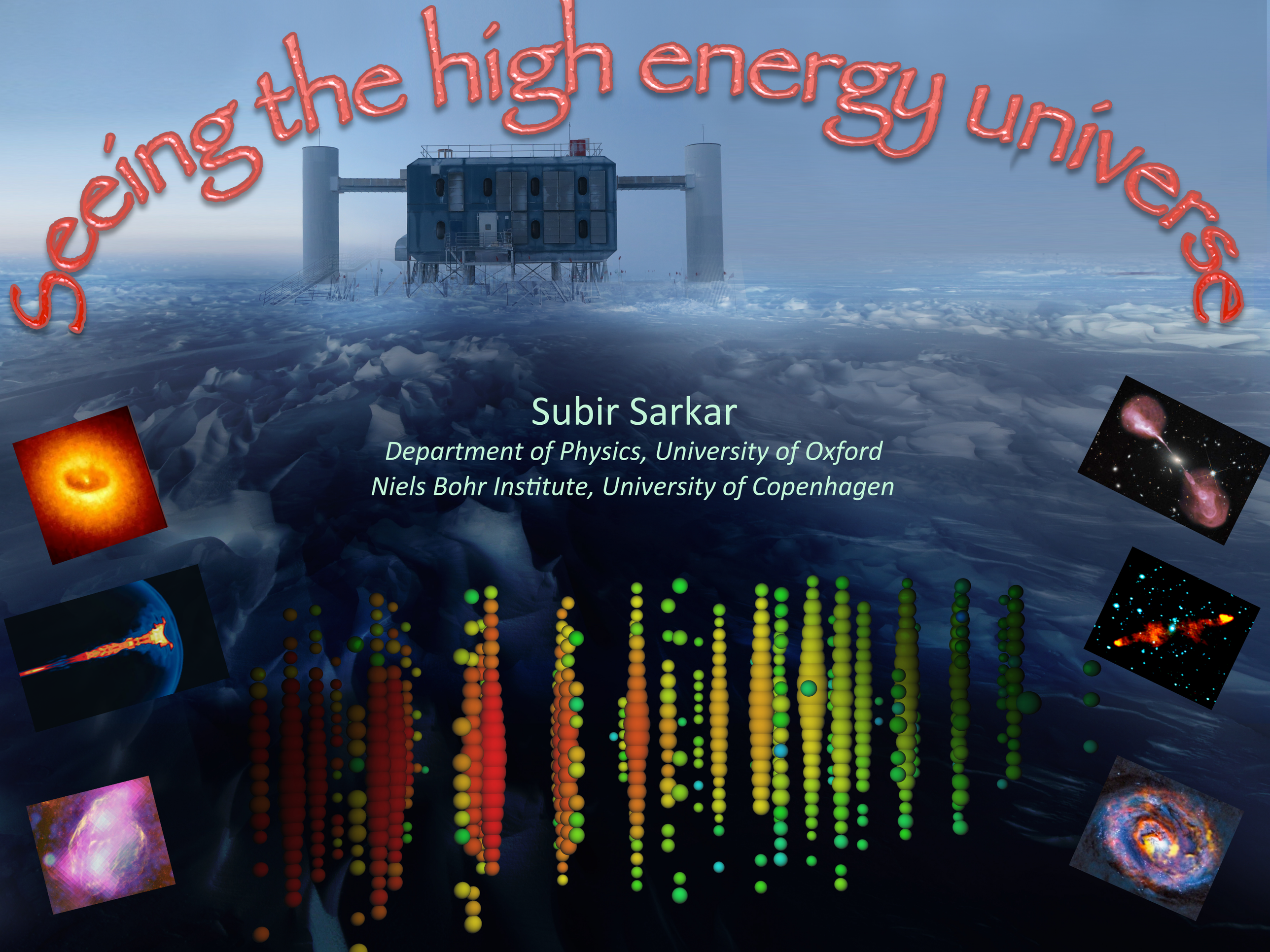
seeing the high energy universe

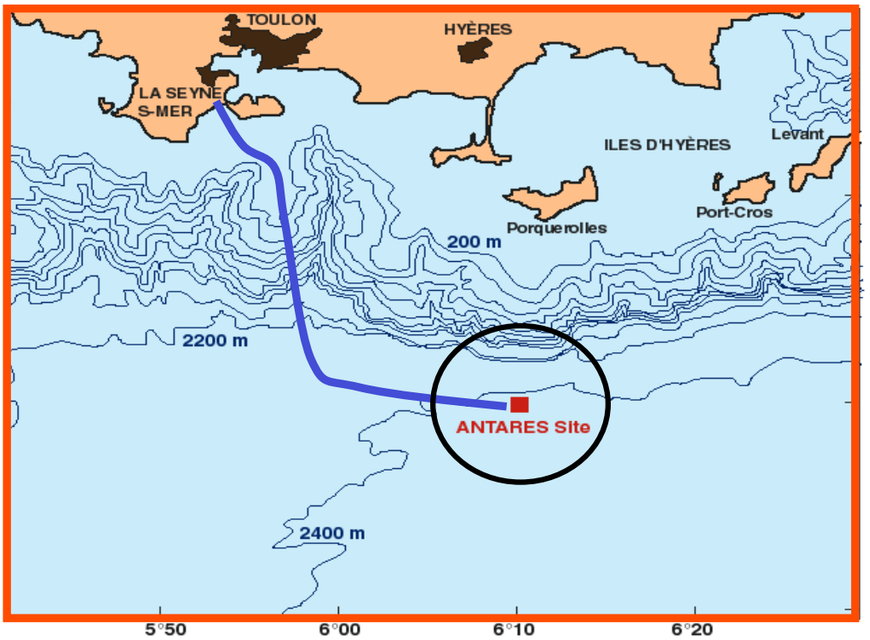


Subir Sarkar

Department of Physics, University of Oxford

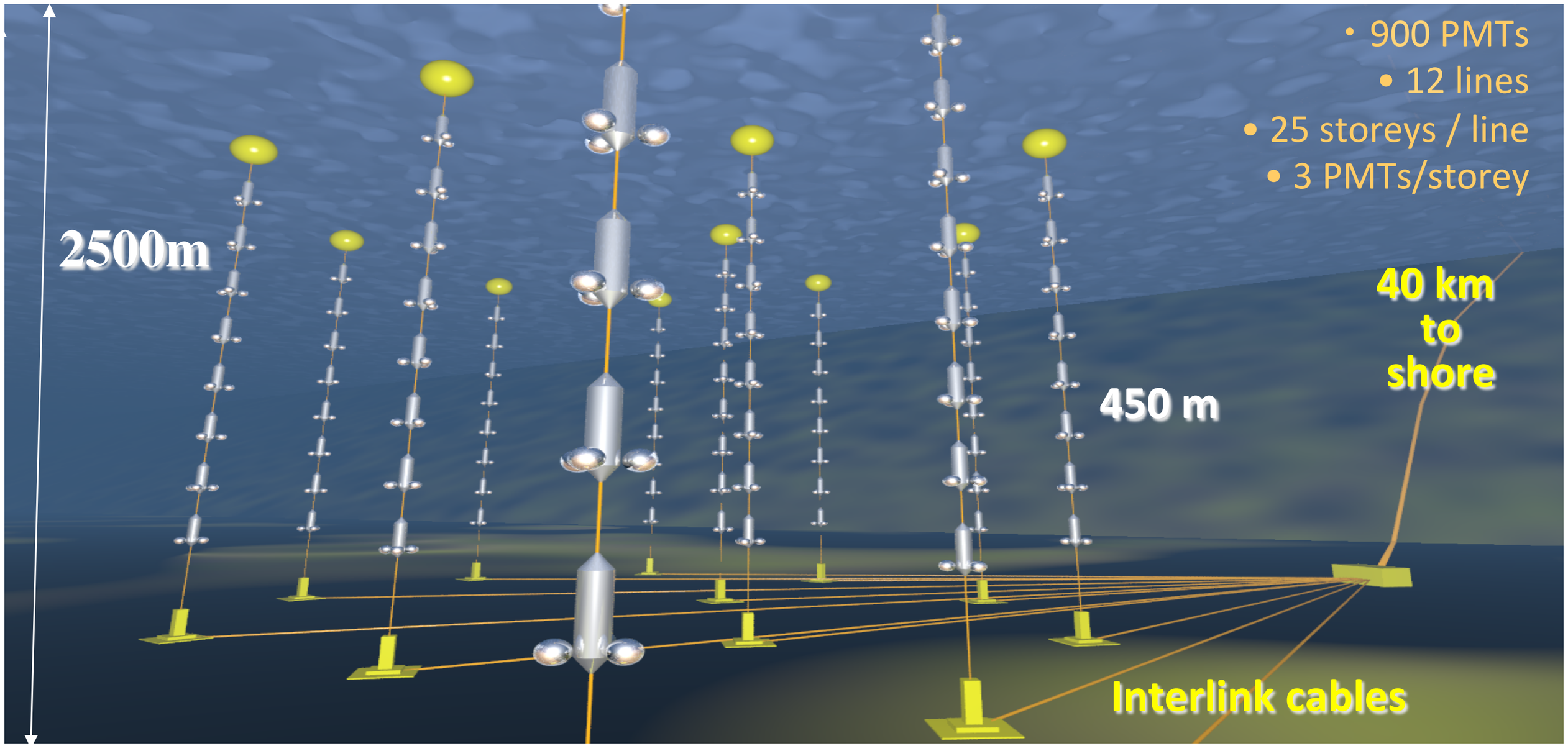
Niels Bohr Institute, University of Copenhagen

‘Summer’ at the South Pole

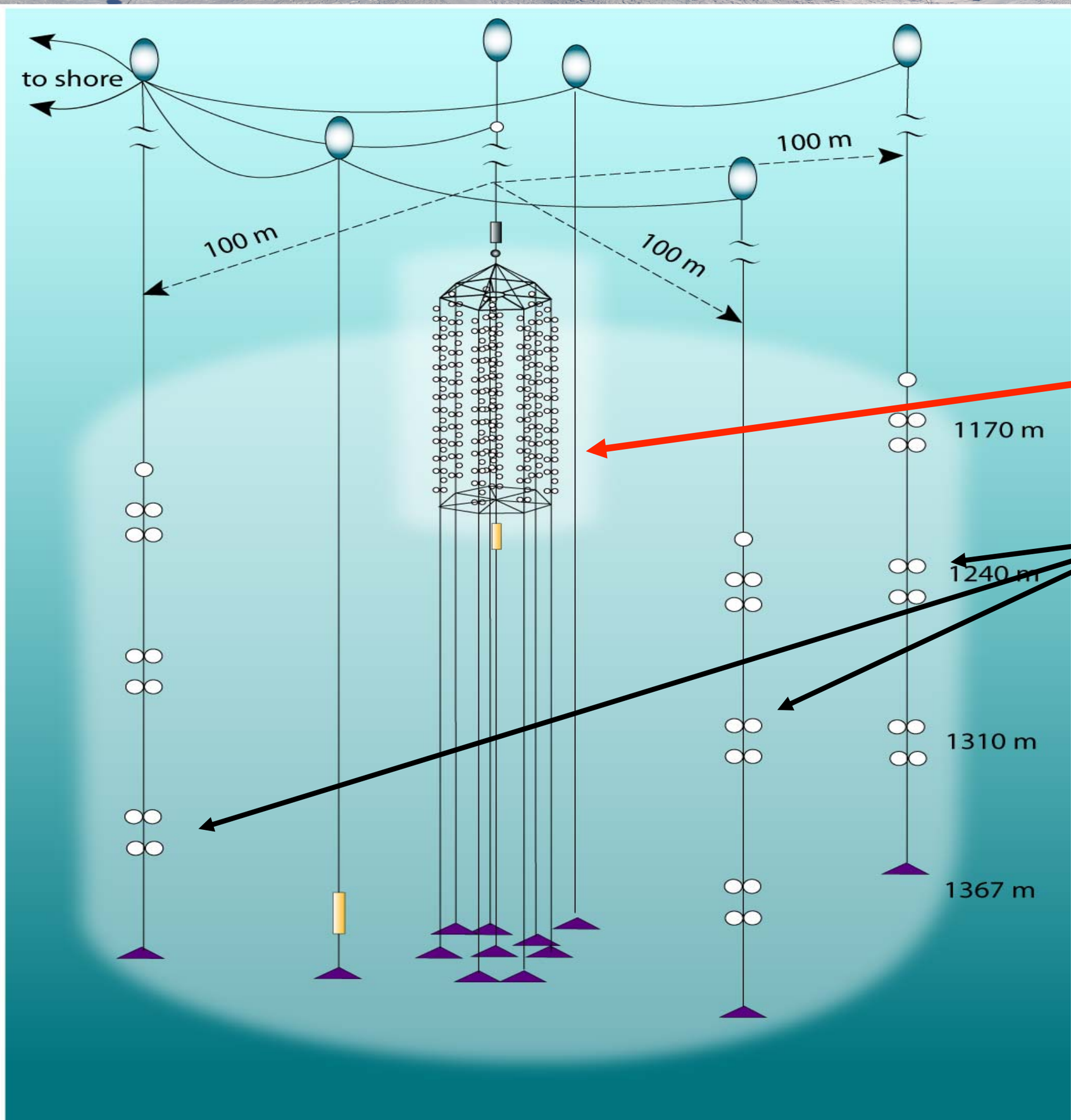


ANTARES

23 Institutes, 7 countries



BAIKAL



NT200+
=>
NT200
+3 long strings

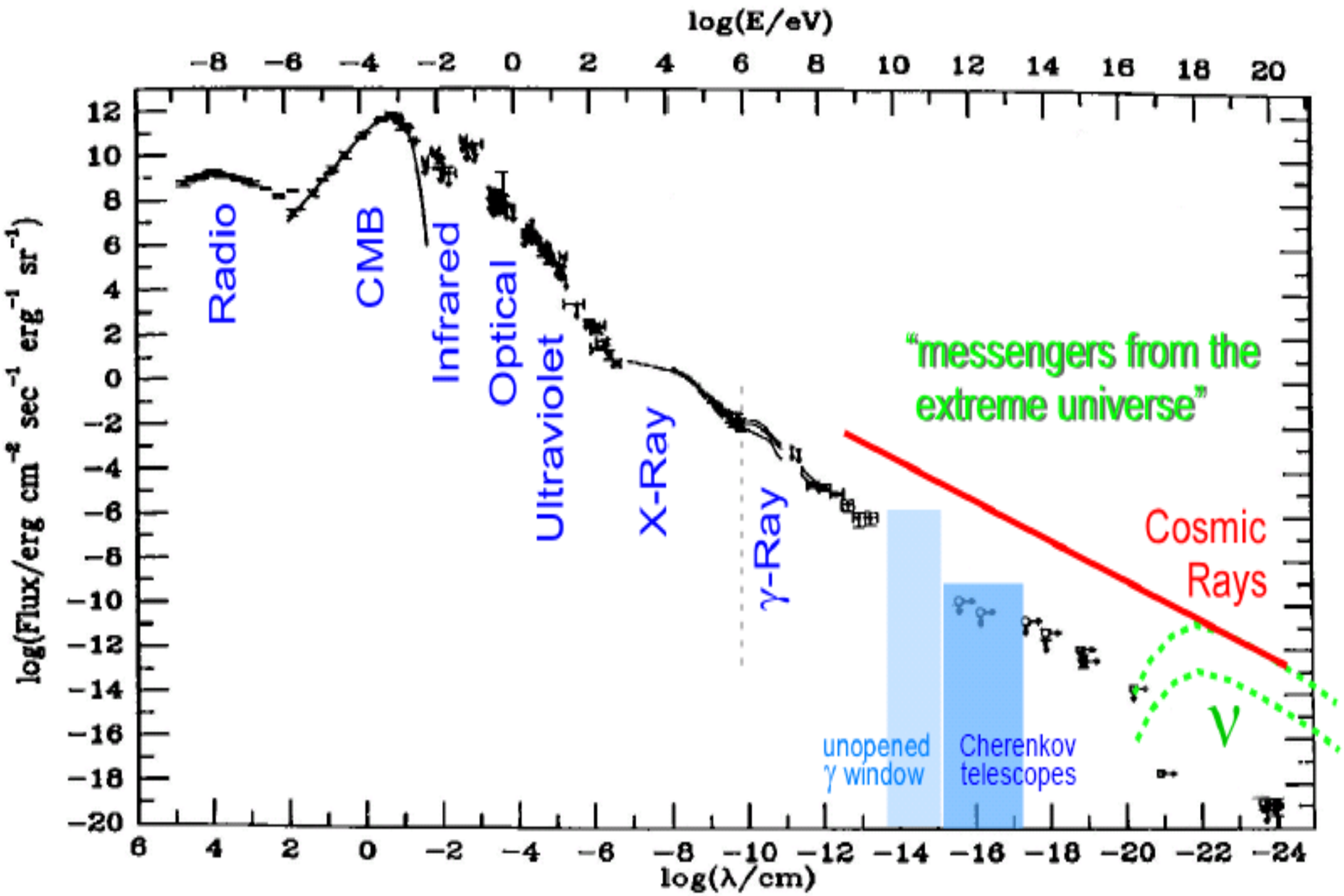
Height = 210 m
∅ = 200 m
Volume ~ 5 Mton

Km³ GVD planned

1st cluster deployed Apr 2015
8-12 such arrays to be deployed

We can *see* the high energy universe directly with **photons** up to a few TeV

Beyond this energy they are attenuated through $\gamma\gamma \rightarrow e^{+}e^{-}$ on the infrared bkgd



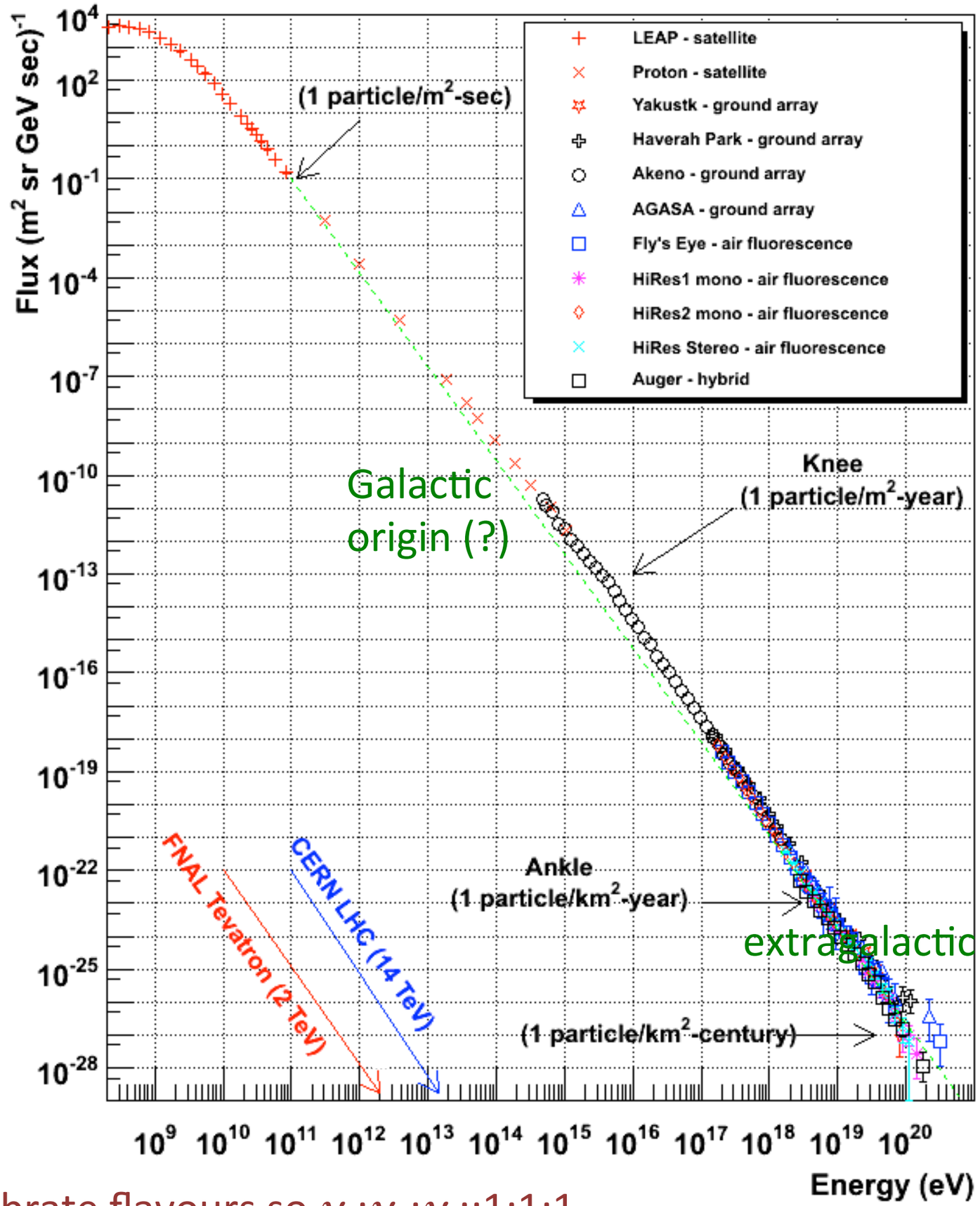
But using **cosmic rays** we should be able to 'see' up to ~ 6 x 10^{10} GeV (before they get attenuated through $p\gamma \rightarrow \Delta^{+} \rightarrow n\,\pi^{+}$ … on the CMB)

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

The Origin of Cosmic Rays

Extraordinary cosmic particle accelerators ***somewhere***, but still **not identified** over a century after the discovery of cosmic rays …

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



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

$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

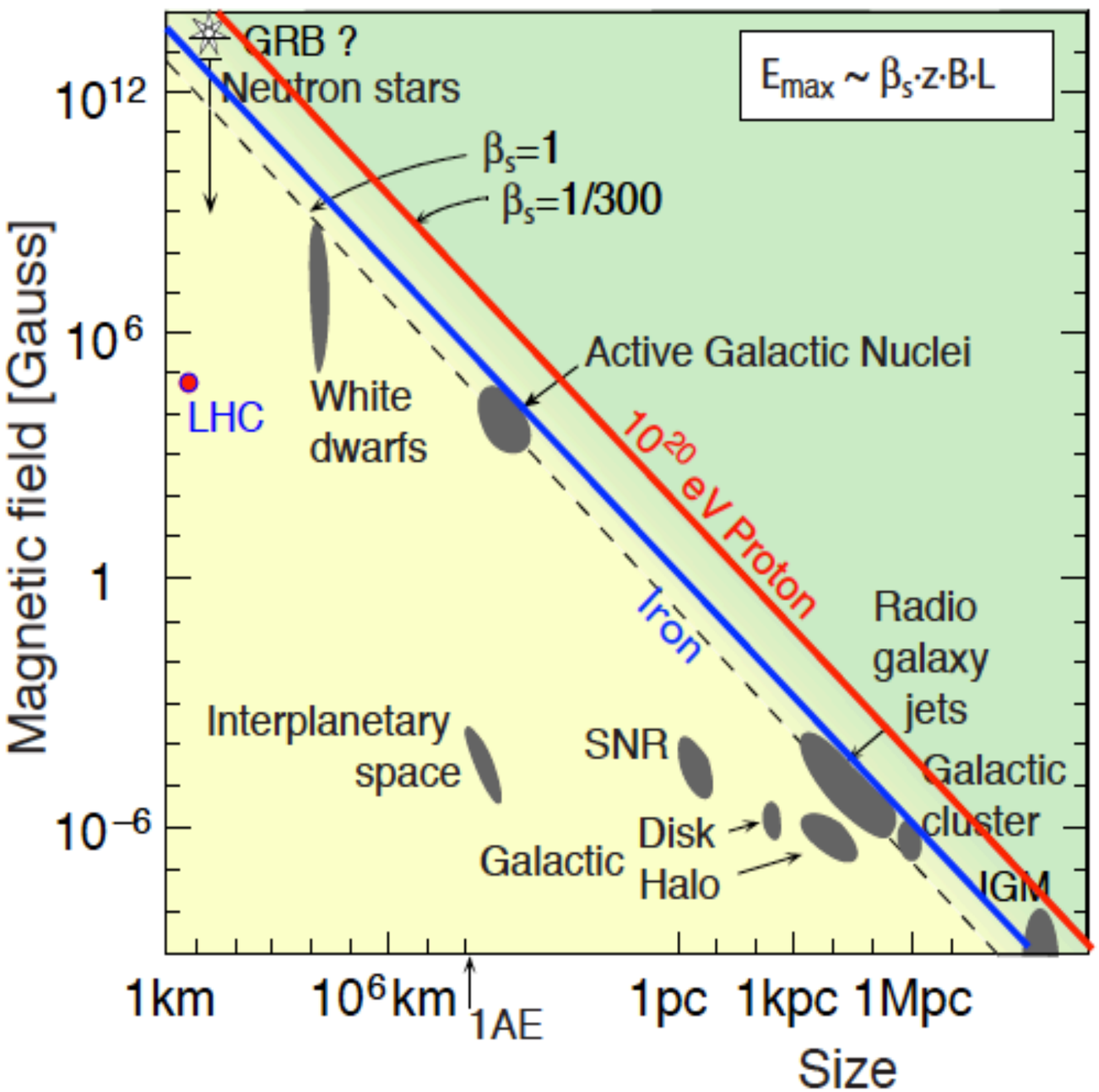
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

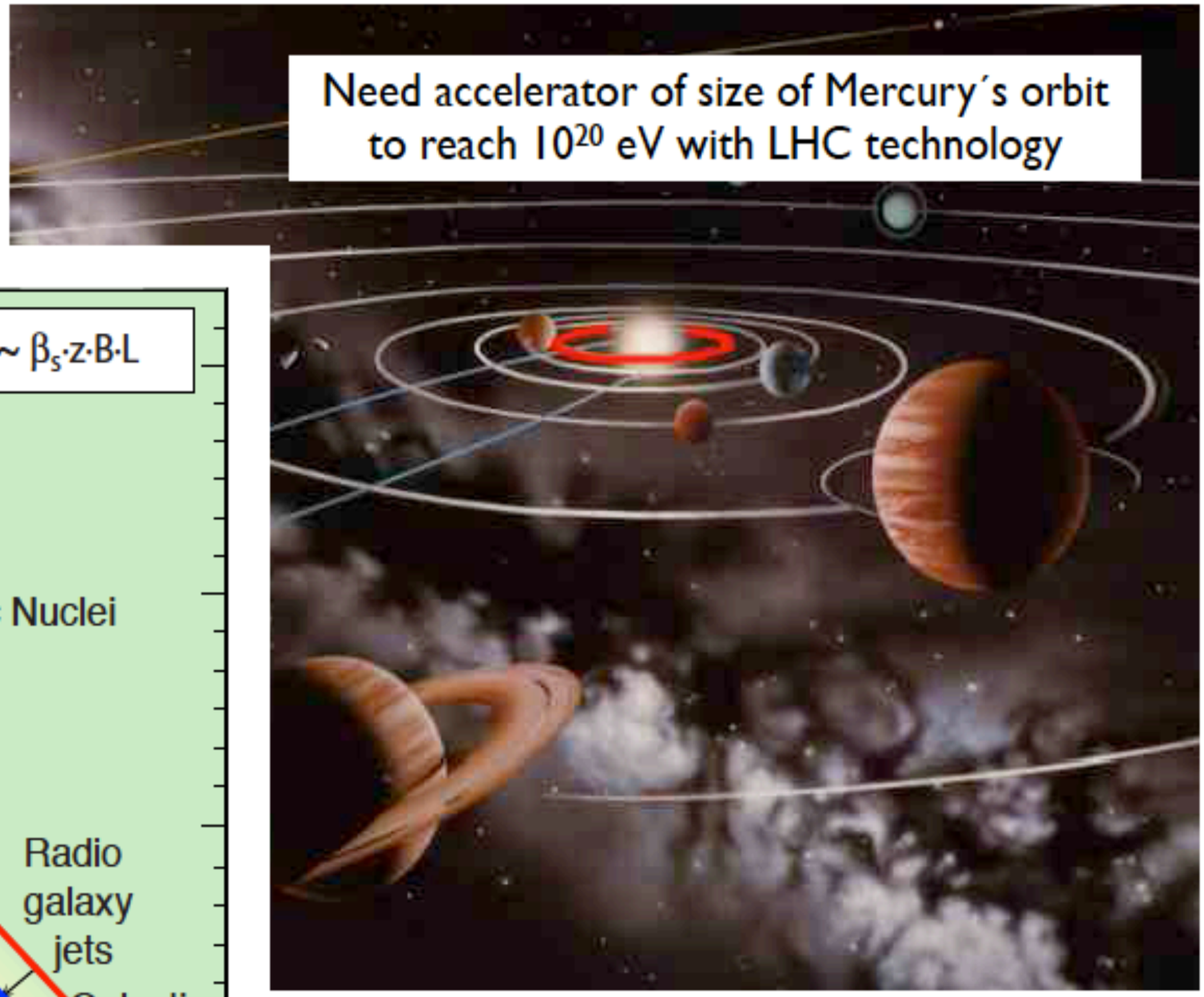
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Neutrino scillations en-route to Earth equlibrate flavours so ν_e:ν_μ:ν_τ::1:1:1

How does Nature manage to accelerate particles to ~ZeV energies?

Hillas plot (1984)





Realistic constraints more severe

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

The sources of cosmic rays *must* also be sources of neutrinos

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 :

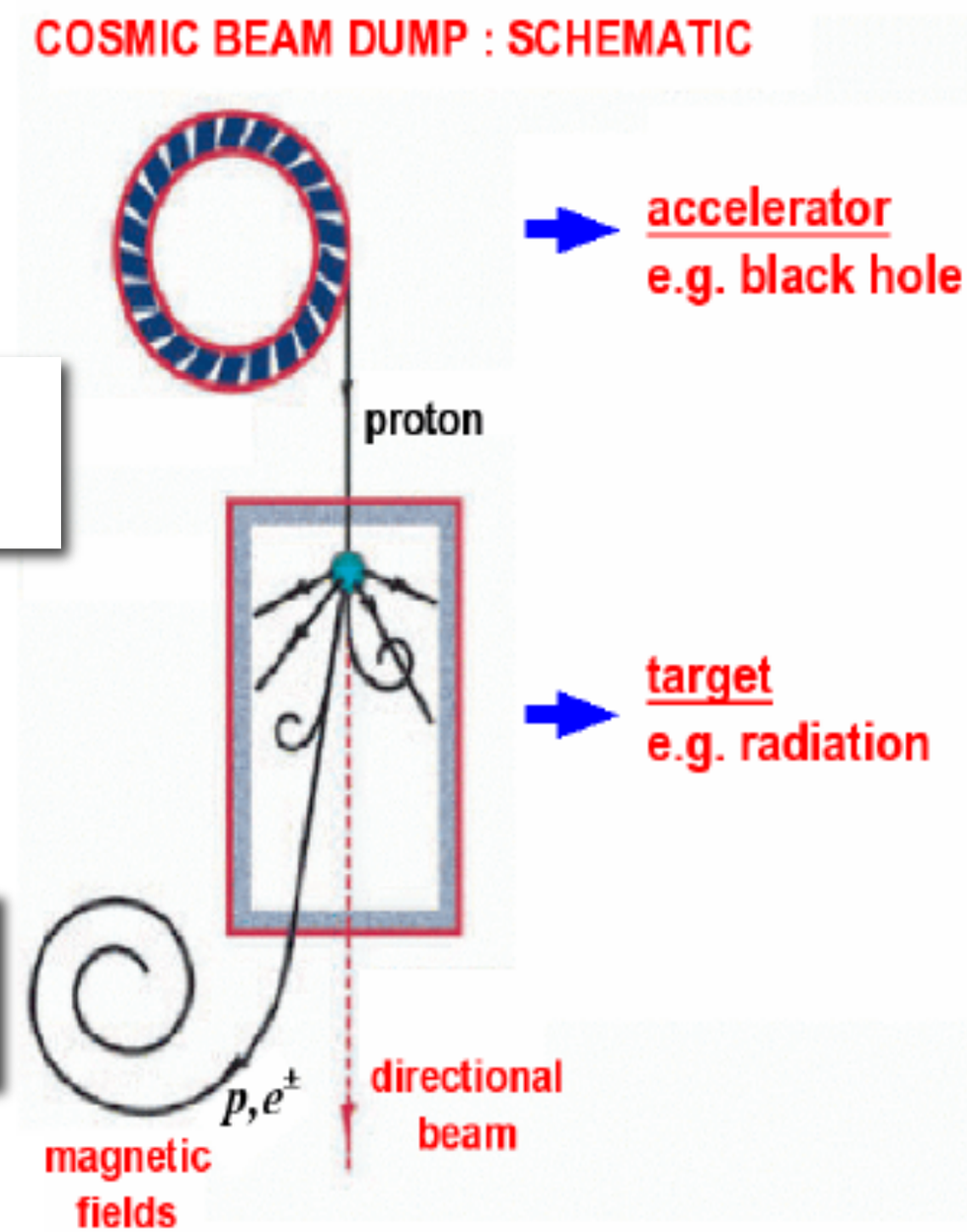
$$[E_\nu^2 \Phi_\nu]_{\rm WB} \approx (3/8)\, \xi_Z\, \epsilon_\pi\, t_{\rm H}\, \frac{c}{4\pi}\, E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$$

Fraction of CR primary energy converted to neutrinos

Hubble time

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

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



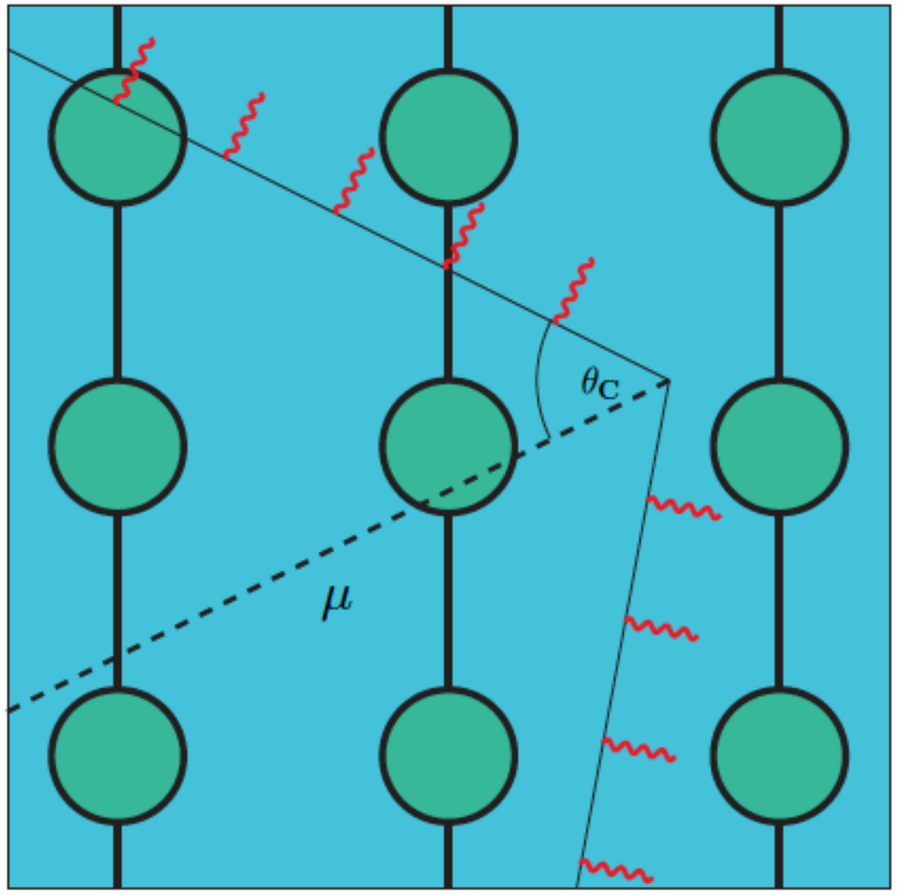
➡Making a reasonable estimate for ε_π etc allows this to be converted into a flux prediction

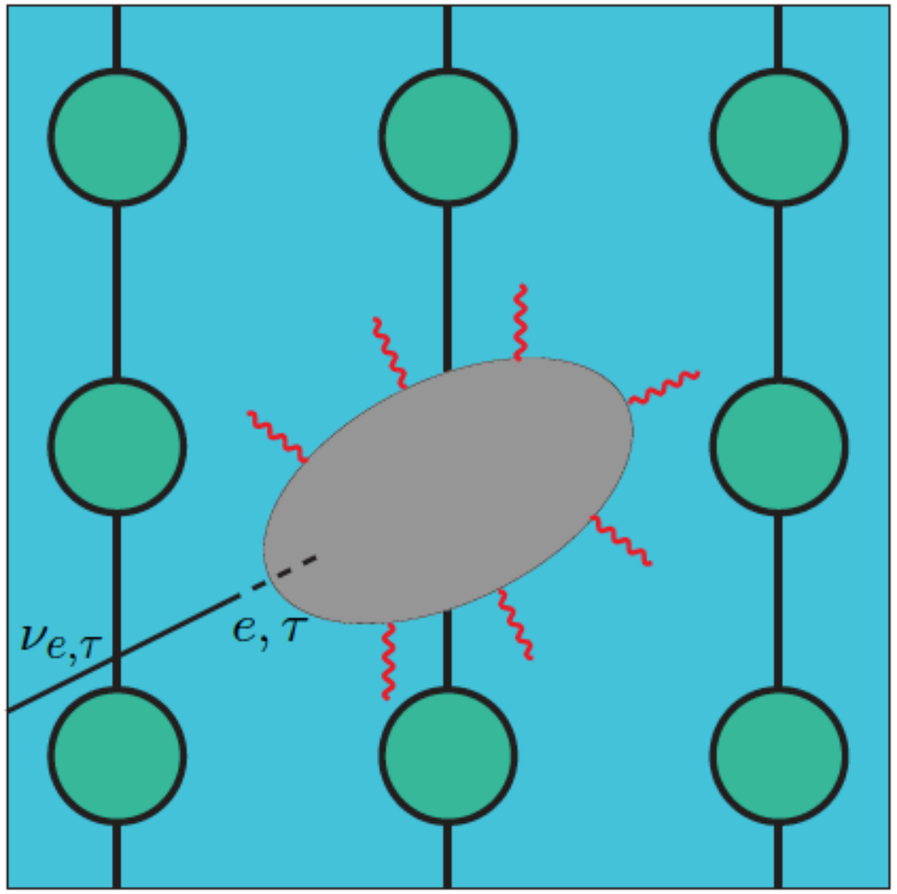
back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

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

→ **rate of events** :

$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$





IceCube Neutrino Observatory

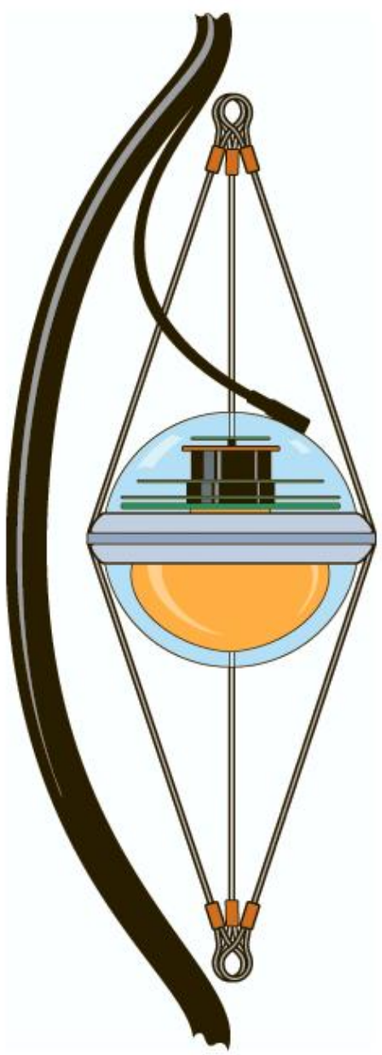
86 strings

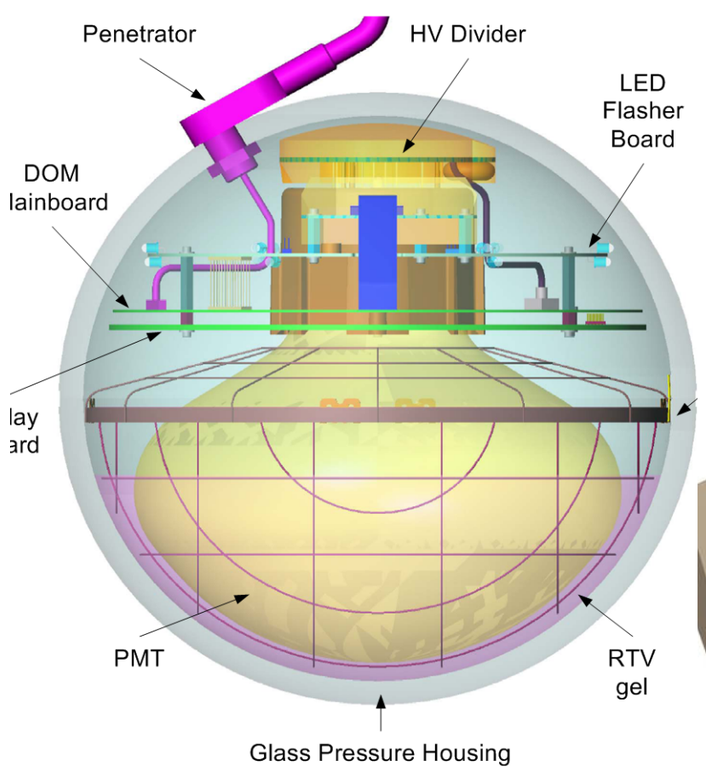
60 Optical Modules per string

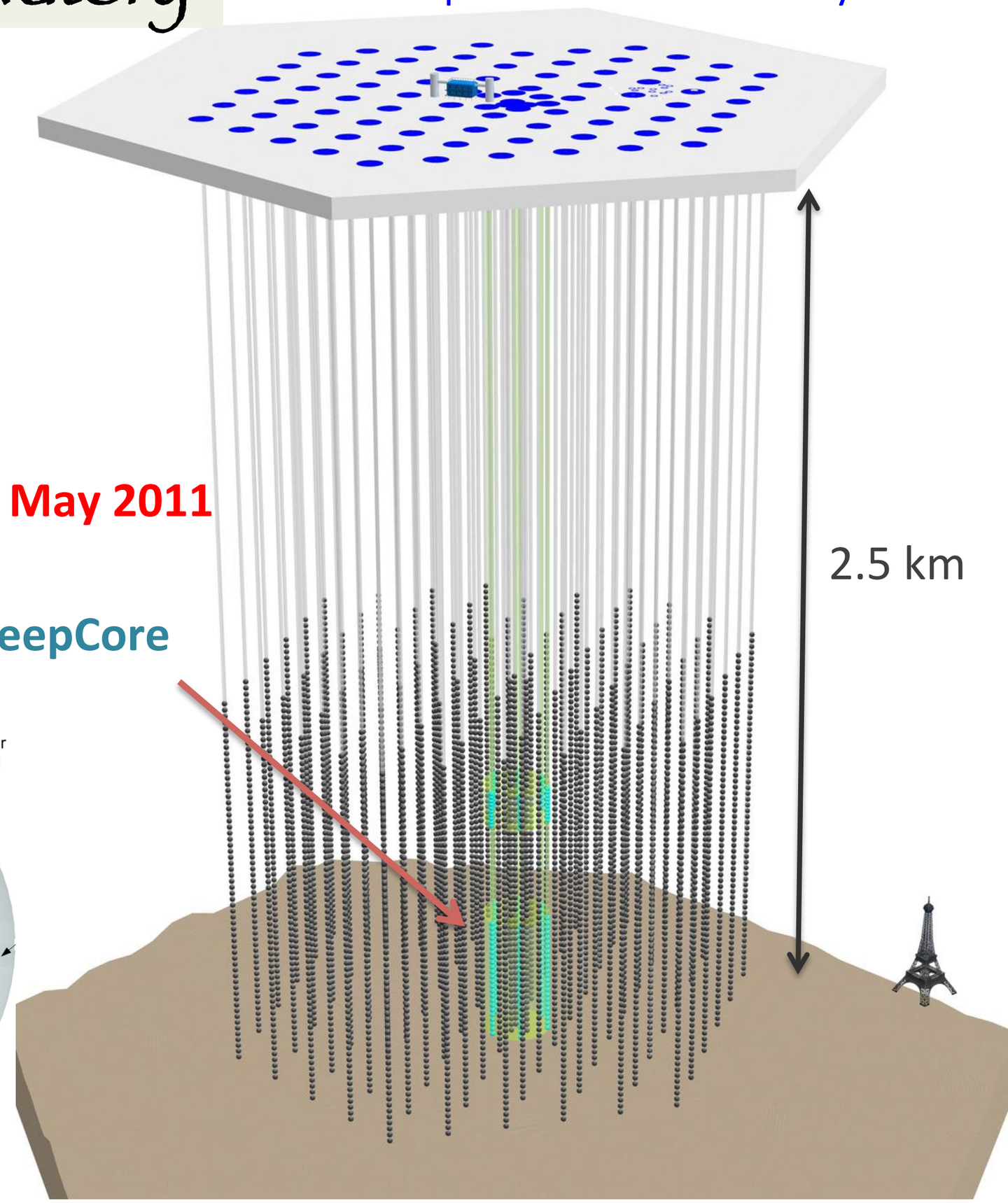
5160 Optical Modules in Ice

1 km^3 = Gton instrumented volume

Completed & began full operations: May 2011

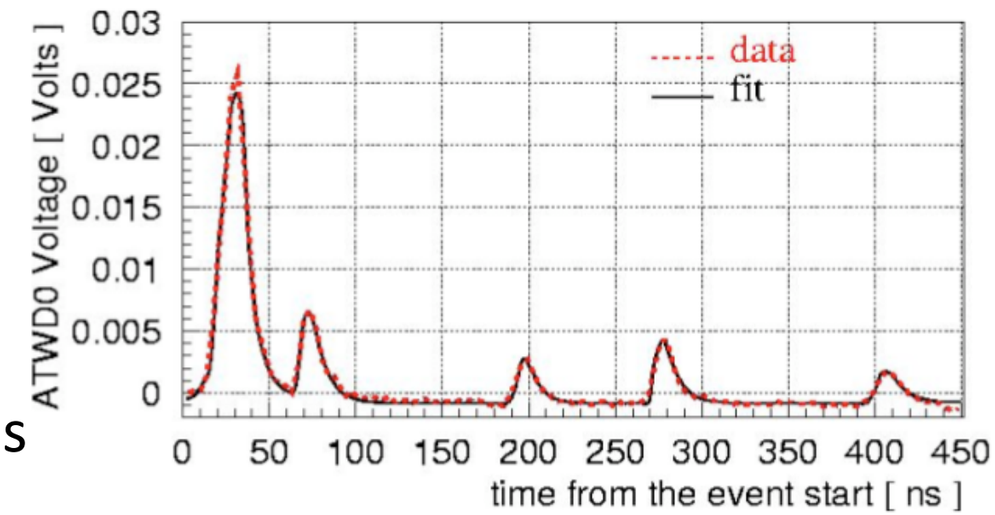


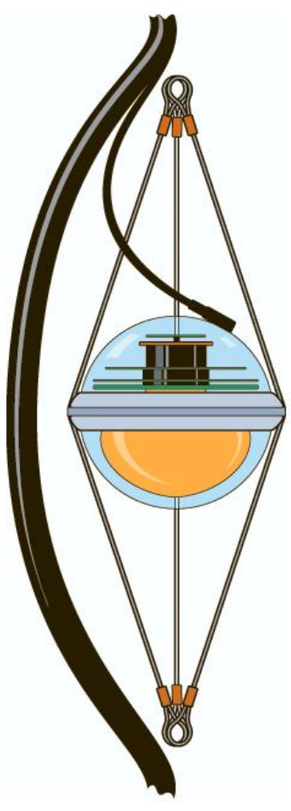


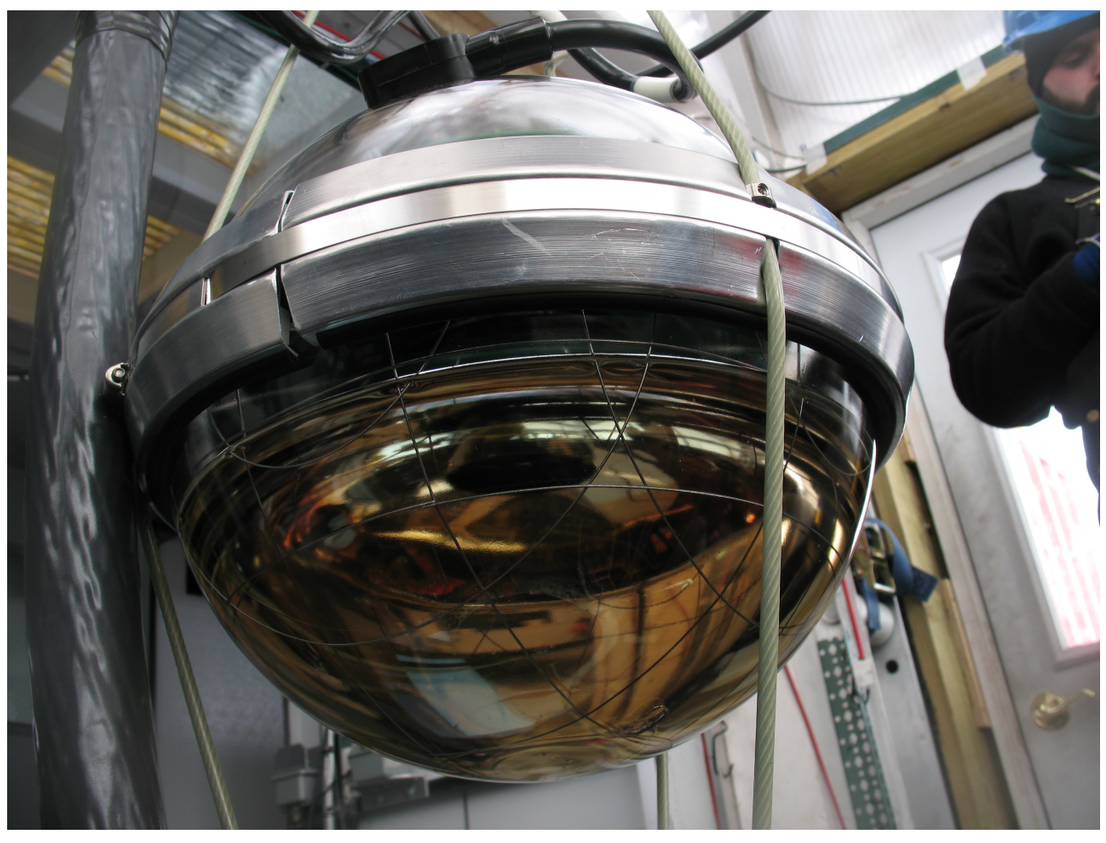


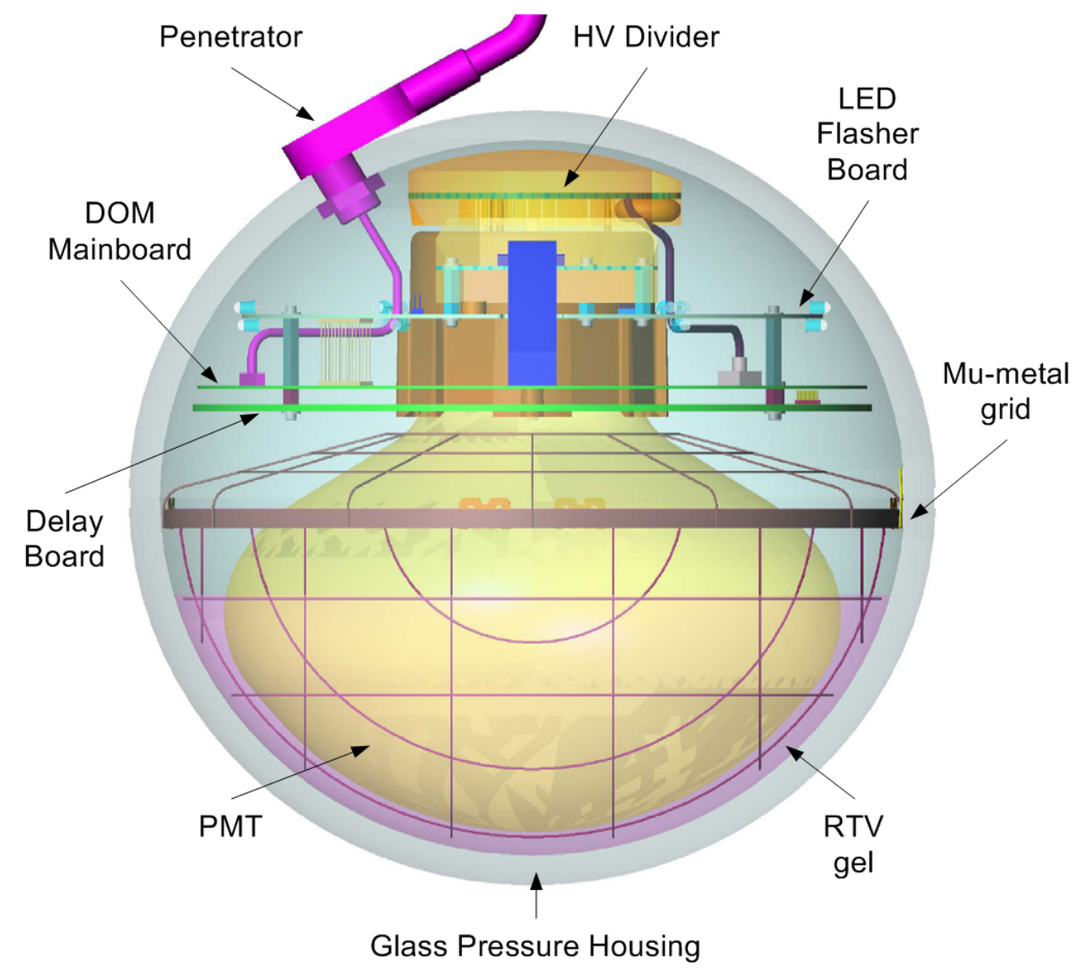
Digital Optical Modules

10” Hamamatsu Photomultiplier tubes (PMT)
3.5 W Power
Internal digitization and timestamping:
 ATWD: 300 MHz (400 ns)
 fADC: 40 MHz (6400 ns)
Dynamic range: from one to thousands of photo-electrons
Transmit digital data to surface

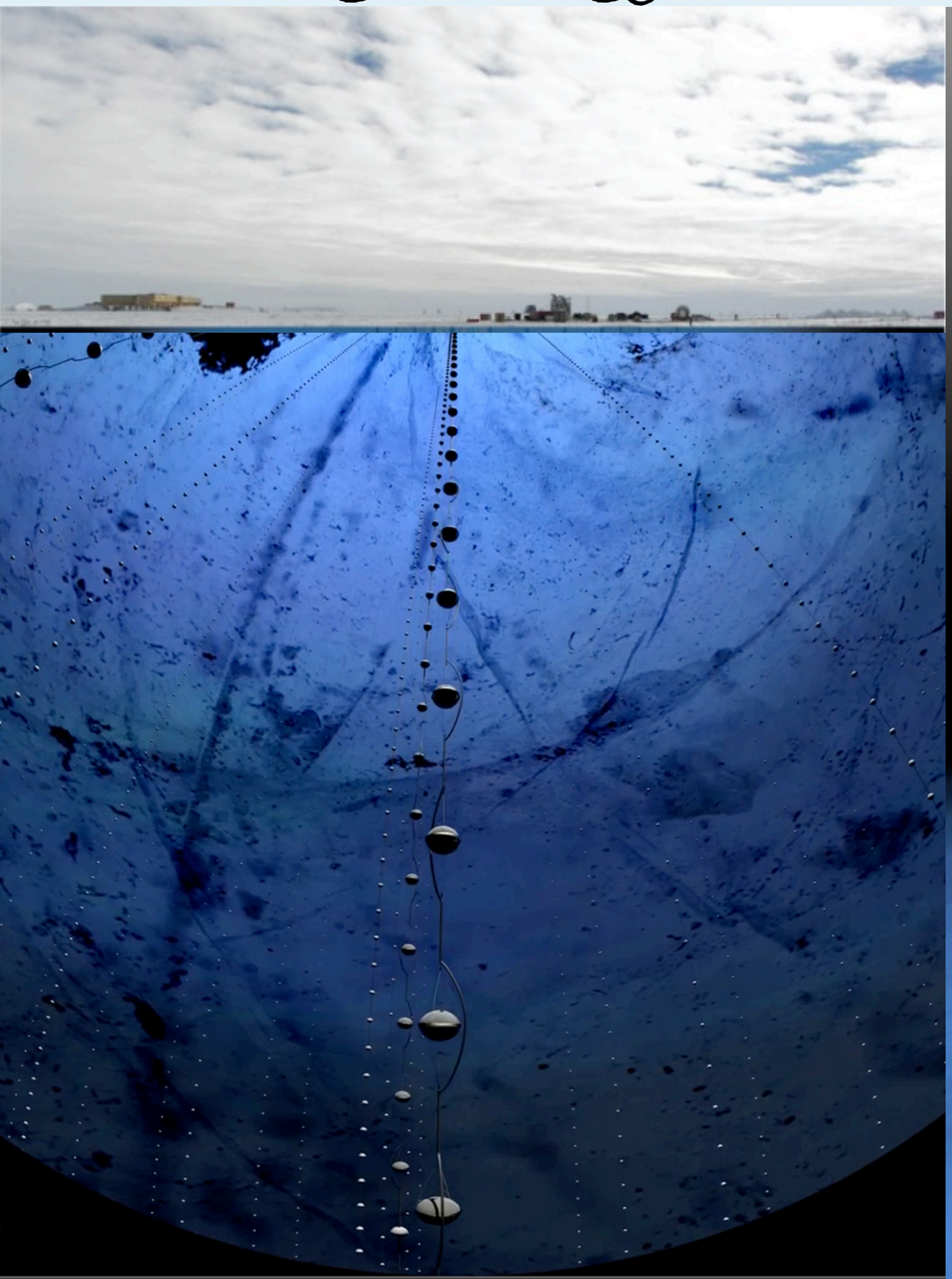


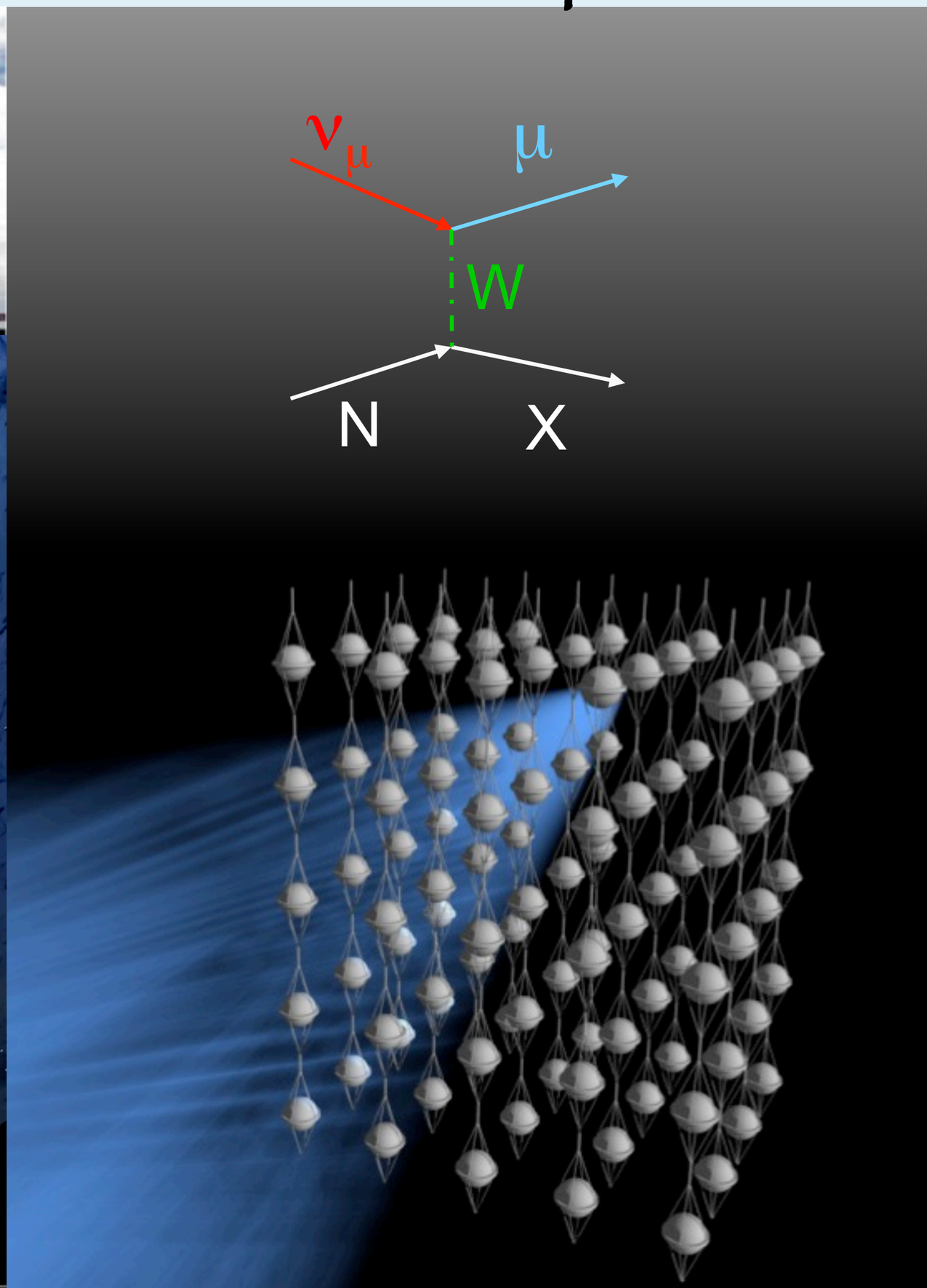


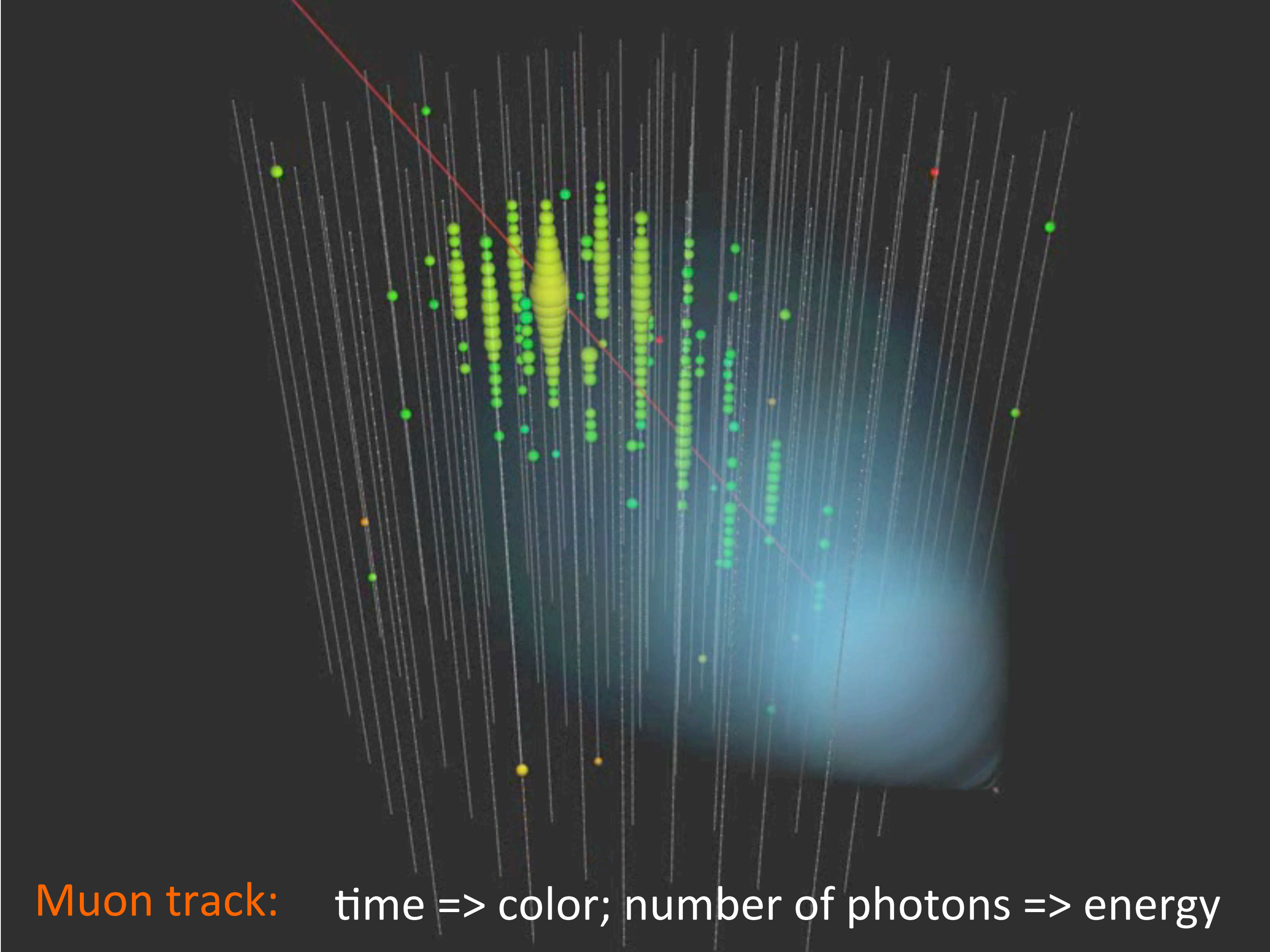




High Energy Neutrino Detection Principle

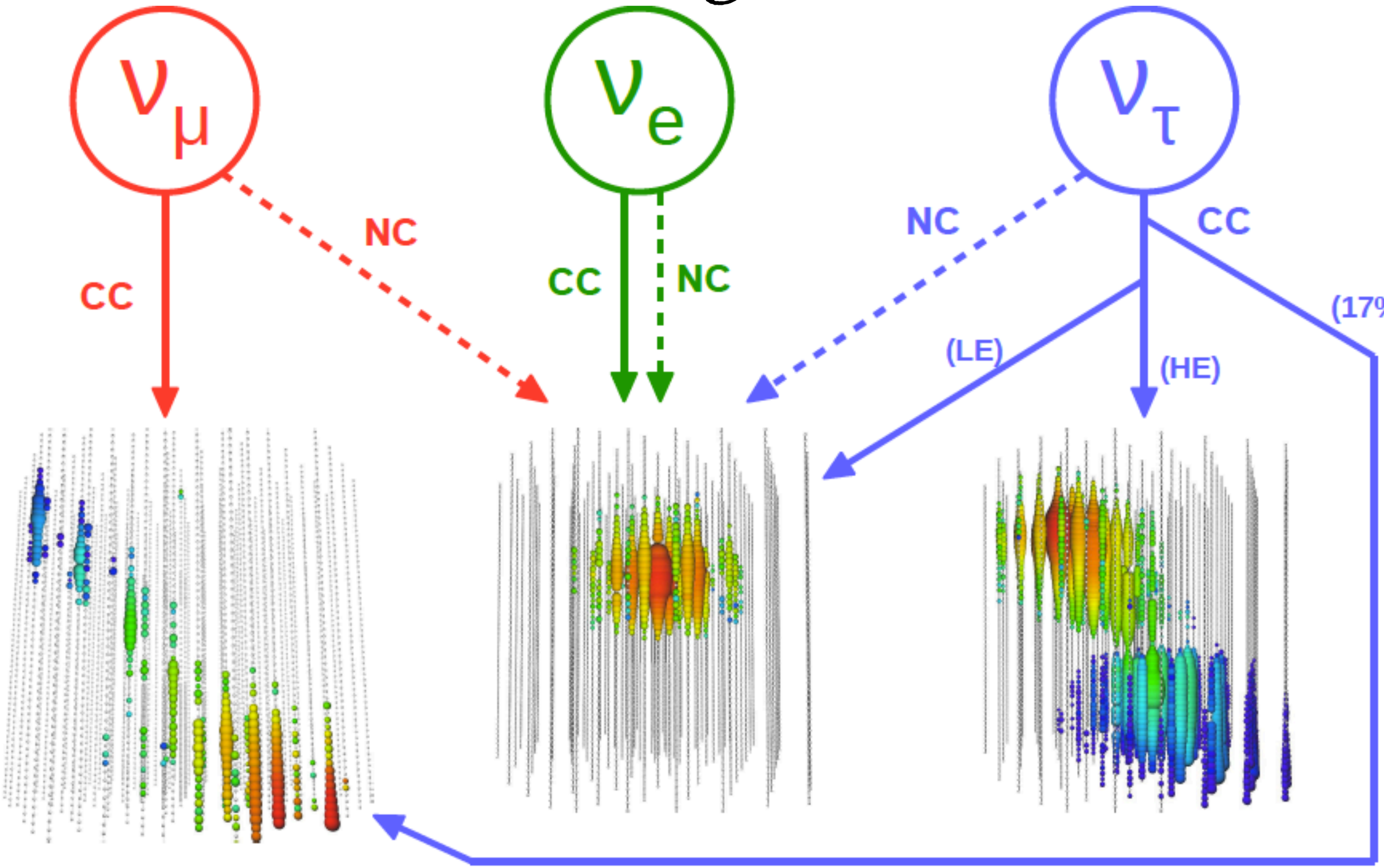






Muon track: time => color; number of photons => energy

Neutrino signatures



Track topology

Good pointing (~0.2° - 1°)

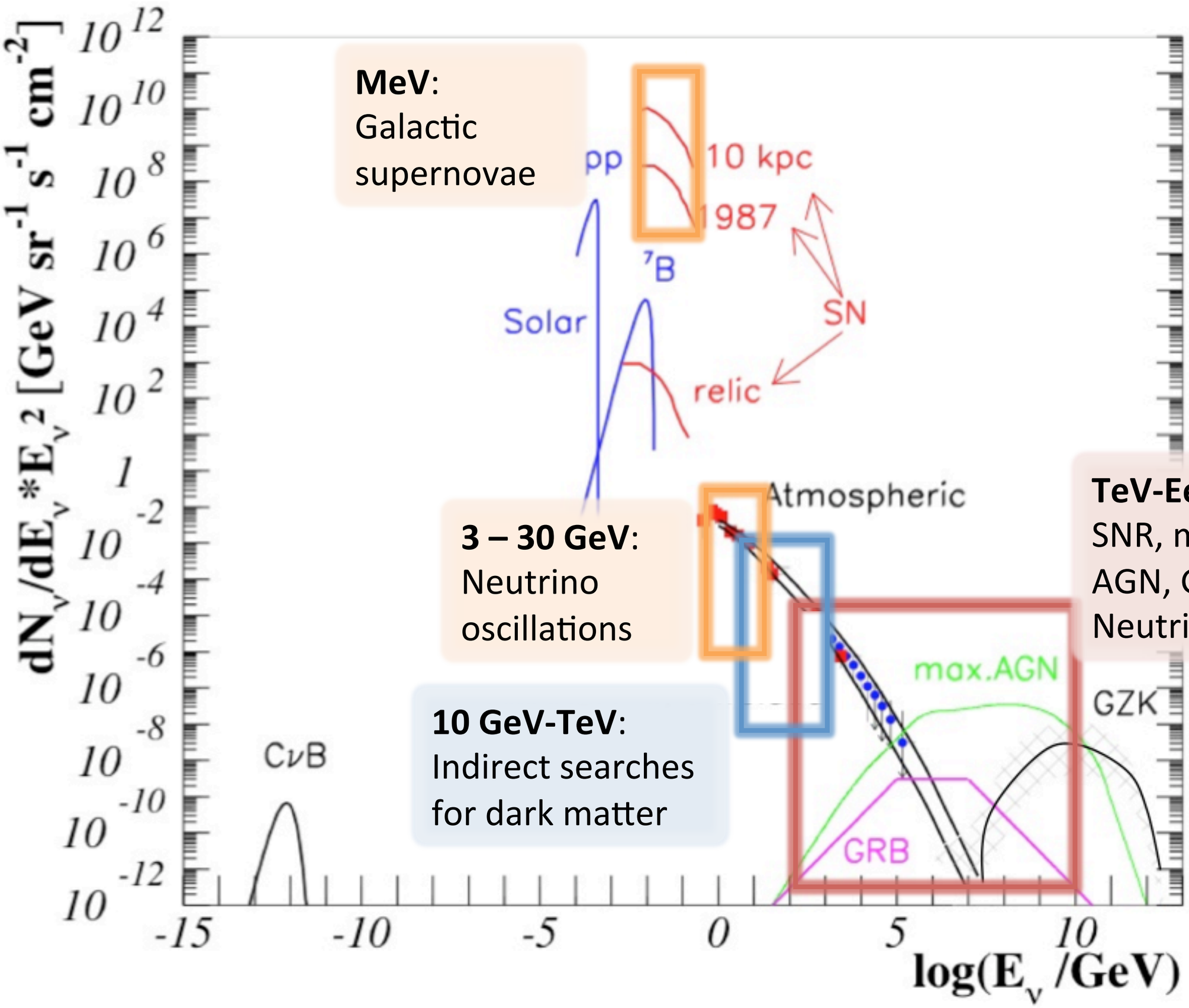
but only *lower bound* on neutrino energy

Cascade topology

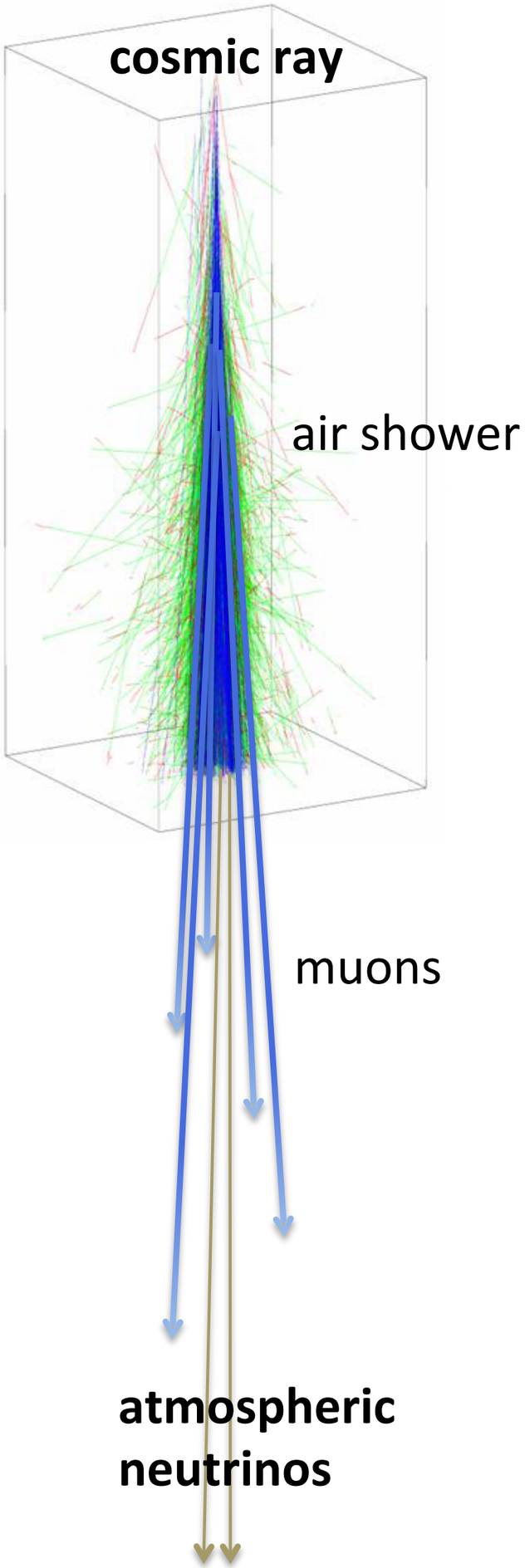
Good energy resolution (~15%)

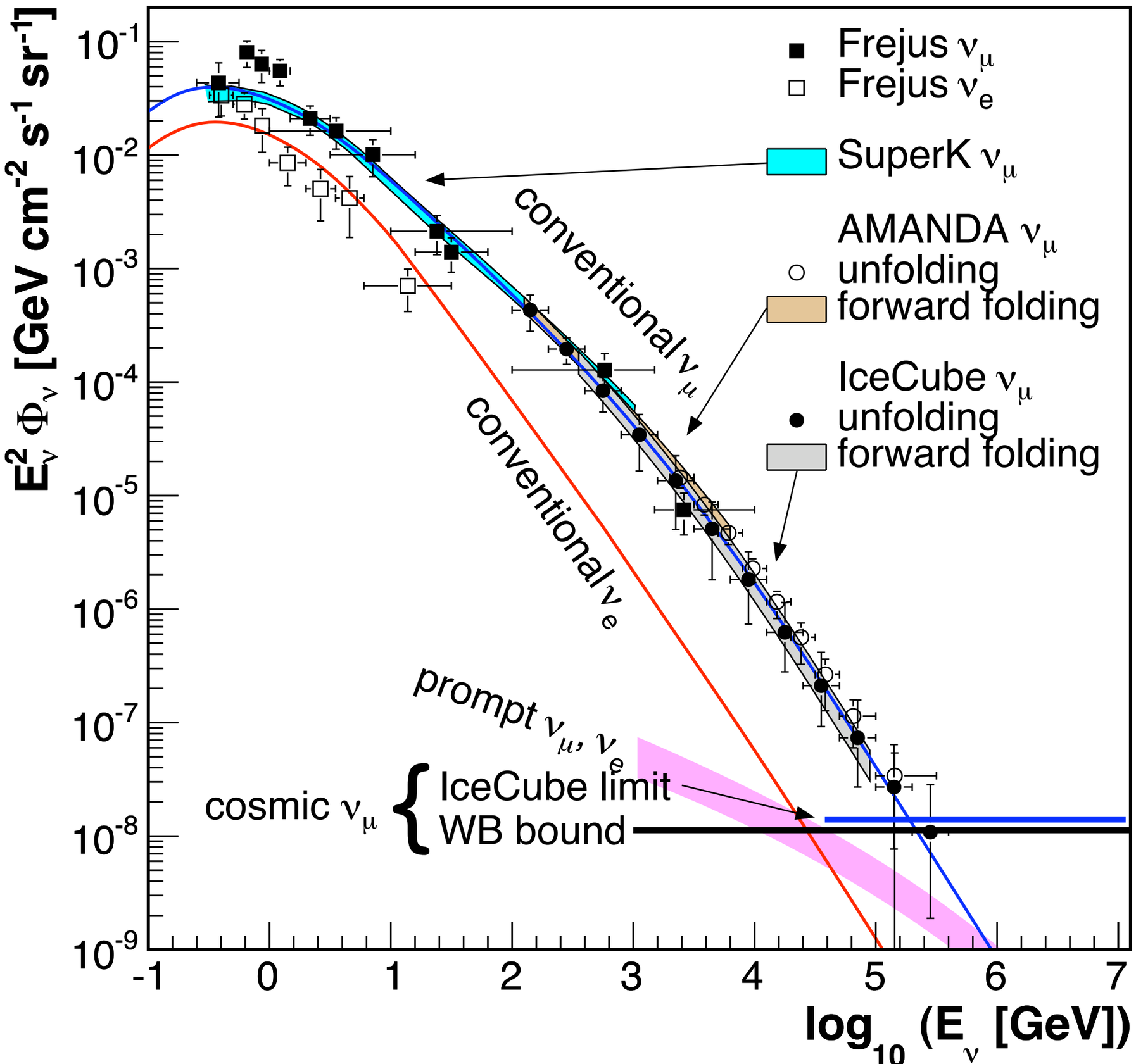
but poor pointing (~10° - 15°)

Physics/astrophysics in & beyond the Standard Model

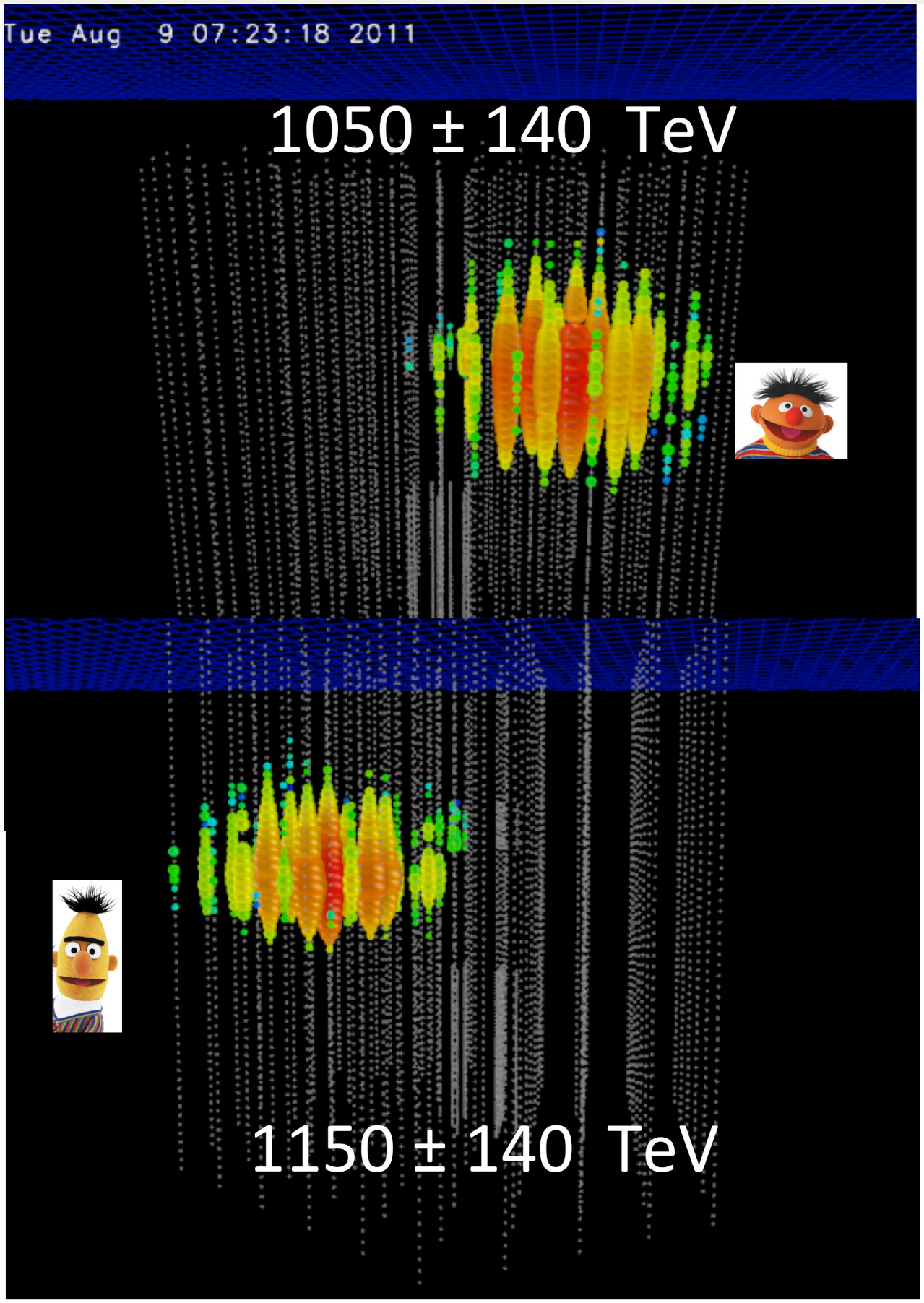


Atmospheric Neutrino Spectrum

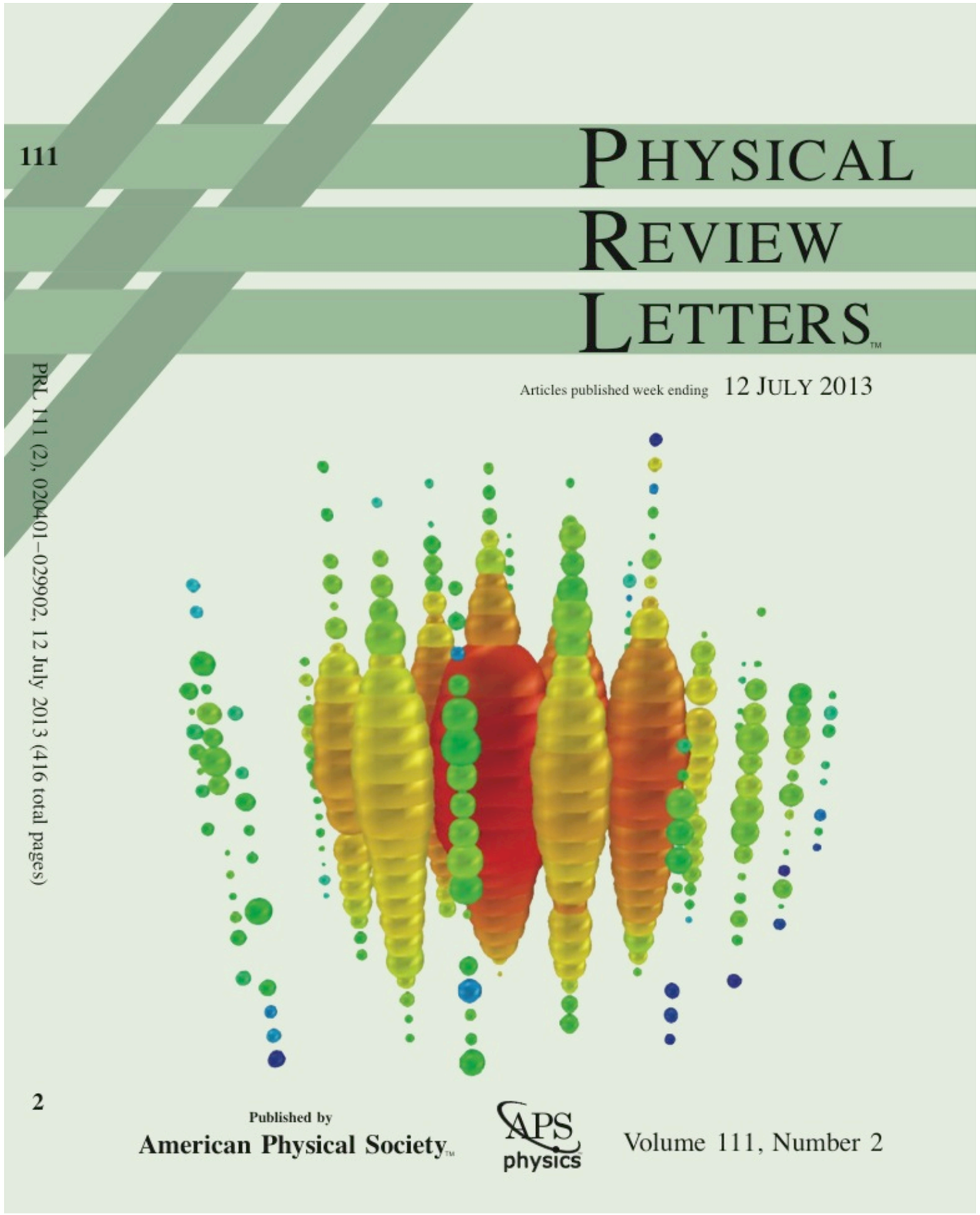


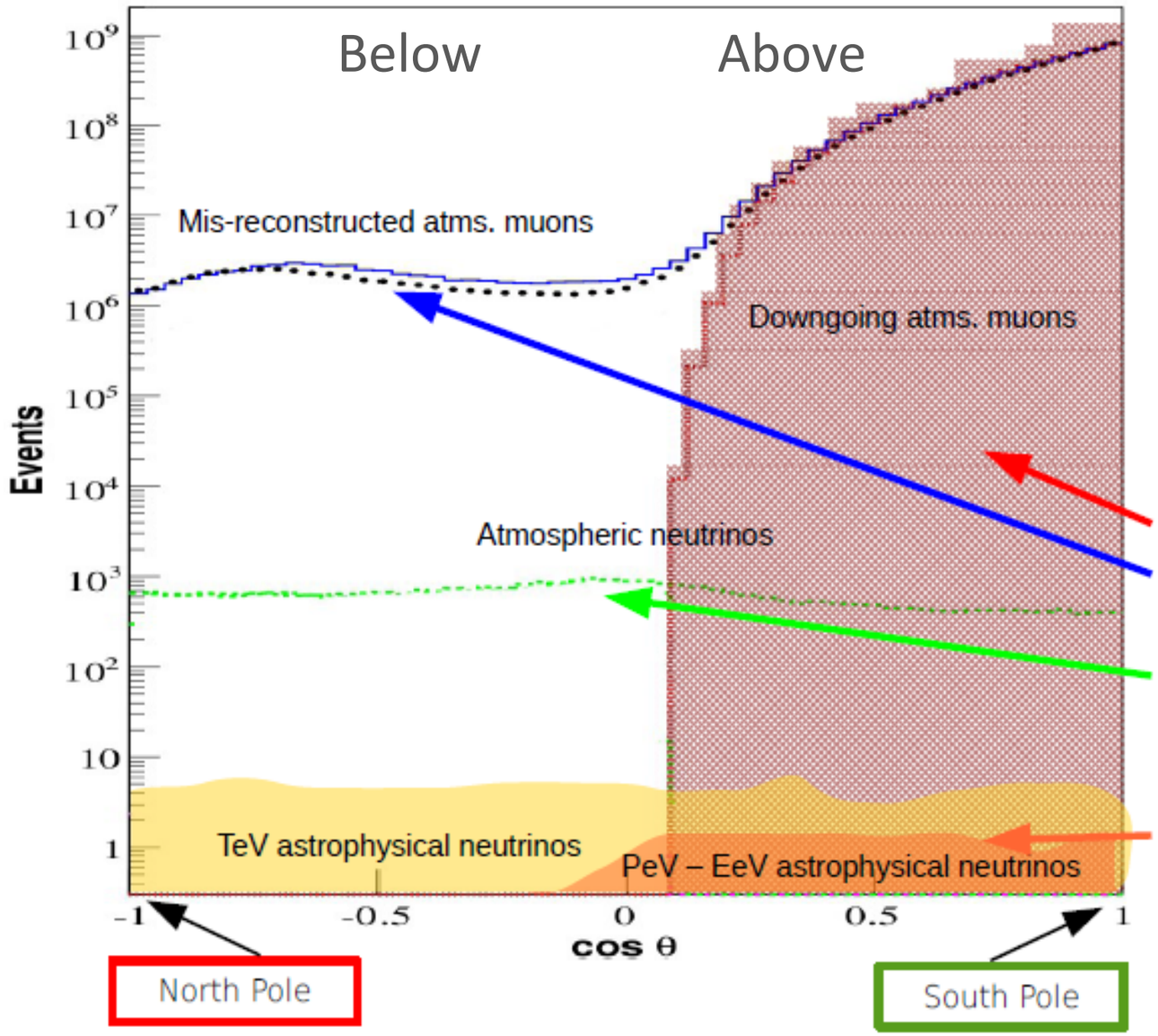


First Observation of PeV-energy Neutrinos



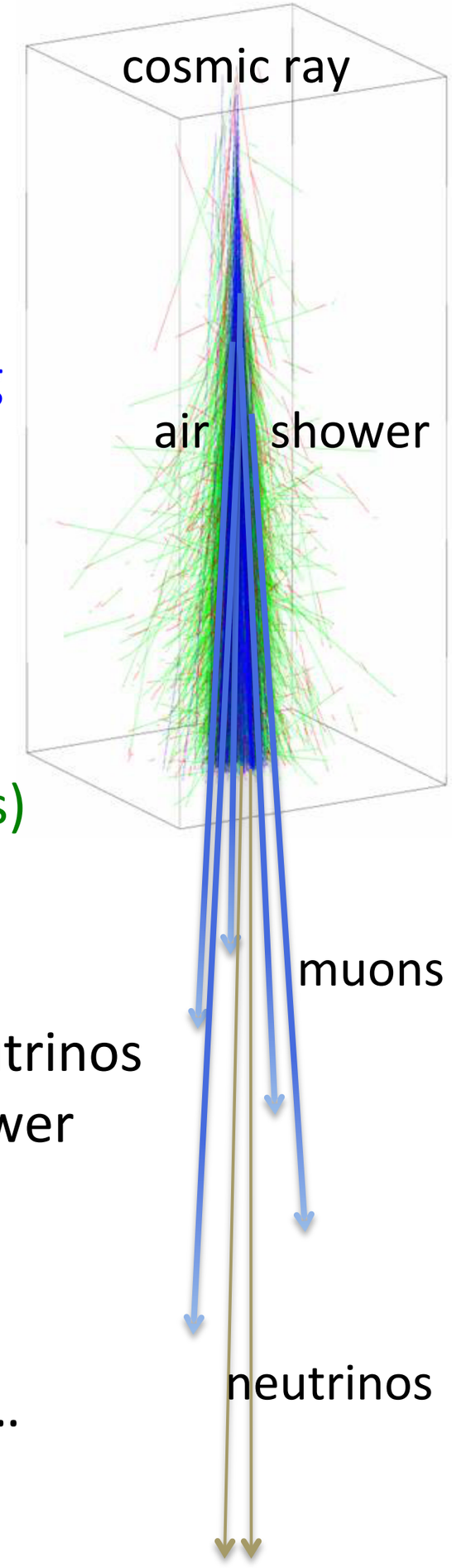
Bert & Ernie





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)



Using a veto for downgoing events, we remove the atmospheric neutrinos … by removing the muons coming from the *same* cosmic ray air shower

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

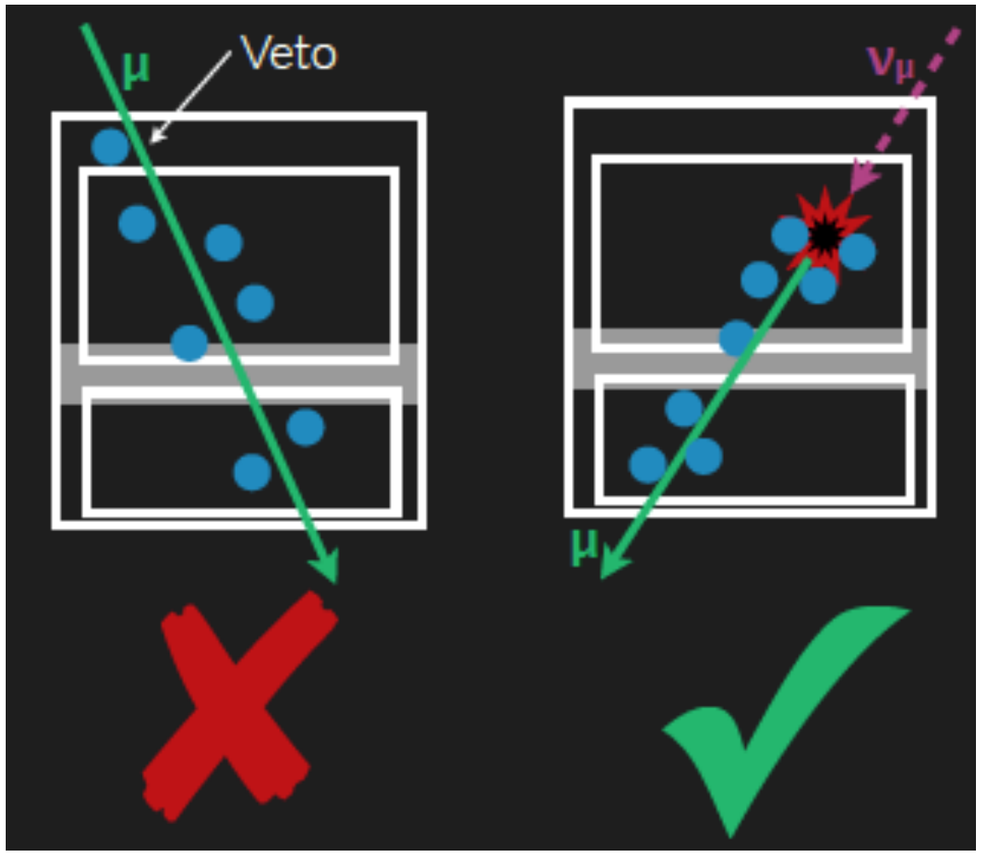
NB: Doesn't work for upgoing, since the Earth absorbed the muons … so southern sky (*downgoing* events) becomes the best channel.

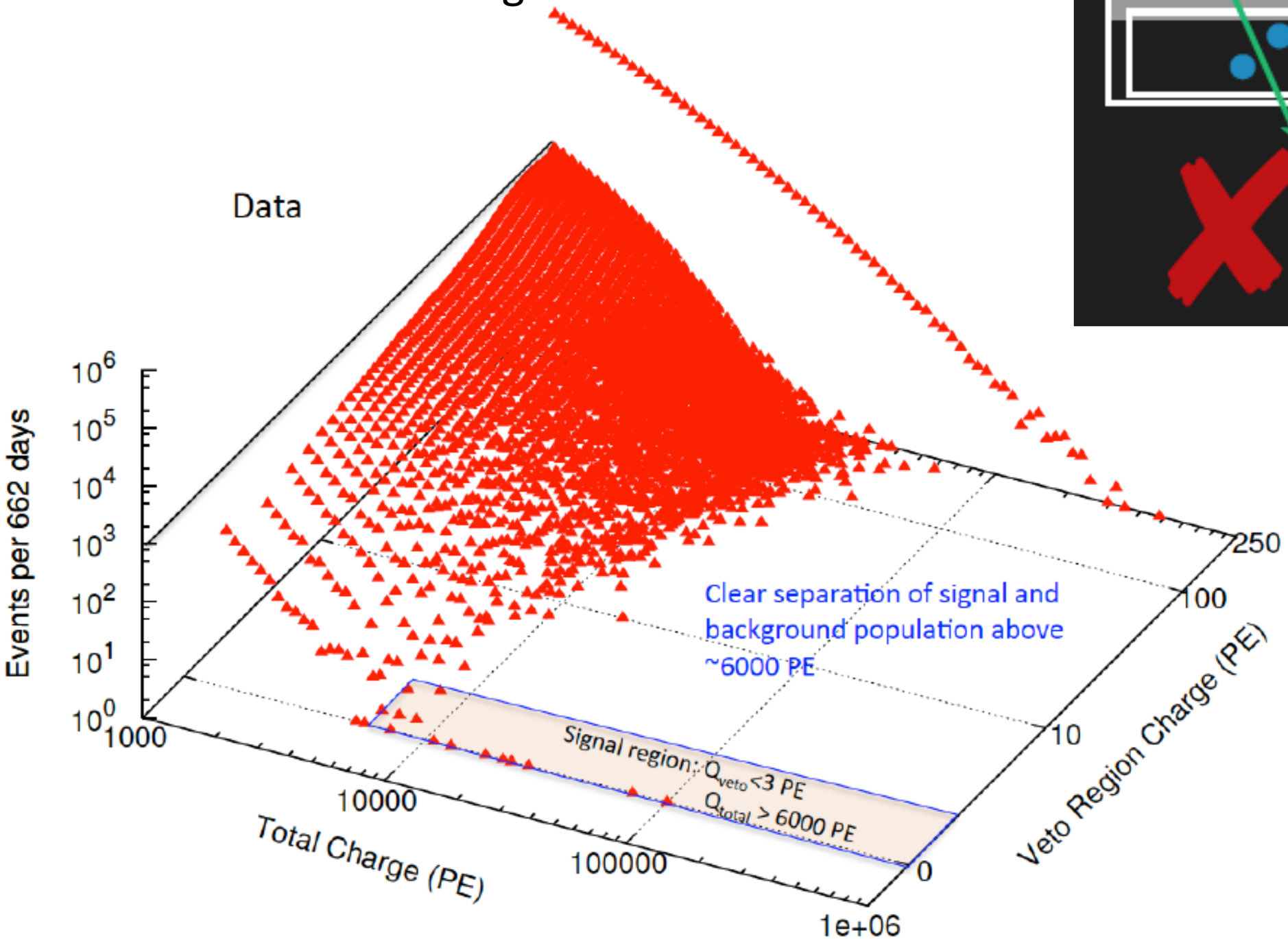
Teasing out the cosmic signal from background

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

Removes atmospheric background (muon + neutrino) **from above**

Earth filters muon background **from below**

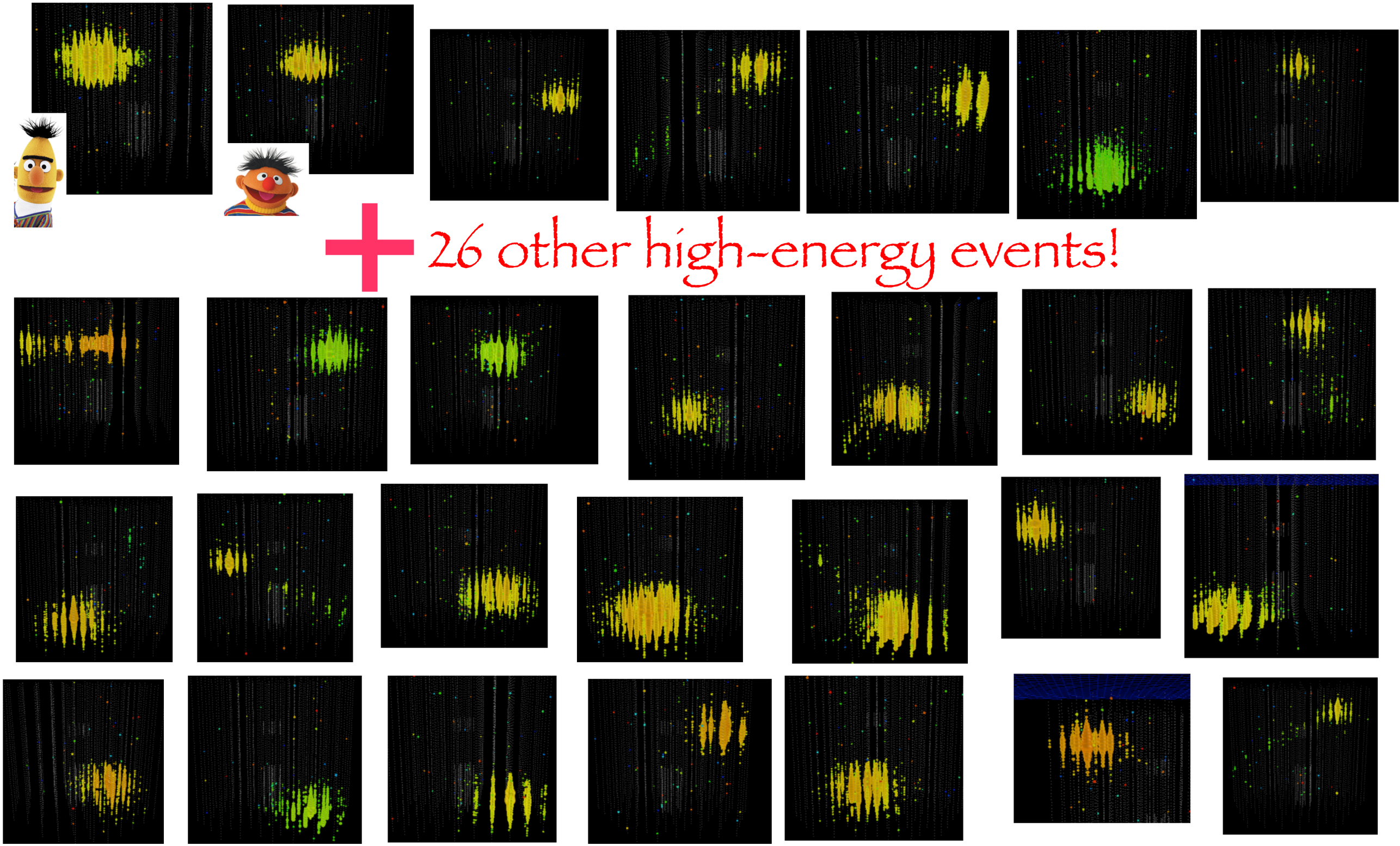




Re-discovery of Bert & Ernie

Atmospheric μ background: 6 ± 3.4

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



High Energy Starting Event Analysis: Results

Science 342:1242856,2013

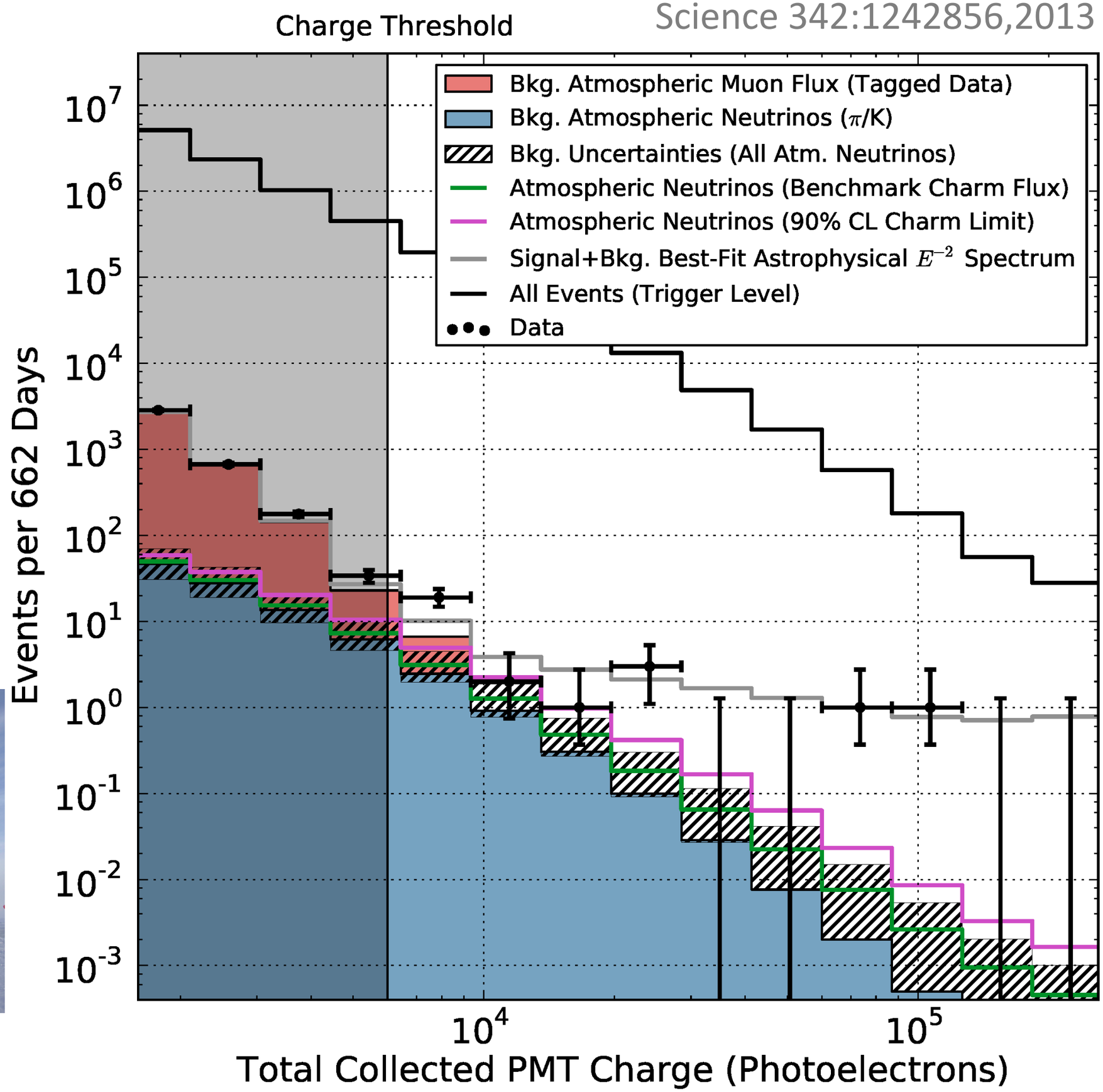
26 new events

Expected background:
10.6 ± 4 atm. events

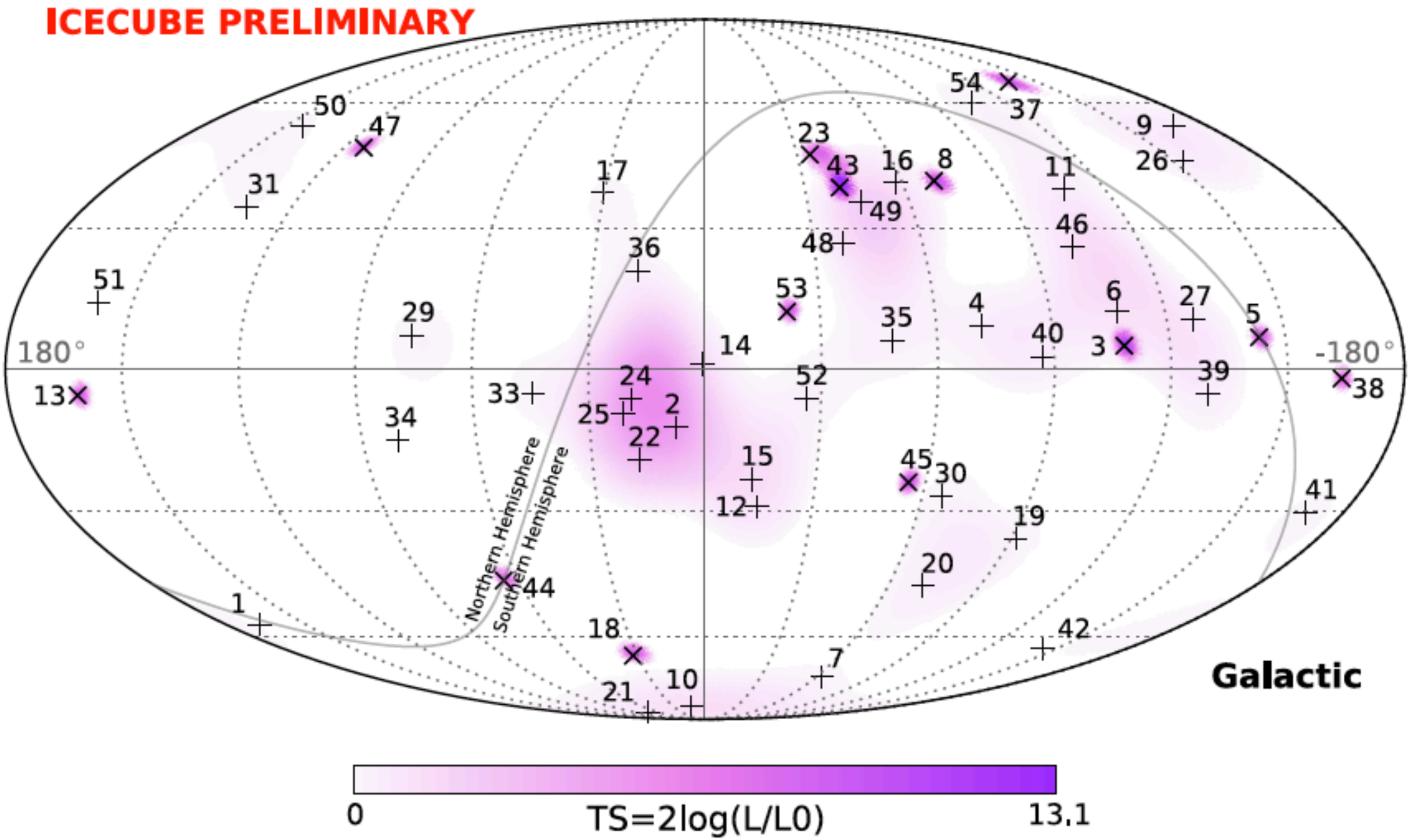
⇨ **4.1σ combining both analyses**

Cutoff beyond ~1 PeV?

Gap at ~0.5-1 TeV?

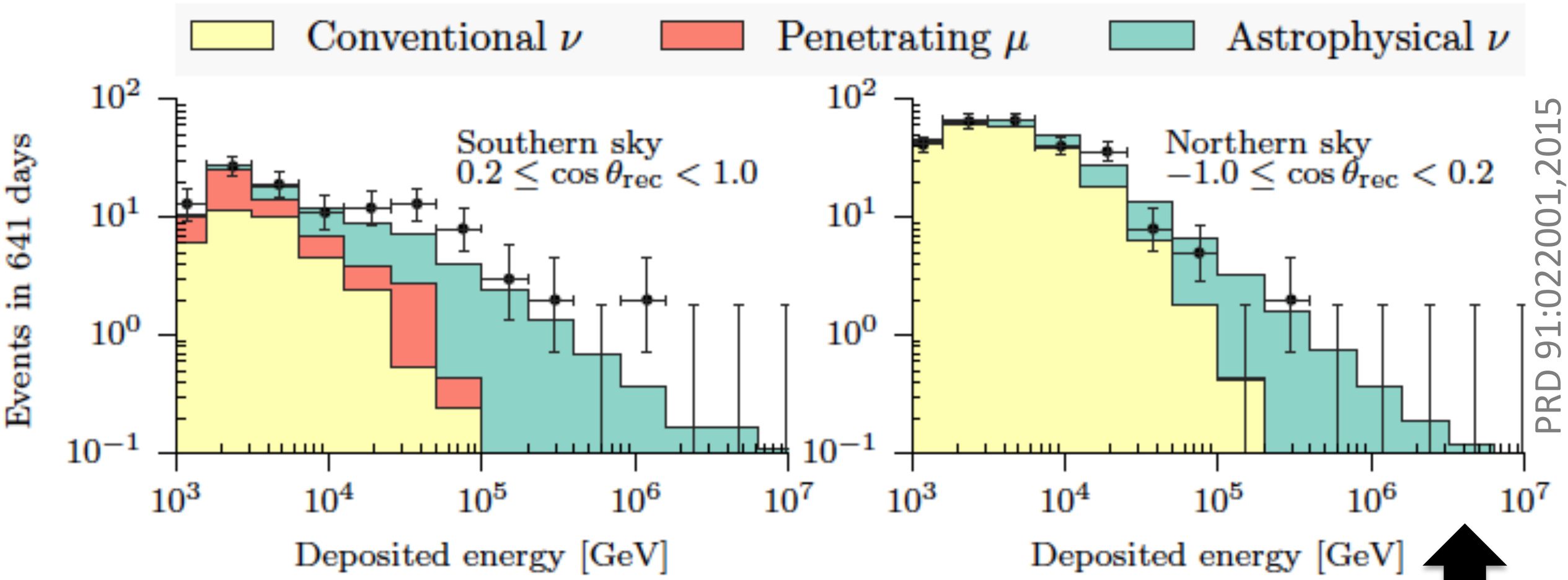


Arrival Directions & Clustering

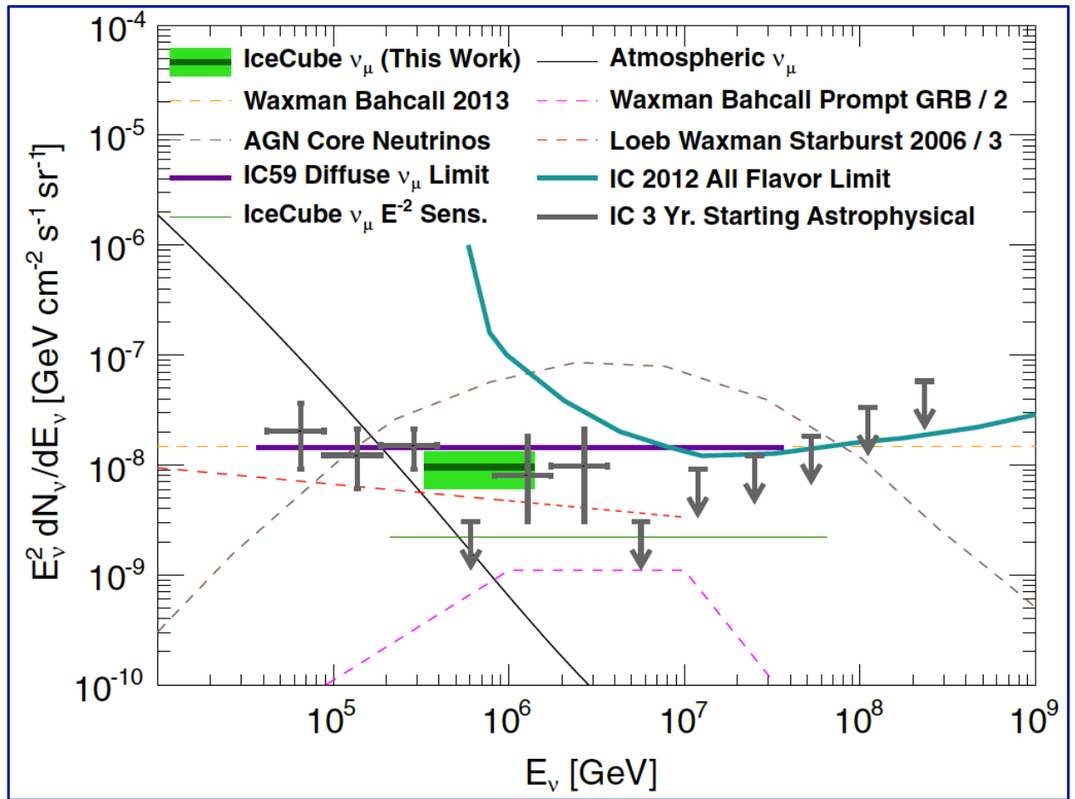


5 events observed in 30°×30° around Galactic Centre (2 more nearby *#12, #15*) while 0.6 events are expected … however in a randomized map, the chance of having such a cluster *anywhere* in the sky is ~ 8% (NB: no clustering in time)

Towards lower energies: Looking through the Earth



PRD 91:022001,2015



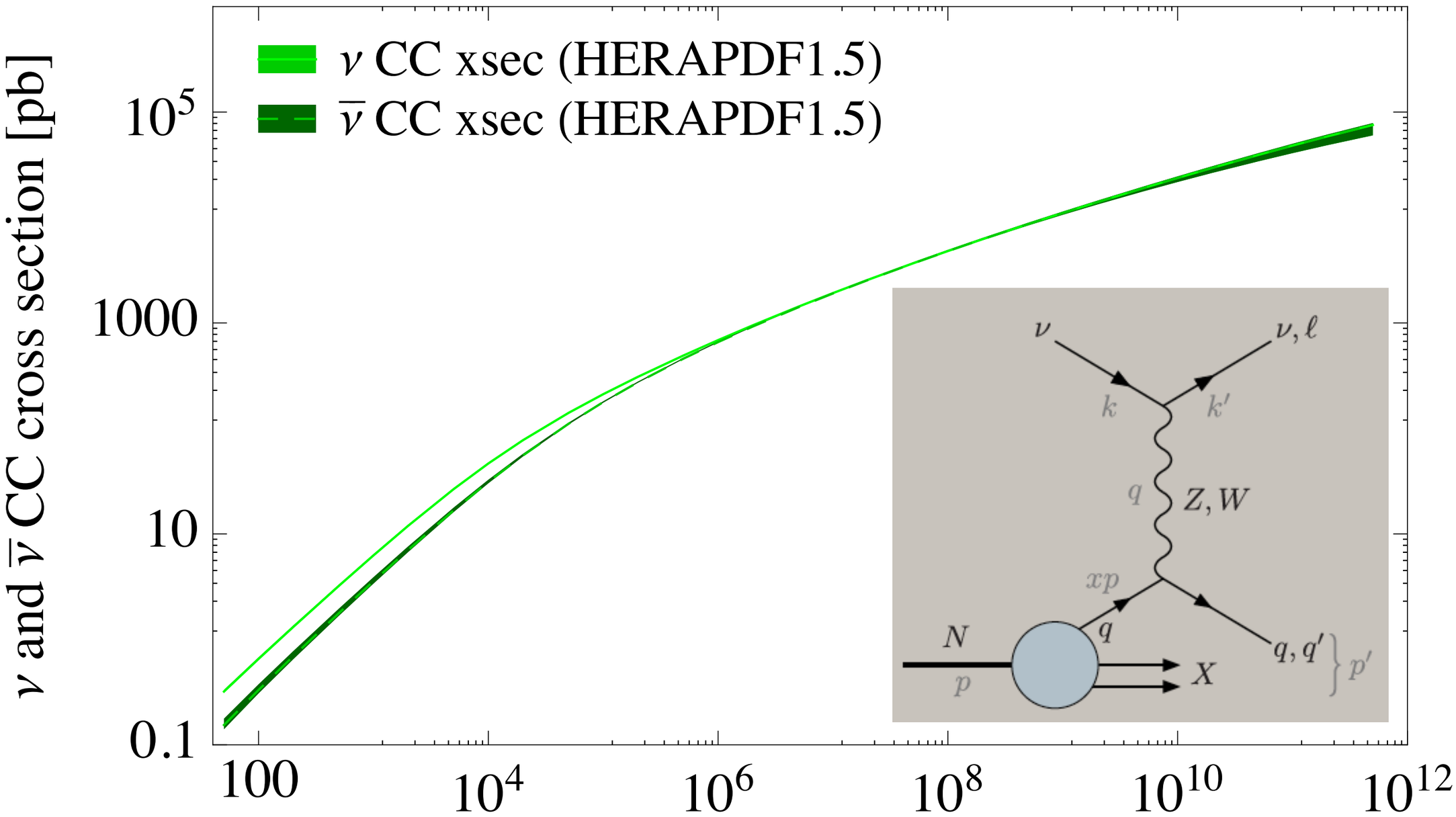
PRL 115:081102,2015

Now 6.5σ for 53 events in 4-yr HESE dataset

+ 3.7σ in μ channel

NB: >PeV energy neutrinos absorbed in the Earth

To calculate the flux given the event rate requires the ν-N scattering cross-section
… We have computed this with few % accuracy @ next-to-leading order in QCD



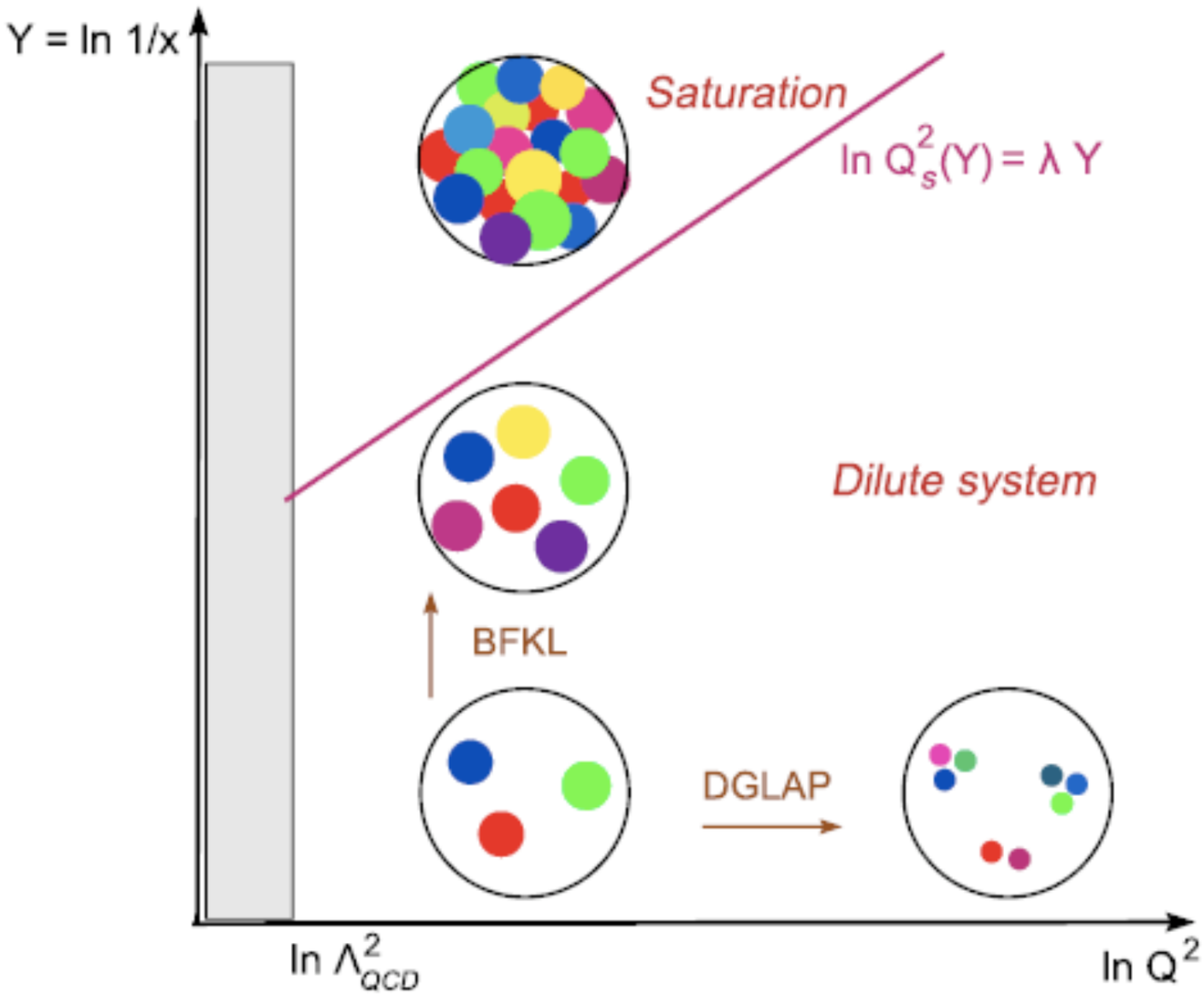
Cooper-Sarkar *et al*, JHEP 1108:042,2011

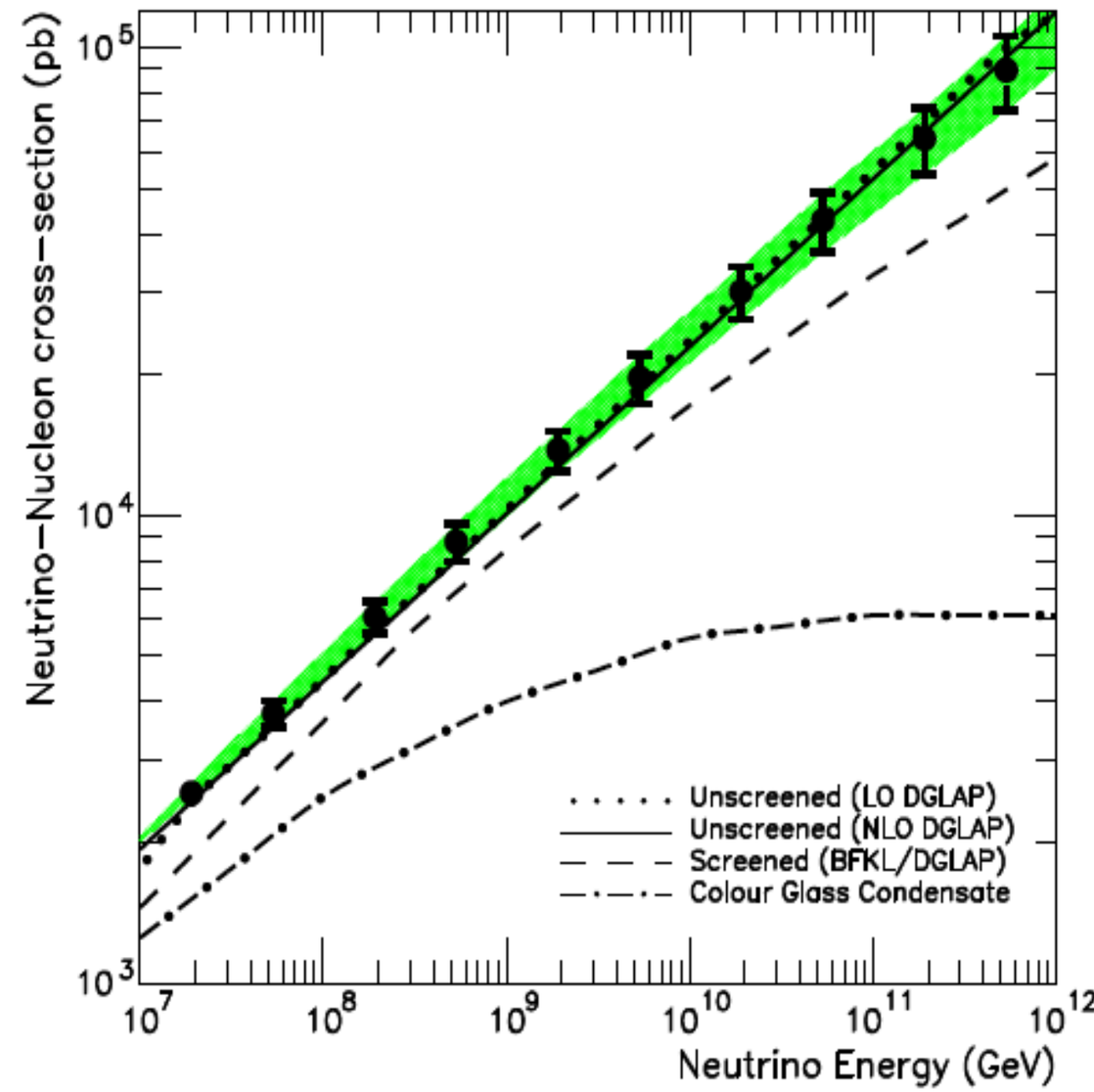
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{G_F^2 M_W^4}{4\pi(Q^2+M_W^2)^2 x}\sigma_r$$

with reduced cross-section

$$\sigma_r = \left[Y_+ F_2^\nu(x,Q^2) - y^2 F_L^\nu(x,Q^2) \pm Y_- x F_3^\nu(x,Q^2)\right]$$

As the gluon density rises at low *x*, non-perturbative effects become important, and a new phase of QCD – Colour Glass Condensate – may form





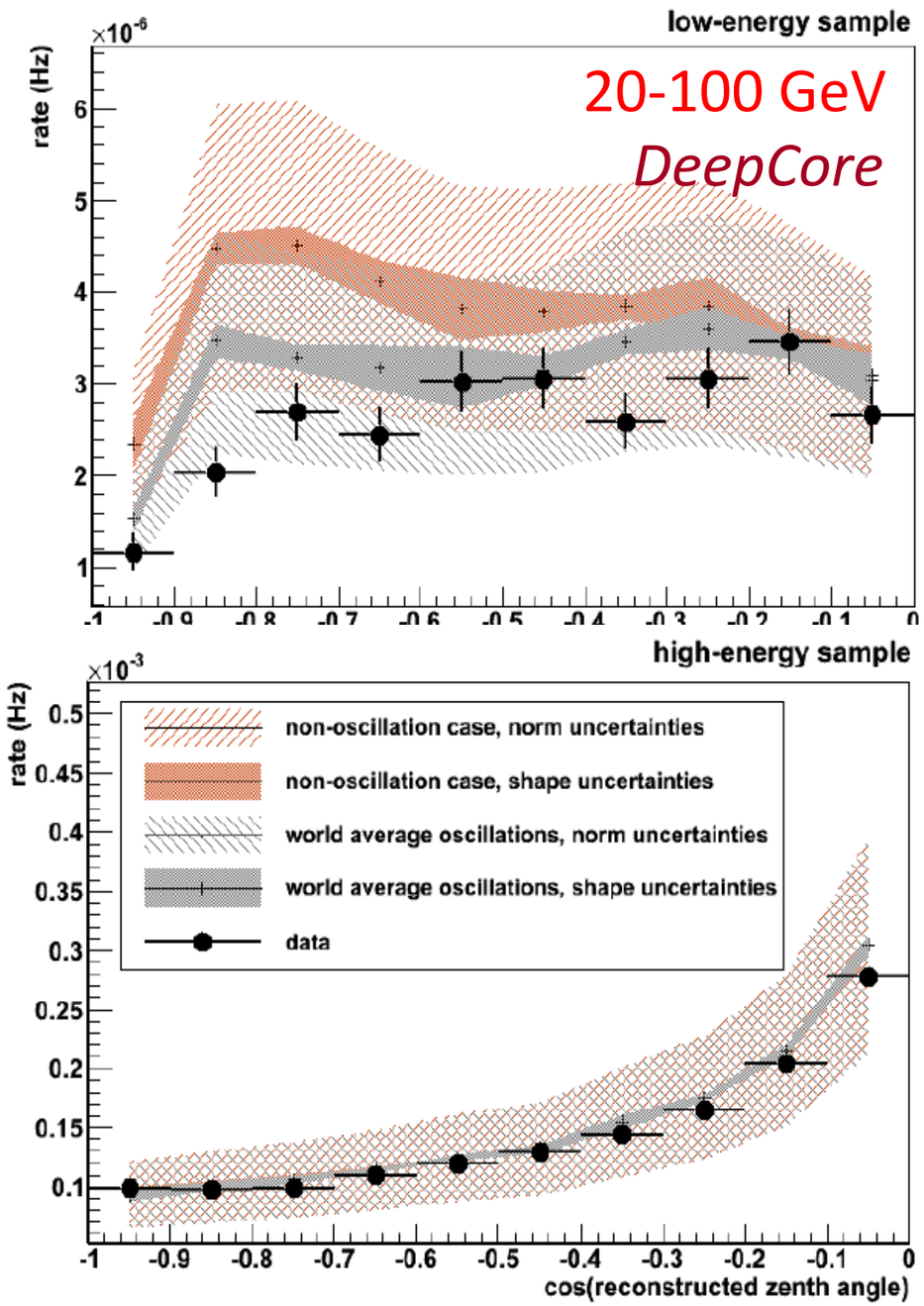
Anchordoqui *et al*, PRD74:043008,2006

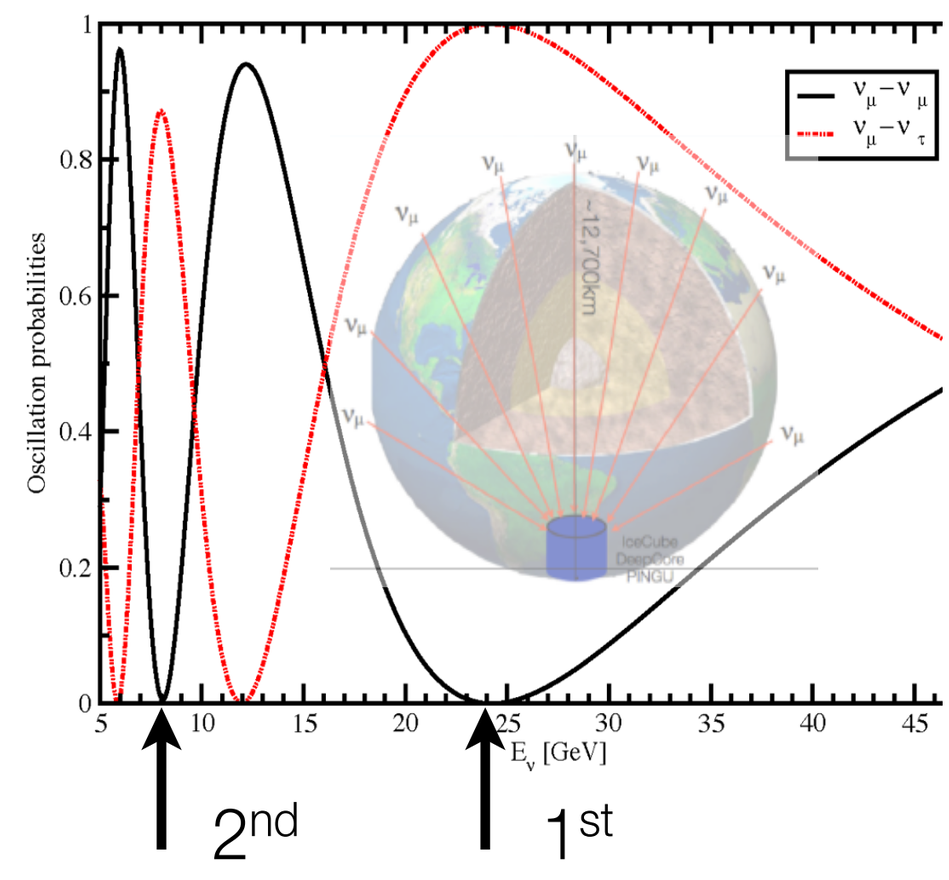
The observed zenith angle dependence of the neutrino flux can provide a measure of the DIS cross-section at ultra high energies where theoretical predictions are uncertain … and thus discriminate between theoretical models

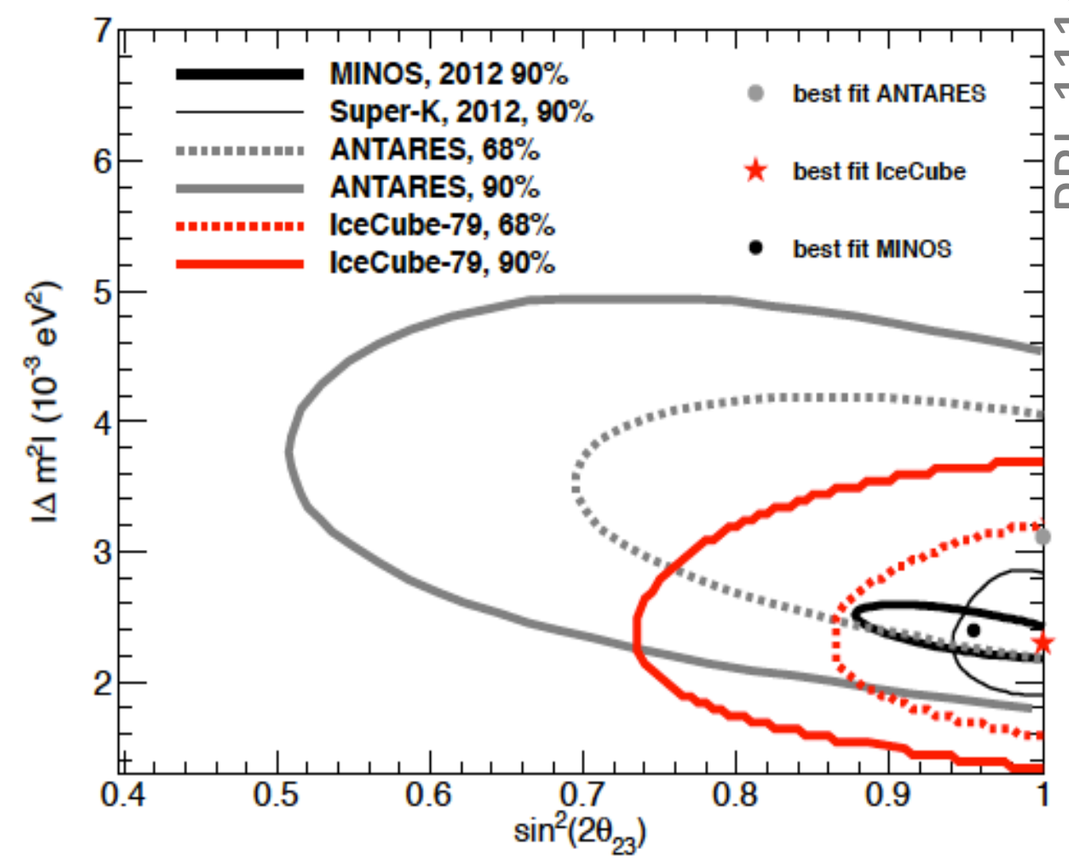
Measurement of Atmospheric Neutrino Oscillations

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

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



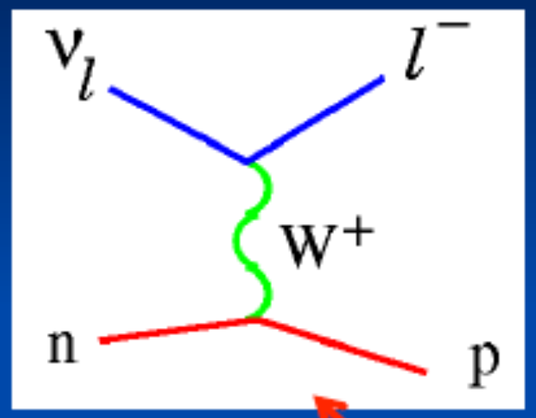




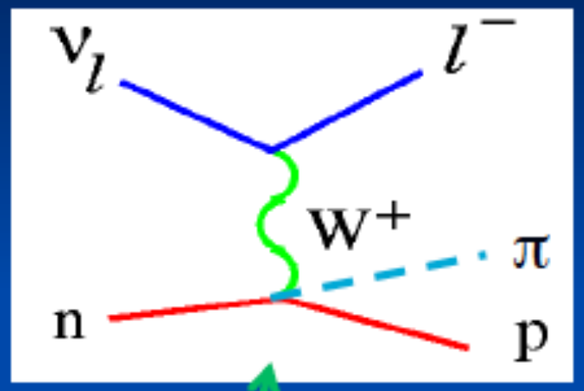
PRL 111:081801,2013

Neutrino-nucleon cross section

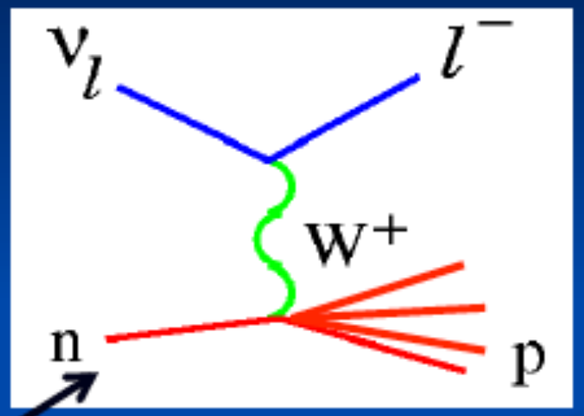
CCQE



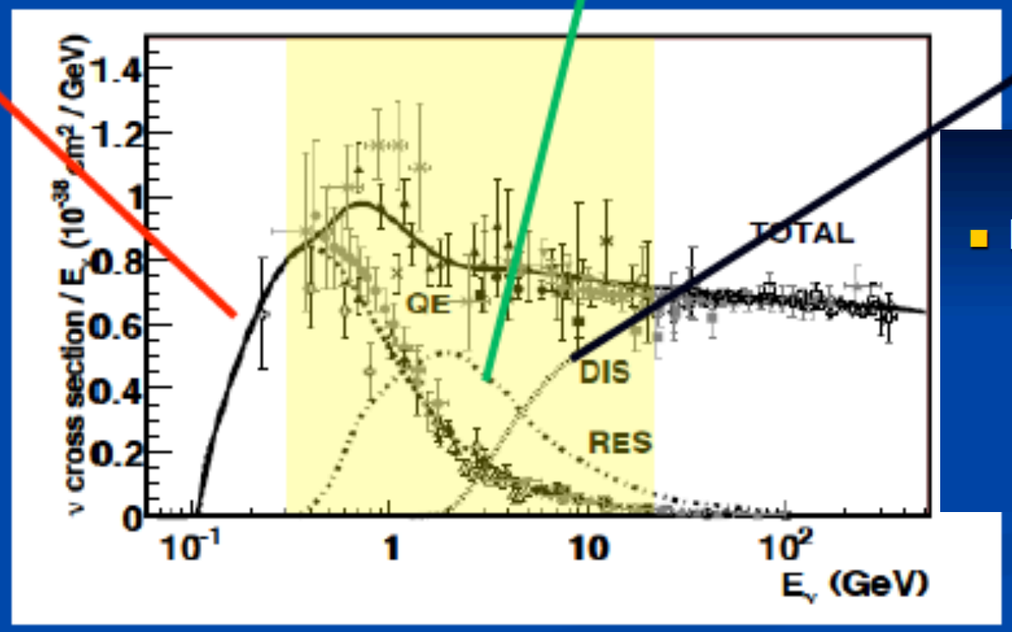
1π



DIS

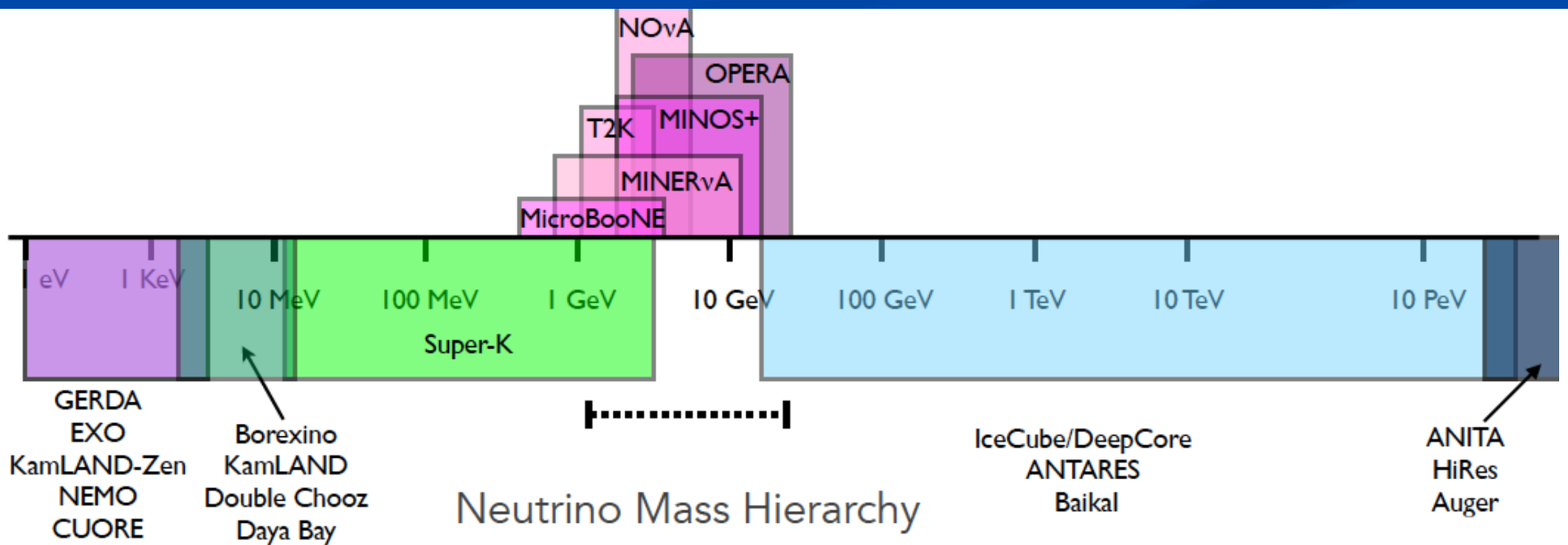


Ulrich Mosel



Nuclear Theory

- Necessary Ingredients
  - Nuclear groundstate (correlations, spectral functions)
  - Nuclear reaction mechanisms (IA vs. 2p2h, coll. excit.)
  - Electroweak interaction vertices, in medium
  - Particle production, also in secondary colls
  - Propagation of all particles to final state, incl fsi



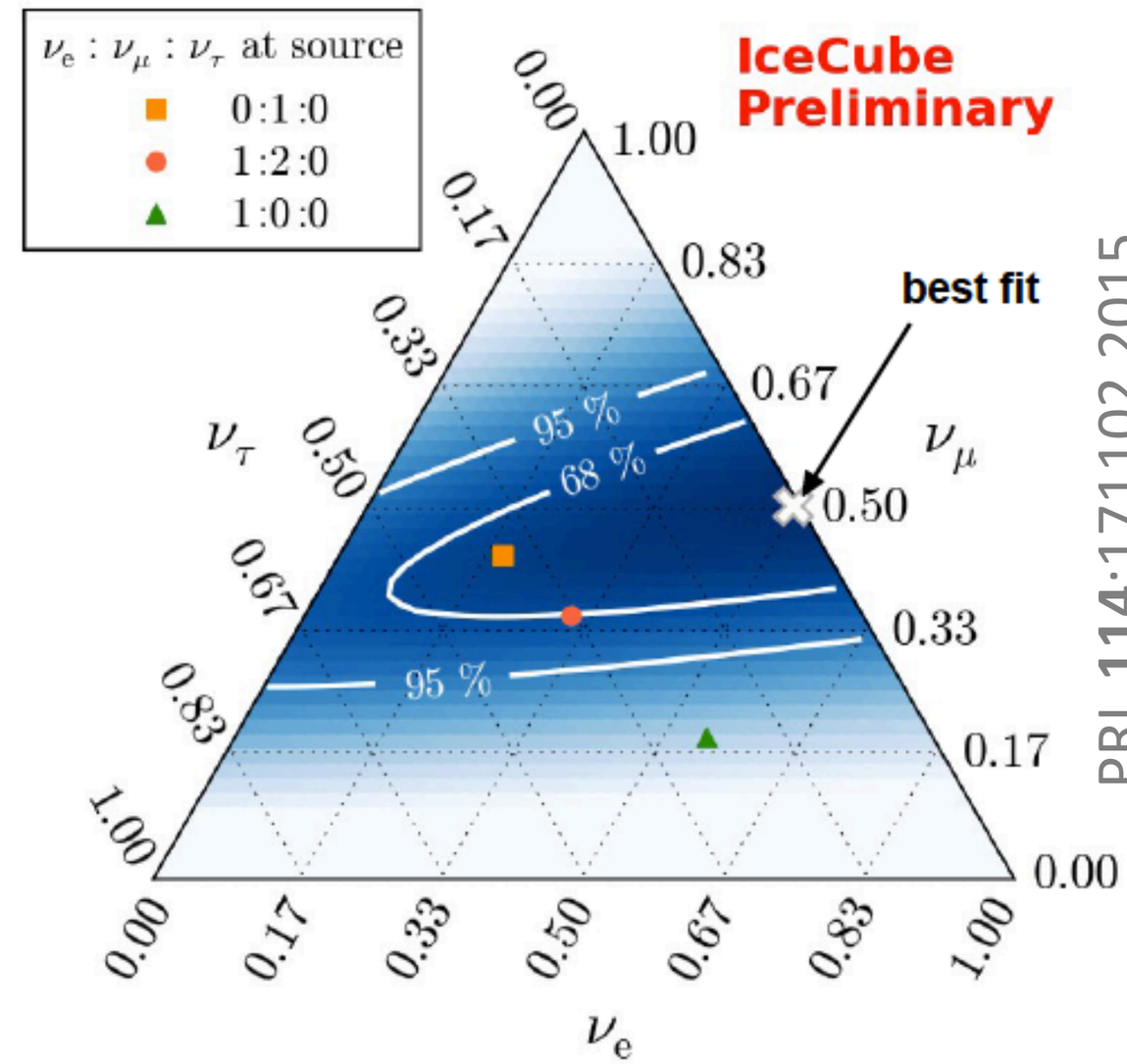
Probing new physics in neutrino oscillations

- **initial composition:** $(\nu_e : \nu_\mu : \nu_\tau)$
  pion & muon decay: $(1:2:0)$
  neutron decay: $(1:0:0)$
  muon-damped pion decay: $(0:1:0)$

$$p + p \to \pi^+ + X$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- oscillation-averaged probability:

$$P_{\nu_\alpha \to \nu_\beta} \simeq \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$



PRL **114**:171102,2015

- "NuFit 1.3": $\sin^2\theta_{12} = 0.304$ / $\sin^2\theta_{23} = 0.577$ / $\sin^2\theta_{13} = 0.0219$ / $\delta = 251°$

✔ observed events **consistent with equal contributions of all neutrino flavors**

We now have a laboratory to test quantum mechanics on cosmological scales at high energies (e.g. Lorentz invariance violation, decoherence by 'space-time foam', …)

Indirect Dark Matter Searches

$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$

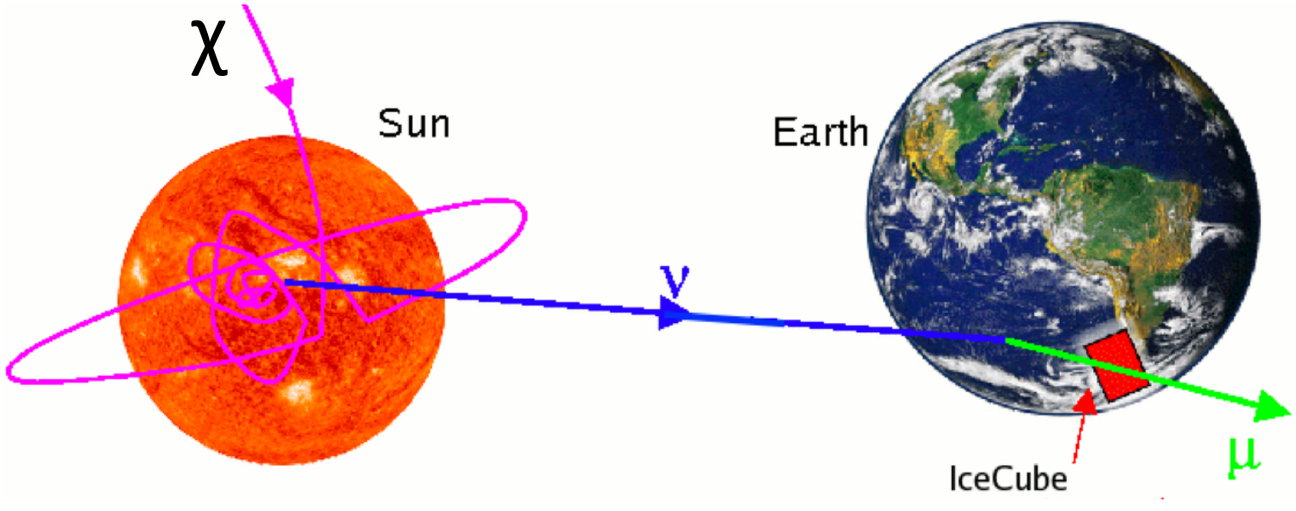
Neutrinos are typical end products of dark matter annihilation

Solar Searches:

Dark matter particles are gravitationally attracted, scatter and get trapped in Sun

As trapped density grows, annihilation rate reaches equilibrium with capture rate

Search sensitive to **scattering cross section**



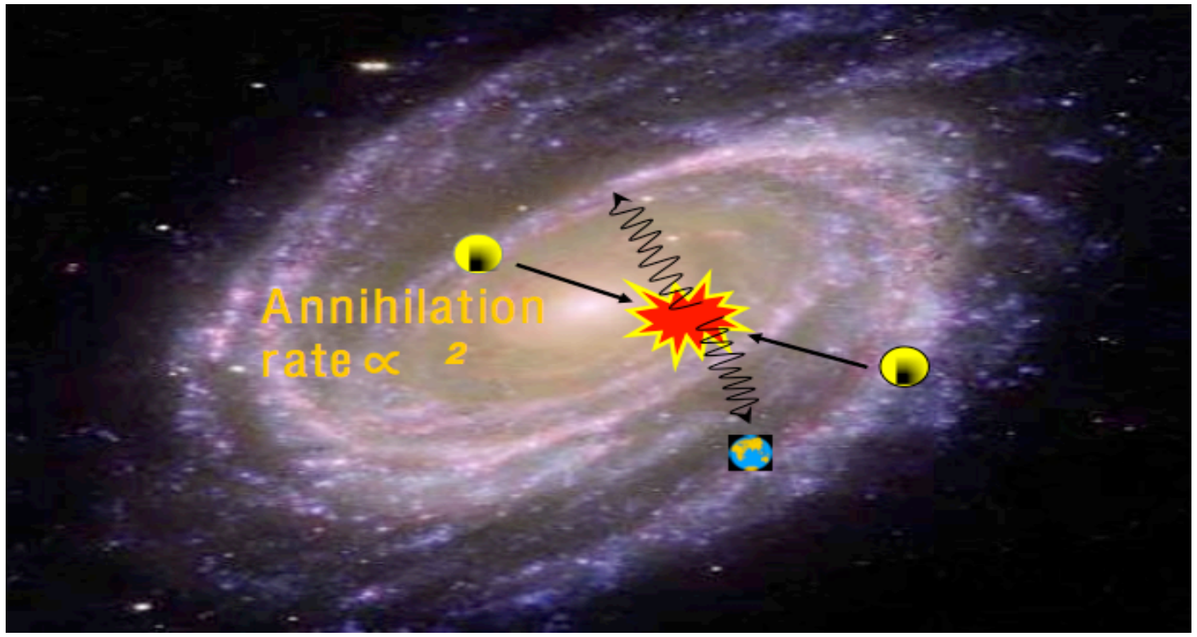
No signals seen so far

PRL **110**:131302,2013

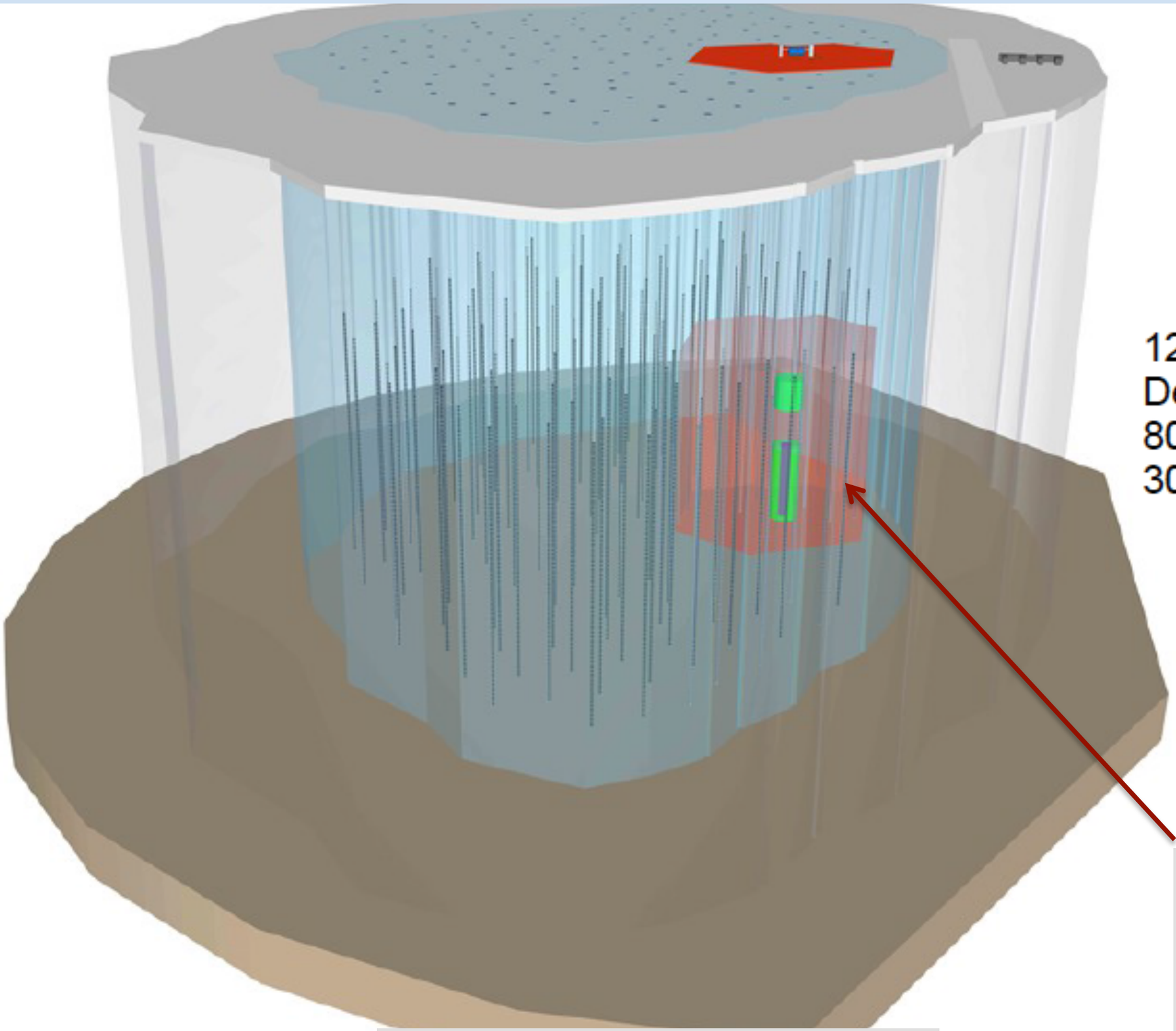
Galactic Halo Searches:

Annihilation rate highest in densest regions of dark matter halo (Galactic Centre or dwarf spheroidal galaxies)

Search sensitive to **annihilation cross section**



The future: IceCube-Gen2



120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

PINGU infill
40 strings
~GeV threshold

instrumented volume: x 10
same budget as IceCube

The future: ANTARES → KM3NeT (detector assembly @ NIKHEF)

ARCA: "*Astrophysical Research with Cosmic in the Abyss*"

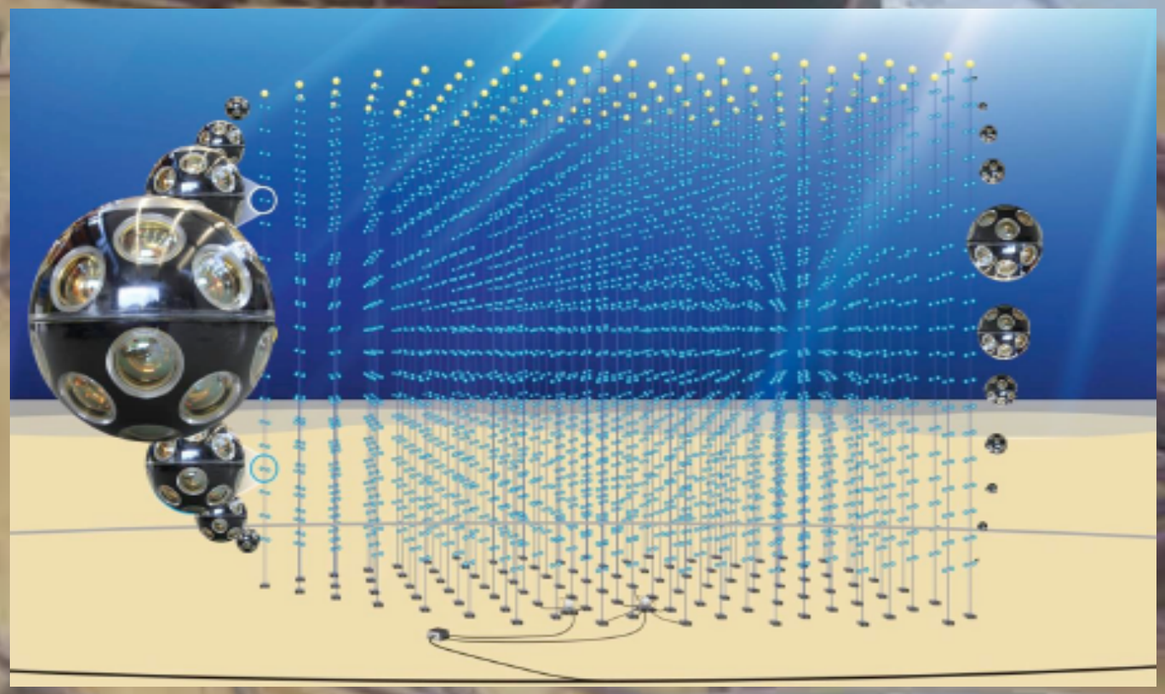
Study astrophysical neutrino fluxes at E > 100 GeV

2 "blocks" at the Italian site (~10% constructed)

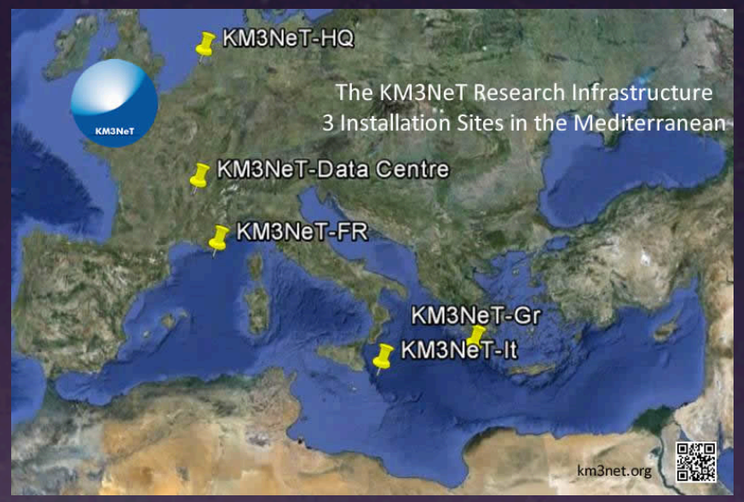
ORCA: "*Oscillations Research with Cosmics in the Abyss*"

Resolve the neutrino mass hierarchy (1 GeV < E < 100 GeV)

1 "block" at the French site (~5% constructed)



First glimpse of astrophysical neutrino flux seen … source(s) unknown



This is likely the beginning of a new astronomy and a new probe of physics beyond the Standard Model