Probing new physics with ultra-high energy cosmic neutrinos

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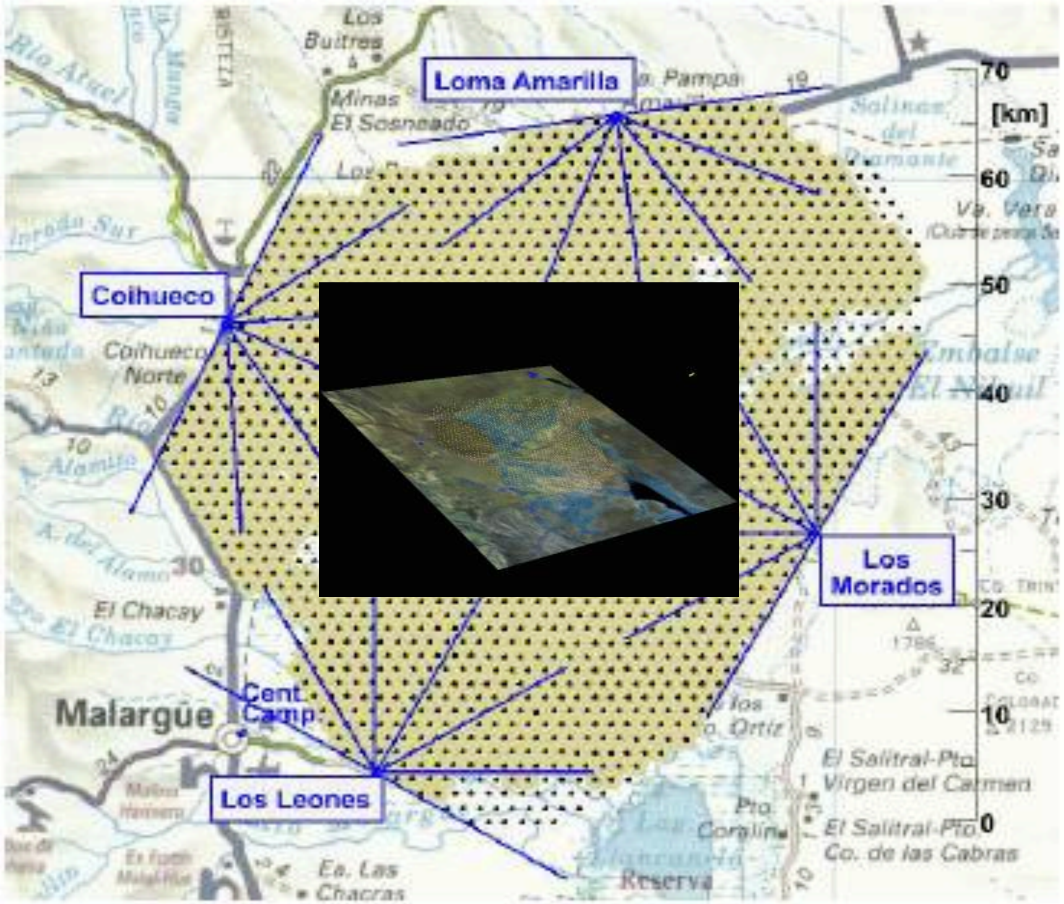
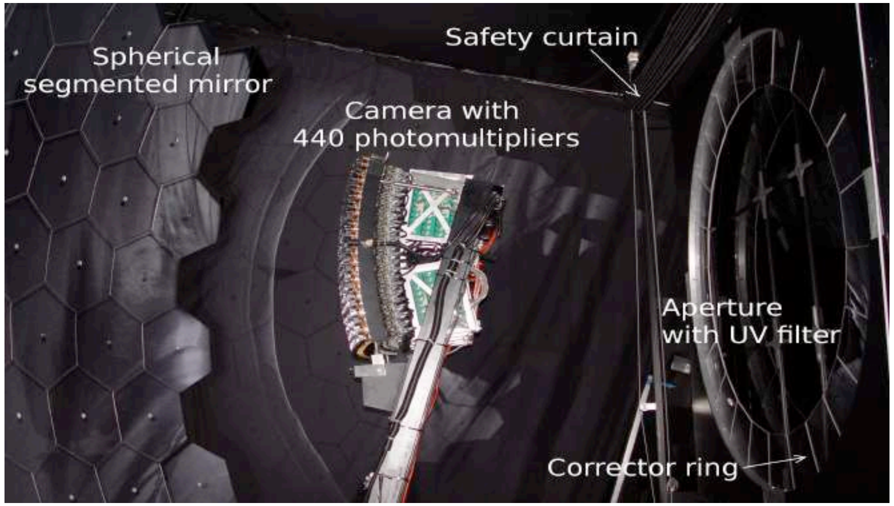
UNIVERSITY OF OXFORD

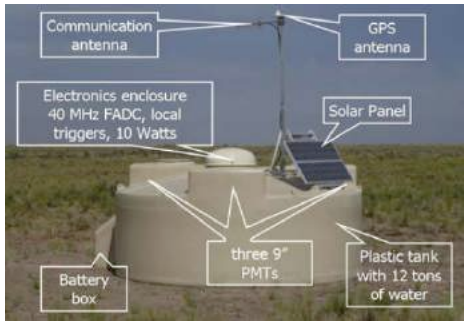
International Conference on Fundamental Physics, BM Birla Science Centre, Hyderabad, 6-9 September 2019

The Pierre Auger Observatory

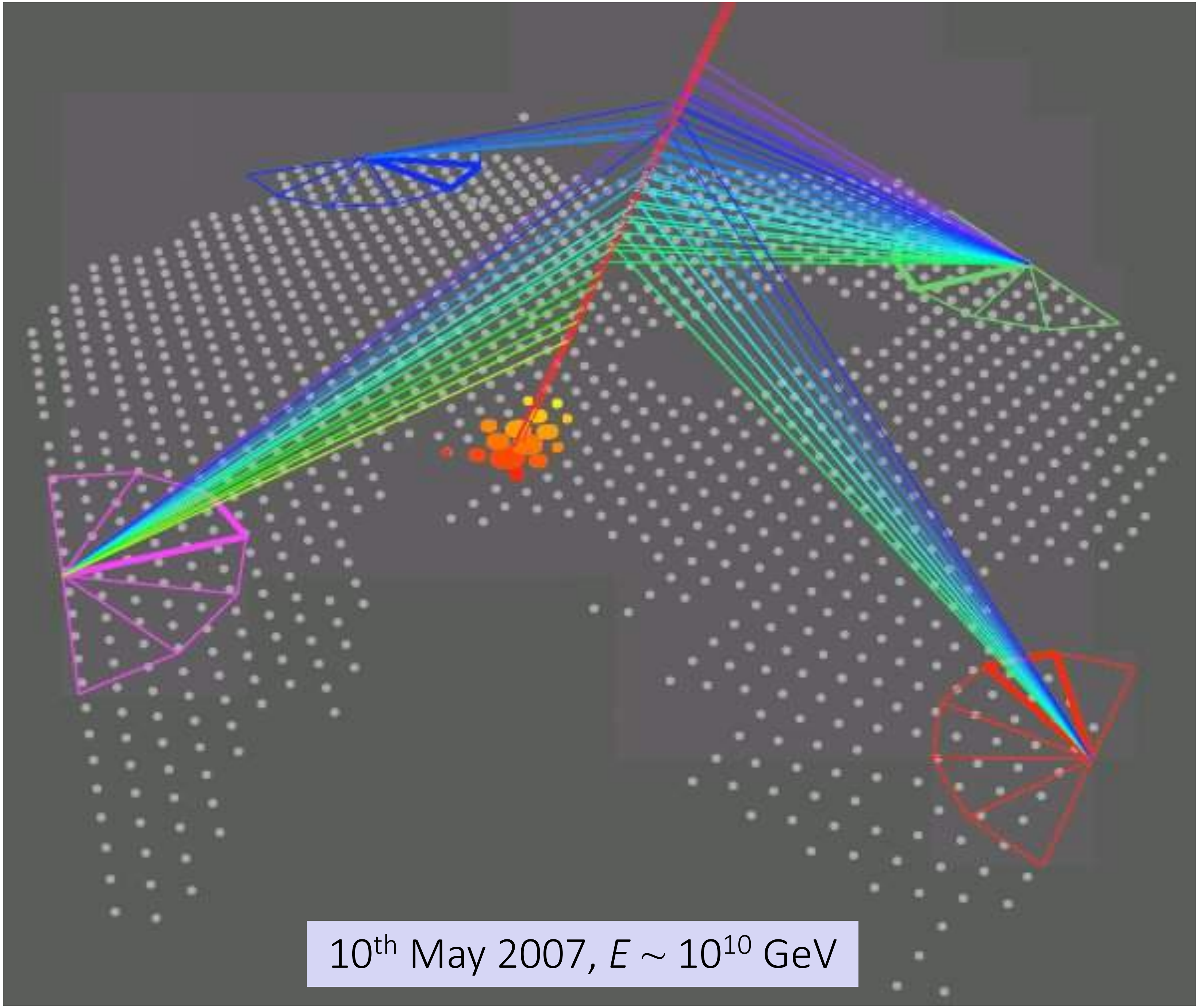




- 1600 water-cherenkov detectors
- Aperture > 7000 km^2 sr yr
- 4 × 6 telescopes

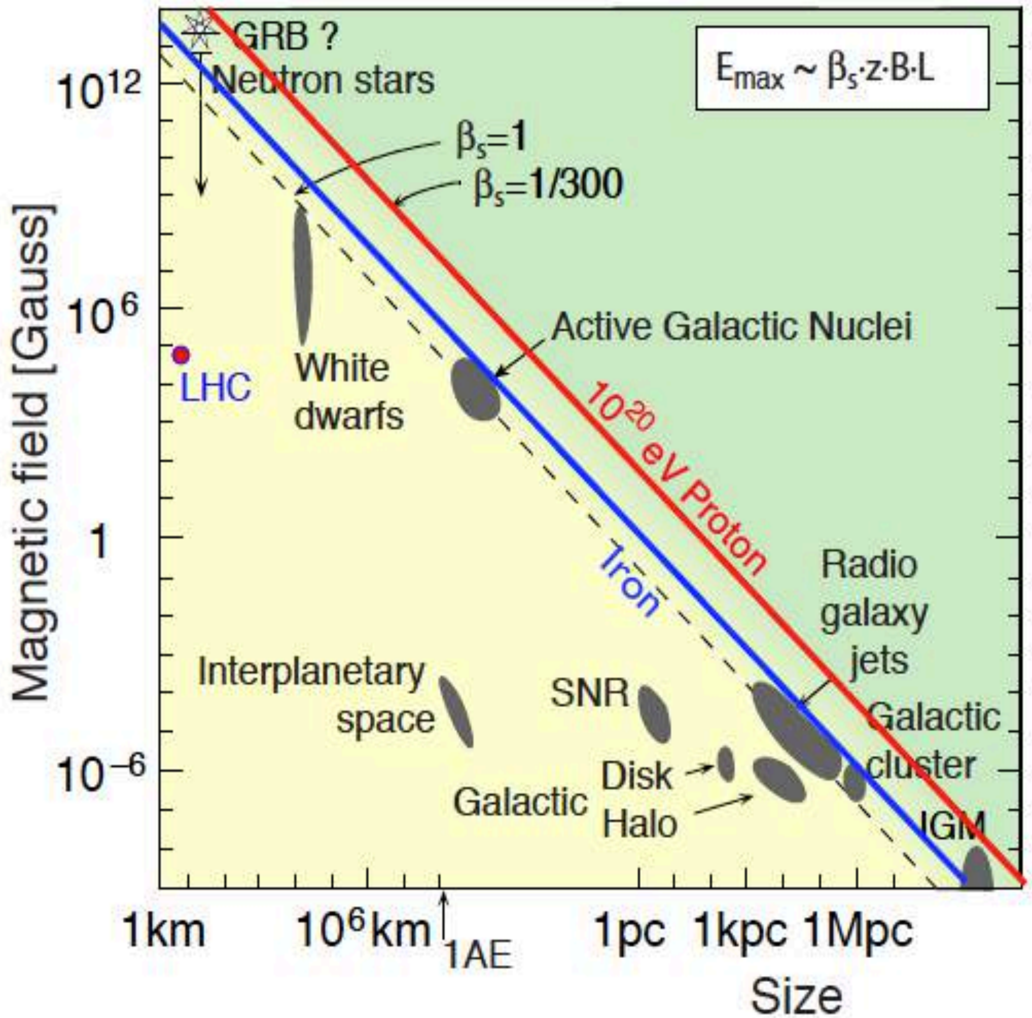


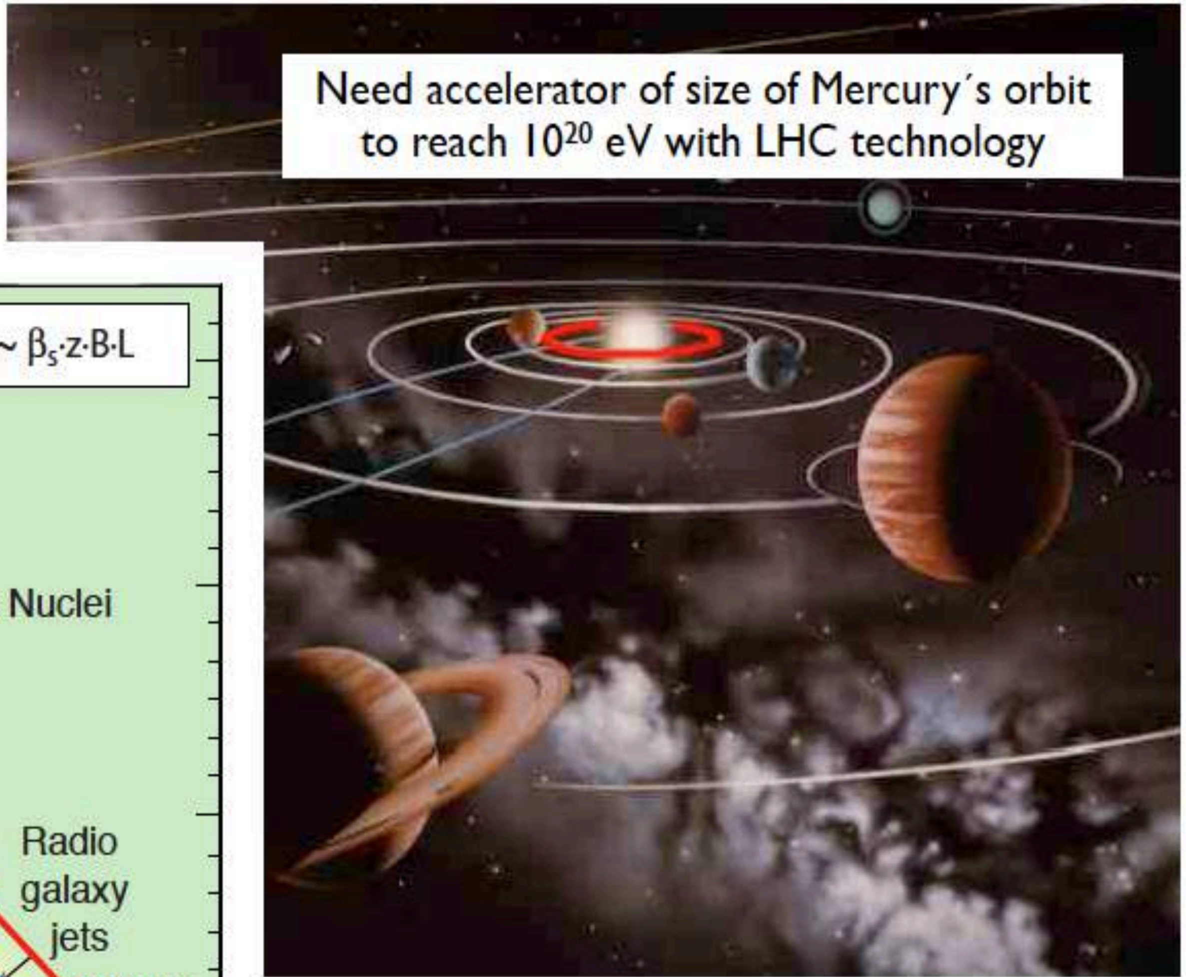
With this detector we see the *highest* energy particles in the universe



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

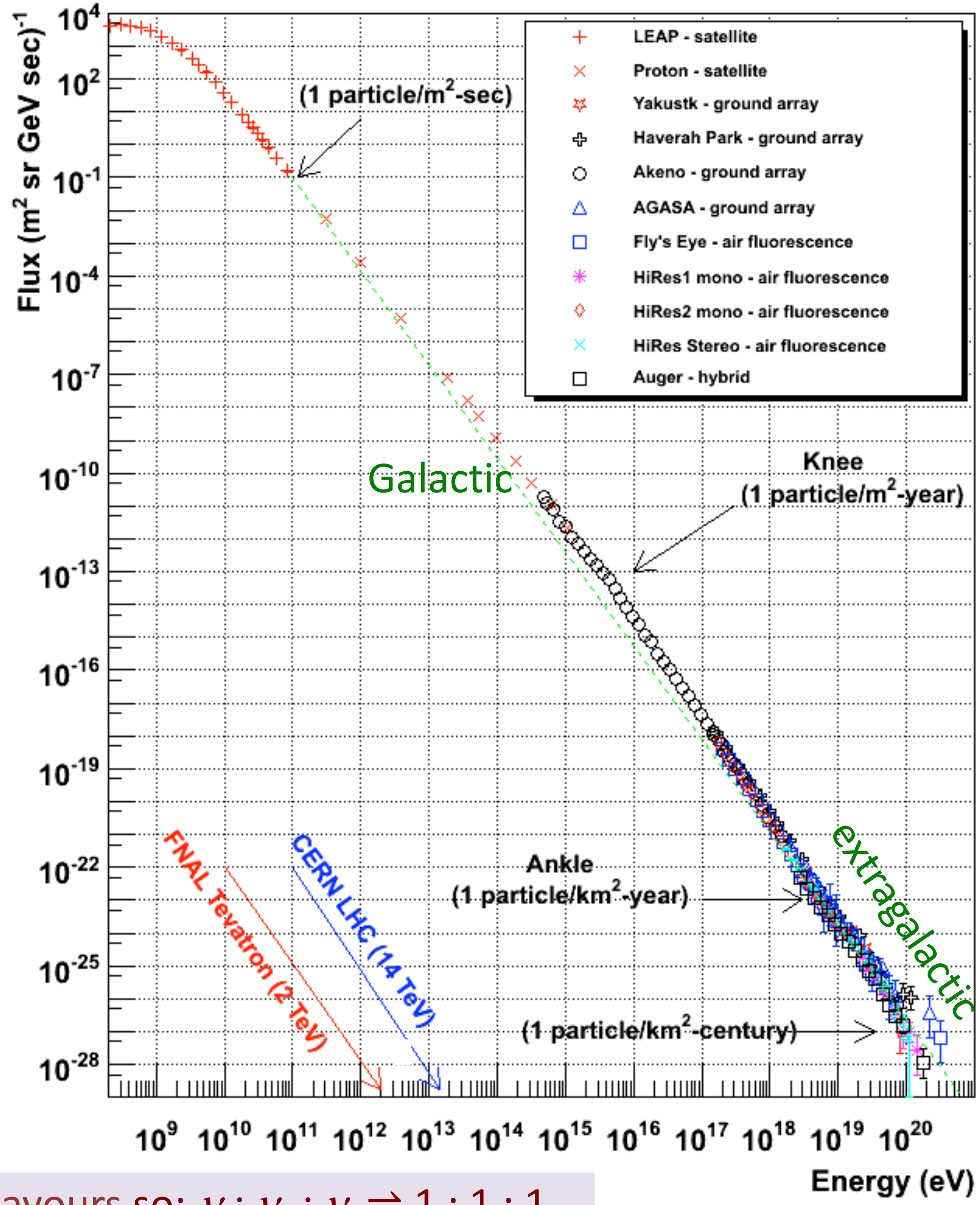
The Origin of Cosmic Rays

Extraordinary cosmic particle accelerators ***somewhere***, but still **poorly identified** a century after the discovery of cosmic rays!

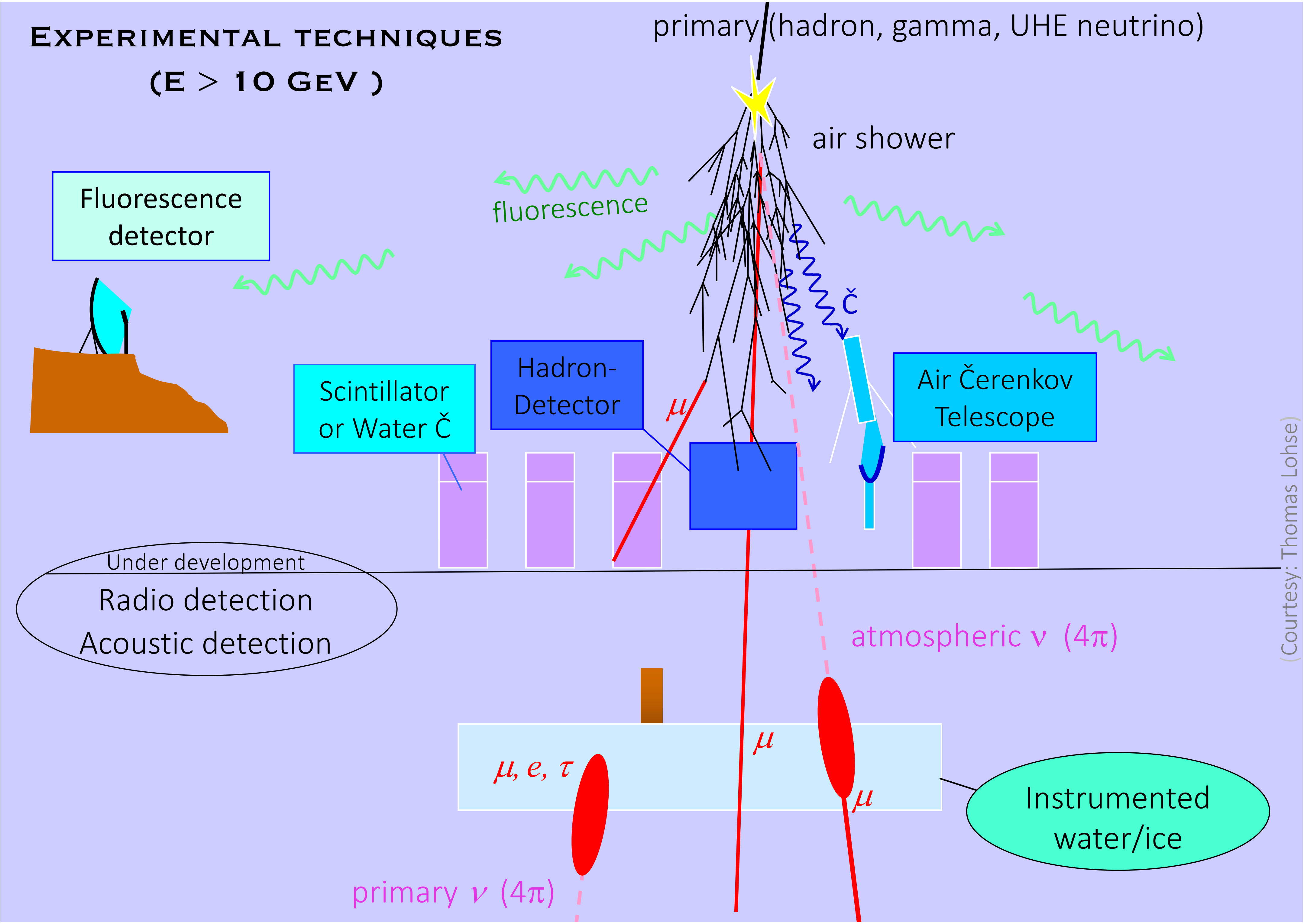
- Supernova remnants ✓
- Active galactic nuclei ?
- Gamma ray bursts ?
- Radio galaxy jets ?
- Starburst galaxies ?
- …

Cosmic ray interactions with matter and photons, near source or during propagation, produce neutrinos:

$$p + N \to X + \{\pi^+, \pi^-, \pi^0\}$$
$$\pi^0 \to \gamma + \gamma$$
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



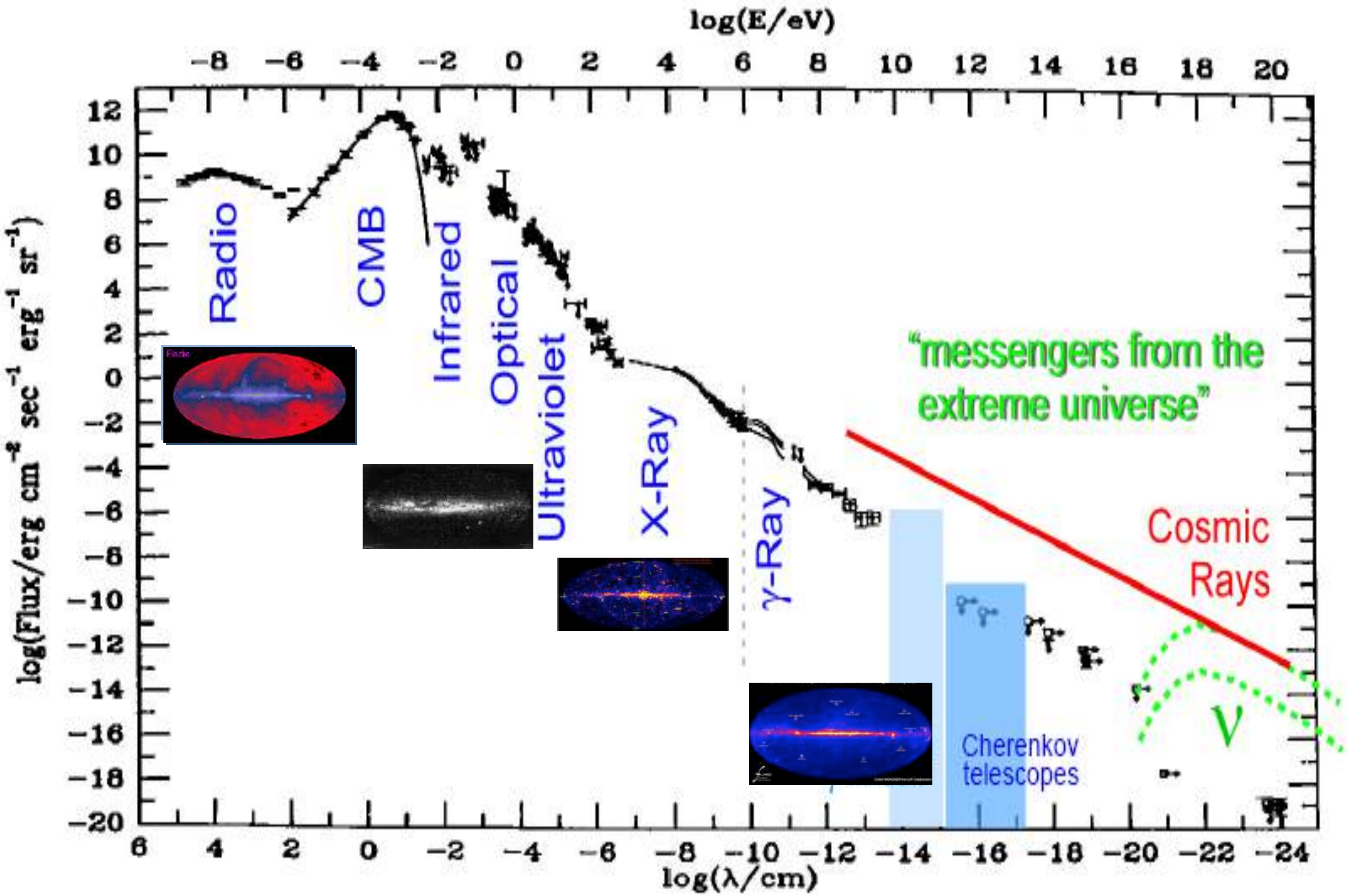
Oscillations en-route to Earth equlibrate flavours so: $\nu_e : \nu_\mu : \nu_\tau \Rightarrow 1:1:1$



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

Most of our knowledge of the universe comes from observing photons

… but above ~10 TeV they are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on the CIB



Using **cosmic rays** we can 'see' (if there are no magnetic fields) up to ~6 x 10^{10} GeV (before they are attenuated $p\gamma \rightarrow \Delta^+ \rightarrow n\,\pi^+$ on the CMB)

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

Colliders versus Cosmic rays

The LHC has achieved 13 TeV cms …

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

$\Rightarrow$ ~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)

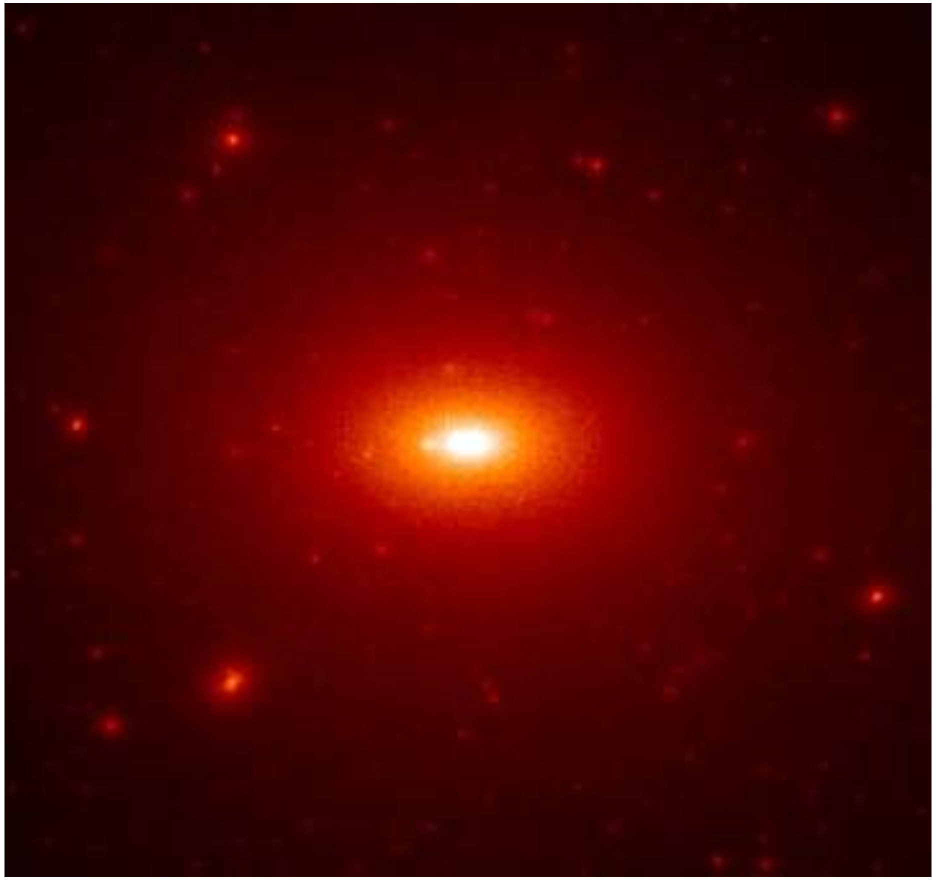
motivated by trans-GZK energy events observed by AGASA

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

Motivated by trans-GZK events seen by AGASA, it was proposed that UHECRs are produced *locally* in the Galactic halo from the decays of metastable supermassive dark matter particles ('WIMPzillas')

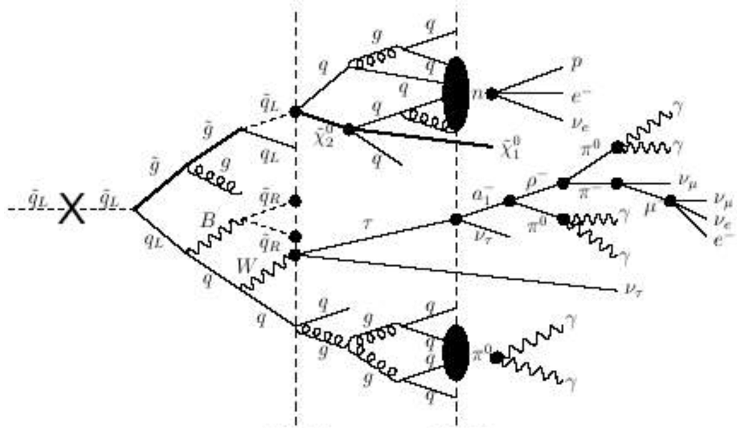
… produced at the end of inflation by the rapidly changing gravitational field

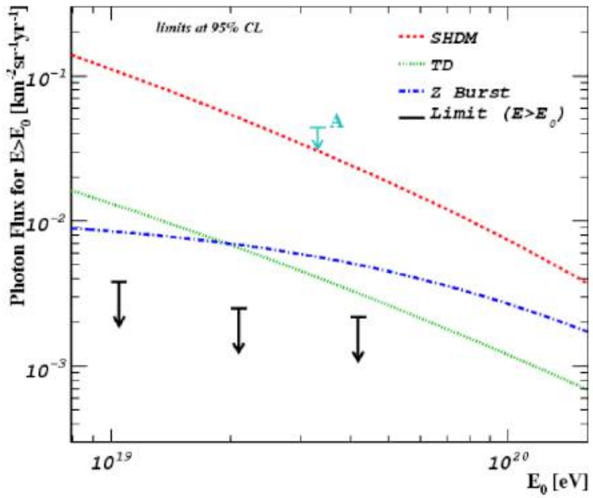
➛ **energy spectrum** determined by QCD fragmentation ✓
➛ **composition** dominated by photons rather than nucleons ✗
➛ **anisotropy** due to our off-centre position ?



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

Berezinsky, Kachelreiss & Vilenkin PRL **79**:4302,1997
Birkel & Sarkar AP **9**:297,1998





arXiv:0712.1147

This has been *ruled out* by Auger

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

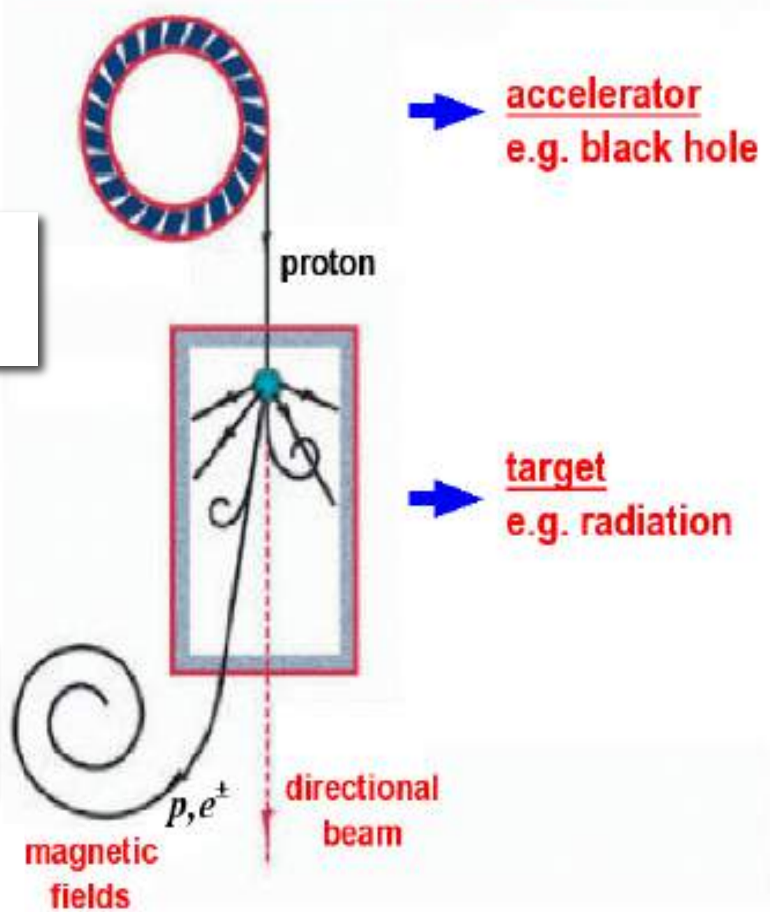
From rate of UHE CR's (10^{19}-10^{21} eV)

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

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

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

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

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

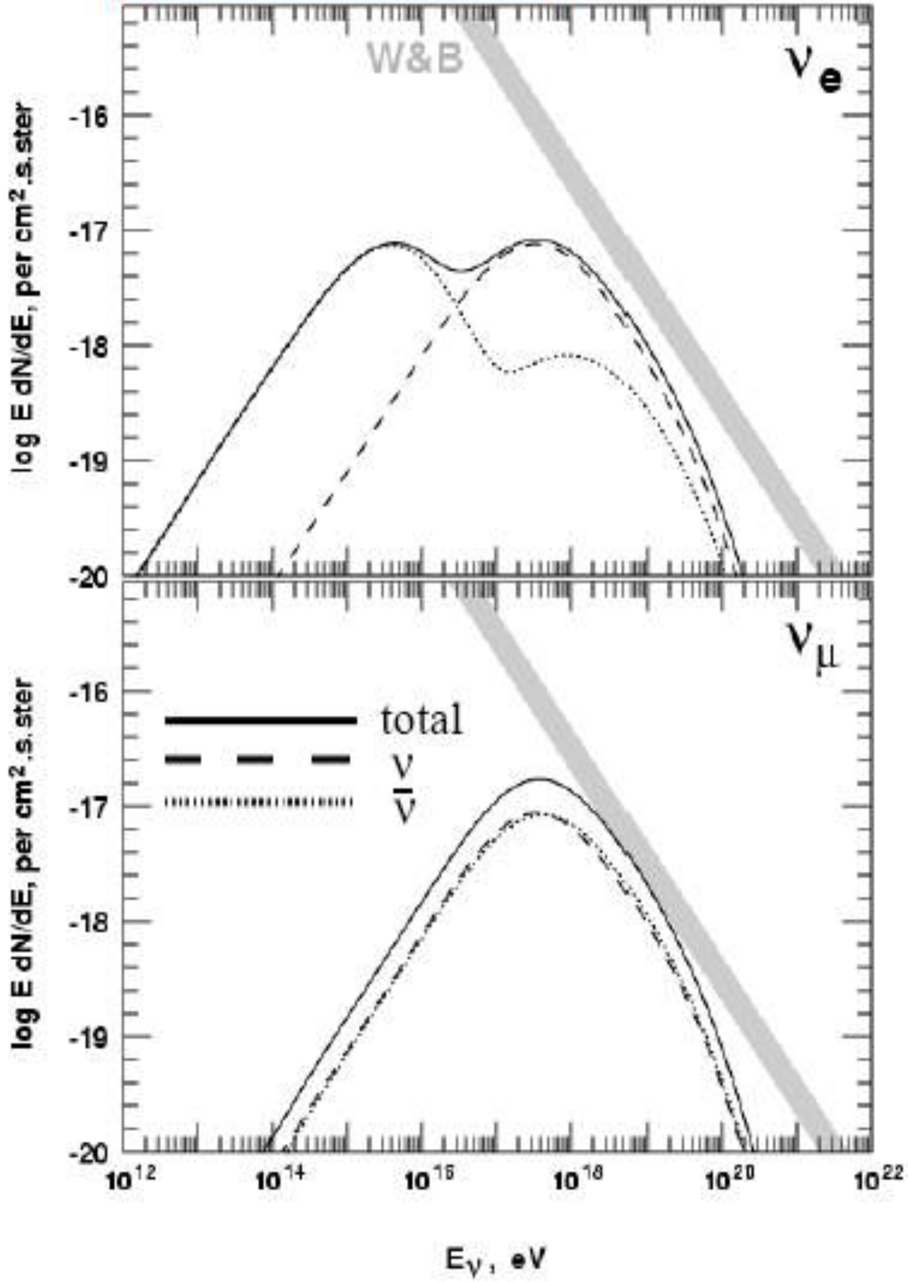
$$\mu^{+} \rightarrow e^{+}+\nu_e+\bar{\nu}_\mu$$

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

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)

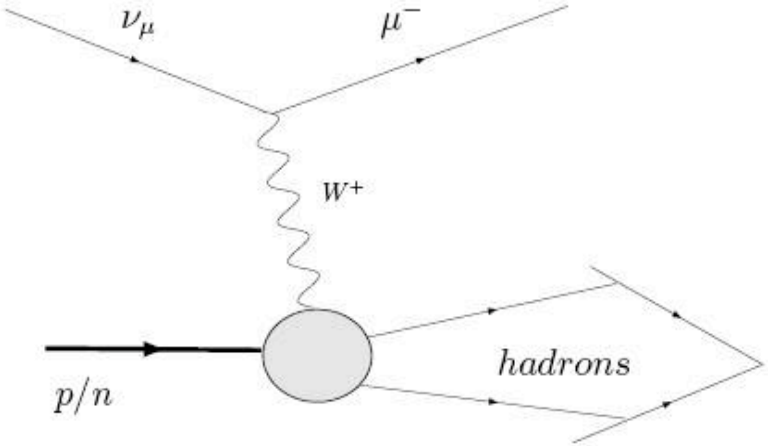
We can work out the interaction rate via ν-N deep inelastic scattering (dominant process above ~10 GeV)

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

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

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

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



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

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

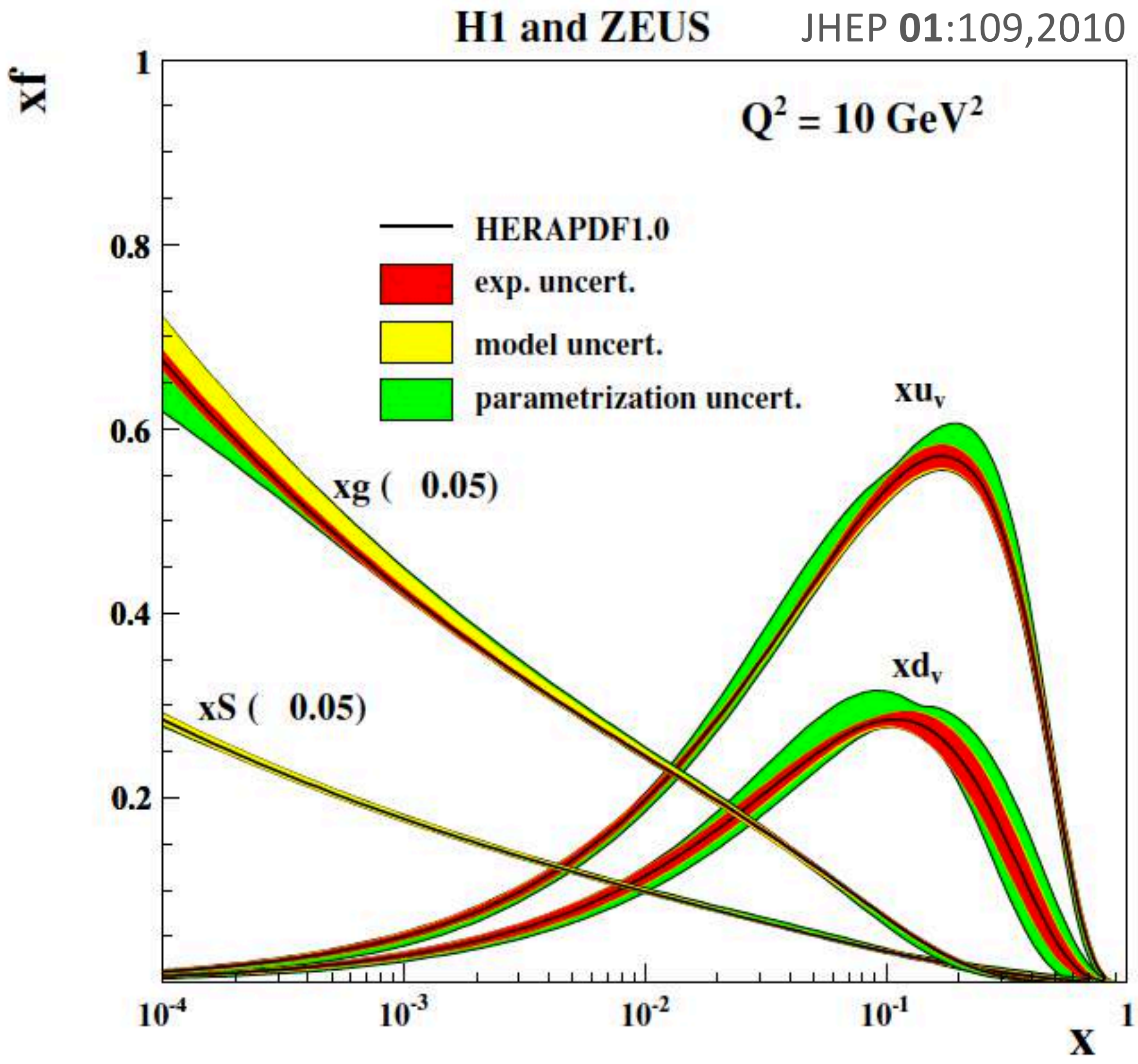
$$\text{At leading order (LO)}: F_{\rm L} = 0, \quad F_2 = x(u_{\rm v} + d_{\rm v} + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c}),$$

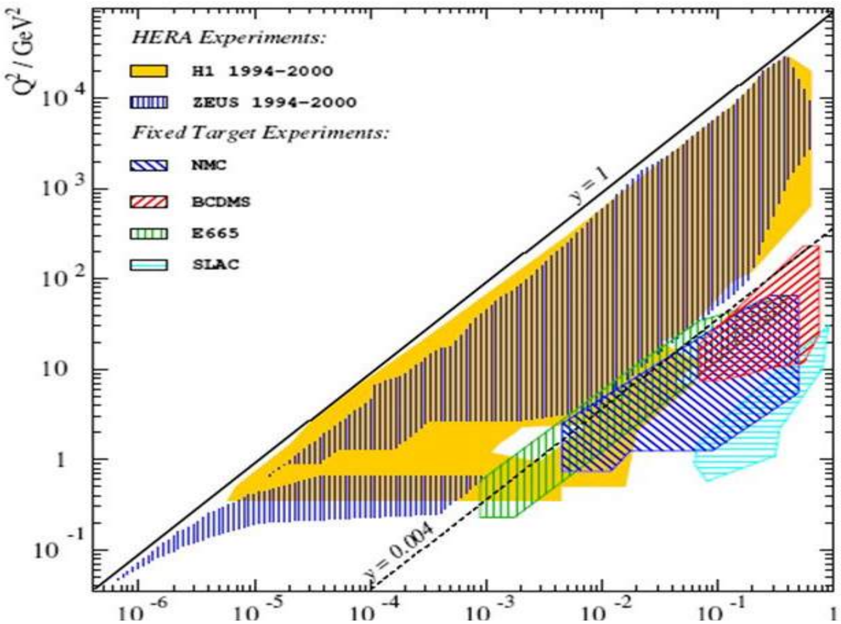
$$xF_3 = x(u_{\rm v} + d_{\rm v} + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_{\rm v} + d_{\rm v} + 2s + 2b - 2\bar{c})$$

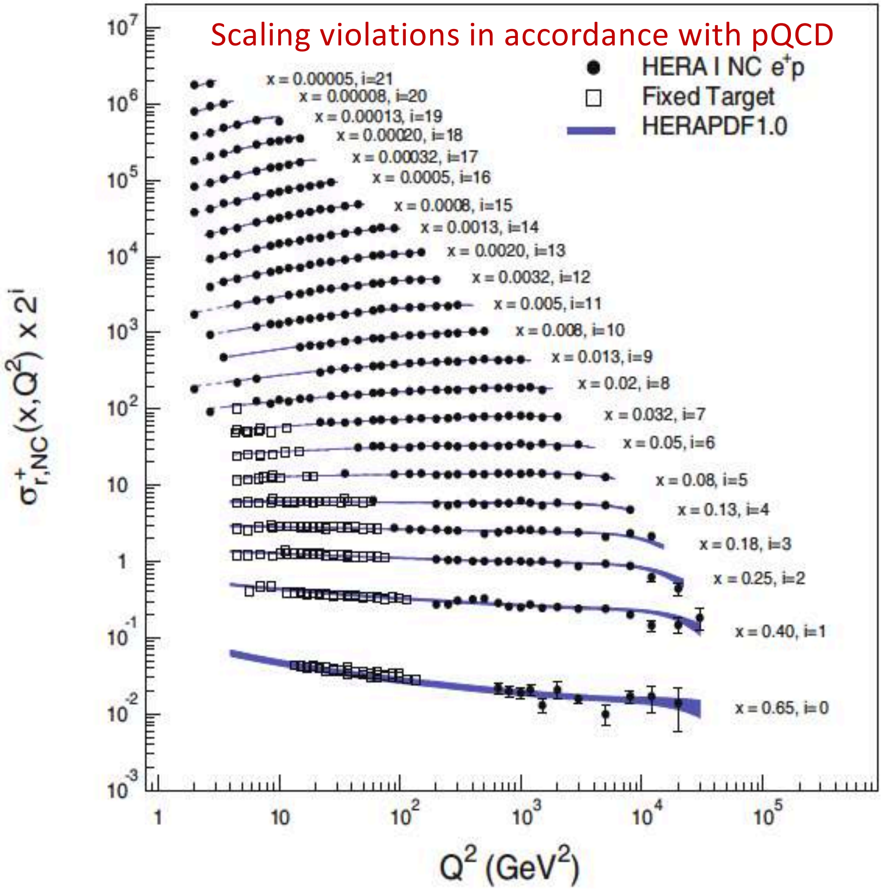
Can calculate numerically at Next-to-Leading-Order (NLO) … *no* significant further change at NNLO

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







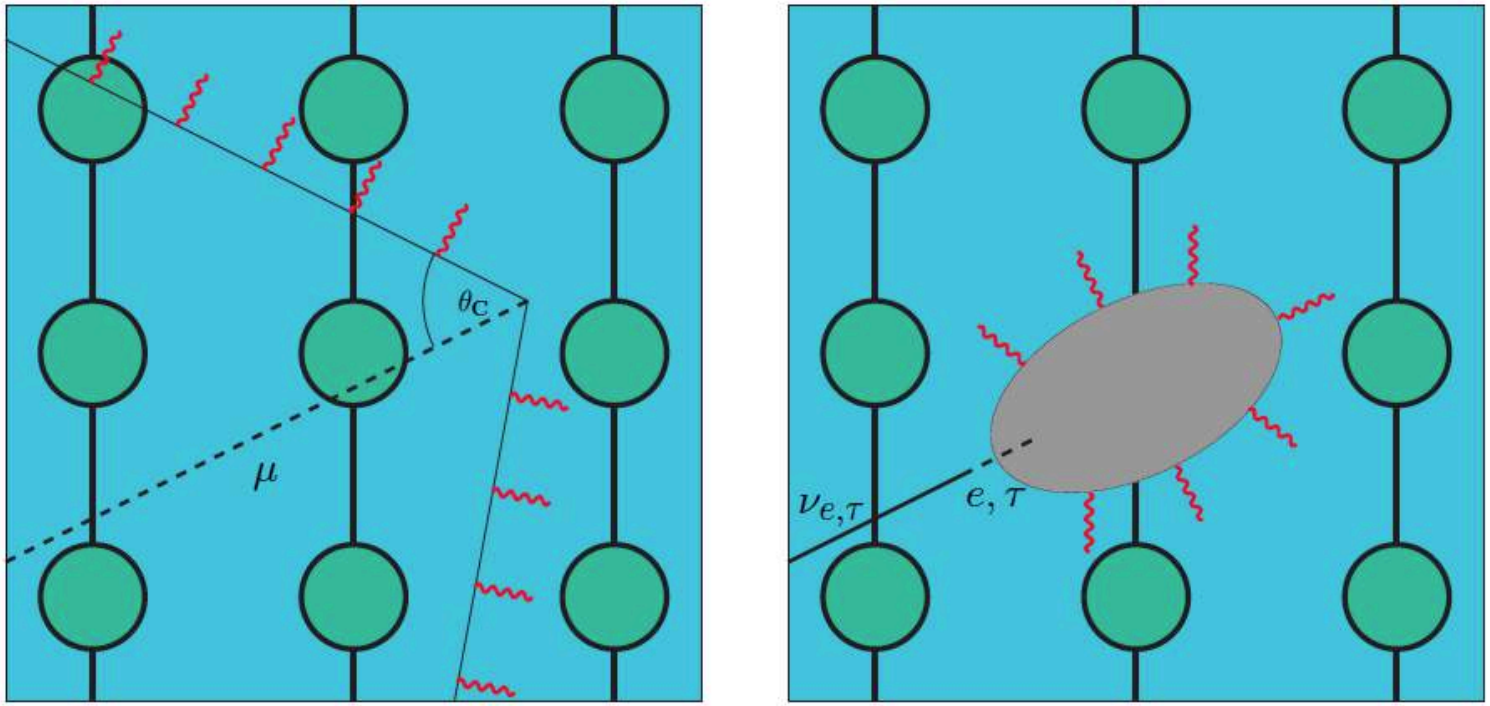
How big a detector do we need to see neutrino interactions?

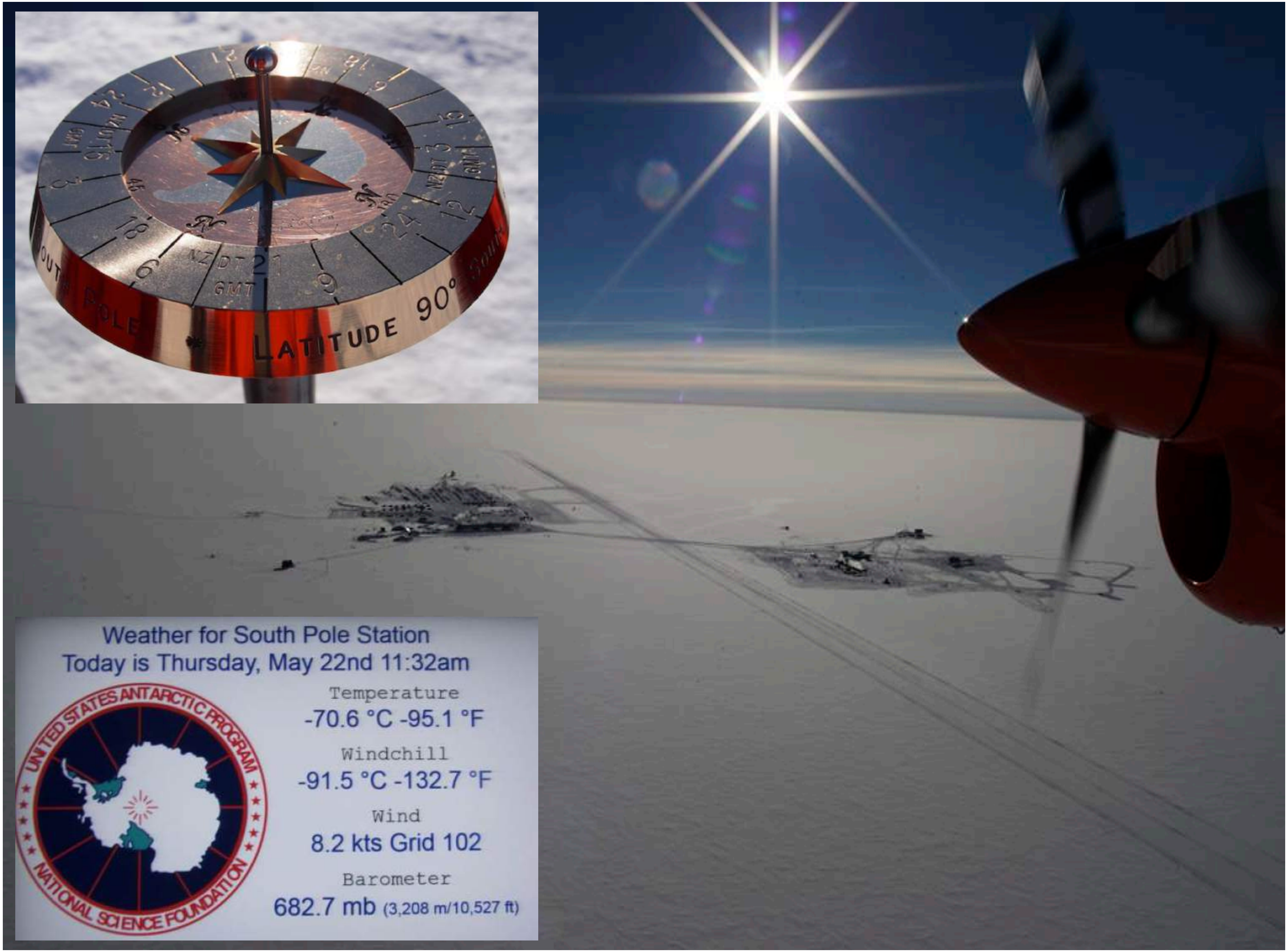
back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

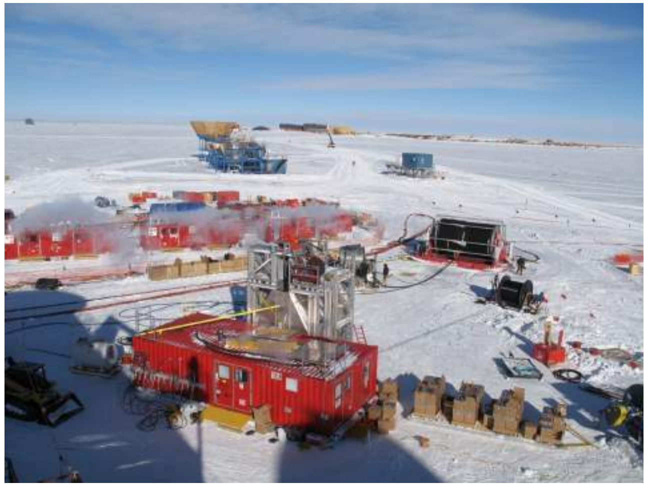
- **flux of neutrinos** : $\dfrac{d^2N_\nu}{dt\,dA} \sim \dfrac{1}{cm^2 \times 10^5 yr}$
- **cross section** : $\sigma_{\nu N} \sim 10^{-33} cm^2$
- **targets**: $N_N \sim N_A \times V/cm^3$

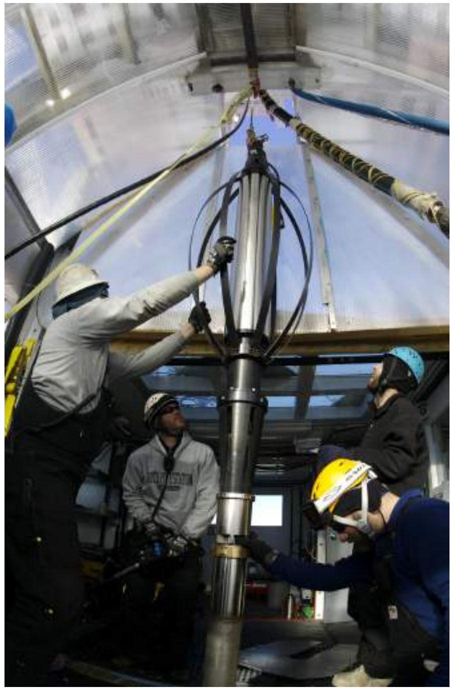
→ **rate of events** :

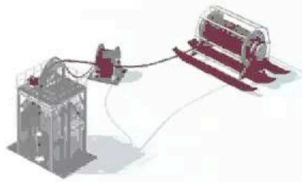
$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{d^2N_\nu}{dt\,dA} \sim \frac{1}{\text{year}} \times \frac{V}{1\text{km}^3}$$




LATITUDE 90°
Weather for South Pole Station
Today is Thursday, May 22nd 11:32am
Temperature
-70.6 °C -95.1 °F
Windchill
-91.5 °C -132.7 °F
Wind
8.2 kts Grid 102
Barometer
682.7 mb (3,208 m/10,527 ft)
UNITED STATES ANTARCTIC PROGRAM
NATIONAL SCIENCE FOUNDATION







IceCube Neutrino Observatory

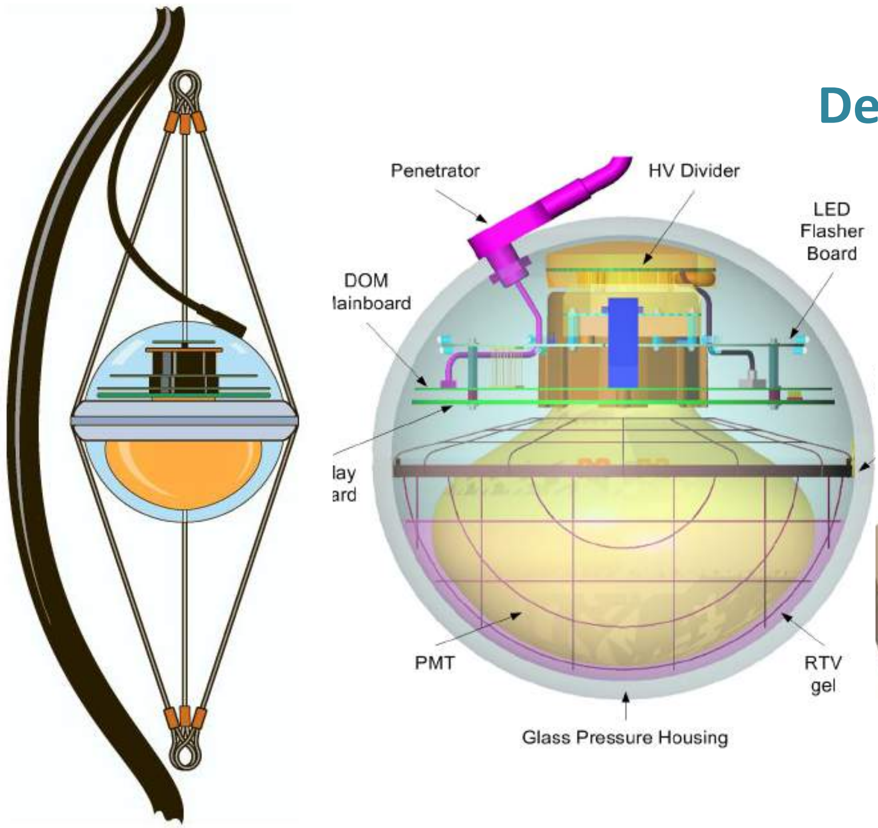
86 strings (125 m between strings)

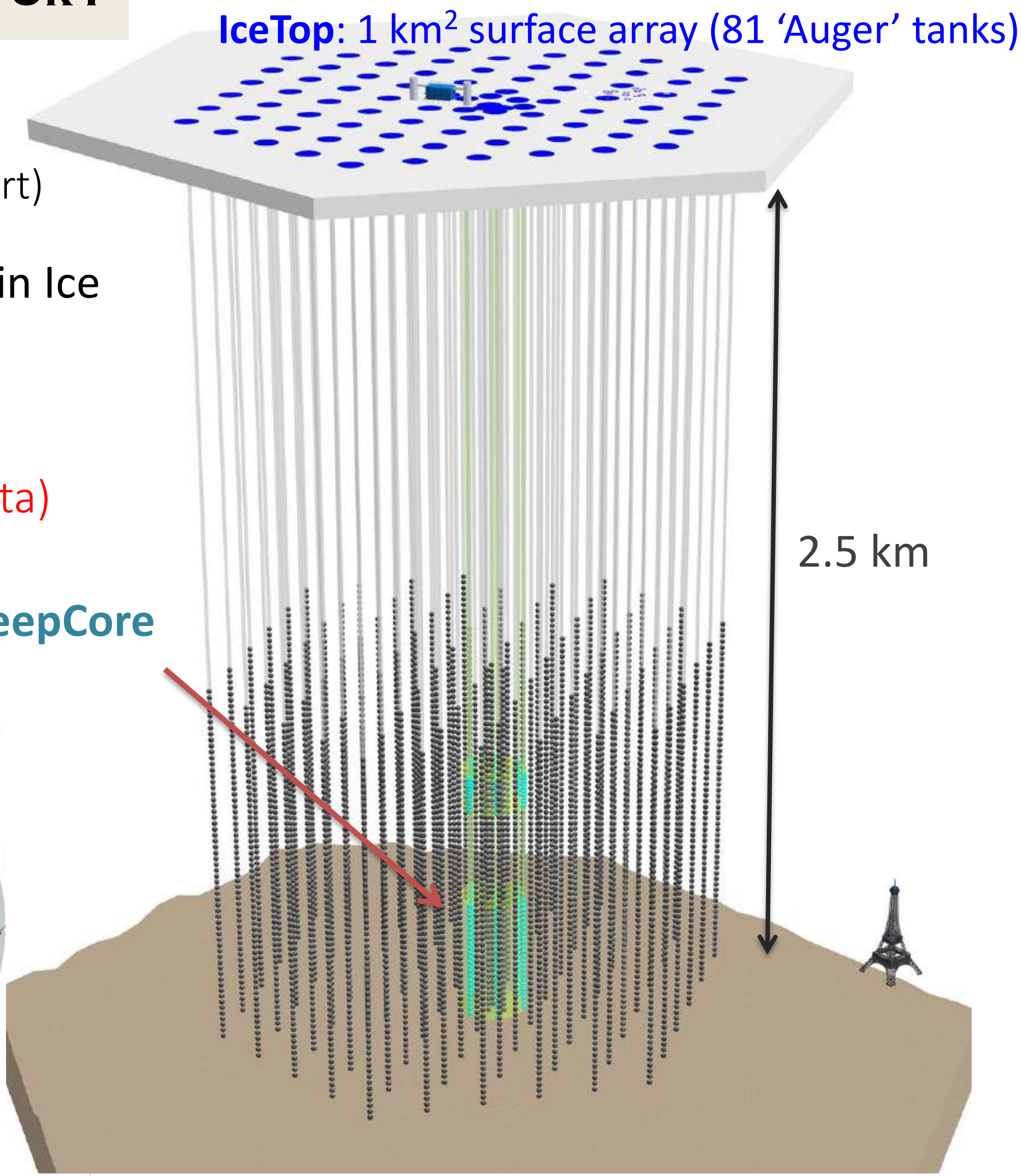
60 Optical Modules per string (17 m apart)

5160 Digital Optical Modules (DOMs) in Ice

1 km³ ⇒ Gton instrumented volume

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





Cost: 279 M$ ⇒ <30 cents per 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

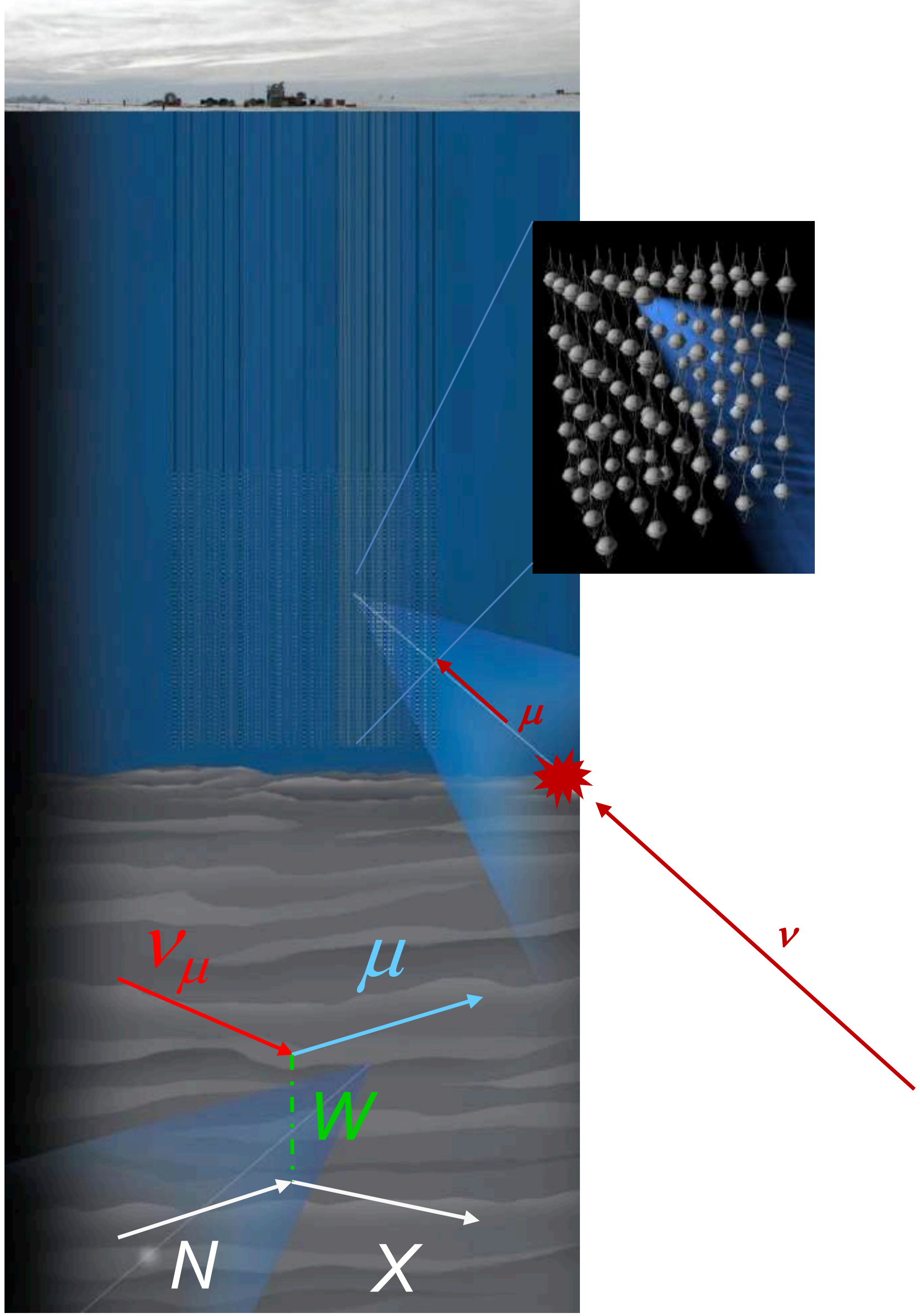
'summer' is coming to the South Pole (it has warmed up to -50°)!

High Energy Neutrino Detection Principle

- A ν interacts with a nucleus
  ... produces a μ (e or τ)
  and/or a 'cascade'

- A charged particle moving at *superluminal* speed gives rise to Cherenkov radiation (cone ∠ 40°)

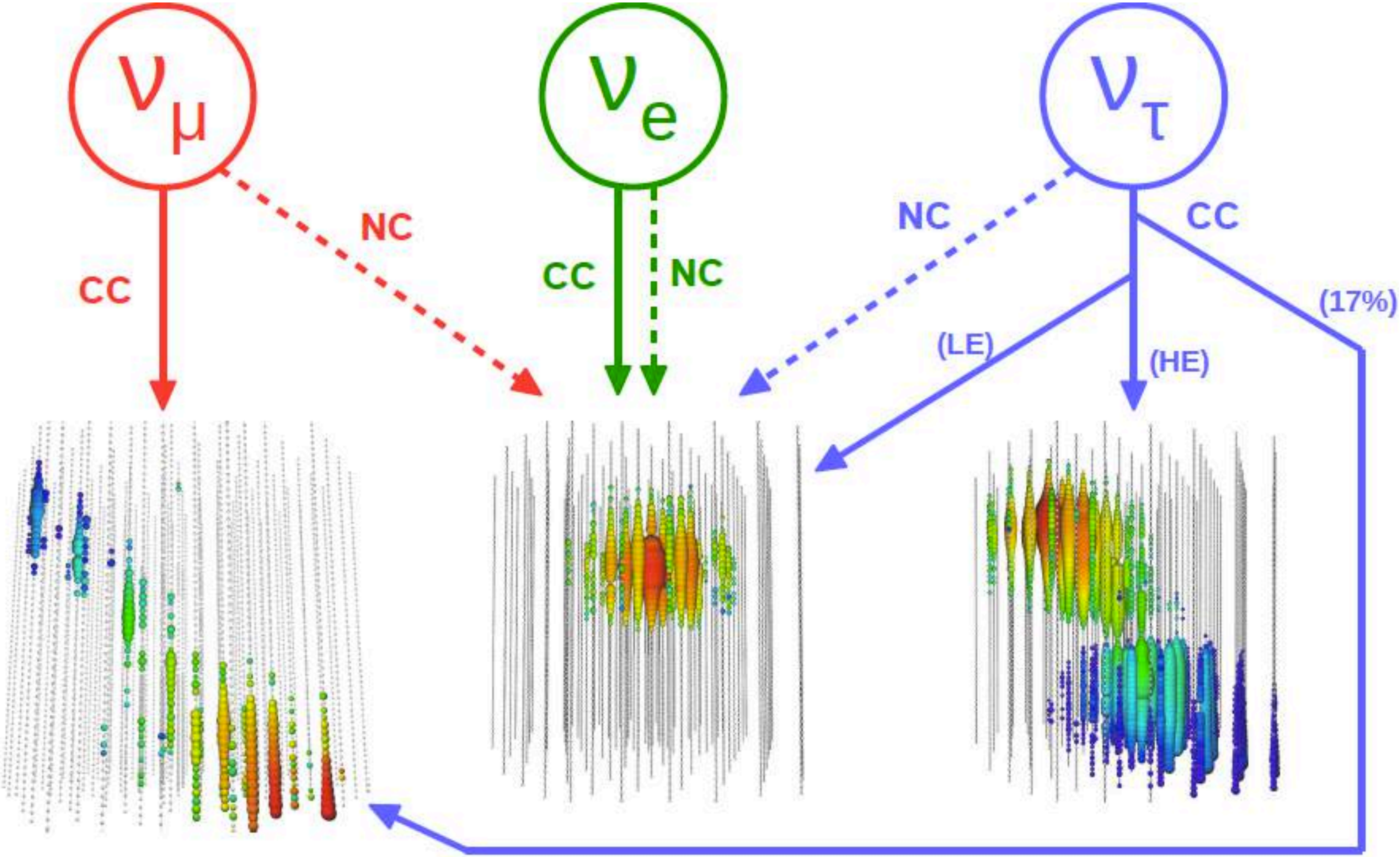
- This radiation is detected by 3D array of optical sensors



Position, time and amplitude of hits allows reconstruction of tracks using likelihood optimisation

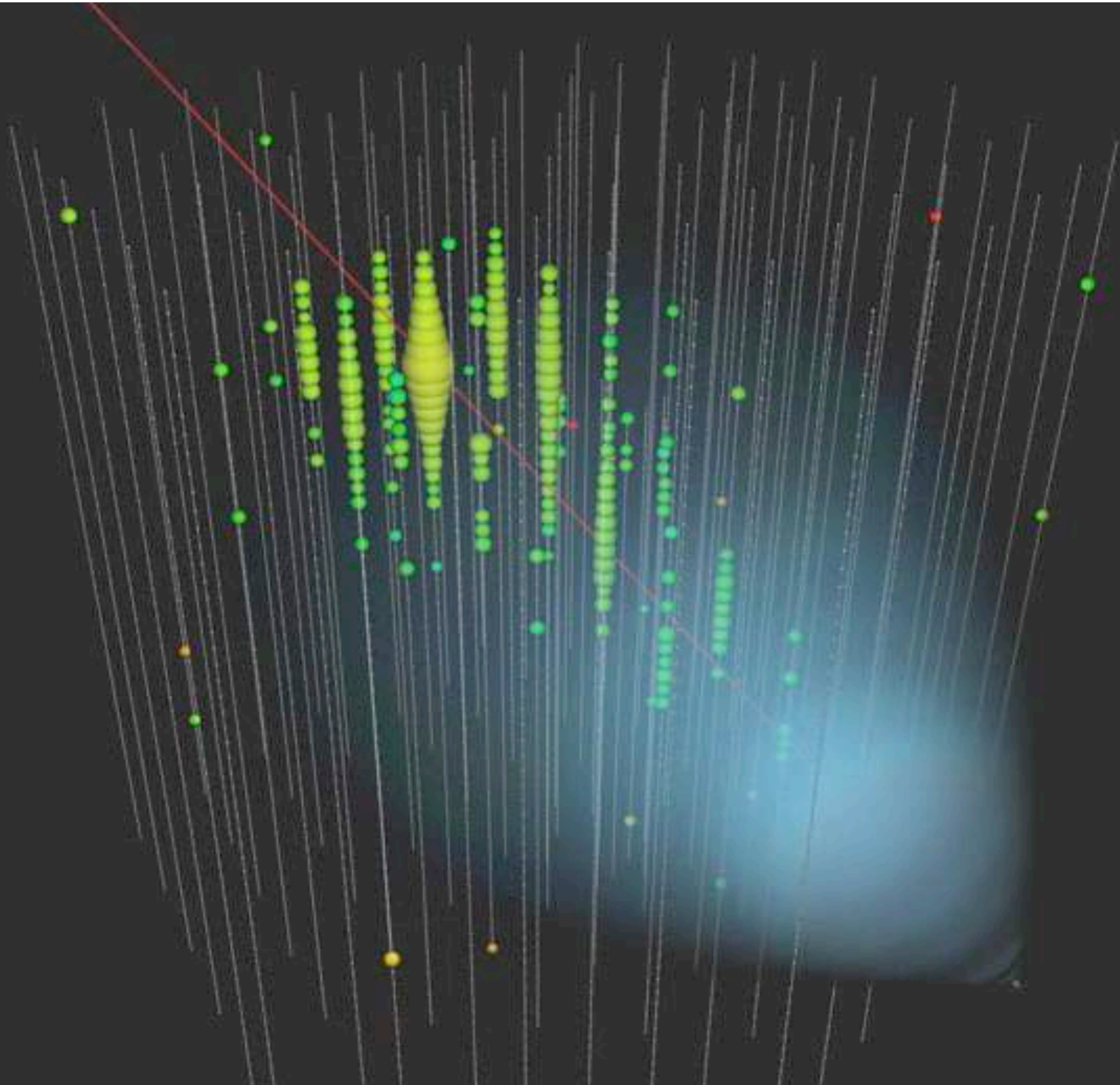
The lepton direction is aligned with the incoming ν ➟ astronomy!

Neutrino flavour discrimination in IceCube



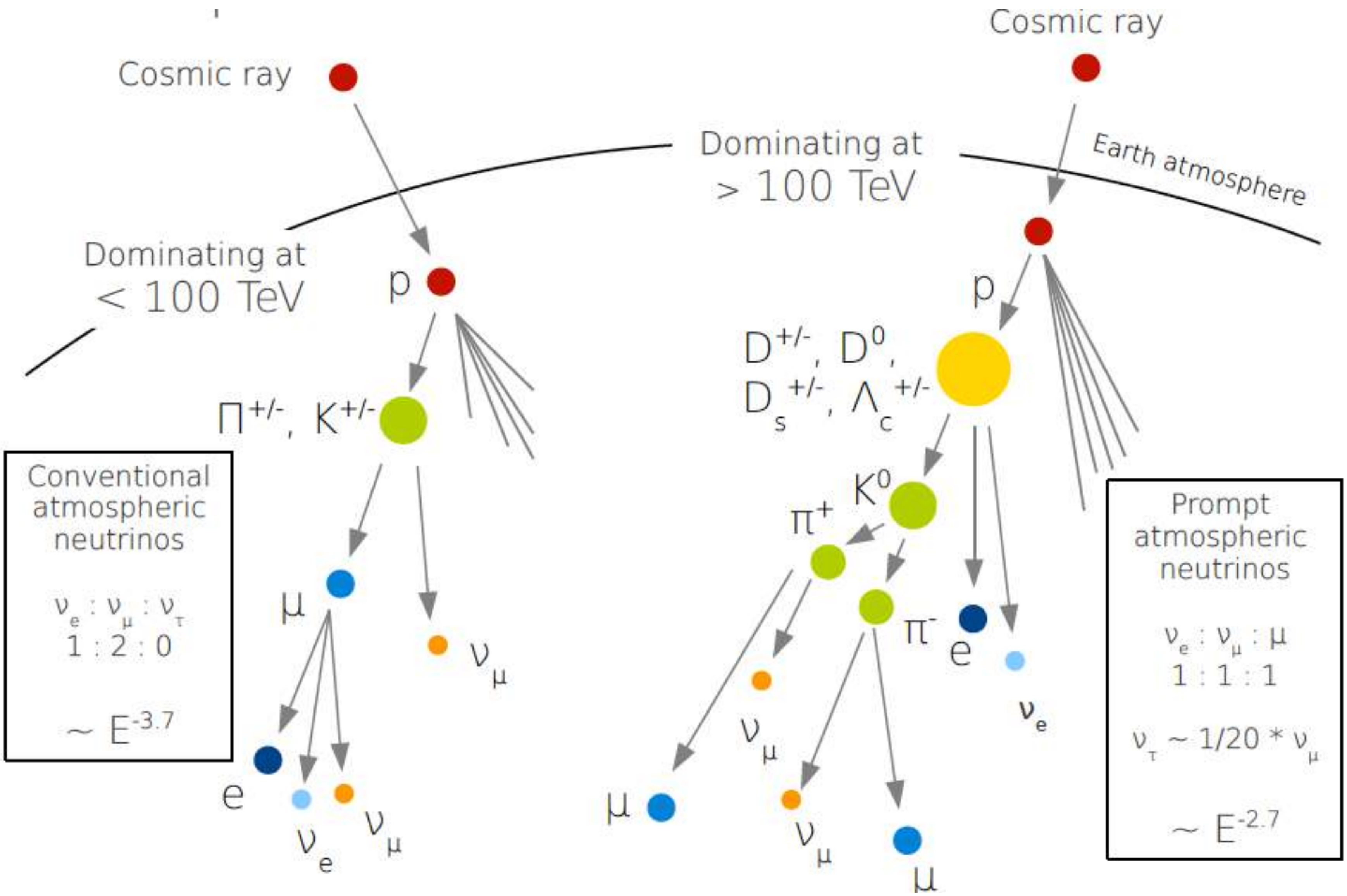
Track topology
Good pointing (~0.2°-1°)
but only lower bound on neutrino energy

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



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

Atmospheric neutrinos

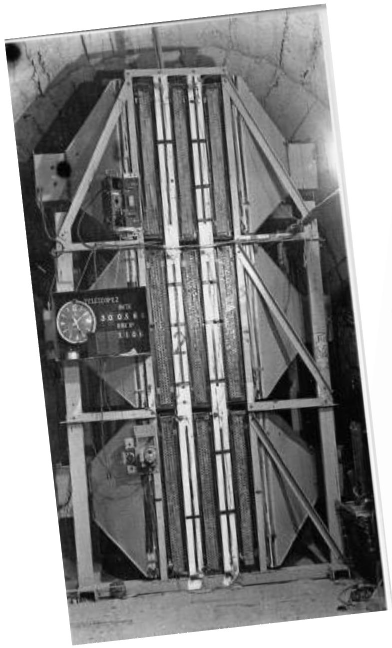


(Courtesy: Anne Schukraft)

Discovery of atmospheric neutrinos: 1965 (KGF India)

Discovery of atmospheric neutrino oscillations: 1998 (Kamioka Japan)

Discovery of atmospheric neutrinos: 1965



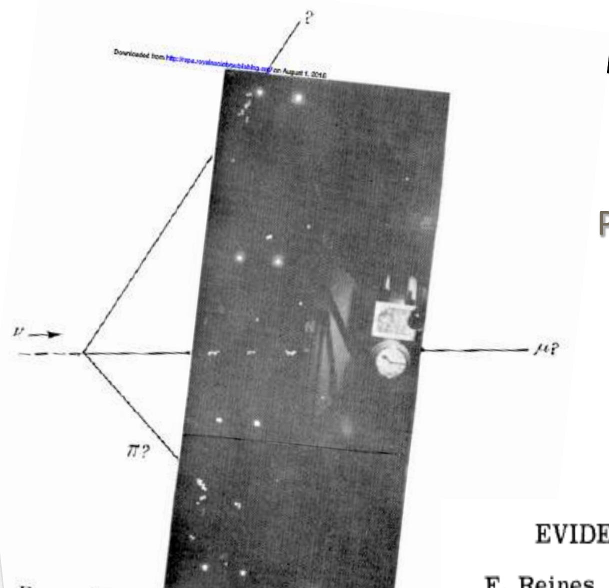


FIGURE 18. A multiple neutrino event (event n

Neutrino detector at the Kolar Gold Fields, India

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

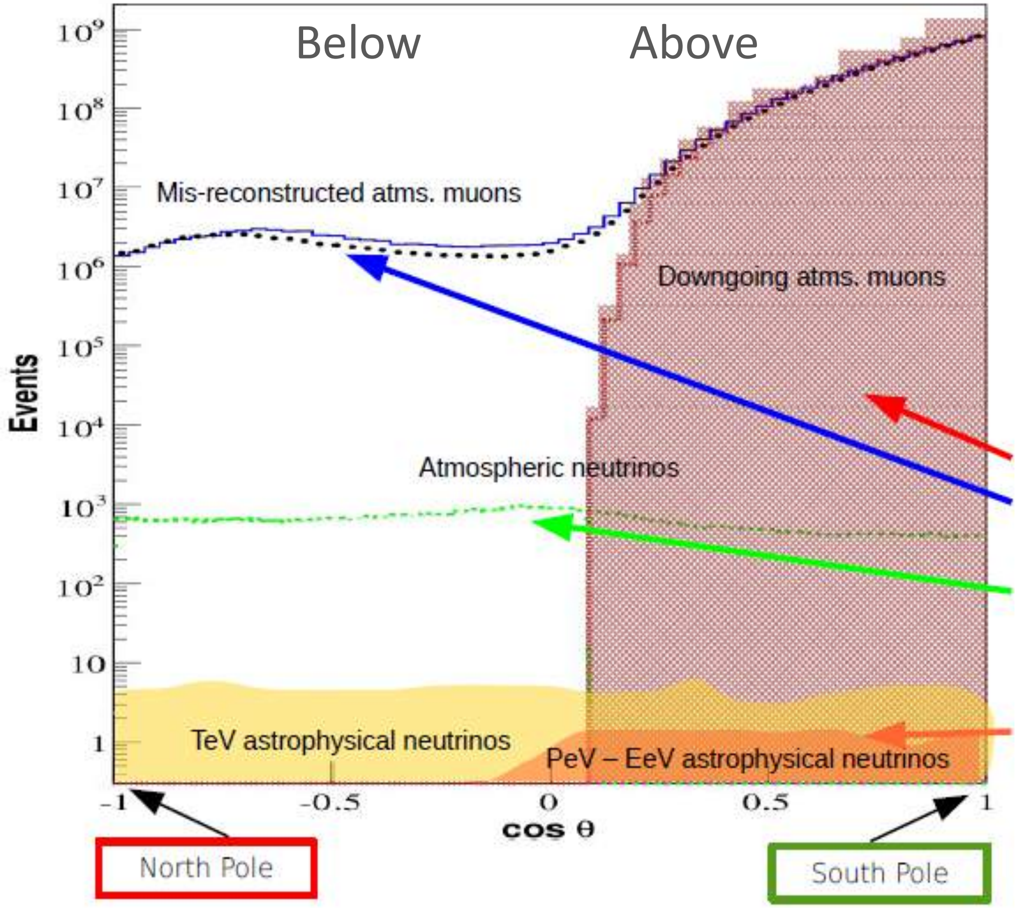
Received 12 July 1965

Physics Letters **18** (1965) 196 - published 15th Aug 1965

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

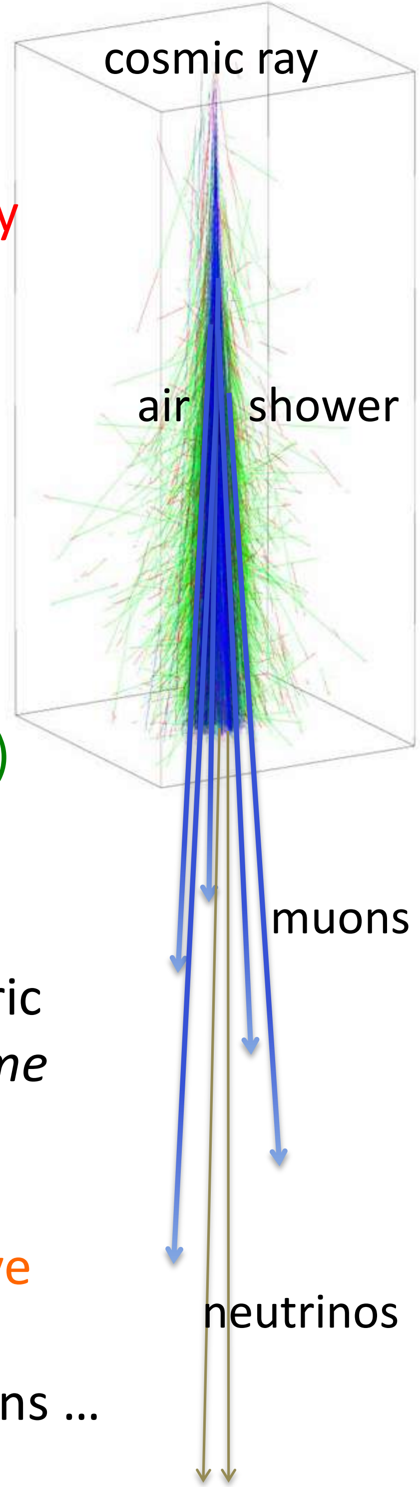
Physical Review Letters **15** (1965) 429 - published 30th Aug 1965



There is an enormous background of cosmic ray muons going *down*

(only *misreconstructed* muons apparently going up since muons are all absorbed in the Earth)

Atmospheric neutrinos come from the *same* showers (1 in 10^6 events)

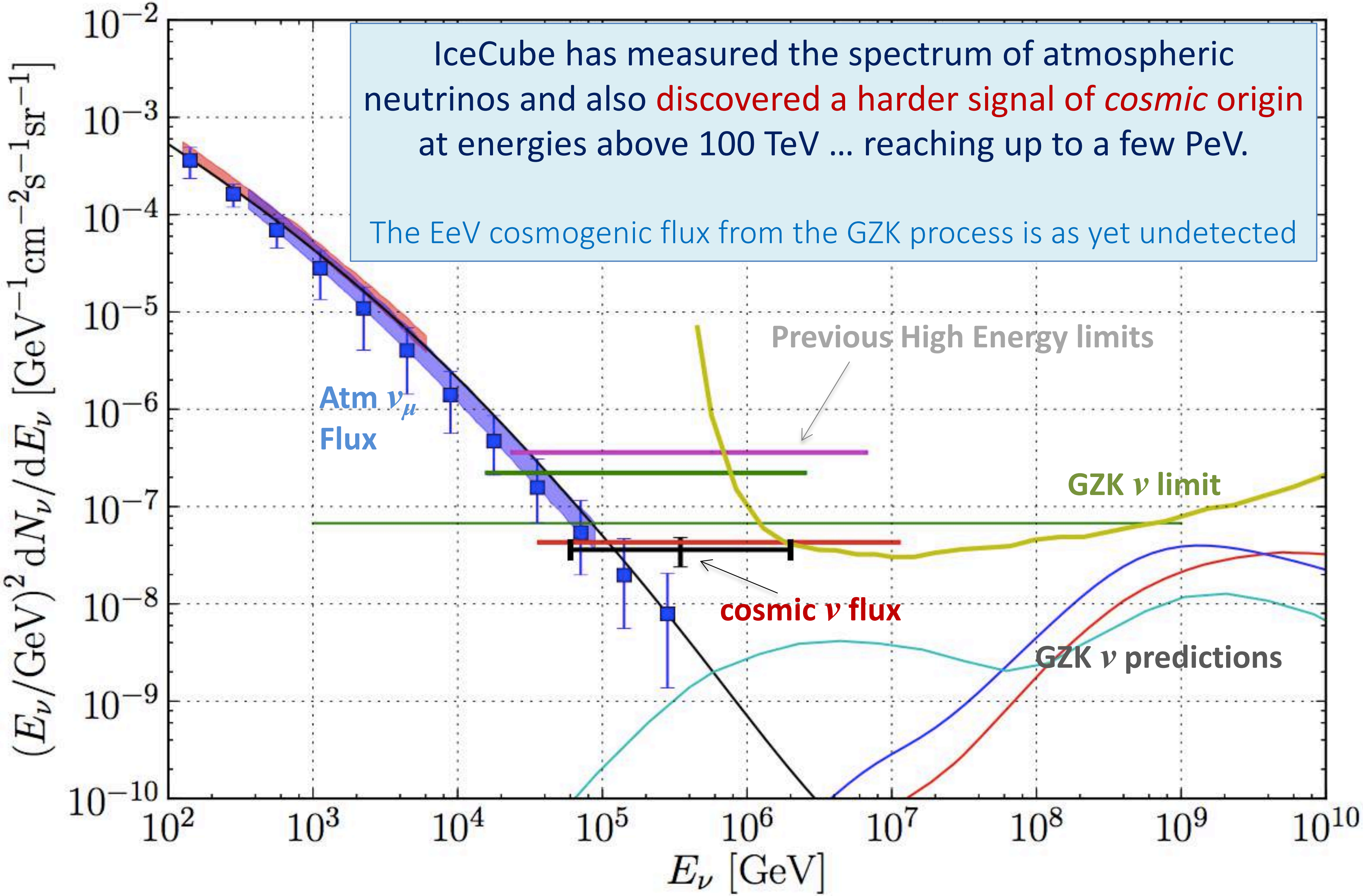


By using a veto for downgoing events, we remove the atmospheric neutrinos … because we remove the muons coming from the *same* cosmic ray air shower

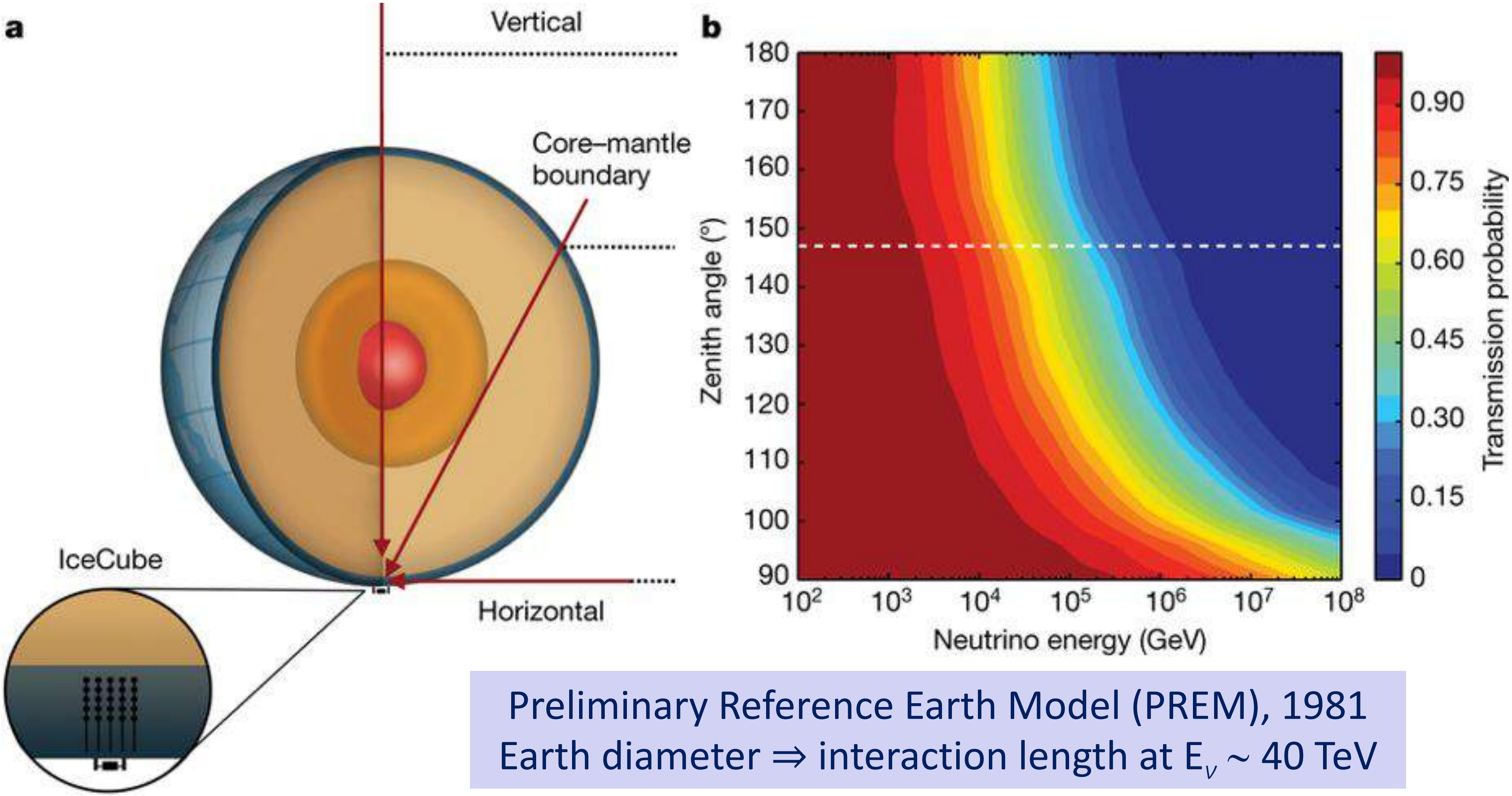
What's left is: PeV-EeV astrophysical neutrinos coming from above

NB: Doesn't work for upgoing, since the Earth absorbed the muons … so Southern Sky (downgoing events) becomes the best channel.

Current picture of high energy neutrino energy spectrum



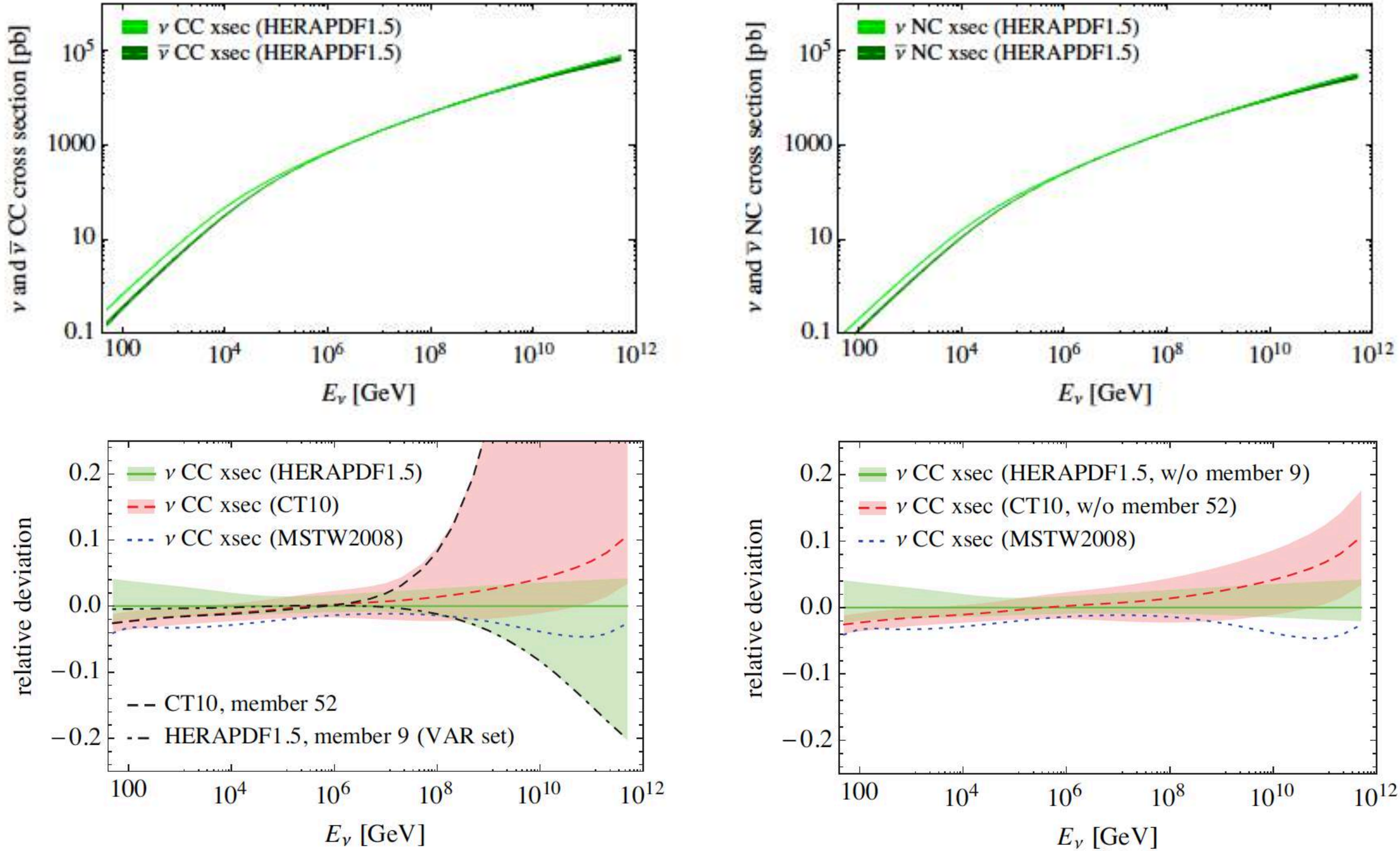
WE CAN NOW *MEASURE* THE ν-N CROSS-SECTION BY EXAMINING THE ZENITH ANGLE DEPENDENCE OF THE ν FLUX SEEN *THROUGH* THE EARTH



Preliminary Reference Earth Model (PREM), 1981
Earth diameter ⇒ interaction length at $E_\nu \sim 40$ TeV

NB: The flux of atmospheric neutrinos (which dominate up to $\sim 10^5$ GeV) is isotropic … also a good approximation for the extragalactic flux … galactic component is <18%

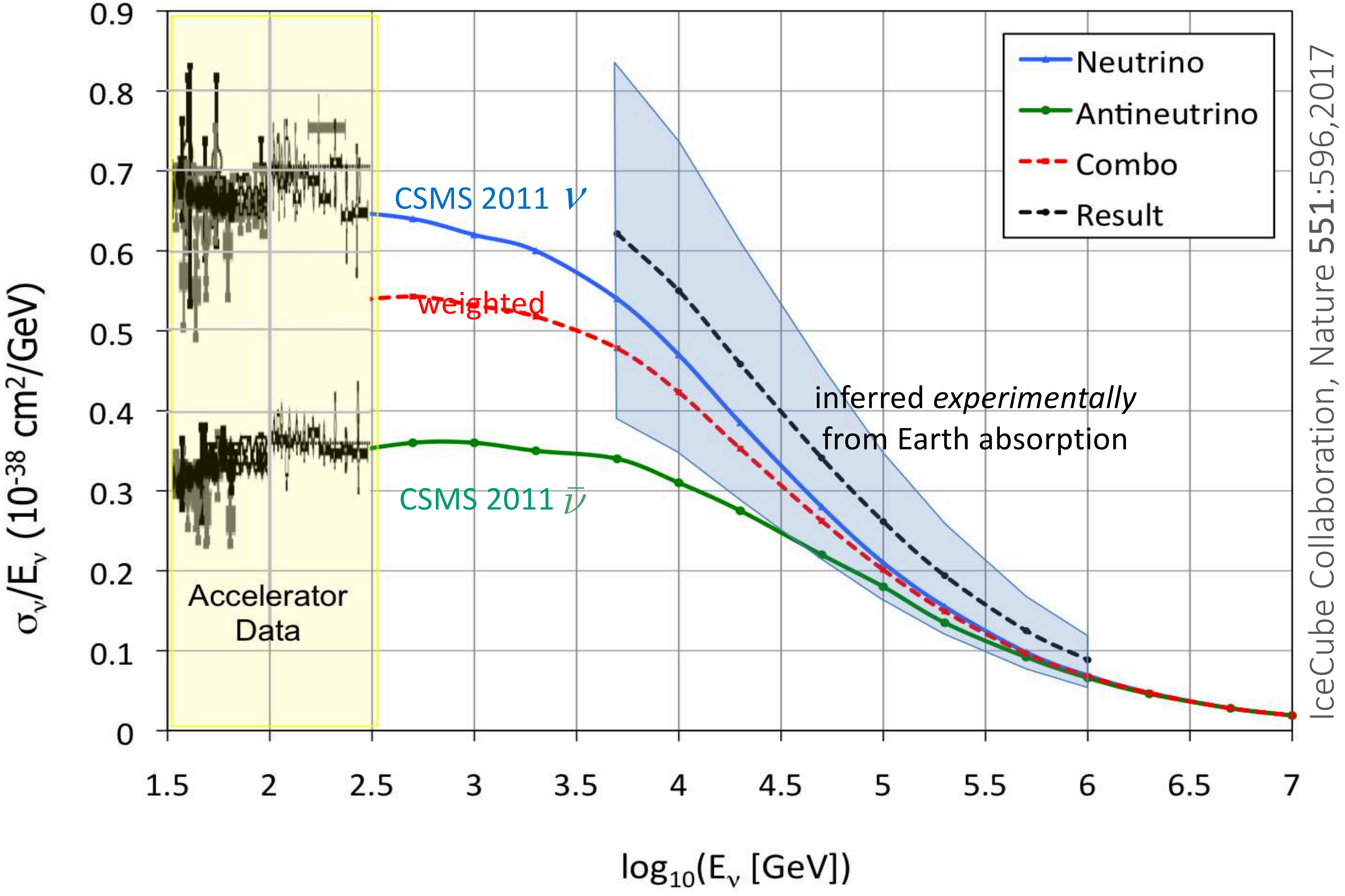
Meanwhile we have recalculated the ν-N cross-section@ NLO with ~few % accuracy using HERAPDF1.5



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)

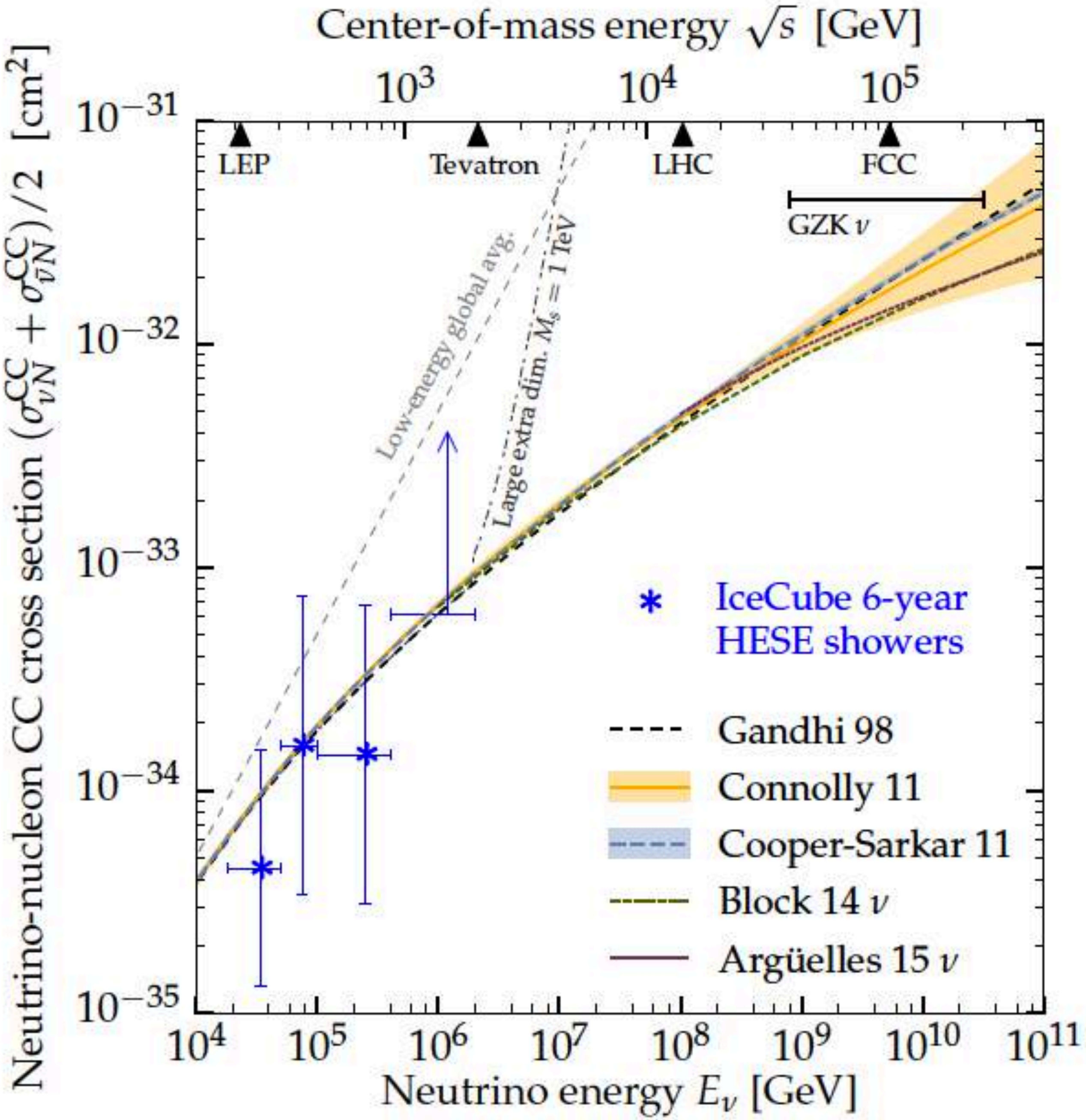
No evidence of deviation (within ±30%) from SM up to 980 TeV!



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

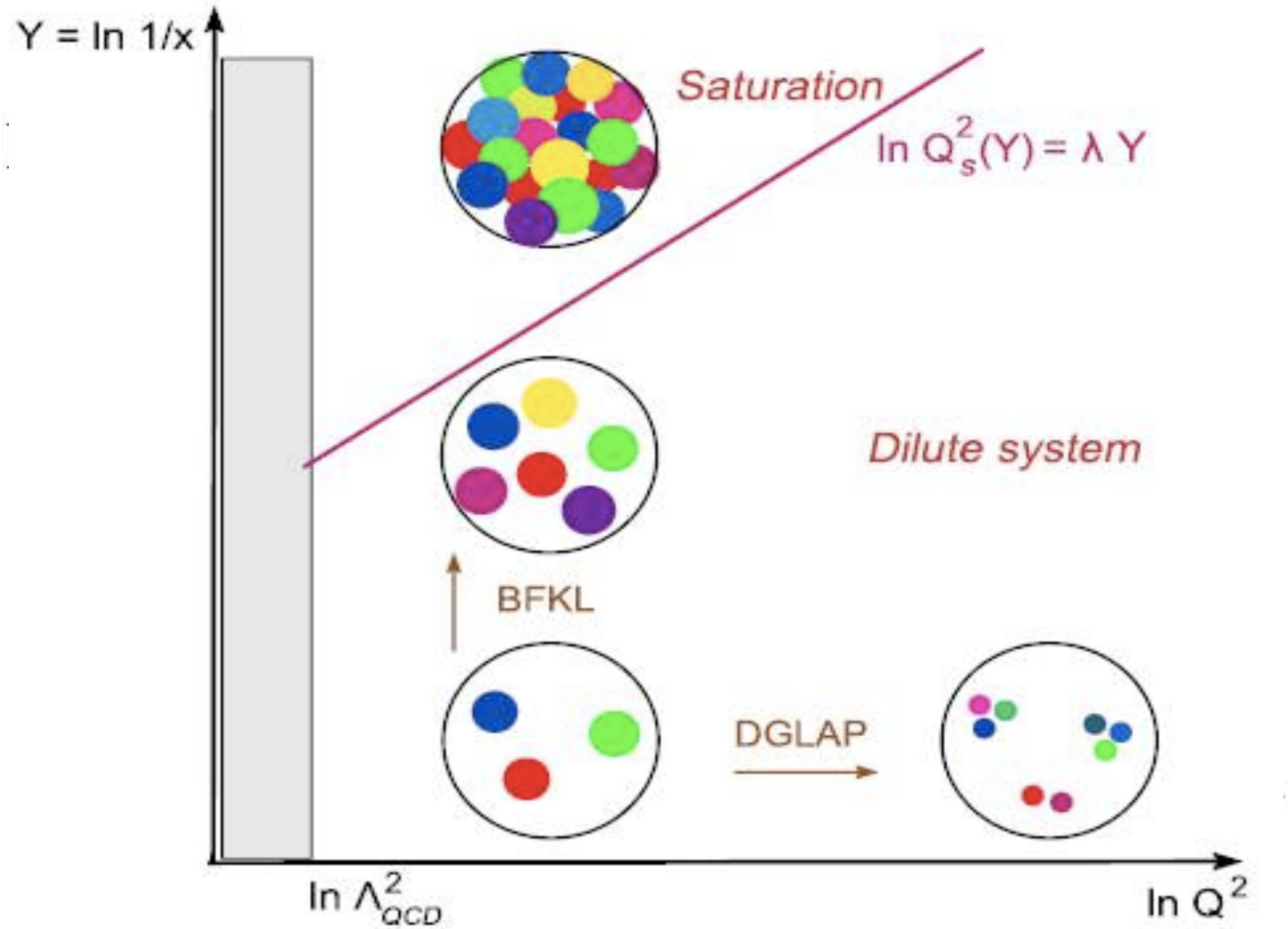
should be able to probe up to ~10^9 GeV using cosmogenic ν ... with **IceCube-Gen2**!

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



Bustamante & Connolly, PRL **122**:041101,2019

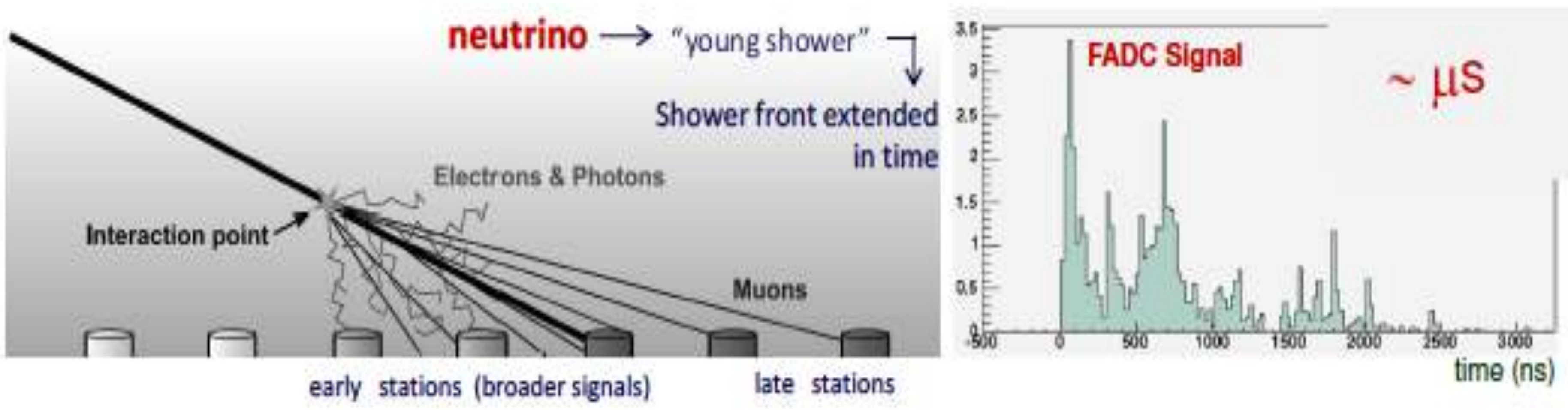
As the gluon density rises at low x, non-perturbative effects must become important … a new phase of QCD - Colour Glass Condensate - has been postulated to exist (and has some support from RHIC and ALICE data)

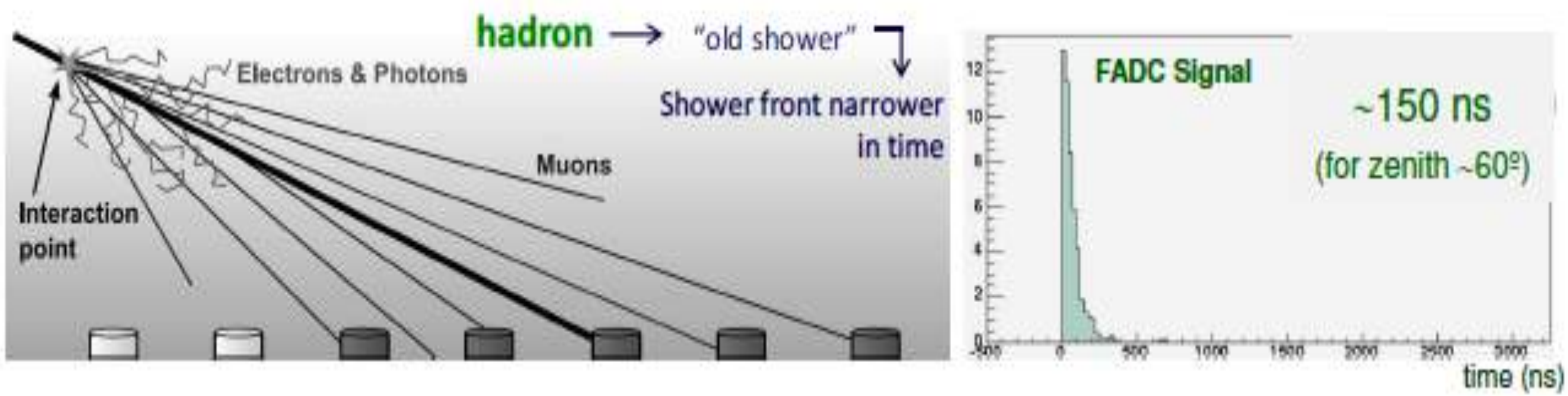


This would strongly suppress the ν-N #-secn below its (unscreened) SM value

… 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

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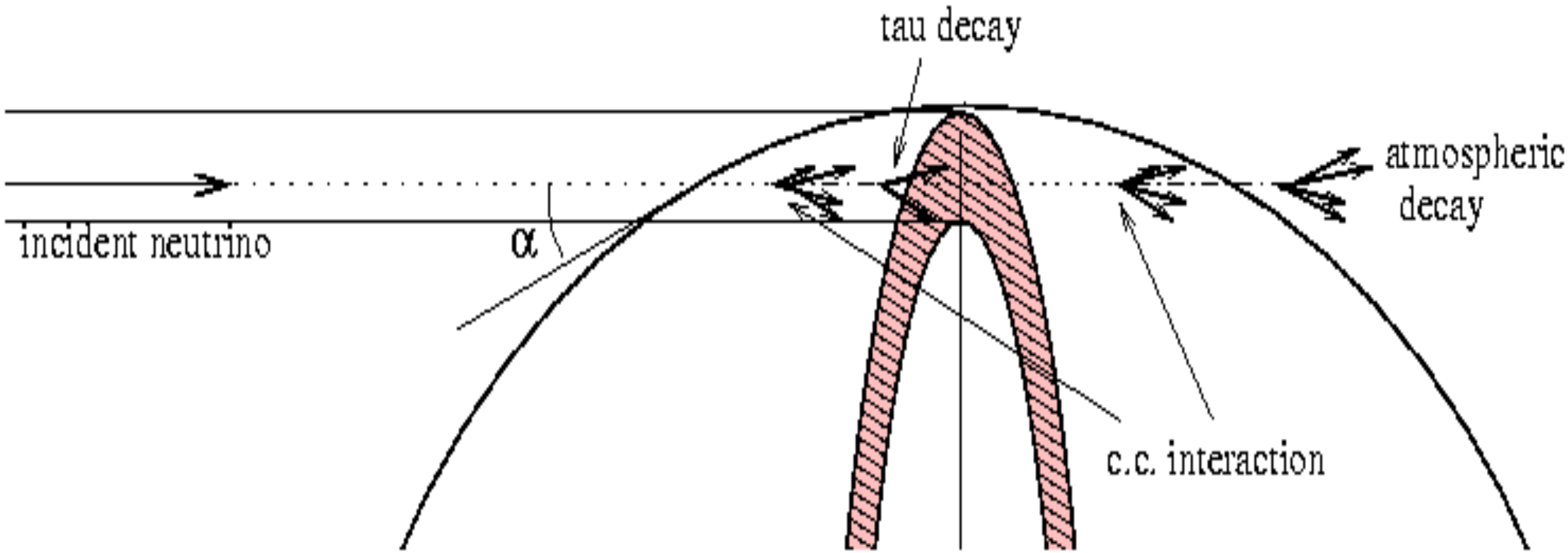
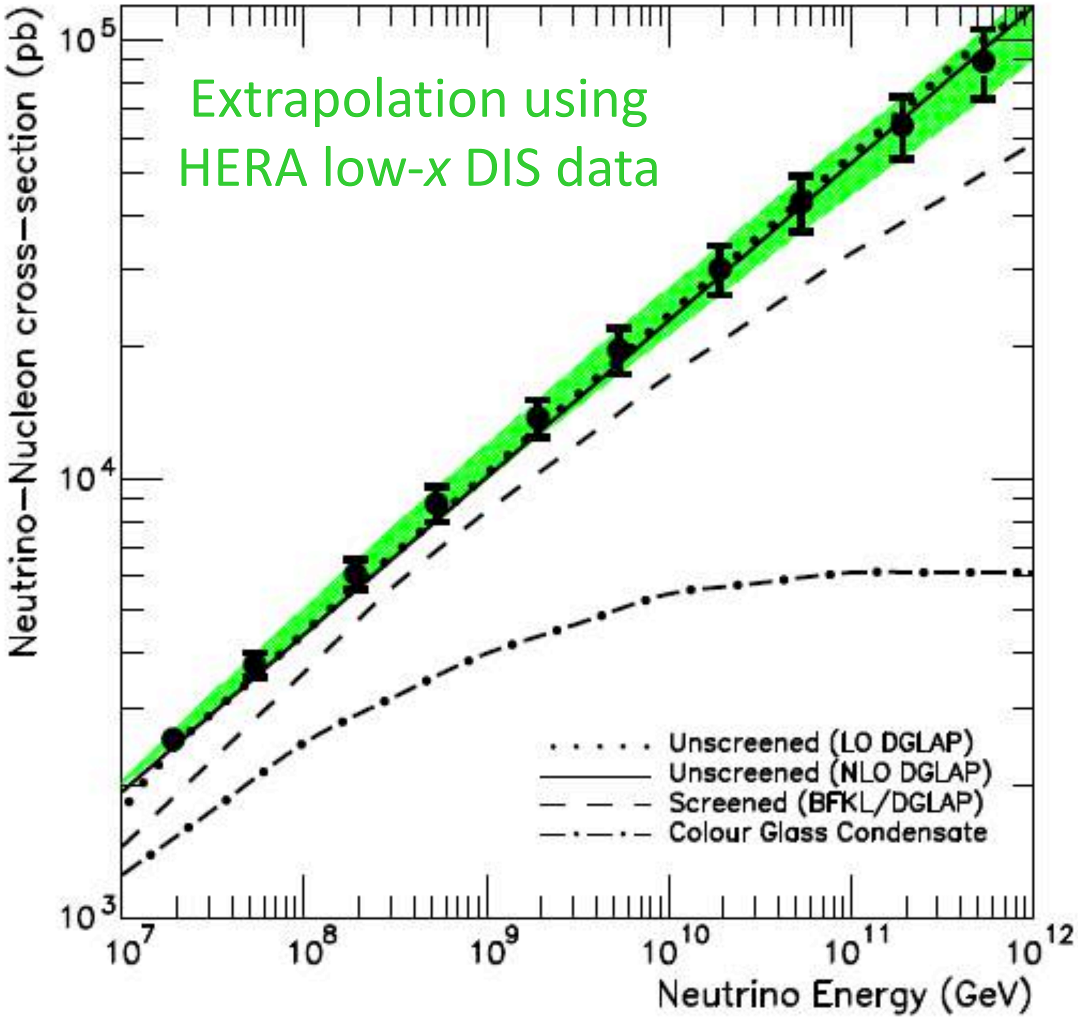
Auger can also see Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower
(detectable only because the surface detector tanks are raised above the ground)

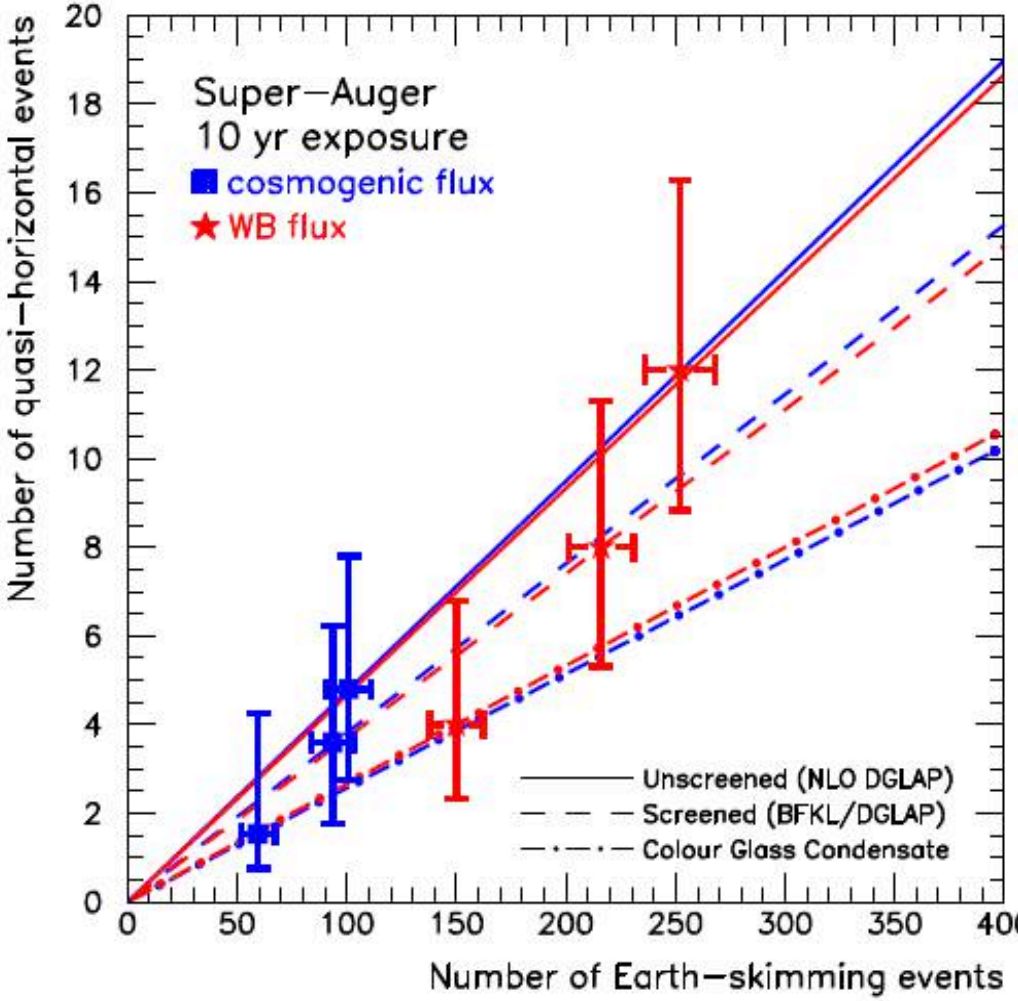
Neutrino oscillations en-route to Earth should *equlibrate* flavours with $\nu_e : \nu_\mu : \nu_\tau :: 1:1:1$
so there will be tau neutrinos in the cosmic beam regardless of initial composition



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 ultra-high energy neutrinos with a *very* large detector



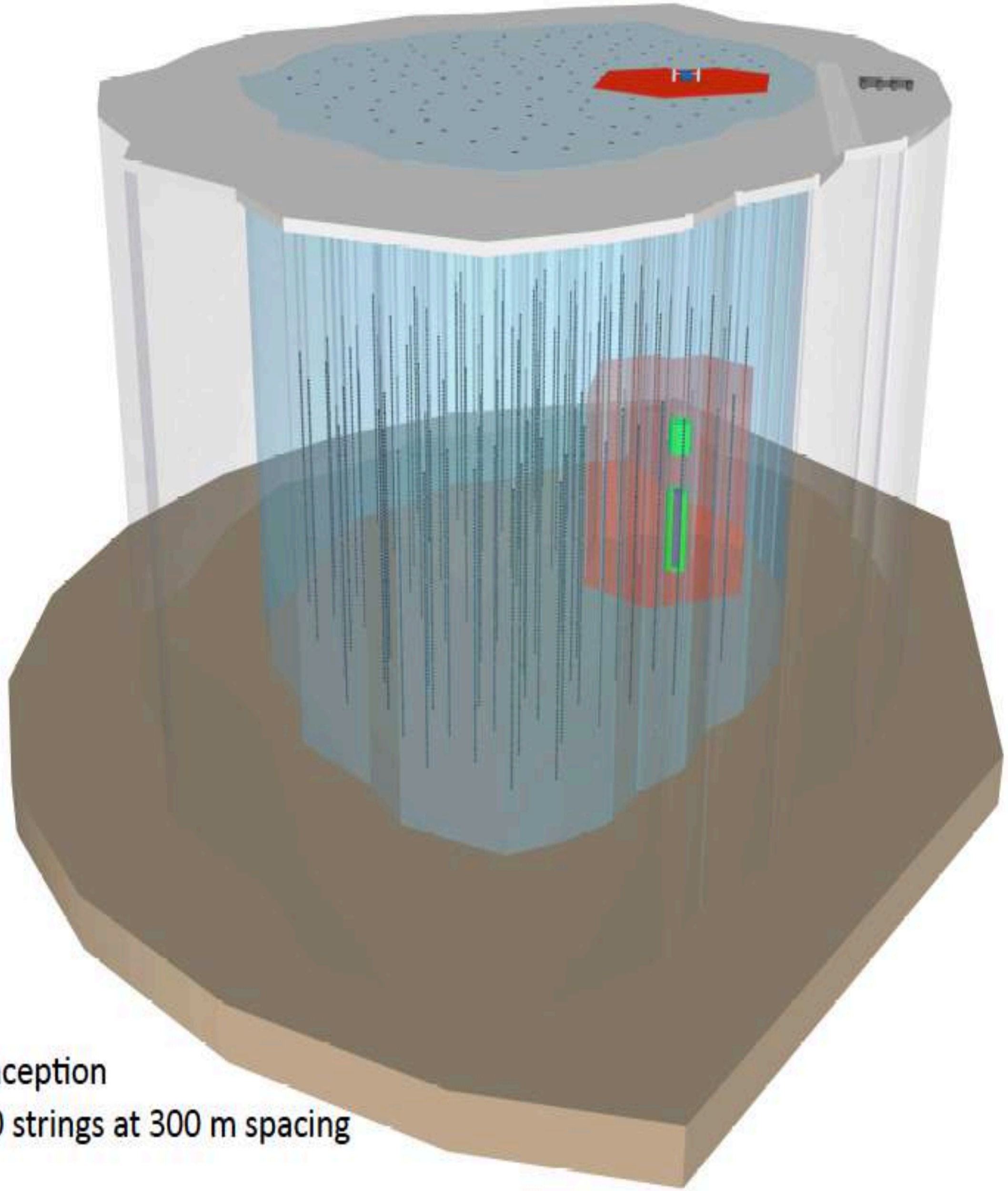


The steep rise of the gluon density at low-x must saturate (unitarity!) $\Rightarrow$ suppression of the ν-N #-section

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

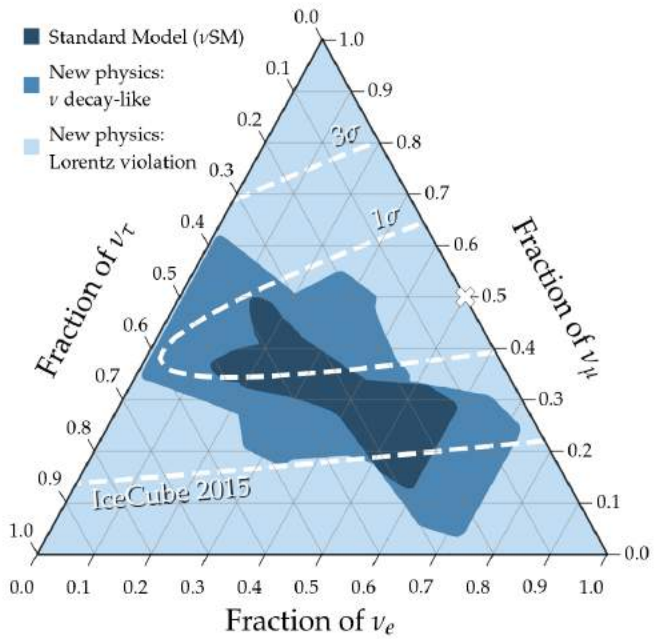
Anchordoqui, Cooper-S.S., Hooper, Sarkar, Phys.Rev.D**74**:043008,2006

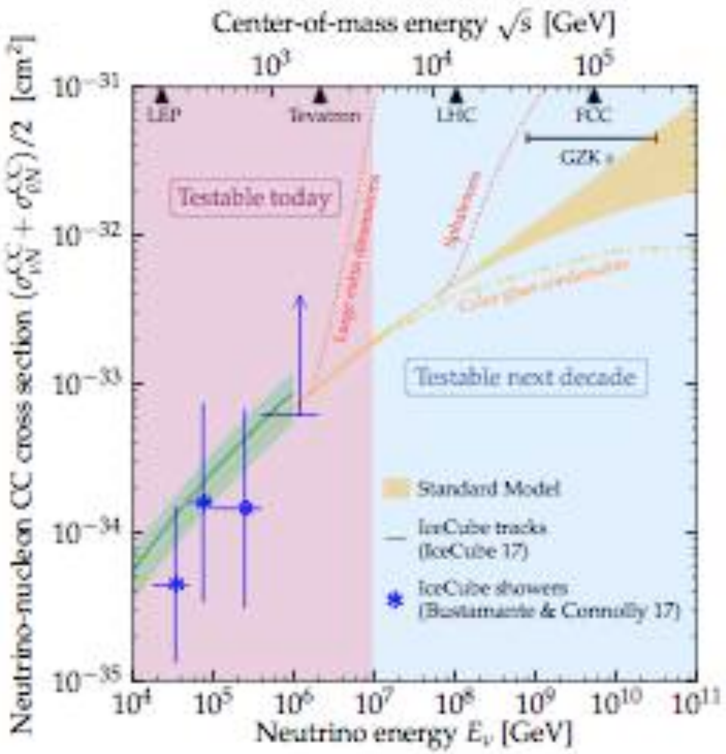
To do astronomy *and* particle physics with cosmic neutrinos we must think BIG!



Artist conception

Here: 120 strings at 300 m spacing





IceCube-Gen2

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