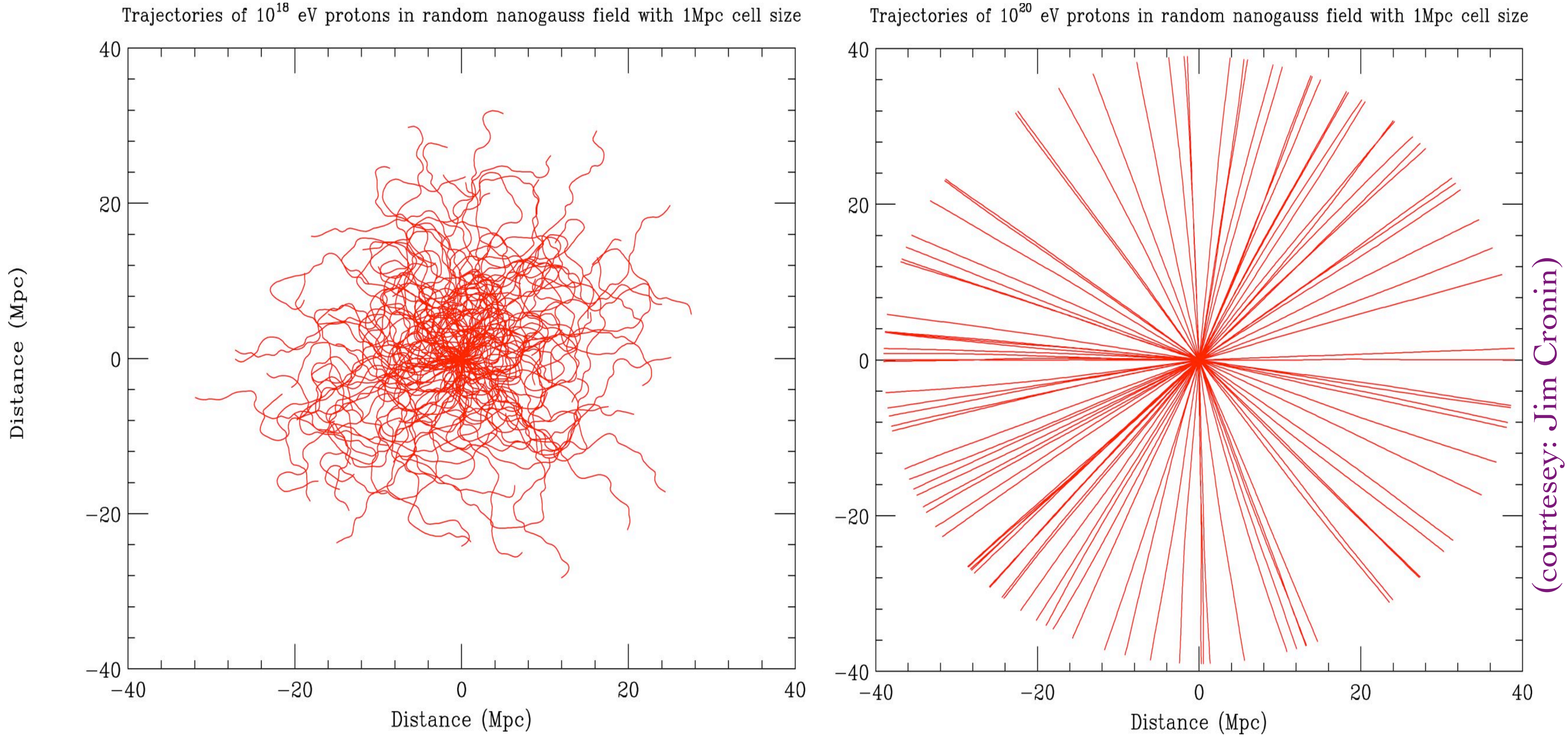
Bhattacharjee & Sigl, PhysRep 327:109,2000

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



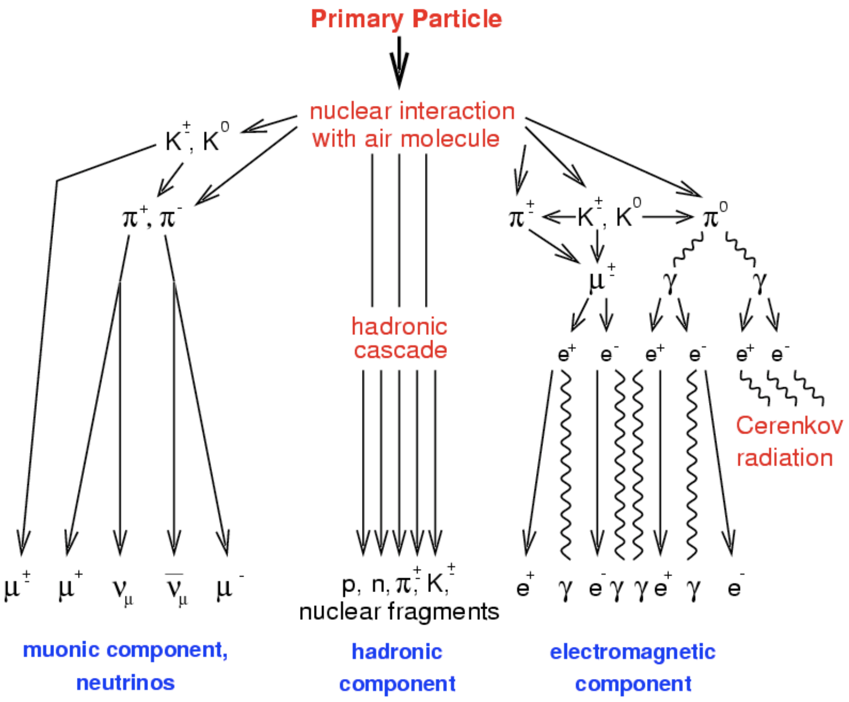
(courtesey: Ralph Engel)

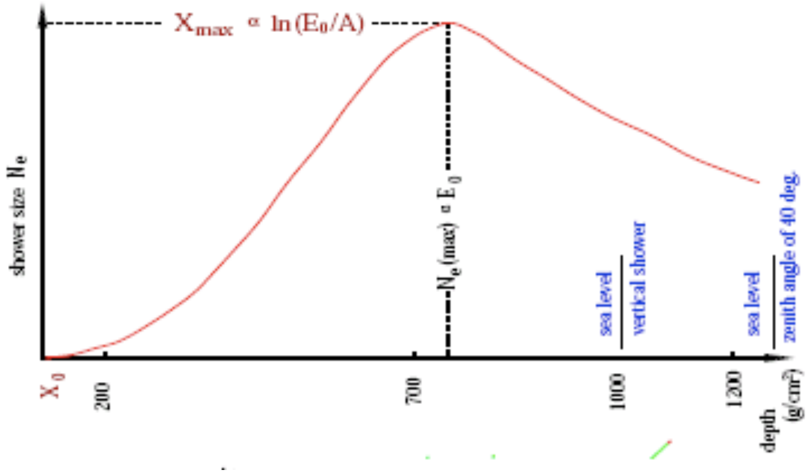
The trajectories of cosmic rays are randomised by cosmic magnetic fields … so need to go to ultrahigh energies to do cosmic ray astronomy



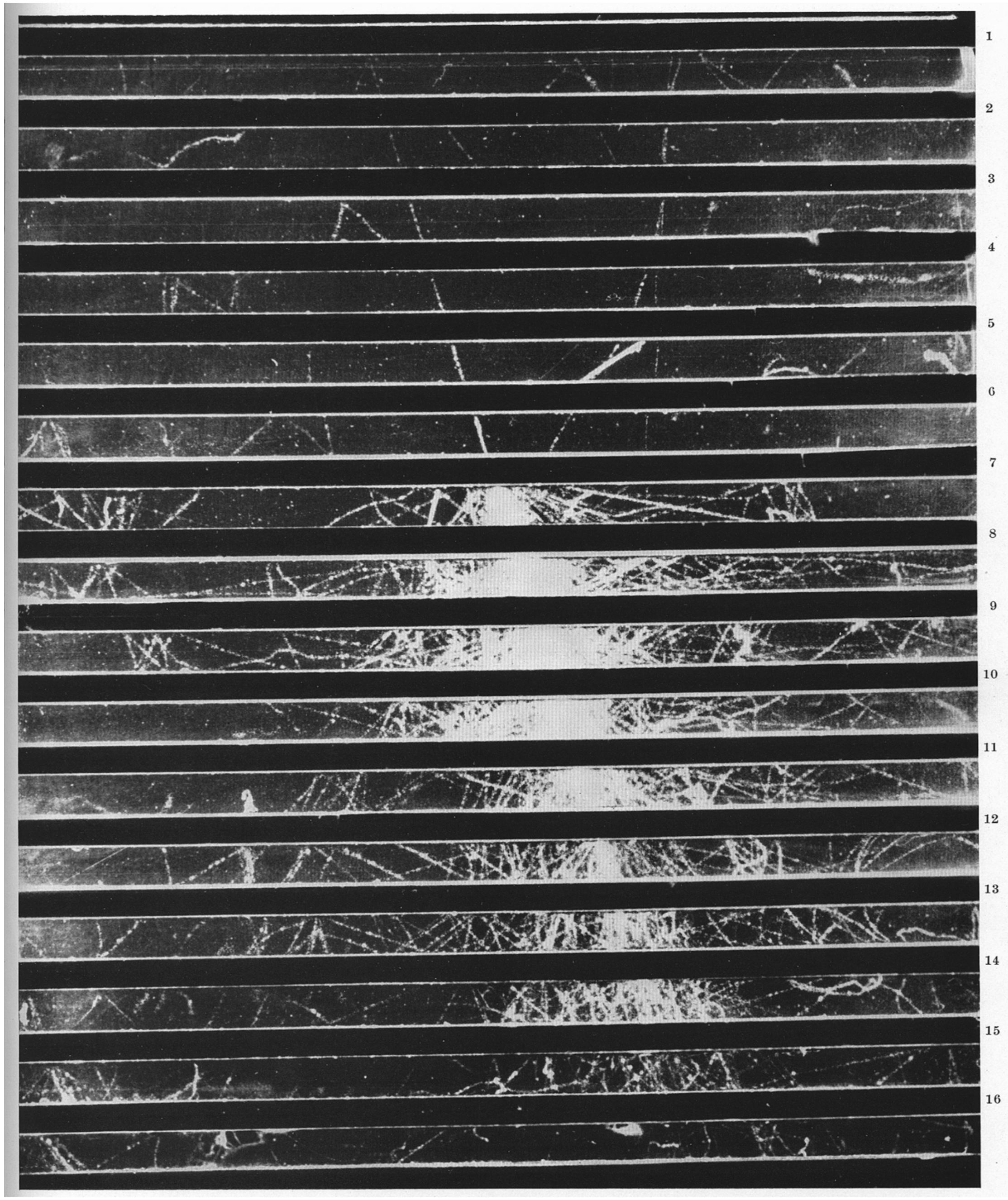
No anisotropies have been detected for cosmic rays up to the 'knee' (~10^{18} eV) – at higher energies they can no longer be deflected by Galactic magnetic fields

To study ultrahigh energy cosmic rays must use the Earth's atmosphere as detector

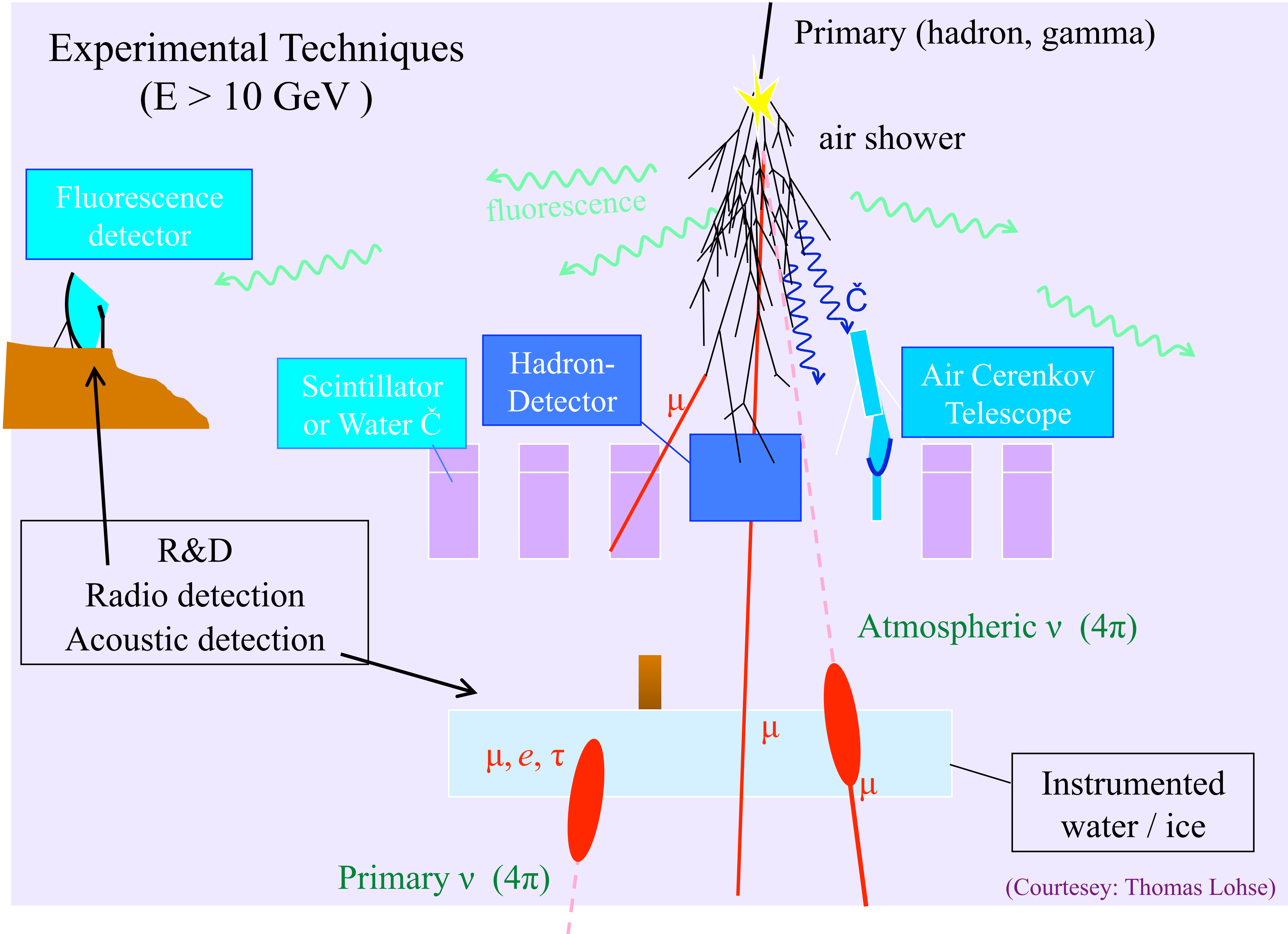




Cosmic ray shower in a cloud chamber

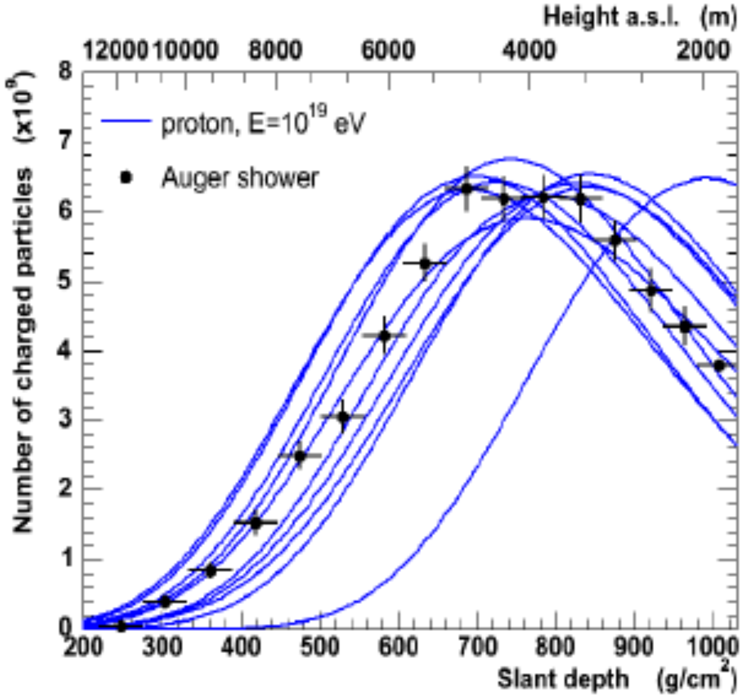


Experimental Techniques (E > 10 GeV)

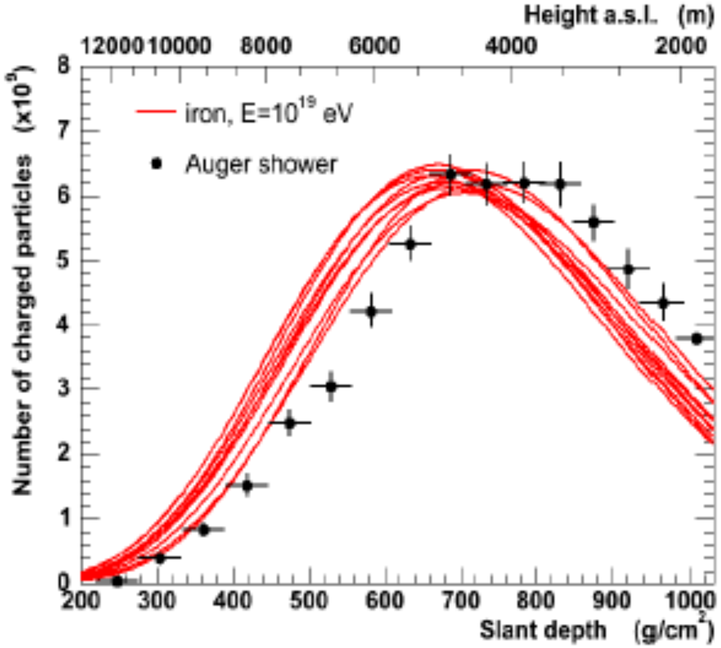


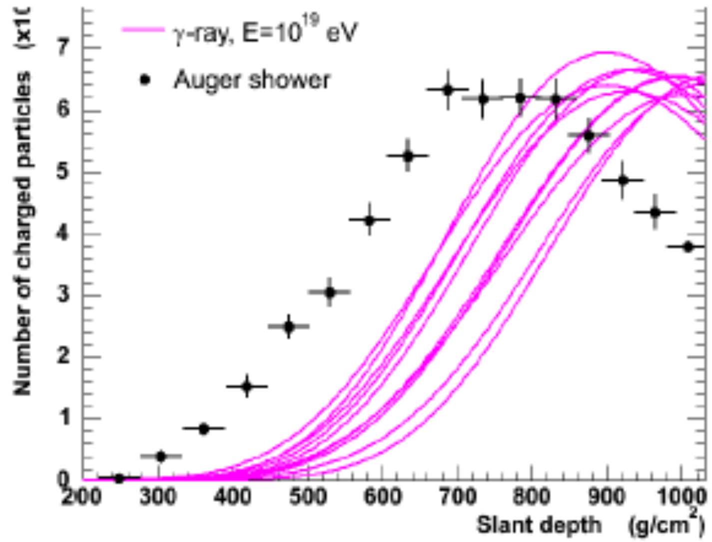
Energy/composition: shower profile

Detailed MC simulation: 10 showers
zenith angle 35°, QGSJET



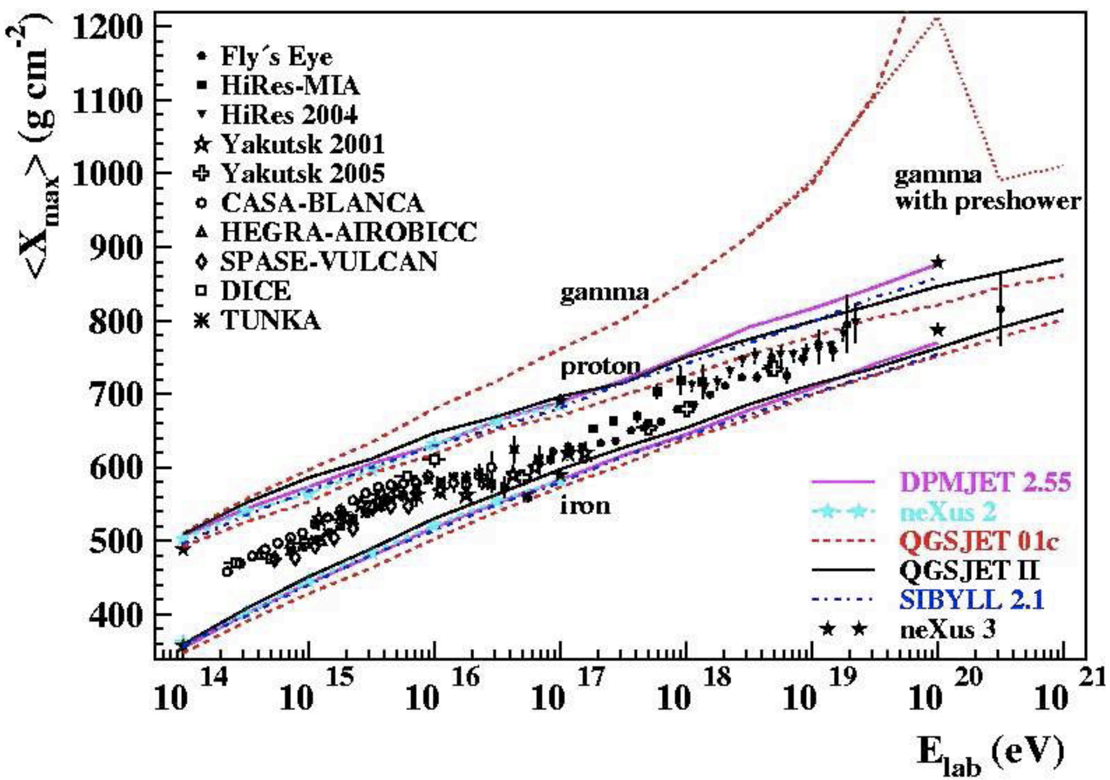
$$N^A_{max} = N_{max}, \qquad X^A_{max} \sim \lambda_e \ln(E_0/A)$$



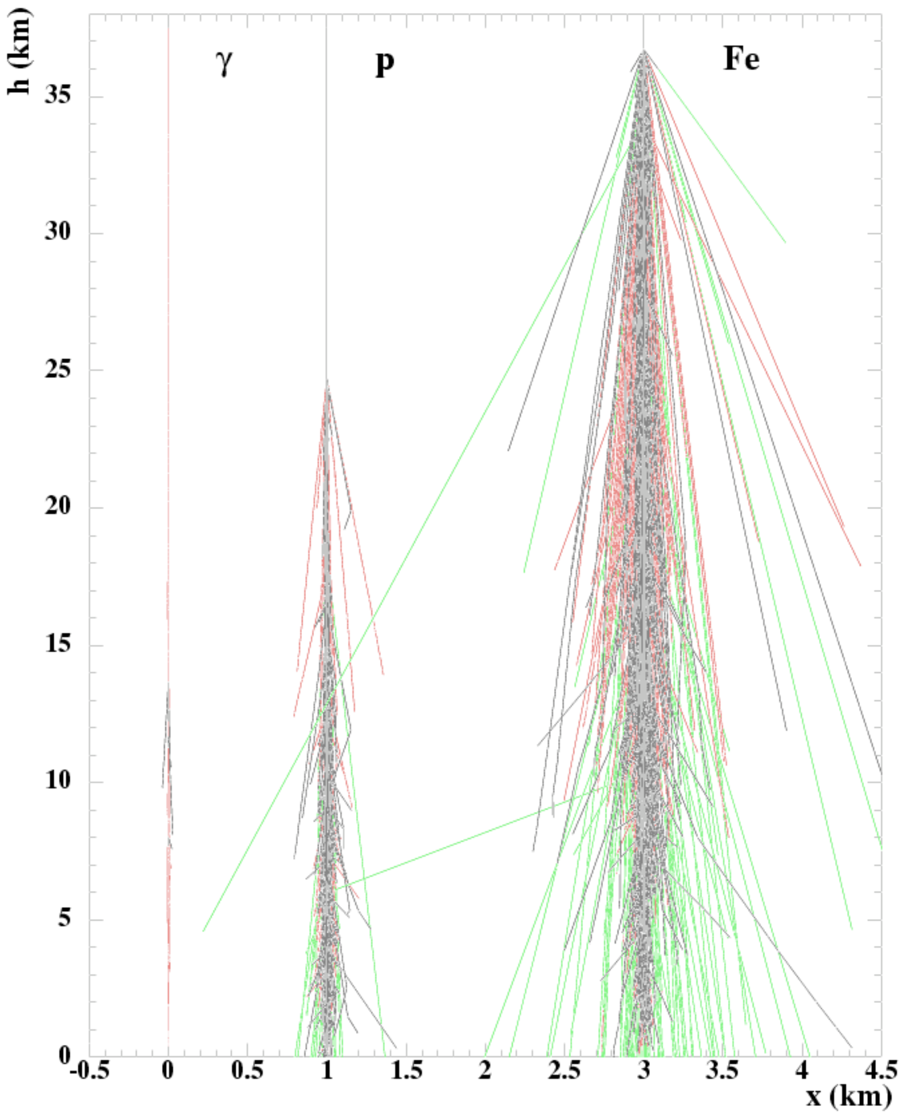


(Courtesey: Johannes Knapp)

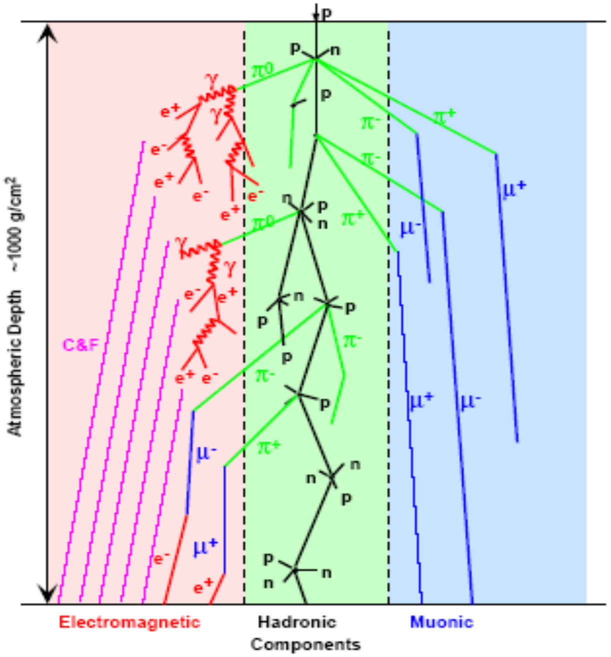
Can discriminate between hadrons and photons … harder to distinguish between p and Fe nuclei



To determine the chemical composition of UHE cosmic rays we rely presently on Monte Carlo simulations … many ongoing attempts to quantify shower variables that correlate with the identity of the primary



Shower Development



Fluorescence & Cherenkov-Light (isotropic) (forward peaked)

p, n, π : near shower axis
μ, e, γ : widely spread

e, γ : from π^0, μ decays ~ 10 MeV
μ : from $\pi^{\pm}$, K, ... decays ~ 1 GeV

$N_{e,\gamma} : N_{\mu}$ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

Details depend on:
interaction cross-sections,
hadronic and el.mag. particle production,
decays, transport, ...
at energies well above man-made accelerators

Complex interplay with many correlations
requires MC simulations

(Courtesey: Johannes Knapp)

Main sources of uncertainty

- Minijet cross-section (parton densities, range of applicability)
- Transverse profile function (total #-secn, multiplicity distribution)
- Energy dependence of leading particle production
- Role of nuclear effects (saturation, stopping power, QGP)

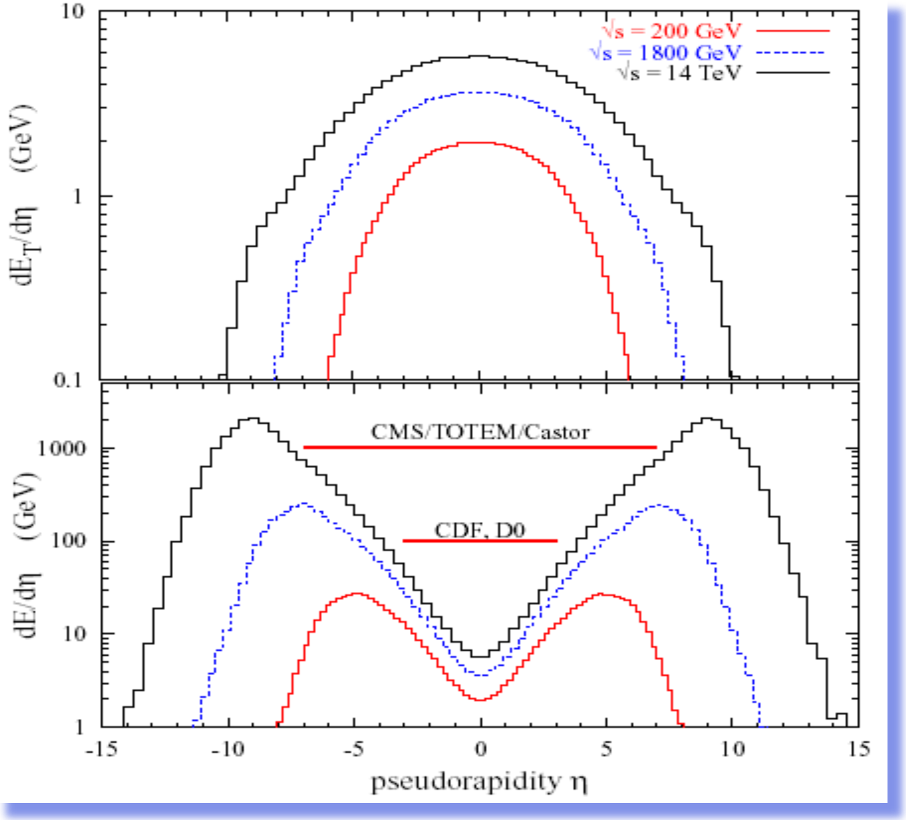
Expect important input from LHC experiments (CASTOR, TOTEM, LHCf …)

Experiment	Rapidity range	Detection capability
ATLAS, CMS	$\|\eta\| < 2.5$	Tracking and charged particle p determination
		Lepton and photon ID, E/p measurement
	$\|\eta\| < 5$	Jet reconstruction and E measurement, calorimetric E-flow
TOTEM (CMS)	$3 < \eta < 7$	Charged particle multiplicity
CASTOR(CMS)	$5.3 < \eta < 7.0$	E measurement
LHCb	$1.9 < \eta < 4.9$	E and p measurement up to ~200 GeV
		Charged/neutral particle ID
ALICE	$\|\eta\| < 0.9$	Charged/neutral particle ID, E/p measurement
	$2.4 < \eta < 4.0$	Muon ID and momentum measurement
	$-5.5 < \eta < 3.0$	Charge particle multiplicity
	$2.3 < \eta < 3.5$	Photon multiplicity

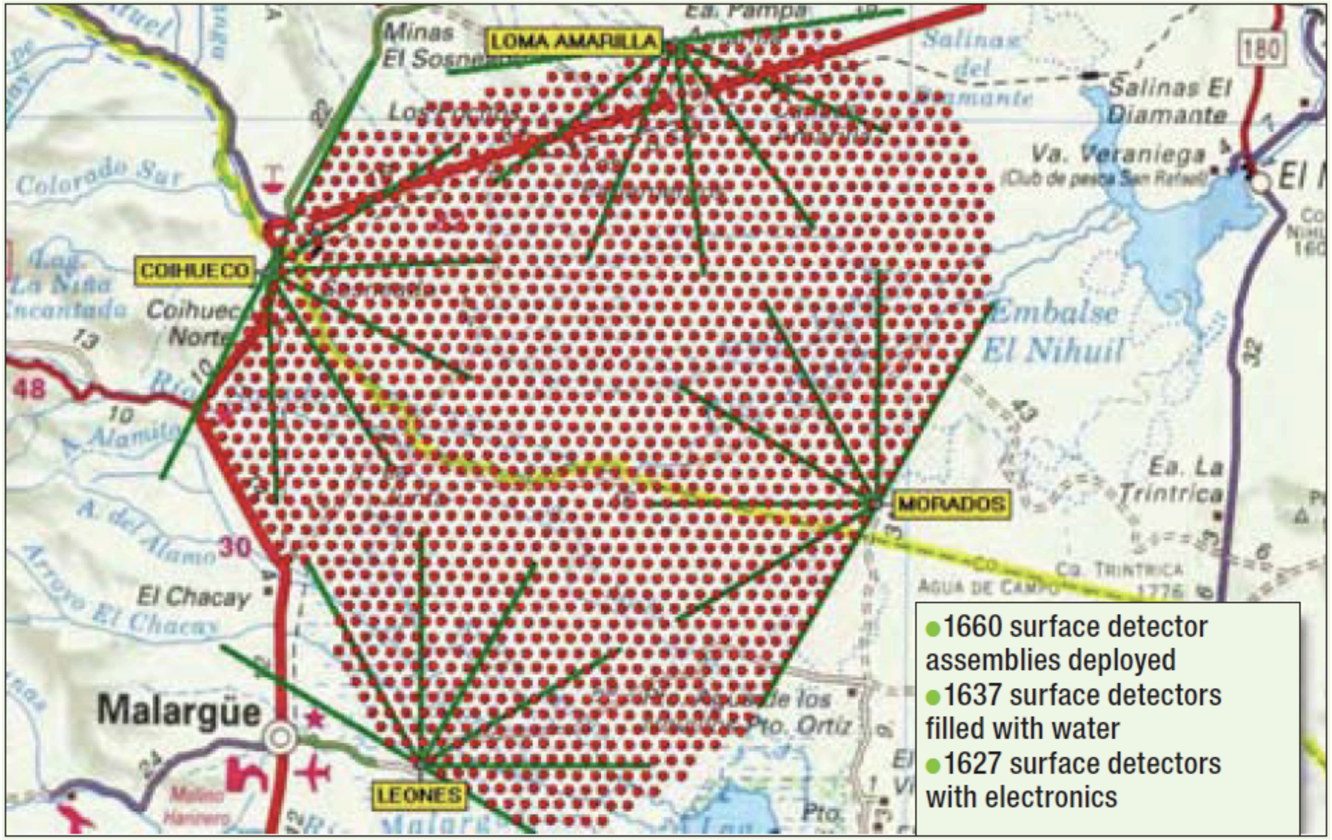
However collider experiments focus mainly on high p_T events, in contrast to the *very* forward region of interest to cosmic ray physics

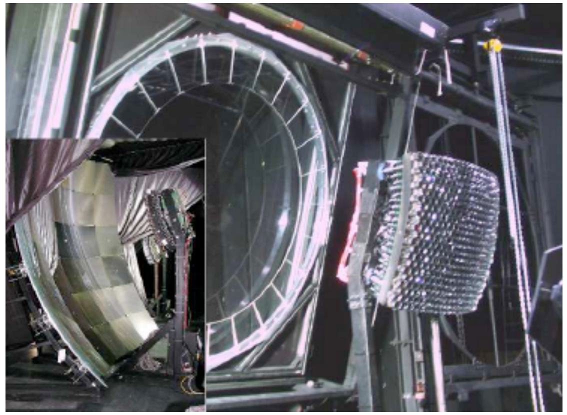
The kinematic region most relevant to cosmic ray shower models is $|\eta| > 10$ … this will *not* be probed even at the LHC

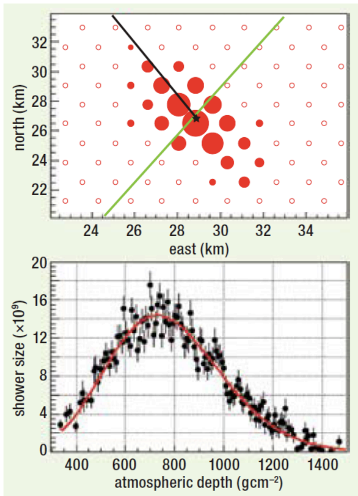
However, CASTOR/CMS/TOTEM/LHCf will perform crucial tests of popular shower MCs (QGSJET, SIBYLL, DPMJET, NeXus …)

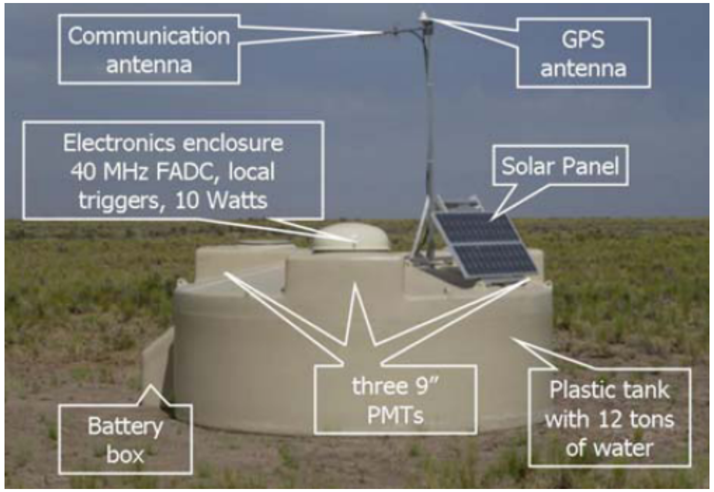


The Pierre Auger Observatory (Malargue, Argentina)









Auger Energy Determination: Step 1

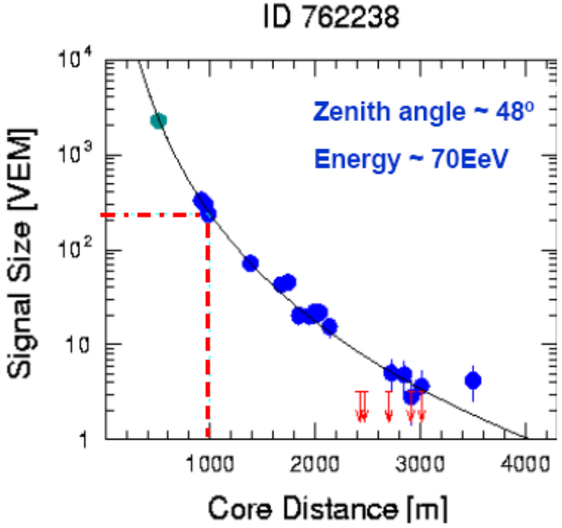
The energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.

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

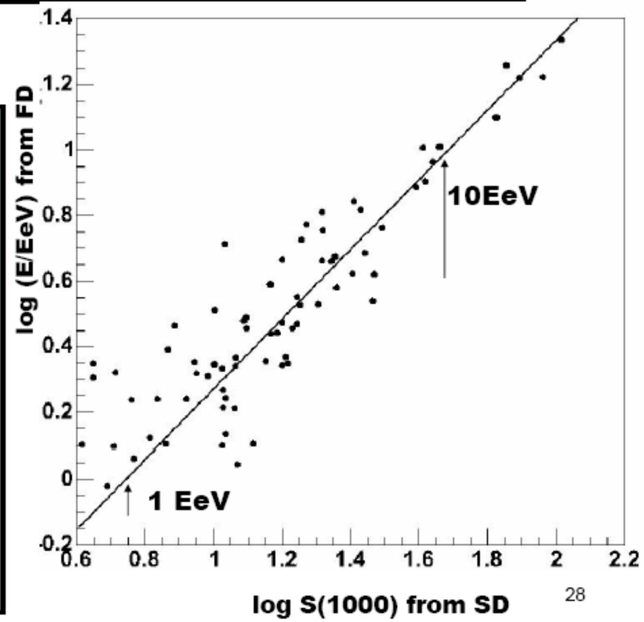
Auger Energy Determination: step 2

Hybrid Events with STRICT event selection:

aerosol content measured

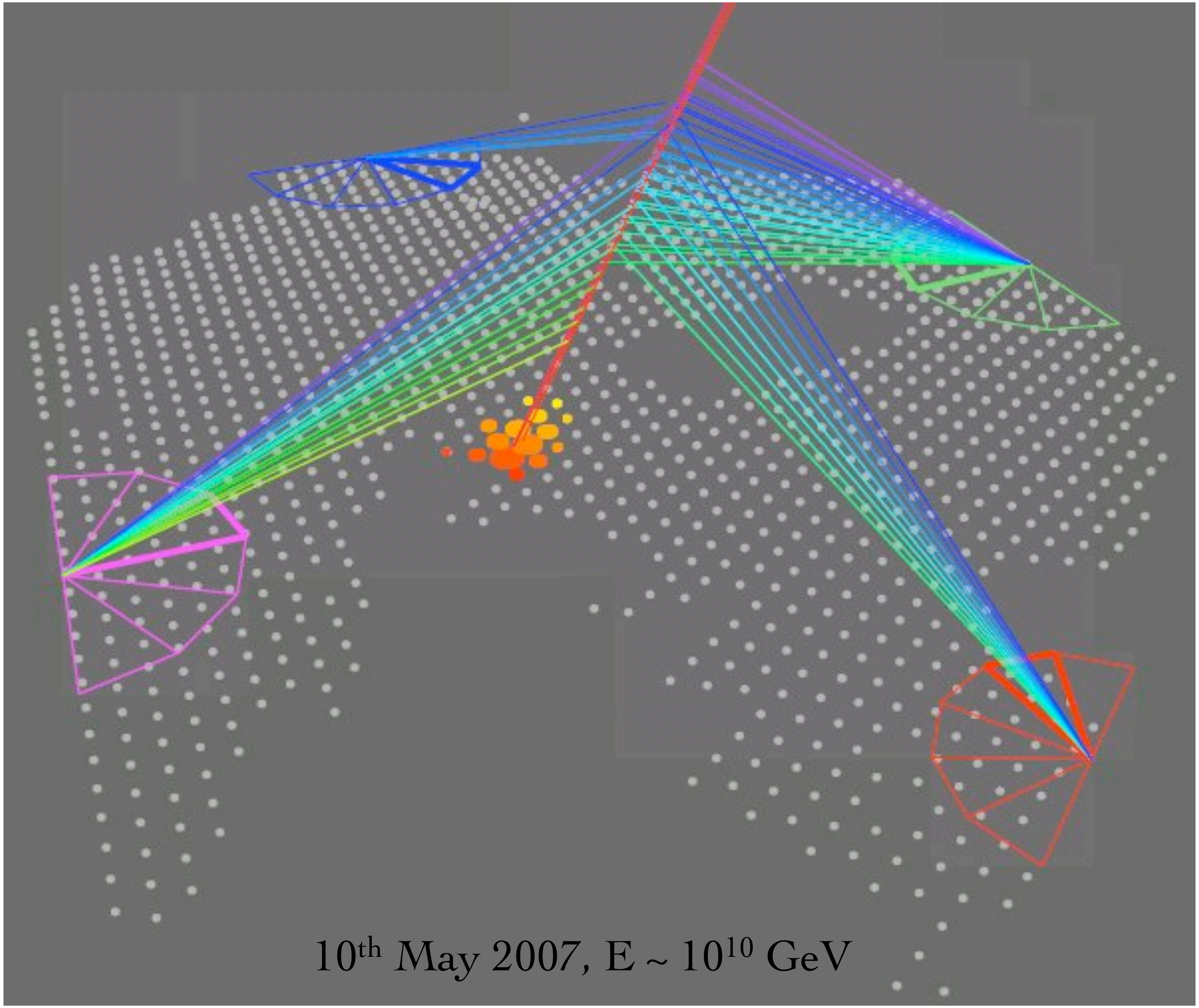
track length > 350 g cm^{-2}

Cherenkov contamination <10%

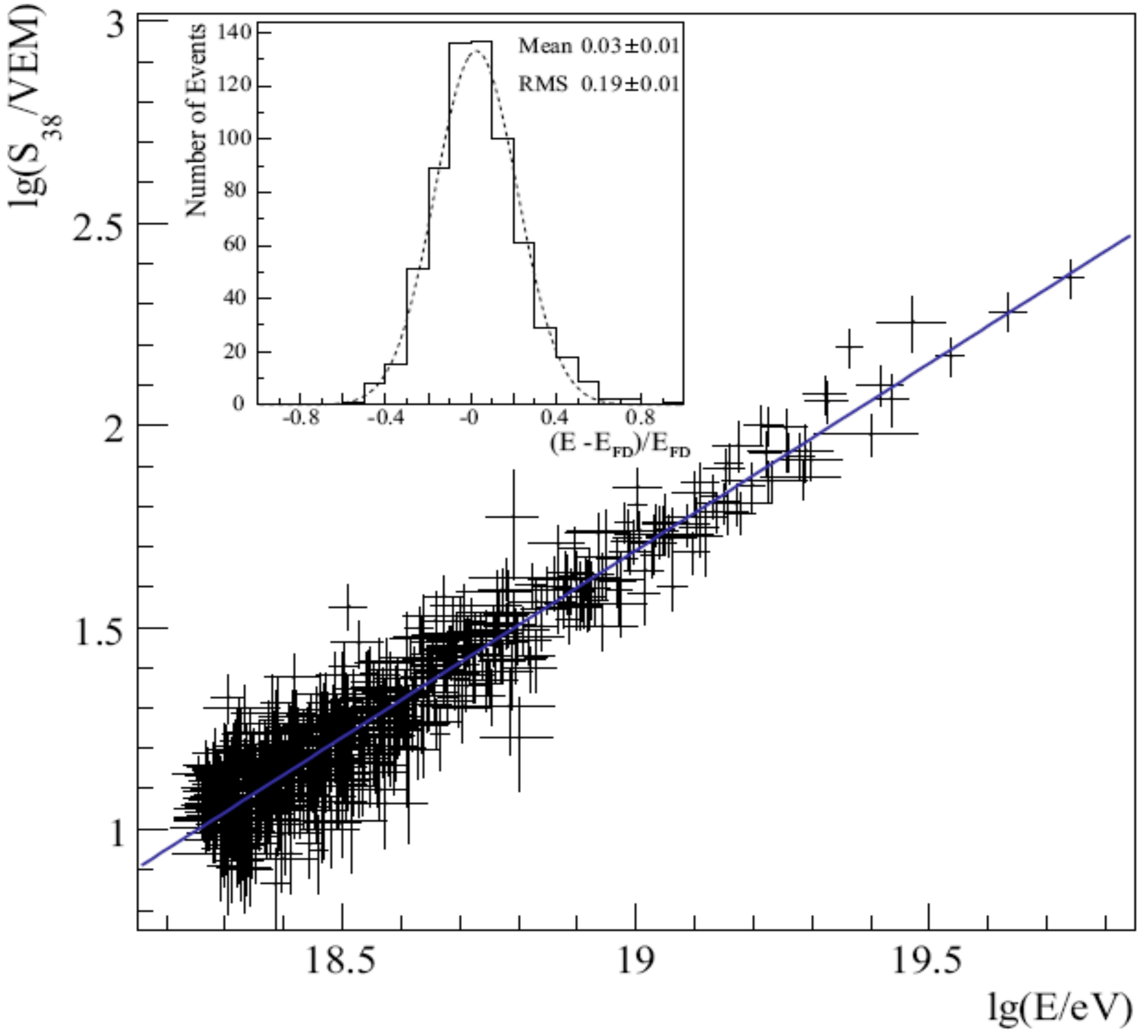


For the fluorescence detectors, the acceptance is harder to estimate and the event statistics are low but the energy determination is essentially calorimetric …

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



Energy Scale from FD



(Auger collaboration, PRL 101:061101,2008)

Major remaining uncertainty ➔ efficiency of fluorescence light emission
… being re-measured at Argonne (also depends on atmospheric conditions)

Where is the GZK cutoff?

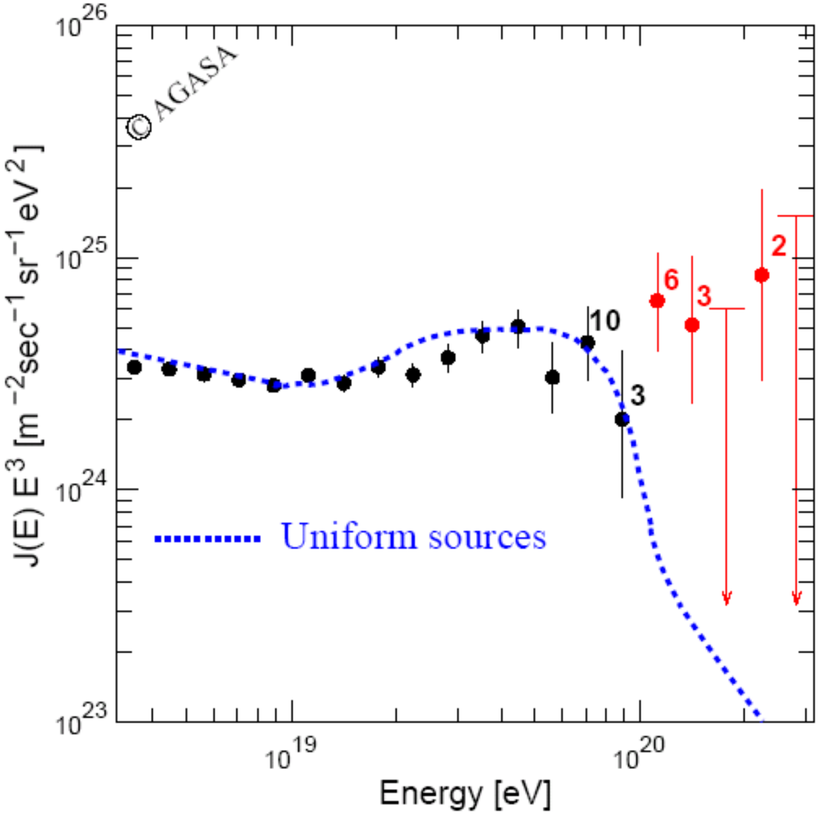
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

$$n \hookrightarrow p + e^{-} + \bar{\nu}_{e}$$

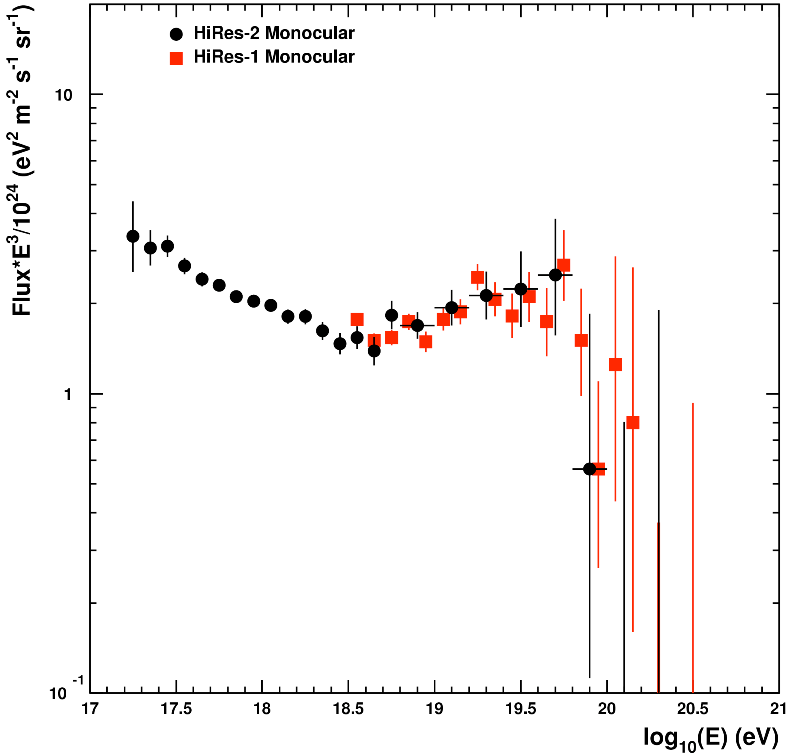
$$\pi^{+} \hookrightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \hookrightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

AGASA spectrum continues smoothly!



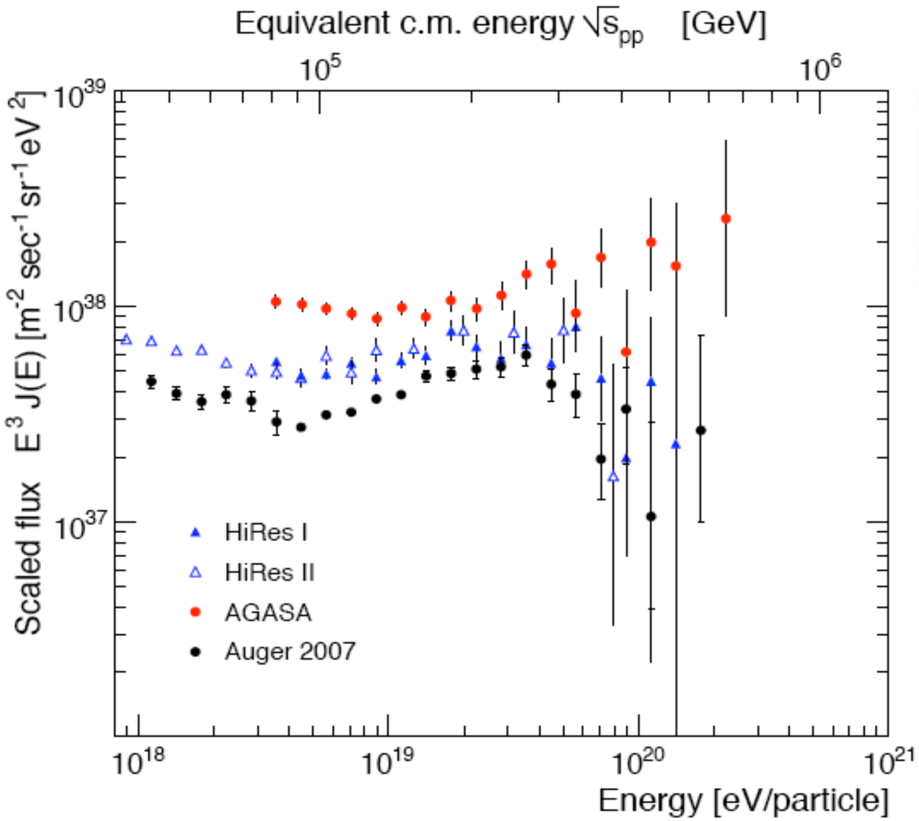
… but HiRes sees expected suppression

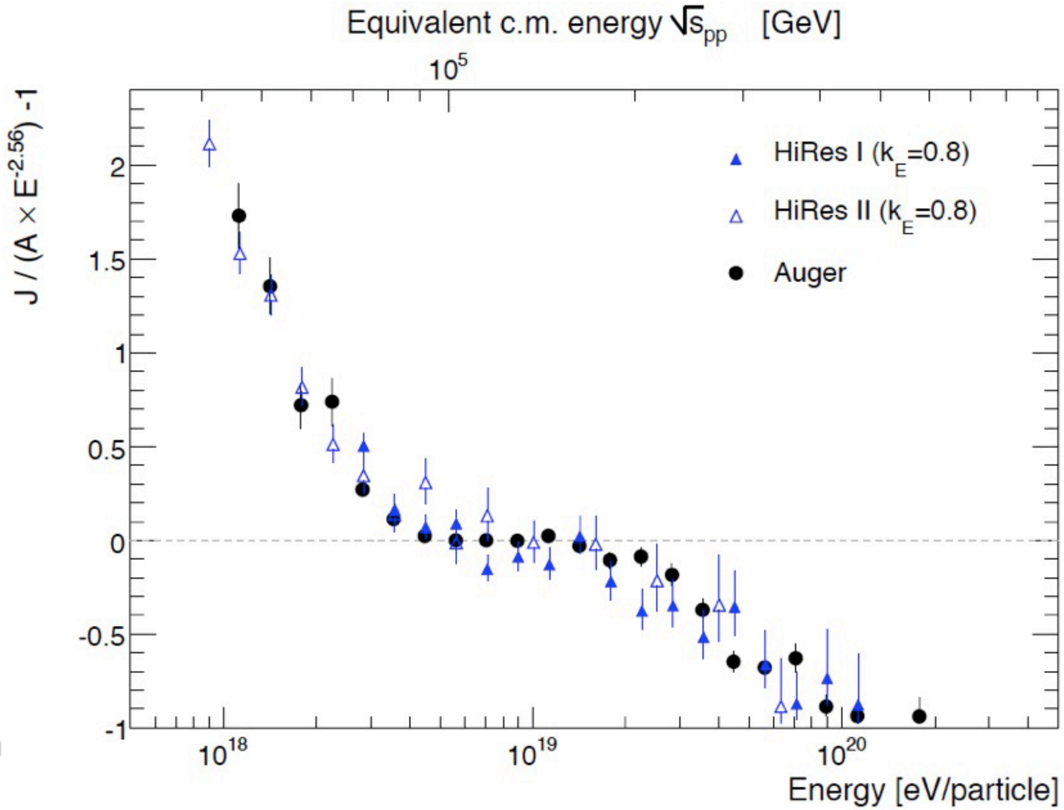


Is there a ~25% energy calibration mismatch between surface arrays and air fluorescence detectors?

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

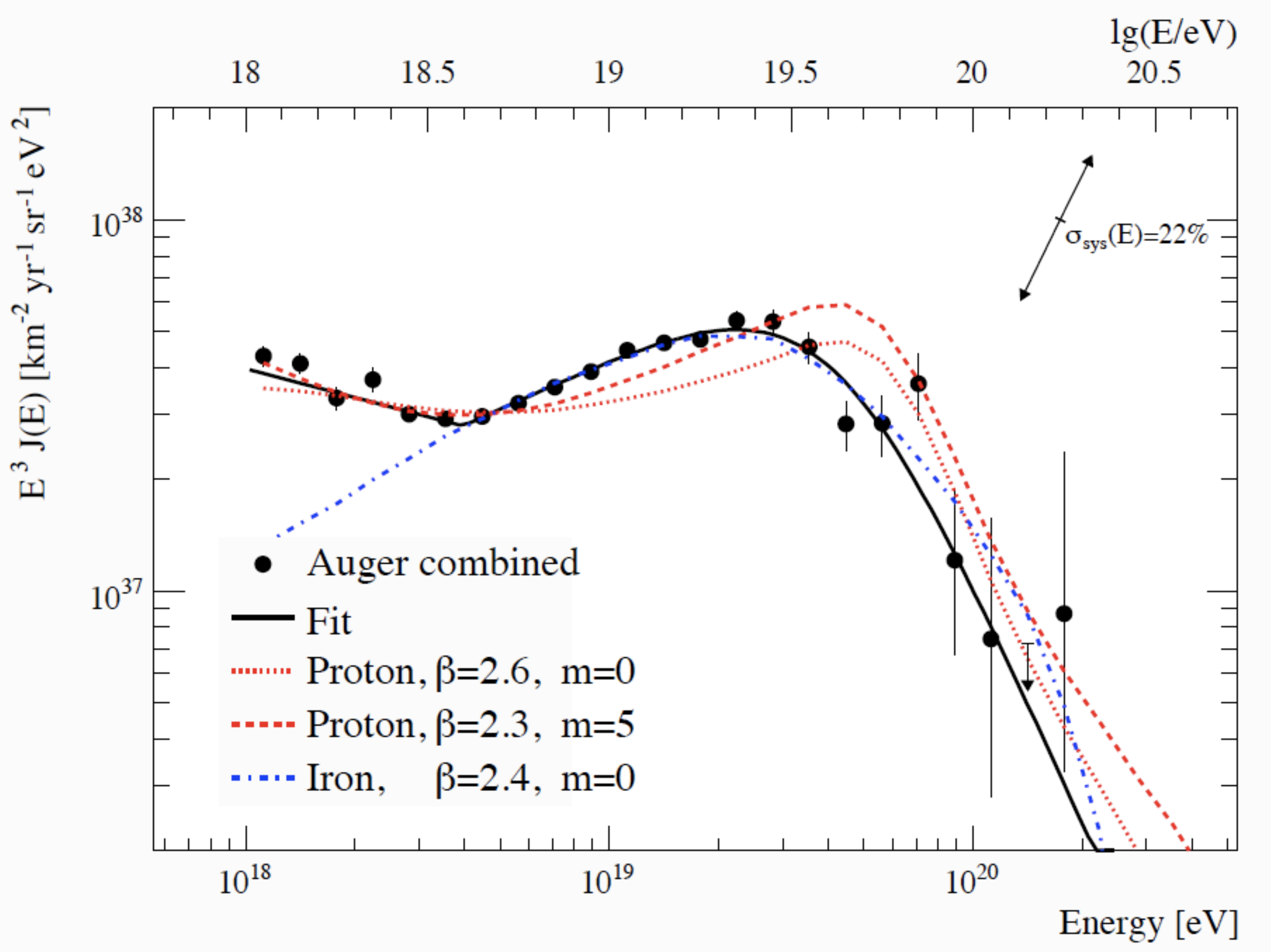
Hence the sources of ultra high energy cosmic rays must be extragalactic





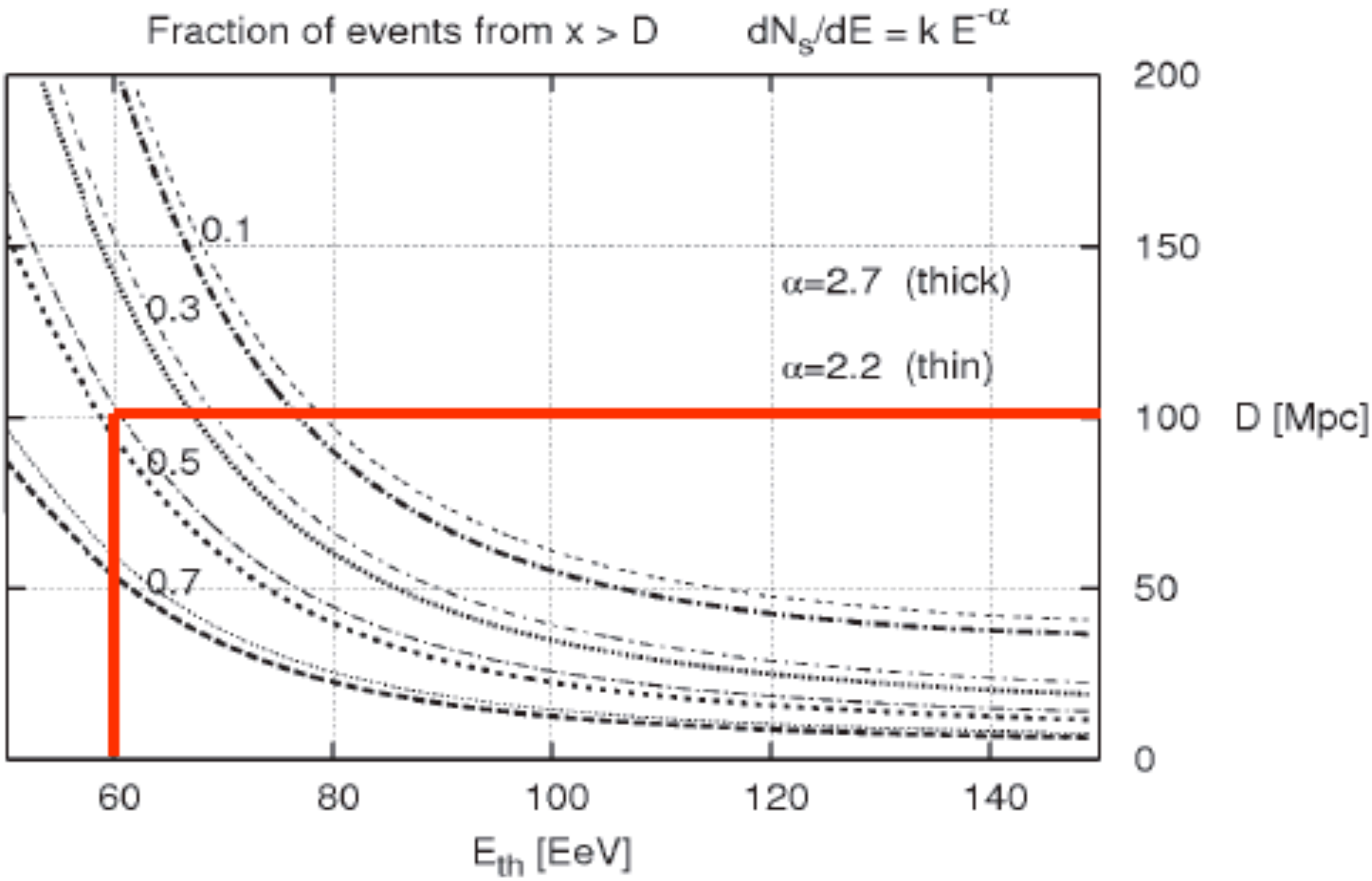
Measurement of the spectral shape near the cut-off will, with sufficient statistics, establish whether this is indeed the 'GZK suppression' (presently the spectrum is also consistent with heavy primary nuclei undergoing photodissociation on the CIB)

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)



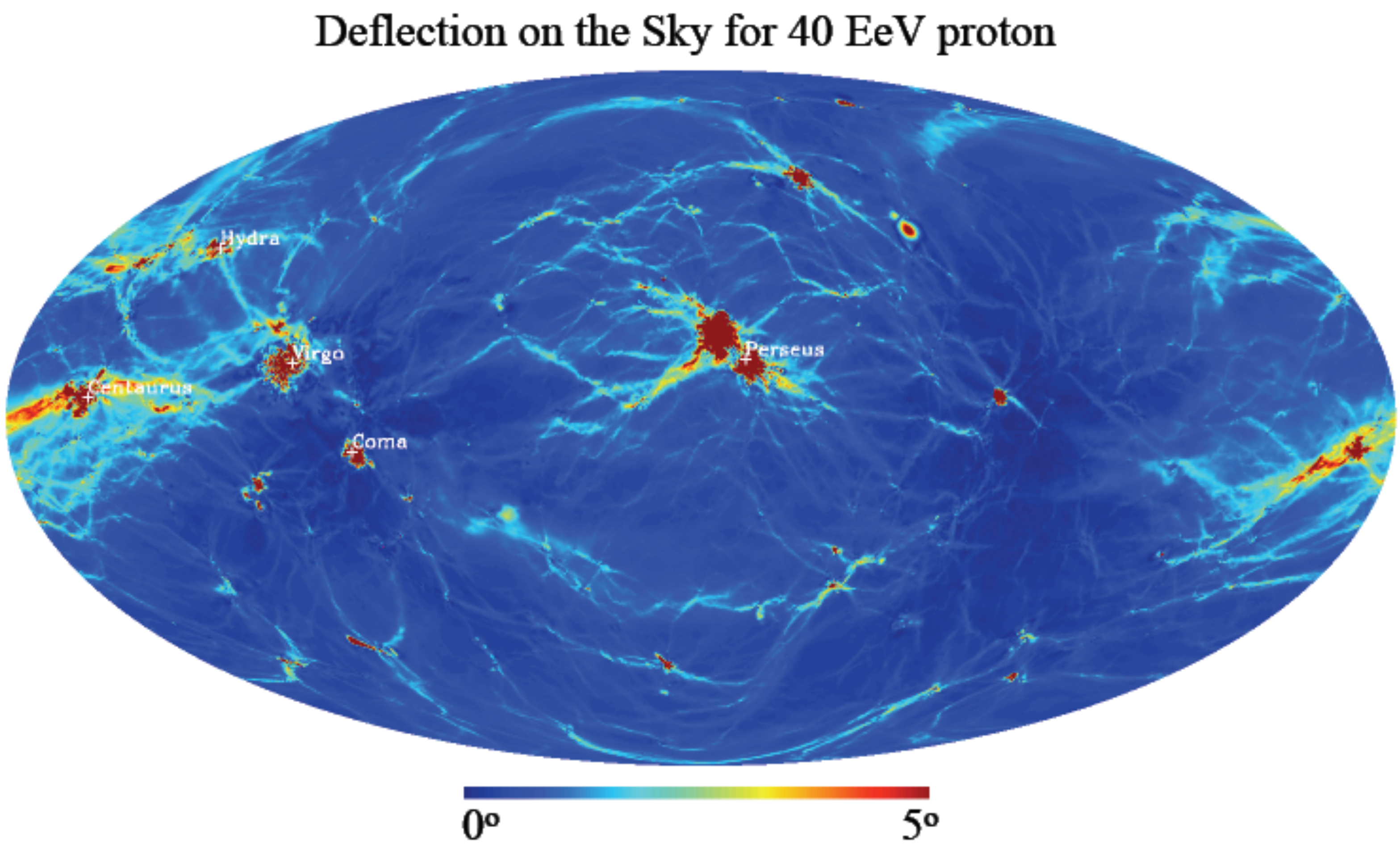
… the 'cosmogenic' neutrino flux is however quite different in the two cases

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



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

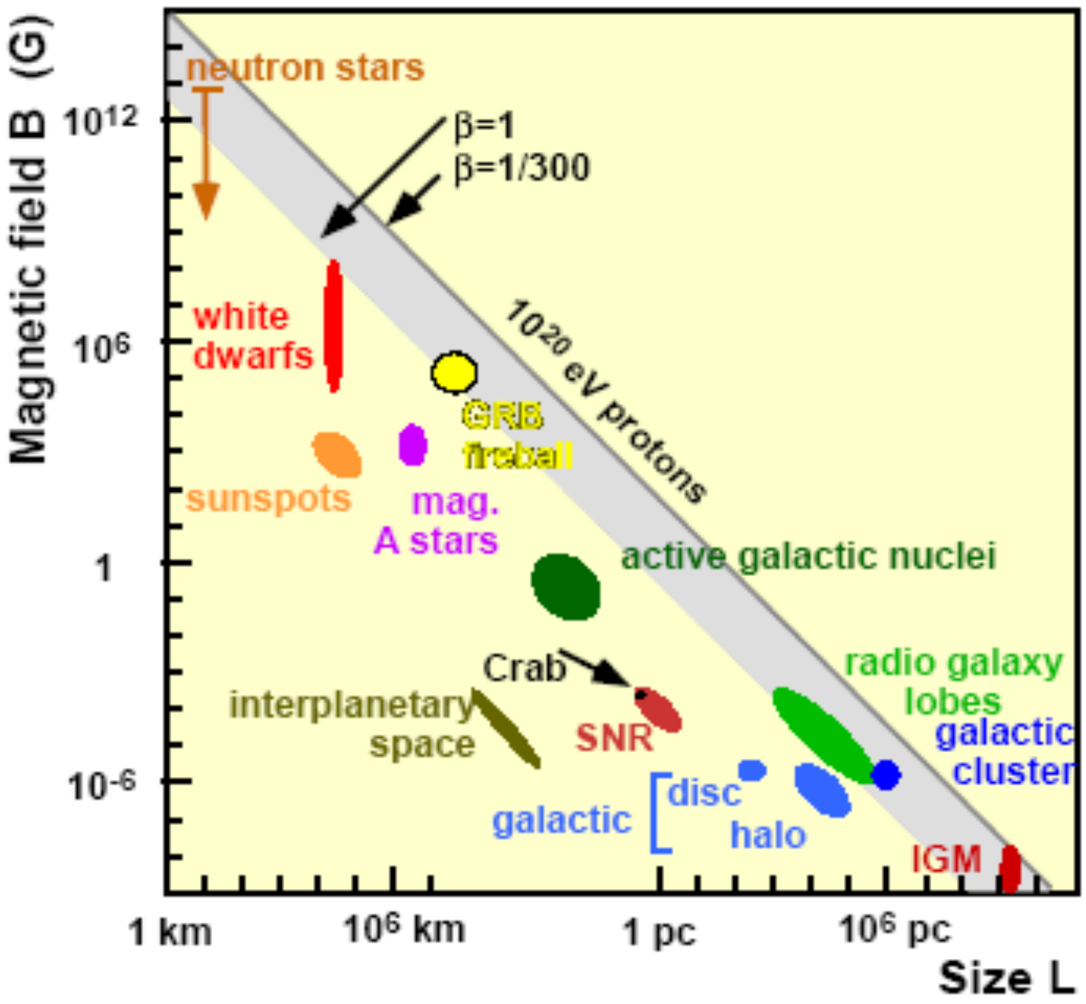
So we should be able to see which objects the UHECRs *point back* to …



'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?



A.M. Hillas 1984

(Courtesey: Johannes Knapp)

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

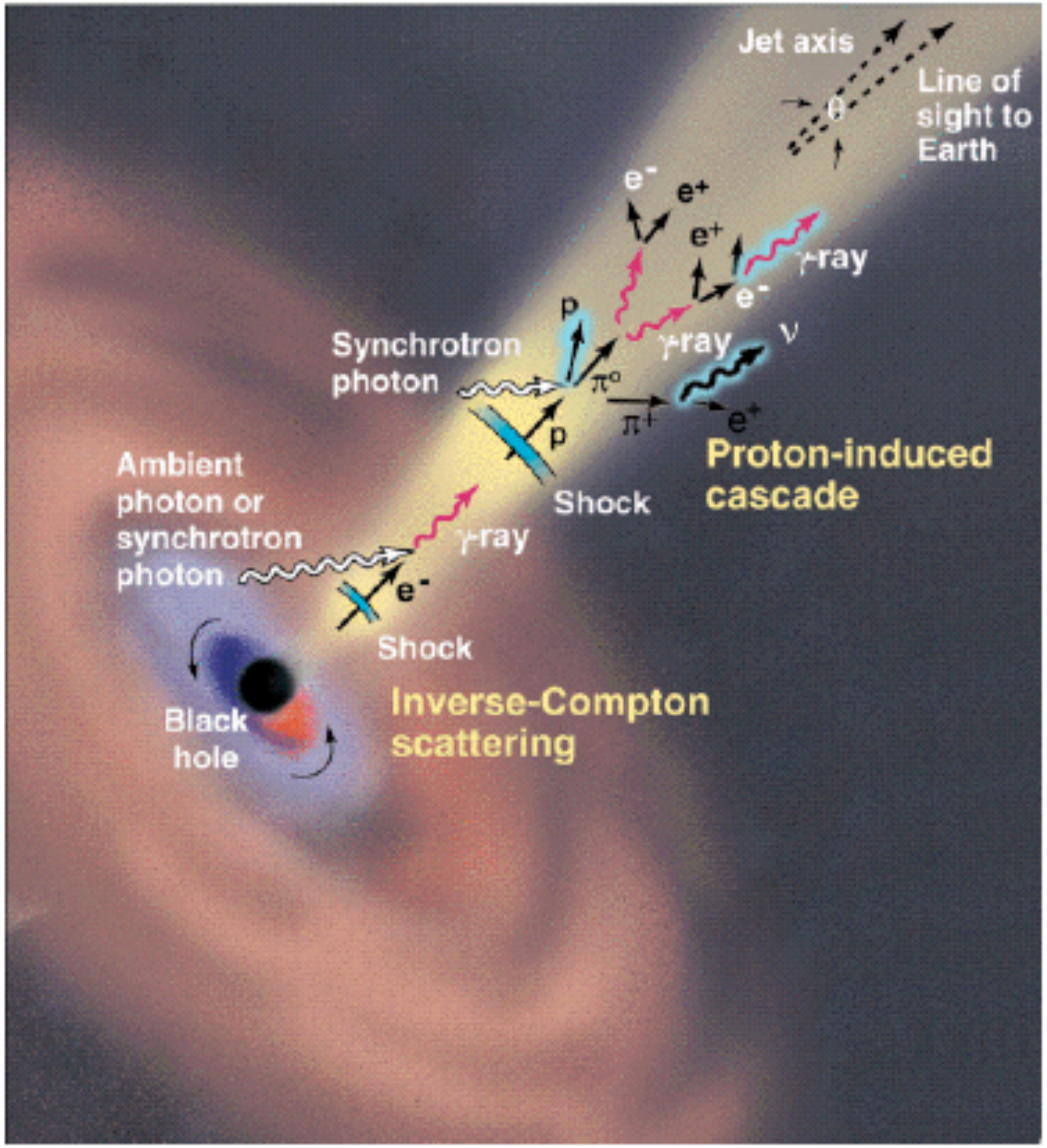
$B_{\mu G} \times L_{kpc} > 2\, (c/v)\, E_{EeV} / Z$

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.

NB: It is much easier to accelerate heavy nuclei, rather than protons

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

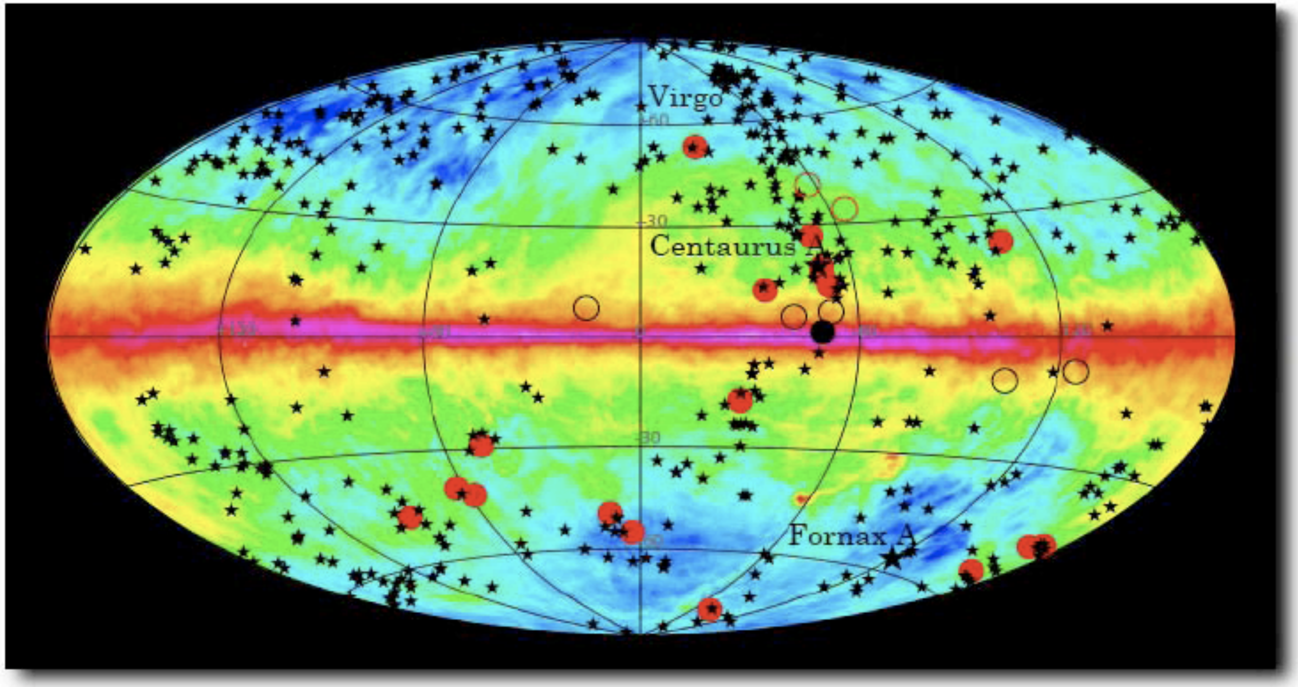
- Current paradigm:
  - **Synchrotron Self Compton**
  - External Compton
  - Proton Induced Cascades
  - Proton Synchrotron

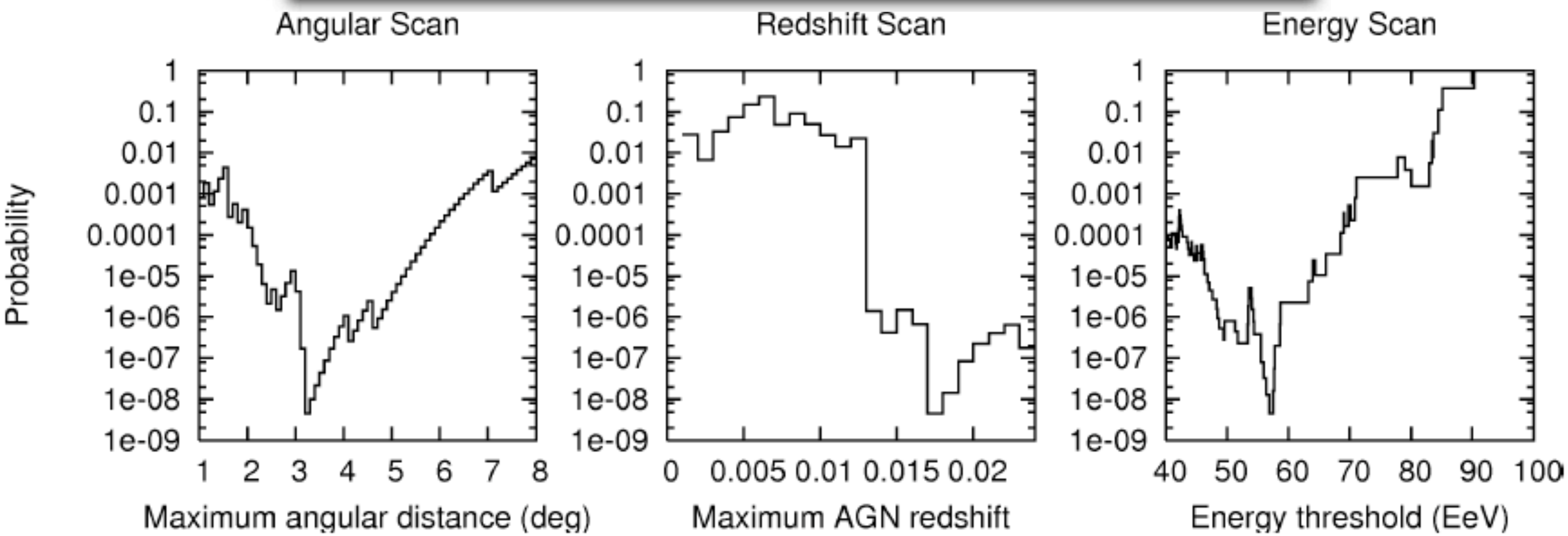
- Energetics, mechanism for jet formation and collimation, nature of the plasma, and particle acceleration mechanisms are still poorly understood.

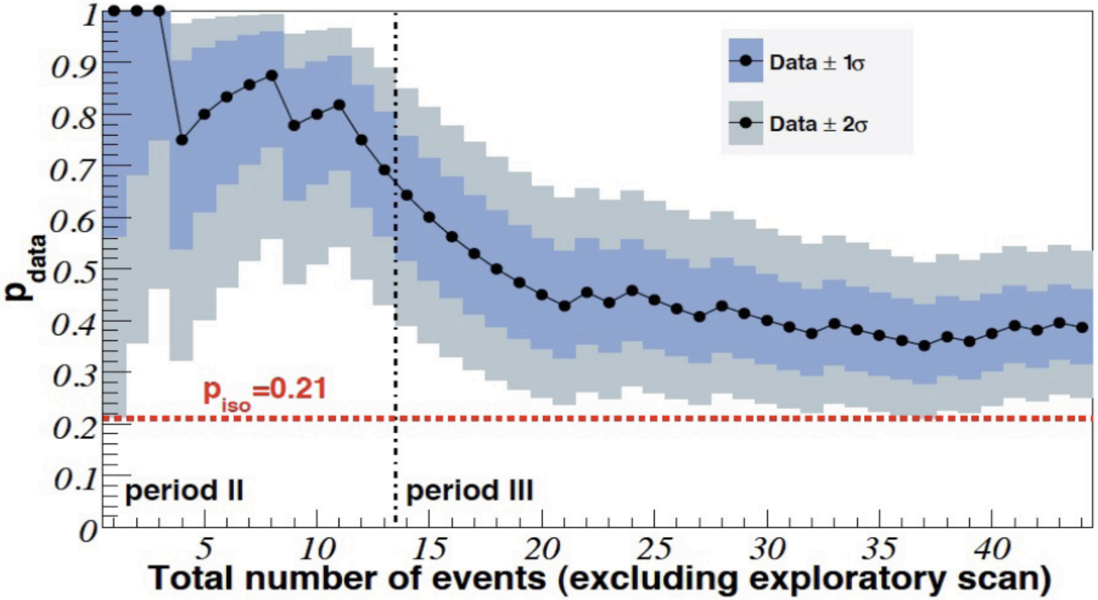
TeV γ-rays have been seen from AGN, however no *direct* evidence so far that protons are accelerated in such objects

… 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 nearby AGN!





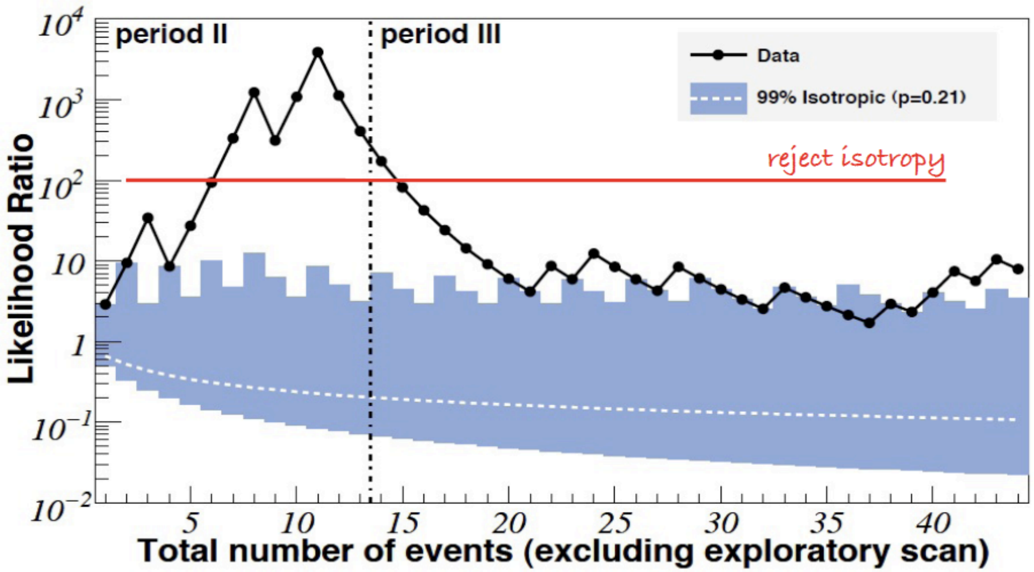


But subsequently the strength of the correlations has diminished

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

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

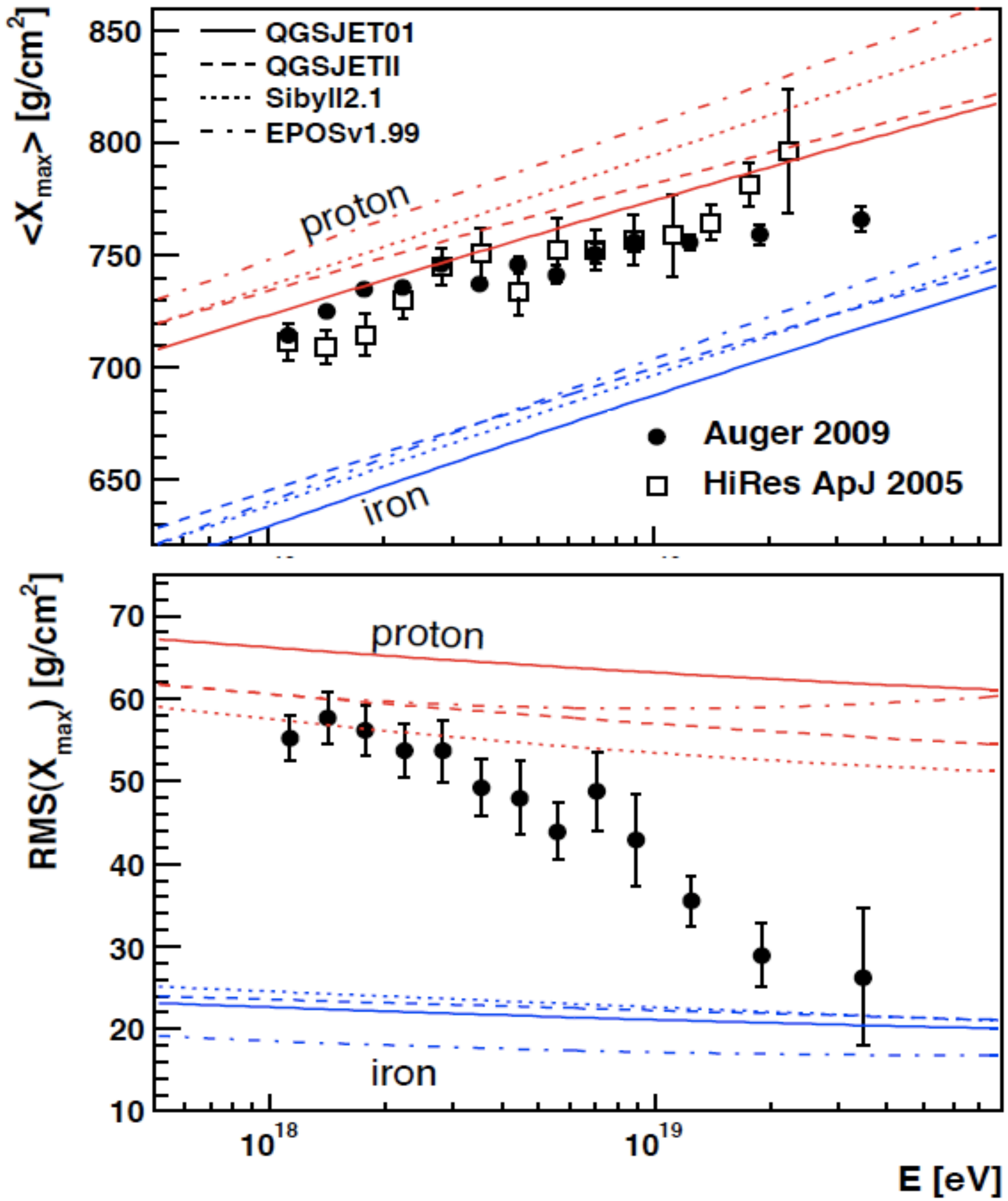
The argument for proton primaries, based on the observed correlations (within 3 degrees), is thus not so strong any longer …



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

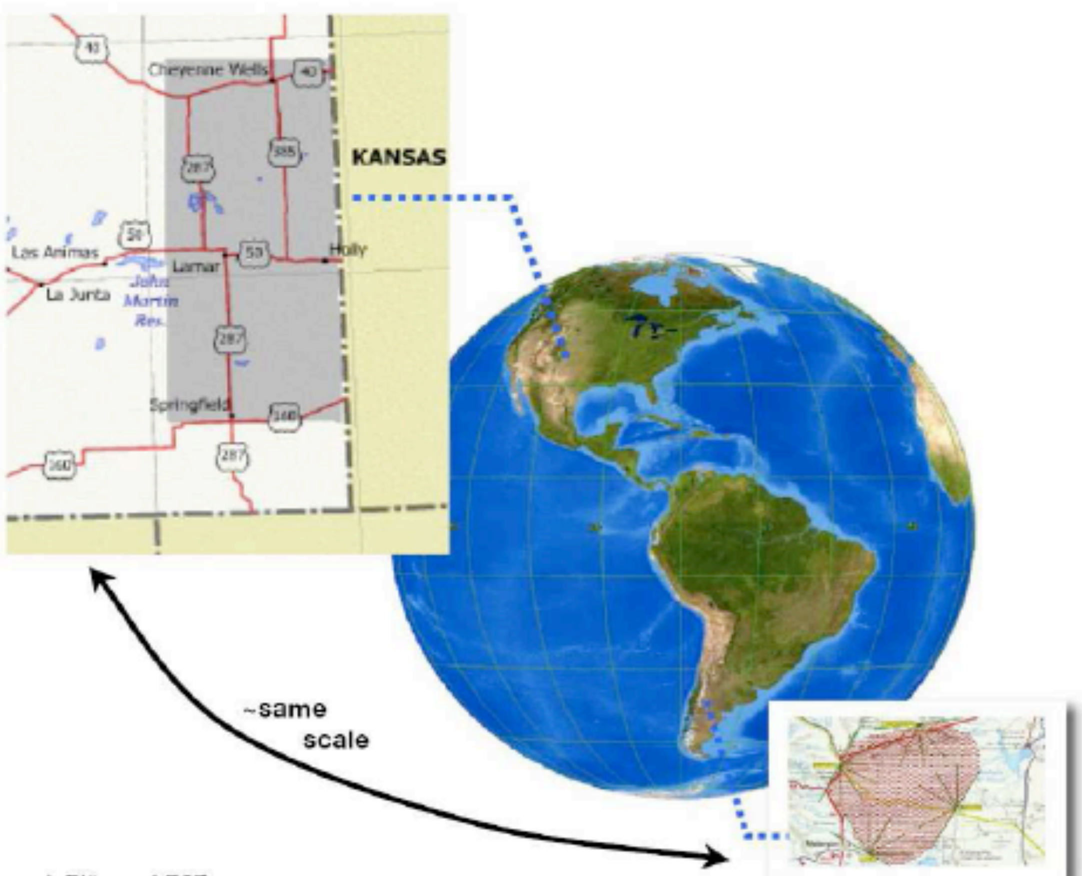
… however an *increase* of the *p*-air #-secn over the usual extrapolation may fake this apparent change

Interesting astrophysics and possible new particle physics are closely coupled … to distinguish between these possibilities will require more data



Outlook: Auger North

- full sky coverage $\longrightarrow$ northern hemisphere
- highest energies $\longrightarrow$ huge detector ($3 - 8 \times \mathrm{AS}$)



J. Blümer, LP07

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

The "guaranteed" cosmogenic neutrino flux

GZK mechanism :

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

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

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

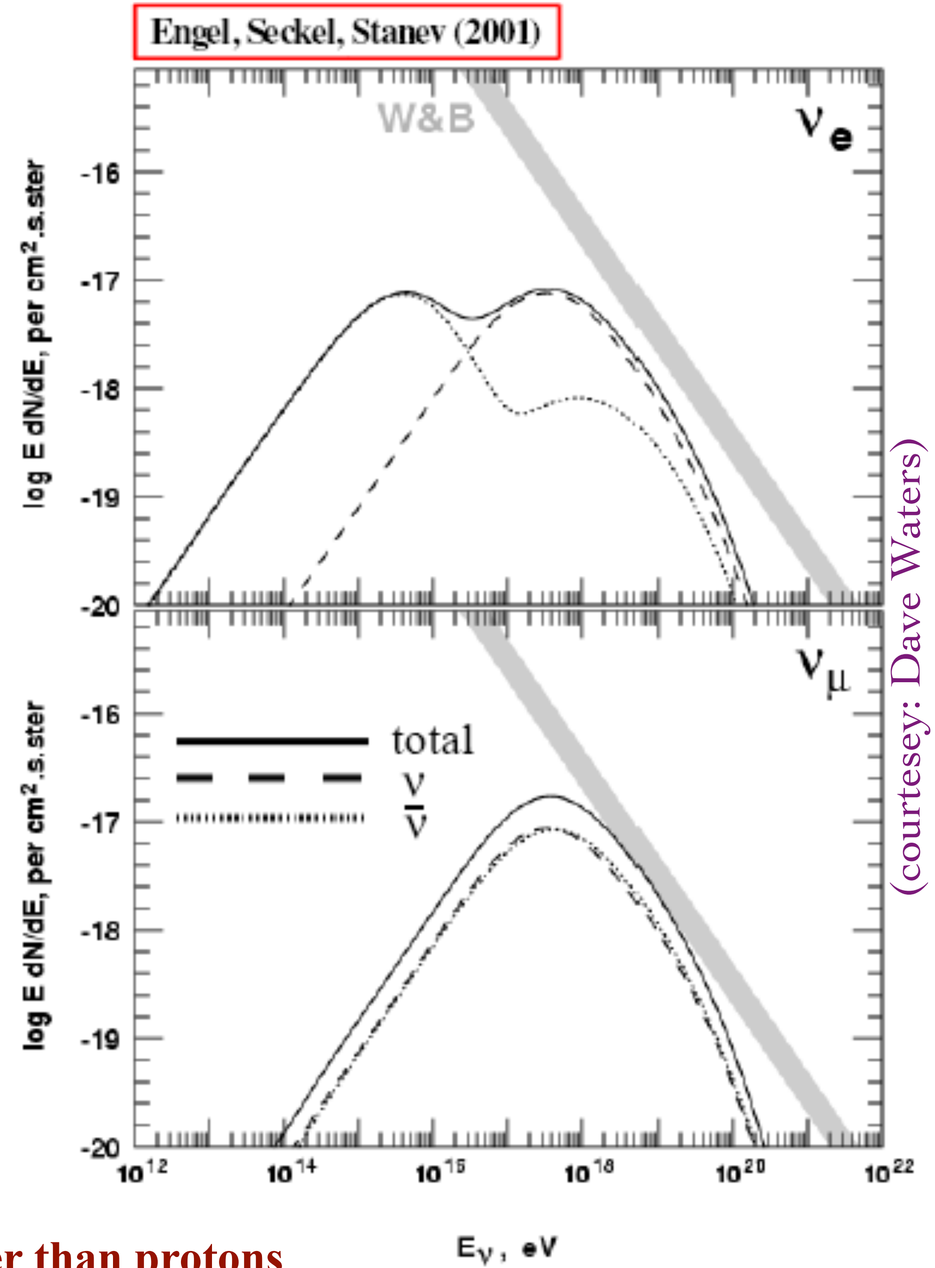
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

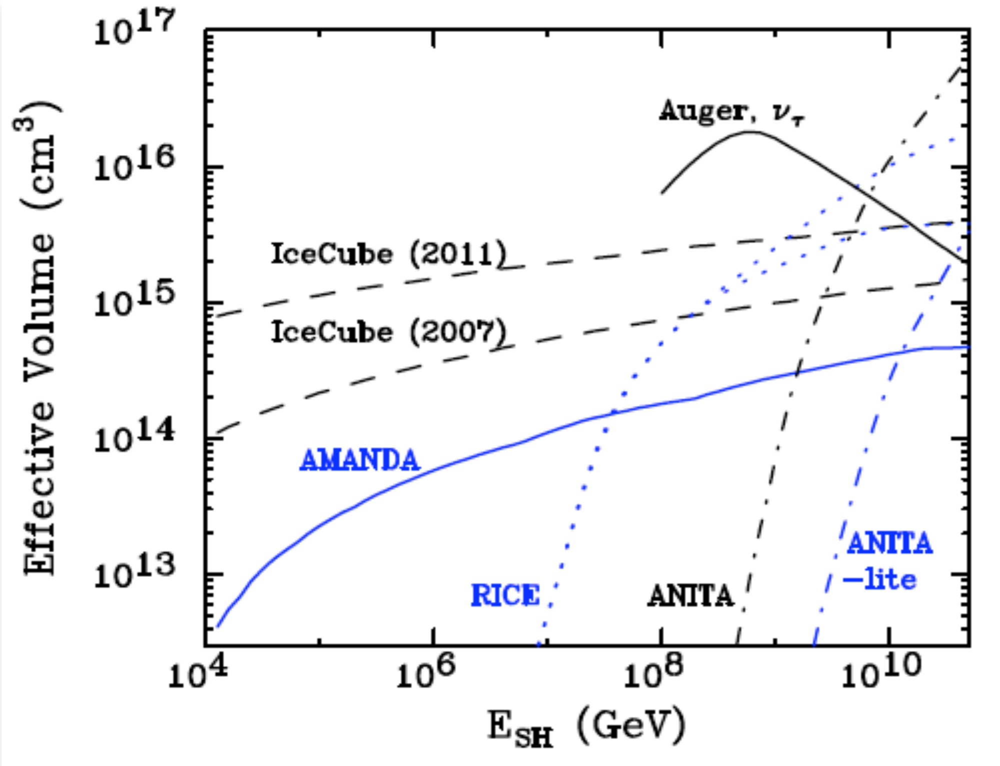
factors of ~2 uncertainty each;
factor of ~4 overall (?)

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



(courtesey: Dave Waters)

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



	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 & Hooper, PRL 97:099901,2006

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

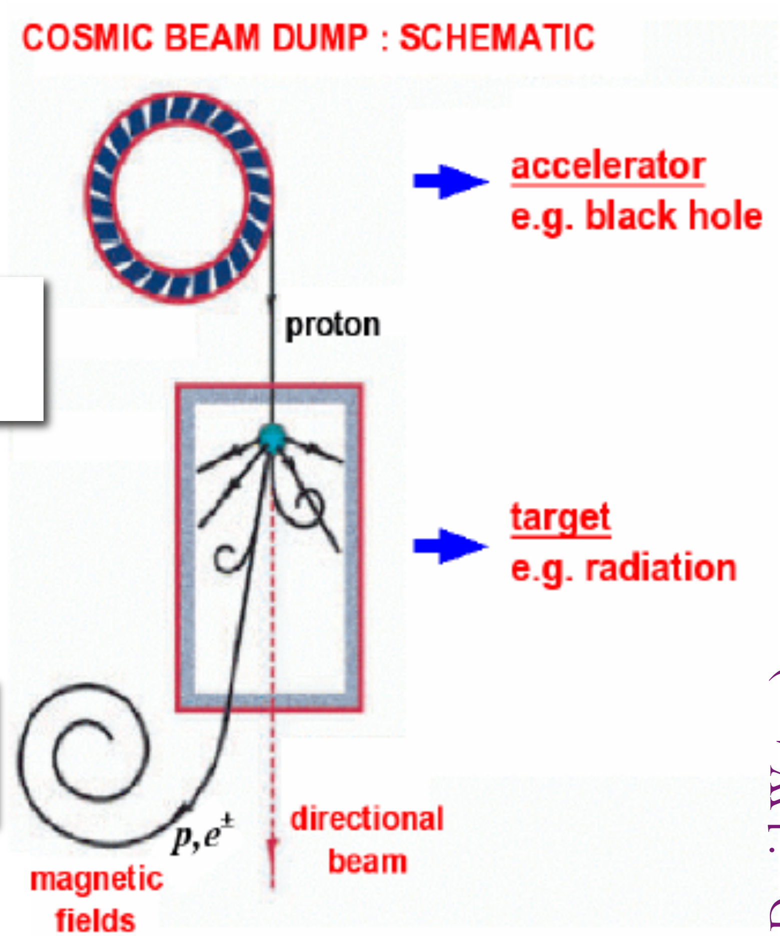
Hubble time

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

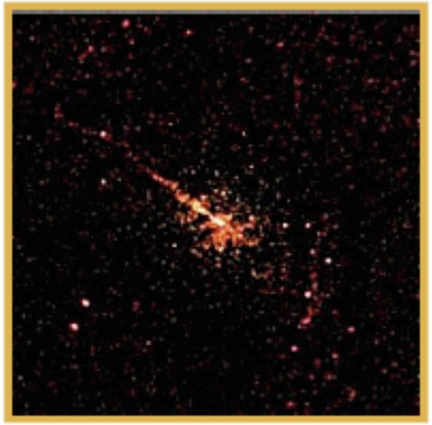
(would be higher if extragalactic cosmic rays become dominant at energies below the 'ankle')



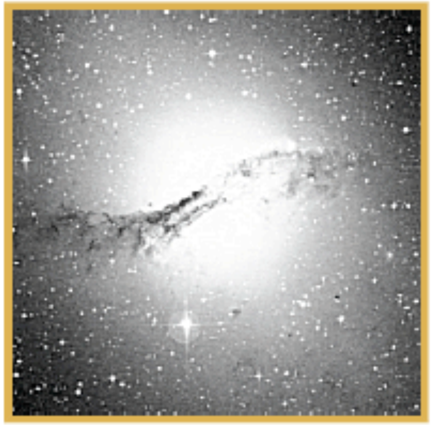
(Courtesey: David Waters)

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

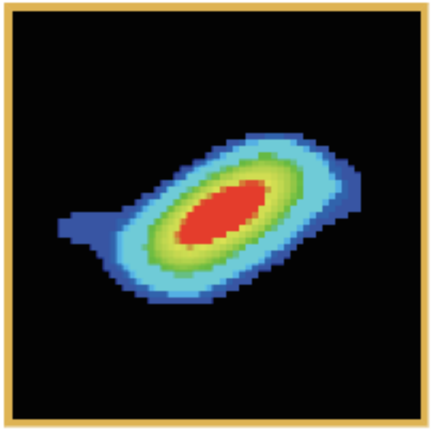

Ultraviolet: GALEX

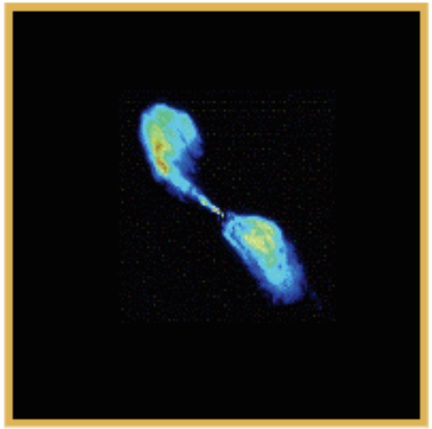

Visible: DSS


Visible: Color ©AAO


Near-Infrared: 2MASS


Mid-Infrared: Spitzer


Far-Infrared: IRAS


Radio: VLA

Estimate of ν flux from *p-p*:

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

~ 0.02-0.8 events/km^2 yr

Halzen & Murchadha [arXiv:0802.0887]

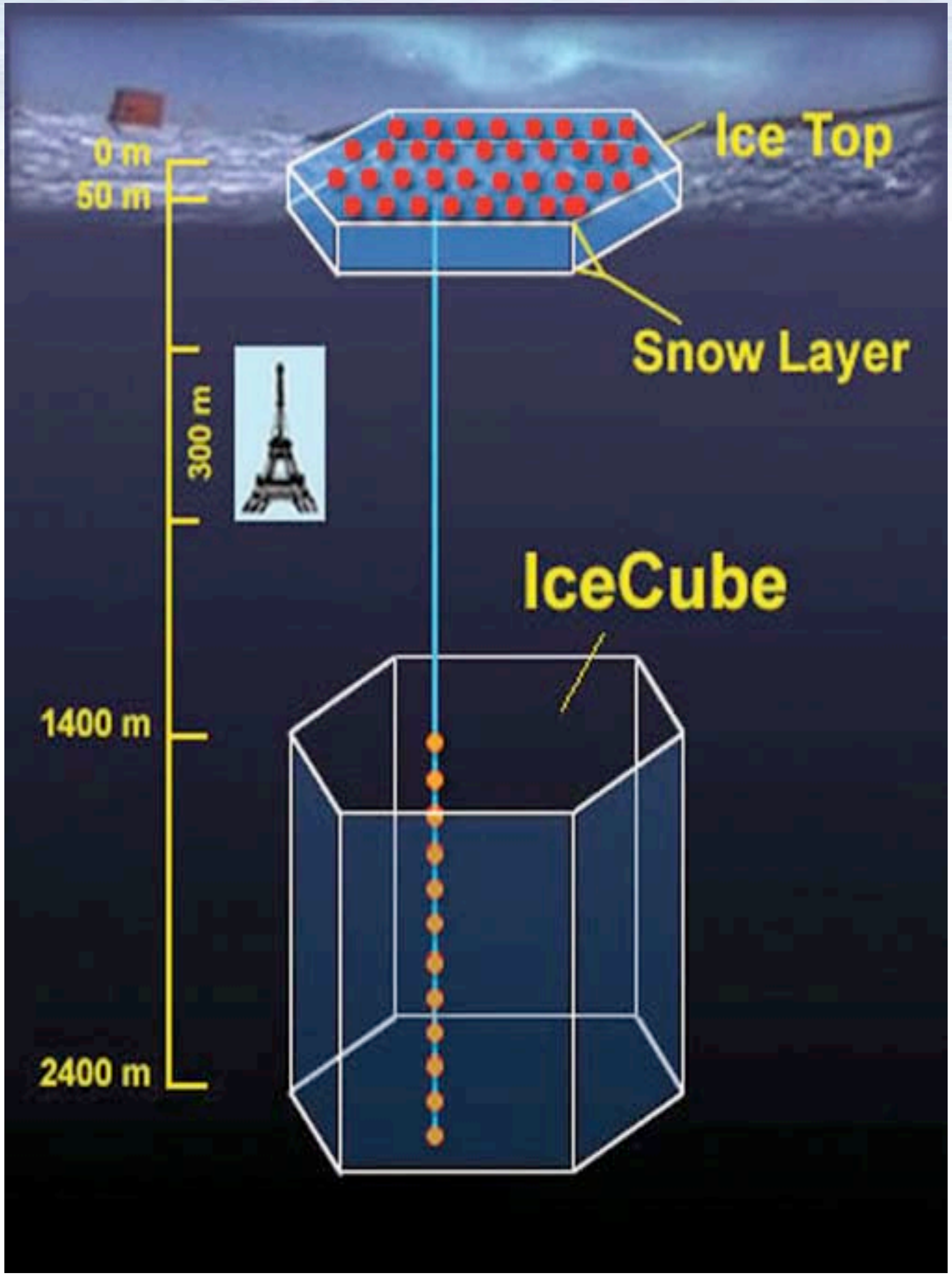
Deep ice array:

- 80 strings/60 OMs each (17 m apart)
- 125 m between strings
- hexagonal pattern over 1 km^2
- geometry optimized for detection of TeV – PeV (EeV) neutrinos

Surface array: **IceTop**

- 2 frozen-water tanks (2 OM's each) on top of every string

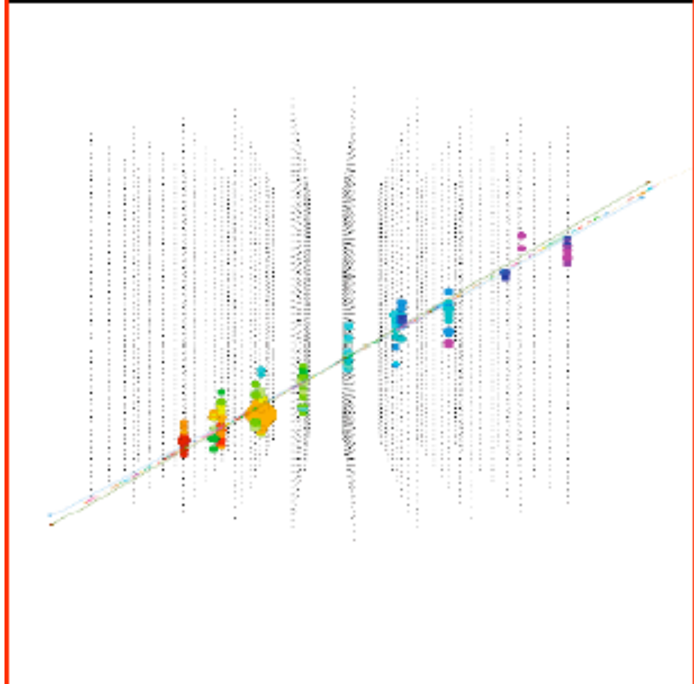
IceCube



ν_μ

E_μ = 10TeV

~90 DOMs hit

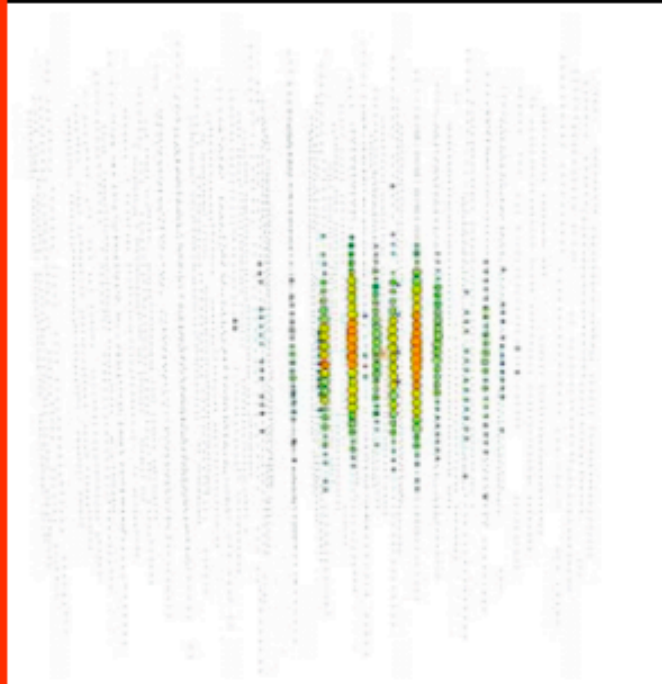


E~dE/dx , e>1TeV
E res. : Δlog(E)~0.3
ang res : 0.8-2 deg

ν_e

E = 375 TeV

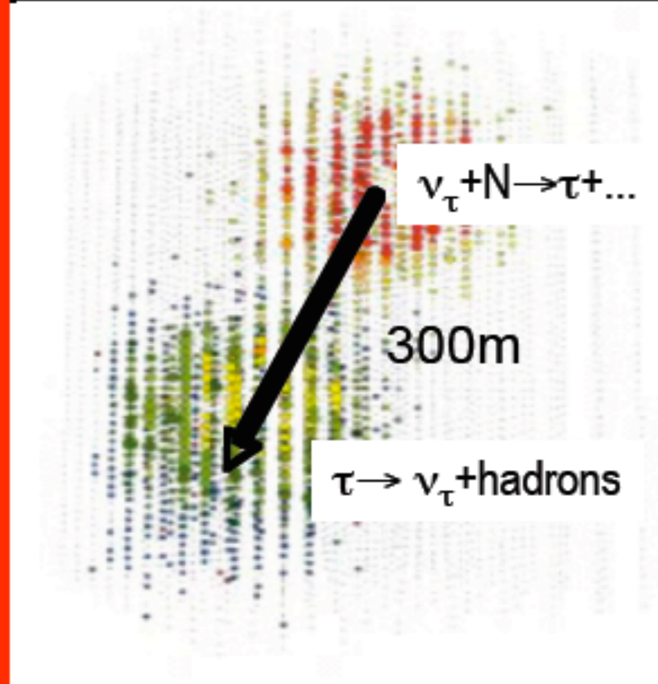
"spherical" shell



poor angular resolution
E res : Δlog(E)~0.1-0.2

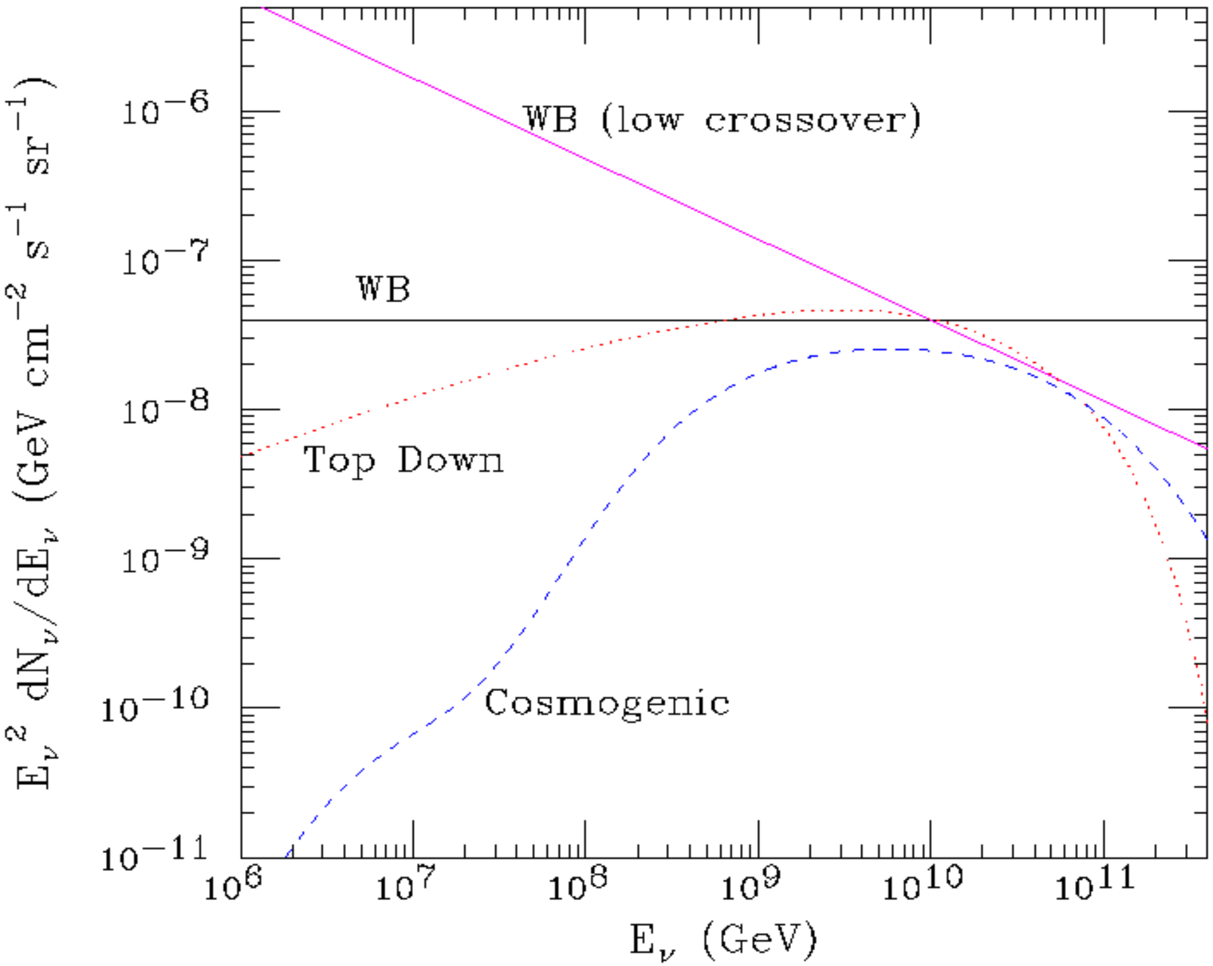
ν_τ

E = 10 PeV
2 bangs separated by
~ 50*(E_τ/PeV)



very low background
pointing capability
good E measurement

Plausible UHE cosmic neutrino fluxes



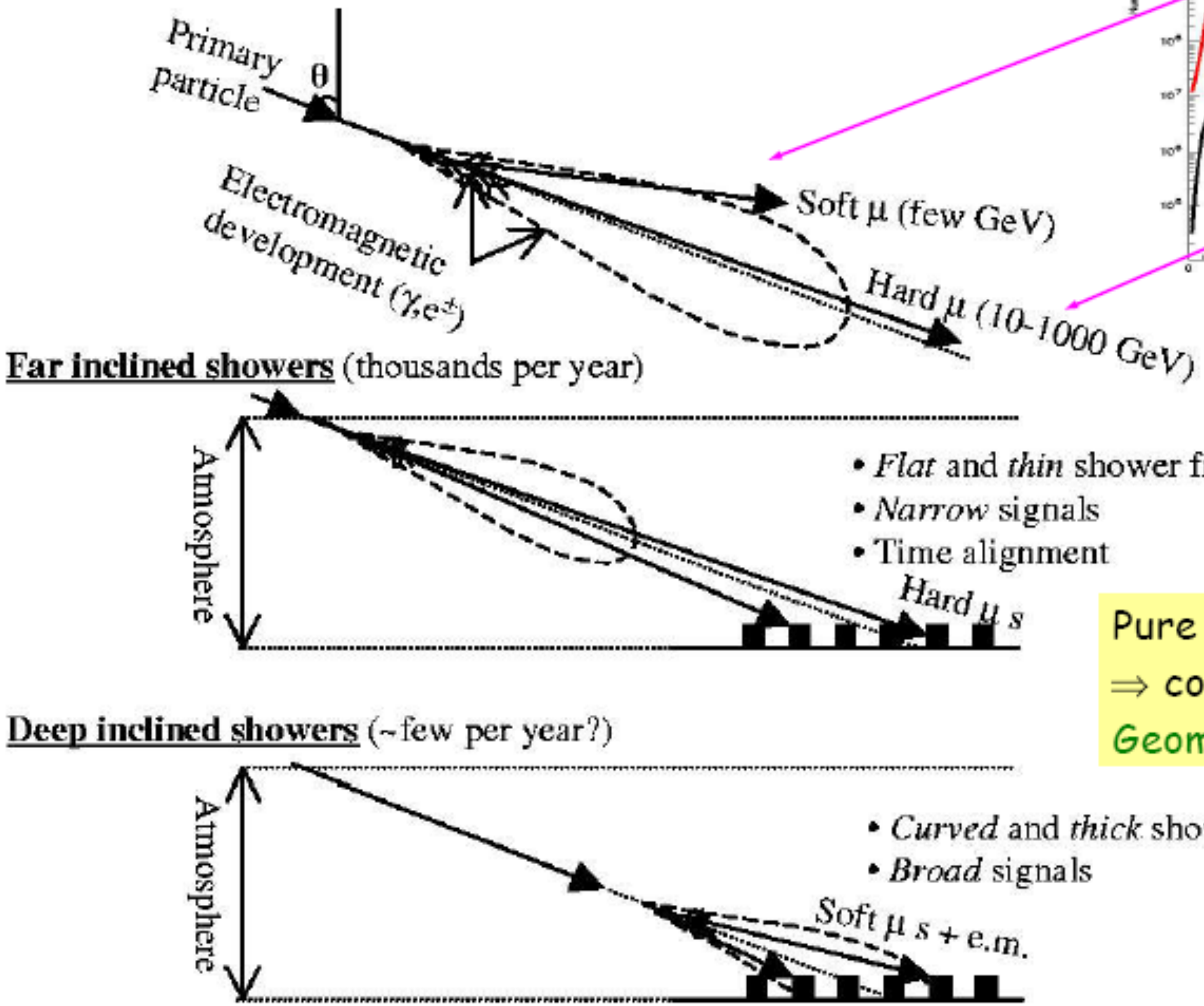
Anchordoqui, Han, Hooper & Sarkar, AP 25:14,2006

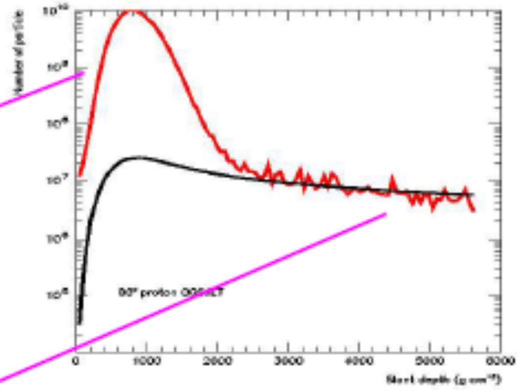
WB flux is enhanced in models where extragalactic sources are assumed to dominate from ~10^{18} eV … close to being ruled out (Ahlers, Anchordoqui & Sarkar, PR D79:083009,2009)

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

An unexpected bonus – UHE neutrino detection with air shower arrays

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



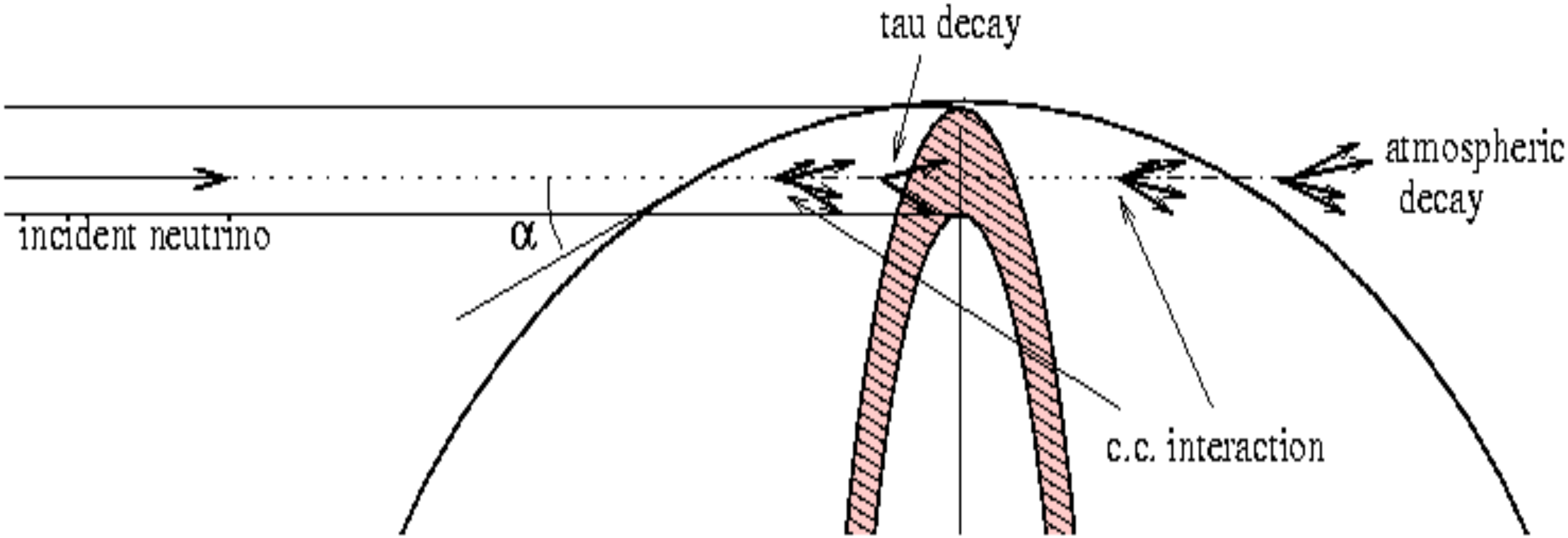


Pure muon beam
⇒ connect to composition
Geomagnetic field effects

Neutrino candidates

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

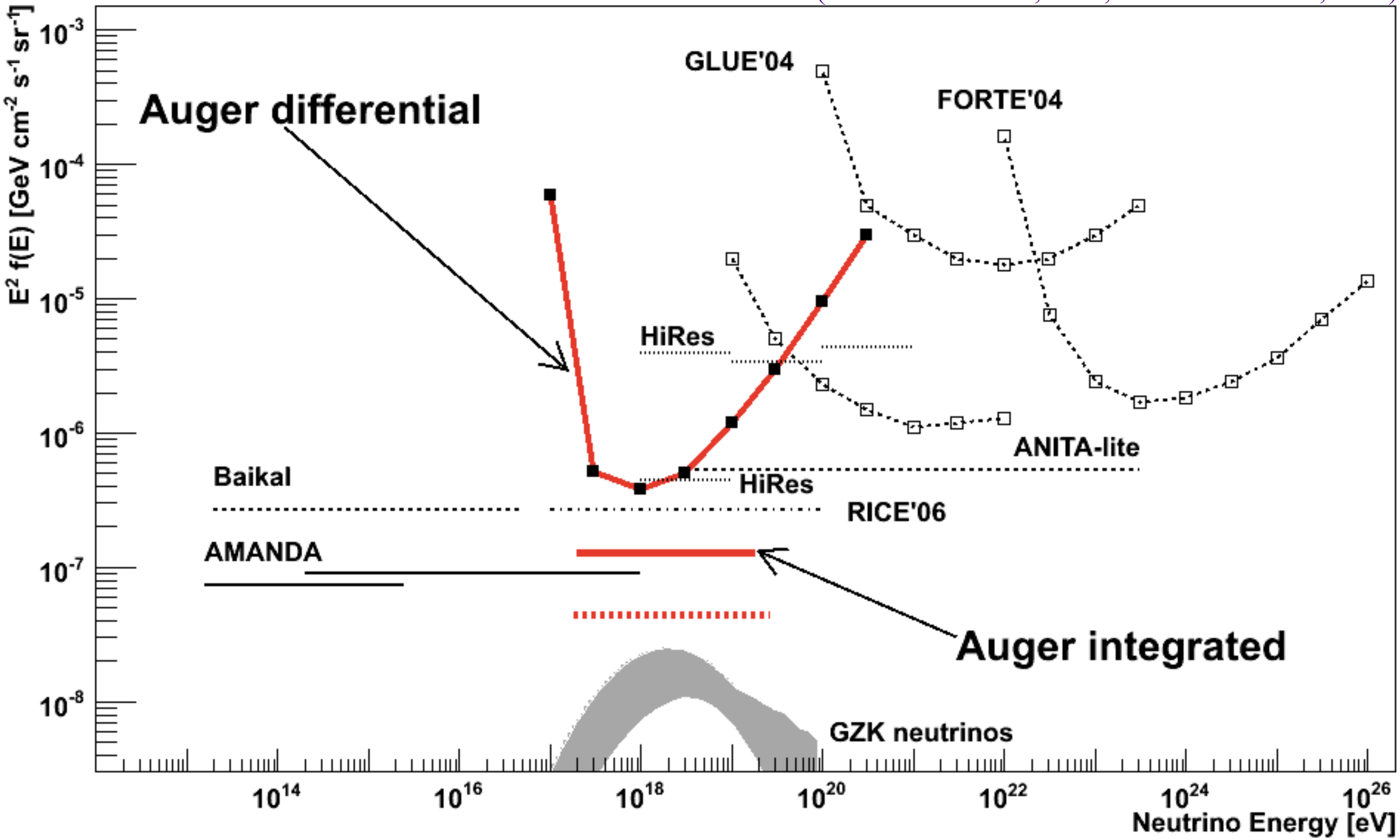
Rate ~ cosmic neutrino flux, but *not* to ν-N #-secn



… 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

⇒ **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

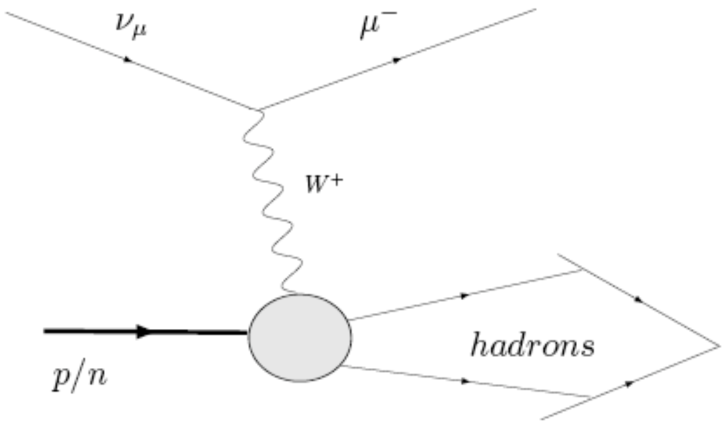
$$\frac{\partial^2\sigma^{CC,NC}_{\nu,\bar{\nu}}}{\partial x\partial y} = \frac{G_F^2 M E}{\pi}\left(\frac{M_i^2}{Q^2+M_i^2}\right)$$

Q^2 ↑ propagator ↓

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

$$\pm y\left(1-\frac{y}{2}\right)xF_3^{CC,NC}(x,Q^2)]$$

Q^2 ↑ parton distrib. fns ↓

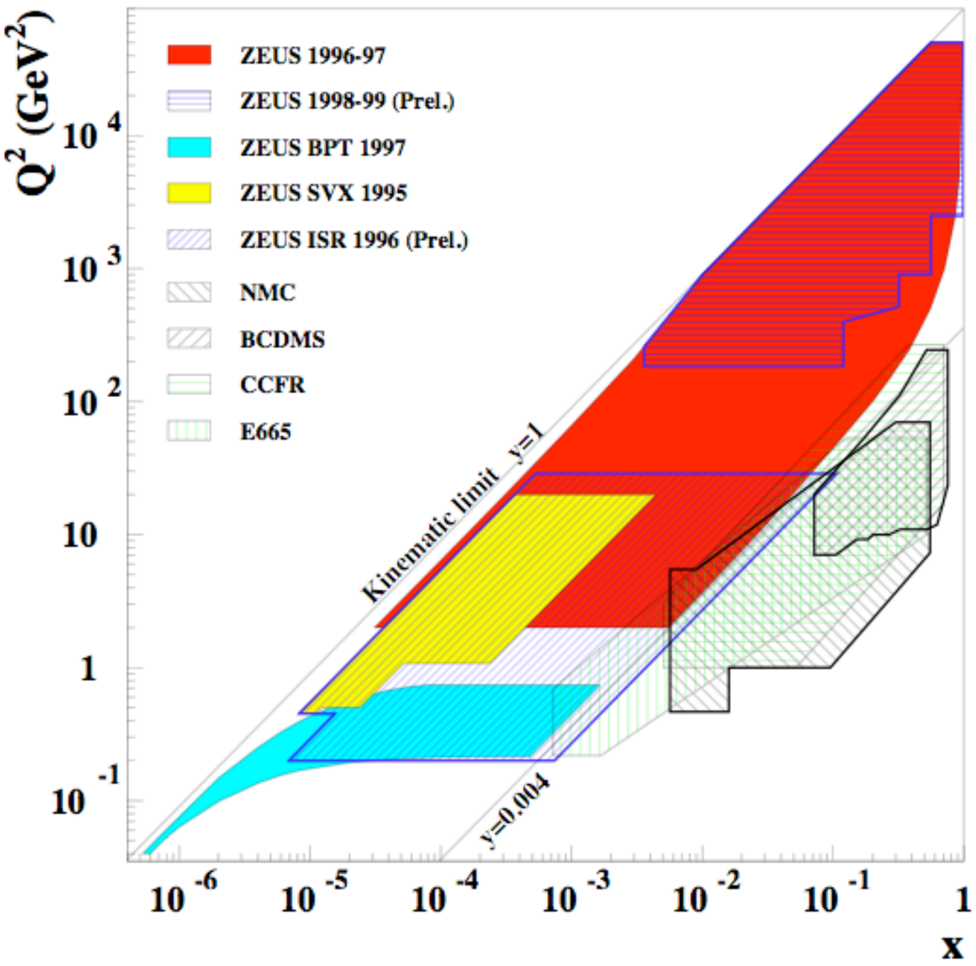


Most of the contribution to #-secn comes from: $Q^2 \sim M_W^2$ *and* $x \sim \frac{M_W^2}{M_N E_\nu}$

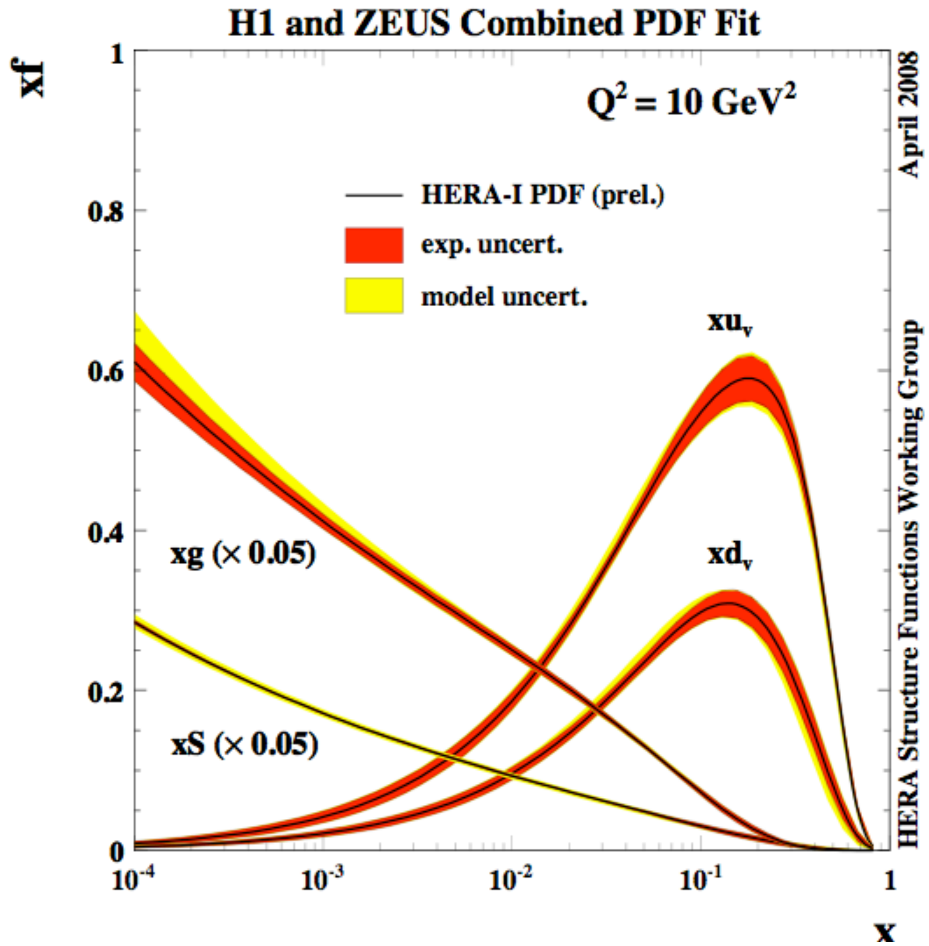
At leading order (LO) : $F_{\rm L} = 0, \quad F_2 = x(u_{\rm v} + d_{\rm v} + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c}),$

$$xF_3 = x(u_{\rm v} + d_{\rm v} + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_{\rm v} + d_{\rm v} + 2s + 2b - 2\bar{c})$$

At NLO in $\alpha_{\rm s}$, it gets more complicated … but is still calculable



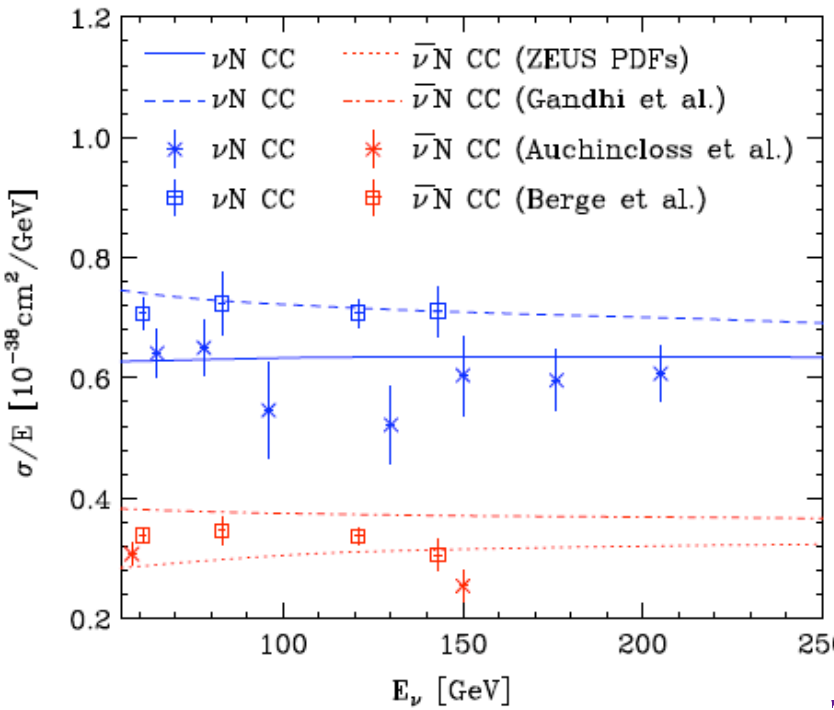
The H1 and ZEUS experiments at HERA have made great progress by probing a much deeper kinematic region

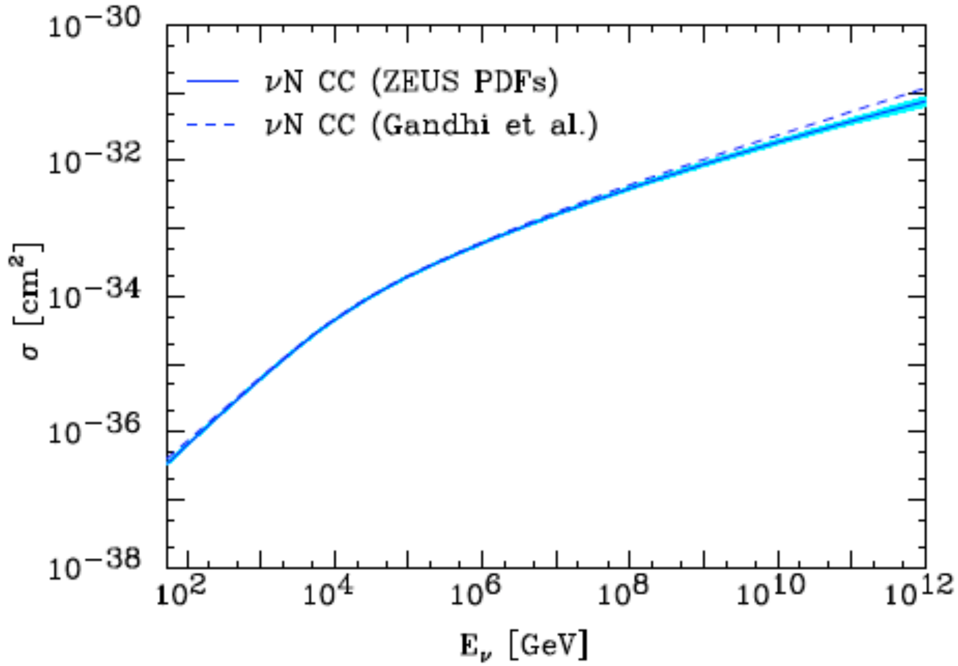


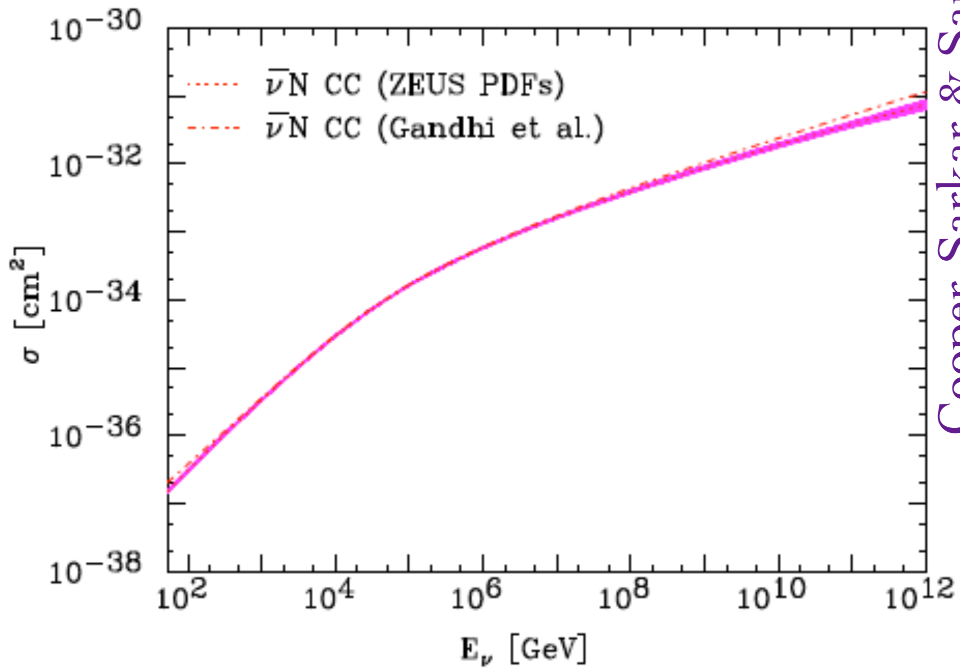
Most surprising result is the steep rise of the gluon structure function at low Bjorken x ➔ significant impact on ν scattering

The σ-section is up to ~40% *below* the previous 'standard' 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

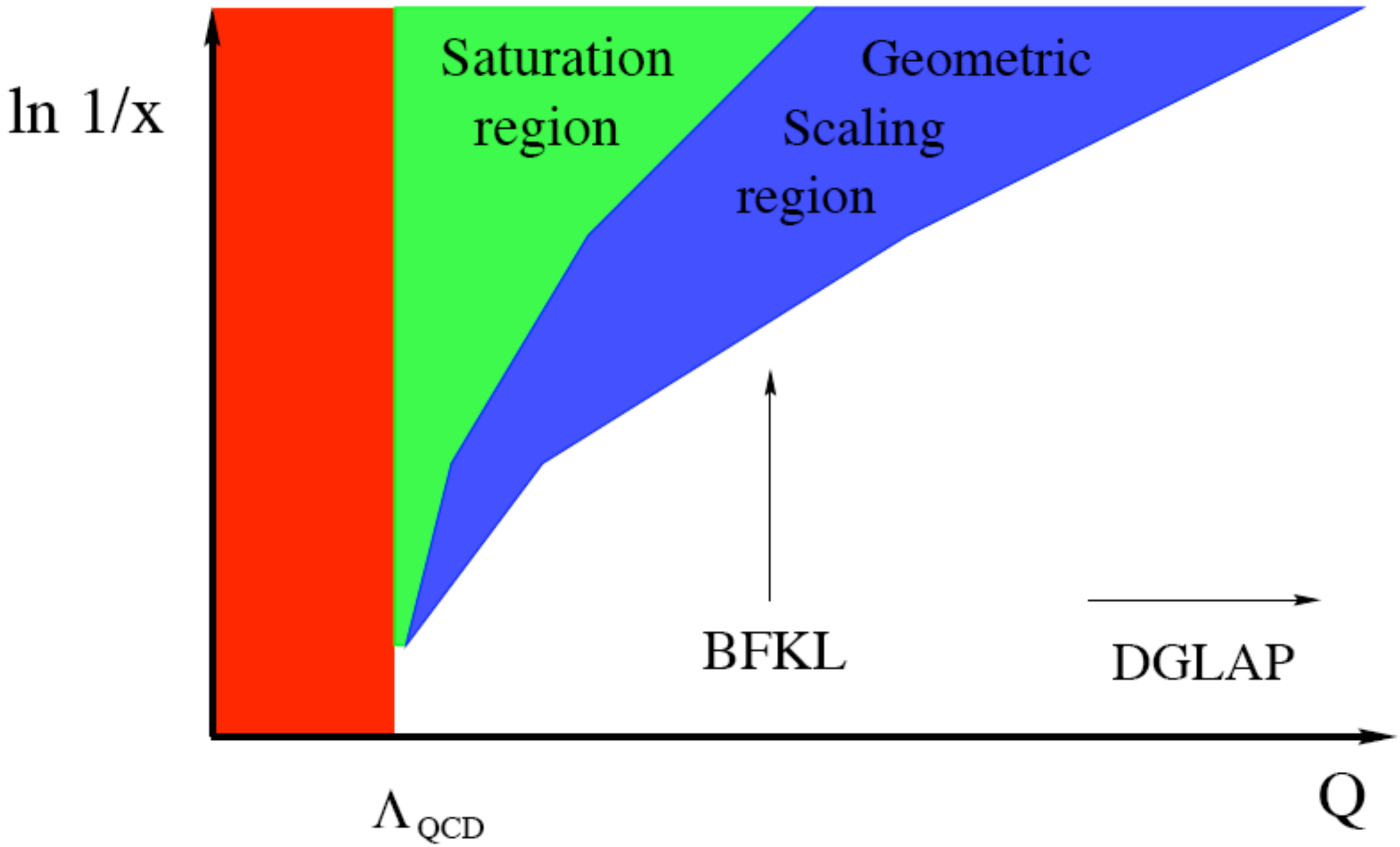






Cooper-Sarkar & Sarkar, JHEP 01:075,2008

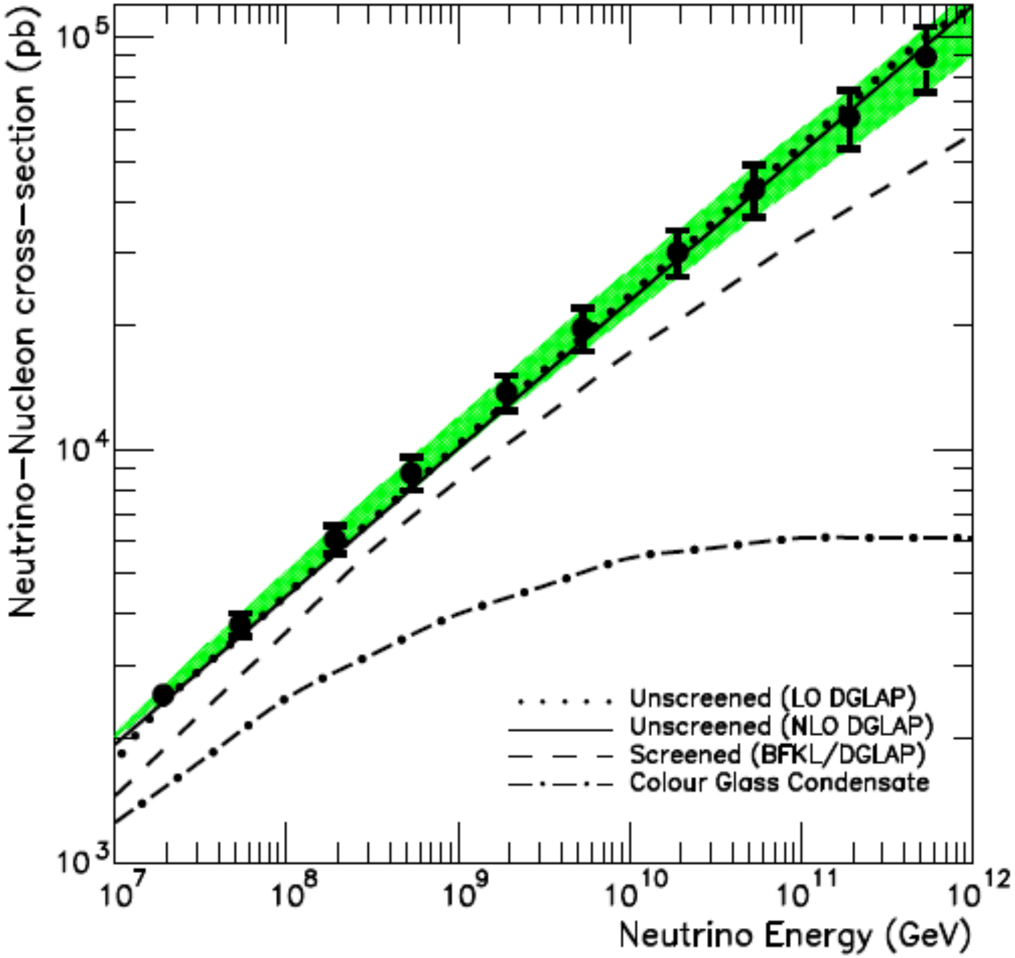
As the gluon density rises at low x, non-perturbative effects become important … a new phase of QCD - Colour Gluon Condensate - has been postulated to form

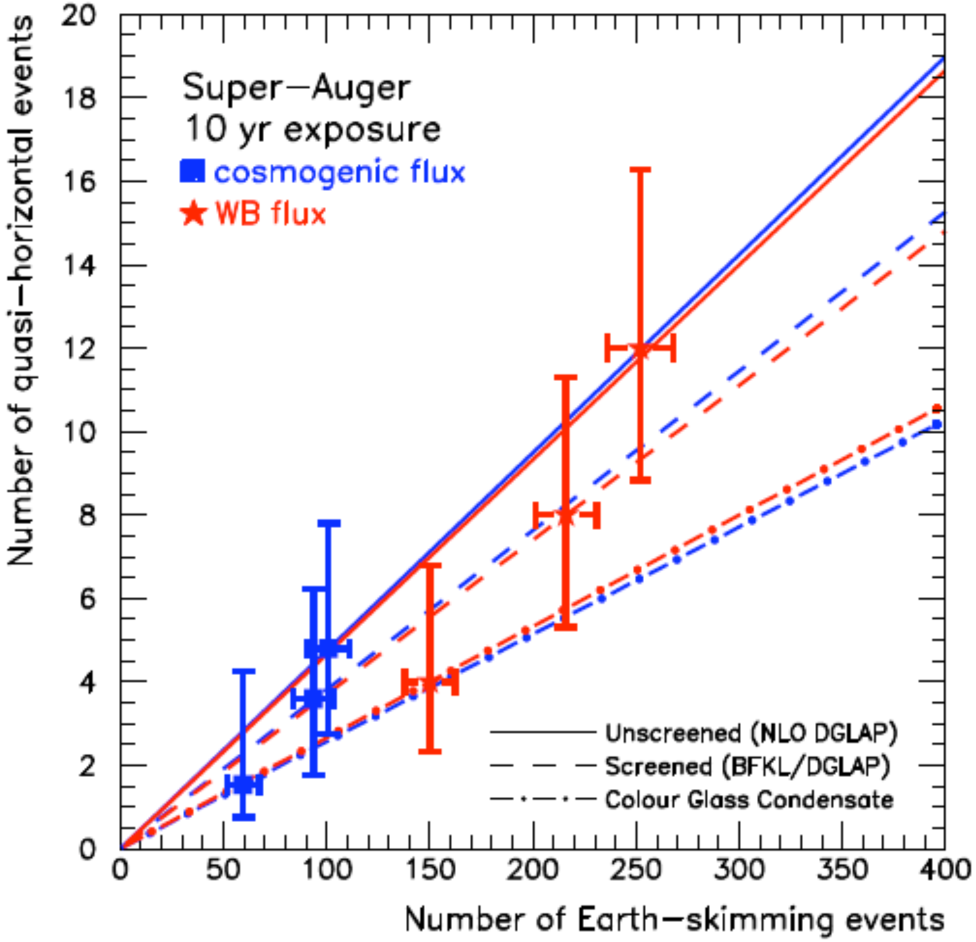


This would *suppress* the ν-N #-secn below its (unscreened) SM value

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

Anchordoqui, Cooper-Sarkar, Hooper & Sarkar, PR D74:043008,2006



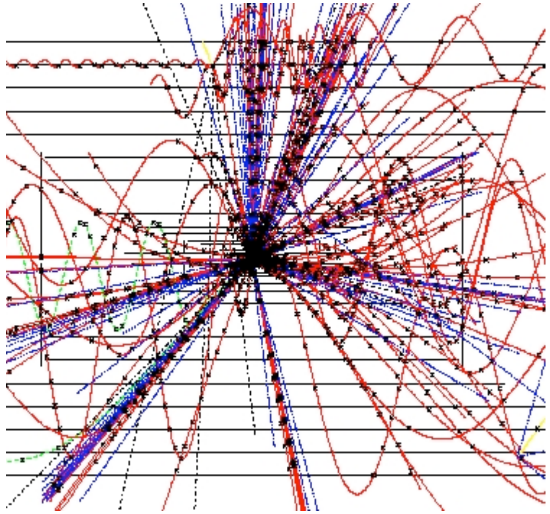


The steep rise of the gluon density at low-x must saturate (unitarity!)
➔ suppression of the ν-N #-secn

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

TeV scale quantum gravity?

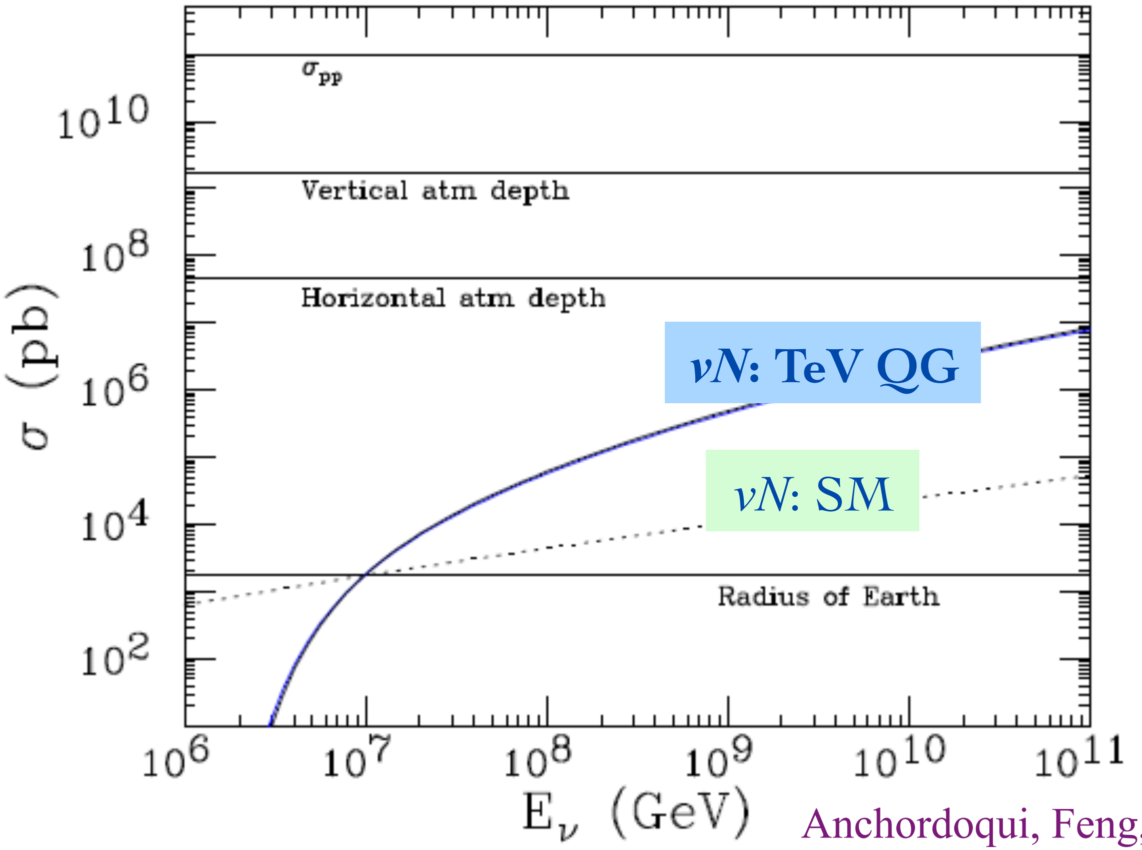
If gravity becomes strong at the TeV scale (as in some brane-world models) then at cms energies well *above* this scale, **black holes** will form with $M \sim \sqrt{\hat{s}}$ and $A \sim \pi R^2_{\text{Schwarzschild}}$



(courtesey: Albert De Rocek)

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

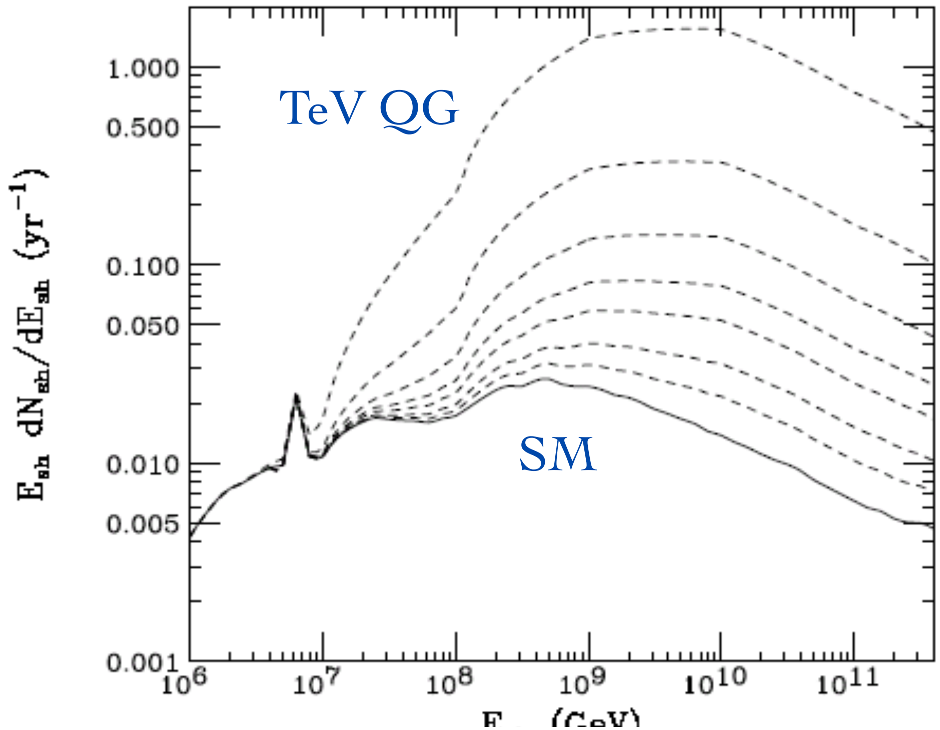
This will enhance the neutrino scattering #-secn significantly



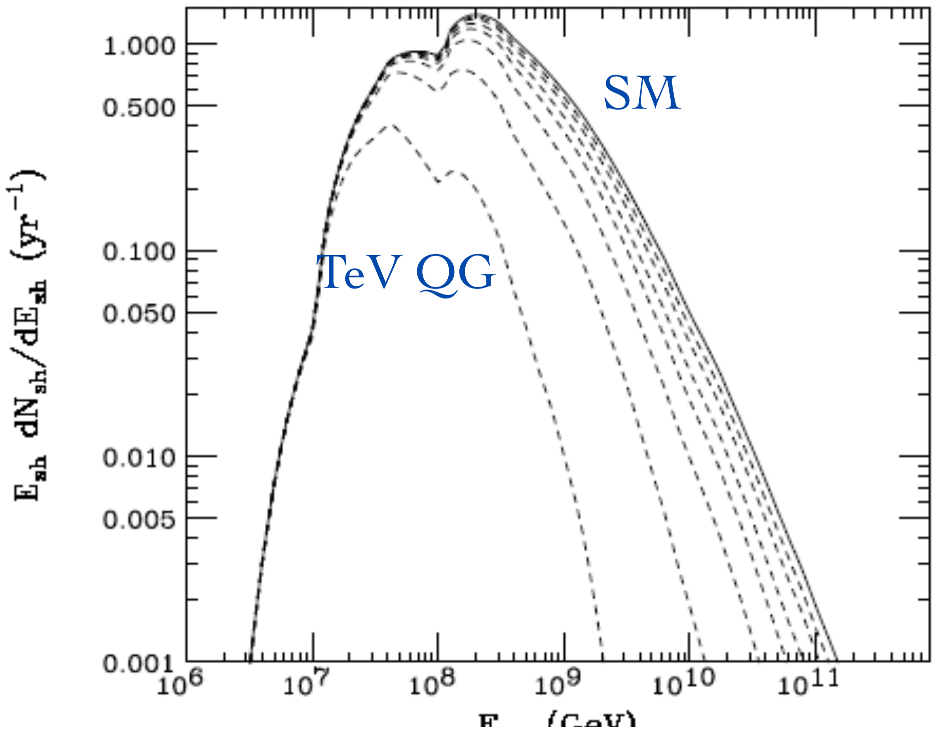
Anchordoqui, Feng, Goldberg & Shapere, PR D68:104025,2003

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

Quasi-horizontal ν showers



Earth-skimming ν_τ 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, AP 25:14,2006;
Anchordoqui *et al*, PR D82:043001,2010

Summary

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

Auger is 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)