解密中微子：幽灵粒子如何揭示微观世界与宇宙演化的奥秘

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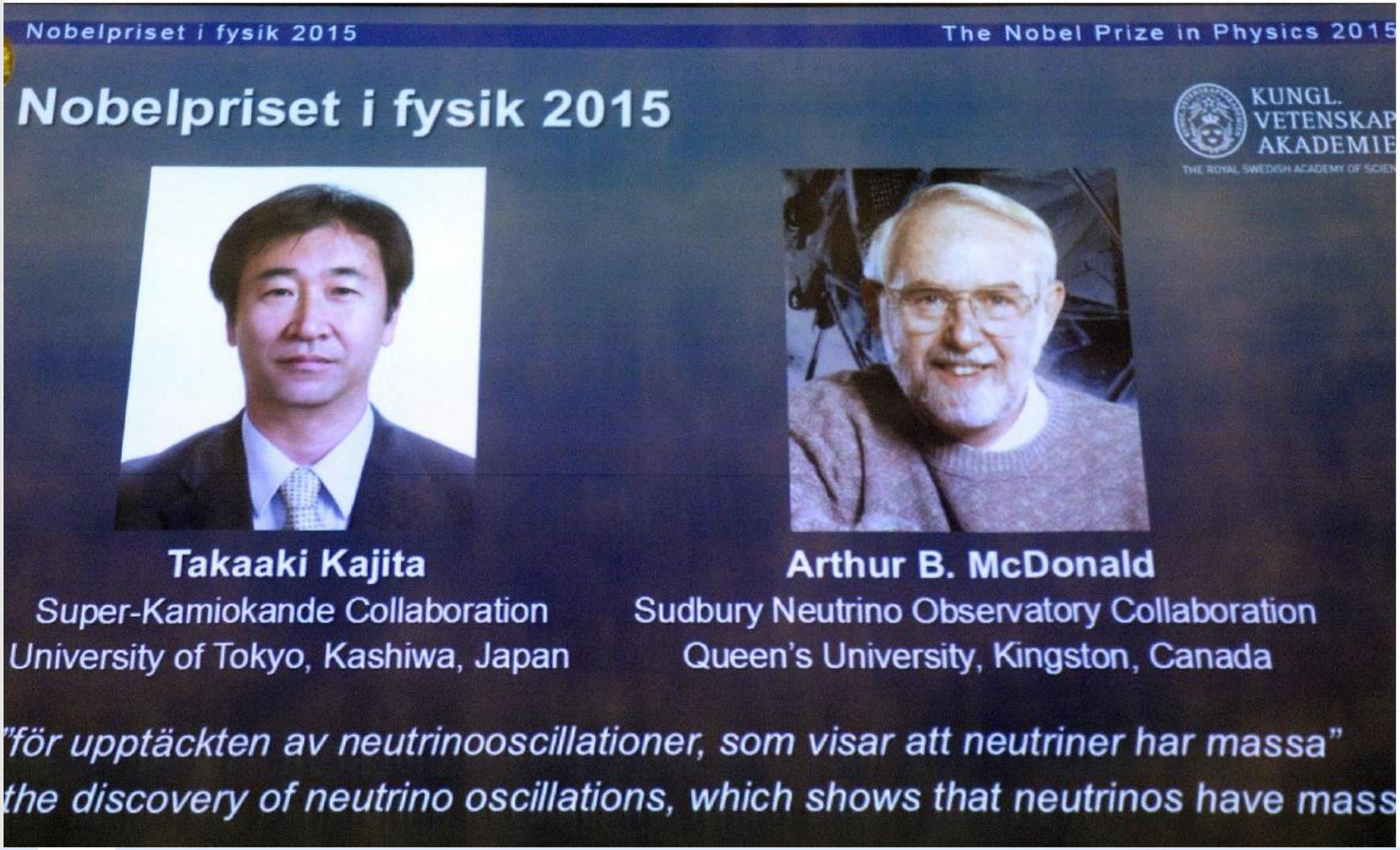
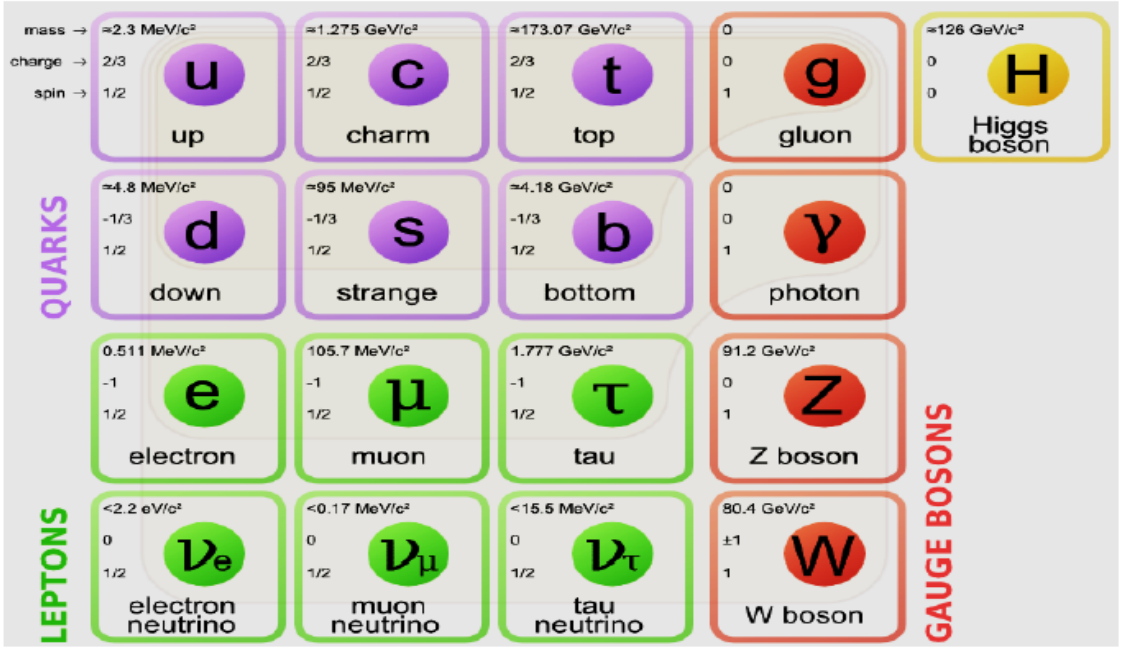
2024-12-22

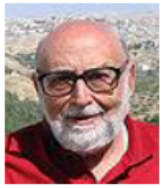
2015年10月6日，瑞典皇家科学院宣布将2015年诺贝尔物理学奖授予日本东京大学Takaaki Kajita教授和加拿大女王大学Arthur B. McDonald教授，以表彰其*发现中微子振荡现象，该现象显示中微子有质量*。



Neutrino as Fundamental Particle



2013年诺贝尔物理学奖



F. Englert

P. Higgs

其理论有助于我们理解基本粒子质量起源，并通过ATLAS和CMS实验中发现该理论预言的新的基本粒子被证实

粒子物理标准模型是目前描述强、弱和电磁相互作用最成功的理论，几乎通过所有实验的精确检验，唯一的例外是中微子振荡

1956年，发现核反应堆产生的反电子中微子 [Reines, 1995年获奖]

1962年，发现muon中微子 [Lederman/Schwartz/Steinberg, 1988年获奖]

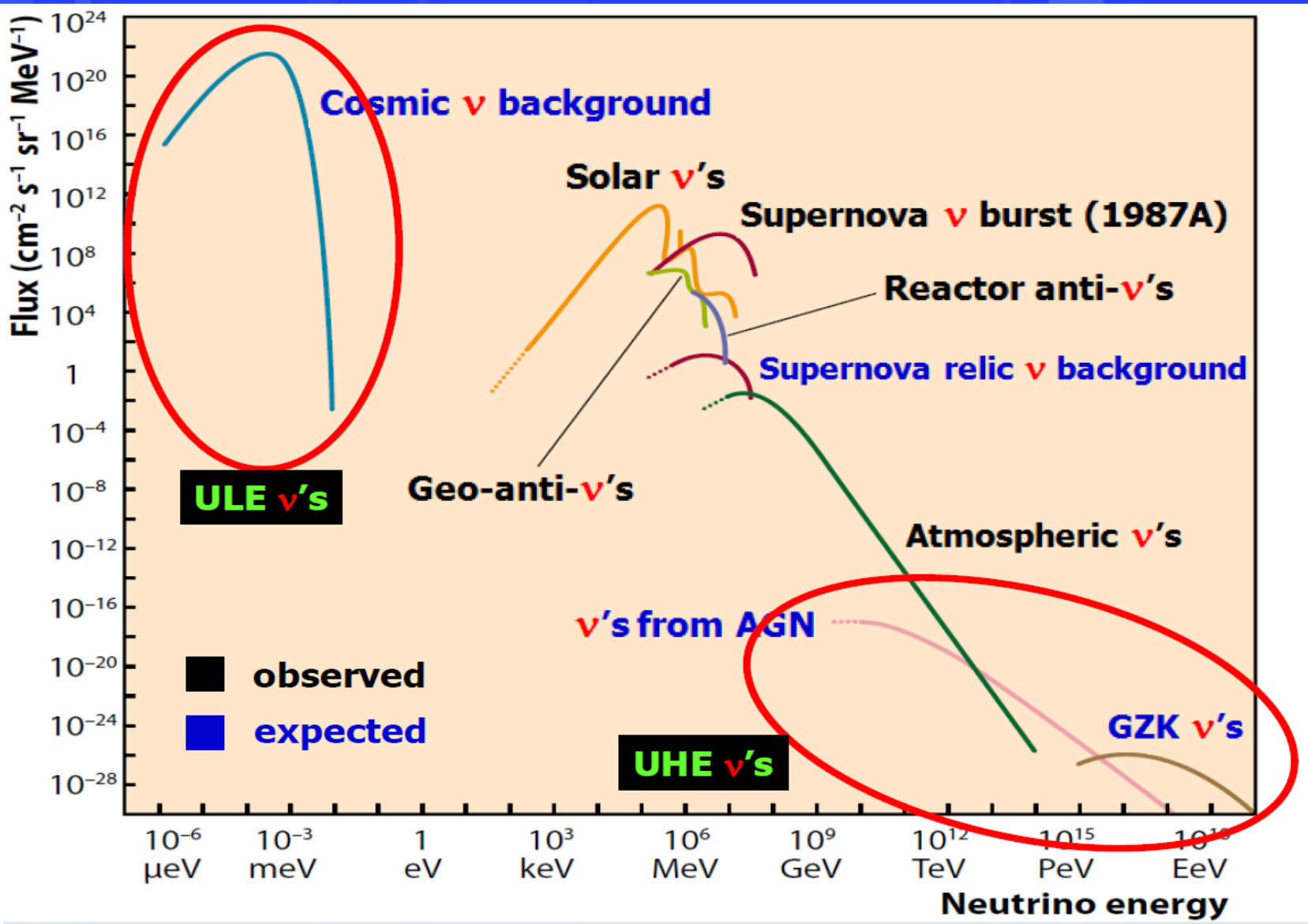
1968年，发现太阳内部核聚变产生的电子中微子 [Davis, 2002年获奖]

1987年，发现超新星SN1987A爆发产生的中微子 [Koshiba, 2002年获奖]

1998年，发现大气中微子振荡 [Kajita, 2015年获奖]

2002年，发现太阳中微子振荡 [McDonald, 2015年获奖]

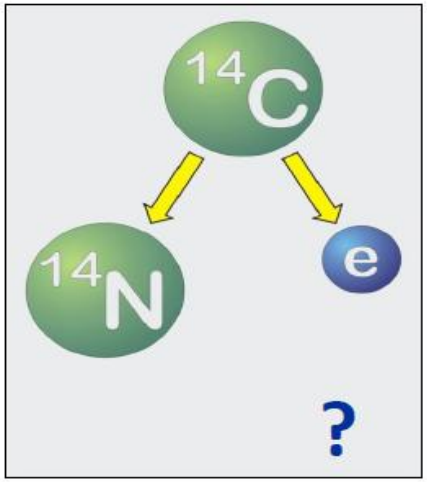
Neutrino as Cosmic Messenger

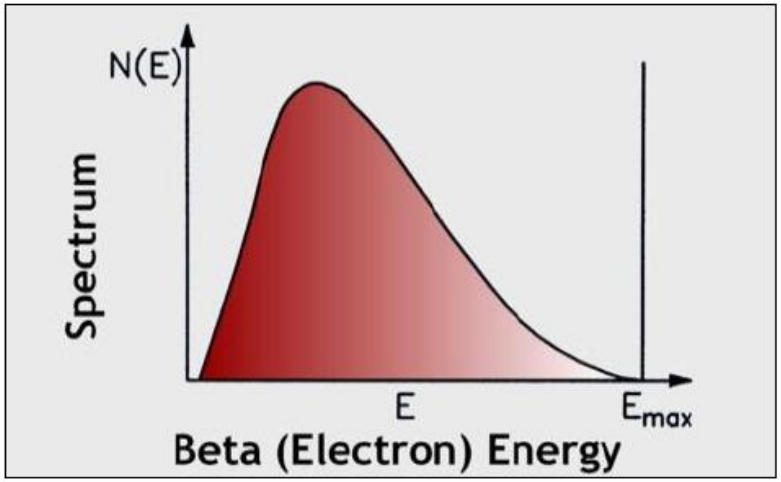


Part I:

中微子的提出与发现

1930年: 泡利的中微子假设





1914年，查德威克发现贝塔衰变末态电子连续能谱，与二体衰变过程不符

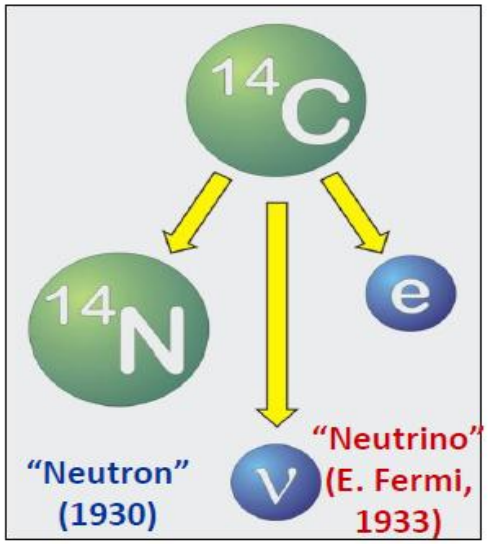
James Chadwick
(1891-1974)
Nobel Prize
1935

Niels Bohr
(1885-1962)
Nobel Prize
1922

Wolfgang Pauli
(1900-1958)
Nobel Prize
1945

1930年，泡利提出原子核里存在质量小且自旋为1/2的电中性粒子(中子)

一石二鸟：

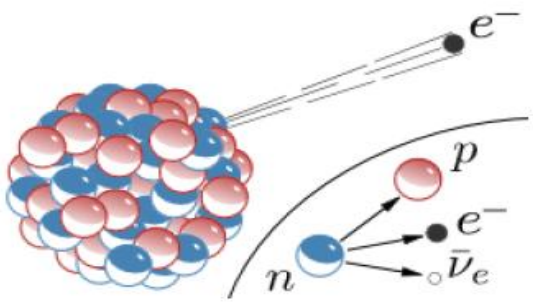


Enrico Fermi
(1901-1954)
Nobel Prize
1938

能量不守恒？存在新粒子？

可同时解释连续能谱和氮原子核自旋

1934年: 中微子无法探测?



Bethe & Peierls (1934)

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad \text{Cross section } \sigma < 10^{-44}\ \text{cm}^2$$

"It is therefore absolutely impossible to observe the processes of this kind with the neutrinos created in nuclear transformations."

Hans A. Bethe
(1906–2005)
Nobel Prize 1967

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.*

$$H + H = D + \epsilon^+. \qquad (1)$$

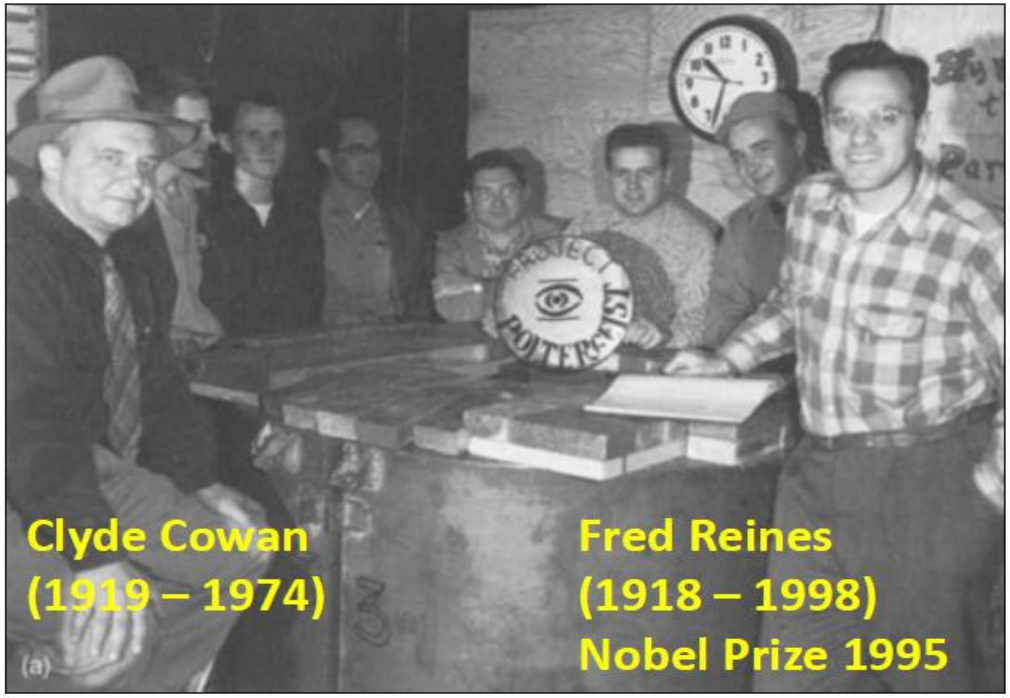
The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

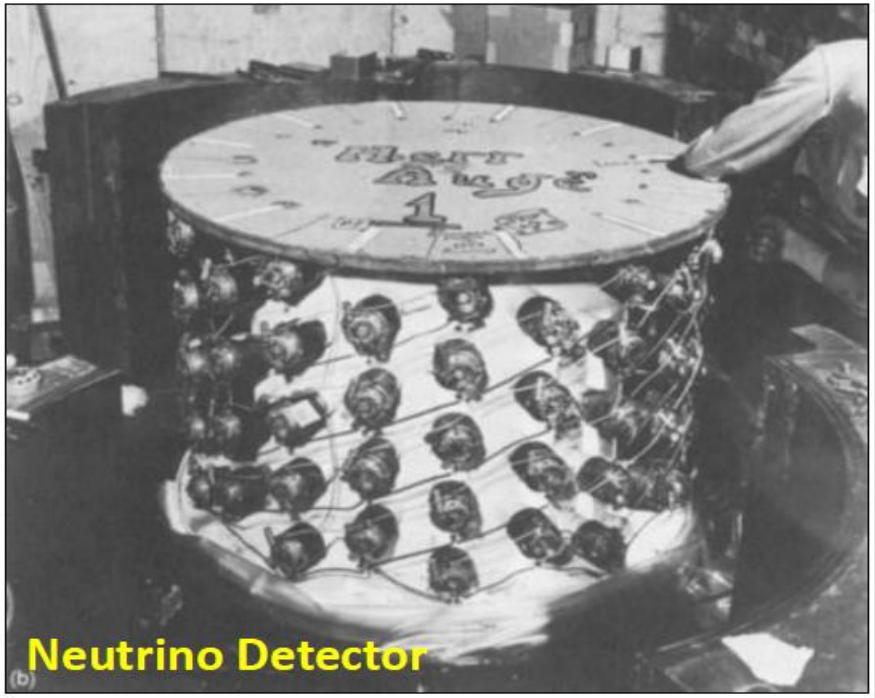
$$\begin{aligned} &C^{12} + H = N^{13} + \gamma, && N^{13} = C^{13} + \epsilon^+ \\ &C^{13} + H = N^{14} + \gamma, \\ &N^{14} + H = O^{15} + \gamma, && O^{15} = N^{15} + \epsilon^+ \\ &N^{15} + H = C^{12} + He^4. \end{aligned} \qquad (2)$$

1939年, 贝特在太阳内部核聚变反应的著名文章中忽略了中微子

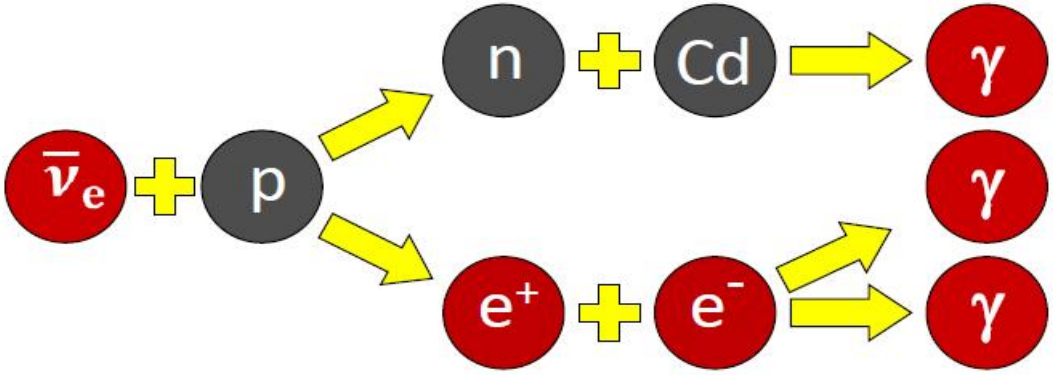
1951年, 莱因斯与费米讨论探测核爆放出的中微子的可能性

1956年: 发现反应堆中微子





1953年, 首次实验看到信号，但是发现即使核反应堆关闭，探测器中仍有信号(主要来自宇宙线背景)

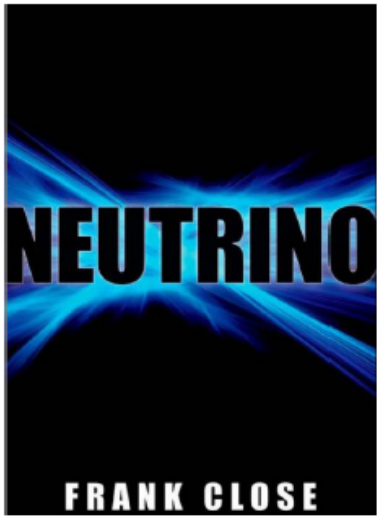


中子被镉俘获，产生 9 MeV γ

正负电子湮灭产生 0.51 MeV γ

5 微秒时间符合窗口可压低背景

1956年: 发现反应堆中微子



6月14日，柯万和莱因斯给泡利发去电报，告知探测到中微子的消息，并赢得一箱香槟 (泡利曾打赌没有人能探测到中微子)

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.”

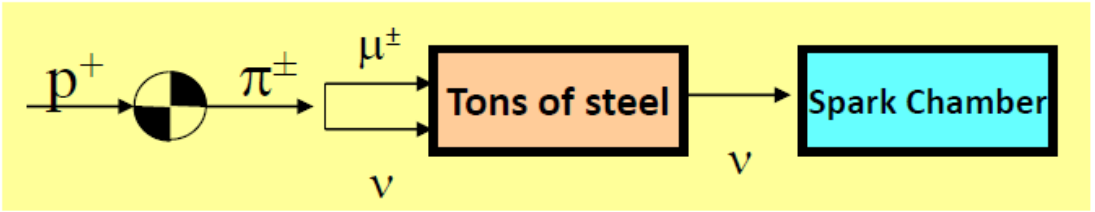
贝特回答“Well, you shouldn't believe everything you read in the papers.”

1962年: 发现muon中微子

Leon Lederman

Melvin Schwartz

Jack Steinberg



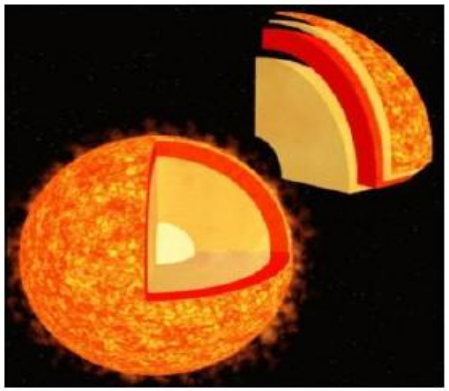
预期: 观测显示中微子总与电子和muon一起产生

结论: 探测器中只有muon出现，所以证明$\nu_\mu \neq \nu_e$

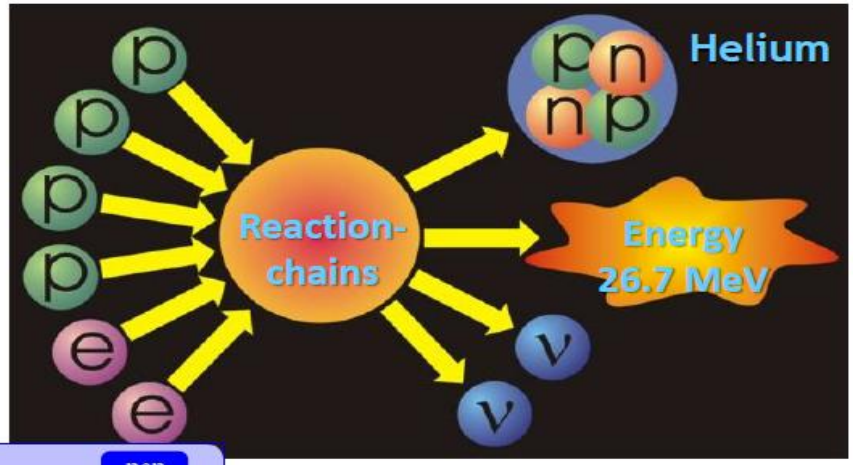
Part II:

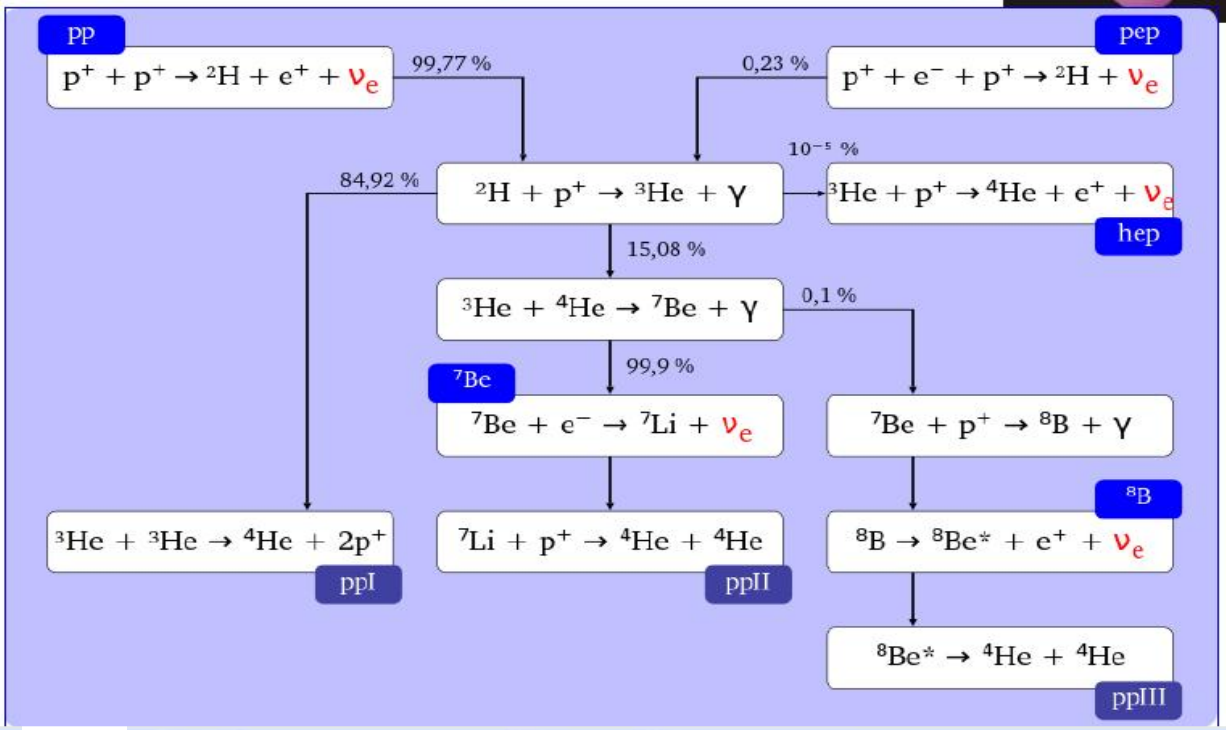
太阳中微子

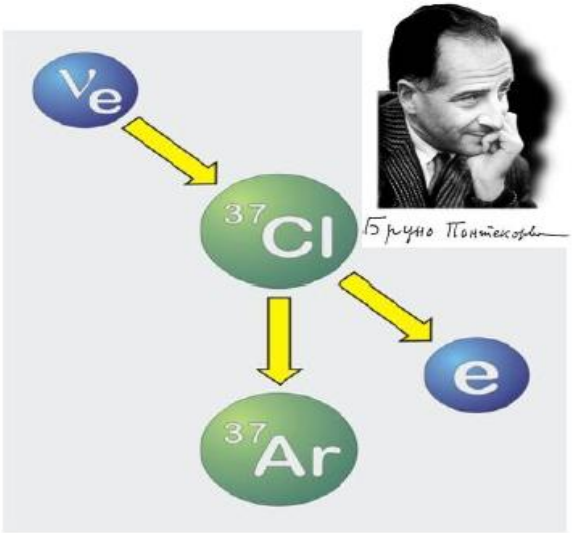
1968年: 发现太阳中微子



太阳为什么会发光？

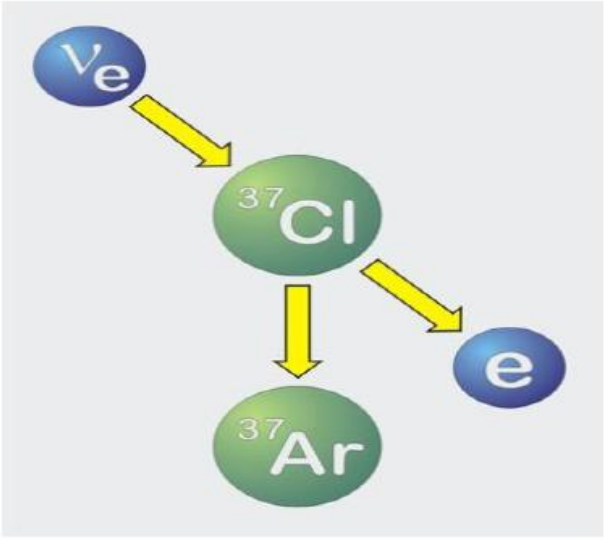






Davis注意到Pontecorvo在1946年提出的探测方法

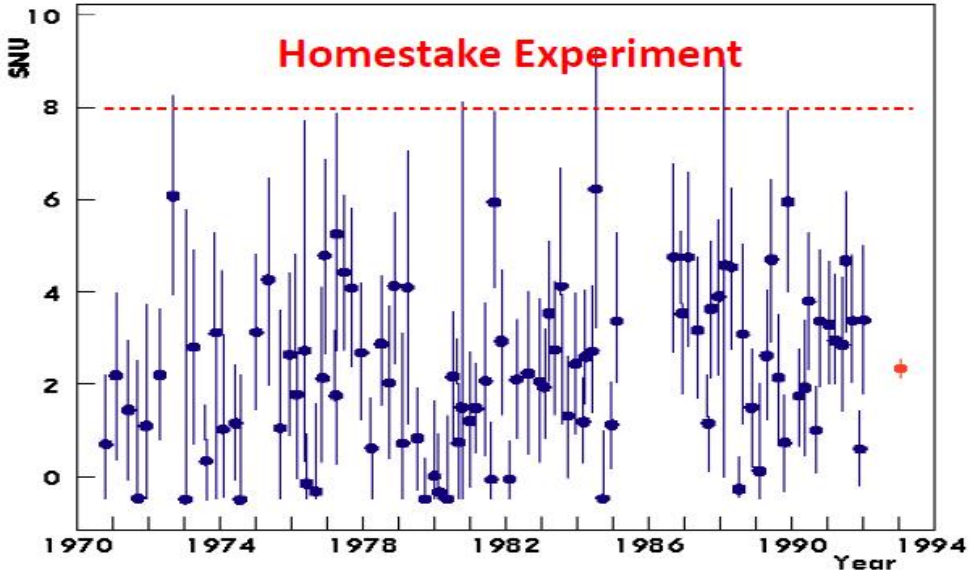
1968年: 发现太阳中微子



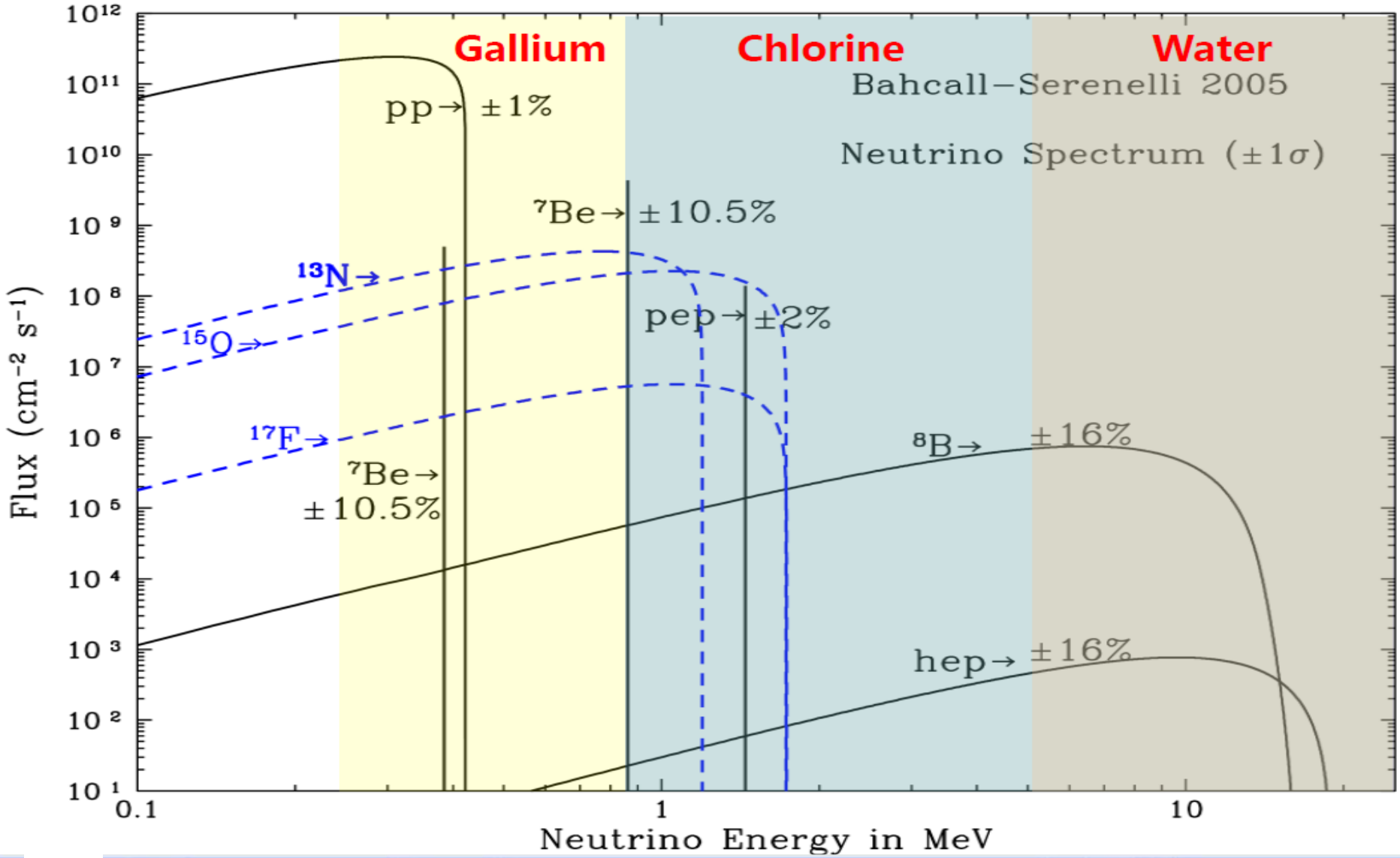
位于美国南达科塔州Homestake金矿，深约1500米，使用600吨四氯乙烯（通常用的干洗剂）

利用化学方法提取氩原子，确定中微子的通量；预期每天1.5事例

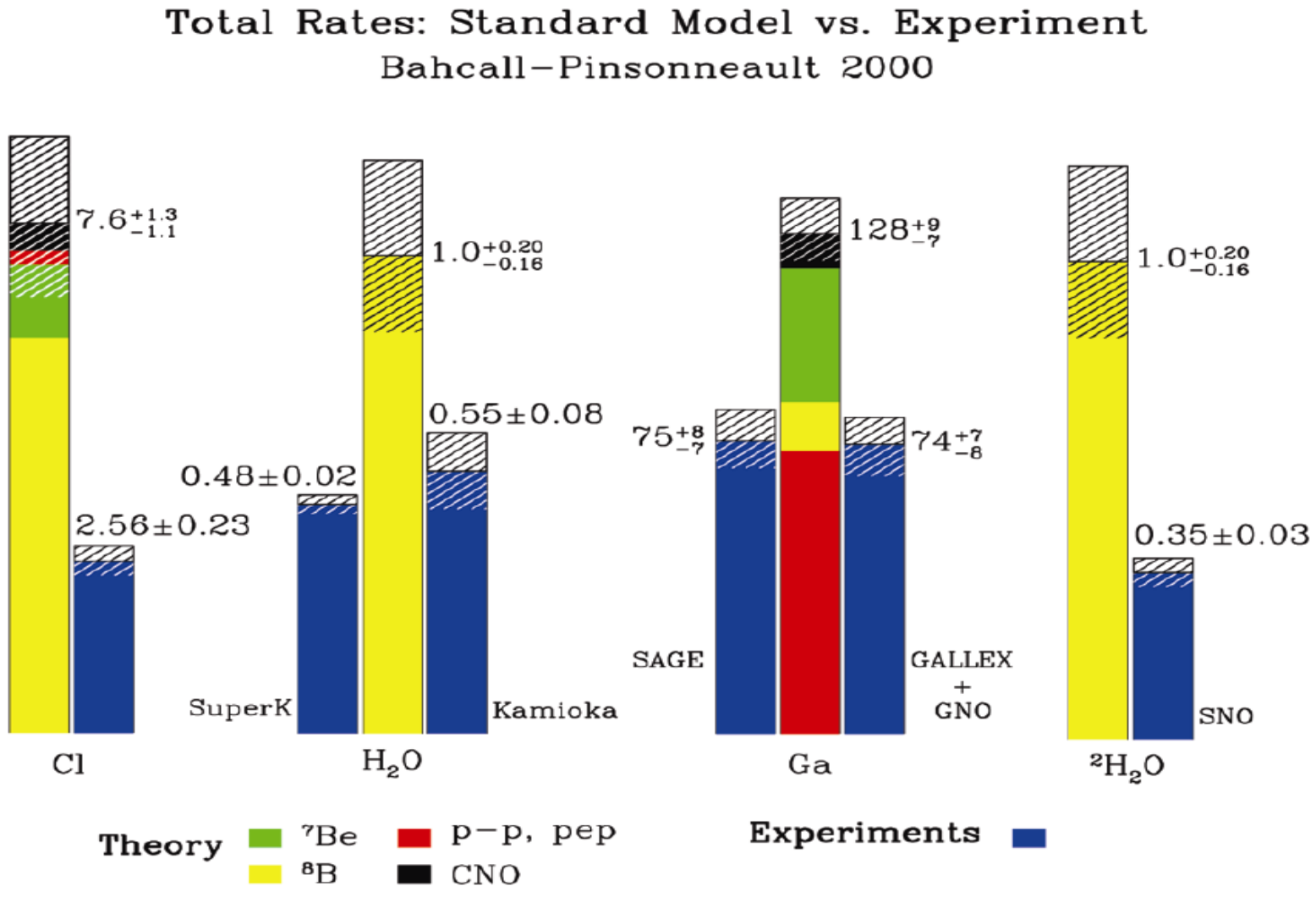
理论家 John Bahcall 负责建立标准太阳模型(SSM)，保证中微子通量的理论预言的正确性



太阳中微子


Gallium
Chlorine
Water
Bahcall–Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
pep→ ±2%
⁸B→ ±16%
hep→ ±16%
¹³N→
¹⁵O→
¹⁷F→
⁷Be→
±10.5%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
0.1
1
10

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
0.48±0.02
$1.0^{+0.20}_{-0.16}$
0.55±0.08
75^{+8}_{-7}
128^{+9}_{-7}
74^{+7}_{-8}
$1.0^{+0.20}_{-0.16}$
0.35±0.03
SuperK
Kamioka
SAGE
GALLEX
+
GNO
SNO
Cl
H_2O
Ga
^2H_2O
Theory
^{7}Be
^{8}B
p–p, pep
CNO
Experiments

SNO实验：另一个途径→利用重水做探测介质

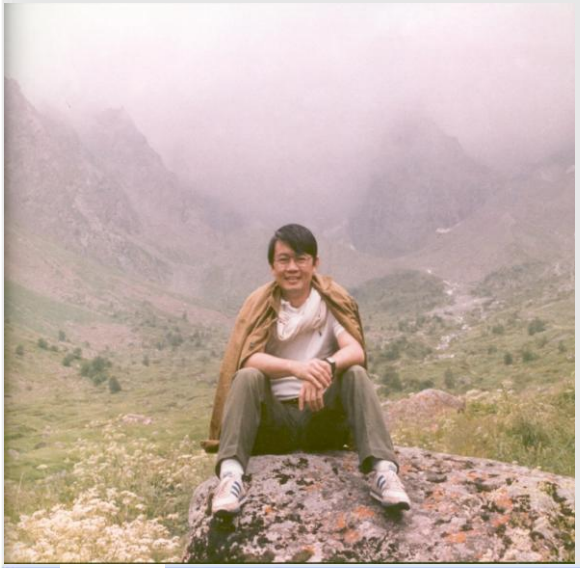
VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

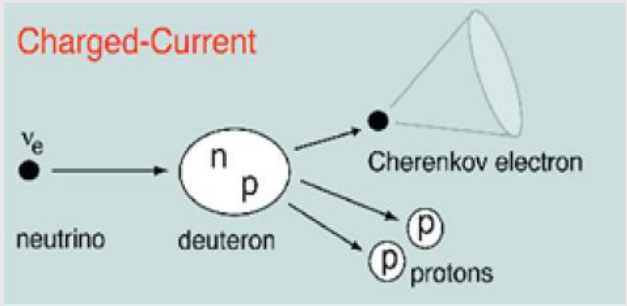
Direct Approach to Resolve the Solar-Neutrino Problem

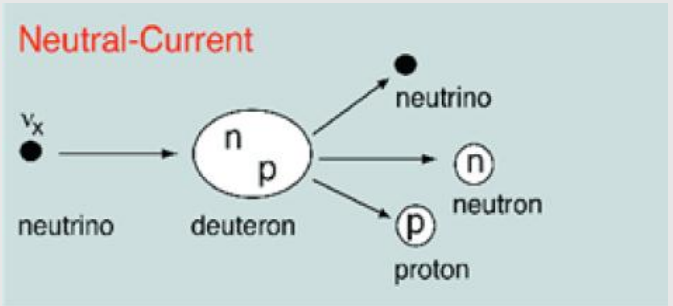
Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

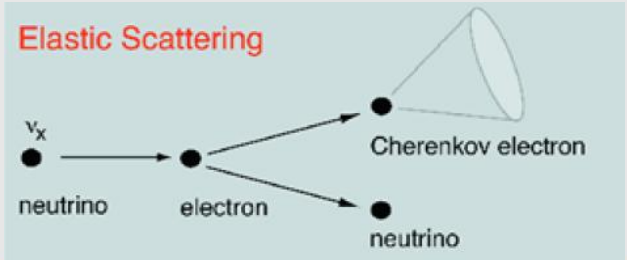
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis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

PACS numbers: 96.60.Kx, 14.60.Gh







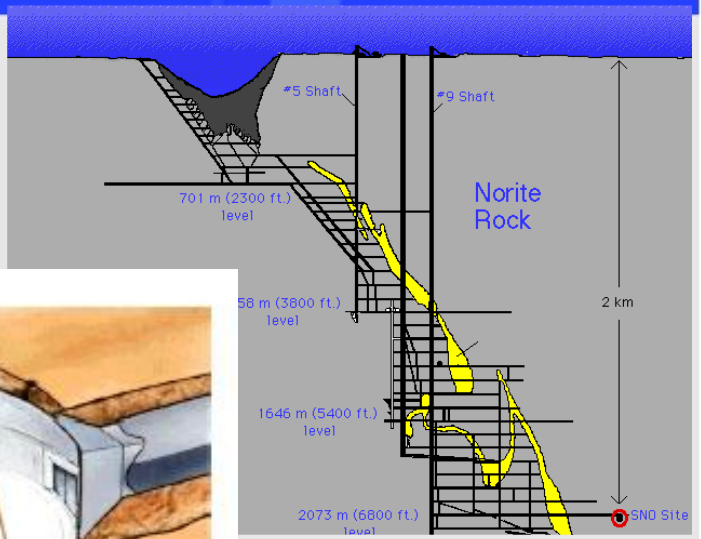


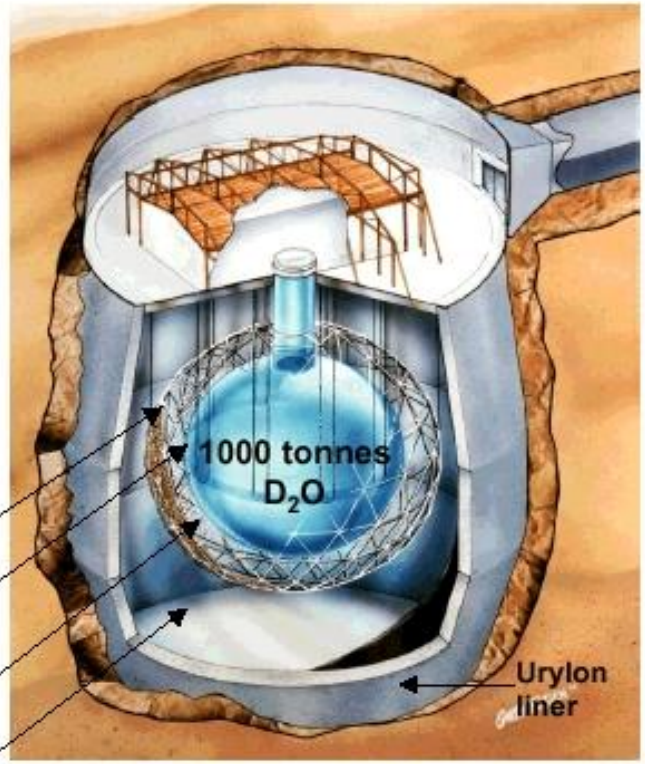
利用重水→一石三鸟
独立于标准太阳模型

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





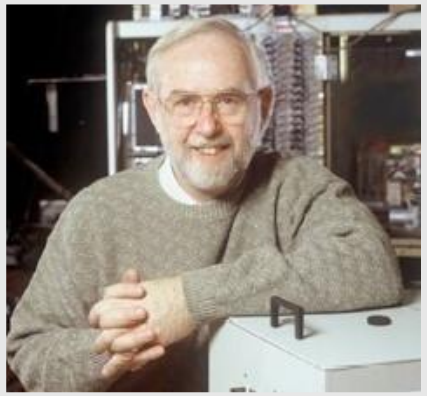
17.8m dia. PMT Support Structure
9456 PMTs, 56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

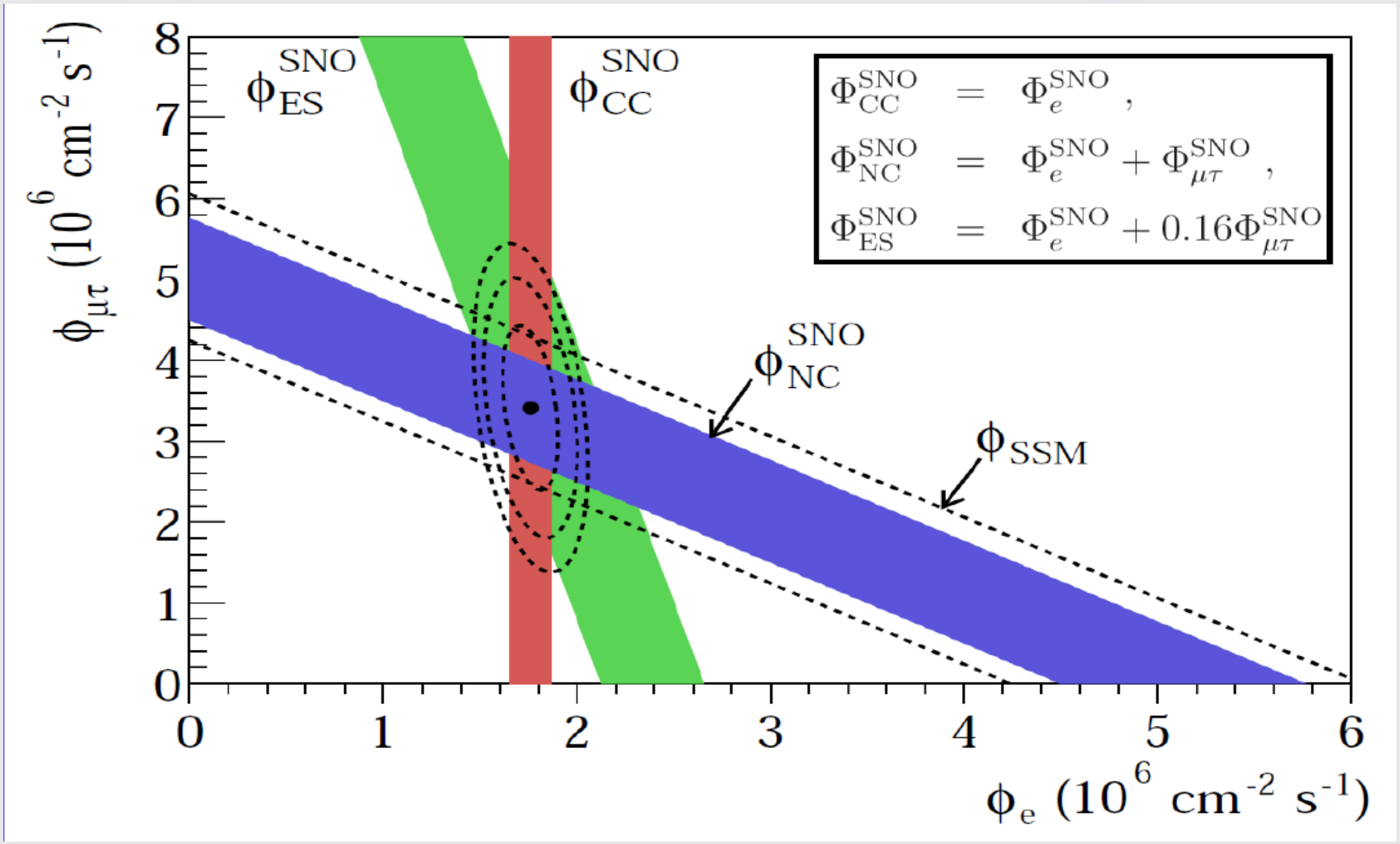
5300 tonnes of outer shielding H_2O

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

太阳中微子振荡证据

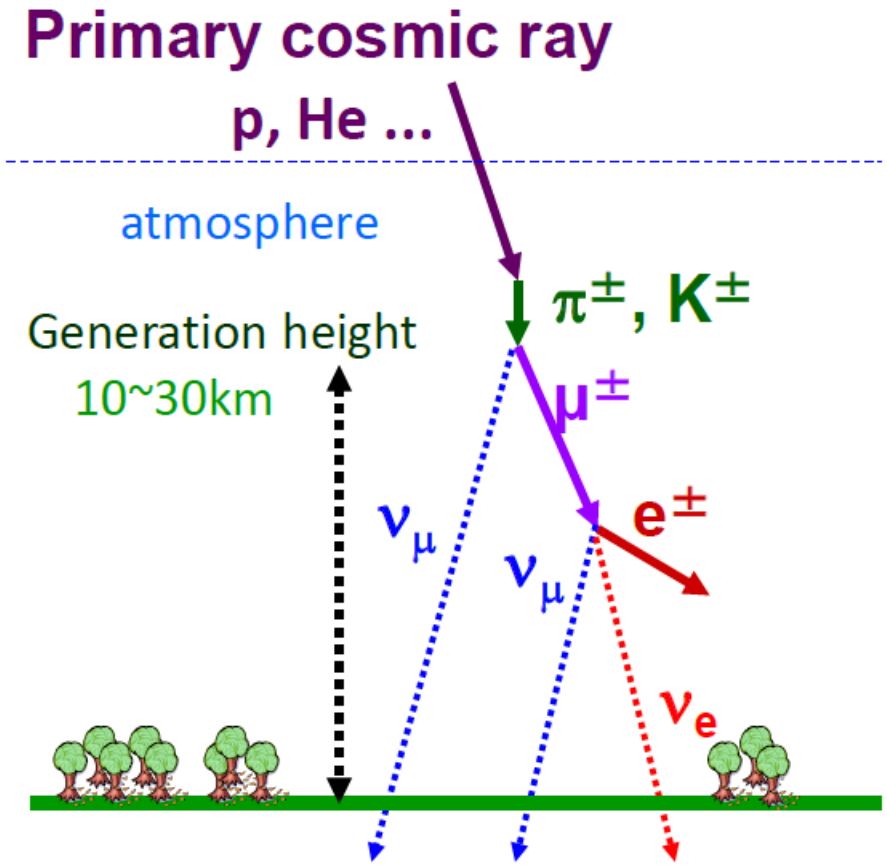

SNO
ϕ_{ES}
SNO
ϕ_{CC}
$\Phi_{CC}^{SNO} = \Phi_e^{SNO}$,
$\Phi_{NC}^{SNO} = \Phi_e^{SNO} + \Phi_{\mu\tau}^{SNO}$,
$\Phi_{ES}^{SNO} = \Phi_e^{SNO} + 0.16\Phi_{\mu\tau}^{SNO}$
SNO
ϕ_{NC}
ϕ_{SSM}
$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8

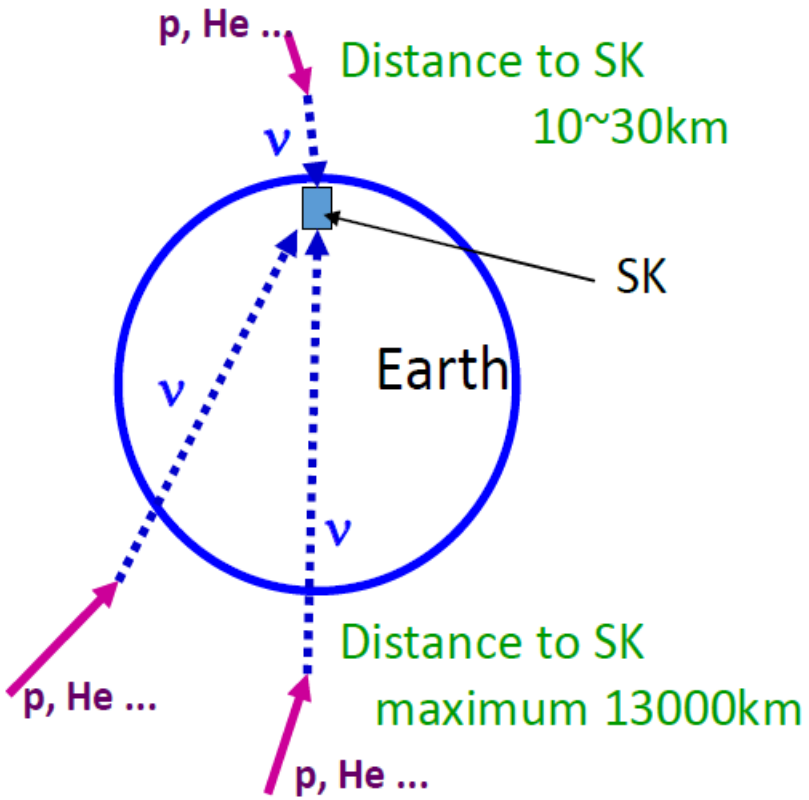
Part III:

大气中微子

大气中微子

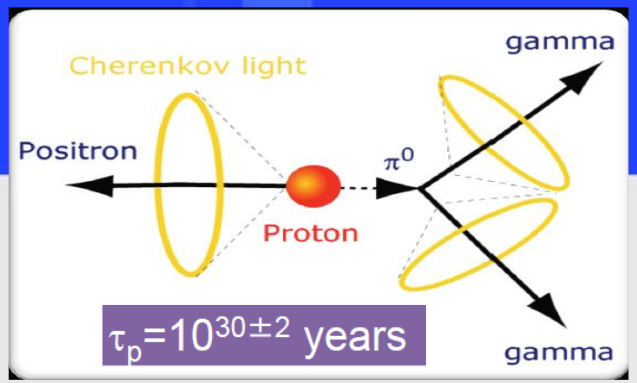
原初宇宙线和大气的相互作用，产生pi，K等粒子，从而产生μ子以及中微子



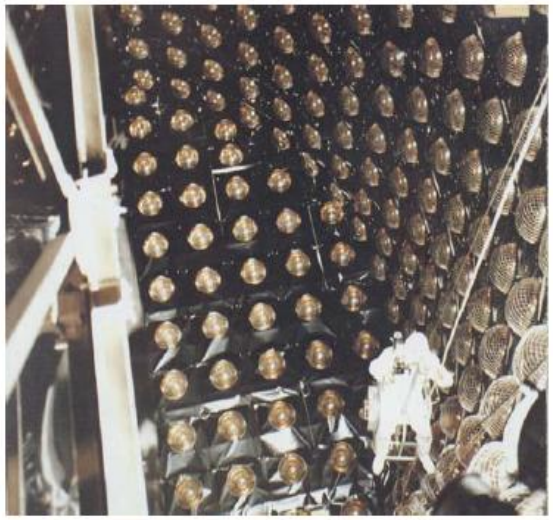


基本性质：四种味道、能量范围广(100 MeV~100 TeV)、传播距离范围广

大气中微子反常：质子衰变

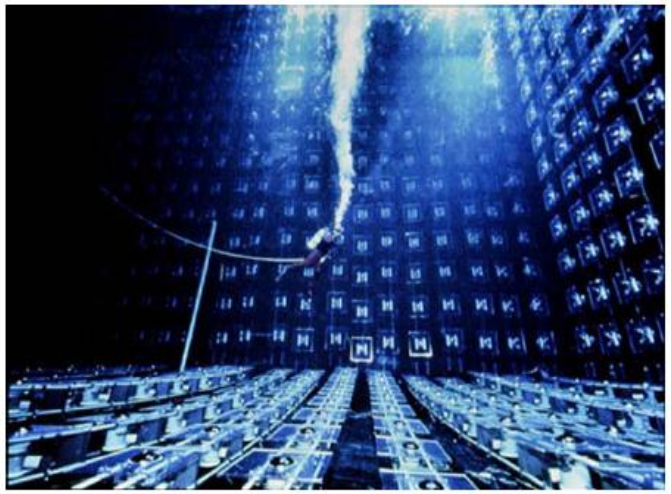


1970年代大统一取得了重要进展→质子不稳定
大气中微子是质子衰变研究的重要本底
1988年Kajita的博士论文发现了大气中微子反常现象



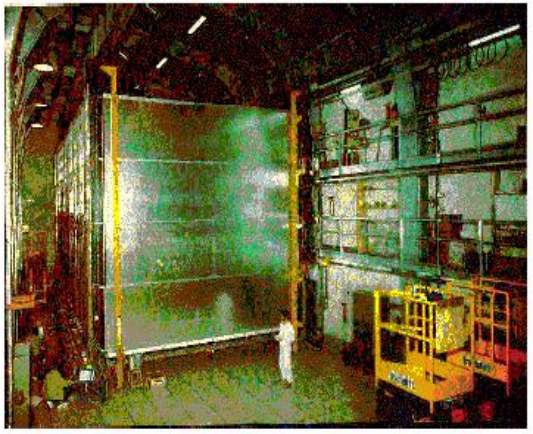
Kamiokande
(1000ton)

IMB
(3300ton)



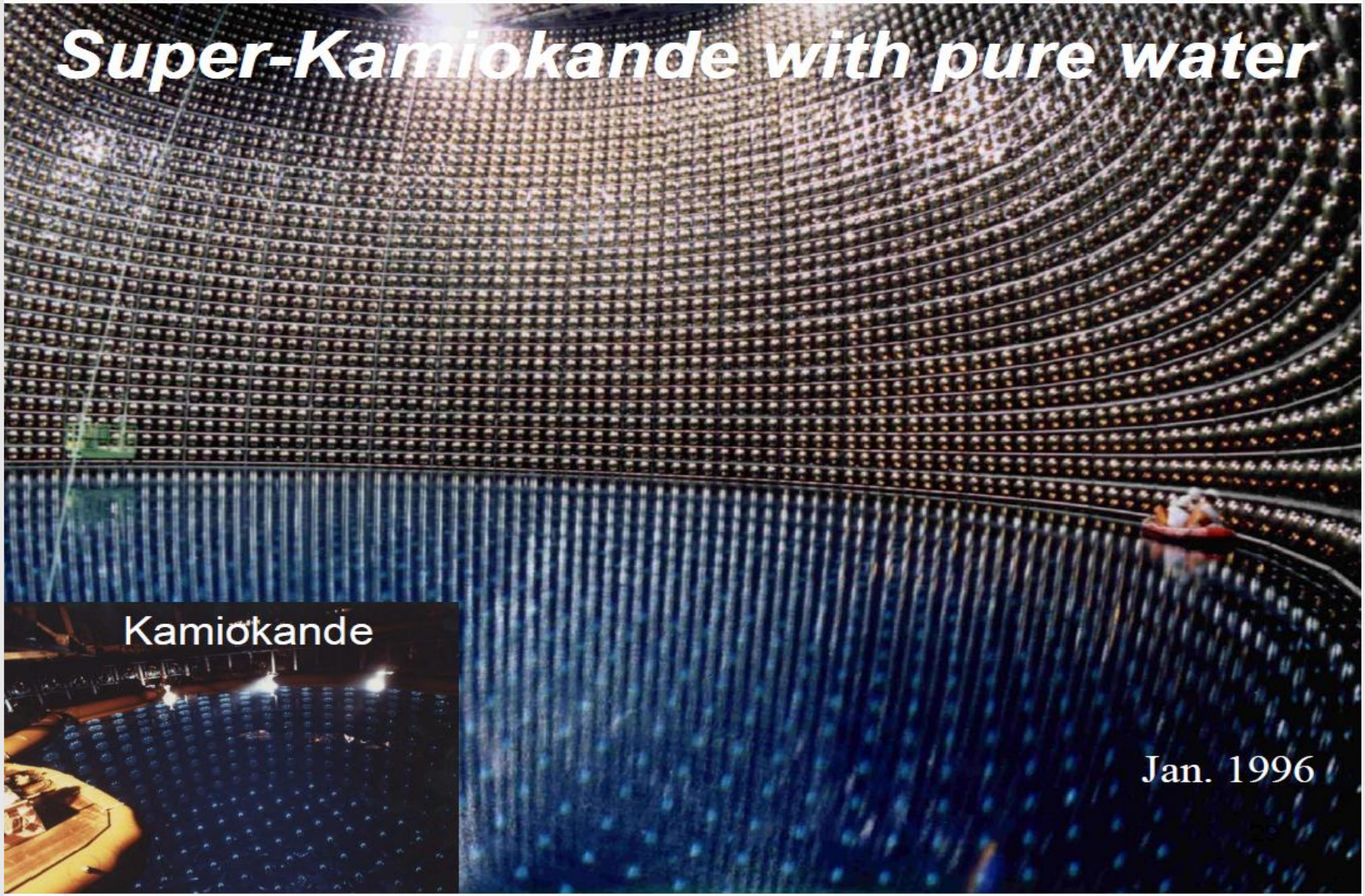
NUSEX
(130ton)

Frejus
(700ton)

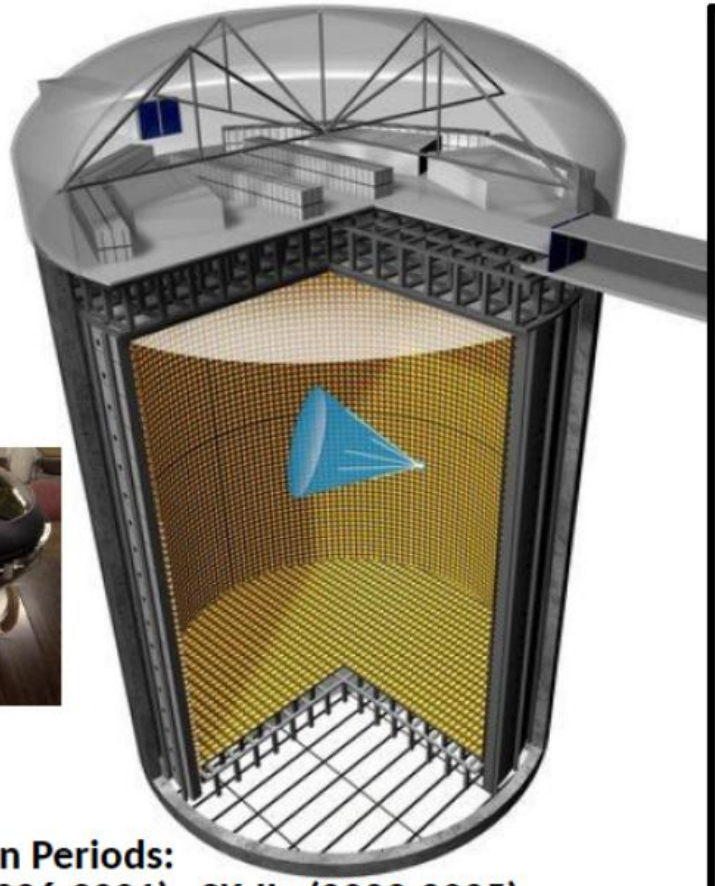


These experiments observed many contained atmospheric neutrino events (background for proton decay).

超级神岗实验：Super-Kamiokande



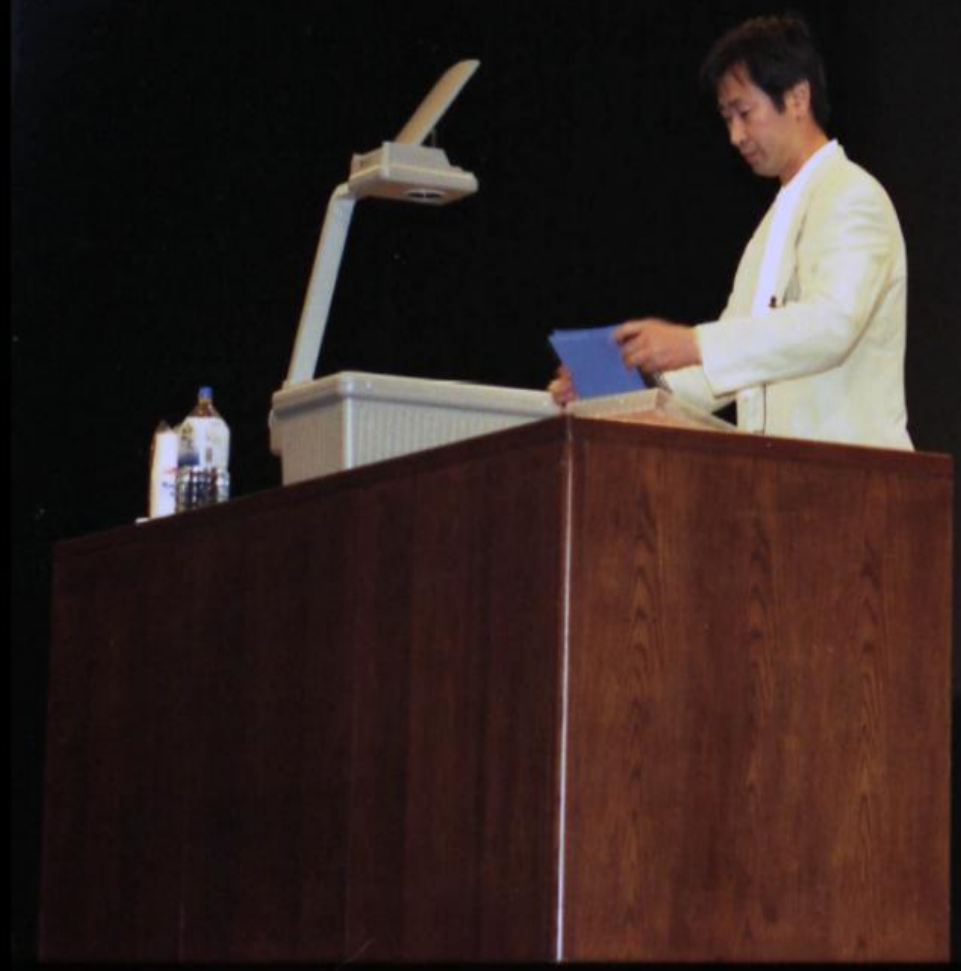
超级神岗实验：Super-Kamiokande



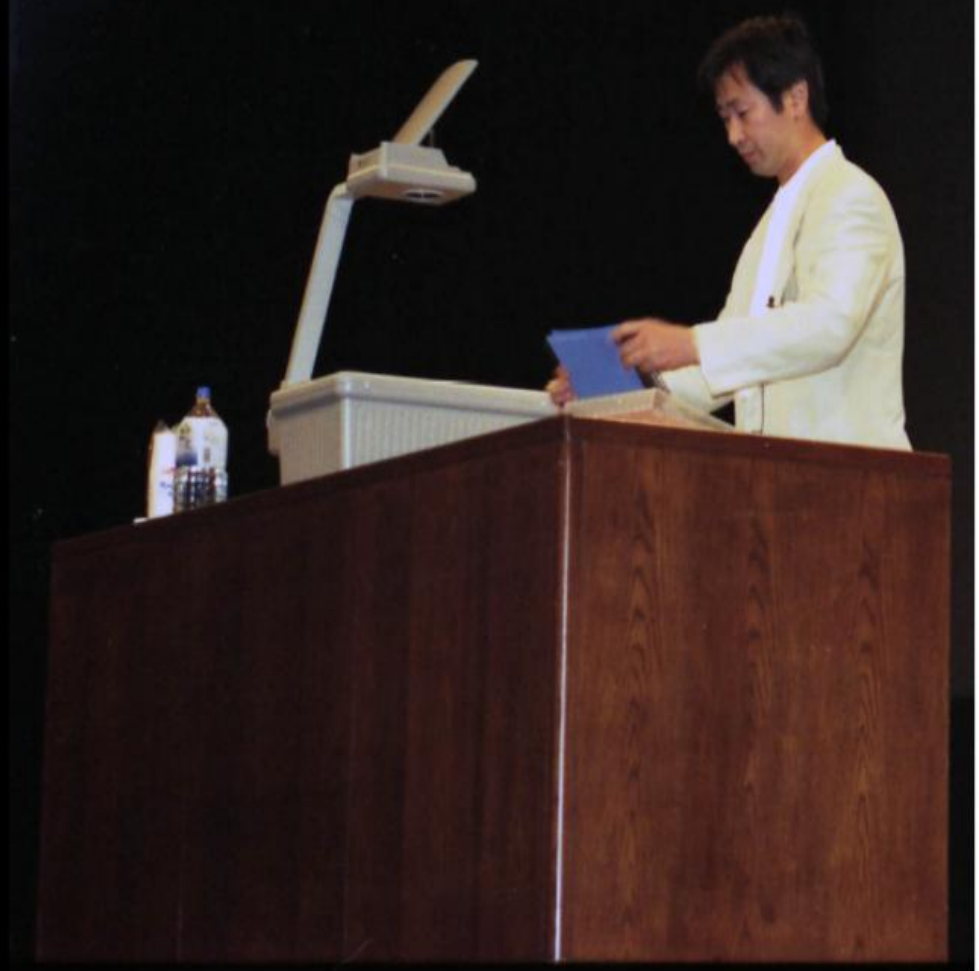
Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III (2005-2008) SK-IV (2008-Present)

- 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

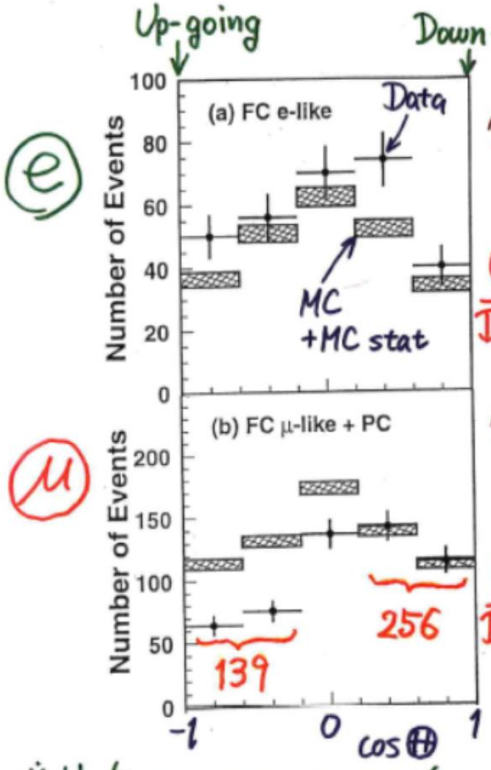
Neutrino 1998, Takayama, Japan
33 kton years of data (535 days)



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



Zenith angle dependence (Multi-GeV)



e: χ^2(shape) = 2.8/4 dof

$\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

μ: χ^2(shape) = 30/4 dof

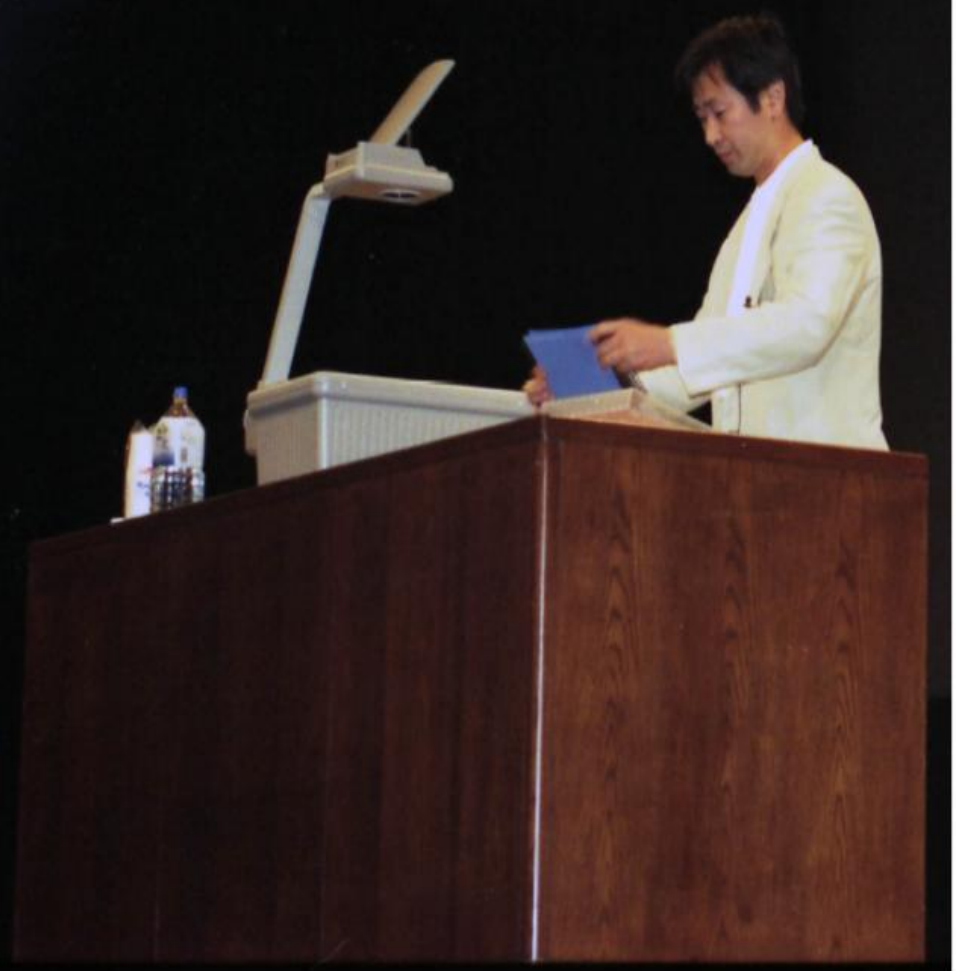
$\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$ (6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation ..... ≲ 1%
1km rock above SK .... 1.5%) 1.8%

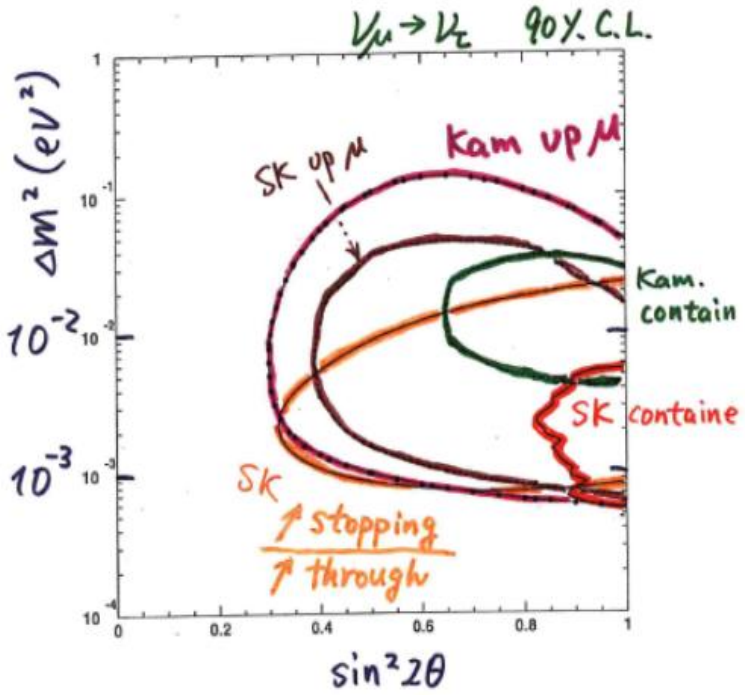
Data (Energy calib. for ↑↓ 0.7%
Non ν Background .....< 2%) 2.1%

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



Summary

Evidence for ν_μ oscillations



- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

Part IV:

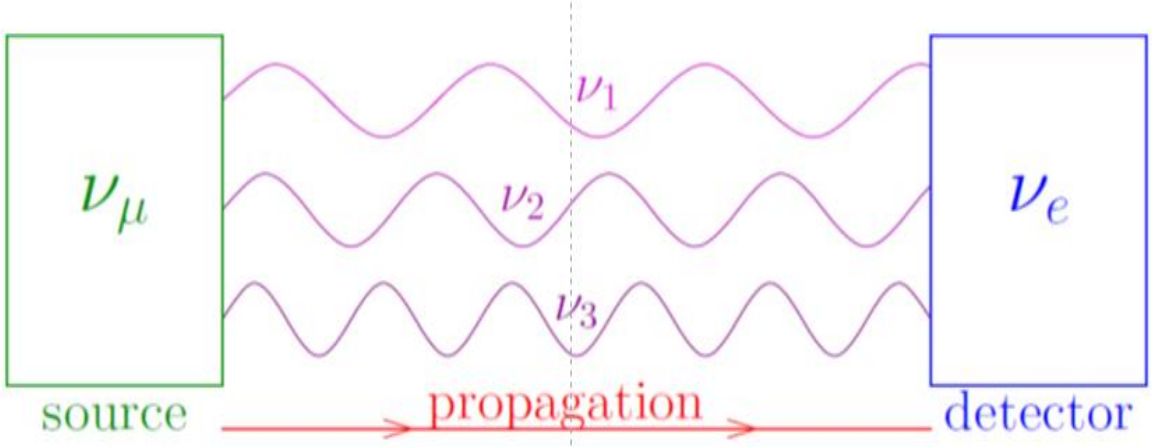
中微子振荡理论

中微子振荡：理论框架

Two-flavor mixing $\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$

Pontecorvo, 1957; Maki, Nakagawa, Sakata, 1962

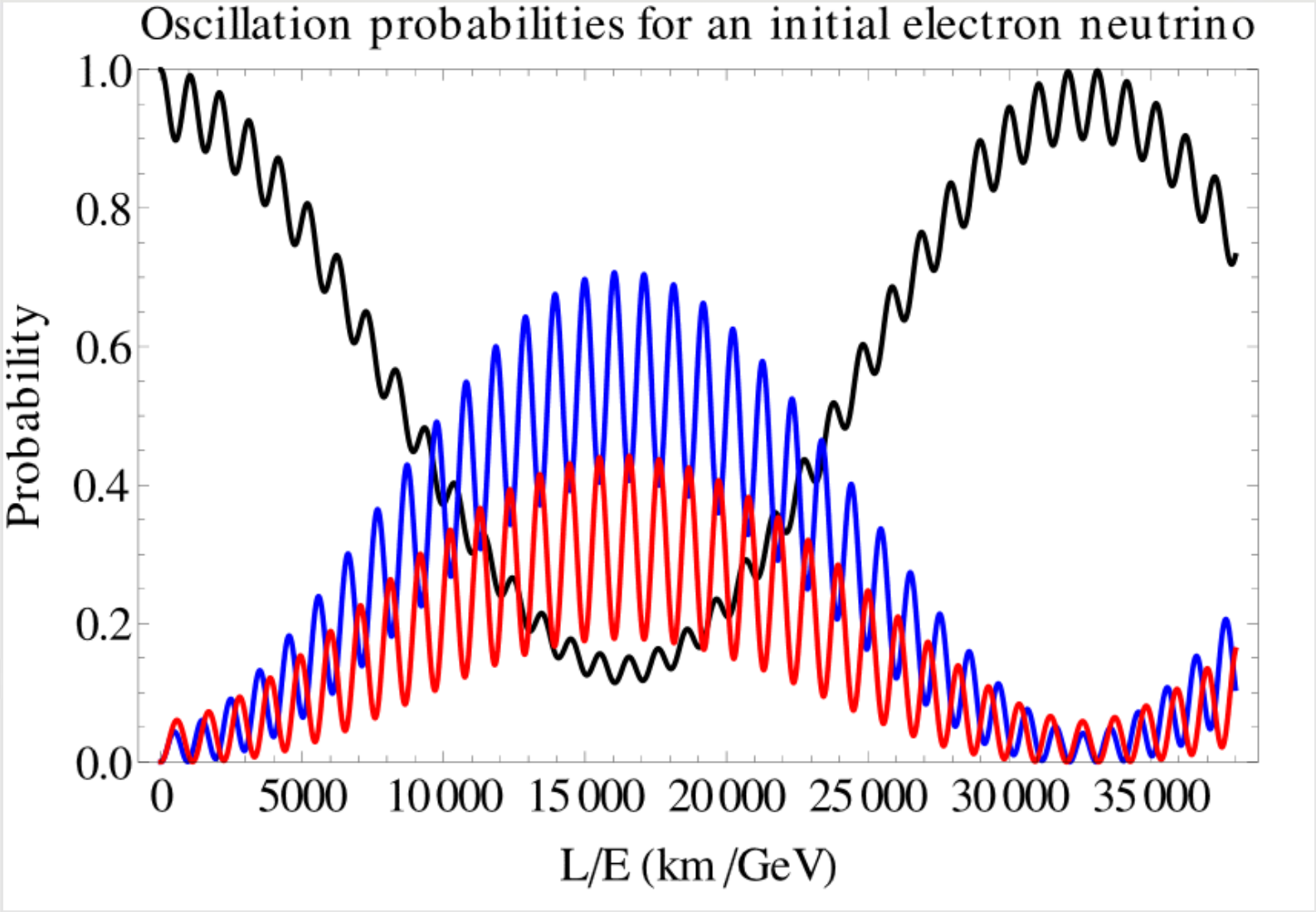
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$$\sum_{k>j} \mathrm{Re}\left[U_{ek}U^*_{\mu k}U^*_{ej}U_{\mu j}\right]\sin^2\left(\frac{\Delta m^2_{kj}L}{4E}\right)$$

Neutrino Oscillations: quantum phenomena of massive neutrinos at the macroscopic distances

中微子振荡：理论框架



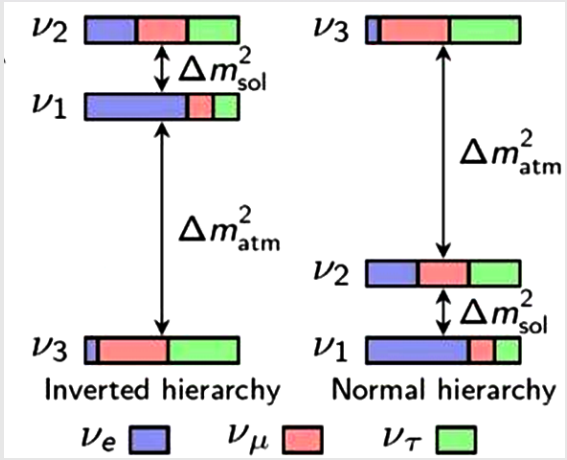
ν_e

ν_μ

ν_τ

中微子的基本参数

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$2.4\times10^{-3}\mathrm{eV}^2$

$7.5\times10^{-5}\mathrm{eV}^2$

- 3 混合角
- 1 或 3 CP破坏相位
- 2 质量平方差

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

$\theta_{23}\sim45°$ **Atmospheric Accelerator**

$\theta_{13}=?$ **Reactor Accelerator**

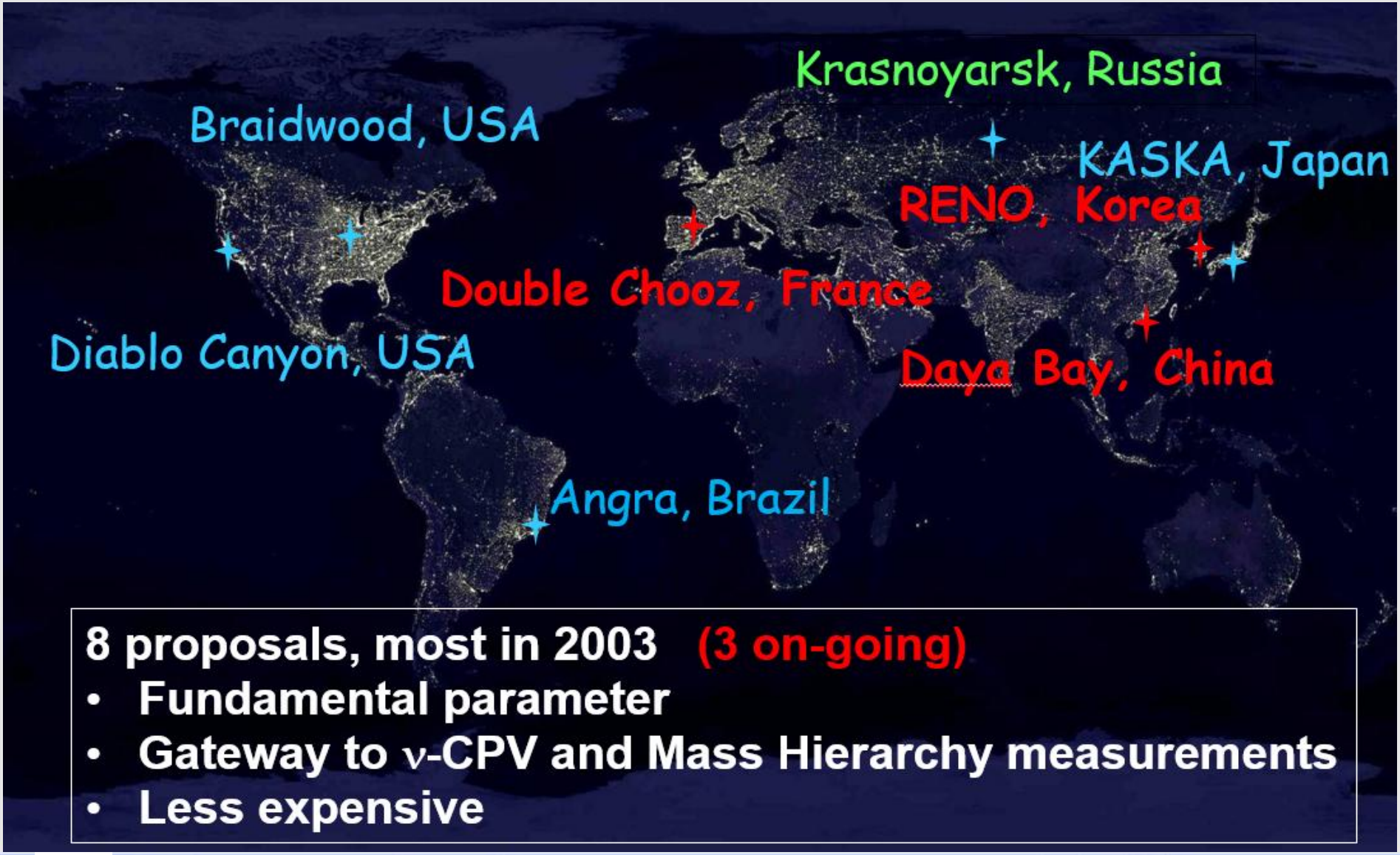
$\theta_{12}\sim34°$ **Solar Reactor**

0νββ

Part V:

大亚湾和江门中微子实验

Why theta(13) ?

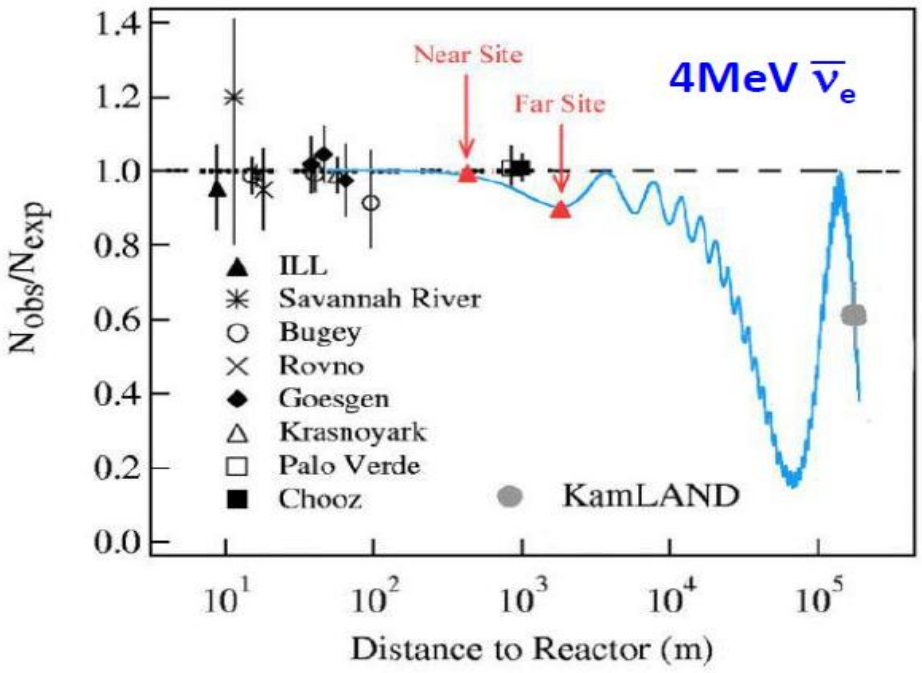


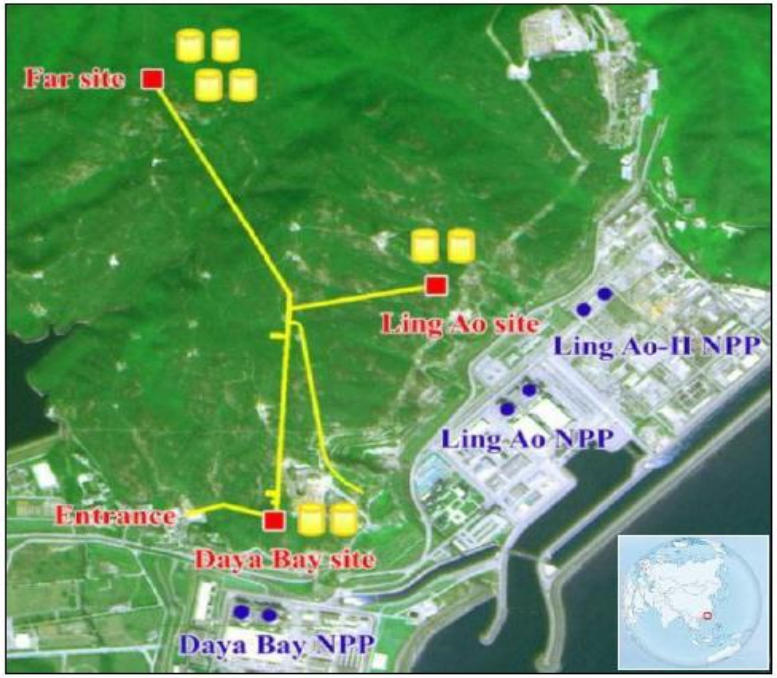
8 proposals, most in 2003 (3 on-going)

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

大亚湾反应堆中微子实验

2003年提议，2007年动工，2011年底开始运行





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

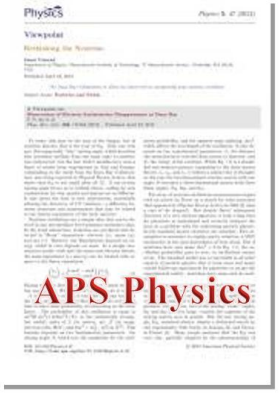
大亚湾实验成果得到国内外专家认可

2016年度国际“基础物理学突破奖”

2019年国际“未来科学大奖”

2016年度国家自然科学奖一等奖

- *Science*：中微子关键参数的测量标志着中国的崛起
- *Science在线*：中国物理学家揭示一个关键的中微子测量
- *Nature*：对中微子振荡的最高精度测量
- *APS Physics*：关于中微子的再思考——中国的大亚湾实验合作组发现超预期的大的中微子振荡
- *Physics Today*：反应堆中微子实验发现中微子振荡的第三个混合角
- *The Economist*：物理学家迫近揭开物质与反物质之谜
- *Discovery News*：中微子“变装”谜底解开



大亚湾实验2020年退役

θ_{13}的精度20% → 3%

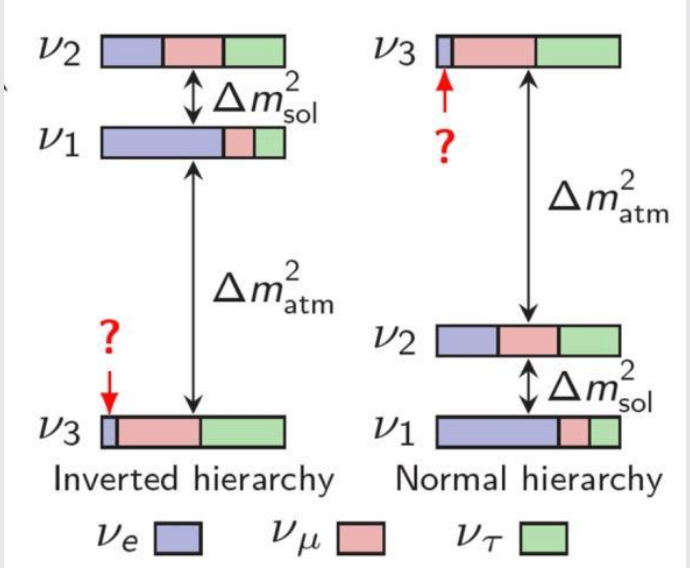
未来二十年保持国际最高精度。

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。

最新的中微子振荡的图像

在三味中微子框架下：

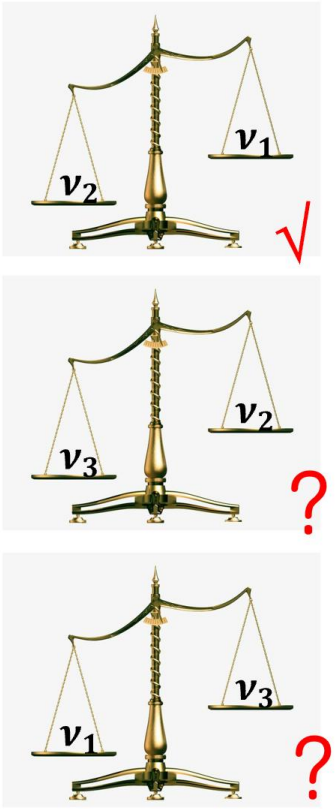
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



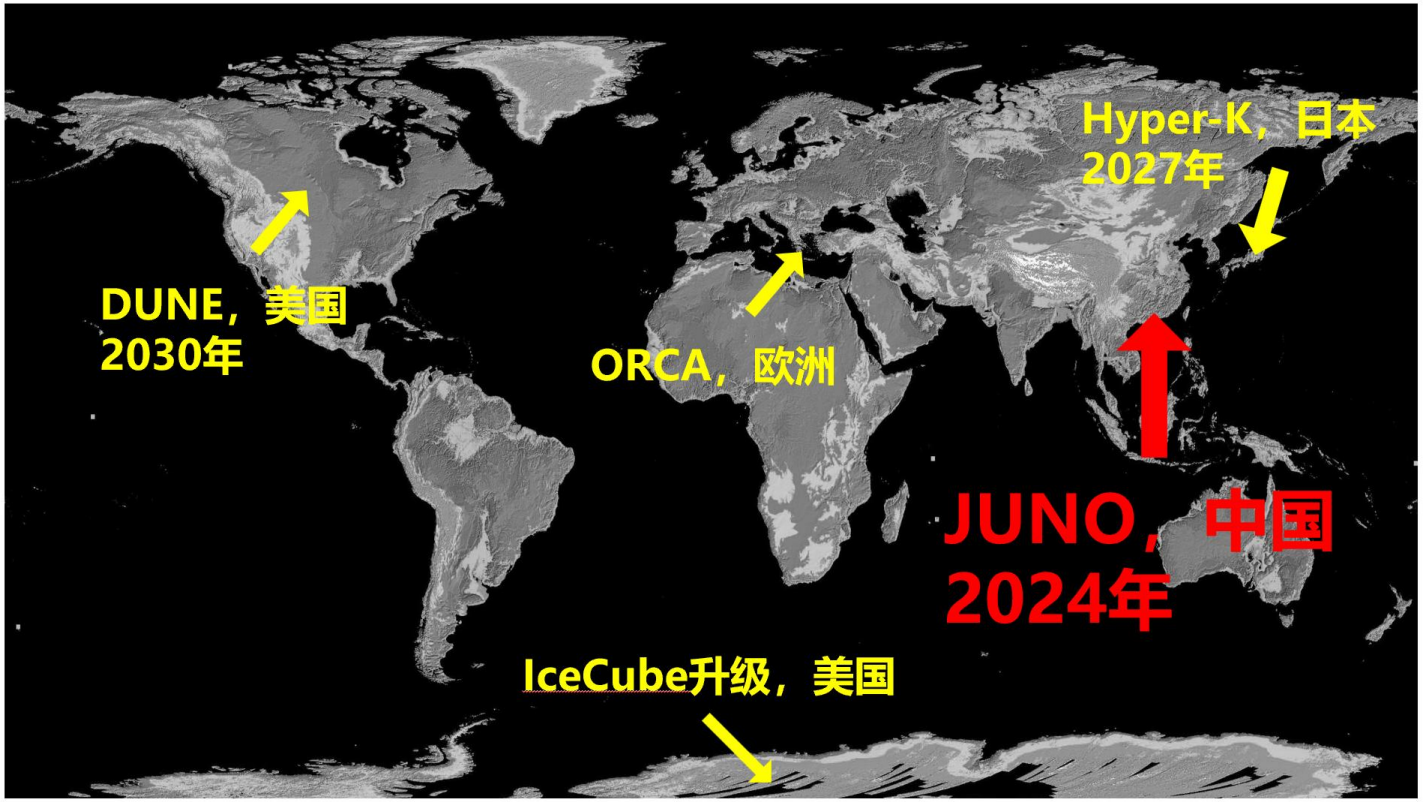
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho}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

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

JUNO: 江门中微子实验



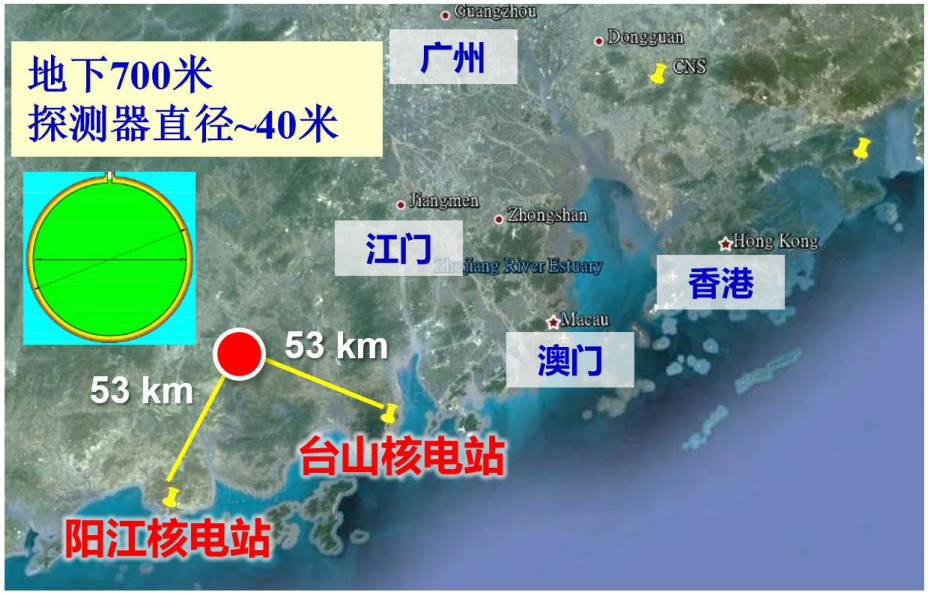
给中微子称重

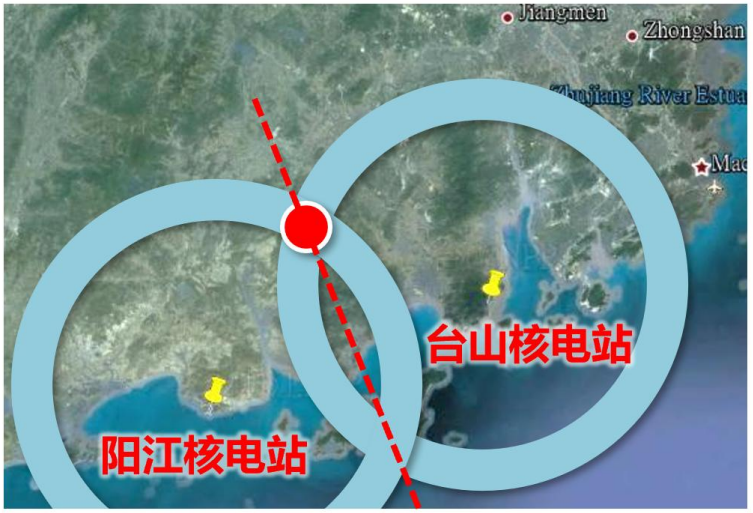


江门实验（JUNO）：唯一一个通过反应堆中微子确定质量顺序的实验。

JUNO: 江门中微子实验

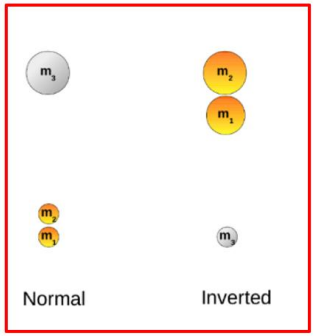
- 中科院先导专项，2013年立项，2015年开始建设，预计2024年运行。
- 国际合作：18个国家和地区，74个单位，725名合作者

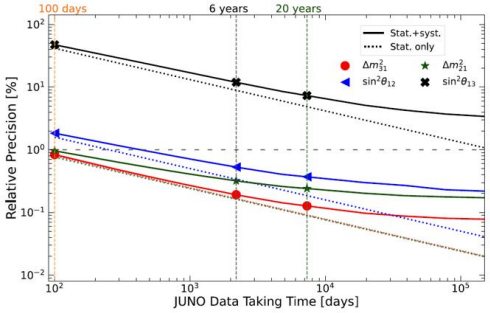




- 物理要求实验点只能在距离反应堆50-60公里之间且到所有反应堆距离相等
- 实验点有山（越高越好）
- 实验点选址：江门开平市金鸡镇打石山

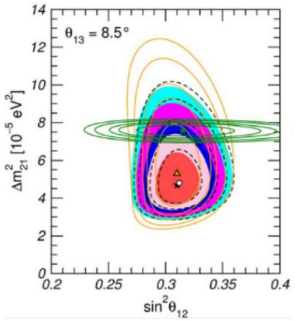
JUNO: 物理目标





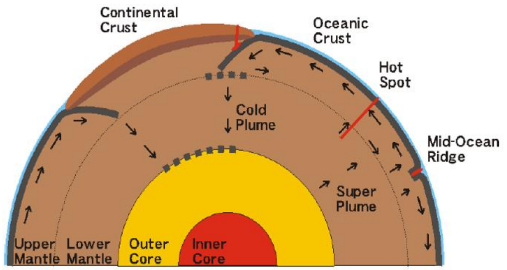
测量振荡参数到1%精度

3年



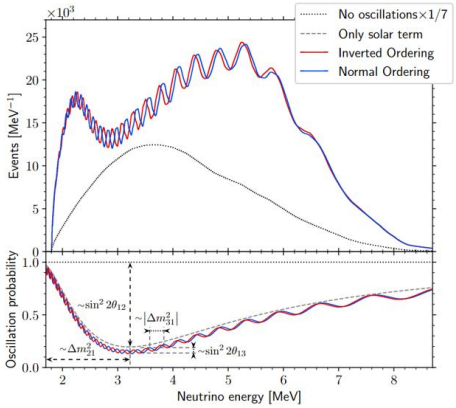
太阳中微子

3-5年



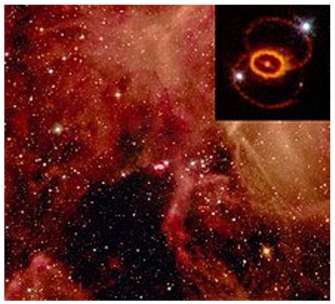
确定地球物理模型

6-10年



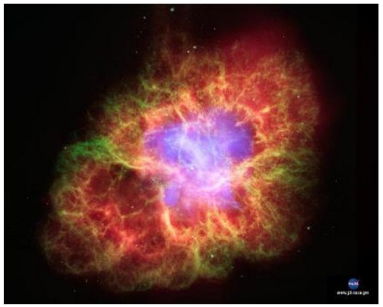
中微子质量顺序

~6年



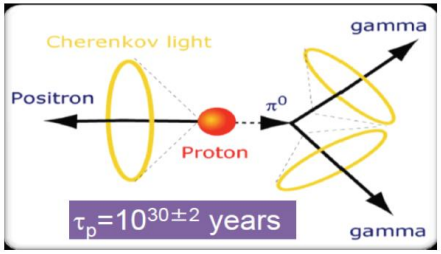
超新星背景中微子

3-5年



等待超新星爆发

任何时间

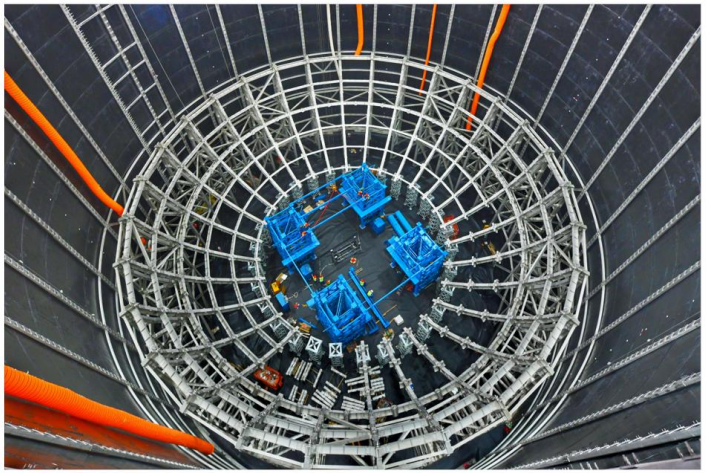
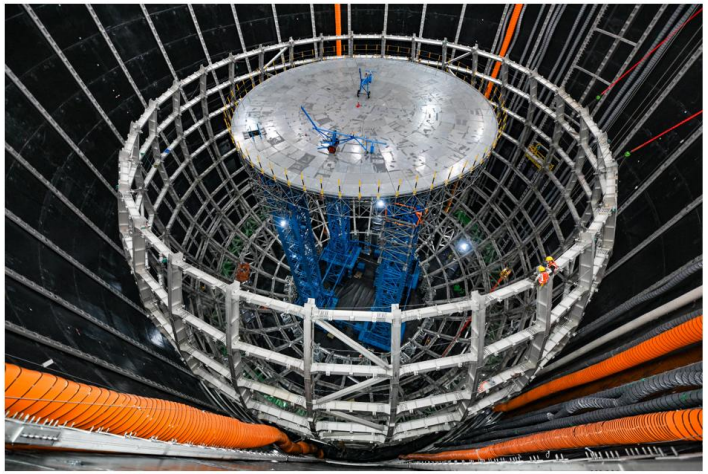
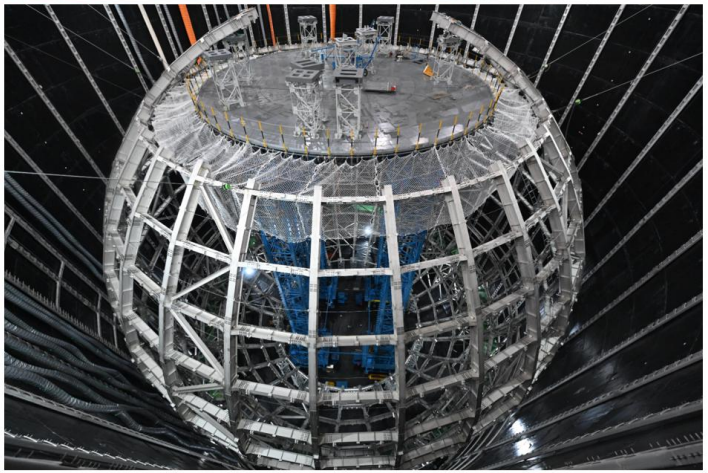
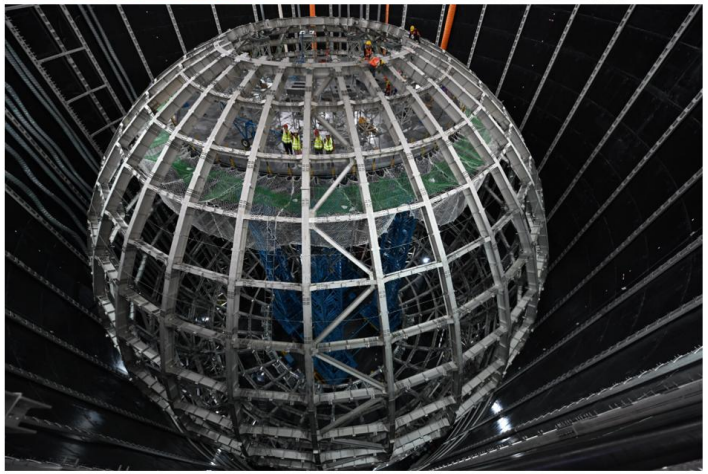


探索核子衰变

5-10年

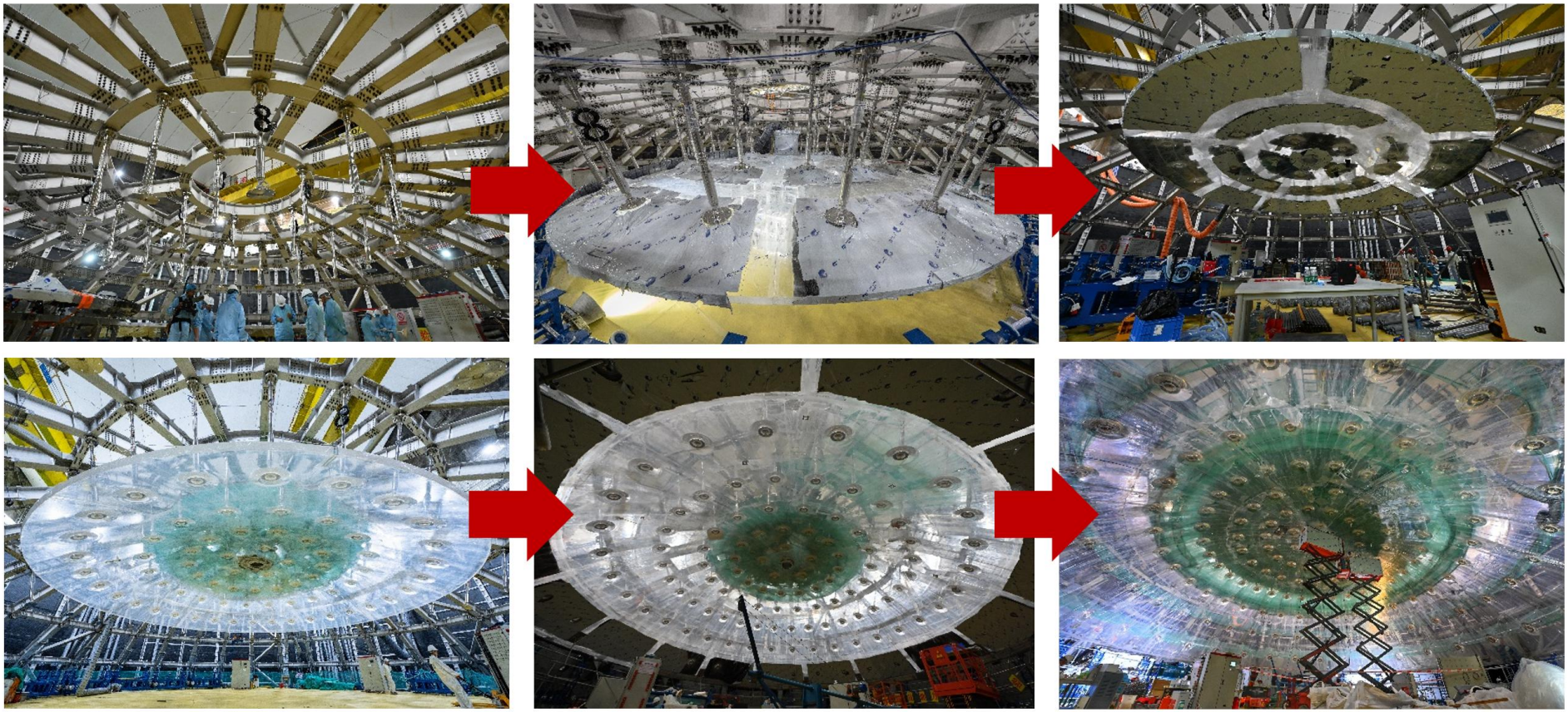
JUNO: 从地上到地下

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

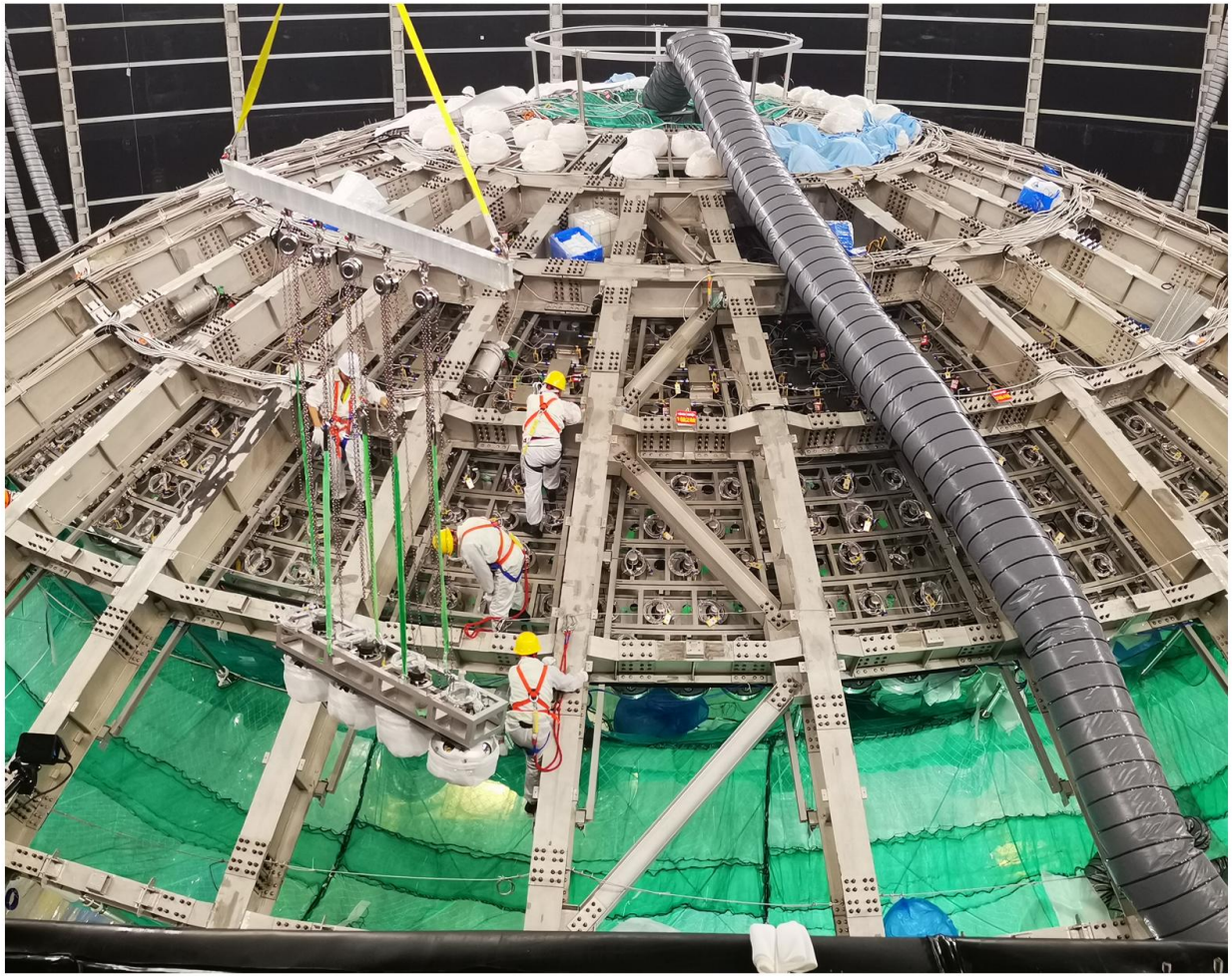
35米直径有机玻璃球是“粘”起来的!

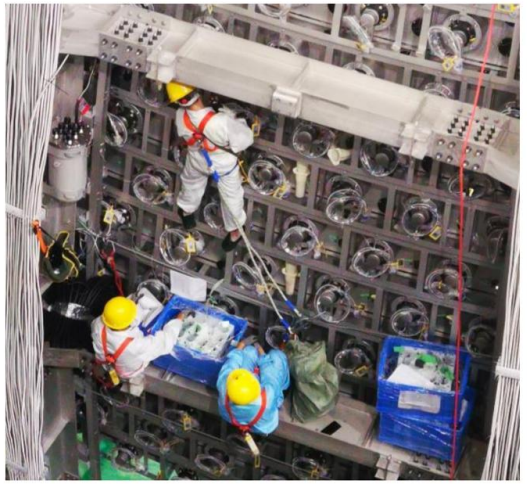
JUNO: 光电倍增管

探测器的眼睛：光电倍增管

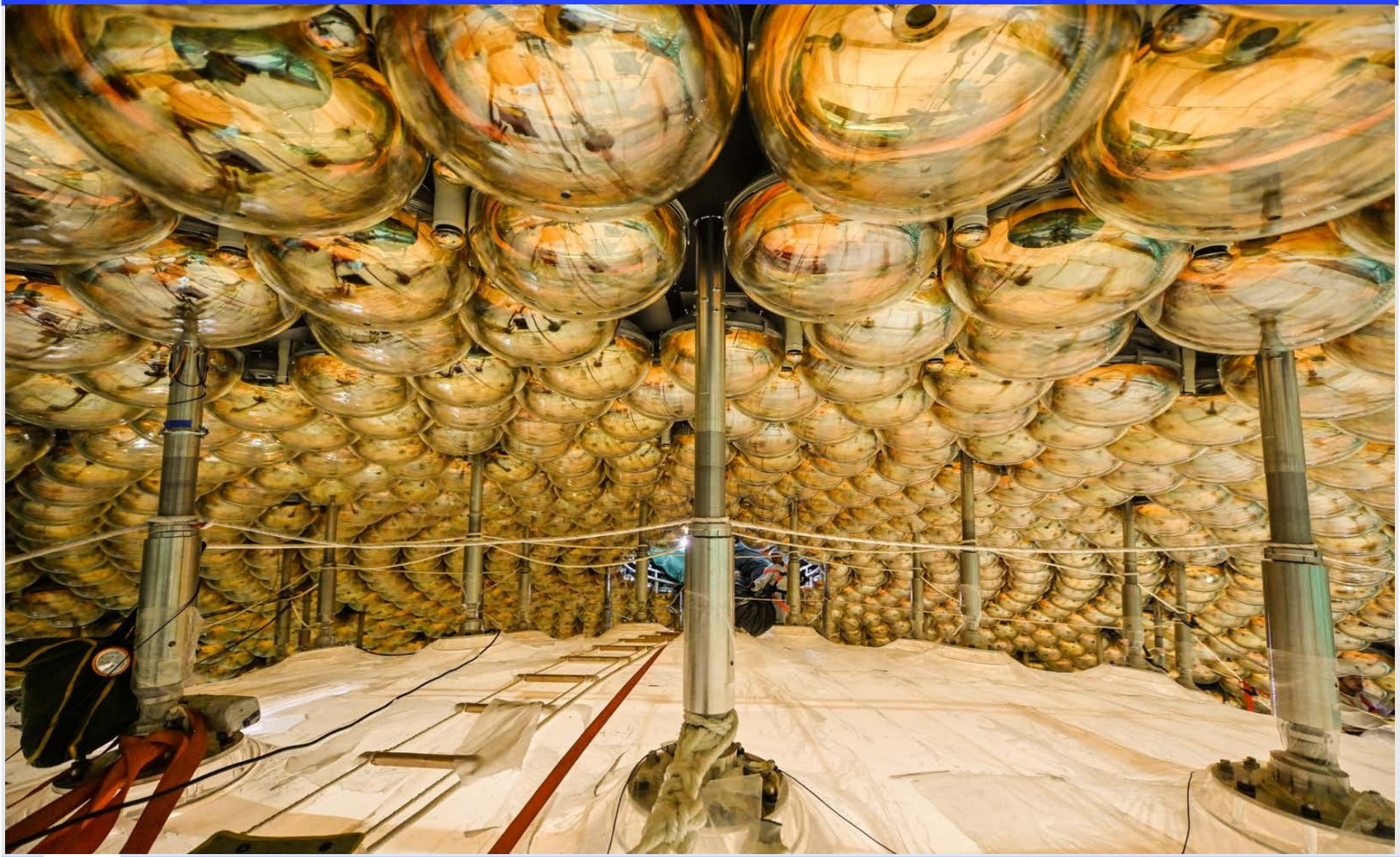
- 共45600支光电倍增管，通过光电效应探测微弱的光

JUNO: 光电倍增管



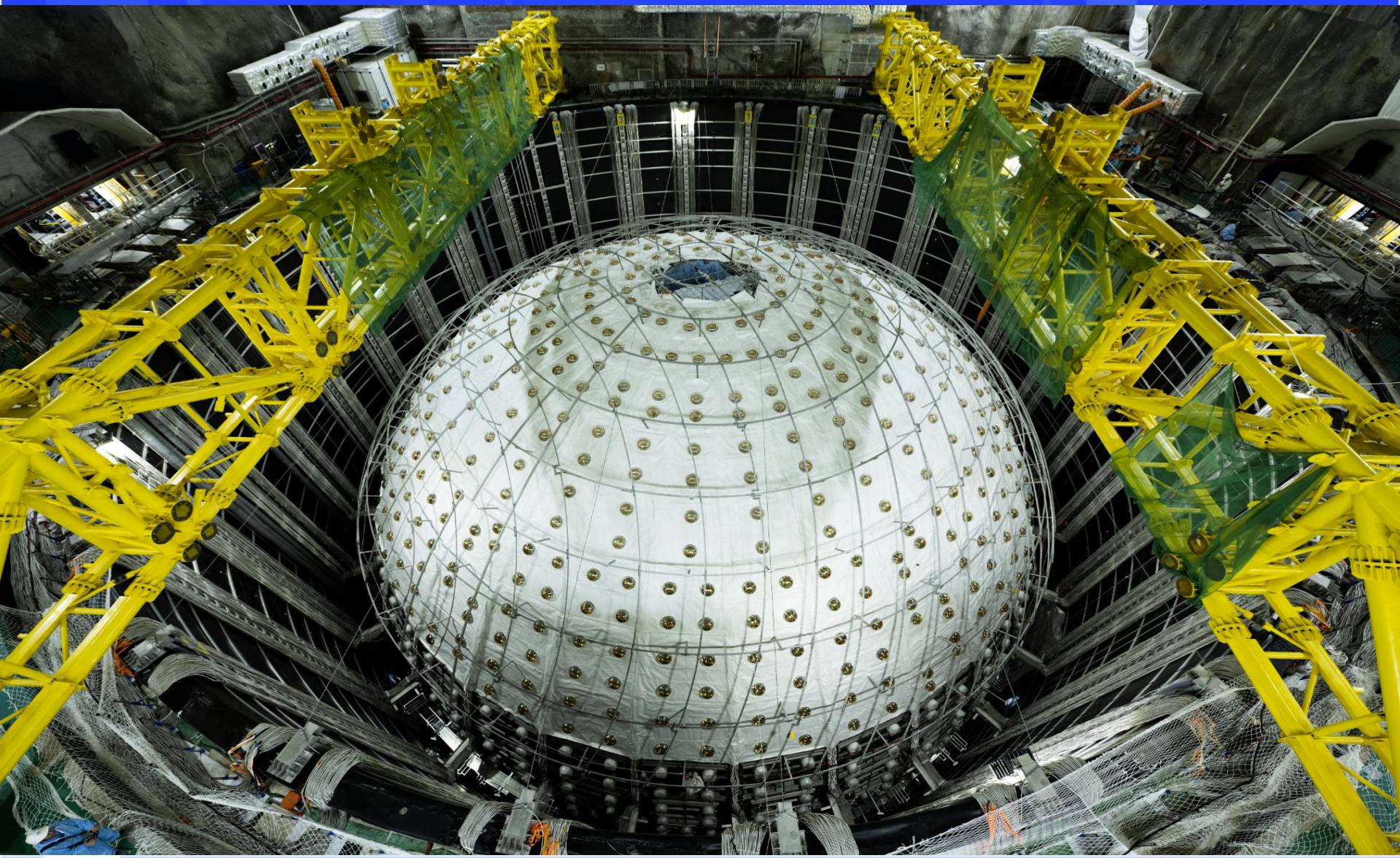


JUNO: 光电倍增管

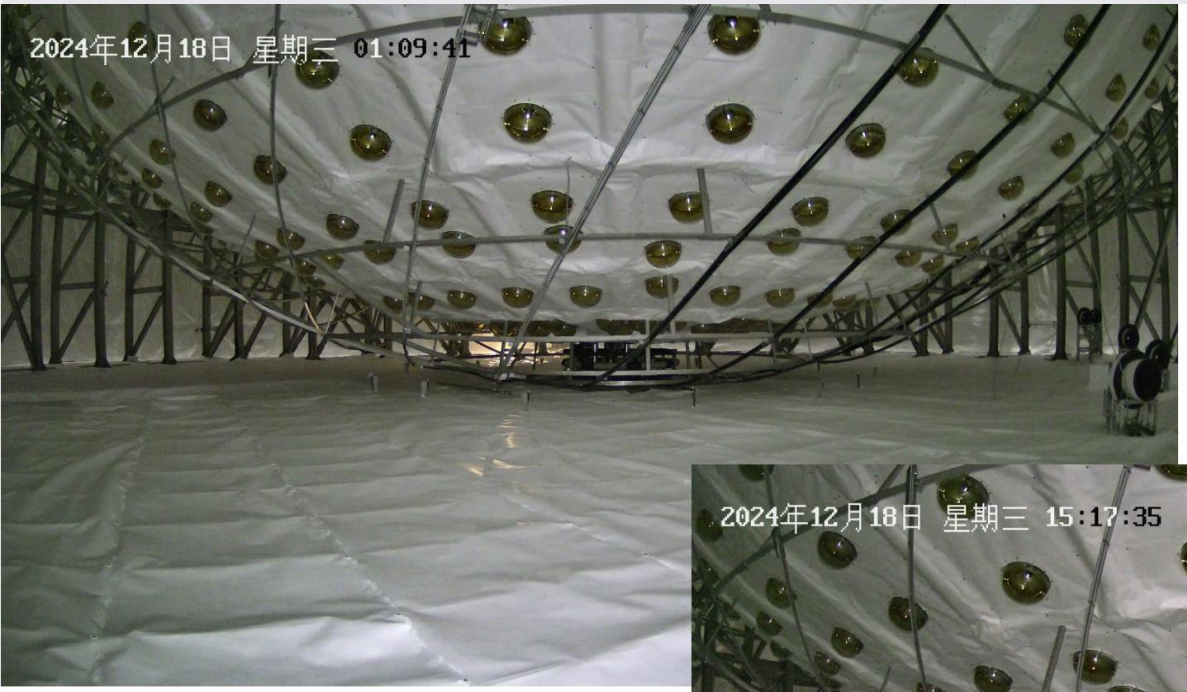


JUNO: 探测器全貌(2023)

JUNO: 探测器全貌(2024)



JUNO: 开始灌装(2024.12.18)



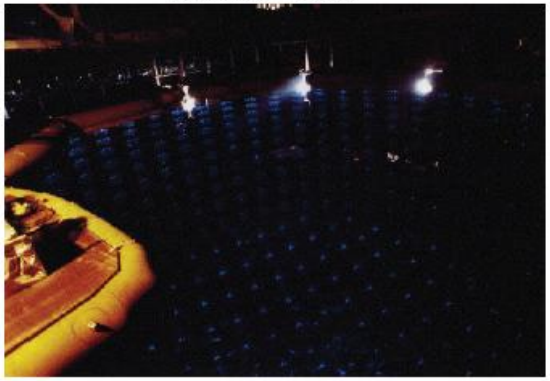
Water level is rising

Part V:

未来展望

日本路线：T2K→T2HK

Kamiokande (1983-1996)
3000 ton

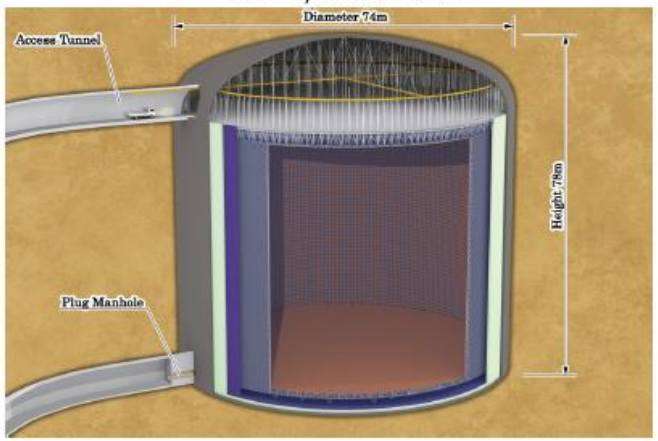


- Neutrinos from SN1987a.
- Atmospheric neutrino deficit.
- Solar neutrinos.

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 2027
260,000 ton



Physics programme:

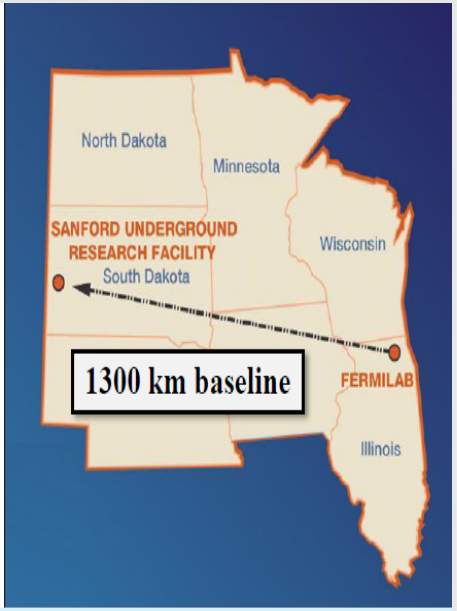
- Neutrino oscillations: Mass Hierarchy, Leptonic CP violation, θ_{23} Octant,...
- Nucleon decay: $p \rightarrow e^+\pi^0$, $p \rightarrow K^+\bar{\nu}$,...
- Neutrino astrophysics: Solar neutrinos, Supernova neutrinos, WIMP searches

美国路线： NOvA→DUNE

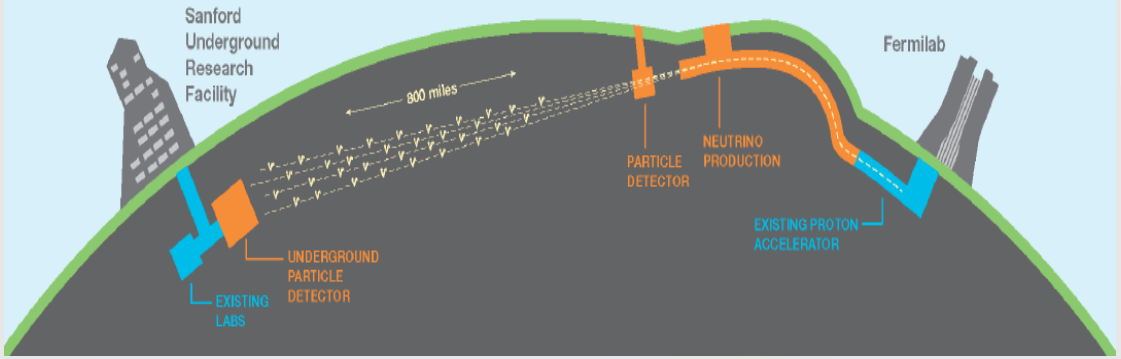
DUNE

Deep Underground Neutrino Experiment

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



2031年



中微子探针：地球

Electron-antineutrino from natural radioactive decay

$\bar{\nu}_e$ $4.1 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$

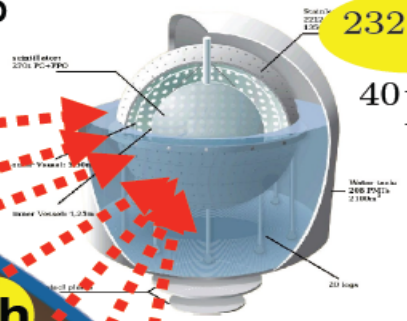
Geo-neutrinos

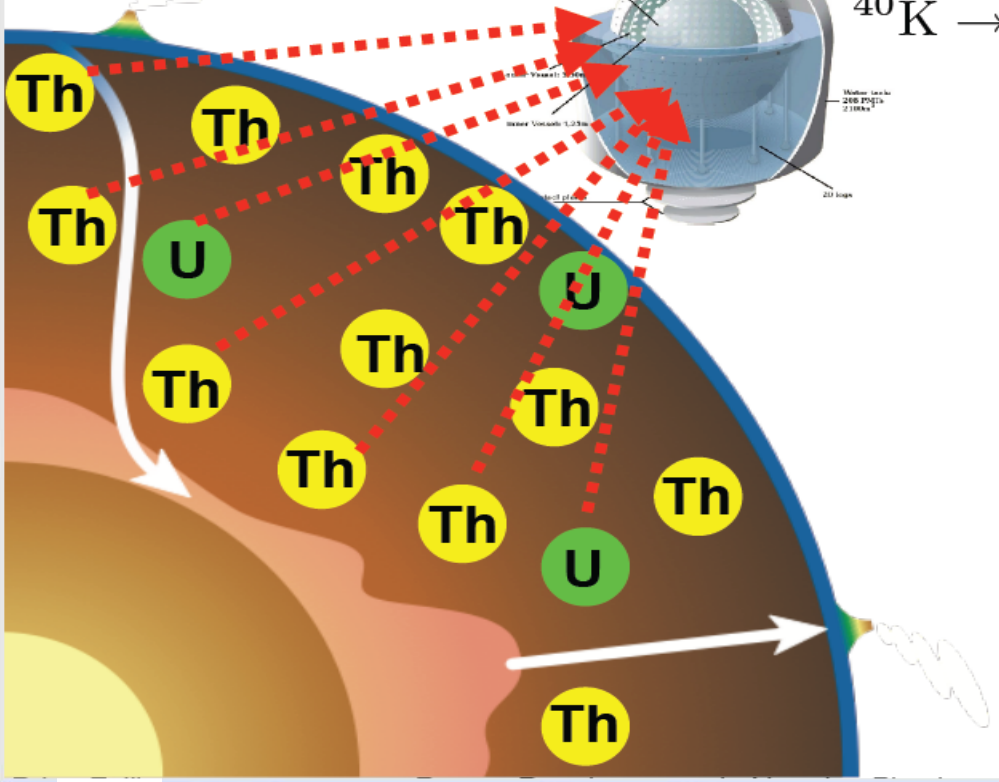
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_e + 51.7\,\mathrm{MeV}$

$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_e + 42.7\,\mathrm{MeV}$

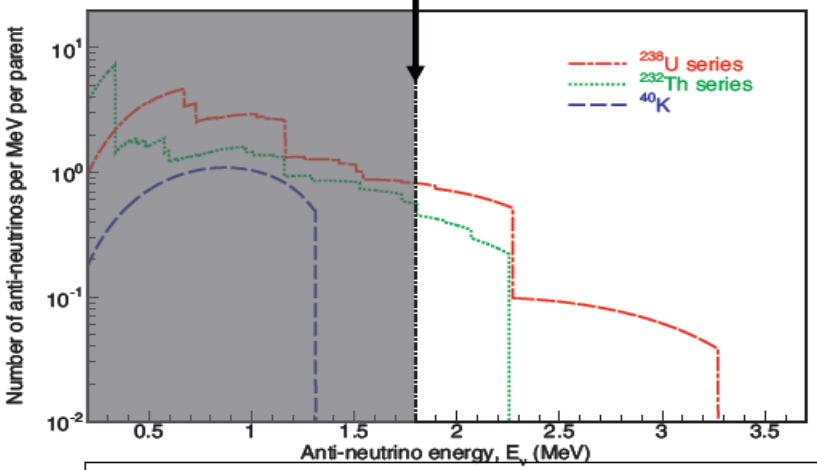
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_e + 1.311\,\mathrm{MeV}\ (89.28\%)$

anti-neutrino detector





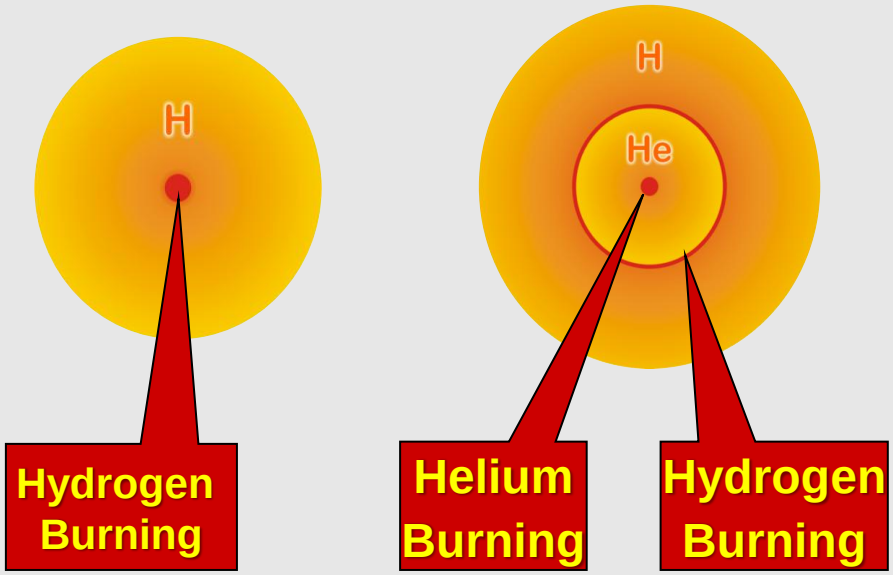
Energy threshold, 1.8 MeV

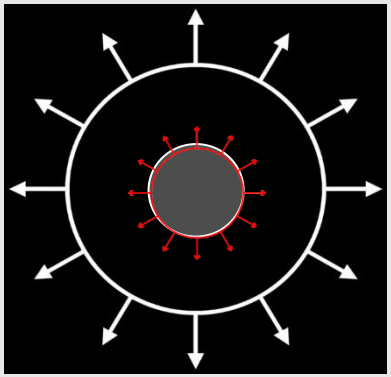


Only geo-neutrinos from U and Th are detectable

中微子探针：超新星爆发

Main-sequence star Helium-burning star





1. > 8...10 Solar Mass
2. Collapse → Bounce
3. Shock wave halted
4. ν energy deposited
5. Final SN explosion

Degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 8000$ km

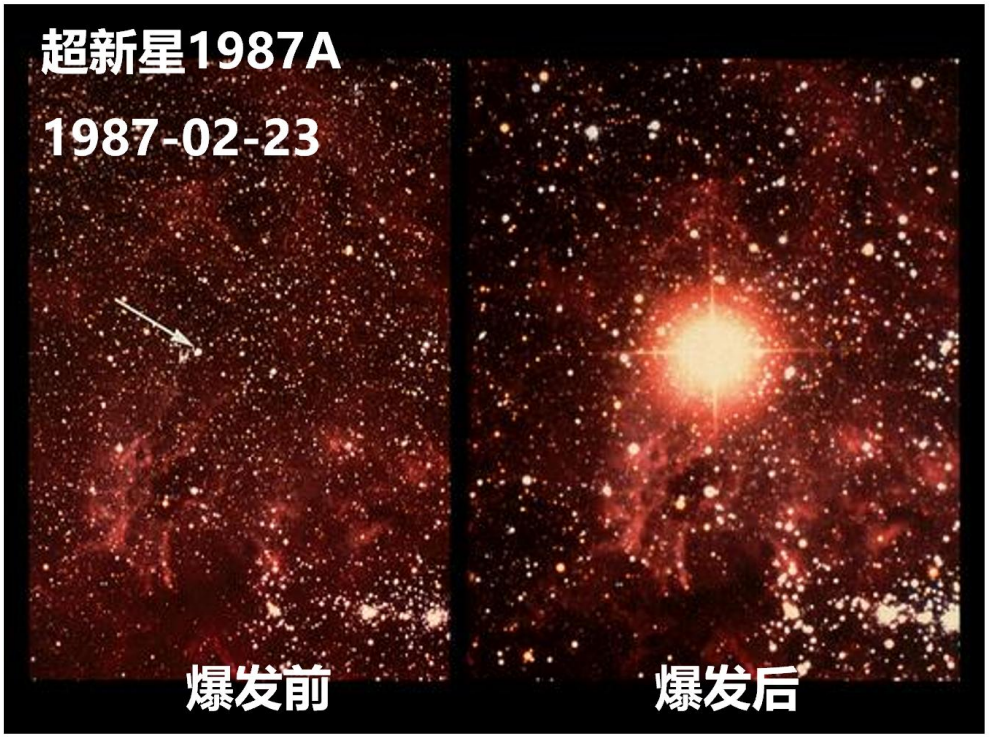
Neutron star:

$\rho = 3 \times 10^{14}$ g cm^{-3}
$T \sim 30$ MeV

Grav. binding energy $E_b \approx 3 \times 10^{53}$ erg
99% Neutrinos
1% Kinetic energy of explosion
(1% of this into cosmic rays)
0.01% Photons, outshine host galaxy

中微子探针：超新星爆发

发生于宋朝的超新星爆发遗迹
（蟹状星云）



超新星爆发需要中微子驱动，
99%的能量被中微子带走

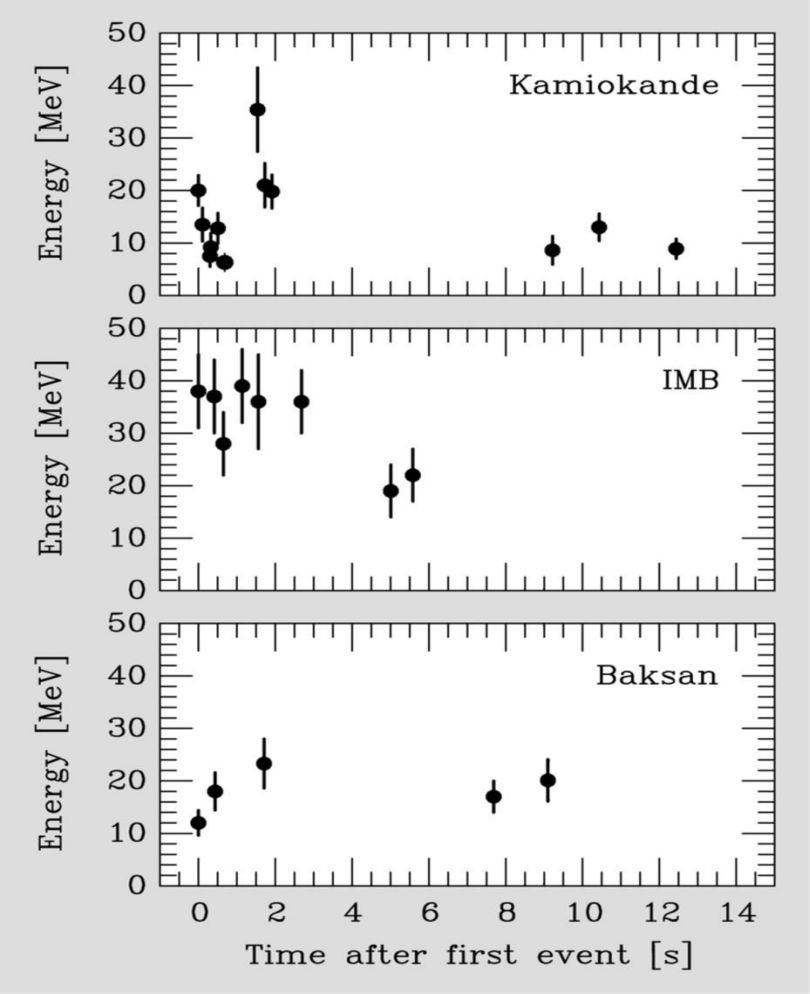
中微子探针：超新星1987A

Kamiokande-II (Japan):
- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

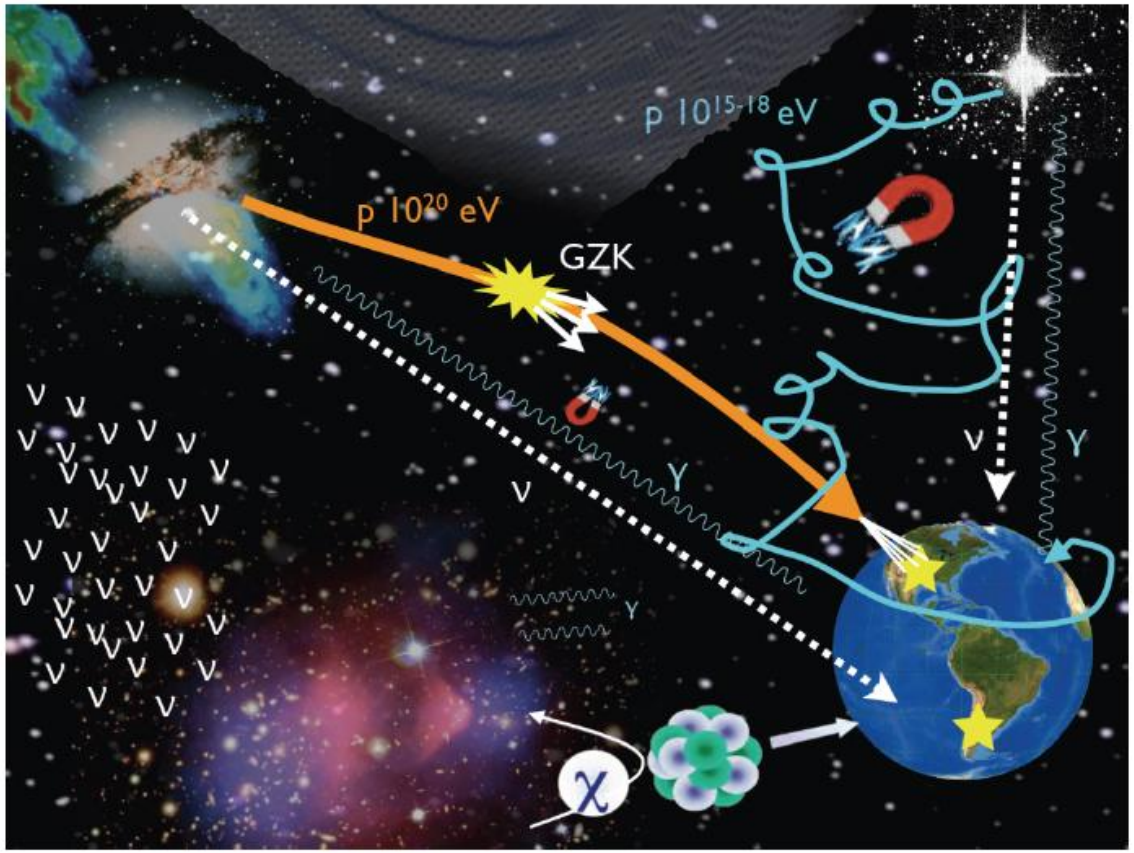
Irvine-Michigan-Brookhaven (US):
- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

Baksan LST (Soviet Union):
- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



中微子探针：多信使天文学



Source: http://web.physik.rwth-aachen.de/~wiebusch/Research.html

Cosmic Rays:

- Abundant
- Origin unknown
- Charged, trajectory deflected
- At highest energy, absorbed by CMB

Gamma Rays:

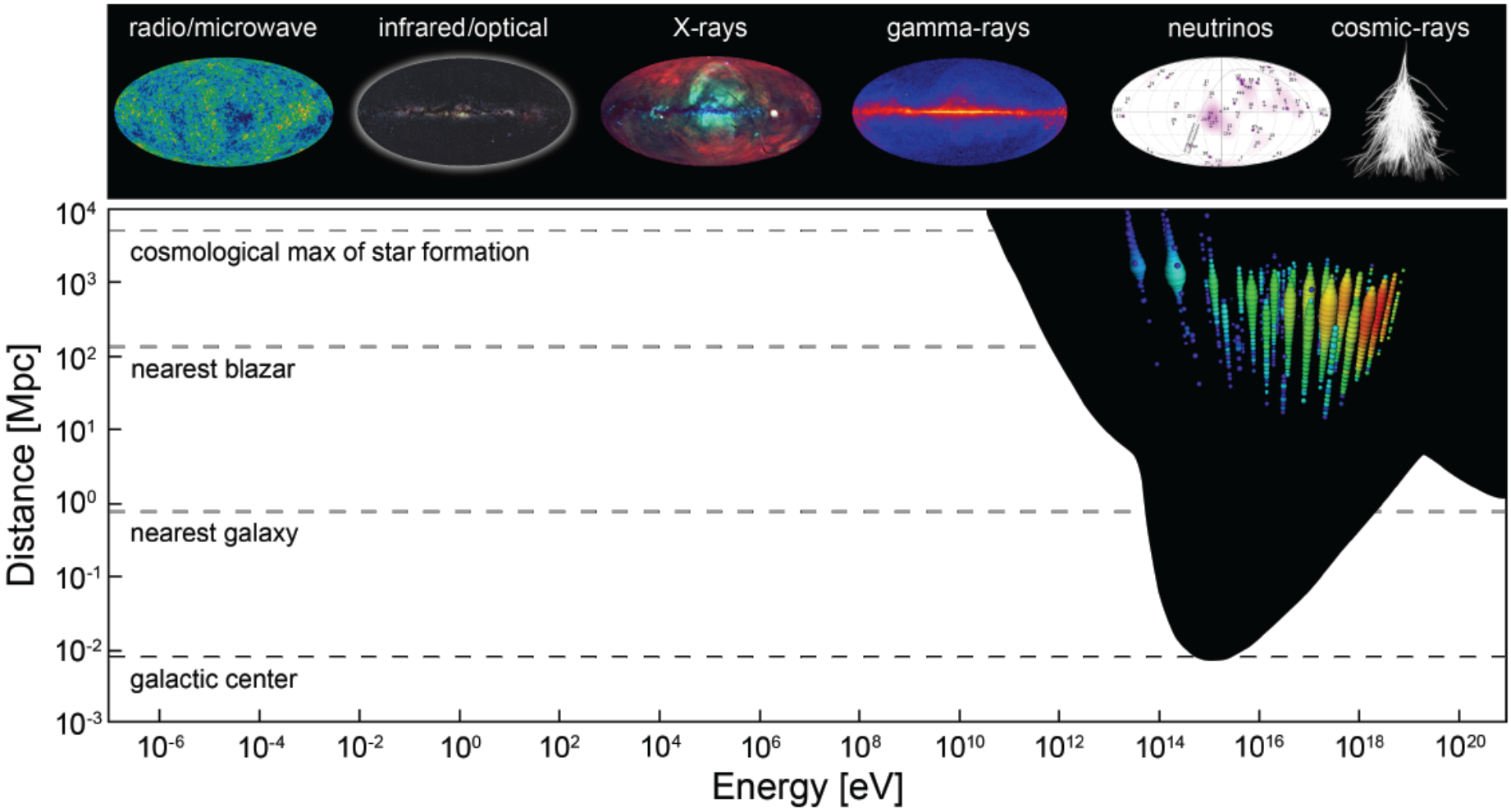
- Interact with CMB
- absorbed by infrared background

Neutrinos:

- Weakly interact
- Point back to source

Unique messenger from the high-energy Universe!

中微子探针：多信使天文学



The Universe is opaque to EM radiation for ¼ of the spectrum,
i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Goal: detecting TeV-PeV astrophysical neutrinos
Construction completed in December 2010

50 m

IceTop

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

1450 m

86 strings of DOMs, set 125 meters apart

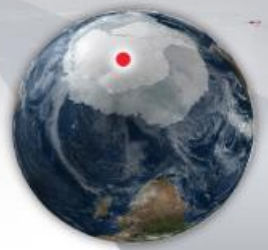
IceCube detector

DeepCore

Antarctic bedrock

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

2450 m



Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

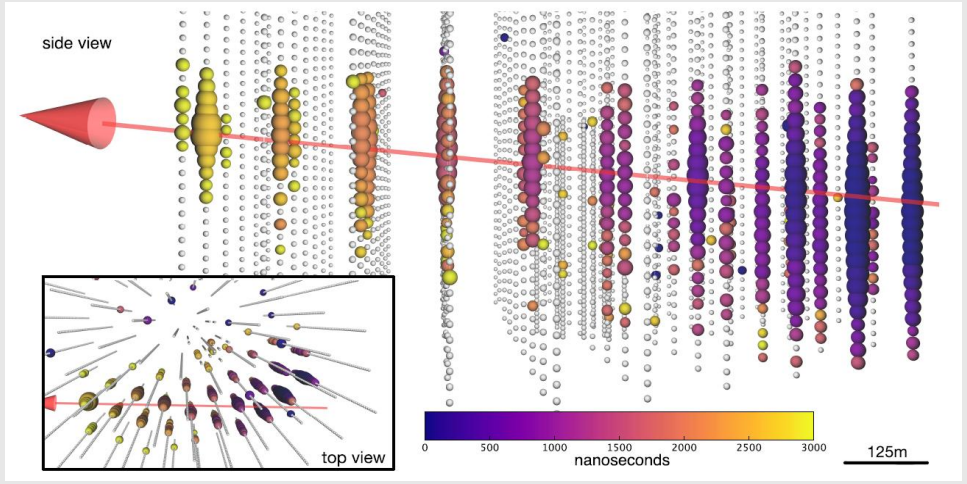
60 DOMs on each string

DOMs are 17 meters apart

首个确定的高能“中微子”源?

2017年9月22日“冰立方”观测到一个能量高达2.9×10^8兆电子伏的中微子事例（IceCube-170922A）

b) 其指向与一个已知的耀变体（TXS 0506+056）一致。



高能所中微子物理方向(理论+实验)

https://ihep.cas.cn/edu/

- 欢迎来高能所主楼B412咨询(liyufeng@ihep.ac.cn)

理论方面：
邢志忠，周顺，李玉峰，许勋杰，等

实验方面：
王贻芳，曹　俊，杨长根，何　苗，温良剑，曹国富，李玉峰，
于泽源，占　亮，丁雪峰，李依宸，罗武鸣，郭万磊，王志民
徐吉磊，赵　洁，路浩奇，张永鹏，王　毅，等

中微子理论： 中微子质量和味混合起源机制，中微子唯象研究和实验解读、中微子天文学，中微子宇宙学

中微子实验： 涵盖中微子振荡和中微子天文学实验的硬件研发，软件开发、模拟、重建、物理分析等全链条领域

Thanks!

谢谢!