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Physics prospects of JUNO

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The Jiangmen Underground Neutrino Observatory

The biggest liquid scintillator experiment ever built

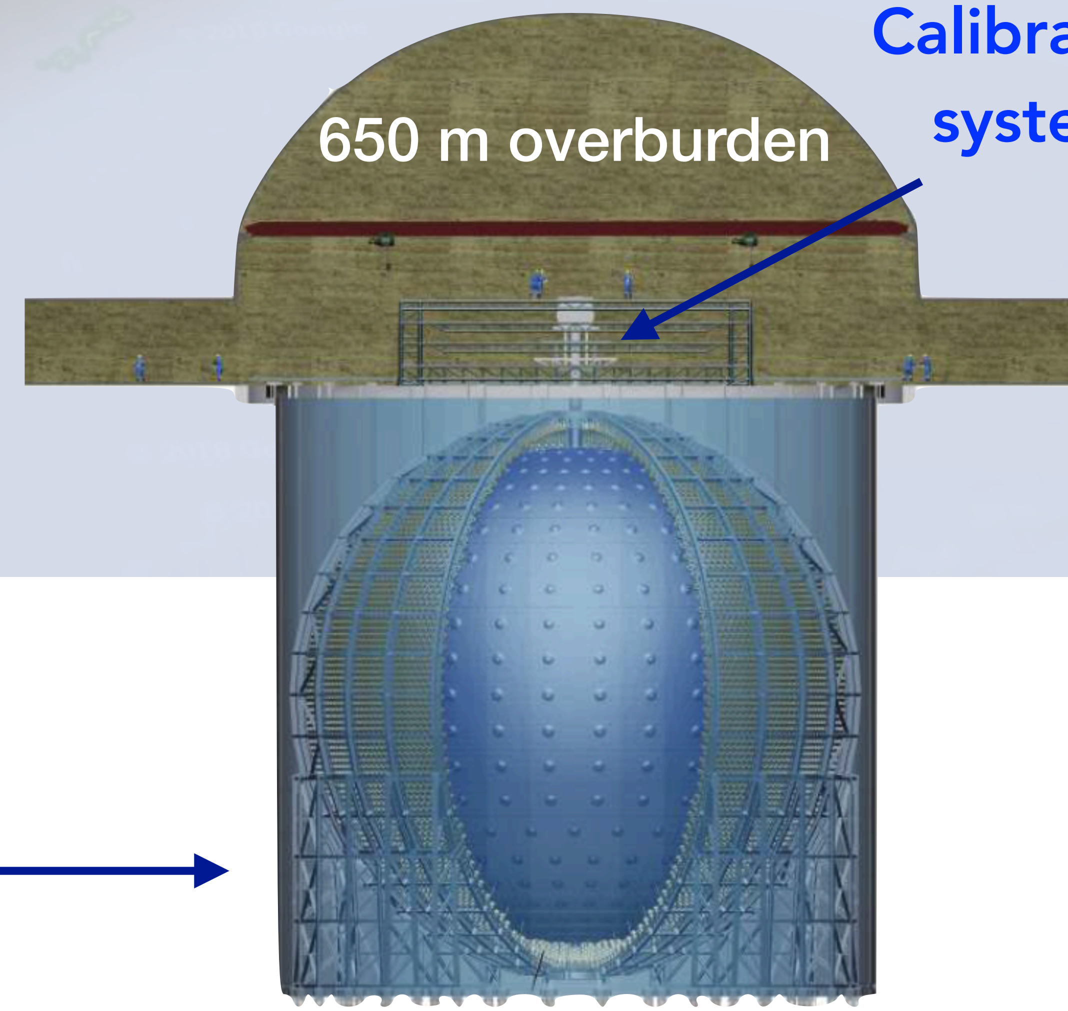
Construction completed in December 2024 *(status and commissioning, R. Zhao's talk)*

In South China, at 52.5 km from 8 nuclear reactors (~26.6 GW_{th}) + Satellite detector TAO

Muon Veto

- **Water pool** (35 kt ultra-pure water + 2000 LPMTs)
- **Top Tracker**

Calibration system



Central Detector

- **20,000 tons Liquid Scintillator** (filling ongoing)
- **17612 LPMT (20") & 25600 SPMT (3")**
- **Acrylic sphere** (r = 17.7m, 12cm thick) and stainless steel structure for mechanical support

A challenging experiment

- **Large event statistics**
  - ➡ large detector volume, large photon yield, liquid scintillator transparency, large photo-coverage and PMT efficiency
- **Background suppression**
  - ➡ 700m overburden, strict radiopurity control of LS and surrounding materials, muon-veto system
- Multi-source **calibration system** and accurate control of the **systematic uncertainties** (dual calorimetry)
- Precise knowledge of the reactor anti-neutrino flux **(TAO satellite detector)**

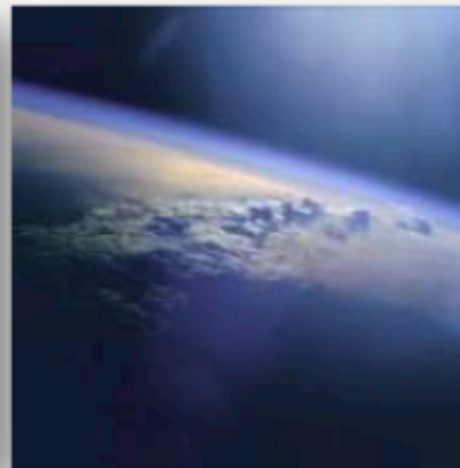
Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
Target mass	20 ton	~ 300 ton	~ 1 kton	**20 kton**
Energy resolution	7.5%/√E	5%/√E	6%/√E	**3%/√E**
Energy calibration	1,5%	~ 1%	2%	**< 1%**
Optical coverage	12%	34%	34%	**78%**
Light yield	160 p.e./MeV	500 p.e./MeV	250 p.e./MeV	**~1600 p.e./MeV**

A multi-purpose experiment

Reactor anti-ν

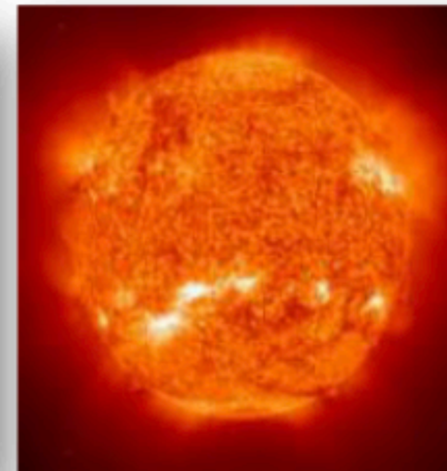
~ 50/day

Atmospheric ν



Several/day

Solar ν



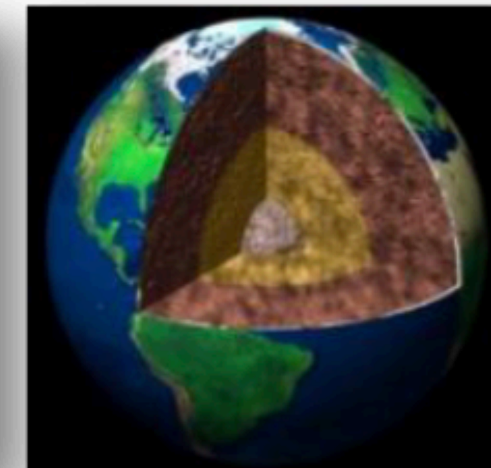
^{8}B: ~50/day
CNO: ~1000/day

^{7}Be: 10000/day

Supernovae (SN) ν

Core Collapse SN at 10 kpc :
~5000 (in ~10 sec)
Diffuse SN: few/year

Geoneutrinos



~ 400/year

Neutrino oscillation & properties

Neutrinos as a probe

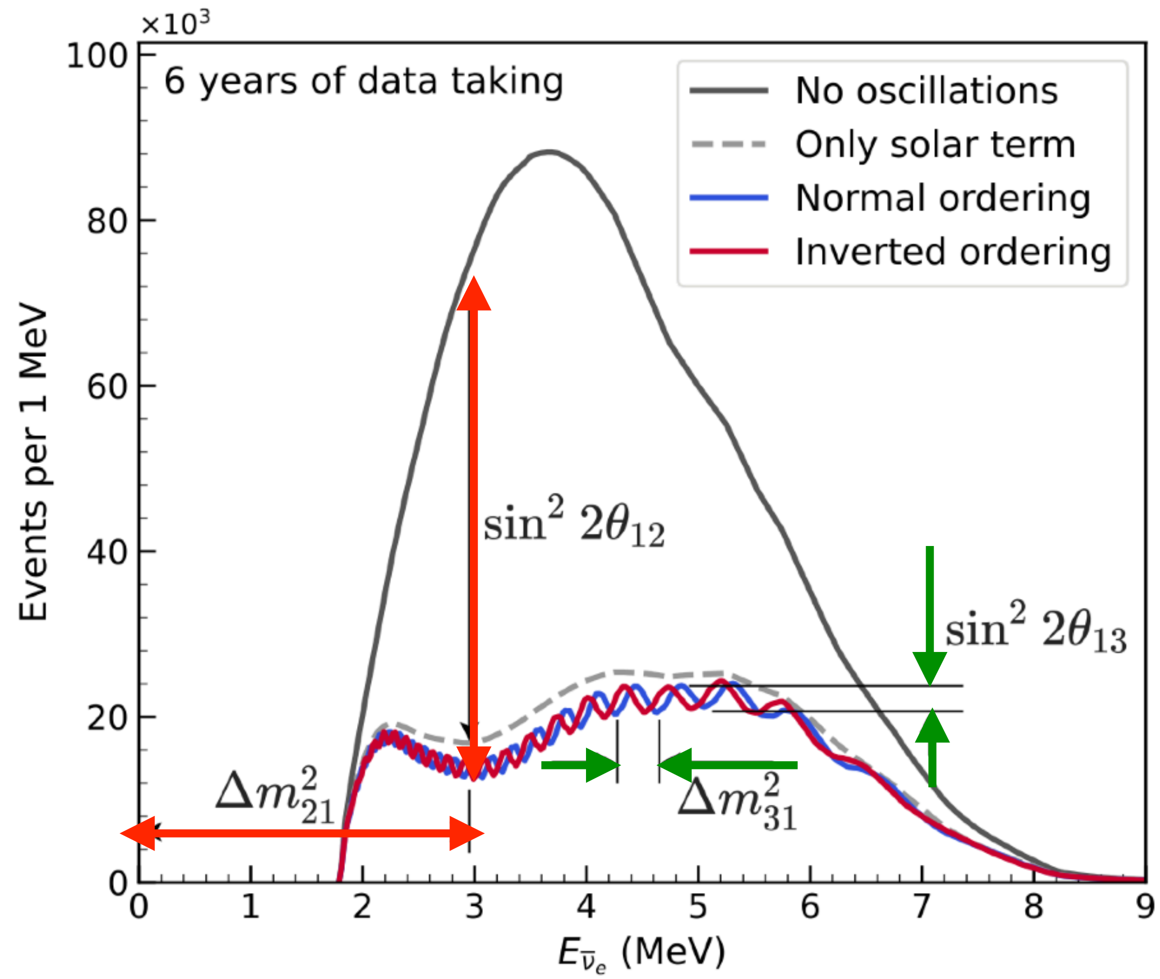
\+ New physics

Proton decay, sterile neutrinos, Dark matter, …

For the full physics program see :
PPNP 123 (2022)103927
J. Phys. G 43 (2016) no.3, 030401

Oscillation physics with reactor neutrinos

- Unique measurement based on **(quasi) in-vacuum oscillations**
- **Complementary to long baseline experiments** based on matter effects (δ_{CP} and θ_{23})
- Simultaneous detection of solar and atmospheric oscillation modes



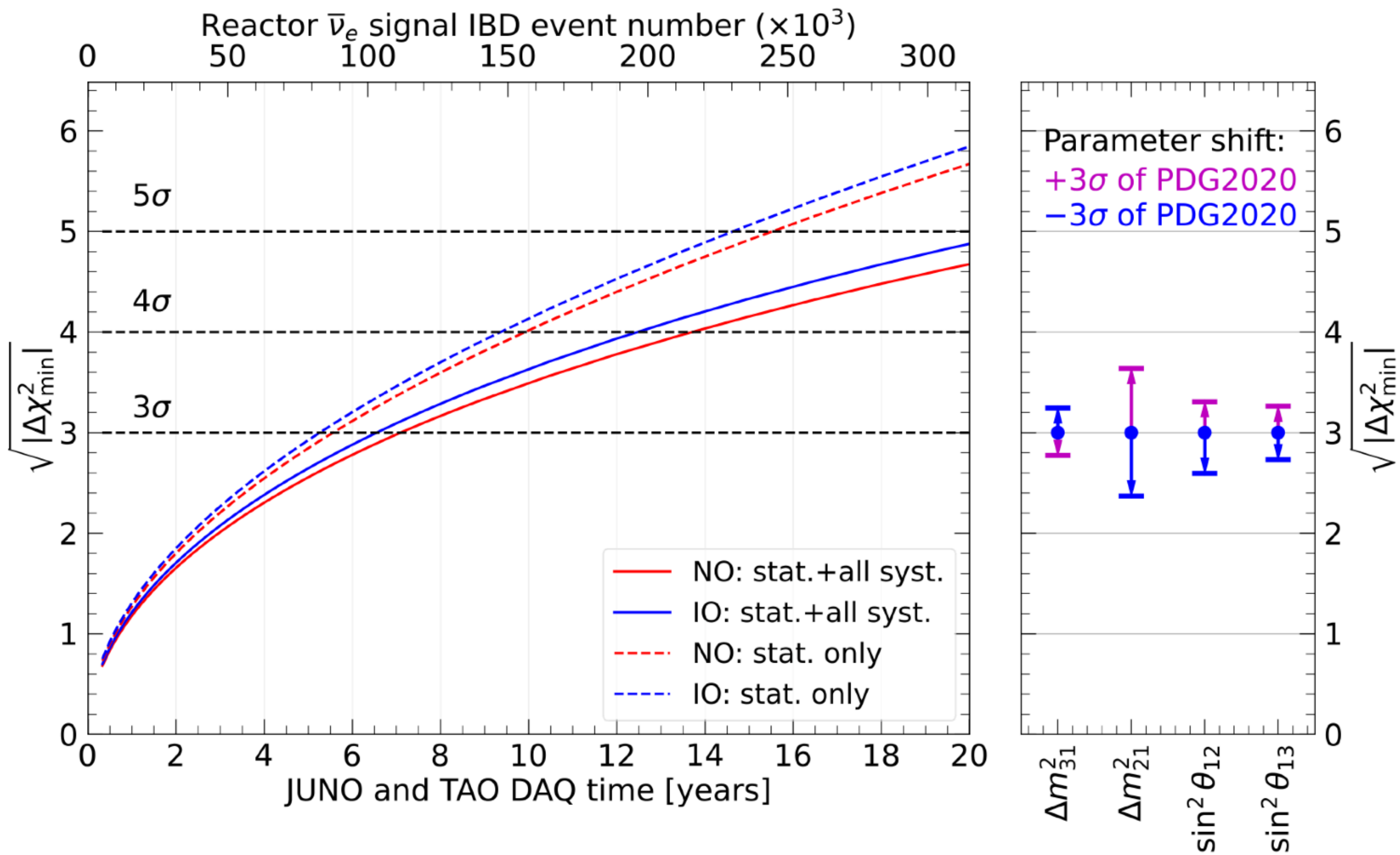
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \frac{\Delta m^2_{12} L}{4E} - \sin^2 2\theta_{13} \left(\cos^2 \theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} \right)$$

Slow oscillations | Fast oscillations

Neutrino Mass Ordering (NMO) from interference effects in the the oscillated spectrum: Excellent **energy resolution (3% at 1 MeV)** and **energy scale accuracy (<1%)**

Sensitivity to Neutrino Mass Ordering

Recent update of the analysis (Chinese Phys. C 49 033104)



3σ sensitivity with 6 years of data (reactor only)

(within 7 years assuming 11/12 months of reactor duty cycle)

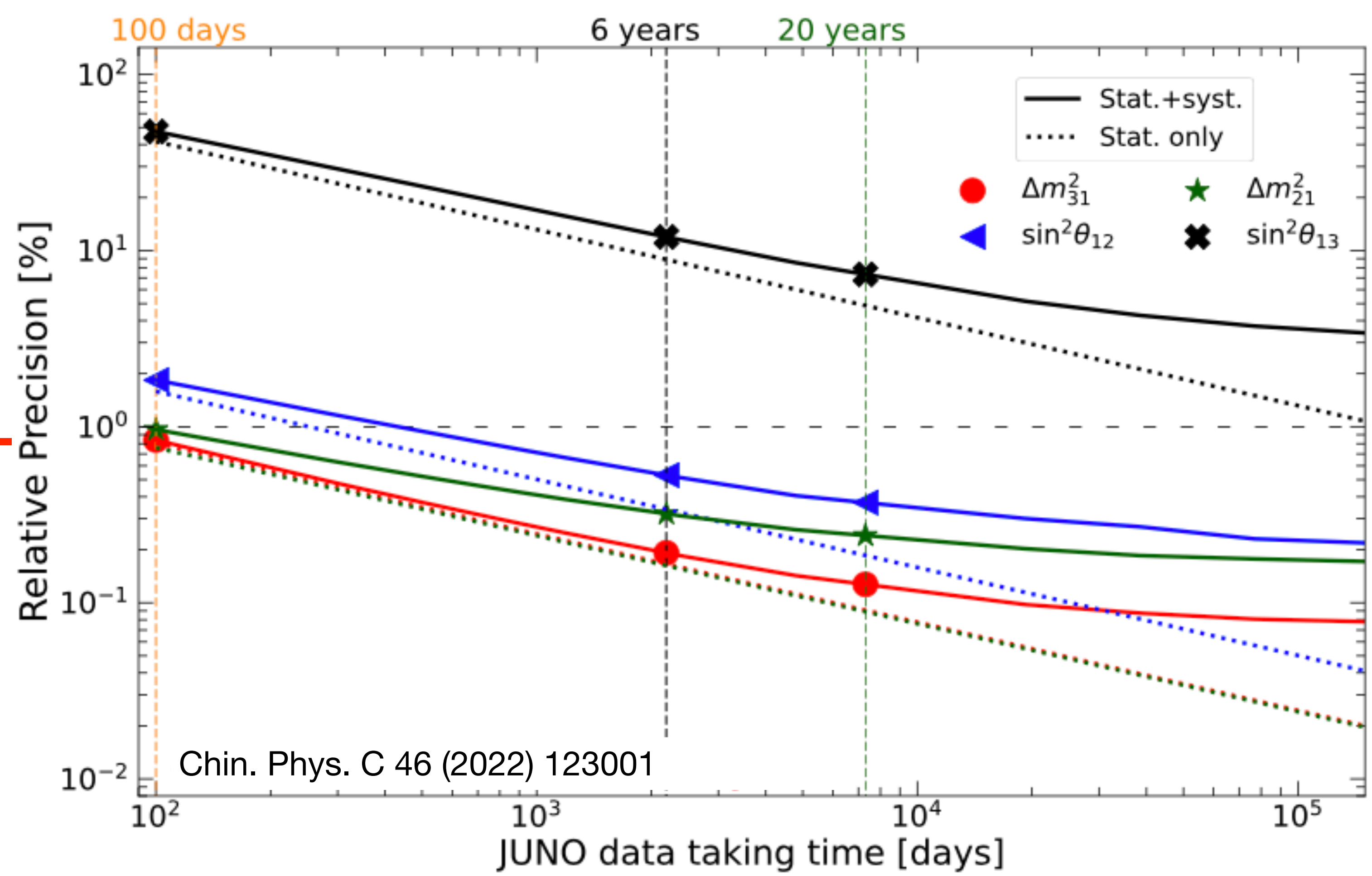
Oscillation parameters

Precision <0.5% on Δm^2_{21}, $\sin^2\theta_{12}$ and Δm^2_{31} in ~6 years of data

~ 1 order of magnitude improvement

	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

Sub-percent precision on Δm^2_{21}, $\sin^2\theta_{12}$ within ~1 year of data-taking



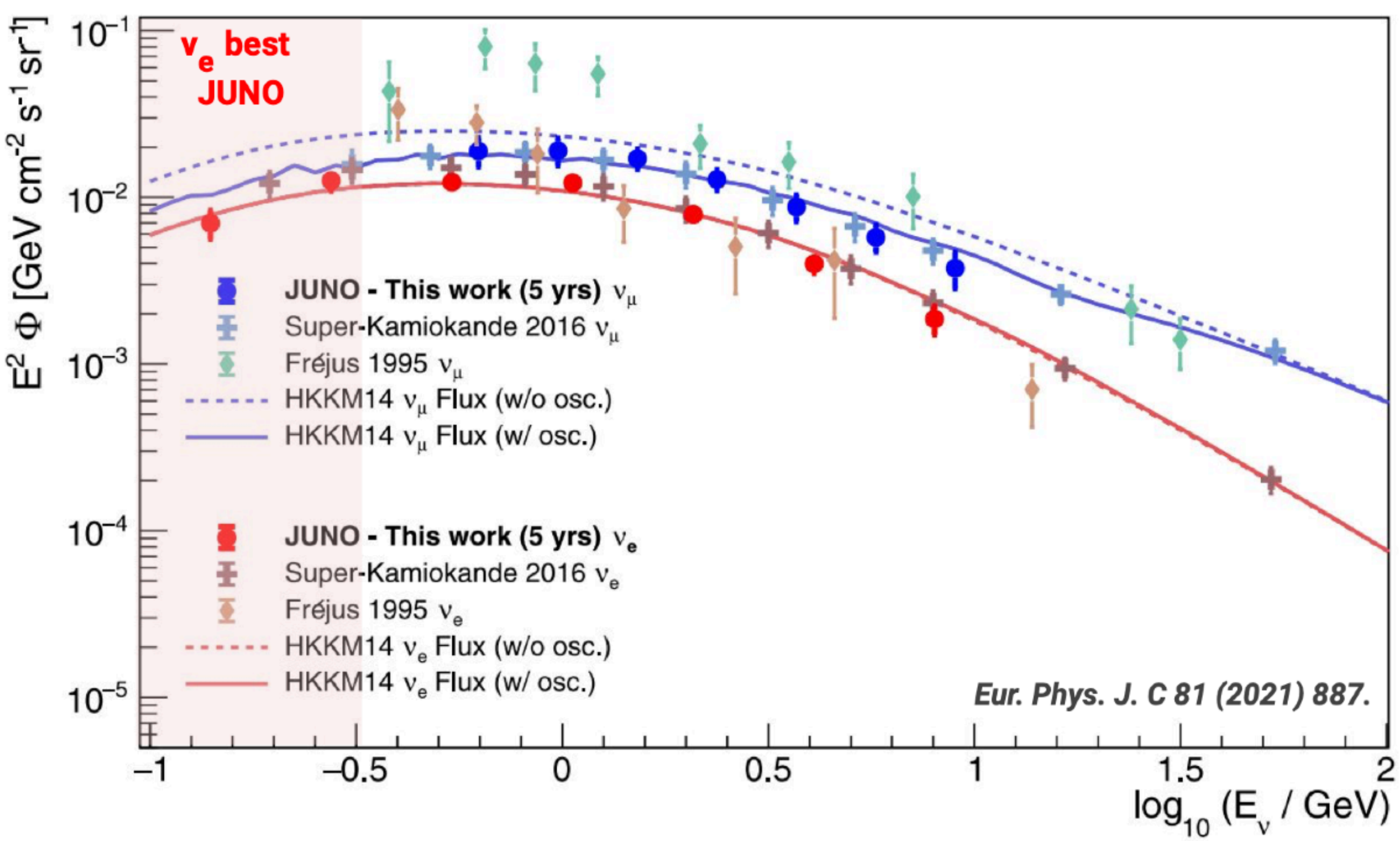
Measurement of $\sin^2\theta_{12}$ and Δm^2_{21} also with ^{8}B solar neutrinos.

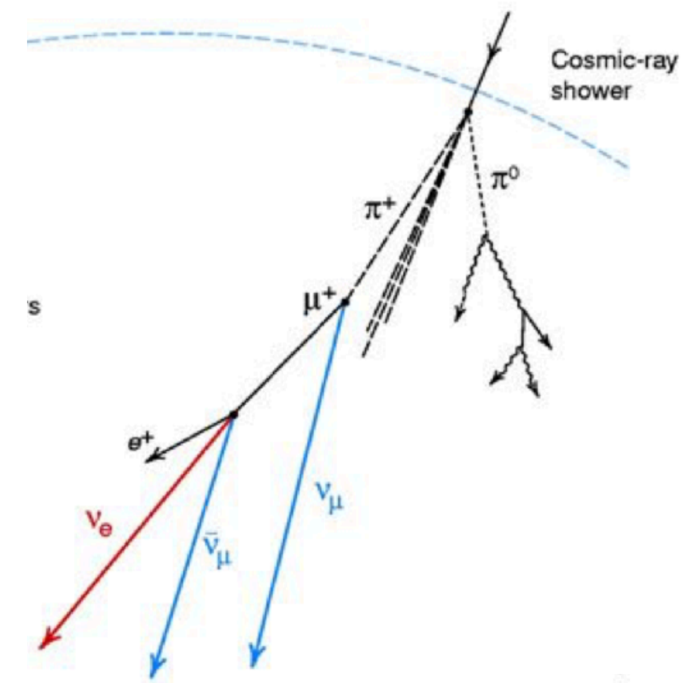

Neutrinos from natural sources

Atmospheric neutrinos

Flux of ν_e and ν_μ from cosmic rays interactions in atmosphere and secondary hadrons decays

- **Spectrum measurement** of ν_e and ν_μ (up to ~ 20 GeV)
- **Complementary NMO sensitivity** via matter effect ~1σ in 6 years
- Promising to **boost the overall NMO sensitivity** of JUNO





ν detection in CC and NC

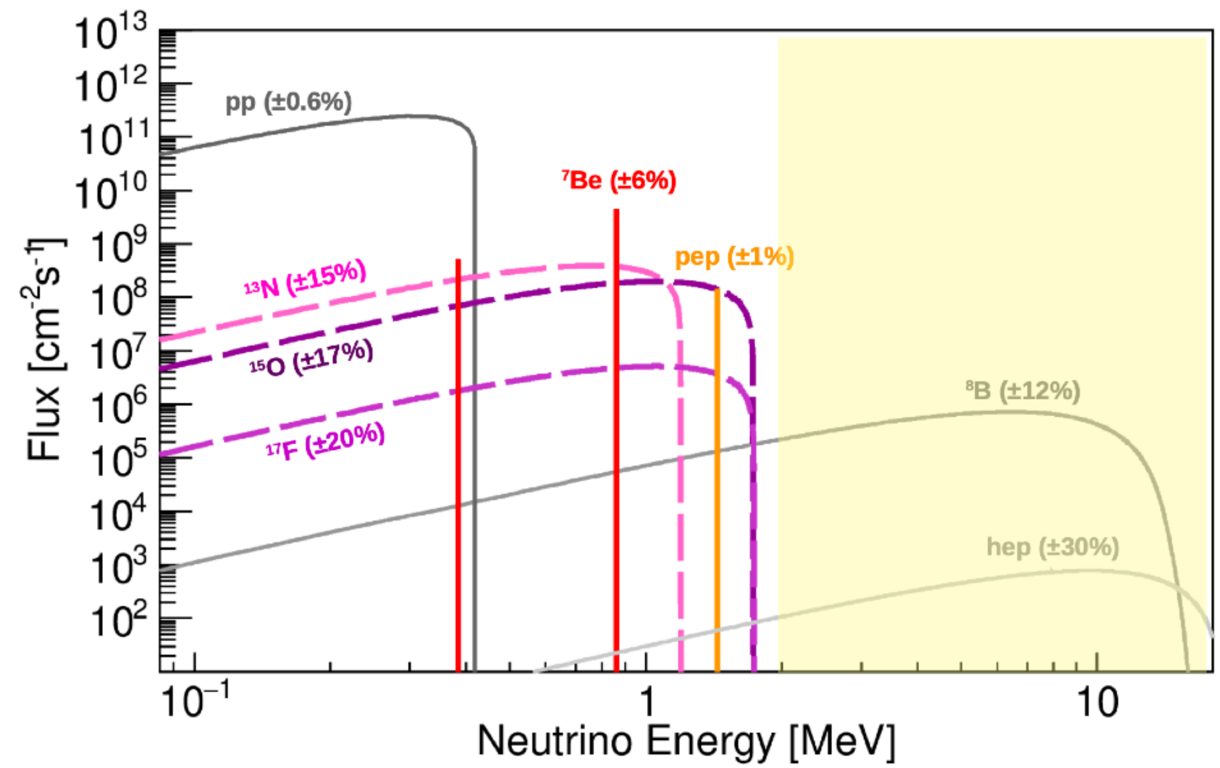
ν_e vs ν_μ discrimination thanks to hit time pattern

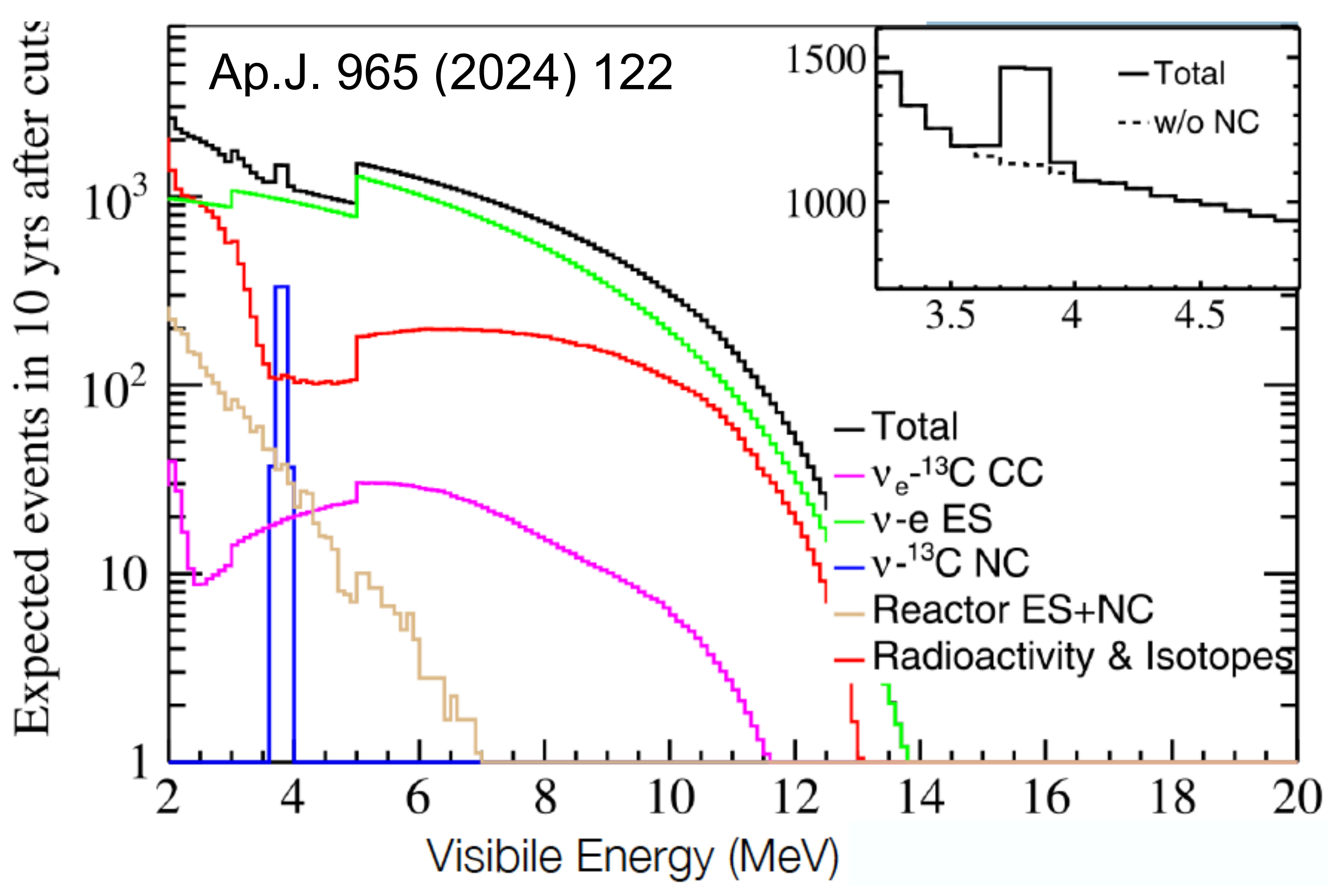
Solar neutrinos physics

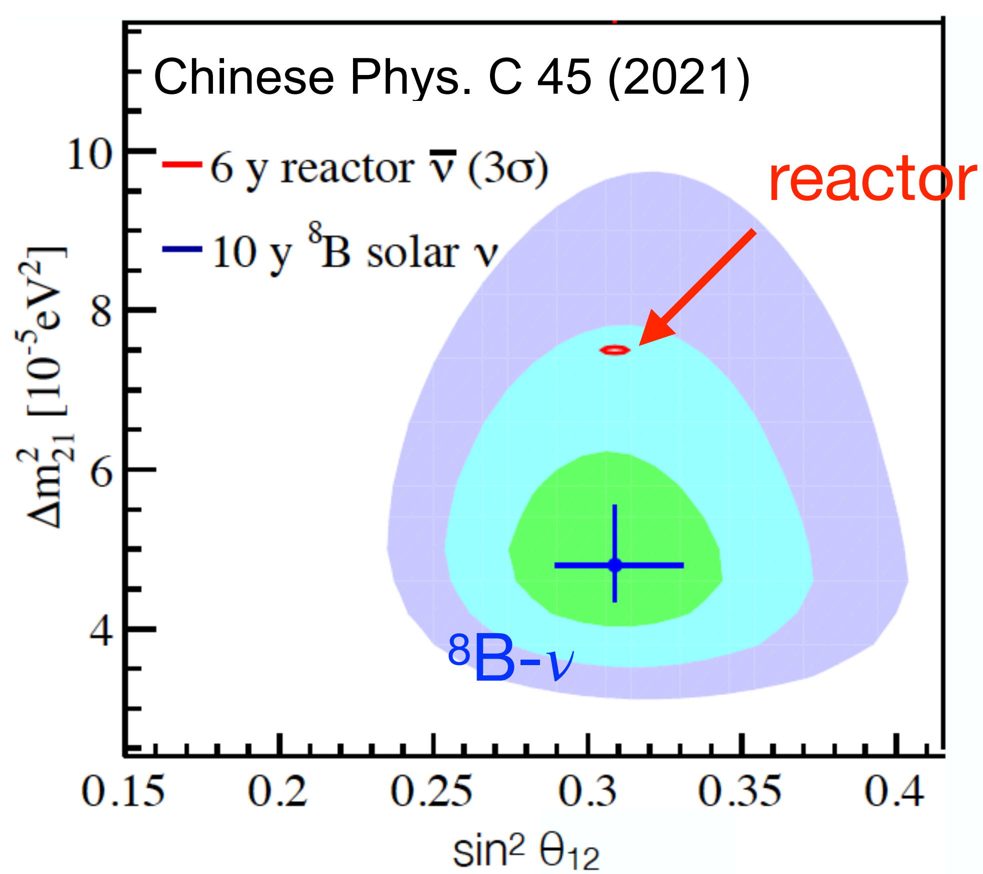
Requires large volume detectors and low-background environment

Sensitivity to ^8B neutrinos (E > 2 MeV)

- Simultaneous and **model-independent measurement of flux, Δm^2_{12} and $\sin^2\theta_{12}$**
- Combined analysis of **multiple detection channels:** νeES + NC and CC on ^{13}C
- **Potentials for discrepancy identification** (vs reactor neutrinos)





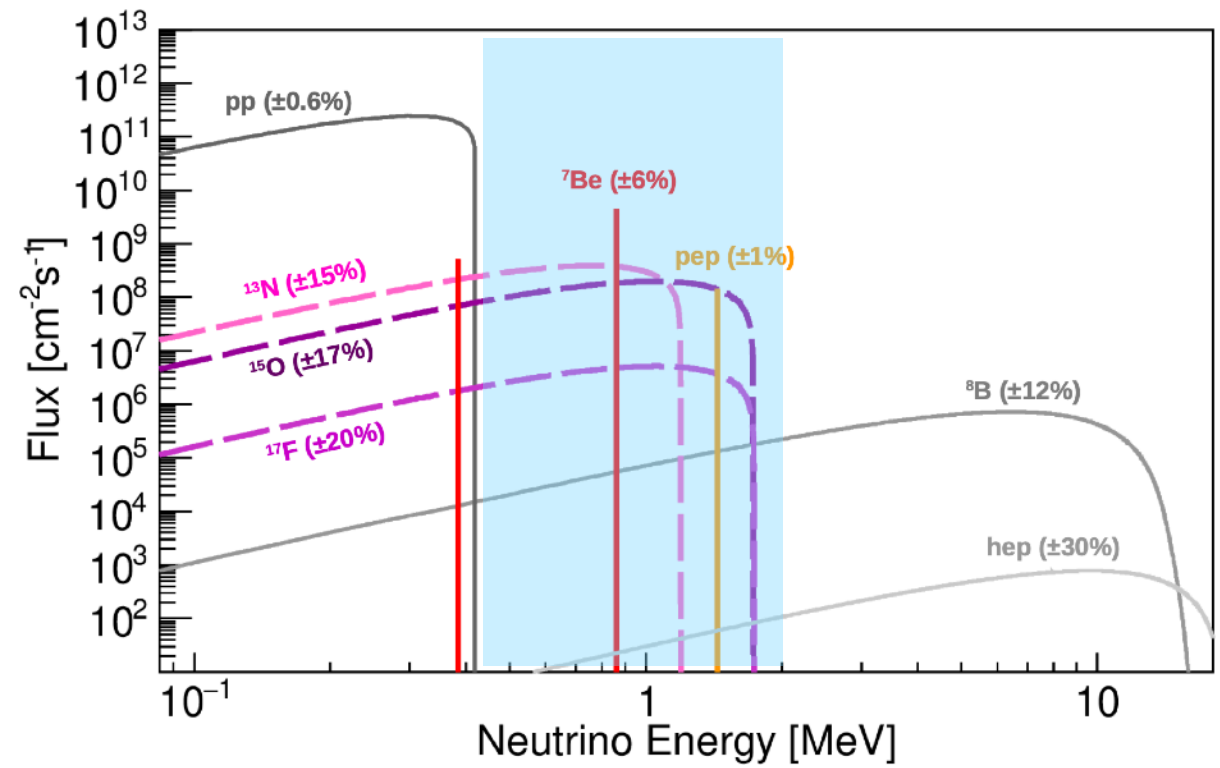


Solar neutrinos physics

Requires large volume detectors and low-background environment

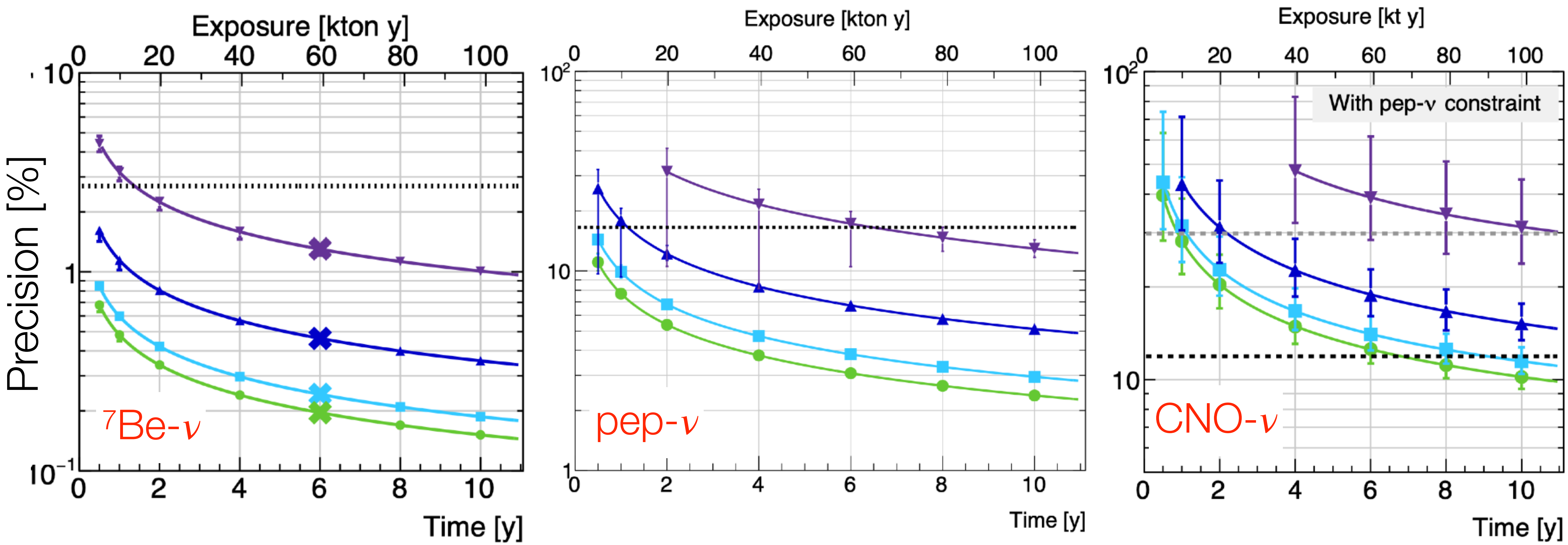
^{7}Be, pep and CNO ν (E> 0.45 MeV)

- Results **depend on the radiopurity of the liquid scintillator**
- Will overcome Borexino results in a few years



U/Th Radiopurity scenario

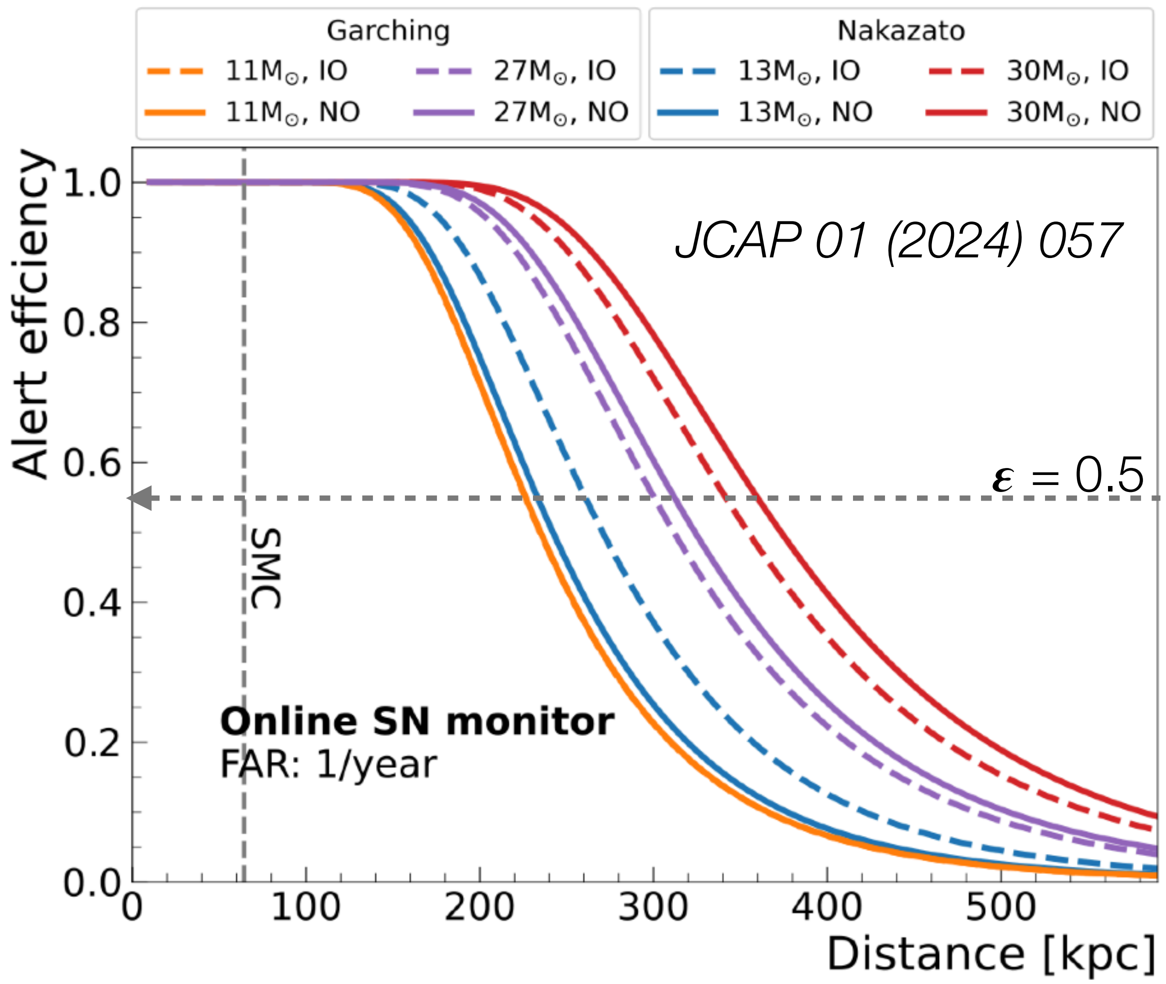
BX-like	Ideal	Baseline	IBD
10^{-19} g/g	10^{-17} g/g	10^{-16} g/g	10^{-15} g/g



Neutrinos from Core Collapse Supernova

Among the most violent events in the Universe.
Only **1-3/century** in our Galaxy: not to be missed!

- **~10^4 ν interactions** for a CCSN @10 kpc
  $E_\nu \sim O(10$ MeV), a few seconds burst duration
- Measure **spectrum, flavor content and time evolution**: models discrimination
- Sensitivity to **pre-SN neutrinos**
  $E_\nu \sim O(1$ MeV), a few hours before the burst
- Redundant **monitoring system**
  alert times 10-30 ms from the CCSN burst



Sensitivity (at $\varepsilon = 0.5$) to **CCSNe within 250-400 kpc and pre-SNe within ~ 1-2 kpc** depending on the model and FAR assumptions

Conclusions

JUNO is a multipurpose experiment with a rich physics program:

- Oscillation physics with reactor neutrinos
  - 3σ sensitivity on **Neutrino Mass Ordering (NMO)** after 6 years of data
  - Sub-percent precision of **oscillation parameters**

- Neutrinos physics from natural sources (non-exhaustive list)
  - Model-independent measurement of **^{8}B solar neutrinos** (flux, Δm^2, $\sin^2\theta_{12}$)
  - Unprecedented precision of **^{7}Be, pep and CNO solar neutrinos** in a few years
  - Complementary **NMO sensitivity with atmospheric neutrinos** (new analysis ongoing)
  - Alert system and multi-flavor spectrum analysis of **Supernovae neutrinos burst** (and Diffuse Supernova Neutrino Background)

Construction completed. Detector filling with liquid scintillator ongoing… completion expected in August!
Exciting results with commissioning data coming soon

Backup

Nuclear reactor physics with TAO

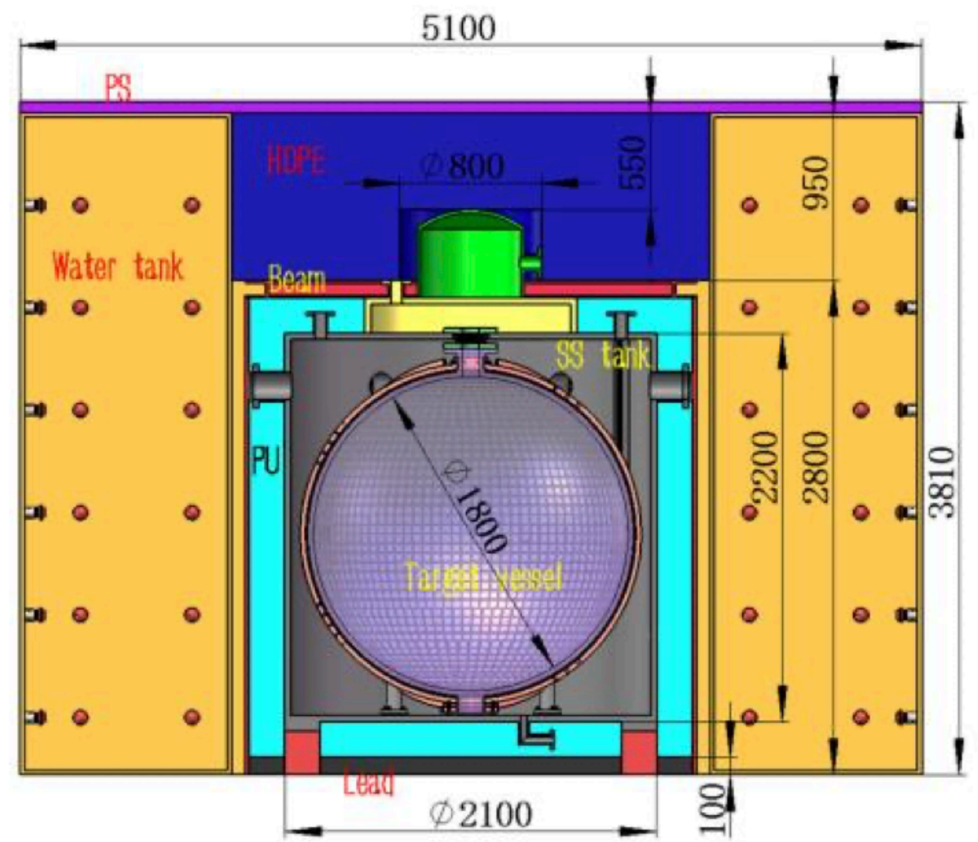
Taishan Antineutrino Observatory (TAO), a ton-size, good energy resolution LS detector at ~44 m from the Taishan reactor (4.6 GWh), a satellite experiment of JUNO

Purposes

- Precise **measurements of reactor anti-υ spectrum**
- **Model independent reference spectrum** for JUNO
- Benchmark data to **test nuclear databases**
- Improve nuclear knowledge and **reactor monitor**
- Search for **sterile neutrinos**

Detector design

- 2.8 ton Gd-LS in acrylic vessel (1t FV)
- SiPM on a spherical Cu shell (~ 94% coverage)
- Working temperature: -50 °C
- Detected Light : 4500 p.e./MeV
- Energy resolution < 2% at 1 MeV
- Muon veto: water tank + PMTs and plastic scintillators



Expected event rates

IBD signal	2000 events/day
Muon rate	70 Hz/m^2
Singles from radioactivity	$<$ 100 Hz
Fast neutron background after veto	$<$ 200 events/day
Accidental background rate	$<$ 190 events/day
^{8}He/^{9}Li background rate	$\sim$ 54 events/day

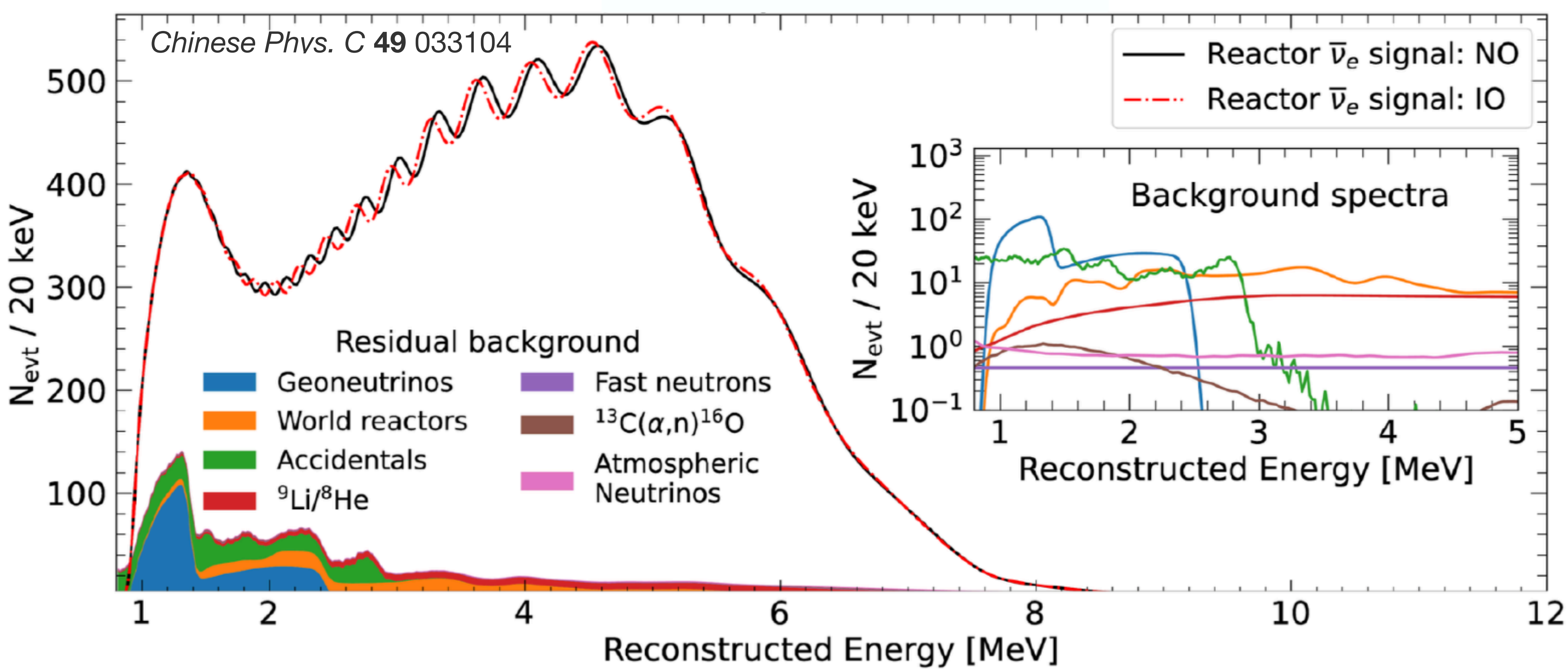
arXiv:2005.08745

NMO recent updates

Chinese Phys. C **49** 033104

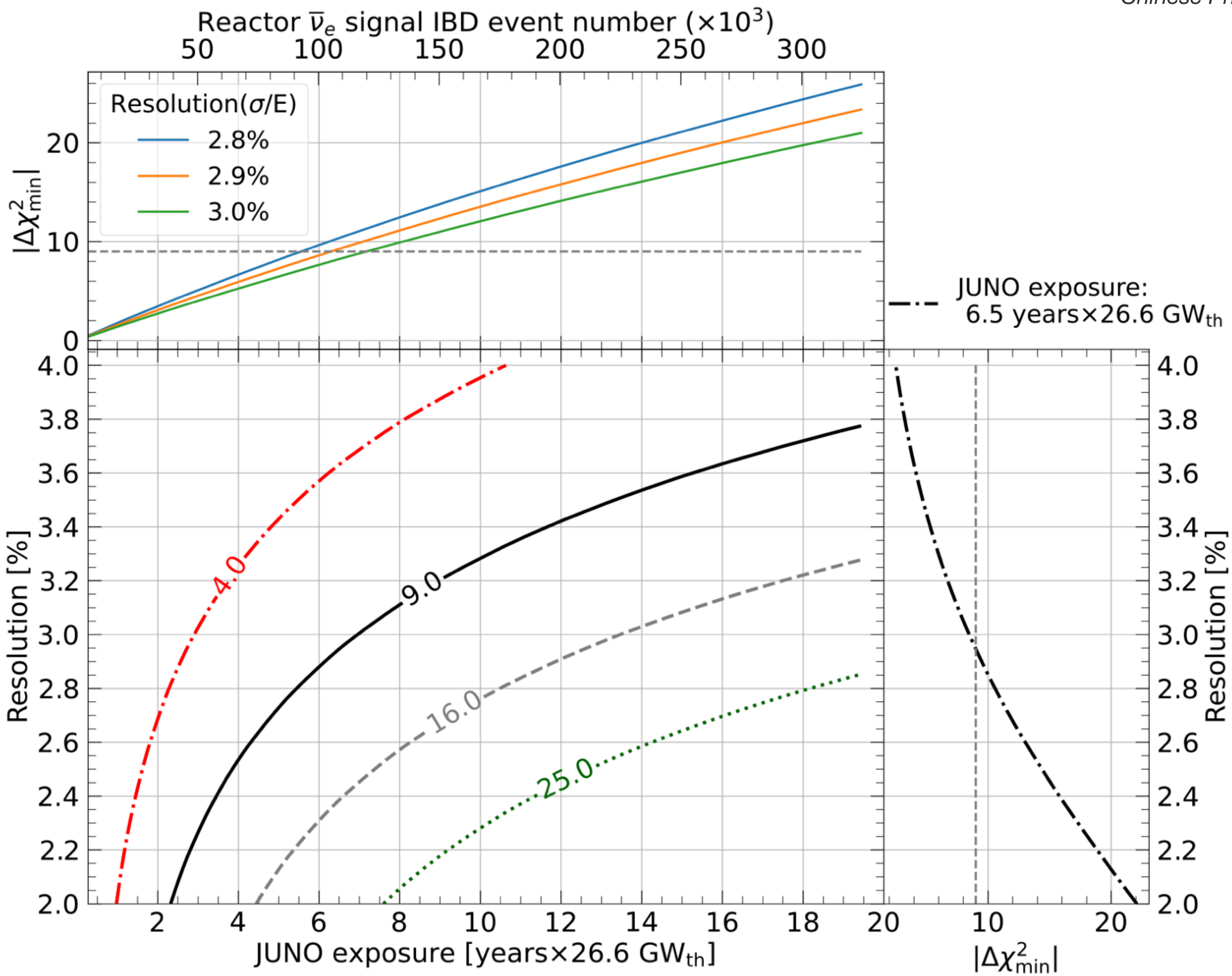
- Only 8/10 nuclear reactors
- Updated simulations (detector geometry, PMT efficiency and optical model, improved energy resolution model)
- Include Taishan Antineutrino Observatory (TAO)
- Actual location and overburden
- New IBD selection and and muon veto efficiencies
- Updated background model

Property	2016	2024
Thermal power	36 GW_{th}	26.6 GW_{th} ↓
Signal rate	60 / day	47.1 / day ↓
Overburden	~700 m	~650 m ↓
Muon flux in LS	3 Hz	4 Hz ↓
Muon veto efficiency	83%	91.6% ↑
Backgrounds	3.75 / day	4.11 / day ↓
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV ↑
Shape uncertainty	Daya Bay	JUNO + TAO ↑



NMO sensitivity and energy resolution

Chinese Phys. C **49** 033104

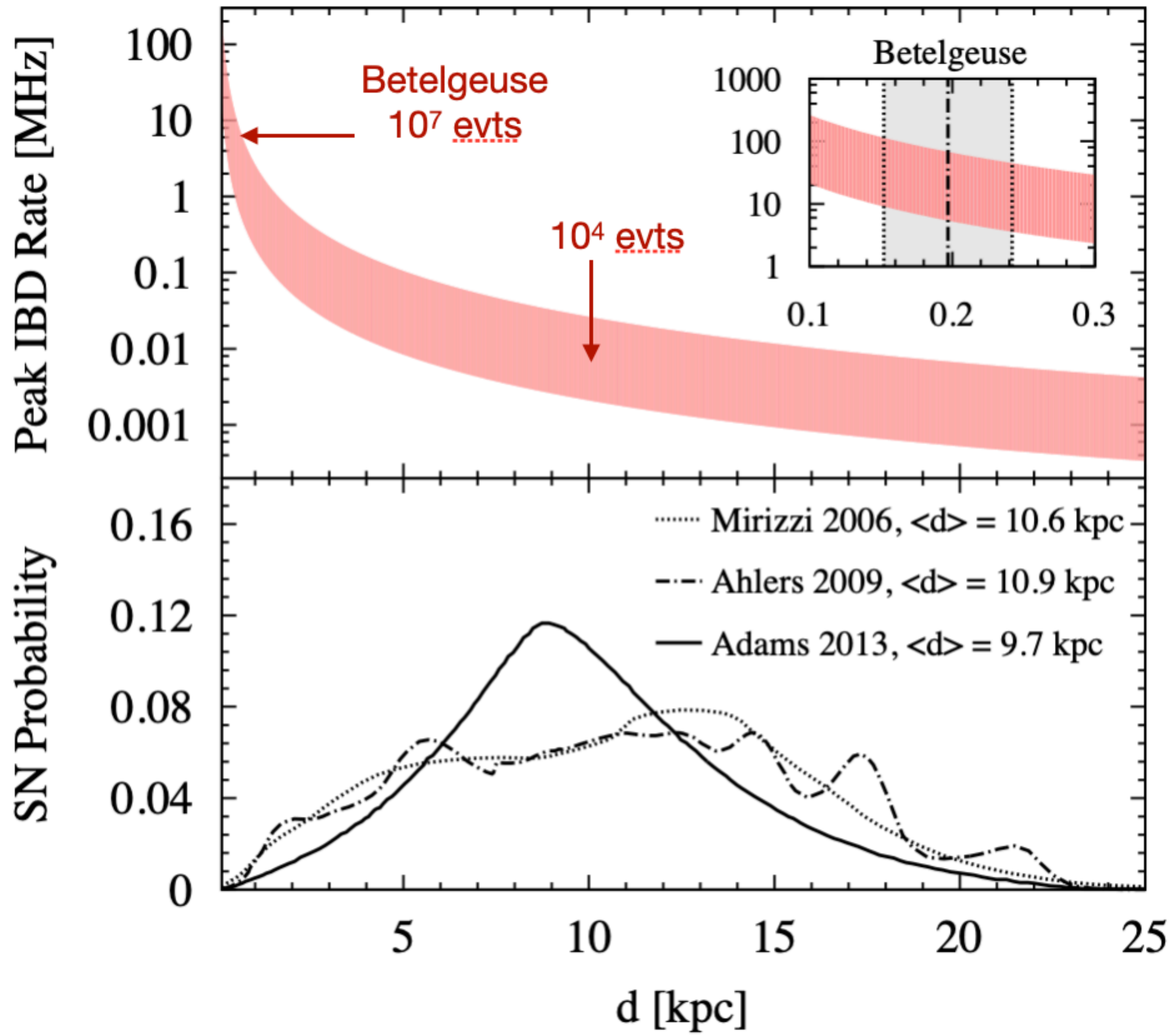


Expected event rates from CCSN in JUNO

IBD (golden channel): $\bar{\nu}_e$

eES, pES for **ν_e and ν_x**

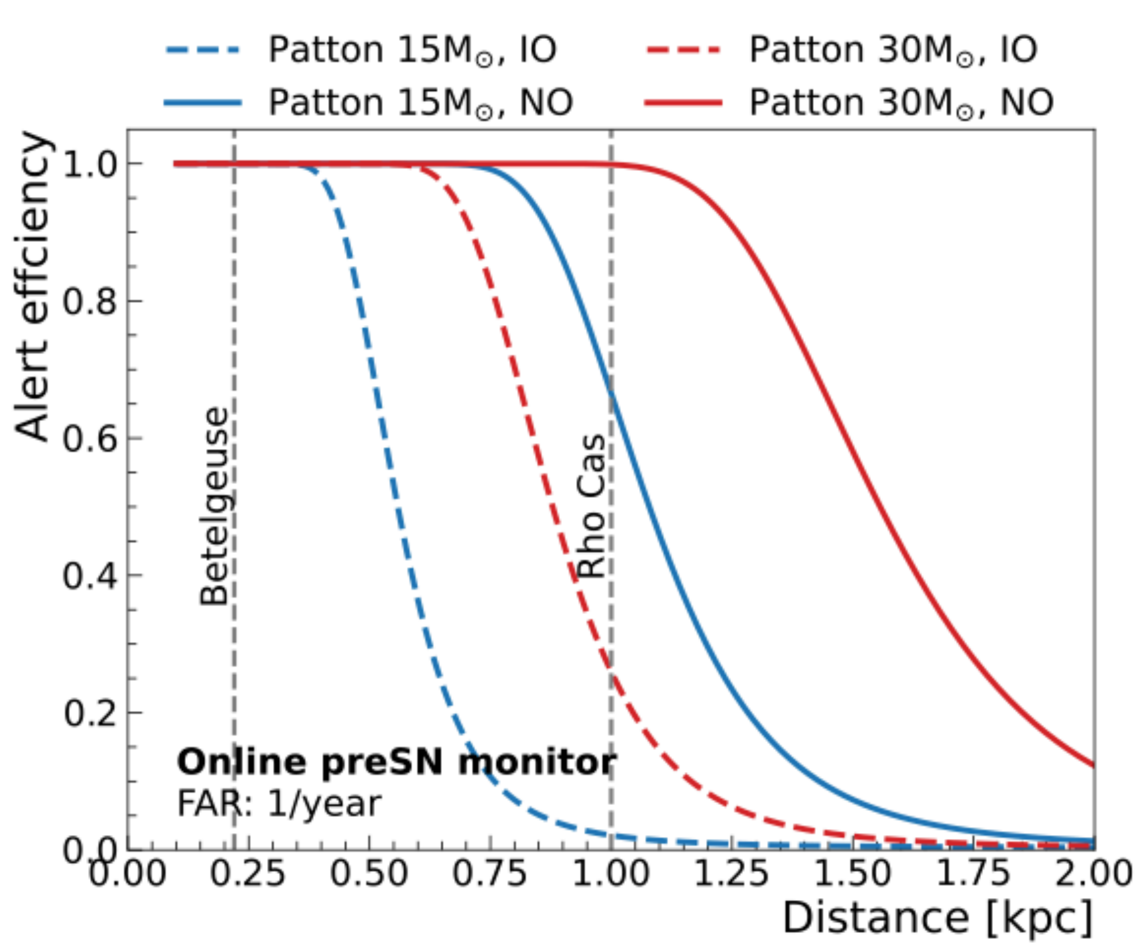
Process		Events (14 MeV)
$\bar{\nu}_e + p \rightarrow e^+ + n$	(CC)	5.0×10^3
$\nu + p \rightarrow \nu + p$	(NC)	1.2×10^3
$\nu + e \rightarrow \nu + e$	(ES)	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	(NC)	3.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	(CC)	0.9×10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	(CC)	1.1×10^2



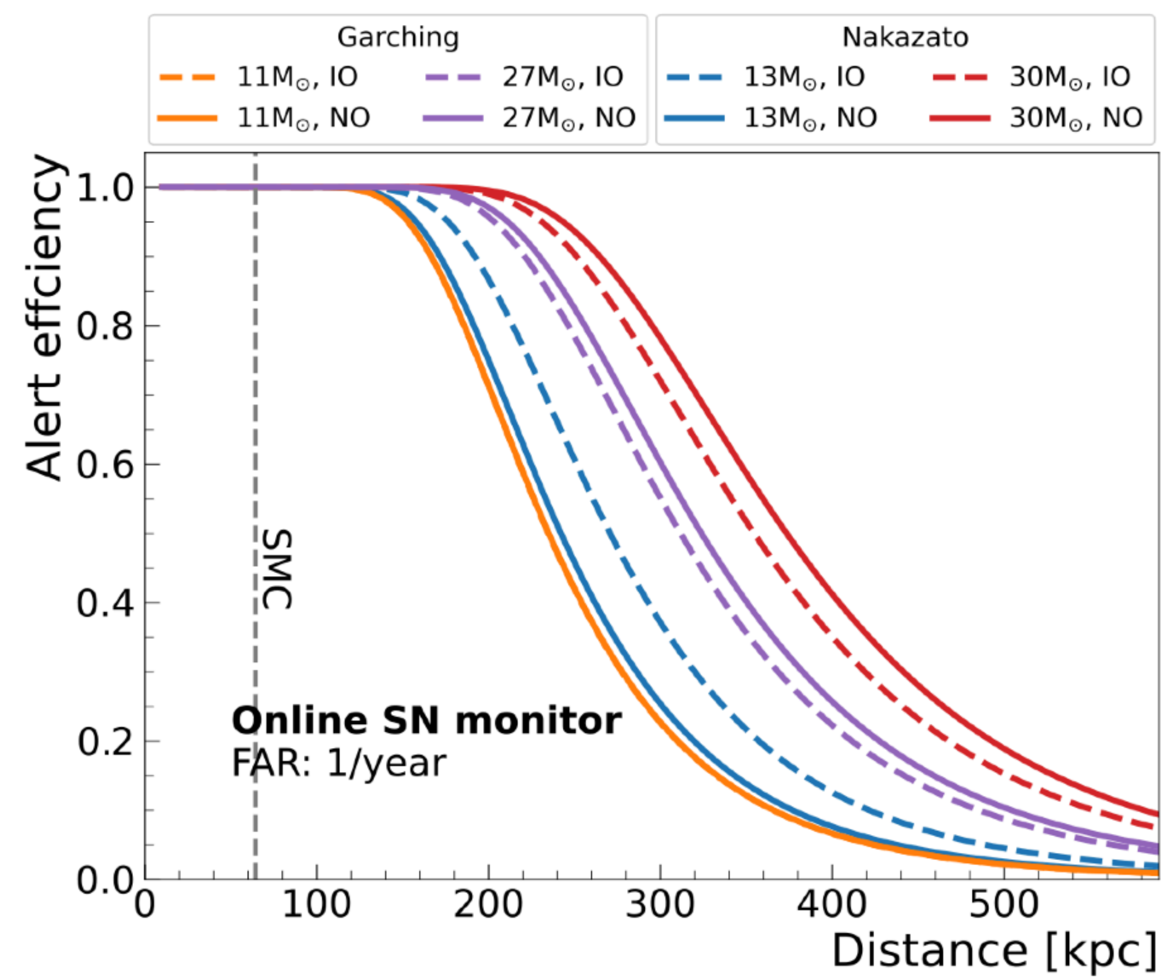
Exceptionally high event rate to handle :
major experimental challenge!

CCSN alert system

Prompt monitor:
- Implemented on electronic boards (FPGA)
- Using the # of fired PMTs
- Fast response

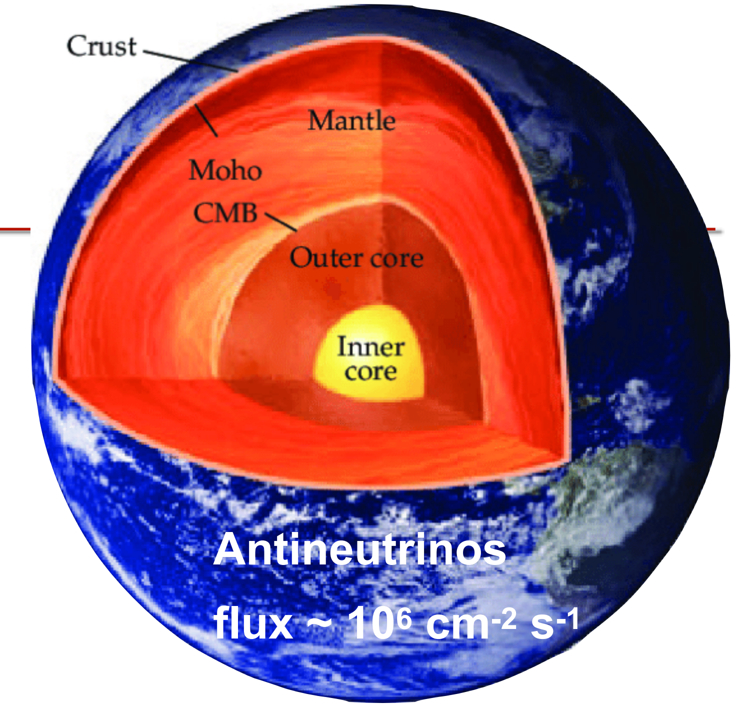


Online monitor:
- Implemented at DAQ for SN and pre-SN
- Uses reconstruction information to maximize alert efficiency



CCSN alert distance: ~250-400 kpc (at ε = 50%) and **alert time ~14-30 ms; pre-SN alert distance within 2 kpc** (at ε = 50%), alert a few hours before the CCSN (Note: model dependence)

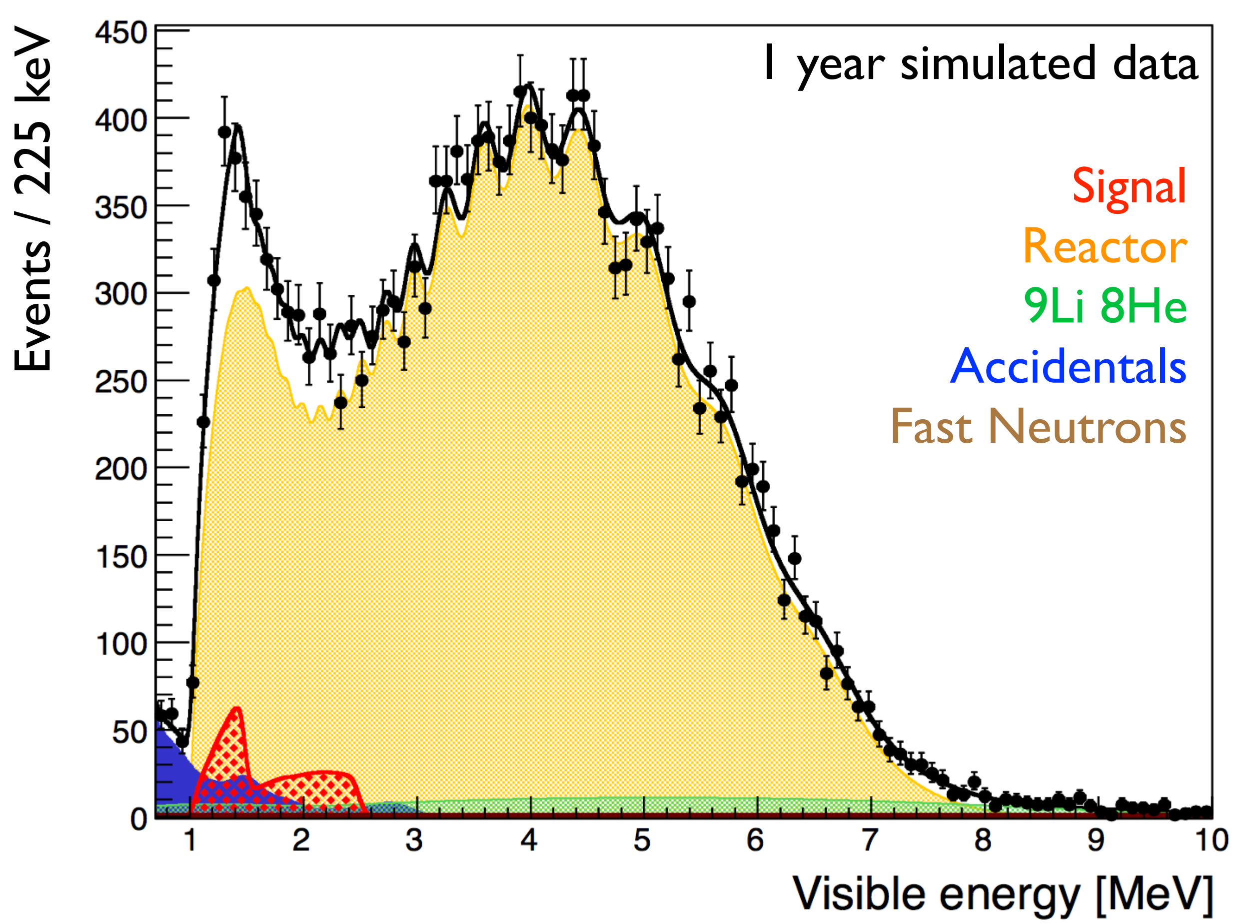
Geo-neutrinos



Earth's surface heat flow: 46 ± 3 TW, part of radiogenic origin (U/Th and ^{40}K decays) :

- $\overline{\nu}_e$ **unique probe of Earth core**
- **Earth's formation and evolution**
- **crust and mantle composition**
- **mantle convection** (driver of plate tectonics)

- 17-25% uncertainty on geo-ν (U + Th) flux from KamLAND + Borexino data



JUNO will collect ~ 400 events/yr
(largest sample so far ~ 150 events)

- geo-v detection by IBD. **Reactor-v as main background source**

- Signal extracted by a template fit.

Estimated uncertainties on (U+Th) flux:

17% after 1 year, 6% in 10 years