大气中微子

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2021.8.22

提纲

一. 大气中微子的产生

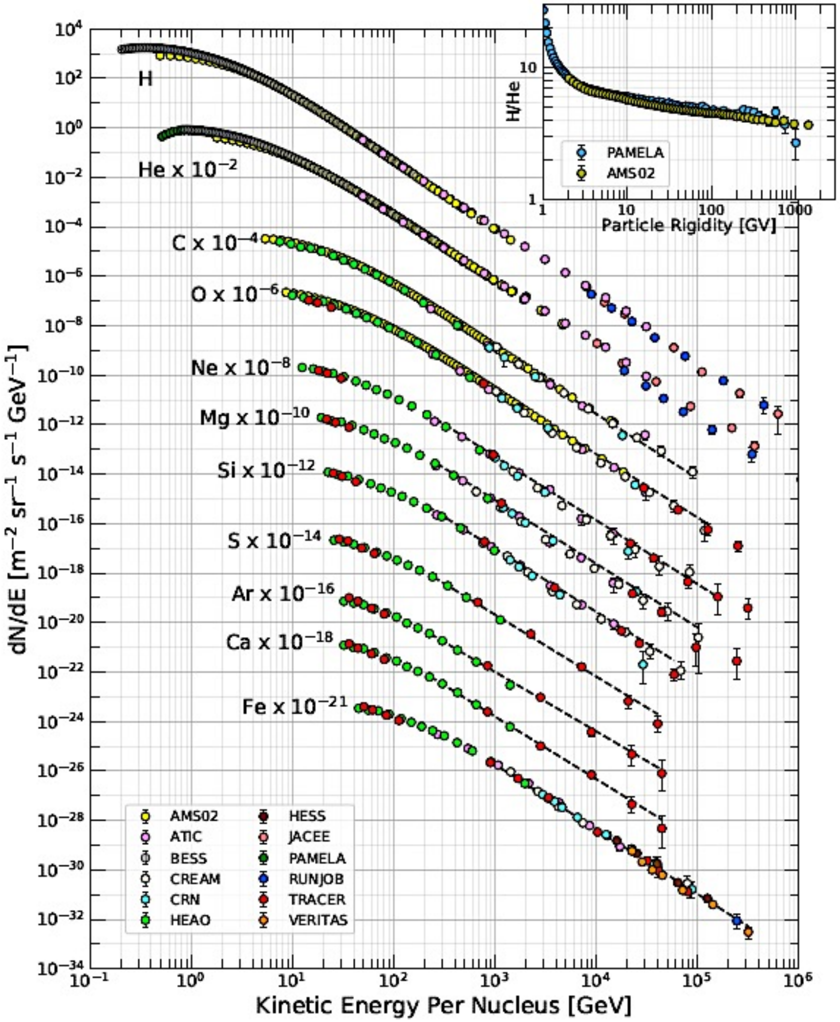
二. 大气中微子实验

三. 大气中微子反常及振荡

四. 总结与展望

一、大气中微子的产生

地球以外的太空并不是真空无物，空间中除了有看不见的“暗物质”和中微子，还有大量由氢、氦、碳与铁等核素构成的原初宇宙线粒子。



原初宇宙线与大气层中的原子核碰撞，产生大量的$\pi^{\pm}$和π^{0}，以及少量的$K^{\pm}$和$K^{0}/\overline{K^{0}}$。

$\boxed{c\tau_{\pi}\sim 7.8\ \mathrm{m}}$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

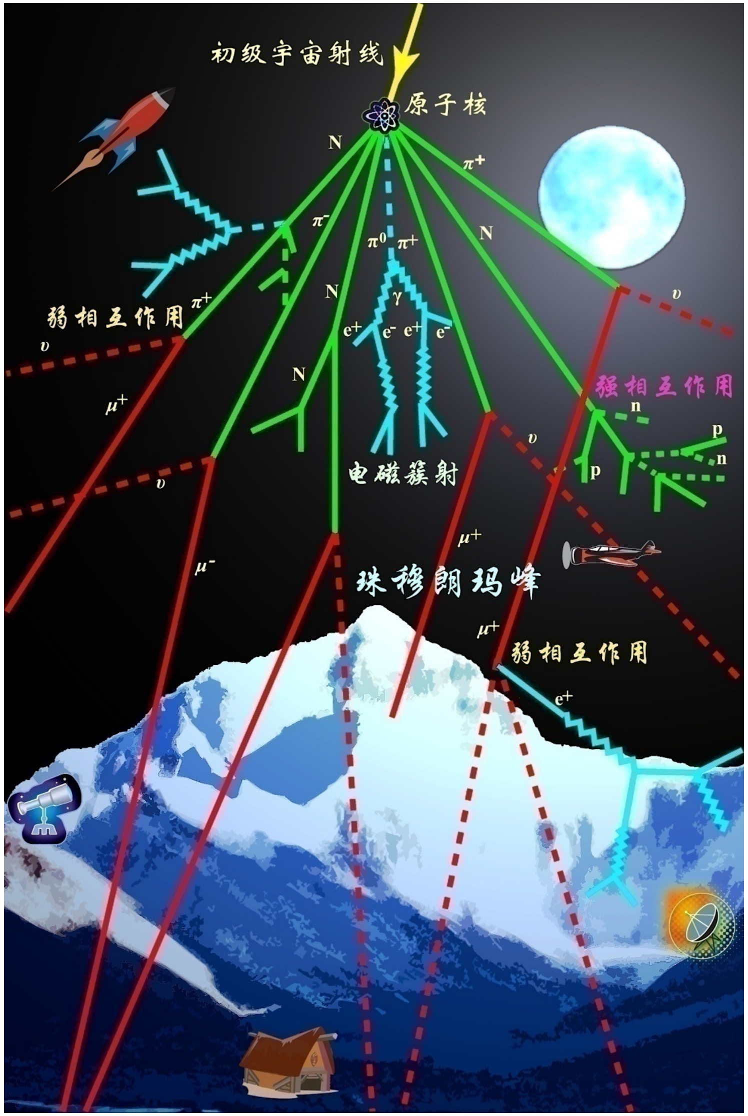
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

$\boxed{c\tau_{K}\sim 3.7\ \mathrm{m}}$

$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \qquad \sim 64\%$$

$$\rightarrow \pi^{\pm} + \pi^{0}{}'s \qquad \sim 22\%$$

$$K_{s}^{0} \rightarrow \pi^{+} + \pi^{-} \qquad \sim 69\%$$



因此，大气中微子各组分流强的比值具有鲜明的特征

$$\frac{\nu_\mu}{\bar{\nu}_\mu}\sim 1$$

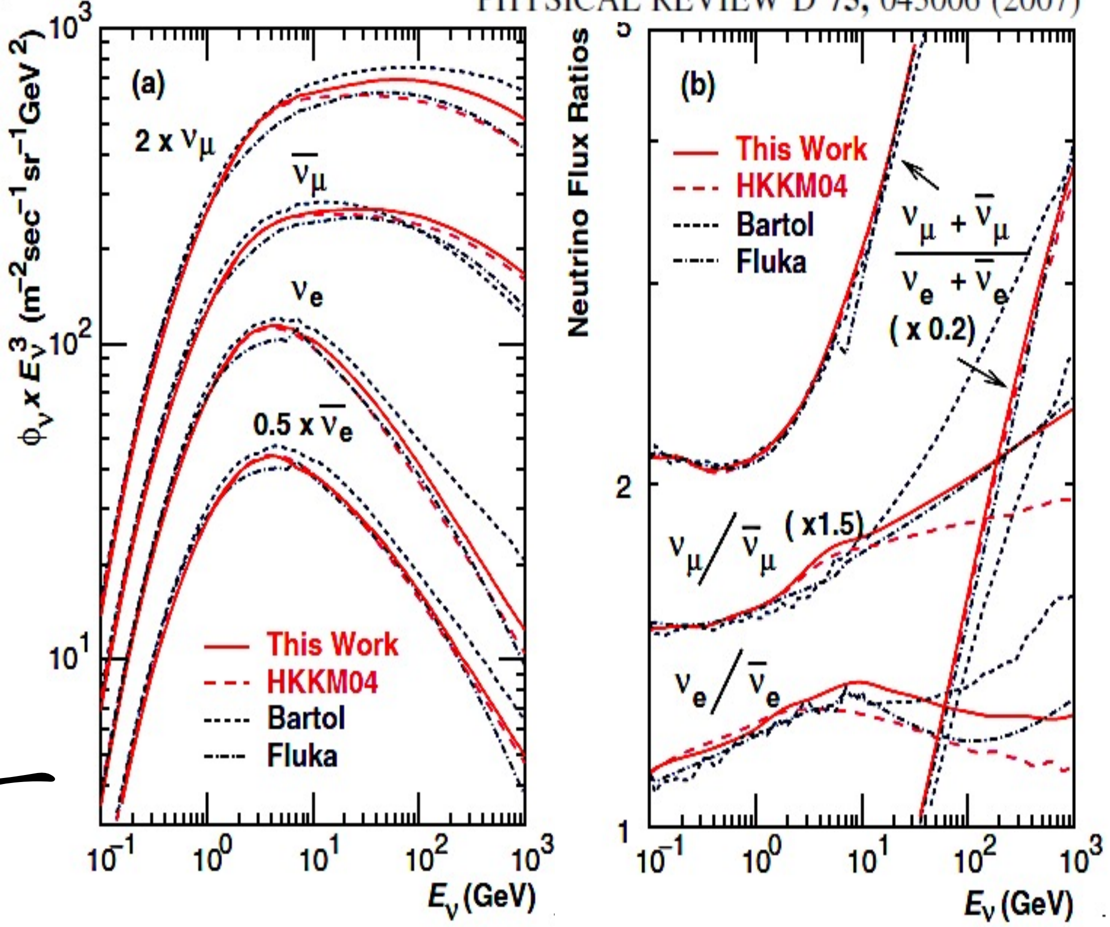
$$\frac{\nu_e}{\bar{\nu}_e}\sim\frac{\mu^+}{\mu^-}$$

几个 GeV 以下

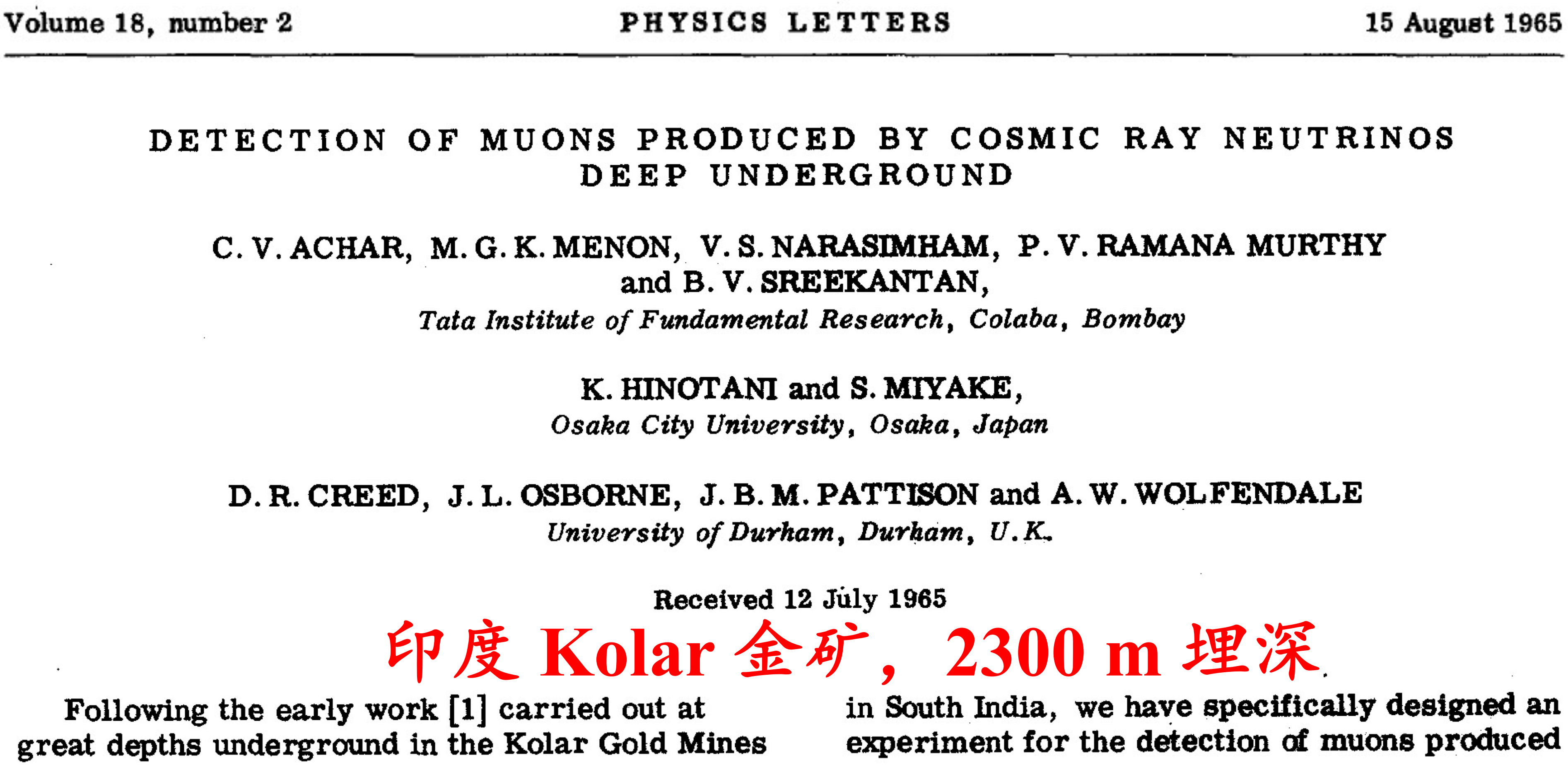
$$\frac{\Phi(\nu_\mu+\bar{\nu}_\mu)}{\Phi(\nu_e+\bar{\nu}_e)}\approx 2$$

除非 μ 不衰变一直到地面。

PHYSICAL REVIEW D **75**, 043006 (2007)



最早研究大气中微子的实验（1960’s）



Volume 18, number 2 PHYSICS LETTERS 15 August 1965

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINOS DEEP UNDERGROUND

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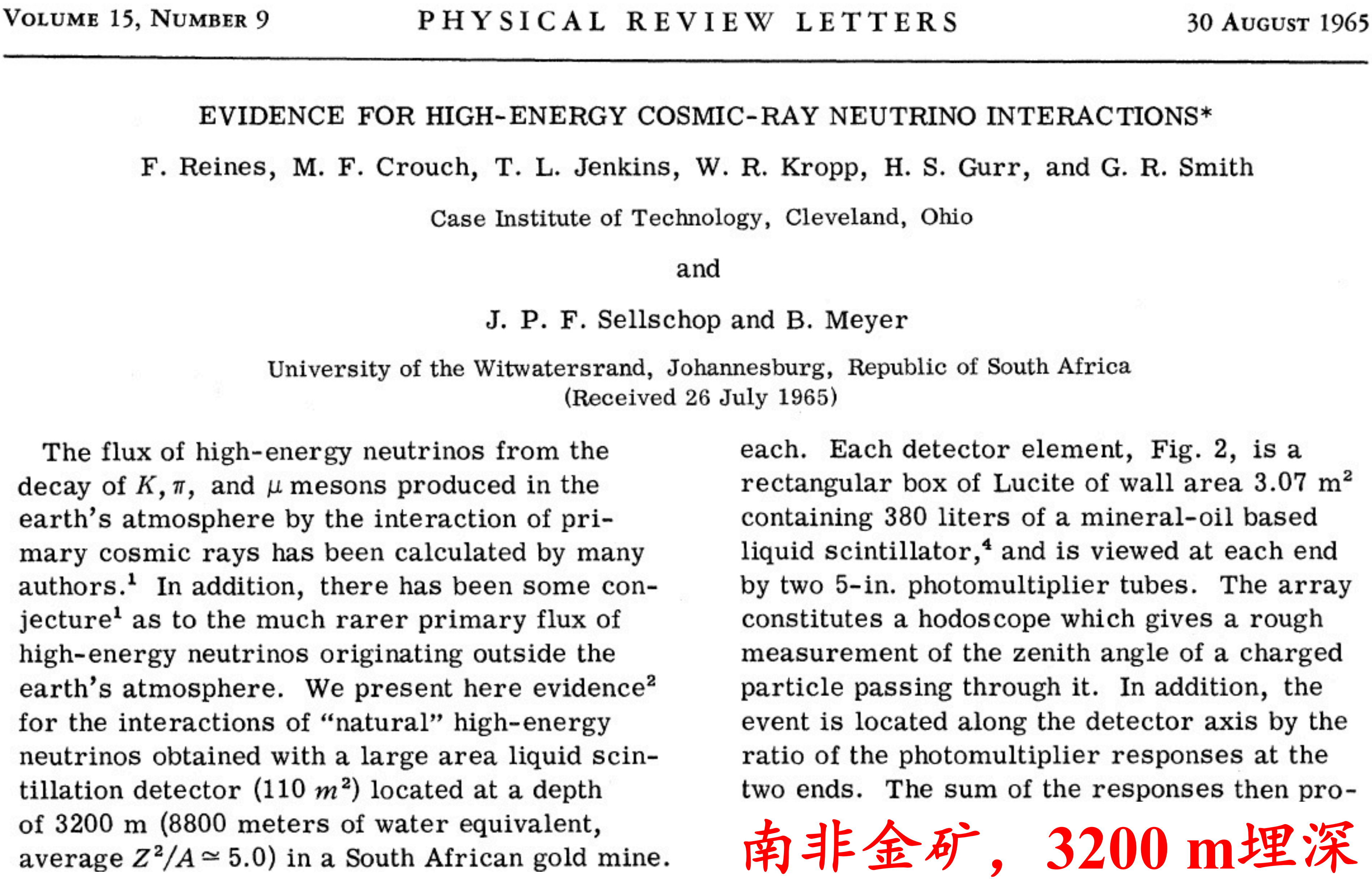
Received 12 July 1965

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



VOLUME 15, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1965

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

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University of the Witwatersrand, Johannesburg, Republic of South Africa

(Received 26 July 1965)

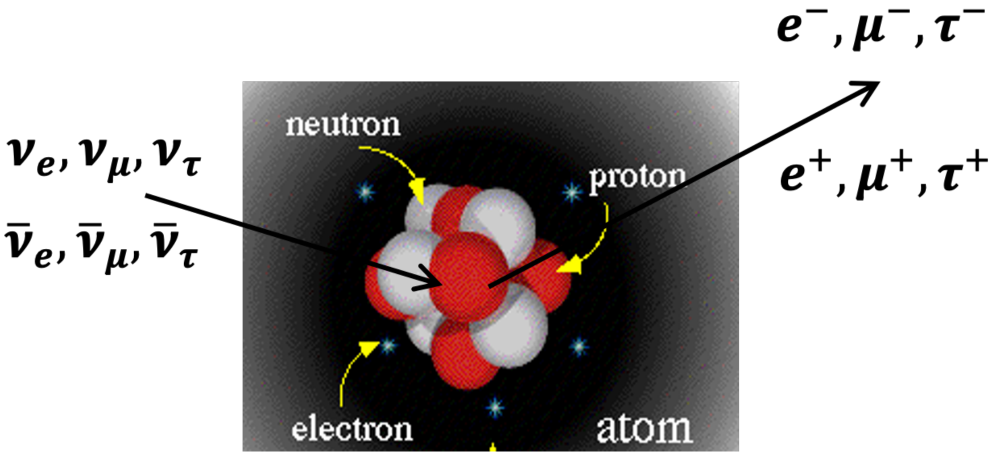
The flux of high-energy neutrinos from the decay of K, π, and μ mesons produced in the earth's atmosphere by the interaction of primary cosmic rays has been calculated by many authors.[1] In addition, there has been some conjecture[1] as to the much rarer primary flux of high-energy neutrinos originating 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

问题：为什么要到地下？

大气中微子中微子只能“间接”看见。

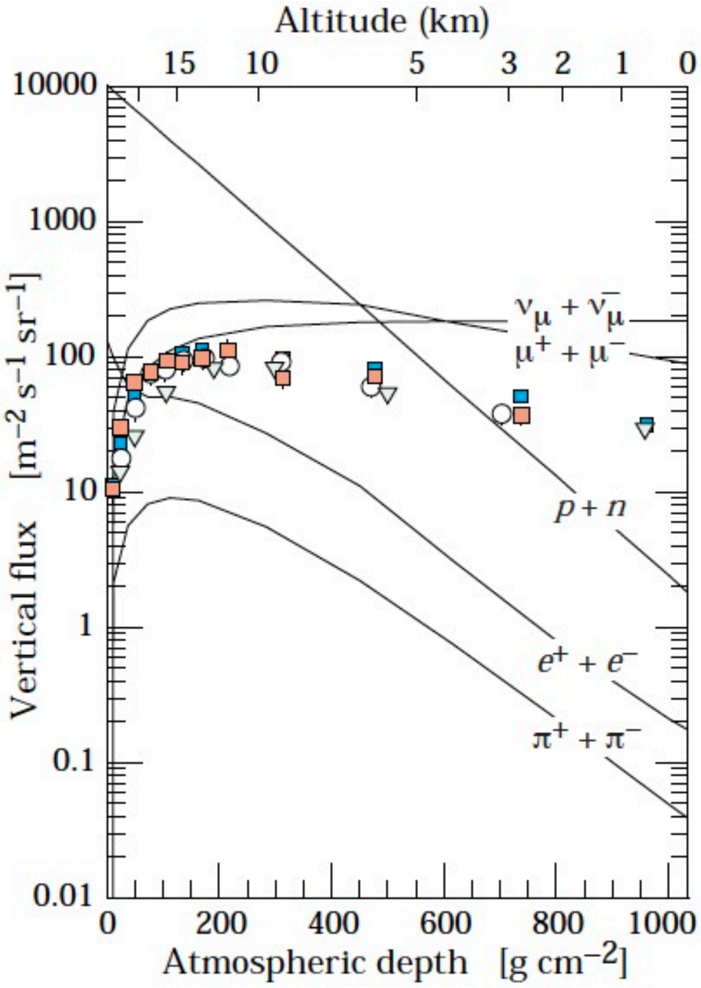


ν_e, ν_μ, ν_τ

$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

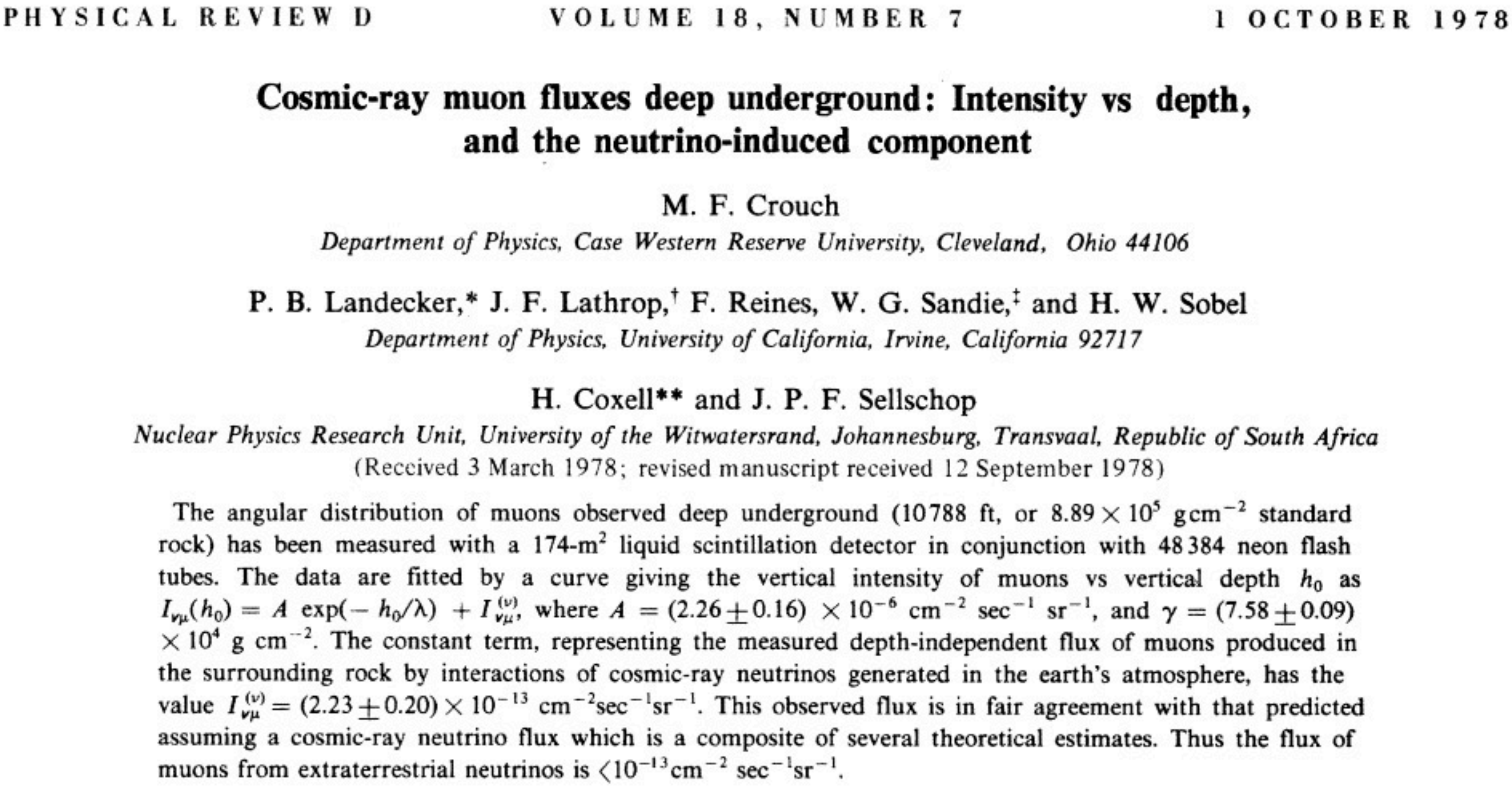
e^-, μ^-, τ^-

e^+, μ^+, τ^+



末态粒子与宇宙线本底非常相同。

最早观察到大气 μ中微子的实验（1970’s）



PHYSICAL REVIEW D VOLUME 18, NUMBER 7 1 OCTOBER 1978

Cosmic-ray muon fluxes deep underground: Intensity vs depth, and the neutrino-induced component

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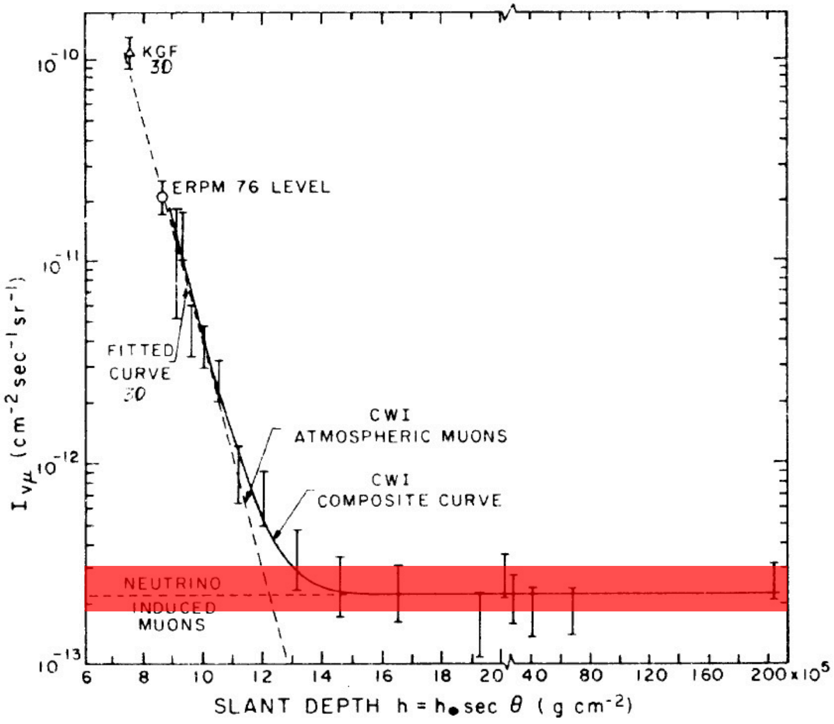
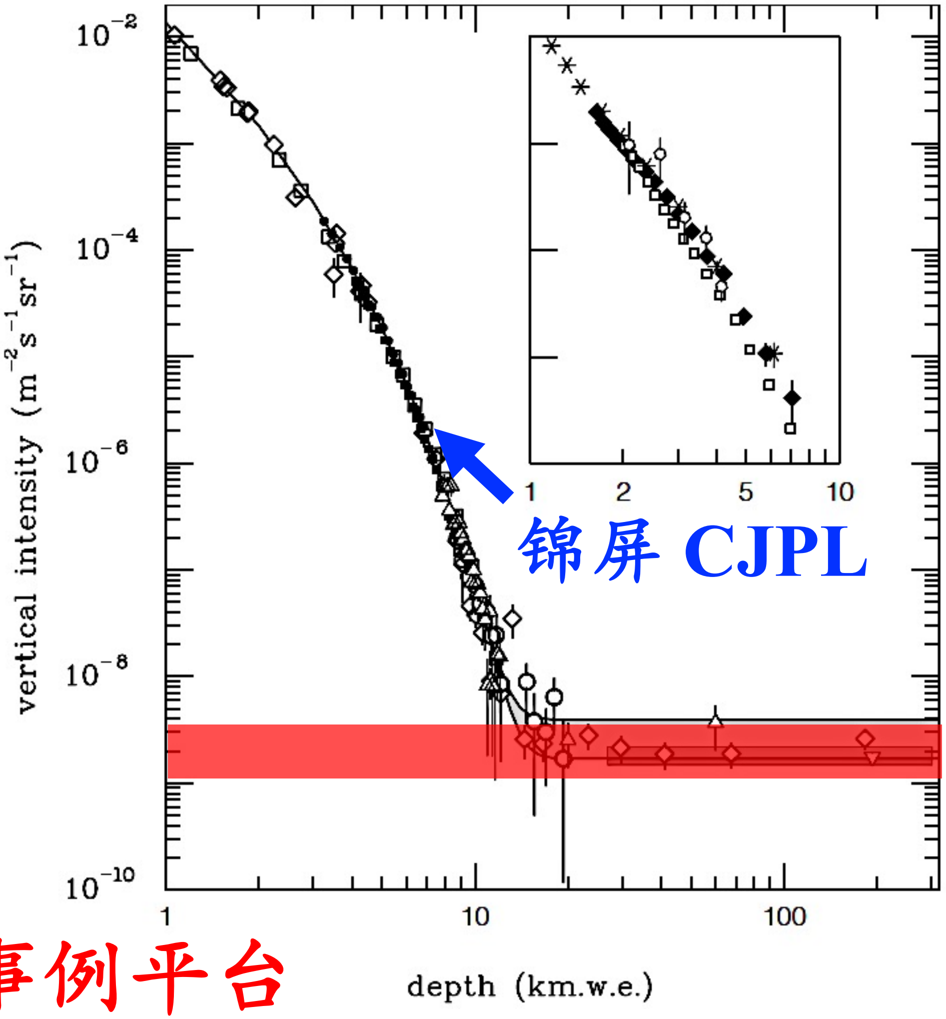
(Received 3 March 1978; revised manuscript received 12 September 1978)

The angular distribution of muons observed deep underground (10788 ft, or 8.89×10^5 g cm^{-2} standard rock) has been measured with a 174-m^2 liquid scintillation detector in conjunction with 48384 neon flash tubes. The data are fitted by a curve giving the vertical intensity of muons vs vertical depth h_0 as $I_{\nu\mu}(h_0)=A\exp(-h_0/\lambda)+I_{\nu\mu}^{(\nu)}$, where $A=(2.26\pm0.16)\times10^{-6}$ cm^{-2} sec^{-1} sr^{-1}, and $\gamma=(7.58\pm0.09)\times10^4$ g cm^{-2}. The constant term, representing the measured depth-independent flux of muons produced in the surrounding rock by interactions of cosmic-ray neutrinos generated in the earth's atmosphere, has the value $I_{\nu\mu}^{(\nu)}=(2.23\pm0.20)\times10^{-13}$ cm^{-2}sec^{-1}sr^{-1}. This observed flux is in fair agreement with that predicted assuming a cosmic-ray neutrino flux which is a composite of several theoretical estimates. Thus the flux of muons from extraterrestrial neutrinos is $<10^{-13}$cm^{-2} sec^{-1}sr^{-1}.

Particle Data Group 2020

1978年的南非实验



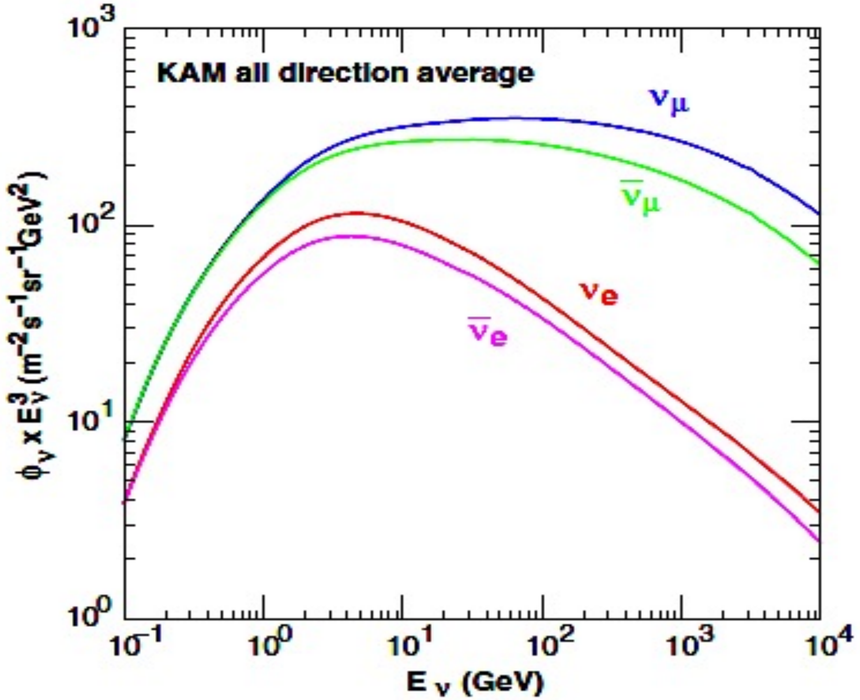


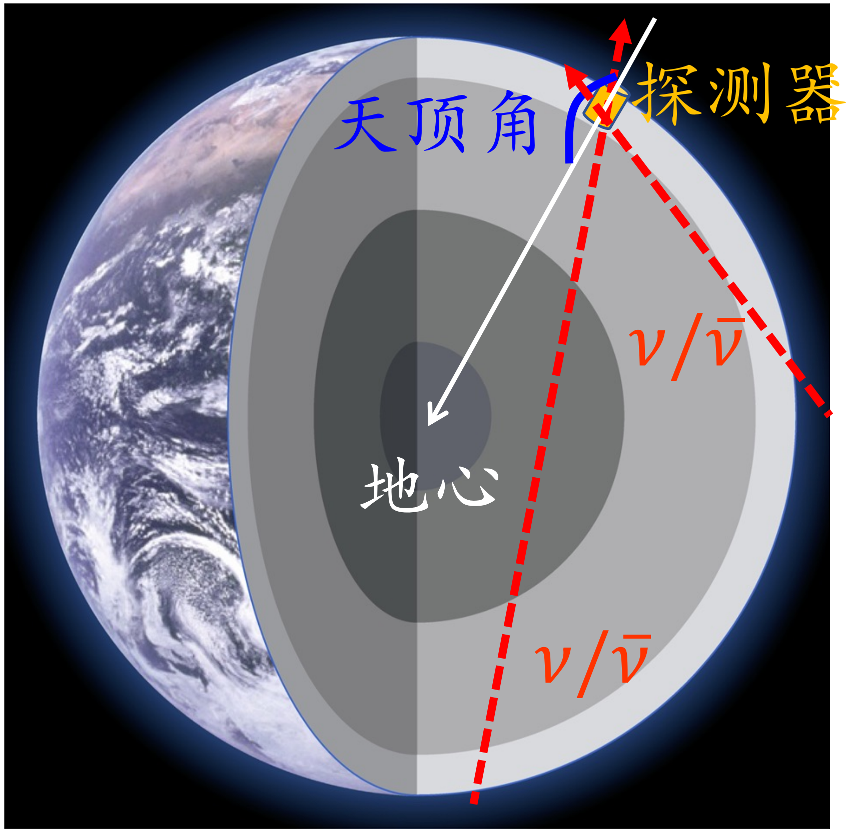
锦屏 CJPL

μ中微子事例平台

问题：为什么选大气中微子？

广谱、多组分、长短基线兼备，而且免费。





KAM LAND

Baseline is limited: 85.3% of signal

has 140 < L < 344 km

People designing future colliders should realize

that it takes....

- ~ 60 GW of electric power or...
- ~ 4% of the world manmade power or...
- ~ 20% of the world nuclear power

to perform this experiment

... and we don't pay a dime !

... smart people !

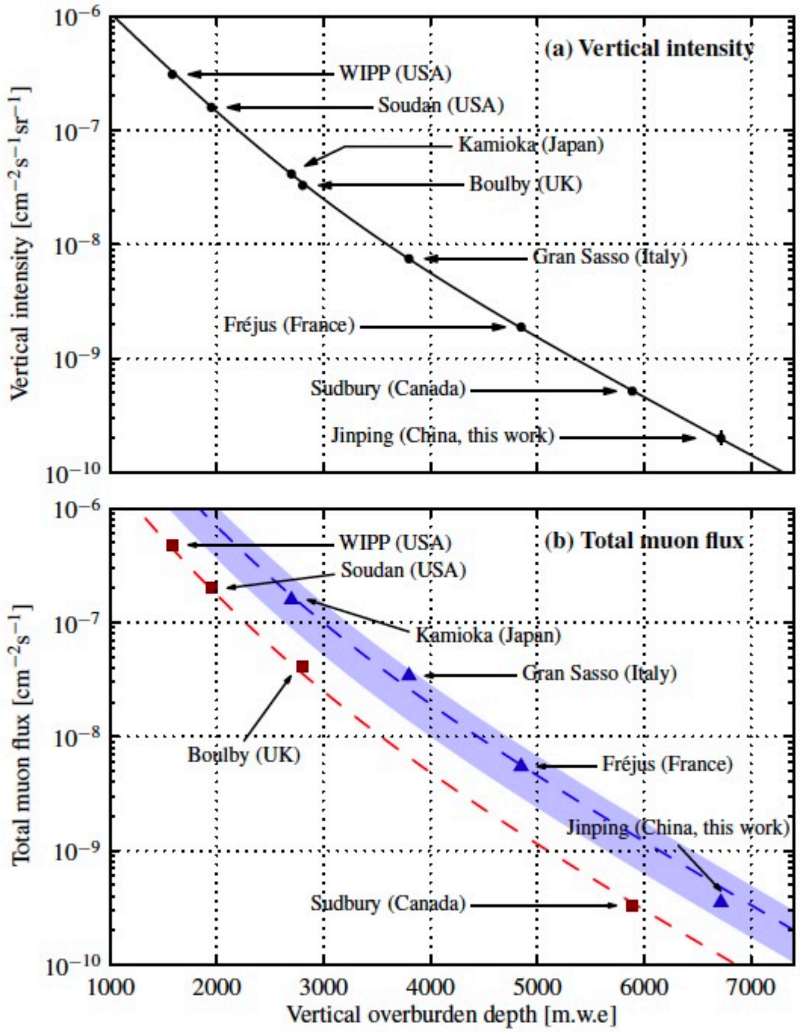
二、大气中微子实验

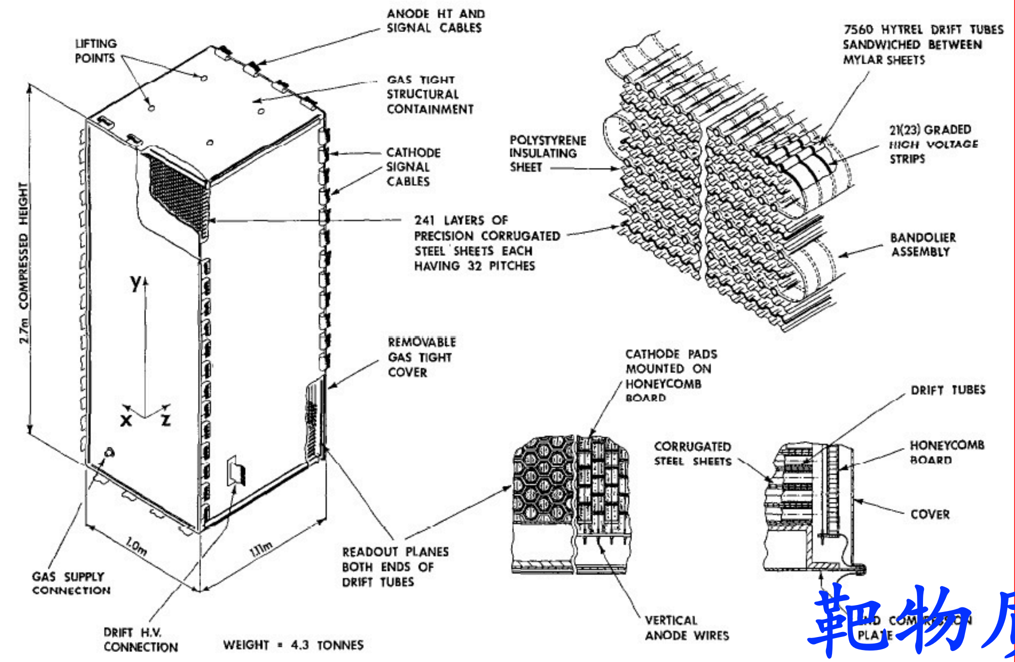
- 径迹量能器
  - Nusex (0.13k 吨铁)
  - Frejus (0.7k 吨铁)
  - Soudan (1k 吨铁)
  - MACRO (5k 吨液体闪烁体)
- 水质切伦科夫实验
  - 神风实验 (1.0k 吨水)
  - IMB 实验 (3.3k 吨水)
  - 超级神风实验 (22.5k 吨水)
  - 顶级神风实验（～500k 吨水）

大气中微子实验所在地

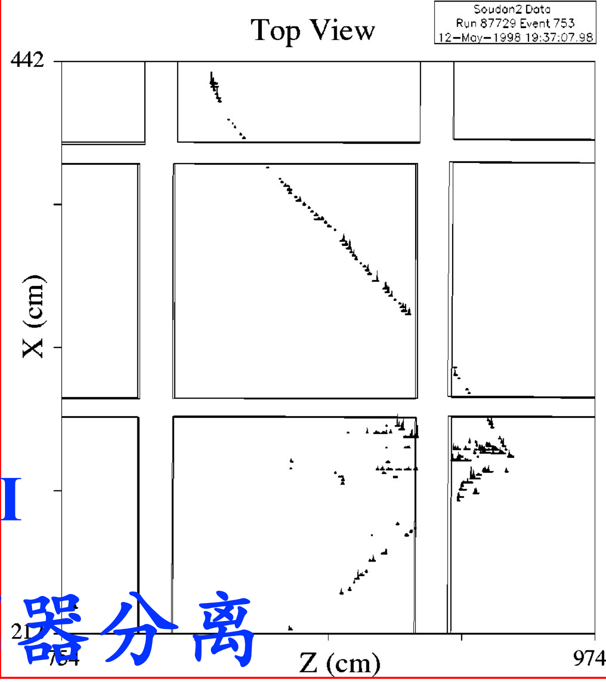
- □ **Kamioka 实验室**
  - ✓ **2700 m.w.e**
- □ **Mortan 盐矿**
  - ✓ **1750 m.w.e**
- □ **Fréjus 实验室**
  - ✓ **4900 m.w.e**
- □ **Soudan 金矿**
  - ✓ **2090 m.w.e**
- □ **Gran Sasso 实验室**
  - ✓ **3800 m.w.e**

Chinese Phys. C 45 025001





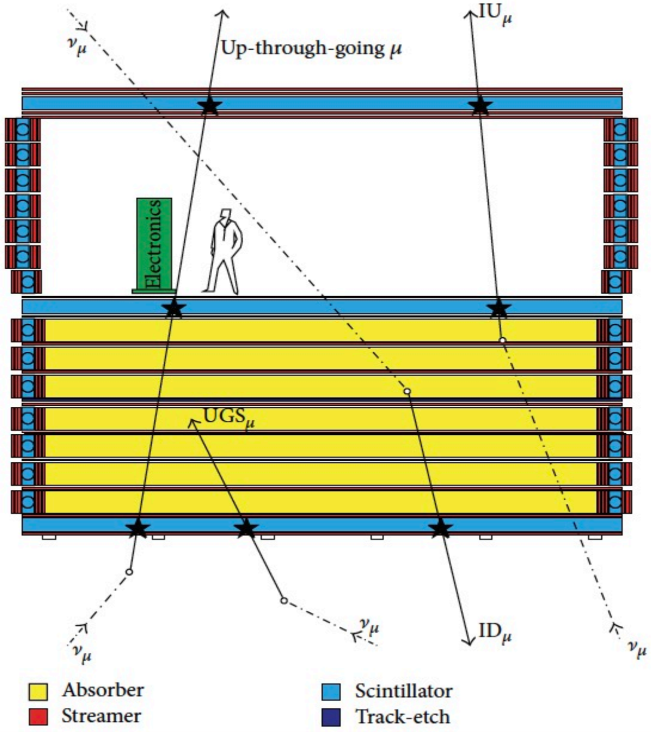
Soudan-II

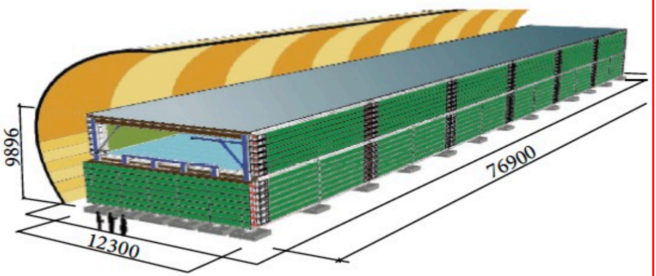


靶物质与探测器分离

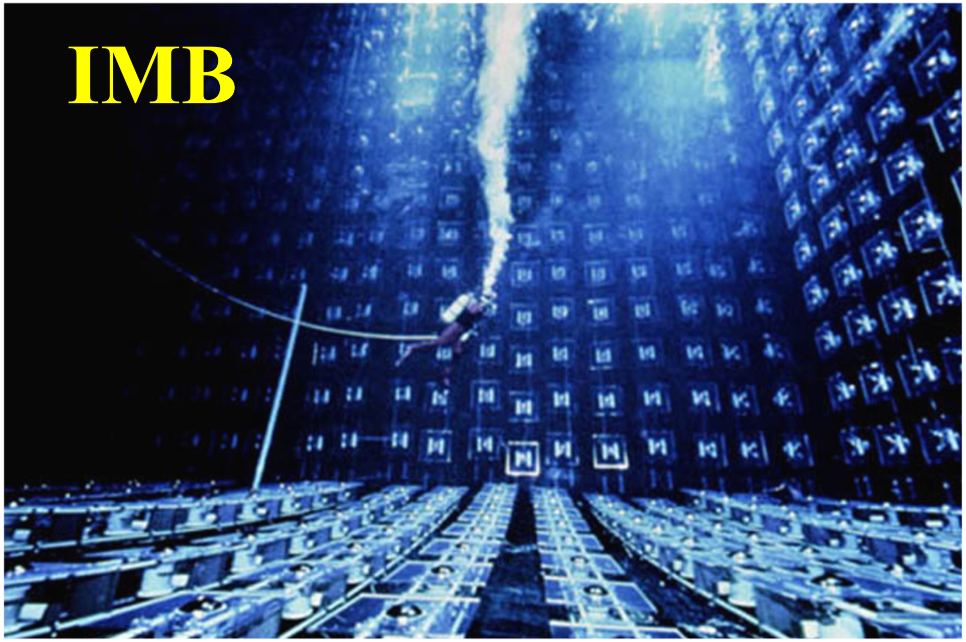
MACRO

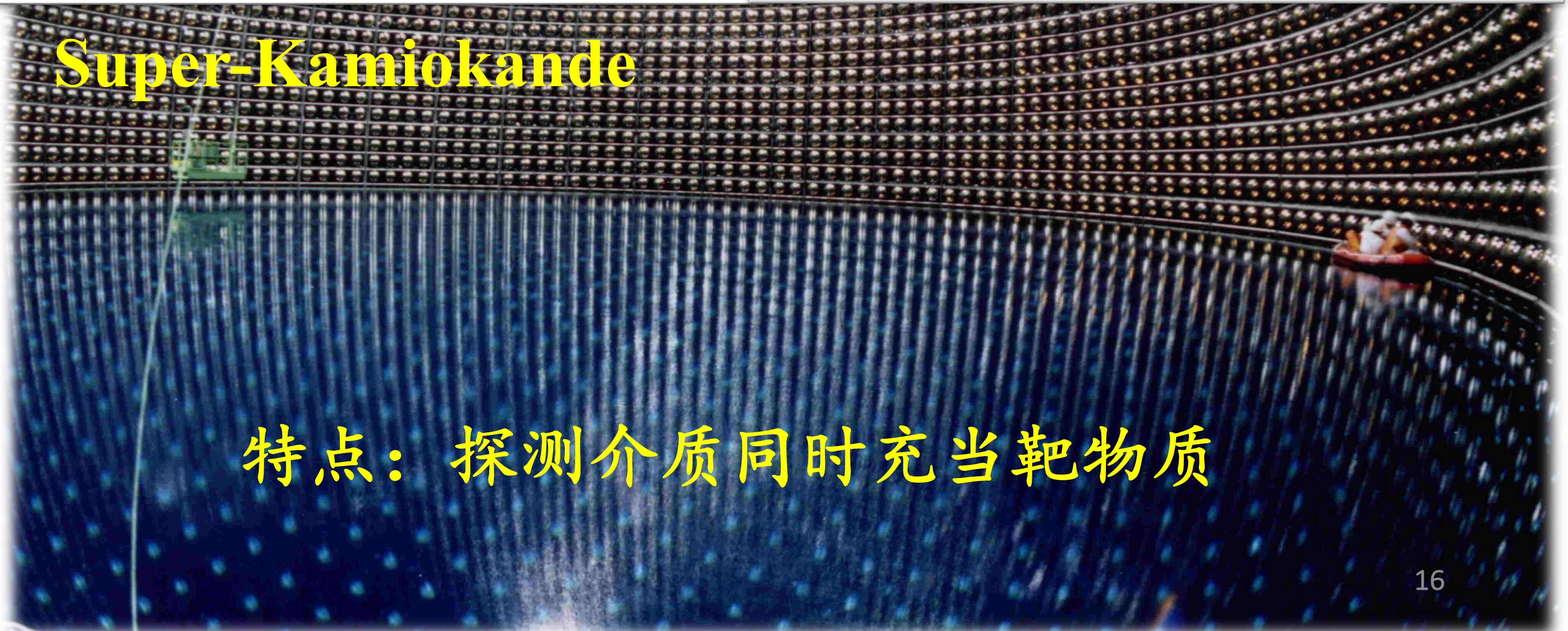
靶物质与探测器组合型





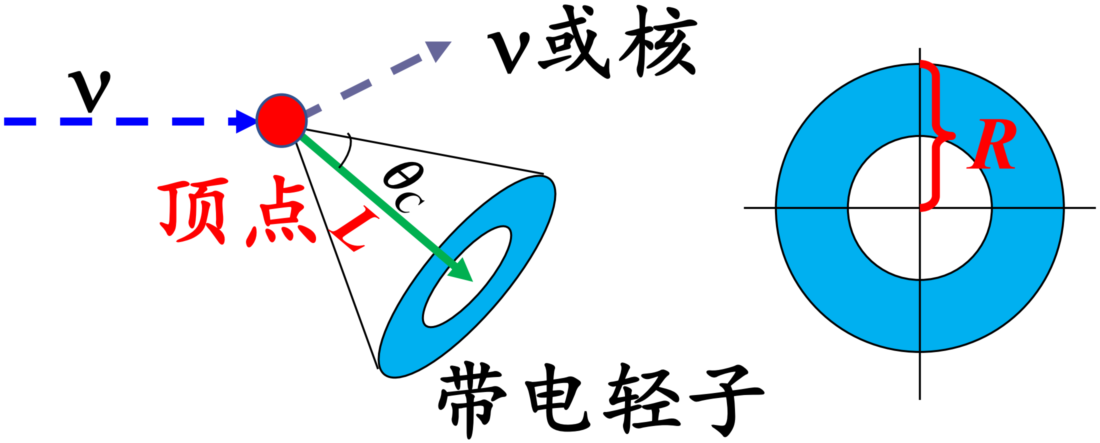

Kamiokande-I/II


IMB


Super-Kamiokande

特点：探测介质同时充当靶物质

问题：用切伦科夫技术怎么研究中微子？



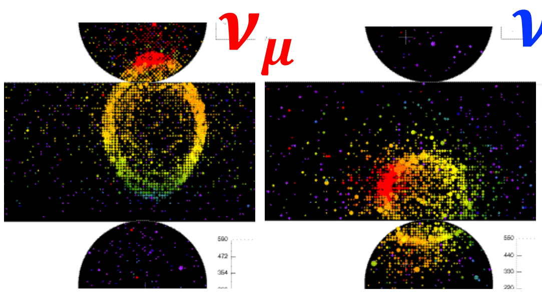
每 MeV 的电子大约发射220个波长250-600nm的切伦科夫光子。

切伦科夫科夫阈 $E = m/\sqrt{1-1/n^2}$

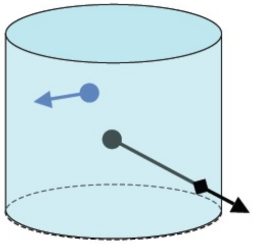
$$\cos\theta_C = \frac{R}{\sqrt{R^2+L^2}} = \frac{R}{\Delta t \times c/n} \qquad E_K \sim L \times \frac{\mathrm{d}E}{\mathrm{d}x}$$

相对论性粒子 $\theta_C \approx 42^0$

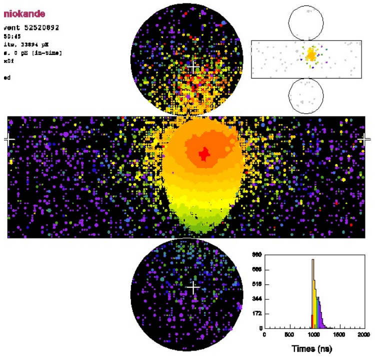
大气中微子事例分类及可测能量范围

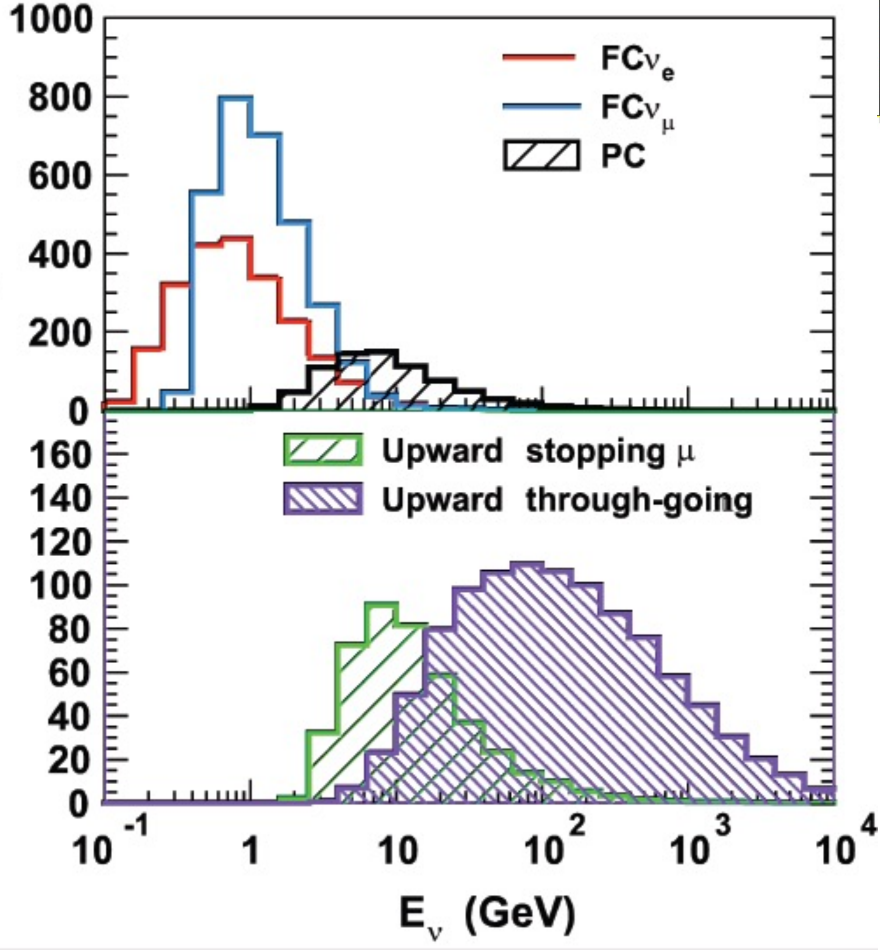


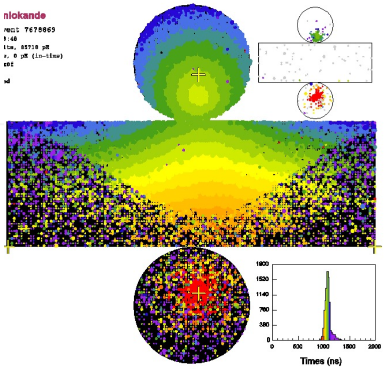
Fully Contained (FC)

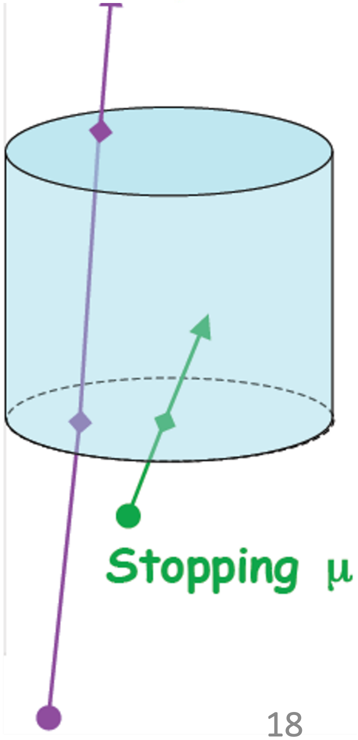


Partially Contained (PC)

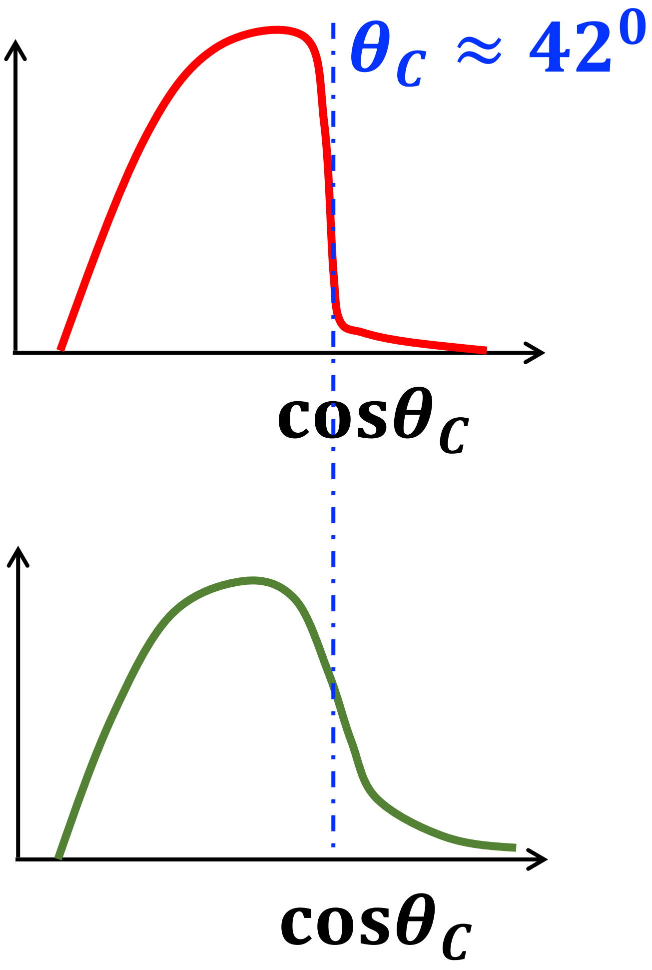


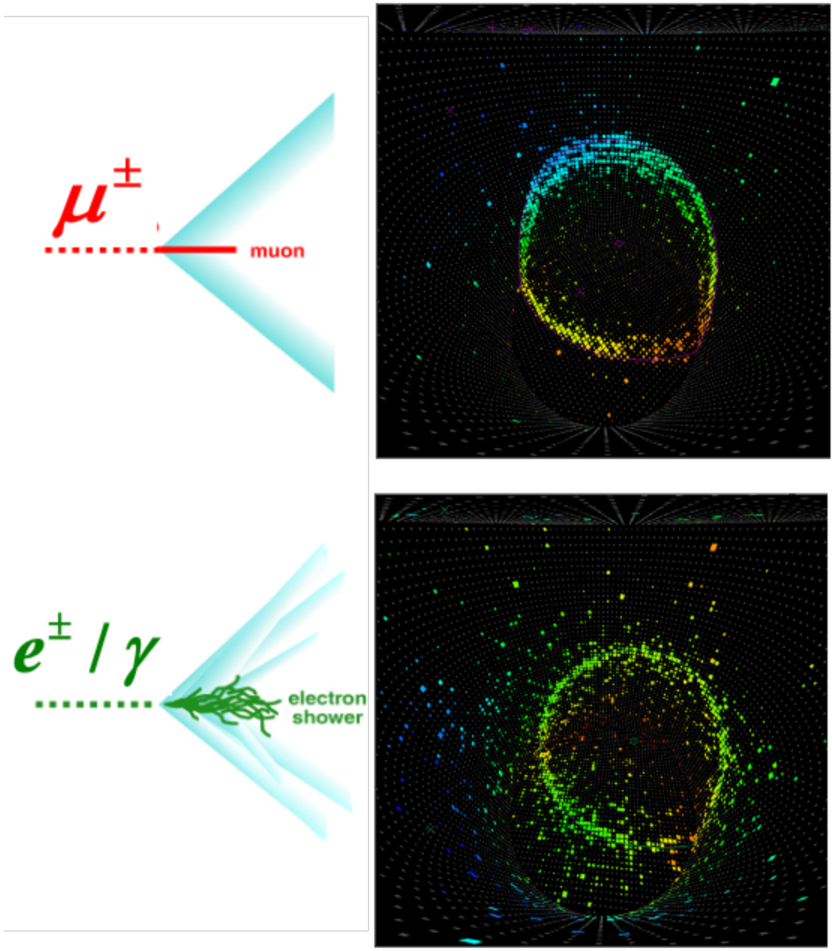




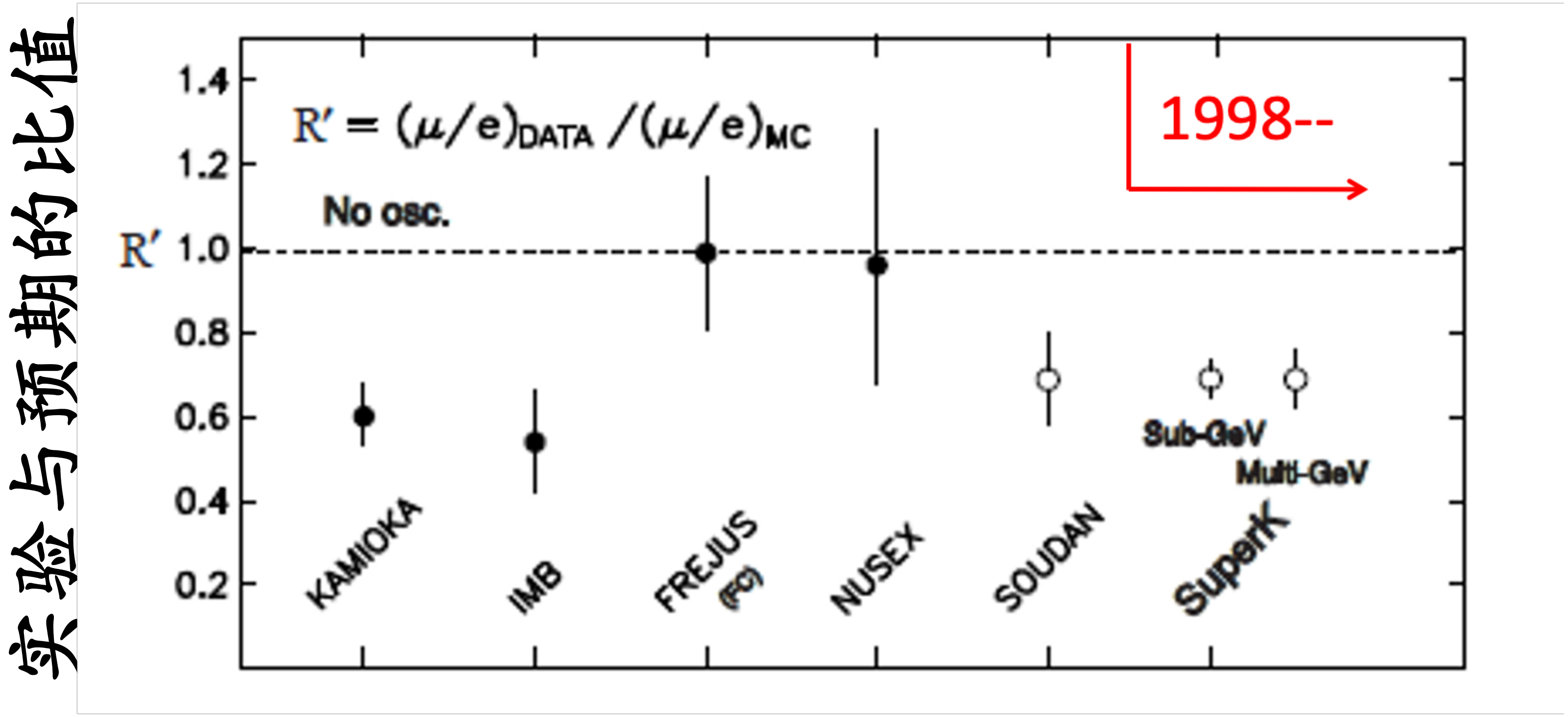


问题：水切伦科夫探测器如何识别粒子？



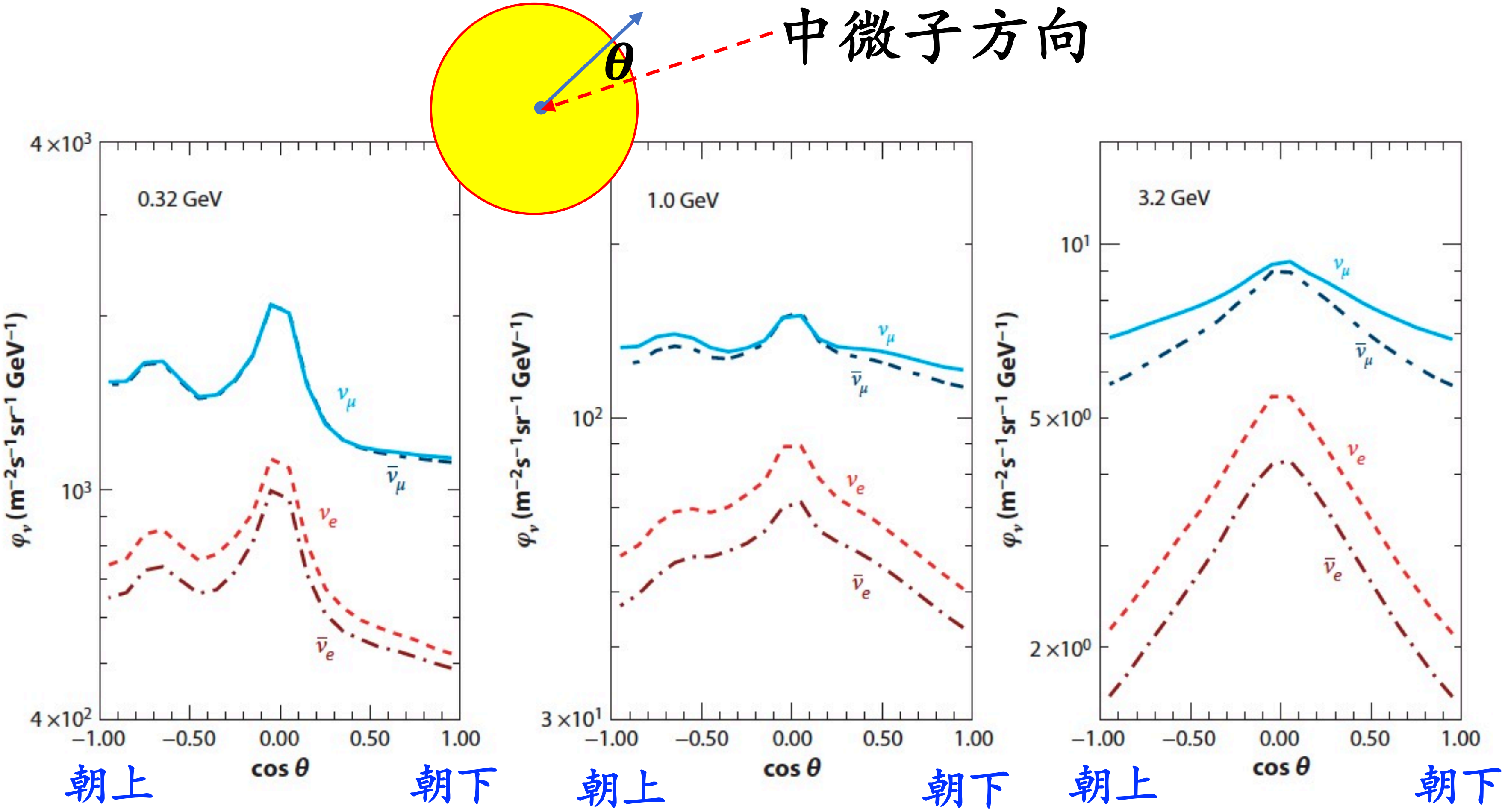


三、大气中微子反常及振荡

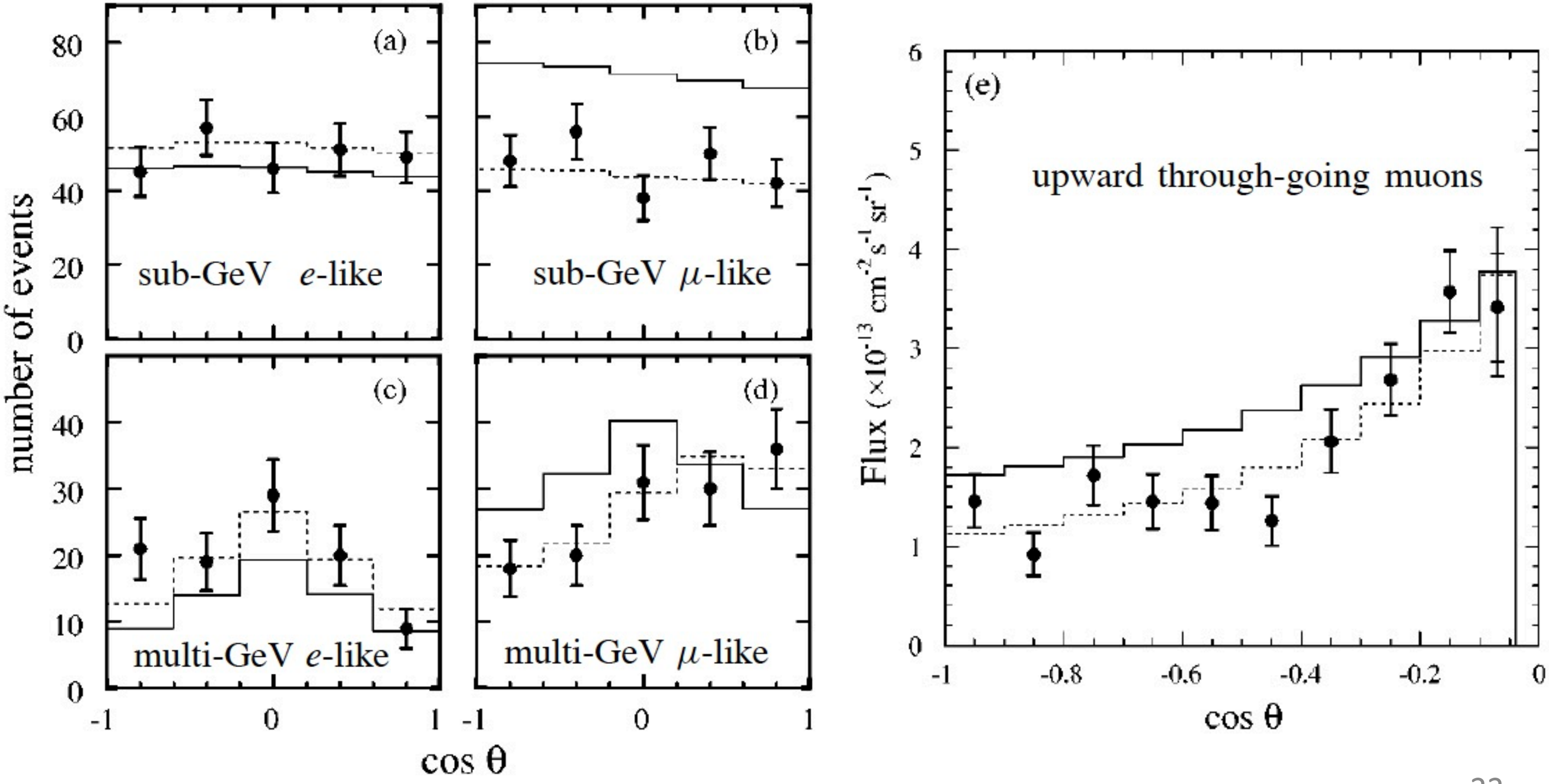


在1998年早期，已观察到三个中微子振荡及质量中微子的迹象，体现在太阳中微子，大气中微子和LSND 实验上。 -- PDG1998

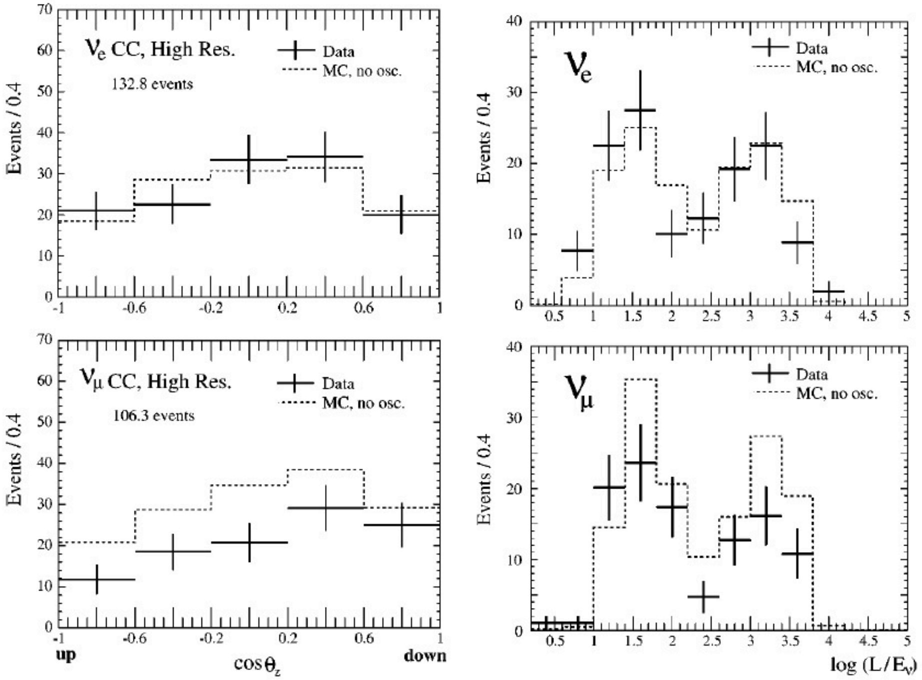
问题：会不会是中微子与不同靶物质相互作用截面的差异所造成的？



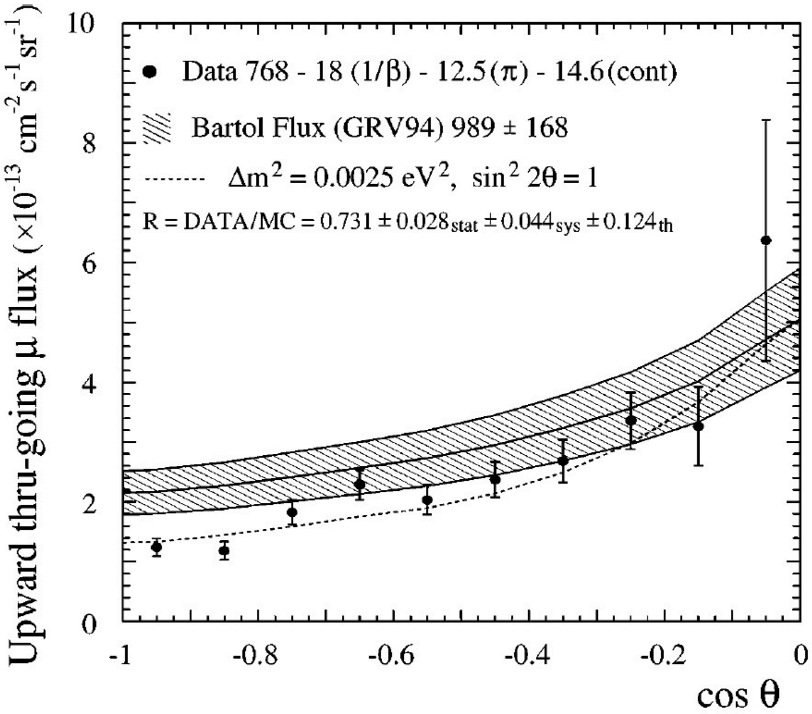
1988年，神冈实验报告，“我们无法解释系统探测器效应或大气中微子通量不确定性导致的数据。



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。

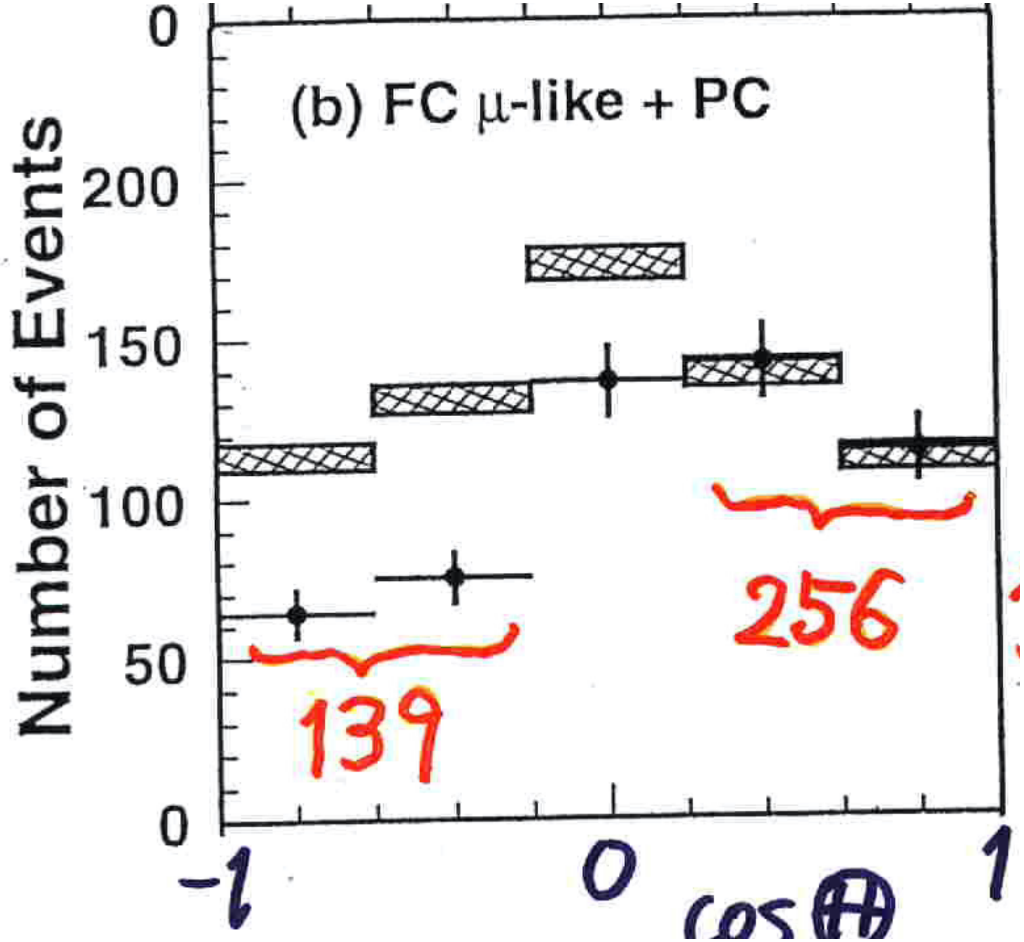


Soudan-2

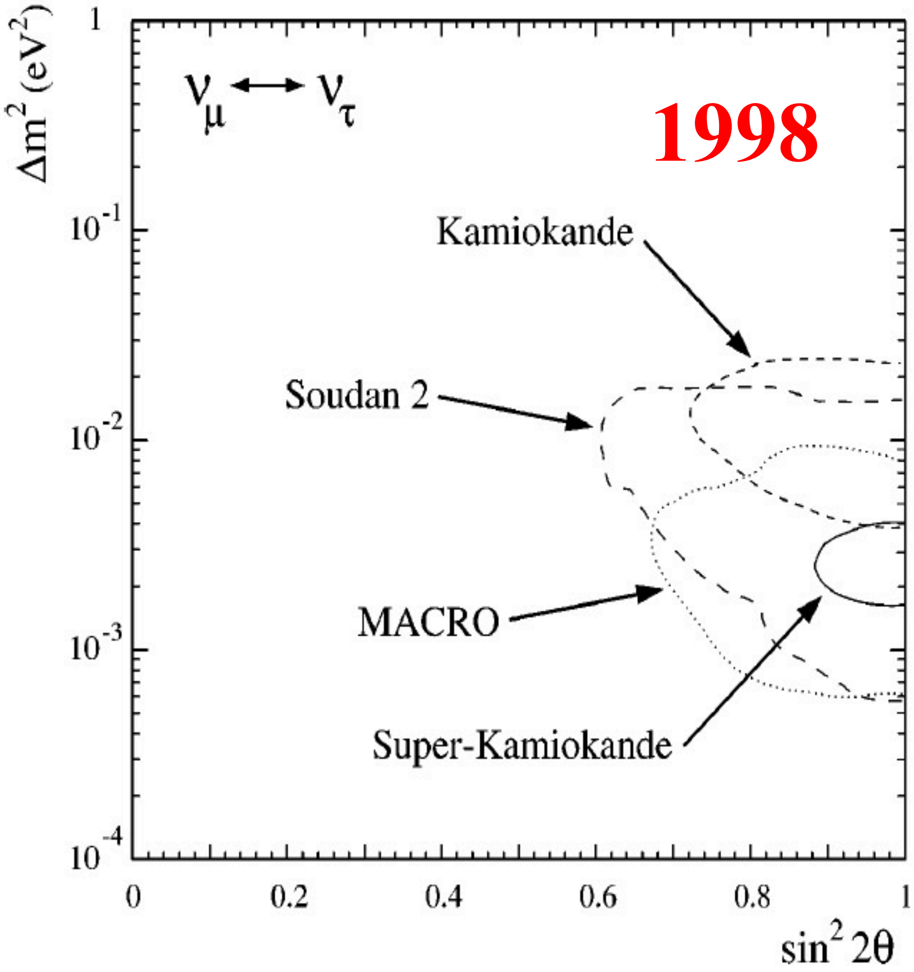


MACRO

Super-K @Neutrino98



$$P_{\nu_\mu\to\nu_\tau} \simeq 1 - \sin^2\theta \sin^2 \frac{1.27\Delta m^2 L}{E_\nu}$$

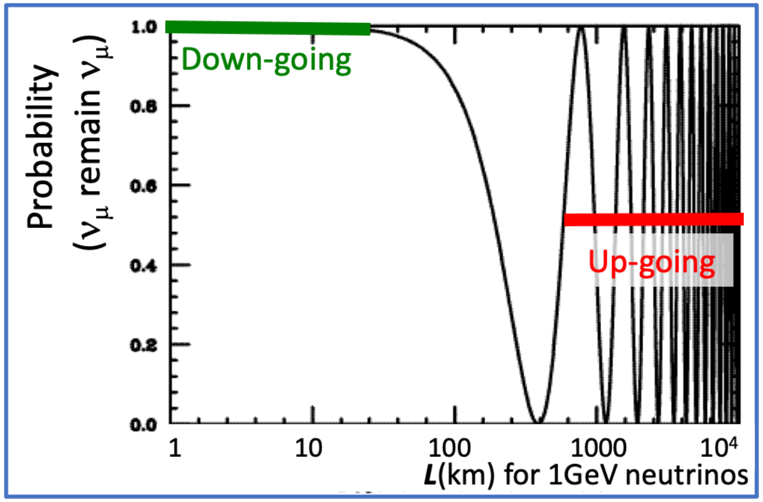


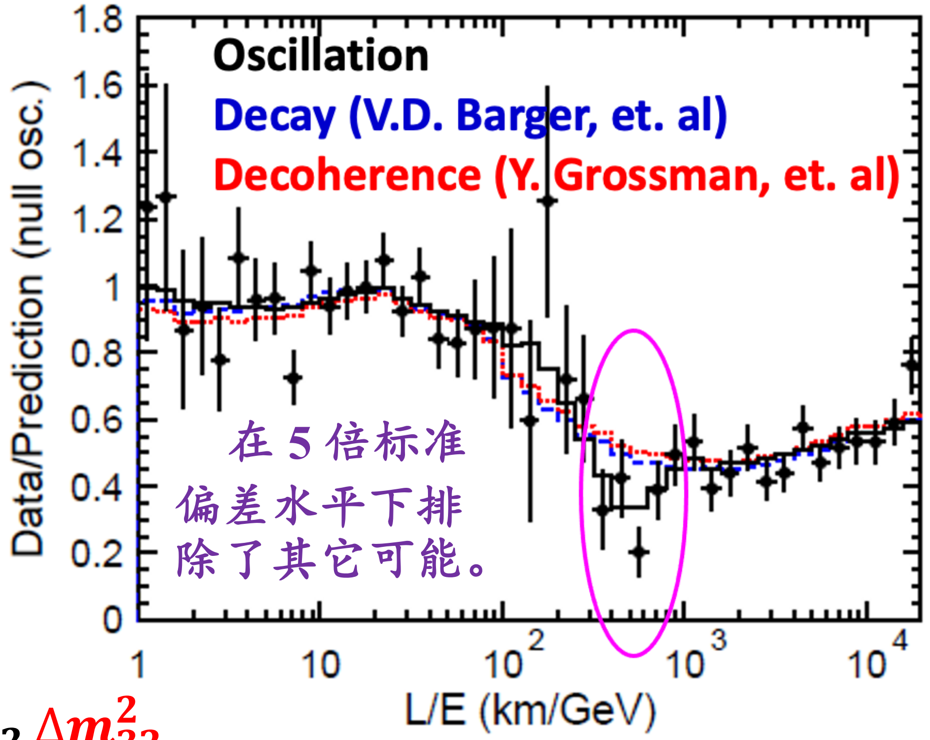
各实验测量到的大气中微子振荡参数在误差范围内符合得很好！但不排除有其它非振荡因素。

大气中微子振荡消失概率的周期变化模式

$$P_{\nu_\mu\to\nu_\mu} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\mu}$$

Phys.Rev.Lett.93:101801,2004





在 5 倍标准偏差水平下排除了其它可能。

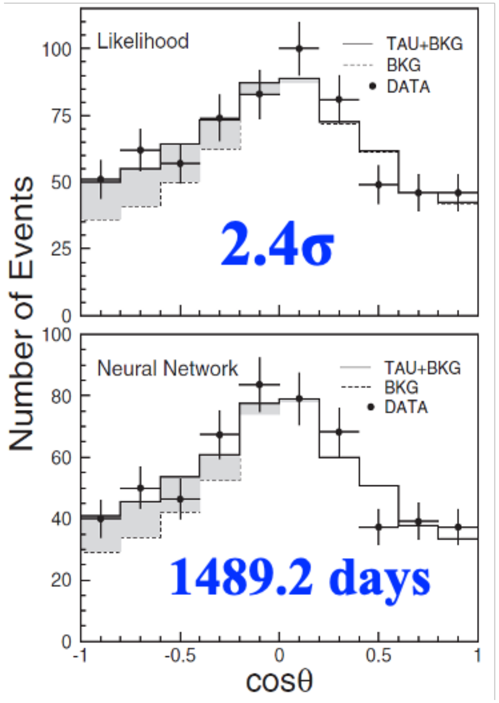
$$\sin^2\theta_{\mu\mu} = \cos^2\theta_{13}\sin^2\theta_{23}$$

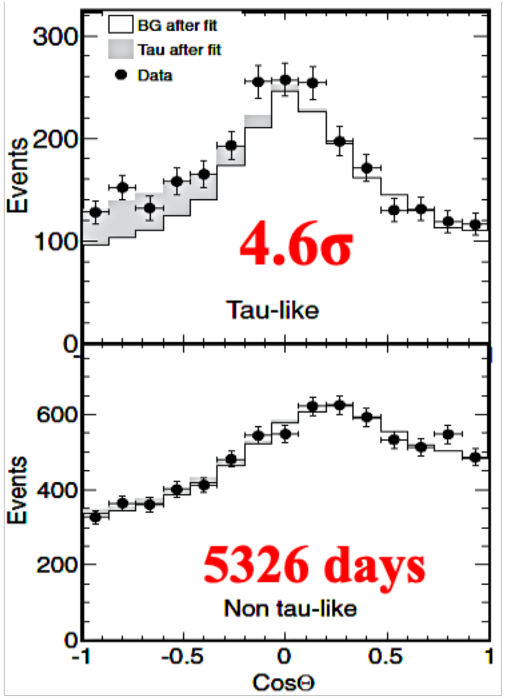
$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\,\Delta m^2_{31} + \cos^2\theta_{12}\,\Delta m^2_{32} + \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\,\Delta m^2_{21}$$

大气中微子振荡 $\nu_\mu \to \nu_\tau$ 的直接证据

$$E_{\nu_\tau}^{th} = \max\left(0, m_\tau \frac{m_{N'}}{m_N} + \frac{m_\tau^2 + m_{N'}^2 - m_N^2}{2m_N}\right)$$

产生阈：～3.5 GeV



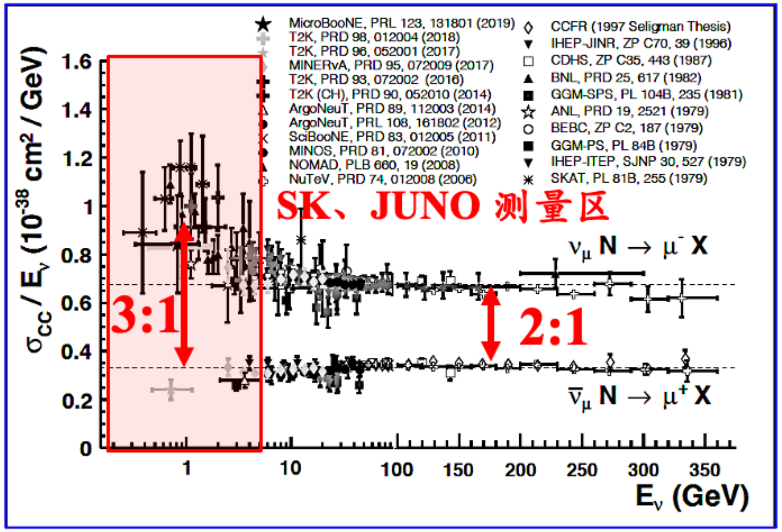


在超级神冈实验看到了 $\nu_\mu \to \nu_\tau$ 的直接证据。

超级神冈实验正反大气中微子振荡分析

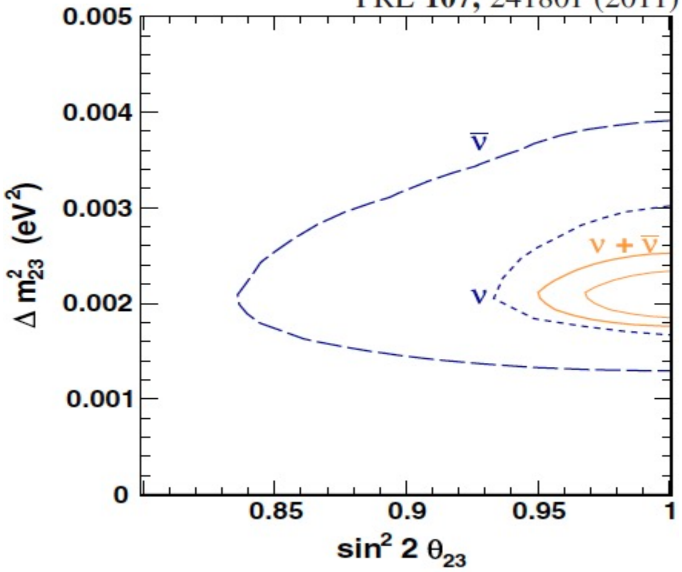
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin\left(\frac{\Delta m^2 L}{4E}\right)$$

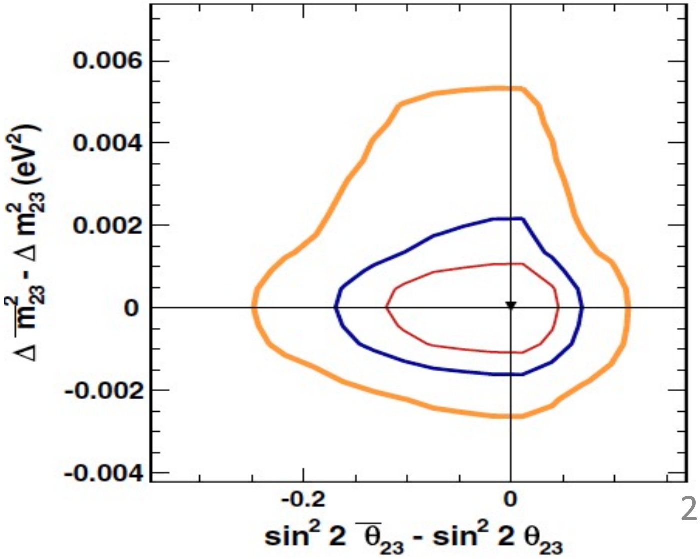
$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2 2\bar{\theta} \sin\left(\frac{\Delta \bar{m}^2 L}{4E}\right),$$



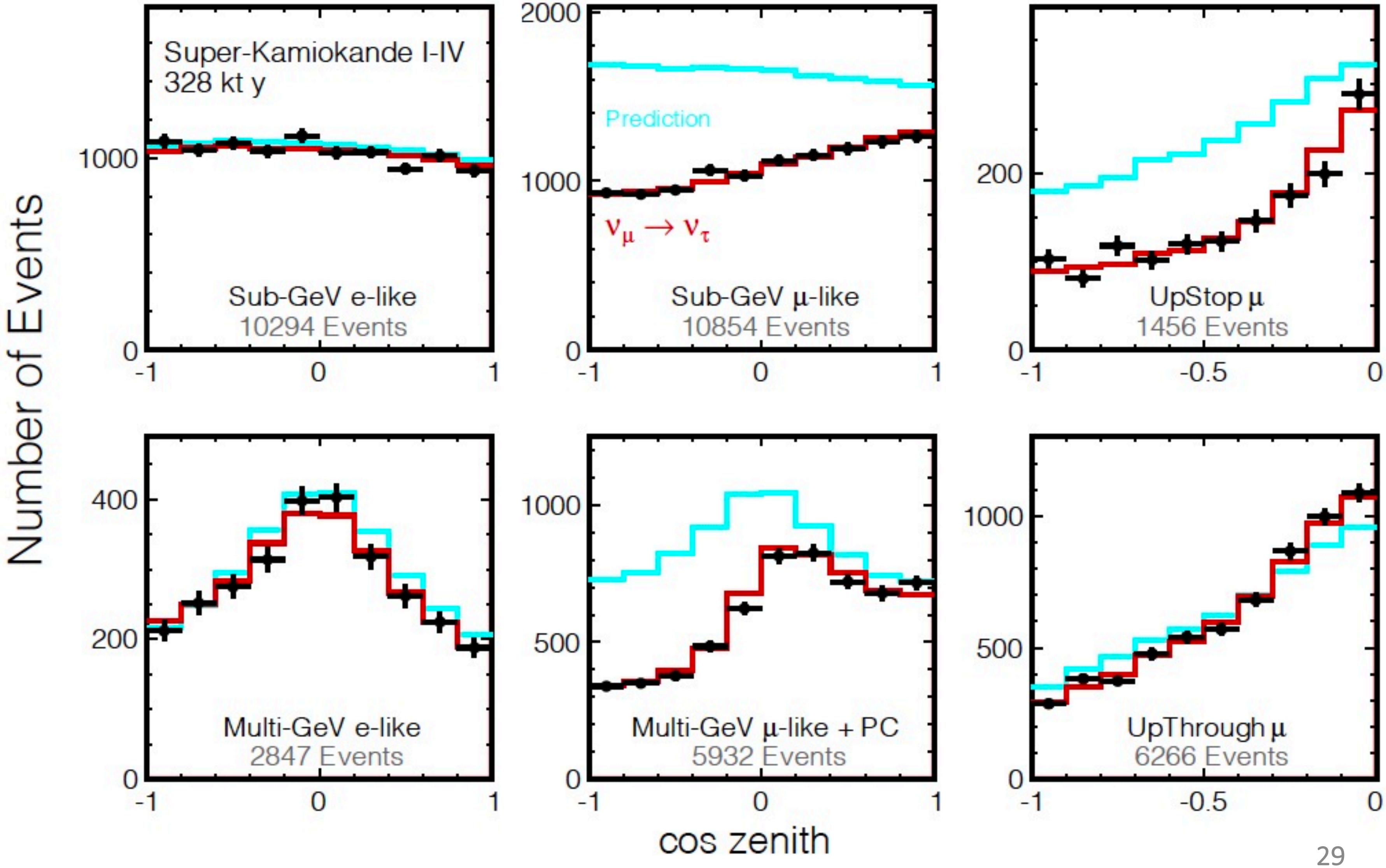
利用正反中微子与核相互作用截面比值~3 来统计区分它们的振荡行为。

PRL **107**, 241801 (2011)

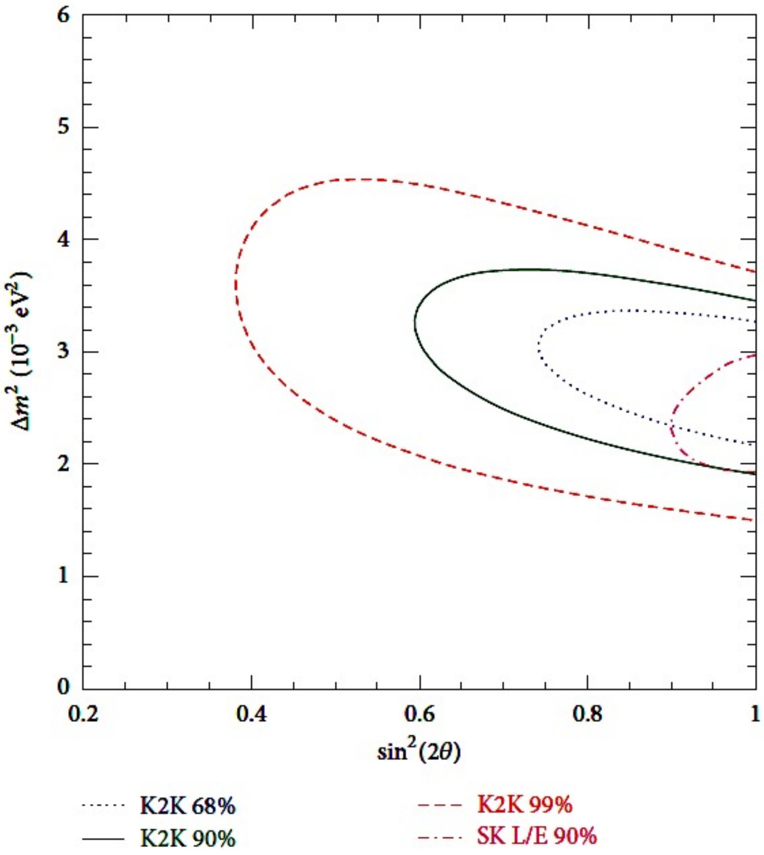


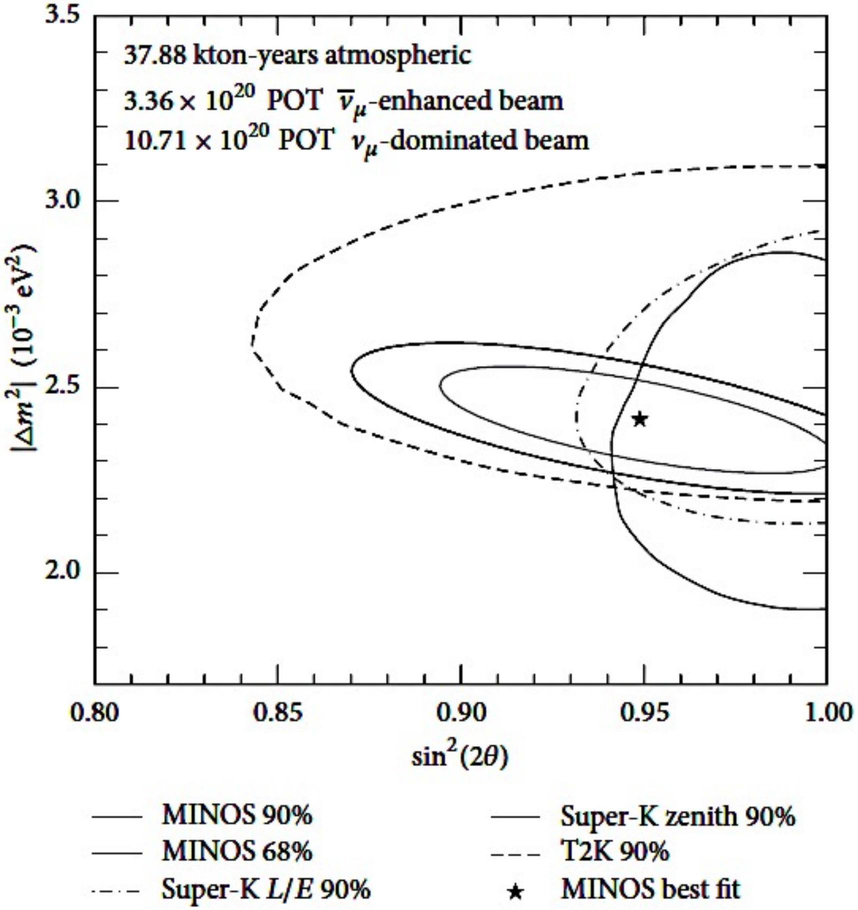


近二十五年的超级神冈大气中微子数据

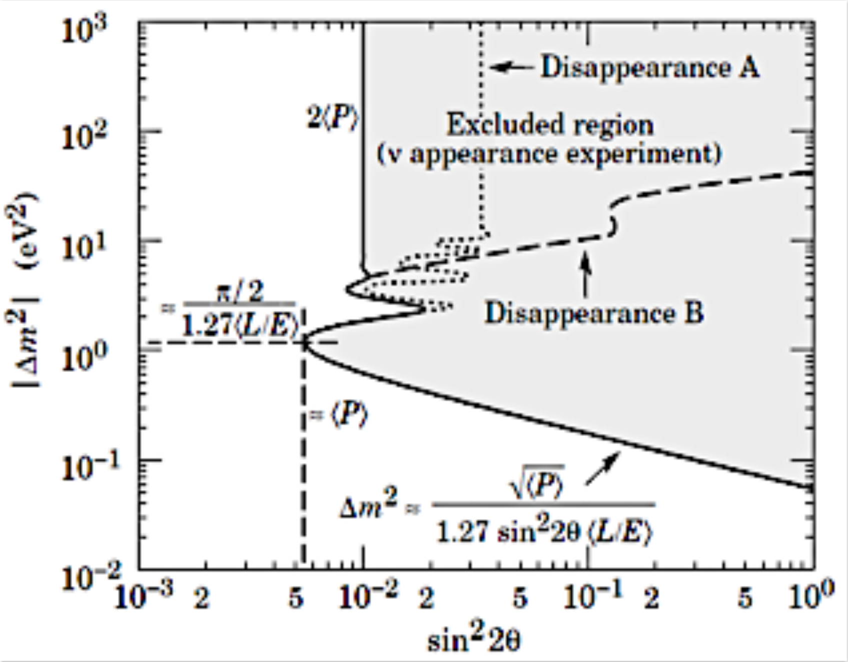


振荡结果与加速器中微子实验一致





中微子振荡发现前

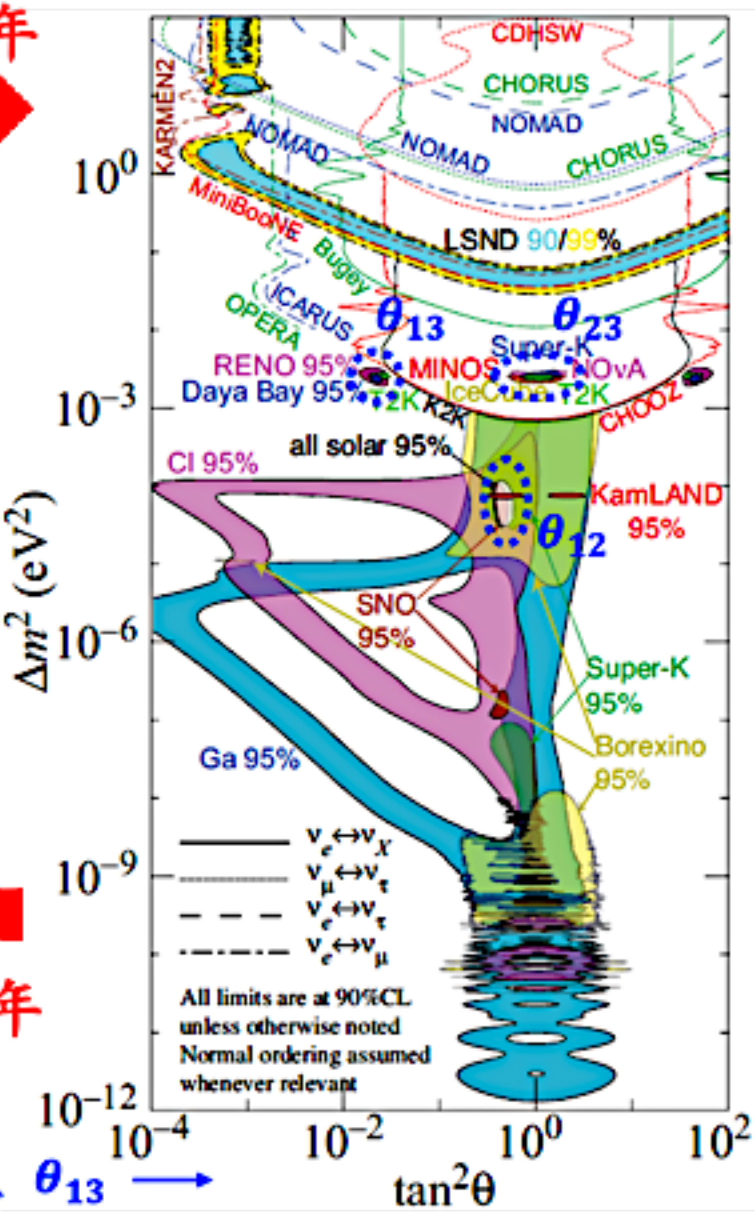


$$P = 1 - \sin^2 2\theta \sin^2\left(1.276\frac{\Delta m^2 L}{E_{\bar{\nu}_e}}\right)$$

2018年

1995年

← Δm^2_{12}、Δm^2_{23}、Δm^2_{13} →

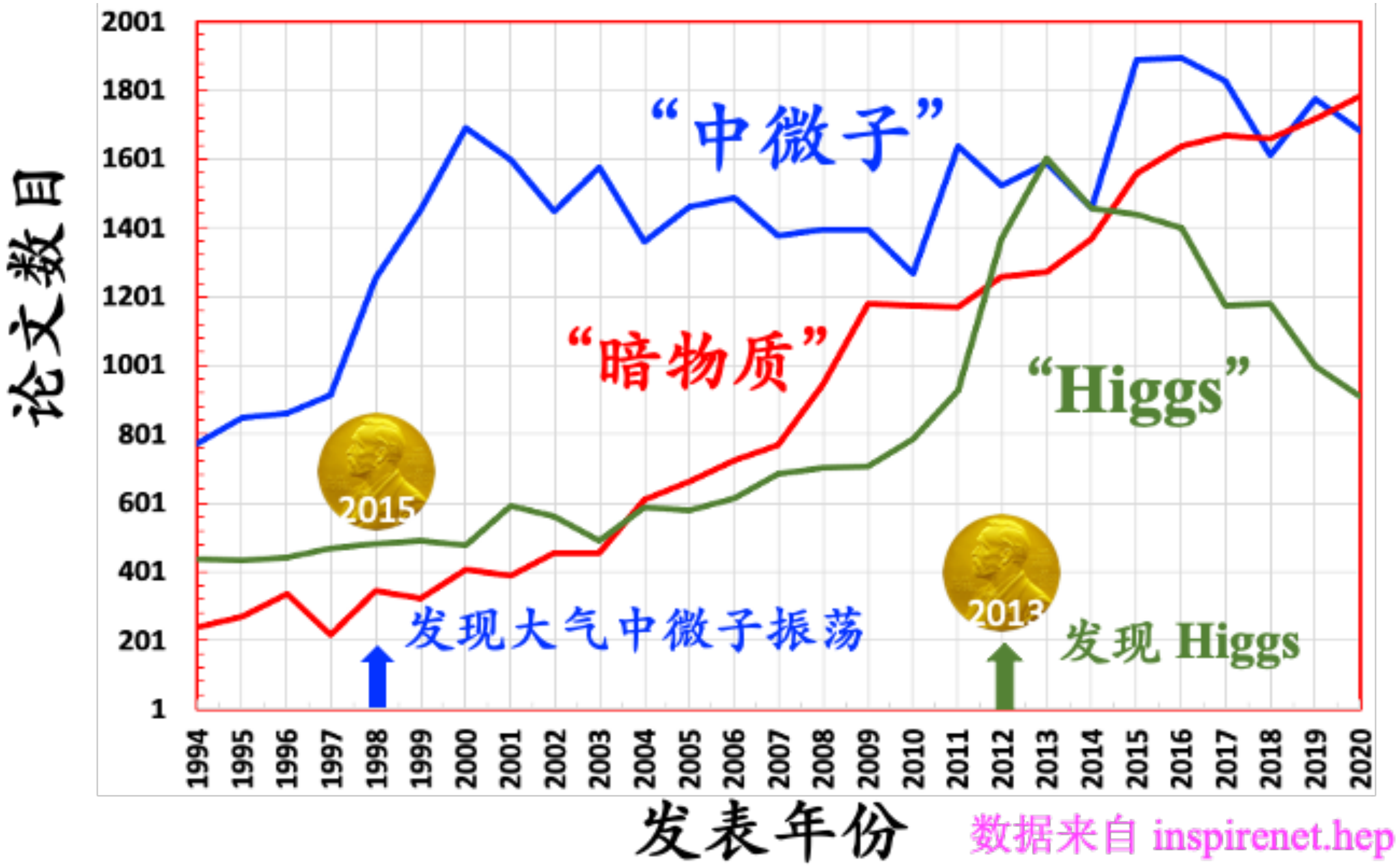


← θ_{12}、θ_{23}、θ_{13} →

四、总结与展望

- 中微子一直以“反常”为标志，窥视着新的物理并提供着新机遇。
- 大气中微子振荡的实验确定，表明中微子有质量，是第一个得到各方面实验证实超出标准模型新物理的明显证据。
- 大气中微子振荡的精确测量也为进一步研究中微子振荡、中微子质量排序、中微子的 CP 破坏等打开了一扇大门。

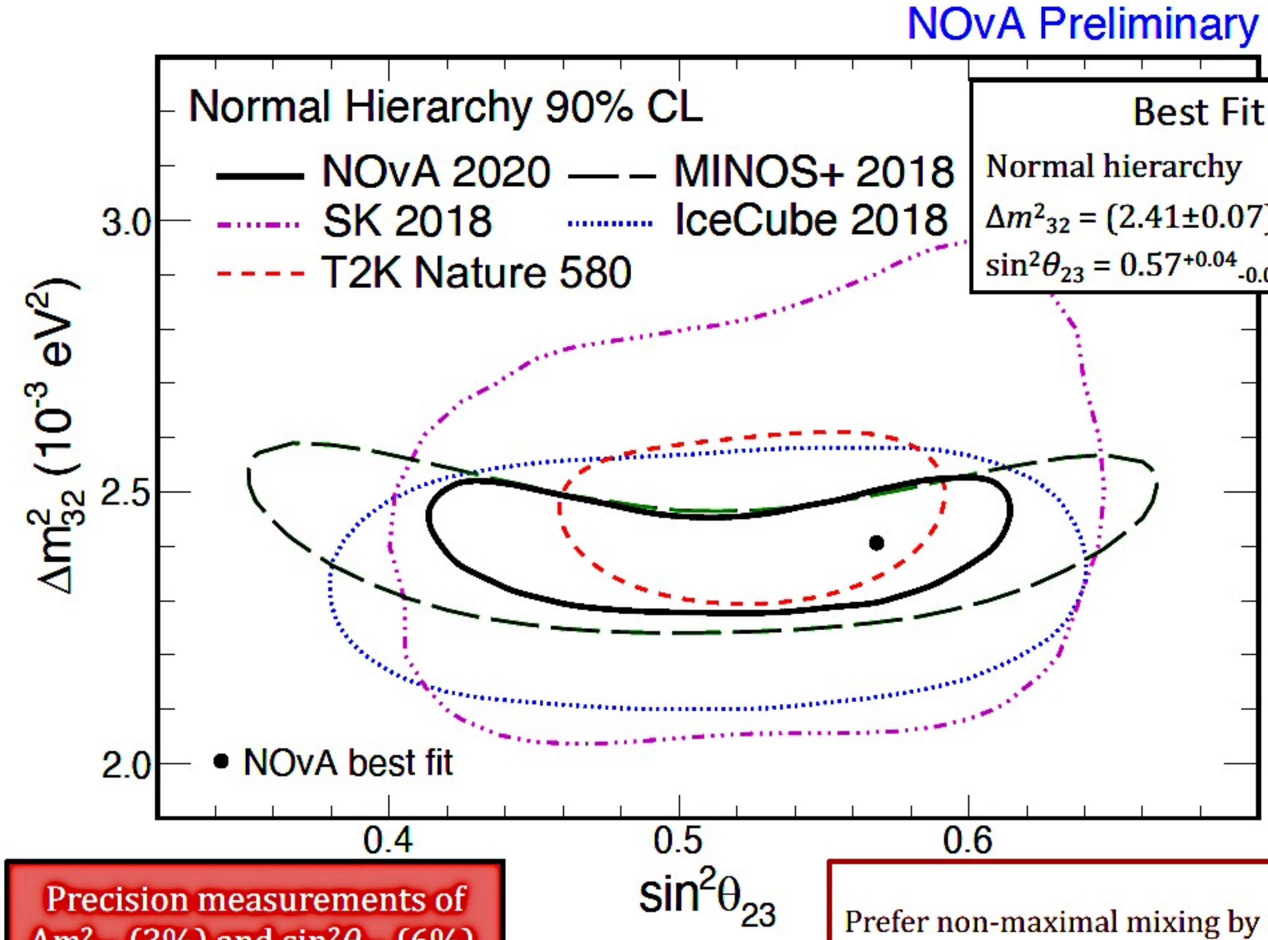
未来中微子依旧是高能物理研究的热点



数据来自 inspirenet.hep

卦限问题 $\theta_{23} < 45^0$ 还是 $\theta_{23} > 45^0$?

Alex Himmel, NEUTRINO2020



Best Fit

Normal hierarchy

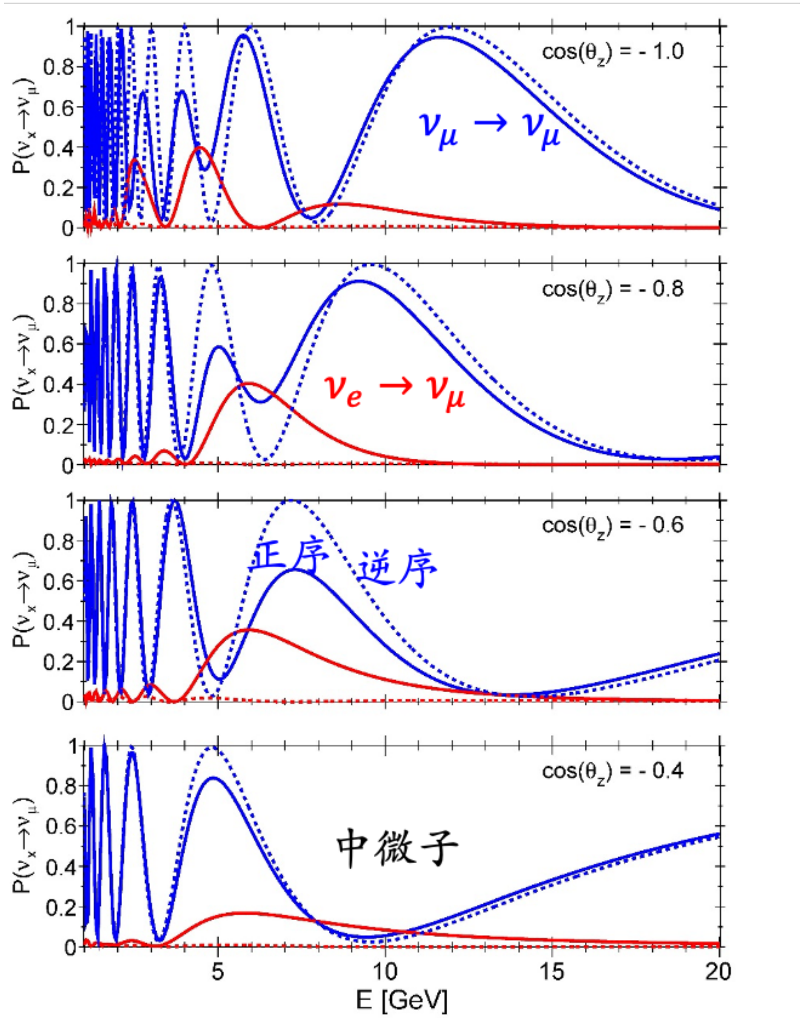
$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

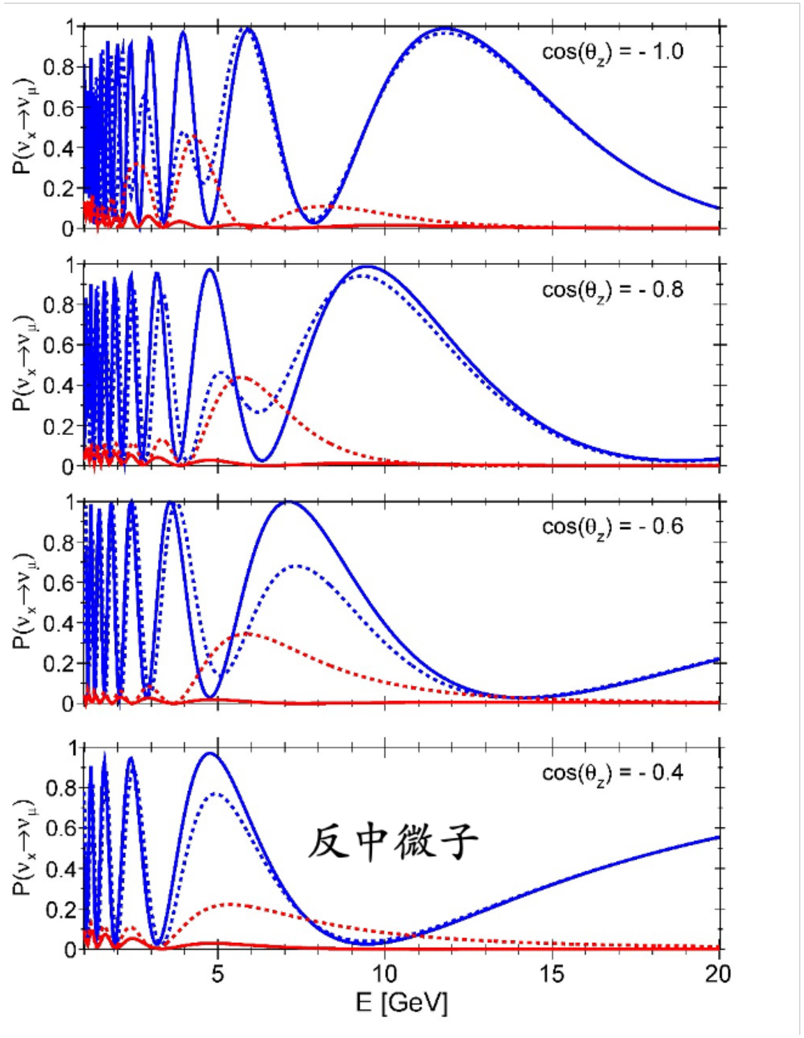
$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

Precision measurements of Δm^2_{32} (3%) and $\sin^2\theta_{23}$ (6%).

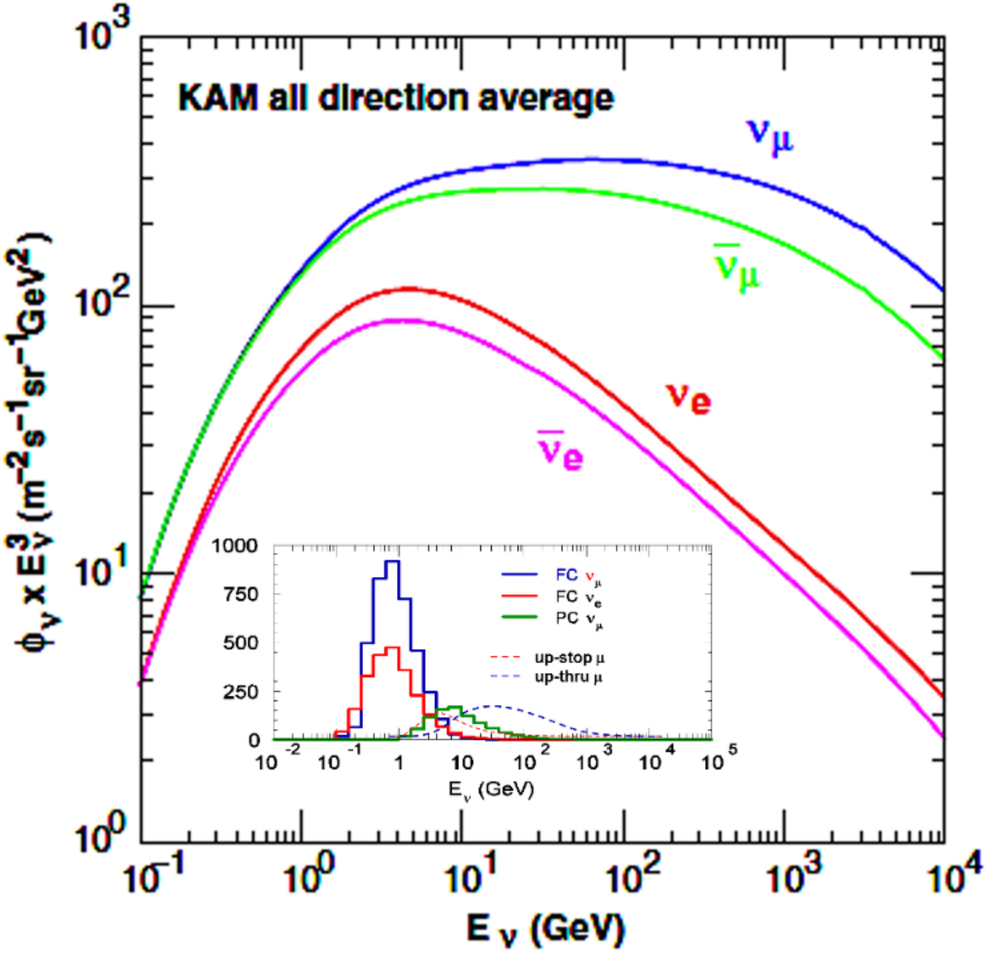
Prefer non-maximal mixing by 1.1σ.

研究 GeV 大气中微子振荡，确定质量排序

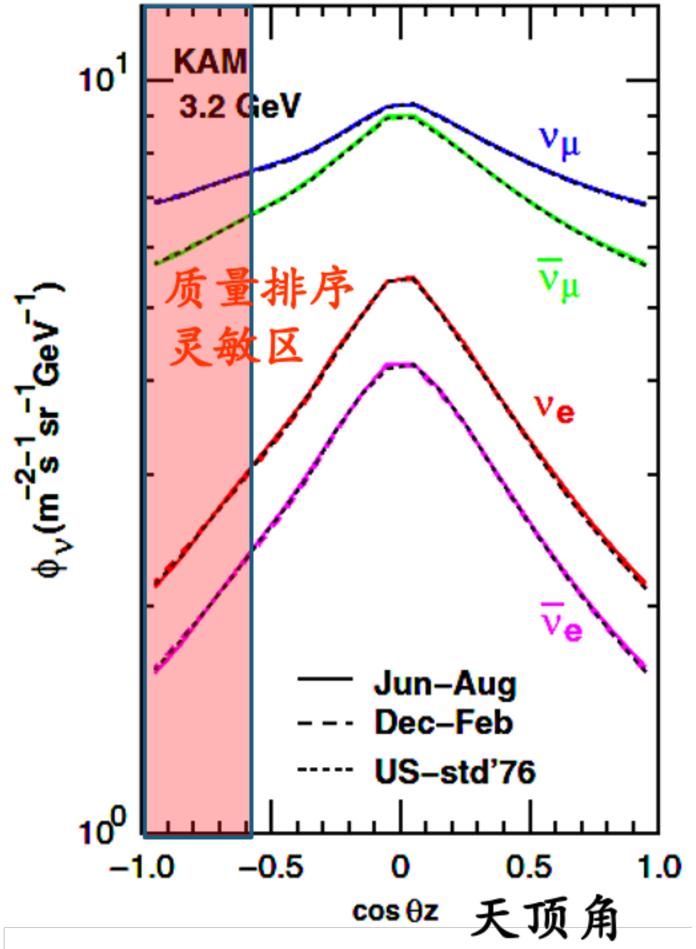




正反大气中微子通量

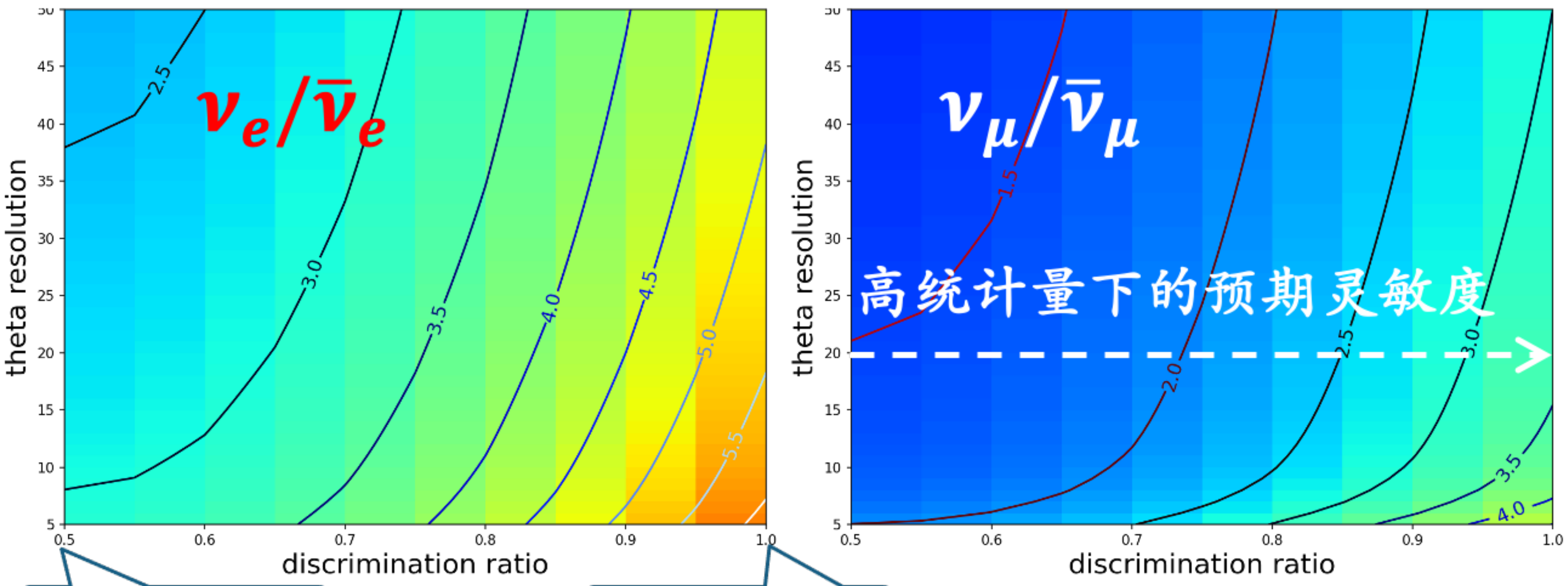


KAM all direction average
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
$\phi_\nu \times E_\nu^3\ (m^{-2}s^{-1}sr^{-1}GeV^2)$
10^0
10^1
10^2
10^3
10^{-1}
10^0
10^1
10^2
10^3
10^4
E_ν (GeV)
1000
750
500
250
0
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
10^5
E_ν (GeV)
FC ν_μ
FC ν_e
PC ν_μ
up-stop μ
up-thru μ



KAM
3.2 GeV
质量排序
灵敏区
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
$\phi_\nu (m^{-2}s^{-1}sr^{-1}GeV^{-1})$
10^1
10^0
Jun–Aug
Dec–Feb
US–std'76
−1.0
−0.5
0
0.5
1.0
cos θz
天顶角

质量排序显著度 $\sigma = \sqrt{\Delta\chi^2}$

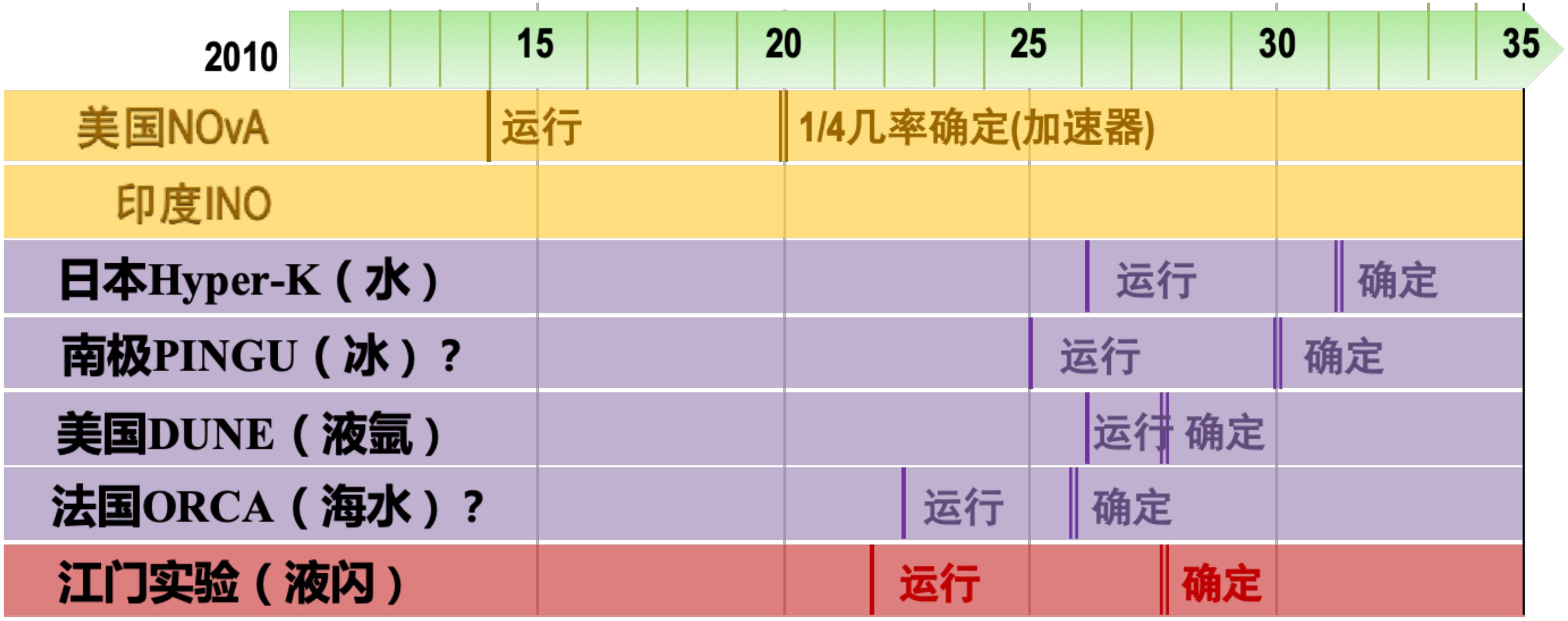


无法区分$\nu/\bar{\nu}$

彻底区分$\nu/\bar{\nu}$

良好的天顶角分辨率和有效的$\nu/\bar{\nu}$识别，对测定质量排序的精度非常重要！

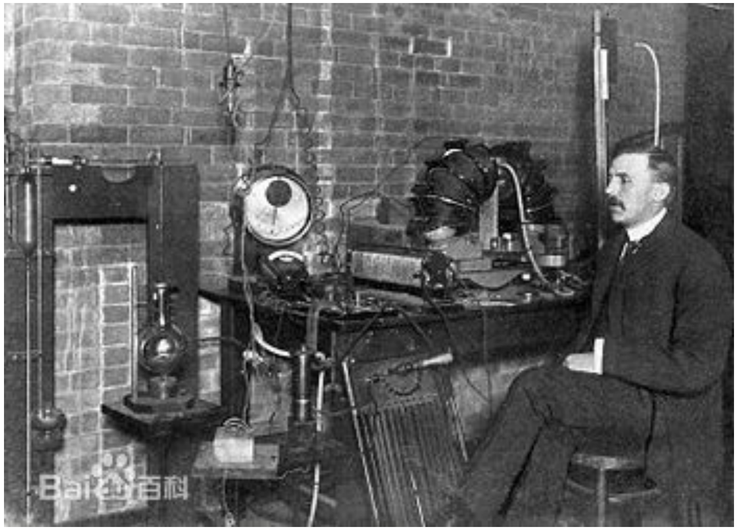
中微子实验未来机遇与挑战并存！



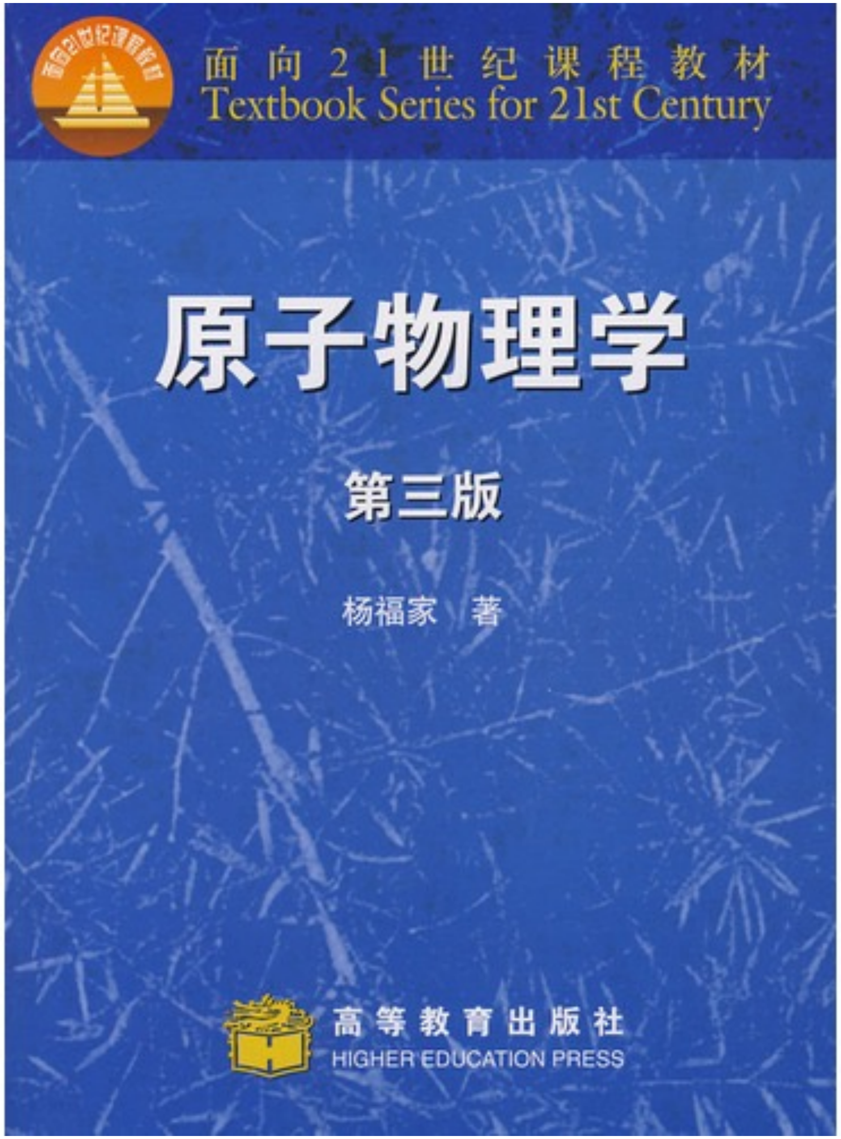
王贻芳 2018

大科学实验与合作是趋势！

1905年卢瑟福做实验



2015年几百名研究人员做LHCb 实验（高能物理实验）



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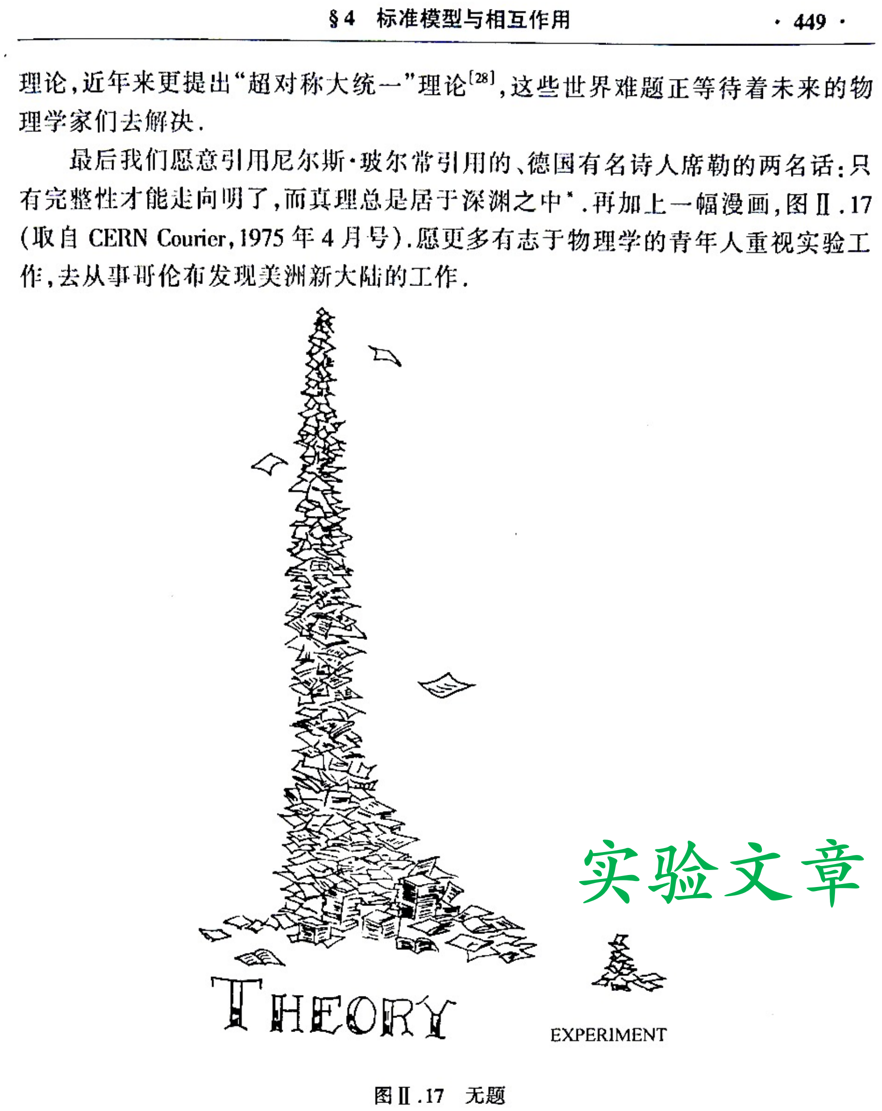

理论，近年来更提出“超对称大统一”理论[28]，这些世界难题正等待着未来的物理学家们去解决.

最后我们愿意引用尼尔斯·玻尔常引用的、德国有名诗人席勒的两名话：只有完整性才能走向明了，而真理总是居于深渊之中*.再加上一幅漫画，图Ⅱ.17（取自 CERN Courier，1975 年 4 月号）.愿更多有志于物理学的青年人重视实验工作，去从事哥伦布发现美洲新大陆的工作.

图Ⅱ.17　无题

实验文章

理论文章

谢谢！