Probing low-x QCD with cosmic neutrinos

Subir Sarkar

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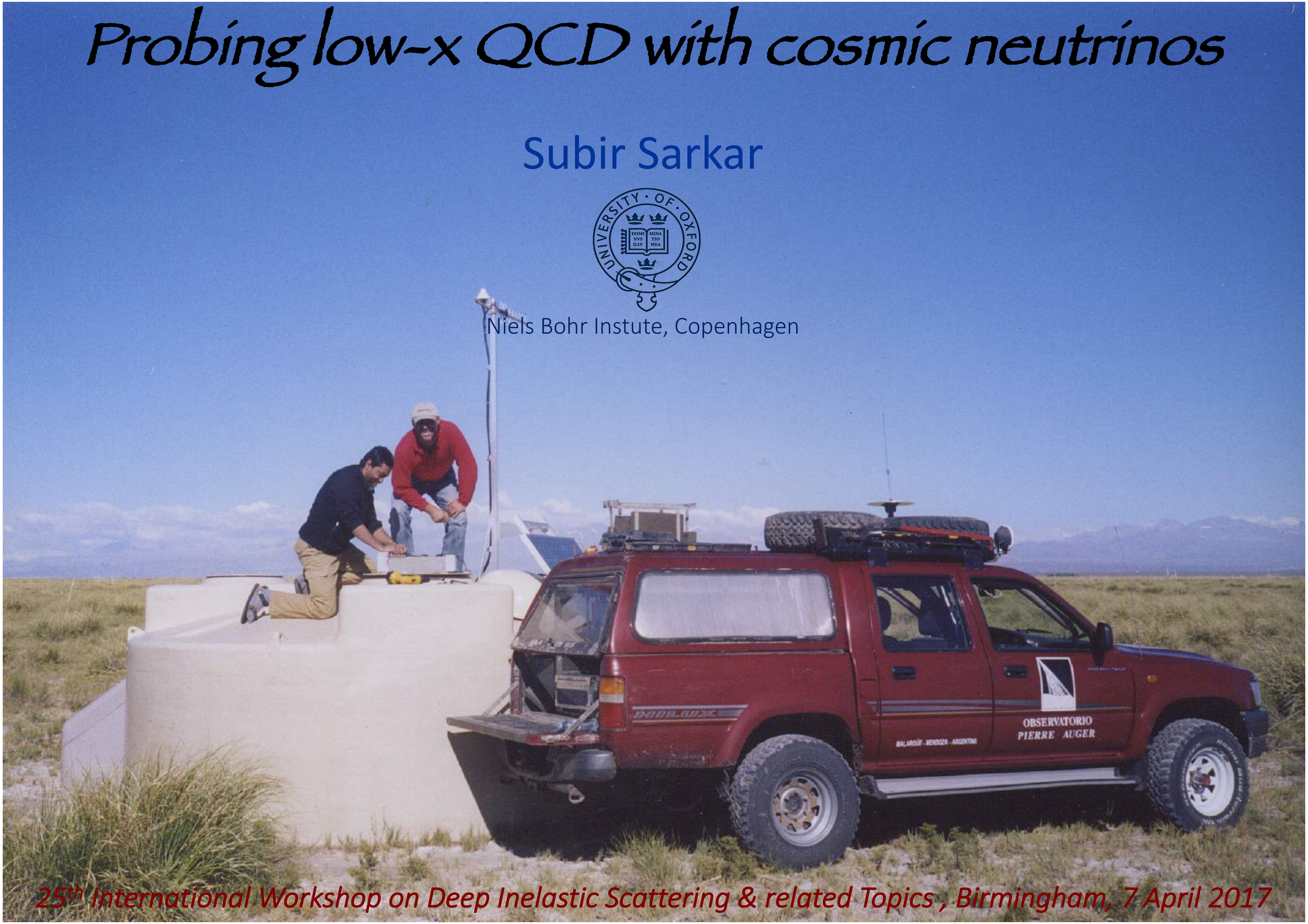
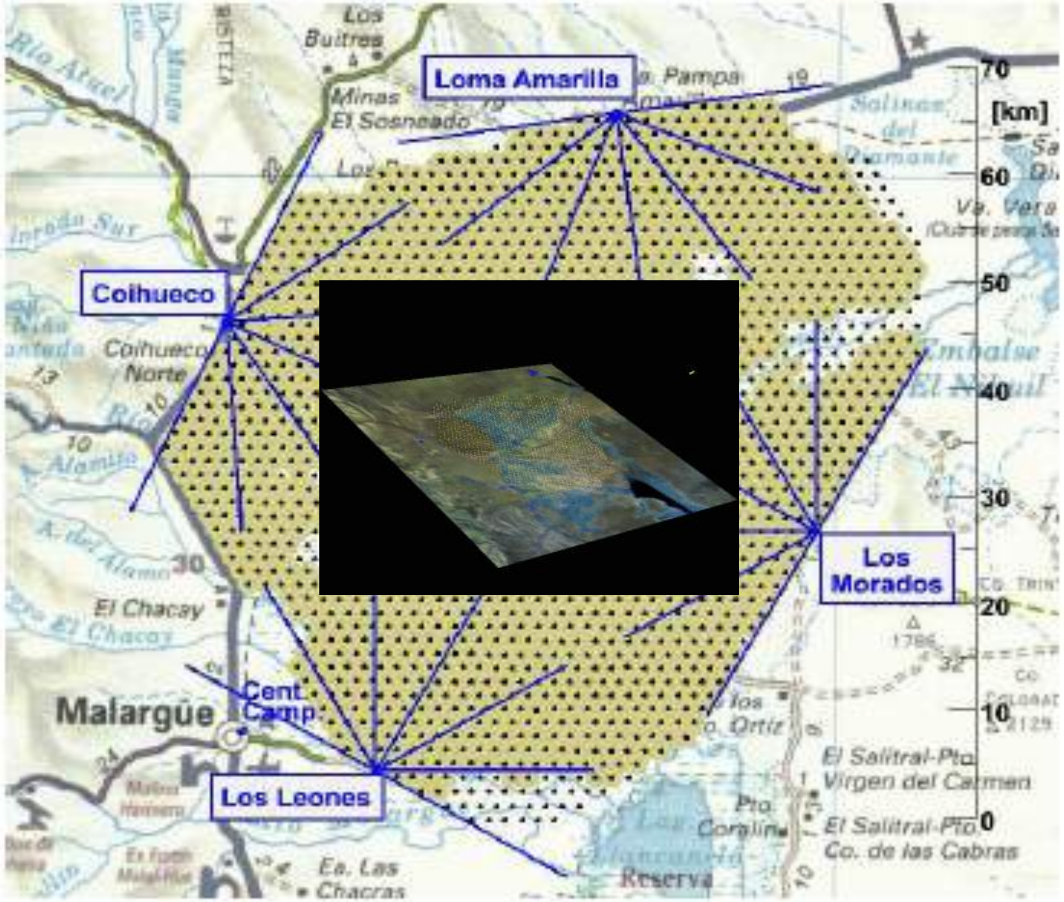
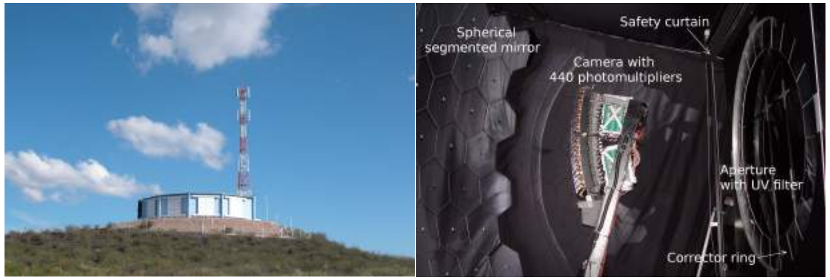


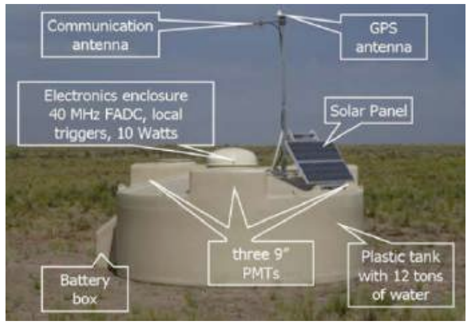
25th International Workshop on Deep Inelastic Scattering & related Topics , Birmingham, 7 April 2017

The Pierre Auger Observatory

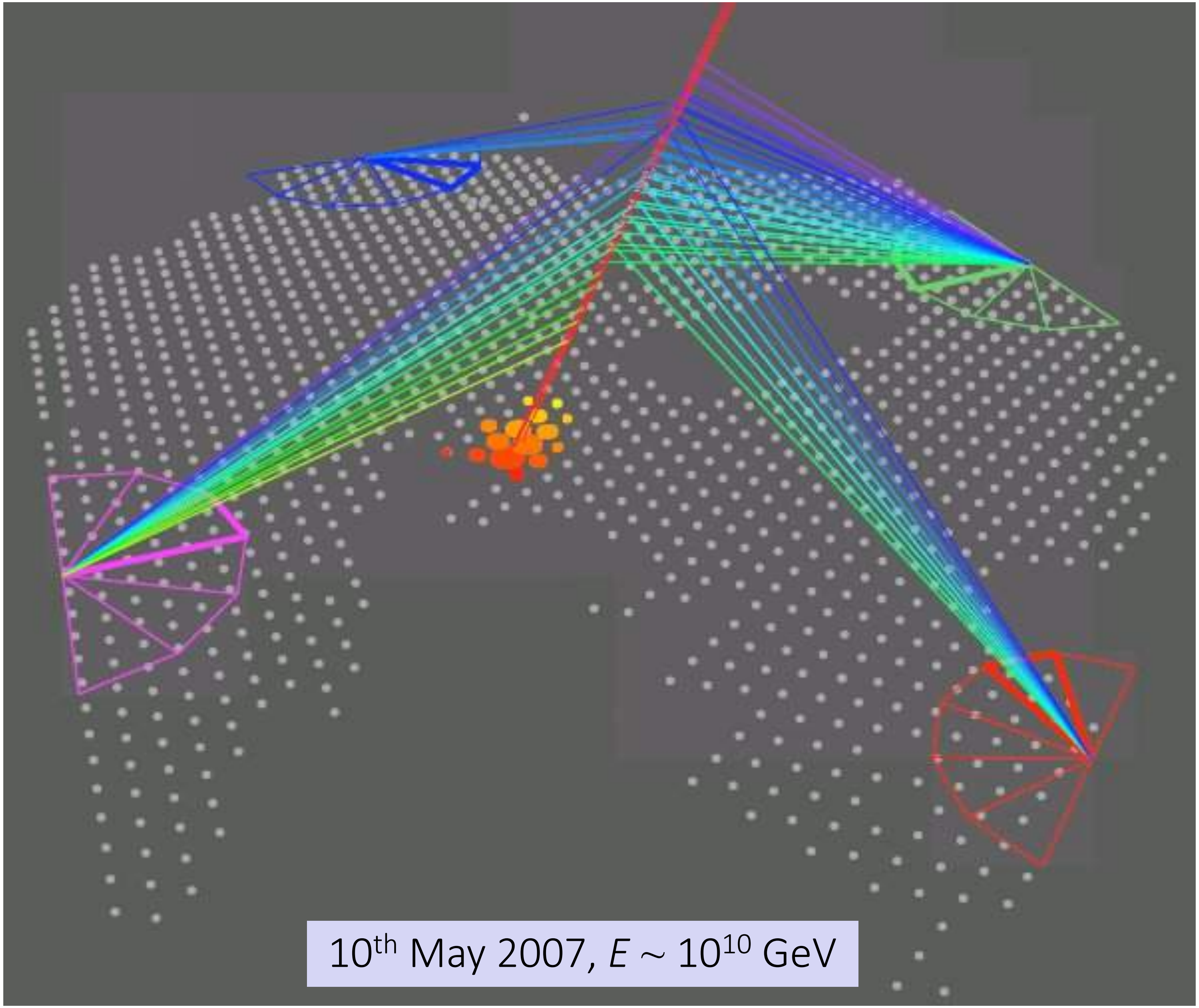




- 1600 water-cherenkov detectors
- Aperture > 7000 km^2 sr yr
- 4 × 6 telescopes

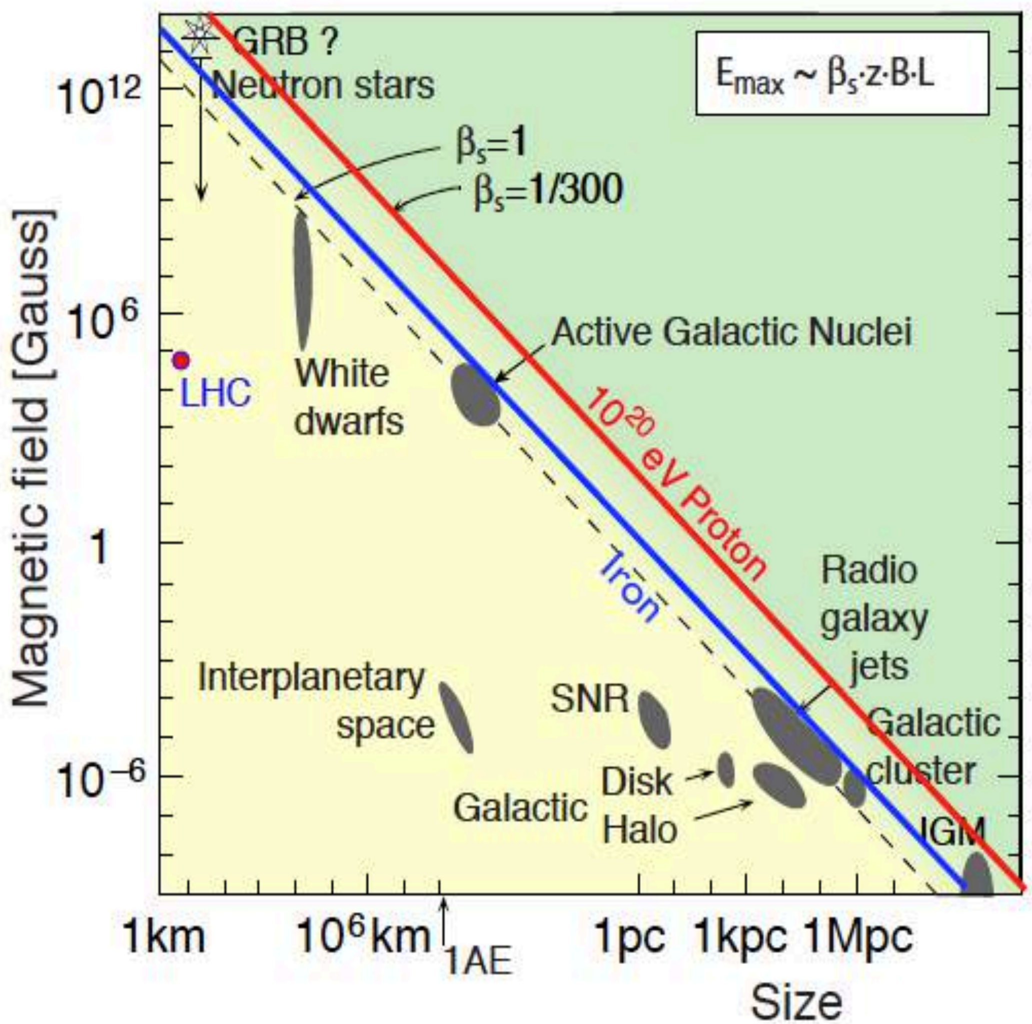


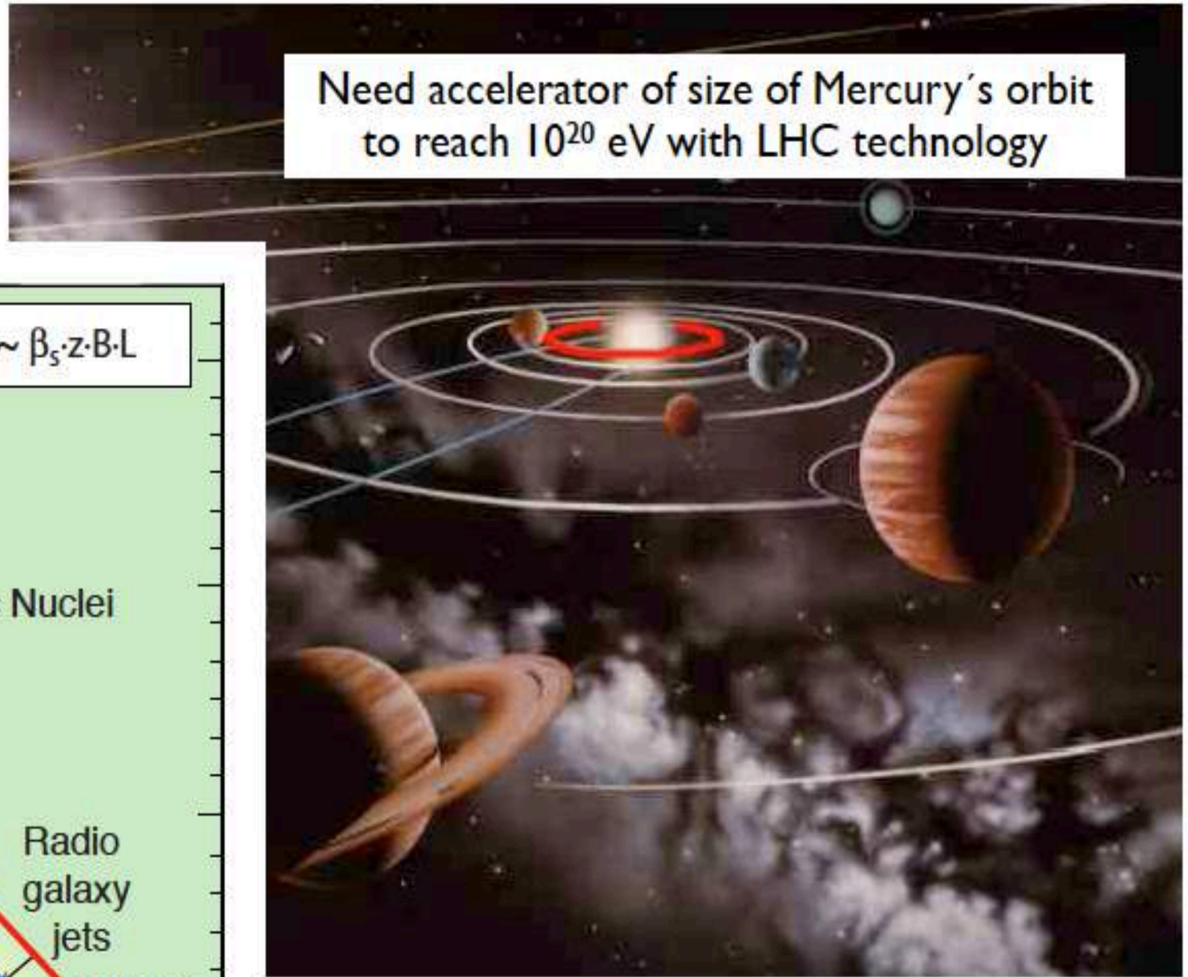
With this detector we see the *highest* energy particles in the universe



How does Nature accelerate particles to such huge energies?!

Hillas plot (1984)



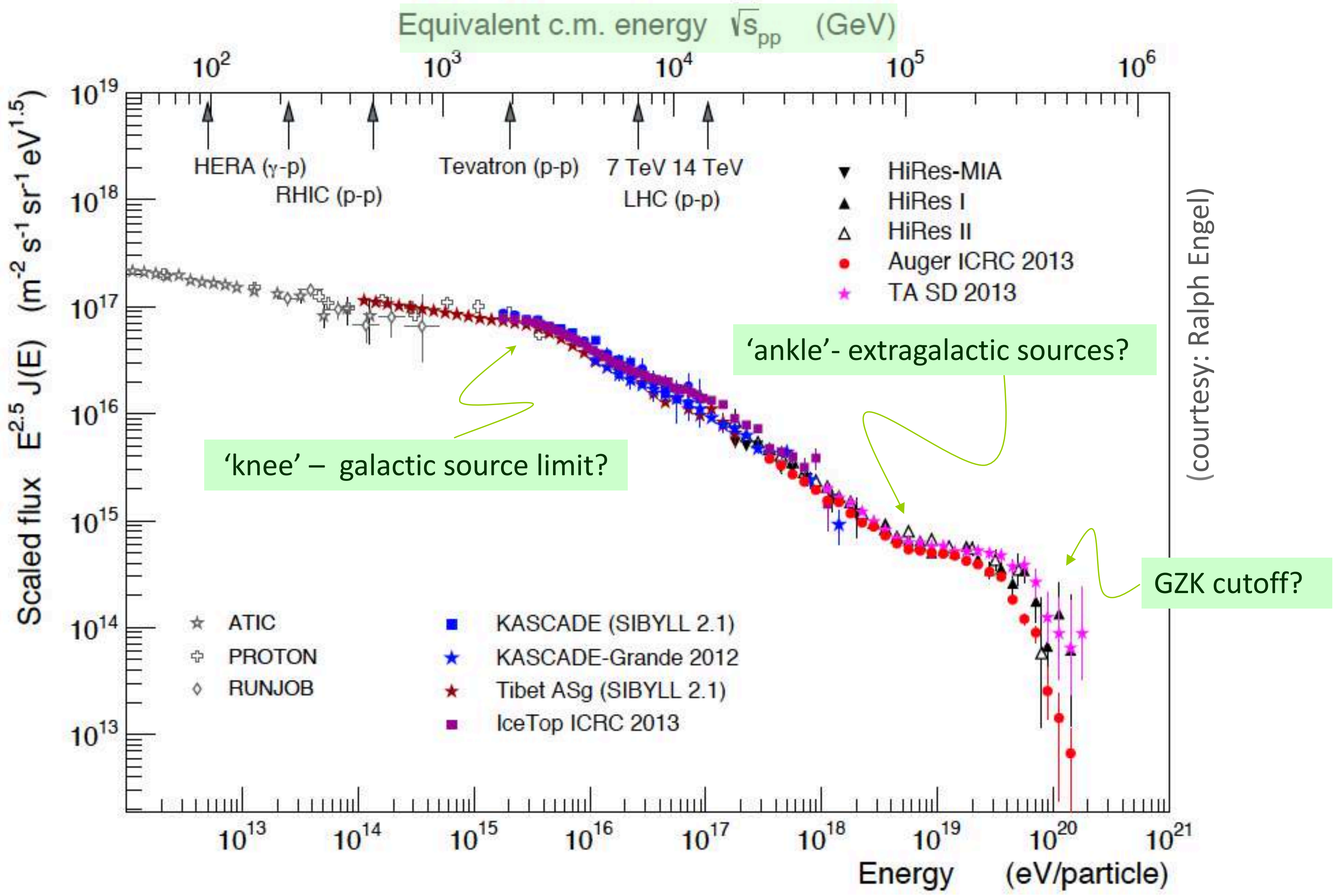


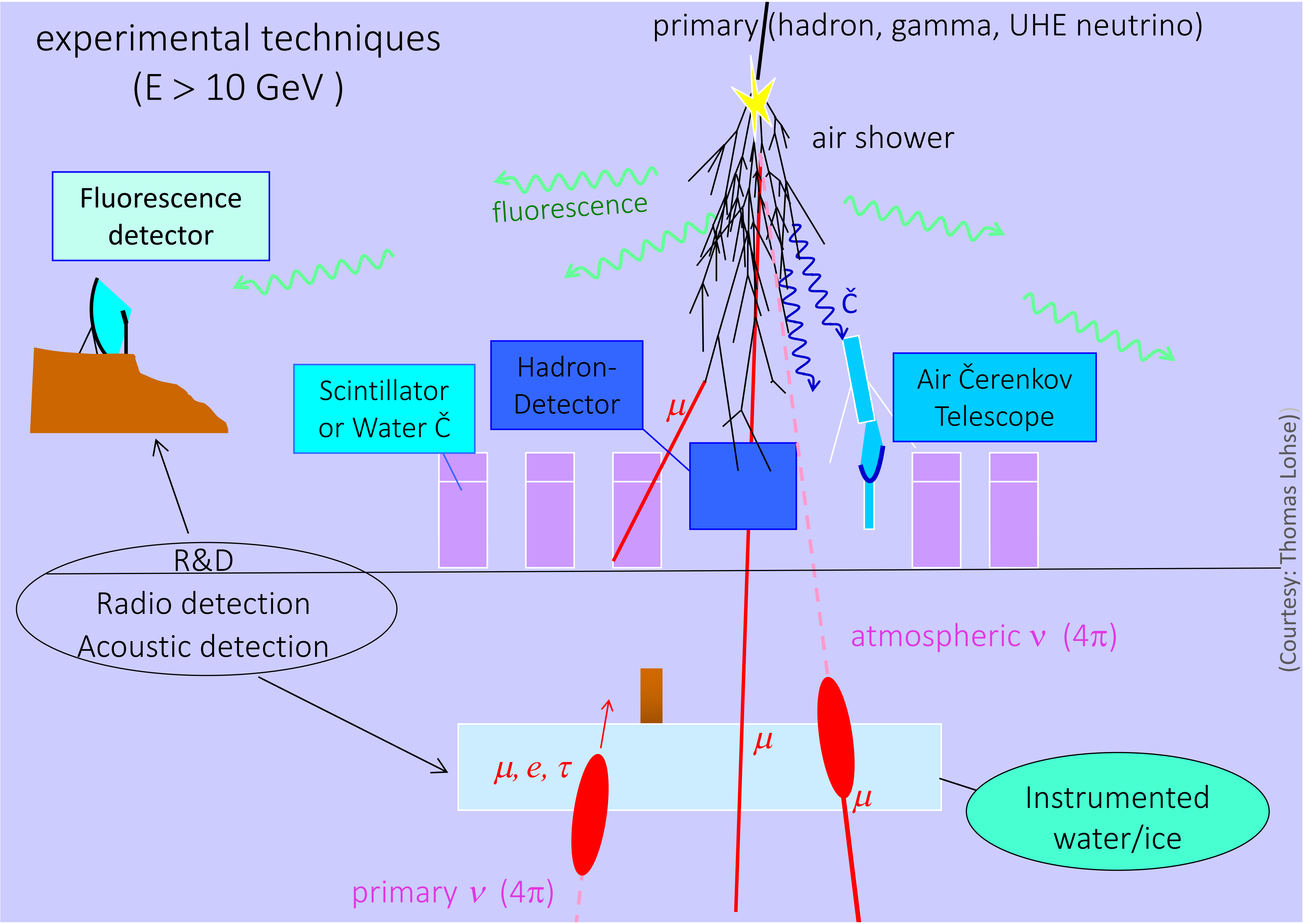
(Courtesy: Ralph Engel)

Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

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

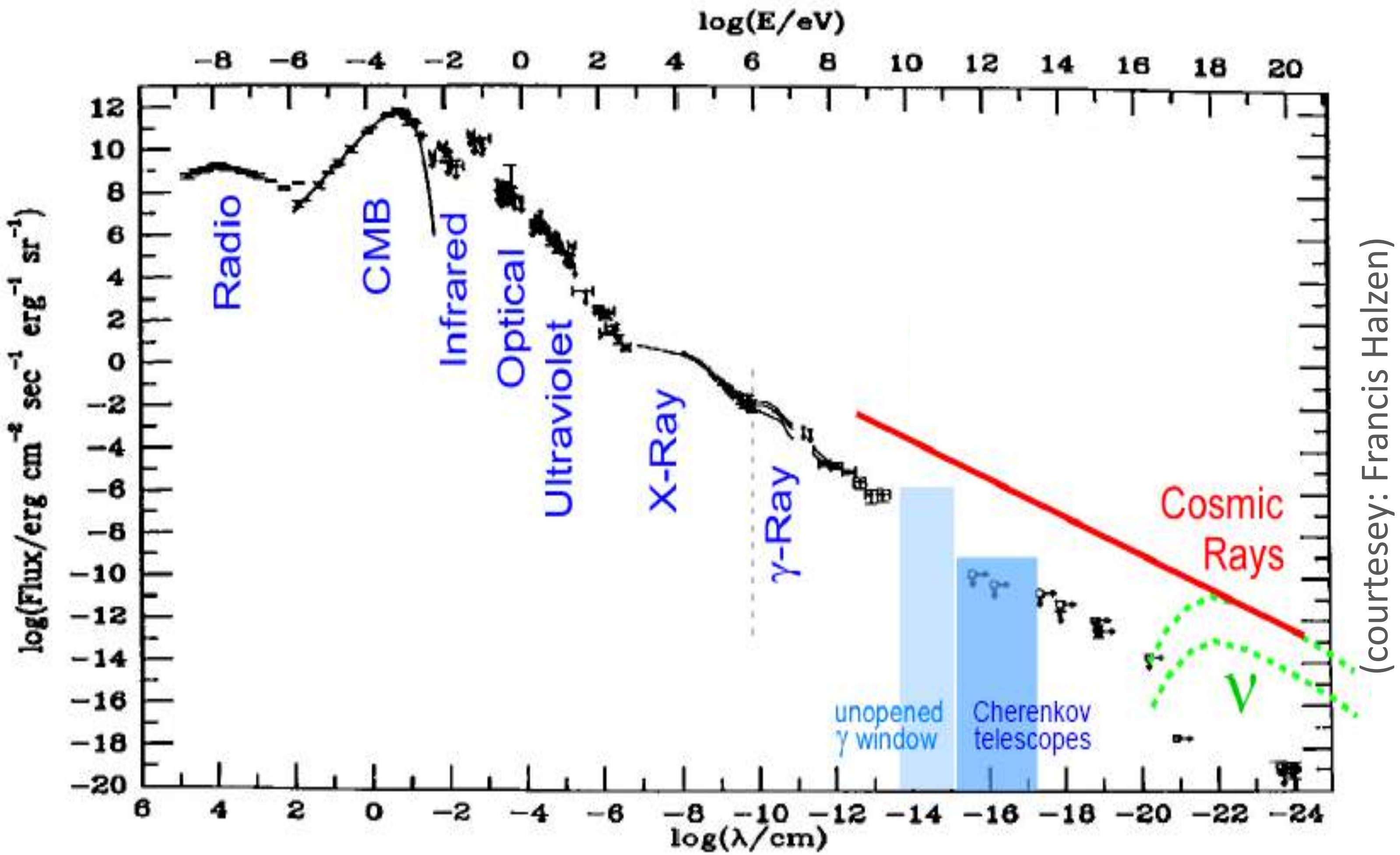




experimental techniques
(E > 10 GeV)
primary (hadron, gamma, UHE neutrino)
air shower
fluorescence
Fluorescence detector
Č
Scintillator or Water Č
Hadron-Detector
Air Čerenkov Telescope
μ
R&D
Radio detection
Acoustic detection
atmospheric ν (4π)
μ, e, τ
μ
μ
Instrumented water/ice
primary ν (4π)
(Courtesy: Thomas Lohse)

We can see the high energy universe with photons up to only a few TeV …

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



But using cosmic rays we can 'see' up to $\sim 6 \times 10^{10}$ GeV (before they are attenuated through $p\gamma \rightarrow \Delta^+ \rightarrow n\,\pi^+$ … on the CMB)

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

Colliders versus Cosmic rays

The LHC has achieved 13 TeV cms ...

But 1 EeV (10^{18} eV) cosmic ray initiating giant air shower

$\Rightarrow$ 50 TeV cms (... although rate only 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
(since the 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 flux dominates

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

motivated by trans-GZK energy events observed by AGASA

… such models are however *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 :

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

Fraction of CR primary energy converted to neutrinos

Hubble time

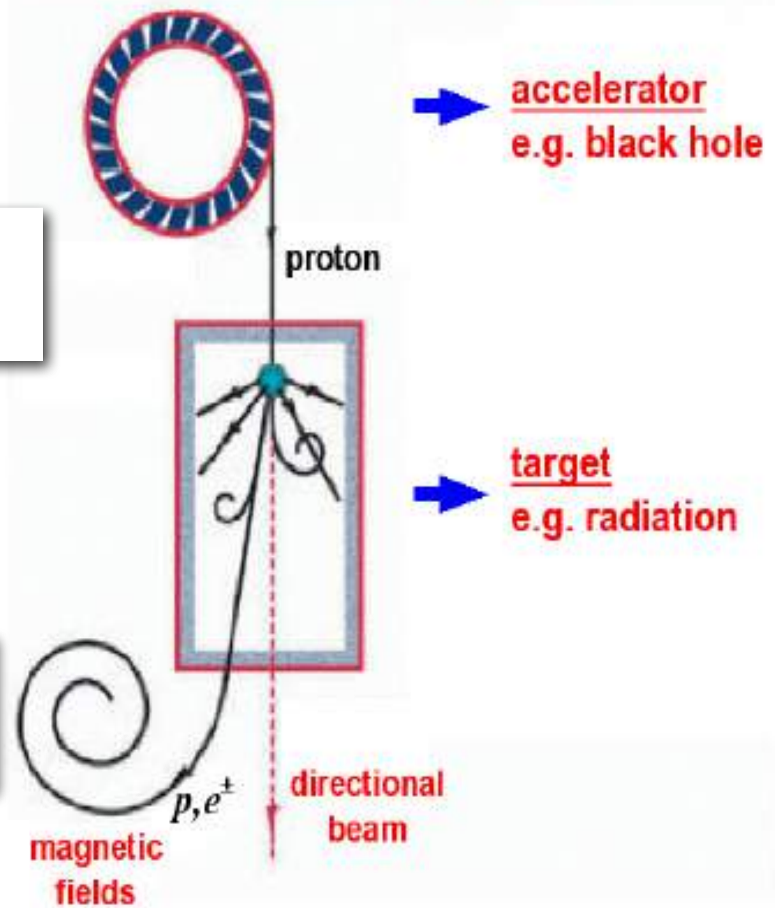
From rate of UHE CR's (10^{19}-10^{21} eV)

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

➡Making a reasonable 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')

COSMIC BEAM DUMP : SCHEMATIC



The "guaranteed" cosmogenic neutrino flux

GZK mechanism :

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

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

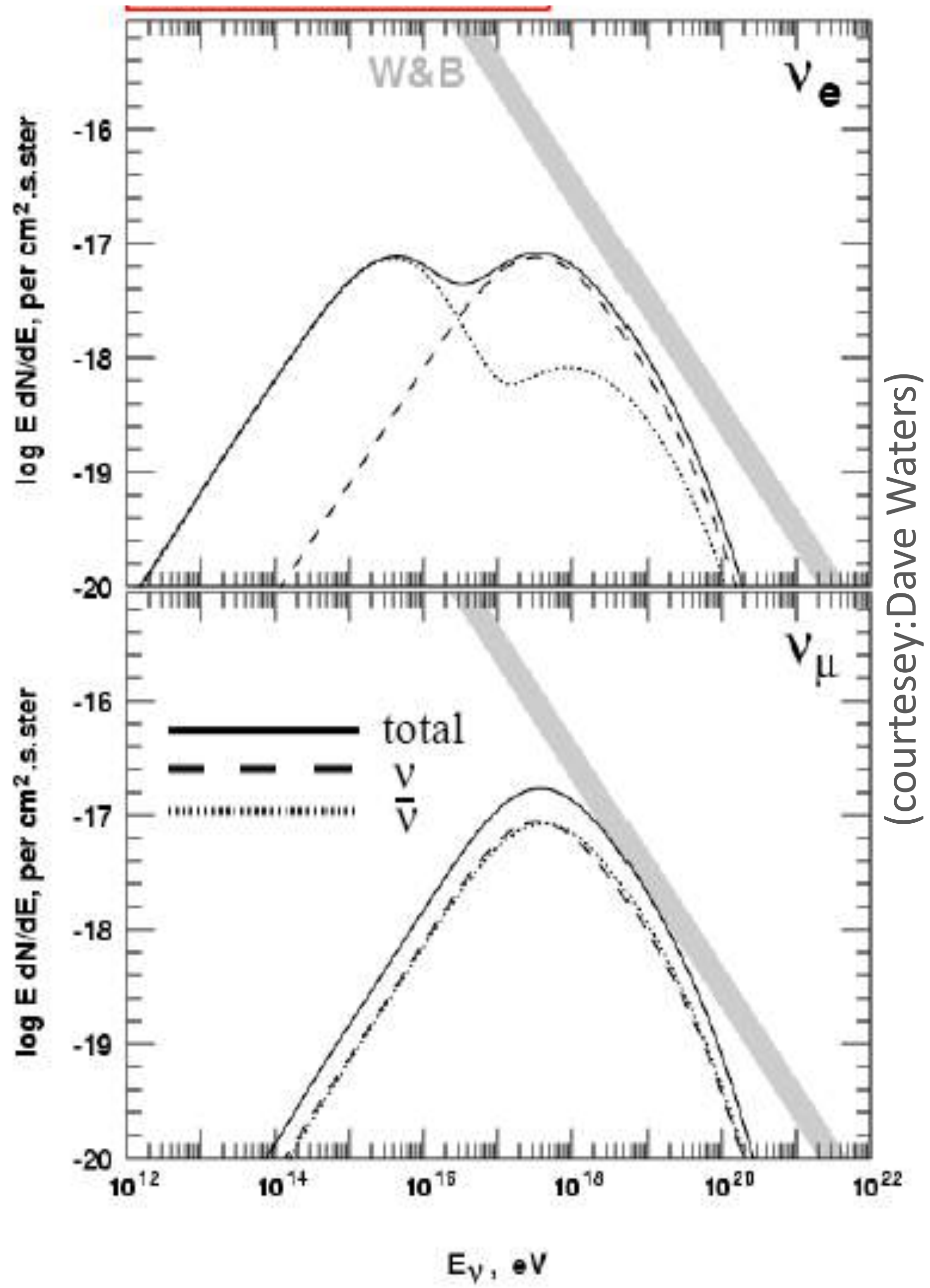
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

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

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



(courtesey:Dave Waters)

… 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 their interaction rate via ***ν-N* deep inelastic scattering**
(dominant process above ~10 GeV)

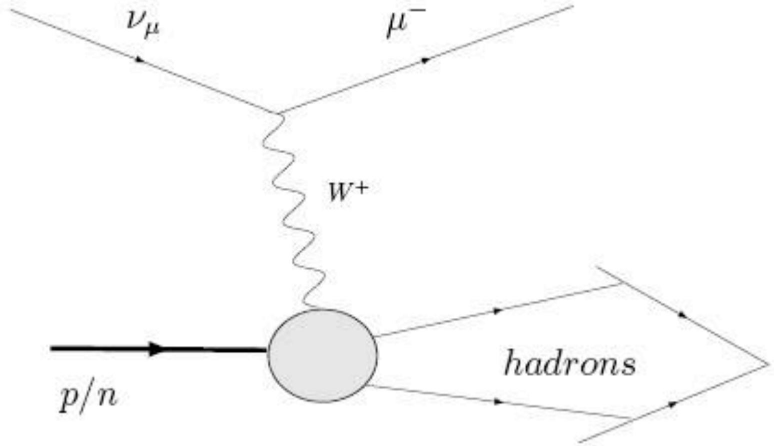
$$\frac{\partial^2 \sigma^{CC,NC}_{\nu,\bar{\nu}}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi} \left(\frac{M_i^2}{Q^2 + M_i^2} \right)$$

$Q^2 \uparrow \Rightarrow$ 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 $\uparrow$



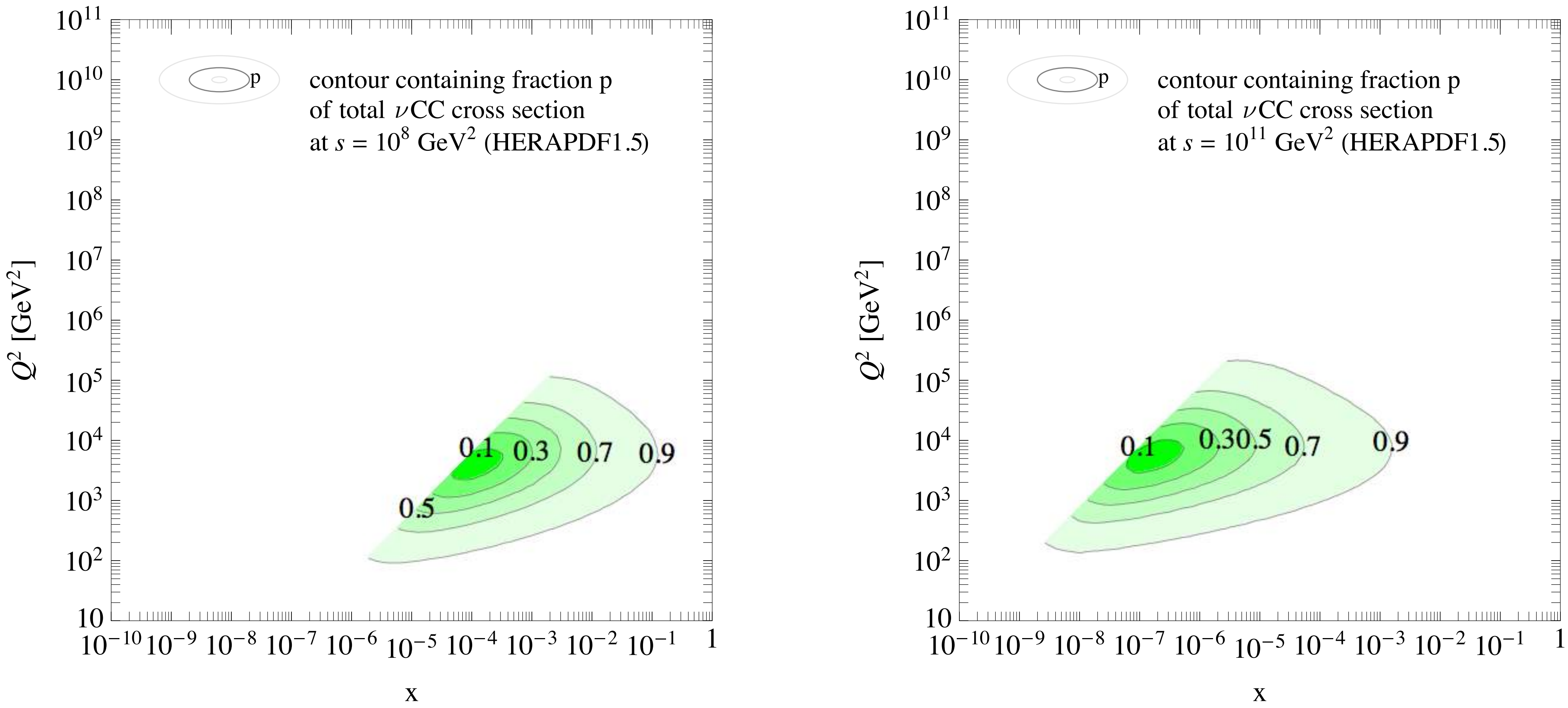
Most of the contribution to #-secn comes from: $Q^2 \sim M_W^2$ *and* $x \sim \frac{M_W^2}{M_N E_\nu}$

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

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

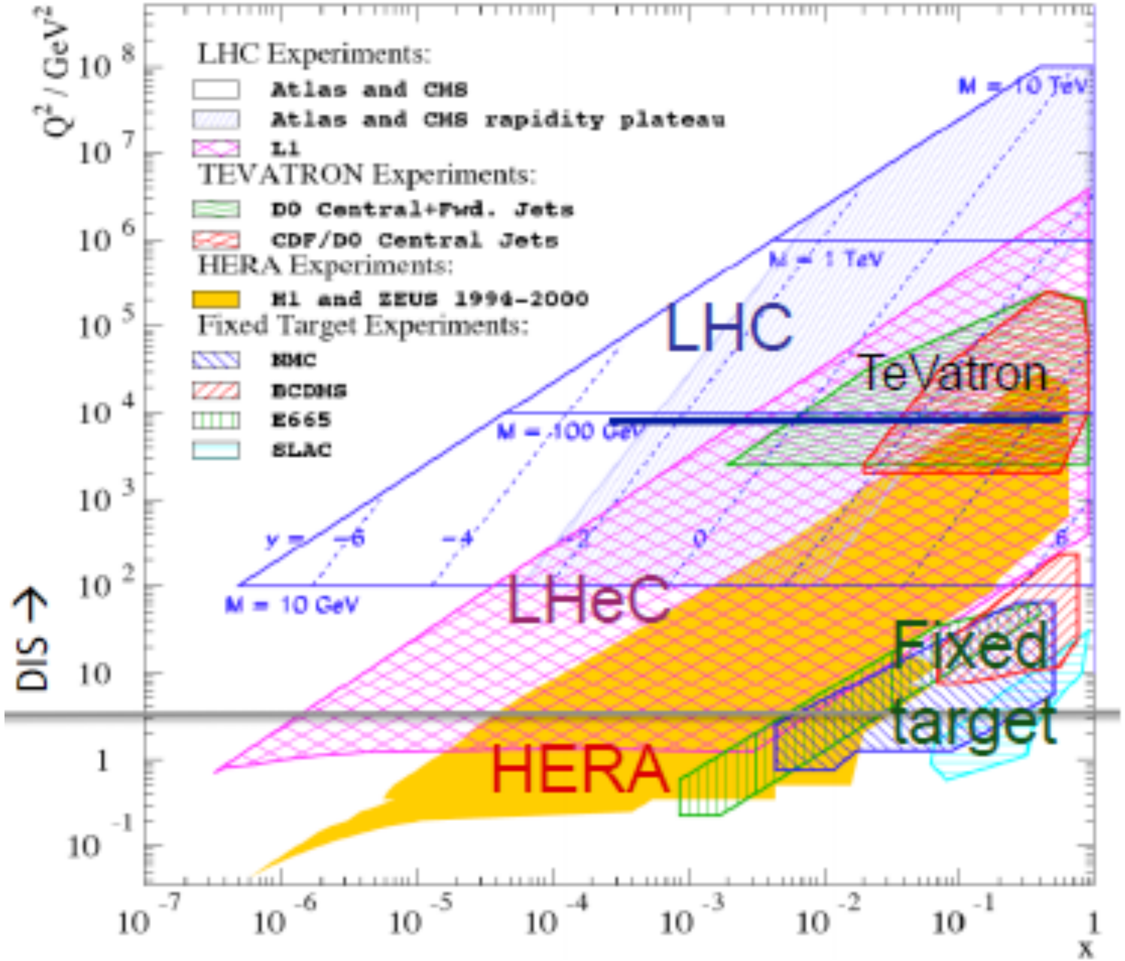
Can calculate numerically at Next-to-Leading-Order (NLO) ... *no* significant further change at NNLO

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

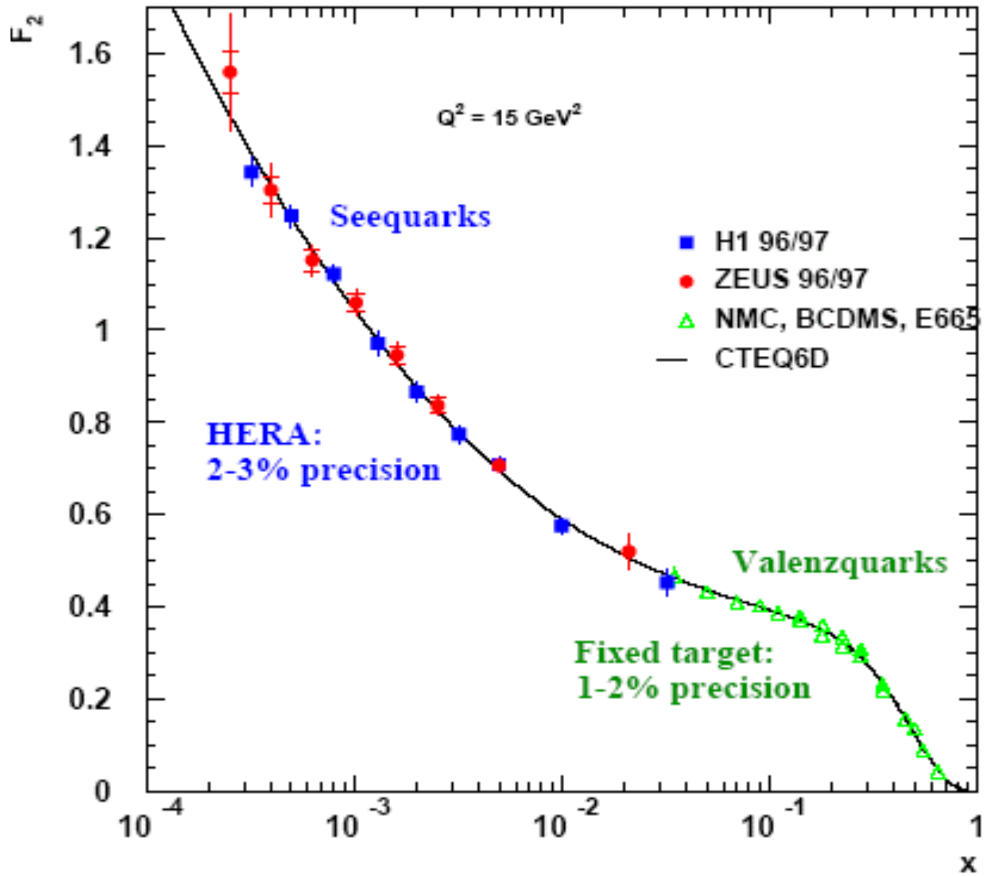


Mertsch, Cooper-Sarkar, Sarkar, JHEP 08:042,2011

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 E_ν much higher than ~10^3 TeV we have to evolve these further (using the DGLAP formalism)

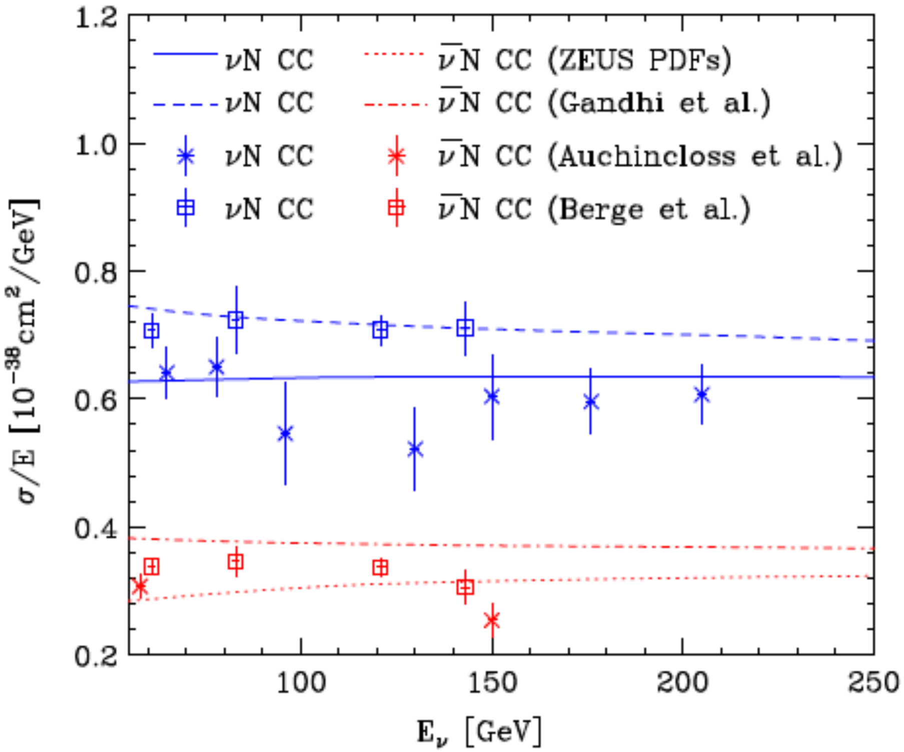


The H1 and ZEUS expts at HERA were the first to measure DIS at very low Bjorken-x and high Q^2 …

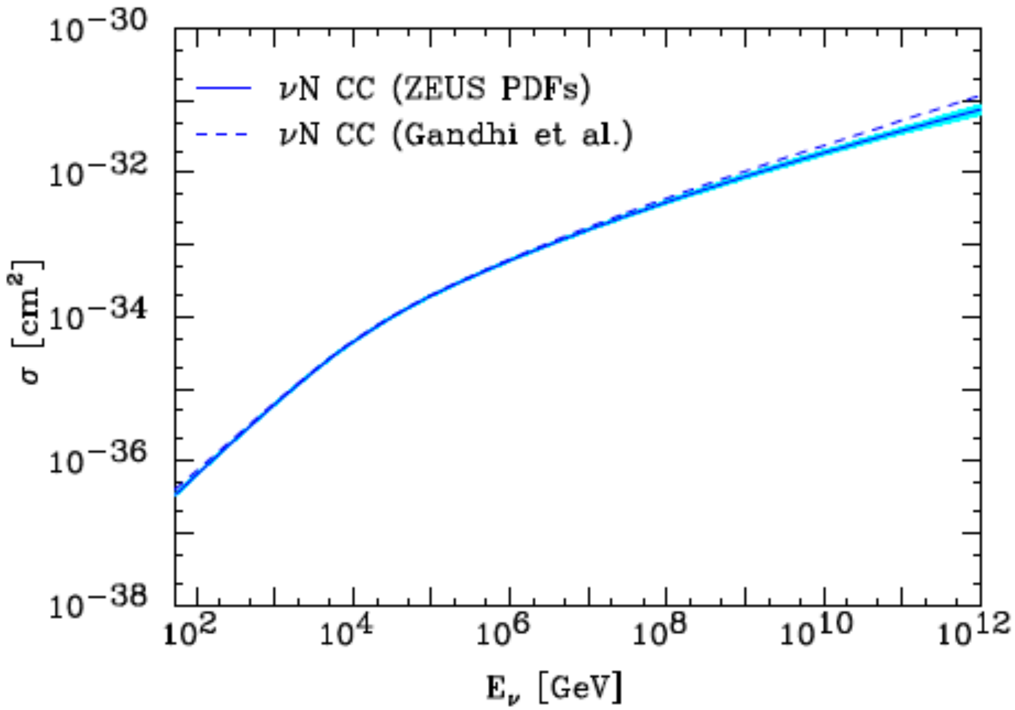


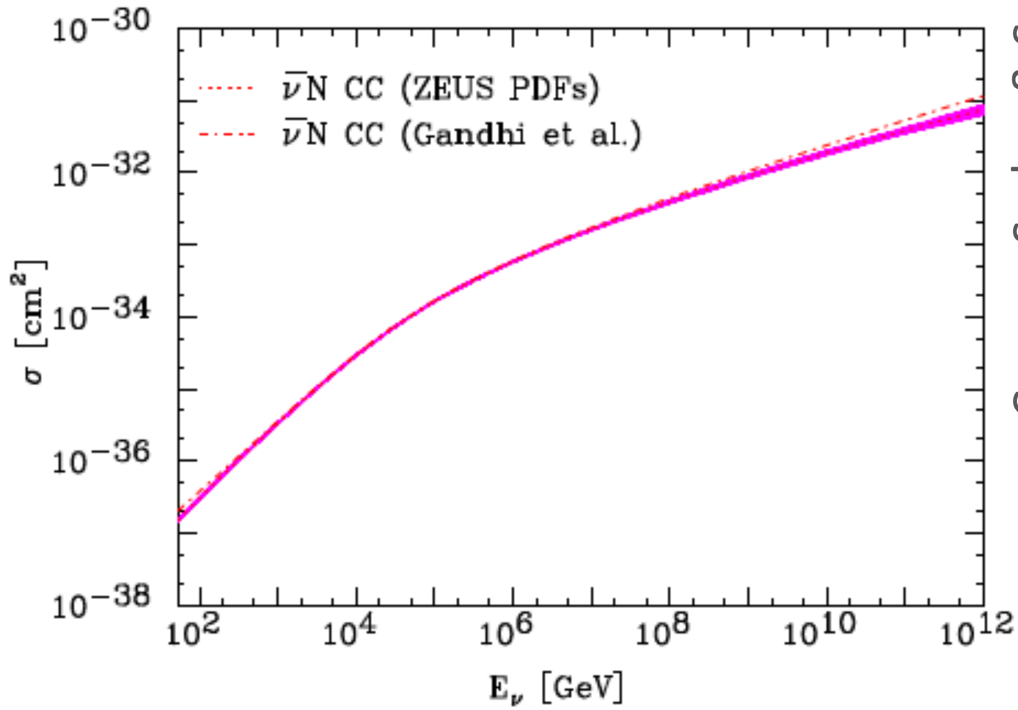
Most surprising finding was the very *steep* rise of F_2 at low x
$\Rightarrow$ significant impact on ν DIS #-secn

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



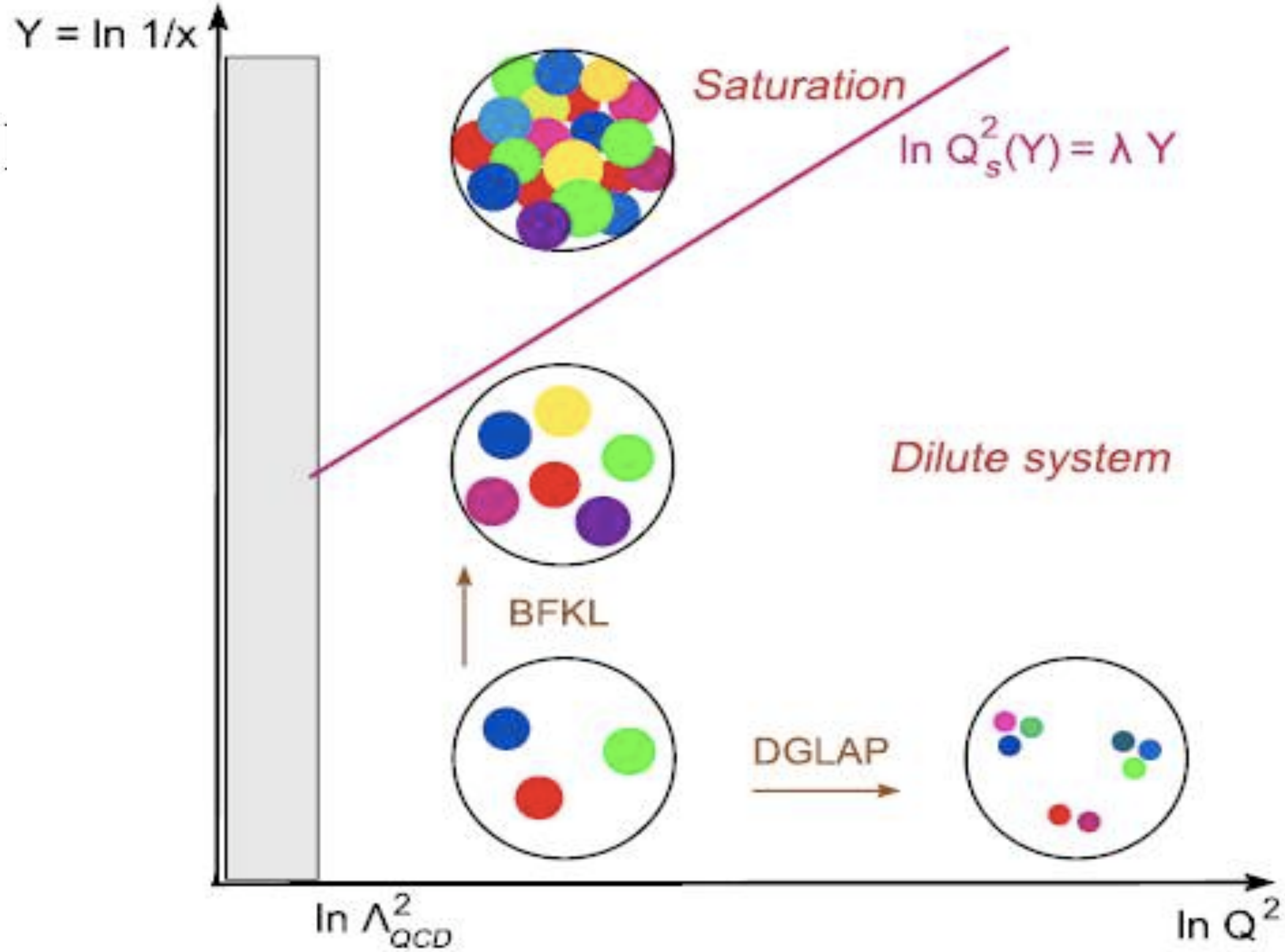
At very high energies where very low-x is being probed, recombination/saturation effects may reduce the #-section by a factor of ~2 …
however DGLAP evolution appears to fit all exptal. data – so *no* imperative for this yet!





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

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?

IceCube Neutrino Observatory

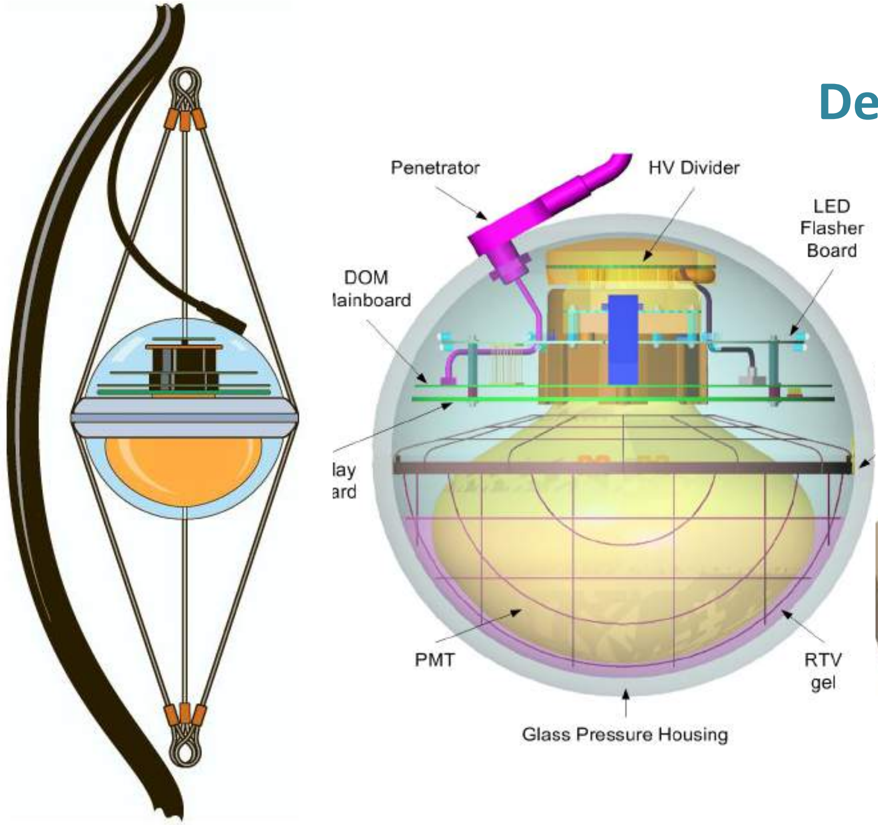
86 strings (125 m between strings)

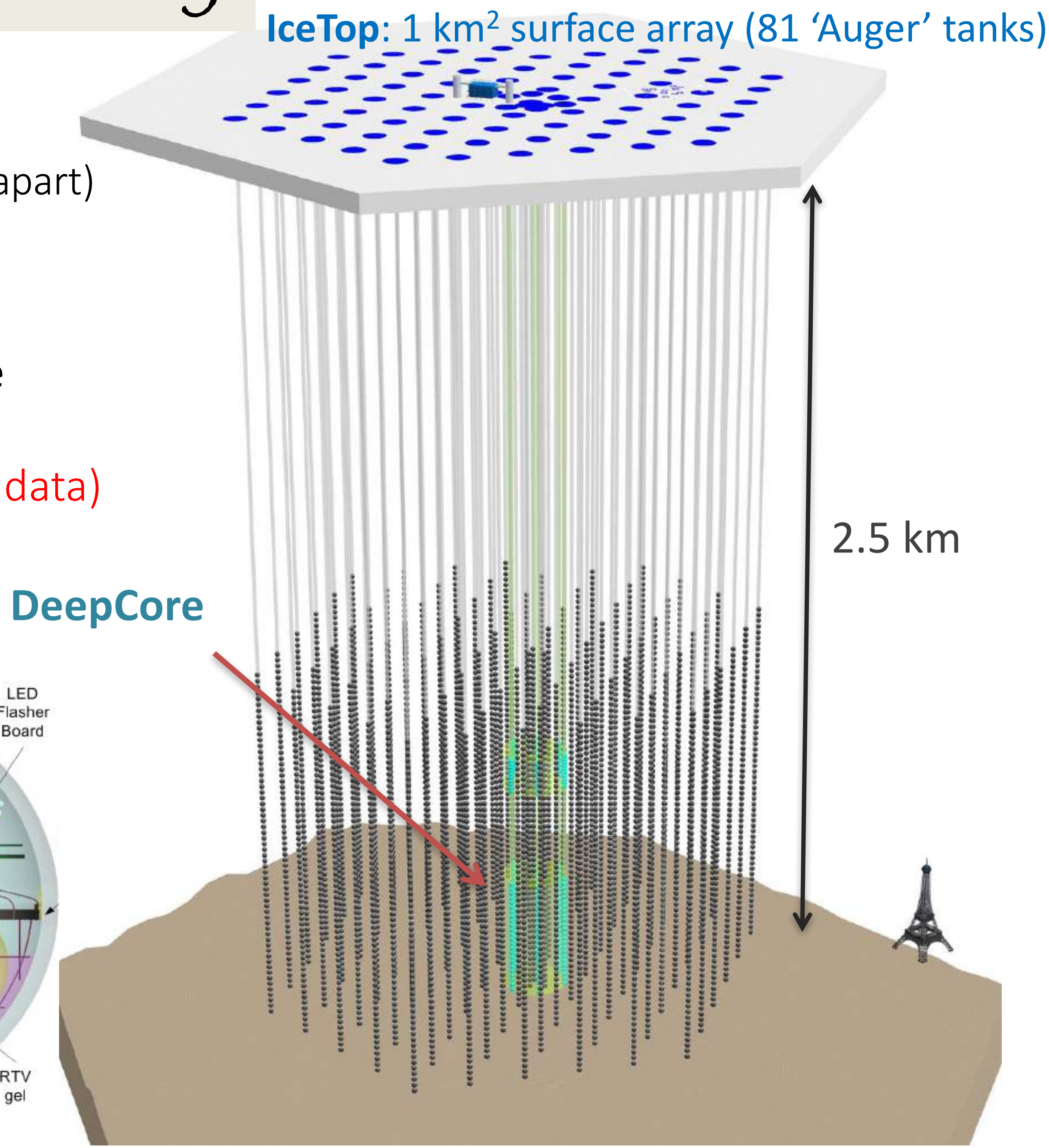
60 Optical Modules **per string** (17 m apart)

5160 Optical Modules in Ice

1 km^3 => Gton instrumented volume

Construction: 2004-11 (now 5 yr+ of data)





Cost: 279 M$ ⇒ <30 cents/ton!

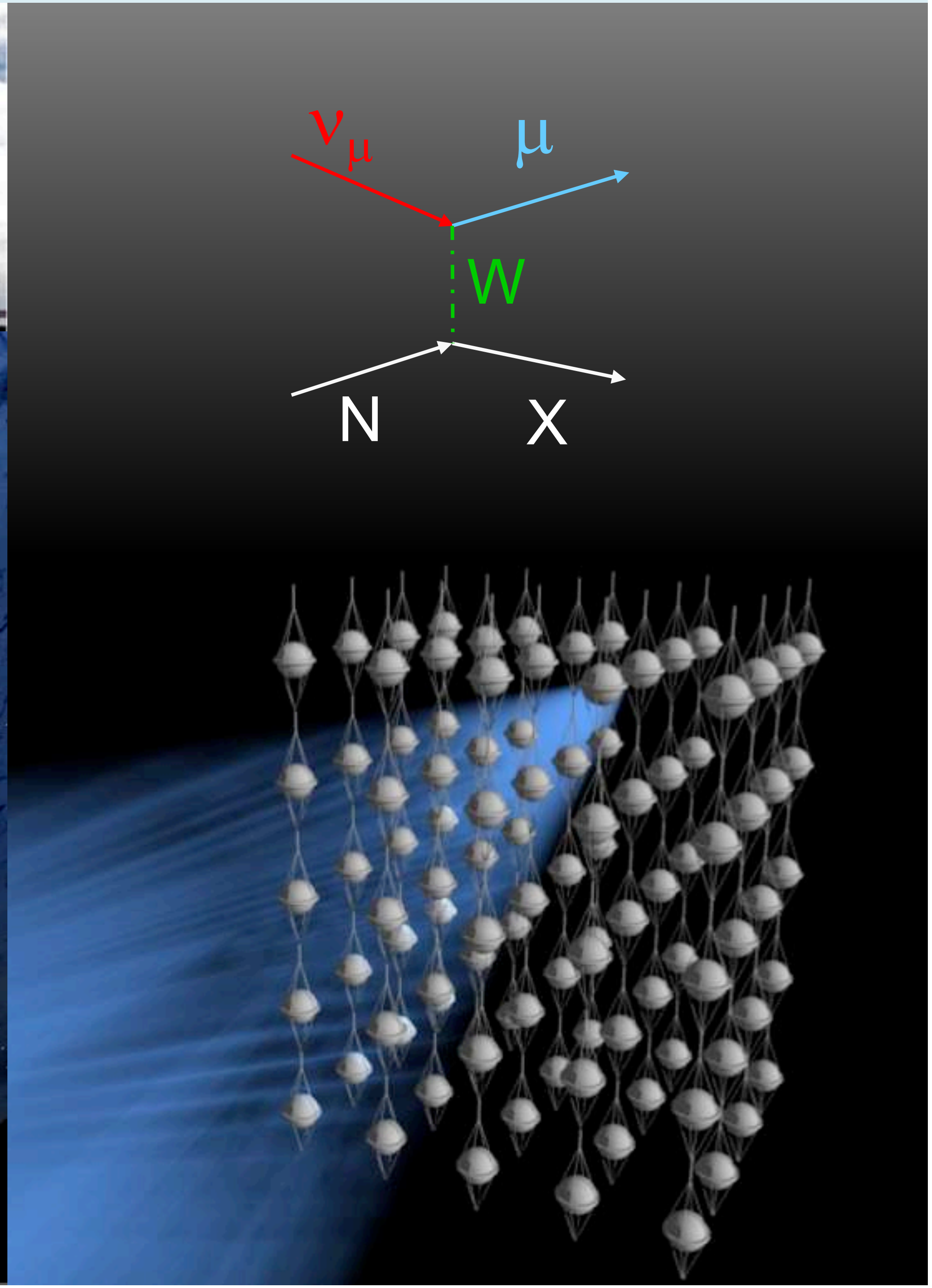
The IceCube Collaboration

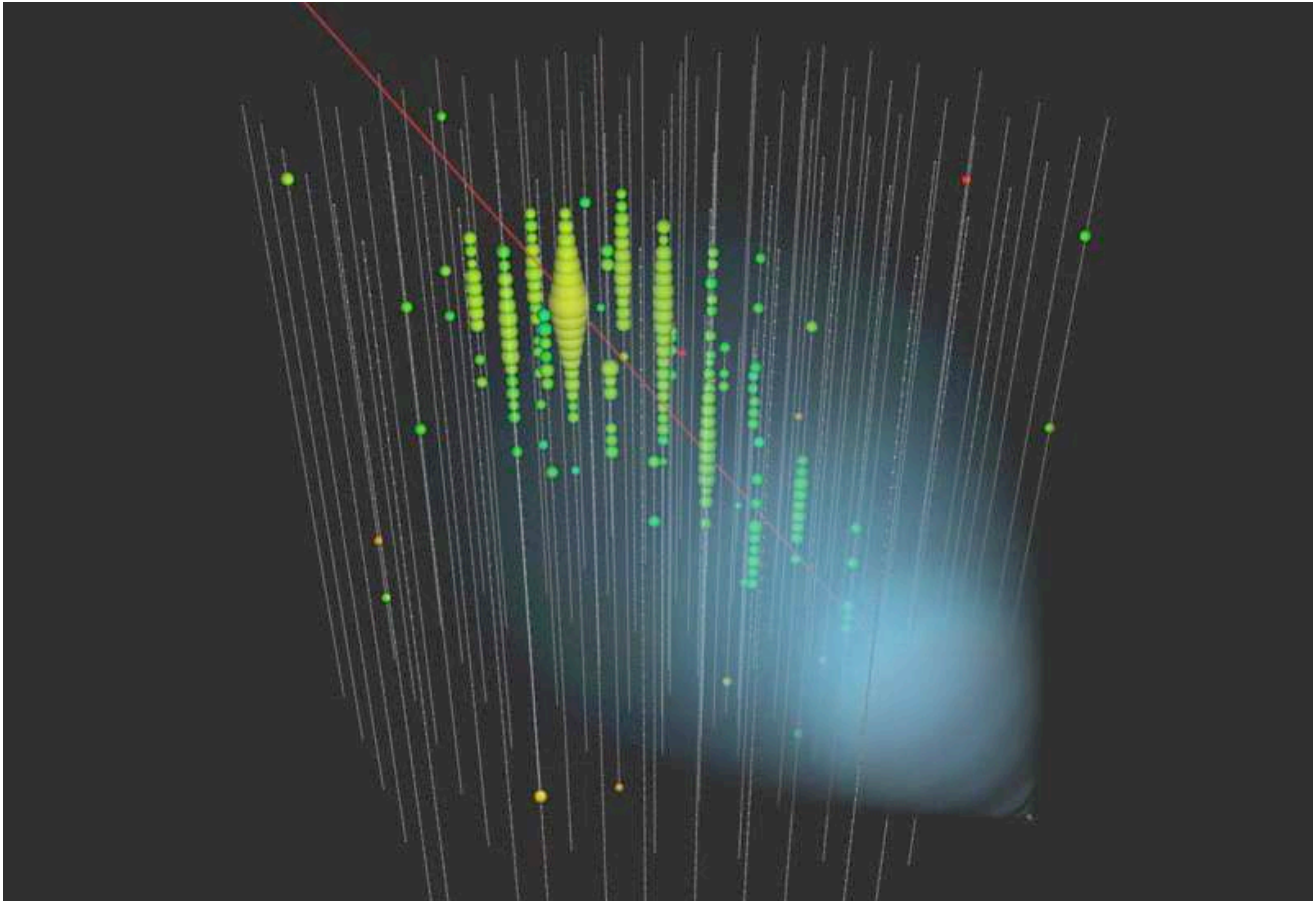
Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

>300 scientists / 48 institutions / 12 countries

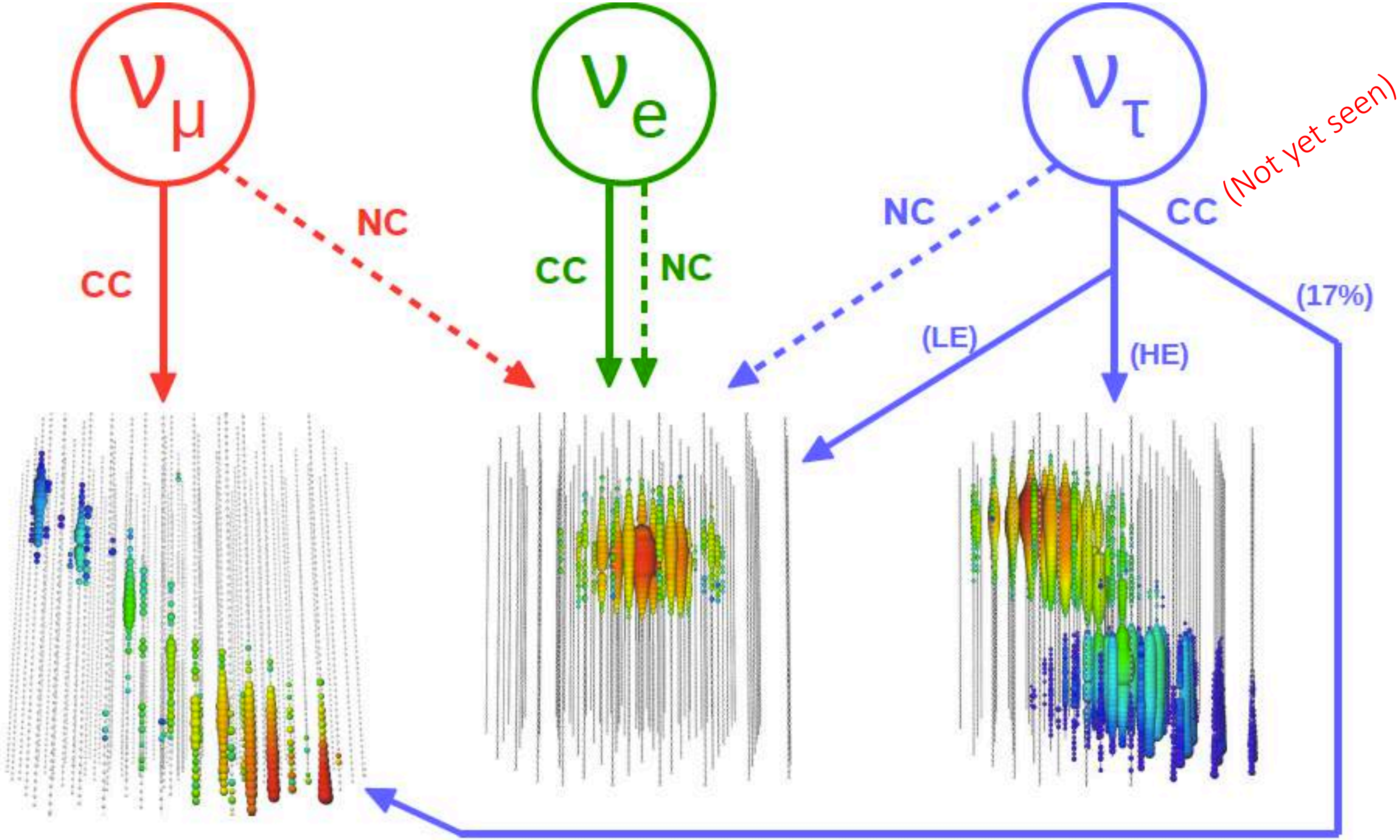
High Energy Neutrino Detection Principle





Muon track: time ⇒ color; number of photons => energy

Neutrino flavour discrimination in IceCube



Track topology

Good pointing (~0.2° - 1°)

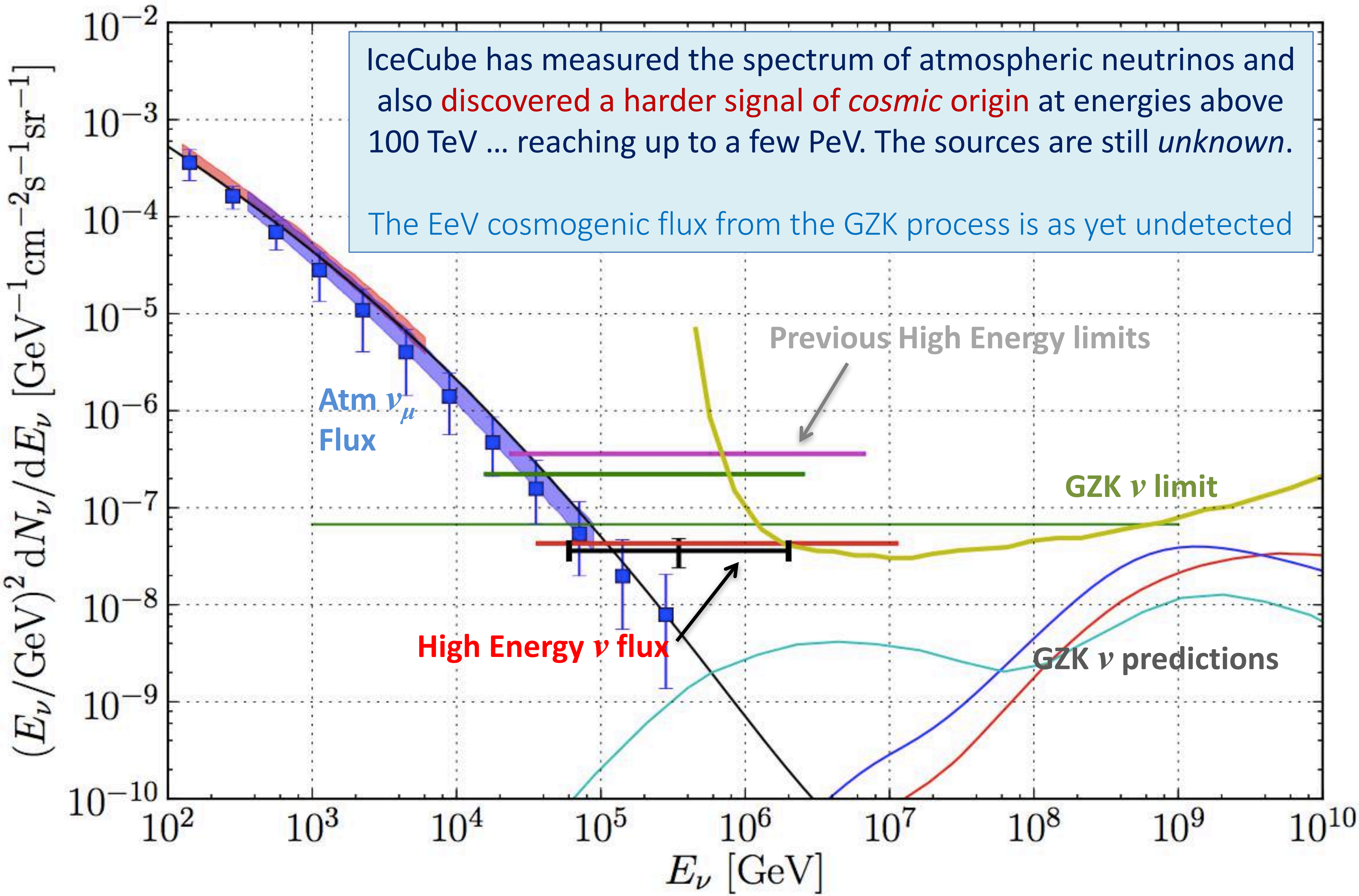
but only lower bound on neutrino energy

Cascade topology

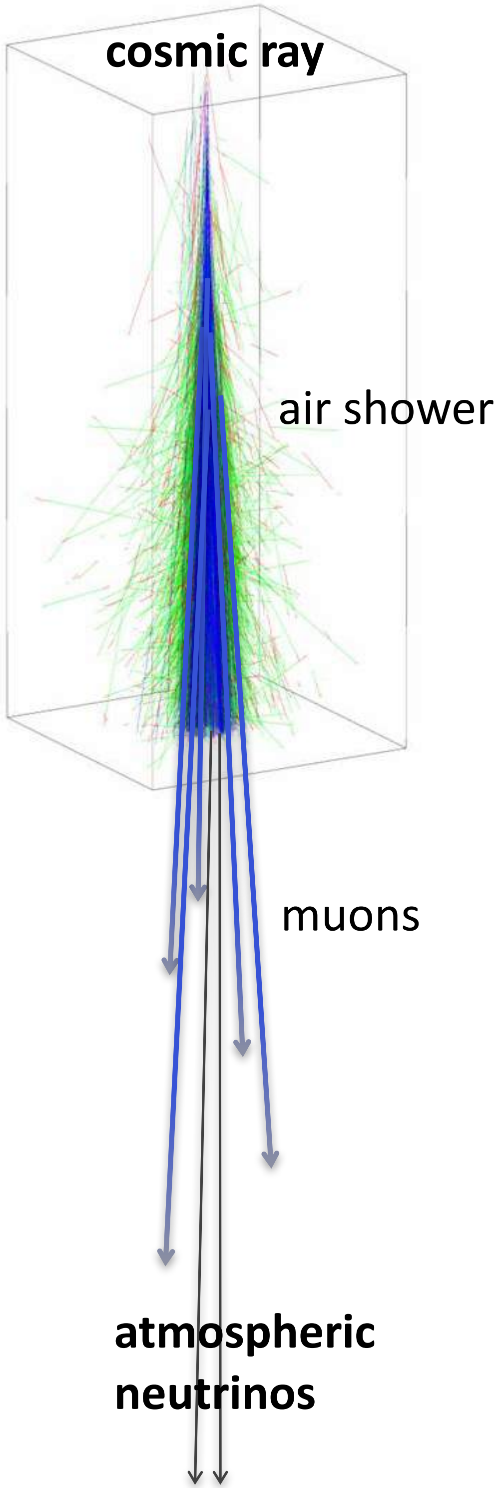
Good energy resolution (~15%)

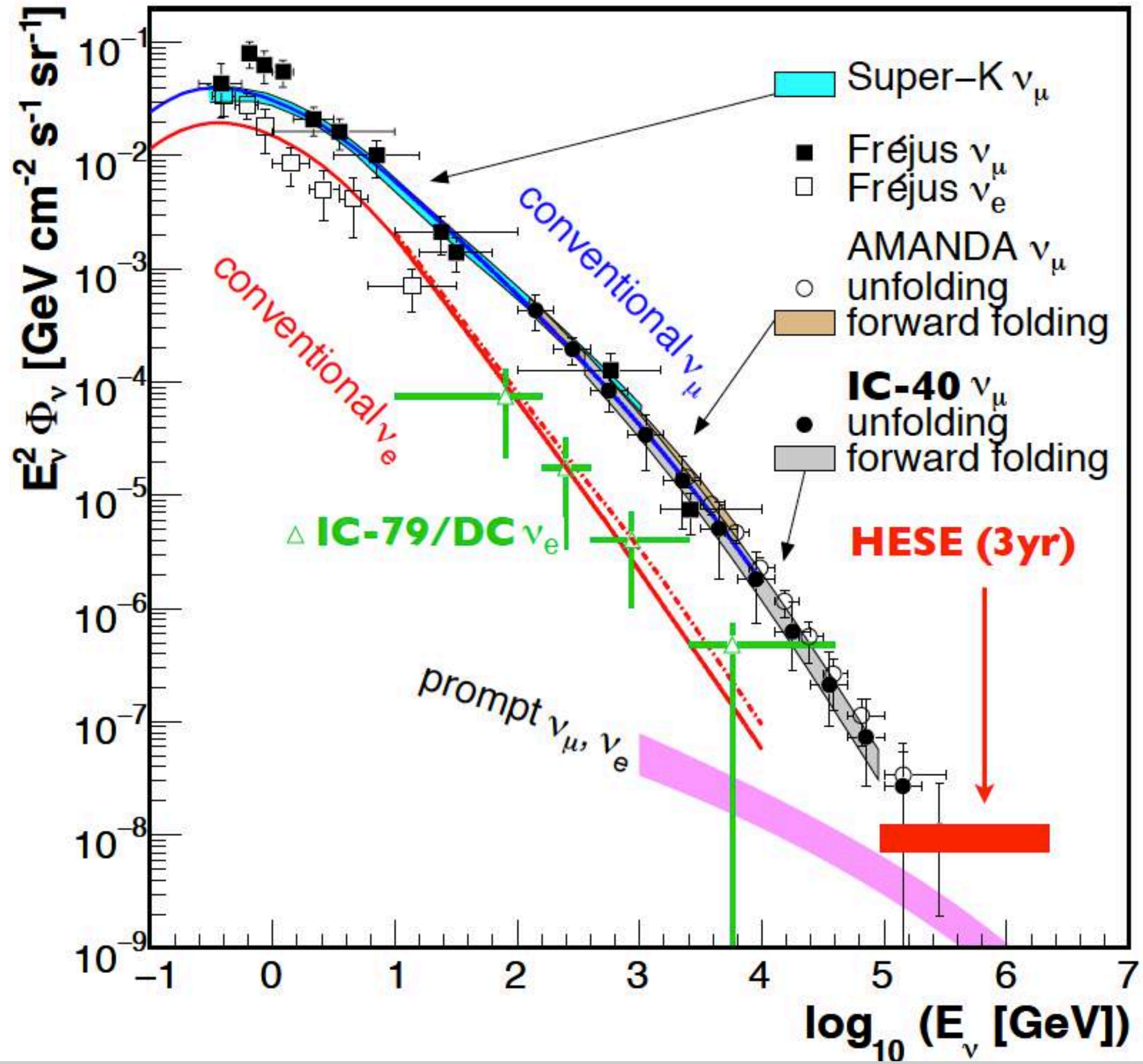
but poor pointing (~10° - 15°)

Current picture of high energy neutrino energy spectrum



Atmospheric Neutrino Spectrum

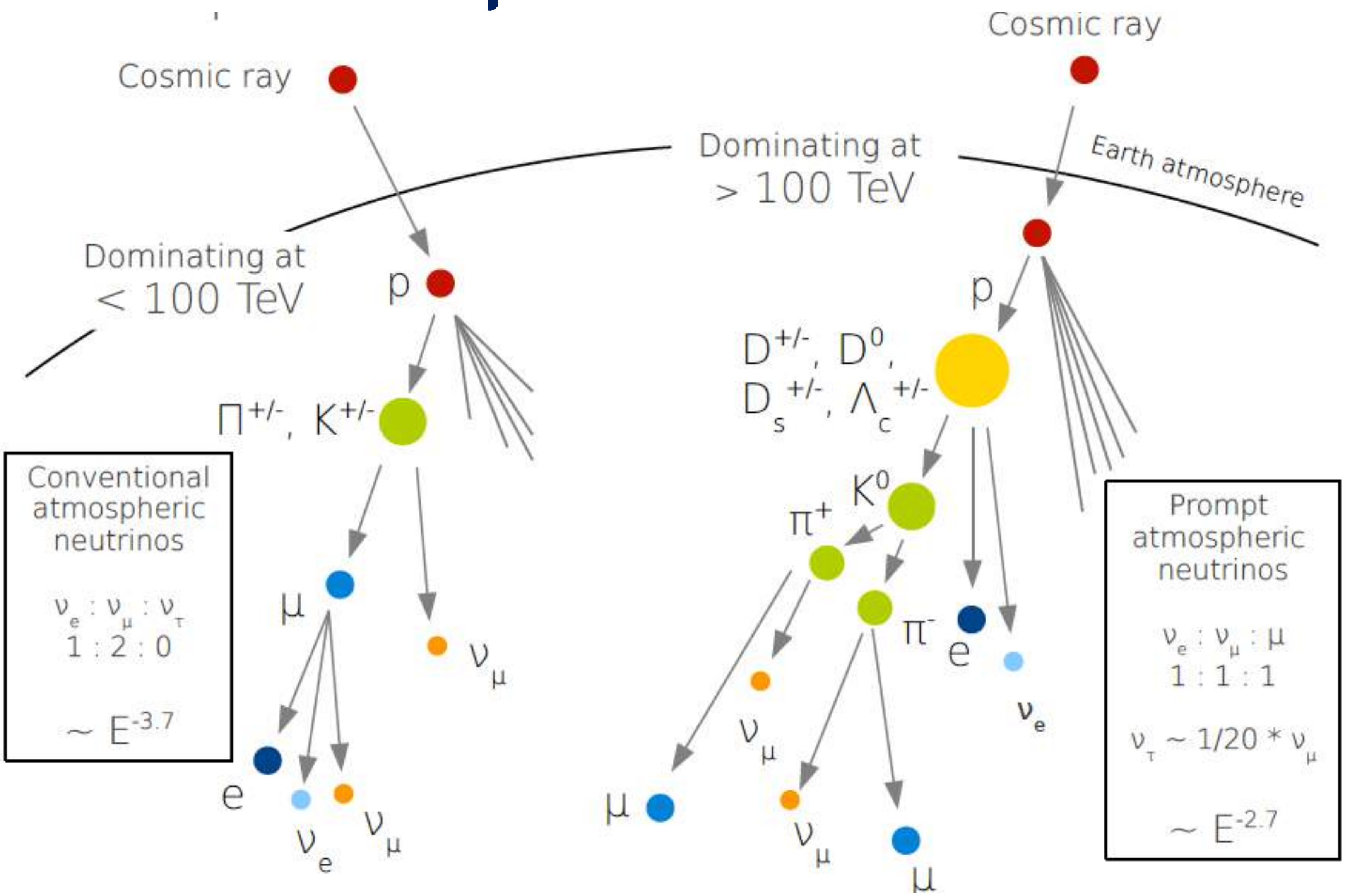




IceCube Collaboration, PRL 110:151105, 2013

IceCube has found the atmospheric neutrino background to be 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)

Atmospheric neutrinos



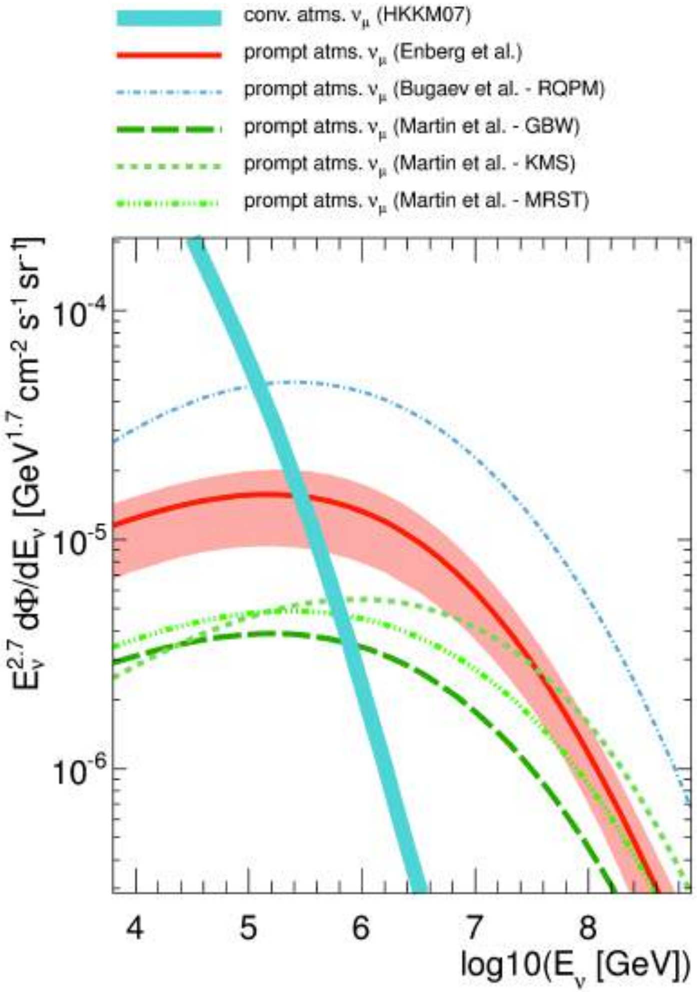
(Courtesy: Anne Schukraft)

Discovery of atmospheric neutrinos: 1965 (KGF India)

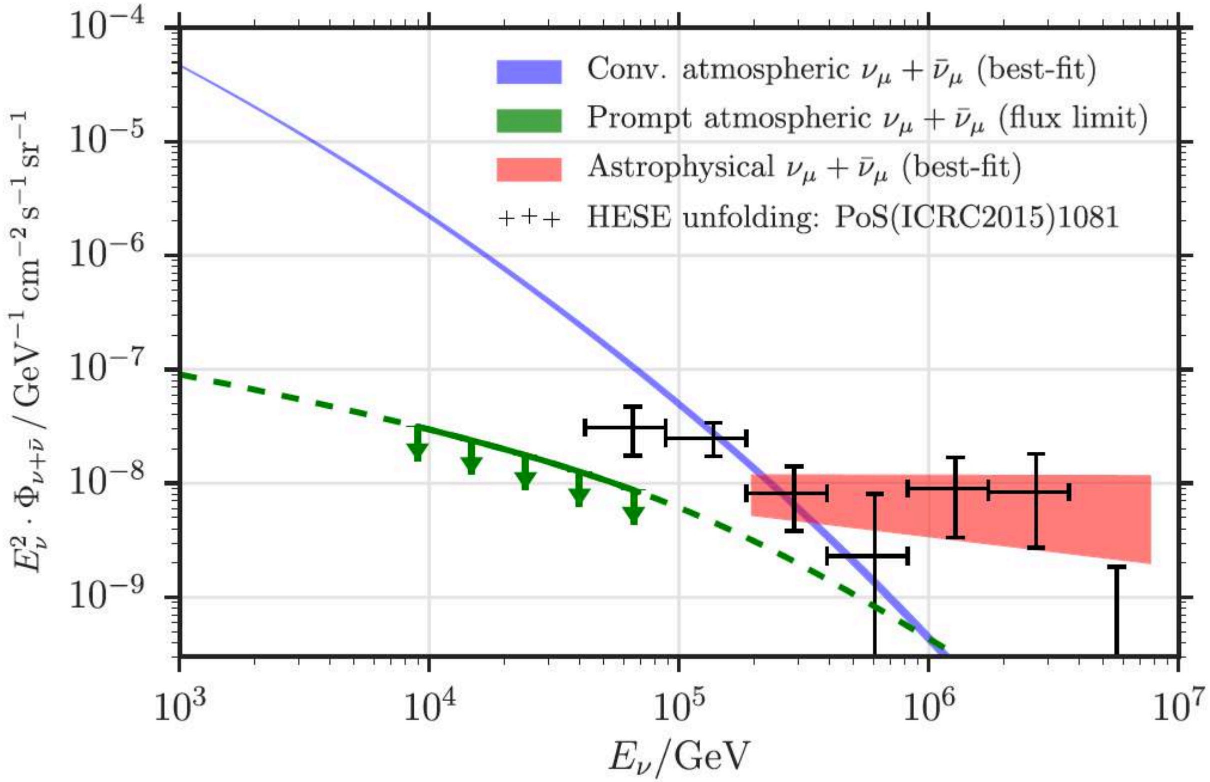
Discovery of atmospheric neutrino oscillations: 1998 (Kamioka Japan)

Where are the prompt neutrinos?

The flux of prompt neutrinos is *harder* than that of conventional neutrinos, and was predicted to dominate the total atmospheric flux at energies above ~10^5 GeV



No prompt flux seen so far … but an astrophysical signal with ~similar spectrum has been discovered!

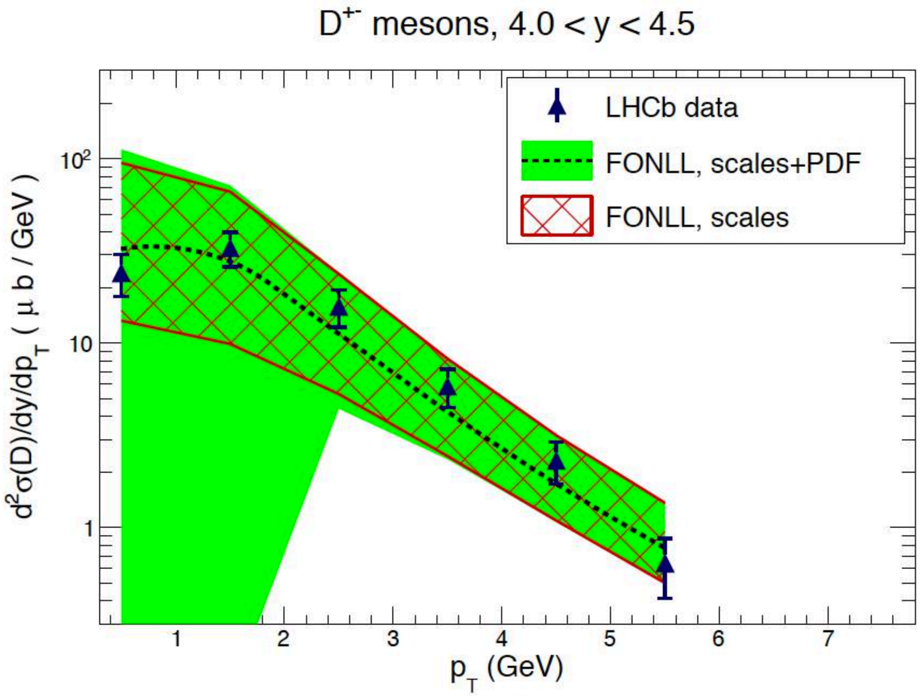


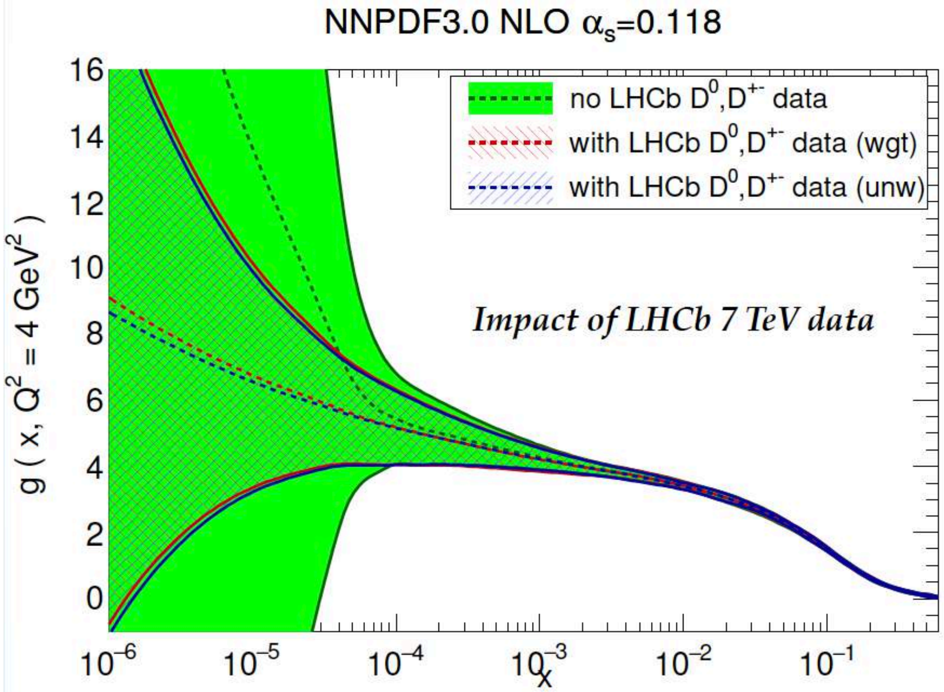
IceCube Collaboration, ApJ 833:3, 2016

The conventional background is well understood as it has been calibrated against many observations

… uncertainties in charm hadroproduction make the prompt flux less so but **it is the most important background for the expected astrophysical flux**!

Calculation of prompt atmospheric ν flux with LHCb data

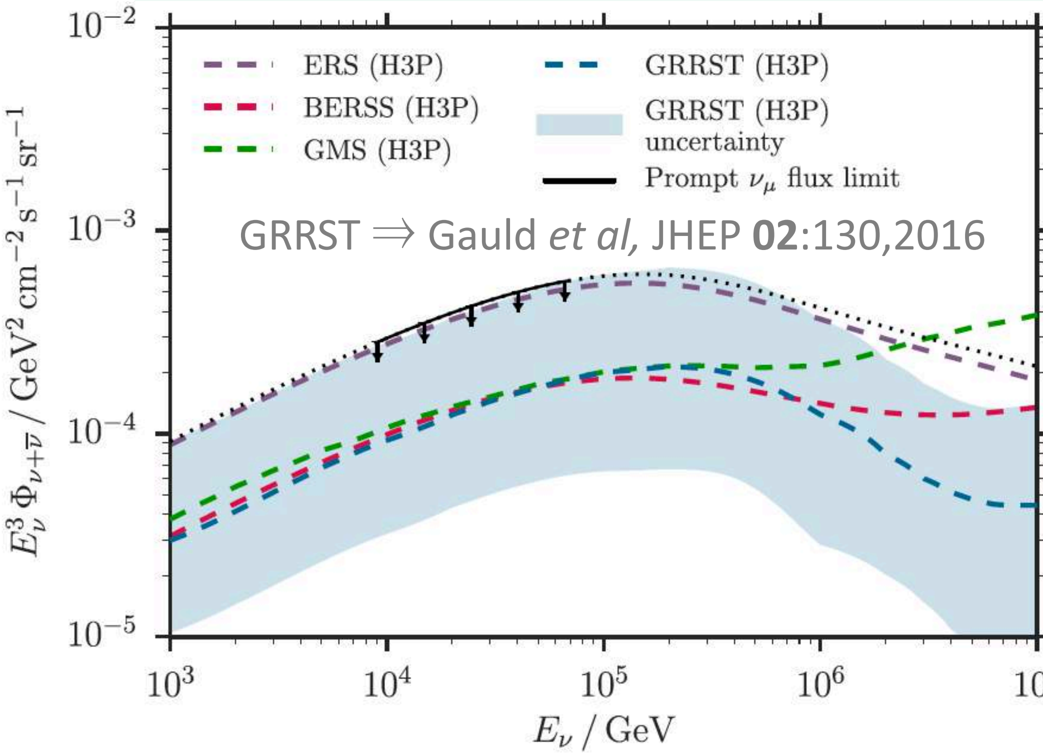




Gauld, Rojo, Rottoli, Talbert, JHEP **11**:009,2015

LHCb charm production covers the relevant kinematical region …
reduces small-x gluon uncertainty

Enables reliable pQCD calculation of *uncertainty* in the atmospheric prompt ν flux
… IceCube should soon see it!

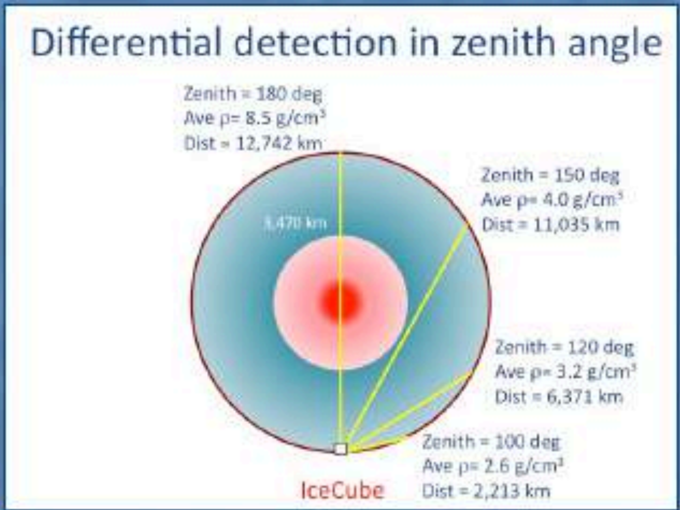


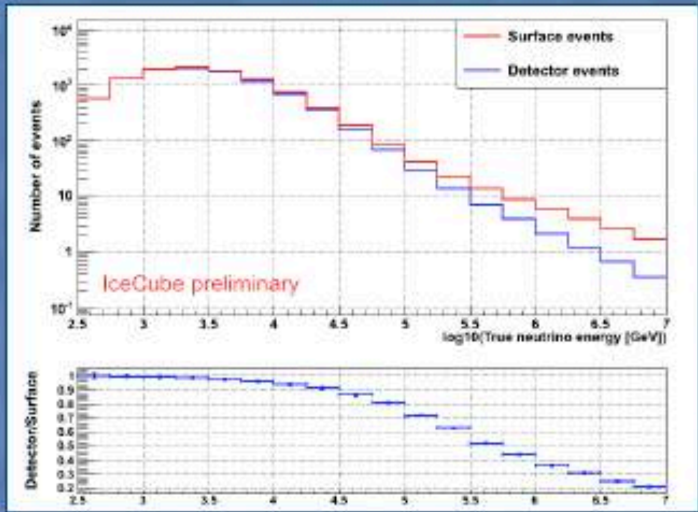
IceCube Collaboration, ApJ 833:3, 2016

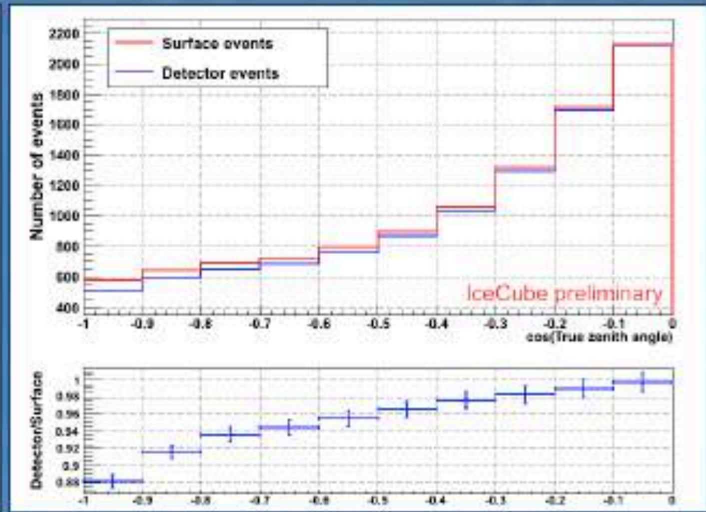
We can also measure the *ν*-N #-secn by looking at the *zenith angle dependence* of the *ν* flux

Target: Earth

- **Earth density model: Preliminary Reference Earth Model [PREM 1981]**
  - Observe/measure neutrino absorption in the Earth
  - Differential density changes spectrum from surface to detector
  - Earth diameter = interaction length ~ 40 TeV





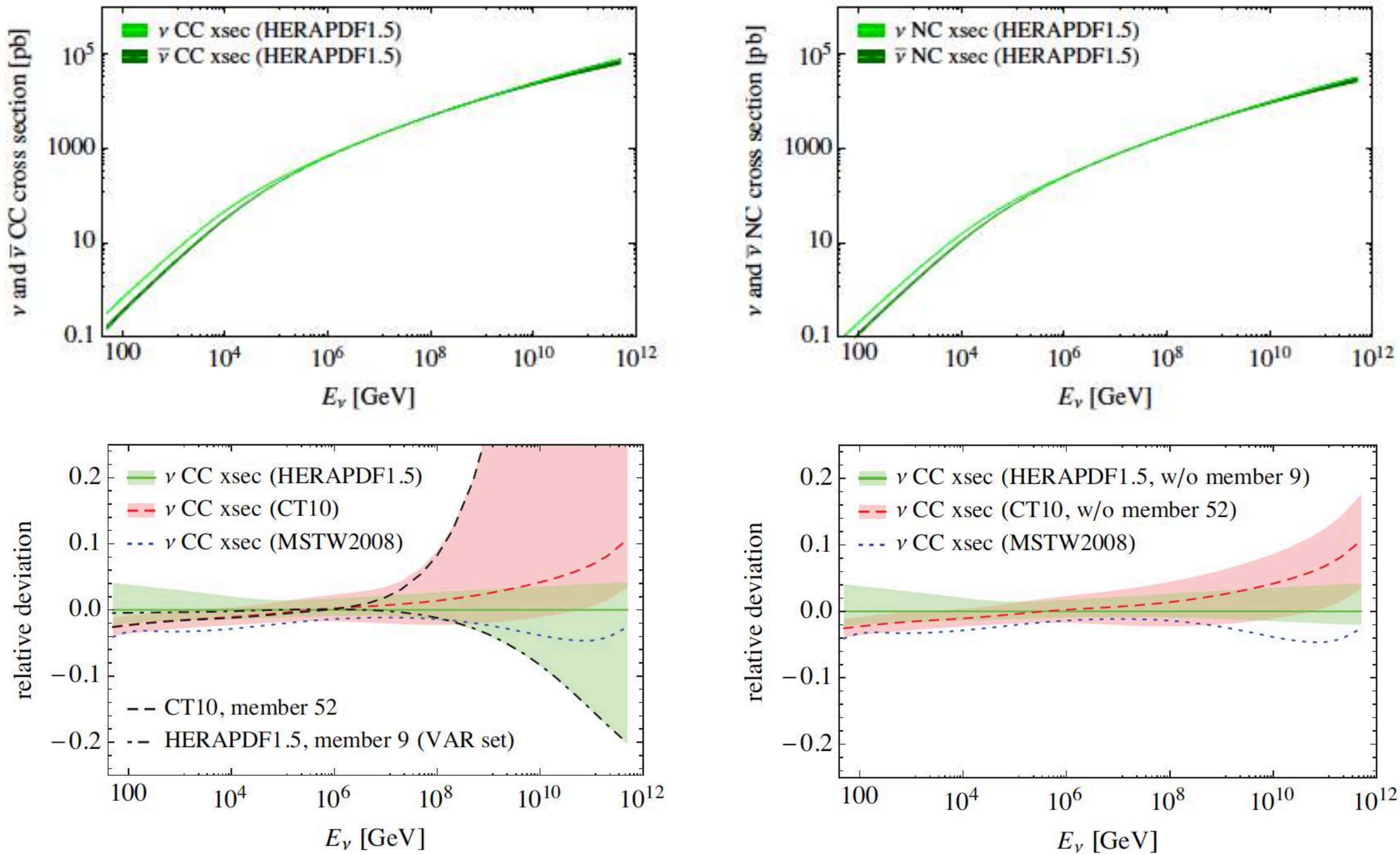


Simulation

- **Source simulation from NeutrinoGenerator (NuGen)**
  - Monte Carlo that creates, propagates, and interacts up-going neutrinoss
  - Can vary cross section models to generate expectations for fitter
- **Background simulation from CORSIKA**
  - Cosmic ray muon (down-going) events for background rejection

Sandy Miarecki, ICHEP 2016

We have updated the ν-N #-section calculation @ NLO with ~few % accuracy using HERAPDF1.5

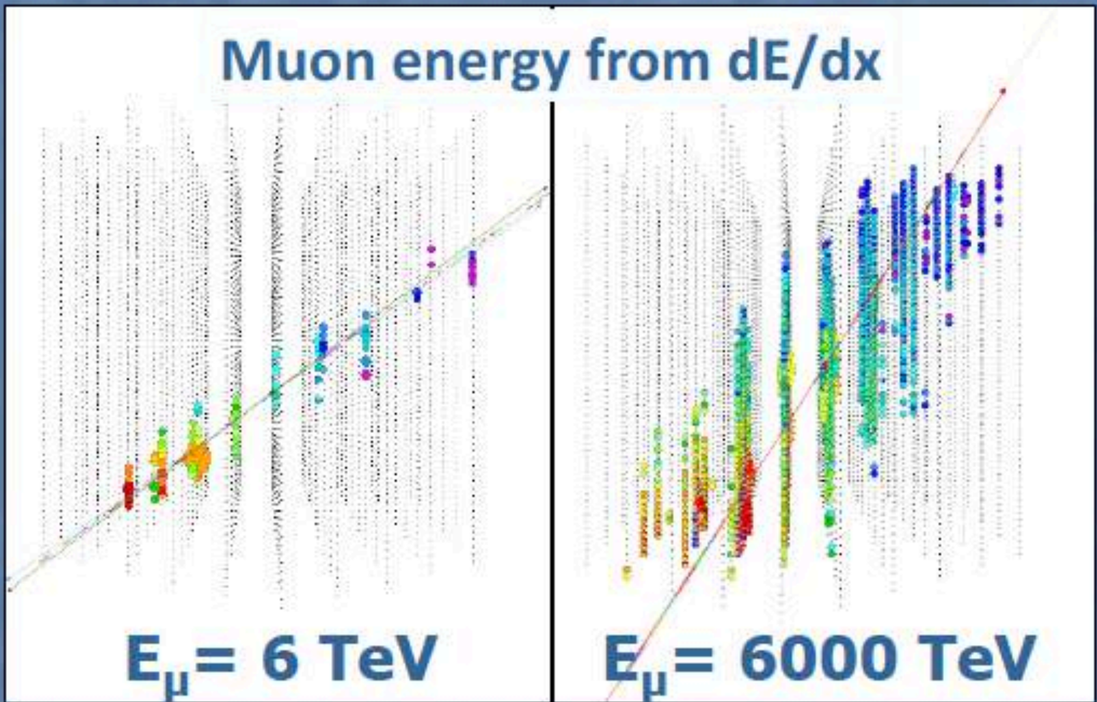


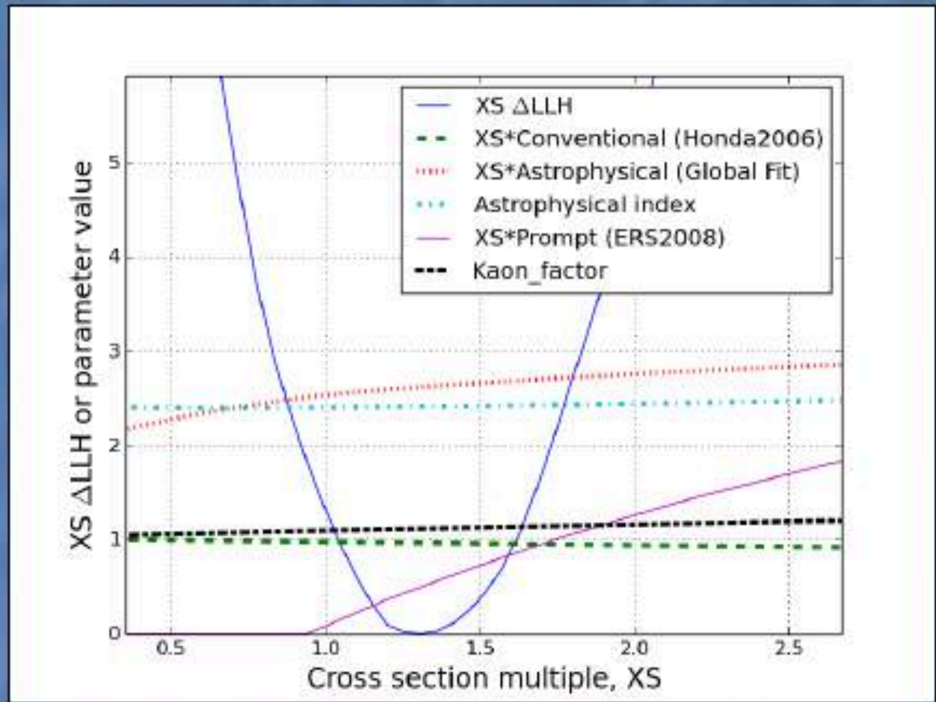
Mertsch, Cooper-Sarkar, Sarkar, JHEP **08**:042,2011 ⇒ CSMS 2011

… finding good agreement between different PDF sets (*after* rejecting unphysical members – which would have yielded e.g. *negative* values for F_L)

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



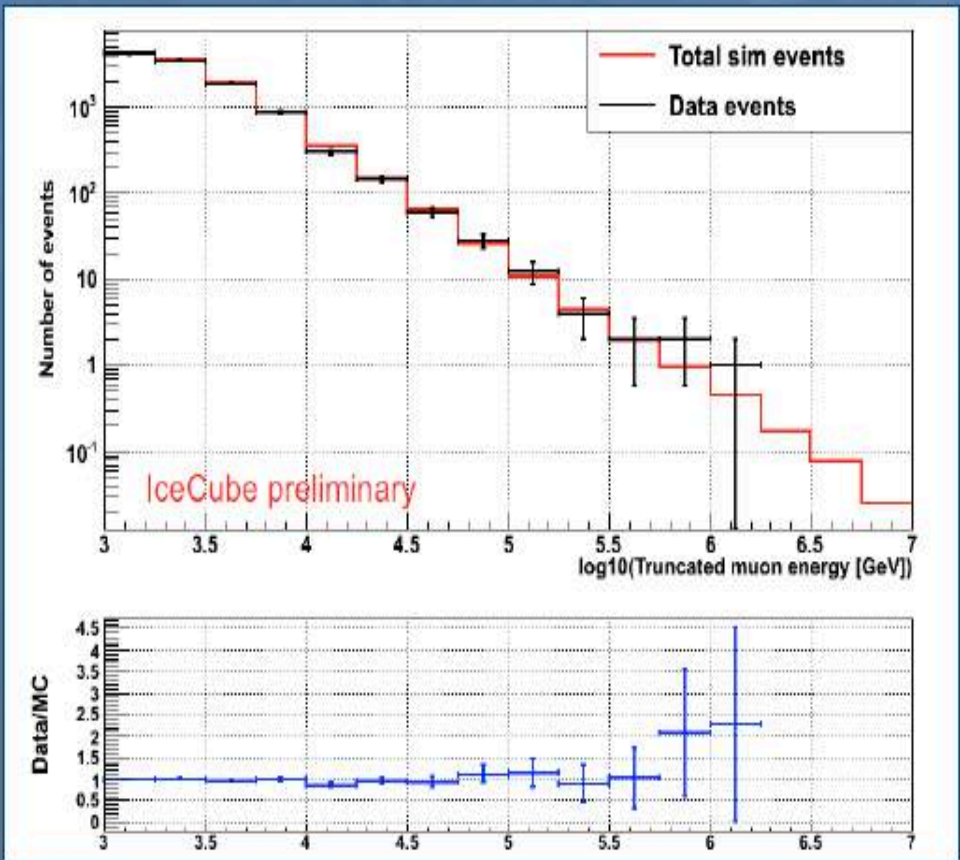


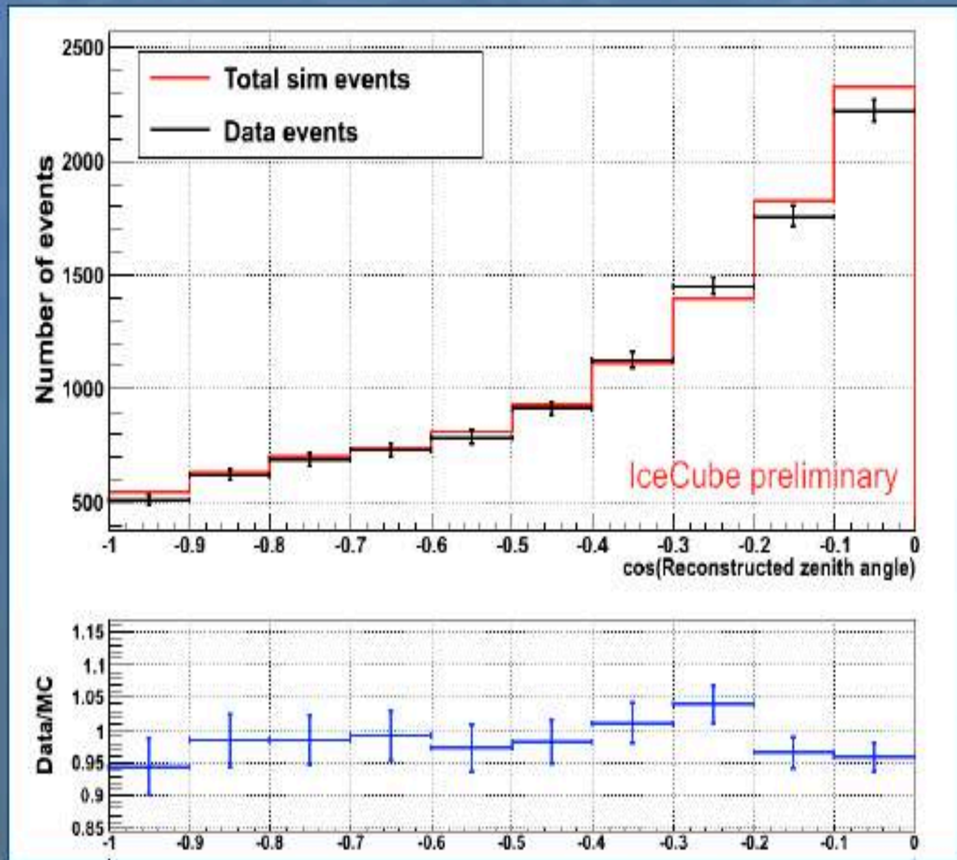
Sandy Miarecki, ICHEP 2016

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

… this has now been done and the energy range is extended up to 980 TeV





Sandy Miarecki, ICHEP 2016

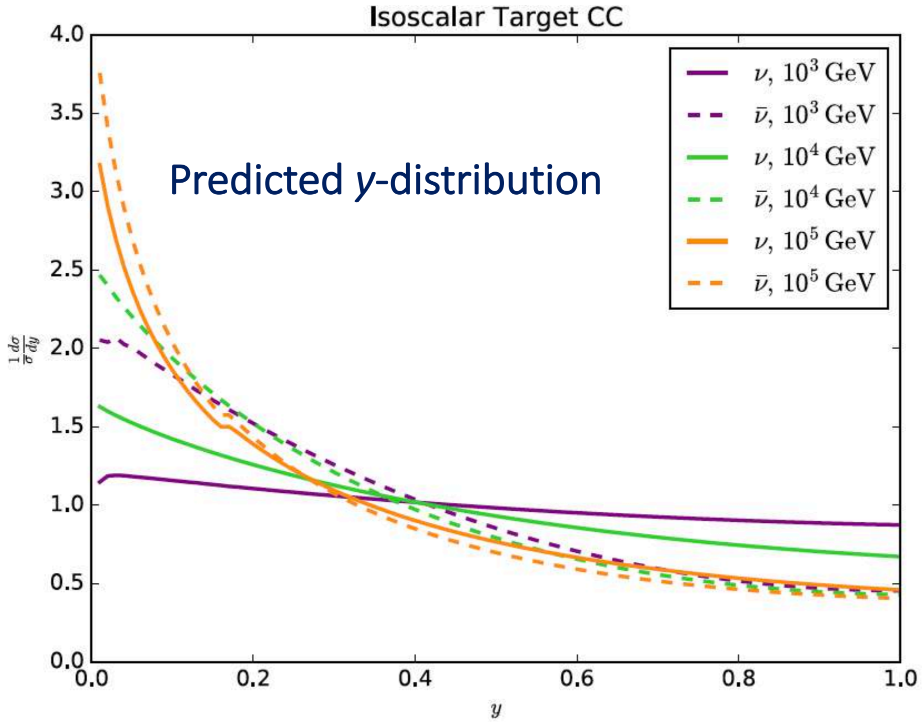
No evidence of deviation (within ±30%) from CSMS 2011 calculation up to 980 TeV

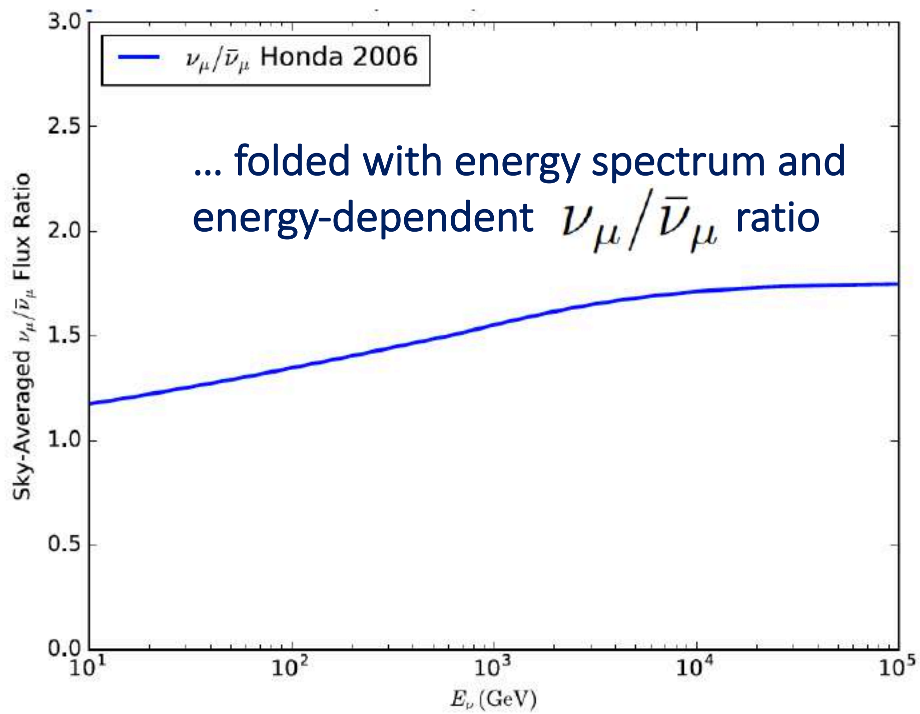
Figure not yet approved for public release

IceCube Collaboration, to appear

Powerful probe of new physics beyond the SM (e.g. leptoquarks, new dimensions) should be able to check up to ~10^{10} GeV using cosmogenic ν - with **IceCube-Gen2**!

Another test of new physics is the inelasticity distribution ..

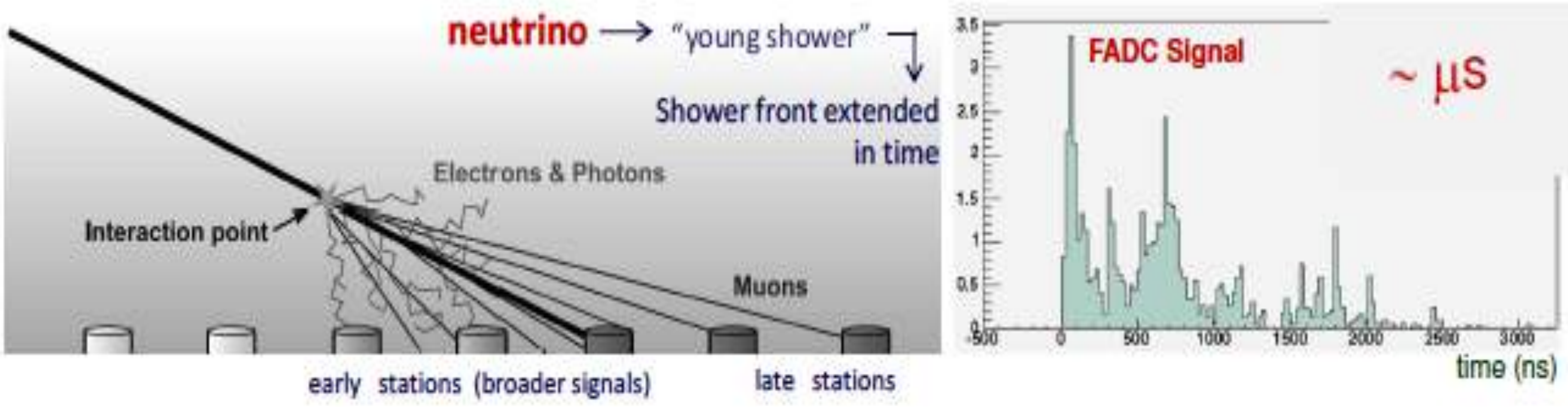


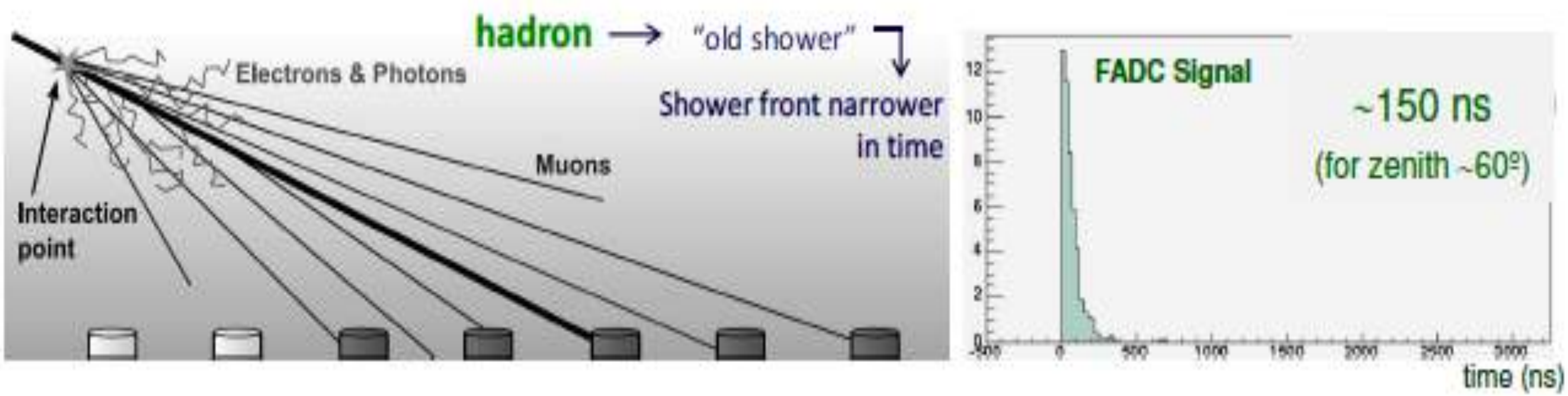


Courtesey Gary Binder, IceCube

Good match to data!

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 ...

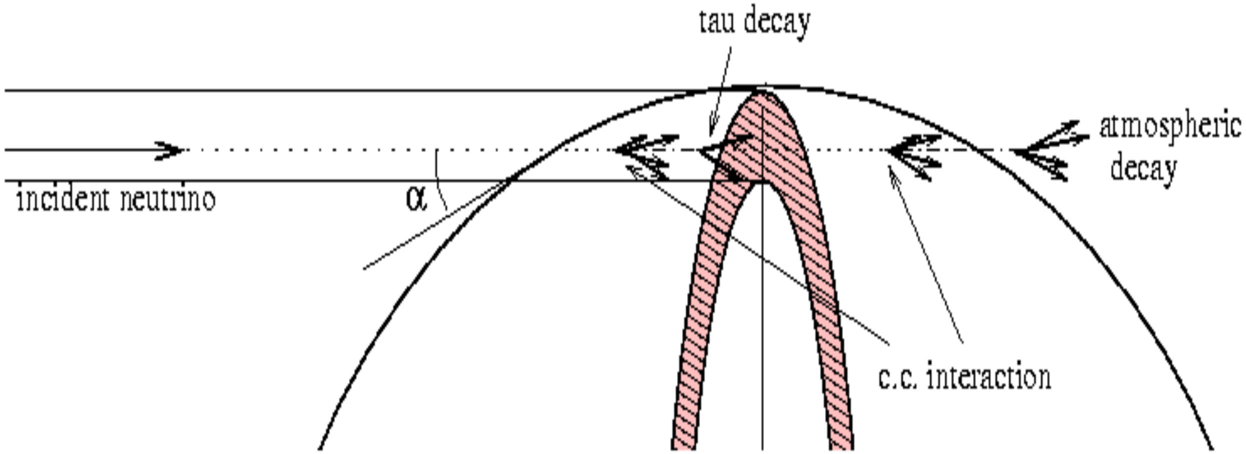
However neutrinos can penetrate through the atmosphere and interact close to the array so if we see a *young* shower at a *large* zenith angle, that is a candidate for a UHE neutrino!

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

An unexpected bonus – UHE neutrino detection with air shower arrays

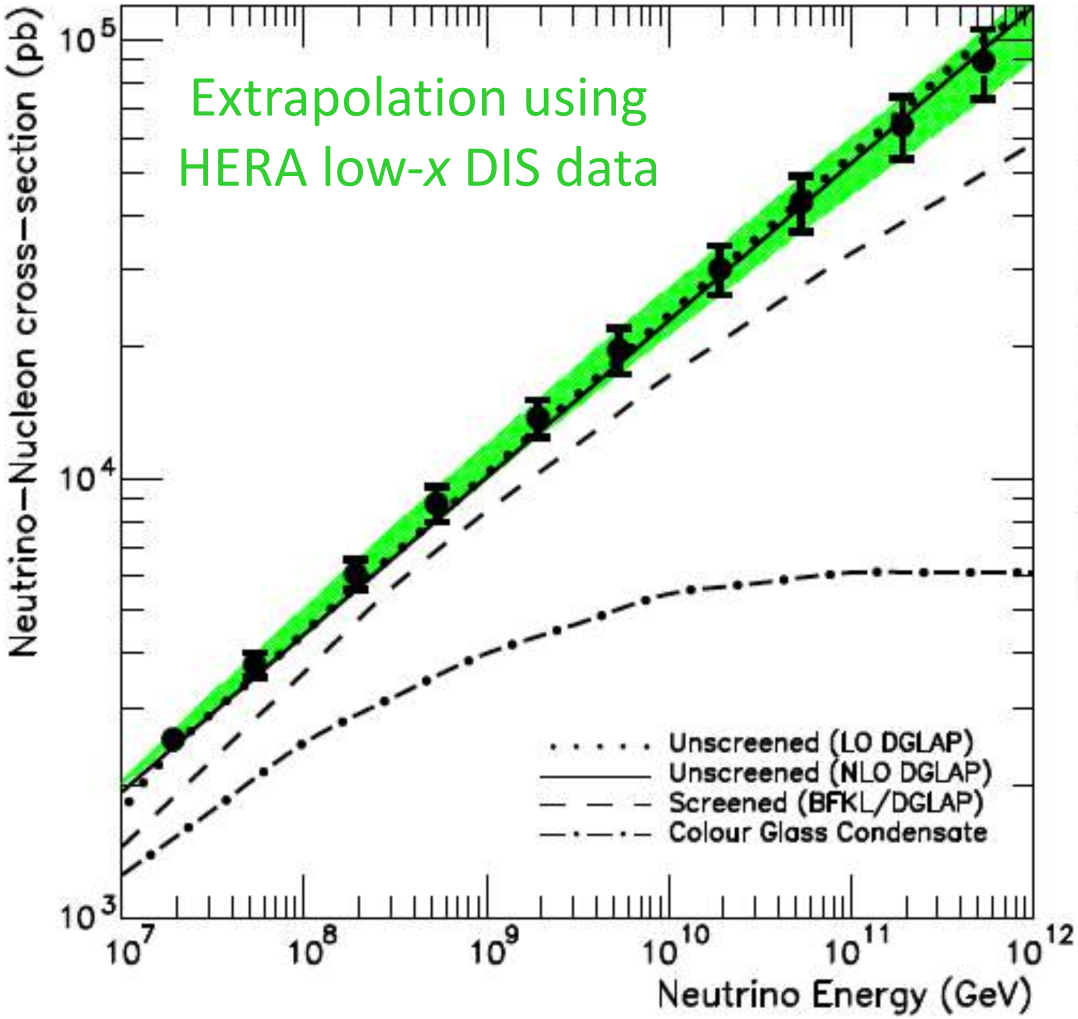
Auger can also see Earth-skimming $\nu_\tau \to \tau$ which generates *upgoing* hadronic shower
(detectable only because the surface detector tanks are raised above the ground)

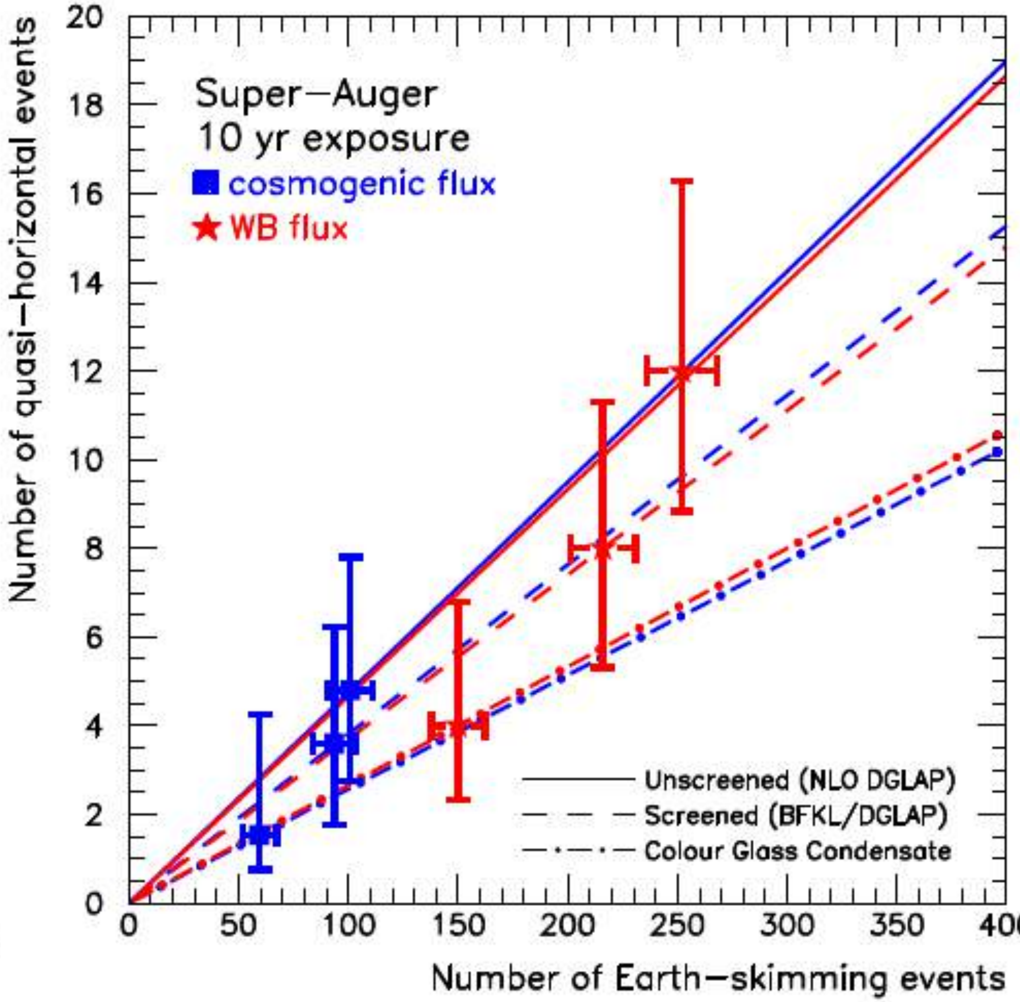
Neutrino oscillations en-route to Earth should *equlibrate* flavours with $\nu_e:\nu_\mu:\nu_\tau::1:1:1$
so there will be tau neutrinos in the cosmic beam regardless of initial composition



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)

Thus low-x QCD *can* be probed with cosmic UHE neutrinos … provided a sufficiently large air shower array is built



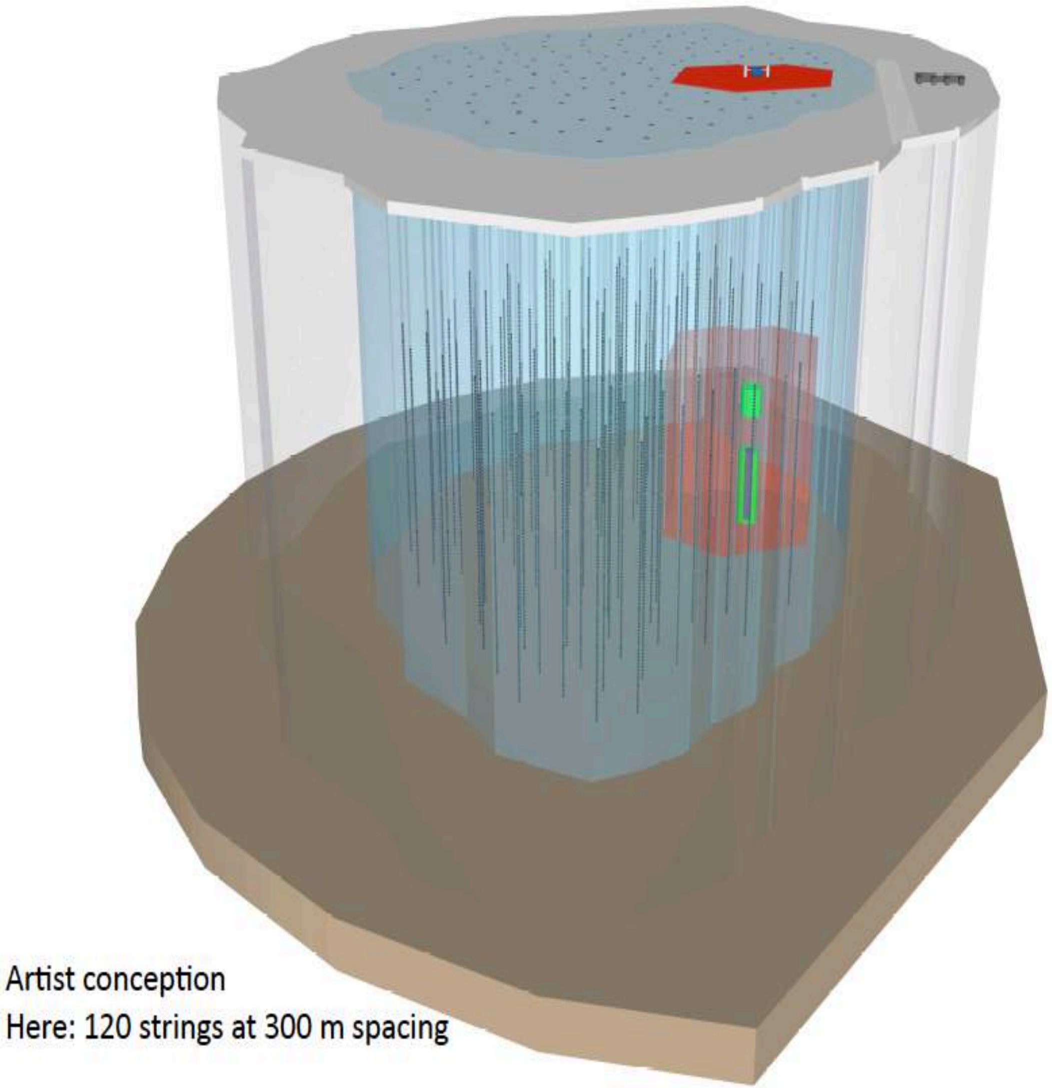


Anchordoqui, Cooper-Sarkar, Hooper, Sarkar, Phys.Rev.D**74**:043008,2006

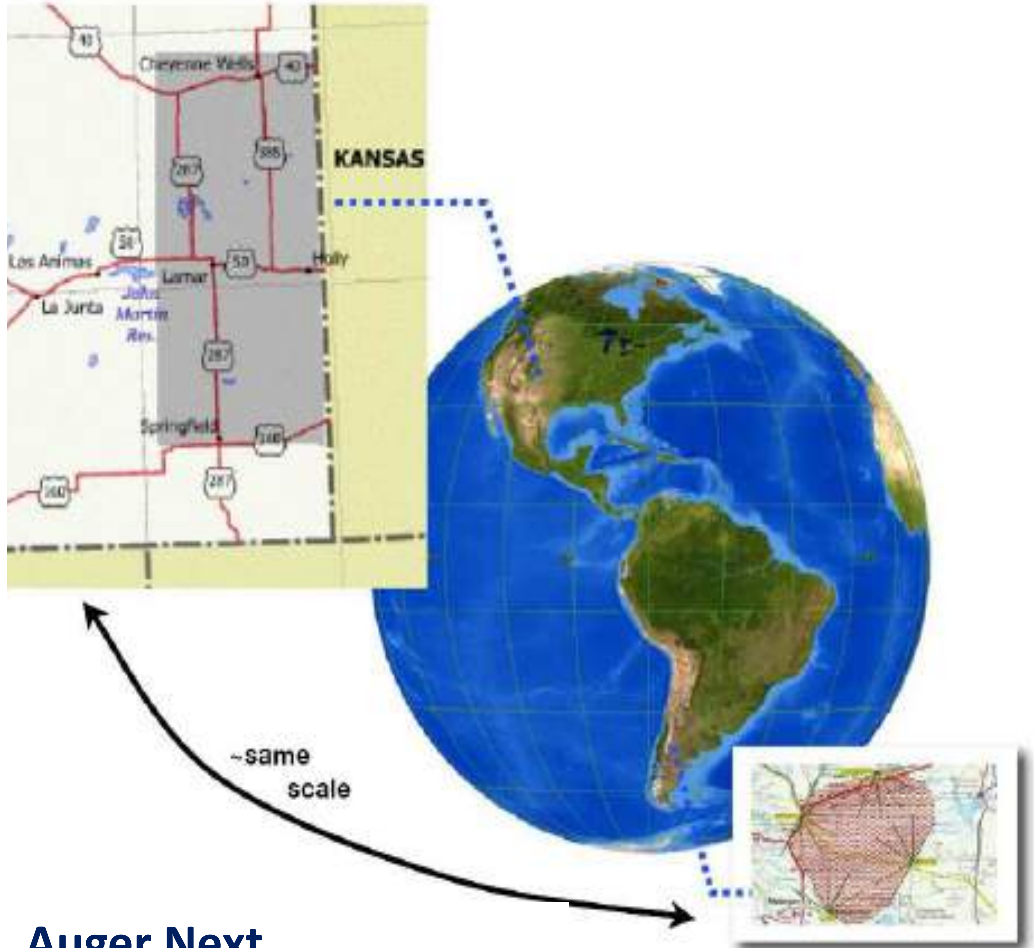
The steep rise of the gluon density at low-x must saturate (unitarity!) $\Rightarrow$ suppression of the ν-N #-section

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

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



IceCube-Gen2, including PINGU



Auger Next
Proposal for Auger-North
(3-8 x Auger South)

'The real voyage of discovery consists not in seeking new lands … but in seeing with new eyes' Marcel Proust