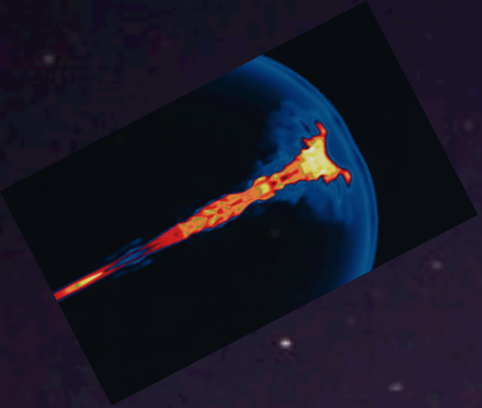
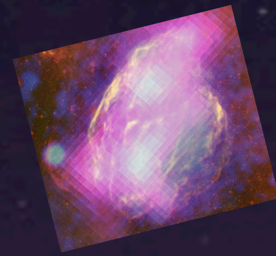
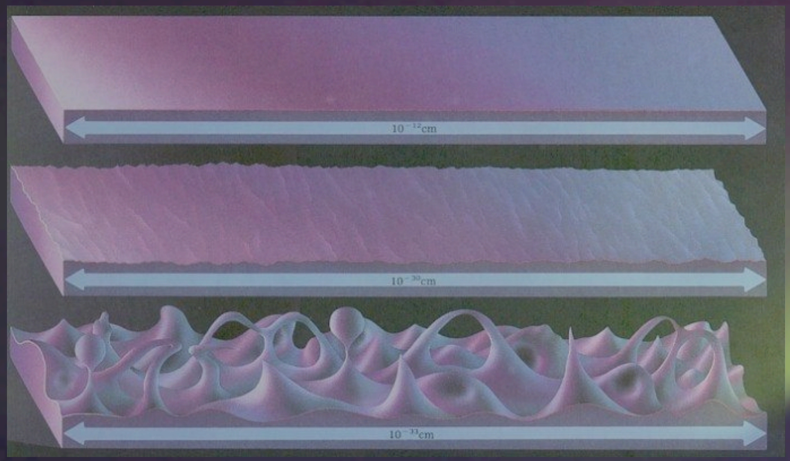
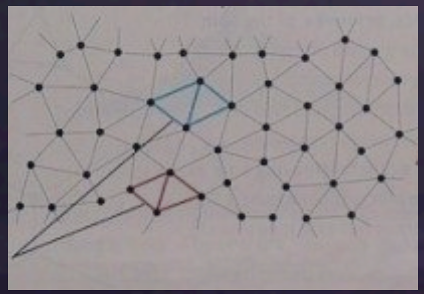
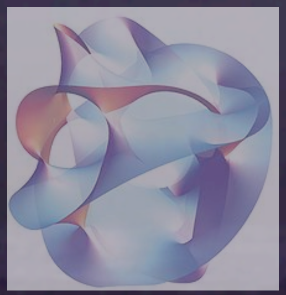
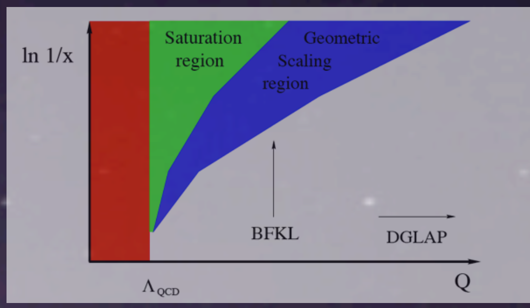
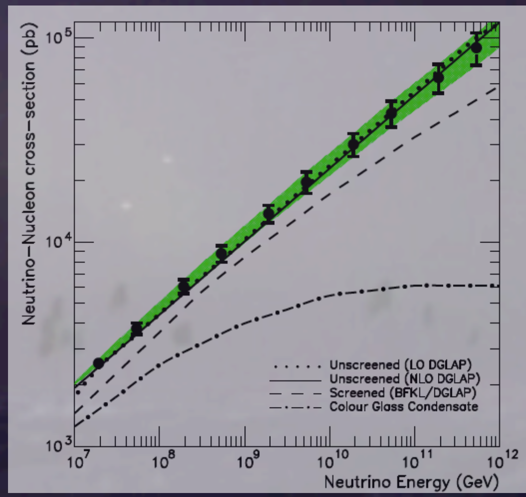




Probing fundamental physics with IceCube



Subir Sarkar

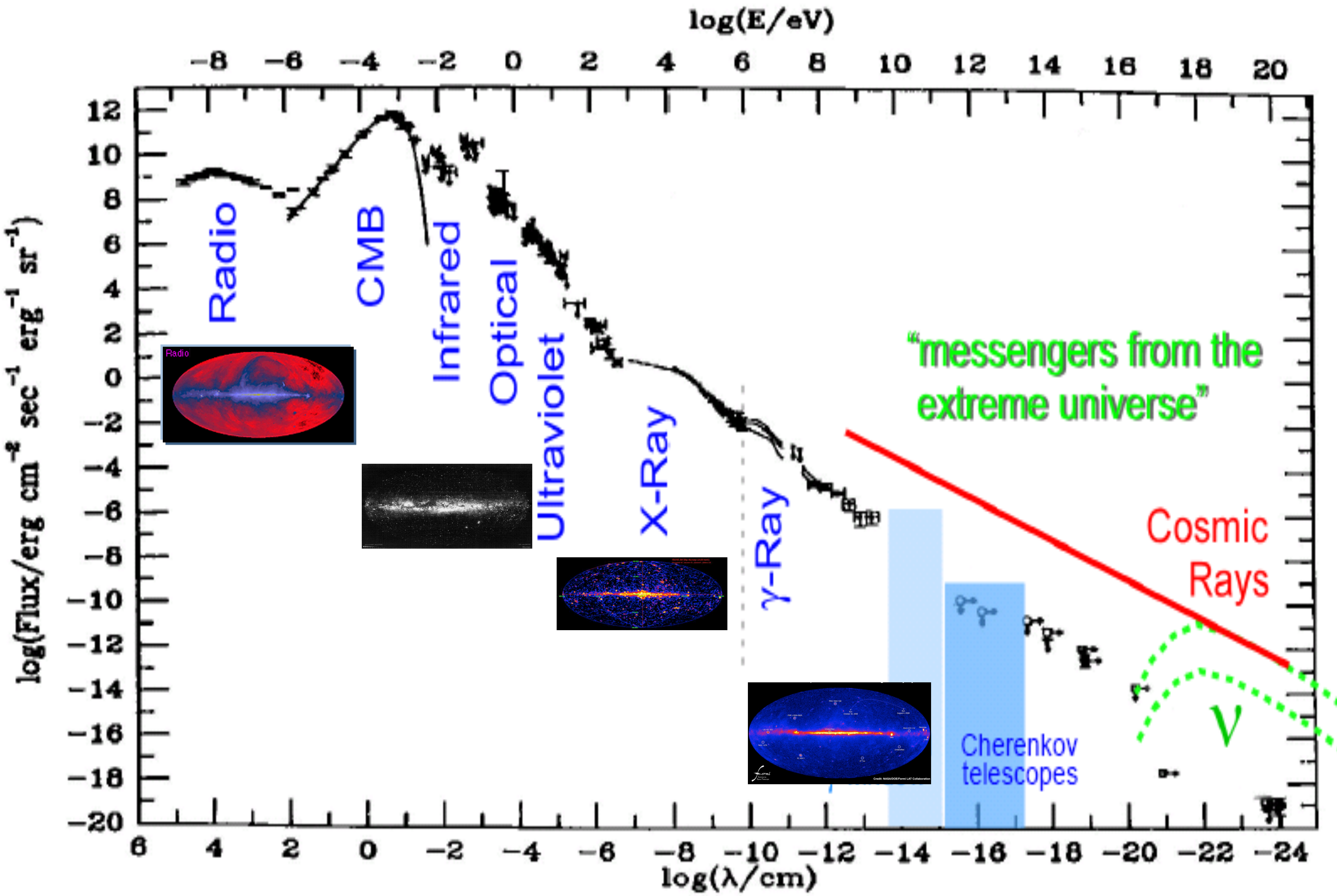
University of Oxford

The Niels Bohr International Academy

New Frontiers in Theoretical Physics, 28-31 May 2014, Cortona

Most of our knowledge of the universe comes from observing photons

... but above ~10 TeV they are attenuated through $\gamma\gamma \to e^+e^-$ 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 $p\gamma \to \Delta^+ \to n\,\pi^+$ on the CMB)

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

The Origin of Cosmic Rays

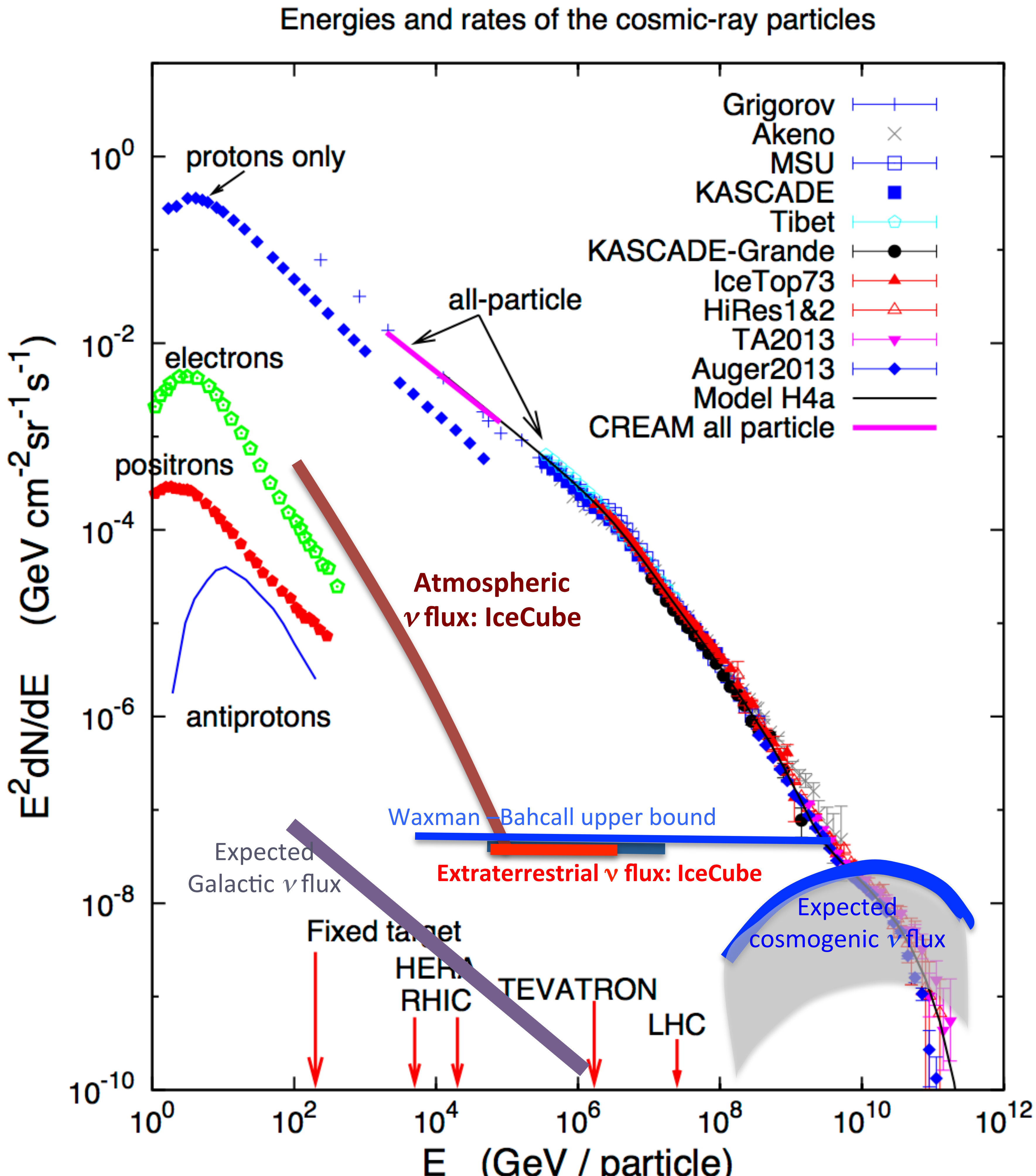
Extraordinary cosmic particle accelerators ***somewhere***, but still **poorly identified** a century after the discovery of cosmic rays!

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

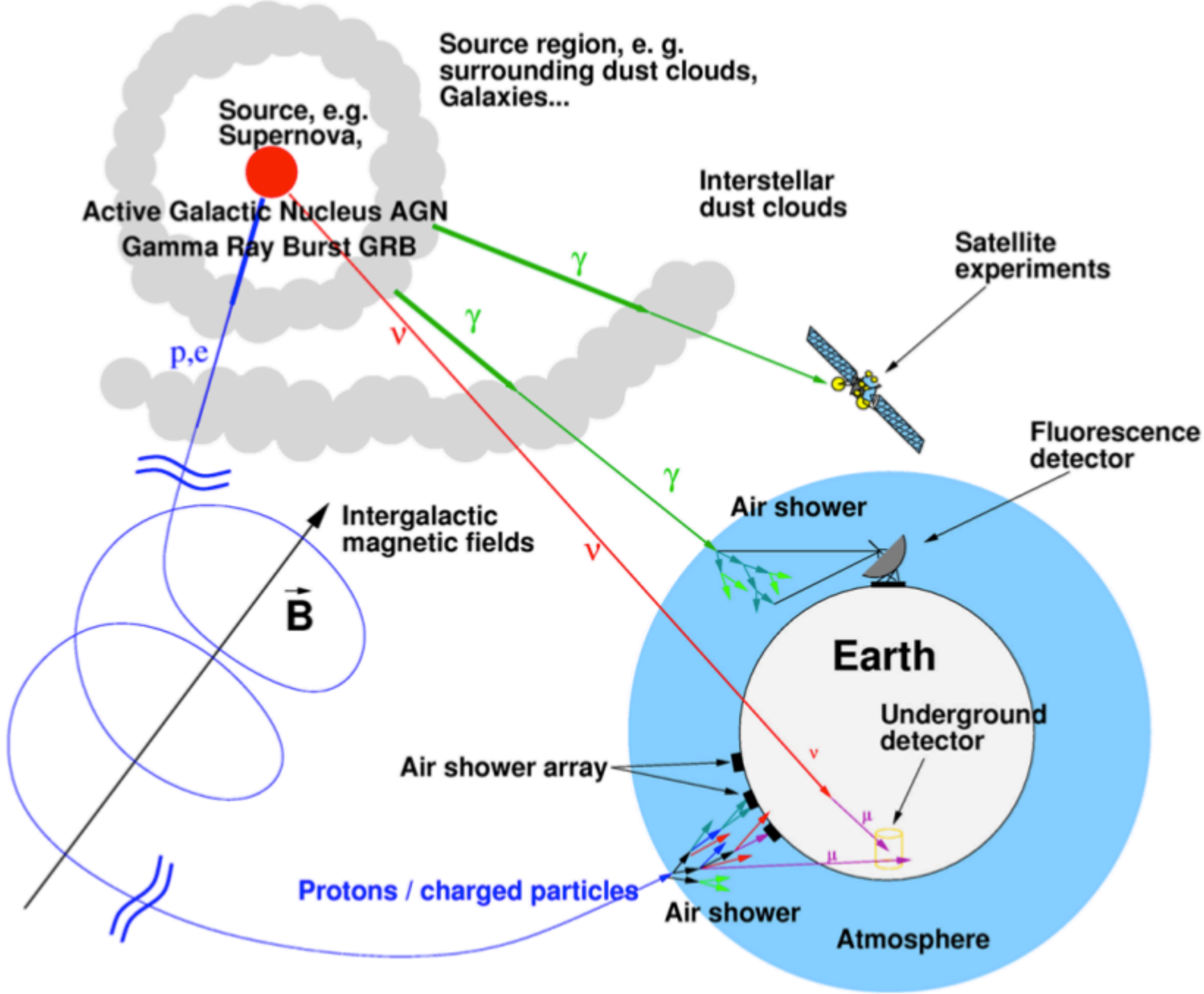
Cosmic ray interactions with matter and photons, near source or during propagation, produce neutrinos:

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

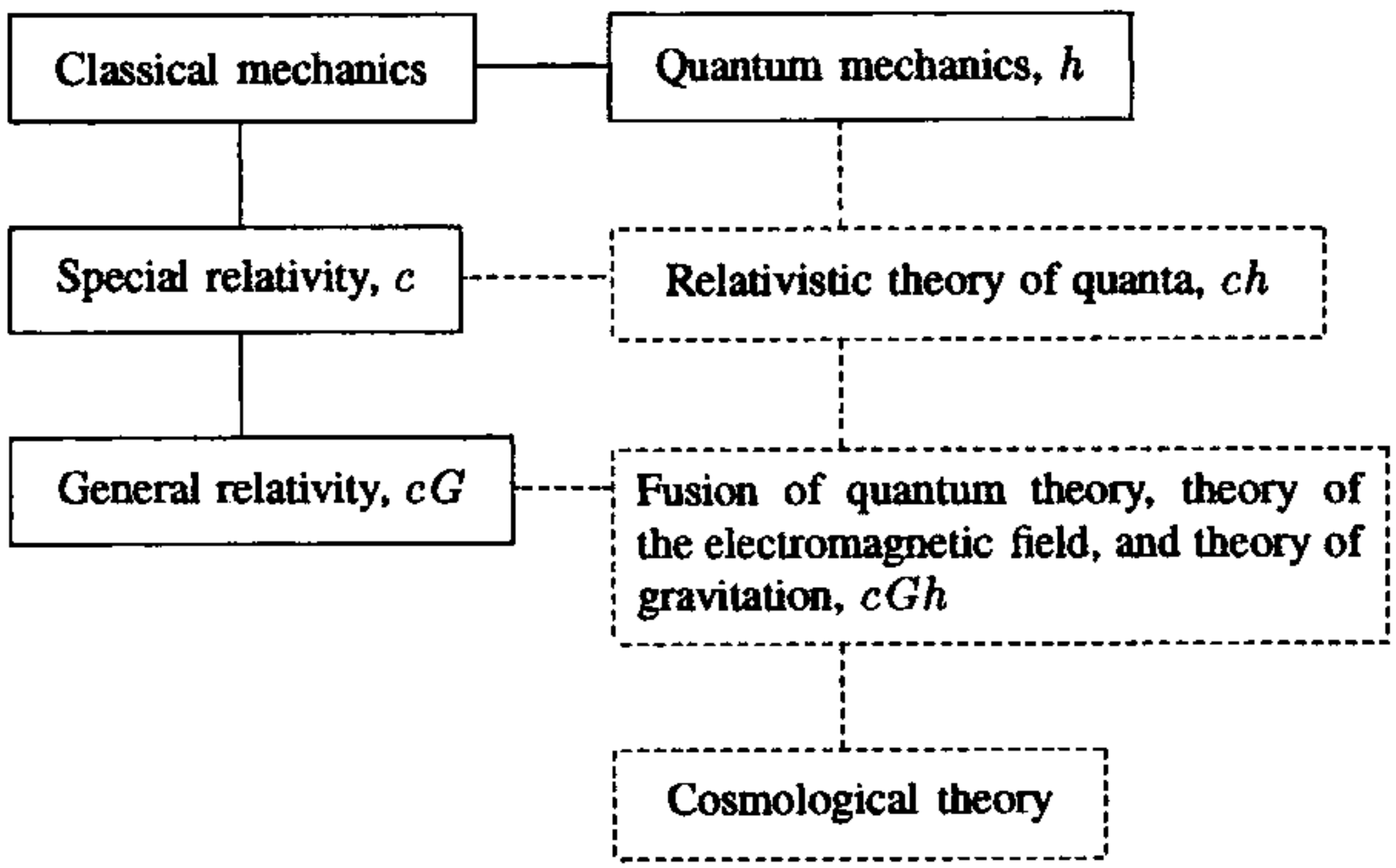
Oscillations en-route to Earth can equlibrate flavours so: $\nu_e : \nu_\mu : \nu_\tau :: 1 : 1 : 1$

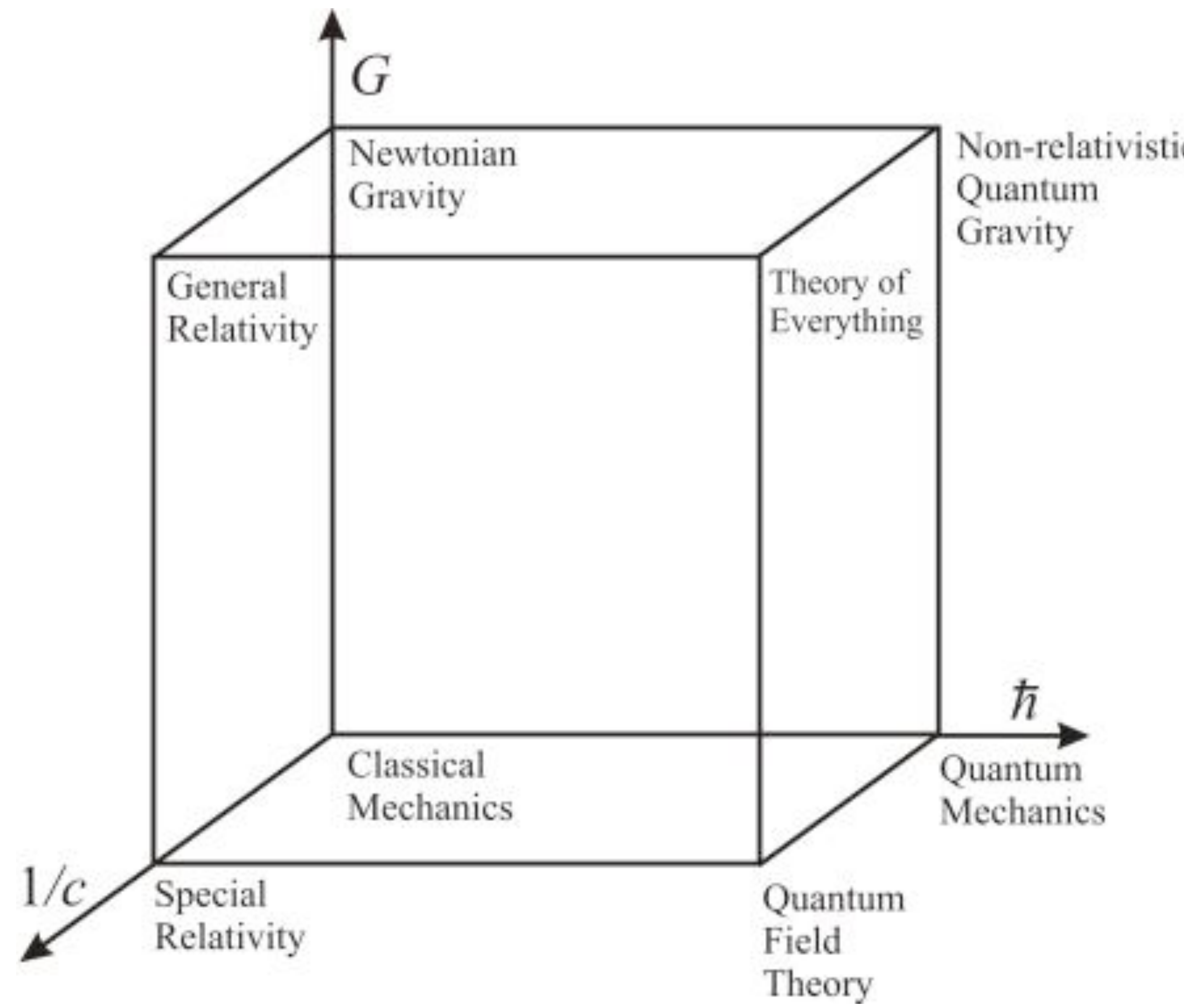


So by detecting extraterrestrial neutrinos, we can study quantum mechanical oscillations over very long baselines … *unaffected* by intervening dust, gas or magnetic fields ➔ *new* probe of space-time



Bronshtein's 'cube of theories'





"After the relativistic quantum theory is created, the task will be to develop the next part of our scheme, that is to unify quantum theory (with its constant h), special relativity (with constant c), and the theory of gravitation (with its G) into a single theory".

Matvei Petrovich Bronshtein (1906-38)

For an update see: Duff, Okun & Veneziano [arXiv:physics/0110060]

May lead to modifications of space-time structure on the quantum gravity scale

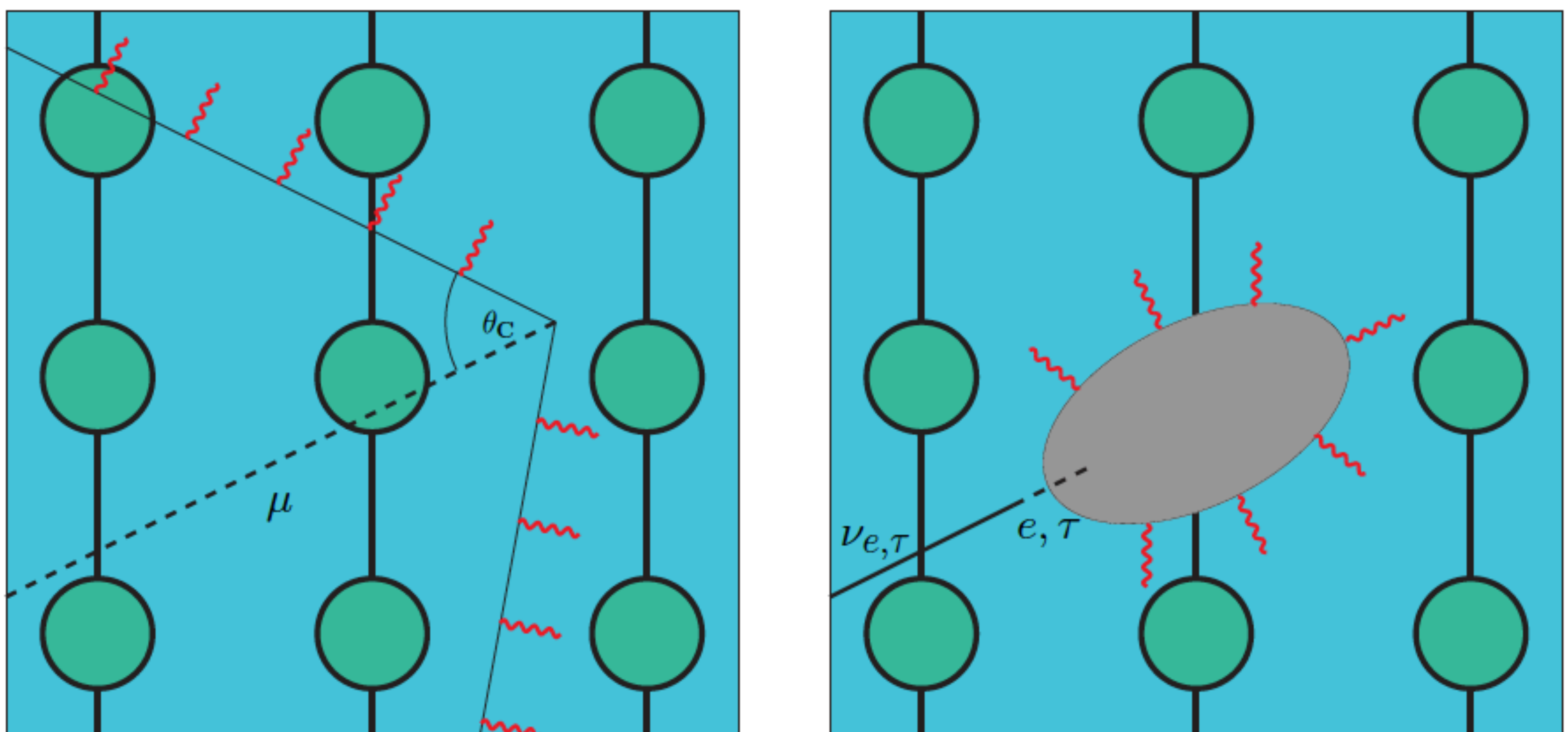
$$\ell_{\mathrm{P}} \equiv \sqrt{\frac{\hbar G_{\mathrm{N}}}{c^3}} \simeq 1.6 \times 10^{-35}\mathrm{m} \Rightarrow 1.2 \times 10^{19}\mathrm{GeV}$$

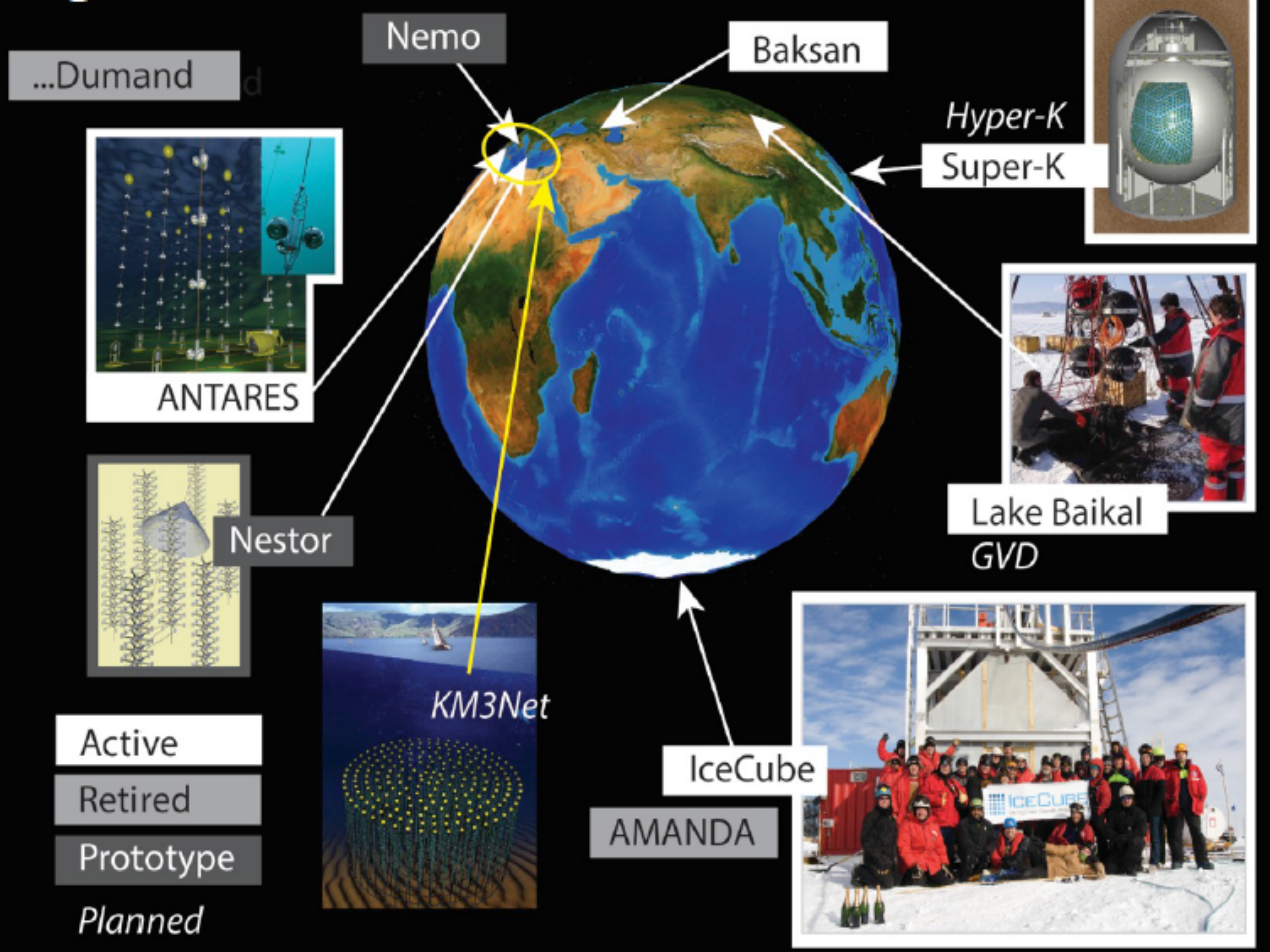
back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

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

→ **rate of events** :

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

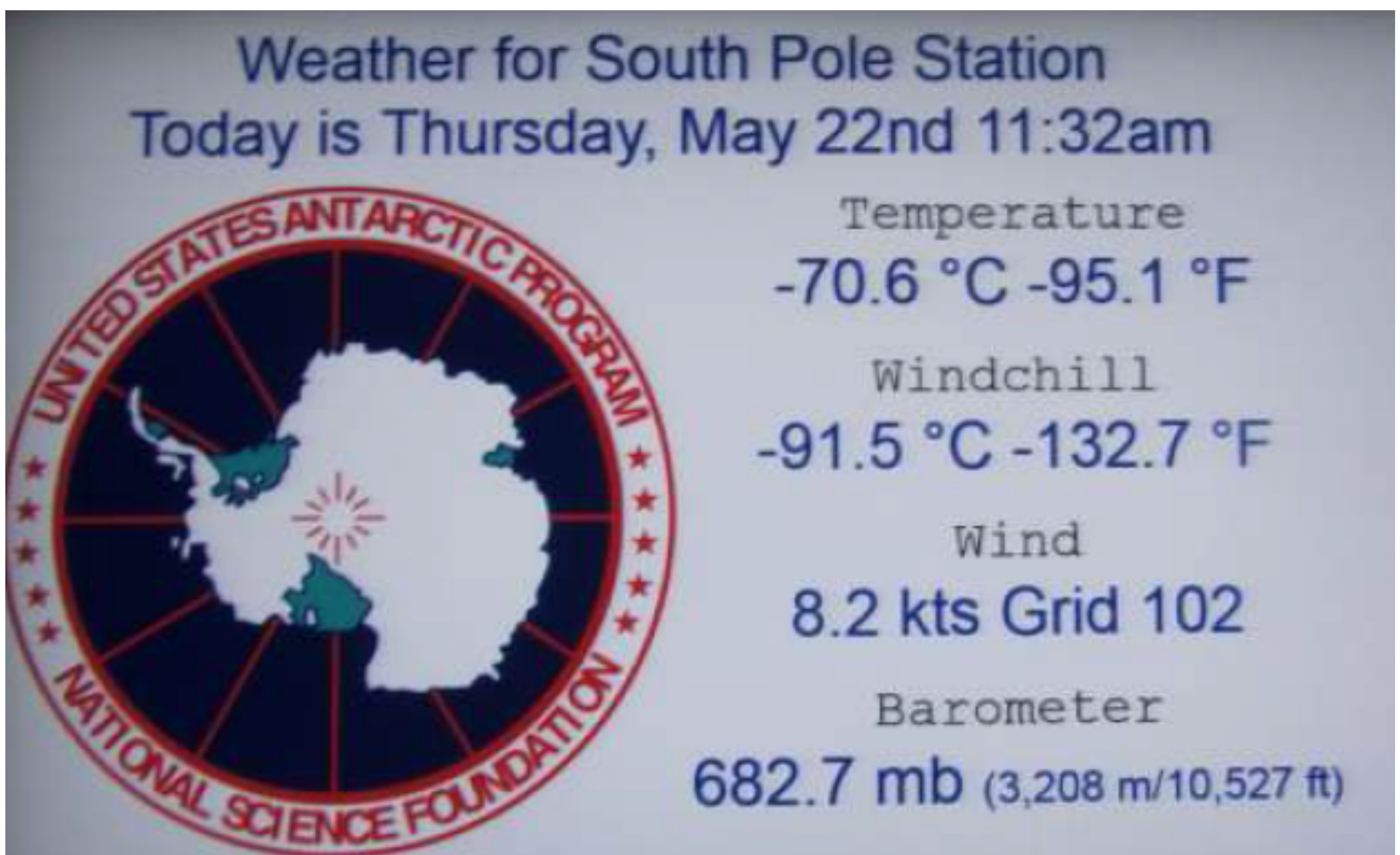


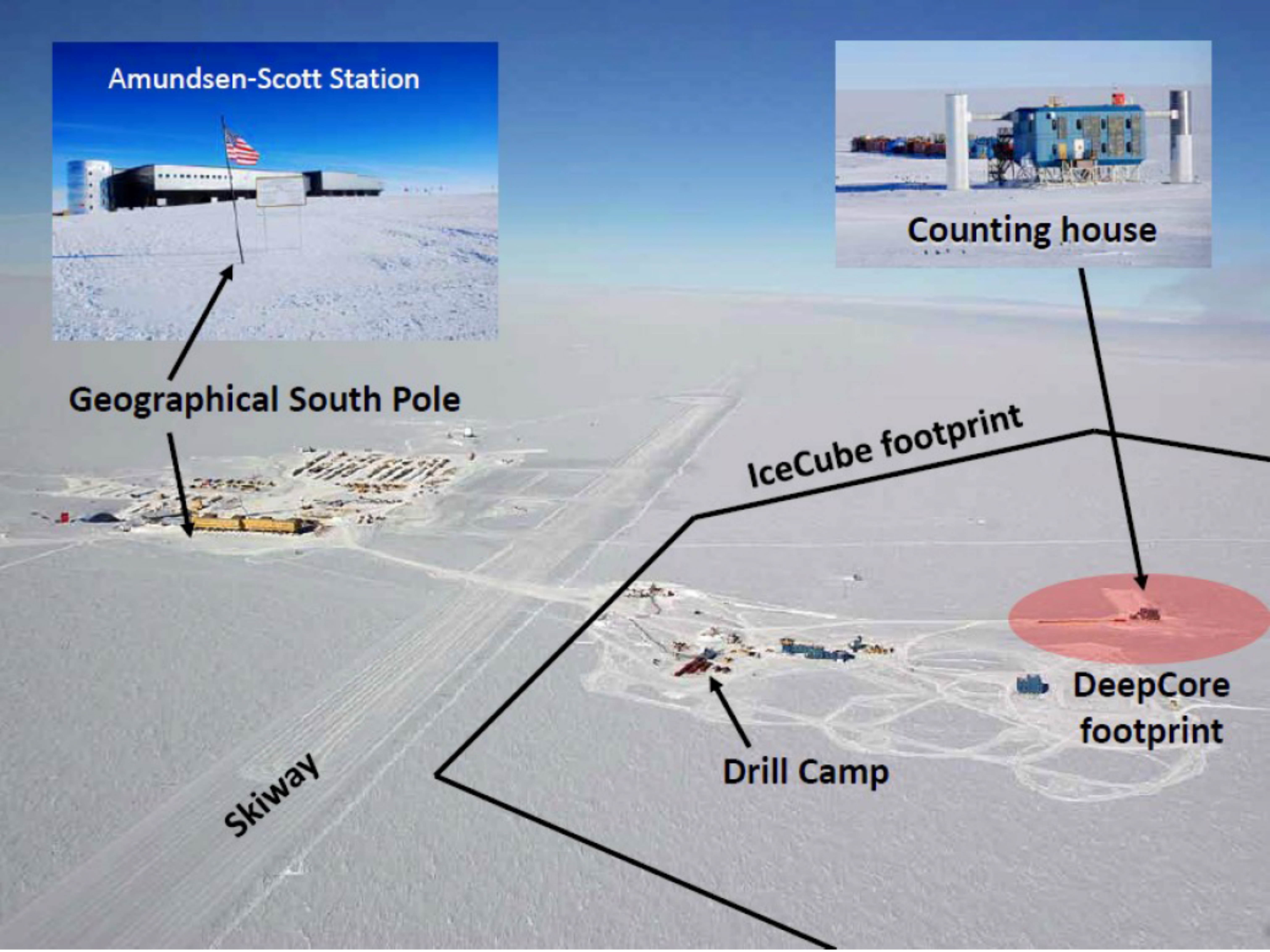


...Dumand
Nemo
Baksan
Hyper-K
Super-K
ANTARES
Nestor
Lake Baikal
GVD
KM3Net
IceCube
AMANDA
Active
Retired
Prototype
Planned


Photo: Haley Buffman


SOUTH POLE * LATITUDE 90°
NZ DT 21
GMT


Weather for South Pole Station
Today is Thursday, May 22nd 11:32am
UNITED STATES ANTARCTIC PROGRAM
NATIONAL SCIENCE FOUNDATION
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)



Amundsen-Scott Station
Counting house
Geographical South Pole
IceCube footprint
DeepCore
footprint
Drill Camp
Skiway

The IceCube Collaboration

~250 scientists
40 institutions
11 countries

International 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)
- Inoue Foundation for Science, Japan
- 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)

IceCube Neutrino Observatory

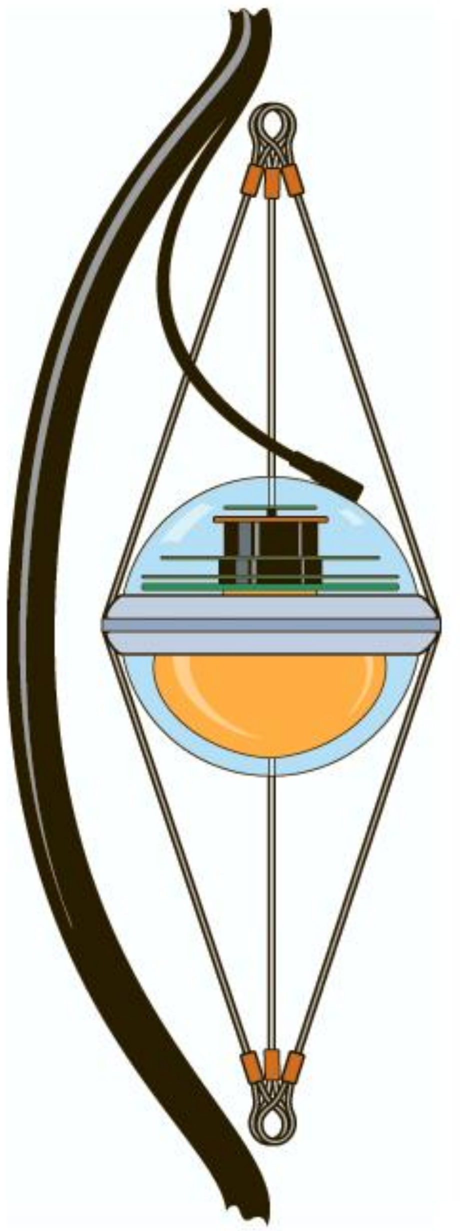
86 strings

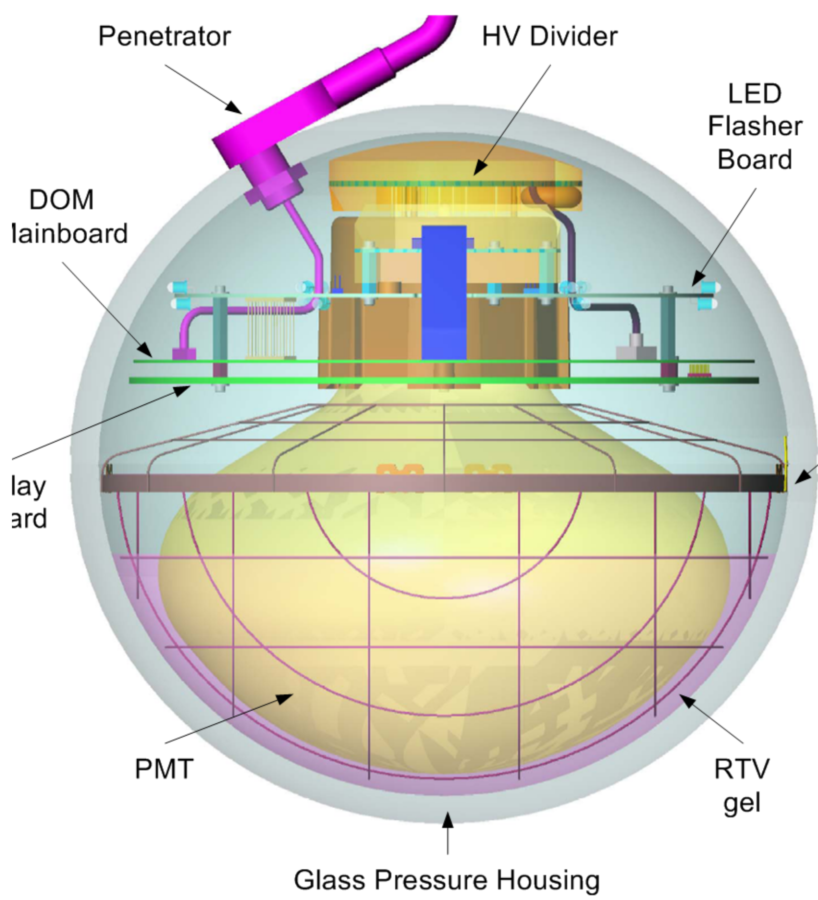
60 Optical Modules per string

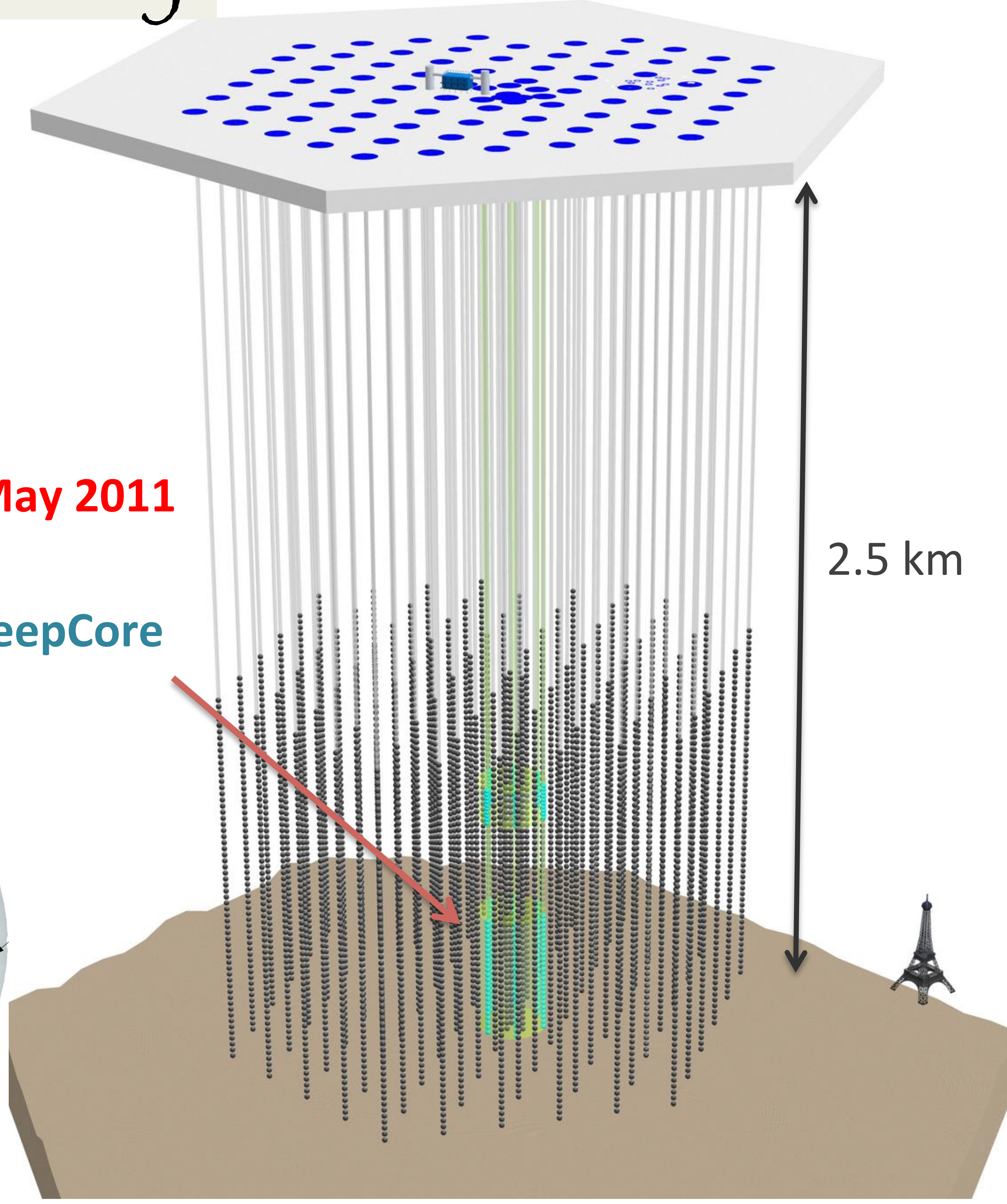
5160 Optical Modules in Ice

1 km³ = Gton instrumented volume

Completed, began full operations May 2011

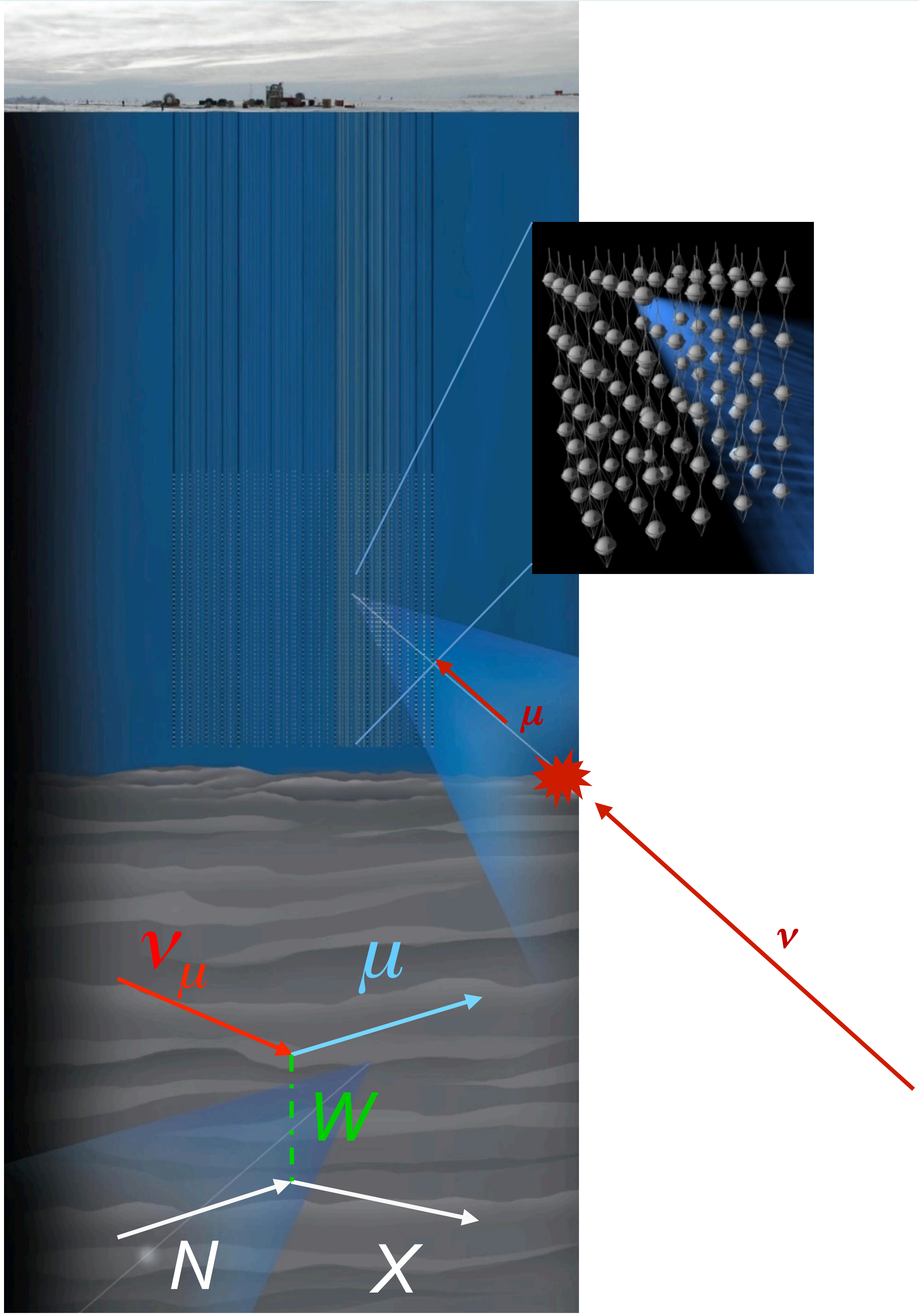






High Energy Neutrino Detection Principle

- 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



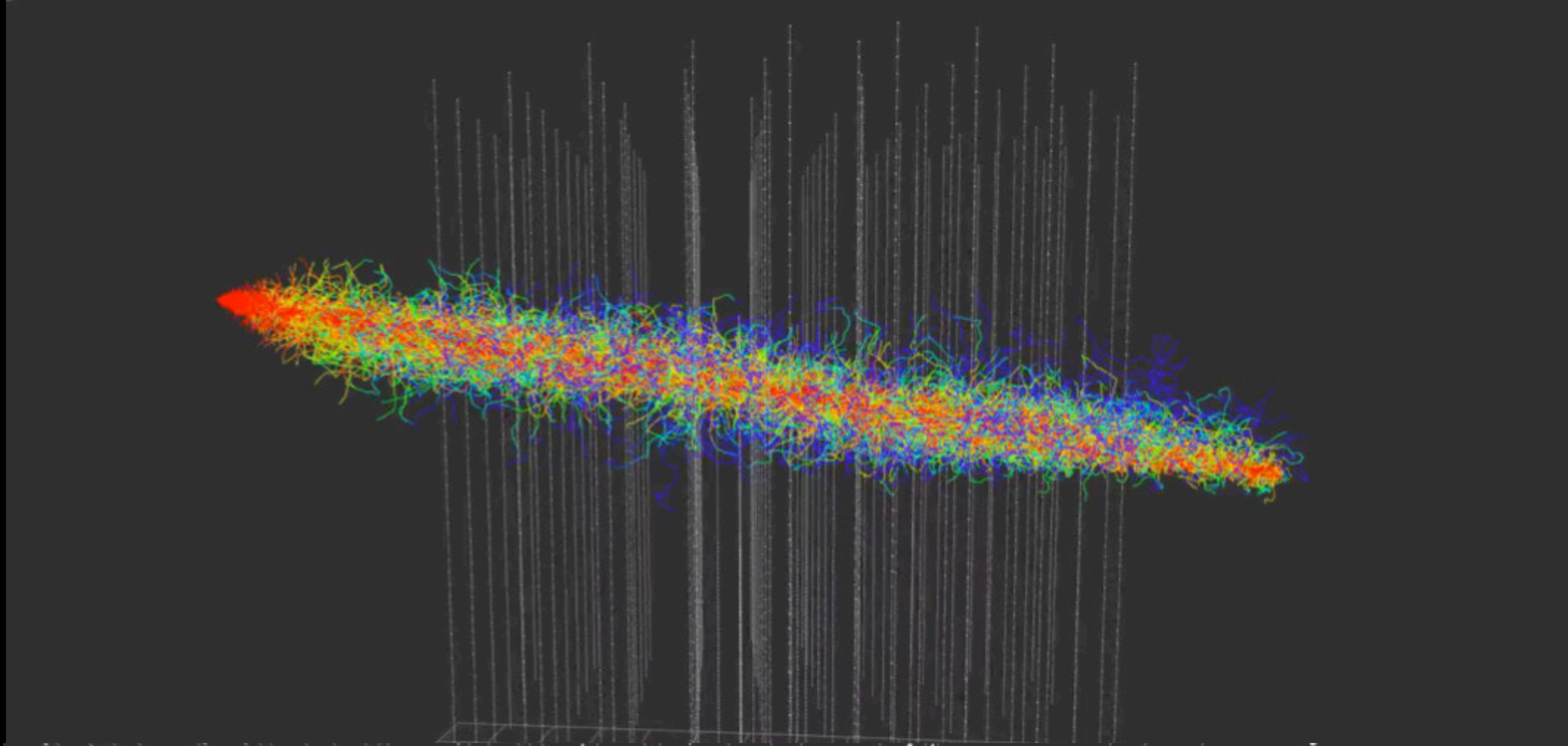
Position, time and amplitude of hits allows reconstruction of tracks using likelihood optimisation

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

Track topology

(induced by ν_μ)

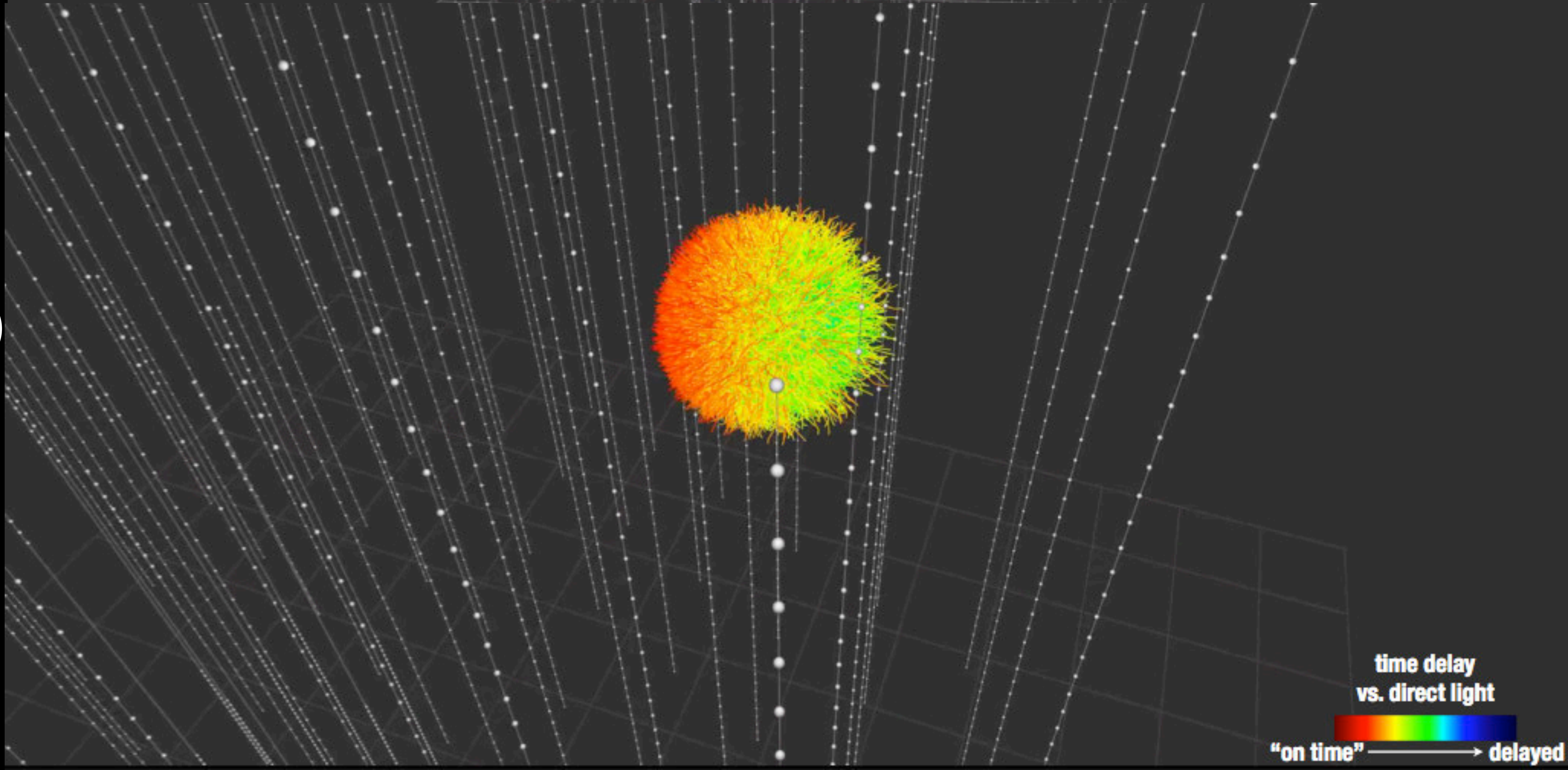
Good pointing (~0.2° - 1°) but only *lower* bound on neutrino energy



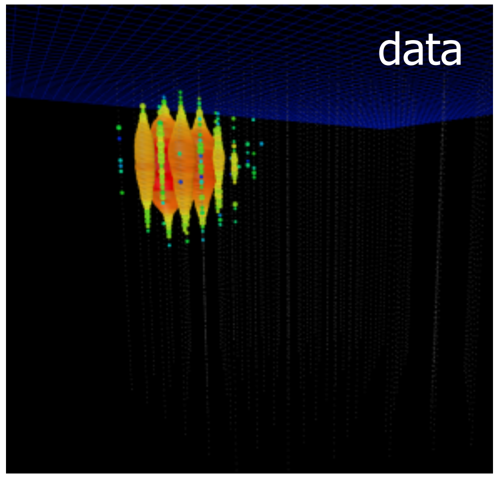
Cascade topology

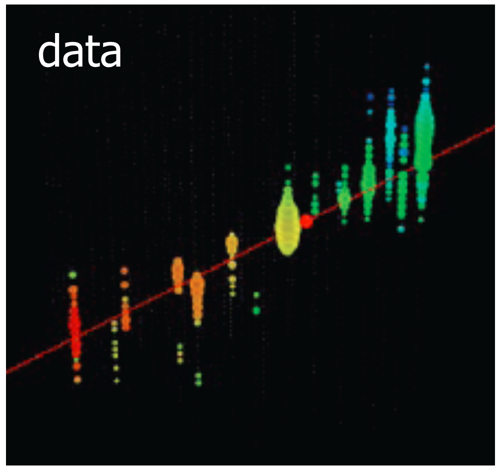
(induced by e.g. ν_e)

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

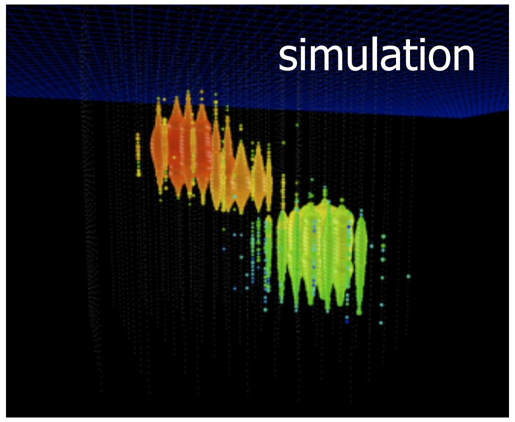


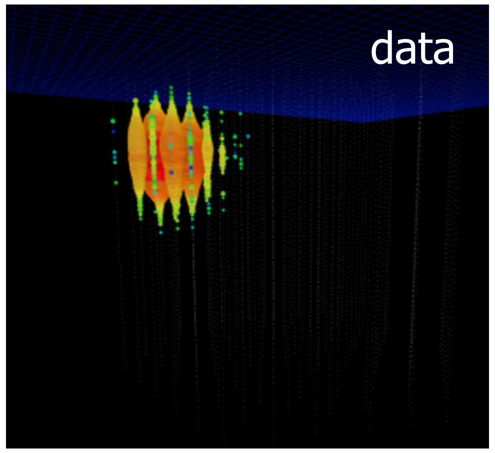
Neutrino signatures in IceCube



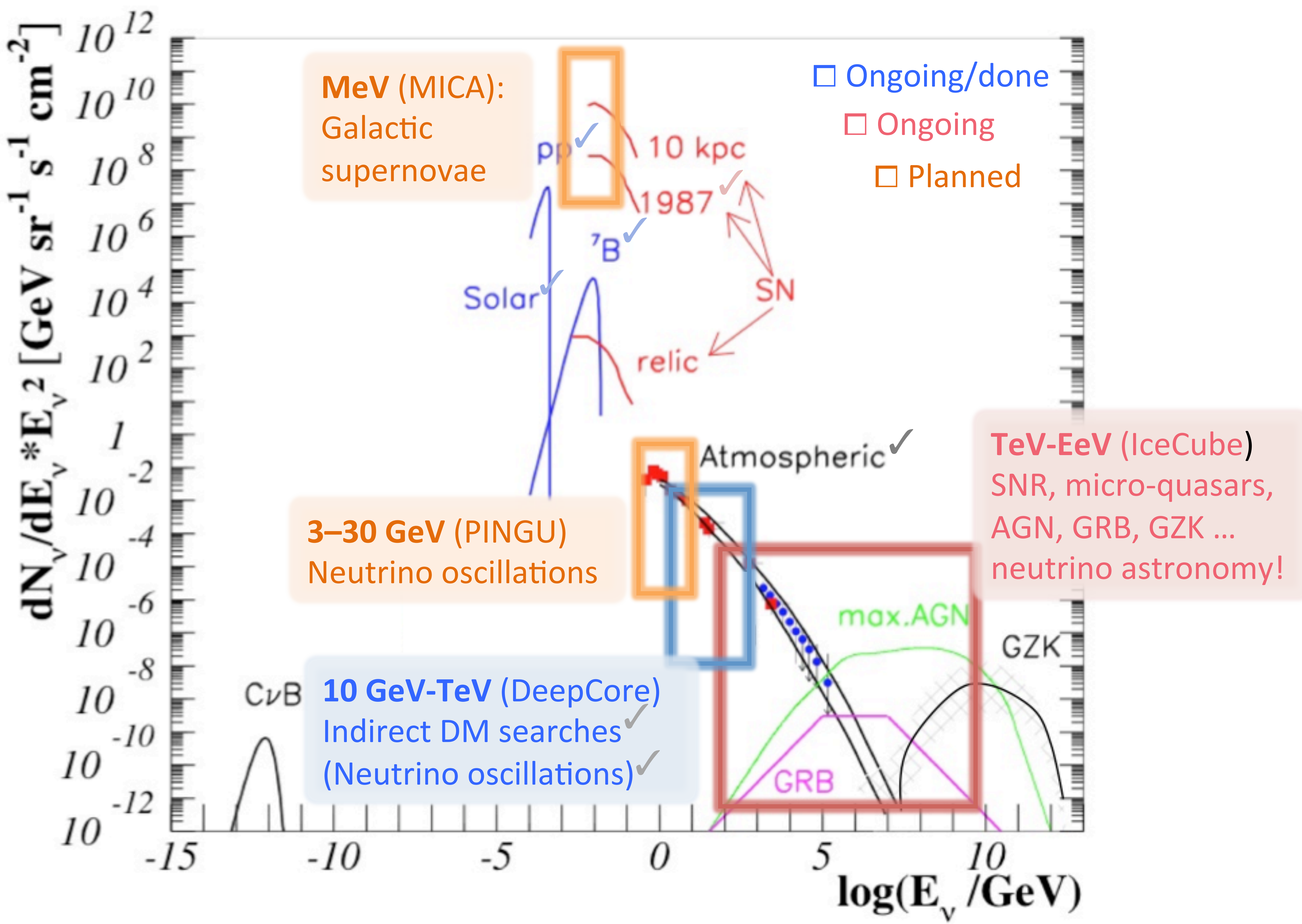


	Charged Current ($W^{+/-}$)	Neutral Current (Z^0)
ν_e	$\nu_e + N \rightarrow e^- + X$	$\nu_e + N \rightarrow \nu_e + X$
ν_μ	$\nu_\mu + N \rightarrow \mu^- + X$	$\nu_\mu + N \rightarrow \nu_\mu + X$
ν_τ	$\nu_\tau + N \rightarrow \tau^- + X$	$\nu_\tau + N \rightarrow \nu_\tau + X$





Reach of IceCube Observatory



IceCube: Recent Highlights

2010 Dec: Construction completed

2011 May: IceCube begins full operations

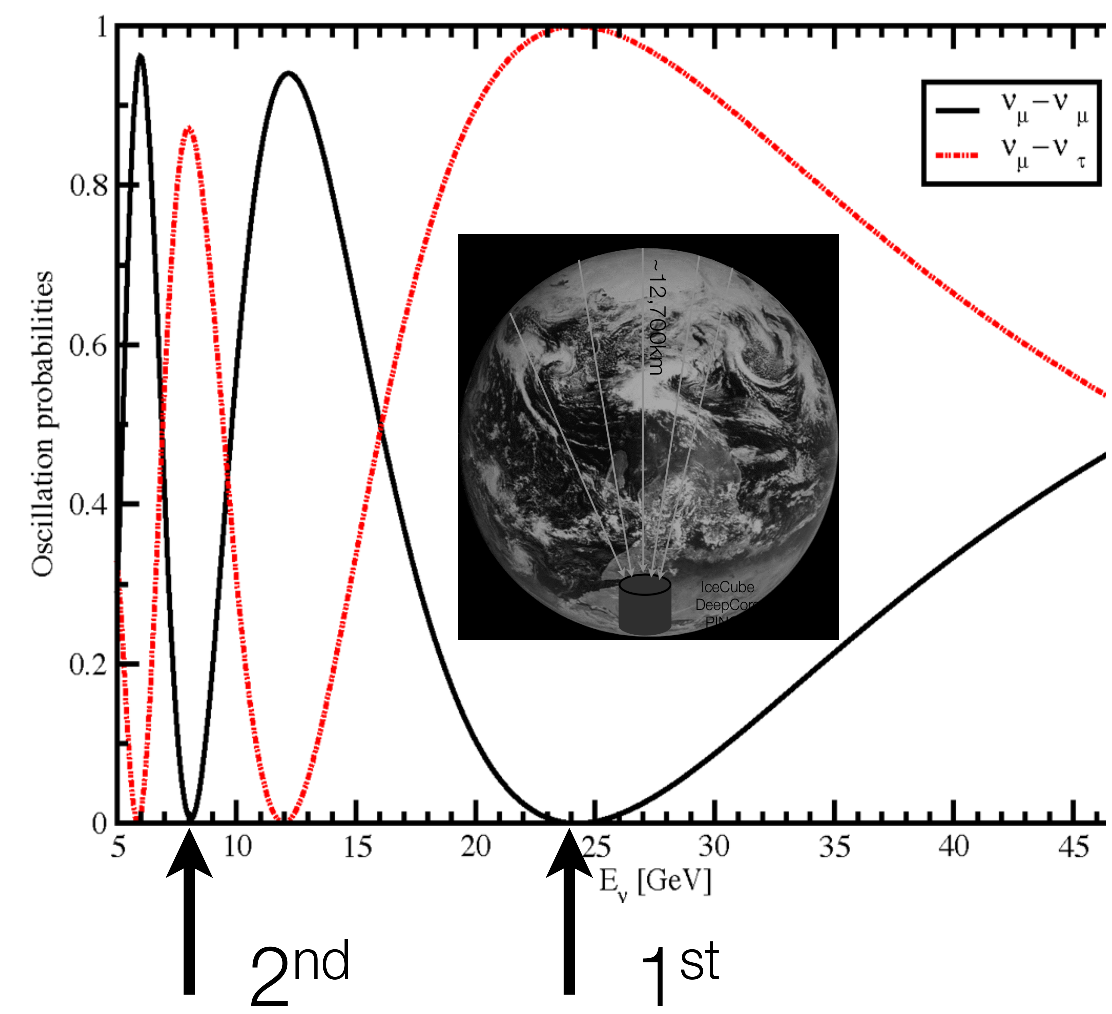
Recent Highlights:

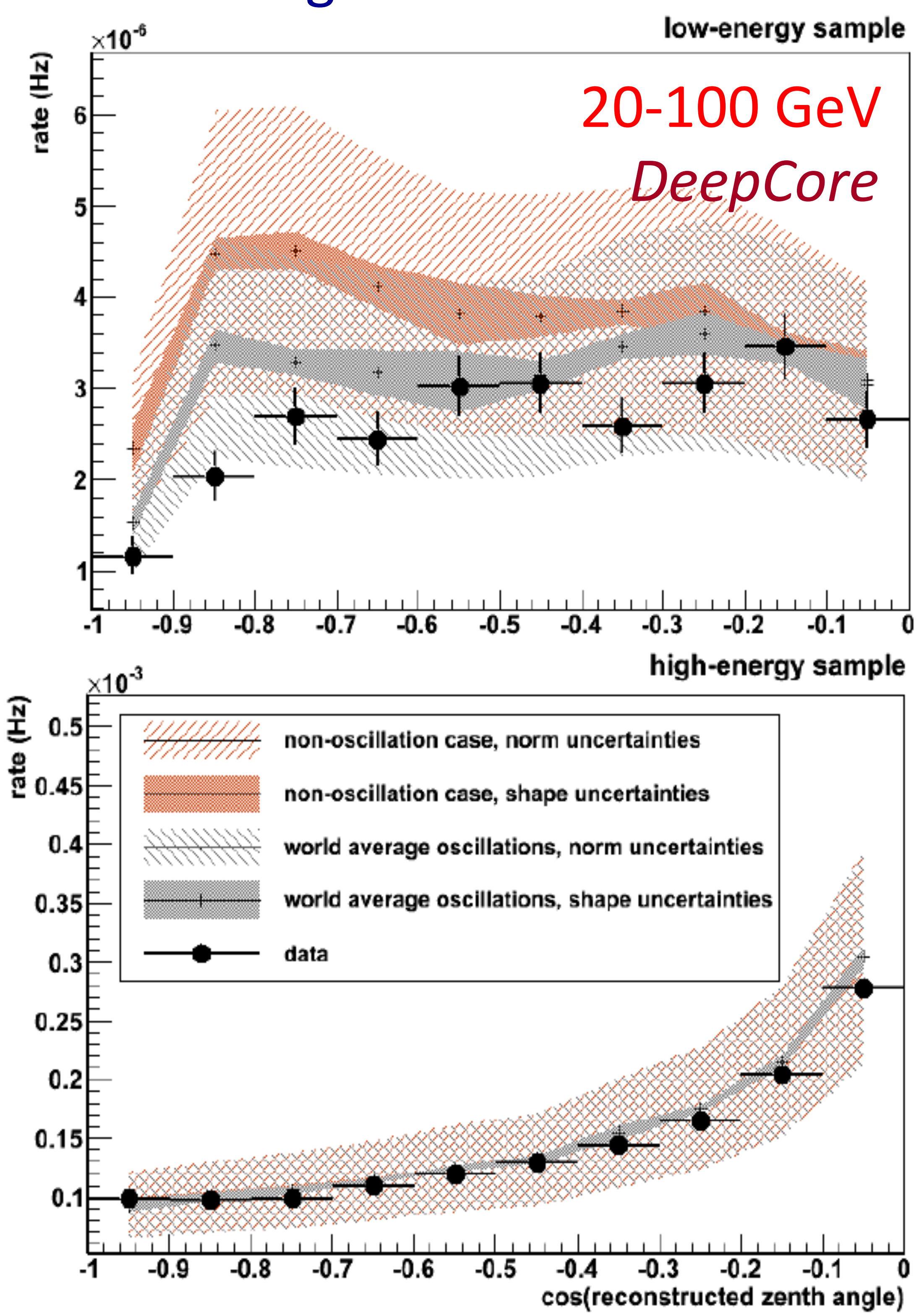
- **Dark Matter (Solar WIMP search)** PRL **110**:131302,2013
  Best spin-dependent limits above 35 GeV
- **Neutrino oscillations** PRL **111**:081801,2013
  Detected at 5σ ⇨PINGU and the 'Neutrino Mass Hierarchy'
- **Flavour separation** PRL **110**:151105,2013
  First measurements of atmospheric ν_e above 100 GeV
- **PeV neutrinos** PRL **111**:021103,2013
  Highest energy neutrinos yet observed
- **High energy neutrino excess**
  > 5σ Evidence of extraterrestrial origin Science **342**:1242856,2013, arXiv:1405.5303

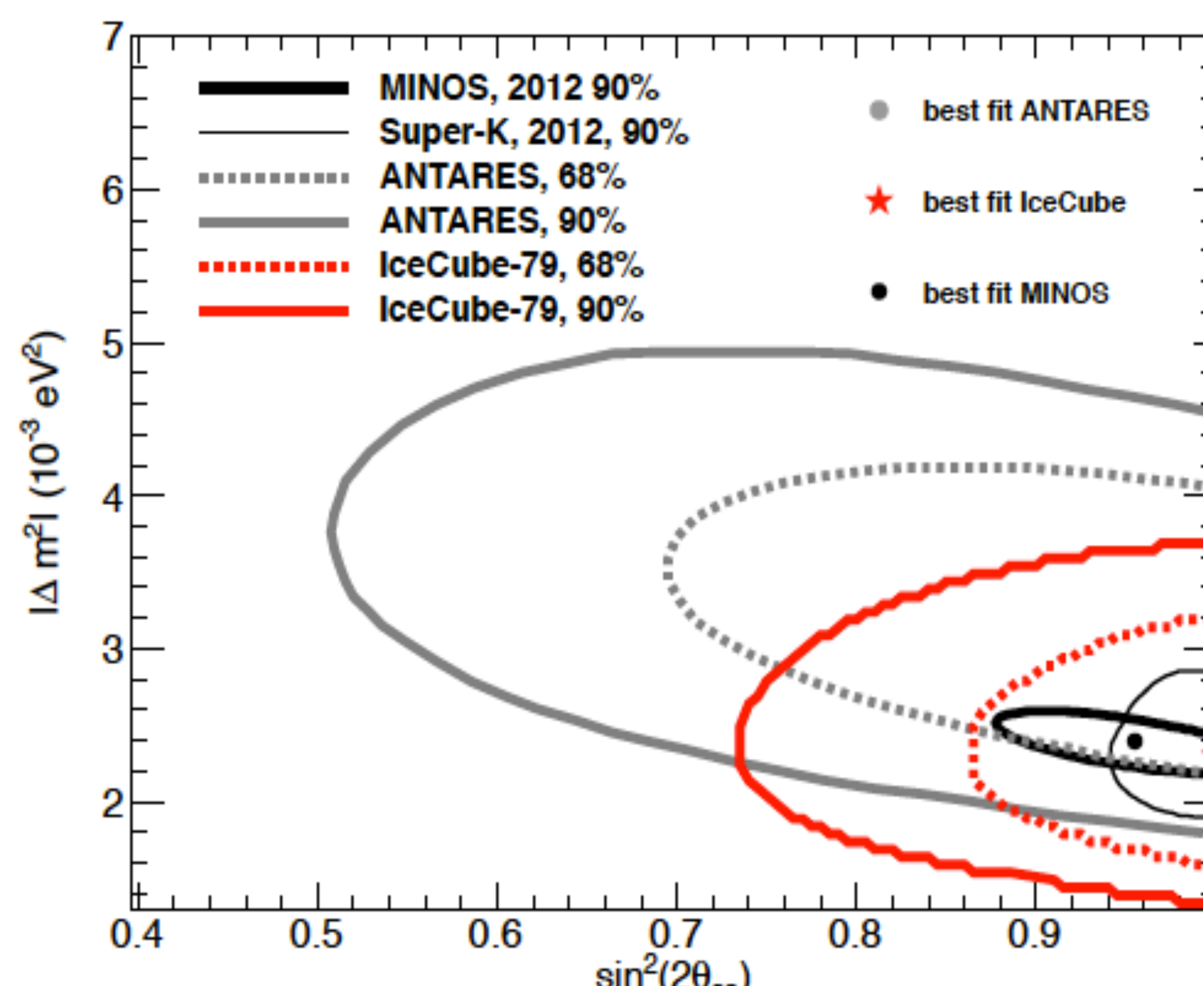
Measurement of Atmospheric Neutrino Oscillations with IceCube

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{23} L/E)$$

Atmospheric ν_μ from Northern hemisphere oscillating over the Earth's diameter have the oscillation minimum at ~25 GeV (detect with DeepCore infill array of IceCube)
⇒ distorted zenith angle distribution wrt no oscillations

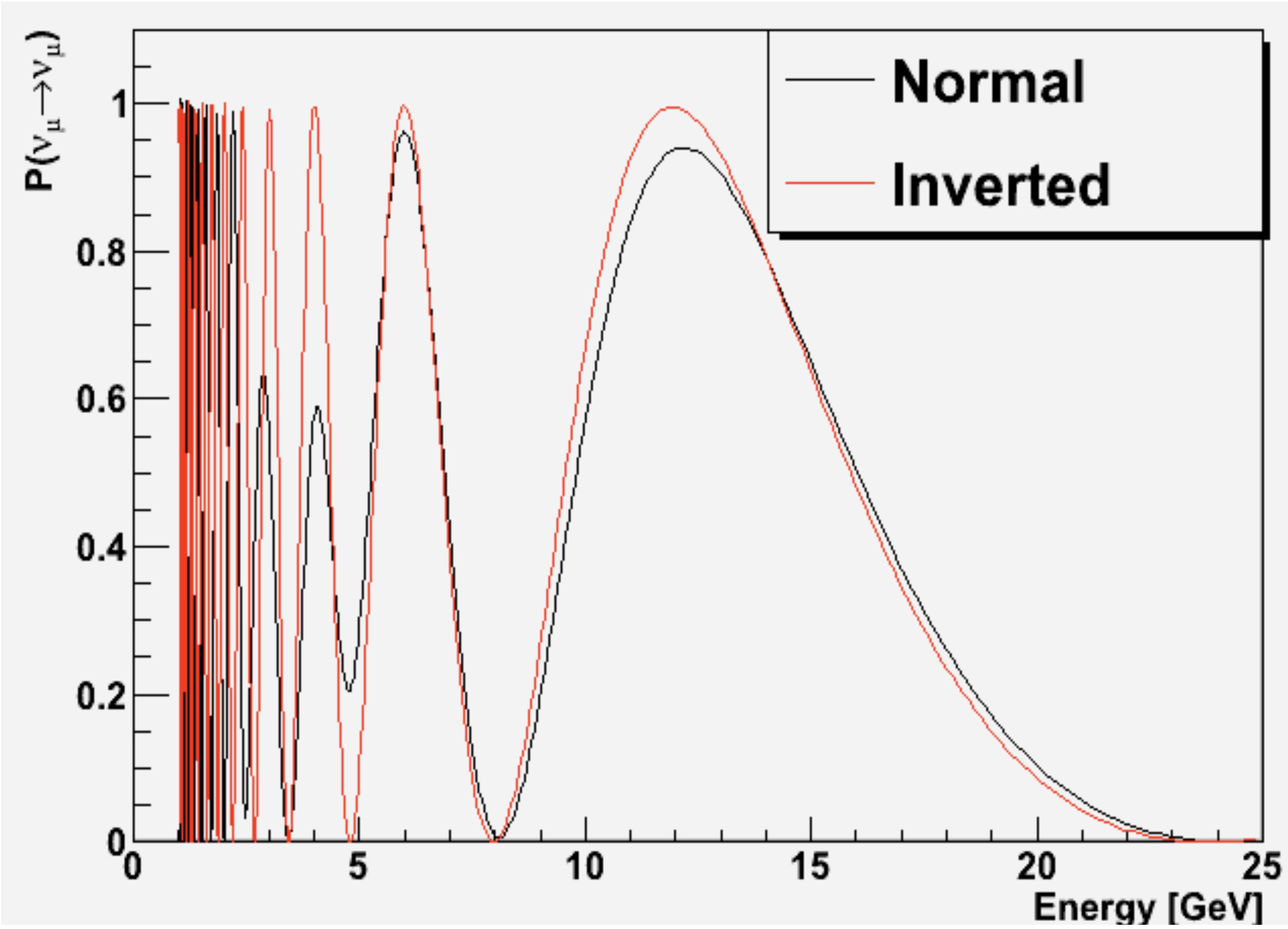




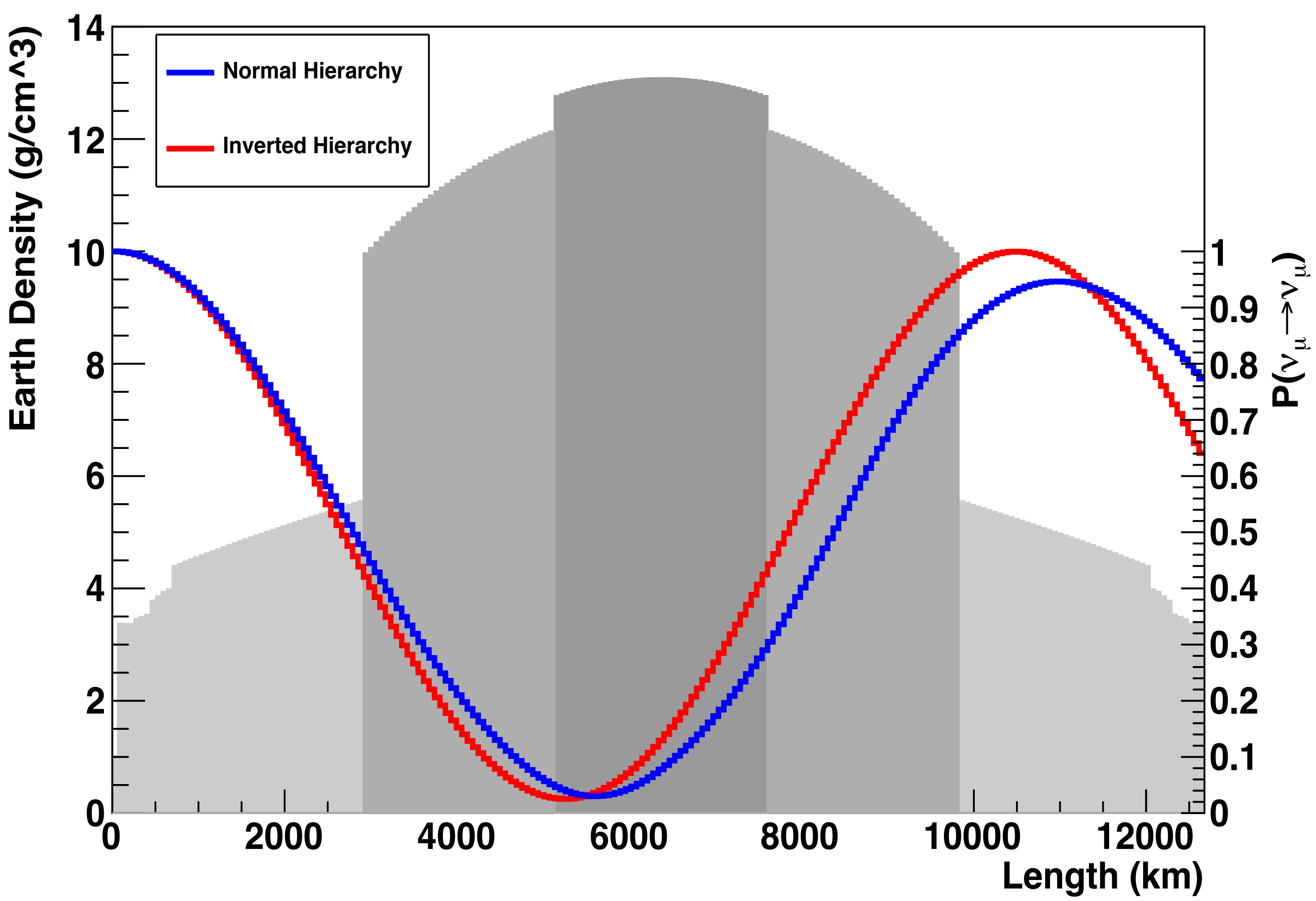


PRL 111:081801,2013

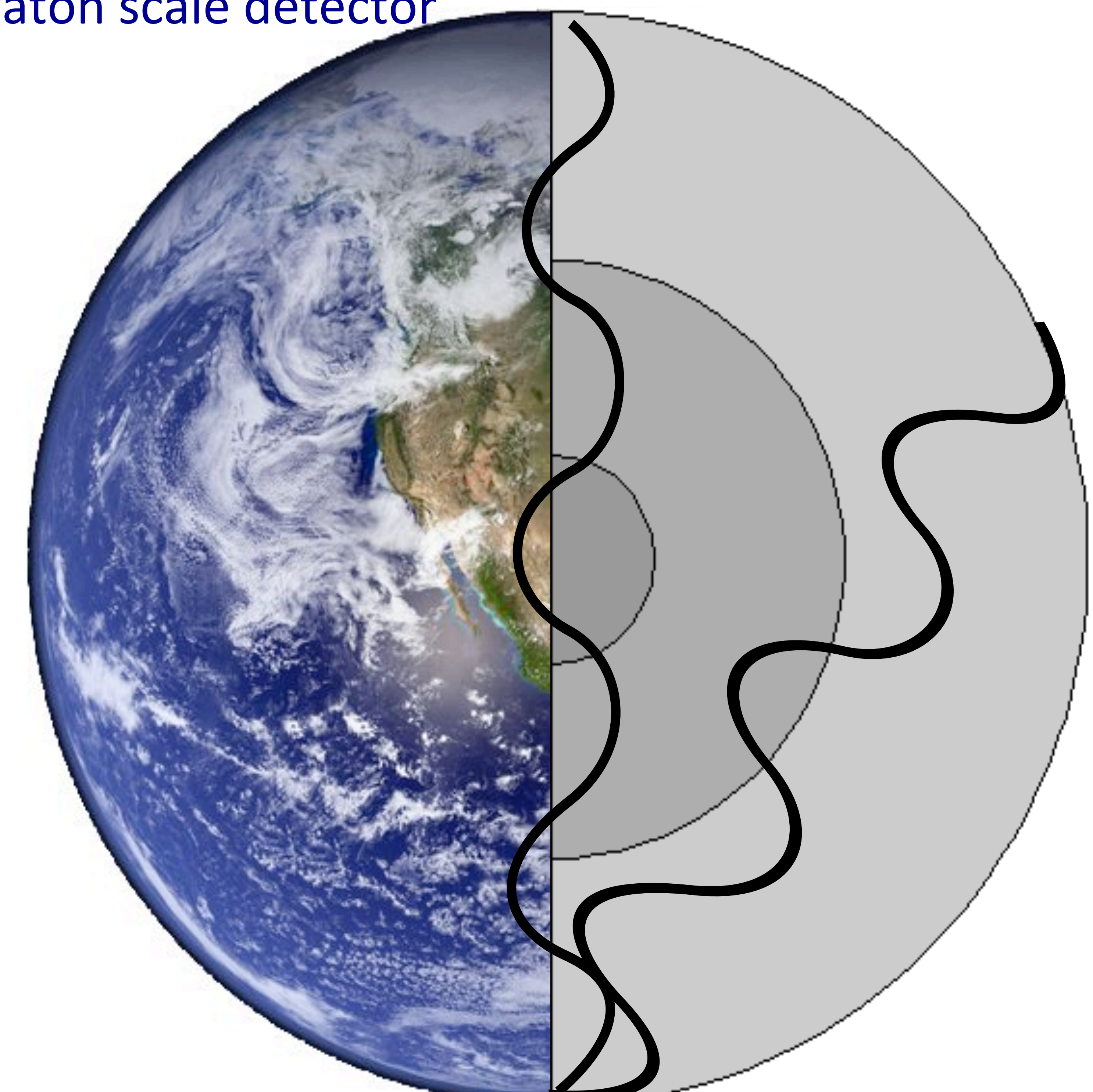
Lower energy threshold → 3 GeV in Precision In-Ice Next Generation Upgrade



$P(\nu_\mu \to \nu_\mu)$ with Travel Through the Earth - 10 GeV, 179°



Inverted/Normal hierarchy has up to ~20% difference in ν_μ oscillation probability for specific energies and zenith angles (baselines), so can determine hierarchy *without* δ_{CP} dependence, exploiting huge statistical power afforded by a megaton scale detector



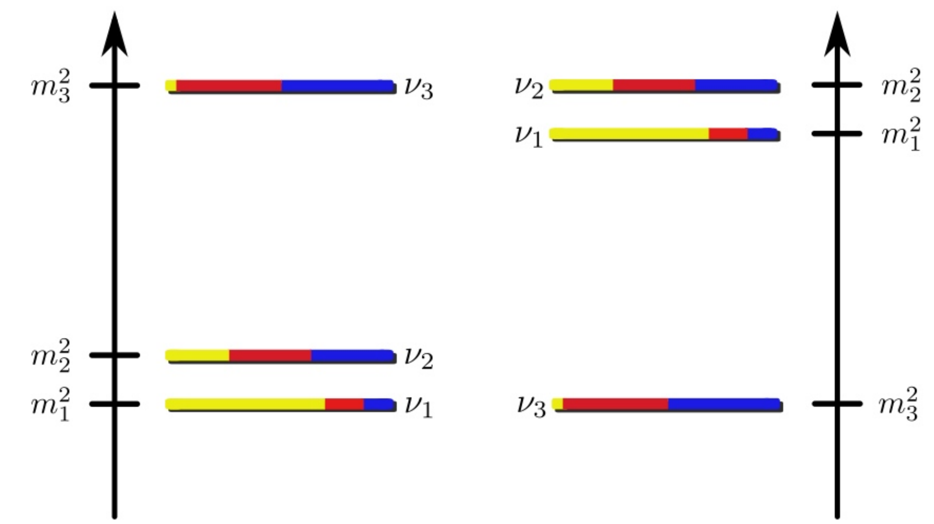
Akhmedov, Razzaque, Smirnov, arXiv:1205.7071

Precision In-Ice Next Generation Upgrade: PINGU

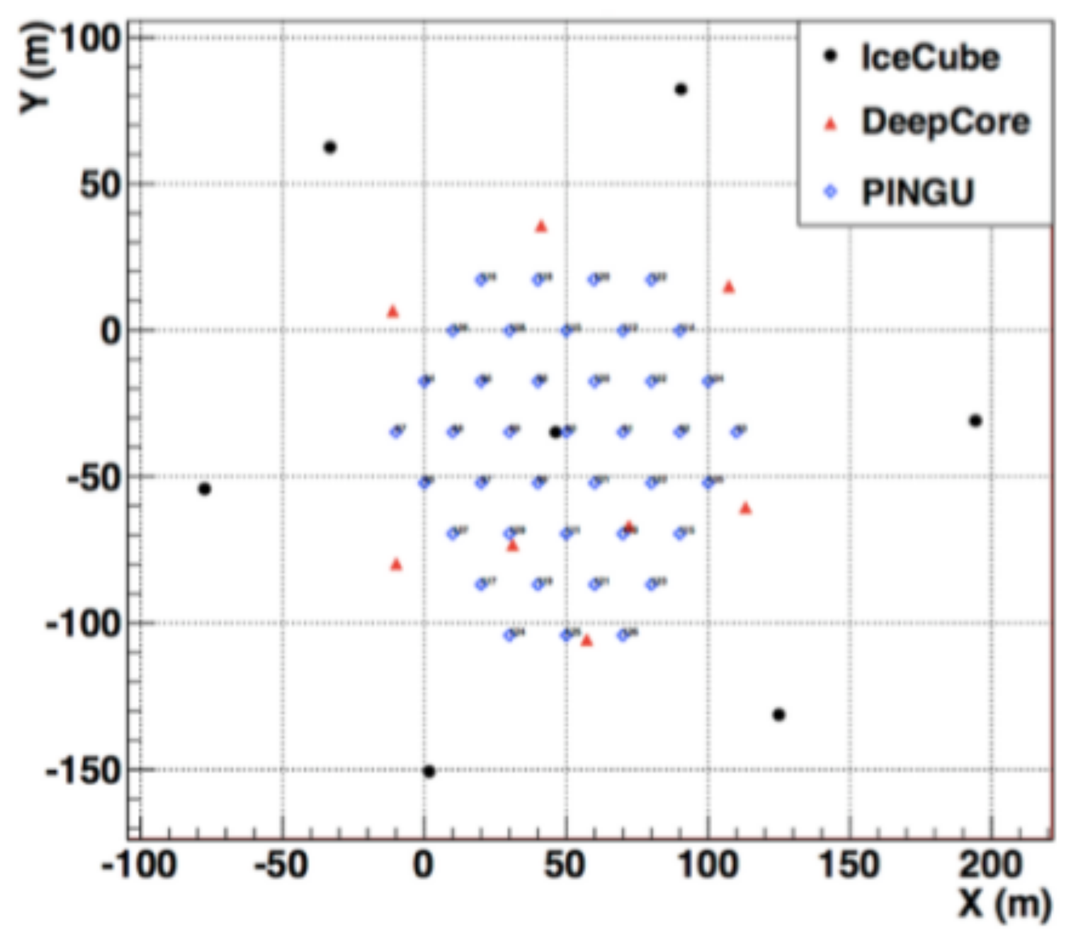
Neutrino Mass Hierarchy measurement (independently of δ_{CP}) is primary goal

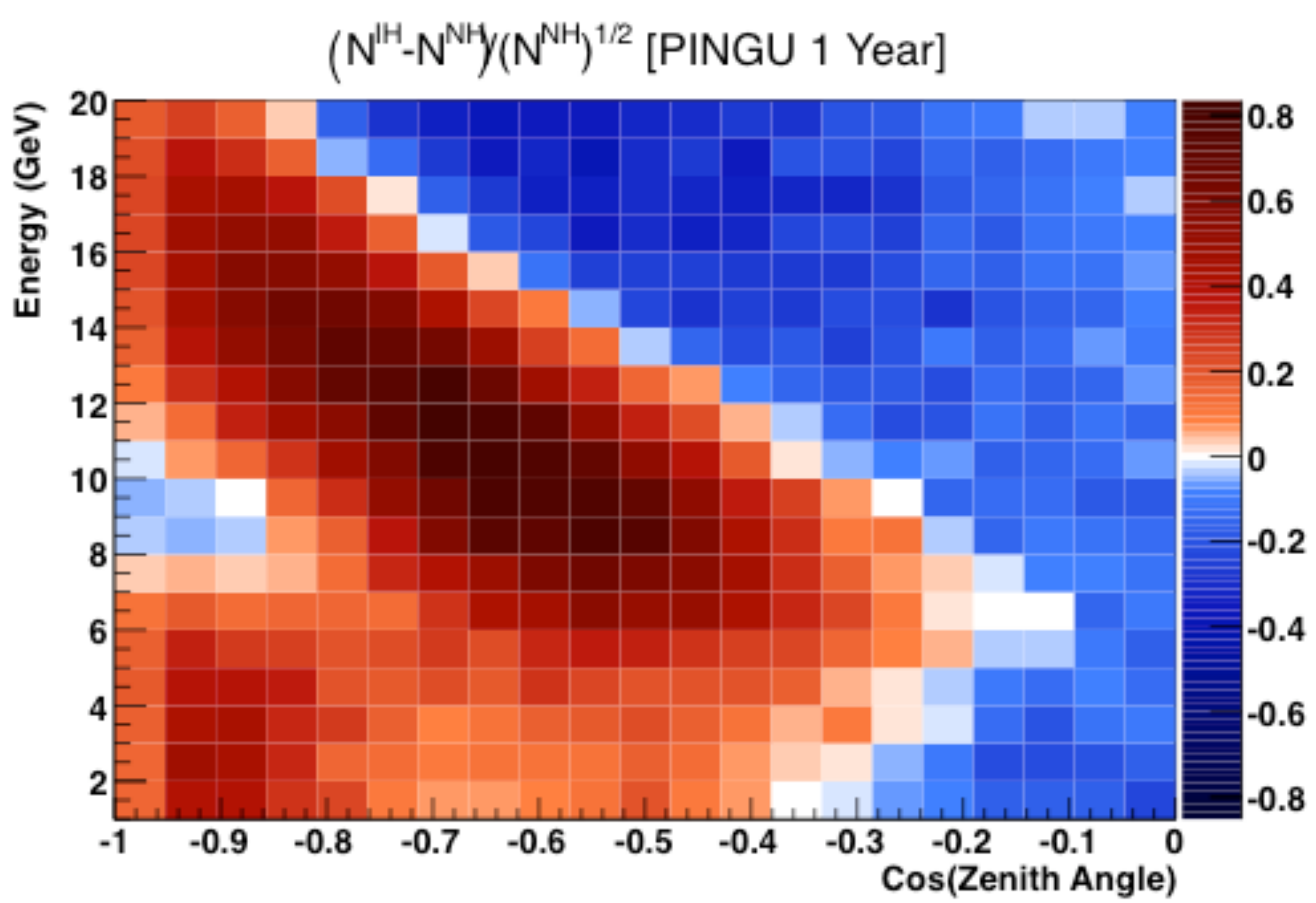
Also sensitive to possible sterile neutrinos

40 string in-fill array
Sensitivity down to ~3 GeV



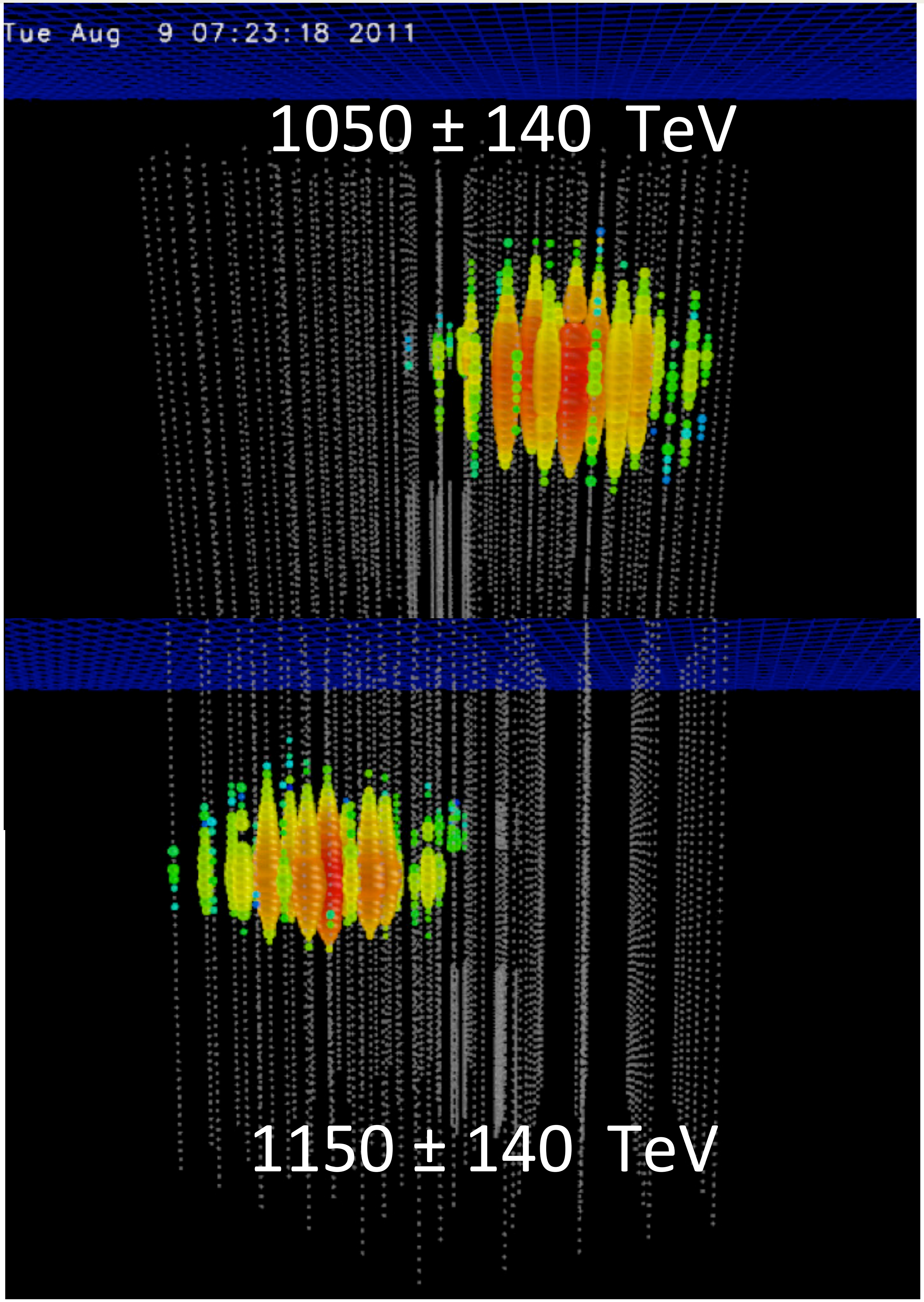
Hierarchy signature is a distinctive structure in energy-angle plane



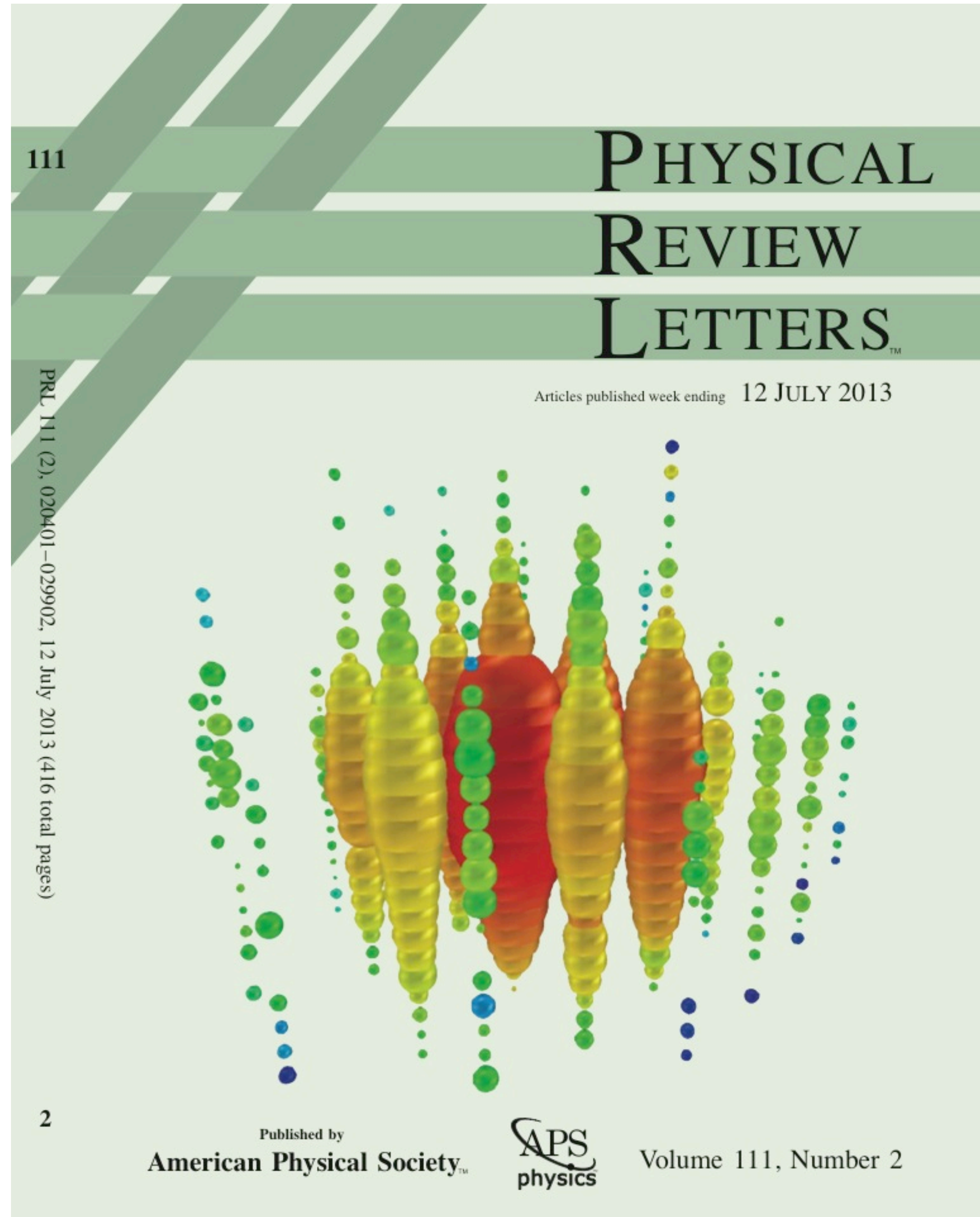


Includes: estimated energy and angular resolution

First Observation of PeV-energy Neutrinos



… discovered in search for GZK neutrinos



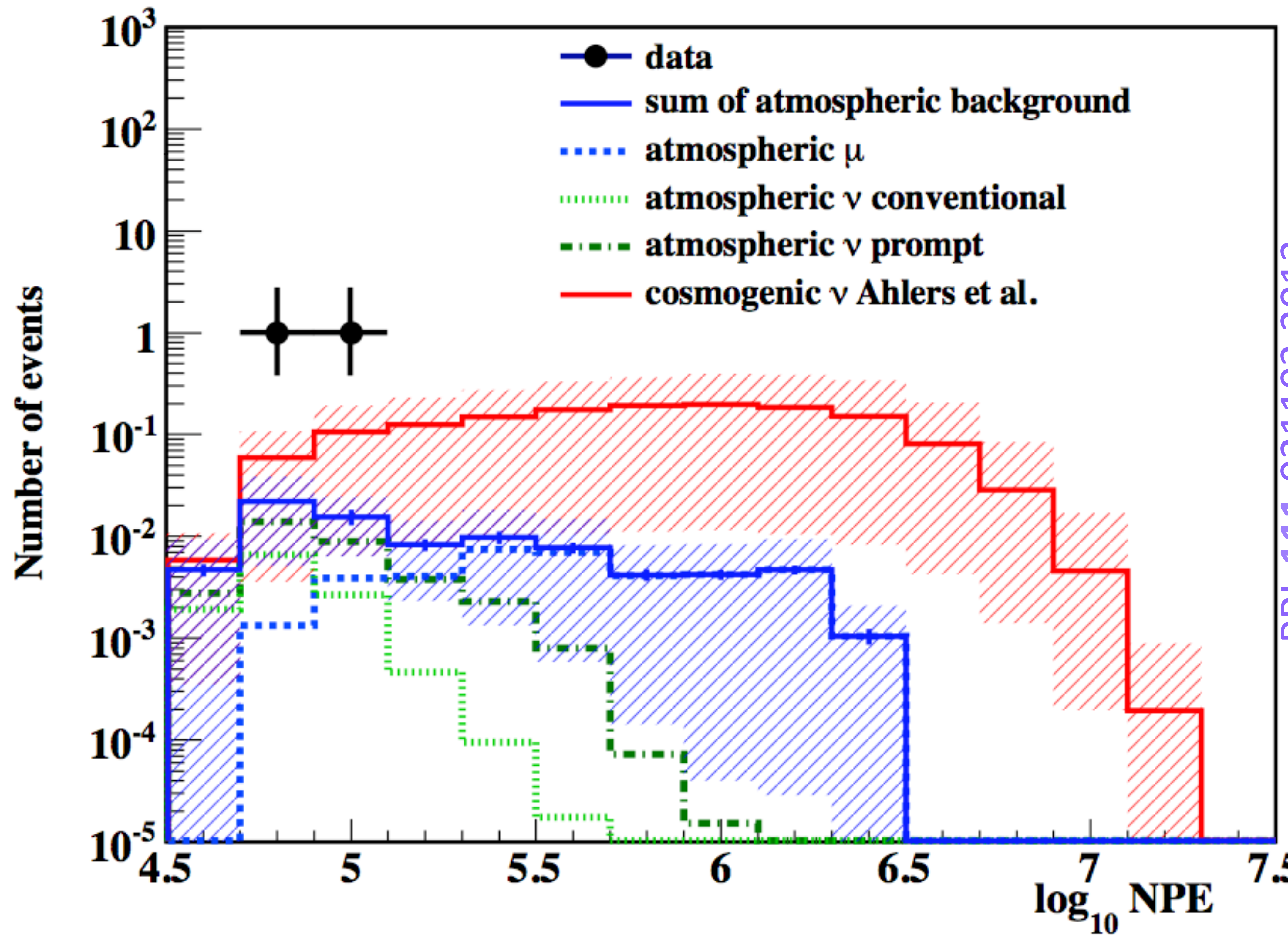
First Observation of PeV-Energy Neutrinos

Combined analysis of **79-string data (1 year)** and **first** analysis of **86-string data (1 year)**

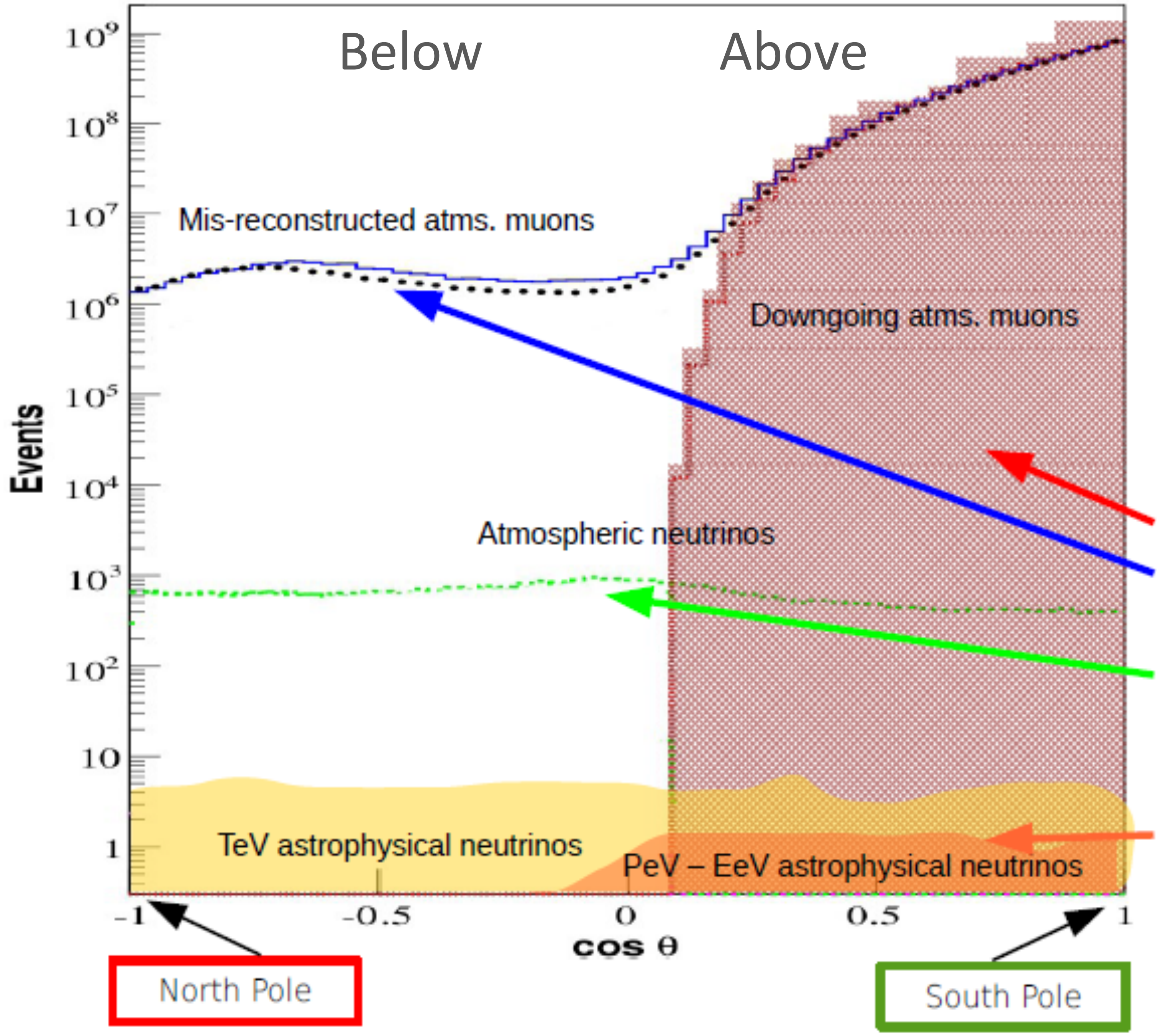
2 PeV events found in a search targeting much higher energy neutrinos (related to GZK cutoff)

Expected background: **0.08 ± 0.05 events**

2.8 σ excess



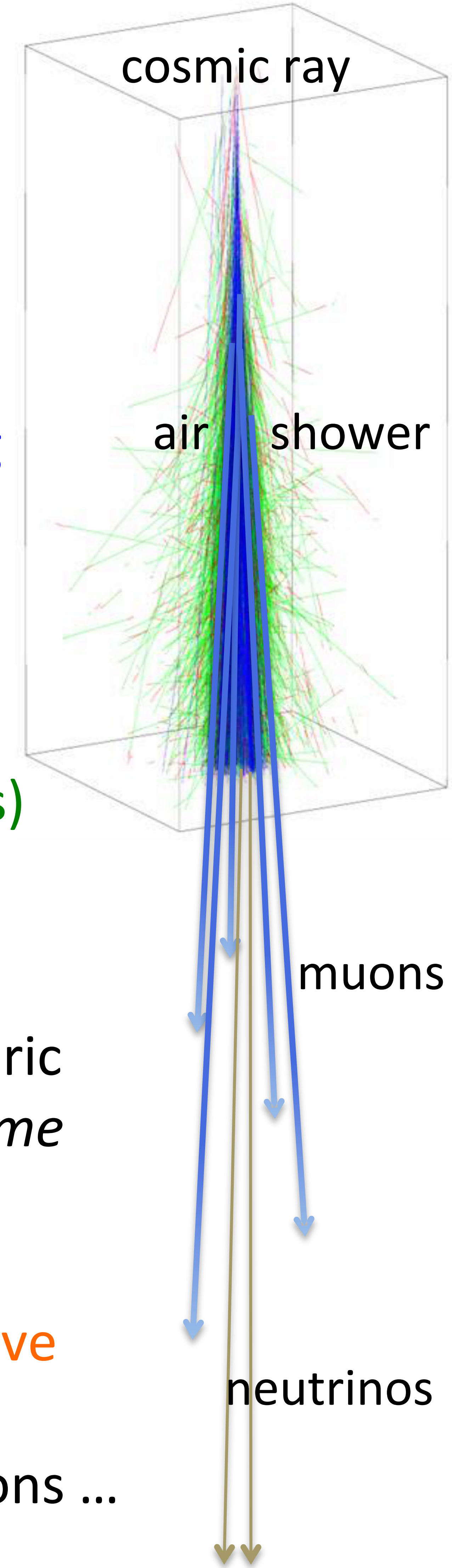
PRL 111:021103,2013



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.

'High Energy Starting Events' analysis

Follow-up based on PeV events

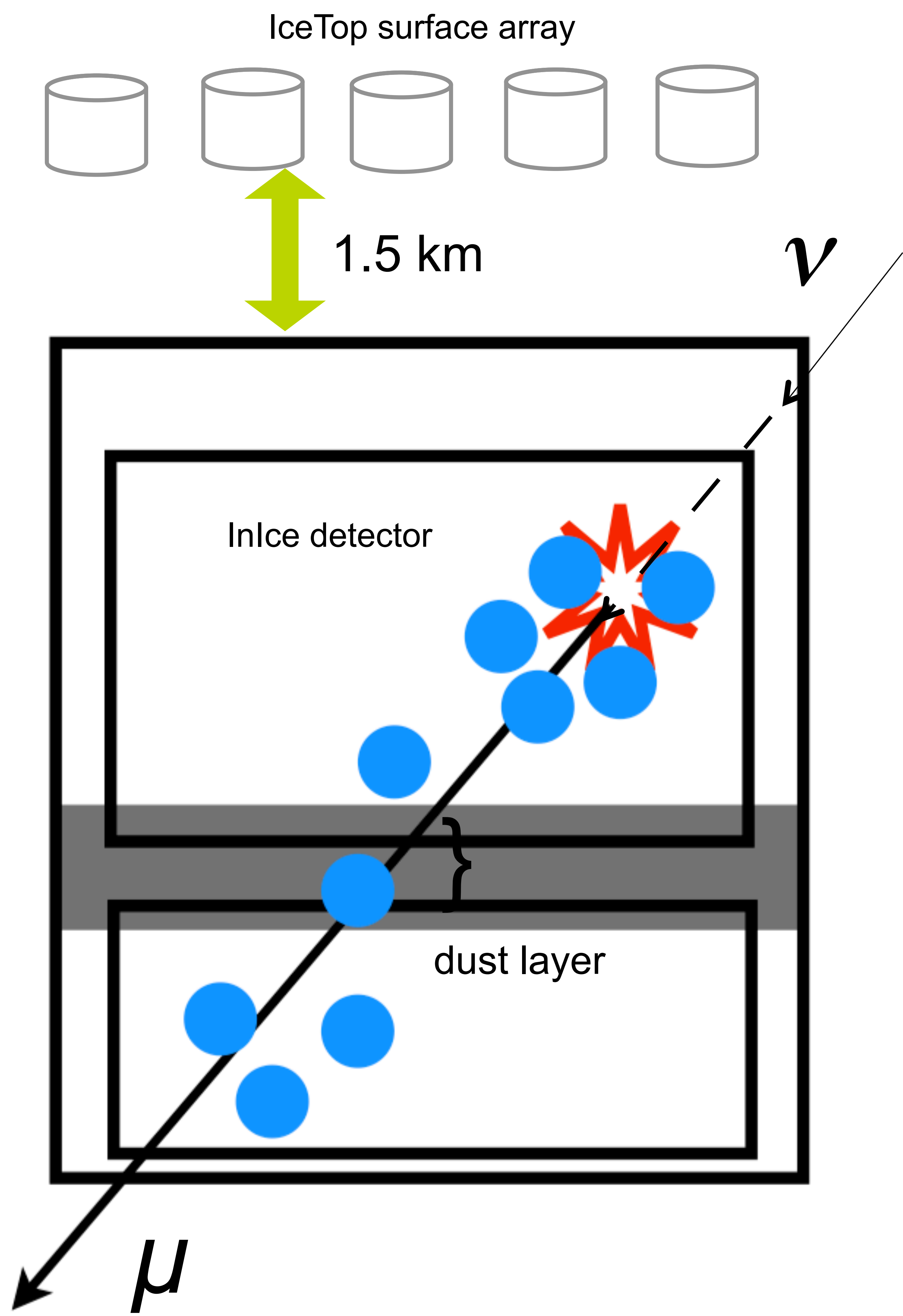
1. **Lower** energy threshold, from ~PeV down to ~40 TeV

(Still very bright events … require > 6000 photo-electrons for trigger)

2. Use outer-most layer of IceCube as a **veto**

Removes atmospheric background (muon + neutrino) **from above**
(Earth filters muon background **from below**)

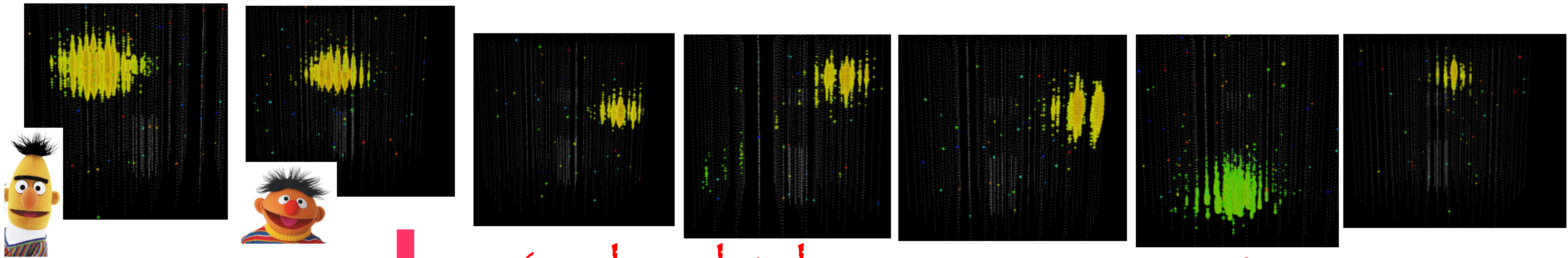
(NB: track-events will be somewhat suppressed when using veto)



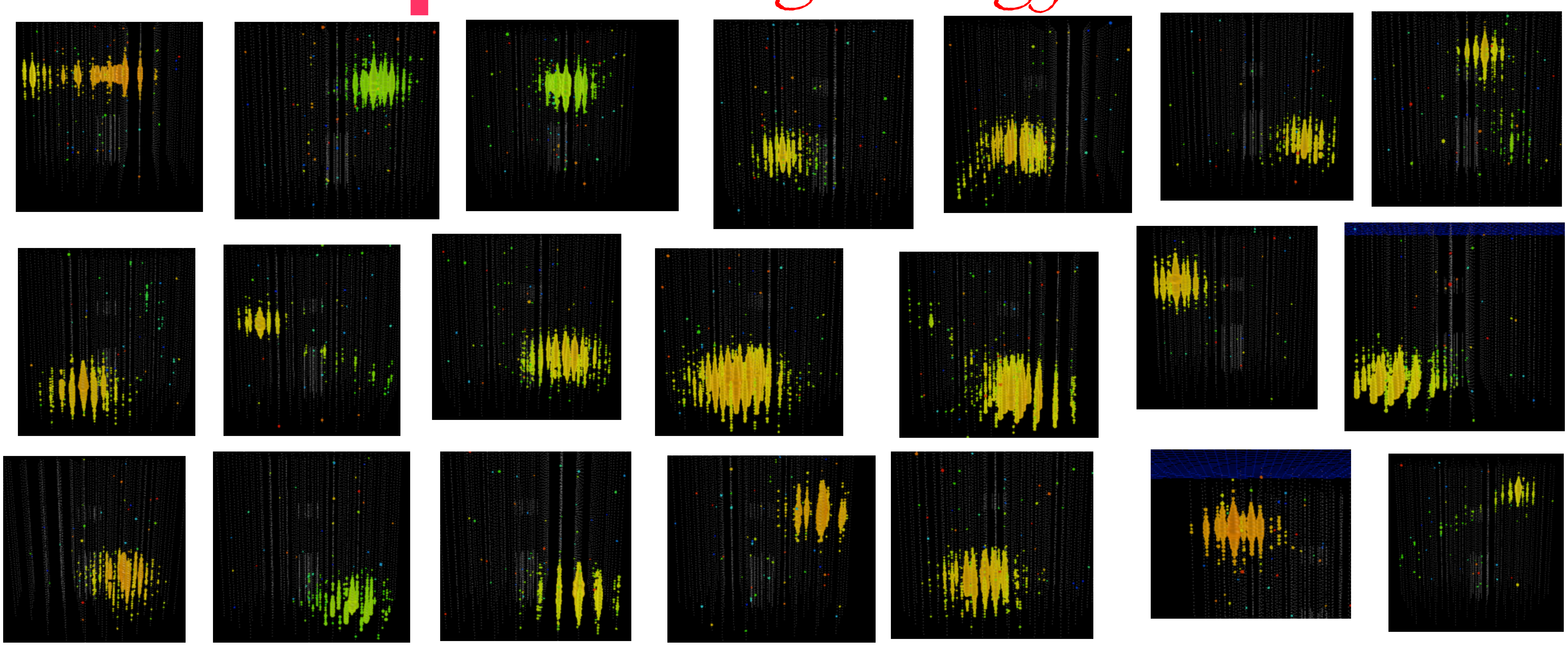
Re-discovery of Bert & Ernie

Atmospheric μ background: 6 ± 3.4

Atmospheric ν background: $4.6^{+3.7}_{-1.2}$

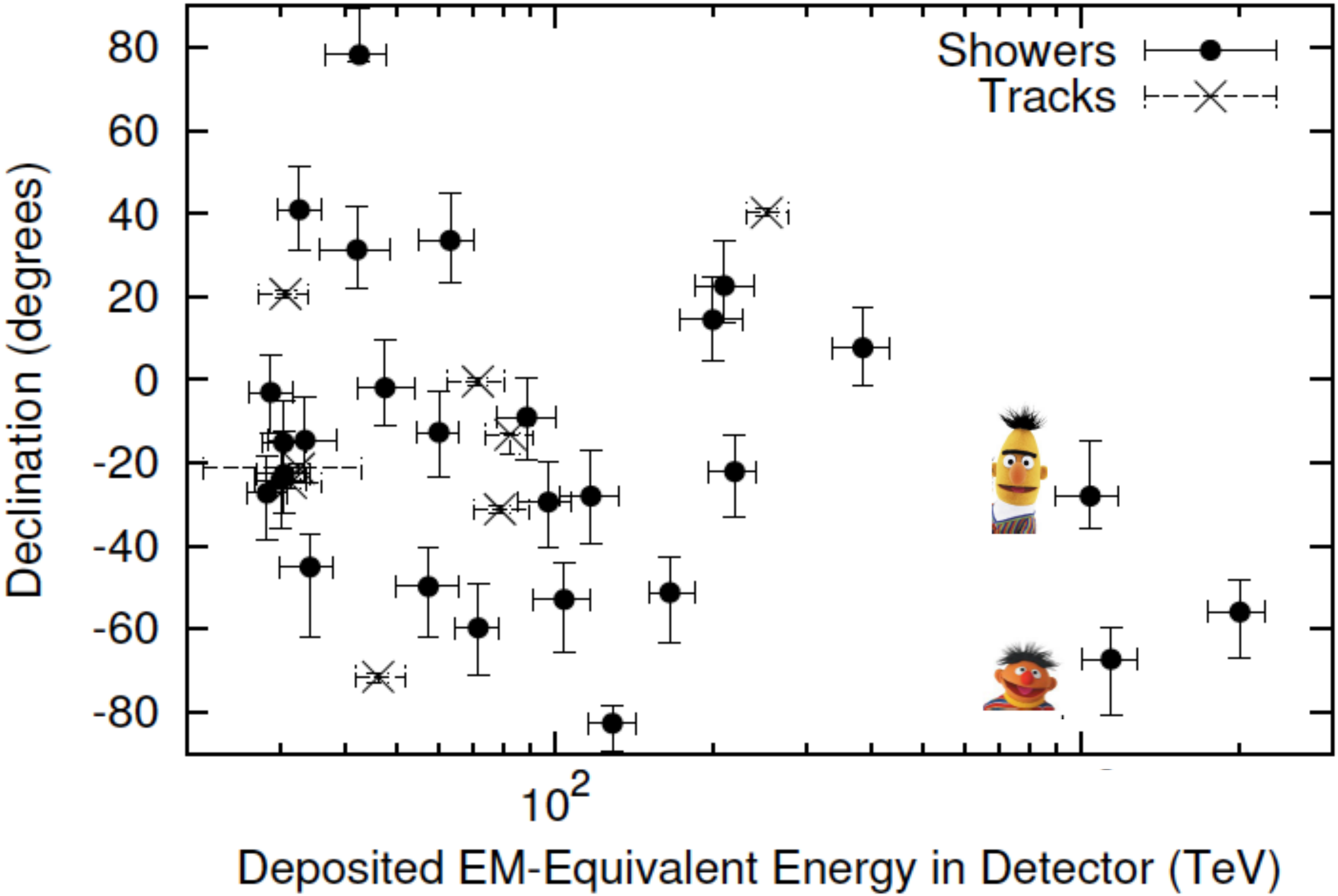


+ 26 other high-energy events!

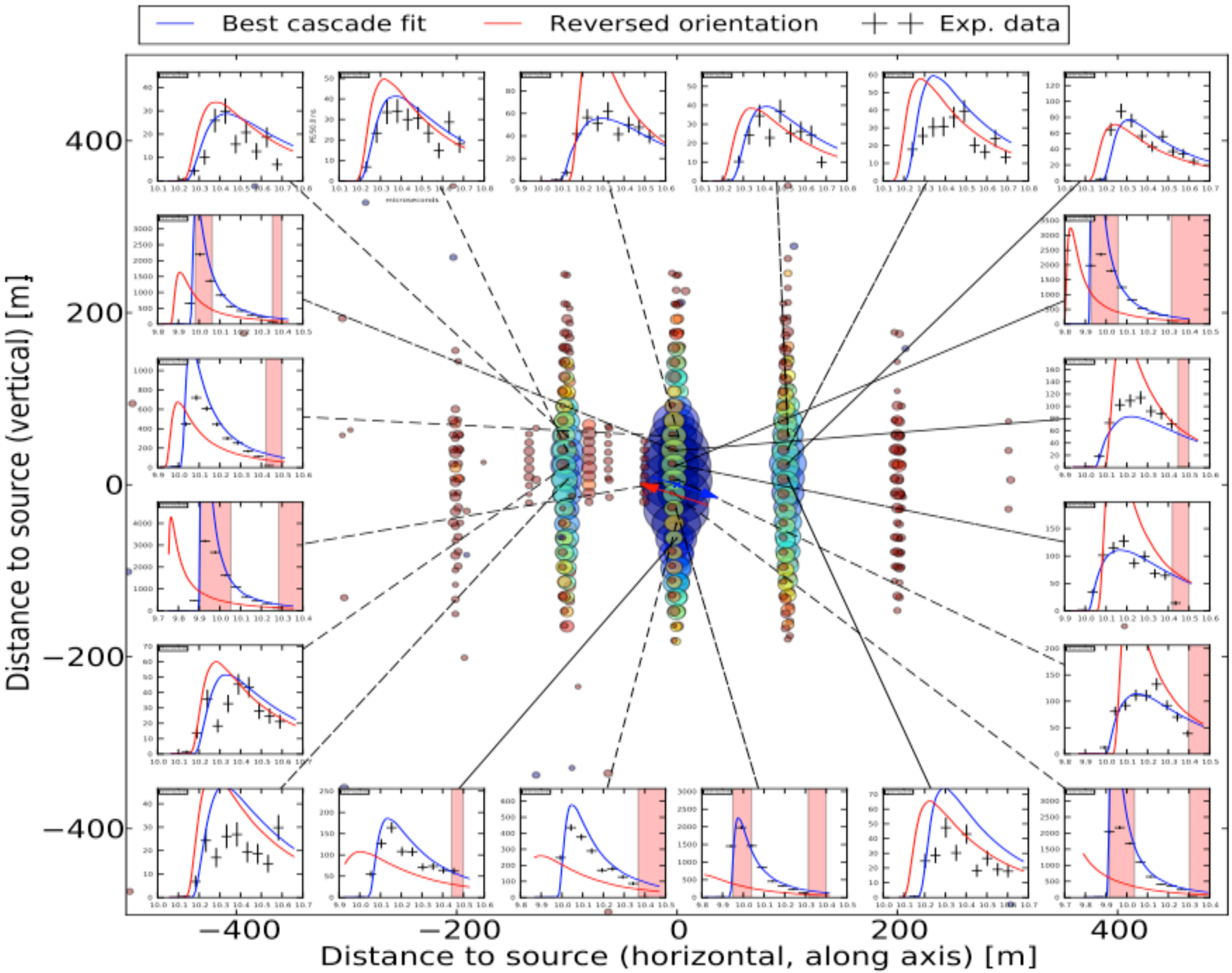


… including the 2012-13 data we now have 37 events (988 day sample)

(NB: Track events can have *higher* true energies than deposited energies)



Waveform Examples from modules at various positions in the detector:



High Energy Starting Event Analysis: Results

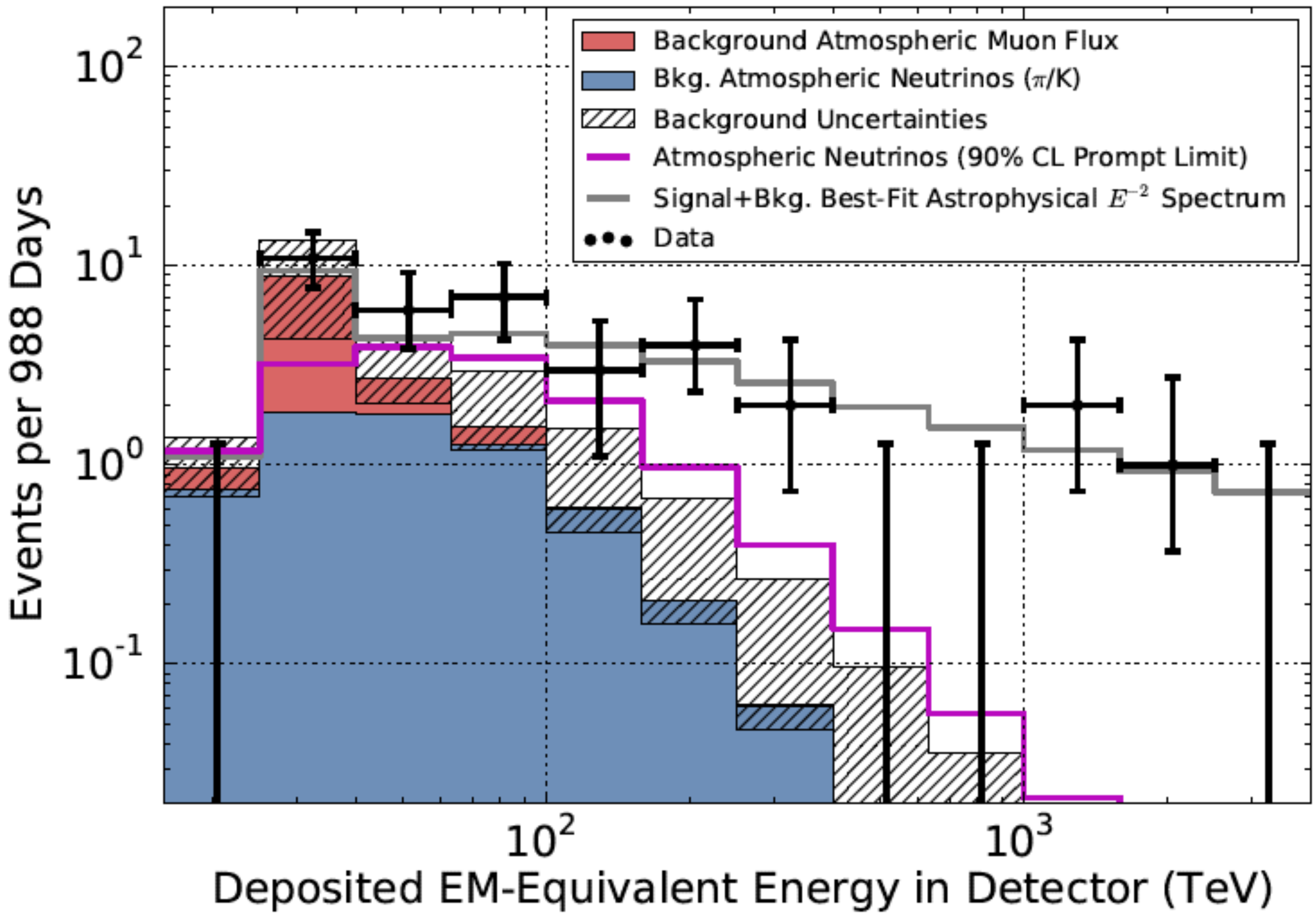
26 + 11 new events

Expected background:
- 8.4 ± 4.2 cr muons
- $6.6^{+5.9}_{-1.6}$ atm. νs

⇨ **>5.7σ detection**

Cutoff beyond ~2 PeV?

Gap at ~0.5-1 TeV?



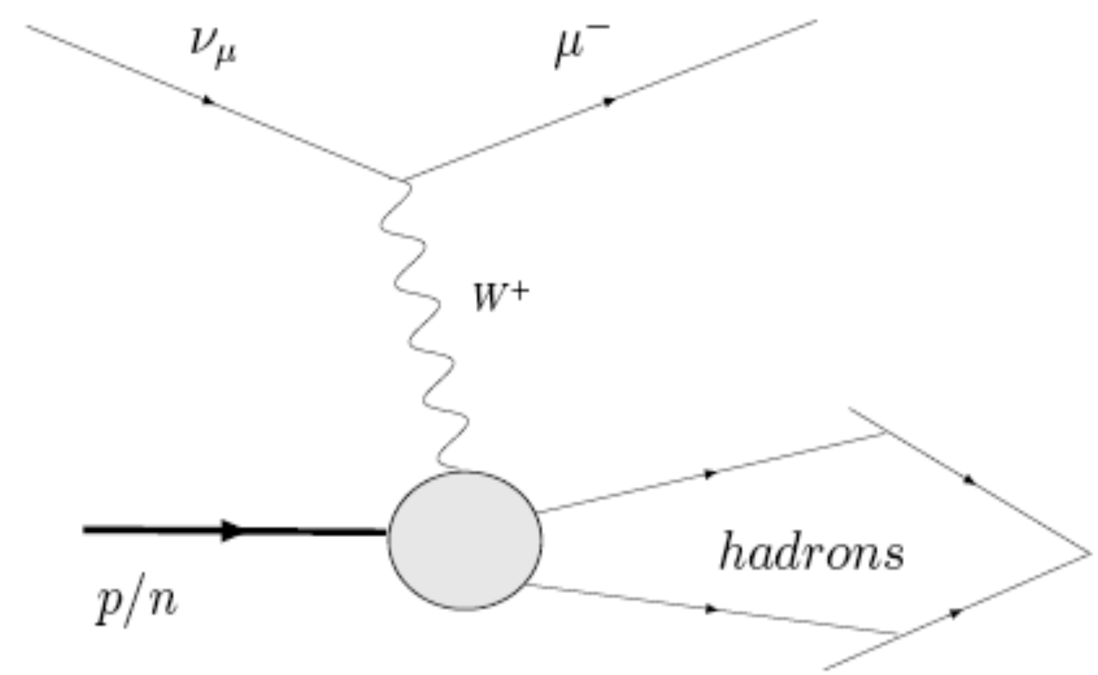
ν-N deep inelastic scattering

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

Q^2 ↑ propagator ↓

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

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



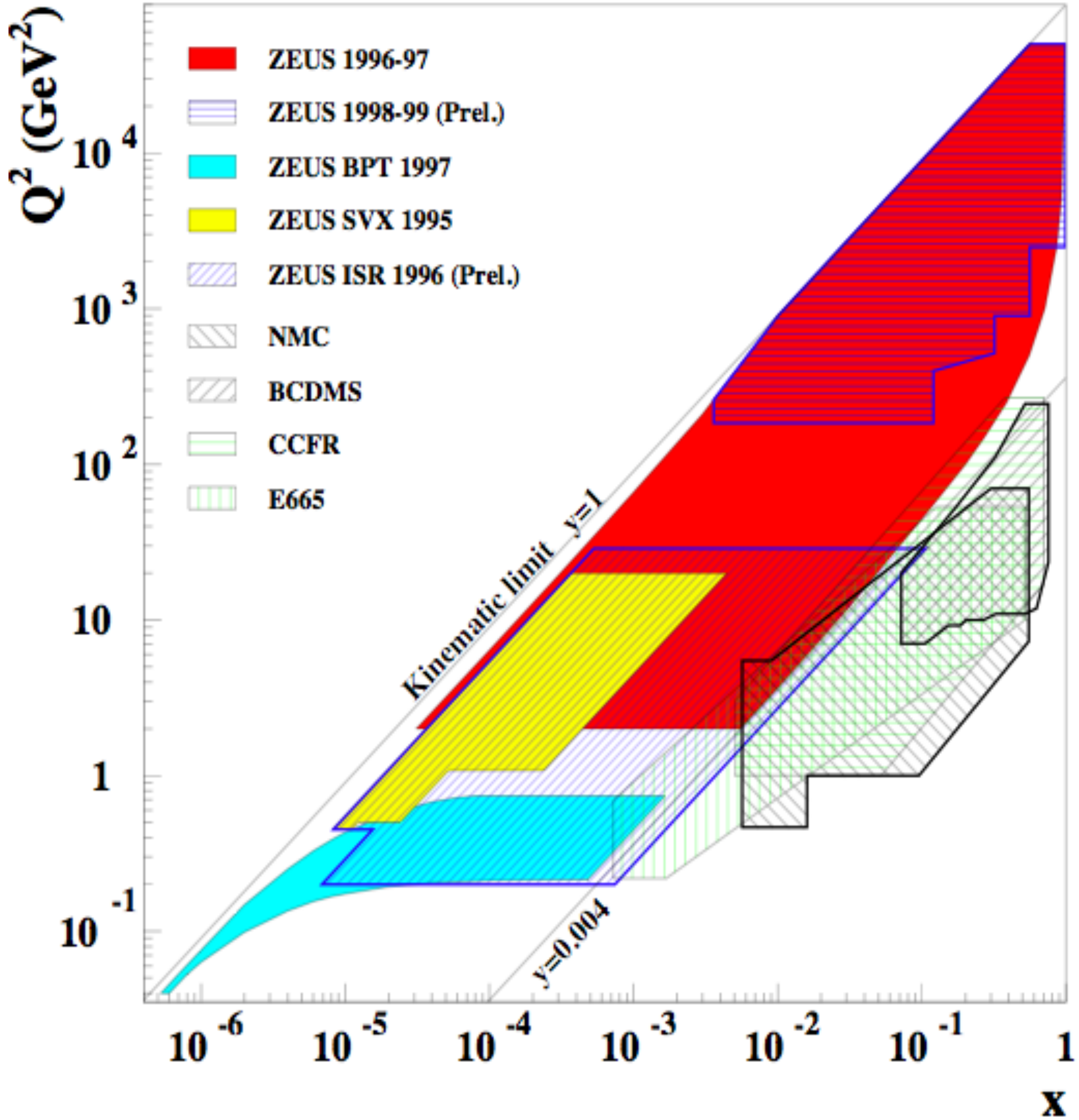
Q^2 ↑ parton distrib. fns ↓

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

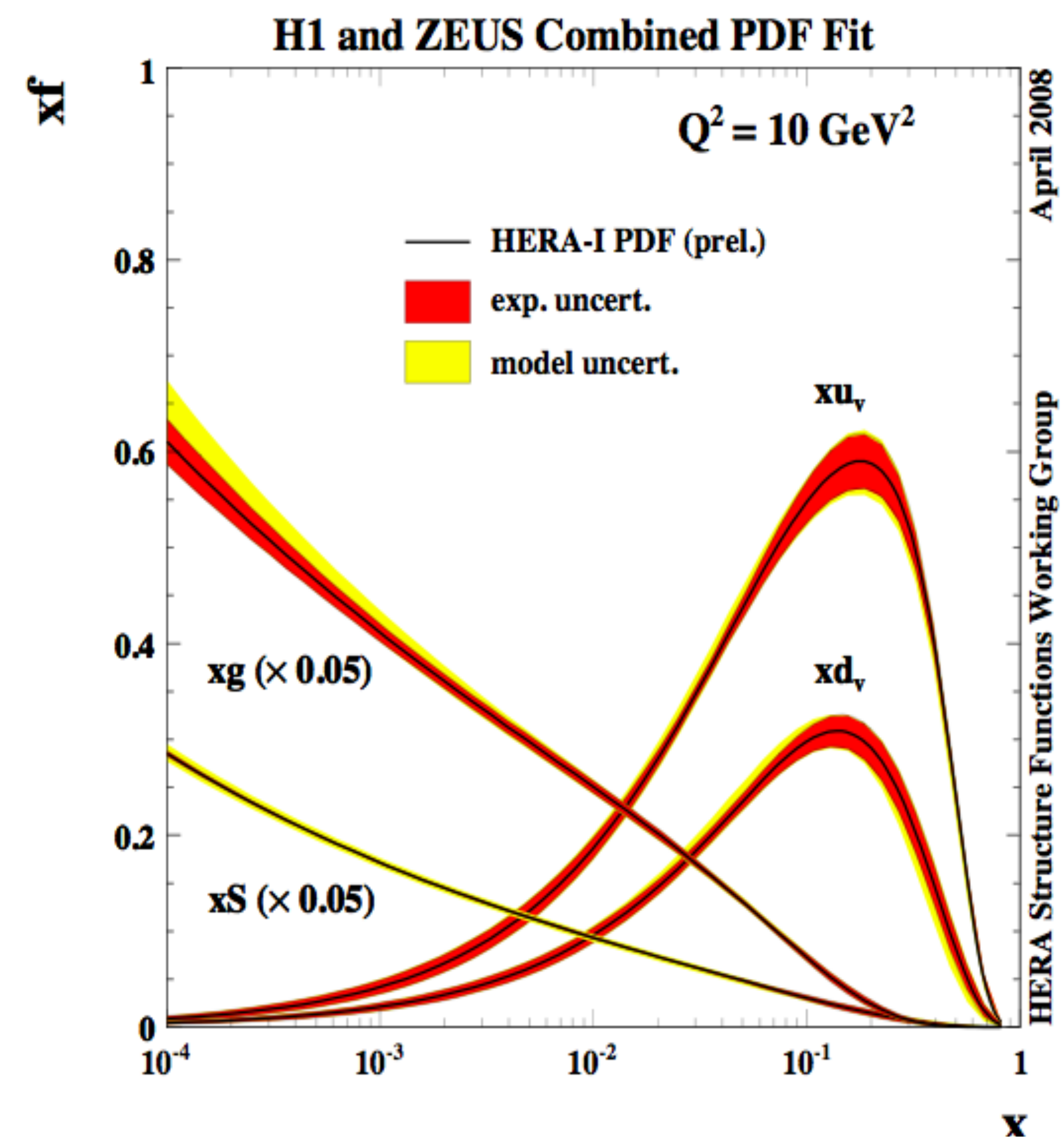
At leading order (LO) : $F_L = 0, \quad F_2 = x(u_v + d_v + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c}),$

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

At NLO in α_s, it gets more complicated … but is still calculable

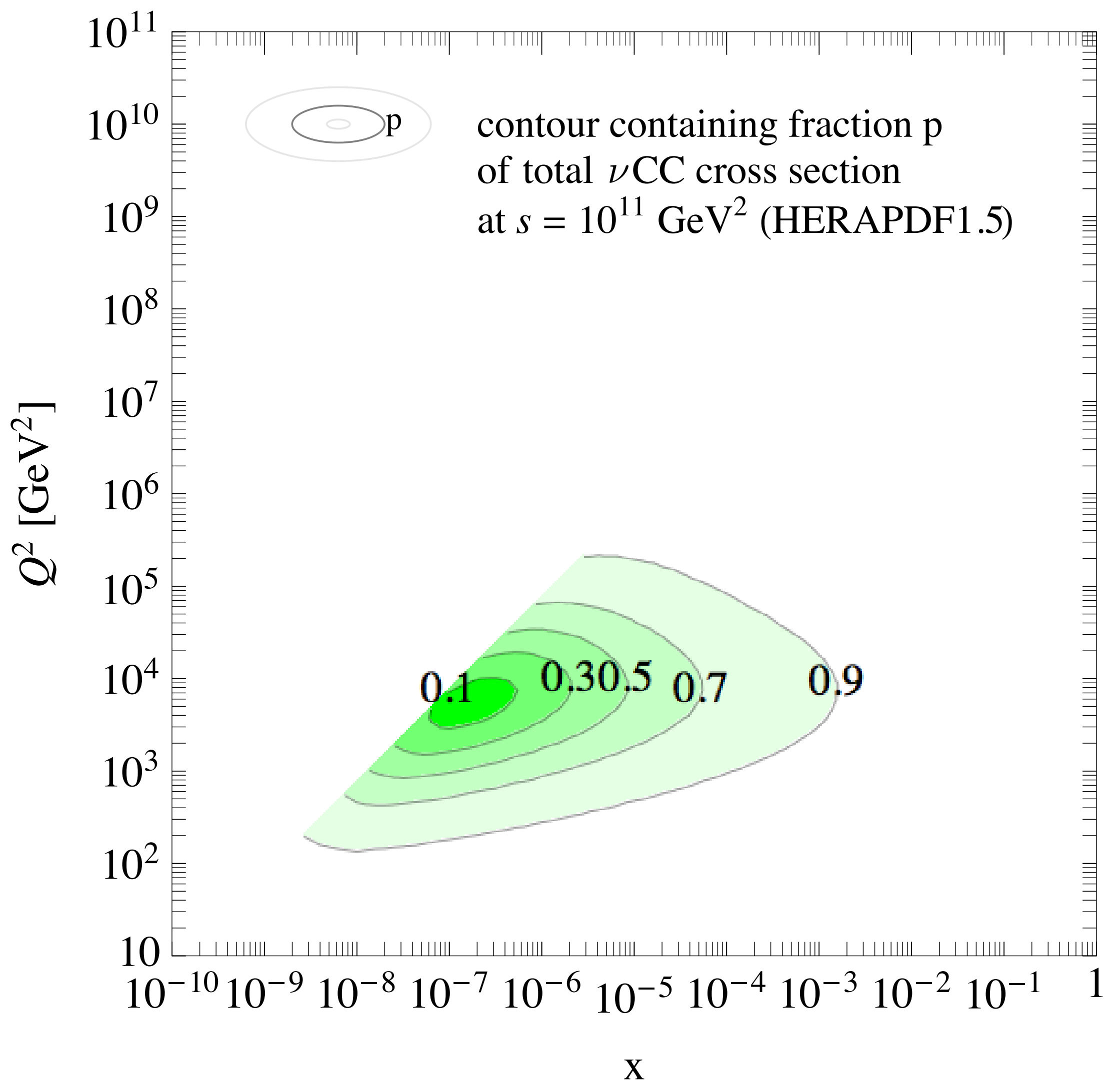


The H1 and ZEUS experiments at HERA have made great progress by probing a much deeper kinematic region



Steep rise of the gluon structure function at low Bjorken x ⇨ significant impact on UHE ν scattering

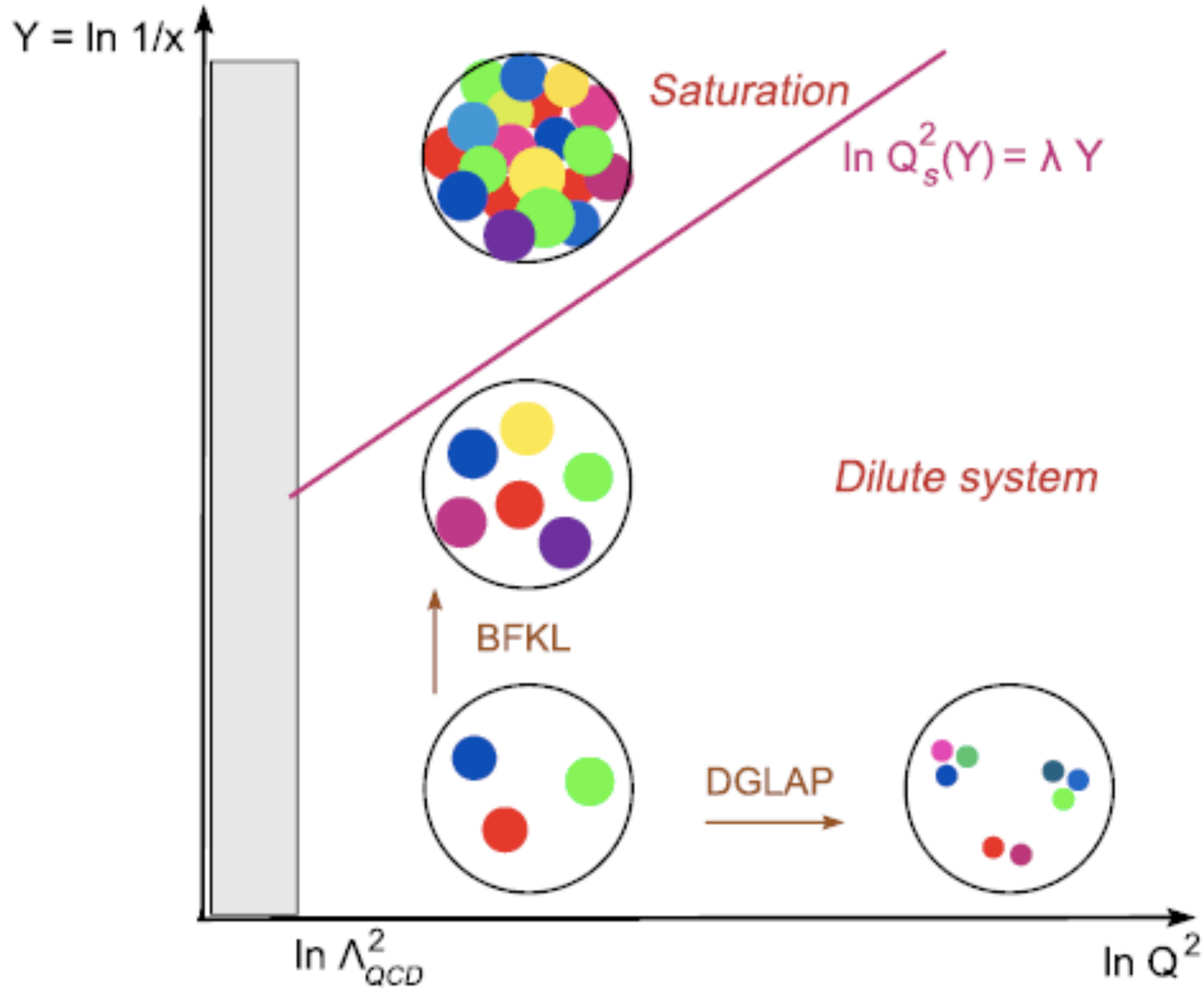
The neutrino DIS cross-section can now be computed with reasonable (few %) accuracy @ NLO



(Mertsch, Cooper-Sarkar & Sarkar, JHEP 1108:042,2011)

and there is good agreement between different PDF sets (after unphysical values are rejected)

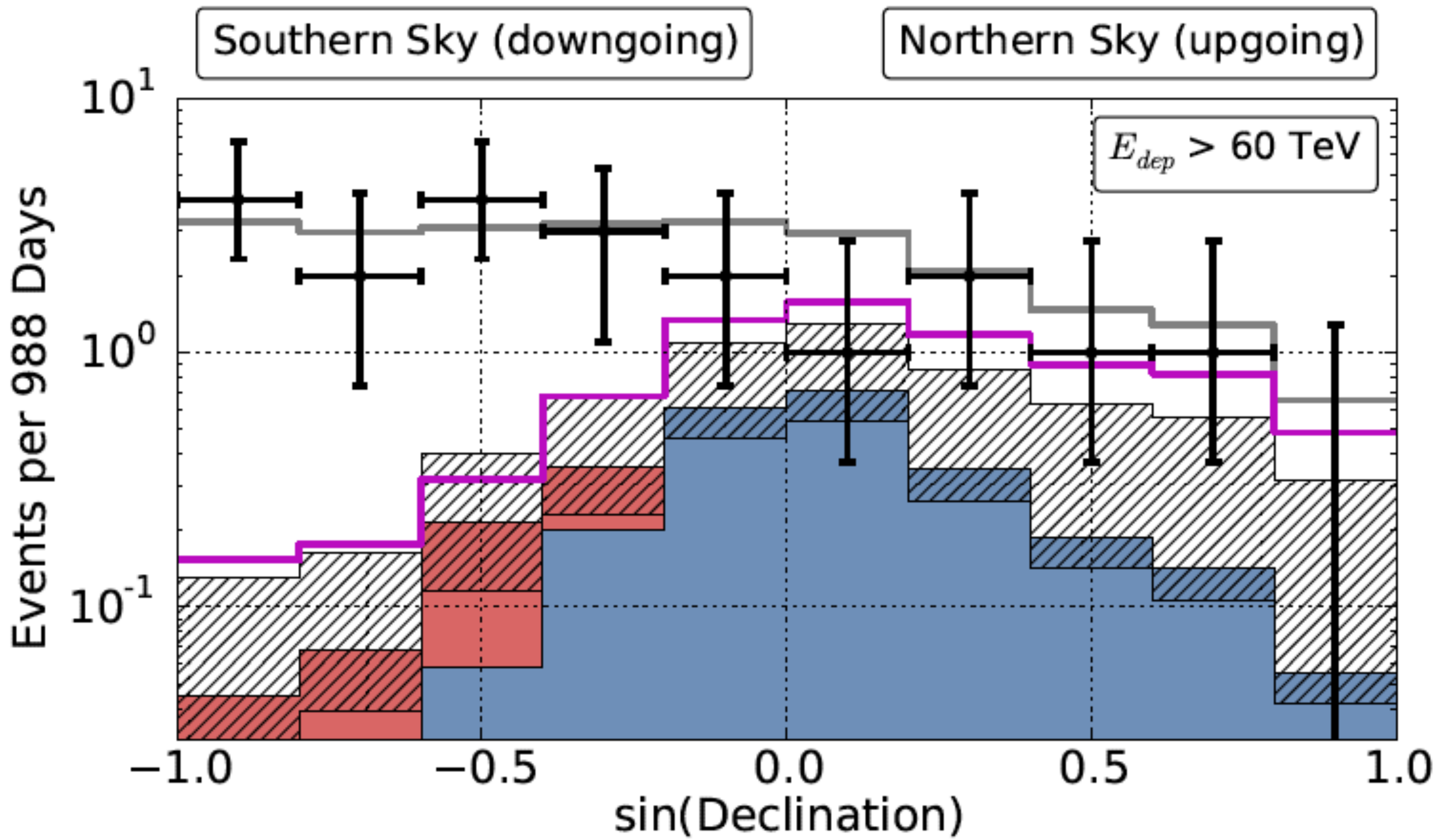
But if there is a new phase of QCD at very low x ('Colour Glass Condensate') then the ν-N #-secn would be suppressed below its (unscreened) SM value



If IceCube can measure deep inelastic scattering of >10^{10} GeV cosmogenic neutrinos, it would provide a probe of low-x QCD

High Energy Starting Event Analysis: Results

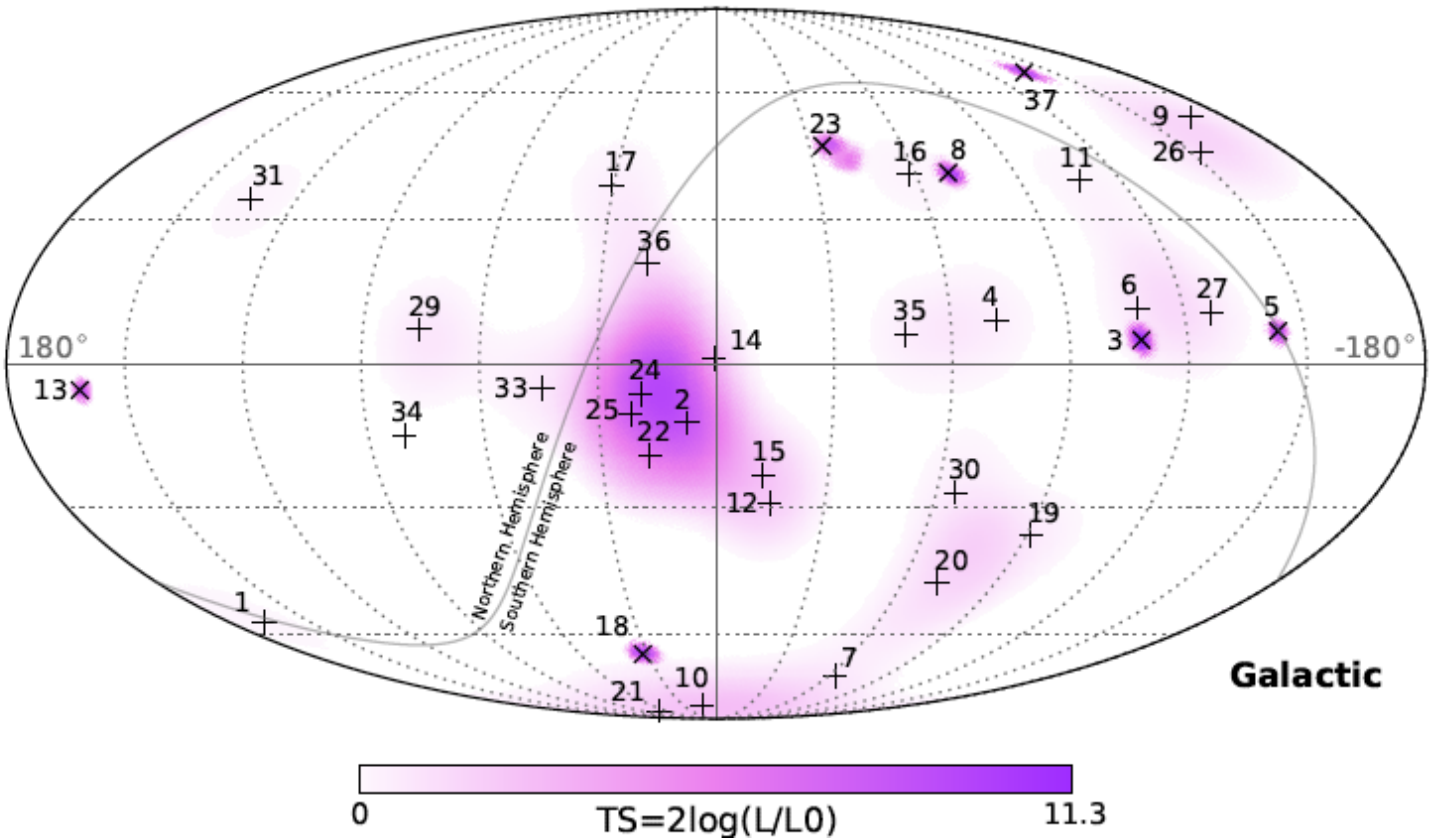
More astrophysical events expected *from above* (South) because of Earth absorption at high energies ….



The zenith angle distribution is consistent with an *isotropic* flux … *not* with production in the atmosphere (e.g. by charm)

High Energy Starting Event Analysis: Results

Point Source Search (likelihood analysis)



No significant clustering either on the sky or in time

Title	Author(s)	Journal reference	ArXiv	Category
IceCube PeV cascade events initiated by electron-antineutrinos at Glashow resonance	Barger, Learned, Pakvasa	PRD 87, 037302 (2013)	1207.4571	Glashow resonance
Neutrino decays over cosmological distances and the implications for neutrino telescopes	Baerwald, Bustamante, Winter	JCAP10(2012)020	1208.4600	Neutrino decay; track deficit
On the interpretation of IceCube cascade events in terms of the Glashow resonance	Bhattacharya, Gandhi, Rodejohann, Watanabe	---	1209.2422	Glashow resonance
PeV neutrinos from the propagation of ultra-high energy cosmic rays	Roulet, Sigl, van Vliet, Mollerach	JCAP01(2013)028	1209.4033	GZK
Explanation for the Low Flux of High-Energy Astrophysical Muon Neutrinos	Pakvasa, Joshipura, Mohanty	PRL 110, 171802 (2013)	1209.5630	Neutrino decay; track deficit
On the origin of IceCube's PeV neutrinos	Cholis, Hooper	JCAP06(2013)030	1211.1974	Extragalactic (GRB)
Diffuse PeV Neutrinos from Gamma-ray Bursts	Liu, Wang	ApJ 766, 73 (2013)	1212.1260	Extragalactic (GRB)
Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons	Kistler, Stanev, Yuksel	---	1301.1703	Extragalactic
PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei	Kalashev, Kusenko, Essey	PRL 111, 041103 (2013)	1303.0300	Extragalactic (AGN)
Diffuse PeV neutrino emission from ultraluminous infrared galaxies	He, Wang, Fan, Liu, Wei	PRD 87, 063011 (2013)	1303.1253	Extragalactic (Infrared galaxies)
Stringent constraint on neutrino Lorentz invariance violation from the two IceCube PeV neutrinos	Borriello, Chakraborty, Mirizzi, Serpico	PRD 87, 116009 (2013)	1303.5843	Lorentz invariance
Neutrinos at IceCube from heavy decaying dark matter	Feldstein, Kusenko, Matsumoto, Yanagida	PRD 88, 015004 (2013)	1303.7320	Exotic (dark matter decay)
Galactic PeV Neutrinos	Gupta	APh 48, 75 (2013)	1305.4123	Galactic
Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy	Fox, Kashiyama, Meszaros	ApJ 774, 74 (2013)	1305.6606	Galactic
Superheavy Particle Origin of IceCube PeV Neutrino Events	Barger, Keung	---	1305.6907	Exotic (Leptoquark)
PeV neutrinos observed by IceCube from cores of active galactic nuclei	Stecker	PRD 88, 047301 (2013)	1305.7404	Extragalactic (AGN)
The fraction of muon tracks in cosmic neutrinos	Vissani, Pagliaroli, Villante	JCAP09(2013)017	1306.0211	Future strategy
TeV–PeV Neutrinos from Low-Power Gamma-Ray Burst Jets inside Stars	Murase, Ioka	PRL 111, 121102 (2013)	1306.2274	Extragalactic (GRB)
Demystifying the PeV cascades in IceCube: Less (energy) is more (events)	Laha, Beacom, Dasgupta, Horiuchi, Murase	PRD 88, 043009 (2013)	1306.2309	Future strategy
Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube	Murase, Ahlers, Lacki	---	1306.3417	Extragalactic
Pinning down the cosmic ray source mechanism with new IceCube data	Anchordoqui, Goldberg, Lynch, Olinto, Paul, Weiler	---	1306.5021	Galactic
Constraining Superluminal Electron and Neutrino Velocities using the 2010 Crab Nebula Flare and the IceCube PeV Neutrino Events	Stecker	---	1306.6095	Lorentz invariance
TeV-PeV neutrinos over the atmospheric background: originating from two groups of sources?	He, Yang, Fan, Wei	---	1307.1450	Two source populations
The Galactic Pevatron	Neronov, Semikoz, Tchernin	---	1307.2158	Galactic
Photohadronic Origin of the TeV-PeV Neutrinos Observed in IceCube	Winter	PRD 88, 083007 (2013)	1307.2793	Extragalactic
Pseudo-Dirac neutrinos via mirror-world and depletion of UHE neutrinos	Joshipura, Mohanty, Pakvasa	---	1307.5712	
Long-lived PeV-EeV Neutrinos from GRB Blastwave	Razzaque	---	1307.7596	Extragalactic (GRB)
Are IceCube neutrinos unveiling PeV-scale decaying dark matter?	Esmaili, Sercipo	---	1308.1105	Exotic (dark matter decay)
Establishing the astrophysical origin of a signal in a neutrino telescope	Lipari	---	1308.2086	
Testing Relativity with High-Energy Astrophysical Neutrinos	Diaz, Kostelecky, Mewes	---	1308.6344	Lorentz invariance
A Simple Explanation of the Ultra-high Energy Neutrino Events at IceCube	Chen, Bhupal Dev, Soni	---	1309.1764	
Galactic Center origin of a subset of IceCube neutrino events	Razzaque	PRD 88, 081302(R) (2013)	1309.2756	Galactic
Probing the Galactic Origin of the IceCube Excess with Gamma-Rays	Ahlers, Murase	---	1309.4077	Galactic
Diffuse PeV neutrinos from hypernova remnants in star-forming galaxies	Liu, Wang, Inoue, Crocker, Aharonian	---	1310.1263	Extragalactic (star-forming galaxies)
Revolution at ICECUBE horizons	Fargion, Paggi	---	1310.3543	Track deficit
Diffuse Neutrino Flux from Cosmic Ray Interactions in the Milky Way	Joshi, Winter, Gupta	---	1310.5123	CR interactions
GeV - PeV Neutrino Production and Oscillation in hidden jets from GRBs	Fraija	---	1310.7061	Extragalactic (GRB)
Detection of ultra high energy neutrinos by IceCube: Sterile neutrino scenario	Rajpoot, Sahu, Wang	---	1310.7075	Exotic (sterile neutrinos)
Reevaluation of the Prospect of Observing Neutrinos from Galactic Sources in the Light of Recent Results in Gamma Ray and Neutrino Astronomy	Gonzalez-Garcia, Halzen, Niro	---	1310.7194	Galactic
Self-consistent neutrino and UHE cosmic ray spectra from Mrk 421	Dimitrakoudis, Petropoulou, Mastichiadis	---	1310.7923	Extragalactic (Blazar, Mrk421)

What are these events?

Very long baseline ν oscillations

Low energy neutrino experiments have a sensitivity of at most:
$\Gamma/m \sim 10^{-4}$ sec/eV … for Solar neutrinos

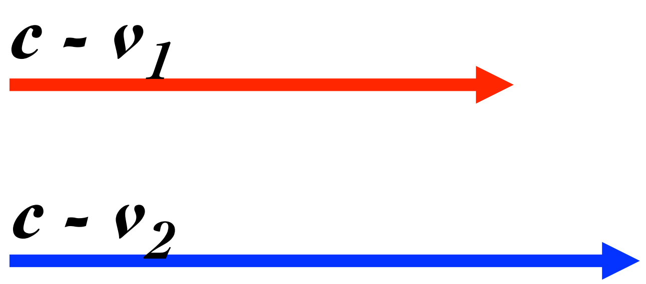
High energy cosmic neutrinos can improve on this by a factor of:
$\sim 10^6$ (L/100 Mpc) (100 TeV/E)
⇒ powerful probe of decoherence/LI violation

Astrophysical accelerators generate neutrinos through pion decay
so neutrinos produced in the ratio: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$
After flavour *equilibration* through oscillations, this becomes:
$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

… but interaction with e.g. 'space-time foam' can change this!

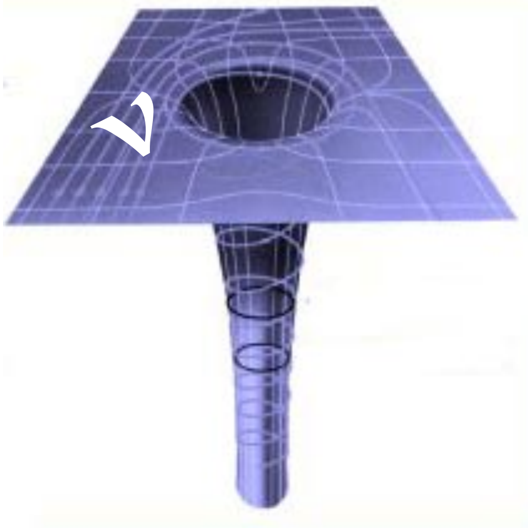
New physics effects in neutrino oscillations

- Violation of Lorentz invariance (VLI) in string theory or loop quantum gravity*



- Violations of the equivalence principle (different gravitational coupling)†

- Interaction of particles with space-time foam ν quantum decoherence of flavor states‡



* e.g. Carroll *et al.*, PRL 87 (2001) 14, Colladay and Kostelecký, PRD 58 (1998) 116002

† e.g. Gasperini, PRD 39 (1989) 3606

‡ e.g. Anchordoqui *et al.*, PRD 72 (2005) 065019

Quantum decoherence induced by 'space-time foam'

Study propagation using density ("dollar") matrix formalism:

$$\dot{\rho} = -i[H, \rho] + \not{\delta} H \rho.$$

dissipative term
(modelled a la ' Lindblad)

Then solve equations for neutrinos to get oscillation probability:

$$P[\nu_\mu \to \nu_\tau] = \frac{1}{2}\Big\{1 - \cos^2(2\theta) M_{33}(E,L) - \sin^2(2\theta) M_{11}(E,L) - \frac{1}{2}\sin 4\theta\,[M_{13}(E,L) + M_{31}(E,L)]\Big\},$$

$$M(E,L) = \exp[-2\mathcal{H}(E)L] \quad \mathcal{H}(E) = \begin{pmatrix} a & b - \frac{\Delta m^2}{4E} & d \\ b + \frac{\Delta m^2}{4E} & \alpha & \beta \\ d & \beta & \delta \end{pmatrix}.$$

e.g. Morgan *et al* [astro-ph/0412628]

… extend to 3-flavour neutrino oscillations

characteristic exponential behavior

$$P[\nu_\mu \to \nu_\mu] = \frac{1}{3} + \frac{1}{2}\Bigg(e^{-\gamma_3 L}\cos^4\theta_{23} + \frac{1}{12}e^{-\gamma_8 L}(1 - 3\cos 2\theta_{23})^2$$

$$+ 4e^{-\frac{\gamma_6+\gamma_7}{2}L}\cos^2\theta_{23}\sin^2\theta_{23}\Bigg(\cos\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}\right]$$

$$+ \sin\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}\right]\frac{(\gamma_6-\gamma_7)}{\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}}\Bigg)\Bigg)$$

1:1:1 ratio after decoherence

Barenboim *et al.* [hep-ph/0603028]

Energy dependence depends on phenomenology: $\gamma_i = \gamma_i^* \; E^n, \quad n \in \{-1, 0, 2, 3\}$

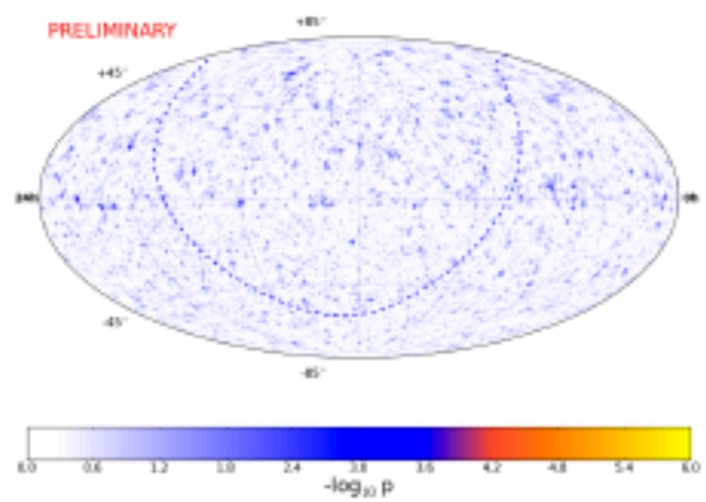
n = 0
simplest

n = 2
recoiling D-branes
Ellis *et al.* [hep-th/9704169]

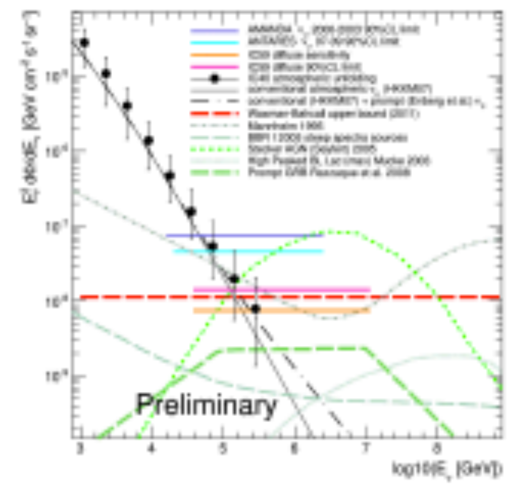
n = 3
Planck-suppressed operators
Anchordoqui *et al.* [hep-ph/0506168]

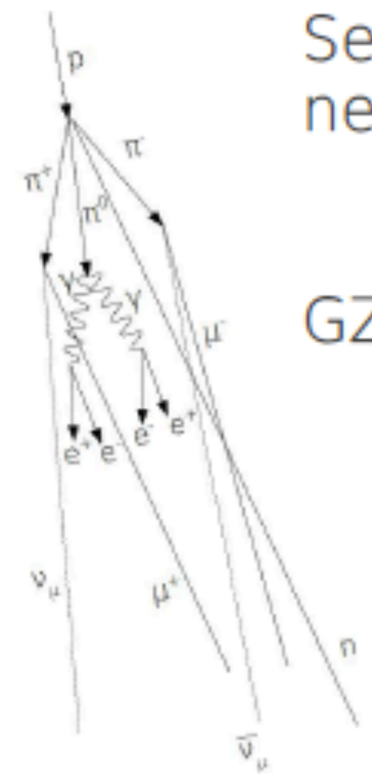
IceCube is sensitive to a dim-6 ($\sim E^3/M_P{}^2$) violation of Lorentz invariance/decoherence!

The IceCube physics program

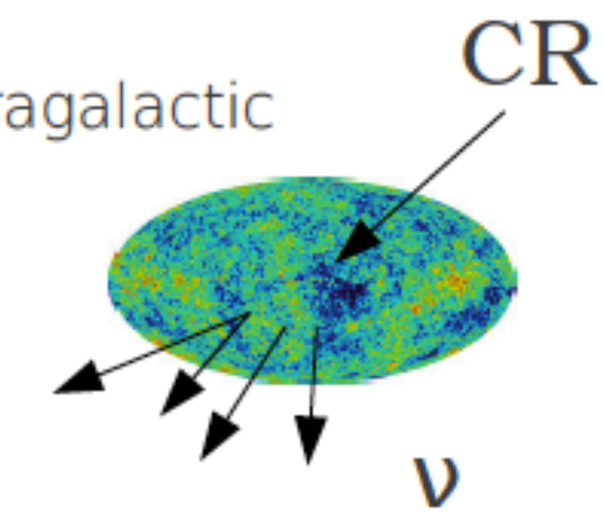


Diffuse/
atmospheric



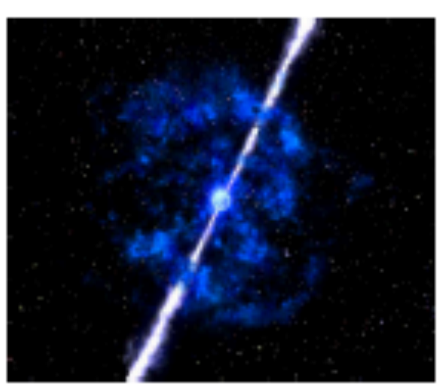


Search for an extragalactic
neutrino signal



GZK neutrinos

Point source

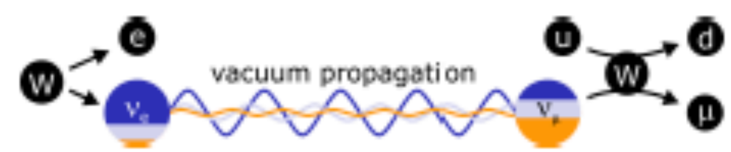


Search for point-like sources
→ galactic (e.g. SNR)
→ extragalactic (e.g. AGN)

Transient sources
→ GRB, flaring objects

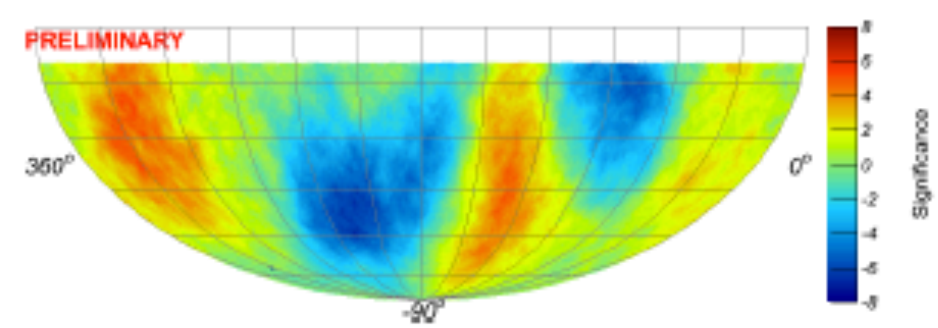
Optical follow-up programs

Prompt atms. neutrinos



Neutrino oscillations

Cosmic ray physics



Dark Matter

Exotic particles

First analyses of data from completed IceCube detector consistent with **detection of extraterrestrial neutrino flux (at > 5σ confidence)**

The real voyage of discovery consists not in seeking new lands … but in seeing the world with new eyes. **Marcel Proust**