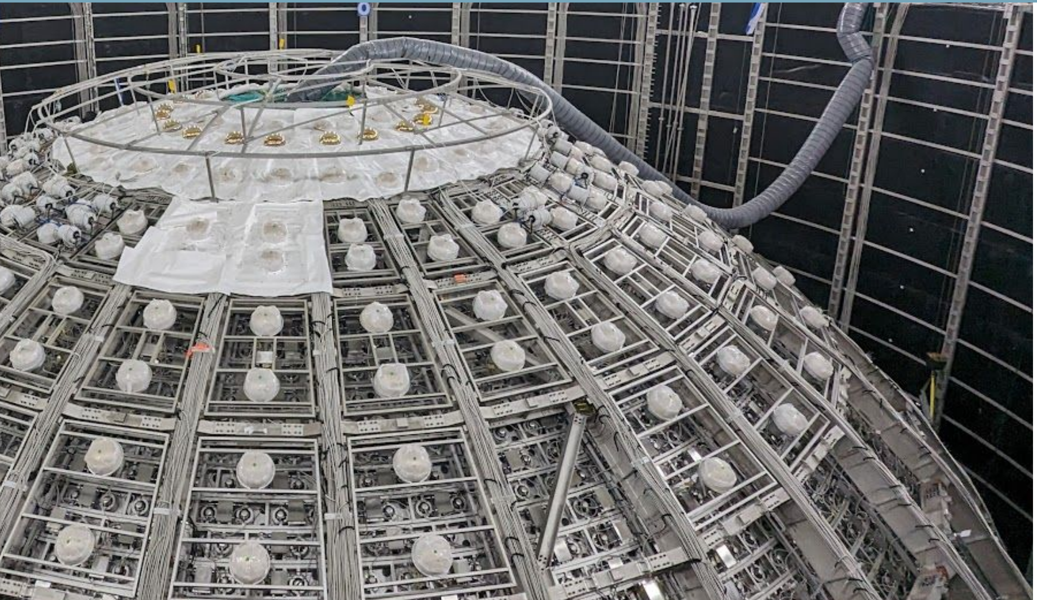
XX International Workshop on Neutrino Telescopes
October 23-27, 2023

The JUNO Experiment

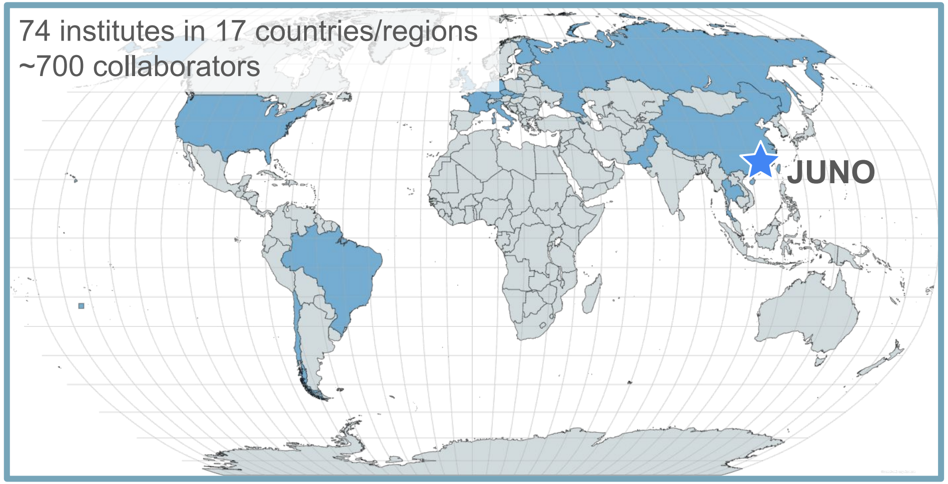


Yury Malyshkin[1,2]
on behalf of the JUNO collaboration

1. GSI Helmholtzzentrum für Schwerionenforschung, Germany
2. Forschungzentrum Jülich GmbH, Germany

Jiangmen Underground Neutrino Observatory

- Located in South China
(~150 km from Guangzhou and Hong Kong)



Jiangmen **U**nderground **N**eutrino **O**bservatory

- Located in South China
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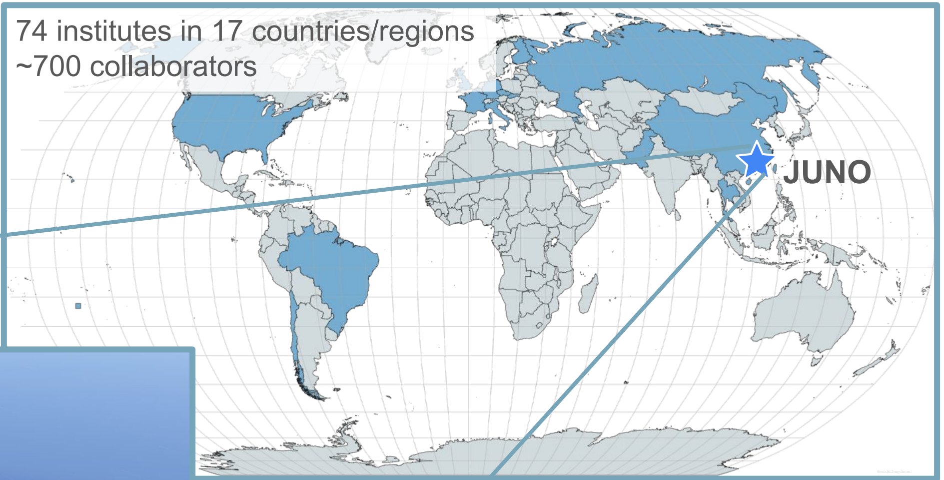
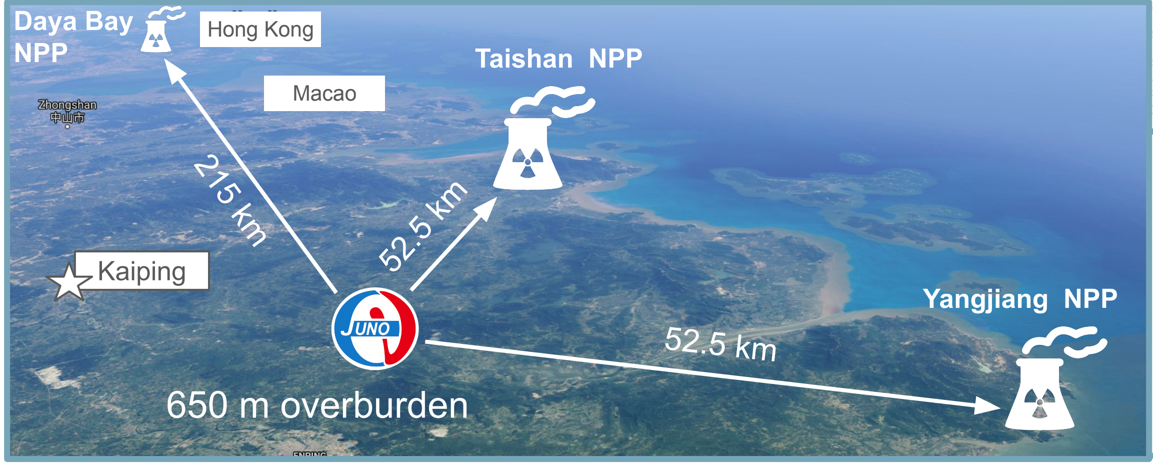
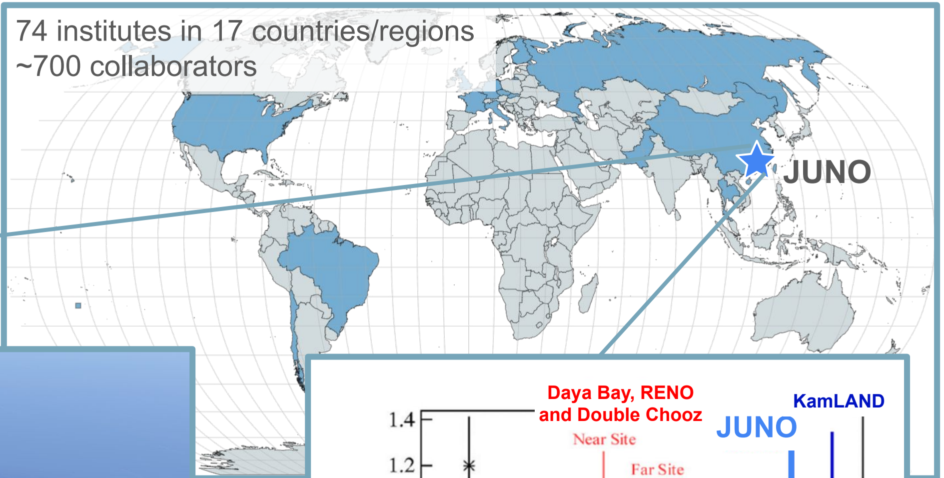
- Designed to measure reactor anti-ν_e

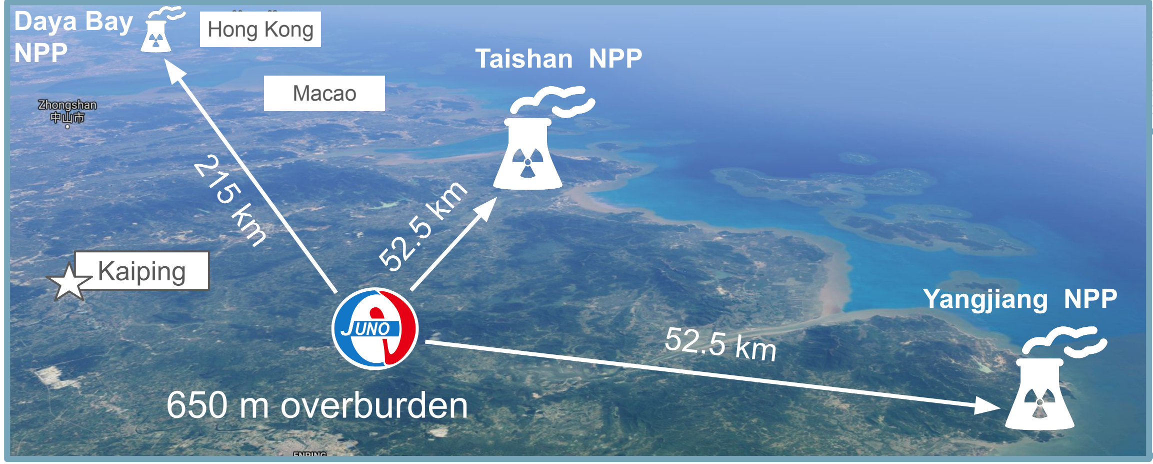


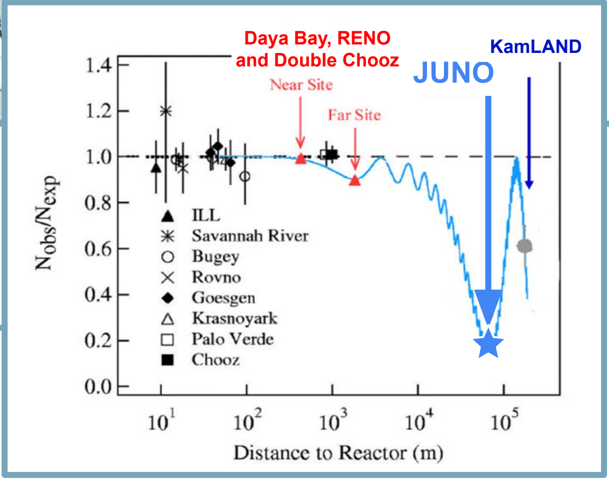


Jiangmen Underground Neutrino Observatory

- Located in South China
  (~150 km from Guangzhou and Hong Kong)
- Designed to measure reactor anti-ν_e
- Optimized position for resolving neutrino mass ordering (NMO)



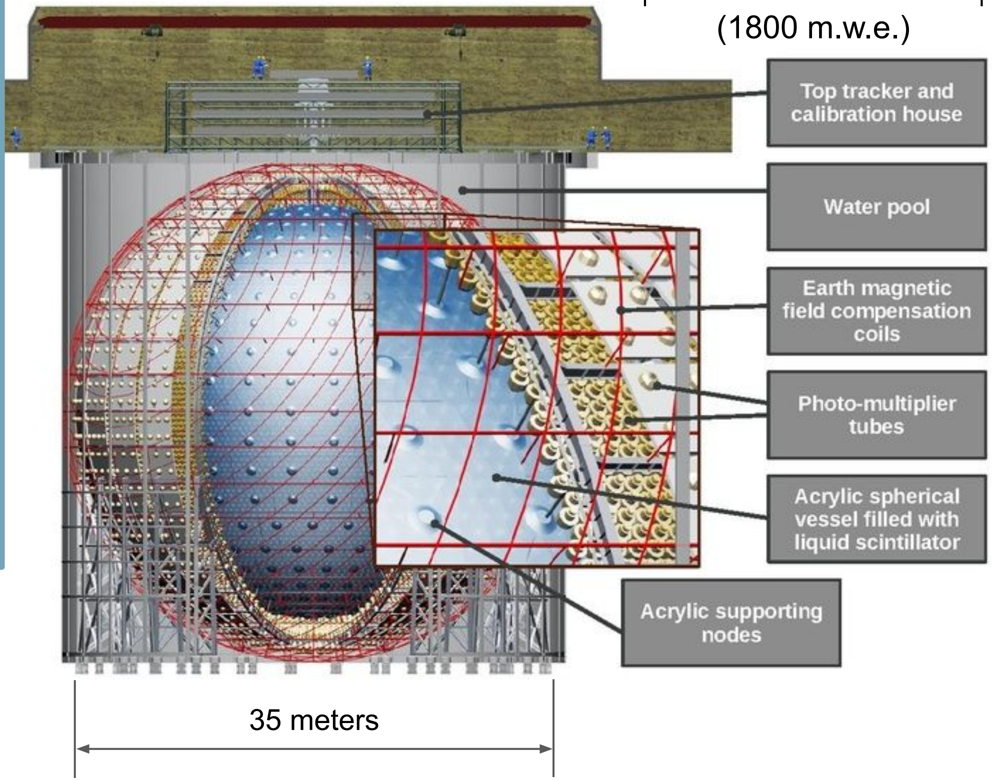




Jiangmen Underground Neutrino Observatory

- Will have **20 kt** liquid scintillator target to ensure large statistics:
  ~100,000 reactor anti-ν_e events in 6 years
- Designed for unprecedented energy resolution of **3% at 1 MeV**:
  - High light yield of liquid scintillator:
    ~10,000 photons / MeV
  - High transparency of liquid scintillator:
    ~20 m attenuation length at 430 nm
  - High photo-coverage:
    ~78% with 17,612 20” PMTs + 25,600 3” PMTs

↑ 650 m to the surface ↑
(1800 m.w.e.)



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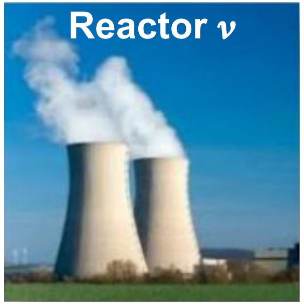
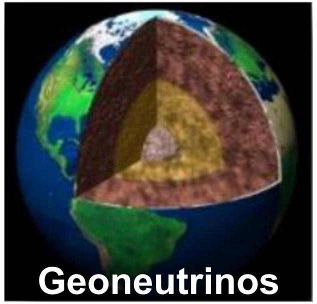
Powerful instrument for observing neutrinos from other sources





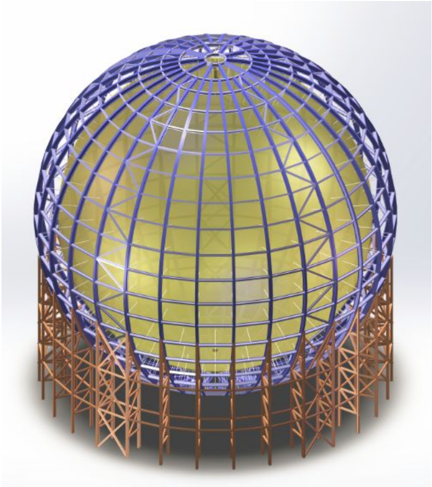
New Physics

- **proton decay**
- **DM searches**
- **…**

Detector Design and Status

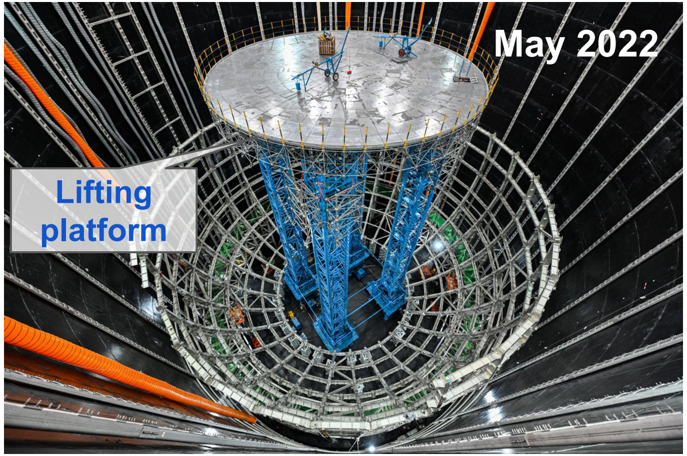
Central Detector: **Stainless Steel Supporting Structure**

From a concept to the physical realization



~40 m in diameter

Sub-cm assembly precision



Central Detector: Acrylic Vessel

- Inner diameter: 35.40 ± 0.04 m
- Thickness: 124 ± 4 mm
- Transparency: >96% in pure water

Measured radio-purity:
>1 ppt ^{238}U/^{232}Th/^{40}K

Photomultiplier Tubes

5000 x 20” Hamamatsu R12860

High QE:	28.5%
Fine TTS:	1.3 ns

15012 x 20” NNVT MCP-PMTs

Highest QE:	30.1%
Good TTS:	7.0 ns

High efficiency of photon detection

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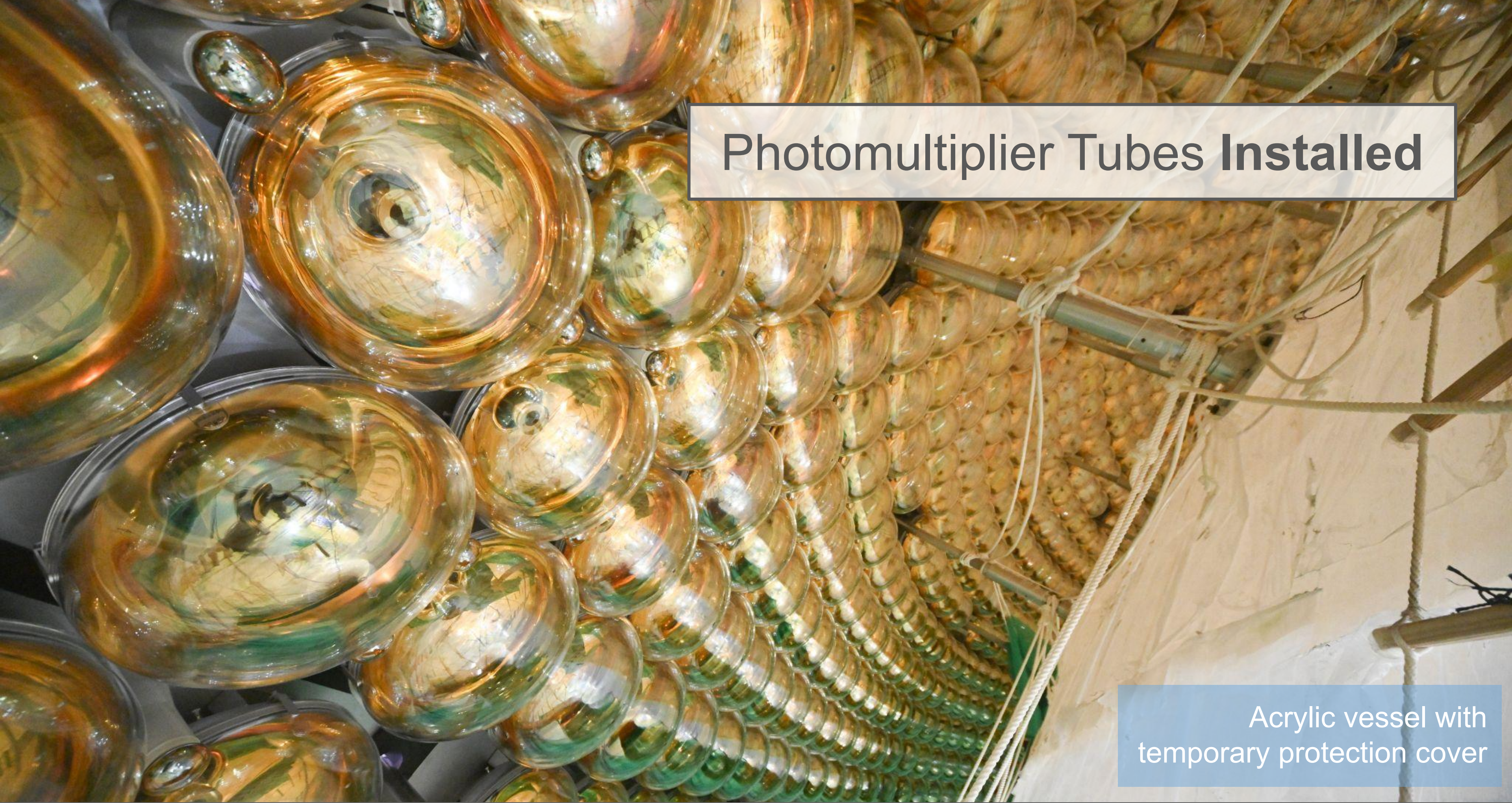
High efficiency of photon detection

25600 x 3" HZC XP72B22

- Calibration of 20" PMTs' non-linearities
- Extension of dynamic range

More details about multi-calorimetry concept in talk by Yang Han on Thursday

Photomultiplier Tubes **Installed**



Acrylic vessel with temporary protection cover

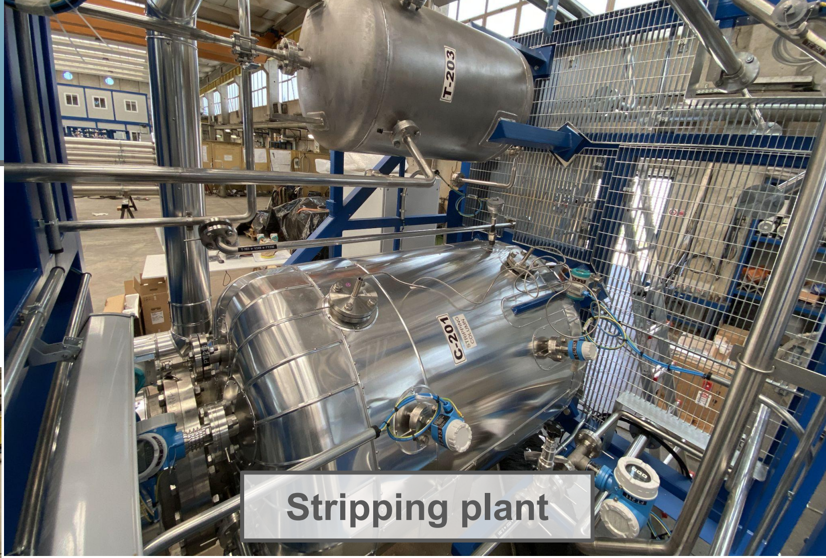
Liquid Scintillator of JUNO

Composition:

LAB + PPO (2.5 g/L) + bis-MSB (3 mg/L)

solvent — fluor — wavelength shifter

Distillation plant



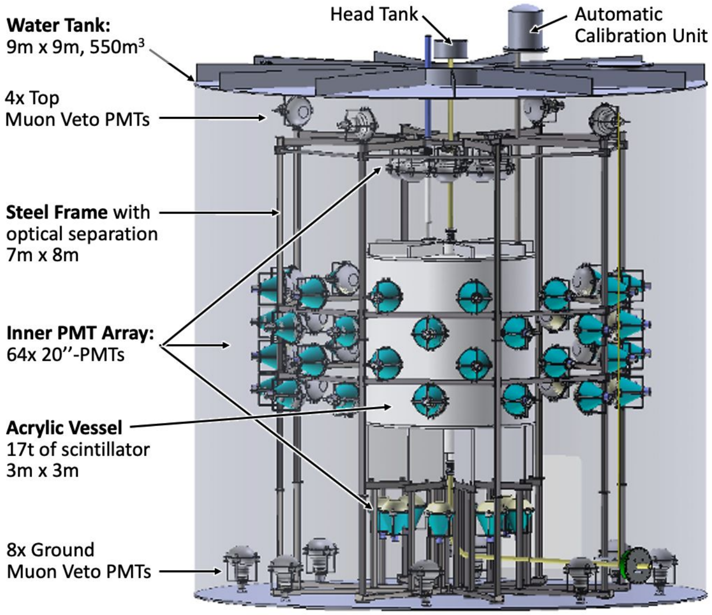
Stripping plant

LAB purification:

Expected radio-purity:
10^{-17} g/g U/Th

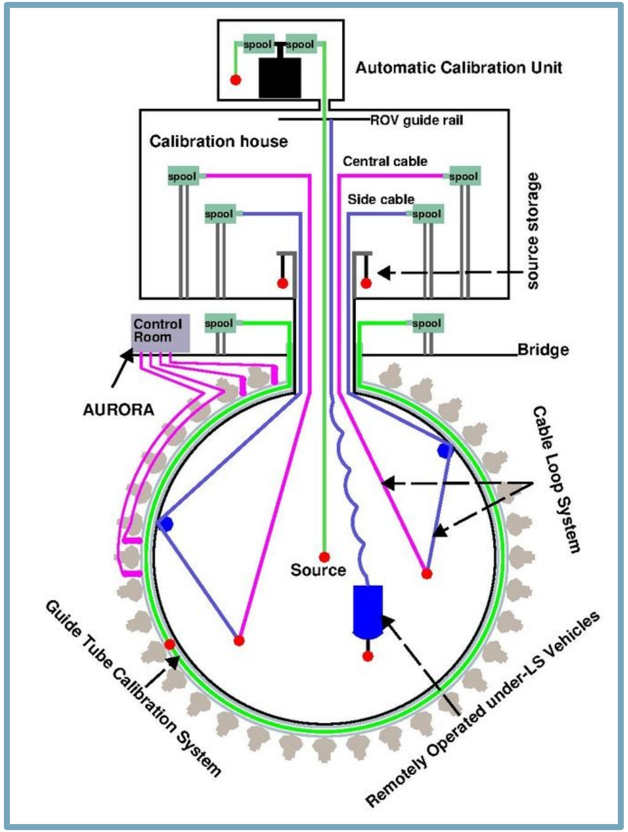
- Al_2O_3 filtration column
  (optical properties improvement)
- Distillation
  (heavy elements removal / transparency improvement)
- Water extraction
  (U/Th/K radioisotopes removal)
- Steam / nitrogen stripping
  (removal of Ar/Kr/Rn gaseous impurities)

OSIRIS **O**nline **S**cintillator **I**nternal **R**adioactivity **I**nvestigation **S**ystem



[Eur. Phys. J. C 81 (2021)]

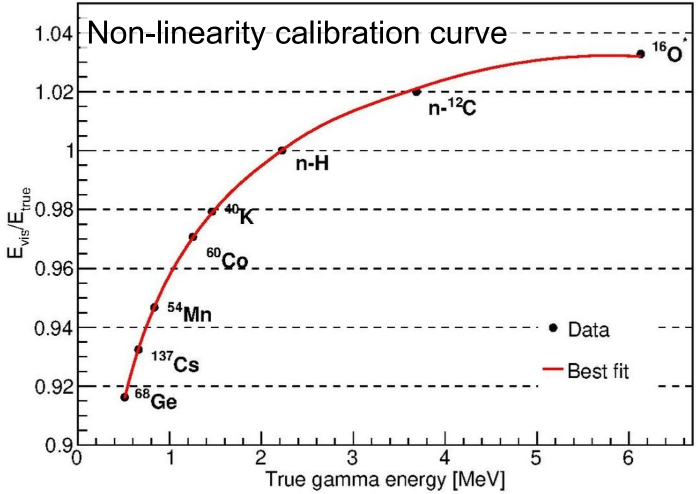
Energy Scale Calibration



Regular insertion of the calibration sources into the detector:

- Understanding of the detector response
- Testing of the reconstruction algorithms
- Calibration of the energy scale non-linearities

[JHEP 2021, 4 (2021)]

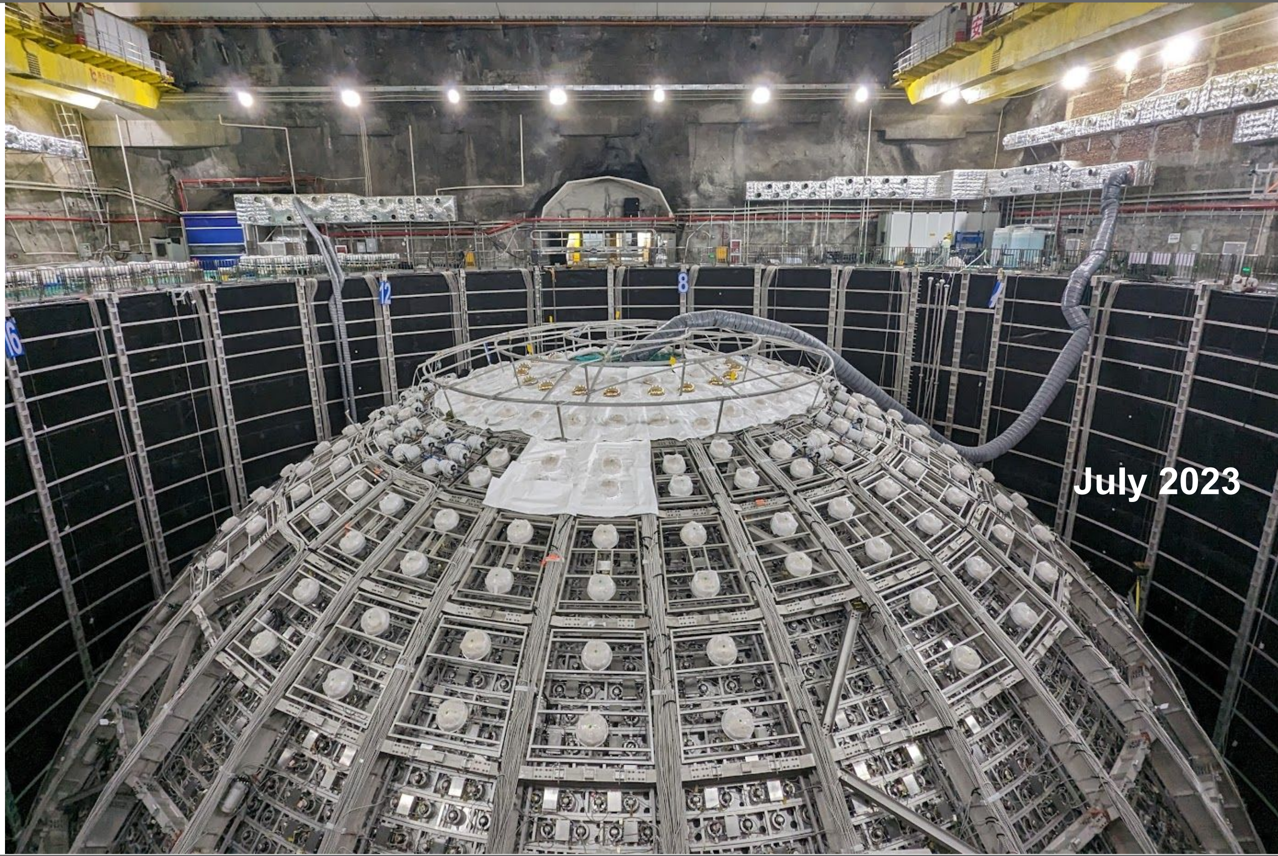


< 1% energy scale uncertainty

More details in talk by Jiaqi Hui on Thursday

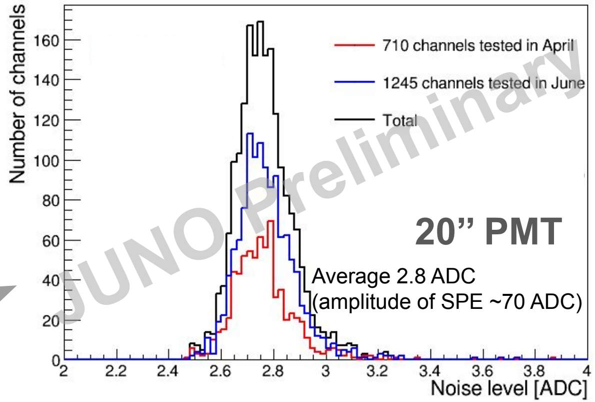
JUNO Timeline

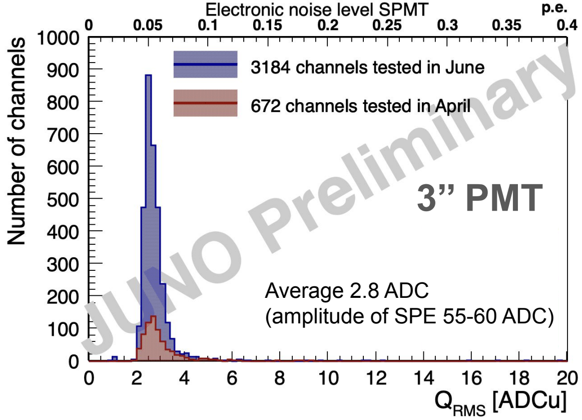
2008	Proposal to determine neutrino mass ordering by detecting reactor electron anti-neutrinos [*Phys. Rev. D* 78 (2008)]
2013	Project approval
2016	Publication of “Yellow Book” [*J. Phys. G* 43 (2016)]
2013-2022	Design and production of components
2015-2021	Civil construction
2022-2023	Installation and commissioning
2024	Filling and **start of data taking!**



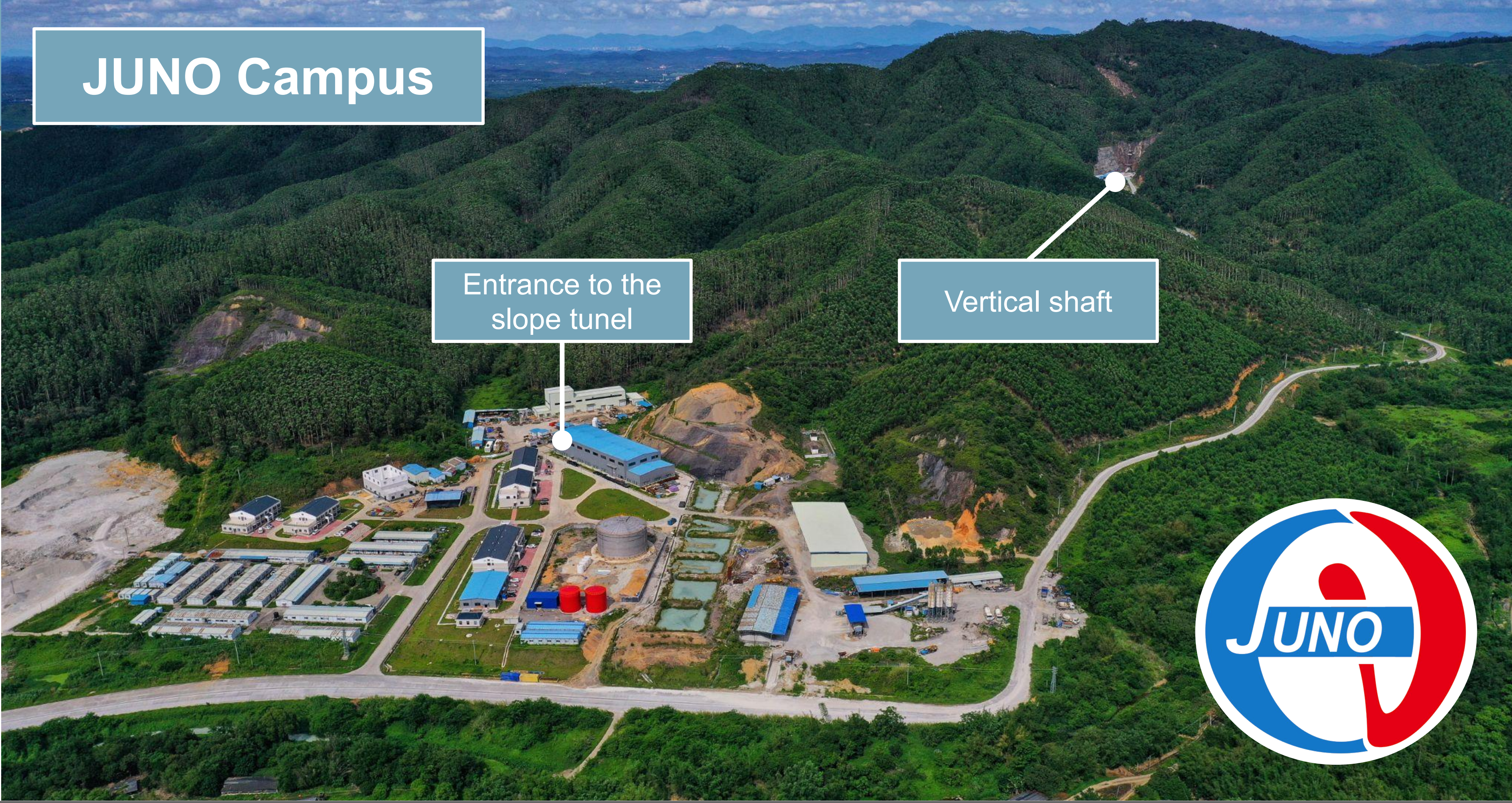
Commissioning

- Regular light-off/on tests during detector assembly started
  - **Light off tests**: full data taking and processing chain with PMT HV on
  - **Light on tests**: joint elec./trigger/DAQ/DCS test with PMT HV off
- Very good electronics, shielding and grounding
  - Electronics noise of 20” PMTs is **2.8 ADC** counts, **4% of SPE** — much better than the design of 10%
  - Electronics noise of 3” PMTs is **2.8 ADC** units, **~5% of SPE** — much lower than the trigger threshold of 1/3 p.e.
- All tested PMTs (710 × 20” and 3184 × 3”) are working well
- More tests will continue as installation progresses





JUNO Campus



Oscillation Physics with JUNO

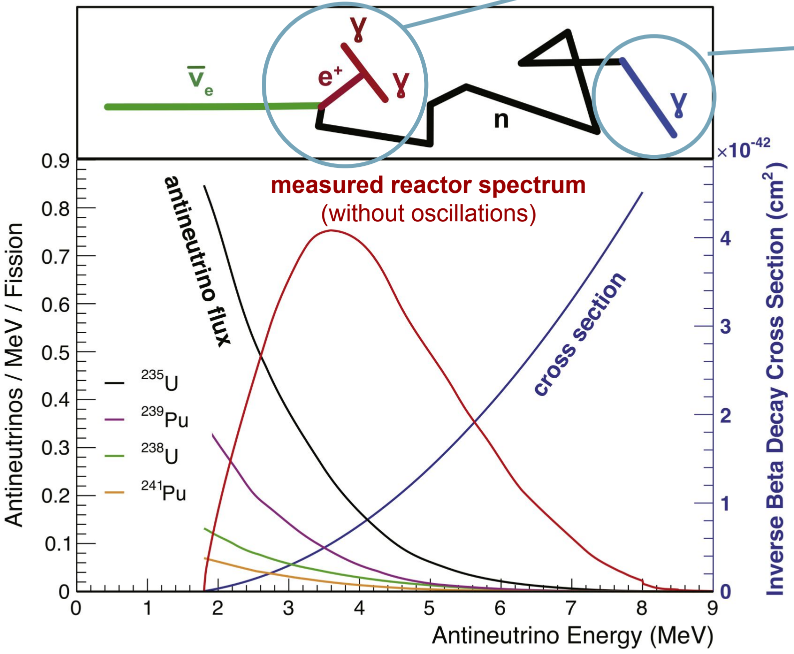
Inverse Beta-Decay (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

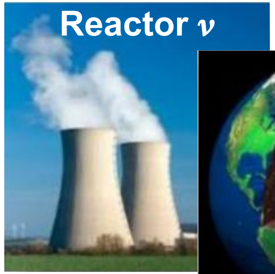
(reaction threshold: 1.8 MeV)

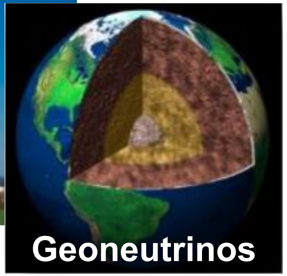
Prompt signal
handle for neutrino energy:
$$E_\nu \simeq E_{e^+} + \Delta m_{n-p} + T_n$$

Delayed signal:
neutron capture: 2.2 MeV (H) or 4.9 MeV (^{12}C) within ~200 μs



The detection channel for:





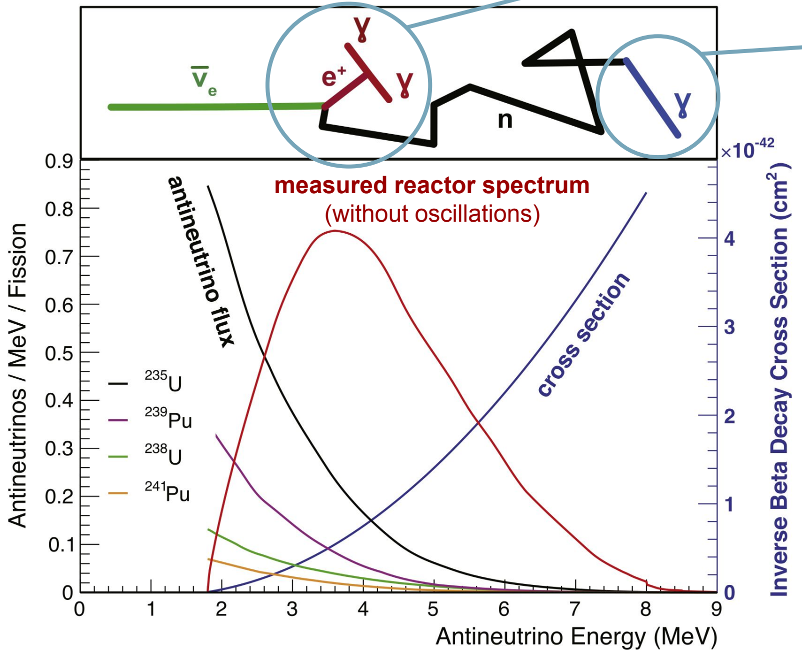
Important detection channel for:

charged current interaction — sensitive to anti-ν_e only

IBD Selection for Reactor and Geoneutrino Analyses

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

(reaction threshold: 1.8 MeV)



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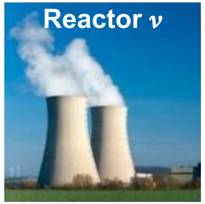
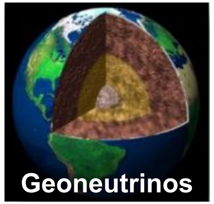


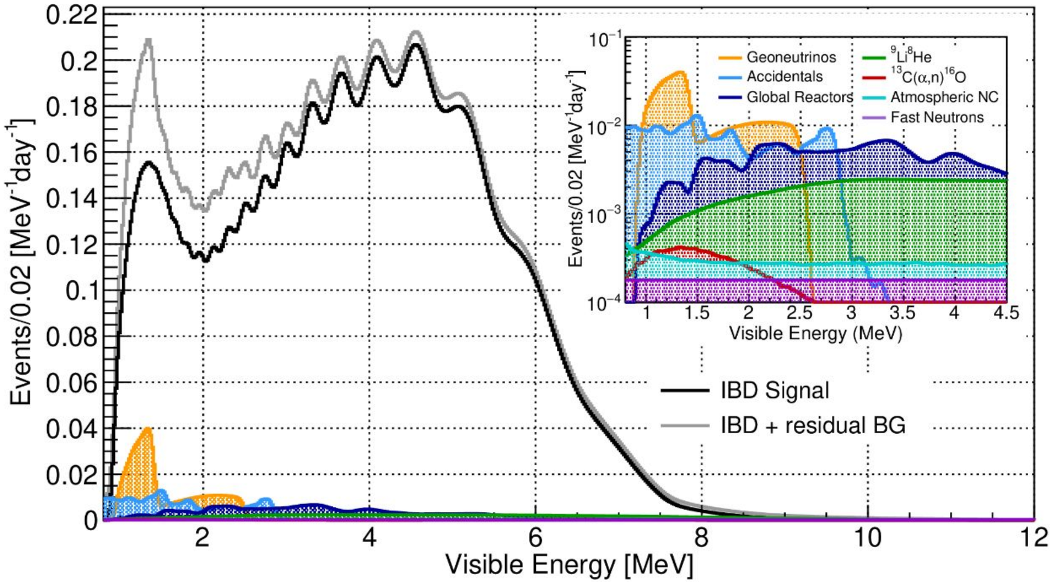


Selection of IBD candidates (82% ν selection efficiency):

- Fiducial Volume (**91.5%** efficiency): r < 17.2 m
- Selection cuts (**98.1%** efficiency):
  - Prompt energy: [0.7, 12.0] MeV
  - Delayed energy: [1.9, 2.5] ∪ [4.4, 5.5] MeV
  - Time difference: 1 ms
  - Distance: 1.5 m
- Muon veto (**91.6%** efficiency)

Backgrounds for Reactor Neutrino Signal

after IBD selection

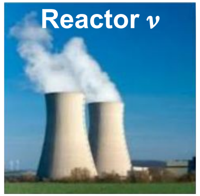


Background	Rate, day^{-1}	Rate Uncertainty, %	Shape Uncertainty, %
Geoneutrinos	1.2	30	5
Global reactors	1.0	2	5
Accidentals	0.8	1	negligible
^{9}Li/^{8}He	0.8	20	10
^{13}C(α,n)^{16}O	0.05	50	50
Atmospheric neutrinos	0.16	50	50
Fast neutrons	0.1	100	20

Reactor neutrino signal: 47.1 day^{-1} ± 1.5% (syst.)

(Yangjiang + Taishan + Daya Bay NPPs, no duty cycle)

Neutrino Oscillation Studies



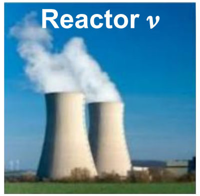
Updates since Yellow Book [JPG 43 (2016)]**:**

- Two less reactor cores at Taishan NPP (Taishan + Yangjiang total: 35.7 GW_{Th} -> 26.6 GW_{Th})
- Actual location and overburden (~700 m -> ~650 m)
- Including TAO (see next slides) [TAO CDR arXiv:2005.08745]
- Improved energy resolution model (3.0% -> 2.95% at 1 MeV)
  - Results of PMT testing (PDE 27% -> 30%) [EPJ C 82 (2022)]
  - Increase of PMT PDE and new PMT optical model [EPJ C 82 (2022)]
  - New central detector geometry
- Improved muon veto strategy based on full MC (exposure fraction 83% -> 91.6%)
- Updated background expectations and radiopurity of materials [JHEP 102 (2021)]
- Extra backgrounds: atmospheric neutrino, world reactors
- PMNS parameters updated to PDG2020

~1350 p.e. / MeV -->
~1600 p.e. / MeV

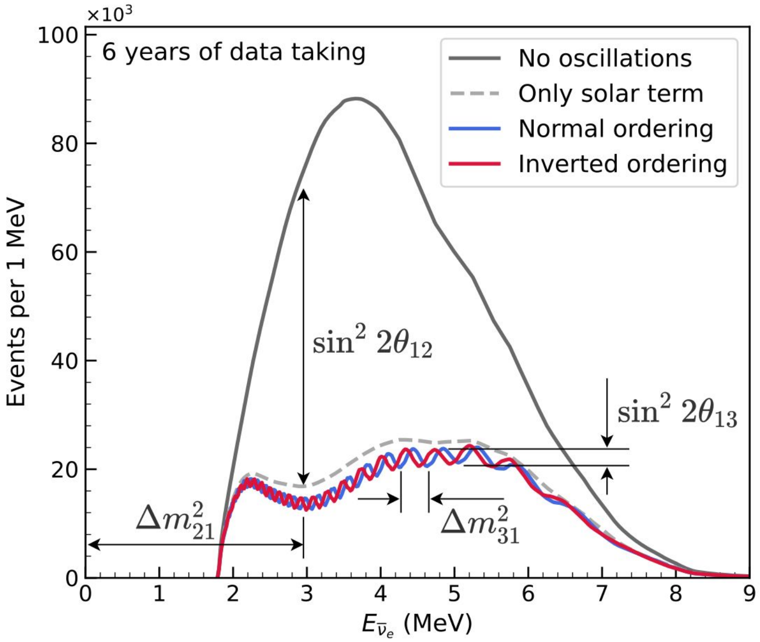
Precision Measurement of Oscillation Parameters

Reactor ν

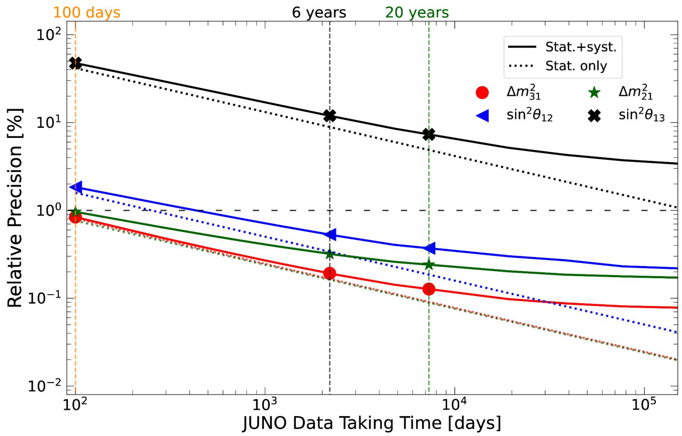


[[Chin. Phys. C 46 (2022)](#)]

Measuring frequencies and amplitudes of "solar" and "atmospheric" oscillation modes:

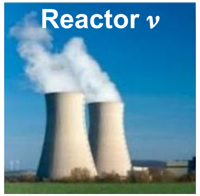


Sub-percent precision for $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31}



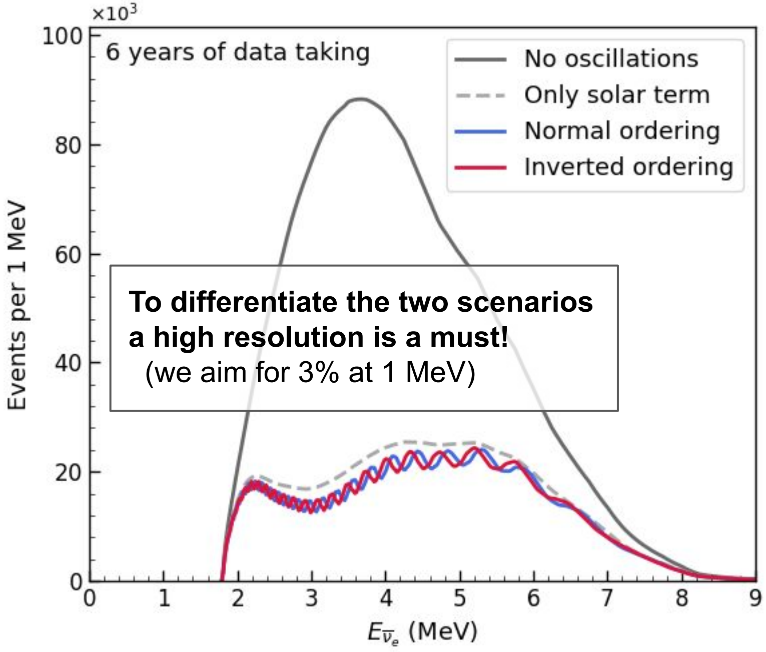
More details in [talk by Andrea Serafini](#) on Thursday

Neutrino Mass Ordering (with Reactor Neutrinos)

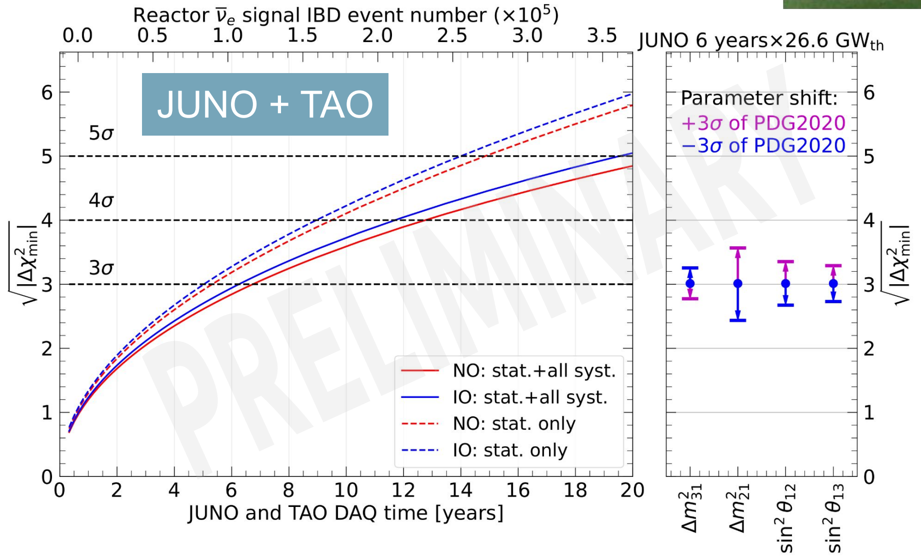


Resolving two scenarios:

3σ in ~6 years



To differentiate the two scenarios a high resolution is a must!
(we aim for 3% at 1 MeV)



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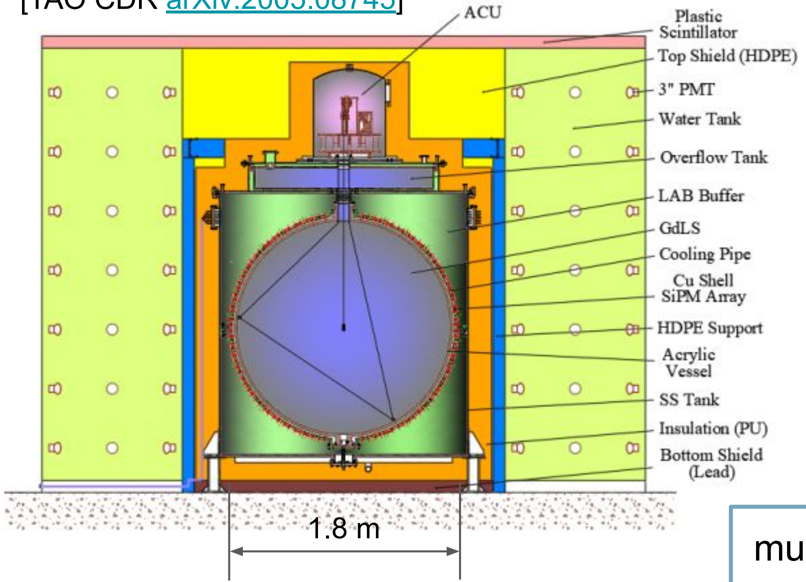
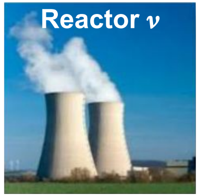
JUNO TAO (Taishan Antineutrino Observatory)

[TAO CDR arXiv:2005.08745]





Measurement of reactor anti-ν_e spectrum **with no oscillations** (within Taishan NPP building)

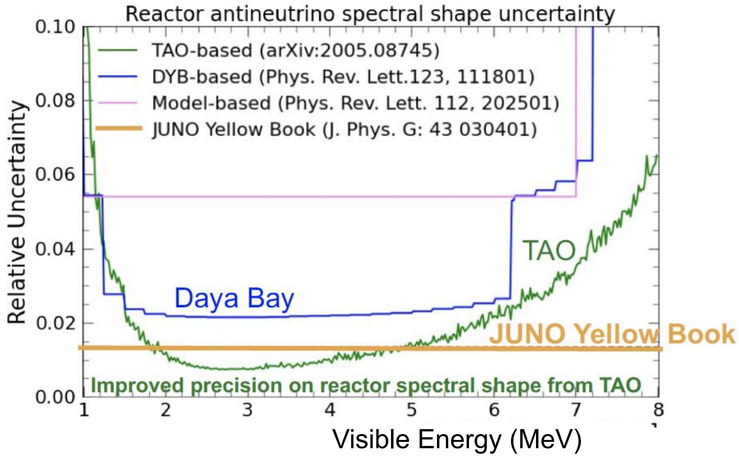
- Sensitive to fine structure with better precision
- Model-independent reference spectrum for JUNO
- Improvement of nuclear databases
- Sensitive to sterile neutrino

An innovative apparatus:

- ~94% coverage with SiPM (~50% PDE)
- Cooling to -50°C
- 1 ton fiducial volume / 2.8 tons of Gd-LS

much higher statistics than in JUNO

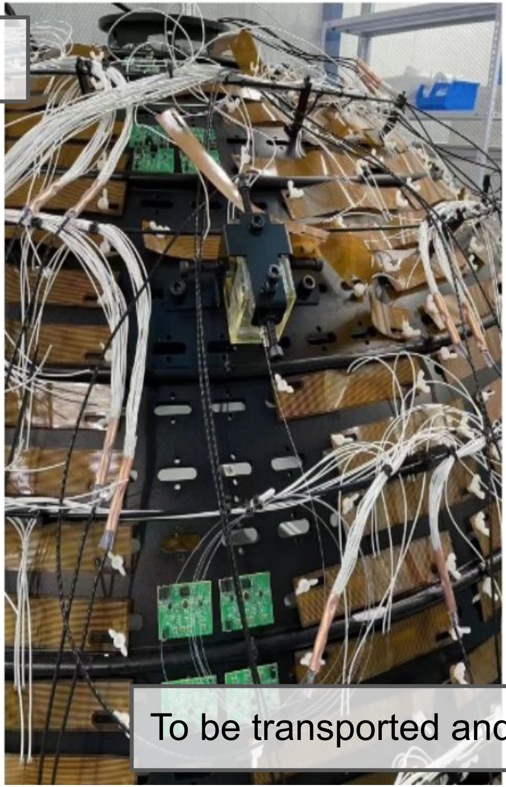
~2% at 1 MeV energy resolution

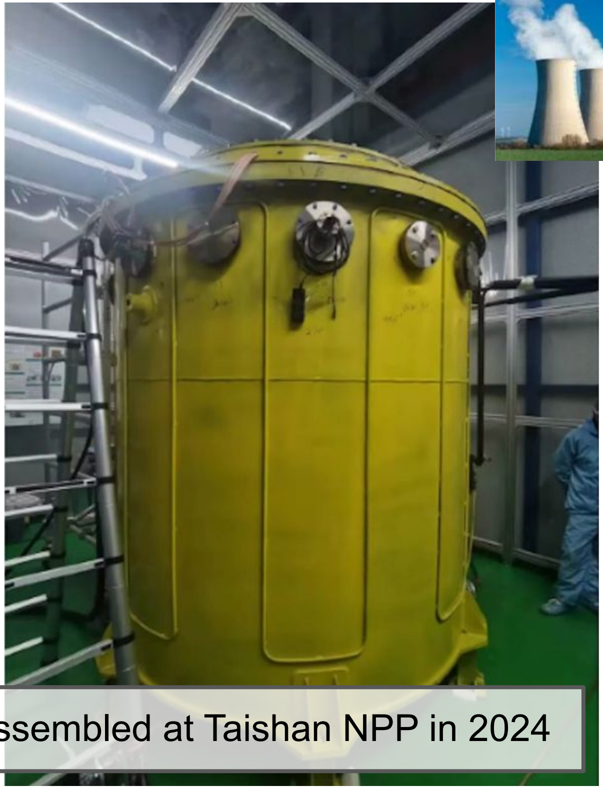


JUNO TAO (Taishan Antineutrino Observatory)

Reactor ν

1:1 prototype in IHEP (Beijing)



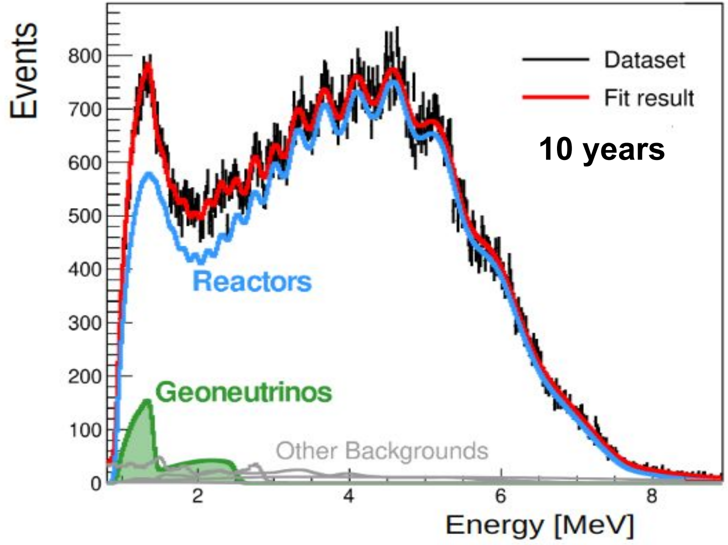


To be transported and assembled at Taishan NPP in 2024

Other Physics Topics in JUNO

Geoneutrinos

- Originate from β-decays of radioactive elements in the interior of the Earth
- Only ^{238}U and ^{232}Th component can be detected via IBD due to the 1.8 MeV reaction threshold
- Reactor neutrinos constitute the largest background



Expected results:

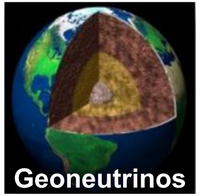
JUNO will collect the largest dataset of geoneutrinos in about 1 year (1–2 events / day)

- Precision of total geoneutrino signal with Th/U mass ratio fixed to 3.9:
  ~8% in 10 years
- Precision of U and Th components **in 10 years:**

^{232}Th	**~35%**
^{238}U	**~30%**
$^{232}Th+^{238}U$	**~15%**
$^{232}Th/^{238}U$	**~55%**

- Separation of crust and mantle signal

PRELIMINARY

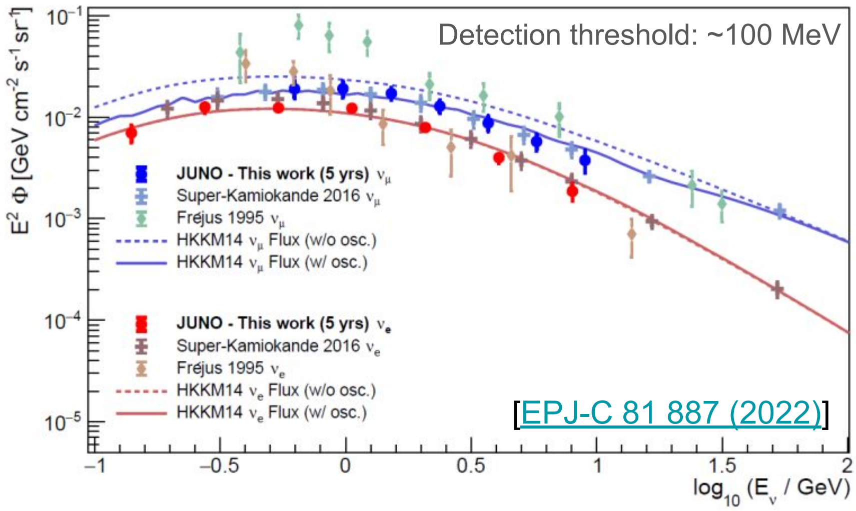


Existing measurements:
Borexino: 17% [PRD 2020]
KamLAND: 15% [GRL 2022]

More details in talk by Zhao Xin on Thursday

Atmospheric Neutrinos

- First measurement with a liquid scintillator detector
- Flavour separation
- Measurement of θ_{23}
- Validation of cross-sections in sub-GeV energy range
- Background for many analyses above the reactor-ν energies: DSNB, proton decay, indirect DM …



More details in talks by Rosmarie Wirth, Zekun Yang and Gaosong Li on Thursday

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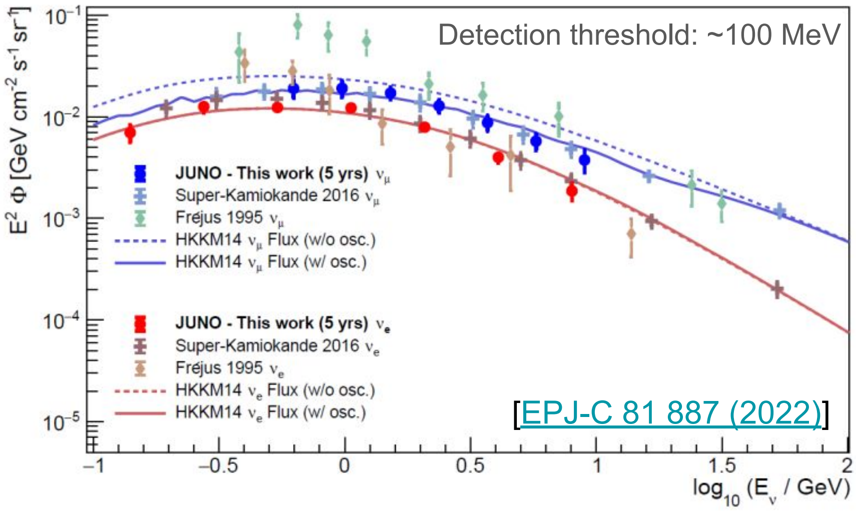
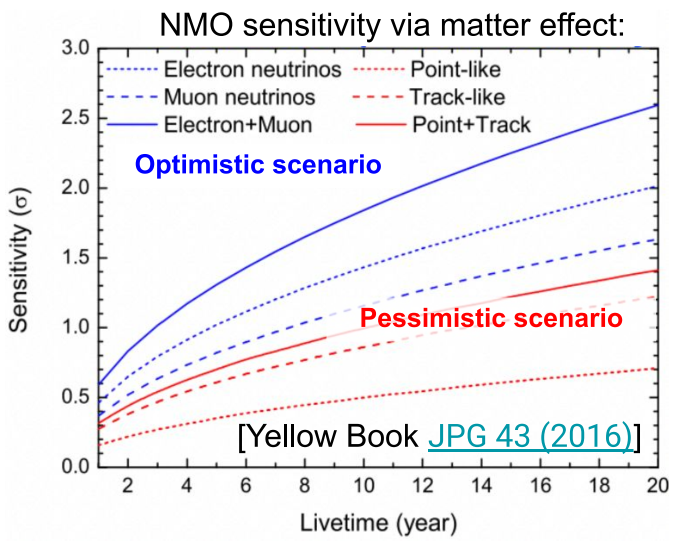
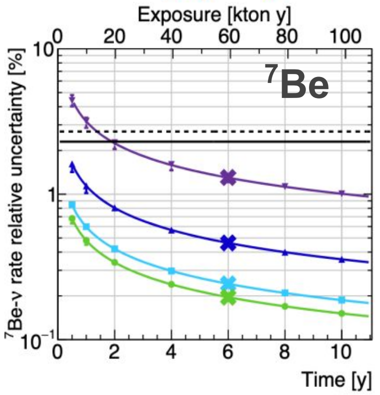


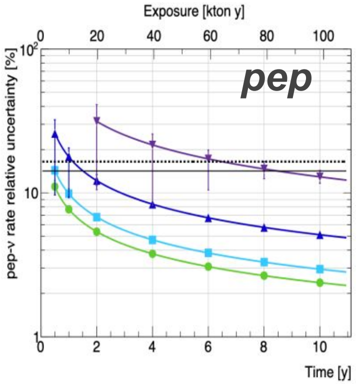


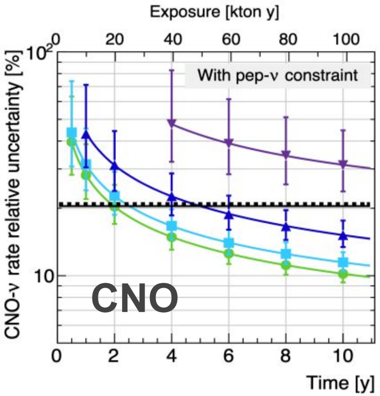
combined with reactor anti-ν_e: **> 3σ in 6 years**

More details in talks by Rosmarie Wirth, Zekun Yang and Gaosong Li on Thursday

Solar Neutrinos







JUNO @ different radio-purity scenarios:

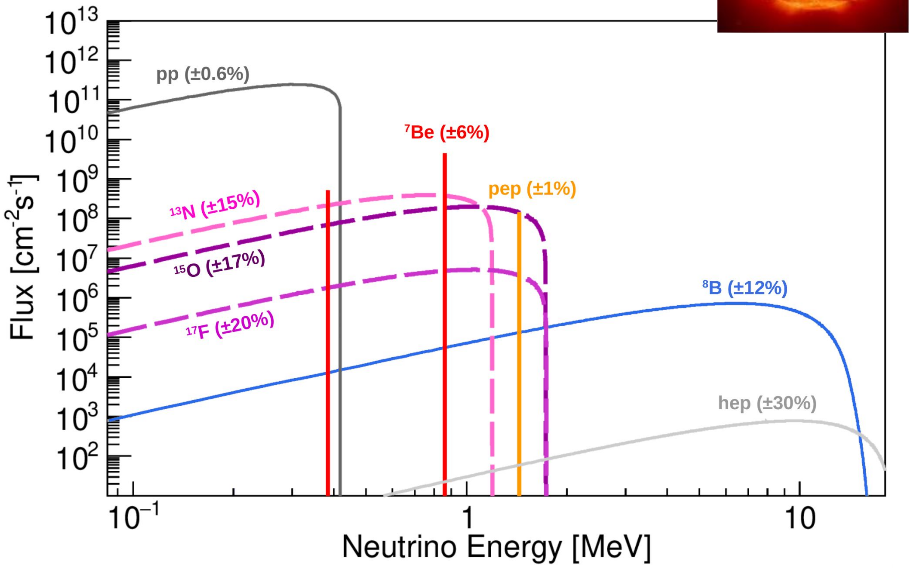
— min. requirement for NMO
— 10 x Borexino Phase-I
— Borexino Phase-I
— Borexino Phase-III (U/Th 10^{-17} g/g)

· · · **Borexino result**

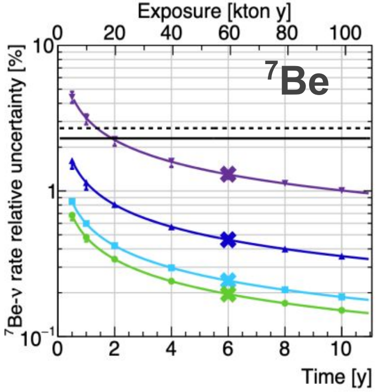
[JCAP 10 (2022)]

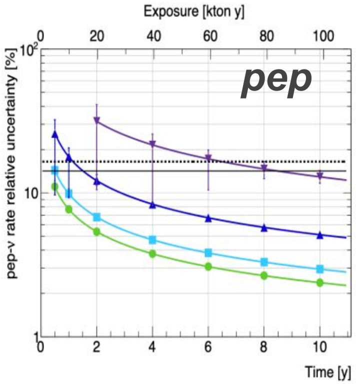
Measurement in the ES channel:

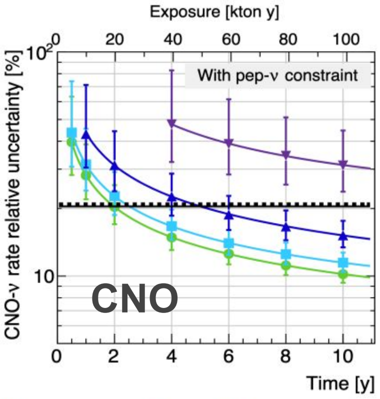
$$e + \nu \rightarrow e + \nu$$



More details in talk by Apeksha Singhal on Thursday







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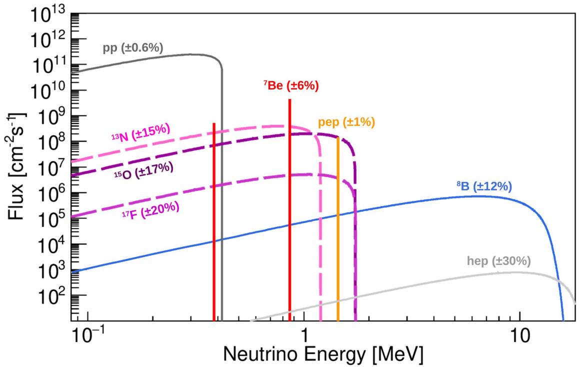
· · · **Borexino result**

[arXiv:2303.03910, accepted by JCAP]



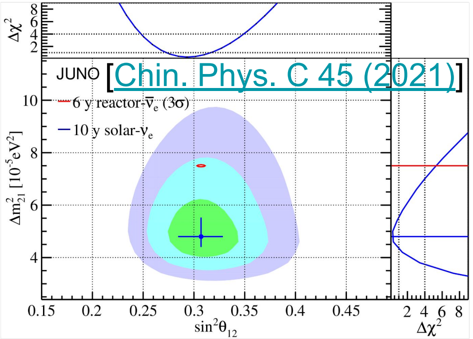
^{8}B measurement

(in NC + CC + ES channels)

Expected precision:

^{8}B	5% (3% with SNO)
$\sin^2\theta_{12}$	8%
Δm^2_{21}	20%

[arXiv:2210:08437]

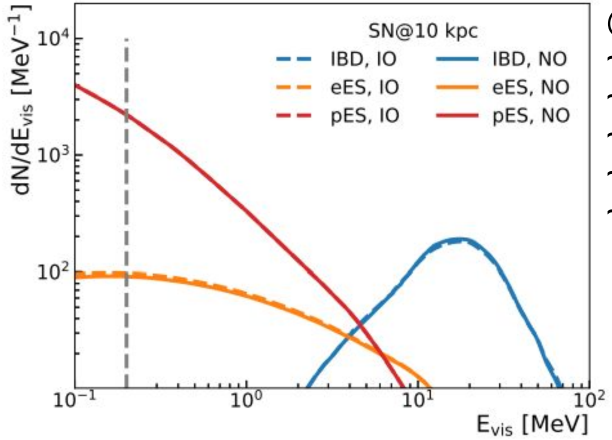


More details in talk by Apeksha Singhal on Thursday

Supernova Neutrinos

Core Collapse Supernova Neutrinos

(multi-channel detection, all flavors)



@ 10 kpc:
~5000 IBD
~300 eES
~2000 pES
~200 CC
~300 NC

Expected alert capability (for >15 $M_\odot$):

preSN	**~1 kpc**	
SN	**~200 kpc**	[arXiv:2309.07109]

More details in talk by Yibing Zhang on Thursday

Supernova Neutrinos

Supernova ν

Core Collapse Supernova Neutrinos

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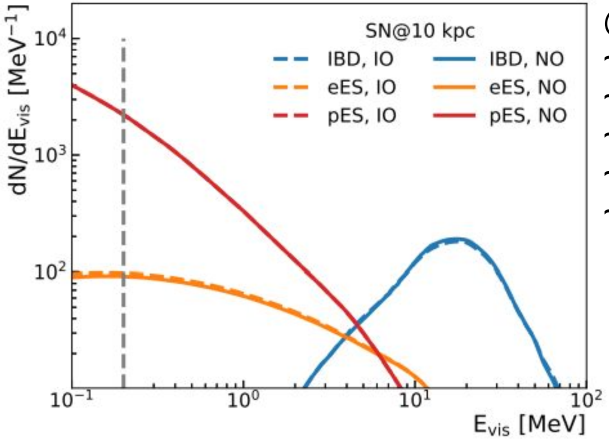

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Expected alert capability (for >15 $M_\odot$):

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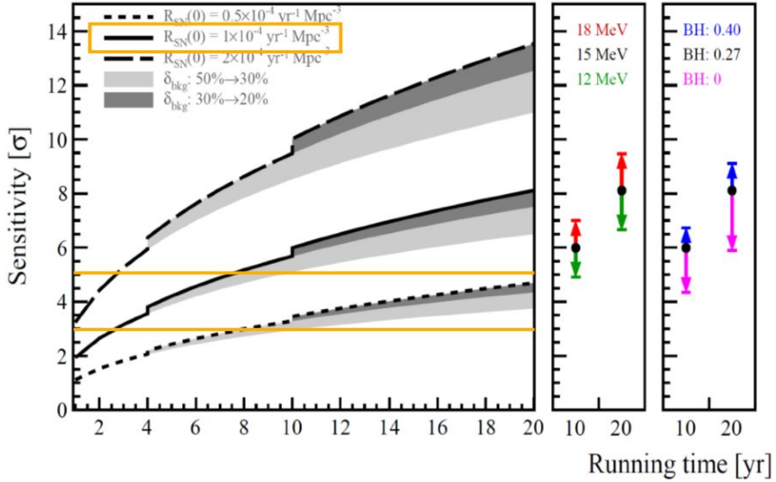
More details in talk by Yibing Zhang on Thursday

Diffuse Supernova Neutrino Background

(IBD, anti-ν_e only)



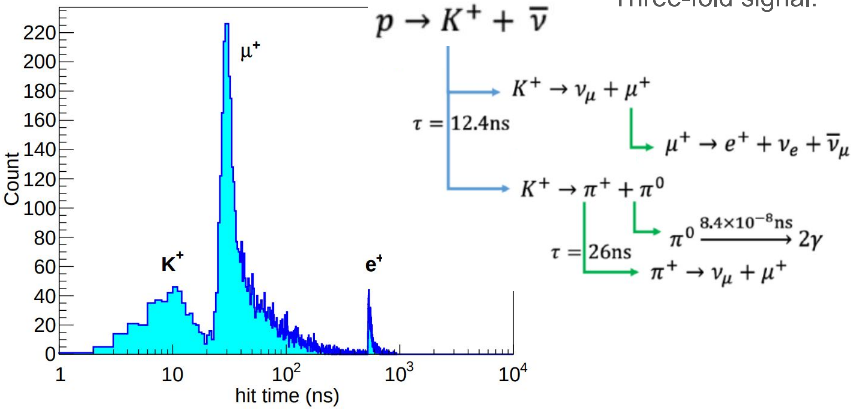
Expected discovery potential (with nominal model)**:**

3 years	**~3σ**	
10 years	**>5σ**	[JCAP 10 033 (2022)]

Other Topics

Proton Decay

Three-fold signal:



Expected sensitivity: **$9.6\cdot10^{33}$ y @ 90% C.L.** in 10 years

[Chin. Phys. C 47 (2023)]

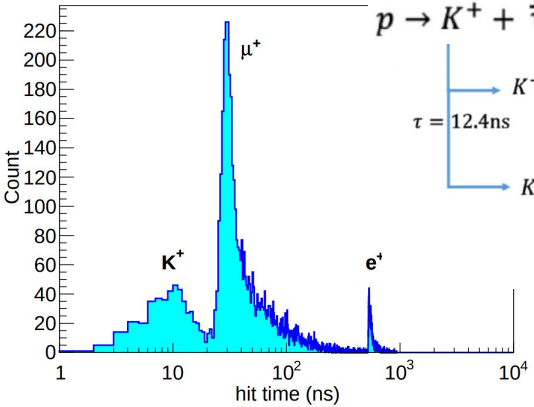
Super-K (90% C.L.)

$\tau/B(p \to e^+\pi^0) > 2.4\times10^{34}$ [PRD 102, 2020]

$\tau/B(p \to \bar{\nu}K^+) > 5.9\times10^{33}$ [PRD 90, 2014]

Proton Decay

Three-fold signal:



$p \to K^+ + \bar{\nu}$

$\tau = 12.4\text{ns}$: $K^+ \to \nu_\mu + \mu^+$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

$K^+ \to \pi^+ + \pi^0$, $\pi^0 \xrightarrow{8.4\times10^{-8}\text{ns}} 2\gamma$

$\tau = 26\text{ns}$: $\pi^+ \to \nu_\mu + \mu^+$

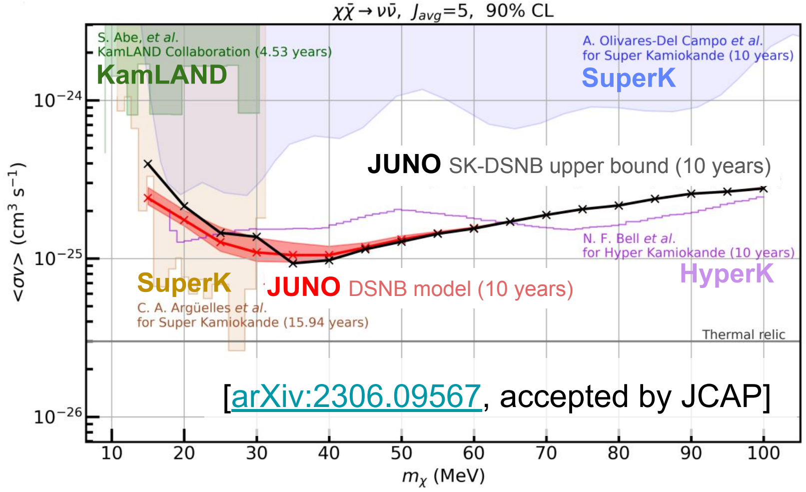
Expected sensitivity: **$9.6\cdot10^{33}$ y @ 90% C.L.** in 10 years

[arXiv:2212.08502, accepted by Chin. Phys. C]

Super-K (90% C.L.)	$\tau/B(p \to e^+\pi^0) > 2.4\times10^{34}$	[PRD 102, 2020]
	$\tau/B(p \to \bar{\nu}K^+) > 5.9\times10^{33}$	[PRD 90, 2014]

Indirect Dark Matter Search (in IBD channel)

– from DM self-annihilation in the Milky Way



[arXiv:2306.09567, accepted by JCAP]

Expected limit (15-100 MeV): **$1.1\ 10^{-25}$ cm^3 s^{-1}** in 10 years

in terms of thermally averaged self-annihilation rate

See also a talk by Yuxiang Hu on invisible nucleon decay

Summary

- JUNO detector construction will be finalized this year.
- Filling liquid scintillator and start of data taking next year!
- Sub-percent precision for $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31}.
- Mass ordering determination in 6 years x 26.6 GW_{th}:
  ~3σ with reactor neutrinos only (completely independent from CP-violation and θ_{23}),
  >3σ with reactor and atmospheric neutrinos.
- Unprecedented physics potential:
  - geo-, atmospheric, solar and supernova neutrinos.
  - proton decay, dark matter search, …

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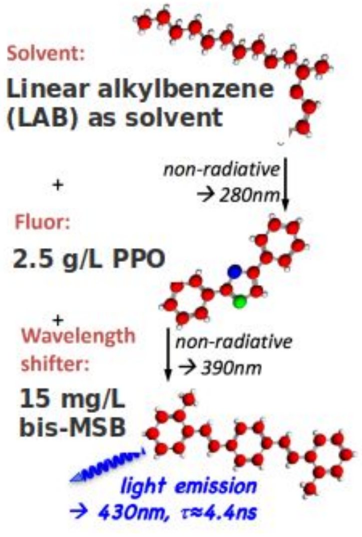
Thank you!

Backup Slides

Liquid Scintillator of JUNO



[NIM-A 988 (2021)]

Composition:

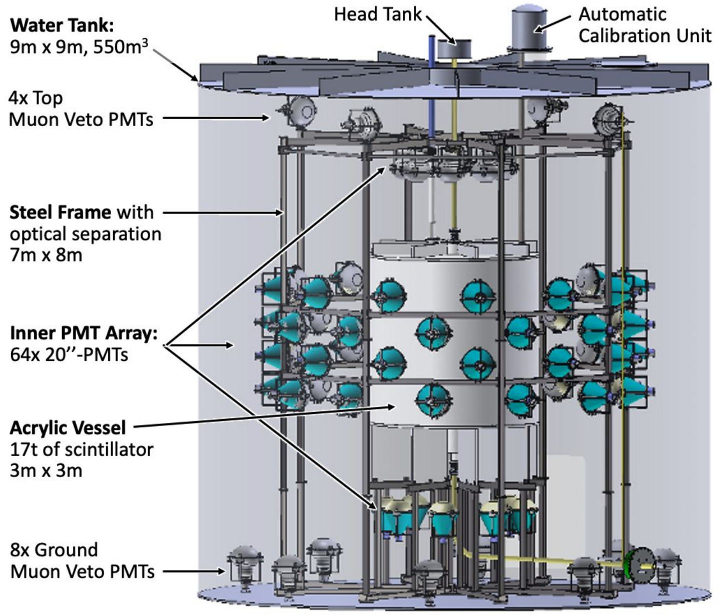
LAB + PPO (2.5 g/L) + bis-MSB (3 mg/L)

LAB purification:

1. Al_2O_3 filtration column
   (optical properties improvement)
2. Distillation
   (heavy elements removal / transparency improvement)
3. Water extraction
   (U/Th/K radioisotopes removal)
4. Steam / nitrogen stripping
   (removal of Ar, Kr, Rn gaseous impurities)

Monitored during filling by OSIRIS

(**O**nline **S**cintillator **I**nternal **R**adioactivity **I**nvestigation **S**ystem)



[Eur. Phys. J. C 81 (2021)]

20 kton in JUNO ≈ $1.45 \cdot 10^{33}$ free protons (target for anti-ν_e)

$\Delta\chi^2$ Contributions from Different Energies

$$\Delta\chi^2 = \chi^2_{false} - \chi^2_{true}$$

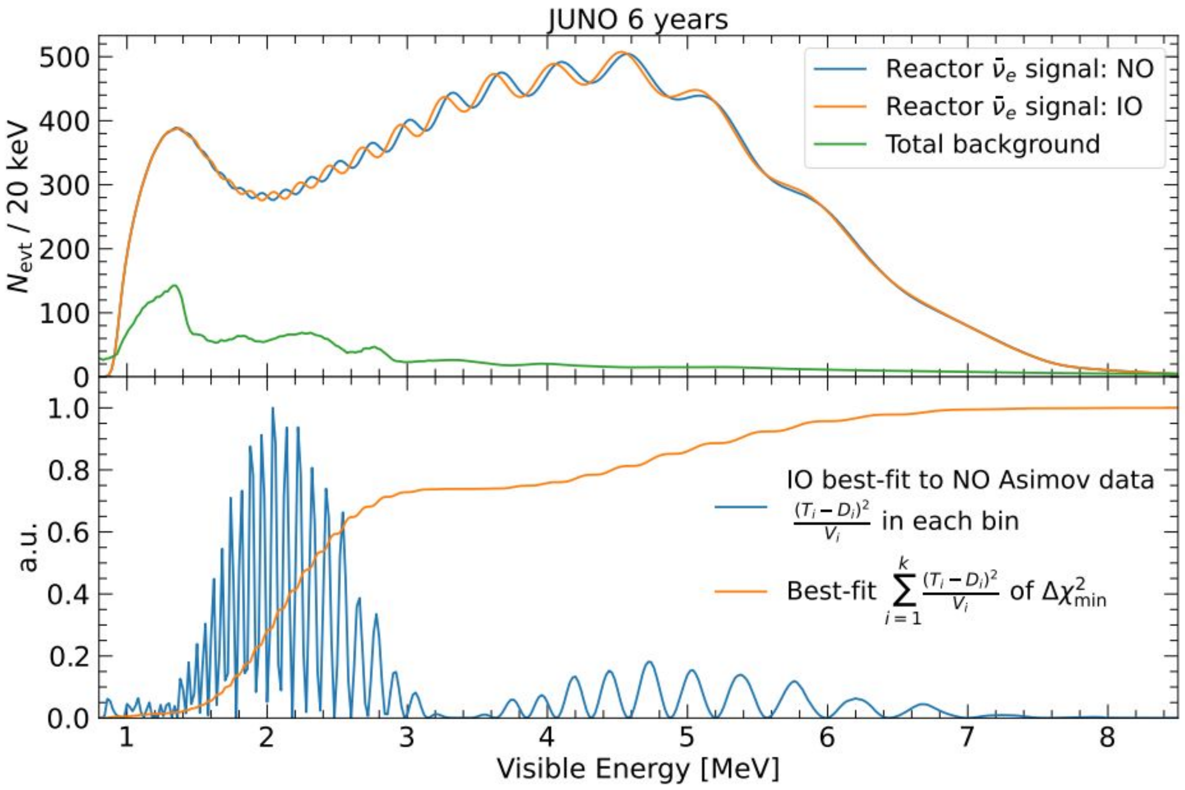
– two independent fits for two NMO assumptions

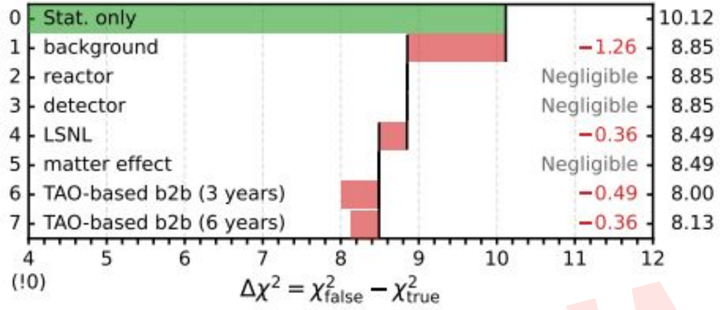
PMNS parameters free in the fit:

Δm^2_{21}, $\sin^2\theta_{12}$, Δm^2_{31}, $\sin^2\theta_{13}$

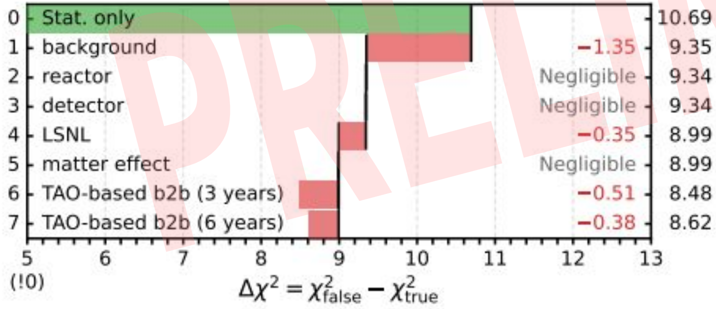
Nuisance parameters (for JUNO and TAO):

- Normalization
- Background rates
- Energy resolution
- Detector response non-linearities
- …





(a) true NO

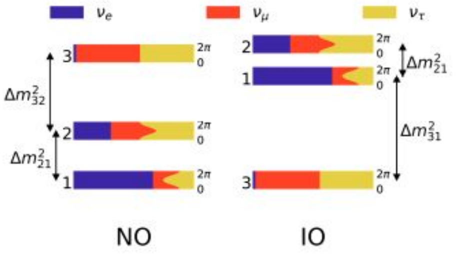


(b) true IO

Uncertainties	$\Delta\chi^2_{\text{min}}$	$\Delta\chi^2_{\text{min}}$ change
Statistics	11.3	0.0
Stat. + Reference spectrum	10.7	−0.6
+ Nonlinearity	10.3	−0.4
+ Geoneutrinos	9.8	−0.5
+ World reactors	9.5	−0.3
+ Accidental	9.2	−0.3
+ ^{9}Li/^{8}He	9.1	−0.1
+ Other backgrounds	9.0	−0.05
Total	9.0	0.0

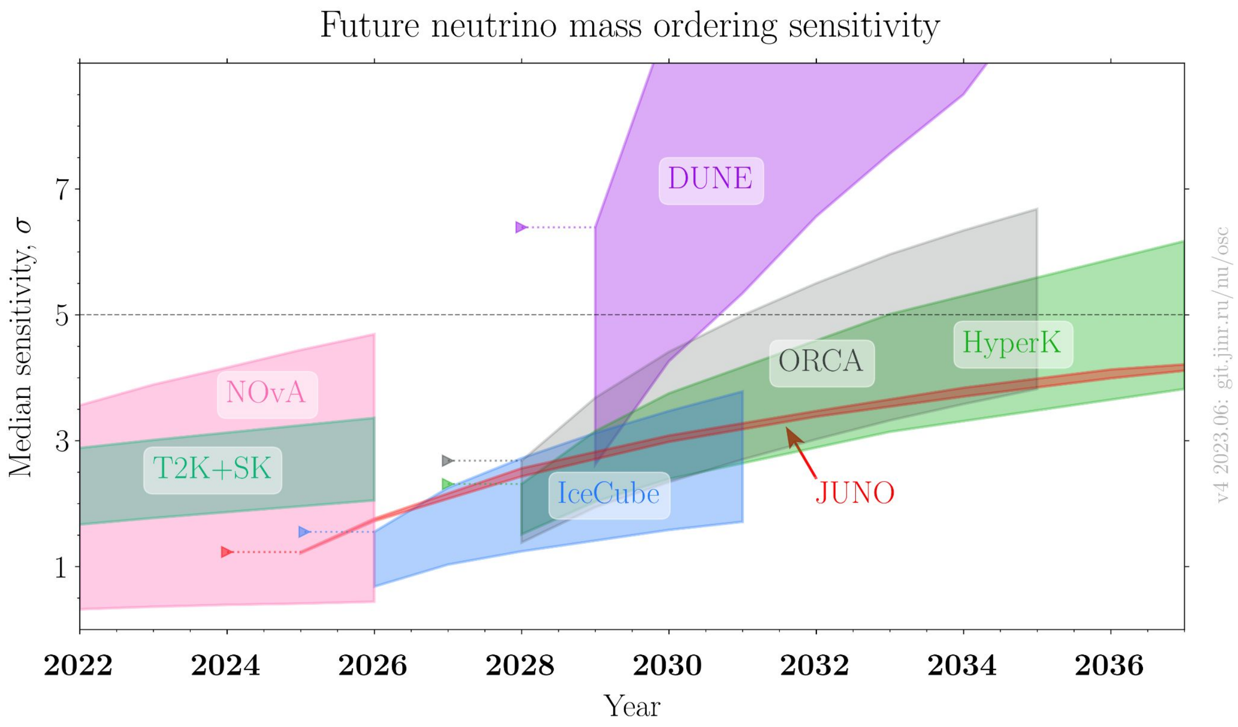
PRELIMINARY

Neutrino Mass Ordering



Probability of finding the α neutrino flavor in the i-th neutrino mass eigenstate. The CP-violating phase is varied (0→2π).

[P.F. de Salas et al, arXiv:1806.11051]



Geoneutrino Signal Prediction at JUNO

1 TNU (Terrestrial Neutrino Unit) = 1 event / 10^{32} target protons (~1kton LS) / year with 100% detection efficiency

Geonu = Lithosphere + Mantle

Lithosphere (crust + CLM) predictions

Lithosphere model	Signal [TNU]	Uncertainty [%]
Global [Prog. in Earth and Planet. Sci. 2, 5, 2015]	$30.9^{+6.5}_{-5.2}$	$^{+21}_{-17}$
JULOC [Phys.Earth.Planet.Inter. 299, 2020]	$40.4^{+5.6}_{-5.0}$	$^{+14}_{-12}$

Three groups of BSE models for **mantle**:

- Cosmochemical (CC): ~2 TNU
- Geochemical (GC): ~10 TNU
- Geodynamical (GD): ~20 TNU

Accessible via anti-ν_e measurement

$$^{238}_{92}\mathrm{U} \to {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} \to {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \mathrm{MeV}$$

$$^{232}_{90}\mathrm{Th} \to {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV}$$

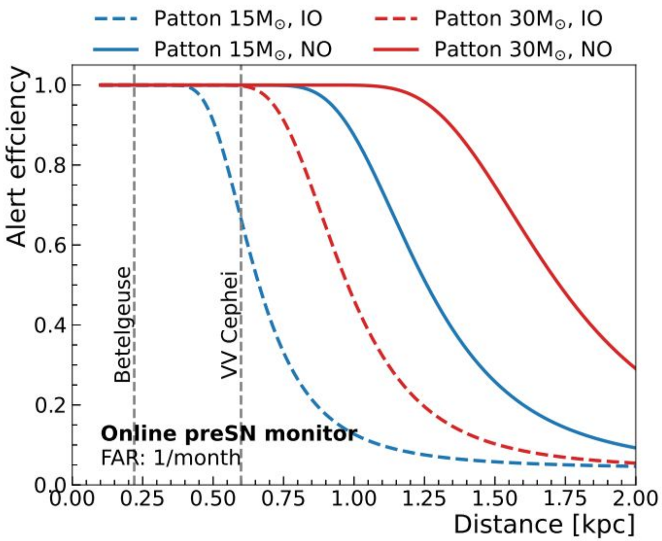
$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

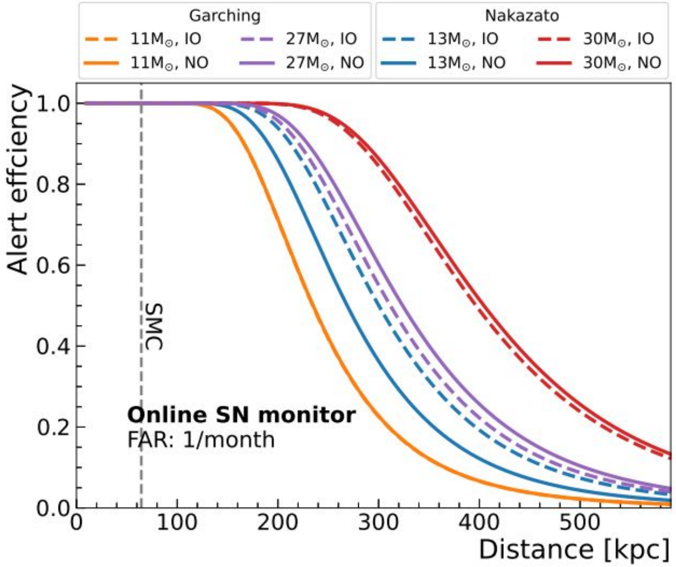
$$^{40}_{19}\mathrm{K} \xrightarrow{10.7\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}$$

Contribution to Earth's heat

More details in talk by Zhao Xin on Friday

Core Collapse Supernova Neutrinos





Multi-channel detection, all flavors:

$\left.\begin{array}{l}\sim 5000 \text{ IBD} \\ \sim 300 \text{ eES} \\ \sim 2000 \text{ pES} \\ \sim 200 \text{ CC} \\ \sim 300 \text{ NC}\end{array}\right\}$ @10 kpc

[arXiv:2309.07109]

More details in talk by Yiqing Zhang on Thursday

DSNB

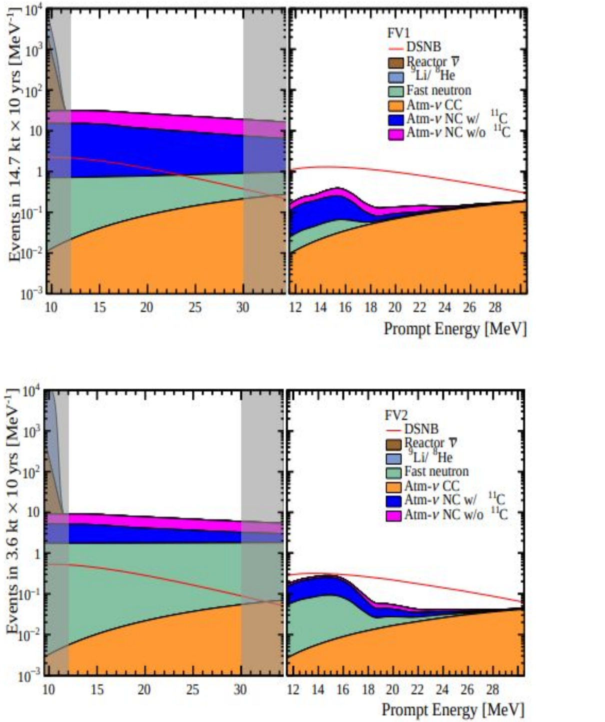
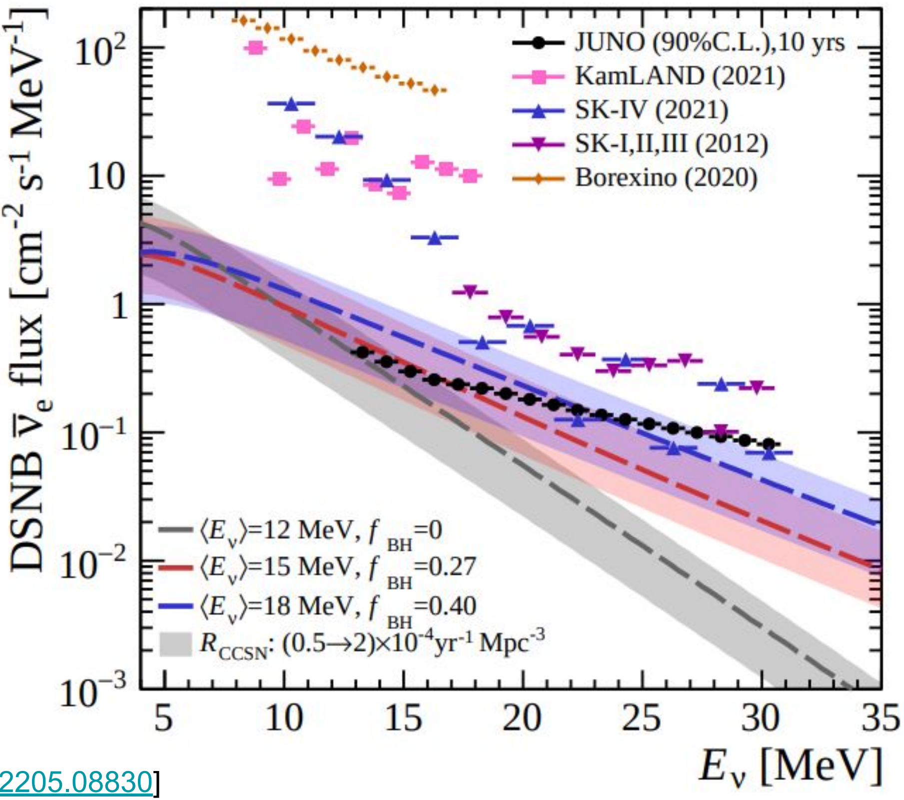


Figure 7: The prompt energy spectra of the reference DSNB signal with $R_{SN}(0) = 1.0 \times 10^{-4}\,\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$, $\langle E_\nu \rangle = 15\,\mathrm{MeV}$, and $f_{BH} = 0.27$ versus all the backgrounds before (left) and after (right) the background reduction techniques. The upper and lower panels are shown for the regions of FV1 and FV2 respectively.



[arxiv:2205.08830]

Three-fold signal:

$$p \rightarrow K^+ + \overline{\nu}$$

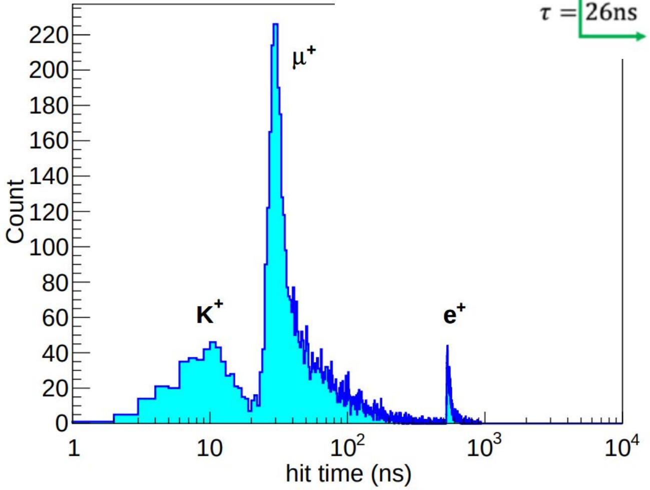
$\tau = 12.4\text{ns}$: $K^+ \rightarrow \nu_\mu + \mu^+$

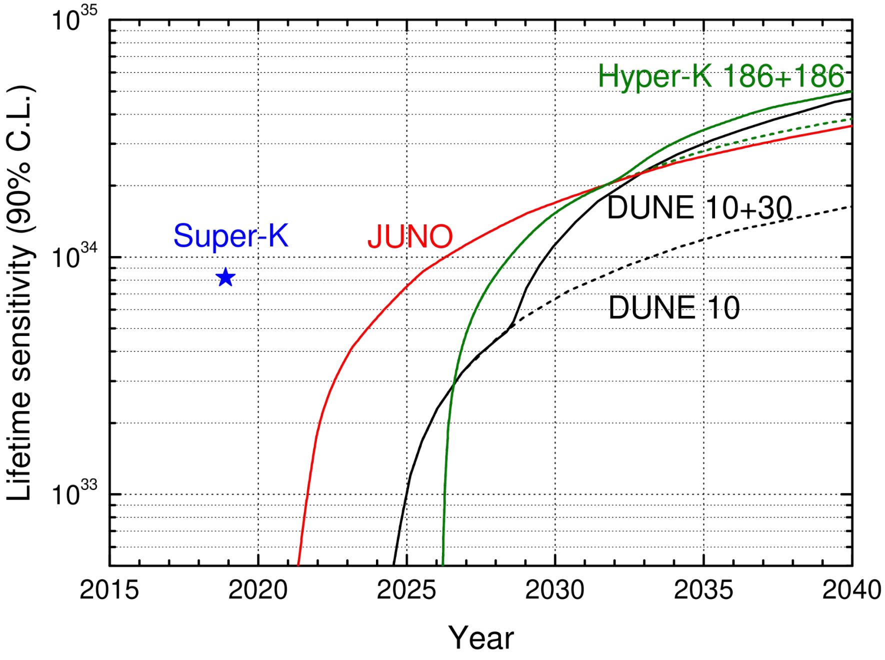
$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$

$K^+ \rightarrow \pi^+ + \pi^0$

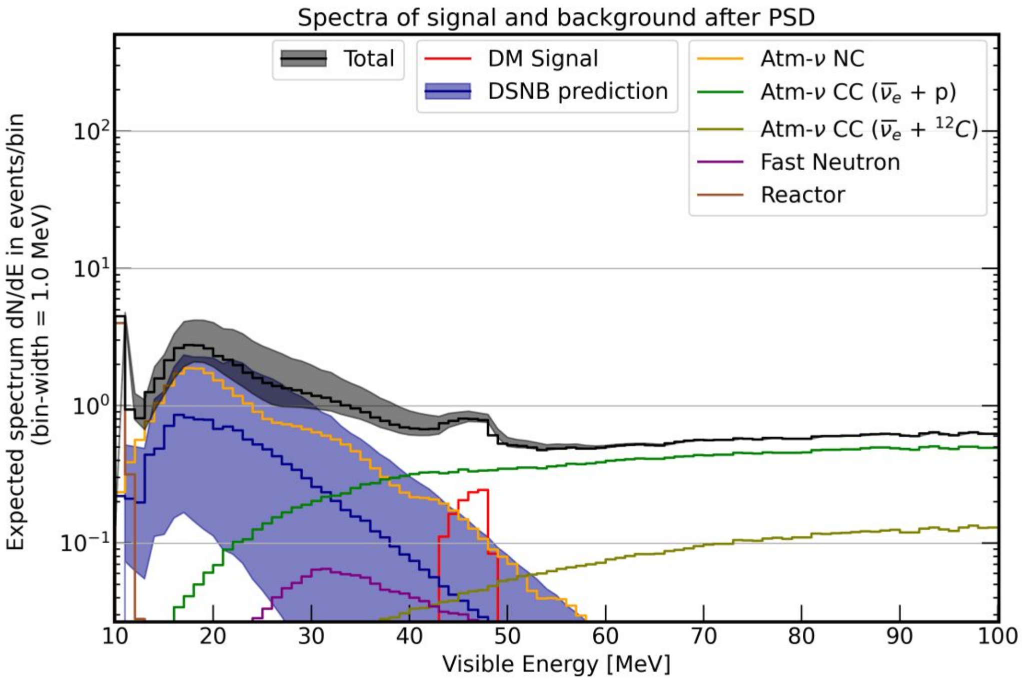
$\pi^0 \xrightarrow{8.4\times10^{-8}\text{ns}} 2\gamma$

$\tau = 26\text{ns}$: $\pi^+ \rightarrow \nu_\mu + \mu^+$





Dark Matter Search



Detection in the IBD channel

PSD for atmo-nu rejection

15-100 MeV range

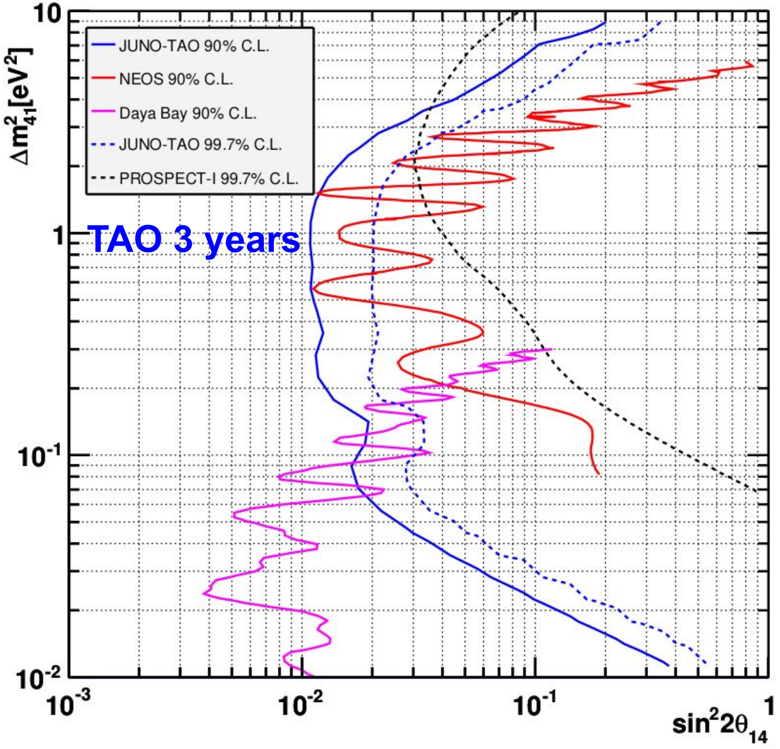
JUNO limit in 10 years

(in terms of thermally averaged self-annihilation rate)

$$\langle \sigma v \rangle = 1.1 \times 10^{-25}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

Sterile Neutrino

- 30 m from the core
- Very high statistics (2000 events / day)
- Fine energy resolution (~2% at 1 MeV)



Sensitivity at the Δm^2 region of 0.05 – 1 eV^2:

complimentary to the longer baseline experiments