

# 中微子探测技术

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# 中微子的基本性质

## Neutrino Properties

$$\frac{\tau}{m} > 7 \times 10^9 \text{ s/eV} \quad m \approx 0.1 \text{ eV} \quad \longrightarrow \quad \tau > 20 \text{ yr}$$

See the note on “Neutrino properties listings” in the Particle Listings.

Mass  $m < 1.1 \text{ eV}$ , CL = 90% (tritium decay)

Mean life/mass,  $\tau/m > 300 \text{ s/eV}$ , CL = 90% (reactor)

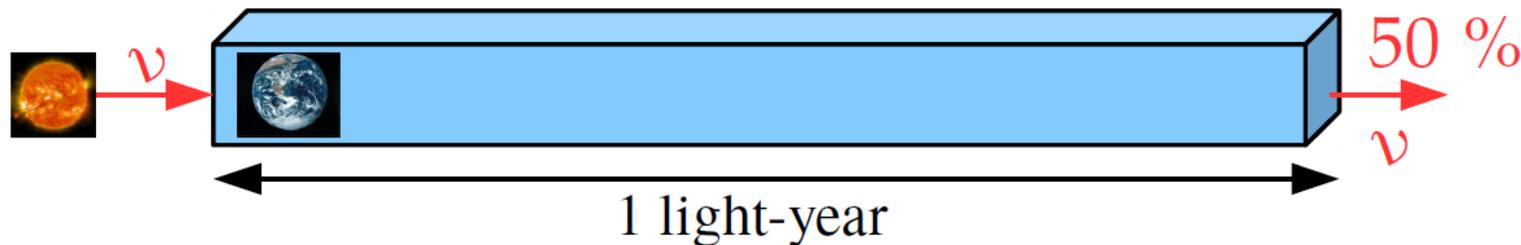
Mean life/mass,  $\tau/m > 7 \times 10^9 \text{ s/eV}$  (solar)

Mean life/mass,  $\tau/m > 15.4 \text{ s/eV}$ , CL = 90% (accelerator)

Magnetic moment  $\mu < 0.28 \times 10^{-10} \mu_B$ , CL = 90% (solar + radiochemical)

PDG2020 (粒子数据组) (<https://pdg.lbl.gov/>)

理解少  
探测难



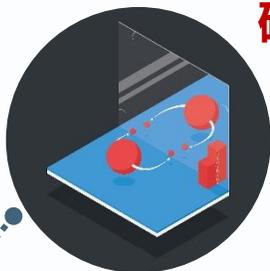
# 与中微子探测相关的科学问题

## 粒子物理相关

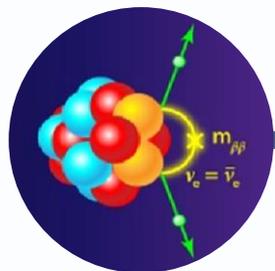
中微子质量顺序?



电荷-宇称破坏的大小?



中微子是否为自身反粒子?



中微子相关的重大科学问题

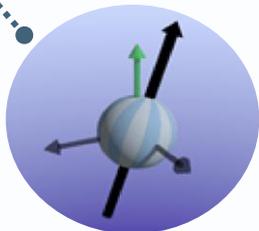
绝对质量大小?



中微子新的振荡模式



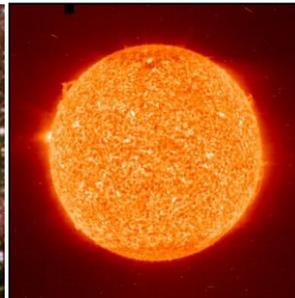
中微子磁矩?



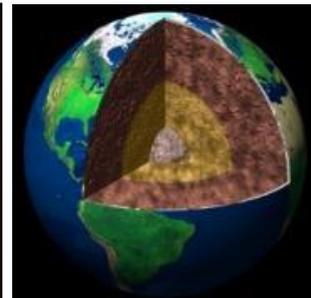
## 天体物理、天文学相关



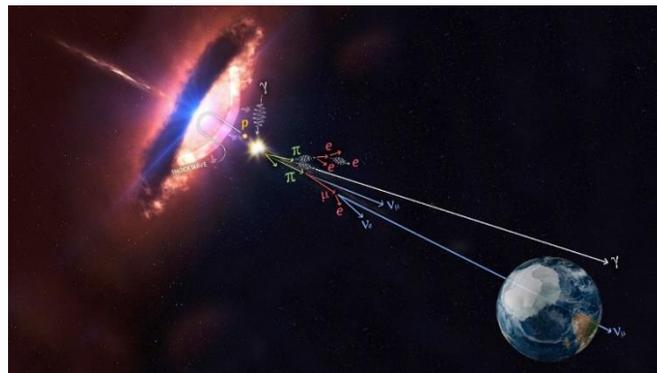
超新星  
(爆发机制、遗迹 $\nu$ )



太阳  
(金属丰度)



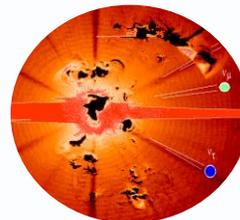
地球  
(地球物理模型)

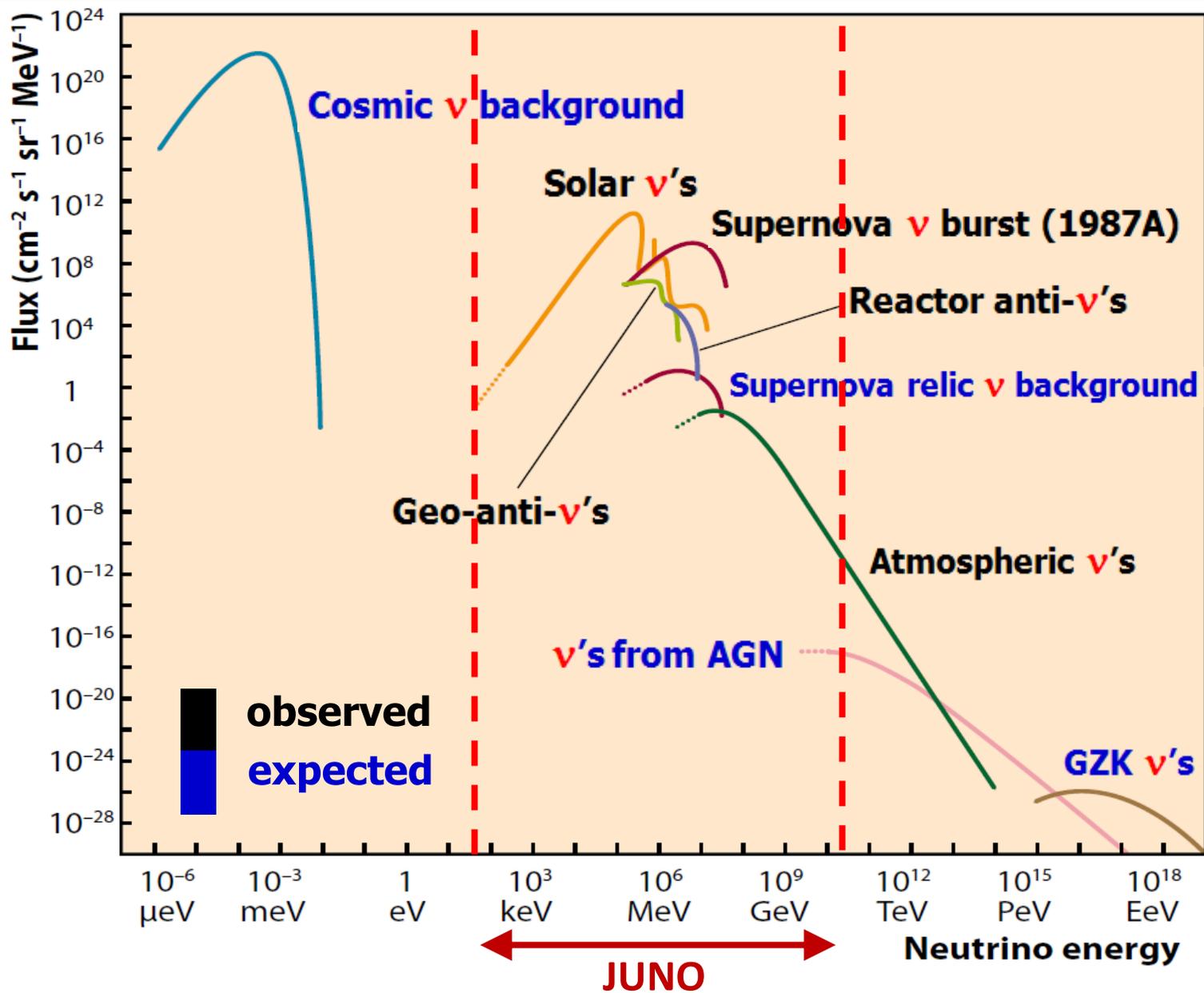


极端天文现象伴随的中微子信号 – 多信使天文  
(NS merger, GAN,  $\gamma$  burst, ...)

高能宇宙线的起源 (是否伴有高能中微子?)

宇宙大爆炸中微子





## 中微子探测

### ■ 什么相互作用过程?

- 信号 vs. 本底?

### ■ 如何选探测介质?

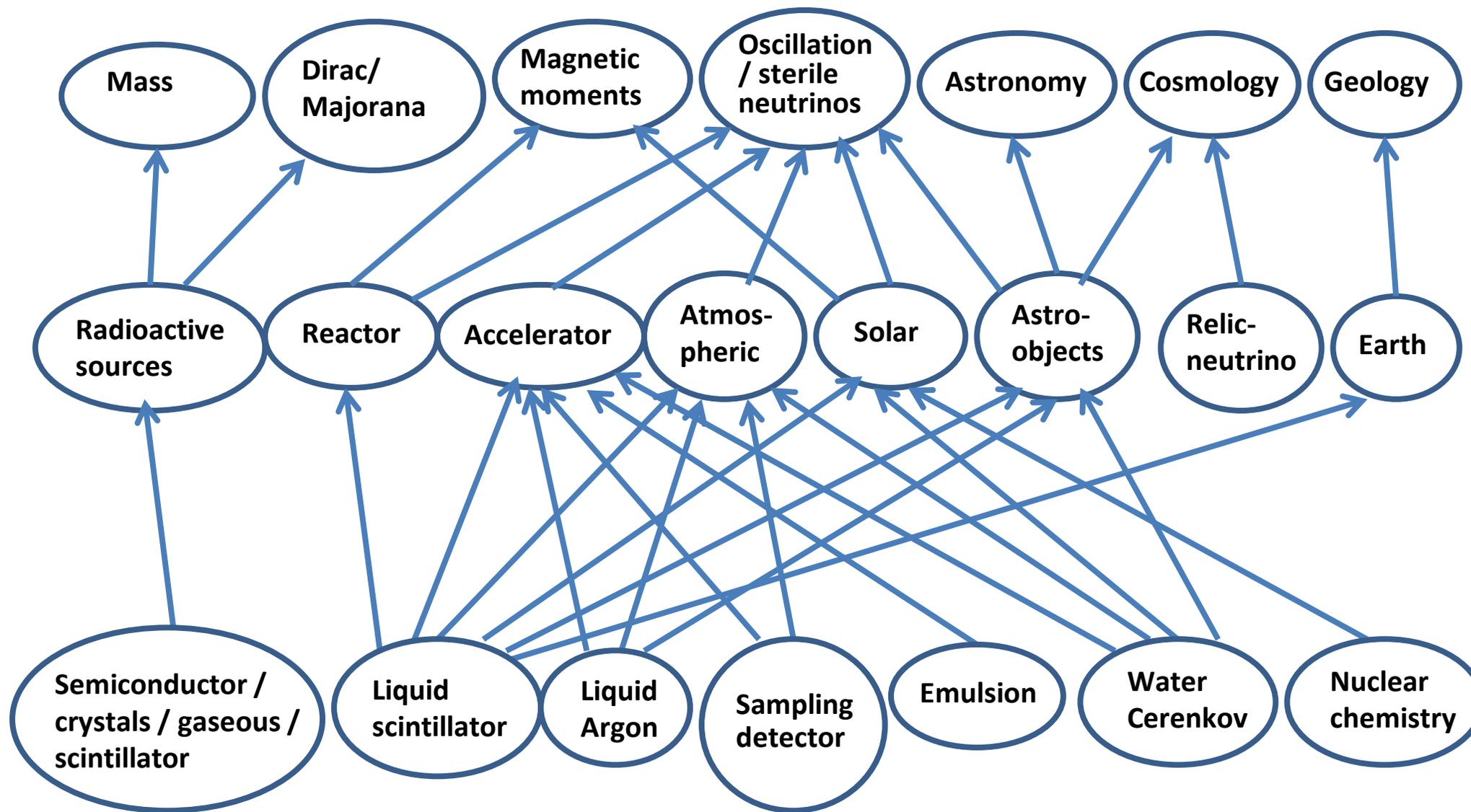
- 怎么做成探测器
- 造价

### ■ 灵敏度 $\rightarrow$ 物理指标 $\rightarrow$ 探测器指标

- 精度 (能量、位置、径迹、...)
- PID (味道、正反)



# 中微子物理：问题和手段



研究  
目标

中微子源

探测  
技术





## Four golden lessons

Nature 426, 389 (2003)

Steven Weinberg

When I received my undergraduate degree — about a hundred years

work of many theoretical and experimental physicists has been able to sort it out, and put everything (well, almost everything) together in a beautiful theory known as

### Scientist

*Advice to students at the start of their scientific careers.*

1. No one knows everything, and you don't have to
2. While swimming and not sinking, aim for rough water
3. Forgive yourself for wasting time
4. Learn something about the history of science, or at a minimum the history of your own branch of science

- 从历史中学习经验方法和重要思想
- 明确**理论**+**实验**工作在其学科发展中的历史定位



**Steven Weinberg**  
(1933 - 2021)  
Nobel Prize, 1979

# 中微子的实验探测

How to experimentally prove the existence of neutrino?

*Tentative Theory of Beta Decays*, E. Fermi, *Nature*, **REJECTED** 1933

*The "Neutrino"*, H.A. Bethe & R. Peierls, *Nature* 133 (1934) 532

Inverse Beta Decays (IBD)



The possibility of creating neutrinos necessarily implies the existence of annihilation processes. The most interesting amongst them would be the following: a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1.

**EXTREMELY small IBD cross section!**



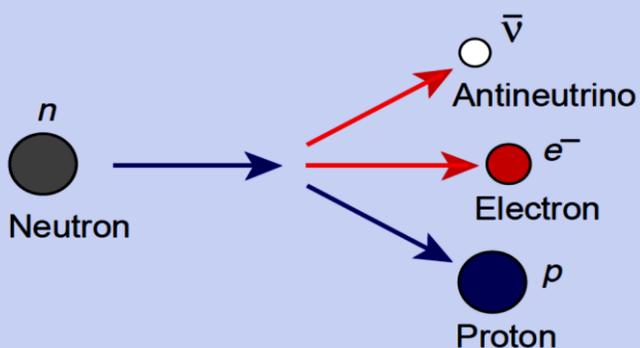
**Hans Bethe**  
(1906–2005)  
Nobel Prize 1967



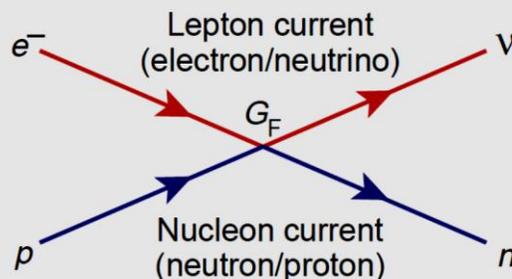
**Rudolf Peierls**  
(1907–1995)

$N(Z, A)$

Neutron Beta Decay



Basic Current-Current Interaction



Lifetime for a  $\beta$ -decaying nucleus:  $t$

$$\sigma [\text{cm}^2] = \frac{A [\text{cm}^2 \text{ s}]}{t [\text{s}]} \rightarrow \frac{\hbar^3}{m^3 c^4 t}$$

$$\sigma \sim 10^{-44} \text{ cm}^2 \quad (m \sim 1 \text{ MeV} \ \& \ t \sim 10^2 \text{ s})$$

penetrating  $10^{16}$  km of solid matter

# 中微子的实验探测

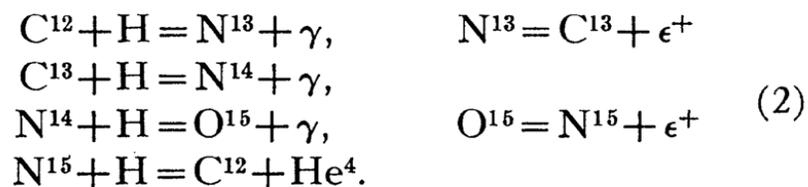
*The "Neutrino", H. Bethe & R. Peierls, Nature 133 (1934) 532*

of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

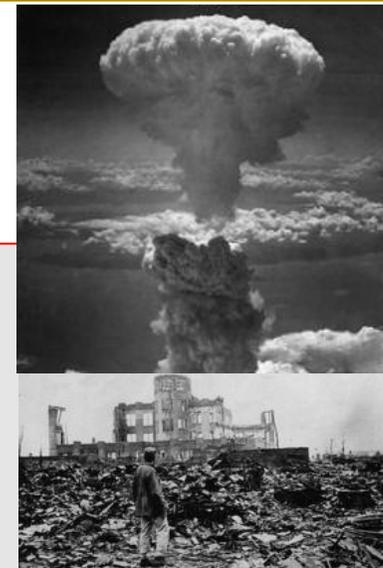
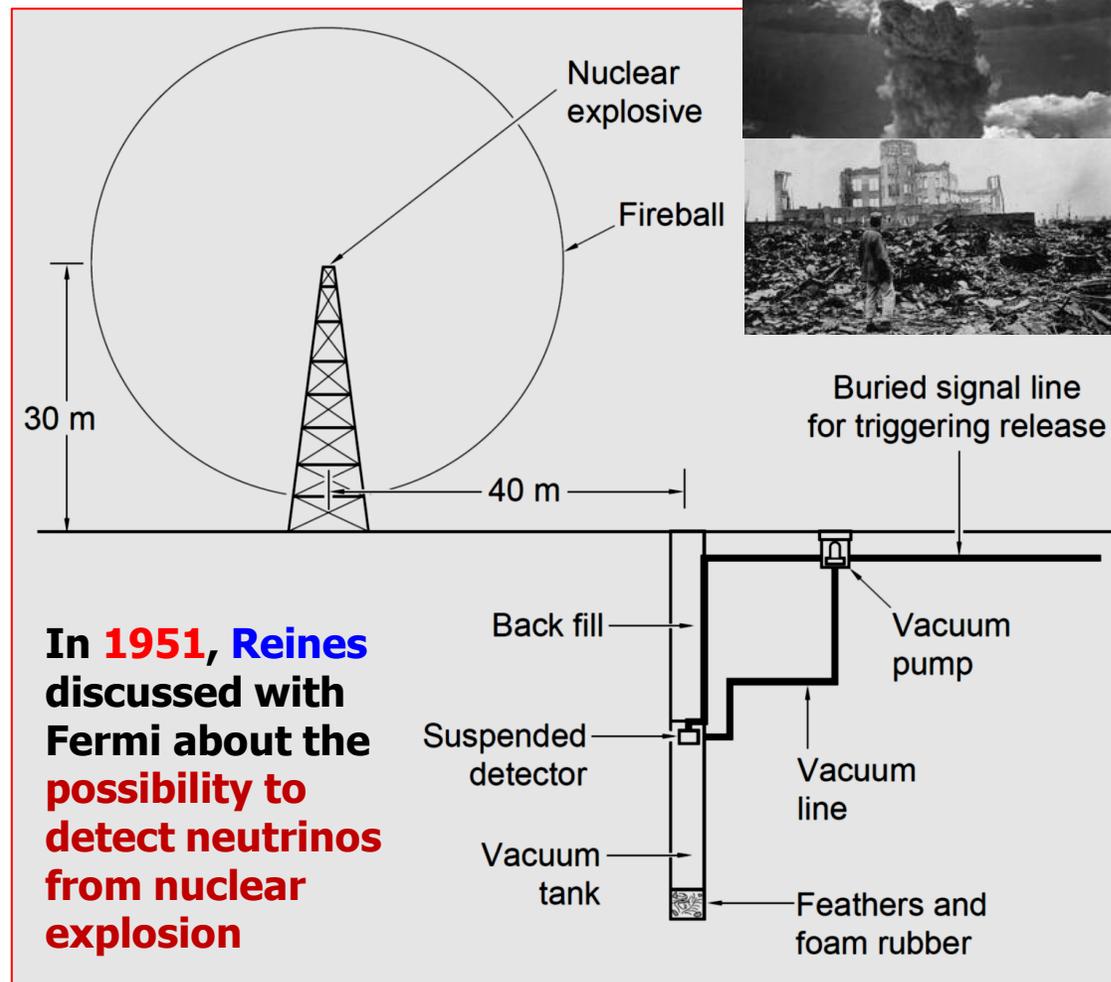
The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*



The deuteron is then transformed into  $He^4$  by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction



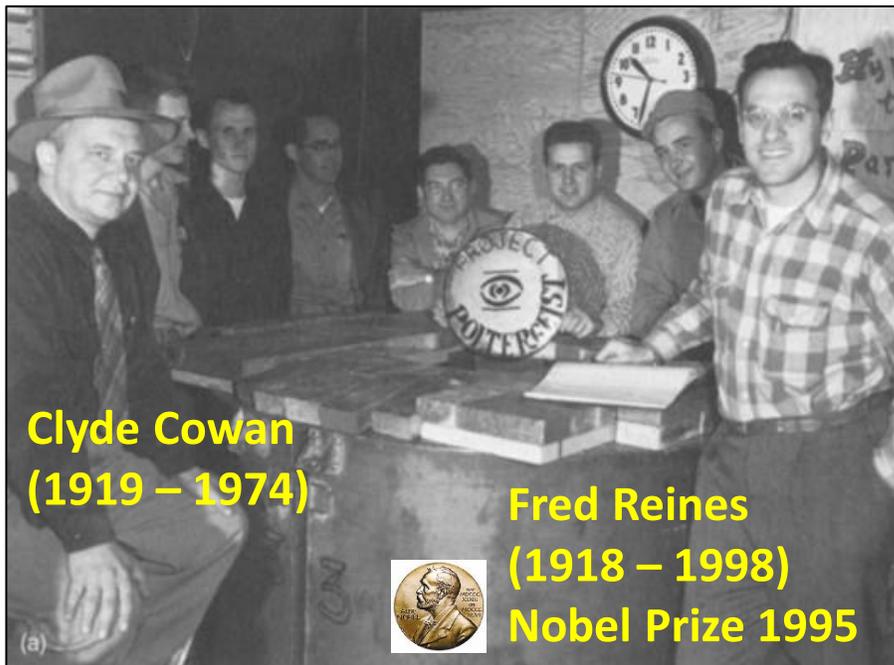
In 1939, Bethe explained in his seminal paper why the Sun is shining. Neutrinos were ignored entirely in all reactions.



# 中微子的实验发现

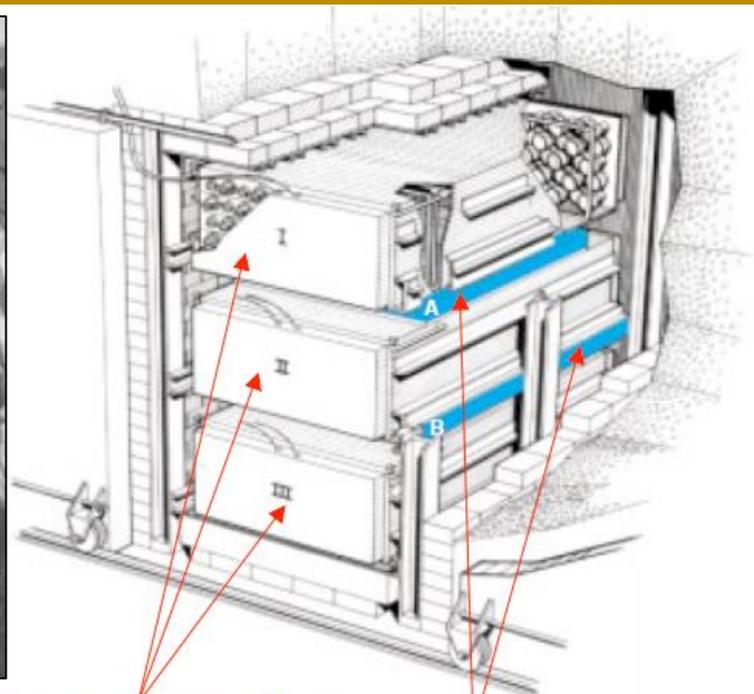
## ■ Cowan–Reines Experiment with reactor $\bar{\nu}_e$ at Savannah River (1953-1956)

反贝塔衰变反应



Clyde Cowan  
(1919 – 1974)

Fred Reines  
(1918 – 1998)  
Nobel Prize 1995



Each with 1000 l of liquid scintillator viewed with PMTs

Each with 200 l of water with  $\text{CdCl}_2$

Frederick REINES and Clyde COWAN  
Box 1663, LOS ALAMOS, New Mexico  
Thanks for message. Everything comes to  
him who knows how to wait.  
Pauli

A telegram from Pauli:

**“Thanks for message. Everything comes to him who knows how to wait.”**

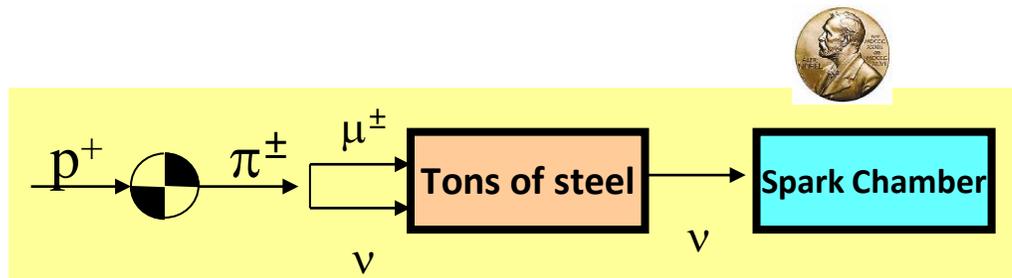
几年后，莱因斯向贝特提起后者1934年的文章中说：

“there is no practically possible way of observing the neutrino.”

贝特回答 “Well, you shouldn't believe everything you read in the papers.”

# 其他中微子的发现

## 1962年: 发现muon中微子



2000年, 费米实验室发现陶中微子

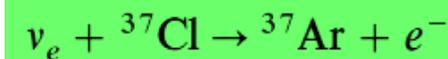


Leon Lederman Melvin Schwartz Jack Steinberger



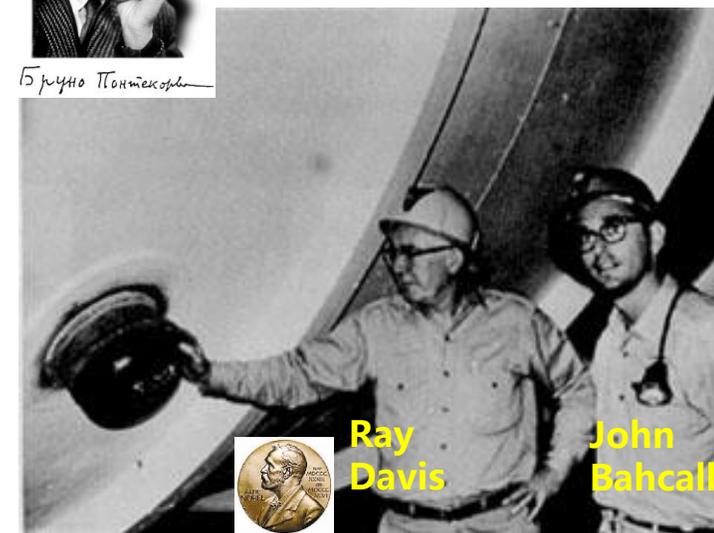
Бруно Понтекорво

## 1968年: 发现太阳中微子



Pontecorvo在1946年提出的探测方法

- 放射化学方法 (B. Pontecorvo, 1946; L. Alvarez, 1949)
- 提出在Homestake Mine开展实验 (Ray Davis, 1964)
- 太阳中微子流强计算 (John Bahcall)



Ray Davis John Bahcall

实验发现

太阳中微子流强计算

# 中微子理论的里程碑：1930s – 1960s



Enrico Fermi

1933年, Fermi 建立β衰变理论, 并给中微子命名 *Neutrino*

测量β衰变能谱末端来确定中微子的静止质量: **运动学测量**



Ettore Majorana

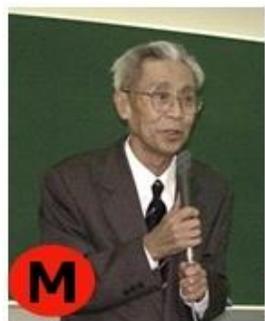
1937年, Majorana 提出中微子可能是其自身的反粒子, 即 **Majorana 粒子** 的定义

带电的费米子, 正反粒子不同, 为 **Dirac 粒子**

1957年, 发现宇称不守恒  
1957年, **BCS** 超导理论  
1957年, 中微子二分量理论  
1957年, 弱作用 **V-A** 理论

- **1957年:** Pontecorvo提出可能存在中微子-反**中微子振荡**现象
- **1962年:** M. N. S. 提出不同味的中微子之间可以相互转化
- **1968年:** Pontecorvo首次提出 $\nu_e \rightleftharpoons \nu_\mu$ 可能性, 并尝试推导了中微子振荡

中微子混合矩阵亦称为 **MNS** 矩阵 (文献中或称 **PMNS**、**MNSP** 矩阵)



Ziro Maki  
(牧二郎)



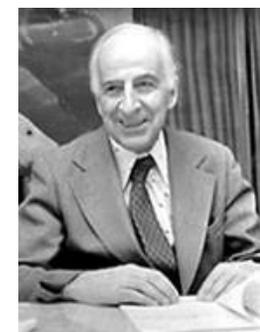
Masami Nakagawa  
(中川昌美)



Shoichi Sakata  
(坂田昌一)

$$\begin{aligned}\nu_1 &= \nu_e \cos \delta + \nu_\mu \sin \delta, \\ \nu_2 &= -\nu_e \sin \delta + \nu_\mu \cos \delta.\end{aligned}$$

Bruno Pontecorvo conjectured  $\nu \leftrightarrow \text{anti-}\nu$  transition in 1957.



Bruno Pontecorvo

# 中微子其他属性

## ■ 1957年: 中微子的螺旋度 (Helicity) : "Left-handed"

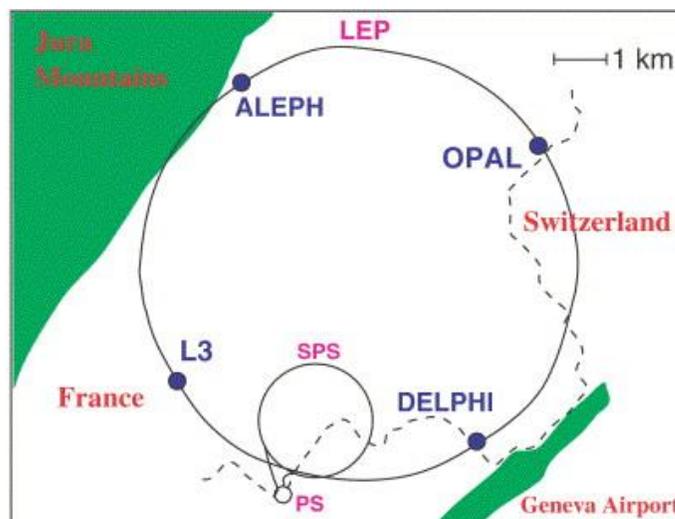
→ 有力的支持了中微子二分量理论

(由李政道与杨振宁、Lev Landau、Abdus Salam于1957年分别提出, 该理论要求中微子质量严格等于零, 且只存在左手征的中微子态)

## ■ 1990s-2000s:

中微子有三代

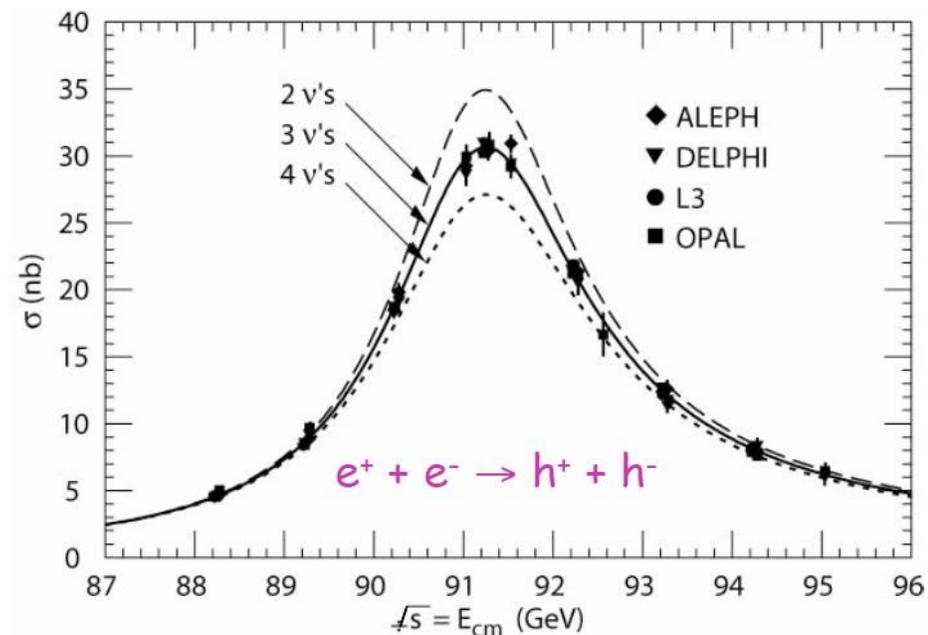
- 对撞机上的实验: ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and LEP Electroweak Working Group



## Helicity of Neutrinos\*

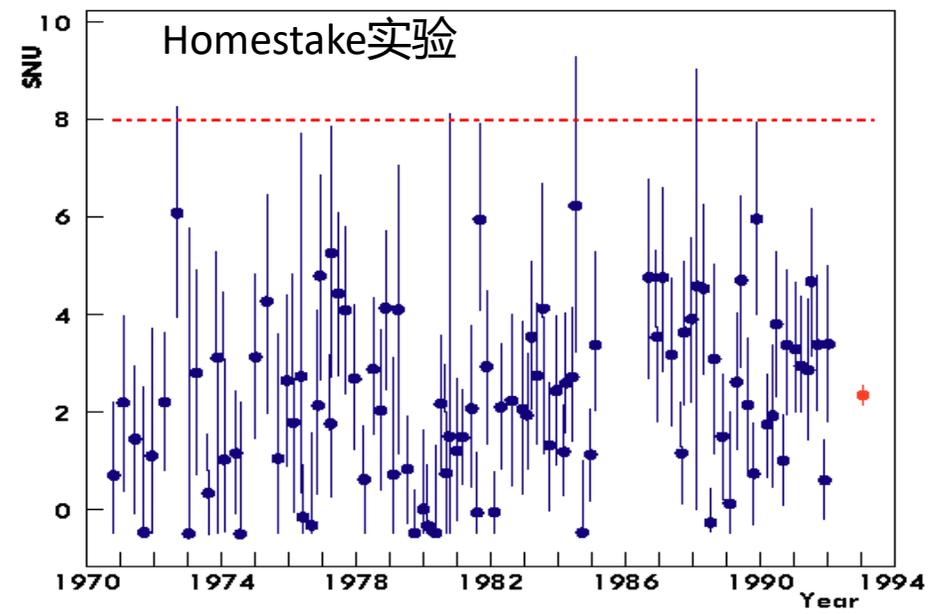
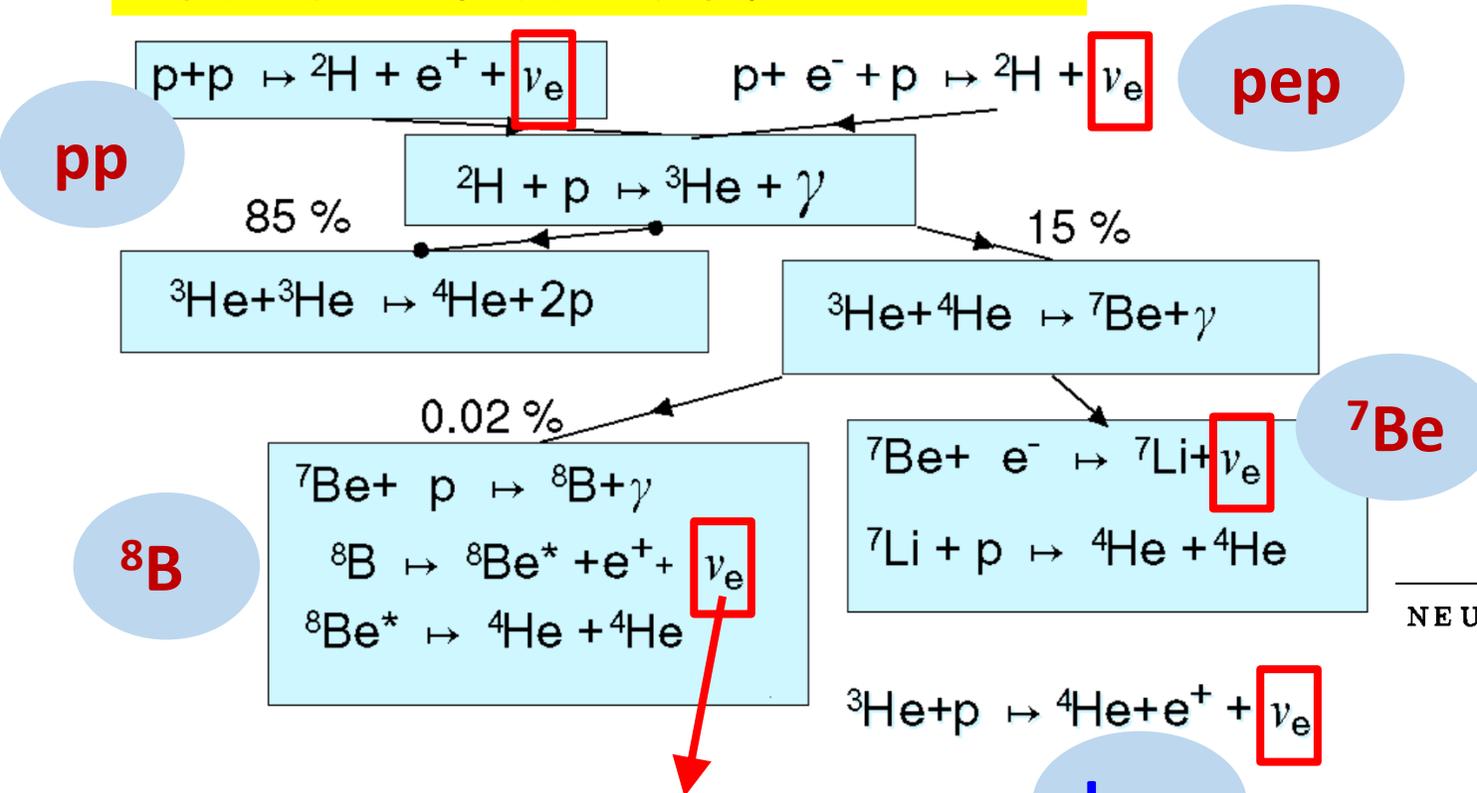
M. GOLDBABER, L. GRODZINS, AND A. W. SUNYAR  
Brookhaven National Laboratory, Upton, New York  
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of  $\gamma$  rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with  $\text{Eu}^{152m}$ , which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,<sup>1</sup>  $0^-$ , we find that the neutrino is "left-handed," i.e.,  $\sigma_{\nu} \cdot \hat{p}_{\nu} = -1$  (negative helicity).



# 太阳中微子丢失之谜：1968 ~ 1990s

太阳内部产生中微子的机制，几百亿  $\nu/cm^2/s$



NEUTRINO ASTRONOMY AND LEPTON CHARGE

V. GRIBOV\* and B. PONTECORVO  
 Joint Institute for Nuclear Research, Dubna, USSR

Received 20 December 1968

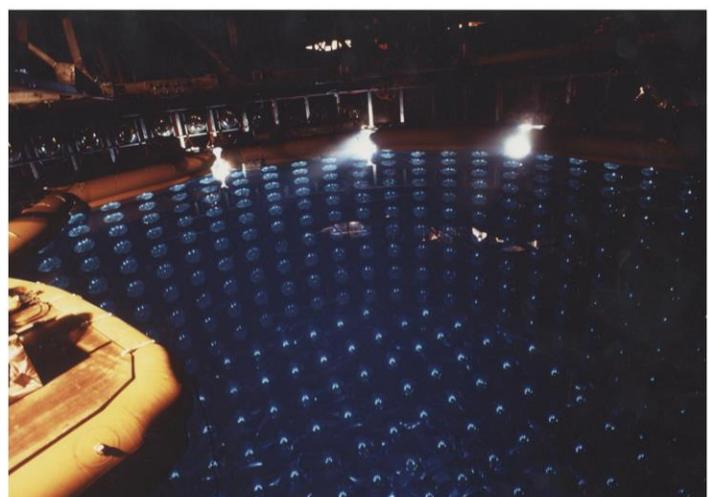
It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because of  $\nu_e \rightleftharpoons \nu_\mu$  oscillations, similar to  $K^0 \rightleftharpoons \bar{K}^0$  oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states.

**1984:** Herb Chen (陈华森) proposes **heavy water** to search for direct evidence of flavor transformation for neutrinos from  $^8B$  decay in the Sun.

**1968:** Gribov and Pontecorvo suggest flavor change (oscillation) of  $\nu_e \rightleftharpoons \nu_\mu$  as a possible reason.

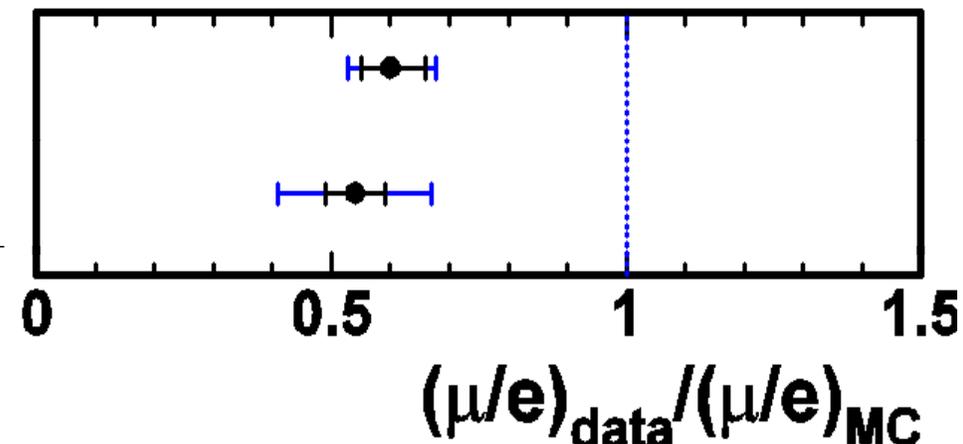
# 1970s – 1980s: 寻找质子衰变, 发现大气中微子反常

Grand Unified Theories (in the 1970's)  $\rightarrow \tau_p = 10^{30 \pm 2}$  years



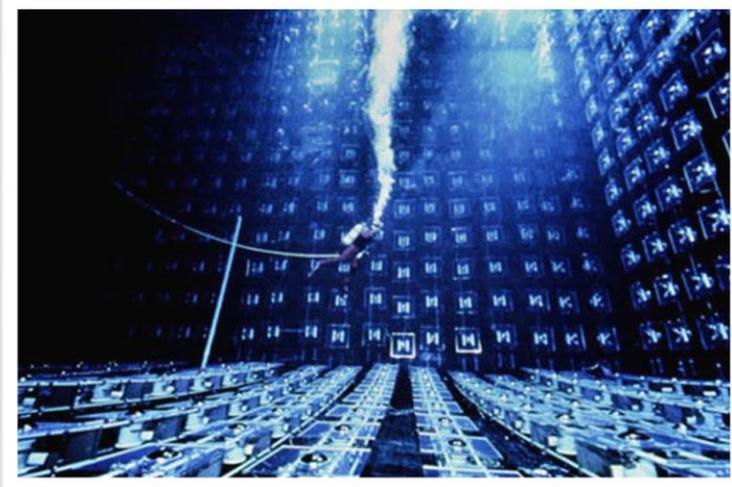
Kamiokande (1988, 92, 94)

IMB (1991, 92)



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

- Kamiokande (1000 ton)
- IMB (3300 ton)  $\rightarrow$
- Frejus (700 ton)
- NUSEX (130 ton)



**A significant deficit of atmospheric  $\nu_\mu$  events was found....**

**$\nu_\mu \rightarrow \nu_e$  and  $\nu_\mu \rightarrow \nu_\tau$  are all possible**

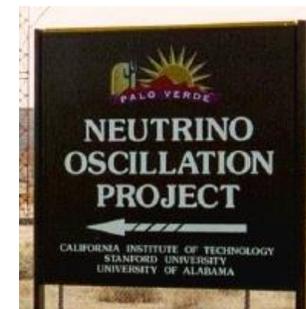
# 1990s ~ 2000s: 寻找中微子振荡

太阳中微子丢失、大气中微子反常的结果刺激了一大批新的实验

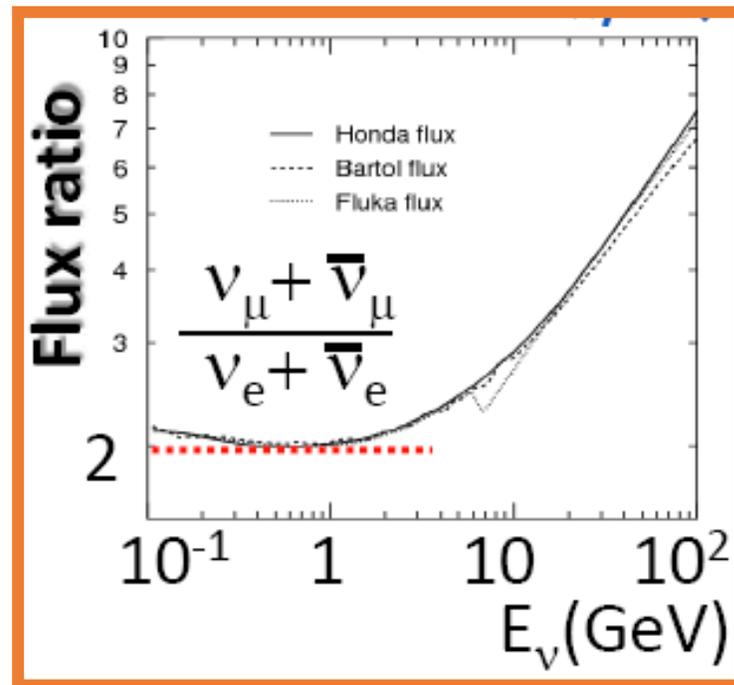
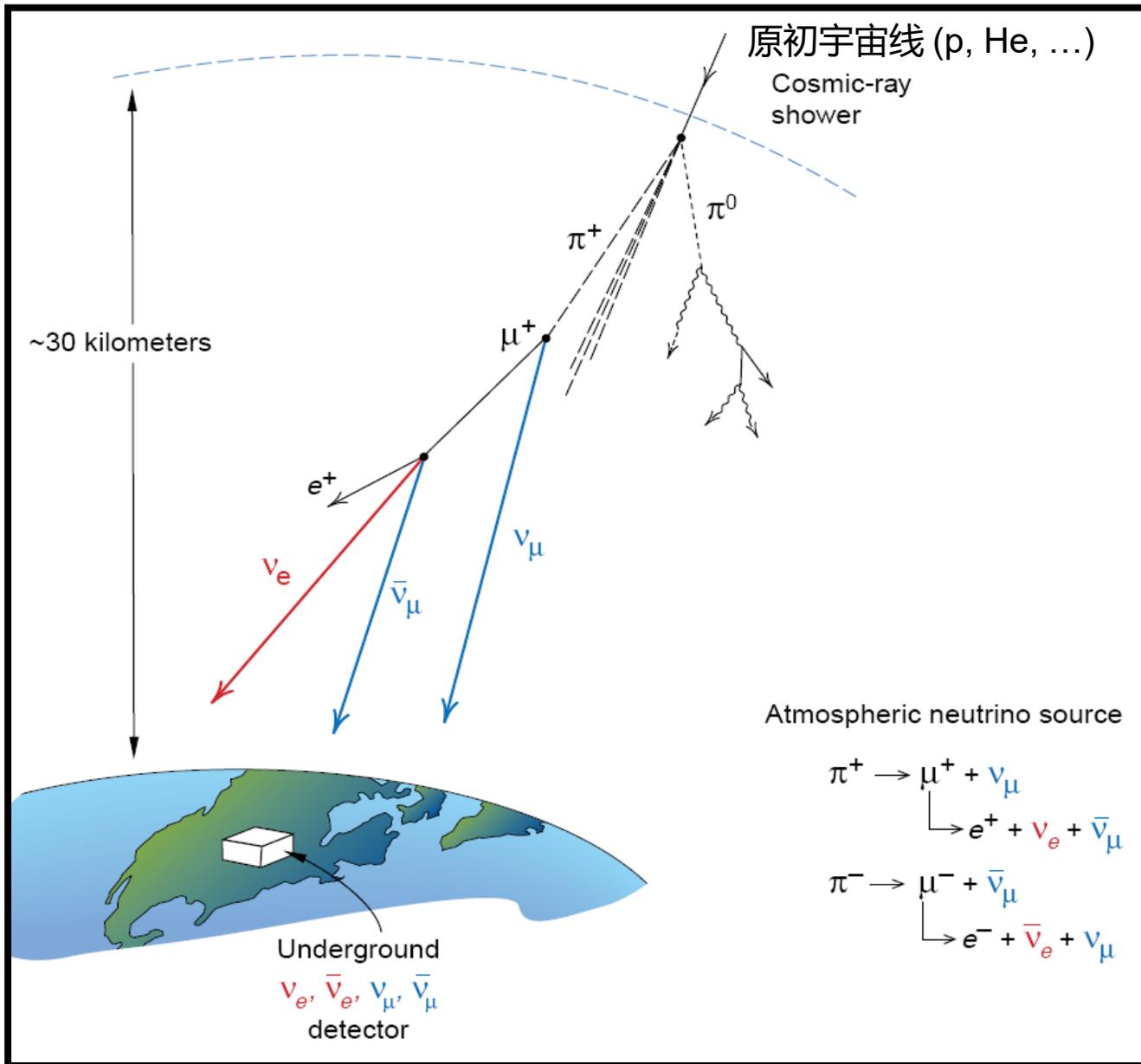


Torn between identities – tau-, electron- or muon-neutrino?

- 反应堆中微子: Goesgen, Palo Verde, Chooz, KamLAND, ...
- 大气中微子: Super-K, MACRO, Soudan-2, ...
- 太阳中微子: SNO, Borexino, ...
- 加速器中微子: K2K, MINOS, OPERA, ...



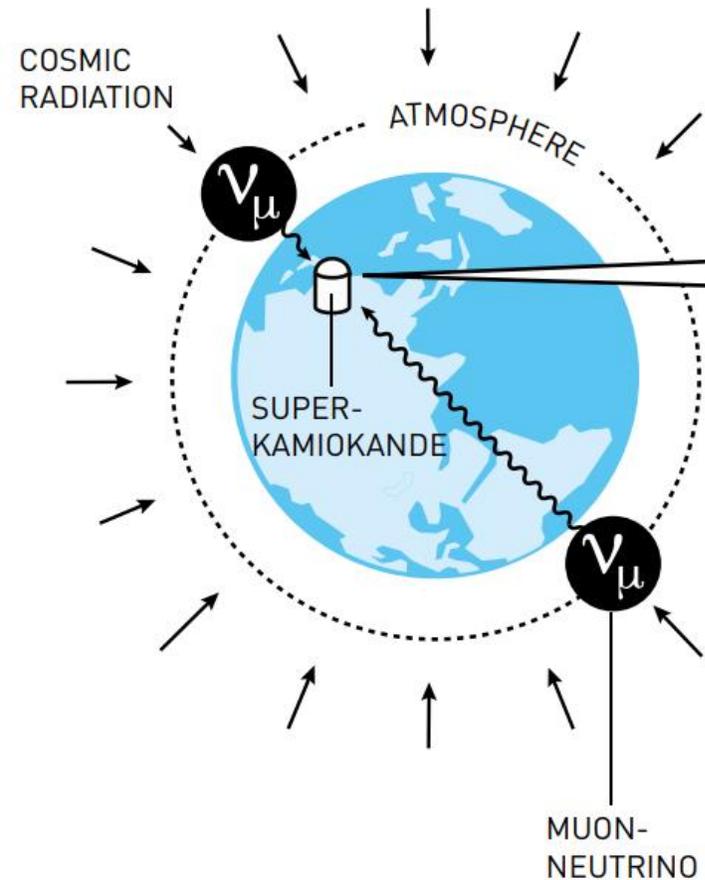
# 大气中微子



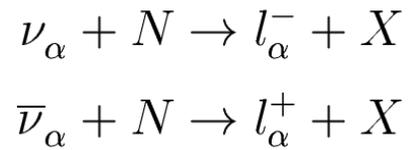
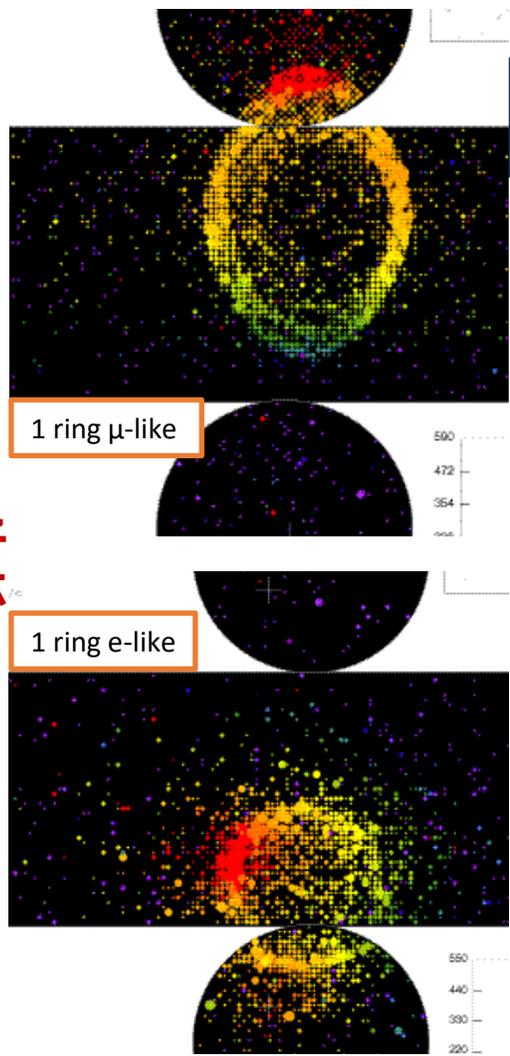
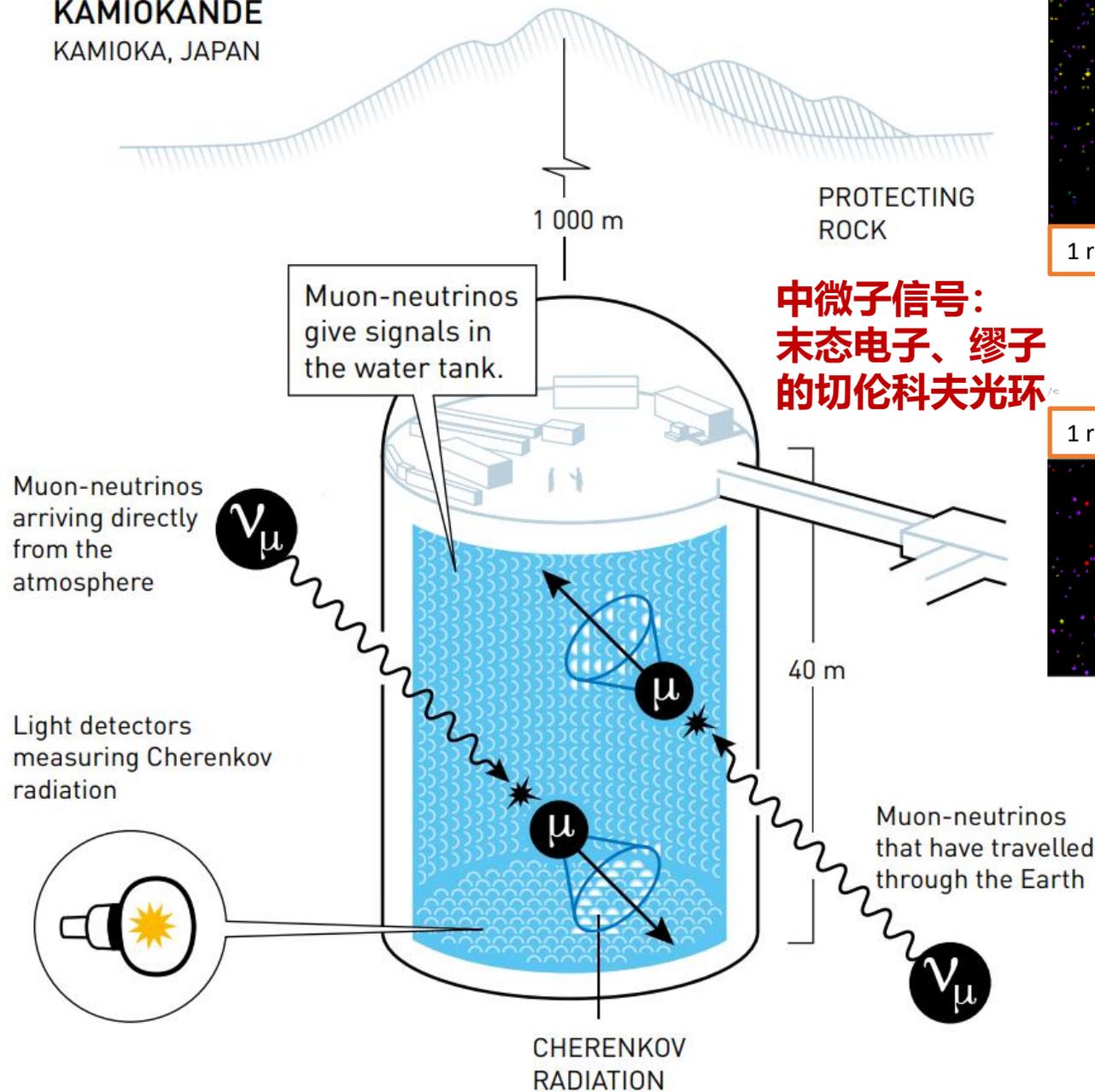
$\nu_\mu/\nu_e \approx 2$  at low energies

$\nu_\mu/\nu_e > 2$  at high energies  
since fewer  $\mu$  decays

# NEUTRINOS FROM COSMIC RADIATION

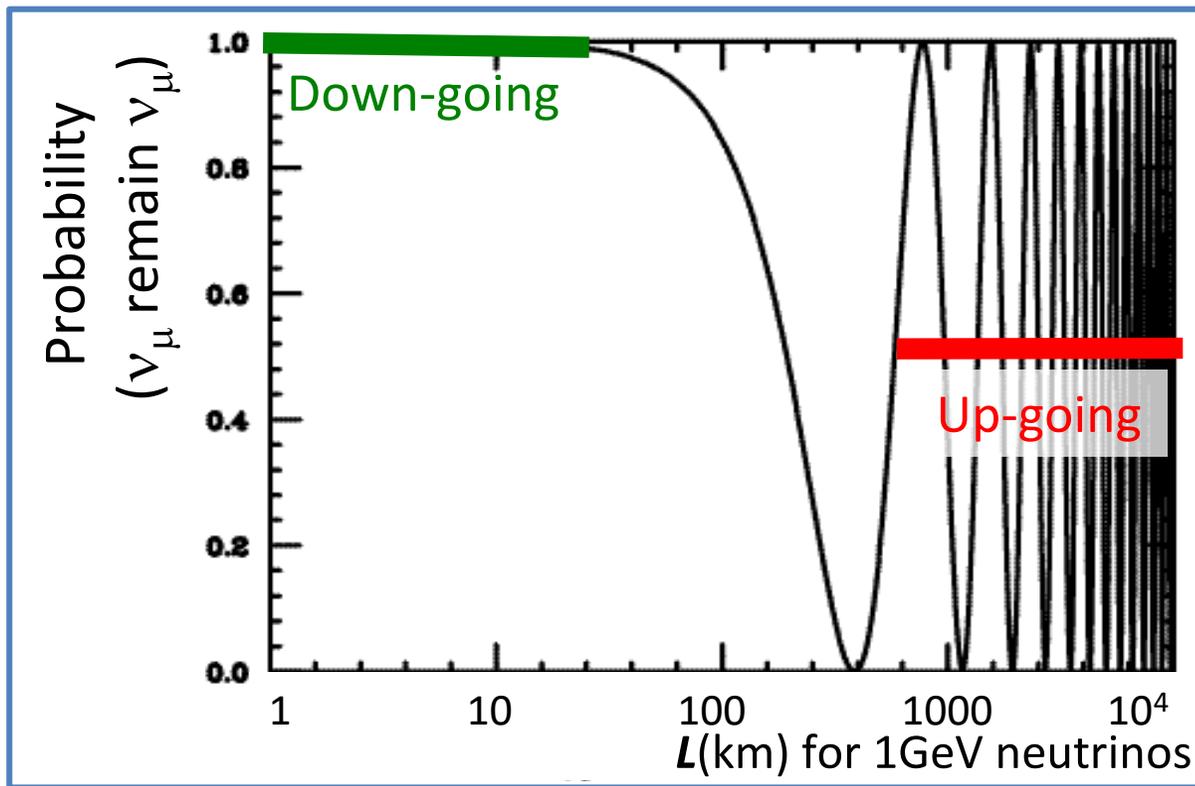
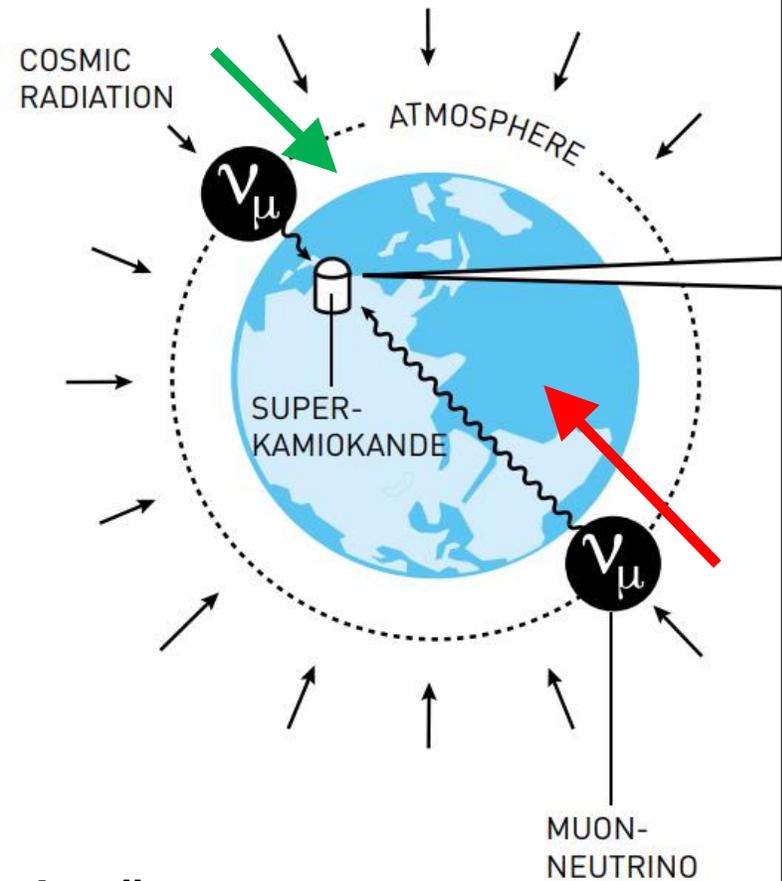


# SUPER-KAMIOKANDE KAMIOKA, JAPAN



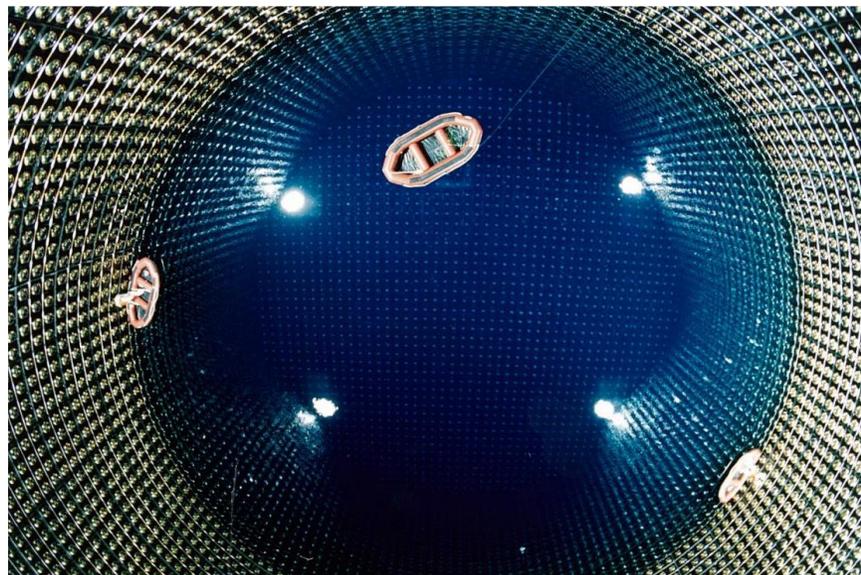
<https://www.nobelprize.org/prizes/physics/2015/press-release/>

# NEUTRINOS FROM COSMIC RADIATION



小插曲:  
KamiokaNDE = Kamioka **Nucleon Decay** Experiment

Super-Kamiokande = Super-Kamioka **Neutrino Detection** Experiment

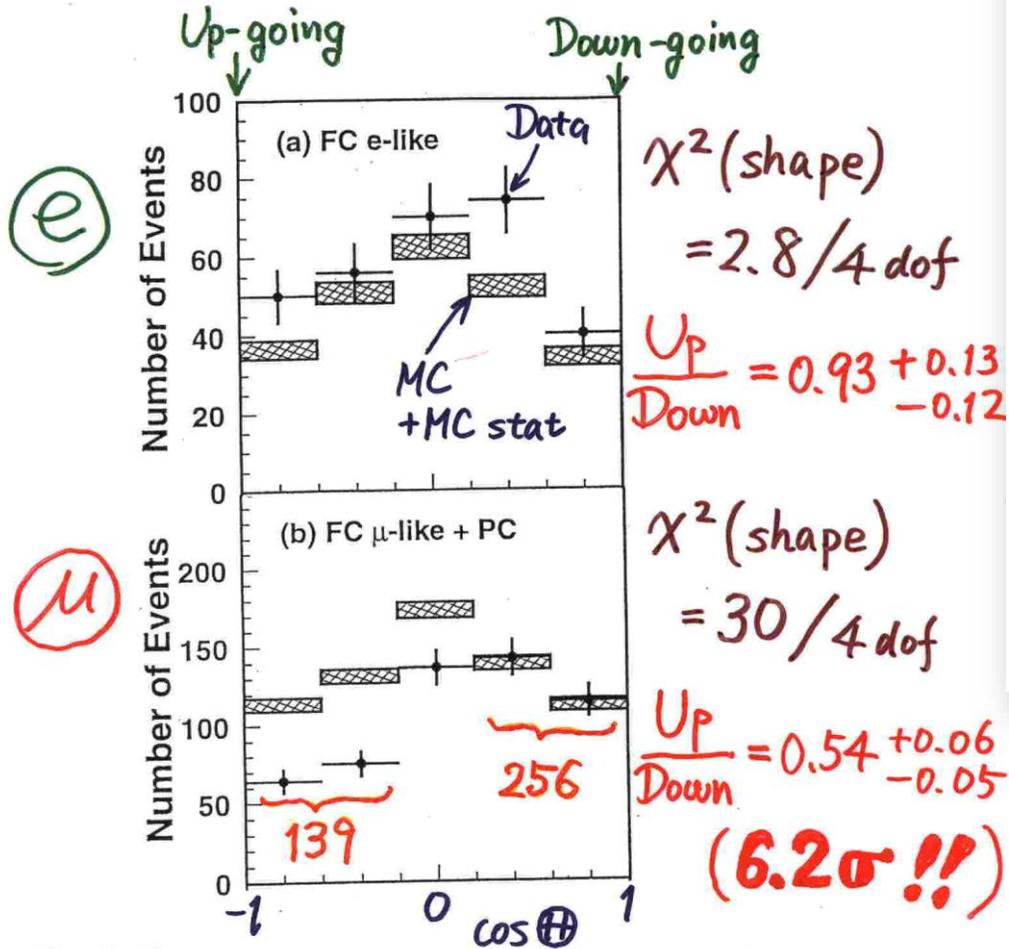


A deficit of upward going  $\nu_\mu$ 's should be observed!  
Kamiokande was too small.  
→ Super-Kamiokande

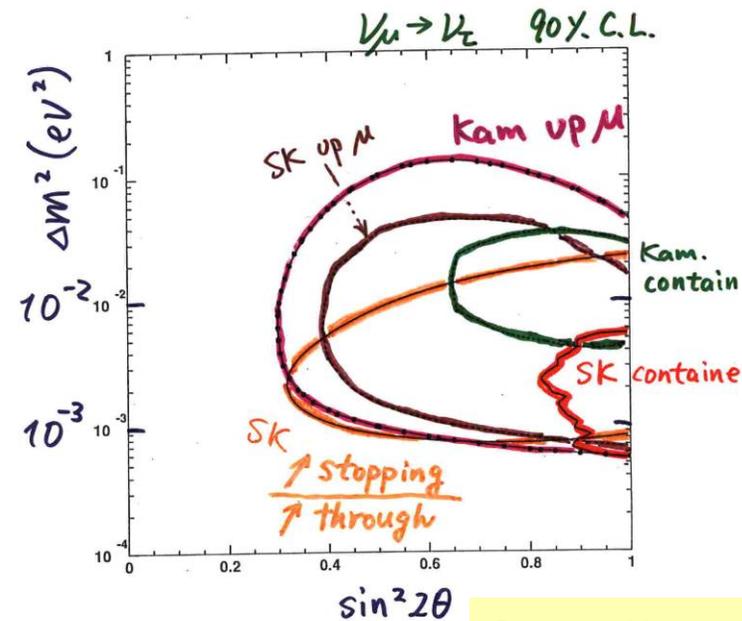
5万吨超纯水

# Super-Kamiokande发现大气中微子振荡 (1998)

## Zenith angle dependence (Multi-GeV)



## Summary Evidence for $\nu_\mu$ oscillations



Y. Fukuda et al., PRL 81 (1998) 1562



Yoji Totsuka  
户塚洋二  
(1942-2008)



Takaaki Kajita  
梶田隆章

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

# 测量太阳中微子的新想法 (1985)

以重水作为探测媒介，一石三鸟

$$\text{CC: } \nu_e + d \rightarrow p + p + e^-$$

$$\text{NC: } \nu_\alpha + d \rightarrow p + n + \nu_\alpha$$

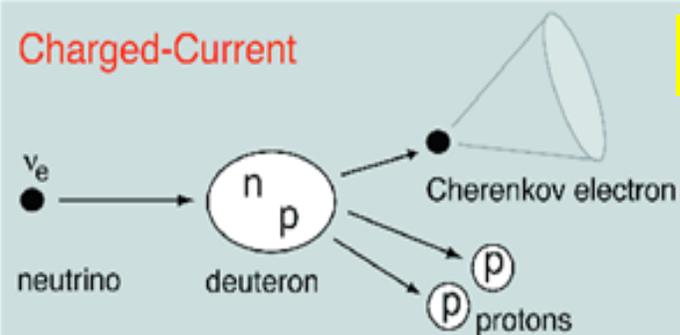
$$\text{ES: } \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

Herbert H. Chen (陈华森)  
(1942 - 1987)



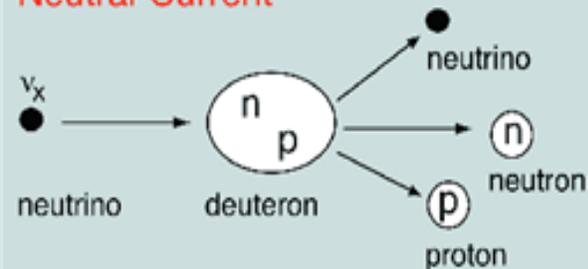
## Neutrino Reactions on Deuterium

### Charged-Current



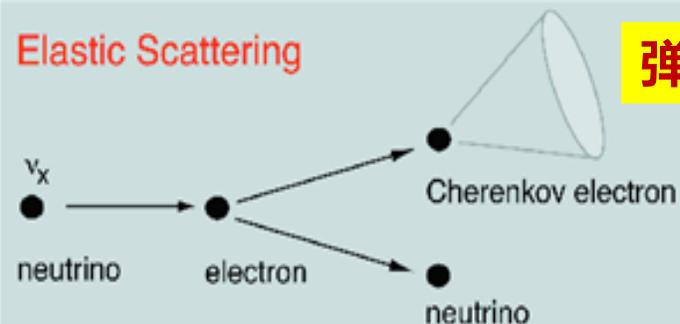
带电流

### Neutral-Current



中性流

### Elastic Scattering



弹性散射

## Direct Approach to Resolve the Solar-Neutrino Problem

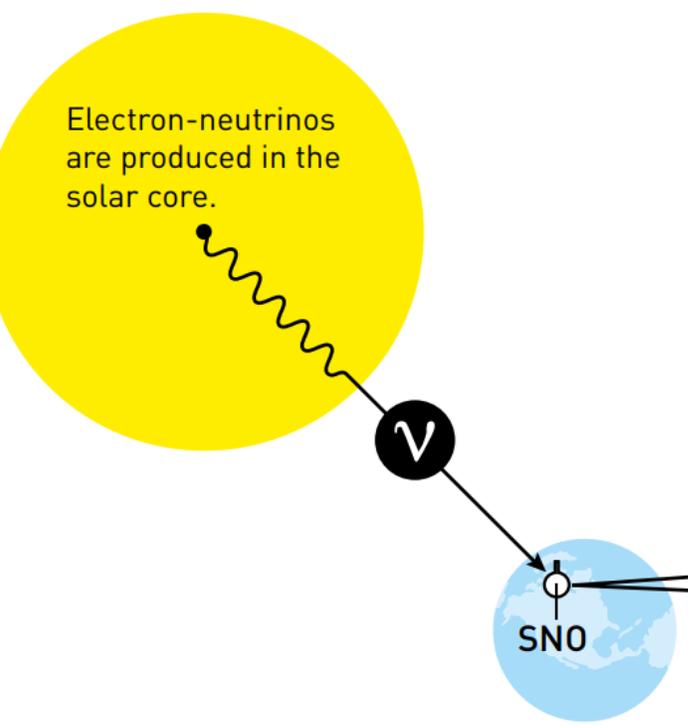
Herbert H. Chen

Department of Physics, University of California, Irvine, California 92717

(Received 27 June 1985)

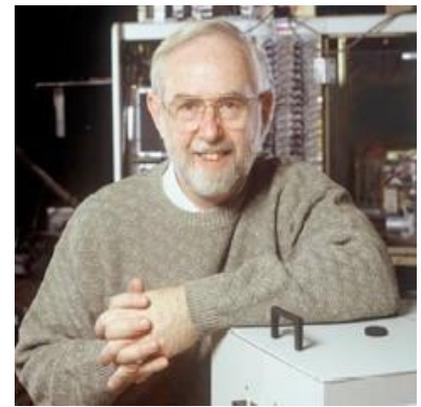
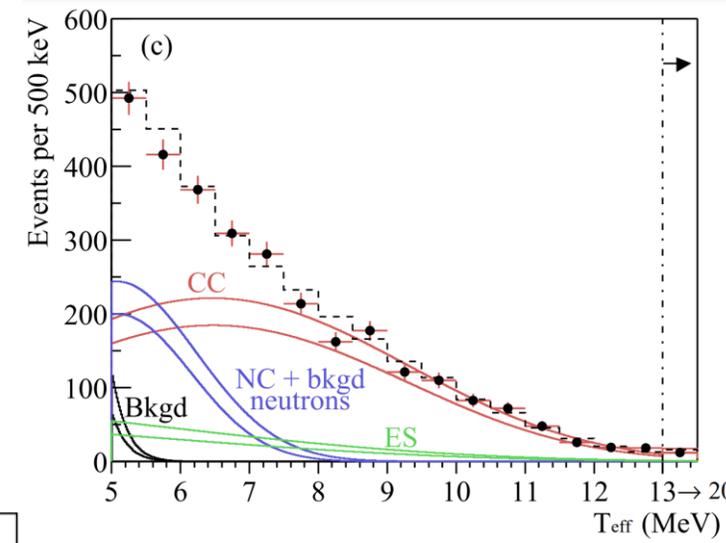
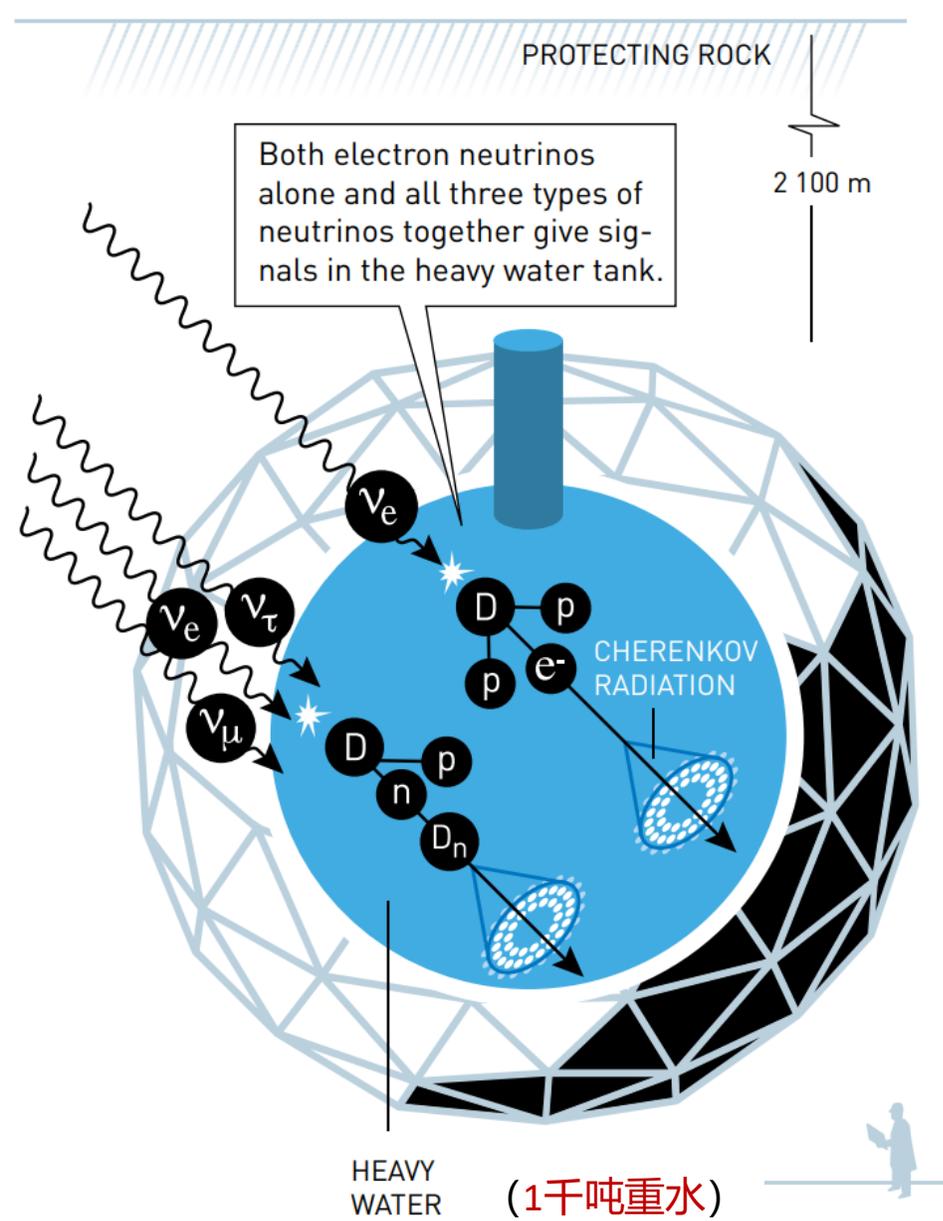
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from  ${}^9\text{B}$  decay via the neutral-current reaction  $\nu + d \rightarrow \nu + p + n$  and the charged-current reaction  $\nu_e + d \rightarrow e^- + p + p$ , is suggested for this purpose.

**NEUTRINOS FROM THE SUN**



**SUDBURY NEUTRINO OBSERVATORY (SNO)**

ONTARIO, CANADA



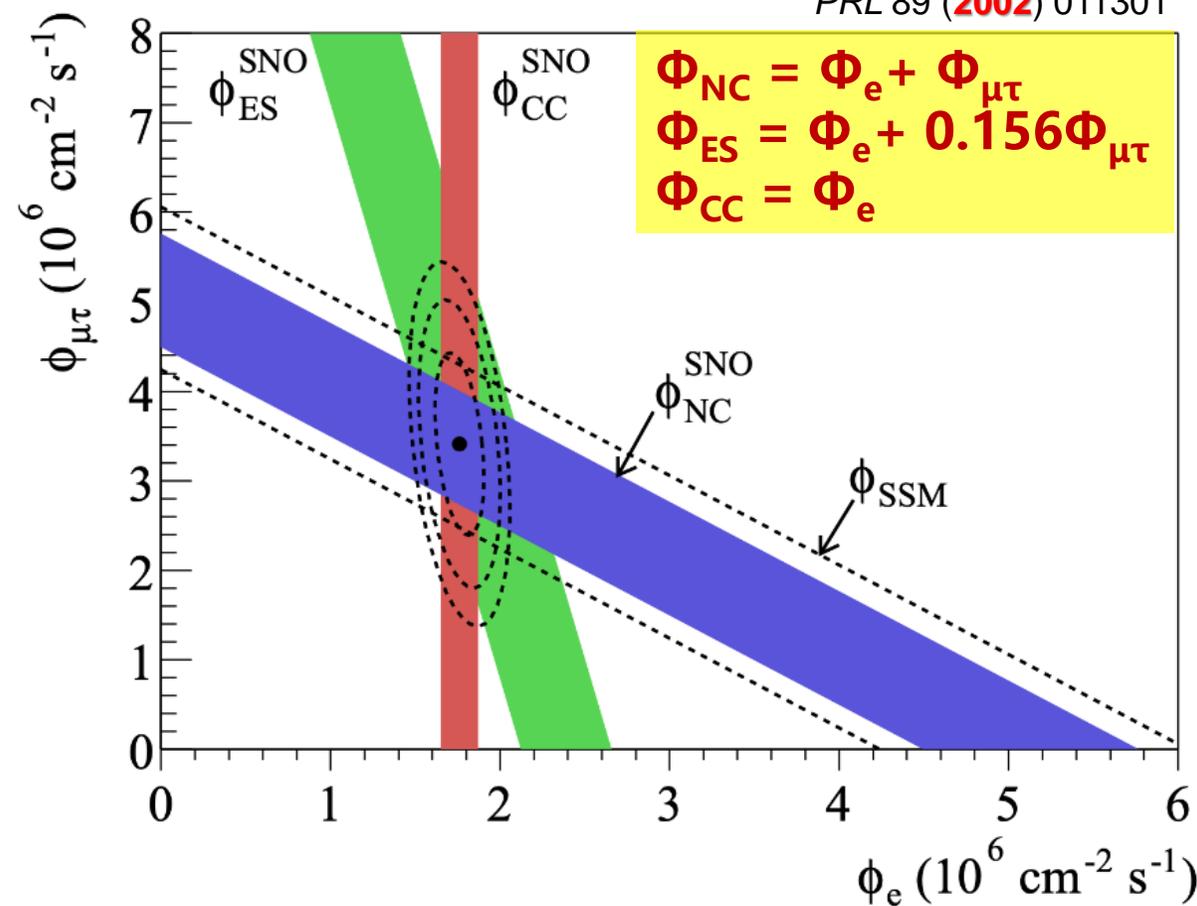
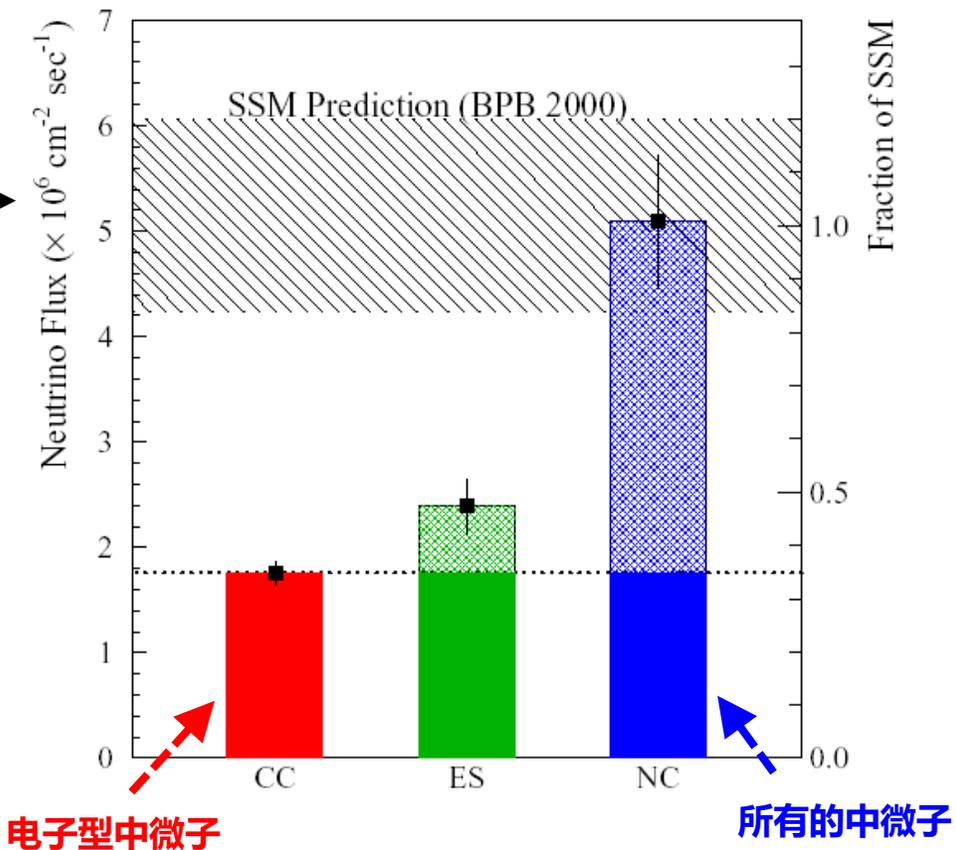
Arthur B. McDonald

<https://www.nobelprize.org/prizes/physics/2015/press-release/>

# SNO实验发现太阳中微子振荡 (2002)

PRL 89 (2002) 011301

太阳模型



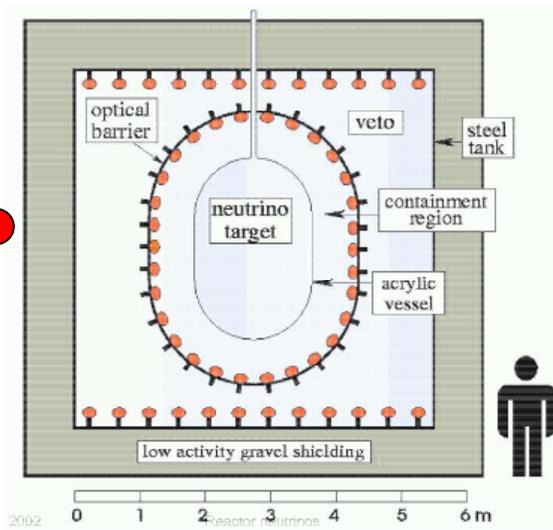
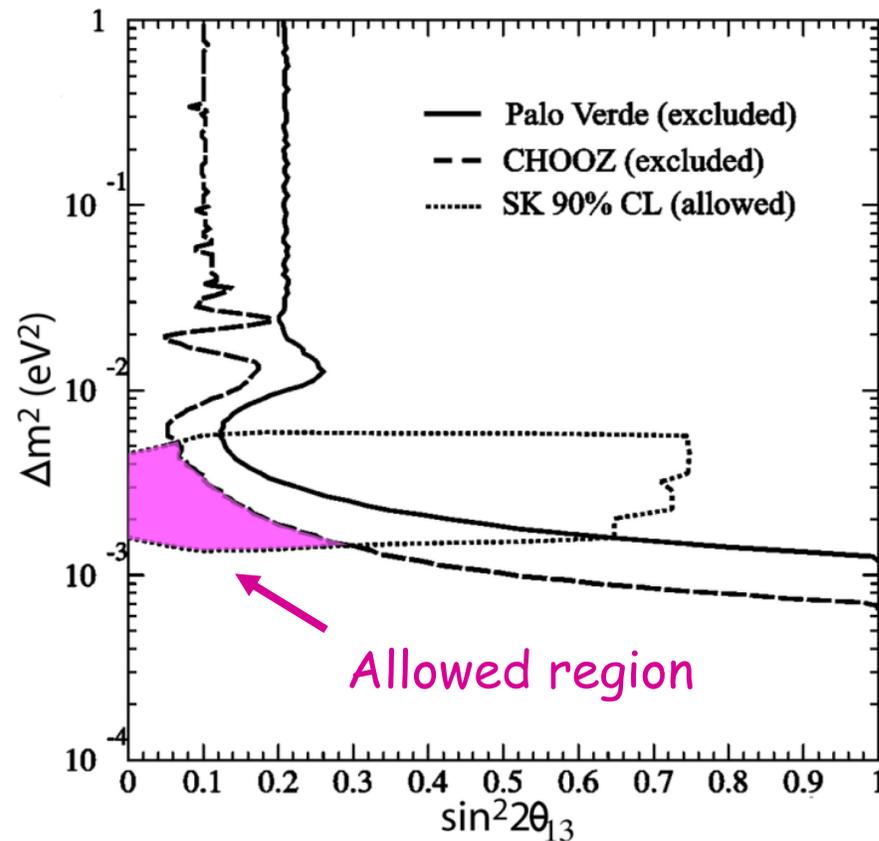
- 2002年发表结果确认太阳中微子丢失问题, 并通过中性流过程验证标准太阳模型的正确性
- 电子中微子从太阳到探测器的过程中转变成muon和tau型中微子 — **中微子振荡的有力证据**

# Palo Verde & Chooz (90s后期) : 短基线实验未能发现振荡

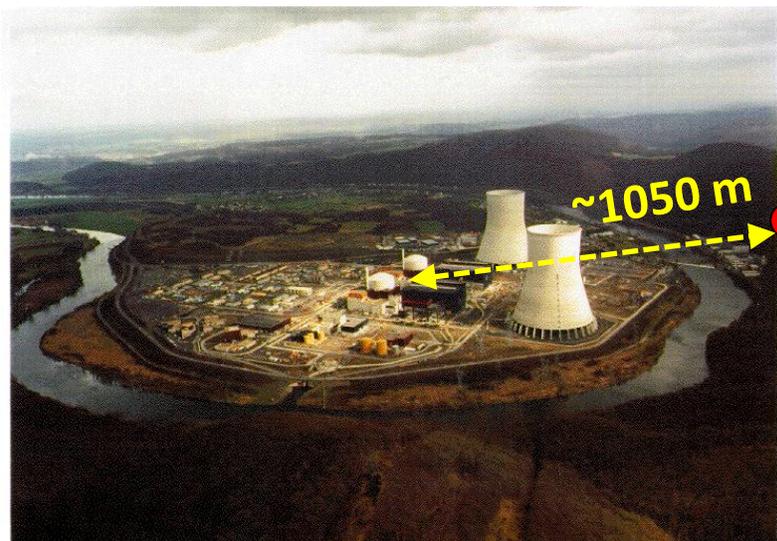
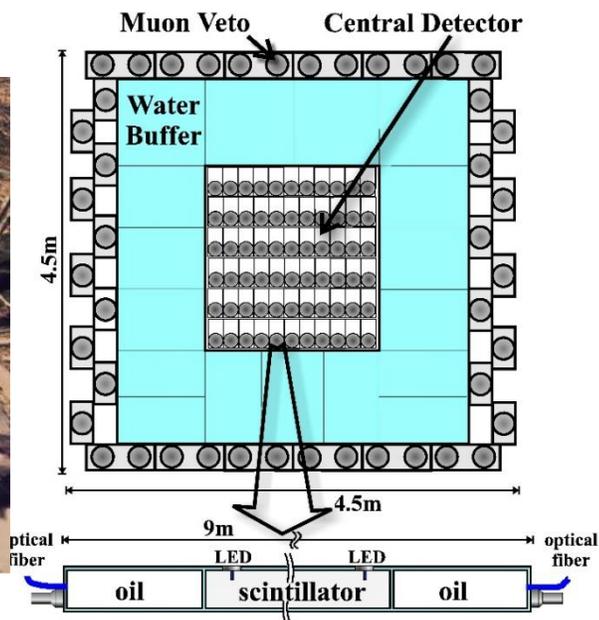
利用反应堆中微子, 试图寻找  $\bar{\nu}_e \rightarrow \bar{\nu}_x$  的振荡, 来解释大气中微子反常

对  $\Delta m^2 \sim 10^{-3} \text{ eV}^2$  区间敏感, 比Kamioka 94' 的最佳拟合值好一个量级

PRD 62 (2000) 072002



2002 reactor neutrinos

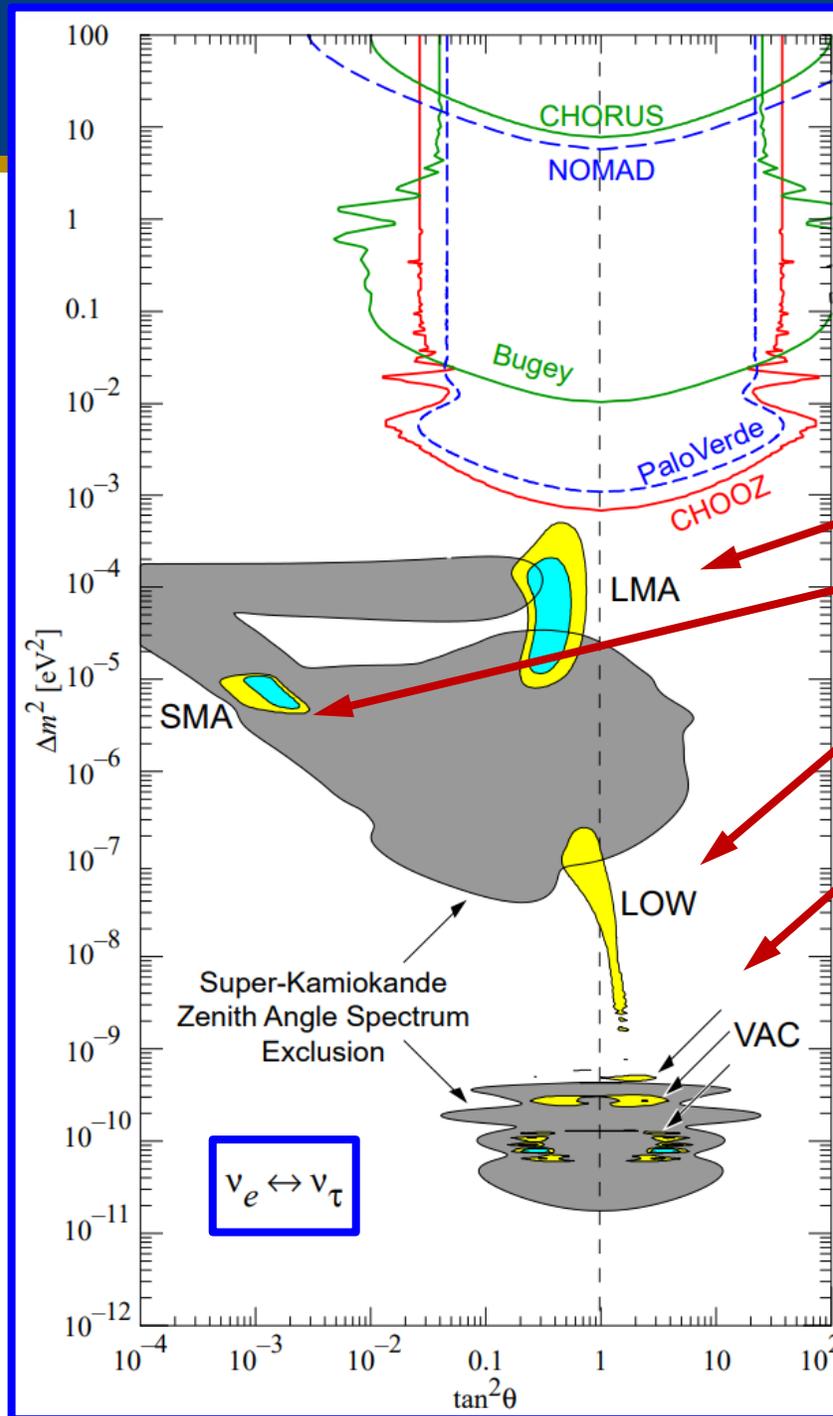
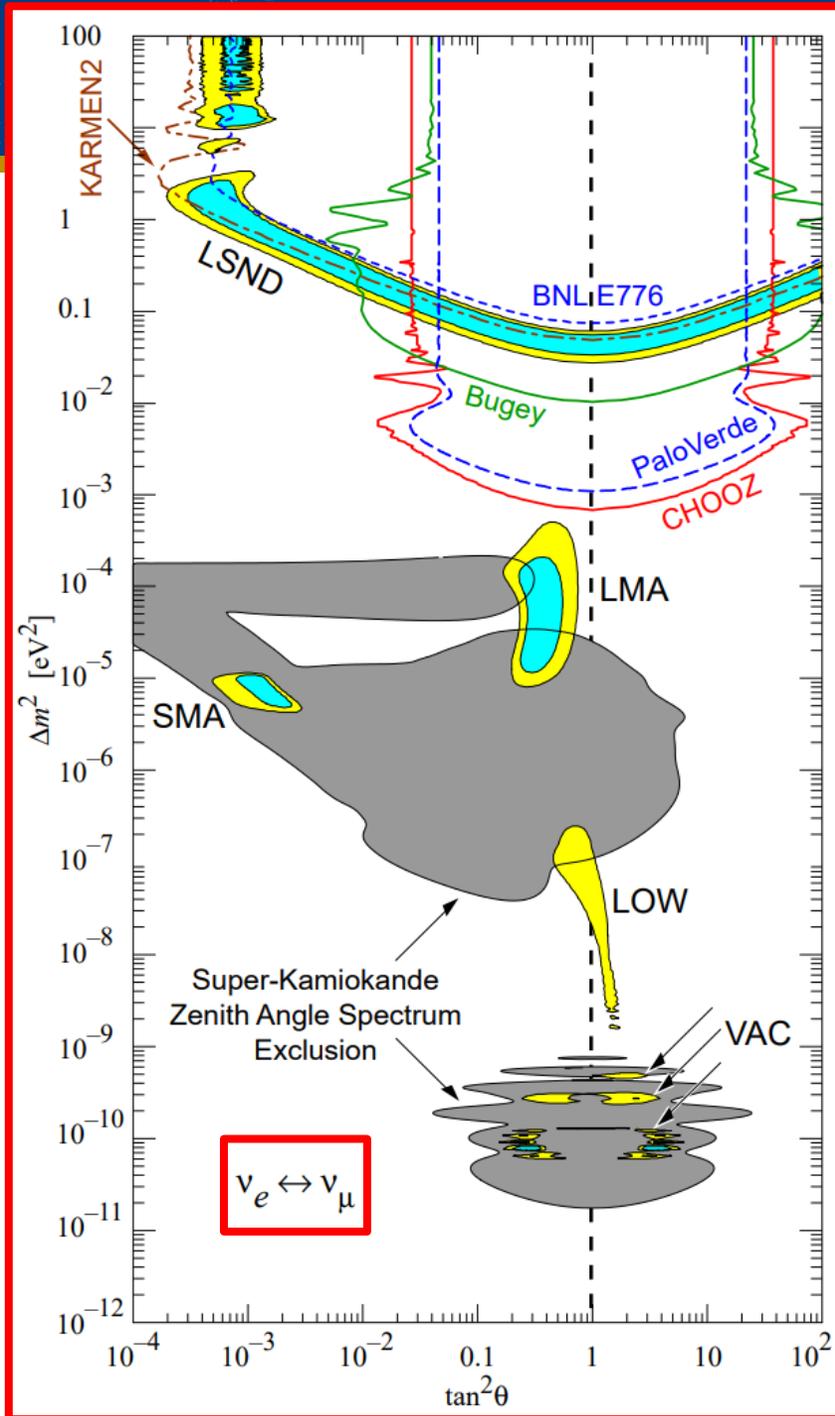


CHOOZ 实验



Palo Verde 实验, 96'

# 中微子振荡@2002



太阳中微子实验给出了四个解

**LMA:** Large Mixing Angle solution

**SMA:** Small Mixing Angle solution

**LOW:** Low  $\Delta m^2$  solution for Large Mixing Angle

**VAC:** Vacuum Oscillation solution

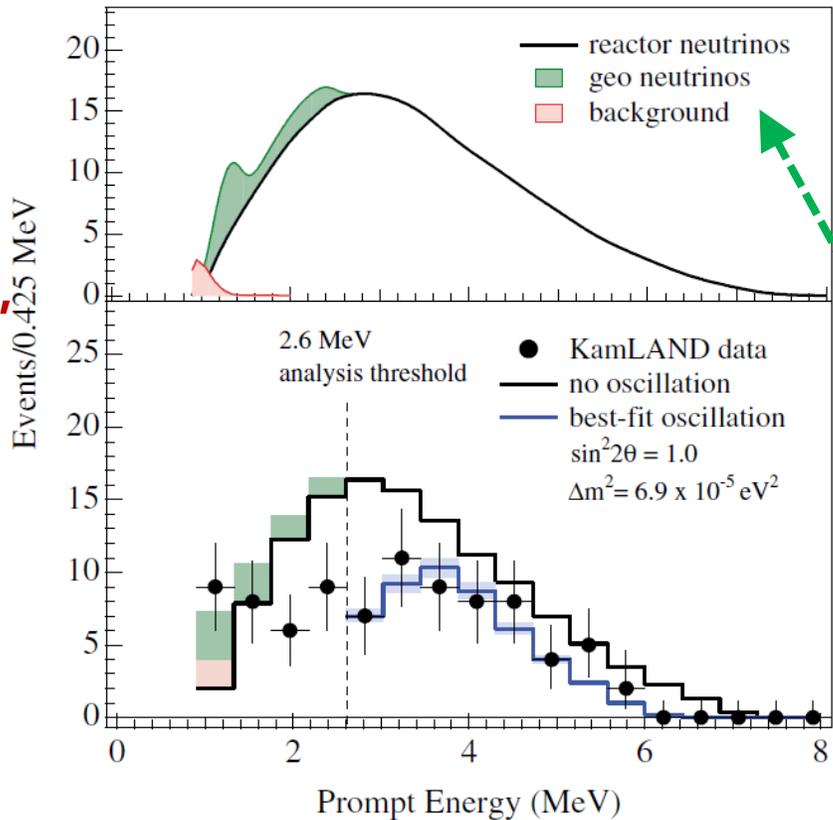
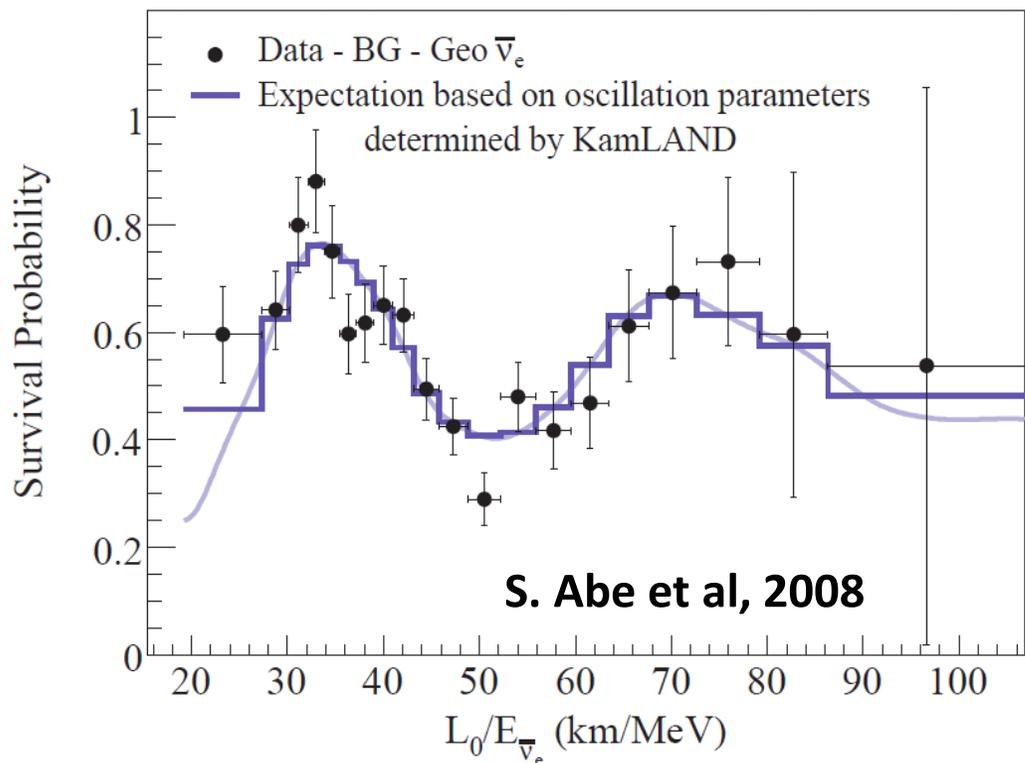
Super-K的太阳中微子分析结果  
“two allowed regions at large mixing are found”  
(Phys.Rev.Lett.86 (2001) 5656)

By Hitosh Murayama, 2002,  
[https://pdg.lbl.gov/2002/two\\_nu\\_plots\\_s805.pdf](https://pdg.lbl.gov/2002/two_nu_plots_s805.pdf)

# KamLAND: 验证太阳中微子振荡的MSW大角解

神冈实验结束后，其地下实验站点开展了新的实验 — **KamLAND**，寻找反应堆中微子振荡，检验大角解 (LMA)

2002年，观测到“中微子丢失” (99.95%置信水平)，挑选了太阳中微子振荡的MSW大角解。



Phys. Rev. Lett. 90.021802

首次观测到地球中微子  
 U/Th的 $\beta$ 衰变产生  $\bar{\nu}_e$



## 三代中微子振荡图像基本成形， 拼图只差 $\theta_{13}$

[Submitted on 26 Feb 2004]

### A New Nuclear Reactor Neutrino Experiment to Measure theta 13

K. Anderson, et al

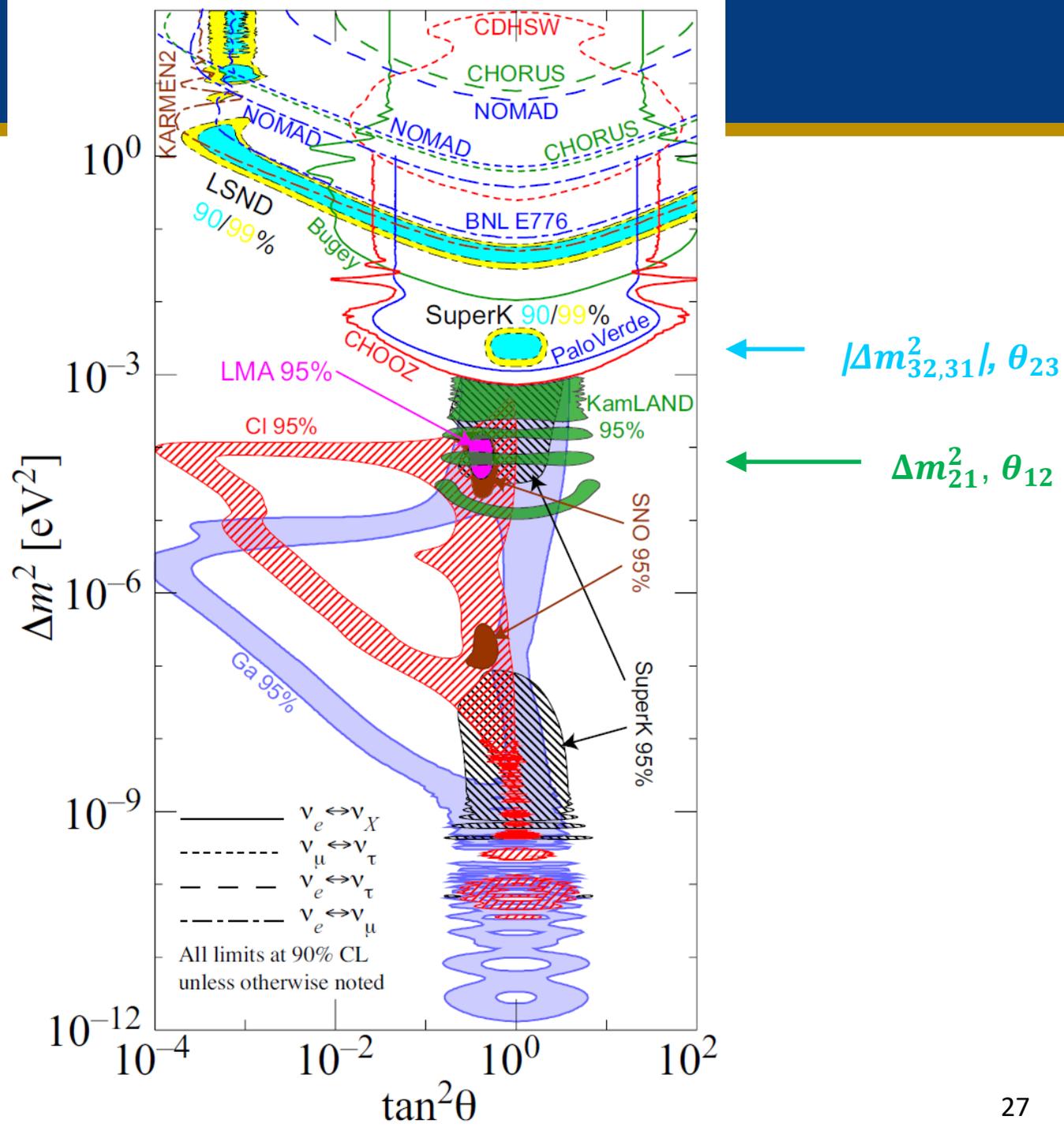
### $\theta_{13}$ 的激烈国际竞争开始

An International Working Group has been meeting to discuss ideas for a new Nuclear Reactor Neutrino Experiment at meetings in May 2003 (Alabama), October 2003 (Munich) and plans for March 2004 (Niigata). This White Paper Report on the Motivation and Feasibility of such an experiment is the result of these meetings. After a discussion of the context and opportunity for such an experiment, there are sections on detector design, calibration, overburden and backgrounds, systematic errors, other physics, tunneling issues, safety and outreach. There are 7 appendices describing specific site opportunities.

Comments: 167 pages, 57 figures, 125 authors, 40 Institutions White Paper Report on Using Nuclear Reactors to search for a value of theta 13

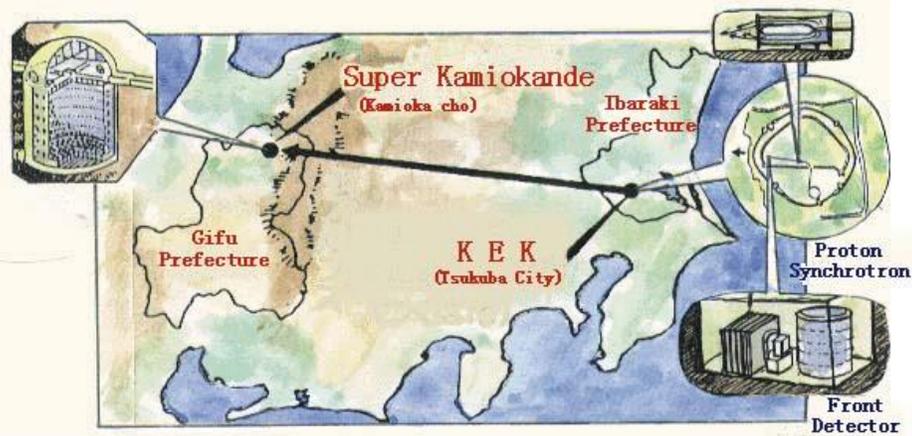
Subjects: **High Energy Physics - Experiment (hep-ex)**

Cite as: arXiv:hep-ex/0402041



# 加速器上的振荡研究

2003, K2K实验确认了 $\mu$ -neutrino 振荡 (丢失)



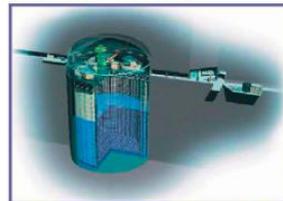
From KEK to Super-Kamiokande  
 $E \sim 1.3 \text{ GeV}$ ,  $L \sim 250 \text{ km}$



2006, MINOS 支持  
 Super-K和K2K的结果

$E \sim 3 \text{ GeV}$ ,  $L \sim 735 \text{ km}$

T2K



Super-Kamiokande  
 (ICRR, Univ. Tokyo)

$$E_\nu \simeq 0.7 \text{ GeV},$$

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 295 \text{ km}}{0.7 \text{ GeV}} \simeq \frac{\pi}{2}$$



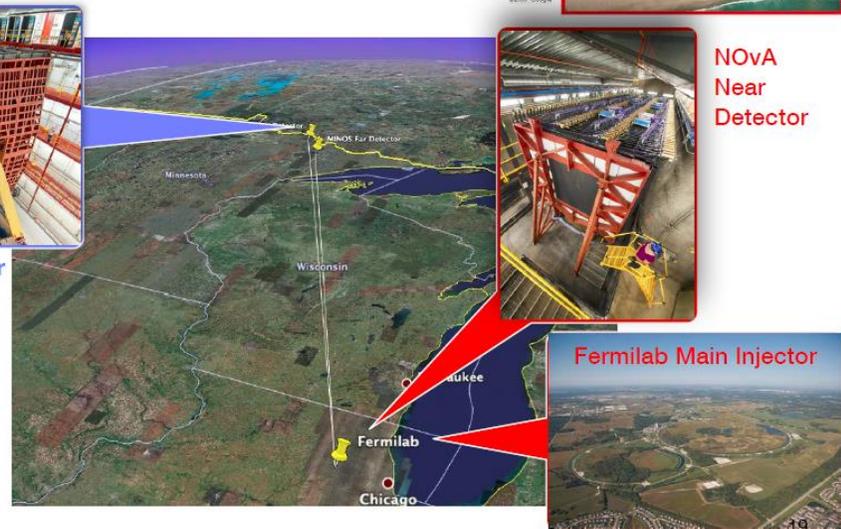
NOvA



NOvA Far Detector

$$E_\nu \simeq 2 \text{ GeV},$$

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 810 \text{ km}}{2 \text{ GeV}} \simeq \frac{\pi}{2}$$



T2K和NOvA以更高精度测量振荡参数, 并利用正反中微子束流的振荡效应差别, 探索CP破坏大小

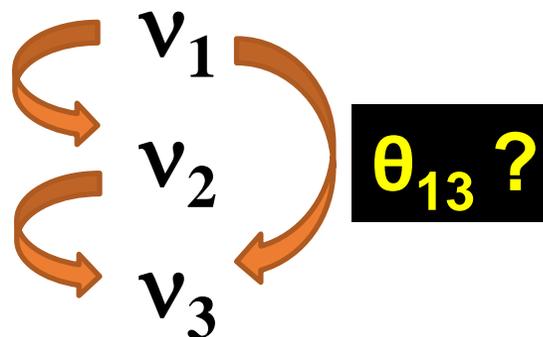
# 寻找第三种振荡模式



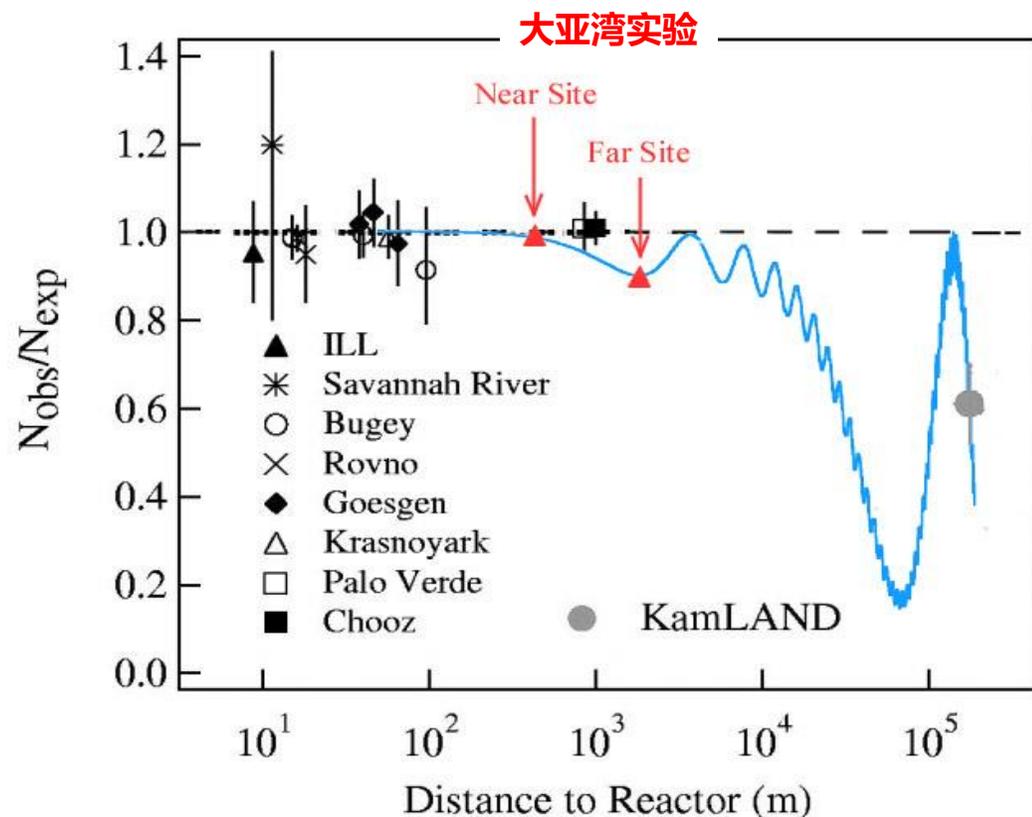
2015

$\theta_{12}$  太阳中微子振荡

$\theta_{23}$  大气中微子振荡



- 基本物理规律：中微子振荡的完整图像
- 基本物理参数：标准模型的28个参数之一
- 决定未来中微子物理研究的方向
- 下一代中微子振荡实验希望测量轻子CP破坏相角和质量顺序：如果 $\theta_{13}$ 太小，这个测量无法进行



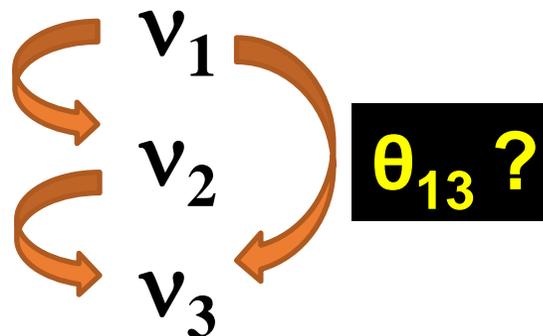
# 寻找第三种振荡模式



2015

$\theta_{12}$  太阳中微子振荡

$\theta_{23}$  大气中微子振荡



■ 过去实验的精度3-6%，无法发现小的 $\theta_{13}$ 振荡

- 中微子通量：~ 2-3 %
- 反应截面：~0.3%
- 靶质量：~1-2%
- **本底**：~1-3%
- **效率**：~ 2-3%

■ 解决办法：远近探测器相对测量

- Mikaelyan and Sinev, hep-ex/9908047



国际上共有7个国家提出8个方案，最终3个得以实施

实验	探测器设计误差	3年灵敏度 (90%CL)
中国 大亚湾	0.38%/√N	~ 0.008
法国 Double Chooz	0.6%	~ 0.03
韩国 RENO	0.5%	~ 0.02

# 大亚湾反应堆中微子实验

## ■ 实验方案与设计创新，提高探测器精度

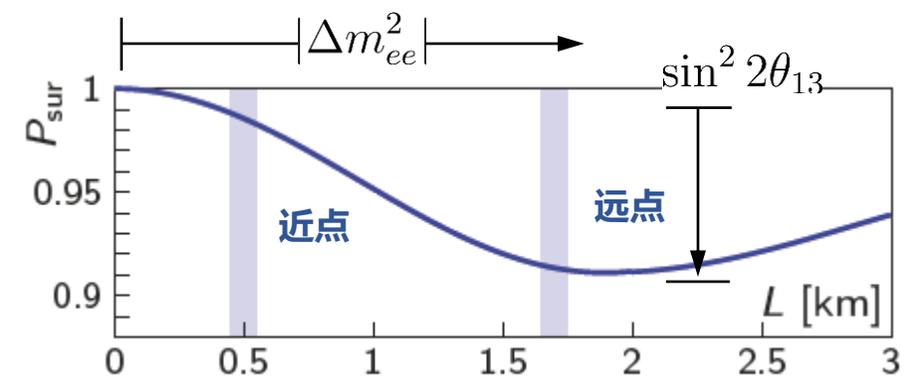
- **多模块测量思想** → 降低探测器误差 $\sqrt{N}$ 倍
- 首次在探测器内**采用反射板**，减少PMT用量一半，大幅度降低造价
- **优化探测器结构**，同类实验取数效率最高（提高统计精度）

## ■ 地理优势，利于提高统计精度，降低本底误差

- **反应堆功率大**
- 附近有山，适合建地下实验室，**屏蔽宇宙线本底**
- 数据积累速度为韩国RENO的5倍，法国Double Chooz的20倍

## ■ 探测器创新

- **新型掺钷液闪**，解决掺钷液闪不稳定的国际难题
- **双层水切伦科夫探测器**，宇宙线探测效率99.7%
- 多种特殊技术



# 大亚湾实验获得结果之前

- 三个实验出现振荡迹象，但不能排除 $\theta_{13}$ 为零

→ 日本T2K: **2.5  $\sigma$**  (2011)

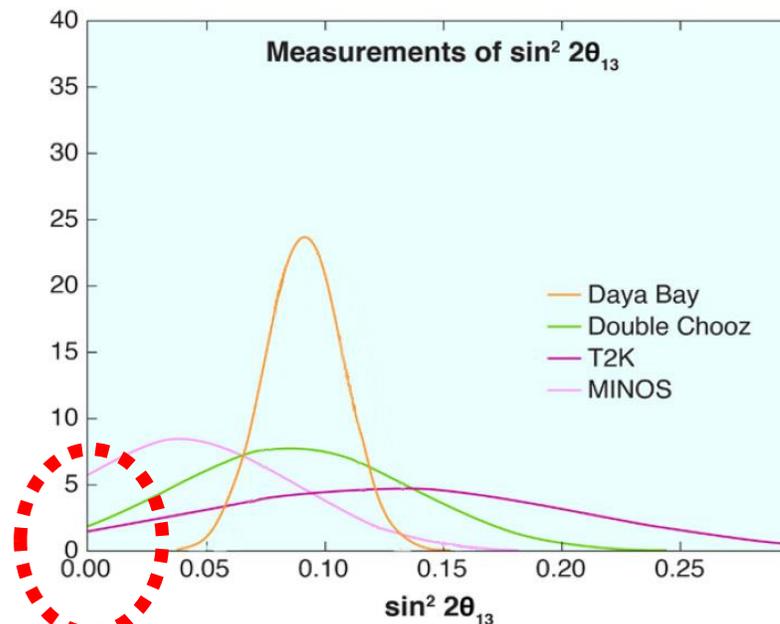
$$0.03 < \text{Sin}^2 2\theta_{13} < 0.28 @ 90\% \text{C.L. for NH}$$
$$0.04 < \text{Sin}^2 2\theta_{13} < 0.34 @ 90\% \text{C.L. for IH}$$

→ 美国Minos: **1.7  $\sigma$**  (2011)

$$0 < \text{Sin}^2 2\theta_{13} < 0.12 @ 90\% \text{C.L. NH}$$
$$0 < \text{Sin}^2 2\theta_{13} < 0.19 @ 90\% \text{C.L. IH}$$

→ 法国Double Chooz: **1.7  $\sigma$**  (2011)

$$0 < \text{Sin}^2 2\theta_{13} < 0.12 @ 90\% \text{C.L. NH}$$
$$0 < \text{Sin}^2 2\theta_{13} < 0.19 @ 90\% \text{C.L. IH}$$



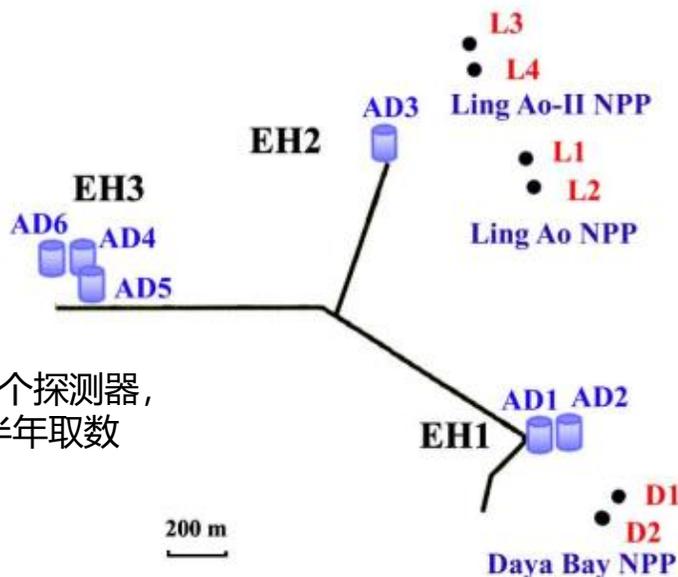
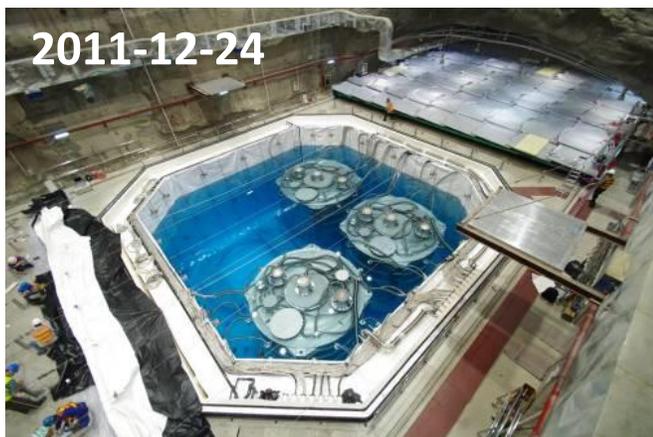
- 假如 $\text{sin}^2 2\theta_{13}$ 真值小于0.03，大亚湾没有竞争对手
- 假如大于0.03，我们落后于韩国，尽快开始远点取数是关键



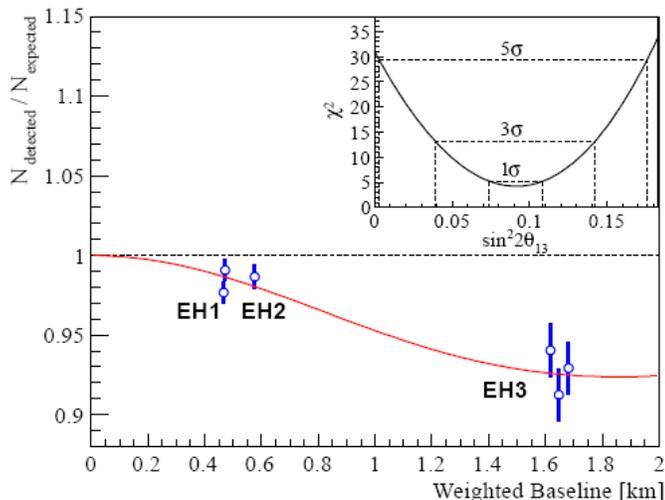
分两步走，想尽一切办法尽快达到 $\text{sin}^2 2\theta_{13} = 0.03$ ，然后精确测量

# 大亚湾实验发现新的中微子振荡模式

大亚湾实验2003年提出，2012年建成，率先测得第3种振荡模式，  
振幅( $\sin^2 2\theta_{13}$ )为 0.092，远大于预期的0.01-0.03



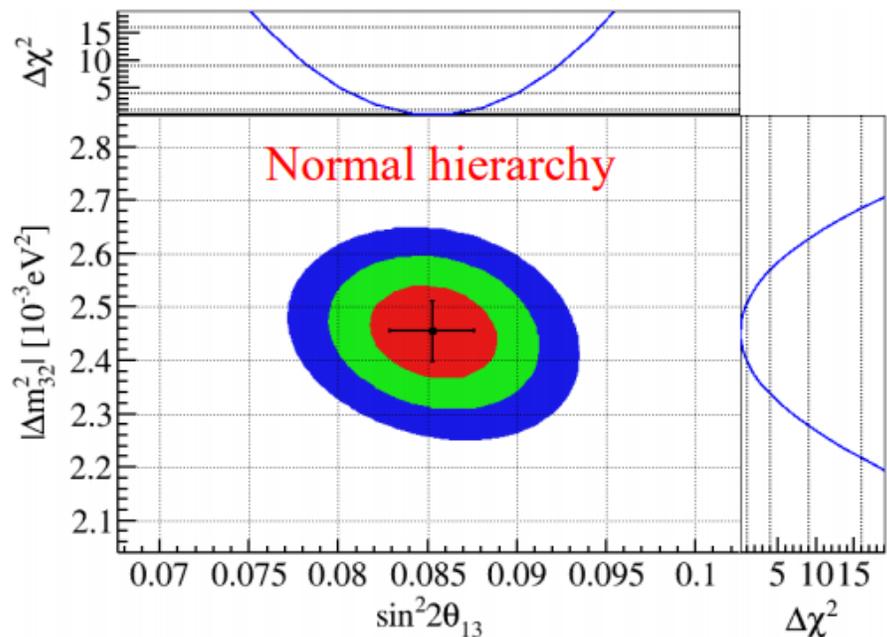
采用6个探测器，  
提前半年取数



2016年度国家自然科学一等奖  
2016年度基础物理学突破奖  
等十多个国内外奖项

- 大的 $\theta_{13}$ 意味着CP效应比较大
- 意味着质量顺序可以测量
- 打开了未来中微子研究的大门

# $\theta_{13}$ 精确测量



**$\sin^2 2\theta_{13}$ 的精度已提高到  $\sim 2.8\%$**

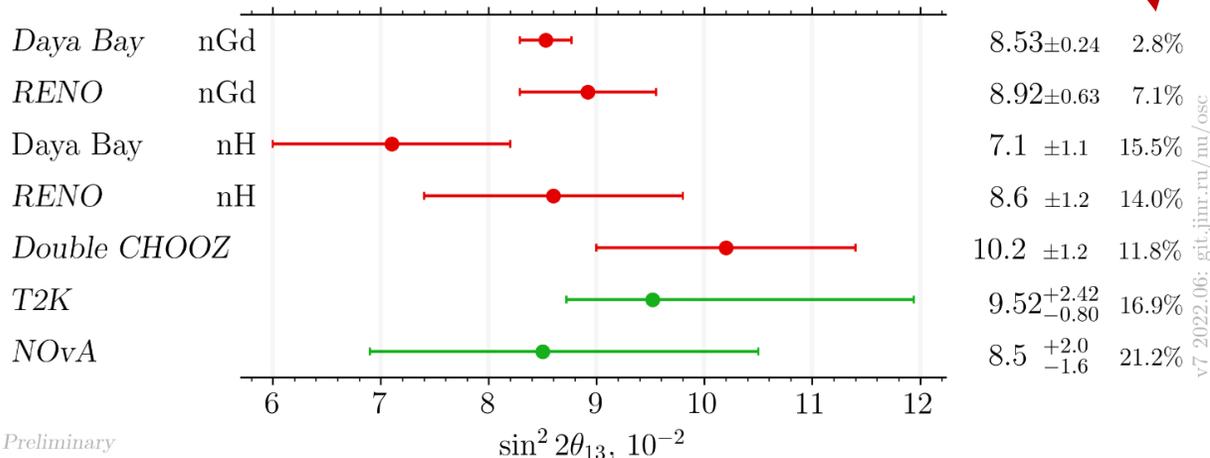
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024} \quad (2.8\% \text{ precision})$$

Normal Mass Ordering:

$$\Delta m^2_{32} = +(2.454^{+0.057}_{-0.057}) \times 10^{-3} \text{eV}^2 \quad (2.3\% \text{ precision})$$

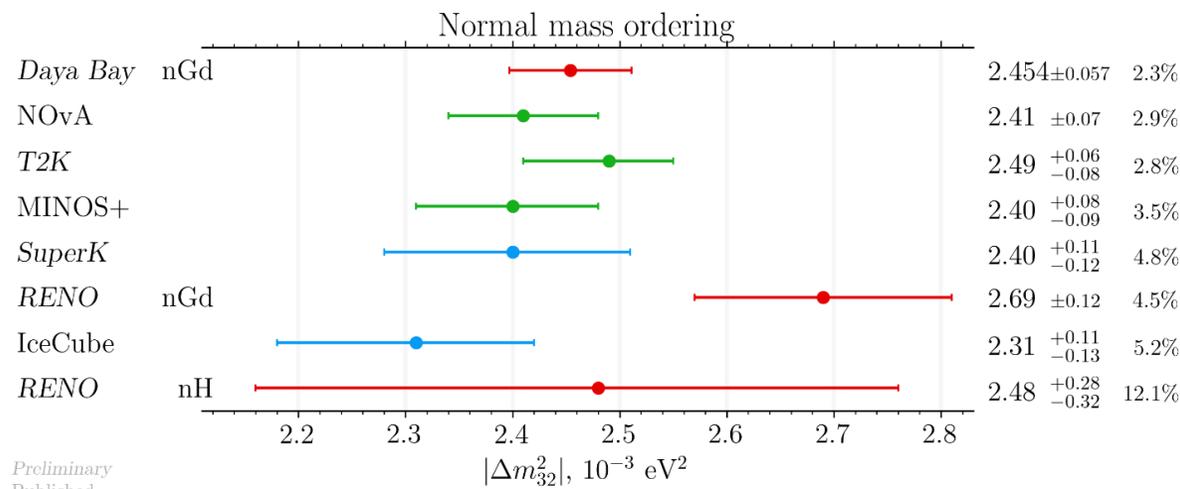
@ Neutrino 2022

Likely be the best measurement in the foreseeable future



Preliminary  
Published

v7 2022.06: git.jinr.ru/nu/osc



Preliminary  
Published

v8 2022.06: git.jinr.ru/nu/osc

# 三代中微子振荡图像

## 中微子混合矩阵

$V =$

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

$\theta_{23} \sim 45^\circ$   $|\Delta m_{32}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2$



$\theta_{12} \sim 34^\circ$   $\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$

$\theta_{13} \sim 8.4^\circ$

## Neutrino Mixing

Status @ PDG 2021

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Masses, Mixing, and Oscillations."

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$

$\sin^2(\theta_{23}) = 0.539 \pm 0.022$  (S = 1.1) (Inverted order)

$\sin^2(\theta_{23}) = 0.546 \pm 0.021$  (Normal order)

$\Delta m_{32}^2 = (-2.536 \pm 0.034) \times 10^{-3} \text{ eV}^2$  (Inverted order)

$\Delta m_{32}^2 = (2.453 \pm 0.033) \times 10^{-3} \text{ eV}^2$  (Normal order)

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

$\delta$ , CP violating phase =  $1.36_{-0.16}^{+0.20} \pi$  rad

$\langle \Delta m_{21}^2 - \Delta \bar{m}_{21}^2 \rangle < 1.1 \times 10^{-4} \text{ eV}^2$ , CL = 99.7%

$\langle \Delta m_{32}^2 - \Delta \bar{m}_{32}^2 \rangle = (-0.12 \pm 0.25) \times 10^{-3} \text{ eV}^2$

Experiment	Dominant	Important
Solar Experiments	$\theta_{12}$	$\Delta m_{21}^2, \theta_{13}$
Reactor LBL (KamLAND)	$\Delta m_{21}^2$	$\theta_{12}, \theta_{13}$
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\theta_{13},  \Delta m_{31,32}^2 $	
Atmospheric Experiments (SK, IC-DC)		$\theta_{23},  \Delta m_{31,32}^2 , \theta_{13}, \delta_{CP}$
Accel LBL $\nu_\mu, \bar{\nu}_\mu$ , Disapp (K2K, MINOS, T2K, NO $\nu$ A)	$ \Delta m_{31,32}^2 , \theta_{23}$	
Accel LBL $\nu_e, \bar{\nu}_e$ App (MINOS, T2K, NO $\nu$ A)	$\delta_{CP}$	$\theta_{13}, \theta_{23}$



# Part II -- 中微子振荡测量

$$|\nu_e\rangle = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = c_1 |\nu_e\rangle + c_2 |\nu_\mu\rangle + c_3 |\nu_\tau\rangle$$

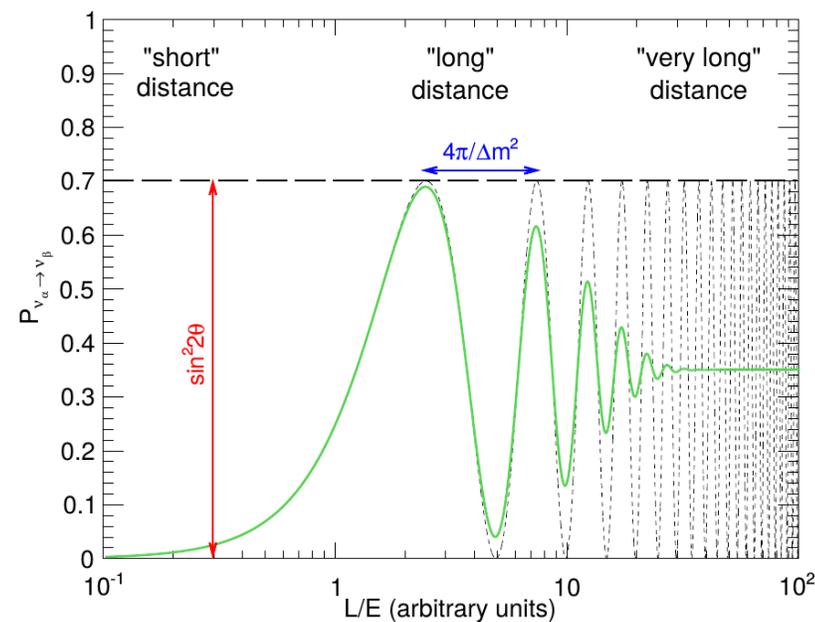
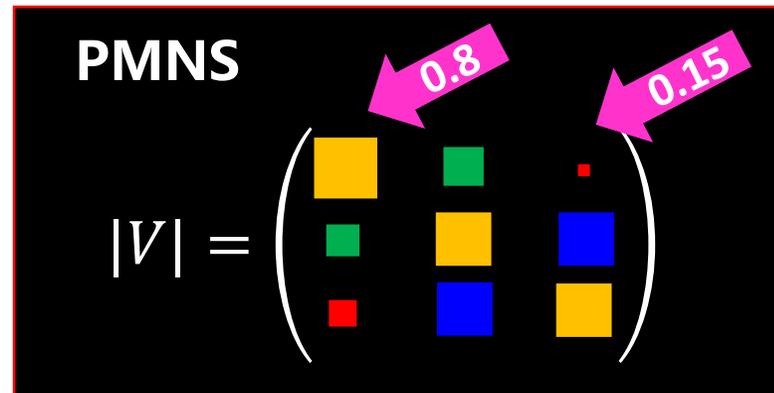
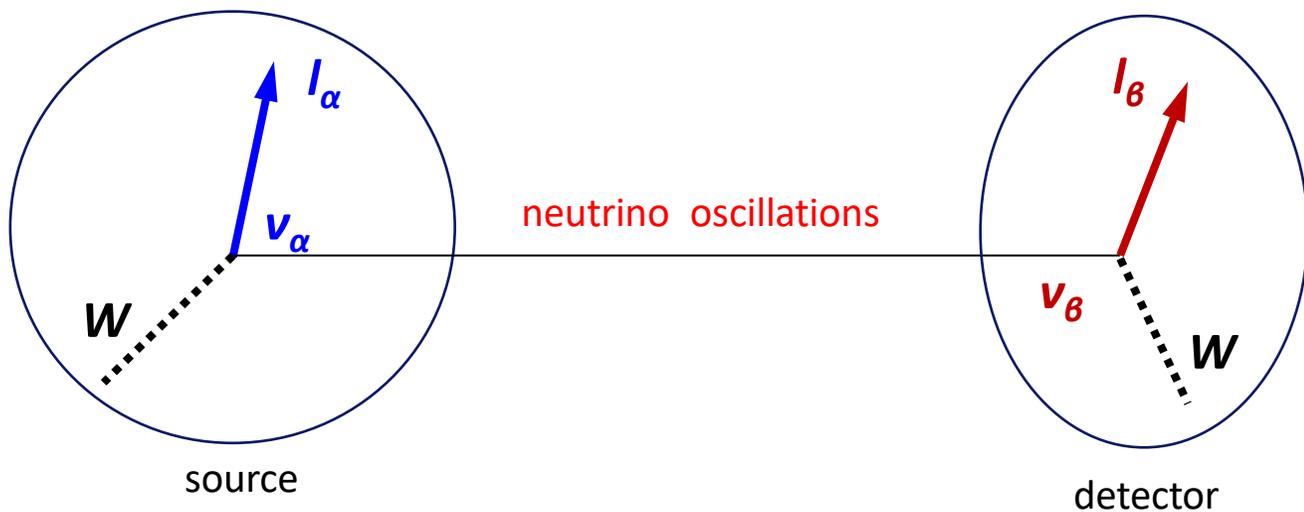
质量本征态 ( $\nu_1, \nu_2, \nu_3$ )

传播

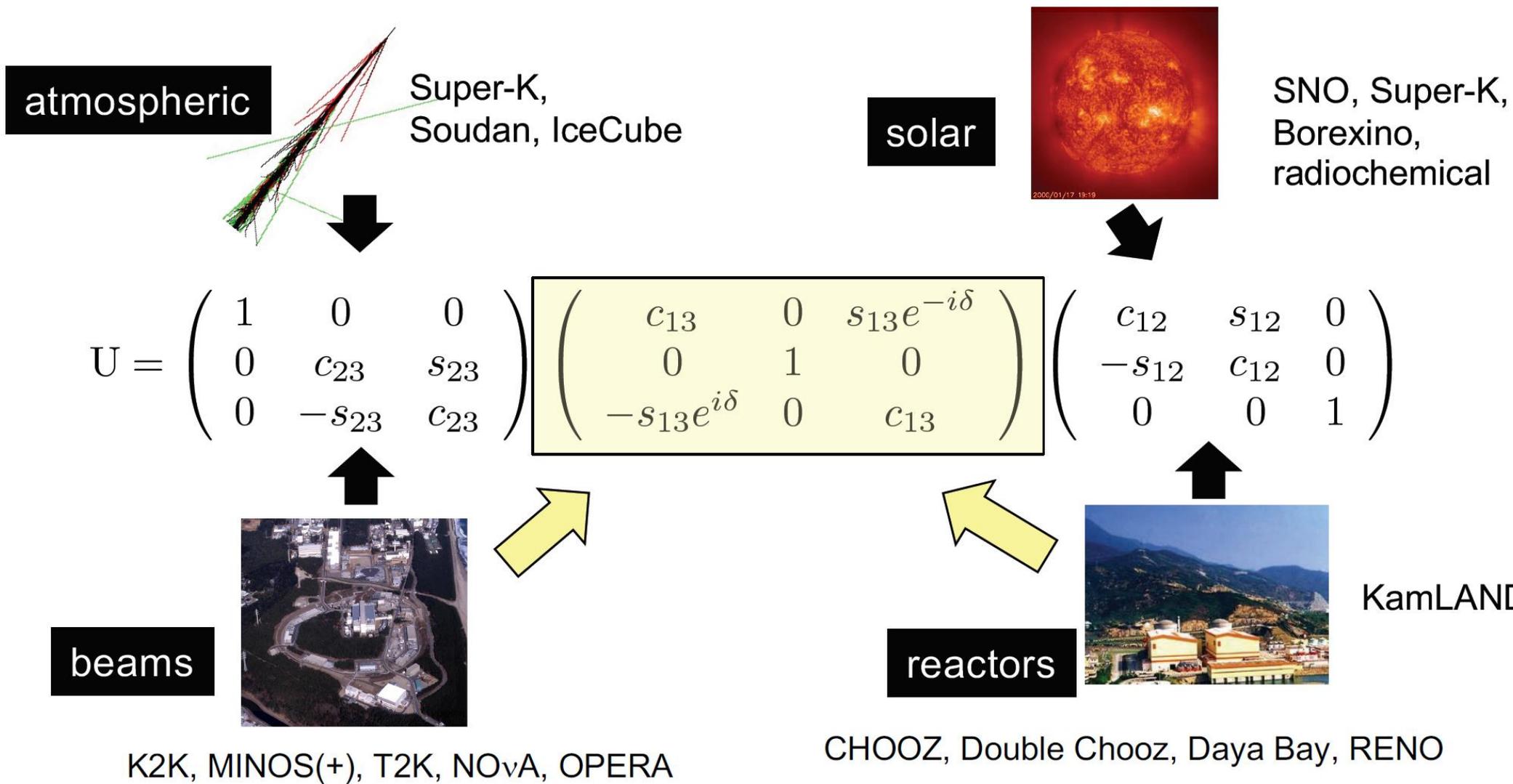
↔  
混合

“味”本征态 ( $\nu_e, \nu_\mu, \nu_\tau$ )

产生、弱相互作用



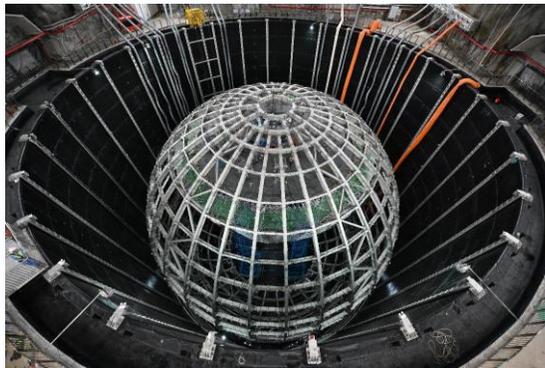
# 中微子振荡测量



K. Scholberg @ TIP2021

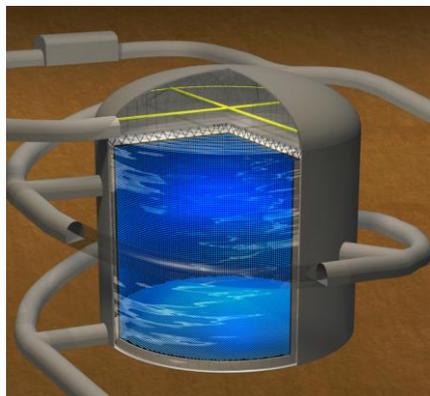
GeV-scale

MeV-scale



- 52.5-km baseline
- 20 kton, ultra-pure LS
- ~700 m depth
- 3% Res. @ 1 MeV

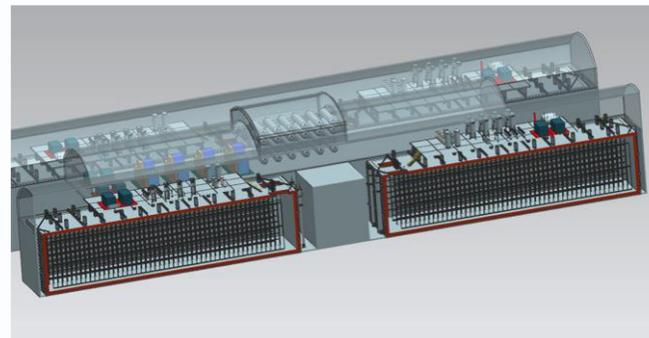
**Liquid Scintillator**  
*High E-resolution*



**Hyper-Kamiokande**

- 295-km baseline
- 260k (188k) ton water
- ~1360 m depth
- upgraded J-PARC beam to 750 kW @ 1.3 MeV

**Water Cherenkov**  
*Proven at very large scale*



- 1300-km baseline
- 4 10-kton LArTPC modules
- ~4850-ft depth
- New 1.2 MW beam (upgradeable to 2.3 MW)

**Liquid Argon**  
*Excellent particle reconstruction*

# 未来中微子振荡实验



Reactor

$\Delta m_{31}^2$  and  $\Delta m_{32}^2$   
interference ( $\phi$ )

$\Delta m_{ee}^2$  and  $\Delta m_{\mu\mu}^2$   
difference

Matter Effect

Atmospheric  
Accelerator

Effective  
Parameters

$$\Delta m_{ee}^2 = \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$$

$$\Delta m_{\mu\mu}^2 = \sin^2 \theta_{12} \Delta m_{31}^2 + \cos^2 \theta_{12} \Delta m_{32}^2 + \cos \delta \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23} \Delta m_{21}^2$$

$$|\Delta m_{ee}^2| - |\Delta m_{\mu\mu}^2| = \pm \Delta m_{21}^2 (\cos 2\theta_{12} - \cos \delta \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23})$$



Hyper-Kamiokande

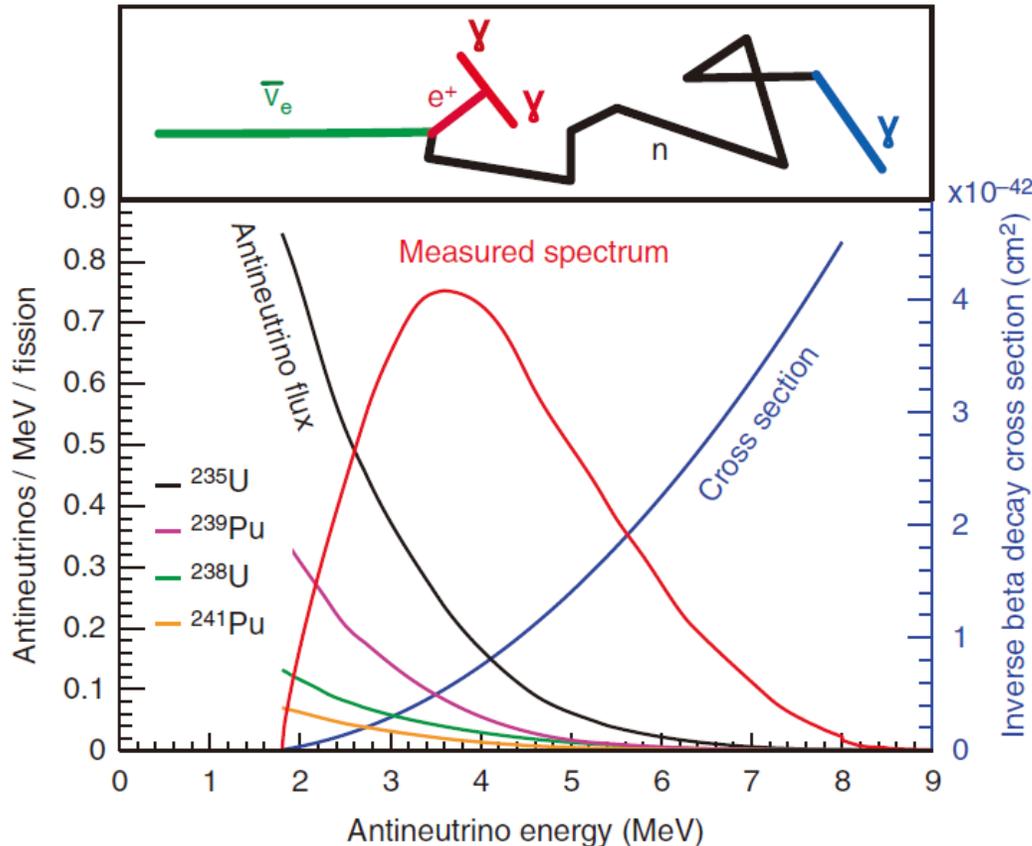


$\delta_{CP}$  : matter-antimatter asymmetry

Strategy: Compare  $P(\nu_\mu \rightarrow \nu_e)$  and  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$  at Acc.

# 中微子探测 - ~MeV能区的反应堆中微子

- Detection via Inverse- $\beta$  reaction  $\bar{\nu}_e + p \rightarrow e^+ + n$



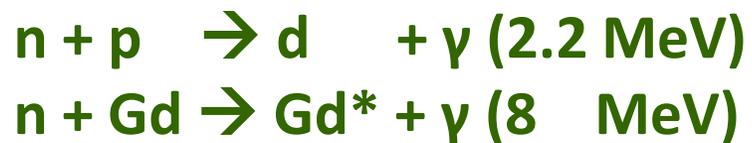
**Neutrino energy:**

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV

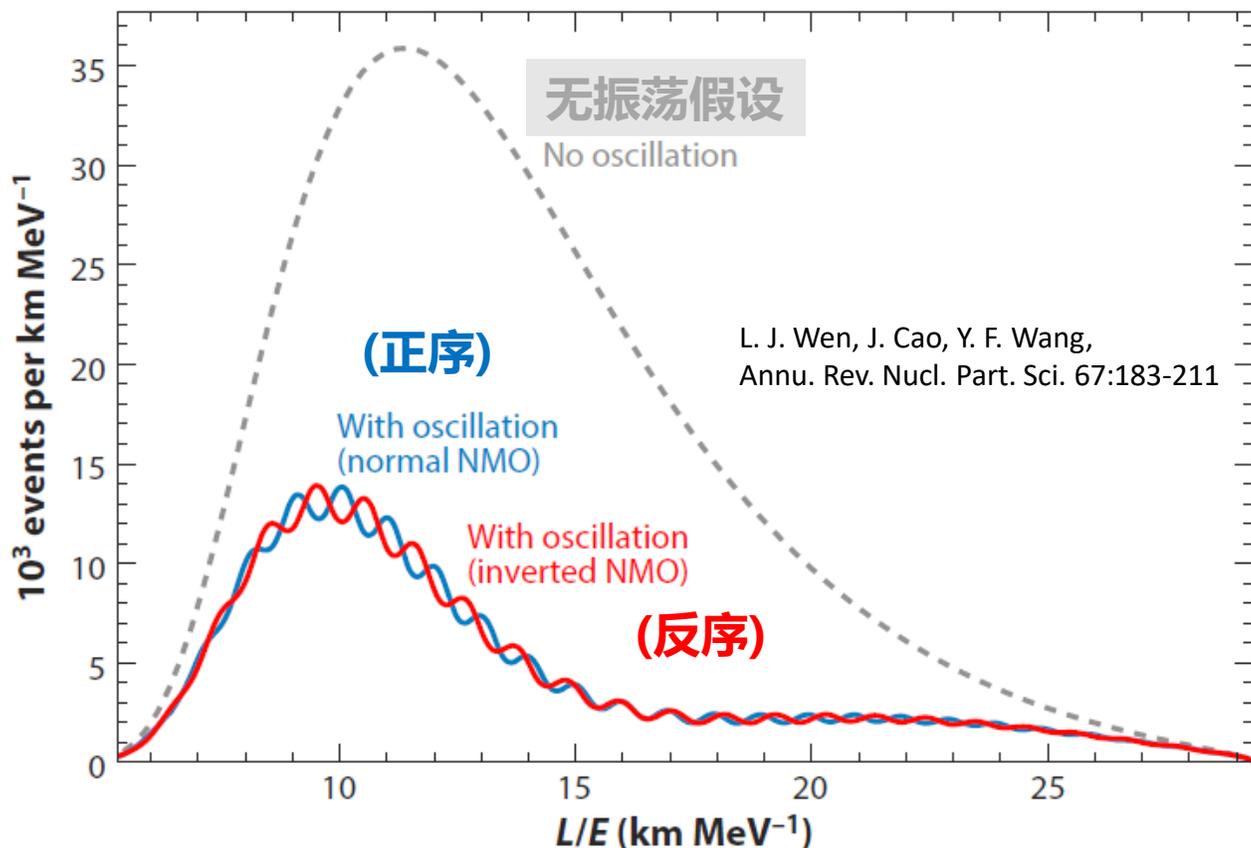
1.8 MeV: Threshold

$\tau \approx 180 \mu\text{s}$   
or  $28 \mu\text{s}$  (0.1% Gd)



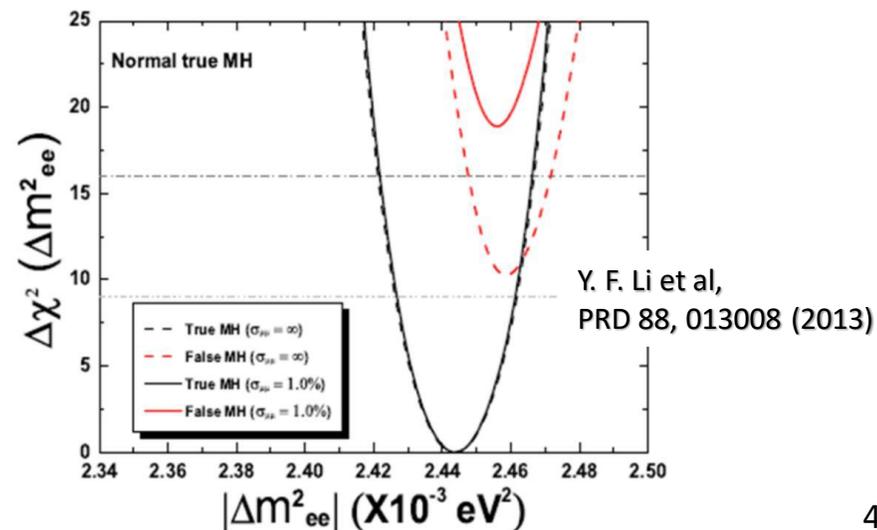
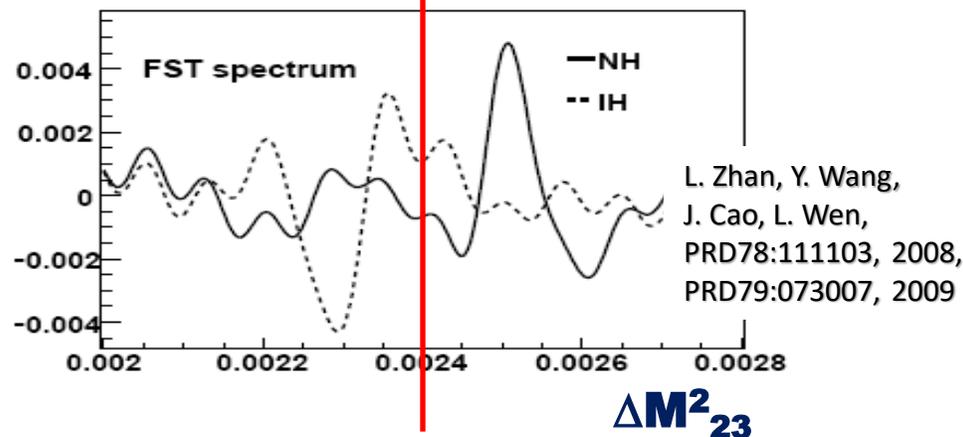
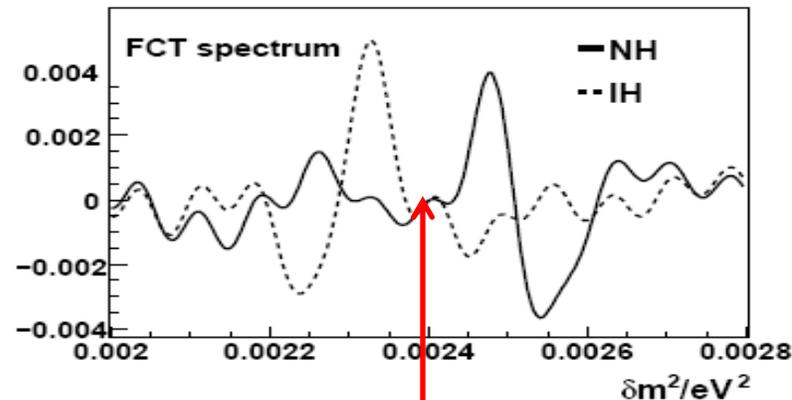
Neutrino Event: coincidence  
in **time, space and energy**

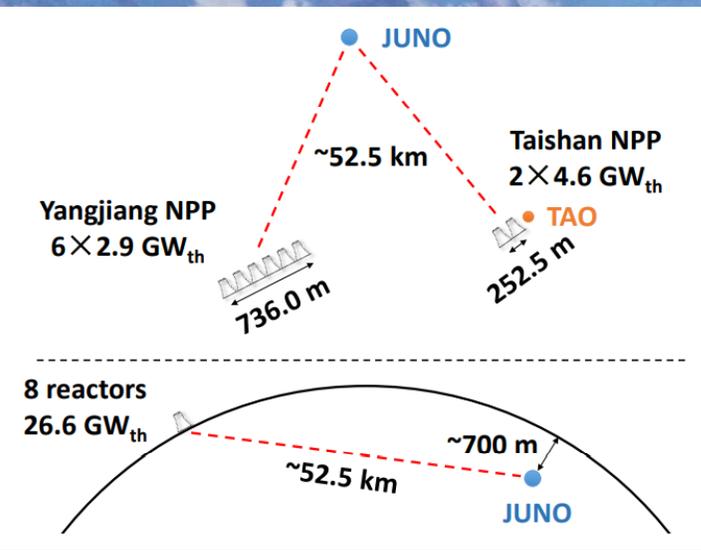
# 用反应堆确定质量顺序



质量顺序、振荡参数的信息隐藏于反应堆中微子的精细振荡能谱中

- 2008年探索可行性 (大亚湾二期)
- 2013年立项 (江门中微子实验 -- JUNO)





# 江门中微子实验



竖井隧道: 563 m

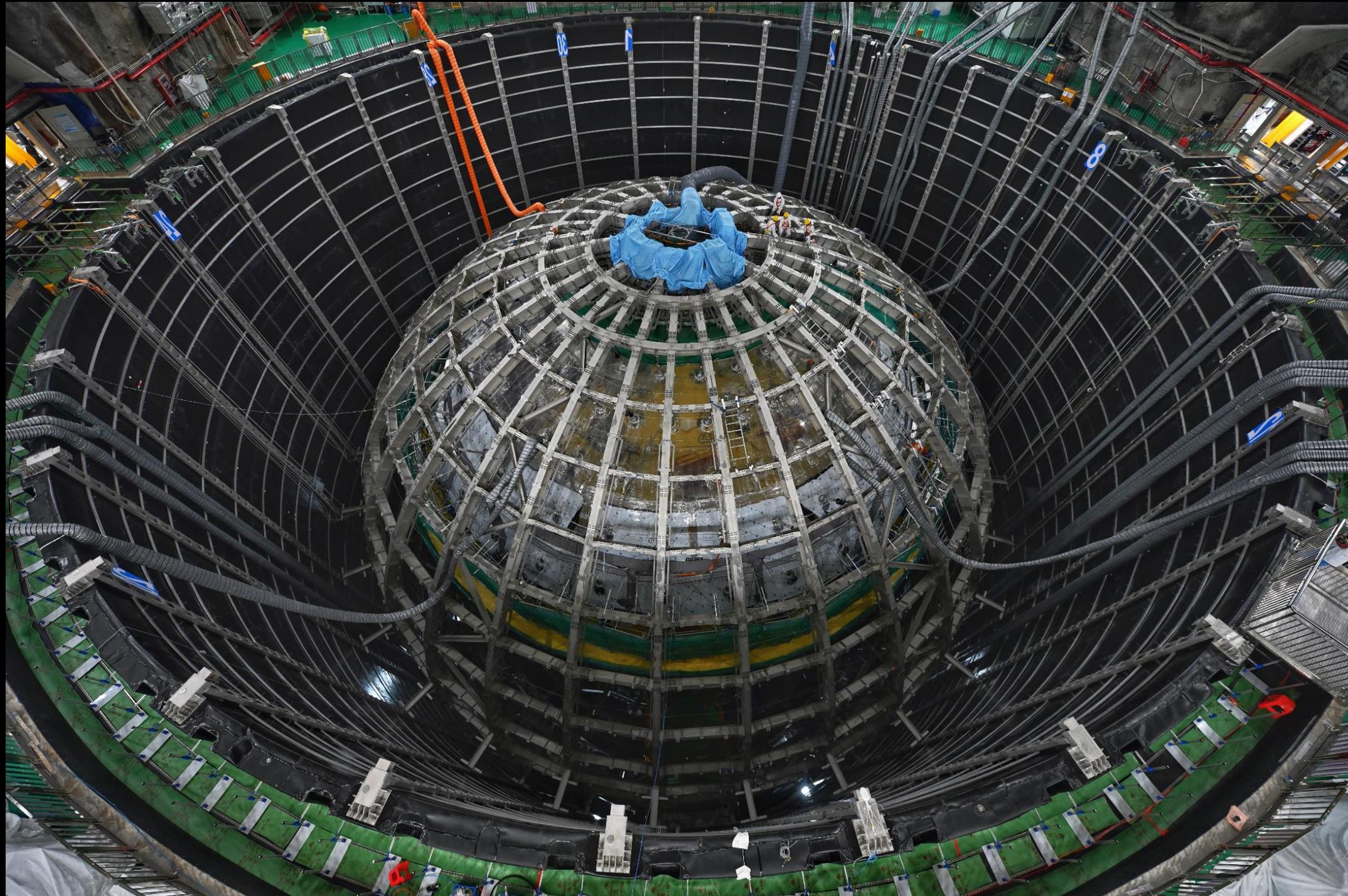
山体覆盖  
~650 m  
(1800 m.w.e.)

斜井隧道: 1265 m @ 坡度42%



土建于2021年12月完工





Photos By  
刘悦湘

2023.3



Photos By  
刘悦湘

23.6.1

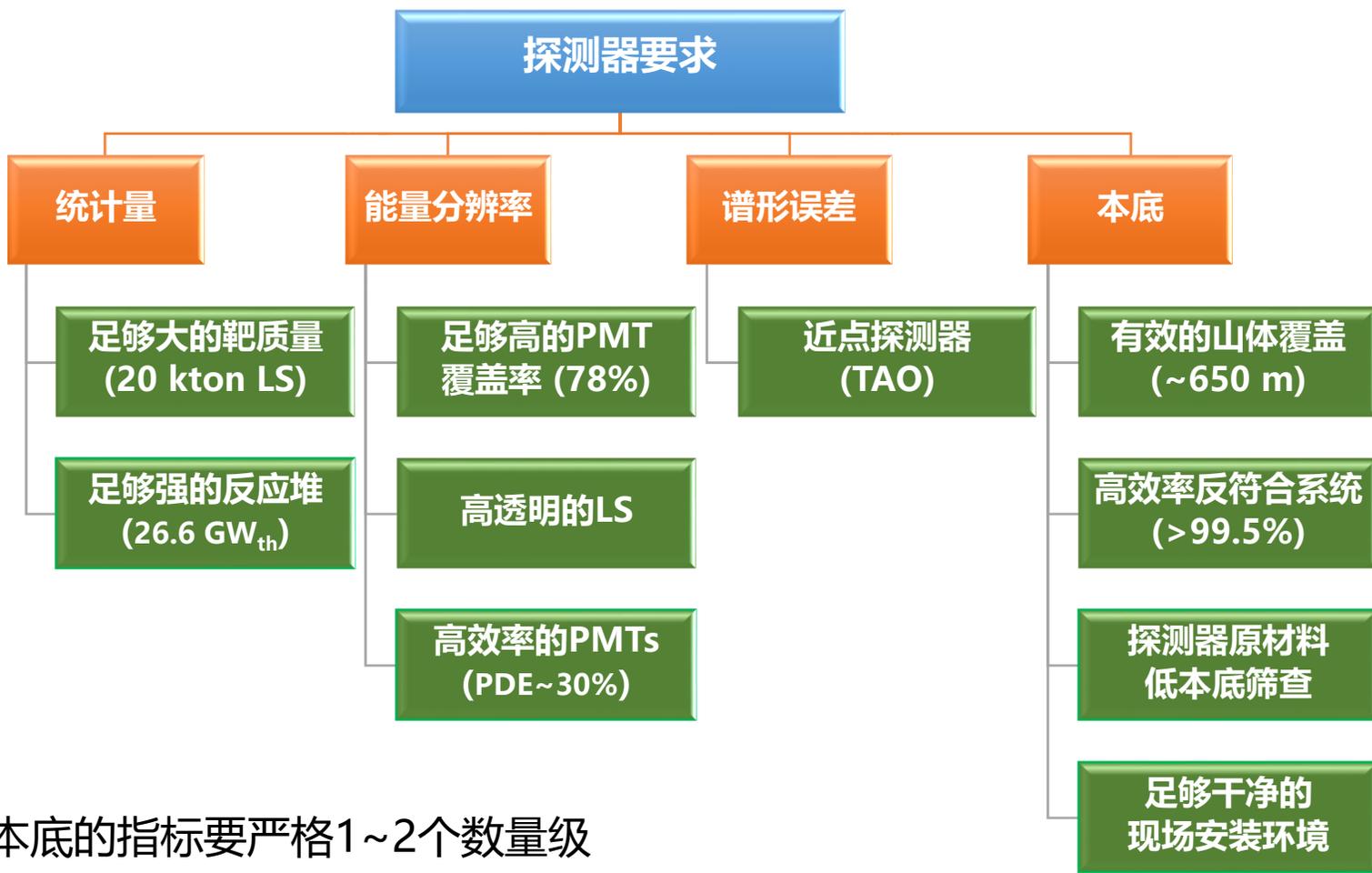
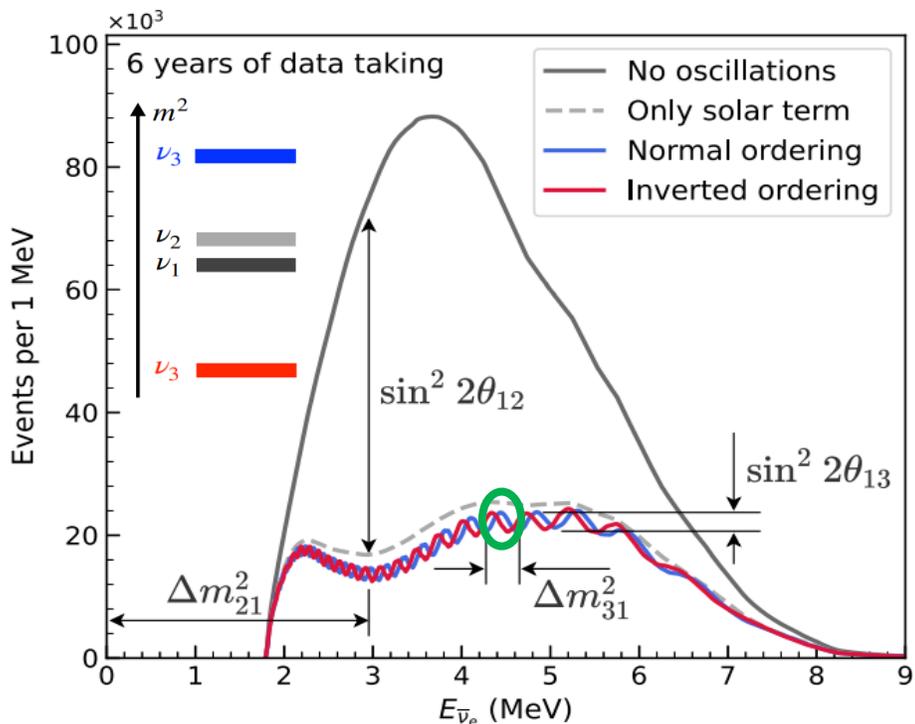


Photos By  
刘悦湘

23.6.14

# 物理目标驱动的探测器要求

例子：中微子振荡参数的精确测量



对于太阳中微子：液闪内禀天然放射性本底的指标要严格1~2个数量级

# 江门中微子探测器

## 中心探测器

刻度系统

(世界上最大)

Φ35.4m 有机玻璃球

Φ41.1m 不锈钢网架

(透明度最好)

2万吨液闪 ( $A_L > 20m$ )

(国产PMT探测效率世界最高)

17612个20吋PMTs

25600个3吋PMTs

(总光学覆盖率: 77.9%)

## 反符合探测器

Moun径迹探测器

3.5万吨高纯水 ( $A_L > 40m$ )

Tyvek遮光膜

地磁屏蔽线圈

2400个20吋PMTs

■ 世界上最大的液体闪烁探测器

■ KamLAND x 20,  
Borexino x 40

■ 性能最好

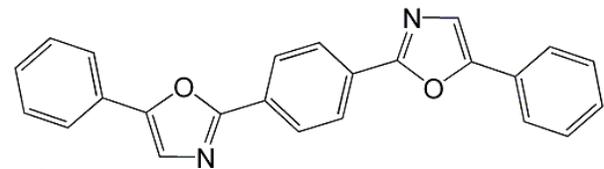
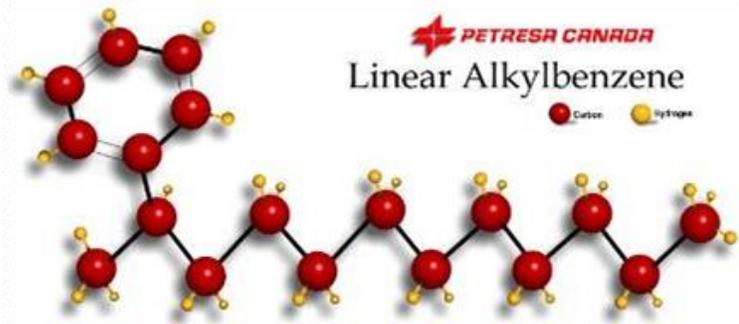
■ 光产额 Borexino x 2,  
KamLAND x 5

科学的发现首先  
需要技术的领先

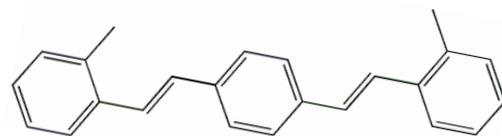
- 13层大楼的规模, 毫米的精度
- 化工规模, 超过半导体要求的纯度
- 普通的商业电子器件, 航天的可靠性
- 几万立方规模, 单光子的灵敏
- 灰尘总量 < 0.01 克/2万吨
- 总空气残留量 < 1 m<sup>3</sup>

# 液体闪烁体

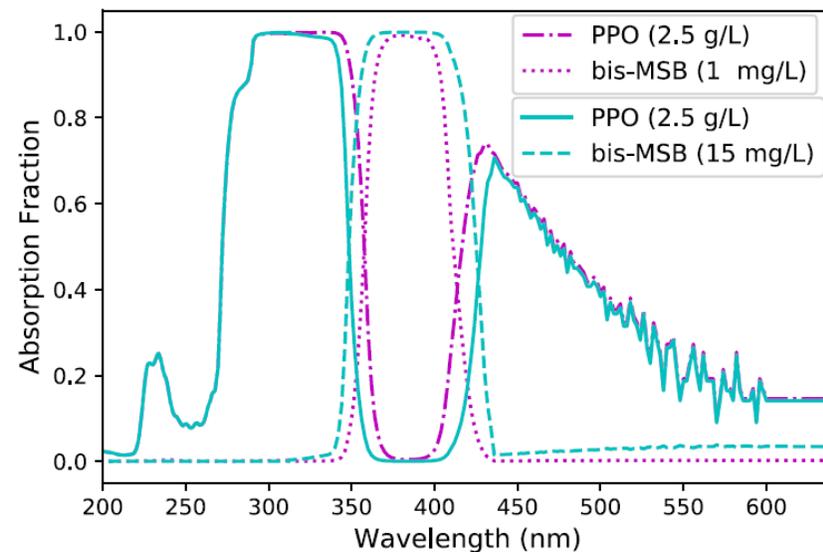
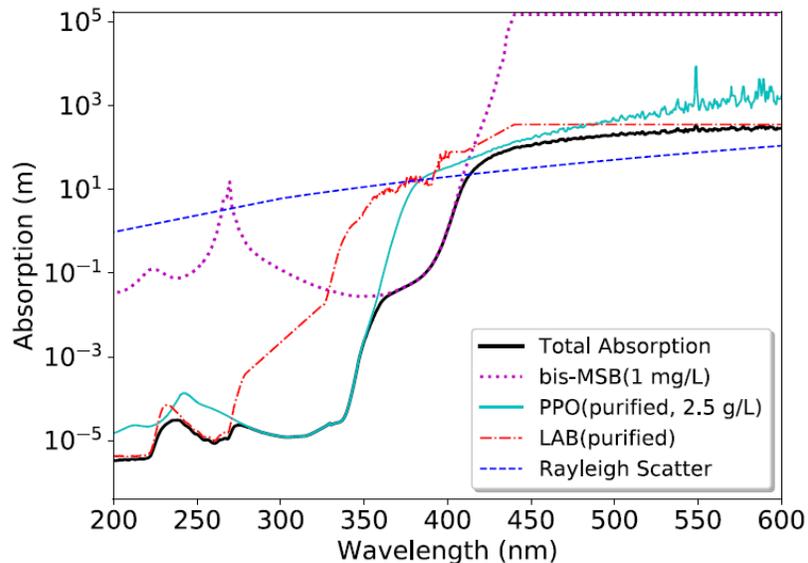
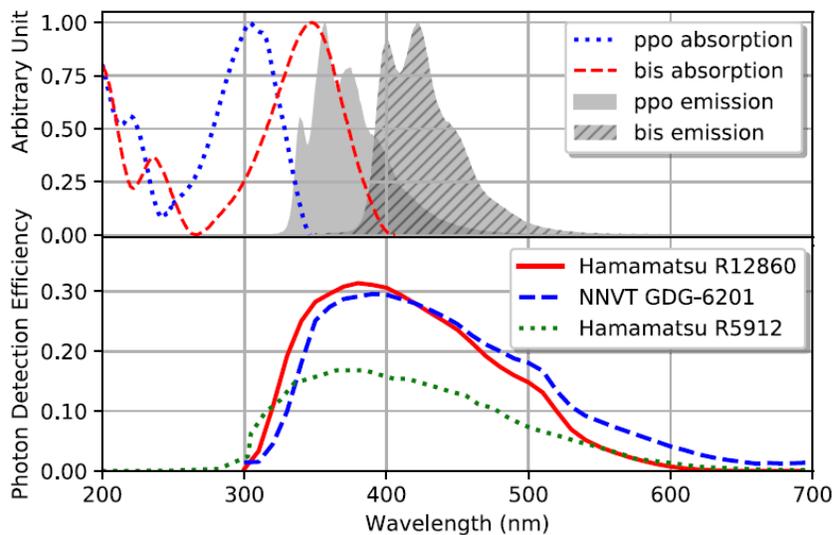
- 吸收谱、发射谱
- 透明度、散射长度
- 吸收重发射
- 纯化技术
- 荧光发光时间 → 粒子鉴别 (solar-ν, CCSNe, DSNB, ...)
- ...



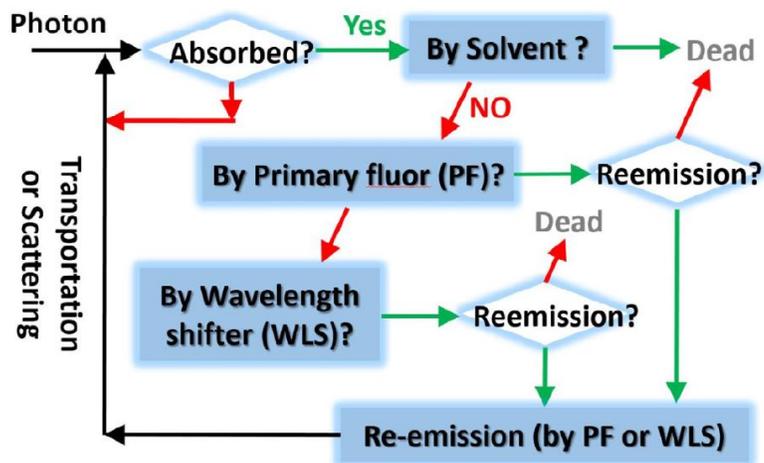
**PPO**  
2,5-二苯基恶唑  
(第一发光物质)



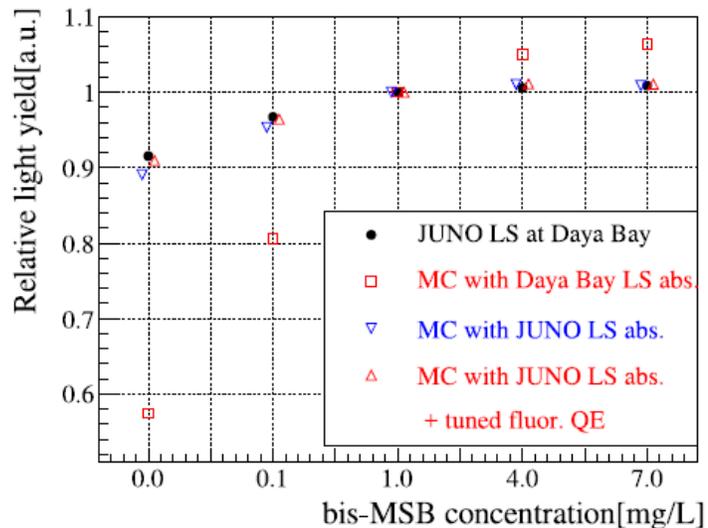
**bis-MSB**  
对-双-(σ-甲基苯乙烯基)苯  
(第二发光物质)



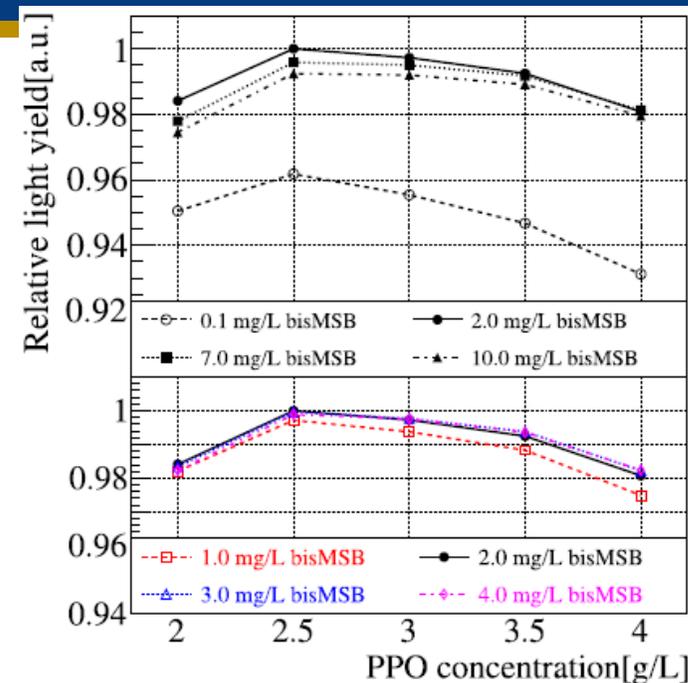
# 理解光学过程、构建光学模型



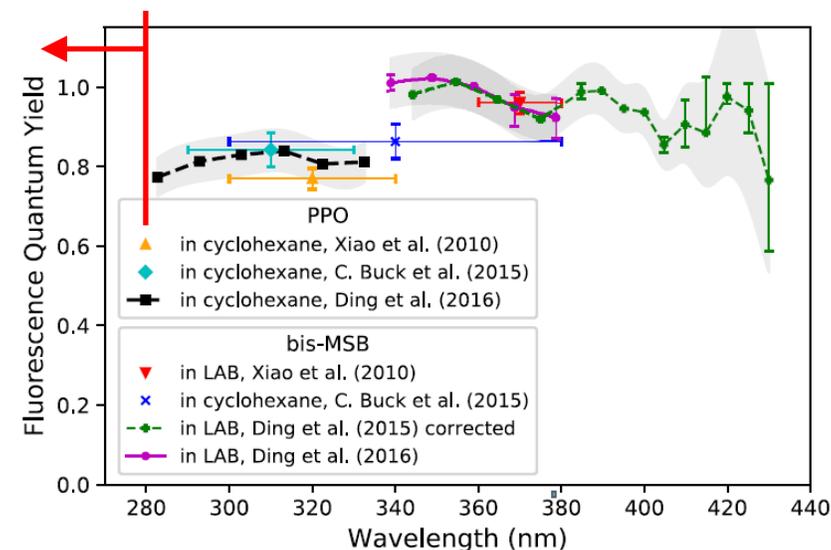
*New Optical Model: NIMA 967 (2020) 163860*



*JUNO LS optimization: NIMA 988 (2021) 164823*



- Developed a LS optical model to handle the competitive photon absorption and re-emission processes of the LS components.
- Validated with JUNO LS test data using one DYB detector, and optimized JUNO LS composition: 2.5 g/L PPO, (1-4) mg/L bis-MSB
- Future's critical task to understand Cherenkov's impact on resolution
  - Refractive indices in VUV region
  - Relative reemission probability of fluors in VUV region
  - Secondary electrons (i.e.,  $\delta e^-$ ) fluctuation

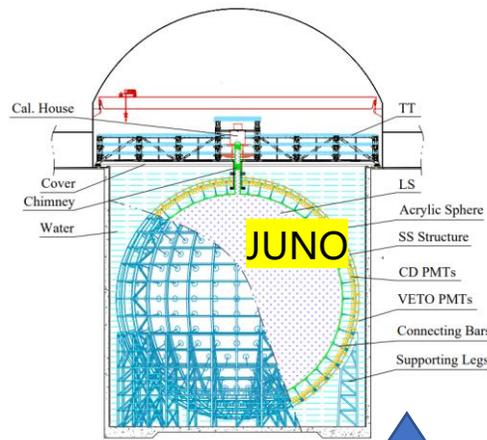


# 液体闪烁体系统

	江门实验 (2万吨)	对比大亚湾 (200吨)
U/Th含量	$10^{-17}$ g/g	低1000倍以上
透明度	>20 m	提高>30%

## • 极低本底挑战:

- 日本KamLAND 1000吨, 意大利Borexino 500吨, 加拿大SNO+ 1000吨, 第一次灌装都未达标, 重新进行了纯化
- 液闪纯化、有机玻璃板表面处理、探测器和环境的洁净、灌装方案



5000 m<sup>3</sup> LAB tank



Al<sub>2</sub>O<sub>3</sub> 吸附系统



混制系统



蒸馏系统

正在单系统调试, 准备全系统联调



OSIRIS系统



气体剥离系统



水萃取系统

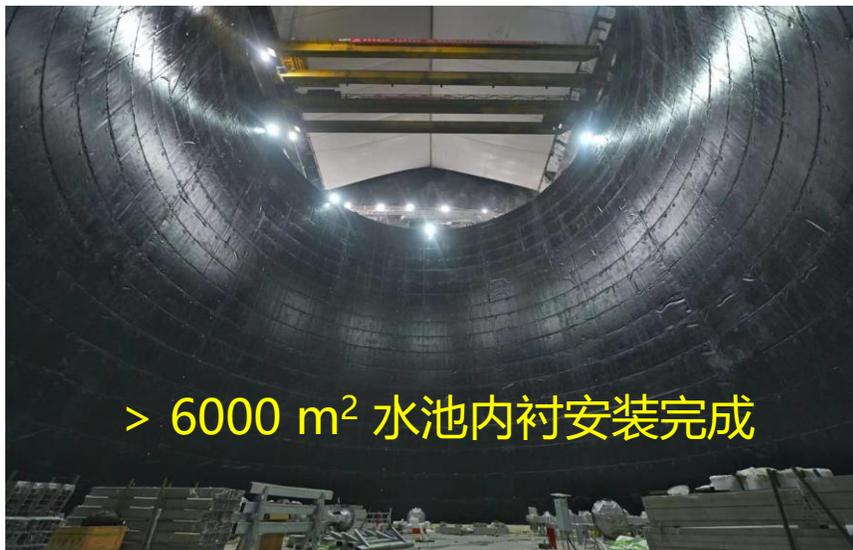
15%

85%

地上  
地下

# 反符合探测器 — 水切伦科夫探测器

实验厅~650 m 岩石覆盖 (1800 m.w.e.) → 中心探测器  $R_\mu = 4 \text{ Hz}$ ,  $\langle E_\mu \rangle = 207 \text{ GeV}$



主体结构: 水池+100t/h 超纯水系统+顶部及侧壁机械结构+抗磁线圈

- 探测器使用多区域触发, 宇宙线缪子探测效率99.5%
- 地磁屏蔽线圈系统: 中心探测器PMT位置处剩磁<0.05 G
- 水池内衬: 5mm厚HDPE 膜, 防水和防止外部的氡渗透
- 水循环净化系统:
  - 流量100吨/小时。中心探测器周围温度控制 $21^\circ\text{C} \pm 1^\circ\text{C}$
  - 研发了微气泡除氡技术, 除镭技术 → 降低本底20倍 ( $<10\text{mBq/m}^3$ )。相比大亚湾水中氡含量, 压低了1000倍



# 为什么要反符合? -- 去除宇宙线本底

- JUNO overburden: 650 m overburden → larger yield of cosmogenic isotopes from  $^{12}\text{C}$ , compared to Kamioka and SNOLab

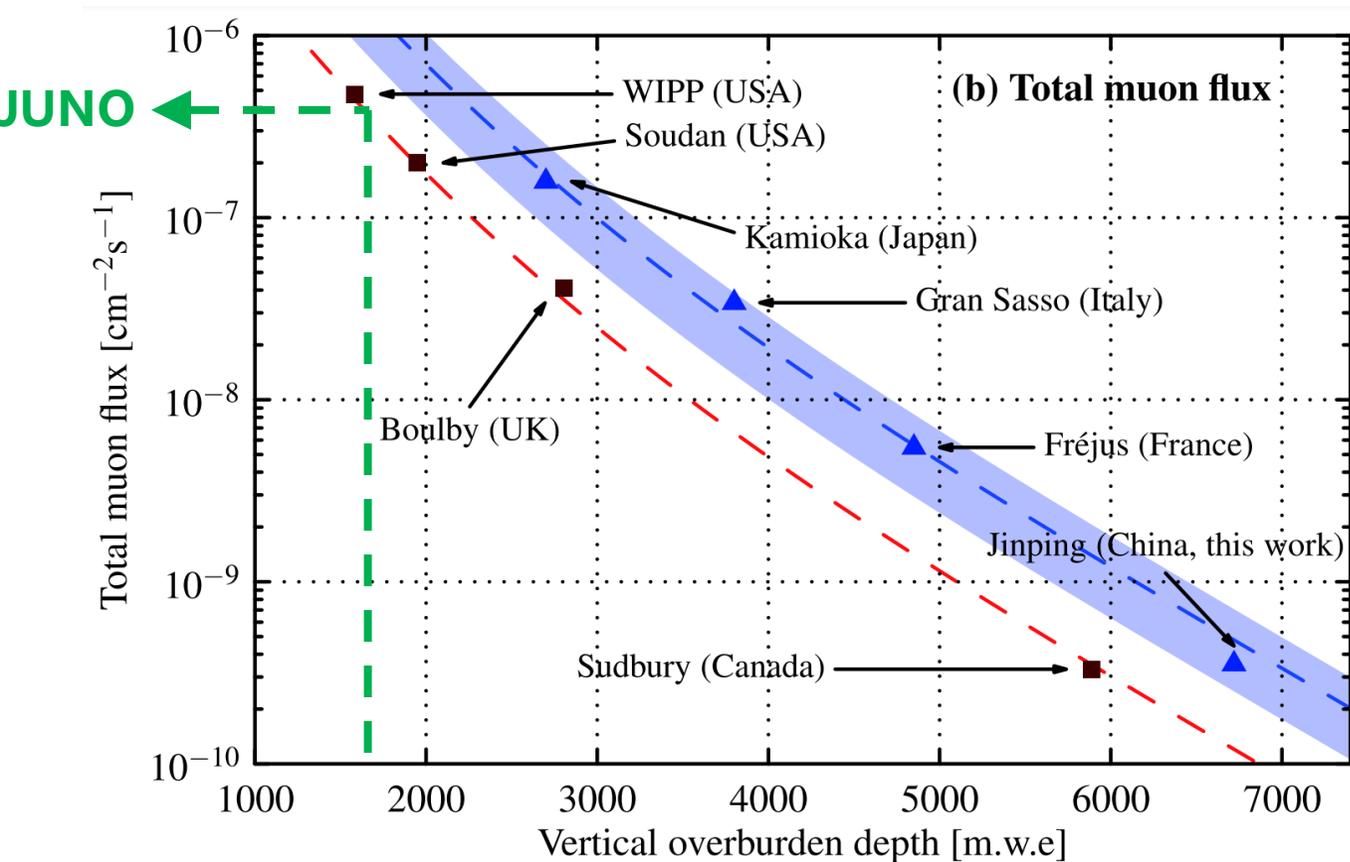
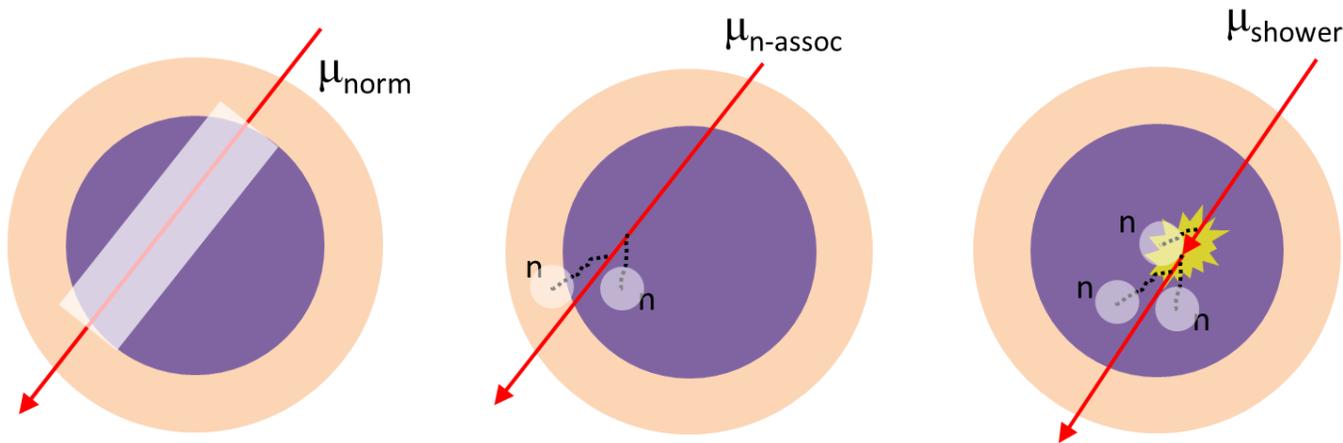


Table A9. The estimated rates for cosmogenic isotopes in JUNO LS by FLUKA simulation, in which the oxygen isotopes are neglected. The decay modes and Q values are from TUNL Nuclear Data Group [475].

Isotopes	Q (MeV)	$T_{1/2}$	Rate (per day)
$^3\text{H}$	0.0186 ( $\beta^-$ )	12.31 year	$1.14 \times 10^4$
$^6\text{He}$	3.508 ( $\beta^-$ )	0.807 s	544
$^7\text{Be}$	$Q_{EC} = 0.862$ (10.4% $\gamma$ , $E_\gamma = 0.478$ )	53.22 d	5438
$^8\text{He}$	10.66 ( $\beta^- \gamma$ : 84%), 8.63 ( $\beta^- n$ : 16%)	0.119 s	11
$^8\text{Li}$	16.0 ( $\beta^-$ )	0.839 s	938
$^8\text{B}$	16.6 ( $\beta^+$ )	0.770 s	225
$^9\text{Li}$	13.6 ( $\beta^-$ : 49%), 11.94 ( $\beta^- n$ : 51%)	0.178 s	94
$^9\text{C}$	15.47 ( $\beta^+ p$ : 61.6%, $\beta^+ \alpha$ : 38.4%)	0.126 s	31
$^{10}\text{Be}$	0.556 ( $\beta^-$ )	1.51e6 year	1419
$^{10}\text{C}$	2.626 ( $\beta^+ \gamma$ )	19.29 s	482
$^{11}\text{Li}$	20.55 ( $\beta^- n$ : 83%, $\beta^- 2n$ : 4.1%)	0.00875 s	0.06
$^{11}\text{Be}$	11.51 ( $\beta^- \gamma$ : 96.9%), 2.85 ( $\beta^- \alpha$ : 3.1%)	13.76 s	24
$^{11}\text{C}$	0.960 ( $\beta^+$ )	20.36 min	$1.62 \times 10^4$
$^{12}\text{Be}$	11.708 ( $\beta^- \gamma$ , $\beta^- n$ : 0.5%)	0.0215 s	0.45
$^{12}\text{B}$	13.37 ( $\beta^- \gamma$ )	0.0202 s	966
$^{12}\text{N}$	16.316 ( $\beta^+ \gamma$ )	0.0110 s	17
$^{13}\text{B}$	13.437 ( $\beta^- \gamma$ )	0.0174 s	12
$^{13}\text{N}$	1.198 ( $\beta^+$ )	9.965 min	19
$^{14}\text{B}$	20.644 ( $\beta^- \gamma$ , $\beta^- n$ : 6.1%)	0.0126 s	0.021
$^{14}\text{C}$	0.156 ( $\beta^-$ )	5730 year	132
$^{15}\text{C}$	9.772 ( $\beta^-$ )	2.449 s	0.6
$^{16}\text{C}$	8.010 ( $\beta^- n$ : 99%)	0.747 s	0.012
$^{16}\text{N}$	10.42 ( $\beta^- \gamma$ )	7.130 s	13
$^{17}\text{N}$	8.680 ( $\beta^- \gamma$ : 5%), 4.536 ( $\beta^- n$ : 95%)	4.173 s	0.42
$^{18}\text{N}$	13.896 ( $\beta^- \gamma$ : 93%), 5.851 ( $\beta^- n$ : 7%)	0.620 s	0.009
Neutron			155 000

# 为什么要反符合? -- 去除宇宙线本底

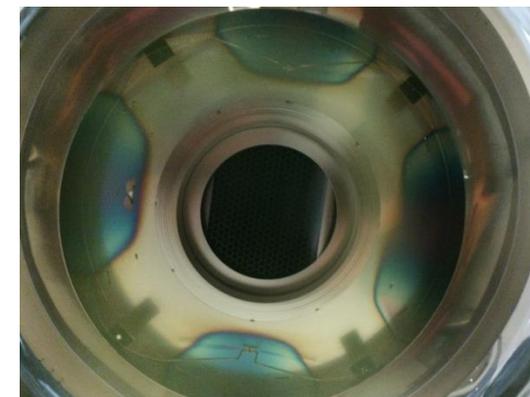
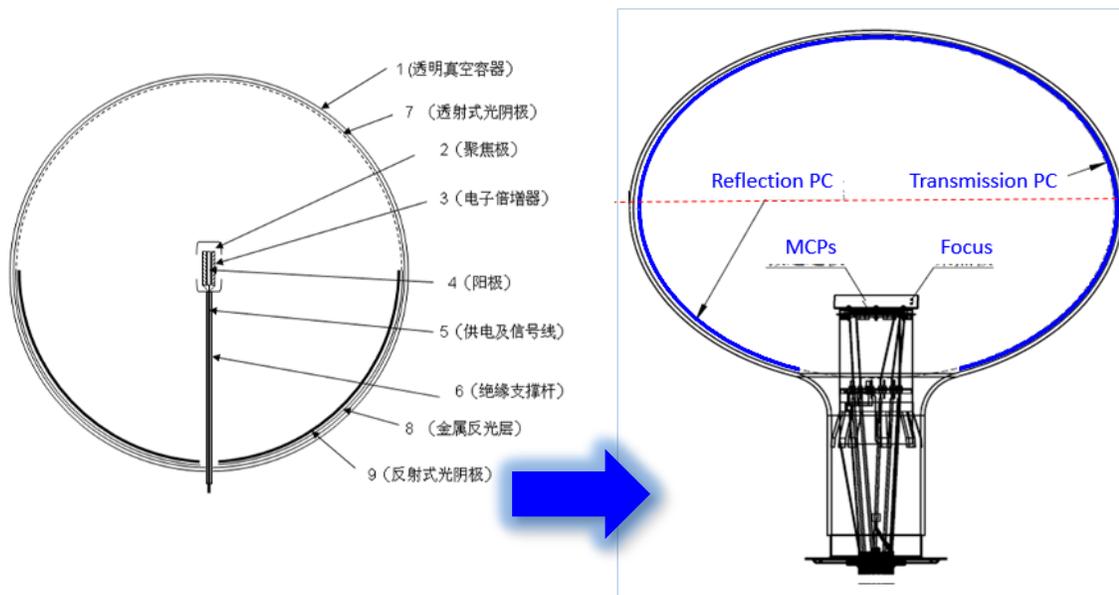
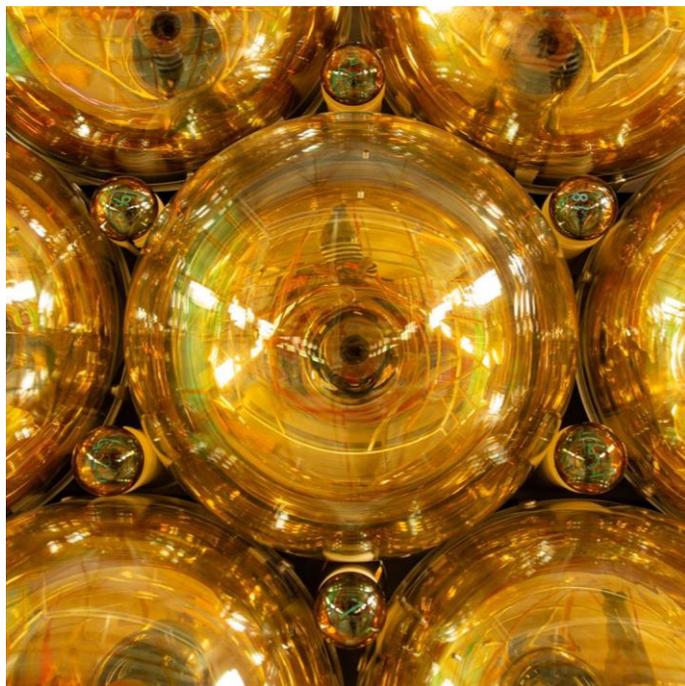
- JUNO overburden: 650 m overburden → larger yield of cosmogenic isotopes from  $^{12}\text{C}$ , compared to Kamioka and SNOLab
- Excellent muon tracking → advanced muon veto strategy to reject the cosmogenic backgrounds



Refs: arXiv:2006.11760, Chin. Phys. C 45 (2021) 023004  
arXiv:1610.07143, Chin. Phys. C 41 (2017) 053001

Cosmogenic Isotopes	Background Index unit: $\text{ROI}^{-1} (\text{ton } ^{136}\text{Xe})^{-1} \text{yr}^{-1}$	
	No veto	w/ veto
$^{10}\text{C}$	16.4	0.053
$^6\text{He}$	4.9	0.063
$^8\text{Li}$	1.5	0.016
$^{12}\text{B}$	1.9	$3.8\text{e-}4$
$^{137}\text{Xe}$	2.3	0.07
Others ( $Z \leq 6$ )	0.51	0.01
<b>Total</b>		<b>2.7</b>

# 光电倍增管- MCP-PMT

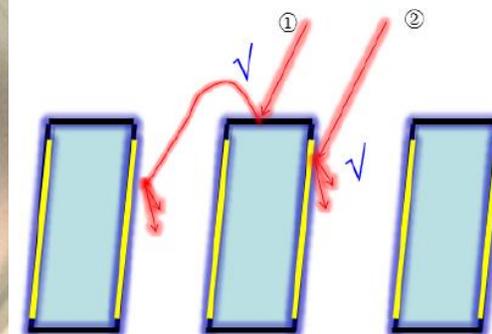
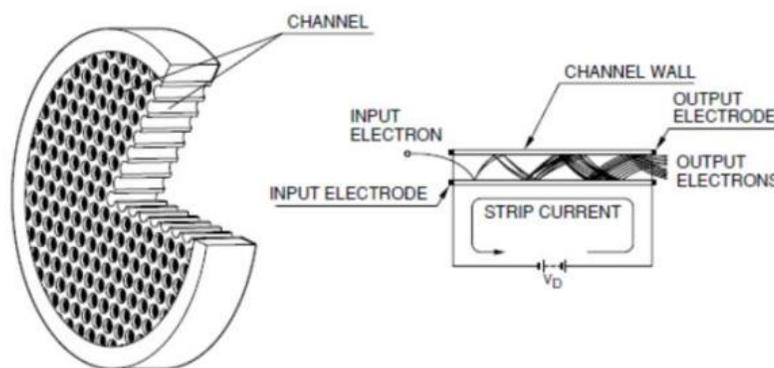


• 20吋PMT: ~20,000

• 3吋PMT: ~25,600

PMT间隙 3 mm →

安装精度要求: < 1 mm



# A quantitative approach to select PMTs for large detectors

**Table 2**

The typical specifications of the 20-inch MCP-PMT and dynode-PMT in 2015. The typical values, as well as the lower or upper limits, are listed.

Characteristics	MCP-PMT	Dynode-PMT (R12860)
Detection Efficiency <sup>a</sup> [%]	27, >24	27, >24
Dark noise rate <sup>b</sup> [kHz]	20, <30	10, <50
	<sup>238</sup> U : <50	<sup>238</sup> U : <400
Radioactivity of glass [ppb]	<sup>232</sup> Th : <50	<sup>232</sup> Th : <400
	<sup>40</sup> K : <20	<sup>40</sup> K : <40
Transit Time Spread <sup>c</sup> (FWHM) [ns]	12, <15	2.7, <3.5
Pre-pulsing/After-pulsing [%]	<1 / <2	<1.5 / <15
Rise time/Fall time <sup>d</sup> [ns]	2 / 12	5 / 9
Peak-to-Valley ratio	3.5, >2.8	3, >2.5

<sup>a</sup>The quoted detection efficiency refers to 420 nm photons.

<sup>b</sup>Measured with a threshold of 1/4 p.e.

<sup>c</sup>Measured on the top point of PMT.

<sup>d</sup>The quoted rise and fall time refers to single photoelectron waveforms.

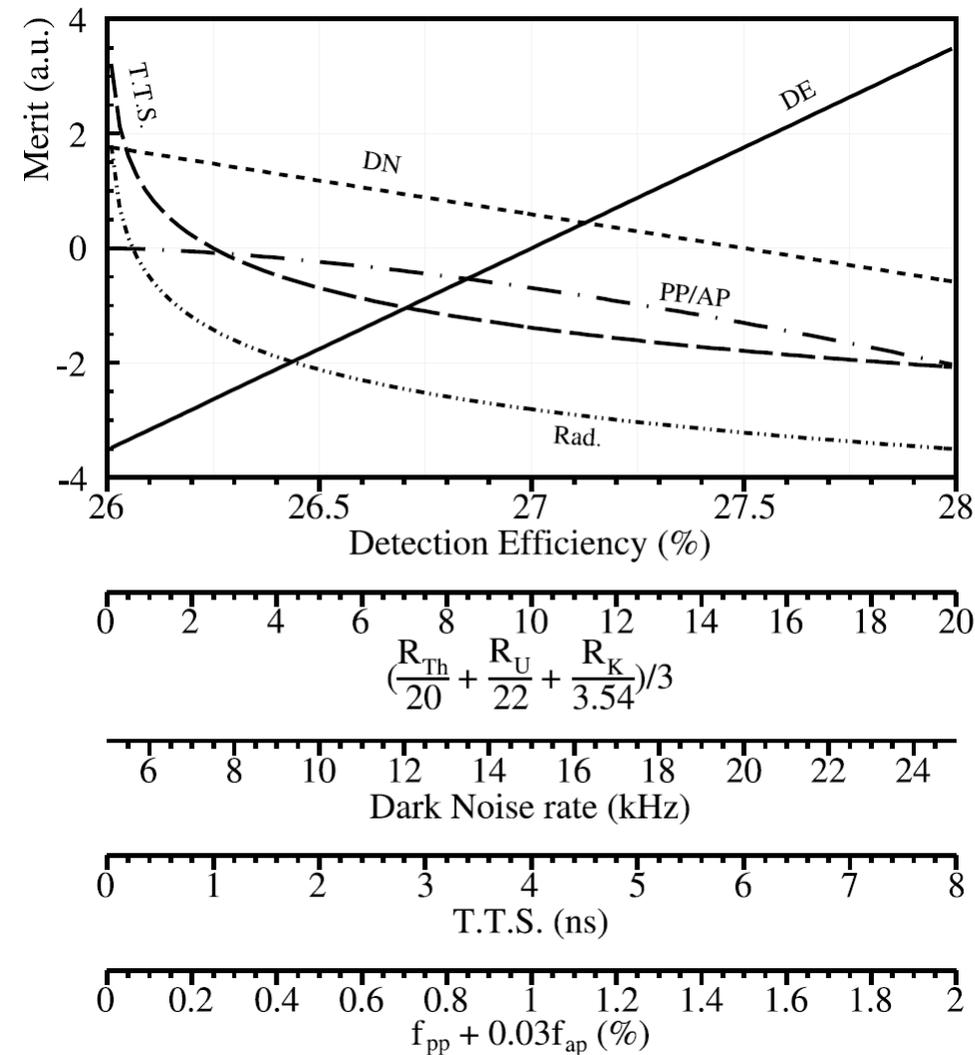
## 构造定量标准:

在物理灵敏度目标不变的情况下, PMT 参数变化导致能量分辨率变化、本底变化  
 → 液闪靶质量变化 → 实验造价变化

$$S = \sum (M_i^{phys} + M_i^{price} + M_i^{committee}) \cdot S_i \cdot N_i / 20,$$

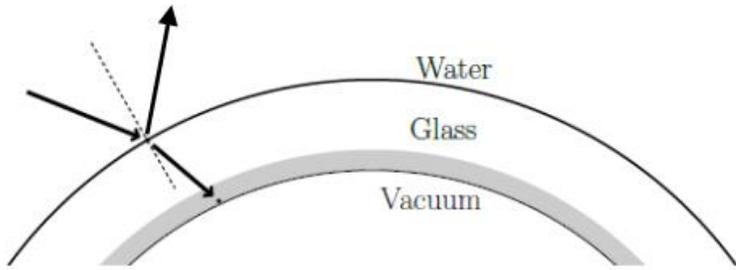
$$M_i^{phys} = M_{DE} + M_{DN} + M_{TTS} + M_{Rad} + M_{PA}$$

$$M_i^{price} = 30 \times (2.5 - M_i),$$



L.J. Wen, M. He, Y.F. Wang et al. NIM A 947 (2019) 162766

# A new optical model for photomultiplier tubes

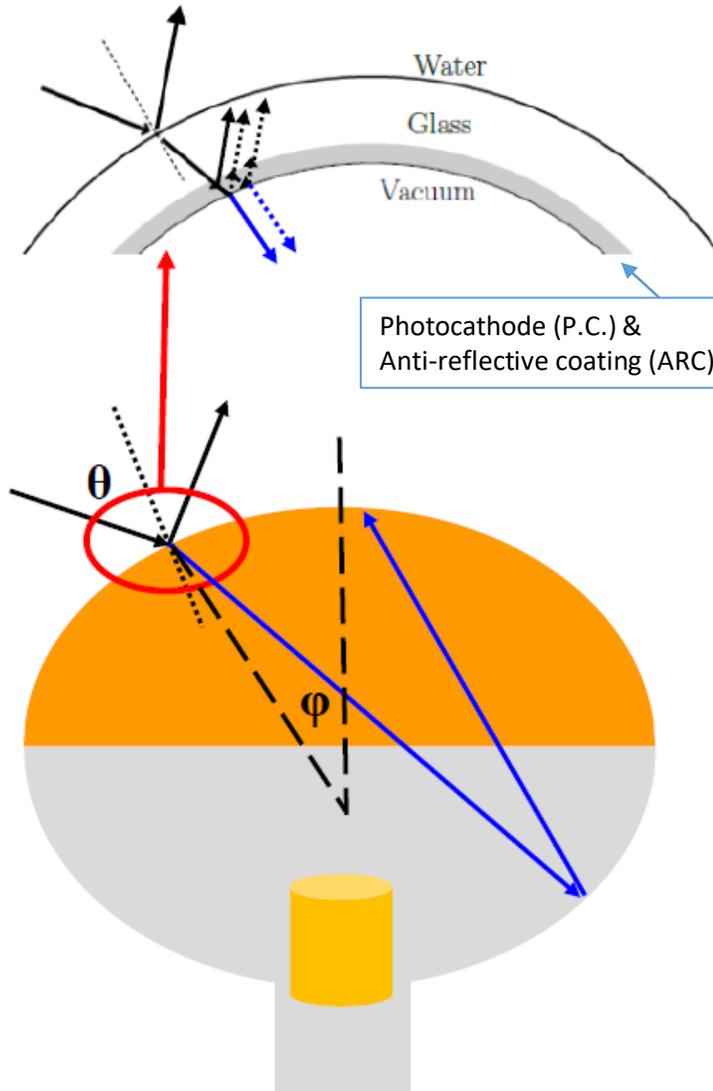


## Old PMT optical model

- Photons hit on P. C. are 100% absorbed, then QE and CE are applied to convert photons to photoelectrons
- Used as default in DYB and JUNO

Absolute light yield in JUNO MC is taken from MC/data tuning at DYB

DYB and JUNO use very different PMTs → deep understanding of PMT optical responses is critical



A new PMT model is developed to take all optical processes into account

## • Reflections

- Surface of glass blub
- Interfaces of glass, anti-reflective coating (ARC), photocathode (P.C.) and vacuum

## • Absorption in photocathode

- Photoelectron conversion, collection

## • Transmission

- Photon propagation inside PMT

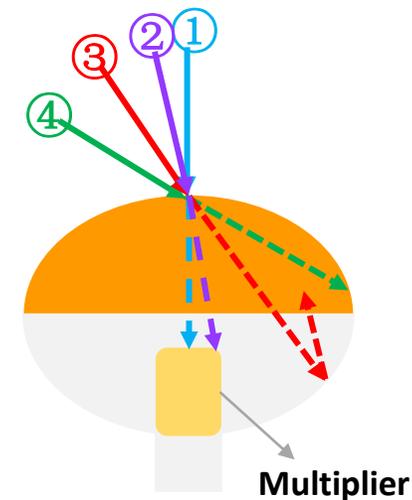
## Goal:

Re-evaluate the light yield extrapolation from DYB to JUNO

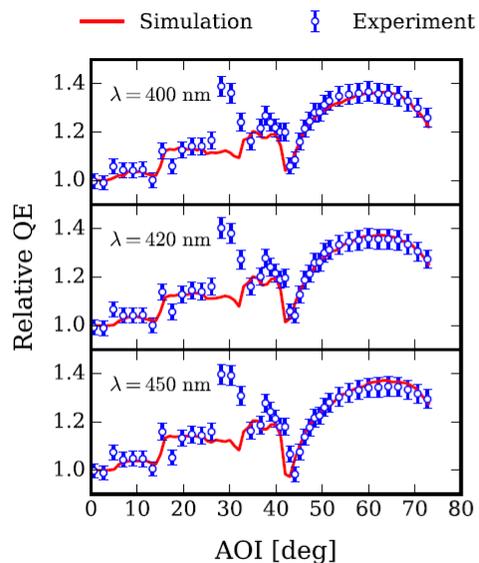
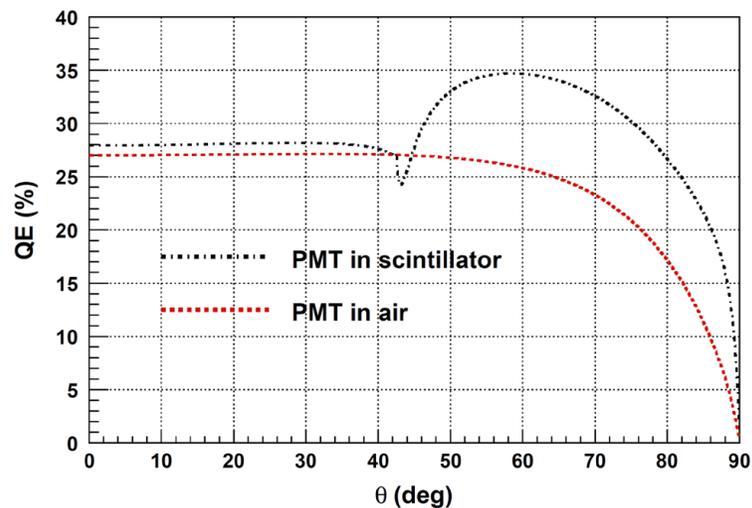
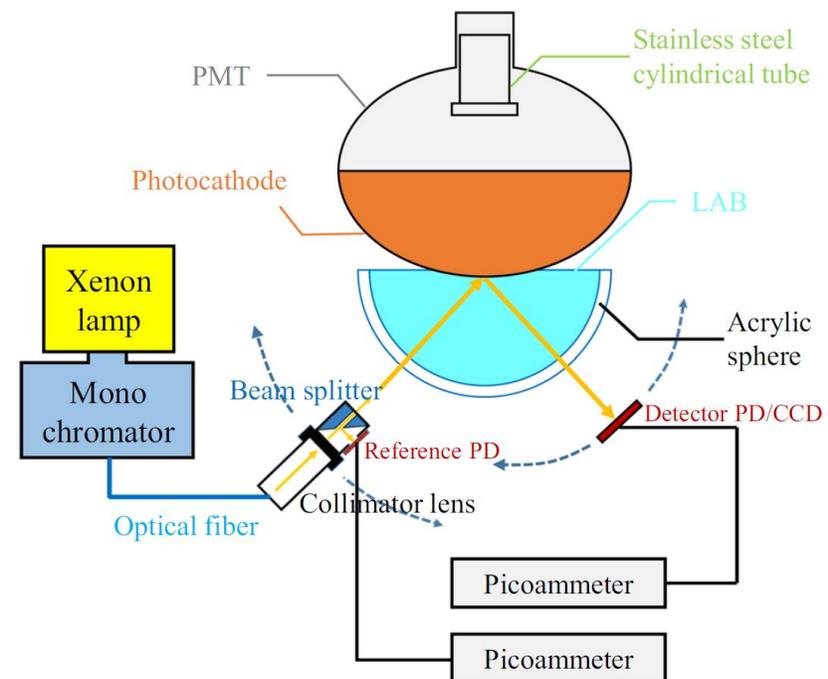
# A new optical model for photomultiplier tubes

Critical optical parameters have been measured

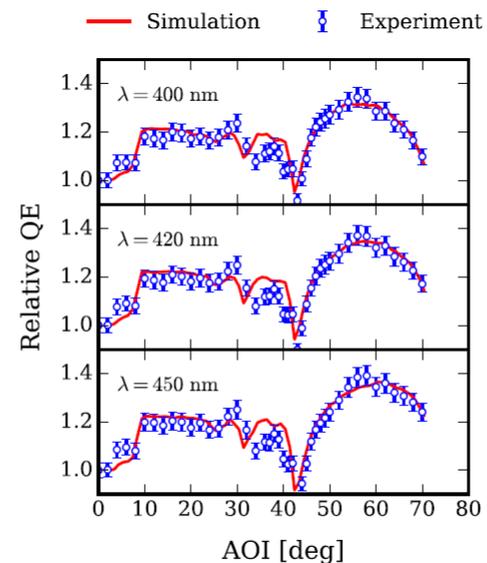
- Reflectivity vs. angle of incident (AOI), to extract
  - Refractive indices and Thicknesses of ARC and P.C.
- Quantum efficiency vs. AOI, to evaluate
  - Impacts of photon transmission inside PMT



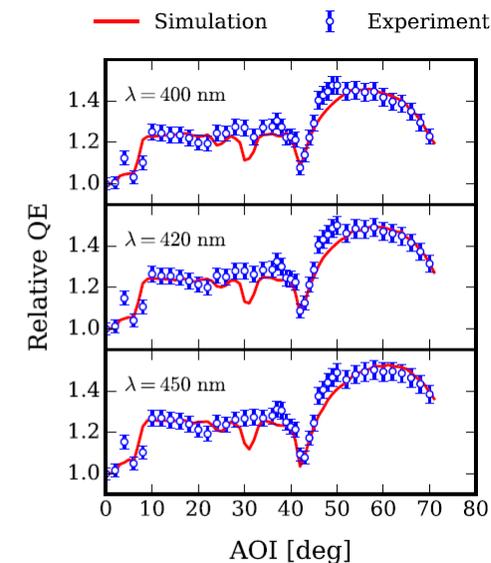
Y. G. Wang et al. *Eur. Phys. J. C* (2022) 82:329



(a) Hamamatsu PMT



(b) NNVT high-QE PMT



(c) NNVT normal-QE PMT

# 深刻解能量分辨率

Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	JHEP03(2021)004
Photon Detection Efficiency (27%→30%)	+11% ↑		arXiv: 2205.08629
New Central Detector Geometries	+3% ↑	2.9% @ 1MeV	
New PMT Optical Model	+8% ↑		EPJC 82 329 (2022)

Positron energy resolution is understood:

$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2}$$

• Photon statistics

• Scintillation quenching effect

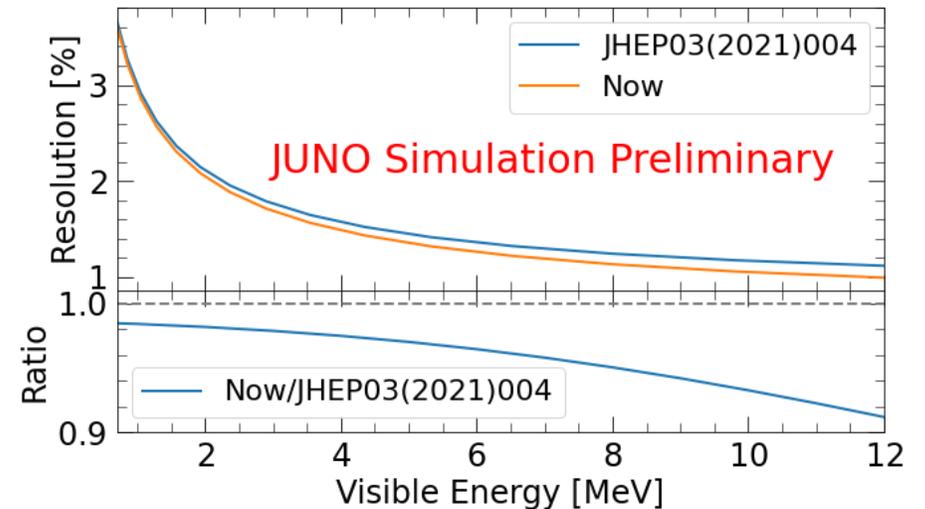
- LS Birks constant from table-top measurements

• Cherenkov radiation

- Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity

• Detector uniformity and reconstruction

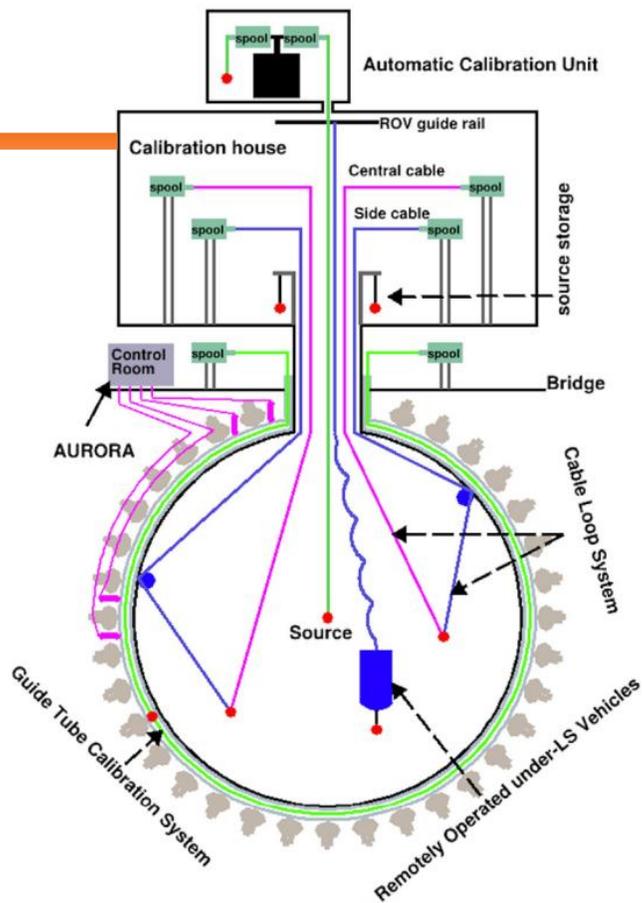
• Annihilation-induced  $\gamma$ s  
• Dark noise



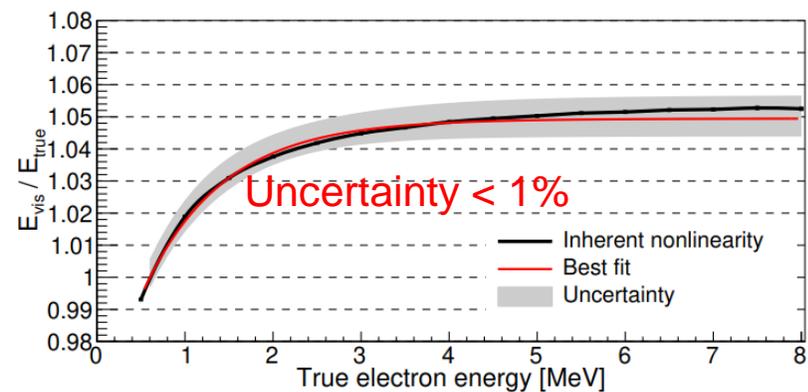
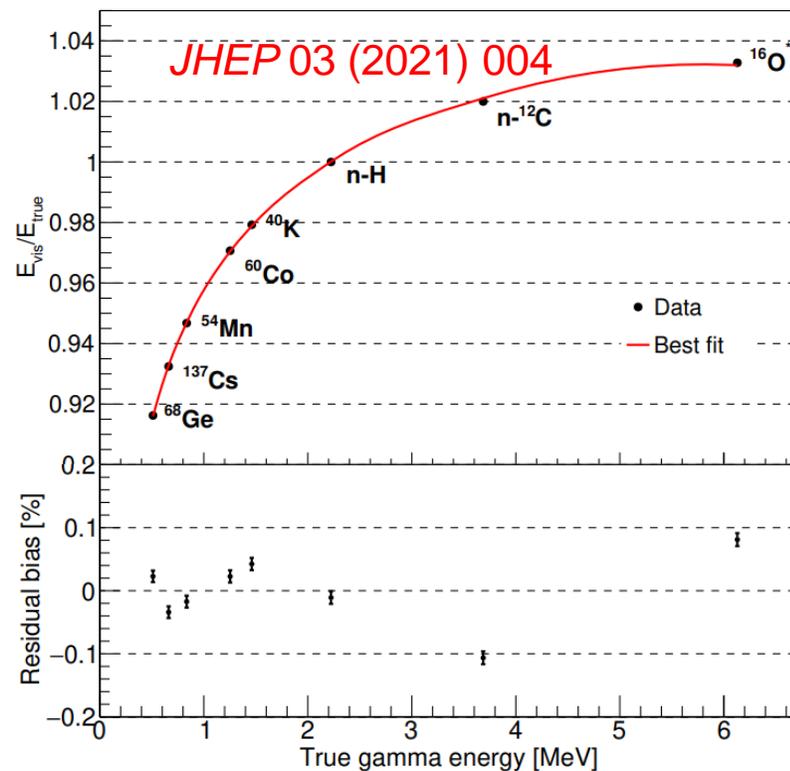
# 探测器刻度系统

1D、2D、3D全方位扫描和多刻度源配置

保证探测器能标、非均匀性响应和<1%的能量非线性



刻度源的特氟龙外包装的挡光效应引起的误差: < 0.15%



Cable系统原型机测试

# 放射性本底控制

探测器最终构件天然放射性带来的单事例率相比黄皮书设计值(*JHEP*11 (2021) 102)降低了15%

单事例率 (R<17.2 m, E > 0.7 MeV)	设计值 [Hz]	改变量 [Hz]	改变的细节描述
LS	2.20	0	
Acrylic	3.61	-3.2	10 ppt -> 1 ppt
Metal in node	0.087	+1.0	Copper -> SS
PMT glass	0.33	+2.47	Schott -> NNVT/Ham
Rock	0.98	-0.85	3.2 m -> 4 m
Radon in water	1.31	-1.25	200 mBq/m <sup>3</sup> -> 10 mBq/m <sup>3</sup>
Other	0	+0.52	Add PMT readout, calibration sys
Total	8.5	-1.3	

## 对探测器原材料的本底控制:

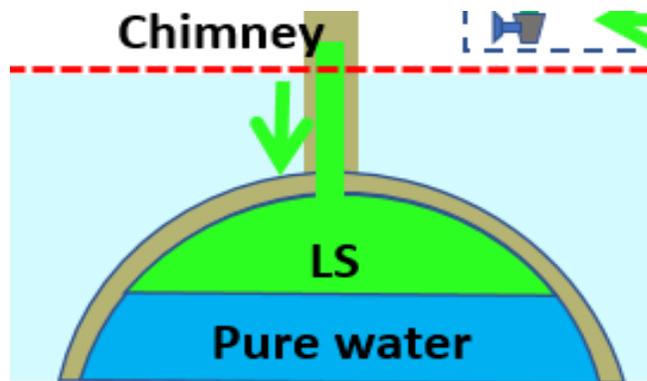
- ✓ 仔细筛查选取最低本底的原料
- ✓ 多方相互校验的MC模拟
- ✓ 严格控制探测器构件生产过程中的外在污染

## 液闪灌装过程本底控制

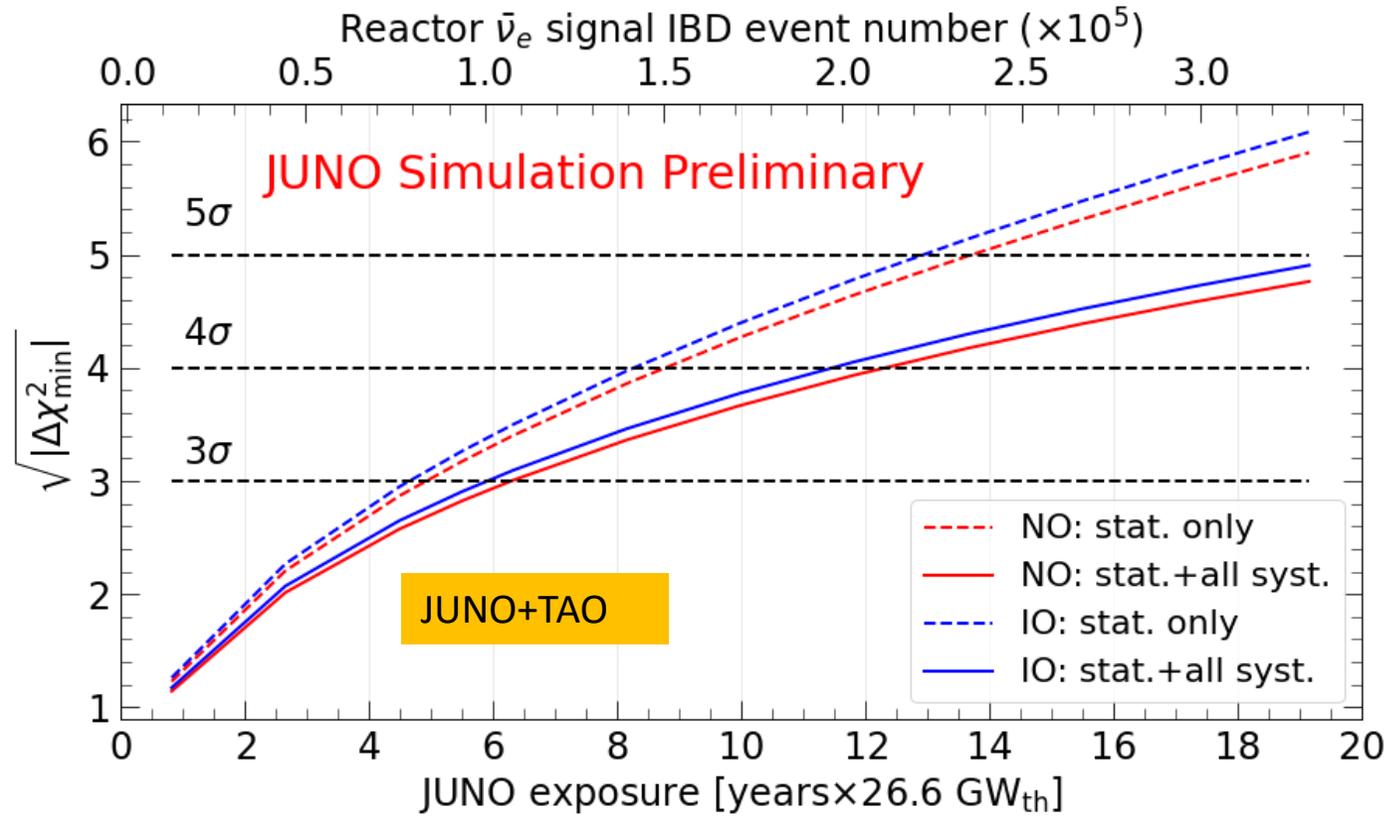
✓ 通过在线循环来降低JUNO 20 kt液闪内禀本底几乎不可能  
→ 意味着液闪中U/Th~10<sup>-17</sup> g/g目标需要从开始灌装就达到

### ✓ 控制策略:

1. 漏率 (单部件 < 10<sup>-6</sup> mbar·L/s)
2. 灌装前彻底清洗有机玻璃内壁
3. 足够干净的安装环境
4. 先灌水, 后置换液闪



# 质量顺序灵敏度



	Design *	Now (2022)
Thermal Power	36 $\text{GW}_{\text{th}}$	26.6 $\text{GW}_{\text{th}}$ ( <b>26%↓</b> )
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz ( <b>33%↑</b> )
Muon veto efficiency	83%	91.6% ( <b>11%↑</b> )
Signal rate	60 /day	47.1 /day ( <b>22%↓</b> )
Backgrounds	3.75 /day	4.11 /day ( <b>10%↑</b> )
Energy resolution	3% @ 1 MeV	2.9% @ 1 MeV ( <b>3%↑</b> )
Shape uncertainty	1%	JUNO+TAO
<b><math>3\sigma</math> NMO sens. exposure</b>	<b>&lt; 6 yrs <math>\times</math> 35.8 <math>\text{GW}_{\text{th}}</math></b>	<b>~ 6 yrs <math>\times</math> 26.6 <math>\text{GW}_{\text{th}}</math></b>

\* J. Phys. G 43:030401 (2016)

- JUNO NMO median sensitivity:  **$3\sigma$  (reactors only) @ ~6 yrs \* 26.6  $\text{GW}_{\text{th}}$  exposure**
- Combined reactor + atmospheric neutrino analysis is **in progress**: further improve the NMO sensitivity

# 中微子探测 - ~GeV量级

## 关键点

- 中微子味道鉴别：末态轻子
- 中微子正反鉴别：强子过程的末态
- L/E精度
  - $\nu$  能量精度
  - $\nu$  方向精度

$$P(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

### CC: Flavor sensitive

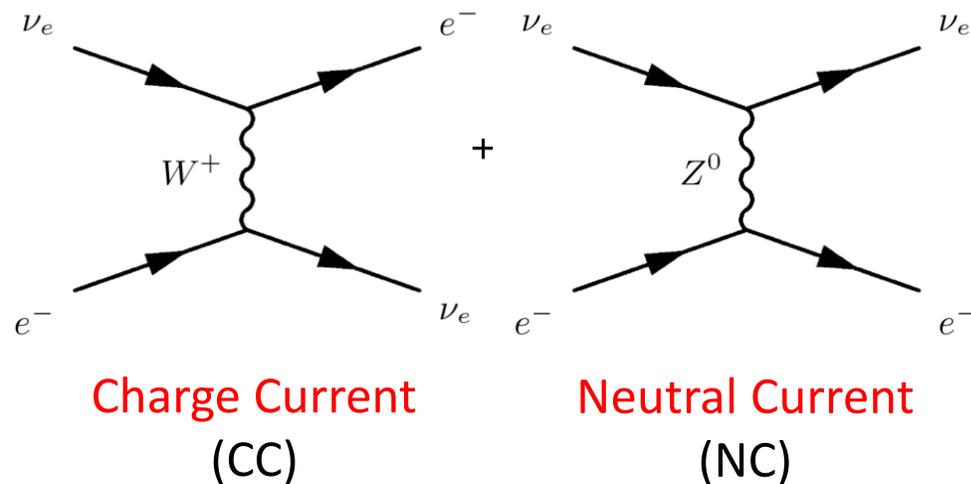
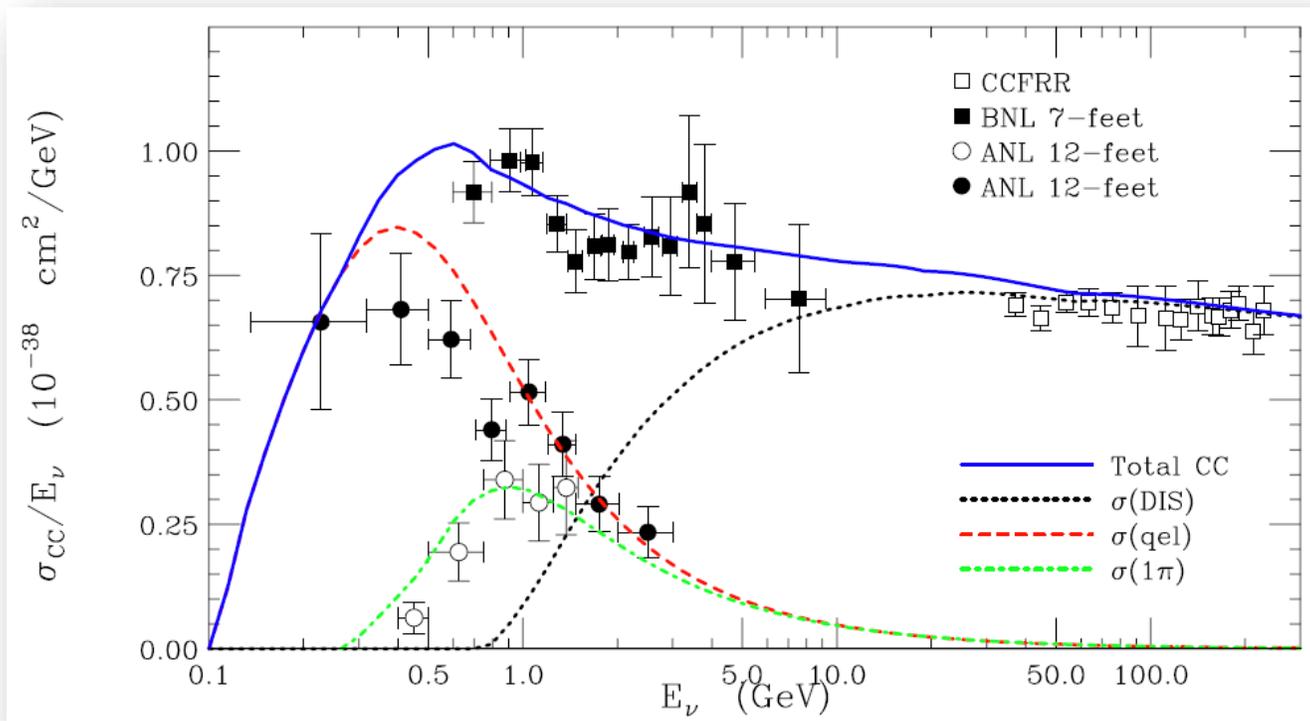
$$\nu_e (\bar{\nu}_e) + X \rightarrow e^- (e^+) + Y$$

$$\nu_\mu (\bar{\nu}_\mu) + X \rightarrow \mu^- (\mu^+) + Y$$

$$\nu_\tau (\bar{\nu}_\tau) + X \rightarrow \tau^- (\tau^+) + Y$$

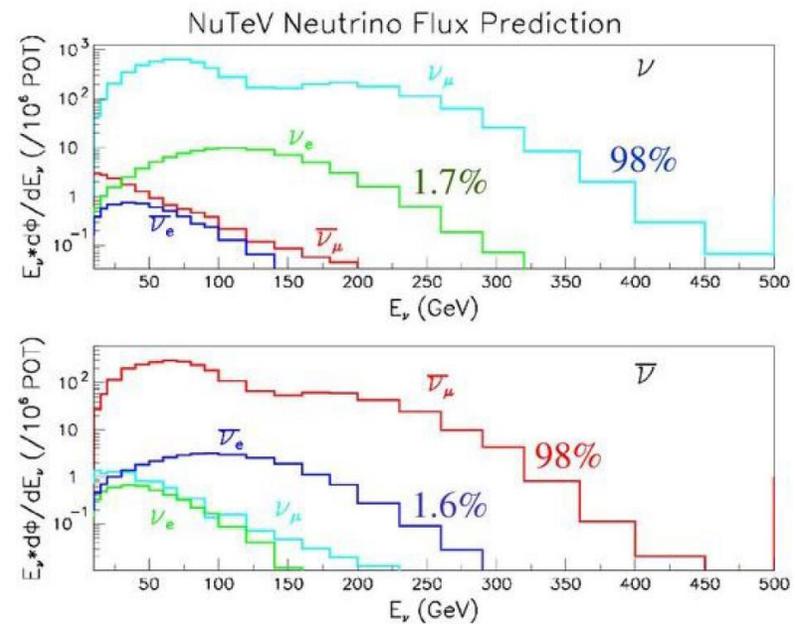
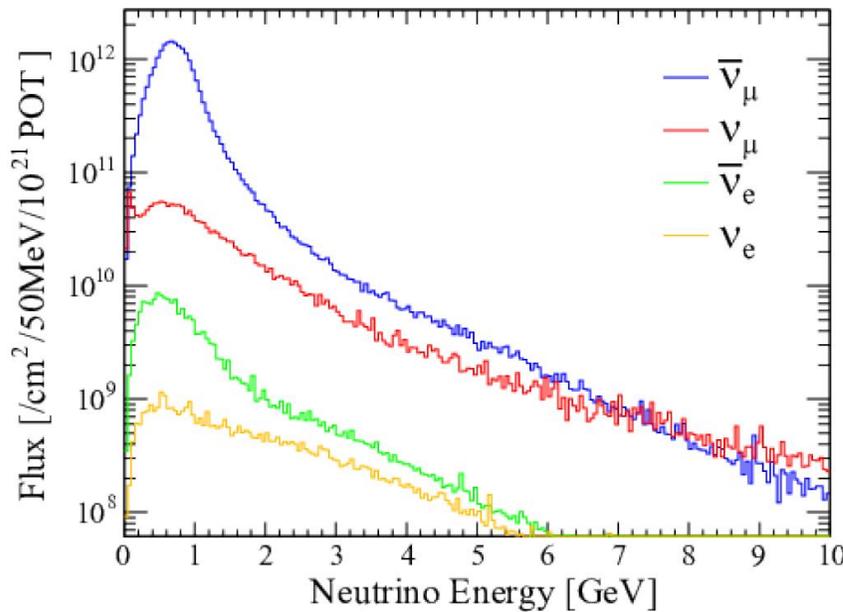
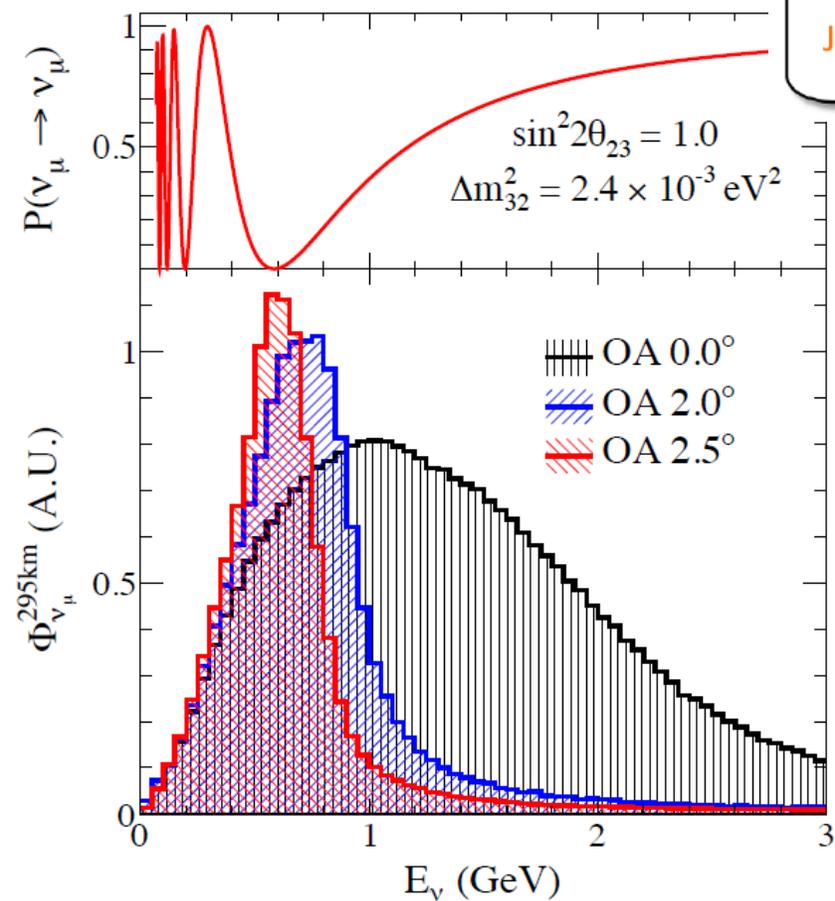
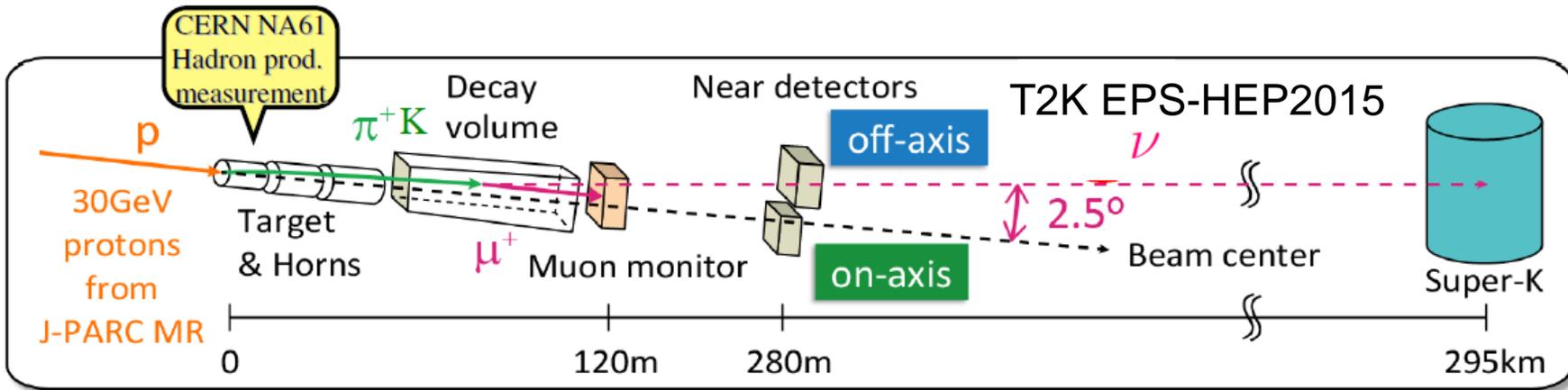
### NC: Flavor insensitive

$$\nu_x + X \rightarrow \nu_x + X$$

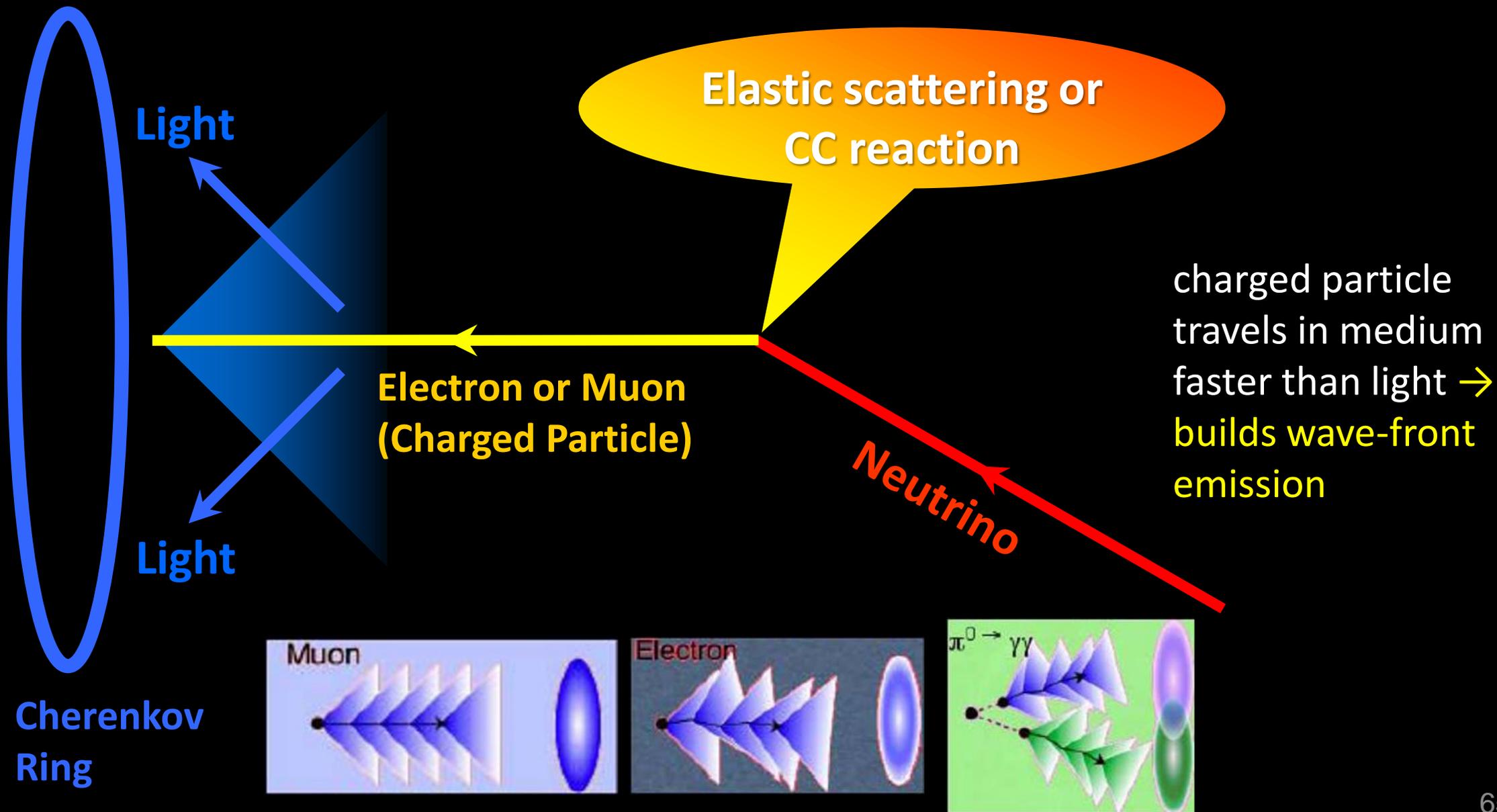


# 加速器中微子

$$\pi \rightarrow \mu + \nu_{\mu}$$



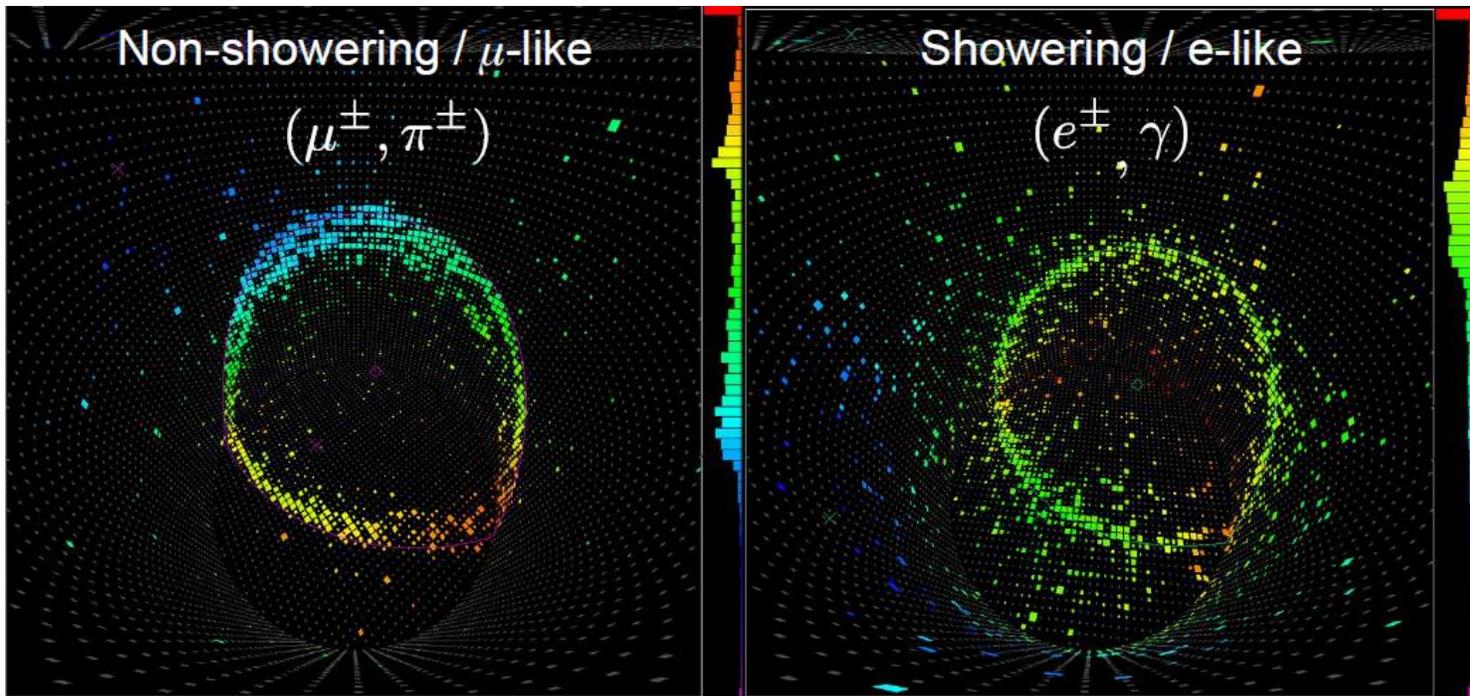
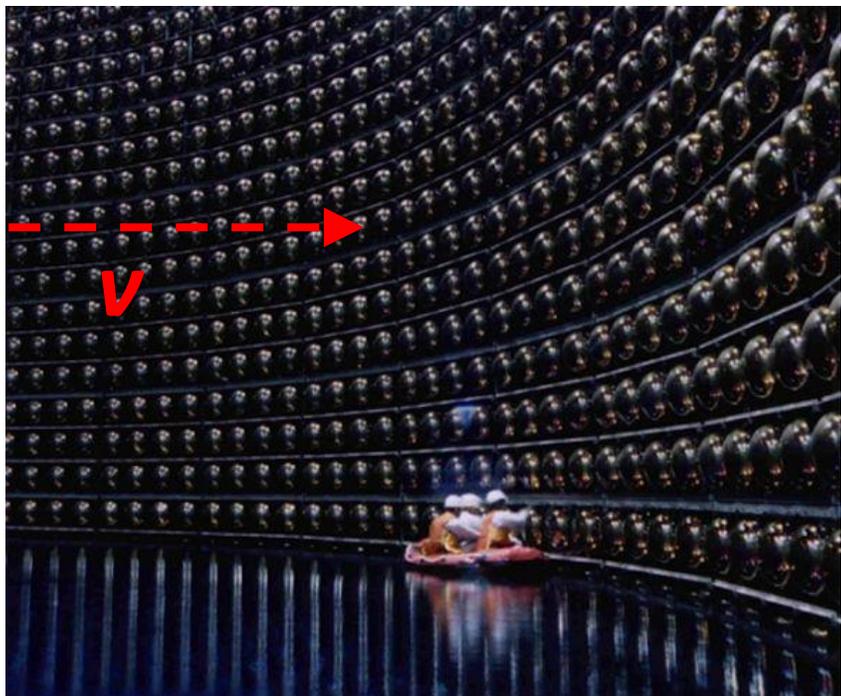
# 契伦科夫 (Cherenkov) 过程





# Cherenkov Ring Imaging in Water

(Super-K real data events from 1998)



## 关键性能:

- 光电倍增管效率、暗噪声
- 超纯水透明度
- 中子tagging

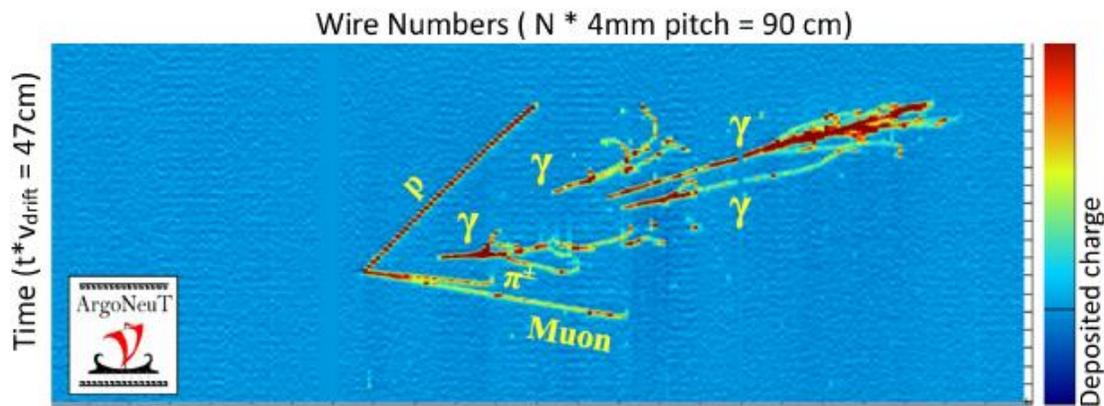
PMTs for the Inner Detector

	Super-K	Hyper-K
Number of PMTs	11,129 50cm PMTs	20,000 50cm PMTs (JPN) (+ additional PDs (Overseas))
Photo-sensitive Coverage	40 %	20 %
Single photon efficiency /PMT	~12%	~24%
Dark Rate /PMT	~4 kHz (Typical)	4 kHz (Average)
Timing resolution of 1 photon	~3 nsec	~1.5 nsec

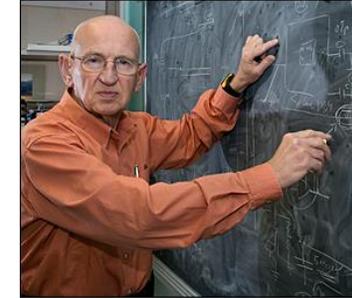
F. Di Lodovico,  
NeuTel 2021

# 液氩时间投影室 (LAr-TPC) 技术

- Idea of Liquid Argon Time Projection Chamber was first proposed in 1970s
  - Dense target
  - Ample Ionization & scintillation:
    - good energy resolution & Low threshold
    - Excellent tracking and PID capabilities
- Challenges for large-scale detector
  - Ultra-high LAr purity (long-drift)
  - Uniform and stable electric field
  - Readout wires or large electron multipliers
  - Cold electronics
  - Cryostat for multi-kiloton TPC



W. Willis



V. Radeka  
*NIMA 120:221 (1974)*



D. R. Nygren  
*eConf. C740805:58 (1974)*



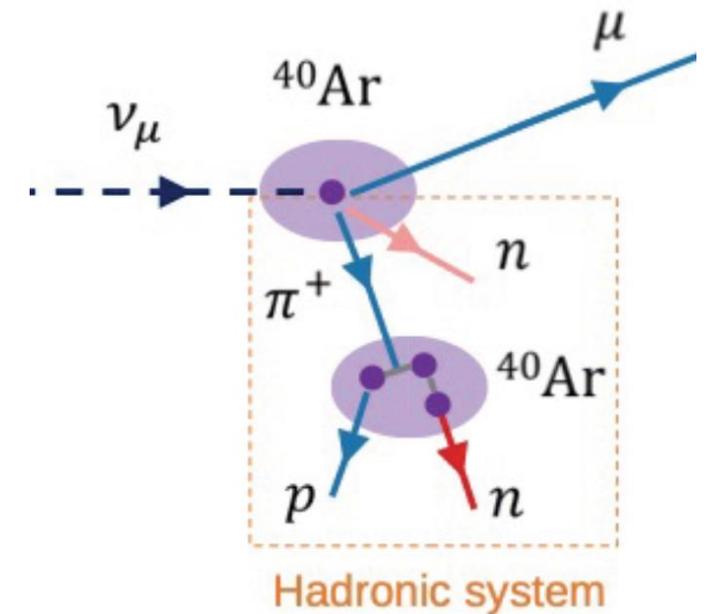
H. H. Chen  
*FNAL-Proposal-0496 (1976)*



C. Rubbia  
*CERN-EP/77-08 (1977)*

# Why Ar?

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm <sup>3</sup> ]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [ $\gamma$ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation $\lambda$ [nm]	80	78	128	150	175	
Price [\$/Liter]	~10	~100	~1	~300	~3000	~1

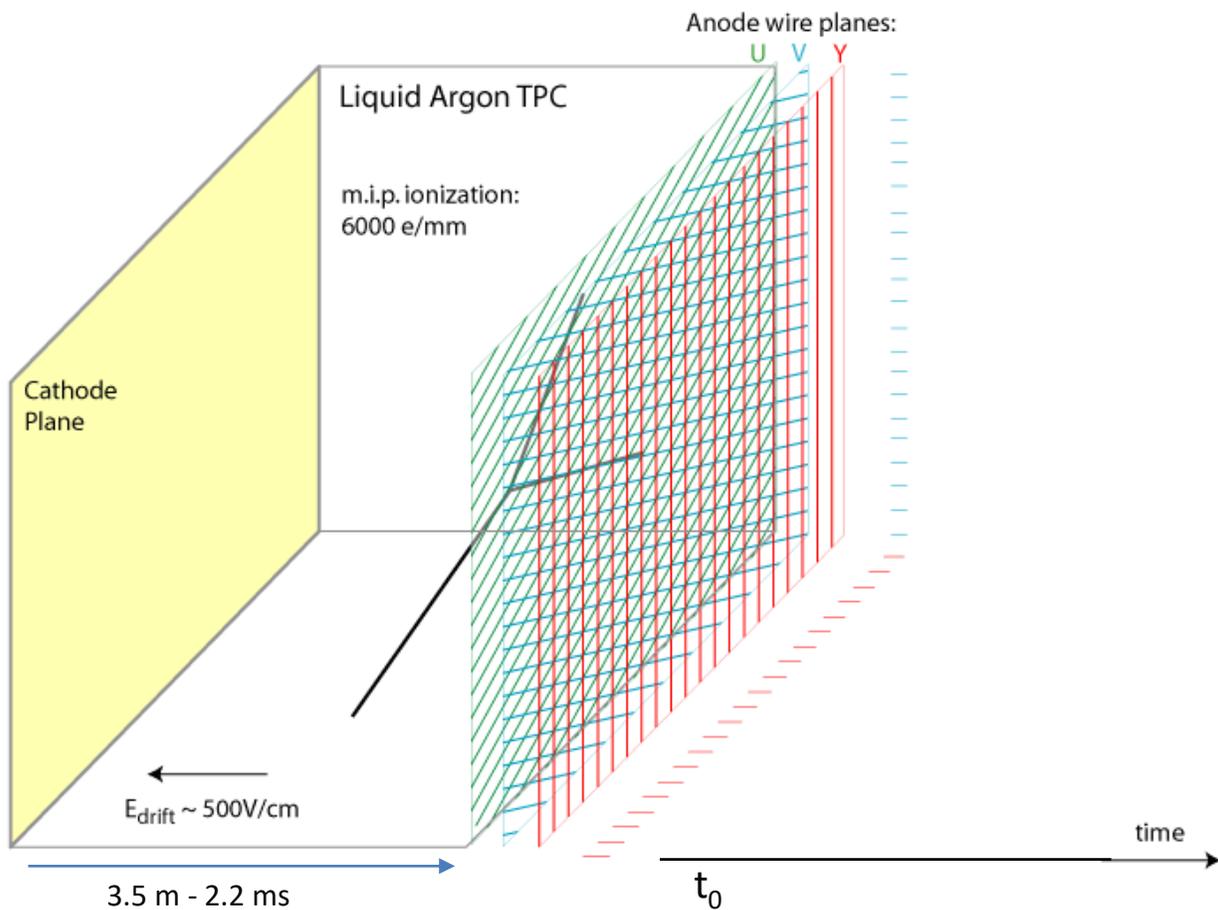


- Abundant ionization electrons and scintillation light can both be used for detection
- If liquids are highly purified (<0.1ppb), ionization can be drifted over long distances
- Excellent dielectric properties accommodate very large voltages
- Argon is relatively cheap and easy to obtain (1% of atmosphere)
- Noble liquids are dense, so they make a good target for neutrinos

Jianming Bian @ CCEPP  
Summer School 2021



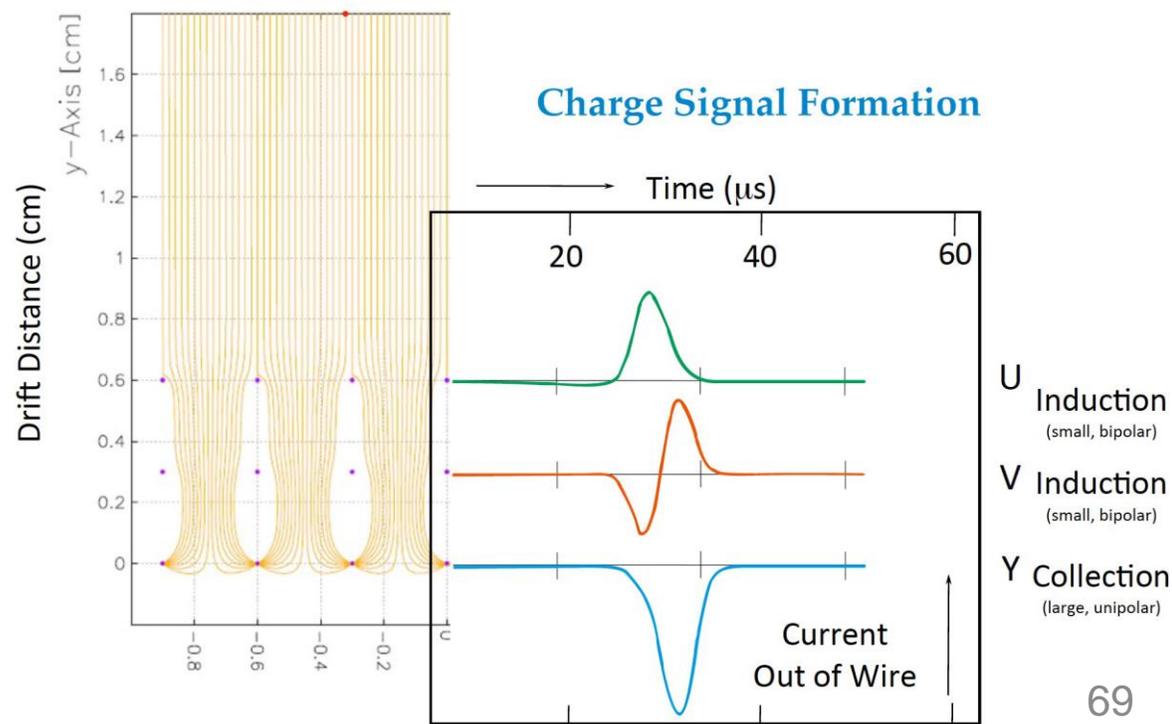
# DUNE的单相LAr-TPC



<https://www.phy.bnl.gov/wire-cell/home/img/signal.gif>

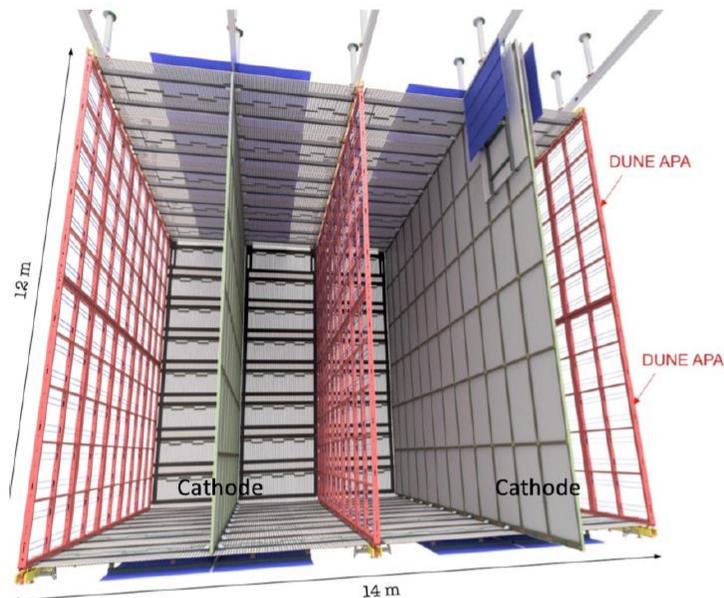
- 带电粒子电离Ar原子
- 电离电子漂移 ( $\sim ms$ )
- 能量沉积位置
  - Z: 漂移时间
  - X, Y: 多层丝信号
- 触发: 闪烁光 ( $\sim ns$ )

→ 3D径迹重建、PID





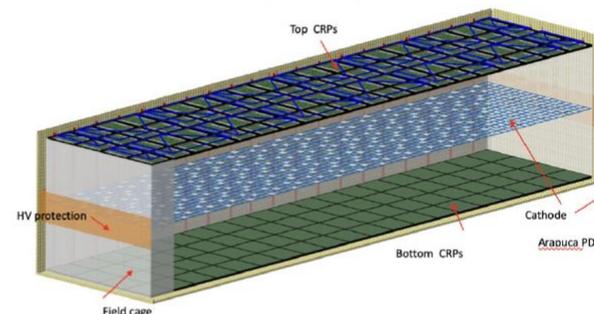
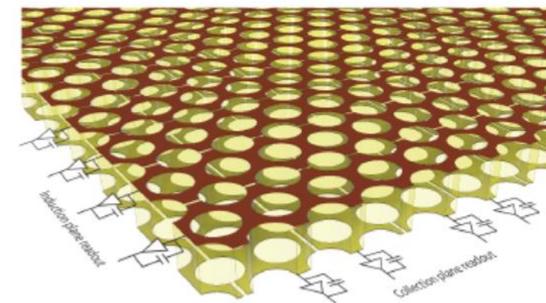
# Far Detector Technologies for DUNE



## Single-phase LArTPC

- 4 3.5-m drift regions, 500 V/cm
- Anode plane w/ 3 5-mm pitch wire readout
- 1500 ARAPUCA (photon sensors)  
[209x12x2 cm<sup>3</sup>]
- 10 kton fiducial mass per module

**NEW**



## Vertical Drift TPC

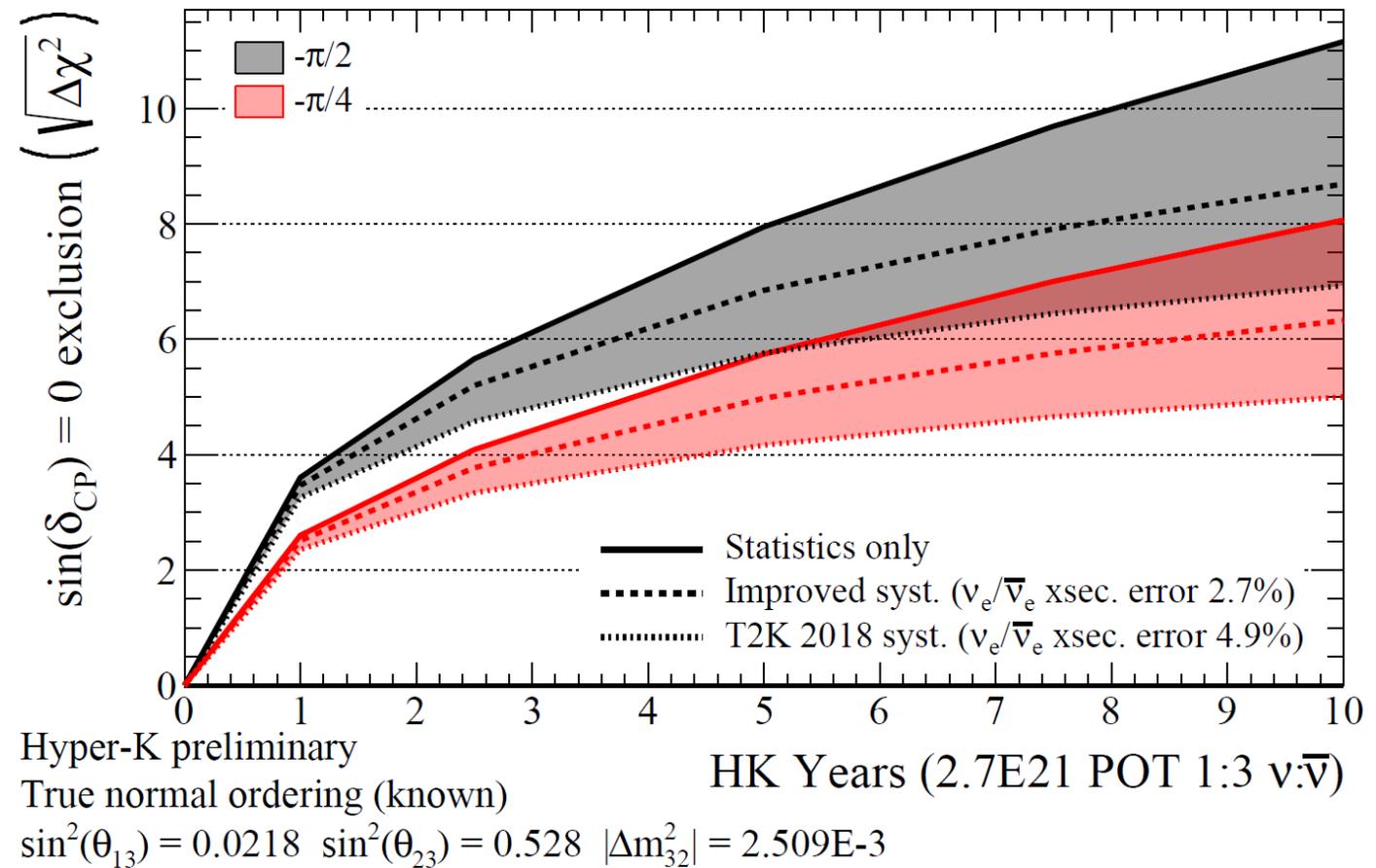
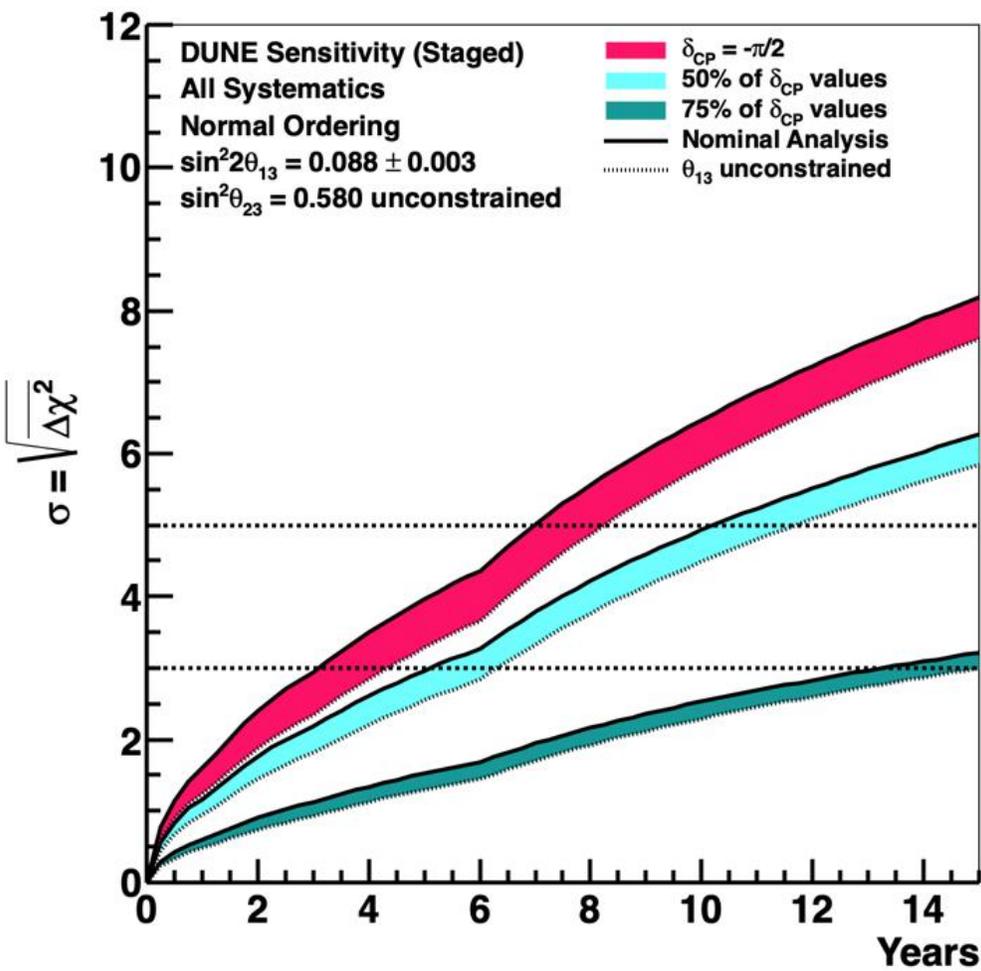
- 2-sided long vertical drift
- Printed-Circuit-Board-based readout
- Photosensors deployed on central cathode plane  
- Potentially higher light yield

Note: fourth module is possible "Module of Opportunity" with different technology...



# DUNE和Hyper-K的灵敏度

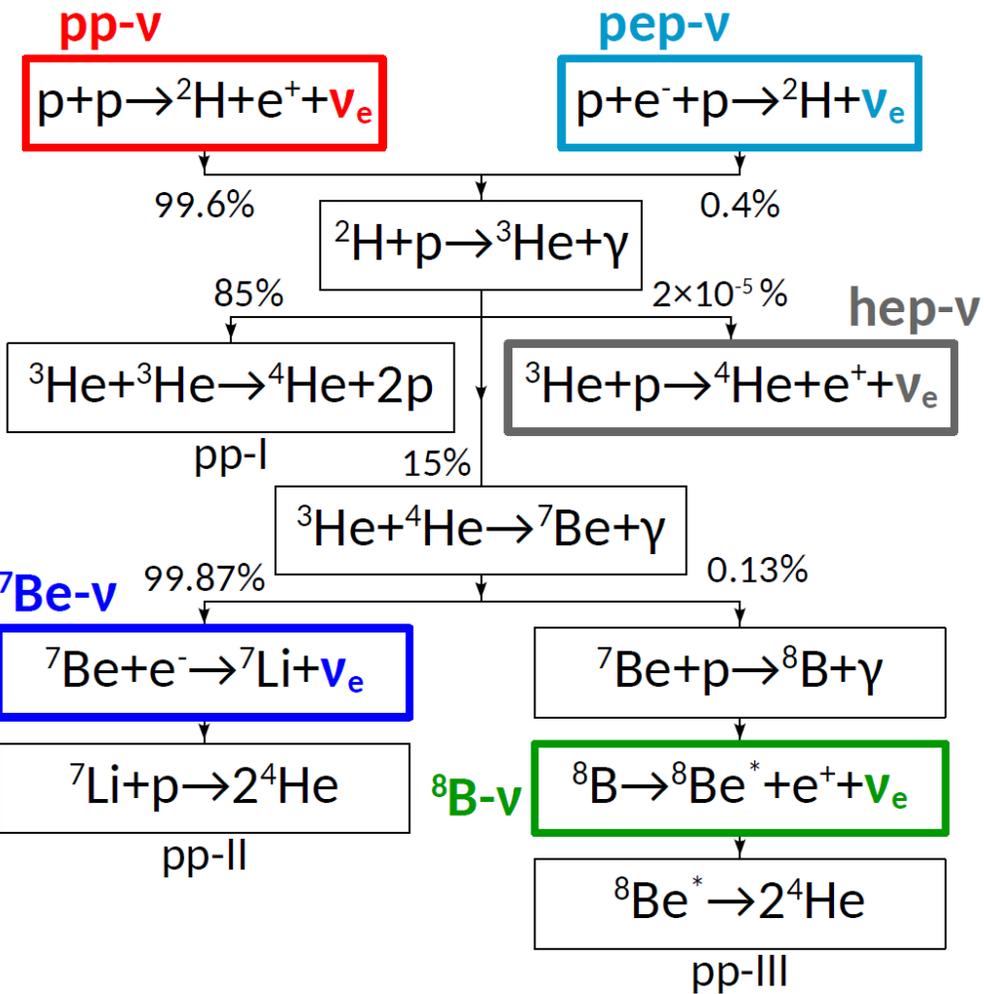
### CP Violation Sensitivity



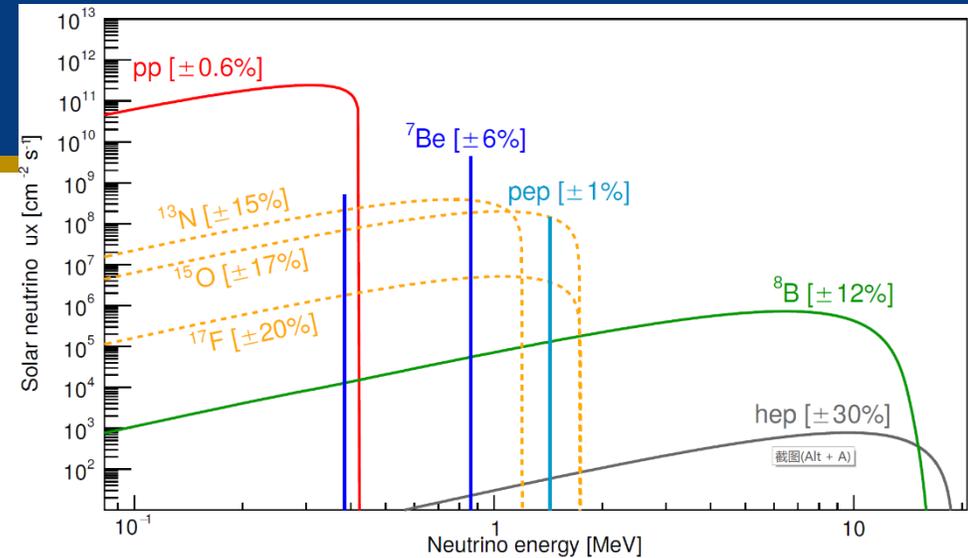
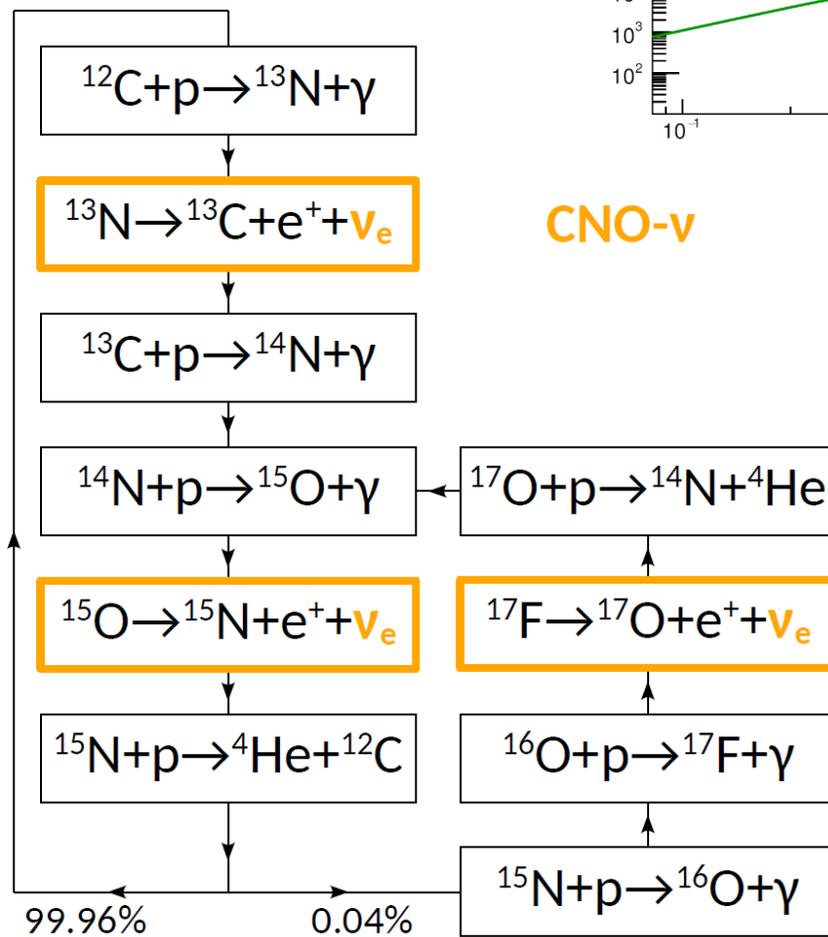
**Thanks!**

# 太阳中微子

## pp chain



## CNO cycle



参考文献: 2111.07586,  
<https://www.iupapneutrino.org/>

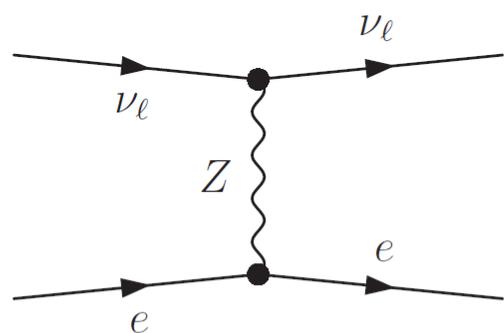
Solar $\nu$	B16-GS98 (HZ)	B16-AGSS09met (LZ)	Measurement	Exp
<i>pp</i> -cycle				
<i>pp</i>	5.98(1.0 $\pm$ 0.006)	6.03(1.0 $\pm$ 0.005)	6.1 $\pm$ 0.5 <sup>+0.3</sup> <sub>-0.5</sub> [48]	10 <sup>10</sup>
<sup>7</sup> Be	4.93(1.0 $\pm$ 0.06)	4.50(1.0 $\pm$ 0.06)	4.99 $\pm$ 0.11 <sup>+0.06</sup> <sub>-0.08</sub> [48]	10 <sup>9</sup>
			5.82 $\pm$ 0.98 [49]	10 <sup>9</sup>
<i>pep</i>	1.44(1.0 $\pm$ 0.01)	1.46(1.0 $\pm$ 0.009)	1.27 $\pm$ 0.19 <sup>+0.08</sup> <sub>-0.12</sub> [48]	10 <sup>8</sup>
<sup>8</sup> B	5.46(1.0 $\pm$ 0.12)	4.50(1.0 $\pm$ 0.12)	5.4 $\pm$ 0.02 $\pm$ 0.1 [50]	10 <sup>6</sup>
			5.25 $\pm$ 0.16 <sup>+0.11</sup> <sub>-0.13</sub> [51]	10 <sup>6</sup>
			5.68 <sup>+0.39+0.03</sup> <sub>-0.41-0.03</sub> [48]	10 <sup>6</sup>
			5.95 <sup>+0.75+0.28</sup> <sub>-0.71-0.30</sub> [52]	10 <sup>6</sup>
<i>hep</i>	7.98(1.0 $\pm$ 0.30)	8.25(1.0 $\pm$ 0.12)	< 23 (90% C.L.) [53]	10 <sup>3</sup>
			< 150 (90% C.L.) [54]	10 <sup>3</sup>
			< 180 (90% C.L.) [55]	10 <sup>3</sup>
CNO	4.88(1.0 $\pm$ 0.11)	3.51(1.0 $\pm$ 0.11)	7.0 <sup>+3.0</sup> <sub>-2.0</sub> [56]	10 <sup>8</sup>

Table 3: Solar neutrino fluxes predicted by the Standard Solar Models B16-GS98 (High Metallicity) and B16-AGSS09met (Low Metallicity) [57] and as measured by various experiments in units of  $\text{cm}^{-2} \text{s}^{-1}$  (with the exponential factor given in the last column). For the measured fluxes, the first error is statistical and the second error systematical.

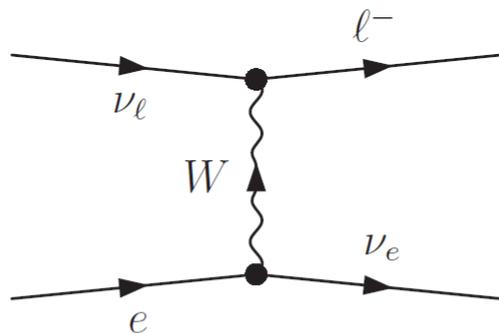
参考文献: 2111.07586,  
<https://www.iupapneutrinopanel.org/>



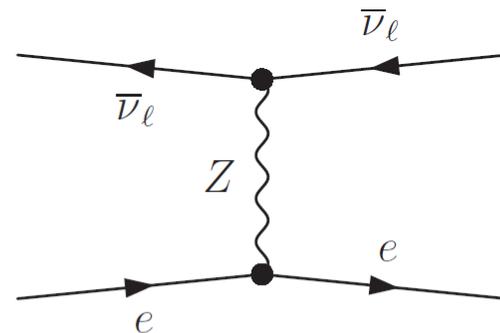
# 中微子相互作用



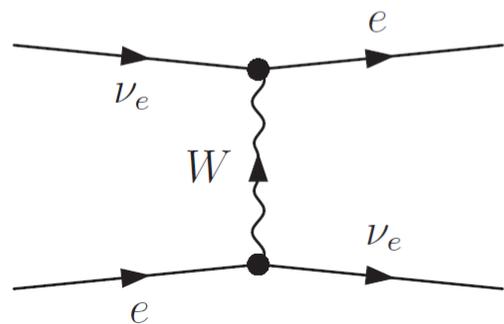
$$\nu_\ell + e \rightarrow \nu_\ell + e$$



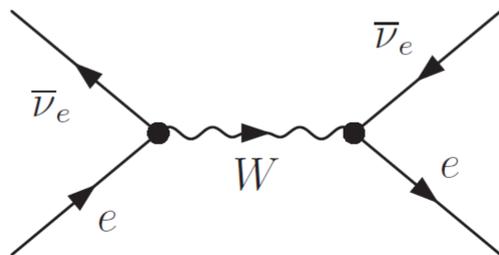
$$\nu_\ell + e \rightarrow \nu_e + \ell^-$$



$$\bar{\nu}_\ell + e \rightarrow \bar{\nu}_\ell + e$$



$$\nu_e + e \rightarrow \nu_e + e$$



$$\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$$

参考文献: 2111.07586,  
<https://www.iupapneutrino.org/>

# 中微子相互作用

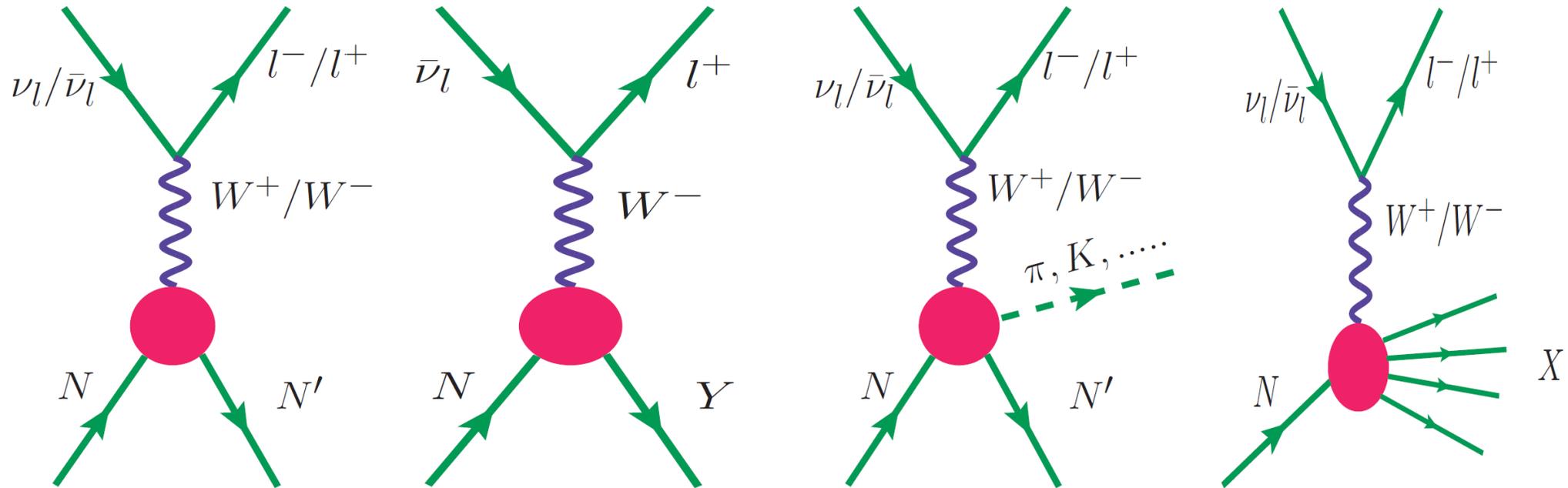


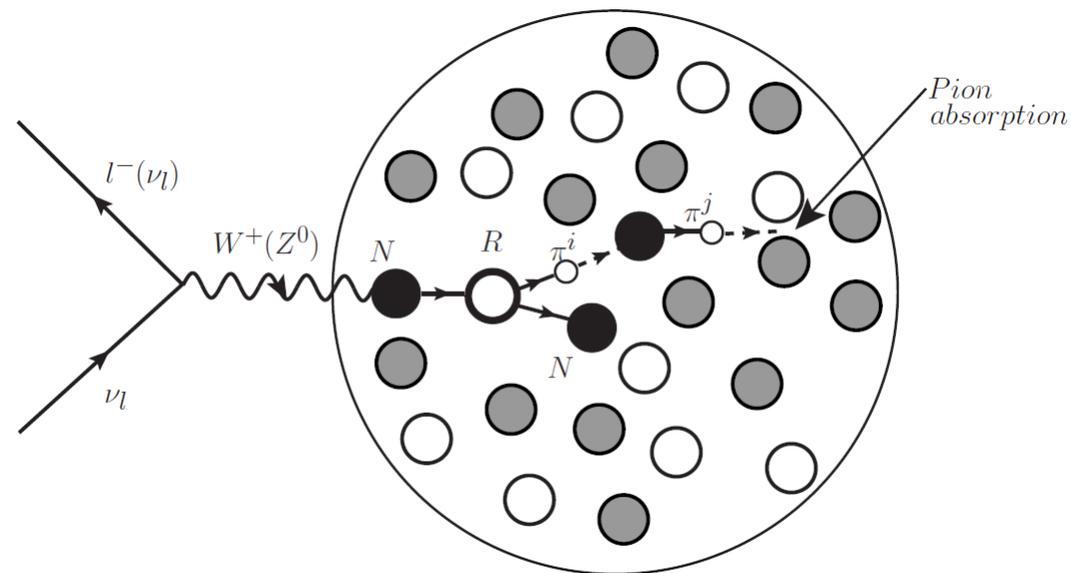
Figure 30: Feynman diagrams representing (from left to right) (a) QE, (b) CC meson, (c) CC pion and kaon production, and (d) DIS processes. In the case of NC-induced processes, the final state lepton  $\ell^- (\ell^+)$  and exchange boson  $W^\pm$  are replaced by  $\nu_\ell (\bar{\nu}_\ell)$  and  $Z$ , respectively.

参考文献: 2111.07586,  
<https://www.iupapneutrino.org/>



S. No.	CC induced $\nu(\bar{\nu})$ reactions	NC induced $\nu(\bar{\nu})$ reactions
1.	$\nu_e(\bar{\nu}_e) + N \longrightarrow l^-(l^+) + N' + \pi$	$\nu_e(\bar{\nu}_e) + N \longrightarrow \nu_e(\bar{\nu}_e) + N' + \pi$
2.	$\nu_e(\bar{\nu}_e) + N \longrightarrow l^-(l^+) + N' + n\pi$	$\nu_e(\bar{\nu}_e) + N \longrightarrow \nu_e(\bar{\nu}_e) + N' + n\pi$
3.	$\nu_e(\bar{\nu}_e) + N \longrightarrow l^-(l^+) + N' + \eta$	$\nu_e(\bar{\nu}_e) + N \longrightarrow \nu_e(\bar{\nu}_e) + N' + \eta$
4.	$\nu_e(\bar{\nu}_e) + N \longrightarrow l^-(l^+) + Y + K$	$\nu_l(\bar{\nu}_l) + N \longrightarrow \nu_l(\bar{\nu}_l) + Y + K$
5.	$\nu_e(\bar{\nu}_e) + N \longrightarrow l^-(l^+) + N' + K(\bar{K})$	$\bar{\nu}_l + N \longrightarrow l^+ + Y + \pi$

Table 12: Charged- and neutral-current-induced inelastic processes. Here  $N, N'$  represent proton and neutron,  $Y = \Lambda, \Sigma$  represents the hyperons,  $K = K^+, K^0$  represents the kaons,  $\bar{K} = K^-, \bar{K}^0$  represents the antikaons and  $l = e, \mu$  represents the leptons.



参考文献: 2111.07586,  
<https://www.iupapneutrinopanel.org/>

# $\nu_\mu \rightarrow \nu_e$ ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ) Oscillation

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \sim & \frac{\sin^2 2\theta_{13}}{-\alpha \sin \delta} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\
 & + \alpha \cos \delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
 & + \mathcal{O}(\alpha^2) \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}
 \end{aligned}$$

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

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

- $\sin^2 2\theta_{13}$  dependence of leading term
- $\theta_{23}$  dependence of leading term: "octant" dependence ( $\theta_{23} = />/ < 45^\circ$ ?)
- CP odd phase  $\delta$ : asymmetry of probabilities  $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$  if  $\sin \delta \neq 0$
- Matter effect through  $x$ :  $\nu_e$  ( $\bar{\nu}_e$ ) enhanced in normal (inverted) hierarchy

MH is more sensitive in the high E region

For  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  transition, the corresponding probability is obtained by replacing  $\delta_{\text{CP}} \rightarrow -\delta_{\text{CP}}$  and  $x \rightarrow -x$

# $\nu_\mu \rightarrow \nu_e$ ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ) Oscillation

Take T2K baseline (295 km) as an example

