第一届新物理冬季学校：
中微子物理（第二/三讲）

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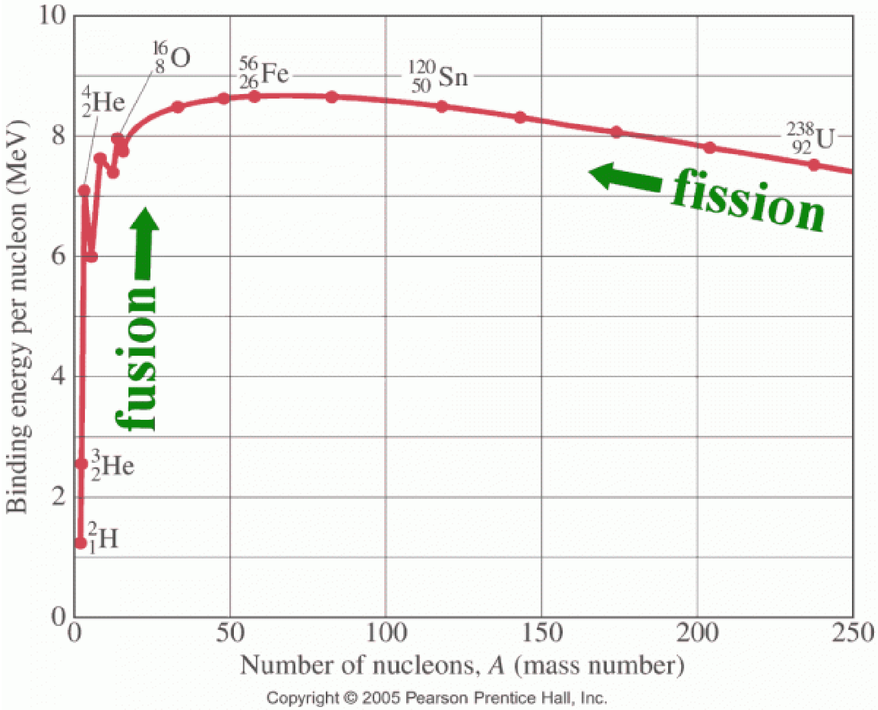
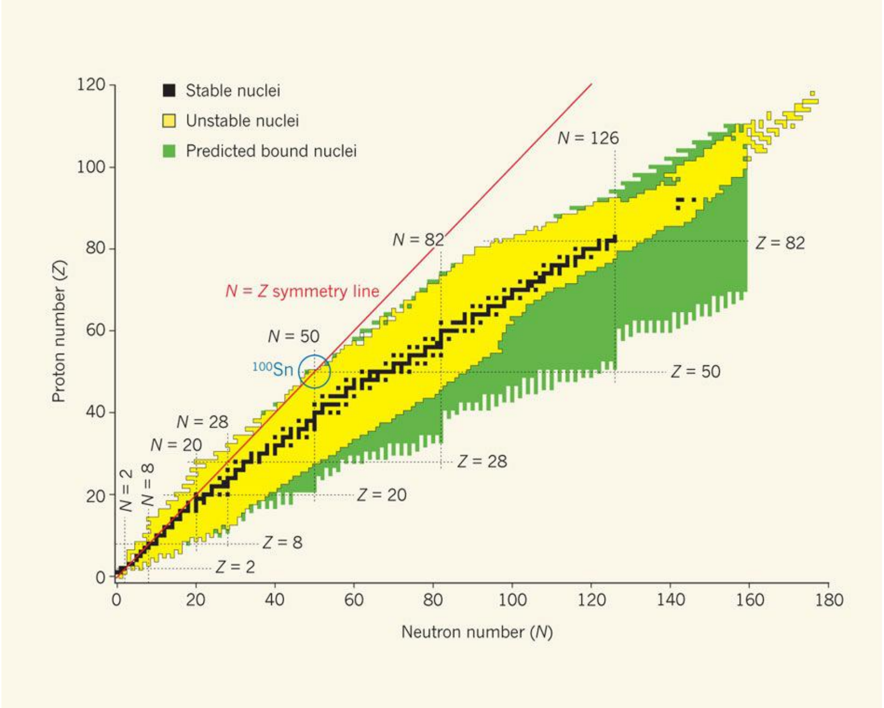
2015年10月6日，瑞典皇家科学院宣布将2015年诺贝尔物理学奖授予日本东京大学Takaaki Kajita教授和加拿大女王大学Arthur B. McDonald教授，以表彰其*发现中微子振荡现象，该现象显示中微子有质量*。

Part III:

太阳中微子振荡

太阳 v.s. 反应堆：中微子和能量的来源





fission fragments: $A(Z,N) \to A(Z+1,N-1) + e^- + \bar{\nu}_e$

solar fusion neutrinos: $4p \to {}^4_2\mathrm{He} + 2e^+ + 2\nu_e$

放出中微子的过程中同时释放大量的能量：太阳能，核能的来源

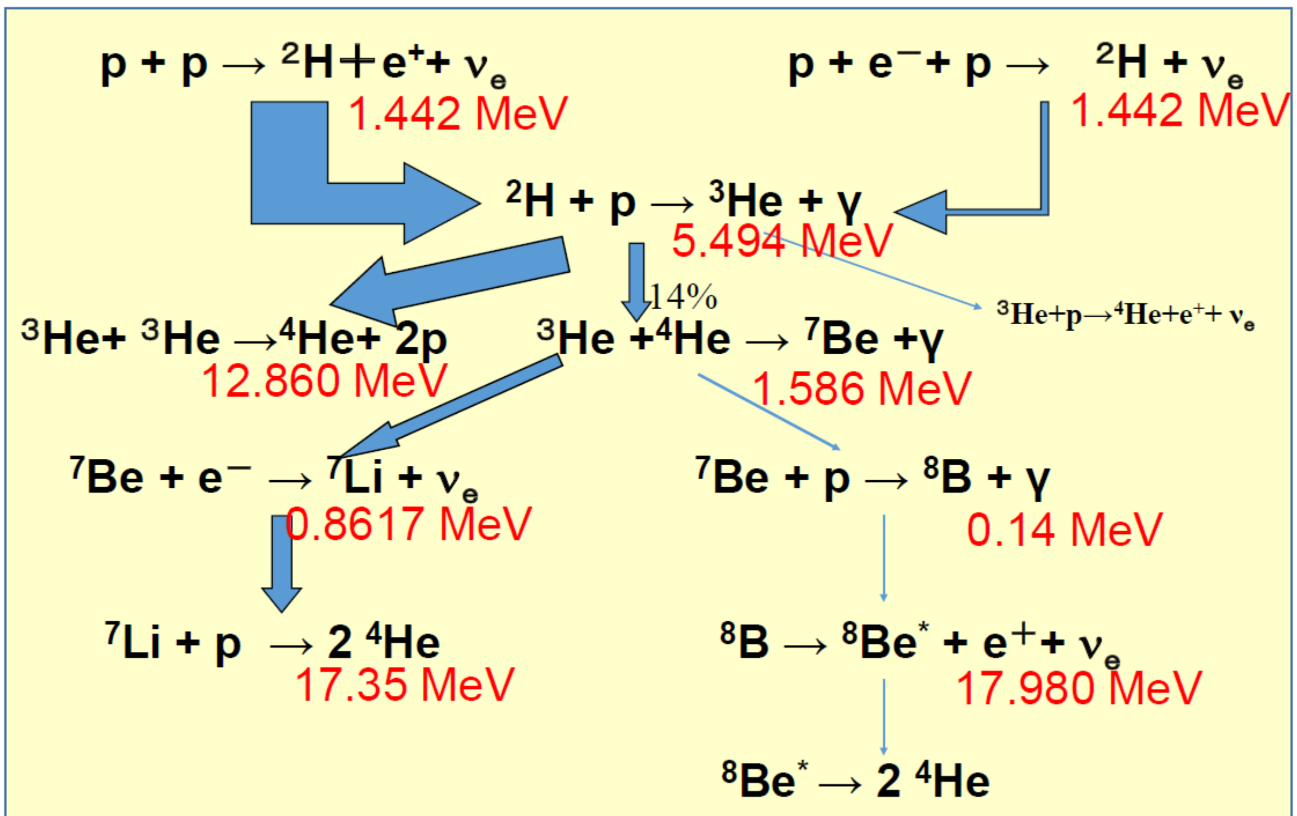
太阳内部的热核聚变

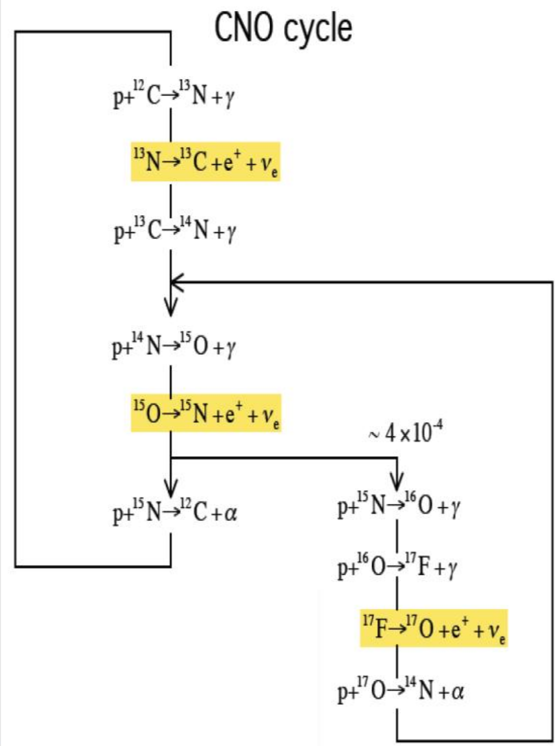
原子核的结合能： $m(A,Z) = Z\,m_p + (A-Z)\,m_n - B(A,Z)$

$$2e^- + 4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}.$$

pp-chain

Energy production of each reaction





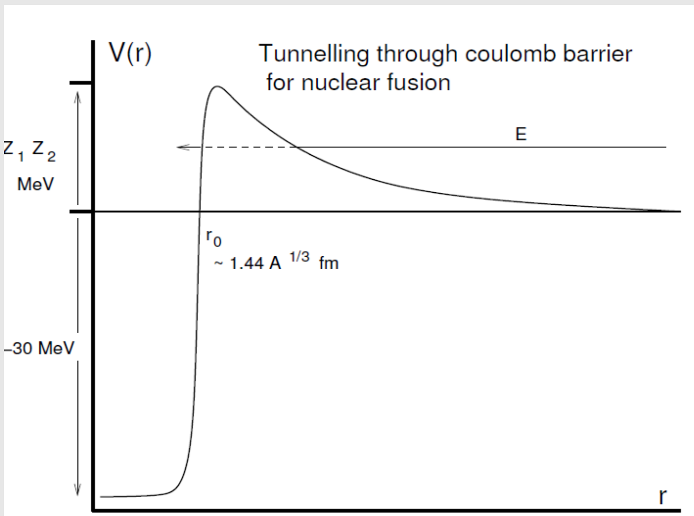
太阳内部的热核聚变

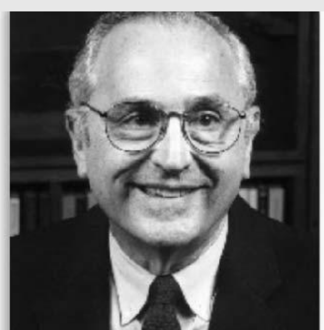
$$2e^- + 4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}.$$

太阳内部温度: 1.5x10^7 K (~keV)

$T \ll Q_i \ll m_N$

$$\langle\sigma v\rangle_{\mathrm{AB}} = \sqrt{\frac{8}{\pi\mu\,(k_B T)^3}}\int_0^\infty \mathrm{d}E\,\sigma(E)\,E\,\exp\left(-\frac{E}{k_B T}\right)$$





量子力学的隧穿效应可以克服库仑势垒，保证弱相互作用可以发生。

从原初的均匀气体，考虑
(1)局域的流体力学的平衡(压力与万有引力)
(2)质量和能量的守恒条件
(3)弱相互作用微观过程
(4)能量在辐射区域和对流区域的传输
(5)物质的状态方程
(6)引力和光学观测的限制条件

包含19个方程的动力学演化

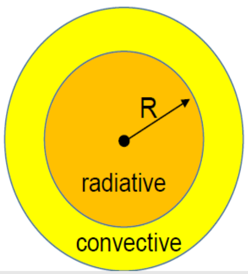
→ 标准太阳模型

标准太阳模型

标准太阳模型让我们对太阳内部的信息和演化有了深入的理解，并且可以被实验检验：

太阳中微子！

Boundary of radiative/convective zone



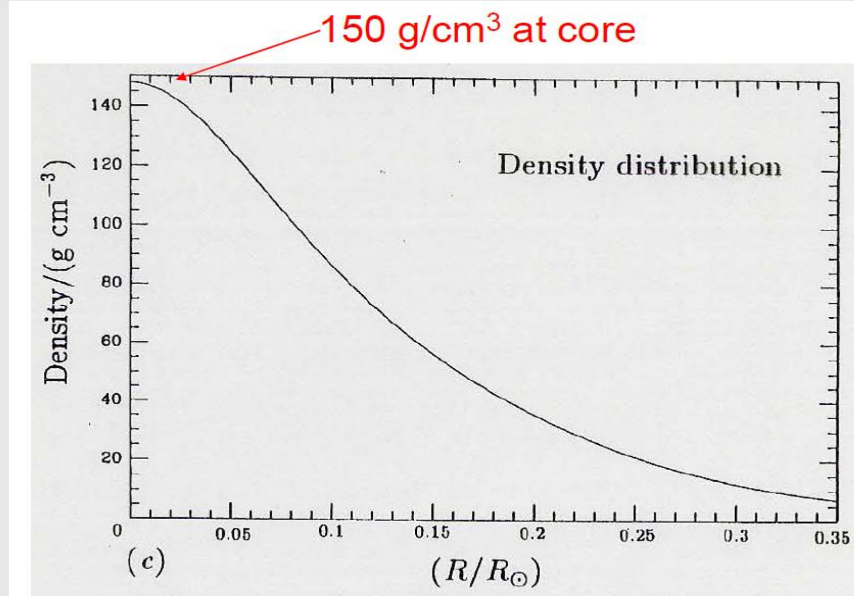
SSM prediction: $0.7138 \times R_\odot$

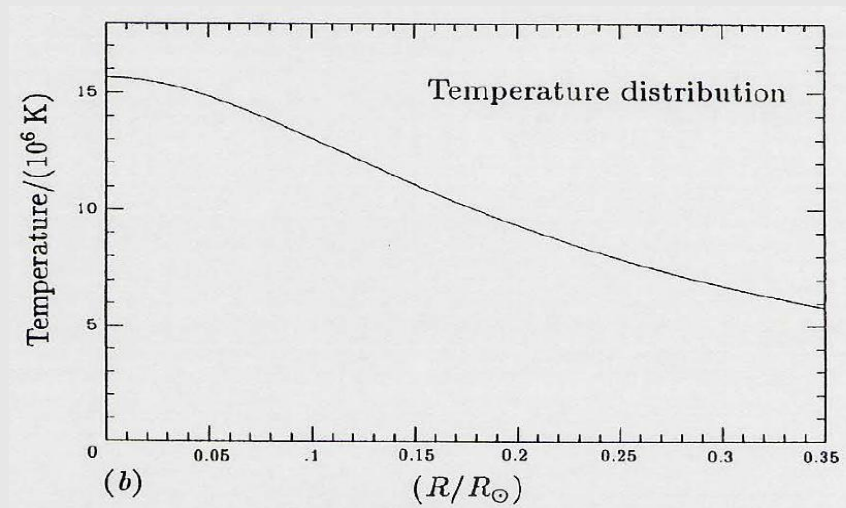
Observation: $(0.713 \pm 0.001) \times R_\odot$

Surface He abundance

SSM prediction: $Y_{surface} = 0.243$

Observation: $Y_{surface} = 0.2485 \pm 0.0034$

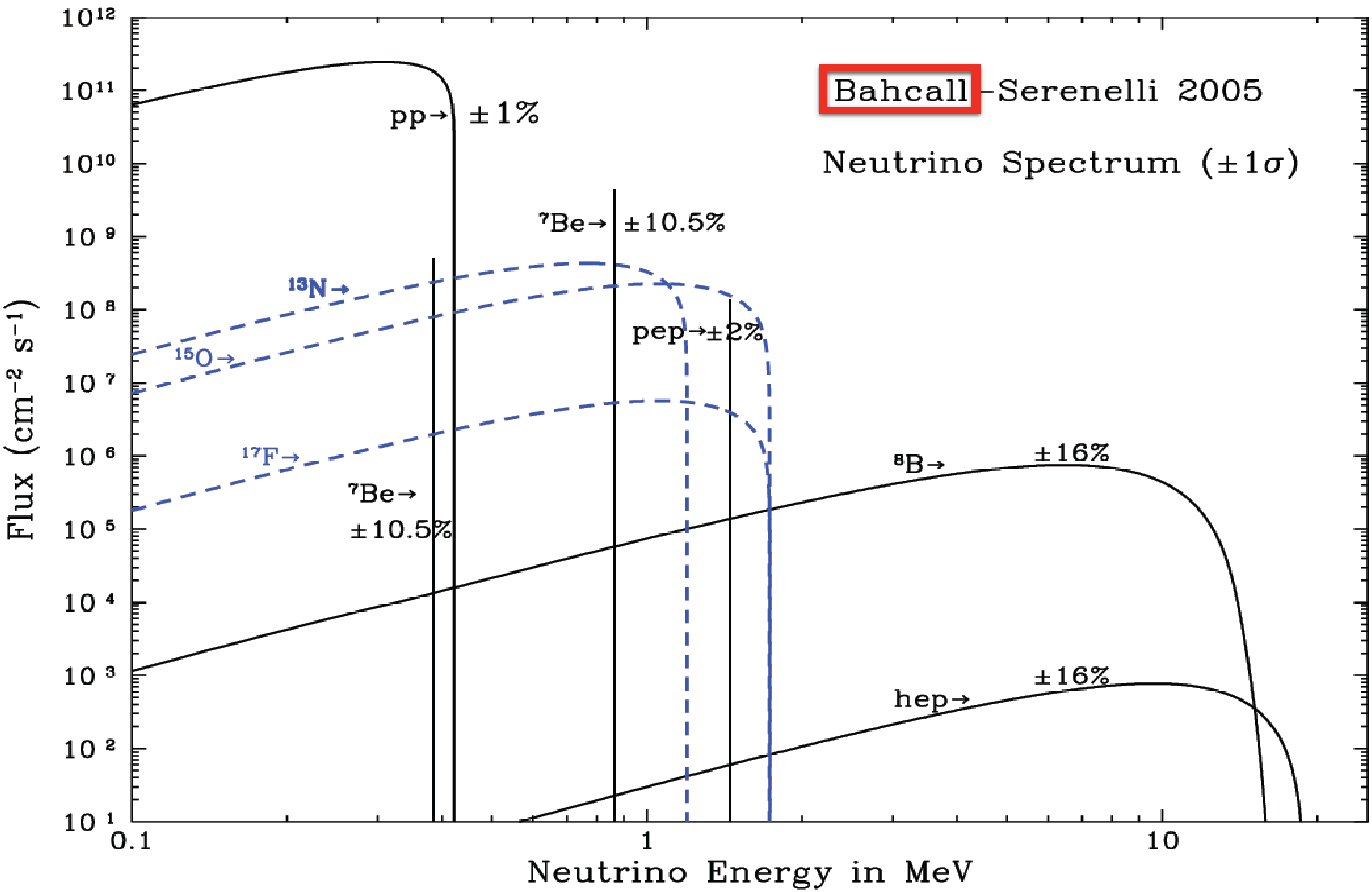




标准太阳模型：太阳中微子

Source	Flux	Energy
pp	$5.99(1\pm0.01)\times10^{10}$ /cm^2/sec	E_{max}=0.42 MeV
pep	$1.42(1\pm0.017)\times10^{8}$ /cm^2/sec	E=1.44 MeV
hep	$7.93(1\pm0.155)\times10^{3}$ /cm^2/sec	E_{max}=18.8 MeV
^{7}Be	$4.84(1\pm0.105)\times10^{9}$ /cm^2/sec	E=0.862MeV 0.384MeV(10.4%)
^{8}B	$5.69(1\pm0.163)\times10^{6}$ /cm^2/sec	E_{max}=~14 MeV
^{13}N	$3.07(1^{+0.31}_{-0.28})\times10^{8}$ /cm^2/sec	E_{max}=1.20 MeV
^{15}O	$2.33(1^{+0.33}_{-0.29})\times10^{8}$ /cm^2/sec	E_{max}=1.73 MeV
^{17}F	$5.84(1\pm0.52)\times10^{6}$ /cm^2/sec	E_{max}=1.79 MeV

标准太阳模型：太阳中微子



每秒有多少太阳中微子产生?

作业：估算太阳中微子到达地球的通量

$$2e^- + 4p \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}.$$

$$\phi = 2 \times \frac{L}{Q} \times \frac{1}{4\pi D^2}$$

Q: local energy deposit

pp-I 26.2 MeV, pp-II 25.6 MeV, pp-III 19.7 MeV

Weighted average: ~ 26 MeV

L: solar luminosity = 3.86×10^{33} erg/sec

D: Distance from the sun to the earth = 1.5×10^{13} cm

$$\phi = 6.6 \times 10^{10}\ \nu_e\ /\mathrm{cm}^2/\mathrm{sec}$$

太阳中微子：1964

Volume 12, Number 11 PHYSICAL REVIEW LETTERS 16 March 1964

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence $^{1}H(p,e^{+}\nu)^{2}H(p,\gamma)^{3}He$ and terminated by the following sequences: (i) $^{3}He(^{3}He,2p)^{4}He$; (ii) $^{3}He(\alpha,\gamma)^{7}Be(e^{-}\nu)^{7}Li(p,\alpha)^{4}He$; and (iii) $^{3}He(\alpha,\gamma)^{7}Be(p,\gamma)^{8}B(e^{+}\nu)^{8}Be^{*}(\alpha)^{4}He$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q=-0.81$ MeV) $^{37}Cl(\nu_{solar},e^{-})^{37}Ar$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo[3] and Alvarez.[4] In this note, we predict the number of absorptions of

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu,e^{-})^{37}Ar$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These results will be reported, and a discussion will be given of the possibility of extending the sensitivity of the method to a degree capable of measuring the solar neutrino flux calculated by Bahcall in the preceding paper.[2]

The apparatus consists of two 500-gallon tanks of perchlorethylene, C_2Cl_4, equipped with agitators and an auxiliary system for purging with helium. It is located in a limestone mine 2300 feet below the surface[3] (1800 meters of water equivalent shielding, m.w.e.). Initially the tanks were swept completely free of air argon by purging the tanks with a stream of helium gas. ^{36}Ar carrier ($0.10\ cm^3$) was introduced and the tanks exposed for periods of four months or more to allow the 35-d ^{37}Ar activity to reach nearly the saturation value. Carrier argon along with any ^{37}Ar pro-

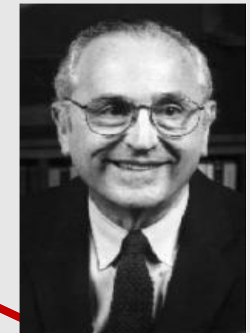
3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \leq 3\times10^{-34}$ sec^{-1} (^{37}Cl atom)$^{-1}$. From this value, Bahcall[2] has set an upper limit on the central temperature of the sun and other relevant information.

On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of C_2Cl_4, so that the expected ^{37}Ar production rate is well above the background of the counter, 0.2 count per day. Using Bahcall's expression,

$$\sum\varphi_{\nu}(\text{solar})\,\sigma_{abs} = (4\pm2)\times10^{-35}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1},$$

then the expected solar neutrino captures in 100 000 gallons of C_2Cl_4 will be 4 to 11 per day, which is an order of magnitude larger than the counter background. On the basis of experience

Bahcall, Davis 1964



the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

$$\nu_e + {}^{37}Cl \rightarrow e^{-} + {}^{37}Ar$$

太阳中微子：1968

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

中微子的能量阈值：0.814 MeV.

^{37}Ar的半衰期35天，利用化学方法每隔一段时间提起^{37}Ar→放射性化学方法

$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$$

pp: 0

pep: 0.22

^{7}Be: 1.16

^{8}B: 6.32

Others: 0.41

Total: $8.1^{+1.4}_{-1.1}$ SNU (solar neutrino unit

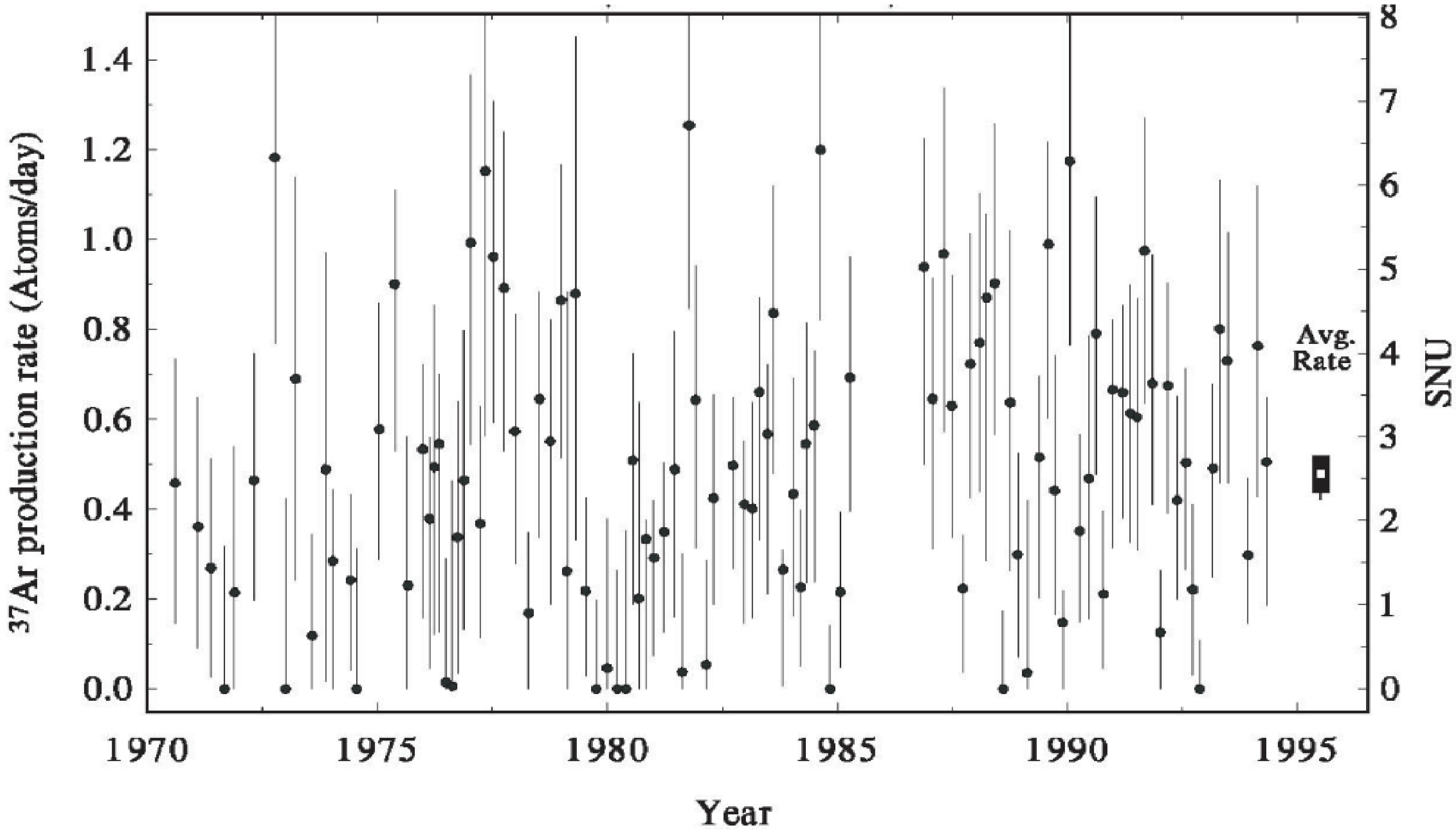
= interactions/10^{36}target/sec)

1968：35天的运行时间→对应11个事例→ 只有理论预期的1/3左右

太阳中微子丢失之谜

实验问题？理论计算问题？传播效应？

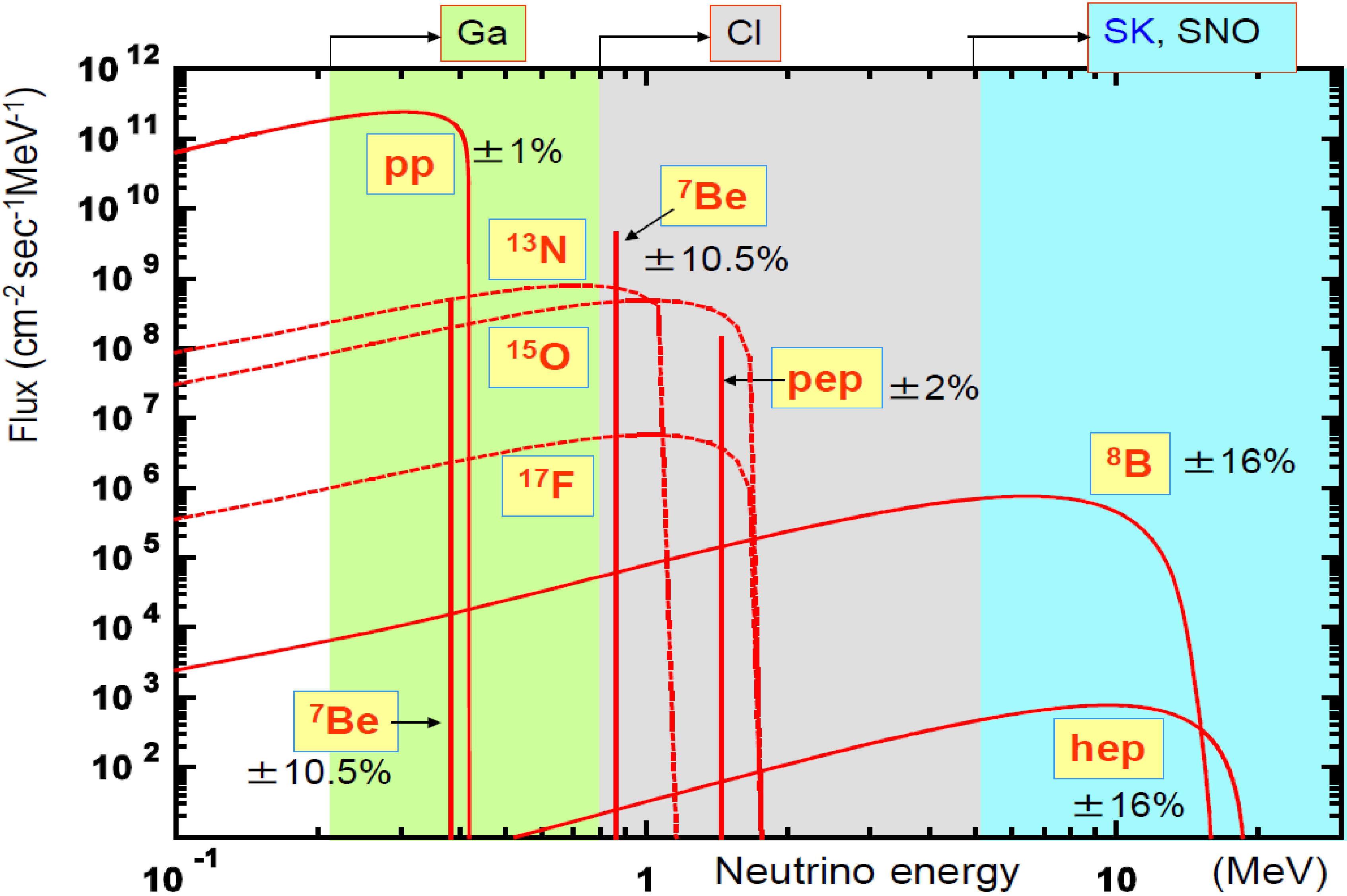
Homestake: 1968-1998



Observed rate (average): 2.56 ±0.16(stat)±0.16(sys.) SNU

SSM prediction (BP2004): 8.5 ±1.8 SNU

太阳中微子的探测阈值



Ga
Cl
SK, SNO
Flux (cm-2sec-1MeV-1)
10 12
10 11
10 10
10 9
10 8
10 7
10 6
10 5
10 4
10 3
10 2
pp
±1%
7Be
±10.5%
13N
15O
pep
±2%
17F
8B
±16%
7Be
±10.5%
hep
±16%
10 -1
1
Neutrino energy
10
(MeV)

Ga放射性化学实验

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$ (threshold = 233 keV)

能否不依赖于标准太阳模型的细节？ Yes! 测量pp中微子→低能量阈值

探测方法最早由前苏联人提出V.A. Kuzmin and G.T. Zatsepin (1966)
SAGE in Baksan, Russia (1990~)： 60t Metallic Ga

GALLEX in Gran SASSO, Italy (1991~)：60t $GaCl_3$
利用化学方法提取^{71}Ge，类似Homestake实验。

pp: 69.9

pep: 2.9

^{7}Be: 34.5

^{8}B: 12.3

others: 9.1

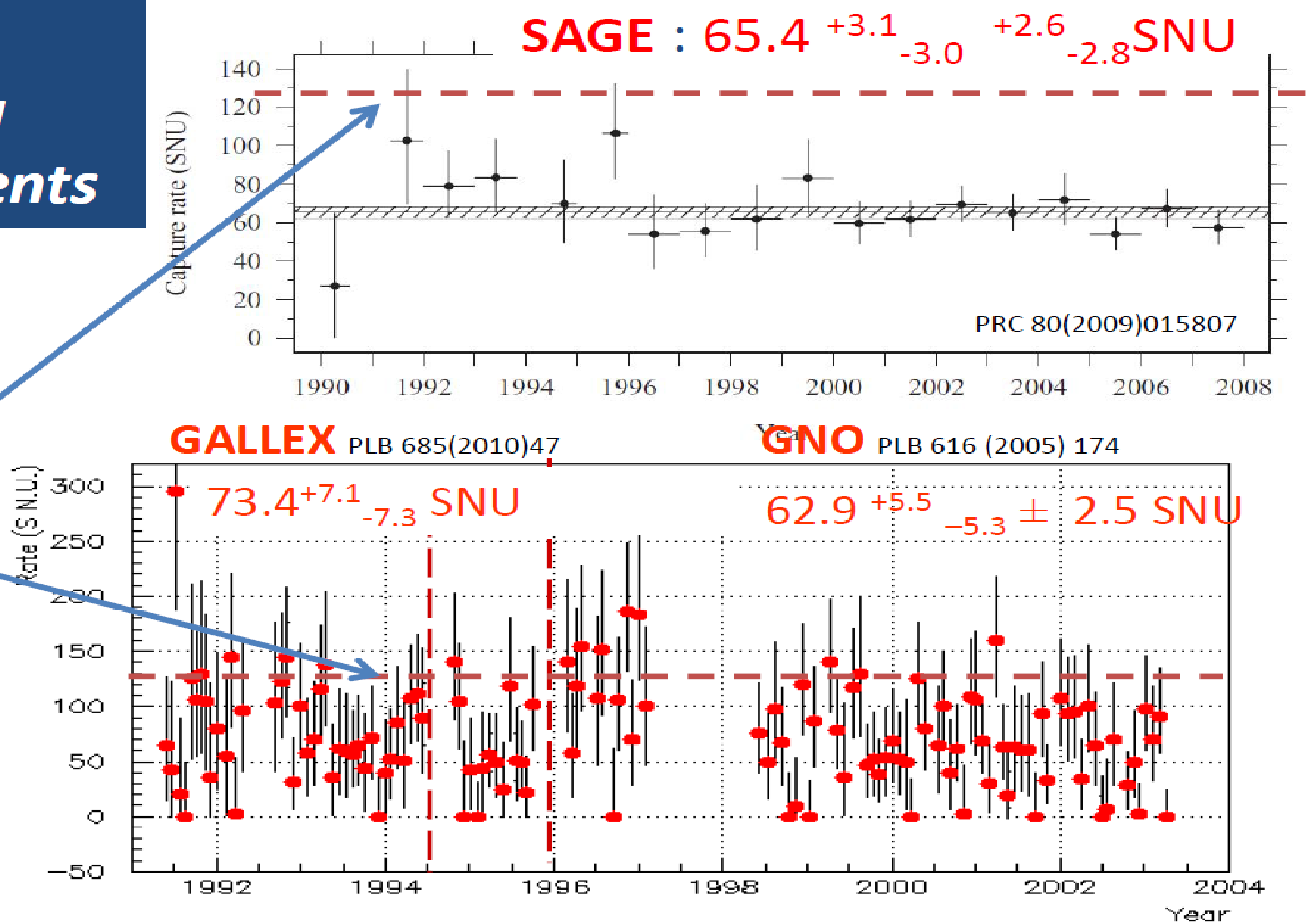
Total: 129^{+9}_{-7} SNU

SAGE (Baksan, Russia)

Gallex/GNO (Gran Sasso, Italy)

Ga放射性化学实验

Results from Ga experiments



SSM prediction

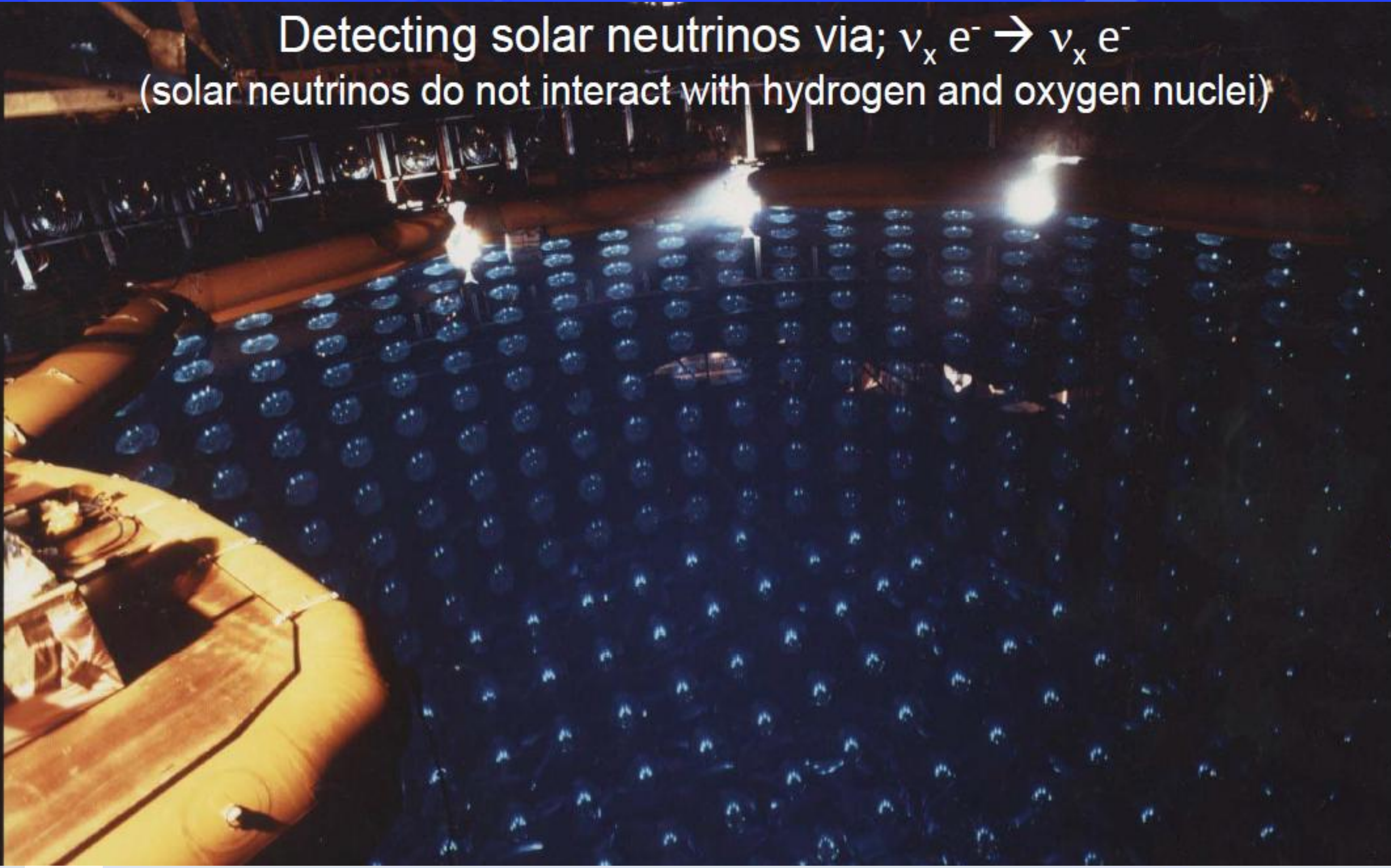
能否说明结论不依赖标准太阳模型的细节?

极端例外情况：pp符合预期，其它中微子受到极大压低 *(He3-He4聚变截面)*

太阳中微子：实时和能量测量

Detecting solar neutrinos via; $\nu_x e^- \rightarrow \nu_x e^-$

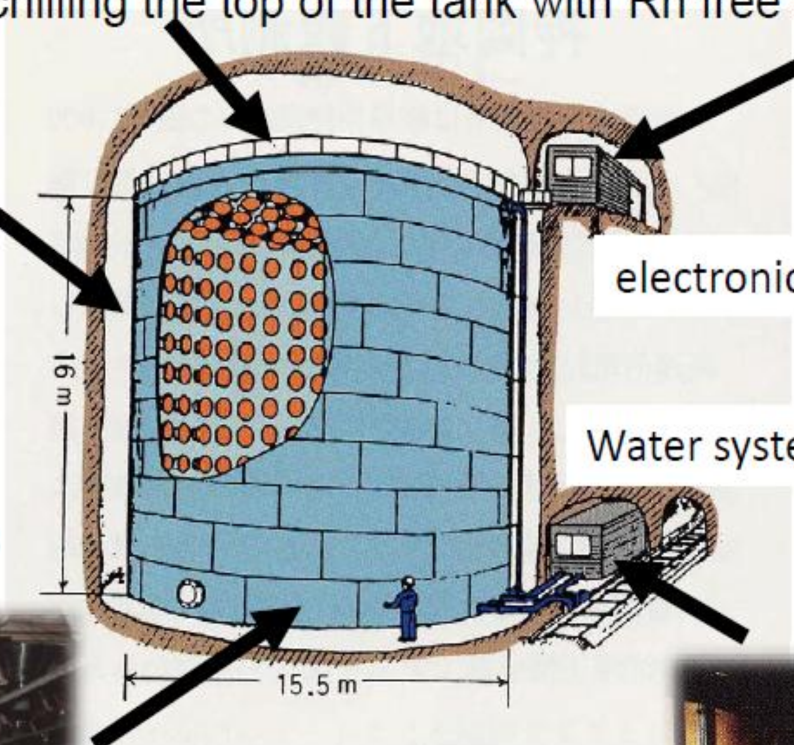
(solar neutrinos do not interact with hydrogen and oxygen nuclei)



Kamiokande-II：从GeV事例→10MeV事例

Installation of anti-counters

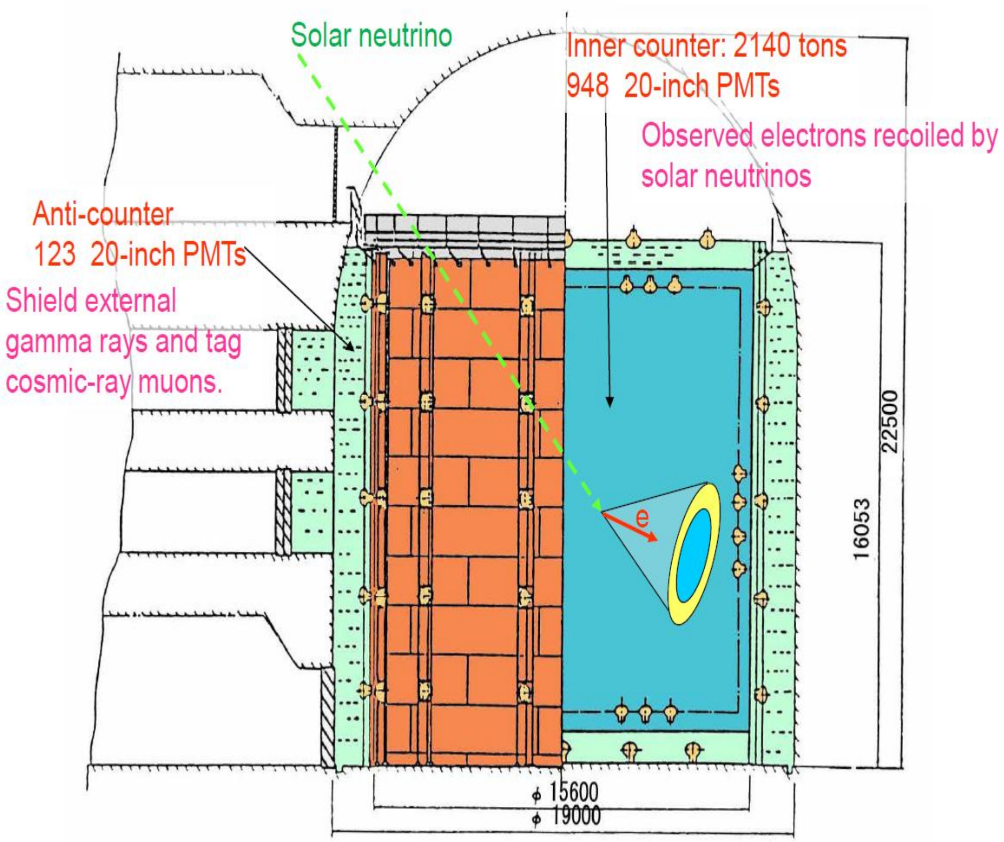
Schilling the top of the tank with Rn free air

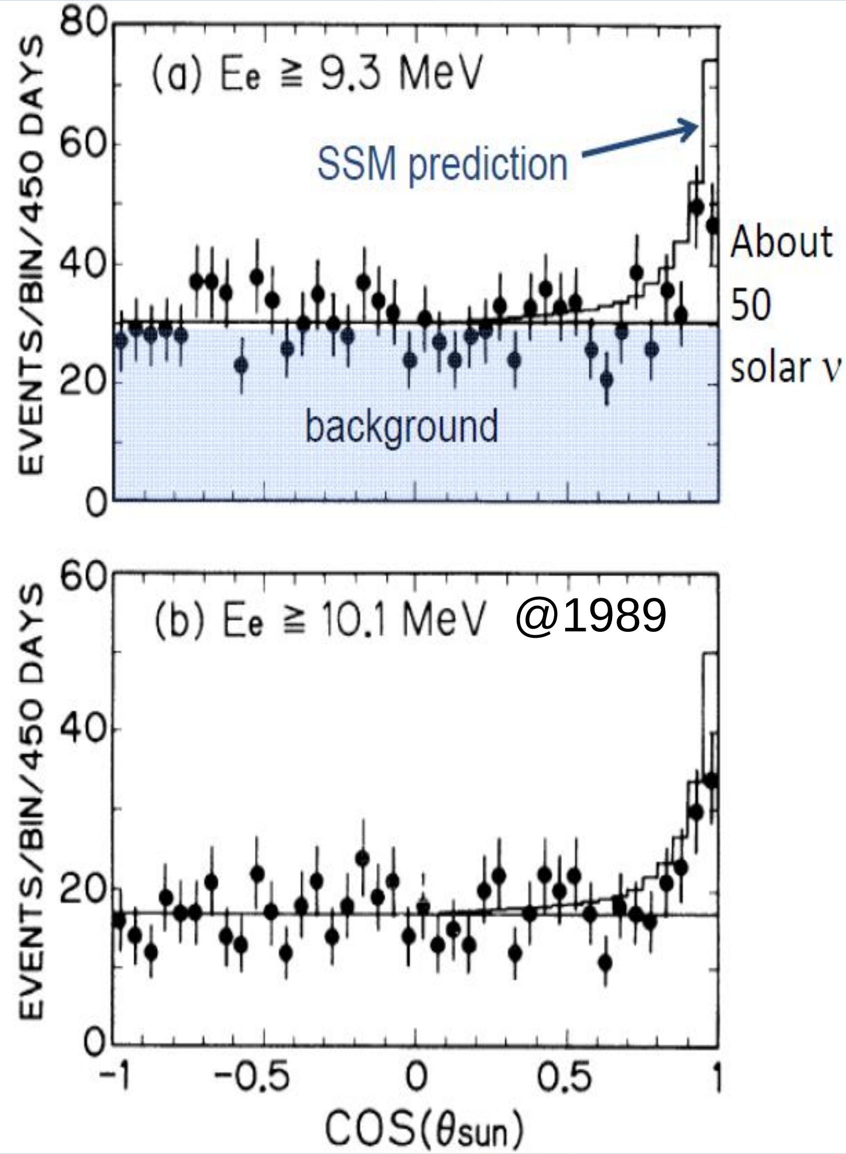


Electronics that measure multi-hit T and Q (U. of Penn)

Improving the water purification system

Kamiokande-II：中微子信号

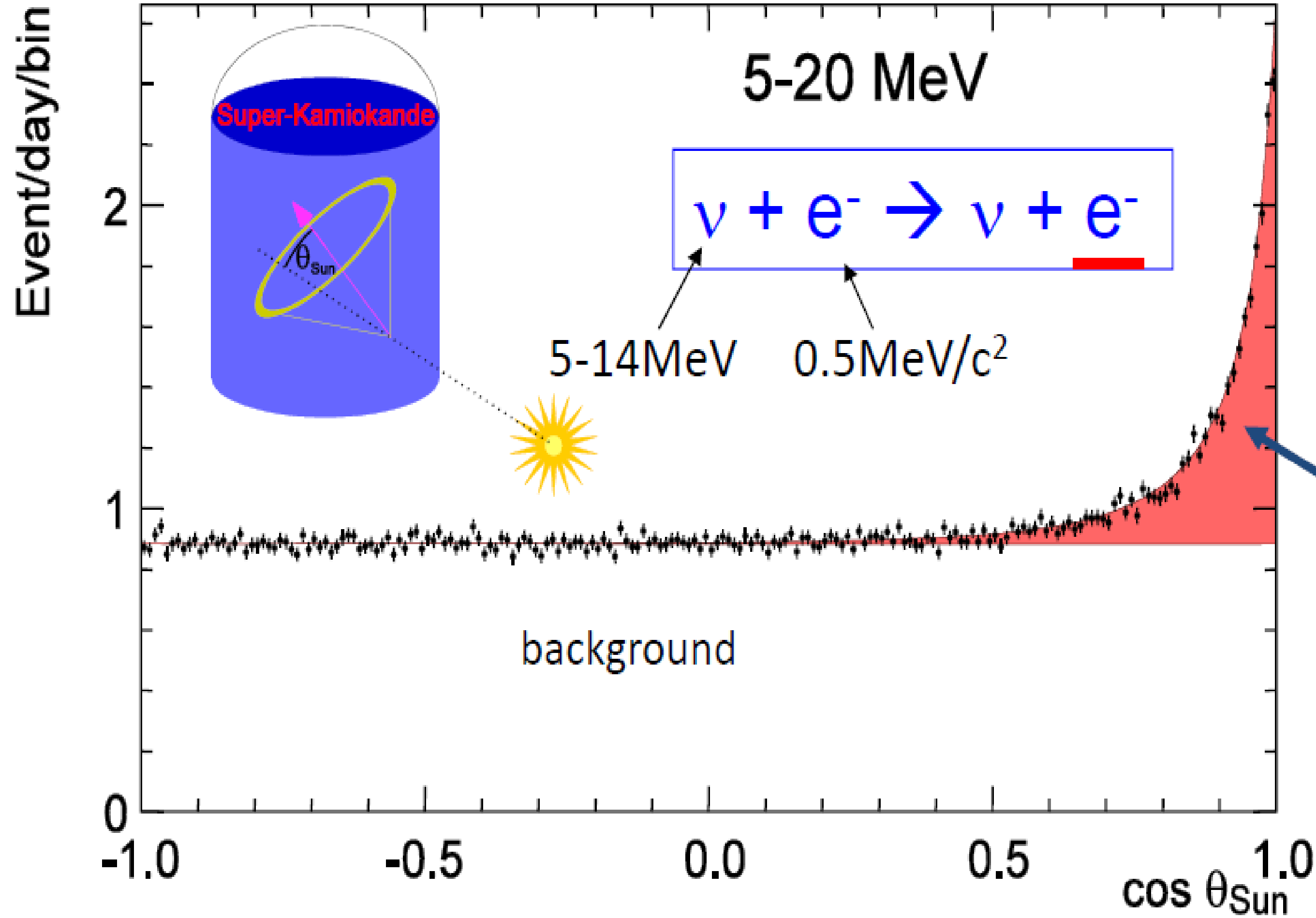




0.46±0.13(stat)±0.08(syst)

不同类型的实验都表明太阳中微子有丢失
实验结果的可能性大大降低

超级神岗实验：SK-1太阳中微子结果



May 31, 1996 –
July 13, 2001
(1496 days)

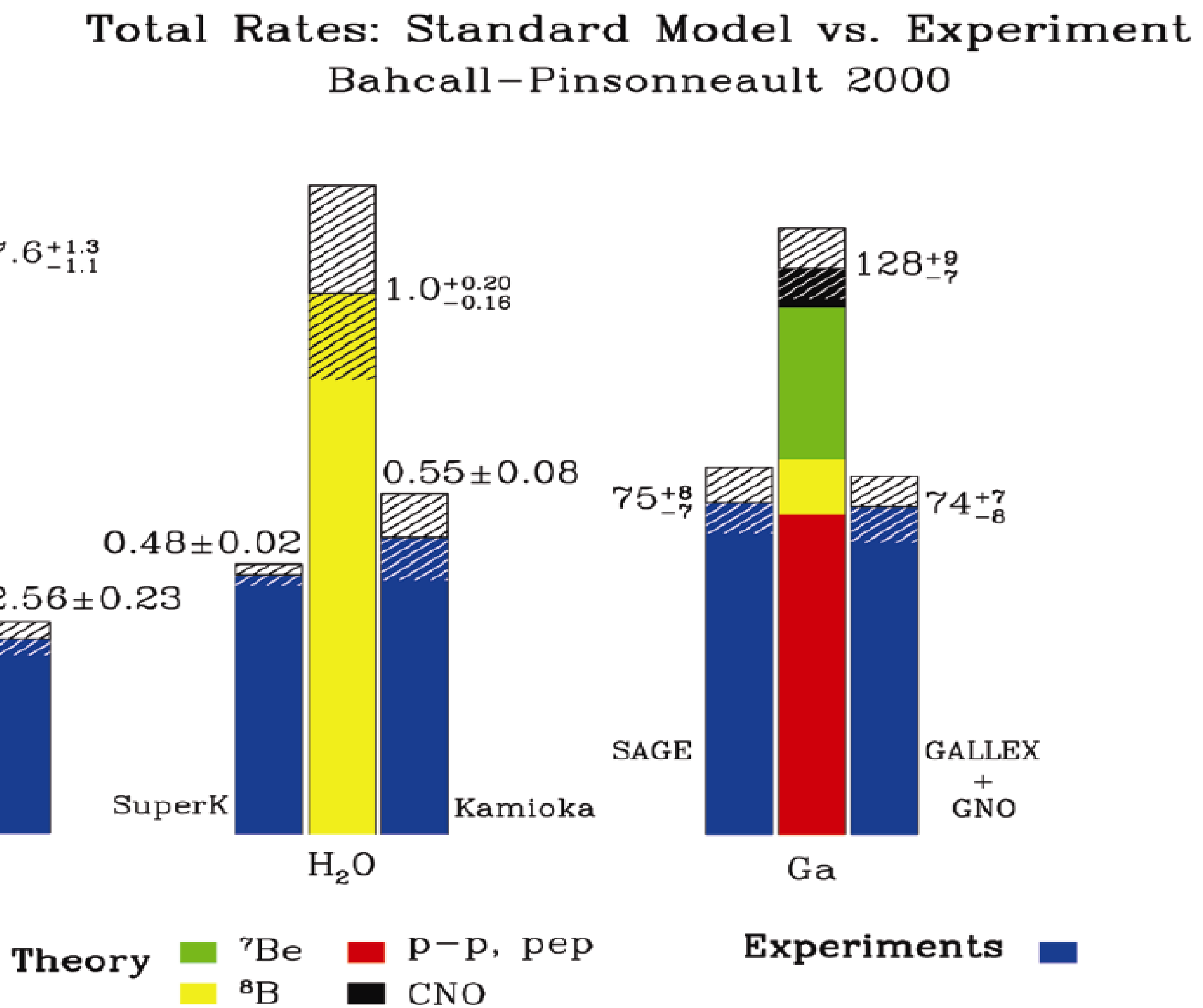
22400±230
solar ν events

(14.5 ev/day)

Assuming ν_e only:

$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.465 \pm 0.005 \, {}^{+0.016}_{-0.015}$$

太阳中微子实验



Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
7.6 +1.3 −1.1
2.56±0.23
Cl
1.0 +0.20 −0.16
0.48±0.02
0.55±0.08
SuperK
Kamioka
H2O
128 +9 −7
75 +8 −7
74 +7 −8
SAGE
GALLEX + GNO
Ga
Theory
7Be
8B
p−p, pep
CNO
Experiments

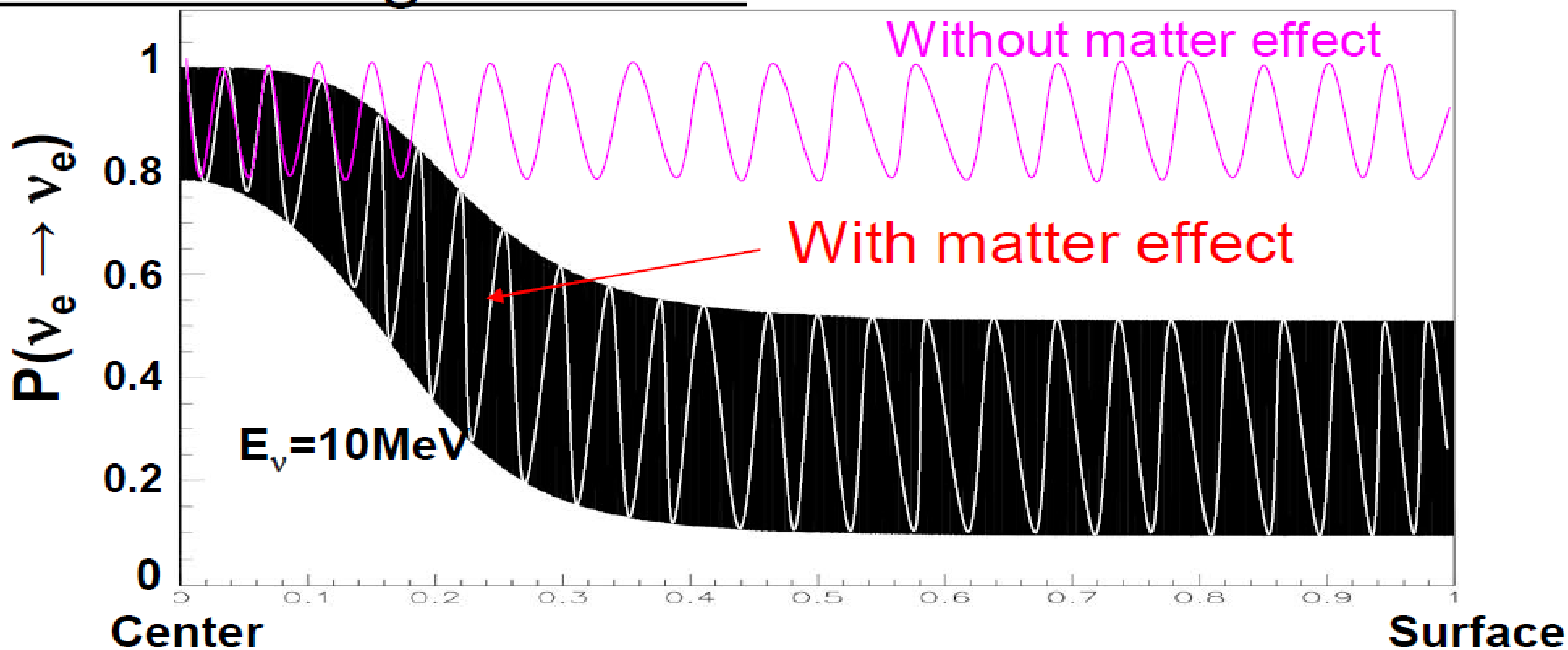
MSW效应

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_{\mu/\tau}\end{pmatrix}=\begin{pmatrix}-\frac{\Delta m^2}{4E}\cos 2\theta+\sqrt{2}G_F n_e & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_{\mu/\tau}\end{pmatrix}$$

Matter effect

G_F : Fermi coupling constant
n_e : Electron density

Travel through the Sun



MSW效应

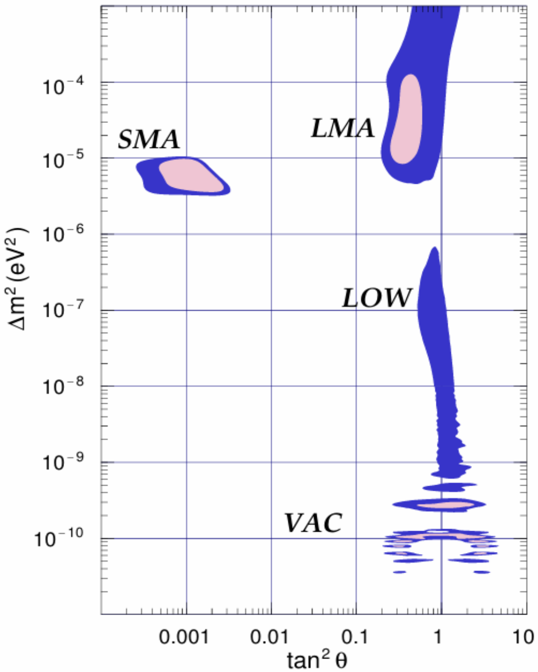
LMA (Large Mixing Angle): $\Delta m^2 \sim 5 \times 10^{-5}\,\text{eV}^2$, $\tan^2\vartheta \sim 0.8$

LOW (LOW Δm^2): $\Delta m^2 \sim 7 \times 10^{-8}\,\text{eV}^2$, $\tan^2\vartheta \sim 0.6$

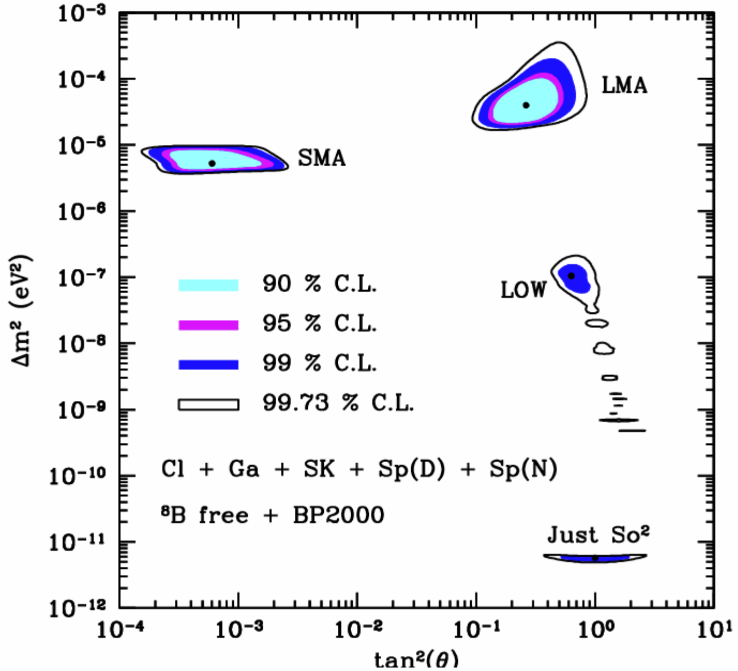
SMA (Small Mixing Angle): $\Delta m^2 \sim 5 \times 10^{-6}\,\text{eV}^2$, $\tan^2\vartheta \sim 10^{-3}$

QVO (Quasi-Vacuum Oscillations): $\Delta m^2 \sim 10^{-9}\,\text{eV}^2$, $\tan^2\vartheta \sim 1$

VAC (VACuum oscillations): $\Delta m^2 \lesssim 5 \times 10^{-10}\,\text{eV}^2$, $\tan^2\vartheta \sim 1$



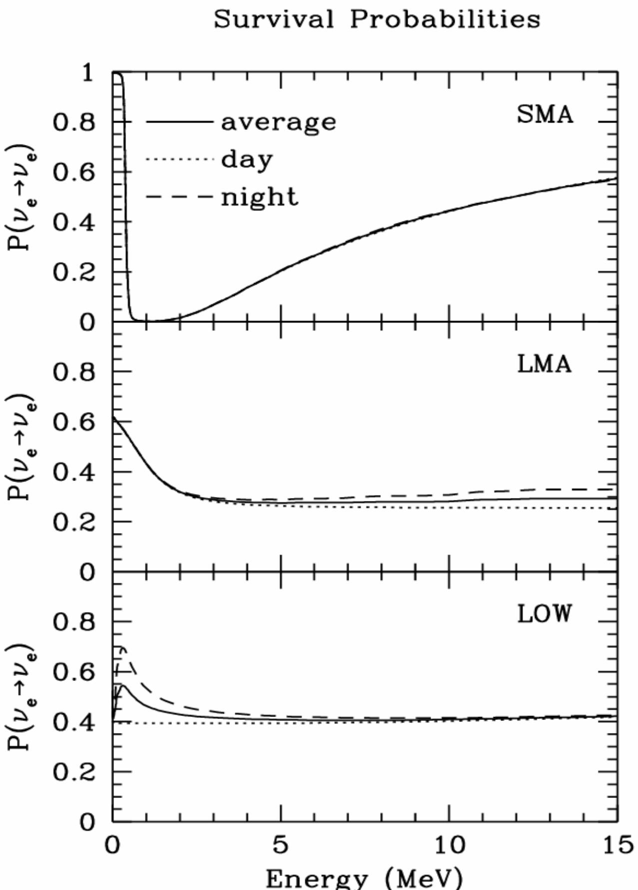
[de Gouvea, Friedland, Murayama, PLB 490 (2000) 125]



[Bahcall, Krastev, Smirnov, JHEP 05 (2001) 015]

MSW效应

[Bahcall, Krastev, Smirnov, PRD 58 (1998) 096016]

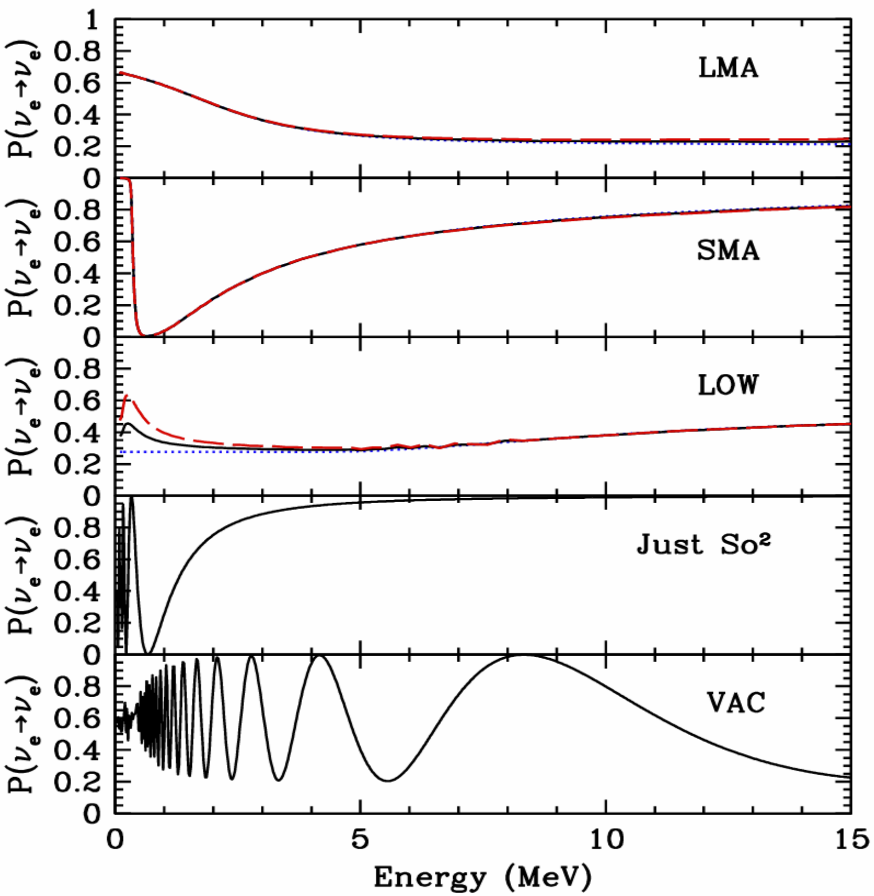


SMA: $\Delta m^2 = 5.0 \times 10^{-6}\ \mathrm{eV}^2$ $\sin^2 2\vartheta = 3.5 \times 10^{-3}$

LMA: $\Delta m^2 = 1.6 \times 10^{-5}\ \mathrm{eV}^2$ $\sin^2 2\vartheta = 0.57$

LOW: $\Delta m^2 = 7.9 \times 10^{-8}\ \mathrm{eV}^2$ $\sin^2 2\vartheta = 0.95$

[Bahcall, Krastev, Smirnov, JHEP 05 (2001) 015]



LMA: $\Delta m^2 = 4.2 \times 10^{-5}\ \mathrm{eV}^2$ $\tan^2\vartheta = 0.26$

SMA: $\Delta m^2 = 5.2 \times 10^{-6}\ \mathrm{eV}^2$ $\tan^2\vartheta = 5.5 \times 10^{-4}$

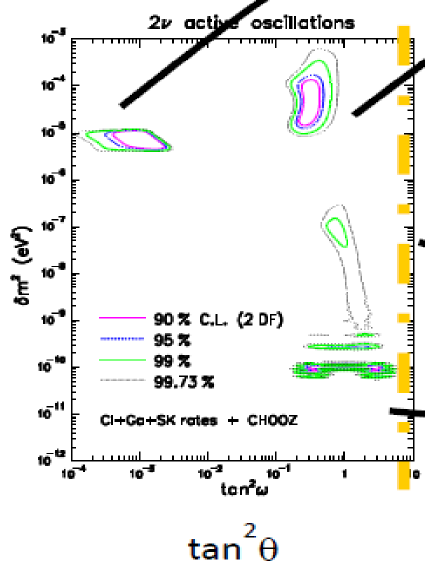
LOW: $\Delta m^2 = 7.6 \times 10^{-8}\ \mathrm{eV}^2$ $\tan^2\vartheta = 0.72$

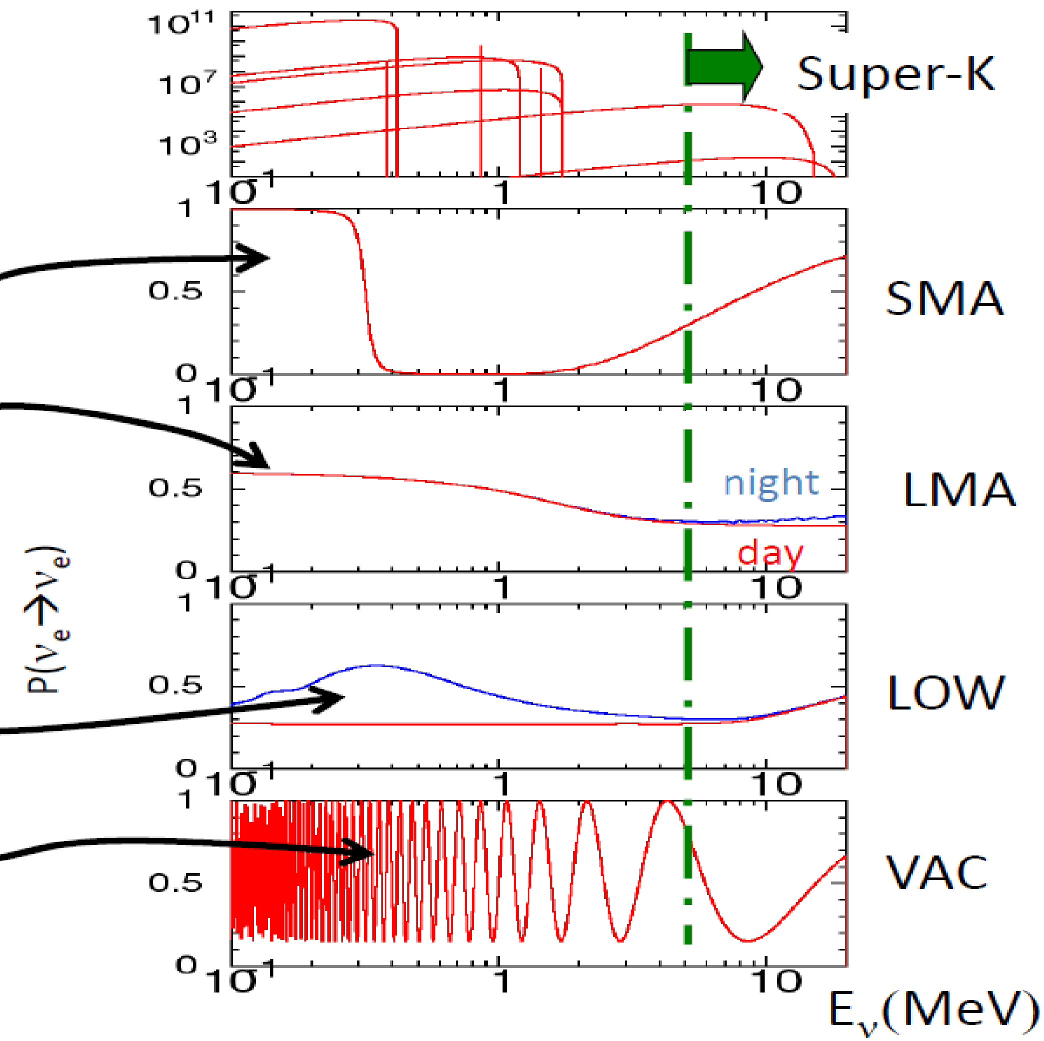
Just So^2: $\Delta m^2 = 5.5 \times 10^{-12}\ \mathrm{eV}^2$ $\tan^2\vartheta = 1.0$

VAC: $\Delta m^2 = 1.4 \times 10^{-10}\ \mathrm{eV}^2$ $\tan^2\vartheta = 0.38$

MSW效应的验证

Oscillation probabilities and Super-K



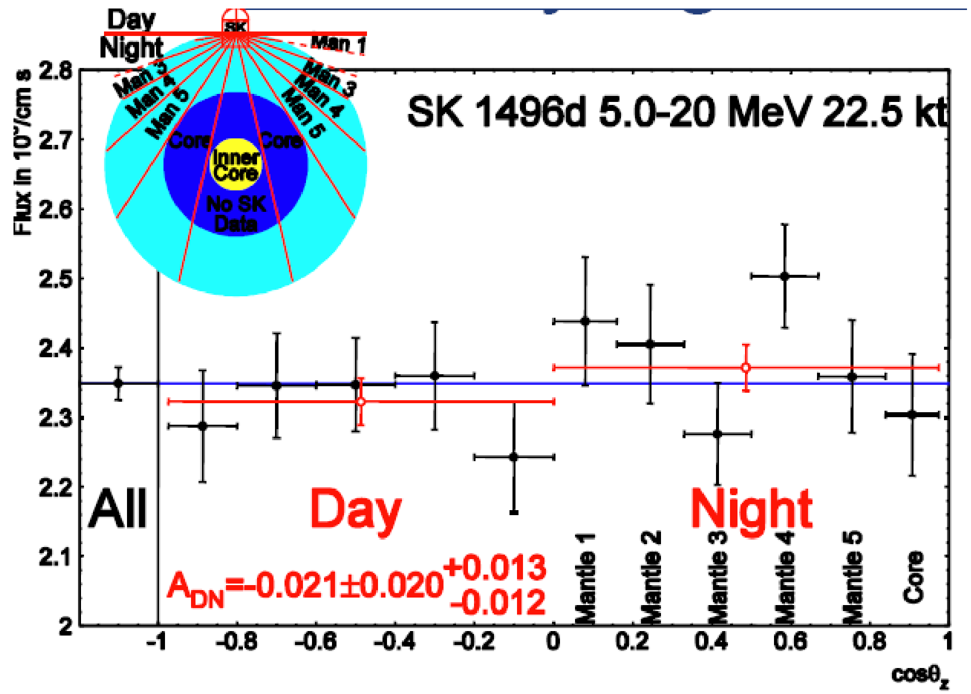


除了总事例数观测外：能谱变形？日夜效应？季节调制效应？

超级神岗实验：SK-1太阳中微子结果

- 没有观测到日夜不对称效应
- 没有观测到季节调制效应
- 没有观测到能谱变形

→ Disfavor SMA & VO solution



结果与大角混合一致

但还无法给出发现性的结论

SNO实验：另一个途径→利用重水做探测介质

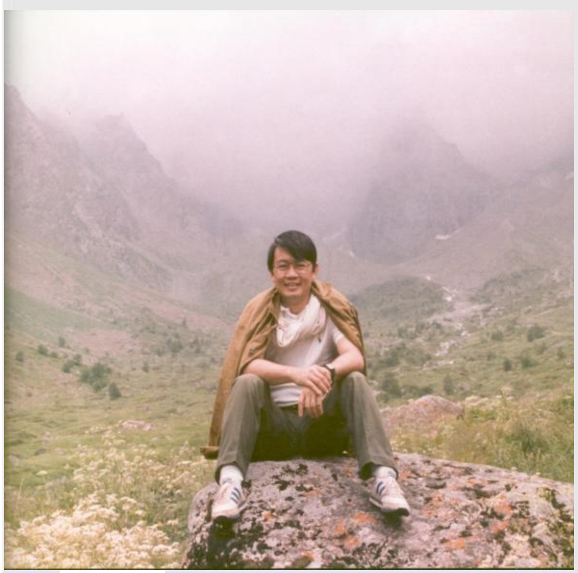
VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

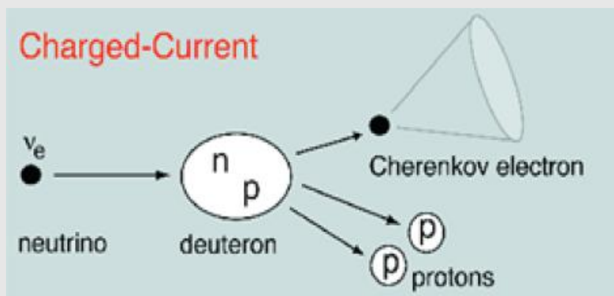
Direct Approach to Resolve the Solar-Neutrino Problem

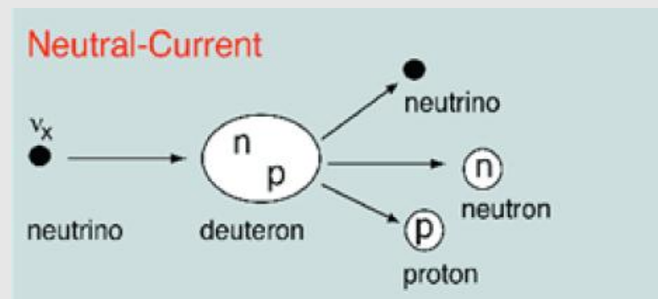
Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

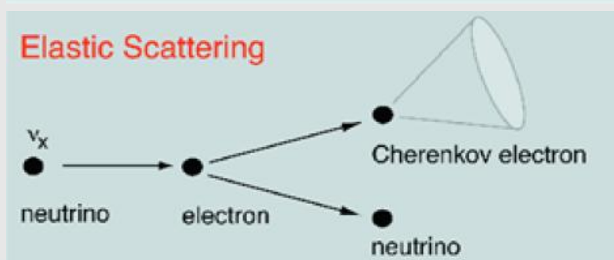
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis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

PACS numbers: 96.60.Kx, 14.60.Gh







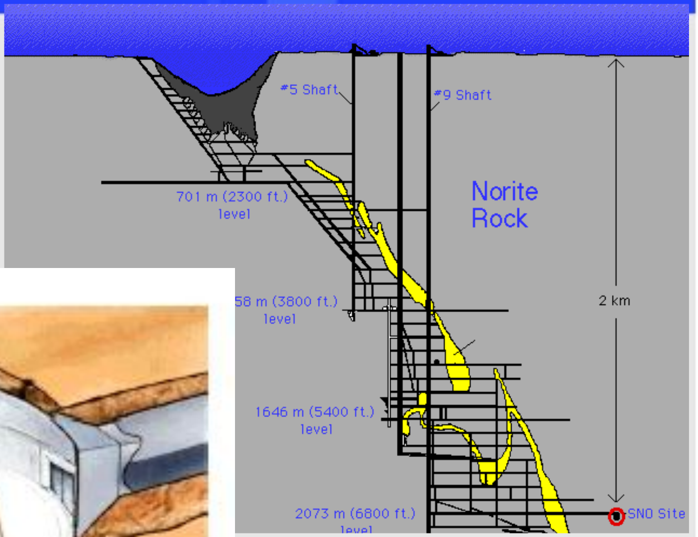


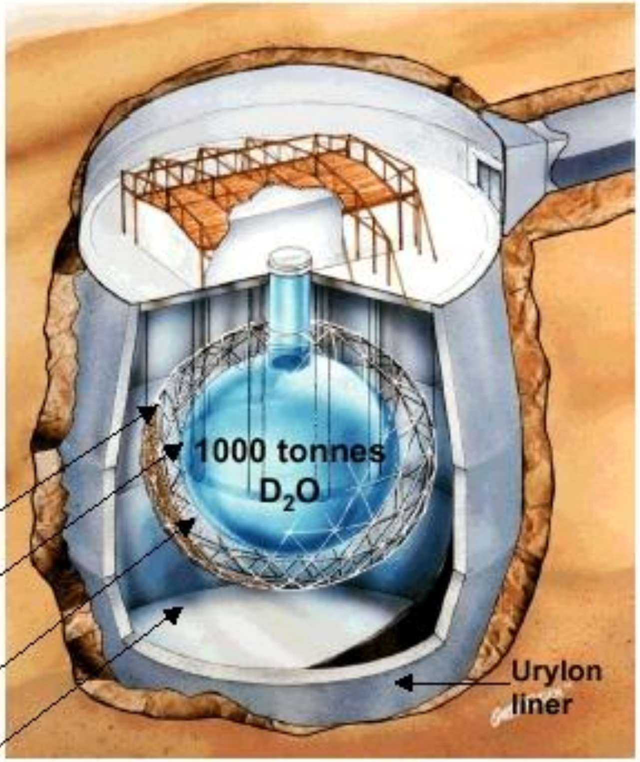
利用重水→一石三鸟
独立于标准太阳模型

陈华森1987年英年早逝

SNO实验：另一个途径→利用重水做探测介质

加拿大：Sudbury Neutrino Observatory





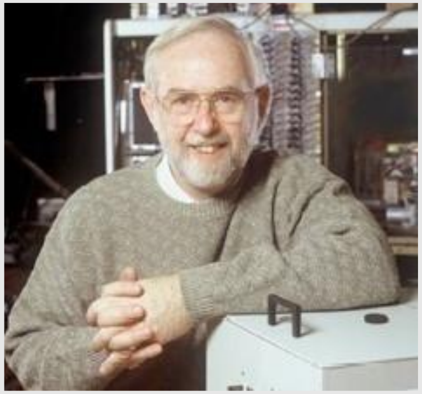
17.8m dia. PMT Support Structure
9456 PMTs, 56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

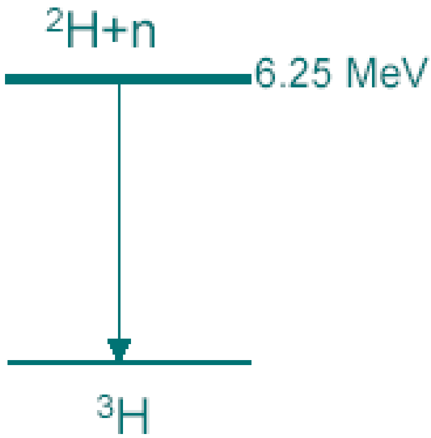
Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 μ day^{-1})

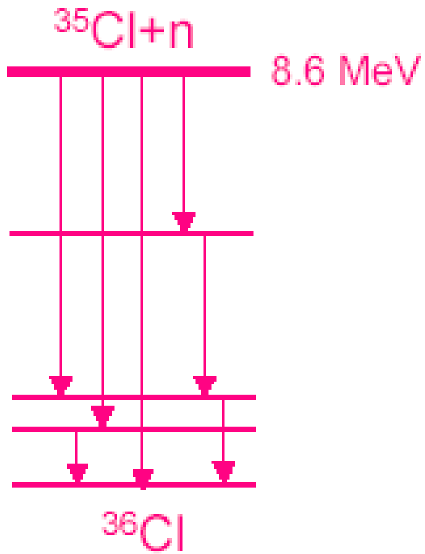


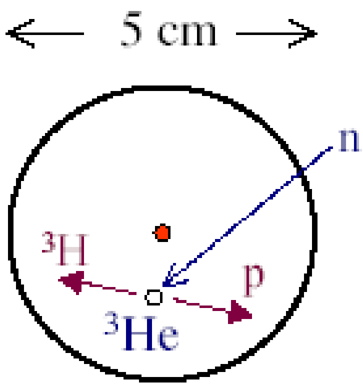
Arthur B. McDonald

SNO实验：提高中性流分辨能力

Phase I (D_2O)	Phase II (salt)	Phase III (^3He)
Nov. 99 - May 01	July 01 - Sep. 03	Summer 04 - Dec. 06
n captures on $^2H(n, \gamma)^3H$	2 t NaCl. n captures on $^{35}Cl(n, \gamma)^{36}Cl$	40 proportional counters $^3He(n, p)^3H$
$\sigma = 0.0005$ b	$\sigma = 44$ b	$\sigma = 5330$ b
Observe 6.25 MeV γ	Observe multiple γ's	Observe p and ^3H
PMT array readout	PMT array readout	PC independent readout
Good CC	Enhanced NC	Event by Event Det.



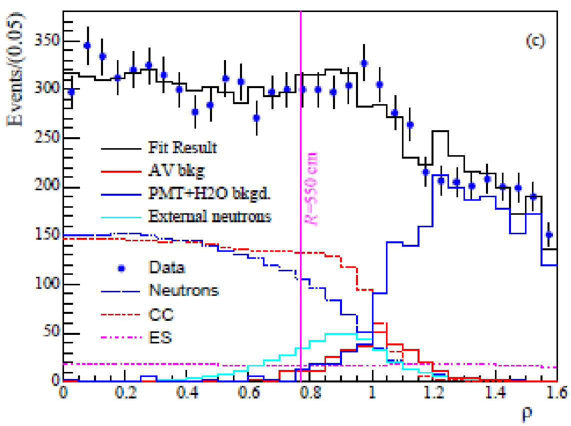




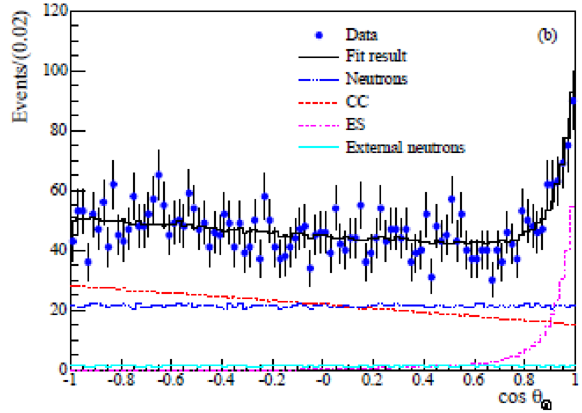
$n + {}^3He \rightarrow p + {}^3H$

SNO实验：Salt Phase

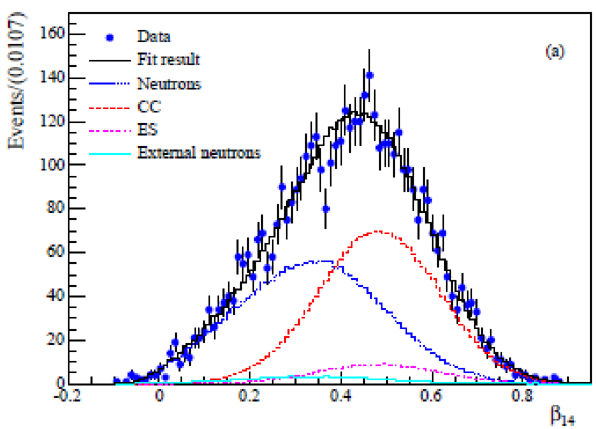
vertex



$\cos\theta_{sun}$



~ isotropy



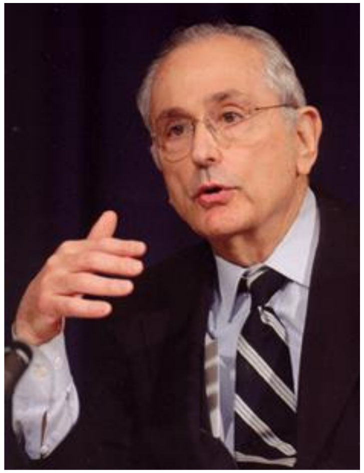
$$\phi_{CC}(\nu_e) = 1.68\ ^{+0.06}_{-0.06}\ (\text{stat.})\ ^{+0.08}_{-0.09}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{ES}(\nu_x) = 2.35\ ^{+0.22}_{-0.22}\ (\text{stat.})\ ^{+0.15}_{-0.15}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{NC}(\nu_x) = 4.94\ ^{+0.21}_{-0.21}\ (\text{stat.})\ ^{+0.38}_{-0.34}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

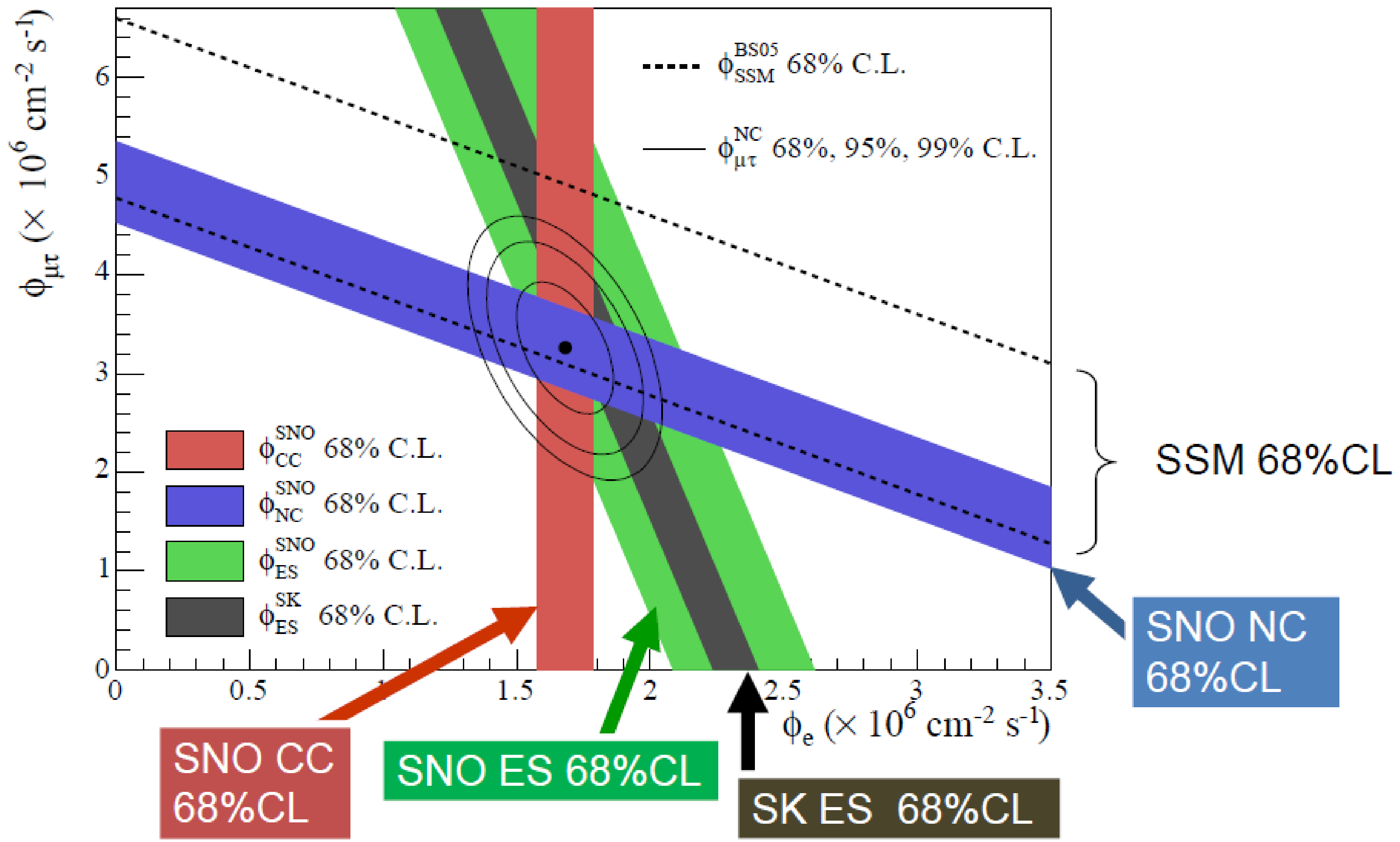
$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023\ ^{+0.029}_{-0.031}$$

- 以大于5-sigma水平观测到太阳中微子的味转换效应
- 标准太阳模型的正确性



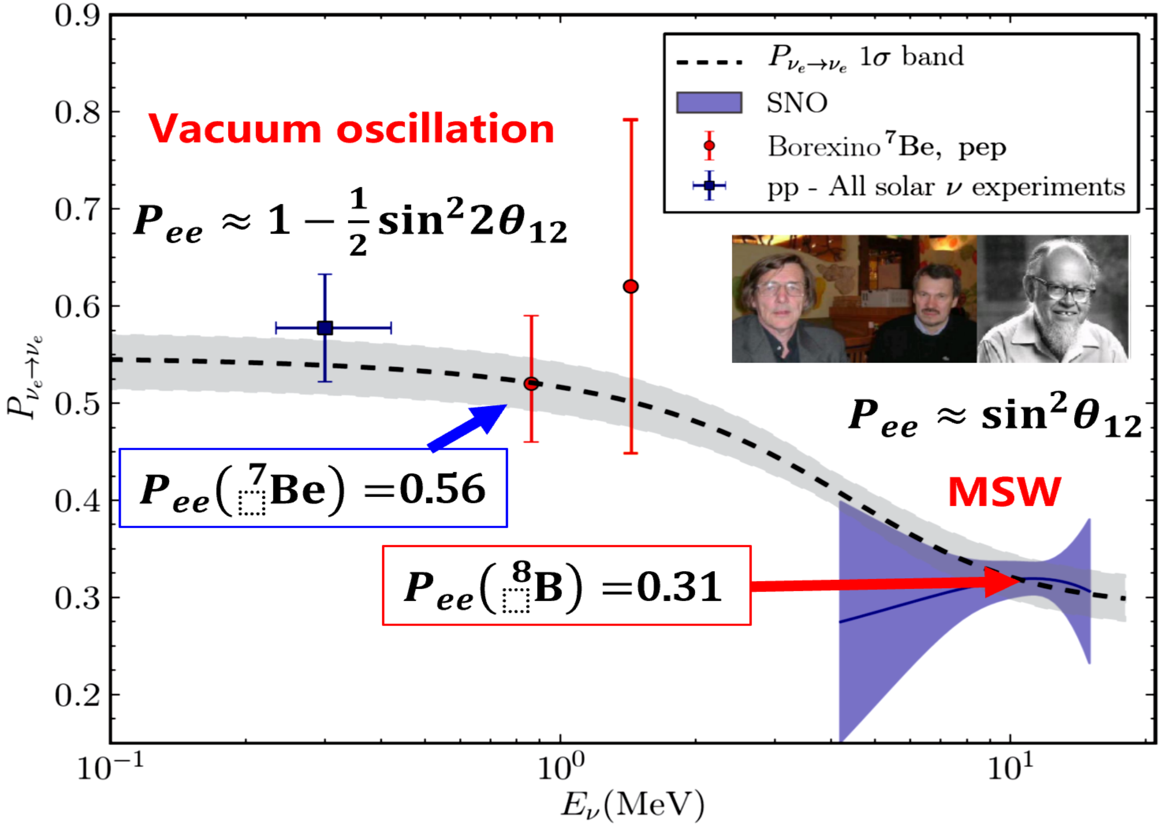
J. Bahcall

SNO实验：味转化的直接证据



Three (or 4) different measurements intersect at a point (➔non trivial).
All the data are consistently explained within the existence of (ν_μ+ν_τ)

LMA-MSW理论解读



For high-energy ^{8}B neutrinos

at production $r = 0$

$$\begin{pmatrix} |\tilde{\nu}_1(0)\rangle \\ |\tilde{\nu}_2(0)\rangle \end{pmatrix} = \begin{pmatrix} c_{\hat{\theta}} & -s_{\hat{\theta}} \\ s_{\hat{\theta}} & c_{\hat{\theta}} \end{pmatrix} \begin{pmatrix} |\nu_e(0)\rangle \\ |\nu_\mu(0)\rangle \end{pmatrix}$$

adiabatic evolution

$$\begin{pmatrix} |\tilde{\nu}_1(R)\rangle \\ |\tilde{\nu}_2(R)\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} |\tilde{\nu}_1(0)\rangle \\ |\tilde{\nu}_2(0)\rangle \end{pmatrix}$$

on the solar surface $r = R$

$$\begin{pmatrix} |\nu_e(R)\rangle \\ |\nu_\mu(R)\rangle \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} |\tilde{\nu}_1(R)\rangle \\ |\tilde{\nu}_2(R)\rangle \end{pmatrix}$$

survival probability

$$P_{ee} = c_{\hat{\theta}}^2 c_\theta^2 + s_{\hat{\theta}}^2 s_\theta^2 = \sin^2\theta$$

$\hat{\theta} \longrightarrow \pi/2$ as $A \gg \Delta m^2$

For the MSW resonance to happen

$\theta \in [0, \frac{\pi}{4}]$, $\Delta m_{21}^2 > 0$ ⟷ $\theta \in [\frac{\pi}{4}, \frac{\pi}{2}]$, $\Delta m_{21}^2 < 0$

$\theta_{12} = 34^\circ$

Normal neutrino mass ordering

For low-energy ^{7}Be neutrinos

$$P_{ee} \approx 1 - \frac{1}{2}\sin^2 2\theta_{12}$$

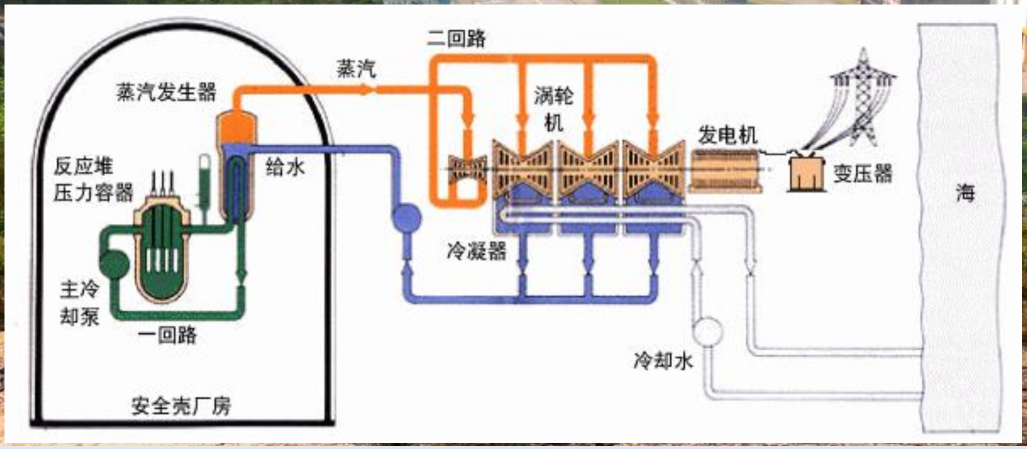
Oscillations in vacuum

Part IV:

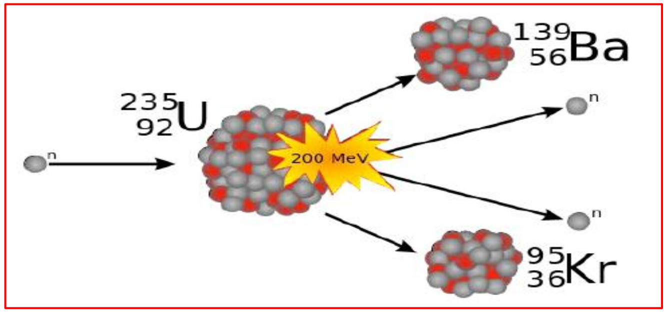
反应堆中微子振荡

反应堆：大亚湾为例

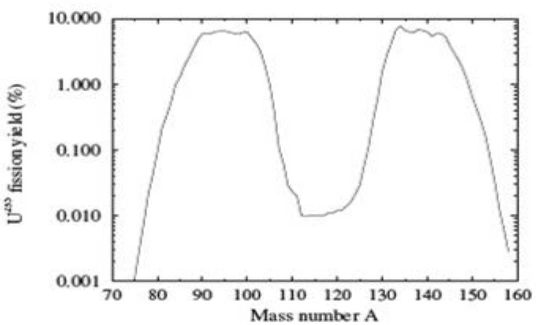
绝大部分商用反应堆为压水堆或沸水堆，两者原理相同
电功率约为热功率的1/3。大亚湾：2.9 GW_{th}，900 $MW_e \rightarrow$1080 MW_e

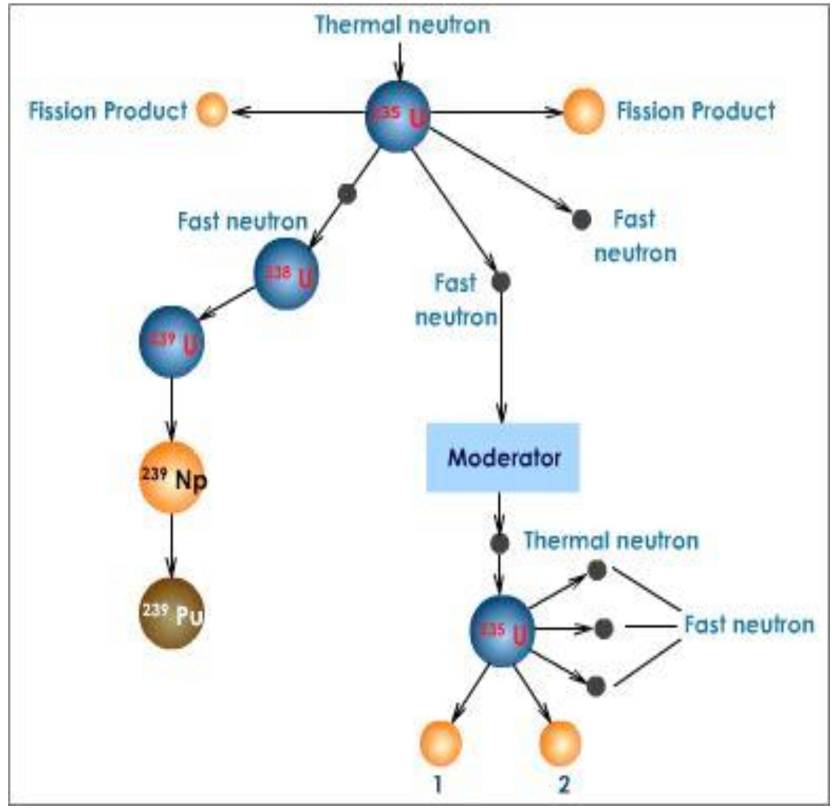


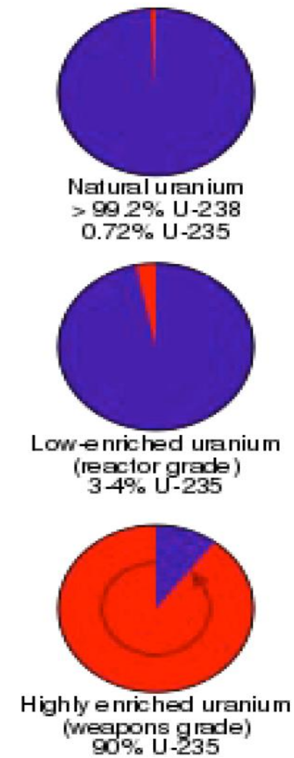
反应堆燃料的裂变

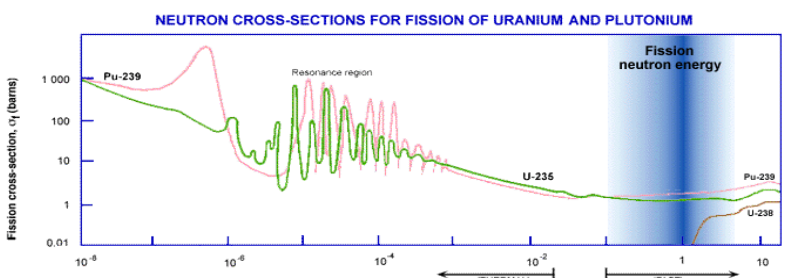


$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$









Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = 10^{-28} m2, 1 MeV = 1.6 x 10^{-13} J

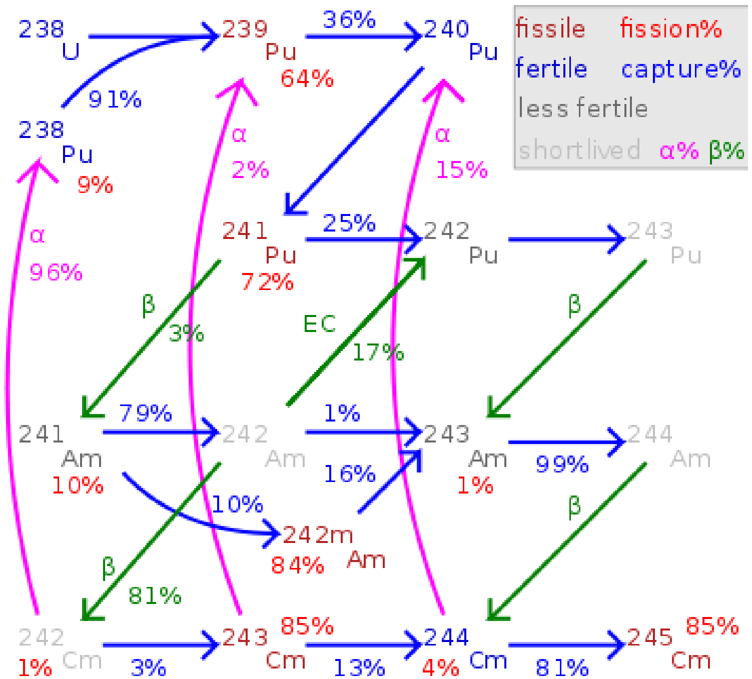
U235/Pu239/Pu241吸收热中子发生裂变

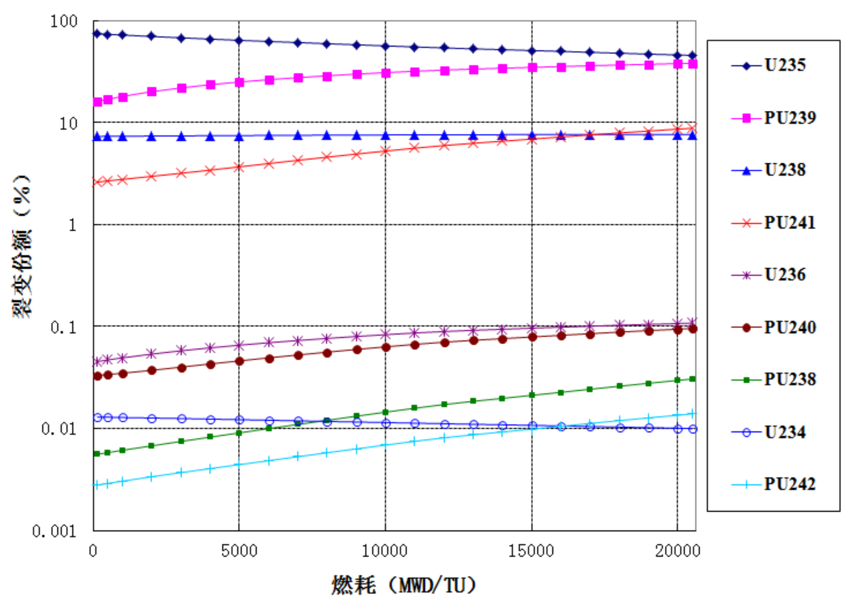
U238只能吸收快中子发生裂变

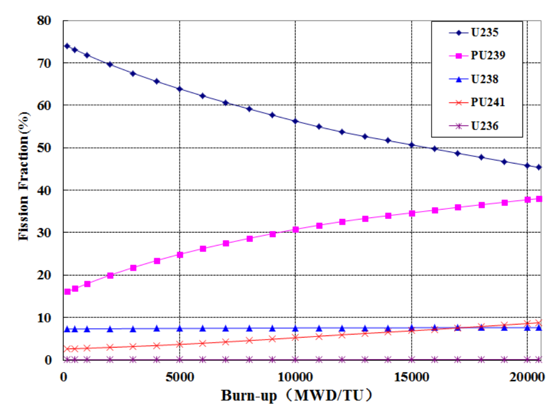
中微子来自裂变产物接下来的beta衰变

反应堆的燃料的演化

- **初始U235：4.45%，其余为U238和O**
- **U238 吸收中子U239，进行beta衰变变成Pu239，再吸收2个中子变成Pu241。**
- **占主要裂变比例(>99%): U238, U238, Pu239, Pu241**
- **燃耗(Burnup)：MW·day/ton U**







反应堆中微子

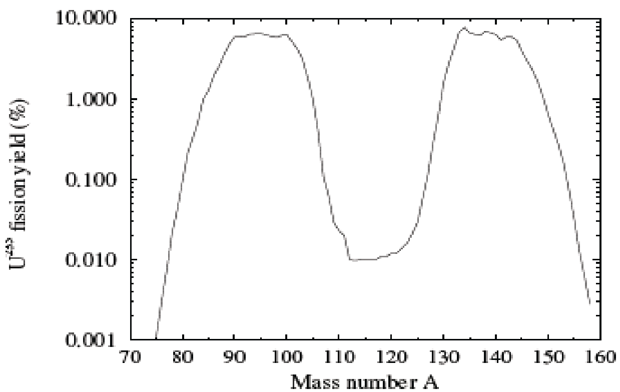
β衰变: $^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e$　　忽略反冲核能量: $E_0 = E_e + E_\nu$

中微子能谱:

$$S_f(E) = \sum_b \left(K_f^b \cdot F(Z_f, A_f, E) \cdot pE(E - E_{0f}^b)^2 \cdot C_f^b(E) \cdot (1 + \delta_f^b(Z_f, A_f, E)) \right)$$

核素裂变的碎片有固定的质量分布

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



核素裂变有固定的中微子能谱

$$S_k = \sum_f A_f \cdot S_f$$

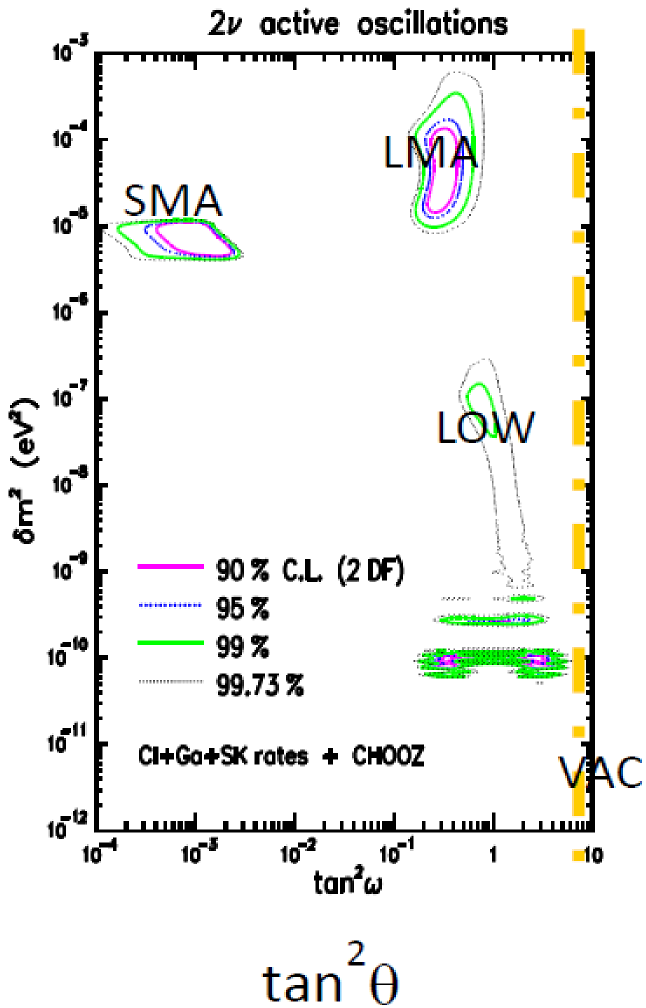
- 裂变产物是富中子核，平均每裂变释放**6个电子型反中微子**

- 直接方法：累加各核素的能谱(1000多种核素/6000道衰变)核数据库不完整
- 简介方法：测量电子能谱/直接测量中微子能谱

KamLAND：实验的起源

Fogli et al.

Atsuto Suzuki



SMA and LMA solutions were equally likely in the 1990's (although many people believed that mixing angles should be small).

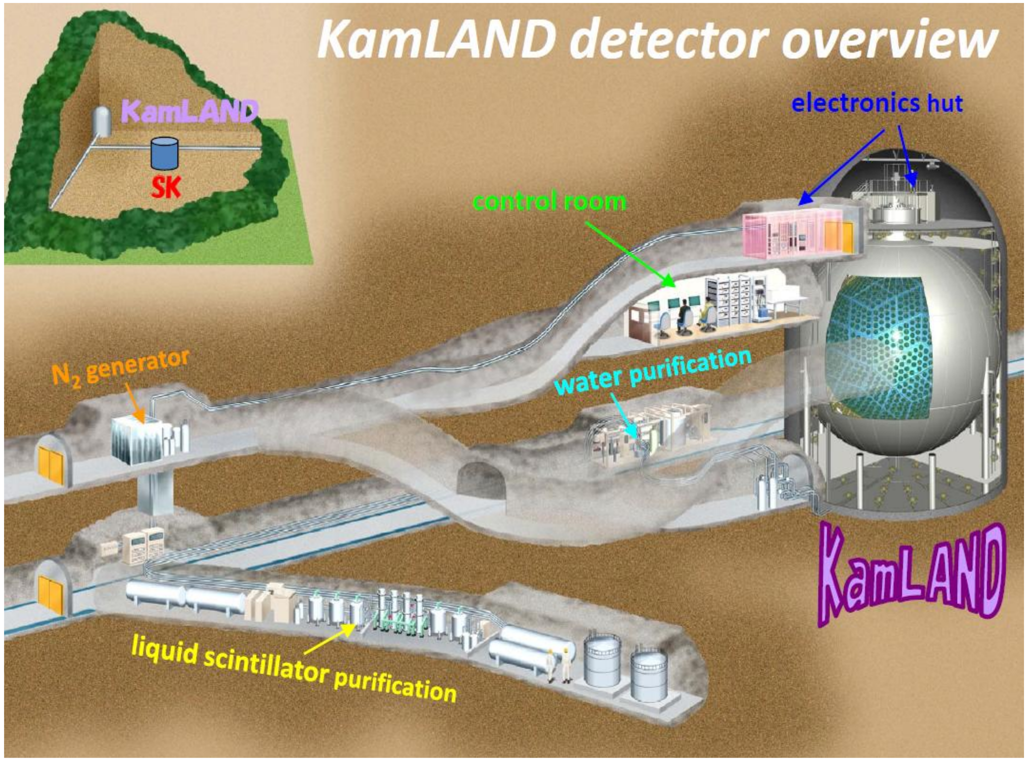
If LMA is the real solution, a reactor long baseline experiment can observe the oscillation.

Even if LMA is not the solution, this experiment can clearly exclude LMA.

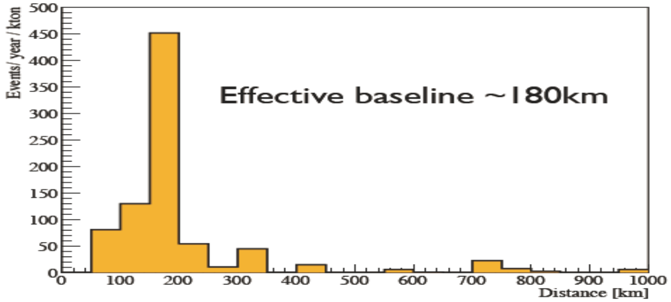
➔Found there were many reactors in Japan…

➔ Kamiokande no more used...

KamLAND：实验基本信息



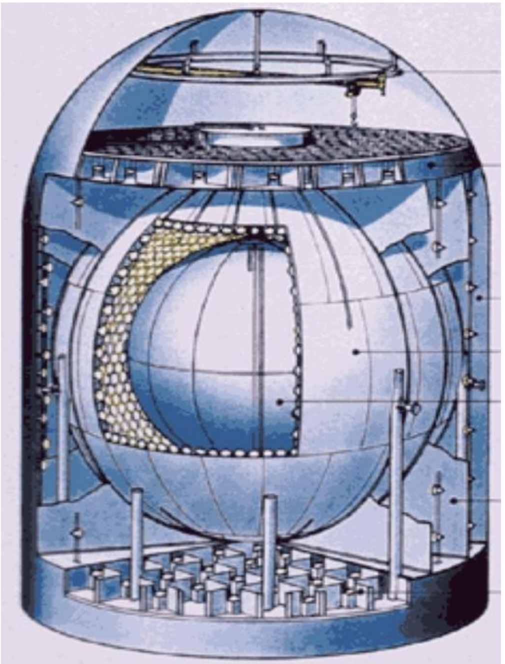
70 GW (7% of world total) is generated at 130-220 km distance from Kamioka

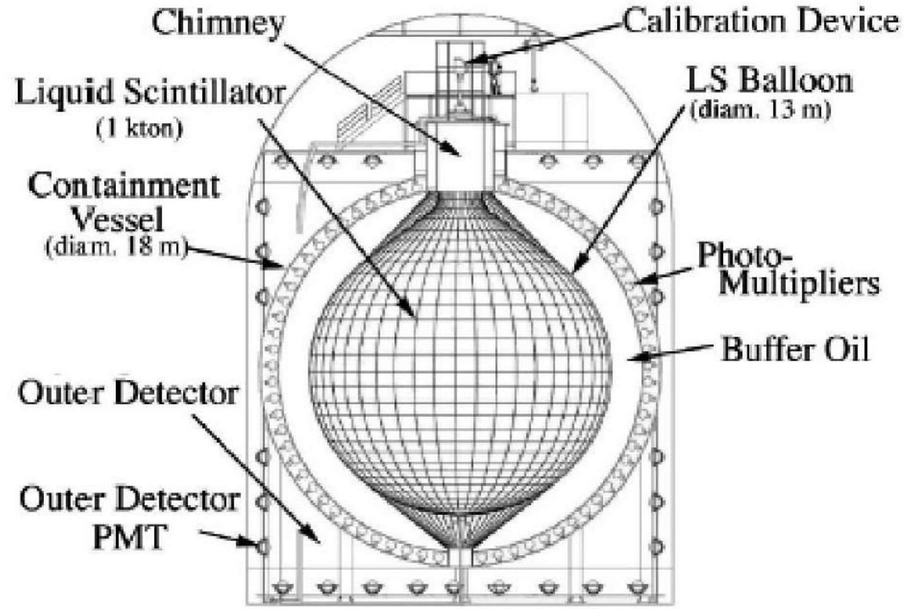


$$\langle L_\nu \rangle = 180 km$$
$$\langle E_\nu \rangle = a \ \ few \ MeV$$

Sensitive to $\Delta m^2 > 10^{-5} eV^2$

KamLAND：探测器





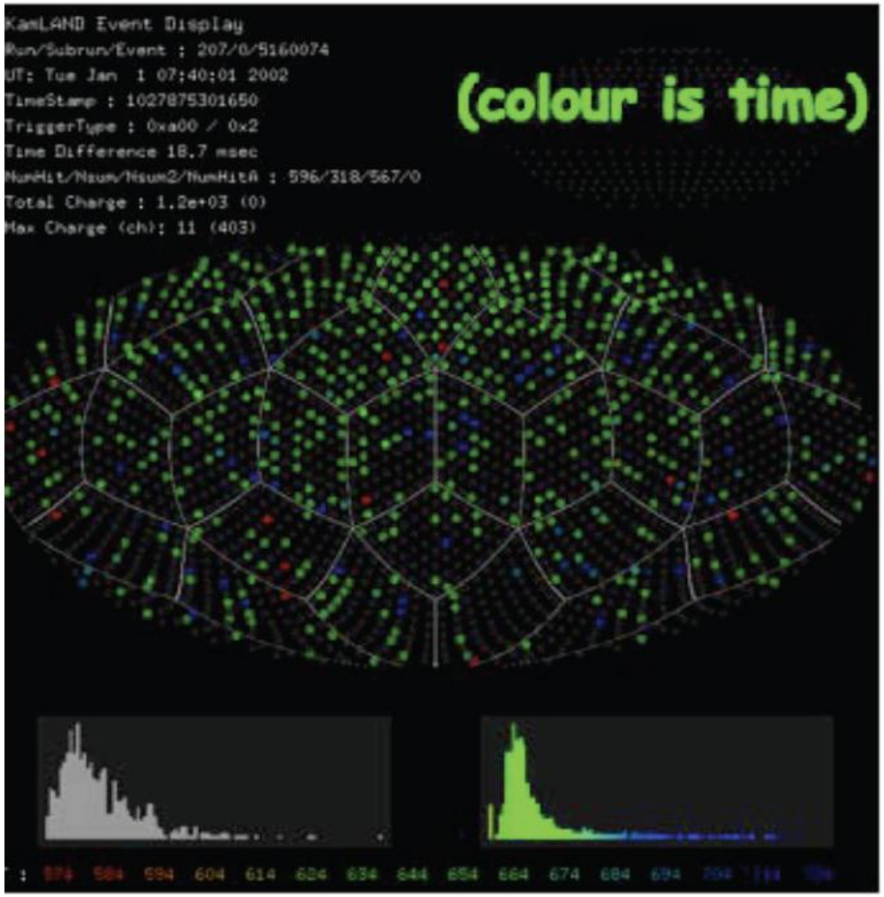
探测器体积：利用液袋装1000t 液体闪烁体
Shielding: 2700 MWE
光产额： 320 p.e./MeV ~6.5%能量分辨率

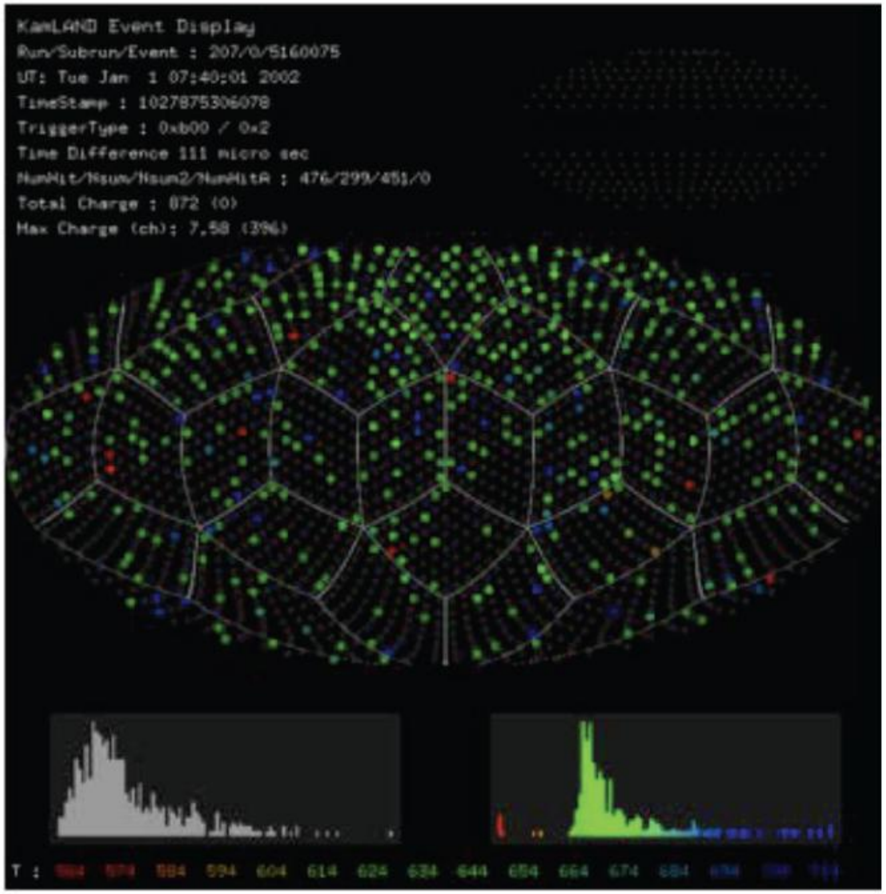
信号： ~0.5/day
本底：correlated: ~0.001/day
Uncorrelated： ~0.01/day

TABLE I: Estimated systematic uncertainties (%).

Fiducial Volume	4.7	Reactor power	2.1
Energy threshold	2.3	Fuel composition	1.0
Efficiency of cuts	1.6	$\overline{\nu}_e$ spectra [3]	2.5
Livetime	0.06	Cross section [5]	0.2
Total systematic uncertainty			6.5

KamLAND：典型反应堆中微子事例





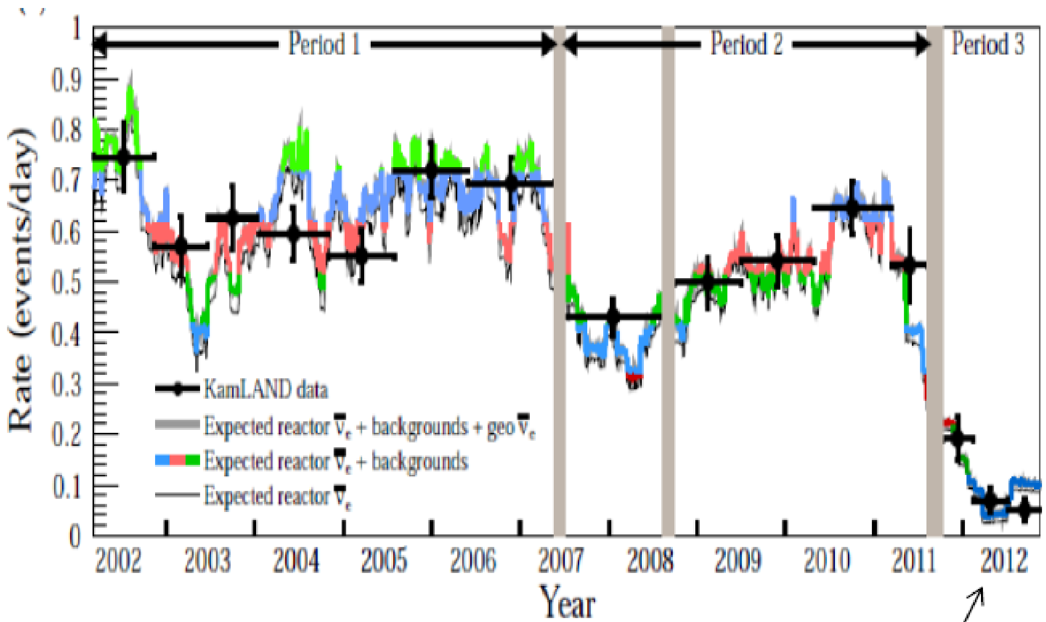
Prompt Signal
E = 3.20 MeV

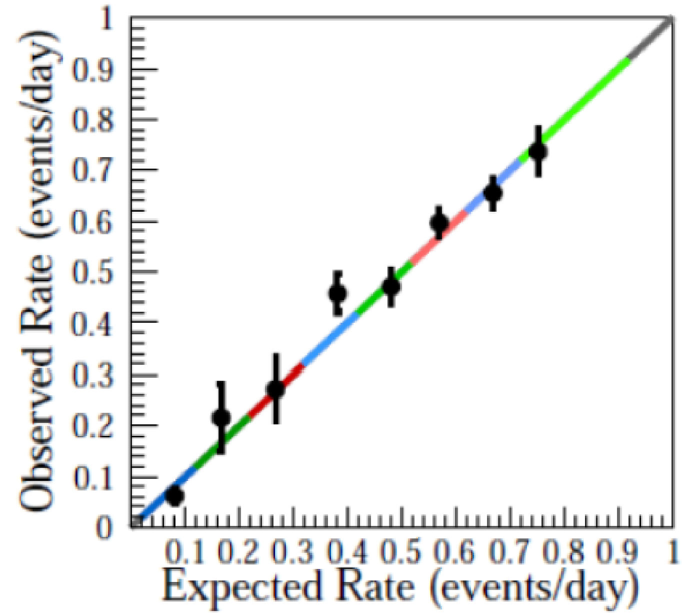
$\Delta t = 111$ ms
$\Delta R = 34$ cm

Delayed Signal
E = 2.22 MeV

KamLAND：事例率

KamLAND: 10 years of event rate





2012年后直接测量本底

事例率和功率信息一致：信号是来自反应堆的事例

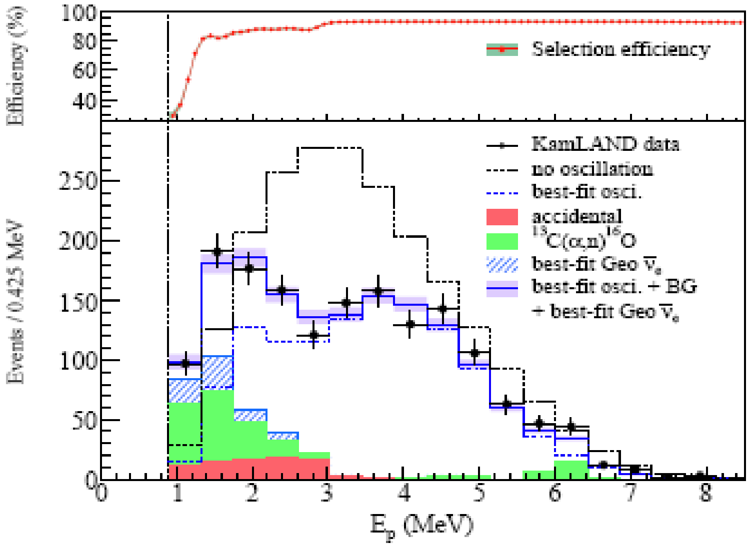
KamLAND：振荡信号

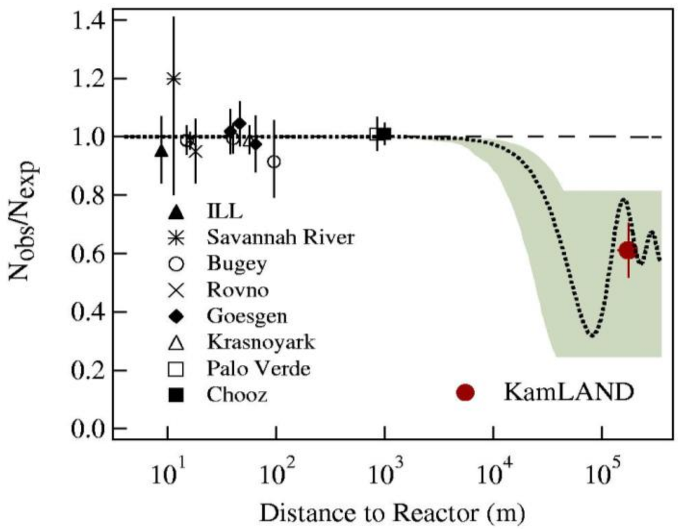
事例数测量

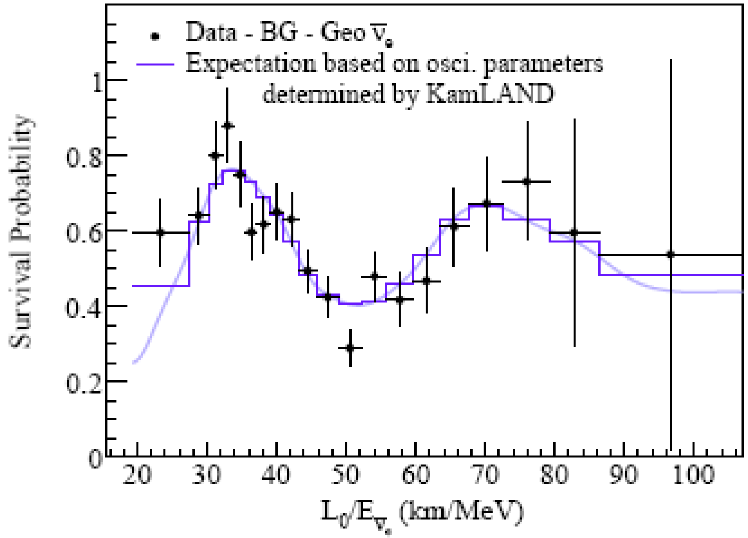
能谱测量

振荡曲线测量

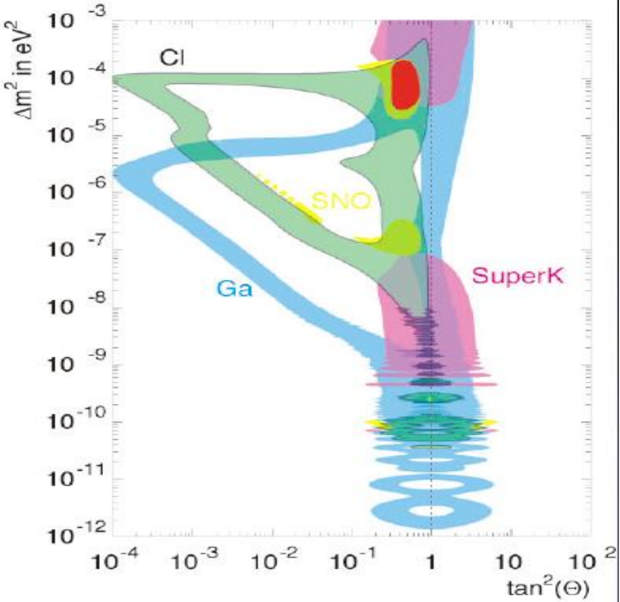
所有测量结果都与振荡一致



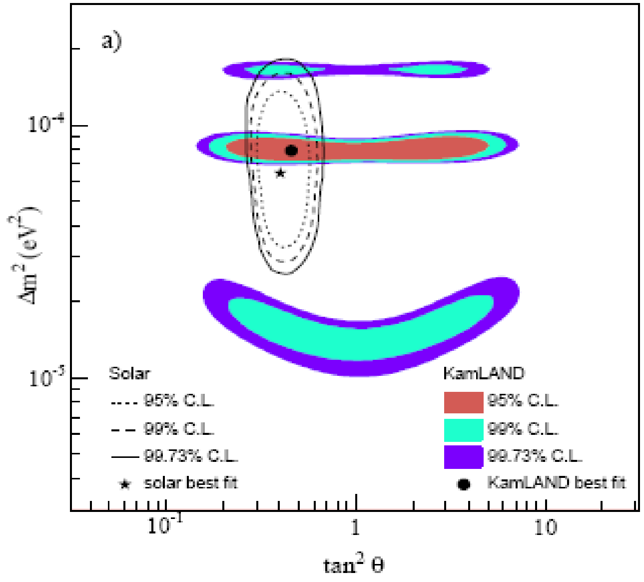


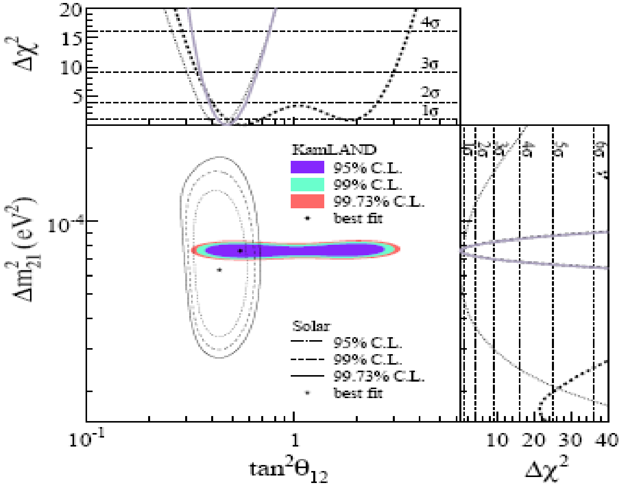


KamLAND：振荡解读



事例率





能谱测量

(1) 确定了太阳中微子消失的大角混合解

(2) 给出了振荡参数的精确测量

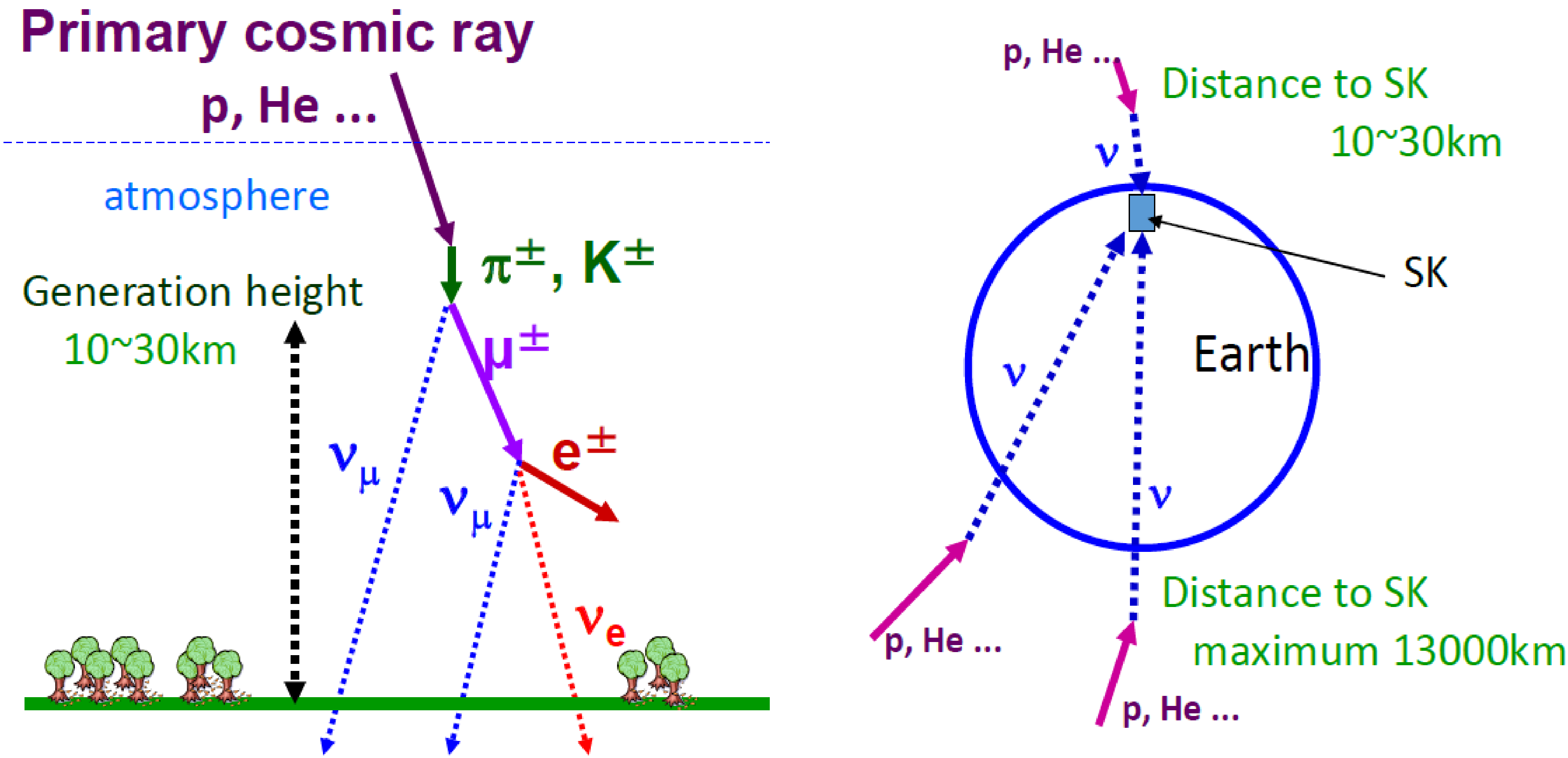
(3) 排除了中微子衰变、中微子退相干的解释

Part V:

大气中微子振荡

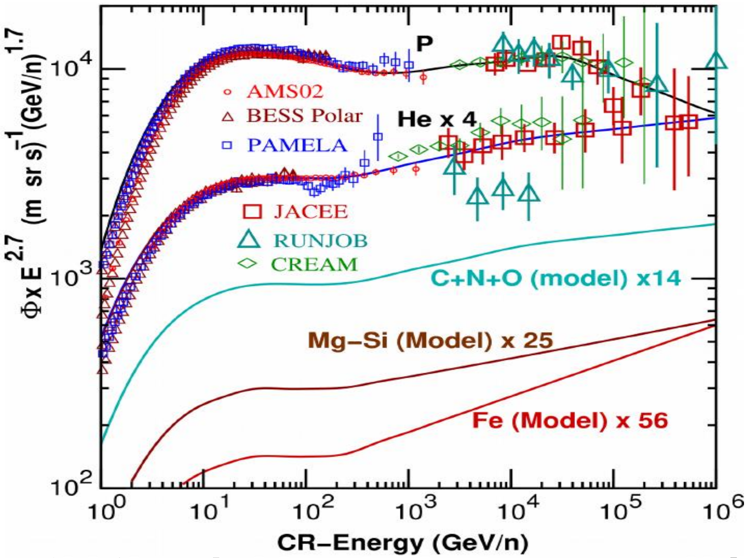
大气中微子的产生机制

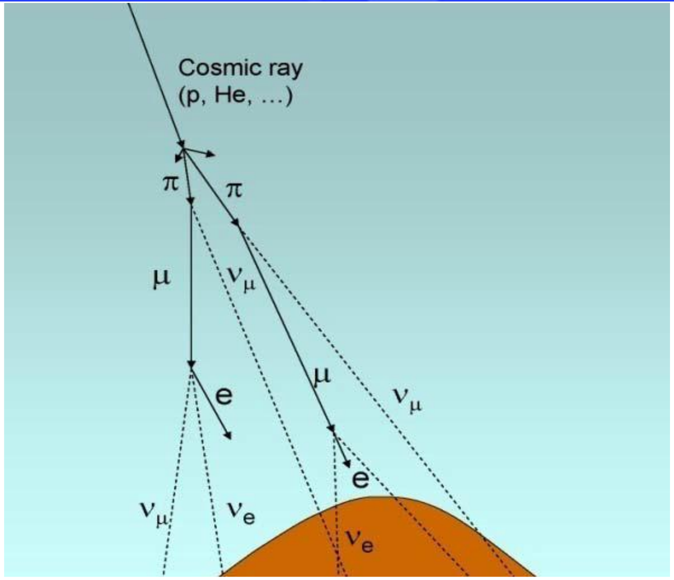
原初宇宙线和大气的相互作用，产生π/K等粒子，从而产生μ子以及中微子

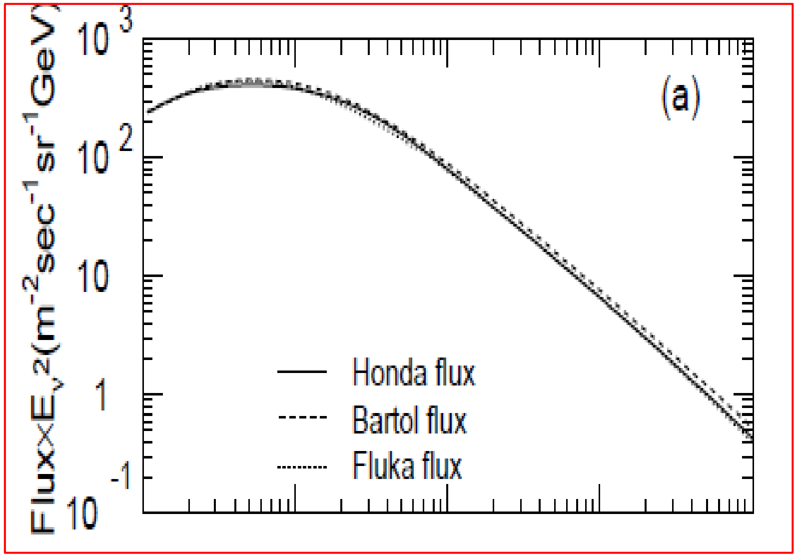


基本性质：四种味道、能量范围广(100 MeV~100 TeV)、传播距离范围广

大气中微子的计算方法





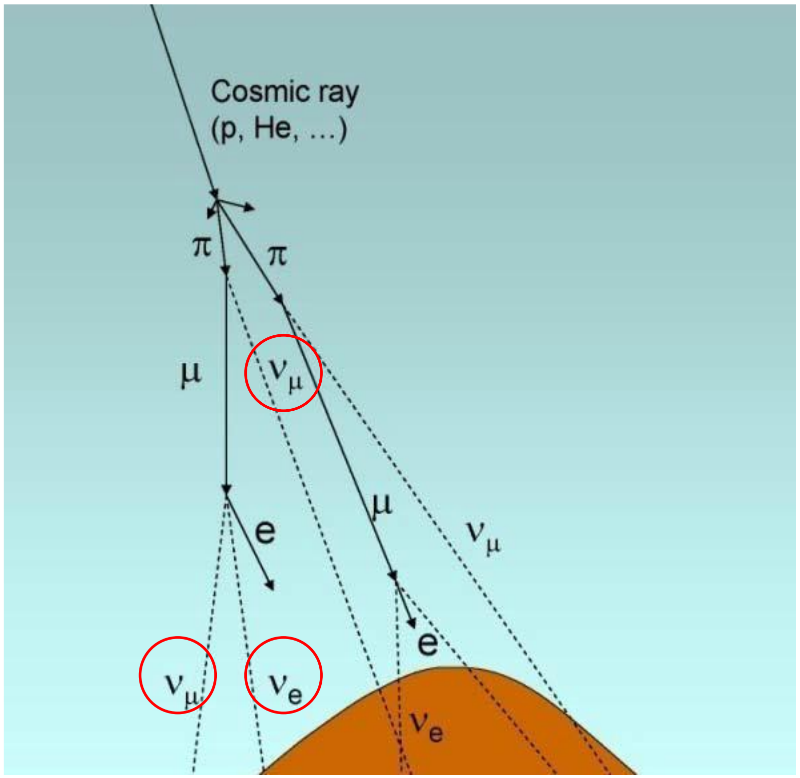


进行整个地球大气层的模拟，需要考虑：

(1) 太阳活动
(2) 传播效应和地磁场的影响
(3) 质子与原子核的相互作用
(4) π/K等介子的衰变过程
(5) … …

具有地点依赖性、方向依赖性(特别是低能大气中微子)，利用μ子束流进行验证

π/μ衰变的性质



5 GeV π(+/-)介子的衰变:

Note:
τ_π=26 ns
m_π=139.6 MeV/c^2
$\gamma=E_\pi/m_\pi$=36 for 5GeV
$c\tau_\mu\gamma$=279 m

➜ most pions decay

$\pi \rightarrow \mu + \nu_\mu$

衰变到电子味的分支比 ~10^{-4}

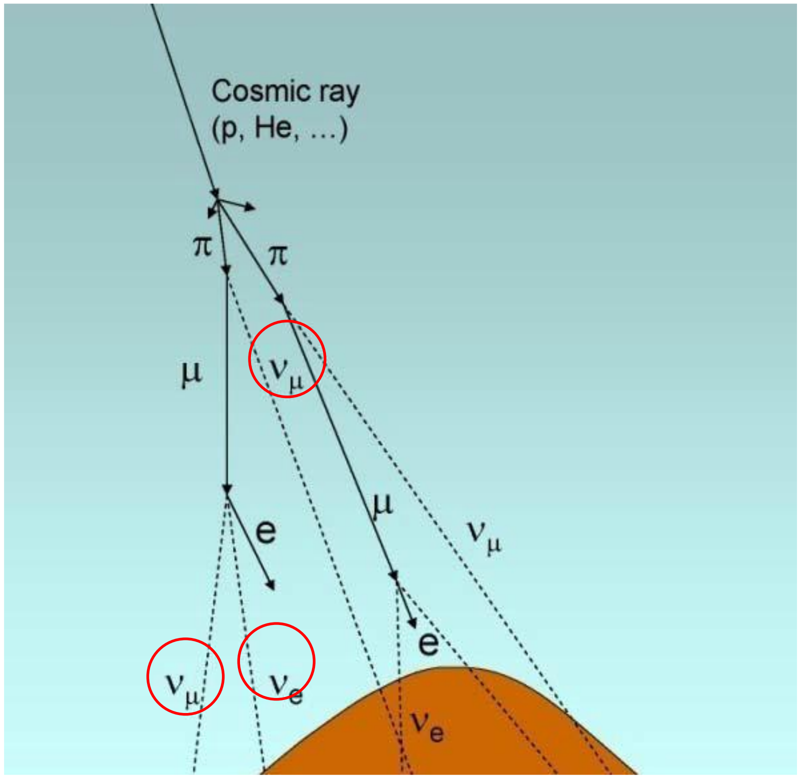
2.5 GeV μ(+/-)子的衰变:

Note:
τ_μ=2.197 μs
m_μ=105.7 MeV/c^2
$\gamma=E_\mu/m_\mu$=24 for 2.5GeV
$c\tau_\mu\gamma$=15.8 km

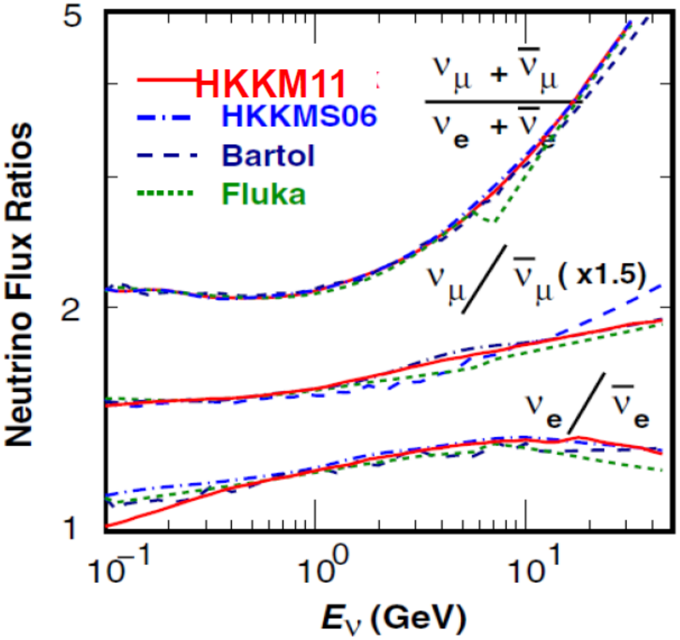
➜
- decay $\mu \rightarrow e + \nu_\mu + \nu_e$
- hit the ground
  - absorption (μ^-)
  - decay

大气中微子的典型特征：味道比例

$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$



M. Honda et al., PRD 83, 123001 (2011)

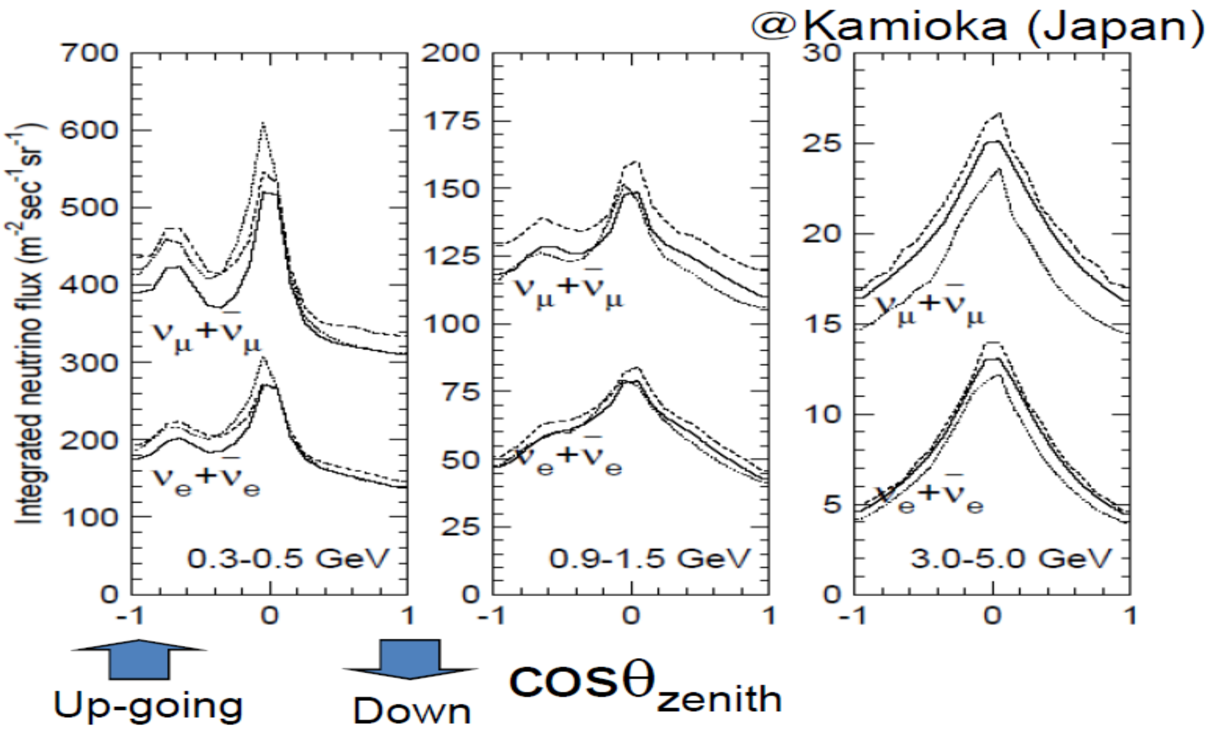


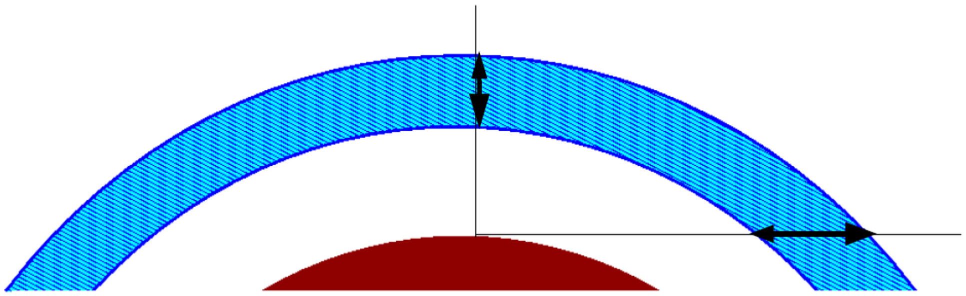
μ/e 味道的比例在< 5 GeV范围非常精确

中微子/反中微子的比例也有很好的精度

大气中微子通量的典型特征：天顶角分布

Zenith angle



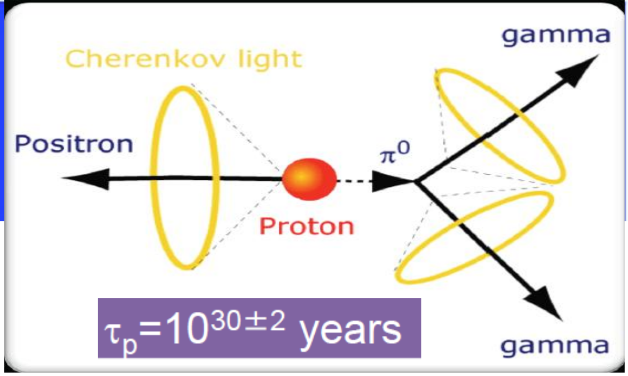


上下之间的比例接近1

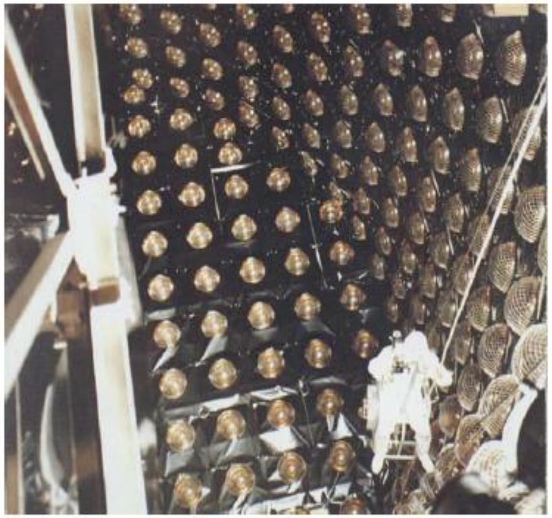
在大于几个GeV计算精度非常高

1%或者更好

大气中微子反常：质子衰变

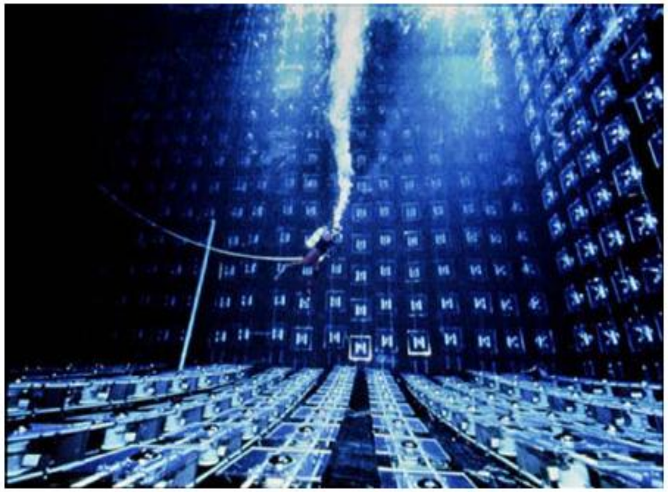


1970年代大统一取得了重要进展→质子不稳定
大气中微子是质子衰变研究的重要本底
1988年Kajita的博士论文发现了大气中微子反常现象



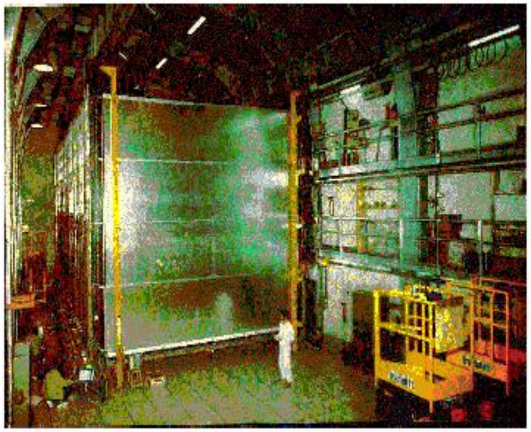
Kamiokande
(1000ton)

IMB
(3300ton)



NUSEX
(130ton)

Frejus
(700ton)



These experiments observed many contained atmospheric neutrino events (background for proton decay).

大气中微子反常：Kamiokande (I&II)

Kamiokande： Kamioka Neucleon Decay Experiment
Kamioka Neutrino Detection Experiment

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

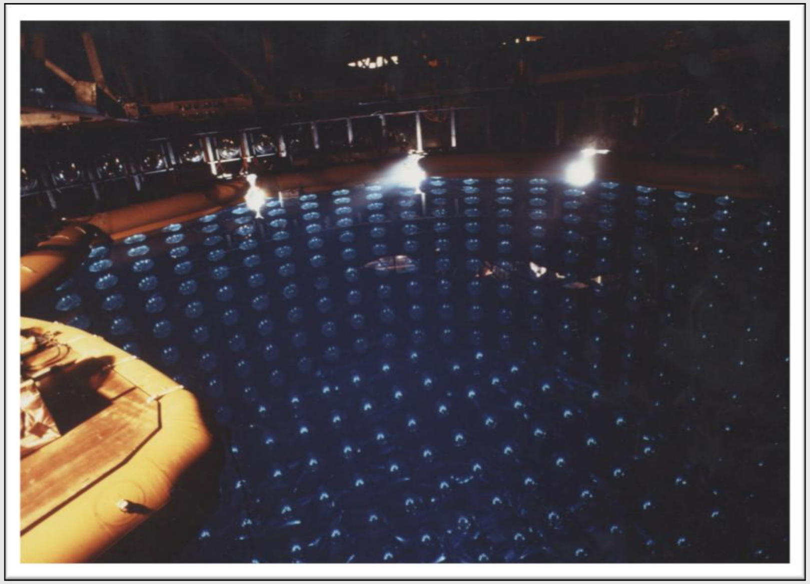
水切伦科夫探测器：3000/1000吨纯水

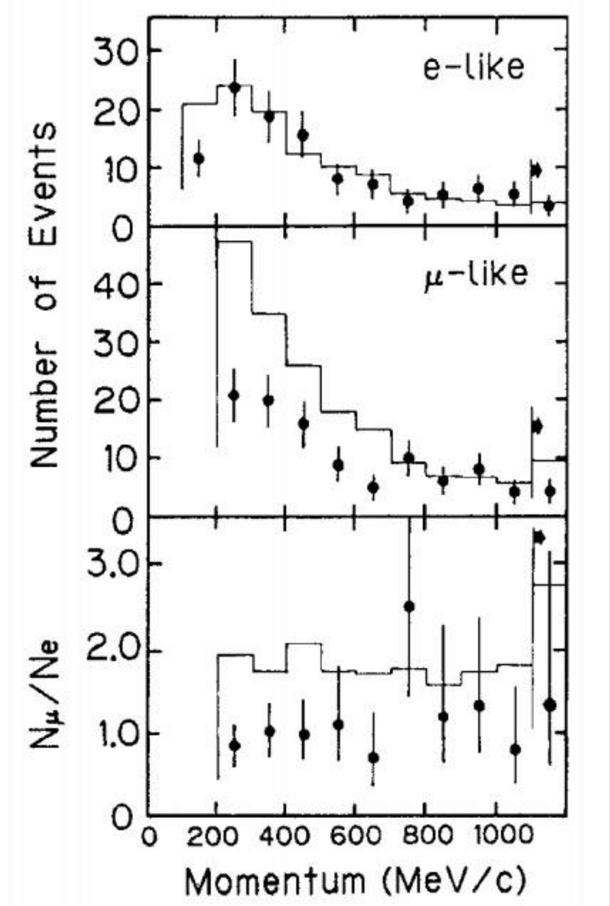
1983-1990年间进行了大气、太阳、超新星中微子的研究。

(1)1987年的超新星中微子探测为小柴昌俊带来了2002年的诺贝尔物理奖

(2) 1988年Kajita的博士论文发现了大气中微子反常

(3) 1990年初的太阳中微子探测验证了Homestake的结果。





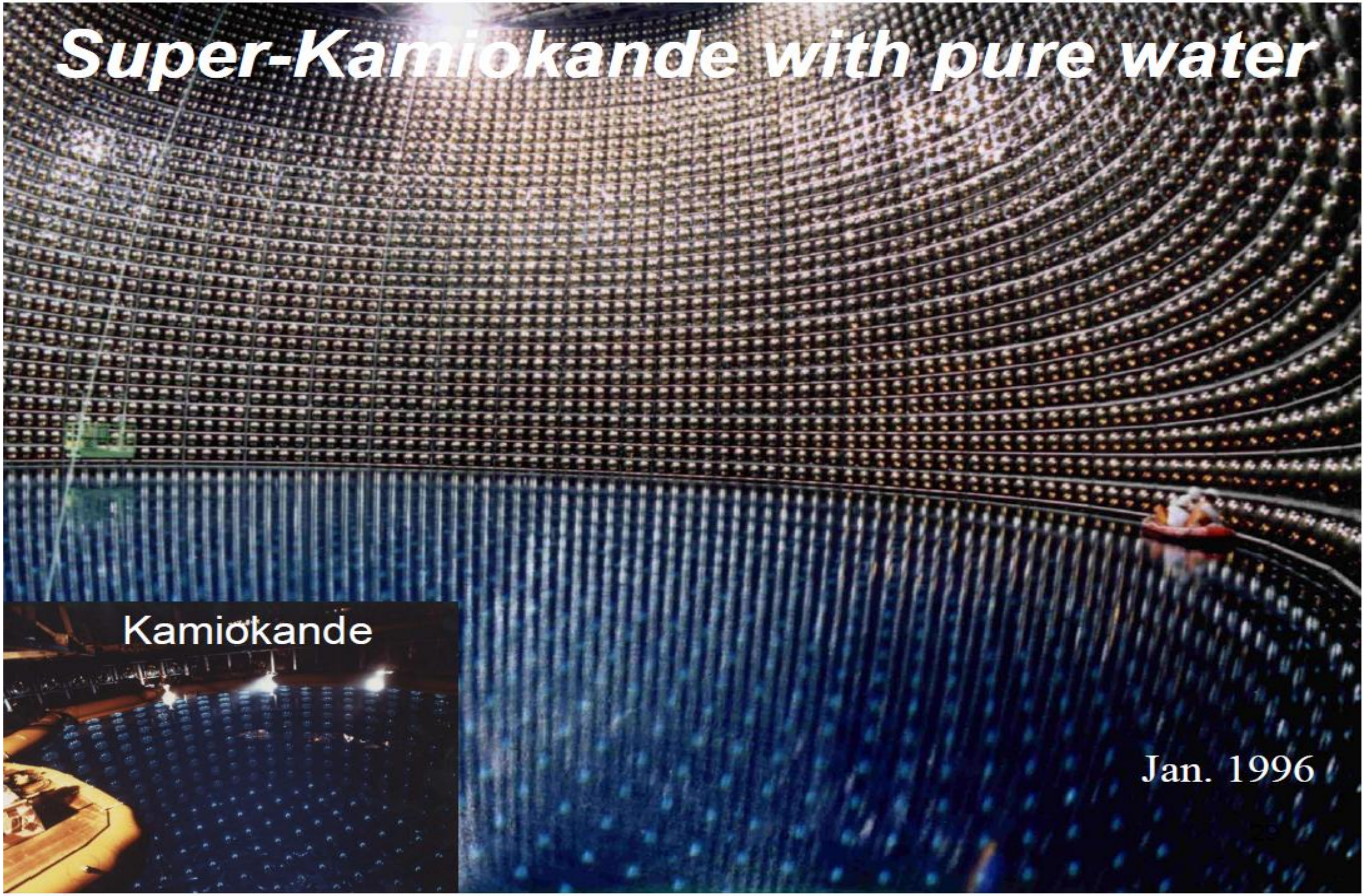
"We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccoundted-for physics such as neutrino oscillations might explain the data."

Expected

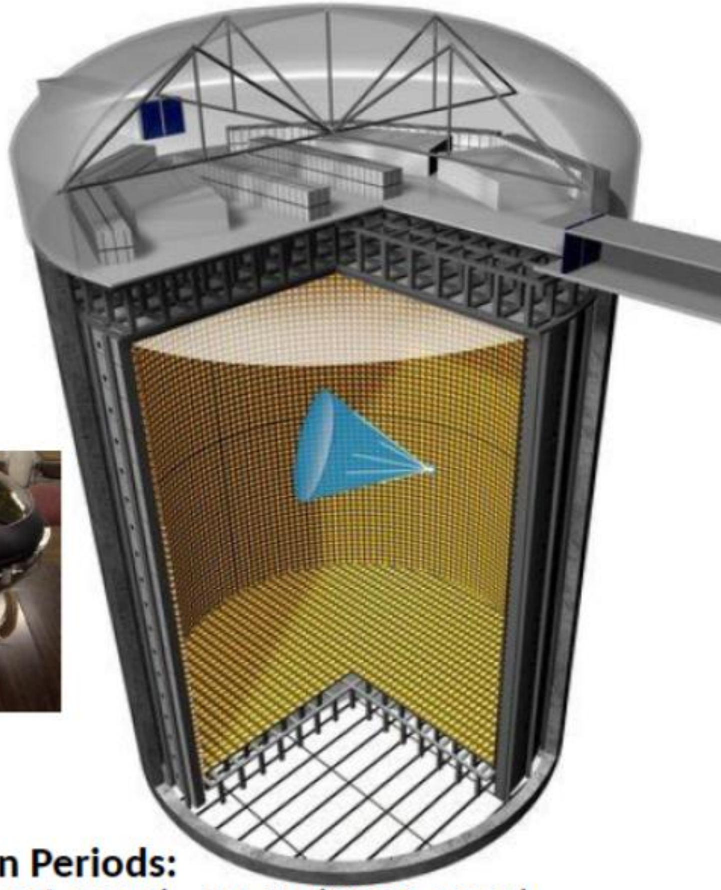
Observed

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

超级神岗实验：Super-Kamiokande



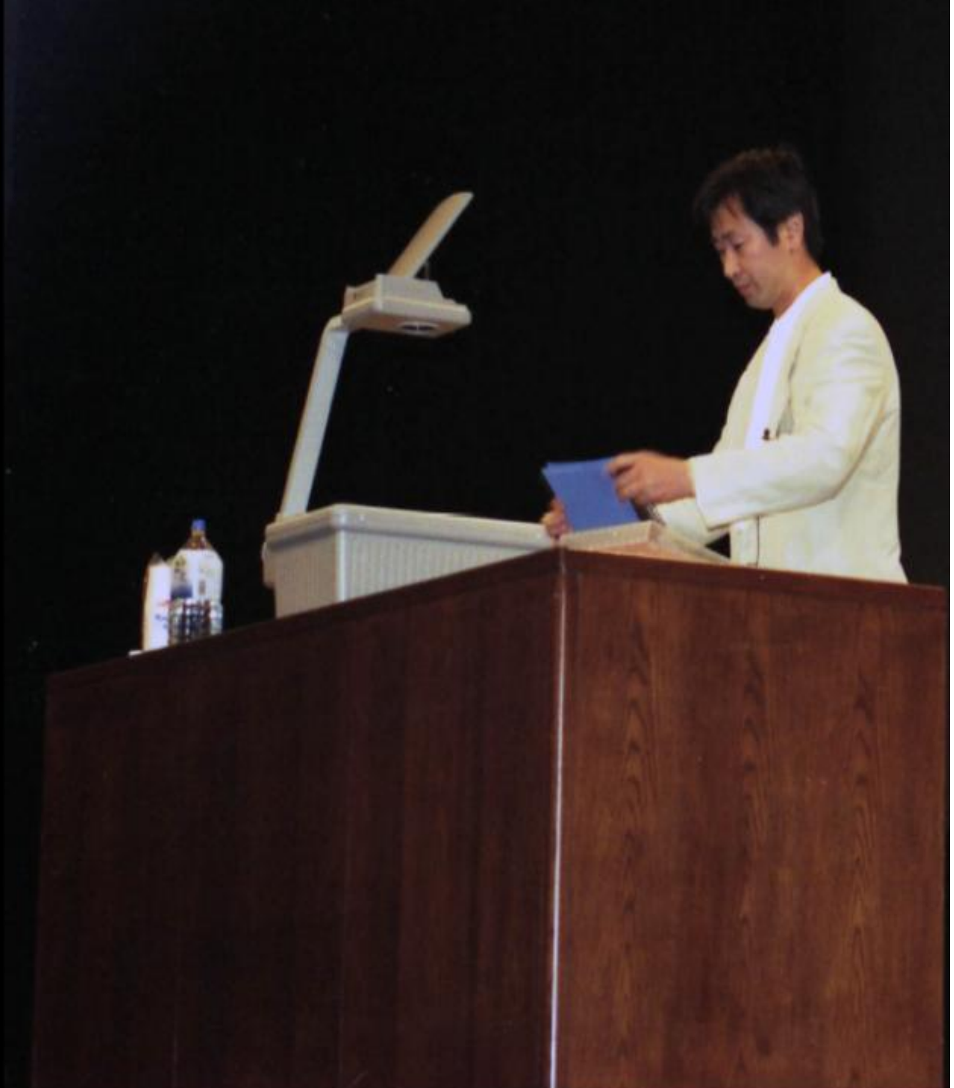
超级神岗实验：Super-Kamiokande



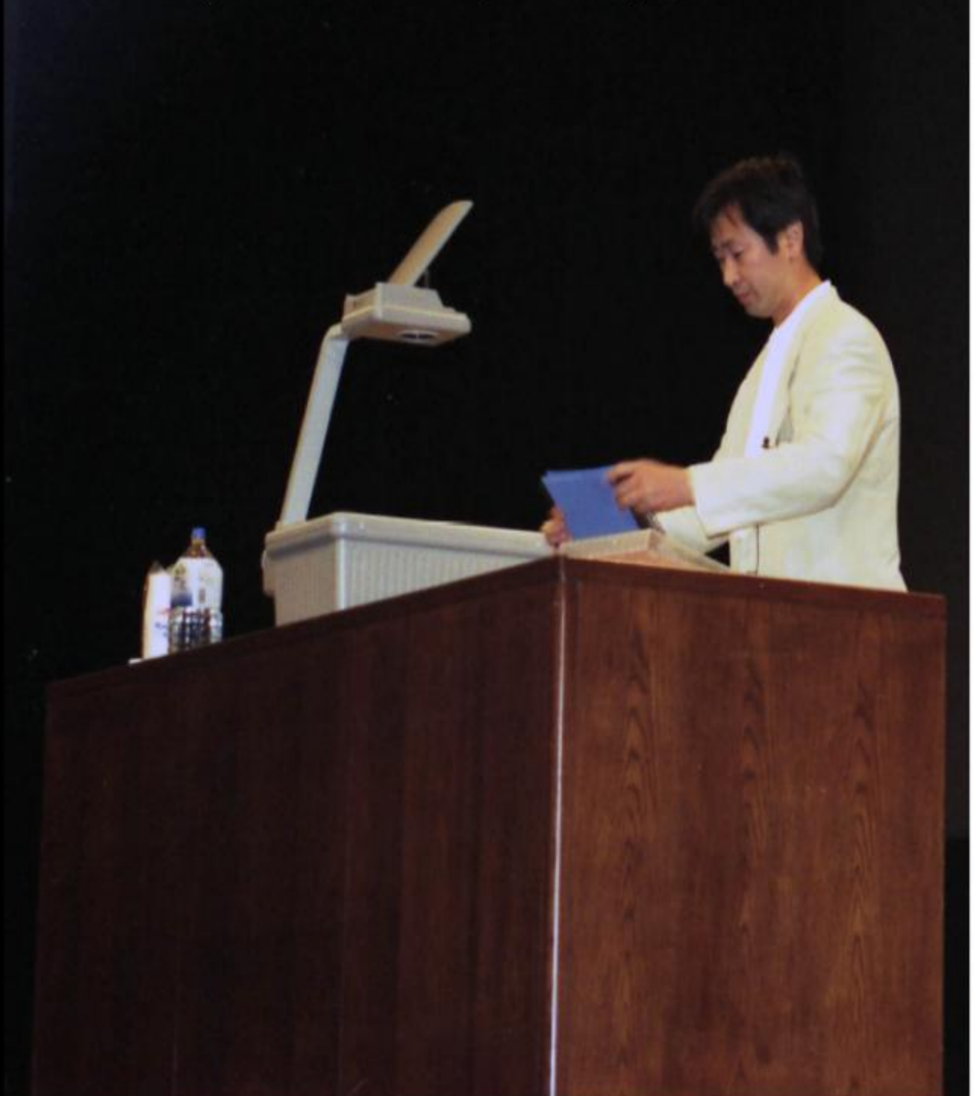
Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III (2005-2008) SK-IV (2008-Present)

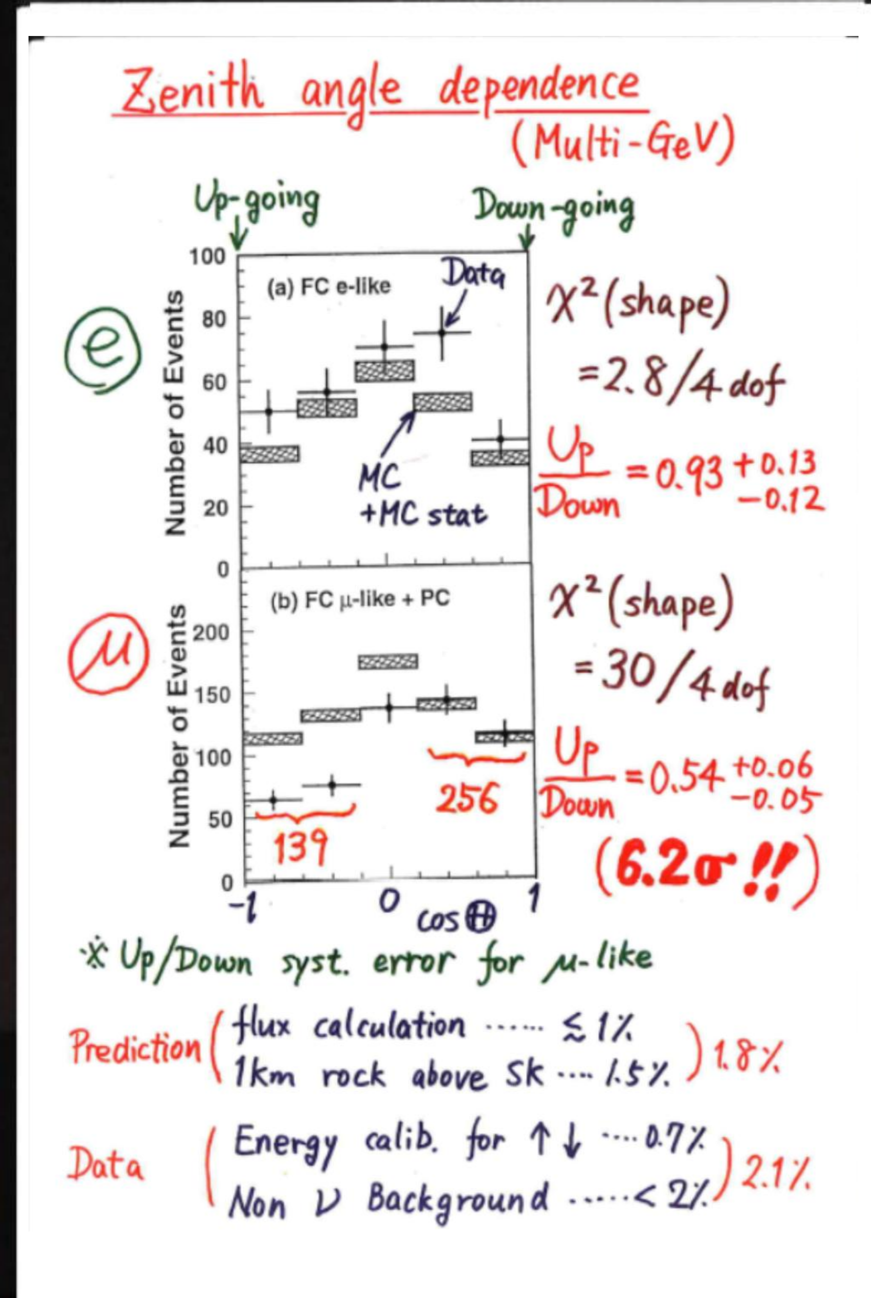
- 22.5 kton fiducial volume
- Optically separated into
  - Inner Detector 11,146 20” PMTs
  - Outer Detector 1885 8” PMTs
- No net electric or magnetic fields
- Neutrino direction and energy are unknown
  - Hard to reconstruct directly
- Excellent PID between showering (e-like) and non-showering (m-like)
  - ~ 1% MIS ID at 1 GeV
- As of Today: 4972 days of data
  - 51,000 Events
- Multipurpose machine
  - Solar and Supernova Neutrinos
  - **Atmospheric Neutrinos (this talk)**
  - Nucleon Decay
  - Far detector for T2K

Neutrino 1998, Takayama, Japan
33 kton years of data (535 days)

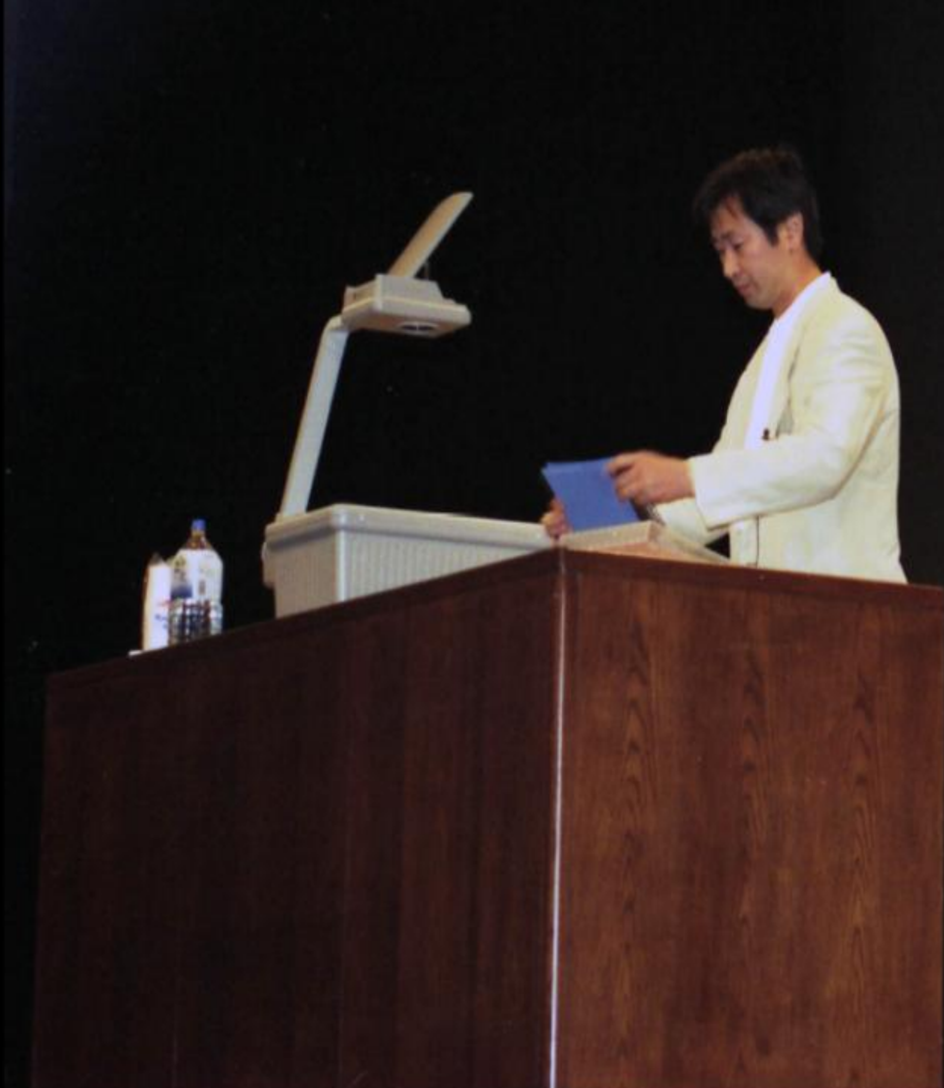


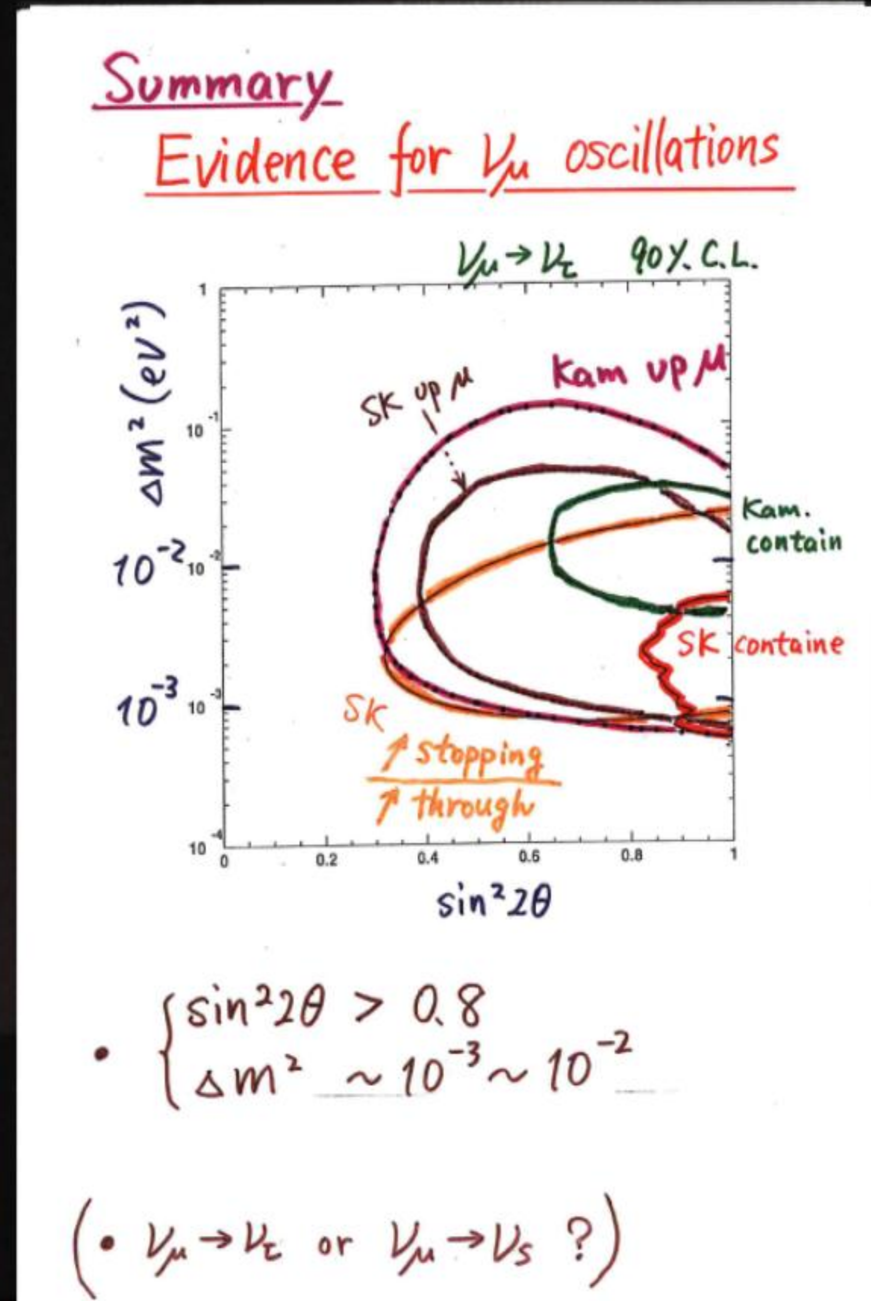
Neutrino 1998, Takayama, Japan
33 kton years of data (535 days)





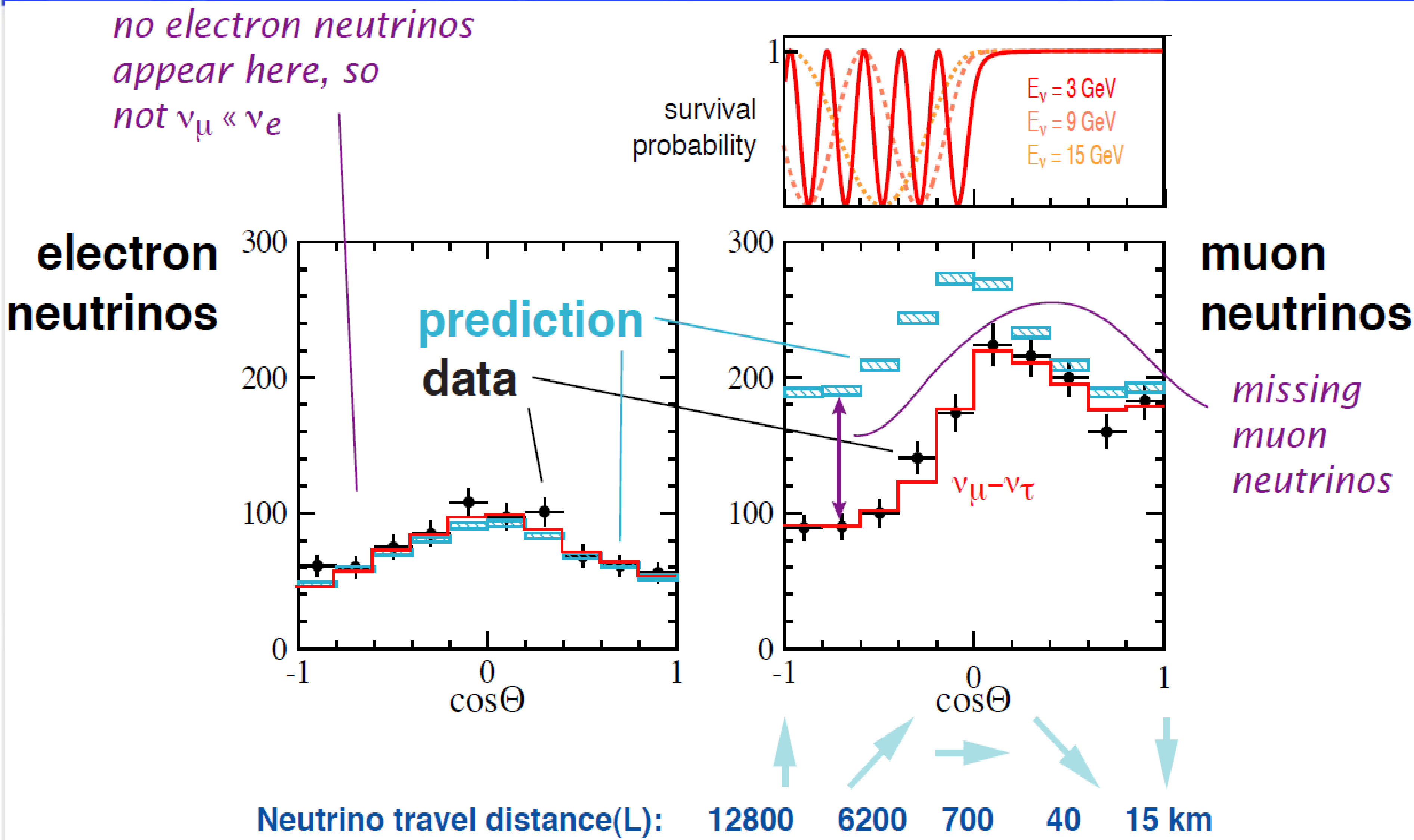
Neutrino 1998, Takayama, Japan
33 kton years of data (535 days)





中微子振荡的解读

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$



如何实验验证？

除中微子振荡解释之外，能否排除其它的解释?

中微子衰变/中微子退相干？

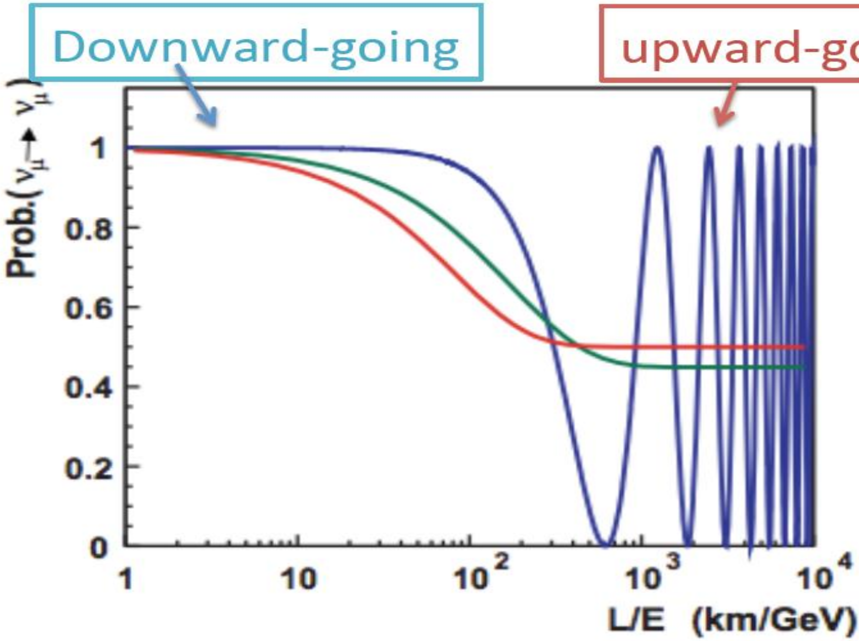
能否验证消失的中微子振荡到何种粒子?

~~ν_e~~, ν_tau, ν_s ?

能否使用其它类型实验验证同样的振荡信号?

加速器中微子实验?

直接探测振荡信号



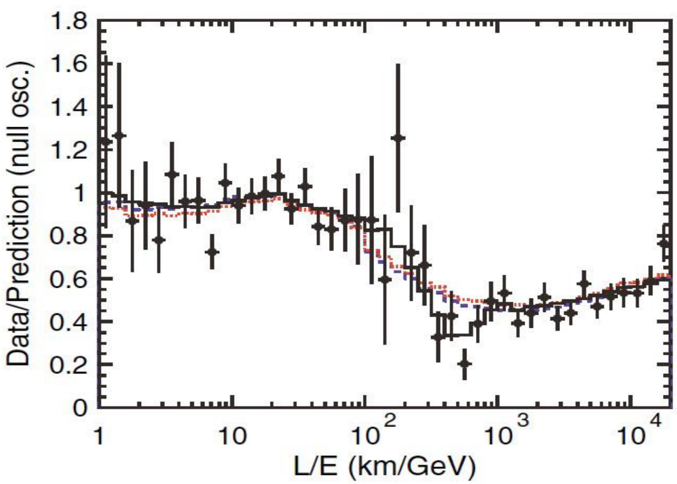
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

Decoherence:

$$P(\nu_\mu \to \nu_\mu) = 1 - \frac{1}{2}\sin^2 2\theta \cdot (1 - \exp(-\gamma_0 \frac{L}{E}))$$

Decay:

$$P(\nu_\mu \to \nu_\mu) = (\cos^2\theta + \sin^2\theta \cdot exp(-\frac{m}{2\tau}\frac{L}{E}))^2$$



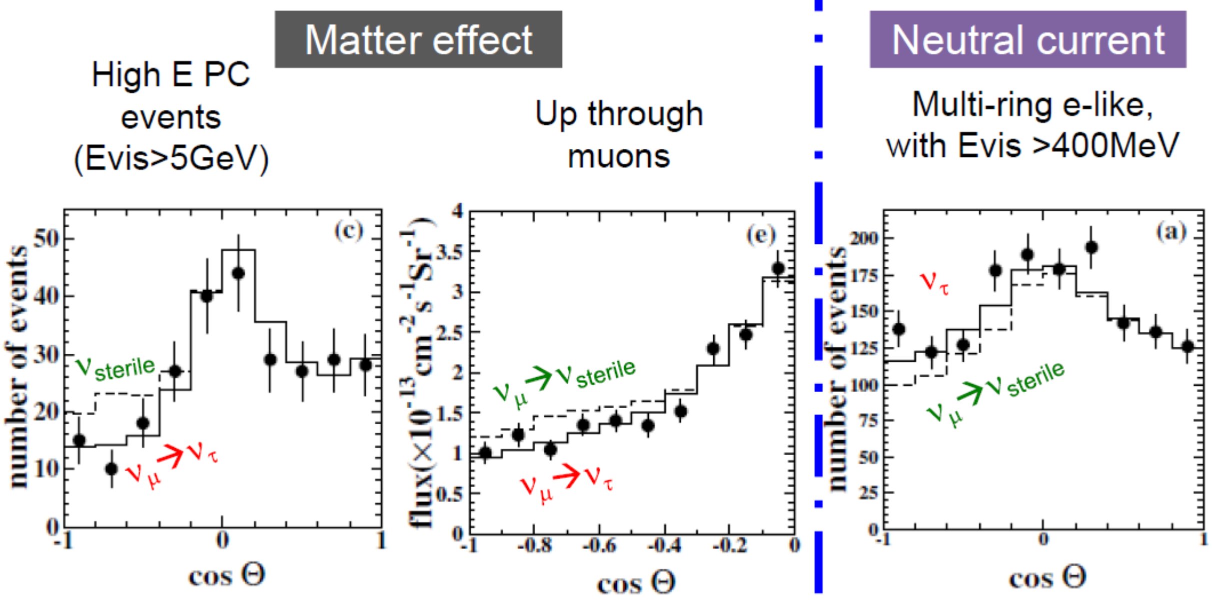
在第一个振荡极大值附近L/E = 500 km/GeV 看到了明显的振荡信号。@2004

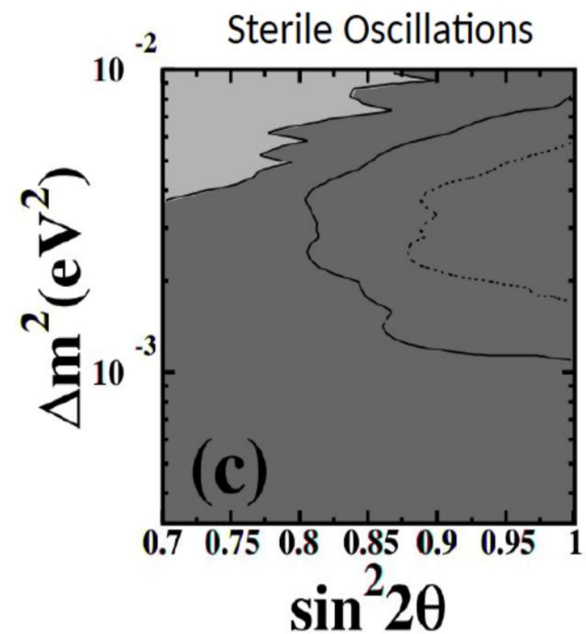
-- ν Decay $\Delta\chi^2 = 3.4\sigma$

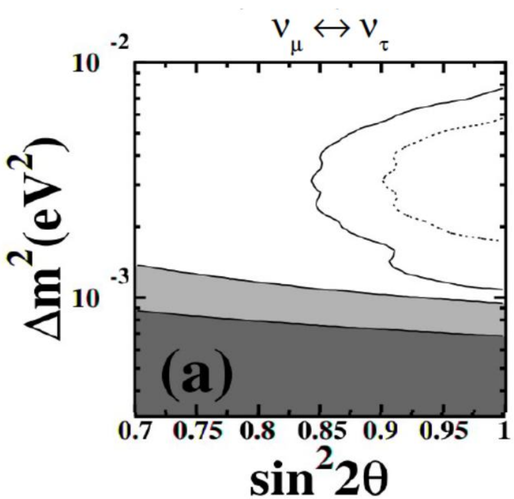
-- ν Decoherence $\Delta\chi^2 = 3.8\sigma$

— $\nu_\mu \leftrightarrow \nu_\tau$ ($\Delta\chi^2 = 0$)

nu(mu)-nu(s) → 寻找中性流相互作用







Excluded at 99% C.L.

Excluded at 90% C.L.

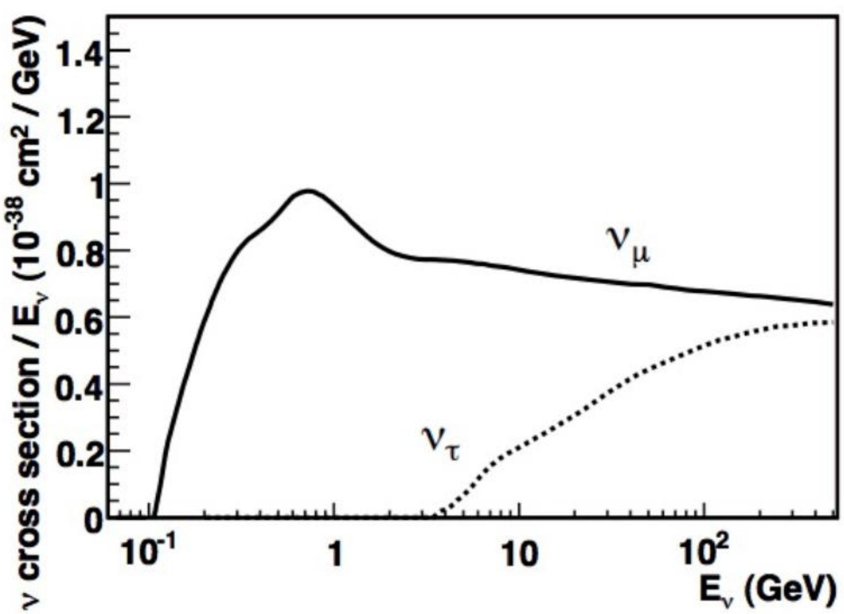
FC Single-Ring Allowed 99%

排除了100%nu(mu)-nu(s)的转化！

NC类型的中微子事例的up/down比例减小

对更高能量的上行事例，nu(mu)-nu(s)受到物质效应的压低

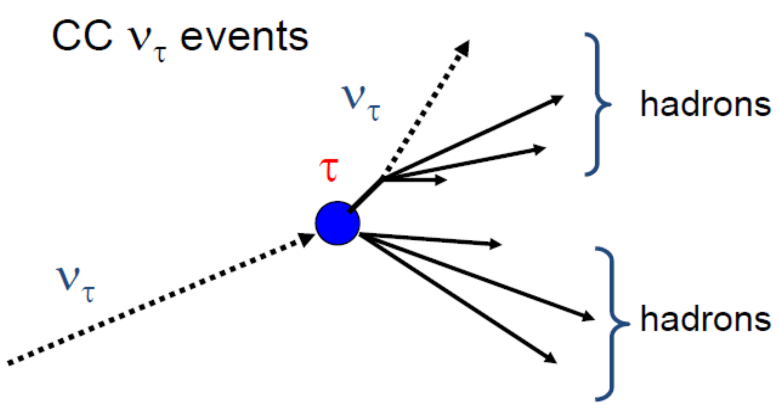
直接测量nu(mu)-nu(tau)

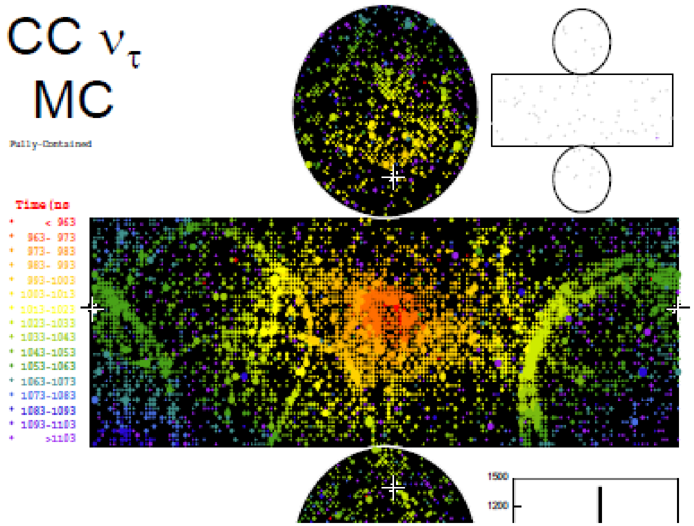


选择富含nu(tau)带电流事例的数据集

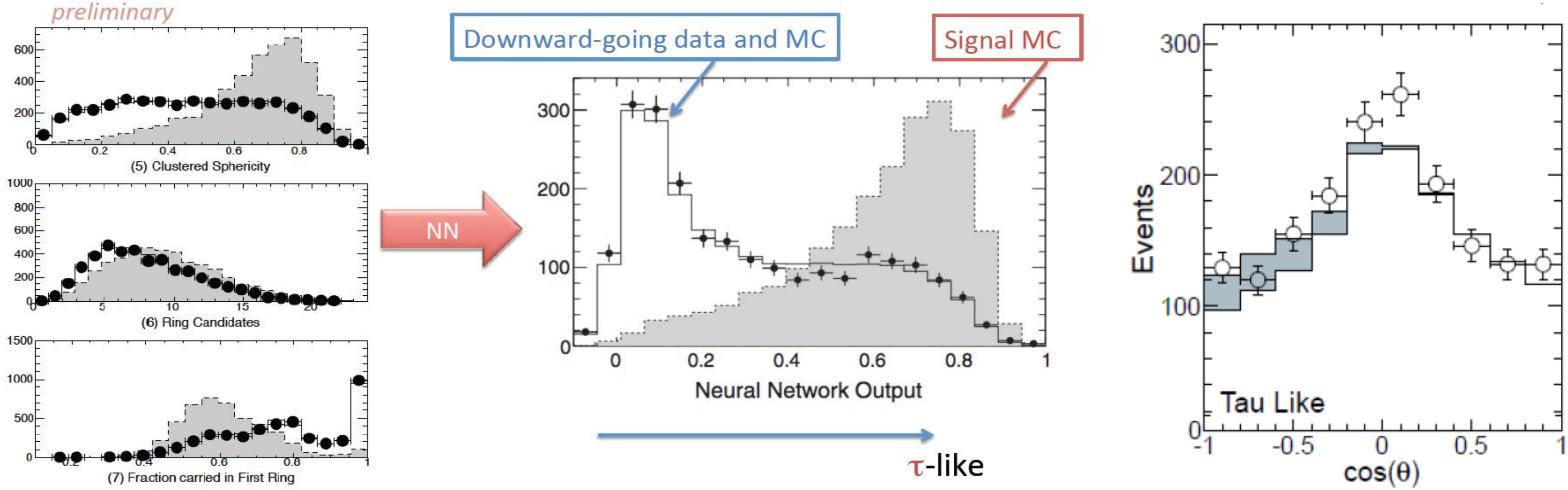
阈值3.4GeV, 对应 1个/kton/year：
无法单独挑选tau事例(10 GeV~0.5 mm)，
信号类似电子型事例

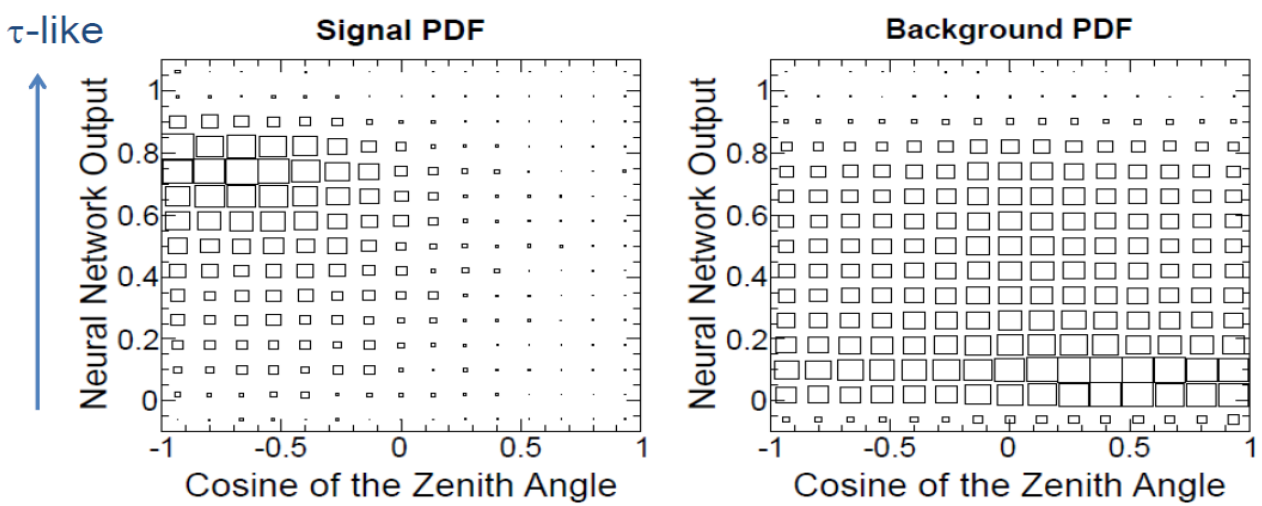
利用多变量分析的神经网络方法(人工智能)





直接测量nu(mu)→nu(tau)





观测到明显的tau信号

180.1±44.3(stat) +17.8 / -15.2(syst)

tau事例的统计显著性在4.6-sigma

直接证明nu(tau)产生

Part VI:

加速器中微子振荡

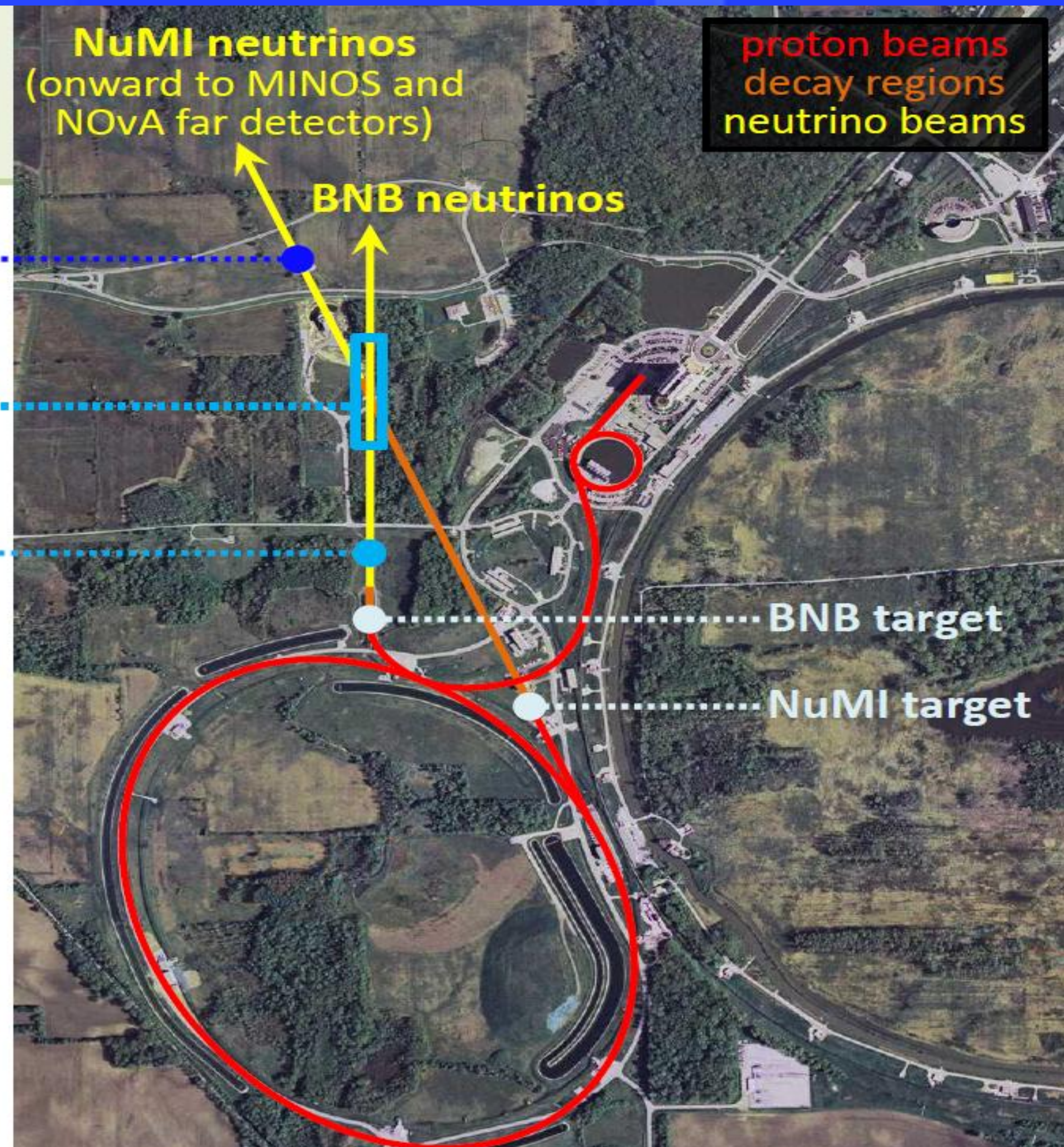
加速器中微子：Fermi 中微子束流为例

Example Neutrino Complex (FNAL)

MINOS ND, NOvA ND, MINERvA, ArgoNeuT

MiniBooNE, MicroBooNE, ICARUS

SciBooNE, SBND



8 GeV Booster supplies Booster Neutrino Beam (BNB)

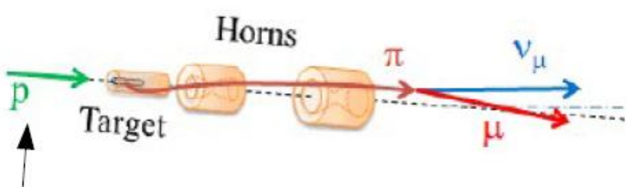
120 GeV MI feeds Neutrinos from the MI (NuMI) beam

加速器中微子束流

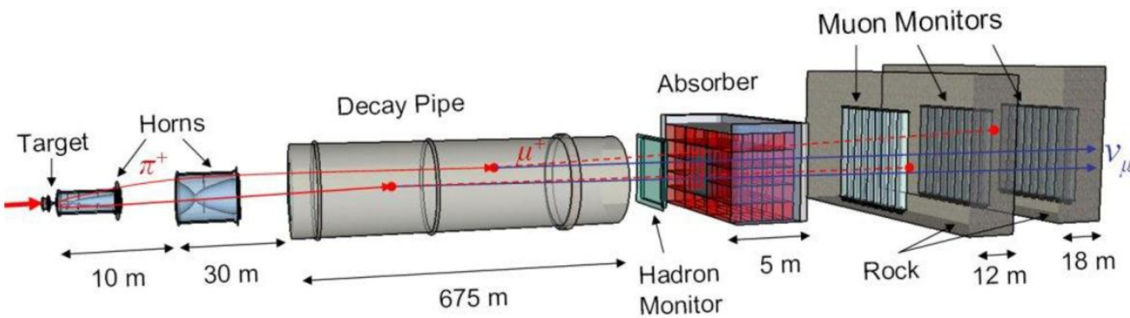
和大气中微子的产生非常类似 (美国FNAL, 日本J-PARC, 欧洲CERN)

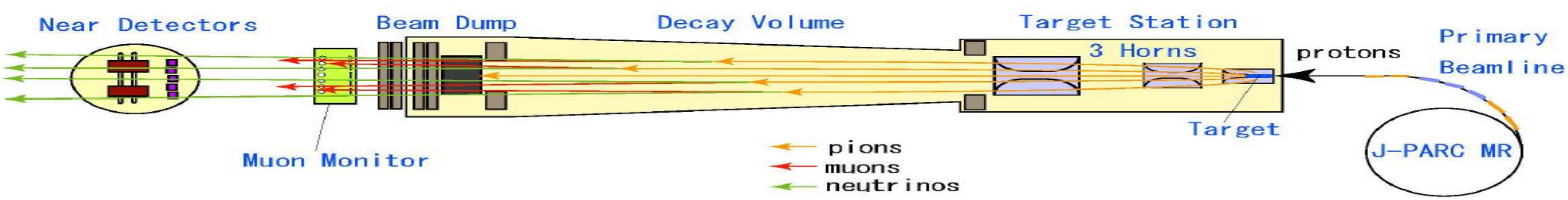
大气中微子的所有条件都是天然环境构成：质子能量非常广，整个大气层作为靶，天然地磁场条件。→ 接近各项同性的中微子束流

加速器中微子所有条件都是人工控制：质子的能量可控并固定，靶站的尺寸形状以及靶核可以特殊选取，聚焦磁场的方向大小可调。→ 能量可控的准直束流

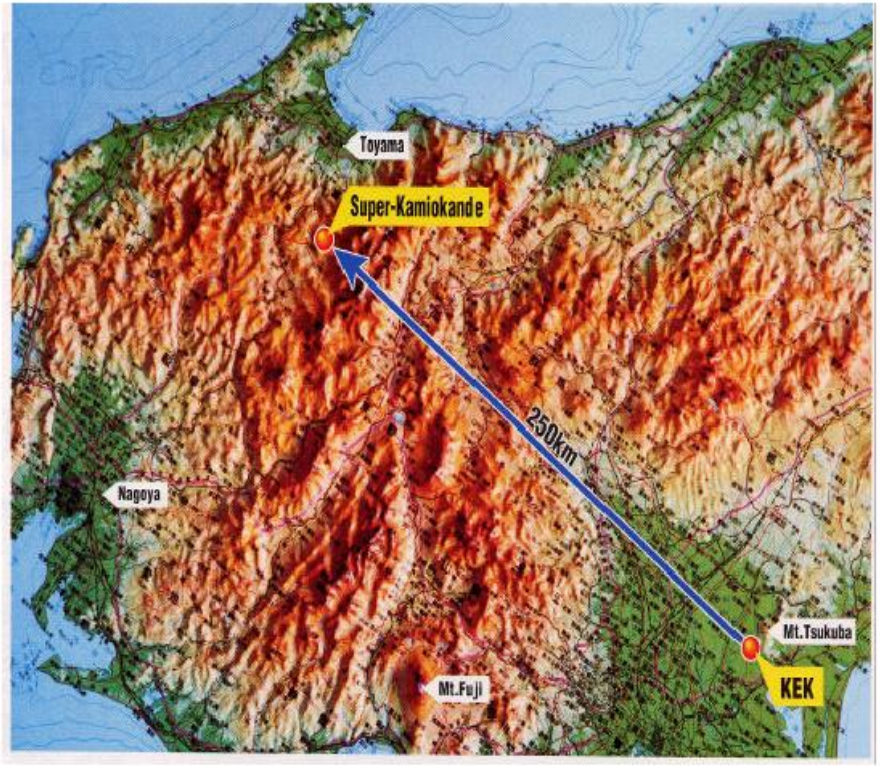


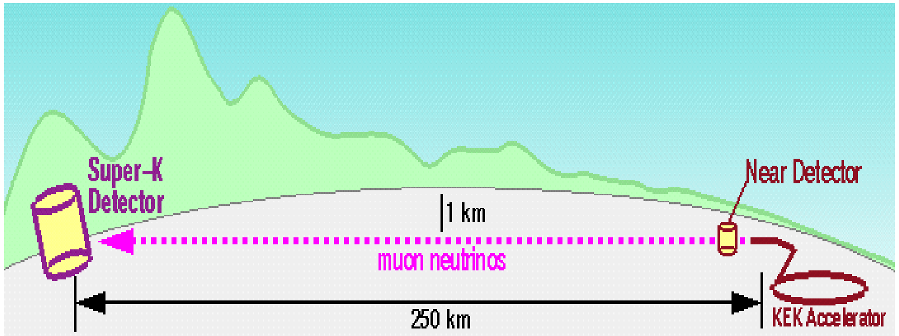
(30 GeV T2K, 120 GeV NuMi)





K2K实验





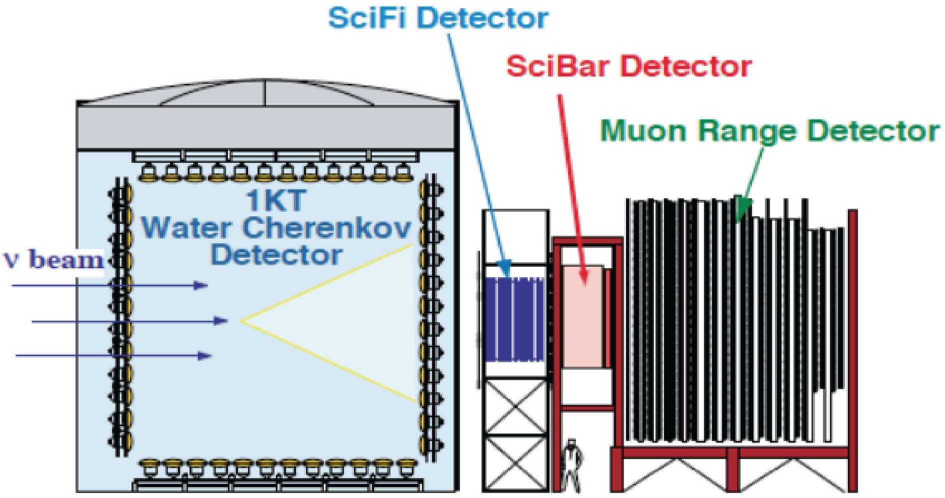
世界上首个长基线加速器中微子实验

研究nu(mu)→nu(mu)的消失

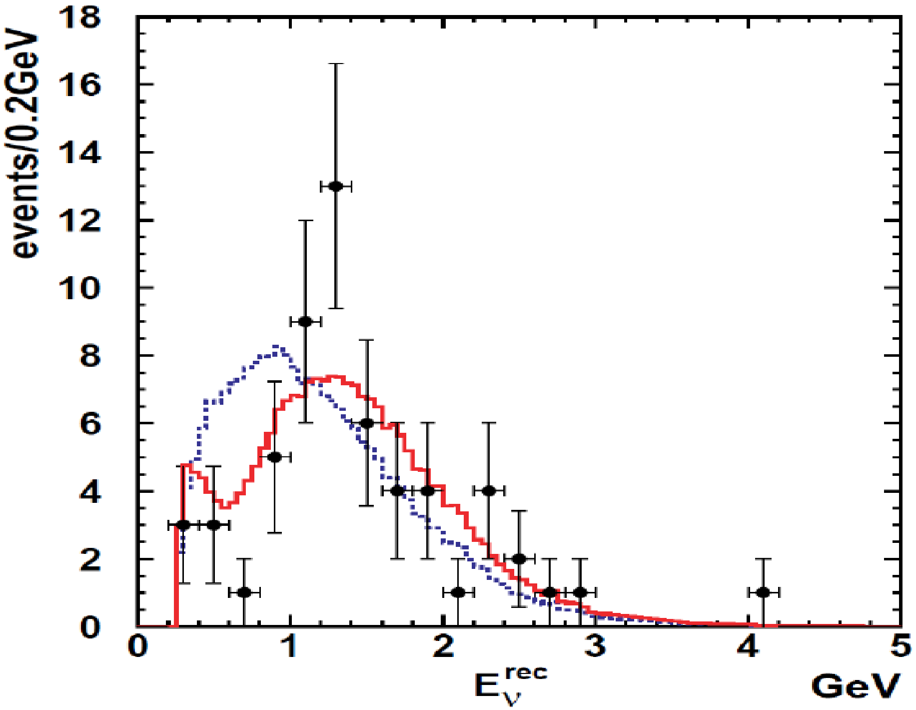
12GeV质子束流，中微子平均能量1.4GeV

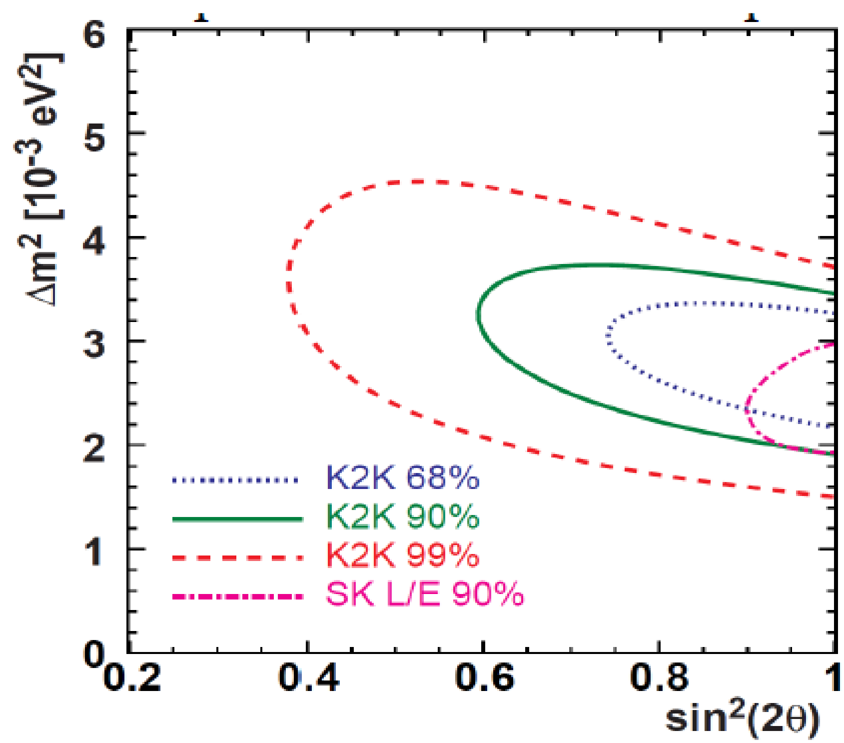
近点探测器的重要性：

直接监测束流通量和能谱



K2K实验结果 (2006)





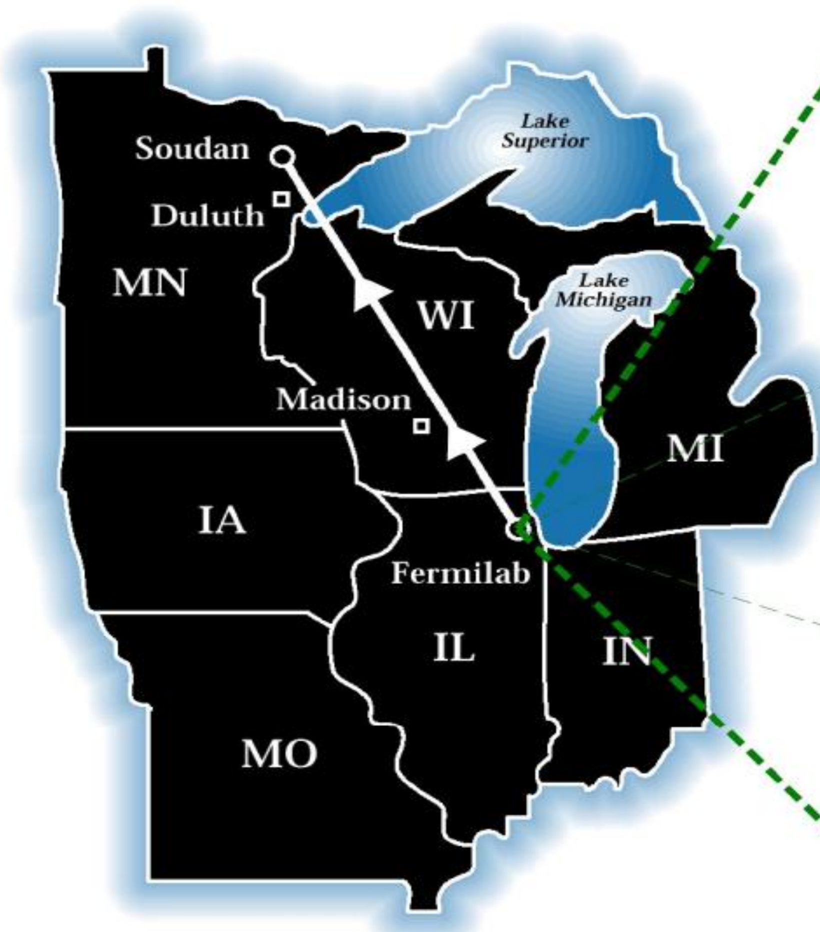
Final publication:

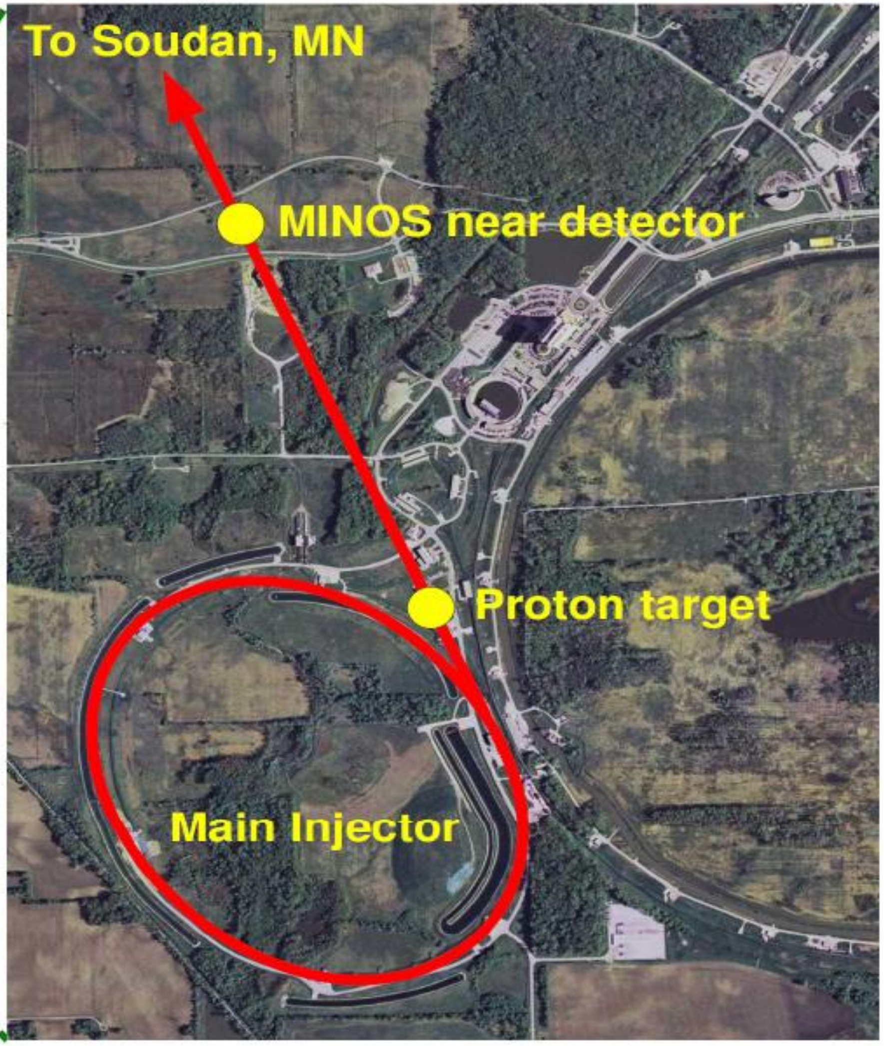
M. H. Ahn *et al.* (K2K), Phys. Rev. D **74**, 072003 (2006)

We present measurements of ν_μ disappearance in K2K, the KEK to Kamioka long-baseline neutrino oscillation experiment. One hundred and twelve beam-originated neutrino events are observed in the fiducial volume of Super-Kamiokande with an expectation of $158.1^{+9.2}_{-8.6}$ events without oscillation. A distortion of the energy spectrum is also seen in 58 single-ring muon-like events with reconstructed energies. The probability that the observations are explained by the expectation for no neutrino oscillation is 0.0015% (4.3σ). In a two flavor oscillation scenario, the allowed Δm^2 region at $\sin^2 2\theta = 1$ is between 1.9 and 3.5×10^{-3} eV^2 at the 90 % C.L. with a best-fit value of 2.8×10^{-3} eV^2.

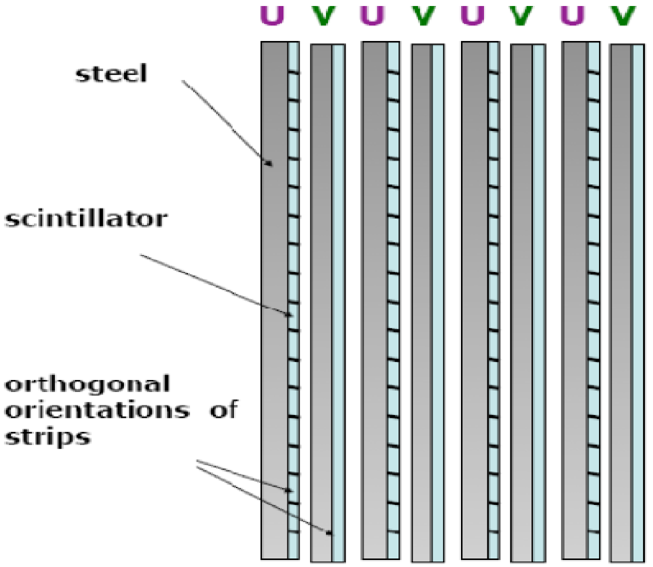
MINOS实验：Main Injector Neutrino Oscillation Search

735 km to the far detector

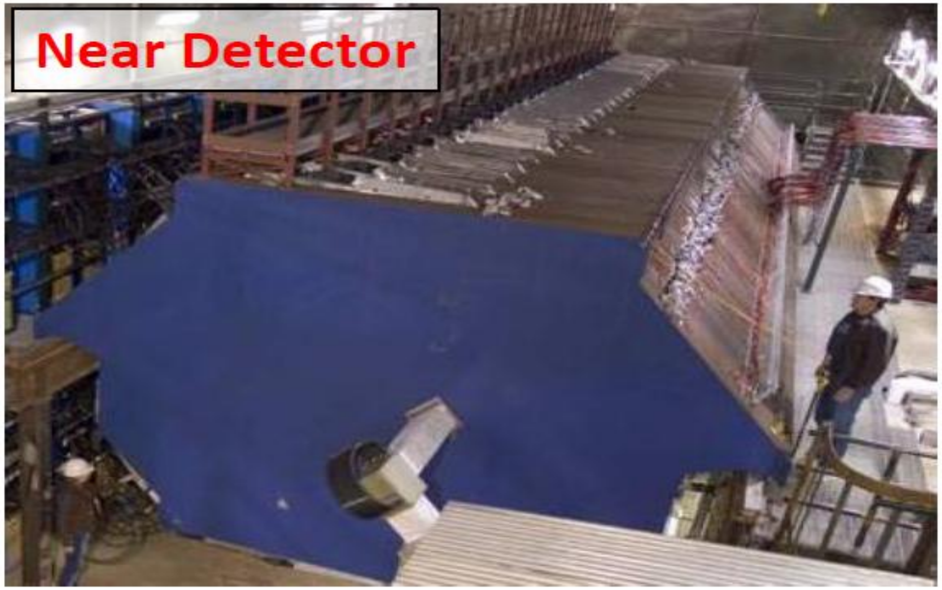


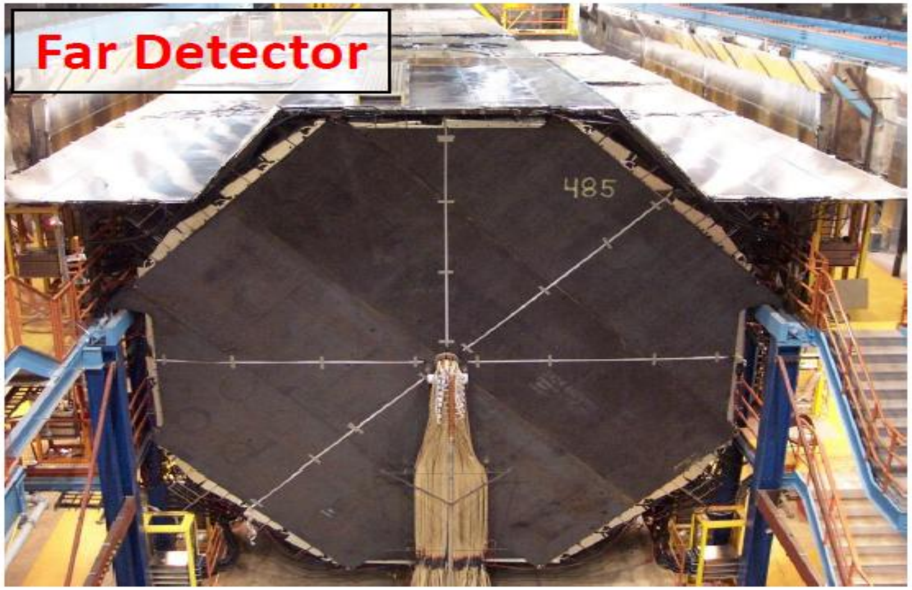


MINOS探测器

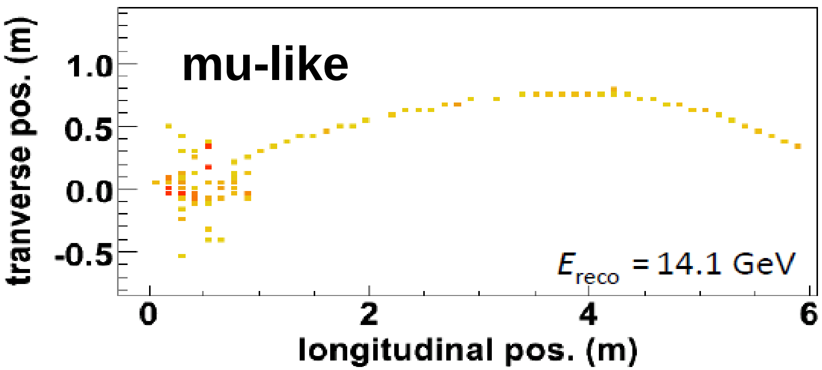


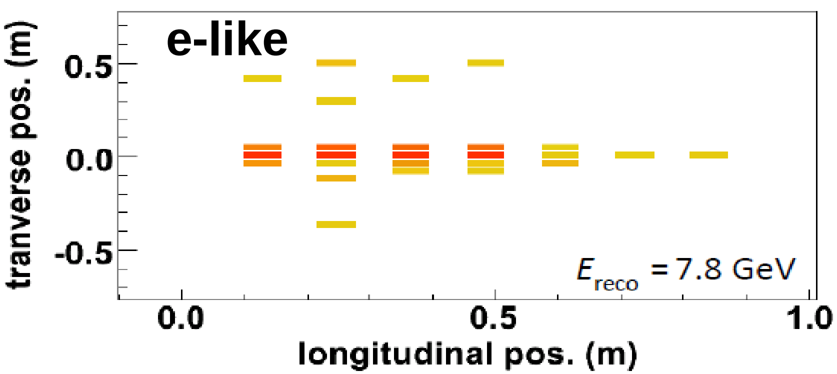
- **"Identical" near and far detectors**
  Magnetized tracking calorimeters
  B = 1.0 to 1.5 T
  1 kton ND / 5.4 kton FD
- **Alternating layers of:**
  steel (1" thick plates)
  scintillator (1 cm thick, 4.1 cm wide strips)
- **Scintillator layers oriented at ±45°**

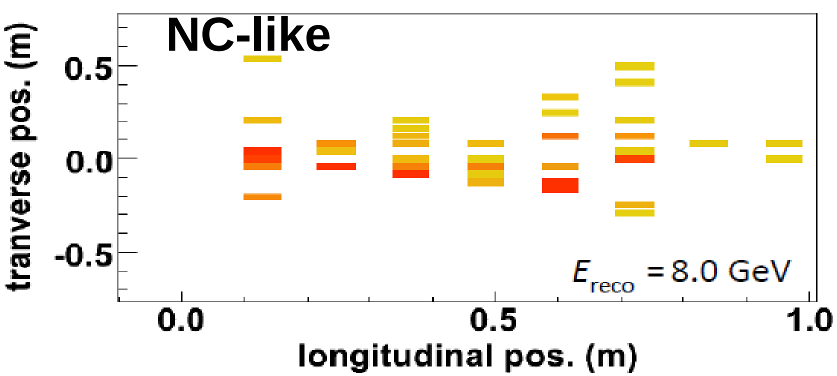


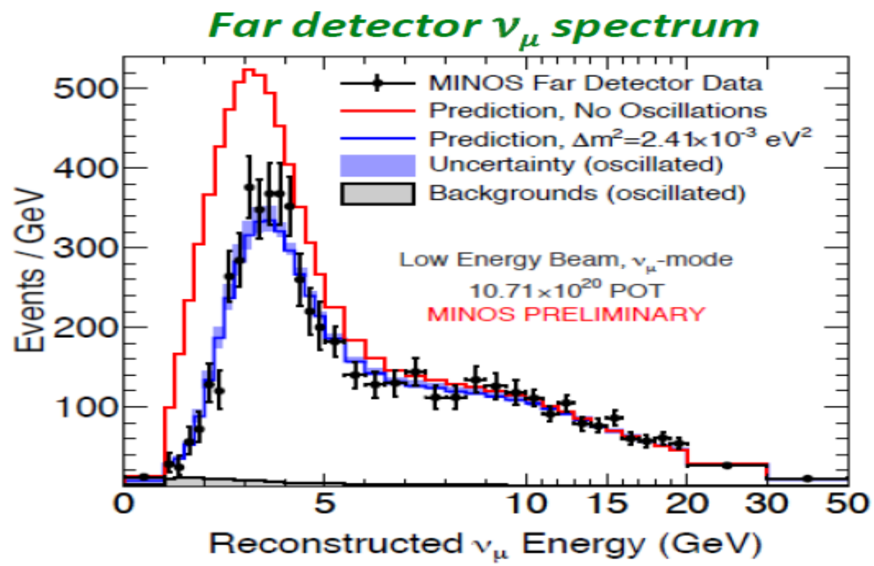


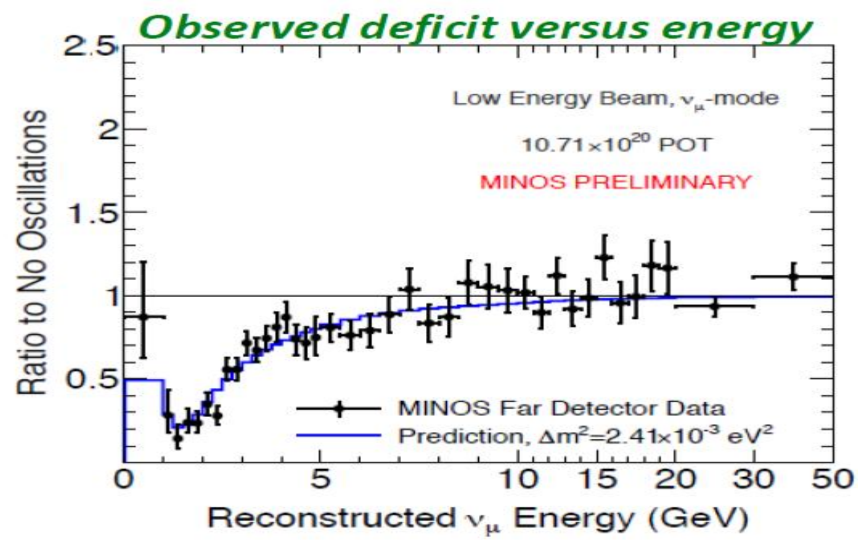
MINOS事例


mu-like
tranverse pos. (m)
1.0
0.5
0.0
-0.5
0
2
4
6
longitudinal pos. (m)
E_{reco} = 14.1 GeV


e-like
tranverse pos. (m)
0.5
0.0
-0.5
0.0
0.5
1.0
longitudinal pos. (m)
E_{reco} = 7.8 GeV

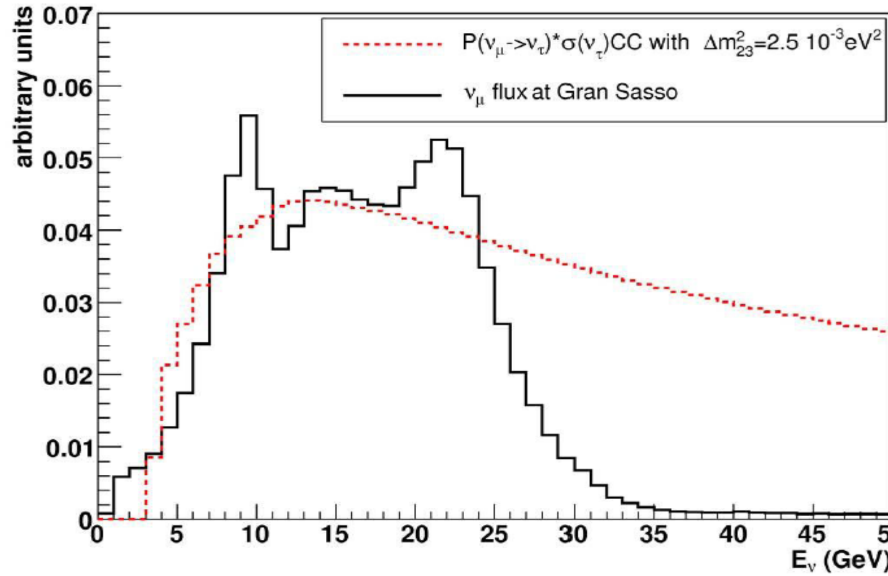

NC-like
tranverse pos. (m)
0.5
0.0
-0.5
0.0
0.5
1.0
longitudinal pos. (m)
E_{reco} = 8.0 GeV

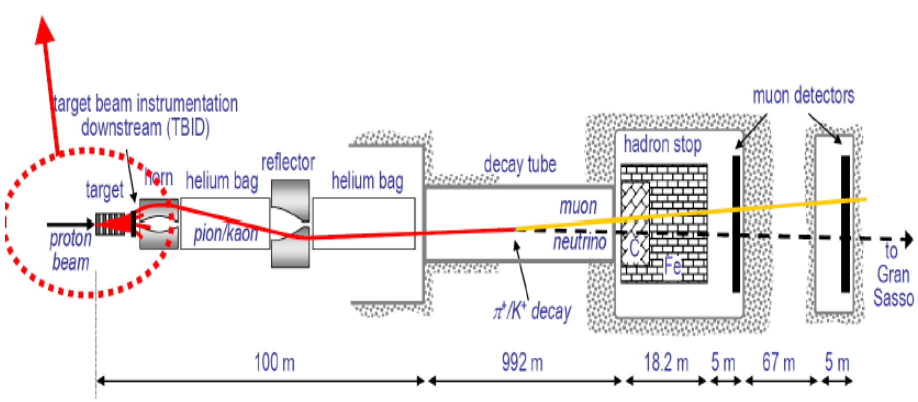

Far detector ν_μ spectrum
MINOS Far Detector Data
Prediction, No Oscillations
Prediction, $\Delta m^2 = 2.41 \times 10^{-3}$ eV^2
Uncertainty (oscillated)
Backgrounds (oscillated)
Low Energy Beam, ν_μ-mode
10.71×10^{20} POT
MINOS PRELIMINARY
Events / GeV
500
400
300
200
100
0
5
10
15
20
30
50
Reconstructed ν_μ Energy (GeV)

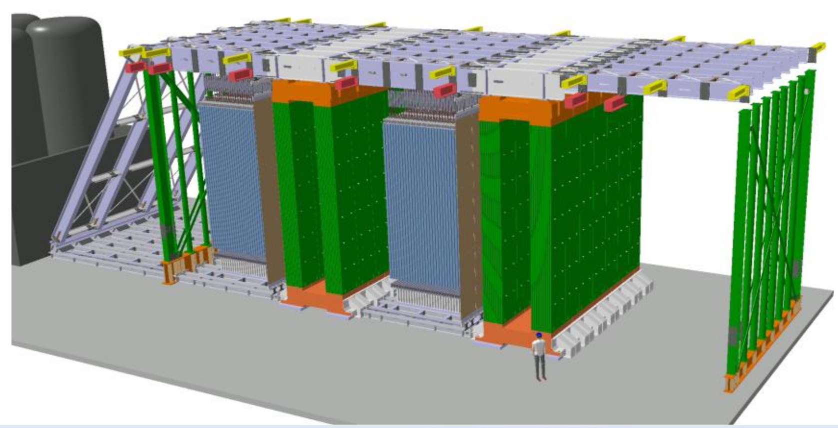

Observed deficit versus energy
Low Energy Beam, ν_μ-mode
10.71×10^{20} POT
MINOS PRELIMINARY
Ratio to No Oscillations
2.5
2
1.5
1
0.5
MINOS Far Detector Data
Prediction, $\Delta m^2 = 2.41 \times 10^{-3}$ eV^2
0
5
10
15
20
30
50
Reconstructed ν_μ Energy (GeV)

OPERA： Oscillation Project with Emulsion-tRacking Apparatus

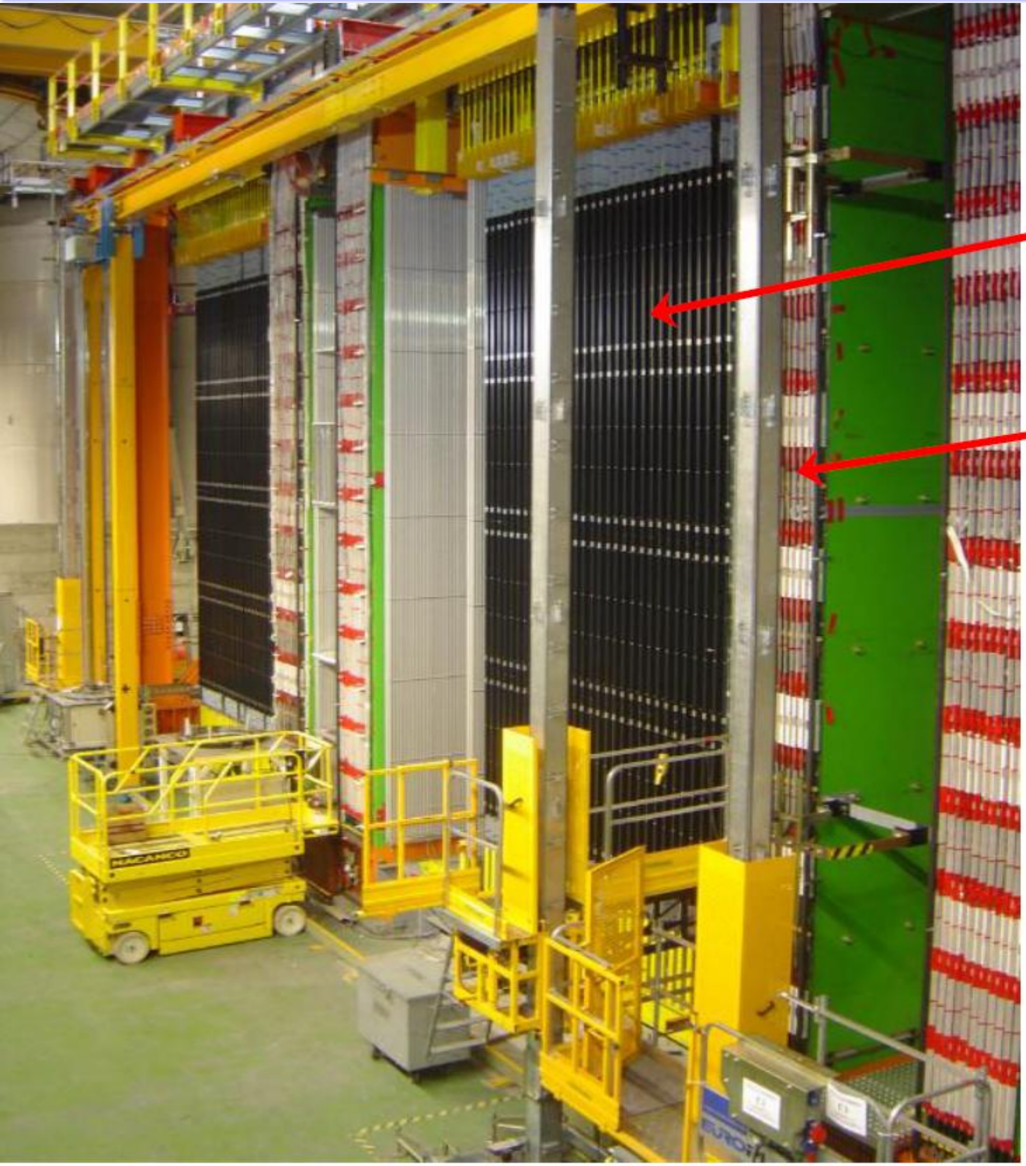
$$P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23} \, \sin^2(\Delta m^2_{32} L/4E)$$







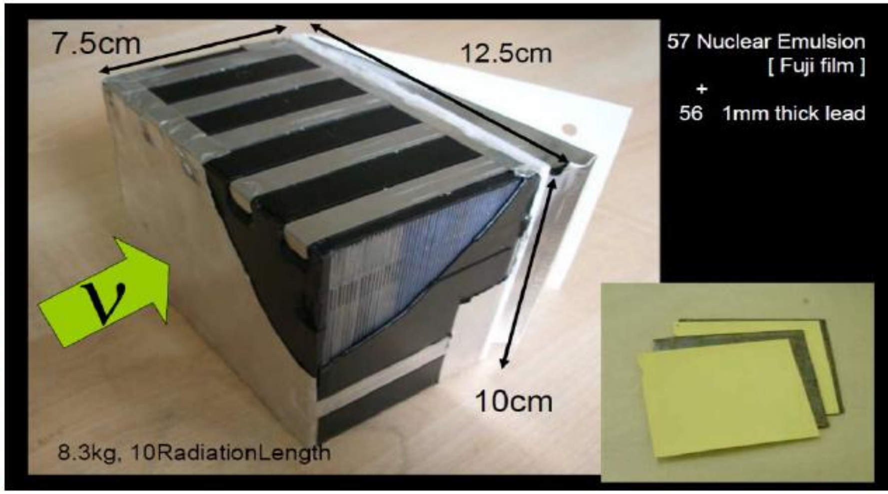
OPERA探测器



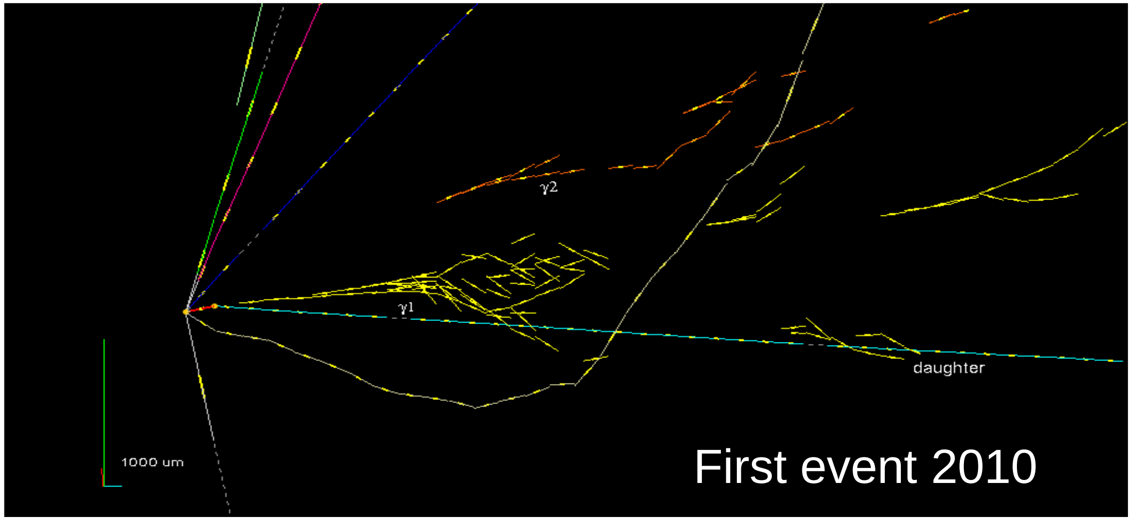
OPERA detector

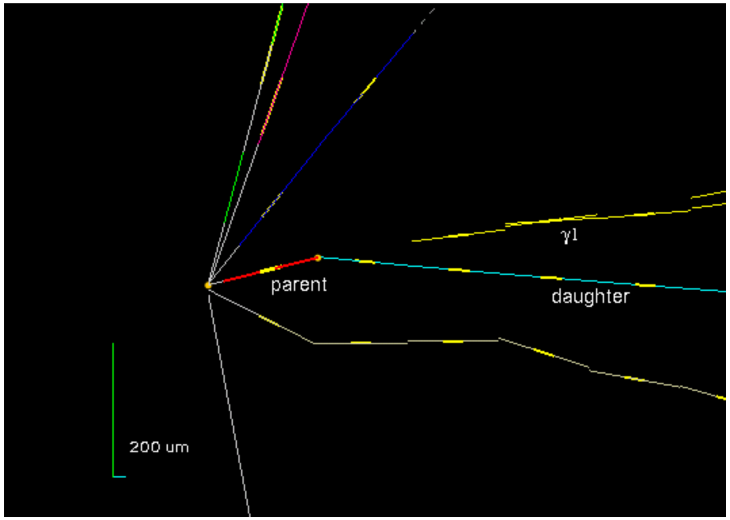
Emulsion and lead layers arranged in "bricks"

Tracking detectors to locate interaction point among the bricks

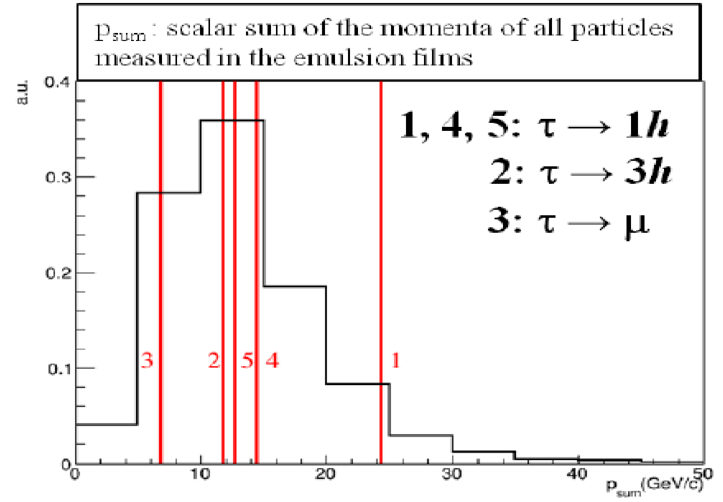


OPERA：tau事例的结果





Decay channel	Expected background				expected signal events $\Delta m^2 = 2.44 \times 10^{-3}\ eV^2$	Observed events
	Charm	*Had. Re-interaction*	*Large μ scattering*	*Total*		
$\tau \to 1h$	0.017±0.003	0.022±0.006	-	0.04±0.01	0.52±0.10	3
$\tau \to 3h$	0.17±0.03	0.003±0.001	-	0.17±0.03	0.73±0.14	1
$\tau \to \mu$	0.004±0.001	-	0.0002±0.0001	0.004±0.001	0.61±0.12	1
$\tau \to e$	0.03±0.01	-	-	0.03±0.01	0.78±0.16	0
Total	0.22±0.04	0.02±0.01	0.0002±0.0001	0.25±0.05	2.64±0.53	5



用本底涨落解释的概率：1x10^{-7}　　**5.1-sigma排除无振荡假设**

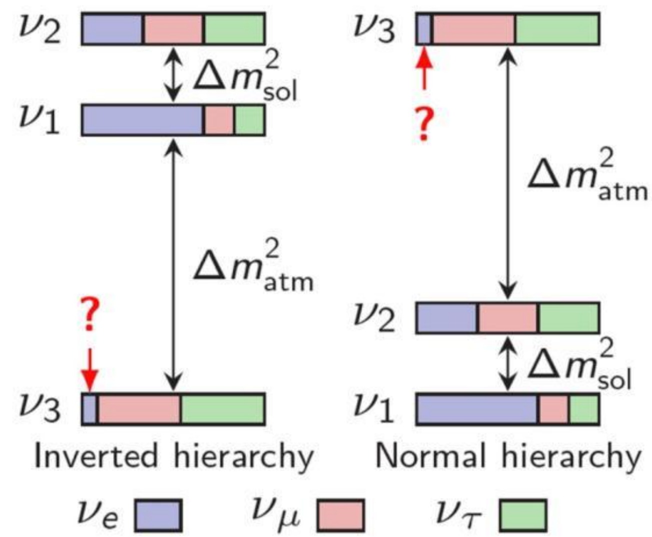
Part VII:

Theta(13)

中微子振荡的图像：circa 2003

在三味中微子框架下：

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



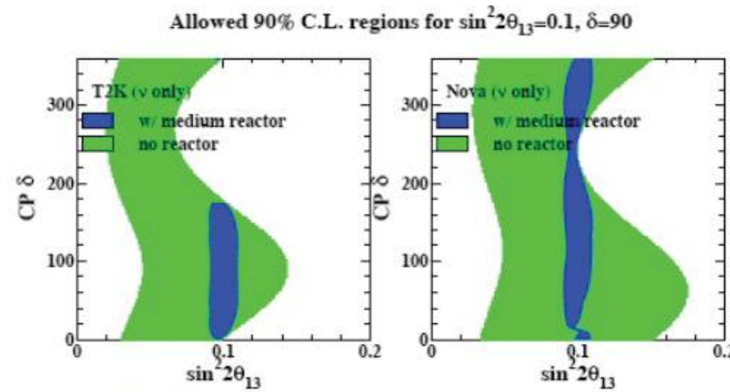
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho}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

$\theta_{23} \sim 45°$	$\theta_{13} = ?$	$\theta_{12} \sim 34°$	
Atmospheric	**Reactor**	**Solar**	**0νββ**
Accelerator	**Accelerator**	**Reactor**	

如何测量Theta13?

加速器中微子实验 (nu(mu)→nu(e)的产生道)，受到CP破坏和物质效应影响

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\Delta m_{31}^2 L/4E\right)$$
$$+ \text{(CPV term)} + \text{(matter term)}$$
$$+ \text{ high order terms}$$



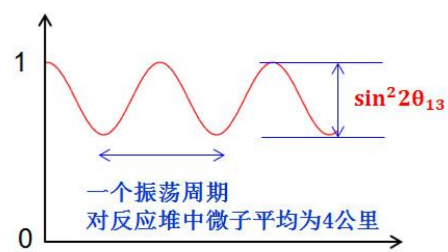
反应堆中微子实验 (nu(e)→nu(e)的消失道)，不受其他物理因素影响

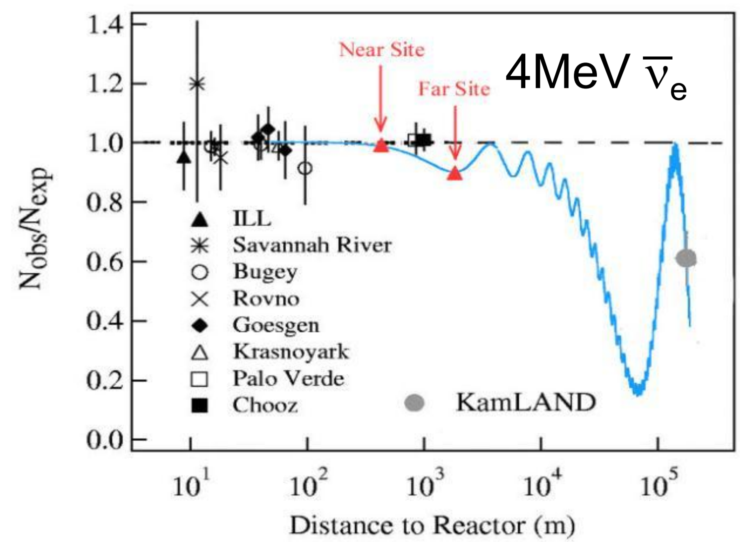
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m_{31}^2 L/4E\right)$$
$$- \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\Delta m_{21}^2 L/4E\right)$$

飞行距离/中微子能量

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27 \cdot \Delta m_{31}^2 \cdot \frac{L}{E}\right)$$

振幅大小　振荡频率





回顾：法国的CHOOZ实验

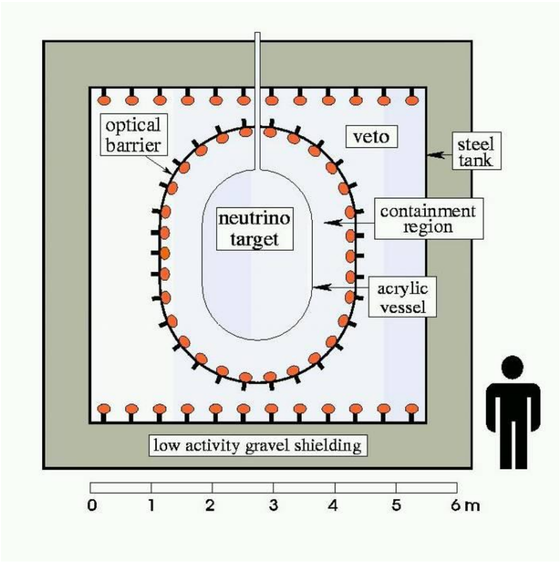
1997-1998, 法国

8.5 GWth

300 mwe

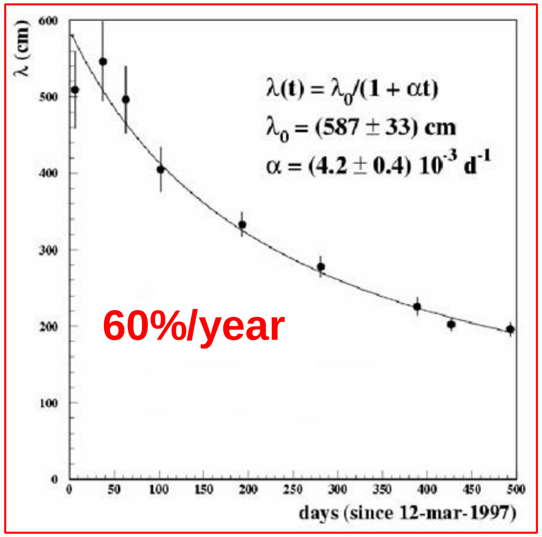
5 ton 0.1% Gd-LS

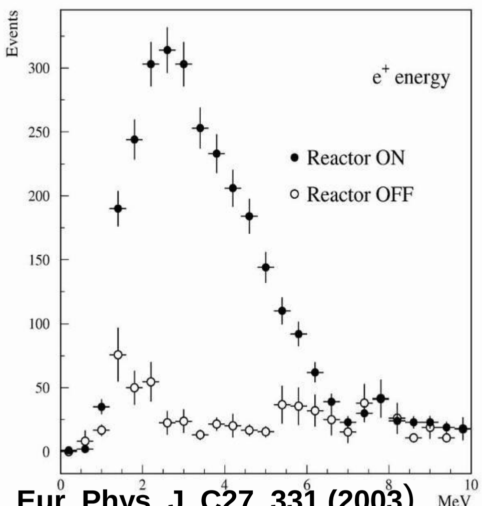
Bad Gd-LS



R=1.01±2.8%(stat) ±2.7%(syst), $\sin^2 2\theta_{13}<0.17$

Parameter	Relative error
Reaction cross section	1.9 %
Number of protons	0.8 %
Detection efficiency	1.5 %
Reactor power	0.7 %
Energy released per fission	0.6 %
Combined	**2.7 %**



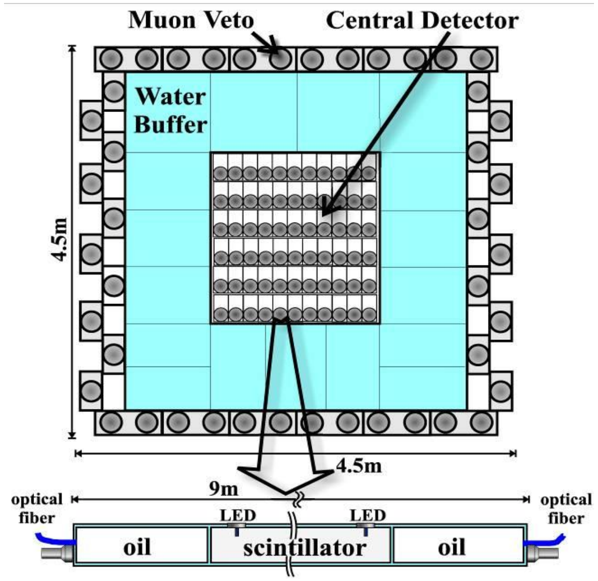


Eur. Phys. J. C27, 331 (2003)

回顾：美国的Palo Verde实验

Baseline 890m & 750m

R=1.01±2.4%(stat) ±5.3%(syst)



1998-1999, 美国

11.6 GWth

Segmented detector

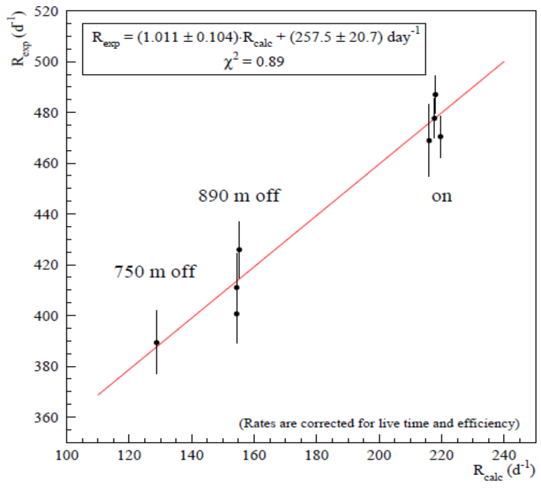
12 ton 0.1% Gd-LS

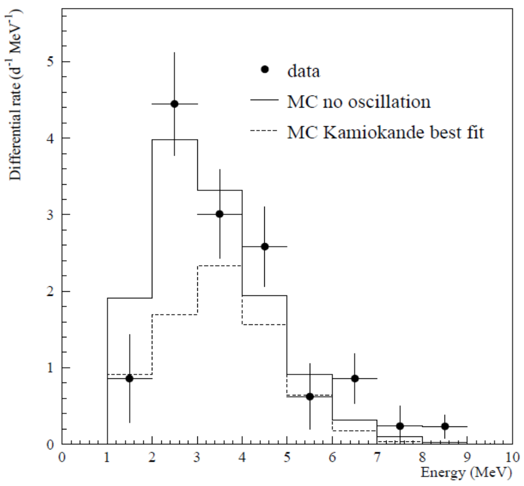
太浅的探测器岩石覆盖

32 mwe

TABLE II. Contributions to the systematic error of the "reactor power" and "swap" analyses.

Error source	"reactor power" (%)	"swap" (%)
e^+ trigger efficiency	2.0	2.0
n trigger efficiency	2.1	2.1
$\bar{\nu}_e$ flux prediction	2.1	2.1
$\bar{\nu}_e$ selection cuts	4.5	2.1
Background variation	2.1	N/A
$(1-\epsilon_1)B_{pn}$ estimate	N/A	3.3
Total	6.1	5.3

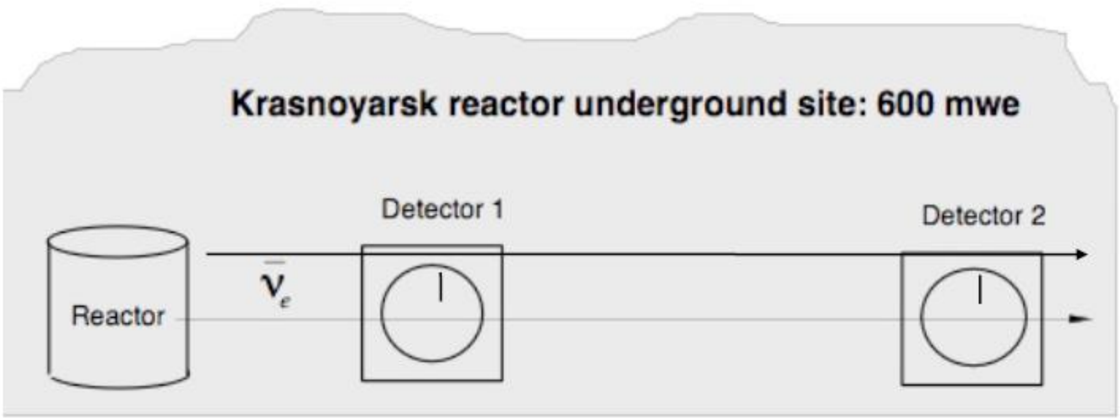




双探测器方案：远近相对测量

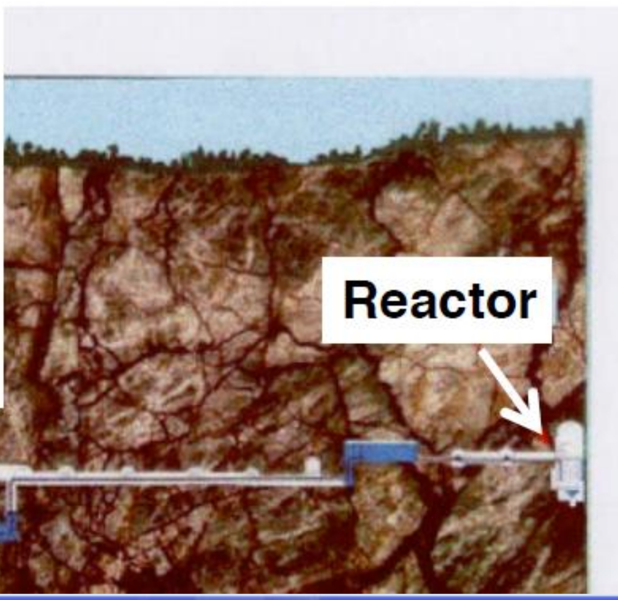
Krasnoyarsk, Russia

first proposed at Neutrino2000



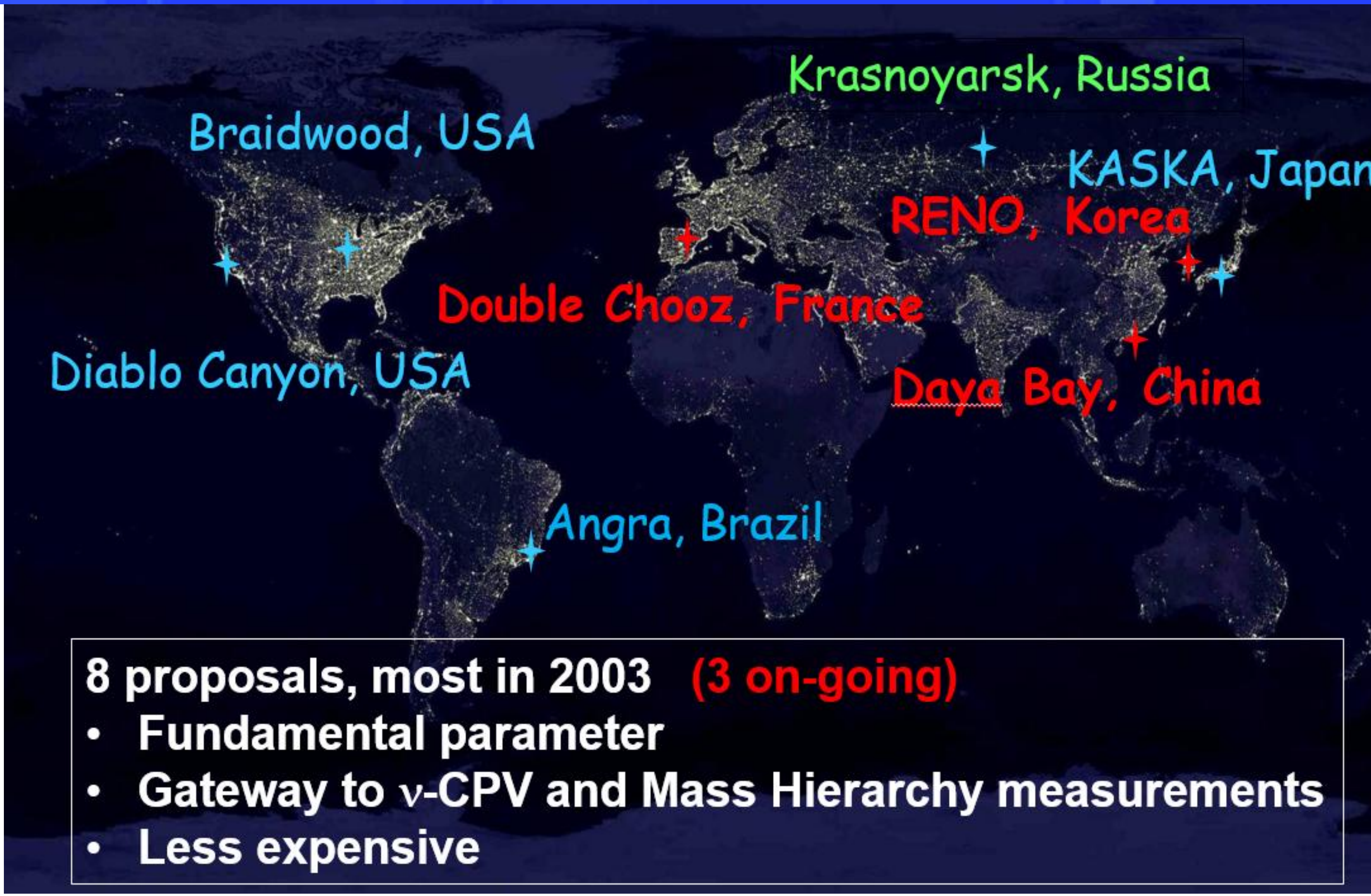
Krasnoyarsk
- underground reactor
- detector locations determined by infrastructure

	115 m	1000 m
Target:	46 t	46 t
Rate:	~1.5 x 10^6 ev/year	~20000 ev/year
S:B	>>1	~ 10:1



Ref: Marteyamov et al, hep-ex/0211070

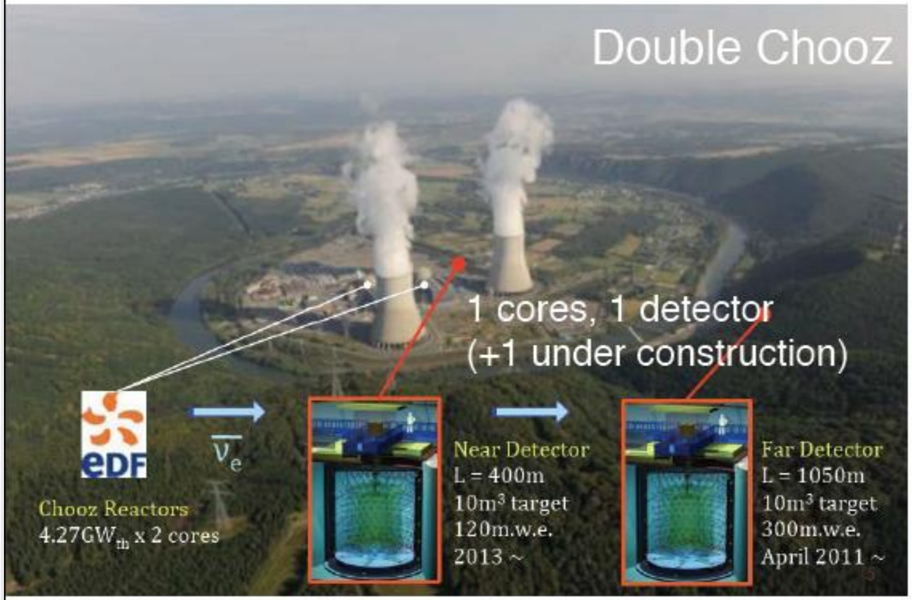
8→3：实际建设的实验

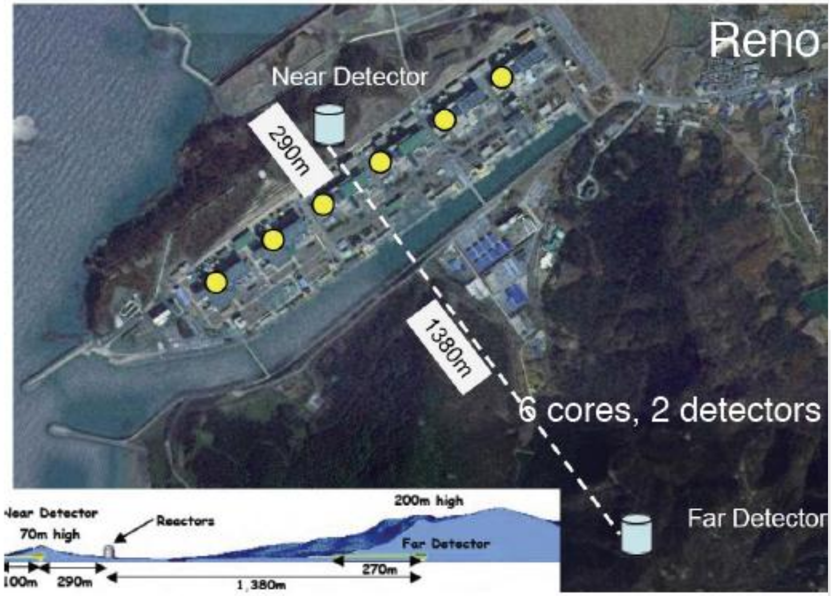


8 proposals, most in 2003 (3 on-going)

- Fundamental parameter
- Gateway to ν-CPV and Mass Hierarchy measurements
- Less expensive

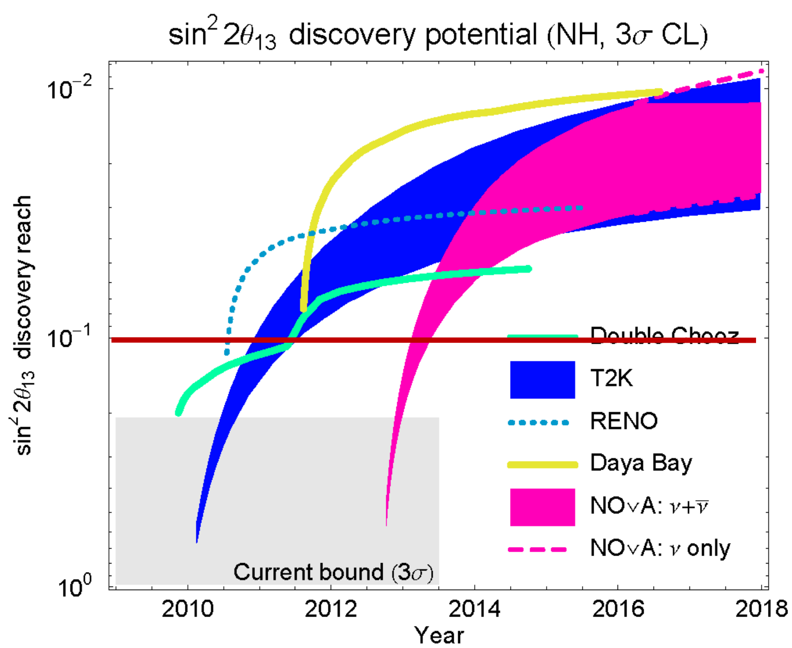
Daya Bay/RENO/Double CHOOZ

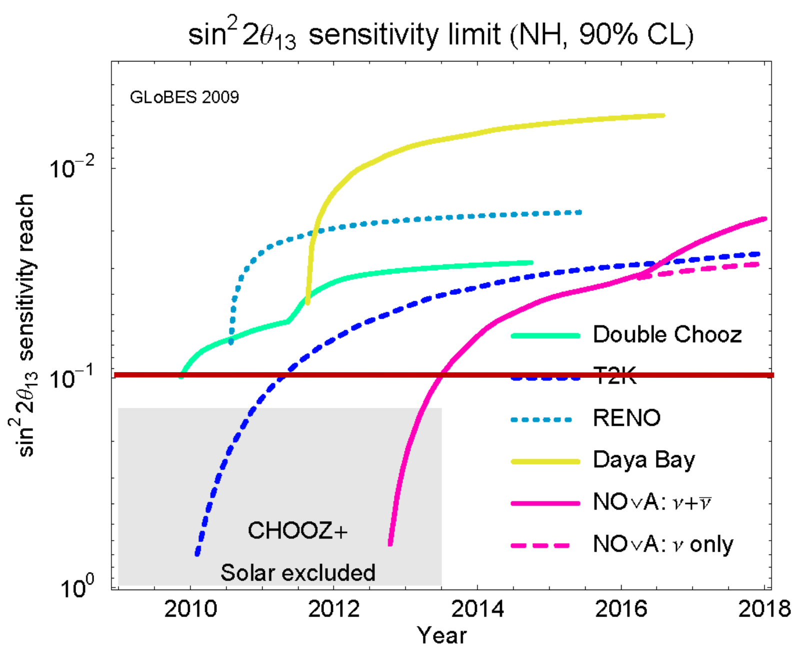




Daya Bay/RENO/Double CHOOZ

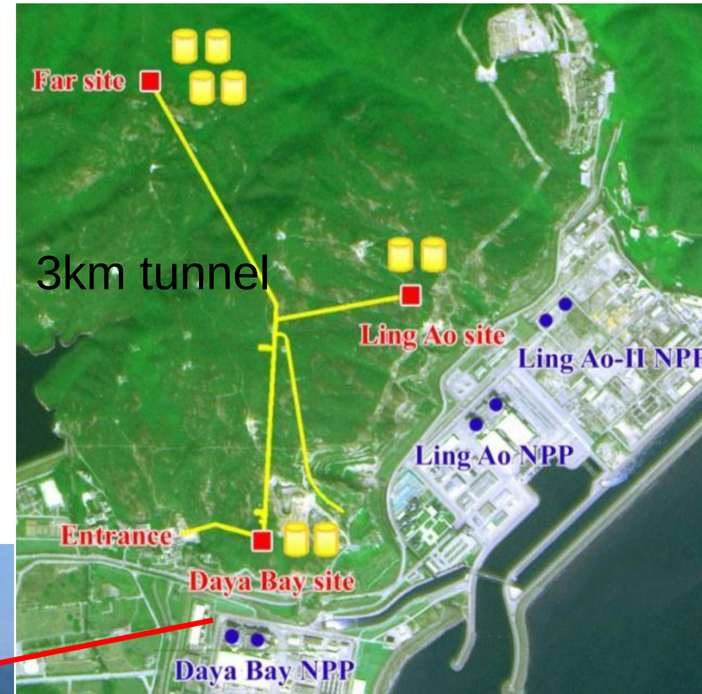
Experiment	Power (GW)	Detector(t) Near/Far	Overburden (m.w.e.) Near/Far	Sensitivity (3y,90%CL)
Daya Bay	17.4	40 / 80	250 / 860	~ 0.008
Double Chooz	8.5	8 / 8	120 / 300	~ 0.03
RENO	16.5	16 / 16	120 / 450	~ 0.02

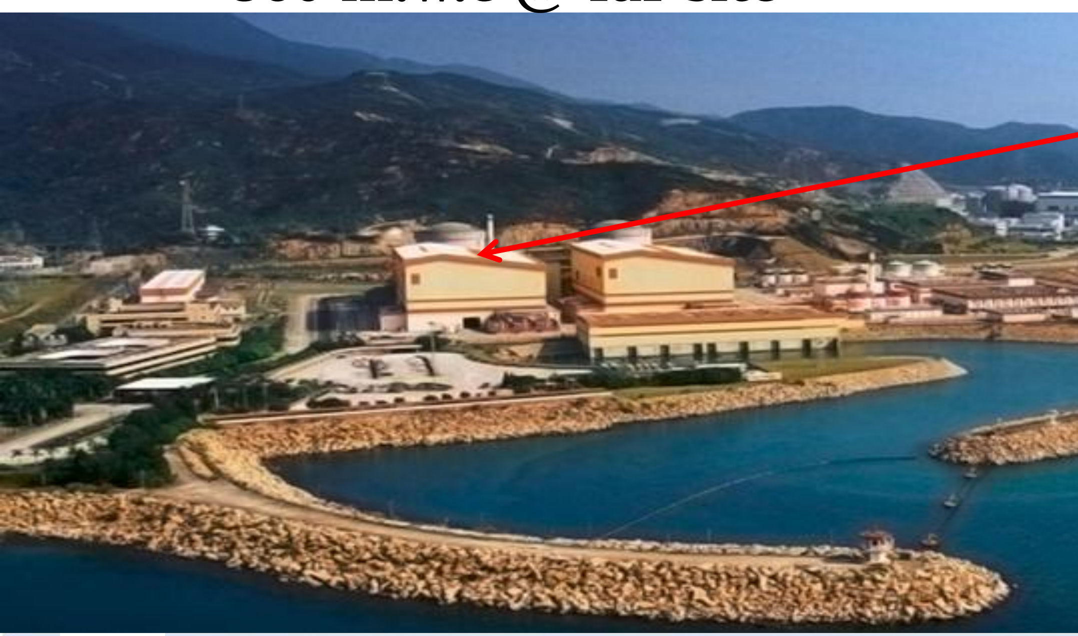


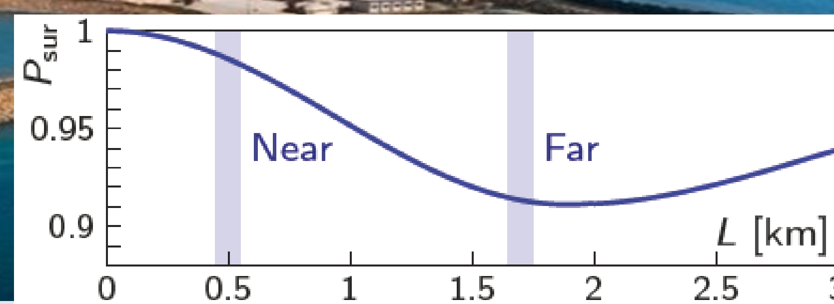


Daya Bay

- **6 reactor cores, 17.4 GW_{th}**
- **Relative measurement**
  - **2 near sites, 1 far site**
- **Multiple detector modules**
- **Good cosmic shielding**
  - **250 m.w.e @ near sites**
  - **860 m.w.e @ far site**

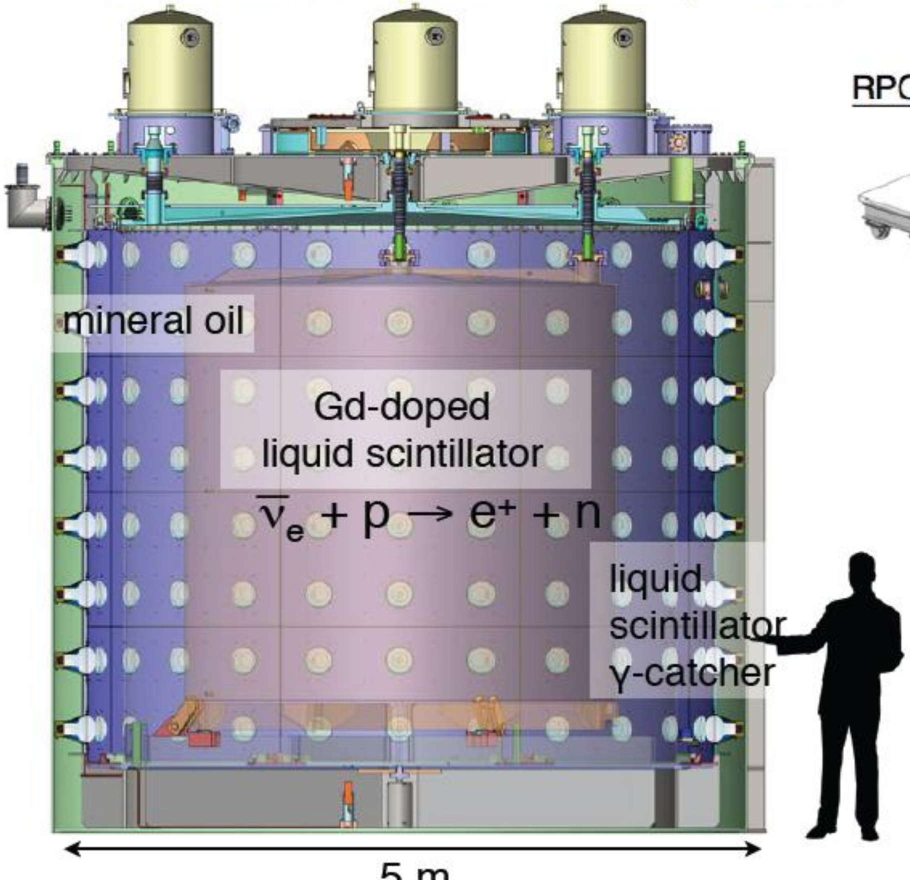






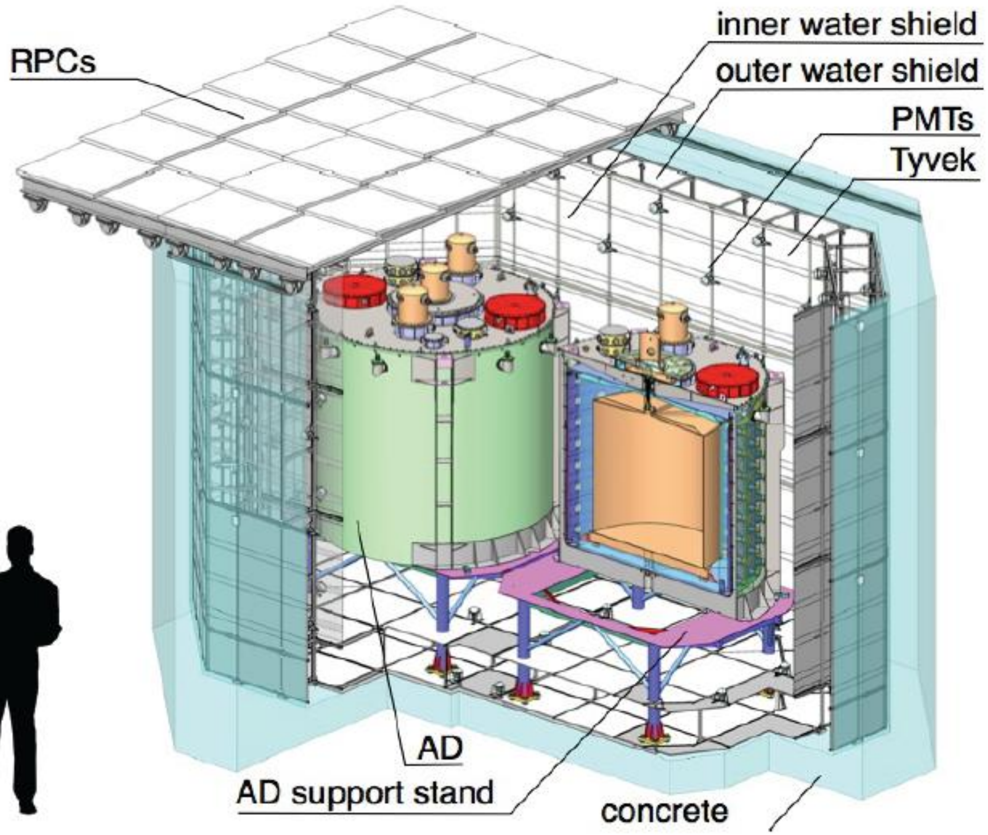
Daya Bay探测器设计

6 “functionally identical” detectors
Gd-LS defines target volume, no position cut



target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

Dual tagging systems: 2.5 meter water shield and RPCs

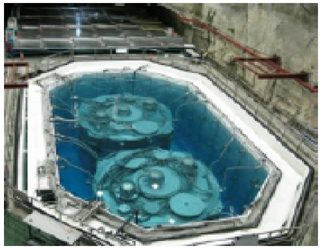


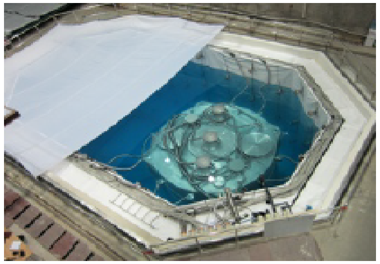
Two-zone ultrapure water Cherenkov detector

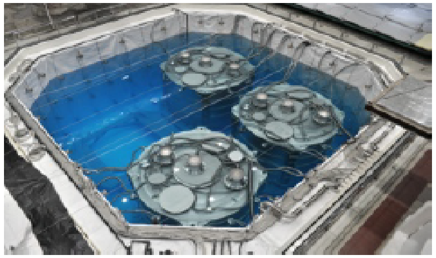
multiple detectors allow comparison and cross-checks

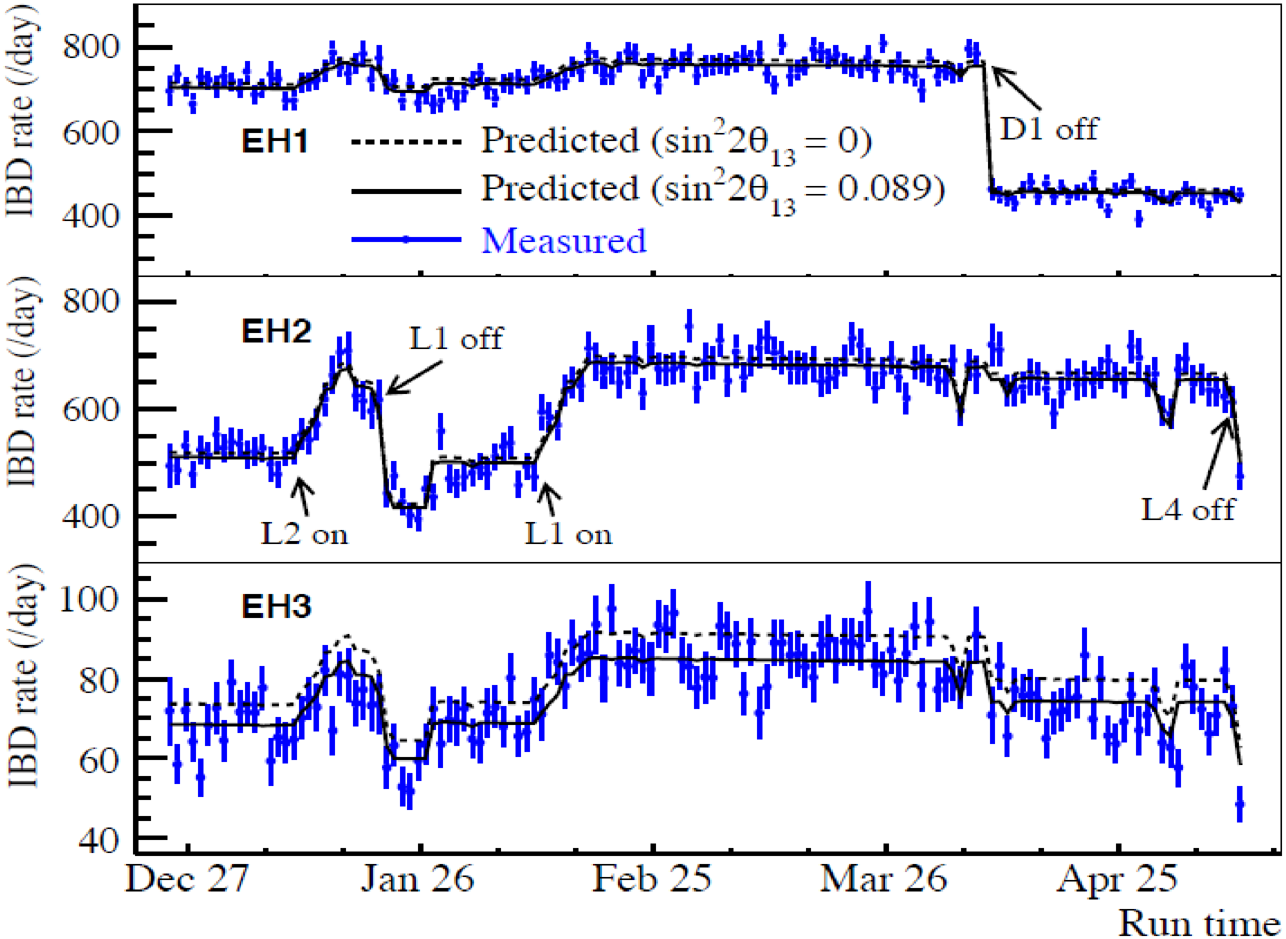
中微子事例率

Detected rate strongly correlated with reactor flux expectations



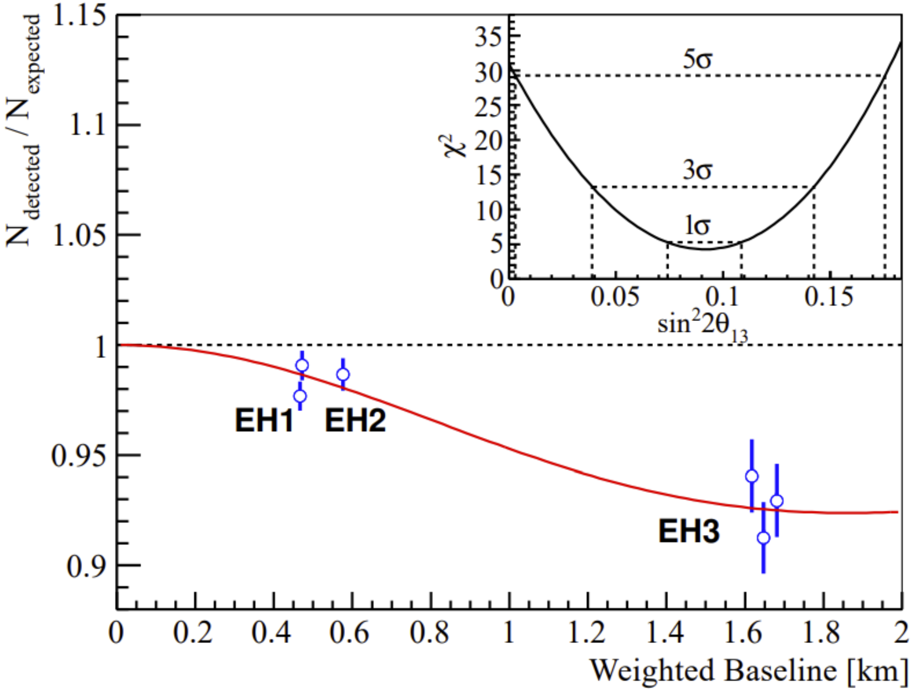


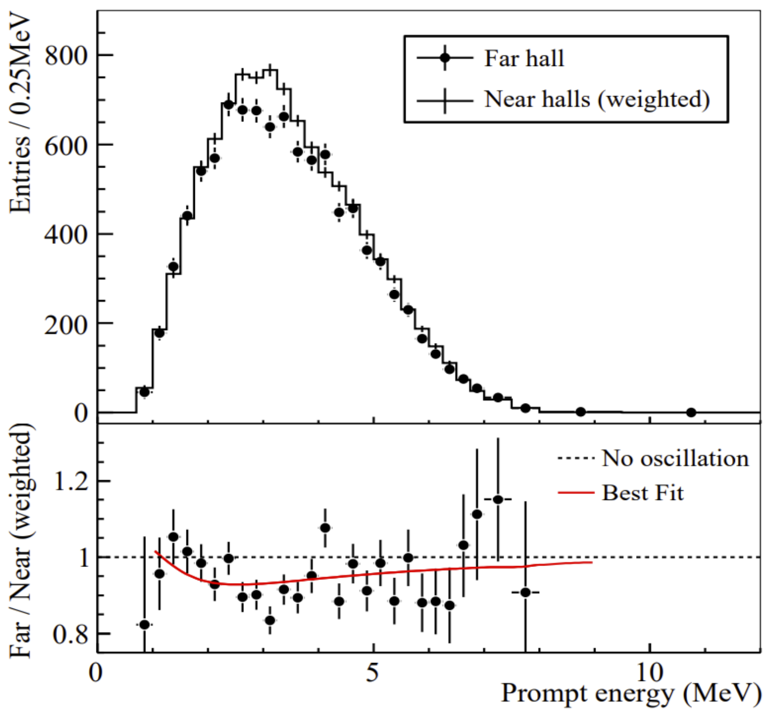




Predicted Rate assumes no oscillation.
Normalization is determined by fit to near detector data.

Theta(13)





Dec. 2011	Double Chooz (far detector):	$\sin^2\theta_{13} = 0.022 \pm 0.013$	1.7σ
Mar. 2012	Daya Bay (near + far detectors):	$\sin^2\theta_{13} = 0.024 \pm 0.004$	5.2σ
Apr. 2012	RENO (near + far detectors):	$\sin^2\theta_{13} = 0.029 \pm 0.006$	4.9σ

大亚湾实验2020年退役

θ_{13}的精度20% → 3%

未来二十年保持国际最高精度。

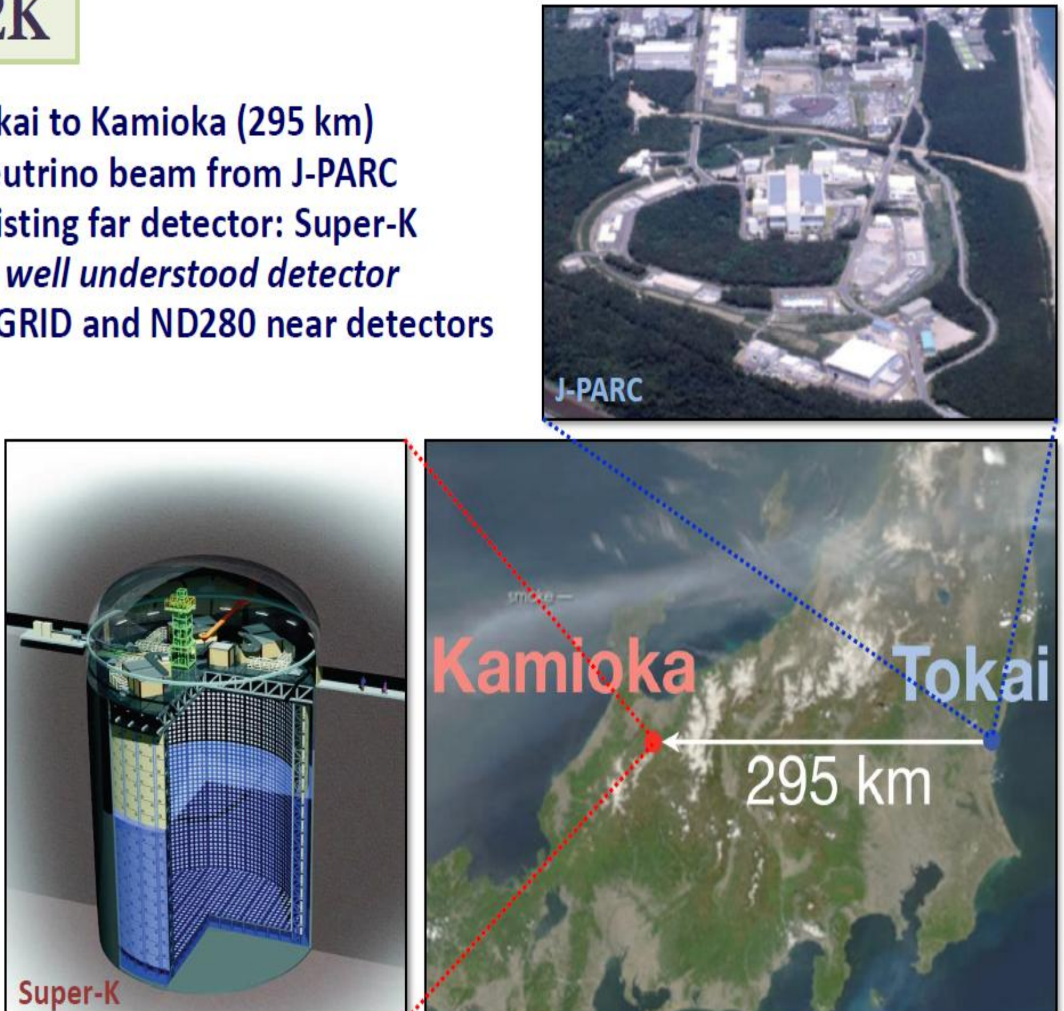
自然界基本参数，几乎所有中微子研究和部分粒子物理研究与之相关。

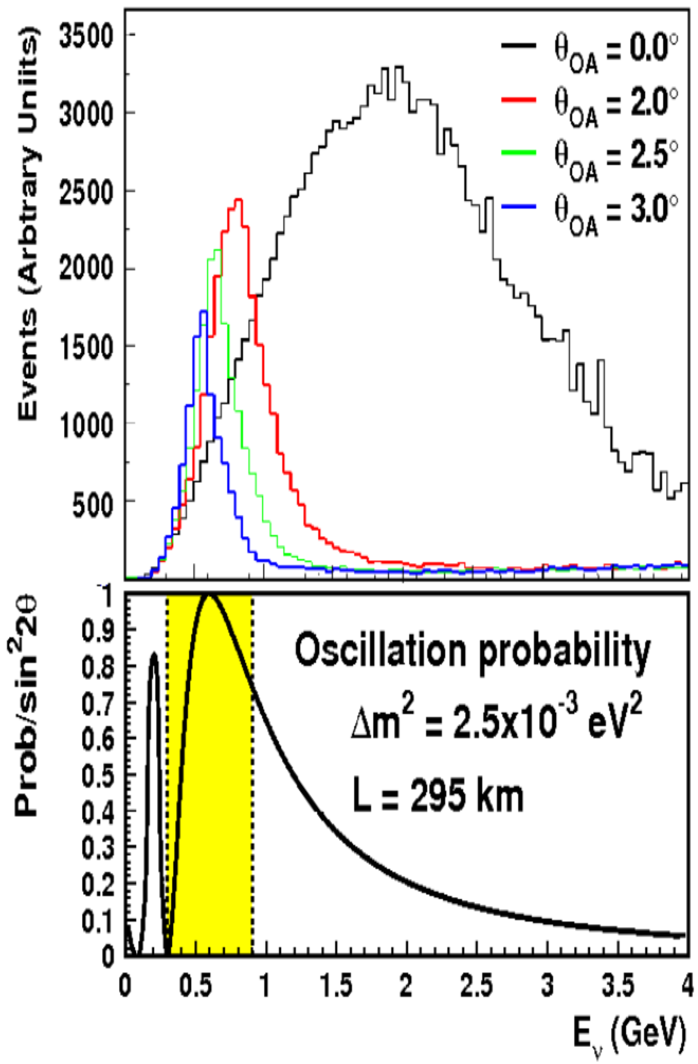
T2K: basic information

T2K

- Tokai to Kamioka (295 km)
- Neutrino beam from J-PARC
- Existing far detector: Super-K
  - *well understood detector*

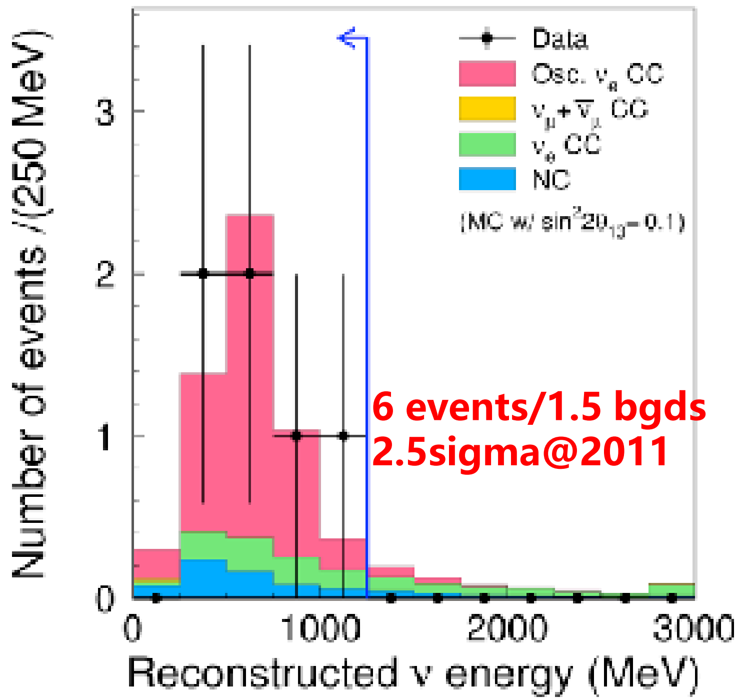
  INGRID and ND280 near detectors

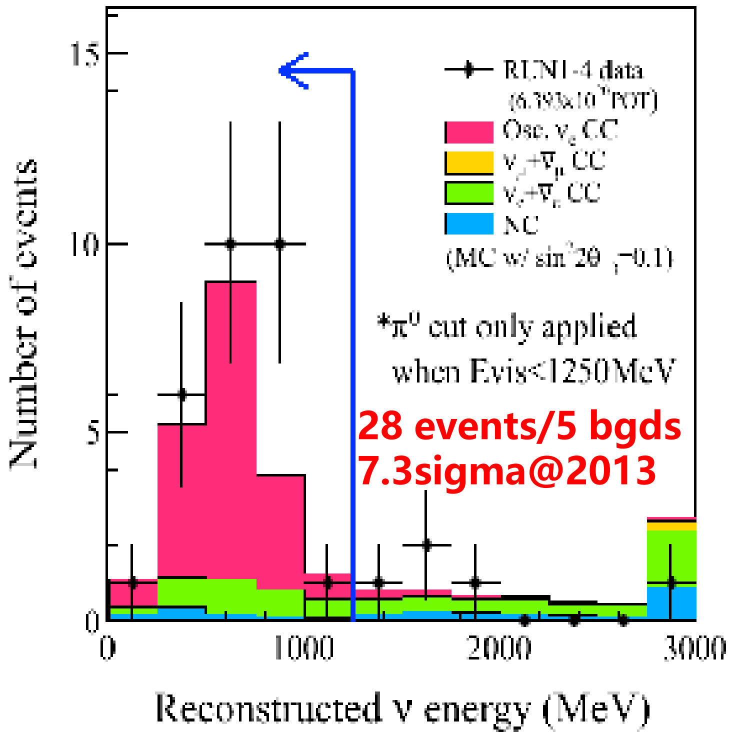




T2K: from 2011-2013

- $\nu_\mu \to \nu_e$ oscillation w/ Δm_{atm}^2 discovered by the T2K experiment
  - Indication in 2011 [PRL 107, 041801 (2011)]
  - Observation in 2013 [PRL 112, 061802 (2014)]





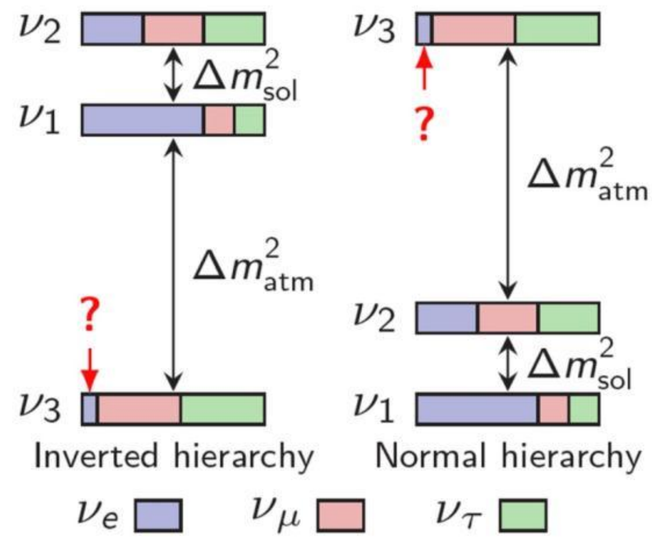
Part VIII:

未来前景

中微子振荡的图像：after 2012

在三味中微子框架下：

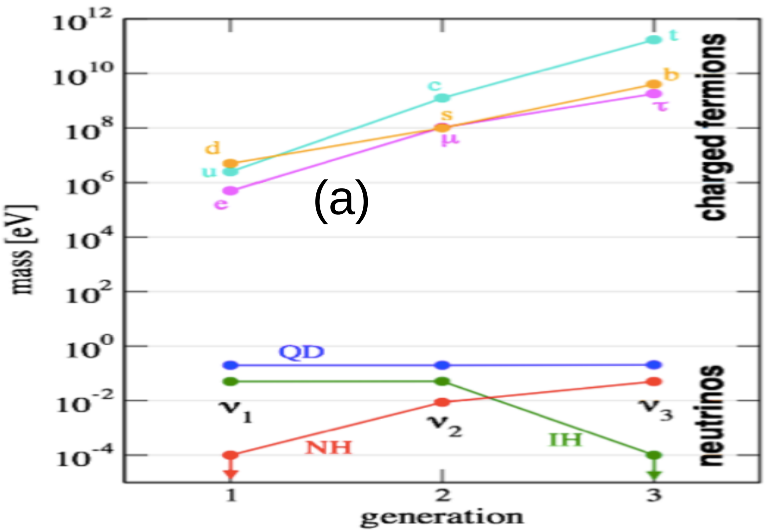
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

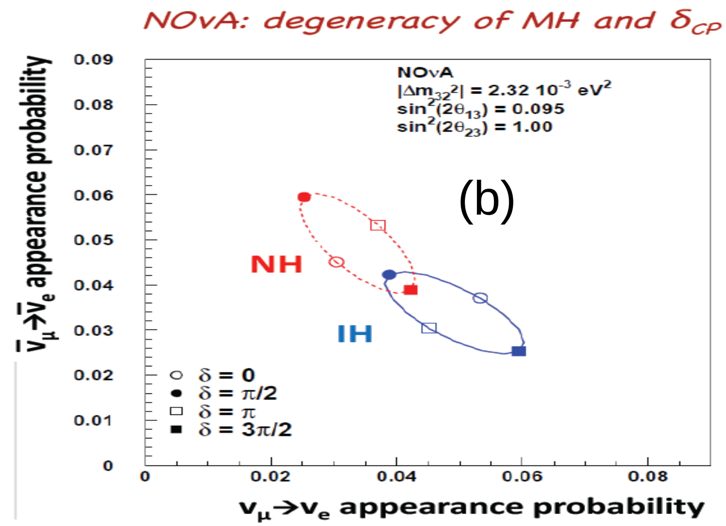


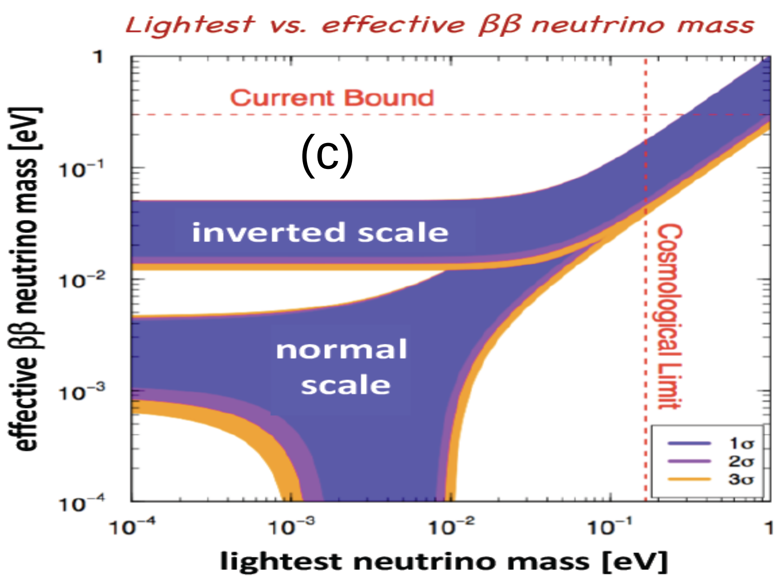
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho}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

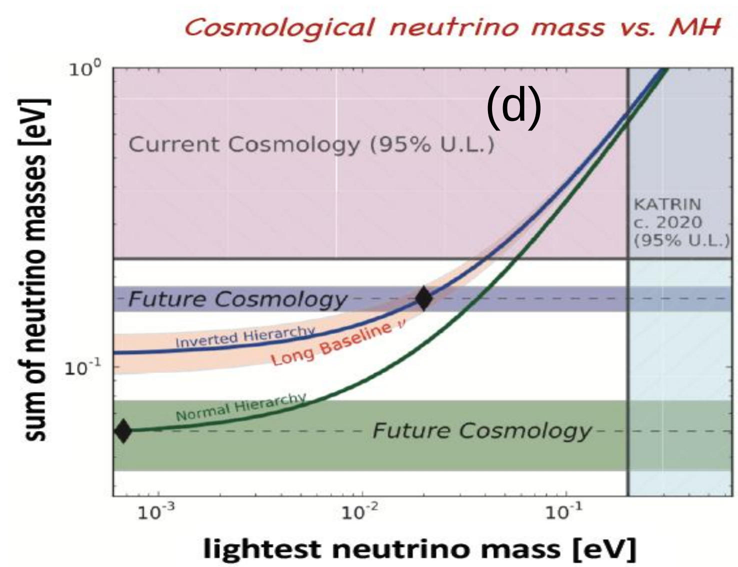
$\theta_{23} \sim 45°$	$\theta_{13} = 9°$	$\theta_{12} \sim 34°$	
Atmospheric	**Reactor**	**Solar**	**0νββ**
Accelerator	**Accelerator**	**Reactor**	

测量质量顺序的意义


(a)
mass [eV]
generation
charged fermions
neutrinos
t
c
b
s
τ
μ
d
u
e
QD
NH
IH
ν1
ν2
ν3
1
2
3


NOvA: degeneracy of MH and δCP
(b)
NOvA
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ13) = 0.095
sin²(2θ23) = 1.00
NH
IH
δ = 0
δ = π/2
δ = π
δ = 3π/2
ν̄μ→ν̄e appearance probability
νμ→νe appearance probability


Lightest vs. effective ββ neutrino mass
(c)
Current Bound
inverted scale
normal scale
Cosmological Limit
1σ
2σ
3σ
effective ββ neutrino mass [eV]
lightest neutrino mass [eV]

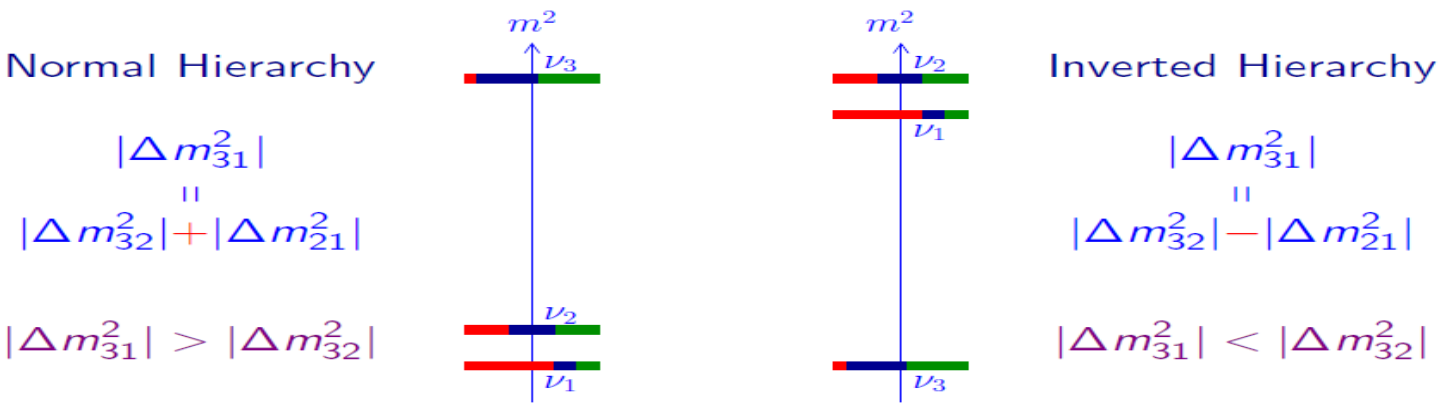

Cosmological neutrino mass vs. MH
(d)
Current Cosmology (95% U.L.)
KATRIN
c. 2020
(95% U.L.)
Future Cosmology
Inverted Hierarchy
Long Baseline
Normal Hierarchy
Future Cosmology
sum of neutrino masses [eV]
lightest neutrino mass [eV]

测量质量顺序的方法

物质效应: Accelerator, atmospheric, supernova neutrinos

- $\nu_e \leftrightarrows \nu_\mu$ MSW resonance: $V = \dfrac{\Delta m^2_{13}\cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} > 0$ NH
- $\bar\nu_e \leftrightarrows \bar\nu_\mu$ MSW resonance: $V = -\dfrac{\Delta m^2_{13}\cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} < 0$ IH

真空振荡的干涉效应: Reactor neutrinos S. T. Petcov et al., PLB 533, 94 (2002)

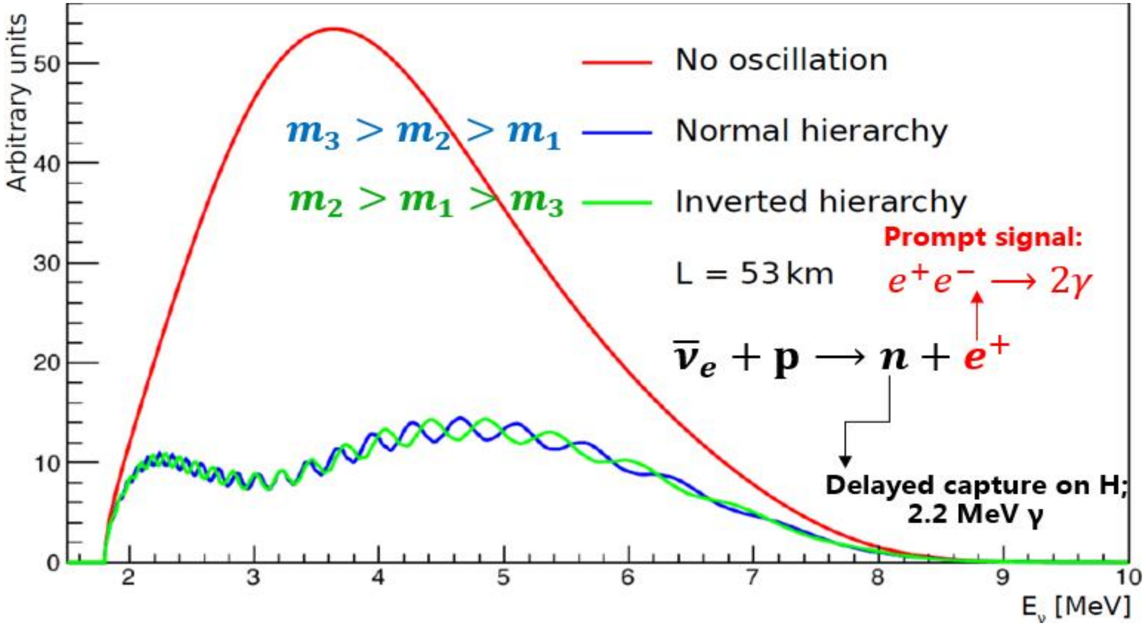


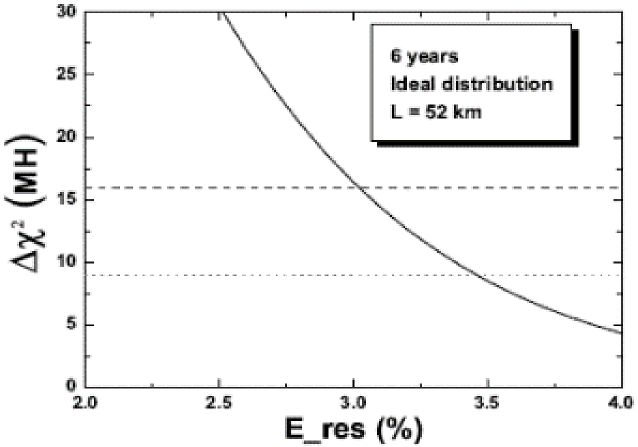
SURVIVAL PROBABILITY

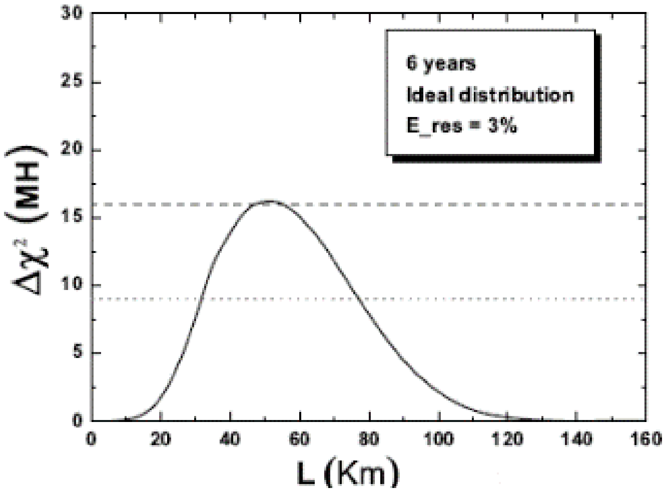
$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \sin^2 2\vartheta_{13} \times \left(\cos^2\vartheta_{12}\sin^2\Delta_{31} + \sin^2\vartheta_{12}\sin^2\Delta_{32}\right)$$ FAST Δm^2_{ATM}

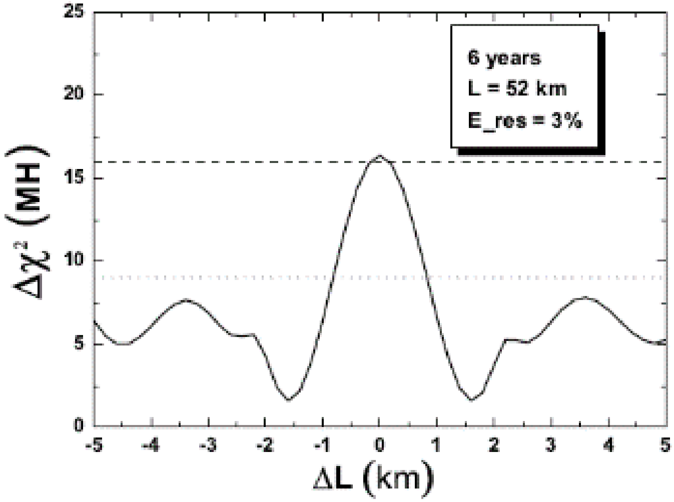
$$-\sin^2 2\vartheta_{12}\cos^4\vartheta_{13}\sin^2\Delta_{21}$$ SLOW Δm^2_{SOL}

反应堆测量质量顺序的原理



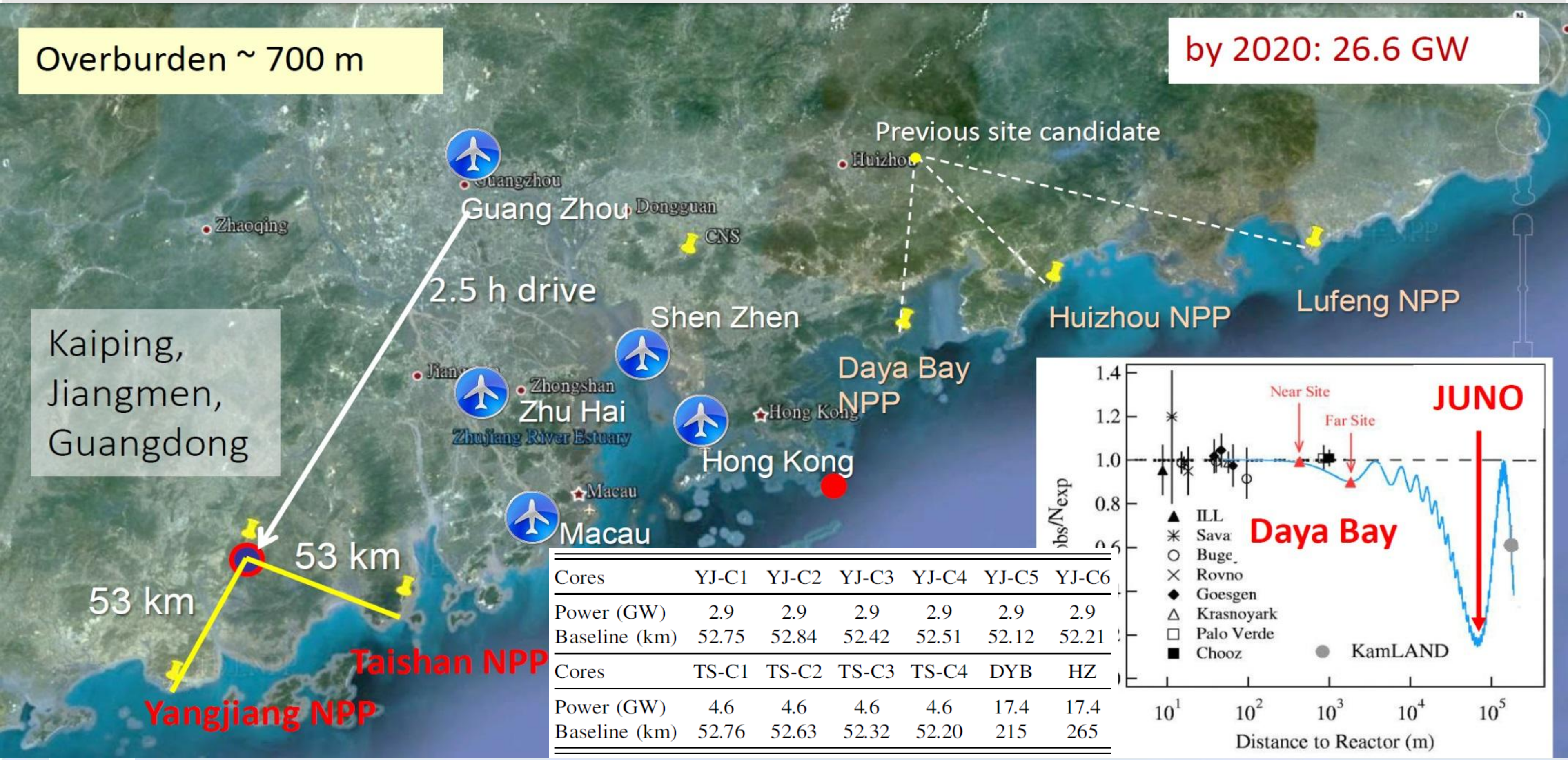






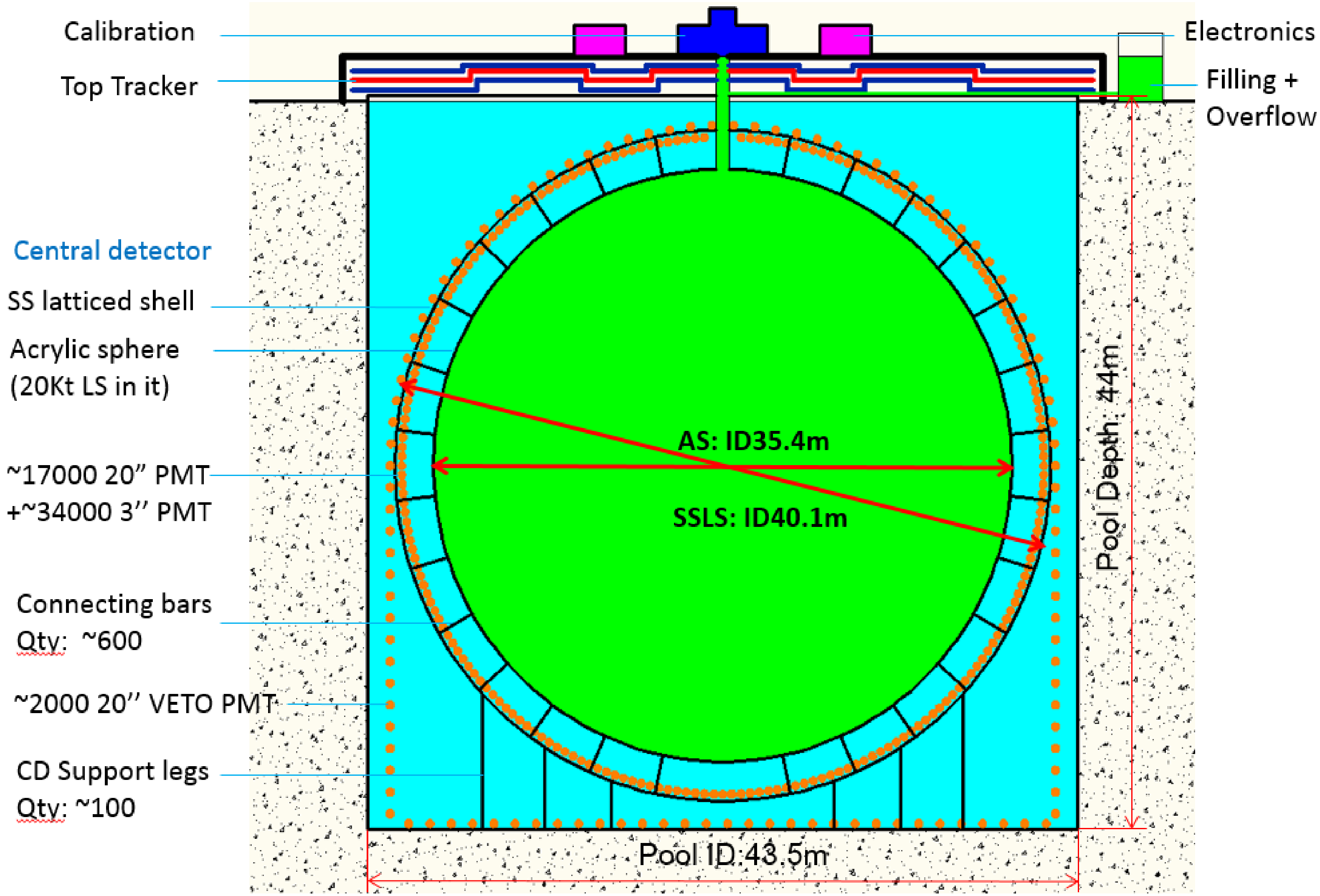
实验选址

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



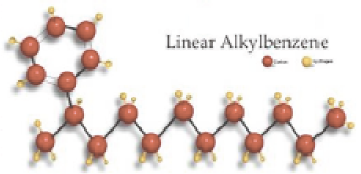
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

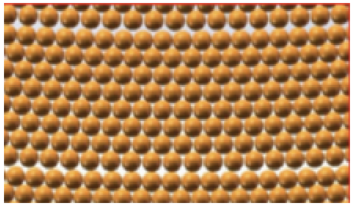
Large and precision Liquid Scintillator detector

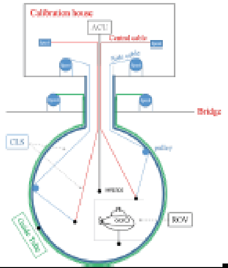


AS: Acrylic sphere; SSLS: stainless steel latticed shell

能量分辨率：如何实现?



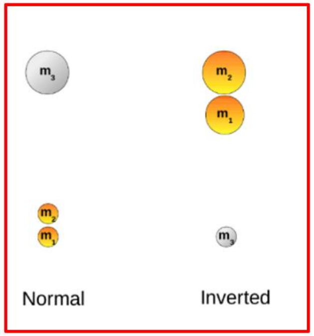


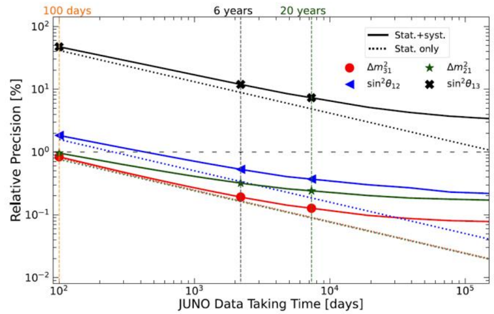


	Daya Bay	BOREXINO	Kamland	JUNO
Target Mass	20 t	300 t	1 kt	20 kt
PE Collection (PE/MeV)	160	500	250	1200
Photocathode Coverage	12%	34%	34%	75%
Energy Resolution	7.5%/√E	5%/√E	6%/√E	3%/√E
Energy Calibration	1.5%	1%	2%	<1%

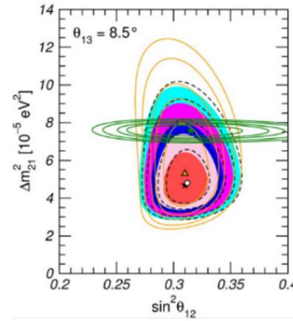
JUNO will be the largest liquid scintillator detector and with the best energy resolution in the world

JUNO: 多物理目标的地下中微子探测器

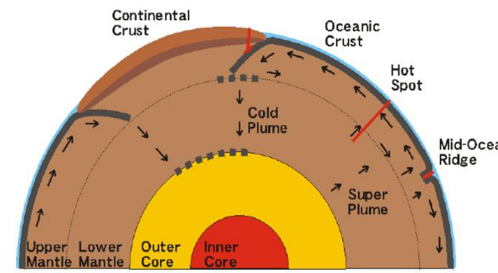




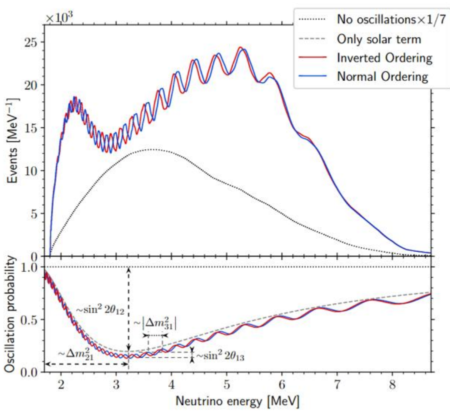
测量振荡参数到1%精度
3年



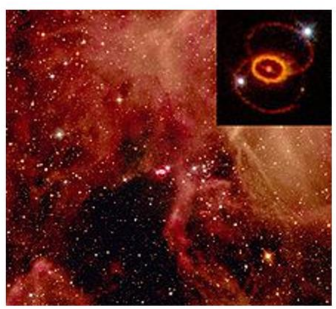
太阳中微子
3-5年



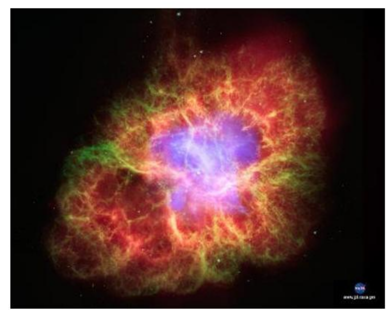
确定地球物理模型
6-10年



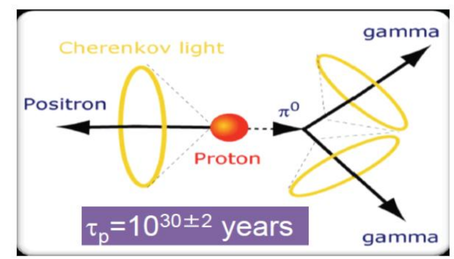
中微子质量顺序
~6年



超新星背景中微子
3-5年



等待超新星爆发
任何时间



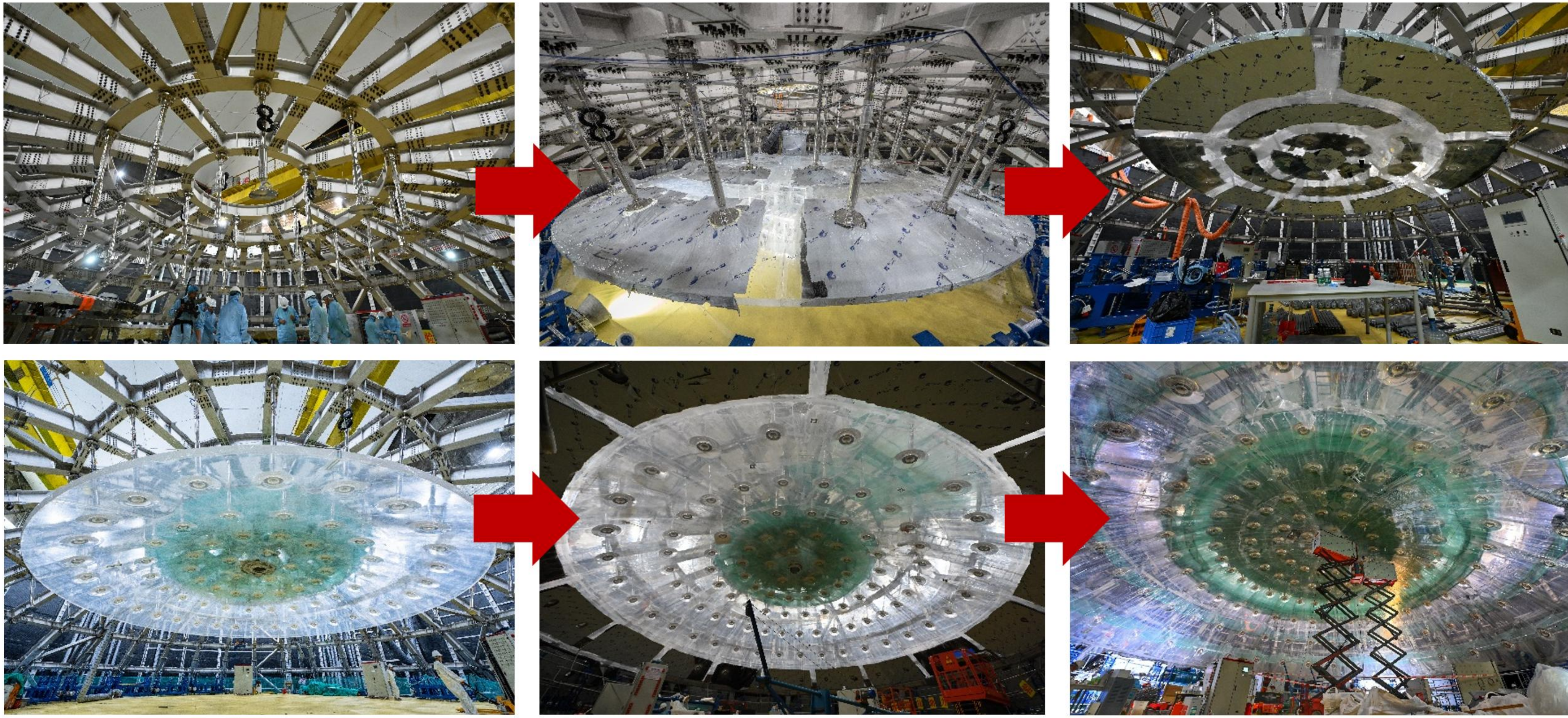
探索核子衰变
5-10年

JUNO: 从地上到地下

JUNO: 主体结构

- 40米直径
- 1千吨低本底不锈钢网架
- 12万套高强度、高摩擦不锈钢螺栓
- 毫米级精度

JUNO: 有机玻璃球



265块12厘米厚有机玻璃弯板利用本体聚合方法在实验现场粘接

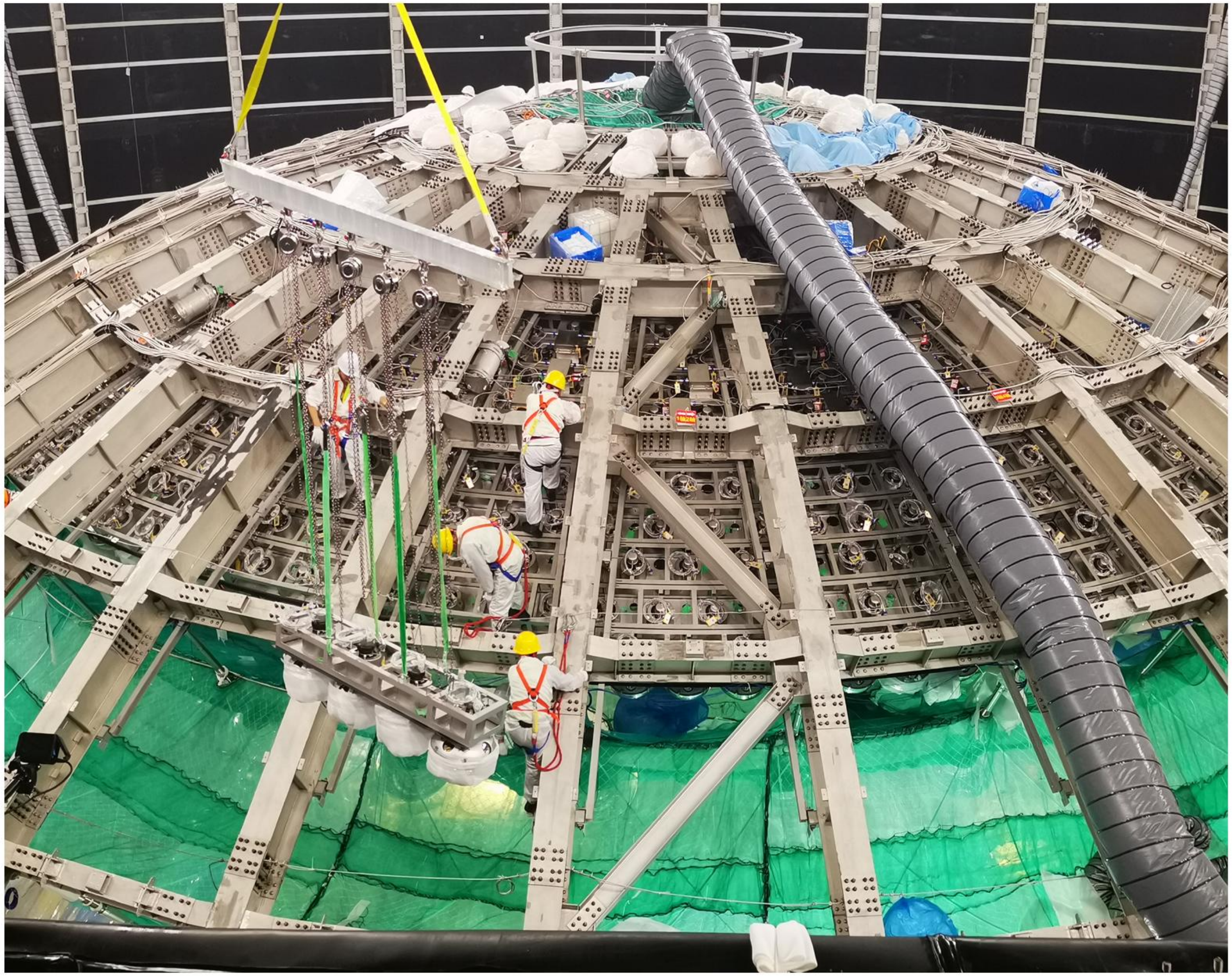
35米直径有机玻璃球是“粘”起来的!

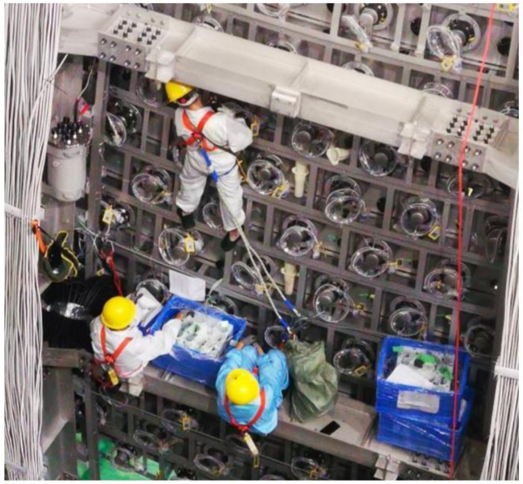
JUNO: 光电倍增管

探测器的眼睛：光电倍增管

- 共45600支光电倍增管，通过**光电效应**探测微弱的光

JUNO: 光电倍增管

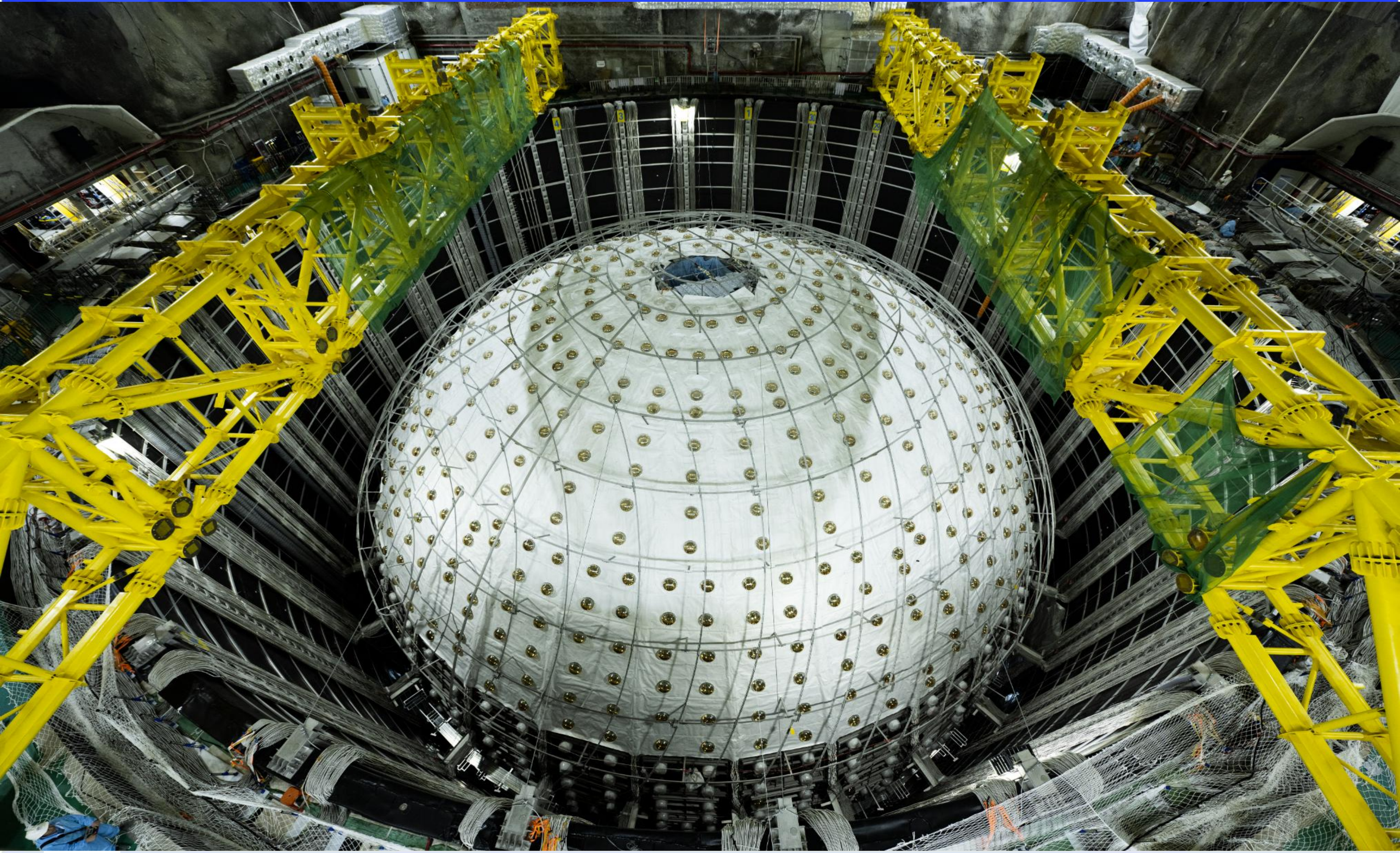




JUNO: 光电倍增管

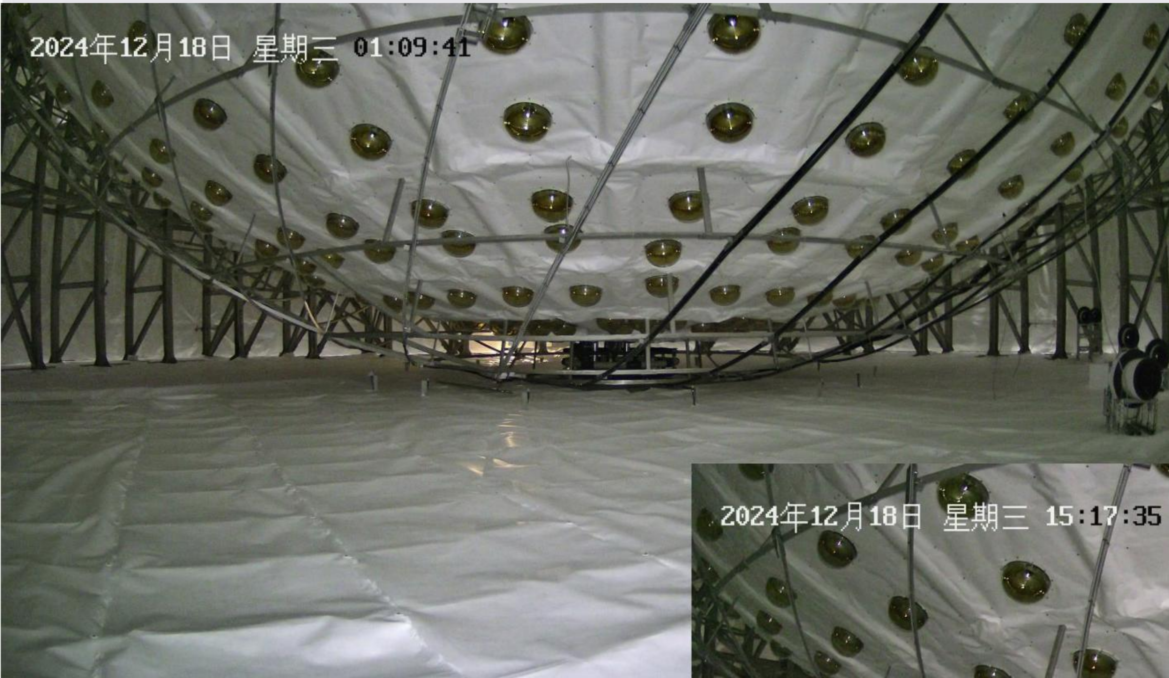
JUNO: 探测器全貌(2023)

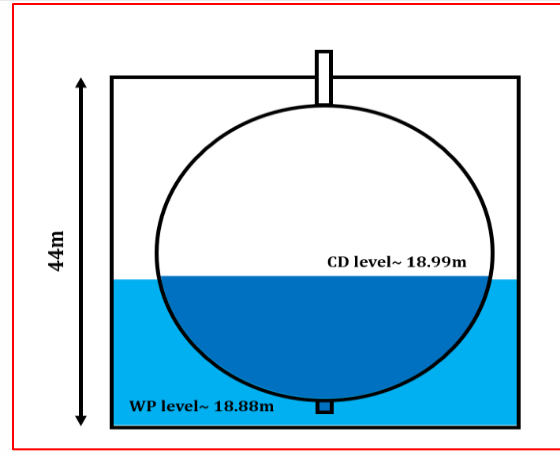
JUNO: 探测器全貌(2024)



安装过程

JUNO: 开始灌装(2024.12.18)





Water level is rising

加速器中微子：CP，MH, Theta23

加速器中微子使用π衰变的中微子束流，可以研究以下中微子振荡过程：

via charged-current interactions:

$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$

$\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2}$$
$$-\alpha \sin\delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta_{31} \frac{\sin[x\Delta_{31}]}{x} \frac{\sin[(1-x)\Delta_{31}]}{1-x}$$
$$+(\text{CP even}) \quad +\mathcal{O}(\alpha^2)$$

constrain by reactor ($\sin^2 2\theta_{13}$, $\sin 2\theta_{13}$)

constrain by ν_μ disp. ($\sin^2\theta_{23}$, $\sin 2\theta_{23}$)

switches sign for $\bar{\nu}_\mu \to \bar{\nu}_e$ ($-\alpha \sin\delta_{CP}$)

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

M. Freund, Phys.Rev. D64 (2001) 053003

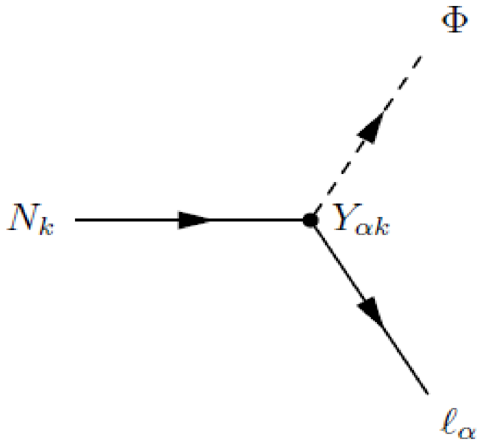
$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2\theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

- Large θ_{23}: enhances both $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
- δ_{CP} =-π/2: enhance $\nu_\mu \to \nu_e$, suppress $\bar{\nu}_\mu \to \bar{\nu}_e$
- $\Delta m^2_{31} > 0$ (normal hierarchy): enhance $\nu_\mu \to \nu_e$, suppress $\bar{\nu}_\mu \to \bar{\nu}_e$

轻子生成机制

Leptogenesis

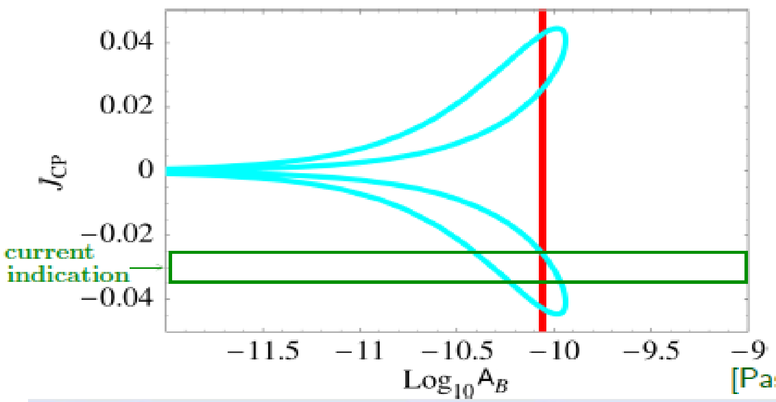
$$\mathcal{L}_I \sim \overline{L_L}\,\Phi^\dagger\, Y\, N_R$$



$$A_L \sim \frac{\sum_{k,\alpha}\left[\Gamma(N_k \to \Phi\ell_\alpha) - \Gamma(N_k \to \bar{\Phi}\bar{\ell}_\alpha)\right]}{\sum_{k,\alpha}\left[\Gamma(N_k \to \Phi\ell_\alpha) + \Gamma(N_k \to \bar{\Phi}\bar{\ell}_\alpha)\right]}$$

Seesaw $\Longrightarrow$ $Y \sim \frac{1}{v}\,\underbrace{M_R^{1/2}\,R}_{\text{inaccessible}}\;\underbrace{m_\nu^{1/2}\,U_{3\times3}}_{\text{measurable}}$ $\quad (RR^T = \mathbb{1})$

CP-violating $U_{3\times3}$ $\Longrightarrow$ plausible CP-violating Y



$M_{R1} = 5 \times 10^{11}$ GeV

$M_{R1} \ll M_{R2} \ll M_{R3}$

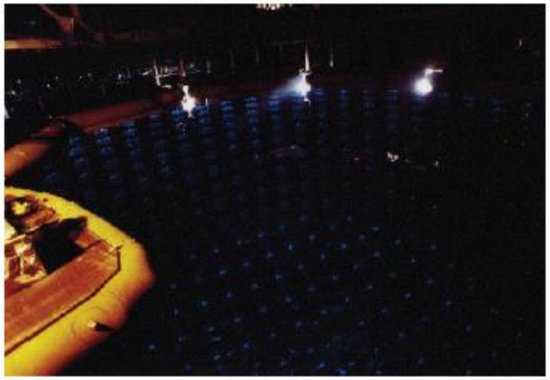
$R_{12} = 0.86$

$R_{13} = 0.5$

[Pascoli, Petcov, Riotto, PRD 75 (2007) 083511, arXiv:hep-ph/0609125]

T2K→T2HK

Kamiokande (1983-1996)
3000 ton

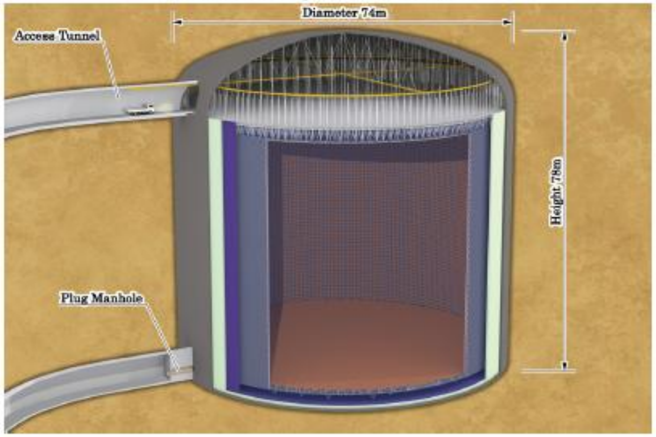


- Neutrinos from SN1987a.
- Atmospheric neutrino deficit.
- Solar neutrinos.

Super-Kamiokande (1996-)
50,000 ton

- Atmospheric neutrino oscillation.
- Solar neutrino oscillation with SNO.
- Far detector for KEK-PS (K2K) and J-PARC beam (T2K): electron neutrino appearance.
- World leading limit on proton lifetime $> 10^{34}$ years.

Hyper-Kamiokande (∼2026-)
$2\times260{,}000$ ton



Physics programme:

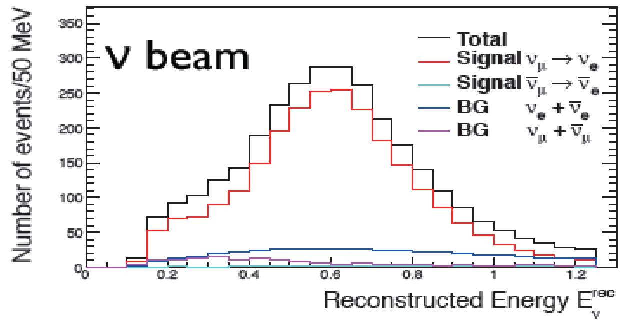
- Neutrino oscillations: Mass Hierarchy, Leptonic CP violation, θ_{23} Octant,...
- Nucleon decay: $p\rightarrow e^+\pi^0$, $p\rightarrow K^+\bar{\nu}$,...
- Neutrino astrophysics: Solar neutrinos, Supernova neutrinos, WIMP searches

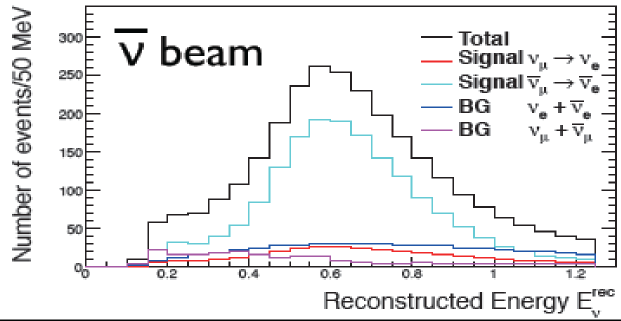
高统计量的精确测量

1.3MW, 10×10^7sec, $\nu:\bar{\nu}=1.3$

ν_e candidates

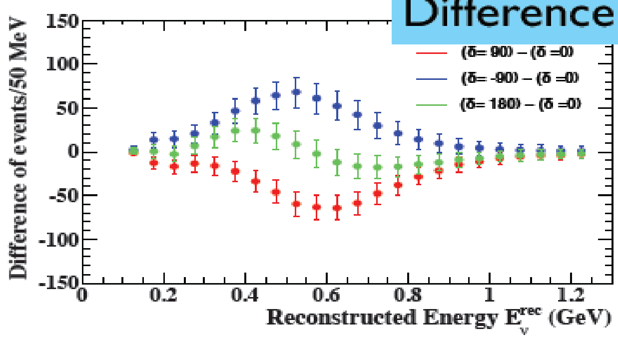
Using fiTQun for π^0 rejection

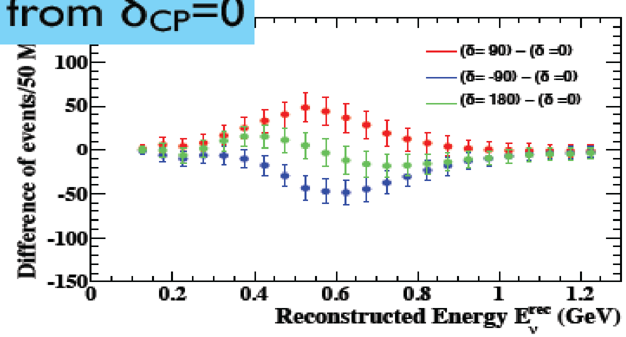




for δ=0	Signal (νμ→νe CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

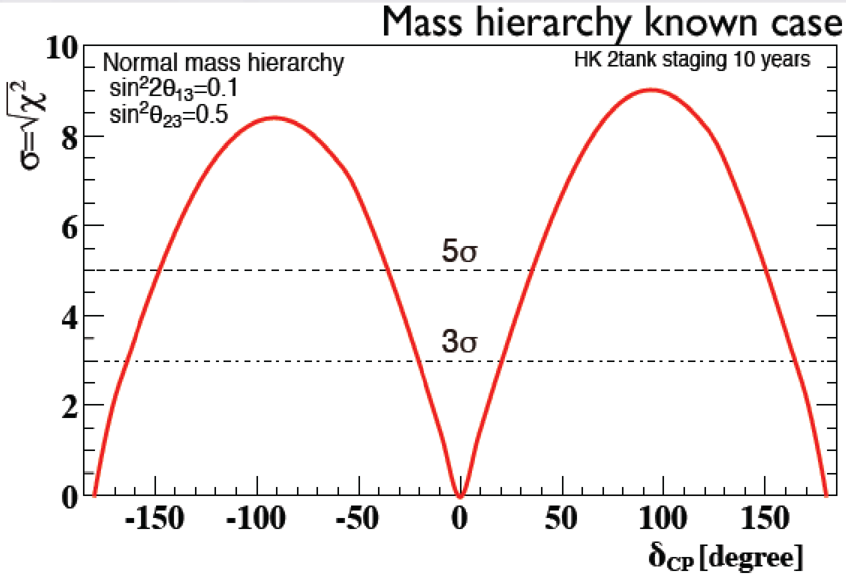
Difference from $\delta_{CP}=0$

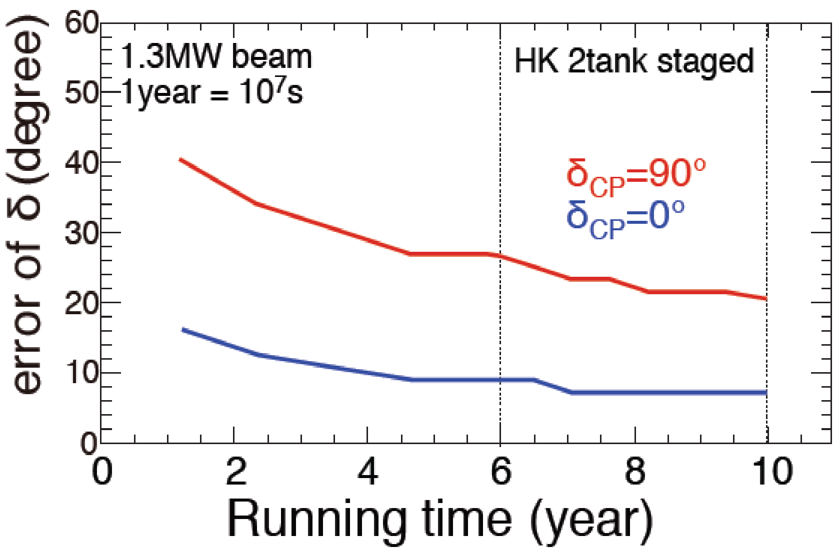




δ=0 and 180° can be distinguished using shape information

CP破坏的分辨率

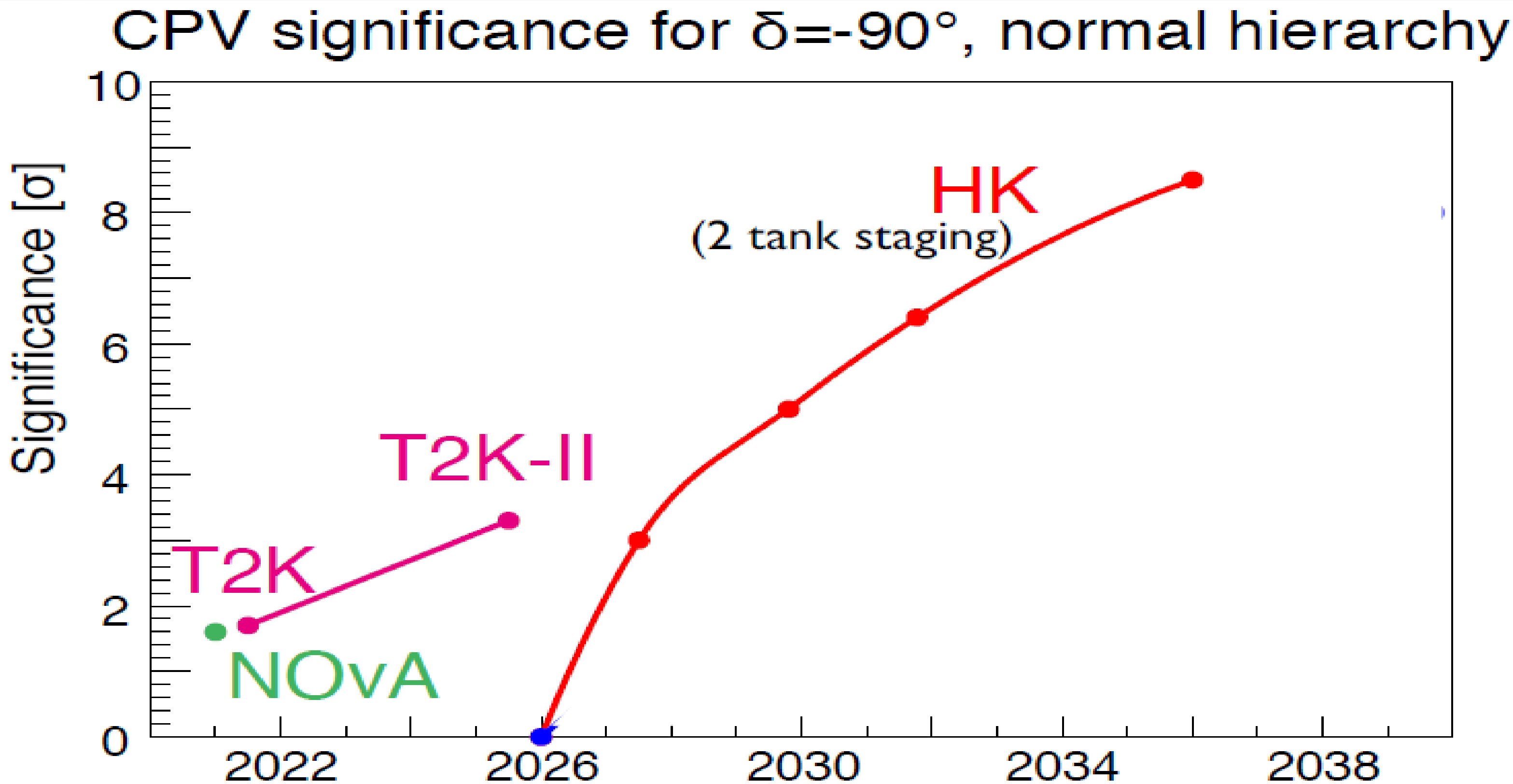




- Exclusion of $\sin\delta_{CP}=0$
  - >8σ(6σ) for δ=-90°(-45°)
  - ~80% coverage of δ parameter space with >3σ
- From discovery to δ_{CP} measurement:
  - ~7° precision possible

sinδ=0 exclusion		error	
>3σ	>5σ	δ=0°	δ=90°
78%	62%	7.2°	21°

总结：CP破坏相位测量的日本路线



Strategy of Japan-based program

~3σ evidence with T2K→T2K-II,

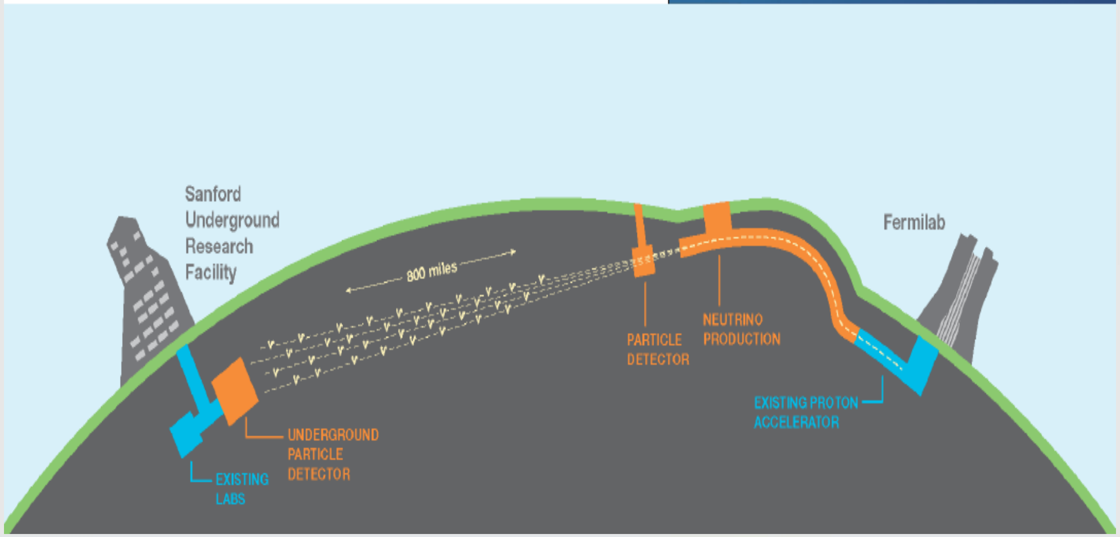
>5σ discovery and measurement with HK

NOvA+DUNE：美国路线

DUNE

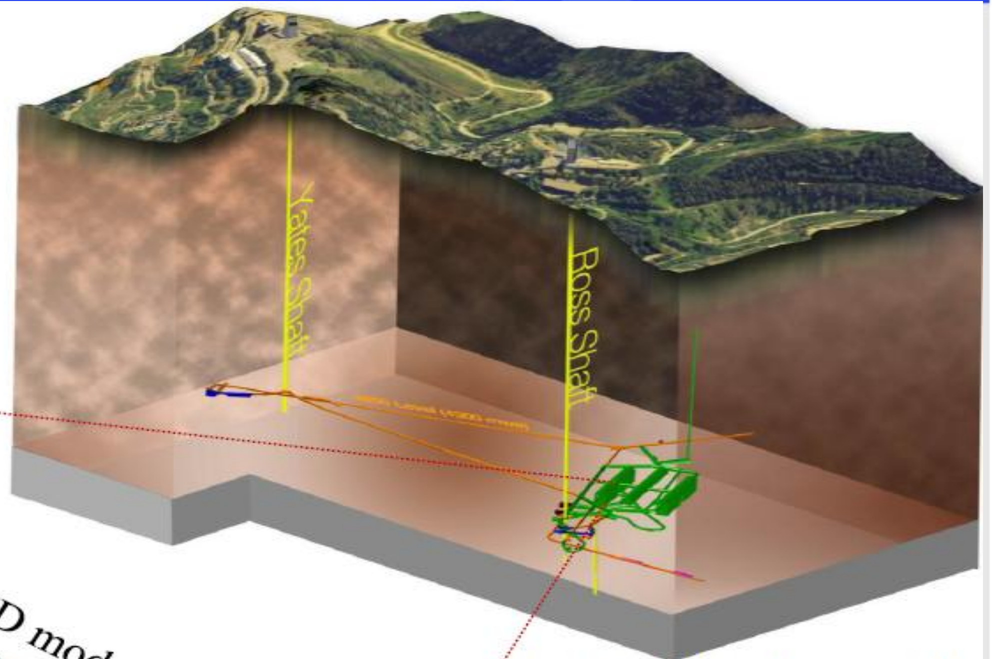
Deep Underground Neutrino Experiment

A next generation experiment for **neutrino science, nucleon decay,** and **supernova physics**

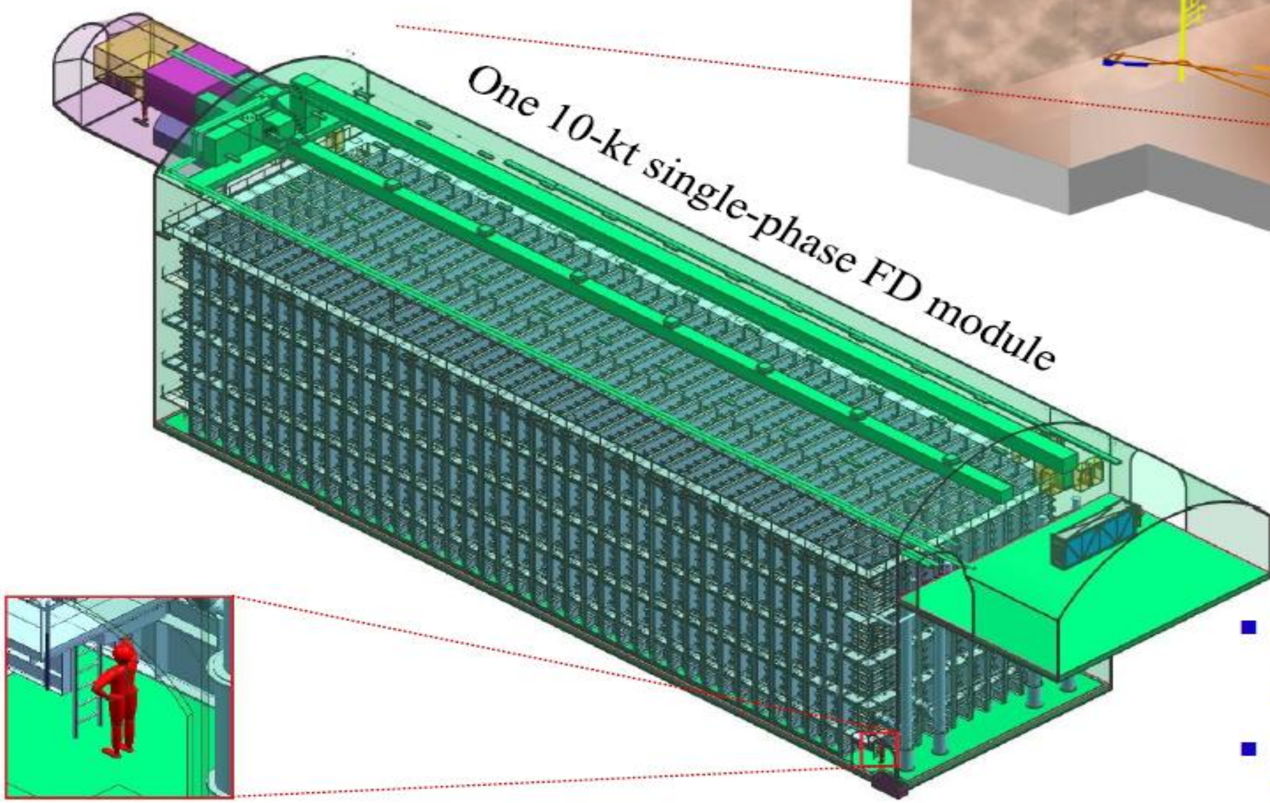


Far Detector

- **40-kt (fiducial)** LAr TPC
- Installed as four 10-kt modules at 4850' level of SURF

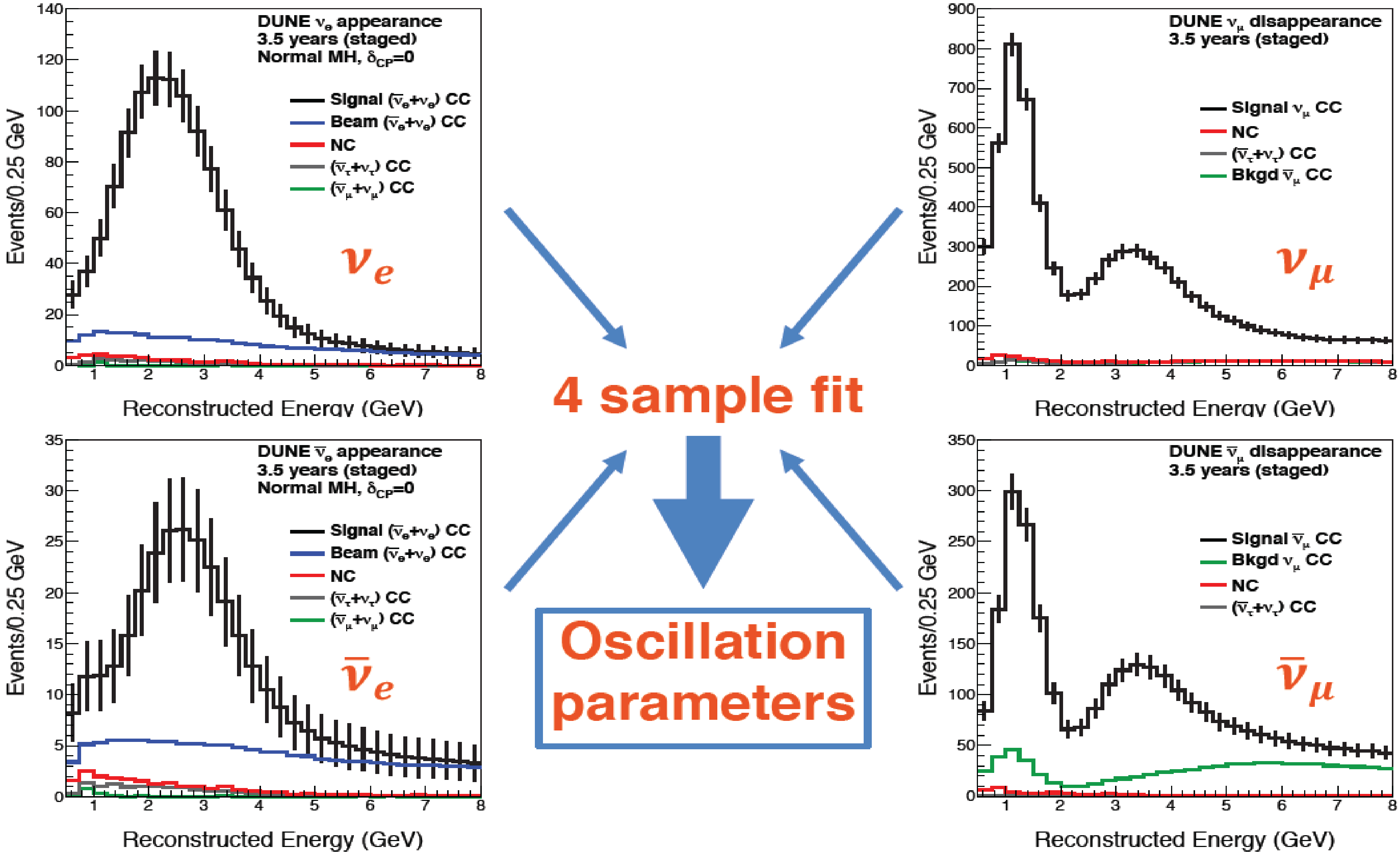


Sanford Underground Research Facility (SURF)

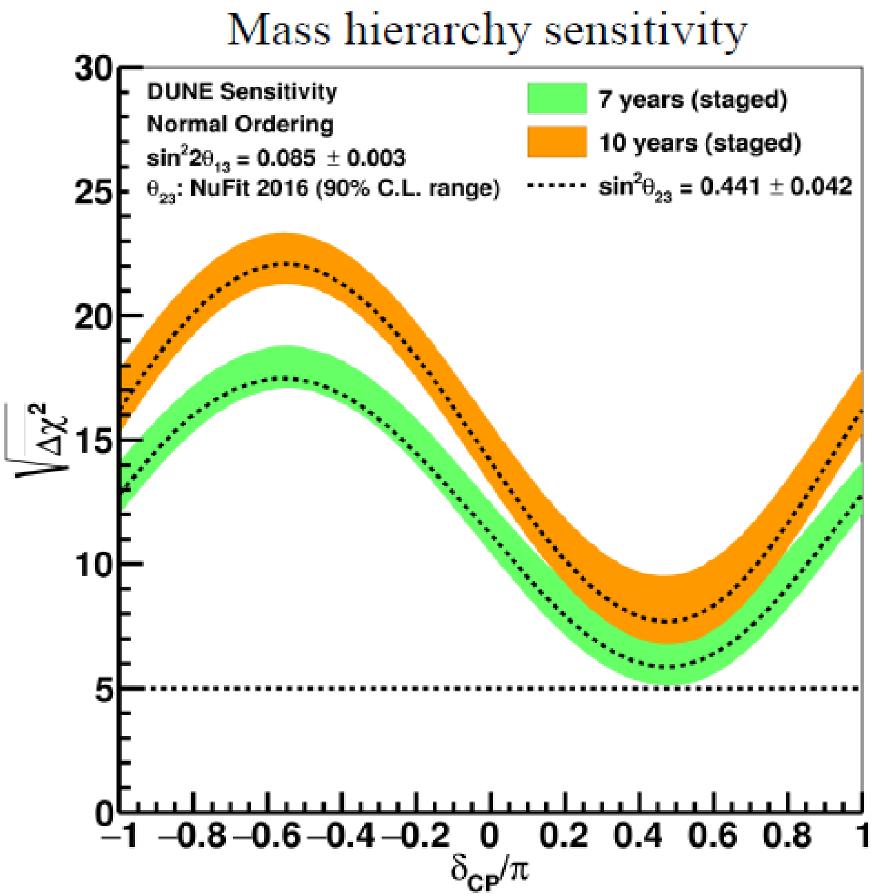


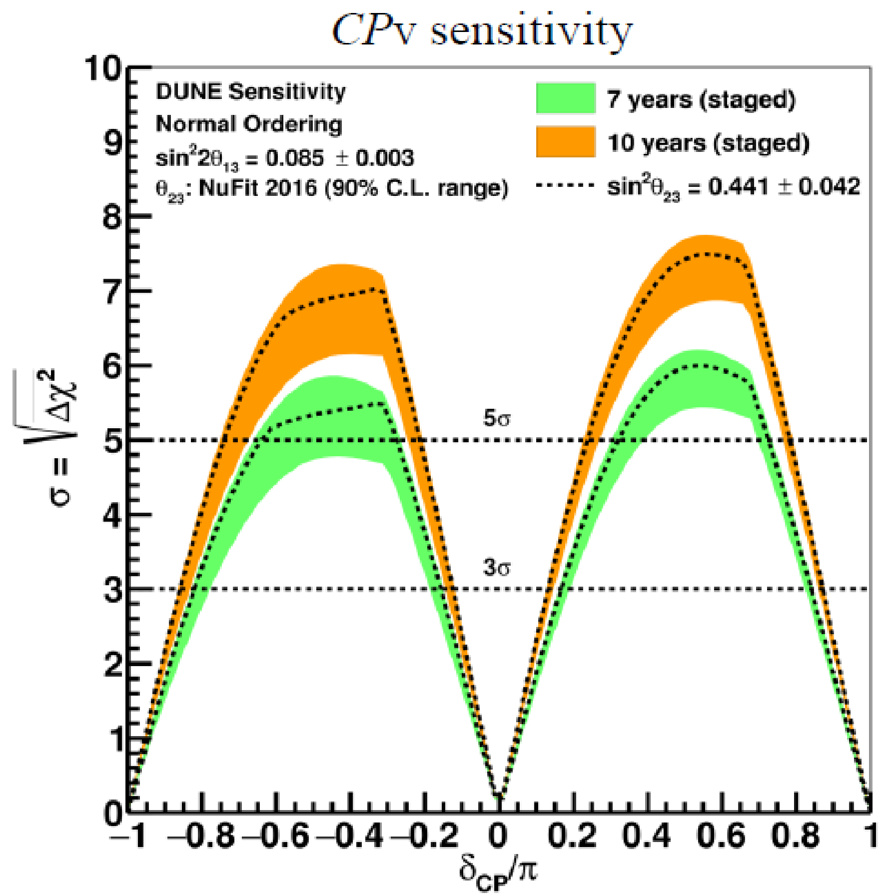
- First module will be a **single phase LAr TPC**
- Modules installed in stages. Not necessarily identical

DUNE： 3.5 yrs +3.5 yrs



DUNE：MH, CP的分辨率

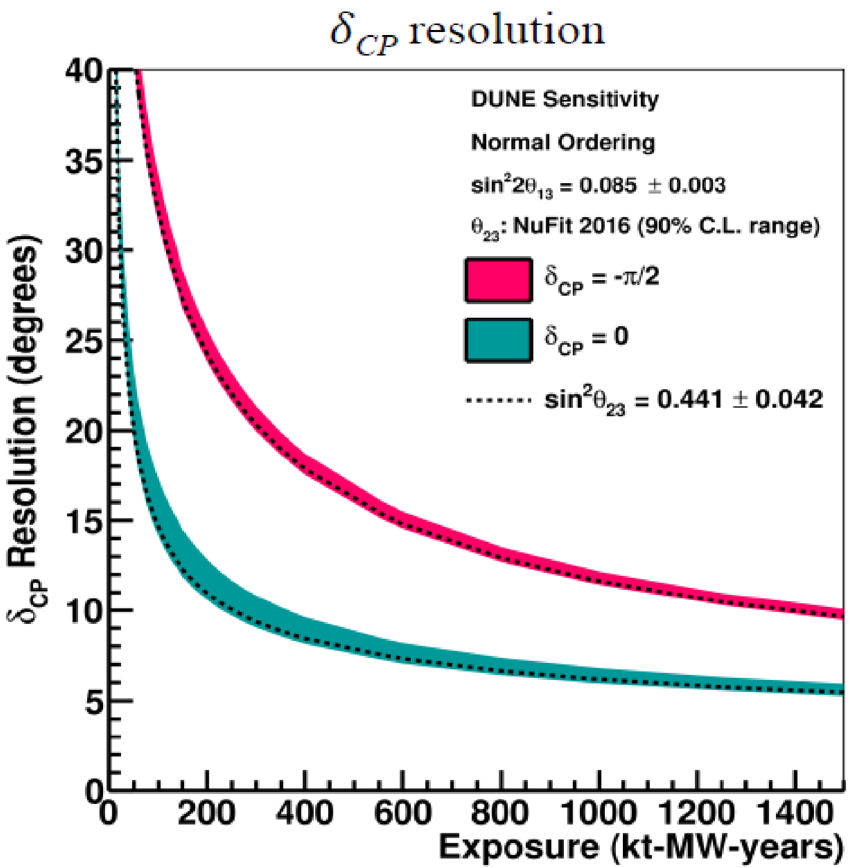


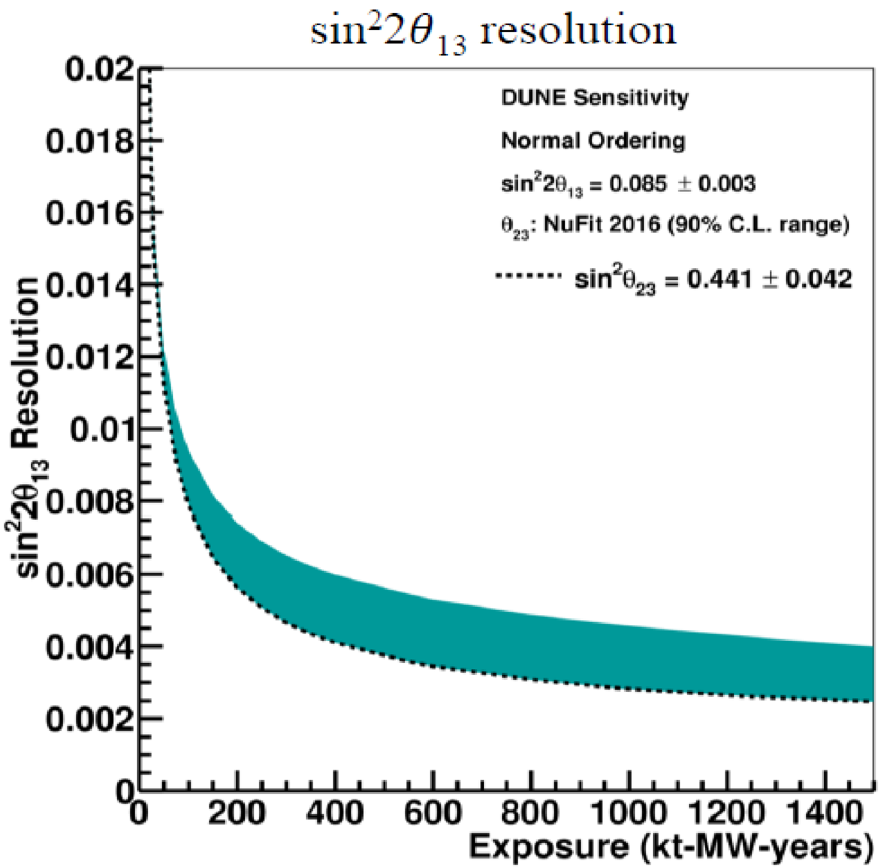


因为物质效应很大， DUNE可以在较短时间内确定质量顺序(3σ@3 yrs; 5σ@6-7 yrs)

CP破坏效应： 5σ@7 yrs(如果是-270度)；65%的参数区间可达到> 3σ @7 yrs (比T2HK稍差)

DUNE：参数的精确测量



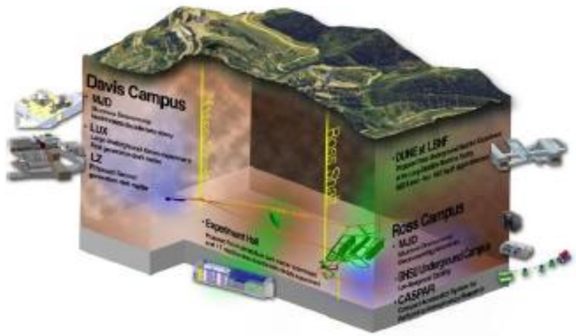


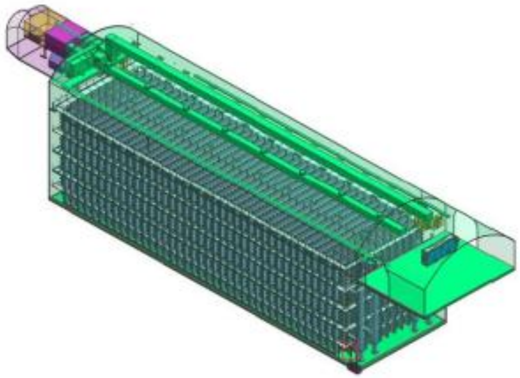
10年的结果：

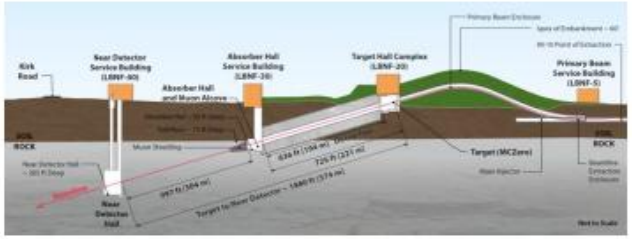
1) CP破坏相位的测量精度：delta=0→6度；delta=270→10度 (好于T2HK)

2) 甚至theta(13)的测量精度也会接近3% (大亚湾2020年的精度)

DUNE：时间表







2017: Far Site Construction Begins

2018: ProtoDUNEs at CERN

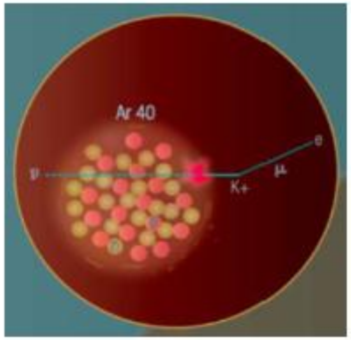
2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available

+5-7 yr → 2031年

The CERN Neutrino Platform



40 kton + 2 MW beam to follow in subsequent years

展望：Neutrino as New Physics Probe

- 中微子振荡现象 -- 以及其确定的中微子质量，是唯一有确凿实验证据的超出粒子物理标准模型的新物理
- 确立标准三味中微子混合振荡框架
- 已知：三个混合角，两个质量平方差
- 未来：质量顺序(质量排序)，轻子CP破坏
- 未来：中微子Majorana属性，绝对质量 （贝塔衰变，双贝塔衰变等)
- 理论研究：中微子质量起源、味混合和CP破坏的机制，轻子生成机制
- 交叉：中微子作为天文学和宇宙学研究的探针

太阳中微子、超新星中微子、超高能宇宙线中微子，宇宙背景中微子

中微子与暗物质，质子衰变、原子核结构、地球科学等方面的联系

欢迎大家加入蓬勃发展的中微子物理研究队伍！

Thanks!

谢谢!