II EU Workshop on Water Cherenkov Experiments
for Precision Physics
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Introduction:
Water Cherenkov Detectors

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Outline

- *Water Cherenkov proton decay detectors*
- *Water Cherenkov neutrino detectors*
- *Water Cherenkov detectors to study the high-energy Universe*
- *Summary*

As an introduction to water Cherenkov detectors, I decided to talk mostly on some highlights from these detectors. I will not discuss the most recent results or future experiments.

Water Cherenkov proton decay detectors

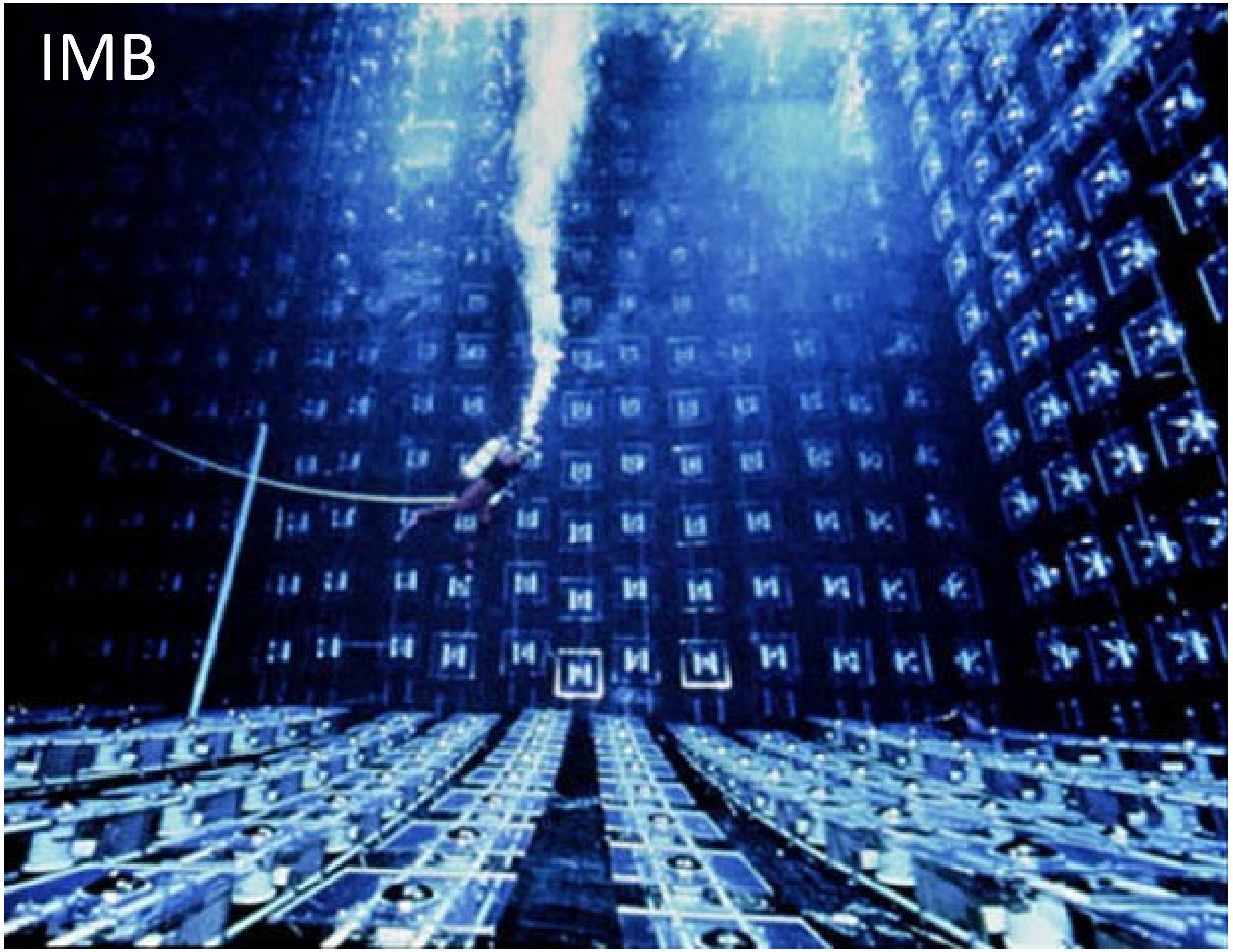
Grand Unified Theories and proton decay

Water Cherenkov detectors have been used to study cosmic rays (and others) probably since 1950's (see, for example, D. Wark, TMEX2018WCP). However, in my opinion (which might be wrong), water Cherenkov detectors began significant contributions to our field since the 1980's.

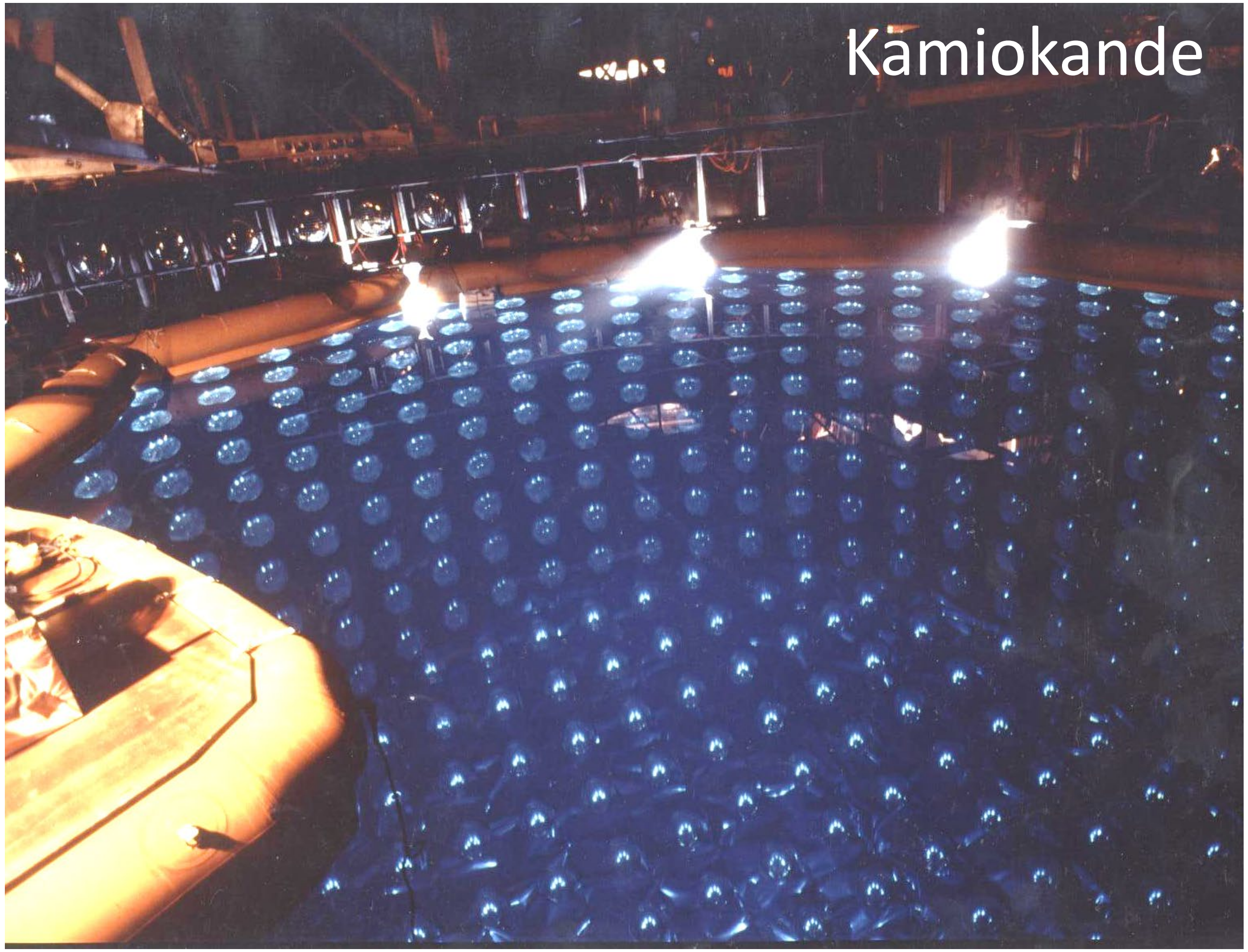
- ✓ In the 1970's, the idea of Grand Unified Theories (GUTs) appeared (for example, H. Georgi and S.L. Glashow, PRL 32 (1974) 438).
- ✓ An important consequence from GUTs was the prediction of proton decays. The predicted lifetime of a proton was about $10^{30 +/- 2}$ years, with the main decay mode of e^++meson (for example, $e^+ + \pi^0$).
- ✓ To observe proton decays in a year with the lifetime of 10^{32} years or shorter, one needs to watch at least ~1,000 tons of matter (assuming that a half of a nucleons are protons and about a half of π^0 should not be affected by nuclear effects).
- ✓ (SUSY-SU(5) and the prediction of p → anti-ν K^+ .)

➔ Large water Cherenkov detector

IMB and Kamiokande



8,000-ton water Cherenkov detector



3,000-ton water Cherenkov detector

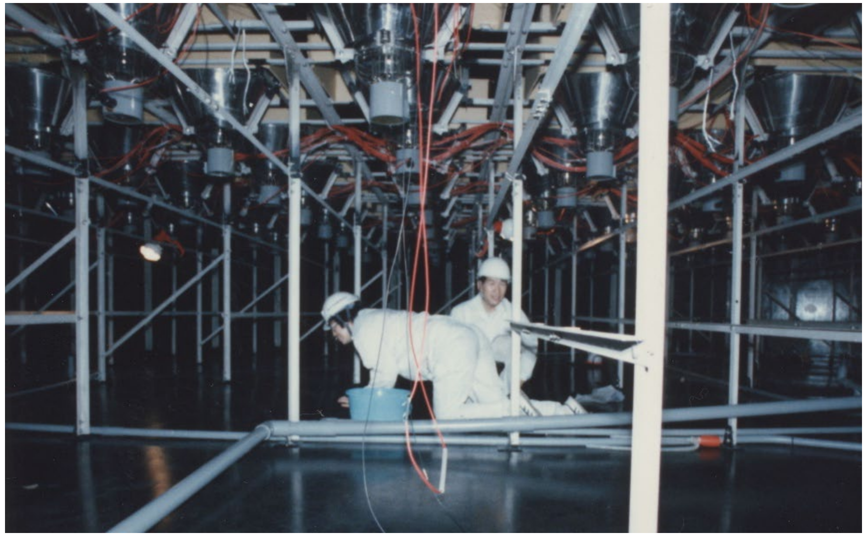
These experiments did not observe proton decays…

Improvements of IMB and Kamiokande

<u>IMB and Kamioknde did not give up:</u>

IMB improved the photon detection by replacing 5-inch PMTs with 8-inch ones. In addition, they installed wavelength shifter plate to each PMT to enhance the light detection.

Kamiokande decided to observe solar neutrinos by largely improving the detector system, namely installing outer detectors, photon timing measurement electronics and radioactivity removal from the water.



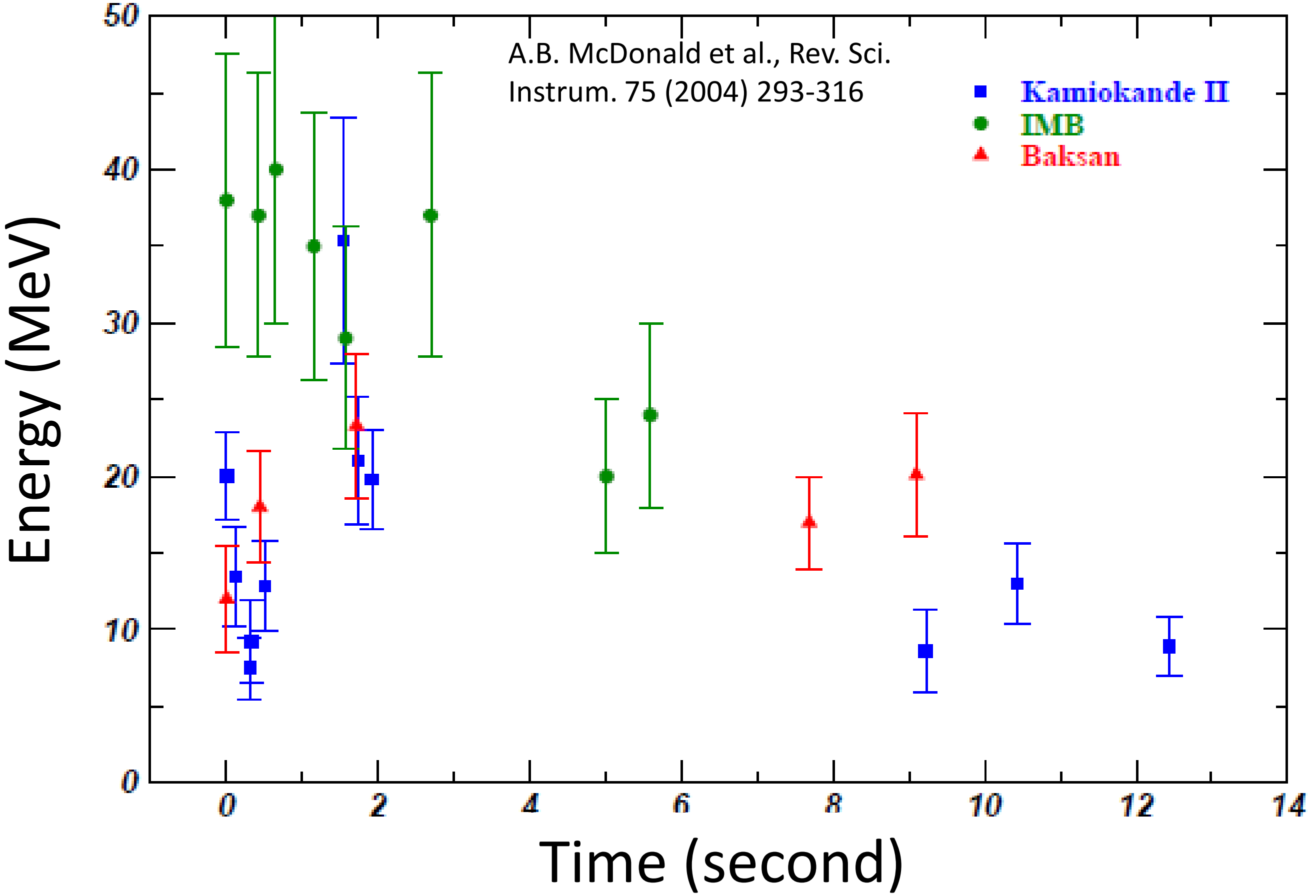
Side and bottom outer detector construction

Supernova SN1987A

Feb. 1987
（Large Magellanic Cloud, 160,000 light-years)

Birth of neutrino astronomy

Total 24 neutrino events were observed by 3 detectors (Kamiokande, IMB-3 and Baksan)



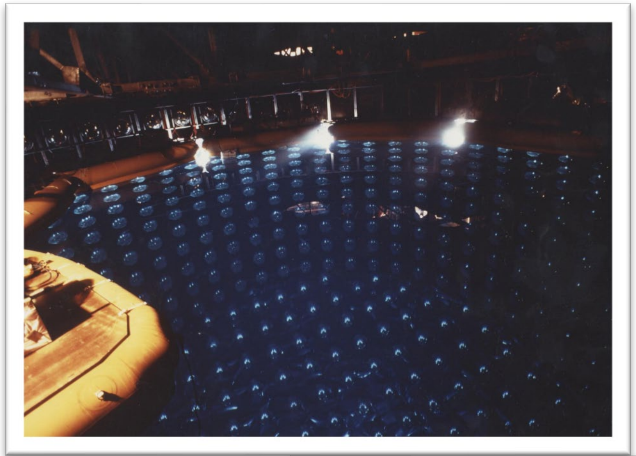
➔ Understood the basic mechanism of the supernova explosion.

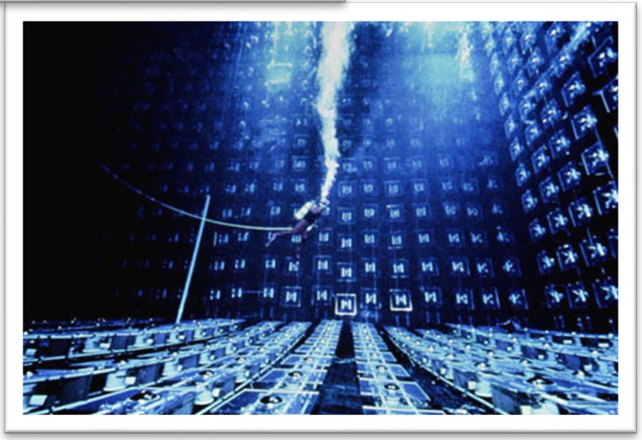
Masatoshi Koshiba
(Nobel prize 2002)

Prof. Kosiba said; "Many people say I am fortunate. However, at that time, neutrinos came to everywhere on the earth. Only people who prepared for them was able to observe them."

Missing atmospheric muon-neutrinos (1980's to 90's)

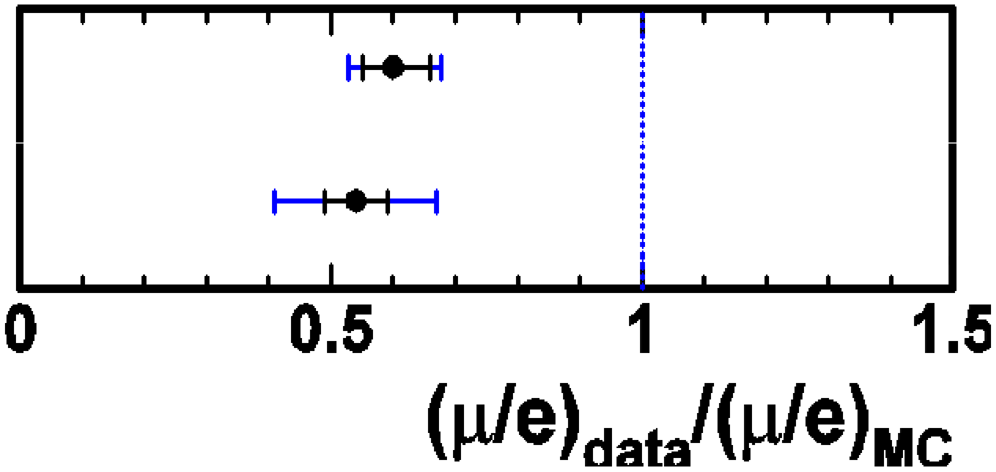
- ✓ Proton decay experiments in the 1980's observed many atmospheric neutrino events.
- ✓ Because atmospheric neutrinos are the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions.
- ✓ During these studies, missing atmospheric muon-neutrino events were observed.



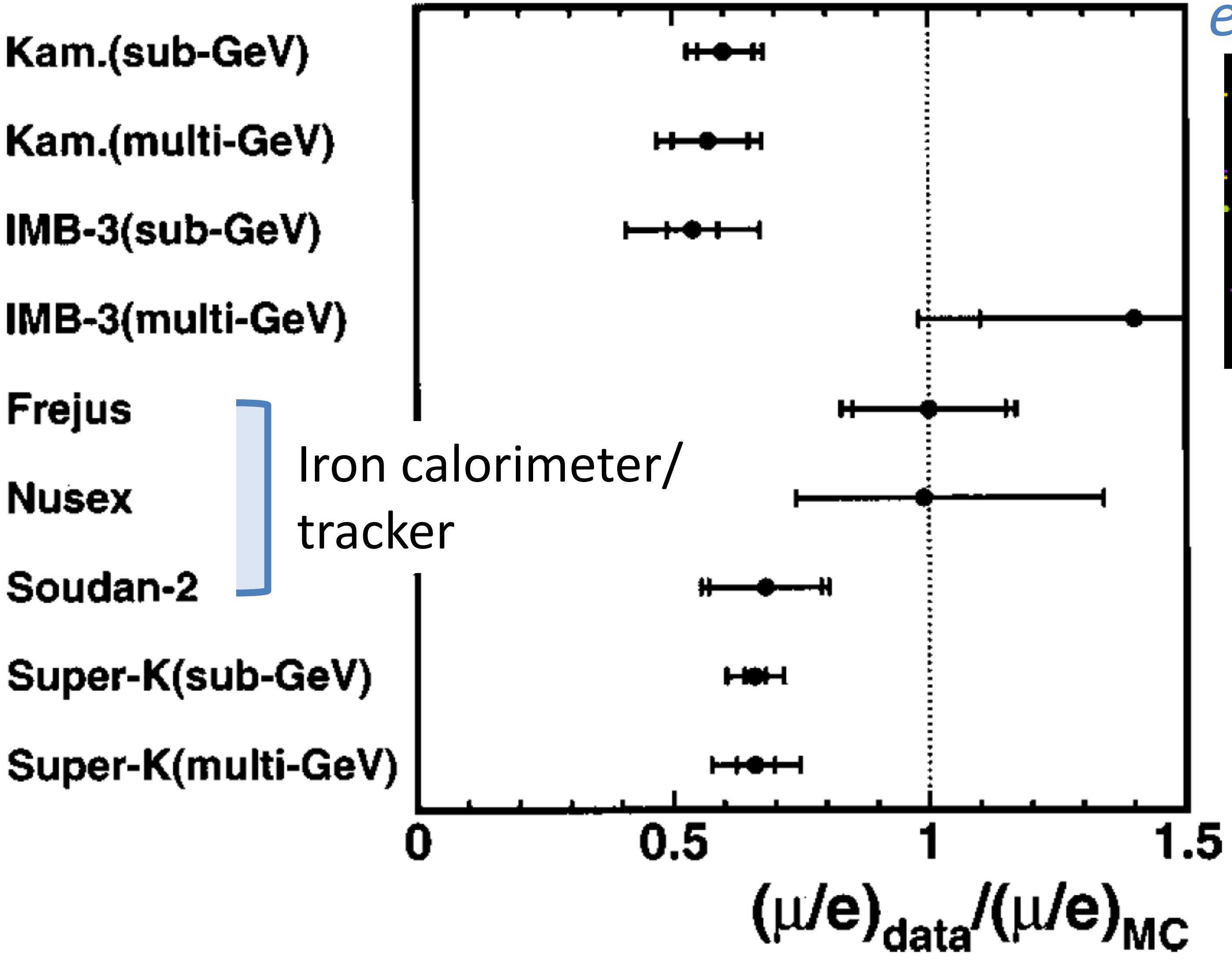


Kamiokande (1988, 92, 94)

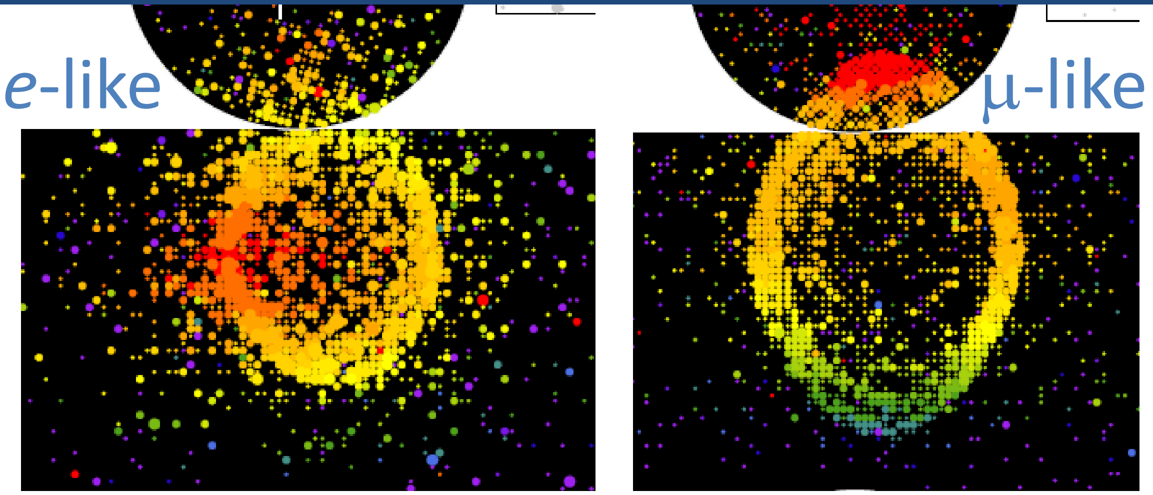
IMB (1991, 92)

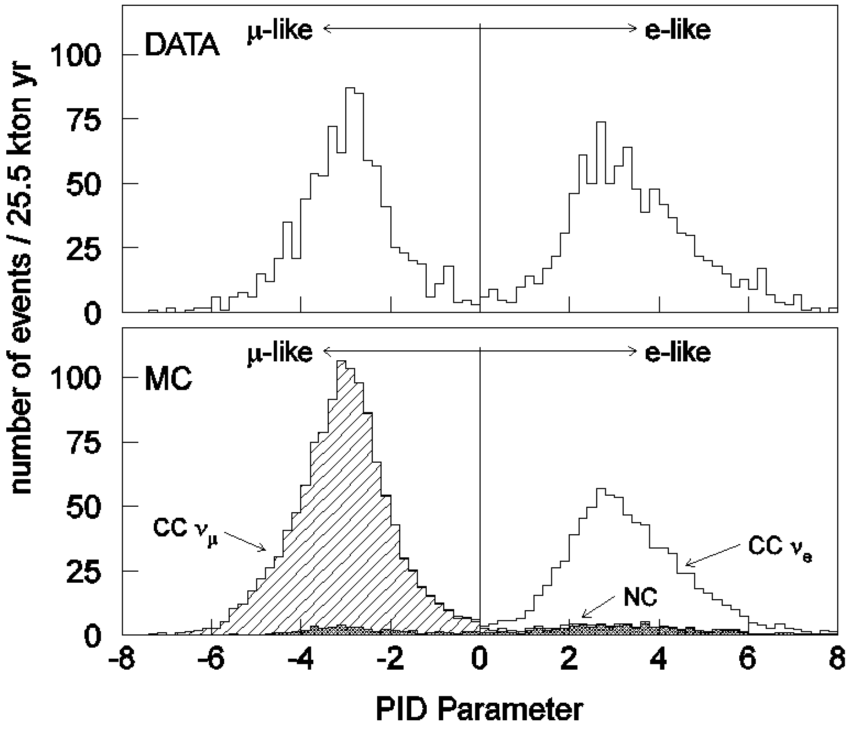


Missing atmospheric muon-neutrinos (1980's to 90's)



TK and Y.Totsuka, Rev. Mod. Phys. 73 (2001) 85, and references there in



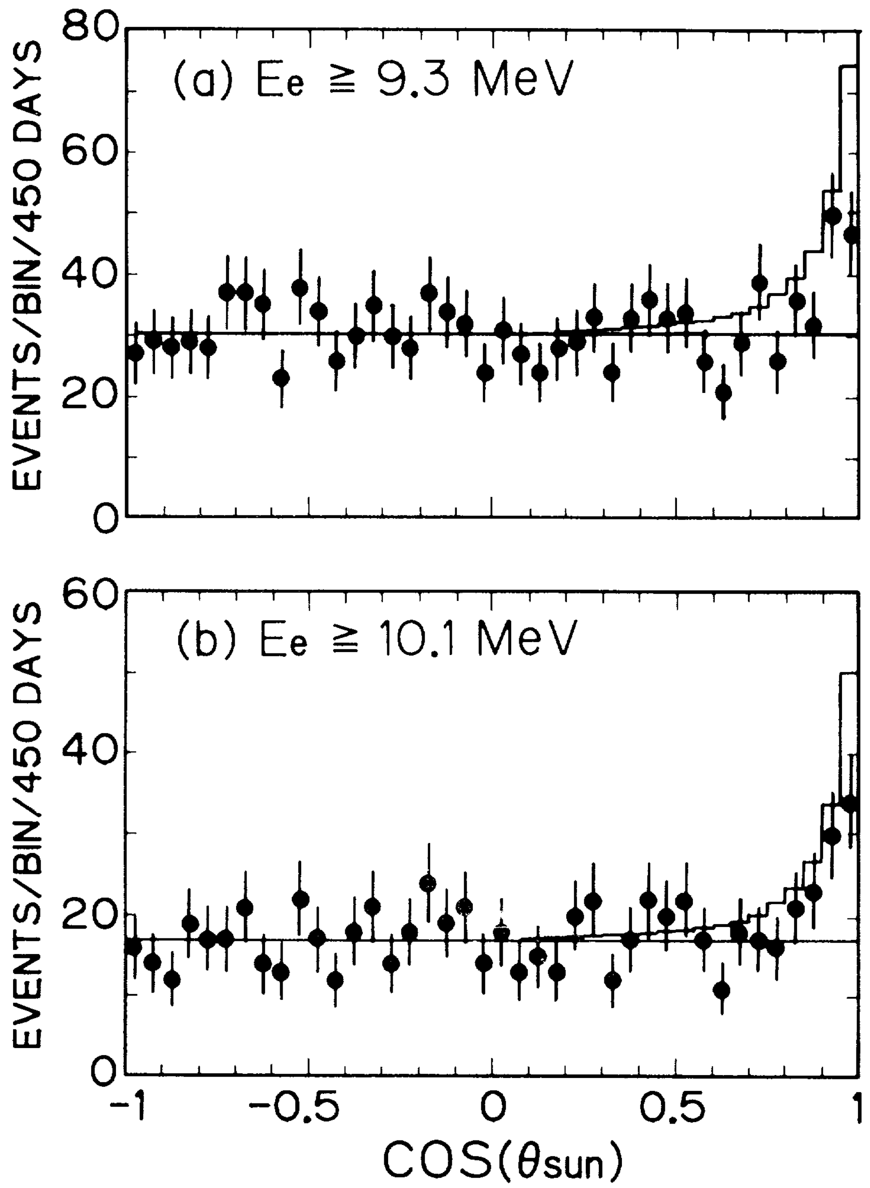


99% efficiency (in 1998)

SuperK, PLB, 433 (1998) 9

Confirmation of missing solar neutrinos

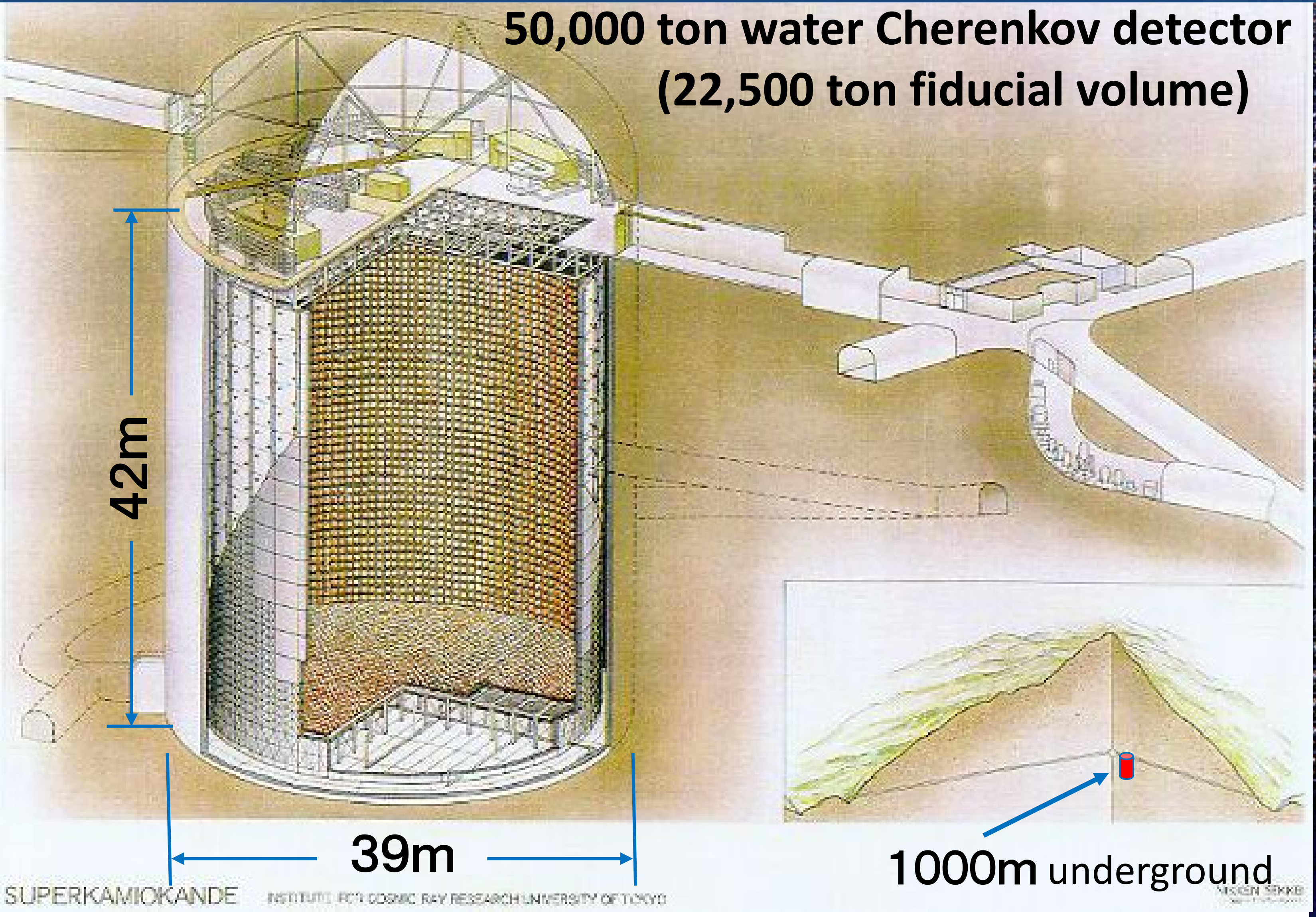
- Kamiokande observed ^{8}B solar neutrinos (K.S. Hirata et al., PRL 63 (1989) 16) and confirmed the missing solar neutrinos, which was claimed by the Homestake experiment (R. Davis, Jr., D.S. Harmer and K.C. Hoffman, PRL 20 (1968) 1205) .
- This observation confirmed that water Cherenkov detectors can detect solar neutrinos and can be used to study them.

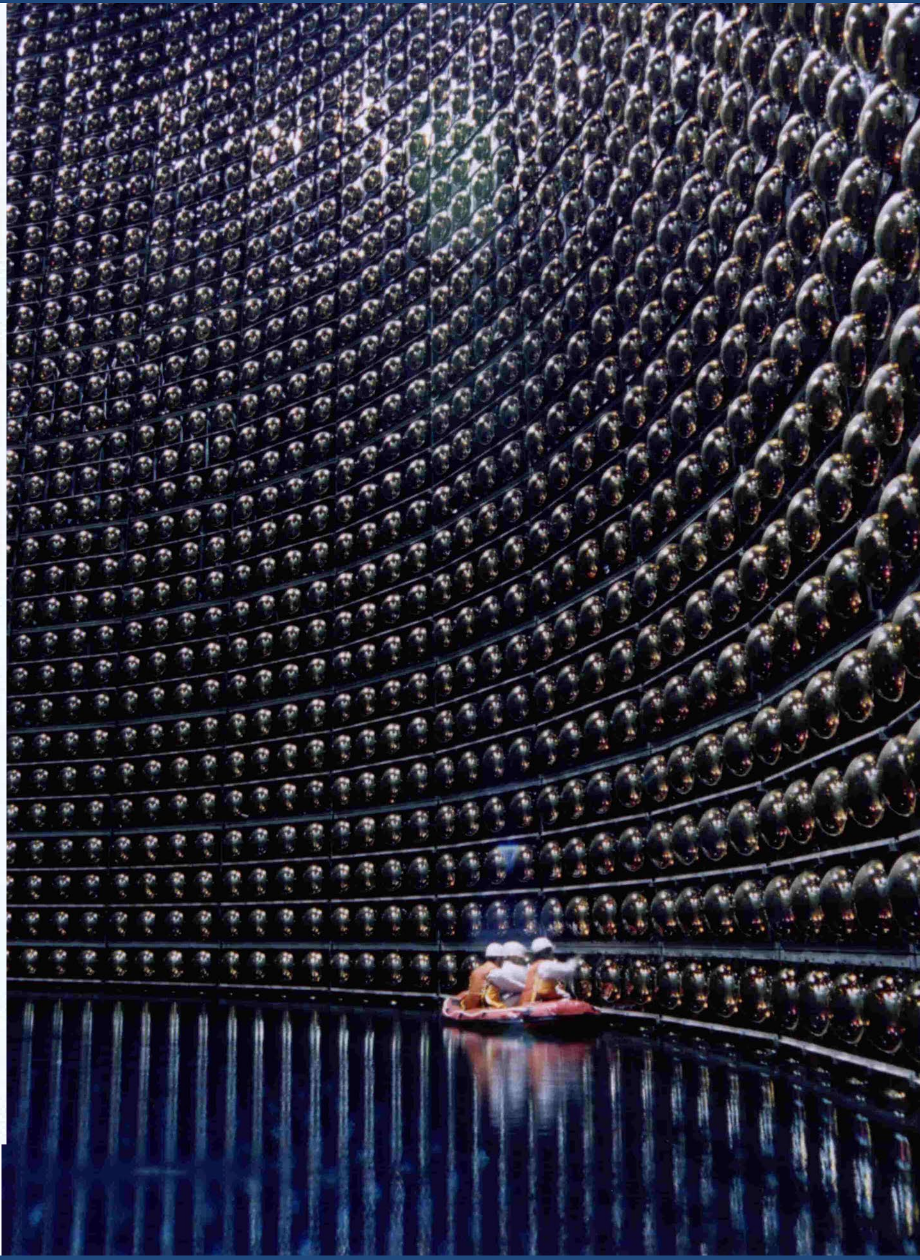


IMB and Kamiokande proton decay detectors strongly indicated that water Cherenkov detectors are extremely powerful to study neutrinos!

Water Cherenkov neutrino detetors

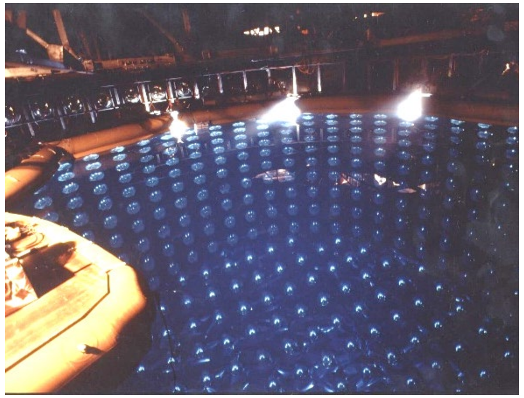
Super-Kamiokande



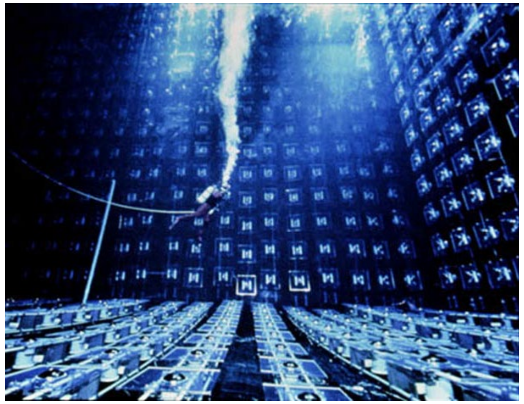


Beginning of the Super-Kamiokande collaboration

At this meeting, people agreed that



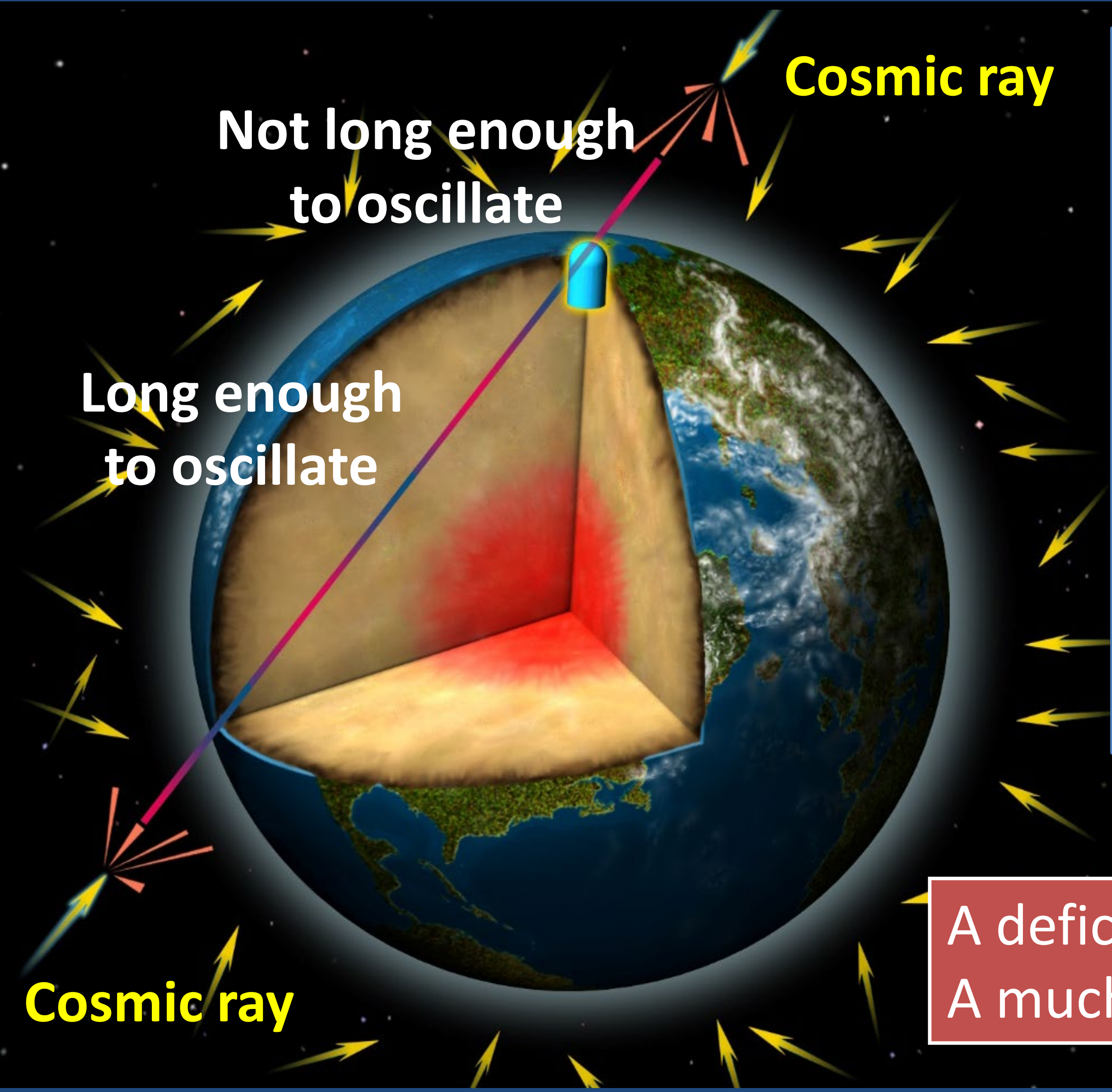
&

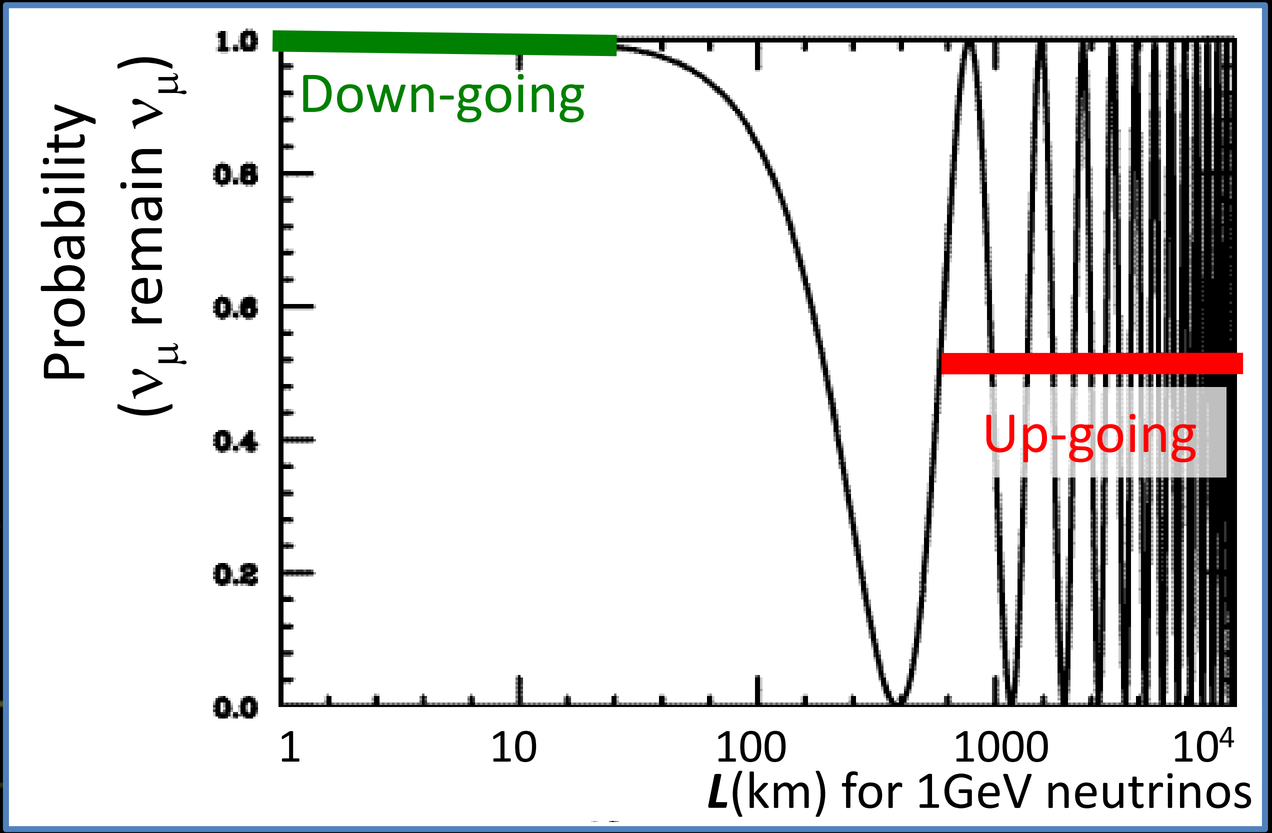


work together.

Institute for Cosmic Ray Research, Aug. 28, 1992

What will happen if the ν_μ deficit is due to neutrino oscillations

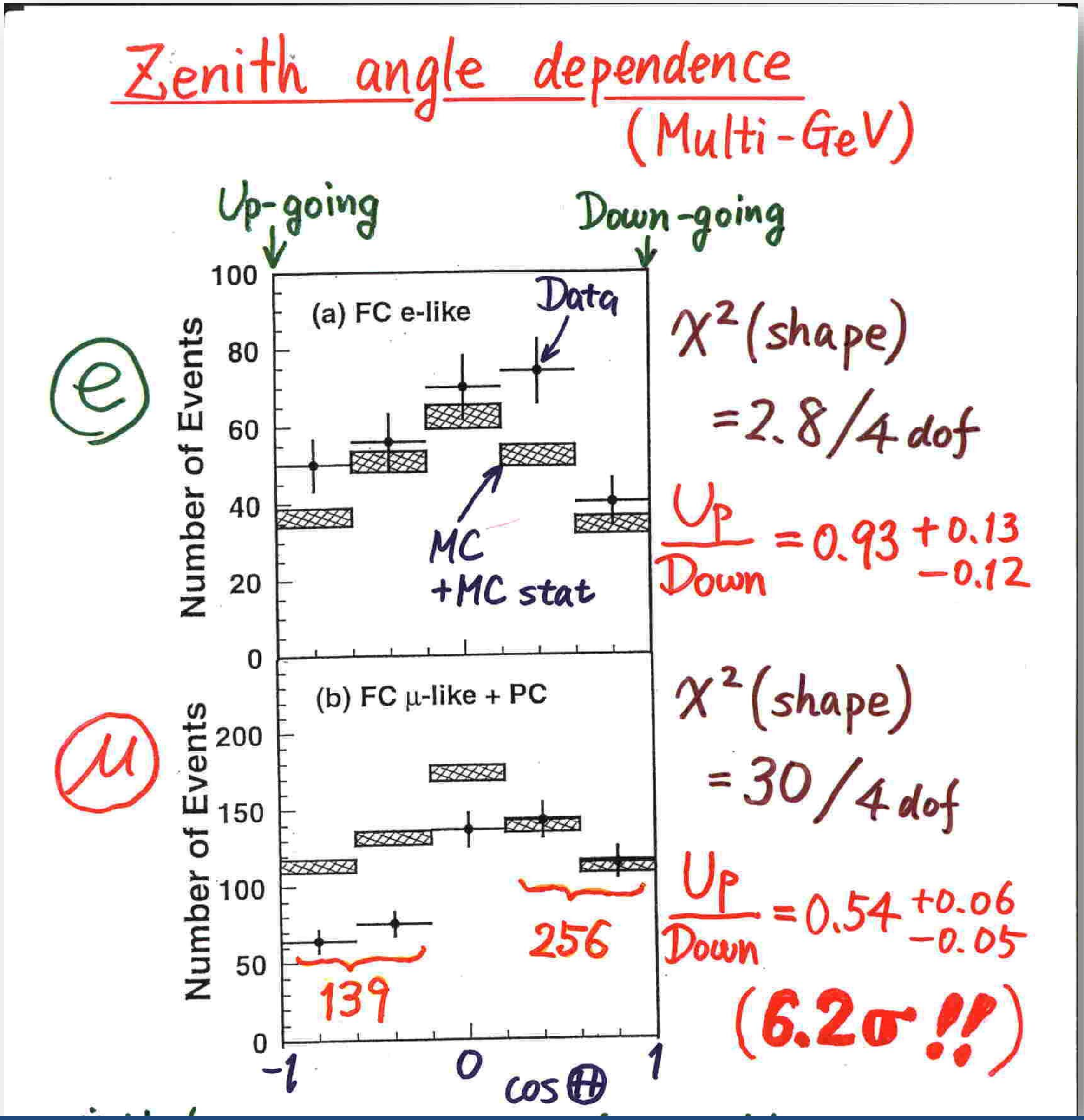


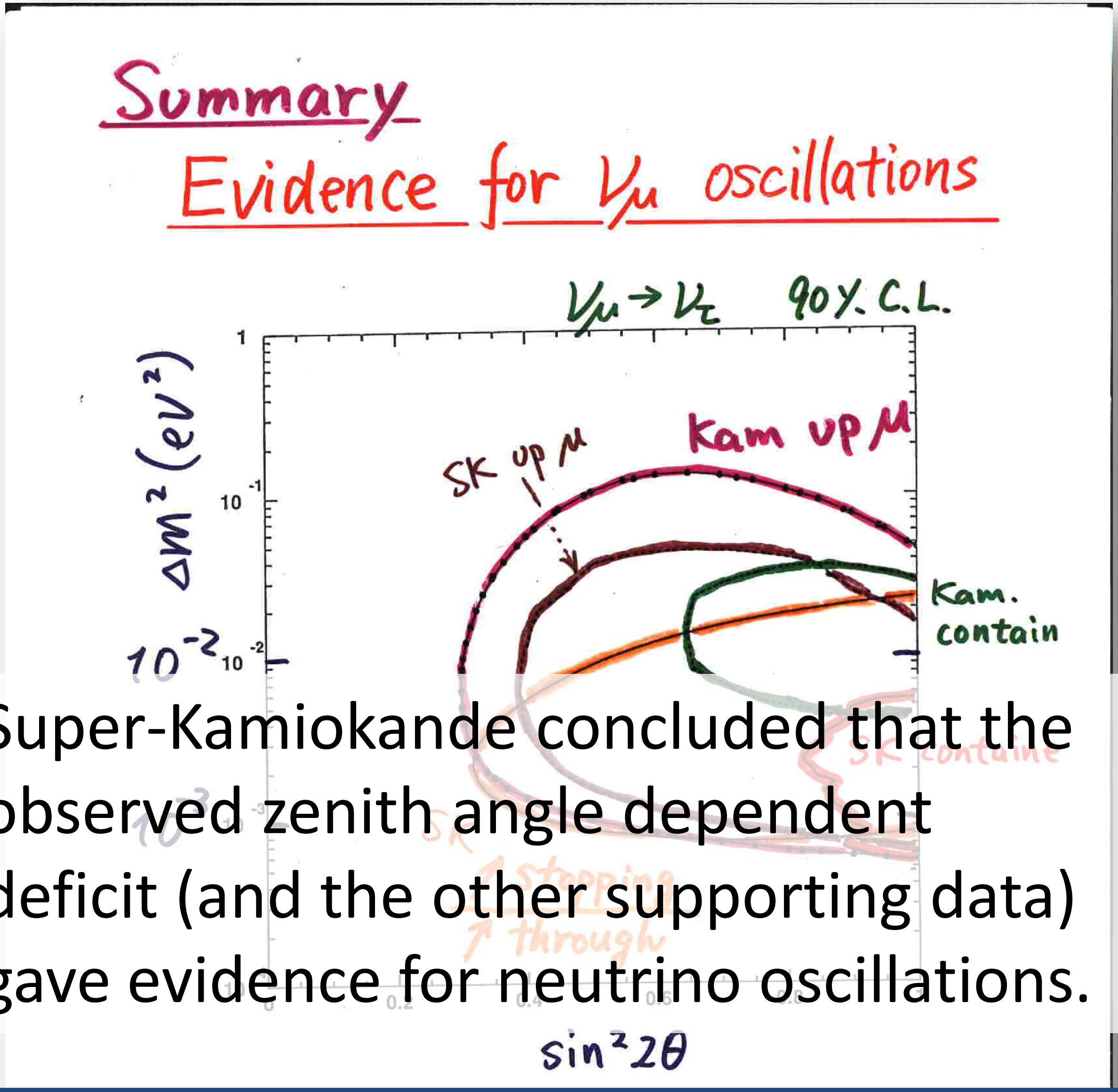


A deficit of upward going ν_μ's should be observed!
A much larger detector ➔ Super-Kamiokande

Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

Super-K, Neutrino 98, Super-K., PRL 81 (1998) 1562



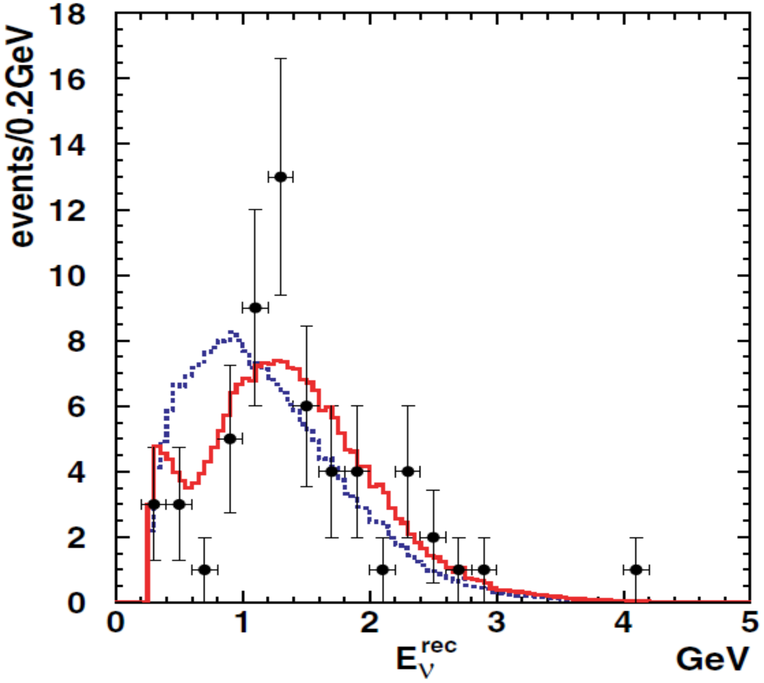


Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

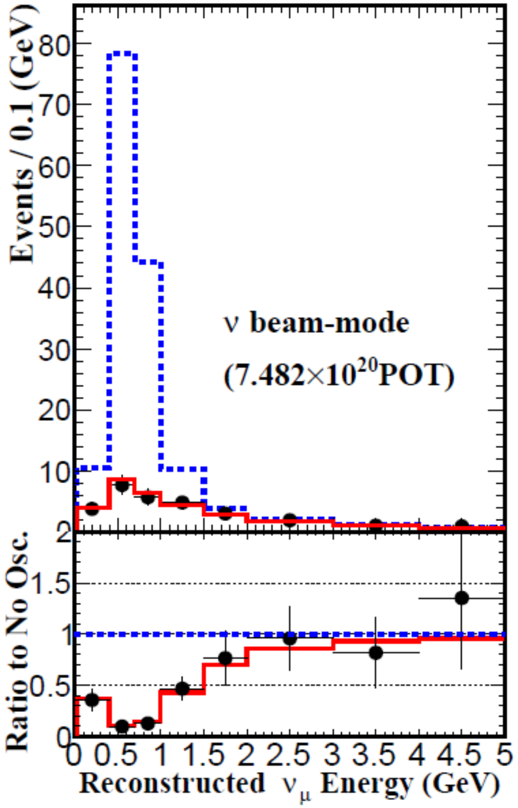
Water Cherenkov detector as the far detector in LBL experiments

K2K

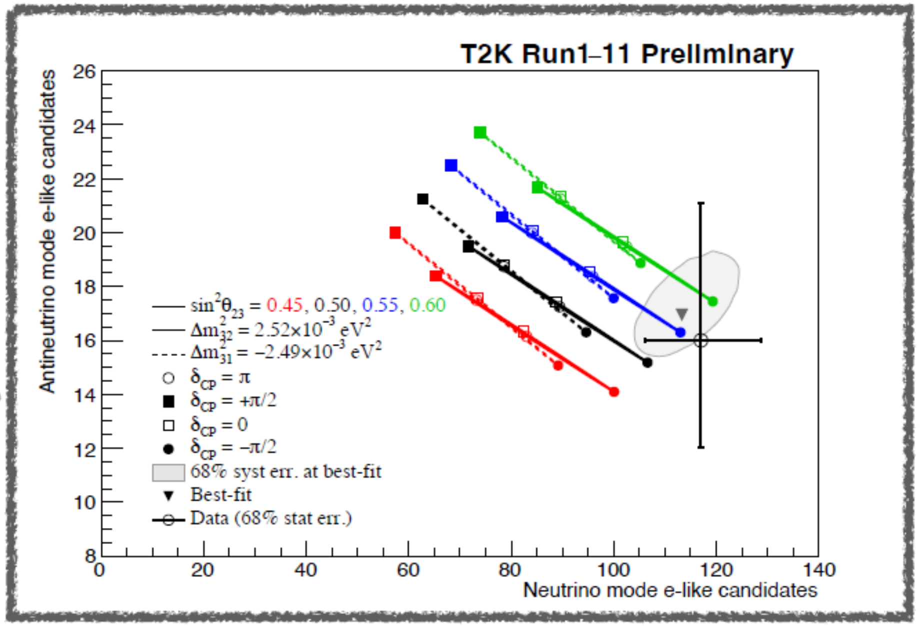
K2K, PRD 74 (2006) 072003



T2K



T2K, Phys.Rev.D 96 (2017) 1, 011102

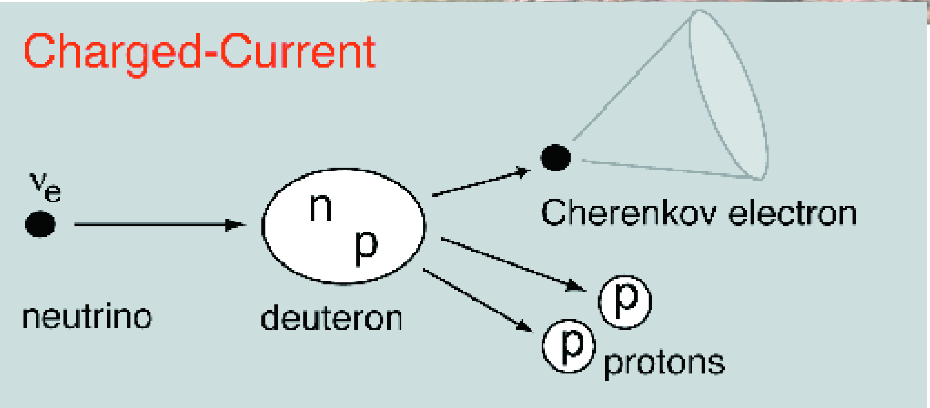


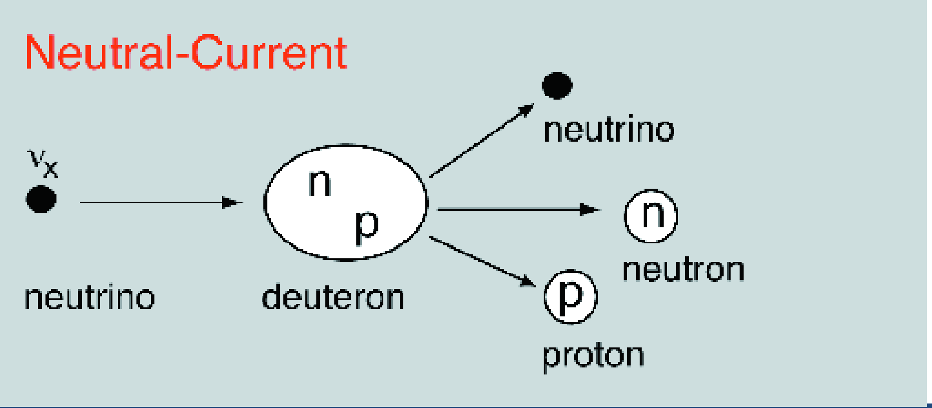
C. Giganti (T2K), Neutrino 2024

Initial idea to resolve the solar neutrino problem

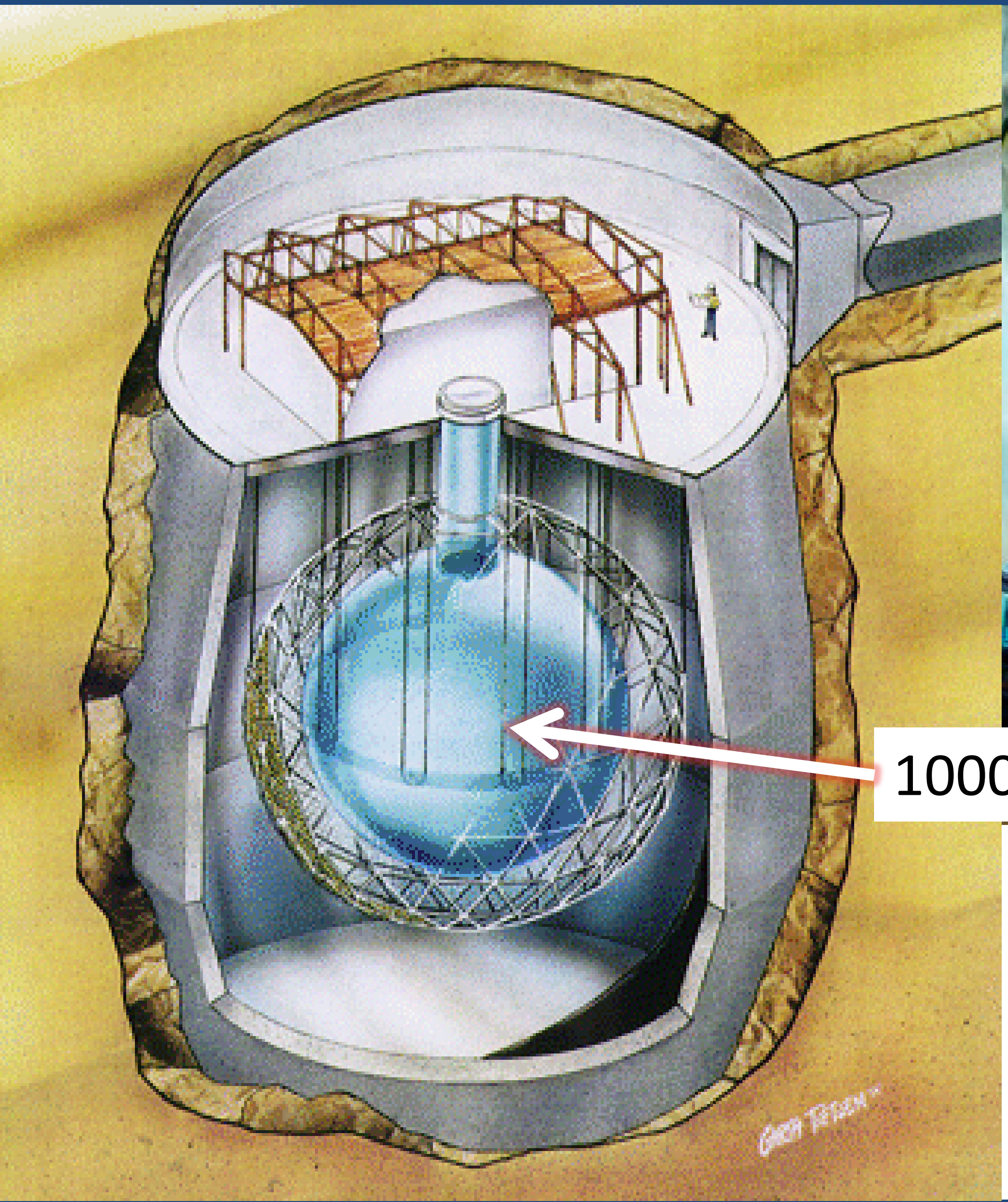
Herbert Chen, PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-current reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.





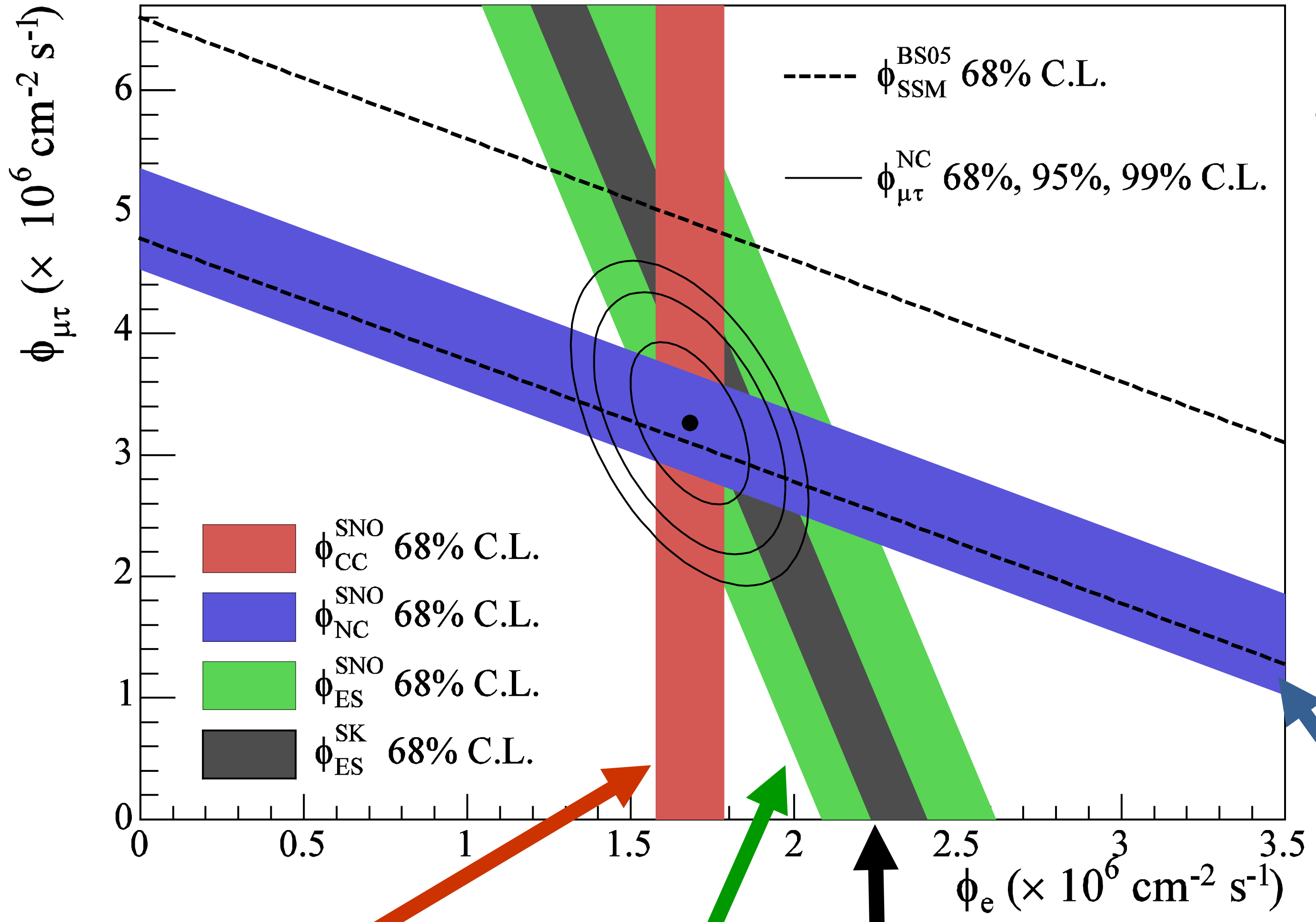
SNO detector



Neutral Current events (ν_x + D → ν_x + p + n) (or produced neutrinos in NC reactions) were observed by 3 methods independently:

1) Pure D_2O (n is absorbed by D, then 6.25 MeV γ ray emitted)
2) 2 tons of salt (NaCl) in D^2O → $^{35}Cl(n, \gamma)^{36}Cl$ ($\Sigma(E\gamma)$=8.6MeV)
3) ^{3}He counters in D_2O → $^{3}He(n, p)^{3}H$

Evidence for solar neutrino oscillations



SNO CC 68%CL

SNO ES 68%CL

SK ES 68%CL

SNO NC 68%CL

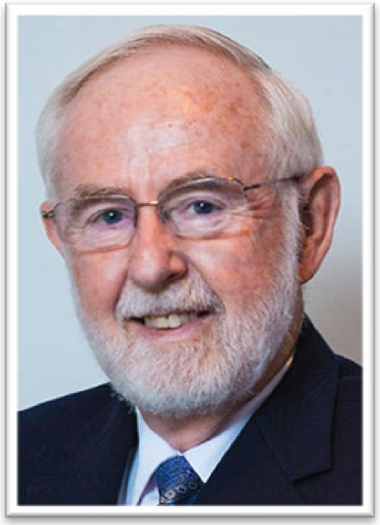
SSM 68%CL

(A plot based on the salt-phase data)

SNO PRL 89 (2002) 011301
SNO PRC 72 (2005) 055502

Three (or four) different measurements intersect at a point.

✓ *Evidence for $(\nu_\mu + \nu_\tau)$ flux*

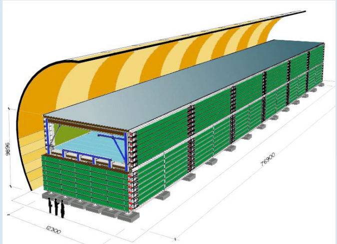


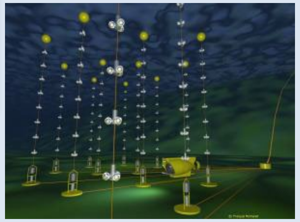
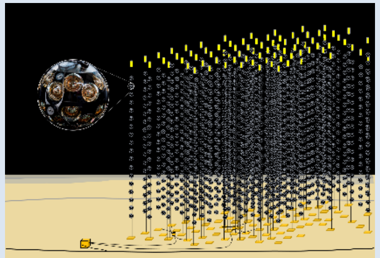
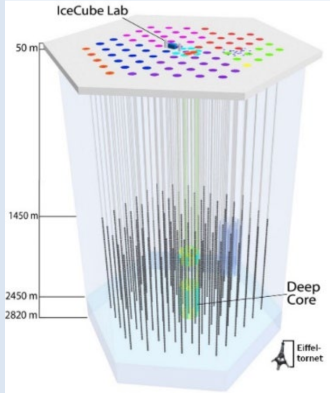
Art McDonald

Photo: K. MacFarlane. Queen's University /SNOLAB

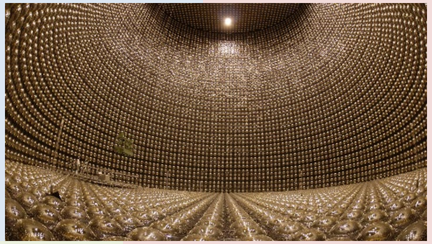
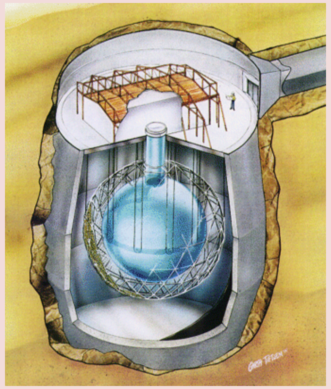
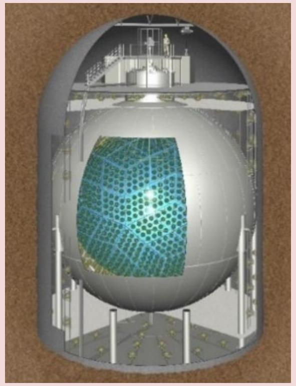
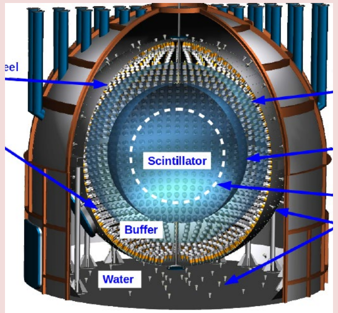
Many exciting results in neutrino oscillations (partial list)

Atmospheric neutrino oscillation experiments

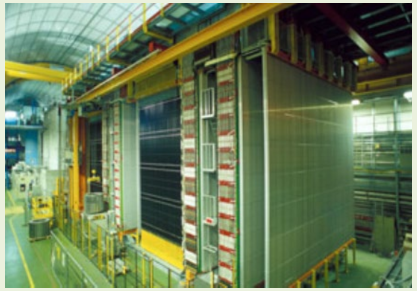


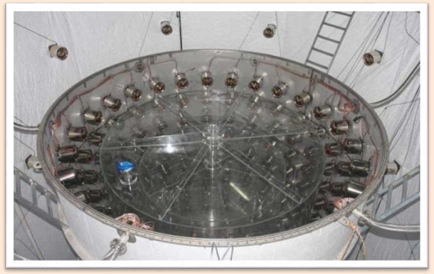
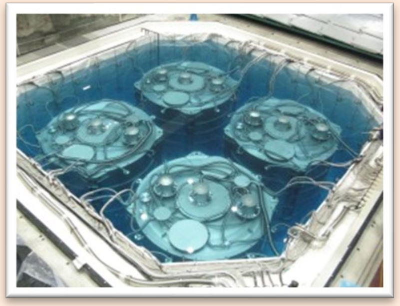
Solar neutrino oscillation experiments

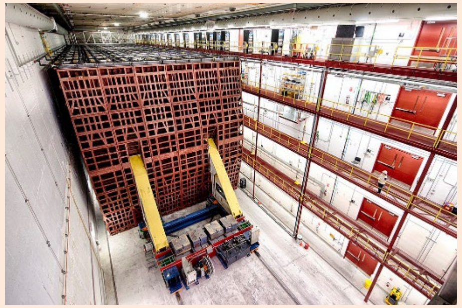





Accelerator based neutrino oscillation experiments



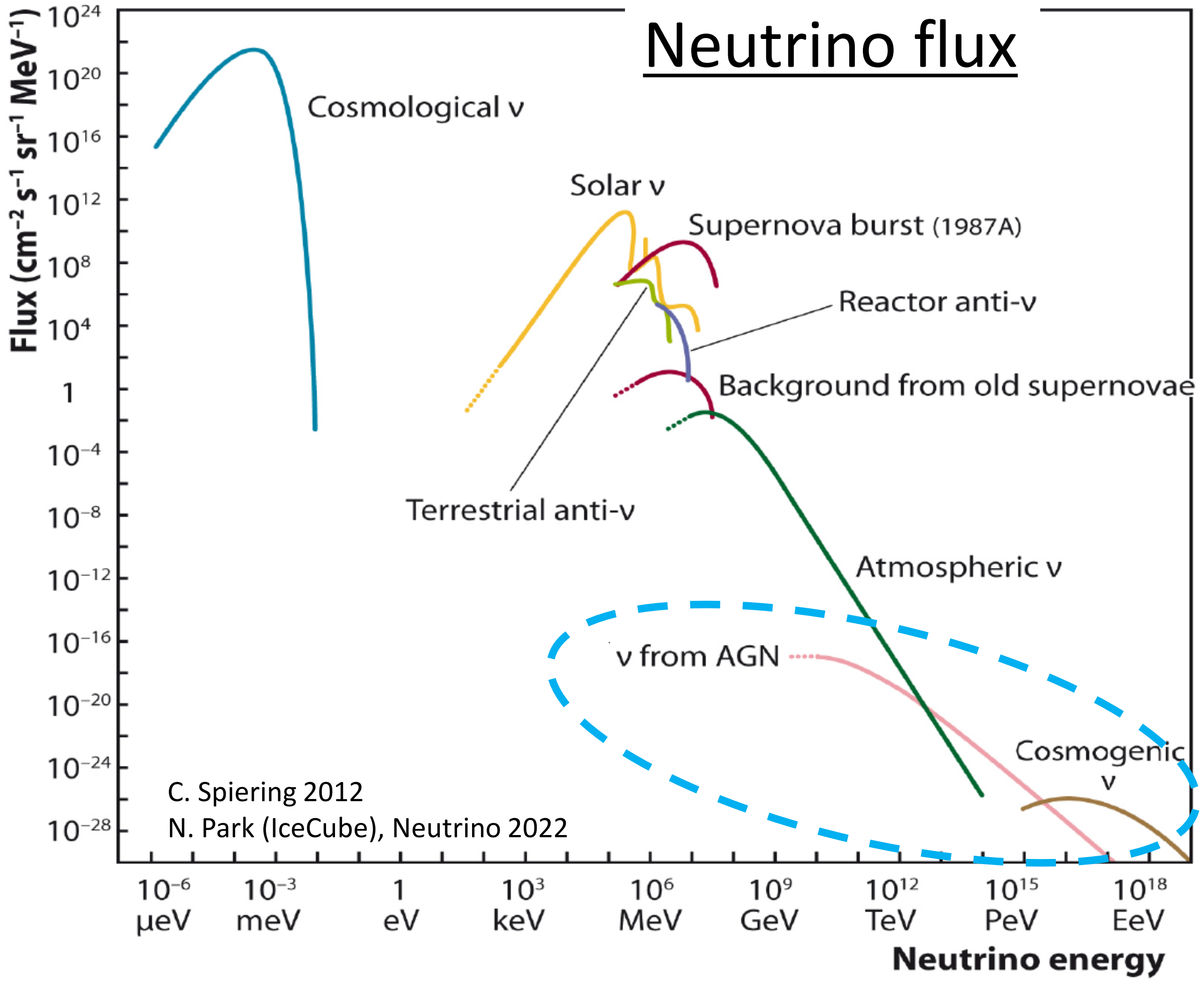
3 flavor(type) neutrino oscillation experiments



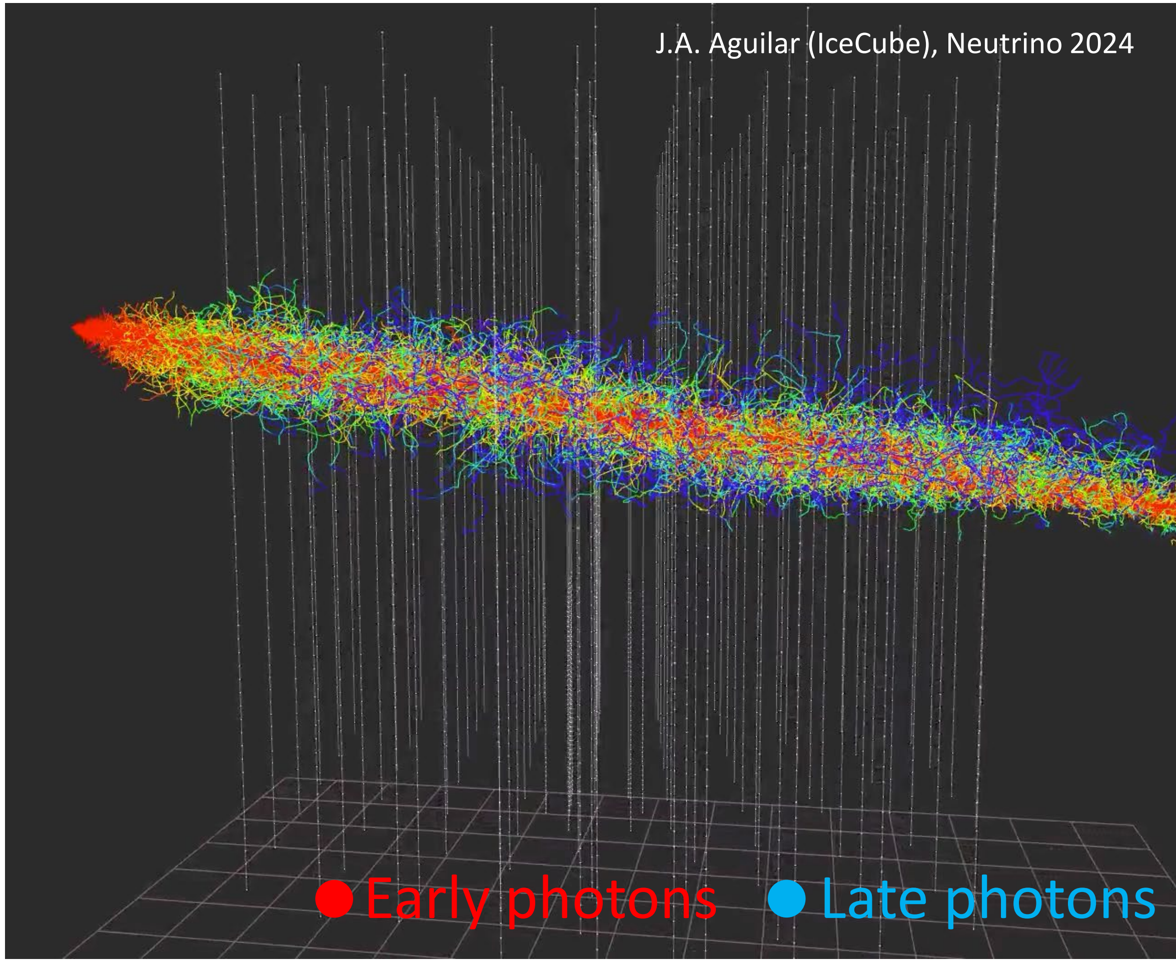
Water Cherenkov detectors to study the high-energy Universe

High energy astrophysical neutrinos



If one wants to measure these high-energy neutrinos, one needs at least ~1km^3 volume.

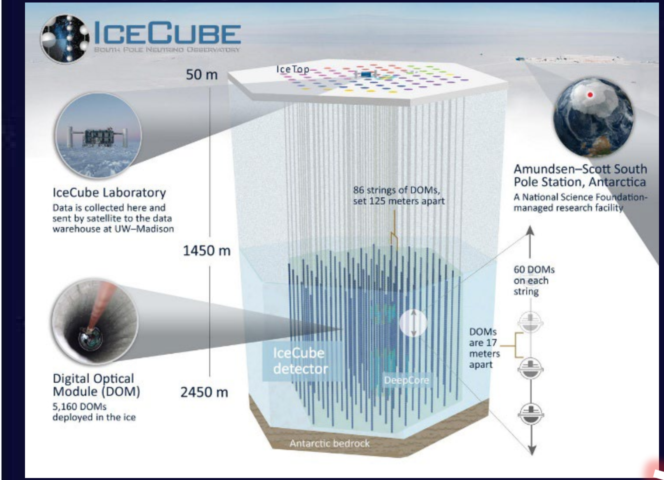
➔ Cherenkov detector

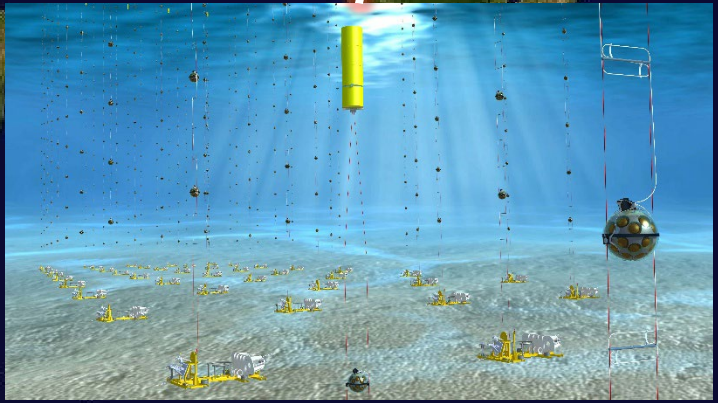


IceCube simulation of Cherenkov photons for a muon-neutrino interaction

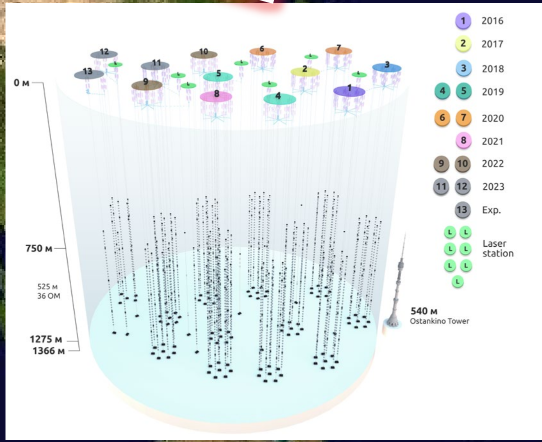
“Water” Cherenkov detectors for high energy astrophysical neutrinos

IceCube https://icecube.wisc.edu/





KM3NeT https://KM3NeT.org/



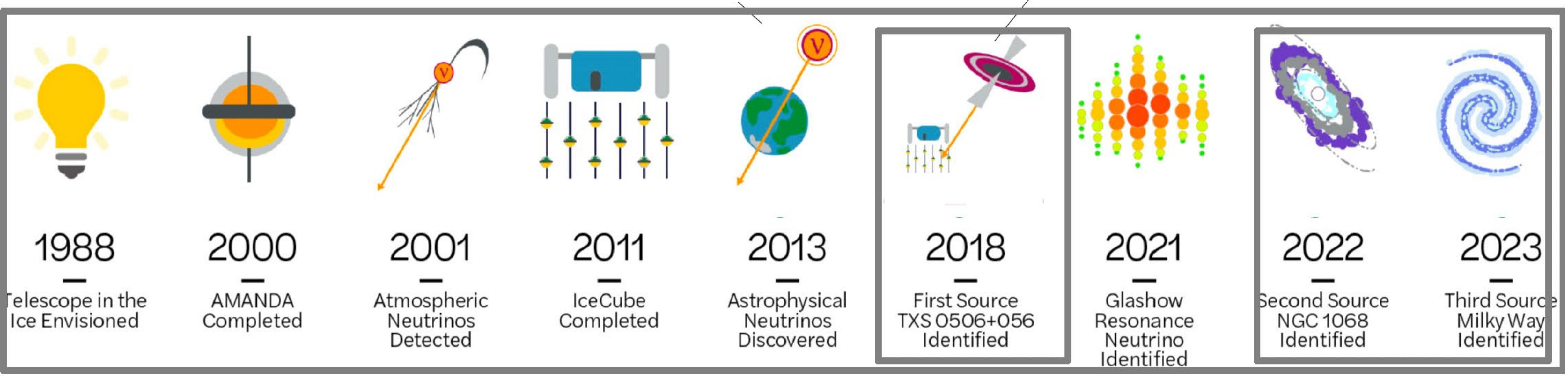
Bikal-GVD

https://bikalgvd.jinr.ru

(More experiments are under preparation)

Highlights on high energy astrophysical neutrinos

Image Credit: IceCube Collaboration (taken from P. Sapienza, TAUP2025)



Astrophysical tau neutrinos (2024)

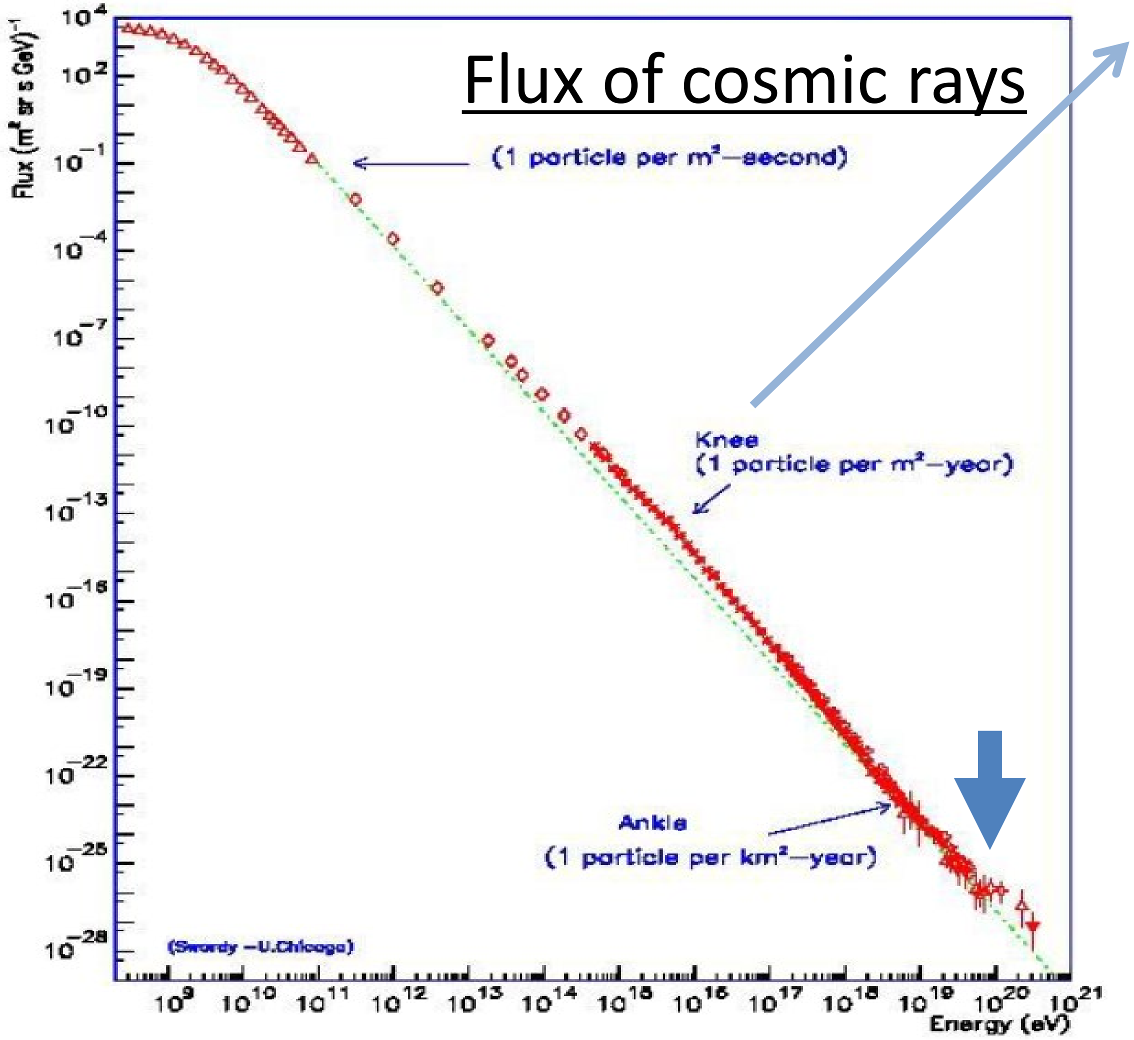
Broken power law observed (2025)

KM3NeT observed the highest energy neutrino ($E_\nu = 220^{+570}_{-110}$ PeV) so far (Nature 638 (2025) 376)

Bikal-GVD independently observed diffuse cosmic neutrino flux (D. Zaborov, TAUP2025)

Cosmic rays and gamma rays

Flux of cosmic rays

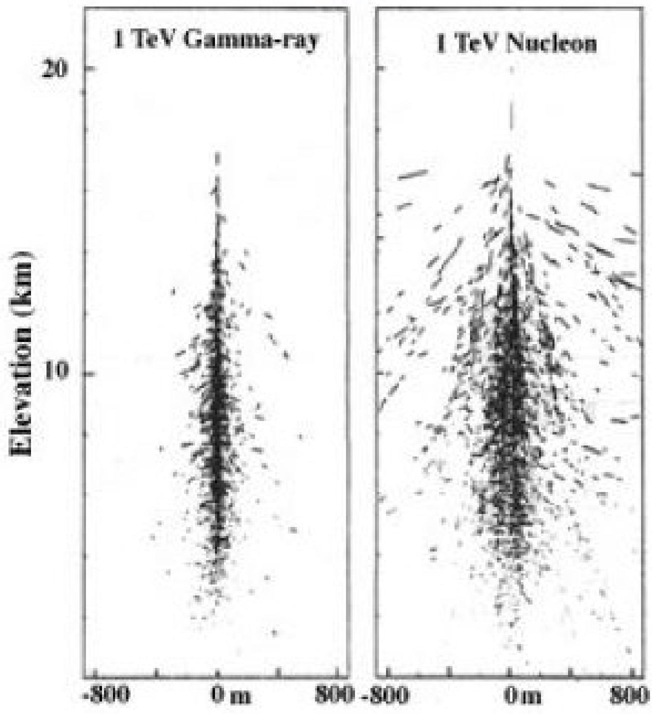


To know the origin of cosmic rays, it is important to measure neutrinos and gamma rays produced by;

Cosmic ray + X → $\pi^{+/-}$ → neutrino

π^0 → gamma ray

→ A very good cosmic ray reduction is necessary to observe gamma rays;

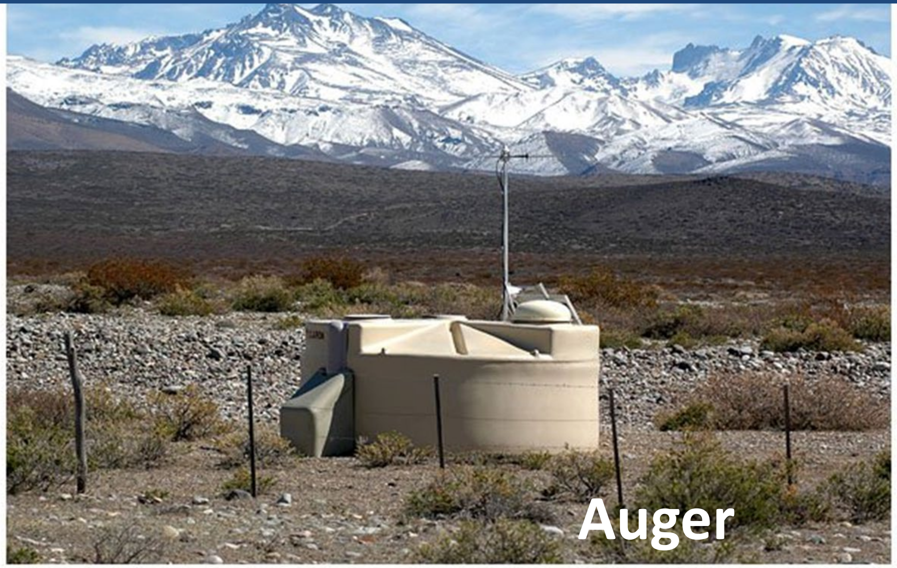


One idea: to select muon poor showers

→ Large area (underground) water Cherenkov muon detector

To study cosmic rays at 10^{20} eV, a detector with ~>1000km² is necessary.

Water Cherenkov detectors for cosmic rays and gamma rays



These experiments with water Cherenkov detectors have been contributing significantly to the understanding of highest energy cosmic rays and TeV-PeV gamma rays.

Summary

- Large water Cherenkov detectors, including heavy, salty, and frozen water Cherenkov detectors, have been contributing significantly to the understanding on neutrinos and high-energy Universe!
- We expect much more from the water Cherenkov detectors!