Status of the JUNO Experiment

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on behalf of the JUNO collaboration

Lake Louise Winter Institute 2022
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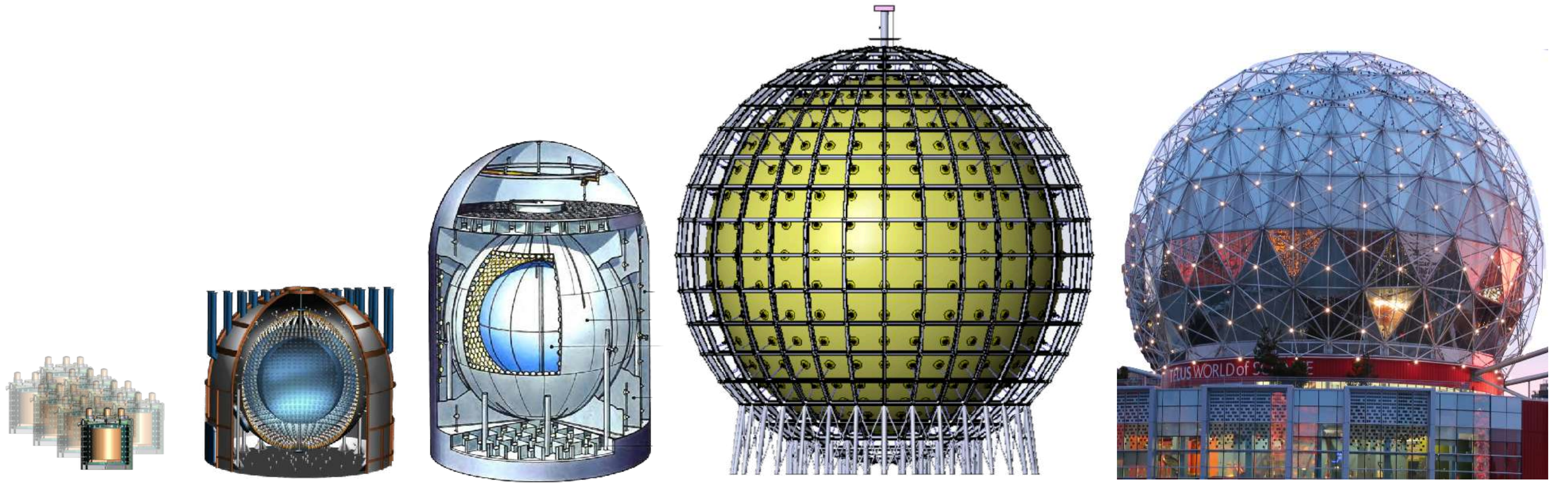
JUNO Overview

- **J**iangmen **U**nderground **N**eutrino **O**bservatory
- Under construction in cavern 700 m underground in Southern China
- Multipurpose experiment - primarily to study neutrino properties through reactor $\bar{\nu}_e$ oscillation
- 52.5 km from two powerful nuclear power plants (NPPs)
- 20 kt of liquid scintillator (LS) - largest of its kind in the world
- Superb energy resolution of ~3% at 1 MeV
- Ready for data taking in 2023

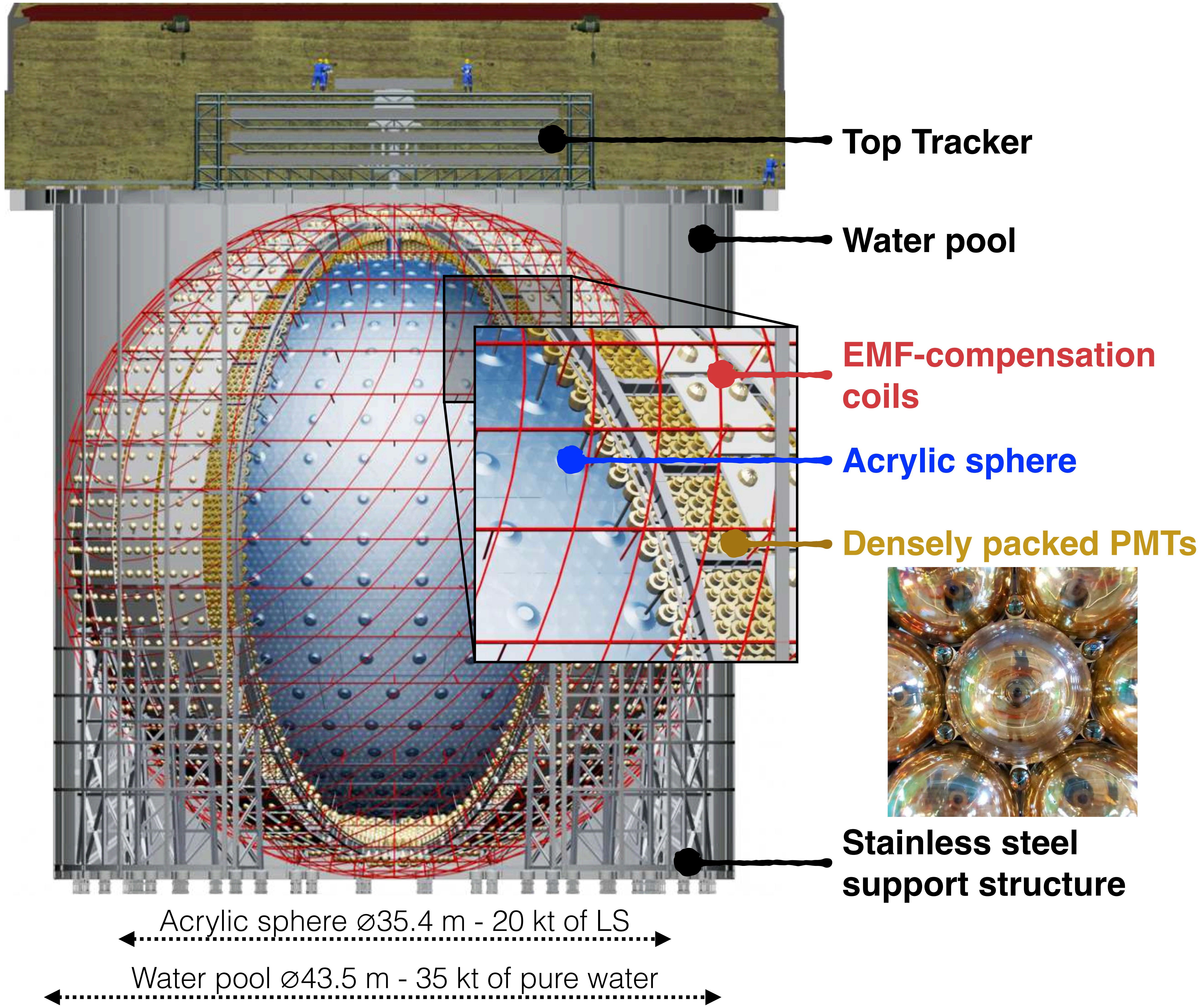
Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass [t]	8×20	~300	~1,000	**20,000**
Collected p.e./MeV	~160	~500	~250	**~1,350**
Energy res. at 1 MeV	~8%	~5%	~6%	**3 %**
U/Th purity of LS [g/g]	-	**10^{-19}**	10^{-17}	$10^{-15}/10^{-17}$*

*baseline/we hope



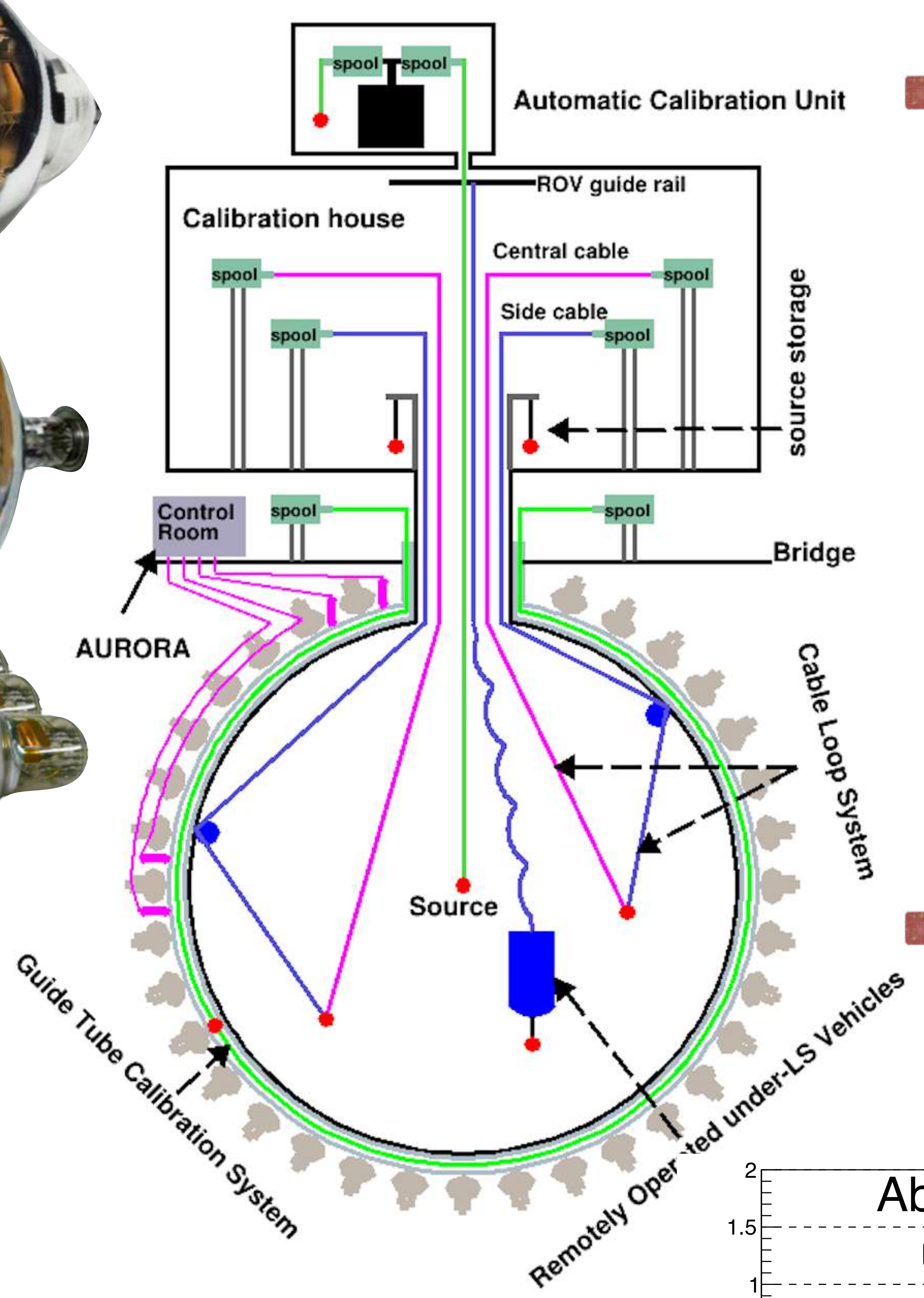
Daya Bay Borexino KamLAND JUNO Science World, Vancouver

- Central detector - neutrino target
  - 20 kt of LS in the acrylic sphere
  - 17,612 20-inch (large) photomultipliers (PMTs)
  - 25,600 3-inch (small) PMTs
  - In total, 78% photo-coverage
  - Coils to compensate Earth magnetic field (EMF)
- Water pool - muon veto
  - Cylinder with 35 kt of pure water
  - Effective shielding
  - Cherenkov detector with 2,400 LPMTs
- Top Tracker - precise muon measurement
  - 3 layers of plastic scintillator reused from the OPERA experiment
  - Covering 60% of the pool area

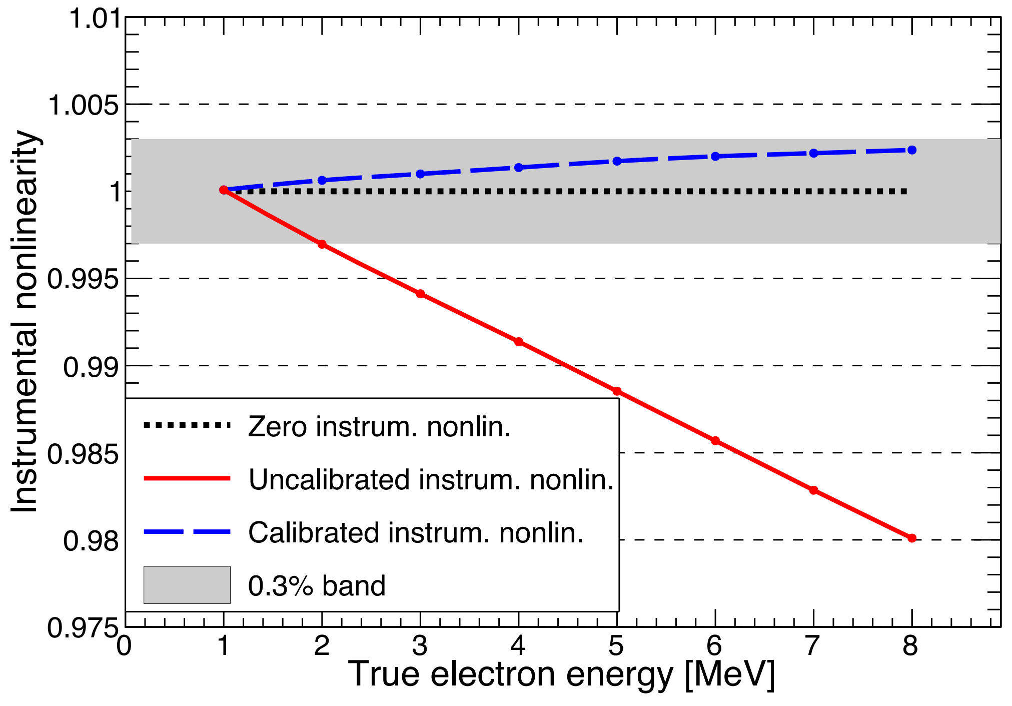


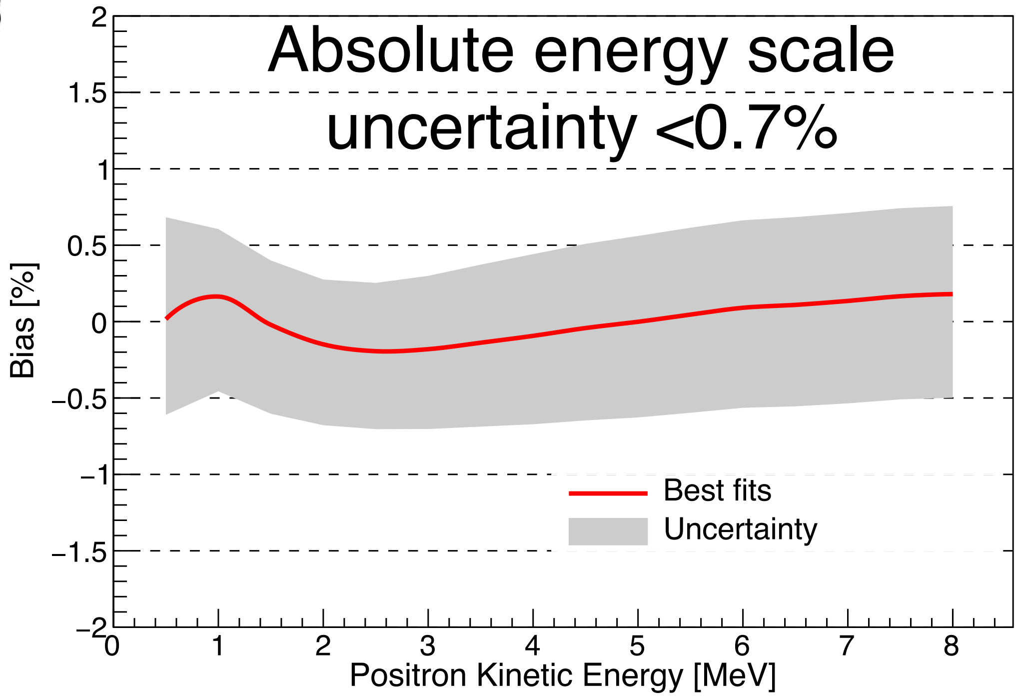
Selection of Detector Features

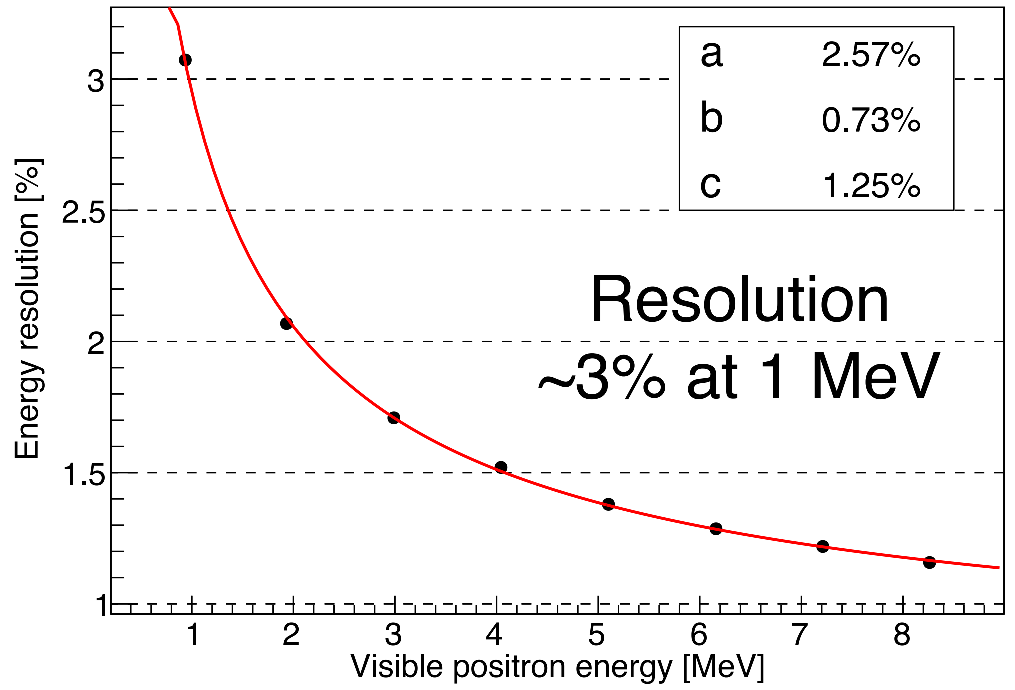
- 20-inch PMTs with ~75% photo-coverage
  - 5,000 dynode Hamamatsu PMTs - excellent time resolution σ_{TTS}=1.2 ns
  - 12,612 MCP NNVT PMTs
- 3-inch PMTs with ~3% photo-coverage
  - 25,600 dynode HZC PMTs
  - Increase dynamic range of the detector
  - Photon-counting mode for <10 MeV - calibrate the instrumental non-linearity of the 20-inch PMTs (dual calorimetry)



- Comprehensive calibration of the detector non-uniformity and non-linearity (*JHEP03(2021)004*):
  - 1D automated calibration unit
  - 2D cable loop system
  - 2D guide tube calibration system
  - 3D remotely operated submarine
  - Laser for LS transparency check
- Energy response well within requirements

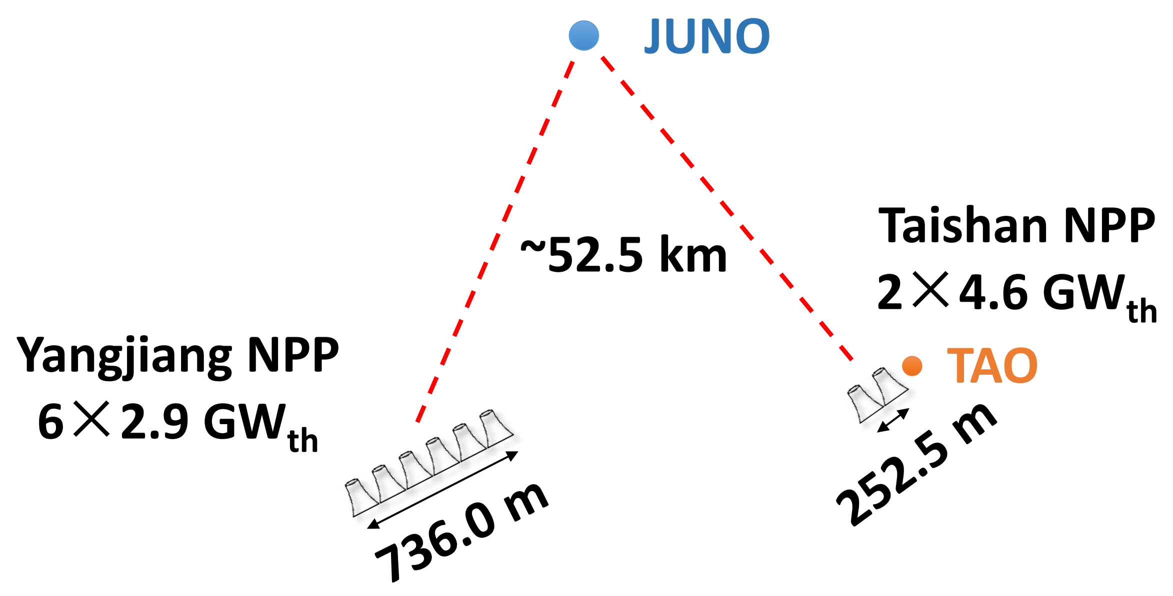


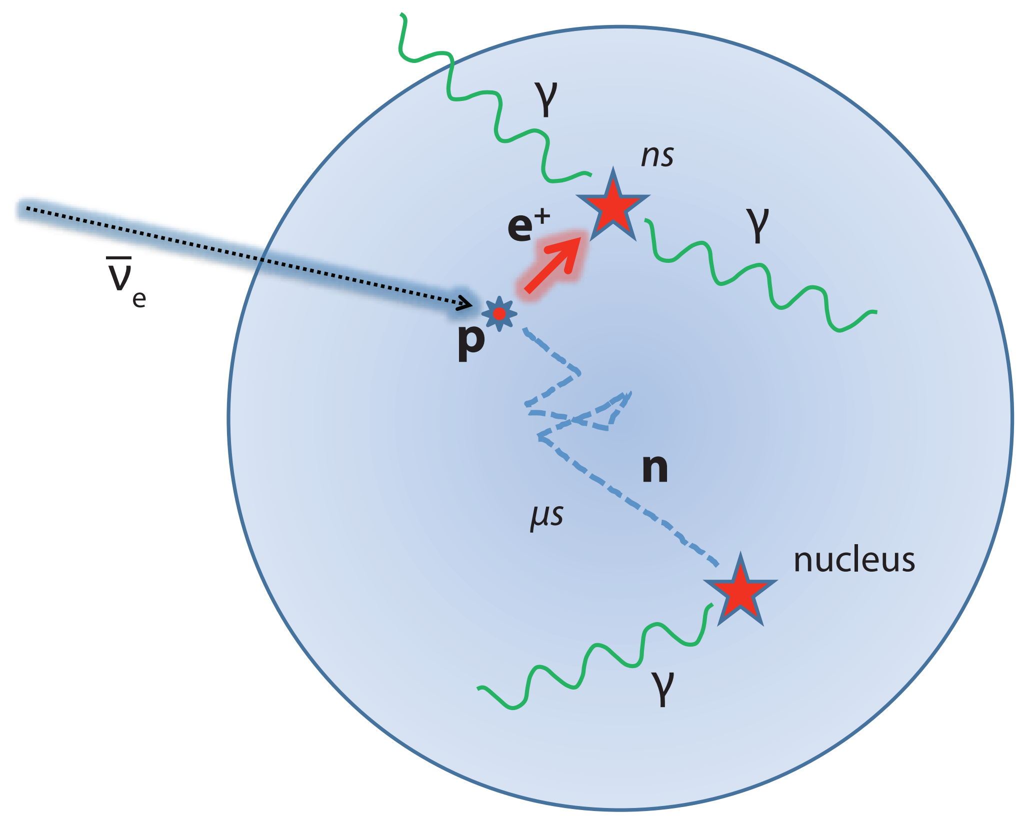




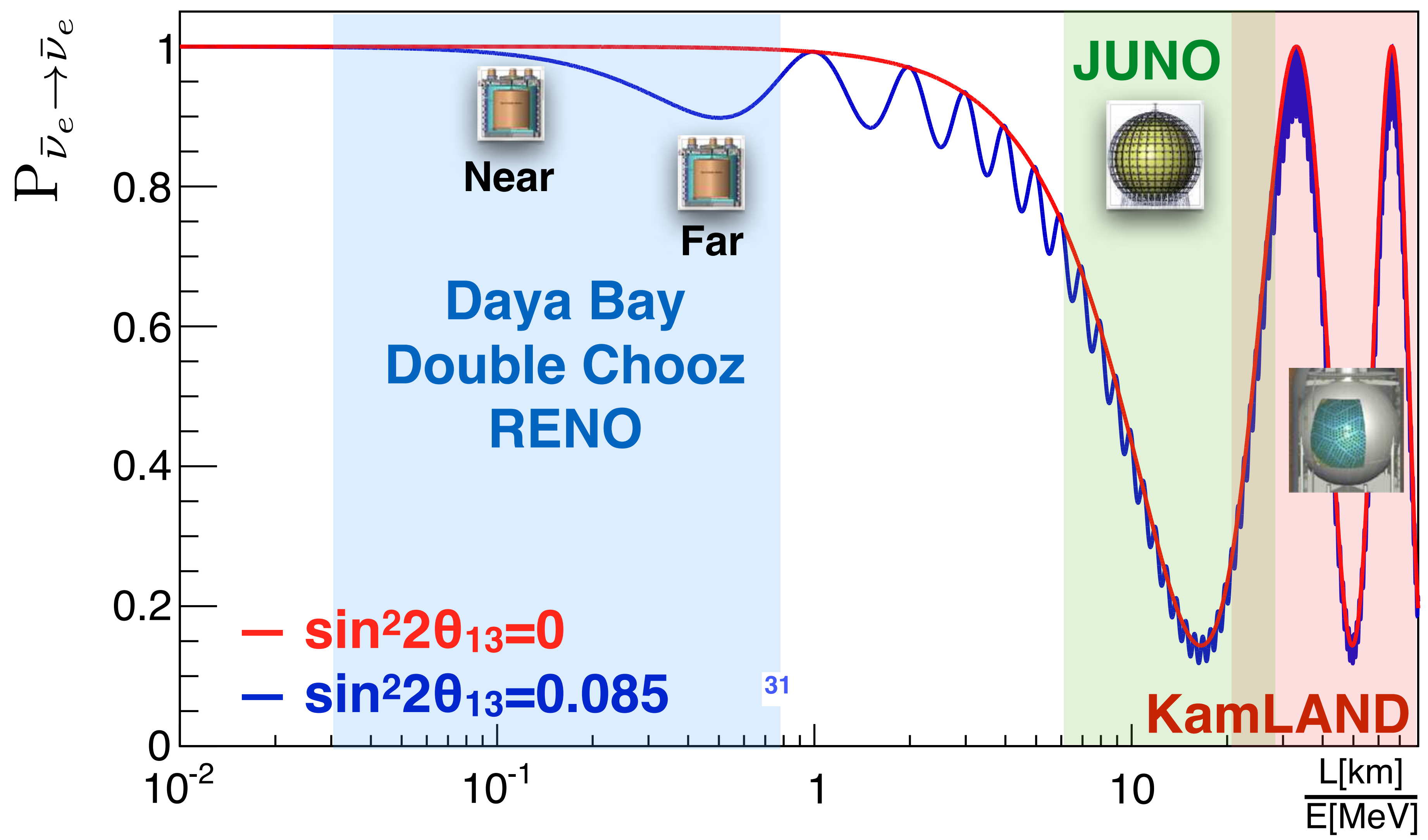
Reactor Antineutrino Oscillations

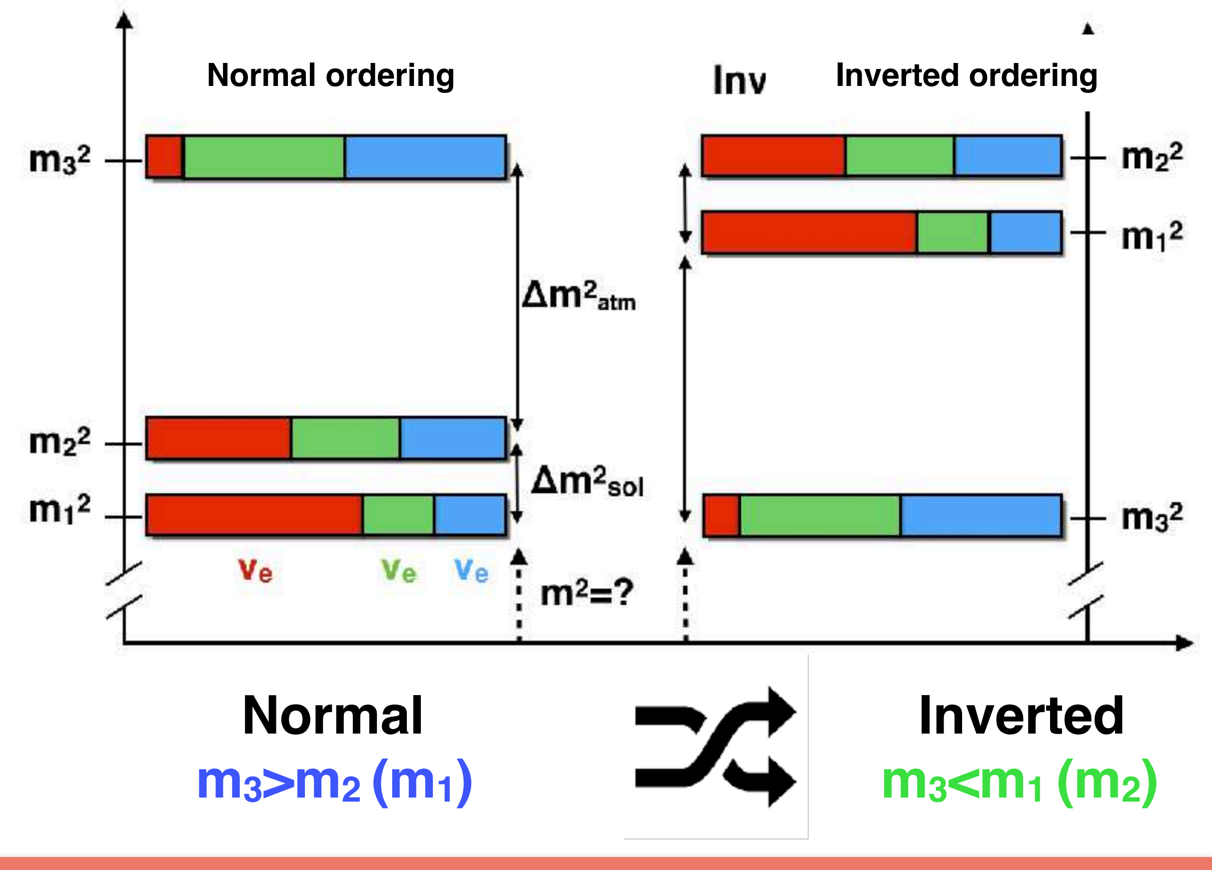
- Nuclear reactors emit ~2×10²⁰ $\bar{\nu}_e/\mathrm{s}/\mathrm{GW_{th}}$ with energy $\mathcal{O}(\mathrm{MeV})$
- Electron antineutrinos detected via inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Prompt-delayed spatial and temporal coincidence ➔ background suppression
- $\bar{\nu}_e$'s oscillate - survival probability depends on θ_{12}, θ_{13} mixing angles and Δm^2_{21}, Δm^2_{31} mass splittings (and neutrino mass ordering)
  - Access to all those parameters thanks to great energy resolution, statistics, etc.
  - First experiment to observe both oscillation modes simultaneously





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





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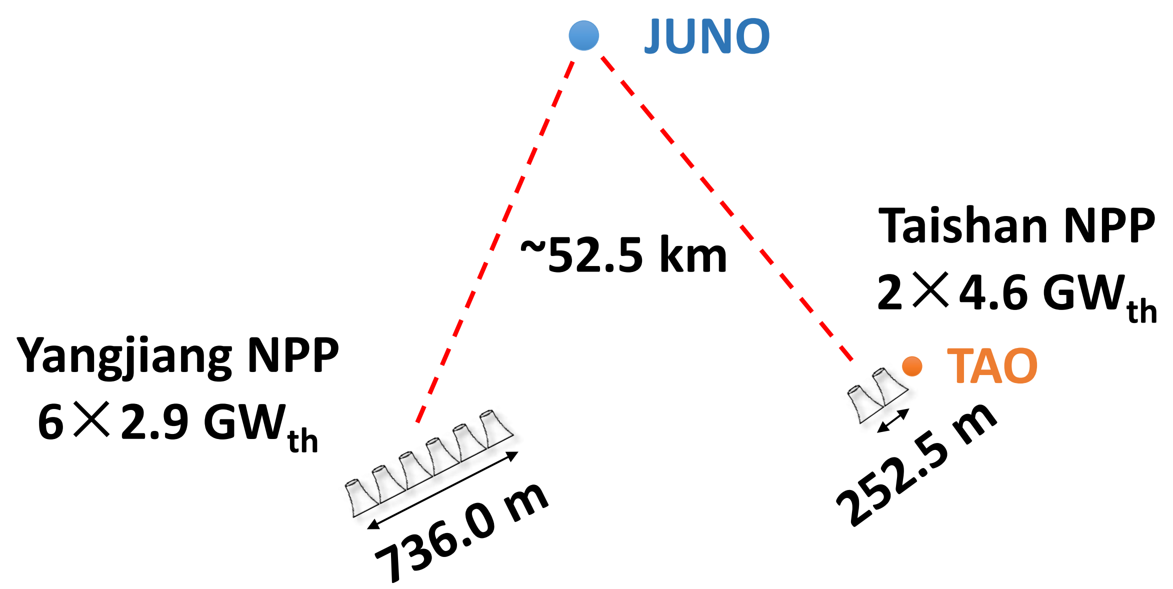

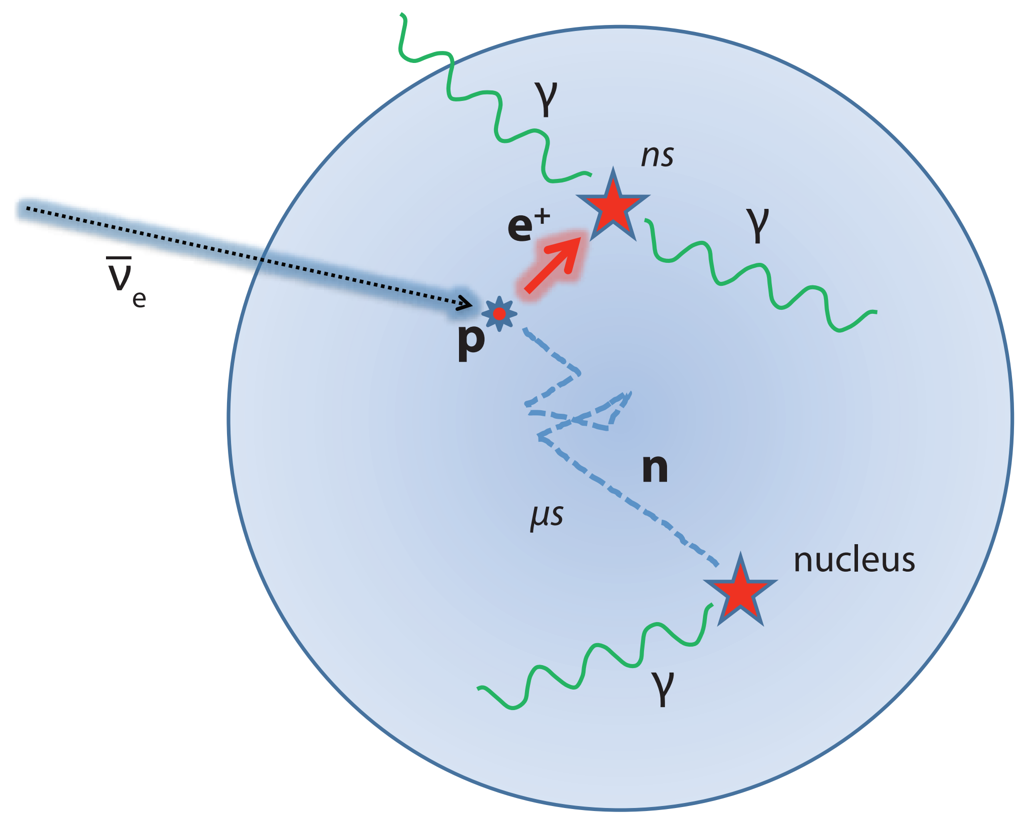

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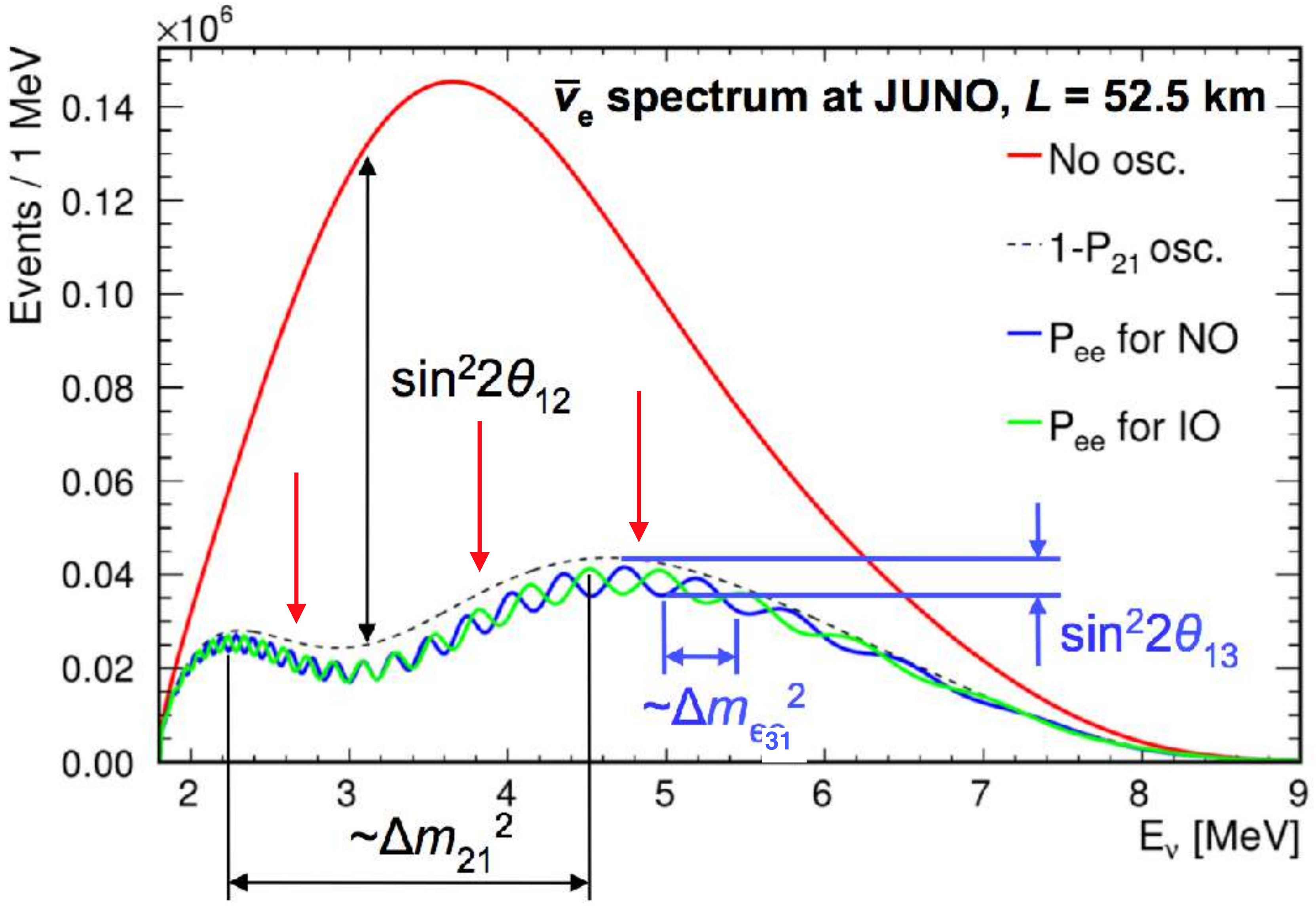
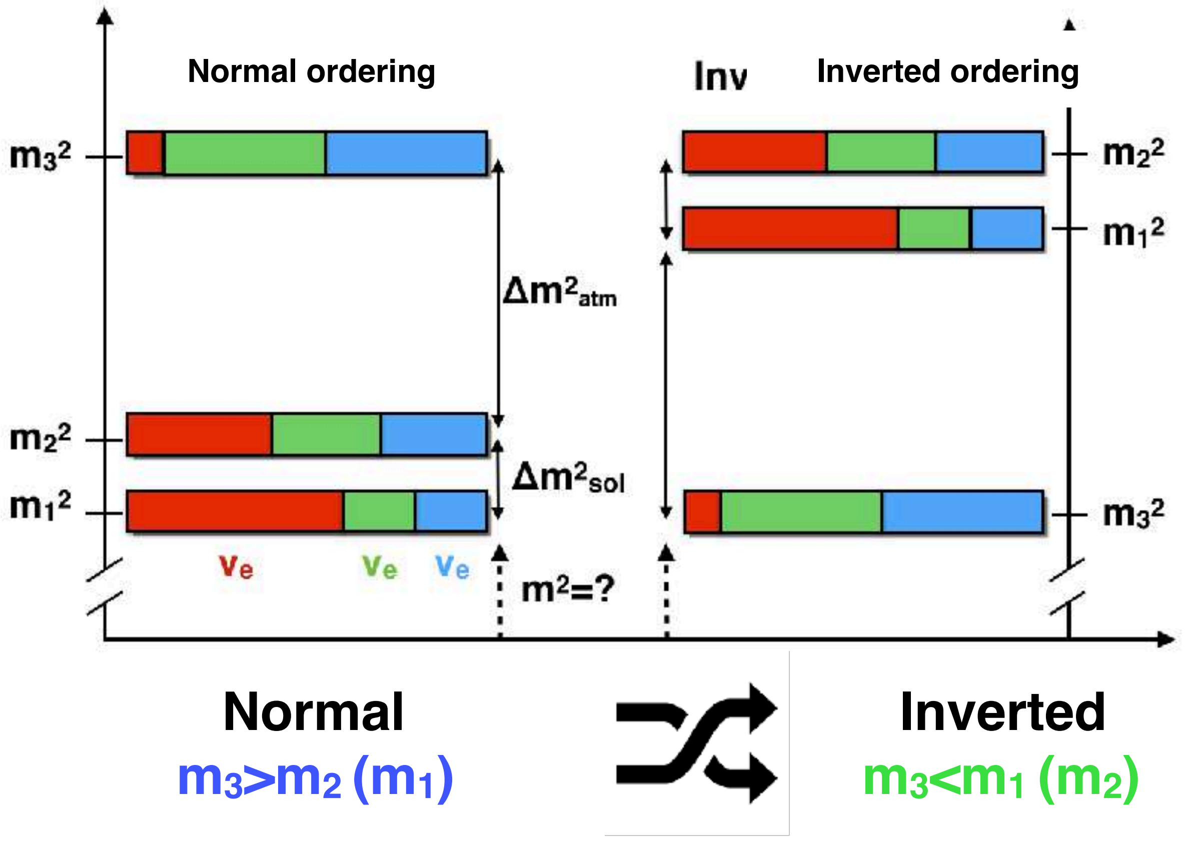
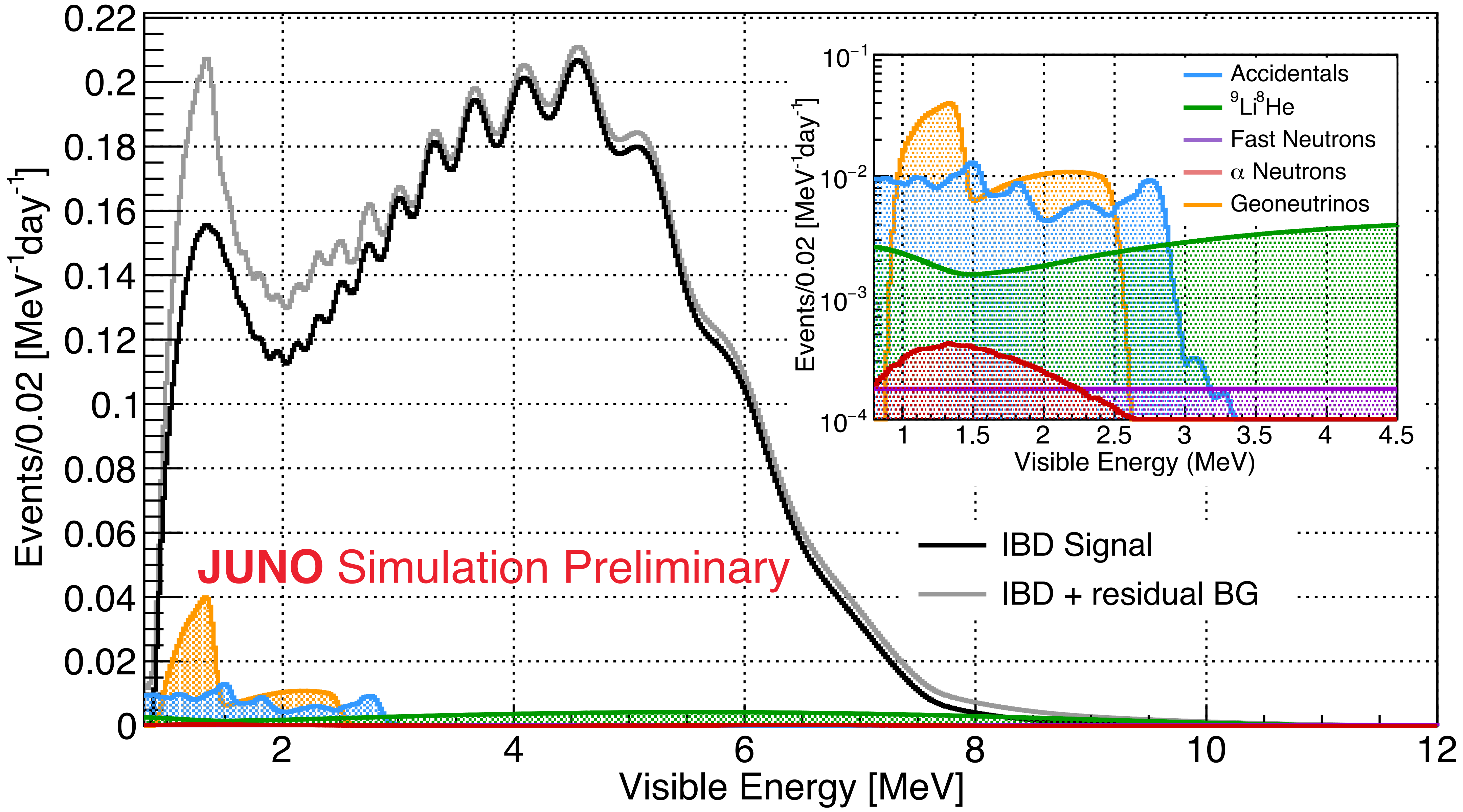


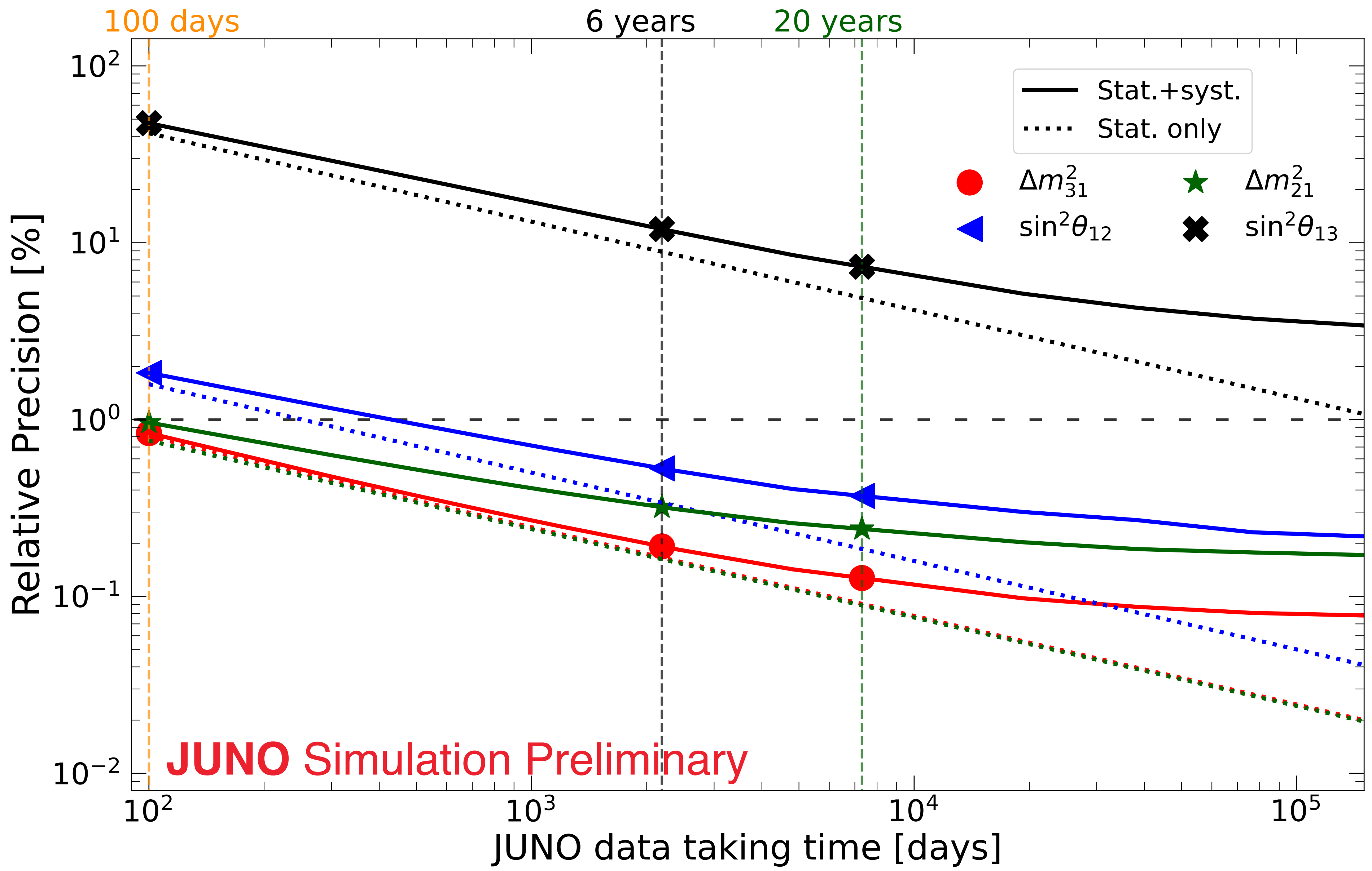


Precision Measurement of the Oscillation Parameters

- ~100,000 $\bar{\nu}_e$'s detected in 6 years
- Backgrounds well under control (e.g. *JHEP11(2021)102*)
- Sub-percentage measurement of θ_{12}, Δm^2_{21}, Δm^2_{31} ➔ improving precision by an order of magnitude in ~6 years!
- Measurement of θ_{13} - JUNO cannot compete with short baseline reactor neutrino experiments such as Daya Bay

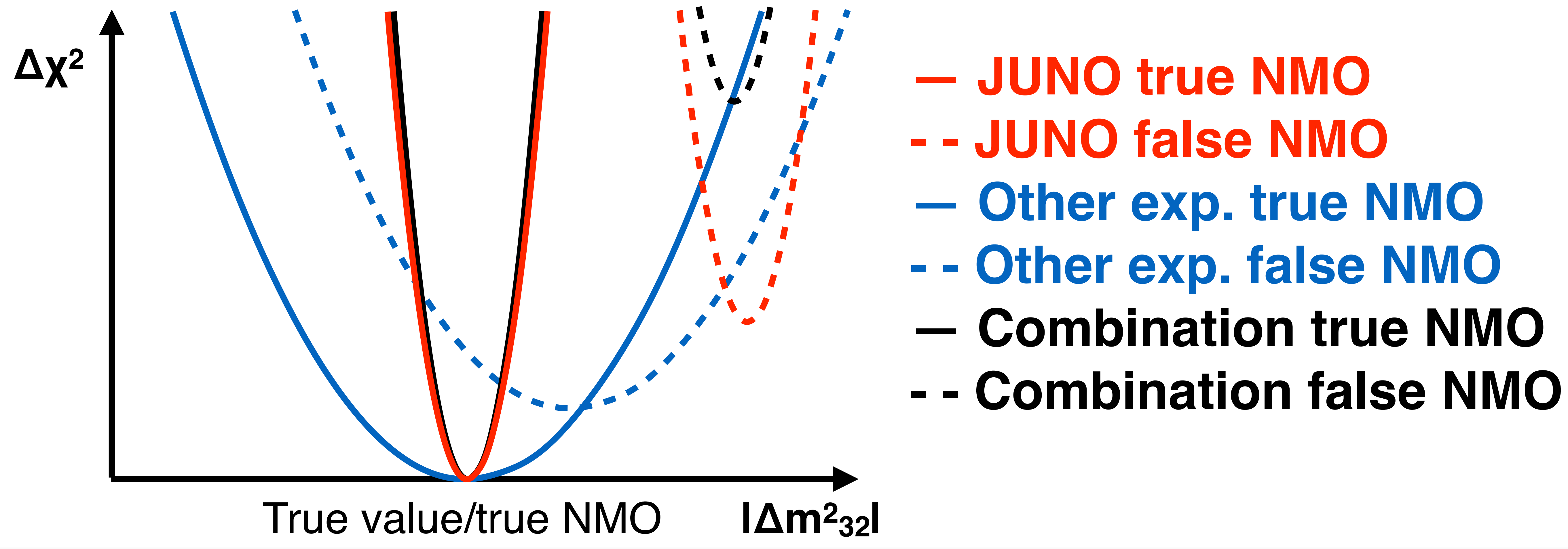
Precision/Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{13}$
JUNO 6 years	~0.5%	~0.3%	~0.2%	~12%
PDG 2020	4.2 %	2.4 %	1.4 %	3.2 %





Neutrino Mass Ordering Measurement

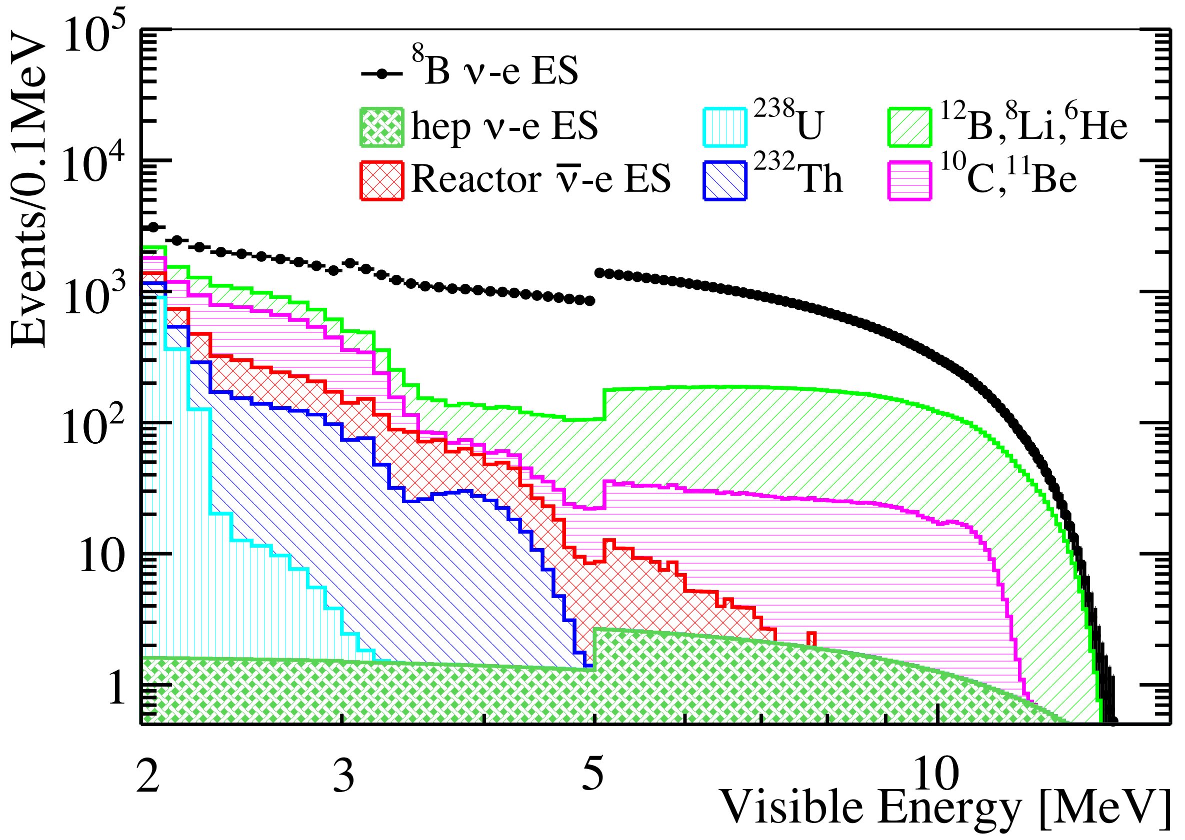
- Measurement independent of matter effects, CP-violation phase and θ_{23} octant
  - Unique information when compared and combined with other experiments
- JUNO determines the neutrino mass ordering (NMO) at just 3σ significance with 6 years of data taking
  - Thanks to the $3\,\%\sqrt{E(\mathrm{MeV})}$ energy resolution, TAO constraints on the unoscillated reactor spectrum, …
- Combination with other experiments greatly boost the potential to determine the neutrino mass ordering
  - Accelerator neutrino experiments, e.g. NOvA and T2K
  - Atmospheric neutrino experiments, e.g. KM3NeT-ORCA, IceCube Upgrade and PINGU

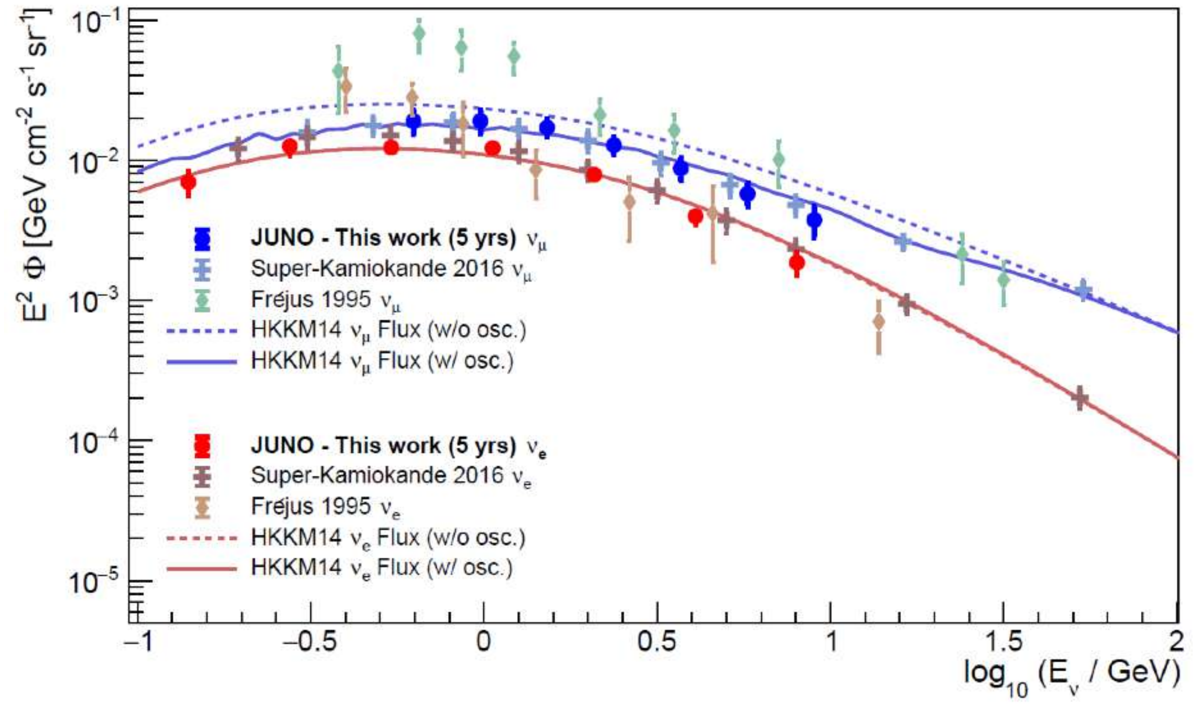


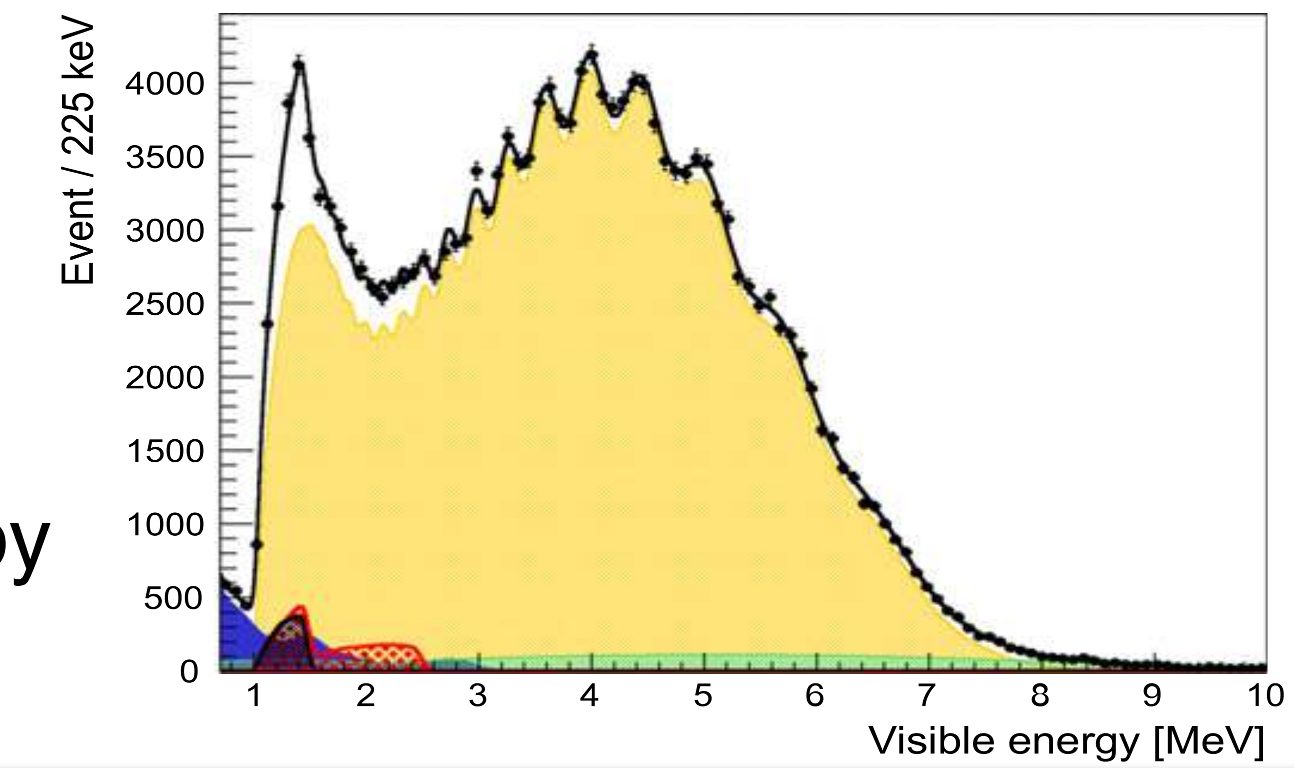
Effect	Change w.r.t. *Phys. G 43 (2016) 030401*
Taishan NPP with 2 cores from original 4	35.8 GW_{th} → 26.6 GW_{th} −
Experimental cavern up by 60 m	30% more muons −
Better 20-inch PMT quantum efficiency	27%→29% +
More light from the LS	1200 p.e. → 1350 p.e. +

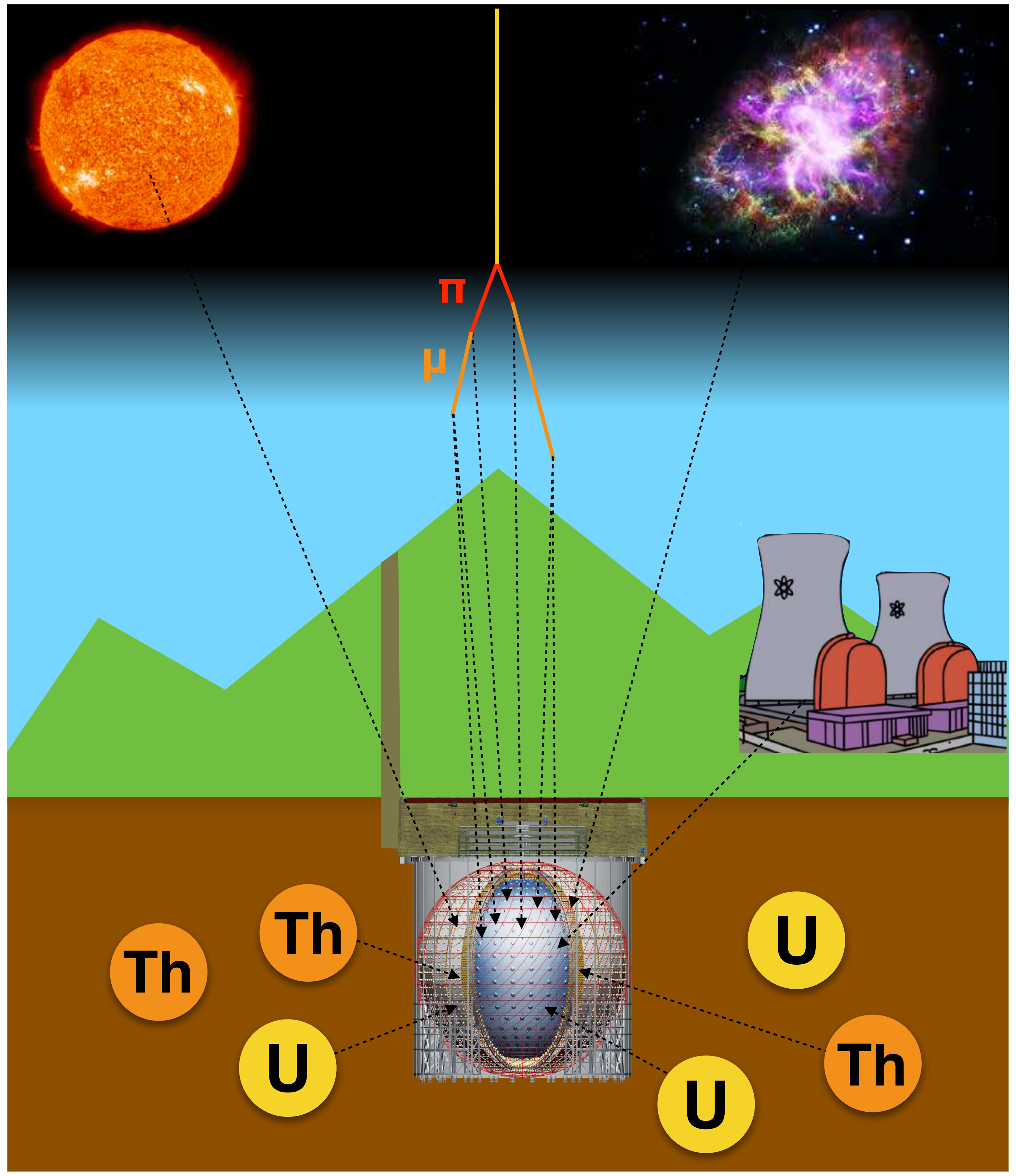
Other Physics with JUNO

- ^{8}B solar neutrinos (*CPC 45 23004 (2021)*)
  - Elastic scattering of ν_e on e^-
  - 60k events in 10 years
  - 2 MeV threshold for LS purity of 10^{-17} g/g
  - Independent measurement of Δm^2_{21}, θ_{12}
- Atmospheric neutrinos (*EPJC, 81 (2021)*)
  - ν_e, ν_μ discrimination based on hit time pattern
  - Low-energy atmospheric neutrino spectrum
  - 1-2σ sensitivity to NMO
- Geoneutrinos (*Phys. G 43 (2016) 030401*)
  - JUNO surpasses world's geoneutrino statistics in a year
  - Geoneutrino flux precision 6% in 10 years
  - Geophysical interpretation of the flux limited by large contribution from local continental crust



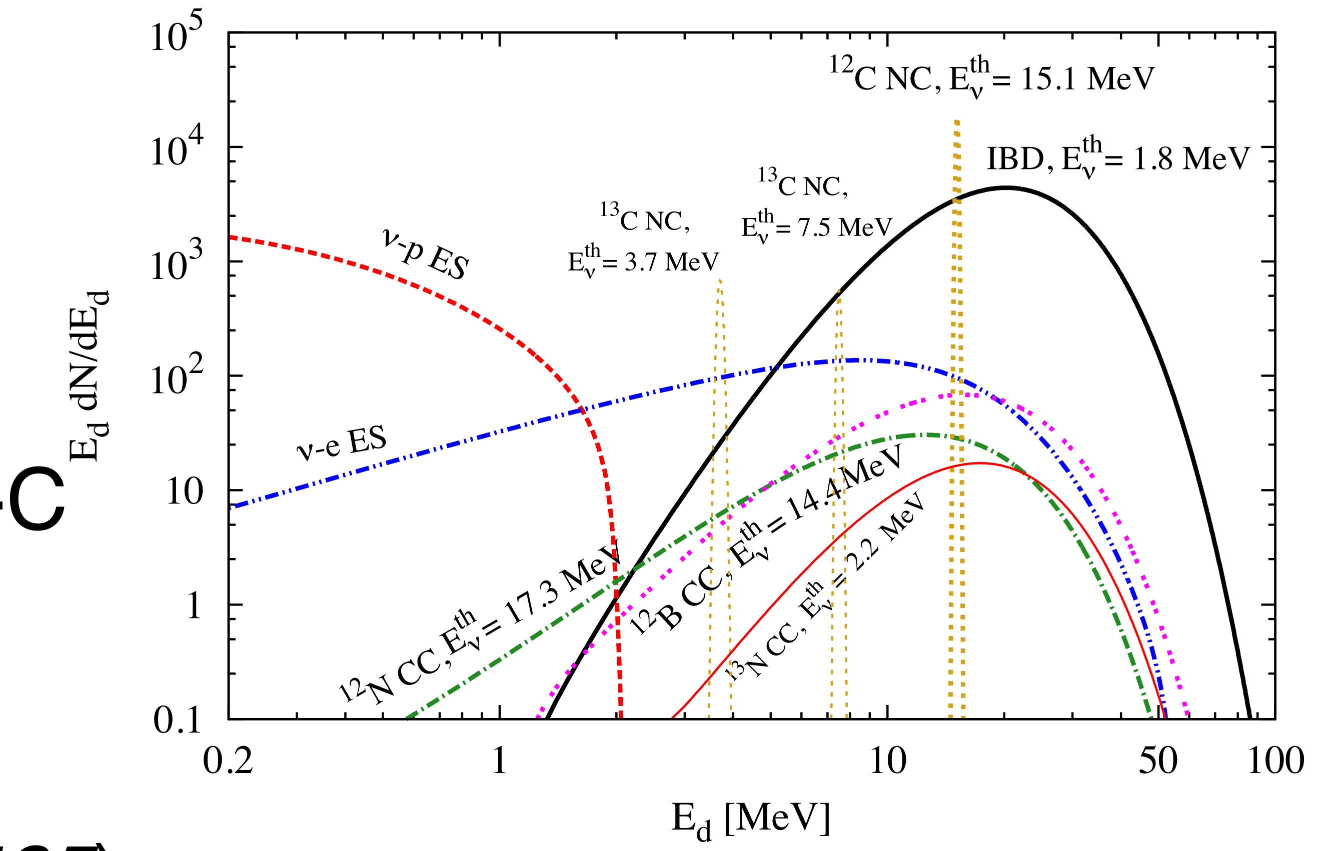




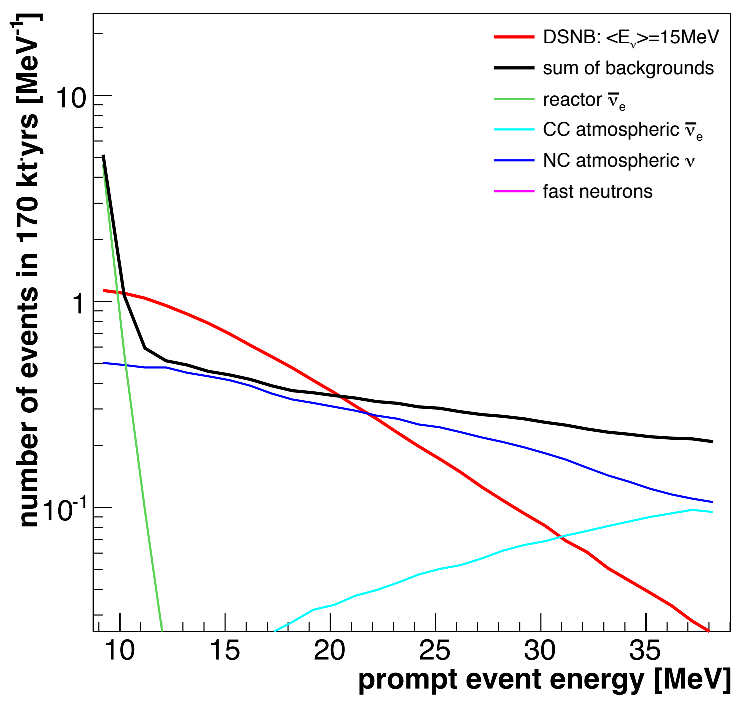


Other Physics with JUNO

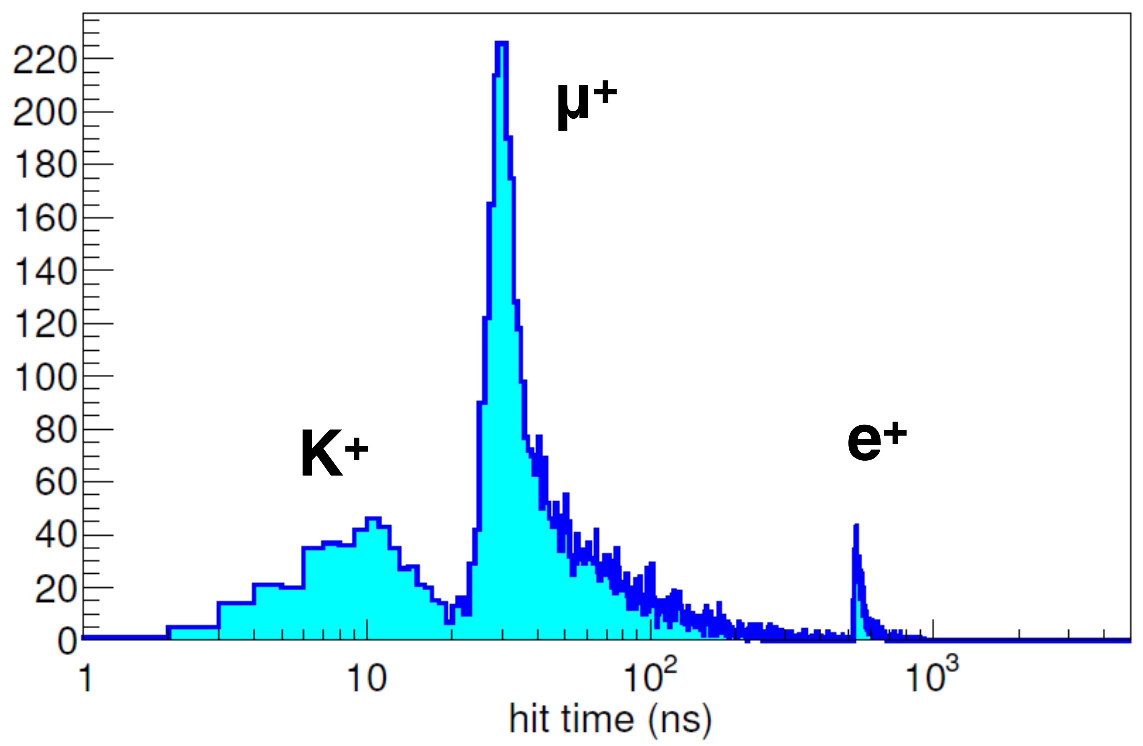
- Core-collapse supernova (SN) neutrinos
  - 10k events for 10 kpc SN
  - Detection of all neutrino flavours: ~5000 IBD, ~2000 pES, ~300 eES, ~300 NC-C
  - Excellent energy resolution, low threshold

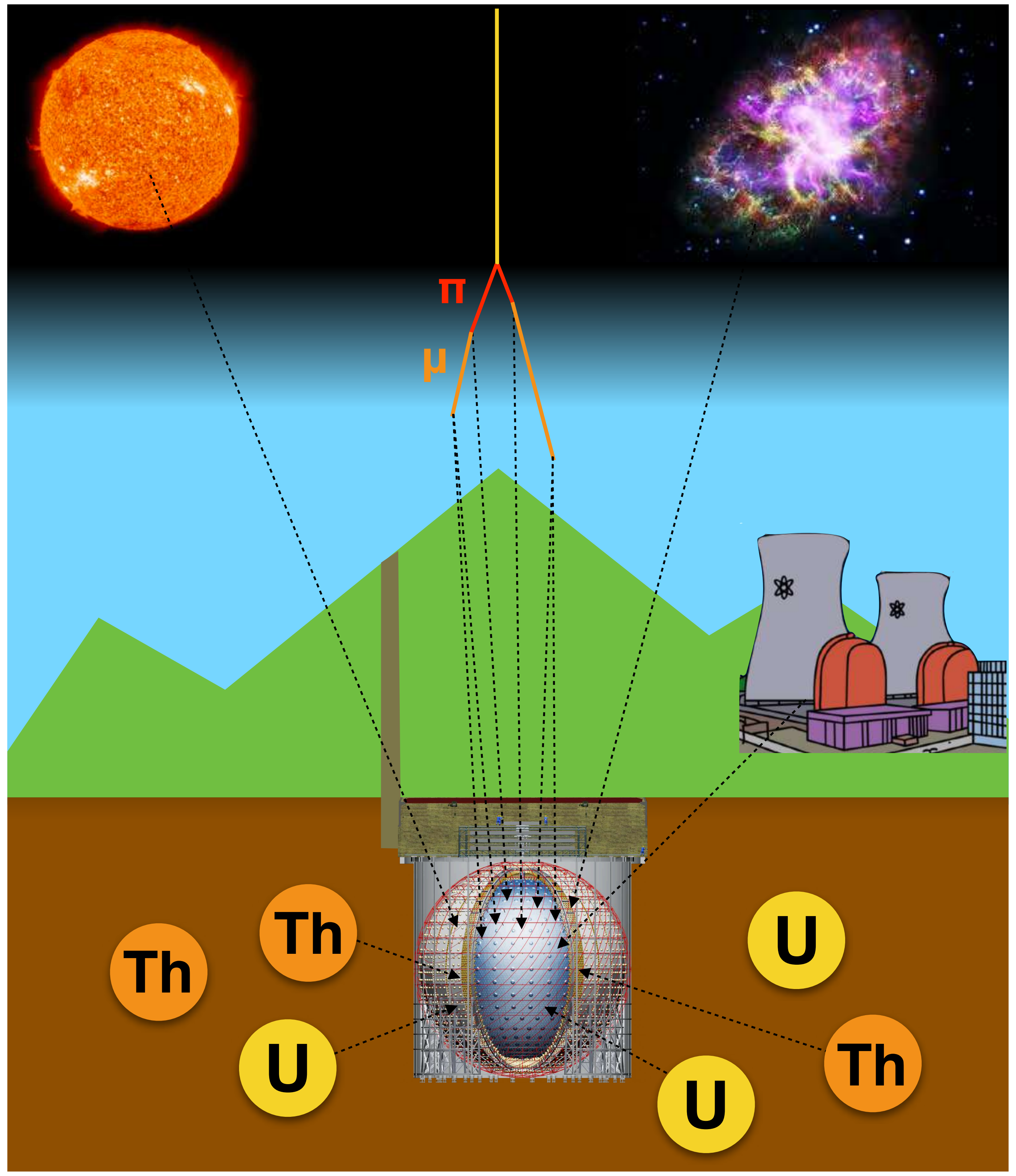


- Diffuse SN neutrino background (*arXiv:2104.02565*)
  - Neutrinos from past SNs aggregated
  - Pulse-shape discrimination greatly reduces background
  - 3σ sensitivity in 10 years for ⟨E⟩=15 MeV



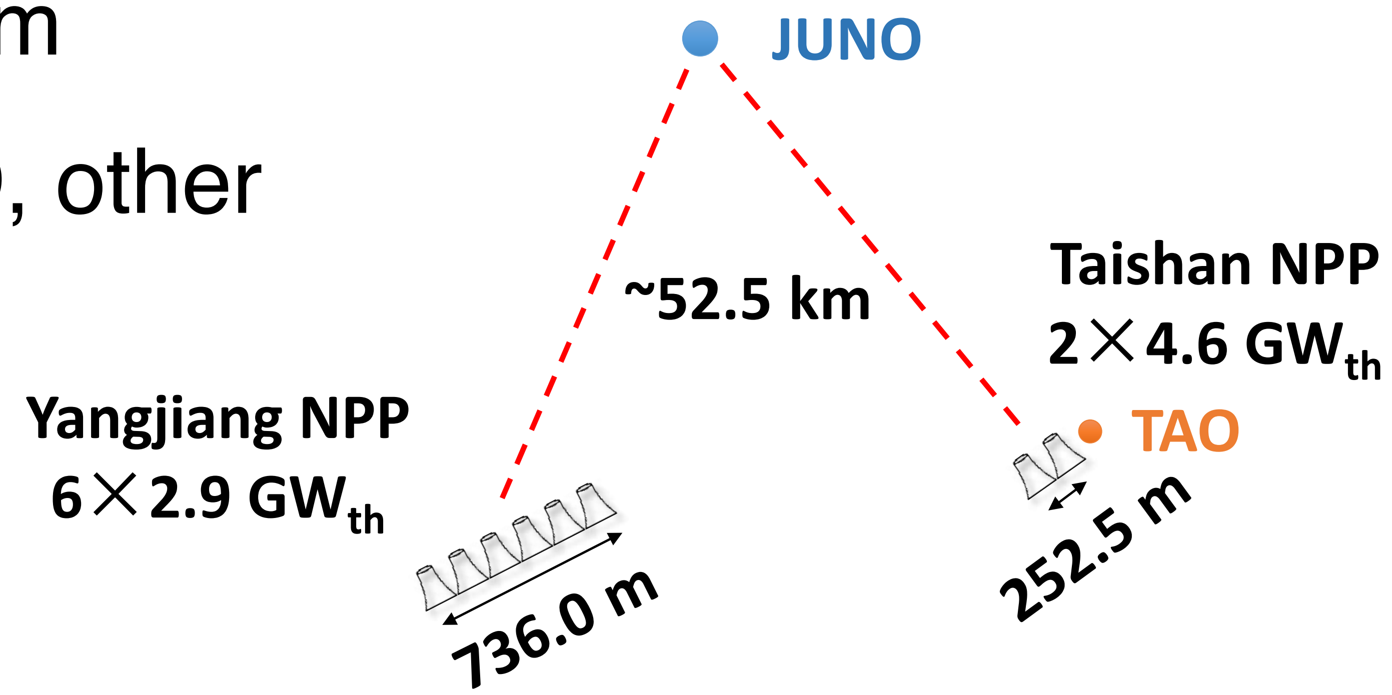
- Exotics
  - Proton decay $p \rightarrow \bar{\nu} + K^{+}$ through 3-fold coincidence
  - τ > 9×10^{33} y in 10 years
  - Others searches: Dark matter, non-standard interaction, etc.

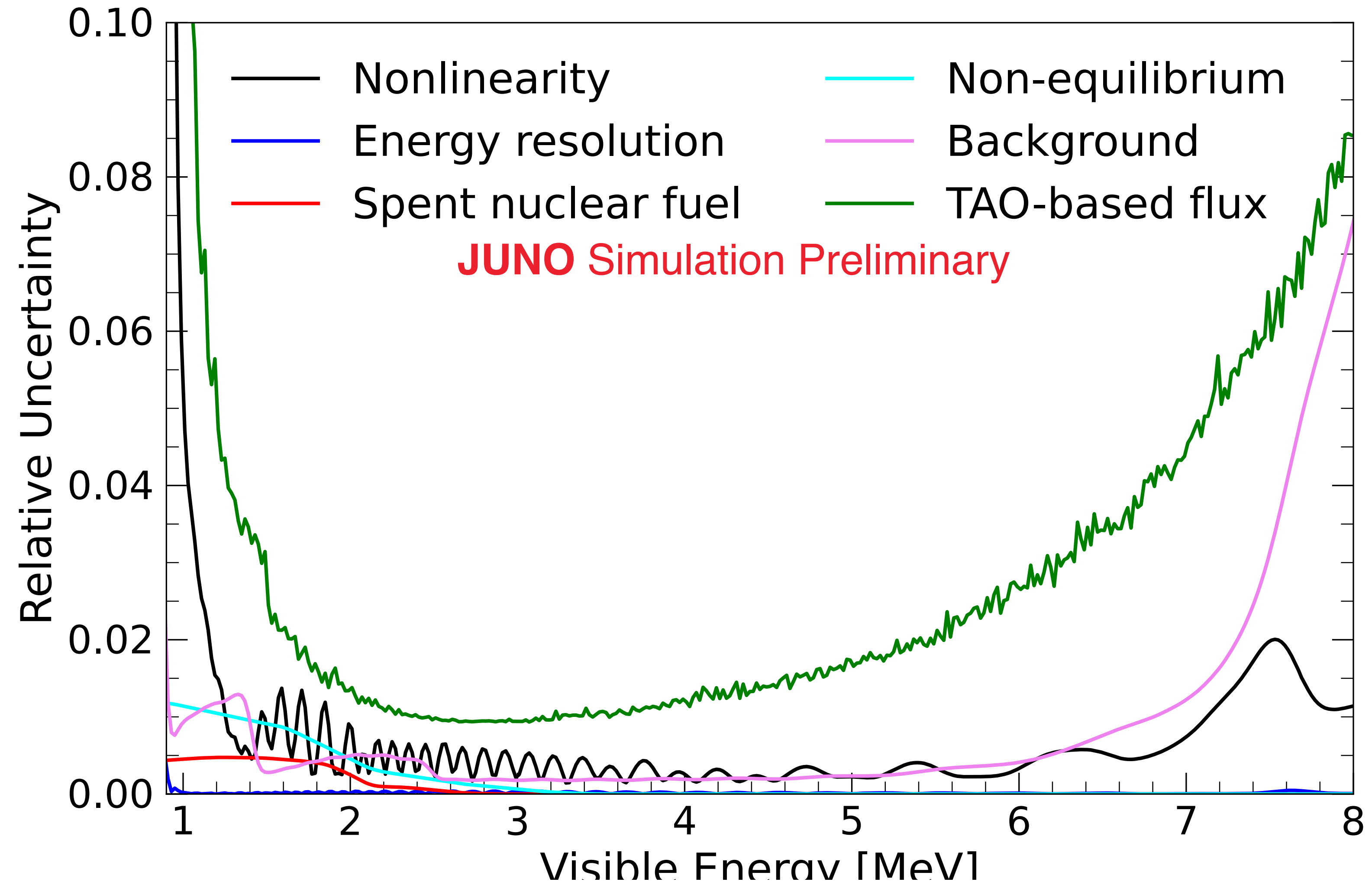


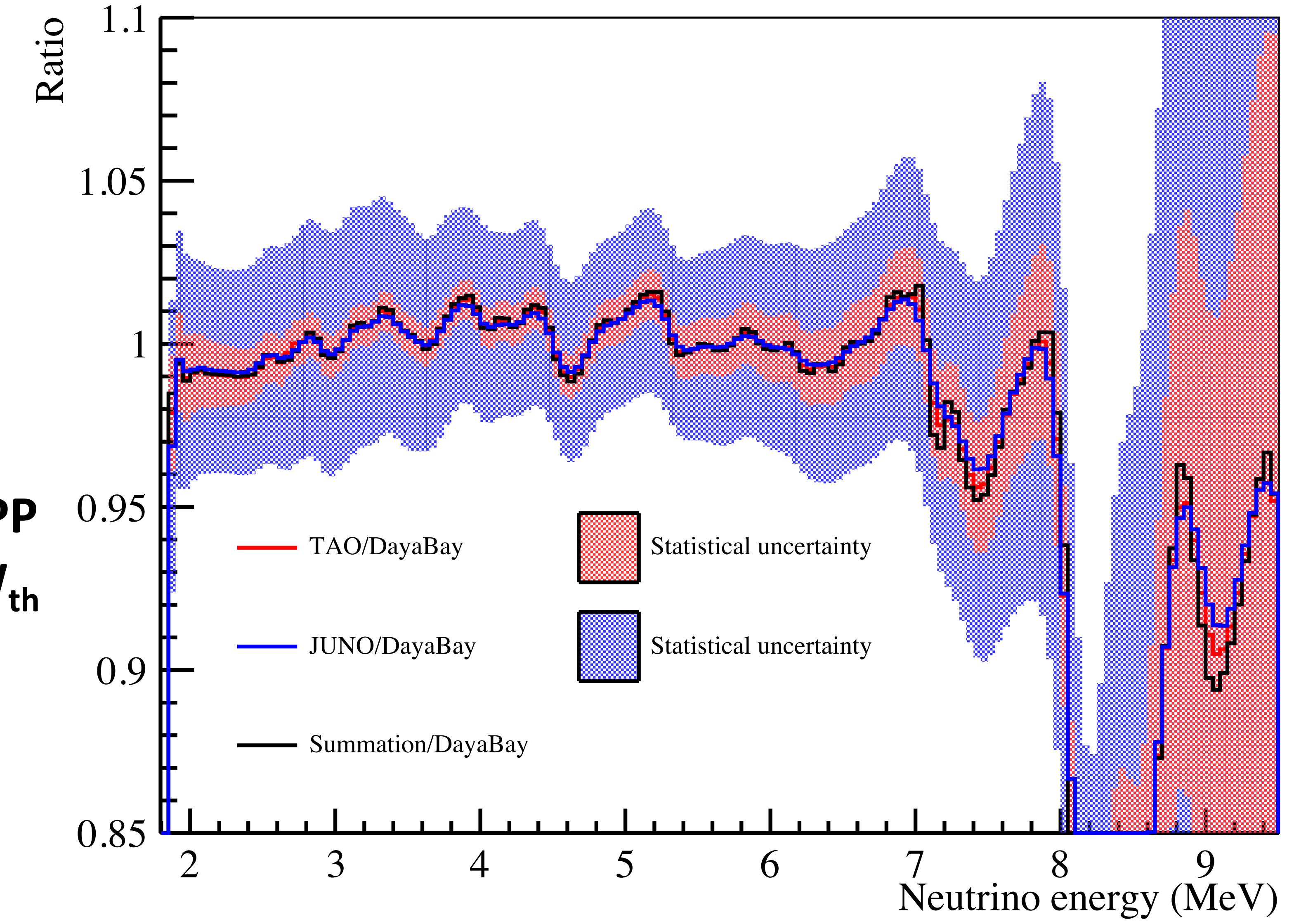


TAO Overview

- The precise knowledge of the reactor antineutrino spectrum important for several analyses
  - Mass ordering determination, sub-percentage oscillation parameters, geoneutrinos, …
  - Models' uncertainty not sufficient for JUNO's precision
- Detector with high precision and JUNO-like energy resolution needed
- **T**aishan **A**ntineutrino **O**bservatory - detector at ~30 m from Taishan NPP core (*arXiv:2005.08745*)
- Not a "near" detector in Daya Bay, NOvA, etc. sense
- Goals:
  - Precise measurement of the $\bar{\nu}_e$ spectrum
  - Model-independent reference for JUNO, other experiments and nuclear databases
  - Reactor monitoring & safeguard
  - Search for sterile neutrinos
  - …

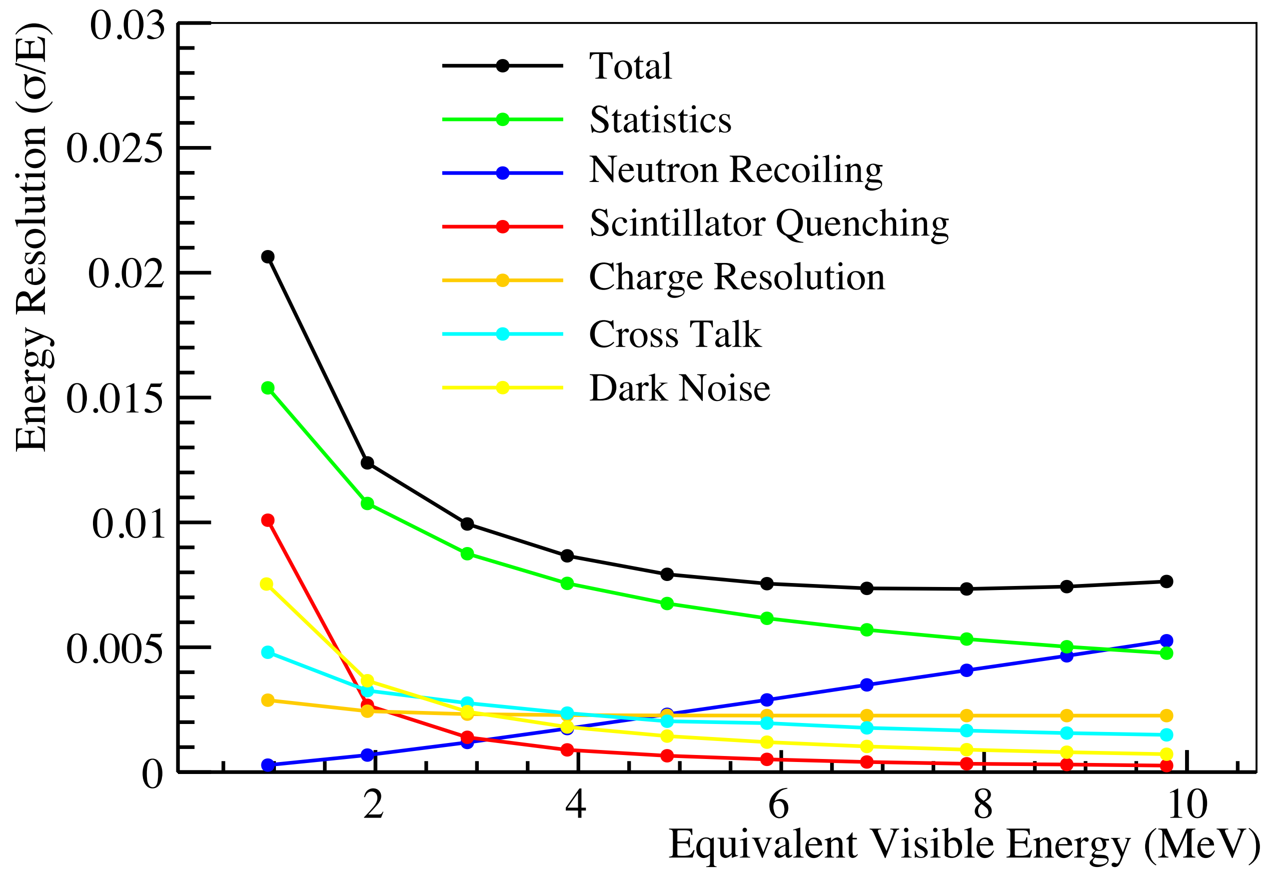


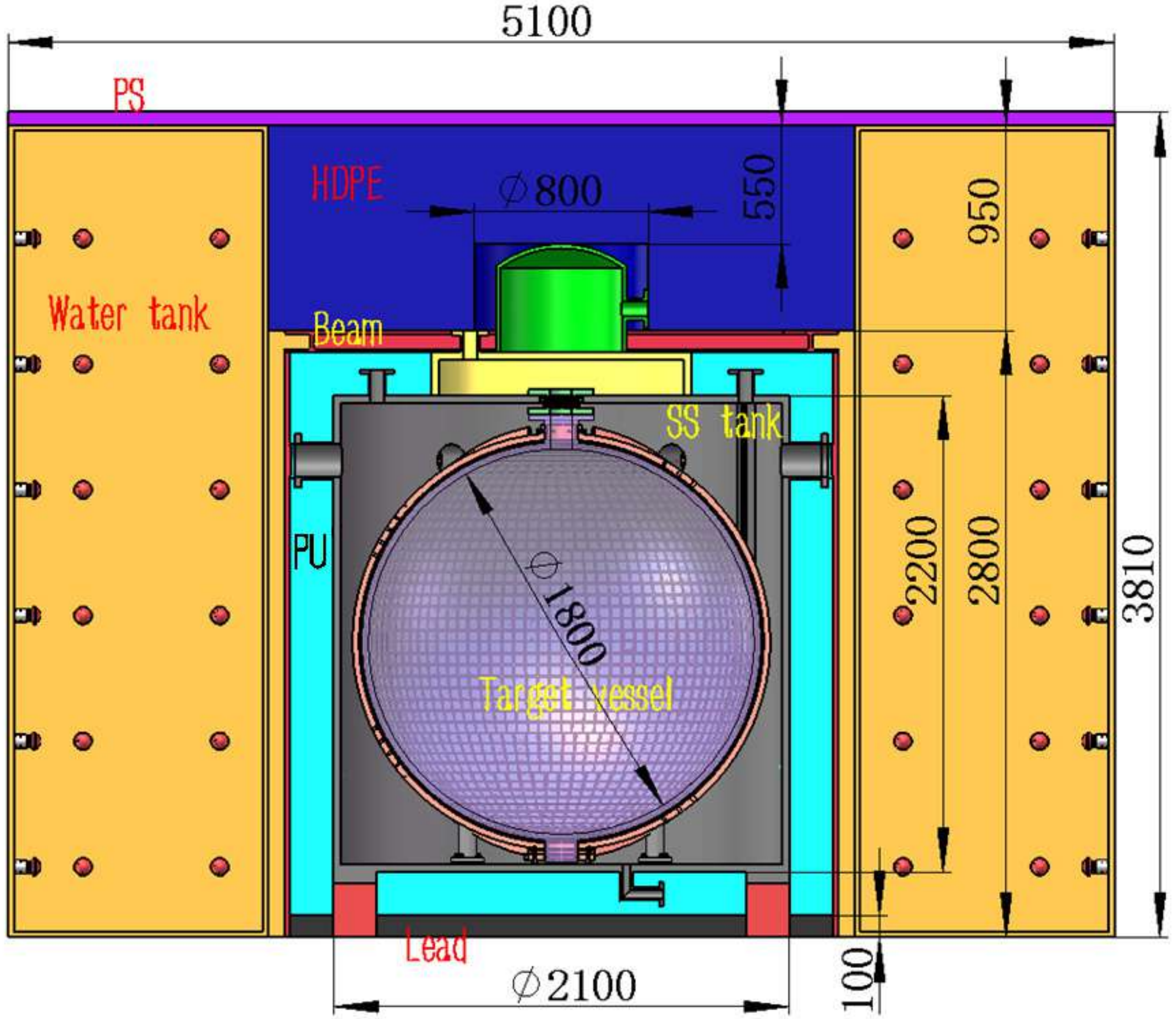




TAO Design

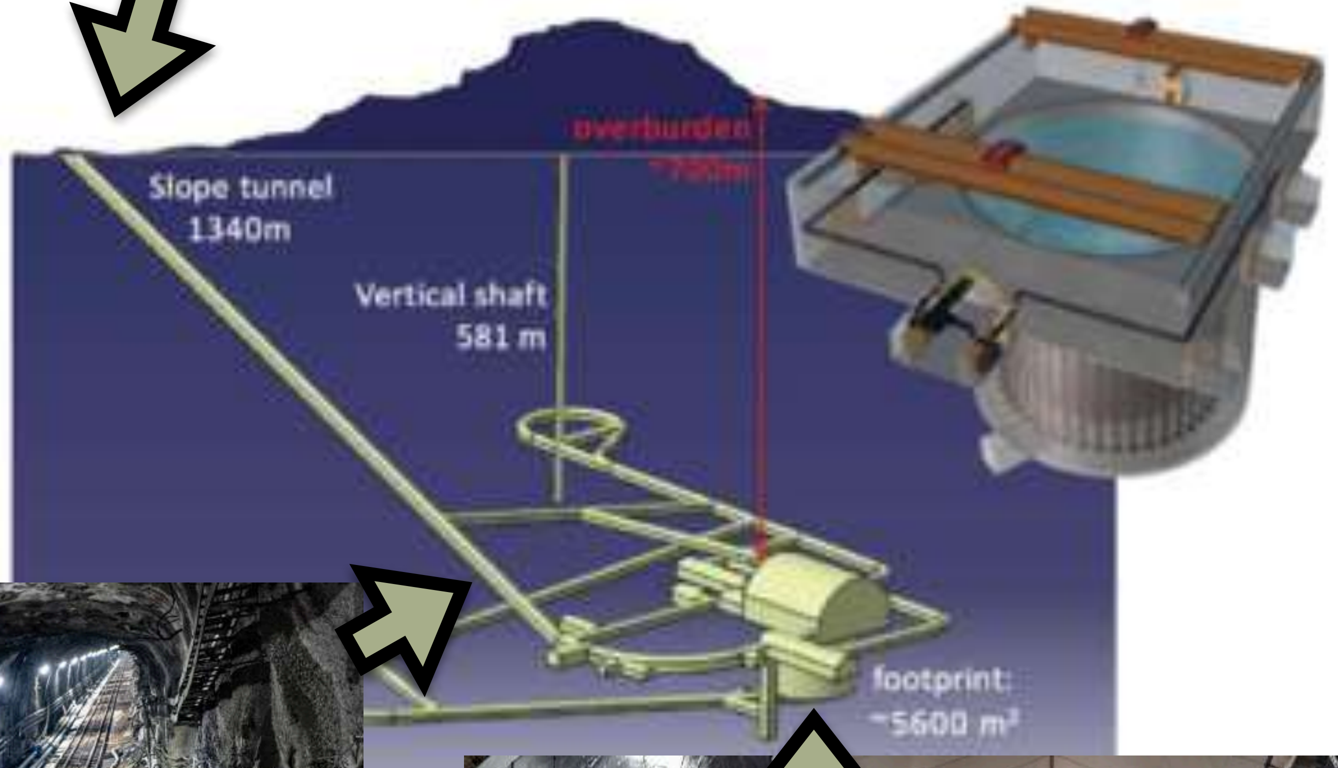
- 1 ton fiducial volume GdLS detector
- At ~30 m from Taishan NPP core, ~5 w.m.e. overburden
- Fully read out by SiPM (photo-coverage>95%, photon det. eff. >50%)
- Operated at -50˚C to suppress SiPM noise
- 4,500 p.e. per MeV ➔ Energy resolution $< 2\,\%\sqrt{E(\mathrm{MeV})}$ (better than JUNO)
- ~2,000 $\bar{\nu}_e$'s per day (comparable to Daya Bay)
- Background under control due to shielding and veto system
- Ready for data taking in 2023 (alongside JUNO)

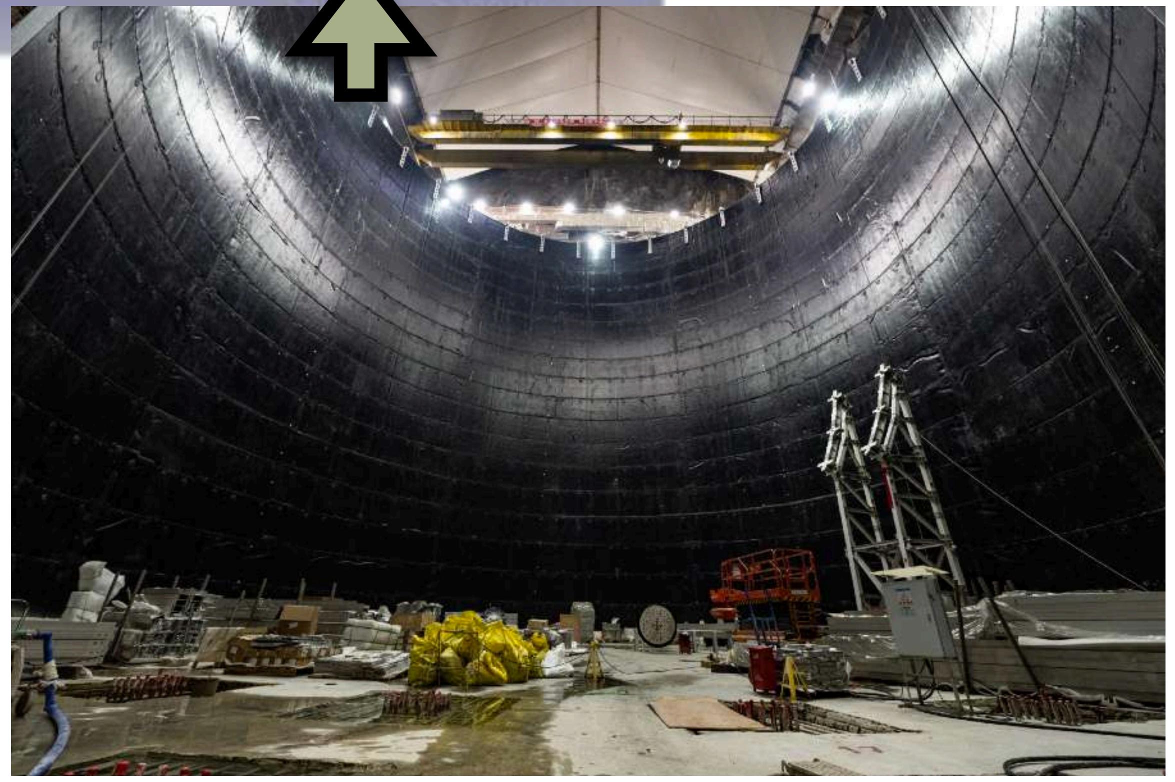


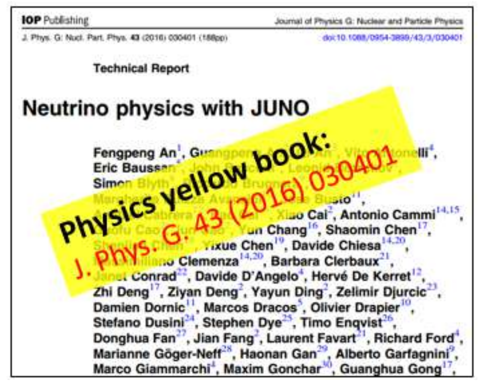


Current Status & Timeline

- Experimental cavern excavation finished - just started detector installation
- All components ready or under production - no serious pandemic-related production issues
- Ready for data taking in 2023







2015
- PMT production line setup
- CD parts R&D
- Civil construction start

2016
- PMT production start
- CD parts production start
- Yellow book published

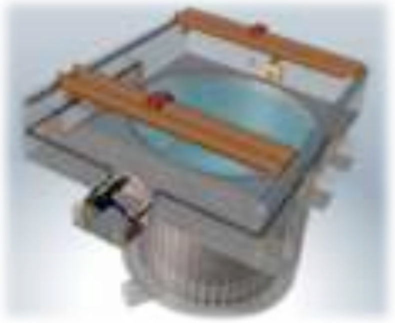
2017
- PMT testing start
- TT arrived

2018
- PMT potting
- Start delivery of surface building
- Start production of acrylic sphere

2020
- Civil construction completed
- Electronics mass production

2021-2023
- Detector installation,
- Detector ready for data taking

Neutrino detection



Conclusions

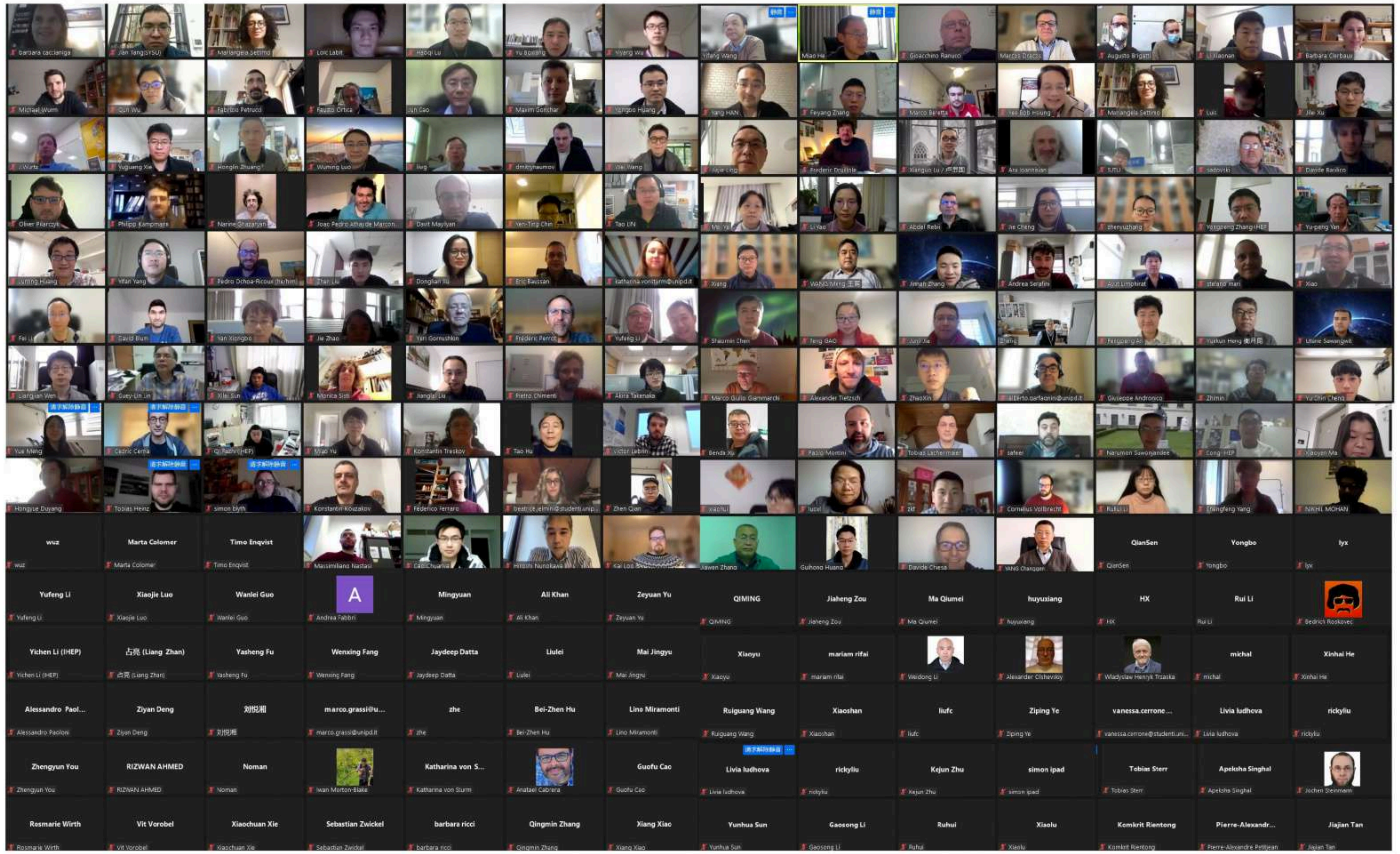
- JUNO is pushing the edge of liquid scintillator neutrino detection
  - Largest of its kind, highest photo-coverage, precise energy calibration, …
- Multipurpose experiment with world-leading potential
  - Sub-percentage measurement of θ_{12}, Δm^2_{21}, Δm^2_{31}
  - Neutrino mass ordering at about ~3σ - synergistic boost when combined with other experiments
  - Sensitivity to diffuse supernova neutrino background
  - Largest geoneutrino sample in a year
  - Others - solar neutrinos, atmospheric neutrinos, search for rare processes, …
- Construction well in progress - ready for data taking in 2023

Extras

Collaboration

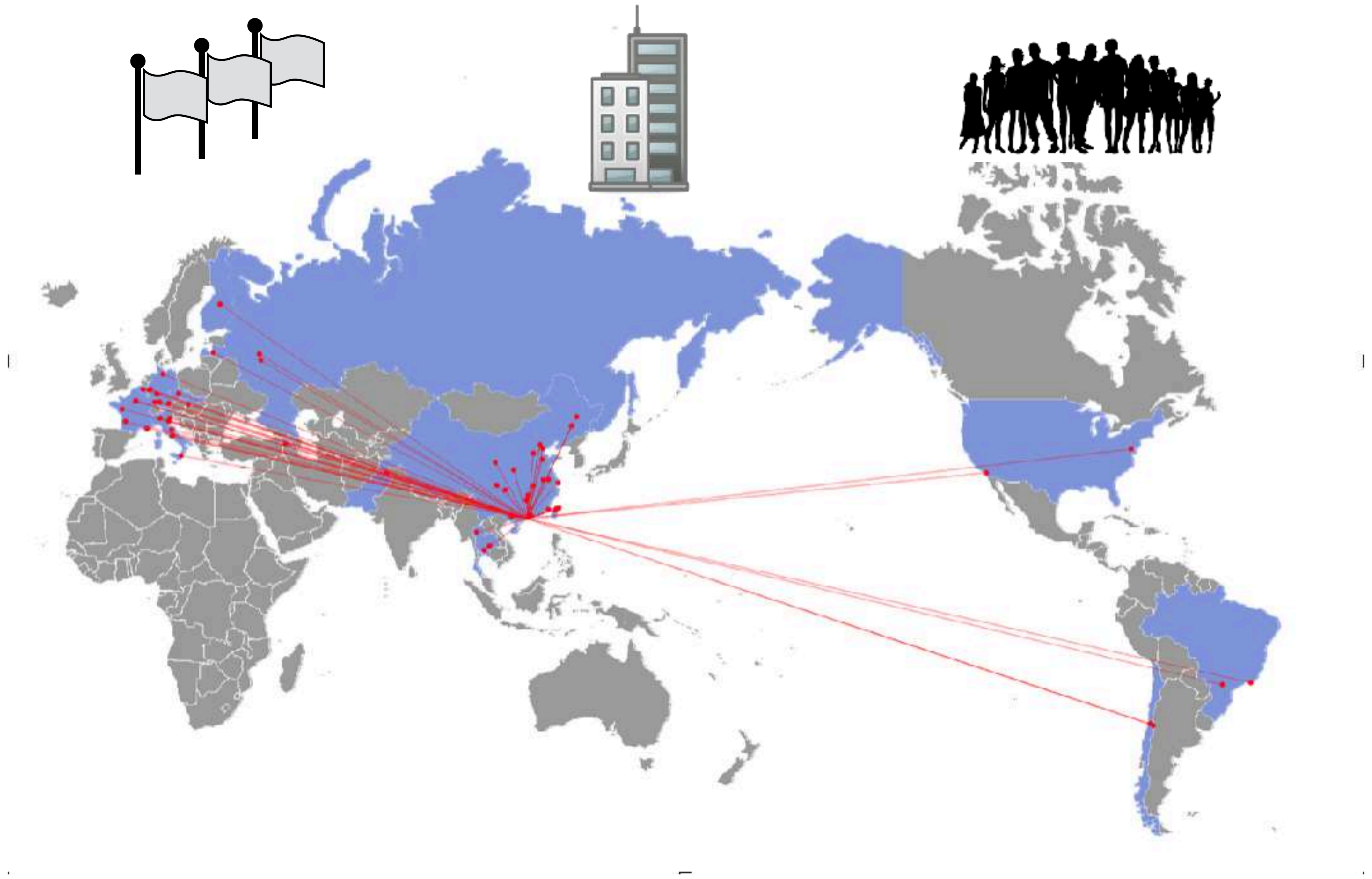
19^{th} JUNO collaboration meeting

Jan. 17-28, 2022, online



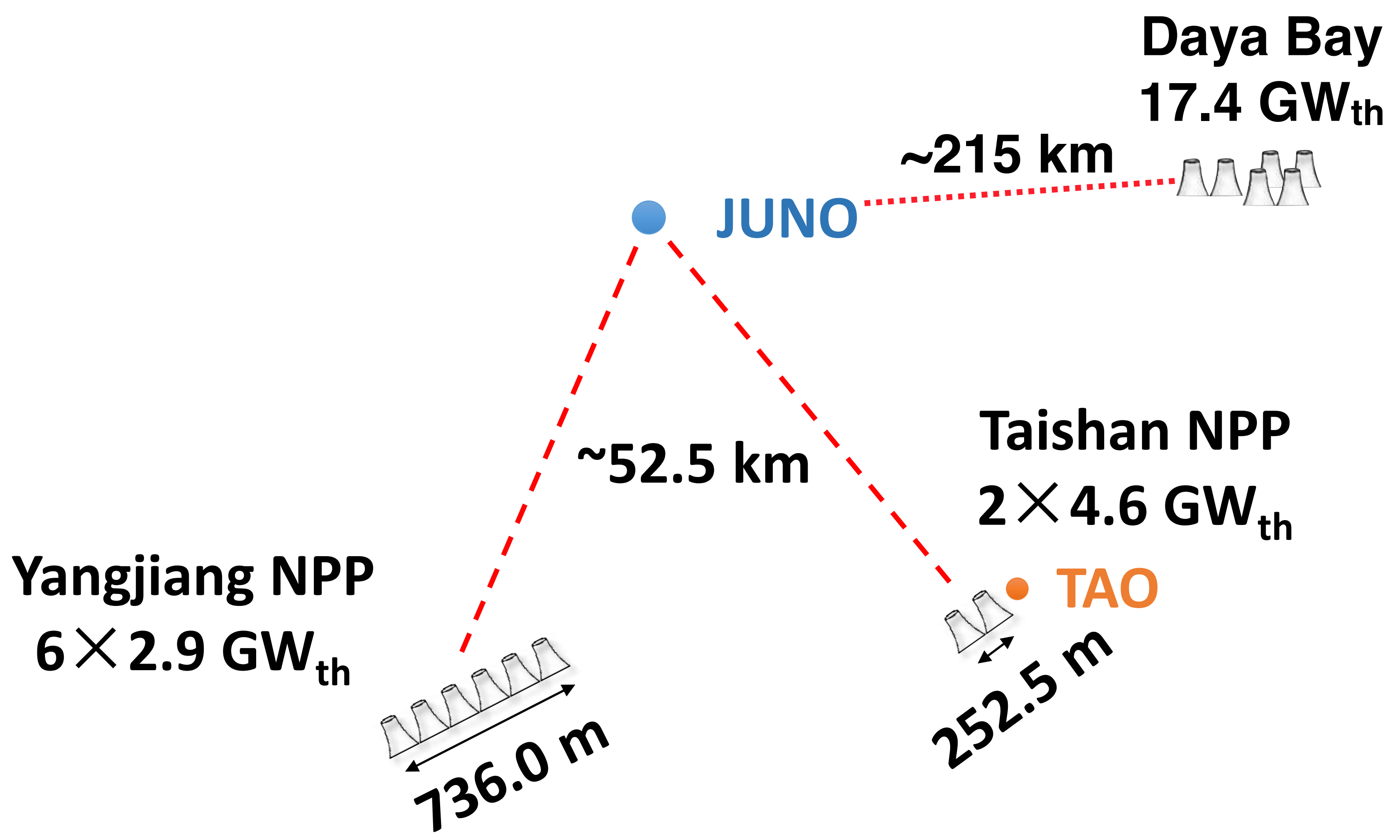
The JUNO collaboration:

18 states **76 institutions** **681 members**



JUNO Nerby Reactors

Reactor	Power (GW_{th})	Baseline (km)	IBD Rate (day^{-1})	Relative Flux (%)
Taishan	9.2	52.71	15.1	32.1
Core 1	4.6	52.77	7.5	16.0
Core 2	4.6	52.64	7.6	16.1
Yangjiang	17.4	52.46	29.0	61.5
Core 1	2.9	52.74	4.8	10.1
Core 2	2.9	52.82	4.7	10.1
Core 3	2.9	52.41	4.8	10.3
Core 4	2.9	52.49	4.8	10.2
Core 5	2.9	52.11	4.9	10.4
Core 6	2.9	52.19	4.9	10.4
Daya Bay	17.4	215	3.0	6.4



Oscillation Parameters Uncertianty Breakdown (6 y)