NEUTRINO: an experimental summary

王为，中山大学

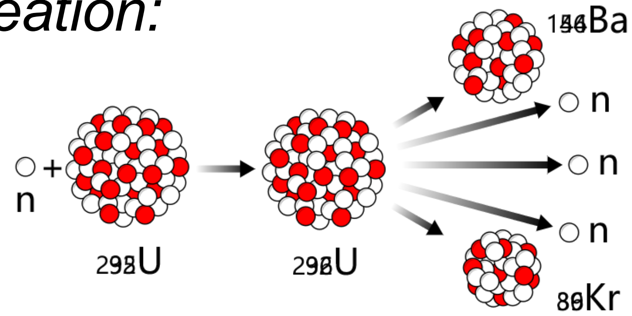
TeV物理工作组研讨会，北京，2021年7月20日

- *The Most Basics: Neutrino Mass Direct Measurements*
- *Neutrino Mixing and Oscillation Experiments*
- *Neutrinos as Messengers and Probes*
- *Summary and Pespectives*

Reines&Cowan Detected Neutrinos in 1956

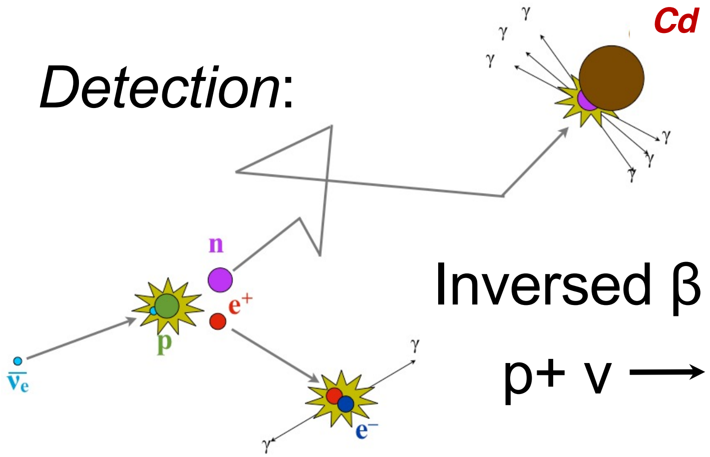
- Cowan and Reines at the Savannah River Power Plant (1956-1959)

Creation:



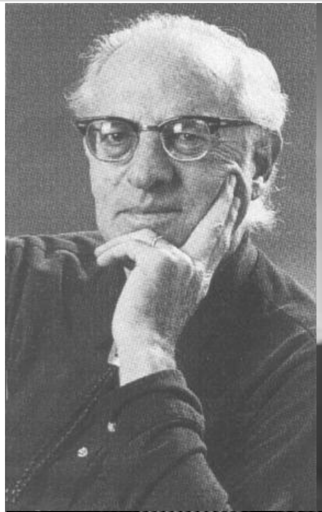
β decay : $N \rightarrow N' + e + v$

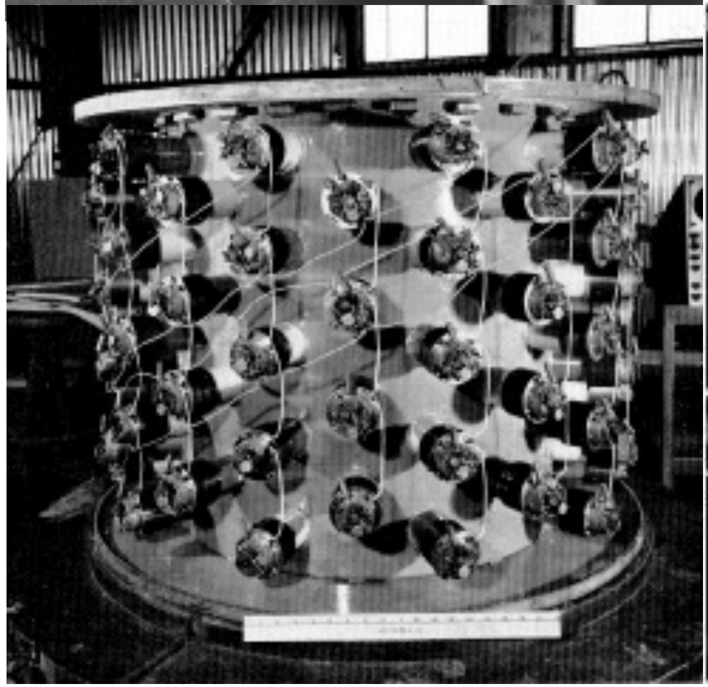
Detection:

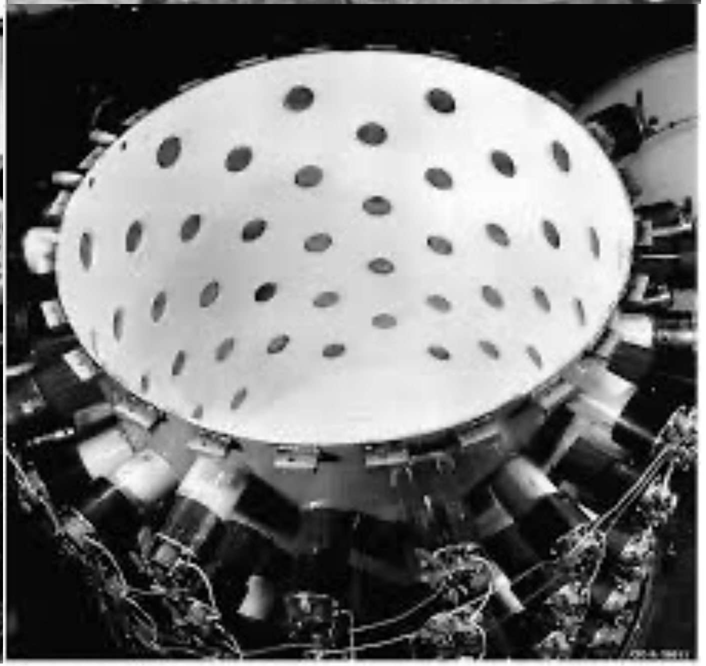


Inversed β decay

$p + v \longrightarrow e^{+} + n$







The First Attempt Detecting Neutrinos

A Suggestion on the Detection of the Neutrino

KAN CHANG WANG

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

October 13, 1941

- 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

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 Be^7 which decays in 43 days with K capture in two different processes:[2]

$$Be^7 + e_K \rightarrow Li^7 + \eta + (1\ \mathrm{Mev})$$

and

$$Be^7 + e_K \rightarrow (Li^7)^* + \eta + (0.55\ \mathrm{Mev}),$$
$$(Li^7)^* \rightarrow Li^7 + h\nu + 0.45\ \mathrm{Mev}.$$

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

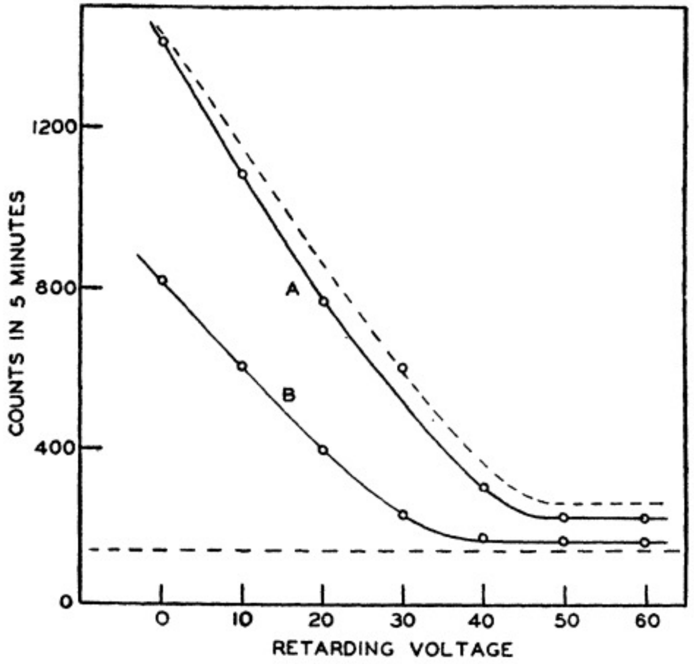
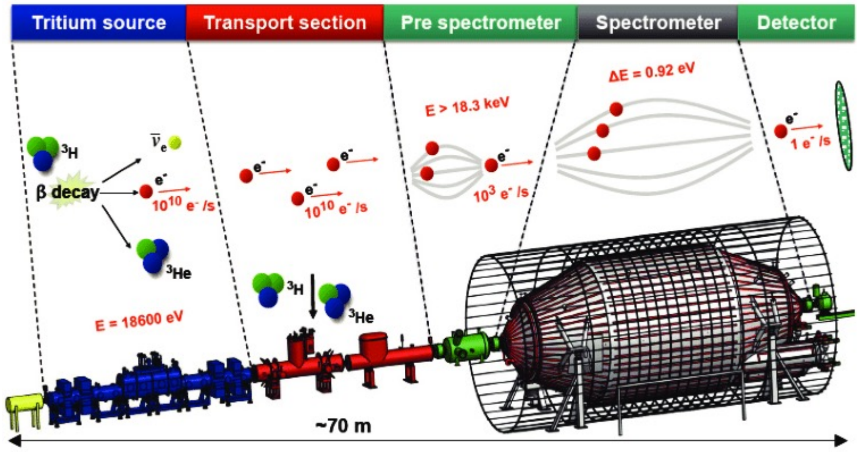
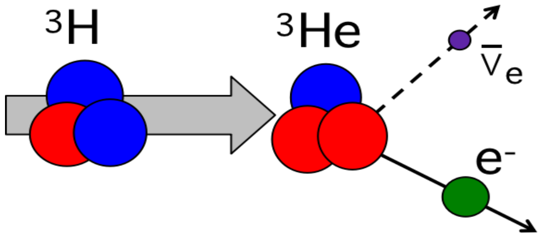


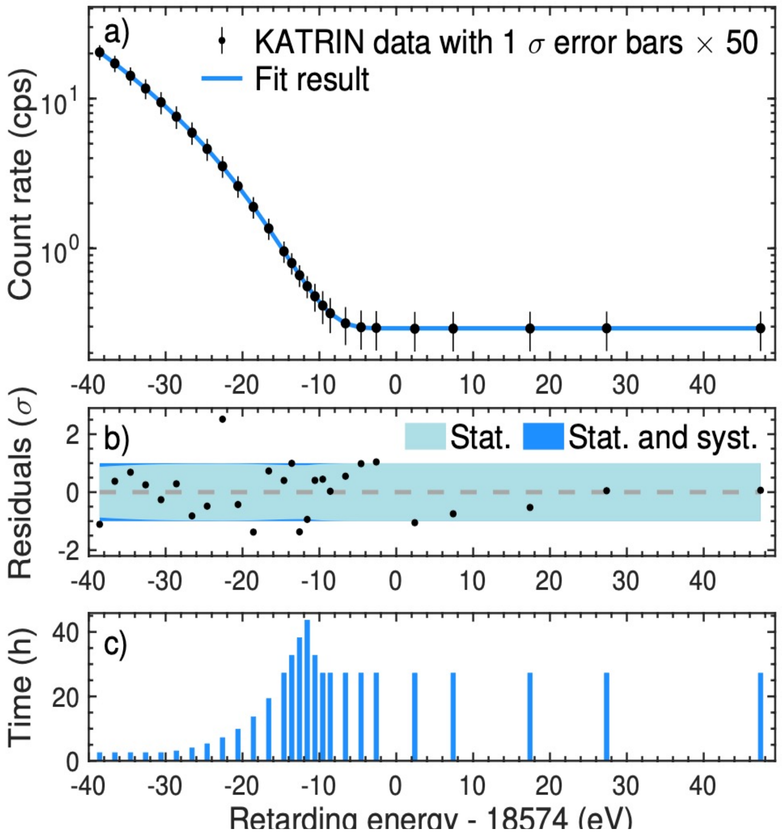
FIG. 3. Retarding potential curves for recoil ions. The horizontal dotted line represents the background counting rate.

Latest Direct Neutrino Mass Measurements: Kinematics

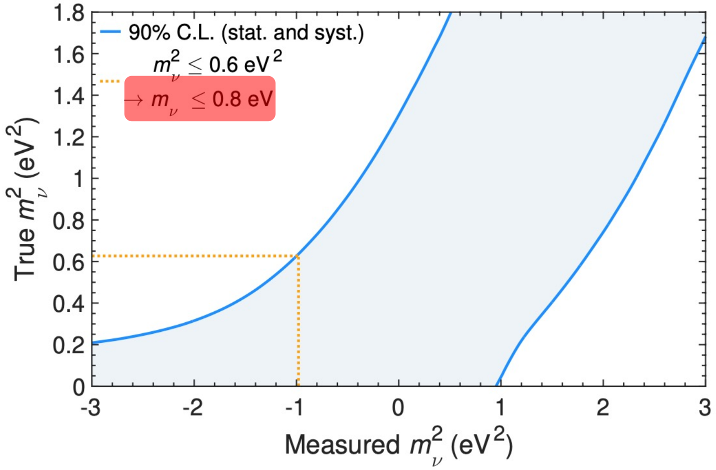


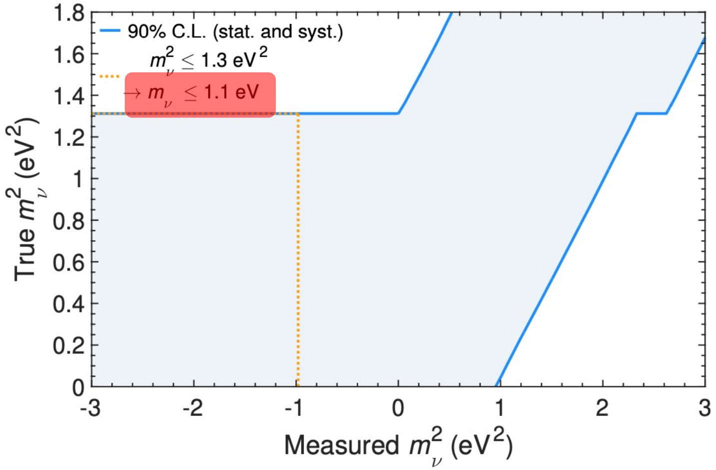
- First result based on the first 4-week data in 2019
- 1000 days planned and eventual sensitivity 0.2eV





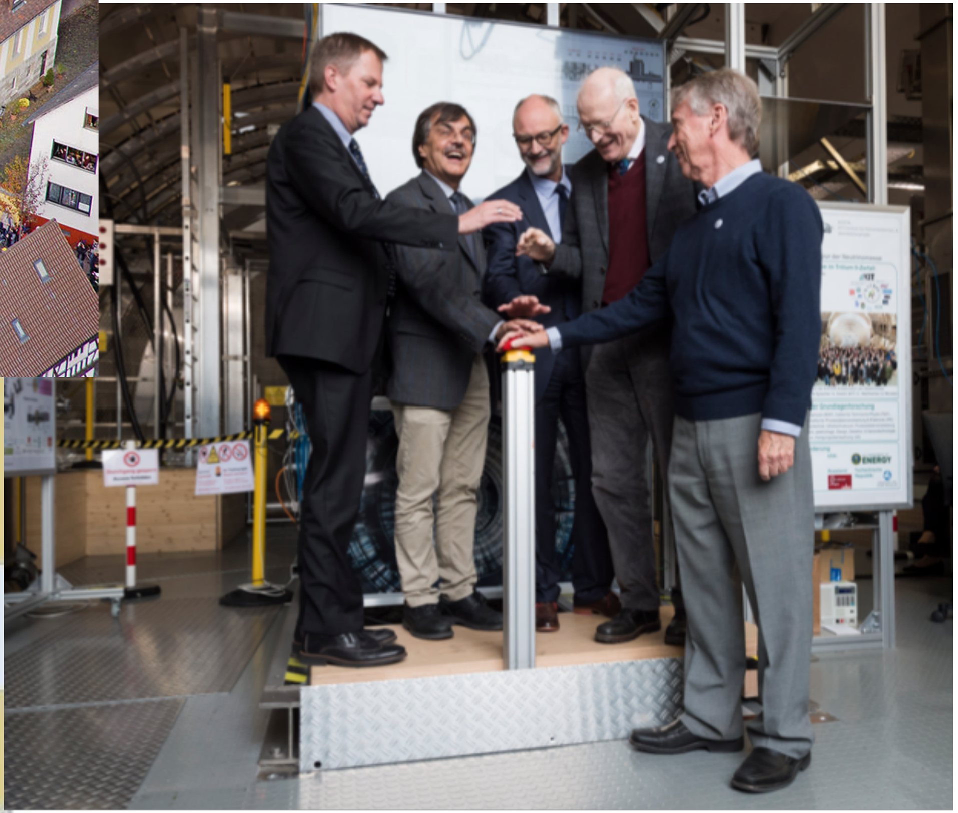
$$m_{\nu_\beta} = \sqrt{\sum_{i}^{3} |U_{ei}|^2 m_i^2}$$





KATRIN Publications&Talks 2020.

KATRIN Efforts: Were They Worth It?



15 Years of Hard Working and Persistence!

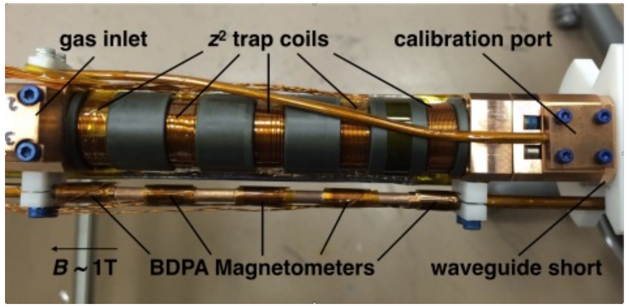
Future Direct Neutrino Mass Measurements

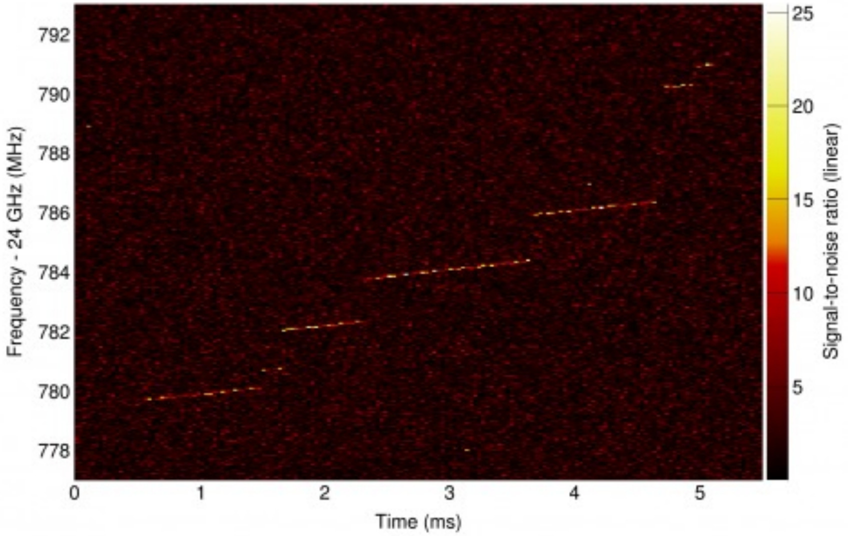
- **Project 8: Phase I-III to 0.040 eV**

PROJECT 8

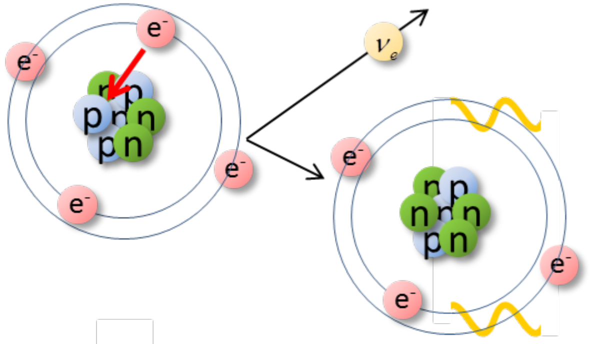
$$f_\gamma = \frac{eB}{2\pi m_e \left(1 + \frac{K}{m_e c^2}\right)}$$

- Electron Capture Strategy Revived:
  - ➢ECHo (钬)
  - ➢HOLMES (钬)



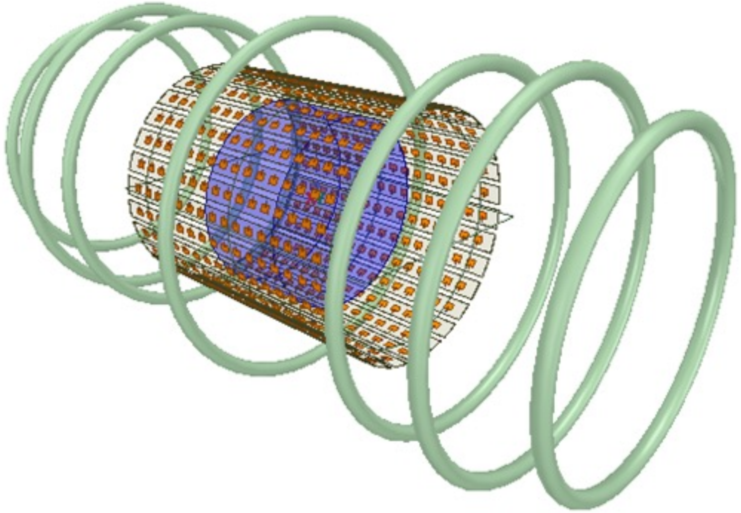


$${}^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

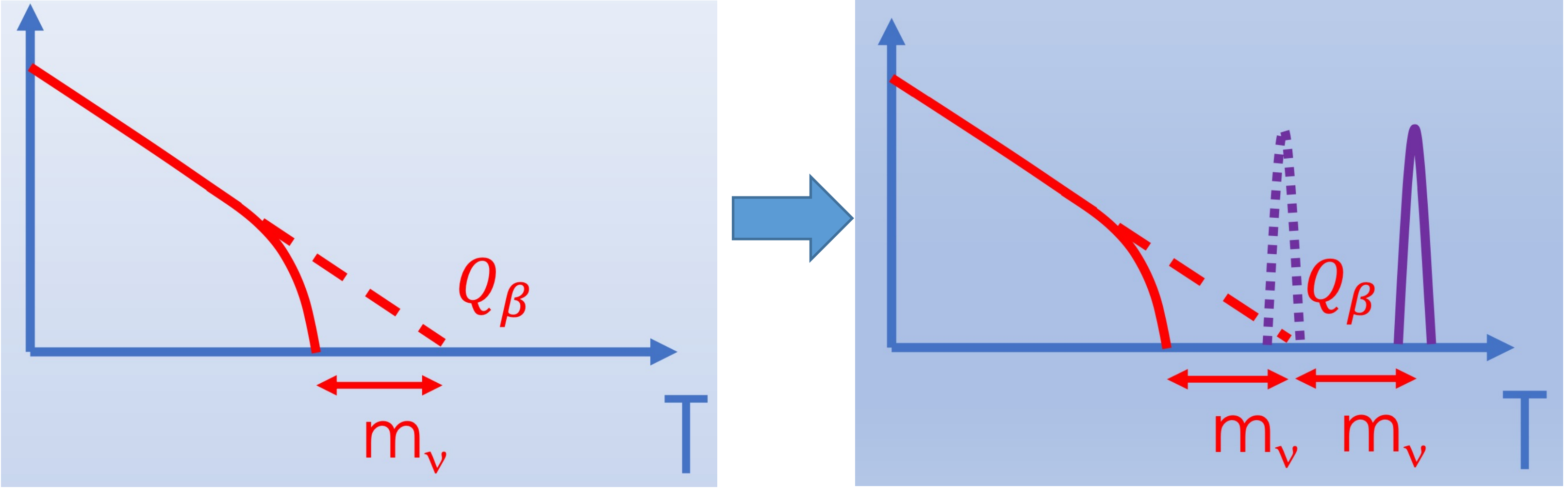


$${}^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

- $Q_{EC} \cong$ 2.3 - 2.8 keV
- $\tau_{1/2} \cong$ 4570 years

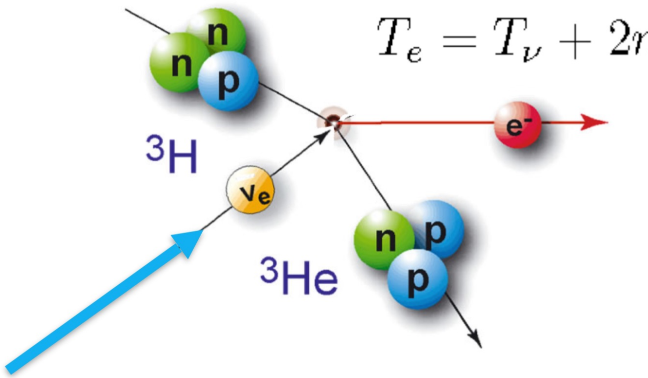


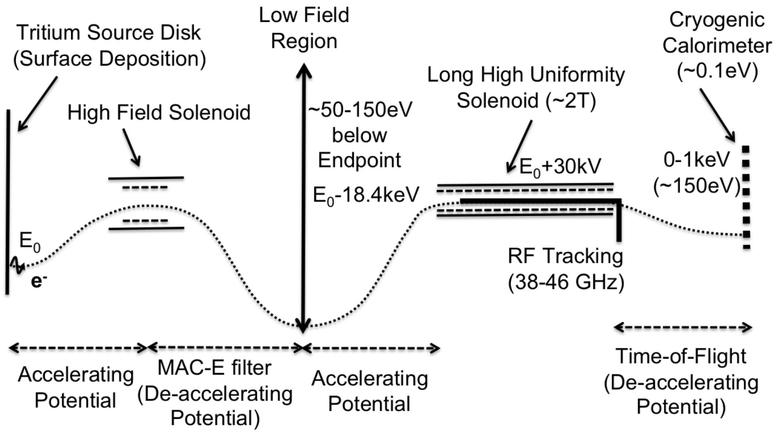
A Very Smart Approach: PTOLEMY

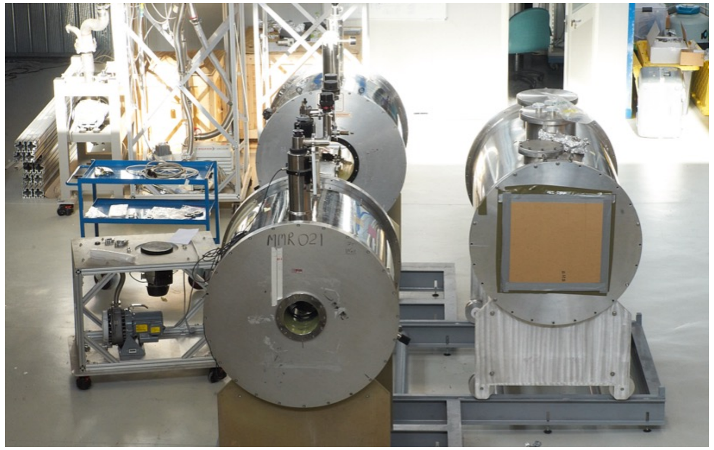


Neutrino capture on Tritium

$$T_e = T_\nu + 2m_\nu + Q$$







PTOLEMY Collaboration, arxiv/1307.4738, presentations etc; Planned at LNGS.

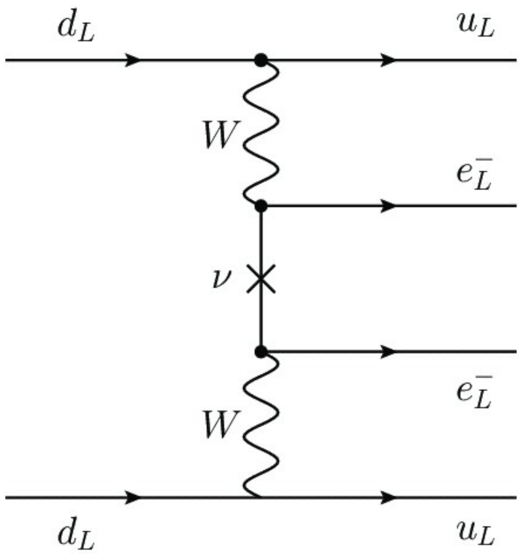
Latest Direct Neutrino Mass Measurements: 0νββ

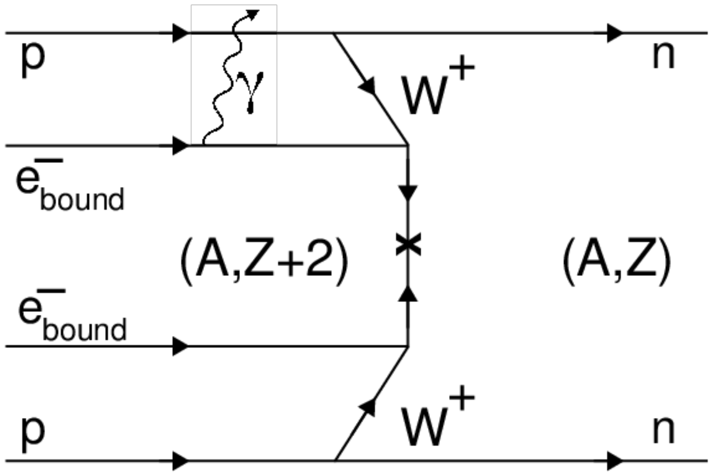
➢Neutrinoless Double Beta Decay

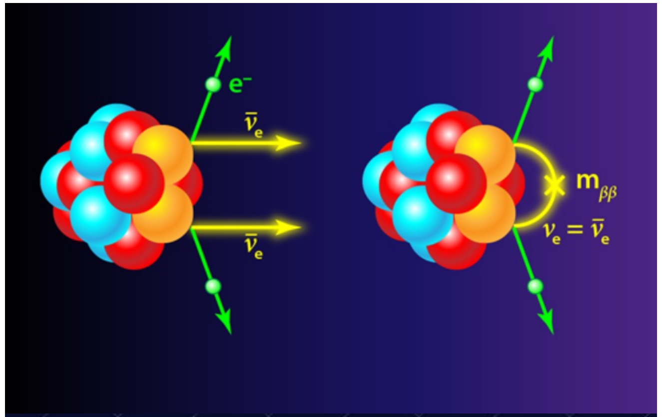
eg. ${}^{136}_{54}Xe \rightarrow {}^{136}_{56}Ba + 2e^- + (2\bar{\nu})$

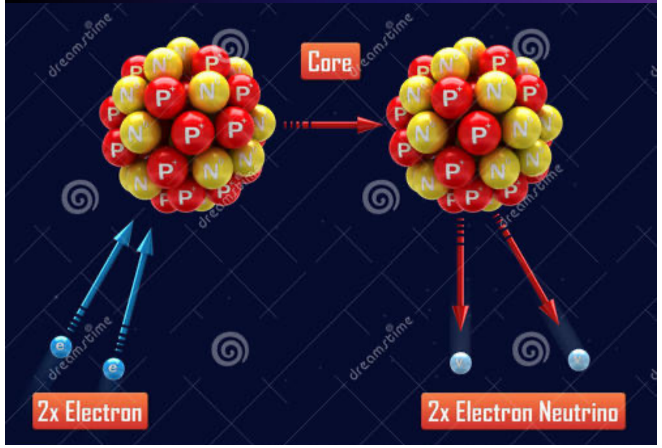
➢Neutrinoless Double Electron Capture

eg. ${}^{124}_{54}Xe + 2e^- \rightarrow {}^{124}_{52}Te + (2\bar{\nu})$





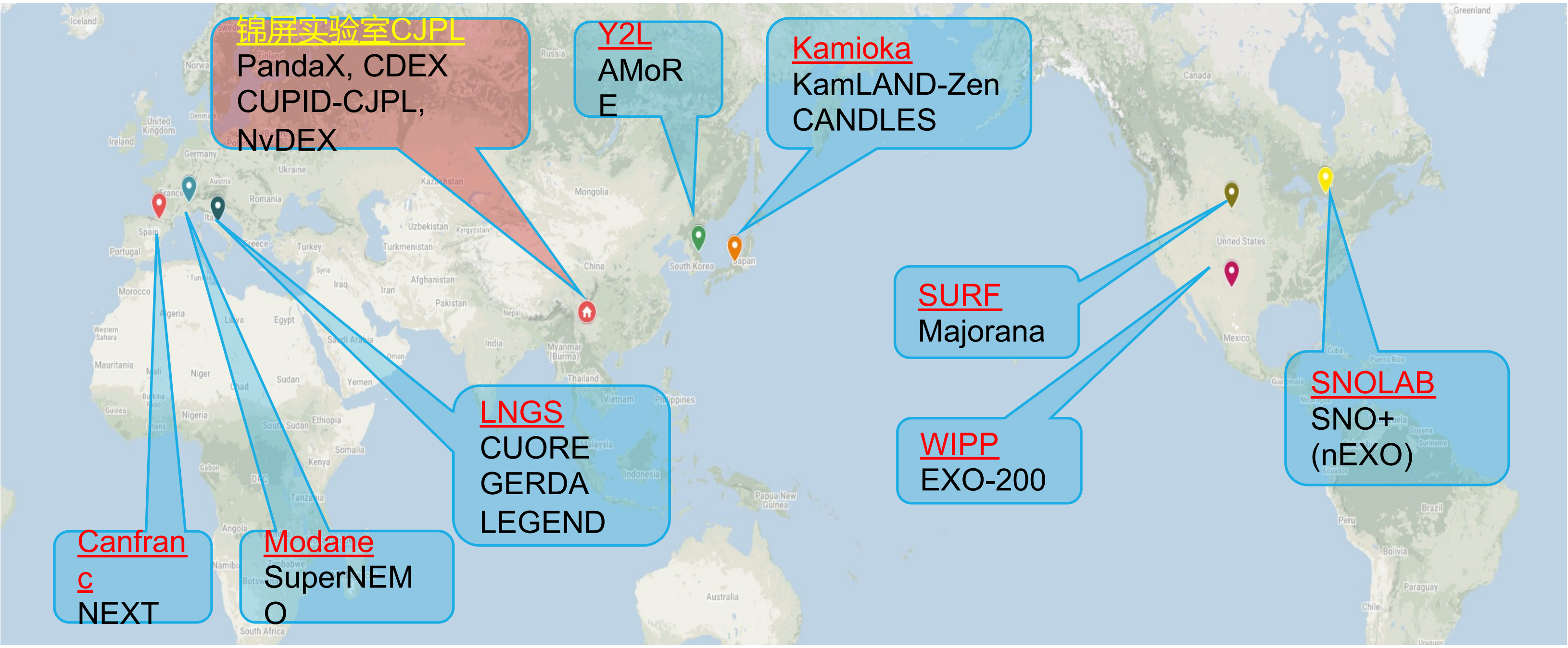


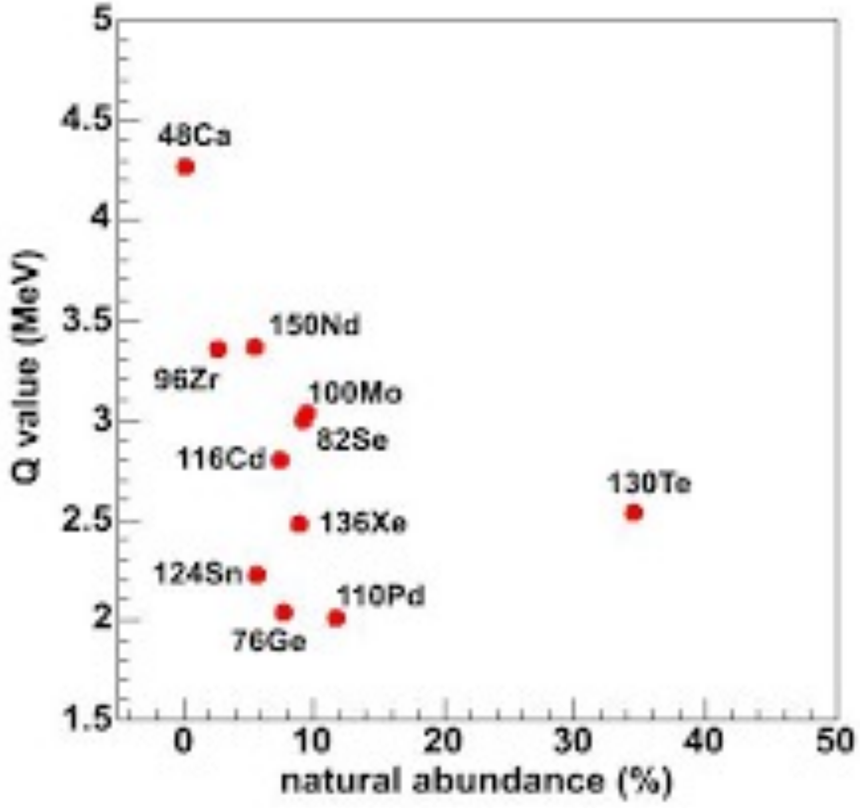


$$m_{\beta\beta} = \left| m_1 \cos^2\theta_{12} \cos^2\theta_{13} e^{i\alpha_1} + m_2 \sin^2\theta_{12} \cos^2\theta_{13} e^{i\alpha_2} + m_3 \sin^2\theta_{13} e^{-2i\delta} \right|$$

Global Competetion in 0νββ

- **0νββ is definitely an overheated battle ground**
  - ➢ **GERDA、Kamland-Zen, and CUORE published highly competitive results on Ge-76, Xe-136, Nd-130**
  - ➢ **In China, PandaX, CDEX, CUPID-CJPL, NvDEX, and JUNO are all making tremendous efforts to catch up**





0νββ Experiment Summary (International)

Isotope	$T^{0\nu}_{1/2}$ (×10^{25} years)	$\langle m_{\beta\beta} \rangle$ (eV)	Experiment	Latest Results & Future Plans
^{48}Ca	$>5.8 \times 10^{-3}$	<3.5–22	ELEGANT-IV	**Tracking calorimeter; CANDLES?**
^{76}Ge	>8.0	<0.12–0.26	GERDA	**> $1.8\text{x}10^{26}$ years (2021); LEGEND-200 running, expected >10^{27} years; LEGEND-1000 expected to be >10^{28} years**
	>1.9	<0.24–0.52	MAJORANA DEMONSTRATOR	
^{82}Se	$>3.6 \times 10^{-2}$	<0.89–2.43	NEMO-3	**Tracker-calorimeter structure can take various source foils; SuperNEMO, AMoRE, MOON, LUCIFER, LUMINEU……**
^{96}Zr	$>9.2 \times 10^{-4}$	<7.2–19.5	NEMO-3	
^{100}Mo	$>1.1 \times 10^{-1}$	<0.33–0.62	NEMO-3	
^{116}Cd	$>2.2 \times 10^{-2}$	<1.0–1.7	Aurora	165
^{128}Te	$>1.1 \times 10^{-2}$	NE	C. Arnaboldi et al.	166
^{130}Te	>1.5	<0.11–0.52	CUORE	**> $3.2\text{x}10^{25}$ years (2021); CUPID >10^{27}**
^{136}Xe	>10.7	<0.061–0.165	KamLAND-Zen	**KamLAND2-Zen 2% resolution**
	>1.8	<0.15–0.40	EXO-200	**nEXO (5t) 7–22 meV ~>10^{28} years**
^{150}Nd	$>2.0 \times 10^{-3}$	<1.6–5.3	NEMO-3	169

M. J. Dolinski,A. W.P. Poon, W. Rodejohann, Annu. Rev. Nucl. Part. Sci. 2019.69:219-251 with 2021 updates

0νββ Experiment Summary (Domestic)

Experiments/ Collaboration	Isotopes	Technology	Schedule	Comments
PandaX	^{136}Xe	Liquid/High Pressure Gas TPC	PandaX-III (R&D) PandaX-4T (commissioned and teaking testing data)	Liquid Xe tech. ready; seeking funding for xT; enrichment
CDEX	^{76}Ge	HPGe	CDEX-50(DM, ongoing) → CDEX-300(0νββ, 2021-26) → CDEX-1000(2027-32)	Ge enrichment, crystal growth, detector technology and low bkg electronics etc
CUPID-CJPL	^{130}Te/^{100}Mo	Bolometer	DEMO(10kg): 2022-2024; 200kg: 2024+	International Tech and Collaboration: Italy, France, US; ^{100}Mo considered; LMO crystal testing; simulation etc
NvDEX	^{82}Se	$^{82}SeF_6$ H.P.(10 atm.) TPC + TopMetal	2022 (NvDEX-100)	TopMetal R&D; LBNL Collaboration; testing system set up already
JUNO-bb	^{136}Xe or ^{130}Te	LS Caloremeter + Target Mass Balloon	2030	50 ton Xenon or 100-200 Te (most sensitive given the target mass and JUNO performance); R&D in parallel with JUNO and nEXO

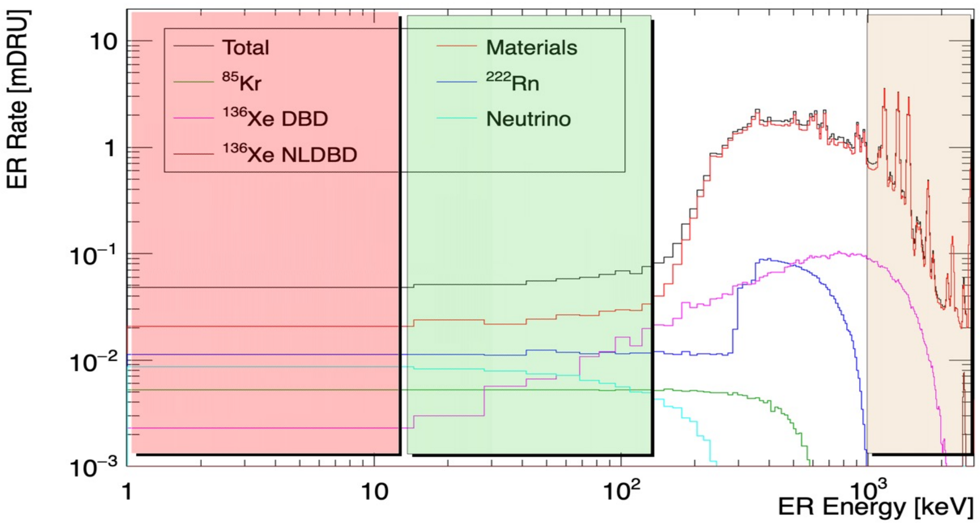
Based on Materials from Chinese Strategy Workshop for Non-Collider HEP, IHEP June, 2021

PandaX Multi-Purpose Platform

暗物质粒子直接探测器

马约拉纳中微子研究

太阳中微子

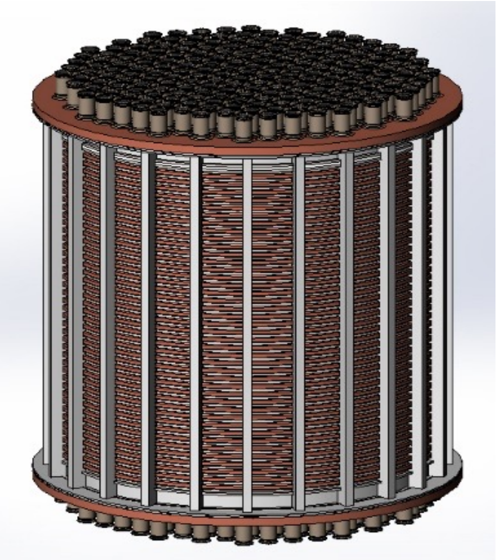


暗物质
信号区

太阳中微子
信号区

马约拉纳
中微子信号区

PandaX
基于液氙时间投影室

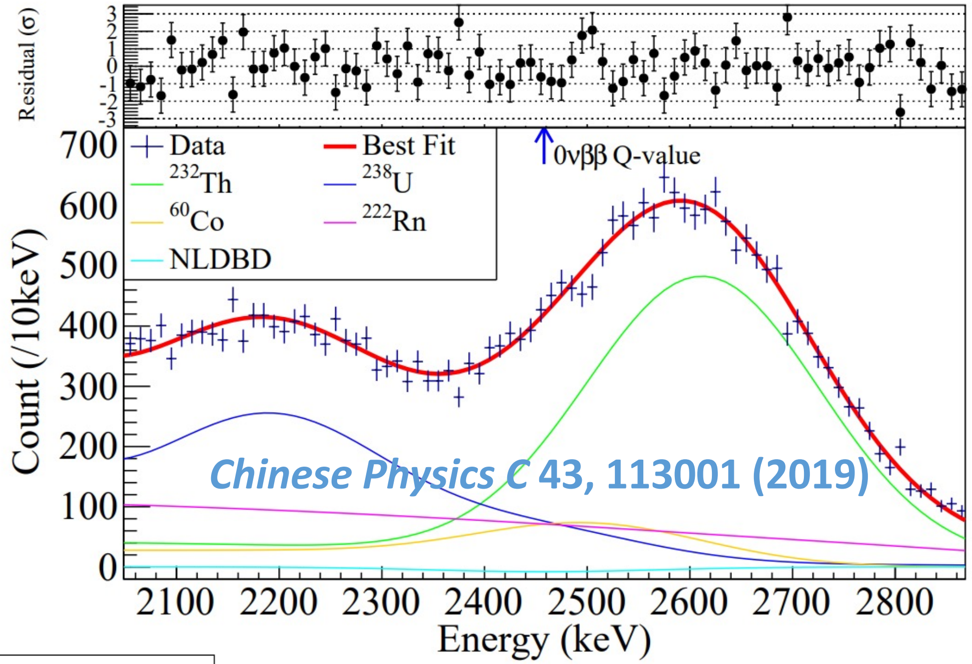


PandaX-4T: LXe

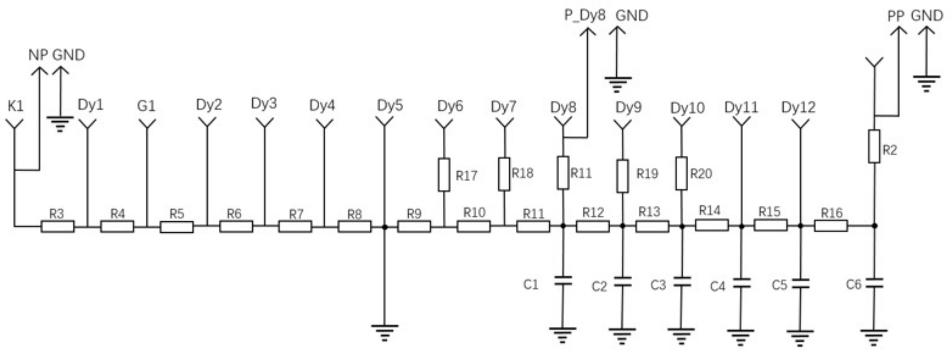
PandaX-xT: 30 FV LXe
(Future)

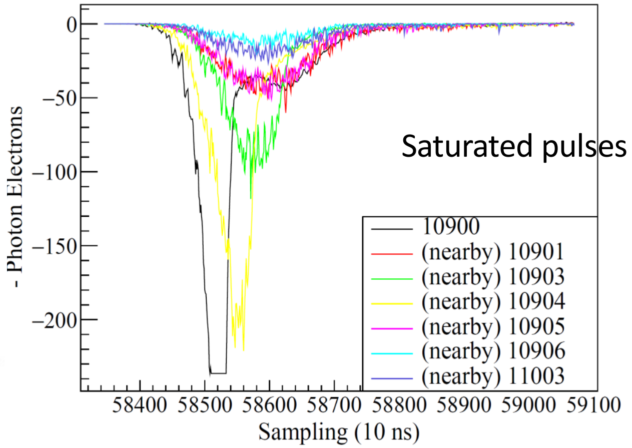
Searching 0νββ at PandaX-II

- 利用PandaX-II实验403.1天的暗物质探测物理数据给出**首个利用双相自然氙实验探测器给出0νββ 结果**
- 半衰期下限为2.4×10^{23} yr at 90% CL，对应的中微子马约拉纳有效质量上限1.3-3.5 eV
- PandaX-4T开始运行取数，中间7个PMT采用双打拿级读出抑制信号饱和
- 进行算法开发，对饱和波形进行修正，提高探测器性能



Chinese Physics C 43, 113001 (2019)

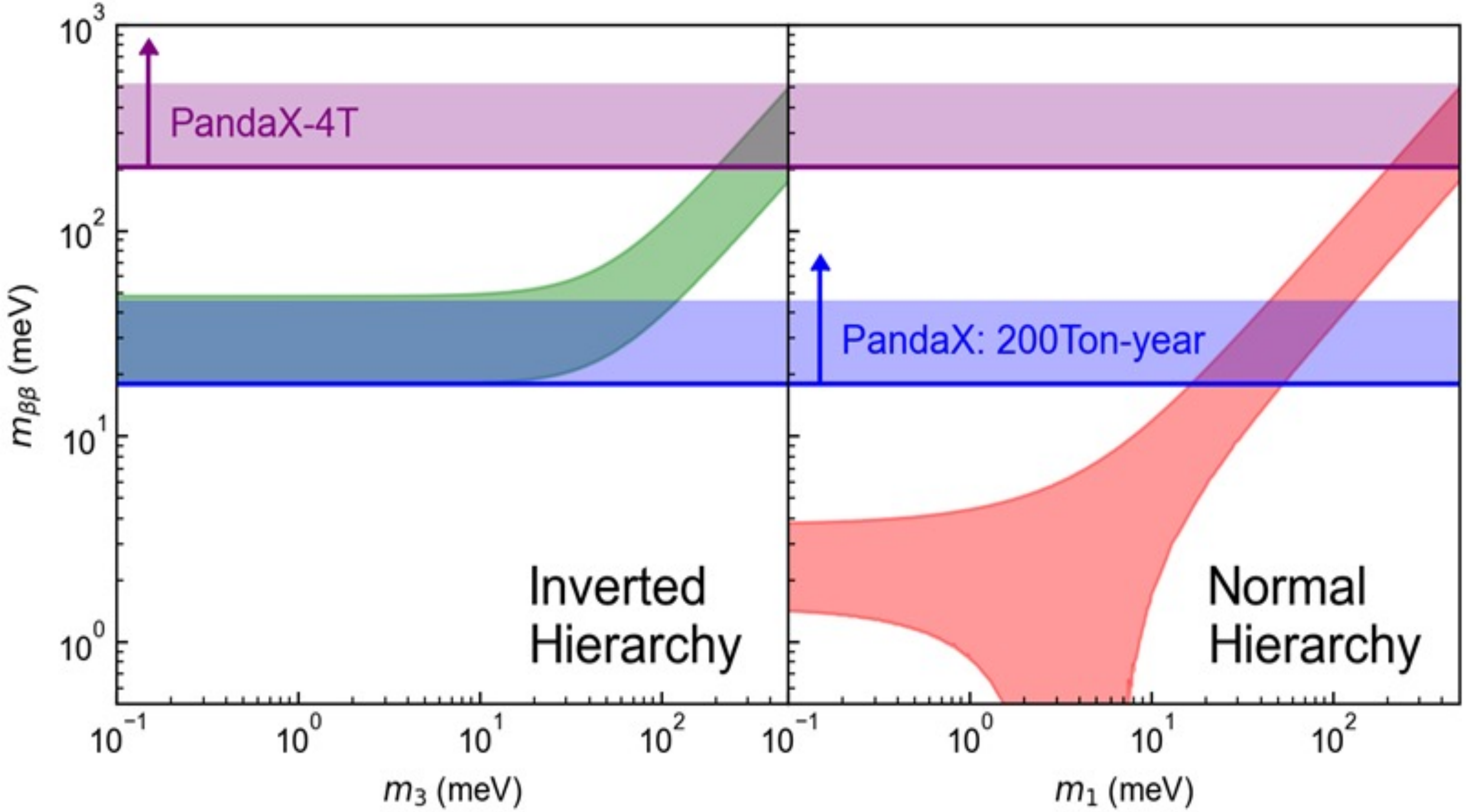




JINST 15 (2020) 12, T12006

0νββ at PandaX-4T and Beyond

研究目标：利用PandaX-4T不同衰变通道寻找马约拉纳中微子，探测灵敏度实现0.2-0.5eV

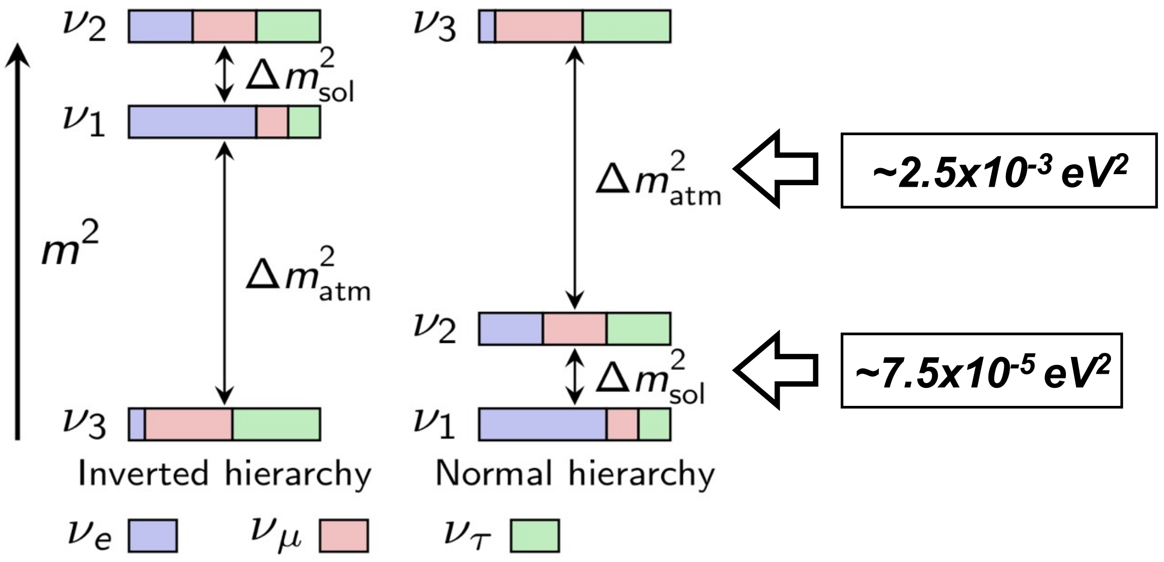


Complications Come from Mixings and Oscillations

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix (with Majorana CP phases),

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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



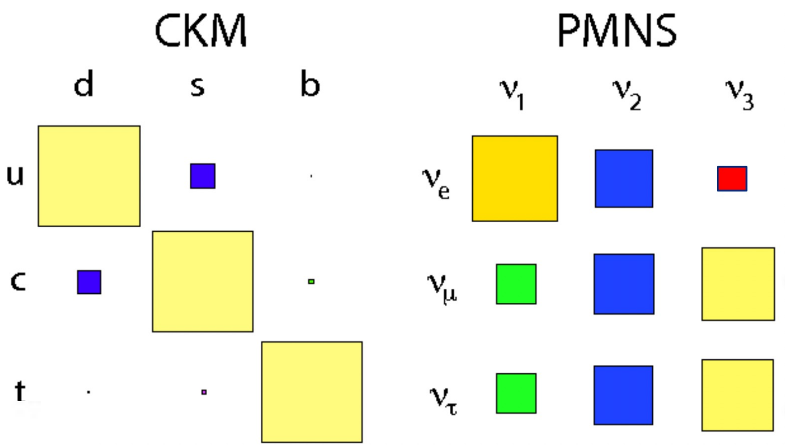
$\Rightarrow$ Neutrino Oscillation Probability:

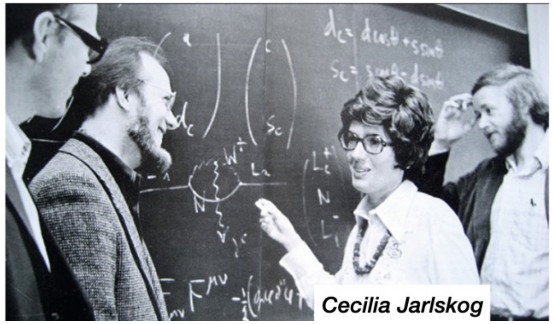
$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4\sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

Amplitude $\propto \sin^2 2\theta$ **Frequency $\propto \Delta m^2 L/E$**

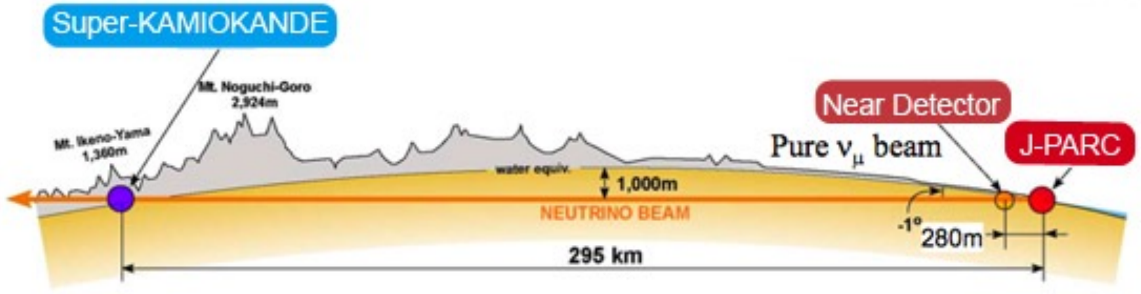
Latest Results from NOvA and T2K

- Offaxis beam, L/E at oscillation maximal
- Disapearance for atmospheric sector
- Appearance for mass ordering and CP

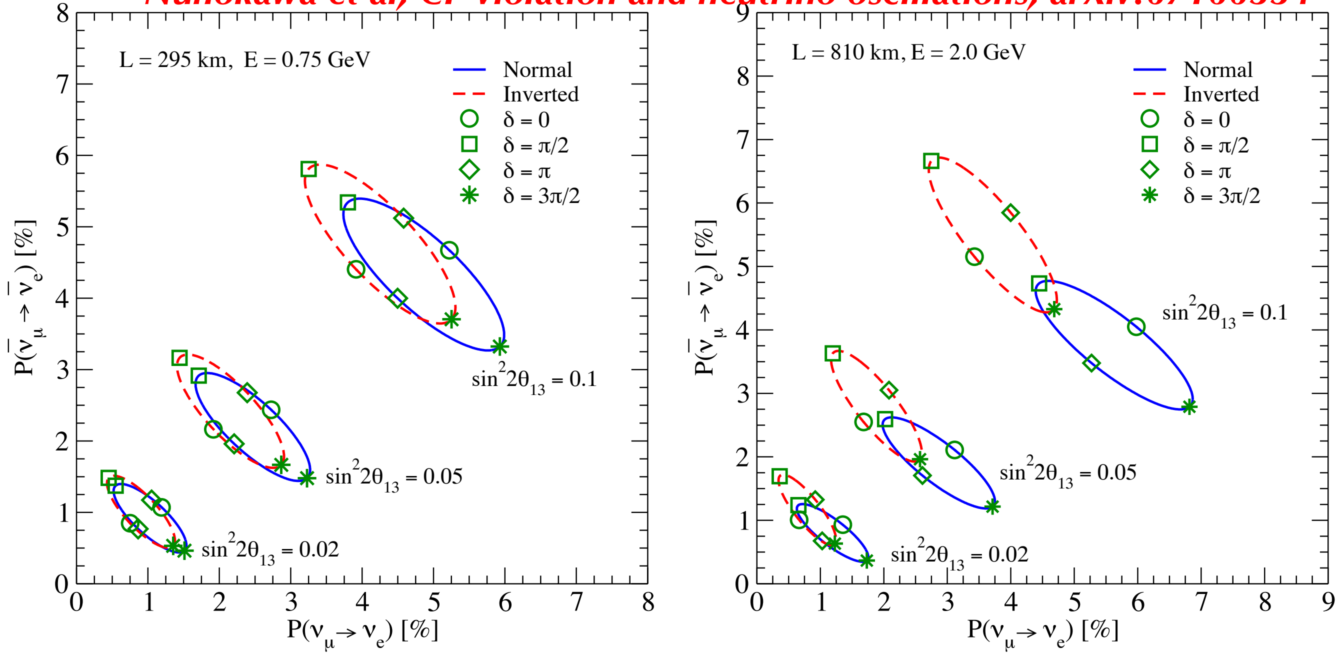


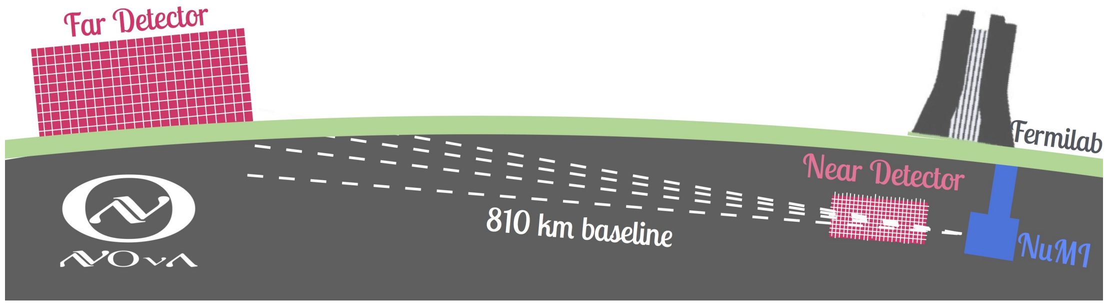


$$\frac{J_{\mathrm{PMNS}}}{J_{\mathrm{CKM}}} = \frac{3\times10^{-2}}{3\times10^{-5}}\sin(\delta_{\mathrm{PMNS}})$$

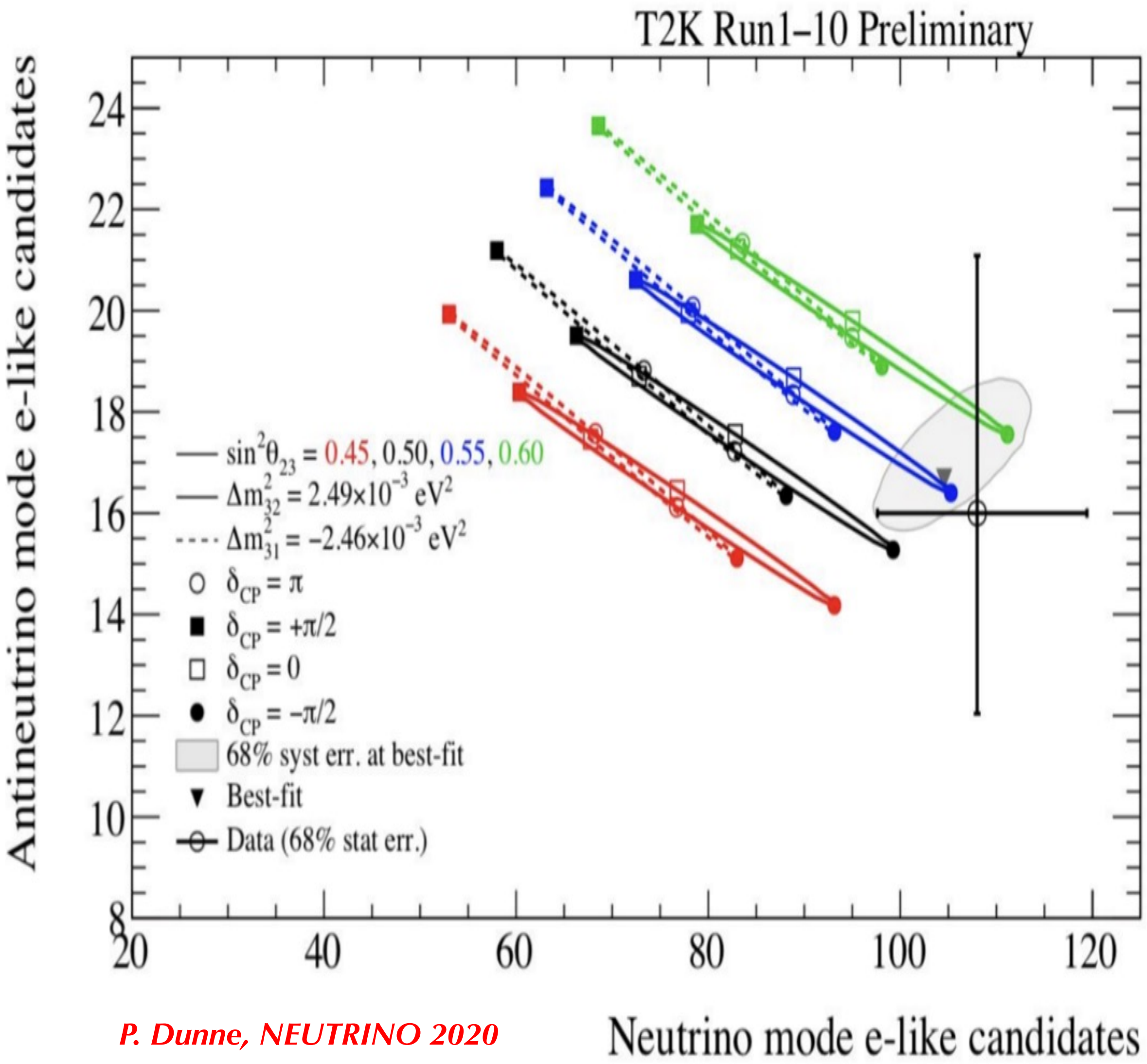


Nunokawa et al, CP violation and neutrino oscillations, arXiv:07100554

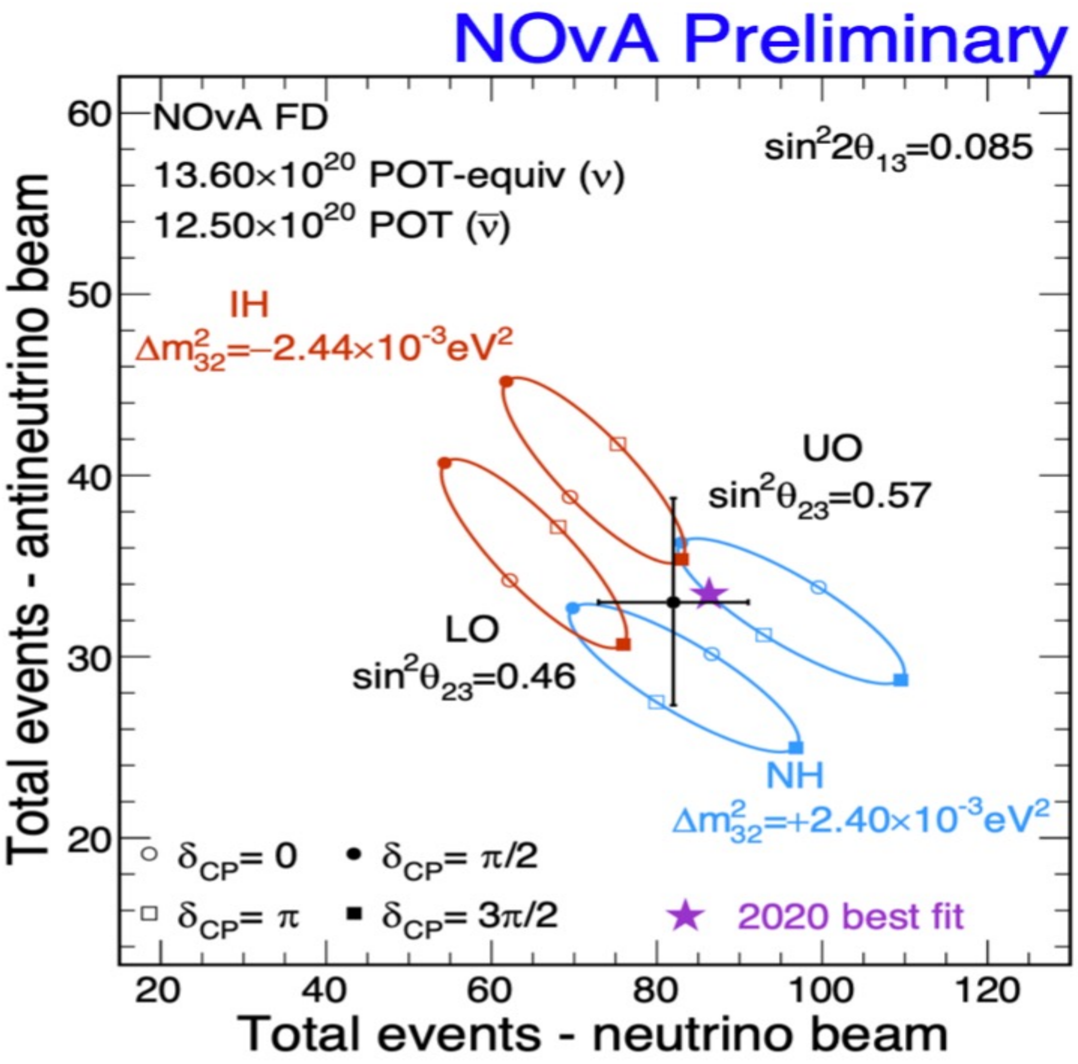




Latest Results from NOvA and T2K

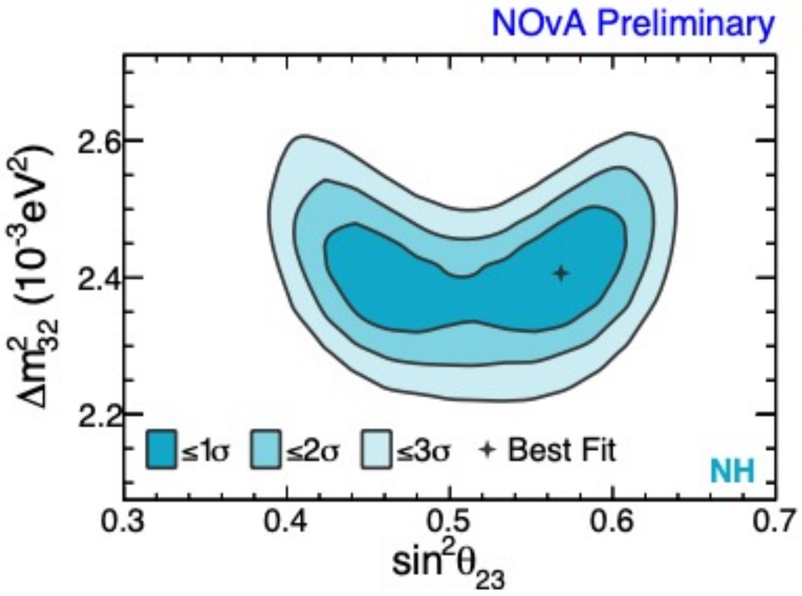


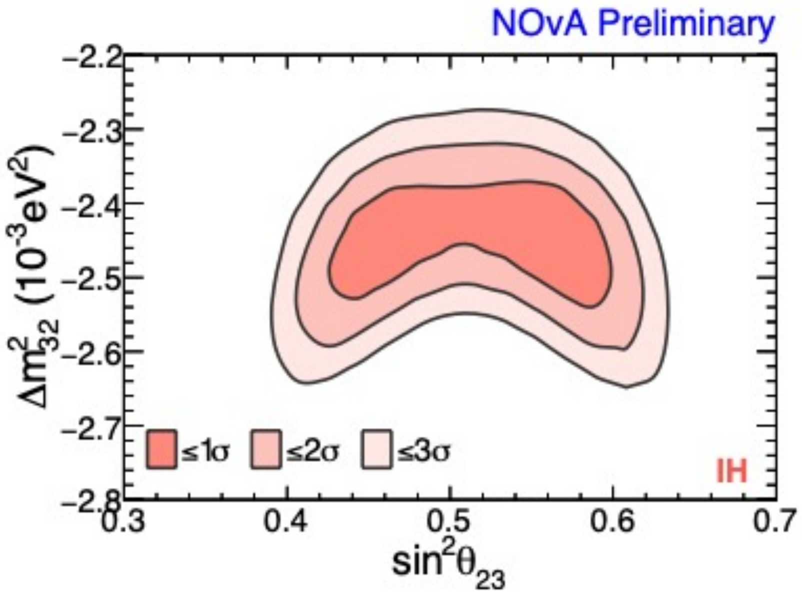
P. Dunne, NEUTRINO 2020

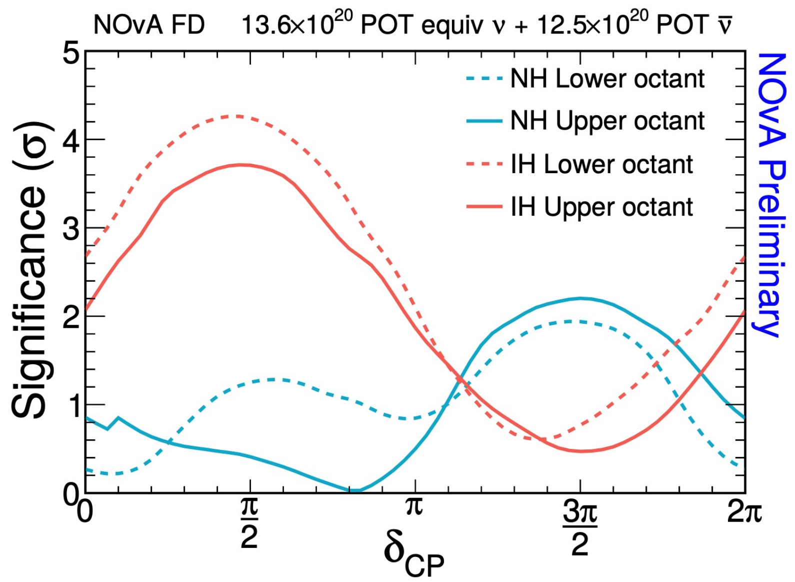


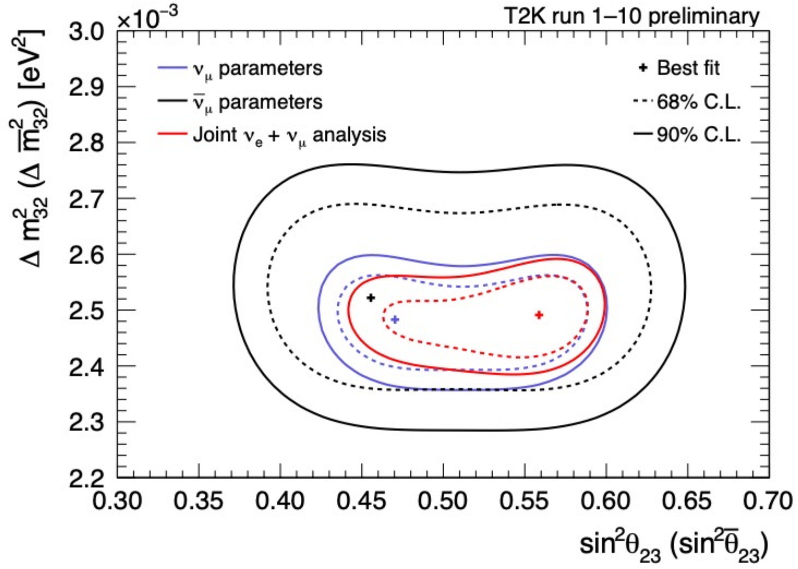
A. Himmel, NEUTRINO 2020

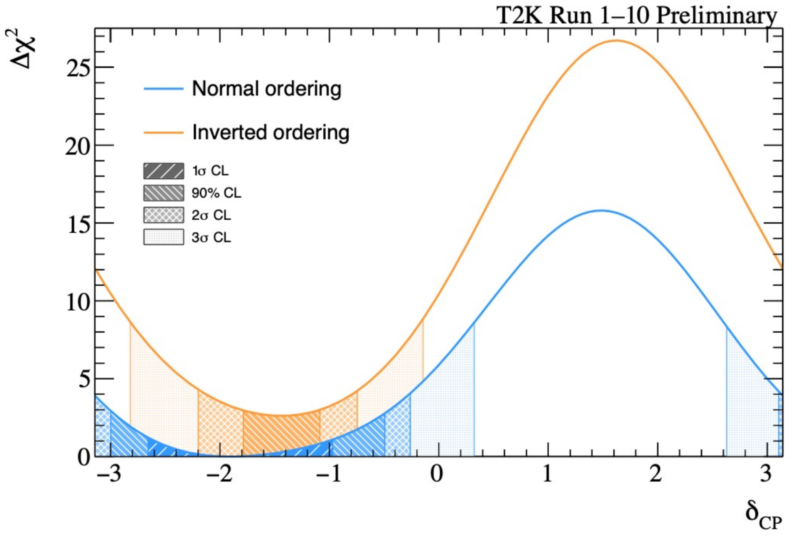
Latest Results from NOvA and T2K







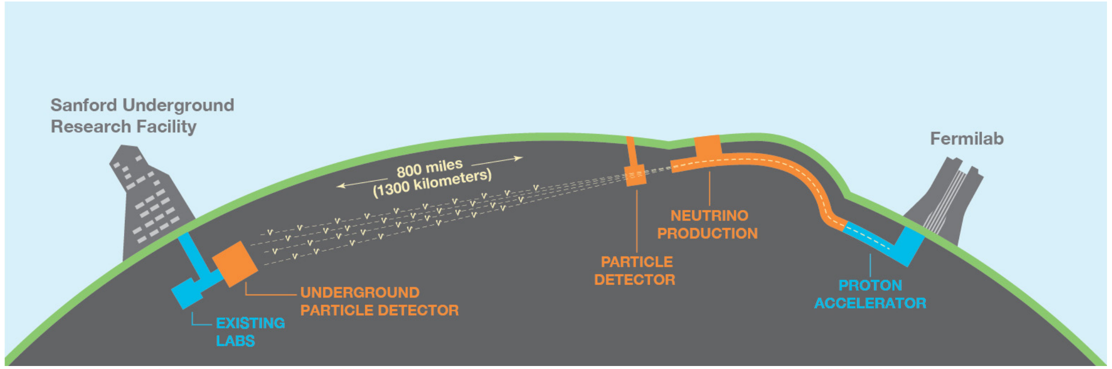


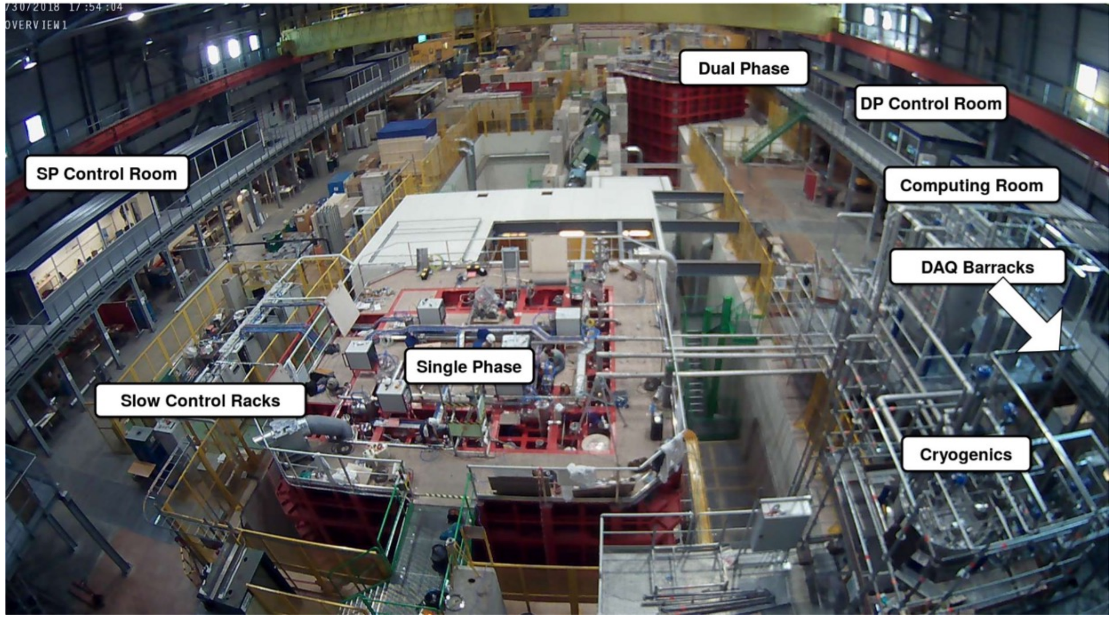


- There is tension in CP between the two experiments, but not inconsistent
- ➢ Global fit: NH indication is less than 3-sigma
- ➢ Joint analysis is being carried out

The U.S. Efforts in Neutrino Oscillations

- **In the U.S., MINOS/MINOS+/NOvA shifting to LBNF → DUNE**

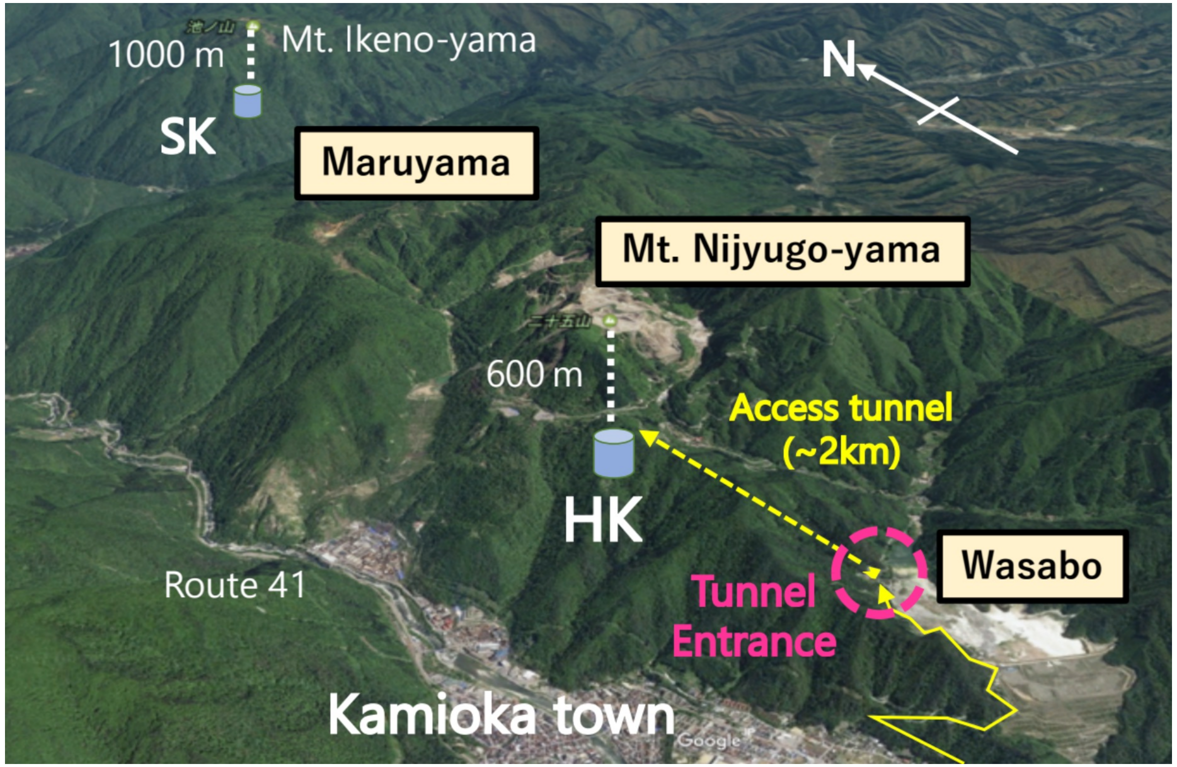


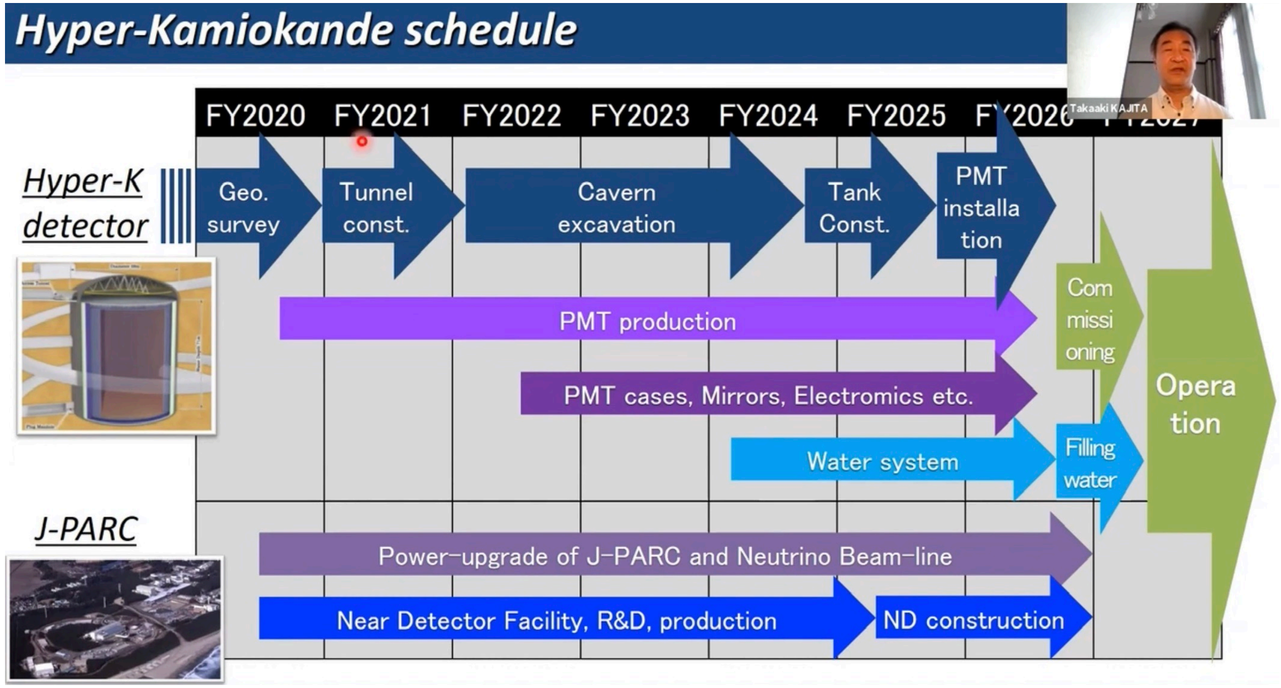


- ~~Late 2021~~: 2022: ProtoDUNE-SP run II
  - **Laser and neutron calibrations**, new DAQ, new instrumentation
- 2024 : Installation of first DUNE module (SP)
- 2025 : Start installing second module
  - **DUNE physics data starts with atmospheric neutrinos**
- 2026: Beam operational at 1.2 MW
  - **Start of DUNE physics data taking with beam**
  - Total fiducial mass of 20 kt
- 2027: Add third FD module
- 2029: Add fourth FD module
- 2032: Upgrade to 2.4 MW beam

The Japanese Efforts in Neutrino Oscillations

- In Japan, Super-K/T2K → Hyper-K/T2HK





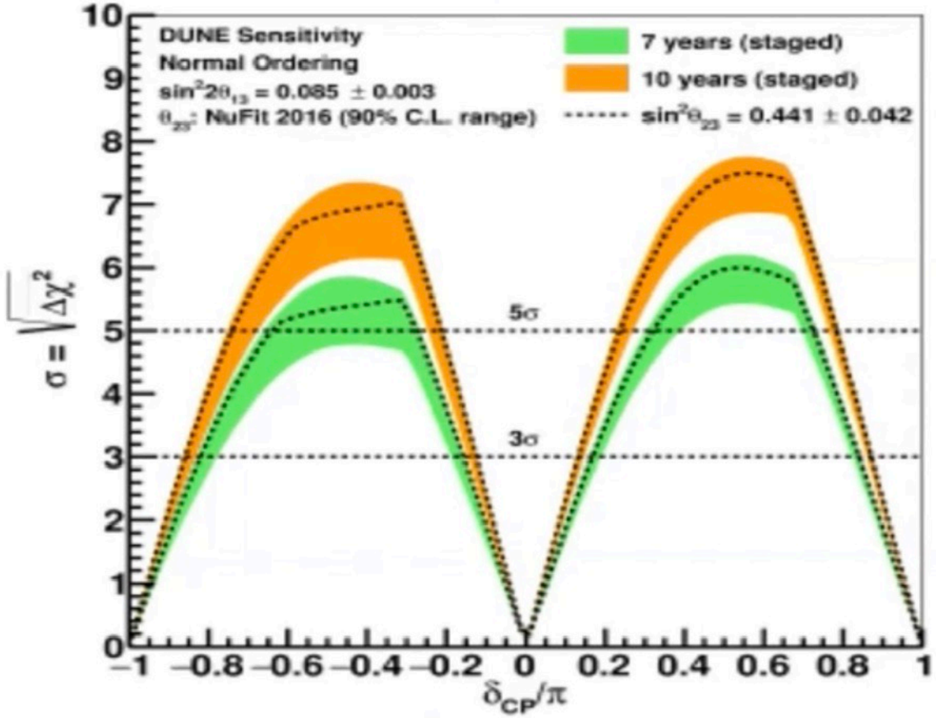
DUNE versus Hyper-K Comparison in CP Phase

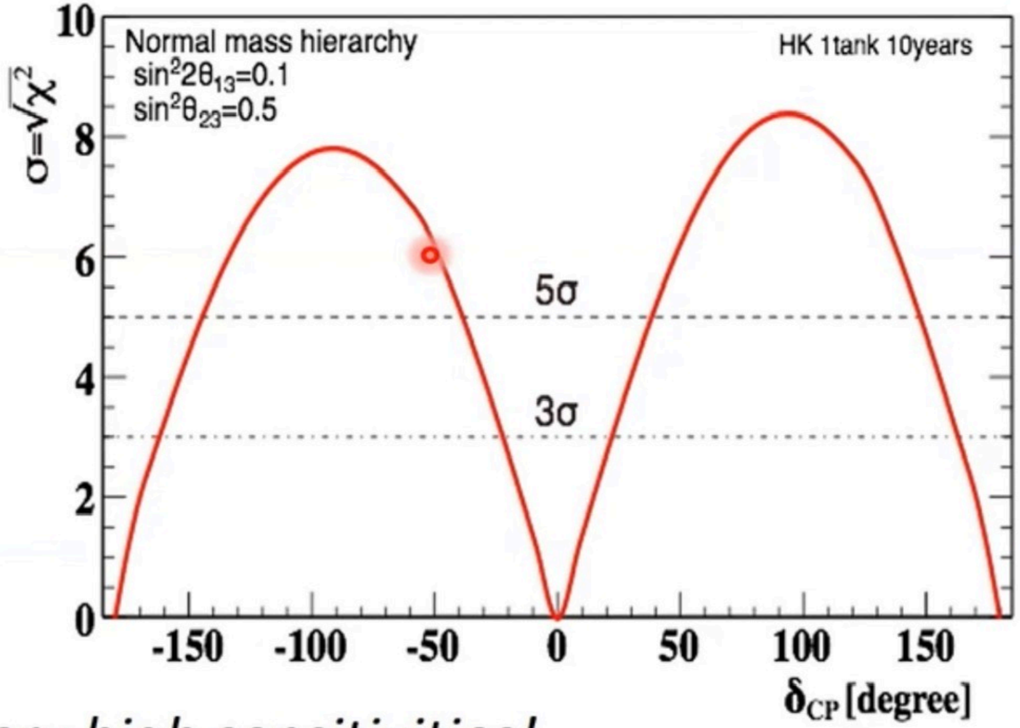
Comparison

DUNE

(Nu2018, E. Worcester)

Hyper-K

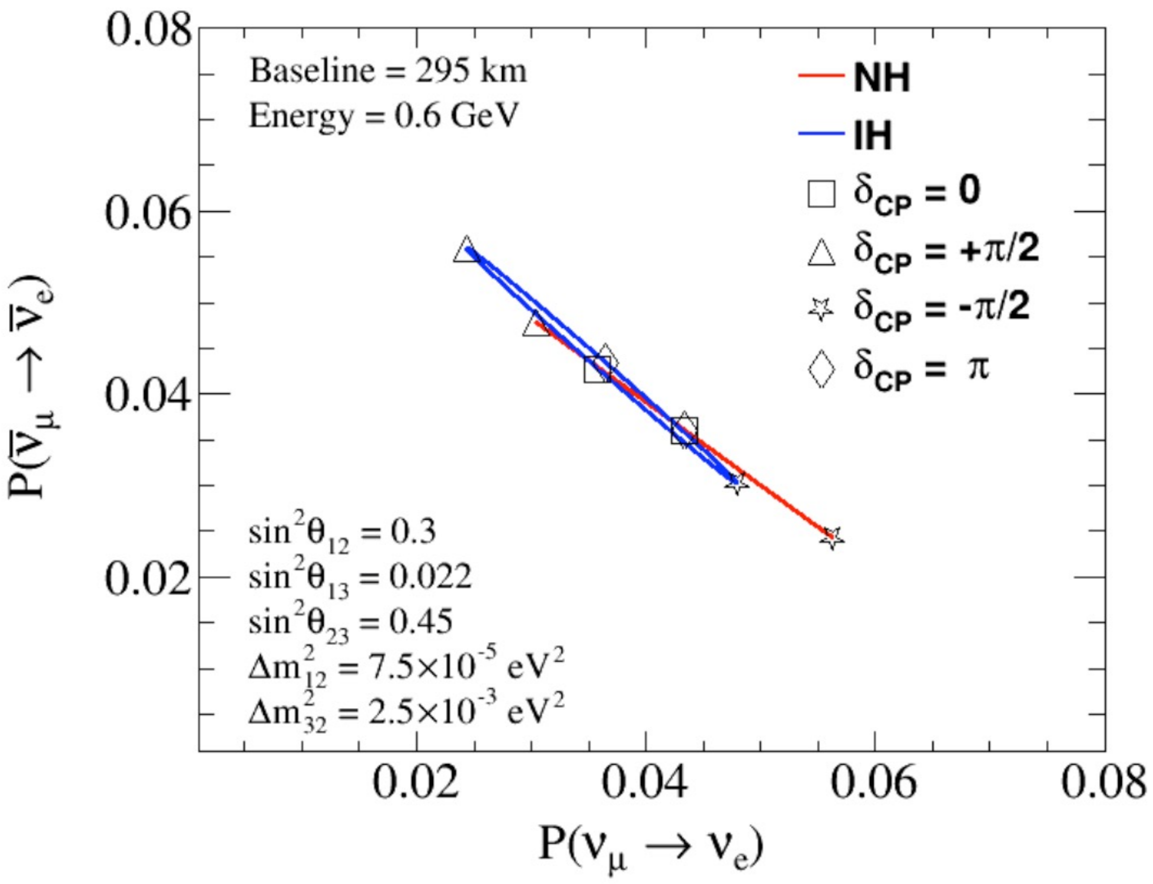




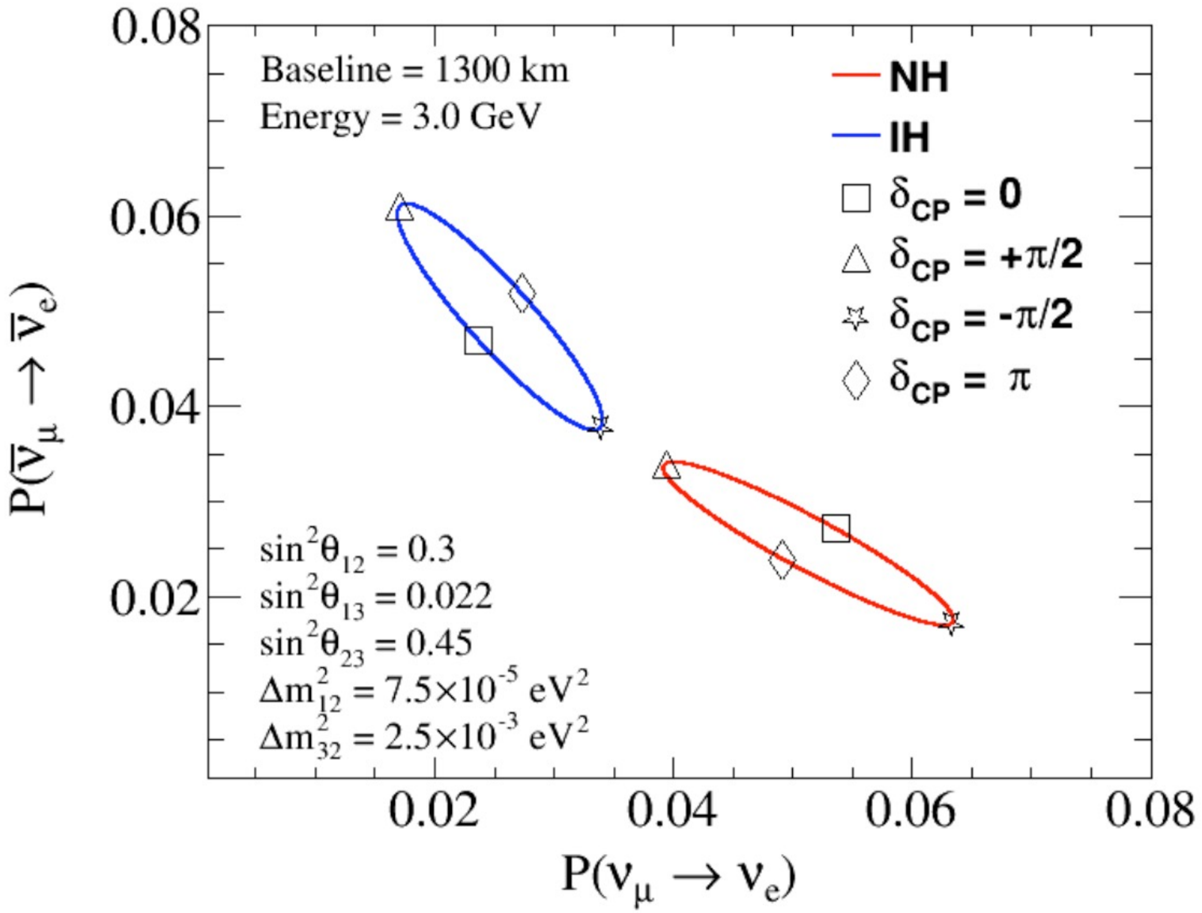
➔ *Both experiments have very high sensitivities!*

DUNE versus Hyper-K Comparison in Mass Ordering

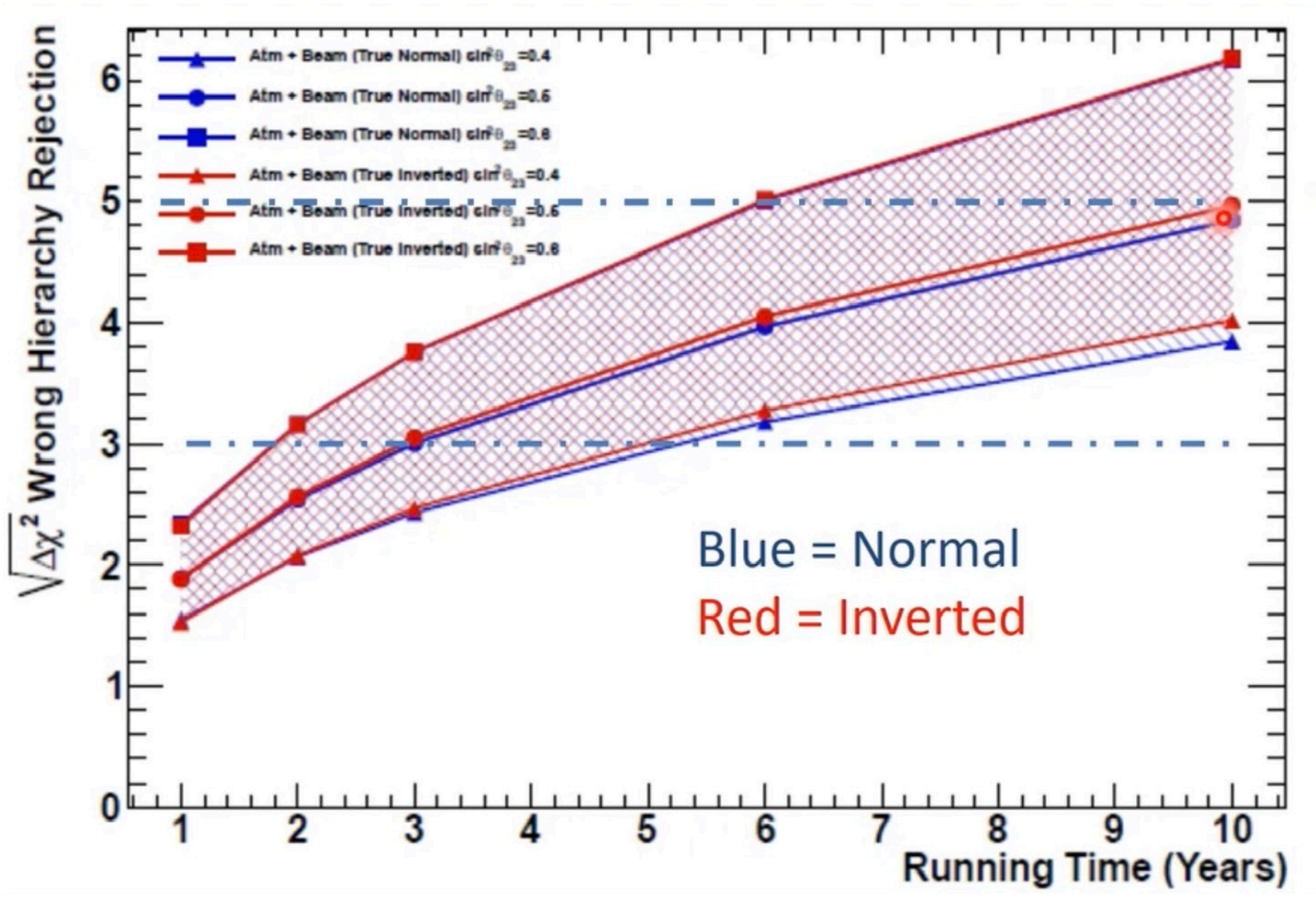
Baseline 295 km
Energy 0.6 GeV

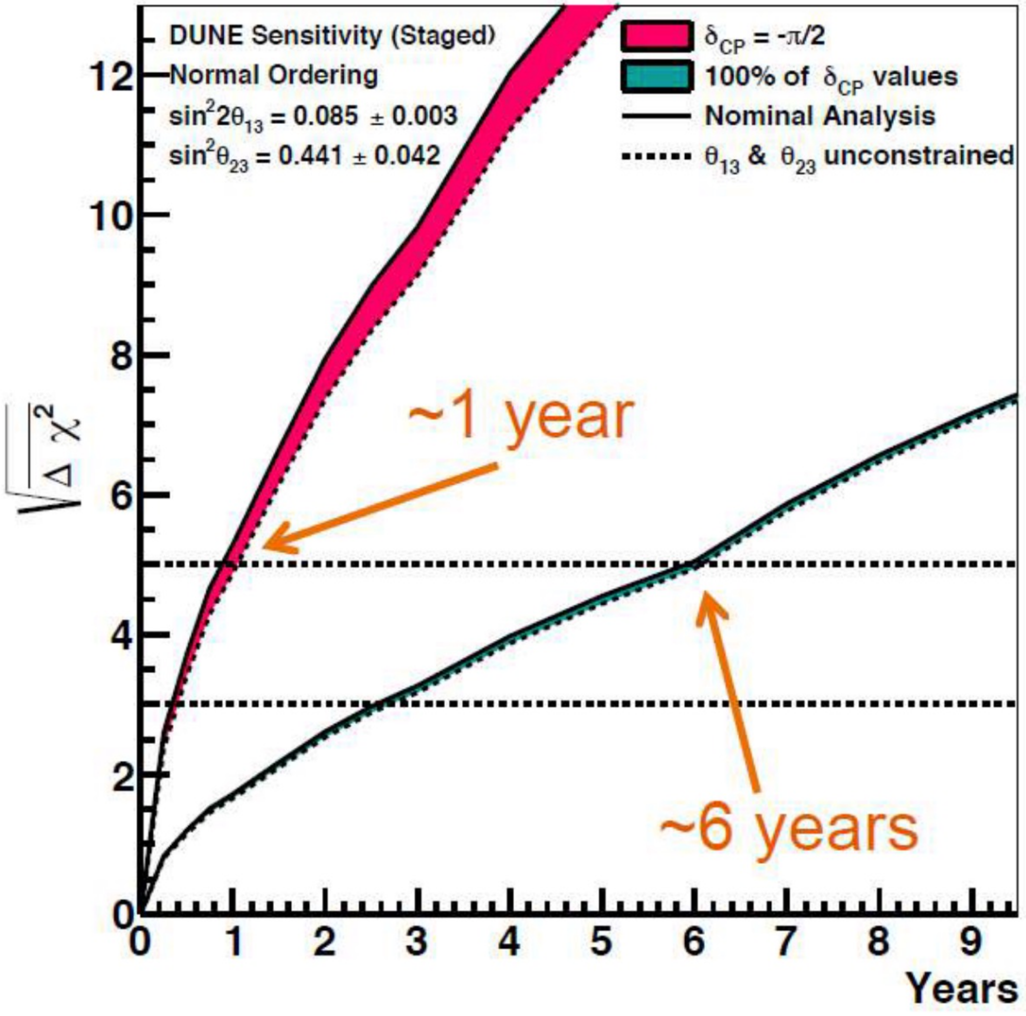


Baseline 1300 km
Energy 3.0 GeV

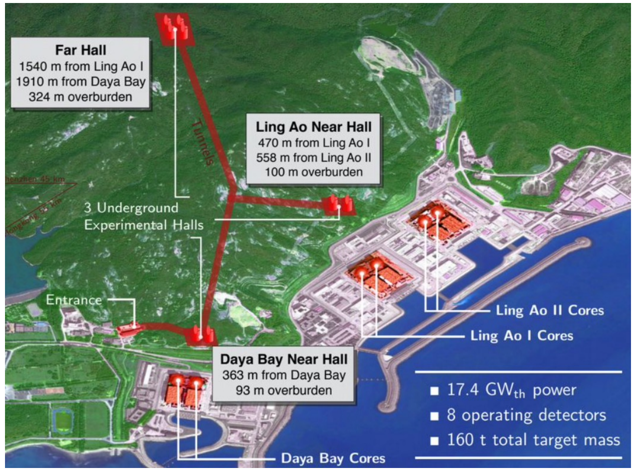


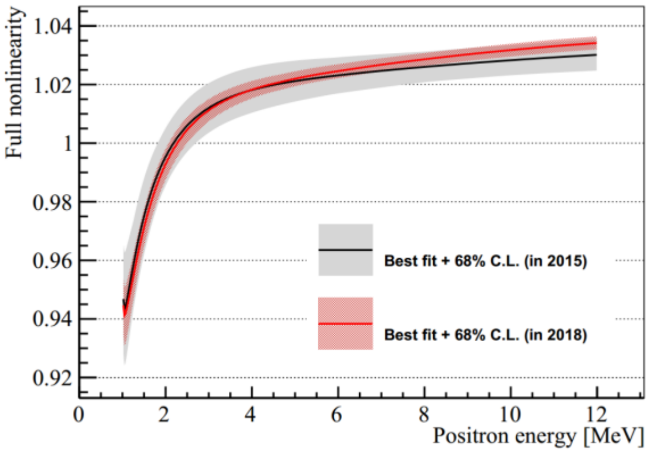
DUNE versus Hyper-K Comparison in Mass Ordering

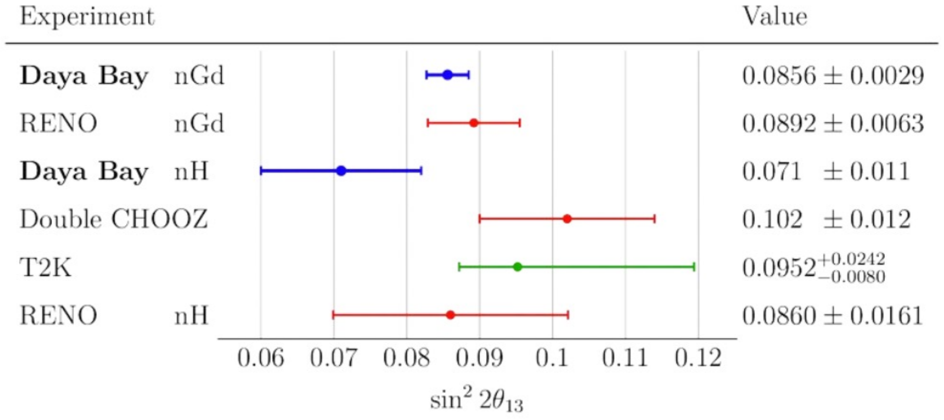


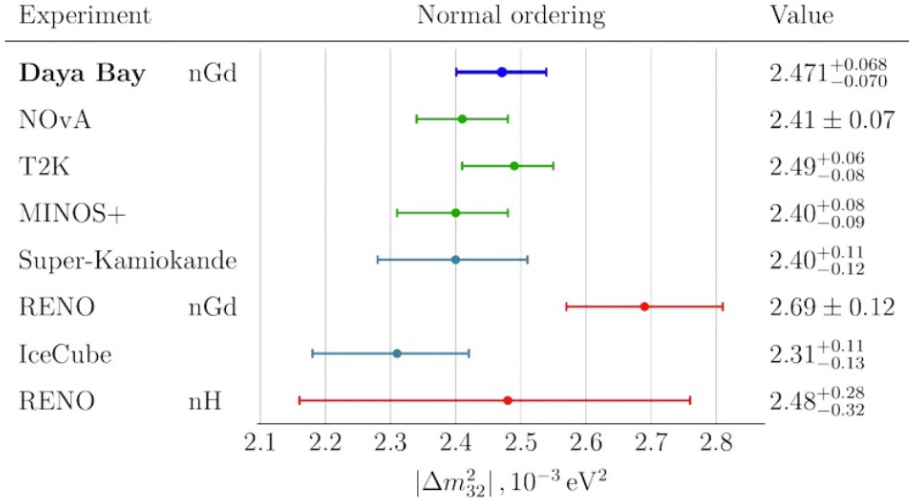


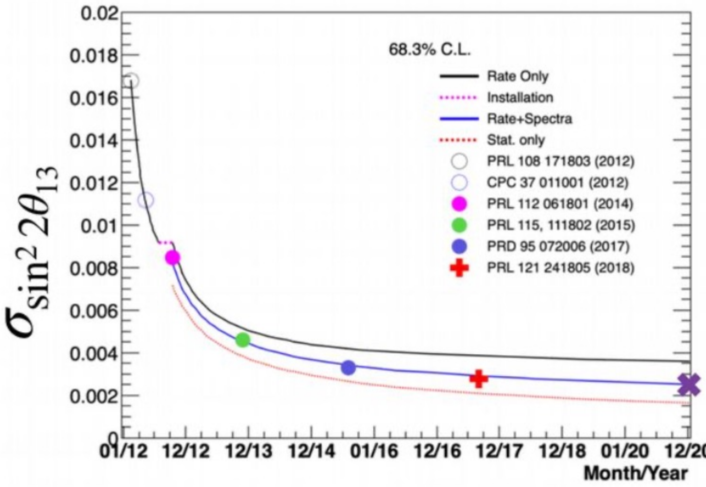
Daya Bay has “Stolen” Some Shows



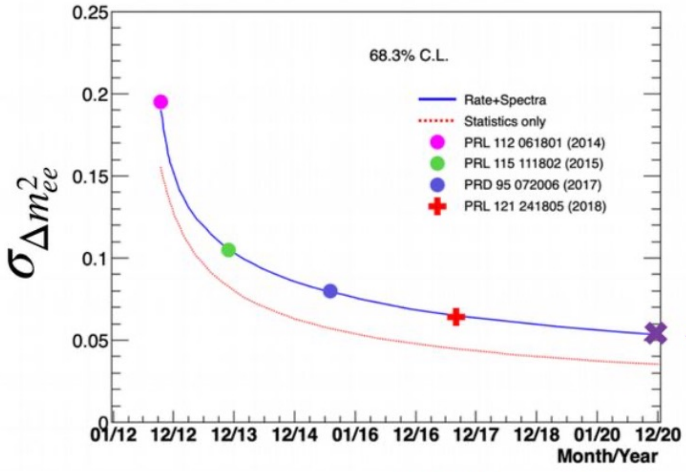








$\sin^2 2\theta_{13}$ uncertainty 3.4% → 2.7%



End of Daya Bay data taking

9

Δm^2_{ee} uncertainty 2.8% → 2.1%

θ_{13} Enables Neutrino Mass Ordering Resolution at Reactors

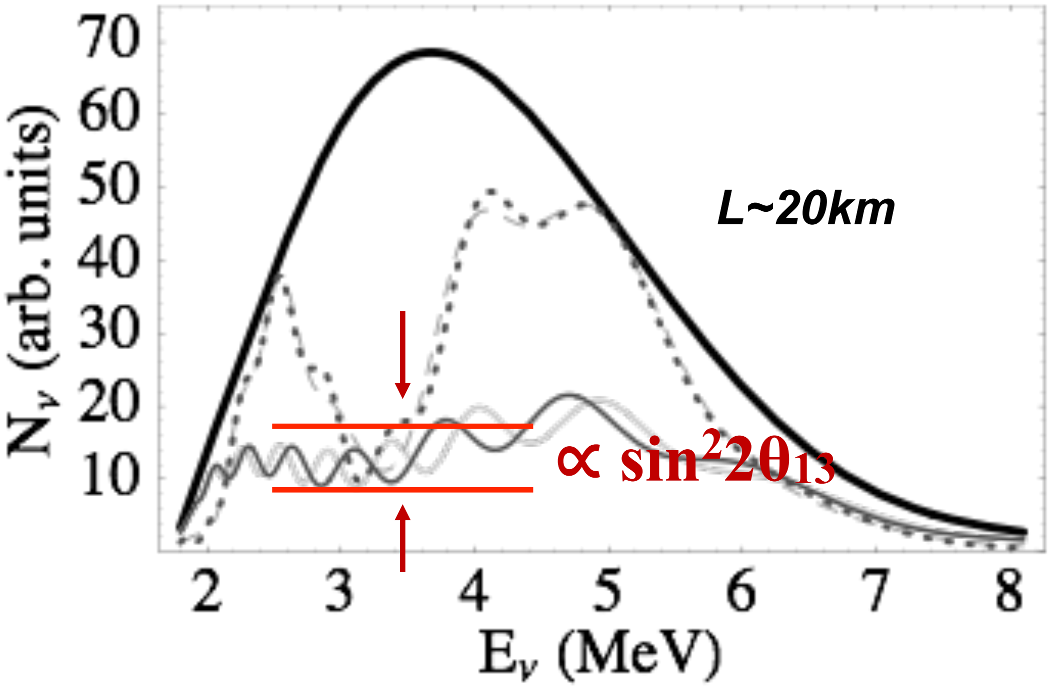
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

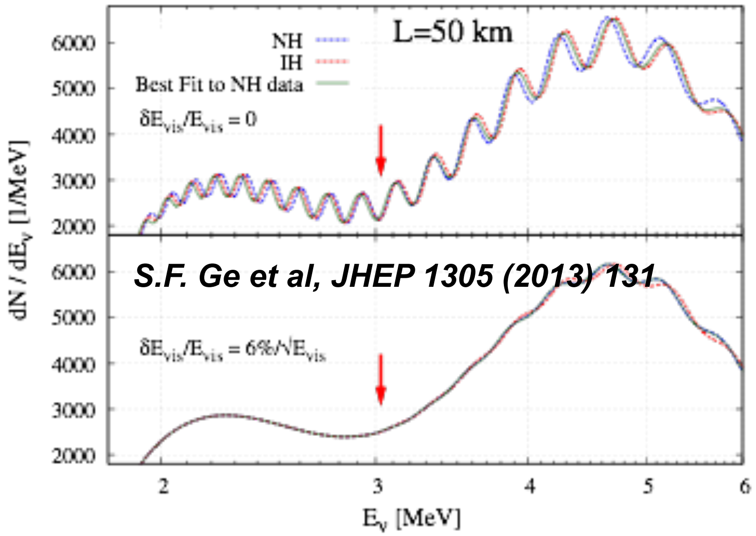
Petcov&Piai, Phys. Lett. B533 (2002) 94-106

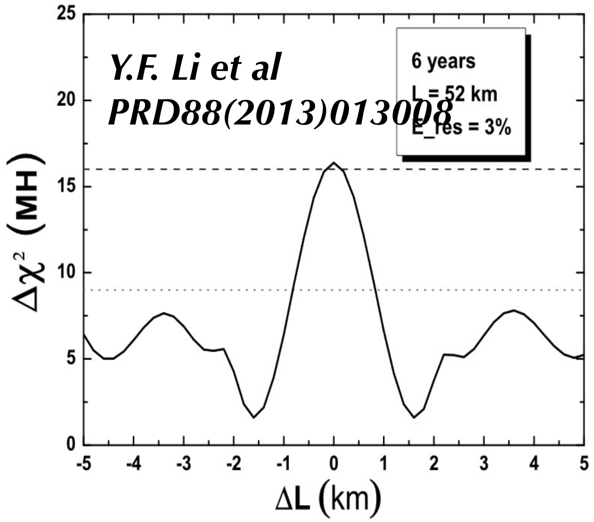
√Mass hierarchy reflected in the spectrum

√Independent of the unknown CP phase

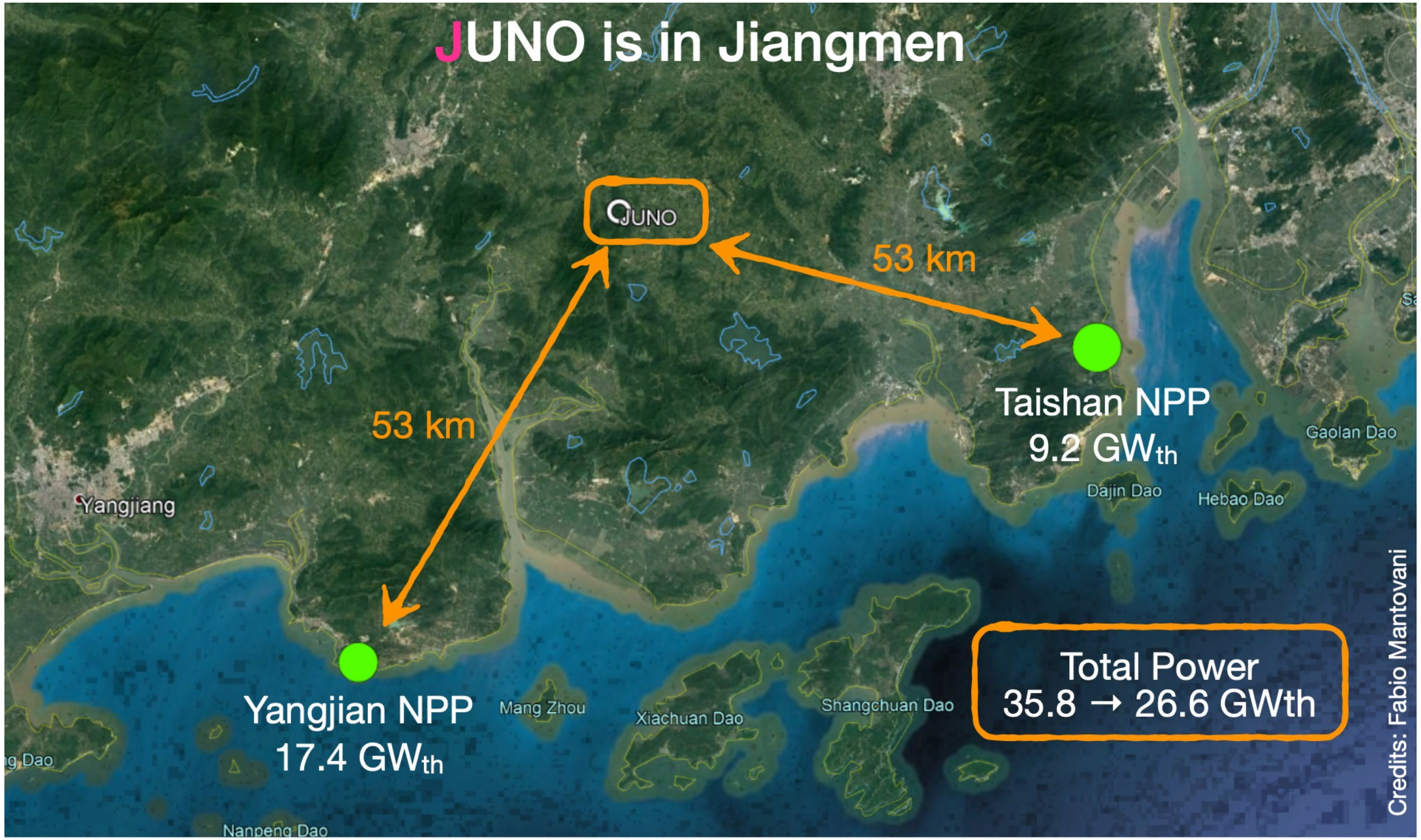
- Energy resolution: ~3%/sqrt(E)
- Energy scale uncertainty: <1%
- Statistics (the more the better)
- Reactor distribution: <~0.5km







The Jiangmen Underground Neutrino Observatory



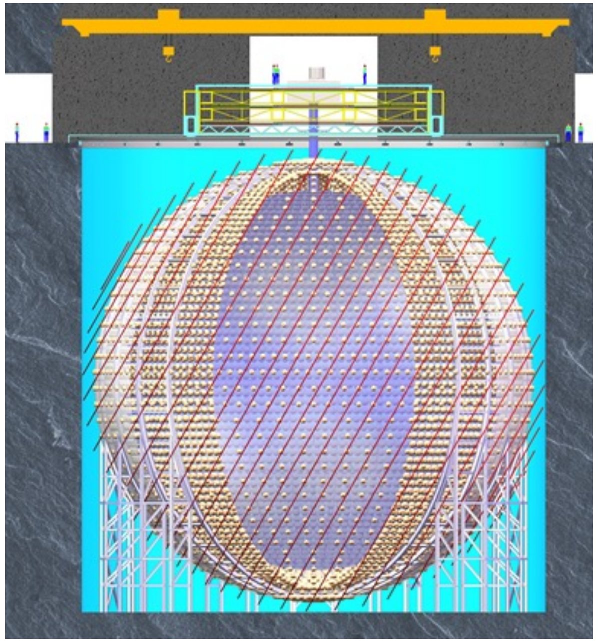
Taishan Power Plant

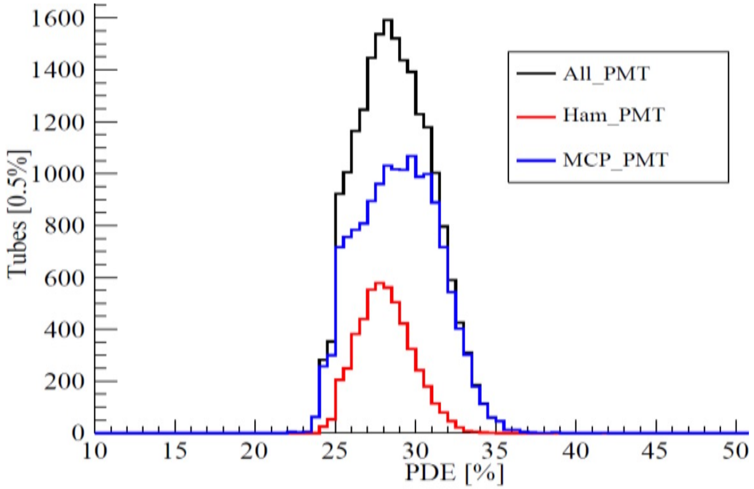
Yangjiang Power Plant

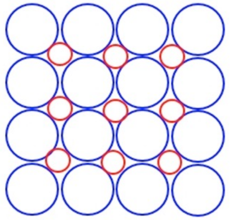
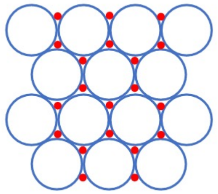
Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

反应堆只剩8个了？！

Inventing & Packing PMTs as Tight as Possible



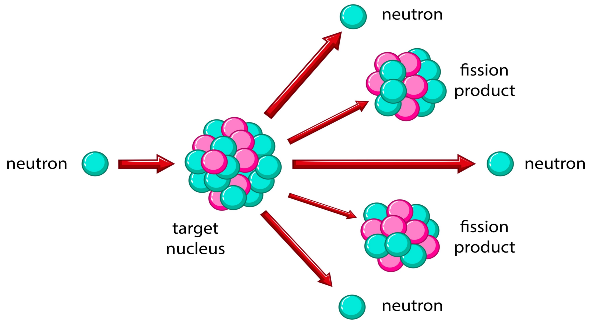


2012	2014	2016	2018
 **20''+8''** *M.He*	 **20''+3''** *A.Cabrera*	Approval by the collaboration **SPMT consortium**	Beginning of production

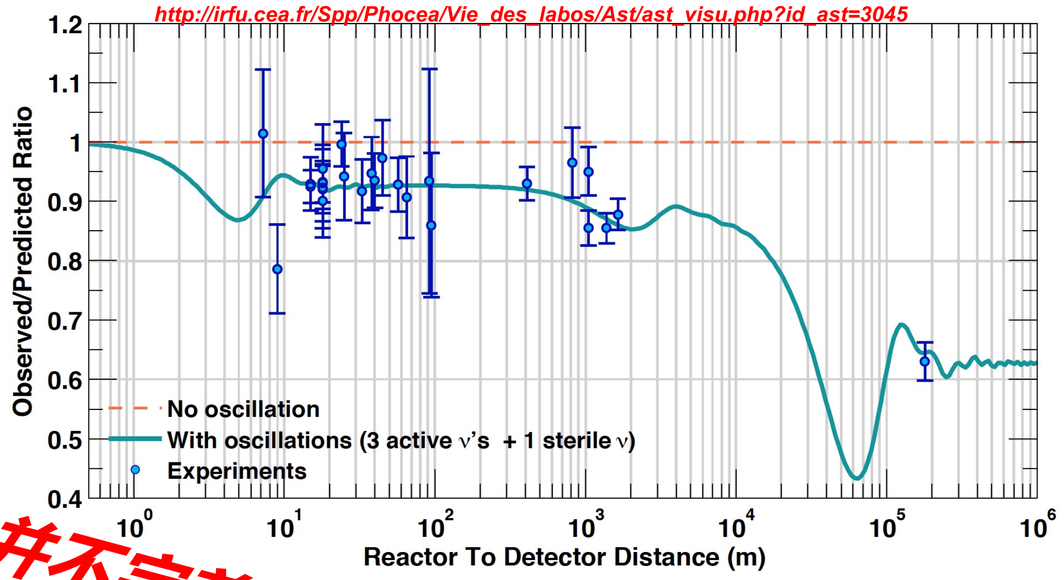
高能所和北方夜视合作出一流的大PMT!

Reactor Antineutrino Anomaly (RAA)

Nuclear Fission

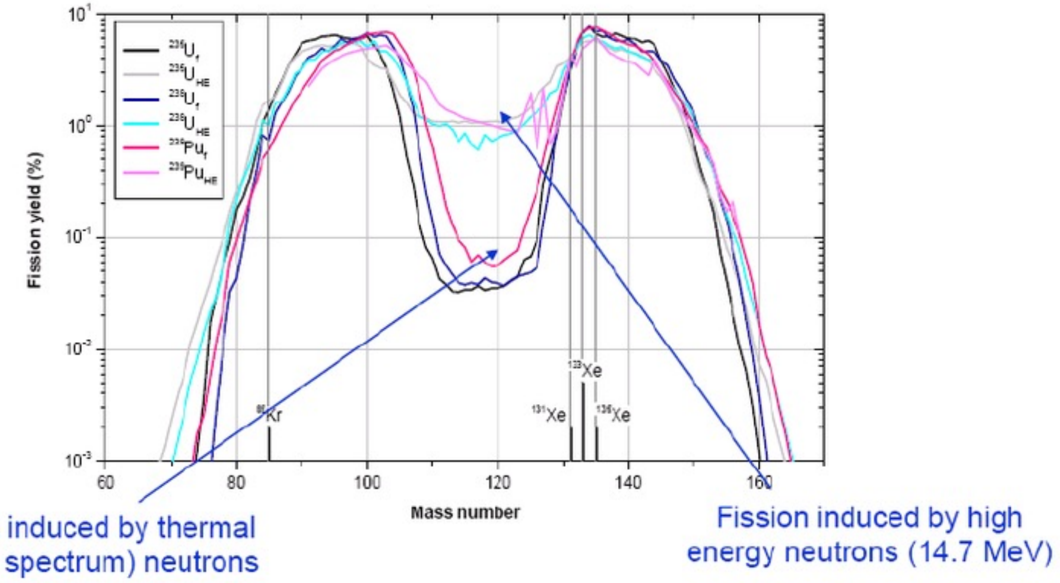


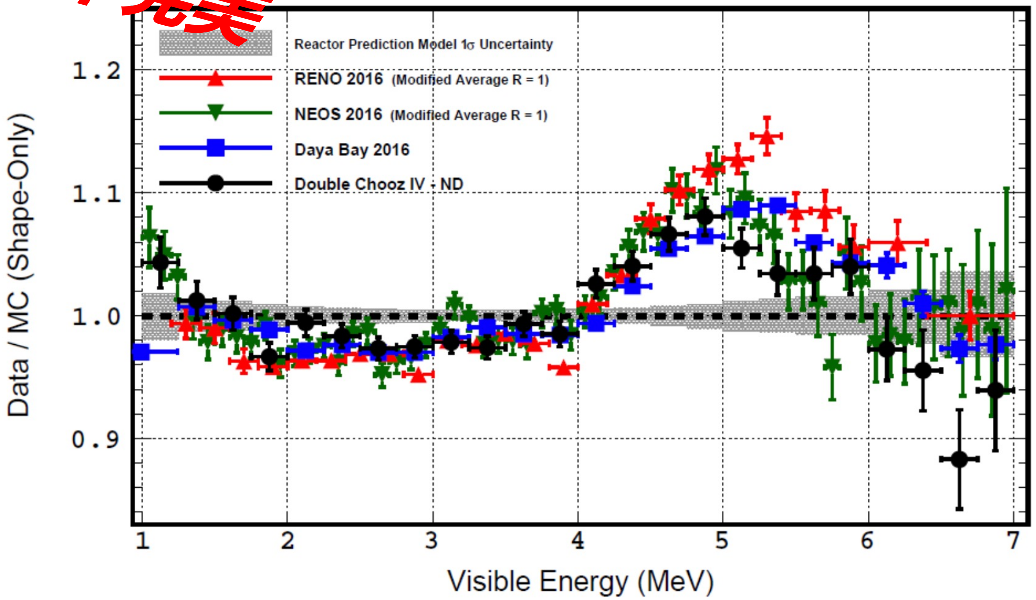
- *T. A. Mueller et al., PRC83, 054615 (2011)*
- *P. Huber, Phys. Rev.C84, 024617 (2011)*
- *Daya Bay, PRL116(2016), PRL123(2019)*
- *RENO, PRL121(2018)*
- *NEOS, PRL118(2017)*
- *Double Chooz, Nature Physics 16(2020)*



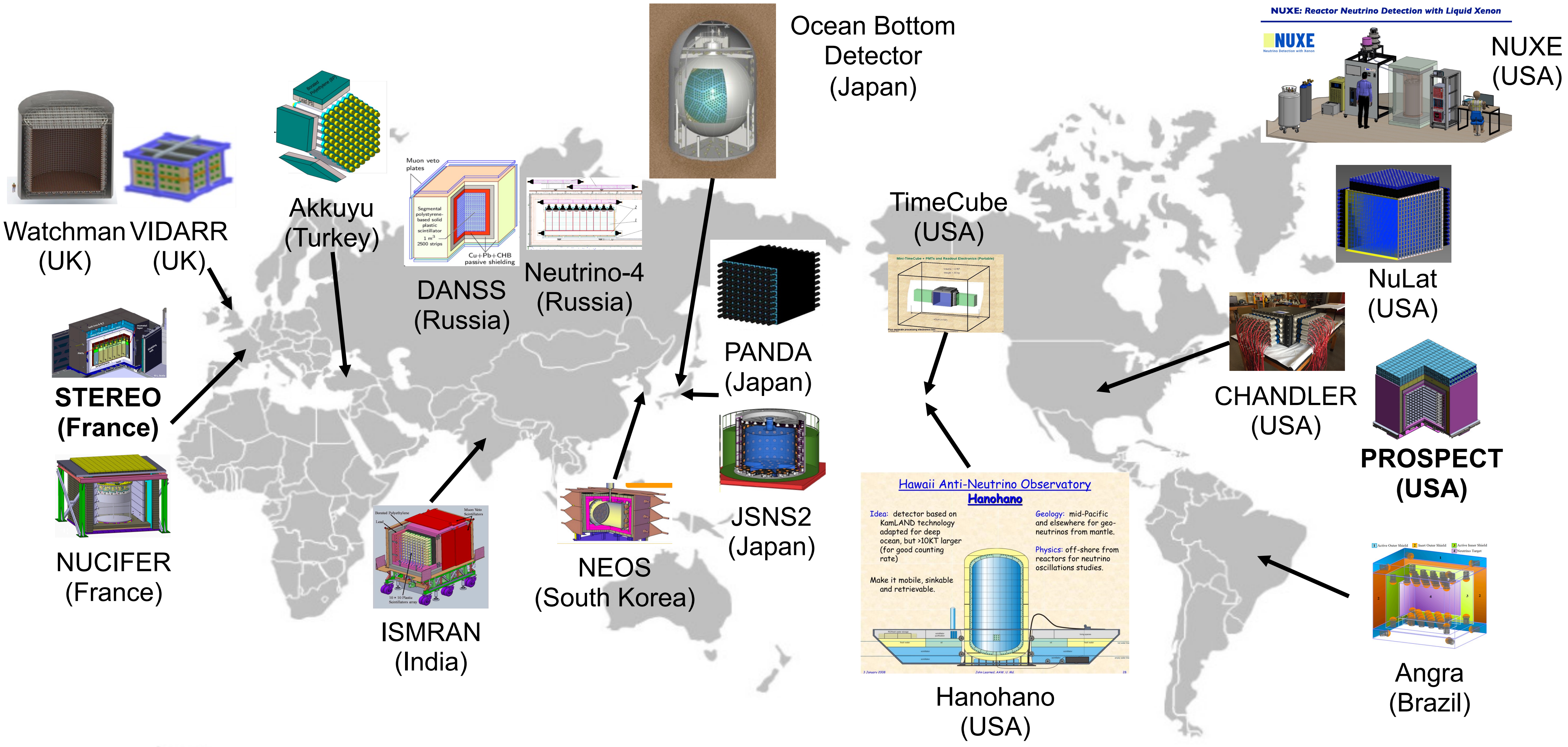
反应堆中微子并不完美

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



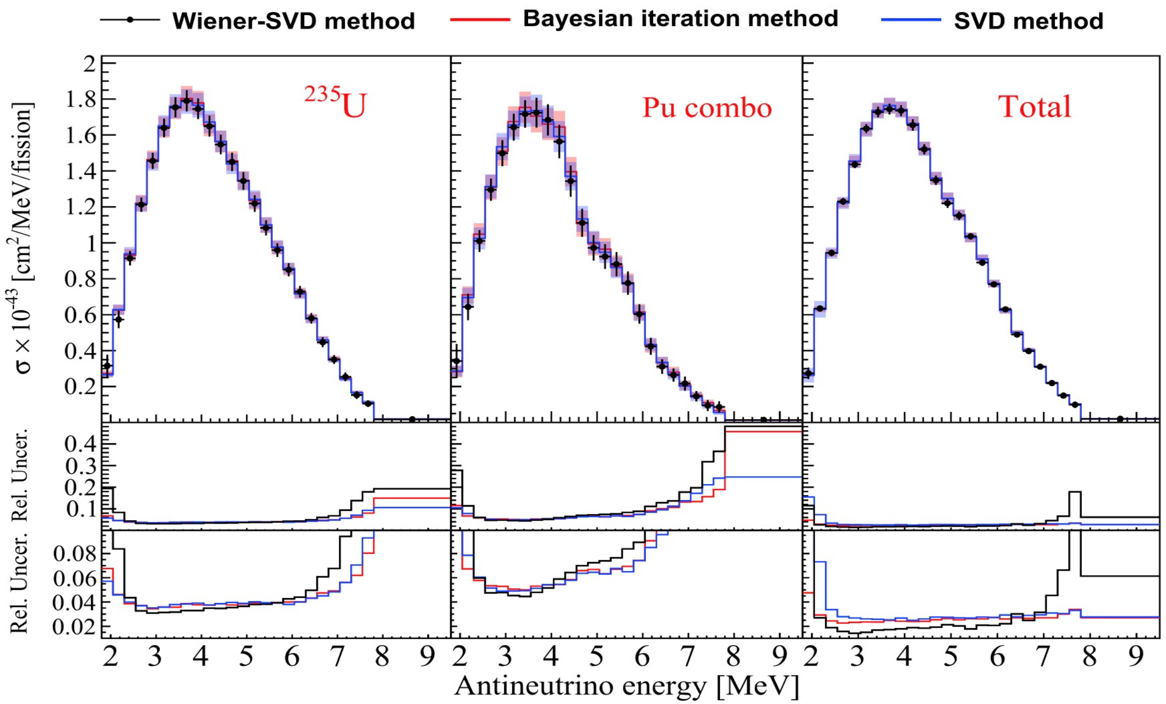


Global Reactor Neutrino Efforts and Non-Proliferation

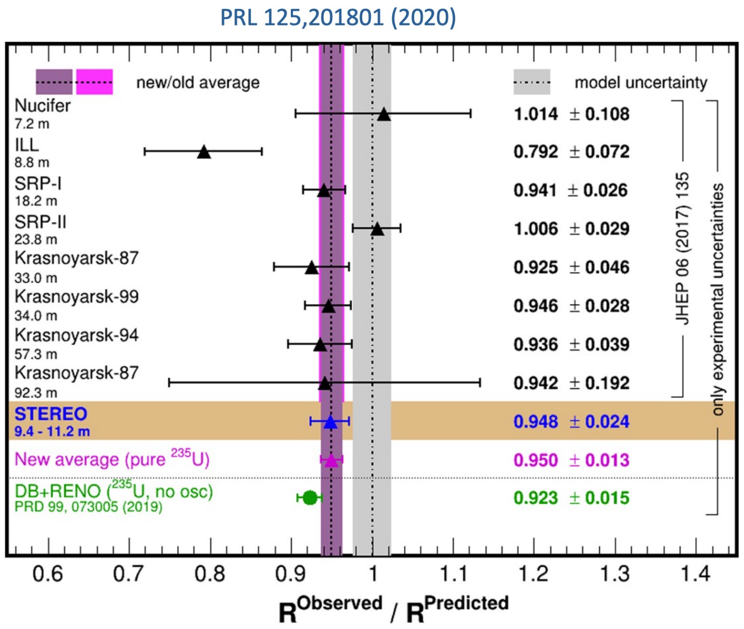


Latest Reactor Antineutrinos Measurements

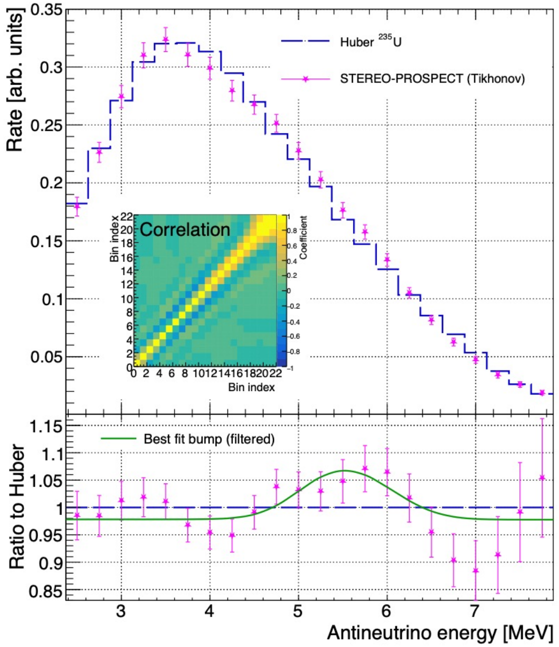
Daya Bay Collaboration, CPC 45(2021)



STEREO Collaboration, PRL 125(2020)



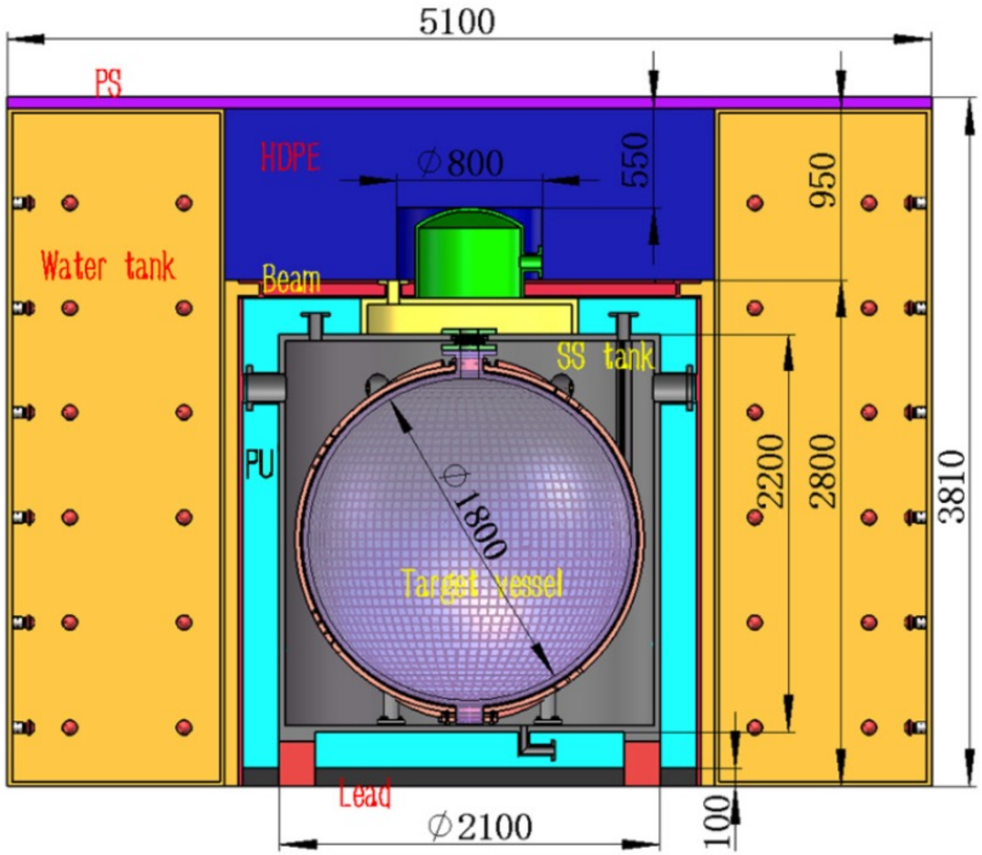
STEREO + PROSPECT



- ❖ Largest reactor neutrino IBD events and most precise results: 235U & ^{239}Pu+^{241}Pu
- ❖ Combined analysis with PROSPECT ongoing

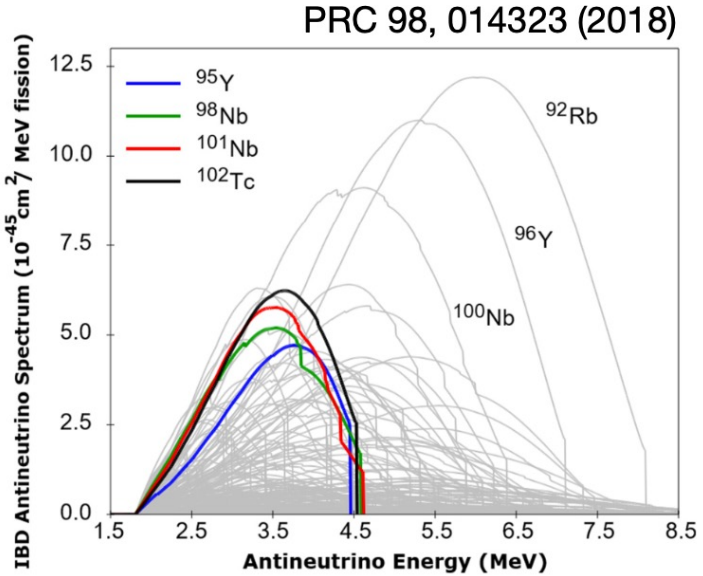
- ❖ Rates consistent with Daya Bay
- ❖ STEREO has the best ^{235}U spec measurement
- ❖ Combined analysis with PROSPECT

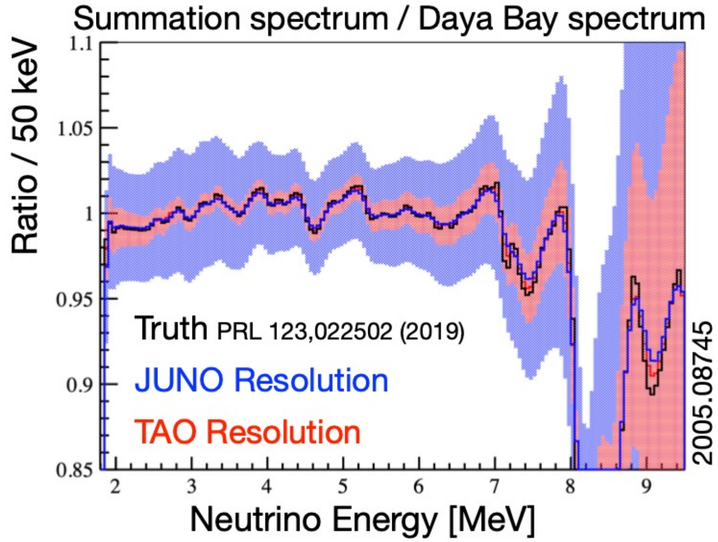
The Future: JUNO-TAO Detector at and Its Potentials



- 2.8t Gd-doped LS
- Sensor: 10 m^2 SiPM, 4500 pe/MeV
- Operated at -50°C (reduce SiPM DCR)
- 30m from reactor core

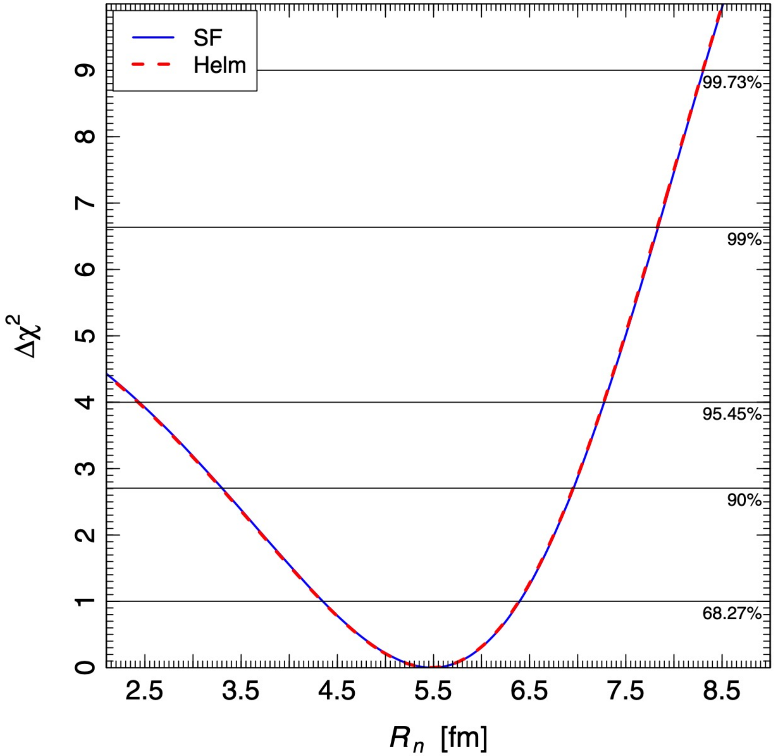
- $2 \cdot 10^6$ evts in 3 years (2000+/day)
- Stat unc. < 1% in [2.5, 6] MeV
- Fast n bkg < 200 evts/day; $^8He+^9Li$ bkg ~54 evts/day





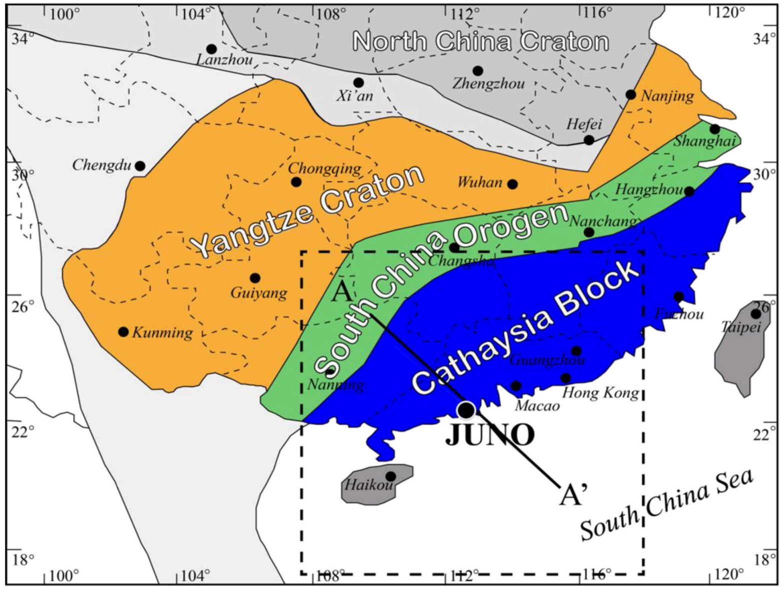
Neutrino as Probes: Nuclear and Earth Sciences

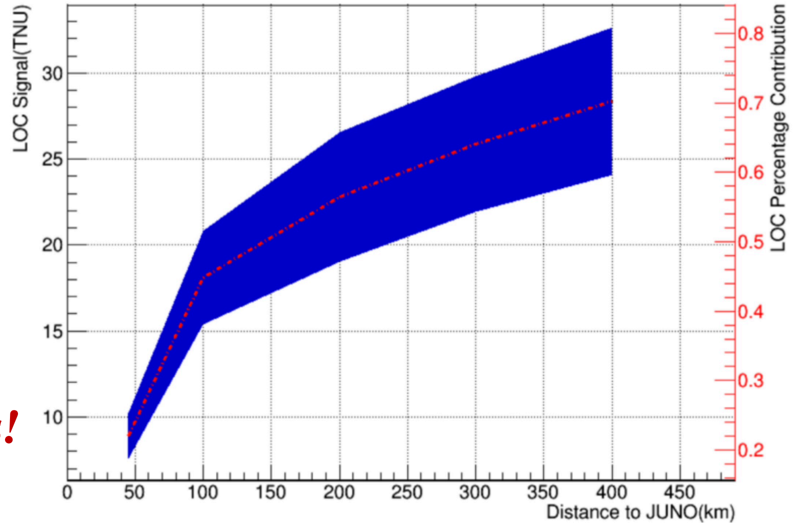
Cadeddu & Y.F. Li et al, PRL120, 072501 (2018)



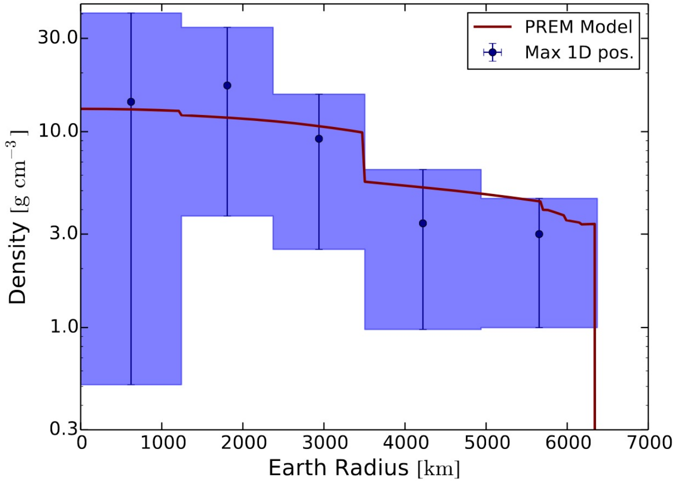
$$R_n = 5.5^{+0.9}_{-1.1}\ \text{fm}.$$

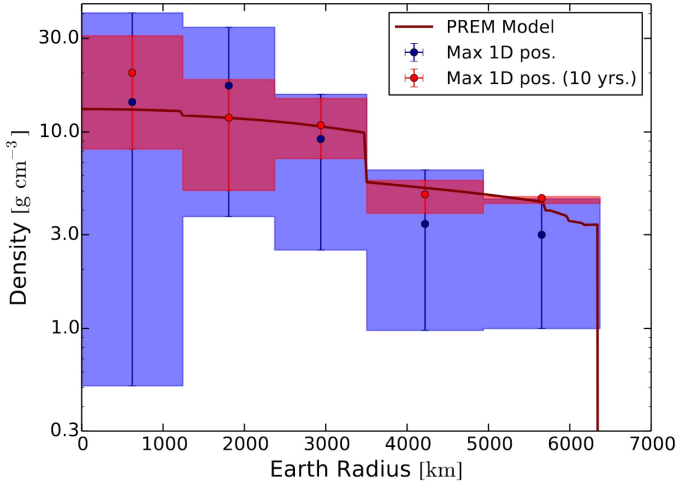
First time measuring neutron radius!





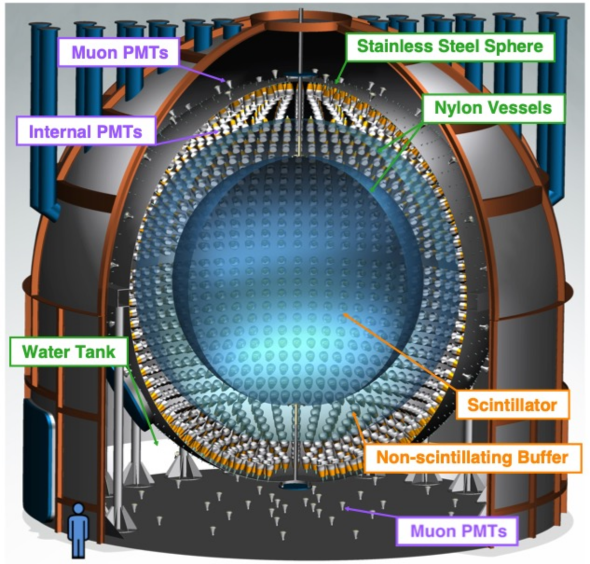
A. Donini et al, Neutrino tomography of Earth, Nature Physics 2018

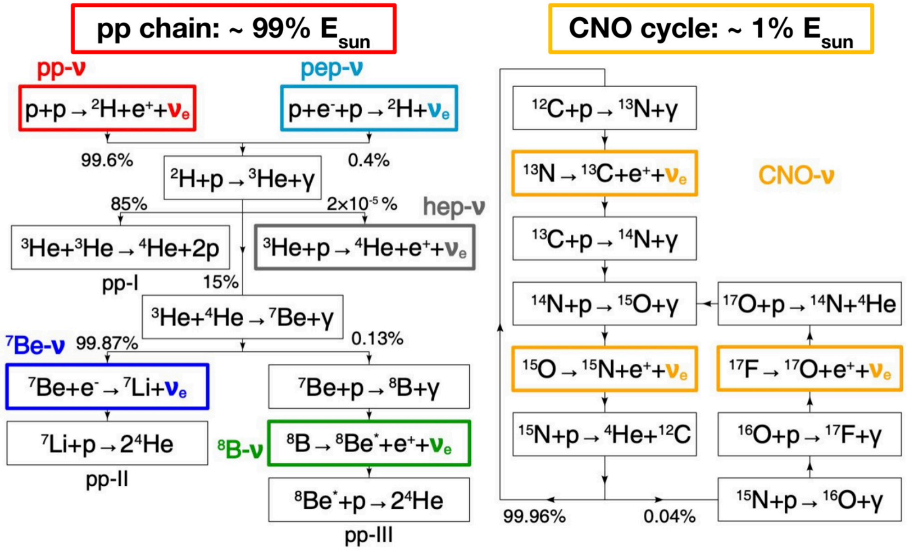


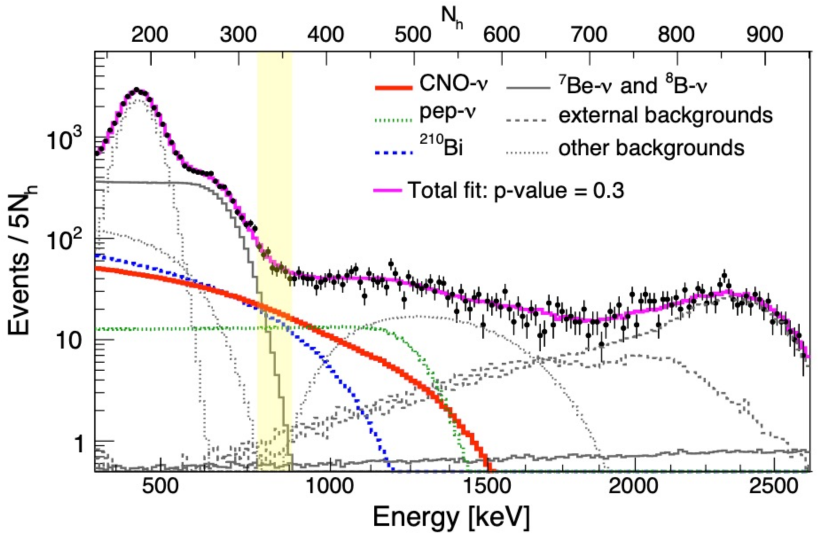


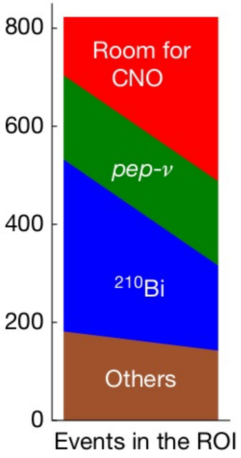
Frontiers at Solar Neutrino

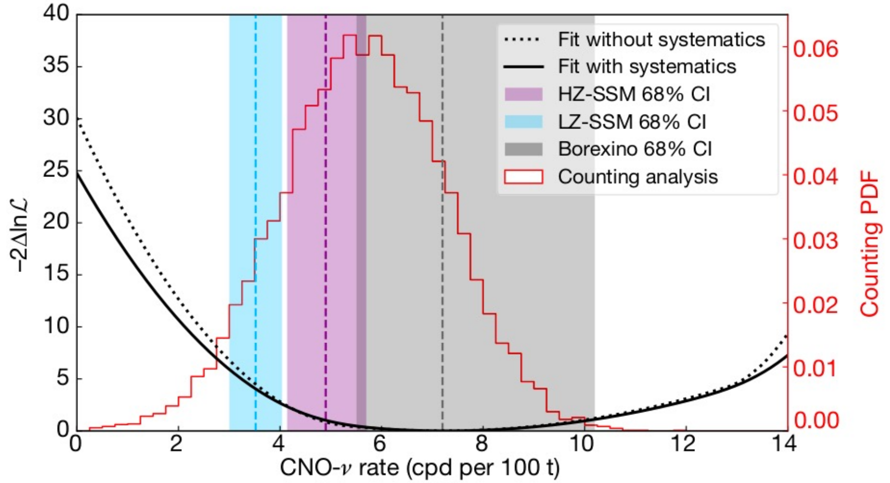
- BOREXINO finally measured CNO!
- Still background challenged due to single hit signals







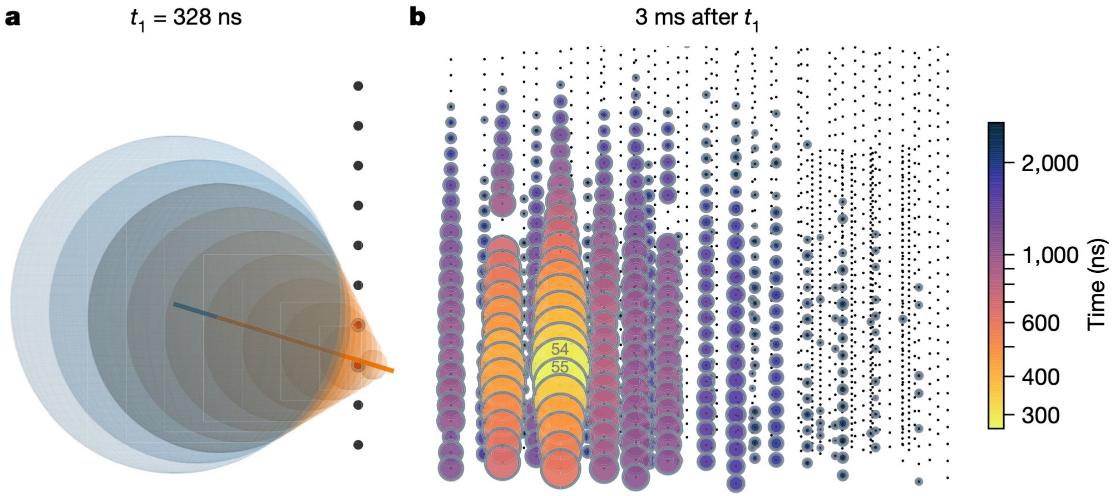


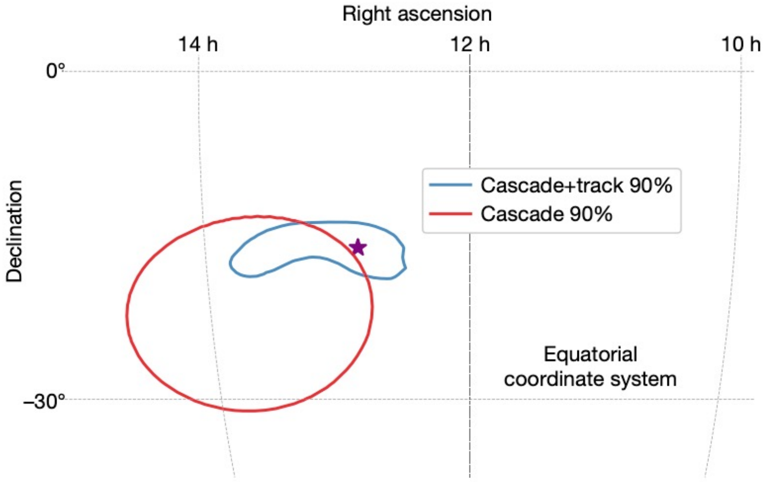


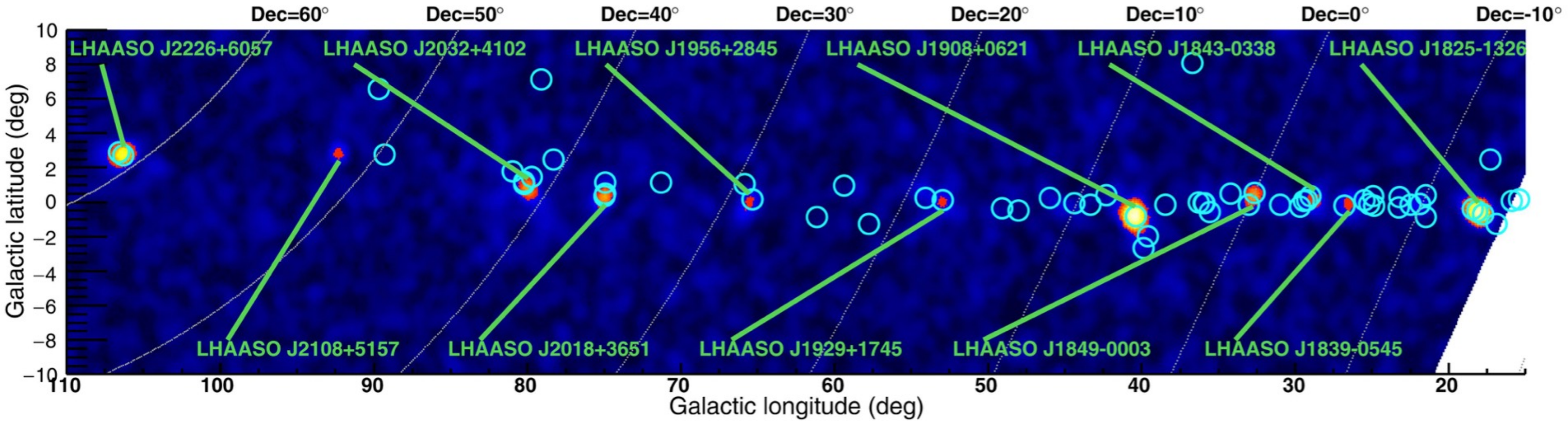
Frontiers at Neutrino Telescope(s)

- Multi-messenger astronomy era has started
- Both IceCube and LHAASO have discovered PeV events

➢ Together with GW observatories, we are definitely on our way to observe coincidences!



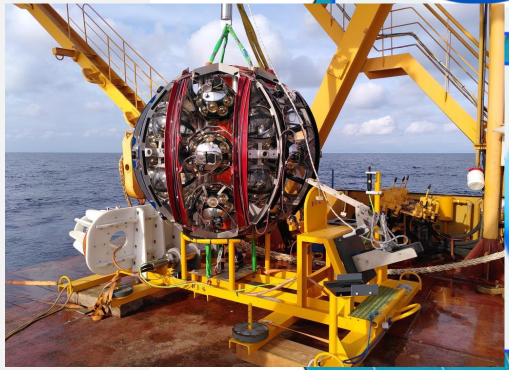




Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

Ice/water Cherenkov neutrino telescopes - global view

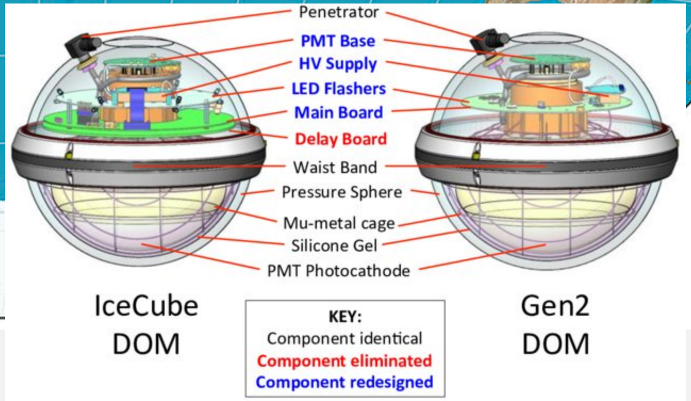
ANTARES
Deep water
0.01 km^3
2008 – 2019



KM3NeT
Deep water
1 + 0.006 km^3
Construction

Baikal/GVD
Deep water
~1 km^3
Construction

IceCube	IceCube-Gen2
Deep ice	Deep ice
1 km^3	~10 km^3
2011 –	Projected, 1st phase imminent



中国未来什么规划？

Summary and Future Perspectives

- ❖Neutrino physics has provided the first new physics beyond the SM and it is now entering the precision phase → **we might get disappointed; but we need to complete it** --- hopefully, oscillation parameters by 2035; Majorana nature quite uncertain
- ❖Encouraged by the Daya Bay success, Chinese HEP projects are attracting more resources, in both funds and manpower; **but far from enough**
- ❖**Technologies are always essential for making progresses in science**; Science always gives technologies more values and, often, leads the developments of technologies; Applications and fundamental science drive new technologies in synergy
- ❖***While collaborating with international partners, we need to build up a larger & better HEP community in all aspects in China***

一校、三城、五校园

物理学院（广州校区）
物天学院（珠海校区）
中法核工程与技术学院（珠海校区）
理学院（深圳校区）

中法核工程与技术学院简介
A Brief Introduction to IFCEN

- 2009年：中山大学与法国格勒诺布尔理工大学为首的民用核能工程师教学联盟（FINUCI)合作成立中山大学中法核工程与技术学院
- 2010年：第一届学生入学
- 2015年：中山大学与-FINUCI签订第二期合作
- 2019年：国家级一流本科专业建设点（双万计划）
- 2021年：基于过去10年经验进行第三期合作讨论

Grenoble INP　cea　instn　Chimie ParisTech　ECOLE DES MINES DE NANTES　enscm CHIMIE Montpellier

学院学科布局、科研领域及团队
Disciplines, Research Fields and Research Teams

核燃料循环与材料
Nuclear Fuel Cycle & Materials

- 核工程材料与力学
- 核化学与放射化学

核能科学与工程
Nuclear Energy Science & Engineering

- 核仿真与安全
- 反应堆热工水力
- 先进核能系统

核物理
Nuclear Physics

中低能核物理、天体物理、核数据

核科学与技术
Nuclear Science & Technology

粒子物理与核物理
Particle & Nuclear Physics

- 核环境辐射监测与应急
- 辐射防护与安全

辐射防护与环境保护
Radiation & Environmental Protection

- 核探测与探测器
- 核技术及应用

核技术及应用
Nuclear Technology & Applications

粒子物理、新型探测器、中微子应用

粒子物理
Particle Physics

中国“核能之父”卢鹤绂与中山大学

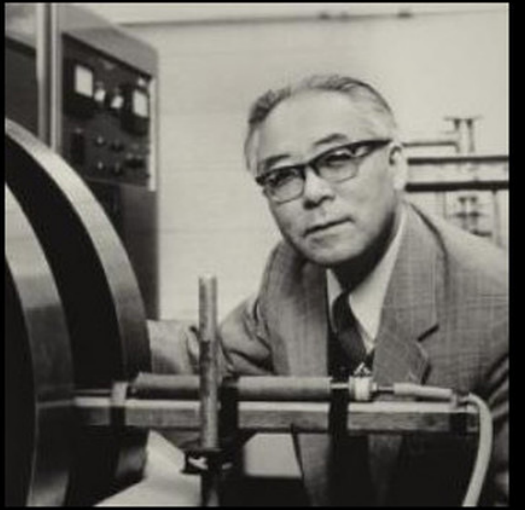
卢鹤绂院士

中国“核能之父”

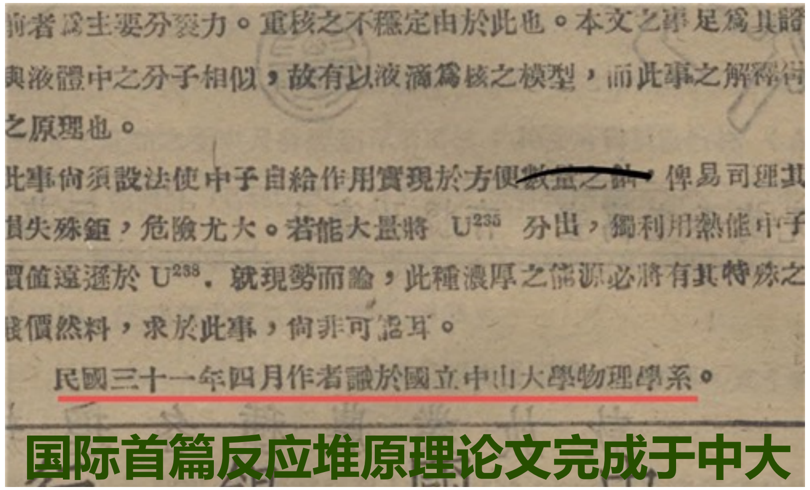
Hoff Lu

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，随即归国来中山大学任教
- 1942年于中山大学撰写《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


者為主要分裂力。重核之不穩定由於此也。本文之罪足爲其
與液體中之分子相似，故有以液滴爲核之模型，而此事之解
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前，俾易司理其
損失殊鉅，危險尤大。若能大量將 U^{235} 分出，獨利用熱能中子
價値遠遜於 U^{238}. 就現勢而論，此種濃厚之能源必將有其特殊之
廉價燃料，求於此事，尚非可諾耳。

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

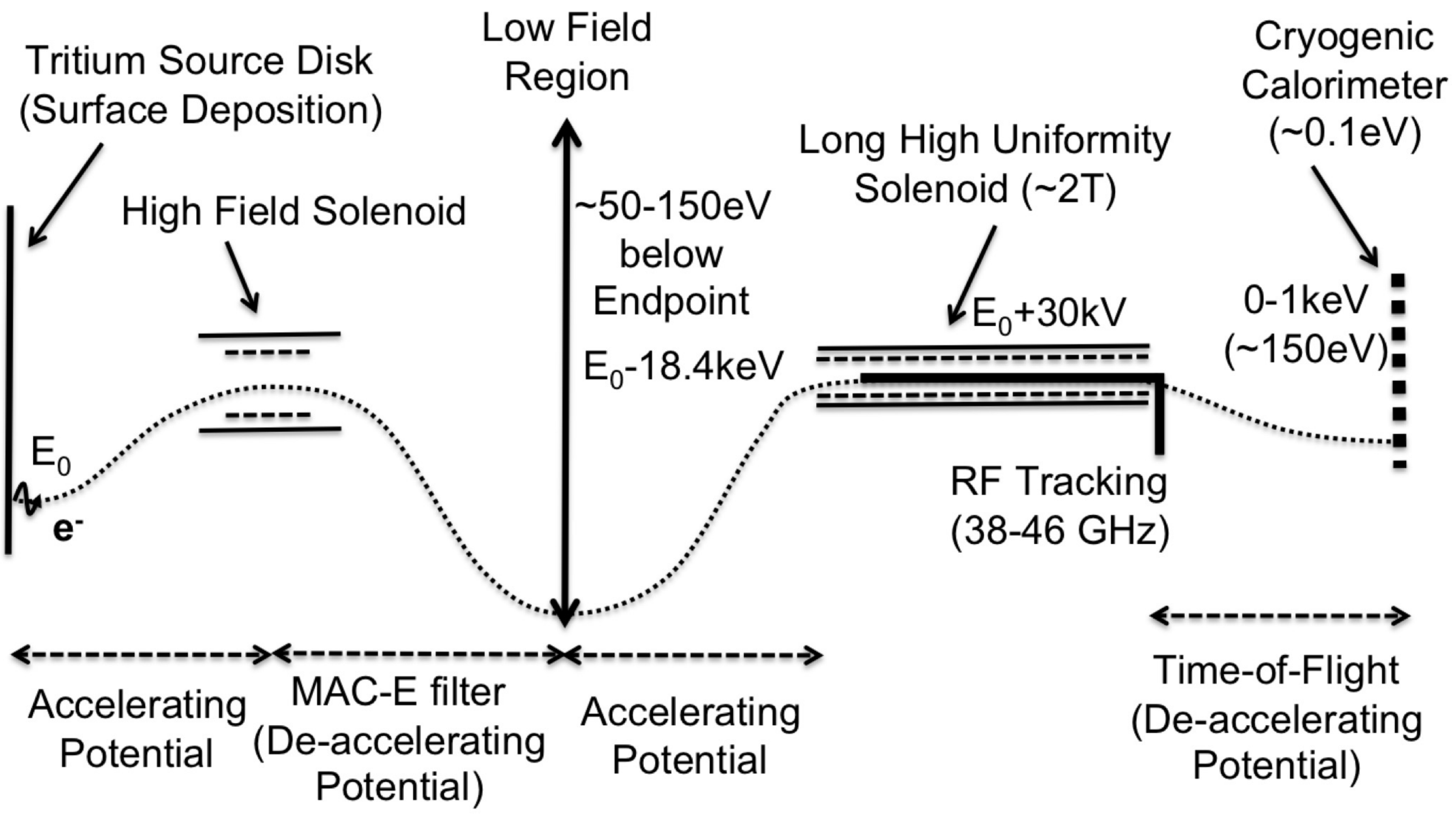
一九九八年八月三十日，在已安放了美国前总统布什雕像的休斯顿第一浸信会教会学院中，隆重举行卢鹤绂科学实验室建立和雕像安放的揭幕仪式，美国科学界及有关方面两千多位来宾参加了盛会。在会上，卢鹤绂的胞弟，曾任格鲁曼飞机制造公司总工程师的卢鹤坤先生代表家属上台致谢词时，全场起立，报以经久不息的掌

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，他为科学研究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

素表，并迄今为世人沿用。他发明了卢鹤绂不可逆性方程。因而他的成就被英国剑桥国际传记中心授予二十世纪成就奖，载入英国剑桥传记中心国际传记辞典，美国传记研究院授予国际承认奖，载入美国传记研究院 《世界五千人物》，并载入美国传记研究院 《五百权威领导人》。

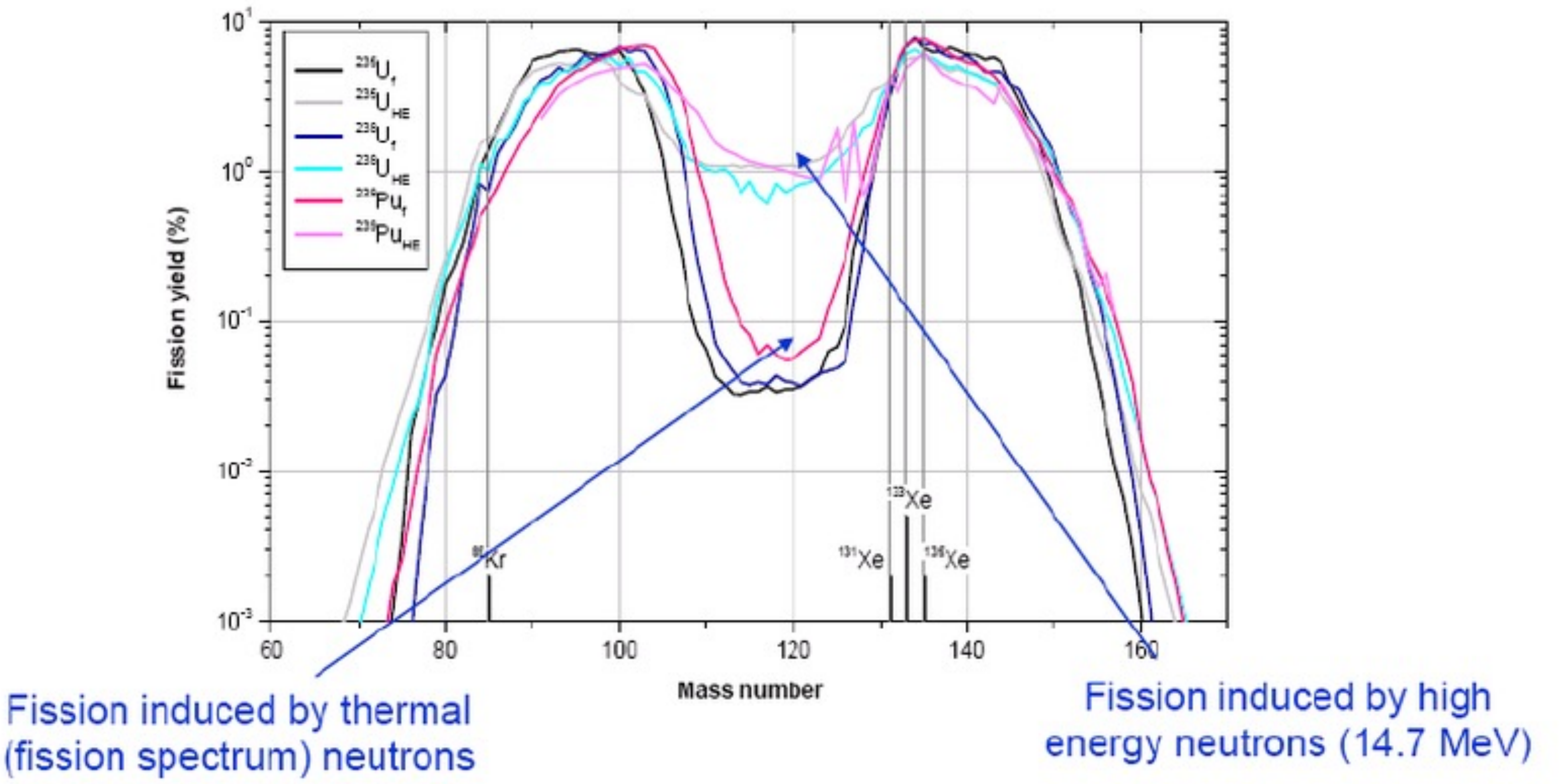
A Very Daring Approach: PTOLEMY



PTOLEMY Collaboration, arxiv/1307.4738

The Complication inside Nuclear Reactors

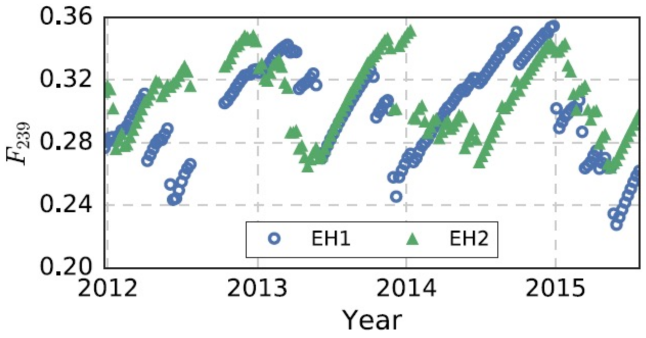
(Fission yield is a function of the fissioning nuclide and the incident neutron energy)

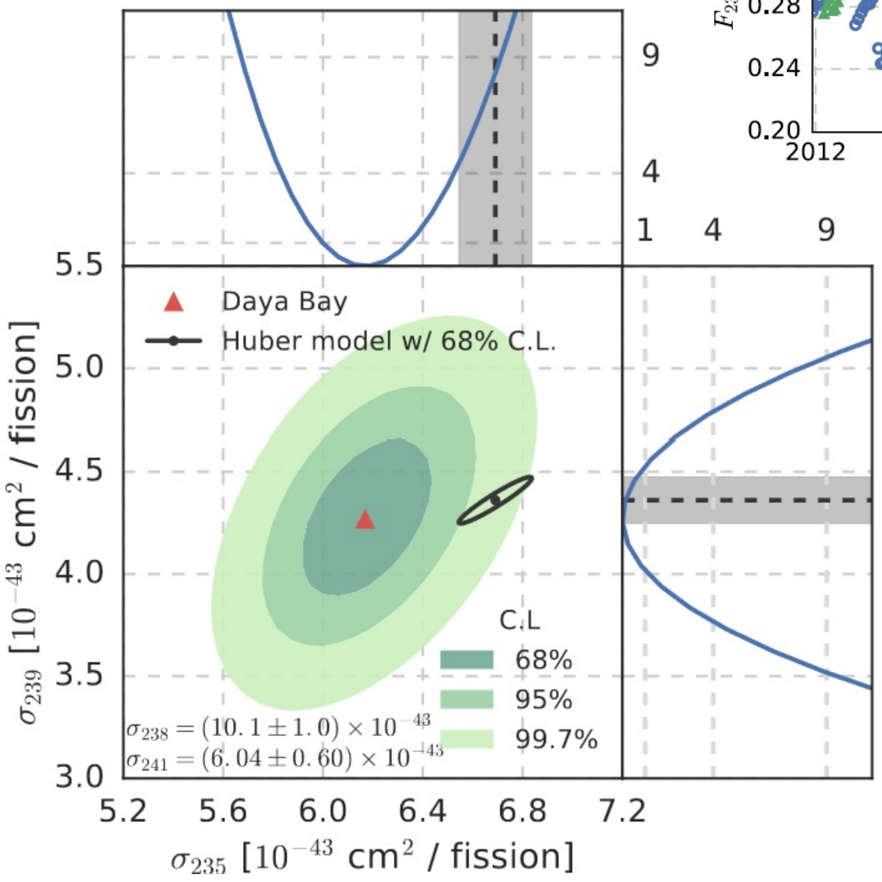


- Asymmetrical fission products: "*One of the most interesting and intriguing problems regarding nuclear physics is the fission of heavy elements into asymmetrical daughter products*"
- Depending on the neutron spectra

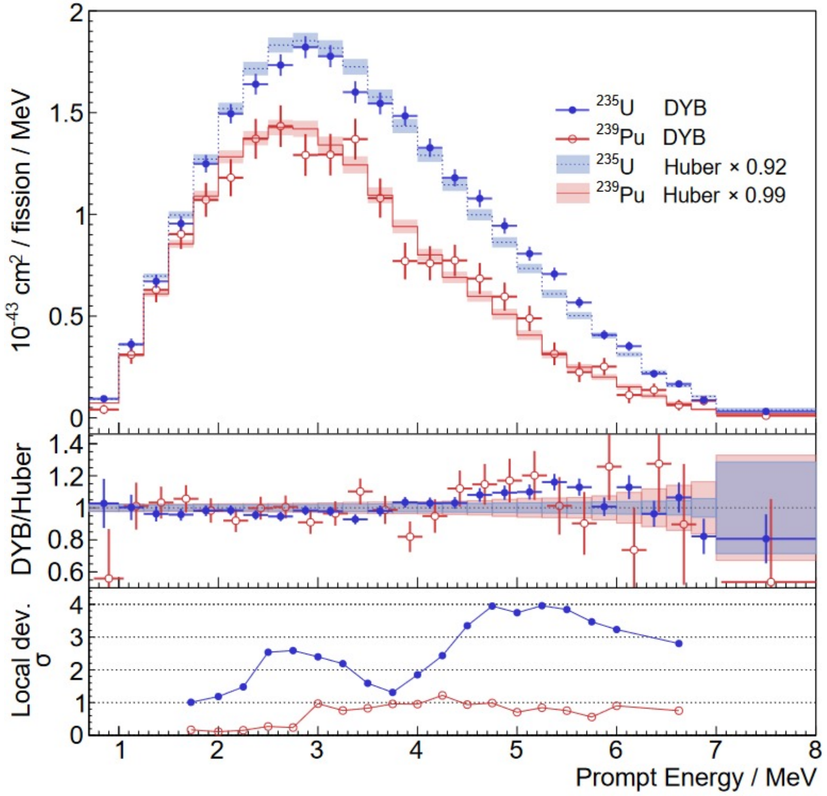
Understanding Reactor Antineutrinos

- ***Fuel evolution: Phys.Rev.Lett. 118 (2017) no.25, 251801***





- **Isotope decomposition**, *PRL 123 (2019) no.11, 111801*



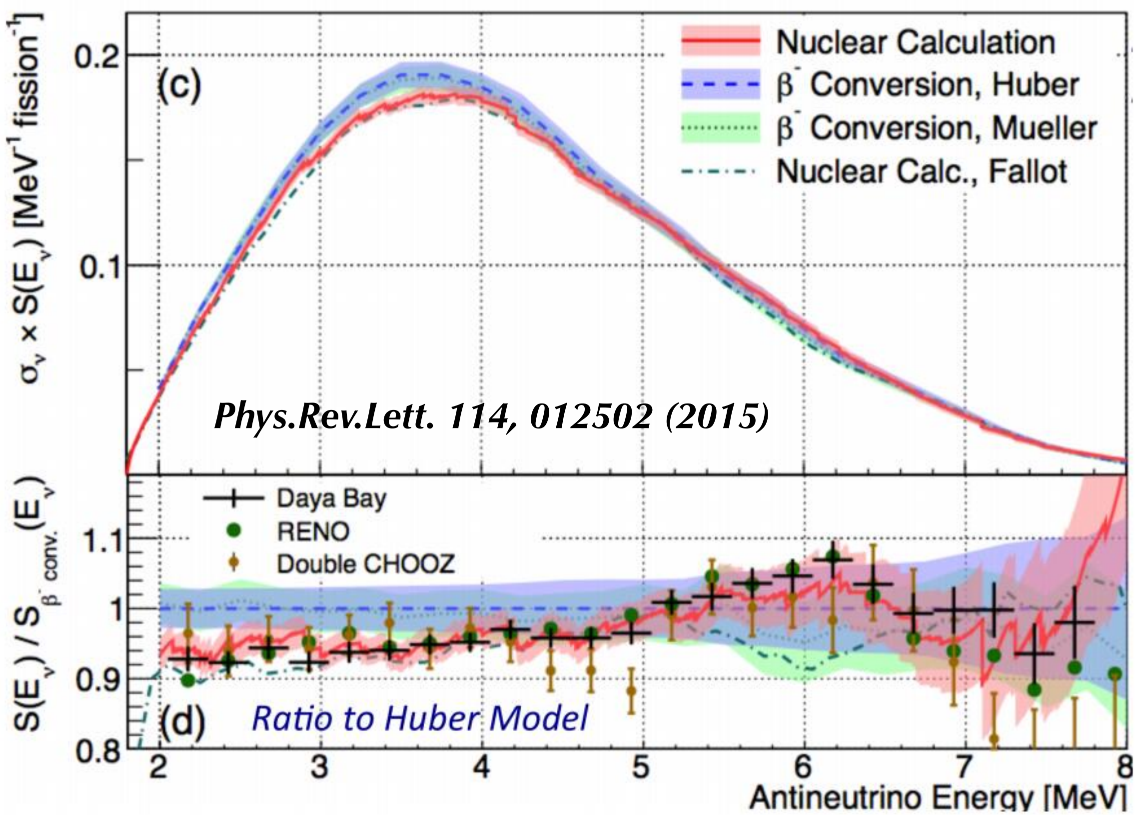
^{235}U: 4-sigma effect

^{235}Pu: 1.2-sigma effect

The "*ab initio*" (summation) Method

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\bar{\nu}})$$

f_{ij} — the branching fraction from isotope i decaying to the energy level j of daughter isotope



R_i — the equilibrium decay rate of isotope i

$$R_i \cong \sum_{p=0}^{P} R_p^f Y_{pi}^c$$

- ✓ R_p^f — the fission rate of the parent *isotope* p
- ✓ Y_{pi}^c — the cumulative yield of isotope i

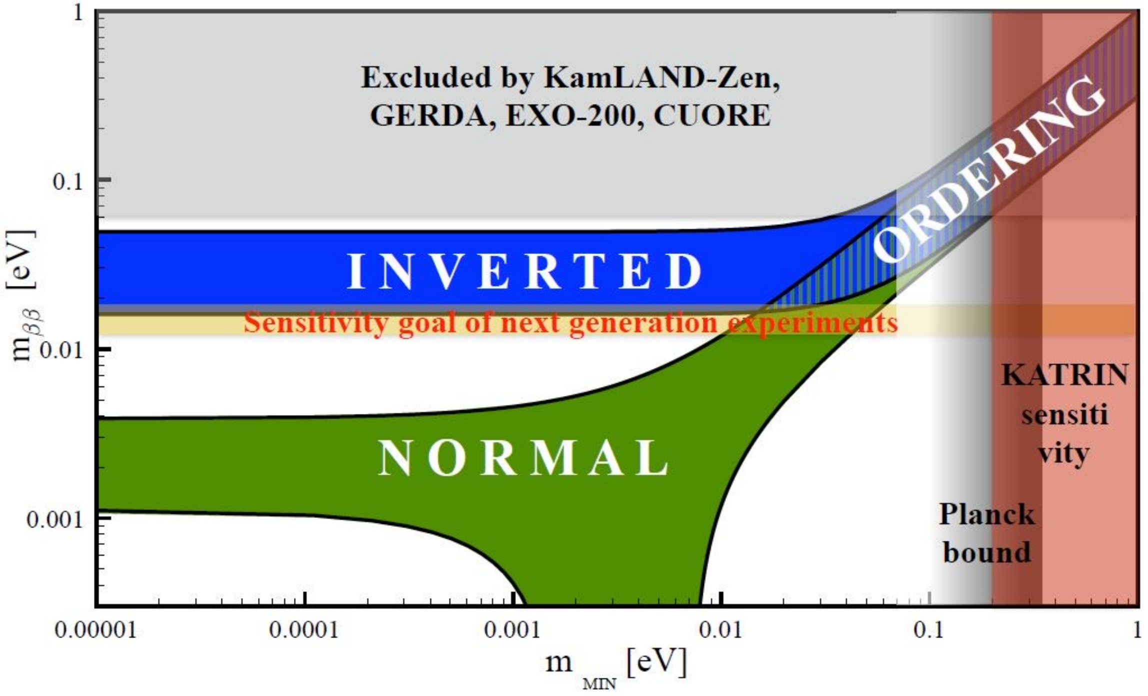
The 5 MeV bump was predicted with **a large uncertainty** from summation calculation.

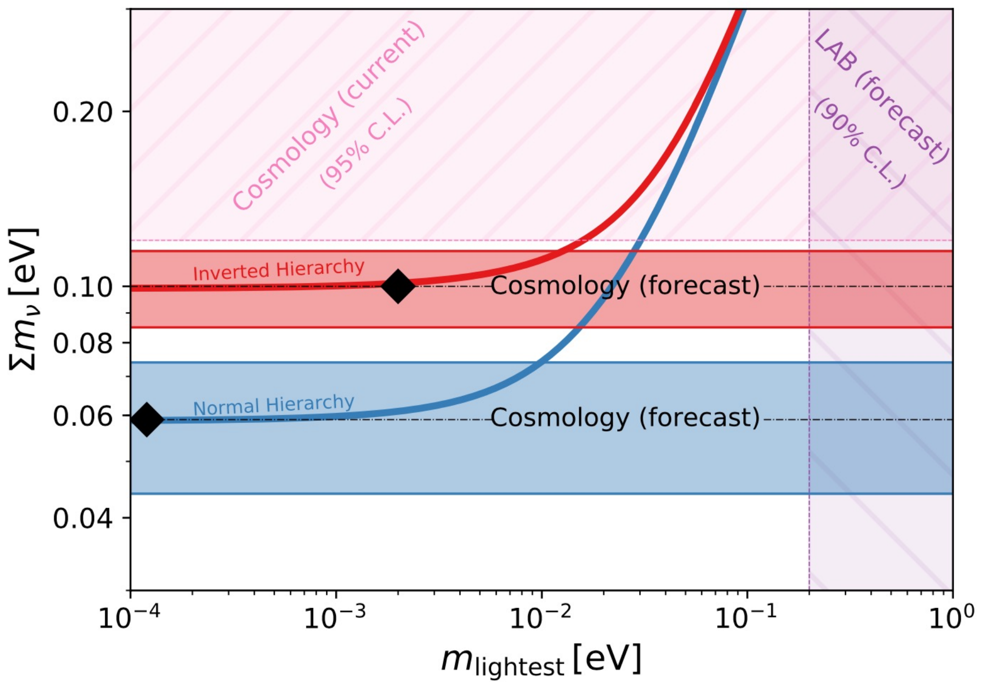
Additionally, the **saw-tooth structures** were also predicted in the summation spectrum.

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, NOνA, T2HKK, DUNE	Beam ν_μ + JUNO		
Reactor ν_e		JUNO, JUNO + Atm/Beam ν_μ		
Supernova Burst ν			Super-K, Hyper-K, IceCube PINGU, ORCA, DUNE, JUNO	
Interplay of Measurements				Cosmo. Data, KATRIN, Proj-8, 0νββ

Cosmological Bound on Neutrino Mass: A Synergy

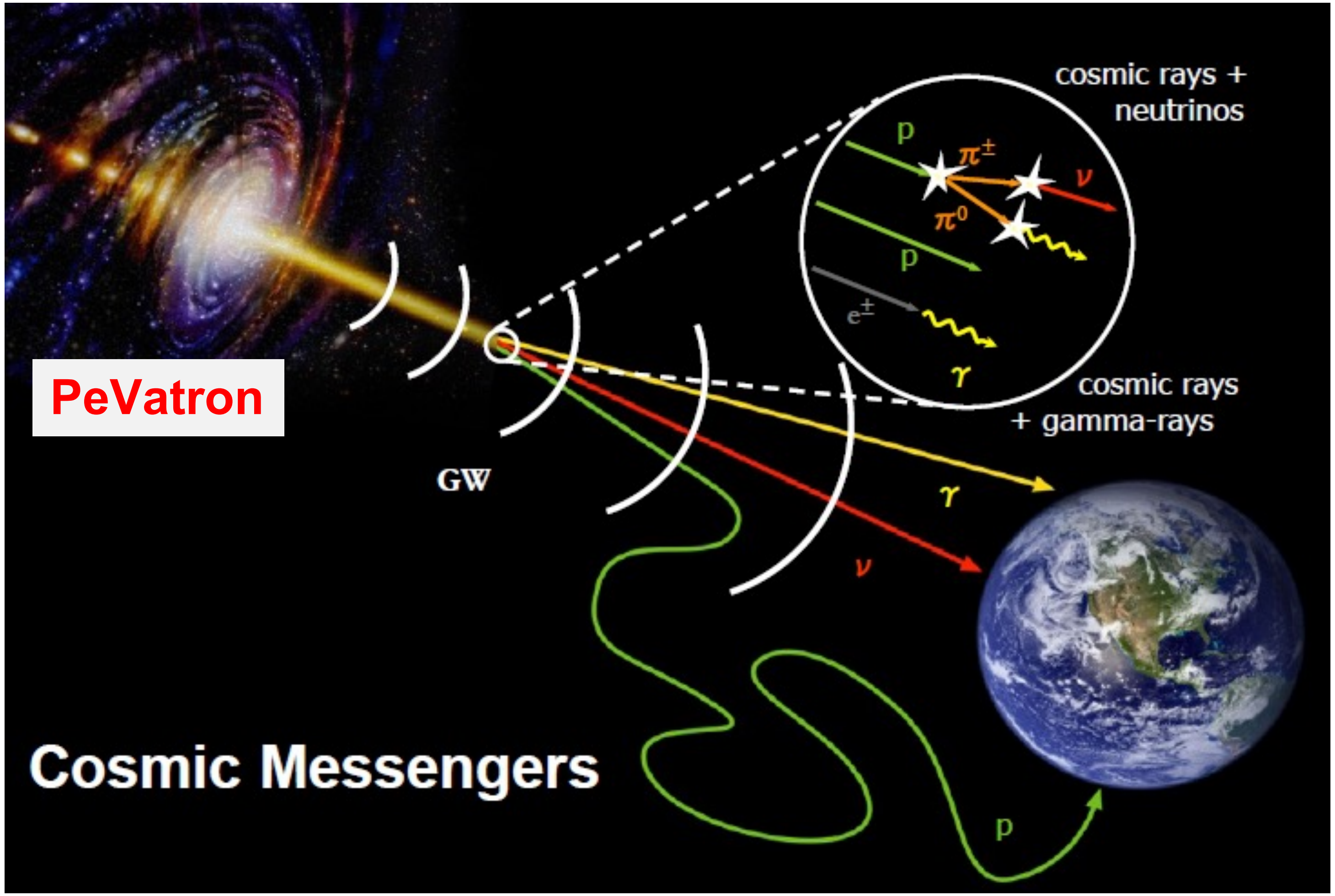




Ref: APPEC Committee, Double Beta Decay APPEC Committee Report

Astro2020 Science White Paper C. Dvorkin et al, Neutrino Mass from Cosmology: Probing Physics Beyond the Standard Model

Frontiers at Comic Neutrinos



- For a Hadronic PeVatron:
  - ❖ $N_\gamma \sim N_\nu$
  - ❖ $E_\gamma \sim E_\nu$
- UHE (>0.1 PeV) neutrinos are expected
- The last nail on coffin!

  --- The origin of galactic CRs

Mingjun Chen's courtesy