Neutrino-Nucleon Cross-Sections at Energies of Megaton-Scale Detectors

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Neutrinos

The well-known history

- Spectra of electrons emitted in 2-body β-decays of nuclei at rest must be practically monochromatic.
- But the observed spectra were continuous, as in 3-body decays. The third particle was invisible.
- To save the energy, momentum and angular momentum conservation laws in

$$(A,Z) \rightarrow (A,Z+1) + e^{-} + \bar{\nu}_e$$

(in ⇔ to N. Bohr) in 1930 **W. Pauli** postulated the existence of "neutrons" - neutral, massless, spin ½ weakly interacting particles.
- In 1932 **J. Chadwick** discovered real massive neutrons

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

- **E. Amaldi ⇒ E. Fermi ⇒ W. Pauli: neutrinos**.

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- At low energies cross-sections of weak interaction processes are small compared to strong and e.-m. ones. But at high energies this is not the case: $\sigma(E)\ \mu\ E$.
- Just in 1956 ν's were discovered by **F.Reines** and **C.Cowan.** $\bar{\nu}_e$-flux from reactor + inverse β-decay $\bar{\nu}_e + p \rightarrow n + e^+$

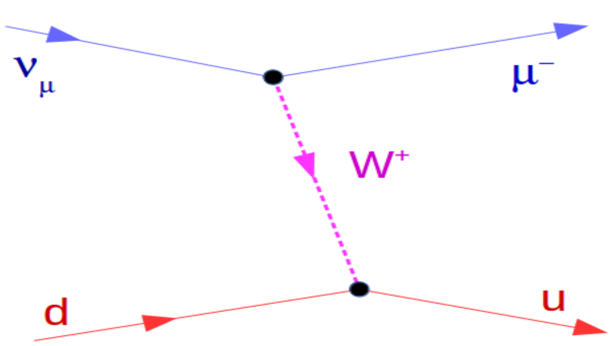
  γ–rays: $e^+ e^- \rightarrow \gamma\gamma$; $n + {}^{108}\mathrm{Cd} \rightarrow {}^{109m}\mathrm{Cd} \rightarrow {}^{108}\mathrm{Cd} + \gamma$.

Muon Neutrinos

- In 1936 **C. Anderson and S. Neddermeyer** discovered μ in CRs.
- μ^- was an analog of the electron but ~210 times more massive.
- In 1962 **L. Lederman, M. Schwartz** and **J. Steinberger** discovered the 2-d type of ν, the muon one – ν_μ.
  They appeared in $\pi^+ \rightarrow \mu^+ + \nu_\mu$ decays (Brookhaven). Muons also decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. $\Rightarrow$ Lepton number conservation.
- After discovery of the 3-d lepton, the heavy τ^- , it was suggested that ν_τ must also exist. In τ^--decays, like in β-decays, the energy and momentum conservation laws were violated.
- In July 2000 DONUT collaboration (Fermilab) announced the observation ν_τ .
- Now OPERA at LNGS announced the detection of **5** τ-leptons in $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with following τ^- –production.

Leptons and Quarks

$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e^- & \mu^- & \tau^- \end{pmatrix} \Leftrightarrow \begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$$



In the Standard Model all leptons and quarks are massive Dirac bispinors $\psi = \psi_L + \psi_R$; ν''s are left-handed and massless. Lepton number is conserved.

In 1963 **N. Cabbibo** suggested

$$d' = \cos\theta_c d + \sin\theta_c s$$
$$s' = -\sin\theta_c d + \cos\theta_c s$$

$\sin\theta_c = 0.23$; θ_c is the Cabbibo angle.

In 1973 **CKM matrix:** **Cabbibo-Kobayashi-Maskawa**

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

C-, P- and CP-violation

$$\sum_i |V_{ij}|^2 = \sum_j |V_{ij}|^2 = 1$$

4 parameters, 1 - complex

Neutrino Masses and Oscillations

- In 1957 **B. Pontecorvo** proposed $\nu \leftrightarrow \bar{\nu}$ oscillation. ($K^0 \leftrightarrow \bar{K}^0$)
- In 1962, in analogy to quarks, **Maki**, **Nakagawa**, and **Sakata** proposed $\nu_\mu \leftrightarrow \nu_e$ mixing $\Rightarrow$ PMNS.
- Now we know than ν's are massive. Eigenstates of the mass operator are ν_1, ν_2, ν_3 with eigenvalues m_1, m_2, m_3.
- Eigenvalues of the flavor operator are mixture of these ν's.

In analogy with **CKM** the **PMNS** matrix **U**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 2} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Confirmation: the 1968 **Devis** experiment found deficit of solar neutrinos: only 50% of predicted by **Bahcall**. MSW effect.
- Later – SNO (heavy water) confirmed solar ν disappearence. Total flux of all ν's is in agreement with the Solar Model.

Parameters and PMNS matrix

- Standard parameterization of the *PMNS* matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, θ_{12} , θ_{23} , θ_{13} – mixing angles, δ – CP-violating phase, α and β – Majorana phases.

- Dirac and Majorana ν's are indistinguishable in most experiments.

- The only test of the ν nature is the neutrinoless 2β–decay $(A,Z) \rightarrow (A,Z+2) + e^- + e^-$. Many experiments at LNGS.

Oscillations

- In the general case of N ν species oscillation formulas are rather complicated. Even the 3-flavor case is difficult.
- But in the simplified 2-ν case the oscillation matrix is just

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix},$$

and the probability for a ν to change its flavor, say $\nu_\mu \leftrightarrow \nu_\tau$,

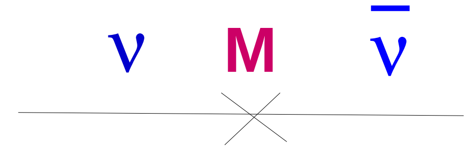
$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2}{eV^2}\frac{L}{km}\frac{GeV}{E}\right).$$

- However, no CP-violation is possible in this case.
- For $\theta \approx 45°$ and a given Δm^2 the probability scales with L/E.

Masses and Hierarchy

- Dirac neutrinos – 4-spinors. $\nu = \nu_L + \nu_R$; $\bar{\nu} = \bar{\nu}_L + \bar{\nu}_R$
  and $\nu \neq \bar{\nu}$; Lepton number conserved

- Majorana neutrinos: $\nu \equiv \bar{\nu} = \nu_L$



  Mass term violates the L-number conservation.

- Neutrino masses: $m_1^2, \quad m_2^2, \quad m_3^2$ are unknown (lightest?)

$$\Delta m_{ij}^2 = m_j^2 - m_i^2 \quad \Rightarrow \quad \Delta m_{12}^2 > 0, \pm \Delta m_{23}^2, \Delta m_{13}^2$$

$\Delta m_{23}^2 > 0$ Normal Hierarchy

$\Delta m_{23}^2 < 0$ Inverse Hierarchy

Neutrino hierachy problem

Global Fit to 3-flavor Oscillation

M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, arXiv:1409.5439

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
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$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
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$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix}+2.325 \to +2.599 \\ -2.590 \to -2.307\end{bmatrix}$

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NuFIT 2.0

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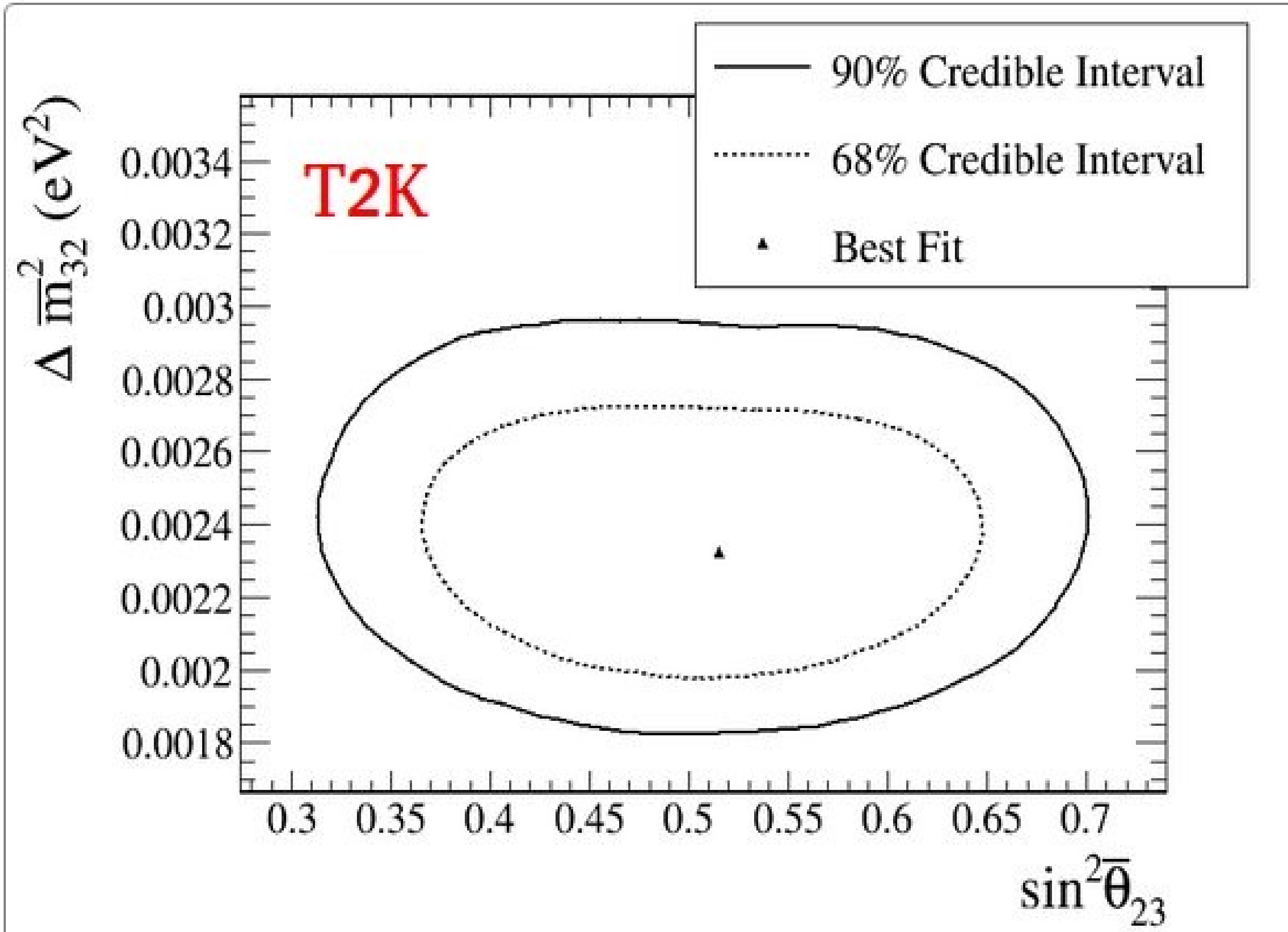

Best-fit values and 68% and 90% credible intervals in $\sin^2\overline{\theta}_{23}$ and $\overline{\Delta m}^2_{32}$

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Neutrino Sources

- ν's are generated in weak decays of nuclei, mesons and heavy leptons: $n \to p + e^- + \bar{\nu}_e$, $\pi^+ (K^+) \to \mu^+ + \nu_\mu$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \ldots$
- in the early Universe;
- in ordinary stars like our Sun;
- in SNe explosions: $p + e^- \to n + \nu_e$, $\gamma + \gamma \to e^+ + e^-$, $e^+ + e^- \to \nu_i + \bar{\nu}_i \ \ldots$
- in AGN due to acceleration of p's on shocks with following $p + p(\gamma) \to \pi^\pm (K^\pm) + X$ etc.
- in artificial sources: reactors, accelerators, A-bombs ...

Neutrino Sources, cont.

- Reactor $\bar{\nu}_e$ are copious, but their energies are small.
- Accelerator ν's, mostly ν_μ and $\bar{\nu}_\mu$, are very expensive.
- SNe did not explode in the vicinity since 23.02.1987 (in LMC 51.4 kps from the Earth).
- Cosmogenic (BZ) ν's to be produced in collisions of UHE, $E > 6\times 10^{19}$ eV, protons with CMB photons

$$p + \gamma \rightarrow \pi^+ + n\,; \quad \pi^+ \rightarrow \mu^+ + \nu_\mu\,; \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

  are yet not observed even with *M ~10⁹ tonn* IceCube and ANTARES detectors. (GZK cut-off is oberved but the nature of UHECRs = ?)
- **Atmospheric neutrinos** are very useful for studies of the neutrino properties.

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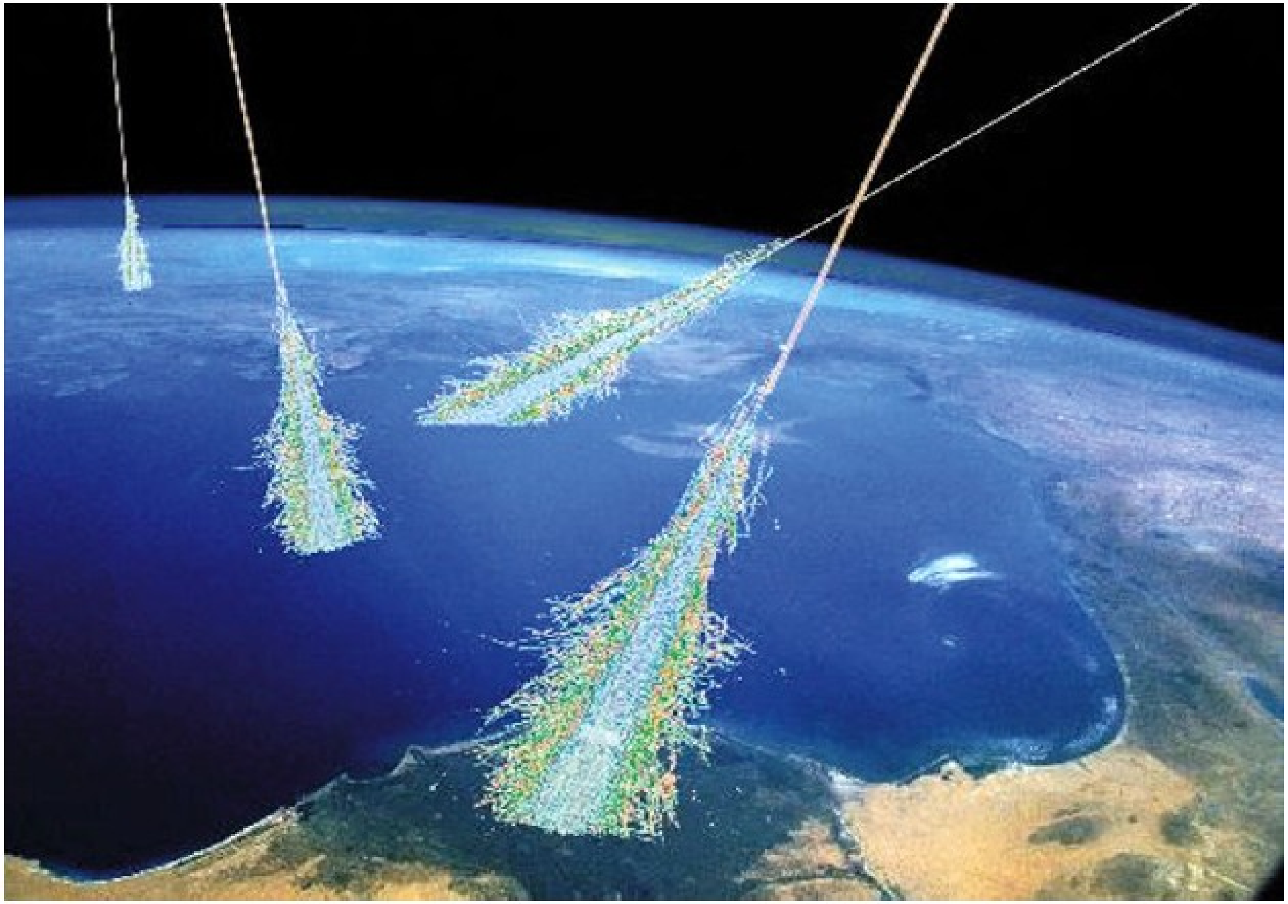

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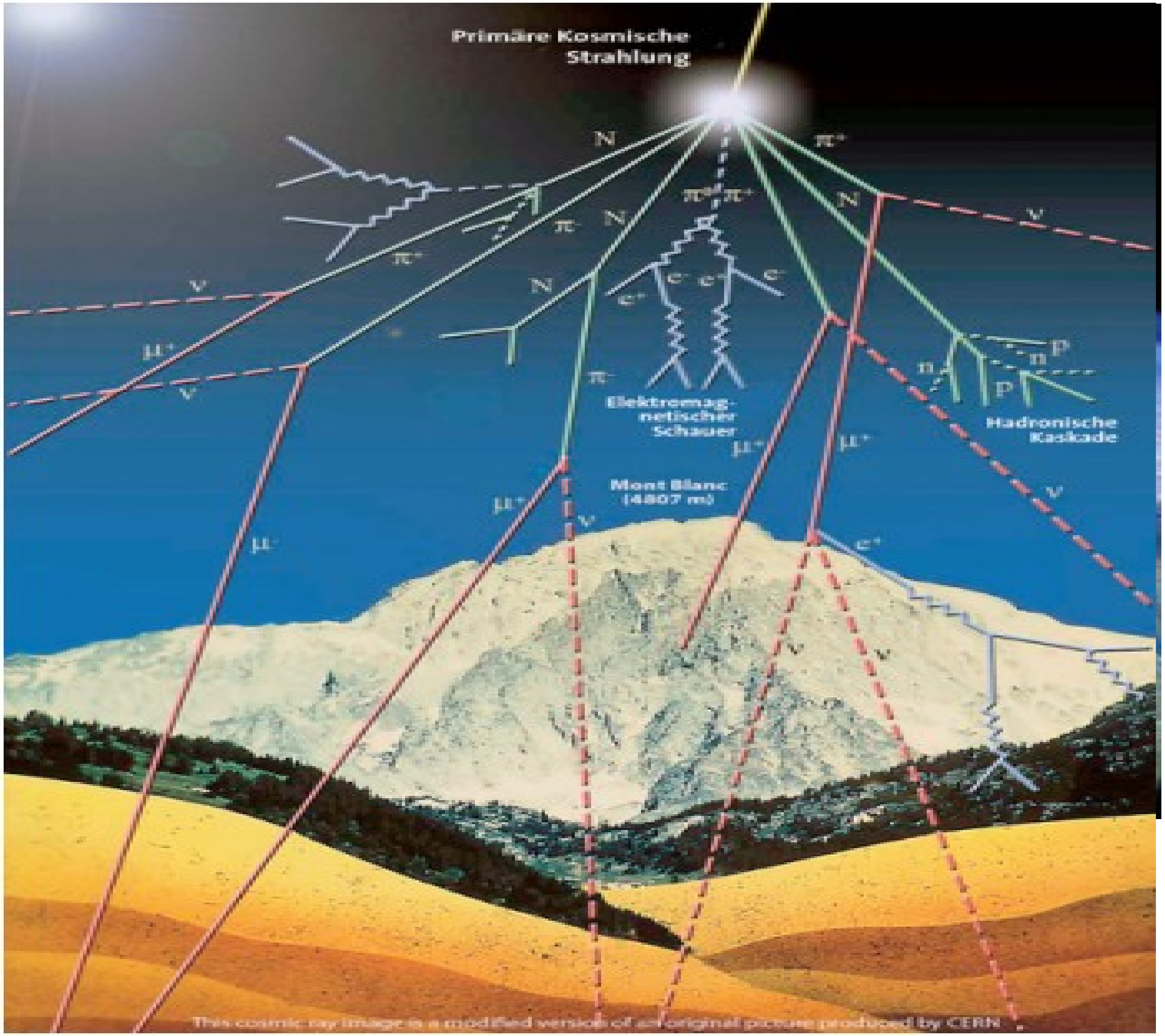

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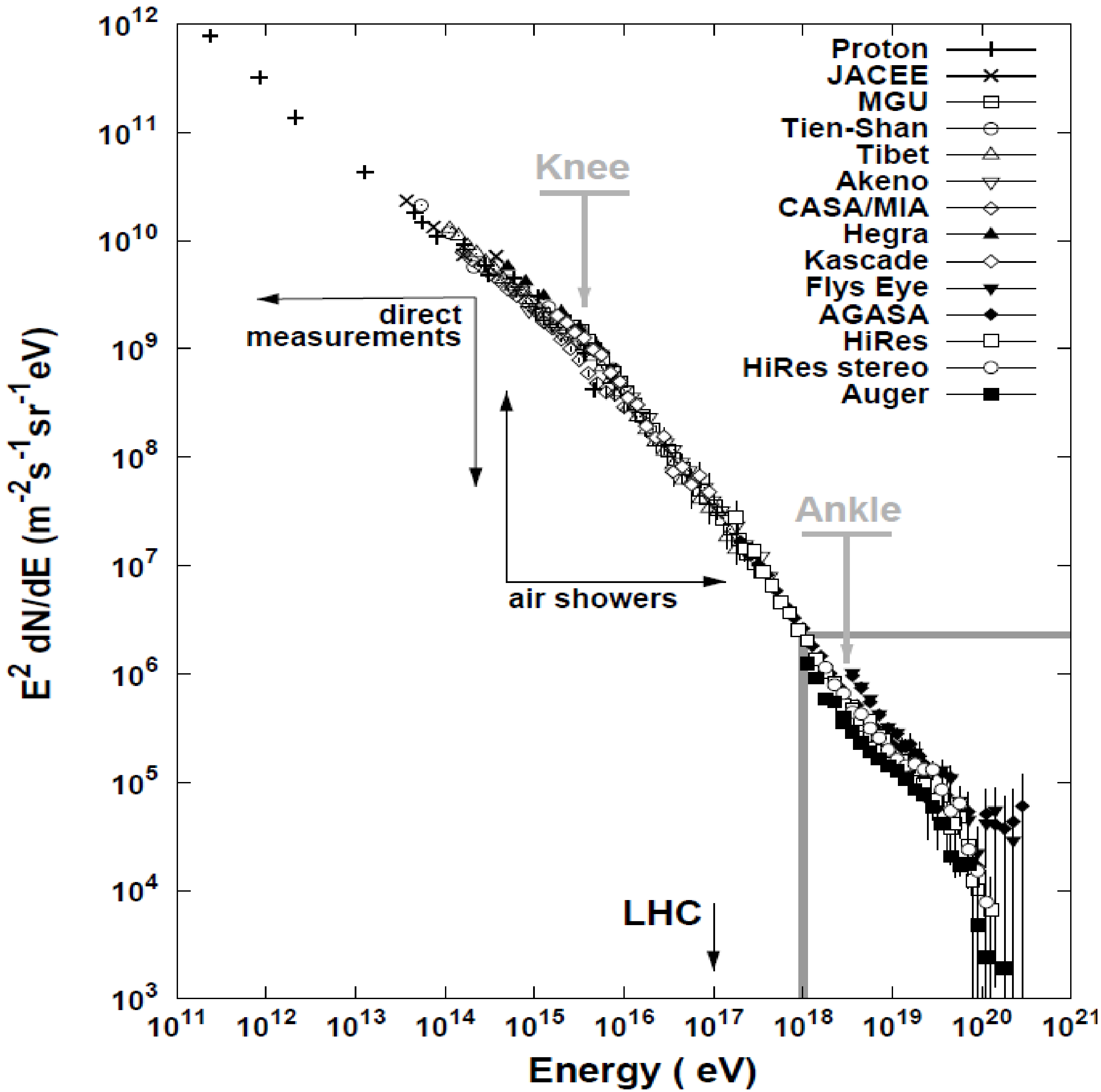
These ν's were observed by MACRO and LVD at LNGS, and by many other experoments, e.g. SK.

CR Spectrum



- Energy spectrum of CRs is power-law decreasing
  $$J(E) \propto E^{-2.7}.$$
- CR fluxes are isotropic.
- HE **ν**-spectra are steeper, but cross-sections and effective volumes grow with energy.
- **ν**-fluxes are also isotropic.
- To register one needs giant detectors.

SuperK

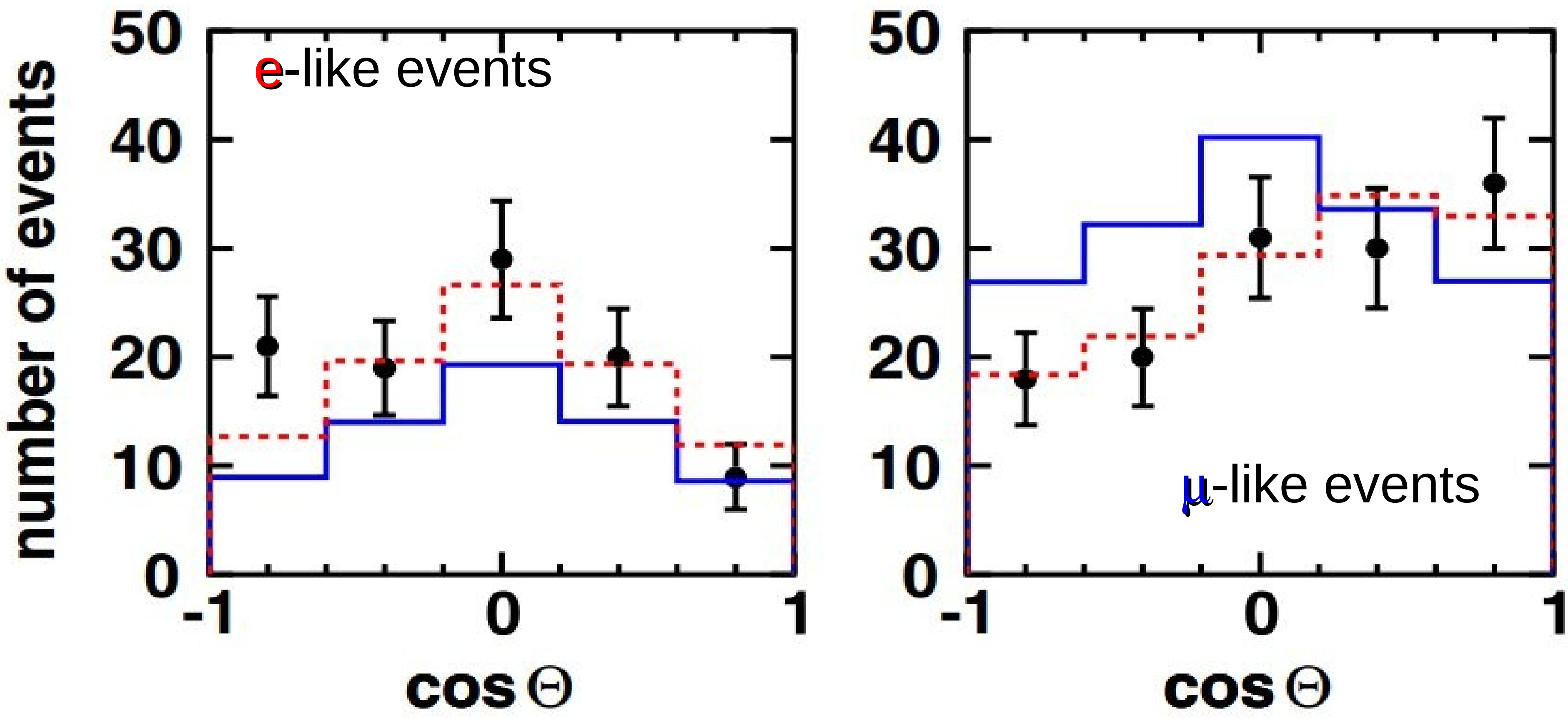
Super-Kamioka Neutrino Detection Experiment

A real breakthrough in the neutrino physics – confirmation of the atmospheric ν_μ disappearence in 1998.

- ~ 50 tons of ultra-pure water 1 km underground.
- SK detects Cherenkov light from charged particle produced in νe^- - and νN–interactions with electrons and nucleons.
- 11200 50 cm PMT – inner detector
- 1900 20 cm PMT – outer detector

Zenith Angle Distribution in SK-98

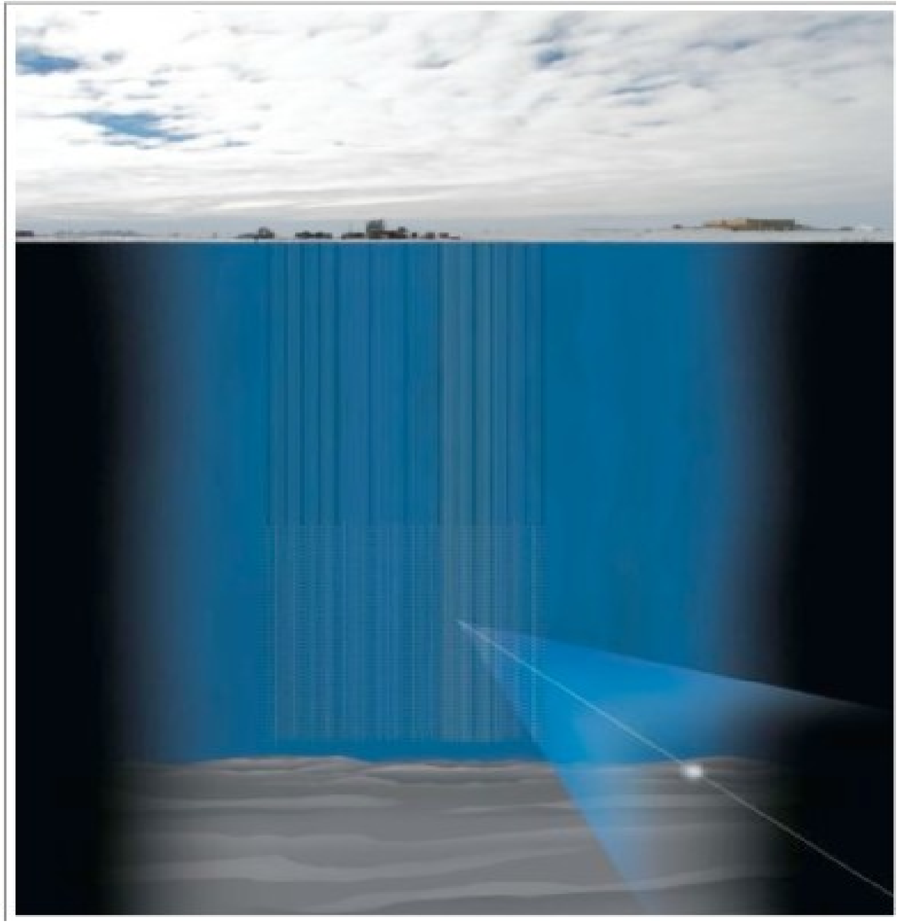
Multi-GeV atm. ν–events reported at Neutrino'98



Oscillations discovered by observation of ν_μ-disappearence on passing through the Earth.

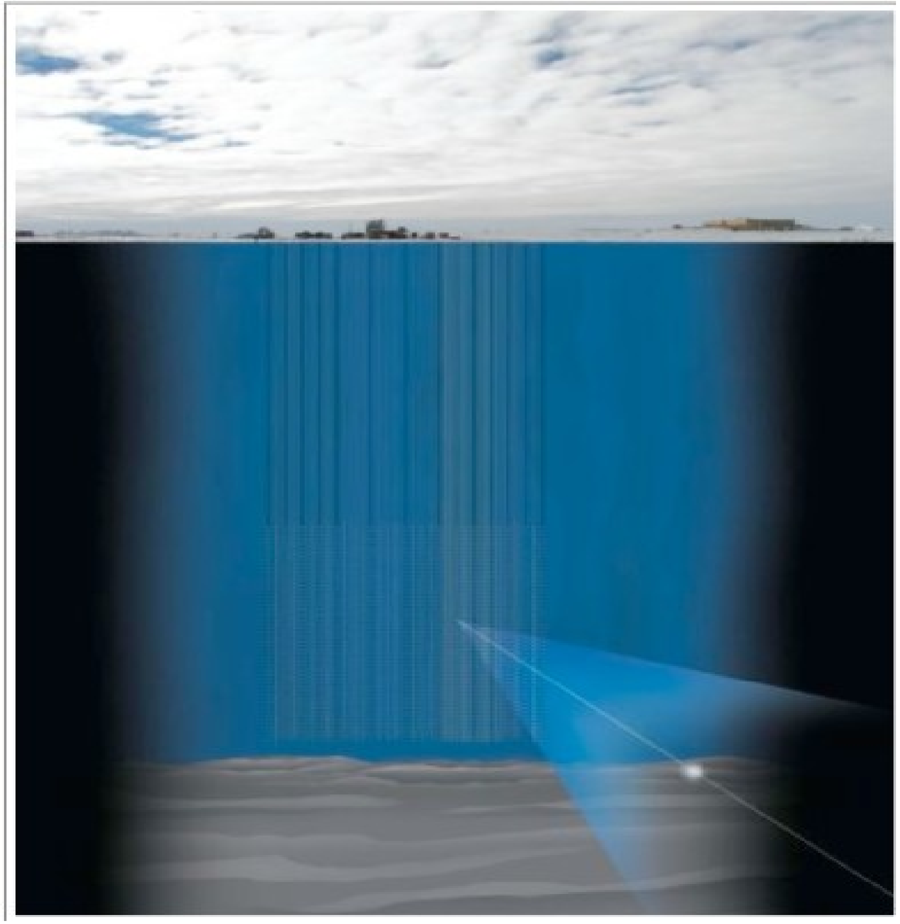
Ice and Water

Ice and Water



Ice and Water

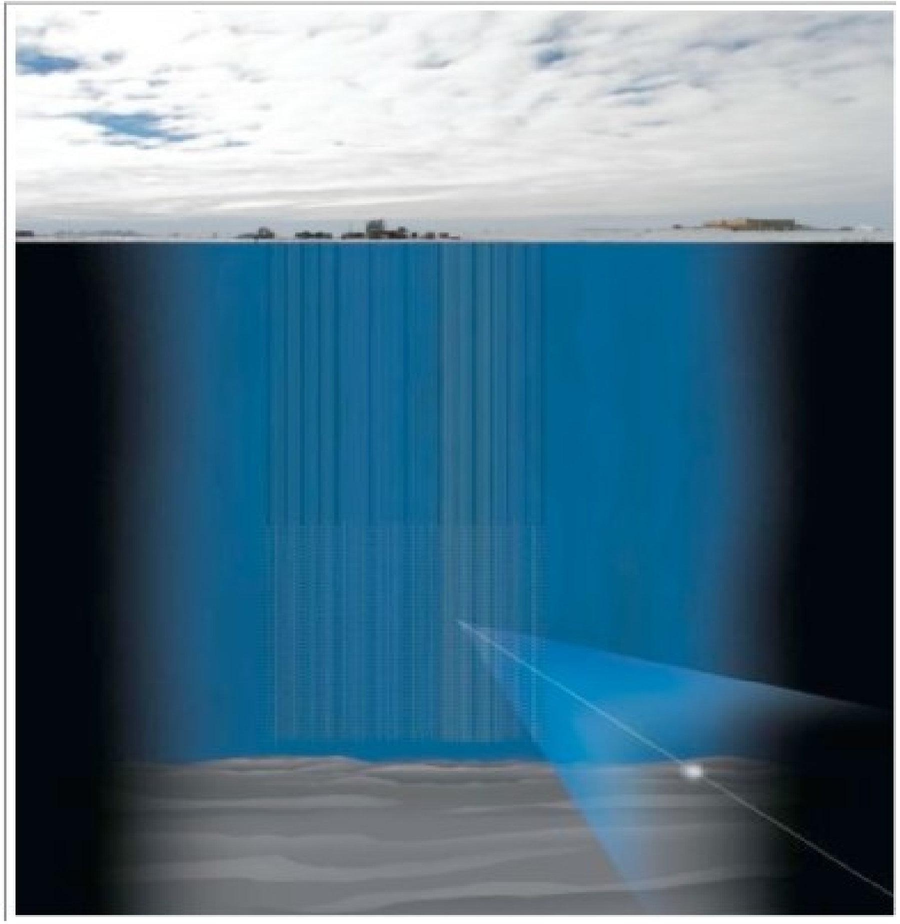
IceCube

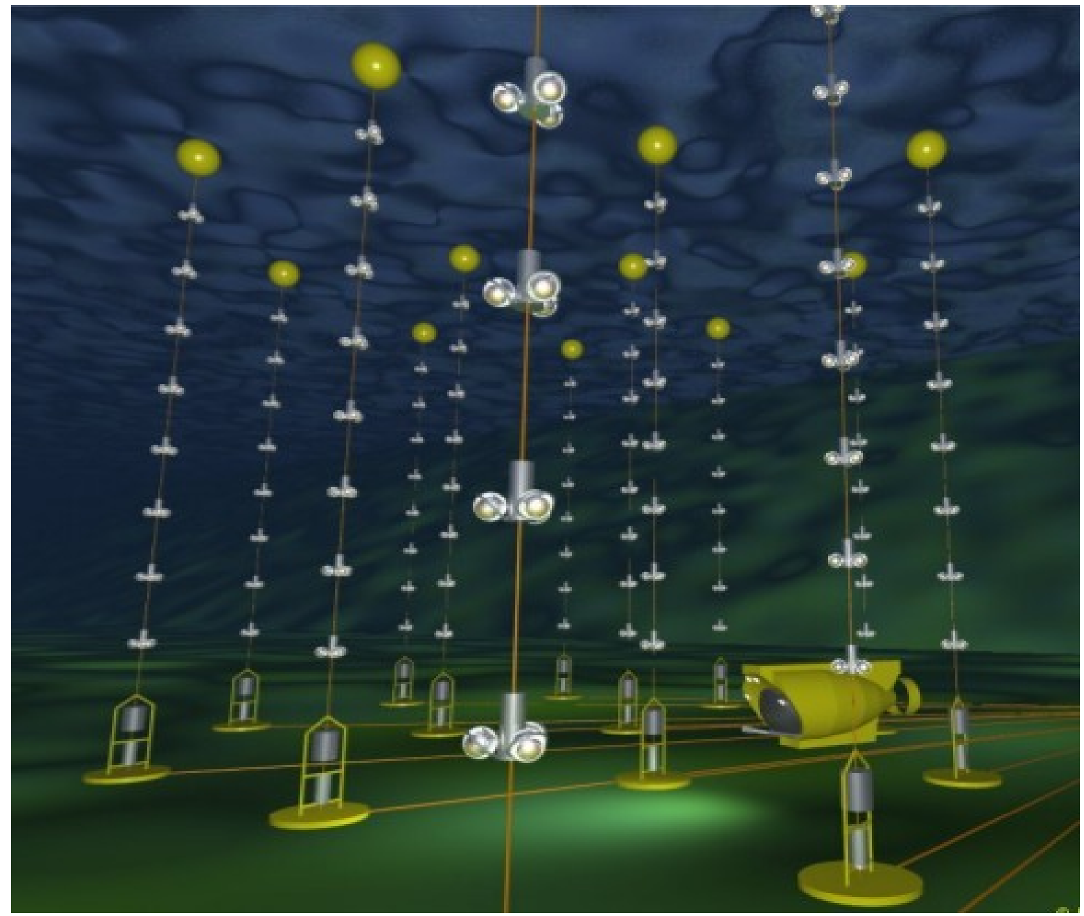


Ice and Water

IceCube

ANTARES





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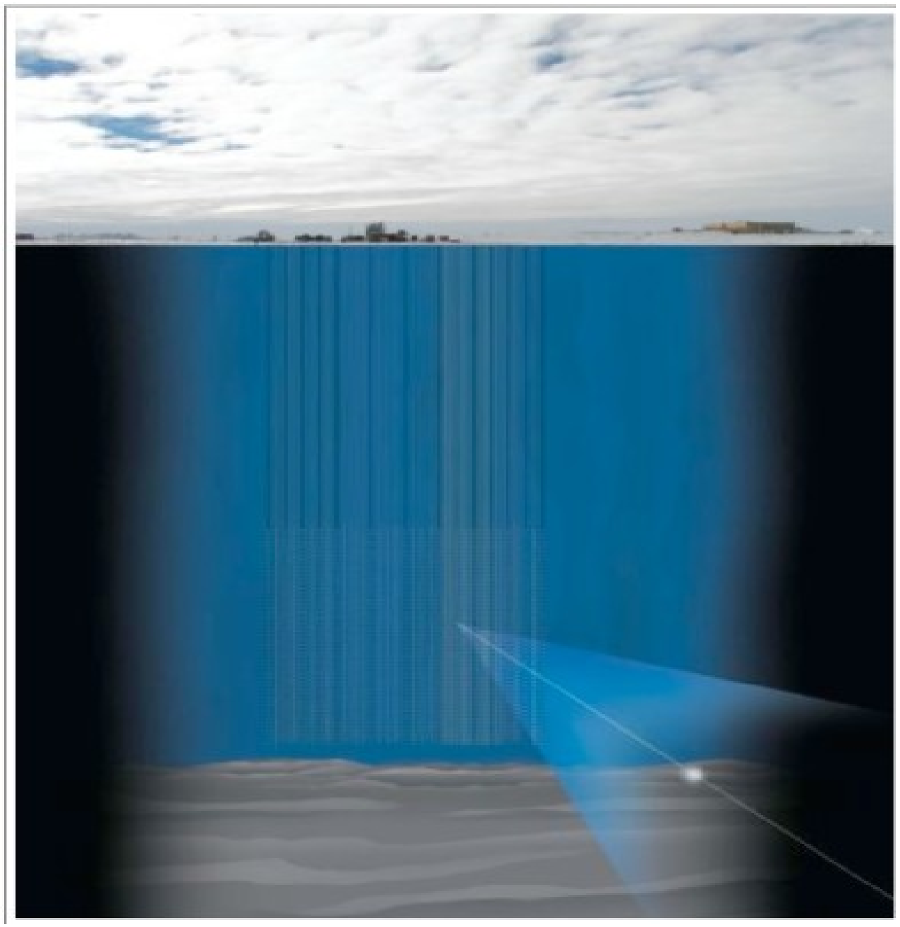
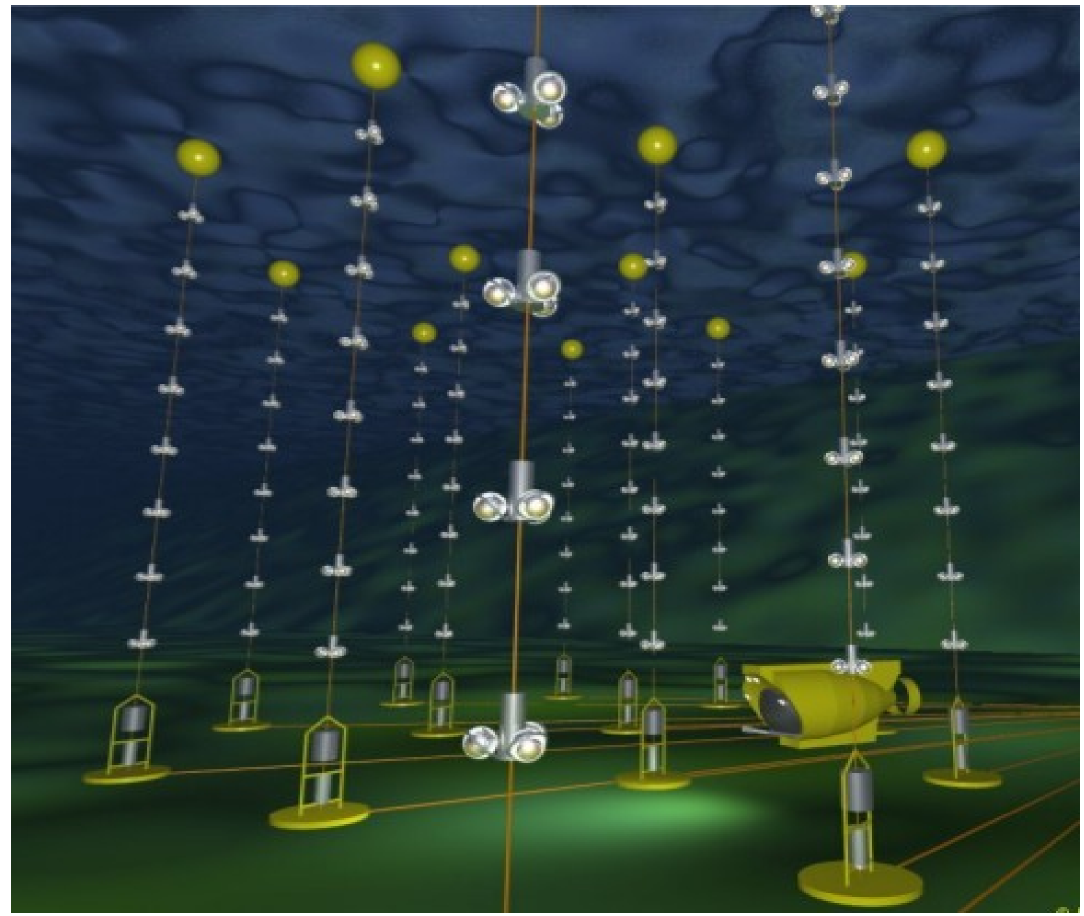


South Pole, 2.5 km

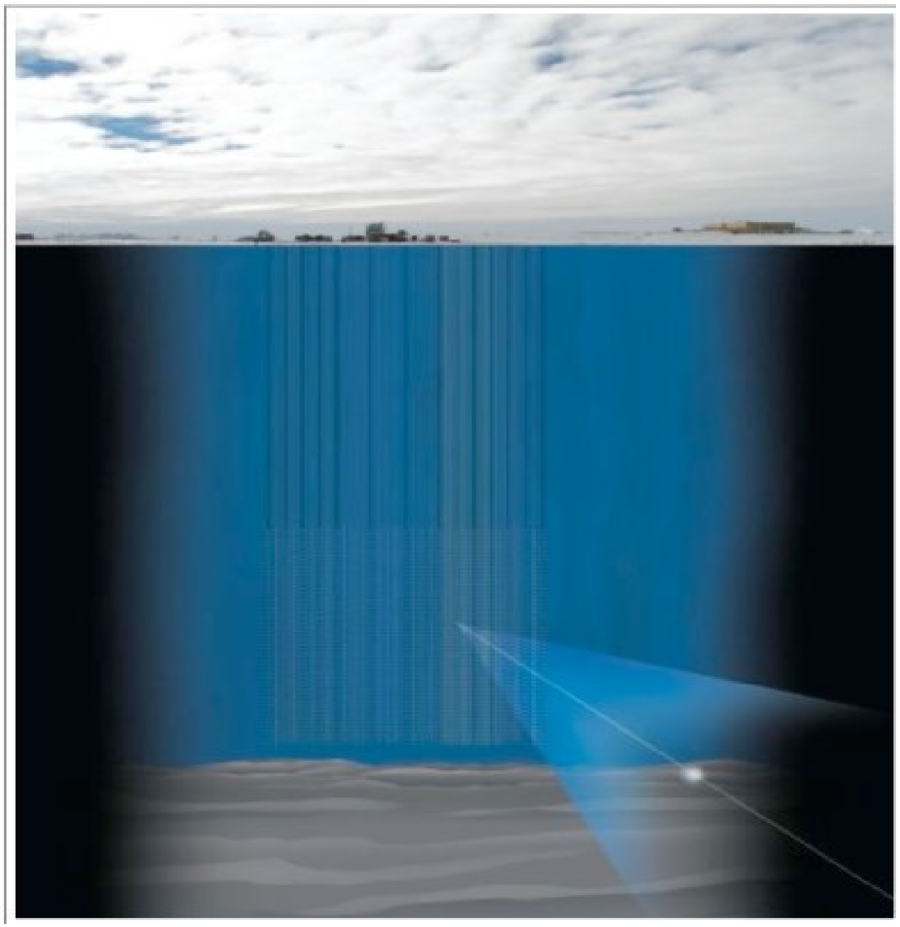


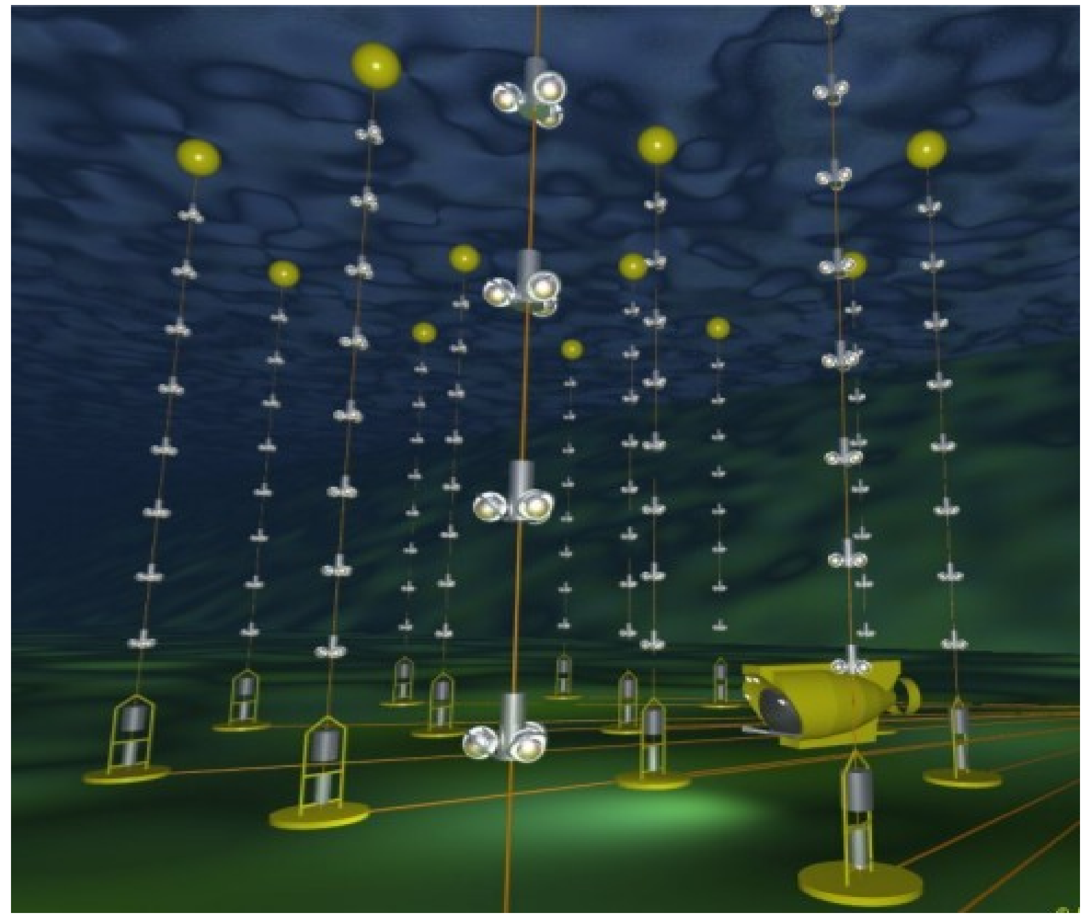
Mediterranean sea, 2.5 km

Ice and Water

IceCube

ANTARES





South Pole, 2.5 km

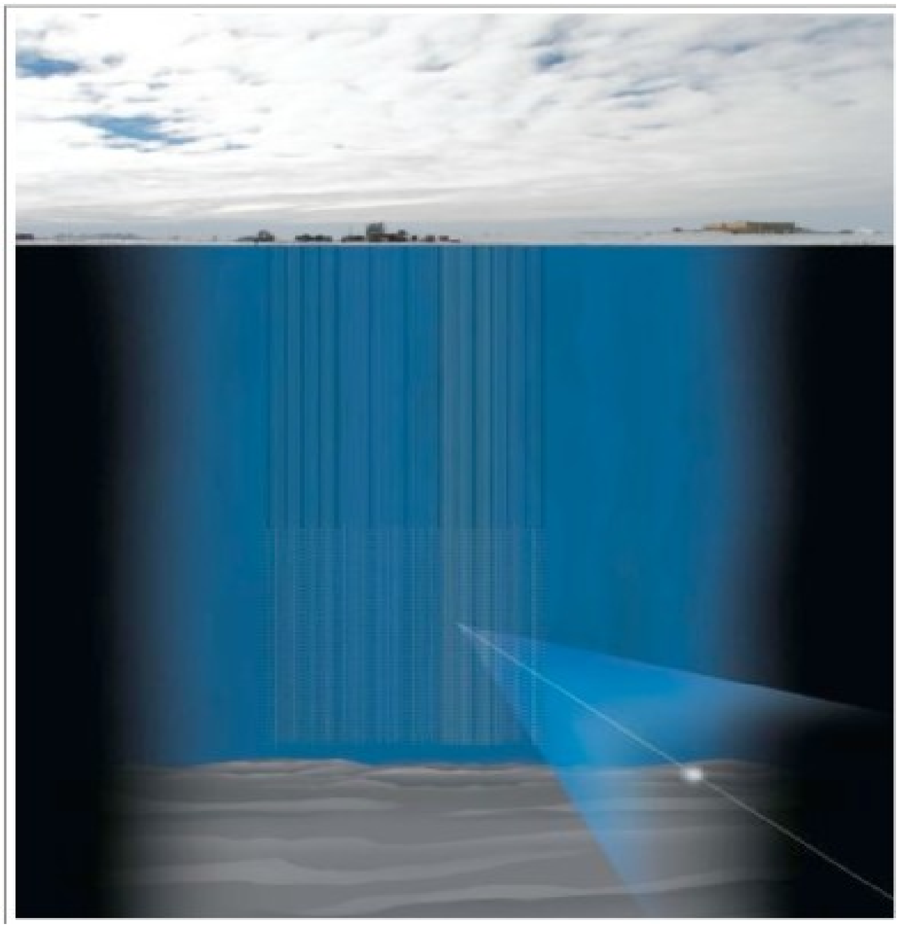
$V \cong 1\ km^3$

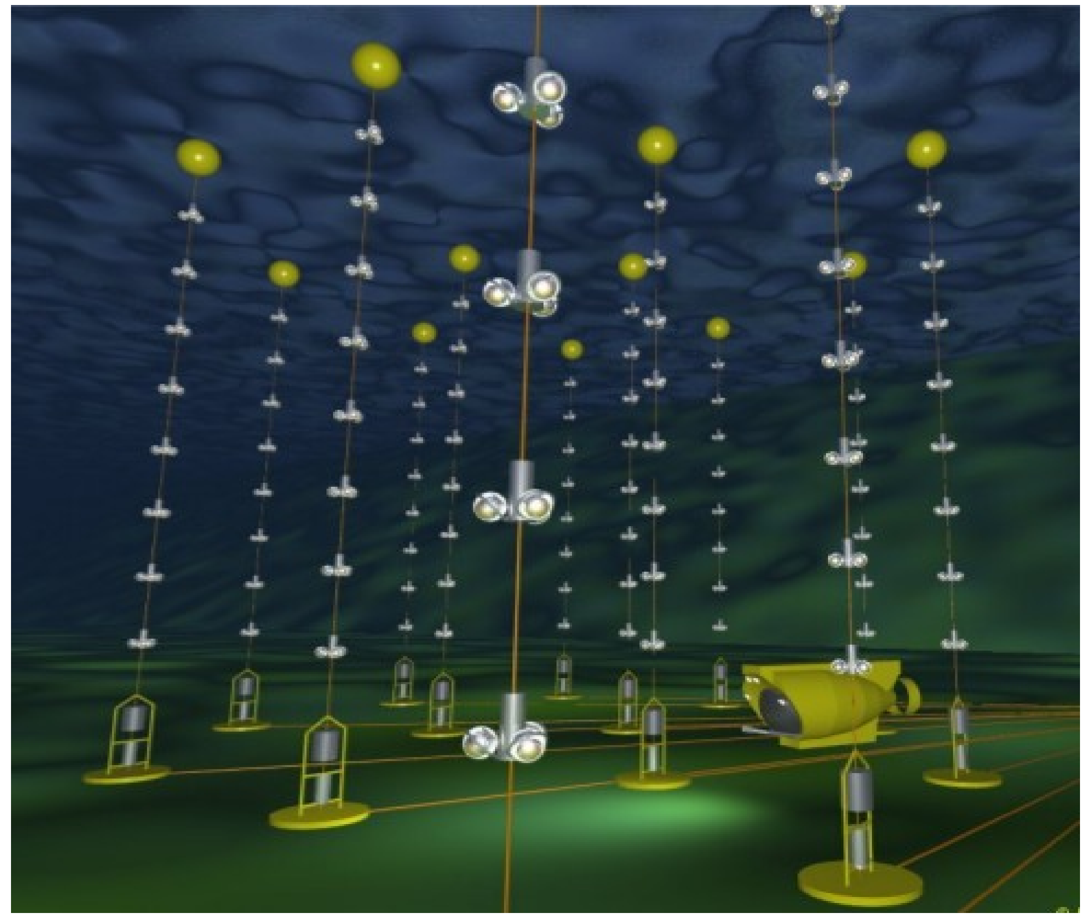
Mediterranean sea, 2.5 km

Ice and Water

IceCube

ANTARES





South Pole, 2.5 km

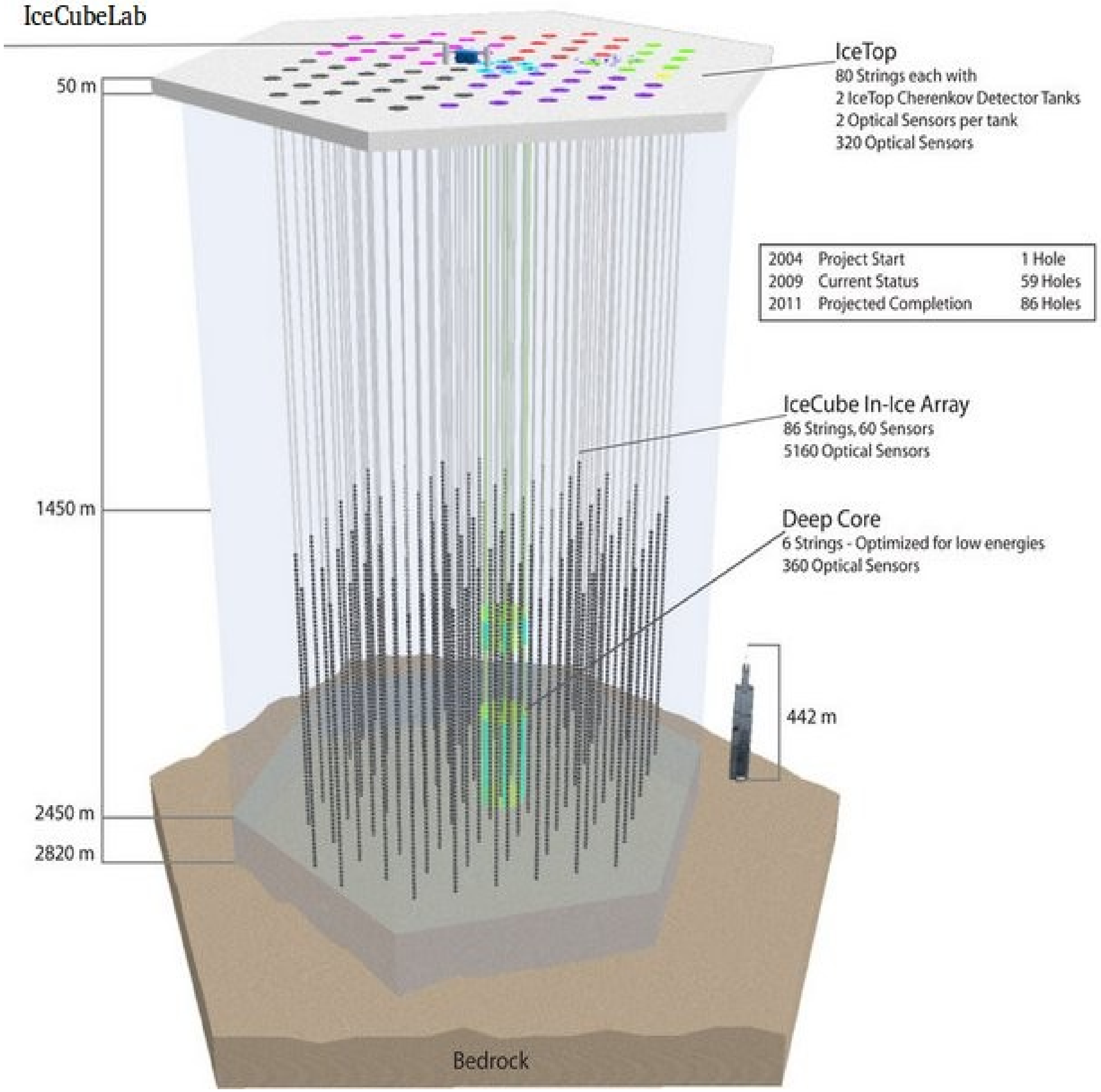
Mediterranean sea, 2.5 km

$V \cong 1\ km^3$

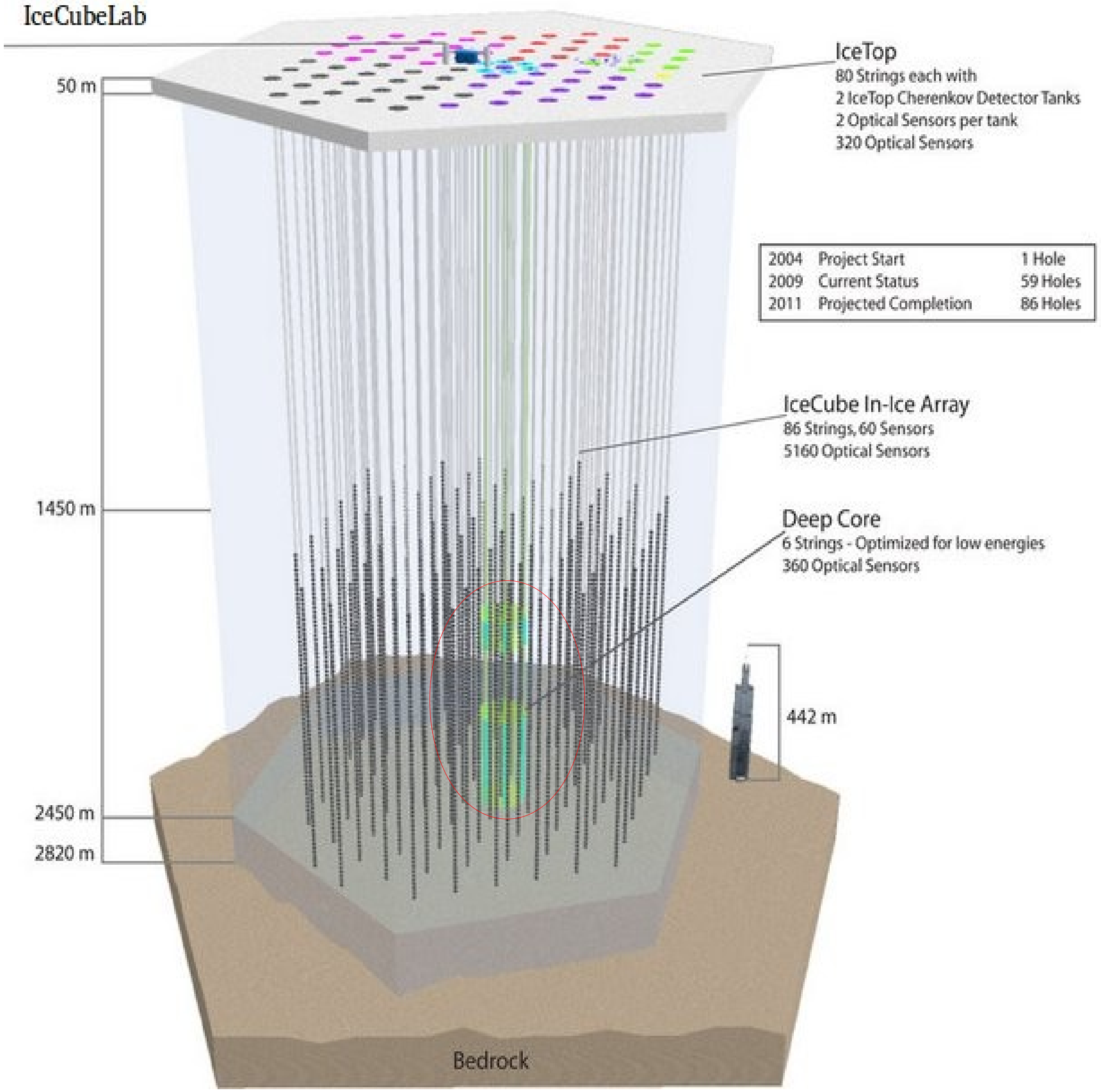
NESTOR – Greece ?

NEMO – Italy ?

IceCube + DeepCore

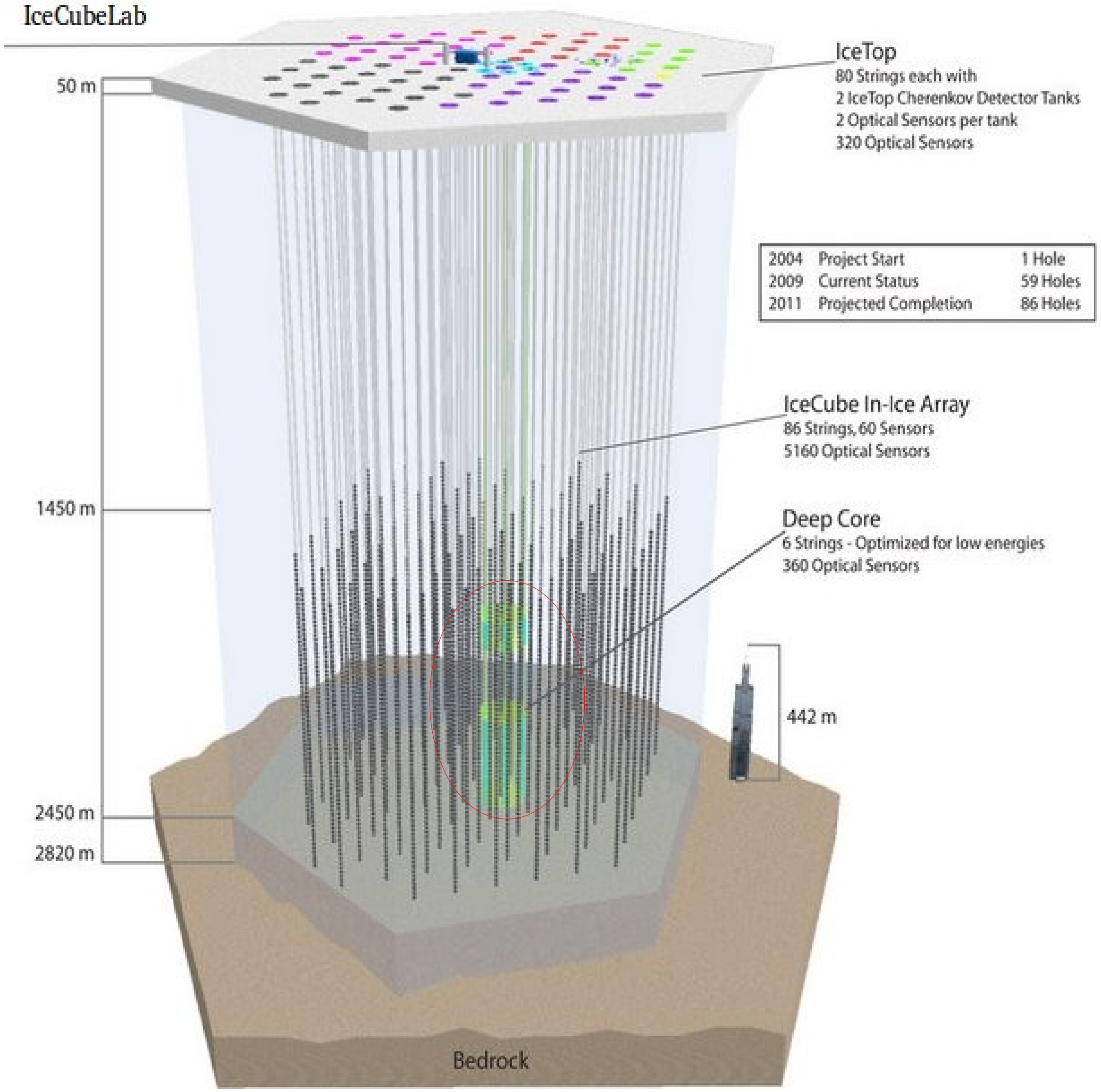


IceCube + DeepCore



IceCube + DeepCore

Purposes



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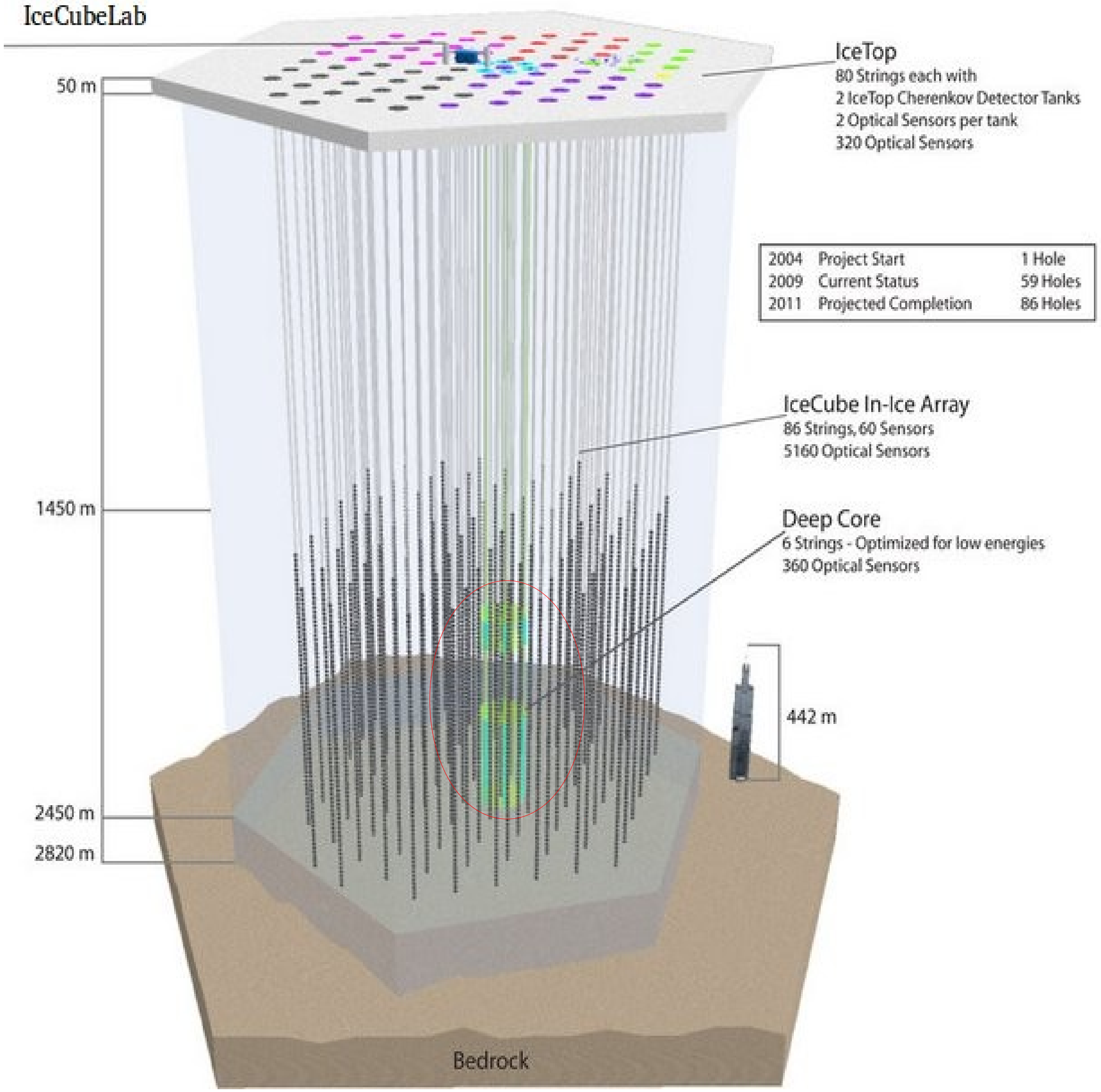
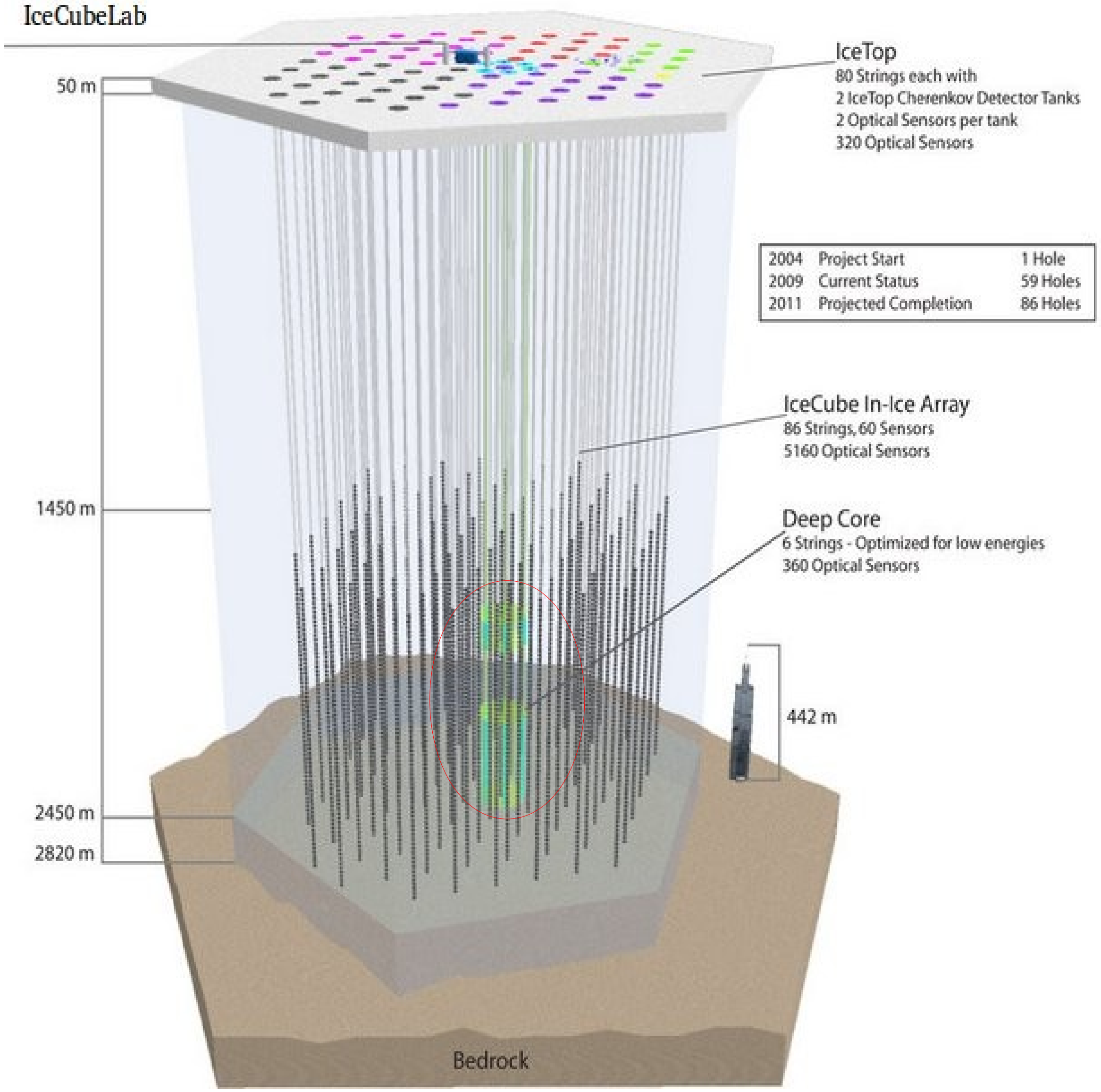


Purposes

- Study of Crs: origin, spectra

IceCube + DeepCore



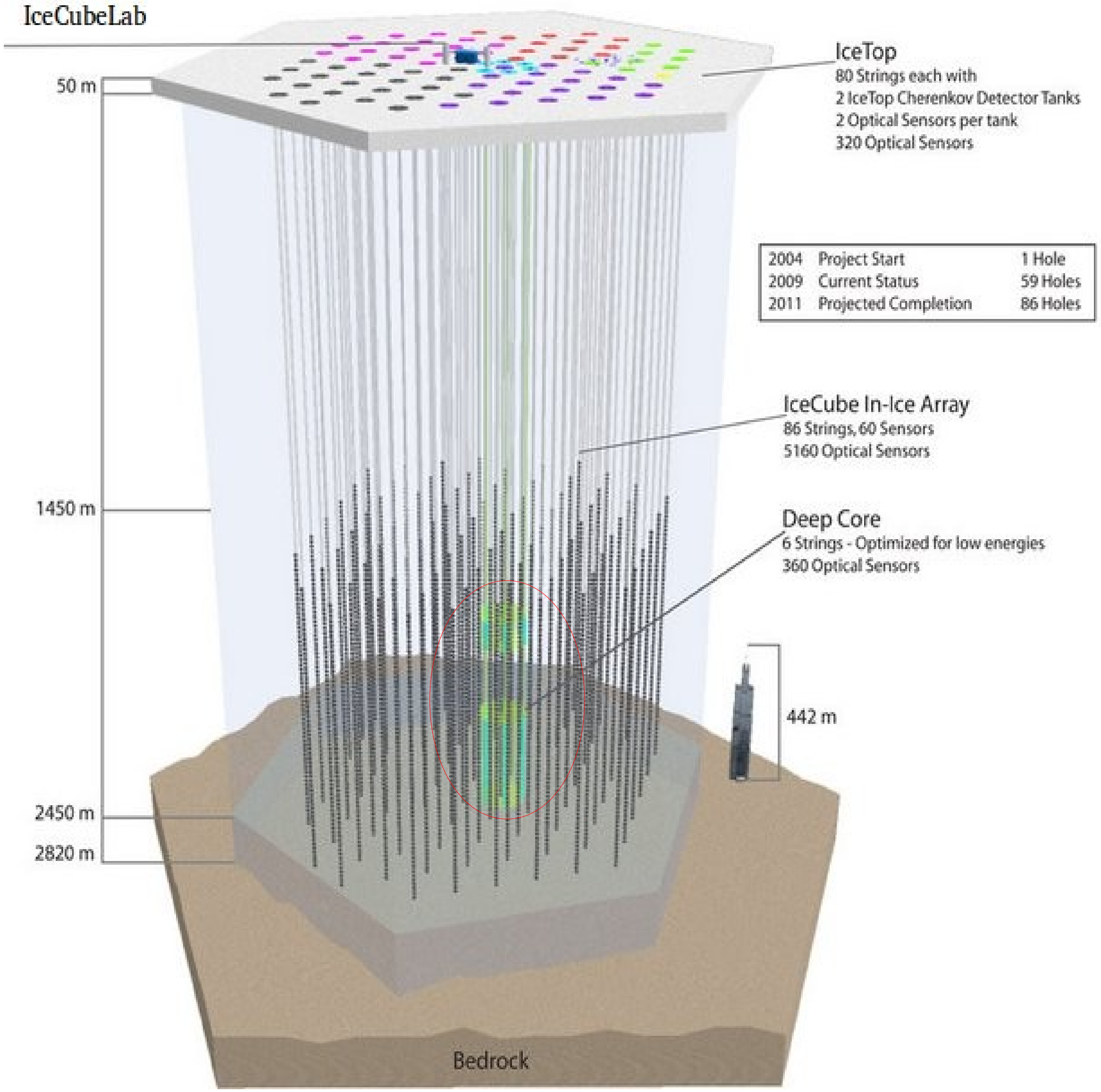
Purposes

- Study of Crs: origin, spectra
- Search for UHE ν's, including cosmogenic ones

$$p + \gamma \to \pi^+ + n;$$

$$\pi^+ \to e^+ + 3\nu$$

IceCube + DeepCore



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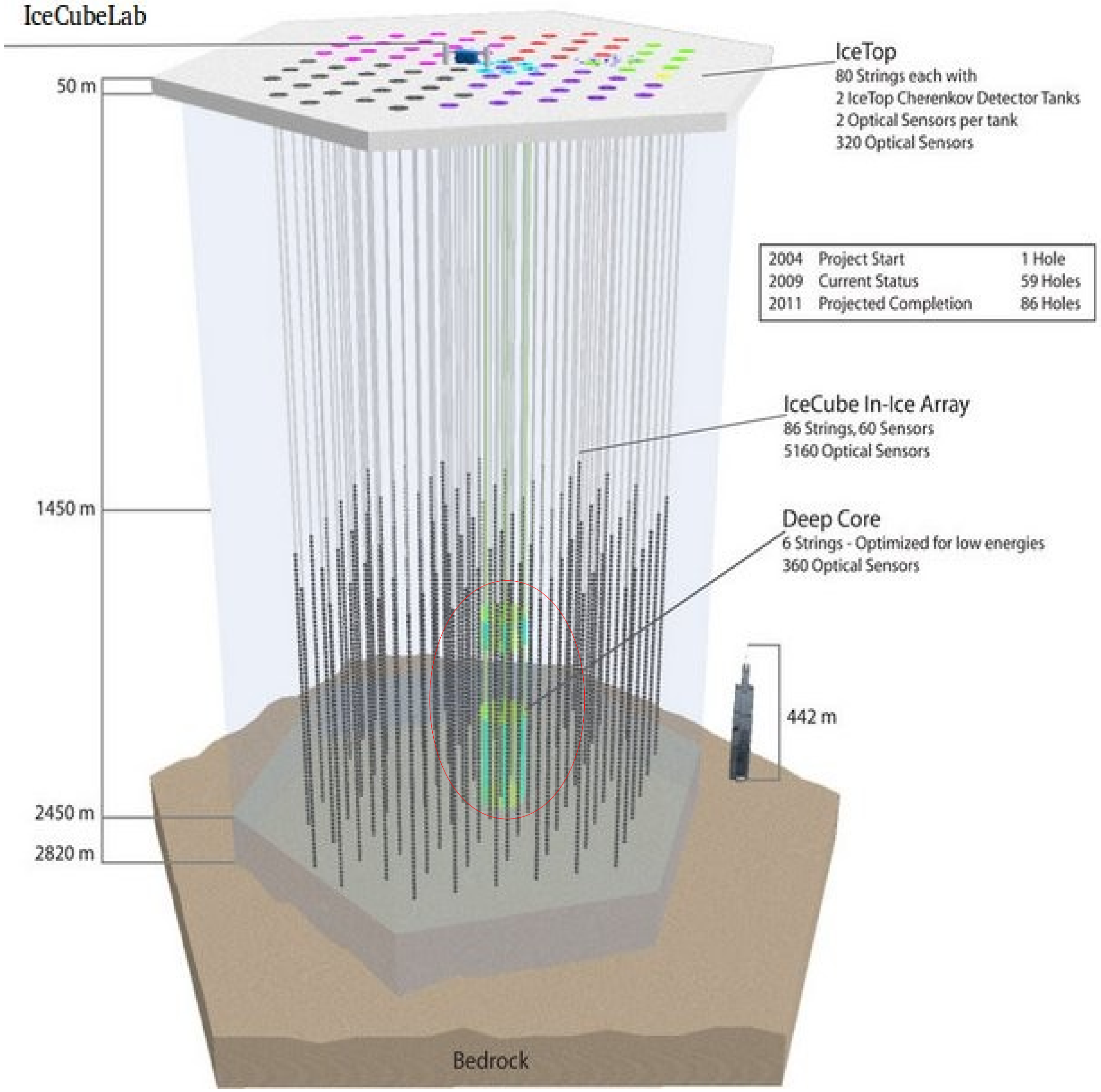
IceCube + DeepCore



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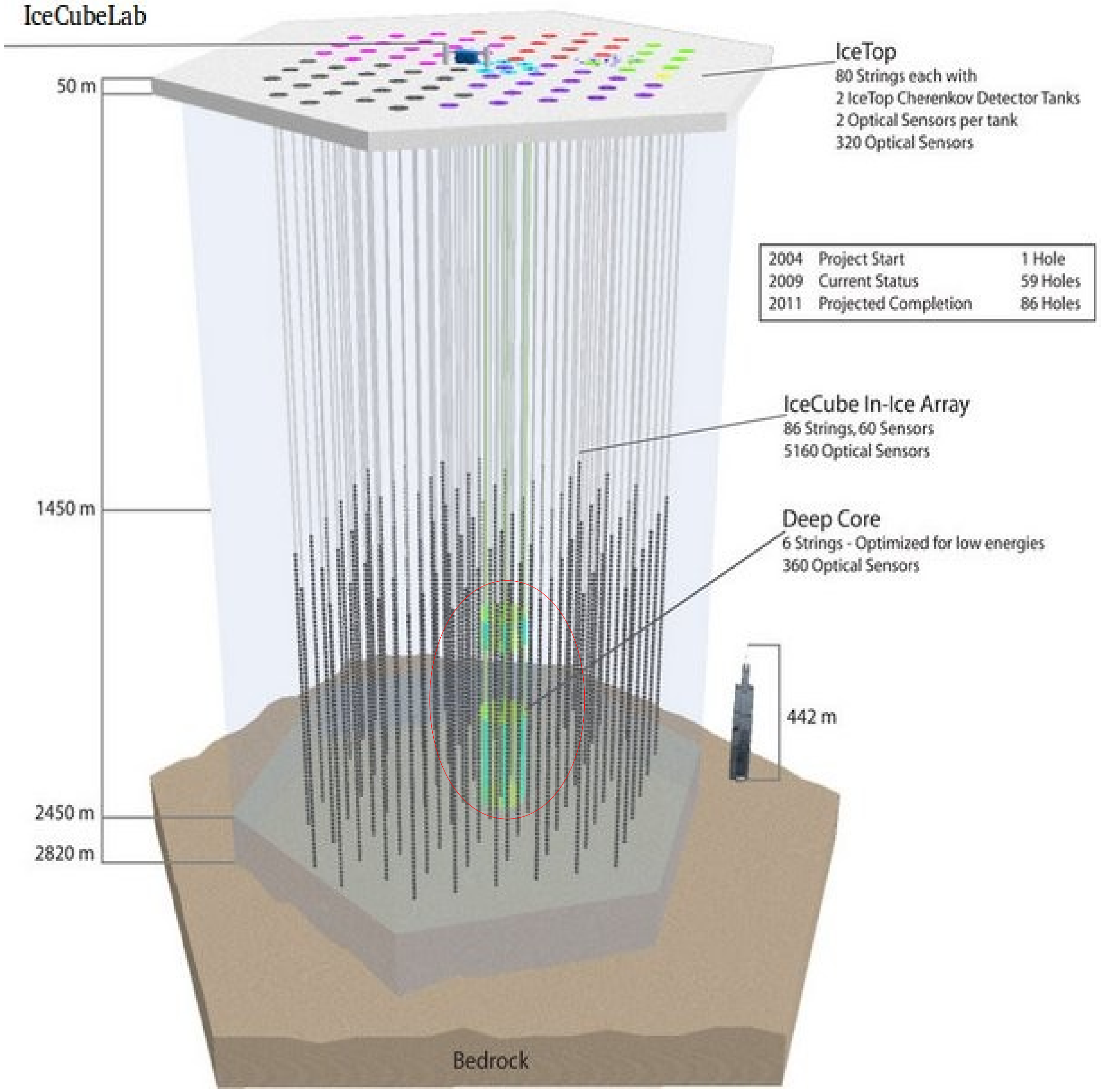
- DUMAND – Baikal – AMANDA – IceCube + DeepCore (V ~ 0.02 km^3)

IceCube + DeepCore



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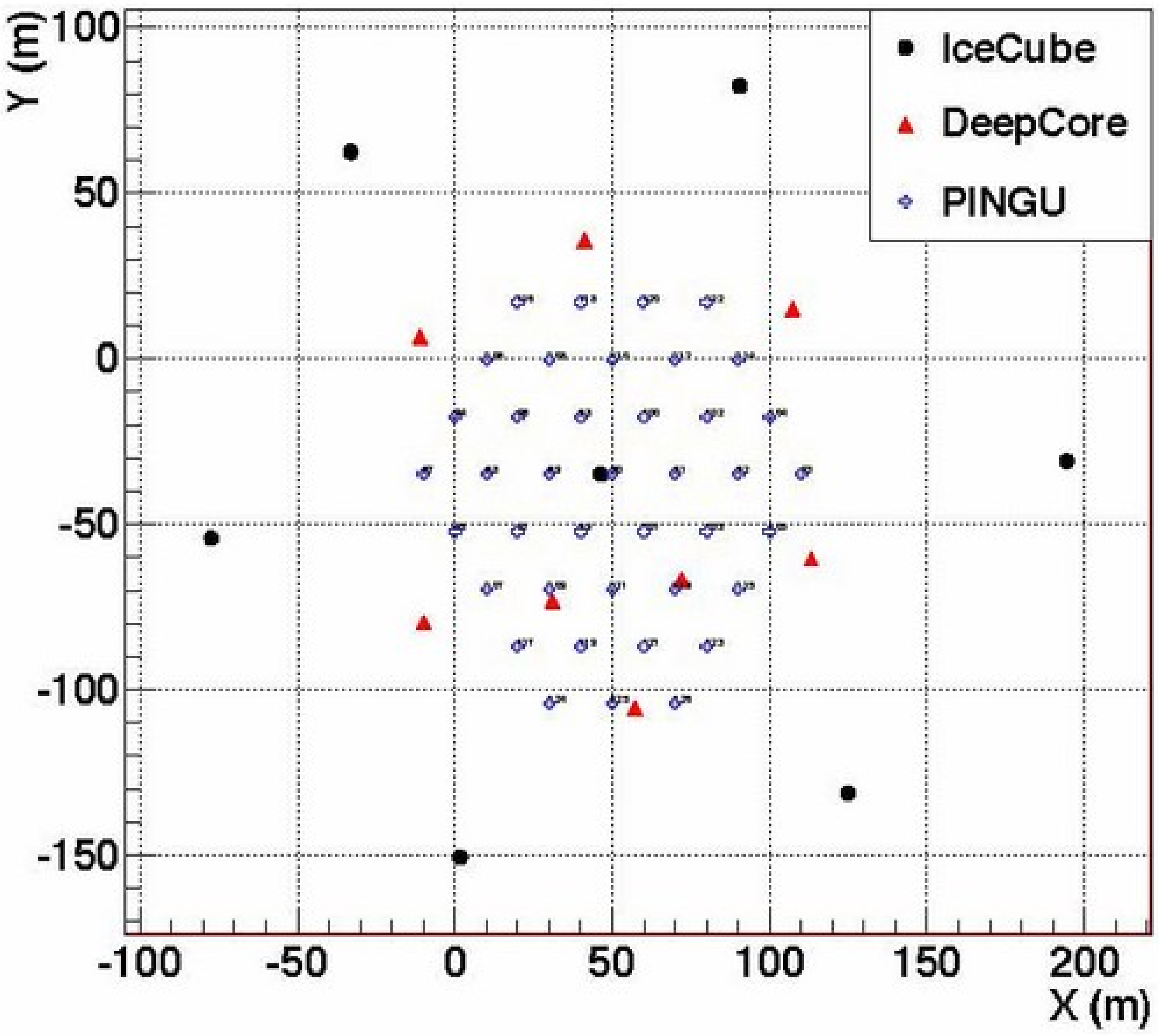
- Study of neutrino properties
- DUMAND – Baikal – AMANDA – IceCube + DeepCore (V ~ 0.02 km^3)
- Cherenkov light from
  1) muons – tracks
  2) cascades – showers from electrons and hadrons

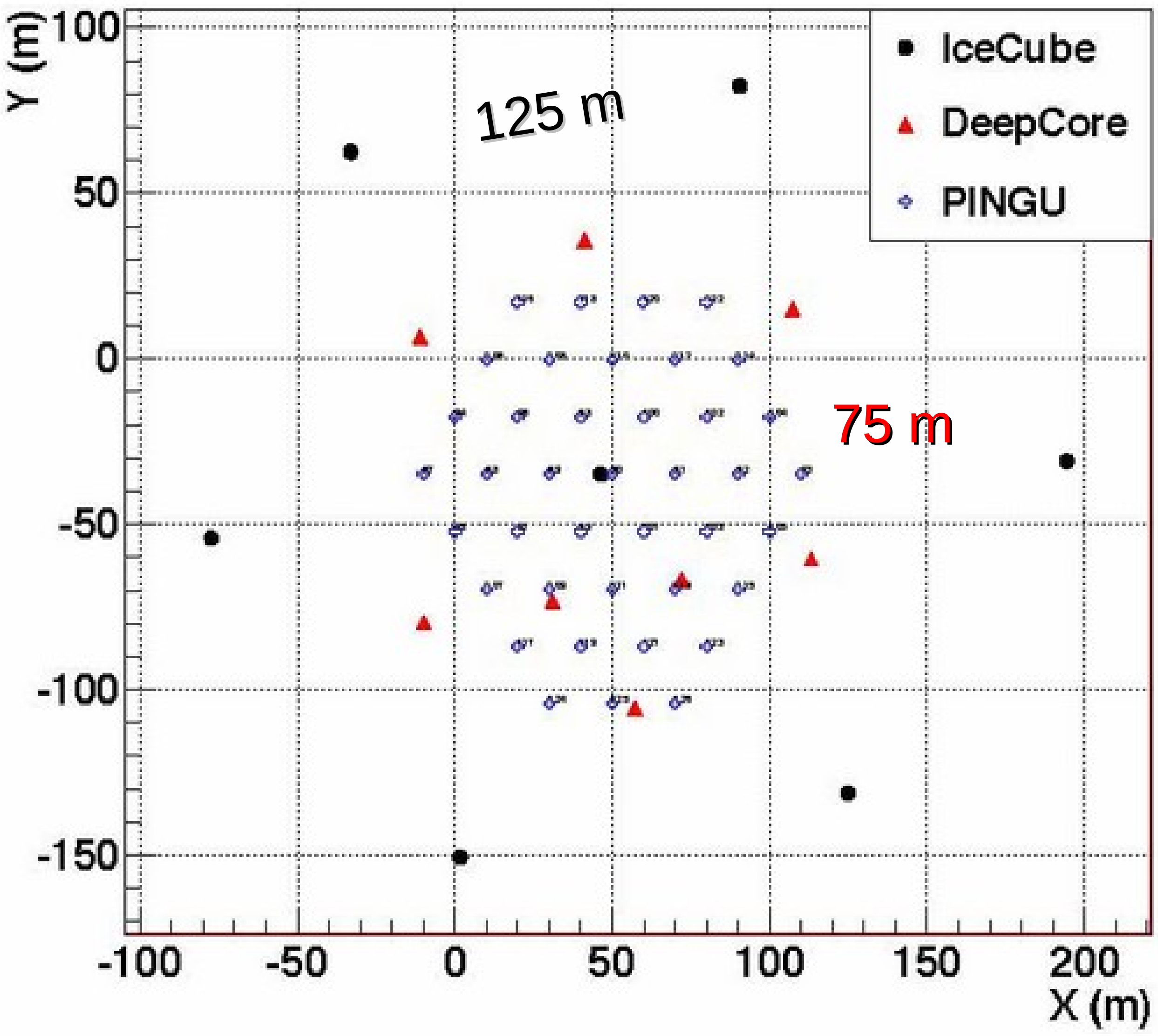
IceCube – DeepCore - PINGU

Precision IceCube Next Generation Upgrade



IceCube – DeepCore - PINGU

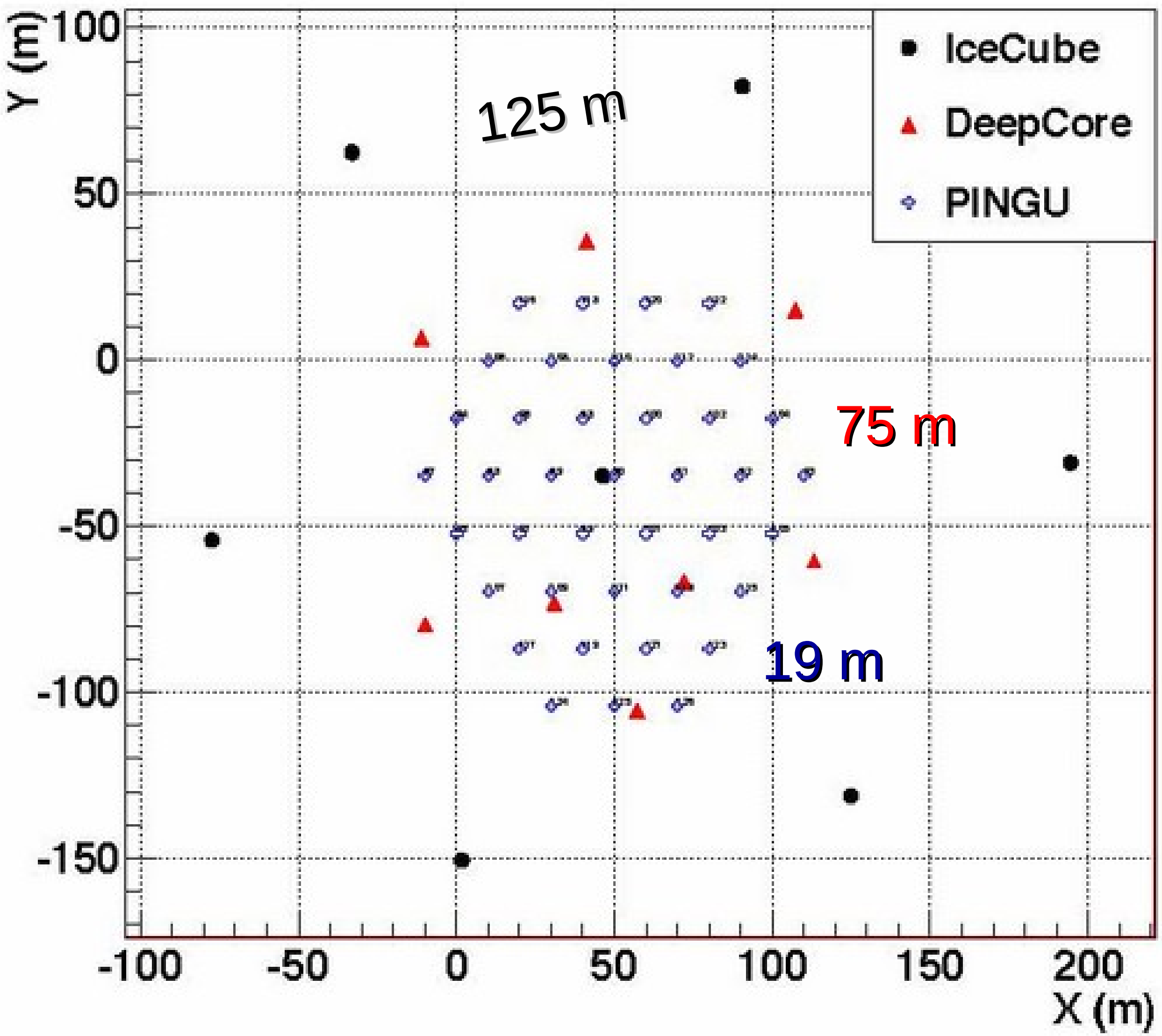
Precision IceCube Next Generation Upgrade



- **IceCube**: 78 strings
  E_{th} = 100 GeV
- DeepCore: 8 strings
  E_{th} = 10 GeV

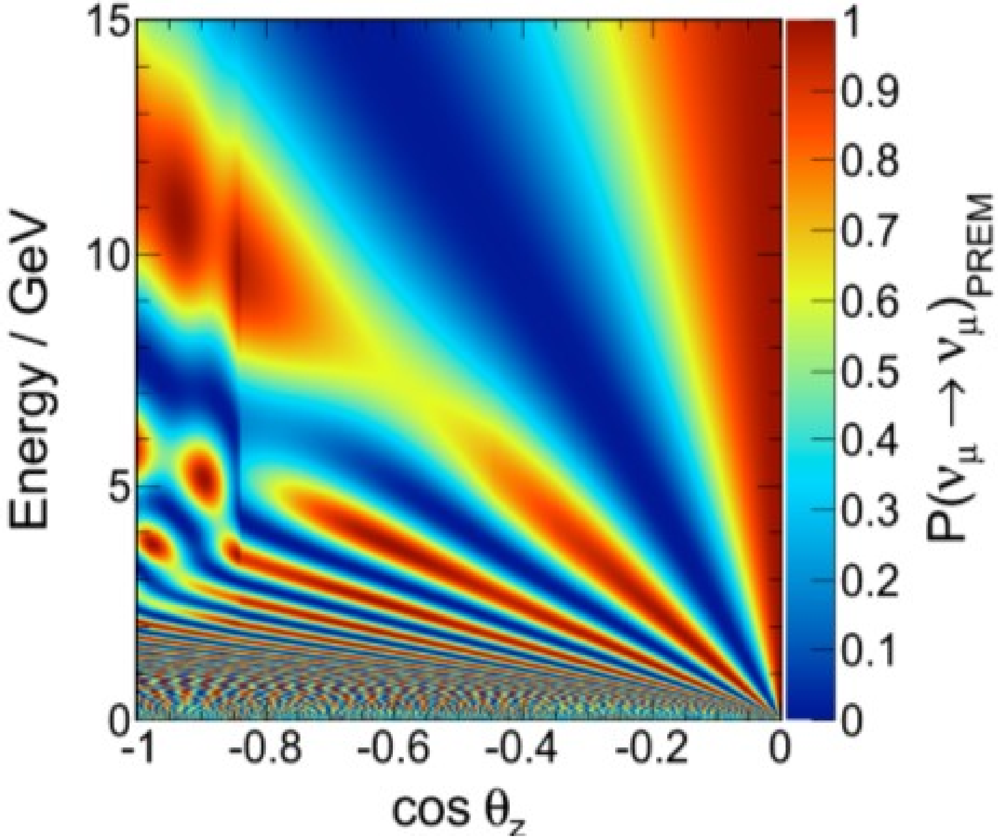
IceCube – DeepCore - PINGU

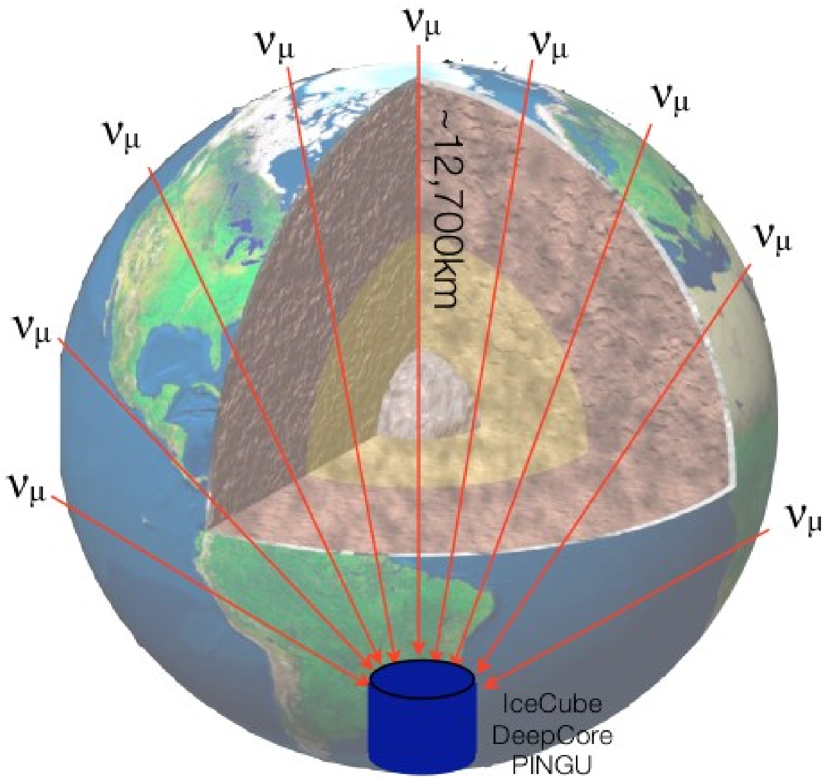
Precision IceCube Next Generation Upgrade



- **IceCube**: 78 strings E_{th} = 100 GeV
- DeepCore: 8 strings E_{th} = 10 GeV
- PINGU: +40 strings E_{th} = 1 GeV
- High statistic ~10^4 atmospheric ν's /yr

Atmospheric ν-Oscillations

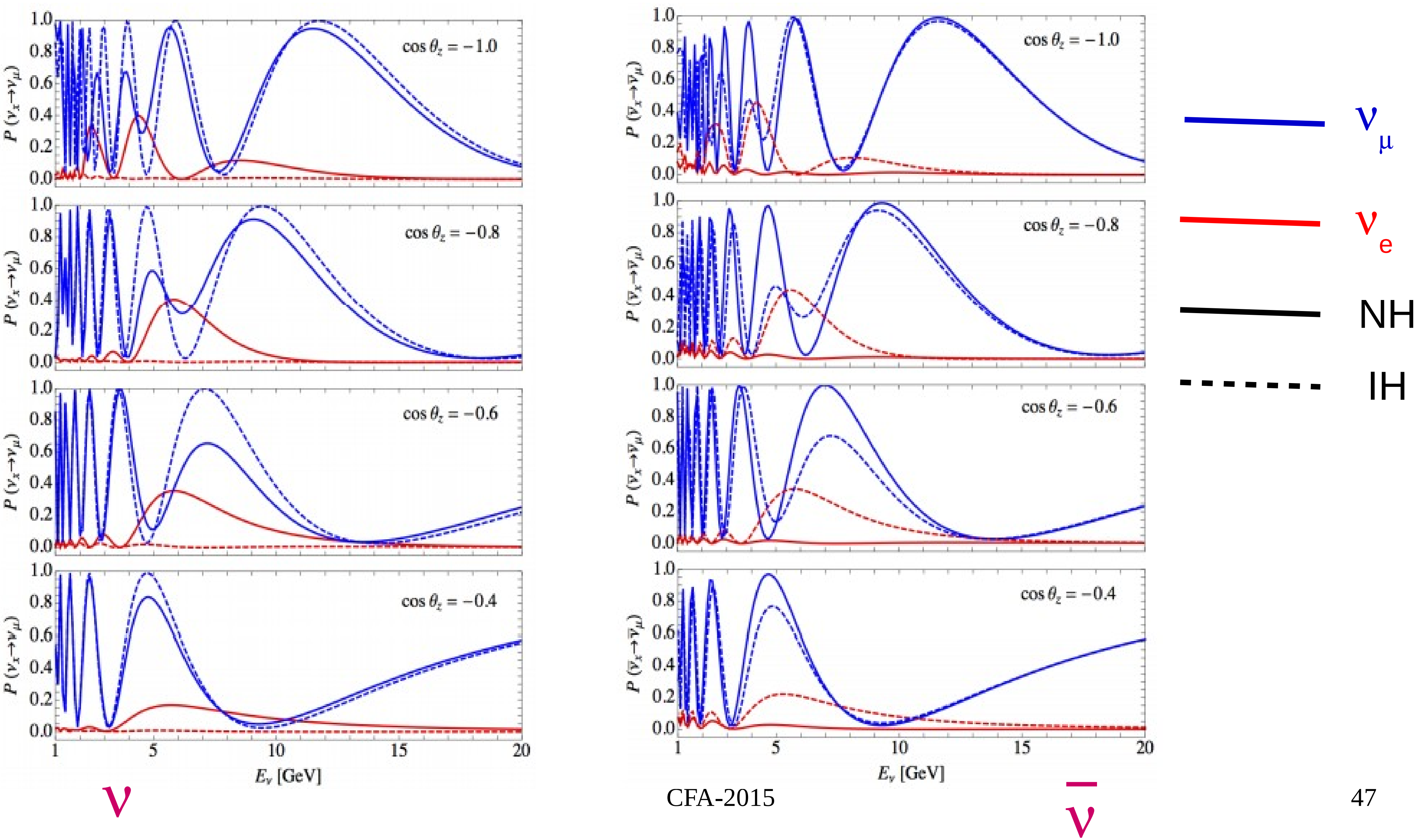




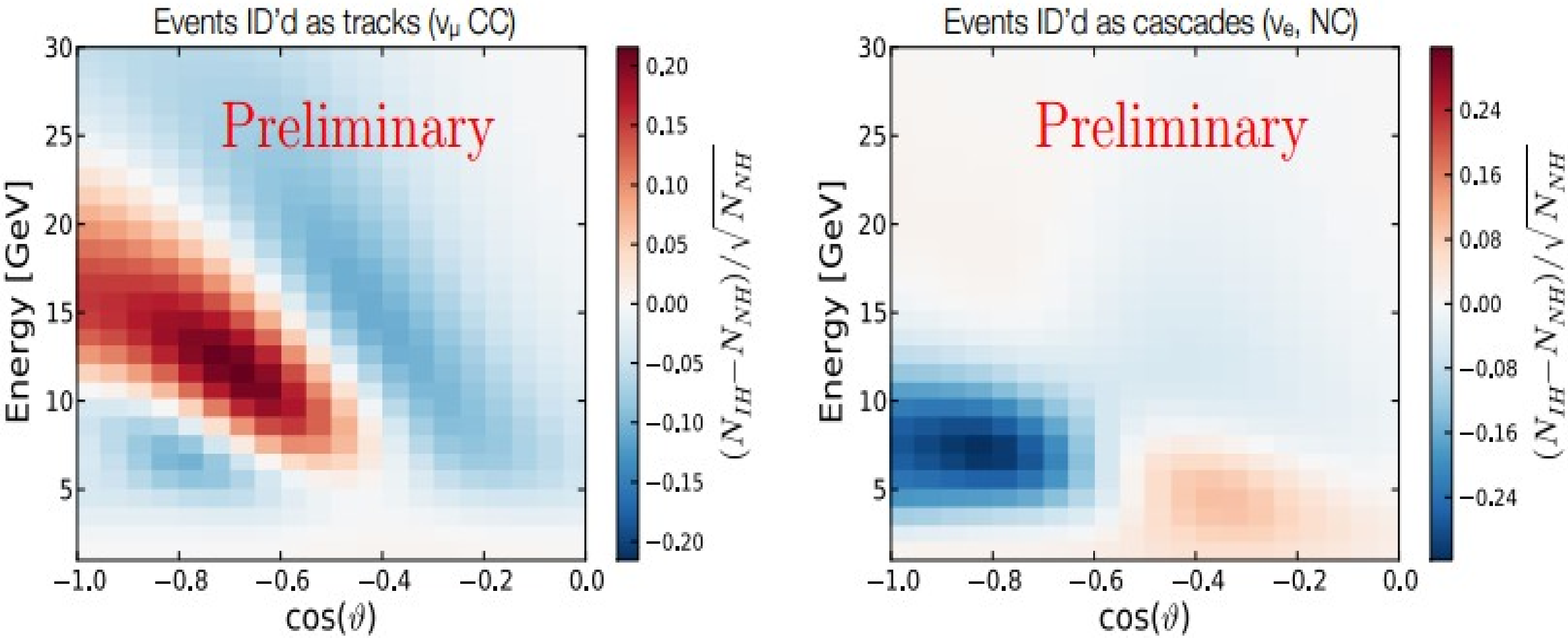
- With +40 strings a sensitivity to the hierarchy ~3.4σ /yr.
- If deployment will start in 2016/2017, the 3σ result is expected in 2020.
- Survival probability for $\bar{\nu}$ in NH is essentially the same as for ν in IH.

Probabilities of Oscillations

Akhmedov, Razzaque, Smirnov, JHEP 1302 (2013) 082, JHEP 1307 (2013) 026; arXiv:1205.7071



Tracks and Cascades in PINGU

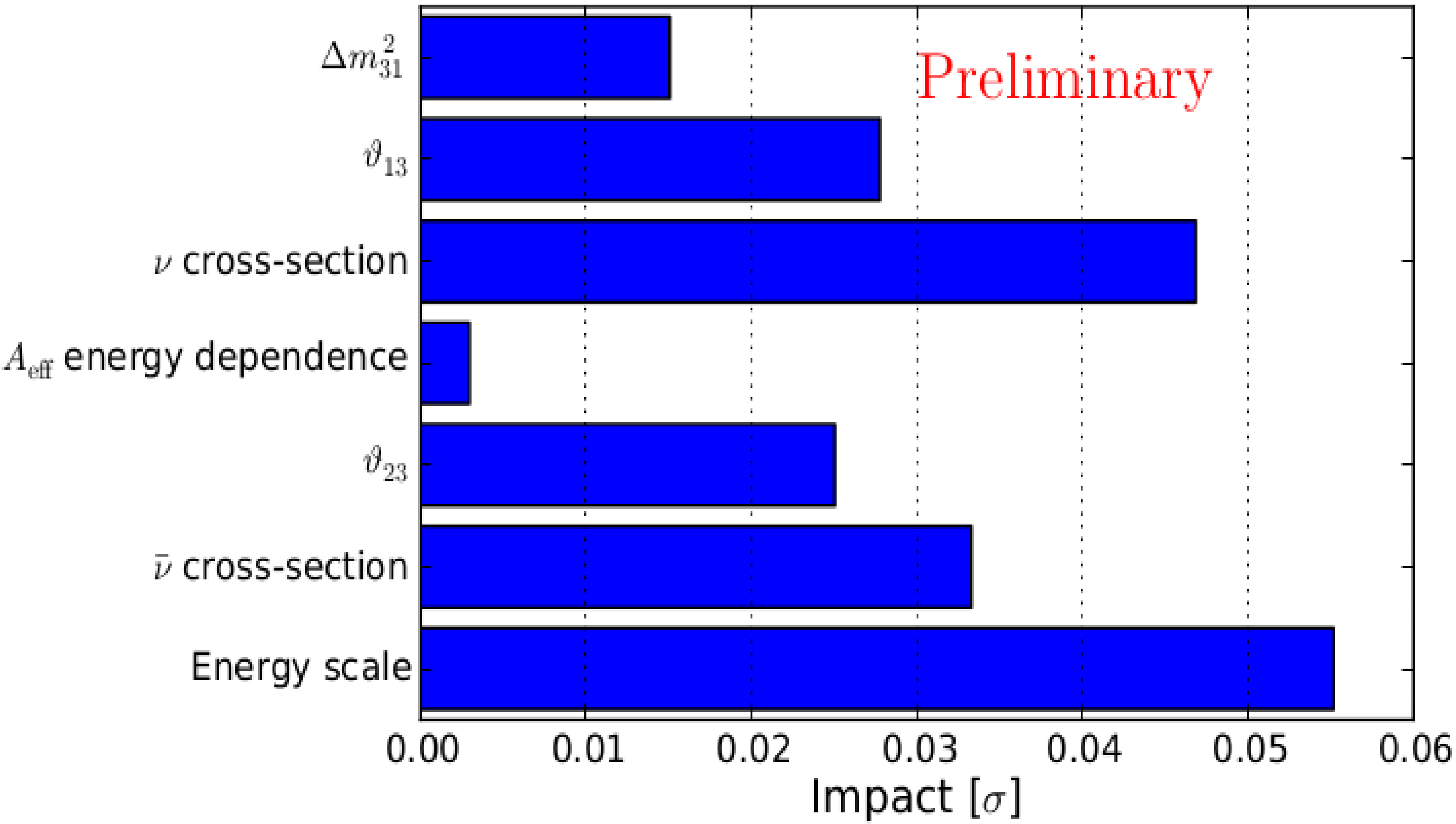


From PINGU's Letter of Intent, arXiv:1401.2046

The fluxes of atm ν and $\bar{\nu}$ are different. And at low energies the νN–cross-sections are ~3 times higher than those for $\bar{\nu}N$.

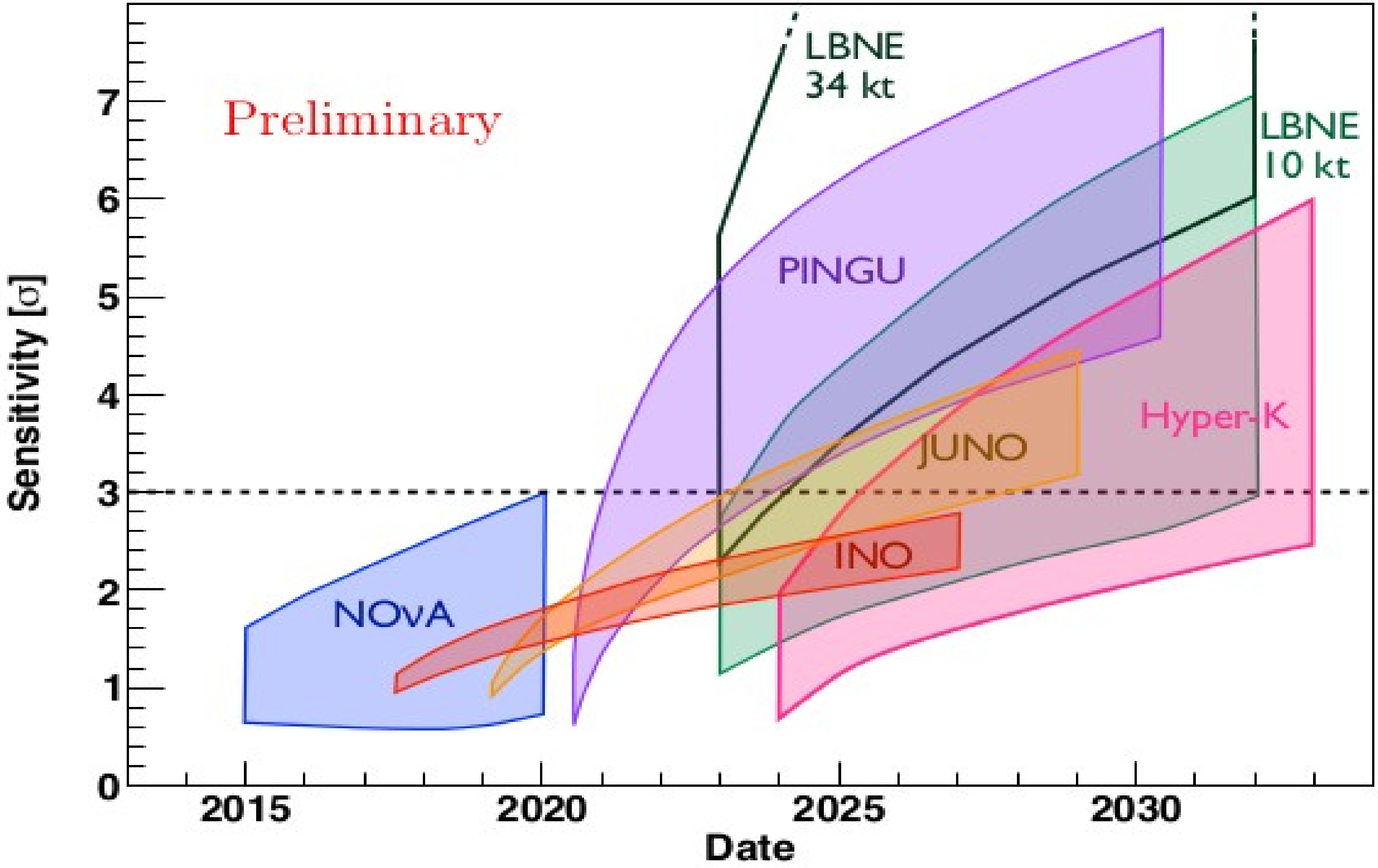
Systematic Errors

Impacts on the estimated 1 year significance of the MH measurement.



- Significance 1.75σ with 1 yr of 40 strings.
- Increases as $\sqrt{t}$ with time.
-

Comparison of Sensitivities



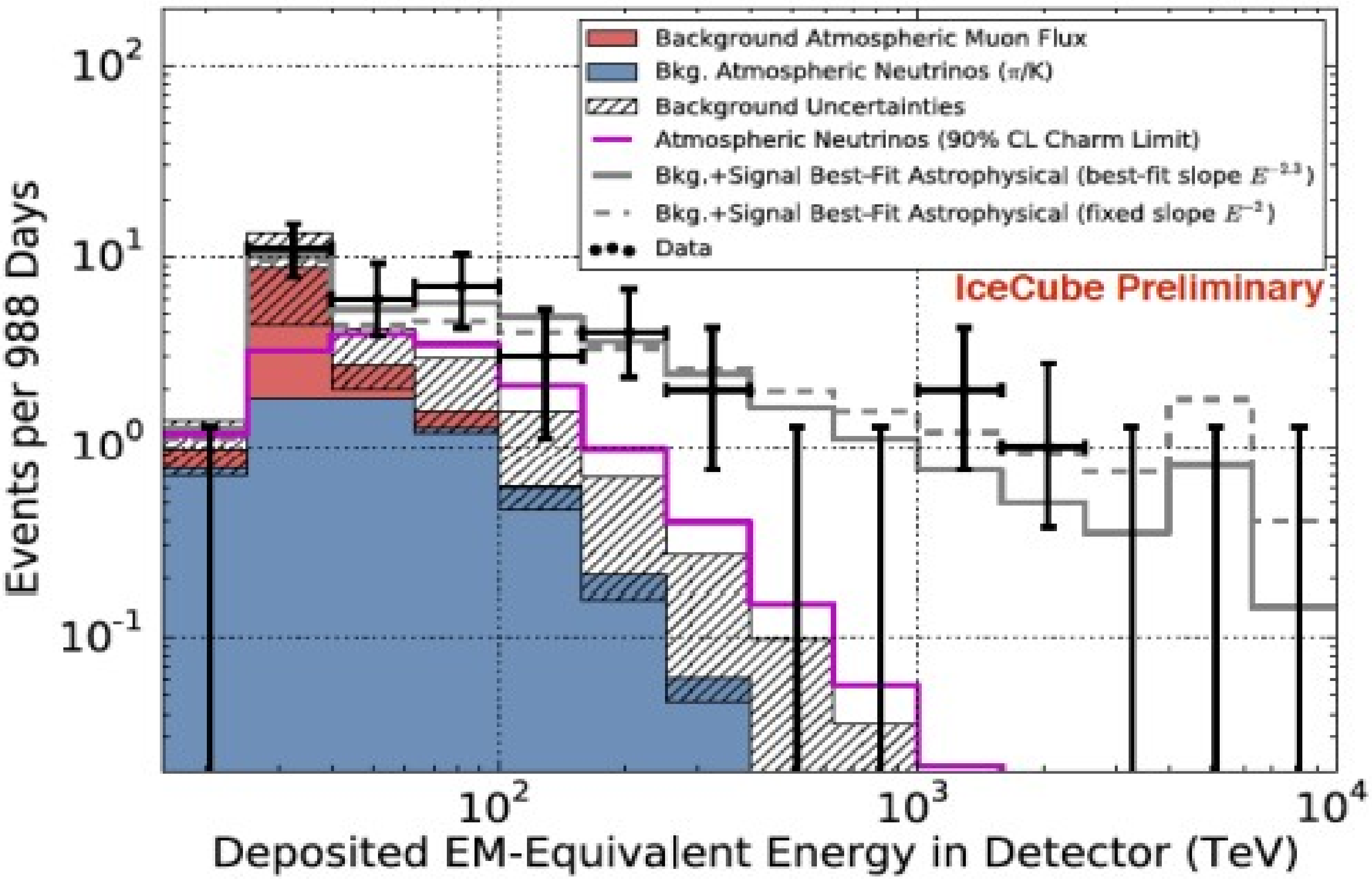
Assuming *NH* and rejecting *IH*. The widths of the is due to maximum sensitivity differences for *NH* and *IH* cases.

νN Cross-Sections at HE

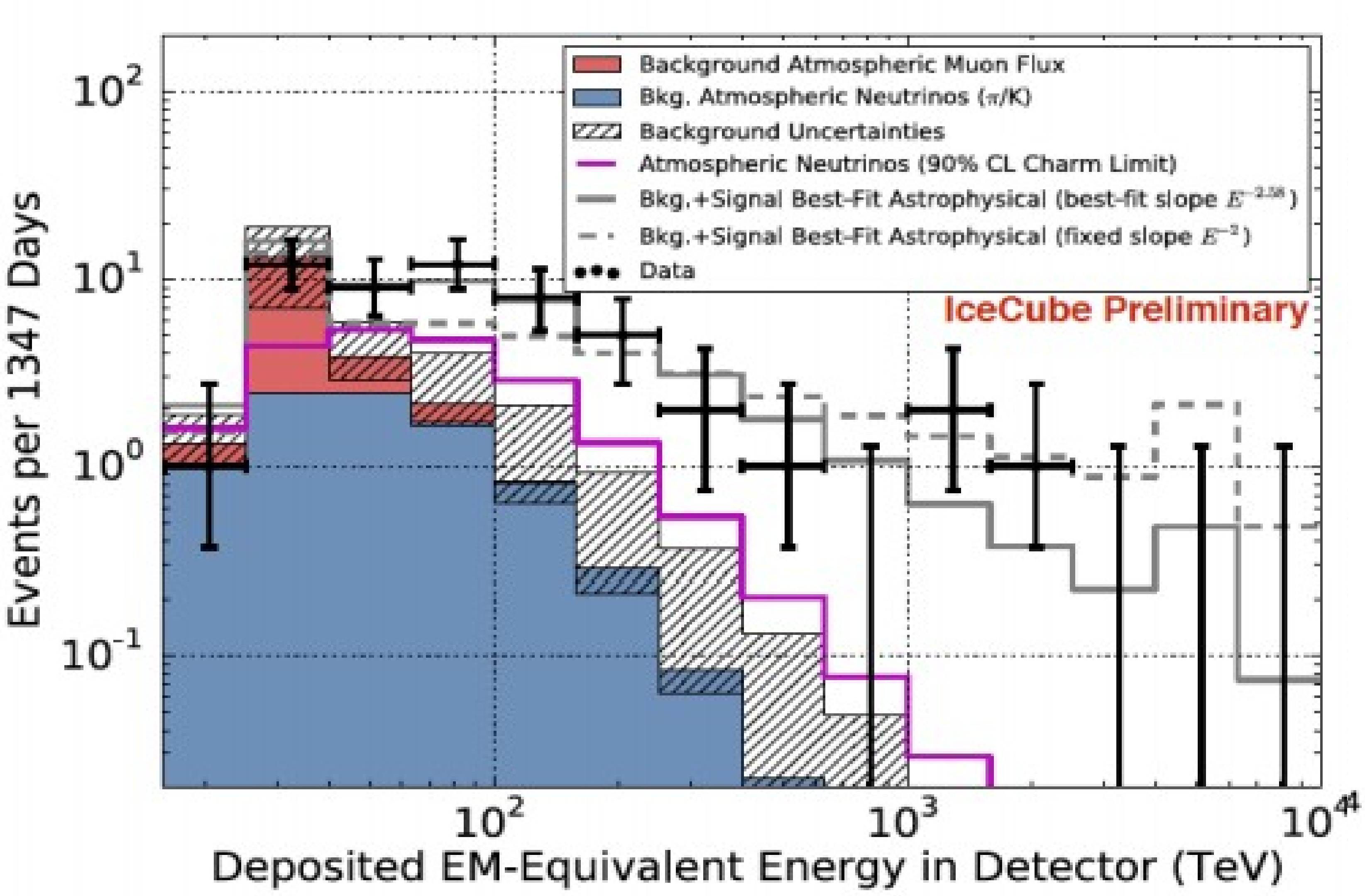
- An accurate account for cross-sections is important also for HE neutrino astrophysics.
- IceCube discovered a statistically significant excess of HE neutrinos over the expected atmospheric flux at E > 30 TeV.
- The number of muon (tracks) events is unexpectedly small as compared to number of showers (electron and tau neutrinos and NC).
- At high energies an accurate account for the pQCD corrections is needed.
- At extreemly high energies non-perturbative effects are to be accounted for.

IceCube HE ν Spectrum

IceCube HE ν Spectrum

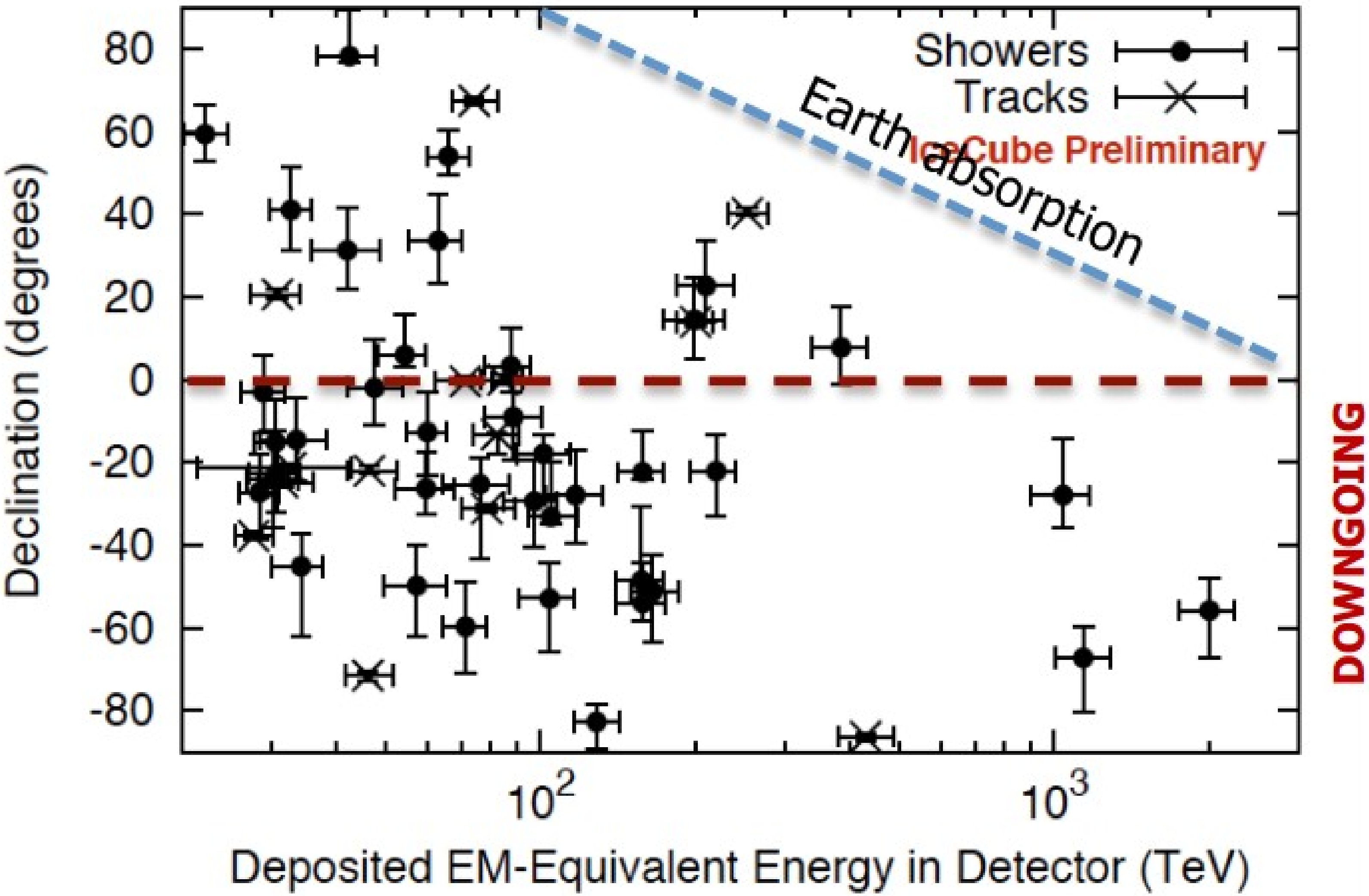


IceCube HE ν Spectrum

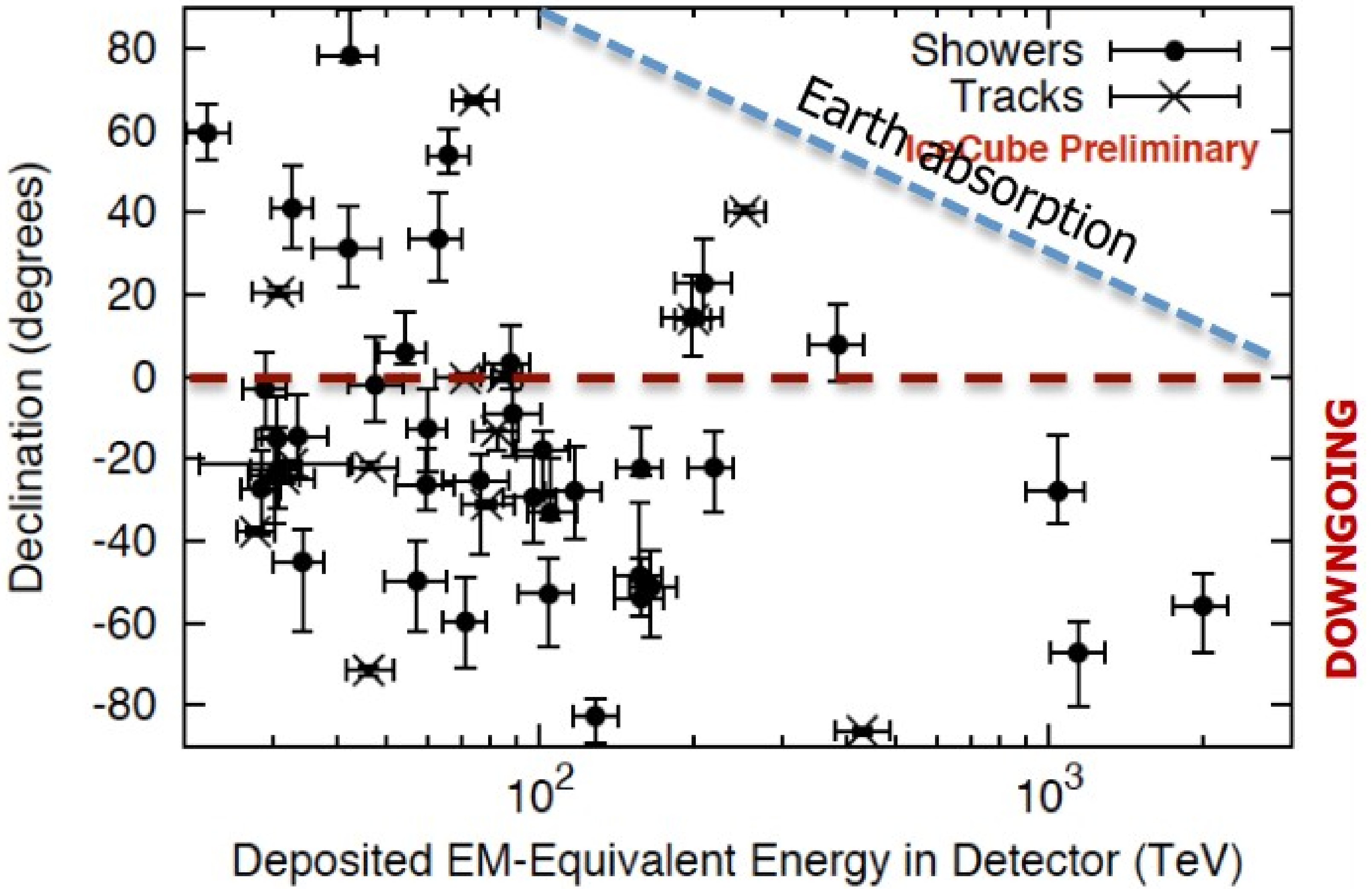


IceCube HE ν-Events

IceCube HE ν-Events

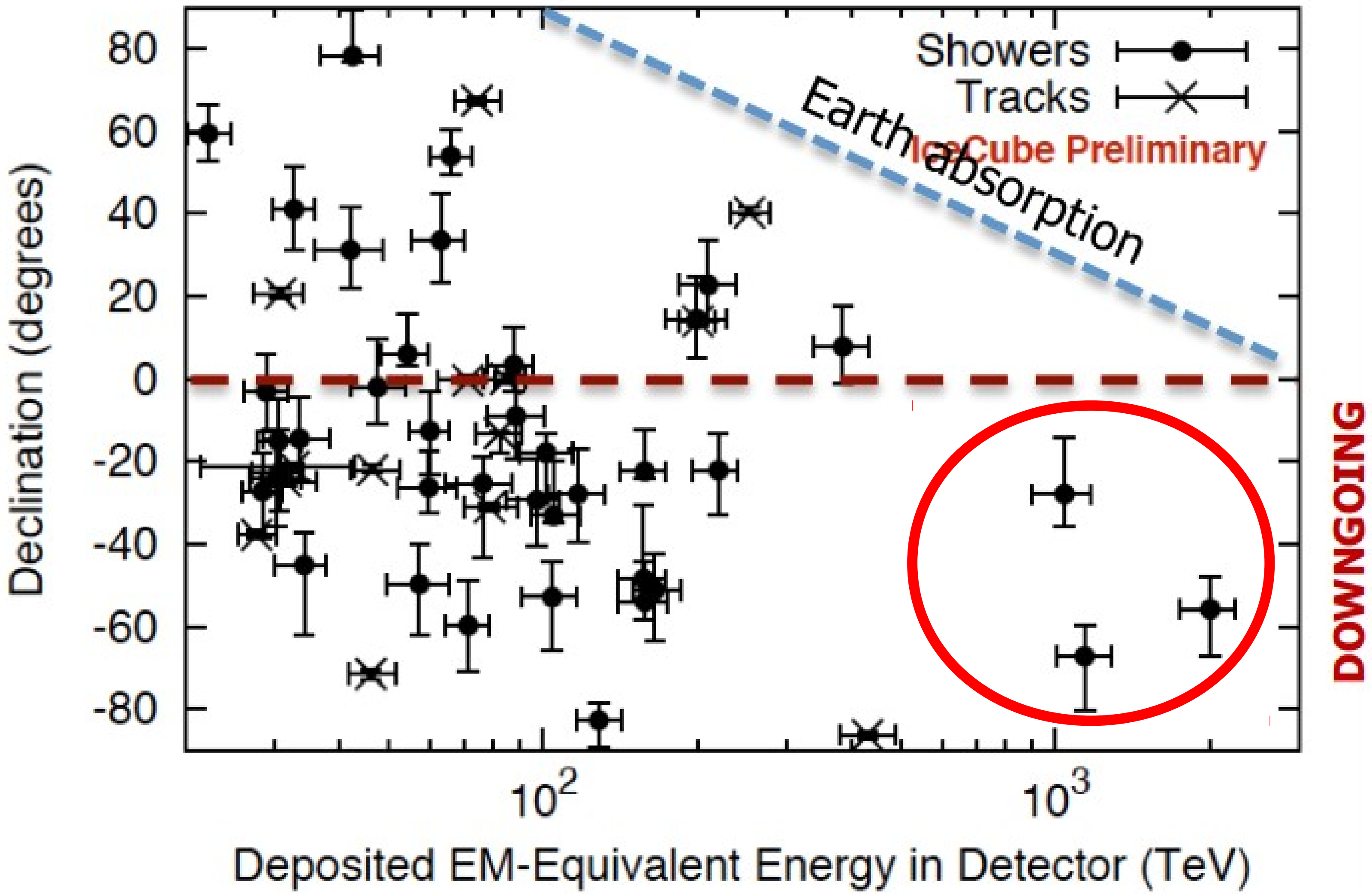


IceCube HE ν-Events



54 HE ν-events in 4 years. ~7σ. Mostly showers. Isotropic. Sources are unknown. Many models are excluded.

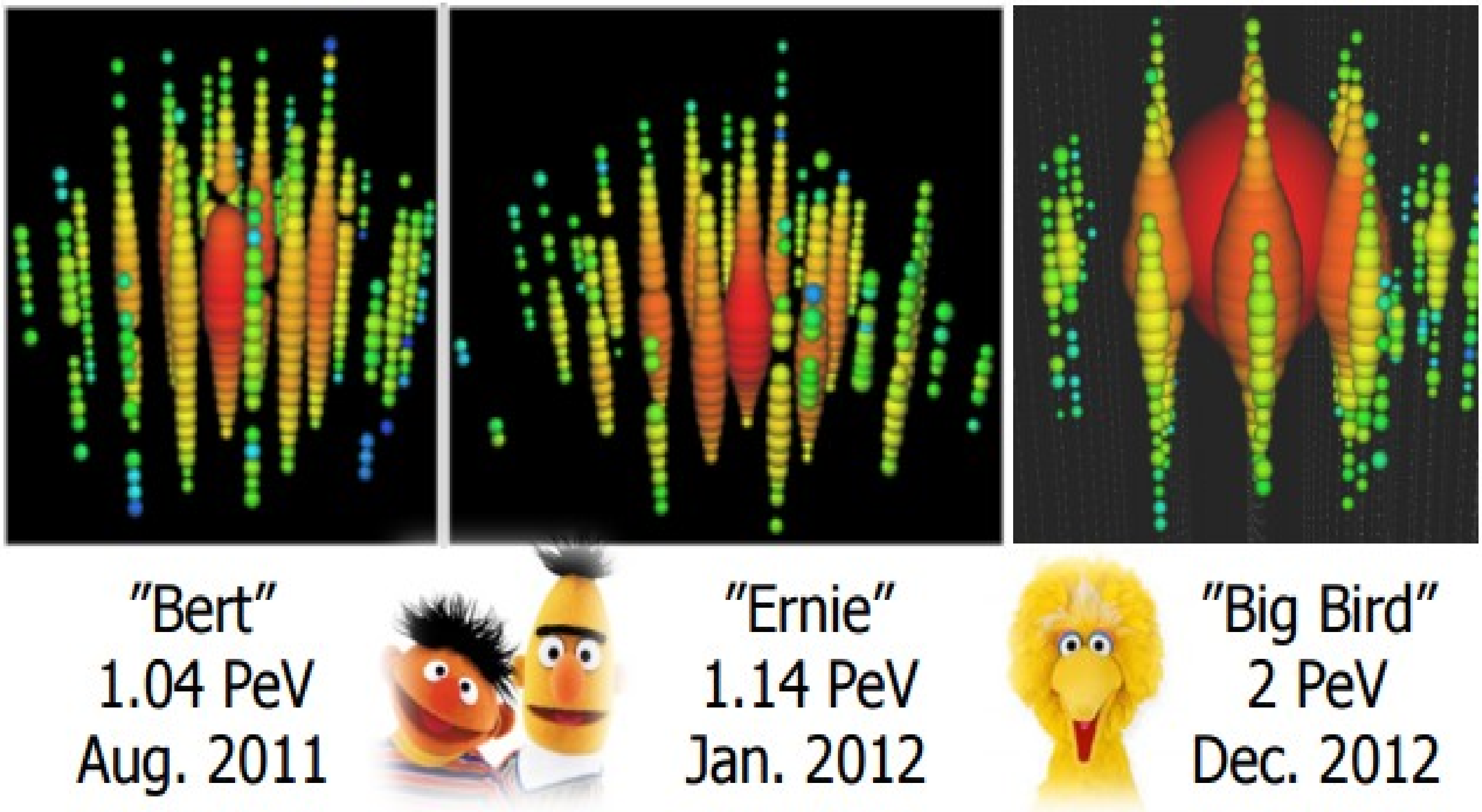
IceCube HE ν-Events



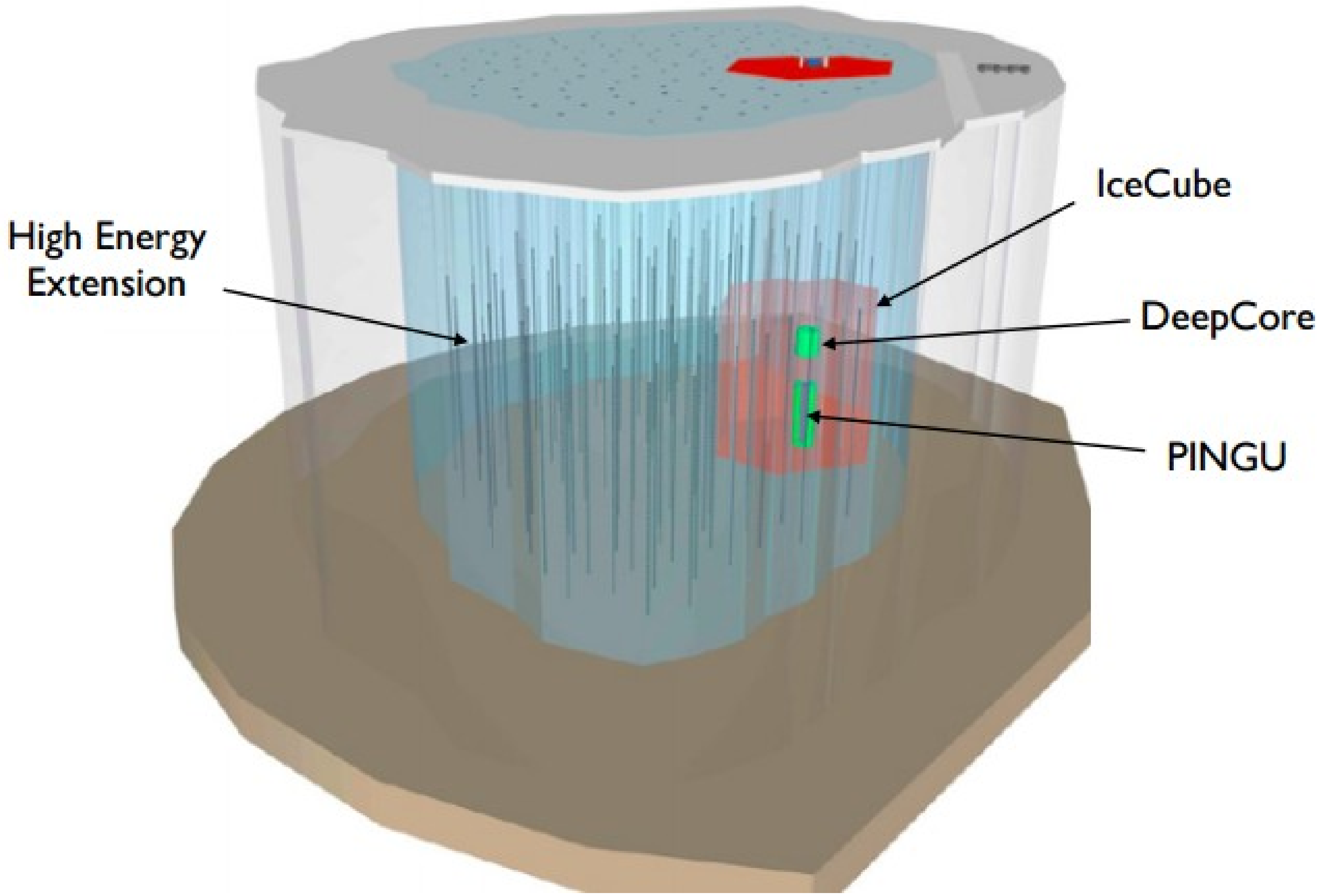
54 HE ν-events in 4 years. ~7σ. Mostly showers. Isotropic. Sources are unknown. Many models are excluded.

Most Energetic Neutrinos

Cascade events



NGIC



Next Lecture

- In spite of the long history of ν physics, the cross-sections of νN-interactions with matter remain the field of intensive study at all ranges of energies.
- In the next lecture I'll try to demonstrate the importance of these studies and to present the main theoretical ideas used for calculations of different cross-sections.
- I'll discuss theoretical models and the parameters involved, and the uncertainties due to these unknown parameters.
- The role of elastic, quasi-elastic, single pion production and deep-inelastic scatterings will be discussed separately.
- I plan to show the dependence of the cross-sections on the axial mass M_A in the single pion production case and on W_{cut} parameter, which separates the single-pion and the deep-inelastic contributions.

Next Lecture, cont.

- I'll discuss the DIS and the role of NNLO pQCD and target mass corrections. The role of final lepton mass effects, especially important in the τ-neutrino scattering case, and the kinematic limits involved in calculations.
- Small x and high Q^2 effects will be considered. The problems with extrapolations of the structure functions to small Q^2, where the pQCD does not work but which is especially important for the future megaton-scale detector experiments like PINGU, ORCA and Hyper-Kamiokande, will be discussed.
- The cross-sections derived using the set of models and parameters obtained in collaboration with my colleagues
  M. Kowalski (DESY-Zeuthen),
  K. S. Kuzmin (JINR and ITHEP, Moscow),
  V. Naumov (JINR, Russia)
  and Ch. Spiering (DESY-Zeuthen)
  will be compared with the predictions of several MC generators.

Thank you!

and see you...