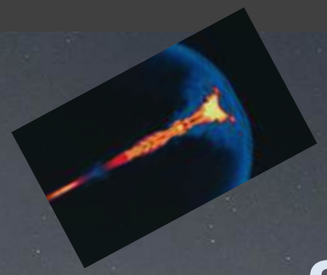
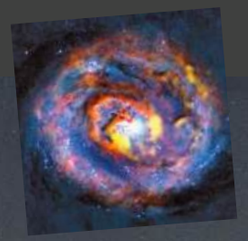
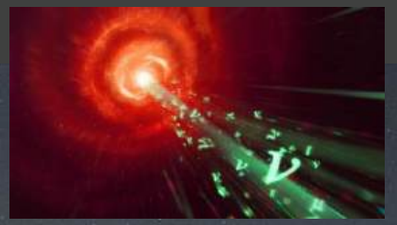
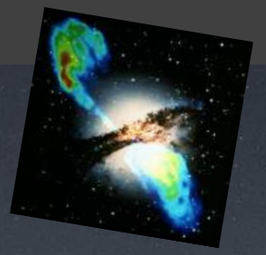
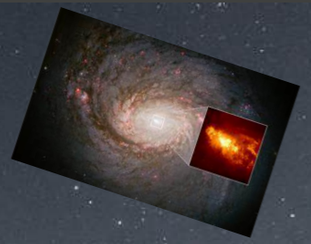
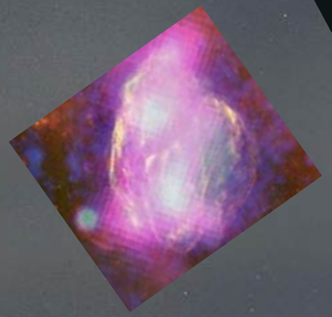
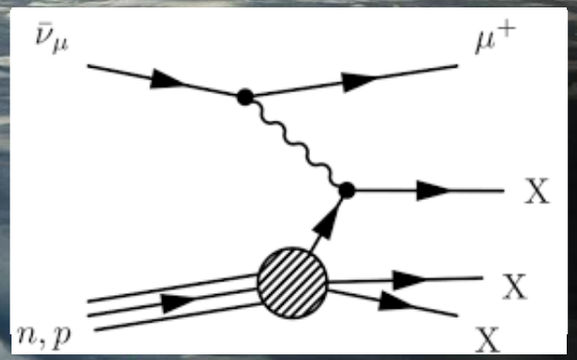
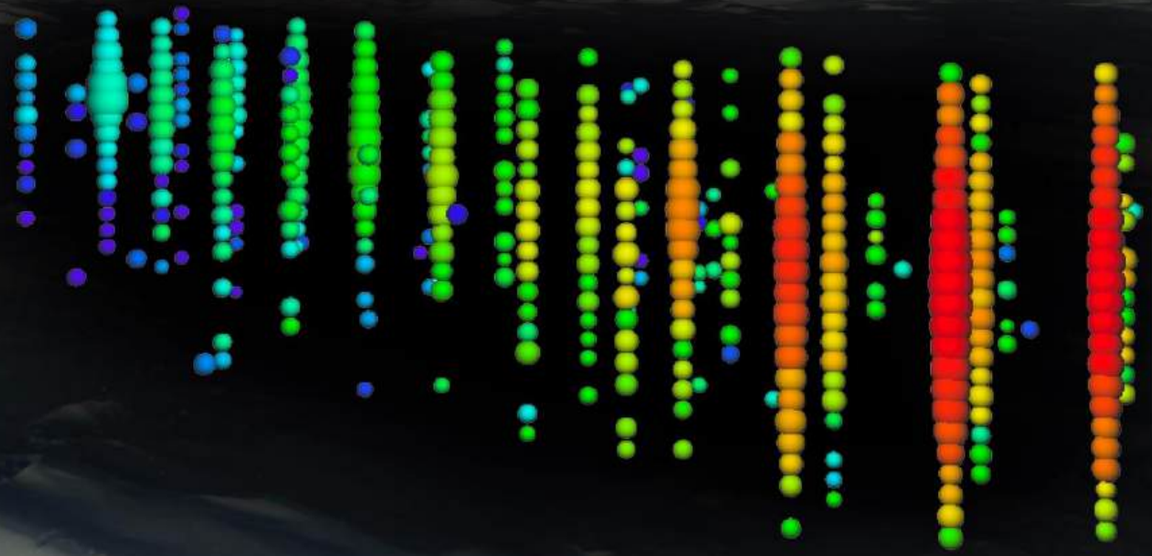








Seeing the universe with high energy νs

Subir Sarkar





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

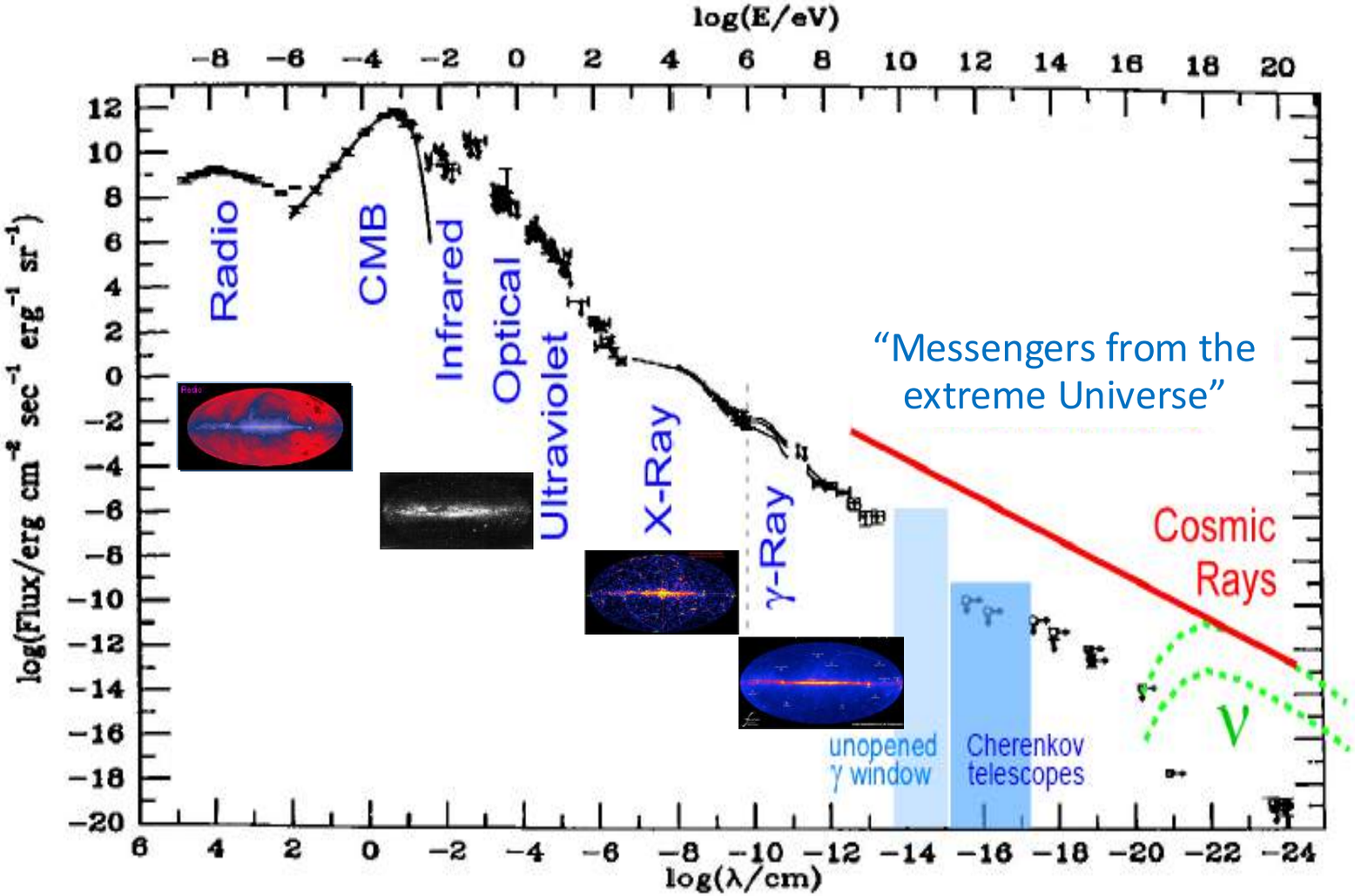
$$[\frac{1+(1-y)^2}{2}F_2^{CC,NC}(x,Q^2) - \frac{y^2}{2}F_L^{CC,NC}(x,Q^2)$$

$$\pm y\left(1-\frac{y}{2}\right)xF_3^{CC,NC}(x,Q^2)]$$

IITB-CFNS-CTEQ School, Mumbai, 9-15 February 2026

Most of our knowledge about the universe has come from observing photons

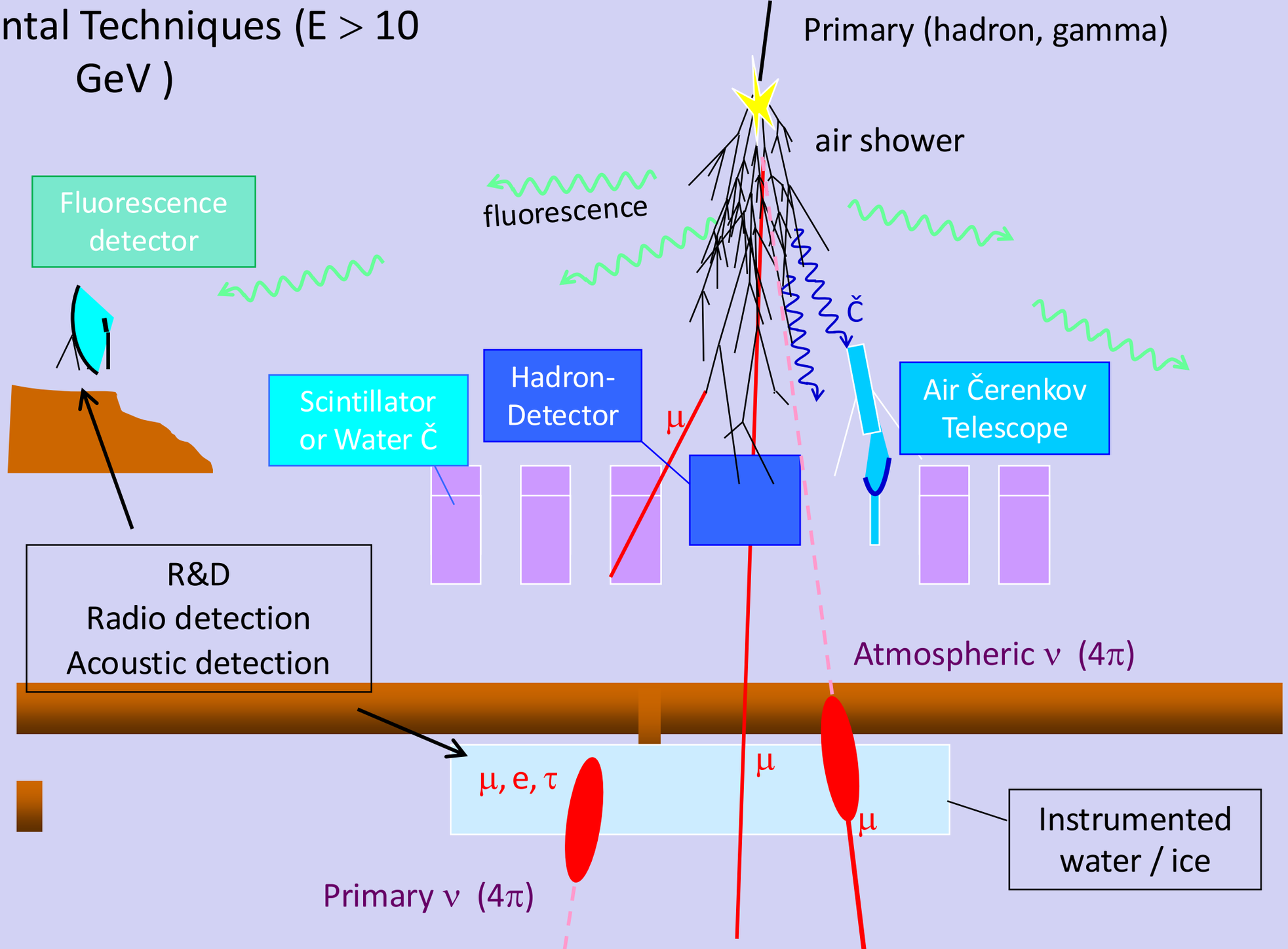
… but above ~10 TeV they are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on the Cosmic Infrared Background



Using **cosmic rays** we can perhaps 'see' (if there are no magnetic fields) up to ~6 x 10^{10} GeV (before attenuation occurs via $p\gamma \rightarrow \Delta^+ \rightarrow n\,\pi^+$ on the Cosmic Microwave Background)

But the universe is transparent to **neutrinos** at nearly *all* energies

Experimental Techniques (E > 10 GeV)



The Origin of Cosmic Rays

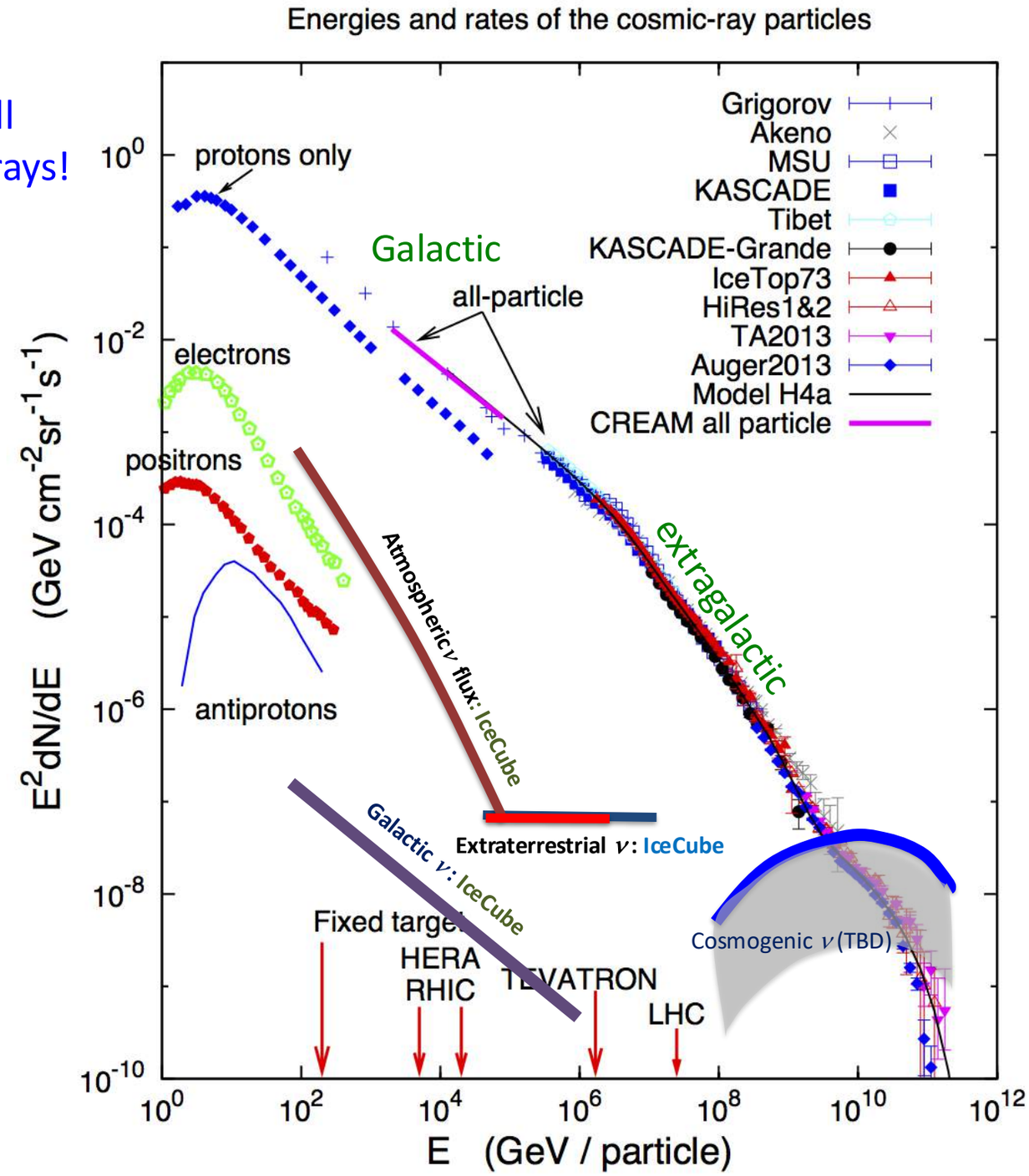
Extraordinary cosmic particle accelerators ***somewhere***, but still poorly identified over a century after the discovery of cosmic rays!

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

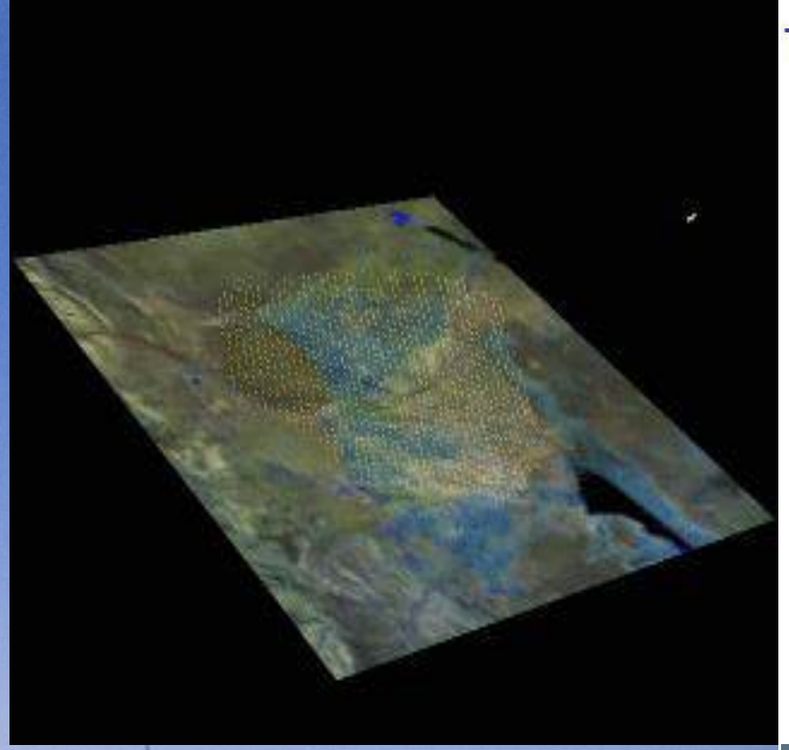
Neutrinos produced by cosmic ray interactions with matter & photons, near source or during propagation:

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

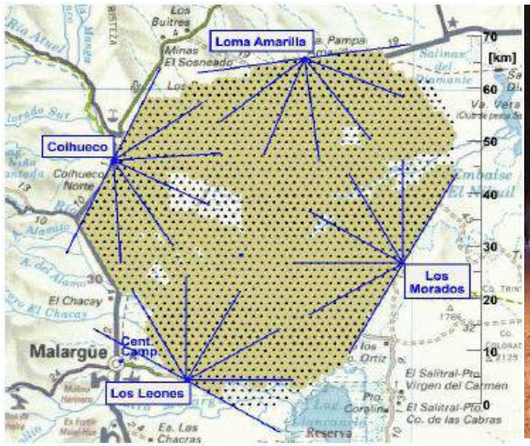
Oscillations en-route to Earth equlibrate flavours so e.g.: $\nu_e : \nu_\mu : \nu_\tau :: 1 : 1 : 1$ for above decay chain



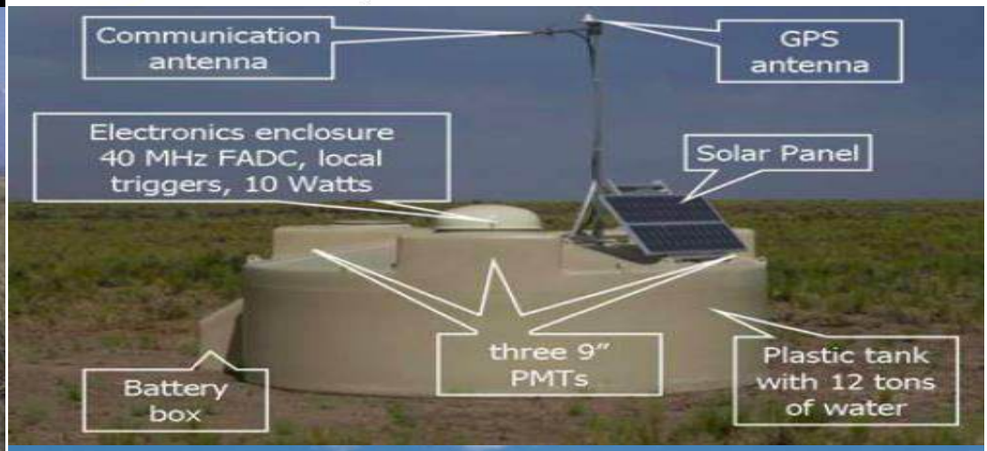
Pampa Amarilla, Argentina



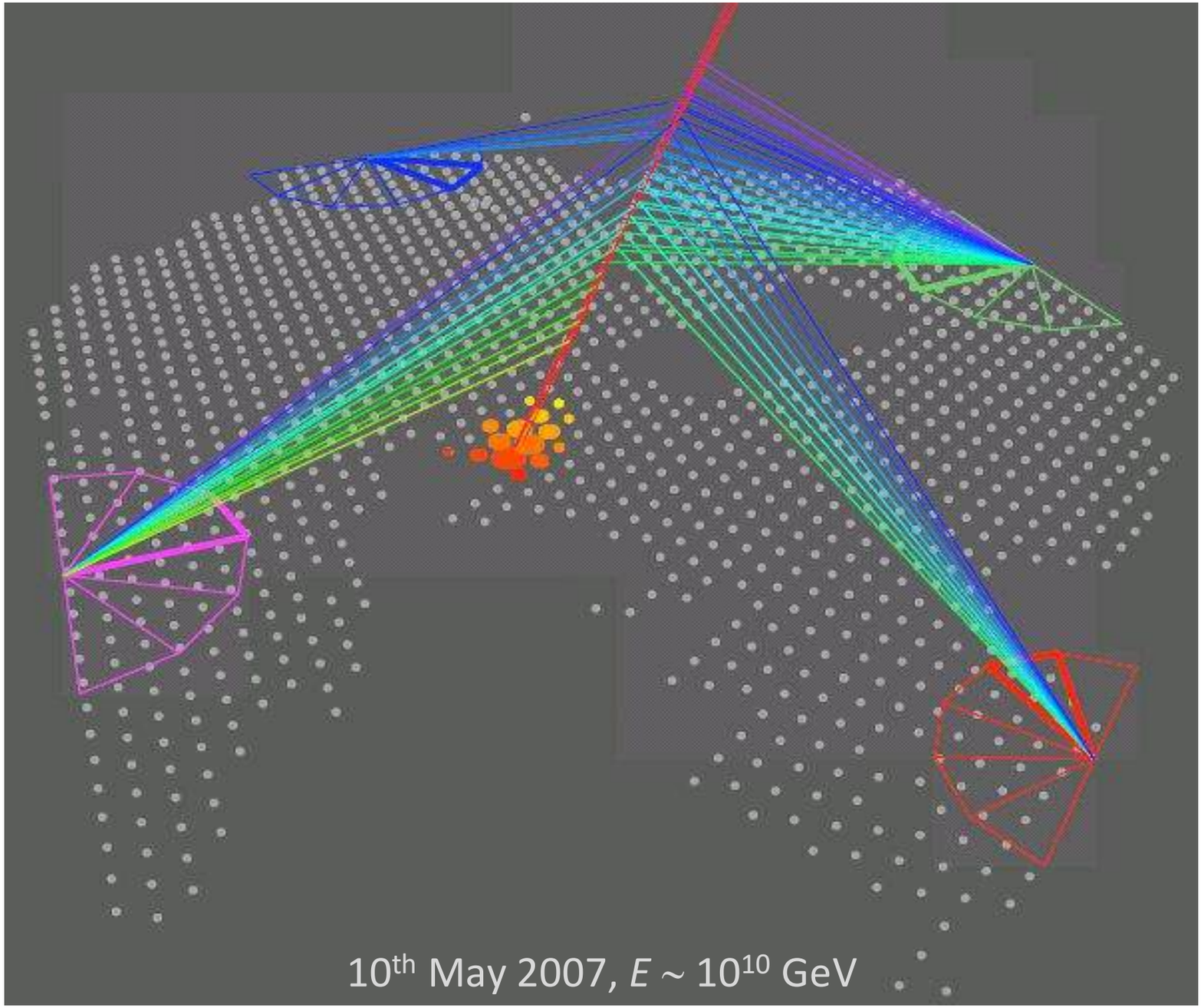
The Pierre Auger Observatory



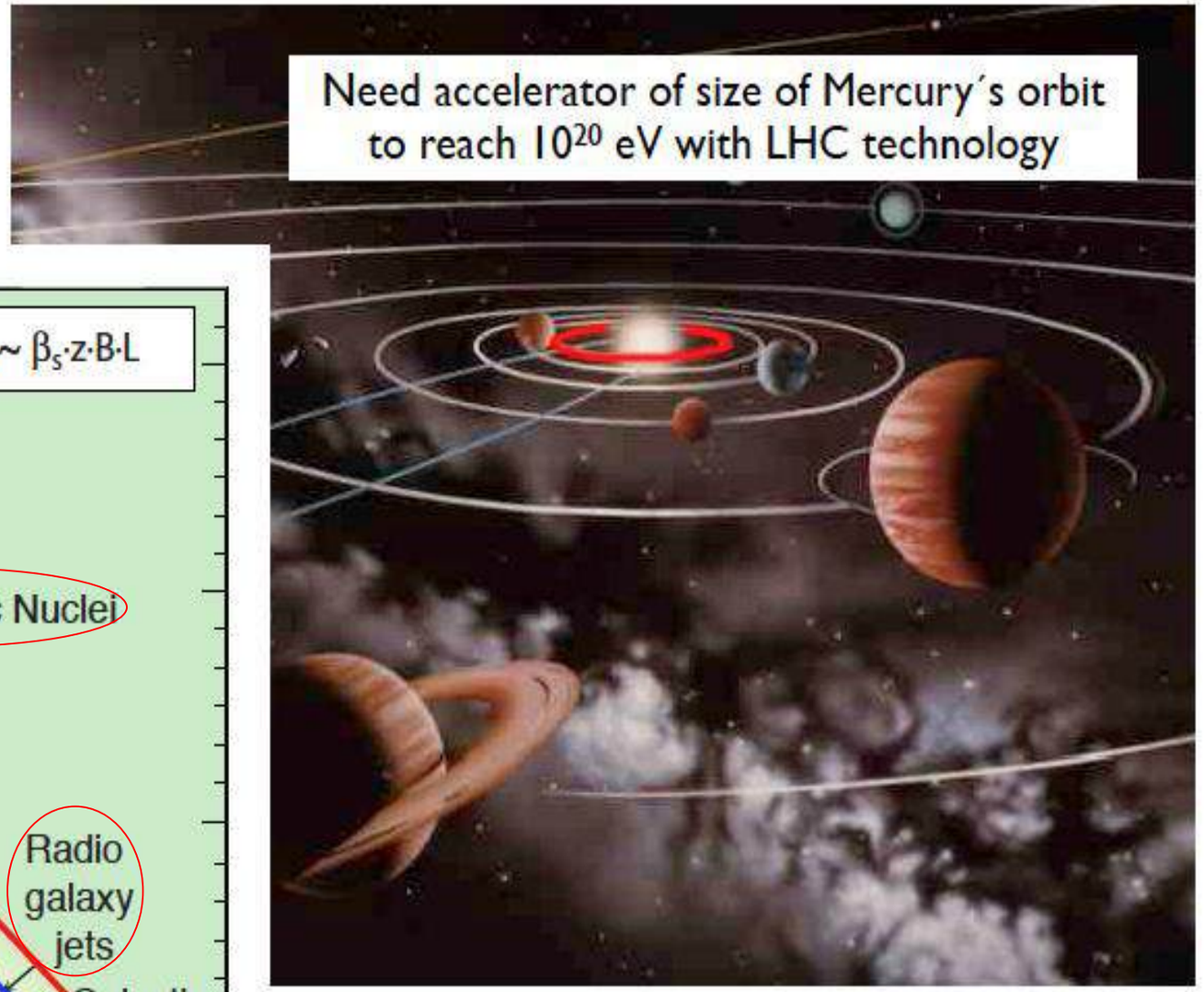
- 1600 water-cherenkov detectors ($\approx$ 1535 active)
- Aperture $>$ 7000 km^2 sr yr $\equiv$ 7000 Linsley
- 4 $\times$ 6 telescopes



The Pierre Auger Observatory detects the highest energy particles in the Universe

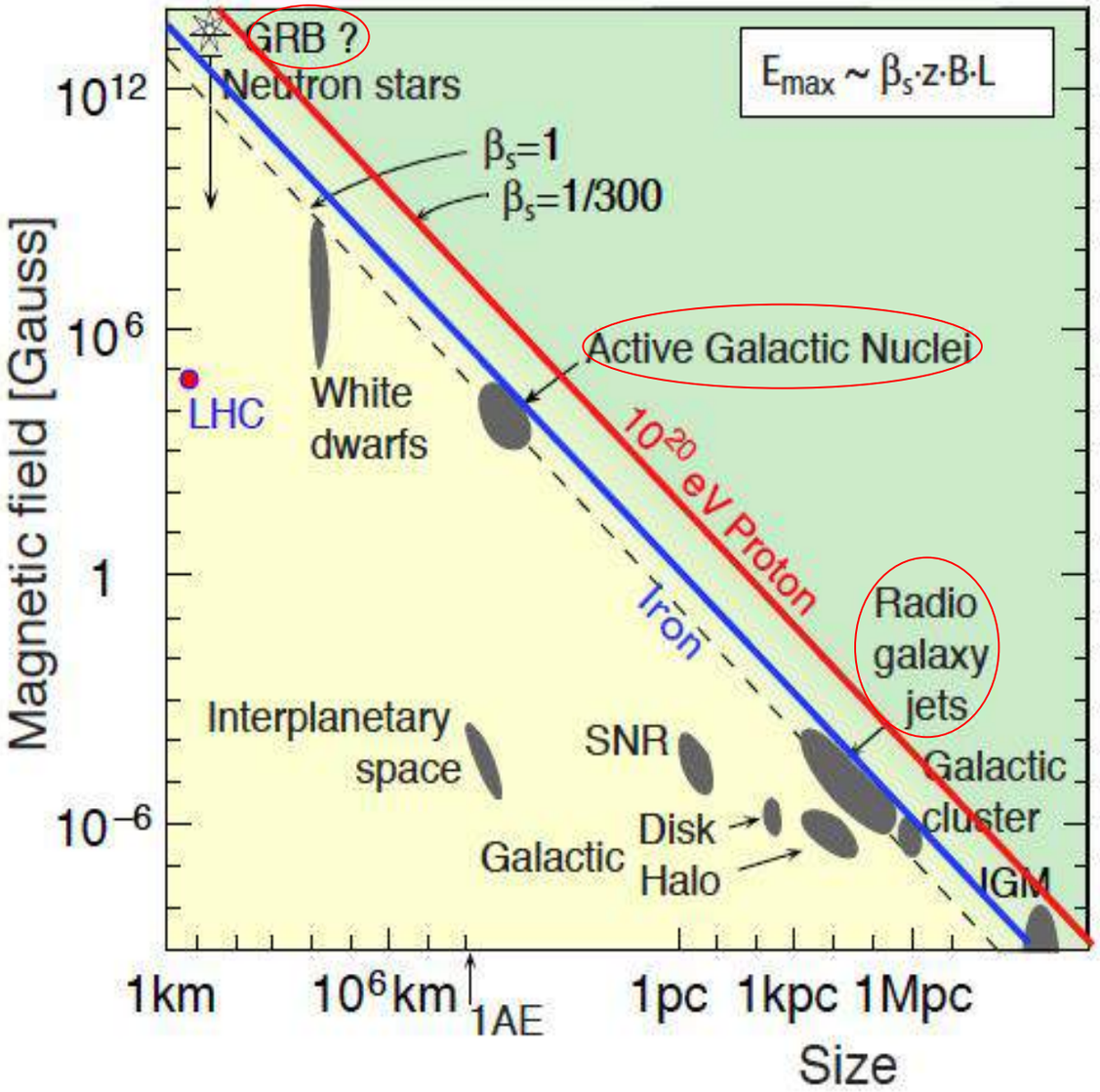


Are there plausible cosmic accelerators for such enormous energies?



(Courtesey: Ralph Engel)

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 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 :

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

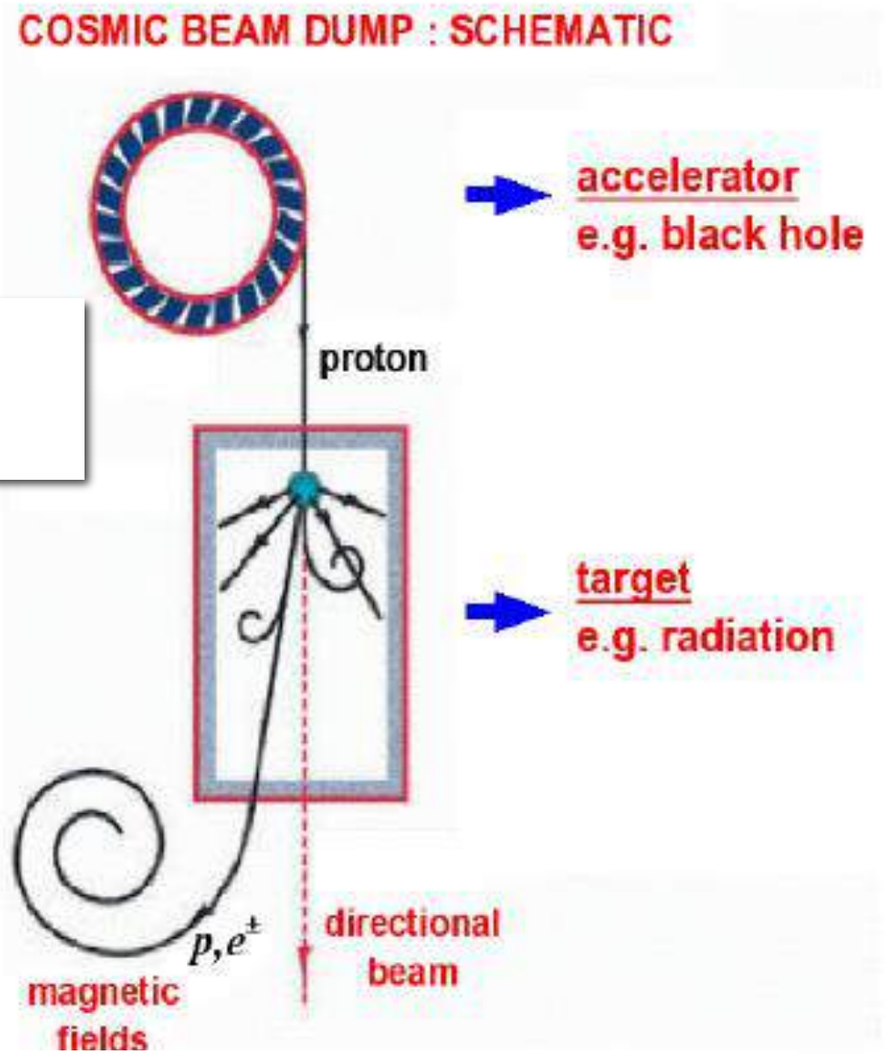
Fraction of CR primary energy converted to neutrinos

Hubble time

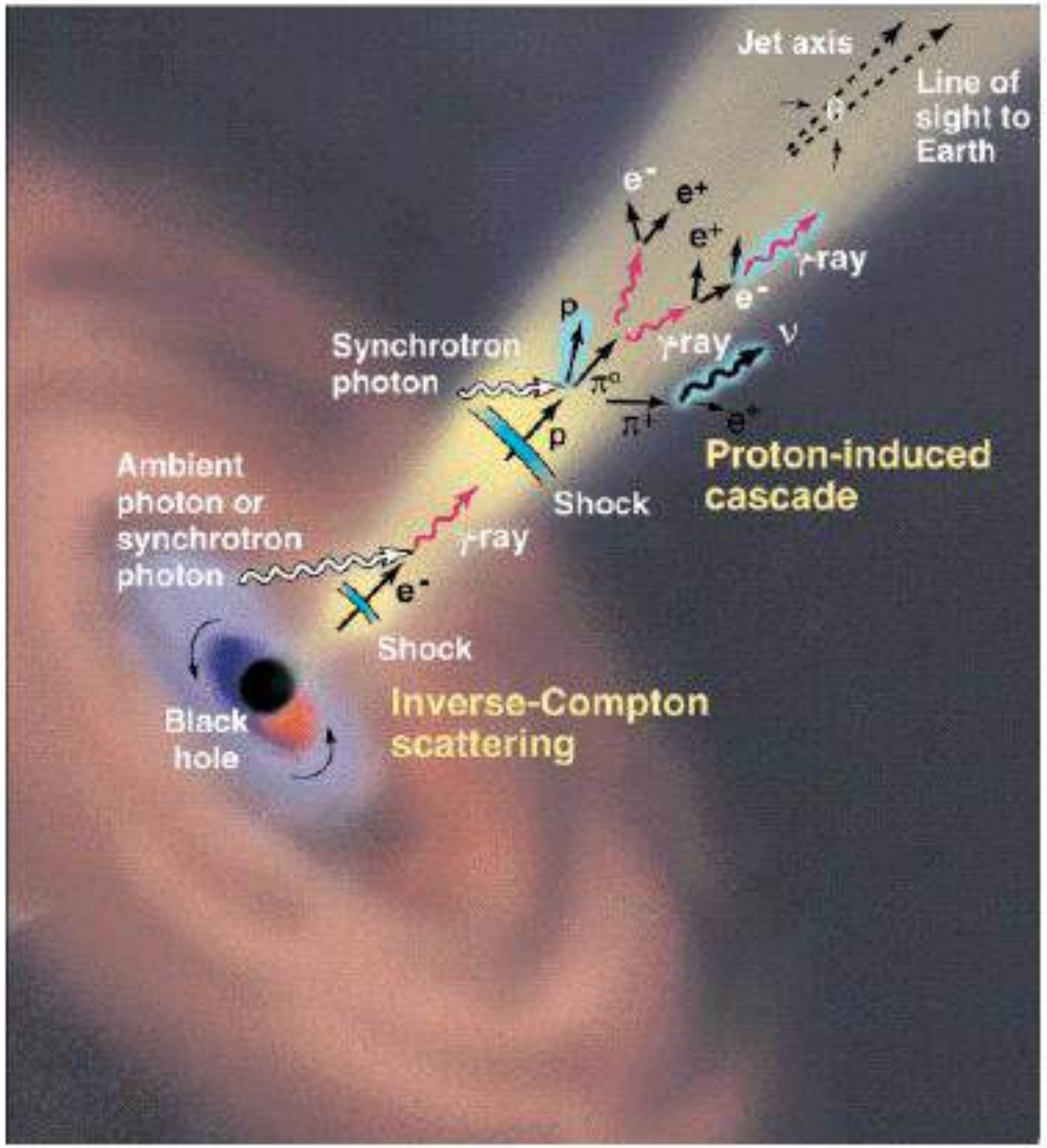
From rate of UHE CR's (10^{19}-10^{21} eV)

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

- *Many* qualifications and caveats.



➡Making a reasonable estimate for ε_π allows this to be converted into a flux prediction … would be higher if extragalactic cosmic rays become dominant at energies below the 'ankle'



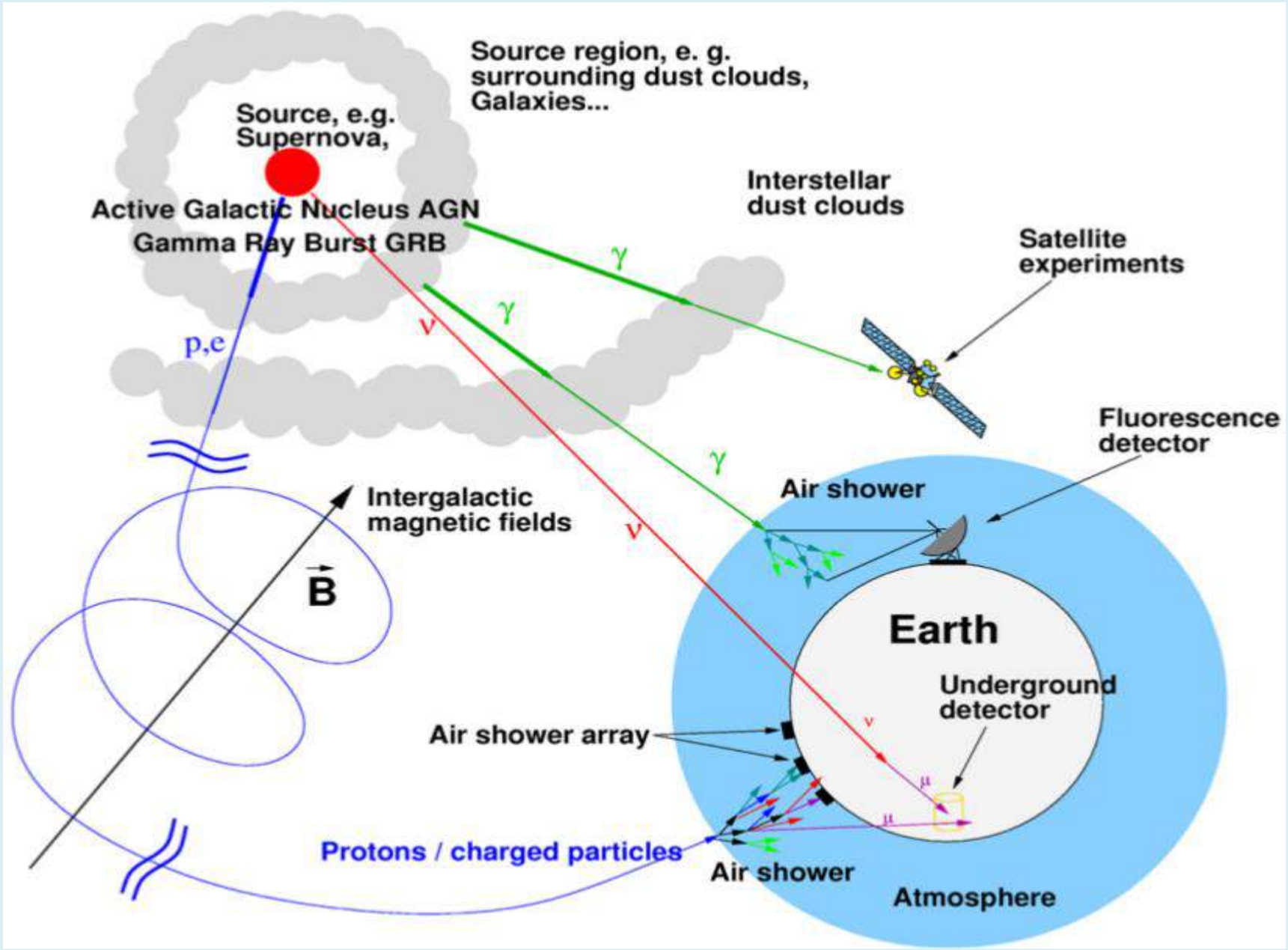
Active galactic nuclei

- Current paradigm:
  - **Synchrotron Self Compton**
  - External Compton
  - Proton Induced Cascades
  - Proton Synchrotron
- Energetics, mechanism for jet formation and collimation, nature of the plasma, and particle acceleration mechanisms are still poorly understood.

TeV ©-rays have been seen from AGN, however no *direct* evidence that protons are accelerated in such objects

… there are possible correlations with UHECRs (e.g. 2 Auger events within 3^0 of Centaurus A) however such associations may be accidental (magnetic deflections are large even at such high energies)

to see *into* the cosmic accelerators we need a messenger unaffected by intervening dust, gas or magnetic fields: **neutrinos**



To detect high energy neutrinos we first need to estimate their interaction cross-section

Above a few GeV energy, neutrinos interact dominantly via ν-N **deep inelastic scattering**
… a process that is well-understood in the **Standard Model** of particle physics

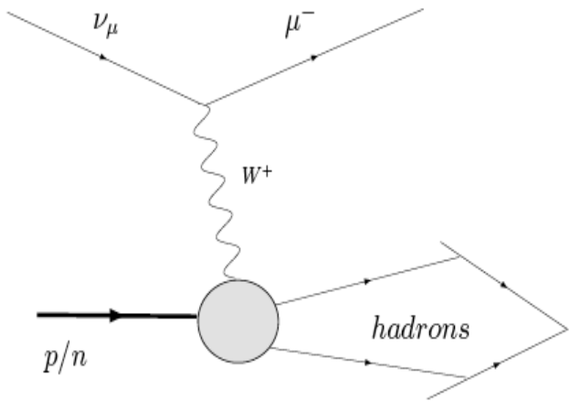
$$\frac{\partial^2 \sigma^{CC,NC}_{\nu,\bar{\nu}}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi} \left(\frac{M_i^2}{Q^2 + M_i^2} \right)$$

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

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

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

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



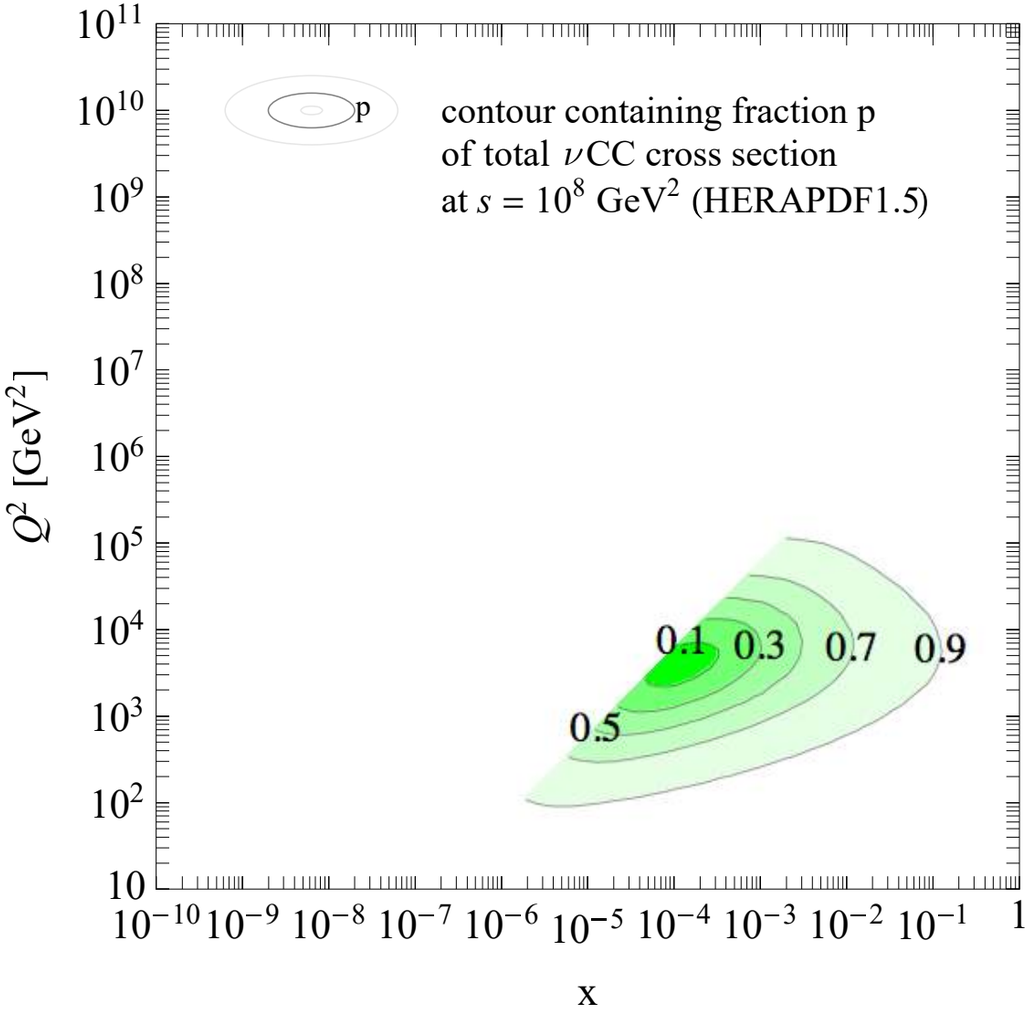
Most of the contribution to #-secn comes from: $Q^2 \sim M_W^2$ *and* $x \sim \frac{M_W^2}{M_N E_\nu}$

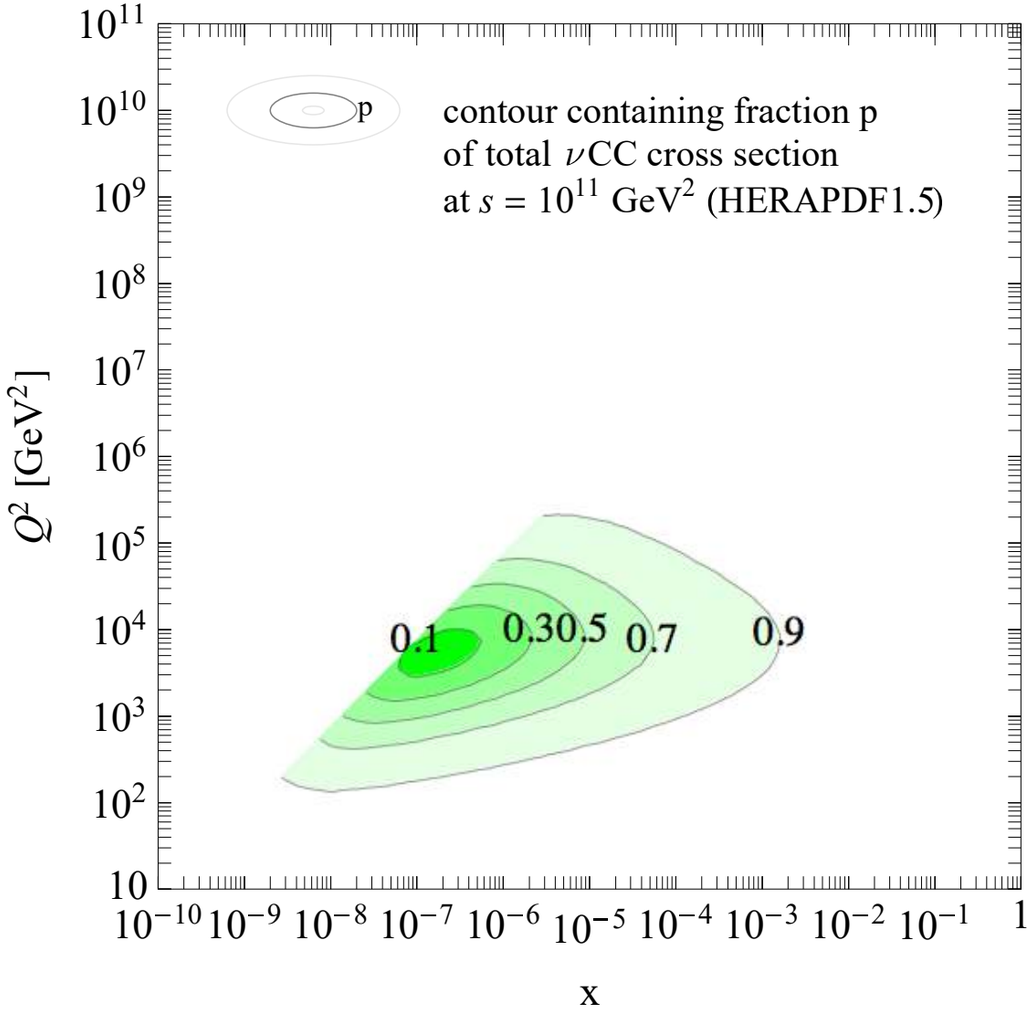
$$\text{At leading order (LO)} : F_L = 0, \quad F_2 = x(u_v + d_v + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c}),$$
$$xF_3 = x(u_v + d_v + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_v + d_v + 2s + 2b - 2\bar{c})$$

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

Use DGLAP evolution of PDFs to low-x for UHE neutrinos (heavy flavour thresholds, (small) correction for nuclear targets, etc)

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



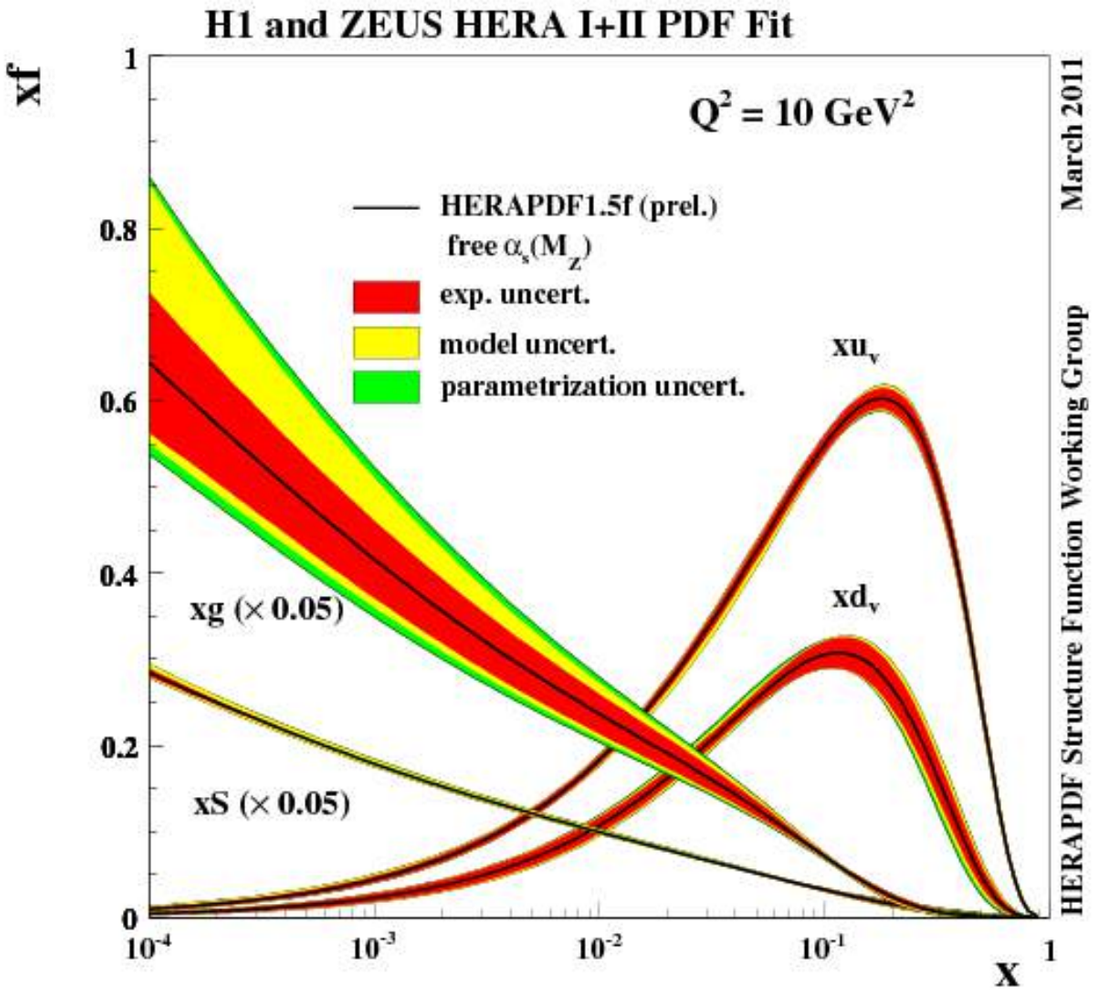


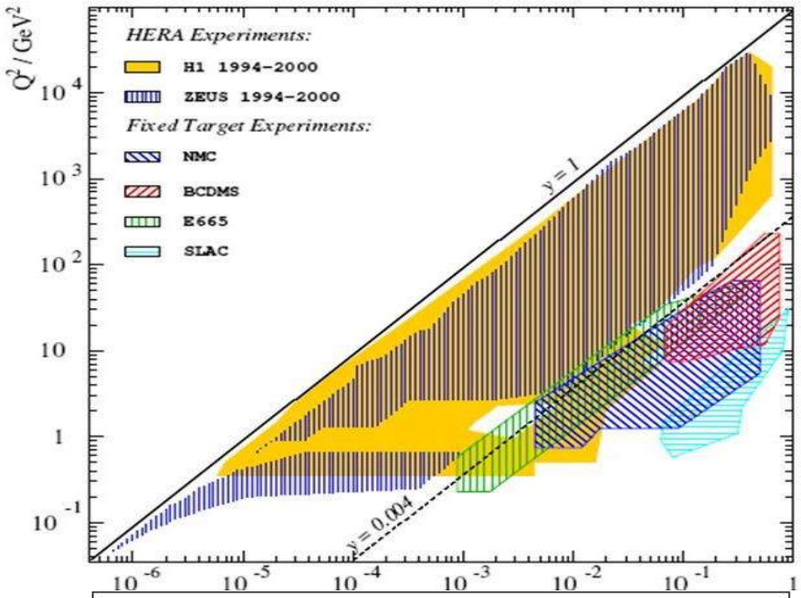
Mertsch, Cooper-Sarkar & Sarkar, JHEP 08:042,2011

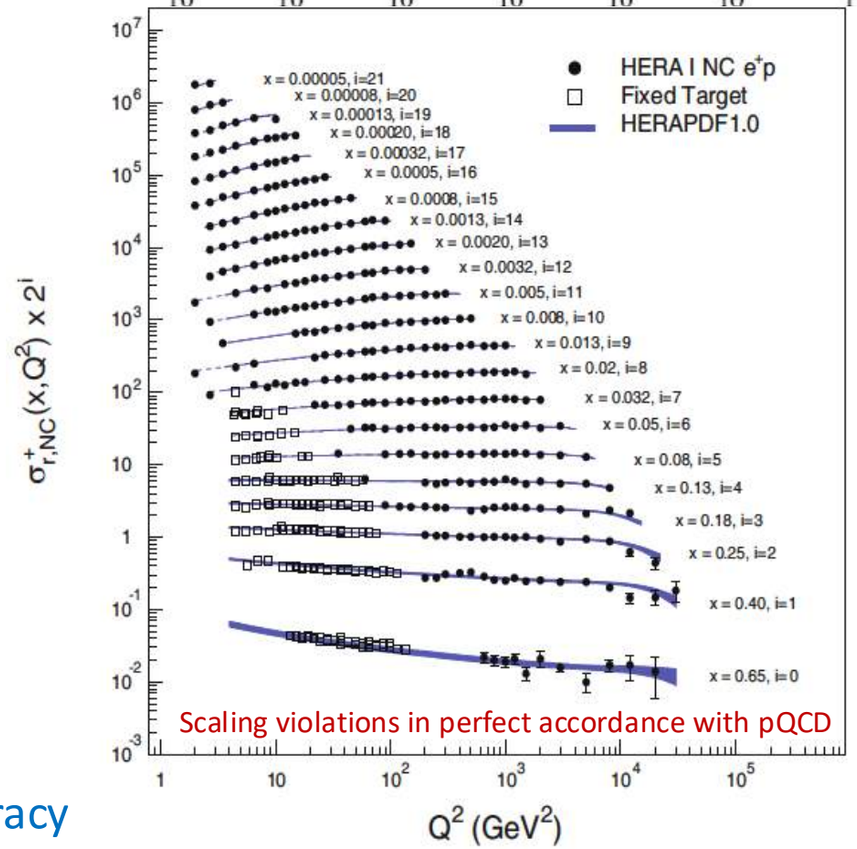
So to determine the high energy DIS cross-section accurately, it is essential to have measurements of PDFs down to as *low x* as is possible … for E_ν higher than ~10^3 TeV we have to evolve these further (using the DGLAP formalism)

(Warning: Off-the-shelf PDFs, e.g. on http://lhapdf.hepforge.org, often 'freeze' below some value of Bjorken-*x* (i.e. values are set to *zero*), so care must be taken at high E_ν to avoid errors)

The H1 & ZEUS experiments at HERA were the first to measure DIS at high Q^2 and low Bjorken-x … an unexpected finding was the very *steep* rise of the **gluon PDF** at low x which is important for ultrahigh energy neutrino interactions







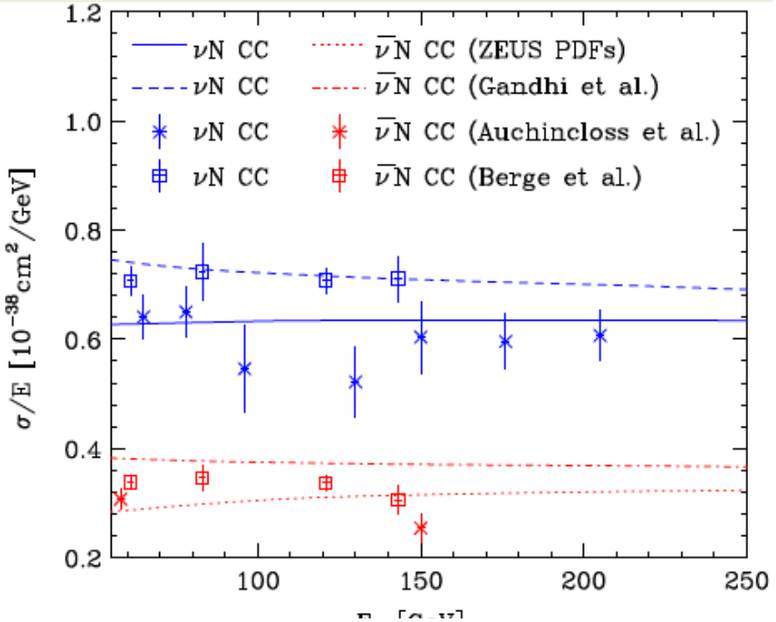
This enables the DIS #-secn to be predicted upto ~10^8 GeV with few % accuracy

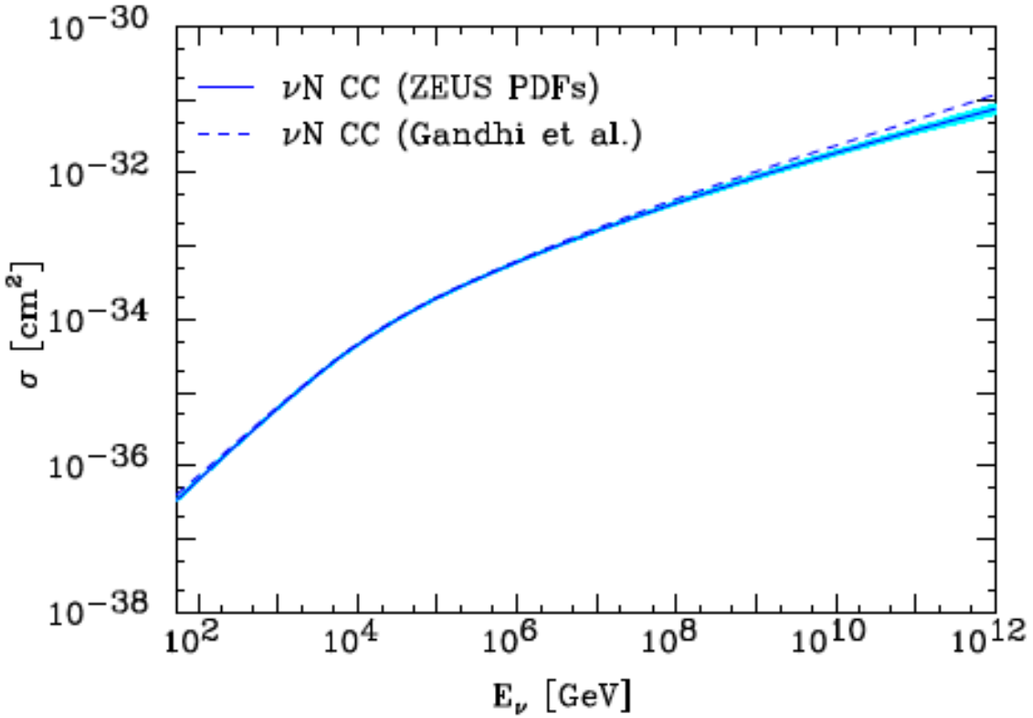
The cross-section using modern PDFs is up to ~40% *below* the previous 'standard' calculation of Gandhi *et al* (1998)

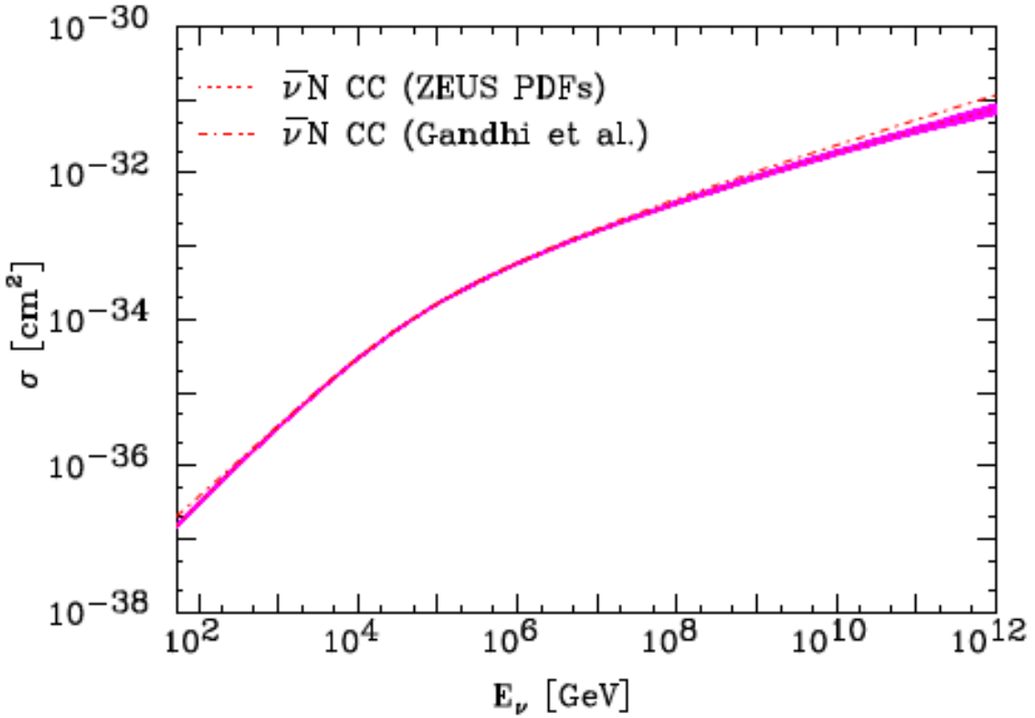
We also quantified the *uncertainty* to be < 5-10% even at the highest energies … in the framework of pQCD

At very high energies where very low-x is being probed, recombination/saturation effects may reduce the cross-section by a factor of up to ~2 … However DGLAP evolution appears to fit well *all* experimental data – so no imperative for this yet! (although fit does improve with BFKL resummation)

Agrees with low energy (>10 GeV) data







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

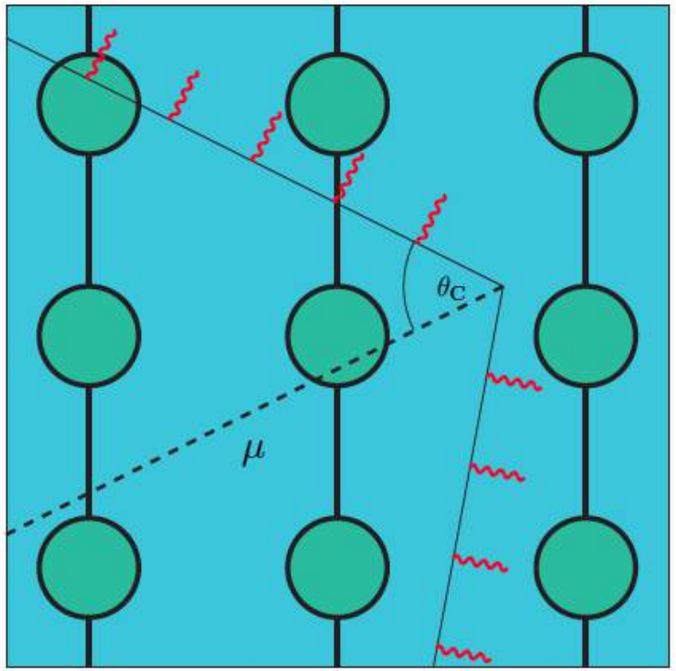
To see in high energy neutrinos requires a *big* detector!

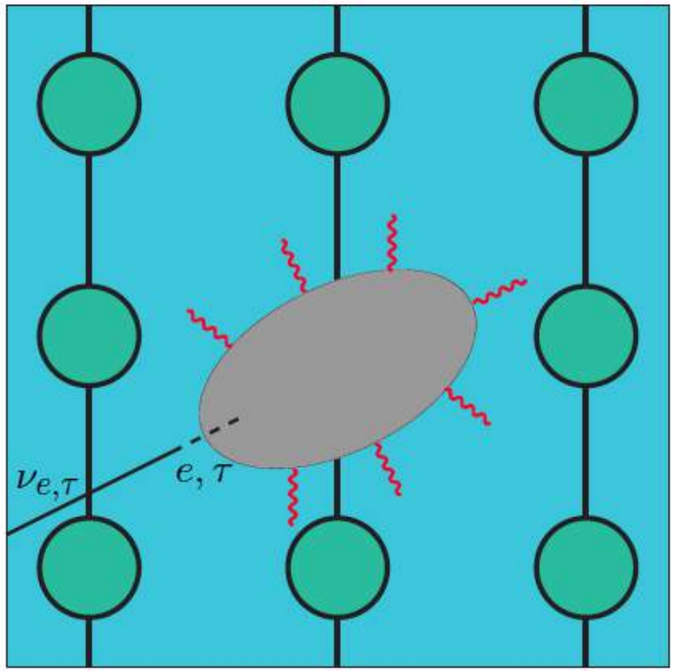
back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

- **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** :

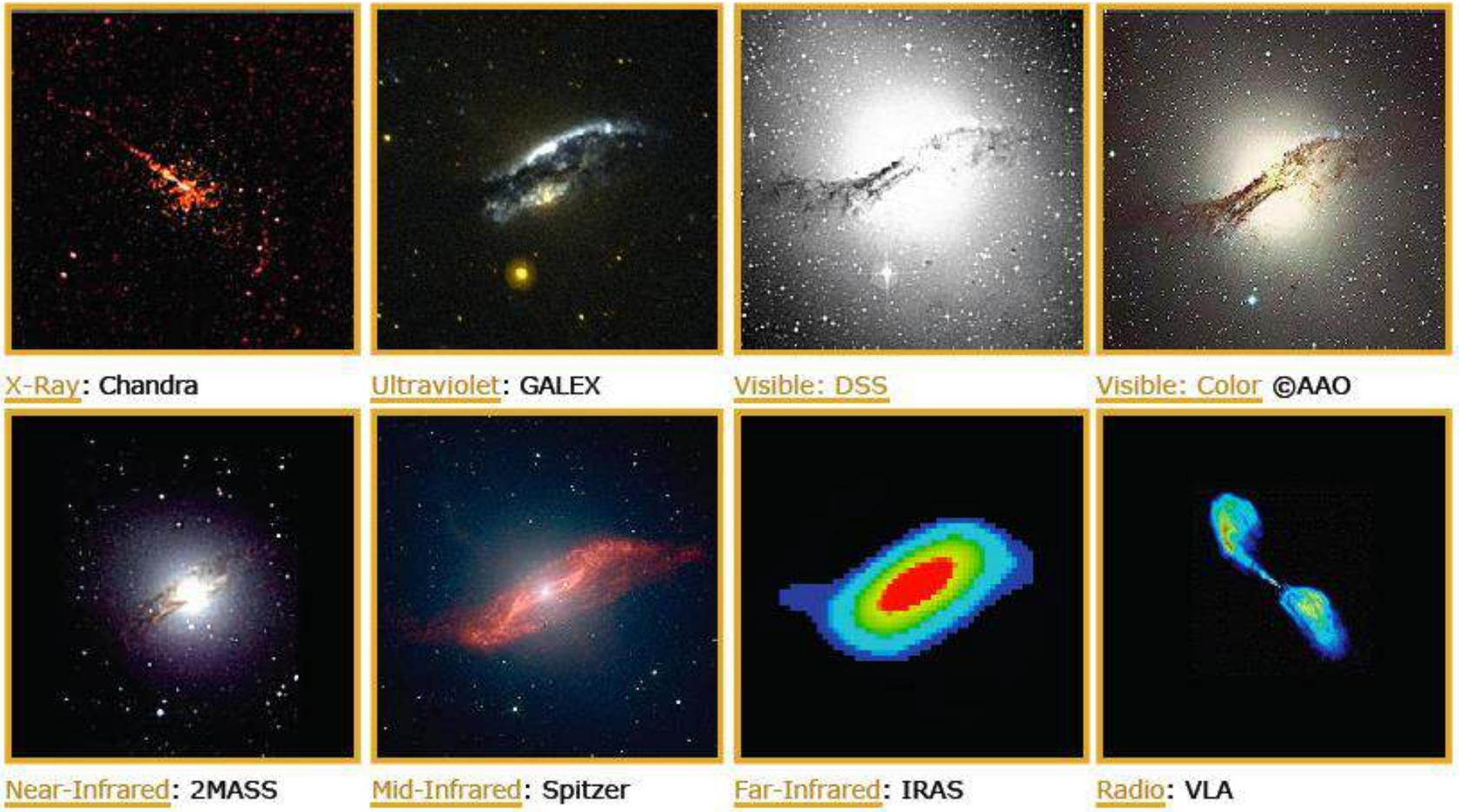
$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$





Centaurus A – Peculiar Galaxy

Distance: 11,000,000 ly light-years (3.4 Mpc) Image Size = 15 x 14 arcmin Visual Magnitude = 7.0



X-Ray: Chandra | Ultraviolet: GALEX | Visible: DSS | Visible: Color ©AAO

Near-Infrared: 2MASS | Mid-Infrared: Spitzer | Far-Infrared: IRAS | Radio: VLA

What would Cen A look like in neutrinos?

Estimated ν flux from p-p:

$$\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left(\frac{E}{\mathrm{TeV}}\right)^{-2} \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

~ 0.02-0.8 events/km^2/yr

Halzen & Murchadha [arXiv:0802.0887]

Cherenkov detectors

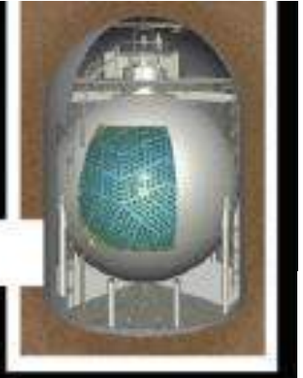
...Dumand

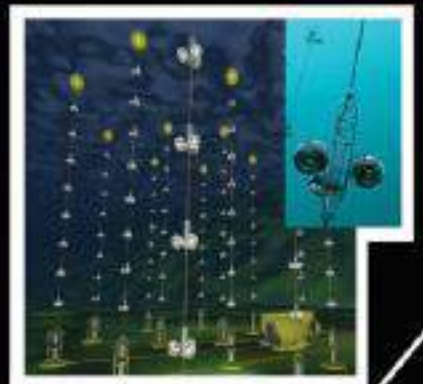
Nemo

Baksan

Hyper-K

Super-K





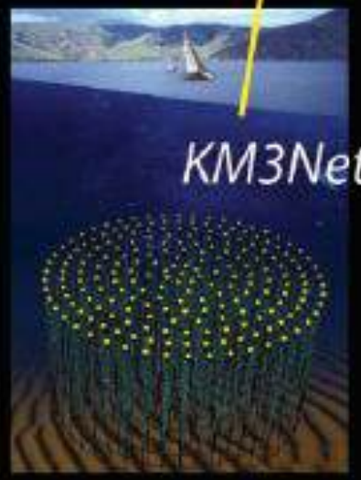
ANTARES

A world of
neutrino detectors

Lake Baikal

GVD

Nestor



KM3Net

IceCube

AMANDA

Active

Retired

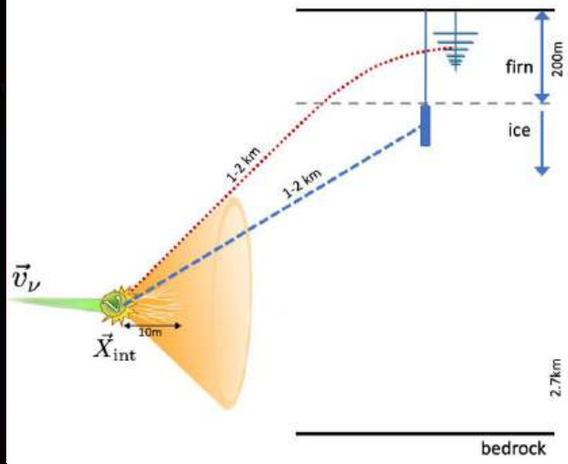
Prototype

~~Planned~~

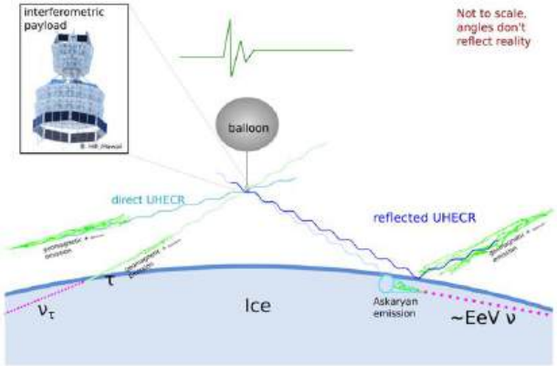
Under construction: + *GVD, P-One, TRIDENT …*

Radio Detection

arXiv:2208.04971



ARIANNA, ARA, RNO-G, … IceCube-Gen2,

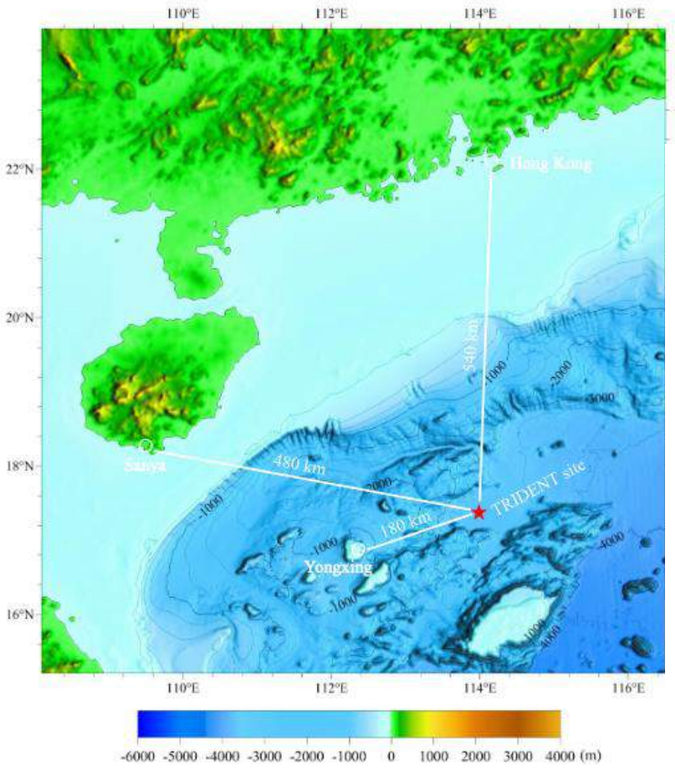


ANITA … PUEO

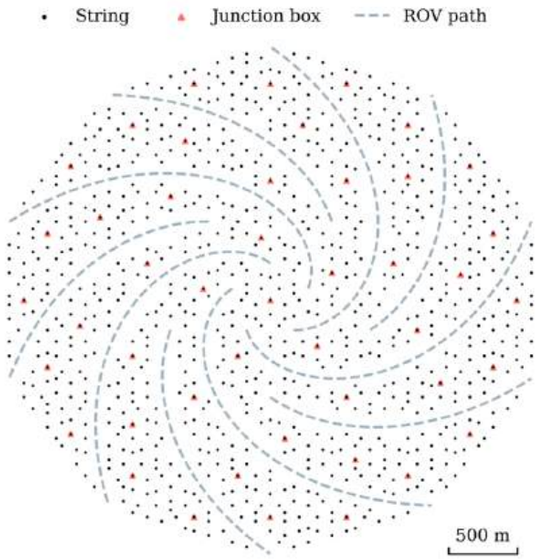
Air shower detection

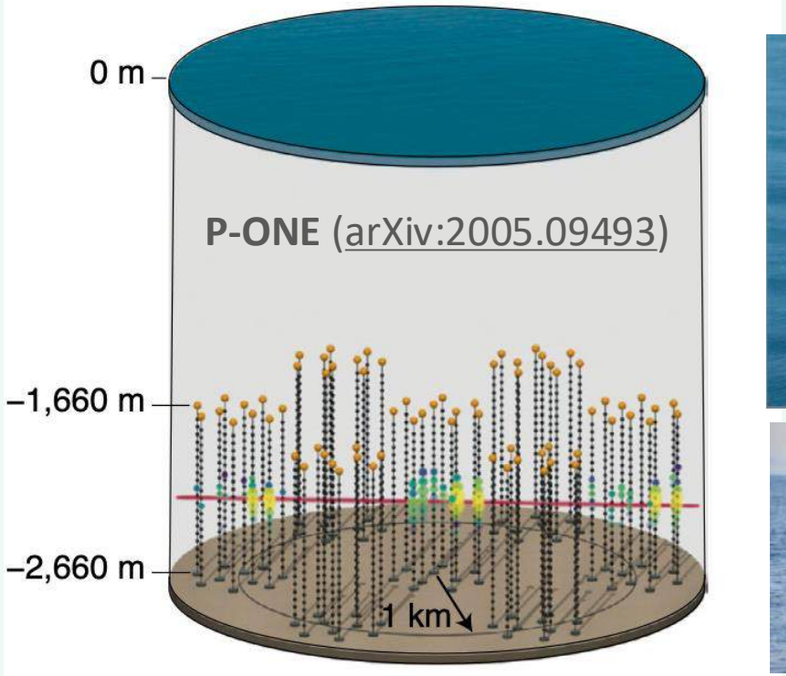
GRAND, Trinity …

GVD-Baikal
(arXiv:2109.14344)

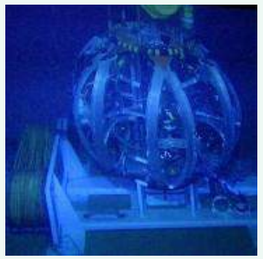


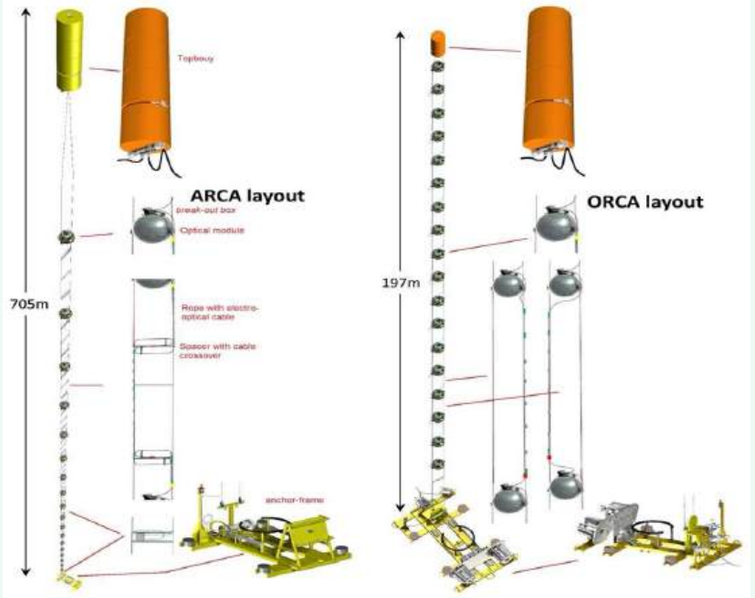
TRIDENT
(arXiv:2207.04519)



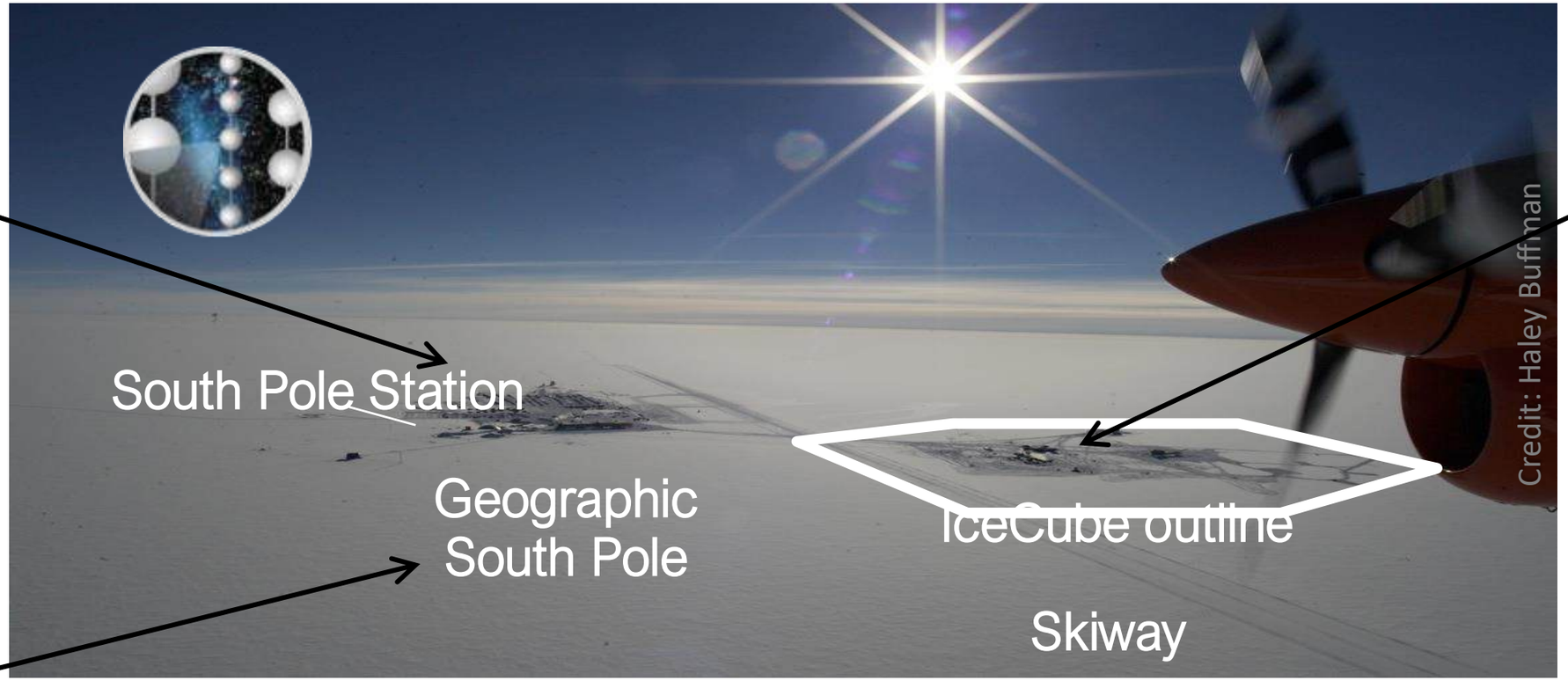


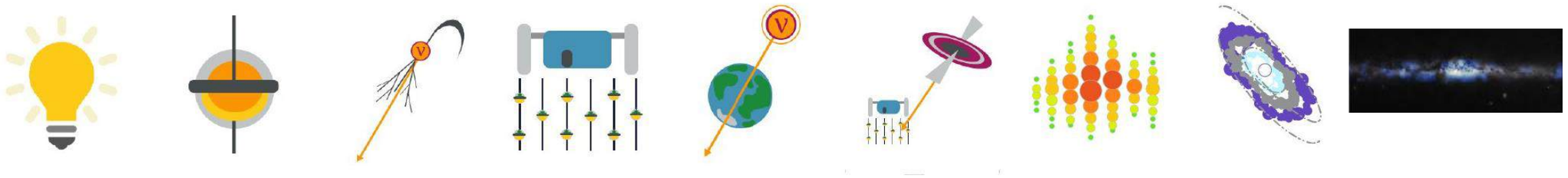
KM3NeT (arXiv:2208.07370)





The IceCube Neutrino Observatory





1988 — Telescope in the Ice Envisioned

2000 — AMANDA Completed

2001 — Atmospheric Neutrinos Detected

2011 — IceCube Completed

2013 — Astrophysical Neutrinos Discovered

2018 — First Source TXS 0506+056 Identified

2021 — Glashow Resonance Neutrino Identified

2022 — Second Source NGC 1068 Identified

2023 — Milky Way observed

IceCube Neutrino Observatory

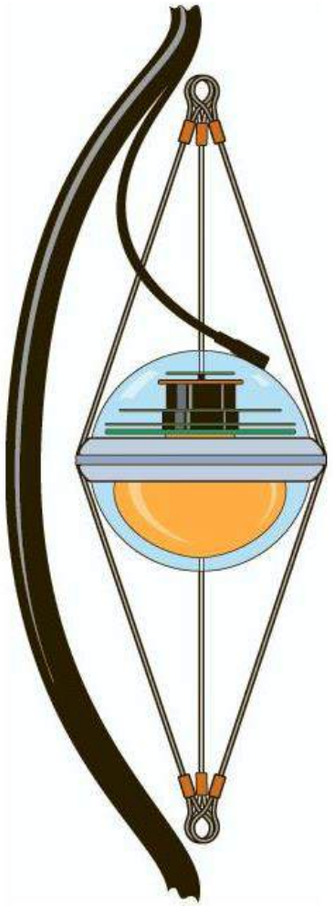
86 strings (125 m between strings)

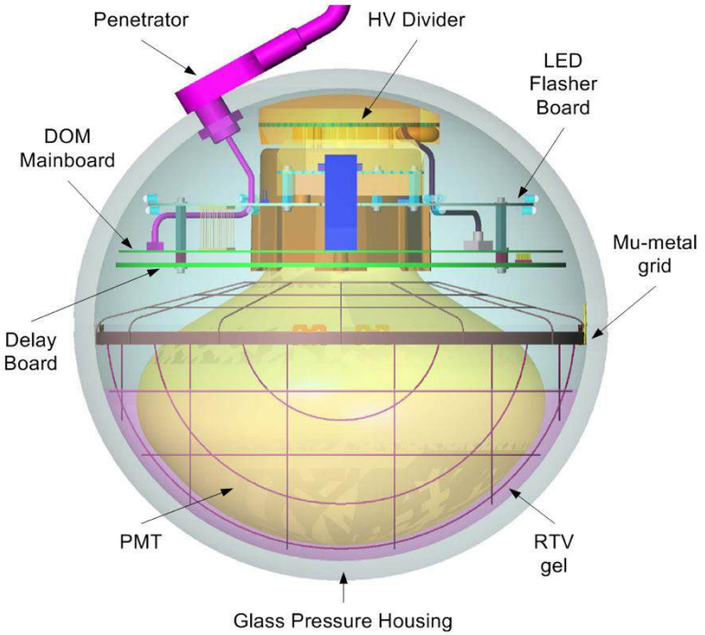
60 Optical Modules per string (17 m apart)

5160 Digital Optical Modules (DOMs) in Ice

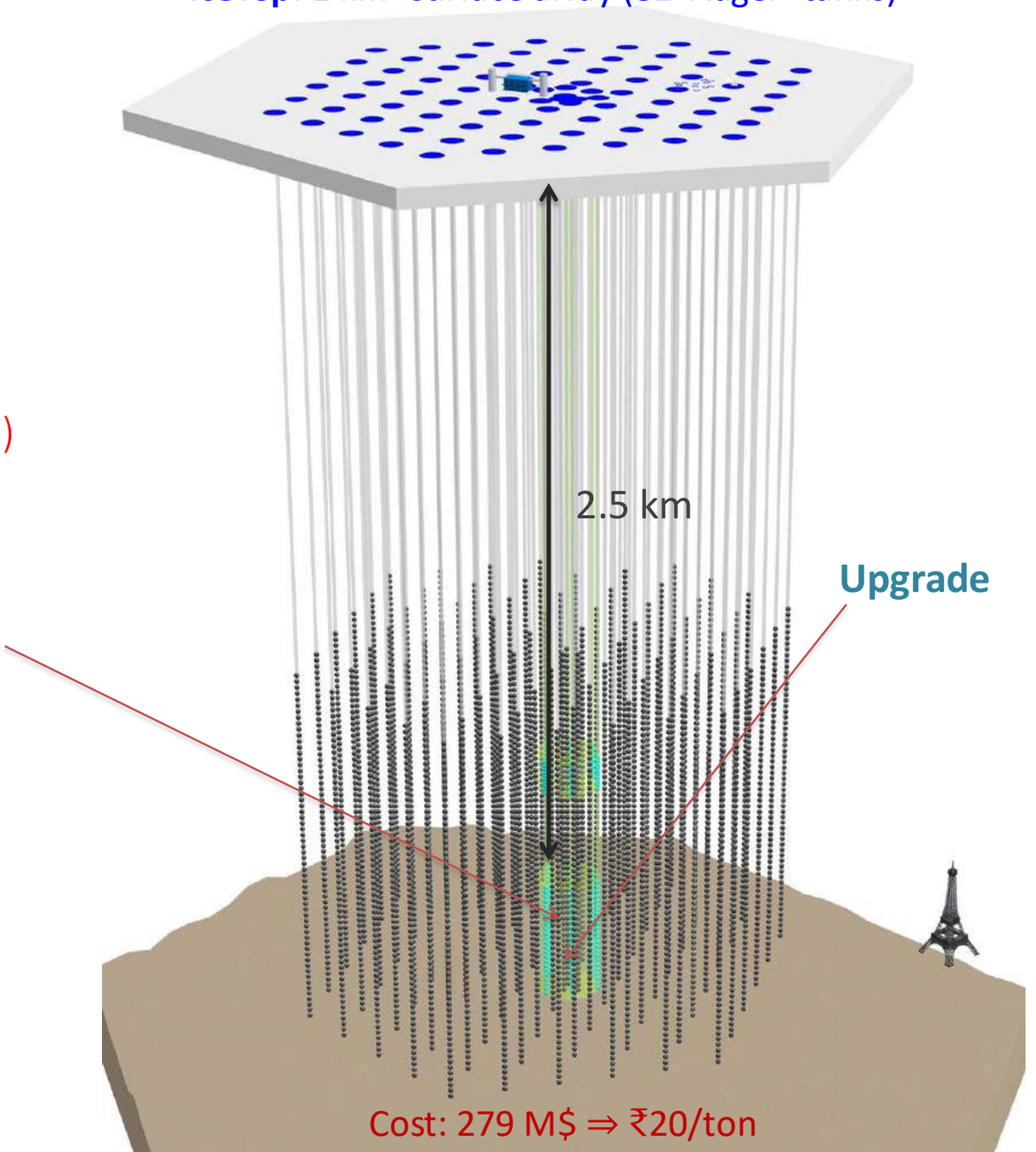
1 km^3 ⇒ Gton instrumented volume

Construction: 2004-11 (by now 14+ yrs of data)

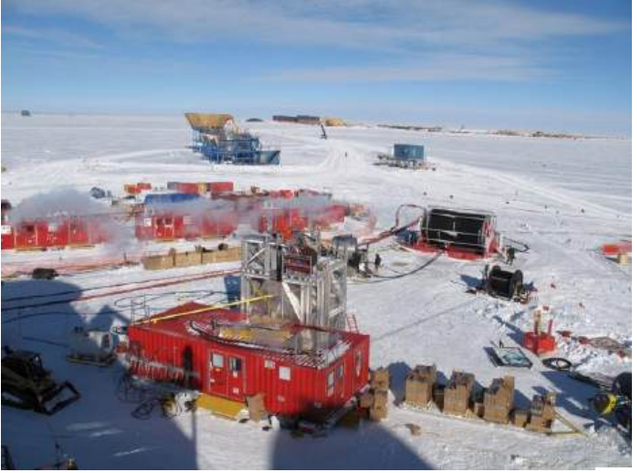


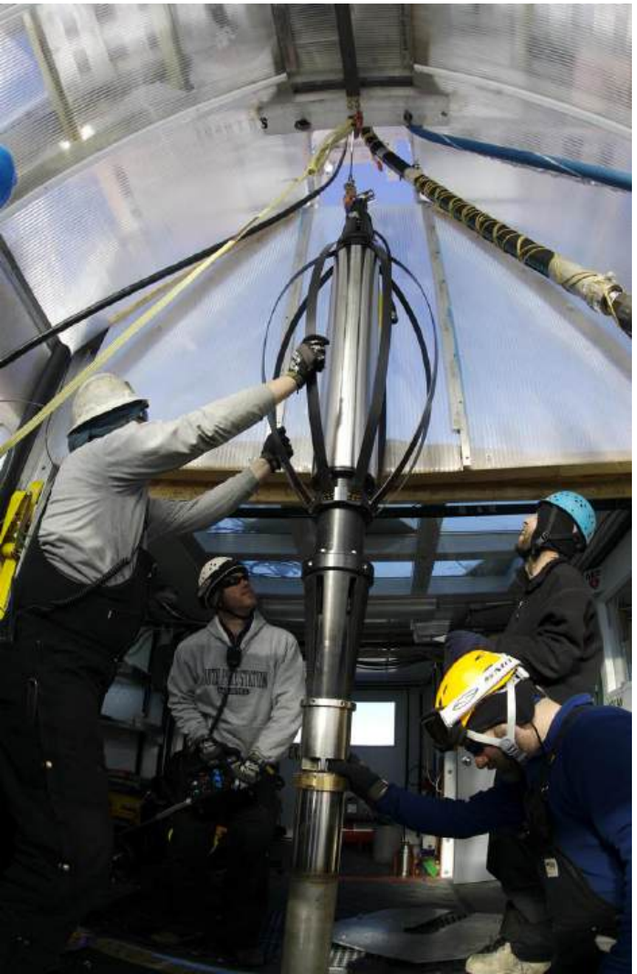


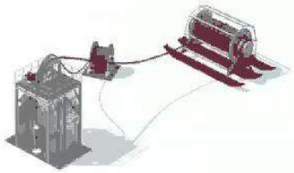
IceTop: 1 km^2 surface array (81 'Auger' tanks)



Cost: 279 M$ ⇒ ₹20/ton



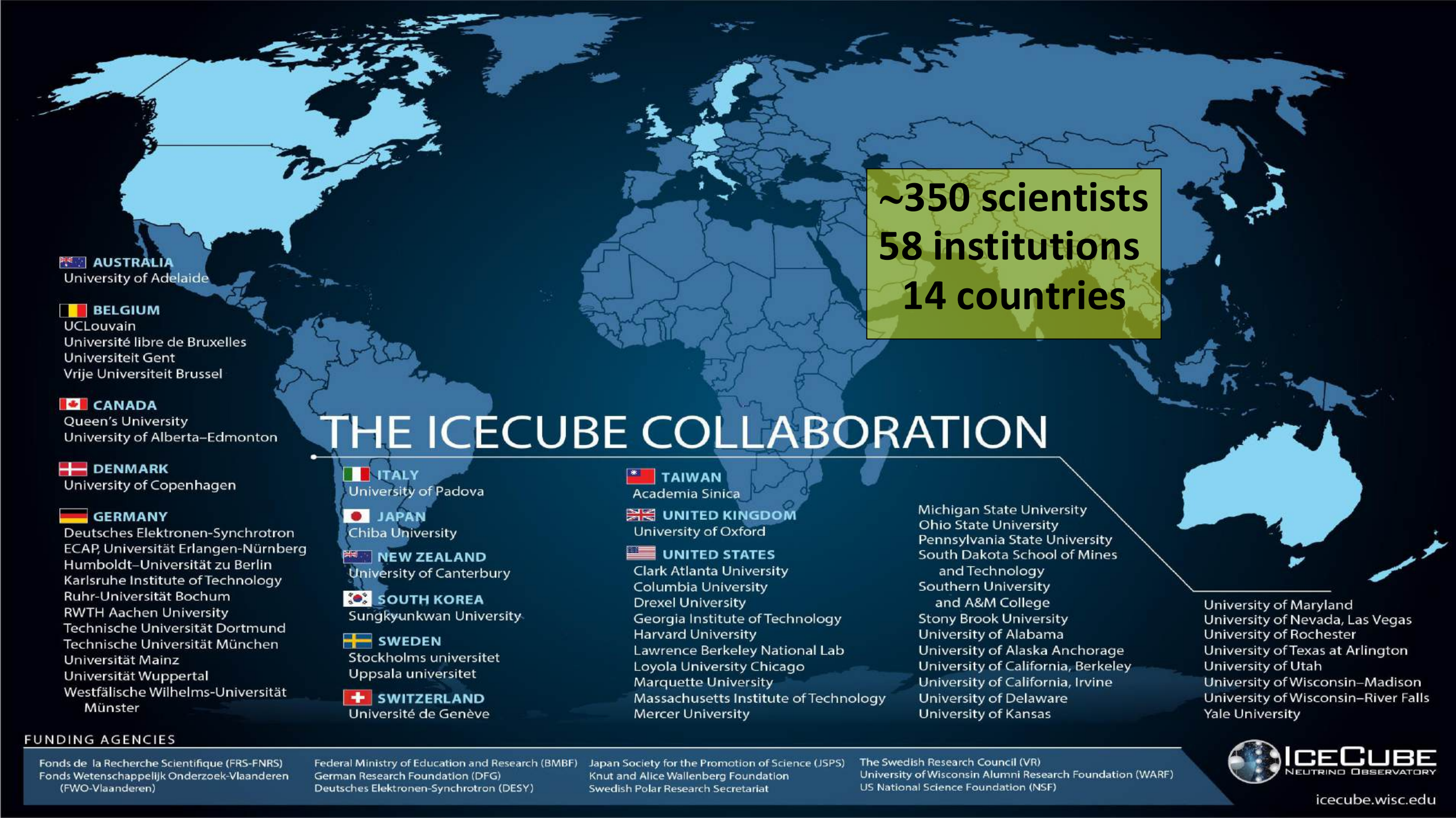




IceCube Upgrade Field Season 3 (FY26)

Weekly Report: 12/21/2025 - 12/27/2025

Figure 2 (left) preparing the first mDOM for deployment (photo: A. Ishihara/Chiba); (center) the first mDOM going down the hole.(photo: A. Karle/UW-Madison); (right) the first D-Egg goes down the hole (photo: A. Ishihara/Chiba)



THE ICECUBE COLLABORATION

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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
Queen's University
University of Alberta–Edmonton

DENMARK
University of Copenhagen

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Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
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Fonds de la Recherche Scientifique (FRS-FNRS)
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Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
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Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube Neutrino Observatory

icecube.wisc.edu

High Energy Neutrino Detection Principle

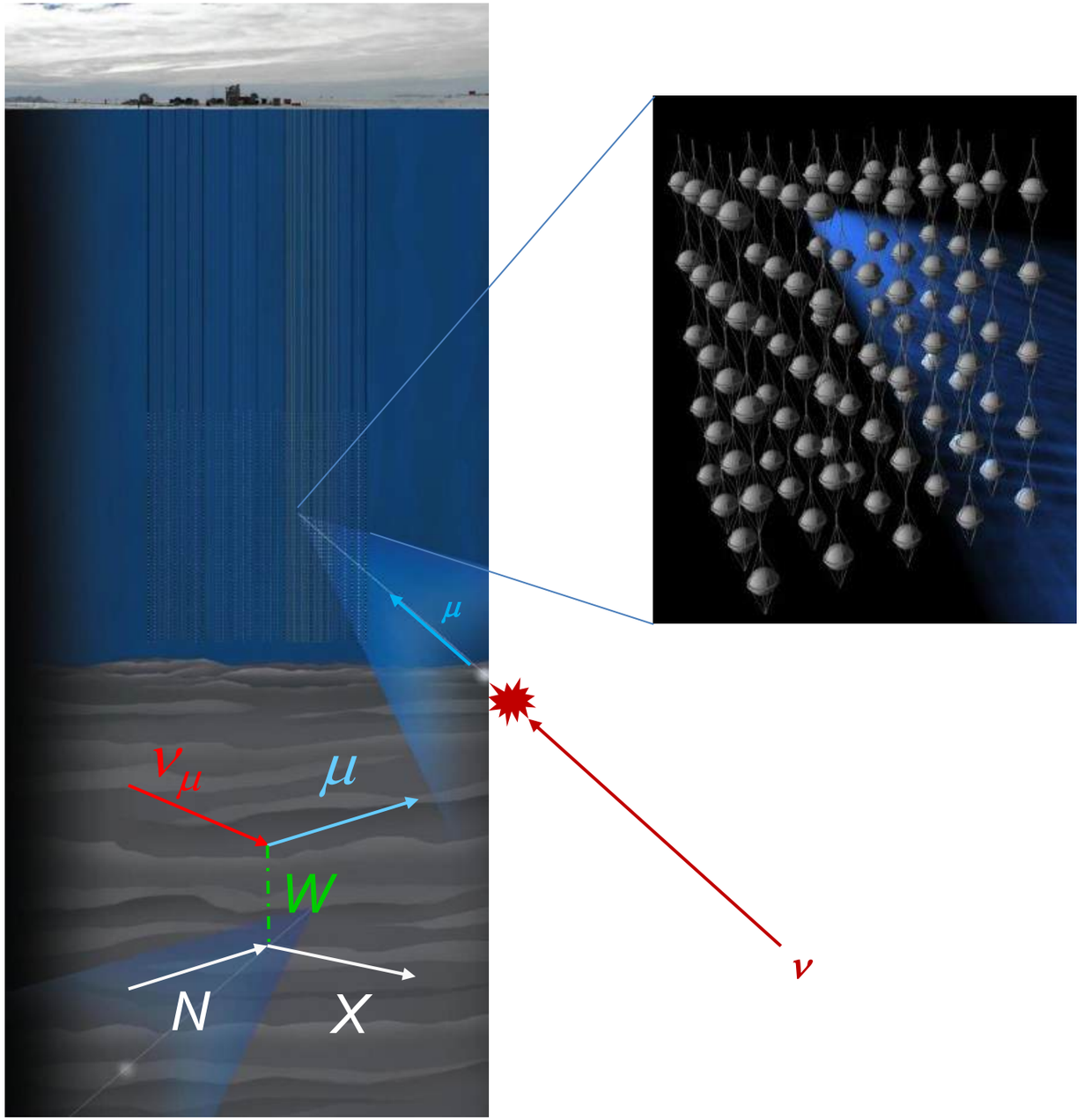
- A ν interacts with a nucleus
  … produces a μ (e or τ)
  and/or a ‘cascade’

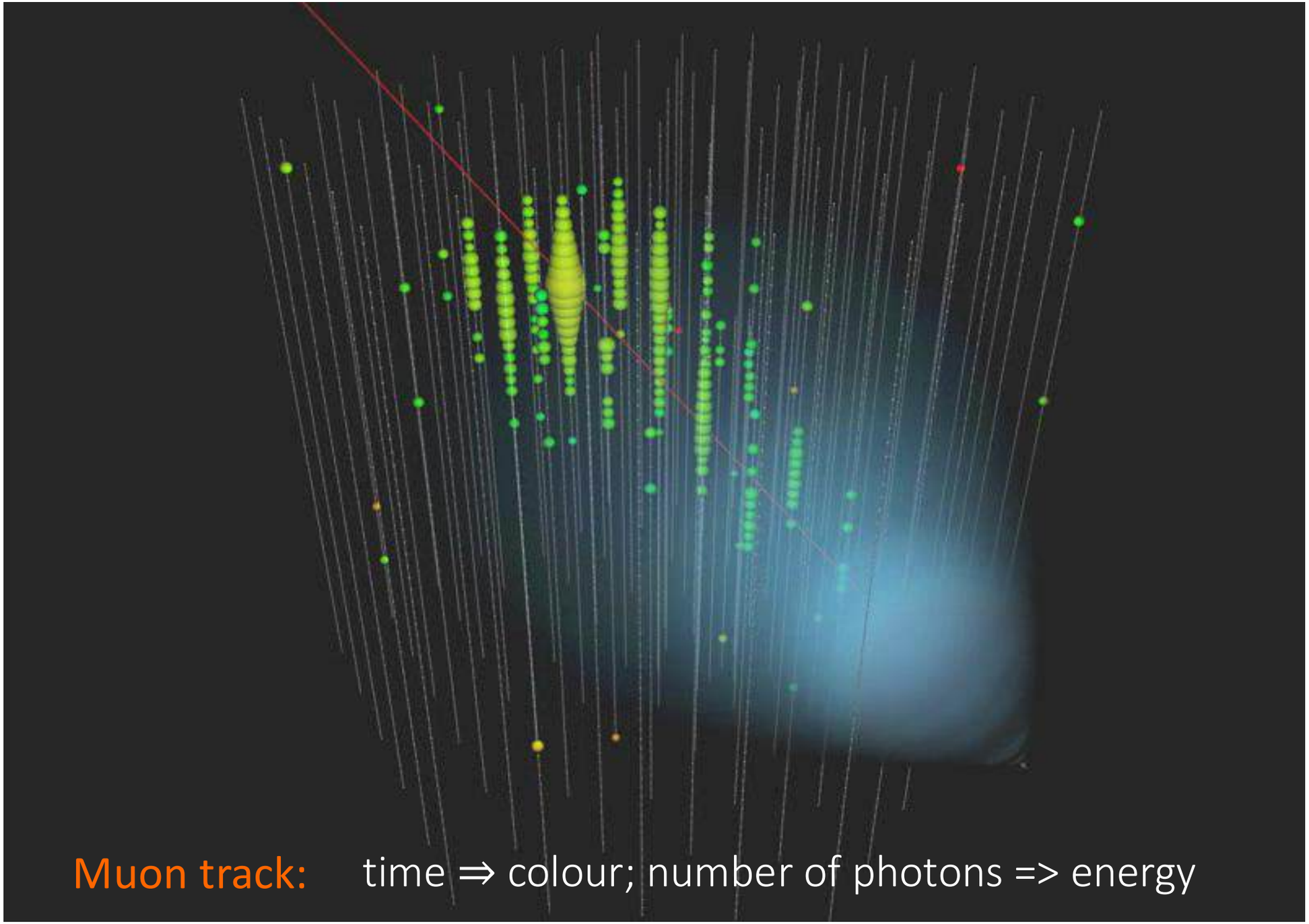
- A charged particle moving at *superluminal* speed gives rise to Cherenkov radiation (cone $\angle$ 40°)

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

Position, time & amplitude of hits allows reconstruction of tracks using likelihood optimisation (machine learning …)

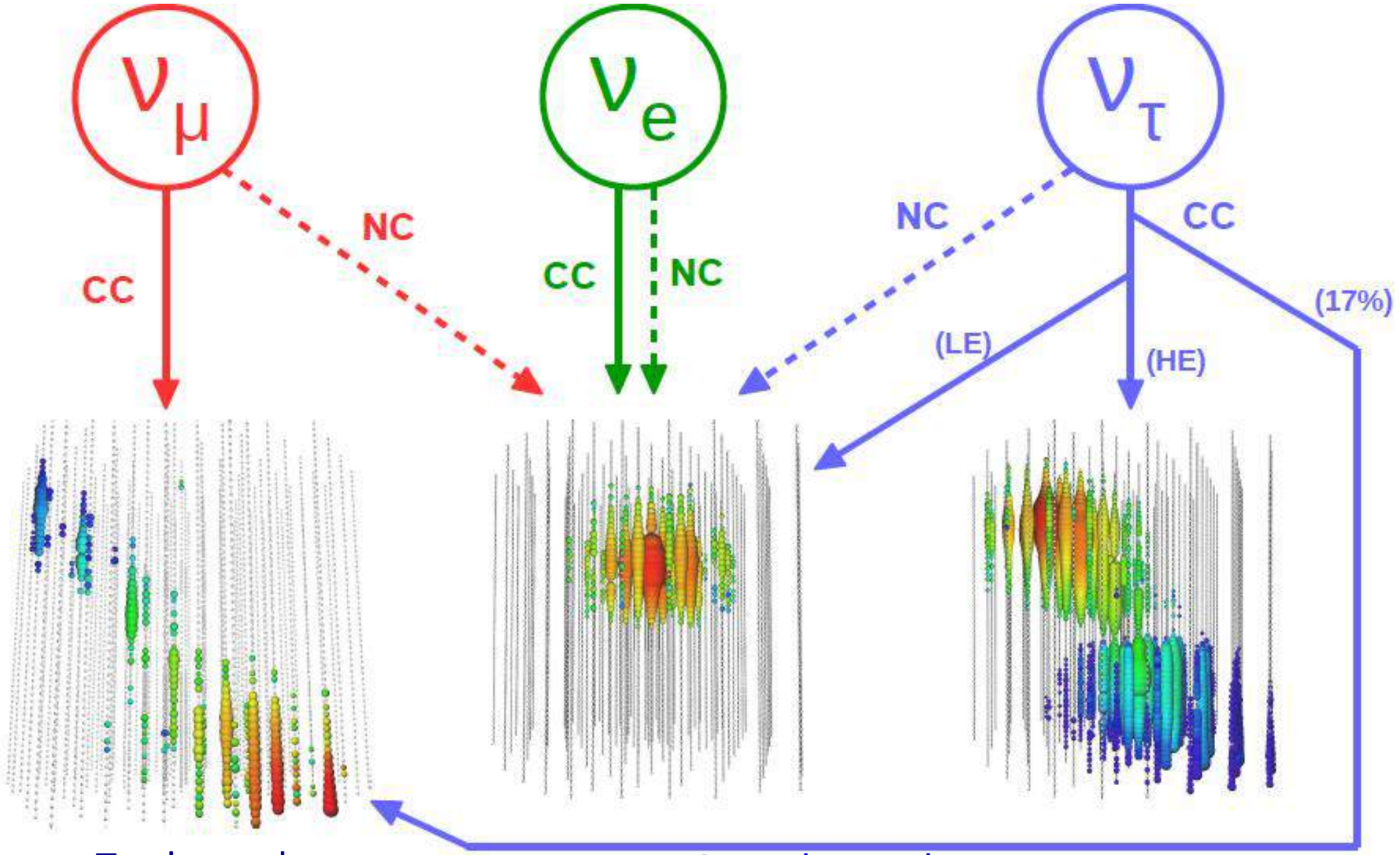
The lepton direction is aligned with the incoming ν ⇢ astronomy!





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

Neutrino flavour discrimination in IceCube



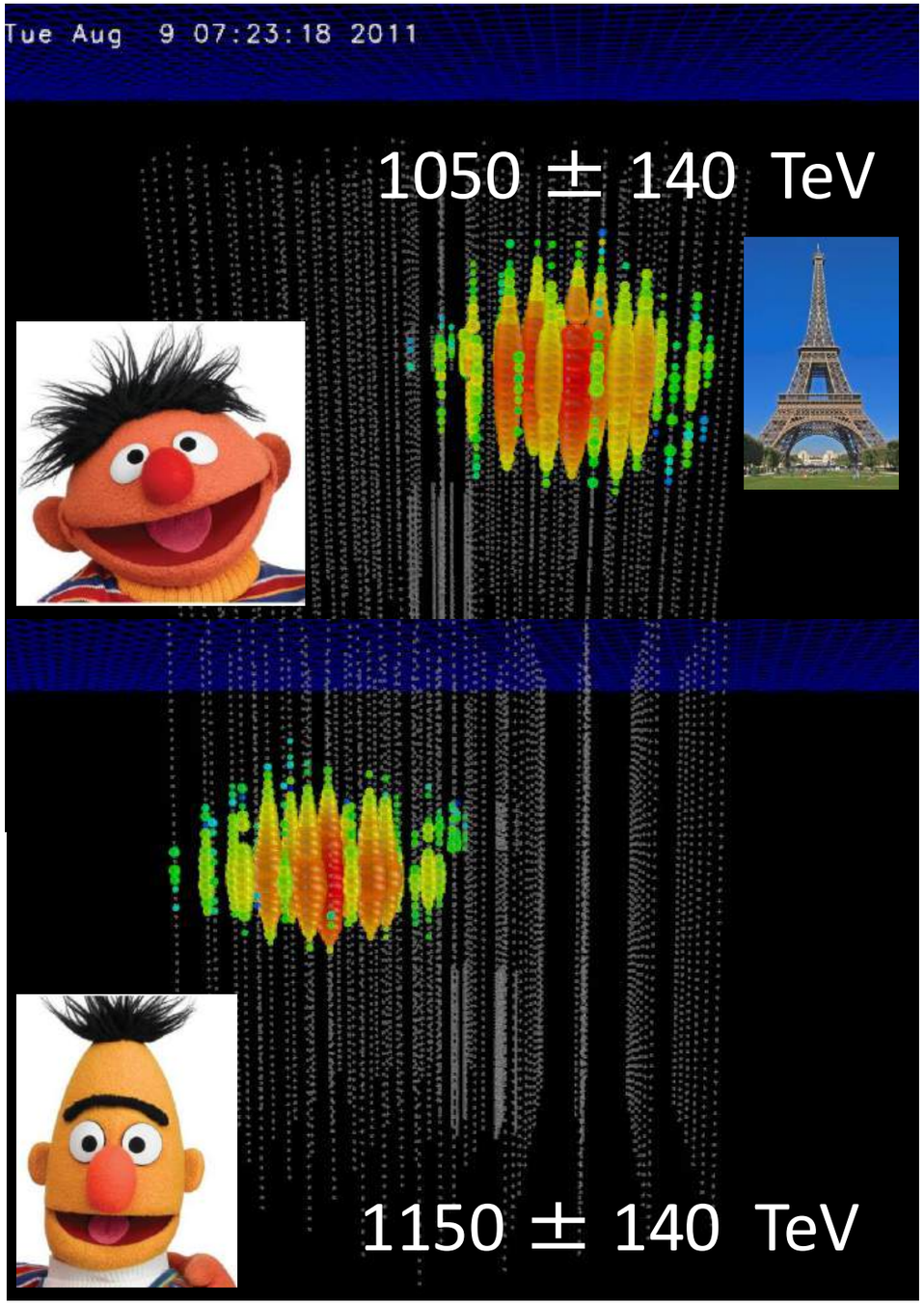
Track topology

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

Cascade topology

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

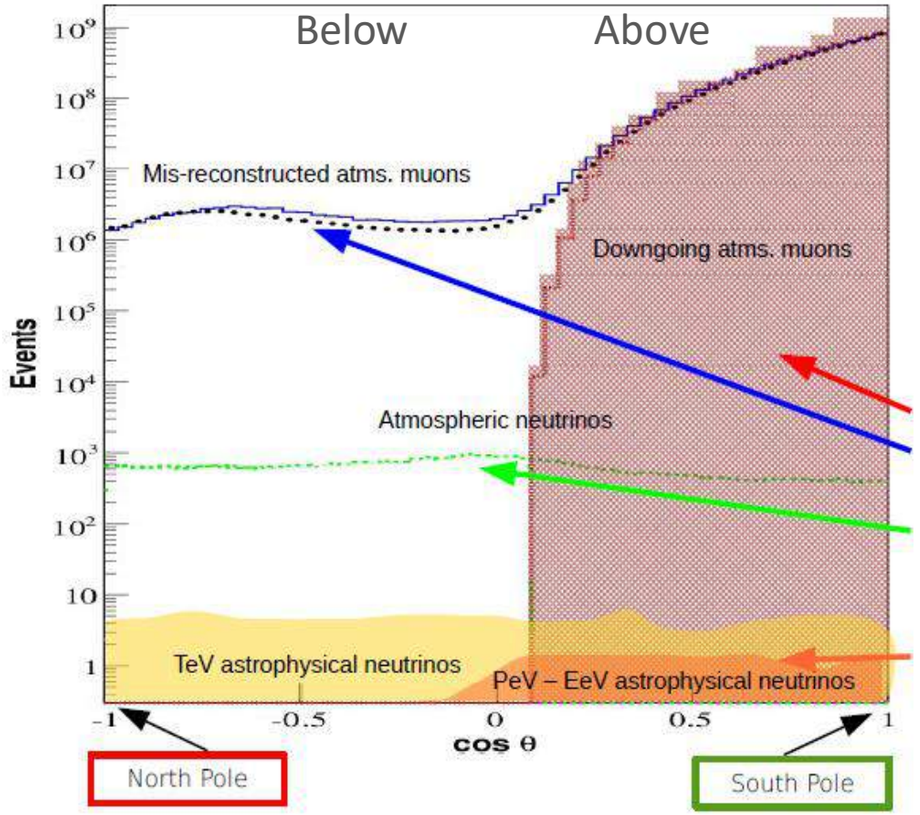
First Observation of PeV-energy cosmic Neutrinos



… discovered in search for GZK neutrinos

IceCube collaboration, PRL 111:021103,2013

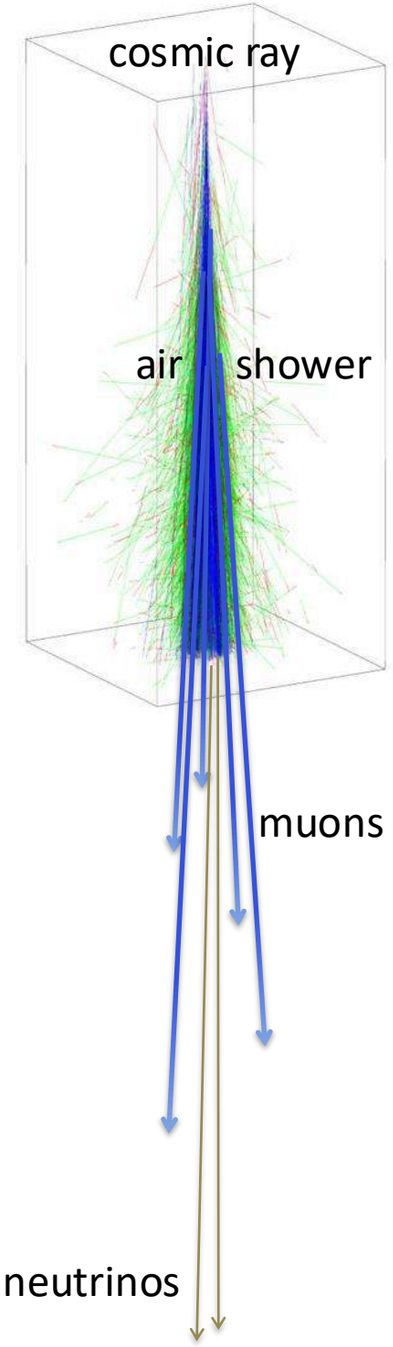
To separate the cosmic signal from atmospheric background is a formidable challenge!



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

~1 in 1000 *misreconstructed* muons apparently going up (in fact muons are all absorbed in the Earth)

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

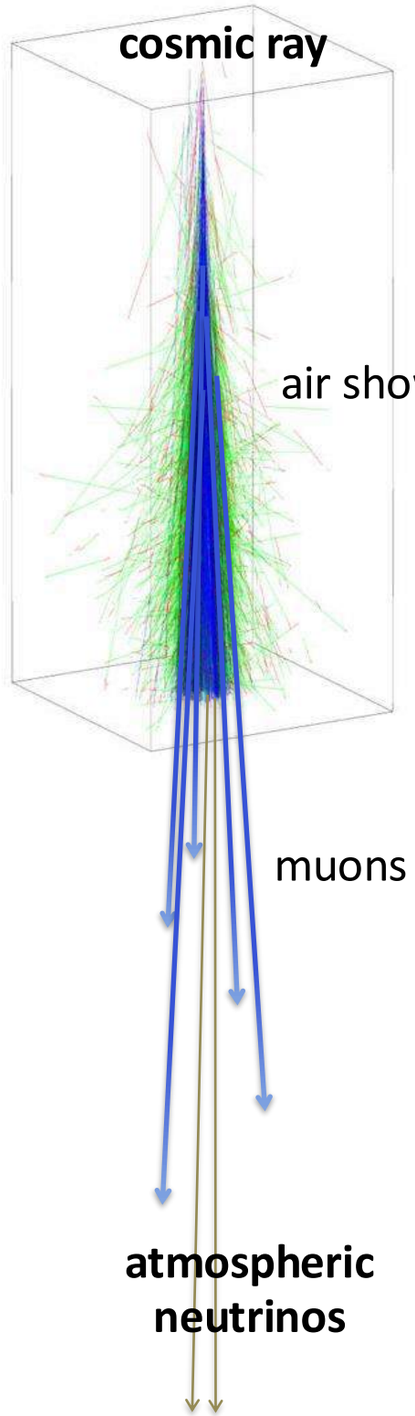


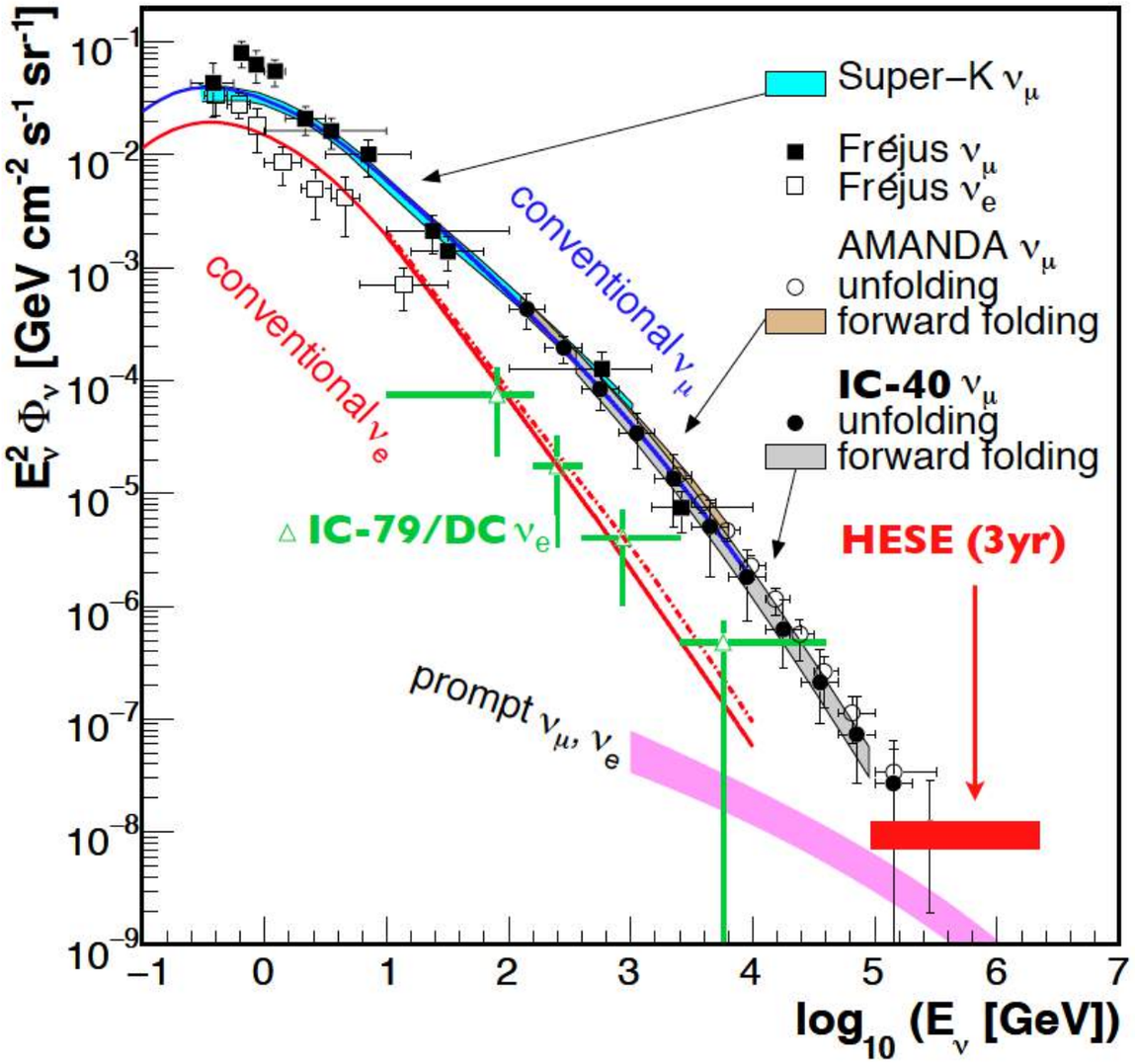
By using a veto for downgoing events, we can remove atmospheric neutrinos
… by triggering on the muons coming from the *same* cosmic ray air shower

What's left: 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.

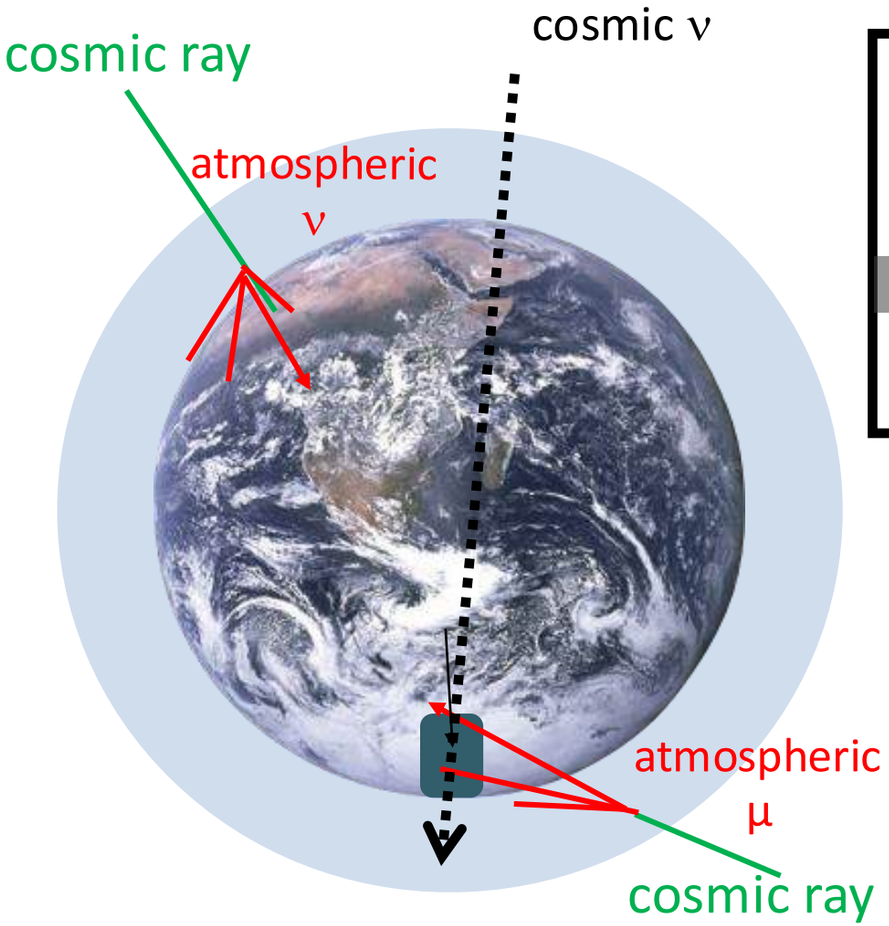
Atmospheric Neutrino Spectrum

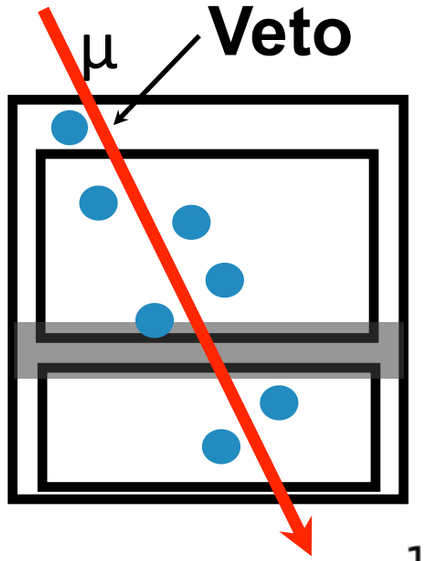




IceCube has measured the atmospheric neutrino background … in good *agreement* with the number expected from cosmic ray interactions in the atmosphere creating pions and kaons ('prompt' flux from charmed meson decays *not* detected yet)

Northern Sky

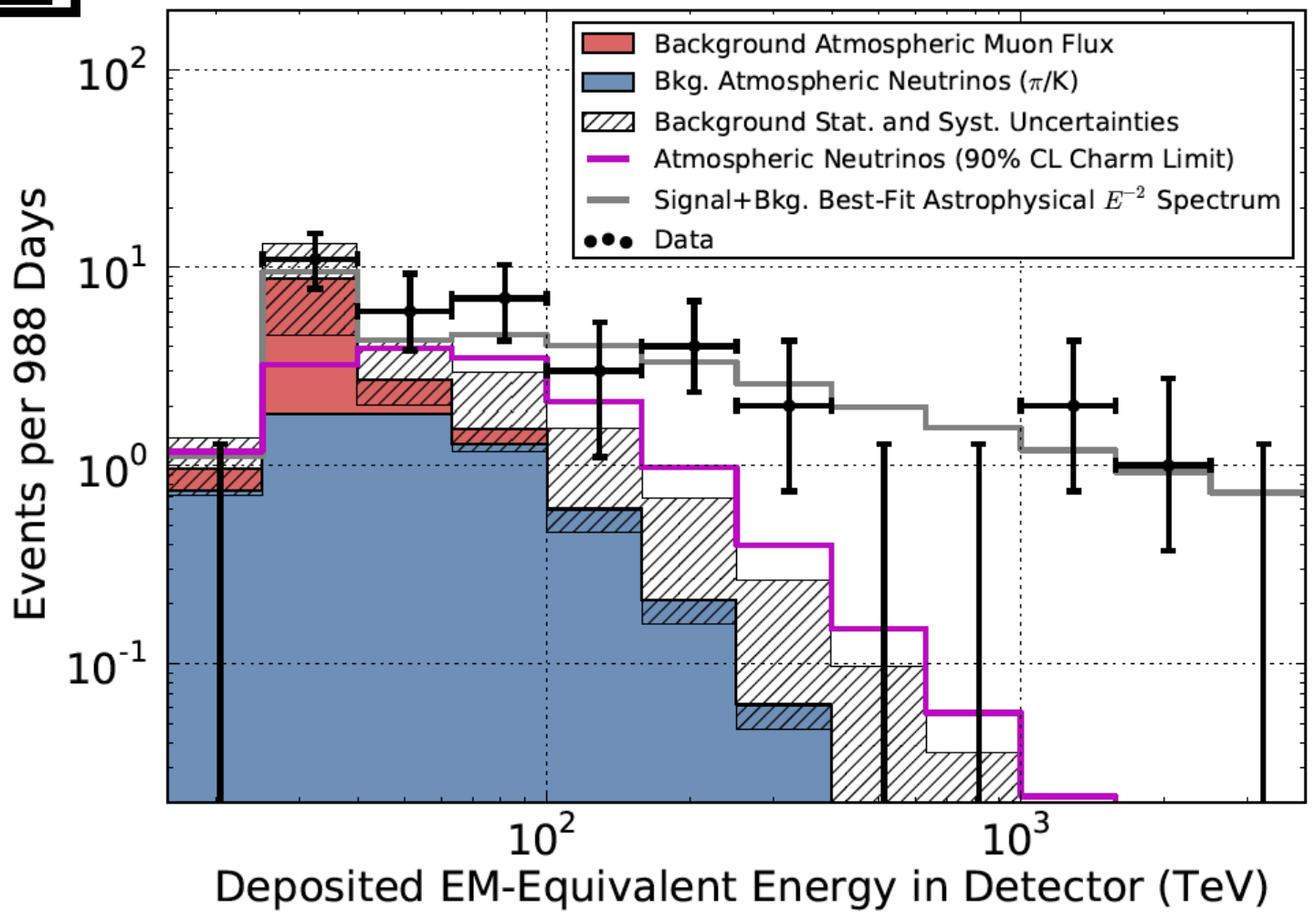




High Energy Starting Events (HESE)

➞ discovery of cosmic neutrinos

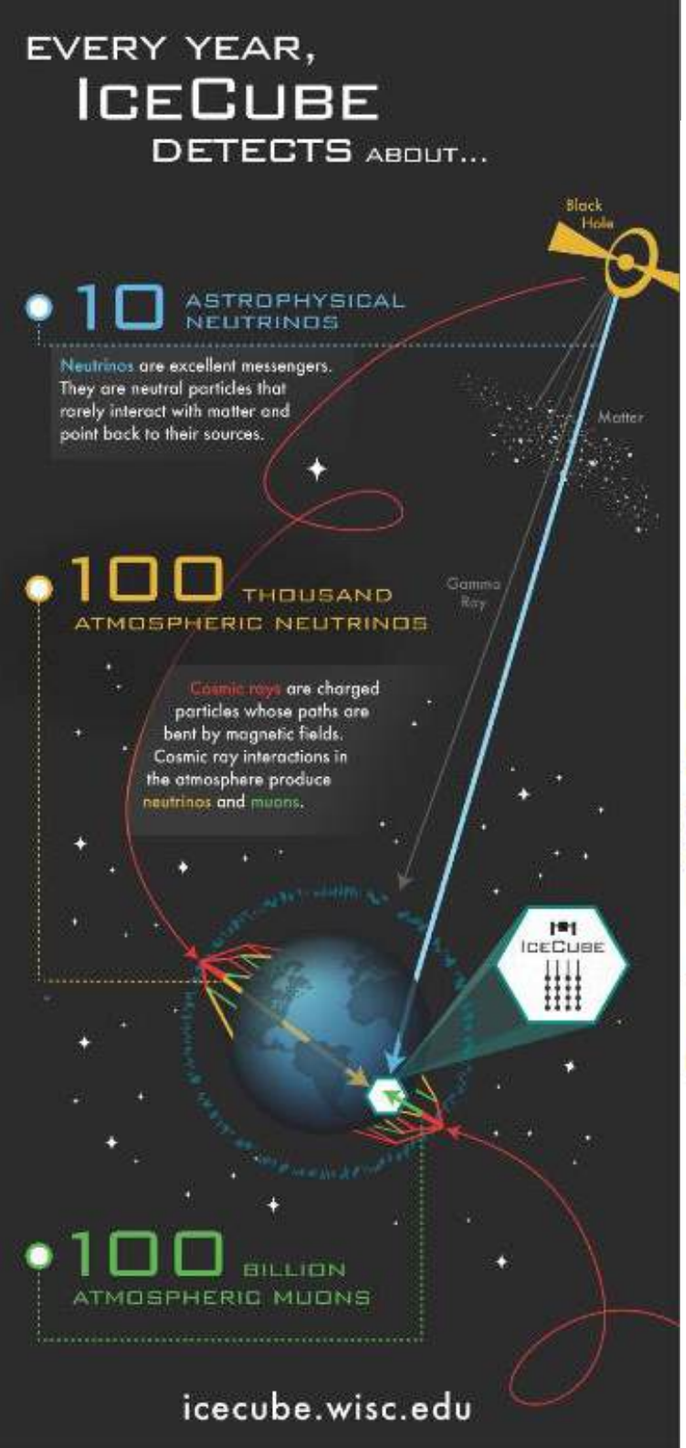
… the correct strategy turned out to be diametrically *opposite* to that first envisaged – which was to look for upward going neutrinos (this was done subsequently)



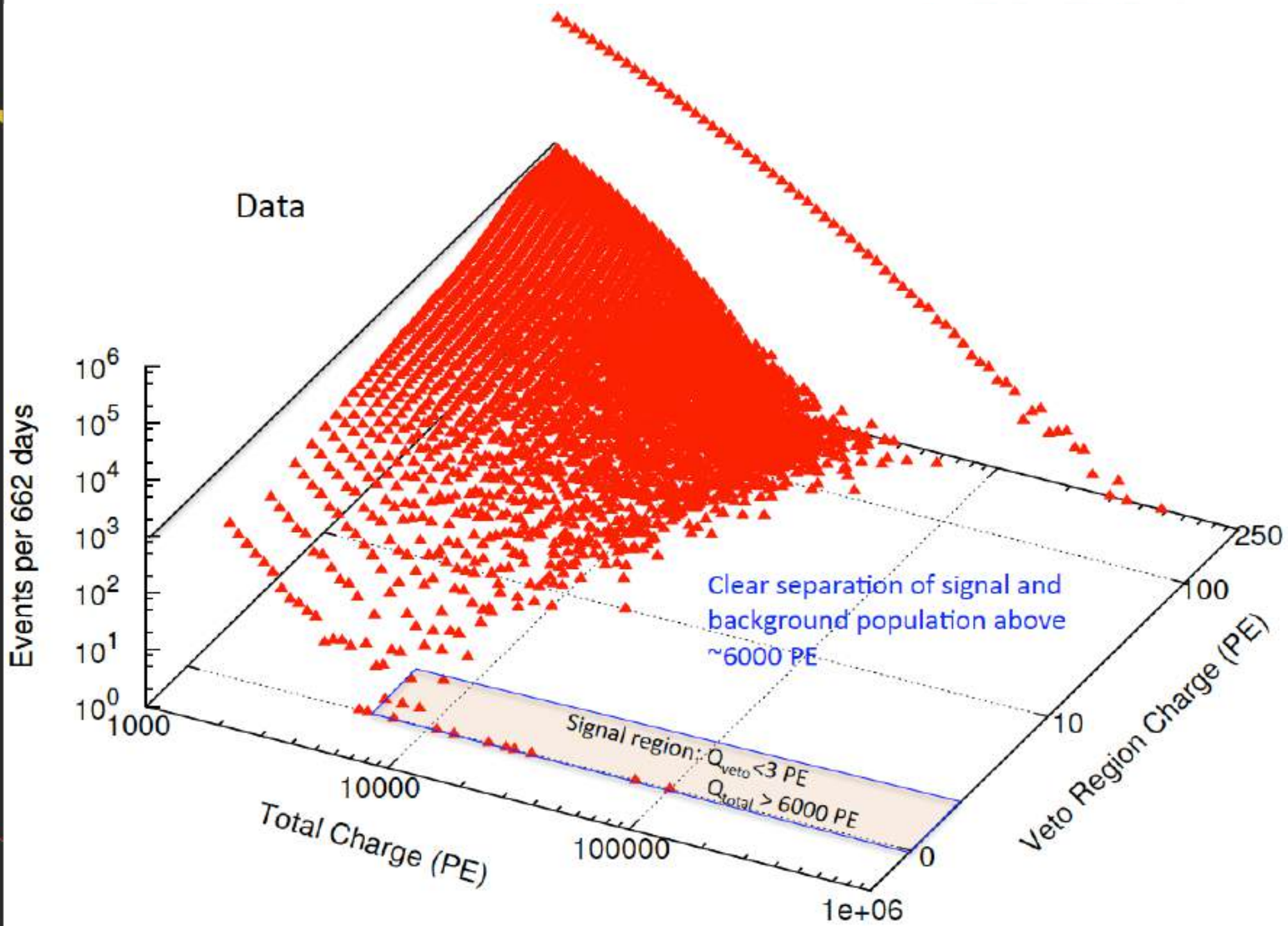
Southern Sky

Expected bkgd: 8.4 ± 1.2 atm. μ + $6.6^{+5.9}_{-1.6}$ atm. ν

⇨ 5.7σ rejection of atmospheric origin



Large muon background **rejected** by veto



Thank you!

You're welcome, Earth!