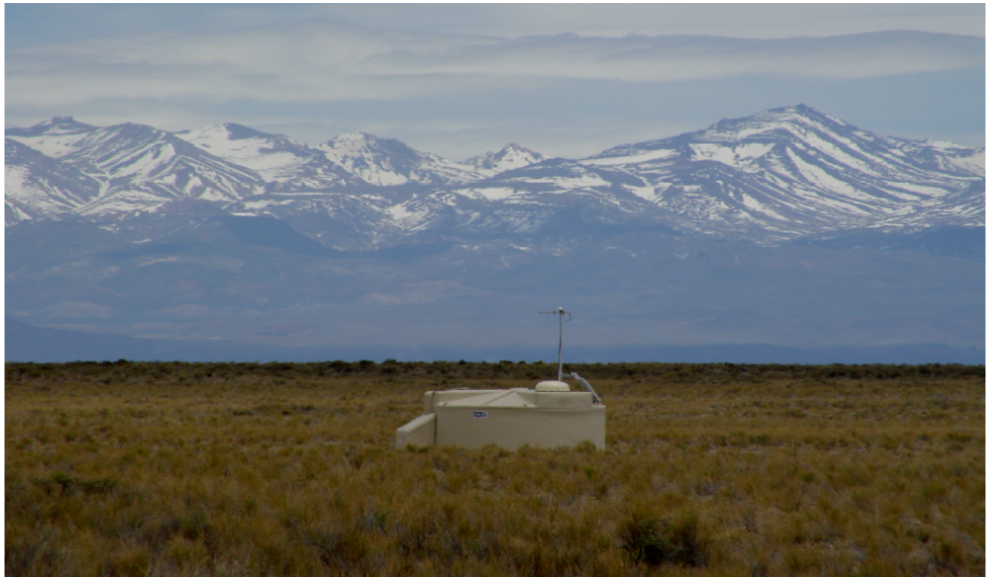
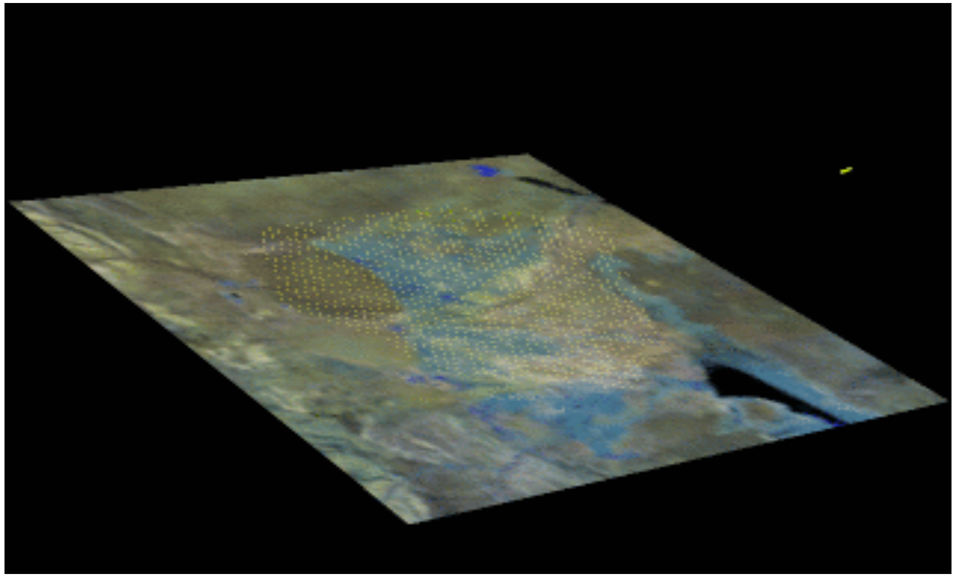




Probing low-x QCD dynamics with ultrahigh energy cosmic neutrinos

Subir Sarkar

University of Oxford

ICTS school on *QCD at high parton densities*

Dona Paula, 8-12 Sept 2008

Colliders & Cosmic rays

The LHC will soon achieve ~14 TeV cms …

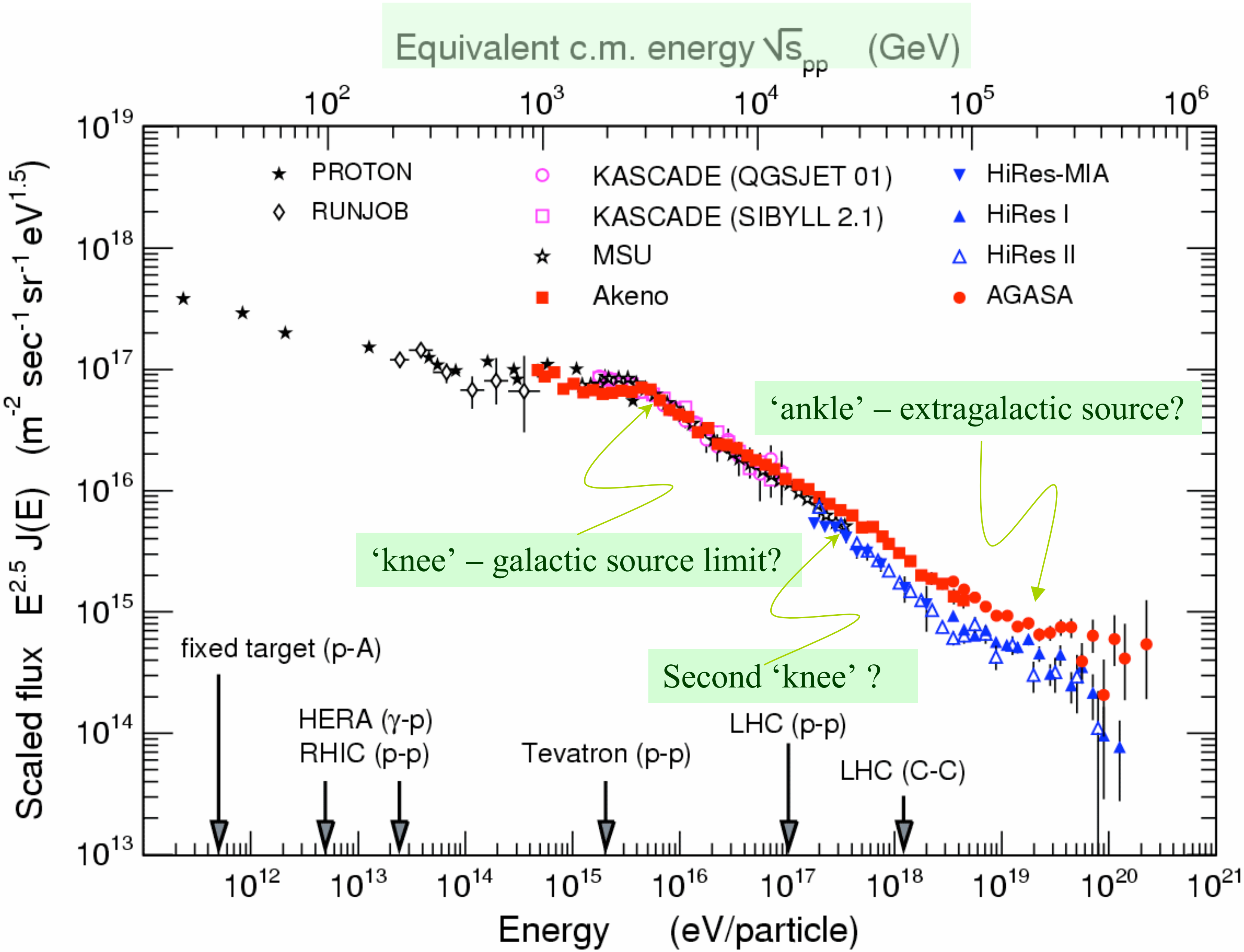
But 1 EeV ($\equiv 10^{18}$ eV) cosmic ray initiating giant air shower
$\Rightarrow$ ***50 TeV*** cms (rate ~ 10/day in 3000 km^2 array)

New physics would be hard to see in hadron-initiated showers
(#-secn TeV^{-2} vs GeV^{-2})

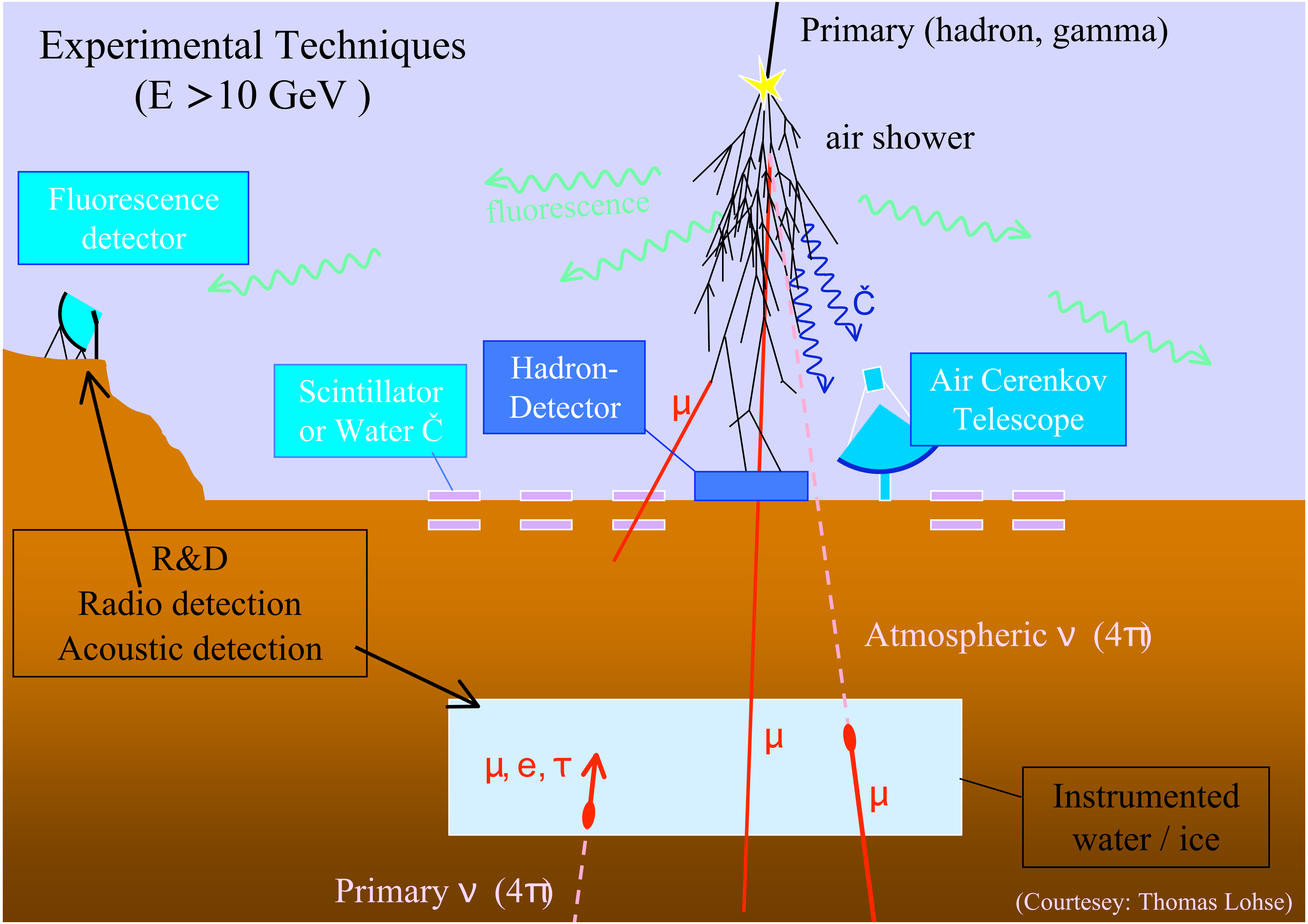
… but may have a dramatic impact on *neutrino* interactions

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

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

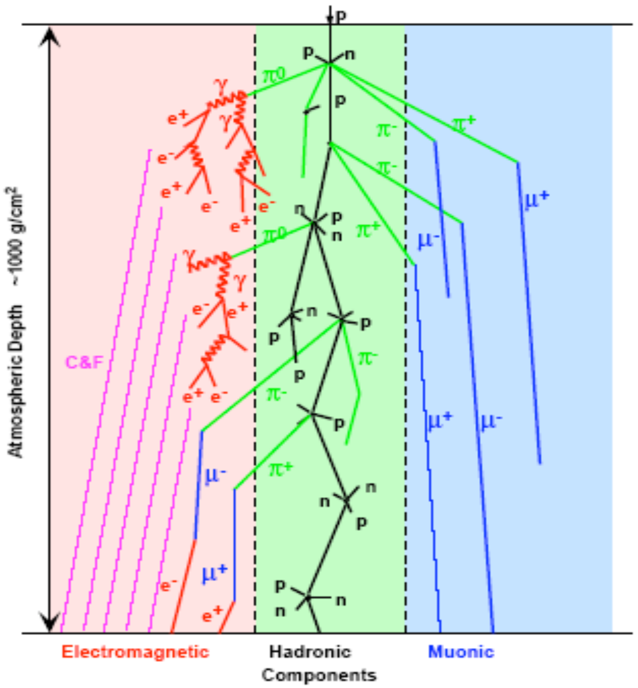


(Courtesey: Ralph Engel)



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

Shower Development



Fluorescence & (isotropic)
Cherenkov-Light (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_{μ} ~ 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

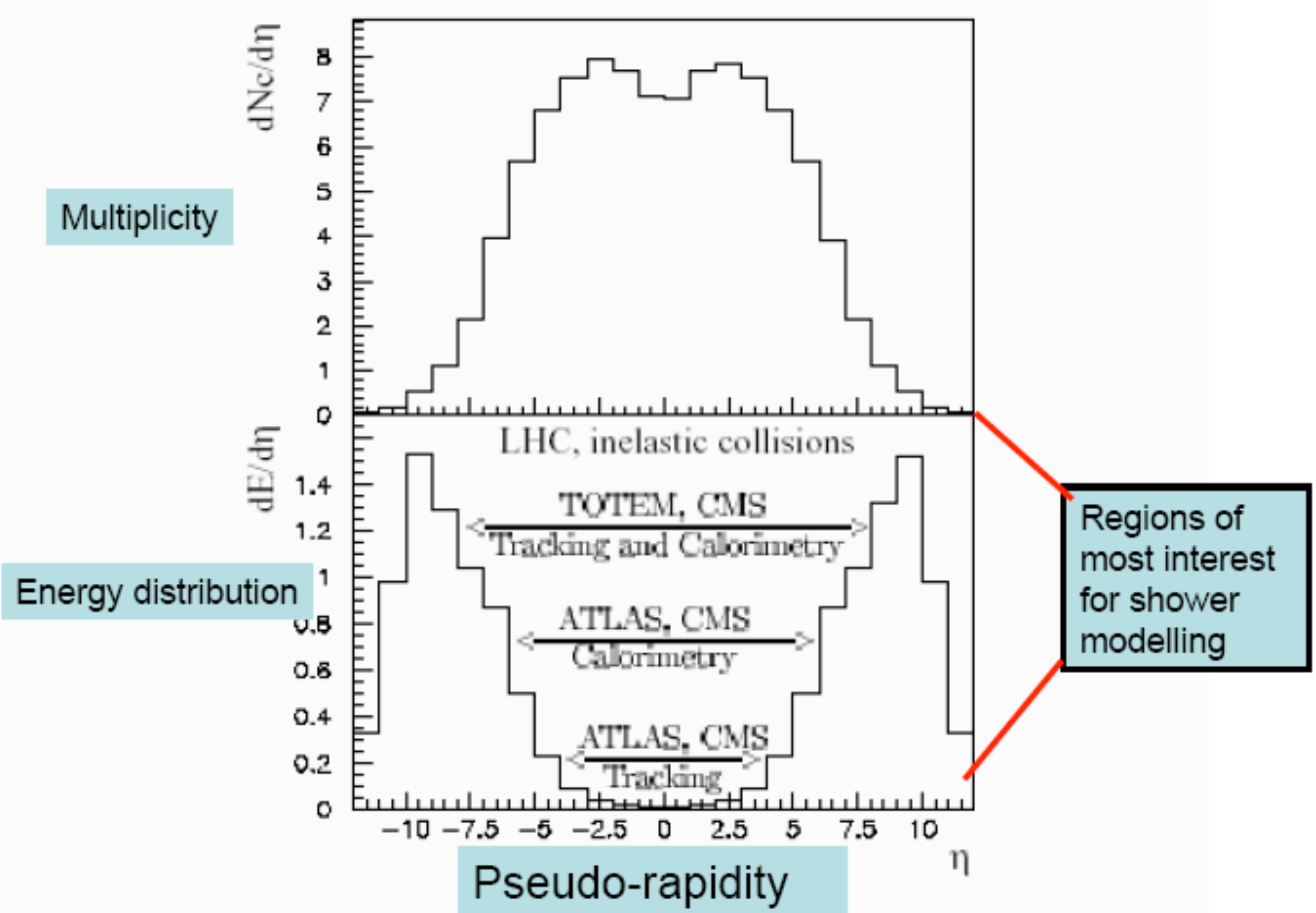
Complex interplay with many correlations
requires MC simulations

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)

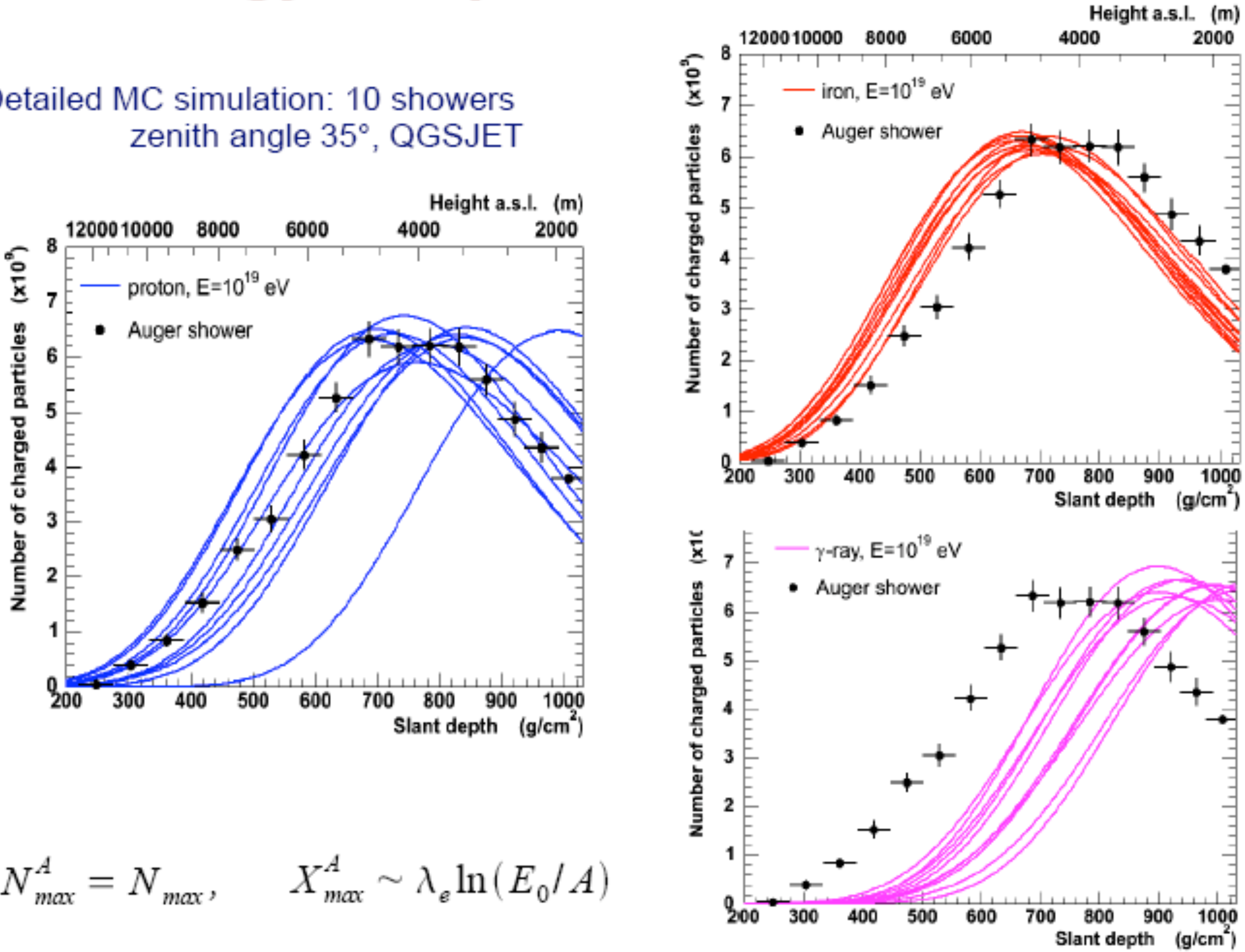
Expect important input from LHC experiments (CASTOR, TOTEM ...)

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



Energy/composition: shower profile

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



$$N_{max}^{A} = N_{max}, \qquad X_{max}^{A} \sim \lambda_{e} \ln(E_0/A)$$

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

Does the UHE cosmic ray spectrum show the predicted GZK cutoff?

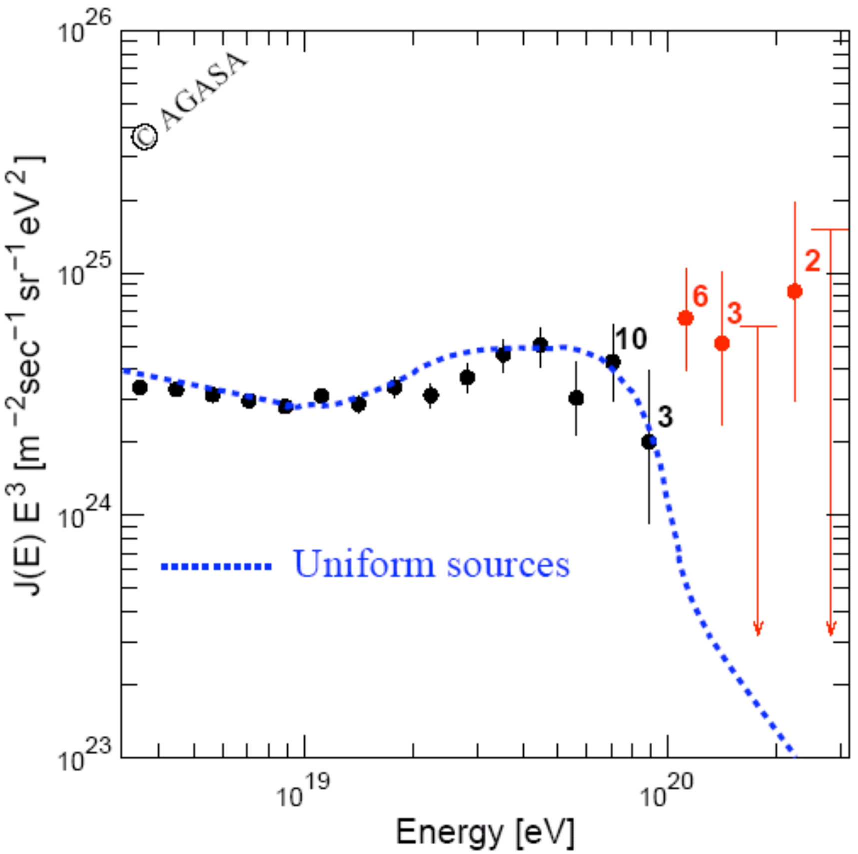
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

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

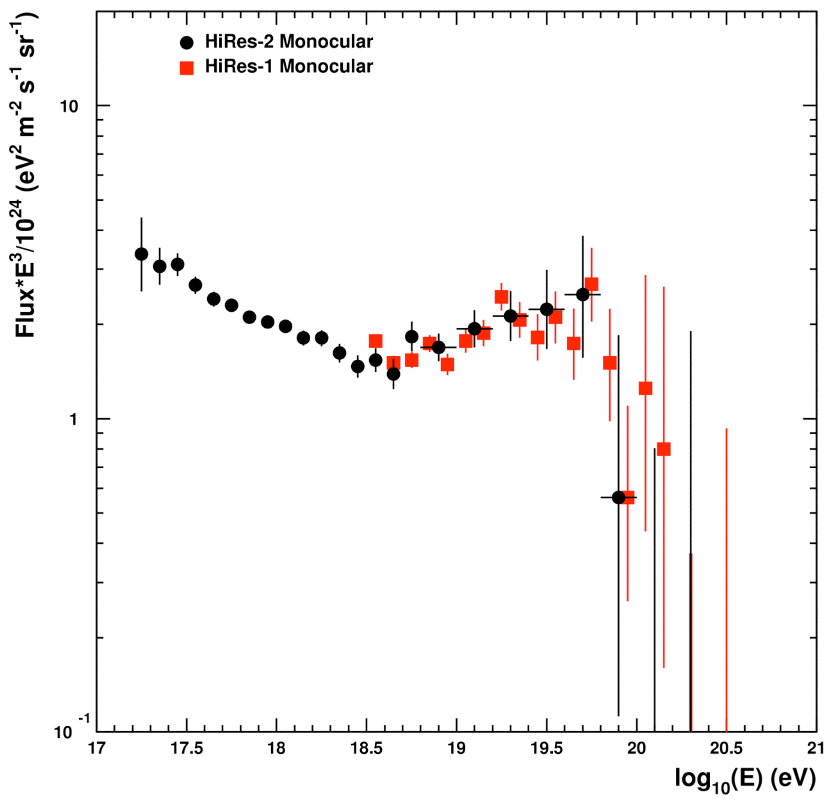
$$\hookrightarrow \mu^{+} + \nu_{\mu}$$

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

AGASA spectrum continues smoothly!

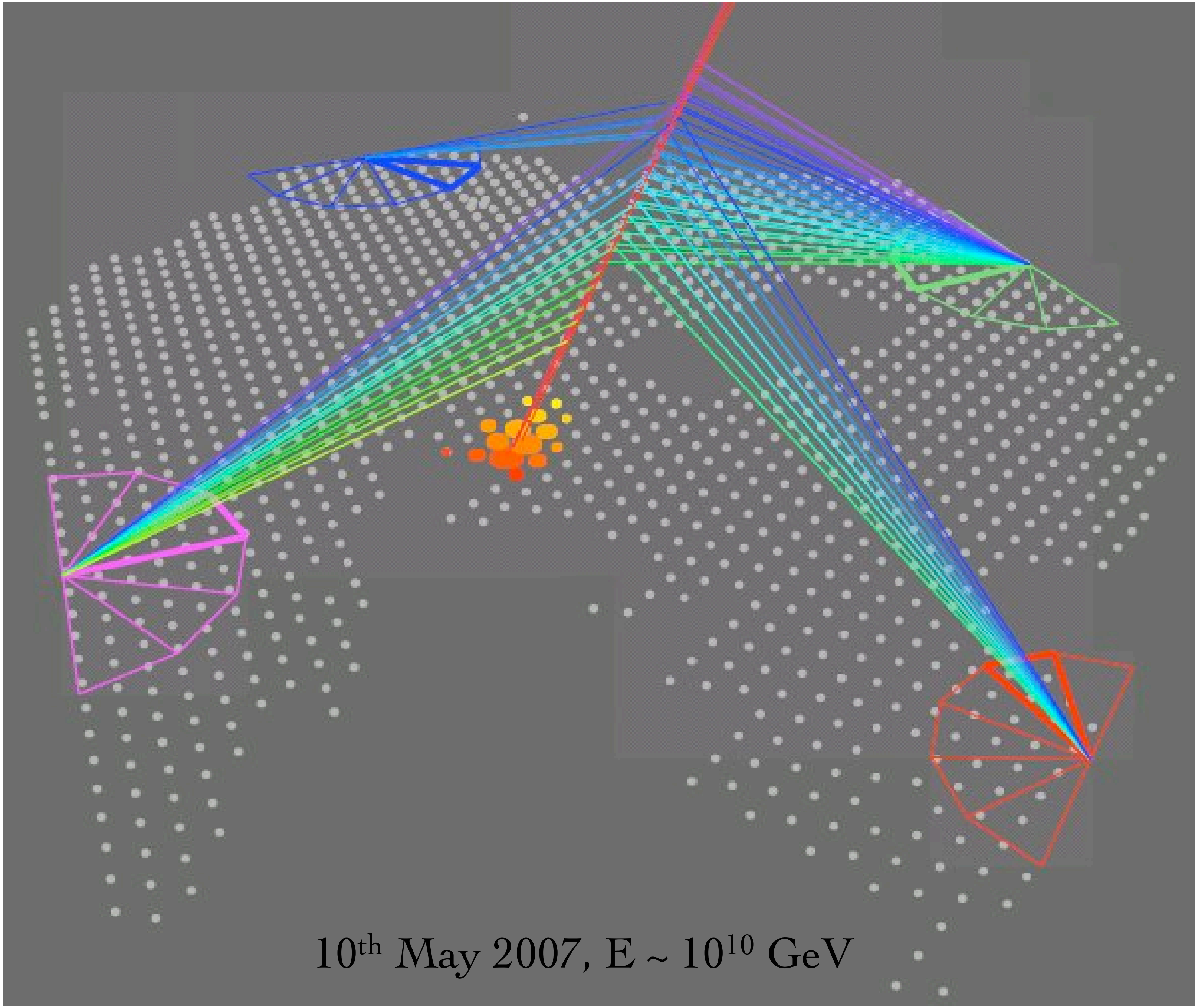


… but HiRes sees expected suppression

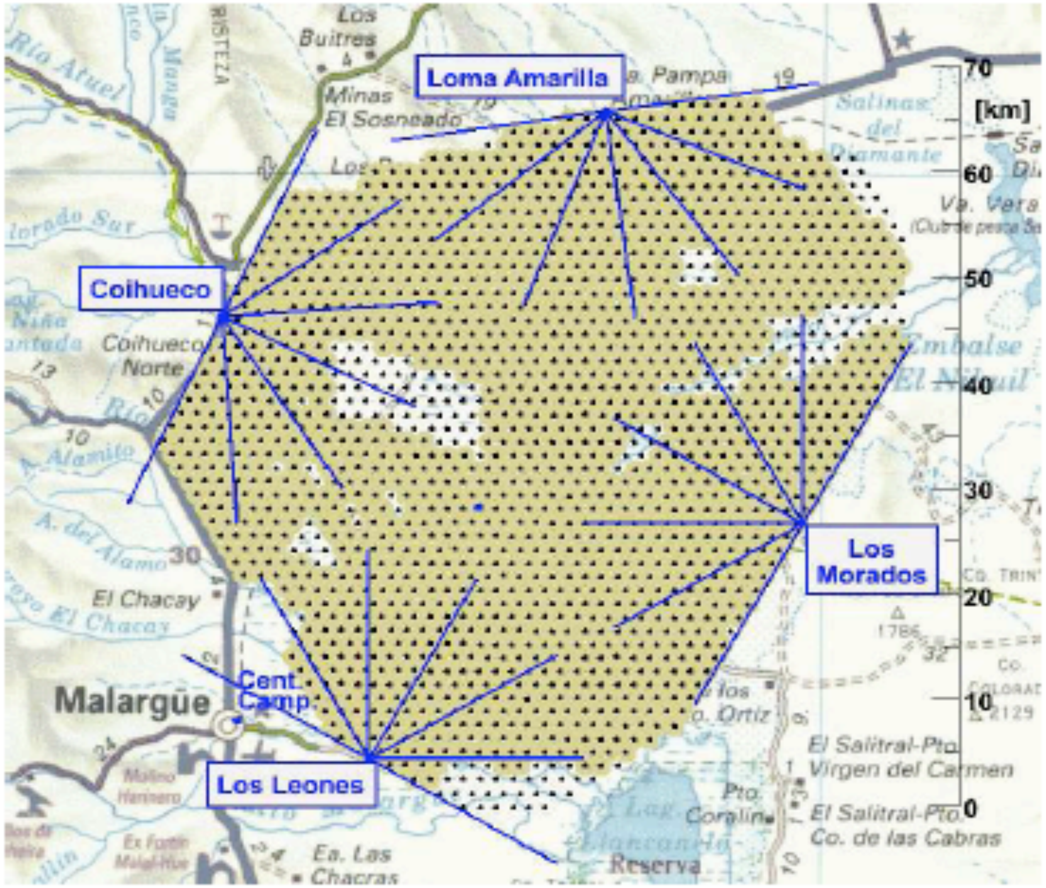


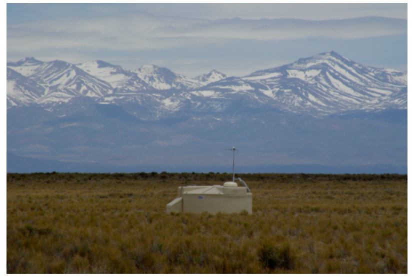
Is there a ~25% energy calibration mismatch between surface arrays and air fluorescence detectors?

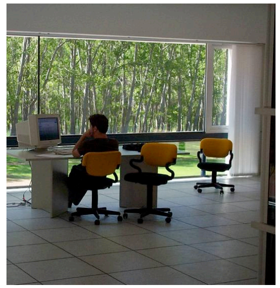
Need a *hybrid* detector, combining the advantages of both techniques ..



The Pierre Auger Observatory







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

Surface detector array: installation of electronics - March 2006

Auger Energy Determination: Step 1

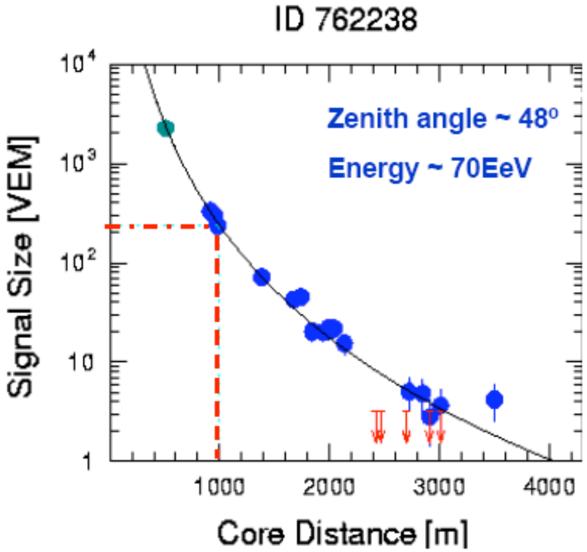
The energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.

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

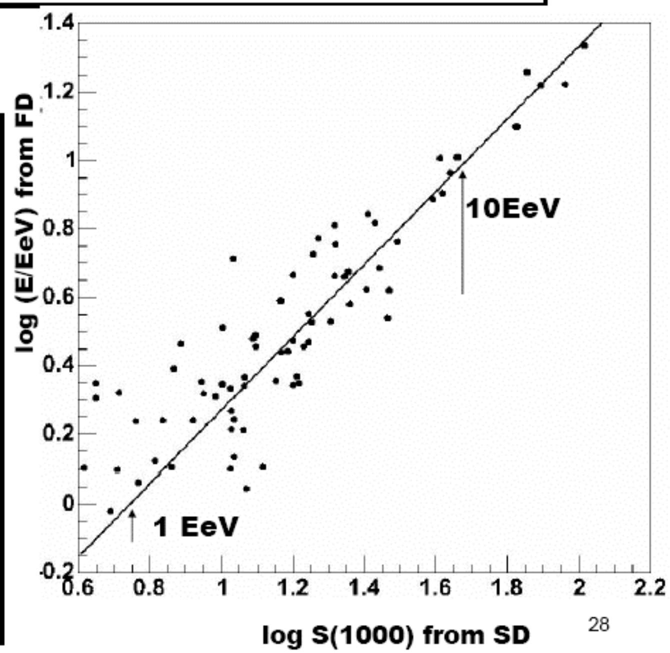
Auger Energy Determination: step 2

Hybrid Events with STRICT event selection:

aerosol content measured

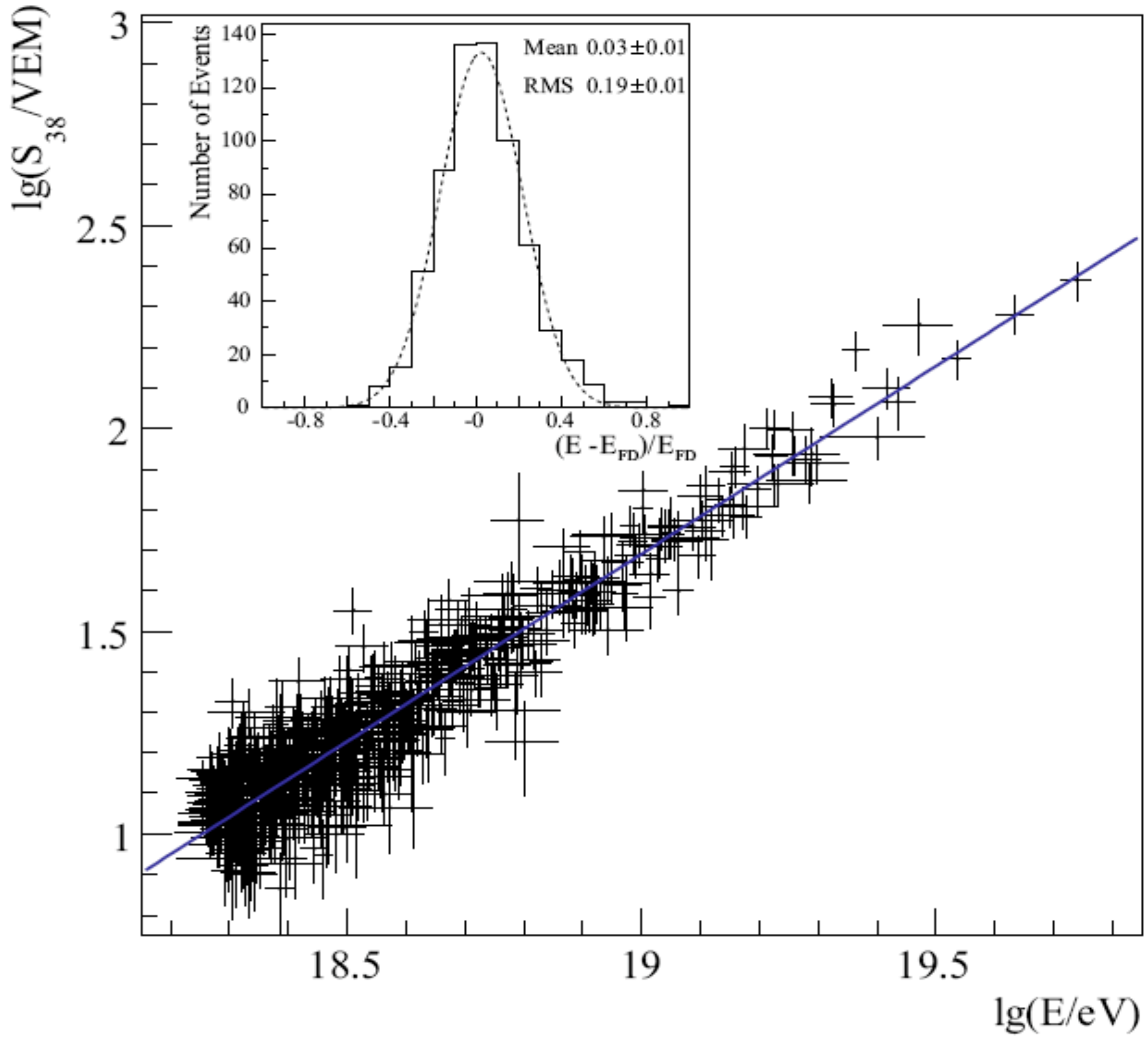
track length $> 350\ g\ cm^{-2}$

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 …

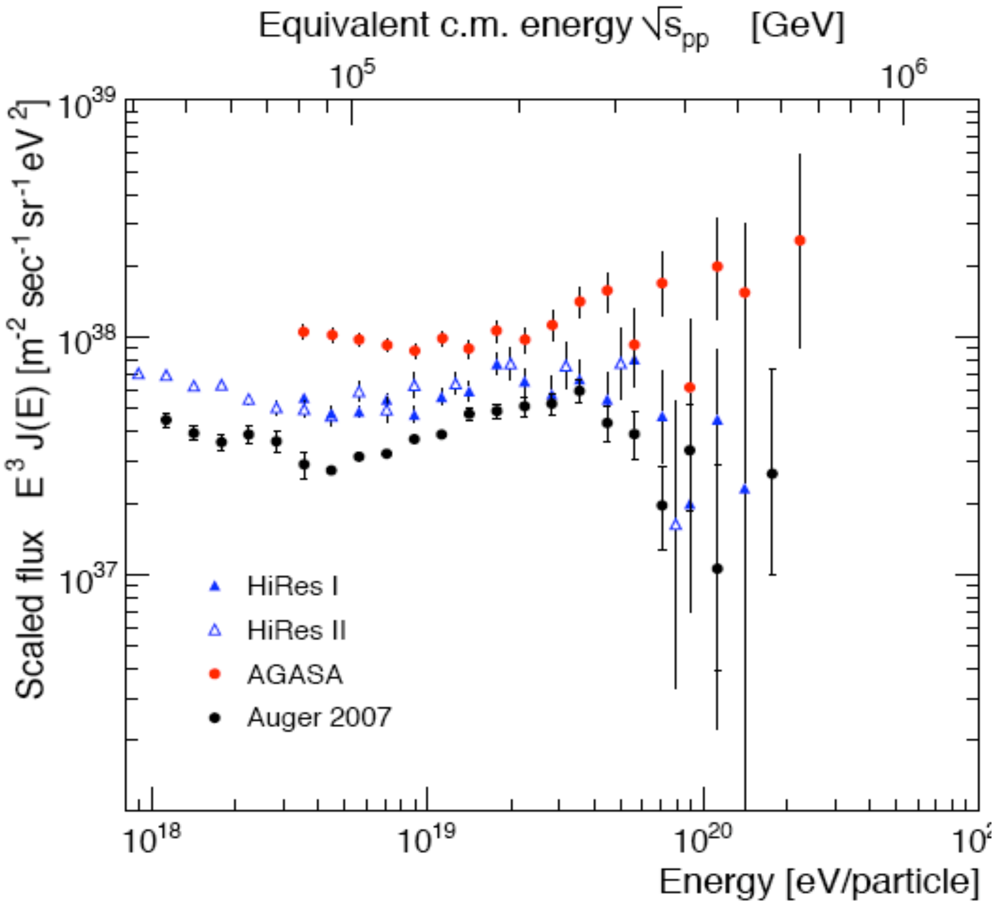
Energy Scale from FD

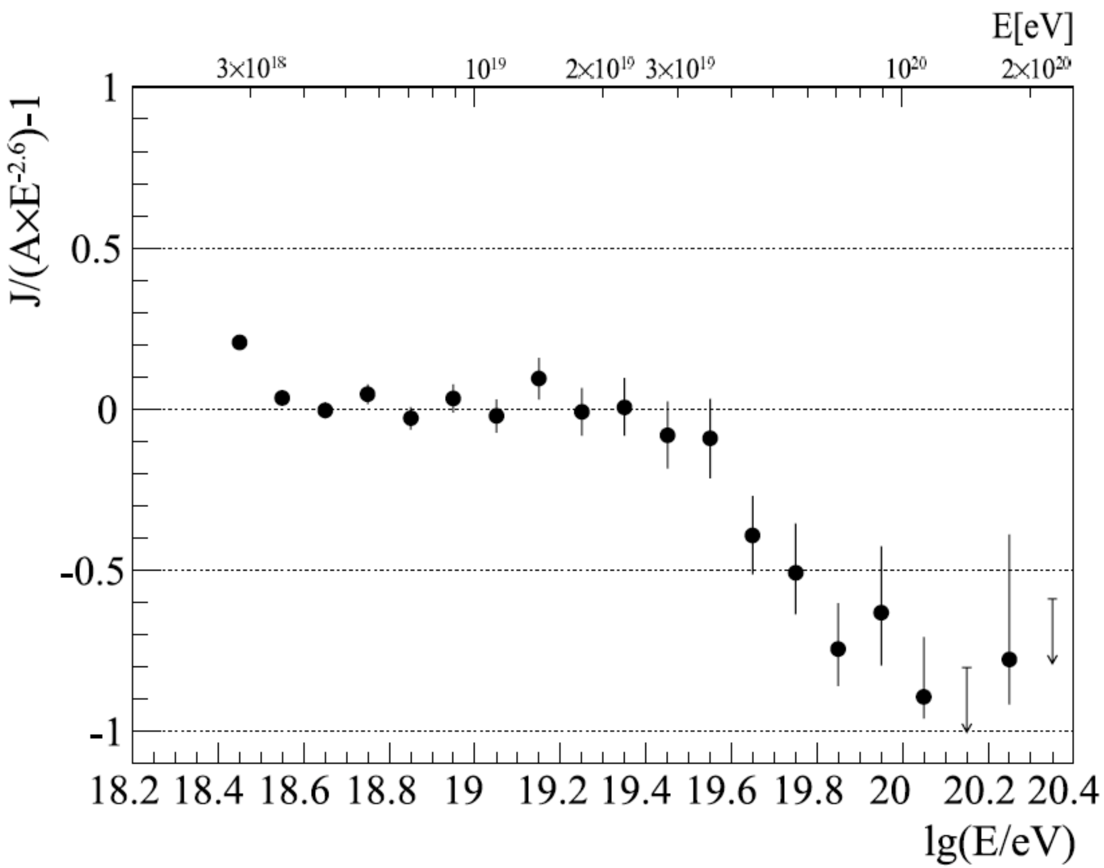


Major remaining uncertainty ➔ efficiency of fluorescence light emission
… being remeasured at Argonne (depends on atmospheric conditions)

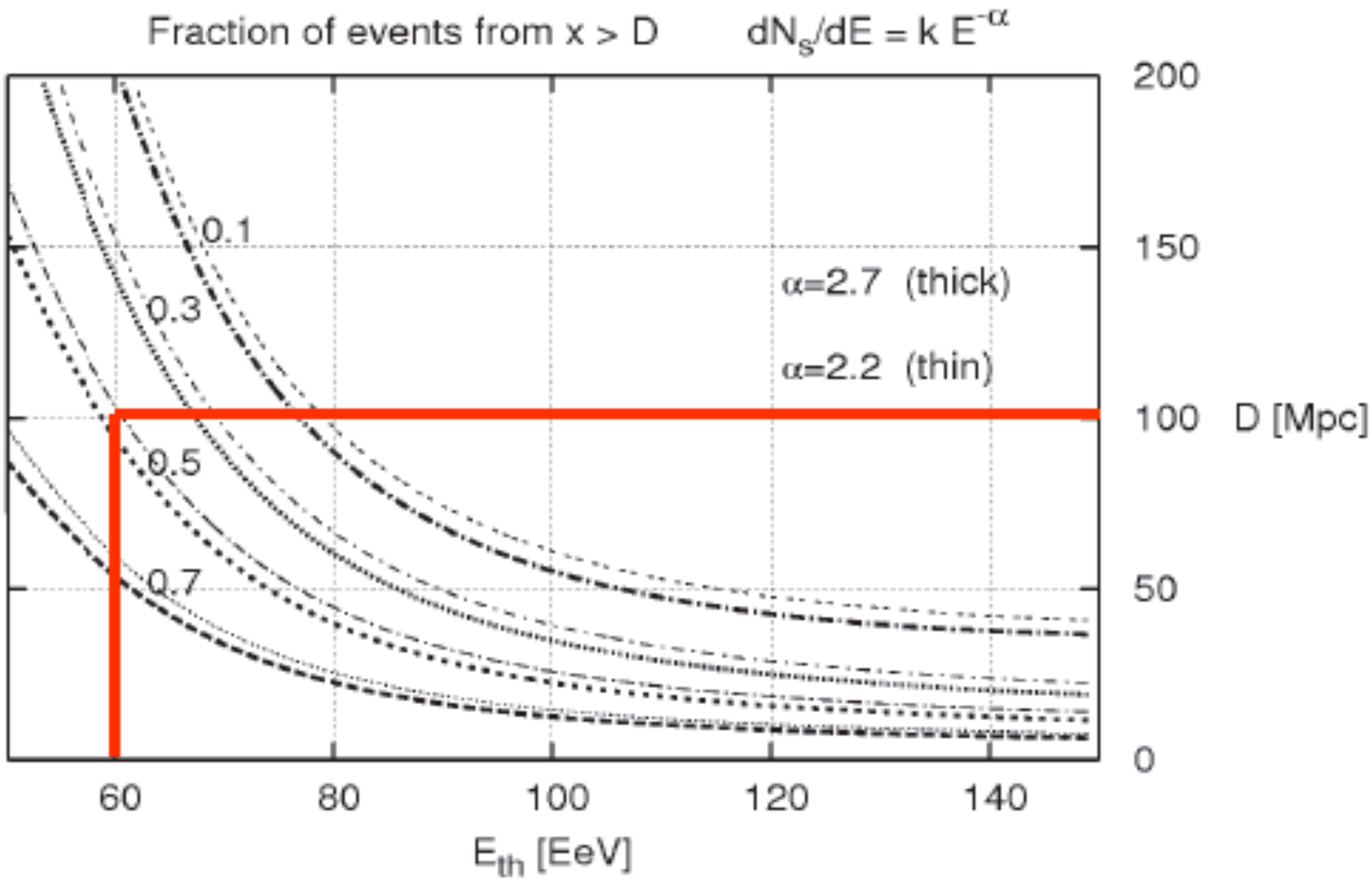
Auger has resolved the puzzle … the flux *is* suppressed beyond E_{GZK}

Hence the UHECRs must be extragalactic [arXiv:0706.2096]

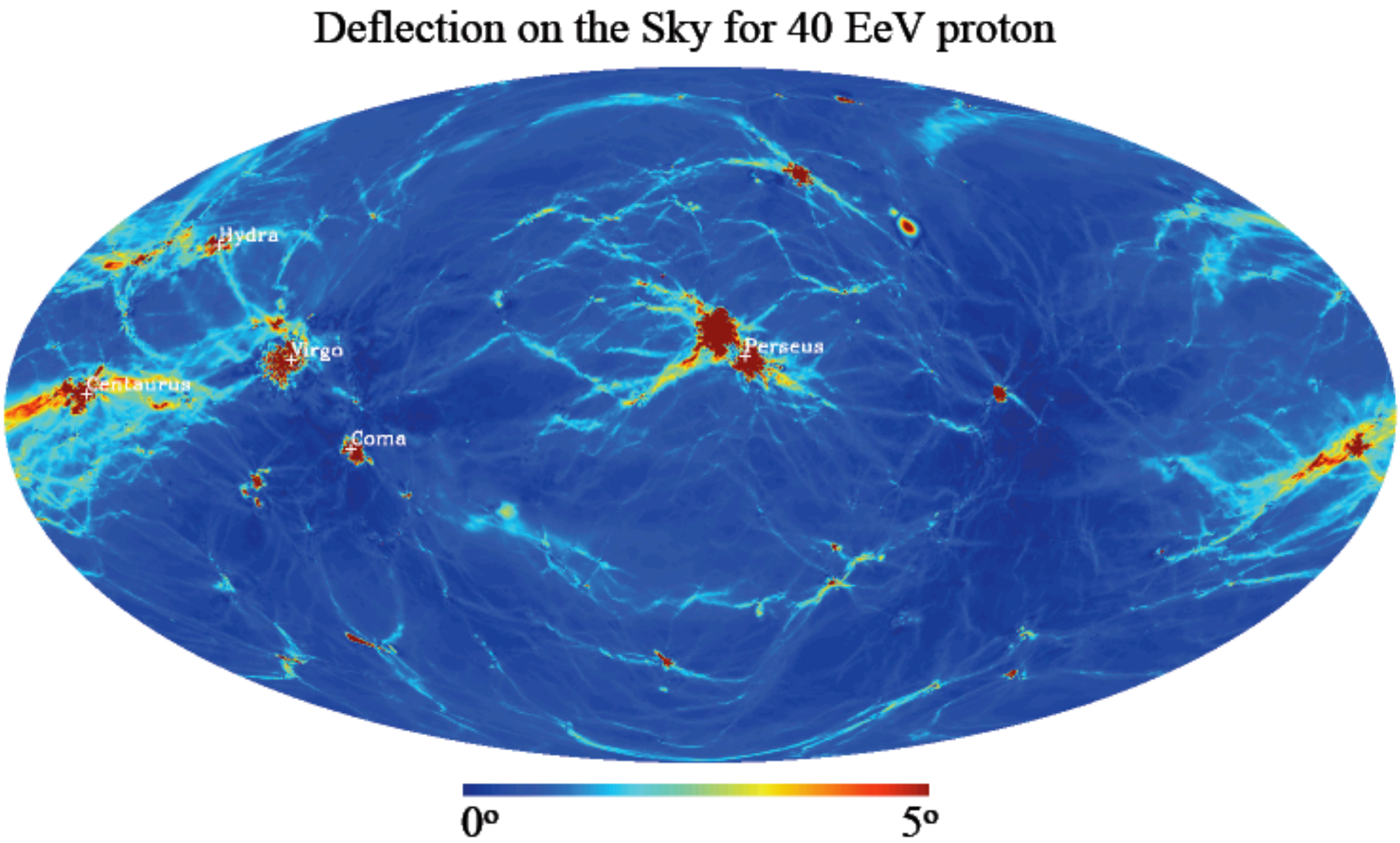




At these high energies the sources must be *nearby* … within the 'GZK horizon'



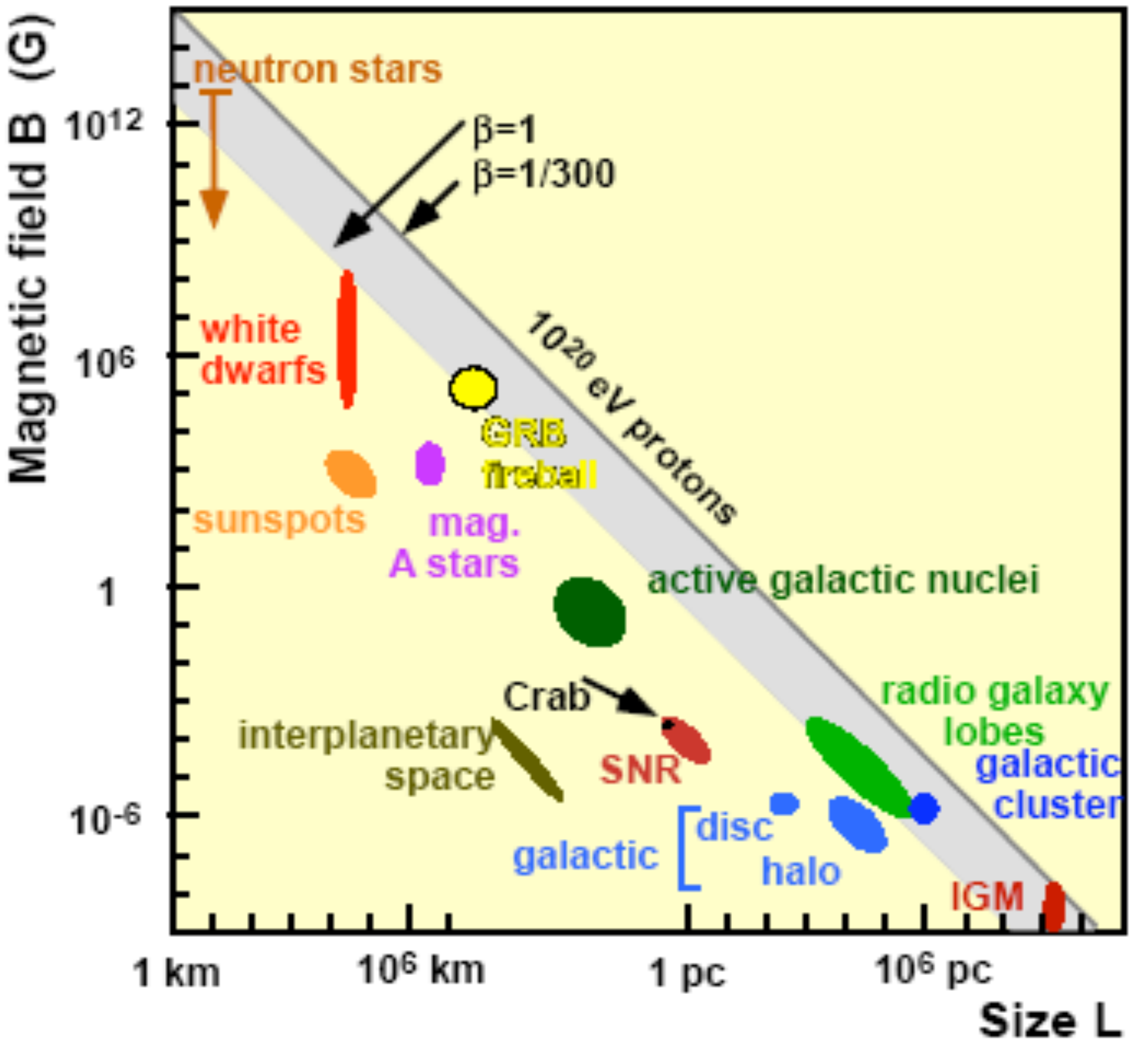
… and the observed UHECRs should *point back* to the sources



'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

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

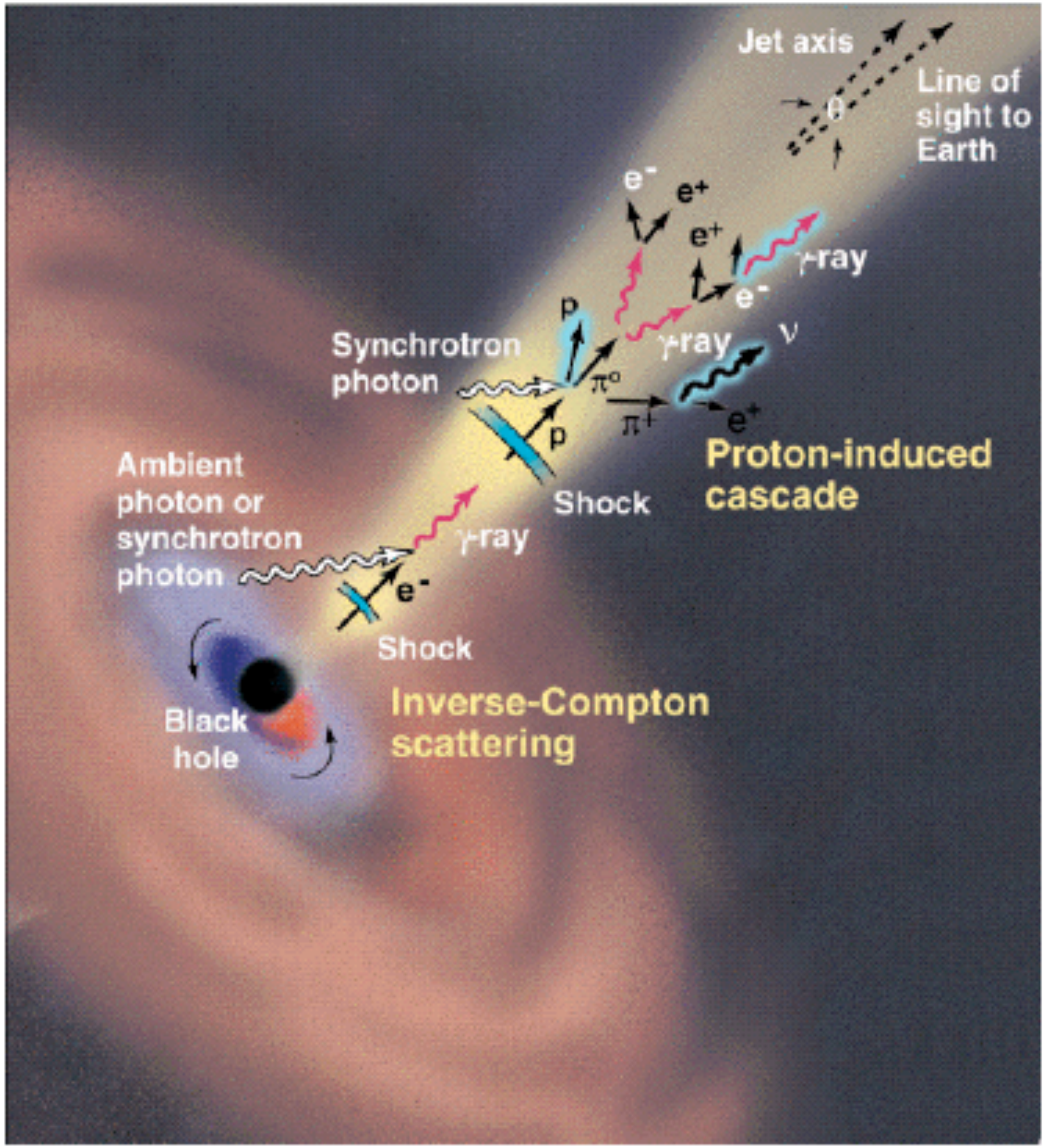
$B_{\mu G} \times L_{kpc} > 2\, (c/v)\, E_{EeV} / Z$

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.

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

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



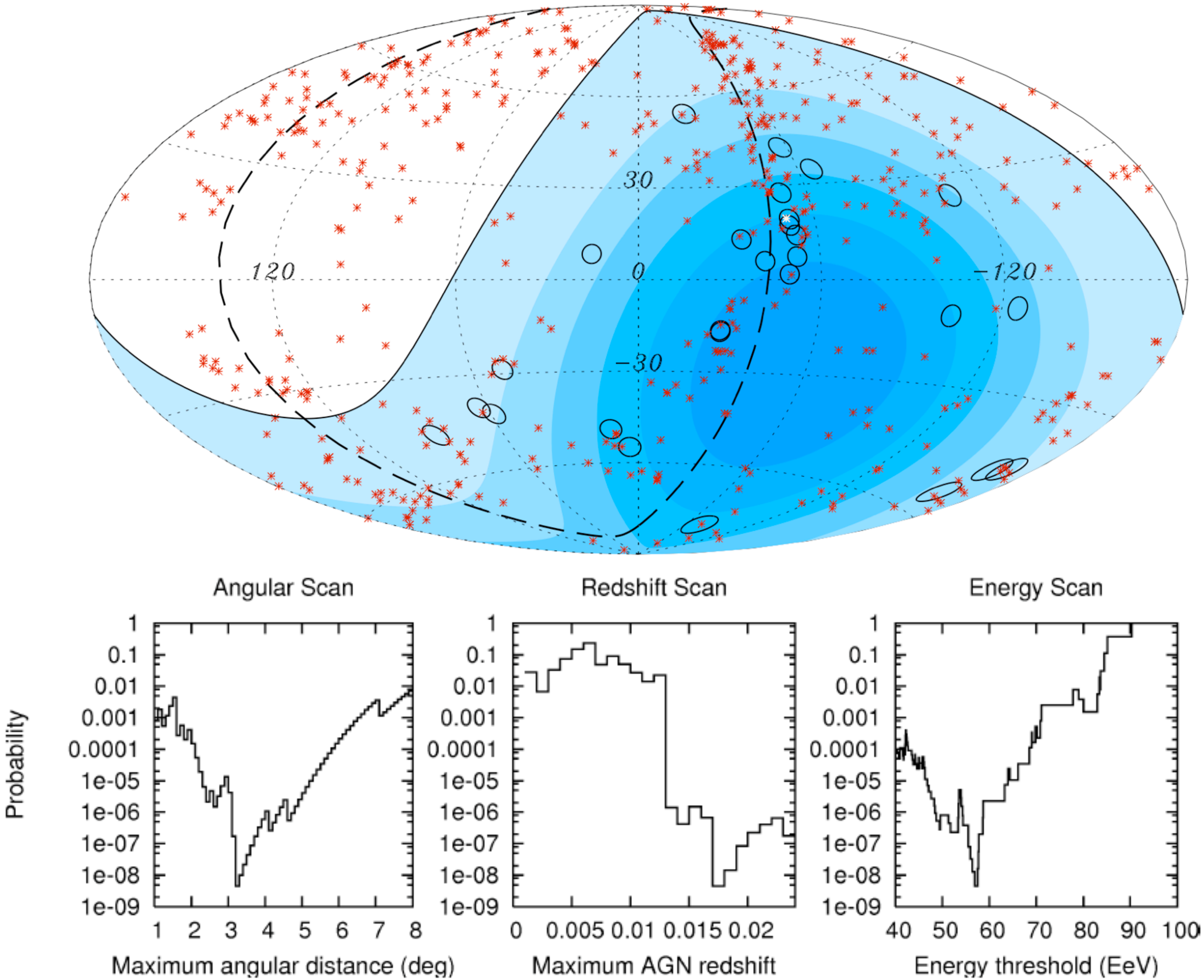
Active galactic nuclei

- 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

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



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

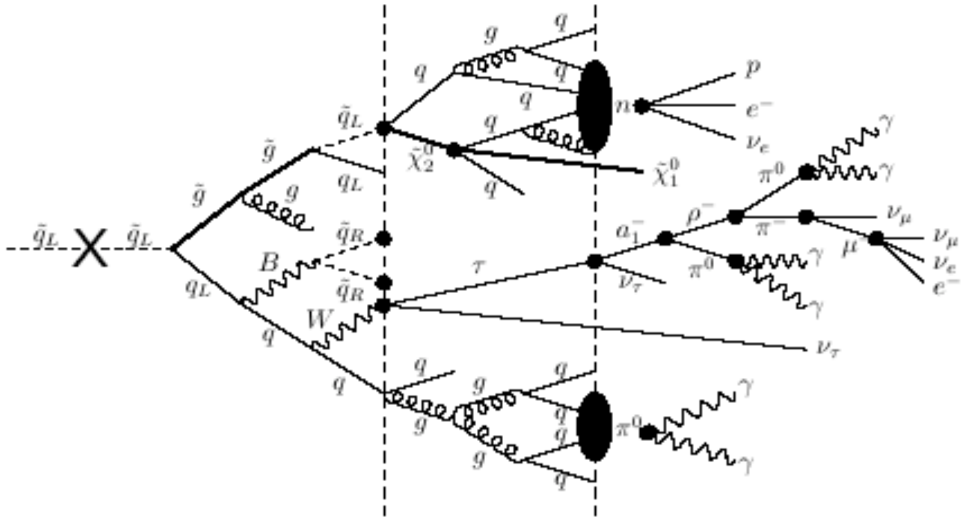
Simulation of galaxy halo (Stoehr *et al* 2003)

(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)



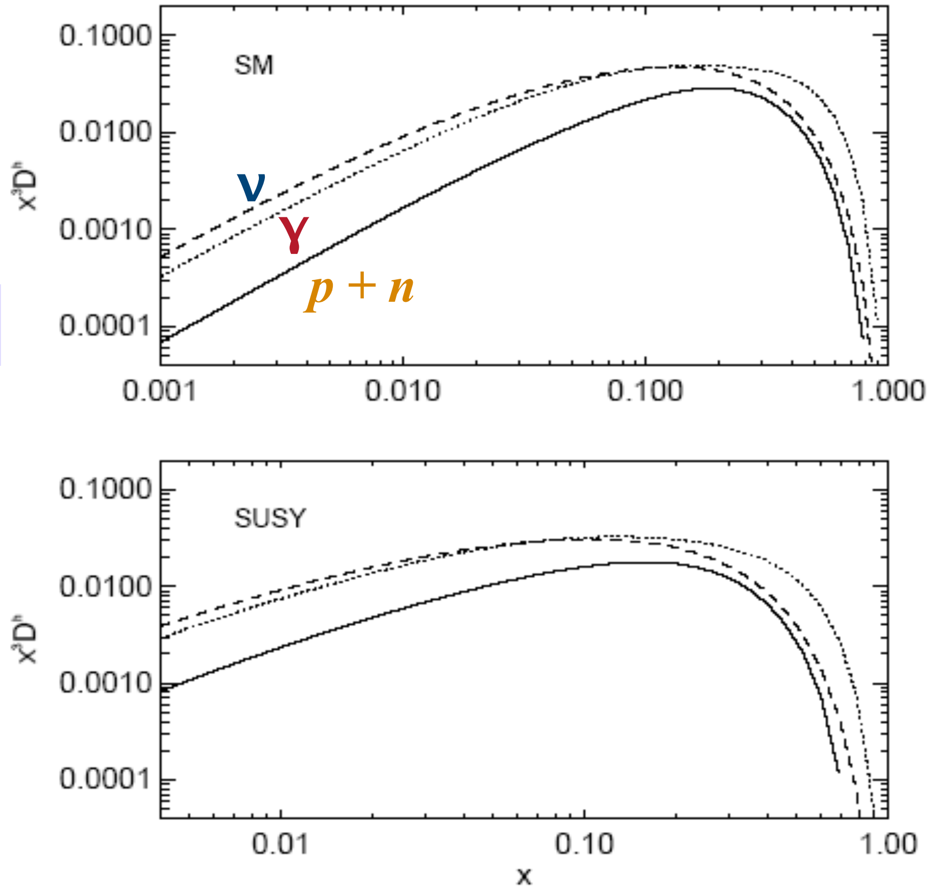


FIG. 6. Fragmentation functions for baryons (solid lines), photons (dotted lines) and neutrinos (dashed lines) evolved from M_Z up to $M_X = 10^{12}$ GeV for the SM (top panel) and for SUSY with $M_{\rm SUSY} = 400$ GeV (bottom panel).

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

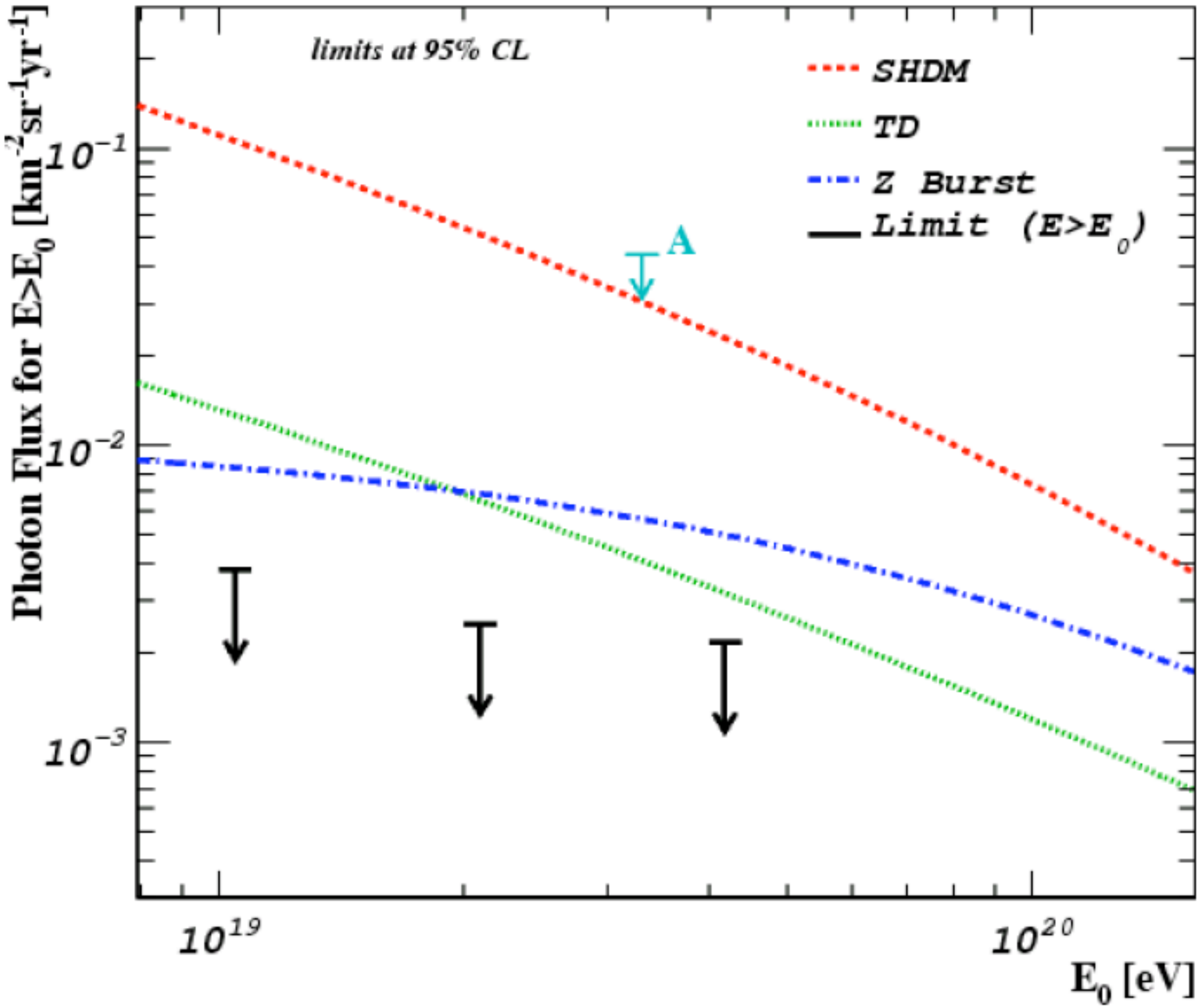
The fragmentation spectrum shape *matches* the AGASA data at trans-GZK energies … but *bad* fit to Auger

(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 all ‘top down’ models of their origin

[arXiv:0712.1147]



The "guaranteed" cosmogenic neutrino flux

GZK mechanism :

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

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

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

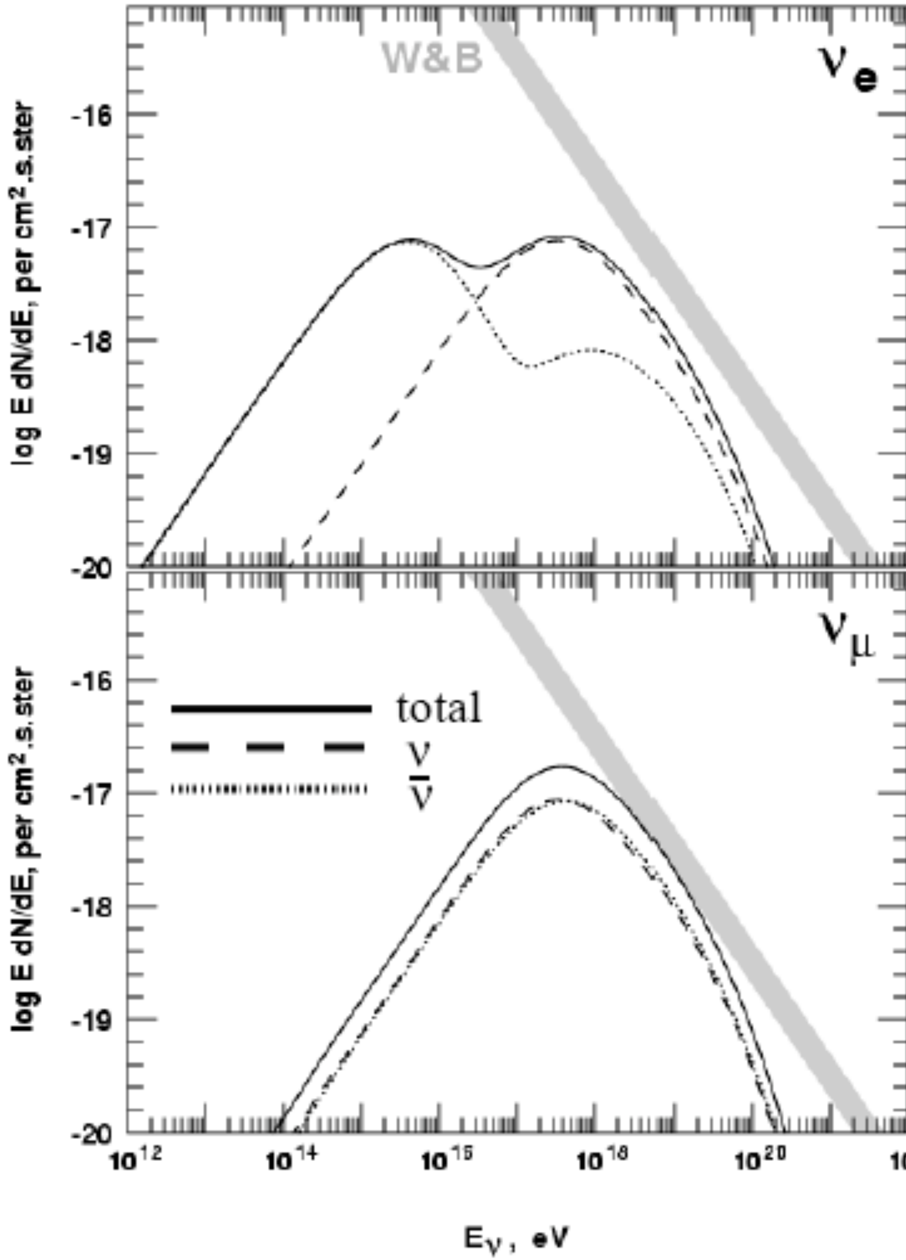
$\mu^{+} \rightarrow e^{+} + \nu_e + \bar{\nu}_\mu$

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

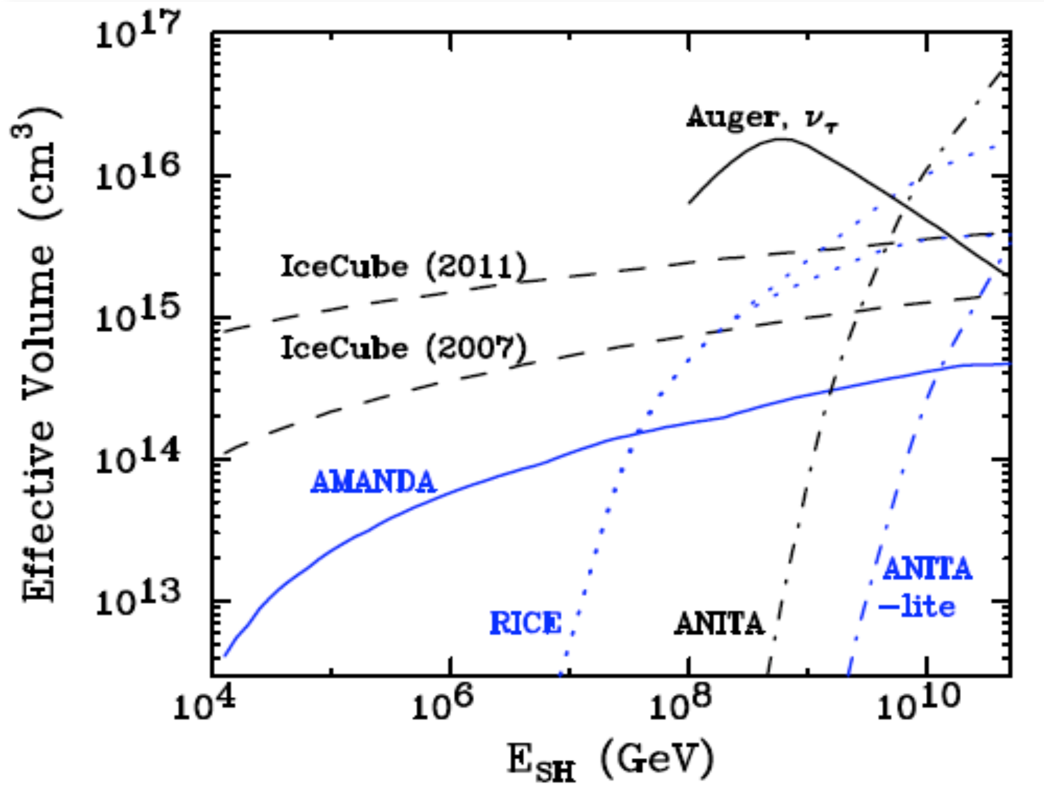
factors of ~2 uncertainty each;
factor of ~4 overall (?)

Engel, Seckel, Stanev (2001)



(Courtesey: David 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 [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

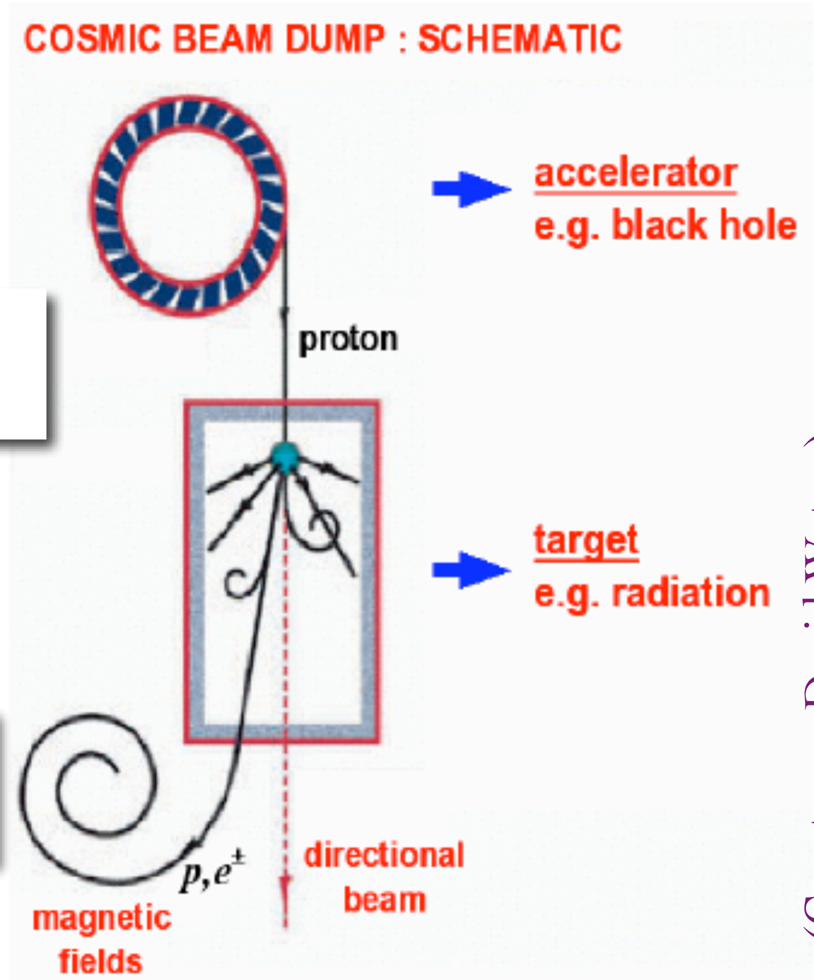
Hubble time

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

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

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

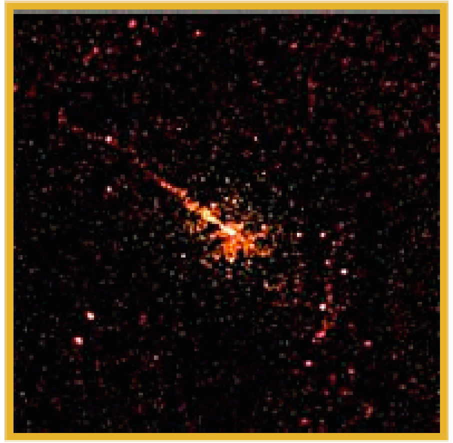
(would be higher if extragalactic cosmic rays become dominant at energies below the ‘ankle’)

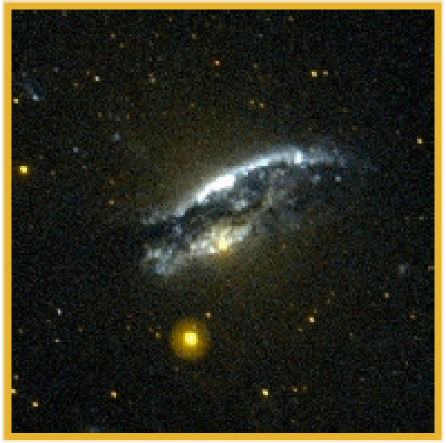


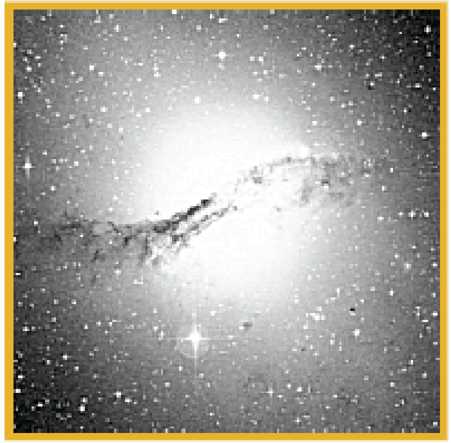
(Courtesey: David Waters)

Centaurus A – Peculiar Galaxy

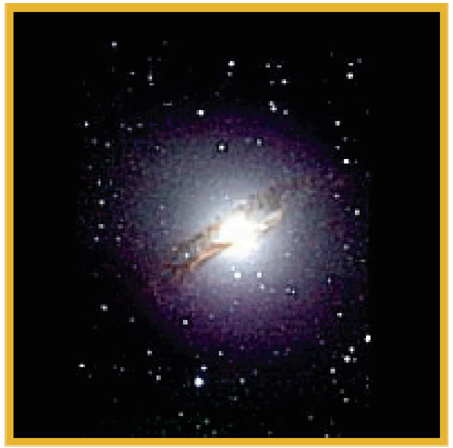
Distance: 11,000,000 ly light-years (3.4 Mpc) Image Size = 15 x 14 arcmin Visual Magnitude = 7.0


X-Ray: Chandra

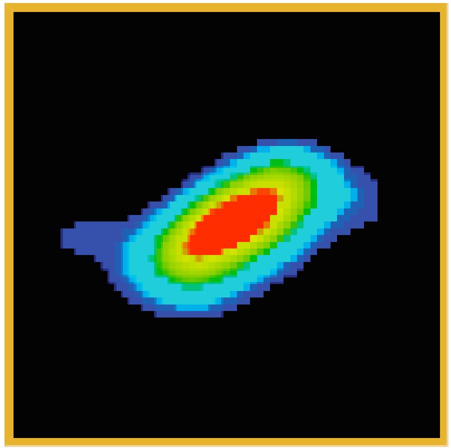

Ultraviolet: GALEX

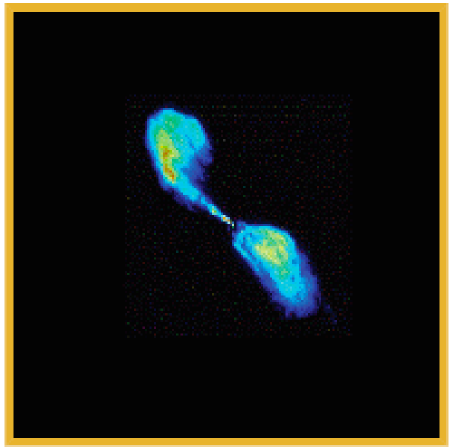

Visible: DSS


Visible: Color ©AAO


Near-Infrared: 2MASS


Mid-Infrared: Spitzer


Far-Infrared: IRAS

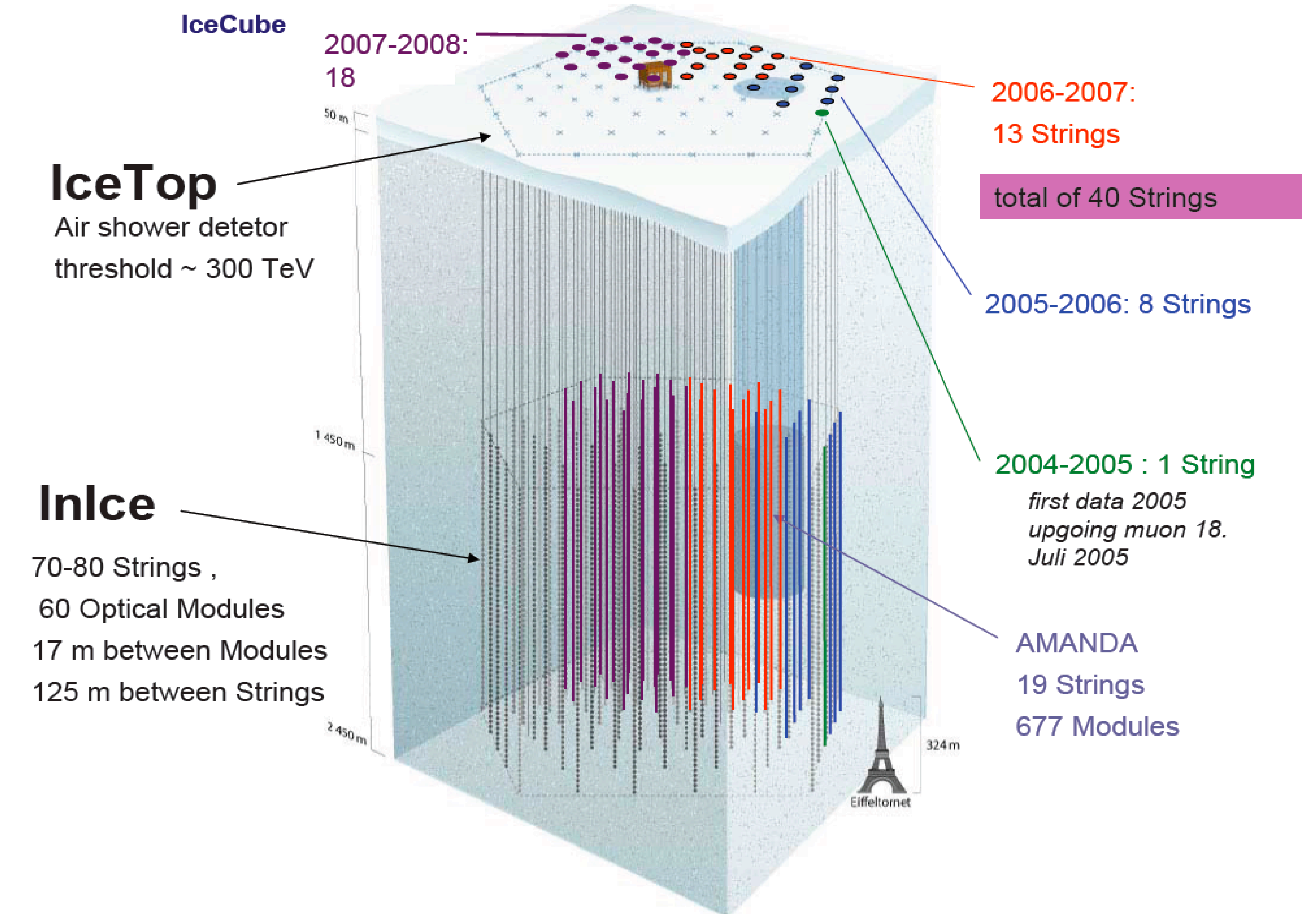

Radio: VLA

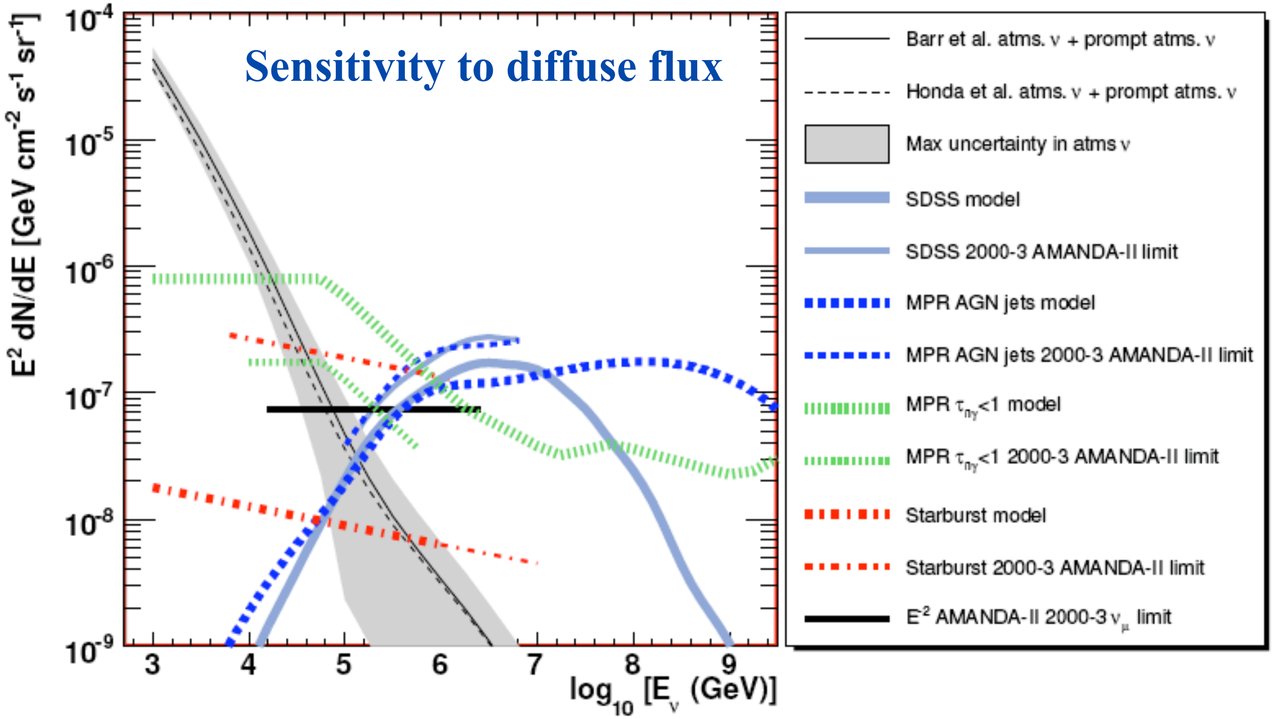
Estimate of ν flux from *p-p*:

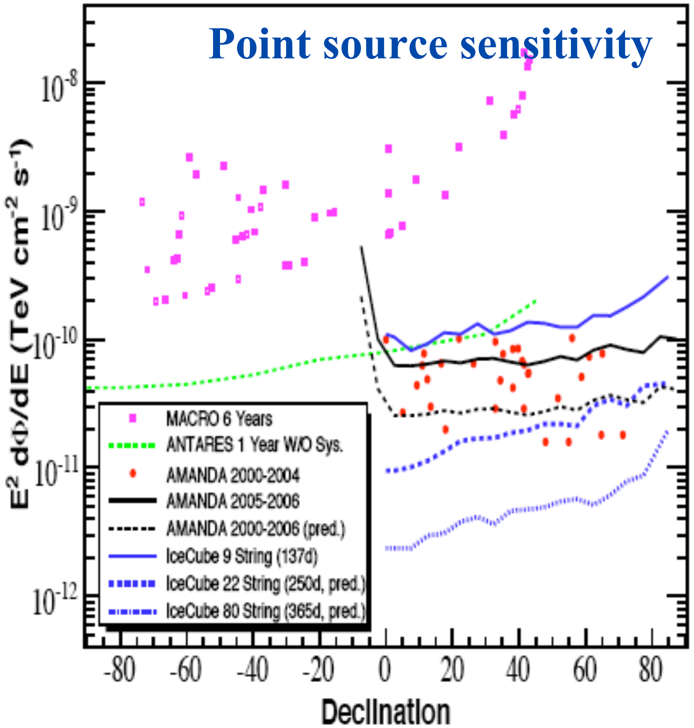
$$\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-2} \text{TeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}$$

⇒0.02-0.8 events/km^2 yr

Halzen & Murchadha [arXiv:0802.0887]

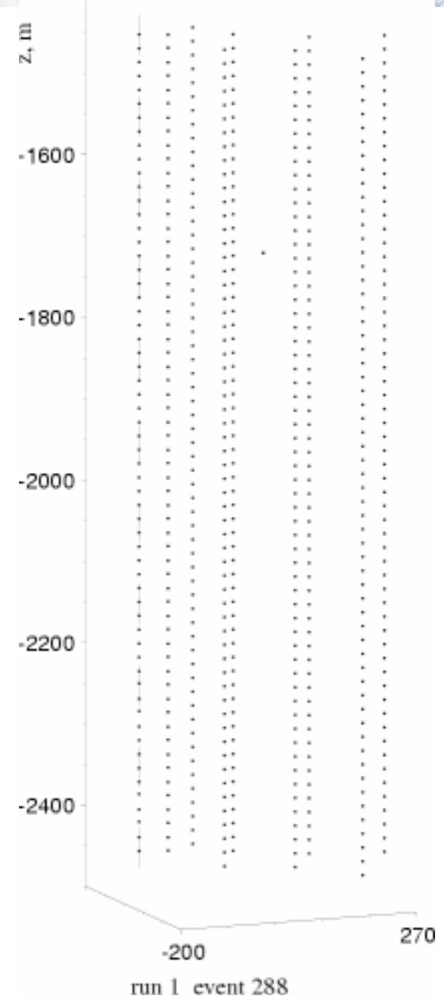

IceCube
2007-2008: 18
2006-2007: 13 Strings
total of 40 Strings
IceTop
Air shower detetor
threshold ~ 300 TeV
2005-2006: 8 Strings
2004-2005 : 1 String
first data 2005
upgoing muon 18. Juli 2005
InIce
70-80 Strings ,
60 Optical Modules
17 m between Modules
125 m between Strings
AMANDA
19 Strings
677 Modules
50 m
1 450 m
2 450 m
324 m
Eiffeltornet



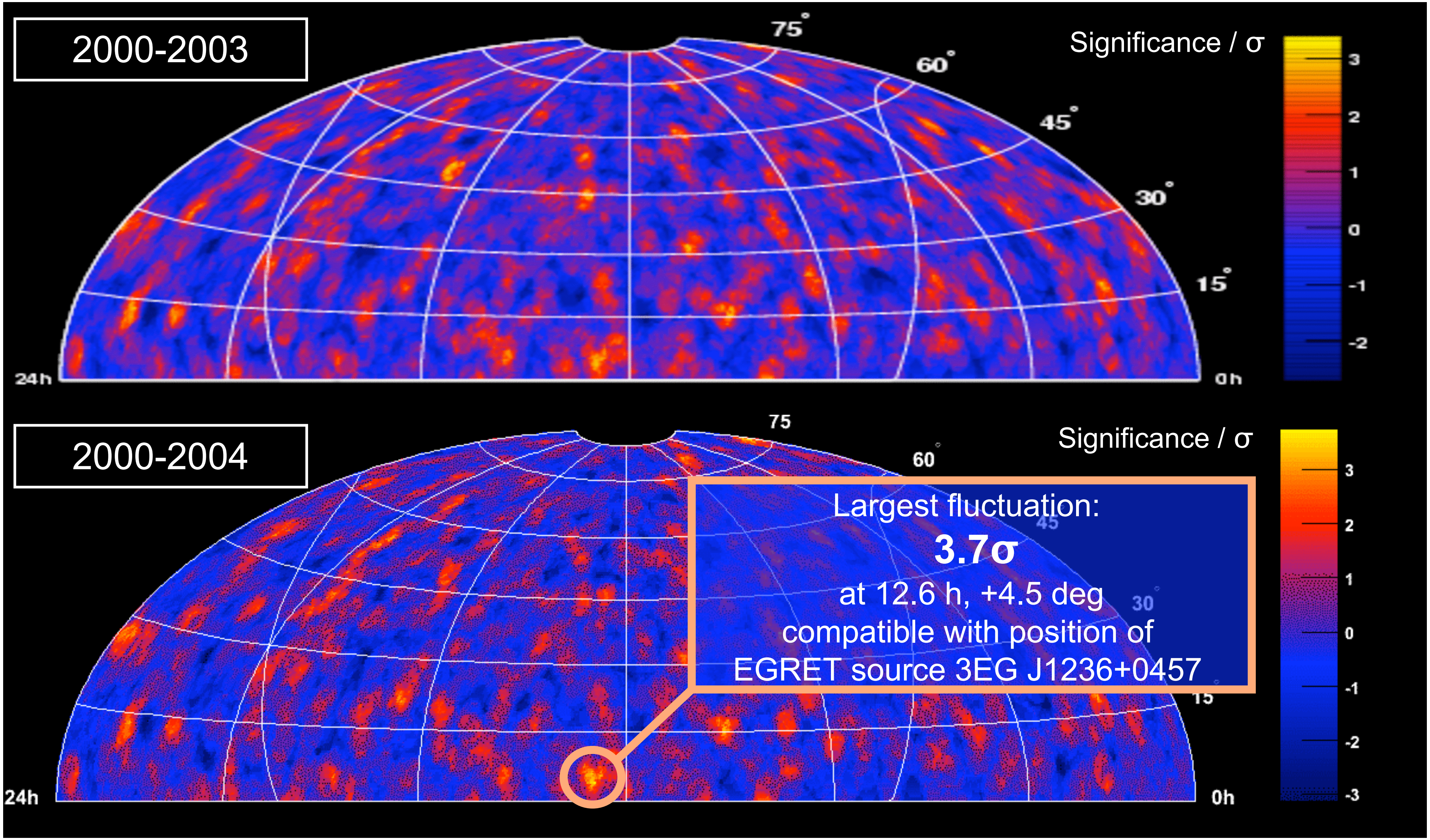


Km-scale ν detection is *already* happening at the South Pole

begining to constrain optimistic models of AGN, GRB … also looking for coincidences with TeV γ-ray flares

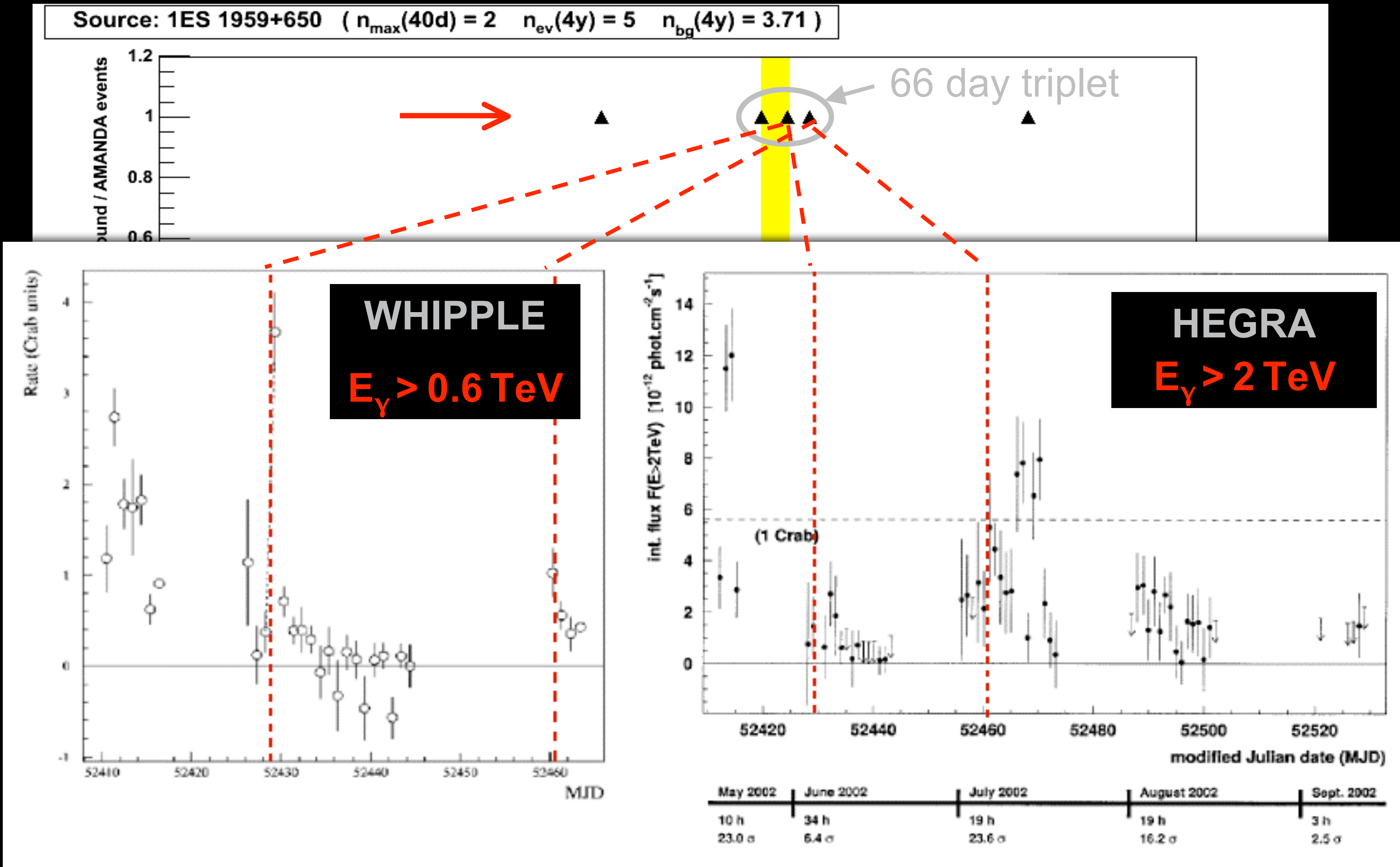


AMANDA search for point sources of TeV-PeV neutrinos

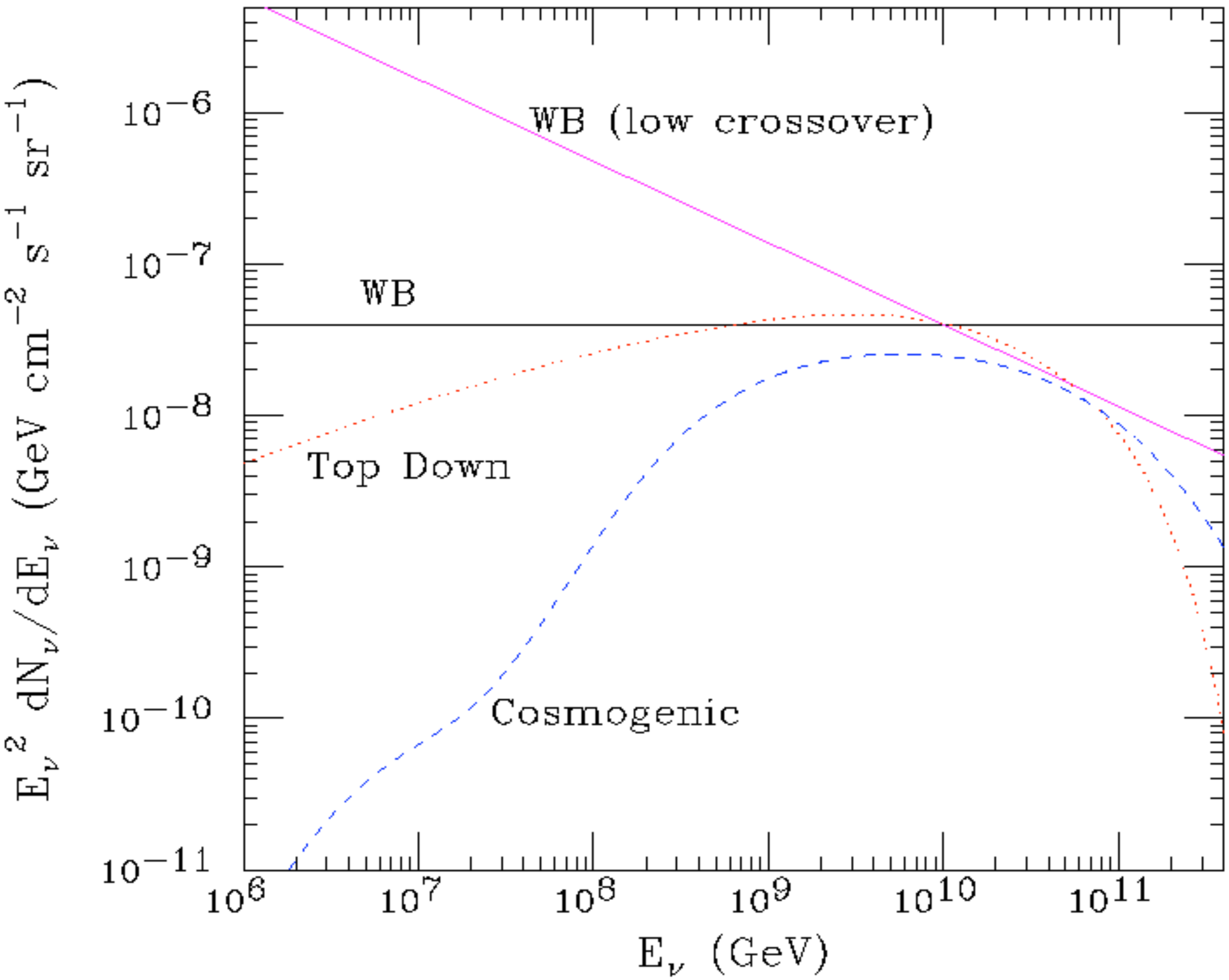


But 69 out of 100 randomised sky maps show a higher excess!

AMANDA events coincident with 'orphan flare' in 1ES1959+650 !



Plausible UHE cosmic neutrino fluxes

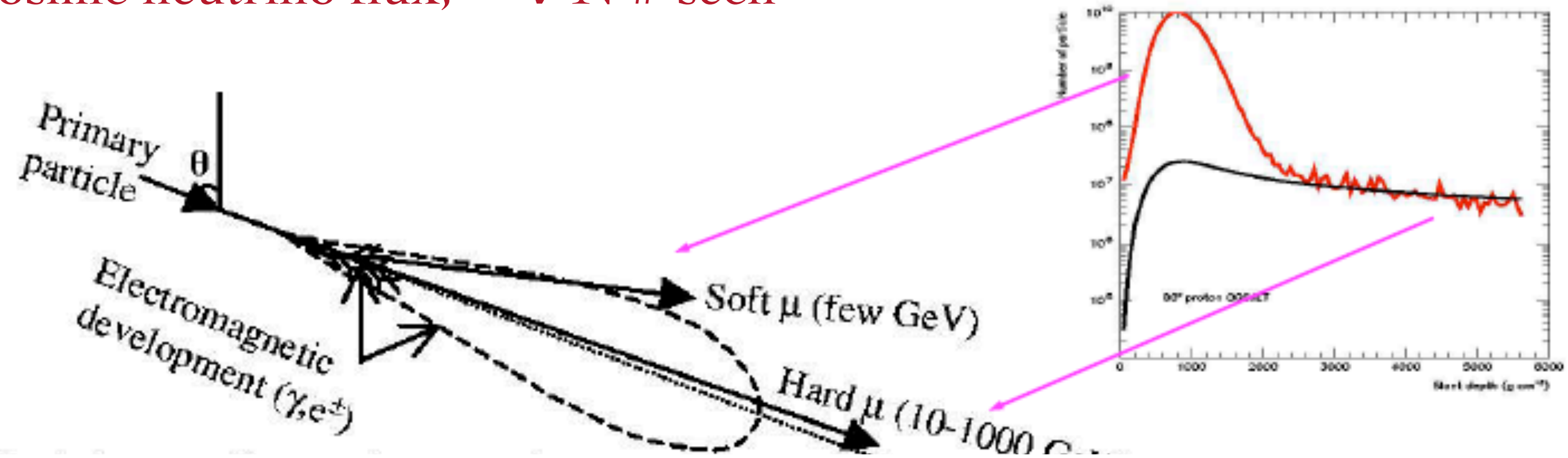


WB flux is enhanced in models where extragalactic sources are assumed to dominate from as low as ~10^{18} eV (Ahlers *et al* 2005) …nearly ruled out already by AMANDA

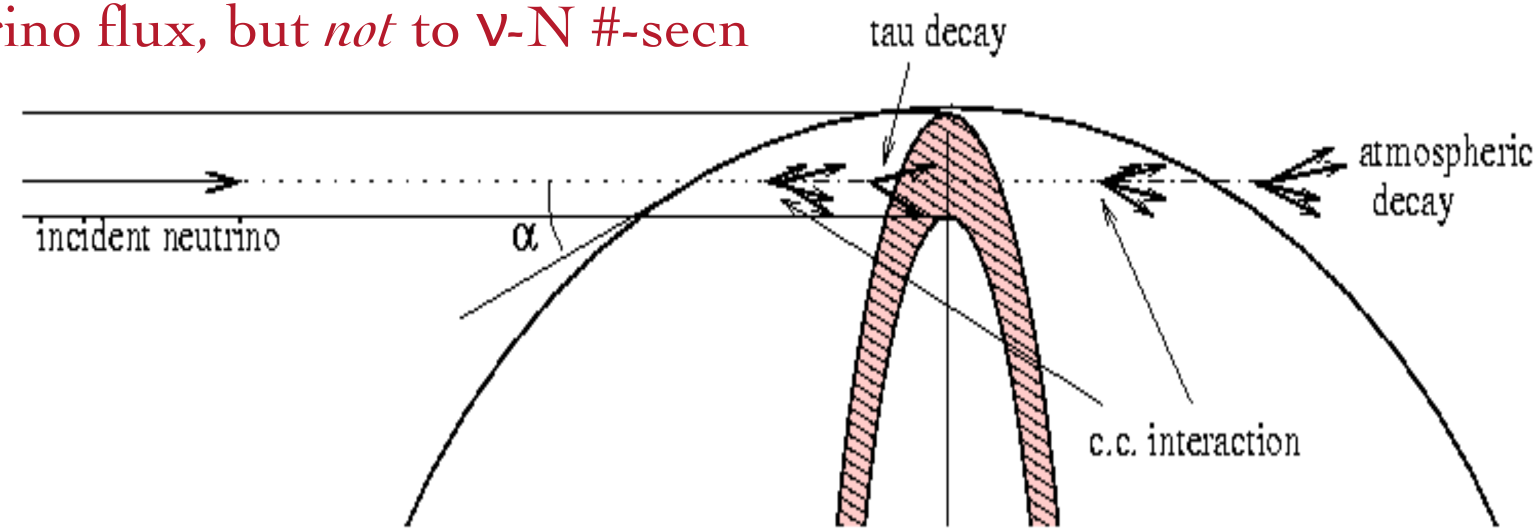
To see cosmic νs may require >100 km³ detection volume (ANITA, IceRay…)

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

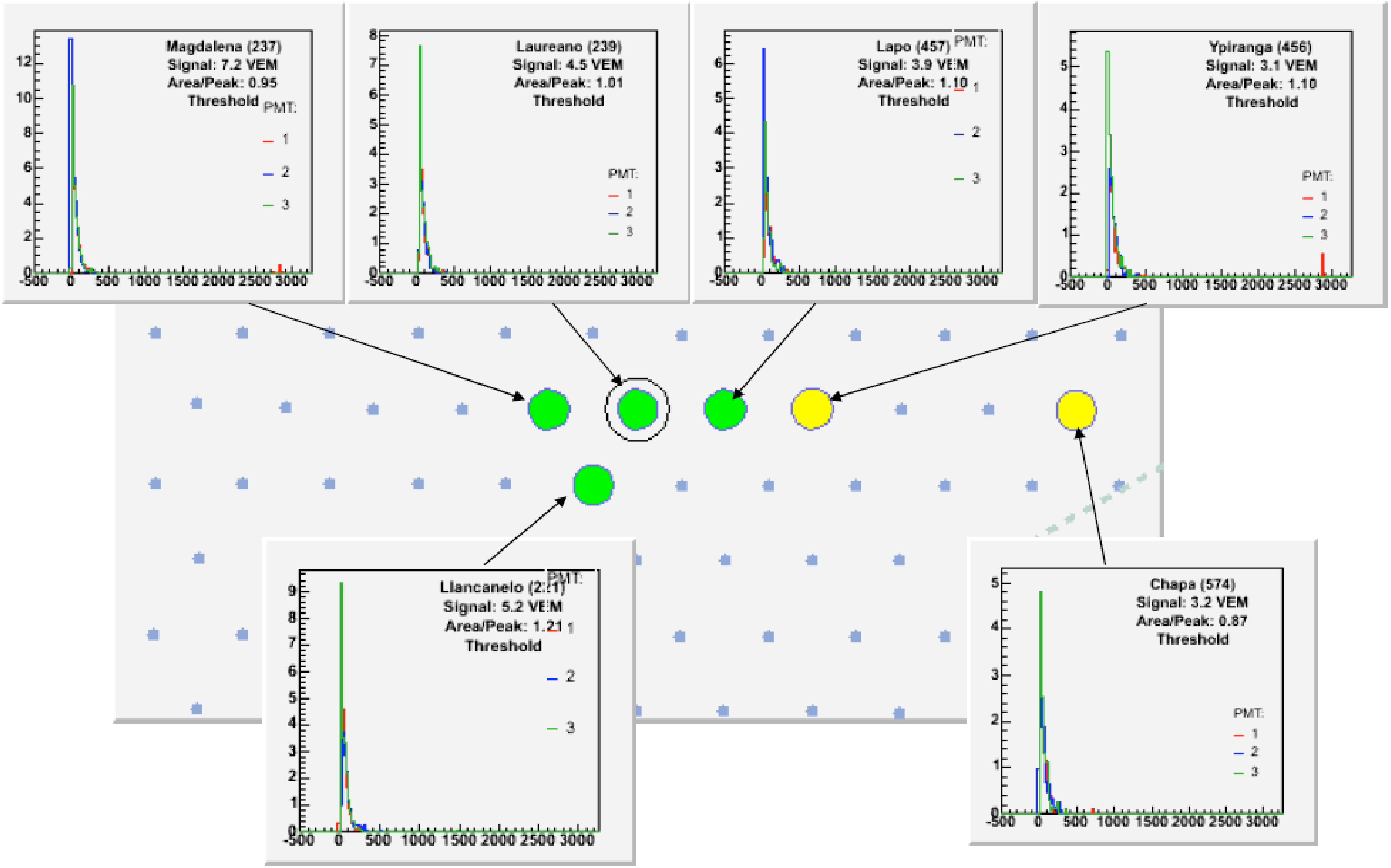


Auger can also see Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower
Rate ∝ cosmic neutrino flux, but *not* to ν-N #-secn

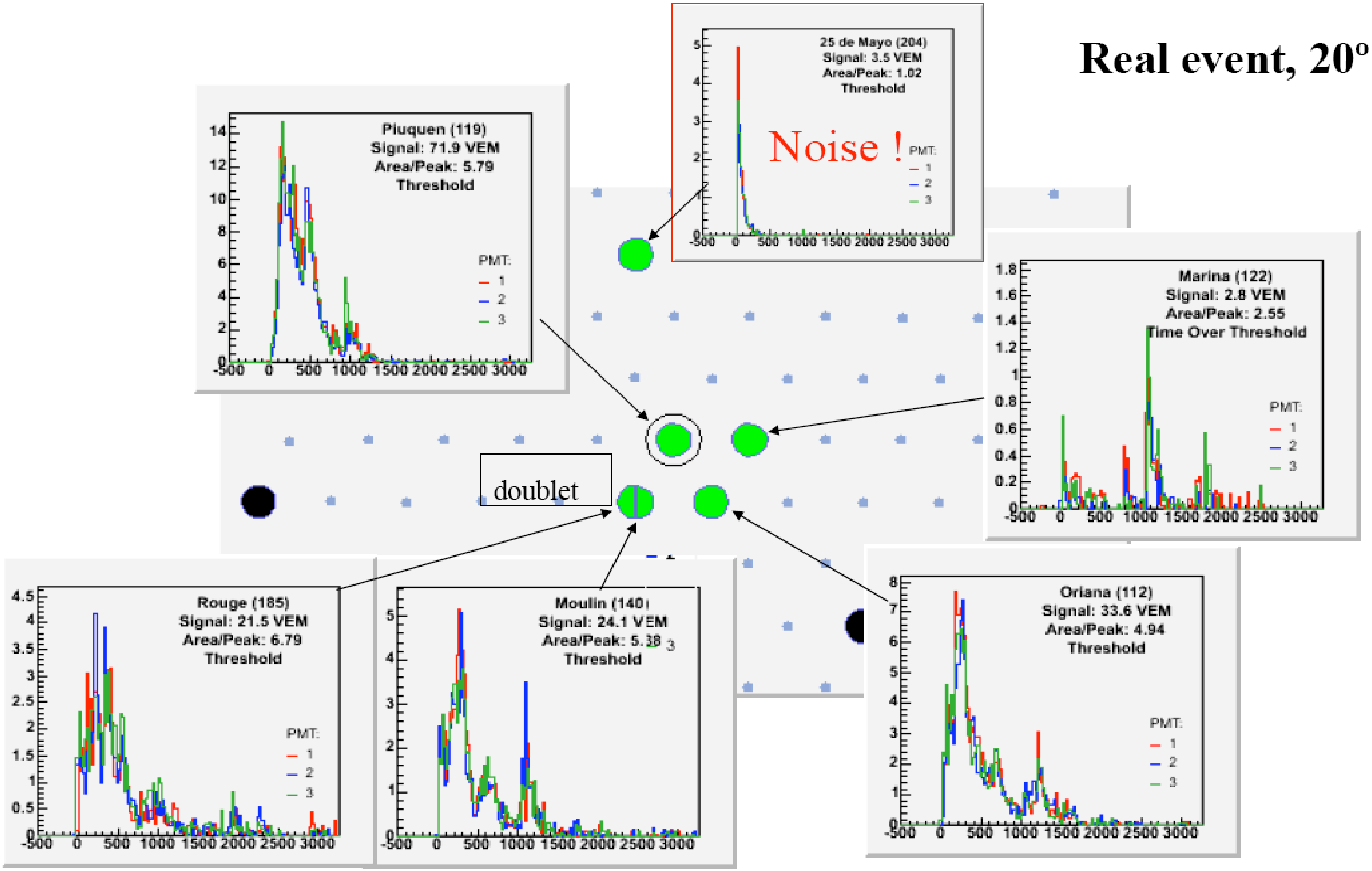


INCLINED EVENT

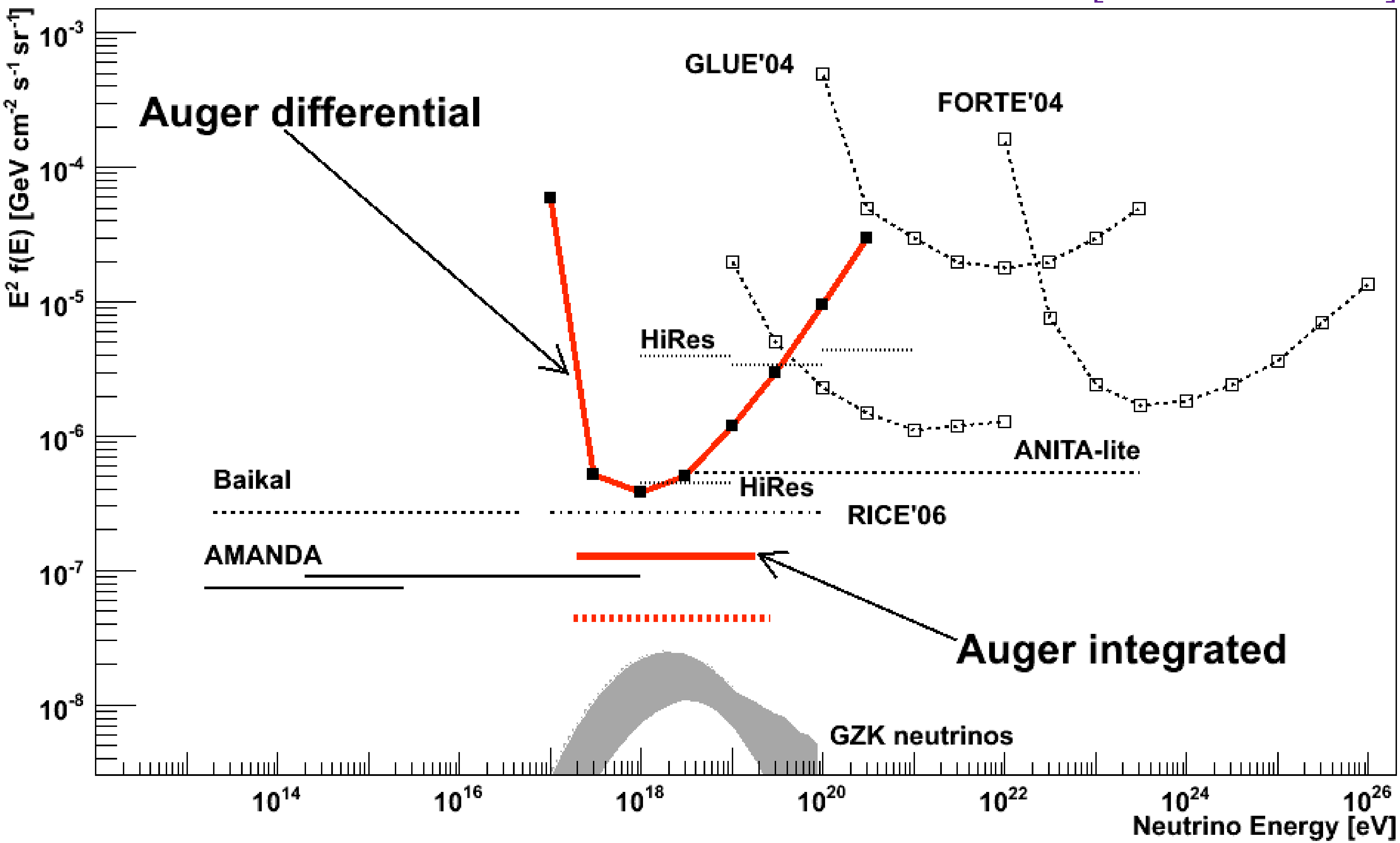
Real event, 80°



VERTICAL EVENT



No neutrino events yet … but getting close to "guaranteed" cosmogenic flux
[arXiv:0712.1909]

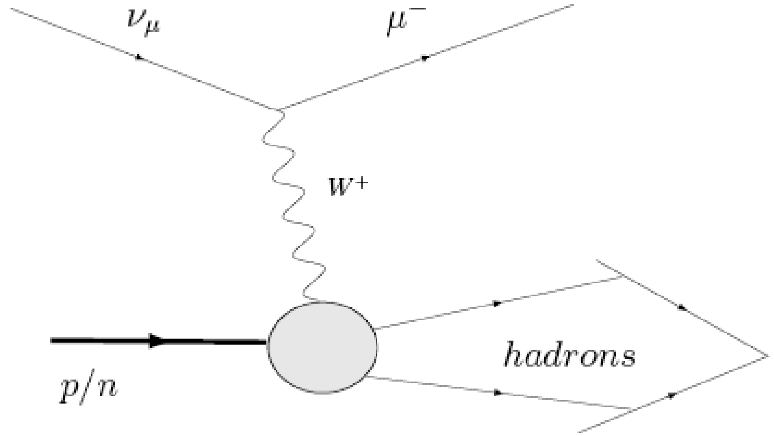


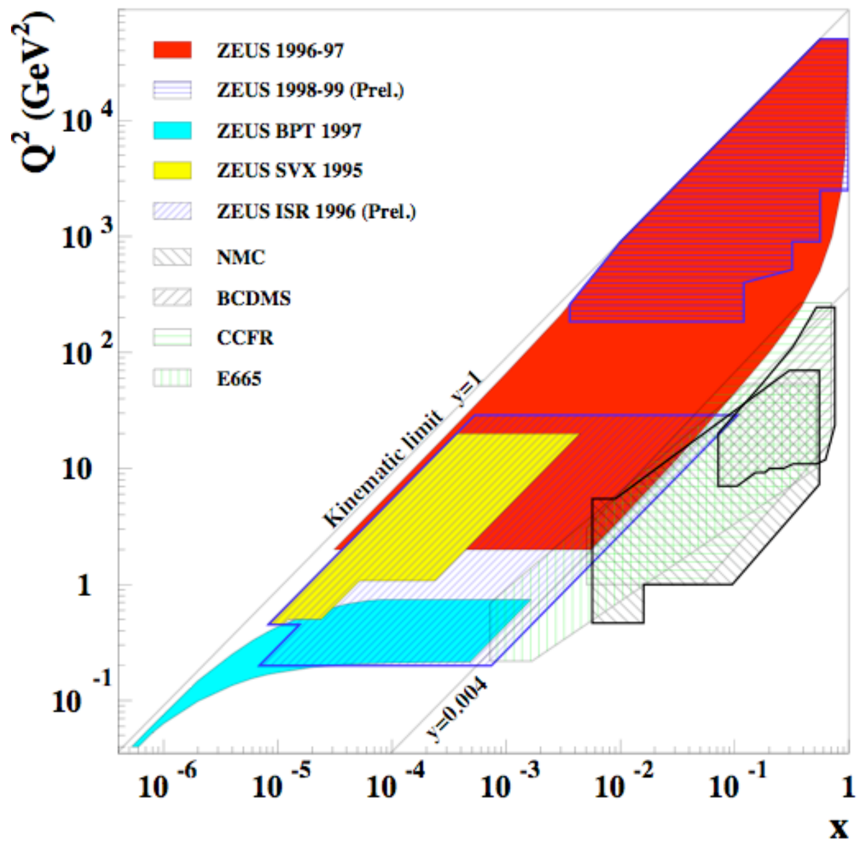
(NB: To do this we must know ν-N cross-section at ultrahigh energies)

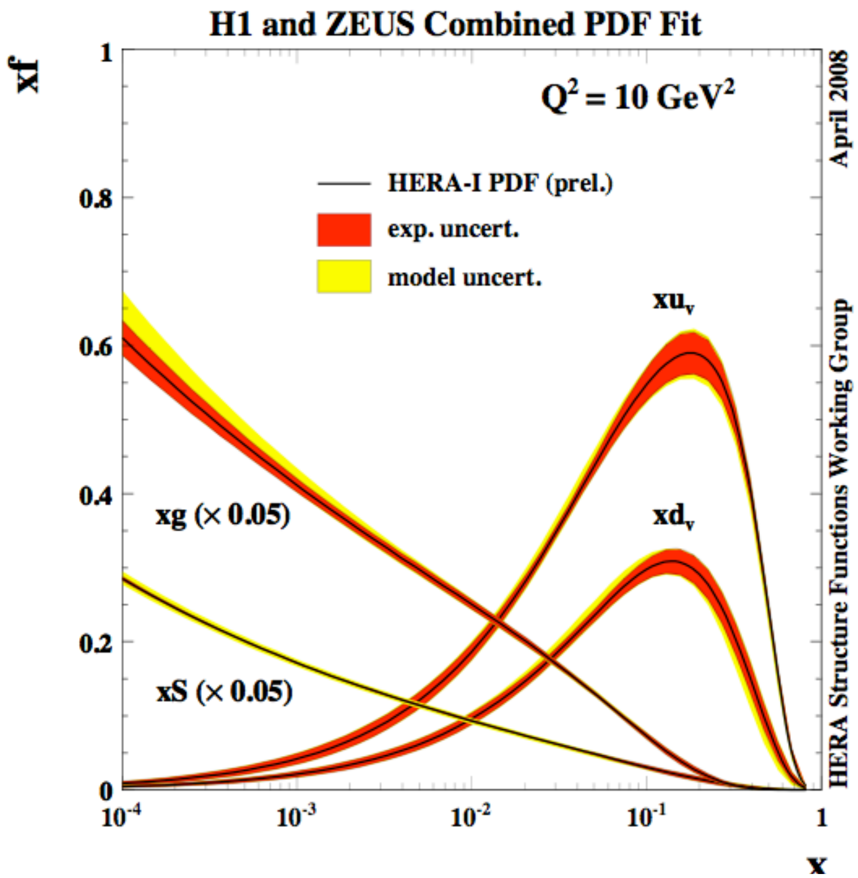
ν-*N* deep inelastic scattering

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

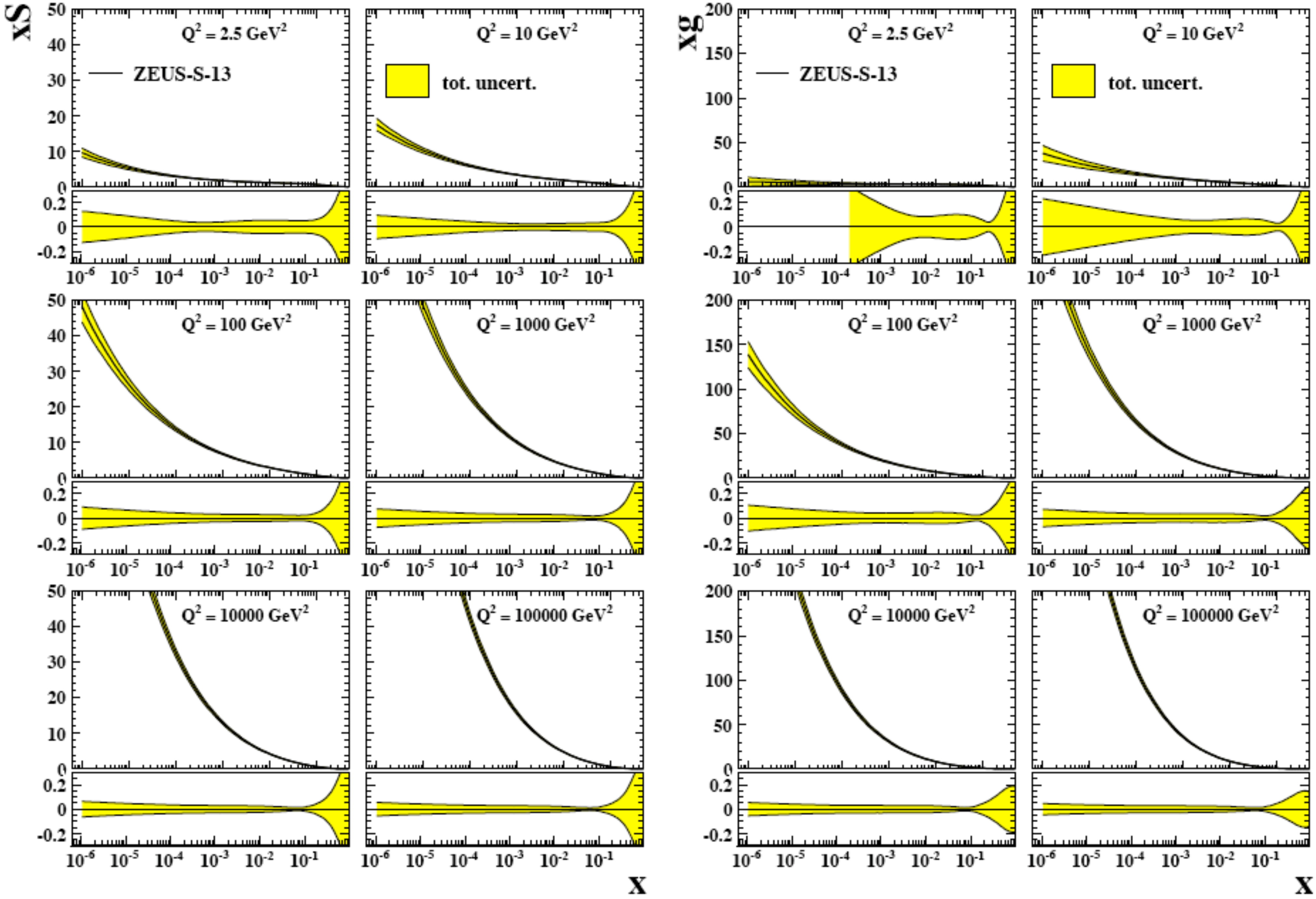
$$\left[\frac{1+(1-y)^2}{2} F_2^{CC,NC}(x, Q^2) - \frac{y^2}{2} F_L^{CC,NC}(x, Q^2) \pm y \left(1 - \frac{y}{2}\right) x F_3^{CC,NC}(x, Q^2)\right]$$







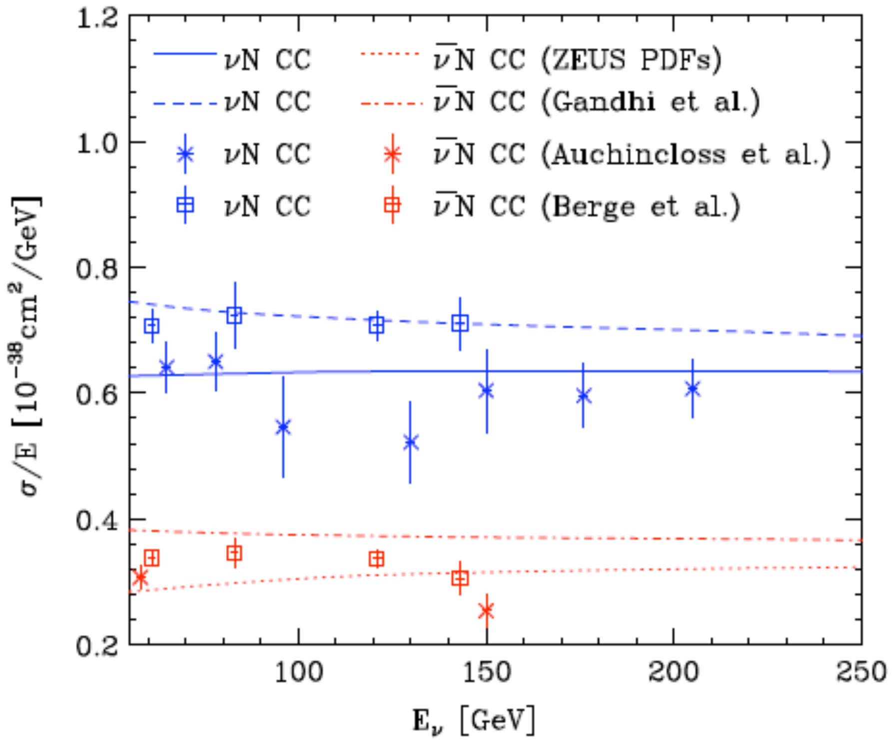
Parton distribution functions from the ZEUS-S global data analysis

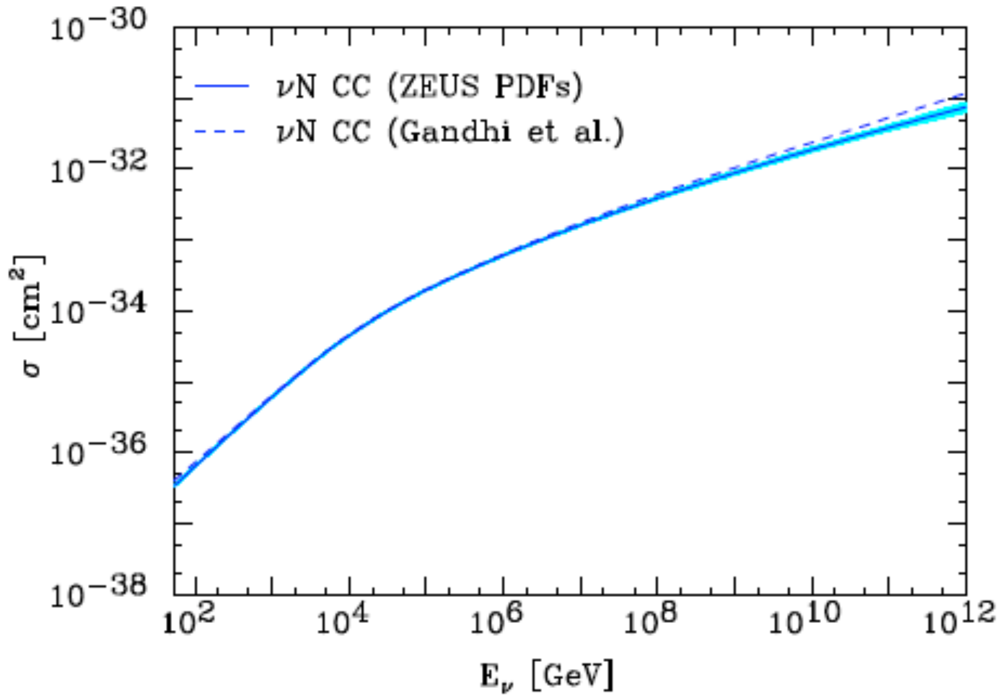


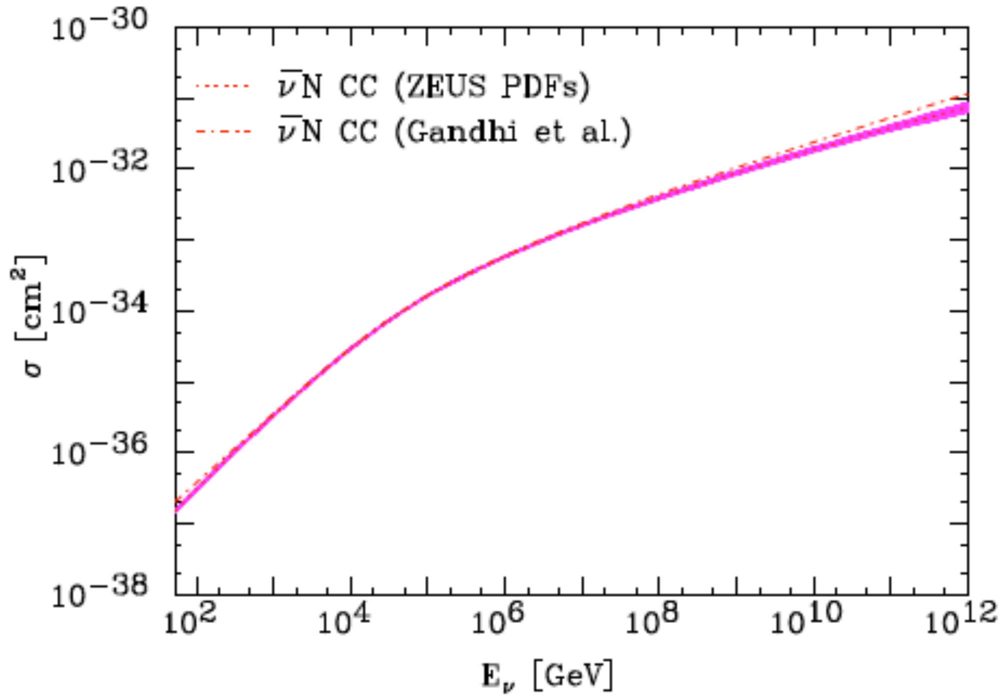
Deep inelastic e-p scattering has probed down to very low x and very high Q^2 values relevant for predicting the UHE neutrino cross-section in the SM … using DGLAP evolution of the PDFs (at NLO, incl. heavy quark corrections)

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

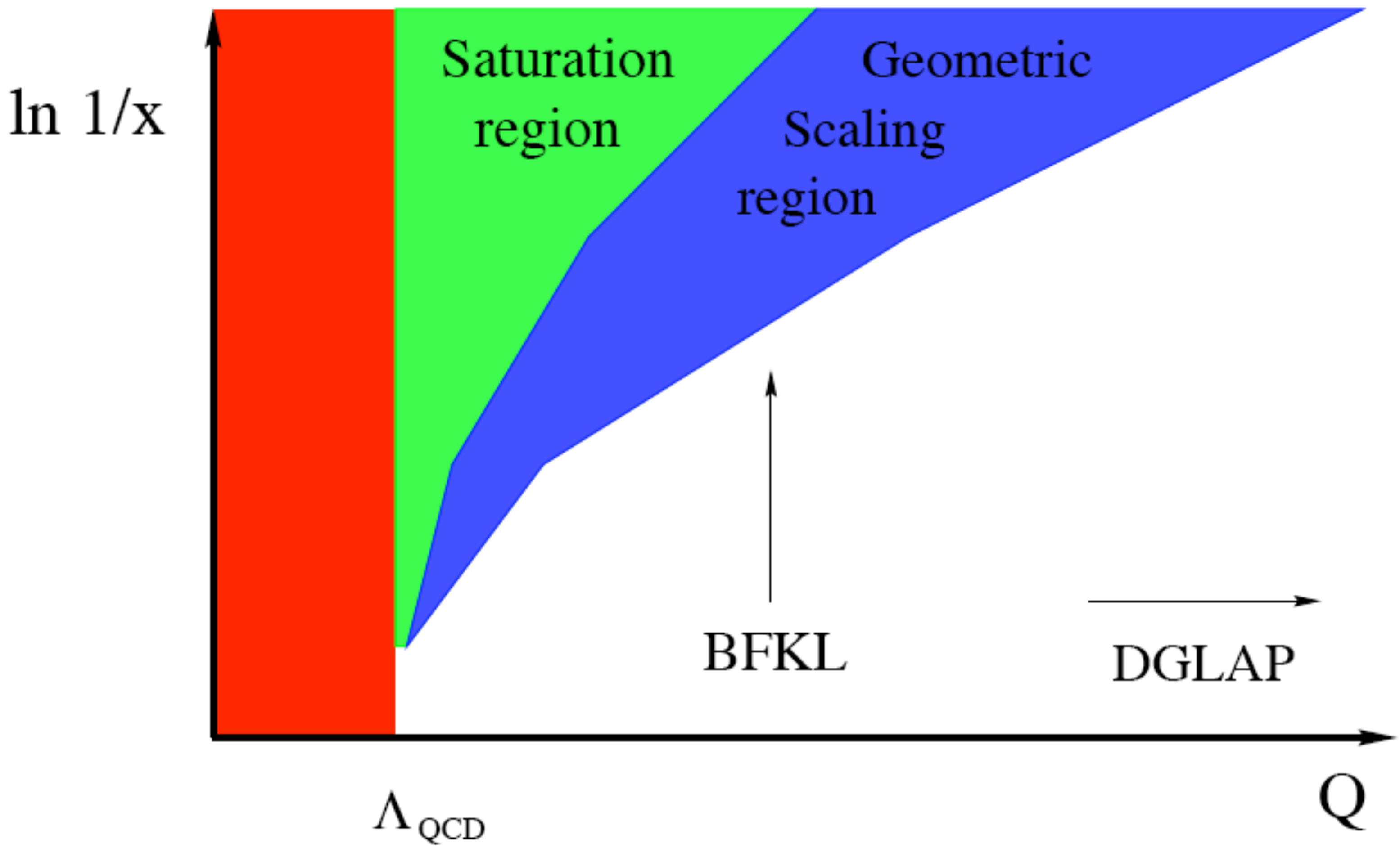
Cooper-Sarkar & Sarkar [arXiv:0710.5303]







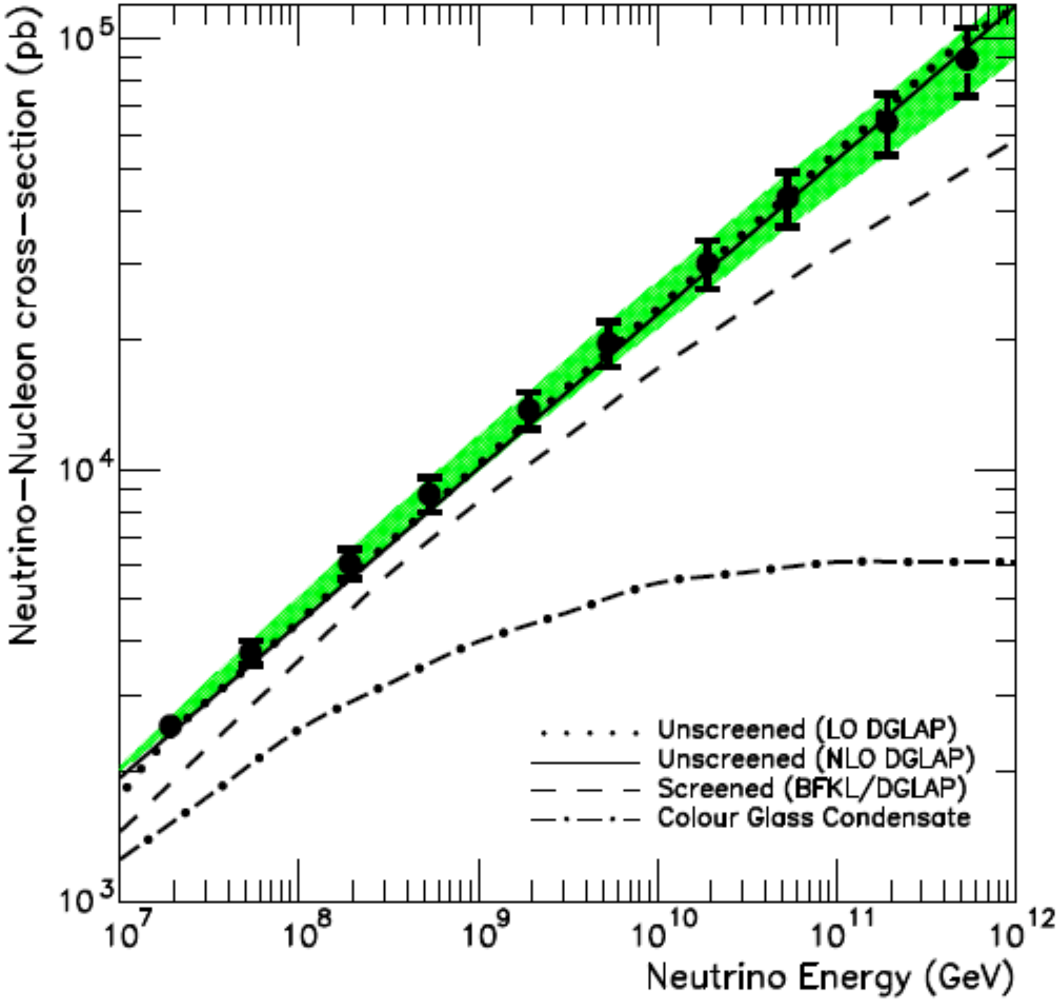
As the gluon density rises at low x, non-perturbative effects become important … a new phase of QCD - Colour Gluon Condensate - has been postulated to form

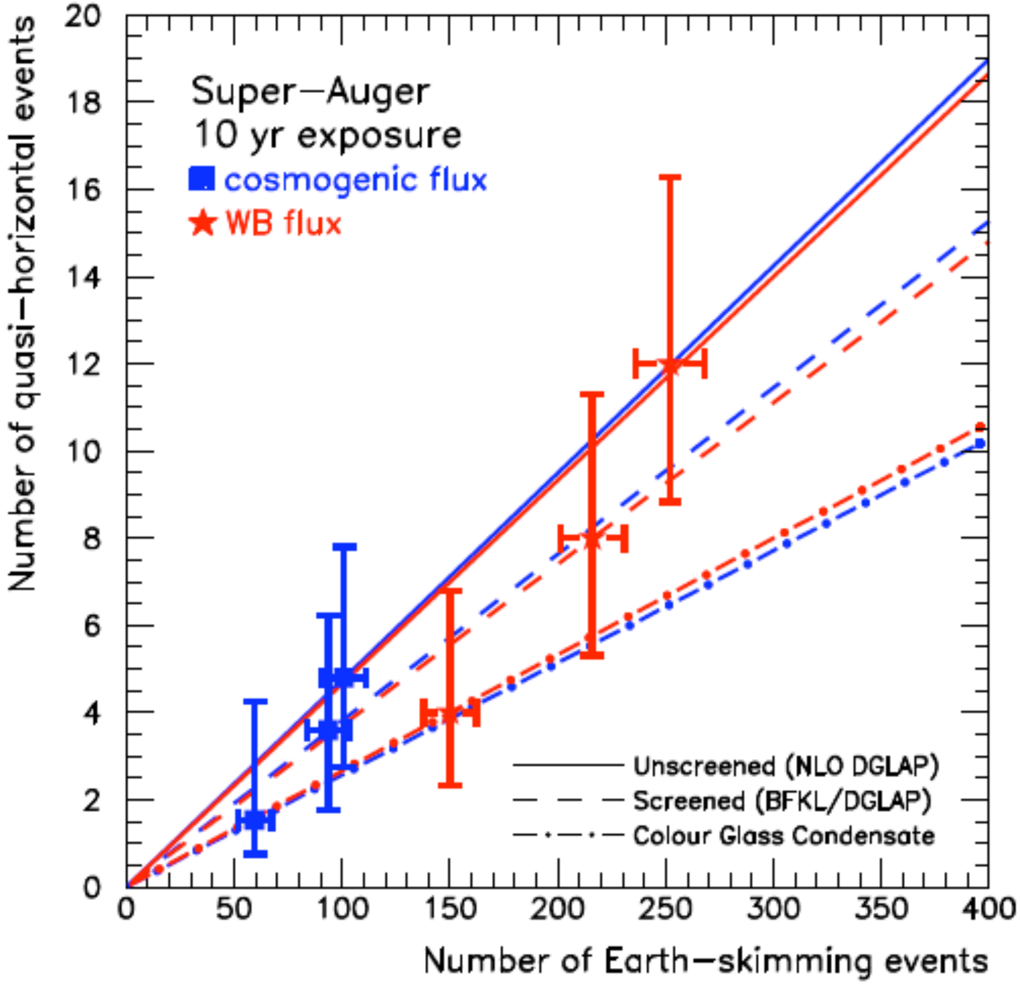


This would *suppress* the ν-N #-secn below its (unscreened) SM value

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

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





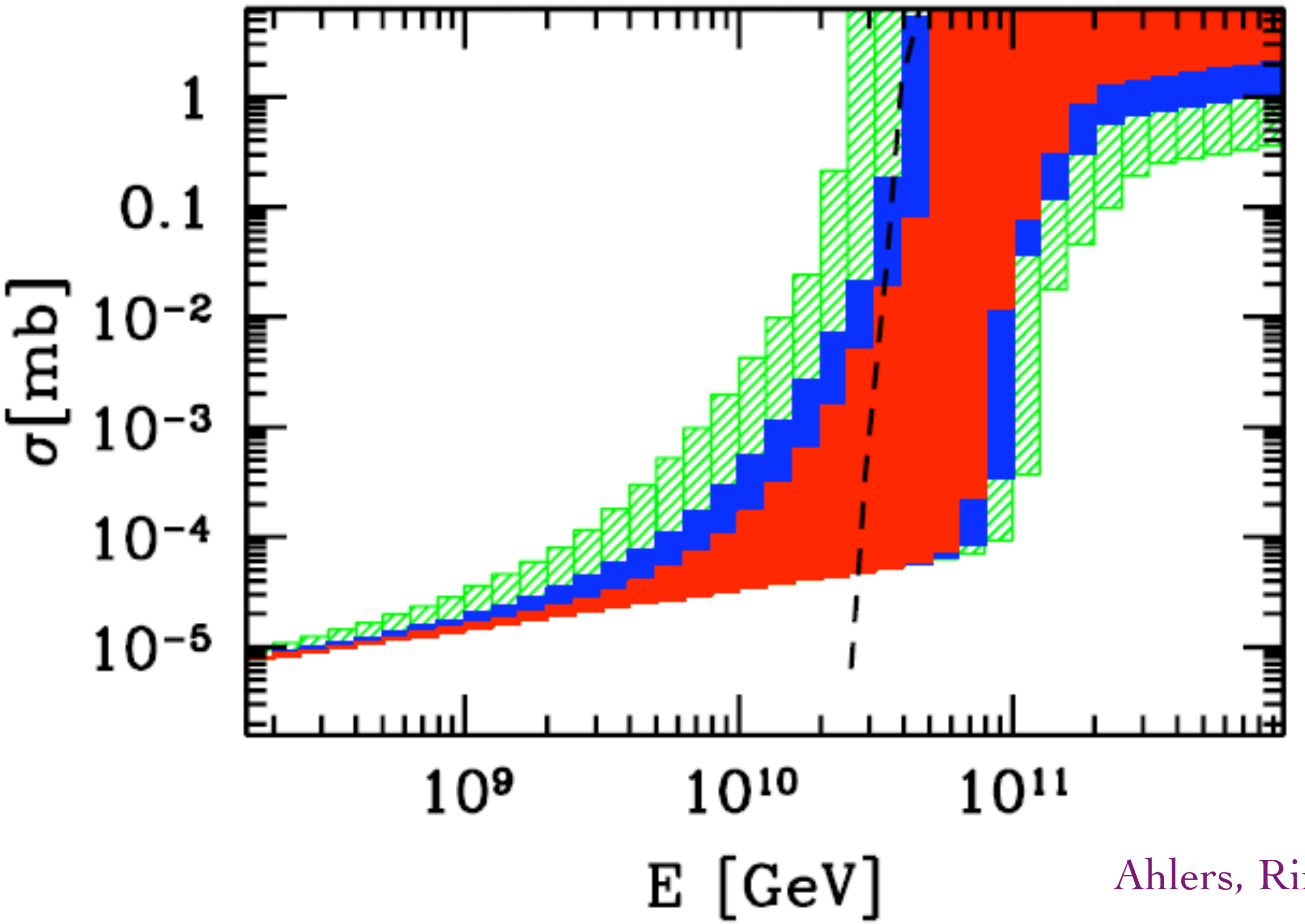
The steep rise of the gluon density at low-x must saturate (unitarity!) ⇒ suppression of the ν-N #-secn

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

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

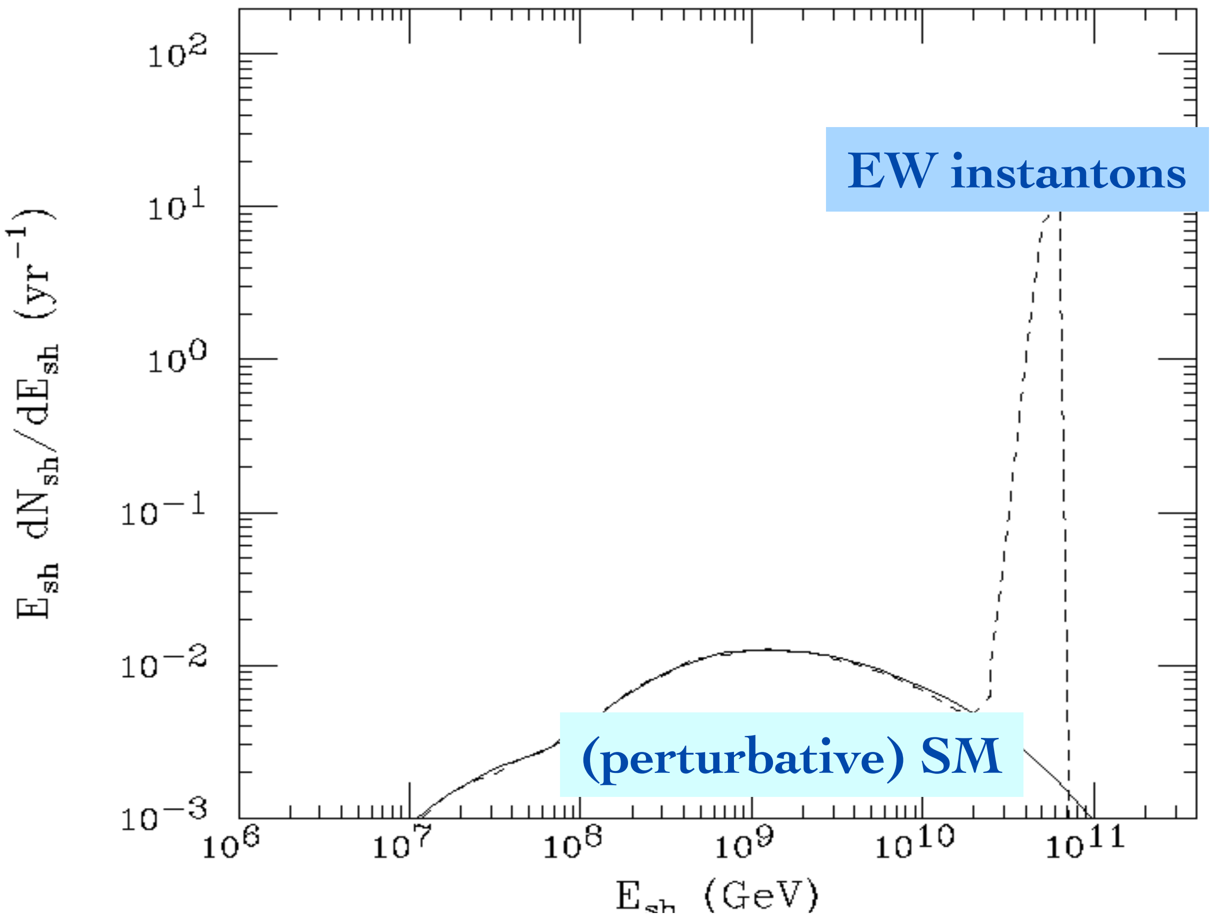
… but huge cross-sections are predicted for ν-N scattering at higher cms energies (would enable neutrinos to generate apparently hadronic super-GZK air showers)



Ahlers, Ringwald & Tu (2005)

Electroweak instantons at Auger

Quasi-horizontal ν showers (assuming cosmogenic flux)



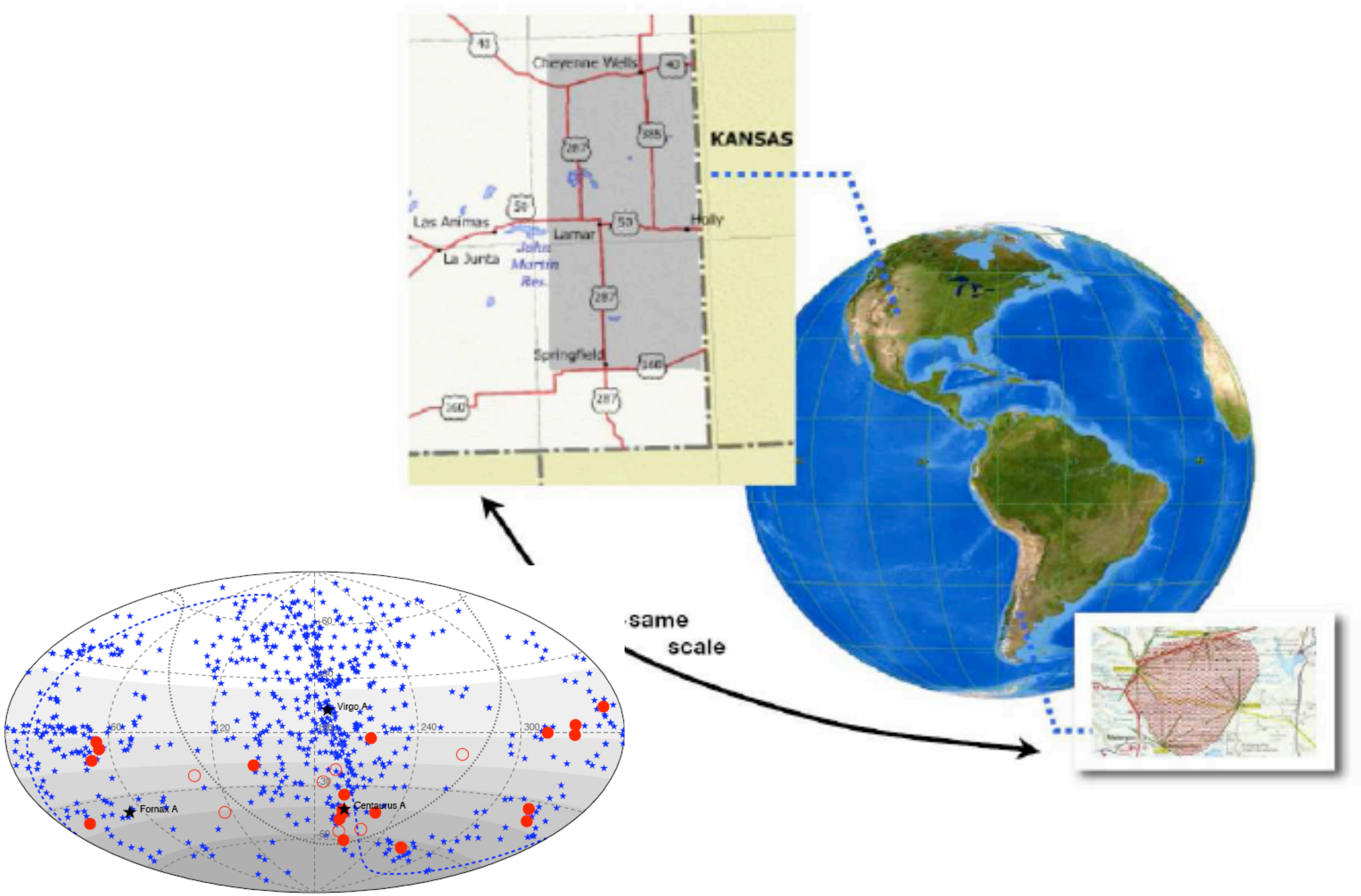
***Large* deviations from perturbative SM expected above 10^{10} GeV**

predict 4.3 QH showers/yr ⇒ probably ruled out already

Anchordoqui, Han, Hooper, Sarkar (2005)

Outlook: Auger North

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



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 testing non-perturbative QCD … complementing colliders

> *"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)