

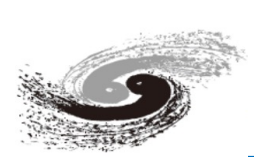
中微子实验研究进展

贾怡, 高能物理研究所
(代表JUNO合作组)



2026-7-15

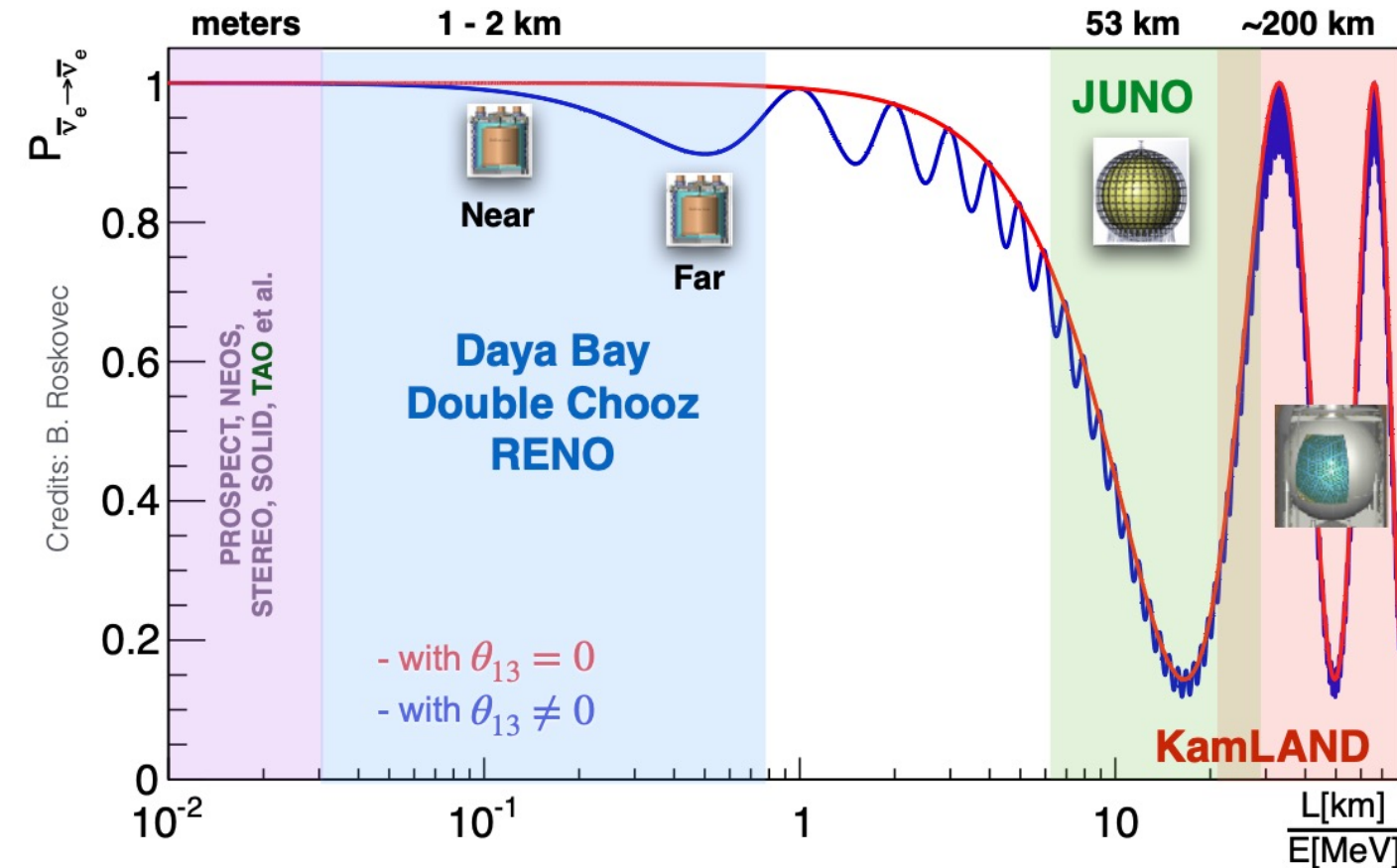
中国物理学会高能物理分会年会, 广州



Reactor Antineutrino Oscillations



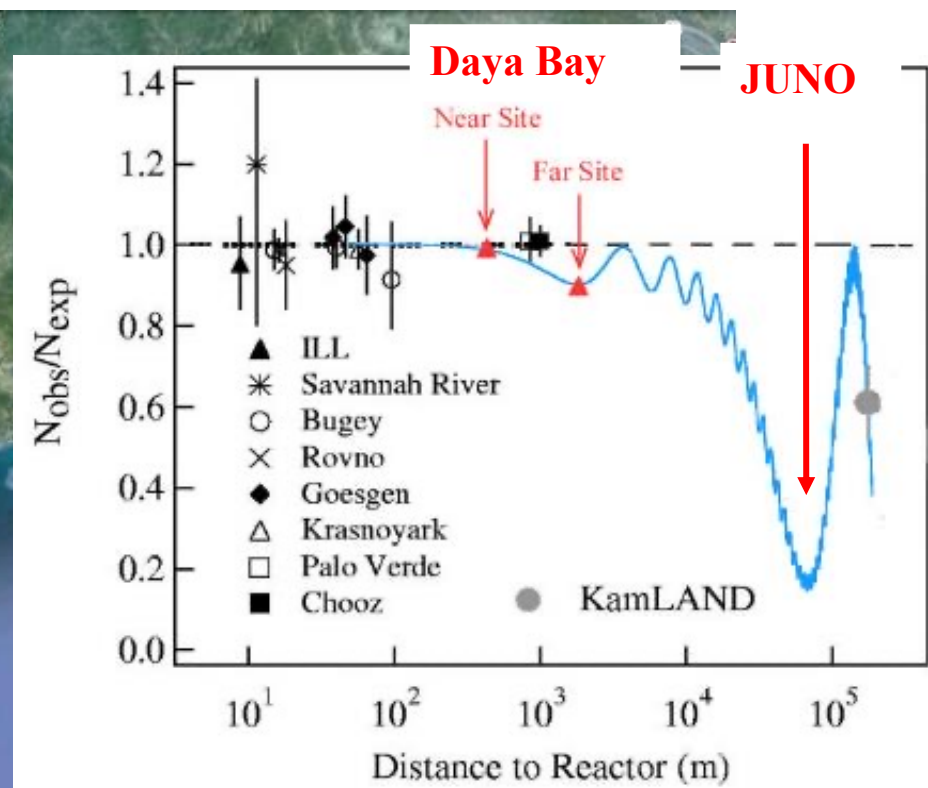
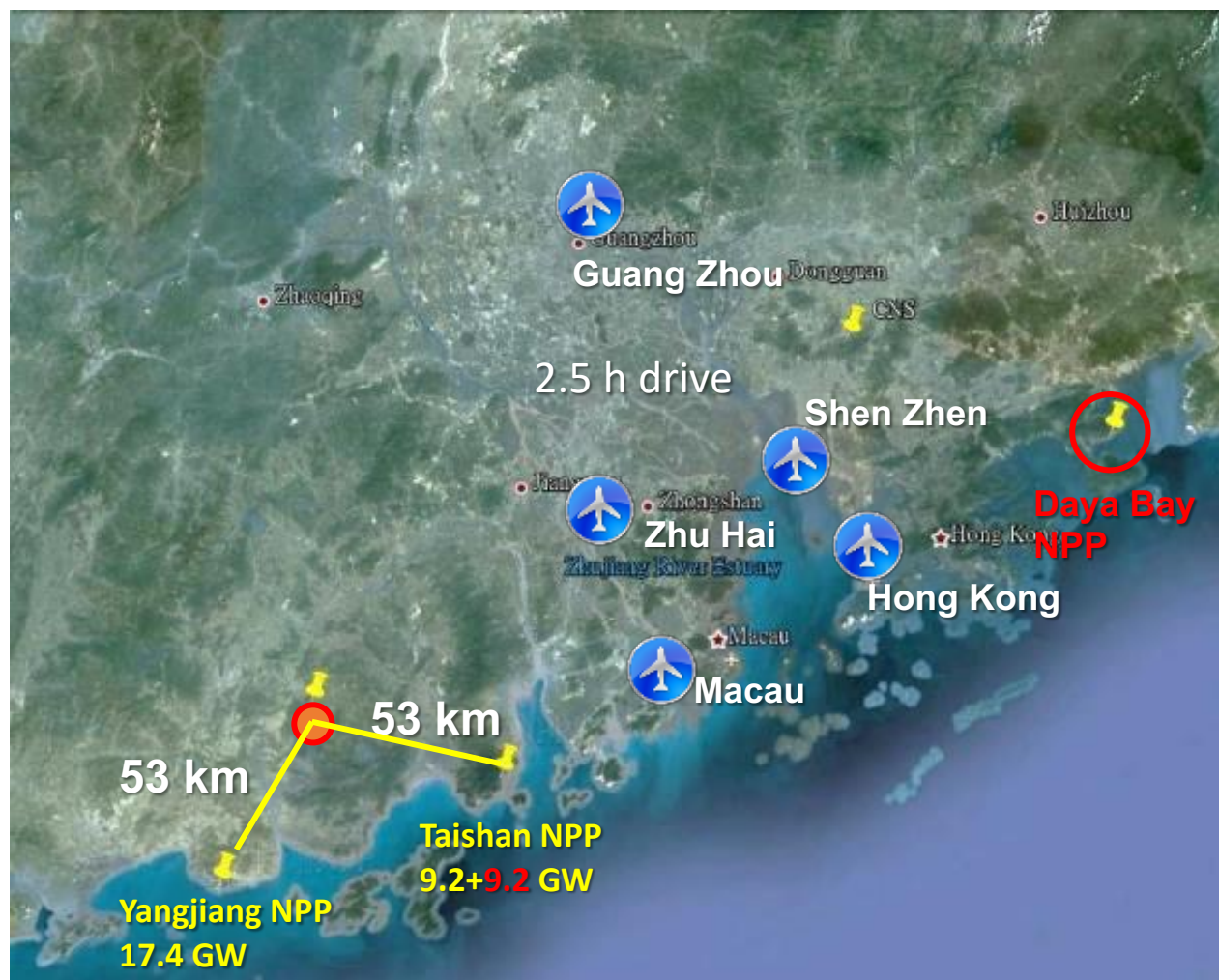
◆ 反应堆中微子是精密测量中微子振荡的一个重要研究途径



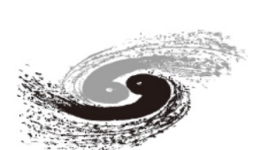
- 测量电子反中微子 $\bar{\nu}_e$ 如何振荡为其他味的中微子
- 可以测量 θ_{12} , θ_{13} , Δm_{21}^2 , Δm_{31}^2 并研究中微子质量顺序
- 测量结果不依赖于 θ_{23} 和 CP 破坏相位 δ_{CP}
- 实验基线长度由物理目标决定

Jiangmen Underground Neutrino Observatory

- ◆ 利用反应堆中微子确定中微子质量顺序 (Δm^2_{32} 的符号)。不依赖于物质效应和 CP 相位 δ
- ◆ 探测器与两座核电站的距离近似相等，从而获得两座核电站的中微子通量，提高总事例率



Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen,
PRD78:111103,2008; PRD79:073007,2009



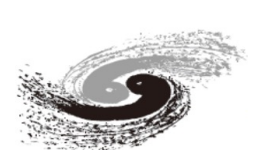
JUNO Project and the Collaboration



- ◆ JUNO 项目在 2013 年首先在中国获批，之后国际合作逐渐形成。土建从 2015 年开始。现在 JUNO 是一个大型国际合作组，有来自 16 个国家和地区、70 个机构的 700 多位合作者。

Country	Institute	Country	Institute	Country	Institute
Armenia	YerPhI	China	SDU	Italy	INFN-CT
Belgium	ULB	China	SJTU	Italy	INFN-FE
Chile	SAPHIR	China	SUSTech	Italy	INFN-LNF
Chile	UNAB	China	SYSU	Italy	INFN-MI
China	BISEE	China	THU	Italy	INFN-MIB
China	CDUT	China	UCAS	Italy	INFN-PD
China	CNPRI	China	WHU	Italy	INFN-PG
China	CUGB	China	WuYiU	Italy	INFN-Roma3
China	DGUT	China	XJTU	Pakistan	PINSTECH (PAEC)
China	ECUT	China	XMU	Russia	JINR
China	GXU	China	ZZU	Slovakia	FMFI-UK
China	HIT	Czech	Charles U.	Taiwan-China	NCTU
China	HunanU	Finland	JyU	Taiwan-China	NKNU
China	IGGCAS	France	CPPM	Taiwan-China	NTU
China	IHEG-CAGS	France	IJCLab	Taiwan-China	NTUT
China	IHEP	France	IPHC	Thailand	CHULA
China	IMP	France	LP2iB	Thailand	NARIT
China	JNU	France	Subatech	Thailand	SUT
China	JXNU	Germany	EKUT	U.K.	U. Liverpool
China	KNRC	Germany	GSI	U.K.	U. Warwick
China	Nankai U.	Germany	U. Hamburg	USA	UC-Irvine
China	NCEPU	Germany	JGUMainz	USA	UMD-G
China	NJU	Germany	RWTH-AC		
China	RNCG	Germany	TUM		

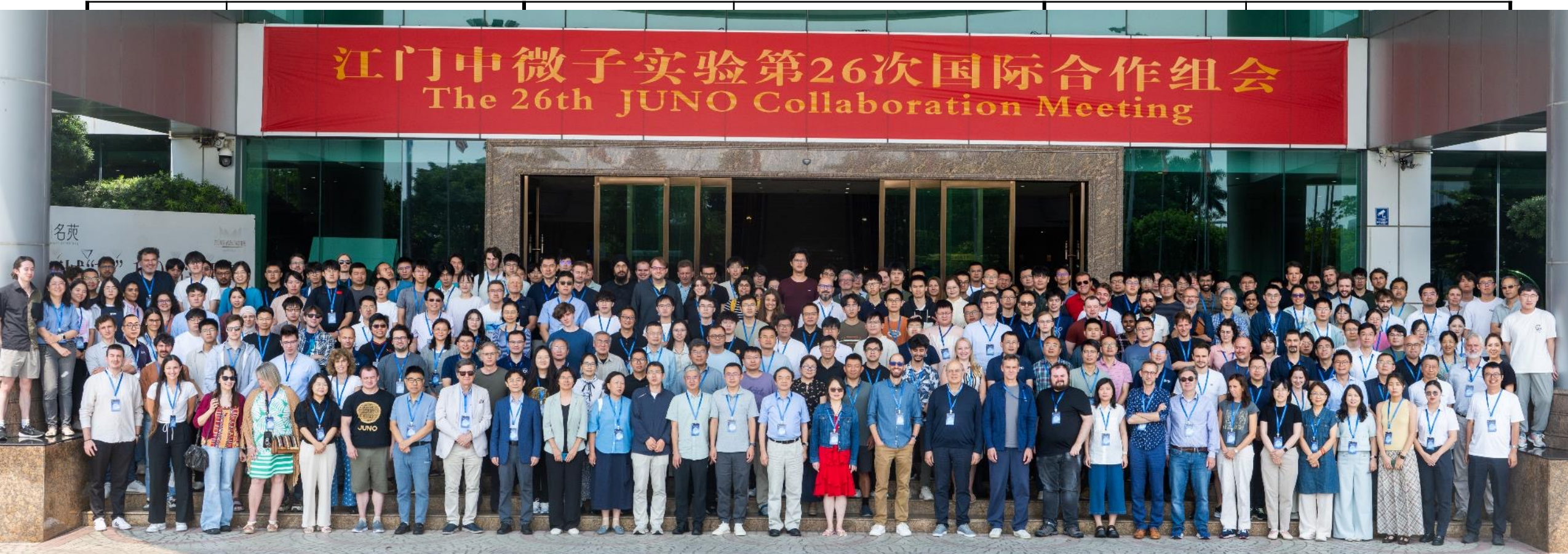
+Observers: USTC, Peking Uni., Jilin Uni., Beijing Normal Uni., CIAE (China), PUC, UEL (Brazil)



JUNO Project and the Collaboration

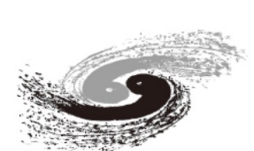


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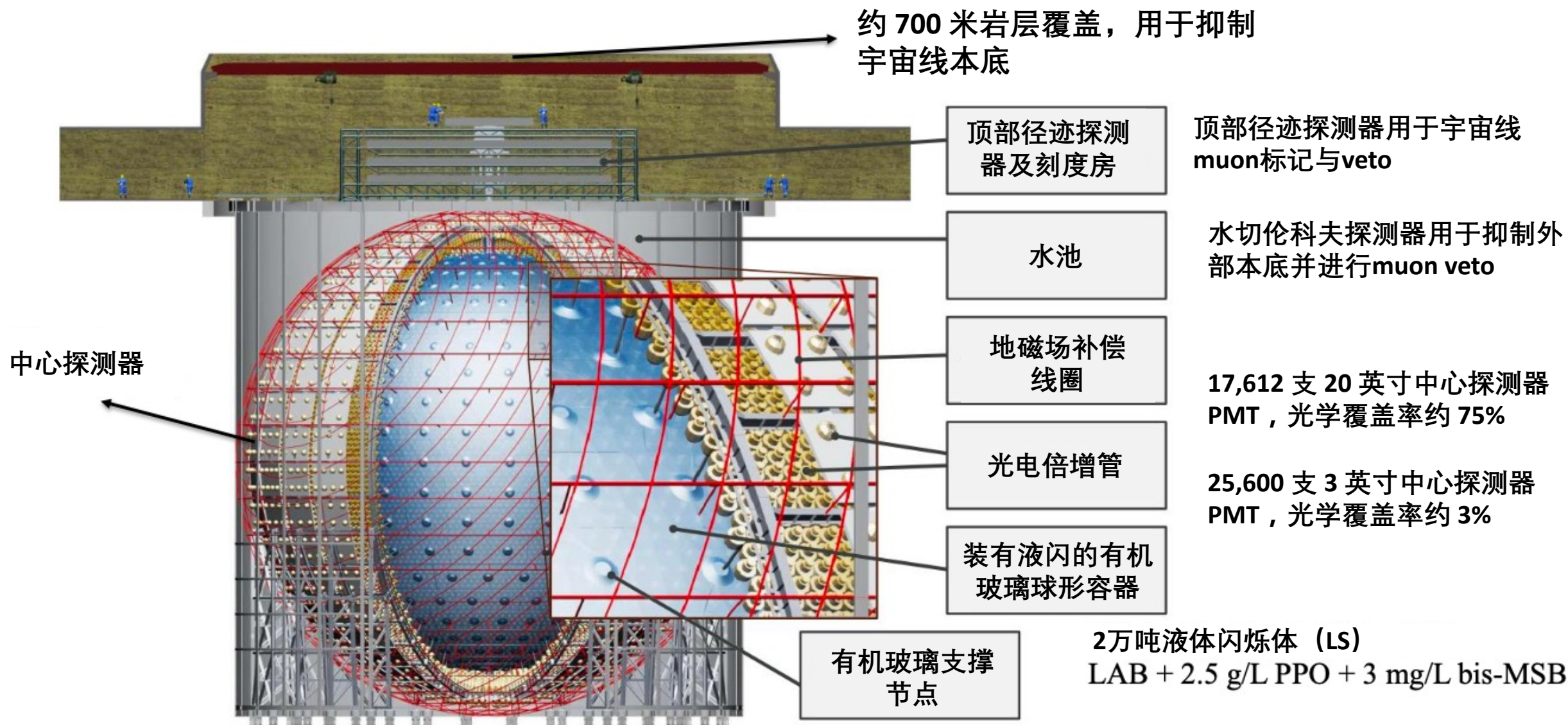


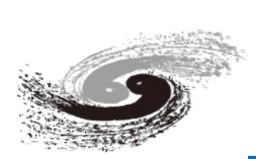
China	Nankai U.	Germany	U. Hamburg	USA	UC-Irvine
China	NCEPU	Germany	JGUMainz	USA	UMD-G
China	NJU	Germany	RWTH-AC		
China	RNCG	Germany	TUM		

+Observers: USTC, Peking Uni., Jilin Uni., Beijing Normal Uni., CIAE (China), PUC, UEL (Brazil)



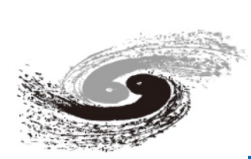
JUNO Detector





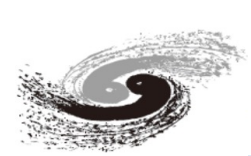
Steel Structure and the Installation Platform





Working for Acrylic on the Platform





JUNO Status in 2024 Summer

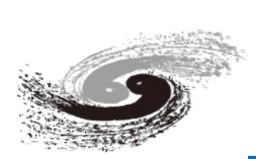


中国物理学会高能物理分会第十四届全国粒子物理学术会议，2024年，青岛

JUNO Detector Installation

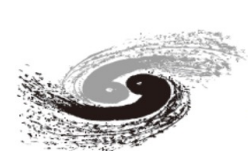


- JUNO construction is close to completion
- PMT and electronics commissioning
- LS purification commissioning
- Detector filling at the end of this year



2024年12月18日开始灌水





2025年2月8日开始灌液闪



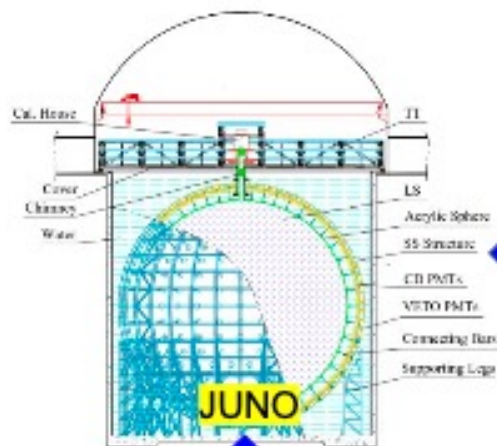
基础溶剂

荧光材料

to guarantee radio-purity and transparency

Recipe: LAB + 2.5g/L PPO + 3 mg/L bis-MSB

NIM.A 908 (2021) 164823

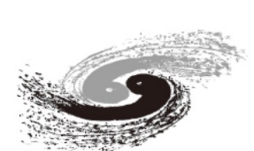


气体剥离去除氢气以及氧气



SS pipes to underground

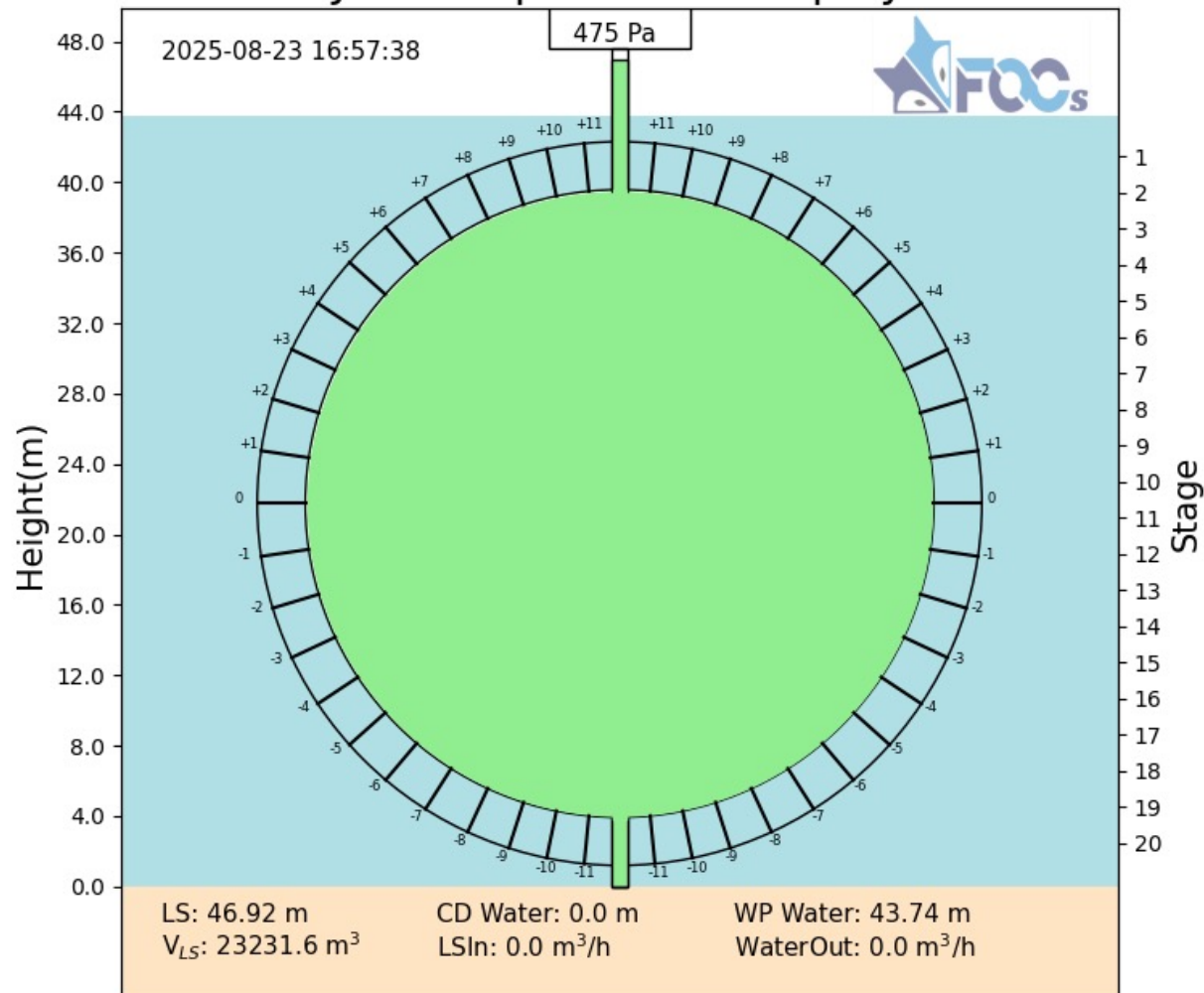
Samples tested by ICP-MS every week for radiopurity, verified by NAA and other methods



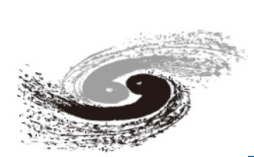
2025年8月26日开始正式取数



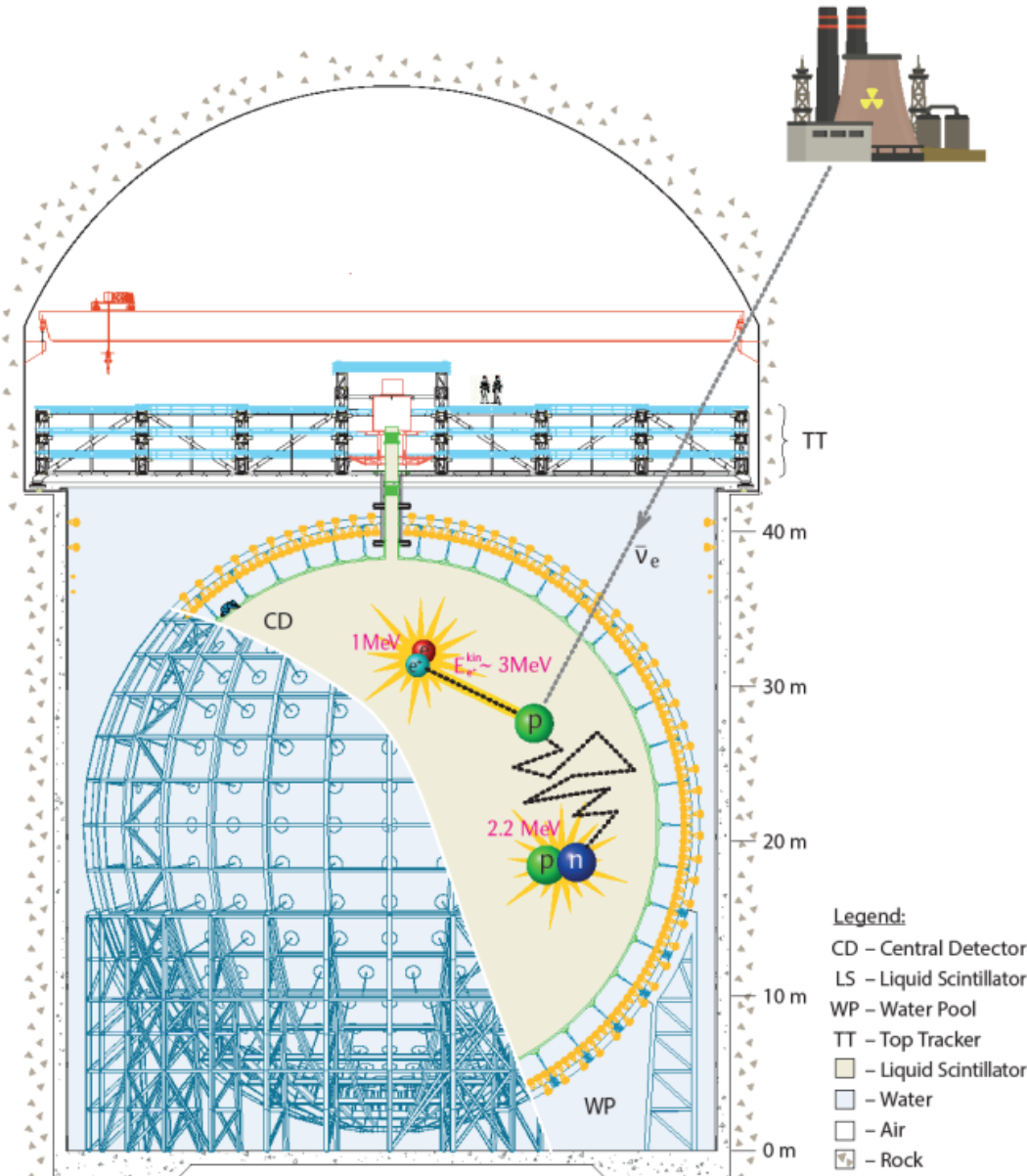
JUNO Liquid Level Display



- On August 22, 2025 at ~22:12, water in Acrylic tank was fully replaced by Liquid Scintillator
- Calibration started at 14:00 of Aug. 23
- Data taking for physics started on Aug. 26 at 5:30 am (Beijing time)
- **Total LS in CD: 23231.6 m^3**
- **Total water in pool: 41225.1 m^3**

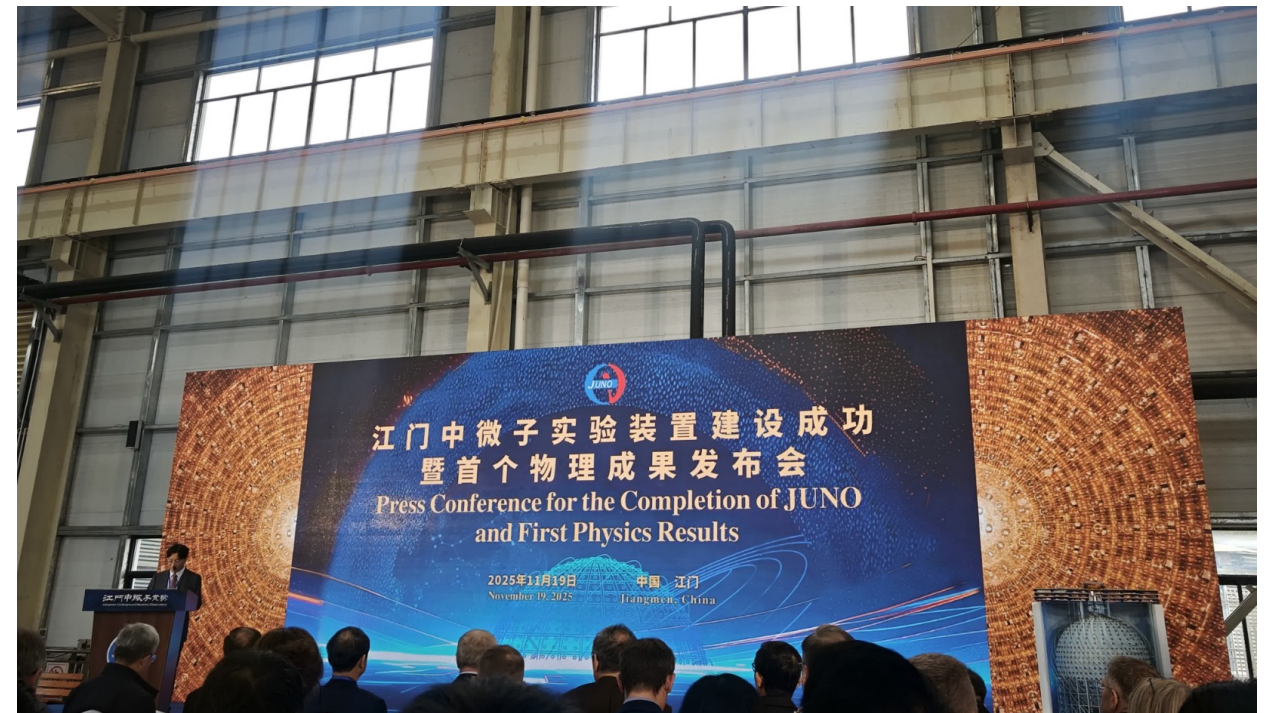


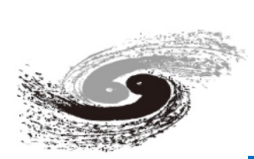
First Results from JUNO



◆ Released on Nov. 19, 2025. “First measurement of reactor neutrino oscillations at JUNO”, [arXiv:2511.14593](https://arxiv.org/abs/2511.14593)

Press Conference in Jiangmen





First Results from JUNO



“Initial Performance of the Detector”
Chinese Phys. C 50, 043001 (2026)

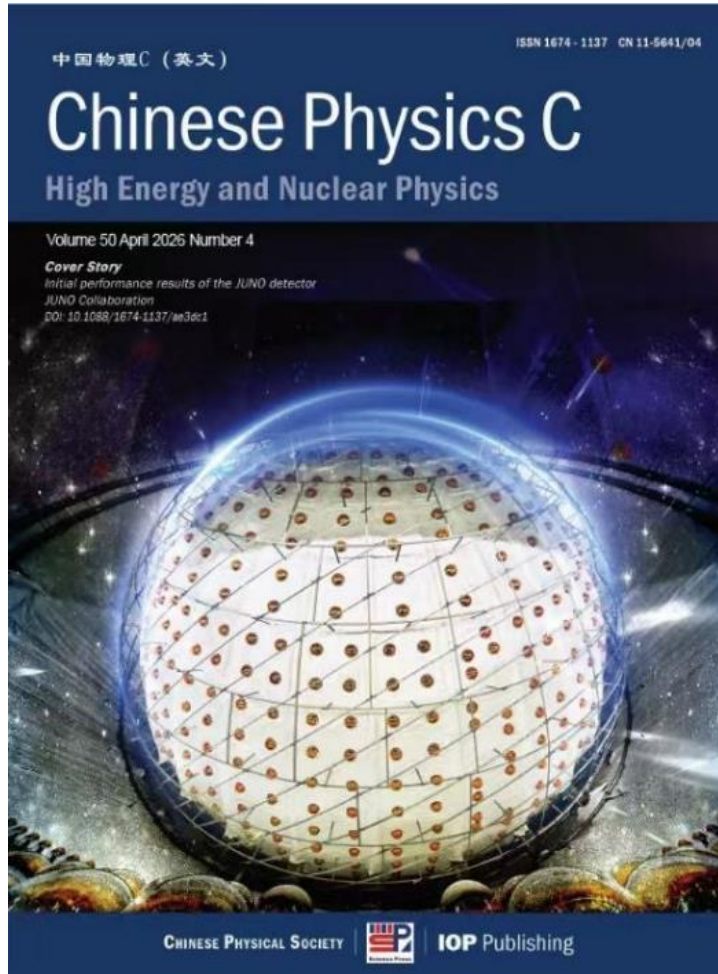
First results using 59 days of data recently published

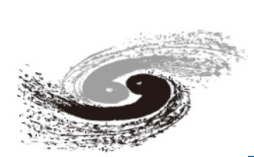
Article | Published: 10 June 2026

Measurement of reactor neutrino oscillation with the first JUNO data

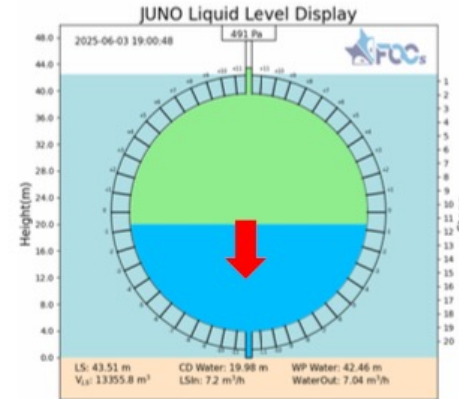
[The JUNO Collaboration](#)

[Nature](#) 654, 343–348 (2026) | [Cite this article](#)





JUNO Timeline



Collaboration
formed

Detector
construction

Start of
LS filling

First Results
announced

2015

2024.12

2025.8.26

2026.6

2014

2022

2025.2

2025.11

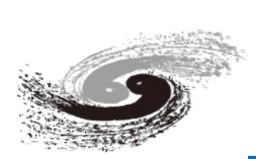
Civil
construction

Start of
water filling

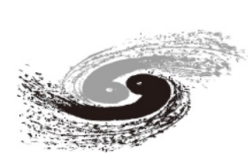
Physics data-
taking start

First Results
published in Nature
**New Results released
in Neutrino 2026!**





Performance of the Detector

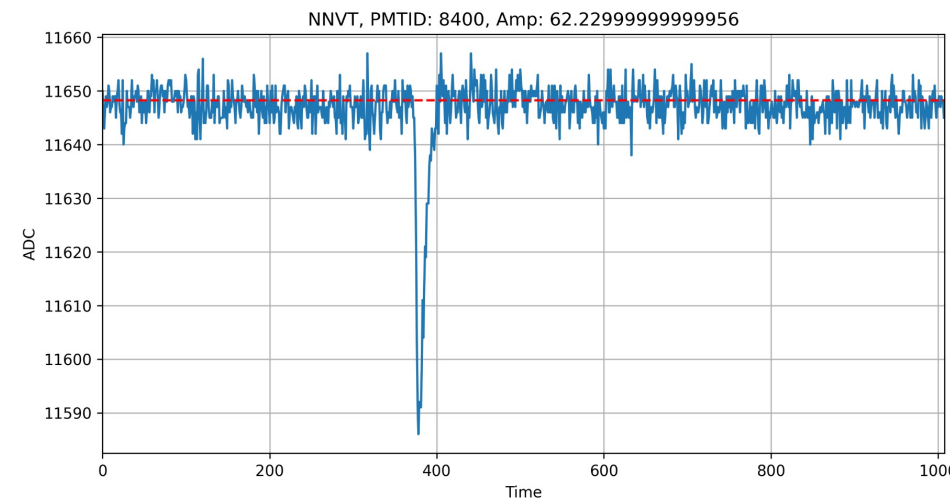


Low-Level Detector Performance



- Large PMTs work fine
 - 17612-16 LPMTs installed for CD, 2400-1 LPMTs installed for VETO
 - ~26 dead PMTs, ~600 flashing PMTs
 - Gains of MCP (Dynode) PMTs are reduced from 7.4×10^6 to 4.0×10^6 (6.5×10^6 to 5.5×10^6), efficiencies not affected

Waveform of a typical PMT



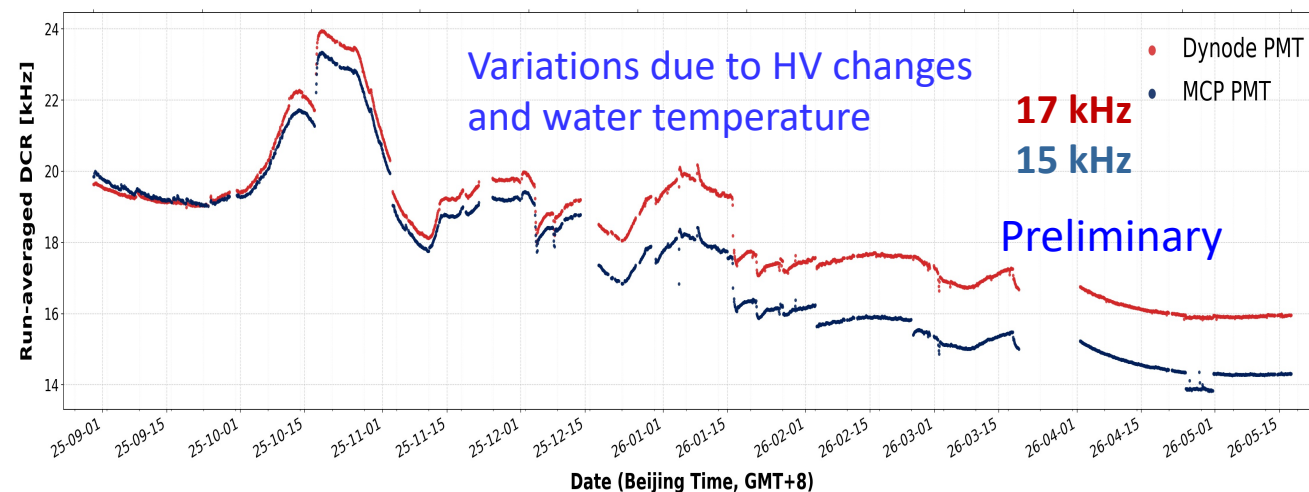
- Great performance of electronics:

- Good grounding and low noise:
 - RMS ~2.8 ADC ch. $\rightarrow$ ~0.055 PE
- PMT threshold: 0.2-0.3 PE/ch.

- Trigger and DAQ work fine

- Trigger threshold: ~200 keV

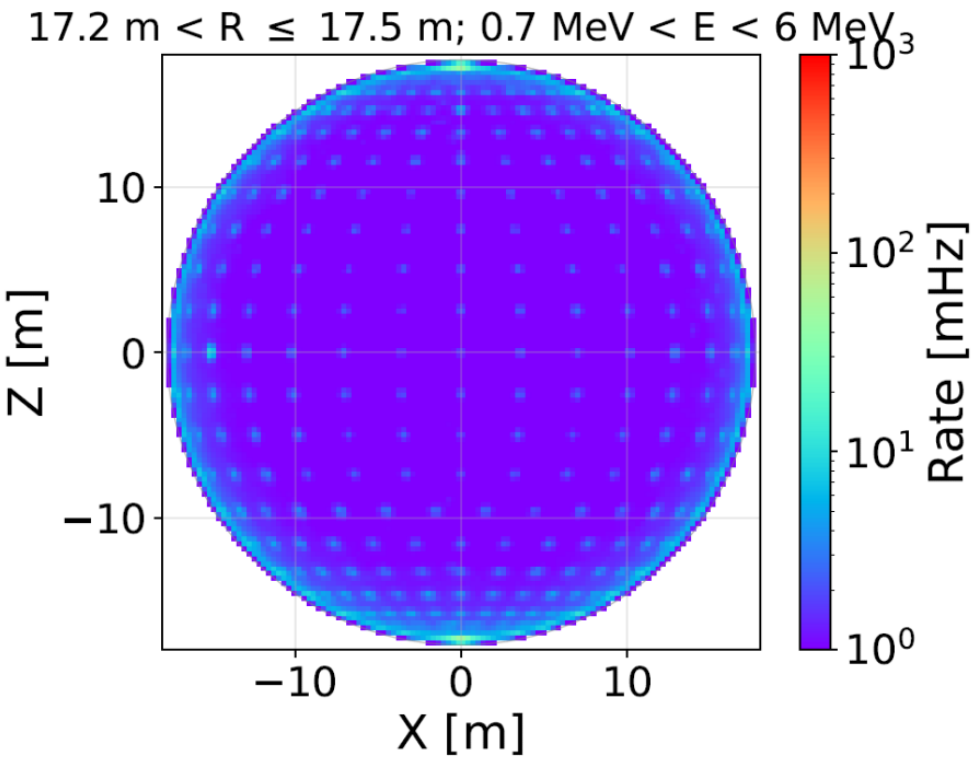
Dark Count Rate continuously decreasing



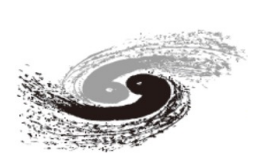
■ Ultra-low natural radioactivity, fulfill reactor neutrino oscillation measurement

Central Detector	Specification	Measure
Singles Rate (Hz)	< 7.2 Hz	< 7 Hz
$^{238}\text{U}/^{232}\text{Th}$ ($\times 10^{-15}$ g/g)	< 1	< 0.1
^{210}Po ($\times 10^4$ cpd/kt)	< 8	< 5

Muon Veto Detector	Specification	Measure
^{222}Rn (mBq/m ³)	< 10	<10
^{226}Ra (mBq/m ³)	< 1	< 0.01
U/Th ($\times 10^{-15}$ g/g)	<10	<0.4



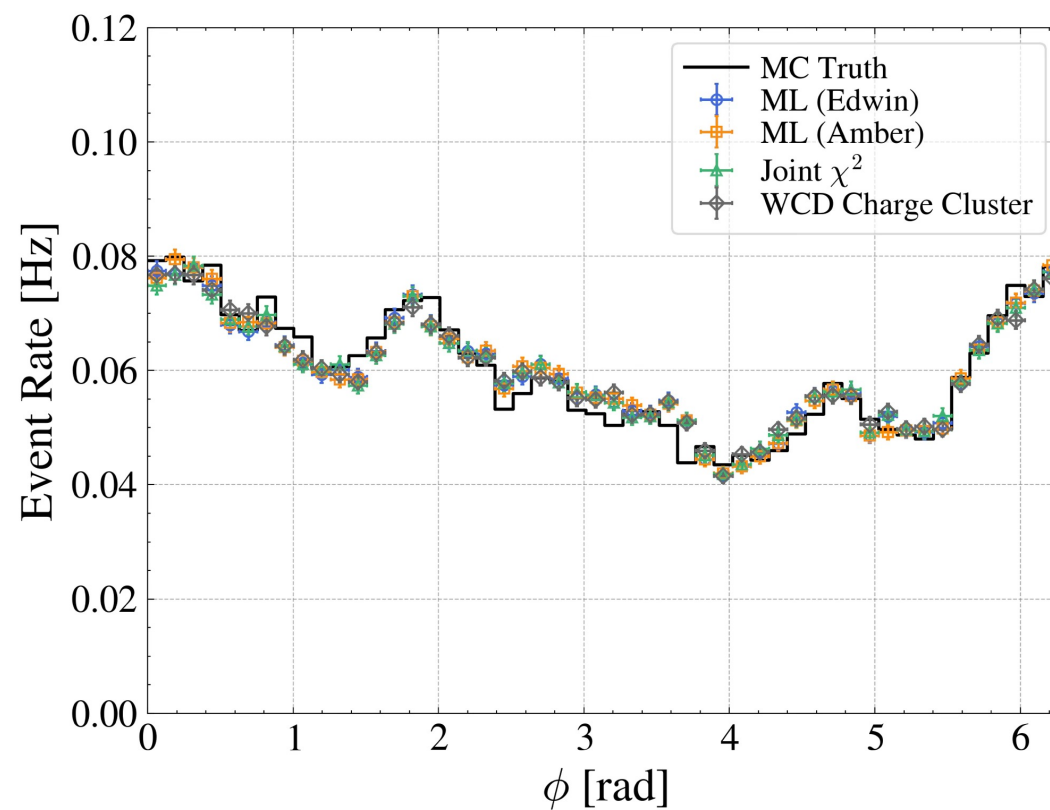
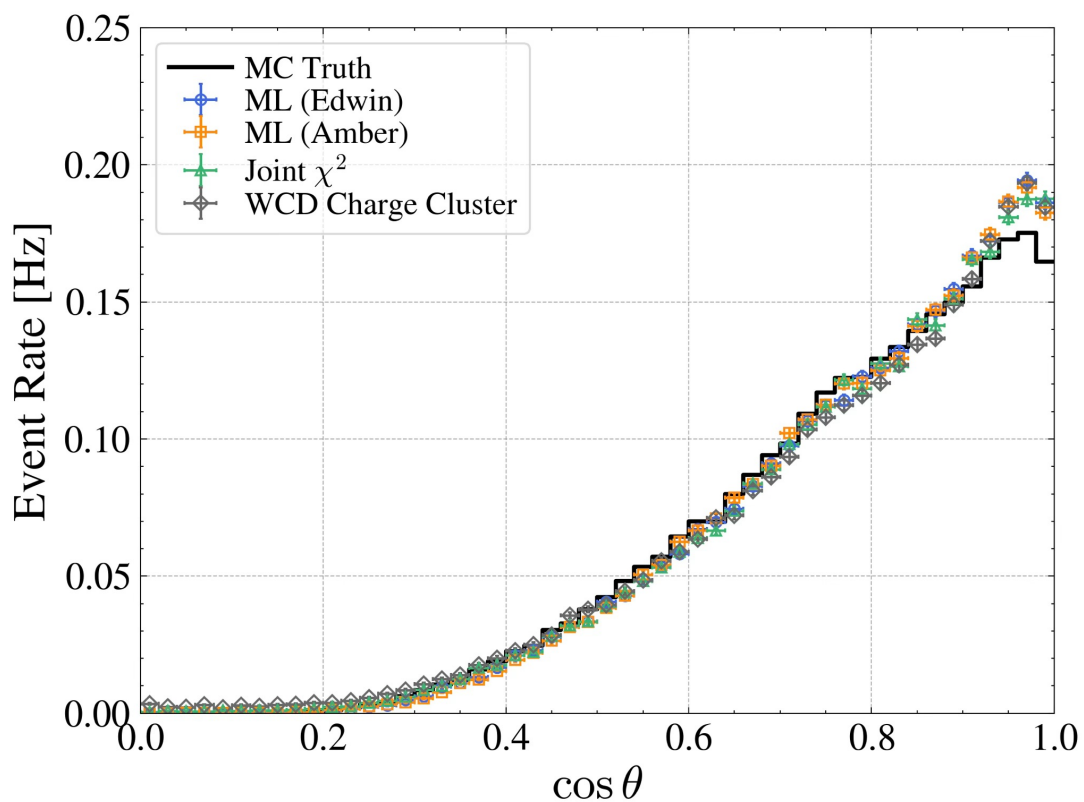
2 万吨液体闪烁体中的粉尘含量控制在约 10 毫克量级。



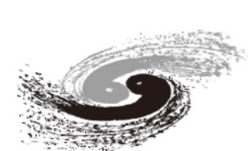
Measurement of Cosmic Muons



- 中心探测器中的muon触发率约为 5 Hz，水池中的触发率约为 4 Hz
- 中心探测器对贯穿型muon的探测效率高于 99.5%
- 实测角分布与蒙特卡洛模拟预期高度一致



Muon通量和能谱，以及山体的轮廓与密度均已得到较好的理解。



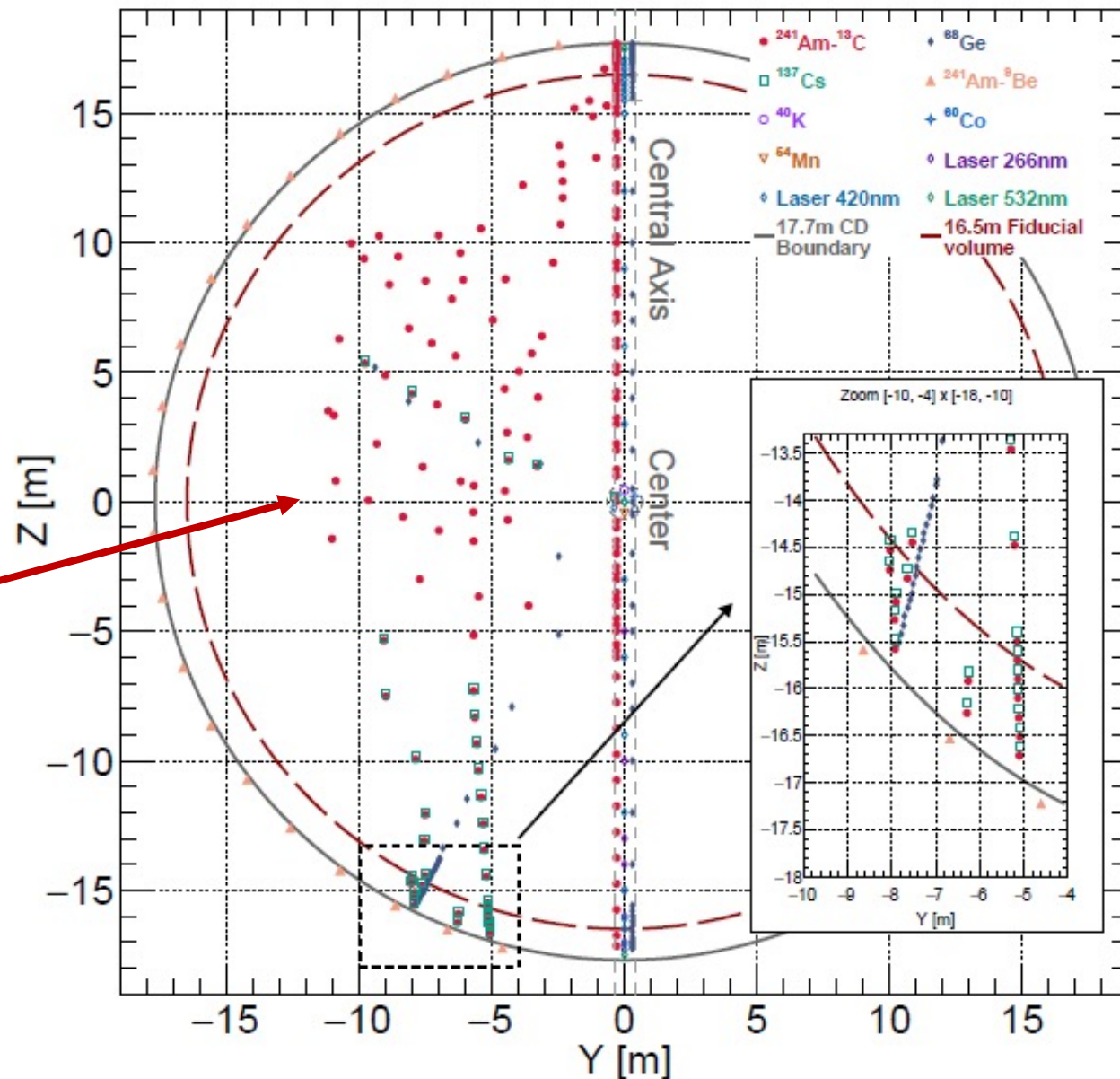
Calibration

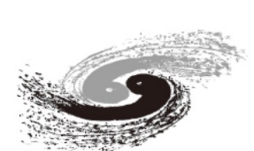


- 1D (central axis): ^{137}Cs , ^{54}Mn , ^{40}K , ^{68}Ge , ^{60}Co , Am-C, Am-Be, sensors, laser
- 2D (cable loop): Am-C, ^{68}Ge , ^{137}Cs
- 3D using cosmogenic backgrounds:
⇒ 氦衰变产生的 Bi-Po214, 散裂中子及其他宇生同位素

- 图中各点表示已开展放射源标定的位置
- 标定过程中未引入 ^{222}Rn 泄漏或其他污染

周三下午分会4, 吴文杰

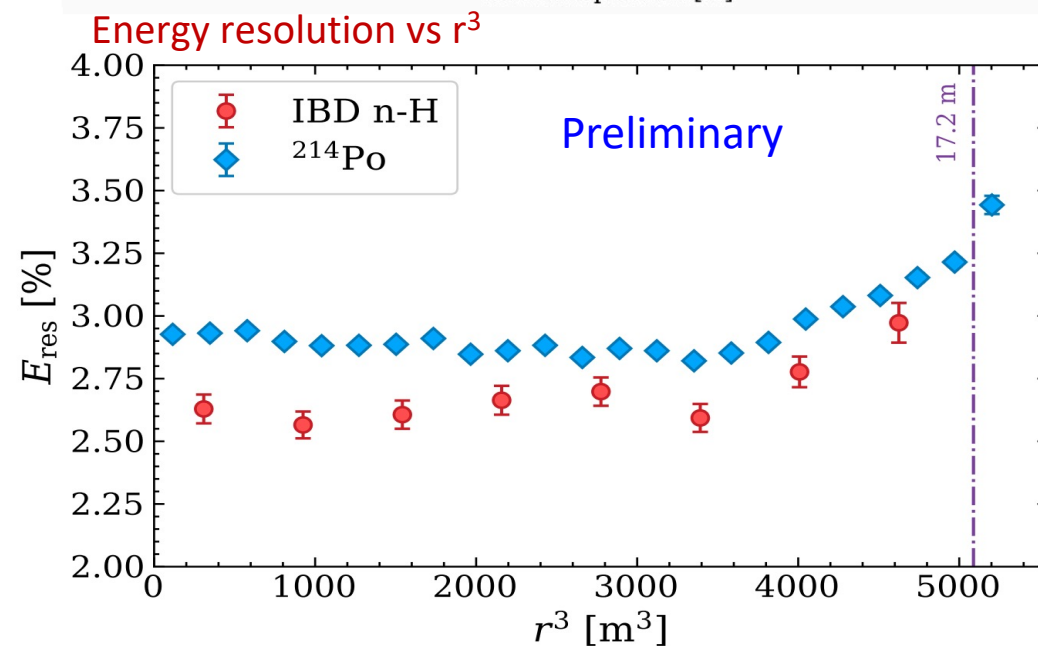
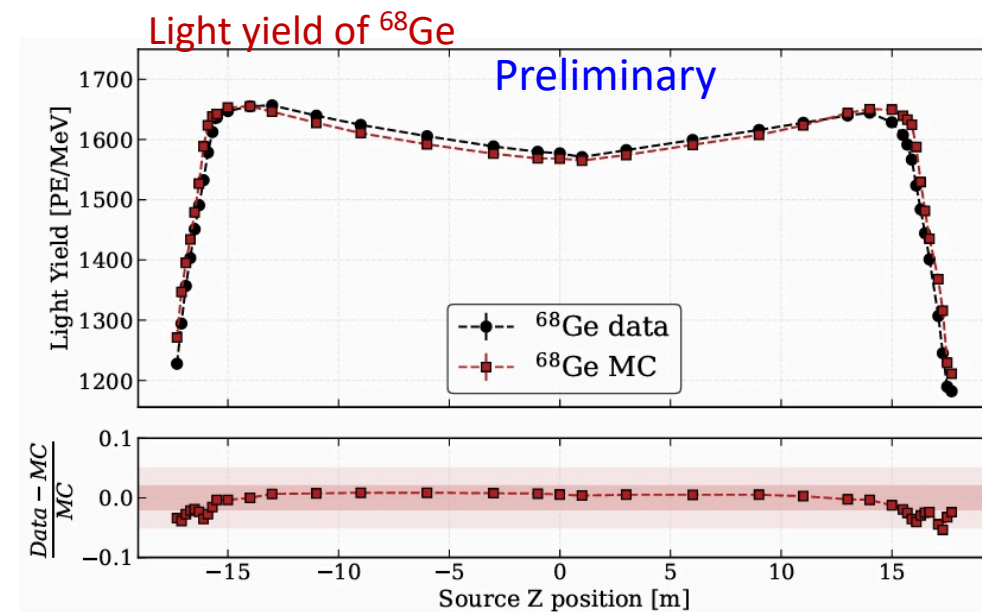
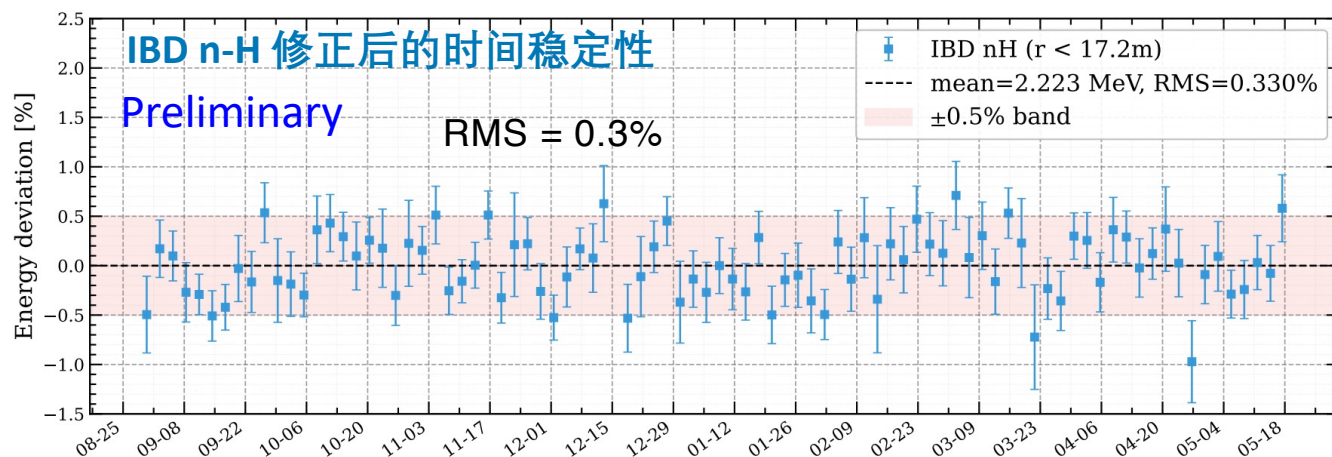


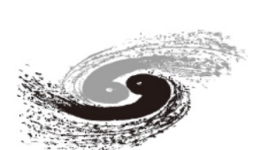


Reconstruction and Energy Correction



- 在探测器中心, ^{68}Ge 的光产额约为 **1600 PE/MeV**, 中子的光产额约为 **1785 PE/MeV**, 与蒙特卡洛模拟结果符合良好
- 在探测器中心, ^{68}Ge 的能量分辨率约为 3.5% @ $2 \times 0.511 \text{ MeV}$
- ^{214}Po 的 α 粒子能量分辨率约为 2.9% @ 0.93MeV
- 以 ^9Li 和 IBD 事例中的 **中子俘获氢 (n-H)** 信号为基准确定能标
- 利用全体积内的 ^{214}Po 修正随**时间变化**的响应, 并使用 IBD 事例中的 n-H 信号进行检验



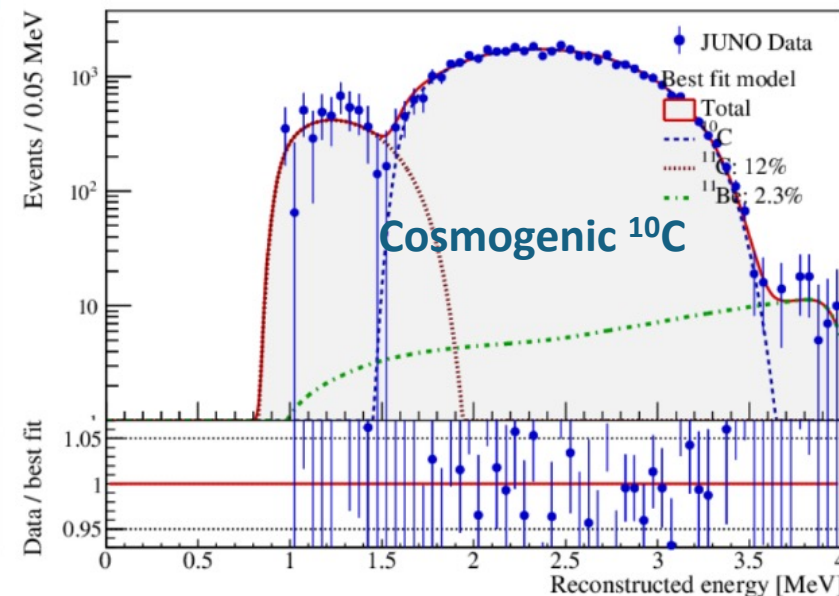
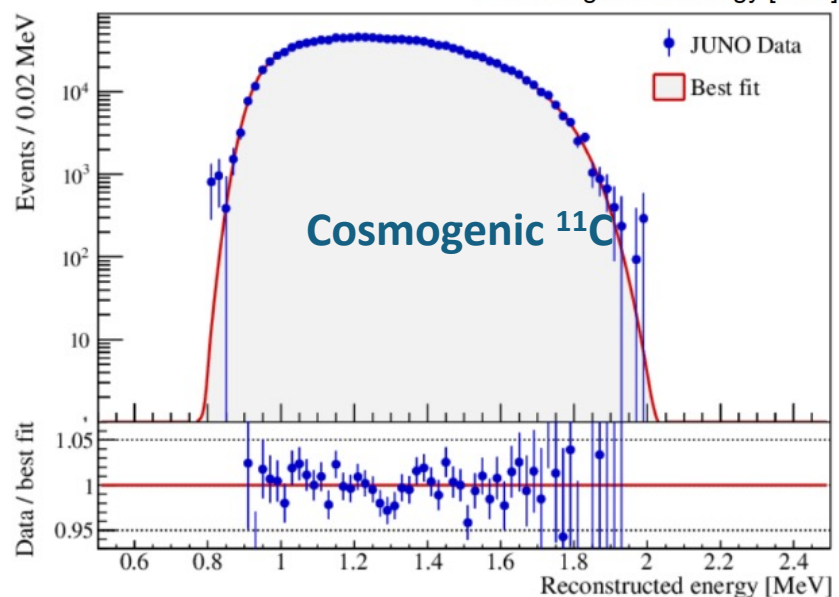
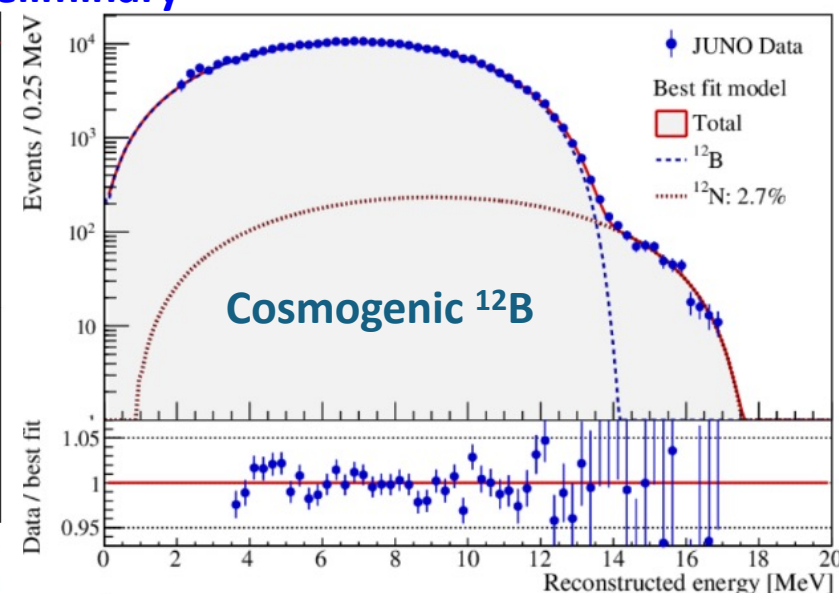
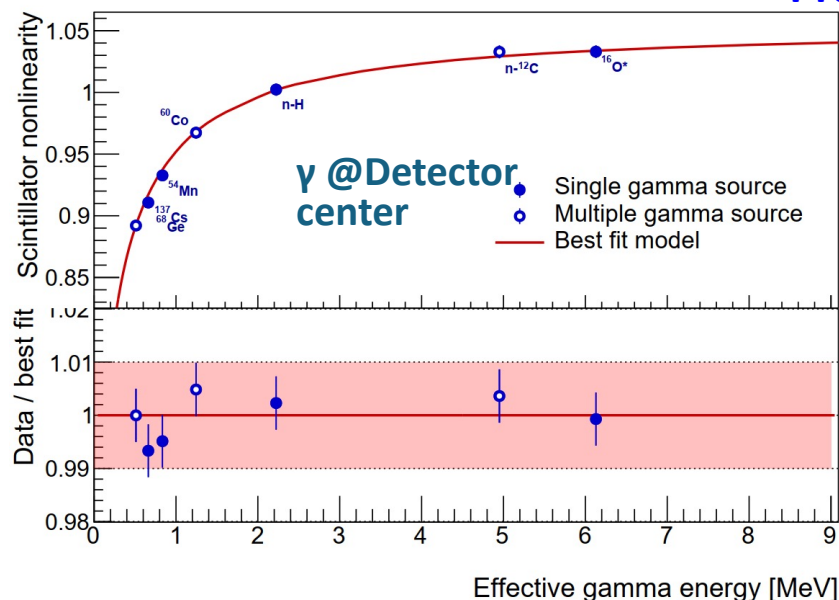


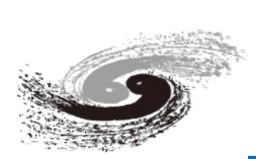
Energy Non-linearity



- 利用探测器中心的标定源确定液体闪烁体和电子学的非线性响应:
 ^{68}Ge , ^{137}Cs , ^{54}Mn , ^{40}K , ^{60}Co , Am-C 和 Am-Be
- e^+ 非线性模型基于 Geant4 模拟和 γ 放射源标定建立
- 利用全体积内的宇生同位素对模型进行约束, 包括 $^{11}\text{C}(e^+)$, $^{10}\text{C}(e^+)$, $^{12}\text{B}(e^-)$, $^8\text{Li}(e^-)$, $^8\text{B}(e^+)$, $^6\text{He}(e^-)$ 等
- 利用sPMT校正并约束LPMT的仪器非线性
- 不确定度小于 1%

Preliminary





New Results released using 207 days of data

周三下午分会4，陈志源

Reactor Neutrino Selection

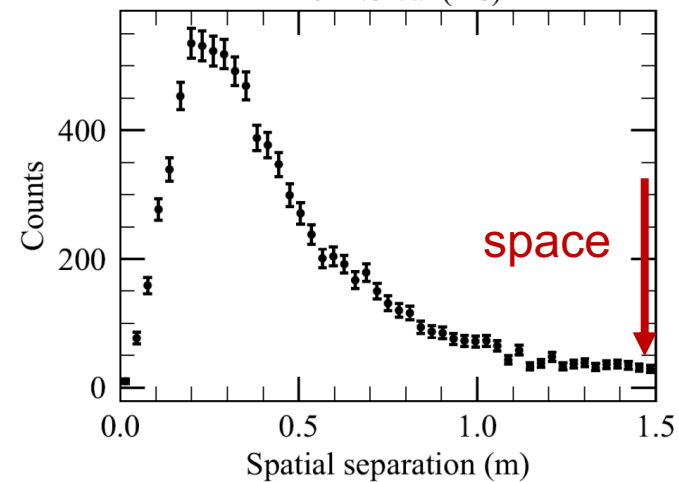
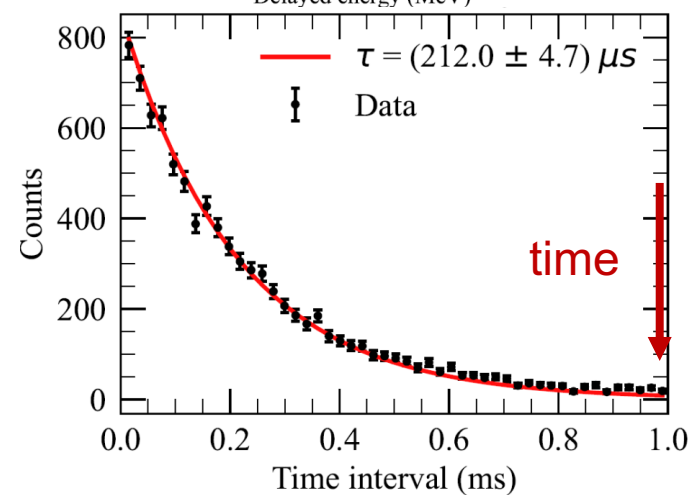
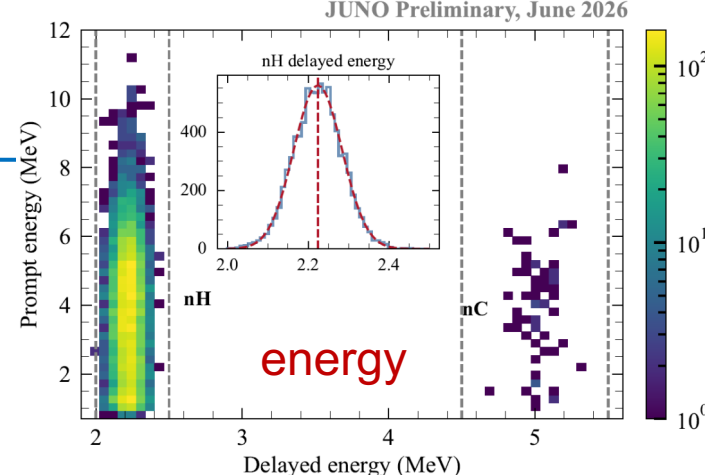
- Prompt and delayed coincidence in **time**, **space** with **energy** features

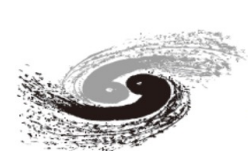
Criterion	Selection
PMT flasher	Applied
Fiducial volume	$r_p < 17.2 \text{ m}, z_p < 15.5 \text{ m}$
Prompt energy	(0.7, 12) MeV
Delayed energy	$(2.0, 2.5) \cup (4.5, 5.5) \text{ MeV}$
Coincidence time	(5, 1000) μs
Relative distance	$< 1.5 \text{ m}$
Multiplicity cut	No other events $> 0.7 \text{ MeV}$ in the FV or (2.0, 6.0) MeV outside the FV within 2 ms before and 1 ms after the delayed event
Water pool muon veto	Veto if the delayed is within (0, 2) ms after NPE > 700 in WP
CD muon veto	Veto if the delayed is within (0, 5) ms after NPE $> 3 \times 10^4$ in CD
Spallation neutron veto	Veto if the delayed satisfies $\Delta r < 4 \text{ m}$ and $\Delta t < 1.2 \text{ s}$ after spallation neutrons with $\text{NPE}_{\text{spn}} \in (3000, 30000)$ and $T_{\text{spn}2\mu} \in (20, 2000) \mu\text{s}$
Muon track veto	Veto if the delayed event: $\frac{\Delta r_{\mu d}}{2.5 \text{ m}} + \frac{\Delta t_{\mu d}}{0.5 \text{ s}} < 1$
Correlated discriminator	$\log(\text{L.R.}) > -1.26$

Similar to our
“Nature” paper

- 本次分析的新改进：

- 有效体积扩大大约 10% ($R=16.5\text{m} \rightarrow 17.2\text{m}$)
- ^9Li 本底降低约 60%
- 采用likelihood cut, 使偶然符合本底降低50 倍
- 对 ^{214}Bi 本底进行与模型无关的估计

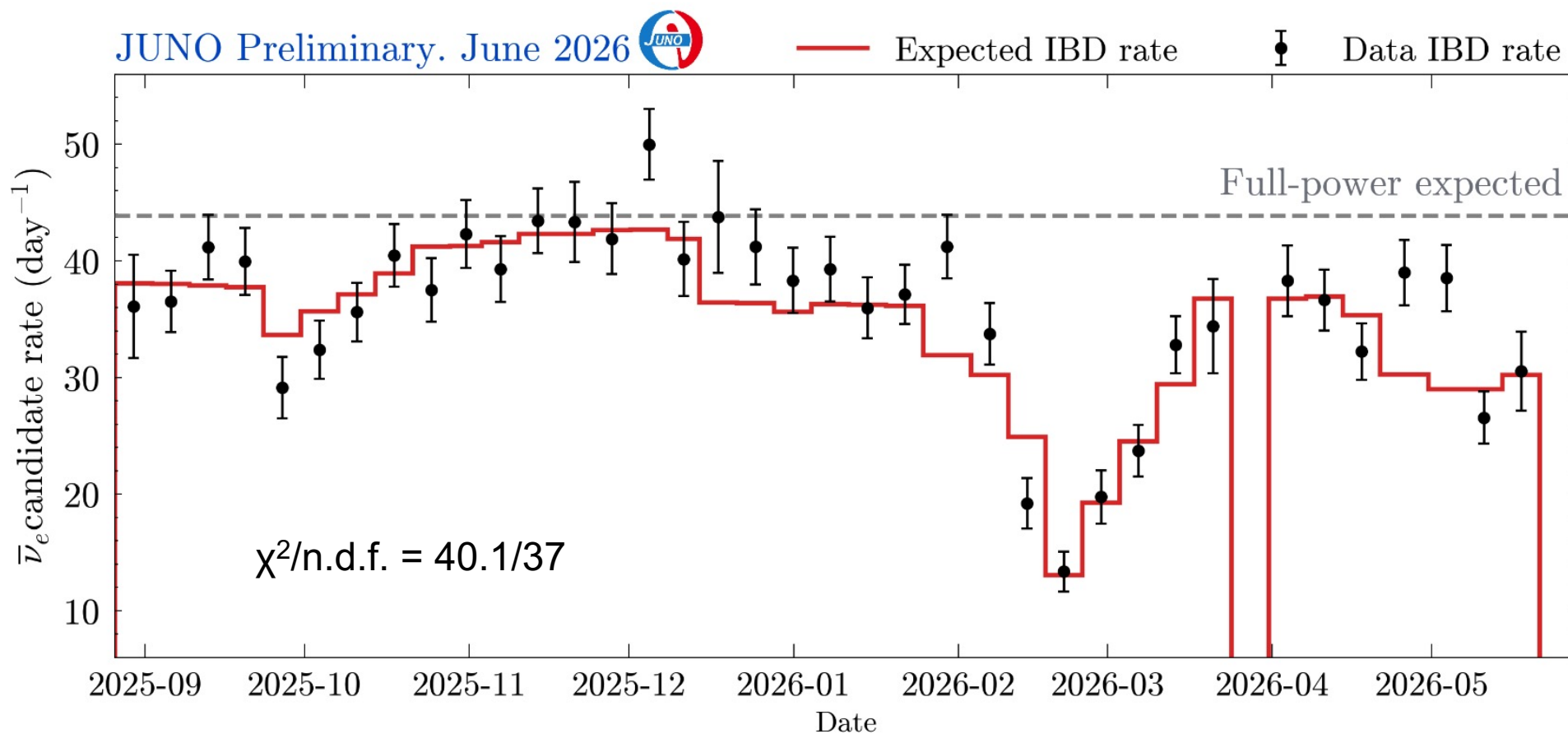


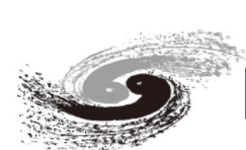


Reactor Neutrino Event Rate versus Time

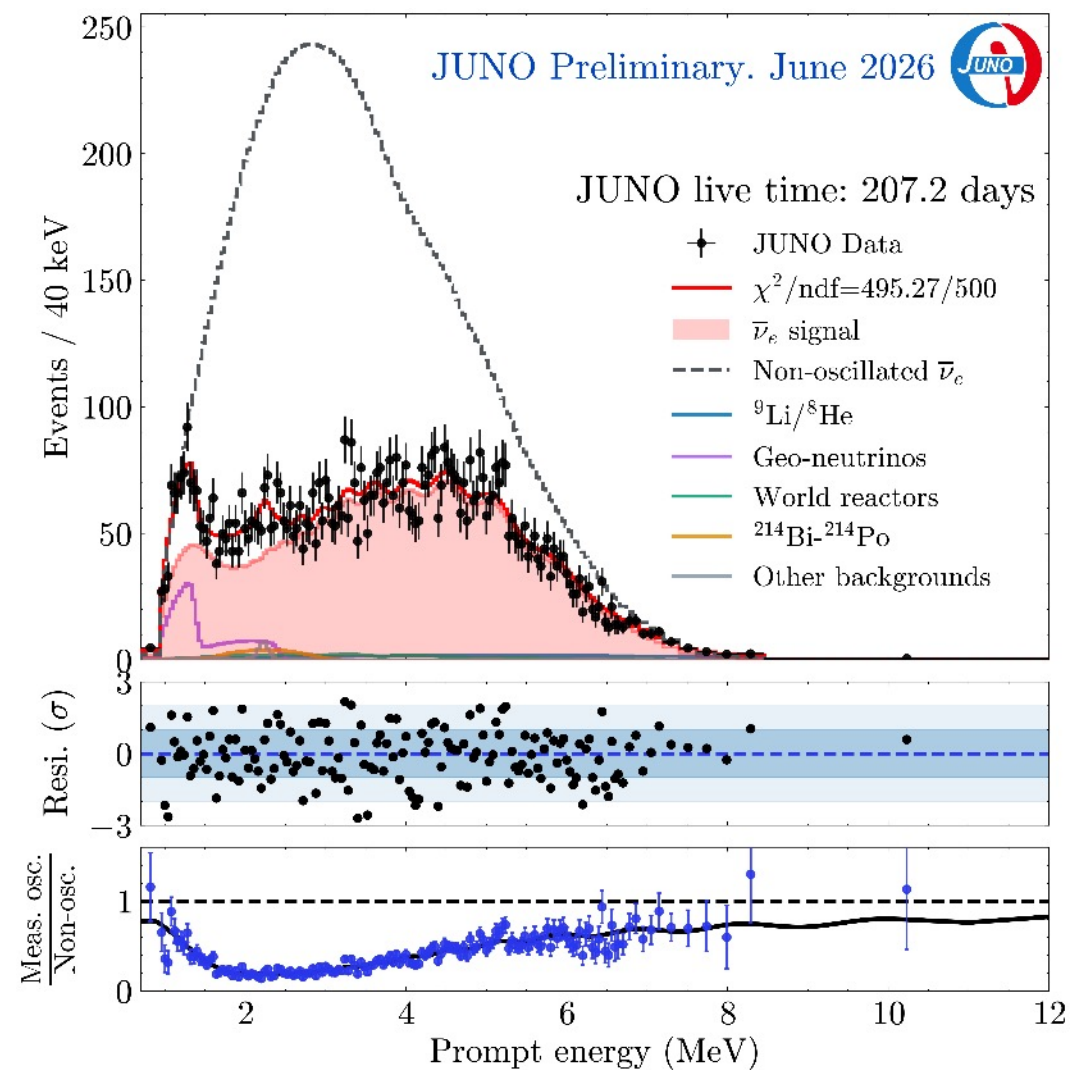


- 实测反应堆中微子事例率与预期一致
- 总有效运行时间为 **207.2 天**





Measured Reactor Neutrino Spectrum

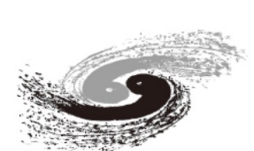


利用 TAO (周三下午分会4, 李茹慧)和大亚湾 (PRL 130 16, 161802)近点探测器能谱对拟合进行约束

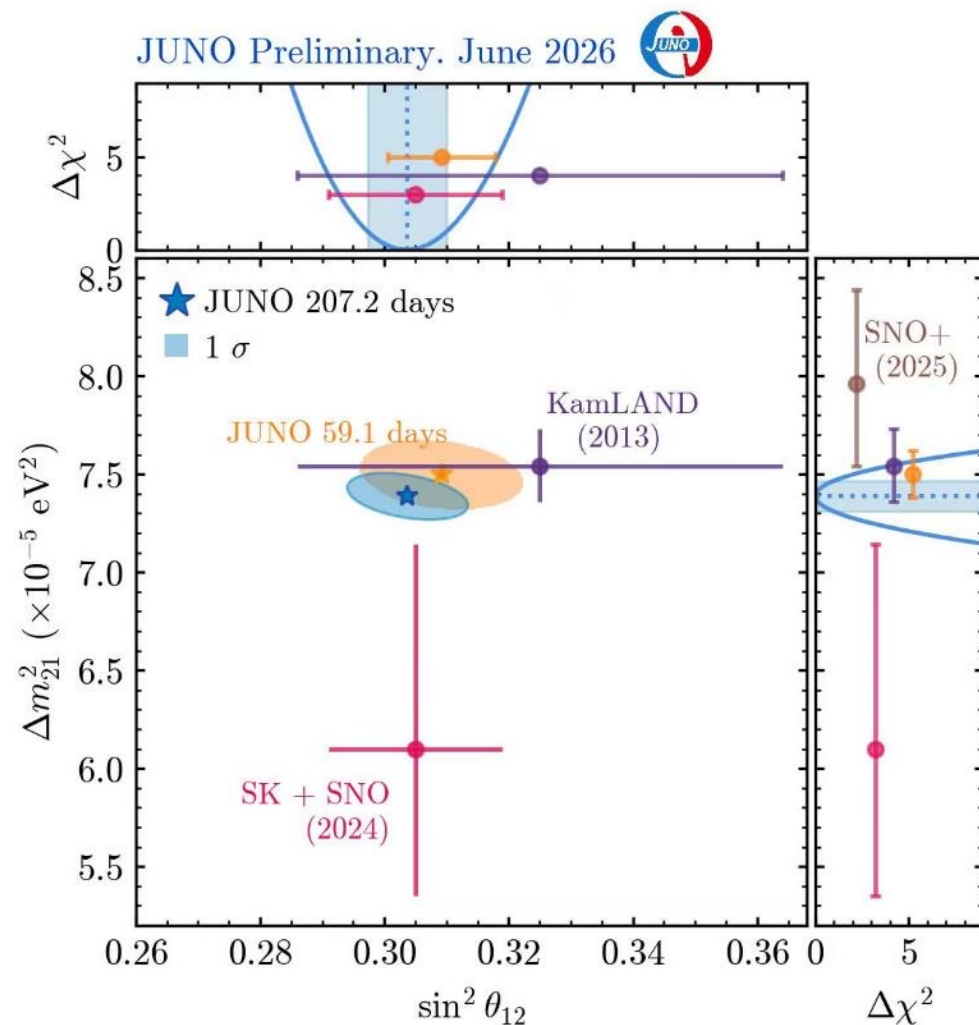
Antineutrinos ($\bar{\nu}_e$) Candidates Summary

DAQ live time (days)	207.2	
$\bar{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ϵ	σ_{rel}
Fiducial volume	87.12%	0.96%
PMT flasher rejection	> 99.9%	Negligible
μ veto	93.67%	0.02%
Multiplicity cut	95.94%	negligible
Prompt-delayed coinc.	95.50%	0.32%
Correlated discriminator	98.99%	0.15%
Total efficiency (ϵ_{tot})	74.01%	1.02%
$\bar{\nu}_e$ signal (cpd)		
w/o ϵ_{tot} corrected	36.02 ± 0.62	
w/ ϵ_{tot} corrected	48.67 ± 1.08	
Backgrounds (cpd)	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	1.05 ± 0.27	1.41 ± 0.26
Geoneutrinos	Free	2.12
World reactors	0.92 ± 0.09	0.92 ± 0.09
$^{214}\text{Bi}-^{214}\text{Po}$	0.42 ± 0.31	0.57 ± 0.34
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	0.05 ± 0.02	0.05 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.10 ± 0.10	0.13 ± 0.10
Atmospheric neutrinos	0.09 ± 0.04	0.11 ± 0.05
Accidentals	0.07 ± 0.01	0.07 ± 0.01

Consistent results from three independent analyses



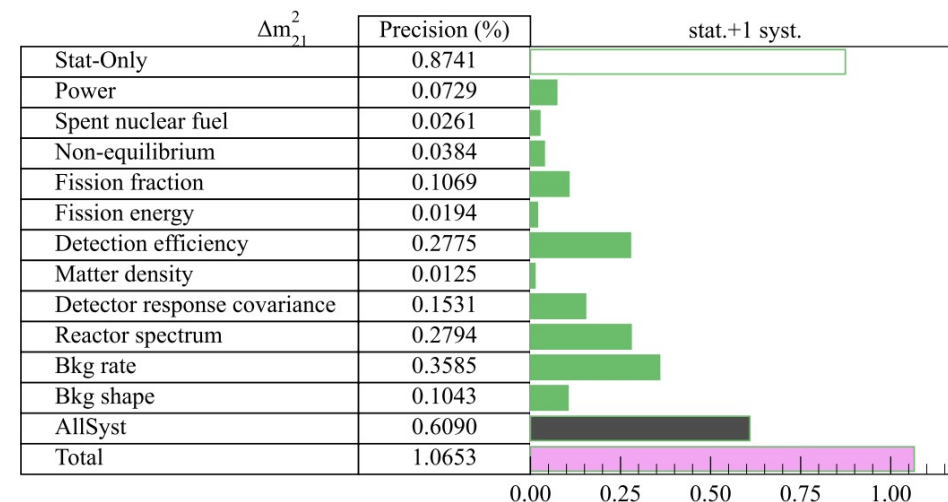
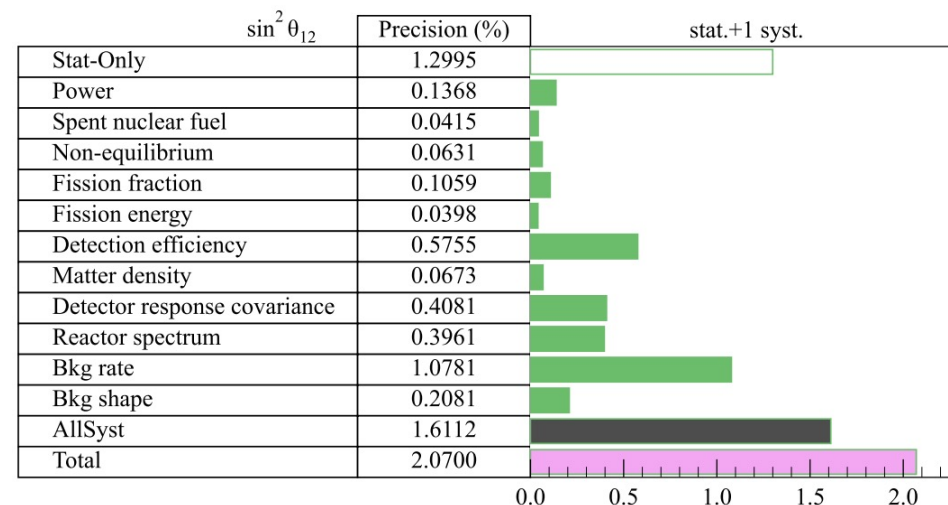
New Results of Solar Oscillation Parameters

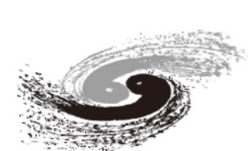


Δm_{21}^2	7.388 ± 0.078 (1.60% $\rightarrow$ 1.06%)
$\sin^2 \theta_{12}$	0.3036 ± 0.0064 (2.8% $\rightarrow$ 2.1%)

- 尽管目前仍以统计误差为主，但系统误差的重要性已经开始显现：

$\Rightarrow$ ^{214}Bi 本底和探测效率仍有进一步改进的空间

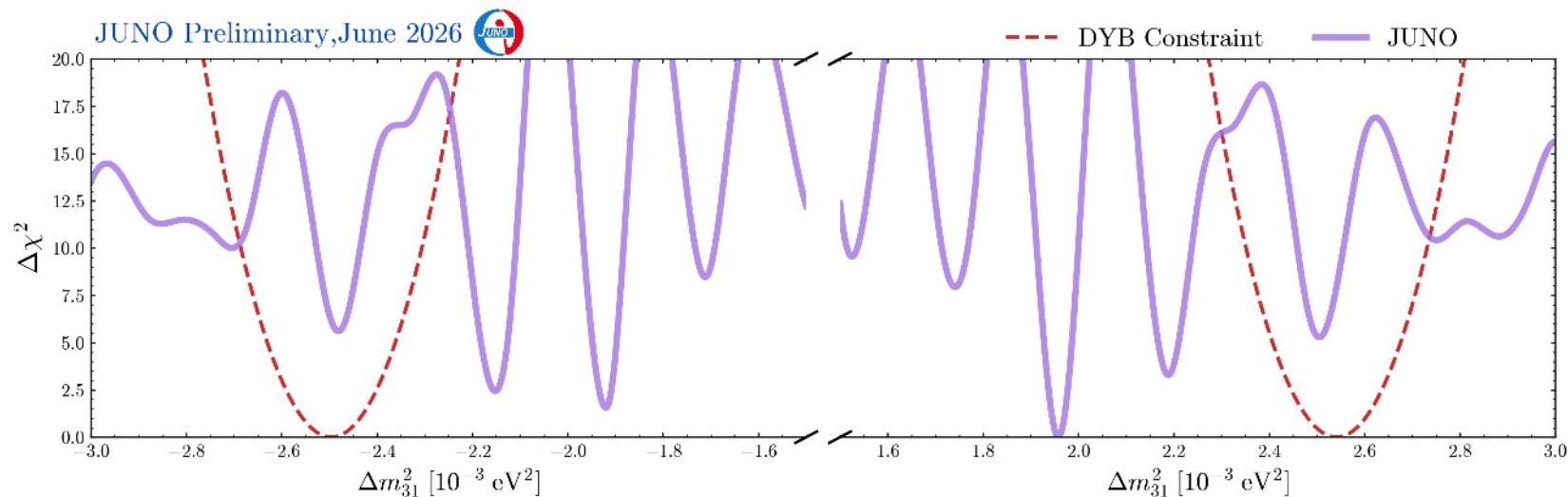




First Result of Δm_{31}^2

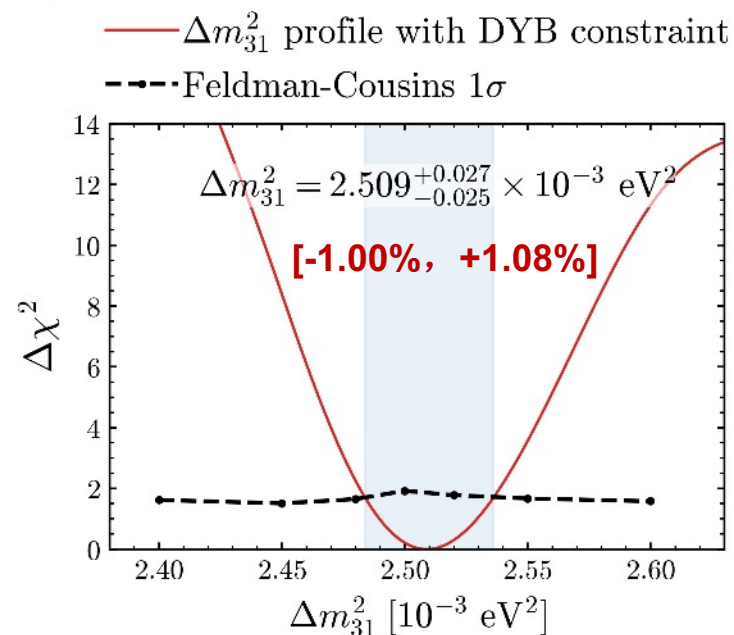
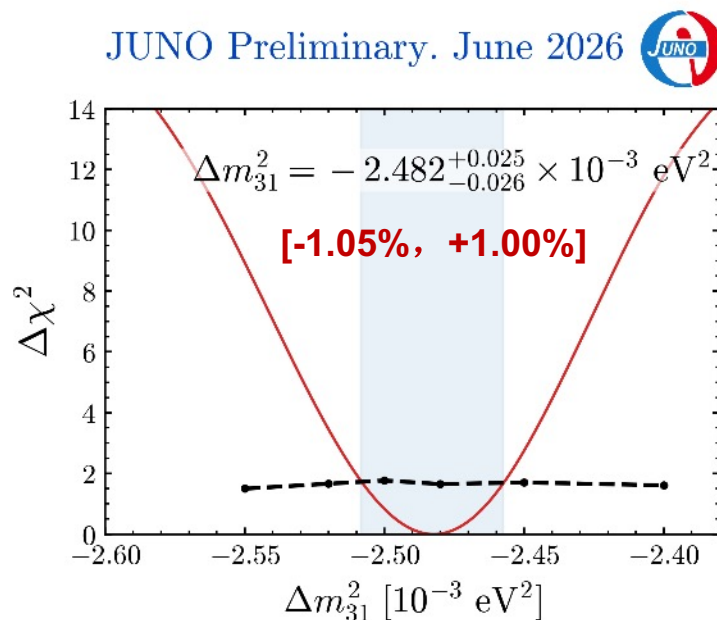


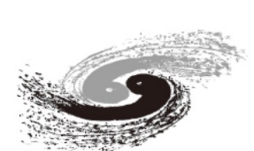
- 由于统计涨落，仅使用 JUNO 数据得到的 Δm_{31}^2 profile 存在多个局部极小值



通过引入大亚湾实验 (PRL 130, 161802) 对 Δm_{31}^2 的测量约束，确定两种质量排序各自的最终极小值。

采用 Feldman–Cousins (FC) 方法确定 Δm_{31}^2 的 1σ 区间，测量精度达到约 1%。

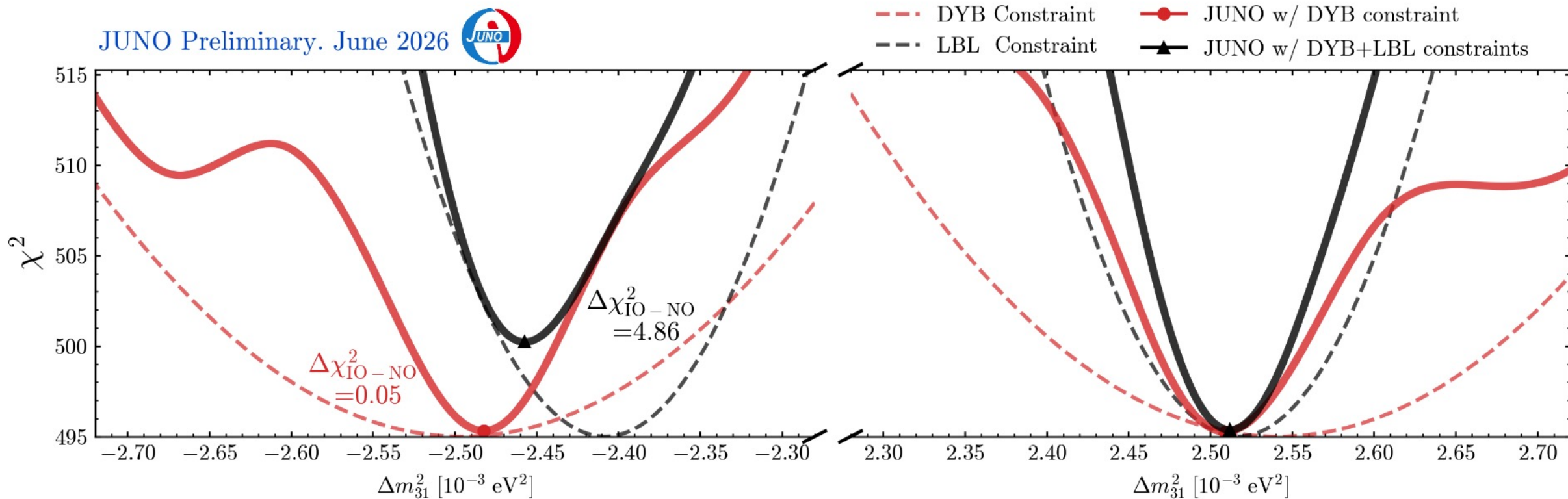




Adding Constraint from NuFit-LBL

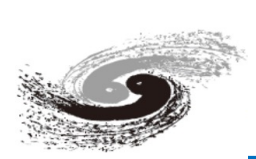


- 在正确的中微子质量排序下，由反应堆中微子实验和加速器中微子实验测得的 Δm^2_{31} 应该是一致的[1]
- 采用文献 [2] 中的 NuFit-LBL 结果作为外部约束后: $\Delta\chi^2 = 4.86$ 倾向于正序.



[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)

[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

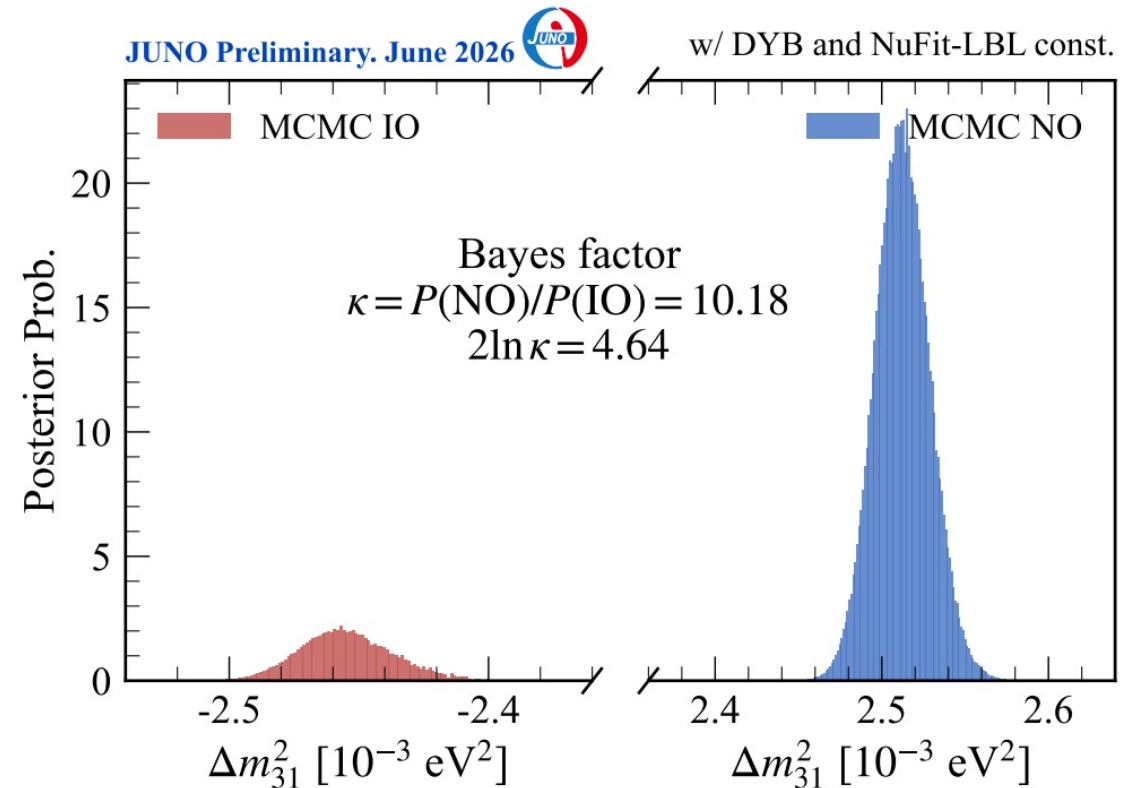
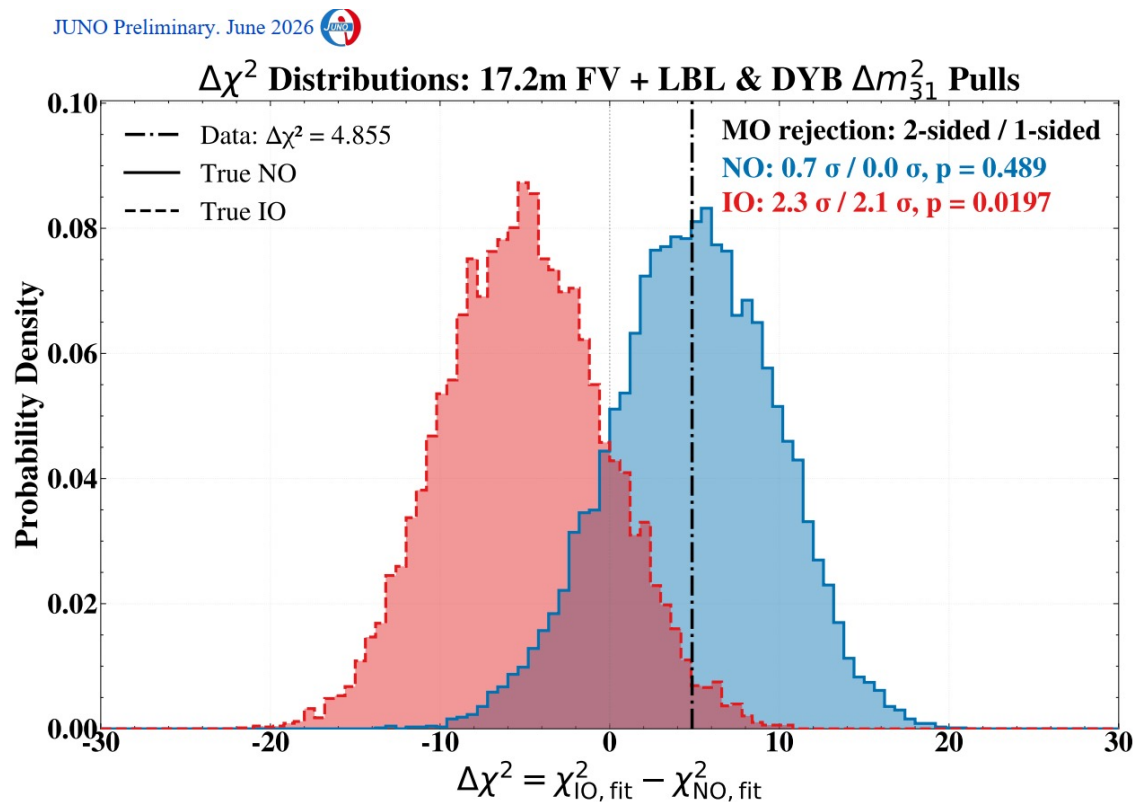


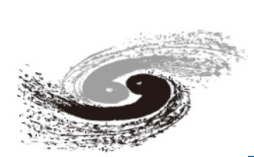
Neutrino Mass Ordering Significance



- Frequentist approach: 利用伪实验将 $\Delta\chi^2$ 转换为显著性
- 考虑（扫描）了 δ_{CP} 的影响
- 数据更倾向于中微子质量正序，显著性为 2.3σ

- Bayesian approach: 采用 Markov Chain Monte Carlo(MCMC) 方法
- 偏向正序，贝叶斯因子为 **10.18** $\rightarrow 2\ln \kappa = 4.64$
 $\Rightarrow$ 与frequentist $\Delta\chi^2$ 分析结果相符





Consistent Results from Independent Analyses

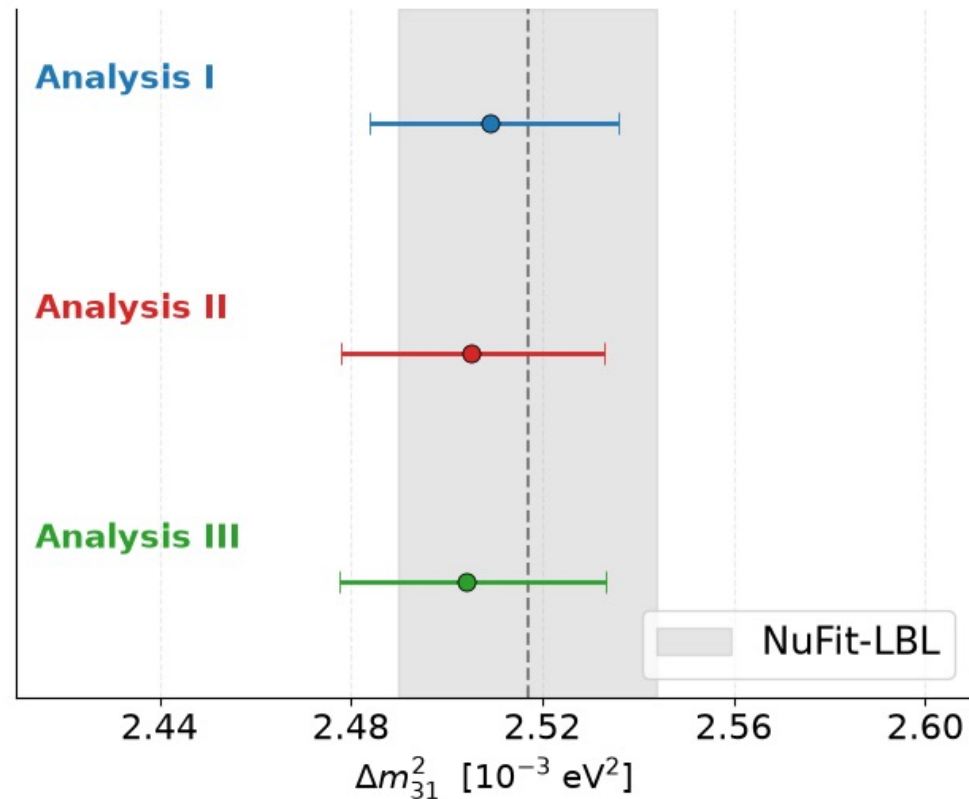


◆ 三套独立分析得到一致的结果 (0.2σ)

⇒ 不同的事例重建、有效体积、筛选条件、探测效率、本底估计、能量响应模型和振荡拟合

JUNO+DYB Feldman-Cousins

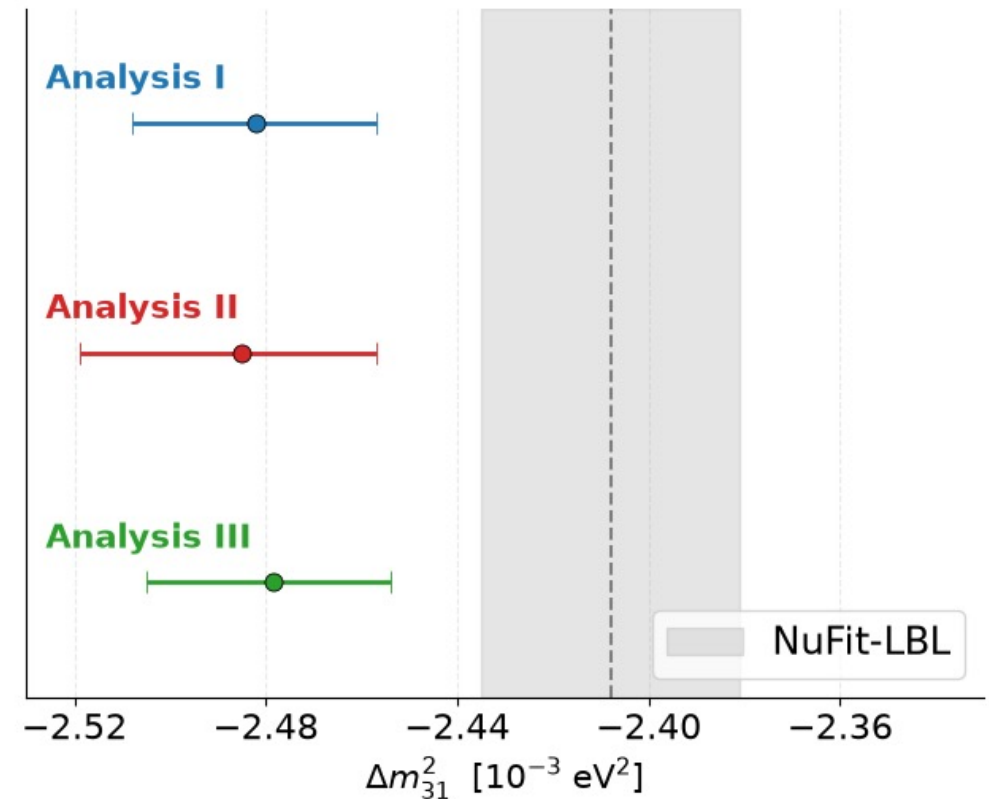
Normal Ordering



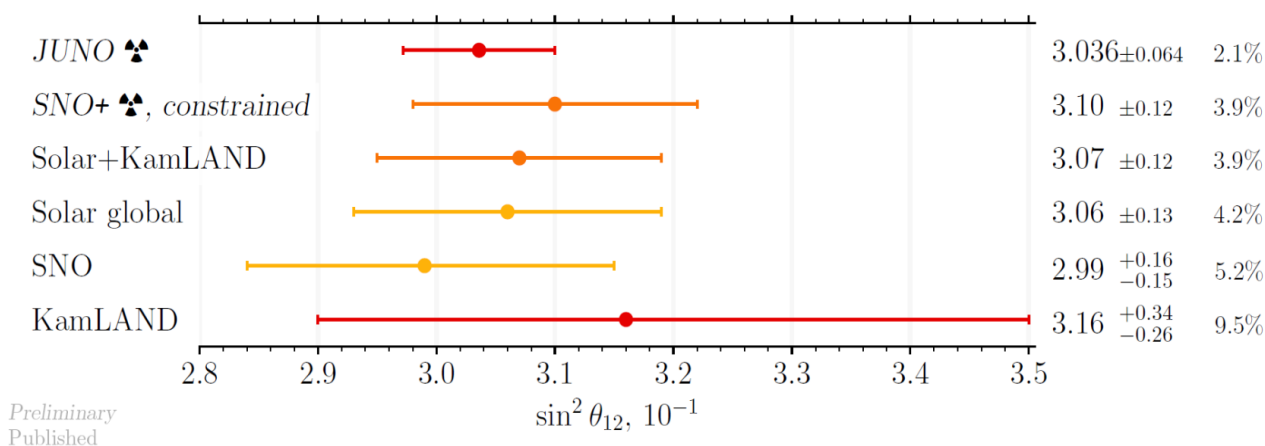
JUNO Preliminary. June 2026



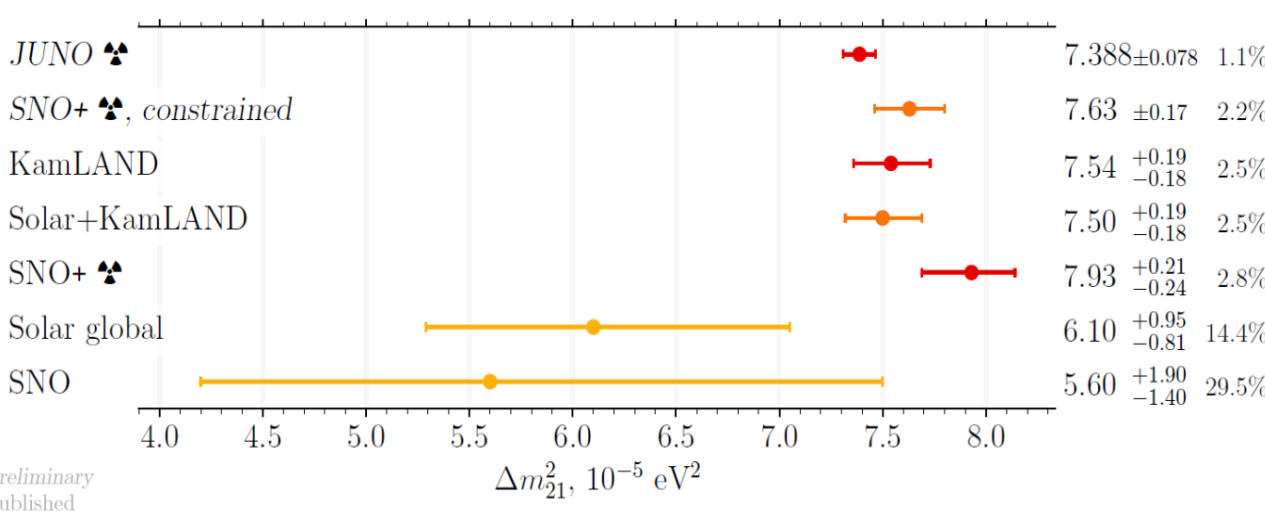
Inverted Ordering



$\sin^2 2\theta_{12}$

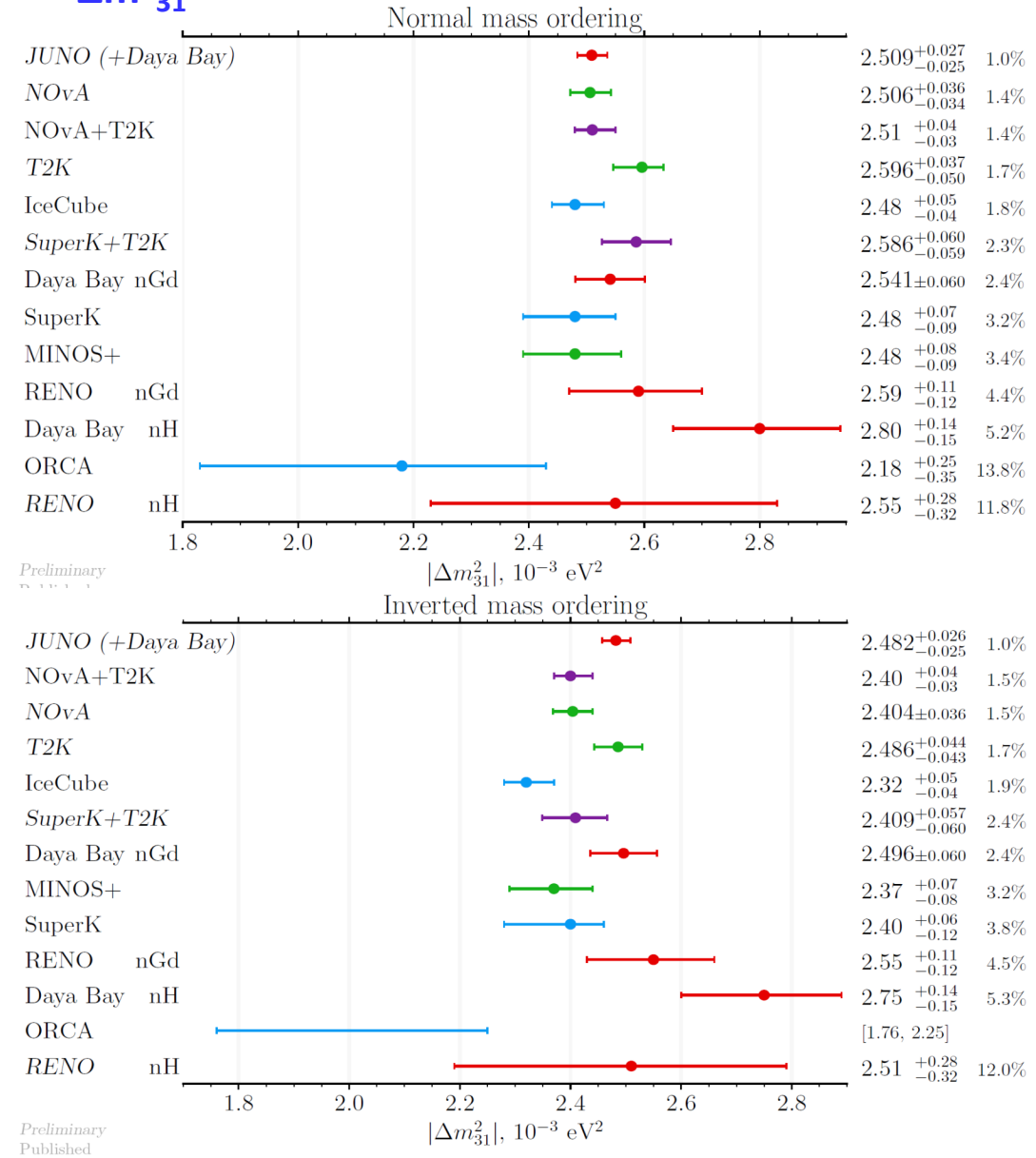


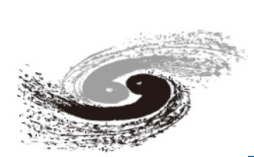
Δm^2_{21}



JUNO 测量结果的不确定度最小

Δm^2_{31}



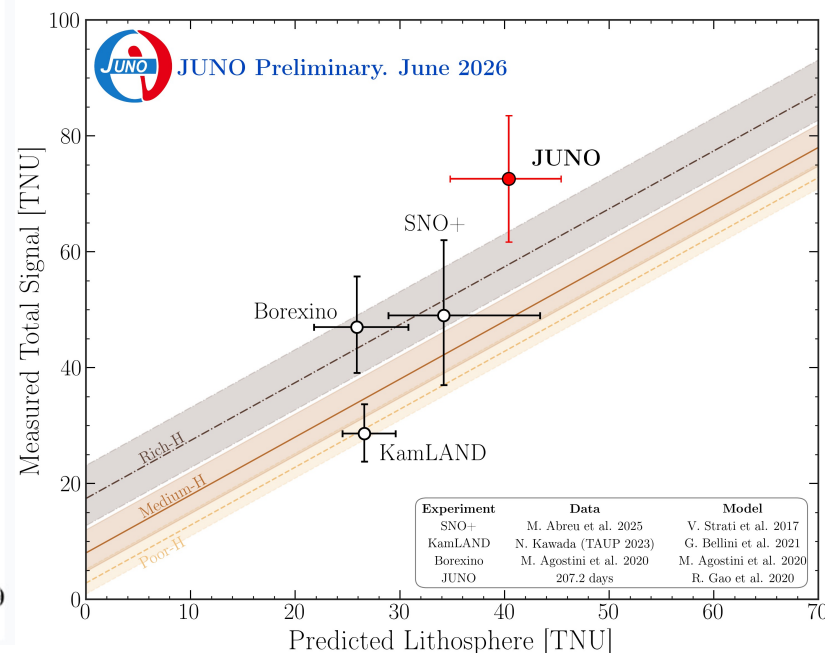
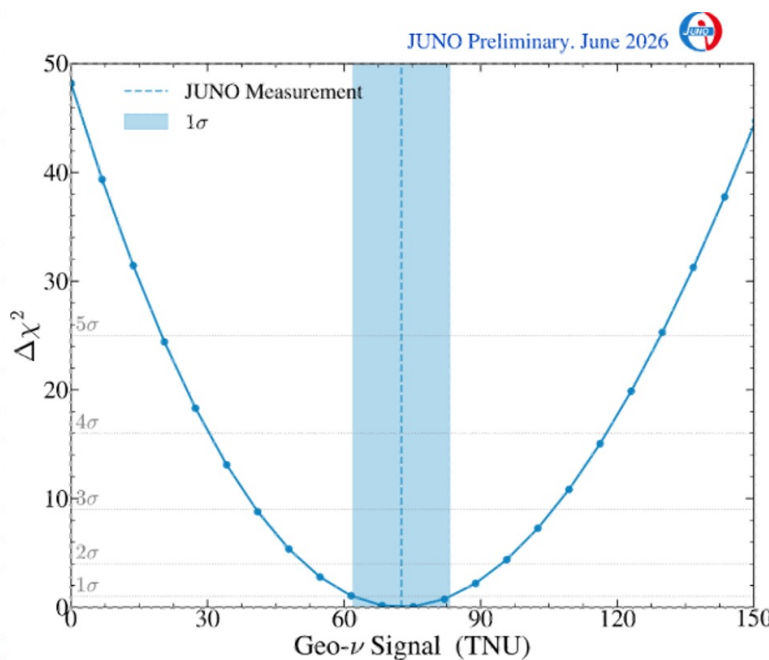
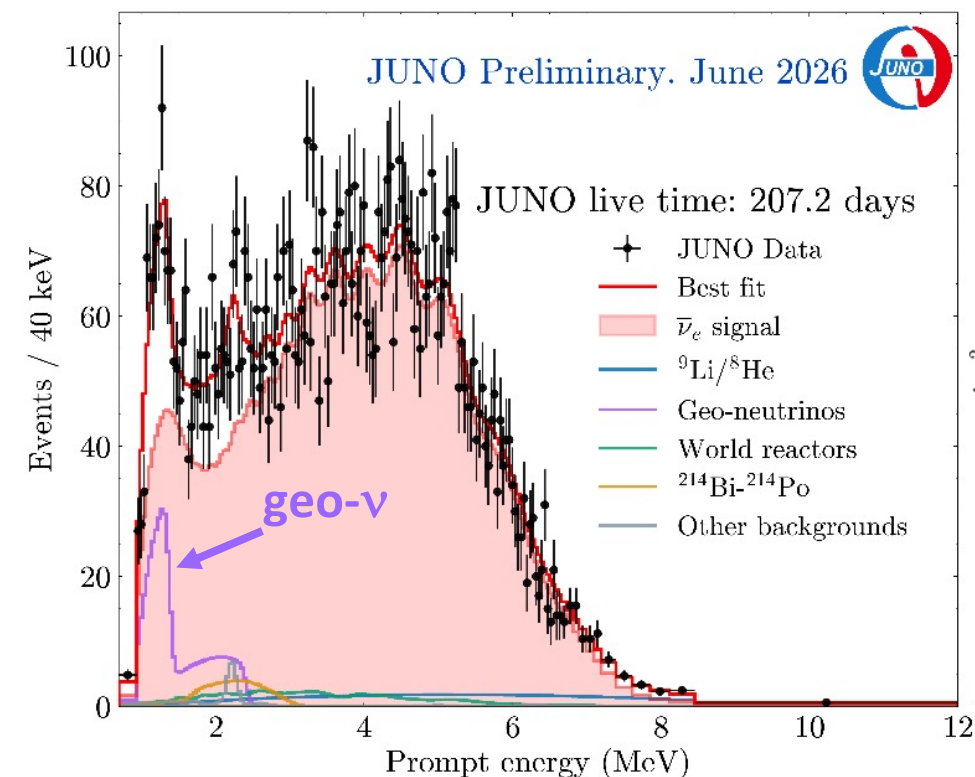


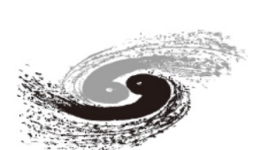
New Results on Geo-neutrinos



- 拟合时不对地球中微子通量施加约束，但将 U/Th (铀/钍) 比固定为 $3.4 \pm 10\%$
 - ⇒ 对地球中微子通量施加约束不改变中微子振荡分析结果
- 在 1–3 MeV 能区观测到清晰的地球中微子信号，测得通量为 73 ± 11 TNU
 - ⇒ 这是迄今统计量最大的地球中微子样本，也是最精确的测量结果
- JUNO 的测量结果高于现有模型的预期，但差异尚不具有统计显著性
- 需要积累更多 JUNO 数据，并进一步完善地质模型的预测

周三下午分会4，刘琪汕



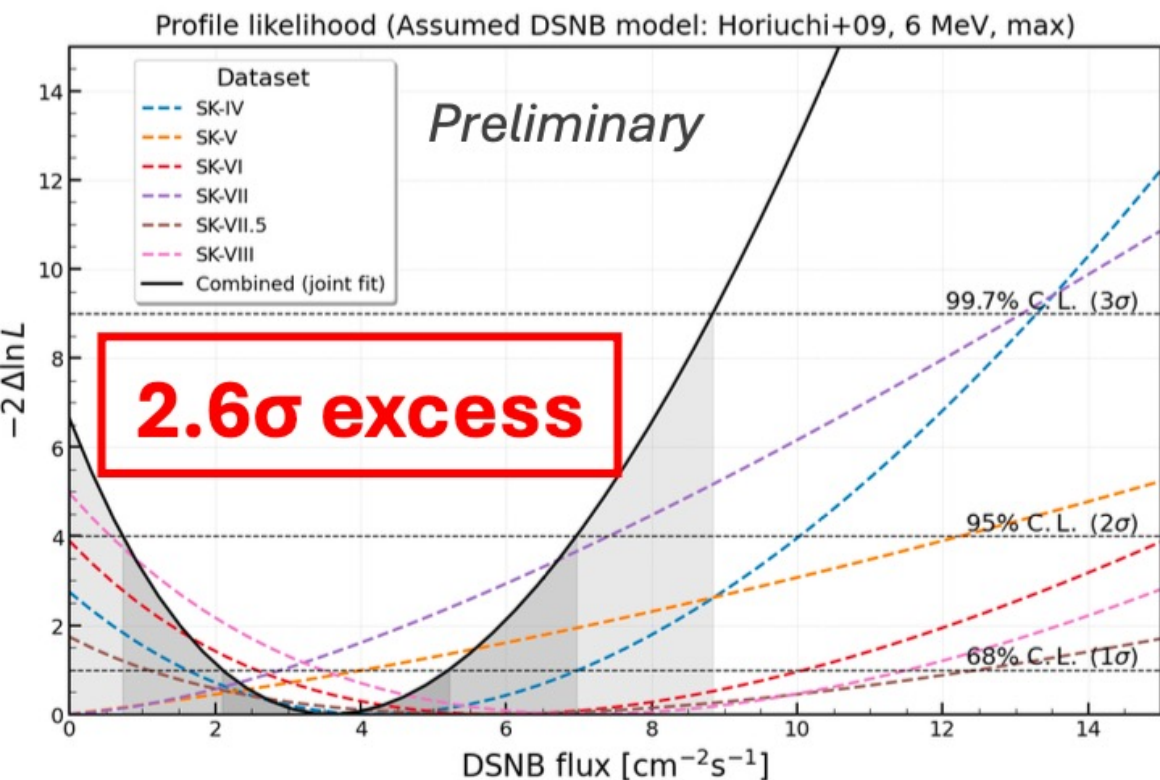


Diffused Supernova Neutrino Background

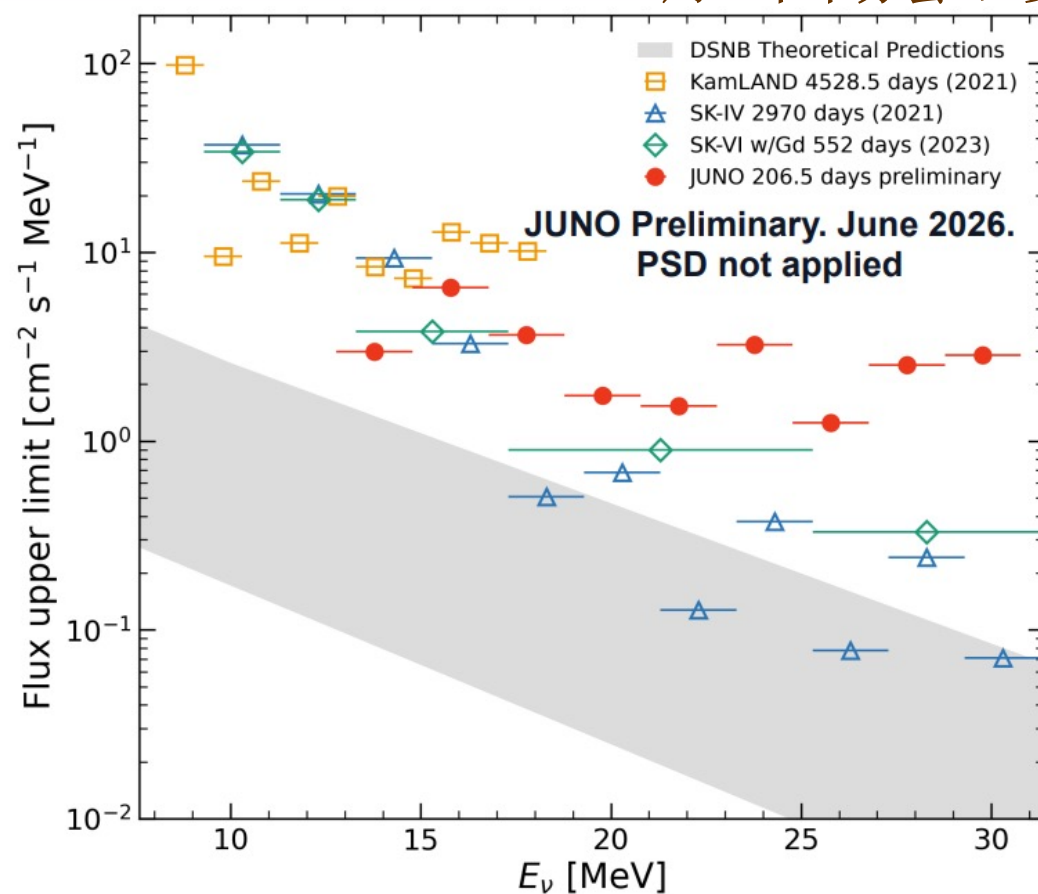


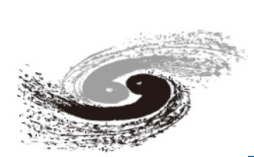
- 宇宙历史上所有核坍缩超新星的中微子**累积**信号
- 为超新星探测提供了一个**持续存在**、**可长期积累**的观测窗口

- New SK result: $2.3\sigma \rightarrow 2.6\sigma$
- 仍未达到发现标准



- 在12–30 MeV 能区观测到 19 个 DSNB 候选事例
 - 与本底预测 21.3 ± 10.5 个事例相符
 - 给出了具有竞争力的通量上限
 - 初步脉冲形状判别 (PSD) 研究表明这些候选事例大多可能来自大气中微子
- 周三下午分会4, 罗晓杰



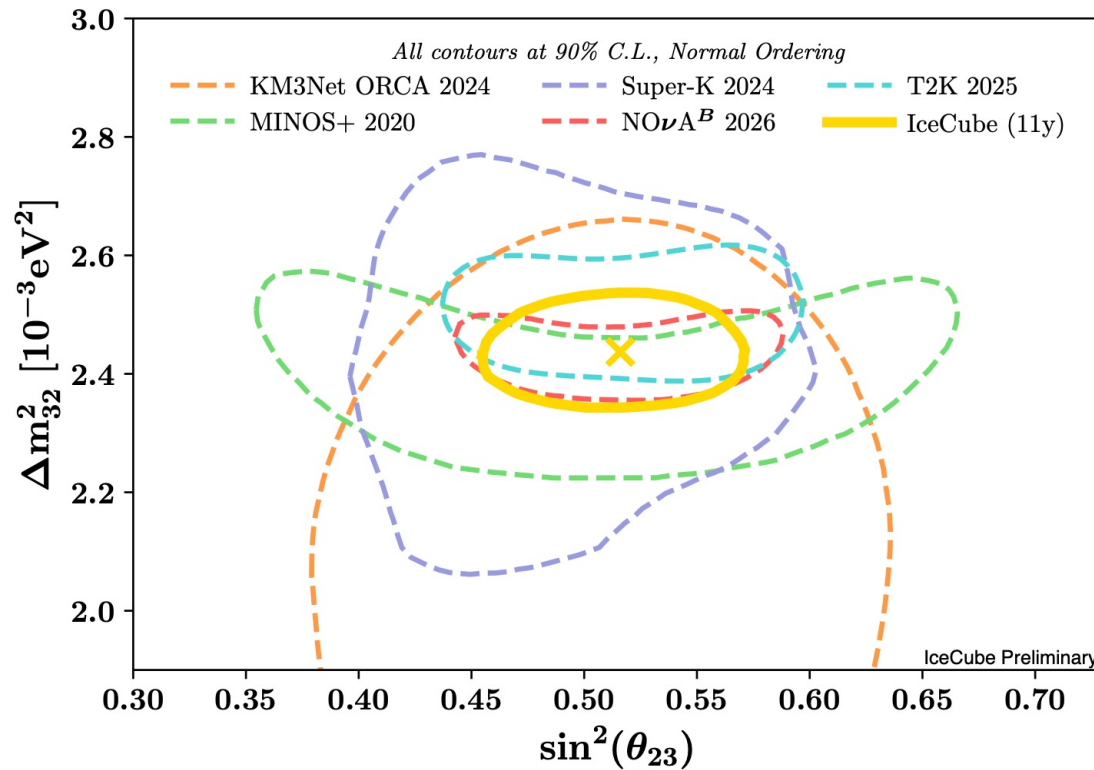


Atmospheric neutrinos



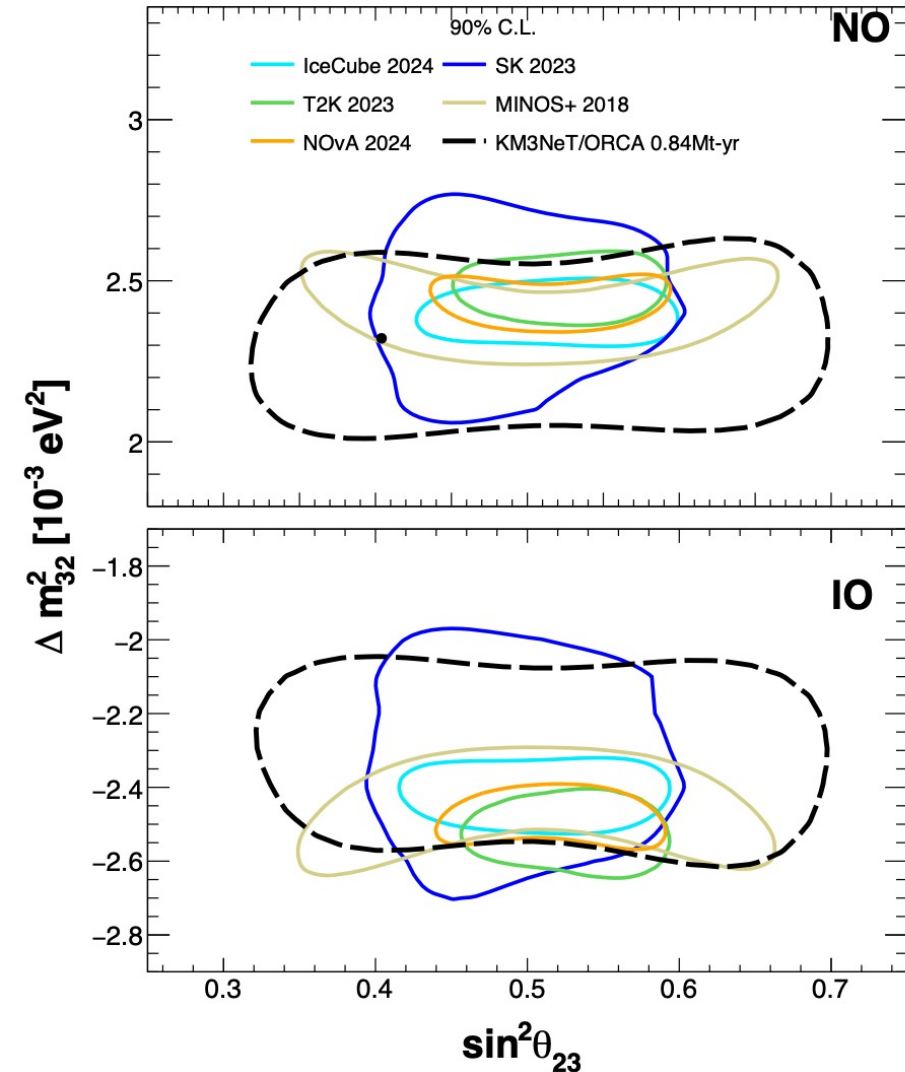
- IceCube 和 KM3NeT/ORCA 公布了新的大气中微子结果
- 对 Δm_{32}^2 和 $\sin^2 \theta_{23}$ 给出了具有竞争力的限制
- 对中微子质量顺序尚无显著偏好

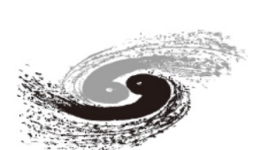
IceCube @Neutrino2026



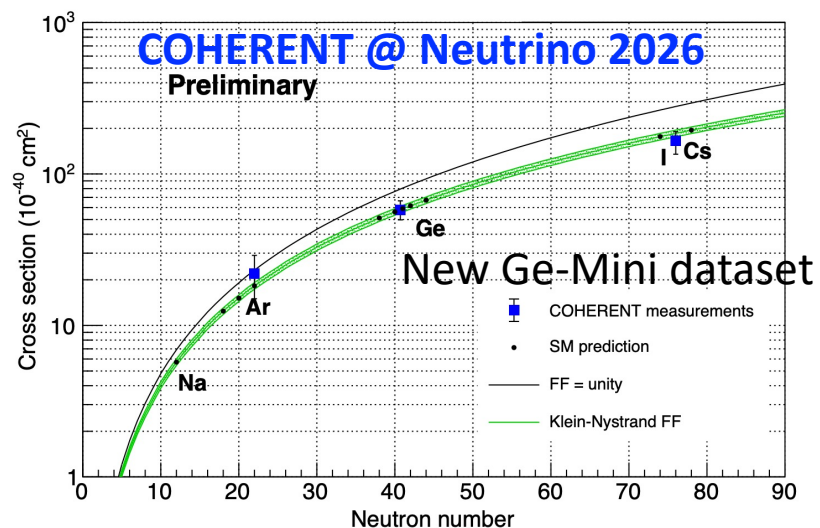
KM3NeT/ORCA @Neutrino2026

KM3NeT/ORCA 0.84Mt-yr Preliminary





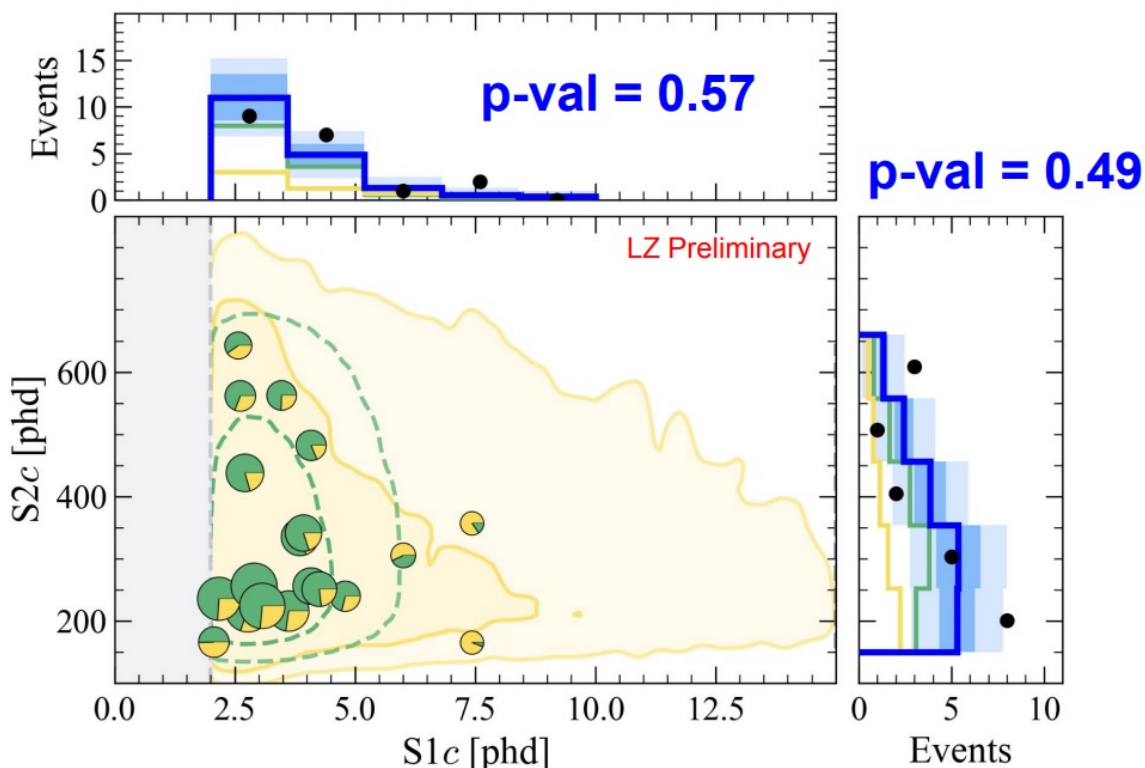
在不到十年的时间里，从首次观测迈向针对多种靶核的精密测量



在“中微子雾”中以 4.5σ 显著性观测到太阳 ^8B 中微子的 CEvNS 信号

LZ @ Neutrino 2026

^8B Accidentals



- PandaX: 2.64σ (PRL 133, 191001)
- XENONnT: 3.3σ (2604.06002)

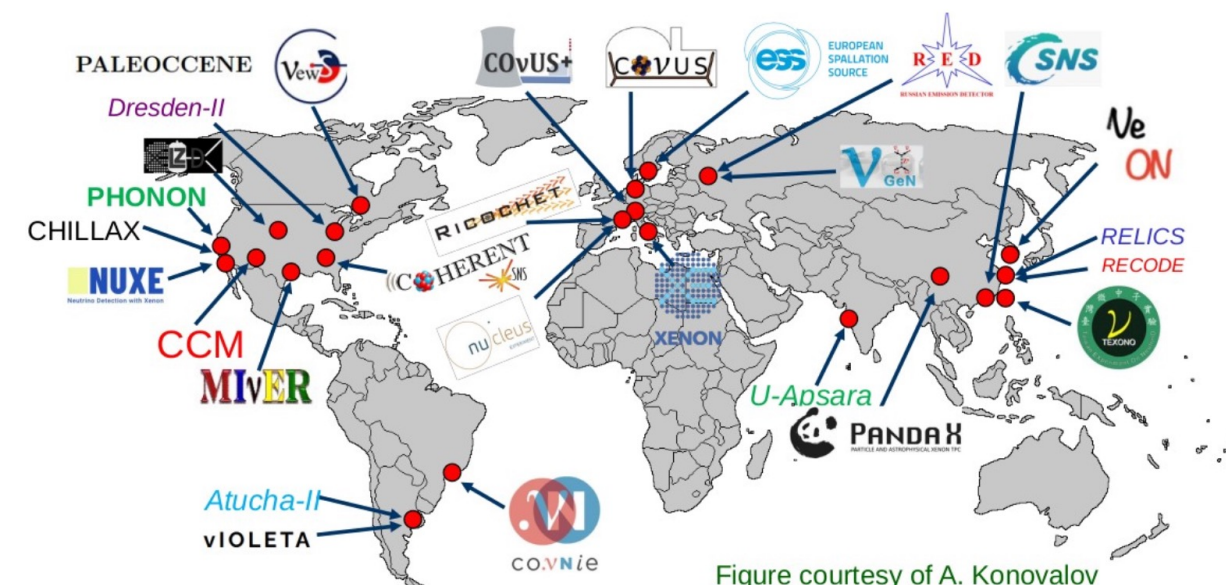
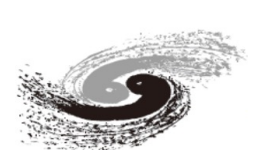


Figure courtesy of A. Konovalov



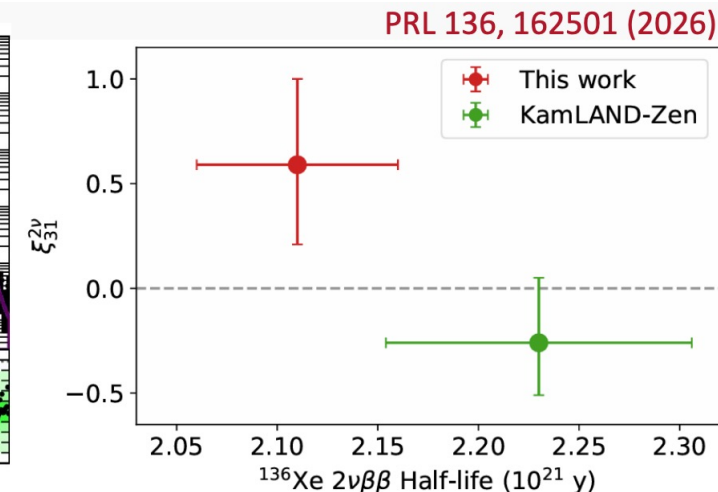
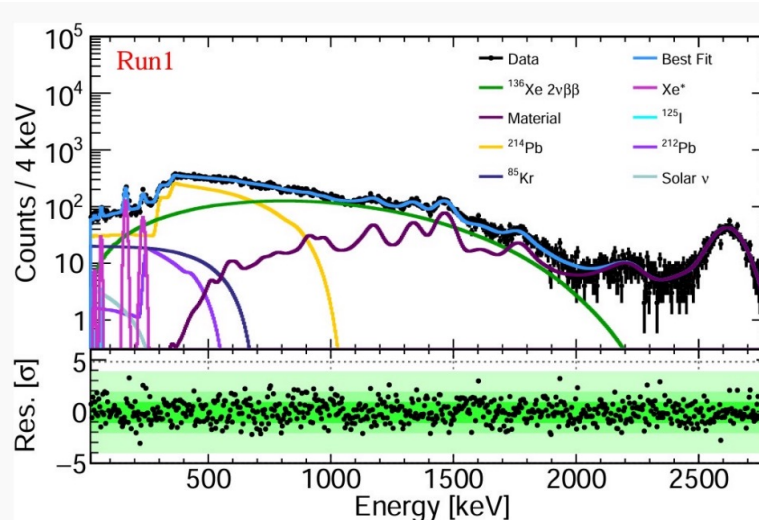
Active Neutrino Program in PandaX :



世界**最精确**的 ^{136}Xe $2\nu\beta\beta$ 半衰期测量:

$$(2.14 \pm 0.05) \times 10^{21} \text{ yr}$$

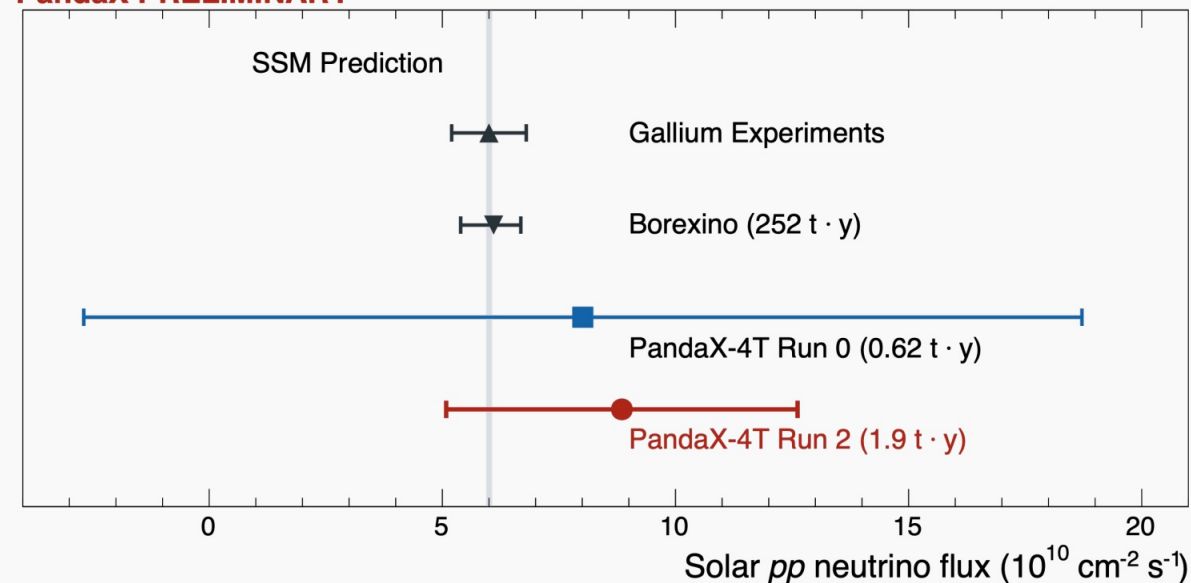
测量覆盖从 20 keV 到端点的近完整能谱, 并约束高阶核矩阵元贡献

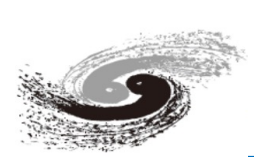


$$(T_{1/2}^{2\nu})^{-1} = (g_A^{\text{eff}})^4 |M_{\text{GT}}^{2\nu}|^2 (G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu})$$

PandaX-4T Run 2 使用 1.9 ton·yr 数据, 通过中微子-电子散射测量**太阳pp中微子**通量。相比 Run 0 不确定度显著降低, 结果与标准太阳模型一致。

PandaX PRELIMINARY





Summary



- ◆ 中微子物理已进入精密测量时代，反应堆中微子实验是高精度测量振荡参数不可或缺的手段。
- ◆ **JUNO** 探测器整体运行良好，达到或优于设计要求。
- ◆ 59天数据实现对 $\sin^2\theta_{12}$ 和 Δm_{21}^2 的世界领先精度测量，207天数据将测量精度进一步提高至原来的 1.3–1.5 倍。
- ◆ JUNO首次实现对 Δm_{31}^2 约 1% 精度的测量 以及对正质量排序的初步偏好。目前结合 NuFIT-LBL 和 Daya Bay 约束，正序偏好约为 2.3σ 。
- ◆ **首批地球中微子**测量结果给出的通量为 73 ± 11 TNU。
- ◆ 随着新一代实验不断发展，中国中微子研究将在精密测量、稀有过程搜索和新物理探索中发挥更加重要的国际作用。

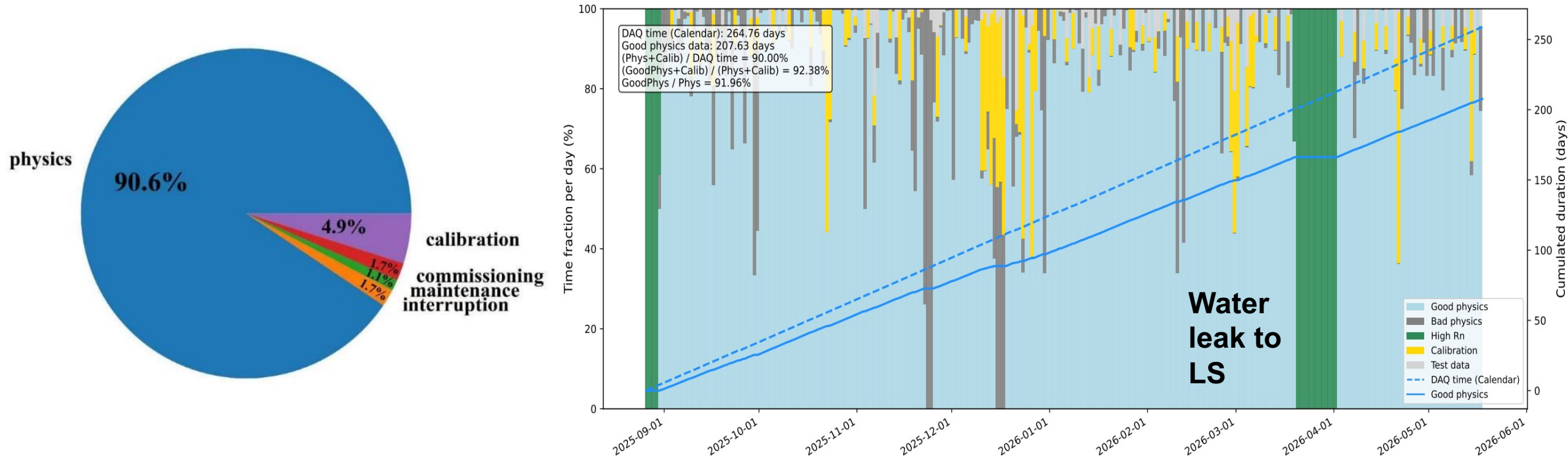
Back up

Data Taking

Posters: 338, 48,
354, 343, 254, 359



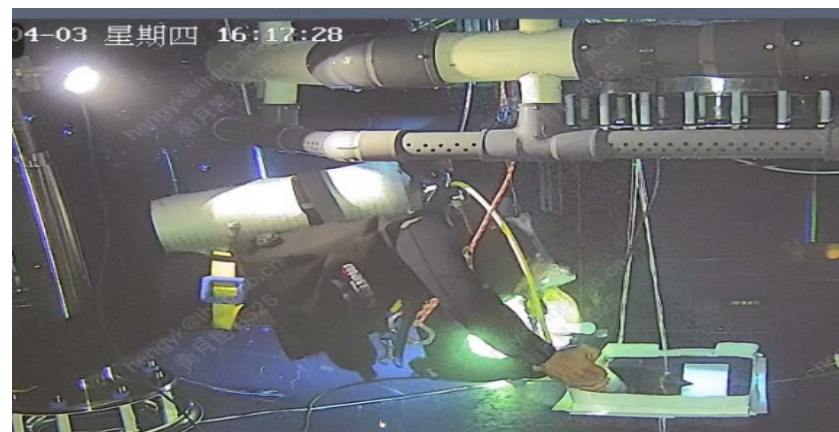
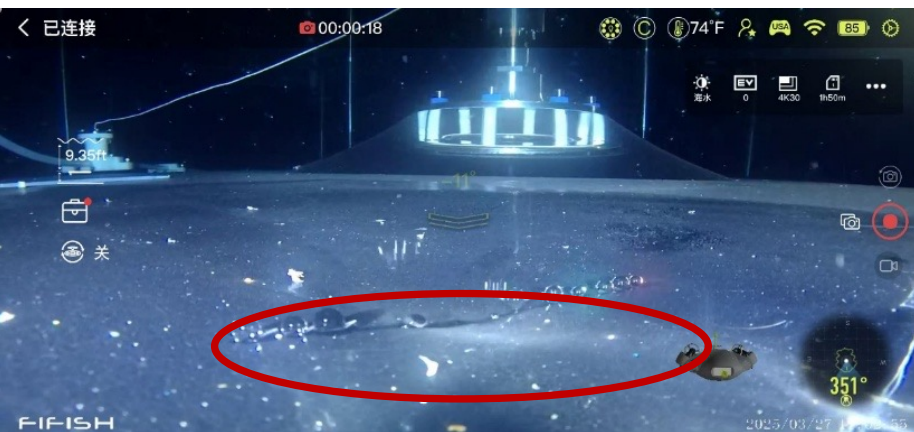
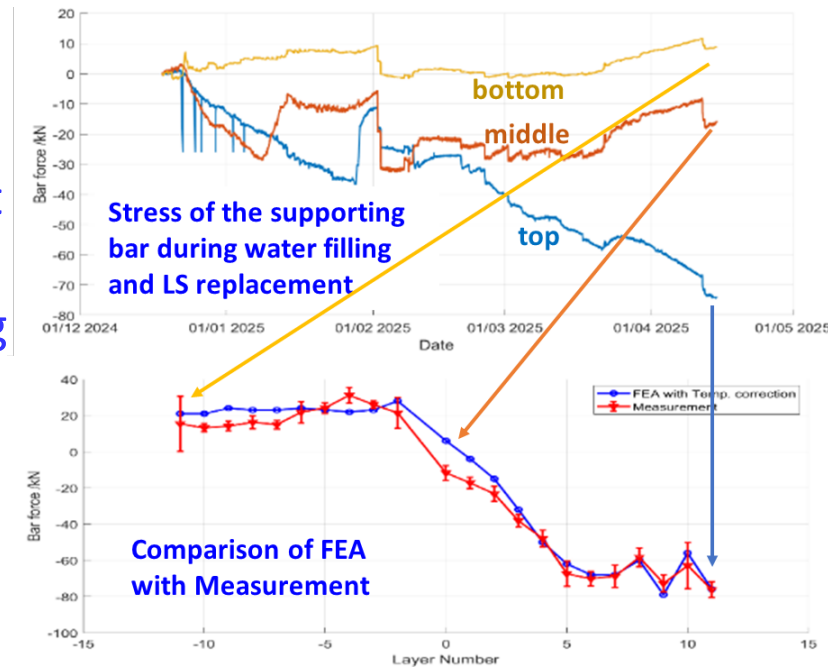
- Data taking period for this analysis: 2025.08.30-2026.05.18
- Golden data are selected for physics analysis



- Power outage due to weather is one of the main causes of interruptions

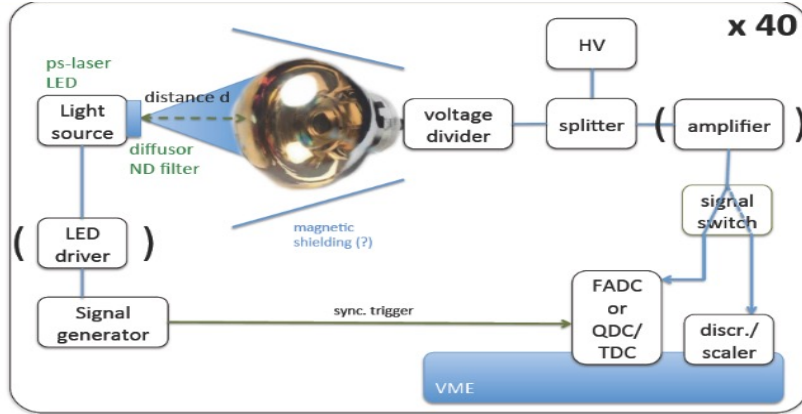
Cracks on the Acrylic Tank

- Main structure is safe, stress within expectations
- However, a LS leak to water happened on March 21, 2025:
 - ⇒ Abnormal trigger rate observed and confirmed by under water robot
 - ⇒ Leak was stopped within 1 week using epoxy and tape by divers
 - ⇒ Further repair by epoxy and acrylic plate to reduce the stress (pulling open the crack) by 50%
- Another leak of water to LS happened on March 19, 2026:
 - ⇒ Experienced divers were called to stop the leak within 2 days
 - ⇒ Further repair in the following two days
 - ⇒ A total of $\sim 1\text{Bq } ^{222}\text{Rn}$ went into LS, 13 days of data excluded
 - ⇒ No other increase of radioactive backgrounds in LS



PMT Testing and Installation

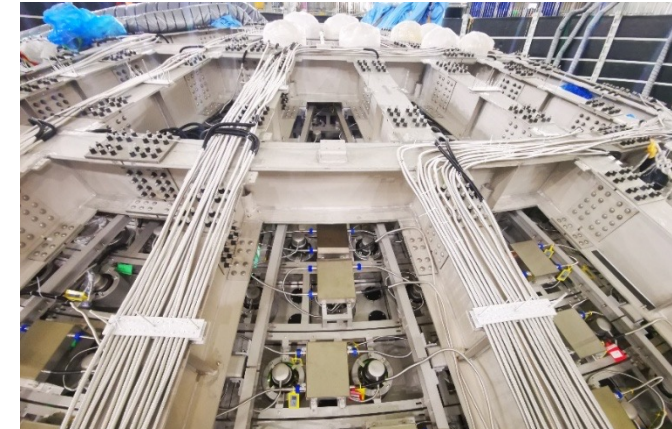
Container test stations



Scanning station



Cables in corrugated pipes



	LPMT (20-inch)		SPMT (3-inch)
	Hamamatsu	NNVT	HZC
Quantity	5000	15012	25600
Charge Collection	Dynode	MCP	Dynode
Photon Detection Efficiency	28.5%	30.1%	25%
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

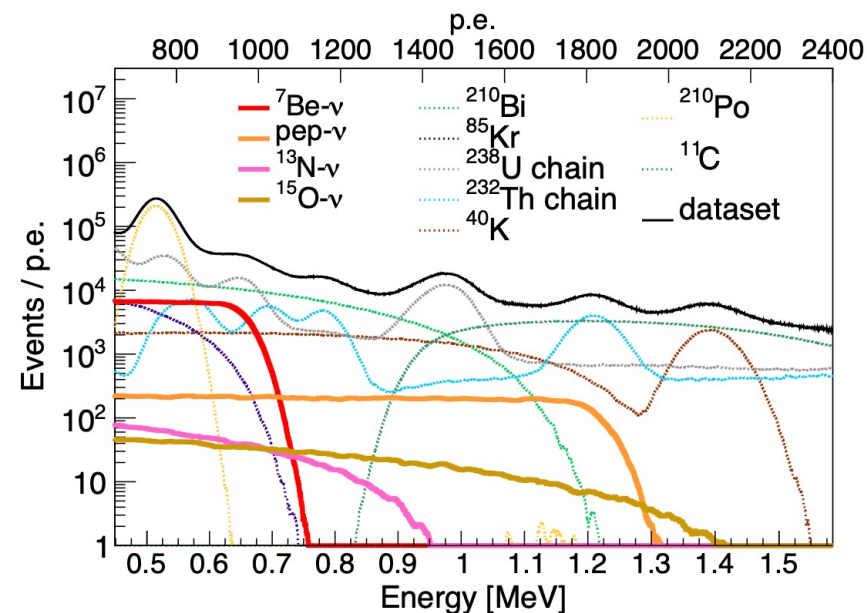


Neutrinos from Sun (Be7, pep and CNO)

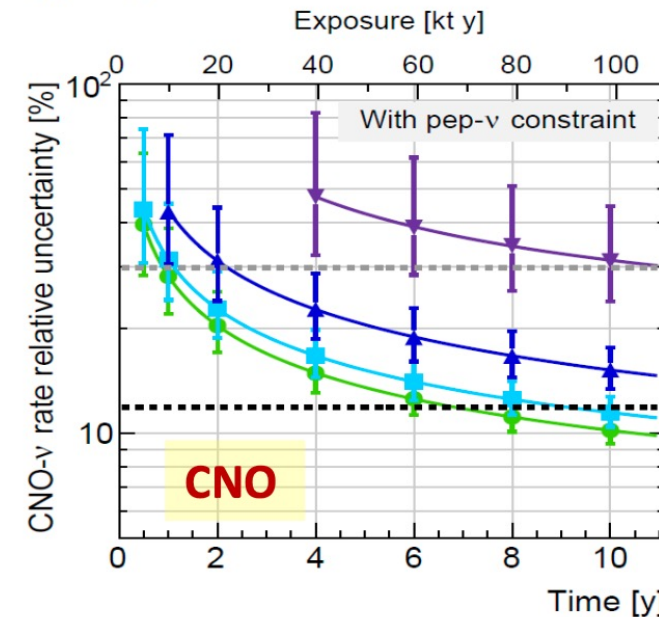
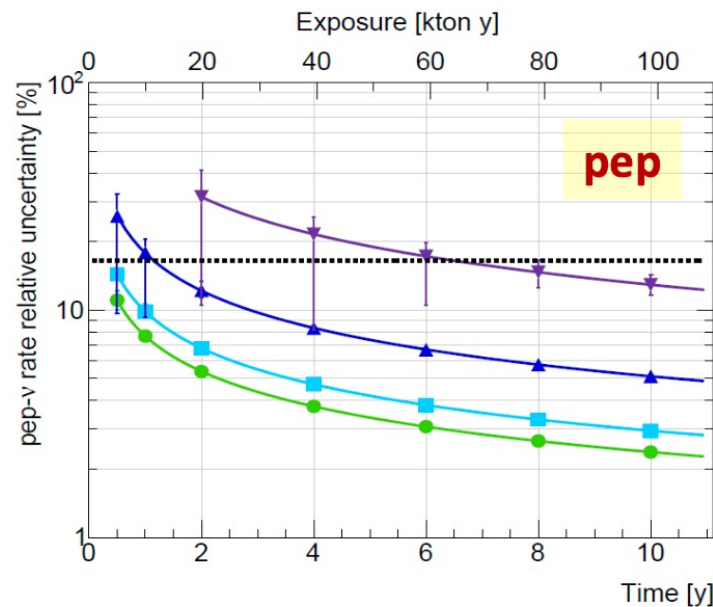
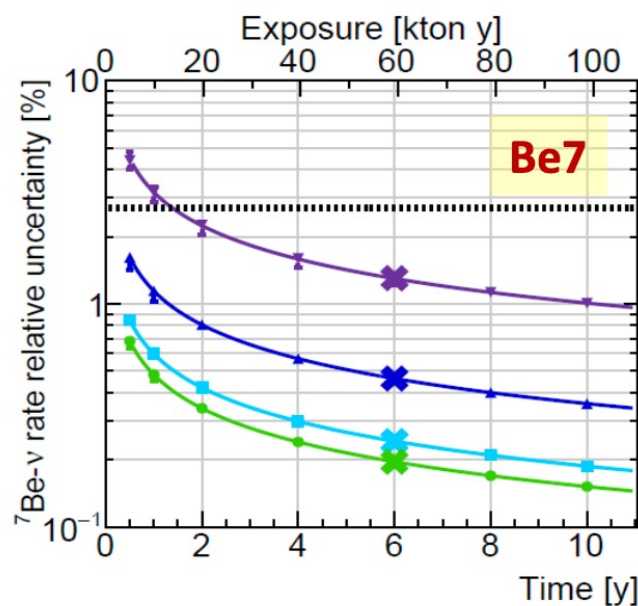
Radio-purity Scenario		^{40}K	^{85}Kr	$^{232}\text{Th-chain}$	$^{238}\text{U-chain}$	$^{210}\text{Pb}/^{210}\text{Bi}$	^{210}Po
IBD	$c \left[\frac{\text{g}}{\text{g}} \right]$	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	$R \left[\frac{\text{cpd}}{\text{kt}} \right]$	2289	5000	3508	15047	12031	12211
Baseline	$c \left[\frac{\text{g}}{\text{g}} \right]$	1×10^{-17}	-	1×10^{-16}	1×10^{-16}	5×10^{-24}	-
	$R \left[\frac{\text{cpd}}{\text{kt}} \right]$	229	500	351	1505	1203	1221
Ideal	$c \left[\frac{\text{g}}{\text{g}} \right]$	1×10^{-18}	-	1×10^{-17}	1×10^{-17}	1×10^{-24}	-
	$R \left[\frac{\text{cpd}}{\text{kt}} \right]$	23	100	35	150	241	244
Borexino	$c \left[\frac{\text{g}}{\text{g}} \right]$	-	-	$<5.7 \times 10^{-19}$	$<9.4 \times 10^{-20}$	-	-
	$R \left[\frac{\text{cpd}}{\text{kt}} \right]$	4.2	100	1.4	2	115	446.9

NOTE: Contribution from pileup and reactor neutrinos found negligible in the ROI

No detector systematics is included

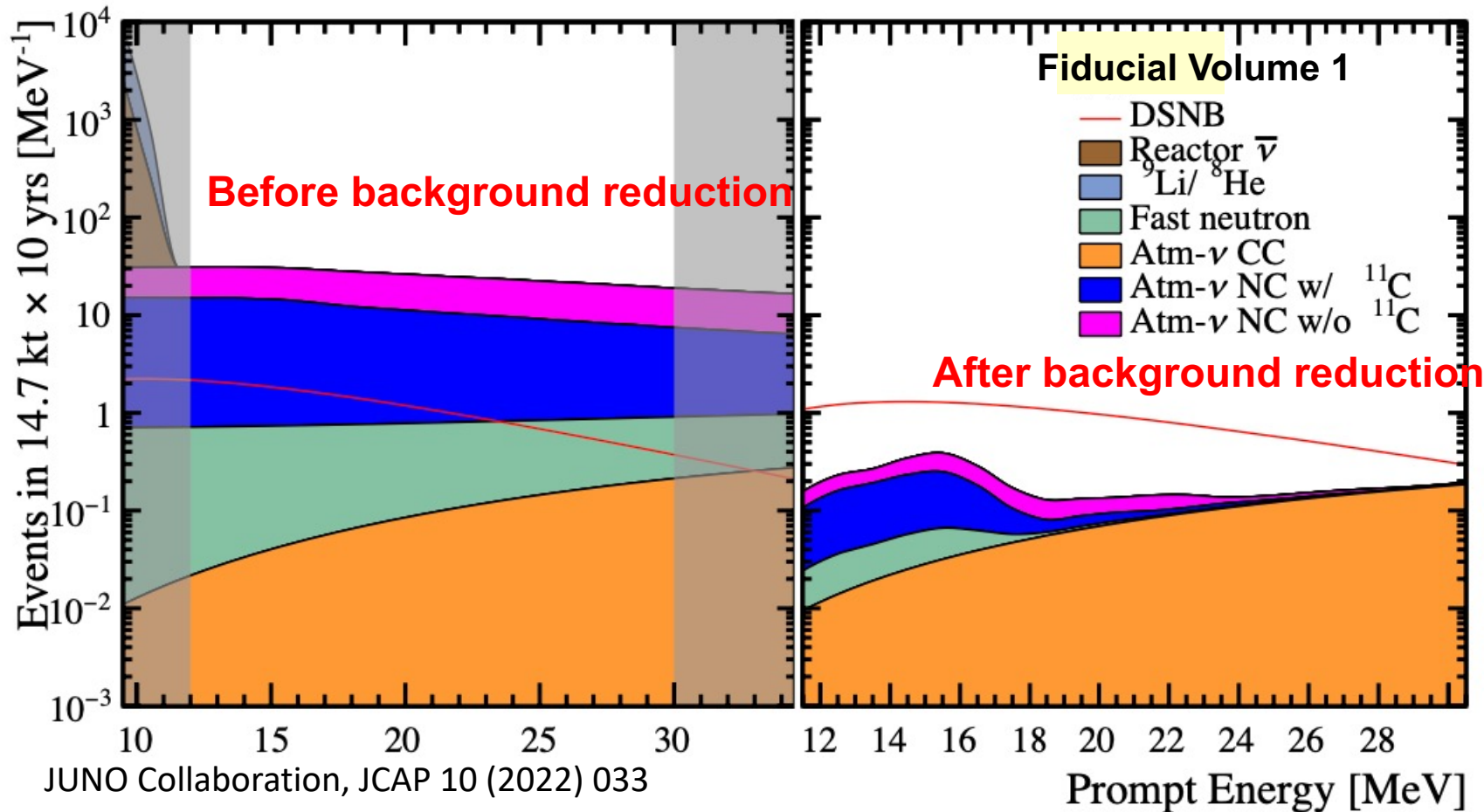


Angel Abusleme et al
JCAP10(2023)022



Supernova Relic Neutrinos

Background Reduction Techniques: Muon Veto, Fiducial Volume Cut, Pulse Shape Discrimination, Triple Coincidence cuts, ...



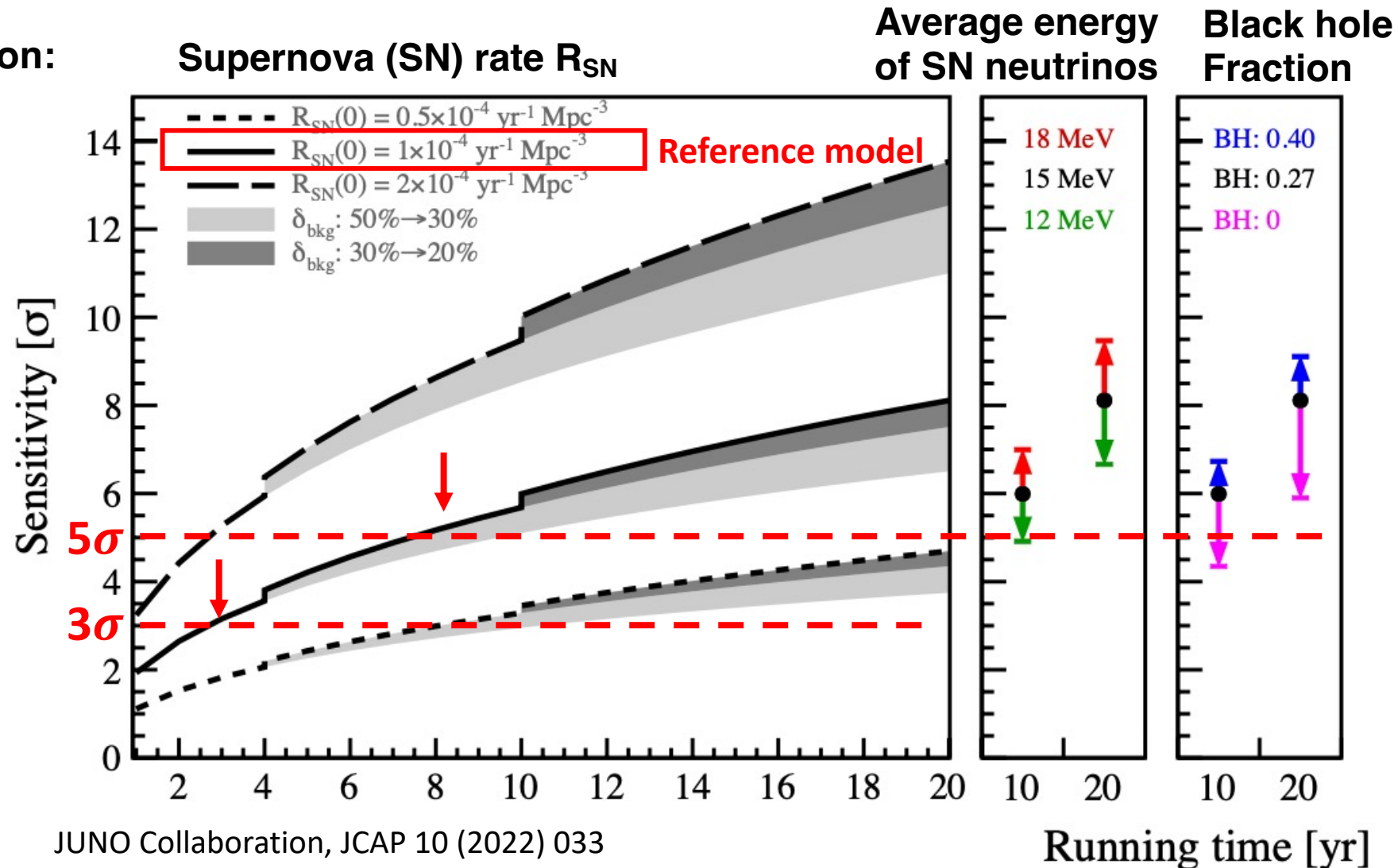
Prompt-like: nuclear de-excitation and recoil

Delayed-like: neutron capture

The dominant background for DSNB detection comes from **atmospheric neutrinos interacting via neutral-current (NC) processes** with ${}^{12}\text{C}$ nuclei in JUNO's liquid scintillator.

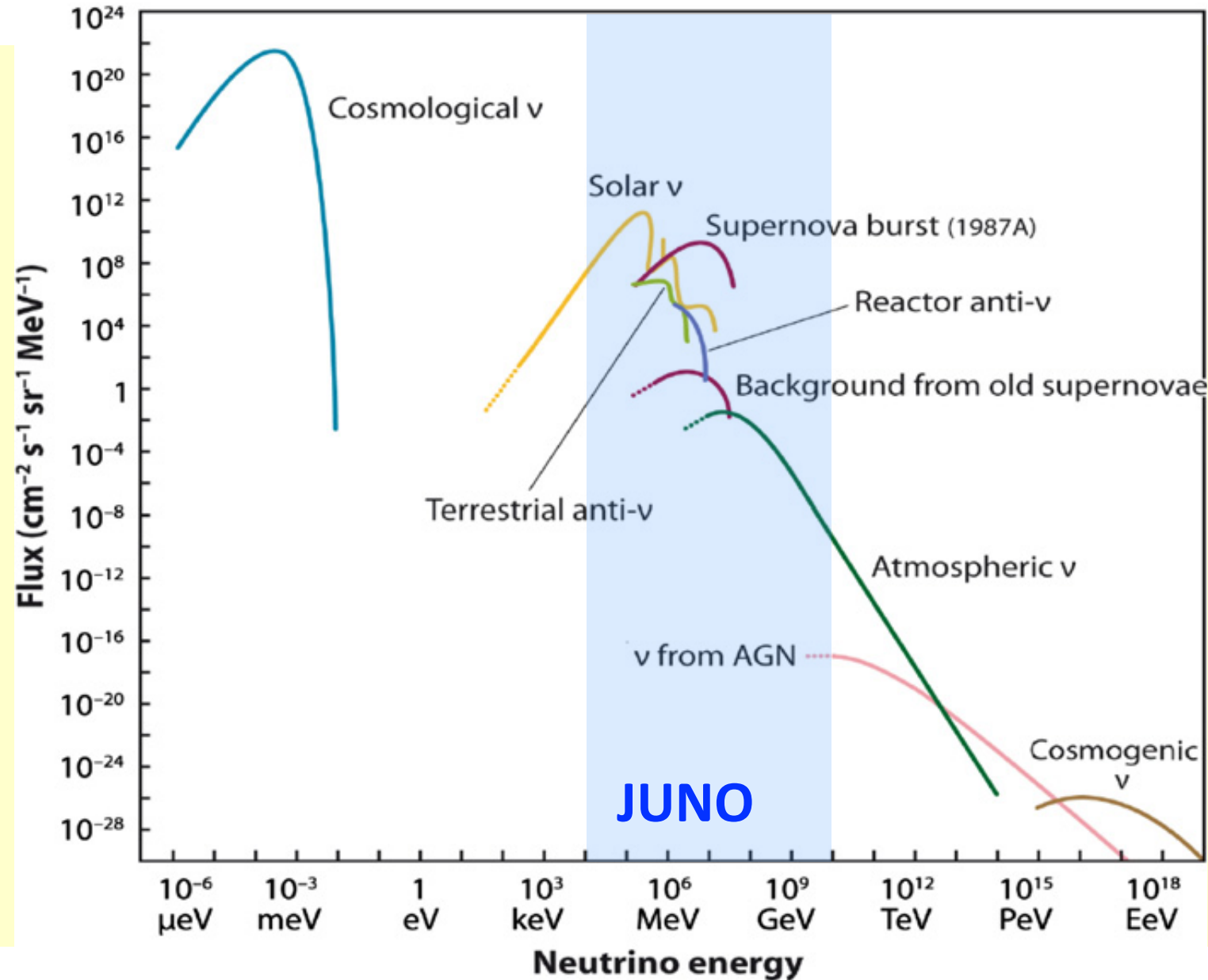
Supernova Relic Neutrinos

Key information:

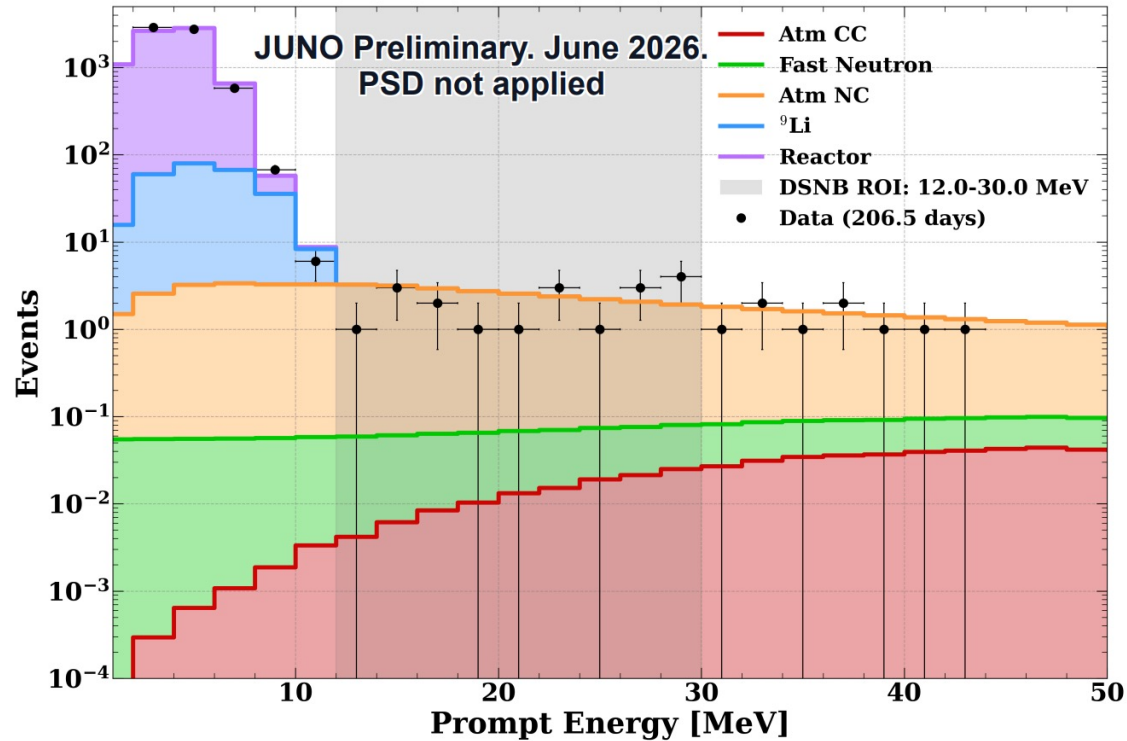


With the reference model: 3σ (3 yrs) and $>5\sigma$ (10 yrs)

Neutrino from Different Sources



New results released in Neutrino 2026

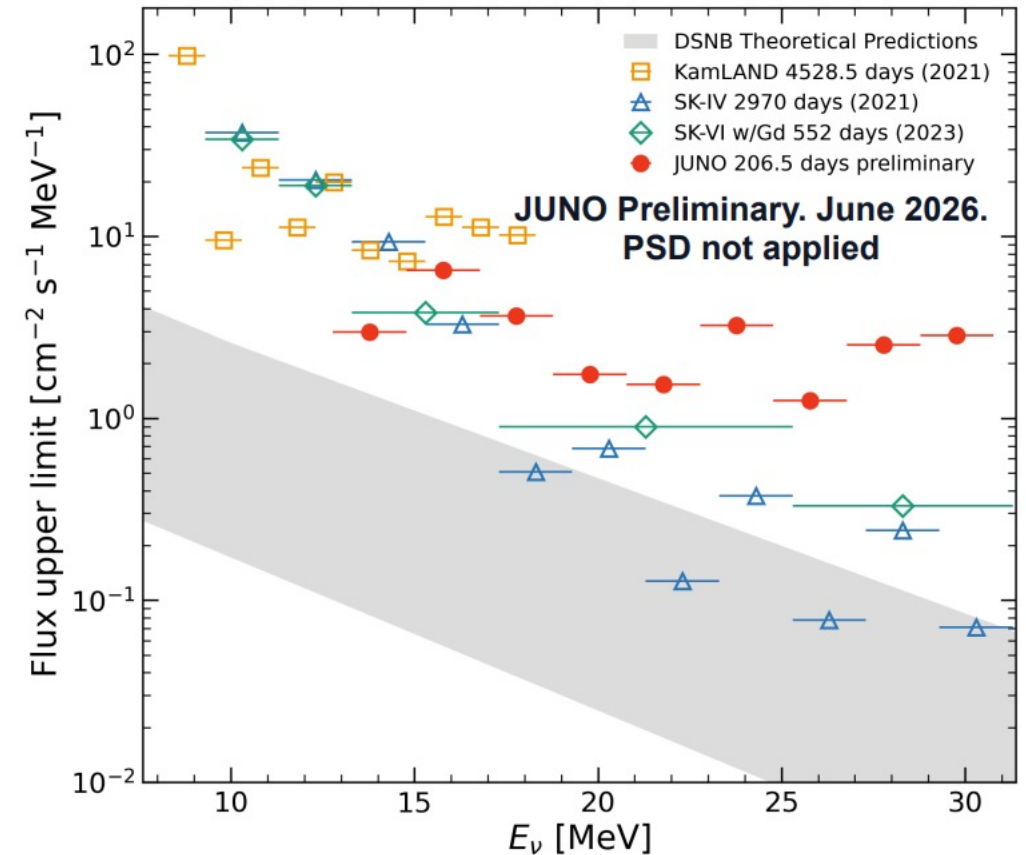


Prompt-energy spectrum; the shaded band marks the DSNB search region.

- 12–30 MeV window: 19 candidates with 206.5-day exposure.
- Total predicted background: 21.3 ± 10.5 events.

$$\phi_{90} = \frac{N_{90}}{N_p \cdot \sigma \cdot \epsilon_{\text{IBD}} \cdot T},$$

N_{90} : Feldman-Cousins 90% C.L. signal-event limit
 N_p : target protons
 ϵ_{IBD} : efficiency
 σ : IBD cross section
 T : exposure



Model-independent 90% C.L. upper limits on the DSNB $\bar{\nu}_e$ flux, compared with SK-IV [3], KamLAND [4], SK-IV-Gd [5] and DSNB predictions [6].

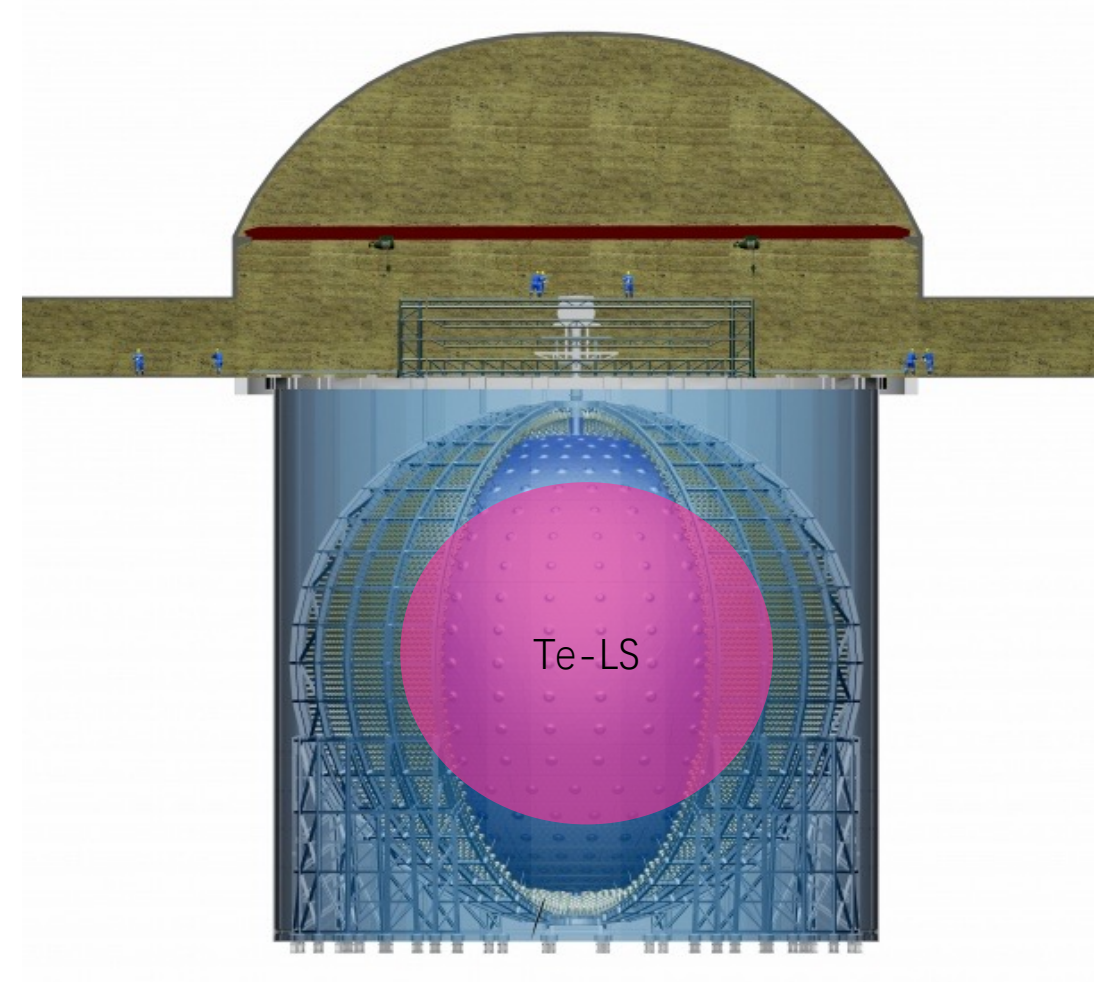
JUNO- $0\nu\beta\beta$ Upgrade

JUNO offers a unique opportunity to search for $0\nu\beta\beta$

- 20 kton LS $\rightarrow$ 100-ton scale isotope loading (e.g., Tellurium)
- Low background
- Energy resolution $< 3\%$ @ 1 MeV

Critical R&D

- Isotope loading technology
- Background control



Concept of the experiment

Parameters in the 3-flavor Neutrino Paradigm

◆ Neutrino oscillation indicates non-zero neutrino mass

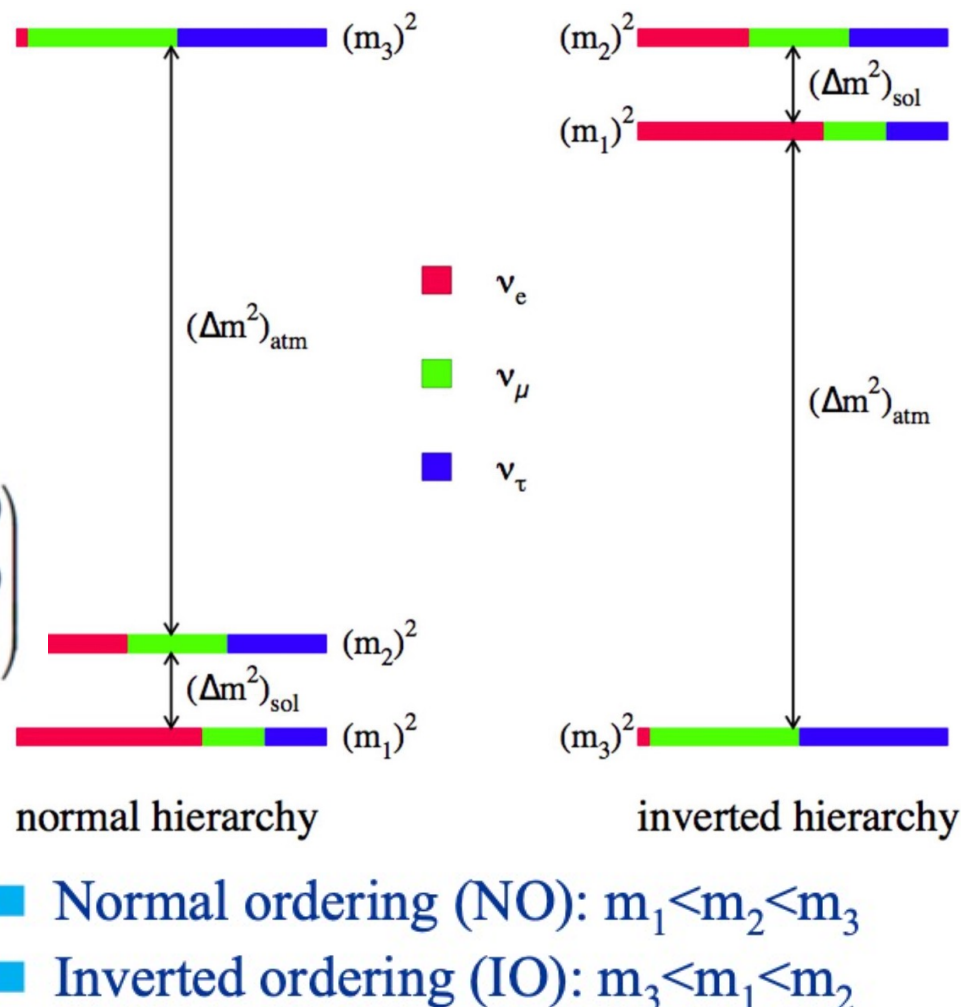
Neutrino flavor states and mass states are connected by a unitary matrix U :

$$\text{味本征态} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \text{质量本征态}$$

PMNS 矩阵 :

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

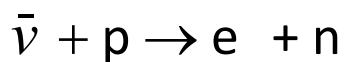
- Known: $\theta_{23}, \theta_{12}, \theta_{13}, |\Delta m_{32}^2|, \Delta m_{21}^2$
- Unknown: sign of $\Delta m_{32}^2, \delta_{\text{CP}}, \text{octant of } \theta_{23}$



第三个质量本征态到底比前两个更重还是更轻？

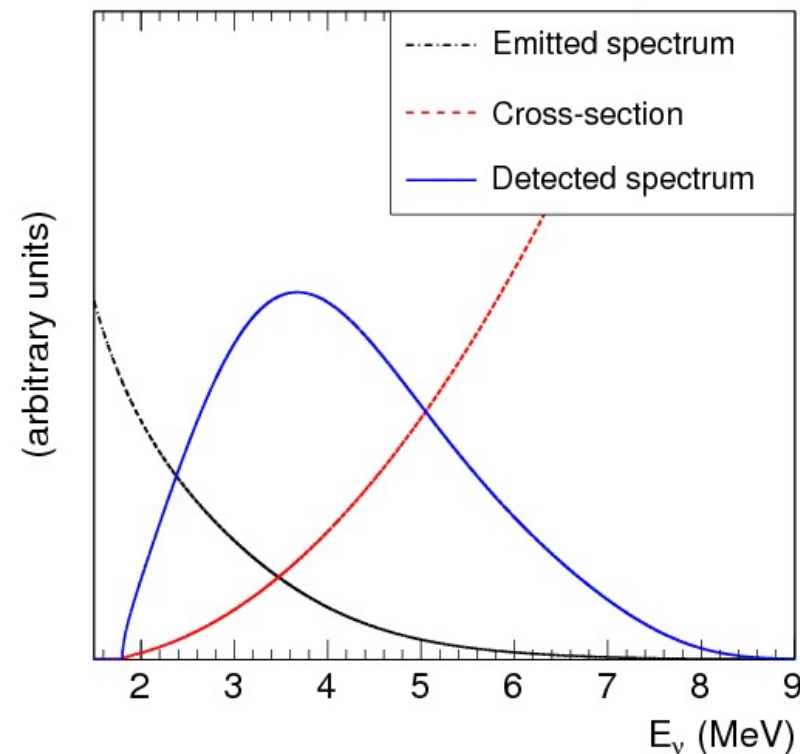
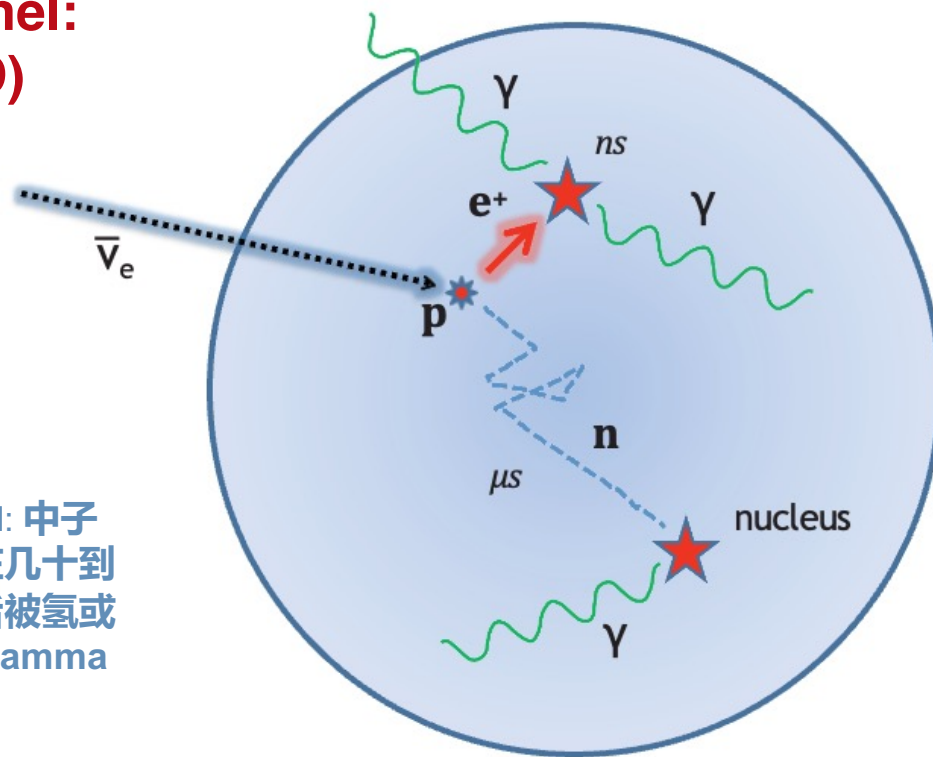
Reactor Antineutrino Detection

Primary detection channel: Inverse Beta Decay (IBD)

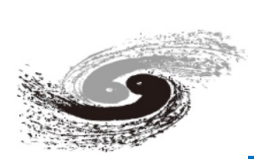


Prompt signal:
 e^+ 在液闪中
沉积能量, 并
最终湮灭产生
两个 gamma

Delayed signal: 中子
会热化, 并在几十到
几百微秒之后被氢或
碳俘获释放 gamma



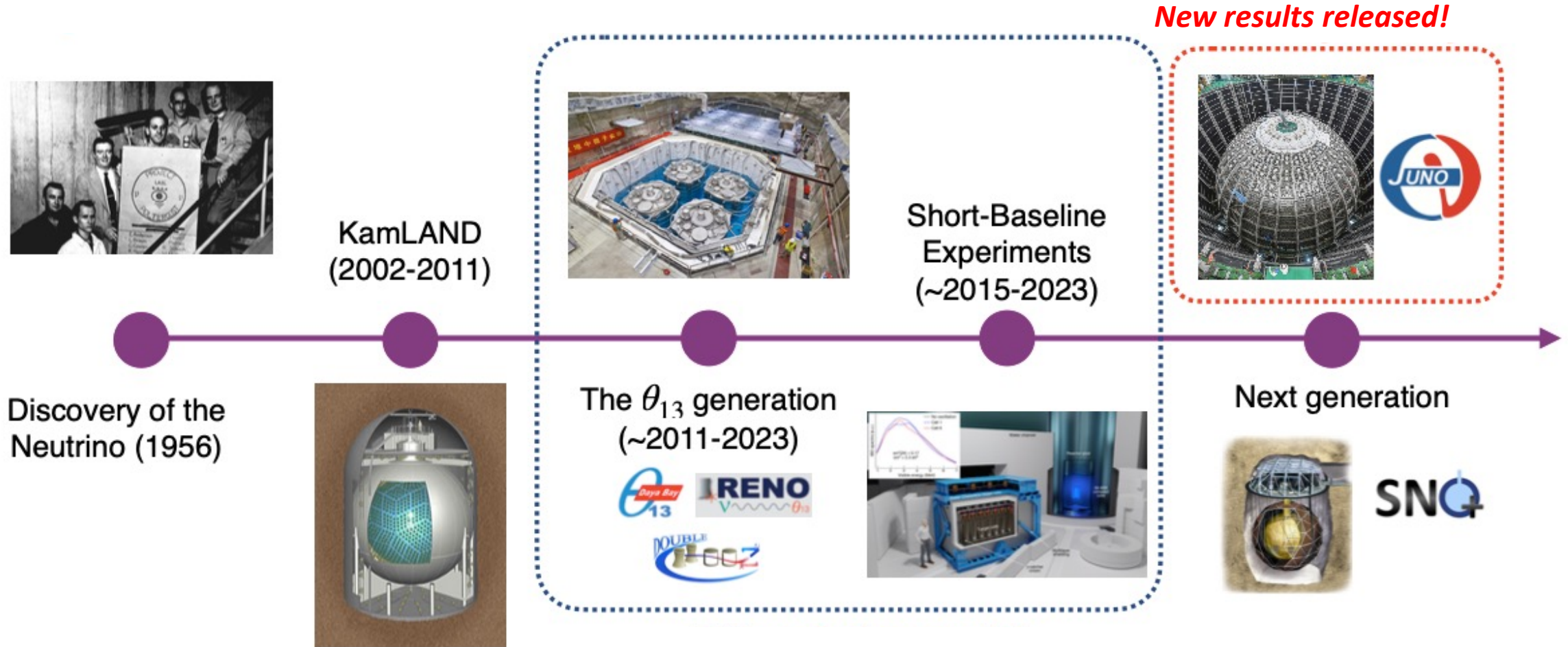
- ◆ 快和慢两个信号在时间和空间上相关, 这使得我们能够非常有效地区分真正的反中微子事件和随机本底。
- ◆ 快信号能量和入射反中微子能量有一个简单关系: $E_{\bar{\nu}_e} \approx E_{e^+} + 0.78 \text{ MeV}$



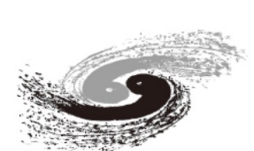
History of Reactor Neutrino Experiments



◆ 我们正进入反应堆中微子实验的新时代



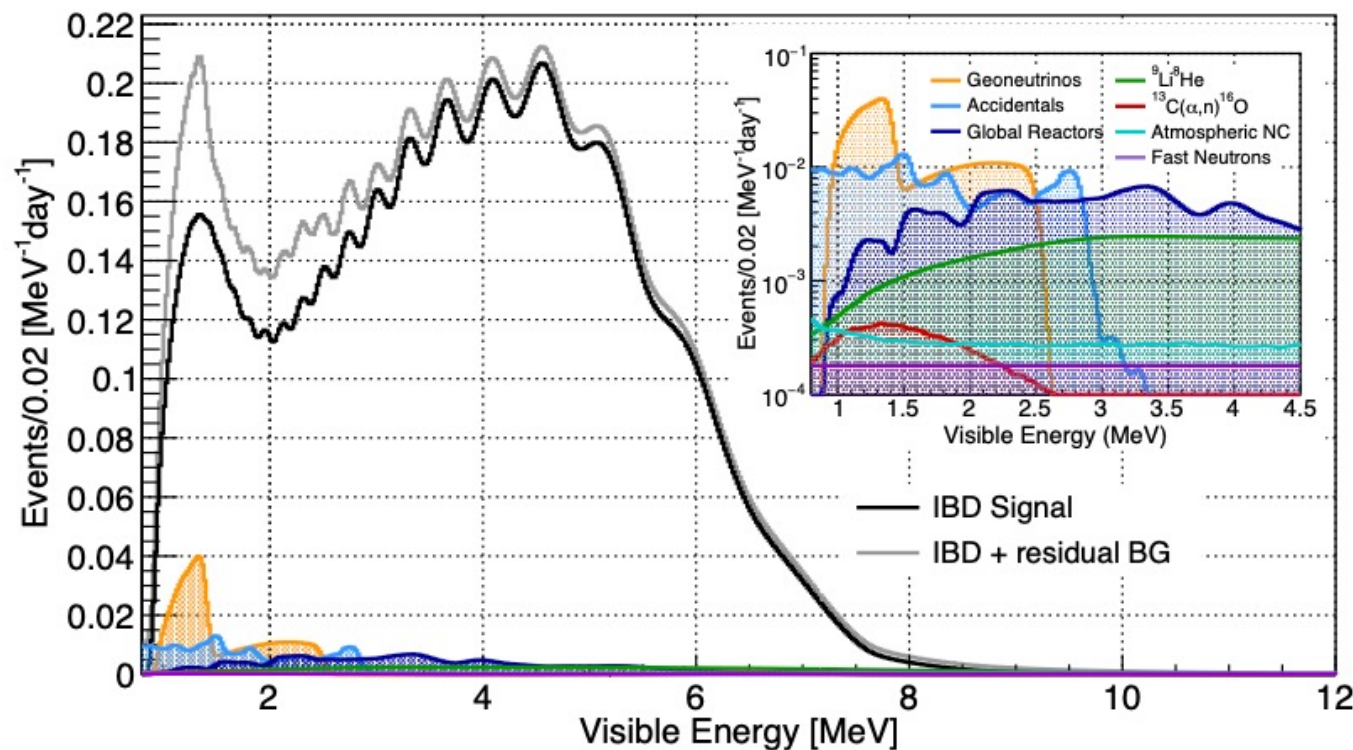
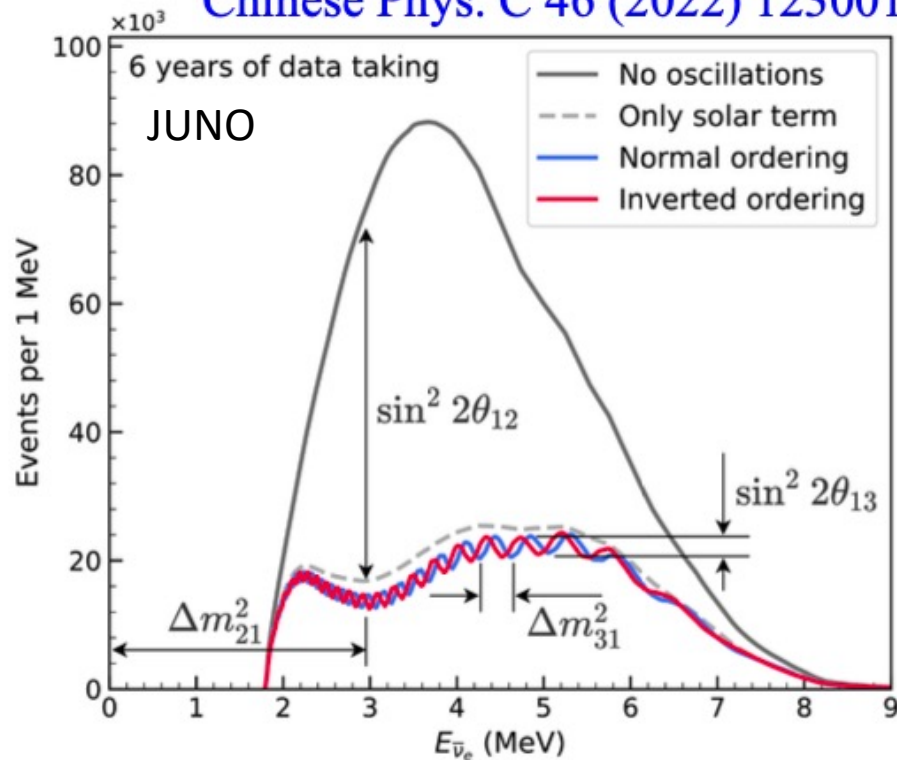
Presented by J. Pedro Ochoa-Ricoux
Physics of the Two Infinities Conference, 2025



Mass Ordering by Reactor Neutrinos



Chinese Phys. C 46 (2022) 123001



$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

$$P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$

$$P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$$

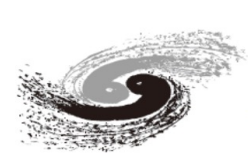
$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

$$\text{NH} : |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$

$$\text{IH} : |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

$$\frac{\Delta m^2_{21}}{|\Delta m^2_{32}|} \sim 3\%$$

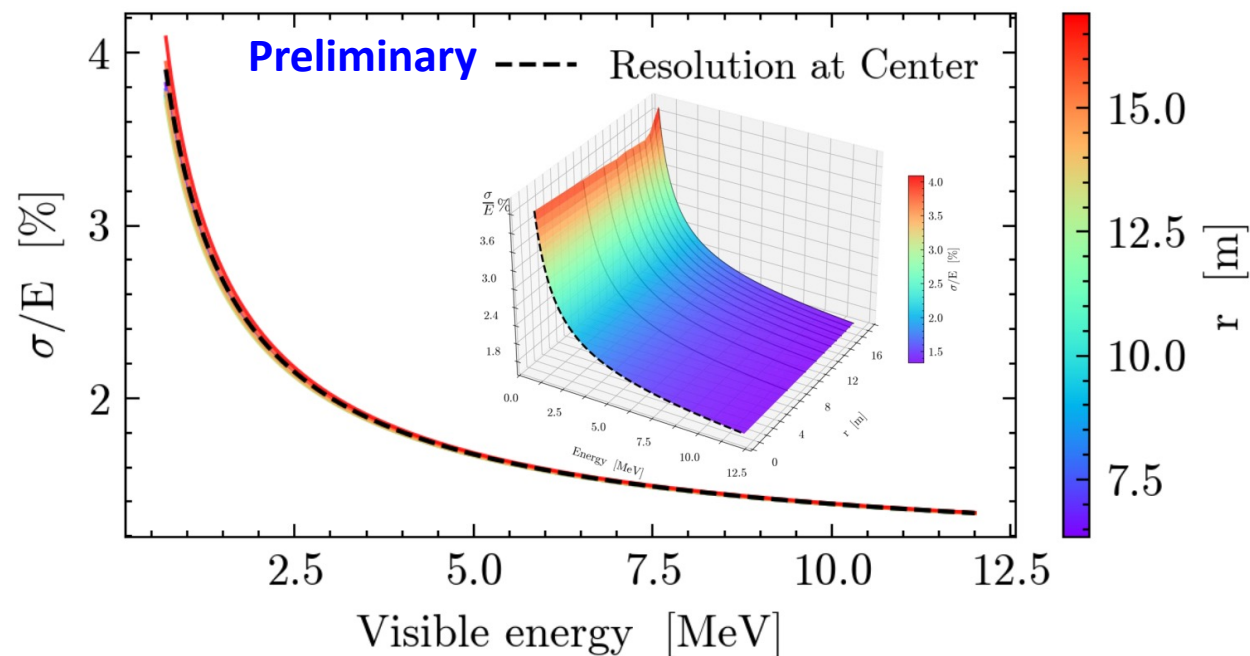
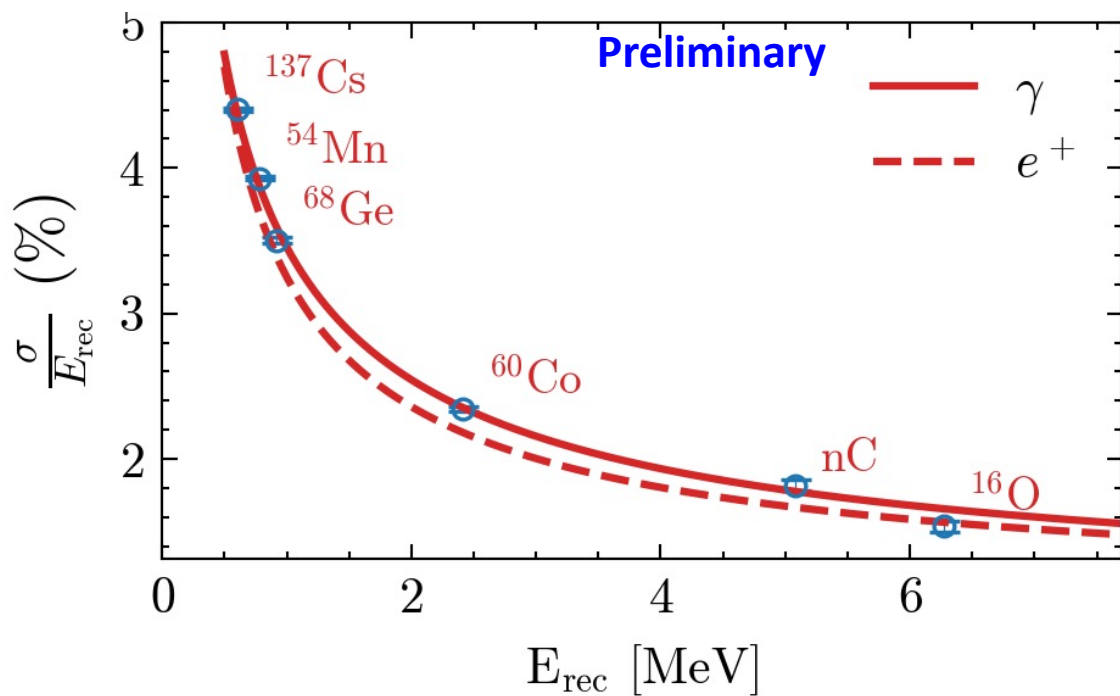
需要很高的统计量、非常好的能量分辨率，以及很低的本底

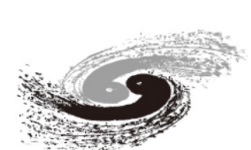


Energy Resolution Model



- 能量分辨率取决于粒子种类、能量和空间位置
- 基于 Geant4 模拟以及 α, γ 标定源数据，建立了随径向位置 R 变化的正电子 (e^+) 能量分辨率解析模型
- 在 5% 的事例中加入 ^{14}C 堆积效应，并利用能量响应矩阵拟合正电子能谱

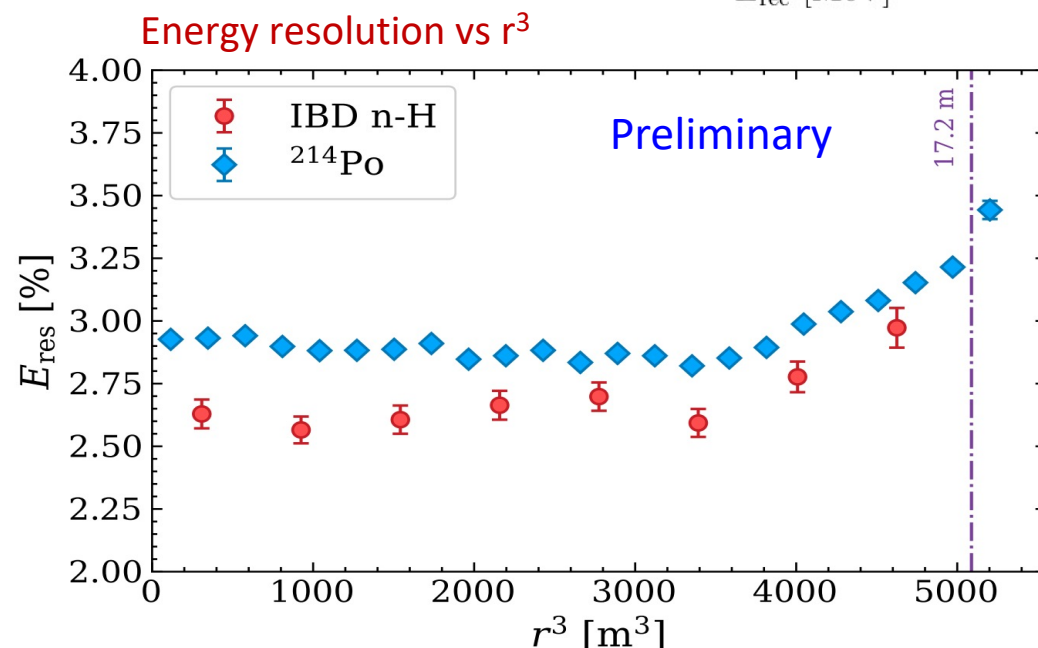
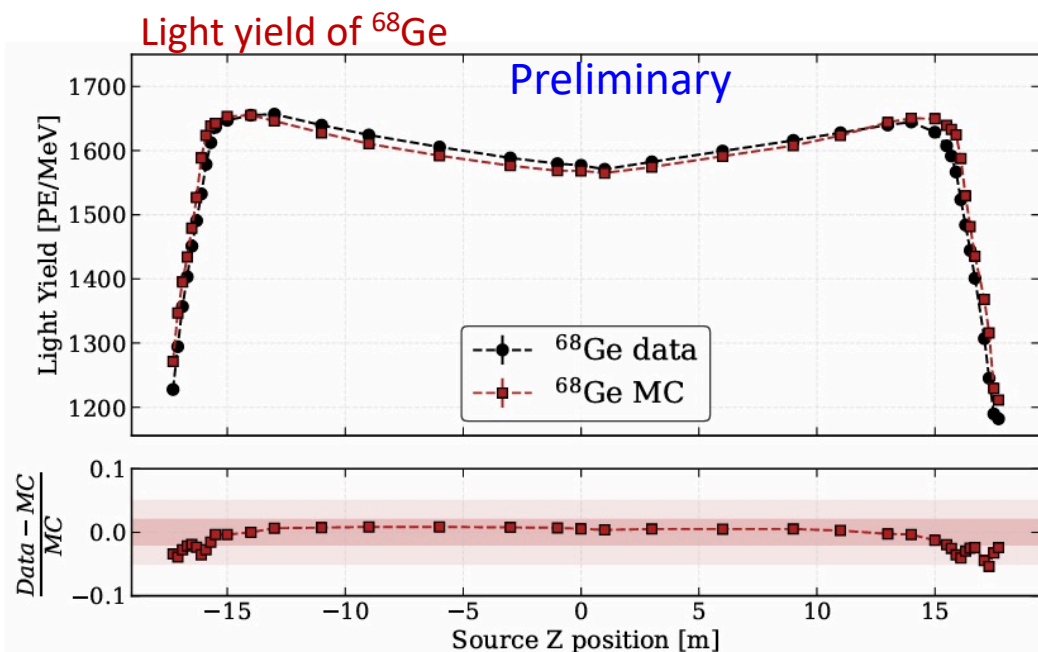
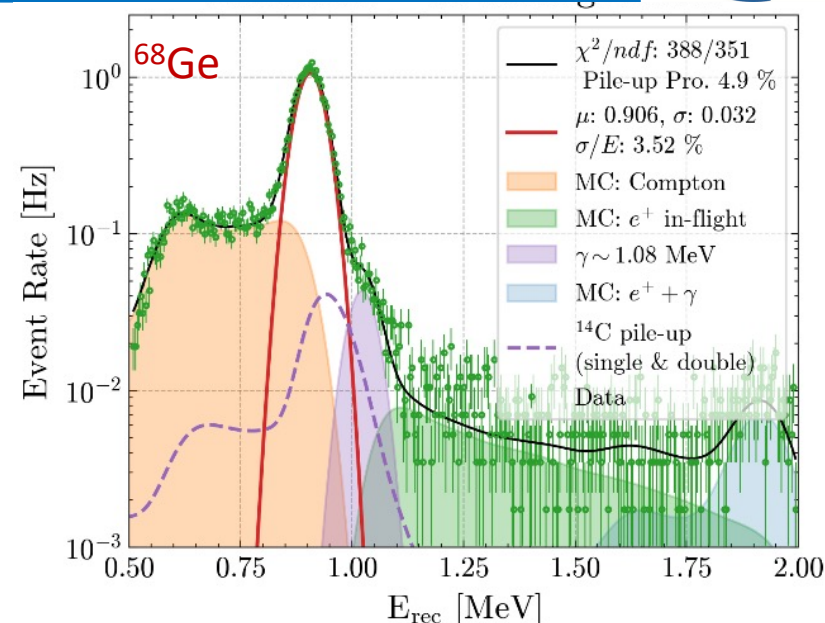


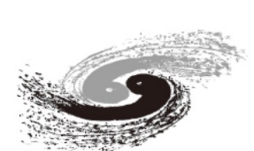


Light Yield and Energy Resolution



- 在探测器中心, ^{68}Ge 的光产额约为 **1600 PE/MeV**, 中子的光产额约为 **1785 PE/MeV**, 与蒙特卡洛模拟结果符合良好
- 在探测器中心, ^{68}Ge 在 $2 \times 0.511 \text{ MeV}$ 处的能量分辨率约为 **3.5%**, 略差于预期的 **3.1%**
 - 需要进一步改进切伦科夫过程、光学边界和 δ 电子等过程的模拟
 - 可能的改进包括: 利用机器学习方法去除 ^{14}C 本底、增加标定数据, 以及改进事例重建和拟合方法等
- ^{214}Po 的 α 粒子在 0.93MeV 可见能量处的能量分辨率约为 **2.9%**





Milestones in Neutrino Physics



◆ Discovery of neutrinos and their properties



◆ Neutrino oscillations



◆ Neutrinos as a tool to explore the universe

