大气中微子

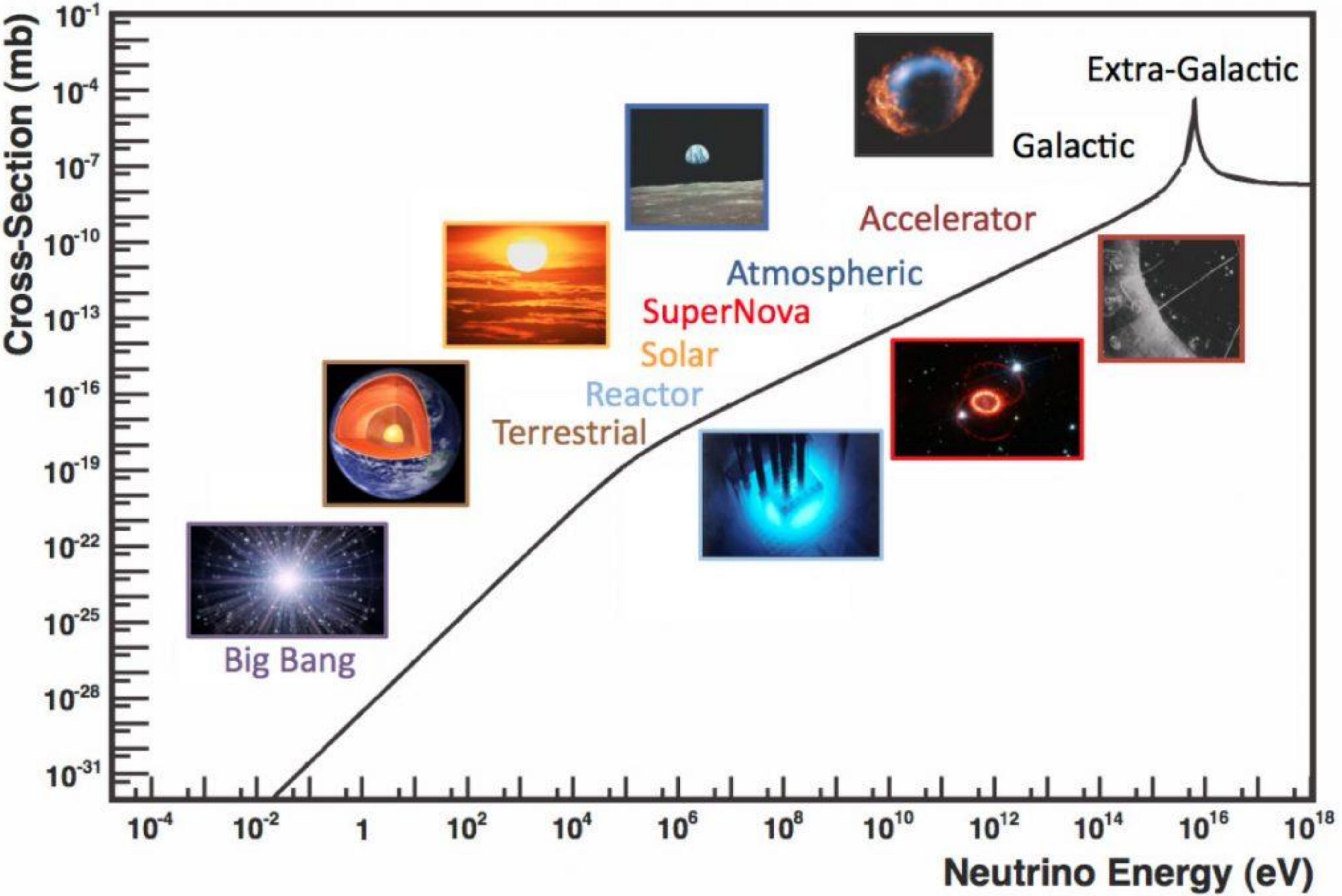
李高嵩

2024年7月6日

中微子夏令营，开平

提纲

- 大气中微子的产生
- 大气中微子的探测历史
- 大气中微子实验
- 江门实验上的大气中微子研究潜力



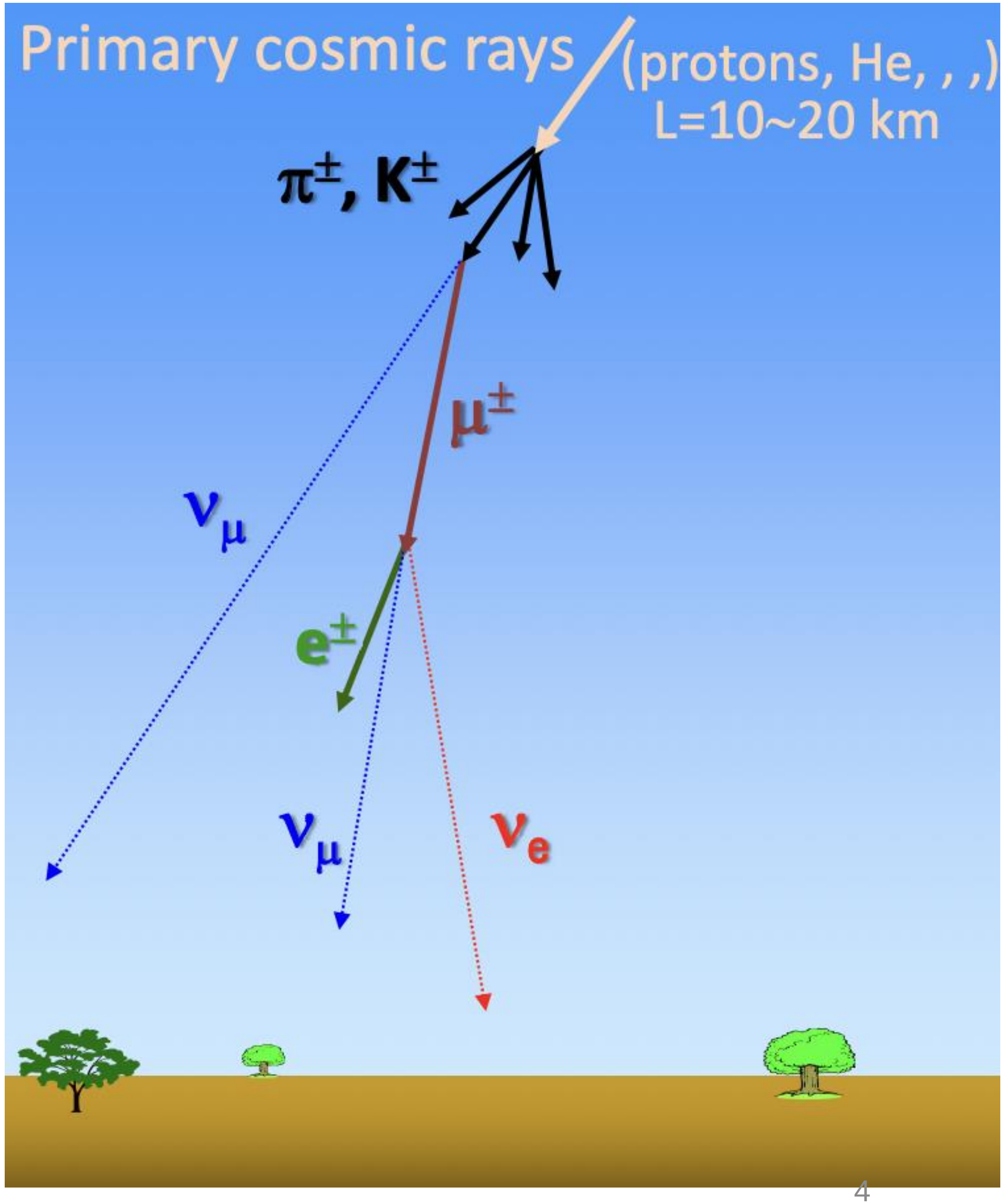
Cross-Section (mb)
10-1
10-4
10-7
10-10
10-13
10-16
10-19
10-22
10-25
10-28
10-31
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang
10-4
10-2
1
10^2
10^4
10^6
10^8
10^10
10^12
10^14
10^16
10^18
Neutrino Energy (eV)

大气中微子的产生

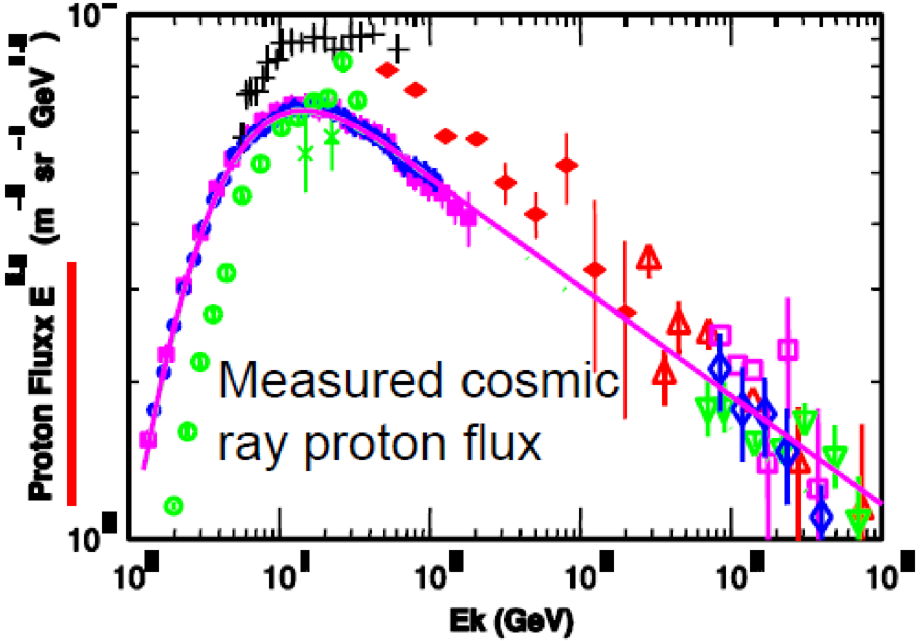
- 源初宇宙线与大气层中的原子核相互作用产生大量π介子，少量K介子
- π、k衰变产生中微子

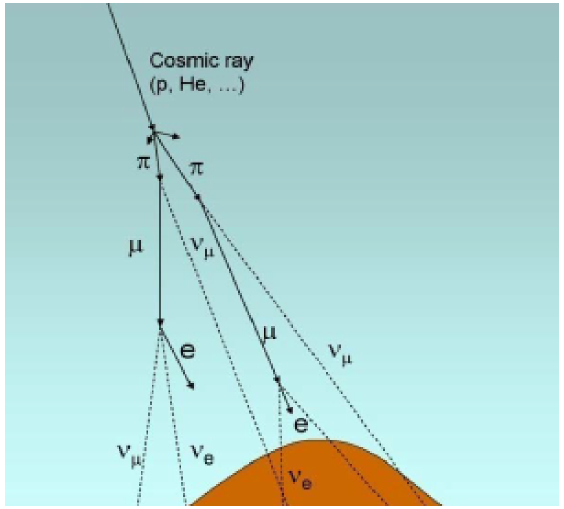
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$\pi^- \longrightarrow \mu^- + \overline{\nu}_\mu$$
$$\mu^- \longrightarrow e^- + \overline{\nu}_e + \nu_\mu$$



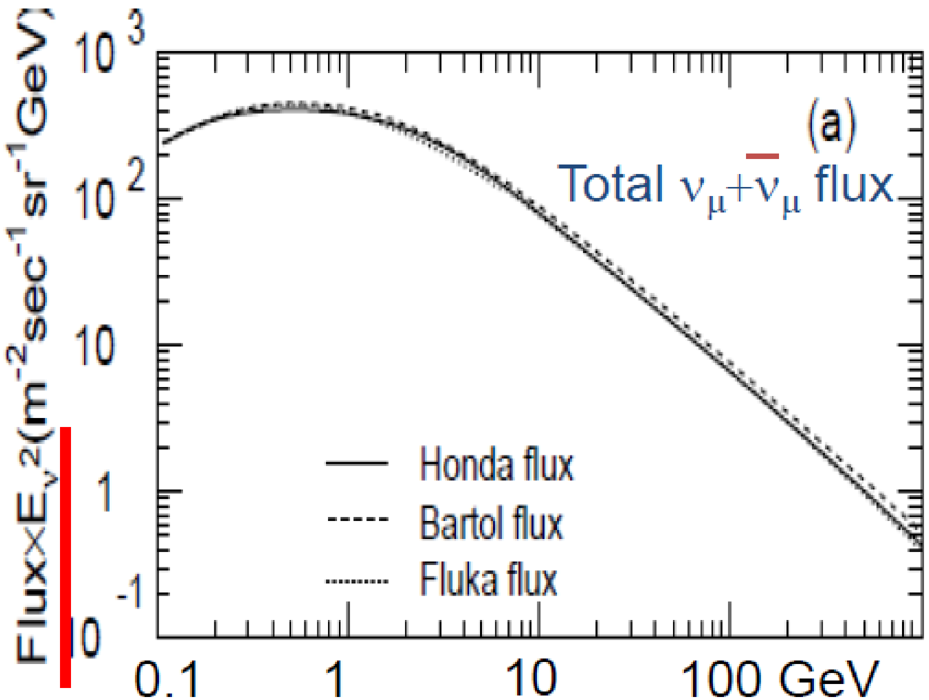
计算大气中微子流强





Carrying out the calculation all over the Earth

+ solar activity
+ geomagnetic field
+ (p+Nucleon) int.
+ decay of π or K
+ ……



中微子流强特征

- 四种味道中微子

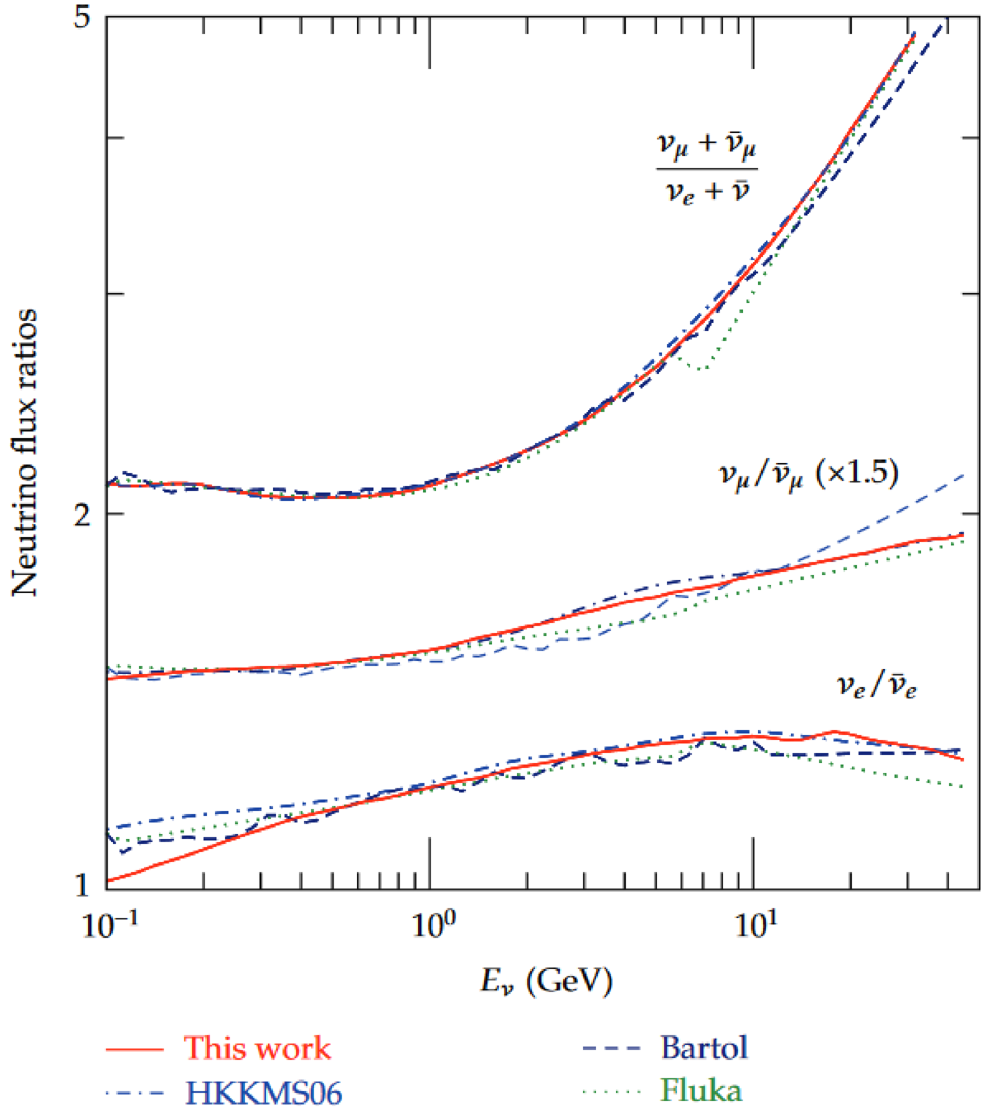
$$\frac{\nu_\mu}{\overline{\nu_\mu}} \sim 1 \qquad \frac{\nu_e}{\overline{\nu_e}} \sim \frac{\pi^+}{\pi^-}$$

- GeV以下

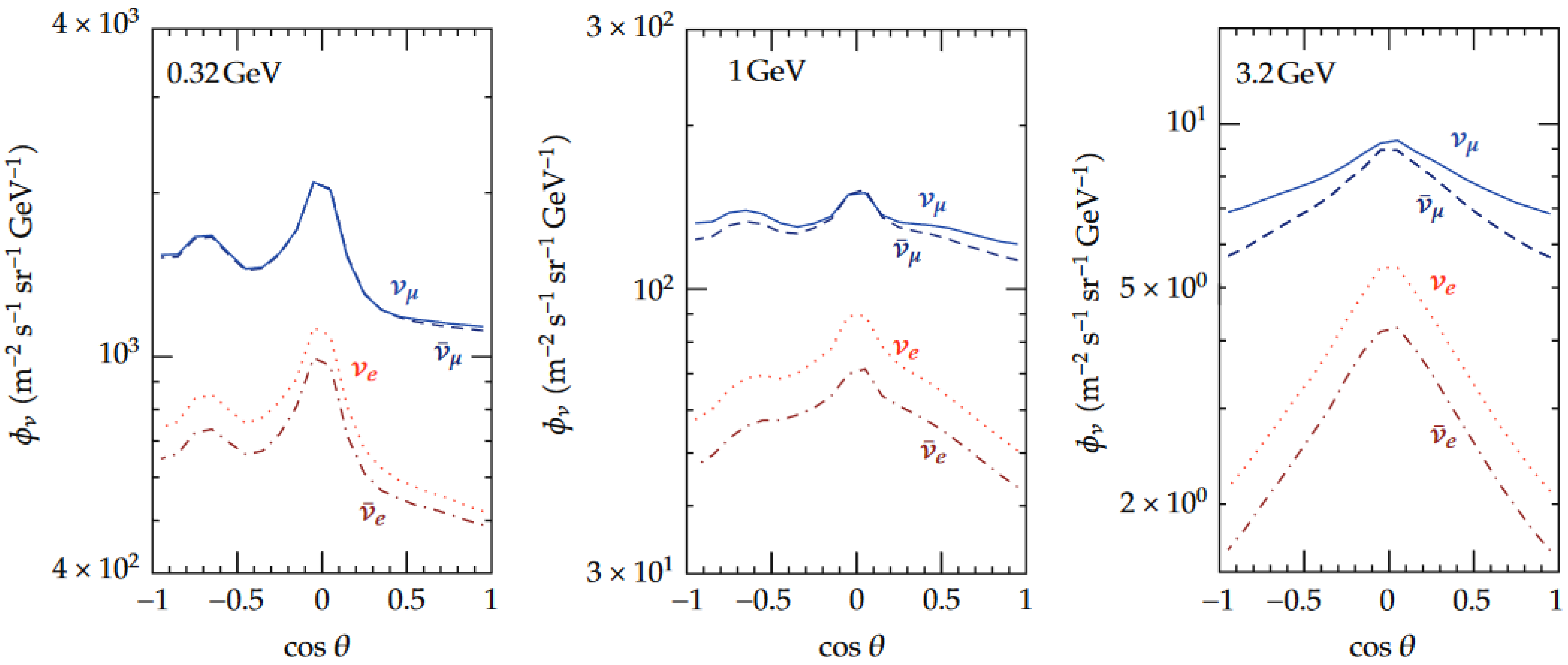
$$\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}} \sim 2$$

- GeV以上

$$\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}} > 2$$



方向分布特征



- GeV以下受地磁场影响，上下不对称
- GeV以上能区上下分布更均匀

大气中微子的历史

First indication of a possibility to detect atmospheric neutrinos:

ON HIGH ENERGY NEUTRINO PHYSICS

M. A. Markov

Joint Institute for Nuclear Research, Dubna, USSR

I will report on investigations in the field of high and intermediate energy neutrino physics carried on at the Joint Institute for Nuclear Research in 1958-60. The full texts of the papers on which I will comment can be found in the pamphlet entitled "On High Energy Neutrino Physics" (Dubna 1960).

Various possibilities of neutrino experiments using accelerators or cosmic rays are discussed in this report. The analyses show that it is possible to carry on neutri-

This (experimentally dictated) cut-off is at a momentum smaller than that at which non-applicability of perturbation theory could be suspected. The decay $\mu \to e + \gamma$ gives the more stringent restriction on the cut-off. In accordance with the experimental upper limit; $\frac{W(e+\gamma)}{W(e+\nu+\bar{\nu})} < 1.2 \times 10^{-6}$ the critical momentum must be chosen, $k_{max} < 50$ BeV.

One natural cut-off mechanism would be an inter-

In 1960, M.A.Markov suggested:

upward and horizontal muons are signature of high energy neutrinos

First idea for water detectors

Ann. Rev. Nucl. Sci. 10, 63(1960)

COSMIC RAY SHOWERS[1]

By Kenneth Greisen

Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y.

I. SIGNIFICANCE OF EXTENSIVE AIR SHOWERS

1. Exploration of Space by Analysis of Received Radiation

Although bound to earth and its immediate vicinity, man has acquired a wealth of knowledge about a volume of space 10^{58} times that of the earth, almost entirely by interpretation of incoming radiation. The richest and clearest information has been conveyed by visible light. Recent years have witnessed a rapid advance in the detection and interpretation of radio signals. Rockets and satellites have opened up the fields of ultraviolet and x-ray astronomy. Gamma-ray astronomy is on the horizon. Each of these bands of radiation has its own peculiar potentialities for telling the story of special processes occurring in different parts of the universe, and about the conditions of matter and fields that make these processes possible.

K. Greisen described:

water detector for atmospheric nu detection

Volume 18, number 2 PHYSICS LETTERS 15 August 1965

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINOS DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY
and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

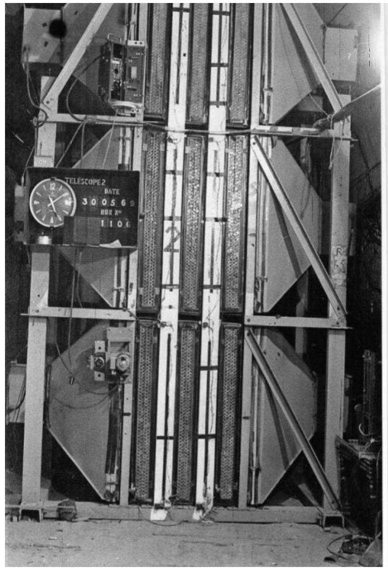
K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

印度 Kolar 金矿，2300 m 埋深

Following the early work [1] carried out at great depths underground in the Kolar Gold Mines in South India, we have specifically designed an experiment for the detection of muons produced



EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

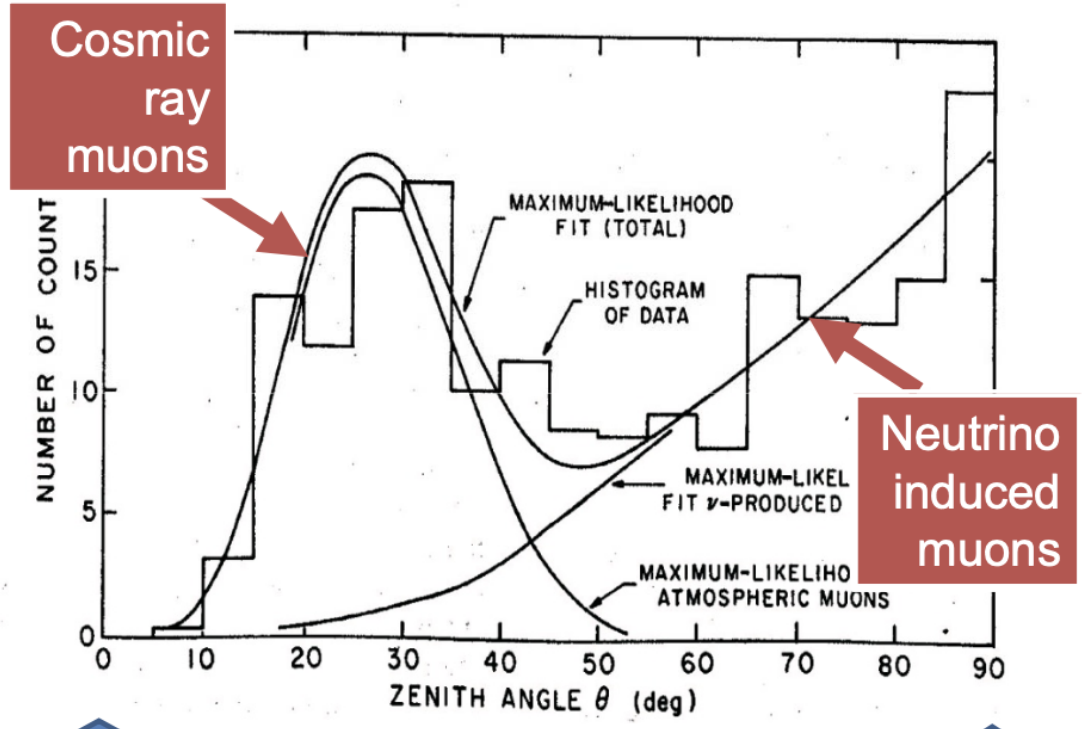
F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

The flux of high-energy neutrinos from the decay of K, π, and μ mesons produced in the earth's atmosphere by the interaction of primary cosmic rays has been calculated by many authors.[1] In addition, there has been some conjecture[1] as to the much rarer primary flux of high-energy neutrinos originating outside the earth's atmosphere. We present here evidence[2] for the interactions of "natural" high-energy neutrinos obtained with a large area liquid scintillation detector (110 m^2) located at a depth of 3200 m (8800 meters of water equivalent, average $Z^2/A \simeq 5.0$) in a South African gold mine.

each. Each detector element, Fig. 2, is a rectangular box of Lucite of wall area 3.07 m^2 containing 380 liters of a mineral-oil based liquid scintillator,[4] and is viewed at each end by two 5-in. photomultiplier tubes. The array constitutes a hodoscope which gives a rough measurement of the zenith angle of a charged particle passing through it. In addition, the event is located along the detector axis by the ratio of the photomultiplier responses at the two ends. The sum of the responses then pro-

南非金矿，3200 m埋深

PRD18, 2239 (1978)



Vertical (up-going or down-going)

Horizontal going

$$\left(\frac{Monte\ Carlo}{Data}\right) = 1.6 \pm 0.4$$

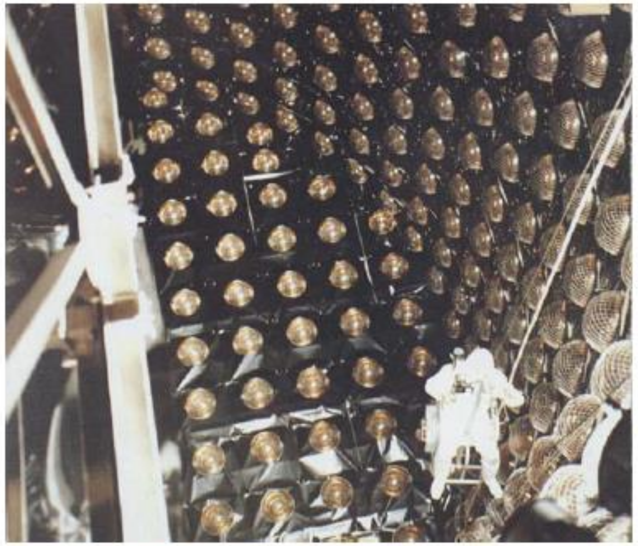
Deficit of muon data

“We conclude that there is fair agreement between the total observed and expected neutrino induced muon flux …”

大气中微子反常及振荡

1980年代: 质子衰变实验

Grand Unified Theories → $\tau_p=10^{30\pm2}$ years

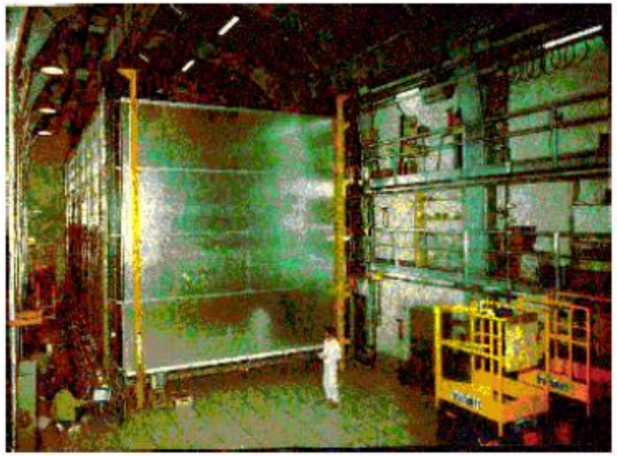


Kamiokande
(1000ton)

IMB
(3300ton)

NUSEX
(130ton)

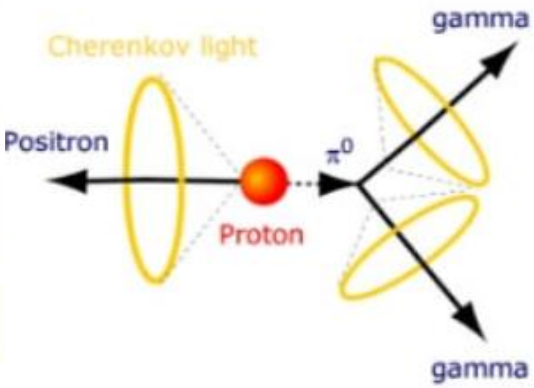
Frejus
(700ton)



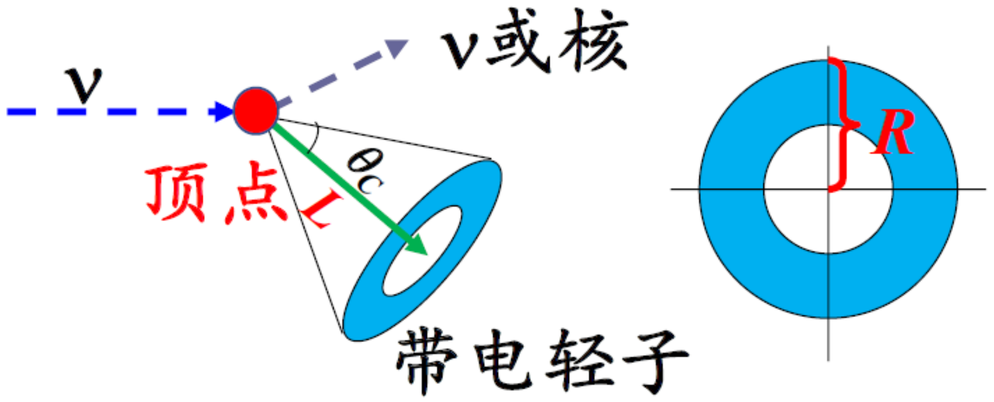
大气中微子是质子衰变实验的本底

主要衰变道

$$p \rightarrow e + \pi_0$$



切伦科夫探测技术



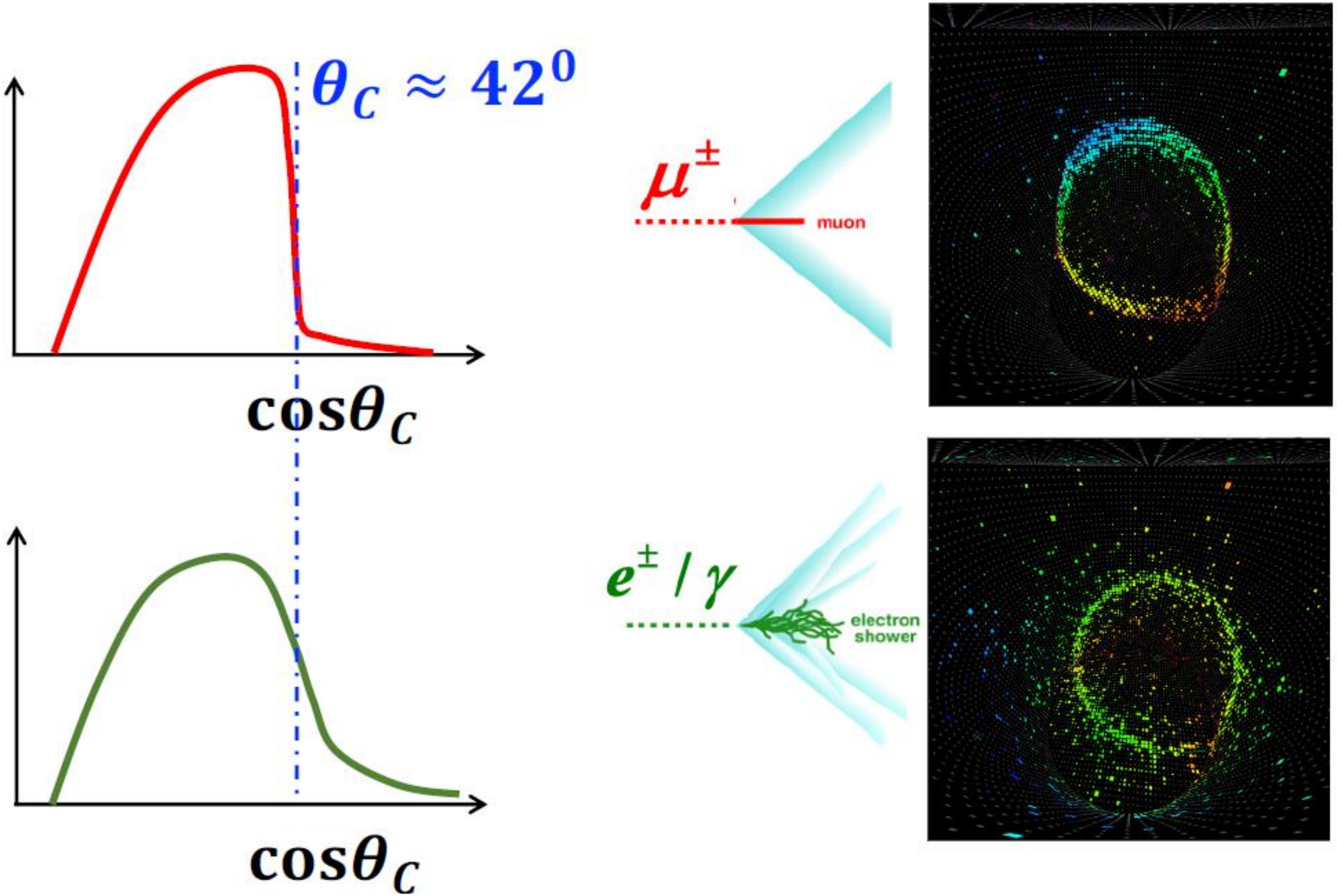
每 MeV 的电子大约发射22个波长250-600nm的切伦科夫光子。

切伦科夫科夫阈 $E = m/\sqrt{1-1/n^2}$

$$\cos\theta_C = \frac{R}{\sqrt{R^2+L^2}} = \frac{R}{\Delta t \times c/n} \quad E_K \sim L \times \frac{\mathrm{d}E}{\mathrm{d}x}$$

相对论性粒子 $\theta_C \approx 42^0$

切伦科夫探测技术



$\theta_C \approx 42^0$
$\cos\theta_C$
$\mu^{\pm}$
muon
$e^{\pm}/\gamma$
electron shower
$\cos\theta_C$

K. Hirata et al (Kamiokande)Phys.Lett.B 205 (1988) 416.

	Data	MC prediction
e-like (~CC ν_e)	93	88.5
μ-like (~CC ν_μ)	85	144.0

Kamiokande

(3000ton Water Ch. ~1000ton fid. Vol.)

2.87 kton・year

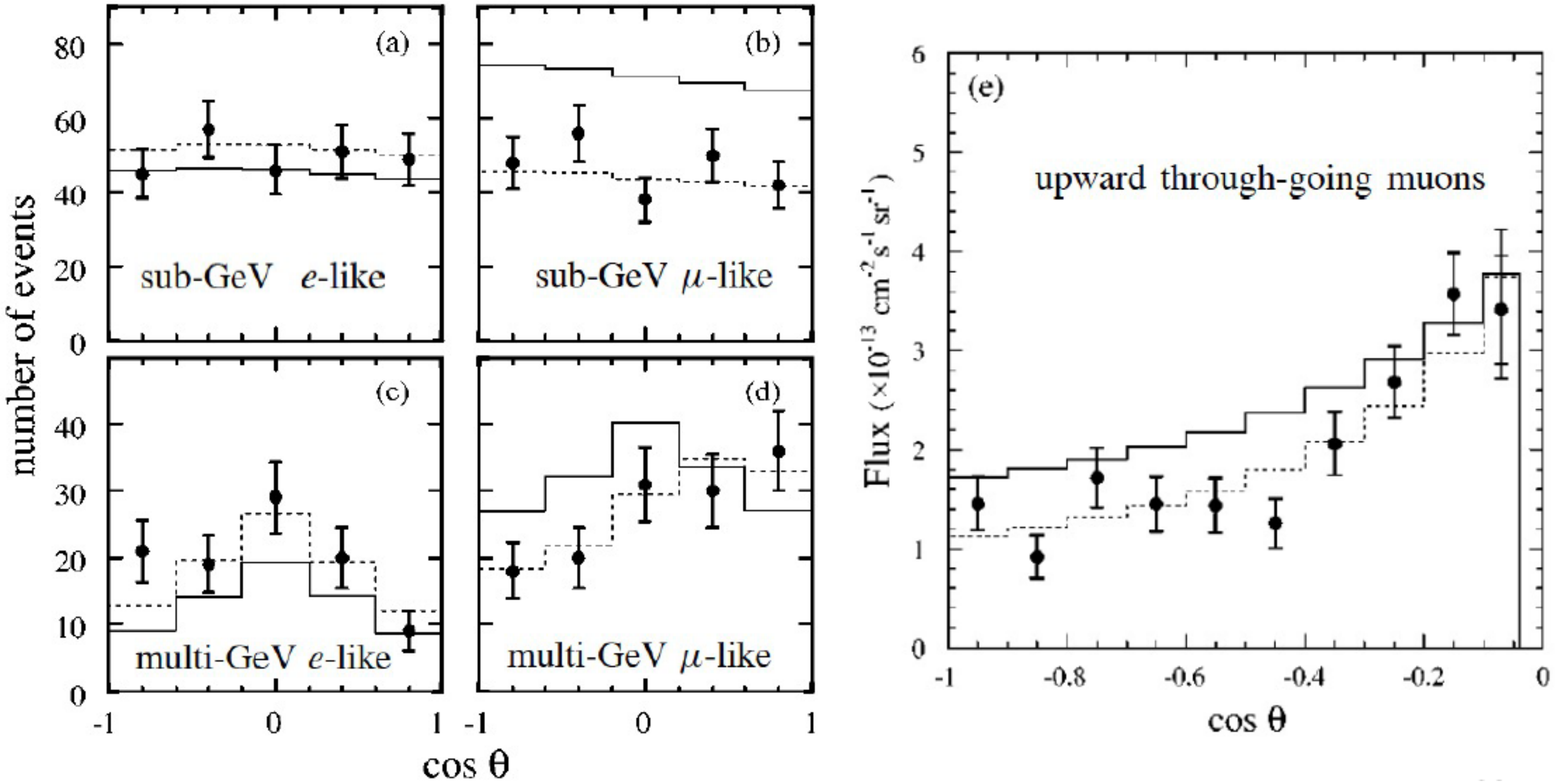
"We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccoundted-for physics such as neutrino oscillations might explain the data."

result was strange. The number of ν_μ events was far fewer than predicted by the simulation. At the same time, no such discrepancy was seen in the number of ν_e events. At first I thought that I had made some serious mistake. In order to find where I had made the mistake, I decided to check the events in the data by eye. Immediately I realized that the analysis software was correctly identifying the particle types. Unfortunately, I thought that this meant that the problem must not be simple. It seemed very likely that there were mistakes somewhere deep in the simulation, data selection, or the event reconstruction software. Together M. Takita and I embarked on various studies to try and find such mistakes late in 1986.

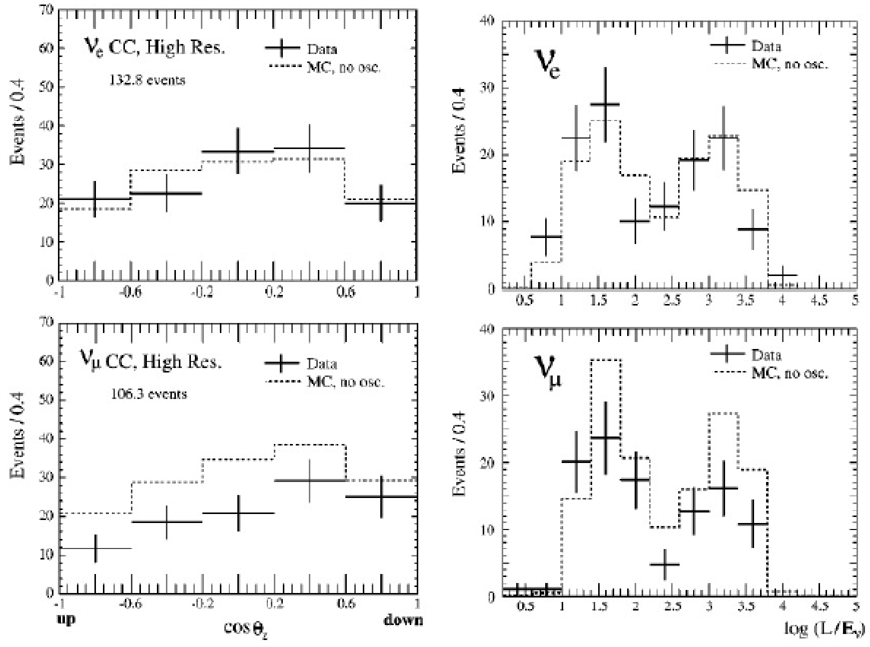
After studies for a year, we did not find any serious mistake and concluded that the ν_μ deficit could not be due to a major problem with the data analysis or the sim-

T. Kajita, Nobel lecture 2015

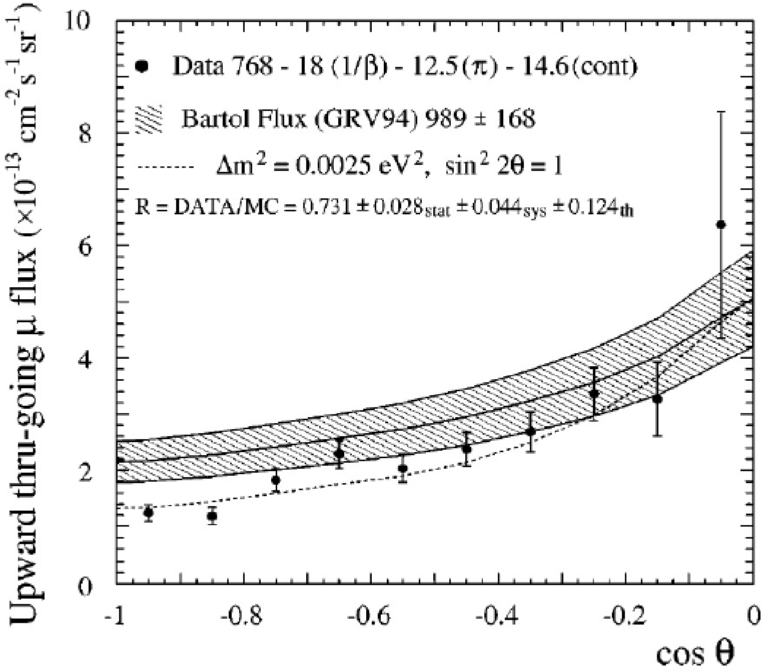
1988年，神冈实验报告，“我们无法解释系统探测器效应或大气中微子通量不确定性导致的数据。



这一反常分别得到基于不同探测技术的 Soudan-2 和 MACRO 实验的证实。

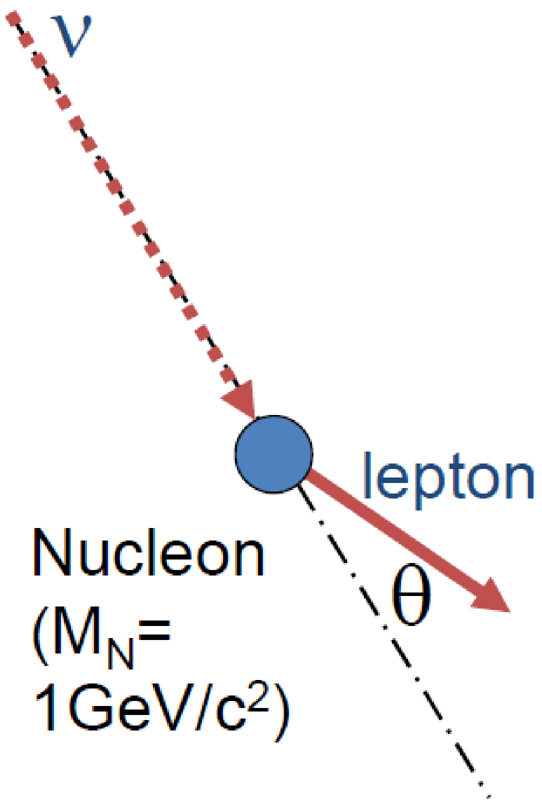


Soudan-2

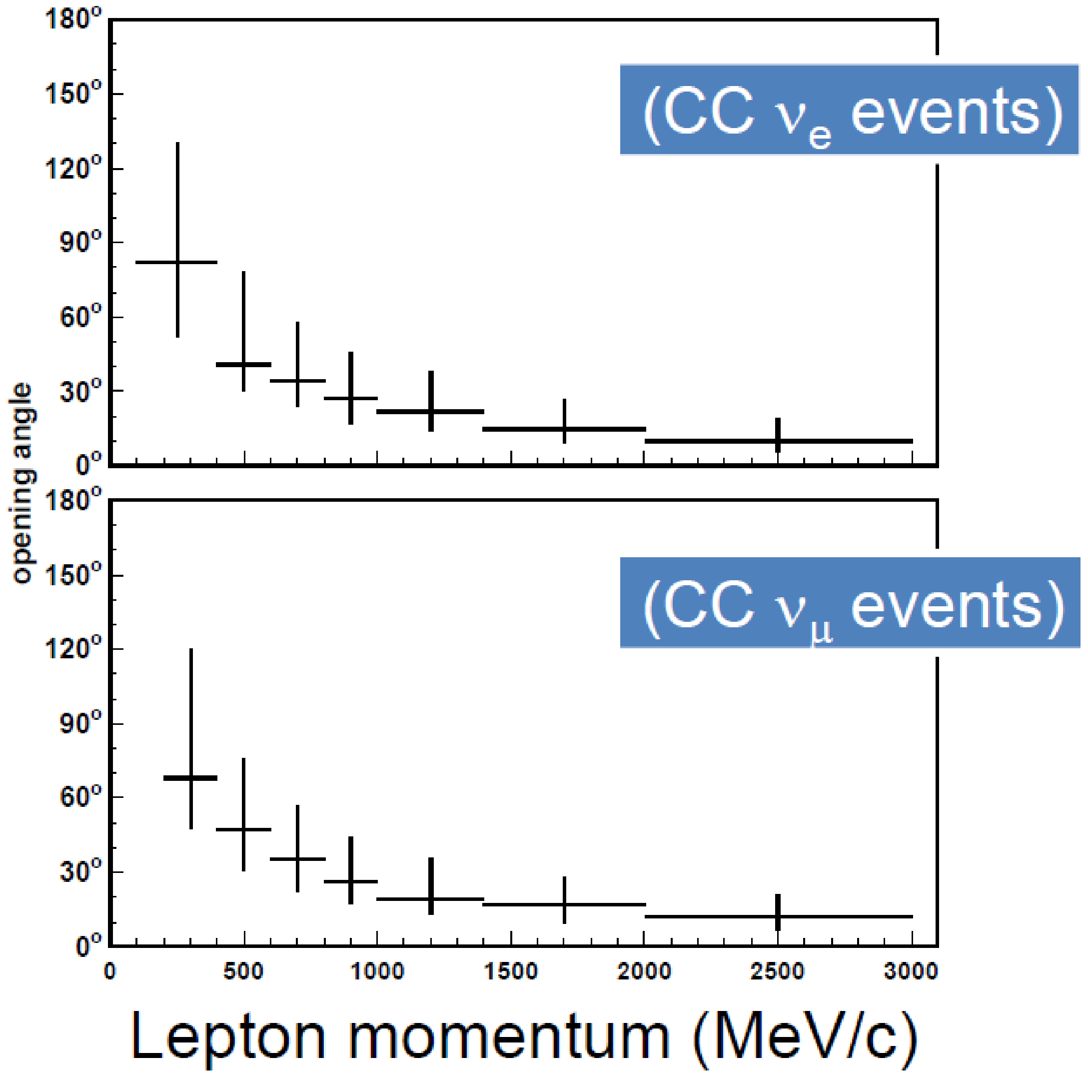


MACRO

中微子-带电轻子方向



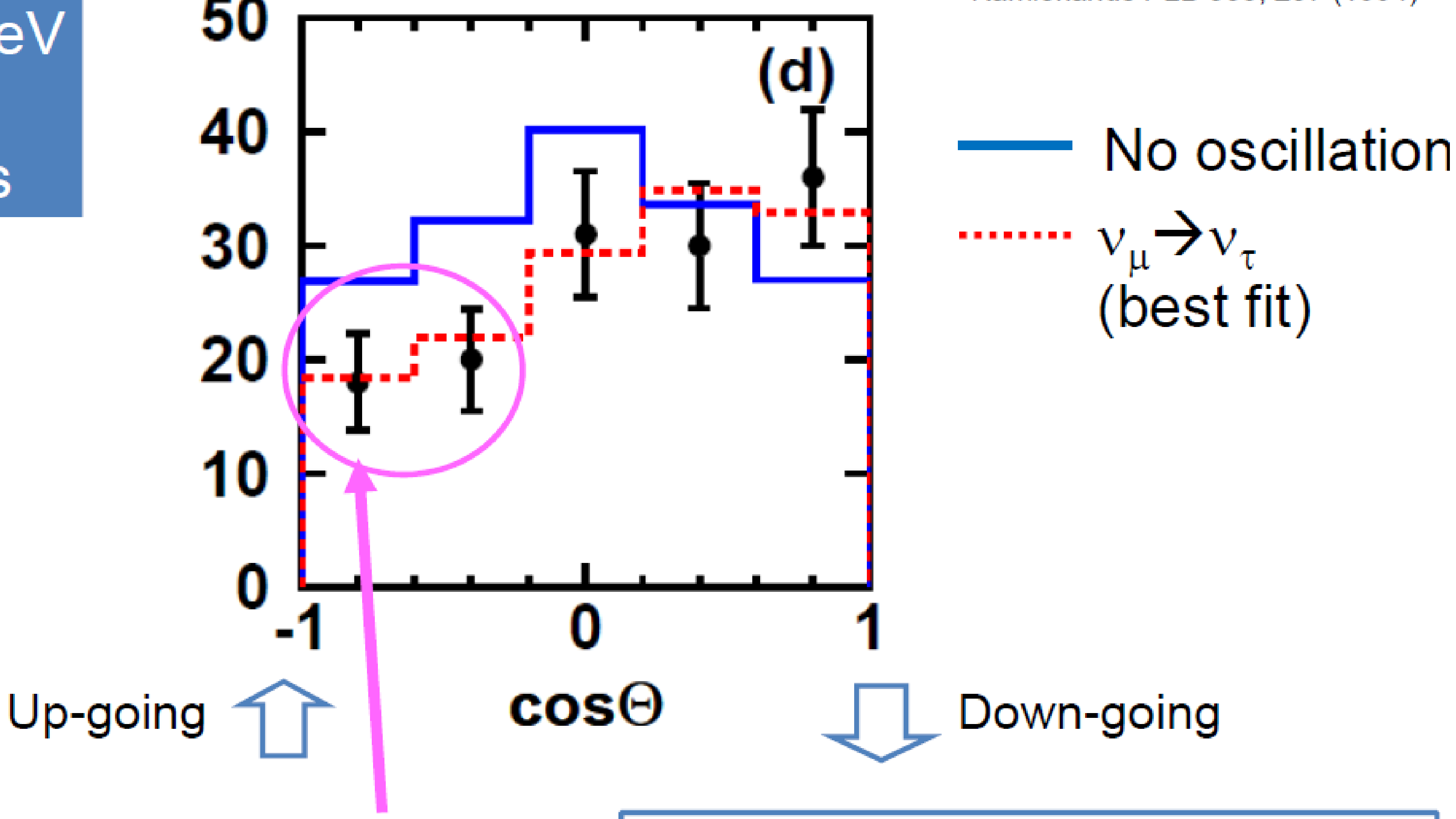
ν
lepton
Nucleon
(M_N=
1GeV/c²)
θ



(CC ν_e events)
(CC ν_μ events)
opening angle
180° 150° 120° 90° 60° 30° 0°
0 500 1000 1500 2000 2500 3000
Lepton momentum (MeV/c)

multi-GeV
μ-like
events

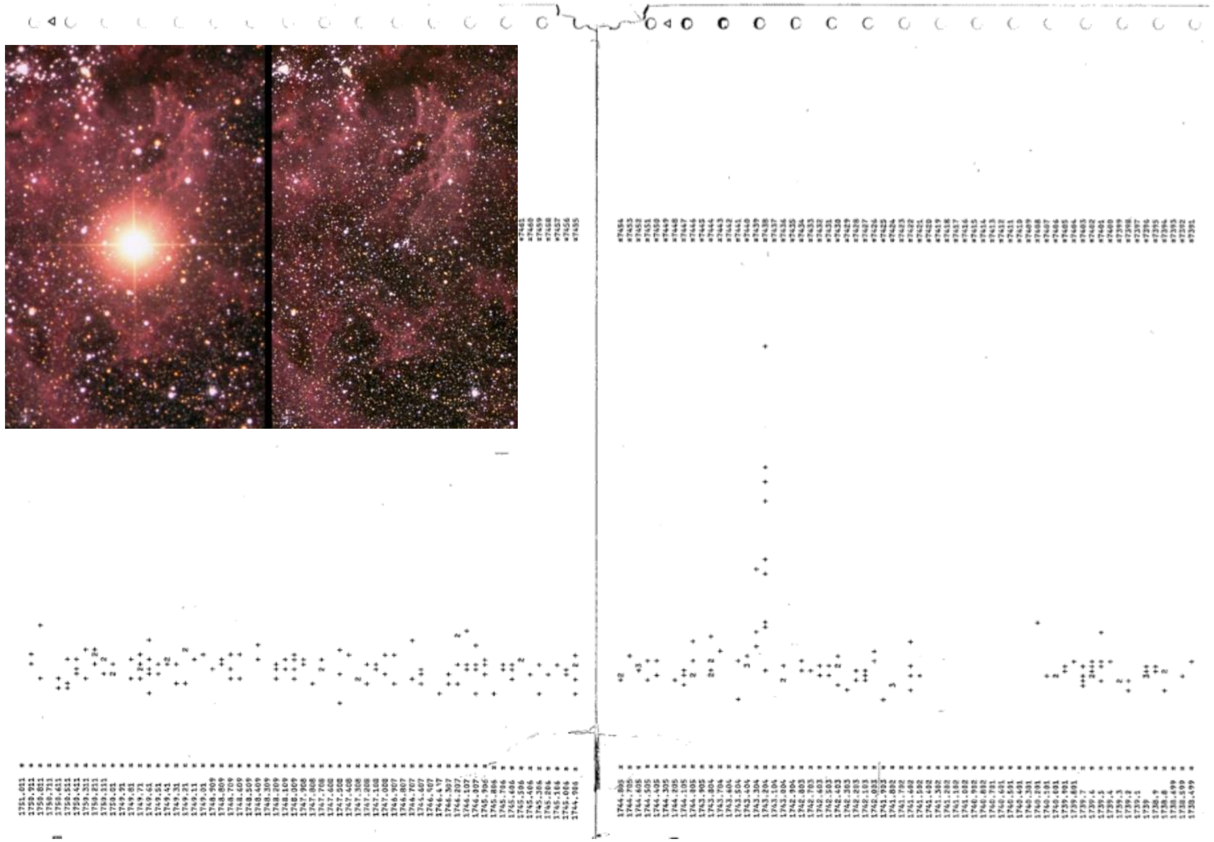
Kamiokande PLB 335, 237 (1994)



Deficit

Up/Down=$0.58^{+0.13}_{-0.11}$ (2.9 σ)

SN1987A，首次探测到超新星中微子




Observation of a Neutrino Burst from the Supernova SN1987a

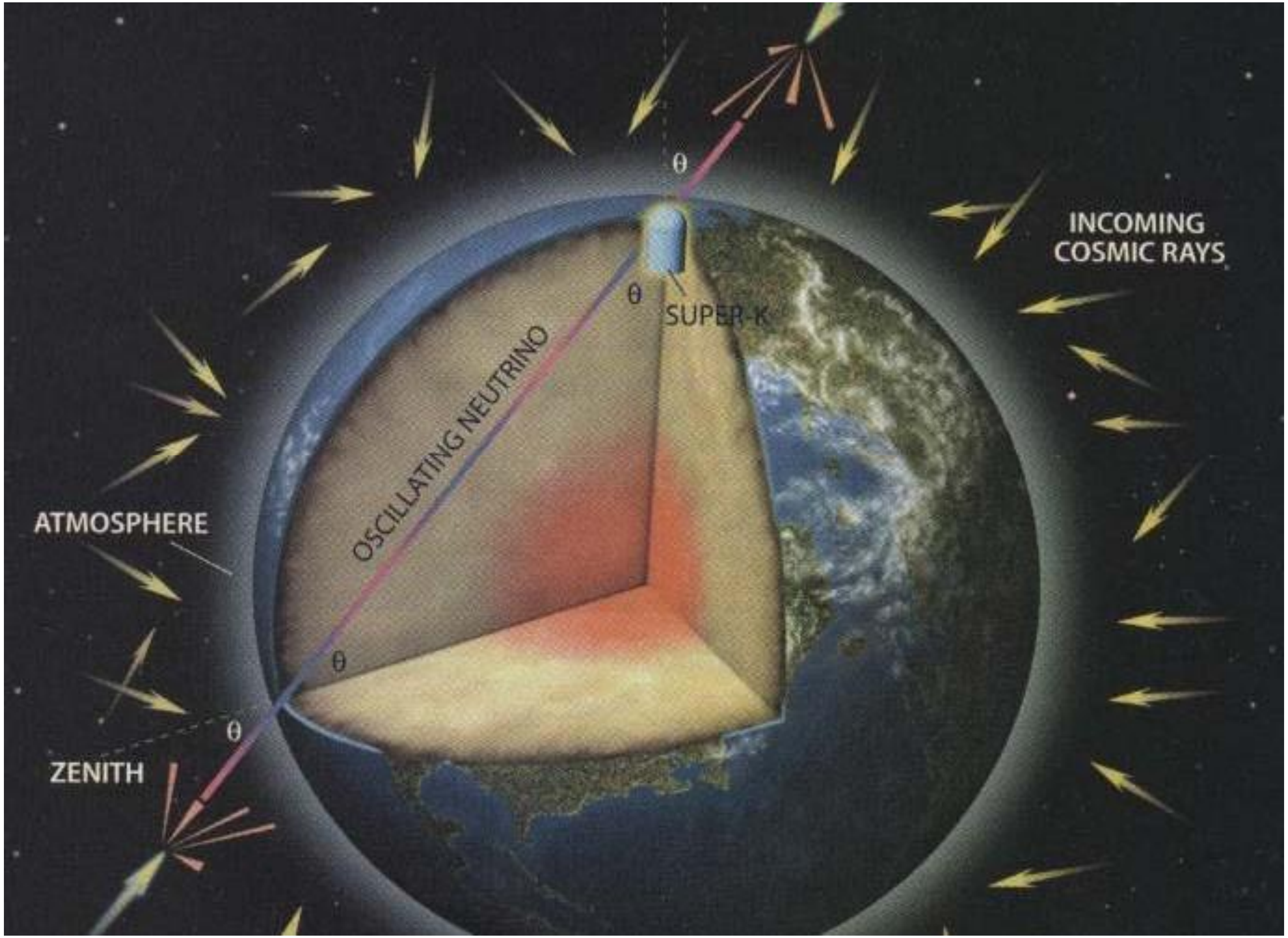
The KAMIOKANDE-II Collaboration

March 6. 1987

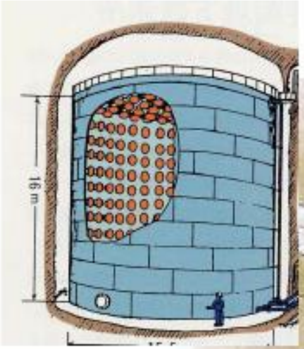
(Submitted for publication in Phys. Rev. Lett.)

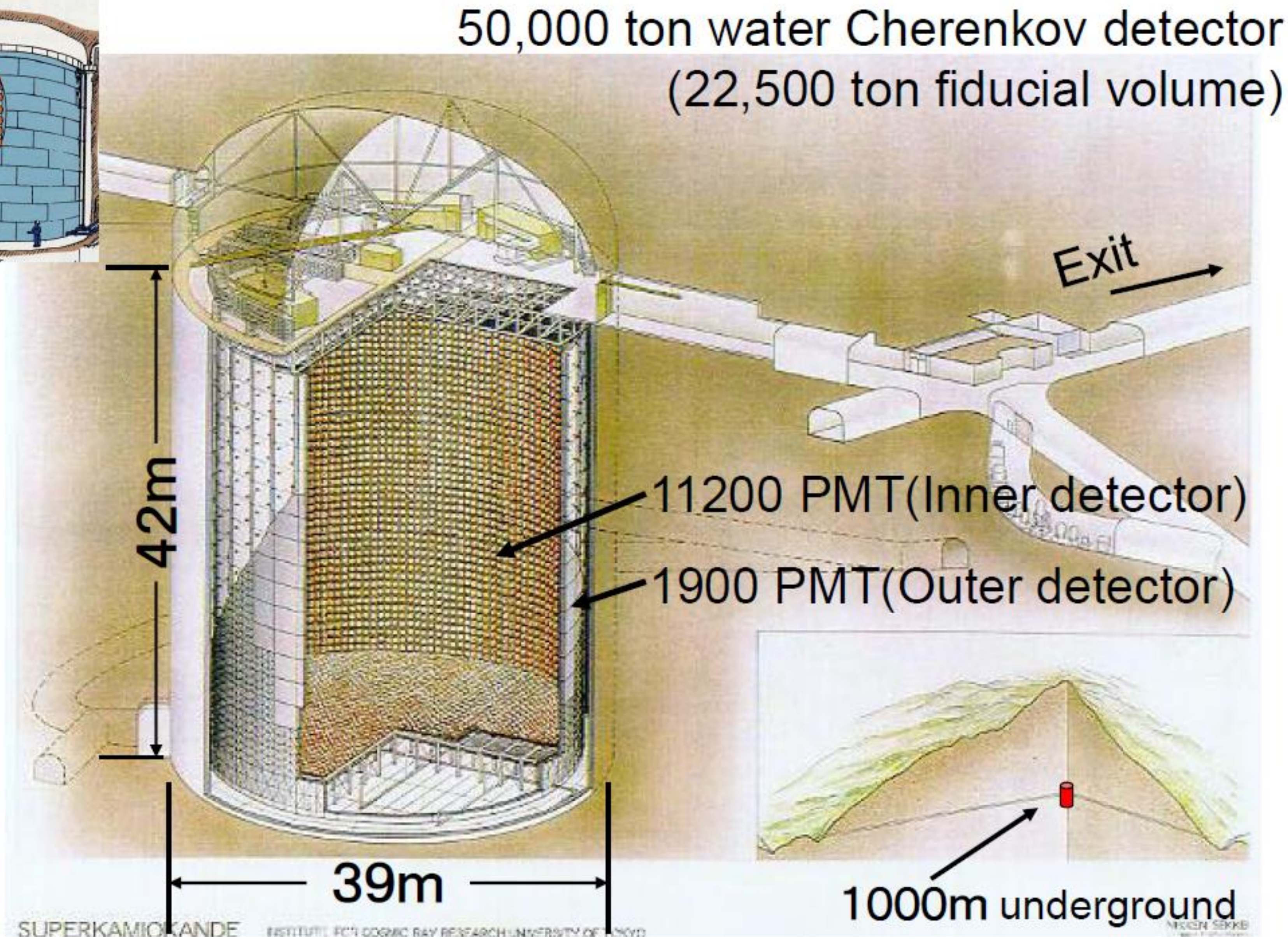
The 2002 Nobel Prize in Physics awarded to Prof. Masatoshi Koshiba for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos.

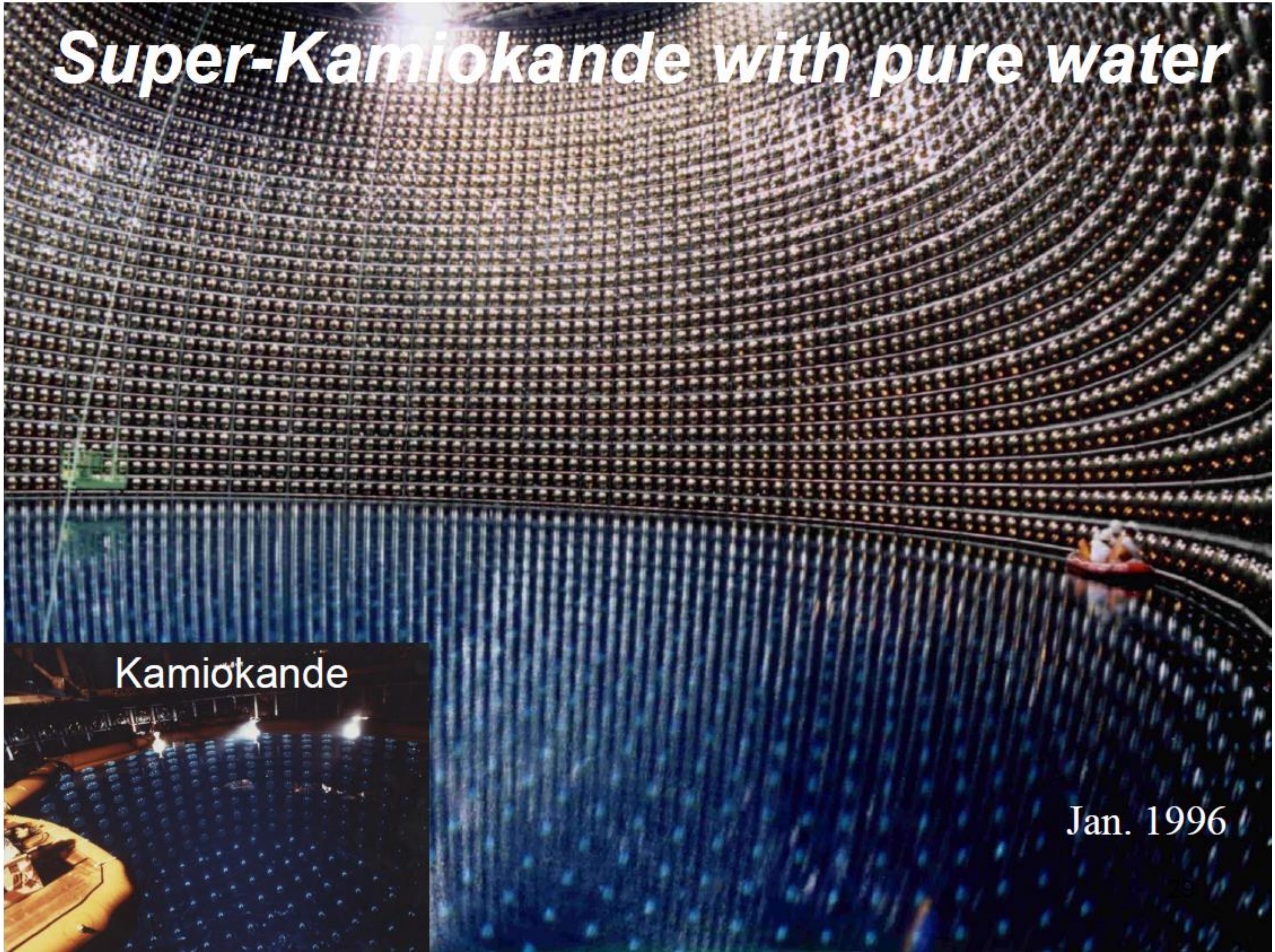
利用大气中微子研究振荡



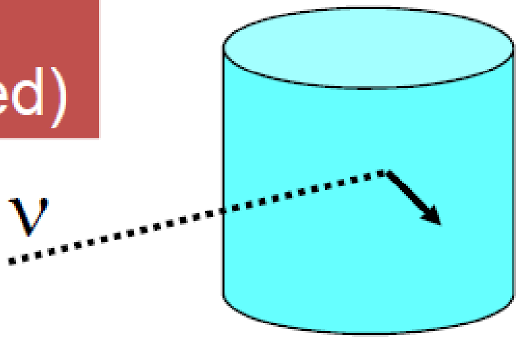
Super-Kamiokande实验





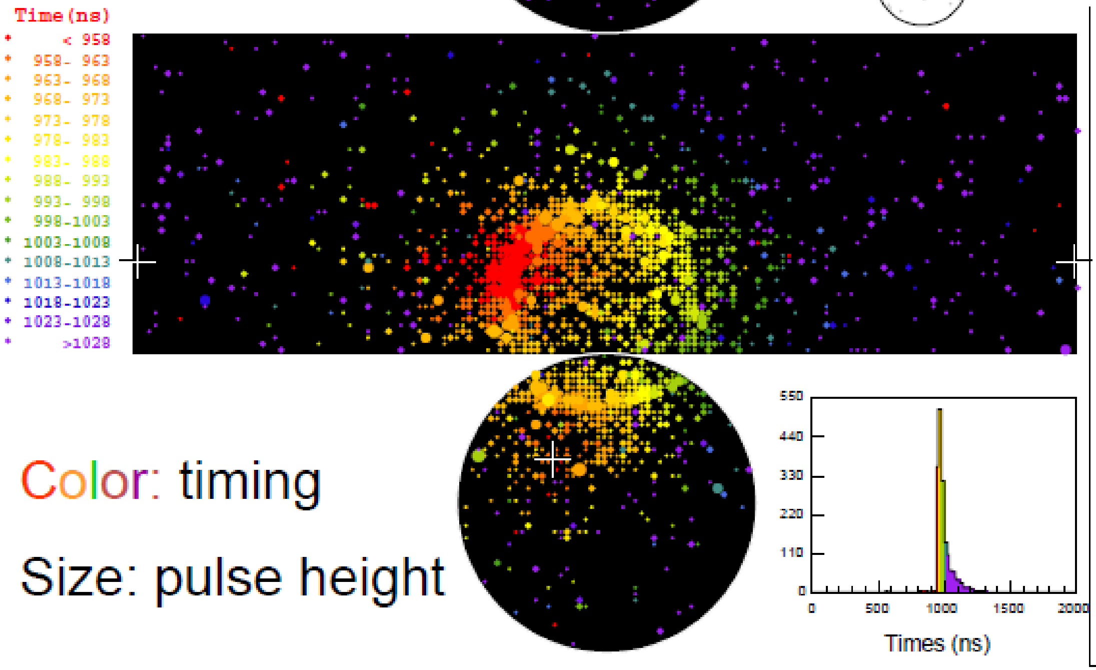

Super-Kamiokande with pure water
Kamiokande
Jan. 1996

FC (fully contained)



- Both CC ν_e and ν_μ (+NC)
- Particle identification separates electrons and muons with ε=99%.

Single Cherenkov ring electron-like event

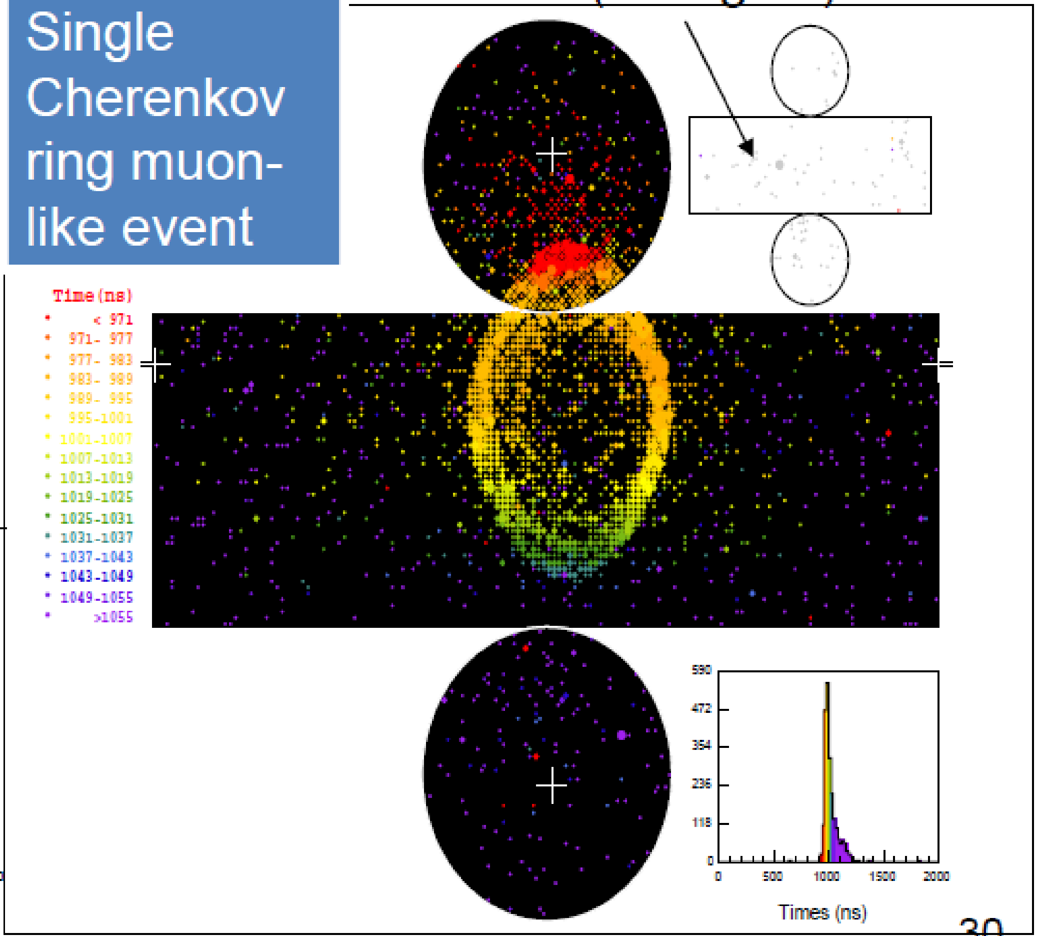


Color: timing

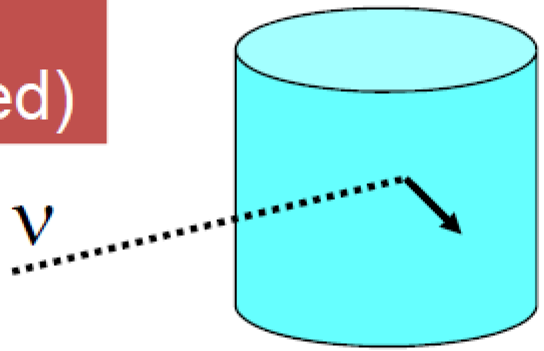
Size: pulse height

Single Cherenkov ring muon-like event

Outer detector (no signal)

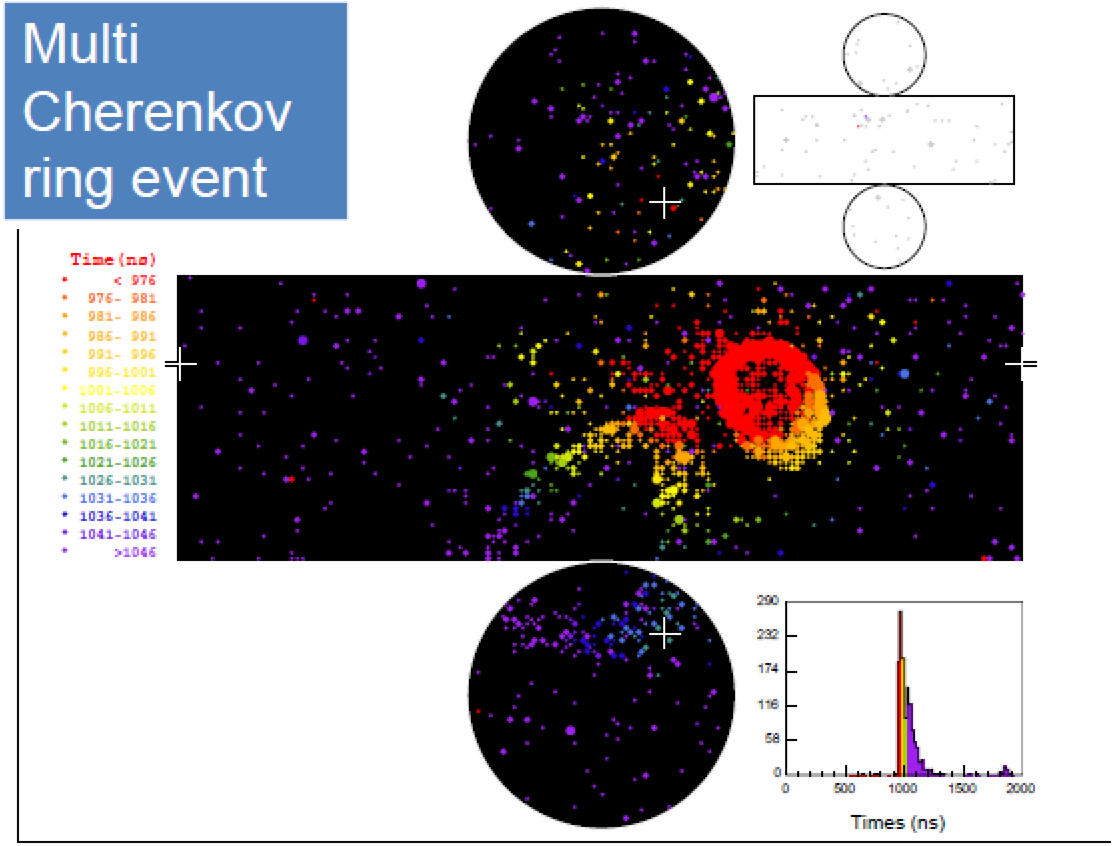


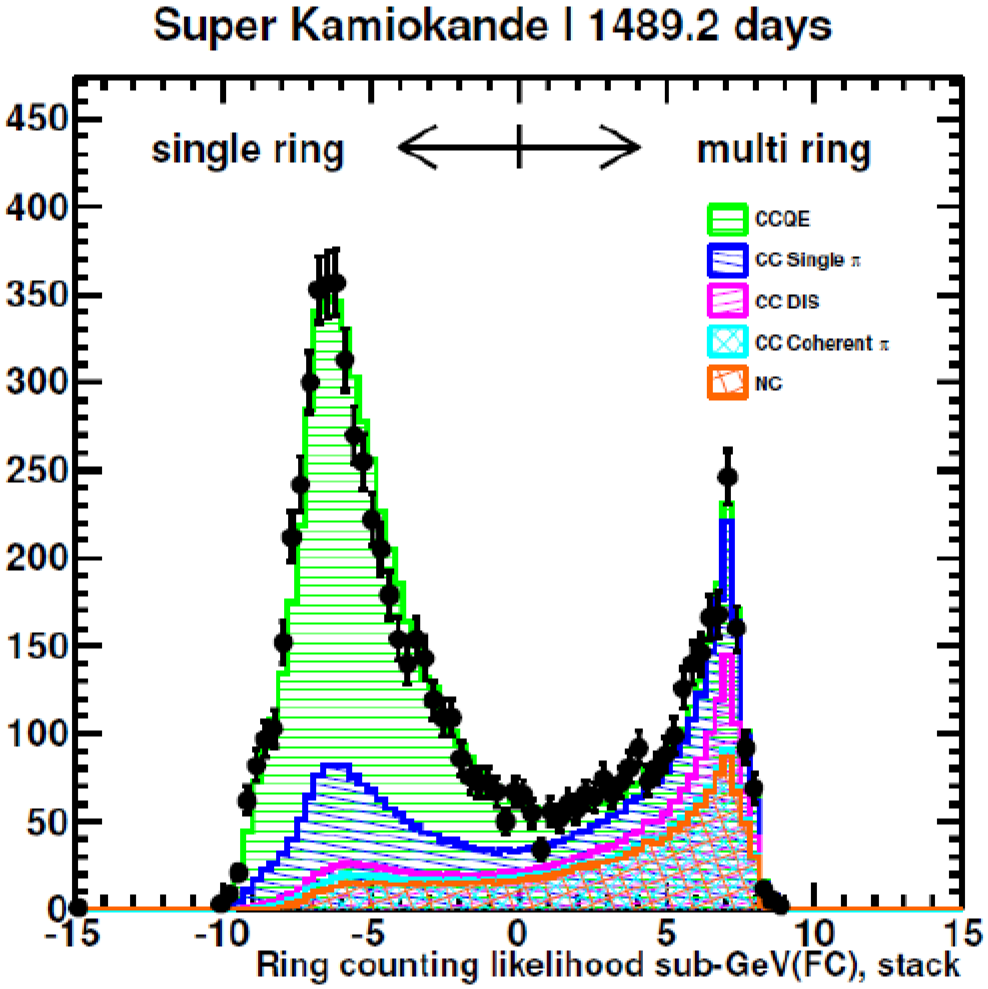
FC
(fully contained)



- Both CC ν_e and ν_μ (+NC)
- multi-ring events are also used in the oscillation analysis if the event is identified as e-like or mu-like.

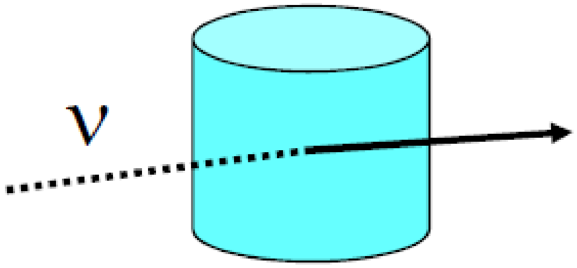
Multi Cherenkov ring event





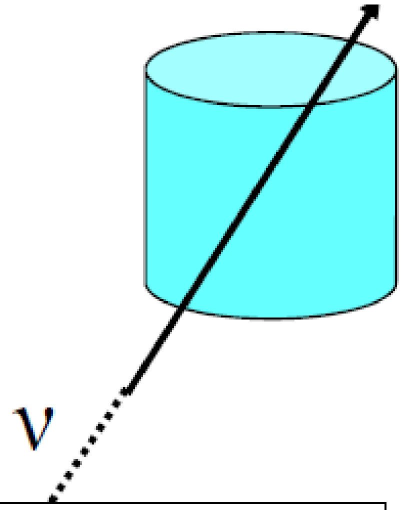
PC (partially contained)

- 97% CC ν_μ

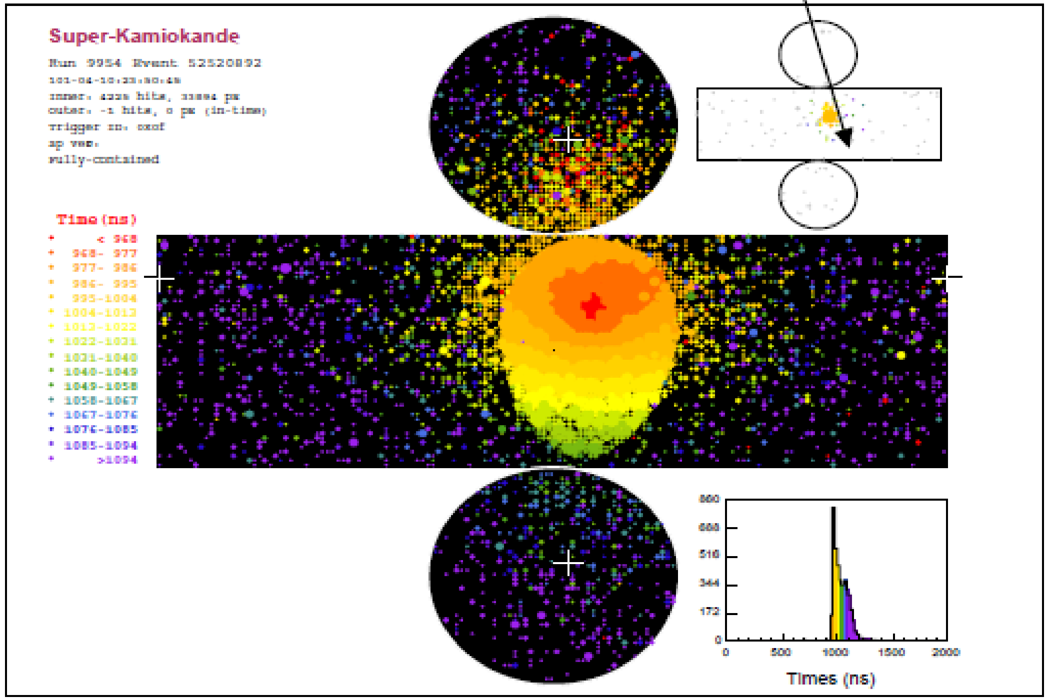


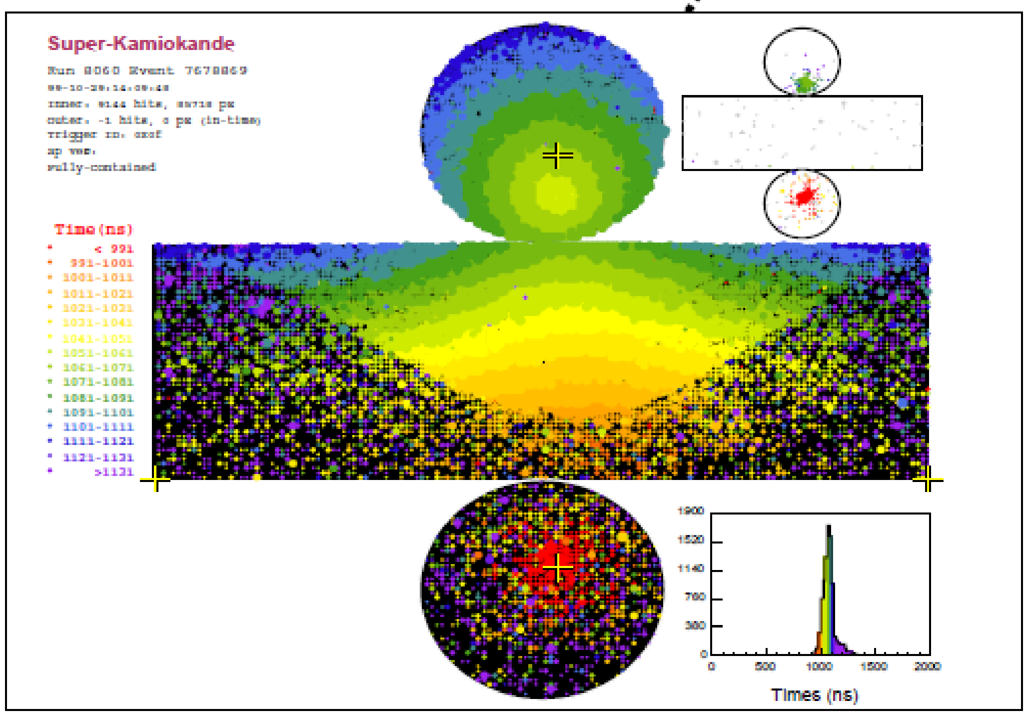
Upward going muon

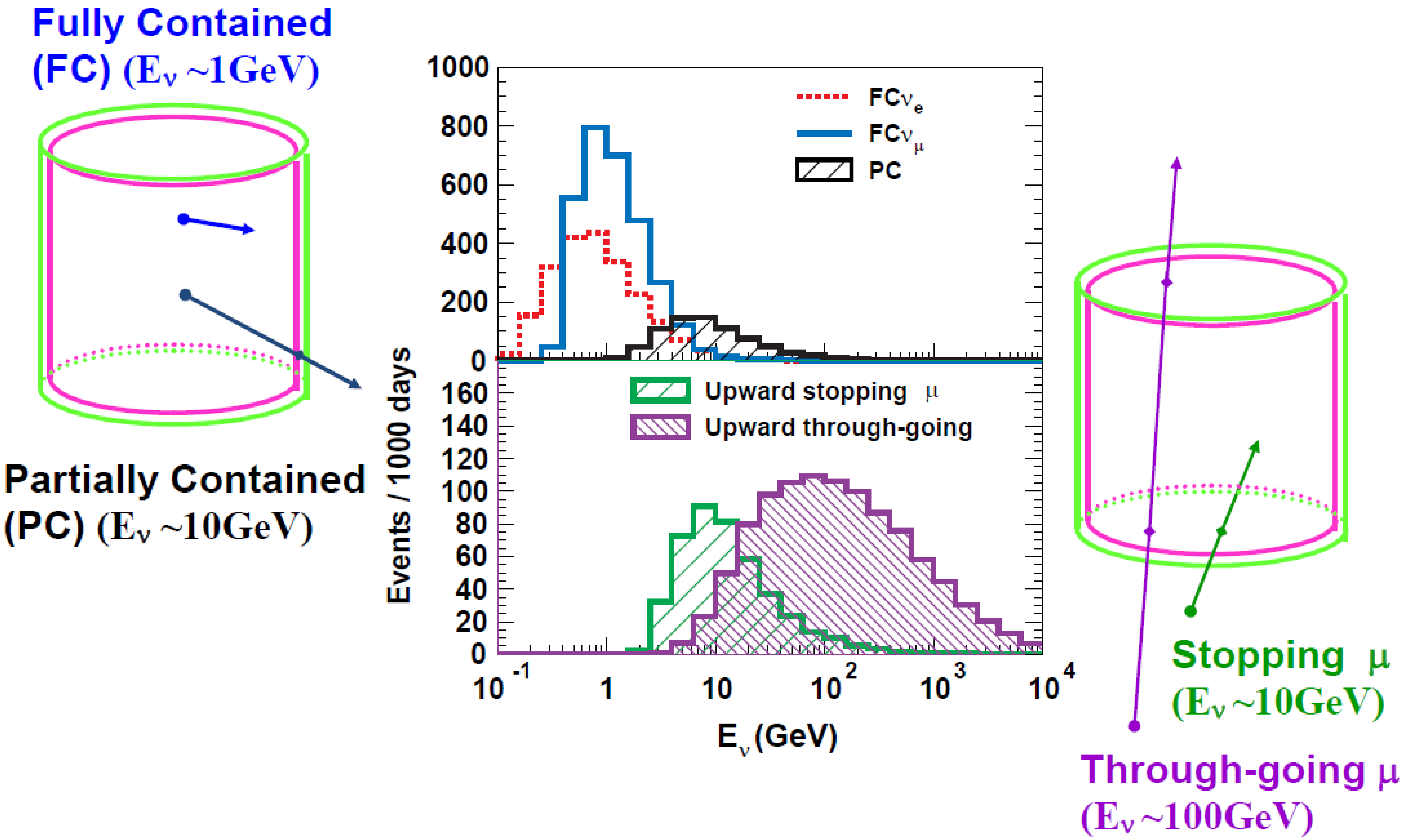
- almost pure CC ν_μ



Signal in the outer detector

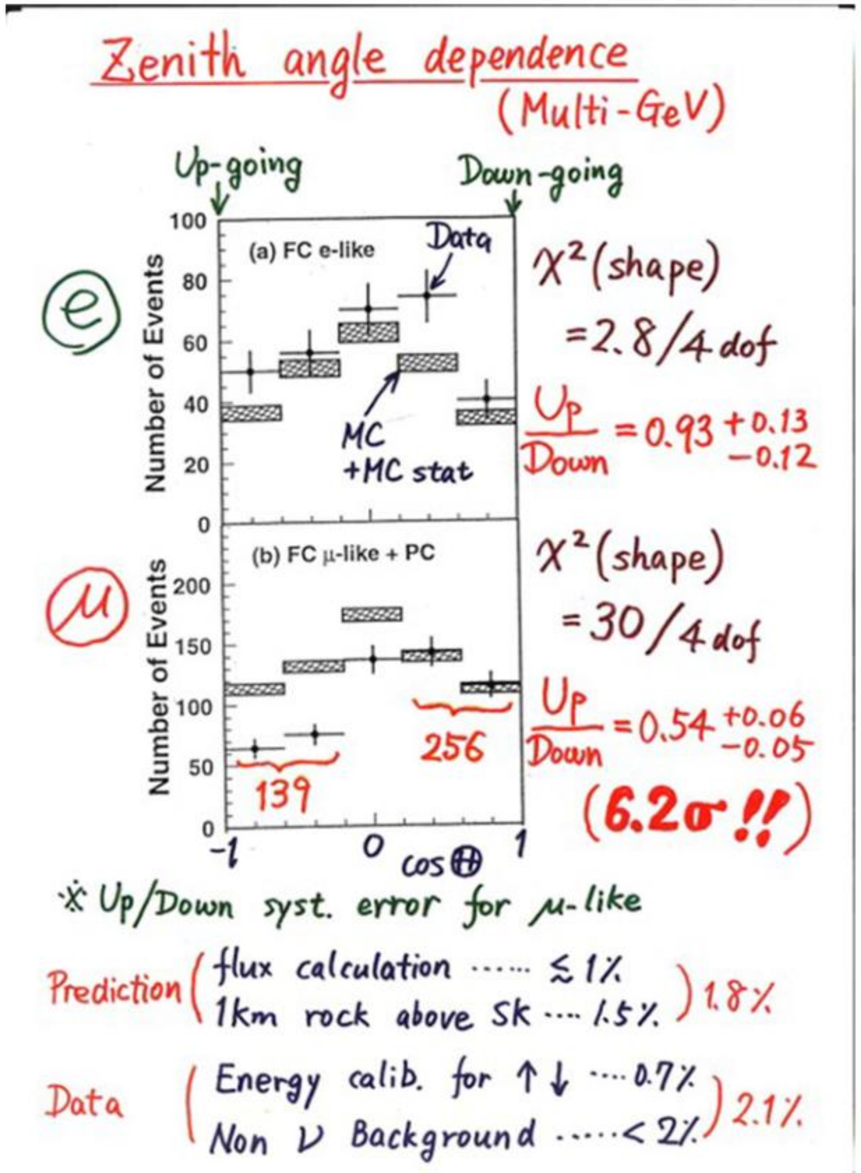


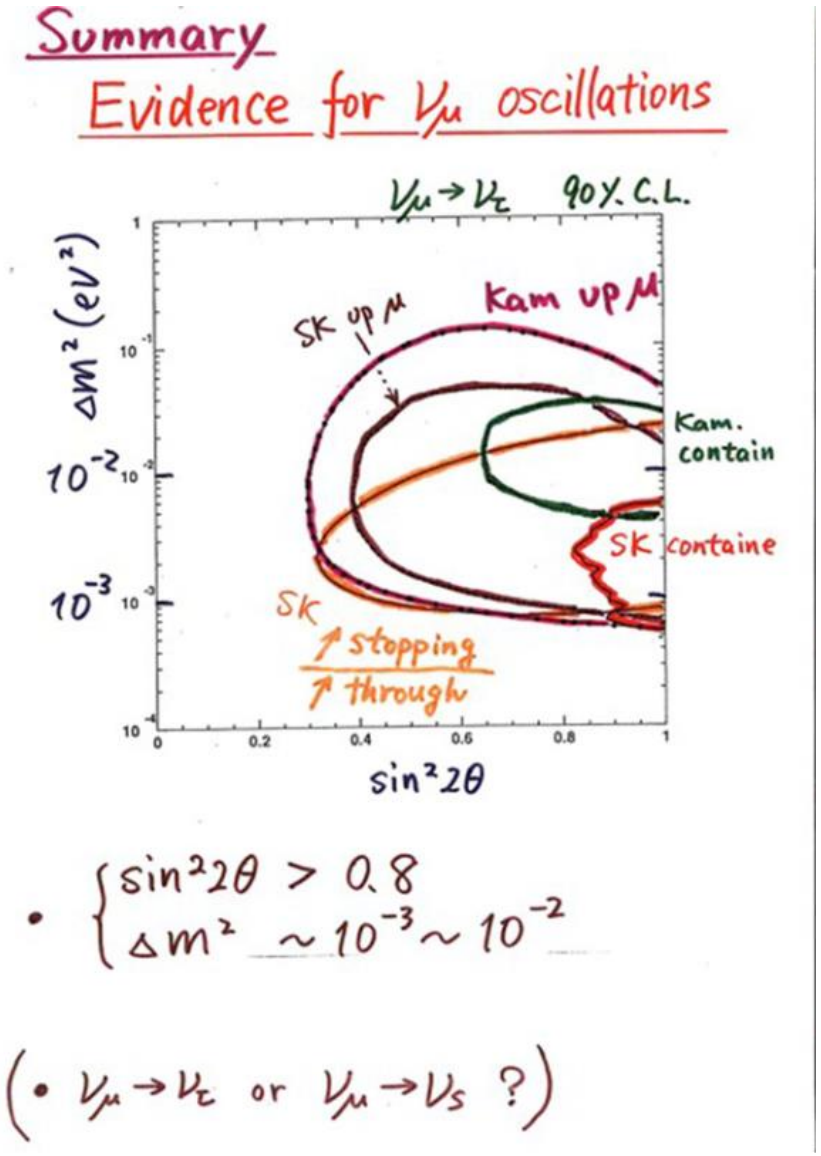



Fully Contained
(FC) (Eν ~1GeV)
Partially Contained
(PC) (Eν ~10GeV)
Events / 1000 days
FCνe
FCνμ
PC
Upward stopping μ
Upward through-going
1000
800
600
400
200
0
160
140
120
100
80
60
40
20
0
10^-1
1
10
10^2
10^3
10^4
Eν (GeV)
Stopping μ
(Eν ~10GeV)
Through-going μ
(Eν ~100GeV)

Neutrino 98

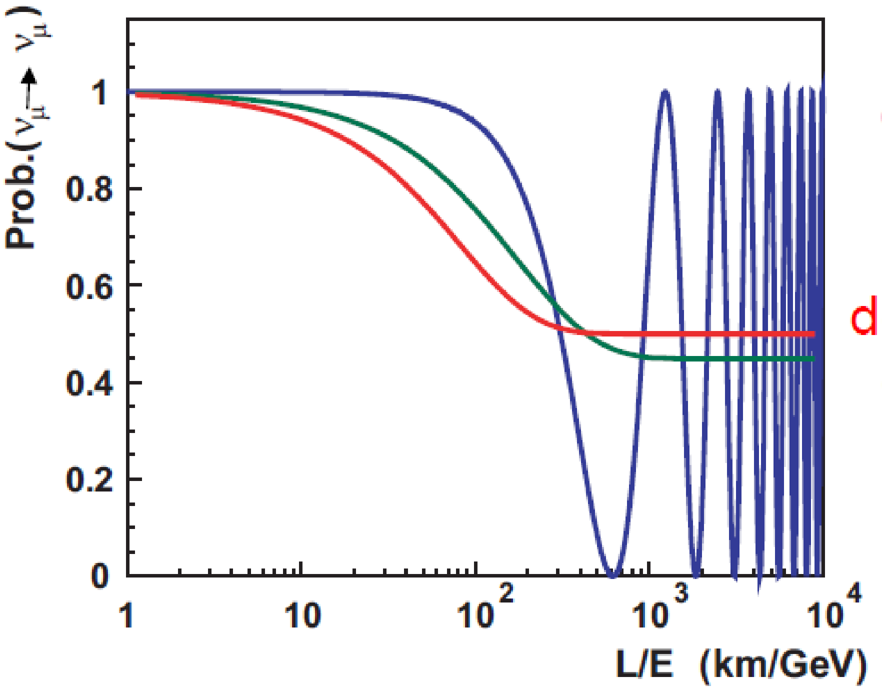
- SK实验发现中微子振荡
- 获2015年诺贝尔物理学奖





L/E分析

SK PRL 93, 101801 (2004)



oscillation

decoherence

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \cdot \left(1 - \exp\left(-\gamma_0 \frac{L}{E}\right)\right)$$

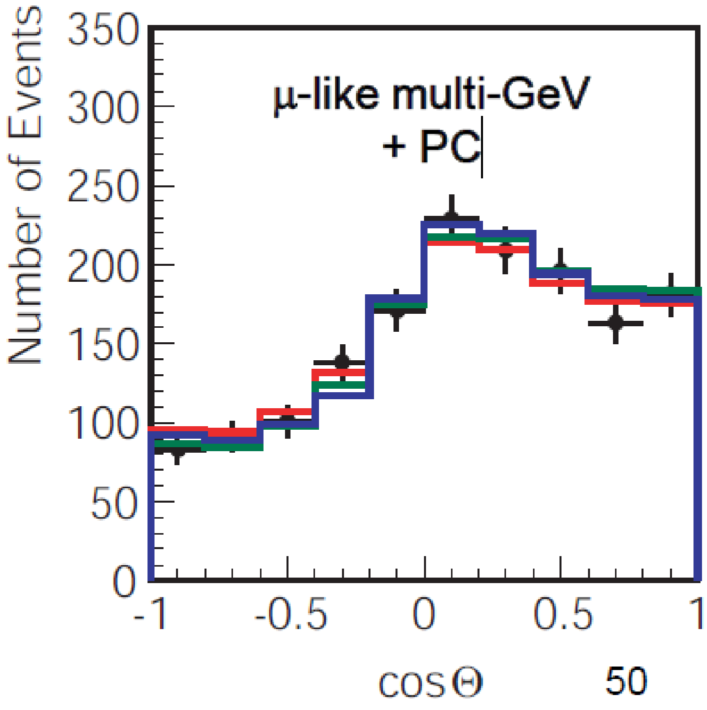
decay

$$P_{\mu\mu} = \left(\cos^2\theta + \sin^2\theta \cdot \exp\left(-\frac{m}{2\tau}\frac{L}{E}\right)\right)^2$$

Should observe this dip!

→ Further evidence for oscillation

→ Strong constraint on oscillation parameters, especially Δm^2



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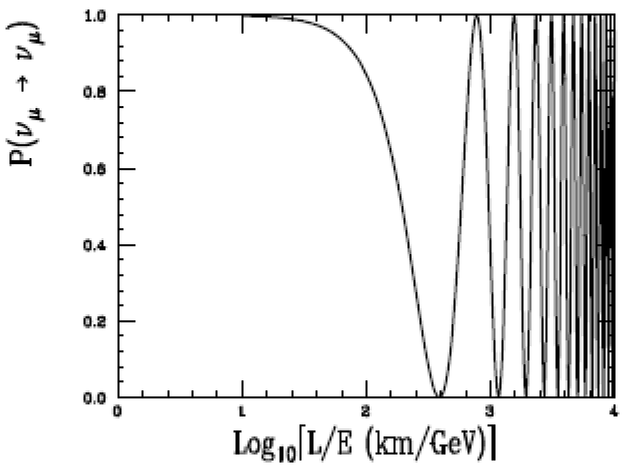
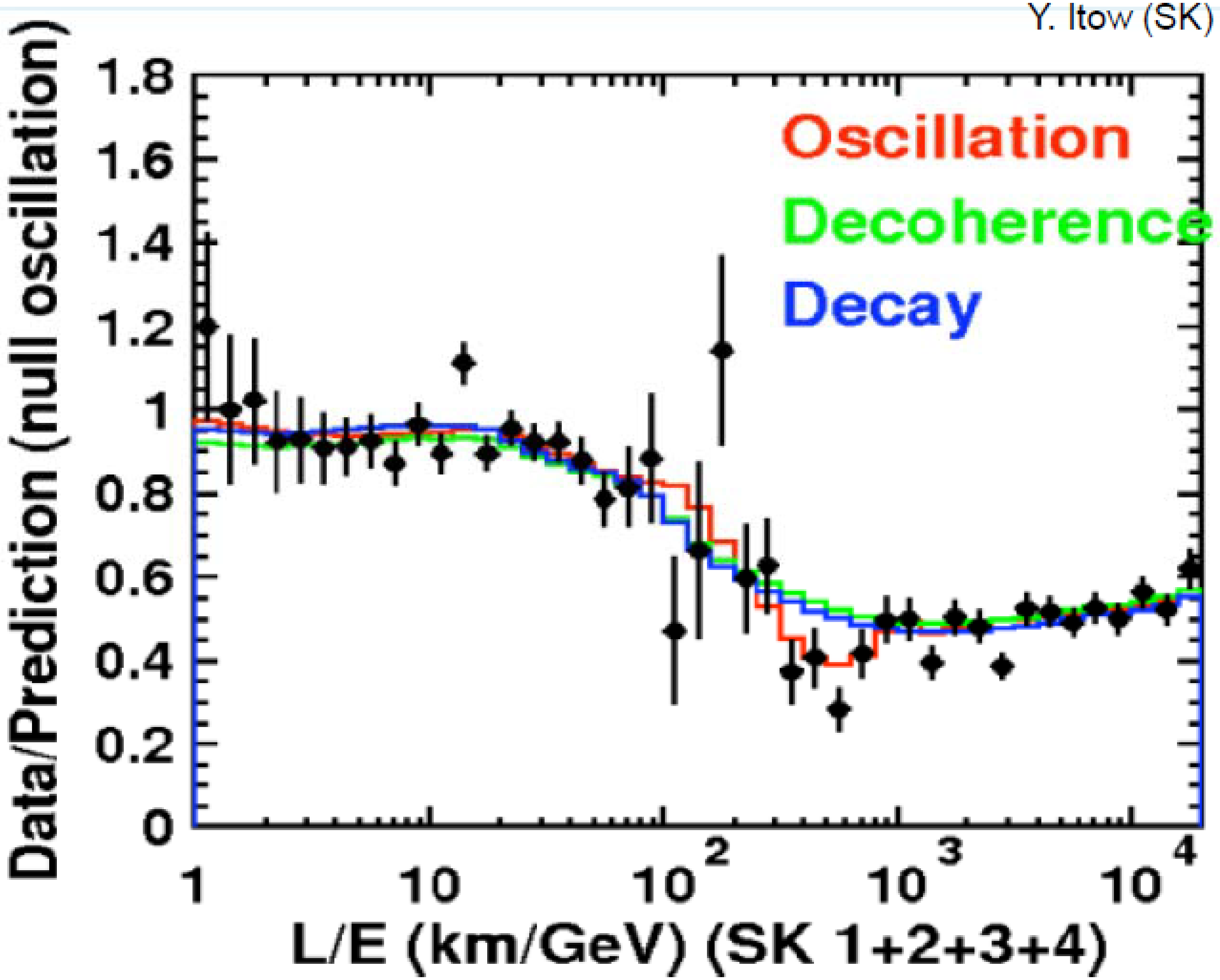
Initial results PRL 93, 101801 (2004)
Y. Itow (SK) nu2012

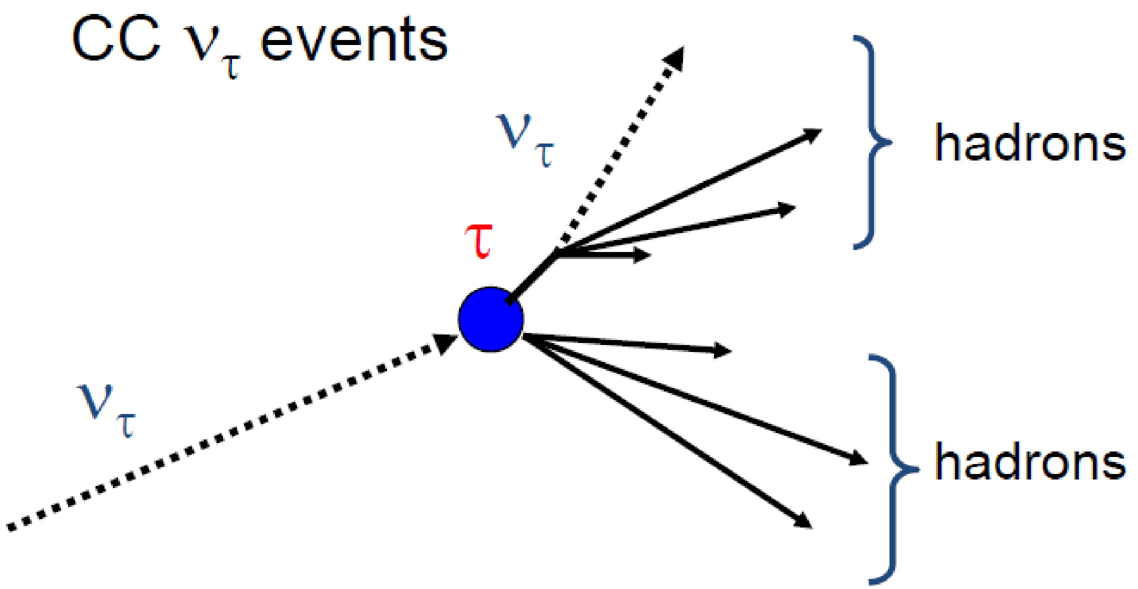
“Perfect” experiment

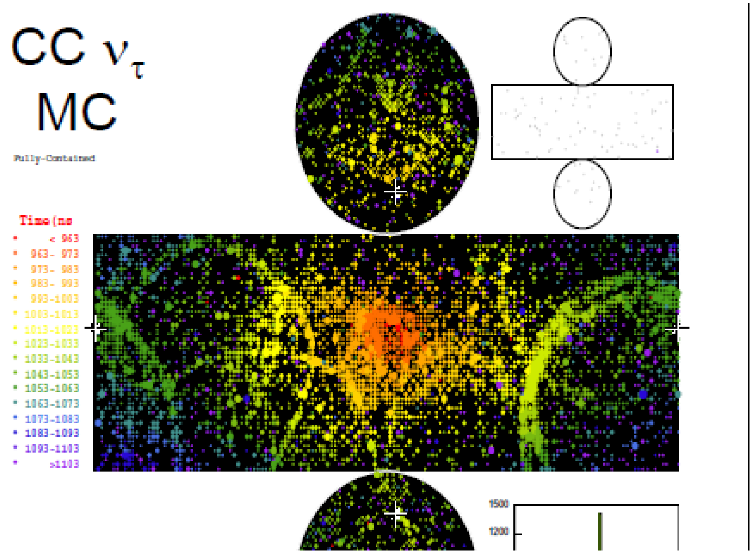




A dip is seem around L/E = 500 km/GeV (first oscillation minimum).
Oscillation gives the best fit to the data.
Decay and decoherence models disfavored by 4.0 and 4.8σ, resp.

探测ν_τ





✓ Many particles (hadrons) ….
(But no big difference with the other (NC) events.)

➥ Neural Network (NN) analysis

✓ Upward going only

➥ Zenith angle

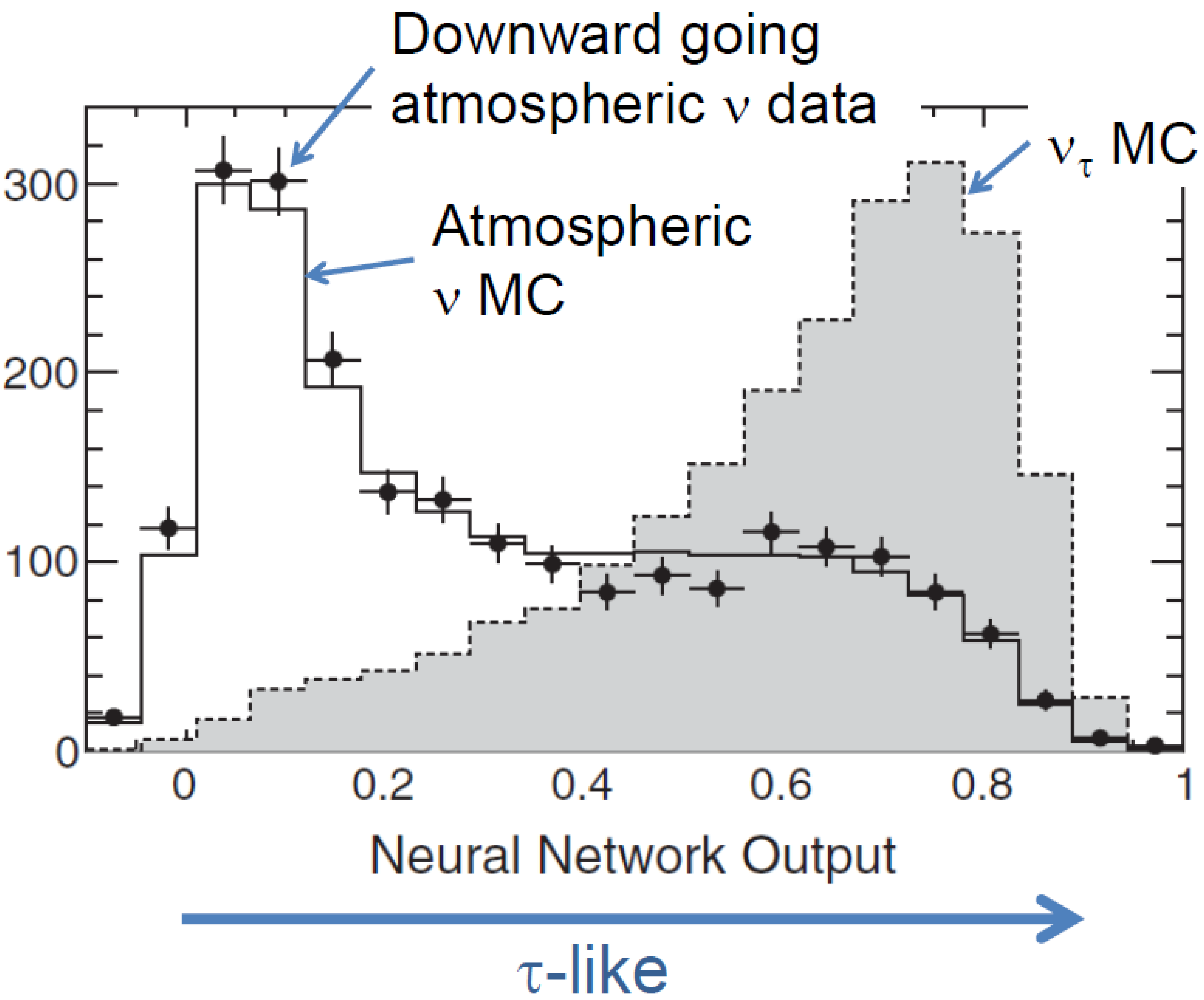
Only ～ 1.0 CC ν_τ FC events/kton・yr

(BG (other ν events) ～ 130 ev./kton・yr)

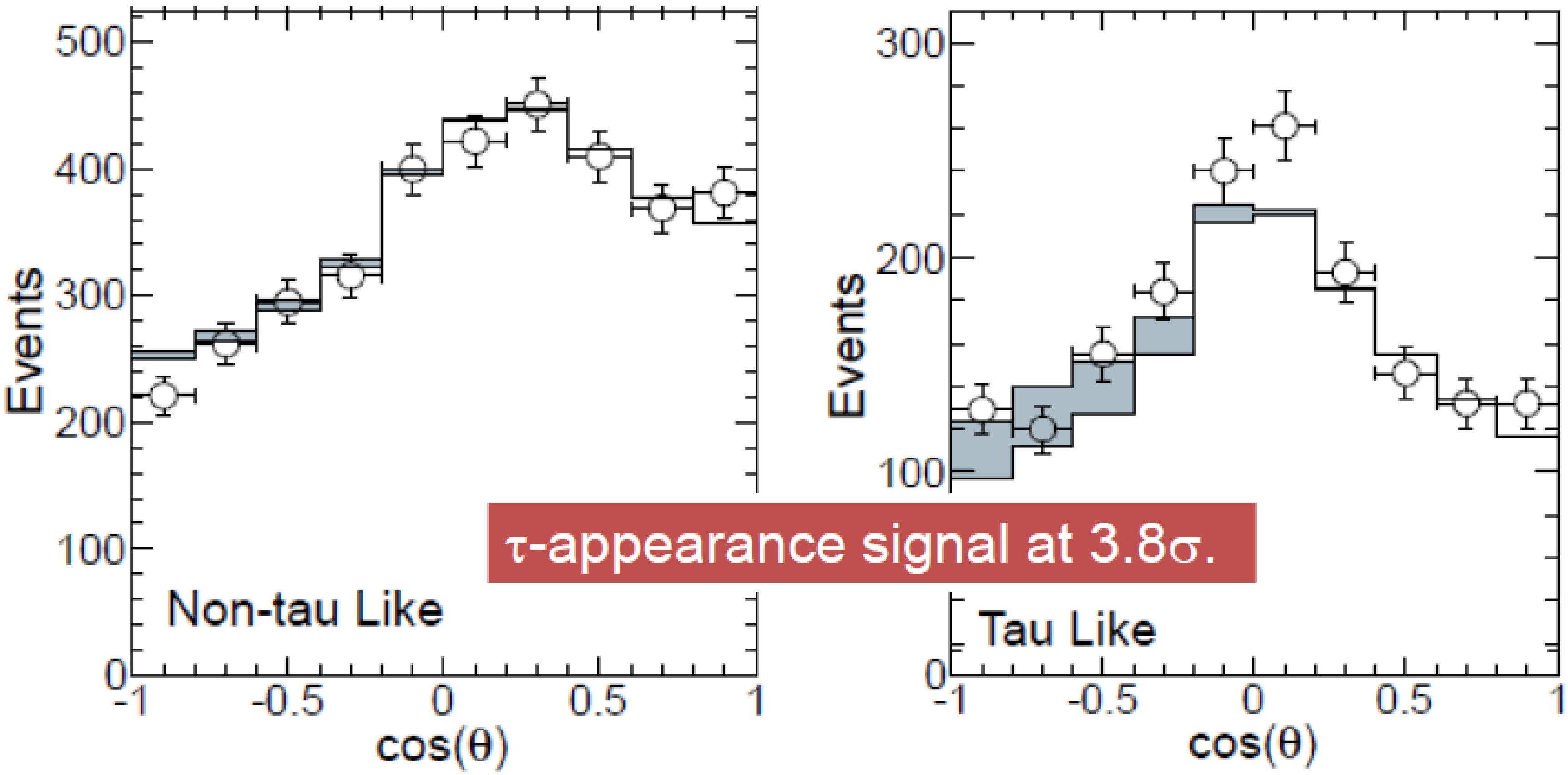
SK PRL 110(2013)181802

NN inputs:

- ✓$E_{visible}$
- ✓PID (highest E ring)
- ✓N($\mu \rightarrow e$)
- ✓Distance (vertex - e-vertex)
- ✓Sphericity
- ✓N (Ch. ring candidates)
- ✓$E_{visible}$ fraction of the 1st ring



SK PRL 110(2013)181802

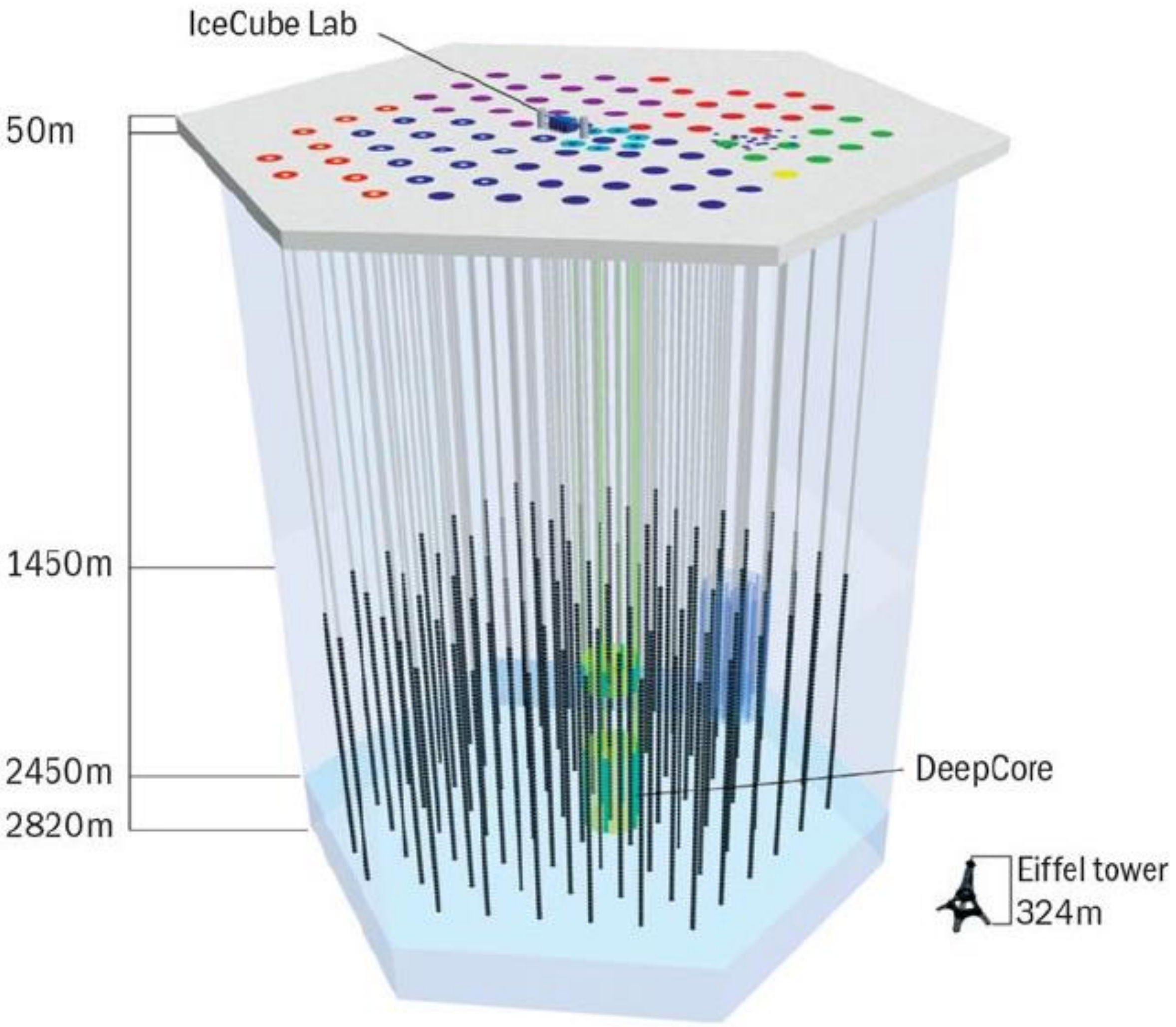


Fitted number of τ events	180.1 $\pm$44.3(stat) +17.8 / -15.2(syst)
Exp'd number of τ events	120.2+34.2/-34.8(syst)

Compared with the previous results (2006), systematic error due to θ_{13} uncertainty was greatly reduced.

当代大气中微子实验

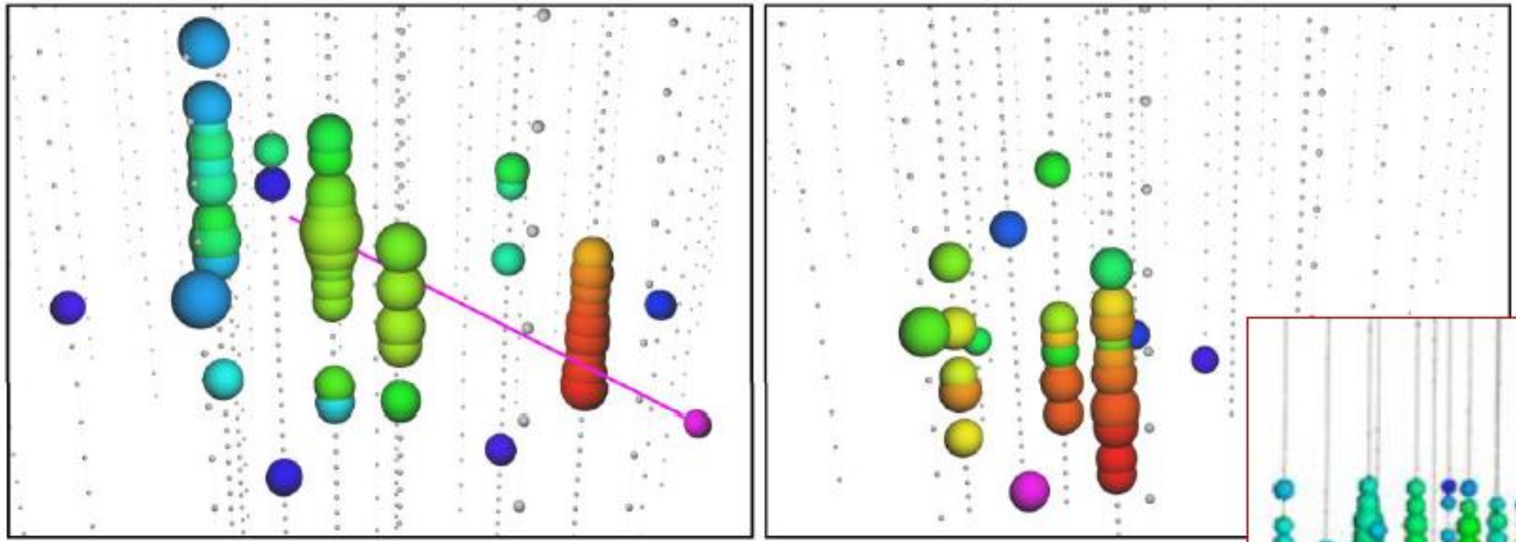
ICECUBE/DeepCore



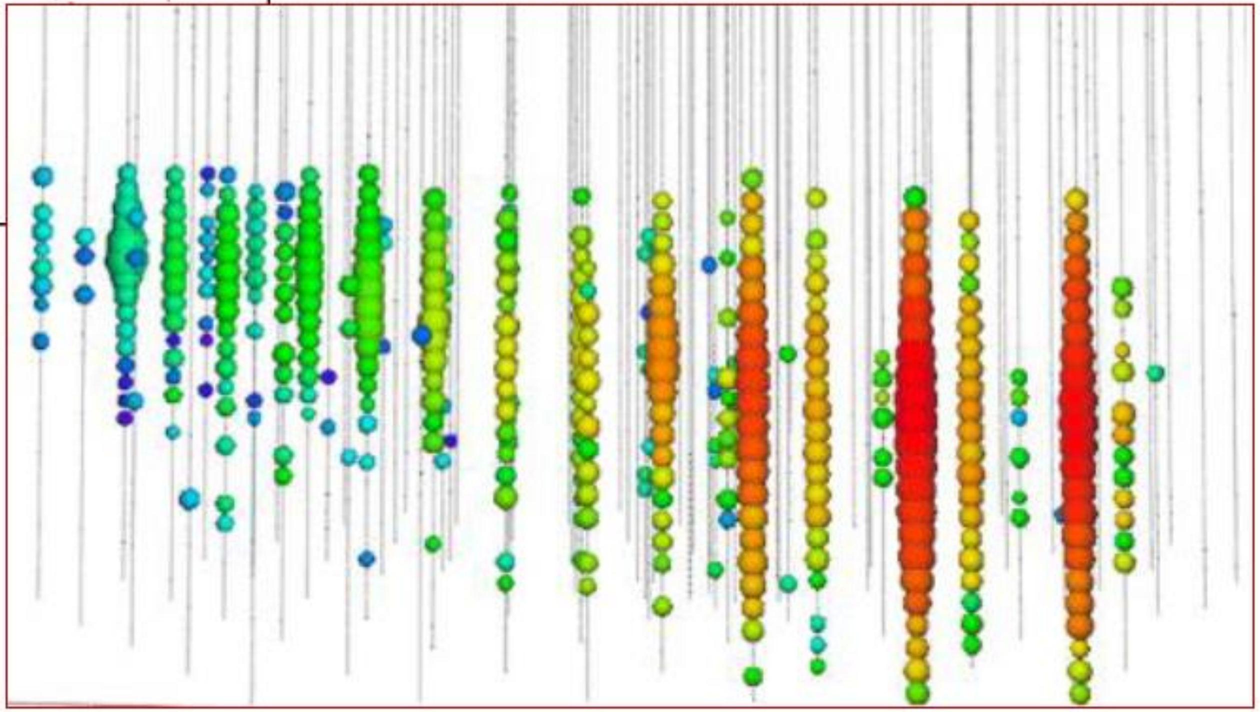
- 86 strings with 60 DOMs instrumenting 1km^3
- Deep Core : dense core for atmospheric neutrino physics at 10-100 GeV
- Operational since 2011

探测事例显示

GeV events in DeepCore for ν oscillations

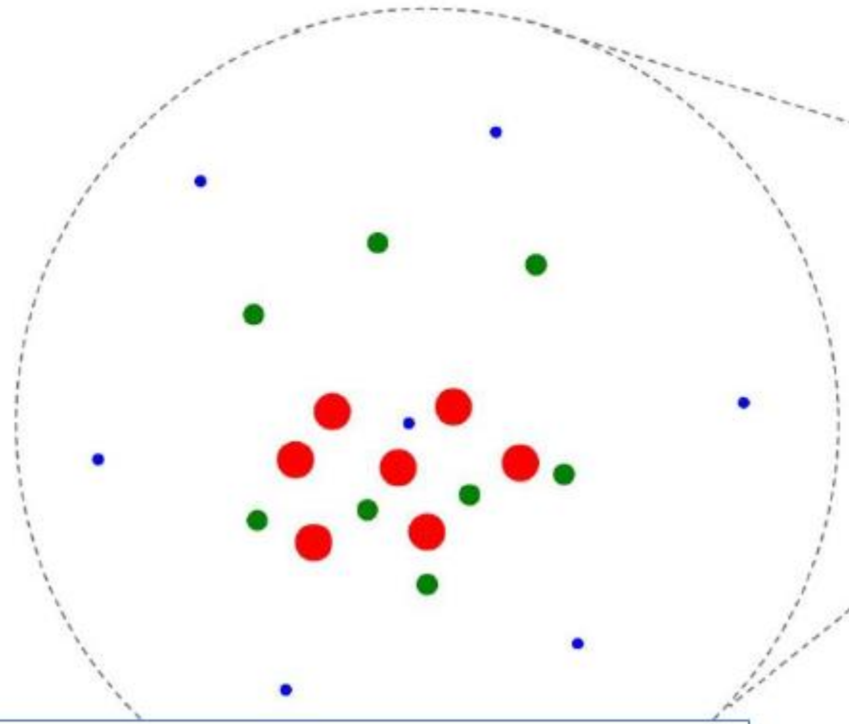


Color indicates time (red=early, blue=late).
Sphere size is proportional to number of photons observed.

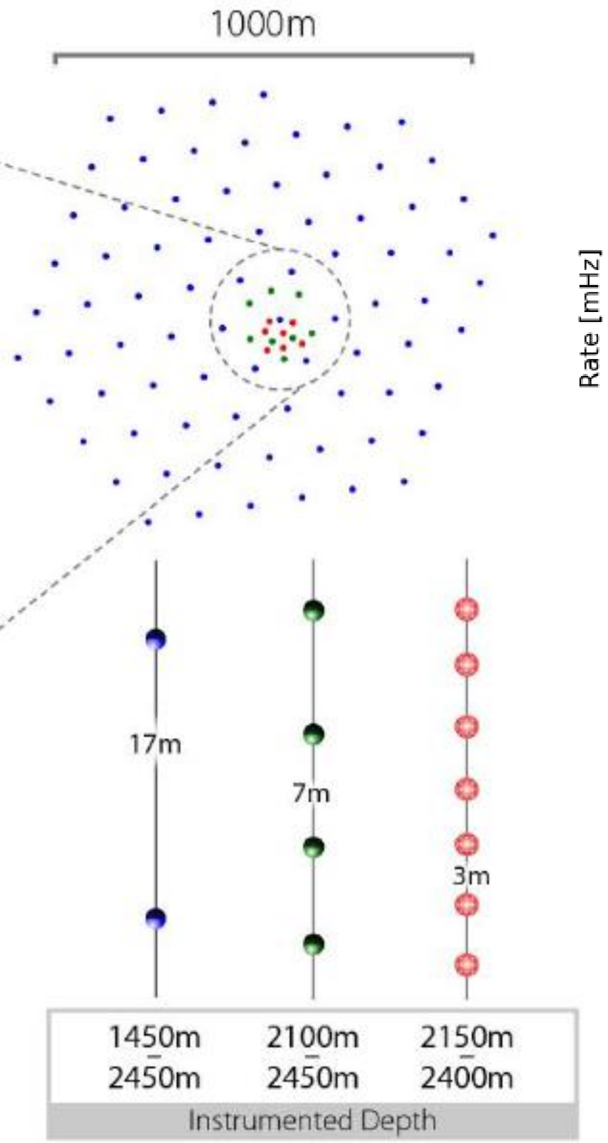


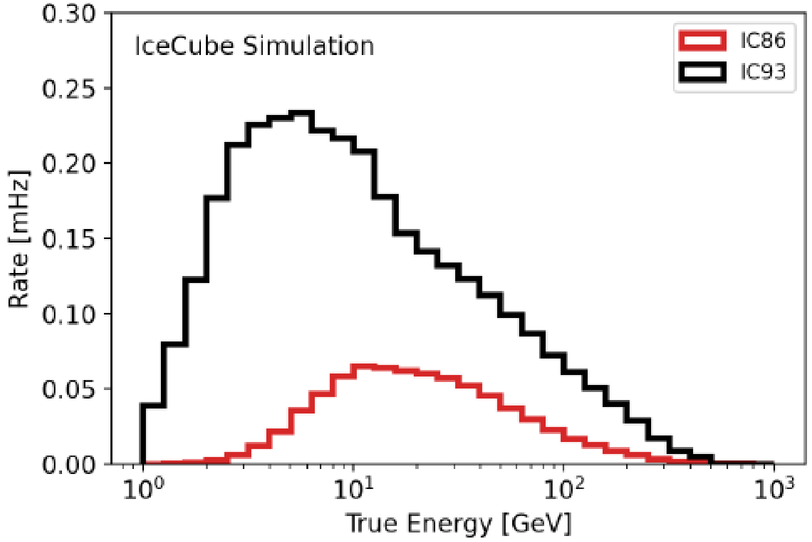
TeV event in IceCube for sterile ν searches

IceCube-upgrade

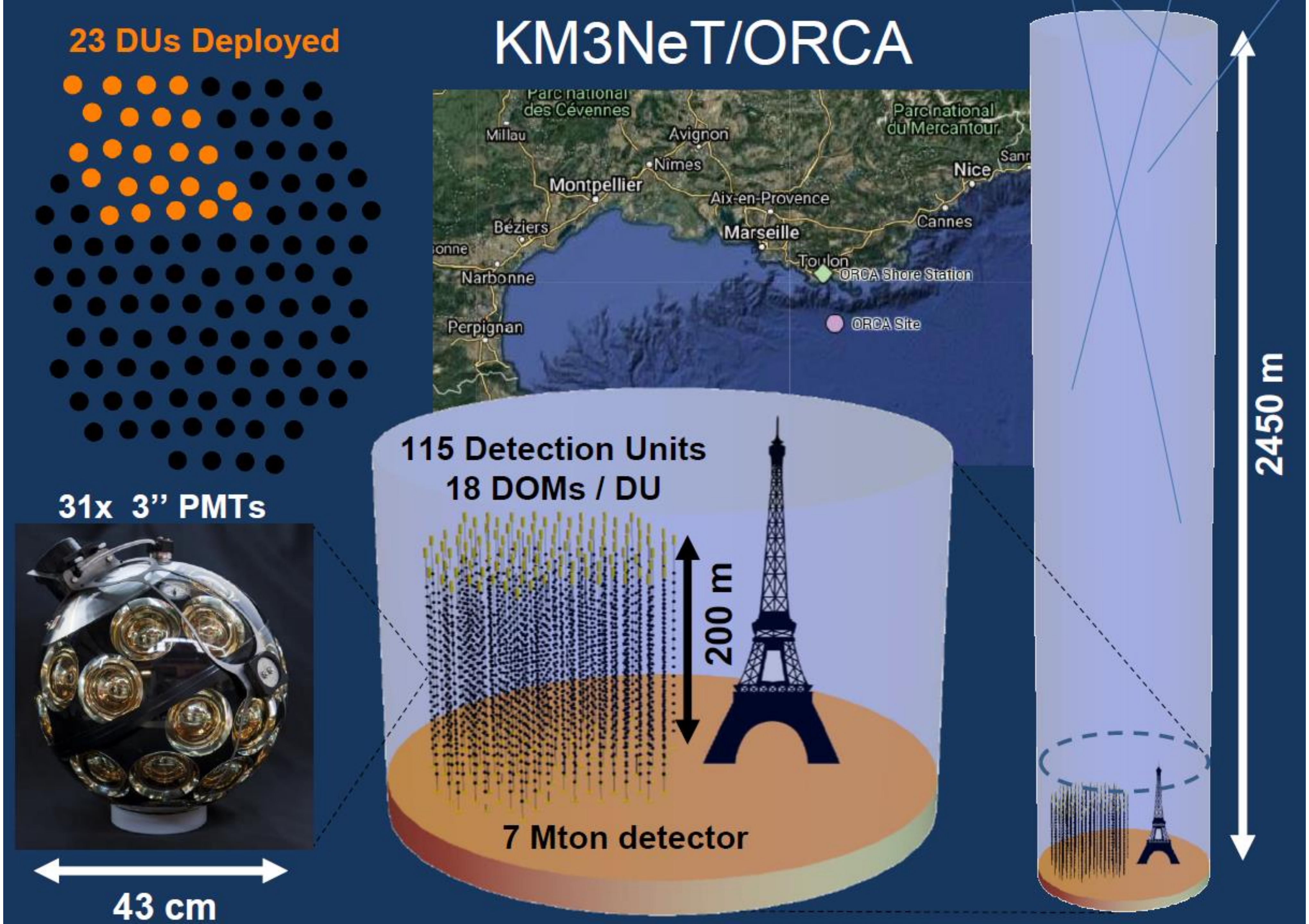


Fully funded (NSF+partners)
Deployment to occur 2025-2026



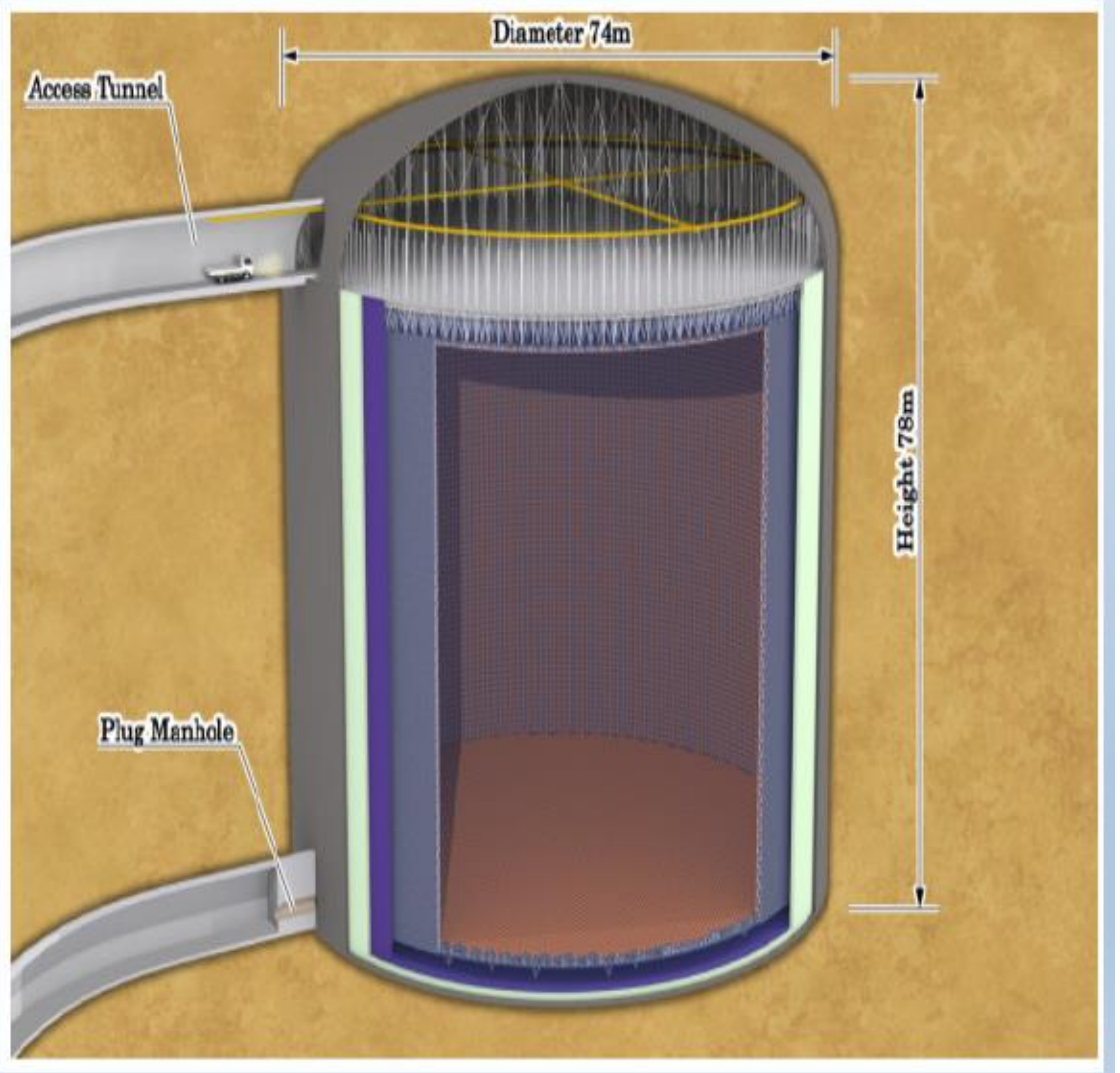


KM3NeT/ORCA

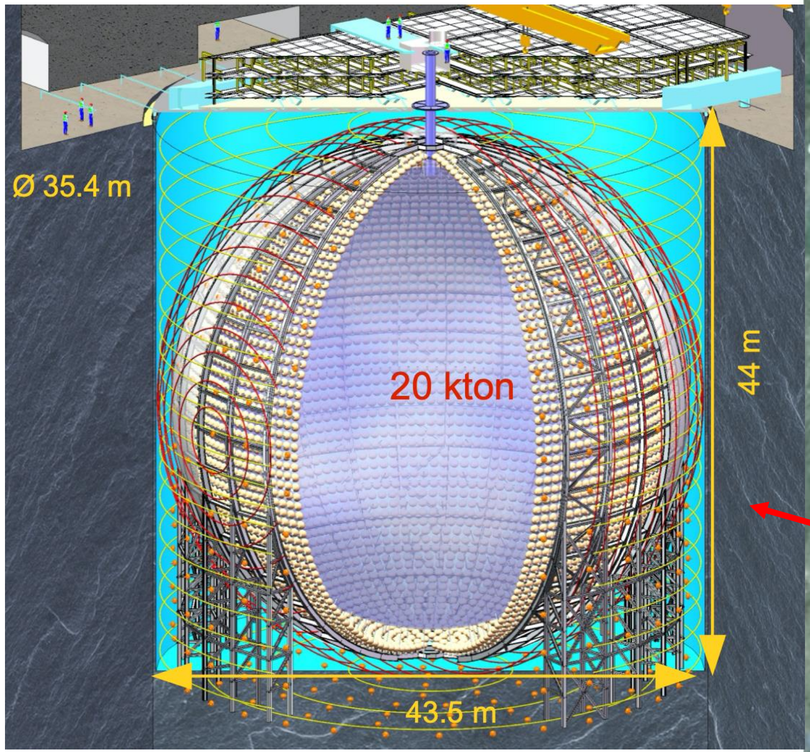

23 DUs Deployed
Parc national des Cévennes
Millau
Avignon
Nîmes
Montpellier
Aix-en-Provence
Béziers
Marseille
Narbonne
Perpignan
Toulon
ORCA Shore Station
ORCA Site
Parc national du Mercantour
Nice
Cannes
115 Detection Units
18 DOMs / DU
200 m
7 Mton detector
31x 3'' PMTs
43 cm
2450 m

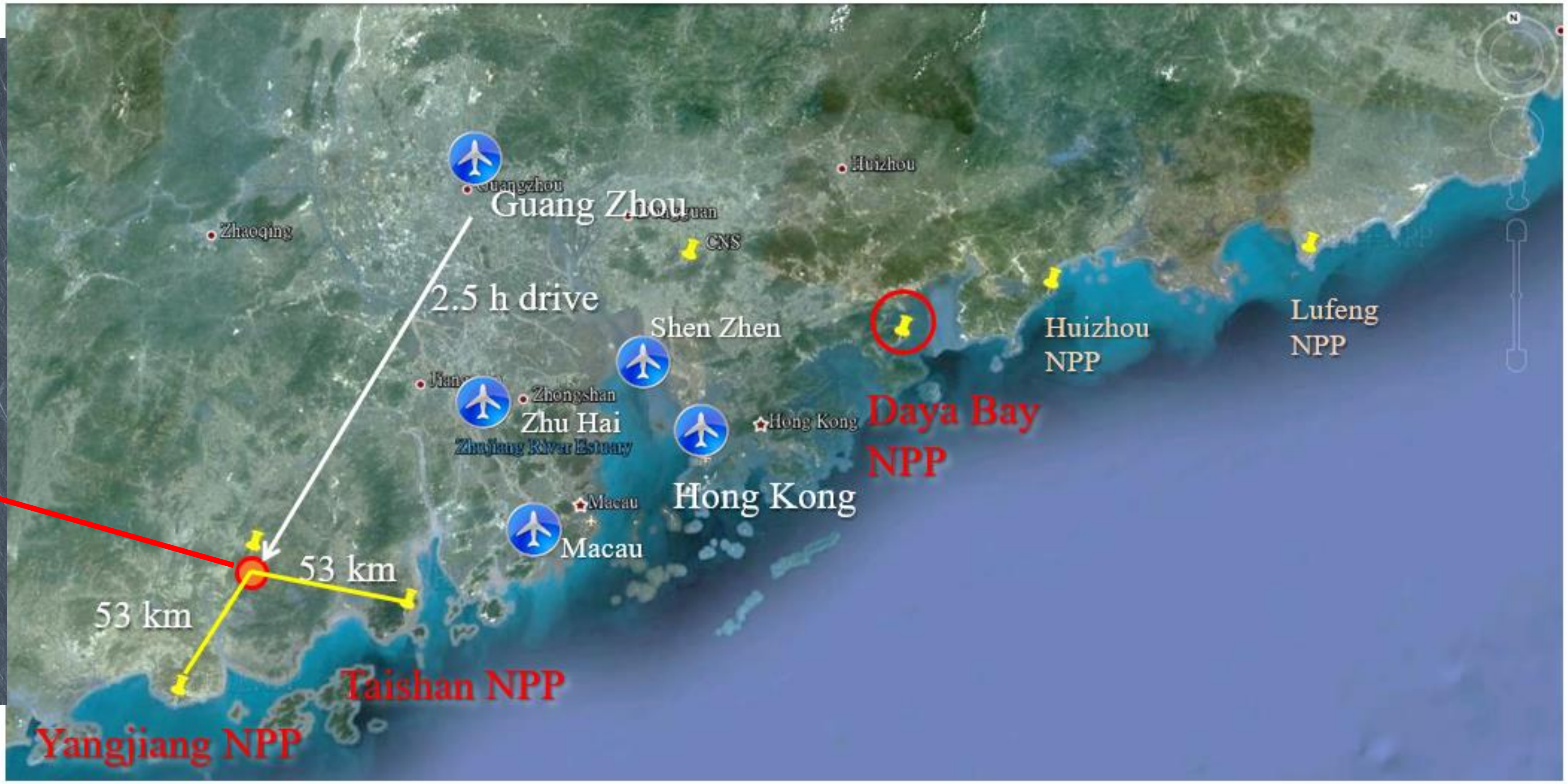
Hyper-Kamiokande

- 258 kton of water
- Fiducial volume ~0.2 Mton
- 20,000 50cm PMTs
- Data taking start planned for 2027



JUNO





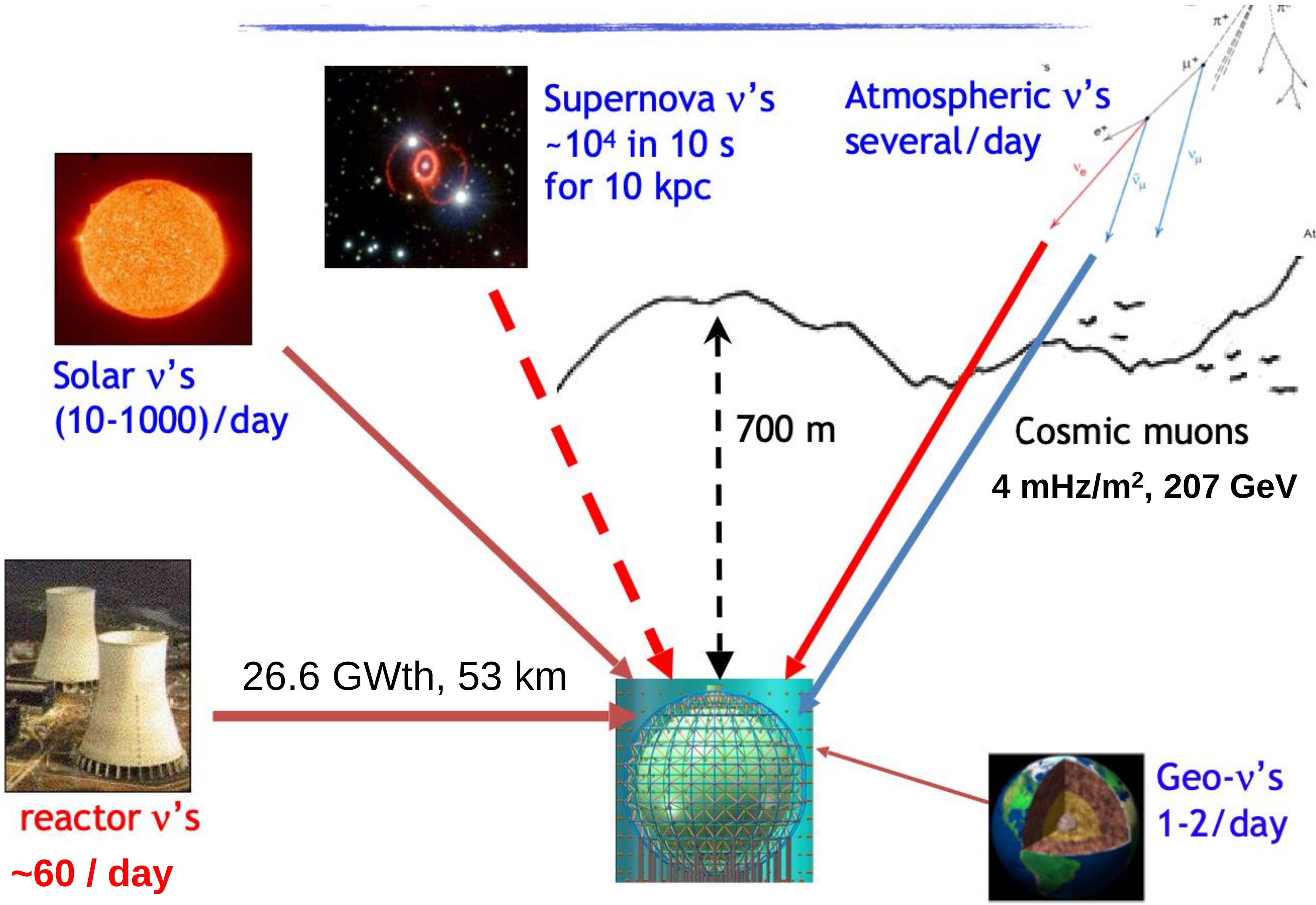
Largest ever LS detector

- 20 kton LS
- 78% photo-coverage
- Designed for low radioactivity background

Jiangmen Underground Neutrino Observatory (JUNO)

- Location optimized for neutrino mass ordering with reactor-ν
- 700m rock overburden to suppress muon flux
- Expected to finish detector construction in 2023

A Multipurpose Neutrino Observatory

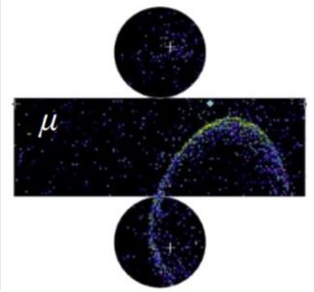


Primary physics goal
- NMO with reactor ν
- Precision meas. of osc. parameters

Rich program of non-oscillation physics:
- Solar ν
- Supernova ν
- Atmospheric ν
- Geo-ν
- Nucleon decays
- Indirect DM search
- …

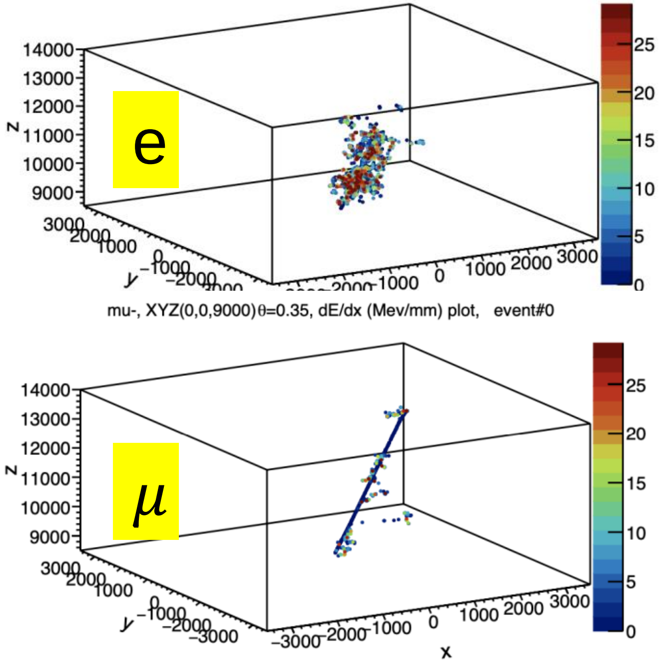
From J. Pedro Ochoa-Ricoux

Atm-ν with large homogenous LS detector

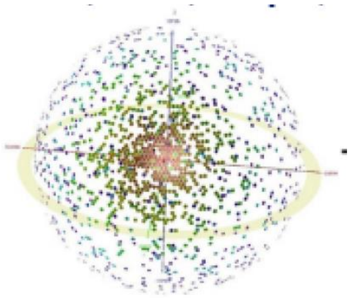
	Cherenkov detector	LS detector
Pros	Cherenkov ring 	Low E threshold High n-tagging efficiency

large homogenous LS detector like JUNO
→ good potential to reconstruct atm-ν

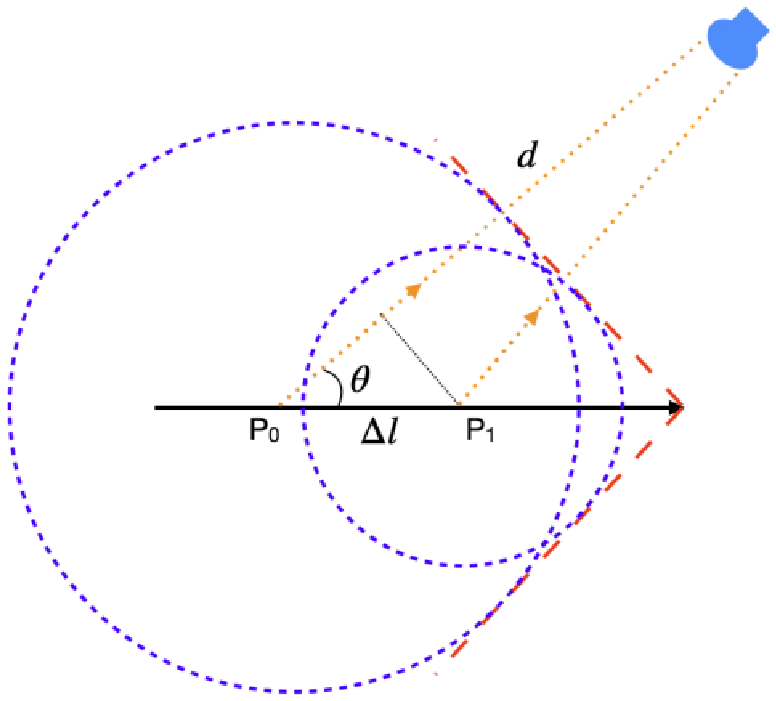
- ✓ Large photo-coverage → image for μ vs e, ν vs $\bar{\nu}$
- ✓ Hadronic information visible → better E/θ rec for $\boldsymbol{\nu}$ (instead of $l^{\pm}$)
- ✓ Excellent neutron tagging → ν vs $\bar{\nu}$
- ✓ Final state isotopes identifiable → measure exclusive channels

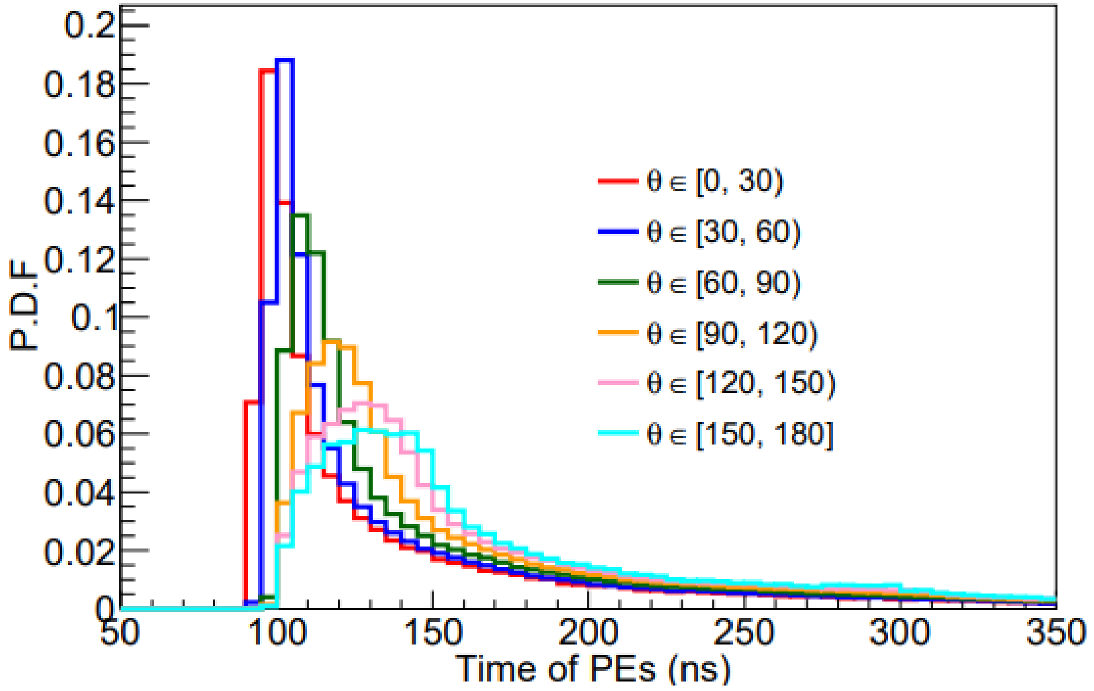


ML models



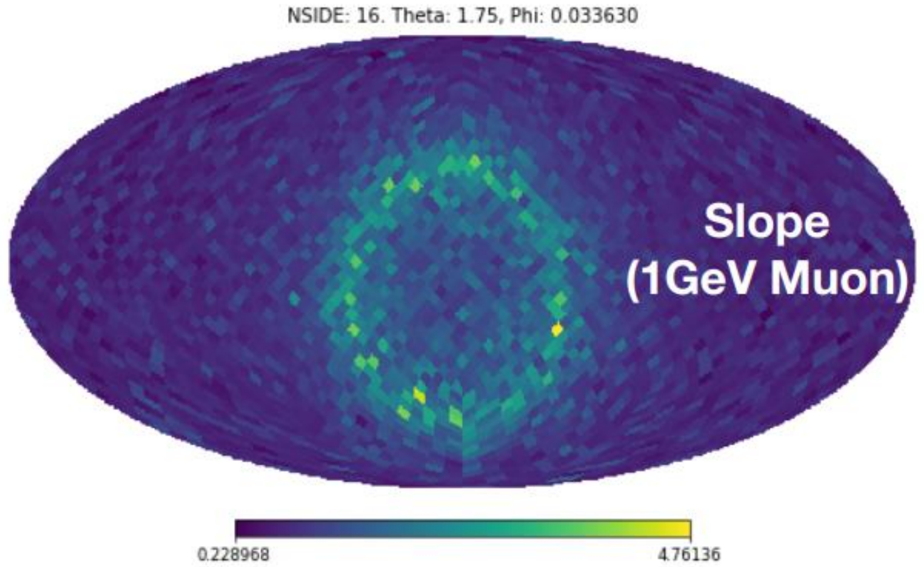
How?

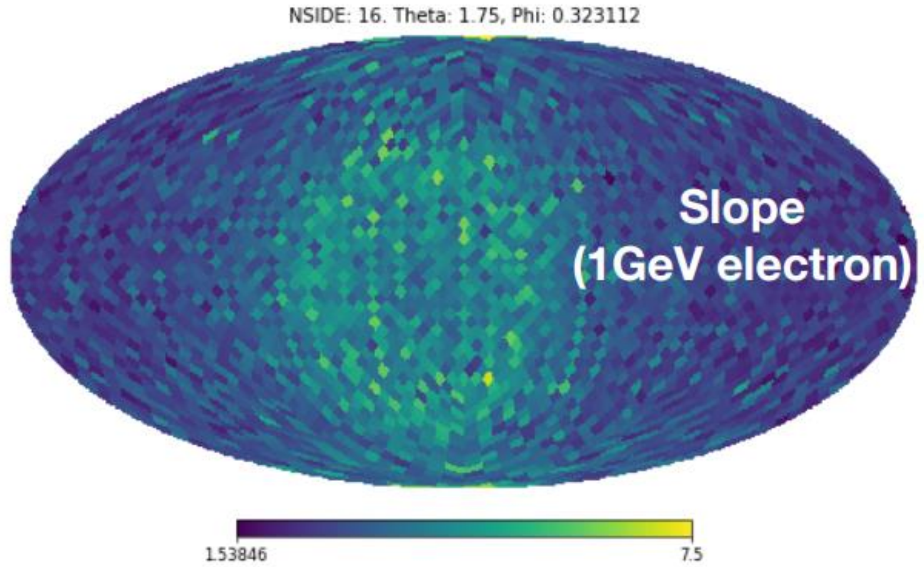




- Scintillation light is isotropic from point sources
- Light from a long track is not
- Hit time distribution is different for PMTs at different angles w.r.t. the track
  - Embedded information on direction, vertex, energy, PID …

Particle Identification μ vs e

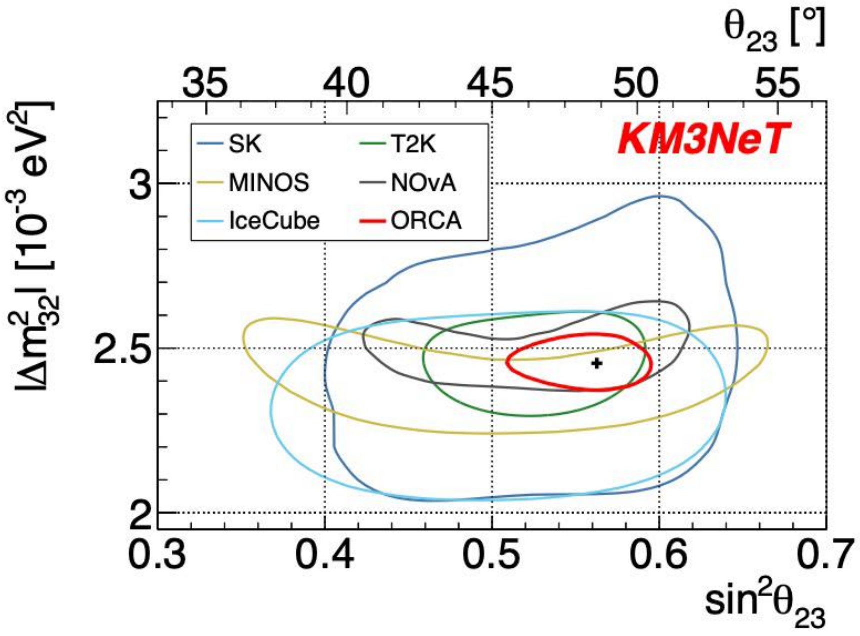


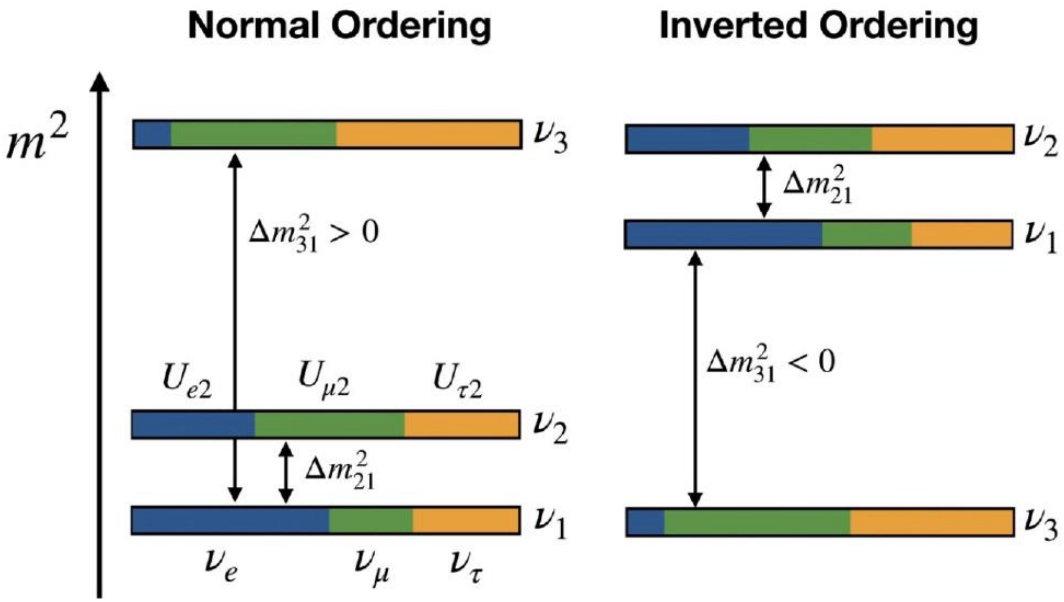


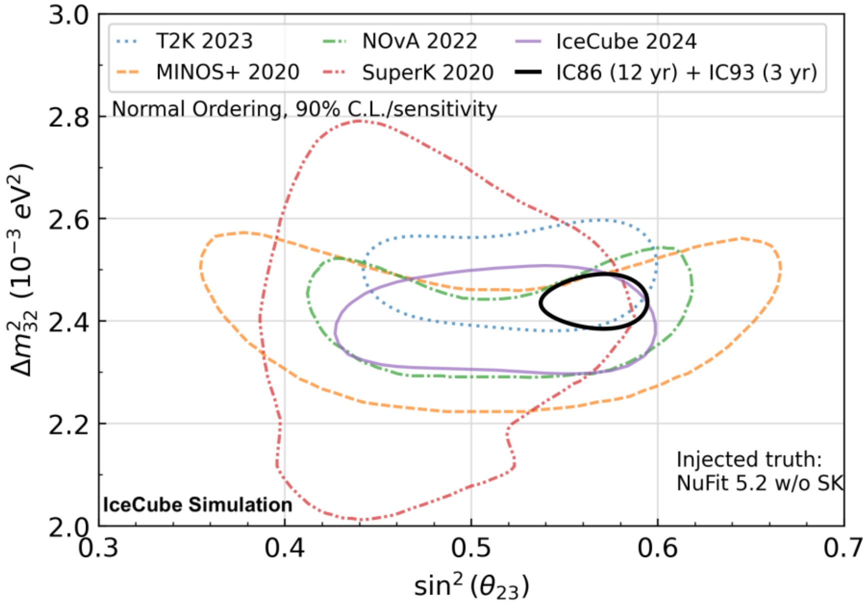
- PMT pattern of slope feature show a ring like pattern for track event

大气中微子实验展望

- 精确测量Δm^2_{31}, θ_{23}
- 质量顺序
- ν_τ反应截面
- …







总结展望

- 对质子衰变实验的本底研究，发现了大气中微子反常
- 对大气中微子反常的研究导致中微子振荡的发现
- 对大气中微子的研究将继续帮助理解中微子的基本性质