

Jiangmen Underground Neutrino Observatory and some brief history and behind-the-scene stories

江門中微子實驗

Jiangmen Underground Neutrino Observatory

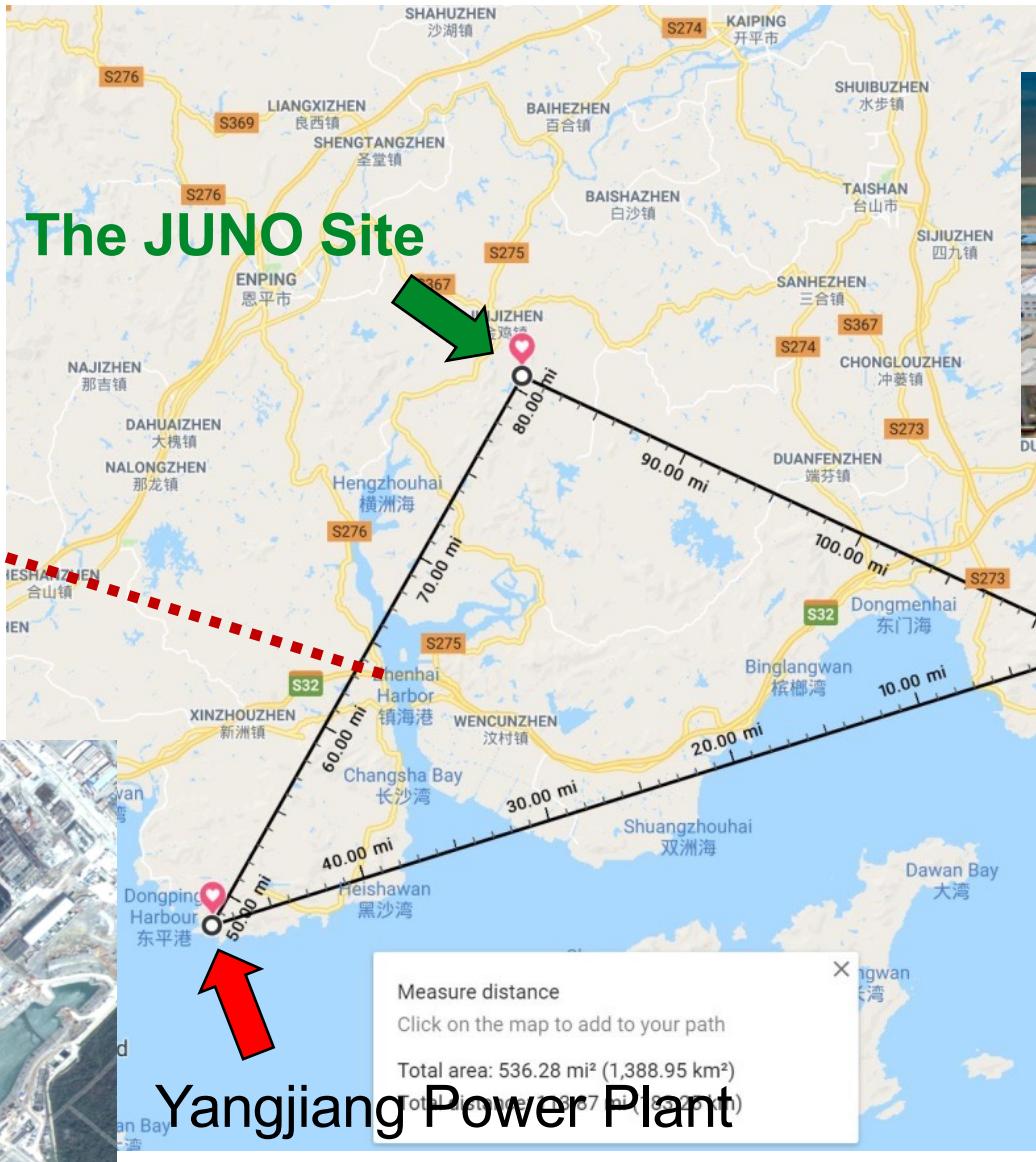
王为，中山大学

第一届粤港澳核物理论坛，珠海，2022.7.3



- *Neutrino History and JUNO*
- *Selected Details and Physics Potential*
- *Summary and Conclusion*

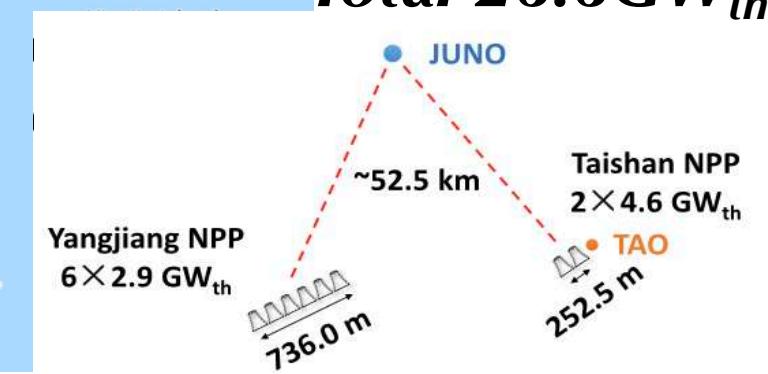
The Jiangmen Underground Neutrino Observatory



Taishan Power Plant



Yangjiang Power Plant



Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

1

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst
ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg
verfallen um den "Wechselsatz" (1) der Statistik und dem Energieverlust
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,
welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen
sollte von derselben Grössenordnung wie die Elektronenmasse sein und
jedemfalls nicht grösser als 0,01 Protonenmasse... Das kontinuierliche
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert
wird, derart, dass die Summe der Energien von Neutron und Elektron
konstant ist.

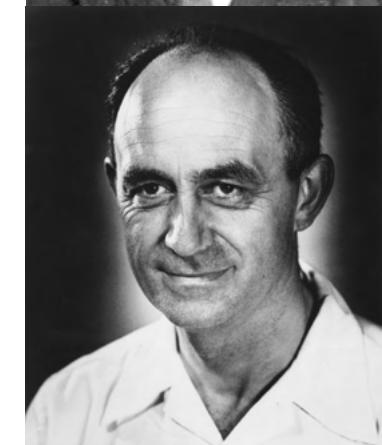
Nun handelt es sich weiter darum, welche Kräfte auf die
Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint
mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer
dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein
magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente
verlängern wohl, dass die ionisierende Wirkung eines solchen Neutrons
nicht grösser sein kann, als die eines gamma-Strahls und darf dann
wohl nicht grösser sein als $e \cdot (10^{-13} \text{ cm})$.

Ich traue mich vorläufig, aber nicht, etwas über diese Idee
zu publizieren und wende mich erst vertrauensvoll an Euch, liebe
Radioaktive, mit der Frage, wie es um den experimentellen Nachweis
eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa
10mal grösseres Durchdringungsvermögen besitzen würde, wie ein
gamma-Strahl.

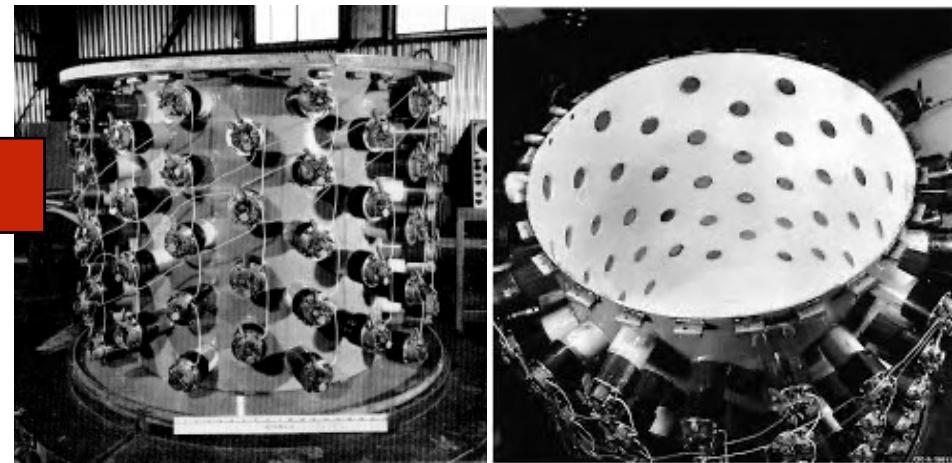
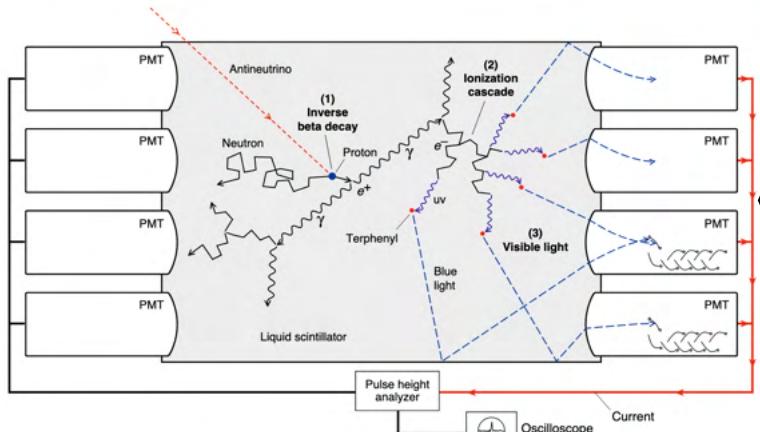
Ich gebe zu, dass mein Ausweg vielleicht von vornherein
sehr wahrscheinlich erscheinen wird, weil man die Neutronen, wenn
sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt,
wagt und der Ernst der Situation beim kontinuierlichen beta-Spektrum
wird durch einen Ausspruch meines verehrten Vorgängers im Amt,
Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat:
"O, daran soll man am besten gar nicht denken, sowie an die neuen
Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.
Also, liebe Radioaktive, prüfen, und richten! Leider kann ich nicht
persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht
vom 6. zum 7. Des. in Zürich stattfindenden Balles hier unabkömmlich
bin. Mit vielen Grüissen an Euch, sowie an Herrn Baek, Euer
untertanigster Diener

ges. W. Pauli

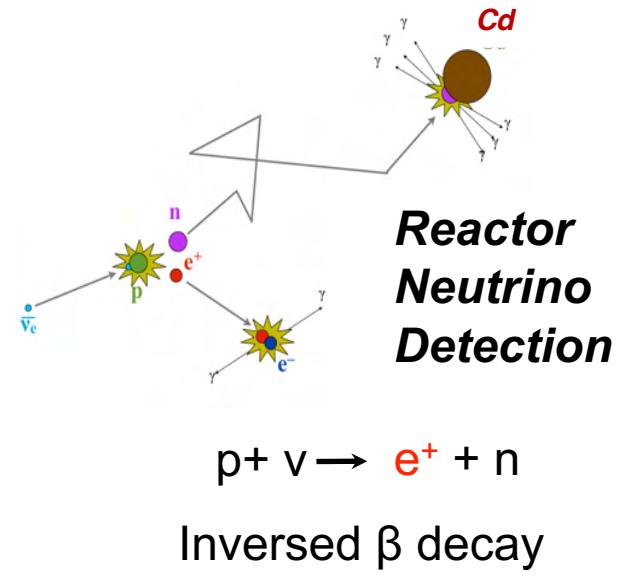
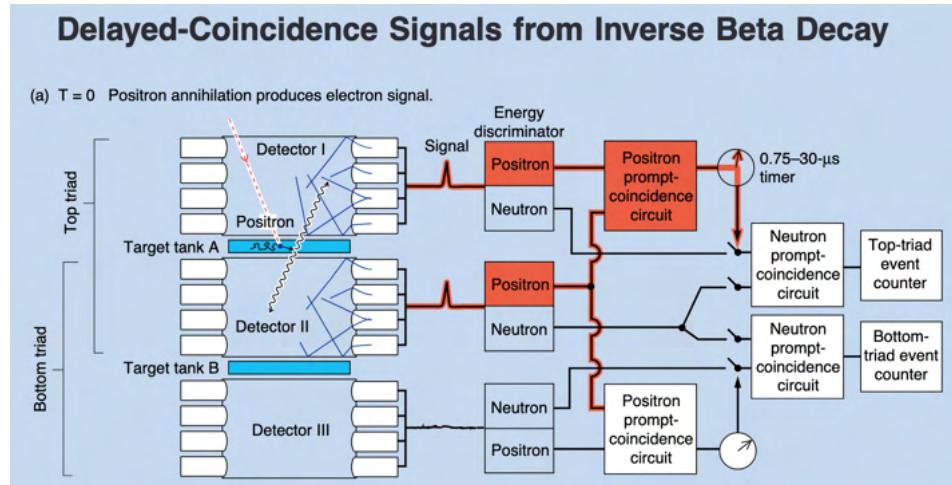
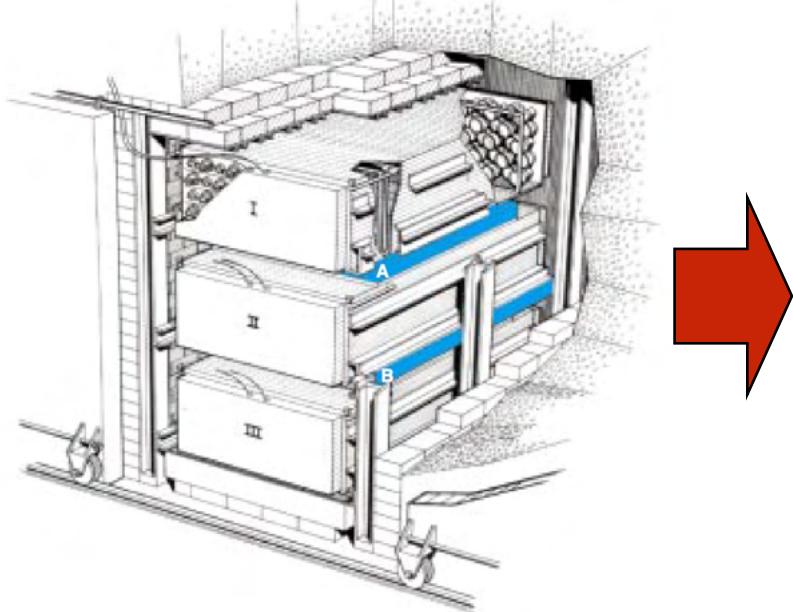
- ① Dear Radioactive Ladies and Gentlemen!
- ② I have hit upon a desperate remedy to save...the law of conservation of energy.
- ③ ...there could exist electrically neutral particles, which I will call neutrons, in the nuclei...
- ④ The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, **a neutron is emitted such that the sum of the energies of neutron and electron is constant**
- ⑤ But so far **I do not dare to publish anything about this idea**, and trustfully turn first to you, dear radioactive ones, with the question of how likely it is to find experimental evidence for such a neutron...
- ⑥ I admit that my remedy may seem almost improbable **because one probably would have seen those neutrons, if they exist, for a long time**. But nothing ventured, nothing gained...
- ⑦ Thus, dear radioactive ones, scrutinize and judge.



The Very First Reactor Neutrino Experiment



Savannah Team 1955



王淦昌先生首次提出如何实验证中微子的存在



浙江大学档案馆藏

- 1941年，王淦昌在《关于探测中微子的一个建议》的论文中提出，通过轻原子核俘获K壳层电子释放中微子时产生的反冲中微子的创造性实验方法。1942年1月，美国《物理评论》（ PHYSICAL REVIEW ）发表了这篇短文，此项成果荣获第二届范旭东先生纪念奖

➤ 1942年美国物理学家J. ALLEN采用王淦昌的方法，证明了中微子的存在。

王淦昌先生首次提出如何实验证中微子的存在

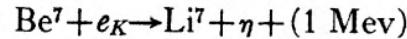
A Suggestion on the Detection of the Neutrino

KAN CHANG WANG

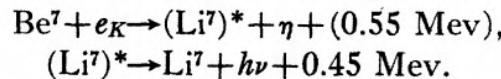
*Department of Physics, National University of Chekiang Tsunyi,
Kweichow, China*

October 13, 1941

atom alone. Moreover, this recoil is now of the same amount for all atoms, since no continuous β -rays are emitted. We take for example the element Be⁷ which decays in 43 days with K capture in two different processes:²



and



The first process is relatively large, about 10 to 1 in comparison with the second process. The recoil energy of the first process is, by assuming the mass of neutrino to be zero, about 77 ev while that of the second process is about one-third of that amount. This recoil energy would have to be detected and measured in some way, and a correction would have to be made for the disturbances due to the γ -rays and the soft x-rays (originating from the replacement of the K electrons by outer electrons). The recoil

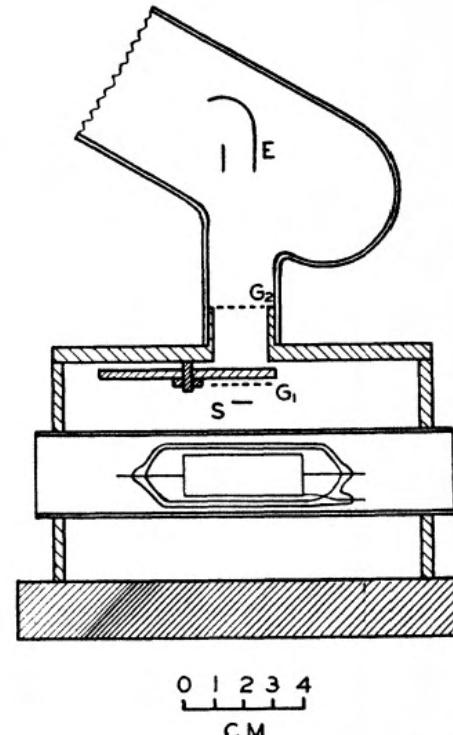


FIG. 1. Experimental arrangement of G-M and electron multiplier tubes.

- 王淦昌先生于1941年提出了K层俘获证明中微子的存在，测量它的质量
- 1942年，James S. Allen carried out the measurement, obtaining ~50 eV recoil E

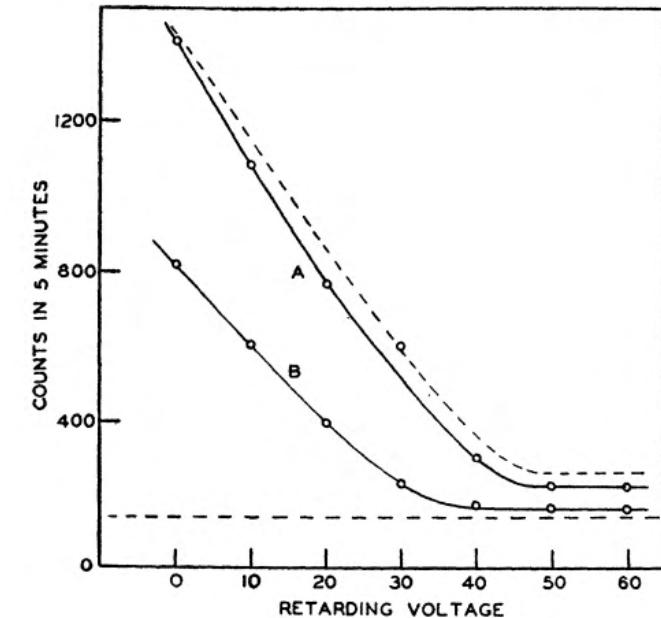
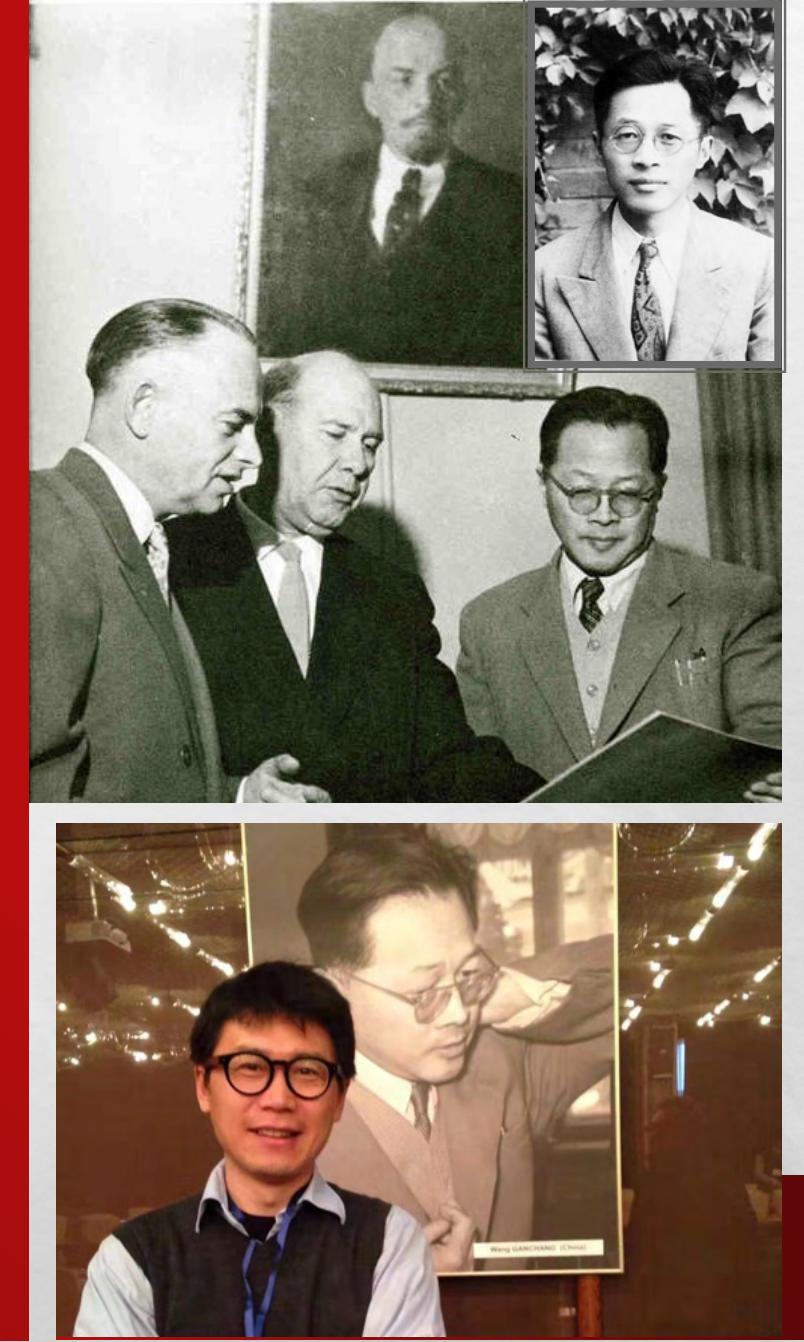


FIG. 3. Retarding potential curves for recoil ions. The horizontal dotted line represents the background counting rate.

向王淦昌先生致敬

- 1950年，调入中国科学院近代物理研究所
- 1952年，王淦昌与吴恒兴、林传骝赴朝鲜战场，完成了探测美军是否使用原子武器、投掷放射性物质的任务。同年，任中国科学院近代物理研究所副所长
- 1955年被选聘为中国科学院学部委员（院士）
- 1956年9月，王淦昌作为中国的代表，到苏联杜布纳联合原子核研究所任研究员，从事基本粒子研究，并被选为副所长。在联合原子核研究所工作期间，他领导的物理小组首次发现了反西格马负超子，首次观察到在基本粒子相互作用中产生的带奇异夸克的反粒子
- 1959年，王淦昌在苏联杜布纳联合原子核研究所的研究中，从4万对底片中找到了一个产生反西格马负超子的事例，发现超子的反粒子，引起国际学术界轰动



中微子混合的提出



Бруно Понтекорво

- Extended to 3 flavor mixing by Maki, Nakagawa and Sakata, after muon neutrino was discovered at BNL in 1962

- Bruno Pontecorvo in 1957:
Interaction Eigenstates \neq Mass Eigenstates
→ **Neutrino Mixing and Oscillation**



S. Sakata
1911-1970

Z. Maki
1929-2005

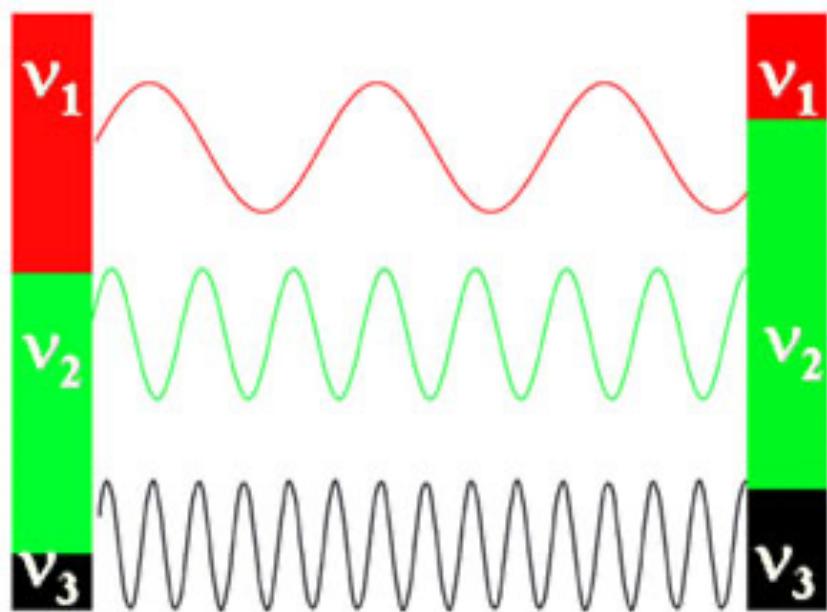
M. Nakagawa
1932-2001

中微子混合与中微子振荡



➤ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix,

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



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

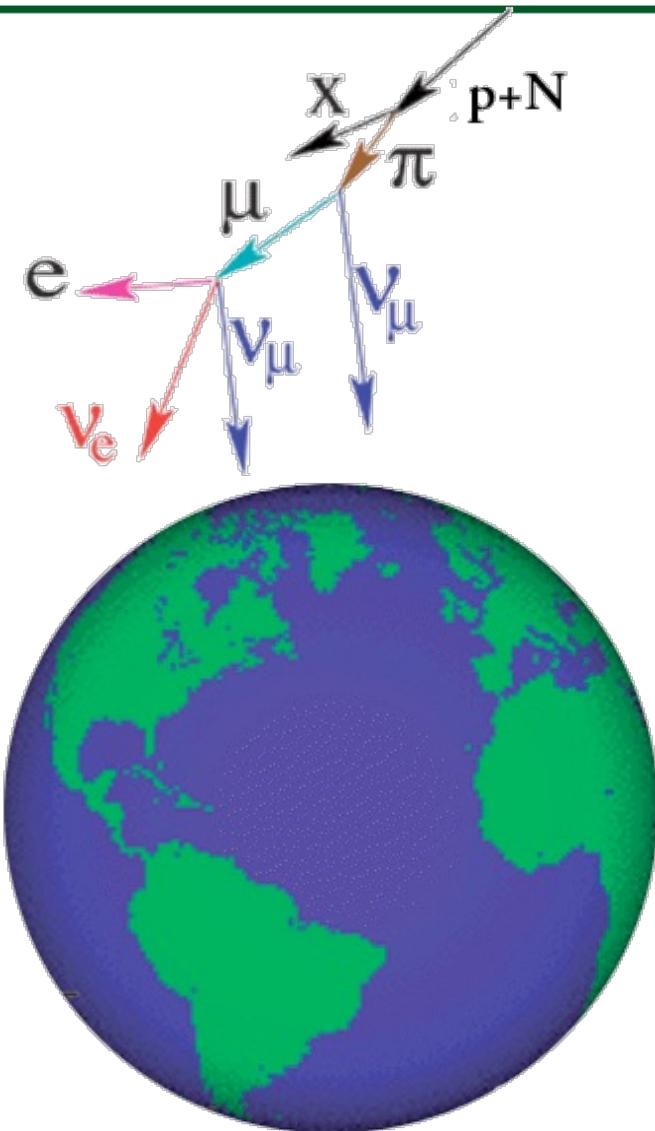
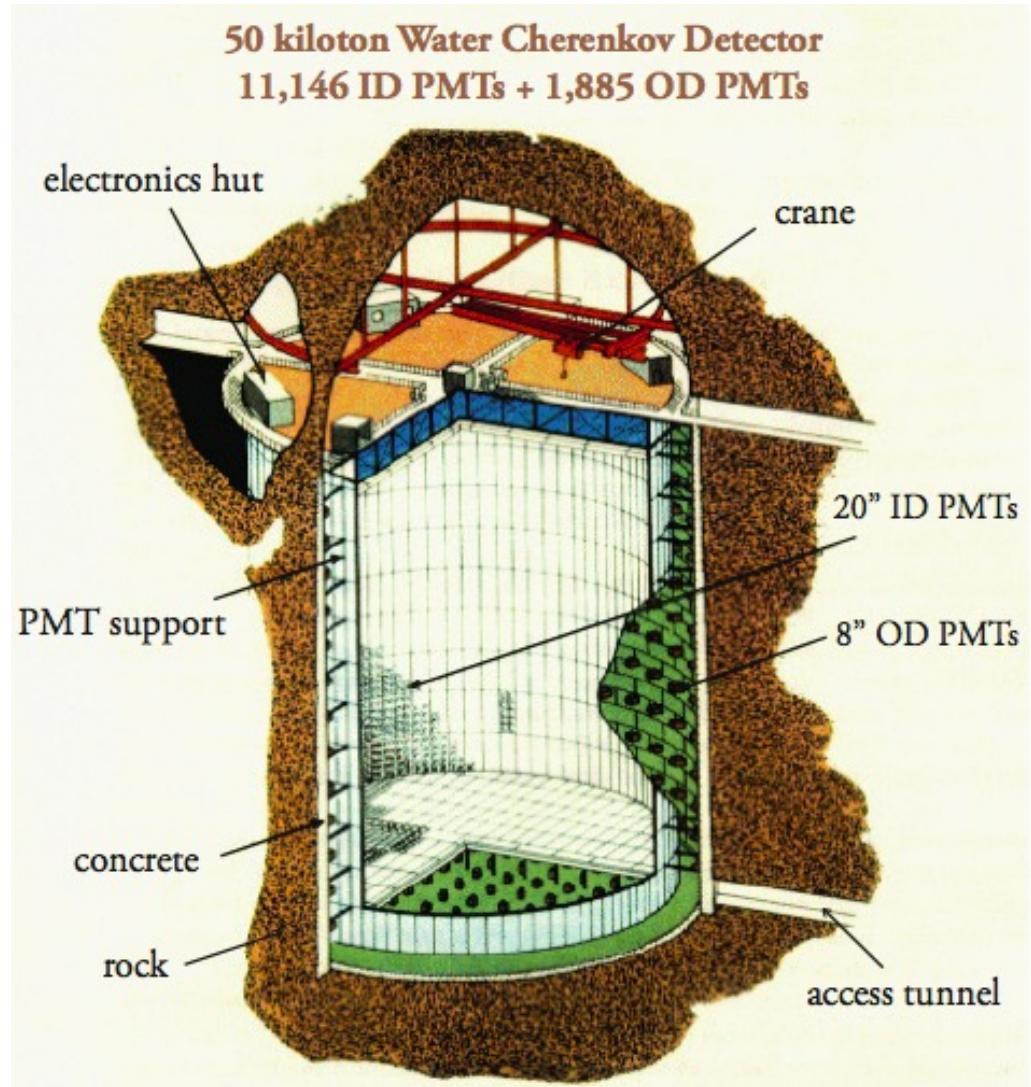
⇒ Oscillation Probability:

$$P_{\nu_\alpha \rightarrow \nu_\beta} = 1 - 4 \sum_{i < j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m_{ji}^2 L}{4E}$$

Amplitude $\propto \sin^2 2\theta$

Frequency $\propto \Delta m^2 L/E$

日本超級神岡中微子實驗

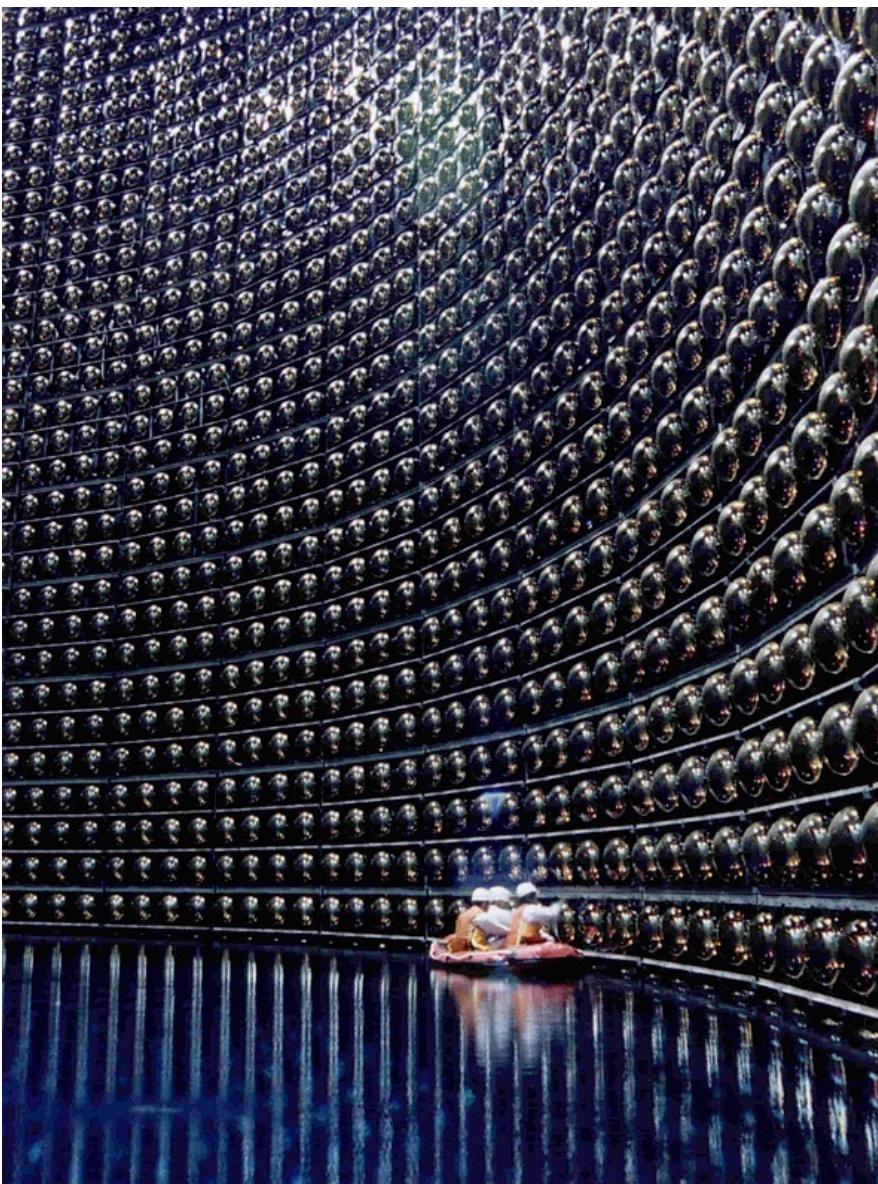
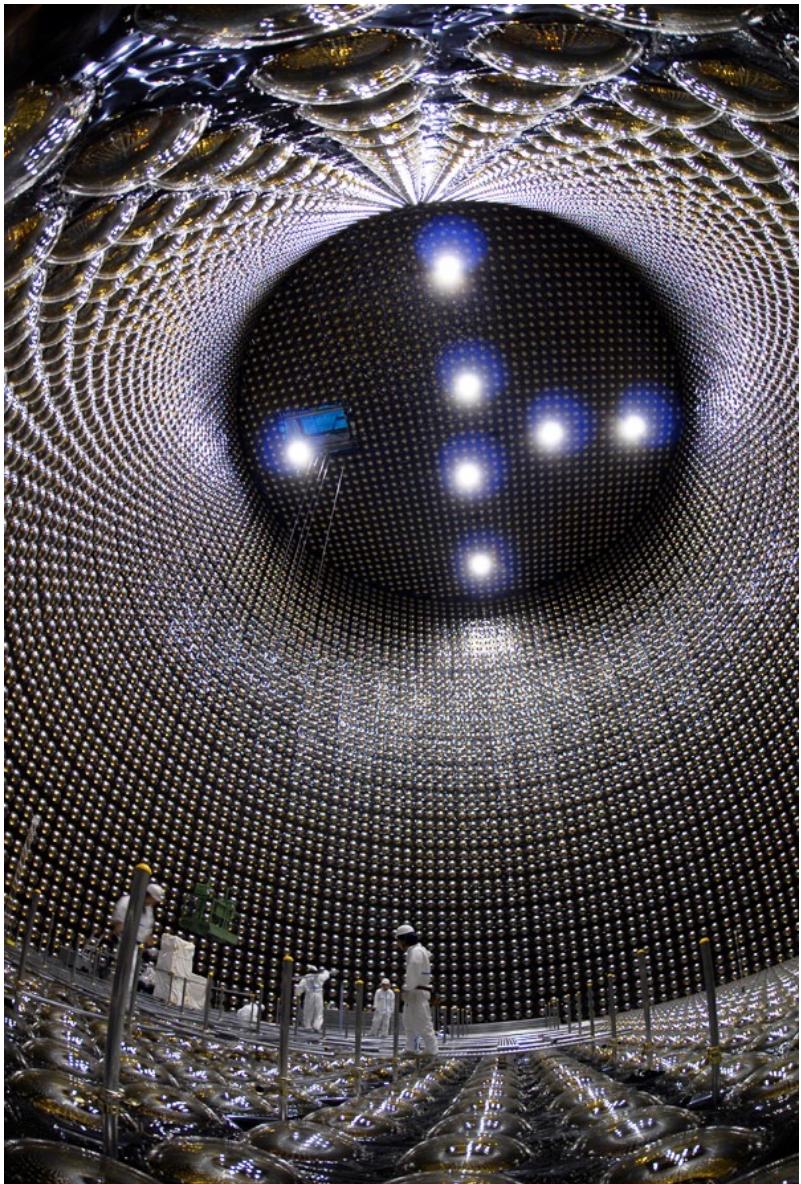


超級神岡中微子實驗
北陸的岐阜縣



设计探测质子衰变
发现了中微子振荡
探测太阳中微子

11,000多只“眼睛”的中微子探测器



日本的超级神冈实验发现中微子振荡：2015年诺贝尔奖

The Nobel Prize in Physics T. Kajita, Neutrino'98 2015



Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

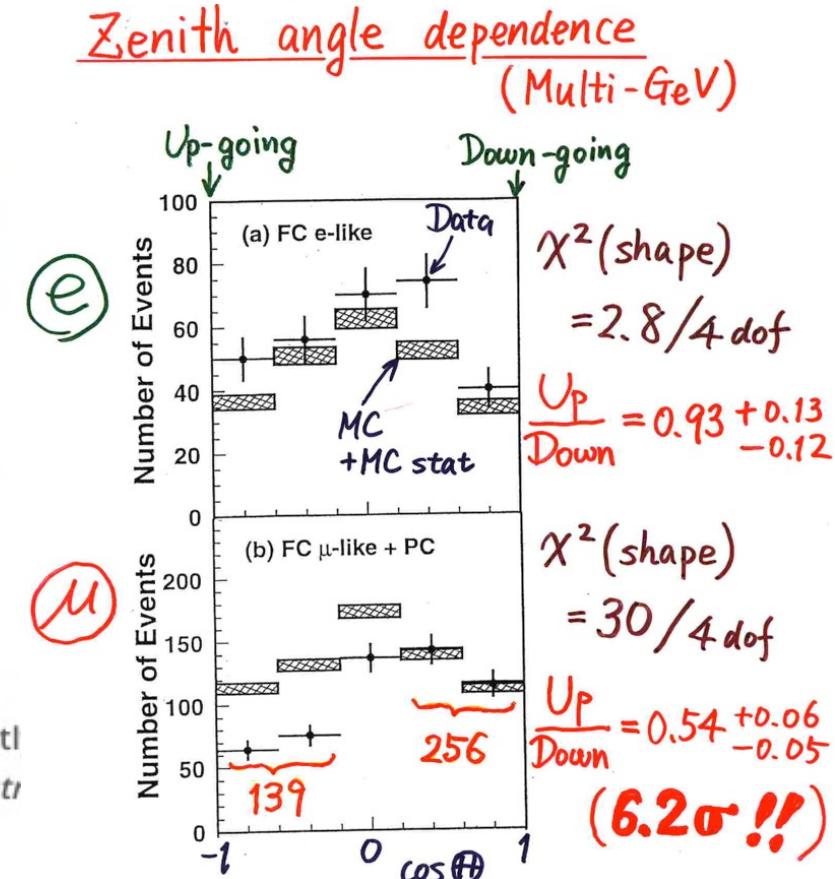


Photo: K. MacFarlane.
Queen's University
/SNOLAB

Arthur B. McDonald

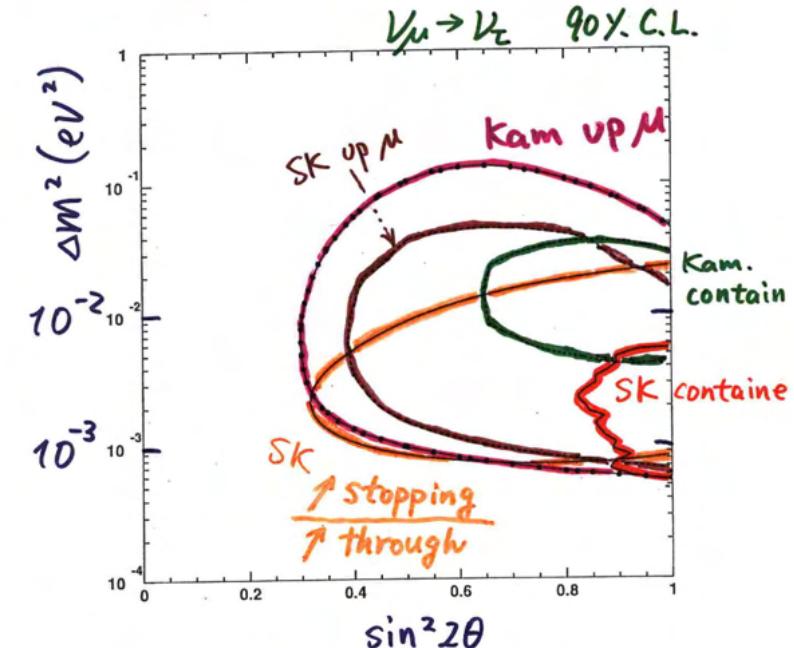
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointl
and Arthur B. McDonald "for the discovery of neutr
which shows that neutrinos have mass"



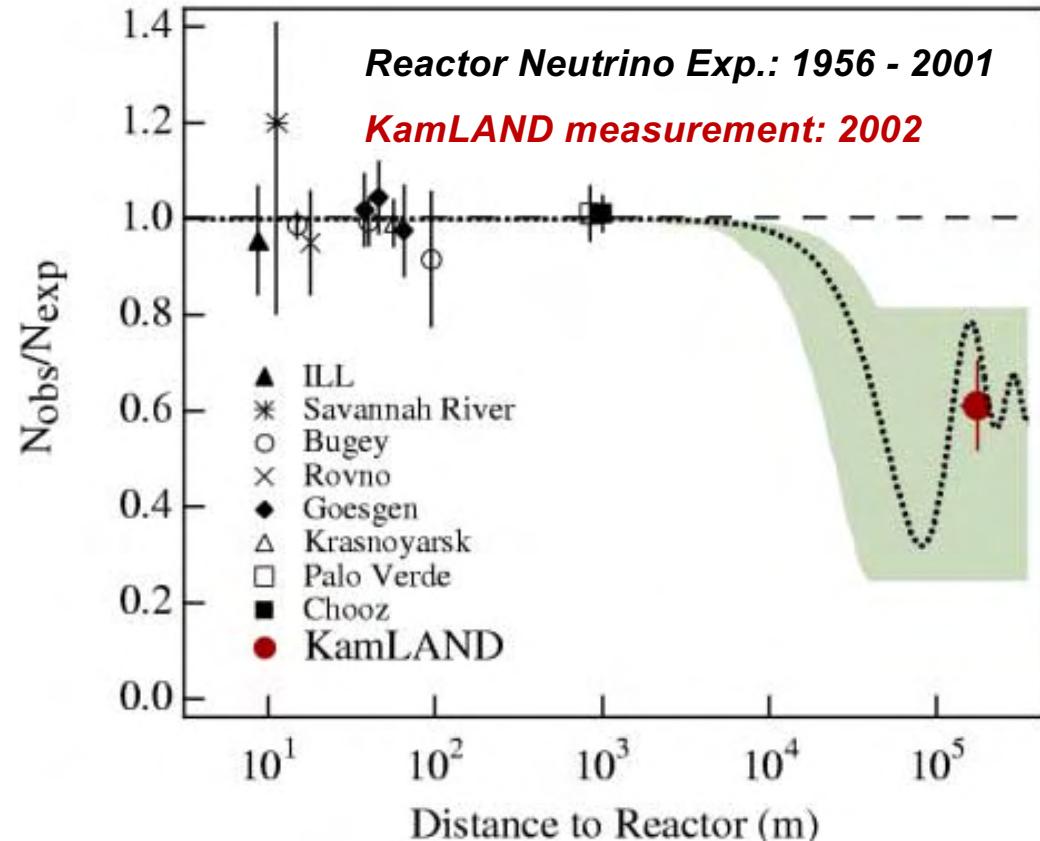
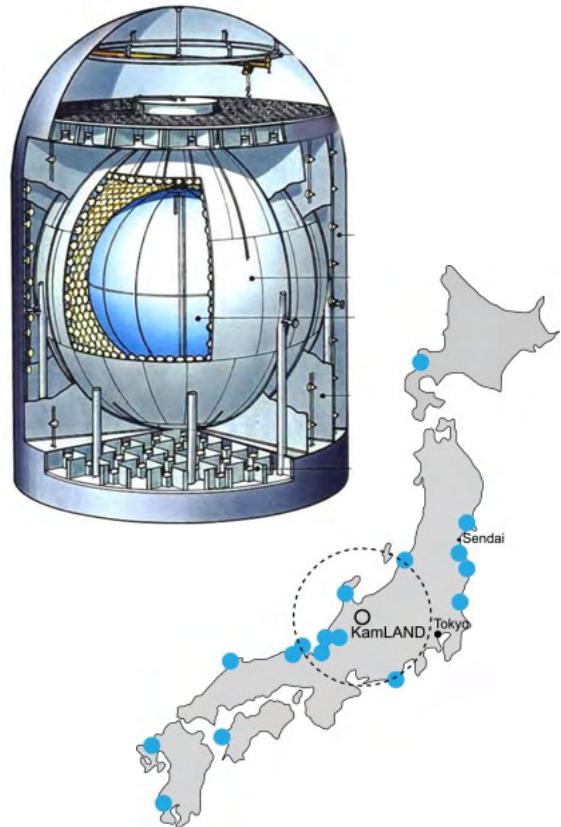
Summary

Evidence for ν_μ oscillations

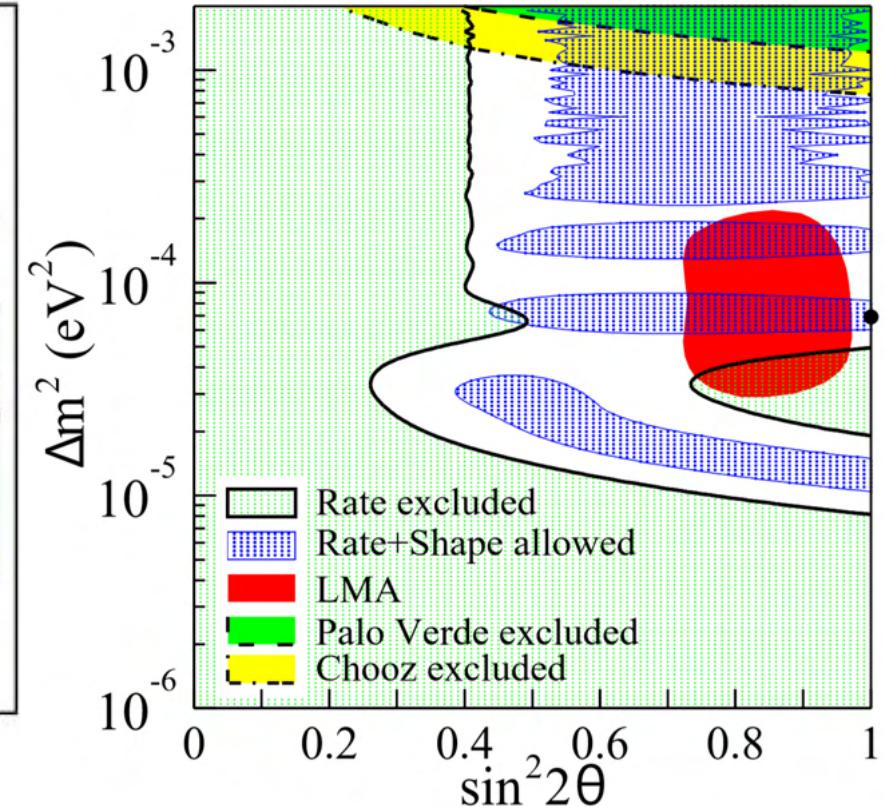


- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

Year 2002: Reactor Neutrinos Finally Oscillated!



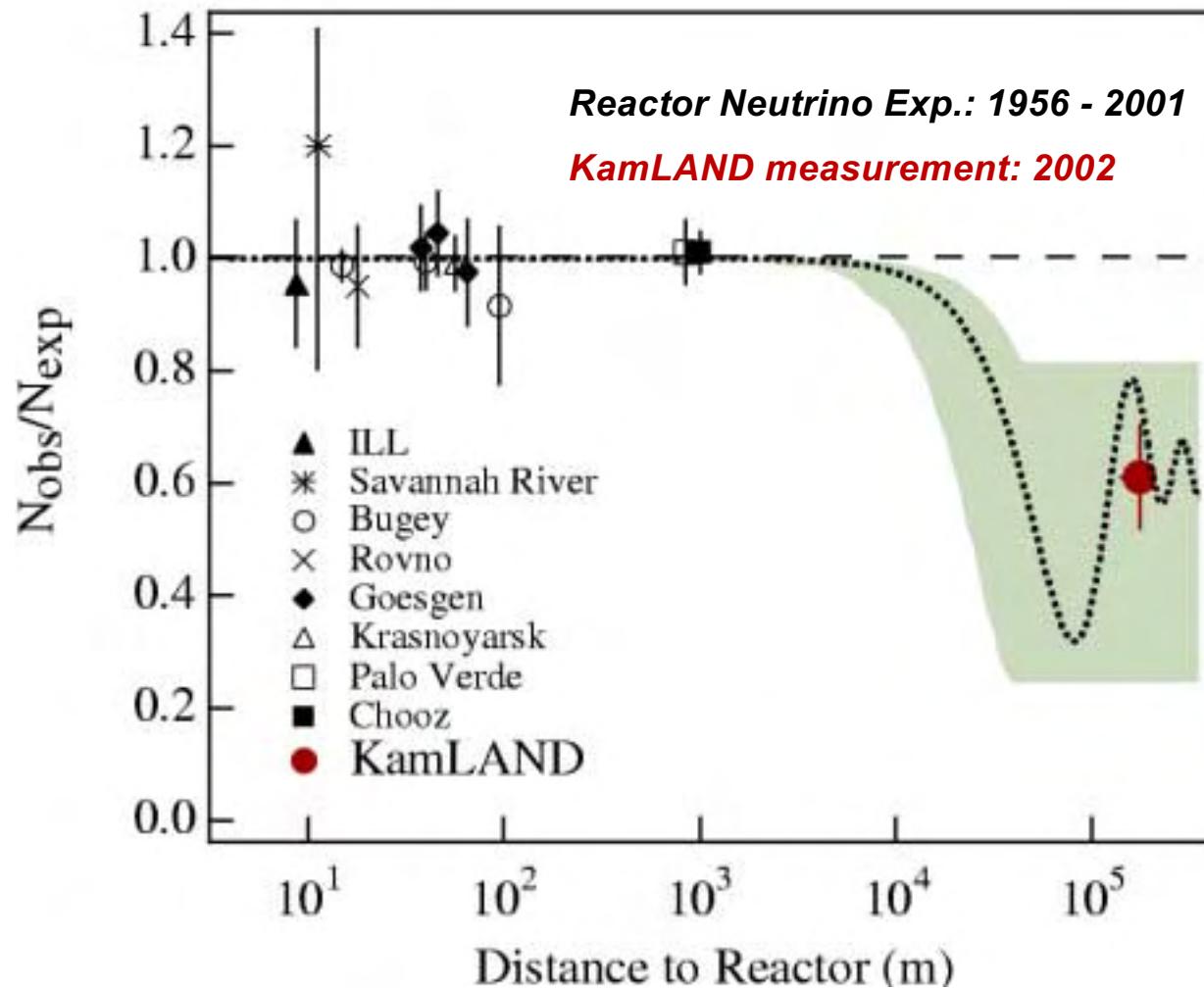
KamLAND data added: $\Delta m^2_{\text{LMA}} \sim 7 \times 10^{-5} \text{ eV}^2$



Year 2002: Reactor Neutrinos Finally Oscillated!



Sometimes, we just need to push it a bit further, and more reactors are better.....



—这下面没有水，再换个地方挖

张新华画

1998-2002 : 中微子大发现、大产出的黄金时代



$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

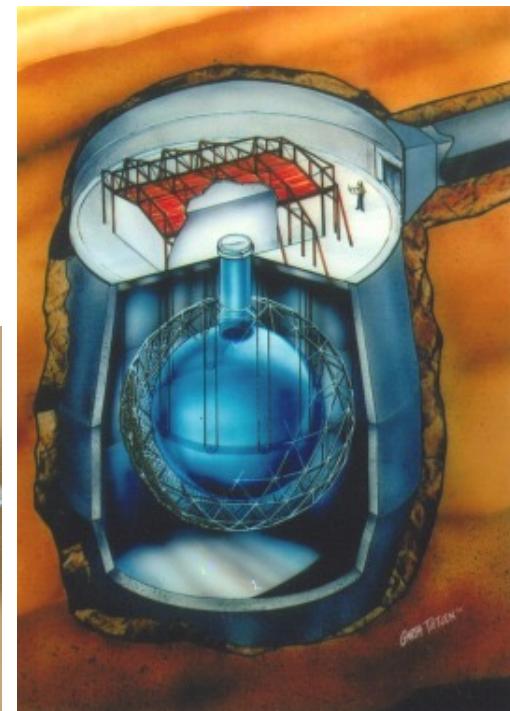
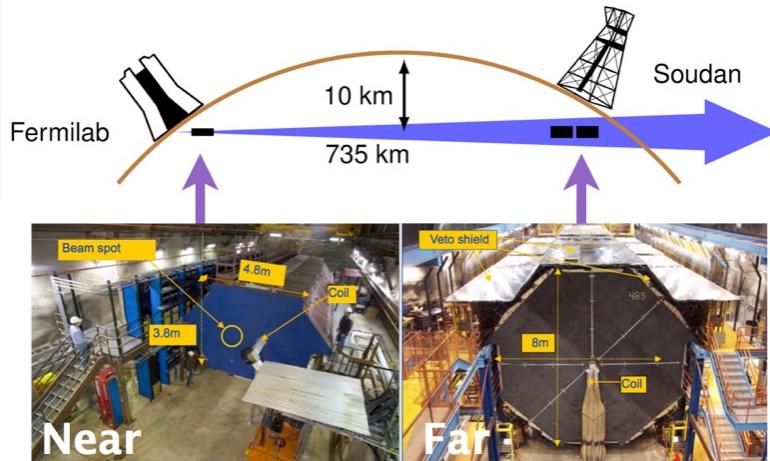
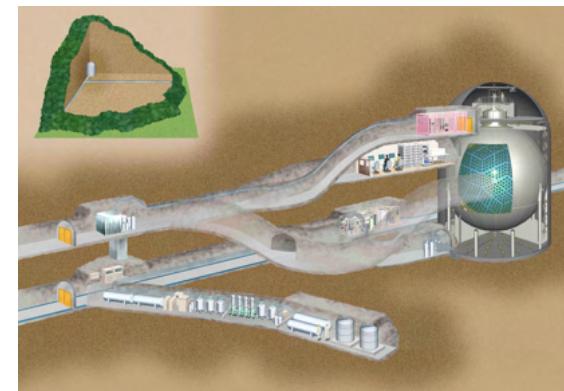
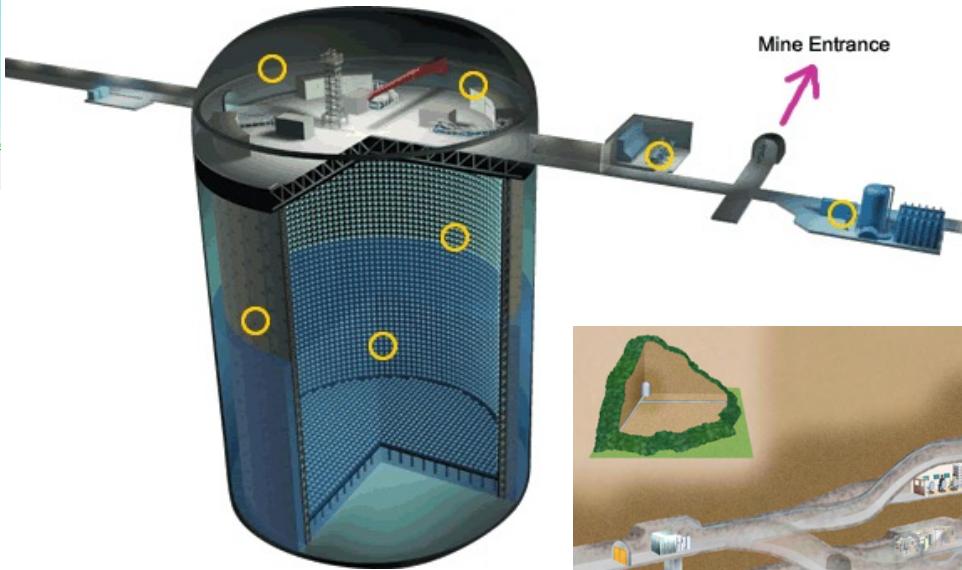
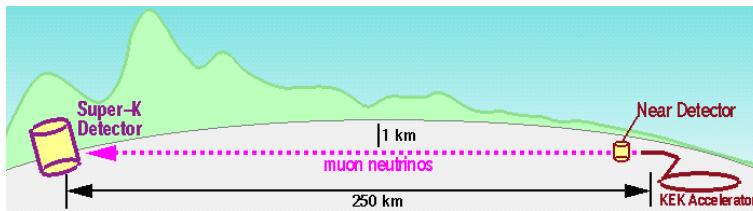
Atmospheric Sector:
SK, K2K, T2K, MINOS, etc

$$\sim 2.5 \times 10^{-3} \text{ eV}^2$$

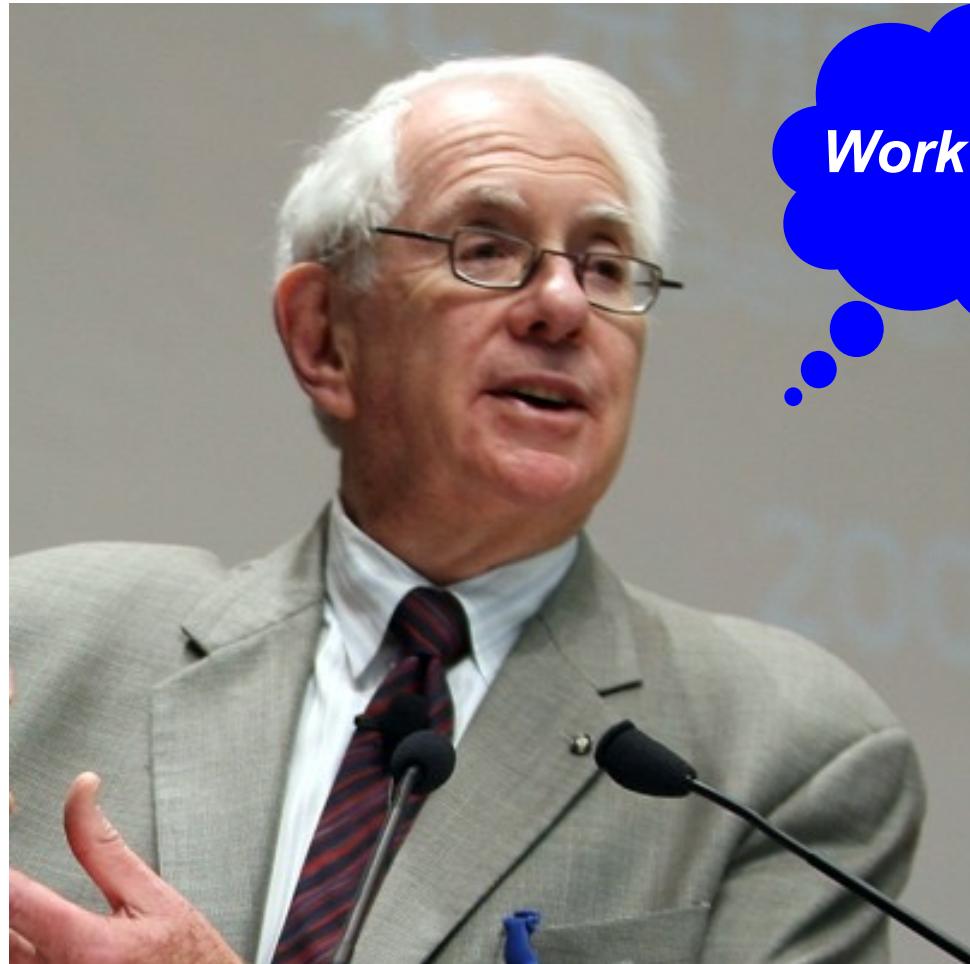
Reactor Sector

Solar Sector:
SNO, SK, KamLAND etc

$$\sim 7.5 \times 10^{-5} \text{ eV}^2$$



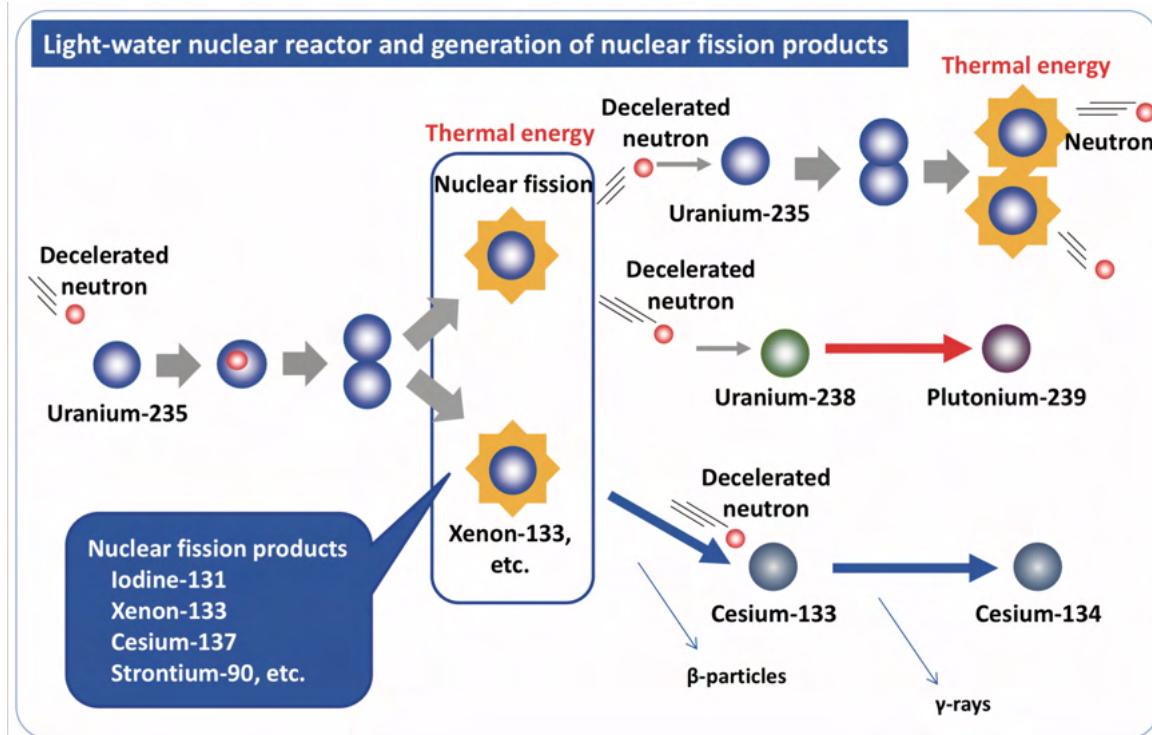
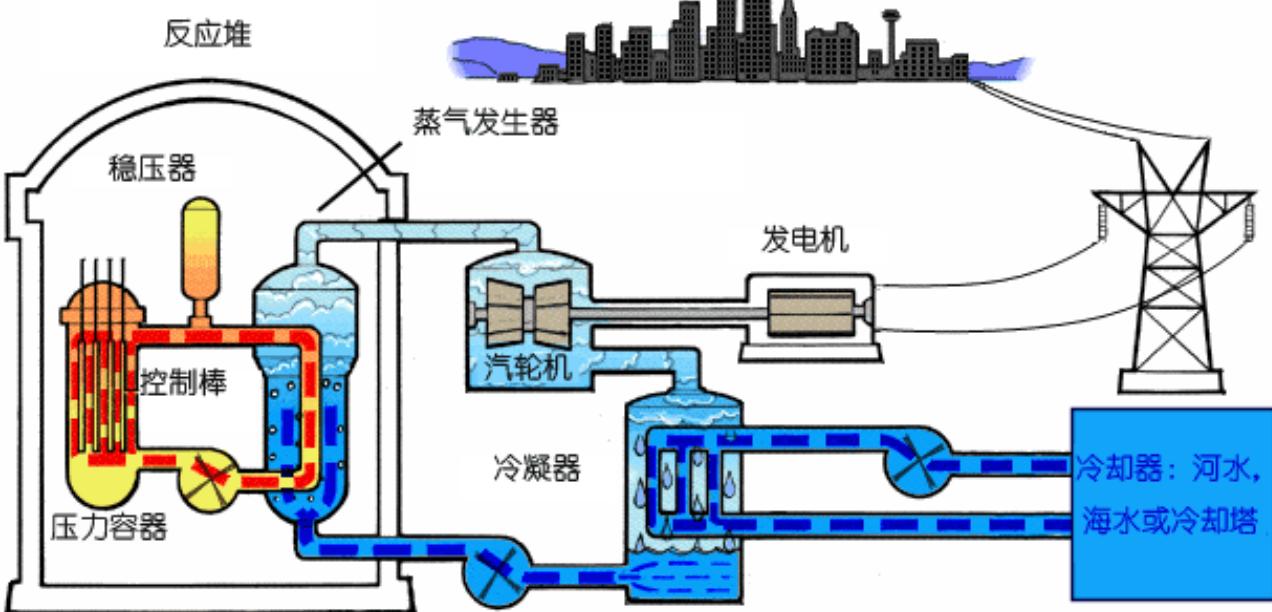
We Were All Quite Desperate



**One of the Funders of the SM, Glashow,
called for the measurement of θ_{13}**

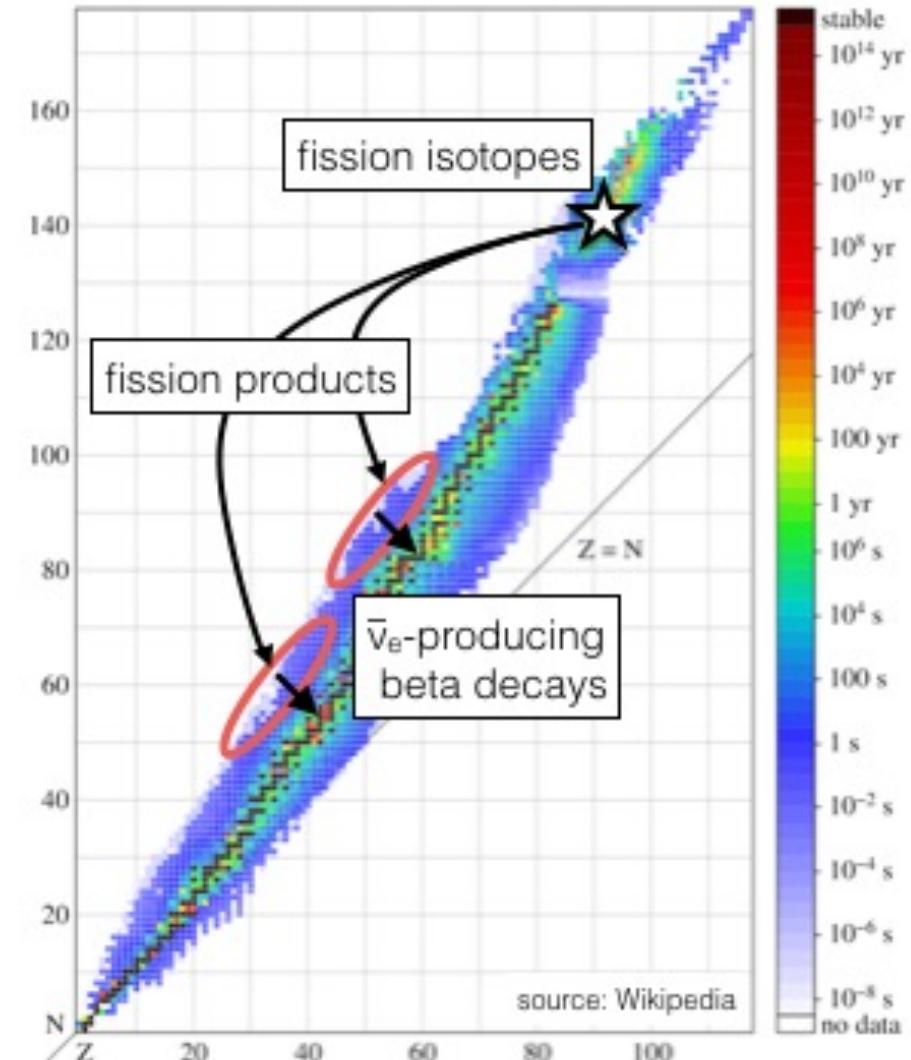
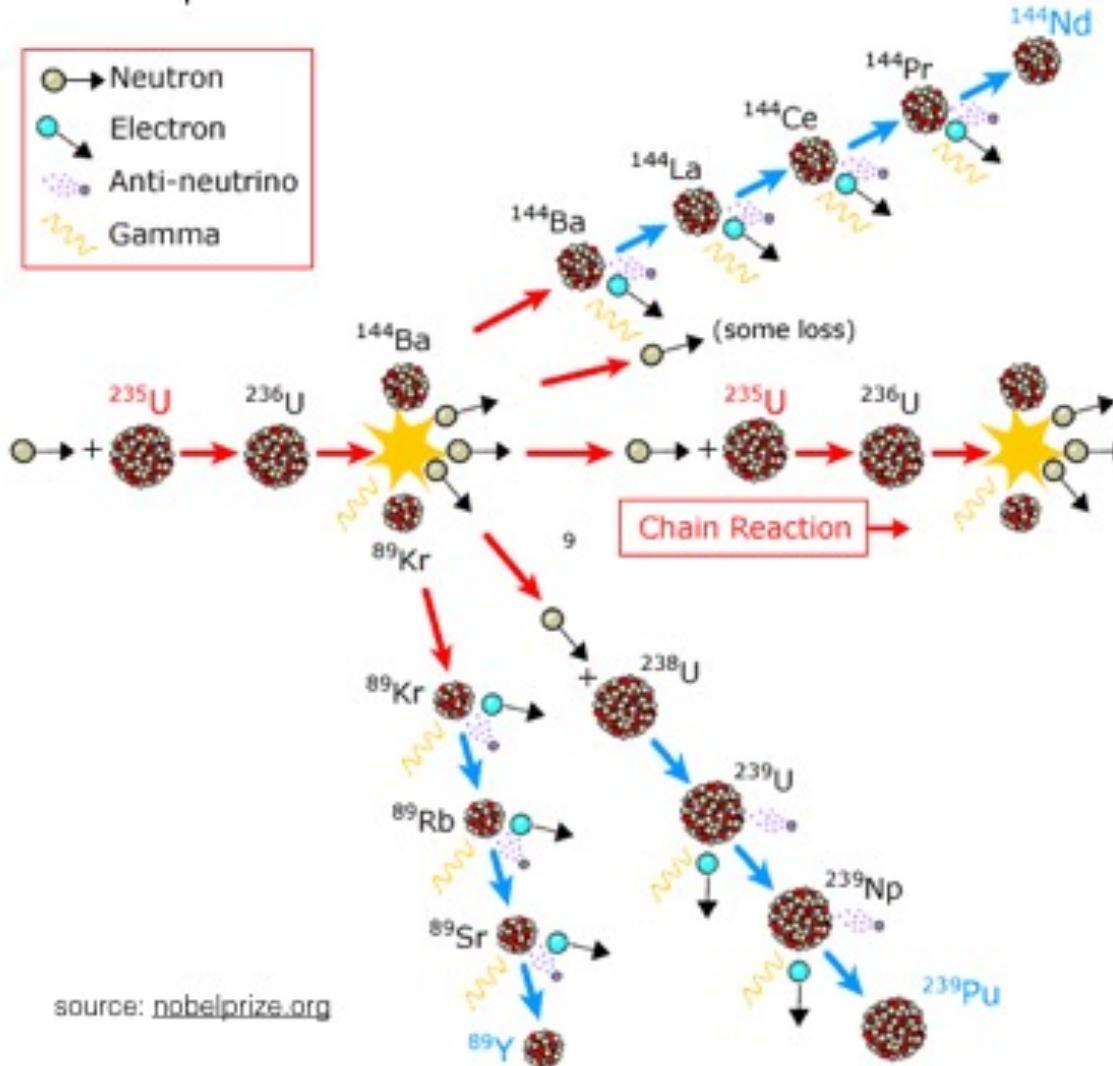
Photo by Kam-Biu Luk

核电站到底如何工作？



反应堆中微子来自裂变产物的贝塔衰变

fission process in a nuclear reactor





- 1964年1月14日，我国生产出第一批铀浓缩合格产品。
- 1964年10月16日，中国第一颗原子弹爆炸成功。
- 1964年10月16日，我国第一颗原子弹爆炸试验成功，标志着我国掌握了核武器技术，打破了超级大国的核垄断核讹诈。
- 1965年5月14日，我国核航弹爆炸试验成功，标志着我国有了可用于实战的核武器。
- 1966年10月27日，我国第一颗核导弹试验成功。标志着我国有了可用于实战的核导弹，武器化进程取得突破性进展。
- 1967年6月17日，我国第一颗氢弹空爆试验成功。从第一颗原子弹爆炸试验成功到第一颗氢弹爆炸试验成功，我国仅用了2年零8个月的时间，在世界核武器国家中是发展速度最快的。
- 1970年2月8日，中国通过了首个核电站计划，并成立了728研究所（现称上海核工程研究设计院）。
- 1991年12月15日，中国第一个核电反应堆，**泰山核电站**288MW（兆瓦）的压水式反应堆（PWR）联入高压电网，首次投入使用。
- 1994年2月1日，我国首座大型商用核电站——广东大亚湾核电站1号机组投入商业运行。

Treaties

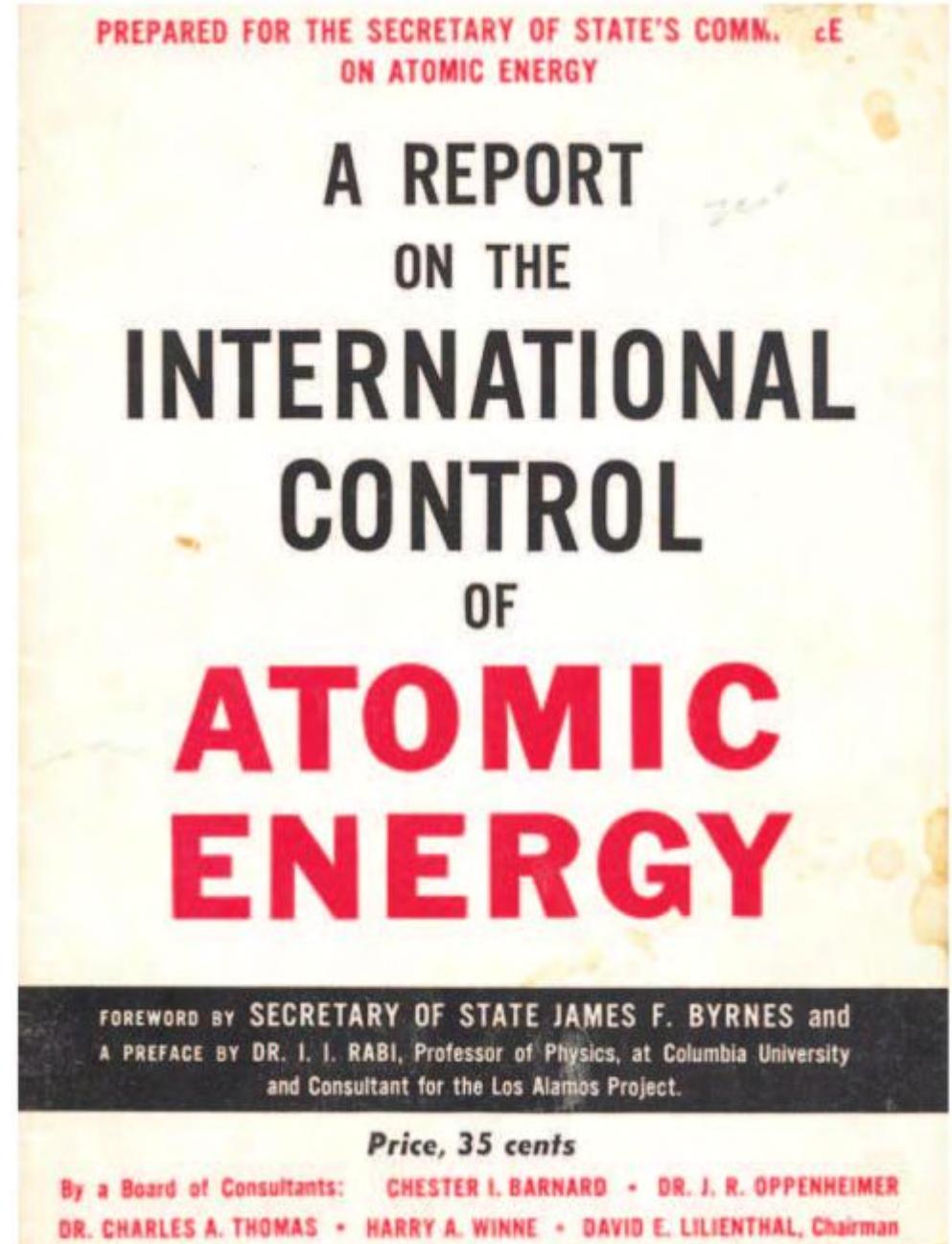
1946 Acheson-Lilienthal report recognizes that control of fissile material is at the center of nuclear non-proliferation

1970 The Treaty for the Non-Proliferation of Nuclear Weapons (NPT) enters into force

1995 NPT extended indefinitely

1996 Comprehensive Test Ban Treaty
(still not ratified)

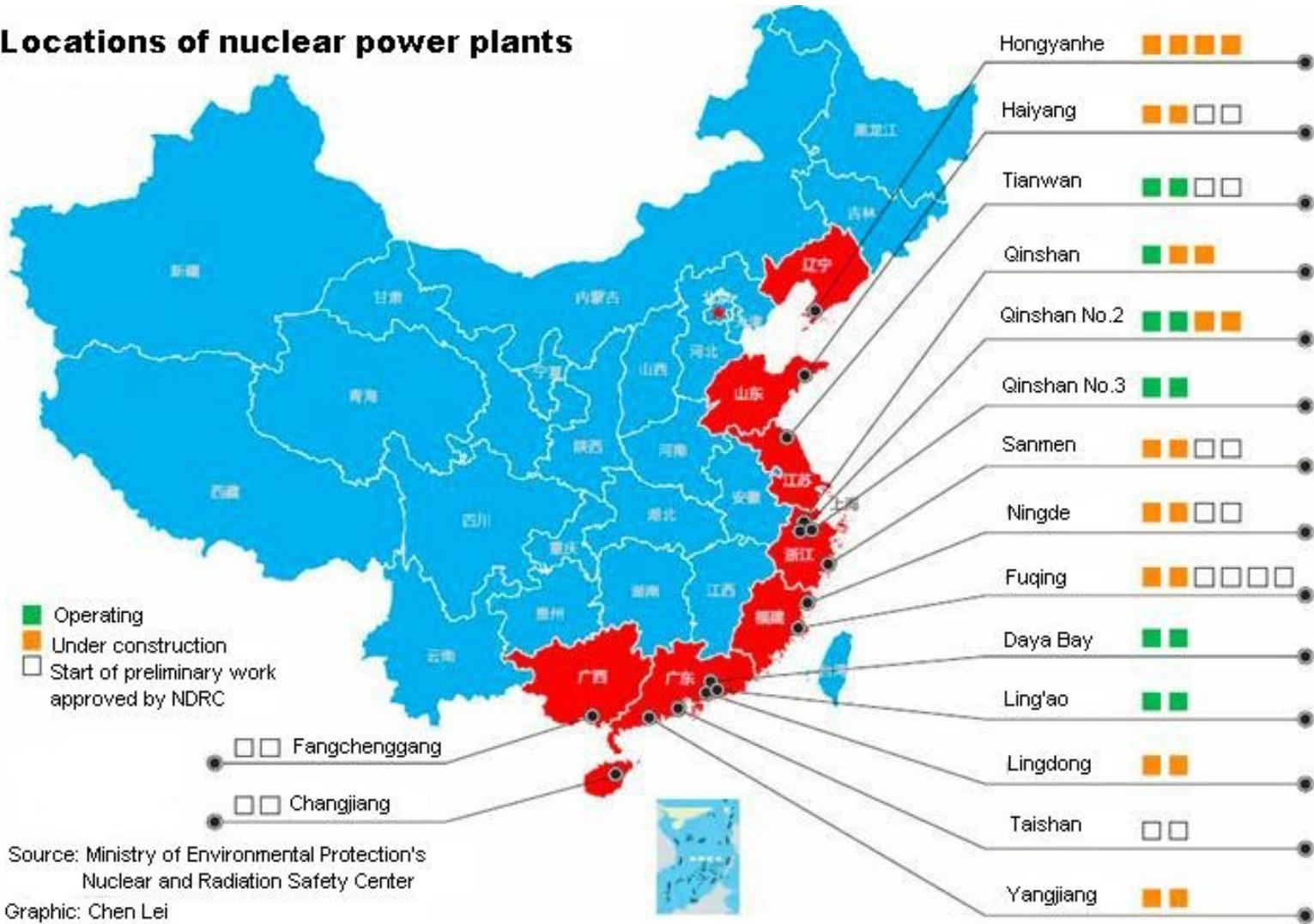
2021 Treaty on the Prohibition of Nuclear Weapons (TPNW)



中国核能的蓬勃发展



Locations of nuclear power plants



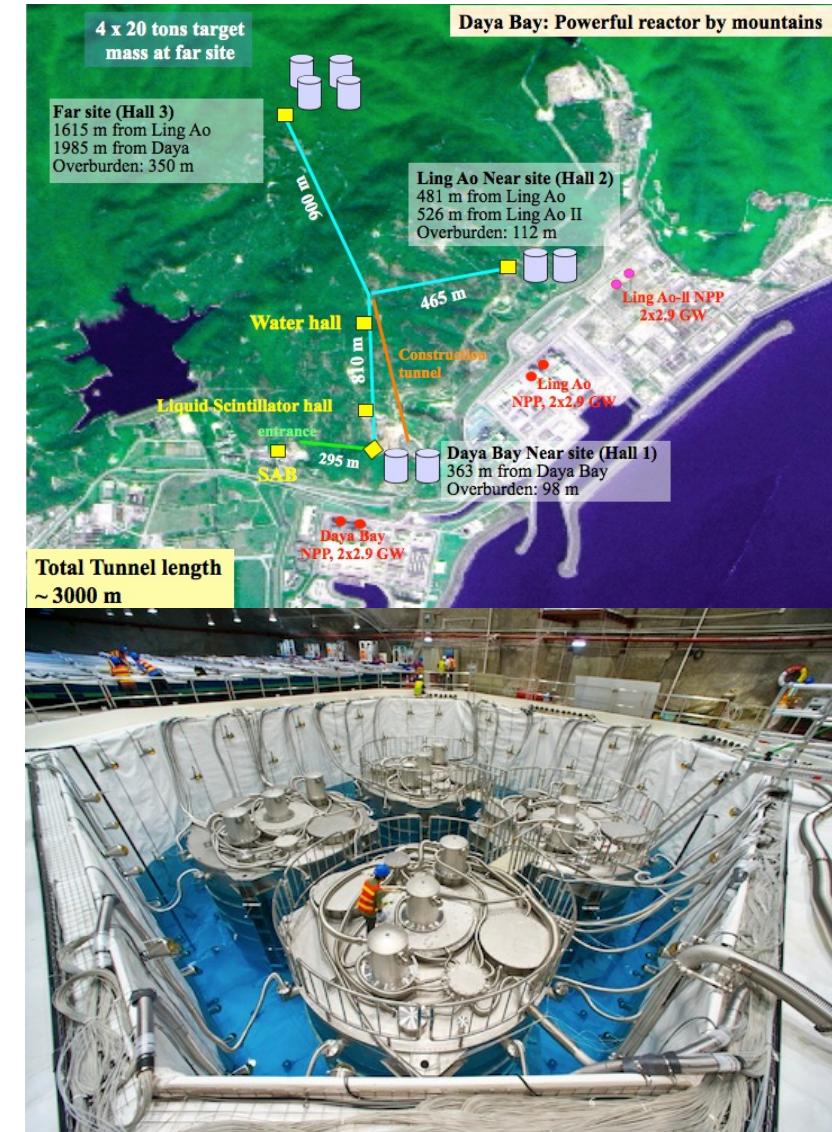
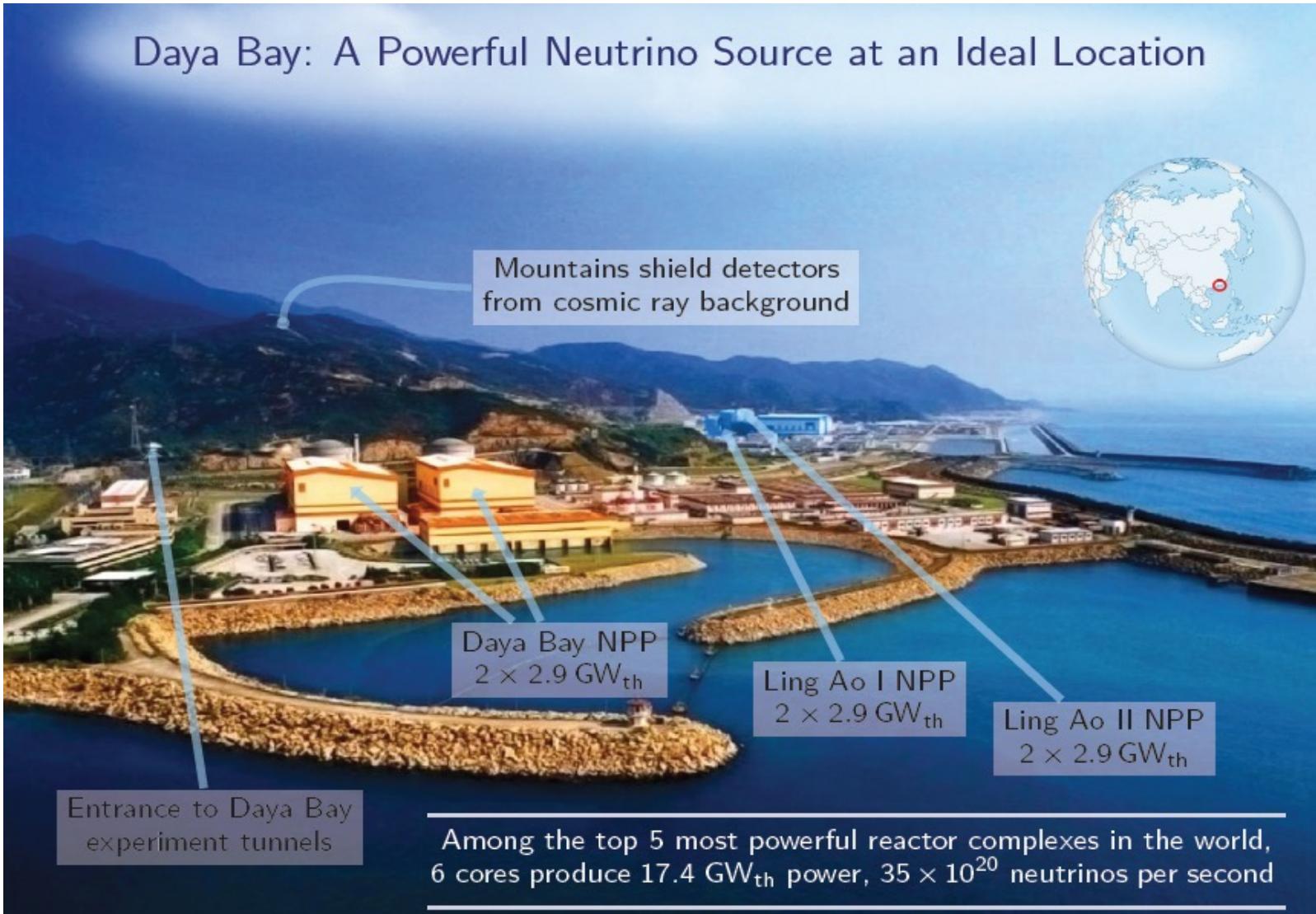
世界第一个EPR



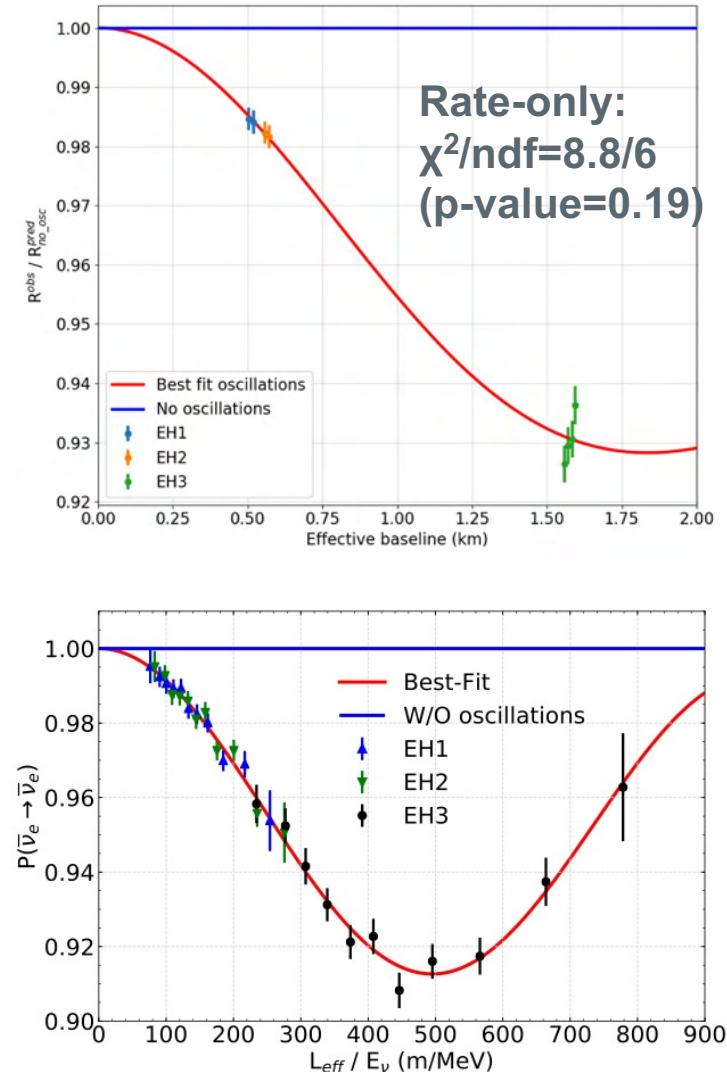
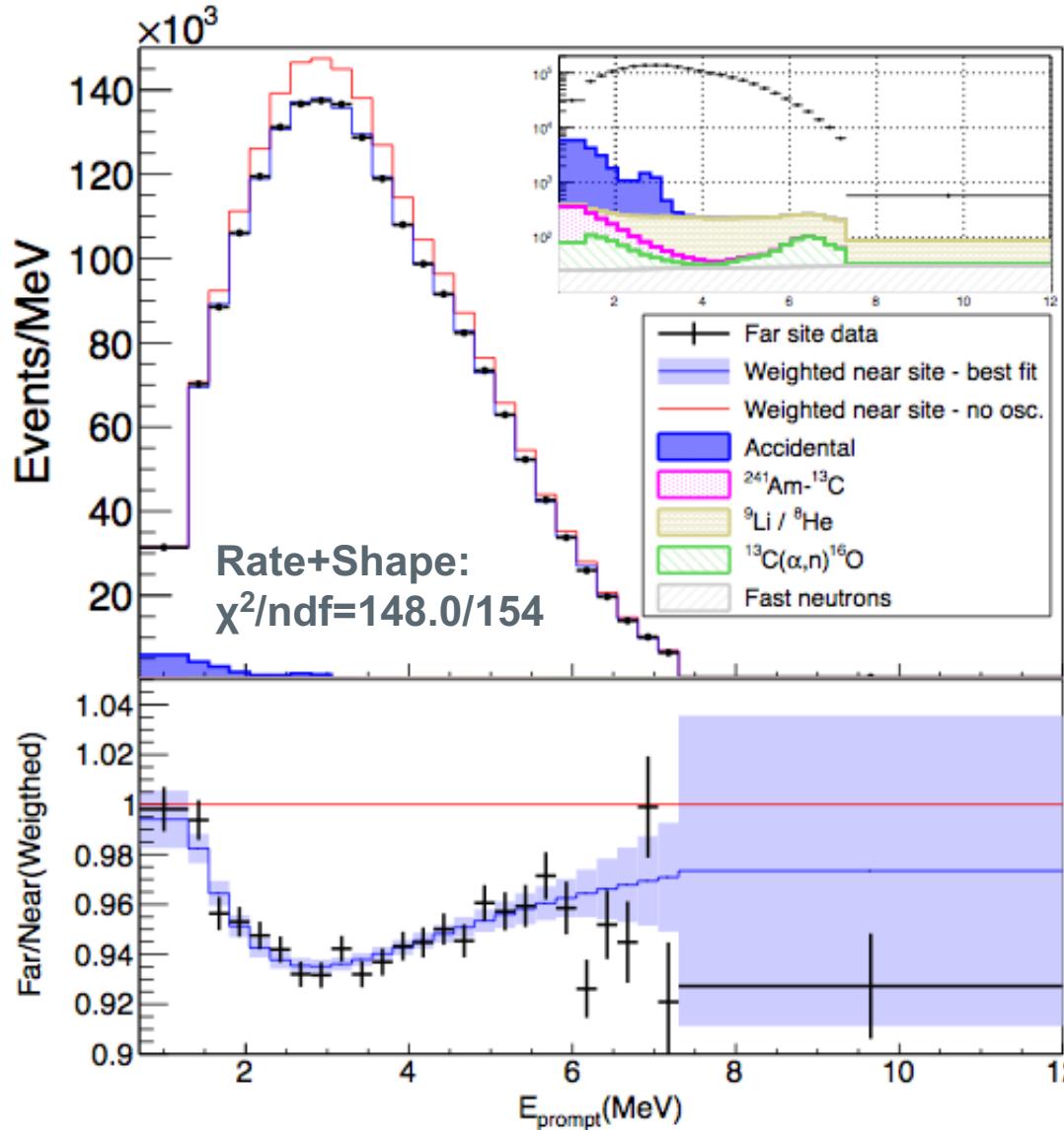
HUALONG ONE NUCLEAR REACTOR
HELPING CHINA MEET CARBON GOALS



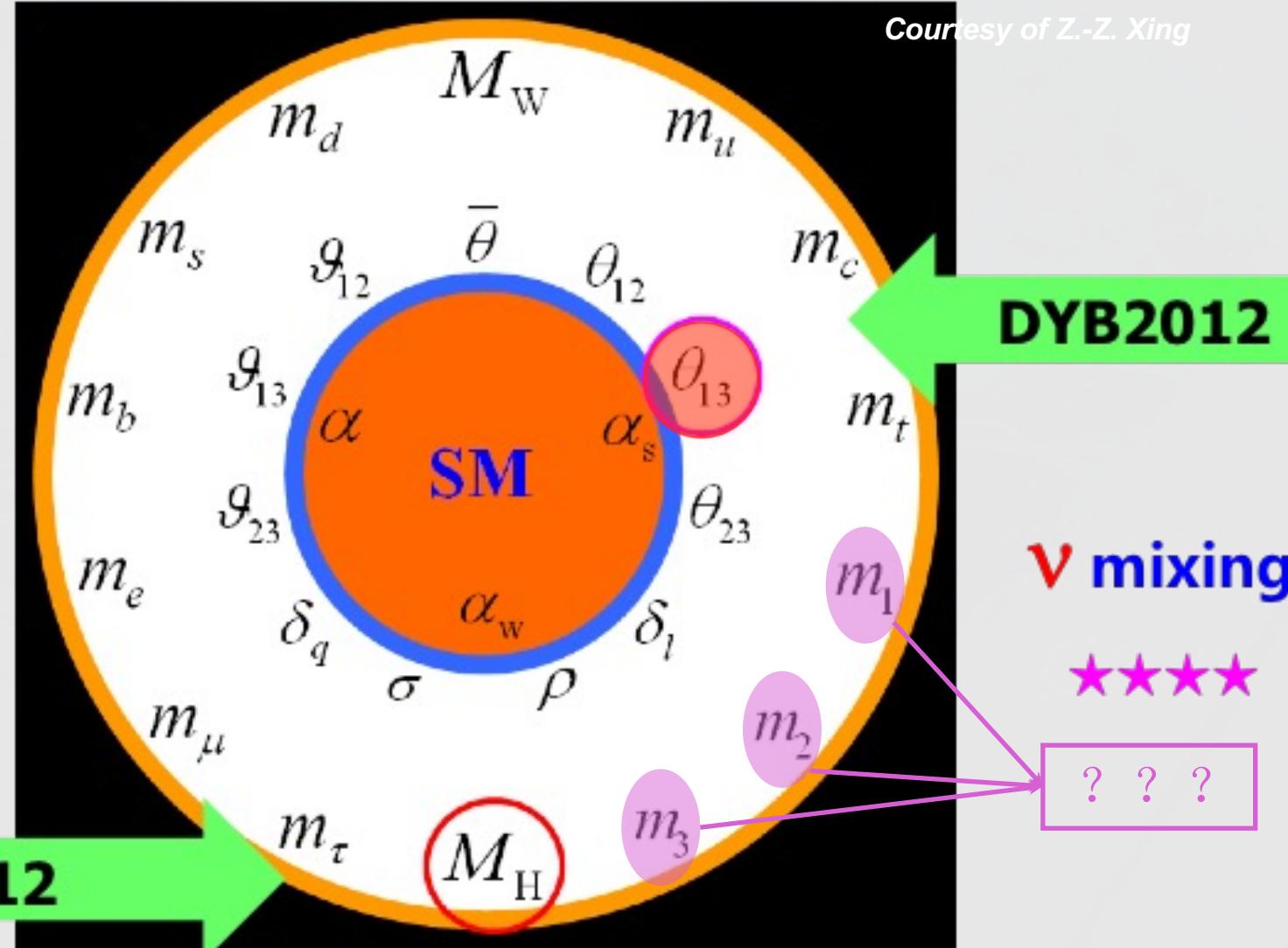
“机会只给有准备的人” → 本世纪初，中国提出大亚湾反应堆实验



大亚湾反应堆中微子实验发现第三种振荡模式



2012年，大亚湾实验到底测量了什么？



Columbia University in the City of New York | New York, N.Y. 10027
DEPARTMENT OF PHYSICS
Theoretical Physics Group

535 West 120th Street
Fax: 212-852-3149

和先生、贊先生：

最热诚的恭贺！

在您们领导下，很精确地
测量了 theta one-three，这是
粒子物理中极基本，极重要的
参数！

李政道

二〇一二年三月八日

“可能是物理领域中国
最大的贡献”

大亚湾获得了2016年基础物理突破奖



LAUREATES

[Breakthrough Prize](#) [Special Breakthrough Prize](#) [New Horizons Prize](#) [Physics Frontiers Prize](#)

2016 [2015](#) [2014](#) [2013](#) [2012](#)



[Kam-Biu Luk and the Daya Bay Collaboration](#)



[Yifang Wang and the Daya Bay Collaboration](#)



[Koichiro Nishikawa and the K2K and T2K Collaboration](#)



[Atsuto Suzuki and the KamLAND Collaboration](#)



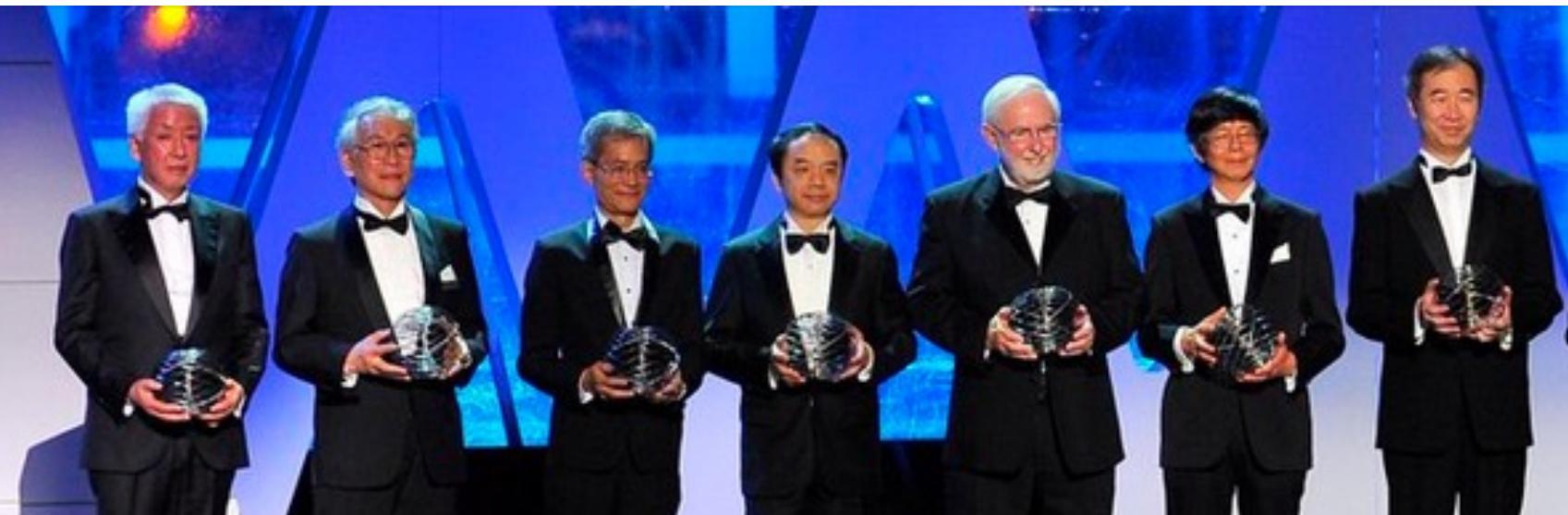
[Arthur B. McDonald and the SNO Collaboration](#)



[Takaaki Kajita and the Super K Collaboration](#)



[Yoichiro Suzuki and the Super K Collaboration](#)



To Complete the Standard Neutrino Picture

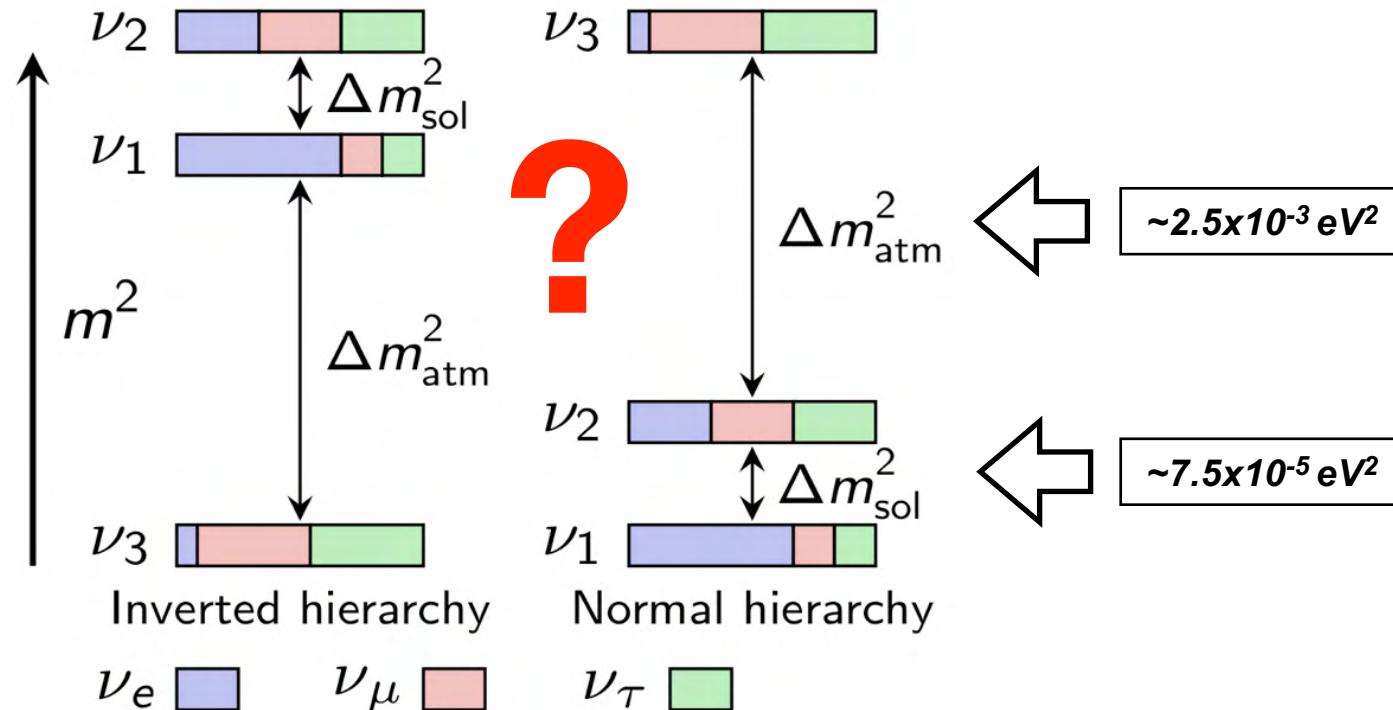


$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Sector:
SK, K2K, T2K, MINOS, etc

Reactor Sector

Solar Sector:
SNO, SK, KamLAND etc



- CP phase?
- **The neutrino mass ordering?**
- Nature of neutrino mass?
-

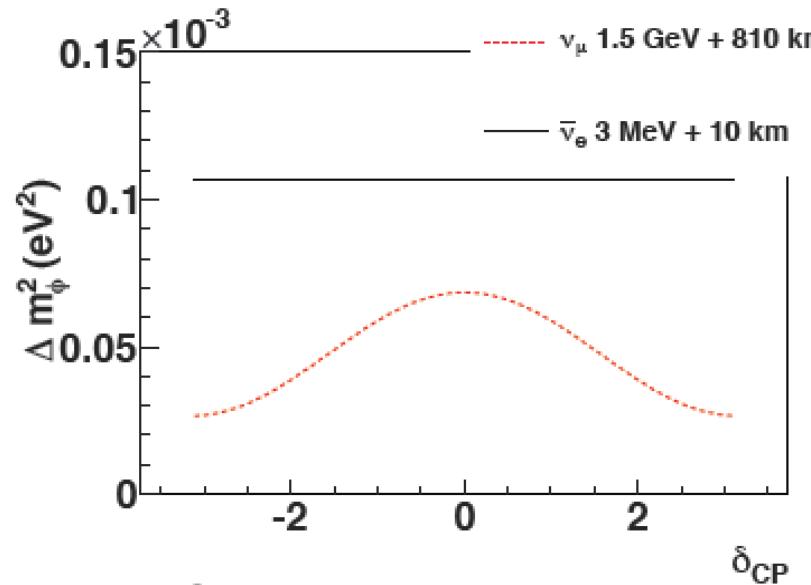
Side Remark: e-Flavor and μ -Flavor Feels MH Effect Differently



$$\begin{aligned} P(\bar{\nu}_e \rightarrow \bar{\nu}_e) &= 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \\ &= 1 - 2s_{13}^2 c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21} + 2s_{13}^2 c_{13}^2 \sqrt{1 - 4s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}} \cos(2\Delta_{32} \pm \phi) \end{aligned}$$

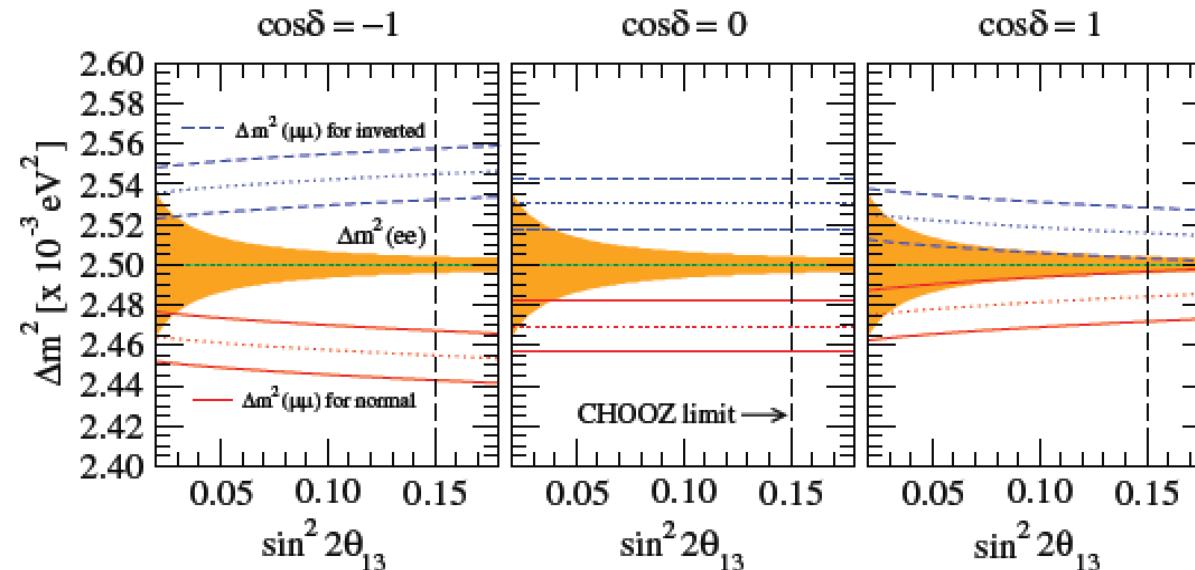
$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - P_{21}^\mu - \cos^2 \theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{(\Delta m_{32}^2 \pm \phi)L}{4E}$$

Extremely Challenging: Need 1% accuracy!



Qian et al, PRD87(2013)3, 033005

FIG. 6: The dependence of effective mass-squared difference $\Delta m_{ee\phi}^2$ (solid line) and $\Delta m_{\mu\mu\phi}^2$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and $\bar{\nu}_\mu$ disappearance measurements, respectively.



Minakata et al PRD74(2006), 053008

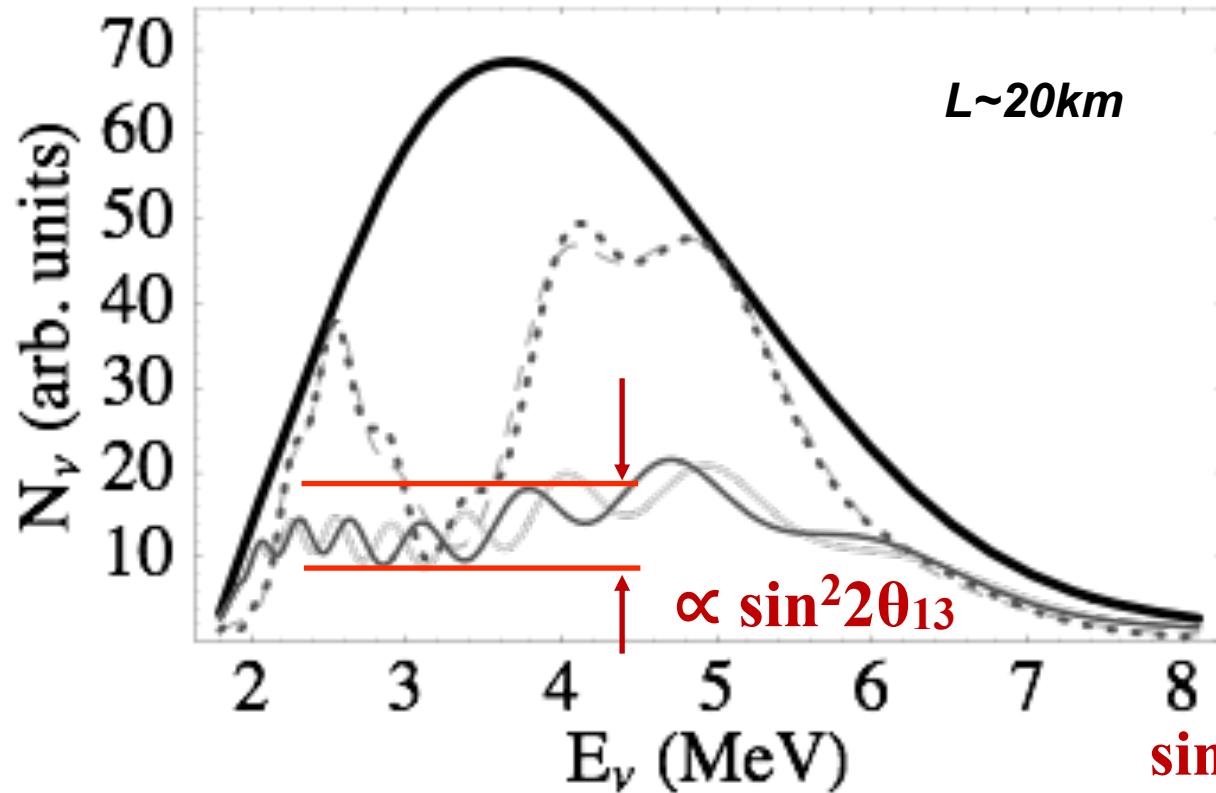
Bo-Qiang Ma et al, Mod. Phys. Lett. A 29 (2014) 1450096

Known θ_{13} Enables Neutrino Mass Hierarchy at Reactors

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

$$- \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

Petcov&Piai, Phys. Lett. B533 (2002) 94-106



- ✓ Mass hierarchy reflected in the spectrum
- ✓ Independent of the unknown CP phase



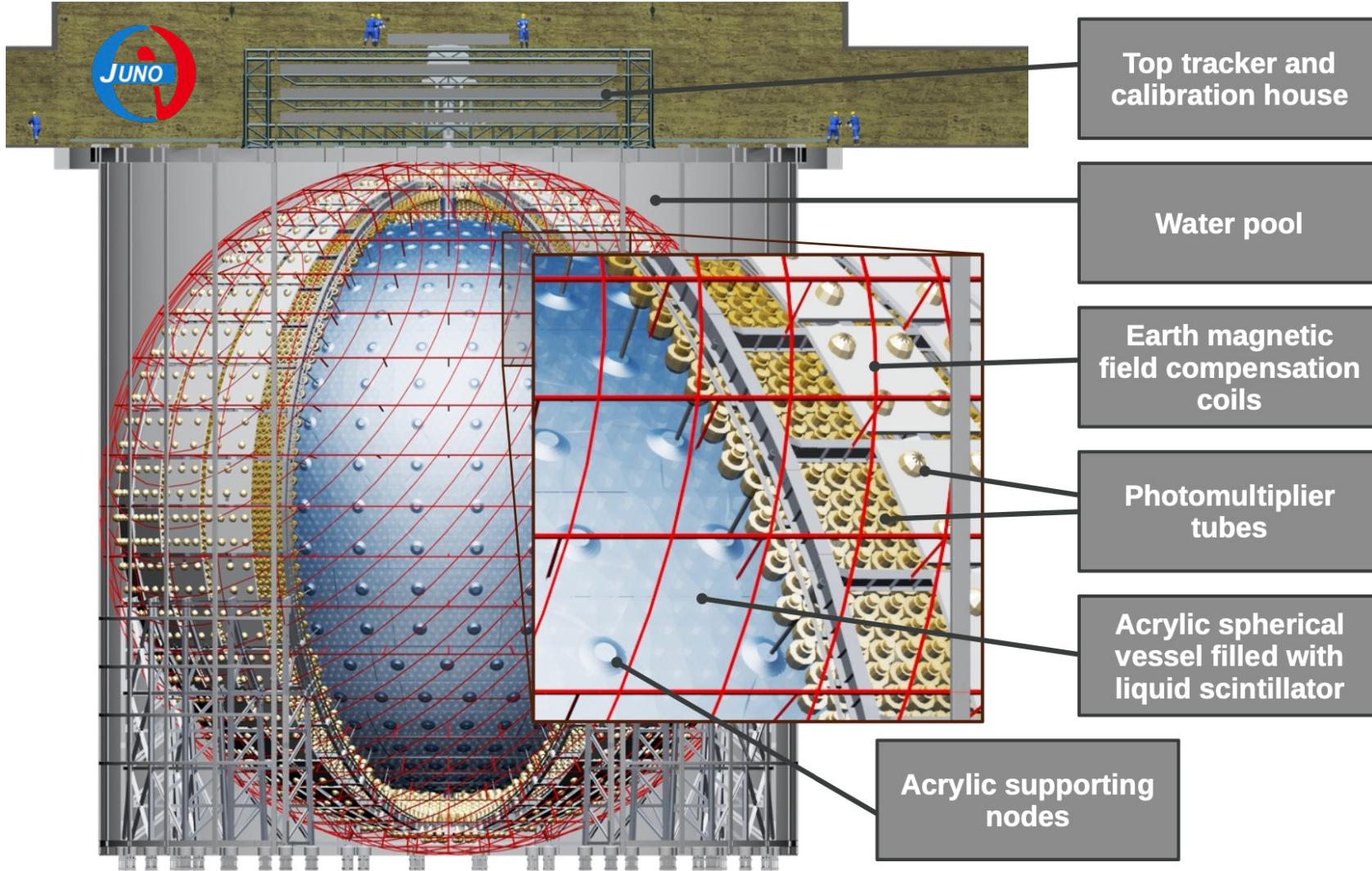
$\sin^2 2\theta_{13}$ Sufficiently large by DYB, RENO, and DC

Global Efforts Resolving ν Mass Hierarchy



Source / Principle	Matter Effect	Interference of Solar&Atm Osc. Terms	Collective Oscillation	Constraining Total Mass or Effective Mass
Atmospheric ν	Super-K, Hyper-K, IceCube PINGU, ICAL/INO, ORCA, DUNE	Atm ν_μ + JUNO		
Beam ν_μ	T2K, NO ν A, T2HKK, DUNE	Beam ν_μ + JUNO		
Reactor ν_e		JUNO, JUNO + ν_μ Data		
Supernova Burst ν			Super-K, Hyper-K, IceCube PINGU, ORCA, DUNE, JUNO	
Interplay of Measurements				Cosmo. Data, KATRIN, Proj-8, 0v $\beta\beta$

We Need an Unprecedented Detector to Face the Challenges



700m Underground

Pool height 44m
Water depth/Diameter: 43.5m

~17612 20" PMT+
~25000 3" PMT

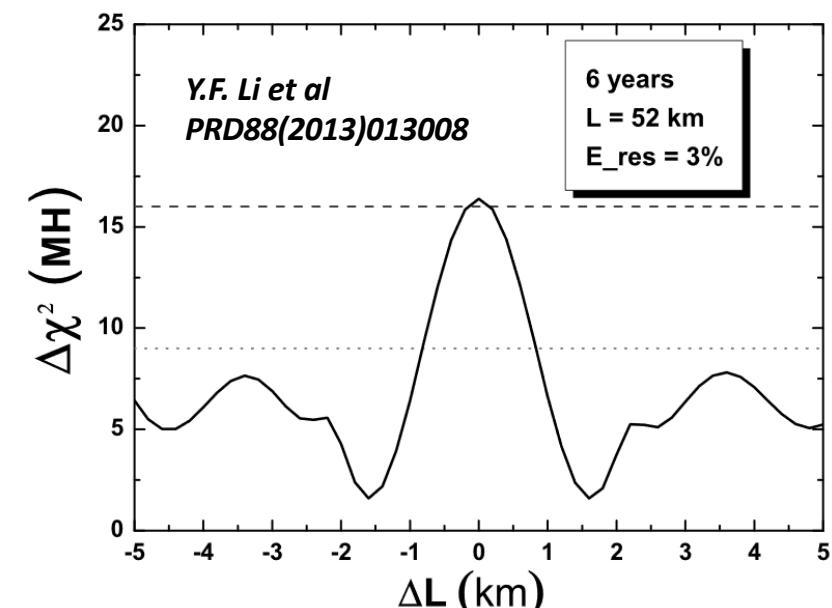
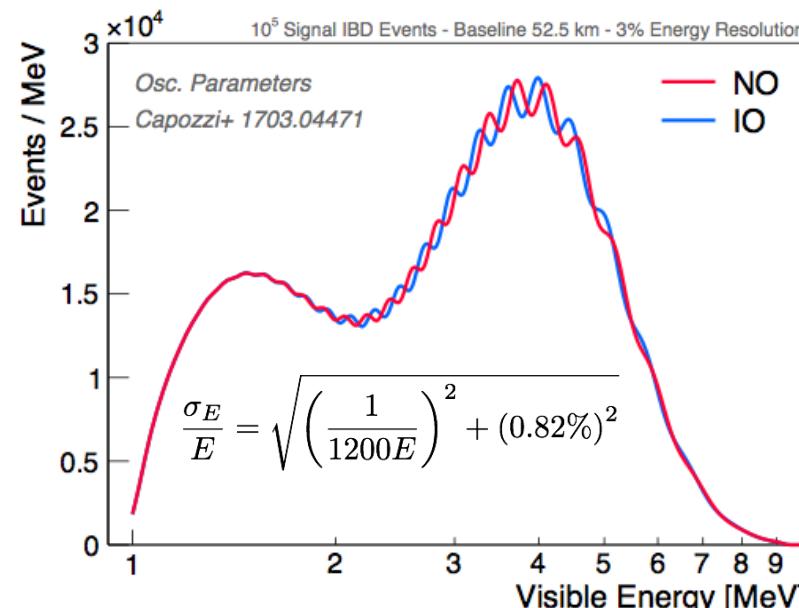
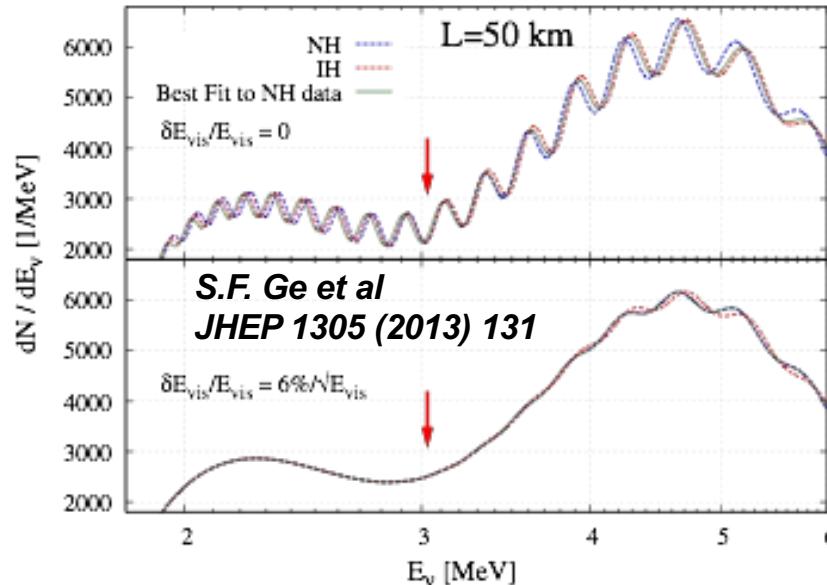
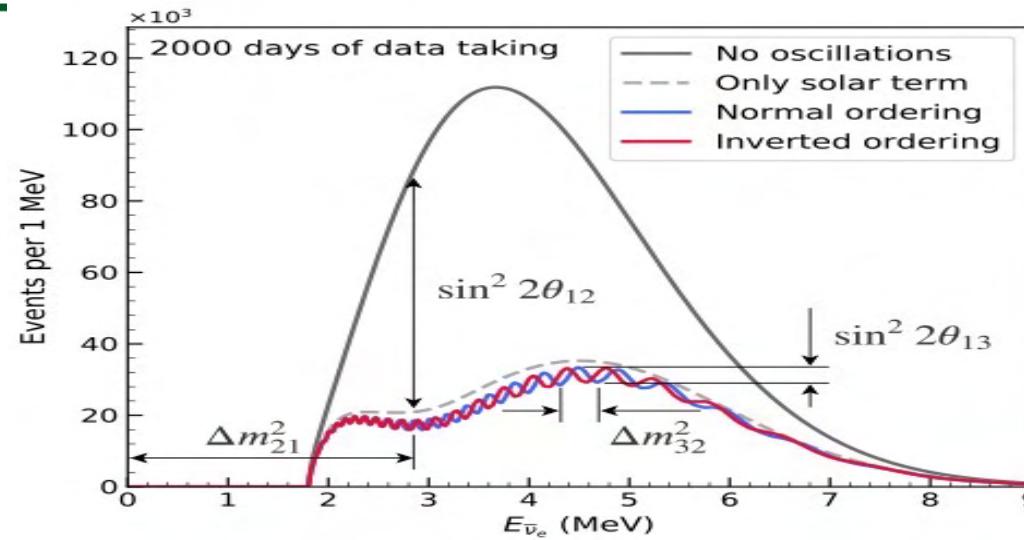
Water Cherenkov
~2400 20" PMT

Central Detector
Steel Structure +
Acrylic sphere +
20kt Liquid Scintillator

Four Major Challenges in Resolving MH using Reactors



- Energy resolution: $\sim 3\%/\text{sqrt}(E)$
- Energy scale uncertainty: $< 1\%$
- Statistics (the more the better)
- Reactor distance differences: $< \sim 0.5\text{km}$



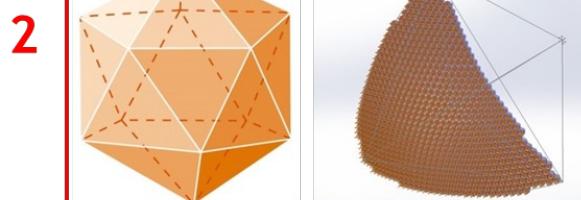
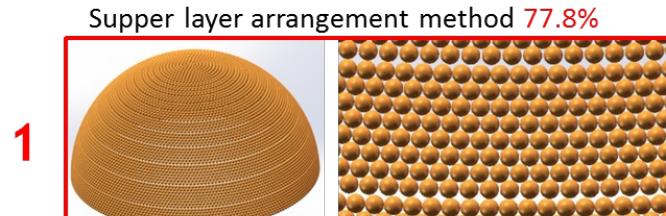
What can Such a Detector Detect?



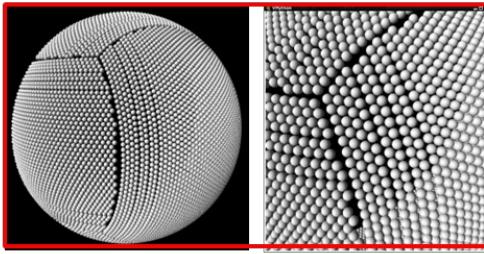
	KamLAND	Daya Bay	PROSPECT	JUNO
Target Mass	$\sim 1\text{kt}$	20t	$\sim 4\text{t}$	$\sim 20\text{kt}$
Photocathode Coverage	$\sim 34\%$	$\sim 12\%$ (Effective)	ESR + PMTs	$\sim 80\%$
PE Collection	$\sim 250 \text{ PE/MeV}$	$\sim 160 \text{ PE/MeV}$	$\sim 850 \text{ PE/MeV}$	$\sim 1345 \text{ PE/MeV}$
Energy Resolution	$\sim 6\%/\sqrt{E}$	$\sim 7.5\%/\sqrt{E}$	$\sim 4.5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Energy Calibration	$\sim 2\%$	$1.5\% \rightarrow 0.5\%$	$\sim 1.5\% (?)$	$<1\%$

Packing PMTs as Tight as Possible

✓

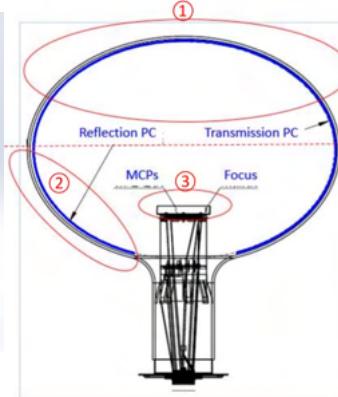
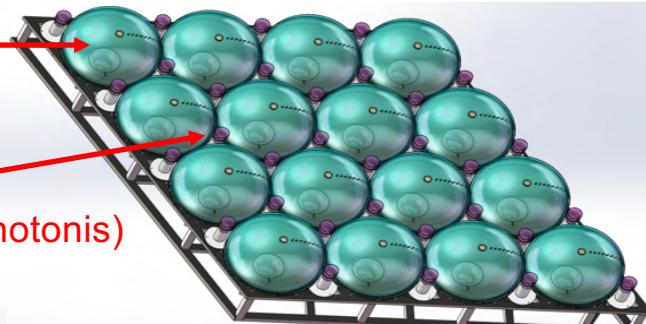


3 Volleyball arrangement method 75.96%

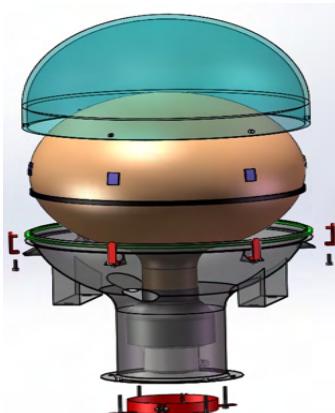
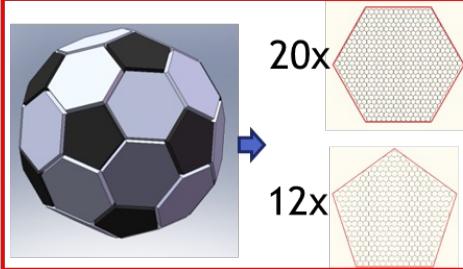


20" PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)

3"sPMT(~25K)
H2C XP72B22 (Photonis)



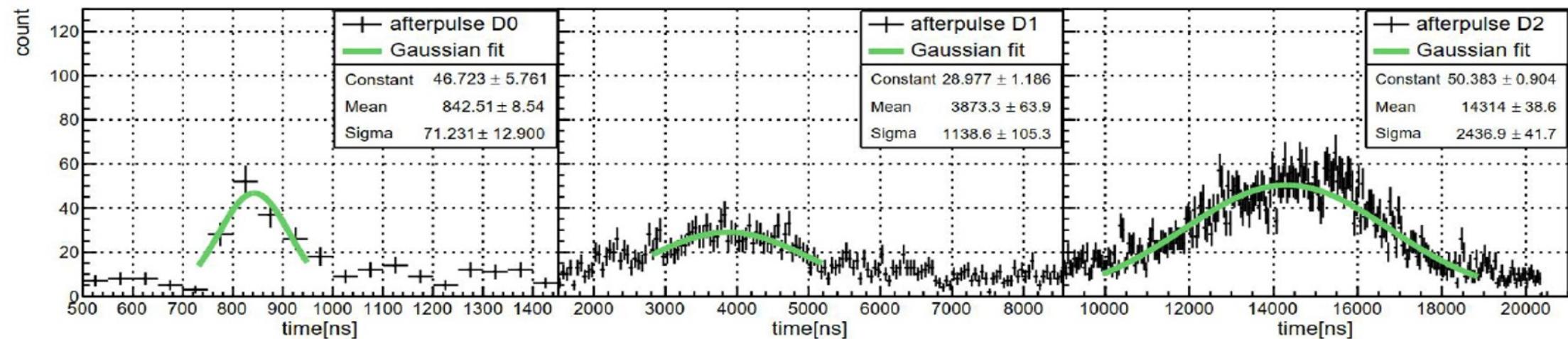
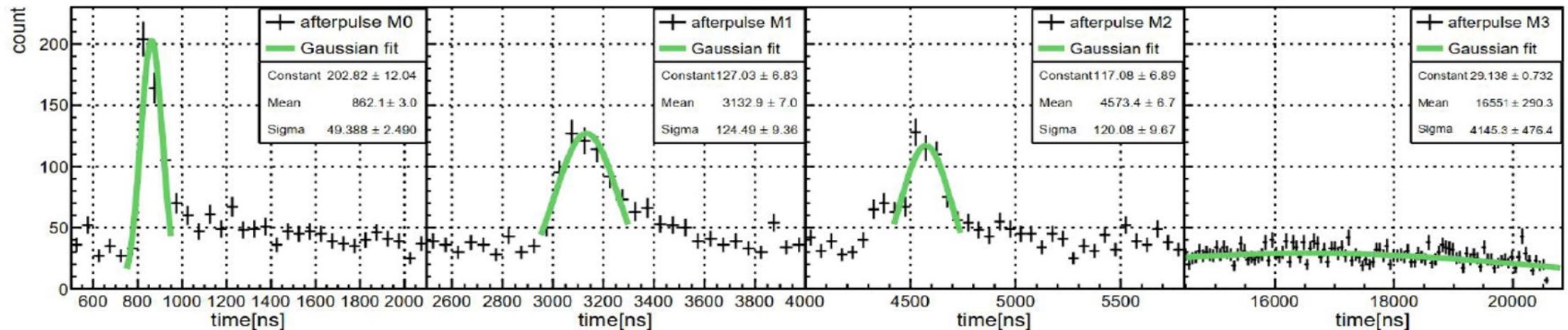
4 Football arrangement method 74.08%



Characterizing Every Single PMT with Great Care: Afterpulses



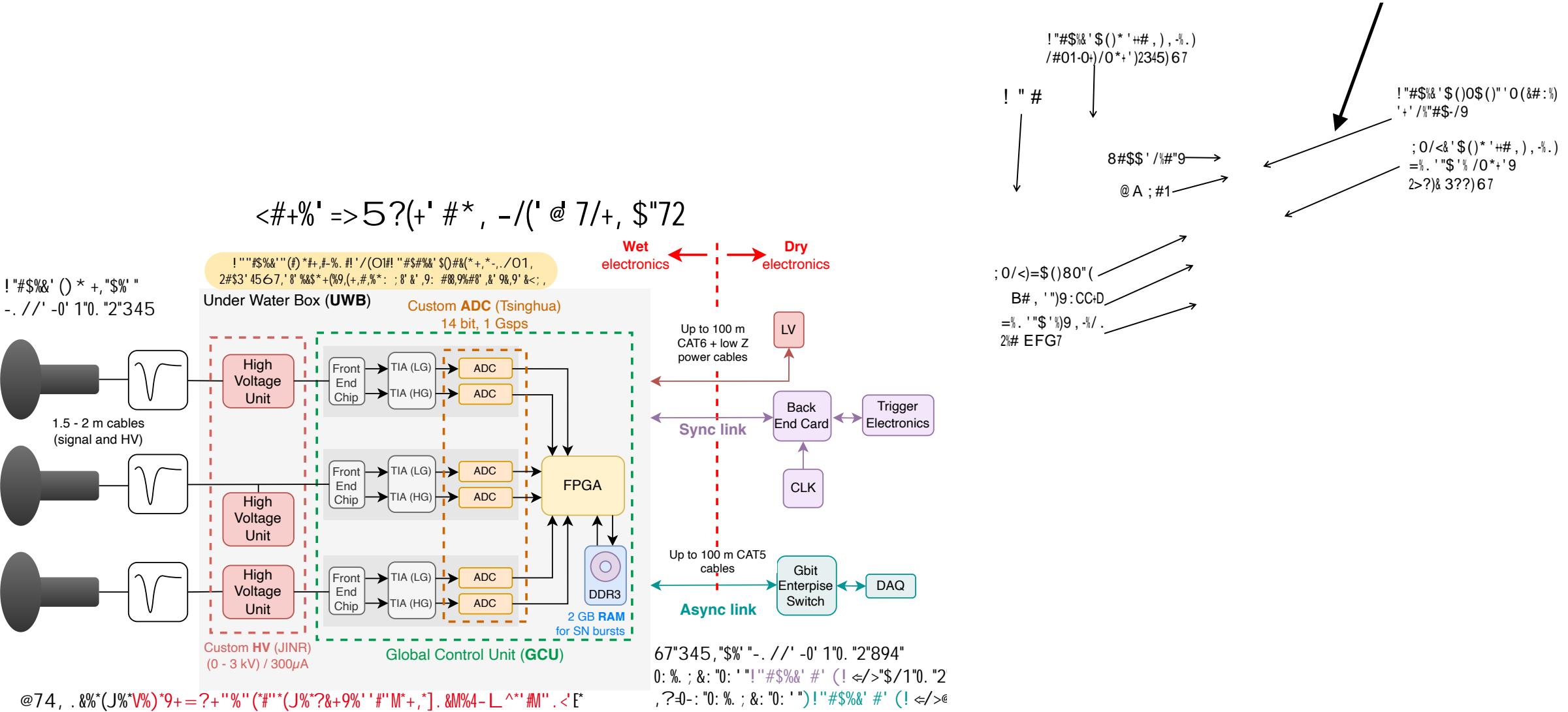
MCP PMT



HAMAMATSU PMT

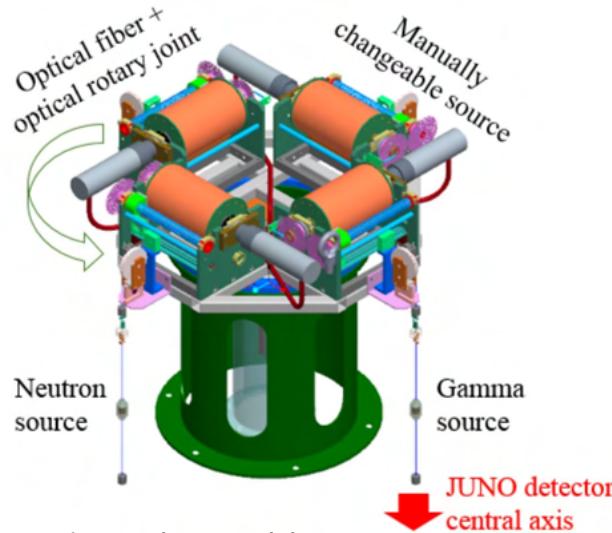
For the complete details, please see our forthcoming publication on 20in PMT characterization

Large PMT Electronics System Overview

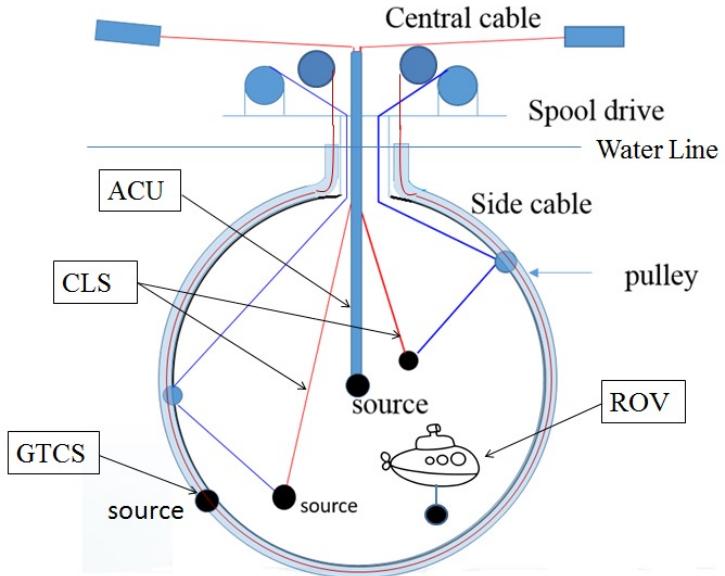
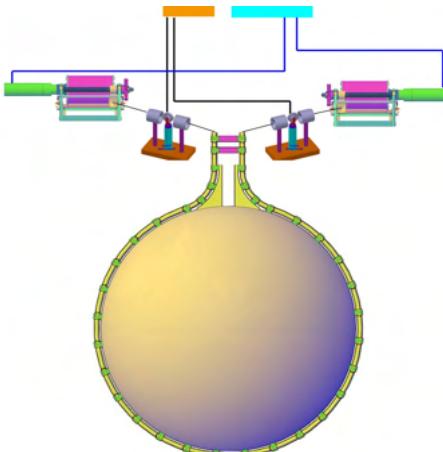


The JUNO Calibration System

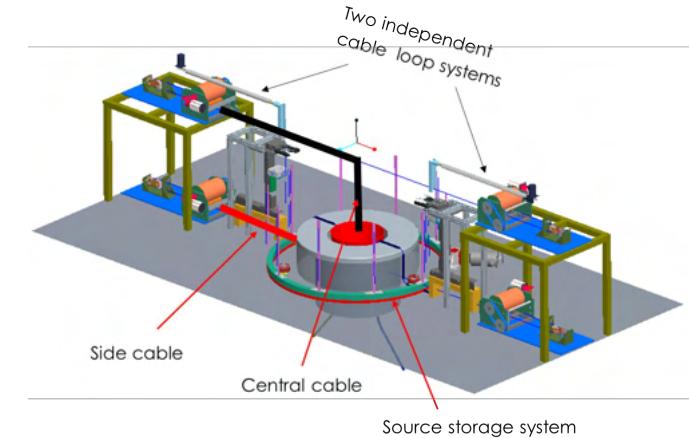
Automatic Calibration Unit (ACU)



Guide Tube Calibration System(GTCS)

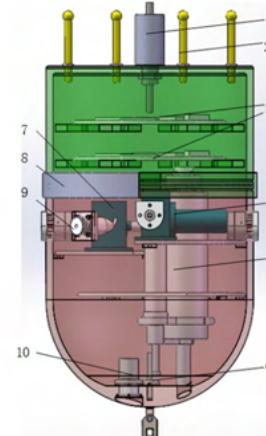


Cable Loop System (CLS)

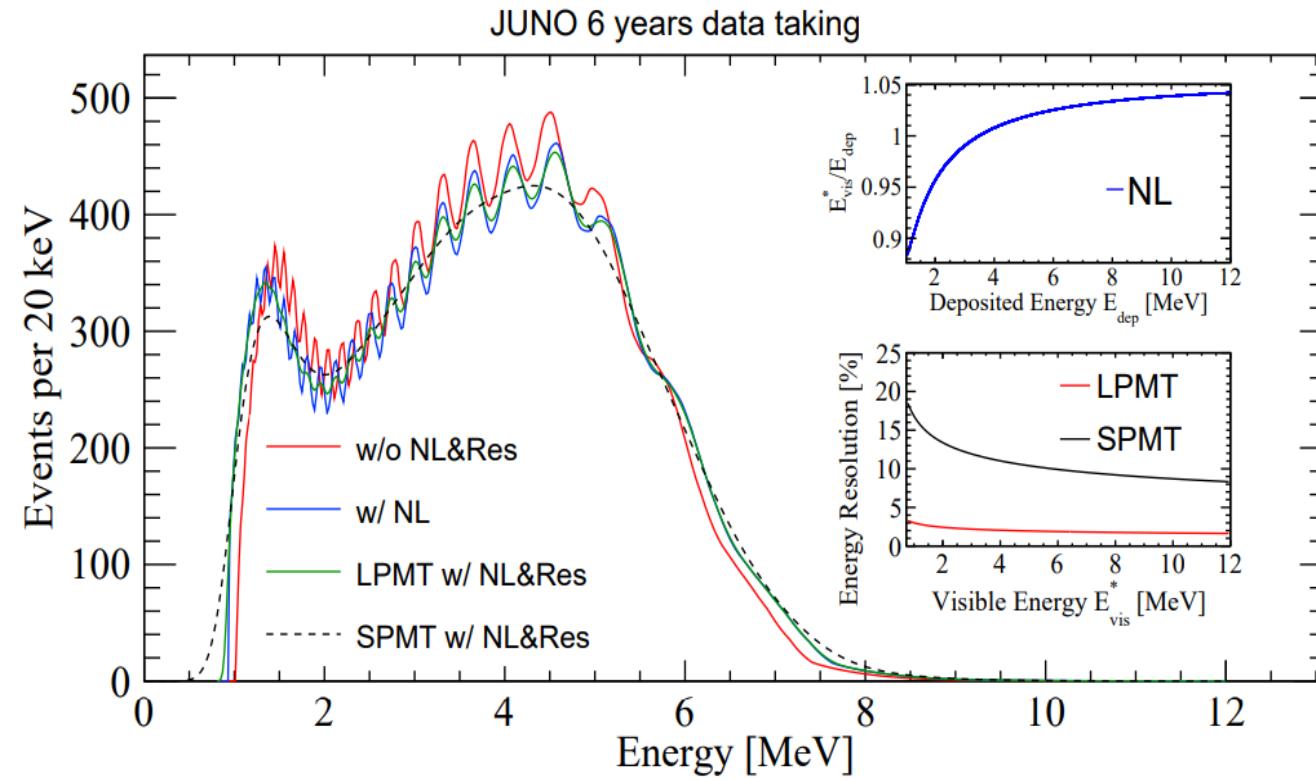
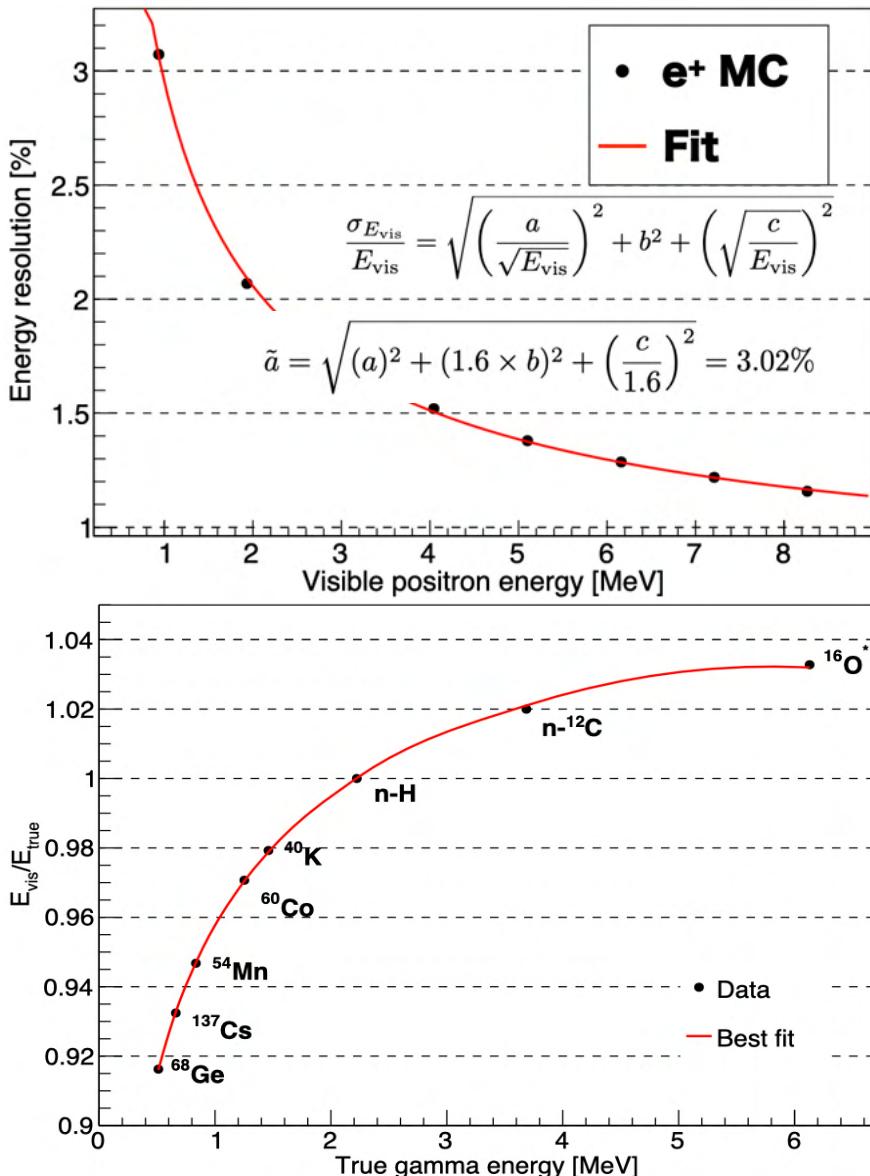


Remotely Operated under-liquid-scintillator Vehicles (ROV)

- Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector



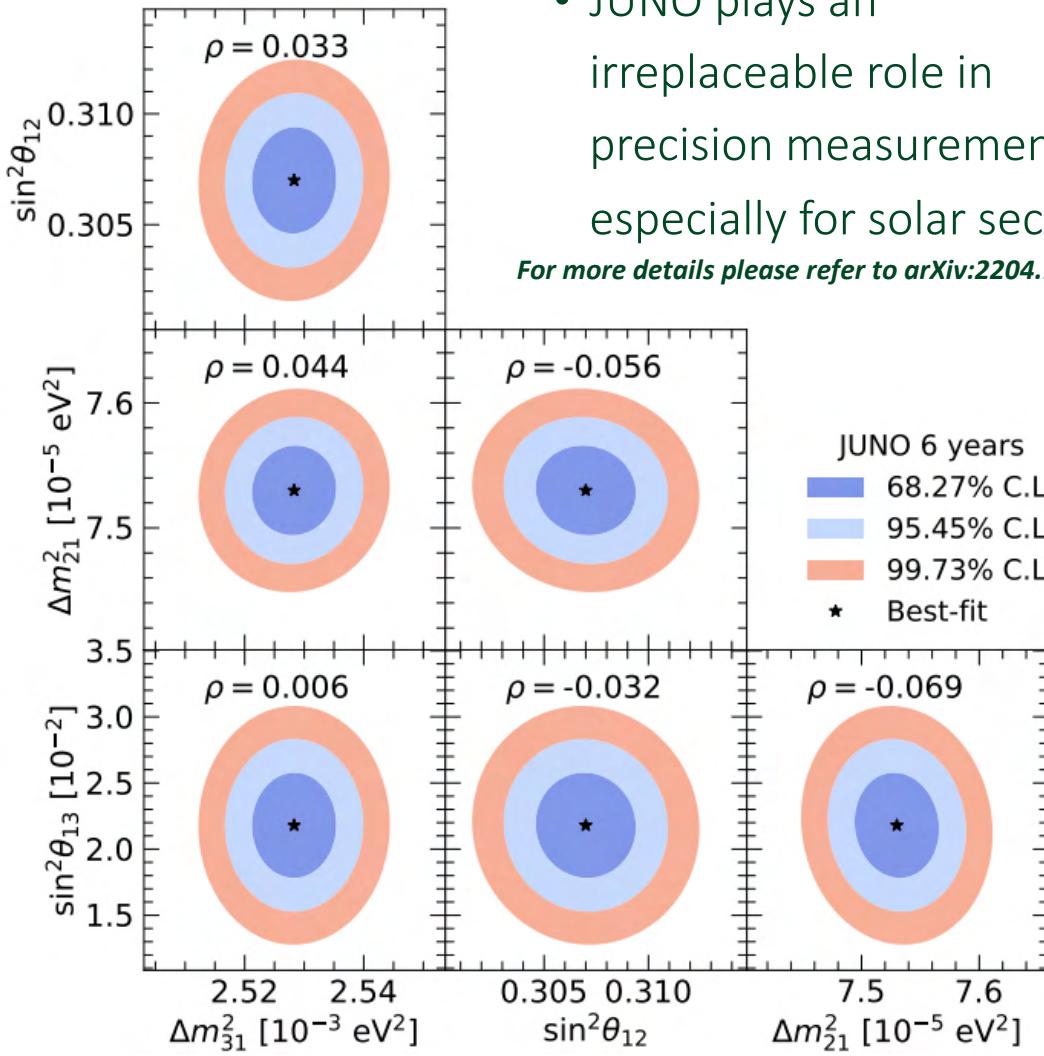
Expected Performance in Energy Responses



JUNO Calibration Publications

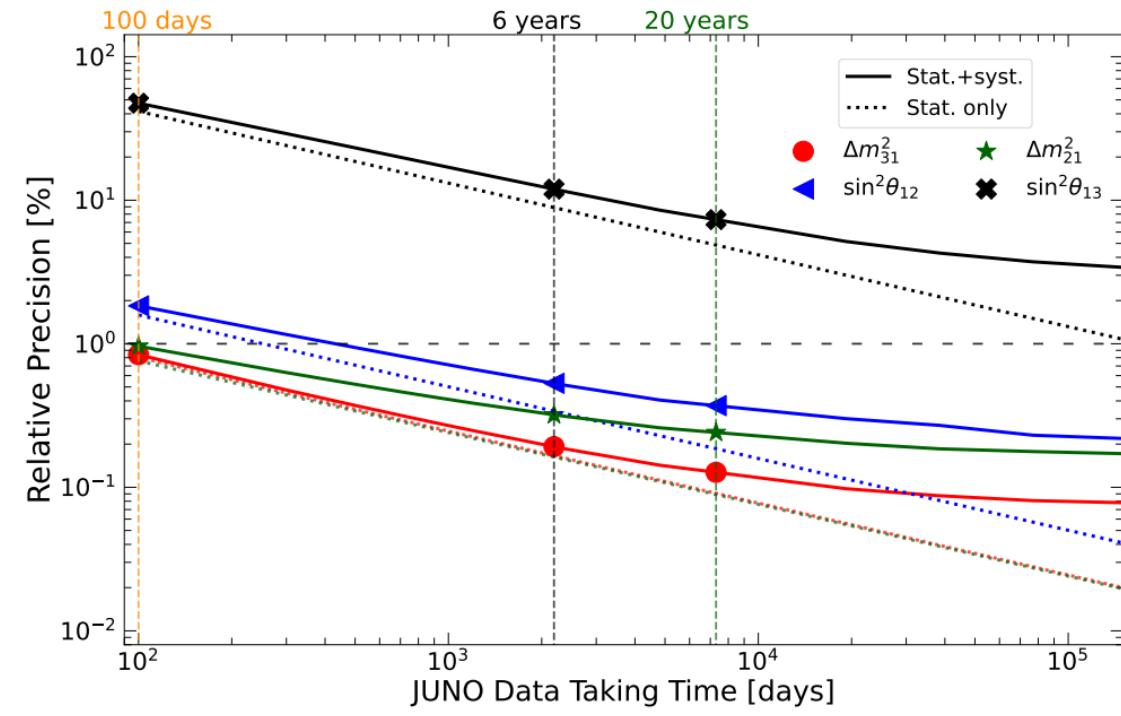
- Calibration Strategy, J. High Energ. Phys. 2021, 4 (2021)
- ACU Hardware, JINST 16 T08008 (2021),
- CLS Hardware, Nucl. Instrum. Meth. A 988, 164867 (2021)
- GTCS Hardware, JINST 14. T09005 (2019).
- ROV Hardware, JINST 13 T12001 (2018).

Expected Sensitivity for Precision Measurements



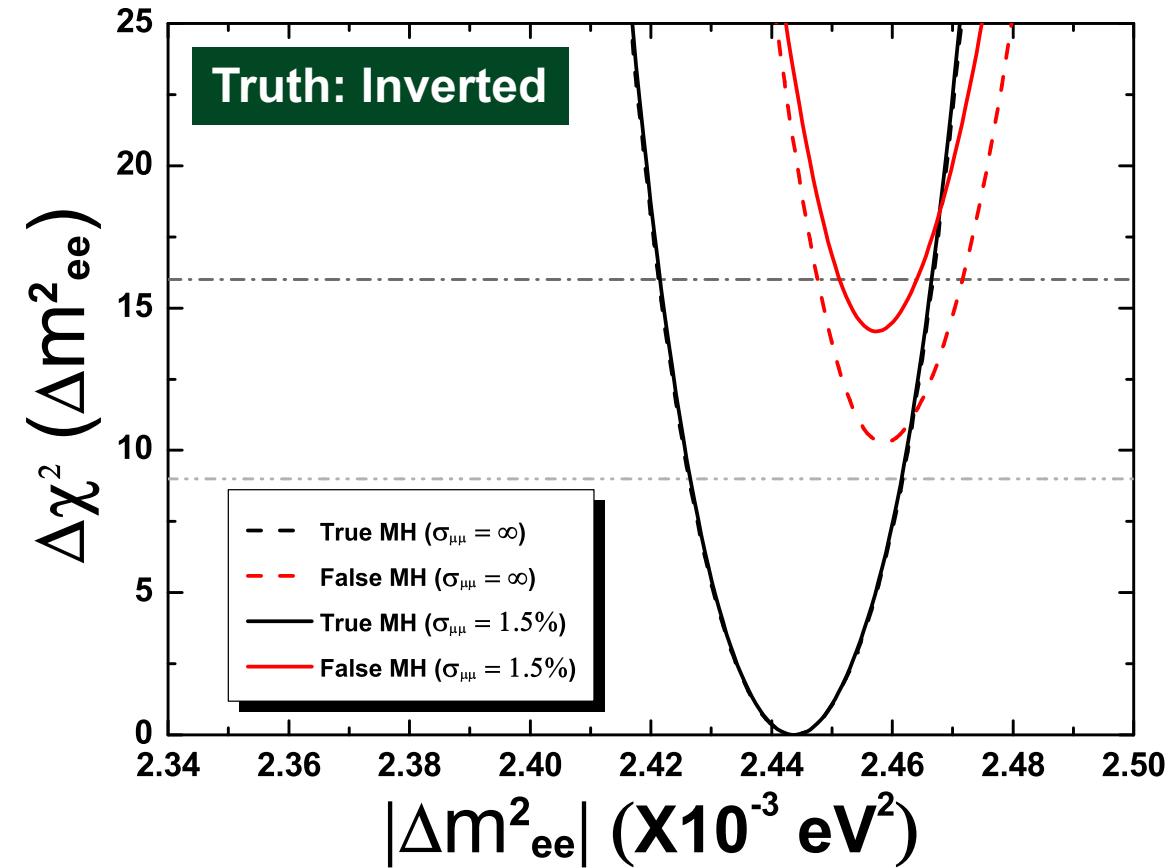
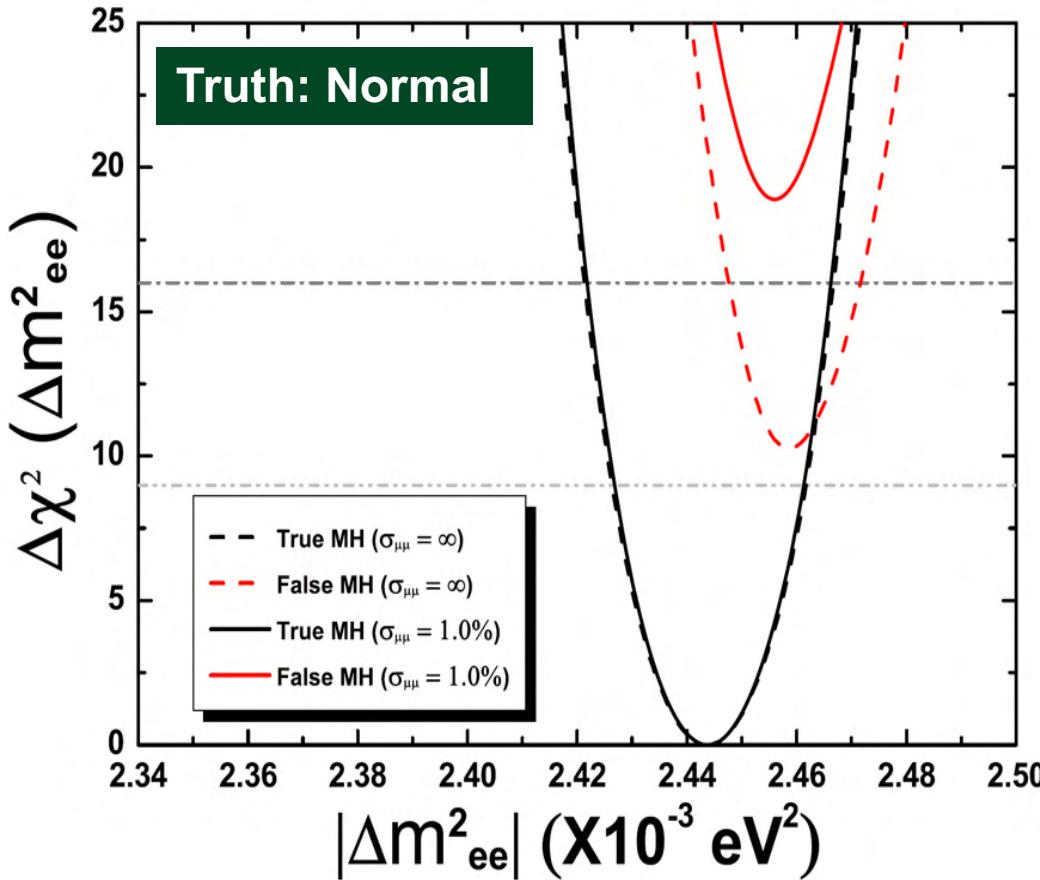
- JUNO plays an irreplaceable role in precision measurements, especially for solar sector

For more details please refer to arXiv:2204.13249



(%)	$\sin^2 \theta_{12}$	Δm^2_{21}	Δm^2_{31}	$\sin^2 \theta_{13}$
Central value	0.307	$7.53 \times 10^{-5} \text{ eV}^2$	$2.5283 \times 10^{-3} \text{ eV}^2$	0.0218
PDG2020	4.2	2.4	1.3	3.2
100 days	1.9	1.0	0.8	47.9
6 years	0.5	0.3	0.2	12.1
20 year	0.3	0.2	0.1	7.3

Expect Sensitivity to Neutrino Mass Ordering

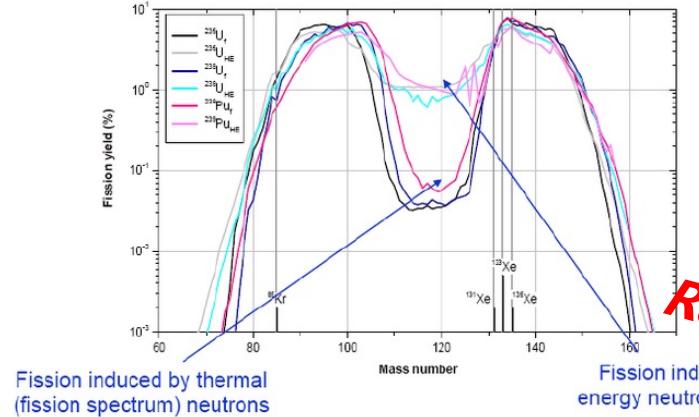


As e-flavor and mu-flavor are complementary thus JUNO alone reaches $\sim 3\sigma$; with external inputs from mu-flavor neutrino beam experiments of 1%, the sensitivity could get improved, 4σ for NH

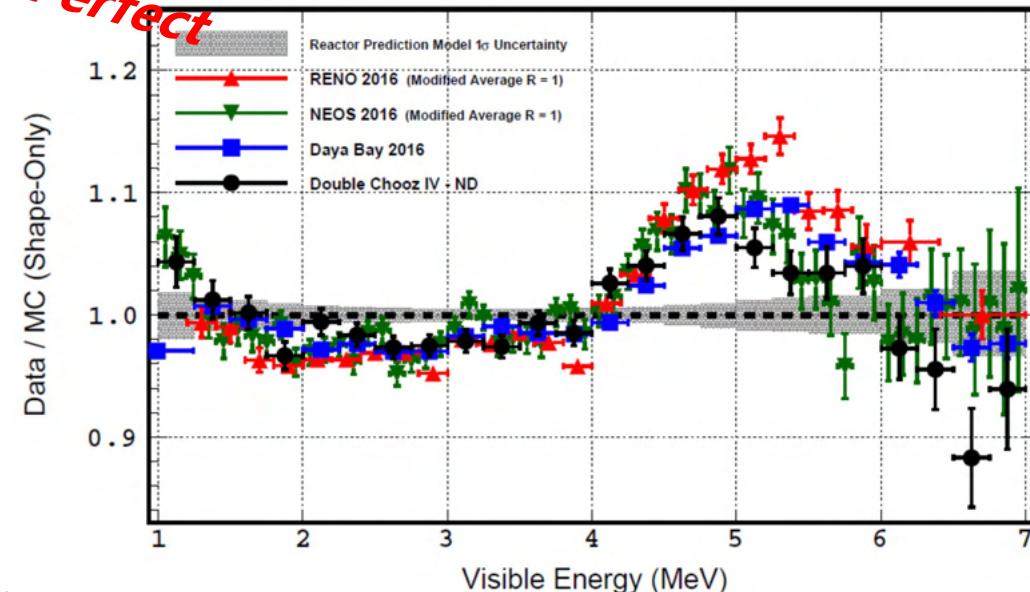
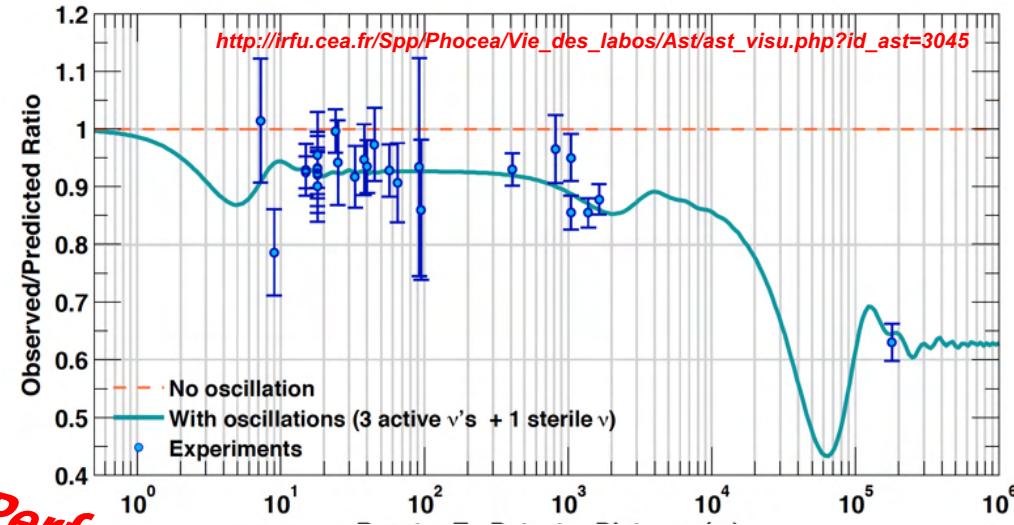
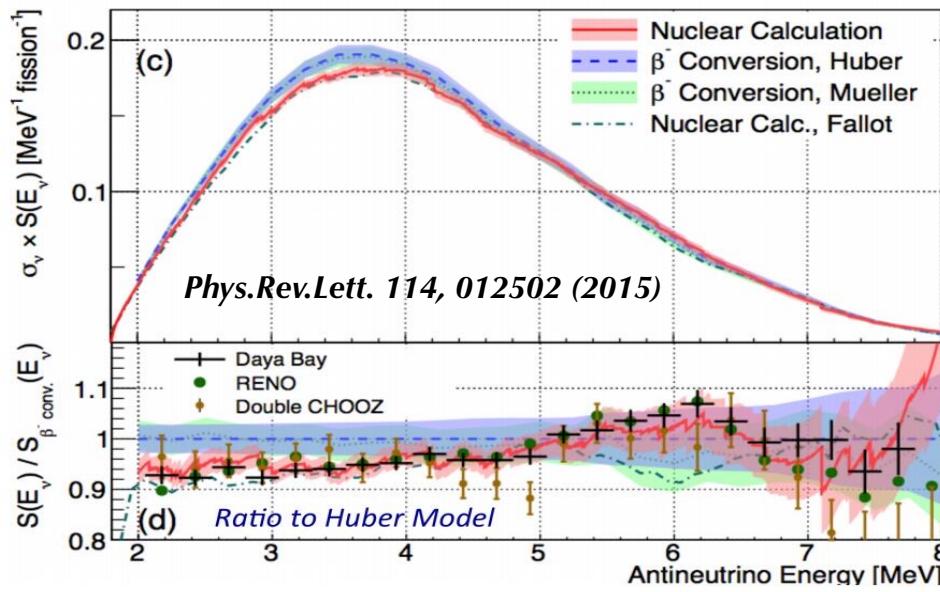
Reactor Neutrinos Need a Resolution Desperately



(Fission yield is a function of the fissioning nuclide and the incident neutron energy)



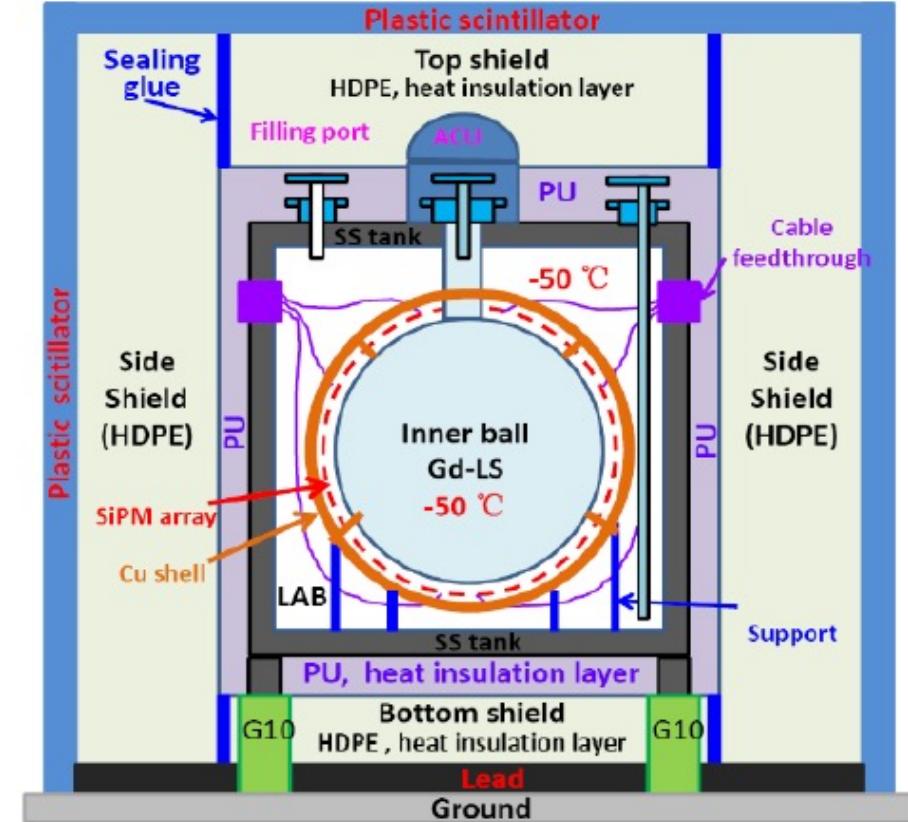
- T. A. Mueller et al., PRC83, 054615 (2011)*
- P. Huber, Phys. Rev.C84, 024617 (2011)*
- Daya Bay, PRL116(2016), PRL123(2019)*
- RENO, PRL121(2018)*
- NEOS, PRL118(2017)*
- Double Chooz, Nature Physics 16(2020)*



Forming the Concept of the JUNO-TAO Experiment

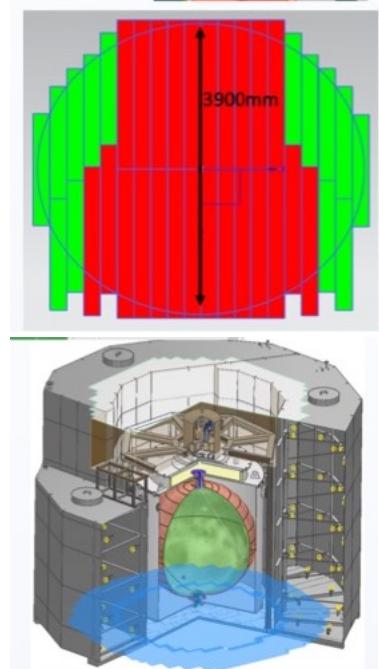
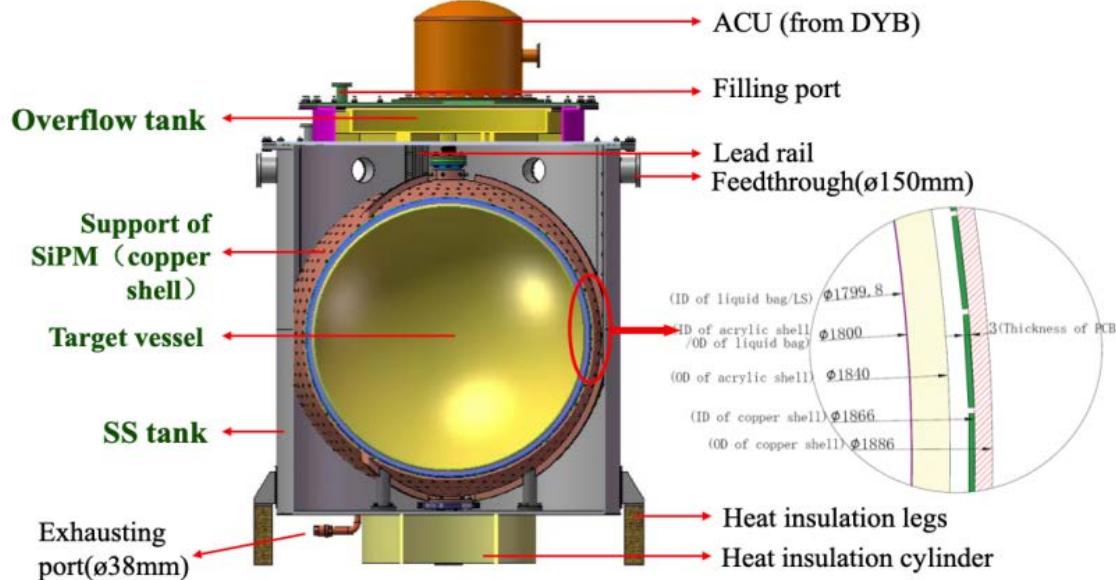


- Measure reactor neutrino spectrum w/ **sub-percent E resolution**
 - Taishan Antineutrino Observatory (TAO), a satellite experiment of JUNO: 30-35 m from EPR core #1: 4.6 GWth
 - Close to core → Ton scale Gd-doped Liquid Scintillator
 - Full coverage of SiPM w/ PDE>50% → Operate at -50°C (reduce SiPM dark noise)
- CDR was released in 2020 (arXiv:2005.08745)



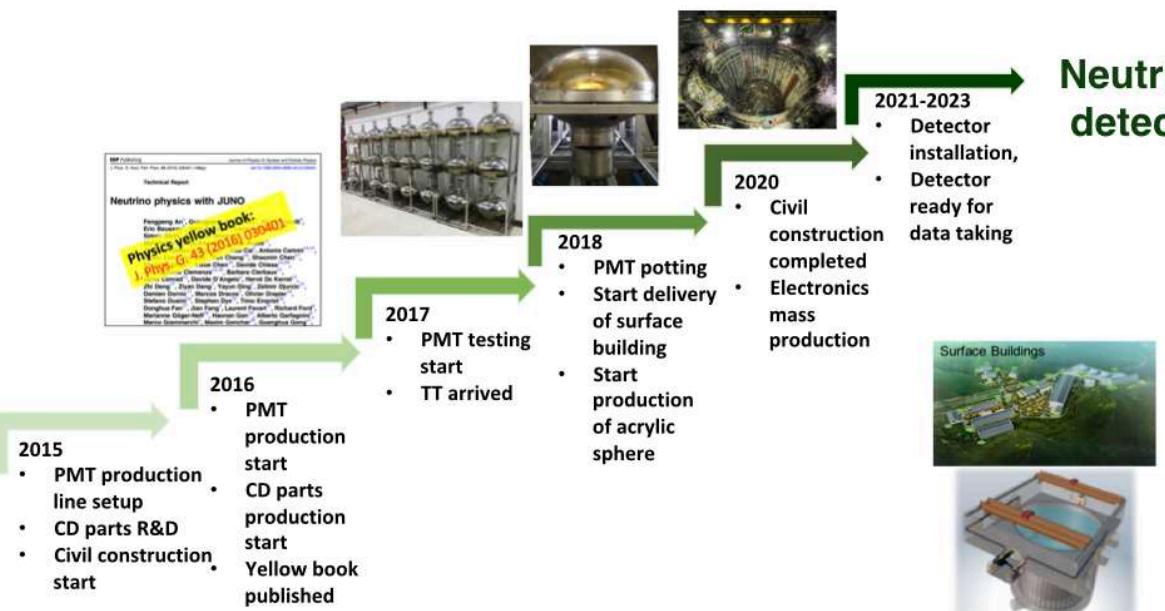
Set to resolve the fine structure in the reactor neutrino spectrum!

Another Unprecedented LS Detector: JUNO-TAO

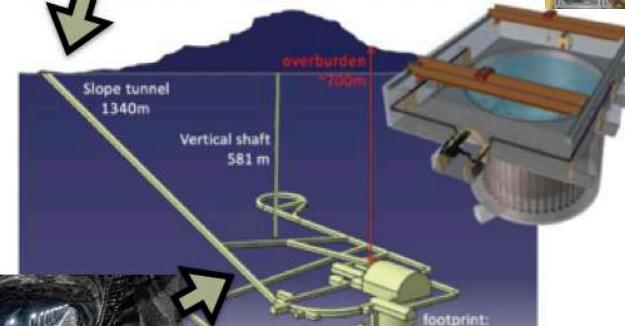


- Provide a ref spectrum for JUNO, to remove model dependence
- Provide a benchmark for nuclear database, measuring fine structures (E resolution $\sim 1\%$ at 1 MeV)
- Measuring isotopic neutrino spectrum: Extend to different fission fraction; test ab initio spectra
- Reactor monitoring, Sterile neutrino, Possible new findings w/ unprecedented resolution

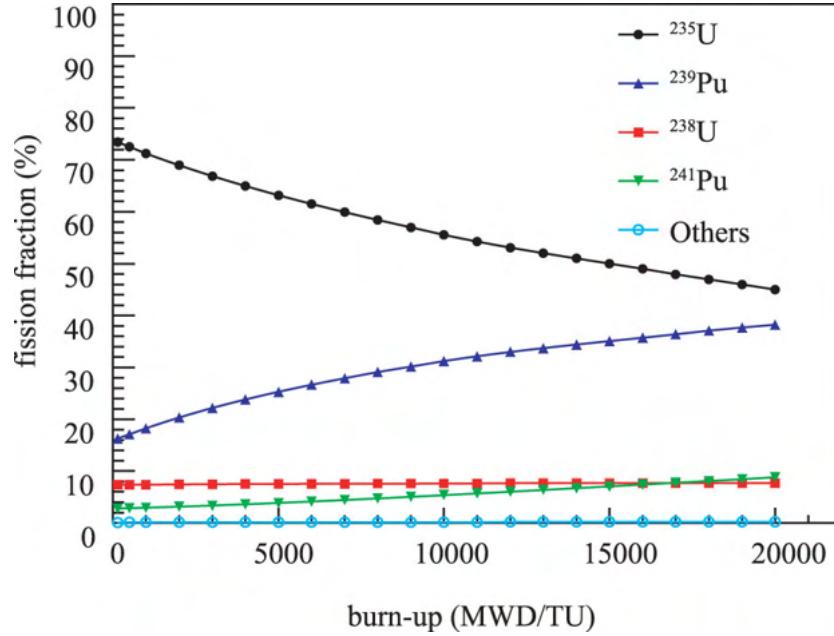
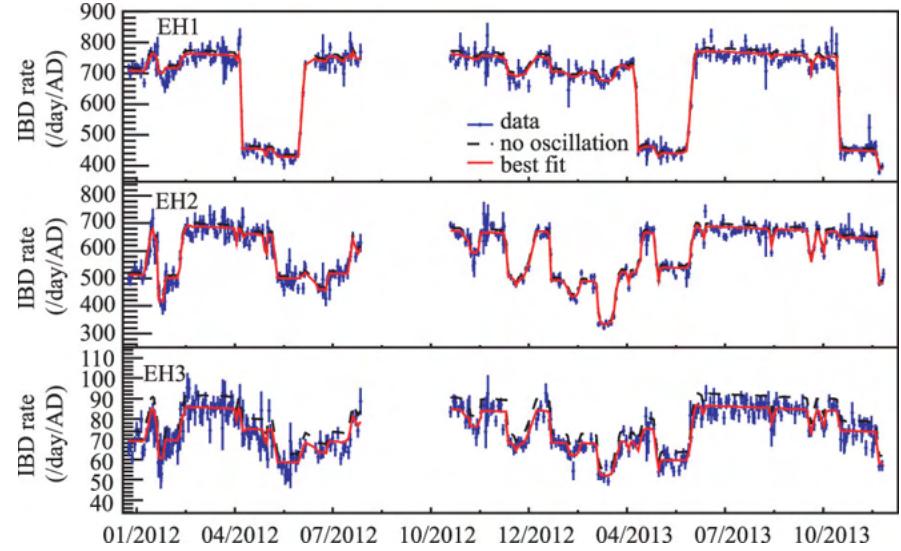
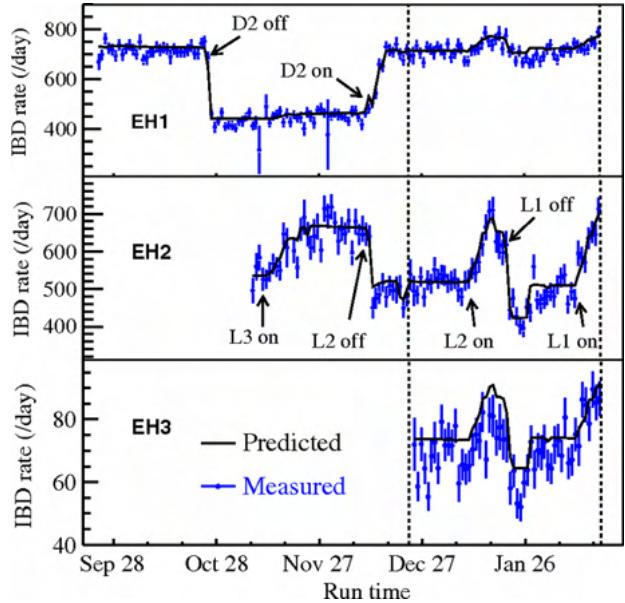
Timeline and Current Status



Neutrinos
detected



中微子事例数可监测反应堆的运行情况与功率



❖ 中微子事例数完美监测反应堆的开、停堆

❖ 中微子事例数完美监测反应堆的功率变化情况（中间停顿的为探测器停止运行时期）

❖ 不同的燃耗，反应堆的裂变同位素不同，因此，裂变产物也不同，因此，监测中微子的产额与能谱可以反推燃耗

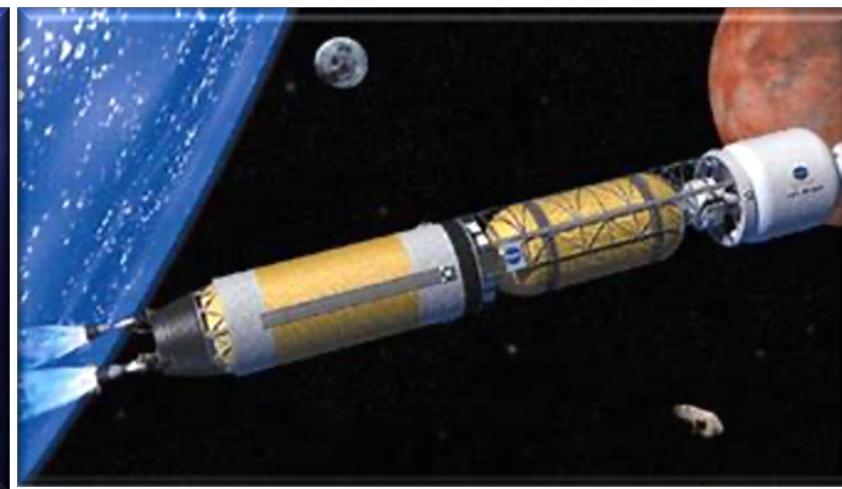
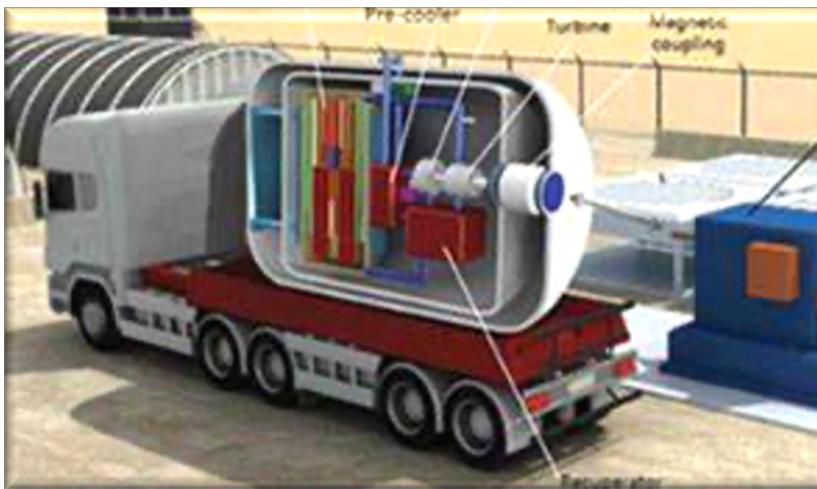
新时代的机遇与挑战：中国核能战略与发展

国家《核电中长期发展规划》

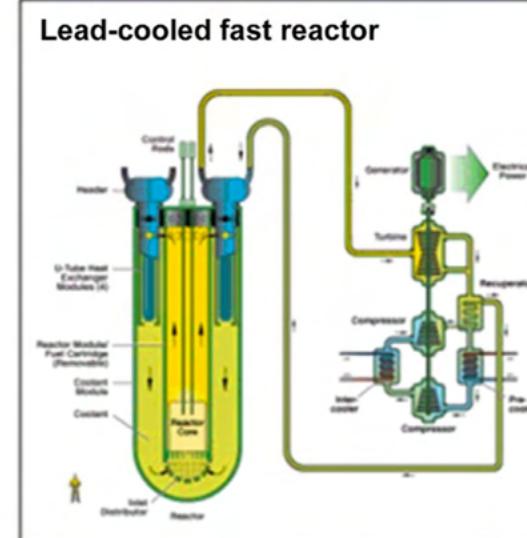
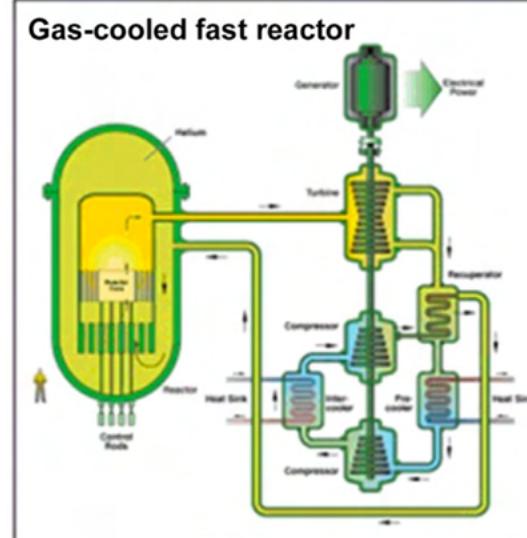
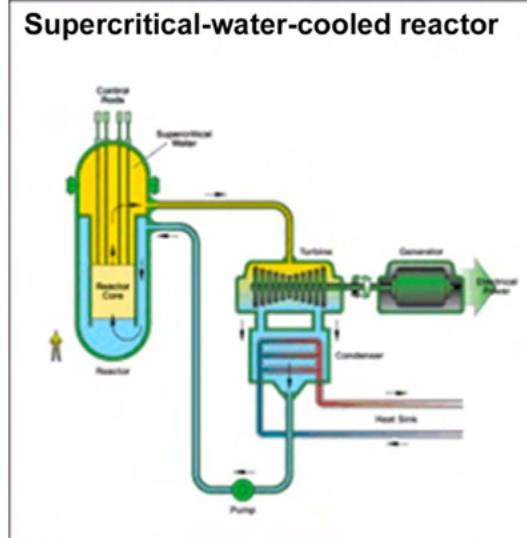
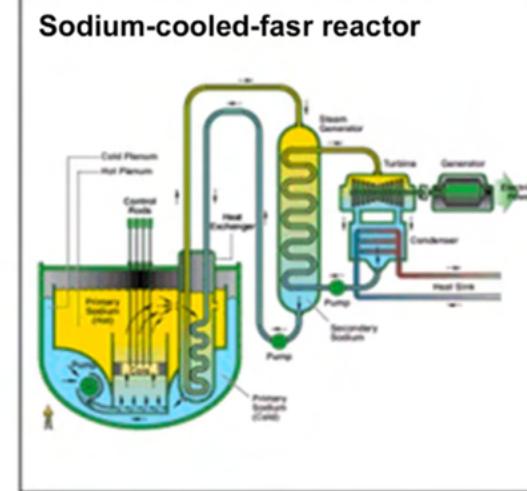
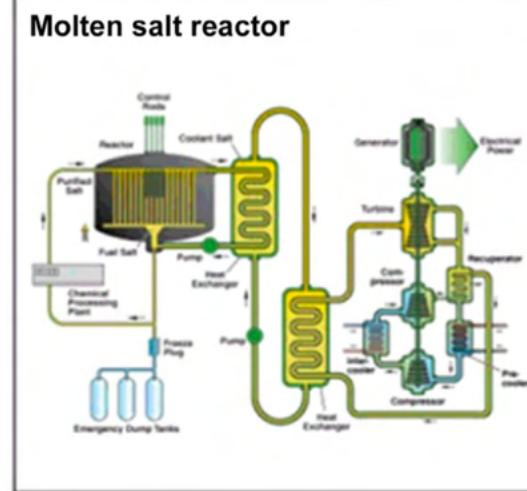
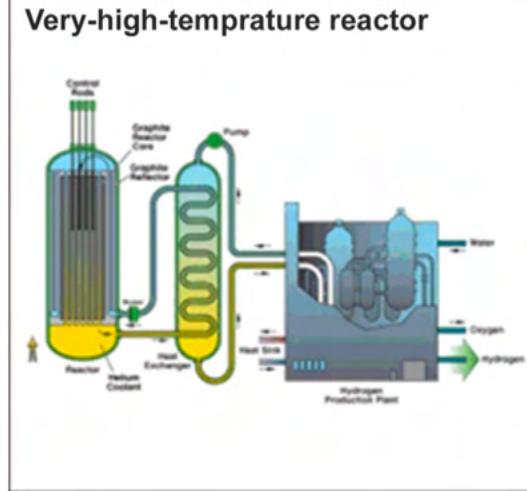


多场景应用：先进核能系统上“天”下“海”

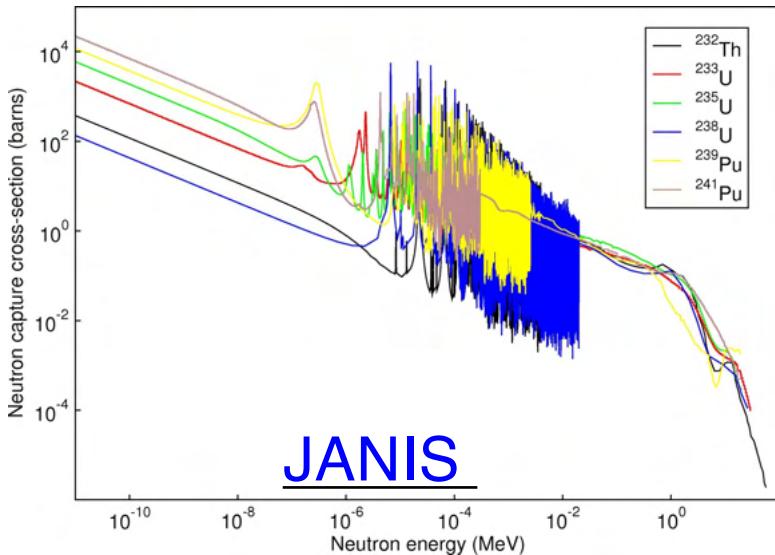
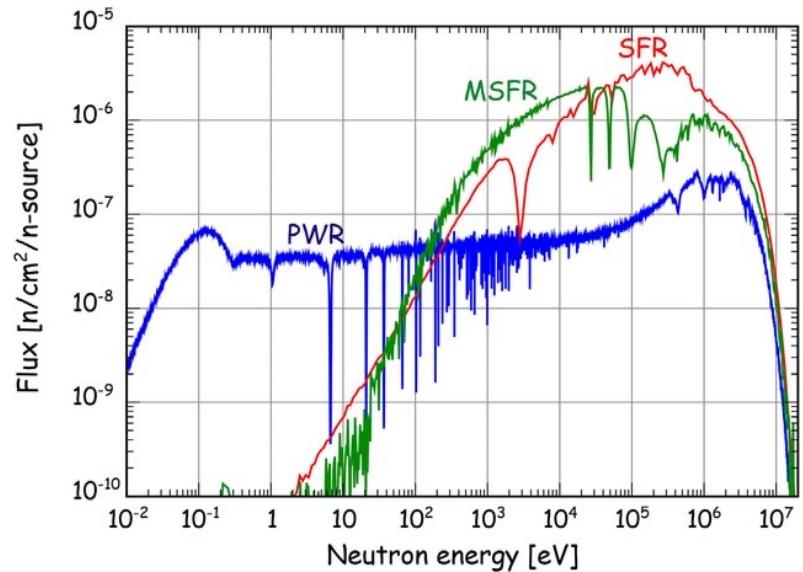
核能发展三步走战略



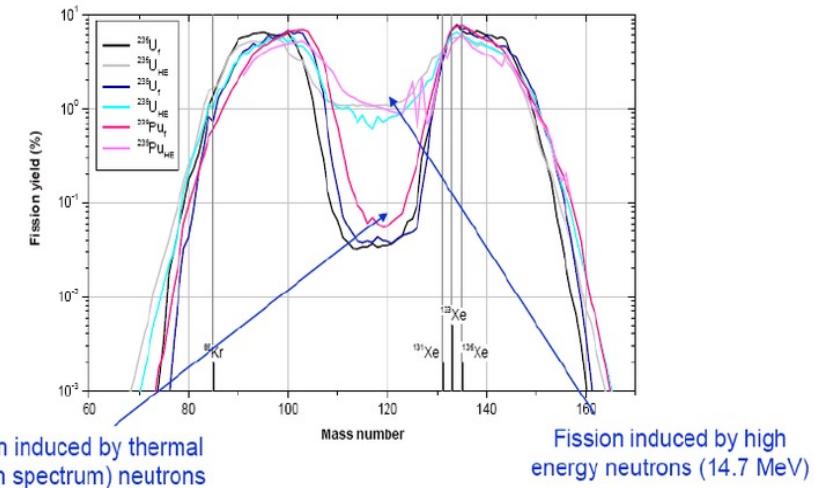
第四代快堆是什么？



热堆与第四代快堆的堆内中子谱与中子反应极为不同



(Fission yield is a function of the fissioning nuclide and the incident neutron energy)

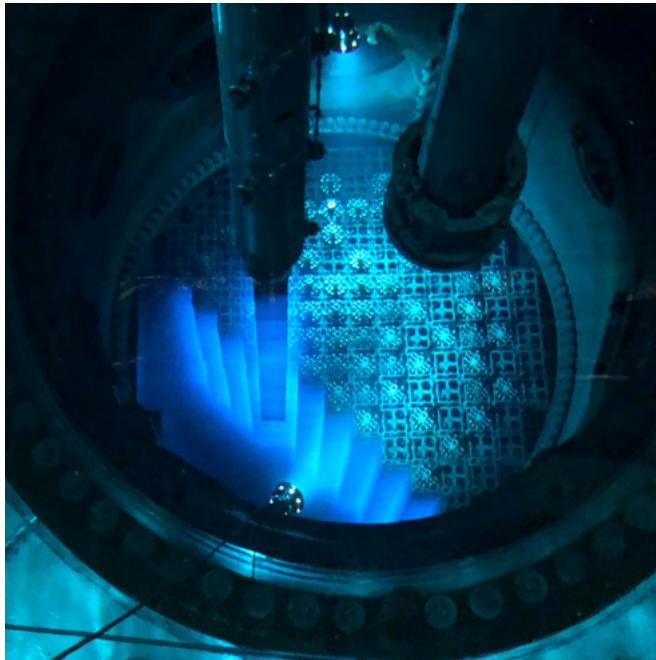


热堆的中子能量较低而快堆的中子能量较高（可达~10MeV），裂变产物在不同的中子能谱下有相当的差别，将反映到反应堆中微子能谱中

M. Brovchenko et al., published by EDP Sciences, 2019

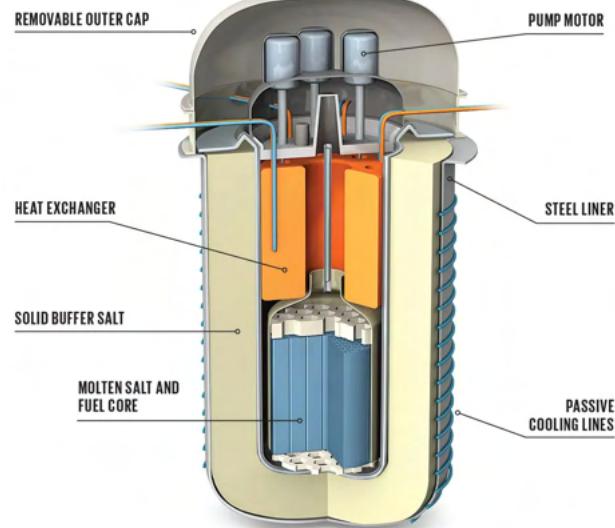
https://www.nuclear-power.com/nuclear-power/reactor-physics/interaction-radiation-matter/#Neutron_interactions

Challenges of advanced reactors



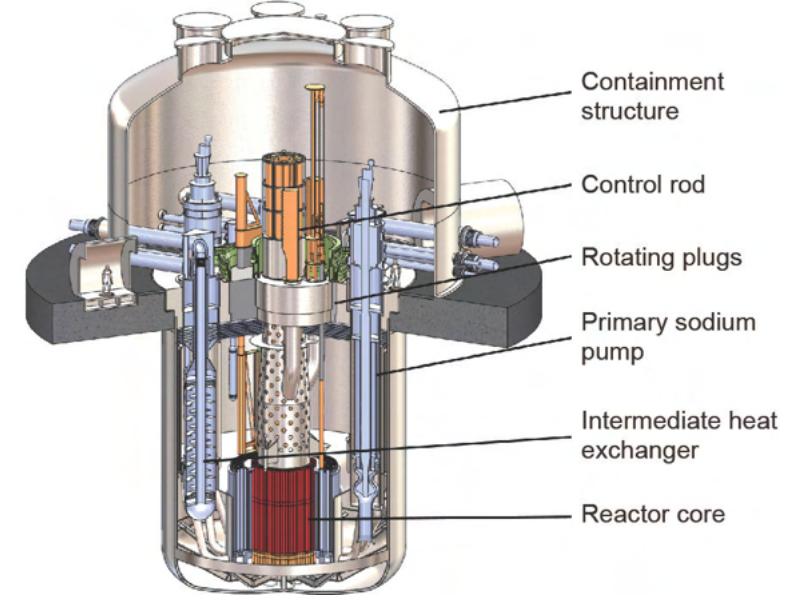
Item accountancy relies on:

- itemizable fuel assemblies
- transparent coolant
- frequent refuelings



Non-itemizable fuel

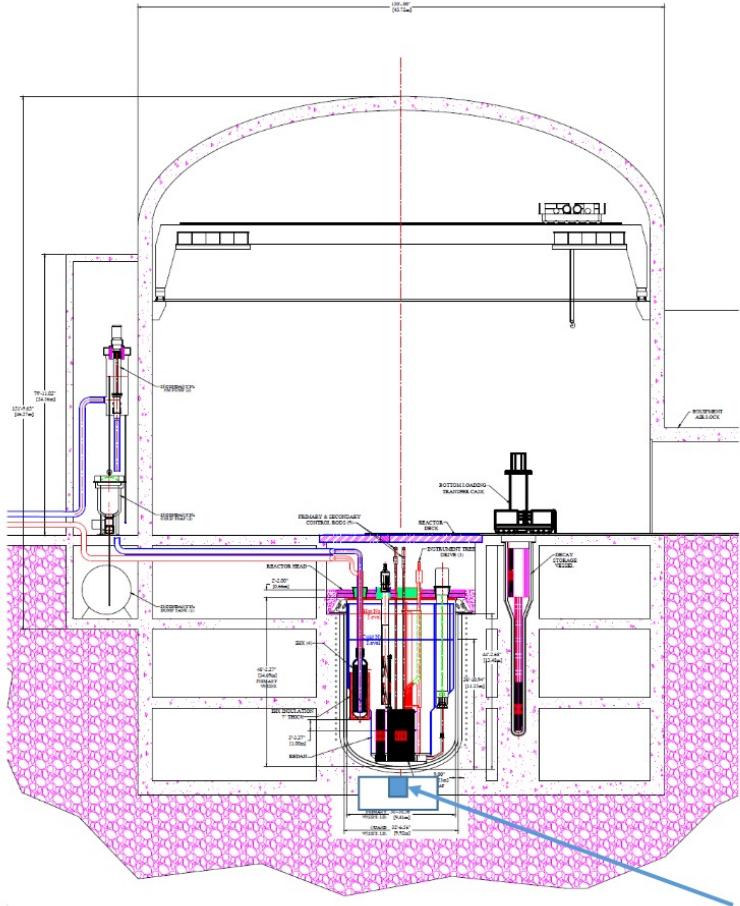
- molten salt reactor
- pebble bed reactor



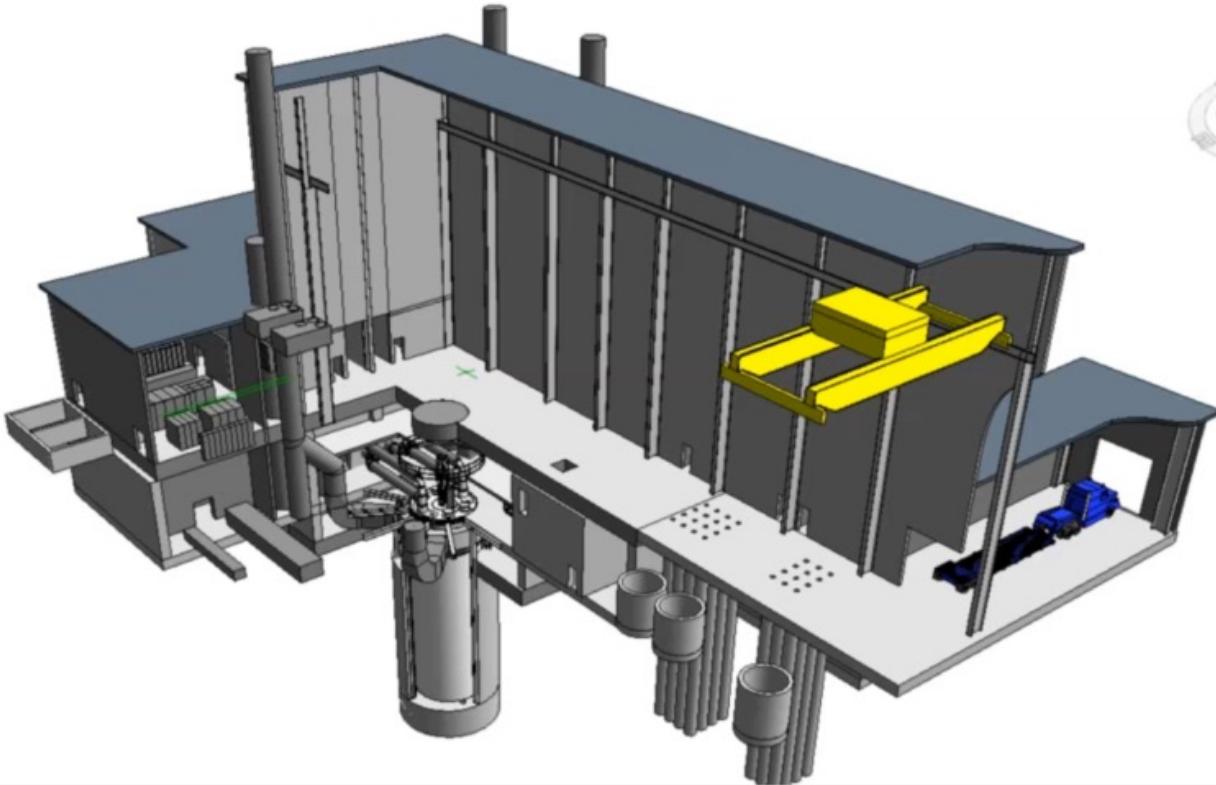
Sodium coolant (intransparent)
Lifetime cores
Reprocessing

Each of these characteristics invalidates some of the current safeguards practices.

四代堆研究平台VTR将装备中微子探测

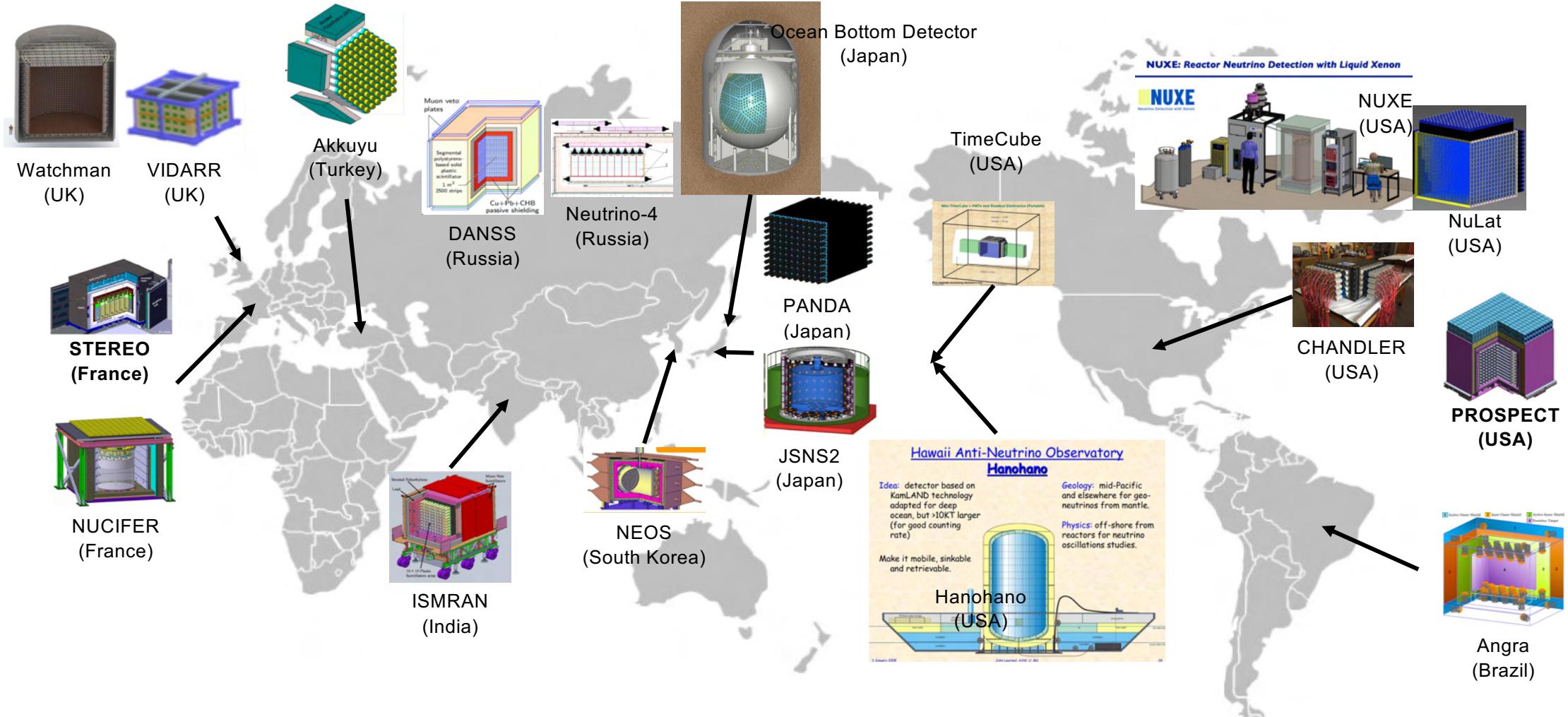


Potential
IBD Detector



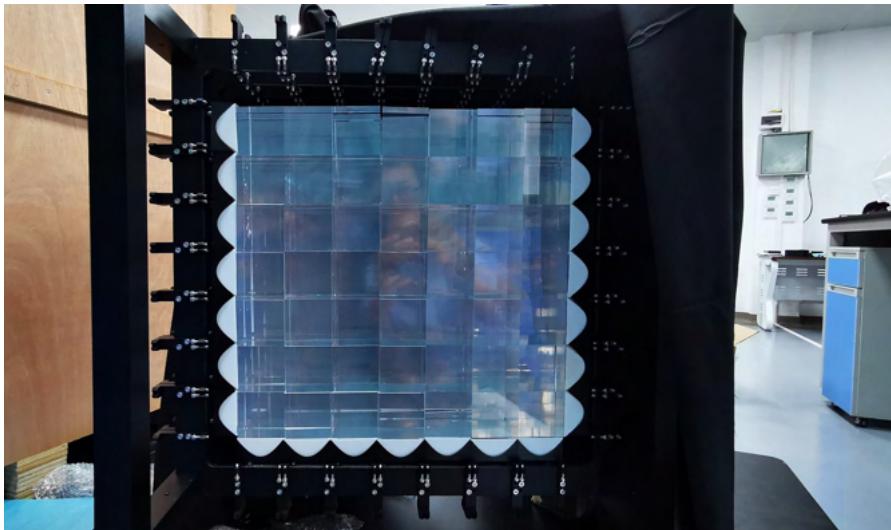
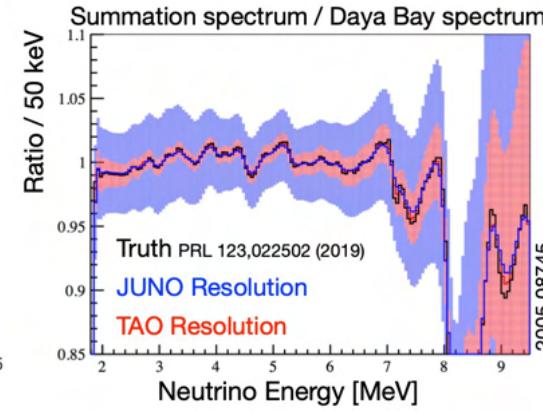
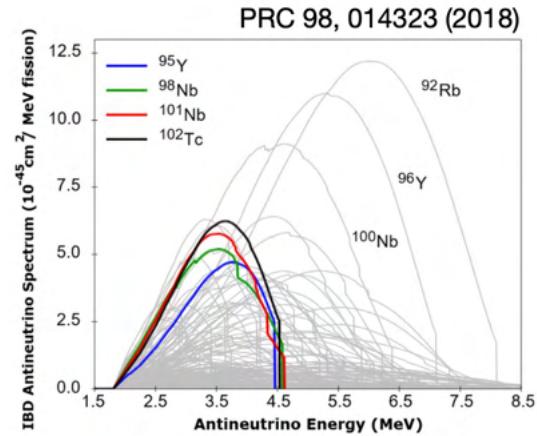
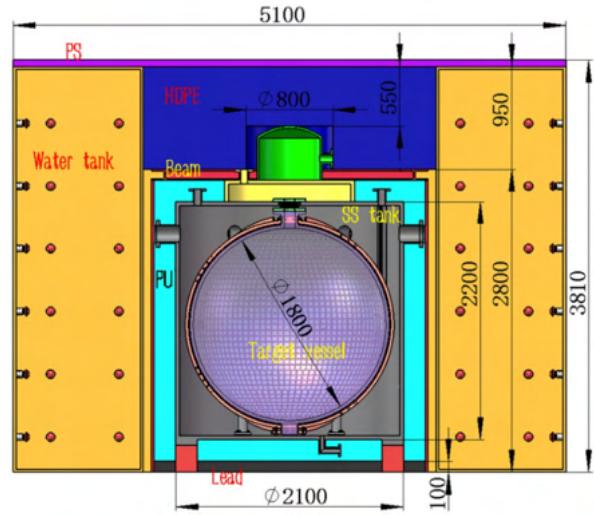
❖ 美国的第四代堆研发平台**VTR**将装备中微子探测器，用来监测堆内的燃耗和功率等数据

先进核能、民用核能的安全需求都需要中微子监测



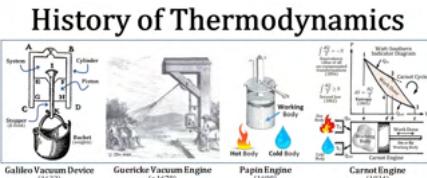
以闪烁体IBD探测器为主，开始布局液态惰性气体的设计

JUNO-TAO (液体) 与中大的固体反应堆监测探测器





牛顿力学

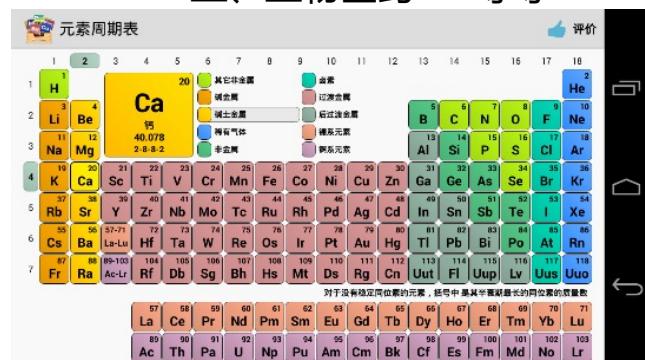


- 人们利用：风、水
- 天文历法：很精确
- 经典物理发展几乎完美



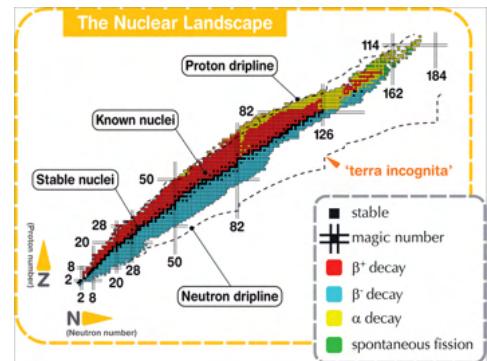
量子力学

- 未解之谜不多（相对）
- 应用研究为主
 - 化工、能源、材料、农业、生物医药.....等等

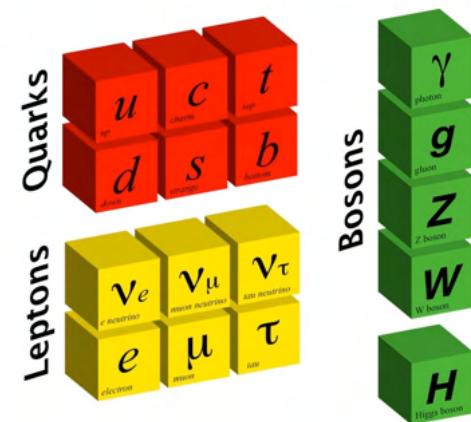


量子场论

Fundamental Particles of the Standard Model



- 仍然有许多未解之谜
- 仍然是最前沿的研究
- 仍然有巨大的应用及基础科学潜力
 - 仍然支撑着应用（能源、材料、军事、农业、生物医药、医学.....）
 - 仍然支撑着基础研究（粒子物理、核化学、天体物理、宇宙学.....）



- 当前人类认知极限——最小尺度的研究
- 同多个基础科学互为支撑，也为其它学科所“用”
- 开始探索一些“应用”、“实用”的可行性



· 反应堆中微子在物理学史上发挥了不可替代的作用，反应堆在未来的能源结构中也是不可替代的

◆核能体系，作为利用最前沿科学知识的跨尺度实践，不仅对社会发展是实用的，对基础研究也是“实用”的，这个地球上最极端人造环境有着不可替代的作用

◆反应堆不仅是粒子物理的战场，更是核物理的战场，典型的多维度交叉领域

◆反应堆中微子研究面向国家重大战略需求、面向学术前沿、面向社会经济发展

➤JUNO让中国的高能物理学家一举从大亚湾时代的并跑变为领跑——期待2023!

➤大湾区是世界上最好的研究反应堆中微子的地方，从基础到应用全面覆盖，请大家继续支持！



卢鹤绂院士

中国“核能之父”

Hoff Lu

1914 – 1997

“第一个揭露原子弹
秘密的人”



- 1941年明尼苏达大学博士毕业，是年11月经香港来中山大学任教
- 1942年春于中山大学撰写《重原子核内之潜能及其利用》，1944年发表在中国《科学》上，在国际上首次公开发表链式裂变反应堆的临界体积的简易方法及全部原理
- 1945年第一颗原子弹爆炸后，1946年完成《原子能与原子弹》，审查一年后发表在《美国物理月刊》，成为“第一个揭露原子弹秘密的人”
- 两弹元勋中7名是他的学生，为科学界，尤其是核学界培养了大量人才

中山大学乐昌坪石办学点



卢鹤绂教授在坪石授课



前者為主要分裂力。重核之不穩定由於此也。本文之事足為其證。與液體中之分子相似，故有以液滴為核之模型，而此事之解釋得之原理也。

此事尚須設法使中子自給作用實現於方便數量之時，俾易司理。其費失殊鉅，危險尤大。若能大量將 U^{235} 分出，獨利用熱能中子價值遠遜於 U^{238} 。就現勢而論，此種濃厚之能源必將有其特殊之價値燃料，求於此事，尚非可謂耳。

民國三十一年四月作者識於國立中山大學物理學系。

国际首篇反应堆原理论文完成于中大



卢鹤绂院士铜像

在美国休斯顿安放

杨丽娣

一九九八年八月三十日，在已安放了美国前总统布什雕像的休斯顿第一浸信会教会学院中，隆重举行了卢鹤绂科学实验室建立和雕像安放的揭幕仪式。美国科学界及有关方面两千多位来宾参加了盛会。在会上，卢鹤绂的胞弟，曾任格鲁曼飞机制造公司总工程师的卢鹤坤先生代表家属上台致词时，全场起立，报以经久不息的掌声。

卢鹤绂教授是我国著名的物理学家、九三学社中央参议委员，他为科学事业奉献了毕生精力，一直奋斗到生命的最后一刻。他的科学成就为中国和世界作出了重大贡献。卢老还是一位杰出的教育家，他为祖国培养了一大批优秀的学生，桃李满天下。

1947年卢老第一个在美国物理杂志上发表了题为《关于热离子发射的同位素效应》的文章。



- **中国第一个观测到核裂变的科学家**

The first scientist to observe nuclear fission in China

- **中国第一个全面讲授原子能应用的科学家**

The first scientist to fully introduce the knowledge and application of atomic energy physics in China

- **第一个提出容变弛豫方程的科学家 → 流体力学中的“卢鹤绂不可逆公式”**

The first to propose basic equations of relaxation and compression— "Hoff Lu irreversible equation" scientist

- **世界首次发现热离子发射的同位素效应**

The first scientist to discover the isotope effect of hot salt ion emission

- **世界上第一个精确测量锂元素的丰度比**

The world's first scientist to accurately measure the abundance ratio of lithium

- **世界上第一个揭示原子弹与核能秘密的科学家**

The first scientist to disclose the secrets of atomic bombs and nuclear energy

