Probing new physics with ultra-high energy cosmic neutrinos

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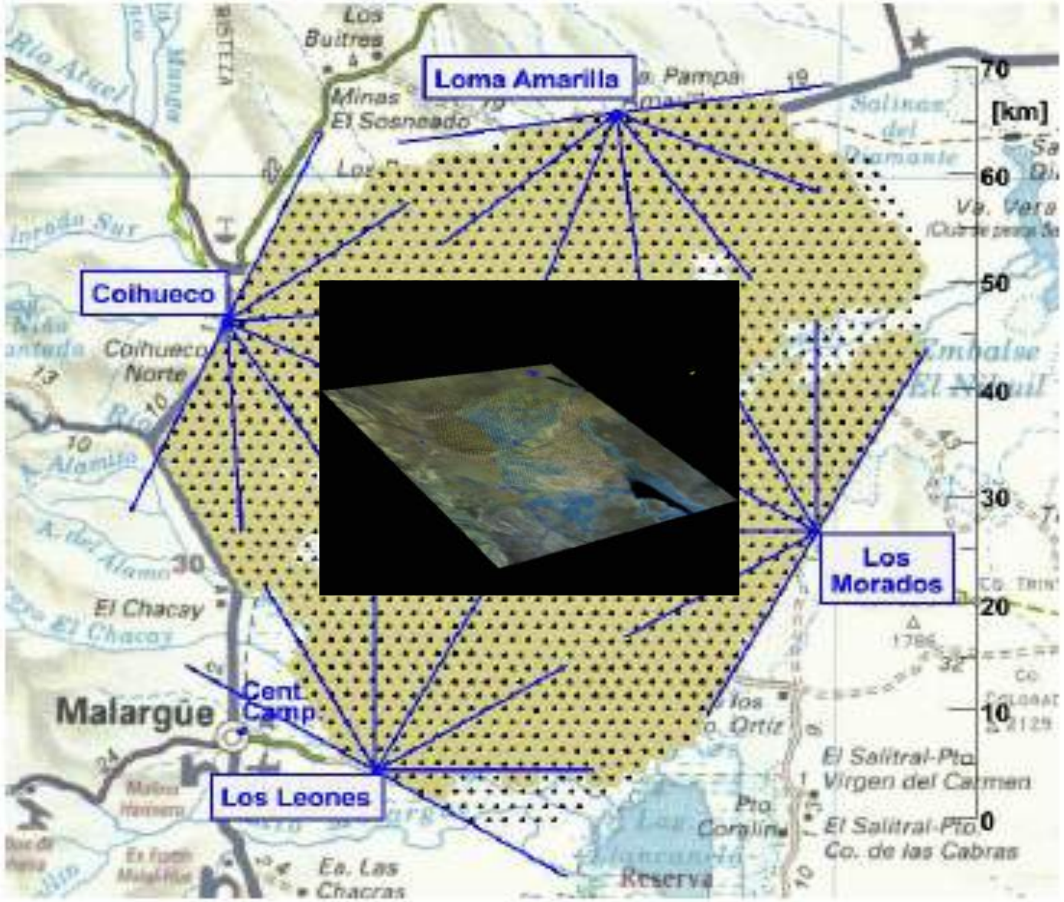
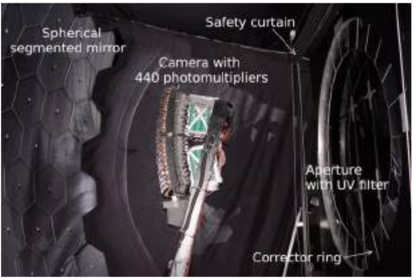
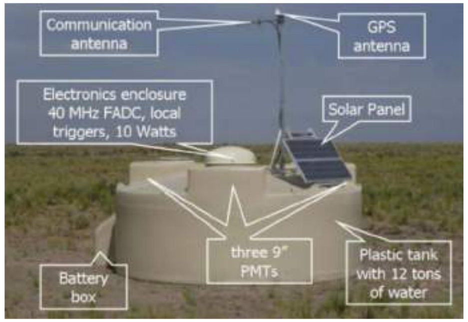
The Pierre Auger Observatory

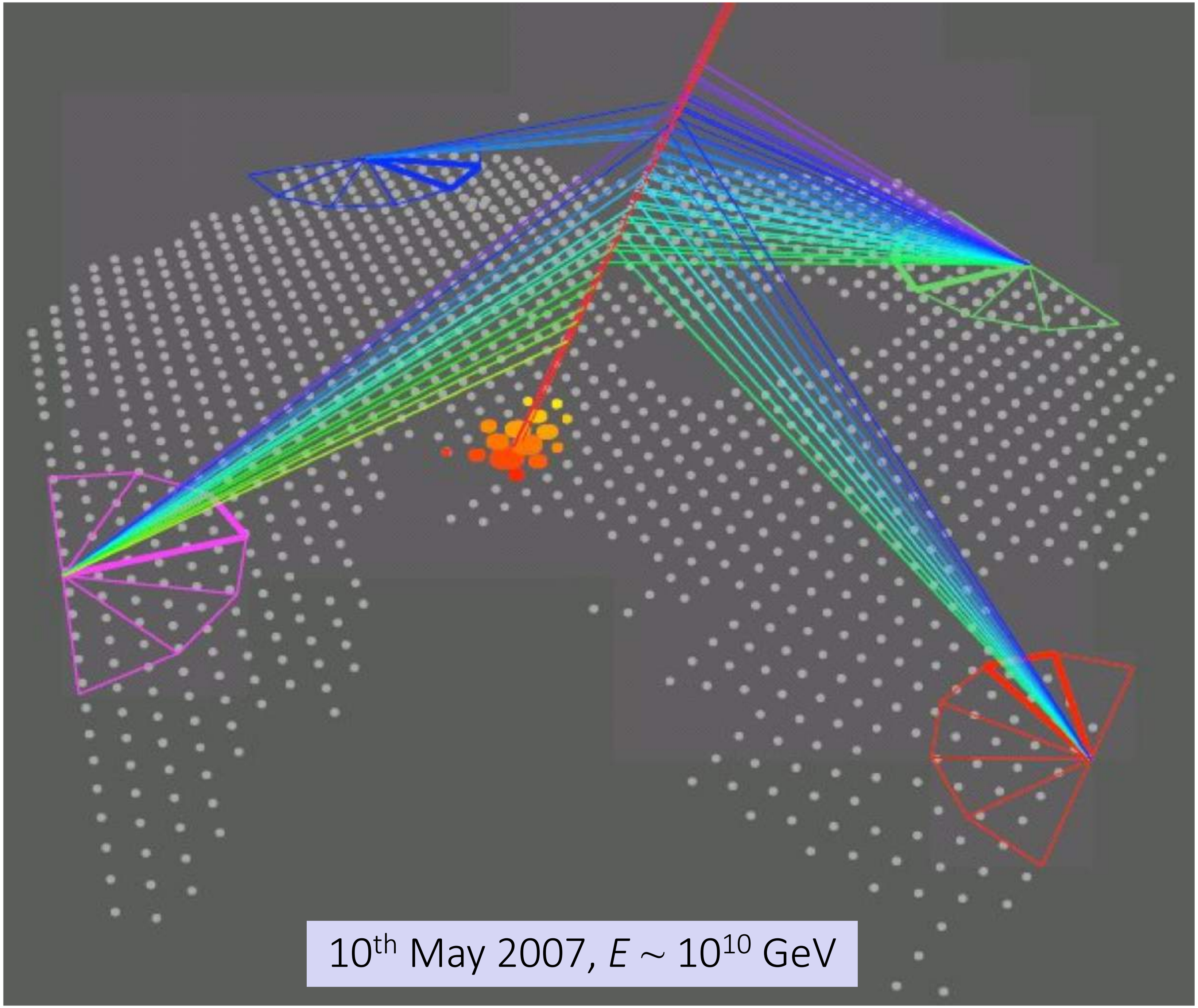




- 1600 water-cherenkov detectors
- Aperture $> \; 7000 \, \mathrm{km}^2 \, \mathrm{sr} \, \mathrm{yr}$
- 4×6 telescopes

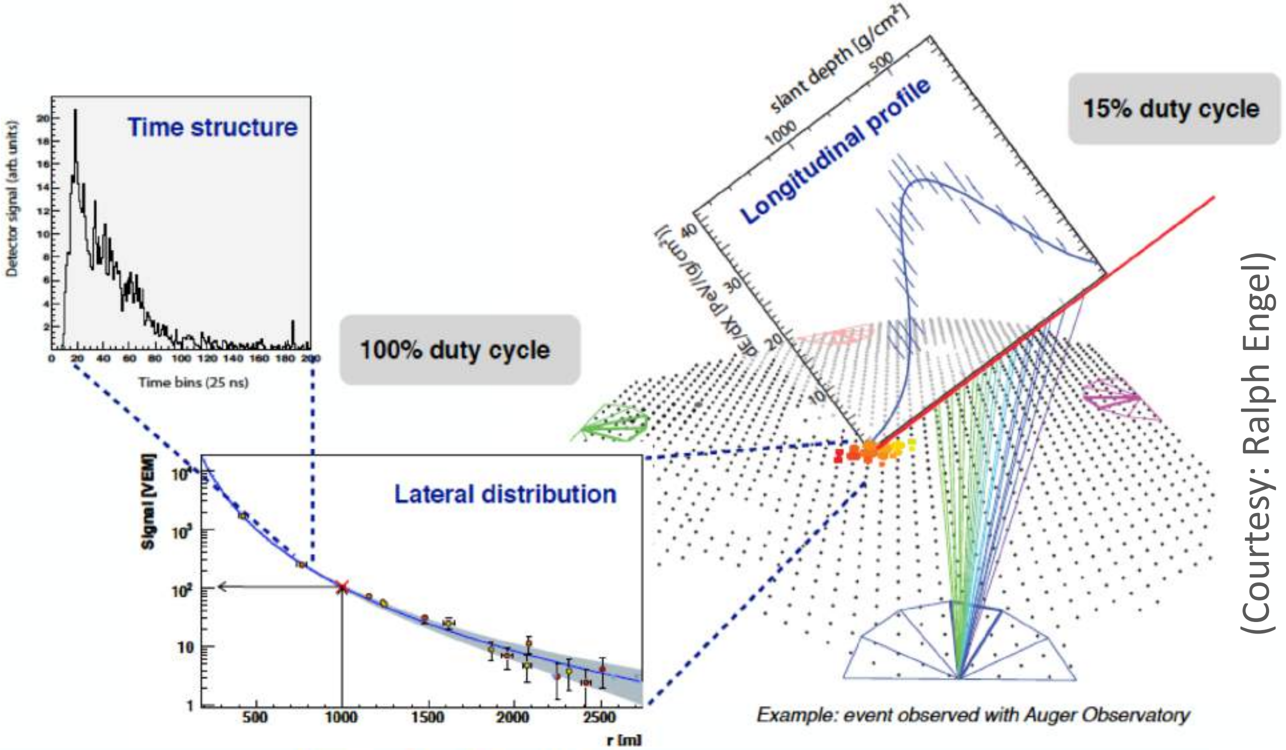


With this detector we see the *highest* energy particles in the universe



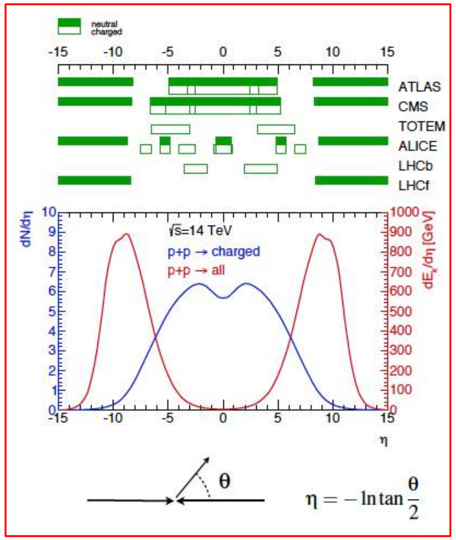
10th May 2007, $E \sim 10^{10}$ GeV

The energy estimate from the lateral distribution of the signal in the **surface detector** array is calibrated *directly* by the (calorimetric) **fluorescence detector** signal … there is *no* reliance on shower simulations

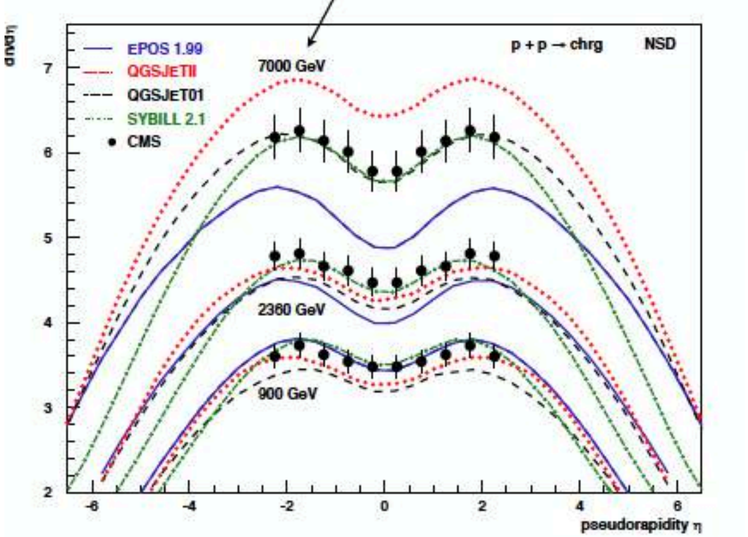


Example: event observed with Auger Observatory

(Courtesy: Ralph Engel)

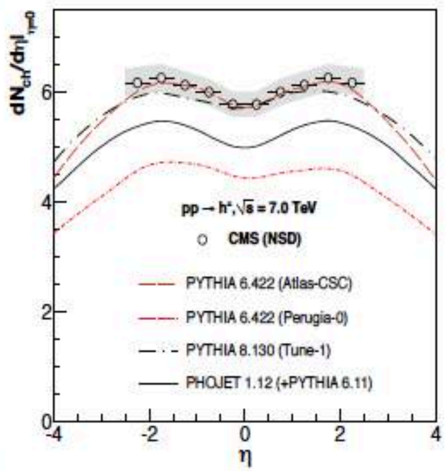


Protons: $E_{lab} = 3 \times 10^{16}$ eV



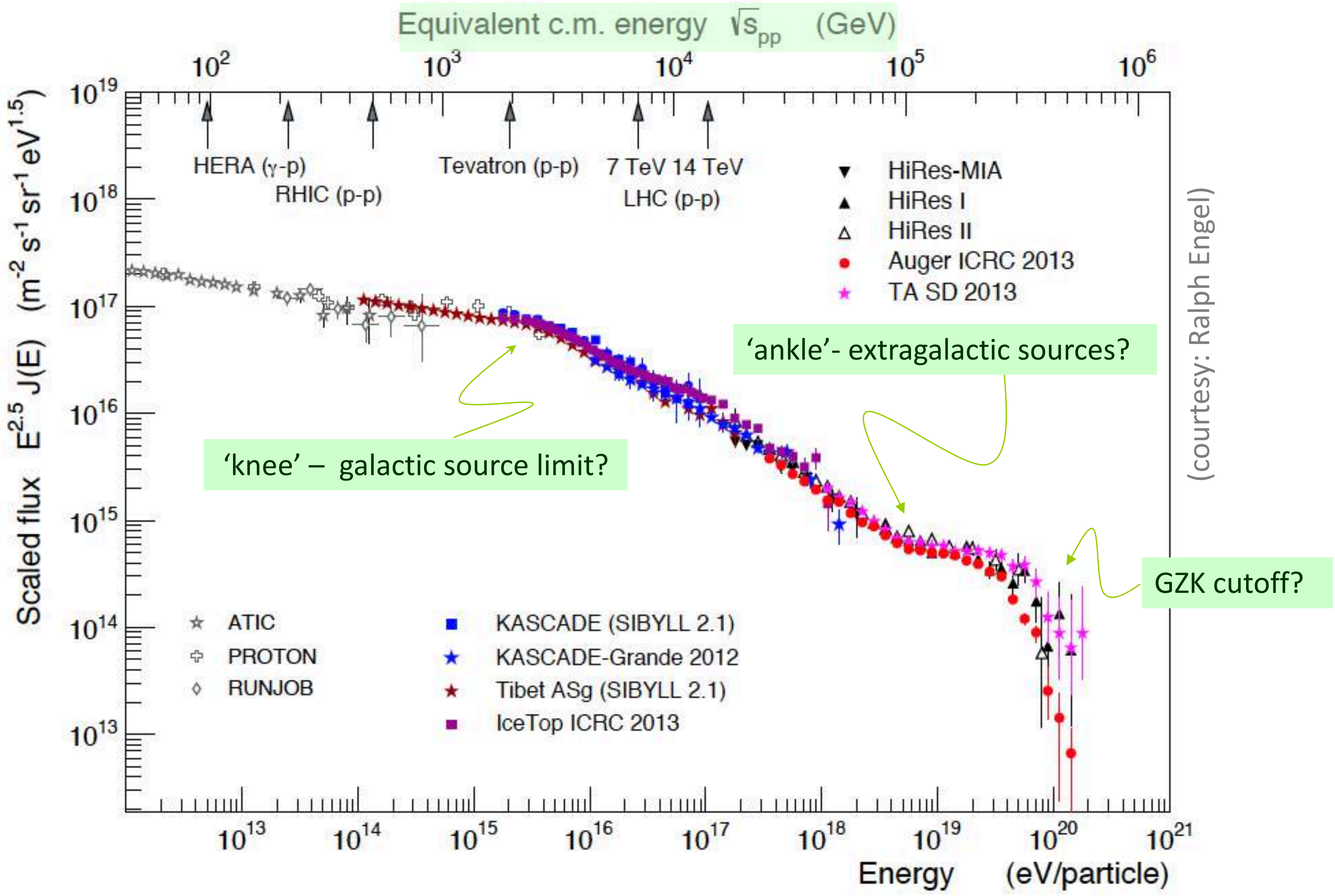
Detailed LHC comparison

(D'Enterria et al., APP 35, 2011)



In any case the CR cascade MCs do very well at matching LHC data … *better* than collider MCs!

By studying cosmic ray interactions we can probe energies well *beyond* the reach of terrestrial accelerators



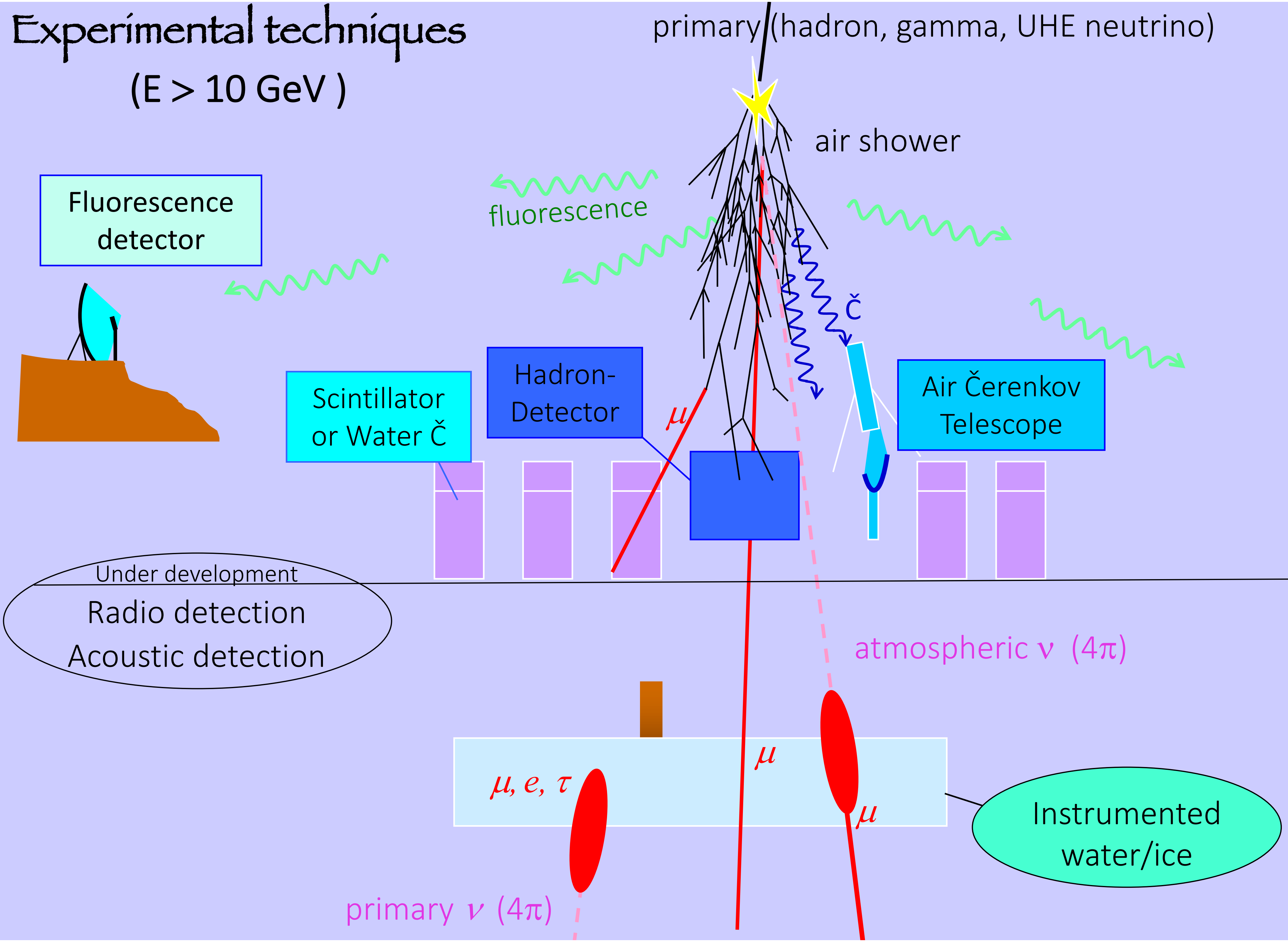
'knee' – galactic source limit?

'ankle'- extragalactic sources?

GZK cutoff?

(courtesy: Ralph Engel)

Experimental techniques
(E > 10 GeV)



primary (hadron, gamma, UHE neutrino)

air shower

fluorescence

Č

μ

Fluorescence detector

Scintillator or Water Č

Hadron-Detector

Air Čerenkov Telescope

Under development

Radio detection

Acoustic detection

atmospheric ν (4π)

μ, e, τ

μ

μ

Instrumented water/ice

primary ν (4π)

(Courtesy: Thomas Lohse)

Colliders versus Cosmic rays

The LHC has achieved 13 TeV cms …

But 10 EeV (10^{19} eV) cosmic ray initiating giant air shower

⇒ ~100 TeV cms (… although rate $\lesssim$1/day in 3000 km^2 array)

New physics would be hard to see in hadron-initiated showers

(BSM cross-section <TeV^{-2} versus hadronic cross-section ~GeV^{-2})

… but may have a dramatic impact on *neutrino* interactions (since the ν-*N* cross-section is very small to start with)

→can probe new physics (both in and) beyond the Standard Model by studying ultra-high energy cosmic neutrinos

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

GZK interactions of extragalactic UHECRs on the CMB

"guaranteed" cosmogenic neutrino flux

… reduced significantly if the primaries are *not* protons but heavy nuclei

UHECR candidate accelerators (AGN, GRBs, …)

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

… sensitive to 'cross-over' energy above which extragalactic component dominates

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

motivated by trans-GZK energy events observed by AGASA

… such models now *ruled out* by the limit from Auger on primary photons
(QCD fragmentation in parton shower dominantly creates photons, *not* nucleons)

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

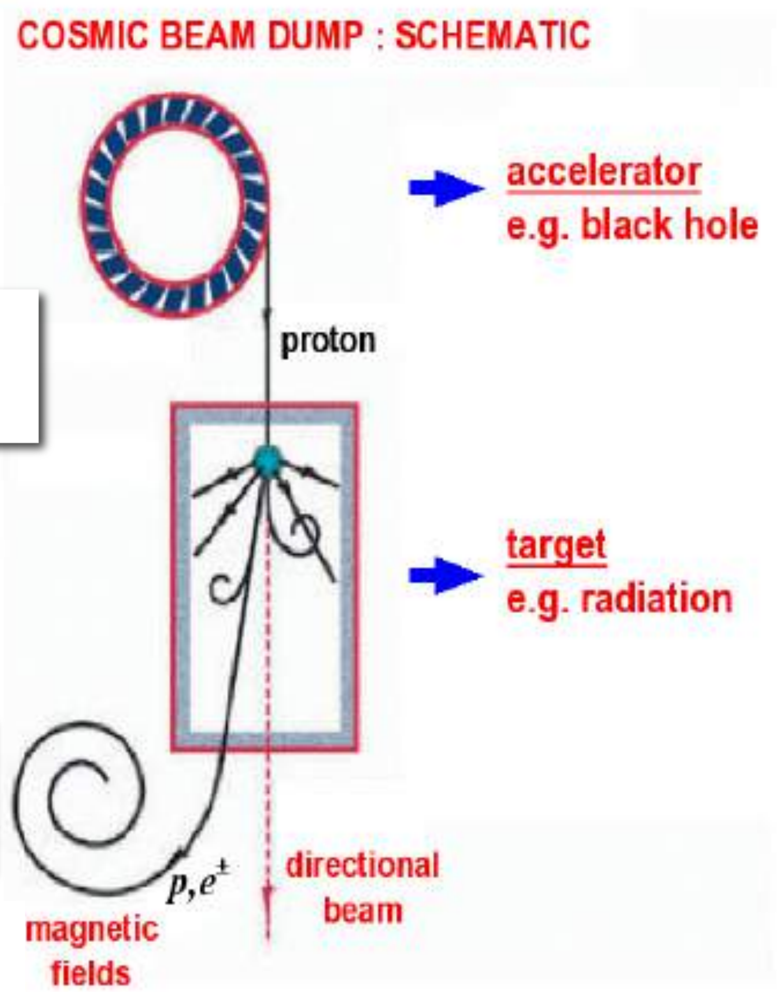
Hubble time

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

$$\approx 2.3\times10^{-8}\,\epsilon_\pi\,\xi_Z\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

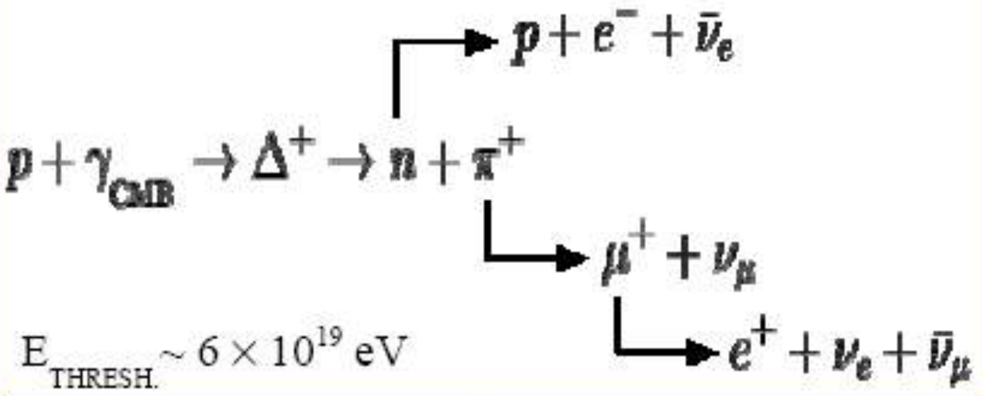
➡Making a reasonable estimate for ε_π etc allows this to be converted into a **flux expectation**

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



The “guaranteed” cosmogenic neutrino flux

GZK mechanism :



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

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

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

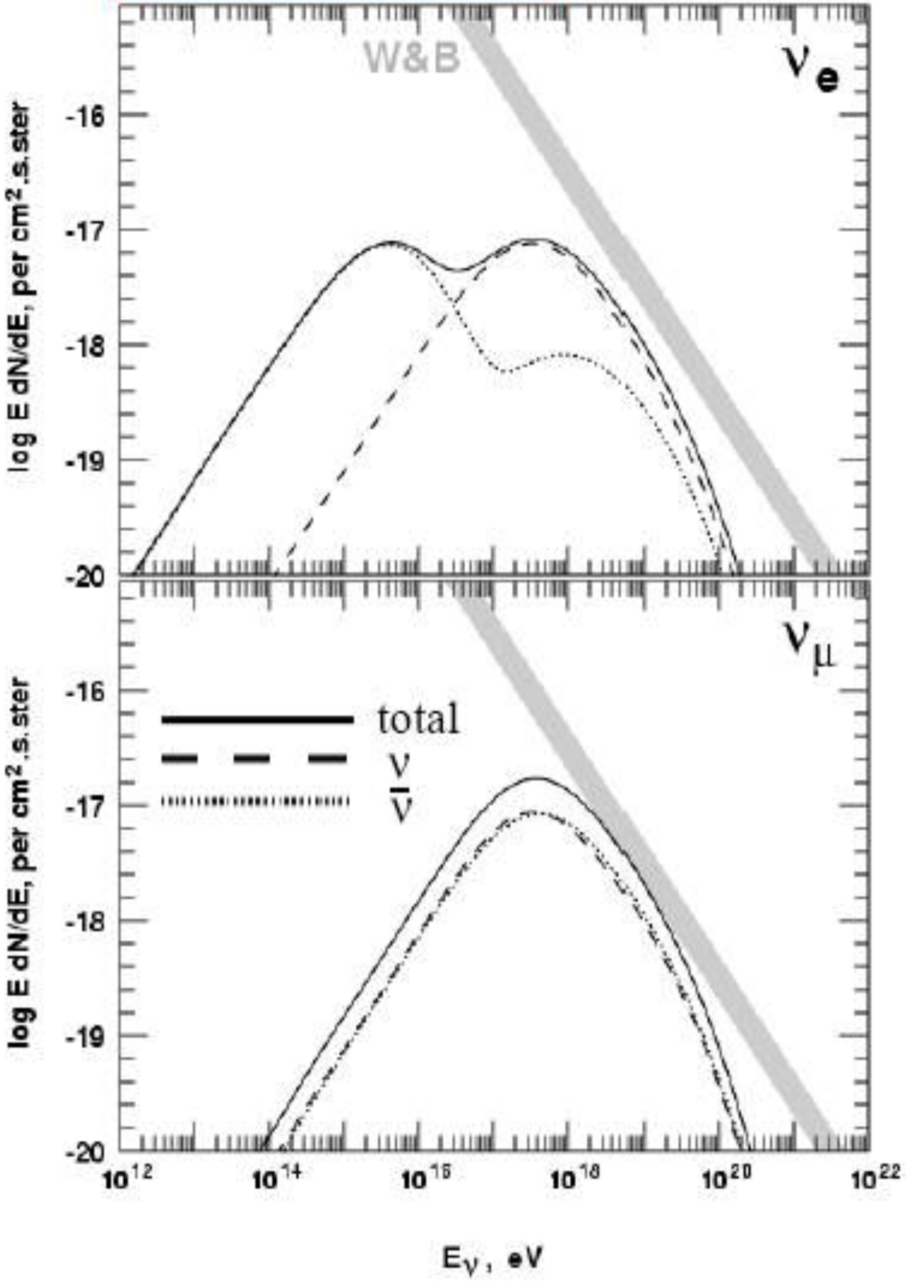
$$\mu^+ \rightarrow e^+ +\nu_e+\bar{\nu}_\mu$$

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

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

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

Engel, Seckel, Stanev (2001)



… can pin down by normalising to the γ-ray flux from GZK process (Ahlers *et al*, Astropart.Phys. **34**:106,2010)

We can work out the interaction rate via *ν-N* deep inelastic scattering

(this is the dominant process above ~10 GeV)

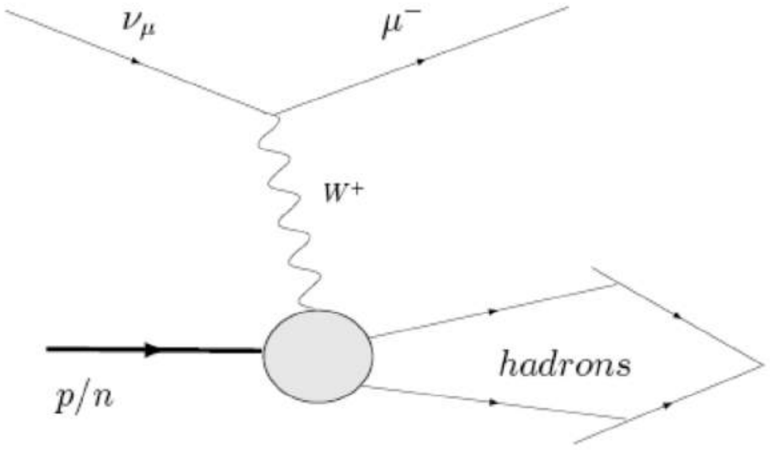
$$\frac{\partial^2 \sigma^{CC,NC}_{\nu,\bar{\nu}}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi}\left(\frac{M_i^2}{Q^2+M_i^2}\right)$$

$Q^2 \uparrow \Rightarrow$ propagator $\downarrow$

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

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

$Q^2 \uparrow \Rightarrow$ parton distribution functions $\uparrow$



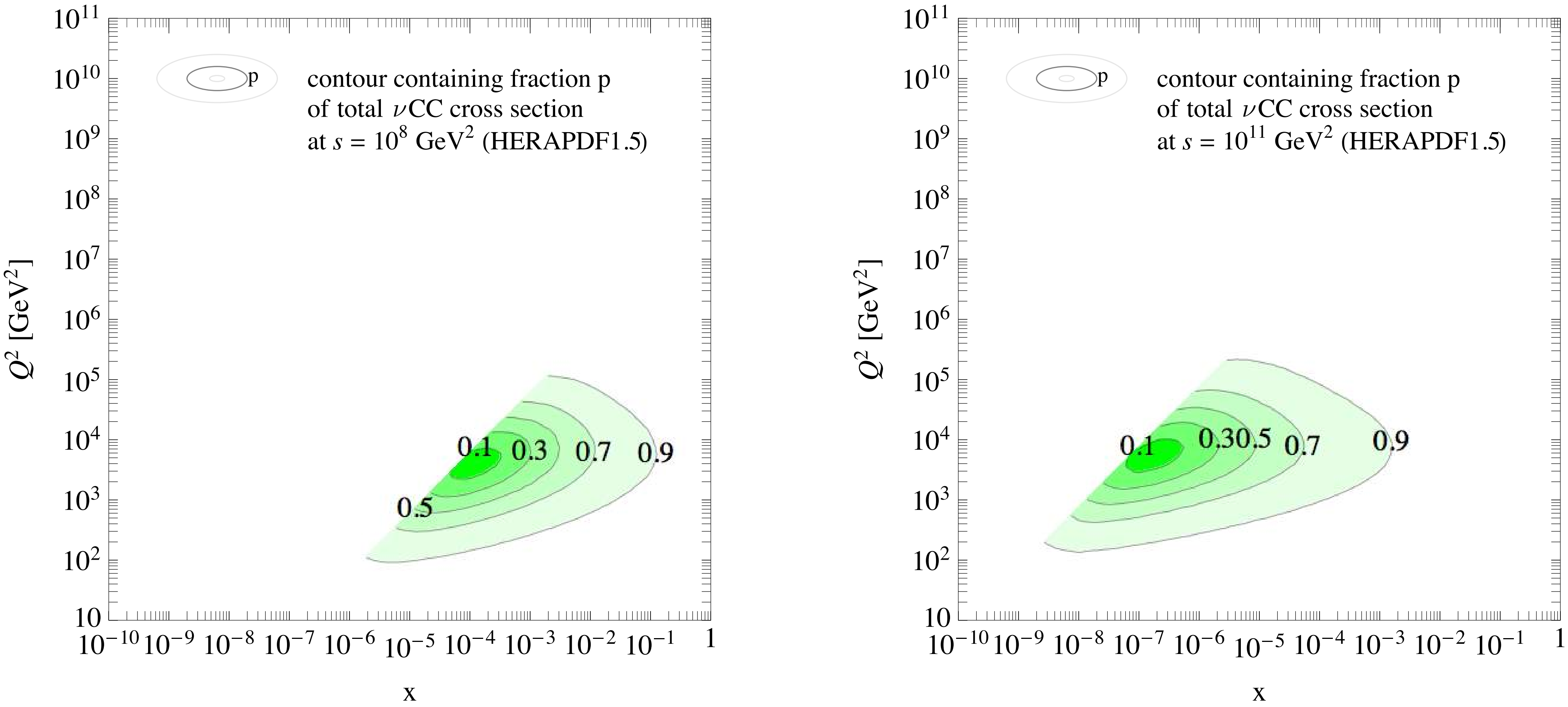
Most of the contribution to #-secn comes from: $Q^2 \sim M_W^2$ and $x \sim \frac{M_W^2}{M_N E_\nu}$

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

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

Can calculate numerically at Next-to-Leading-Order (NLO) … *no* significant further change at NNLO

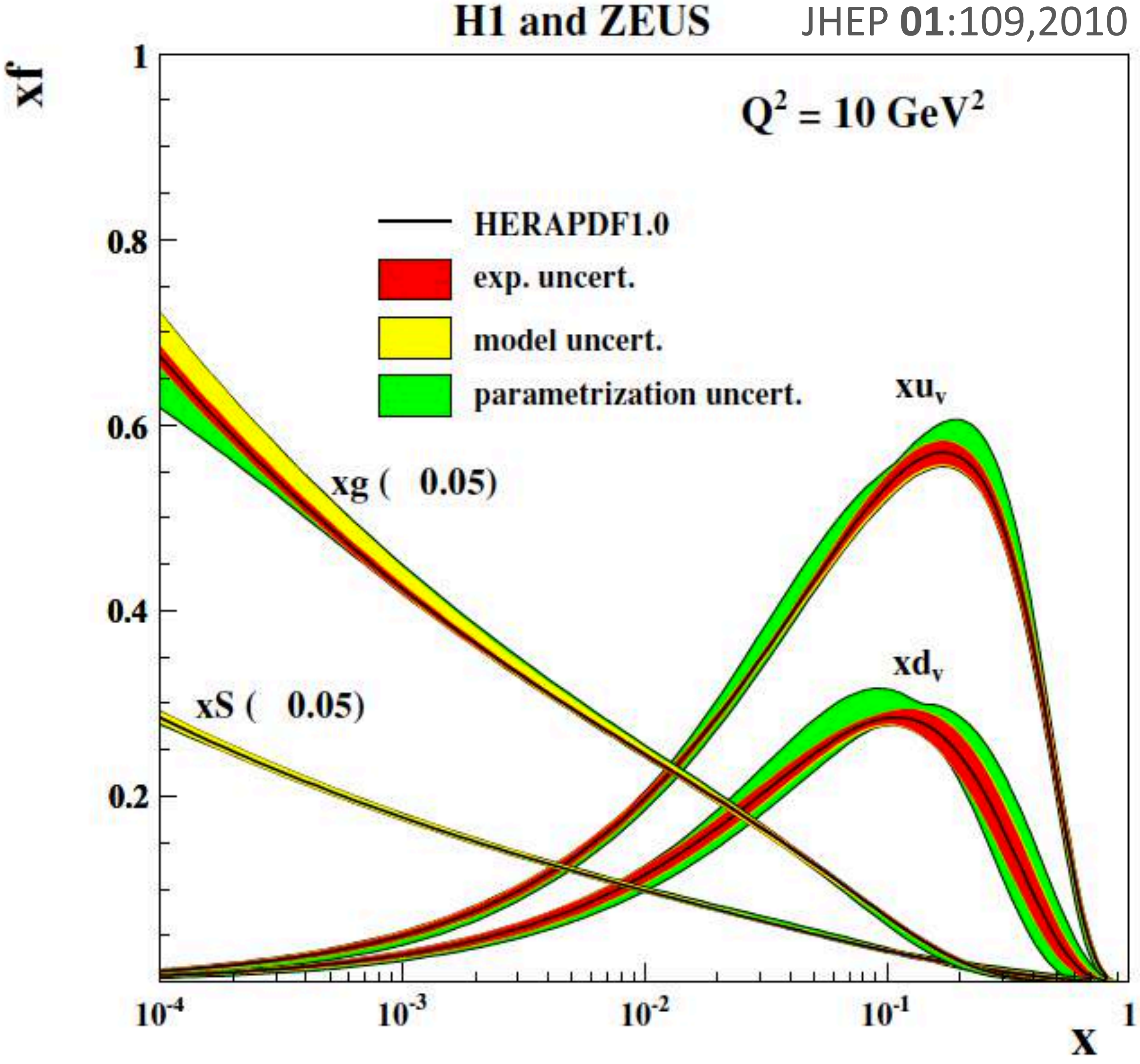
As the neutrino energy increases, *lower* values of Bjorken-*x* are being probed



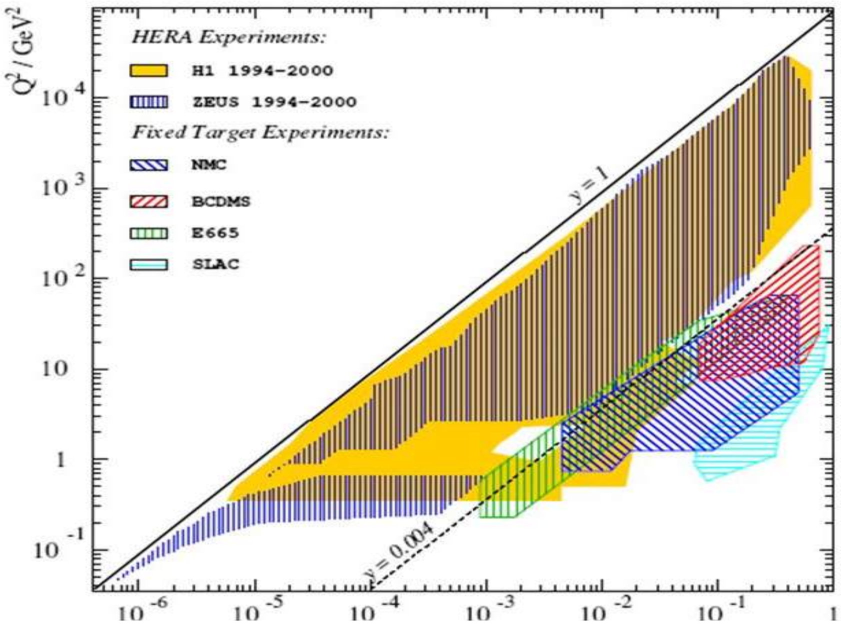
Mertsch, Cooper-Sarkar, Sarkar, JHEP **08**:042,2011

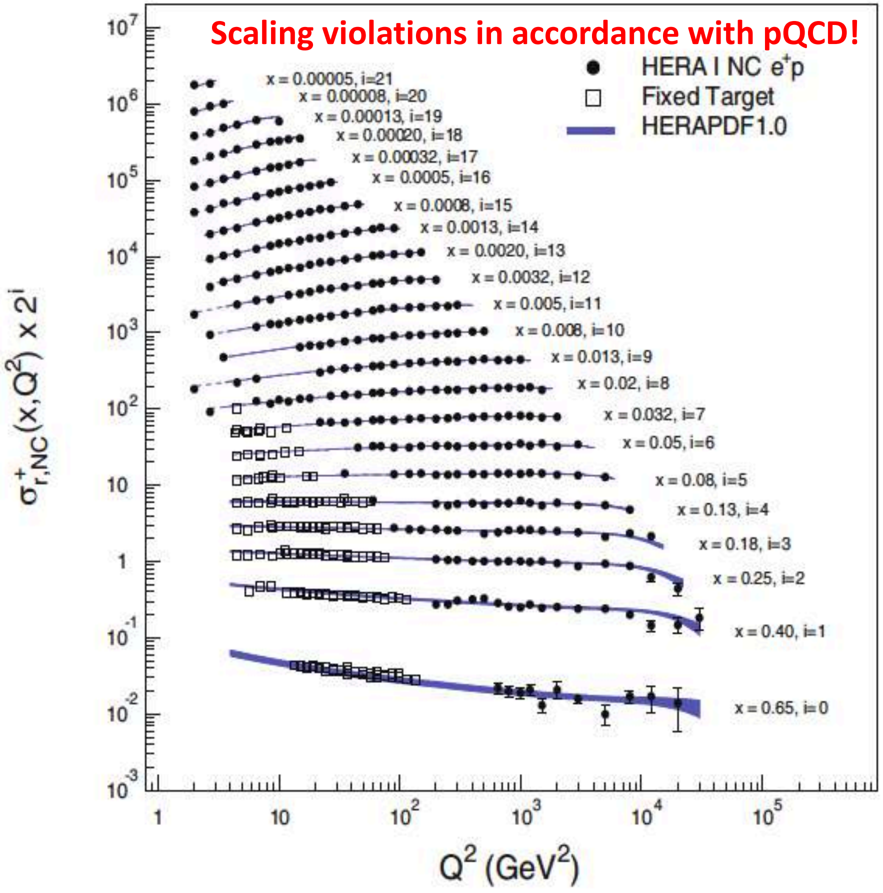
So to determine the DIS cross-section accurately it is essential to have measurements of PDFs down to as low *x* as is possible … for energies > PeV we need to evolve these further using the pQCD DGLAP formalism

The H1 & ZEUS experiments at HERA were the first to measure DIS at high Q^2 and low Bjorken-x… surprising finding was the *steep* rise of the **gluon PDF** at low *x*

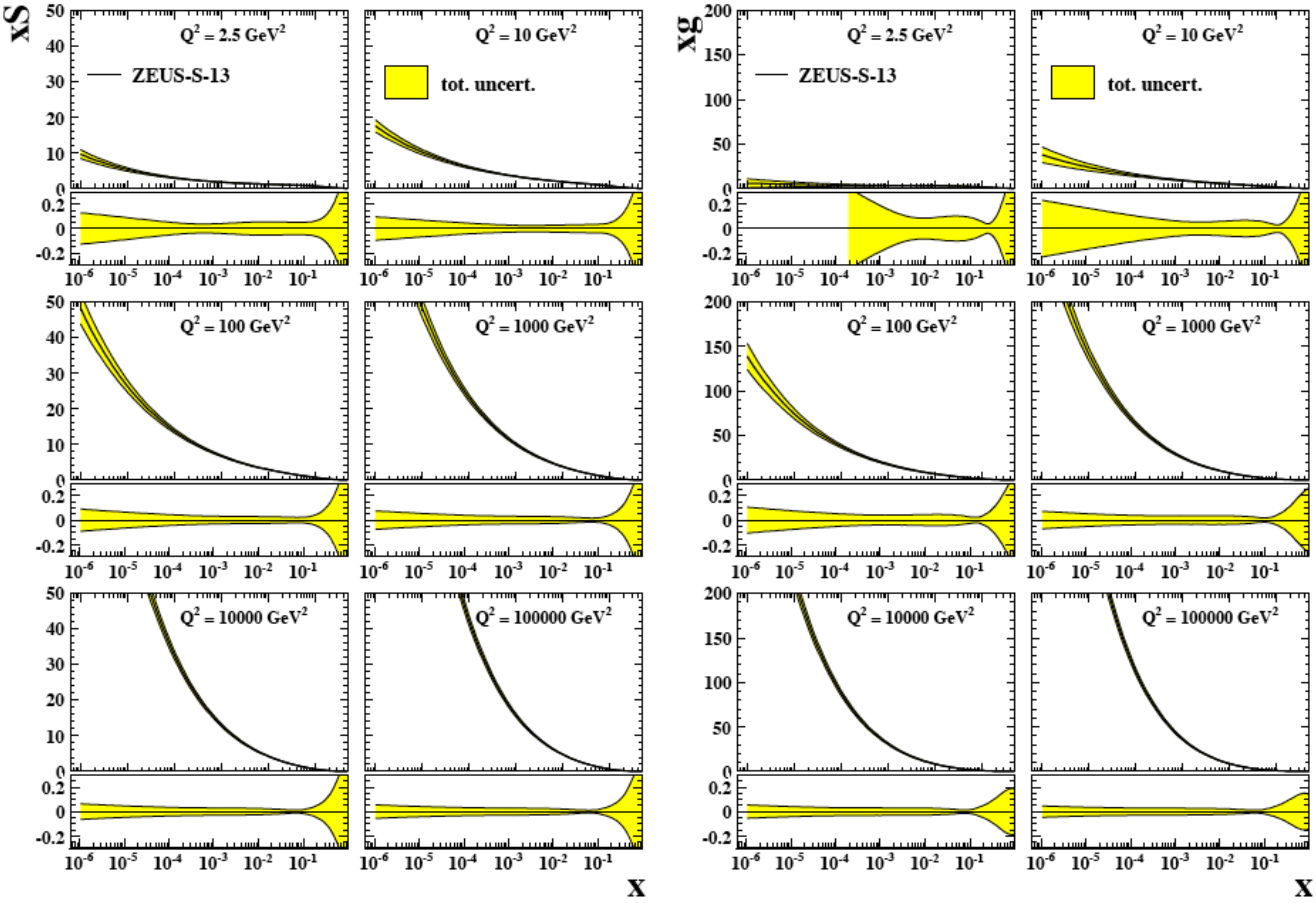


JHEP **01**:109,2010




Scaling violations in accordance with pQCD!

Parton distribution functions from the ZEUS-S global data analysis

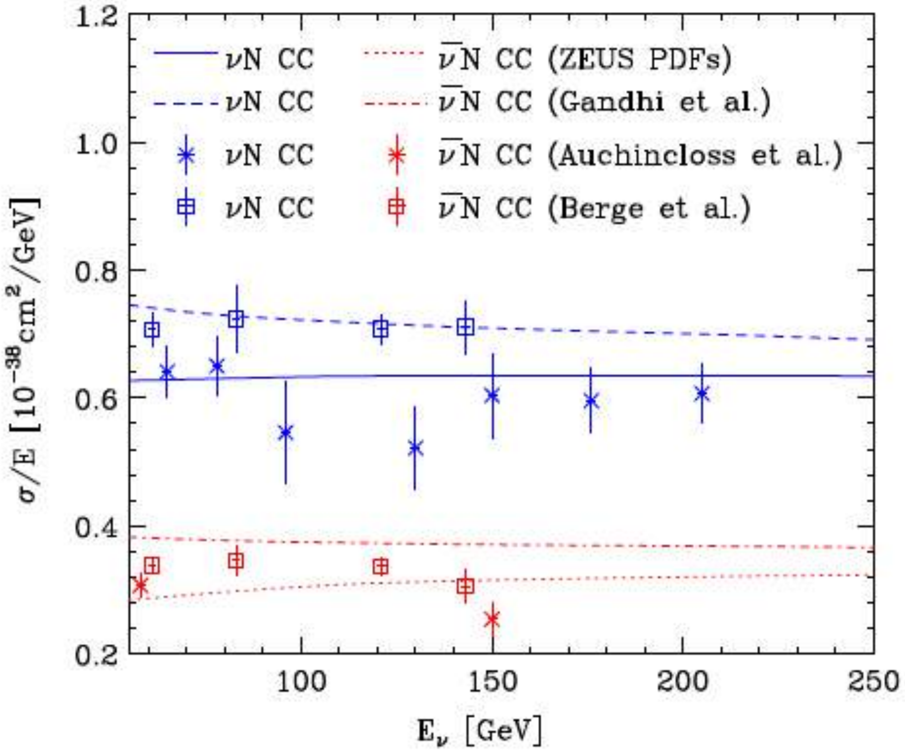


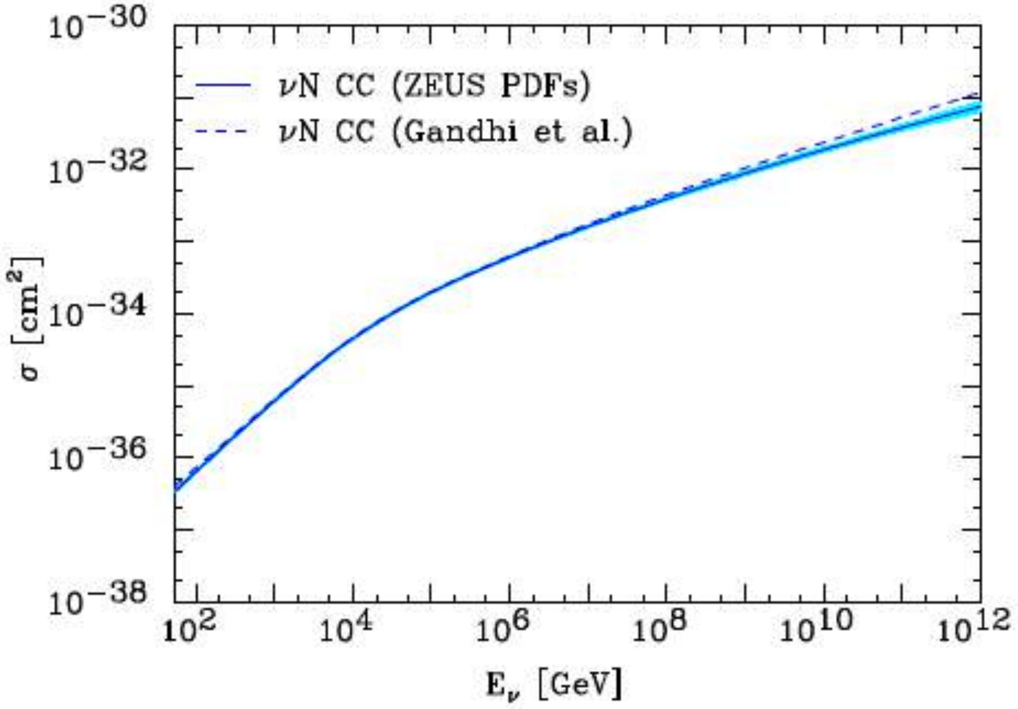
Cooper-Sarkar & Sarkar, JHEP **01**:075,2008

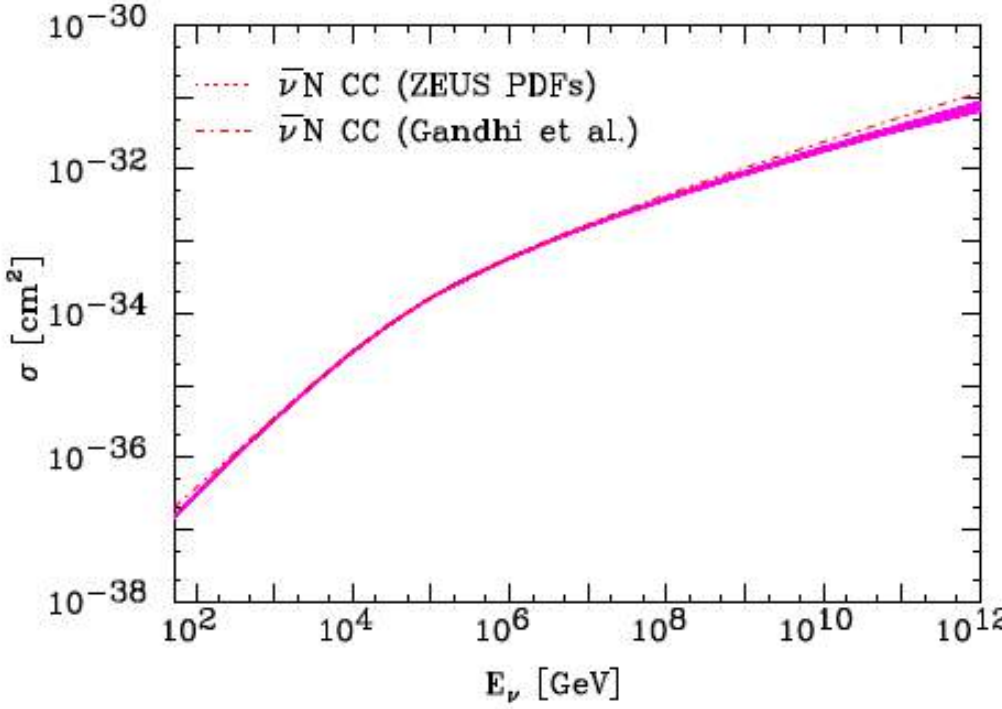
using DGLAP evolution of the PDFs (at NLO, *including* heavy quark corrections)

The #-section we found using ZEUS-S PDFs was up to ~40% different from the previous 'standard' calculation (based on CTEQ4) … More importantly we could quantify the *uncertainty* in the perturbative calculation

At very high energies where very low-x is being probed, recombination/saturation effects may alter the cross-section by a factor of ~2 … however DGLAP evolution appears to fit *all* exptal. data – so *no* imperative for this yet!







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

IceCube Neutrino Observatory

IceTop: 1 km^2 surface array (81 'Auger' tanks)

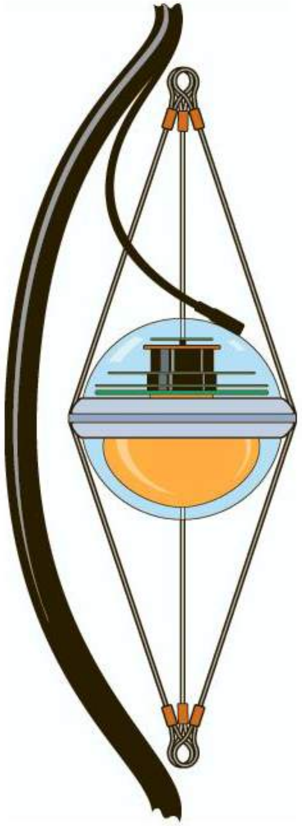
86 strings (125 m between strings)

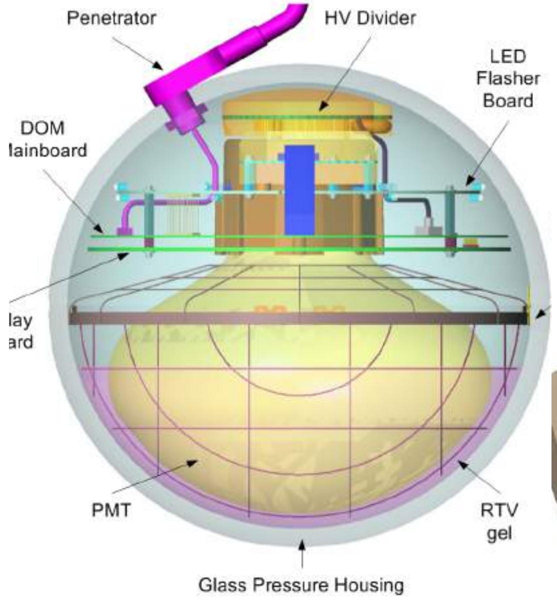
60 Optical Modules per string (17 m apart)

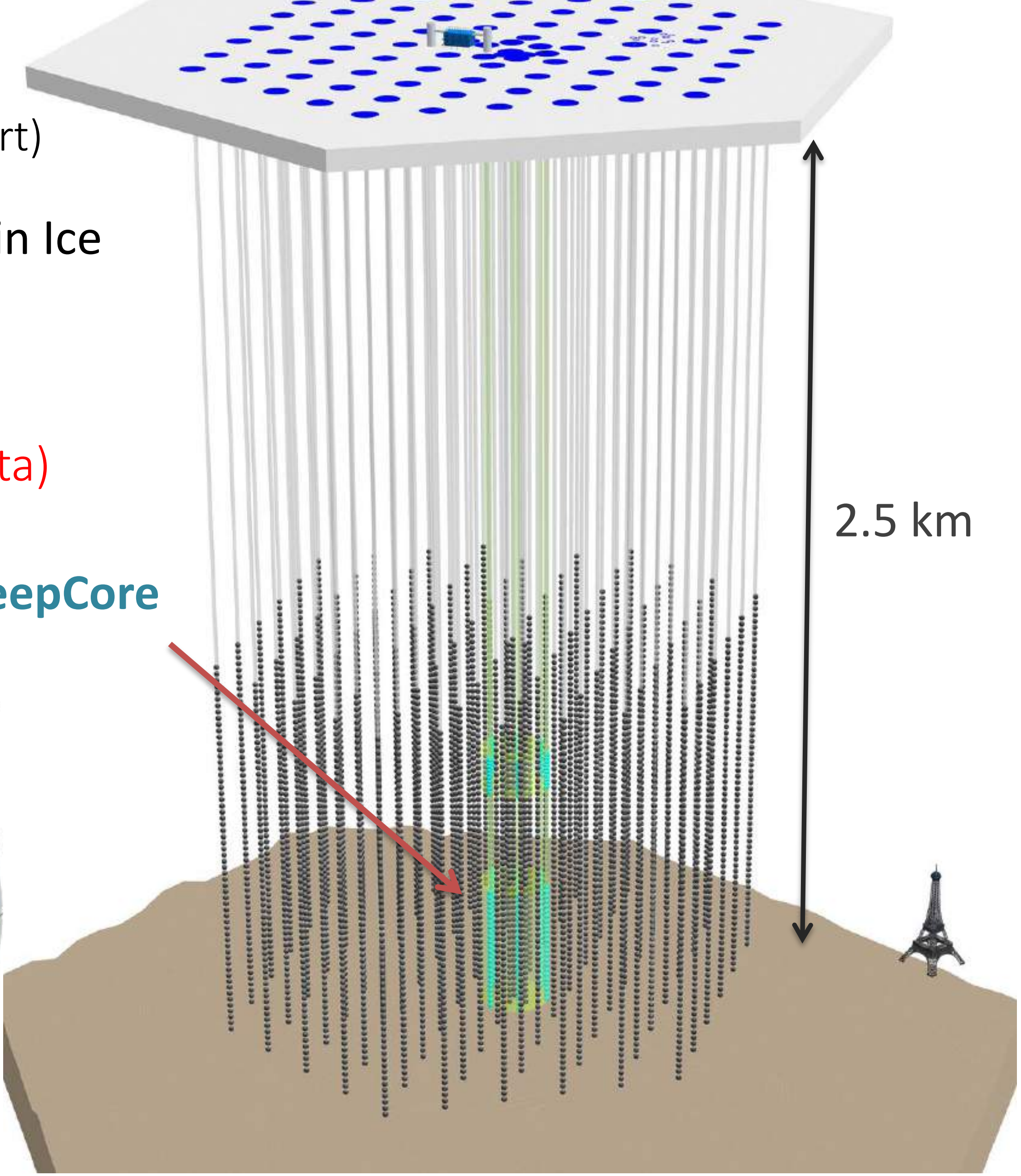
5160 Digital Optical Modules (DOMs) in Ice

1 km^3 ⇒ Gton instrumented volume

Construction: 2004-11 (now 7 yr+ of data)

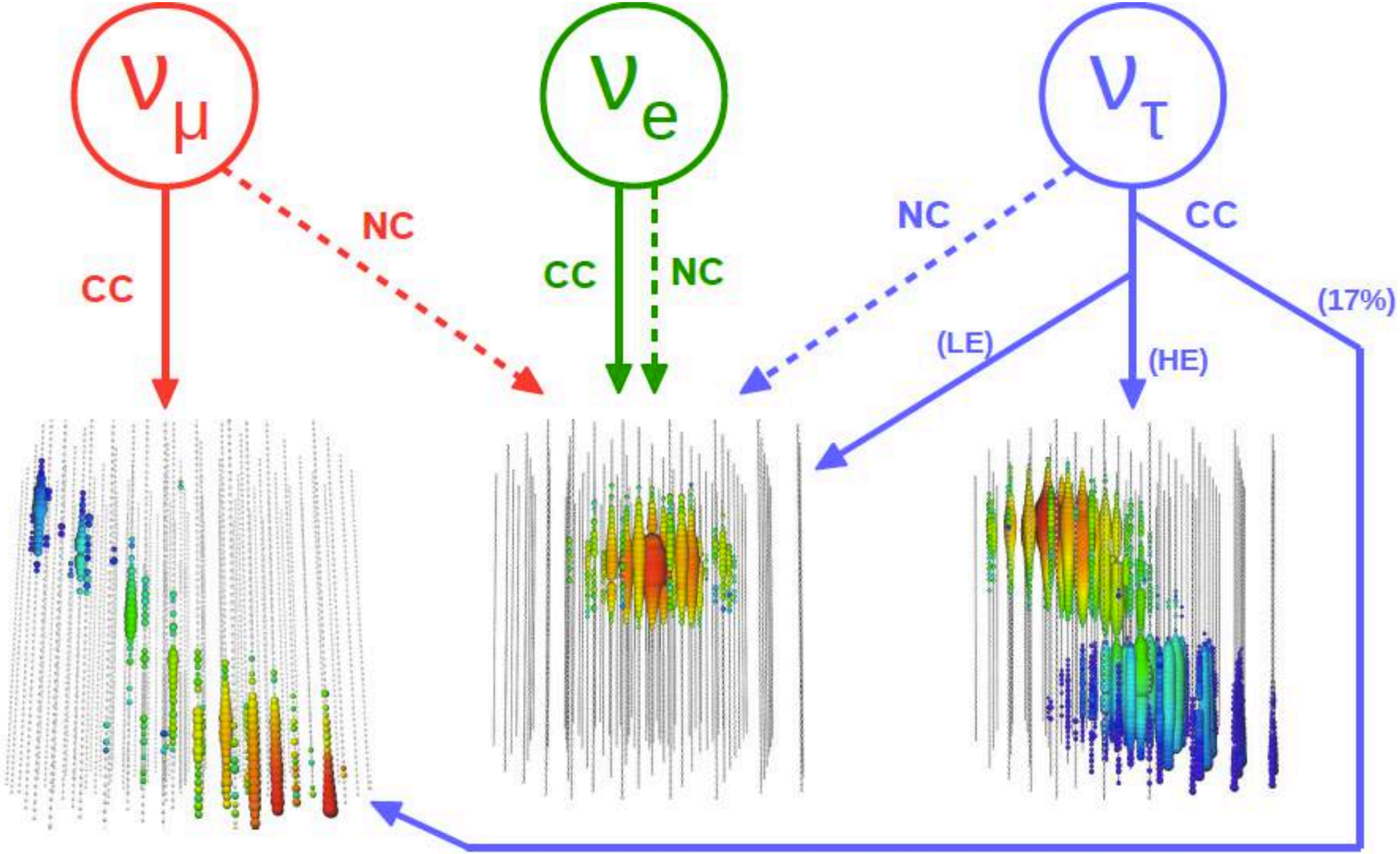






Cost: 279 M$ ⇒ <30 cents per ton

Neutrino flavour discrimination in IceCube



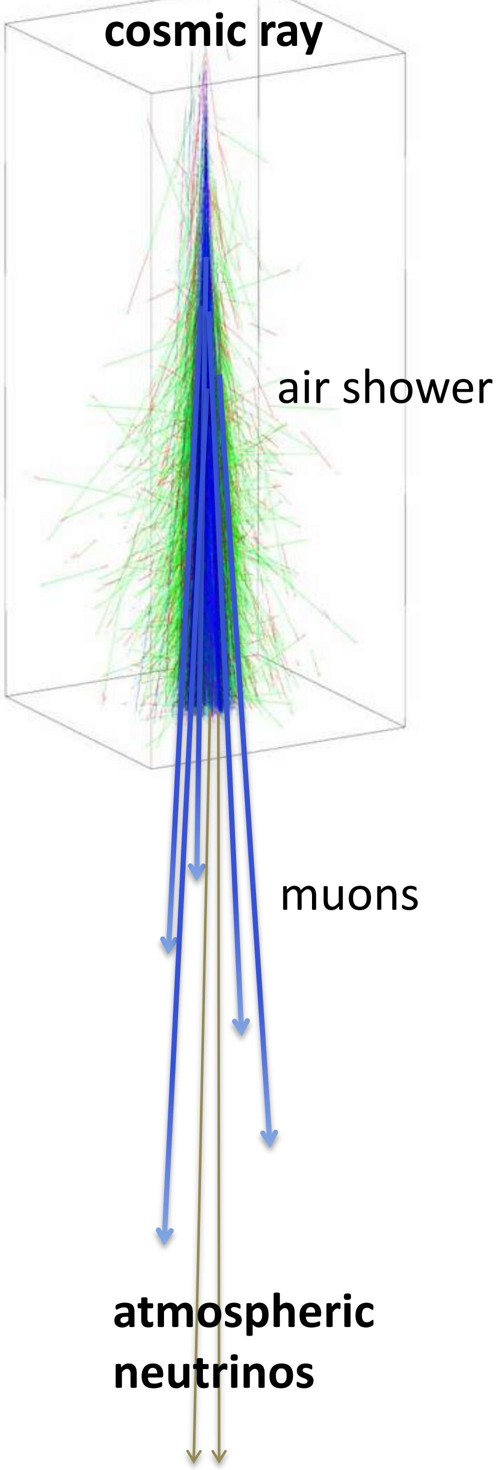
Track topology

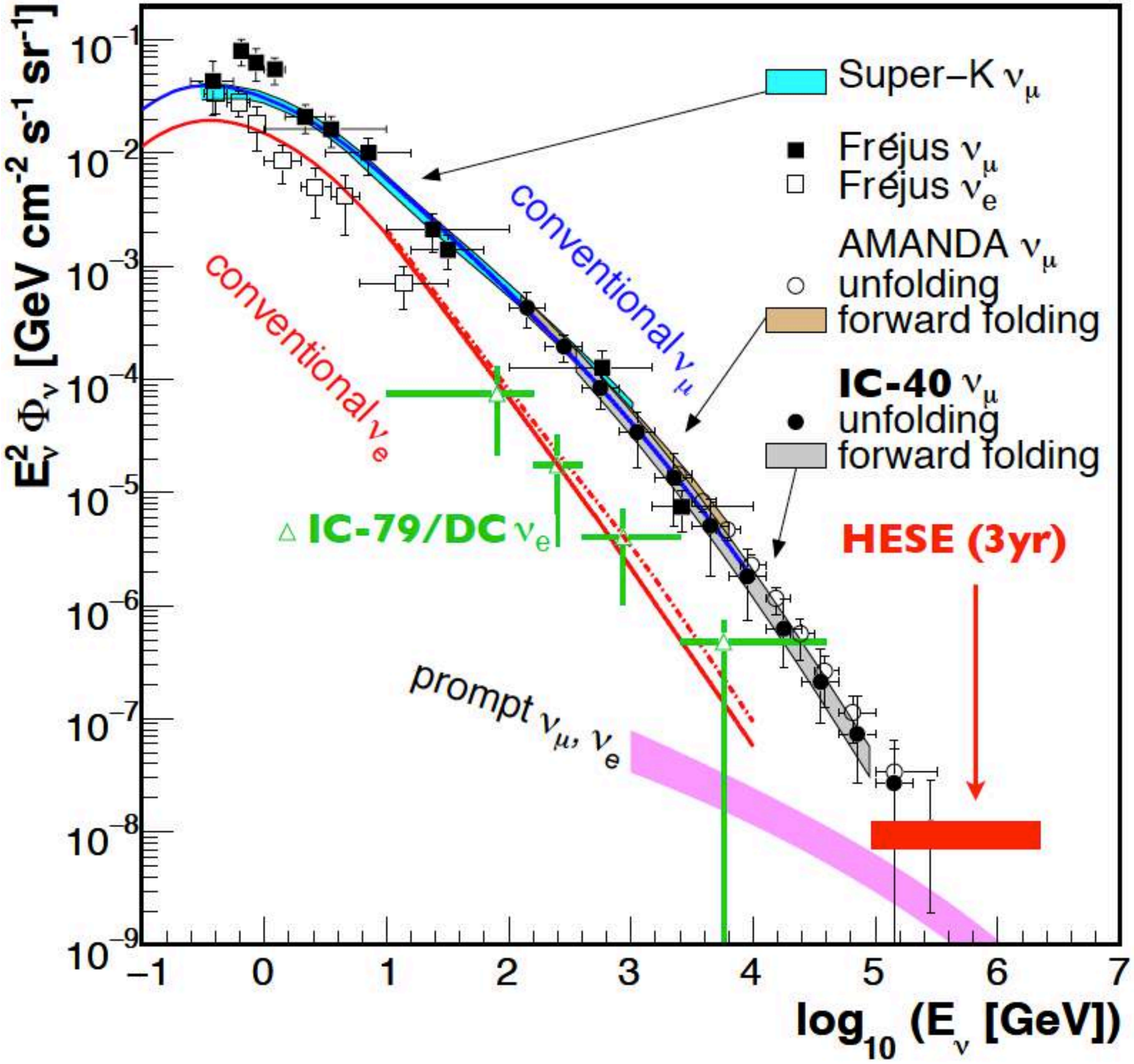
Good pointing (~0.2° - 1°)
but only lower bound on neutrino energy

Cascade topology

Good energy resolution (~15%)
but poor pointing (~10° - 15°)

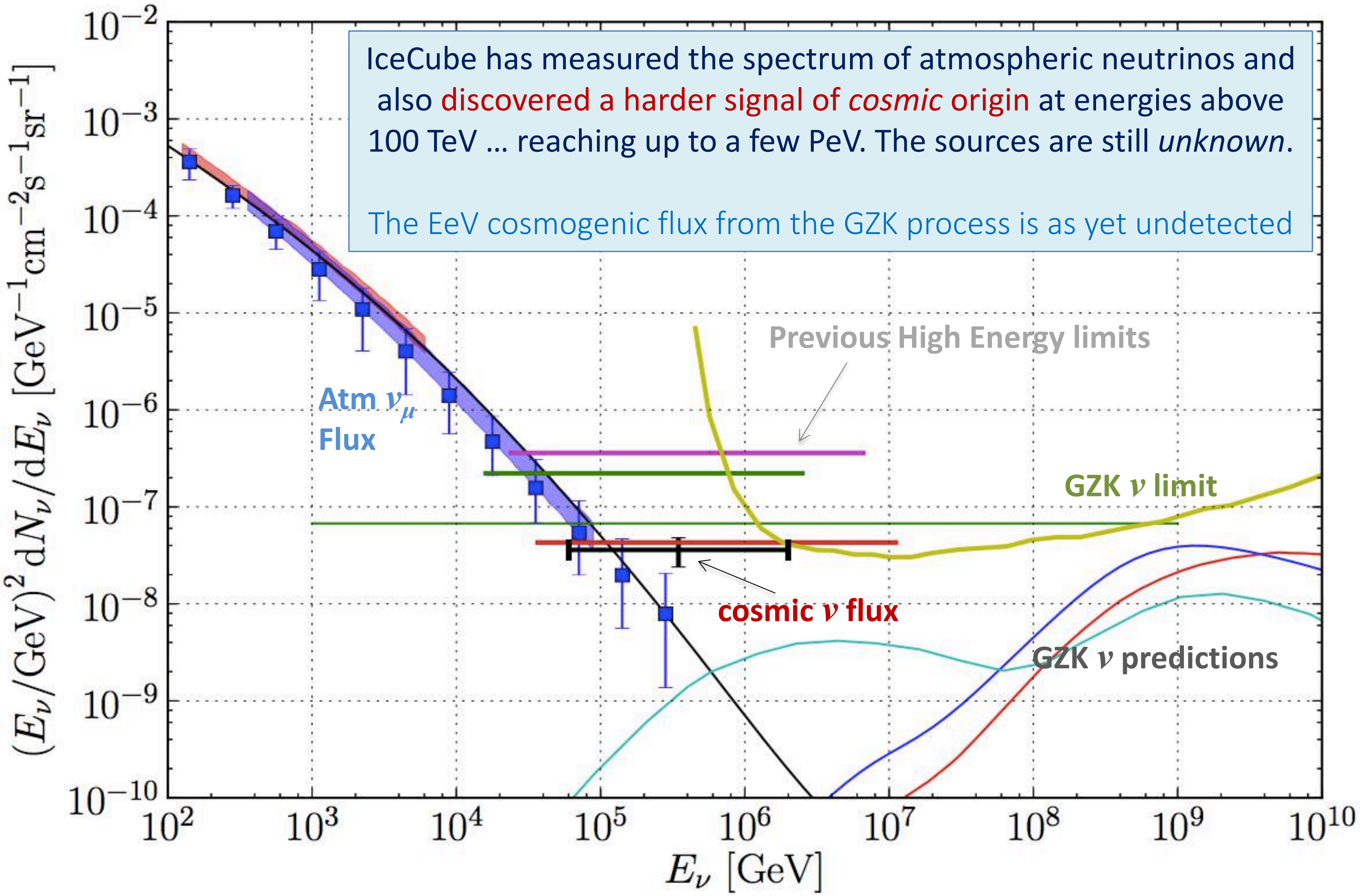
Atmospheric Neutrino Spectrum





IceCube has measured the atmospheric neutrino background … in good *agreement* with the number expected from cosmic ray interactions in the atmosphere creating pions and kaons (the ‘prompt’ flux from charmed meson decays not detected yet)

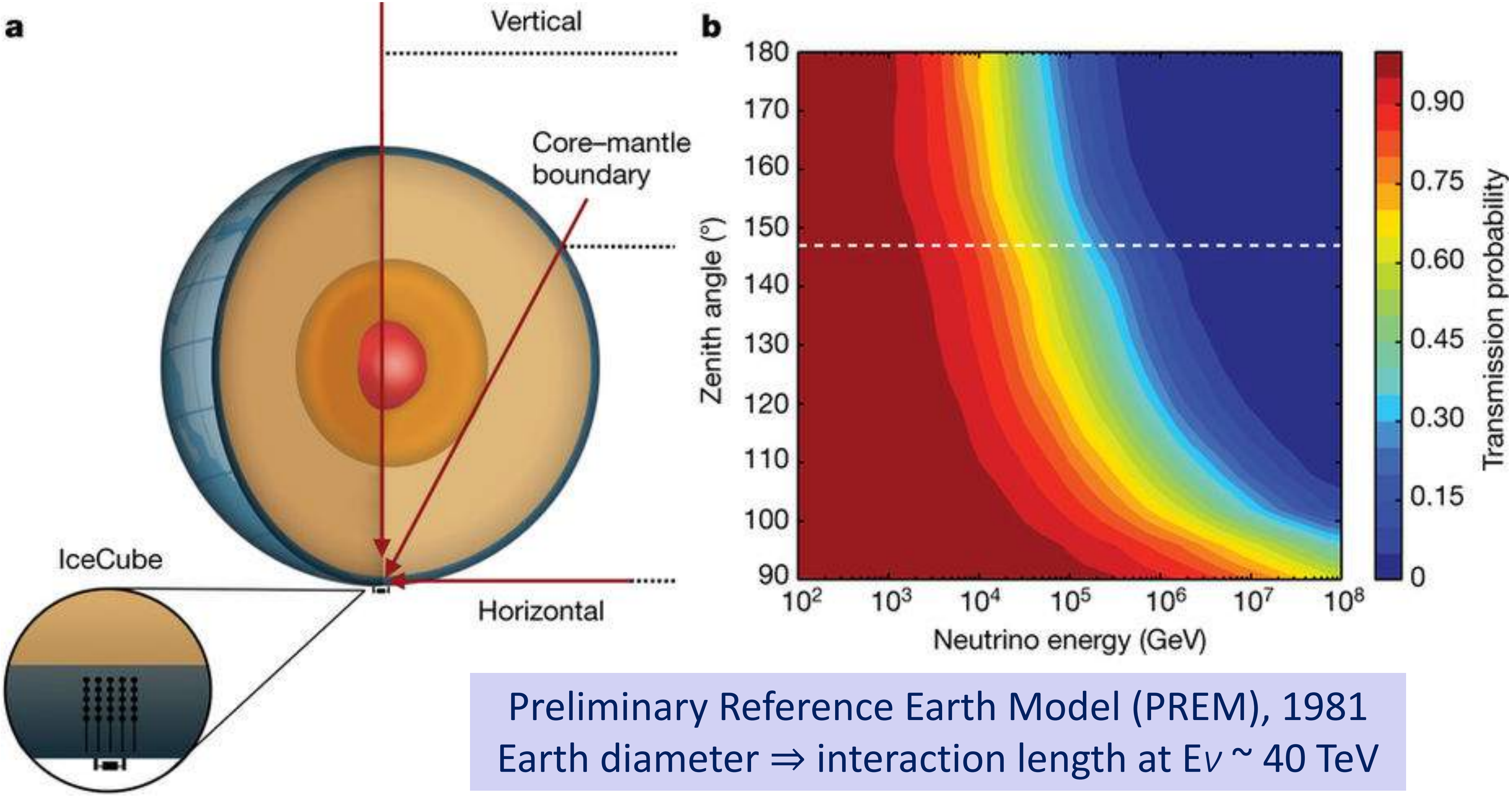
Current picture of high energy neutrino energy spectrum



IceCube has measured the spectrum of atmospheric neutrinos and also discovered a harder signal of *cosmic* origin at energies above 100 TeV … reaching up to a few PeV. The sources are still *unknown*.

The EeV cosmogenic flux from the GZK process is as yet undetected

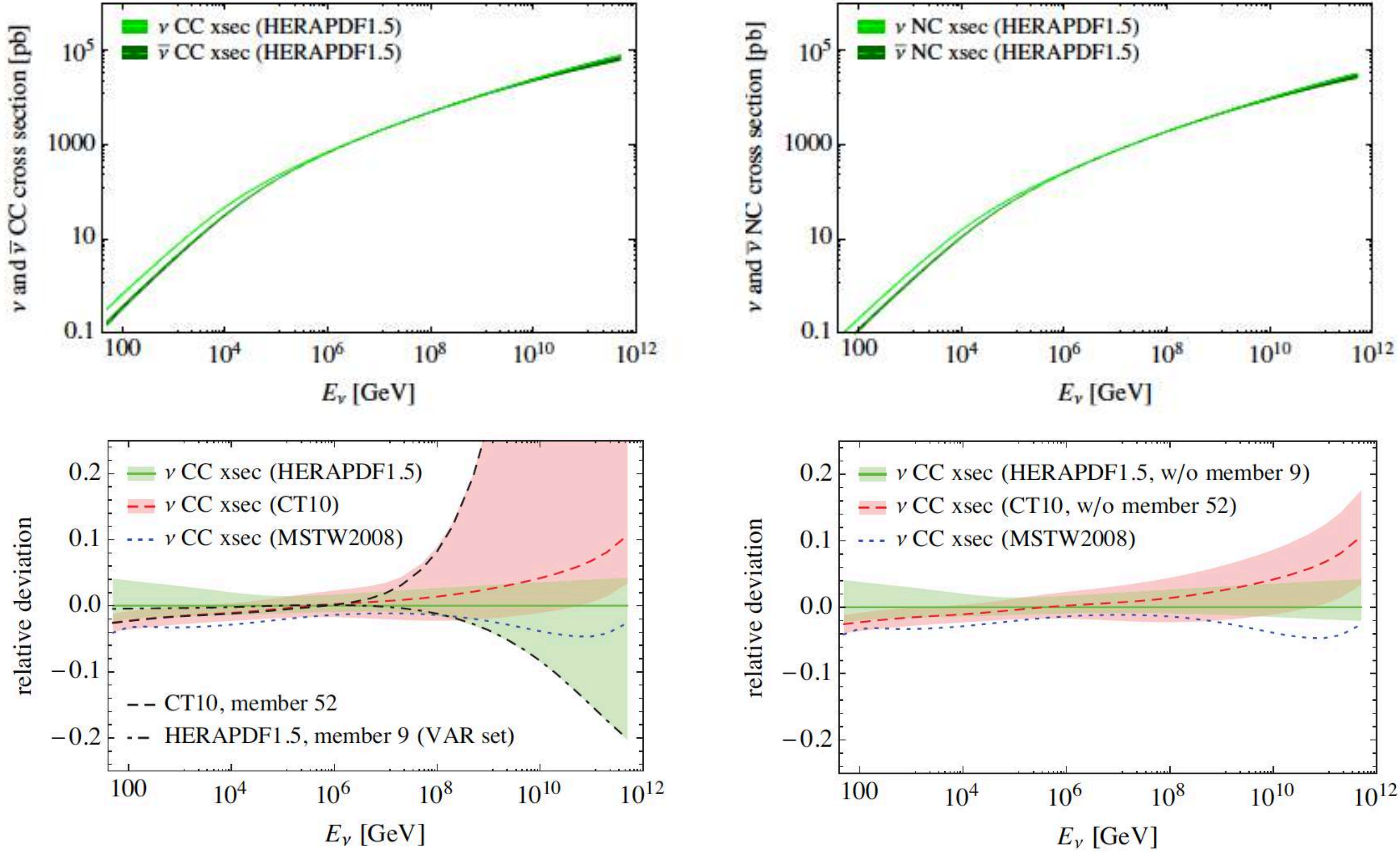
We can now *measure* the *ν-N* cross-section by examining the zenith angle dependence of the *ν* flux (assumed* to be isotropic)



Preliminary Reference Earth Model (PREM), 1981
Earth diameter ⇒ interaction length at E$_\nu$ ~ 40 TeV

*Isotropy certainly true for atmospheric neutrinos (which dominate up to ~10^5 GeV) and for extragalactic flux too … galactic component is <18%

Meanwhile we have recalculated the ν-N #-section @ NLO with ~few % accuracy using HERAPDF1.5

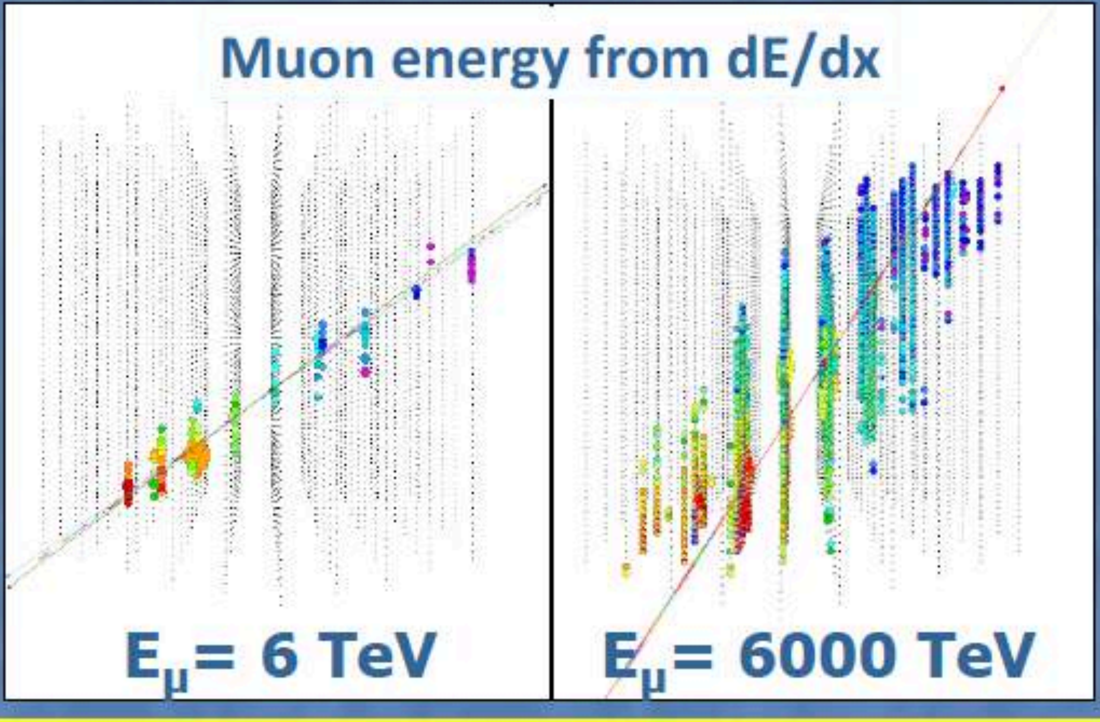


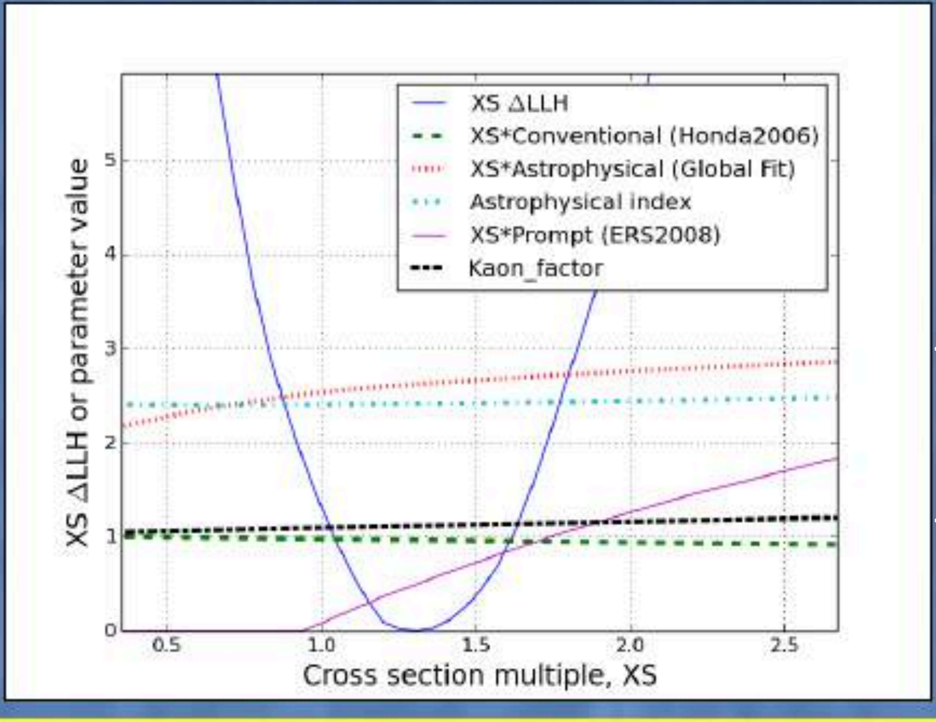
Mertsch, Cooper-Sarkar, Sarkar, JHEP 08:042,2011 (CSMS 2011)

… finding good agreement between different PDF sets (*after* we reject unphysical members – which would have yielded e.g. a *negative* F_L or too steep rise in #-section)

Experimental method

- **Event selection yielded 10,784 muon neutrinos in 2010 data year**
  - Muon energy determined by Truncated Energy method [IceCube 2013]
- **Two-dimensional LLH fit in muon energy and zenith angle**
- **Constrained by priors from other experiments**
  - Astrophysical and prompt fluxes from IceCube [IceCube 2015]
- **Best fit is multiple of Standard Model expectation from CSMS 2011**
  - Fit parameters include fluxes of conventional, astrophysical, prompt, plus $\nu_\mu\bar{\nu}_\mu$ ratio, kaon-pion ratio, DOM efficiency
  - Systematics include ice model, Earth model, atmospheric temperature model, and choice of astrophysical and prompt flux priors

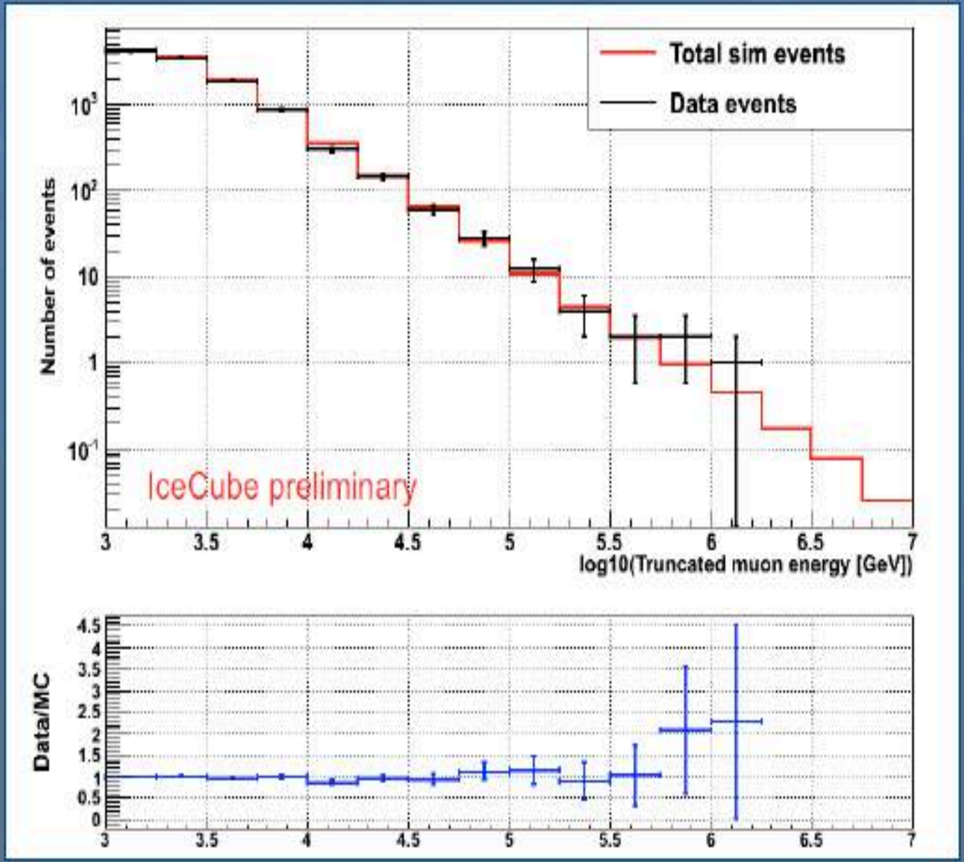


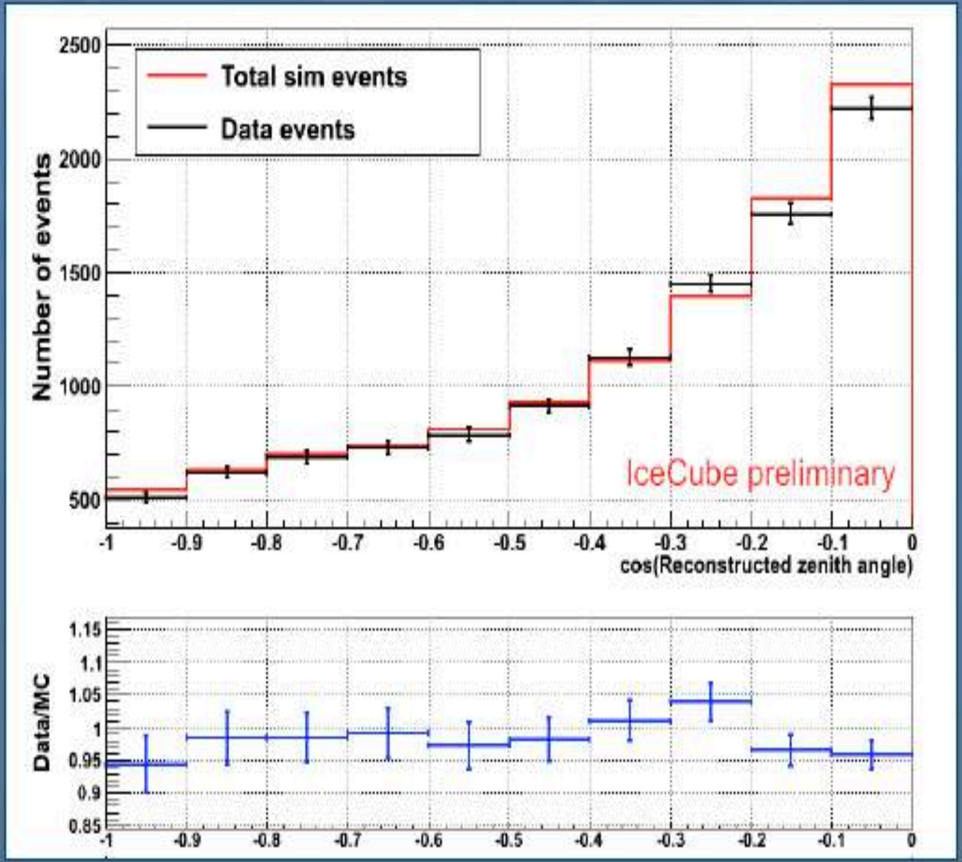


Sandy Miarecki, ICHEP 2016

Results

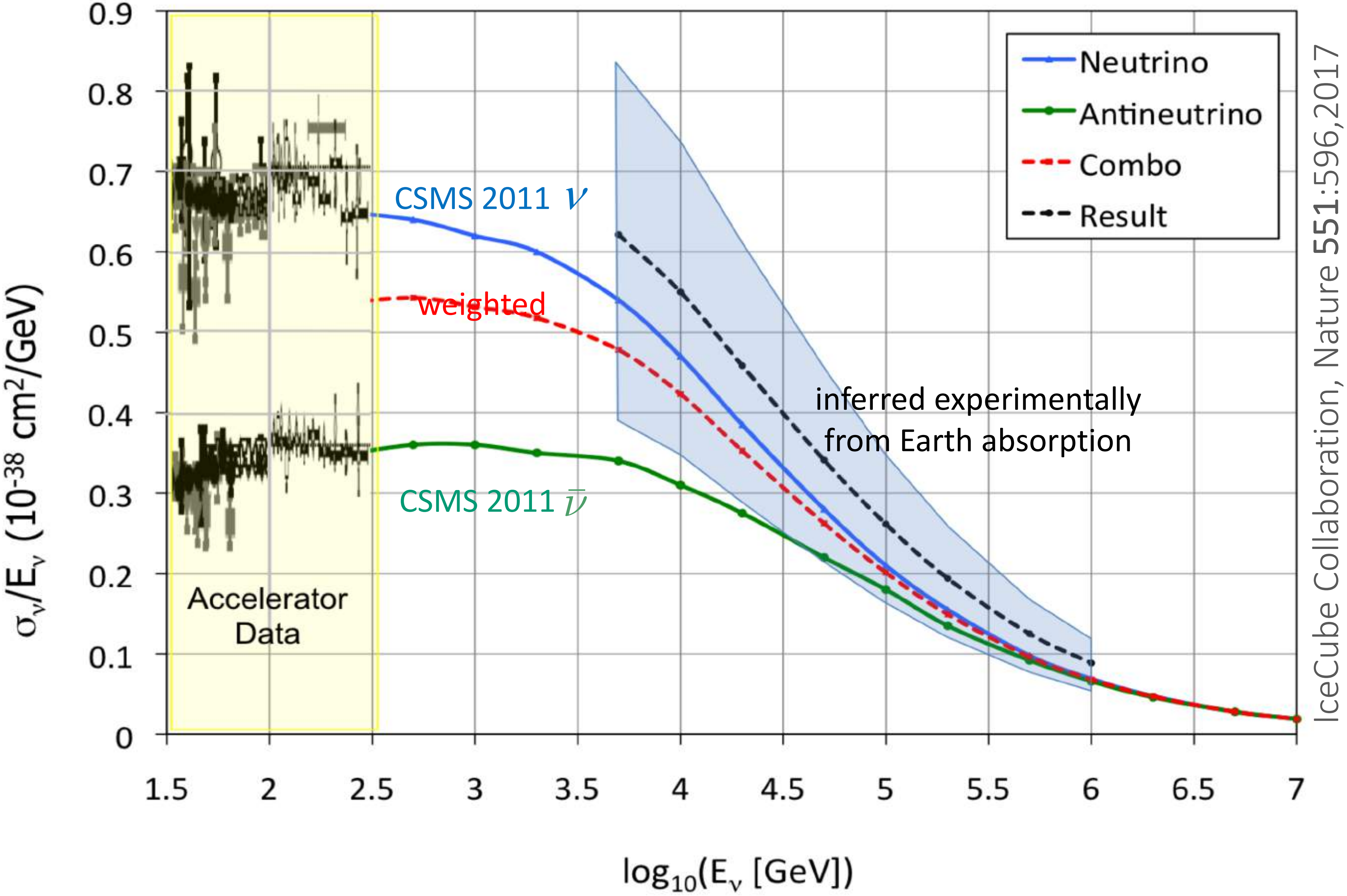
- Total ν_μ-nucleon cross section = $1.30\ ^{+0.30}_{-0.26}$ (stat.) $^{+0.32}_{-0.39}$ (syst.) times CSMS 2011 expectation
    - Energy range 5.6 TeV to 620 TeV
- In agreement with the Standard Model cross section at high energy
- Plans for follow-up analysis using 5+ years of data





Sandy Miarecki, ICHEP 2016

No evidence of deviation (within ±30%) from SM up to 620 TeV

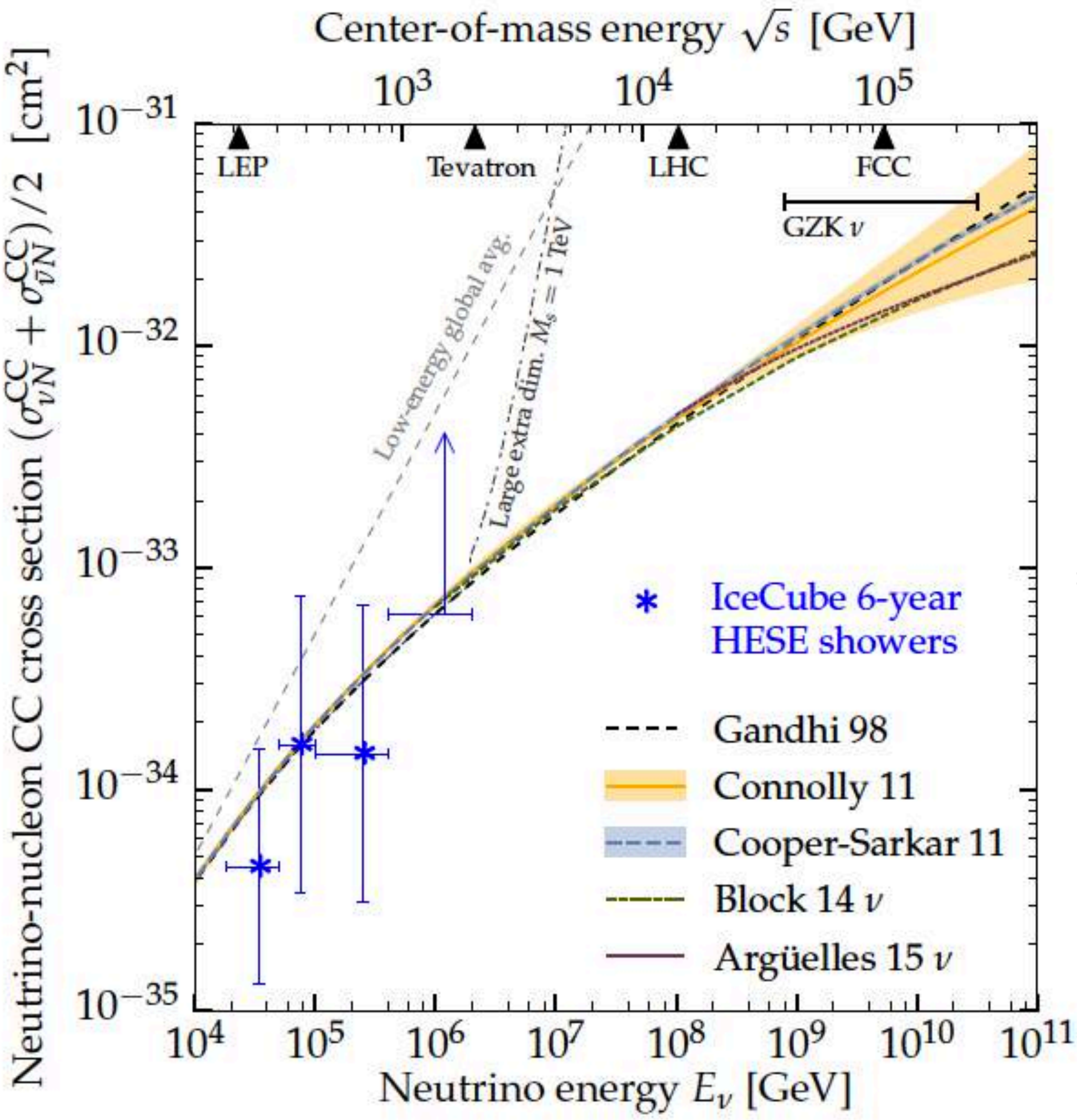


IceCube Collaboration, Nature **551**:596,2017

Powerful probe of new physics beyond the SM – from an *astroparticle* experiment ...

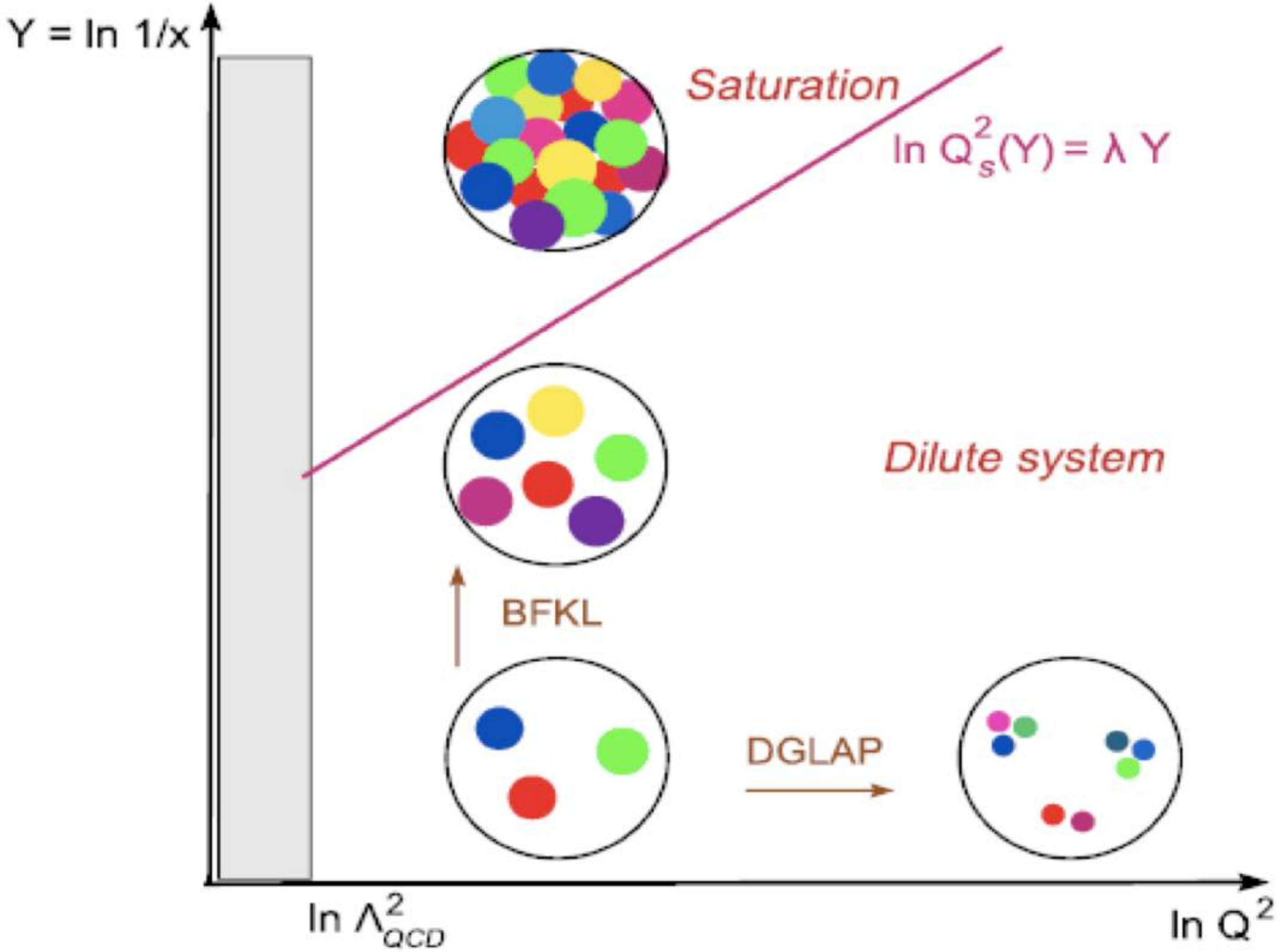
should be able to probe up to ~10^9 GeV using cosmogenic ν ... with **IceCube-Gen2**!

Constrains e.g. large new dimension at low scales (but LHC got there first!)



Bustamante & Connolly, arXiv:1711.11043

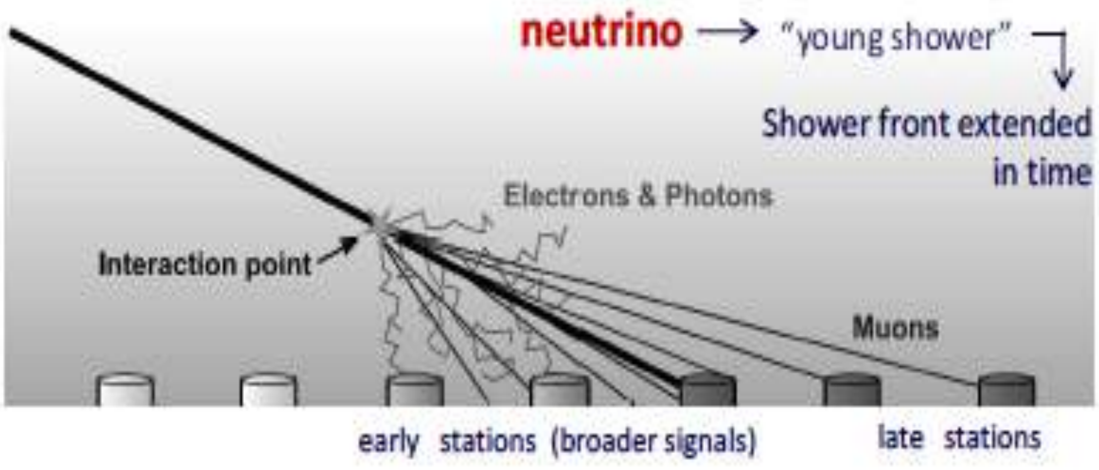
As the gluon density rises at low x, non-perturbative effects must become important … a new phase of QCD – Colour Glass Condensate – has been postulated to exist (and has some support from RHIC and ALICE data)

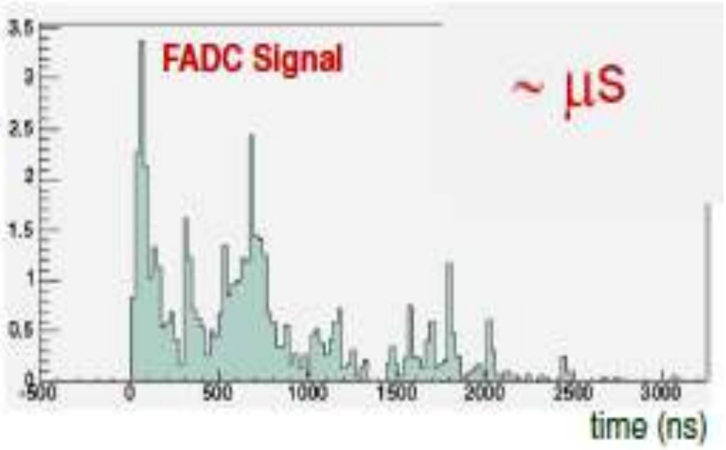


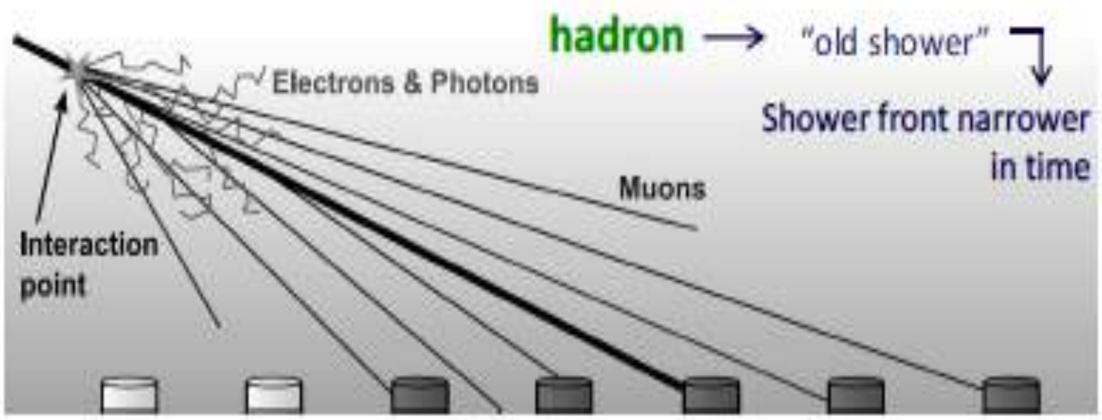
This would strongly suppress the ν-N #-secn below its (unscreened) SM value

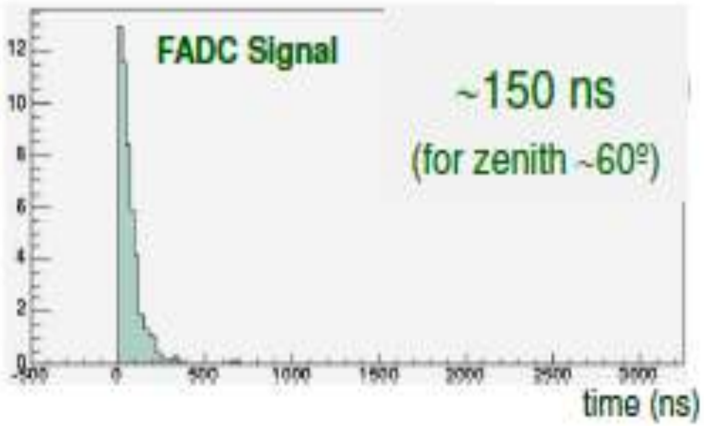
… can we test this experimentally with UHE cosmic neutrinos?

An unexpected bonus – UHE neutrino detection with air shower arrays









(courtesey:Sergio Navas)

When a cosmic ray (hadron) interacts close to the horizon, the large path length in the atmosphere ensures absorption of charged particles apart from very high energy muons ...

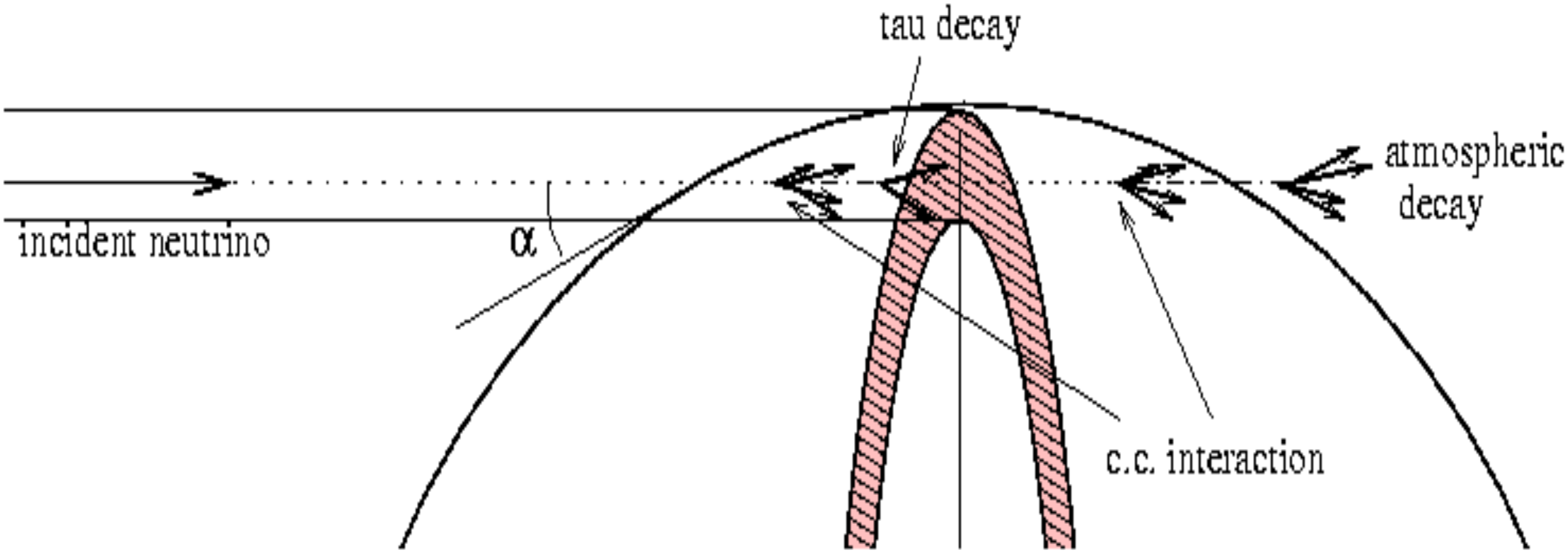
However neutrinos can penetrate through the atmosphere and interact close to the array so if we see a *young* shower at a *large* zenith angle, that is a candidate for a UHE neutrino!

Event rate ∝ cosmic neutrino flux (all flavours) *and* ν-N DIS cross-section

An unexpected bonus – UHE neutrino detection with air shower arrays

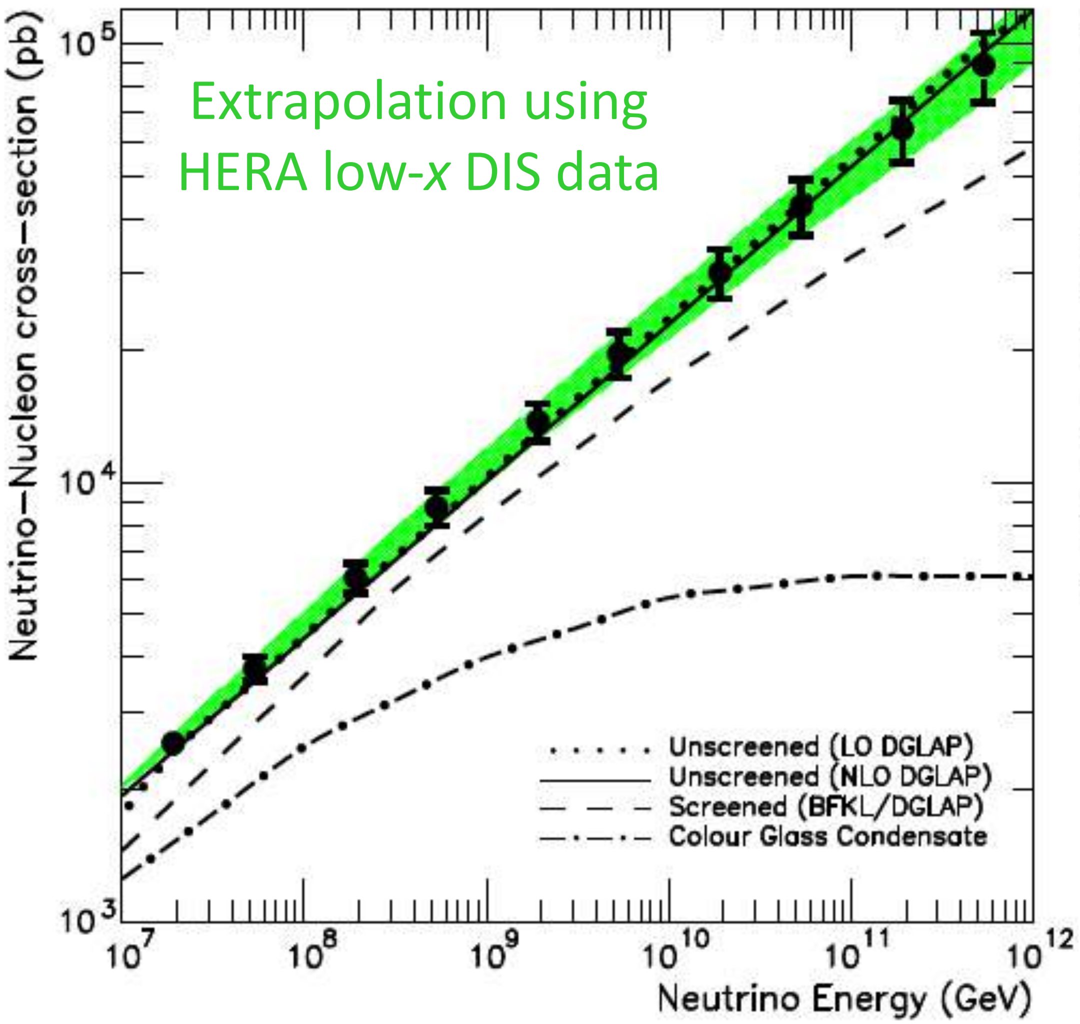
Auger can also see Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower (detectable only because the surface detector tanks are raised above the ground)

Neutrino oscillations en-route to Earth should *equlibrate* flavours with $\nu_e : \nu_\mu : \nu_\tau :: 1:1:1$ so there will be tau neutrinos in the cosmic beam regardless of initial composition

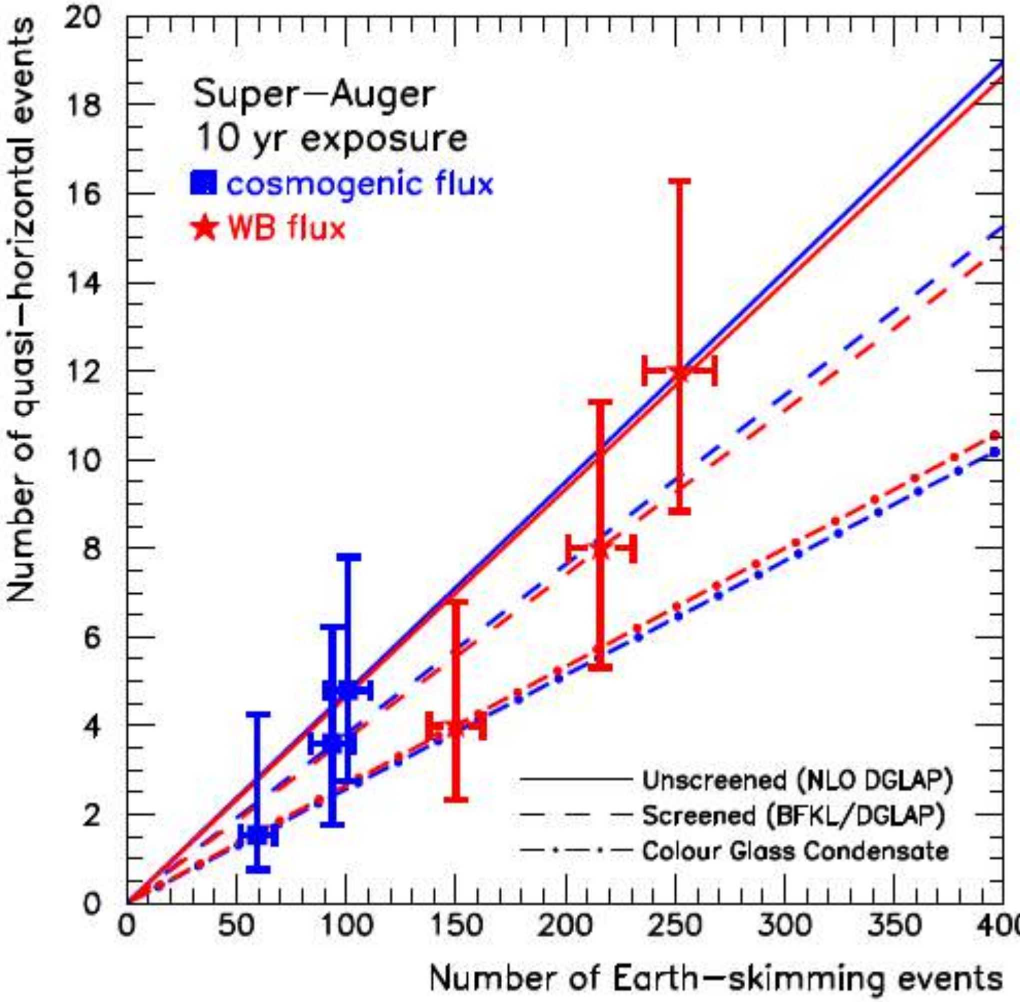


The rate is still ∝ the cosmic neutrino flux, but *not* to the ν-N #-section (since higher values also imply stronger *absorption* in the Earth)

Hence low-x QCD *can* be probed with cosmic UHE neutrinos with a *very* large detector … unfortunately Auger-N was *not* built



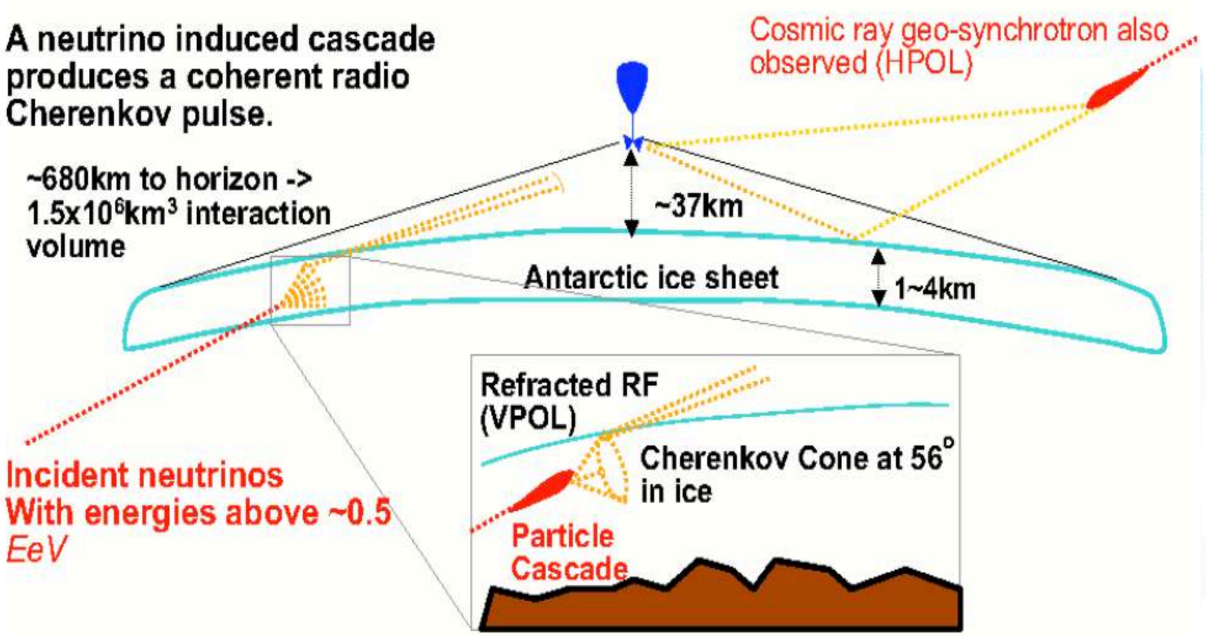
The steep rise of the gluon density at low-x must saturate (unitarity!) ⇒ suppression of the ν-N #-section



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

Anchordoqui, Cooper-Sarkar, Hooper, Sarkar, Phys.Rev.D**74**:043008,2006

Meanwhile radio signals spotted from unusual *upward*-going air showers



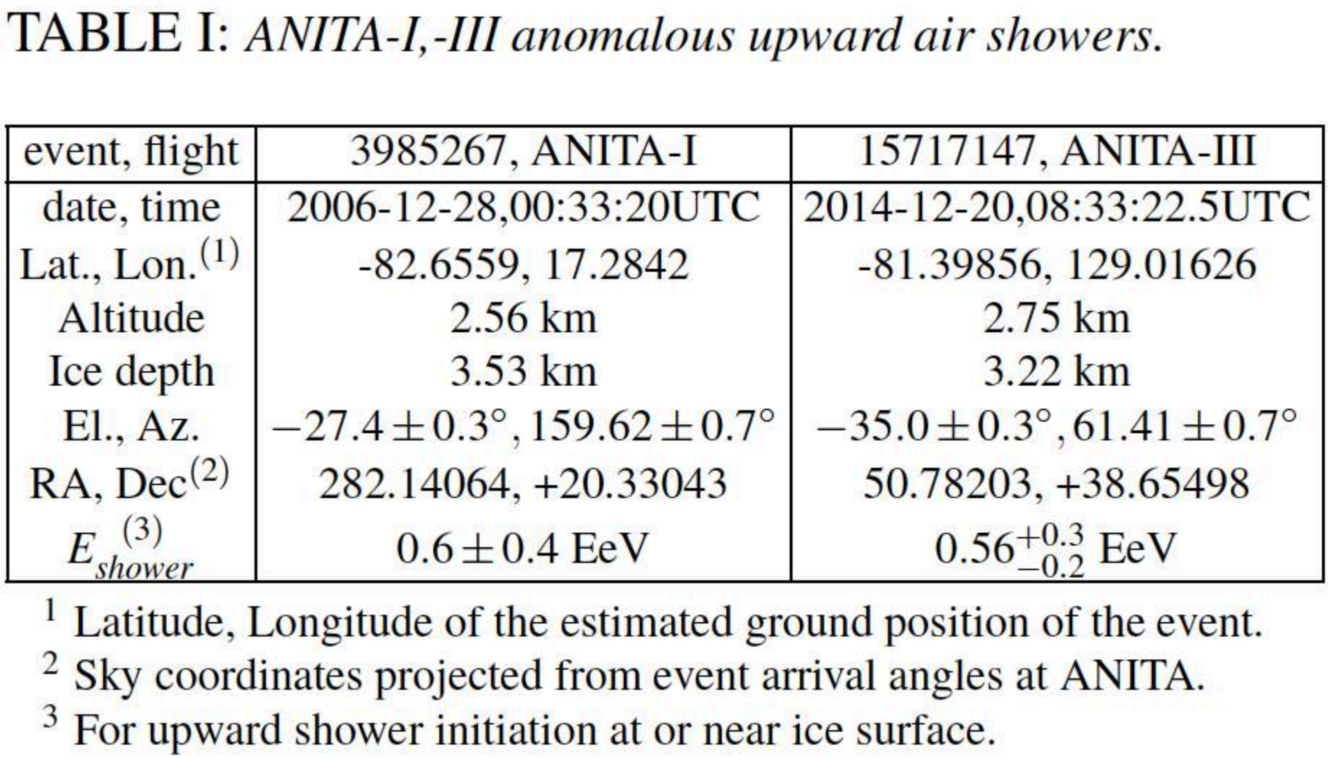


TABLE I: *ANITA-I,-III anomalous upward air showers.*

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.(1)	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4\pm0.3^\circ, 159.62\pm0.7^\circ$	$-35.0\pm0.3^\circ, 61.41\pm0.7^\circ$
RA, Dec(2)	282.14064, +20.33043	50.78203, +38.65498
$E_{shower}^{(3)}$	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

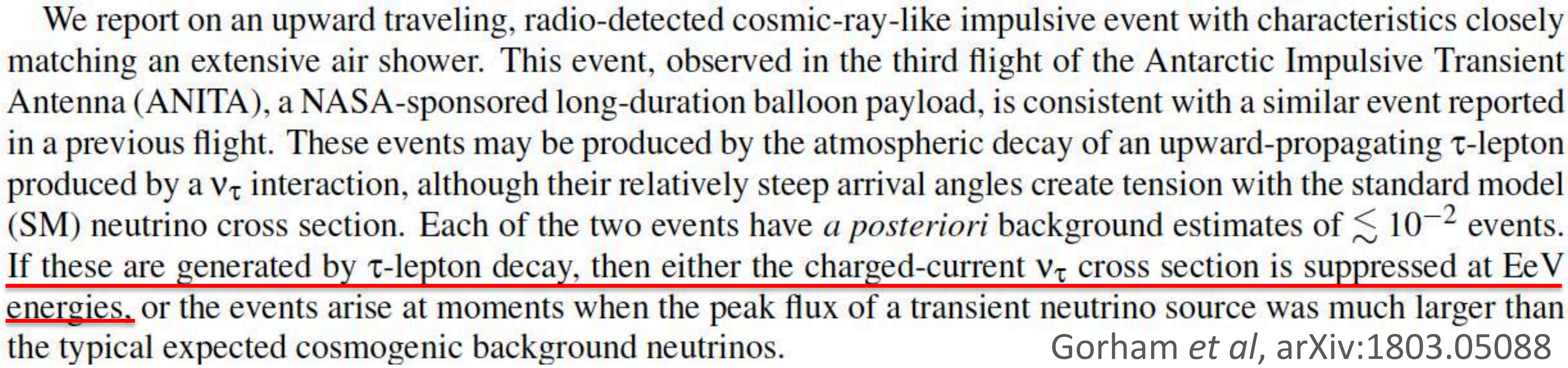
[1] Latitude, Longitude of the estimated ground position of the event.

[2] Sky coordinates projected from event arrival angles at ANITA.

[3] For upward shower initiation at or near ice surface.

Gorham *et al*, arXiv:1803.05088

Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA



We report on an upward traveling, radio-detected cosmic-ray-like impulsive event with characteristics closely matching an extensive air shower. This event, observed in the third flight of the Antarctic Impulsive Transient Antenna (ANITA), a NASA-sponsored long-duration balloon payload, is consistent with a similar event reported in a previous flight. These events may be produced by the atmospheric decay of an upward-propagating τ-lepton produced by a ν_τ interaction, although their relatively steep arrival angles create tension with the standard model (SM) neutrino cross section. Each of the two events have *a posteriori* background estimates of $\lesssim 10^{-2}$ events. If these are generated by τ-lepton decay, then either the charged-current ν_τ cross section is suppressed at EeV energies, or the events arise at moments when the peak flux of a transient neutrino source was much larger than the typical expected cosmogenic background neutrinos.

Gorham *et al*, arXiv:1803.05088

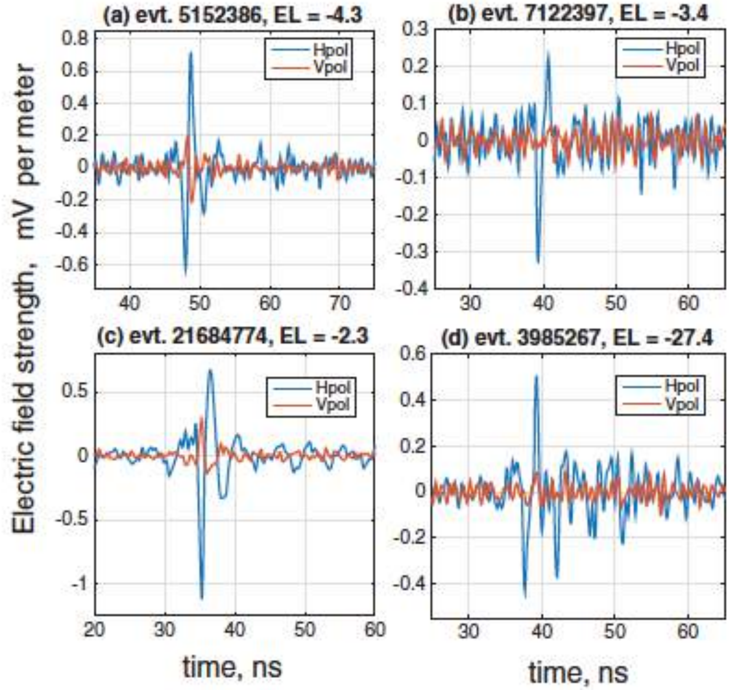
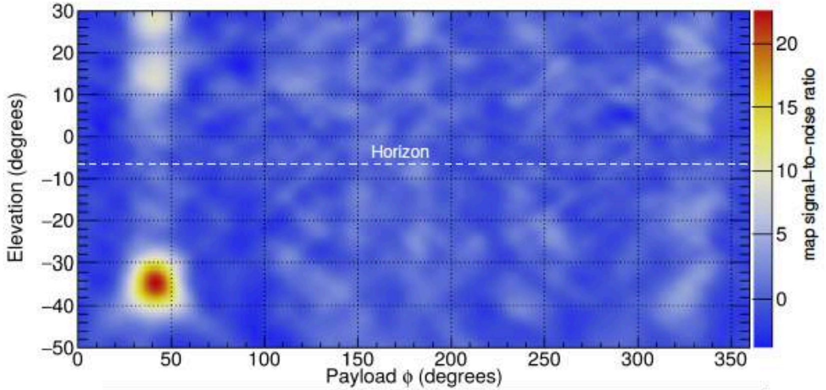
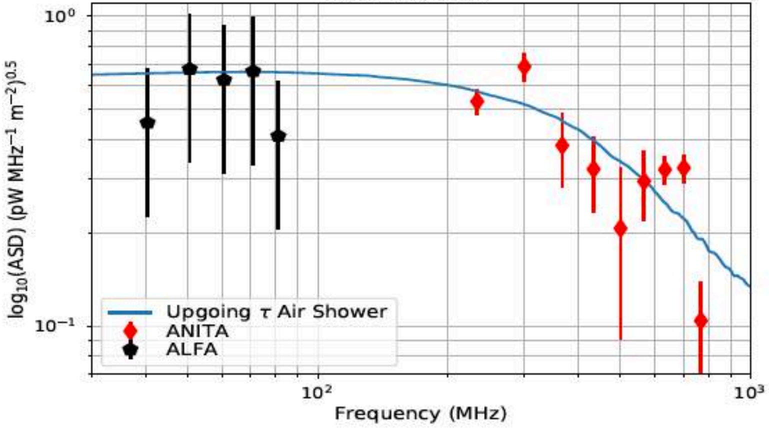


FIG. 1. Waveforms for the four events described here. Events are indexed here and in the text by the letters A, B, C, and D.



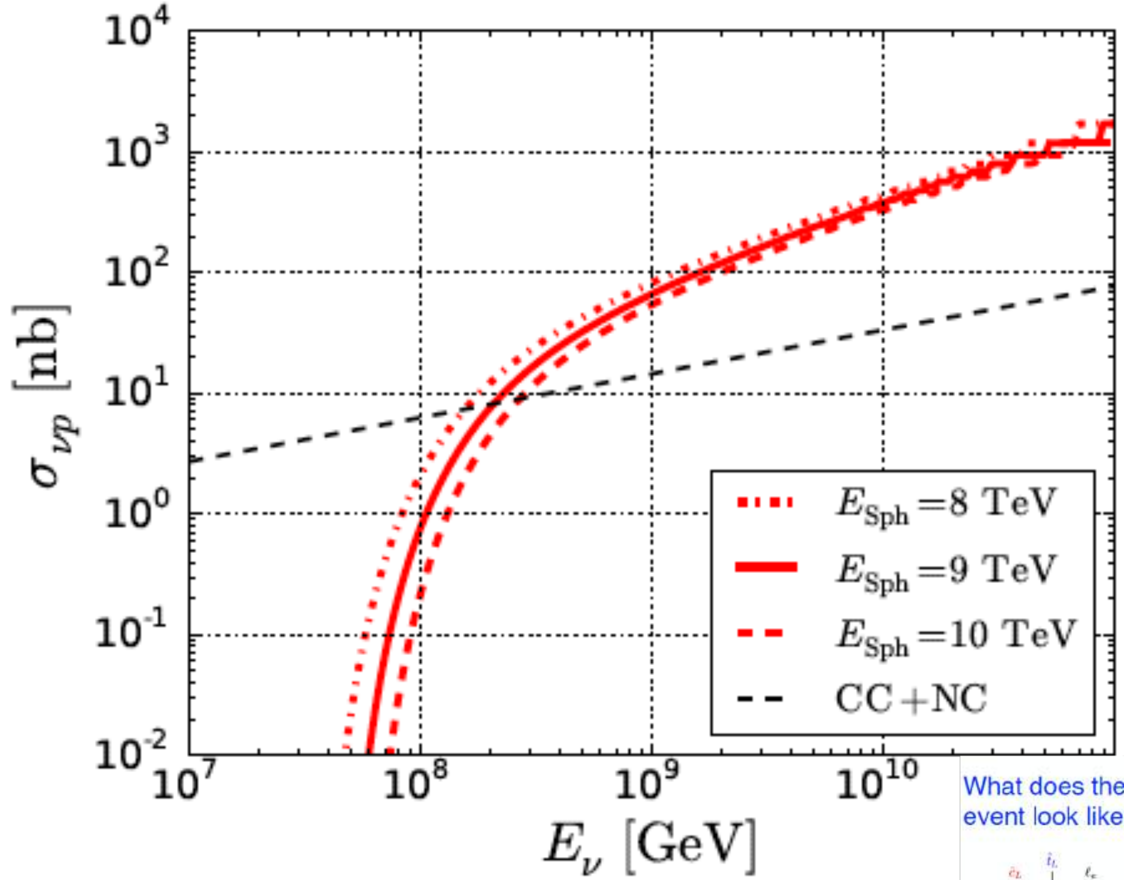


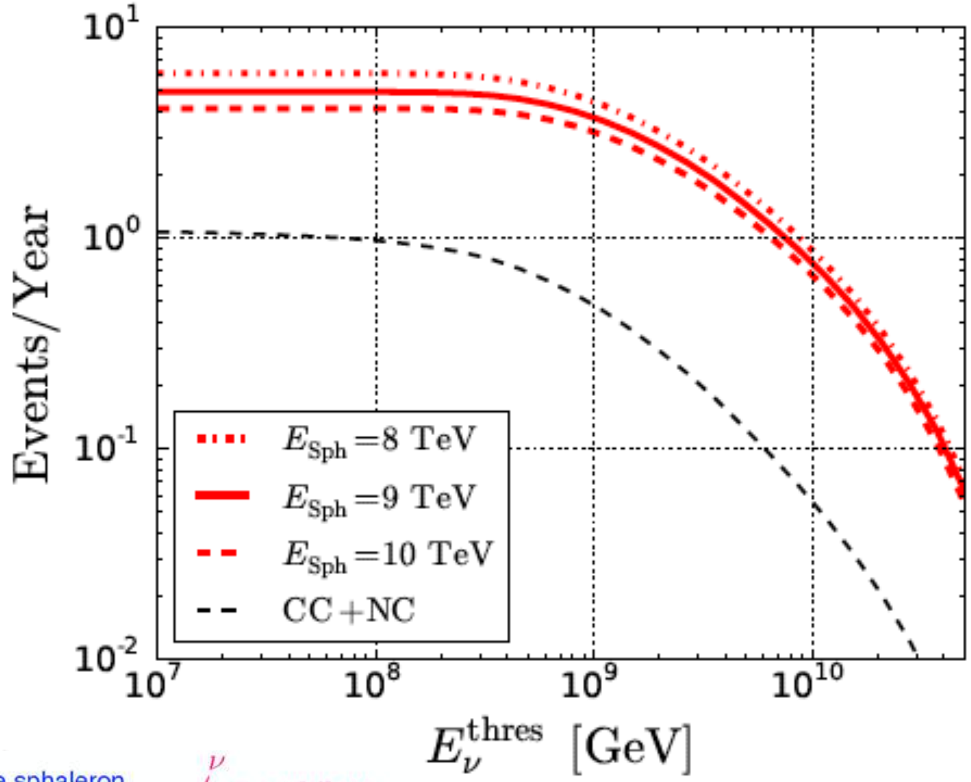
… or the *ν-N* cross-section may be much *higher* than in the SM

Non-perturbative transitions between degenerate *SU*(2) vacuua (with different *B*+*L* #) are *exponentially* suppressed below the "sphaleron" mass: $\sim M_W/\alpha_W \sim 9$ TeV (update by Tye & Wong, PRD **92**:045005,2015) … *large* cross-sections are predicted for *ν-N* scattering at higher cms energies

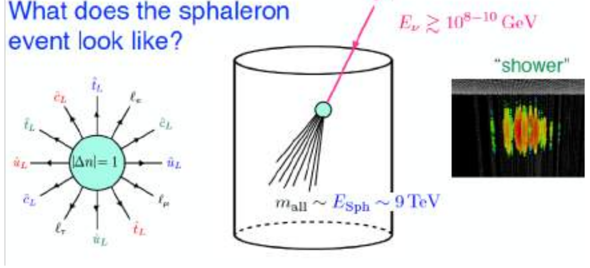
$$\boxed{E_\nu \geq E_{\rm sph}^2/2xm_N \simeq 4 \times 10^7/x \sim 10^{9-11}\ {\rm GeV}}$$

Han & Hooper, PLB **582**:21,2004



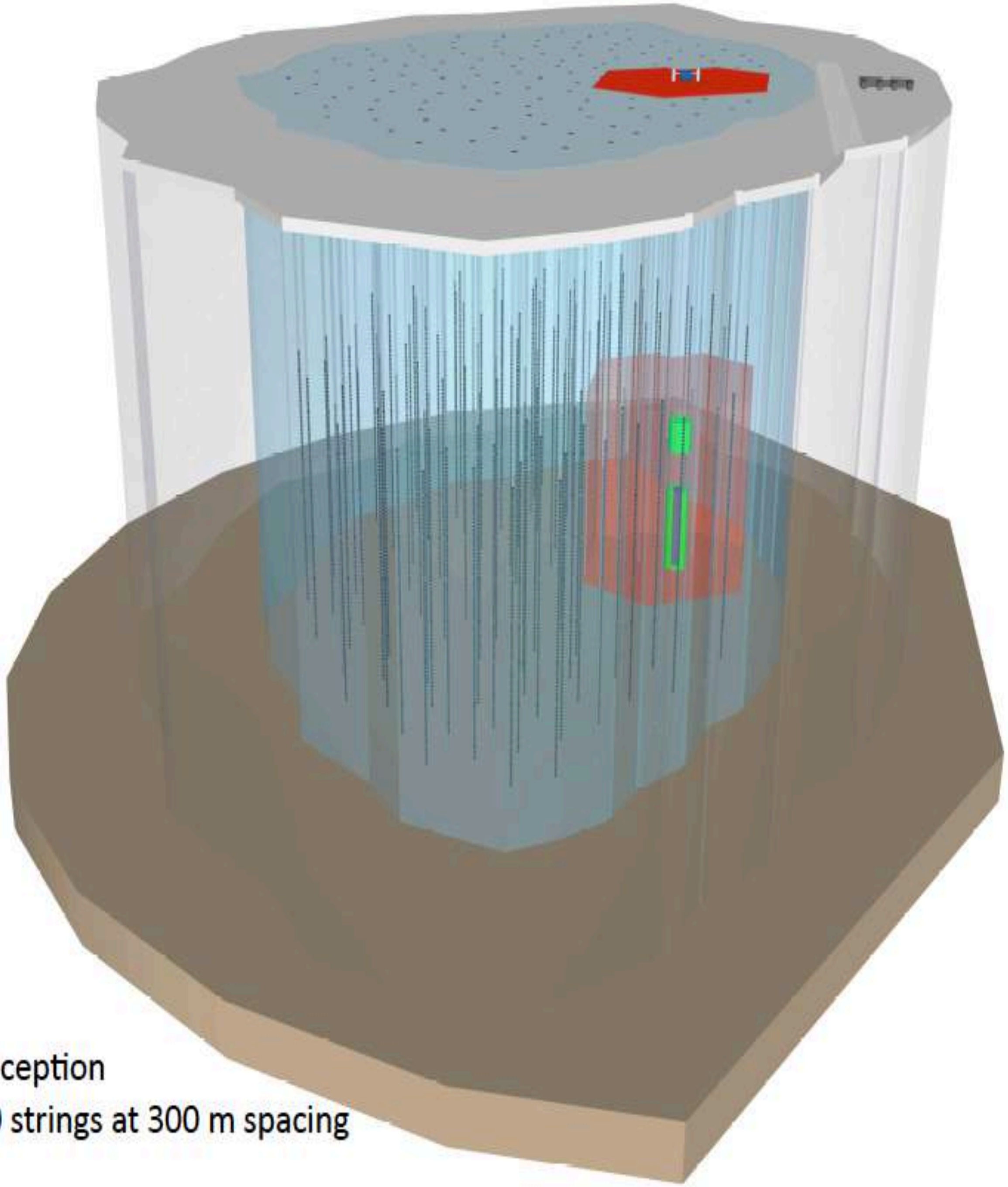


Ellis, Sakurai & Spannowsky, arXiv:1603.06573


What does the sphaleron event look like?

IceCube has sensitivity to EW sphalerons comparable to LHC!

To do astronomy *and* particle physics with cosmic neutrinos we must think BIG!



Artist conception

Here: 120 strings at 300 m spacing

IceCube-Gen2