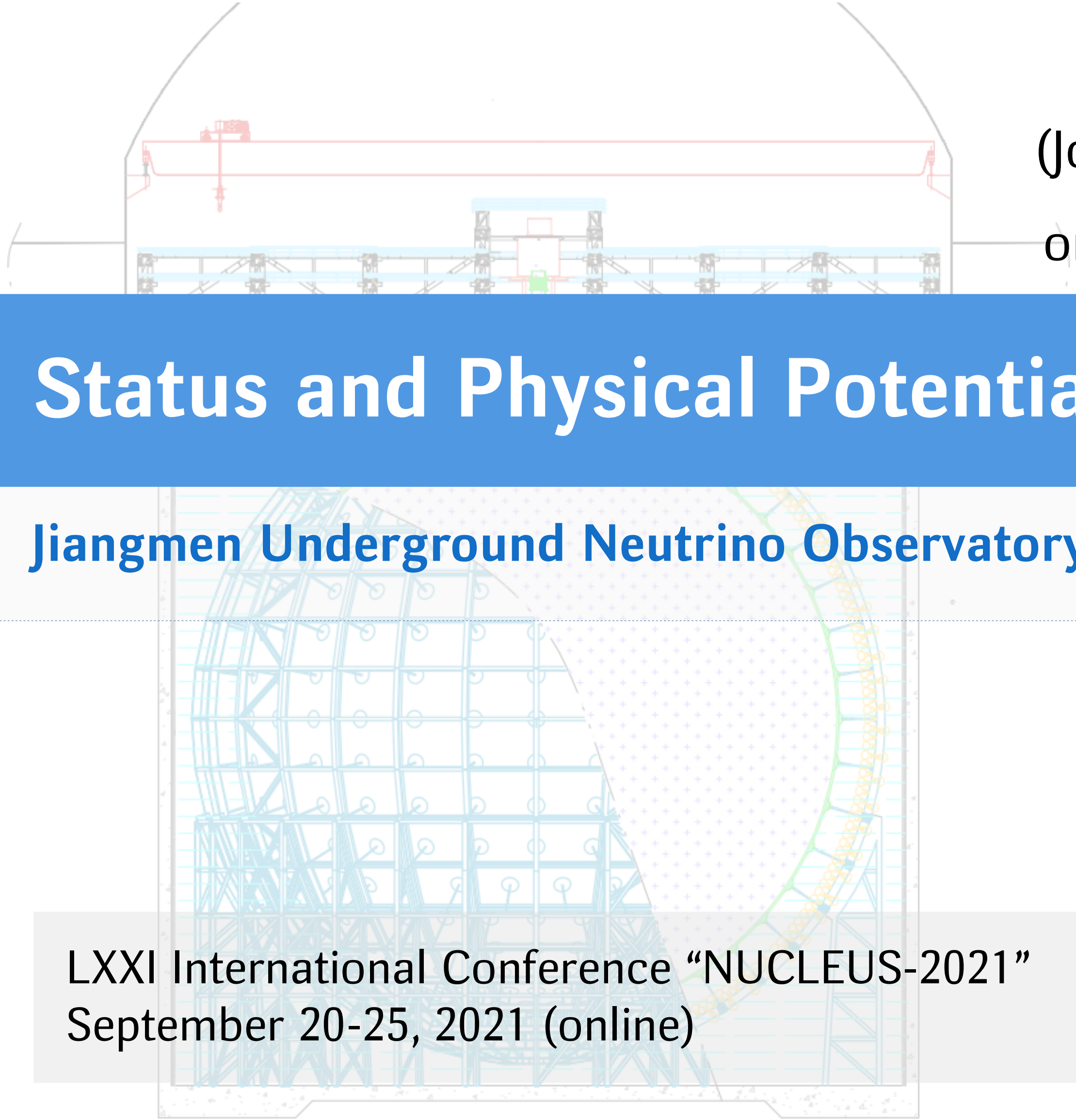
Yury Malyshkin

(Joint Institute for Nuclear Research)

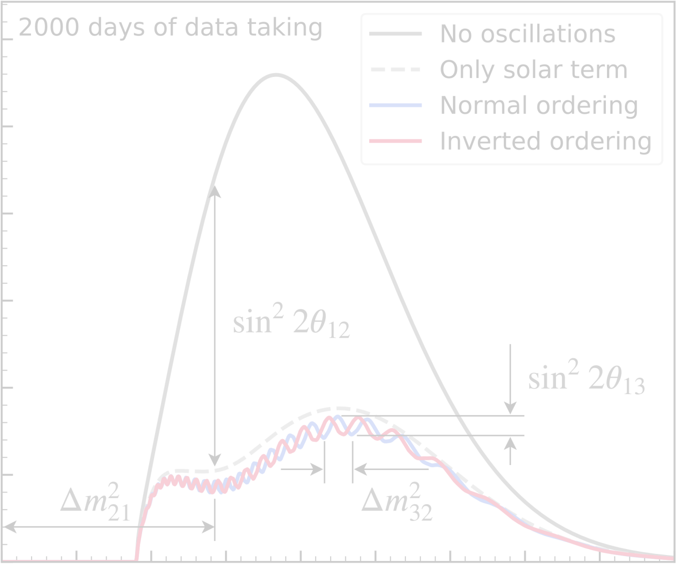
on behalf of the JUNO Collaboration

Status and Physical Potential of JUNO

Jiangmen Underground Neutrino Observatory



LXXI International Conference “NUCLEUS-2021”
September 20-25, 2021 (online)



Neutrino Mixing and Flavor Oscillations

Mass (flavor) eigenstates mix:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

$$\left(|\nu_i\rangle = \sum_\alpha U_{\alpha i}\,|\nu_\alpha\rangle \right)$$

where

$|\nu_\alpha\rangle\ (\alpha = e, \mu, \tau)$ – neutrino states with definite flavor

$|\nu_1\rangle\ (i = 1, 2, 3)$ – neutrino states with definite mass

U is Pontecorvo-Maki-Nakagawa-Sakata matrix:

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \qquad \begin{aligned} c_{ij} &= \cos\theta_{ij} \\ s_{ij} &= \sin\theta_{ij} \end{aligned}$$

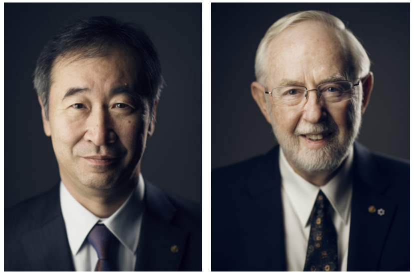
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Бруно Понтекорво

Predicted by Bruno Pontecorvo in 1957

Experimentally confirmed by Super-Kamiokande and SNO (2015 Nobel Prize)

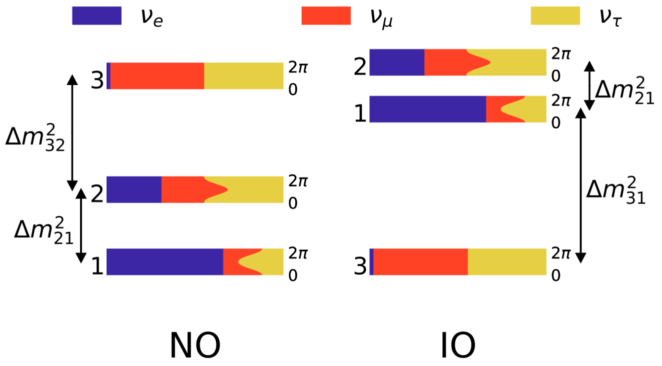


Probability of oscillation from flavor α to flavor β:

$$P_{\alpha\to\beta} = \left|\langle \nu_\beta(L)|\nu_\alpha\rangle\right|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i\frac{m_i^2 L}{2E}} \right|^2$$

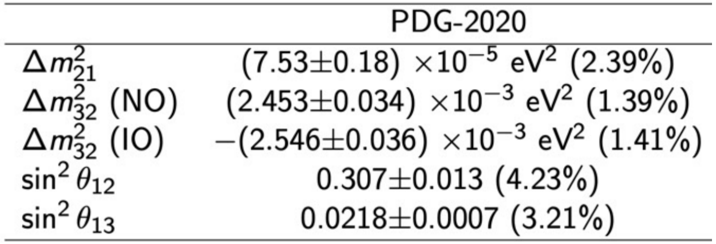
Open Questions in Neutrino Oscillation Physics

- Neutrino mass ordering:
  normal ordering (NO): $m_1 < m_2 < m_3$
  or
  inverted ordering (IO): $m_3 < m_1 < m_2$?
- CP violation: $\delta_{CP} \neq 0, \pi$?
- Octant of θ_{23}? Maximal mixing with $\theta_{23} = 45°$?
- Precise values of mixing angles and mass splittings
- Majorana (neutrino identical to anti-neutrino) or Dirac particles?
- Sterile states or only 3 flavors?
- Lorenz Invariance Violation?
- Non-standard interactions?



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]

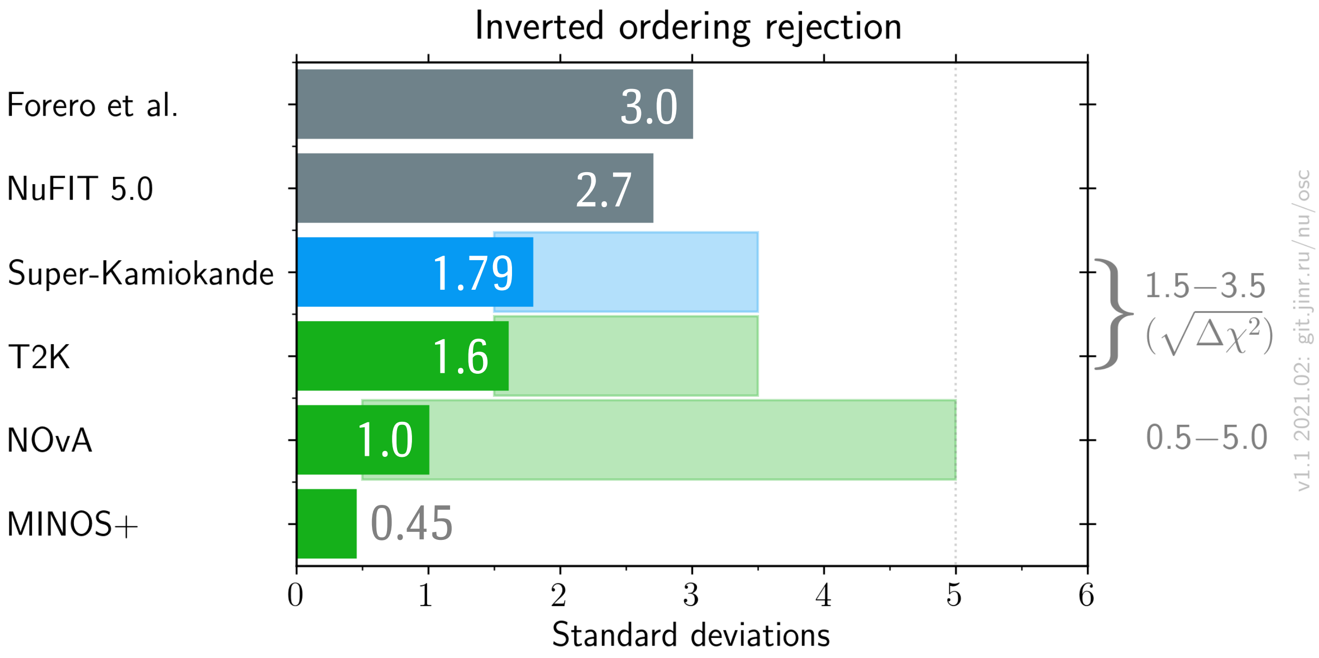


	PDG-2020
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2 (2.39%)
Δm^2_{32} (NO)	$(2.453 \pm 0.034) \times 10^{-3}$ eV^2 (1.39%)
Δm^2_{32} (IO)	$-(2.546 \pm 0.036) \times 10^{-3}$ eV^2 (1.41%)
$\sin^2\theta_{12}$	0.307 ± 0.013 (4.23%)
$\sin^2\theta_{13}$	0.0218 ± 0.0007 (3.21%)

[P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. (2020)]

Neutrino Mass Ordering Status

Currently the normal mass ordering is slightly more favored: (as of Neutrino-2020)



Atmospheric and accelerator experiments rely on matter effects.

Their final sensitivities depend on (yet unknown) oscillation parameters.

Resolving 5σ sensitivity is not guaranteed.

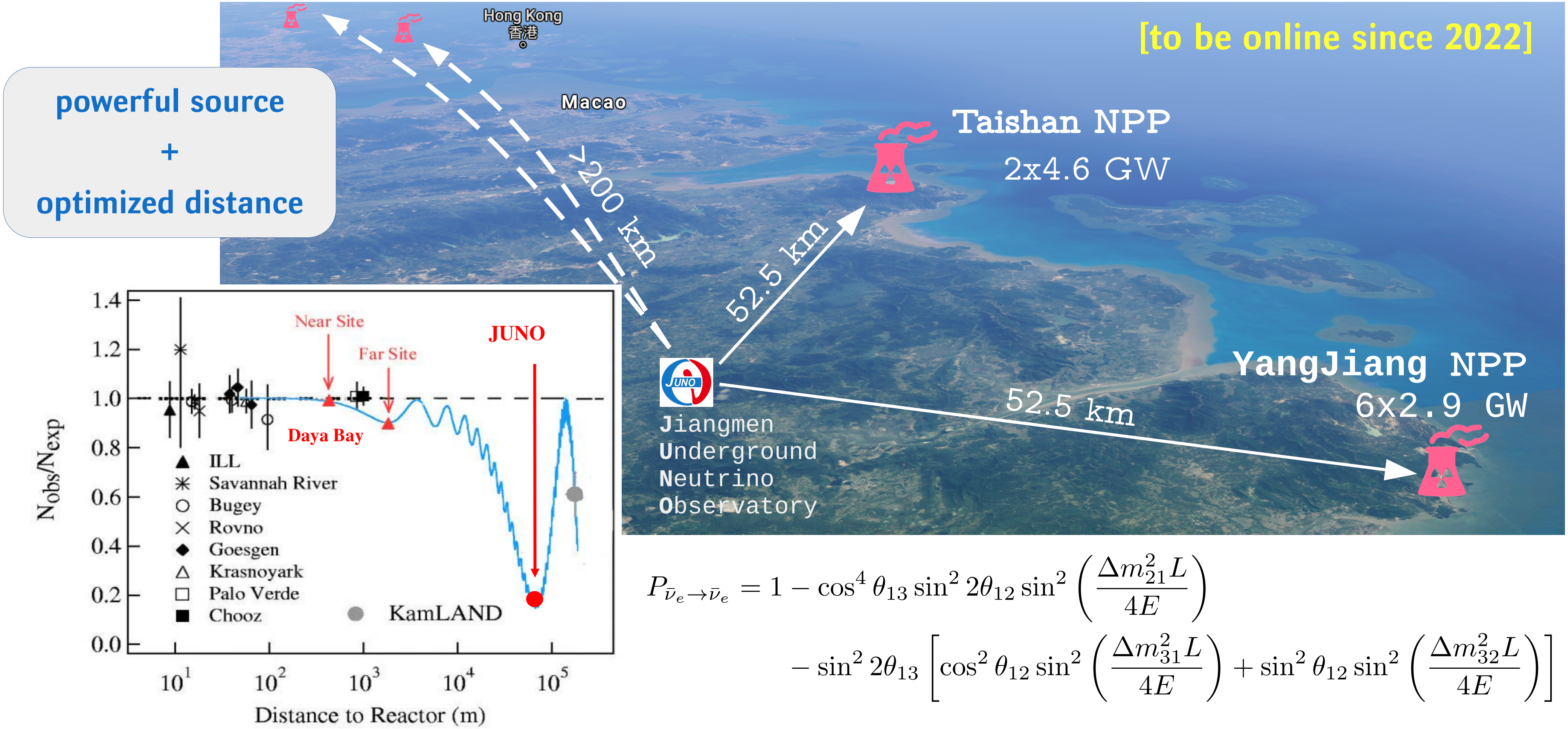
Additional experimental efforts via other channels are crucial

JUNO Experiment Layout

powerful source

+

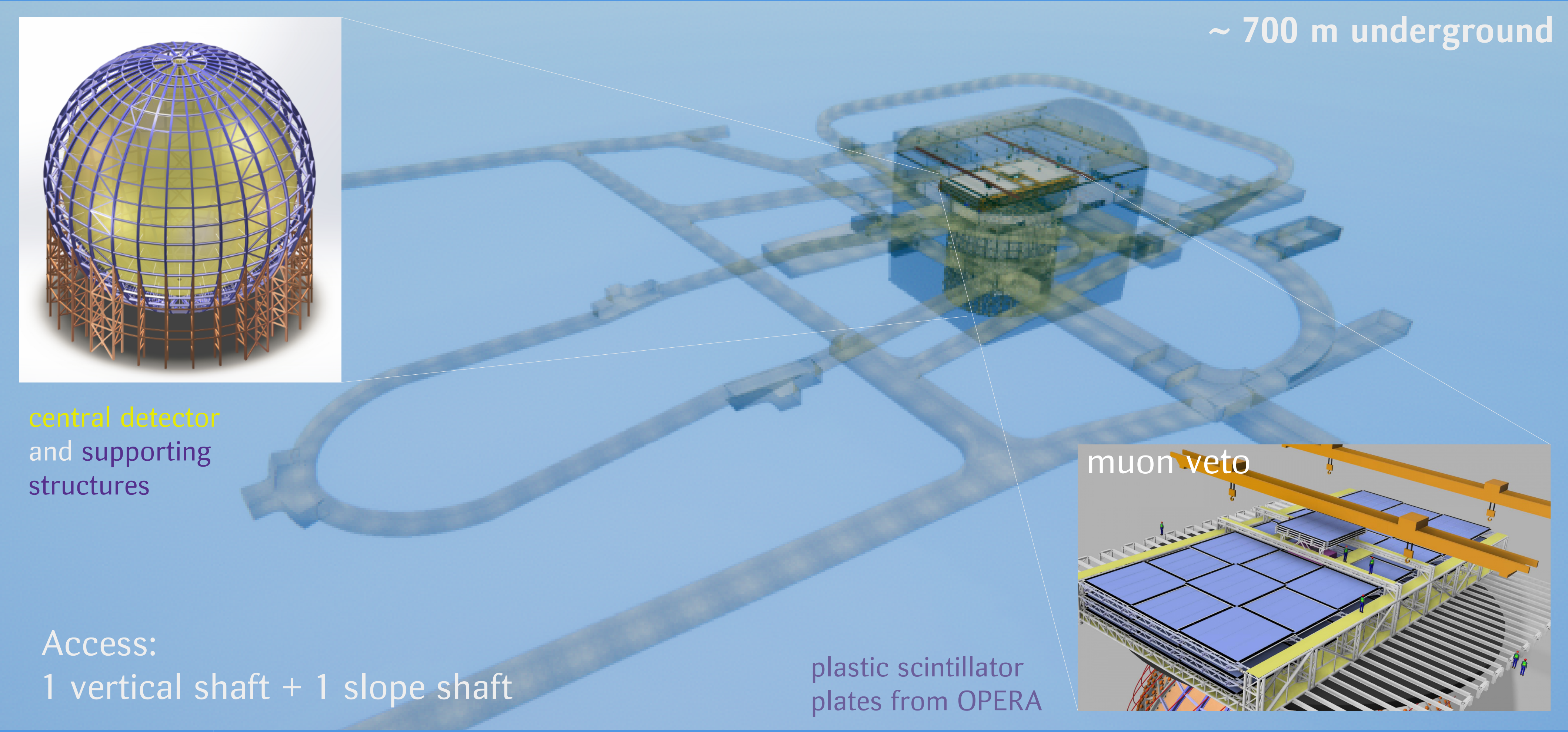
optimized distance



[to be online since 2022]

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]$$

JUNO: Underground Lab



~ 700 m underground

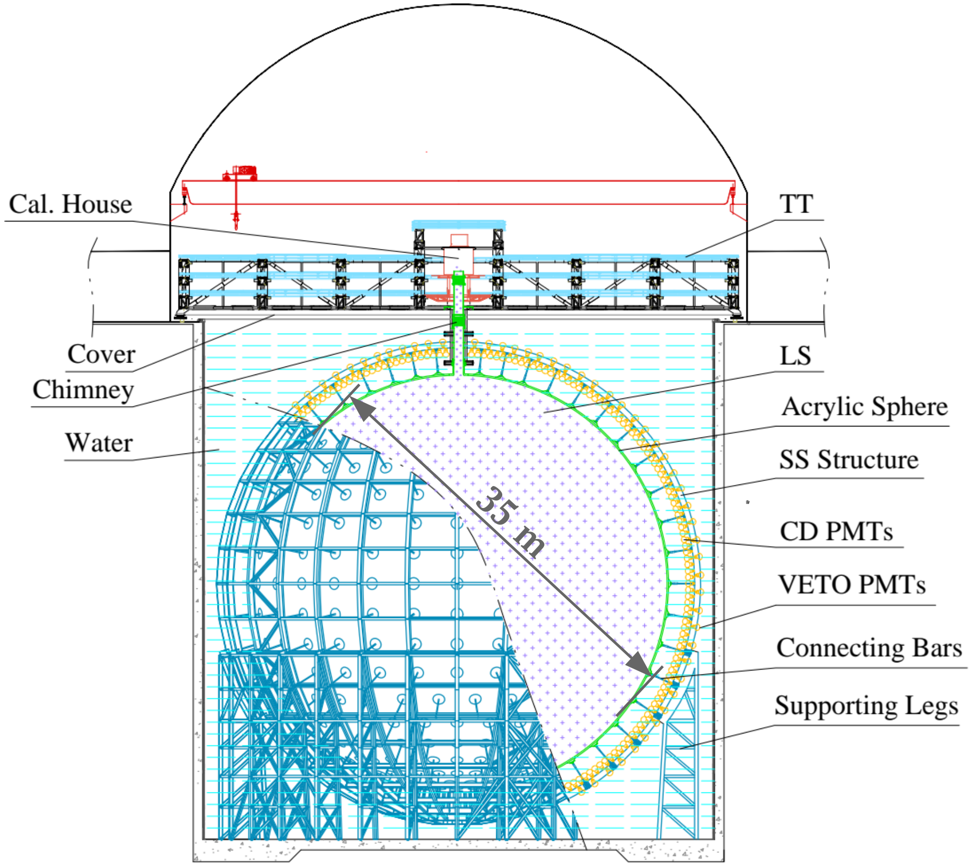
central detector
and supporting
structures

muon veto

plastic scintillator
plates from OPERA

Access:
1 vertical shaft + 1 slope shaft

JUNO Detector



- **Detection channel:** Inverse Beta-Decay (IBD)

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

  - ▻ Temporal and spatial coincident signal
  - ▻ Positron carries energy information
- **Target:** 20 kton of LAB-based liquid scintillator
  - ▻ high light yield ~10^4 photons / MeV
  - ▻ highly transparent
- **Light detection:** 17612 20'' PMTs + 25600 3'' PMTs
  - ▻ >75% photo-coverage
  - ▻ two independent PMT systems
  - ▻ ~1300 p.e. / MeV

3% energy resolution @ 1 MeV
(Gaussian sigma)

O(100k) events in 6 years

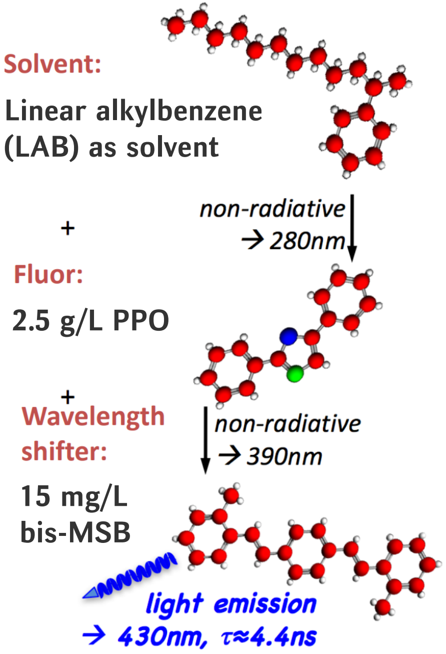
JUNO Scintillator

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)



Solvent:

Linear alkylbenzene (LAB) as solvent

non-radiative → 280nm

+

Fluor:

2.5 g/L PPO

+

Wavelength shifter:

15 mg/L bis-MSB

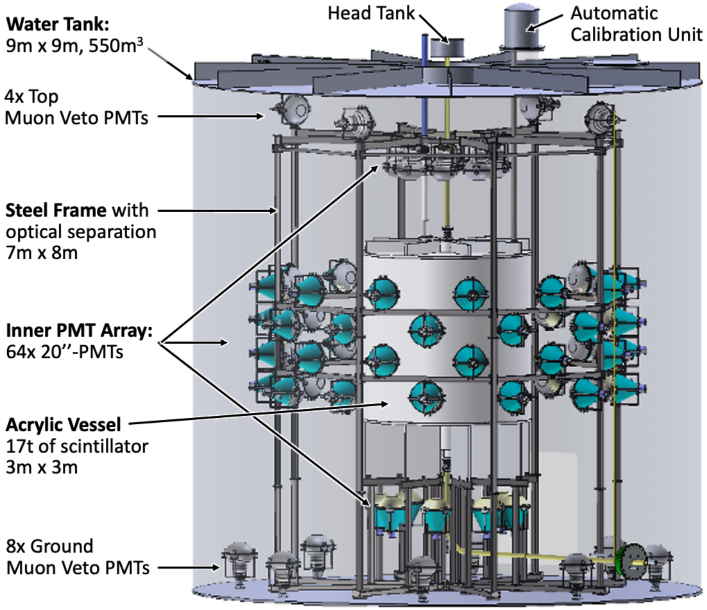
non-radiative → 390nm

light emission → 430nm, τ≈4.4ns

[JUNO collaboration, NIM-A 988, 2021]

Monitored during filling by OSIRIS

(Online Scintillator Internal Radioactivity Investigation System)



Water Tank:
9m x 9m, $550m^3$

4x Top
Muon Veto PMTs

Steel Frame with
optical separation
7m x 8m

Inner PMT Array:
64x 20’’-PMTs

Acrylic Vessel
17t of scintillator
3m x 3m

8x Ground
Muon Veto PMTs

Head Tank

Automatic
Calibration Unit

[arXiv:2103.16900 (2021)]

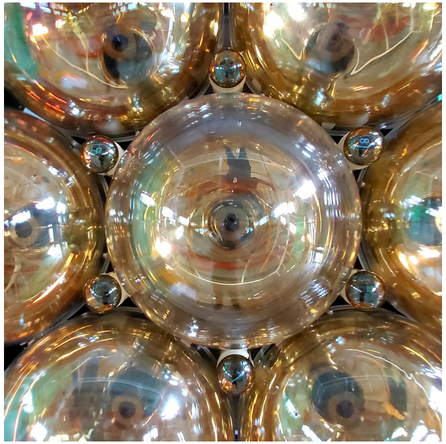
JUNO Photo-multiplier Tubes

20" PMTs: 17612 for CD + 2400 for veto

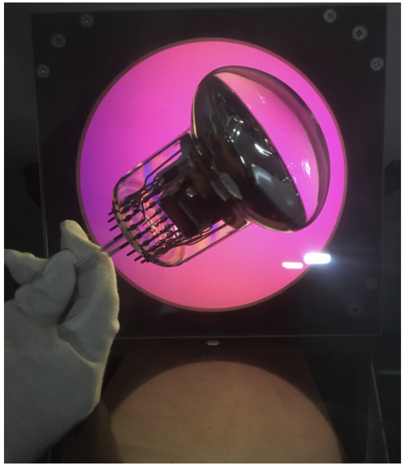
- Maximize photo-coverage (~75%)
- Two types:

NNVT Micro-Channel Plate
(¾ of total amount)
- Developed for JUNO
- Transmission and reflection cathodes → >30% QE

Hamamatsu R12860
(¼ of total amount)
- New type of bialkali photocathode
- Excellent TTS (2.7 ns FWHM)



3" PMTs: 25600 for CD



HZC Photonics
- Systematics control: determine nonlinear response of 20-in PMTs
- Increased dynamic range:
  - better resolution of muon reconstruction
  - ready for very near supernova
- Standalone measurement of solar parameters

JUNO Spectrum Ingredients

- **Neutrino generated in reactor cores:**

  thousands of β-decay branches of fission reactions in reactor core (up to several MeV)

- **Observed via Inverse Beta-Decay (IBD):**

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

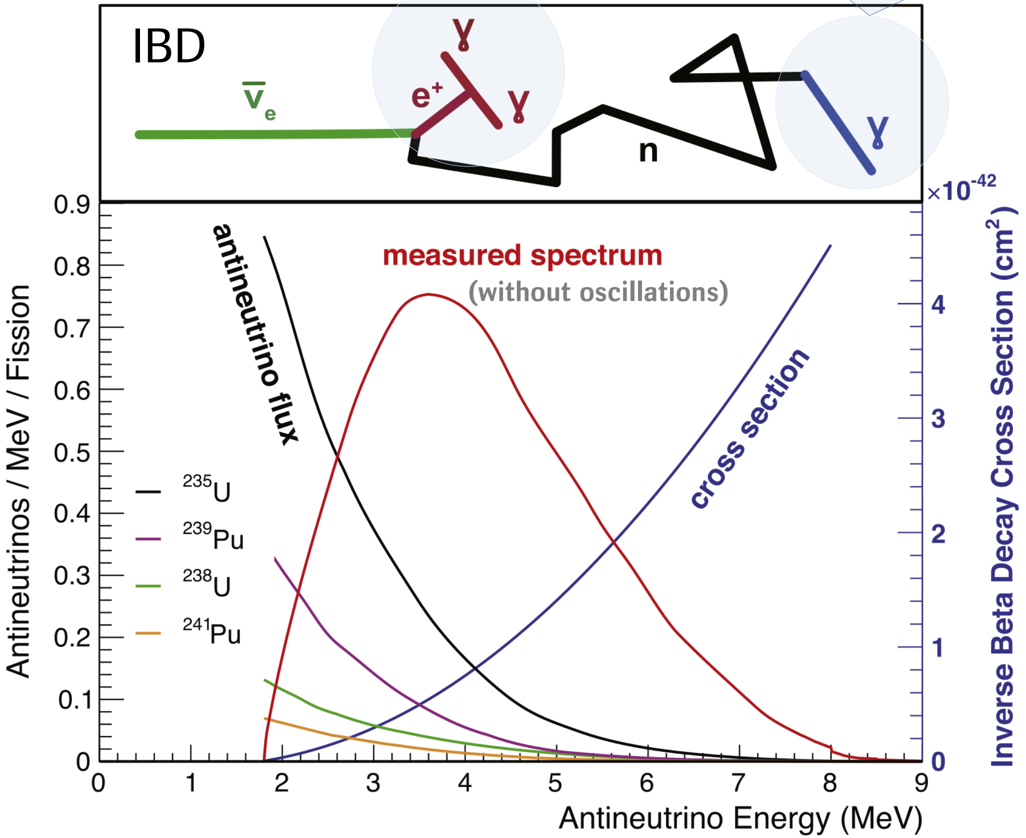
  (reaction threshold: 1.8 MeV)

- **Positron energy used to recover neutrino energy:**

$$E_\nu \simeq E_{e^+} + \Delta m_{n-p} + T_n$$

handle for neutrino energy

IBD tag: 2.2 MeV within ~200 μs



Information in JUNO Spectrum

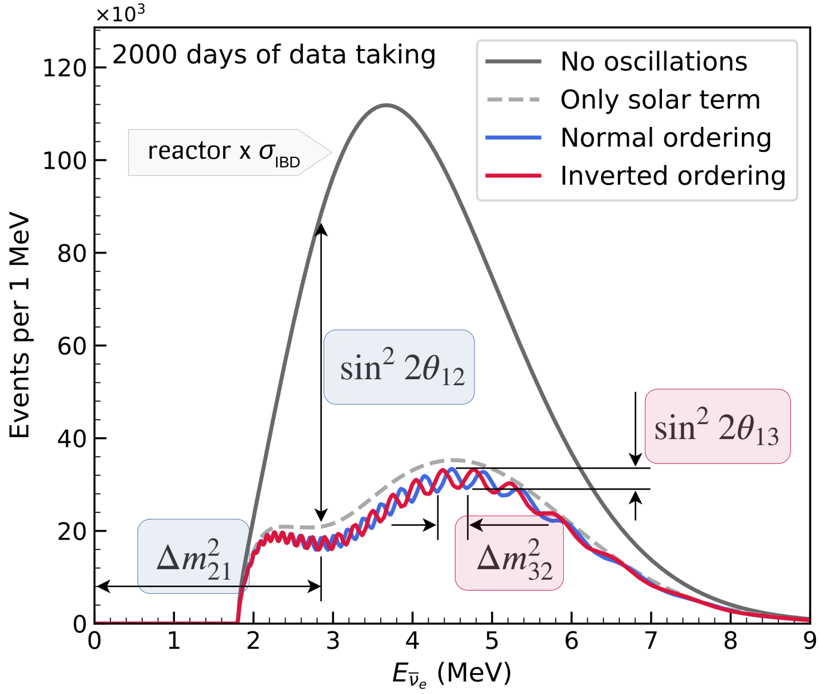
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

← slow component (solar oscillation mode)

+

$$-\sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)+\sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]$$

← fast component (atmospheric oscillation mode)



Mass ordering:

$$\text{NO: } |\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$$
$$\text{IO: } |\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$$

- Results in a slight difference of the oscillation pattern
- Accessible for JUNO thanks to large θ_{13}!

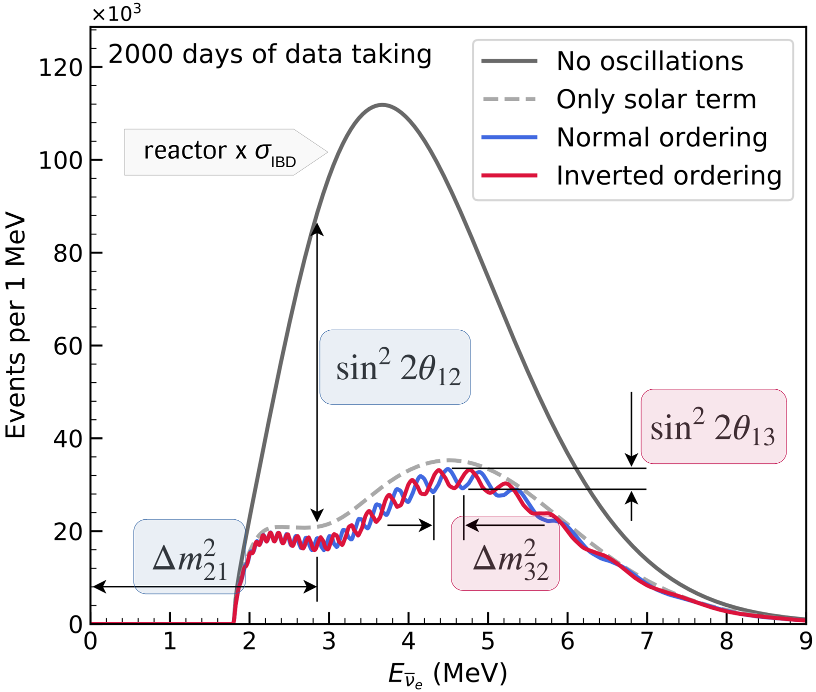
Information in JUNO Spectrum

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]$$

← **slow component (solar oscillation mode)**

+

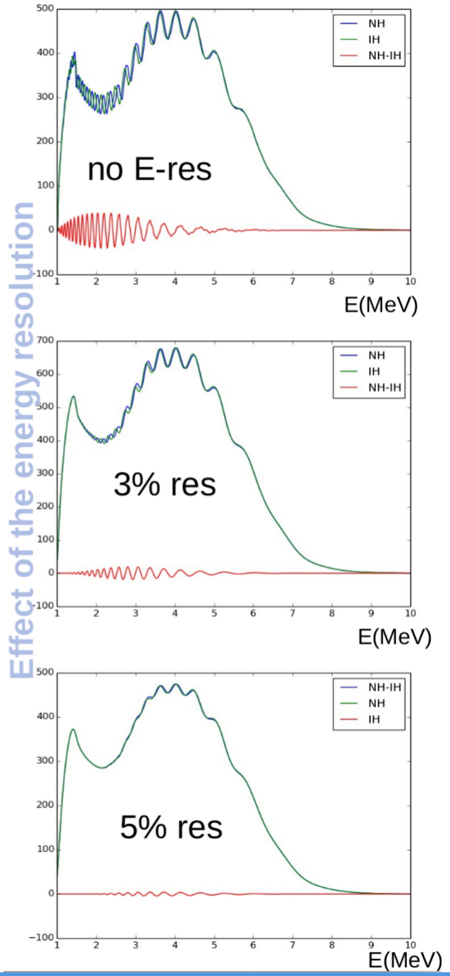
← **fast component (atmospheric oscillation mode)**



Oscillation parameters:

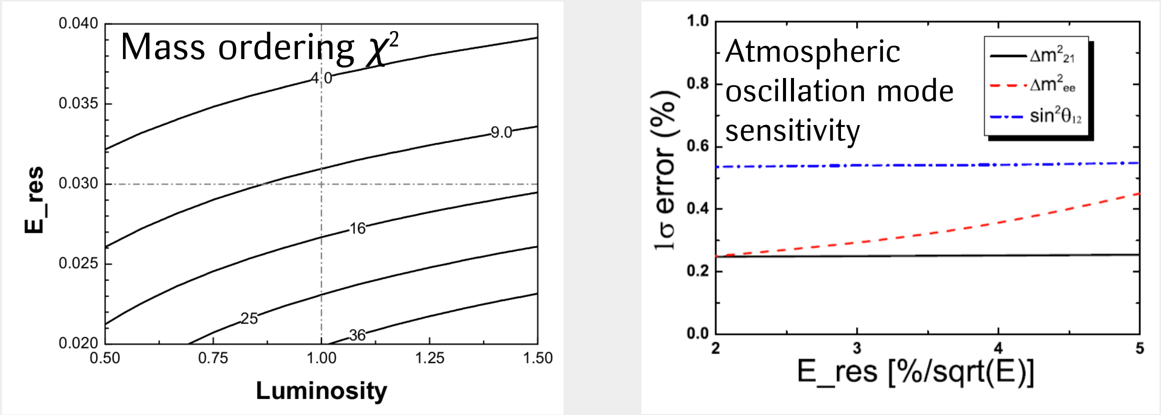
- Two oscillation modes: **solar** and **atmospheric**
- Very pronounced minimum in **solar** mode
- Many (~20) oscillation cycles in **atmospheric** mode

Energy Resolution in JUNO



Crucial for sensitivity to:

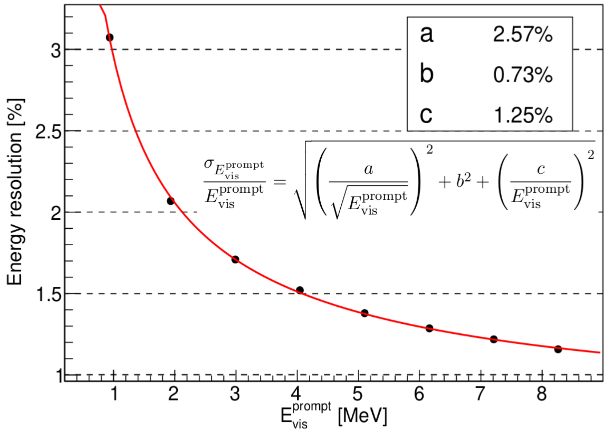
[J.Phys. G 43 (2016)]



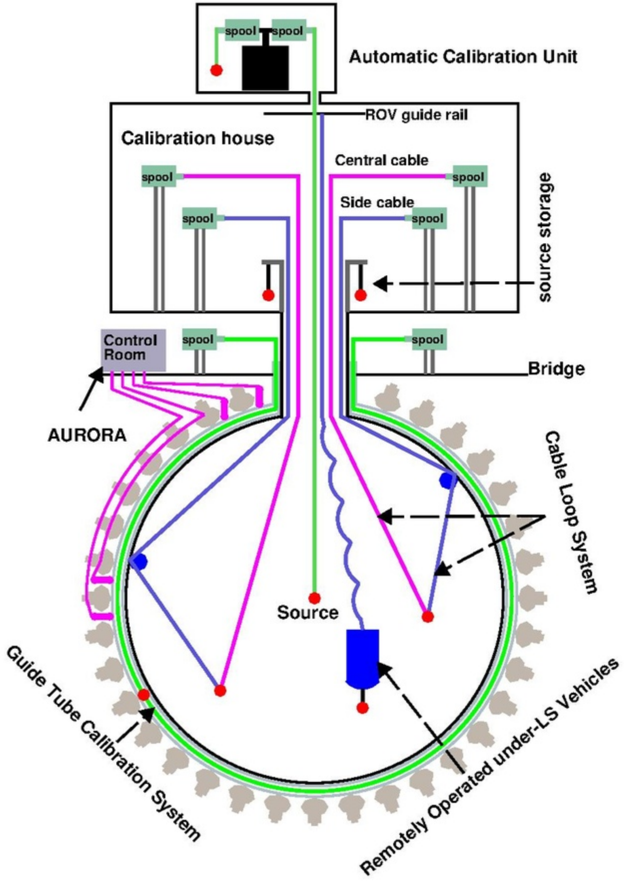
Mainly defined by:

- LS light yield (photon statistics)
- PMT detection efficiency
- Performance of energy reconstruction

The goal is 3% at 1 MeV

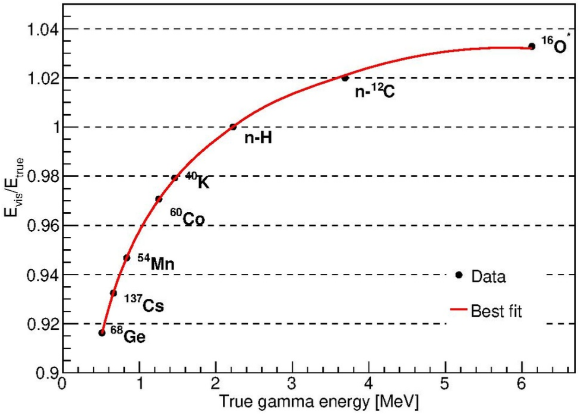


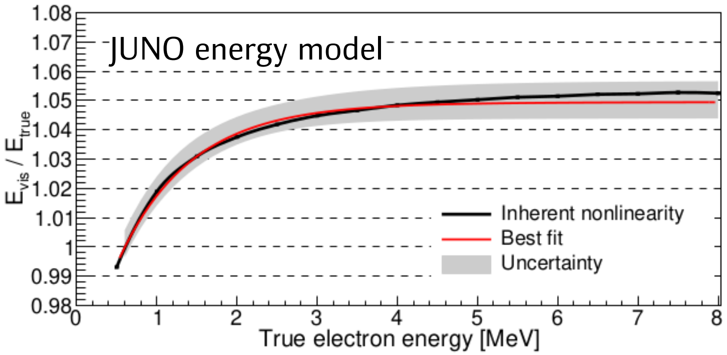
Energy Scale Calibration



[JUNO collaboration, JHEP 2021, 4 (2021)]

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV

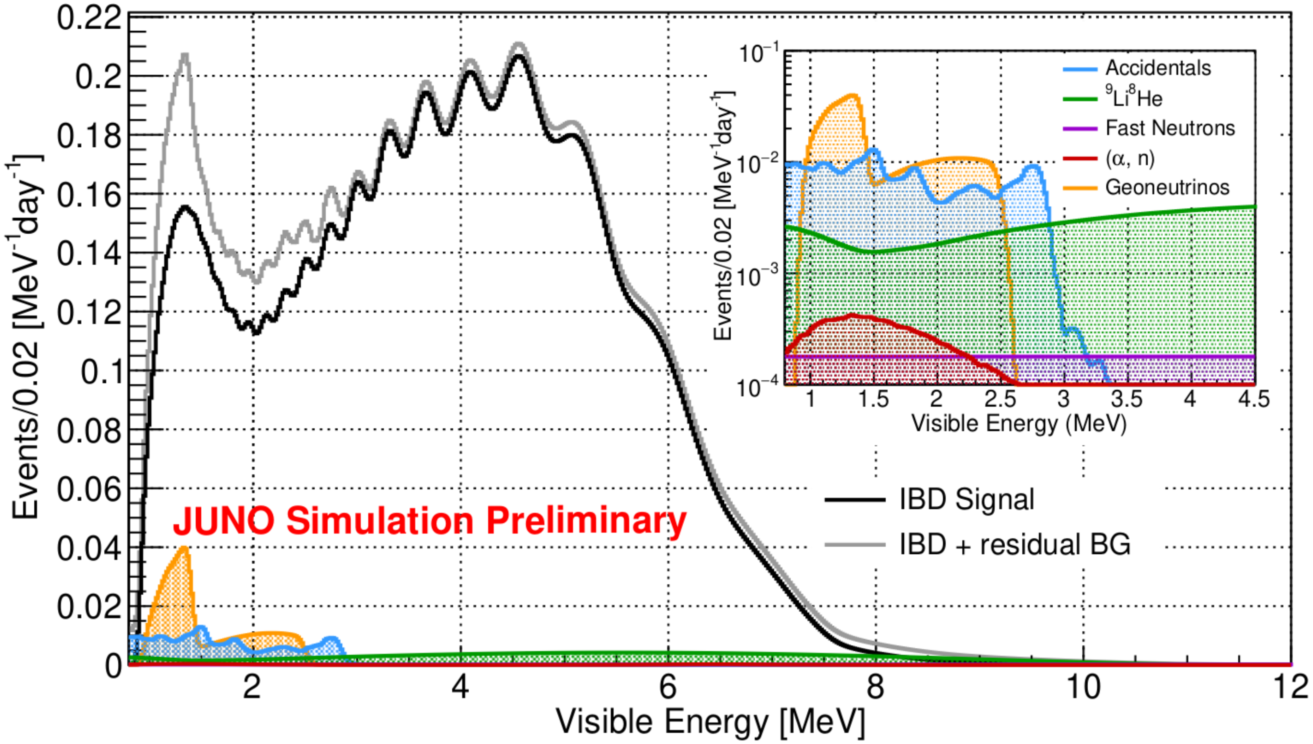




< 1% energy scale uncertainty

IBD signal and backgrounds

	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100	57.4
After Selection	82.2	47.1



Selection criteria:

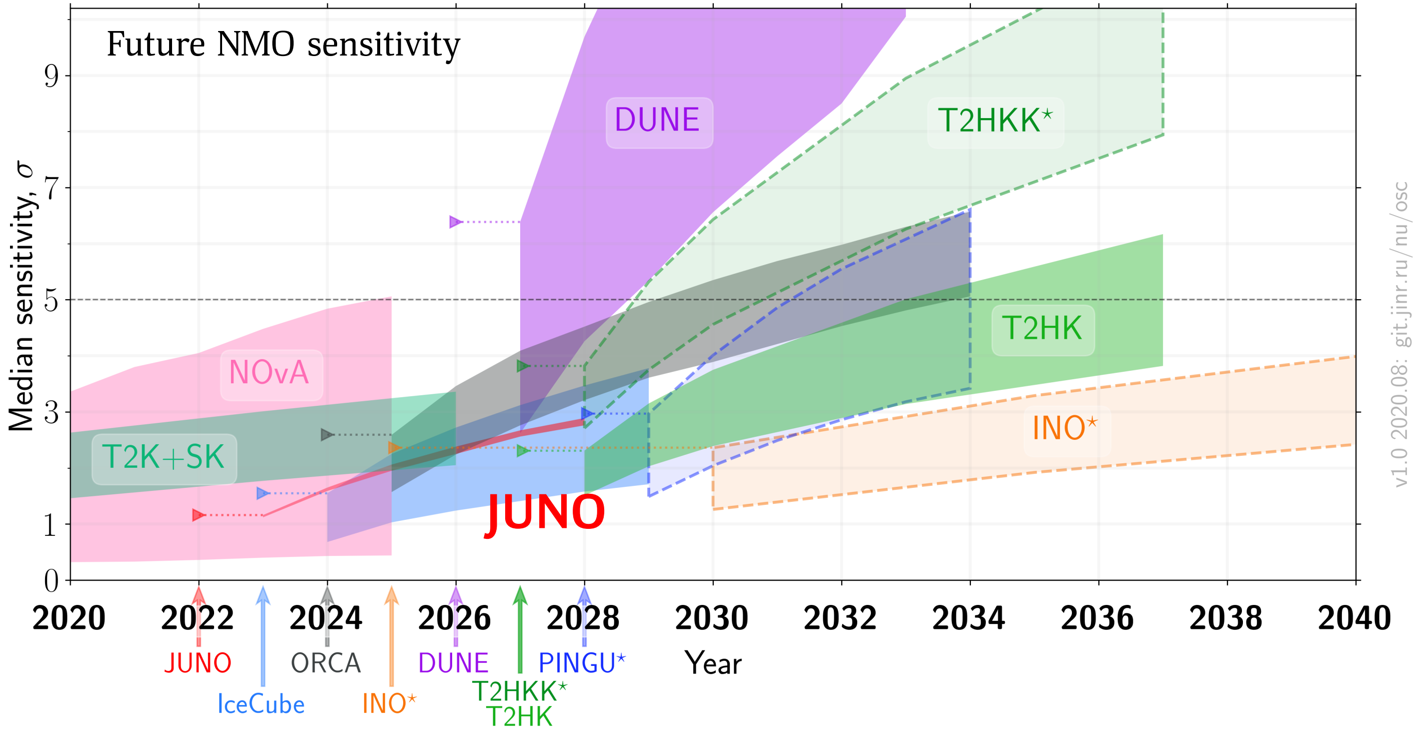
- muon veto
- volume fiducialization
- energy cuts for e+ and neutron capture
- e+ / neutron capture time coincidence
- e+ / neutron capture spatial proximity

Background	Rate (day^{-1})
Geo-neutrinos	1.2
Accidentals	0.8
^{9}Li/^{8}He	1.4
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05

Mass Ordering Determination Prospects

JUNO is the **only** experiment using vacuum oscillation:

- independent on δ_{CP} and θ_{23}
- little dependence of matter effects (MSW contribution ~4%)



3σ sensitivity
in 6 years of data taking

An update on JUNO NMO sensitivity is under preparation

Mass Ordering Determination Prospects

- JUNO is the **only** experiment using vacuum oscillation: independent on δ_{CP} and θ_{23} , little dependence of matter effects

- With $|\Delta m^2_{\mu\mu}|$ input JUNO sensitivity might be further improved

- Strong synergies with other experiments:
  - through Δm^2_{31} for atmospheric neutrinos (KM3NeT/ORCA [arXiv:2108.06293] and IceCube [Phys. ReV. D 101 (2020)])
  - through Δm^2_{32} for accelerator neutrino (NOvA and T2K [arXiv:2008.11280], [Phys. Rev. D 103 (2021)])

3σ sensitivity
in 6 years of data taking

> 4σ (in 6 years)
with external $|\Delta m^2_{\mu\mu}|$
(assuming 1% uncertainty)

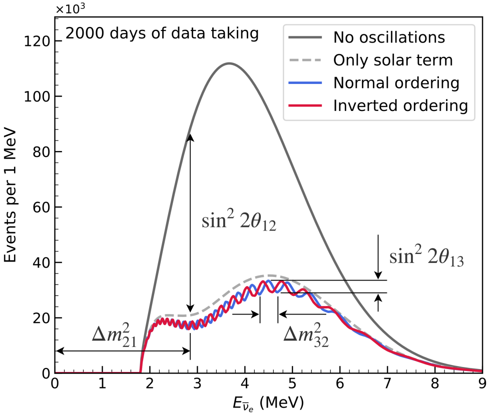
> 5σ (in 6 years)
in case of **joint** analysis

Measurement of Oscillation Parameters

JUNO will be the first experiment to observe two modes of neutrino oscillations simultaneously:

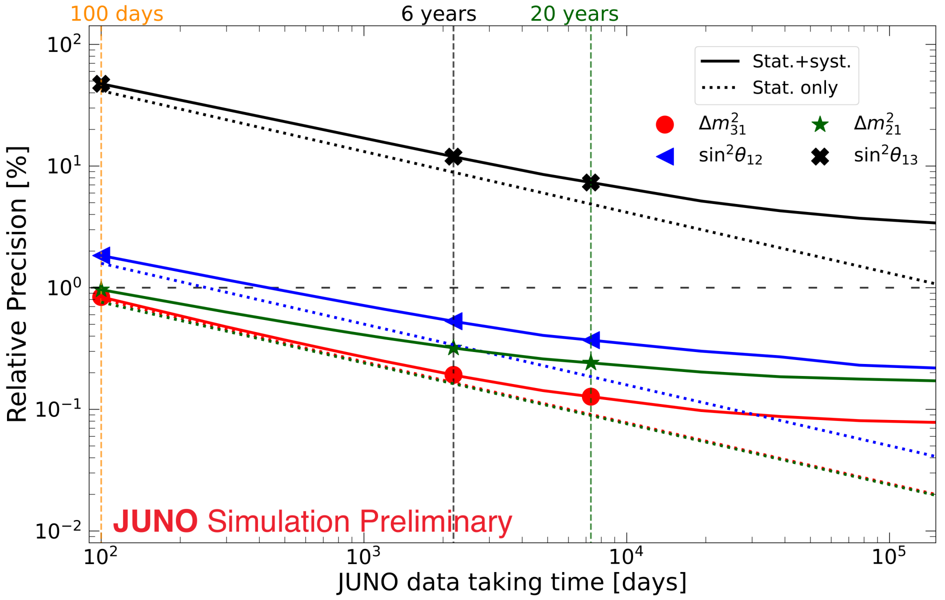
‘solar’, driven by $\sin^2\theta_{12}$ and Δm^2_{21}

‘atmospheric’, driven by $\sin^2\theta_{13}$ and Δm^2_{31} (Δm^2_{32})



Main factors affecting sensitivity to oscillation parameters:

- reactor rate and shape uncertainty ← *TAO helps here!*
- backgrounds: mainly accidentals and geo-neutrino



(in %)	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	$\lvert\Delta m^2_{32}\rvert$
Current precision (NuFIT)	4.0	2.8	2.8	1.1
JUNO (6 years)	**~0.5**	**~0.3**	12	**~0.2**

Solar ^{8}B Neutrinos

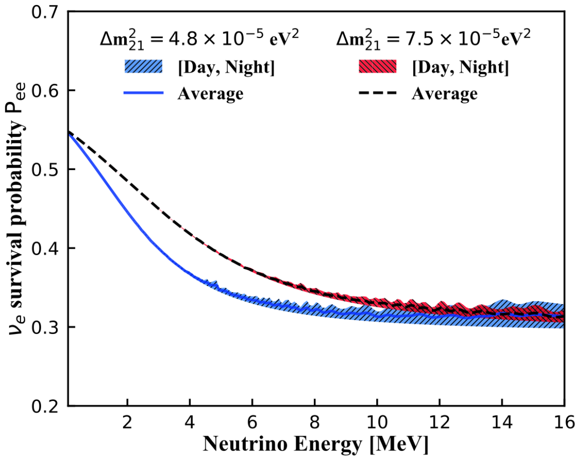
Another channel to measure solar oscillation parameters!

Oscillation media: Sun + Earth

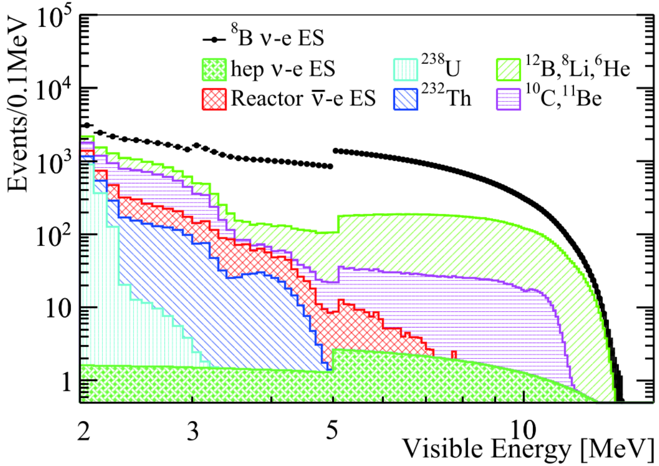
Detection channel: elastic scattering on electrons

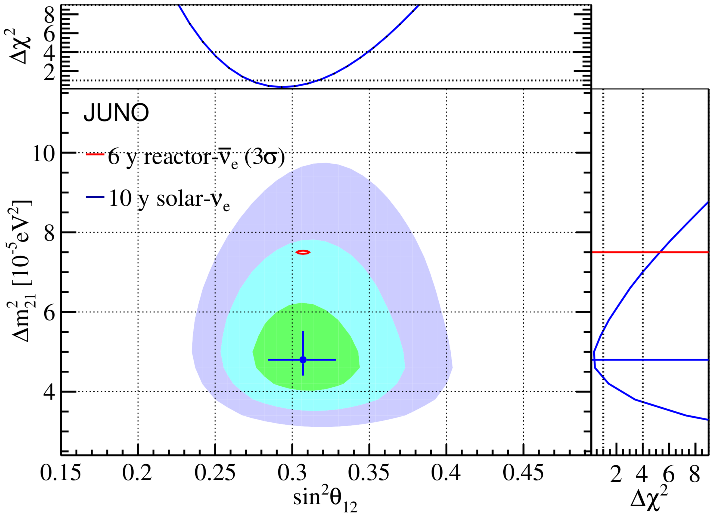
Energy threshold: 2 MeV

Signal / background: 60k / 30k (10 years)



10^{-17} g/g ^{238}U and ^{232}Th



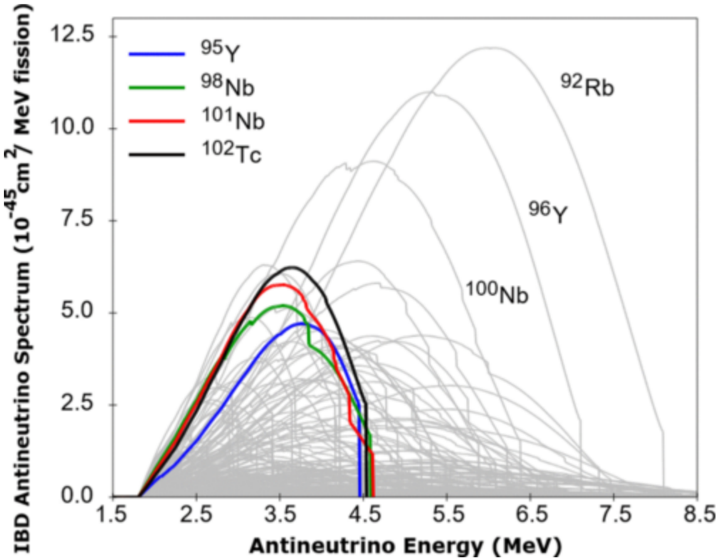


- 0.9% sensitivity to Day/Night asymmetry (1.1% in Super-K)
- Smaller Δm^2_{21} leads to a larger Day-Night asymmetry
- Δm^2_{21} precision similar to other solar measurements

Slight 1.4σ tension for Δm^2_{21} between KamLAND ($7.5 \cdot 10^{-5}$ eV^2) and SNO+SK ($6.1 \cdot 10^{-5}$ eV^2)

Fine Structure in Reactor Anti-Neutrino Spectrum

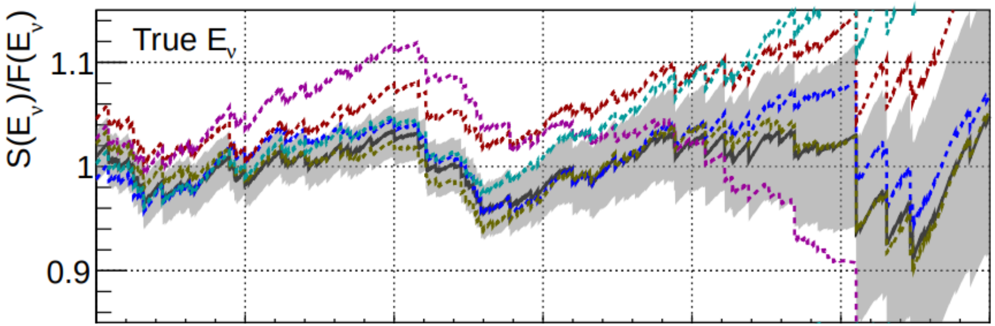
Reactor $\bar{\nu}_e$ spectrum is composed of thousands of β-decay branches and might have fine structures.



[Sonzogni et al, PhysRevC 98 014323]

State-of-the-art knowledge does not provide reliable detailed spectrum:

- 5-8% @ 1 MeV in Daya Bay, Double Chooz and RENO
- Huber-Mueller model uses about 30 virtual β-spectra without detailed structure
- Summation model has large systematic uncertainties and depends on choice of database (some data may be missing)



[Dwyer and Lingford, Phys.Rev.Lett. 114]

An unknown fine structure might produce pseudo-oscillation pattern → harmful for JUNO mass ordering measurement!

TAO: Taishan Antineutrino Observatory

An innovative apparatus:

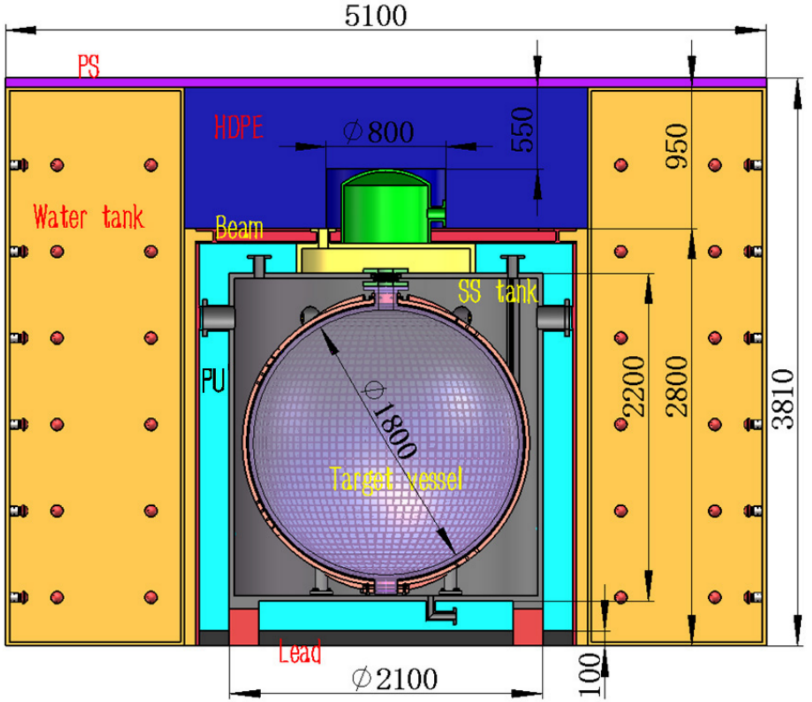
- 1 ton fiducial volume / 2.6 tons of Gd-LS
- Almost full coverage with SiPM (~50% PDE @ -50°C)

30 x JUNO statistics

~2% at 1 MeV energy resolution
(Gaussian sigma)

Measurement of reactor $\bar{\nu}_e$ spectrum at 30 m distance from a Taishan NPP core (almost no oscillations):

- → will be sensitive to fine structure at least at the precision of JUNO
- → Provide model-independent reference for JUNO
- → Improvement of nuclear databases



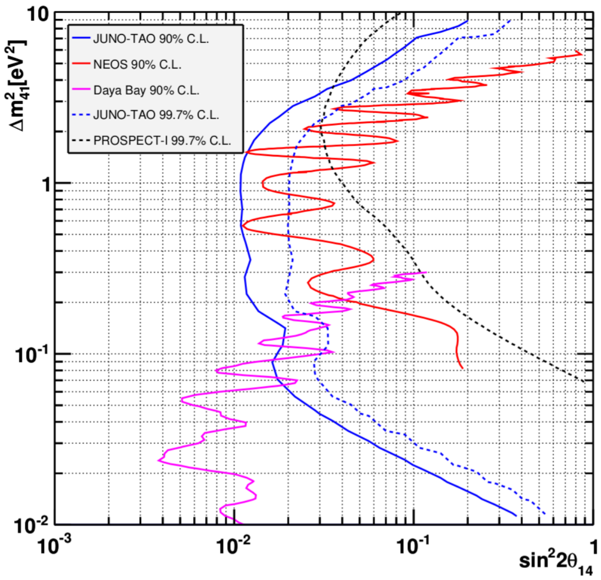
Planned to be online in 2022

TAO Light Sterile Neutrino

Motivation – observed tensions with 3-flavor paradigm:

- Reactor $\overline{\nu}_e$ deficit with respect to the state-of-the-art prediction models
- Anomalous $\overline{\nu}_e$ appearance in the $\overline{\nu}_\mu$ beam at the LSND and MiniBooNE
- Deficit in number of ν_e from radioactive calibration source in gallium experiments

Sterile neutrino could explain these anomalies



Setup:

baseline: ~30 m

detection efficiency: 50%

3 years of data taking (~1.8M events)

5% bin-to-bin uncertainty in 50 keV bins

TAO will provide new constraints in 0.1–3 eV² Δ*m*² region

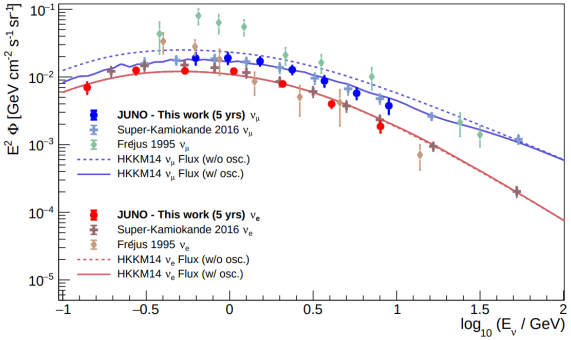
More Physics Studies

[arXiv:2104.02565]

Atmospheric neutrino

hundreds / year

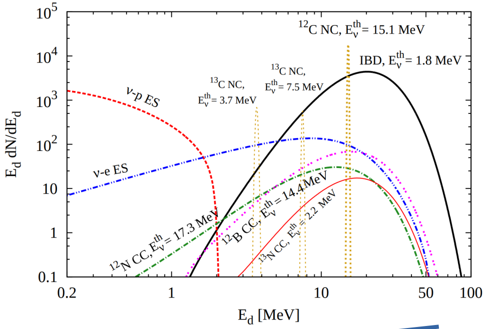
- Complimentary NMO sensitivity via matter effect
- Atmospheric neutrino flux and spectra measurement



Supernova burst

5000 IBD / 2300 elastic scattering @ 10 kpc

- Determination of flavor content, energy spectrum and time evolution
- Part of Multi-messenger effort

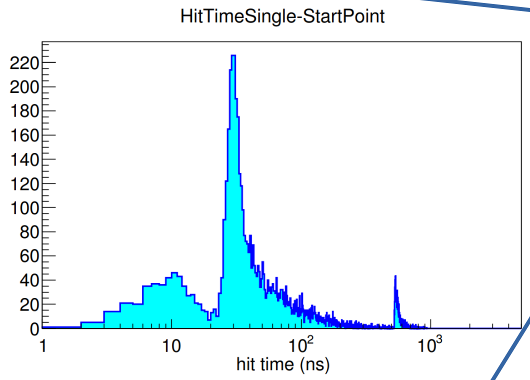


Proton decay

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

three-fold time coincidence:

1) **kinetic energy of K^+**
2) **decay daughters**
3) **Michel electron**



- sensitivity $8.34 \cdot 10^{33}$ years (90% C.L.) – comparable to leading experiments

Geo-neutrino

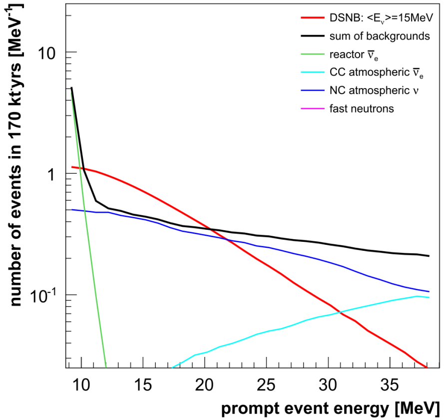
~400 IBD per year

- Explore origin and thermal evolution of the Earth
- 5-6% flux precision in 10 years

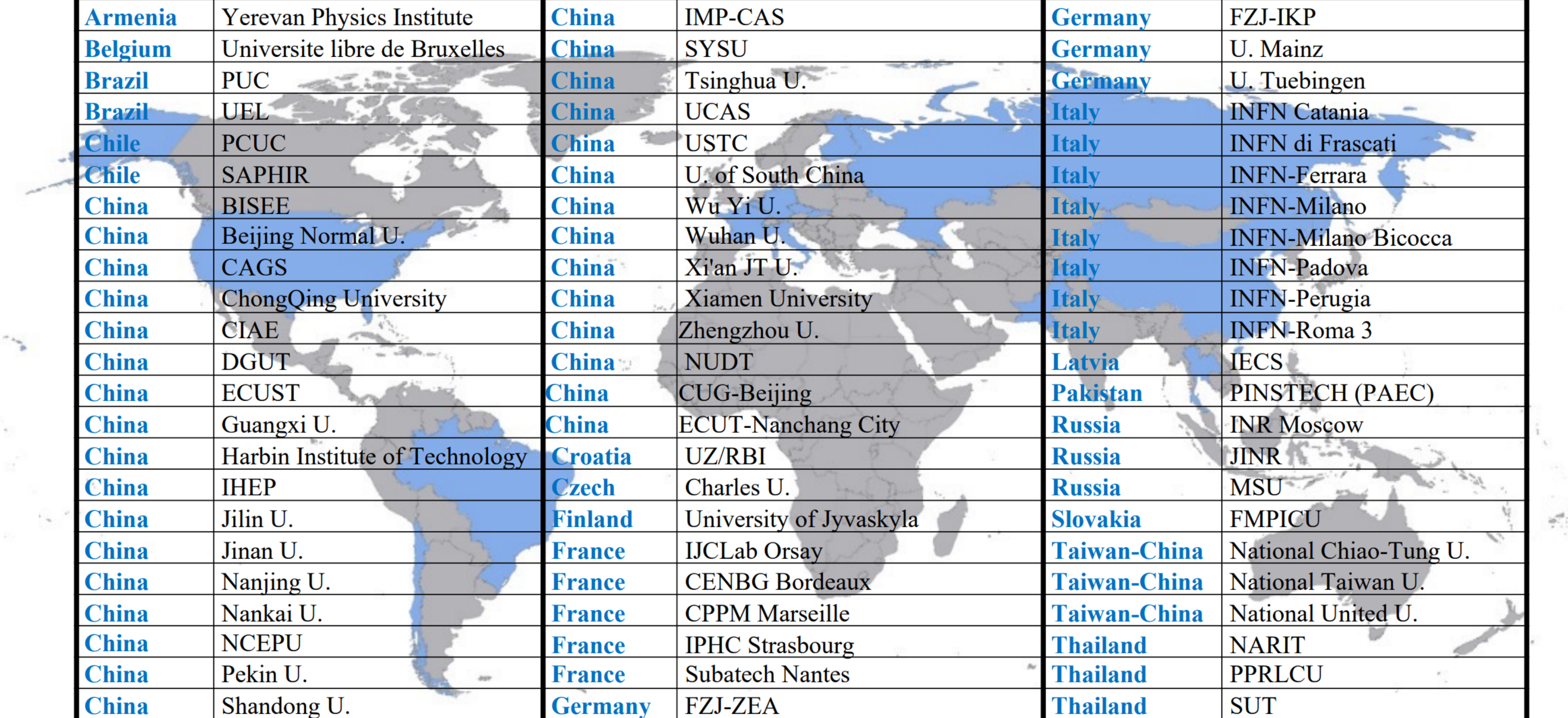
Diffuse supernova flux (DSNB)

2-4 IBD per year

- Provide info for star formation rate, emission from CCSN and BH
- Expected 3σ in 10 years of data taking



JUNO Collaboration



Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	**China**	IMP-CAS	**Germany**	FZJ-IKP
Belgium	Universite libre de Bruxelles	**China**	SYSU	**Germany**	U. Mainz
Brazil	PUC	**China**	Tsinghua U.	**Germany**	U. Tuebingen
Brazil	UEL	**China**	UCAS	**Italy**	INFN Catania
Chile	PCUC	**China**	USTC	**Italy**	INFN di Frascati
Chile	SAPHIR	**China**	U. of South China	**Italy**	INFN-Ferrara
China	BISEE	**China**	Wu Yi U.	**Italy**	INFN-Milano
China	Beijing Normal U.	**China**	Wuhan U.	**Italy**	INFN-Milano Bicocca
China	CAGS	**China**	Xi'an JT U.	**Italy**	INFN-Padova
China	ChongQing University	**China**	Xiamen University	**Italy**	INFN-Perugia
China	CIAE	**China**	Zhengzhou U.	**Italy**	INFN-Roma 3
China	DGUT	**China**	NUDT	**Latvia**	IECS
China	ECUST	**China**	CUG-Beijing	**Pakistan**	PINSTECH (PAEC)
China	Guangxi U.	**China**	ECUT-Nanchang City	**Russia**	INR Moscow
China	Harbin Institute of Technology	**Croatia**	UZ/RBI	**Russia**	JINR
China	IHEP	**Czech**	Charles U.	**Russia**	MSU
China	Jilin U.	**Finland**	University of Jyvaskyla	**Slovakia**	FMPICU
China	Jinan U.	**France**	IJCLab Orsay	**Taiwan-China**	National Chiao-Tung U.
China	Nanjing U.	**France**	CENBG Bordeaux	**Taiwan-China**	National Taiwan U.
China	Nankai U.	**France**	CPPM Marseille	**Taiwan-China**	National United U.
China	NCEPU	**France**	IPHC Strasbourg	**Thailand**	NARIT
China	Pekin U.	**France**	Subatech Nantes	**Thailand**	PPRLCU
China	Shandong U.	**Germany**	FZJ-ZEA	**Thailand**	SUT
China	Shanghai JT U.	**Germany**	RWTH Aachen U.	**USA**	UMD-G
China	IGG-Beijing	**Germany**	TUM	**USA**	UC Irvine
China	IGG-Wuhan	**Germany**	U. Hamburg		

Summary

Neutrino Oscillations

- Mass Ordering sensitivity:
  - 3σ in 6 years via oscillations in vacuum
  - 4σ with external $|\Delta m^2_{\mu\mu}|$
  - 5σ+ in combination with atmospheric and long-baseline experiments
- Precise Measurement of Oscillation Parameters
  - sub-percent level for Δm^2_{21}, $|\Delta m^2_{32}|$ and $\sin^2\theta_{12}$ in reactor IBD channel
  - independent measurement through solar channel

Data taking starts in 2022

Other Physics

- Atmospheric neutrino: spectrum + NMO info
- Geo-neutrino: 6% flux measurements is 6 years
- Supernova bursts: flavor composition, energy and time info
- DSNB sensitivity: few events per year
- Solar neutrino: B^8 (60k/30k signal/background in 10 years)
- Proton decay and other rare events

TAO – a satellite detector

- Measurement of reactor spectrum fine structure – a proxy for JUNO and valuable data for future experiments
- Improved constraint on sterile neutrino in 0.1-3 eV^2 Δm^2 region