Gerarchia di Massa
JUNO

Corso di

Fisica Astroparticellare

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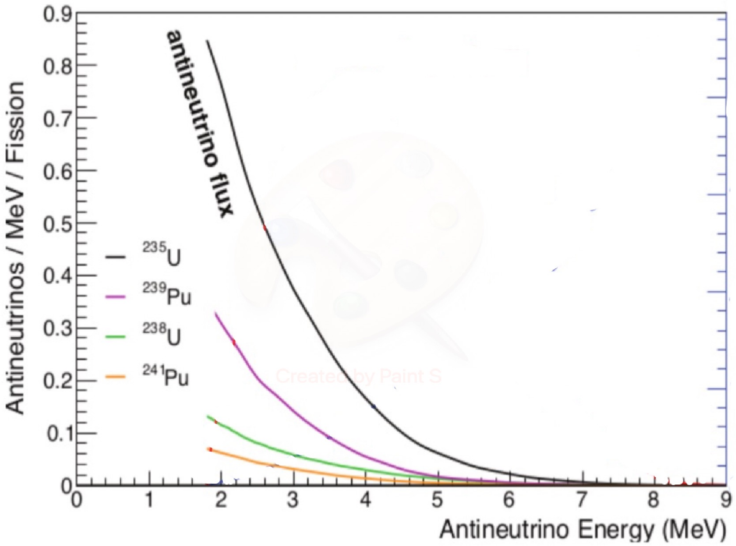
Testi consigliati

https://warwick.ac.uk/fac/sci/physics/staff/academic/boyd/warwick_week/neutrino_physics/lec_oscillations.pdf

Giorgio Bendiscioli - Fenomeni radioattivi. Dai nuclei alle stelle-Springer Milan (2013)

JUNO YELLOW BOOK: https://arxiv.org/abs/1507.05613 J. Phys. G **43** (2016) n.3 030401

Nuclear power plants are an intense source of **electron antineutrinos**



$$Source: \quad pure\ \overline{\nu}_e$$

$$\approx 200\ MeV\ /\ fission$$

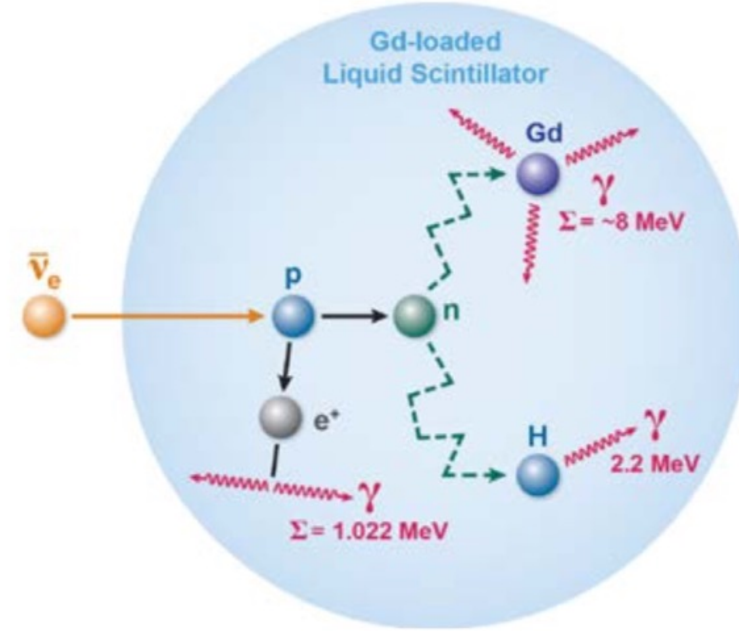
$$\approx 6\ \overline{\nu}_e\ /\ fission$$

$$\approx 2 \cdot 10^{20}\ \overline{\nu}_e\ /\ GW_{th}\ /\ \sec$$

- Il flusso degli anti-ν_e è approssimativamente dato da

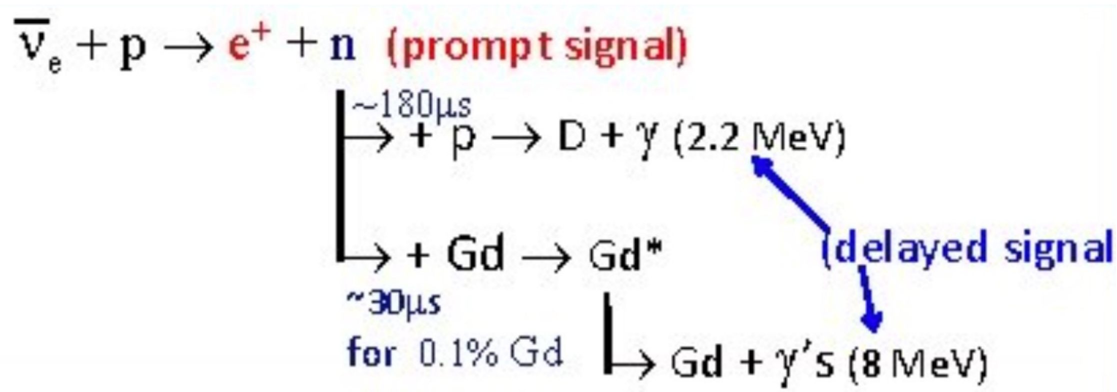
$$\phi \sim 1.5 \times 10^{15}\ P/L^2\ cm^{-2}\ s^{-1}$$

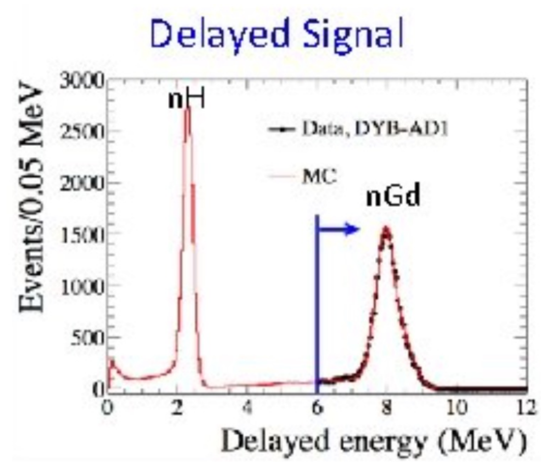
dove P è la potenza termica del reattore espressa in GW e L la distanza espressa in metri electron anti-neutrino are detected through IBD (Inverse Beta Decay)



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

$$E_{vis}(e^+) = E_{\bar{\nu}} - 1806\ keV + 511\ keV + 511\ keV = E_{\bar{\nu}} - 784\ keV$$





- Coincidence signals to suppress background

Cinematica dell'Inverse Beta Decay

- Inverse beta-decay: $\overline{\nu_e} + p \rightarrow e^+ + n$
- Momentum conservation:

$$\overrightarrow{p_{\nu_e}} + \overrightarrow{p_p} = \overrightarrow{p_{e^+}} + \overrightarrow{p_n}$$

Most of the time $\overrightarrow{p_p} = \vec{0}$ (lab frame)

- Energy conservation:

$$E_{\nu_e} + E_p = E_{e^+} + E_n$$

neglecting neutron recoil

$$E_{\nu_e} + m_p c^2 = E_{e^+} + m_n c^2$$

$$E_{\nu_e} = E_{e^+} + (m_n - m_p)c^2 = E_{e^+} + \Delta$$

$$E_{e^+} = T_{e^+} + m_e c^2$$

$$E_{\nu_e} = T_{e^+} + m_e c^2 + \Delta$$

- Energy threshold:

$$\Delta \approx 1.293 \text{ MeV}$$

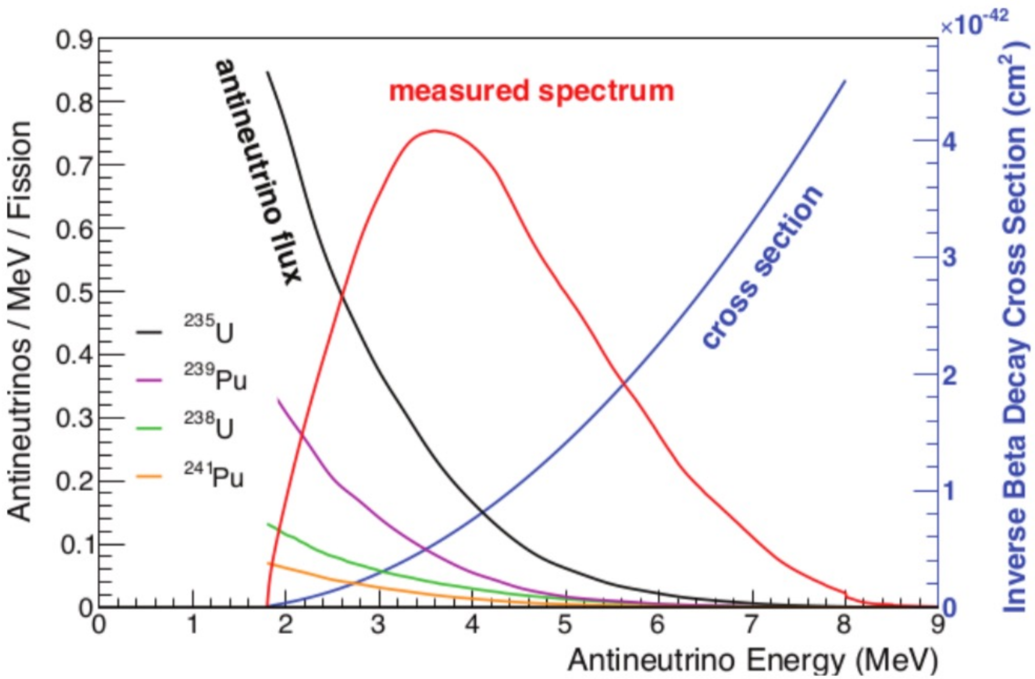
$$m_e c^2 \approx 0.5 \text{ MeV}$$

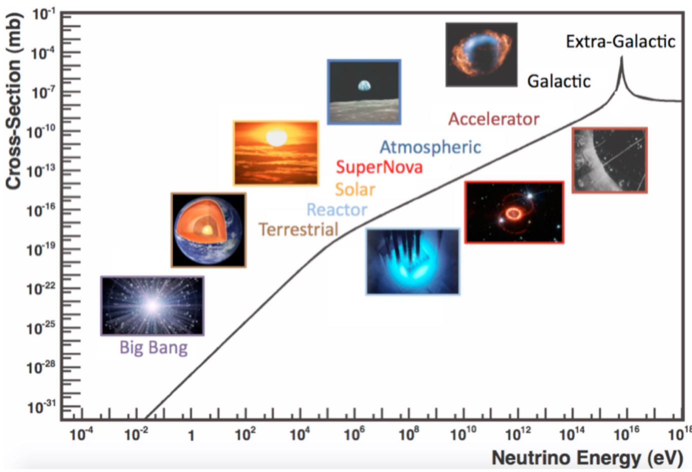
$$T_{e^+} = \Delta + m_e c^2 - E_{\nu_e}$$

$$T_{e^+} = 0 \rightarrow E_{\nu_e} = 1.804 \text{ MeV} = E_{\text{th,approx}}$$

But exact threshold given by:

$$E_{\text{th,true}} = \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = 1.806 \text{ MeV}$$



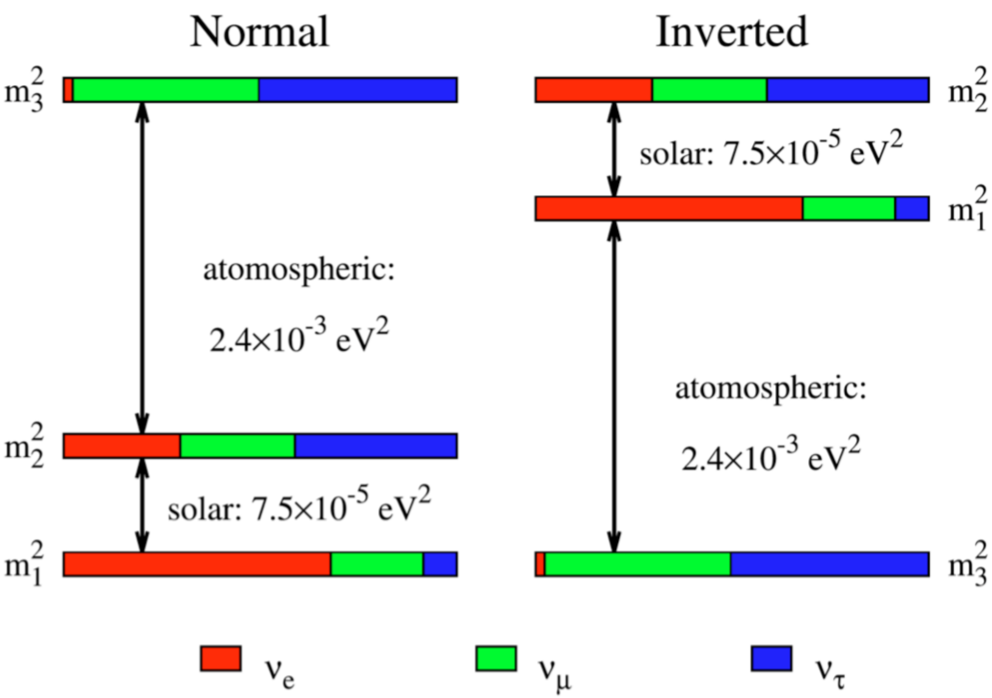


$$S(E_\nu) \approx c \cdot \sum_i f_i \cdot S_i(E_\nu) \cdot \sigma(E_\nu)$$

Observed $\bar{\nu}_e$ spectrum	Isotope fission fraction	Isotope neutrino spectra	IBD Xsec

- Threshold: 1.8 MeV

Determination of the Neutrino Mass Ordering (NMO)



- ν_1, ν_2, ν_3 defined according to fraction of ν_e
- ν_2 is heavier than ν_1 (sun+MSW)
- We do not know if ν_3 is

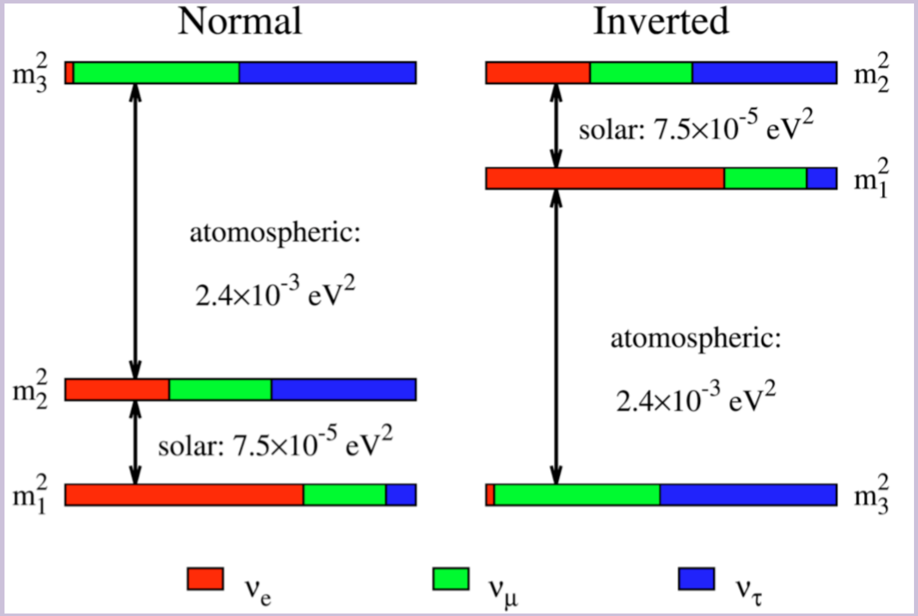
  heavier (Normal Ordering) or

  lighter (Inverted Ordering) than ν_2

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

$$\textbf{NO:}\quad |\Delta m_{31}^2| = |\Delta m_{32}^2| + \Delta m_{21}^2$$

$$\textbf{IO:}\quad |\Delta m_{31}^2| = |\Delta m_{32}^2| - \Delta m_{21}^2$$



$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i} |\nu_i\rangle \qquad \nu_\alpha \equiv \nu_e, \nu_\mu, \nu_\tau$$

$$\nu_i \equiv \nu_1, \nu_2, \nu_3$$

$$|\nu_i\rangle = \sum_{\alpha=1}^{n} U_{\alpha i} |\nu_\alpha\rangle$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\mathcal{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} .$$

$\vartheta_{13} \simeq 8.5°$

$\vartheta_{12} \simeq 34°$

$\vartheta_{23} \simeq 45°$

Tralasciamo la fase **δ** di Dirac ed introduciamo i valori degli angoli di mescolamento <u>senza il loro errore</u>:

Otteniamo:

$$U = \begin{pmatrix} 0.8199313105799922 & 0.5530506522119778 & 0.14780941112961063 \\ -0.48205764462508816 & 0.5277729040674154 & 0.6993398236842793 \\ 0.308760543446031 & -0.6446632747567932 & 0.6993398236842793 \end{pmatrix}$$

Per passare alla Probabilità dobbiamo elevare al quadrato:

$$m_i^2 =< \nu_i \,|\nu_i > = |U_{ei}|^2 < \nu_e|\nu_e > + |U_{\mu i}|^2 < \nu_\mu|\nu_\mu > + |U_{\tau i}|^2 < \nu_\tau|\nu_\tau >$$

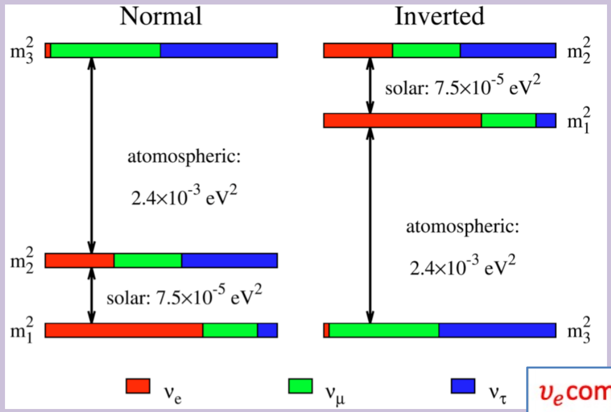
67.25%	**30.55%**	**2.2%**
23.25%	**27.85%**	**48.9%**
9.5%	**41.60%**	**48.9%**

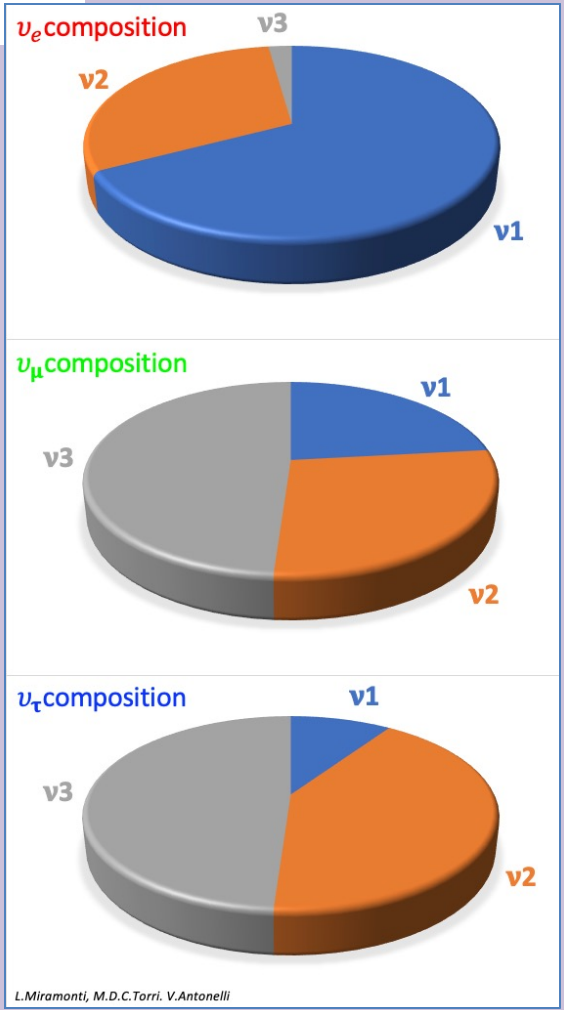
Abbiamo poi arrotondato I valori (espressi in percentuale) in modo che, sia la somma delle righe che quella delle colonne sia pari al 100%. ***UNITARIETA':*** $U \cdot U^* = 1$

Ad esempio: $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$

$|U_{e1}|^2 + |U_{\mu 1}|^2 + |U_{\tau 1}|^2 = 1$

	ν_1	ν_2	ν_3
ν_e	67.25 %	30.55 %	2.2 %
ν_μ	23.25 %	27.85 %	48.9 %
ν_τ	9.5 %	41.60 %	48.9 %





Il ν_1 è composto per la maggior parte da ν_e

Il ν_3 è quello che ha il minor contributo di ν_e

Per tanto:

Un fascio di ν_e è composto per la maggior parte da ν_1

Un fascio di ν_τ è quello che ha il minor contributo di ν_1

It is possible to infer the **Neutrino Mass Ordering** studying the interference effect between the oscillations driven by Δm^2_{sol} and Δm^2_{atm} using reactor experiments (2002 Petcov and Piai)

$$\frac{\Delta m^2_{31}, \Delta m^2_{32}}{\Delta m^2_{21}} \approx \frac{\Delta m^2_{atm}}{\Delta m^2_{sol}} \approx \frac{2.4 \cdot 10^{-3}}{7.5 \cdot 10^{-5}} \approx \frac{1}{30}$$

$$\sin^2 2\vartheta_{12} \approx \sin^2 2 \cdot 34° \approx 0.86$$

$$\sin^2 2\vartheta_{13} \approx \sin^2 2 \cdot 8.5° \approx 0.085$$

$$\sin^2 2\vartheta_{23} \approx \sin^2 2 \cdot 45° \approx 1$$

ϑ_{23} Non rientra nell'equazione

Electron antineutrino
survival probability:

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

(slow) (fast)

$$\cos^4 \vartheta_{13} \approx \cos^4 8.5° \approx 0.96$$

Solar (slow)

Atmospheric (fast)

Per ϑ_{13}= 0

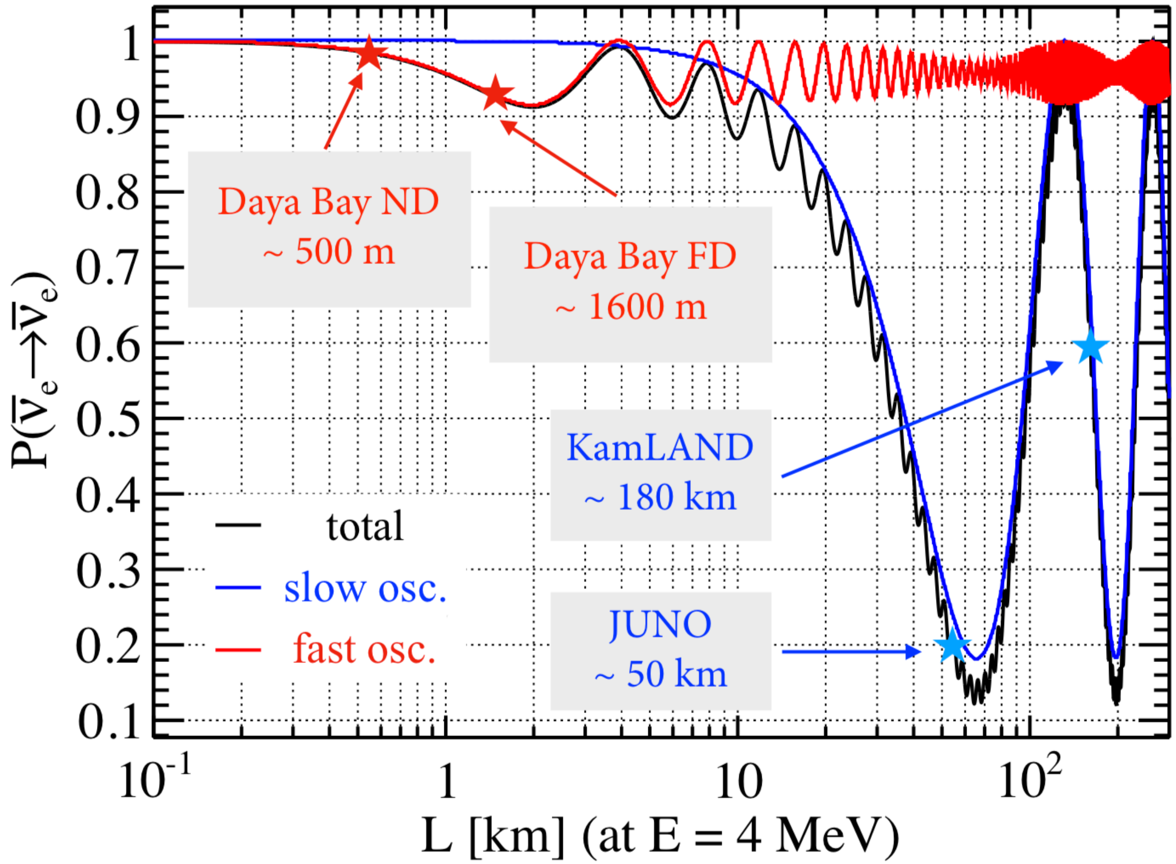
$$P_{\overline{\nu_e} \to \overline{\nu_e}} = 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

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

(slow) (fast)

Solar (slow)

Atmospheric (fast)



- La gerarchia di massa è misurabile perchè **θ_{13} è sufficientemente 'grande'**.
- Best L/E ratio for **maximum interference** is ~10 km/MeV, i.e. **~50-60 km** distance for reactor antineutrinos energy.

JUNO will be the first experiment able to measure **simultaneously** the fast (Δm^2_{31}) and slow (Δm^2_{21}) oscillations

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

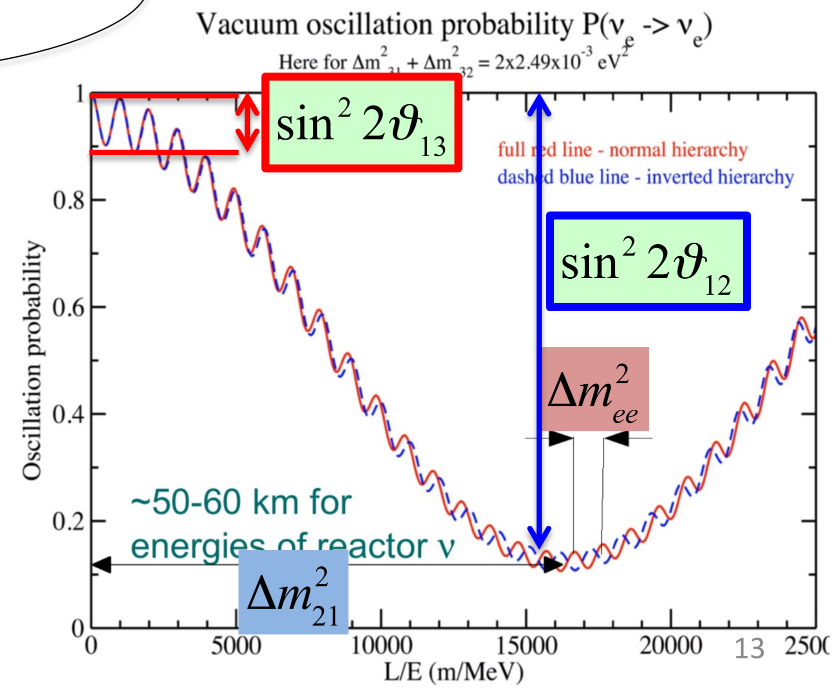
(slow) (fast)

Effective neutrino mass-squared difference:
(*beat frequency*)

$$\Delta m^2_{ee} = (cos^2\vartheta_{12}\Delta m^2_{31} + sin^2\vartheta_{12}\Delta m^2_{32})$$

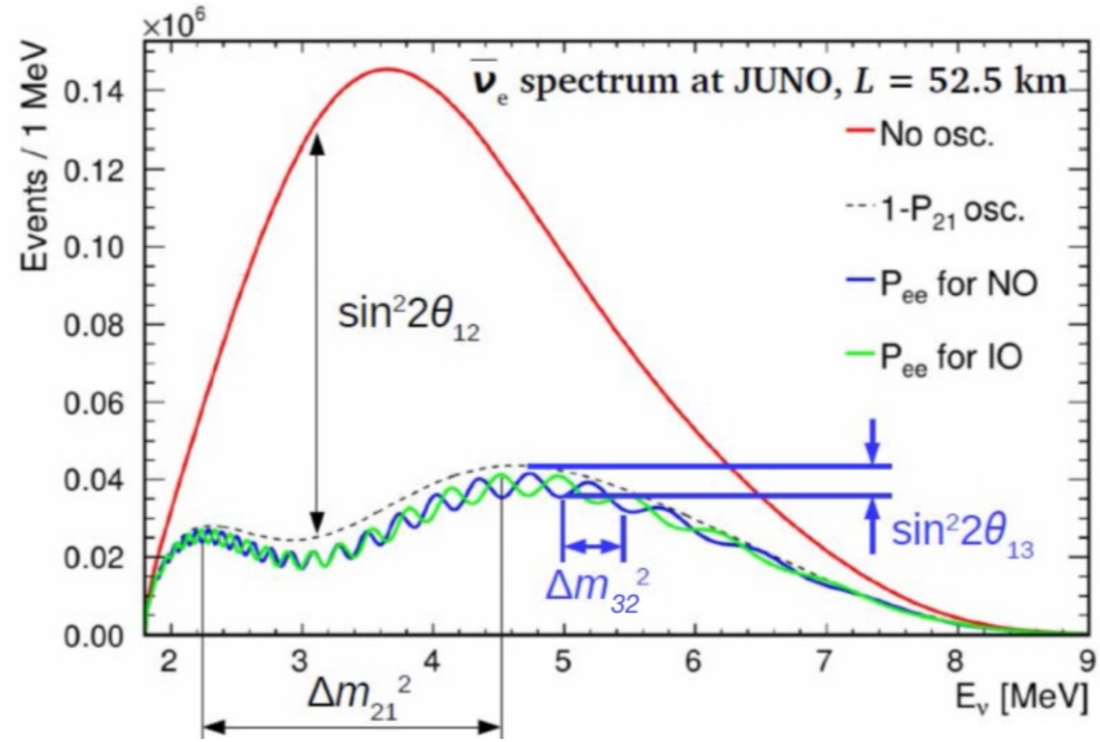
Difference between:

- Normal Ordering
- Inverted Ordering



Spettro atteso in JUNO (L=52.5 km)

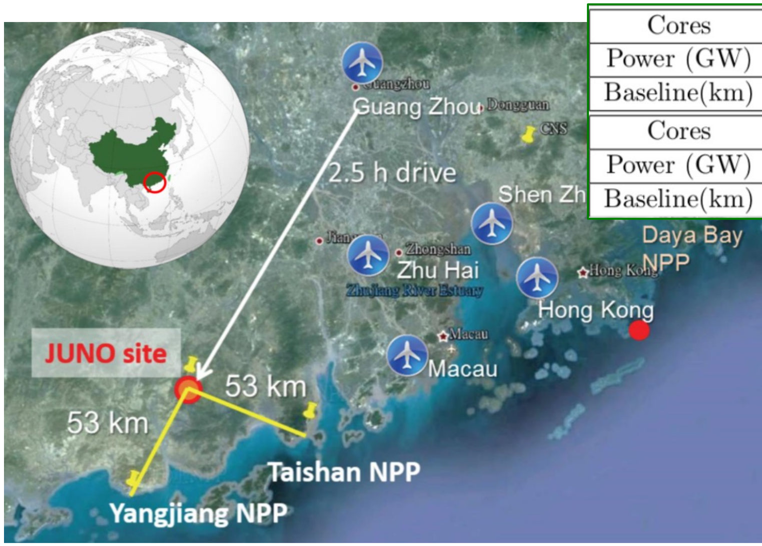
$$F(E) = \Phi(E)\sigma(E)P_{\bar{\nu}_e \to \bar{\nu}_e}\left(\frac{L}{E}\right)$$



The Jiangmen Underground Neutrino Observatory (JUNO)

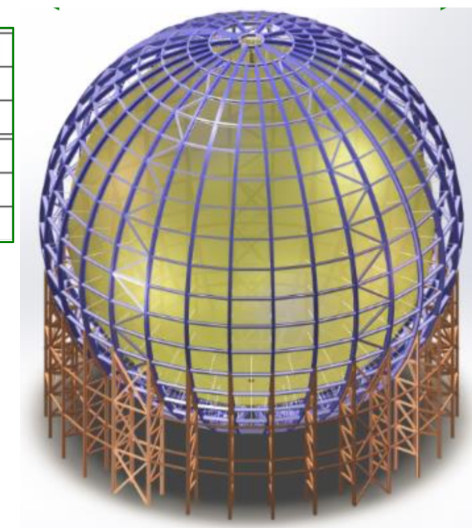
large liquid scintillator detector under construction in China.

- ~ **20 ktons** of liquid scintillator contained in an Acrylic Sphere of **35.4 m in diameter**
- **~53 km** from two nuclear power plants: Yangjian and Taishan



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline(km)	52.76	52.63	52.32	52.20	215	265

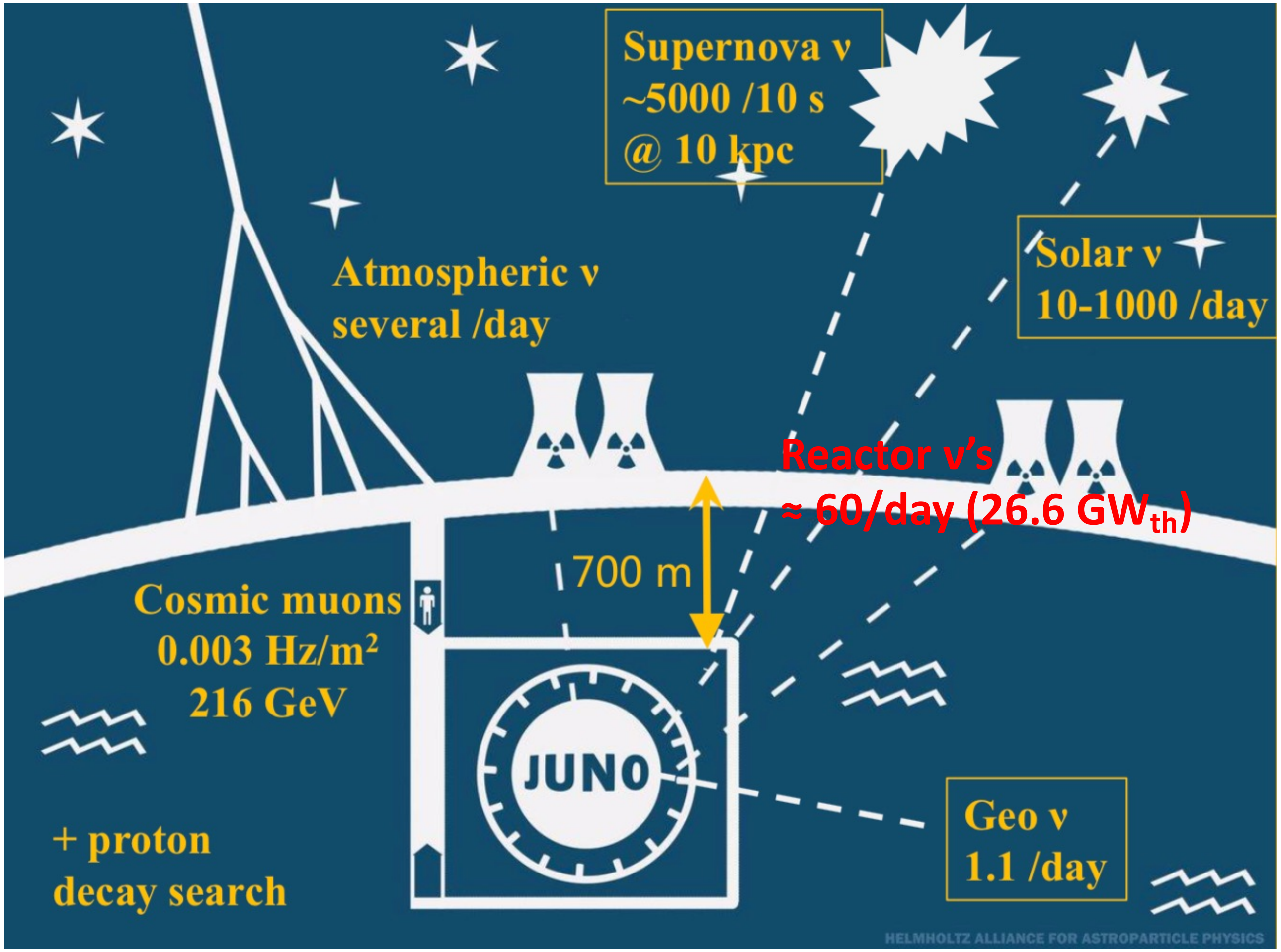
Total power: 35.8 GW
by 2020: **26.6 GW**



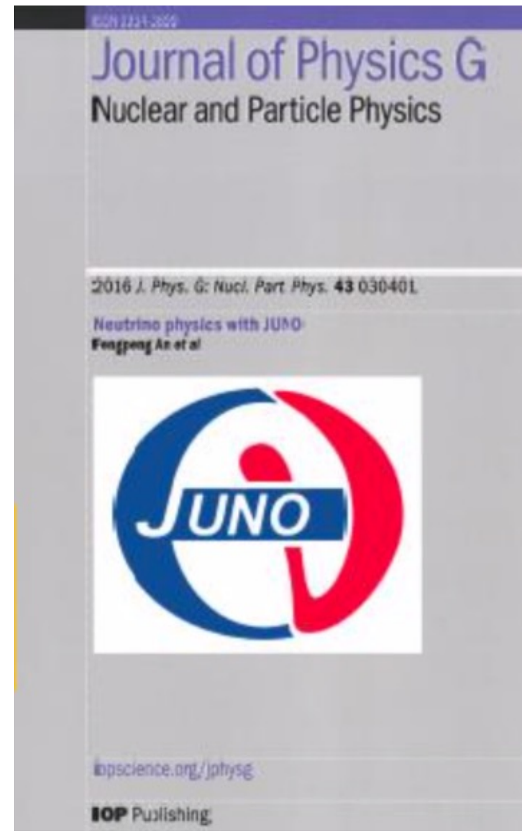
Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass (tons)	20 /detector	~300	~1,000	20,000
Nb of collected p.e. per MeV	~160	~500	~250	~1200
Energy resolution @ 1 MeV	~7.5%	~5%	~6%	~3%

A Multipurpose Neutrino Observatory

…..not only anti-ν_e from reactors



Neutrino Physics with JUNO
J. Phys. G **43** (2016) n.3 030401



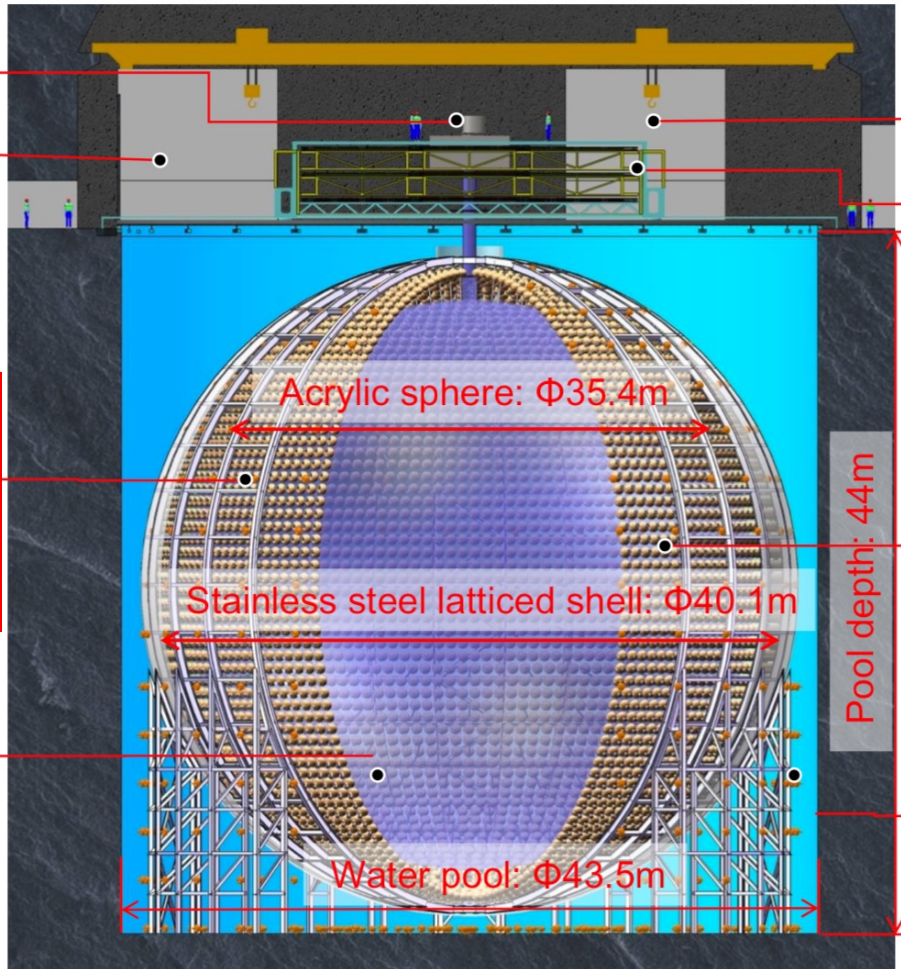
JUNO Detector Concept

Calibration room

Pure water room

LS Filling room

Top Tracker



Central Detector

Acrylic Sphere

Stainless Steel Shell

Liquid scintillator
20 kton

700 m underground

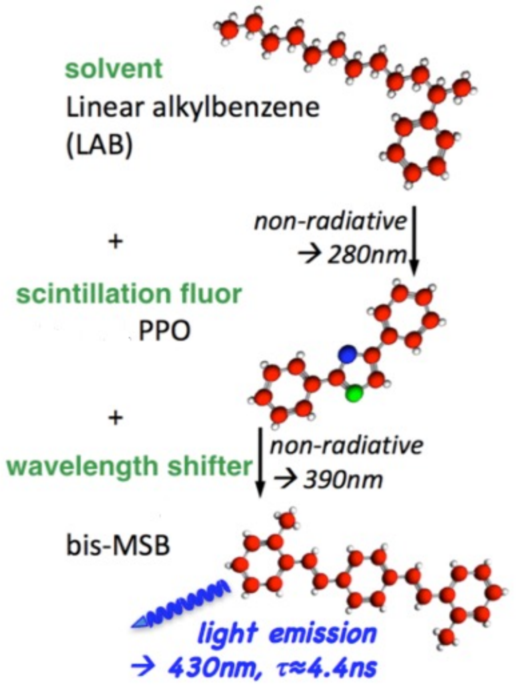
PMT
~18,000 20” PMTs +
~25,000 3” PMTs:
coverage >75%

Cylindrical Water Pull

35 kton pure water

~2000 20” veto PMTs

JUNO Liquid Scintillator



Composition:

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

(60 ton of PPO and 72 kg of bis-MSB in total)

Requirements:

- High light yield (10^4 photons/MeV)
- Attenuation length: > 20 m @ 430 nm
- Good radiopurity:
  $^{238}U/^{232}Th < 10^{-15}$ g/g, $^{40}K < 10^{-16}$ g/g.

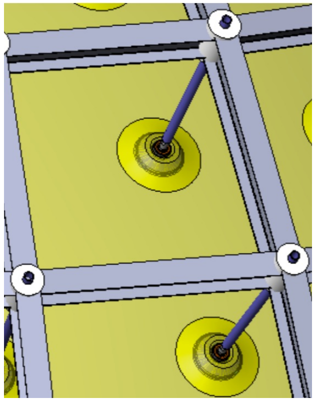
LS & purification are being tested in a Daya Bay detector

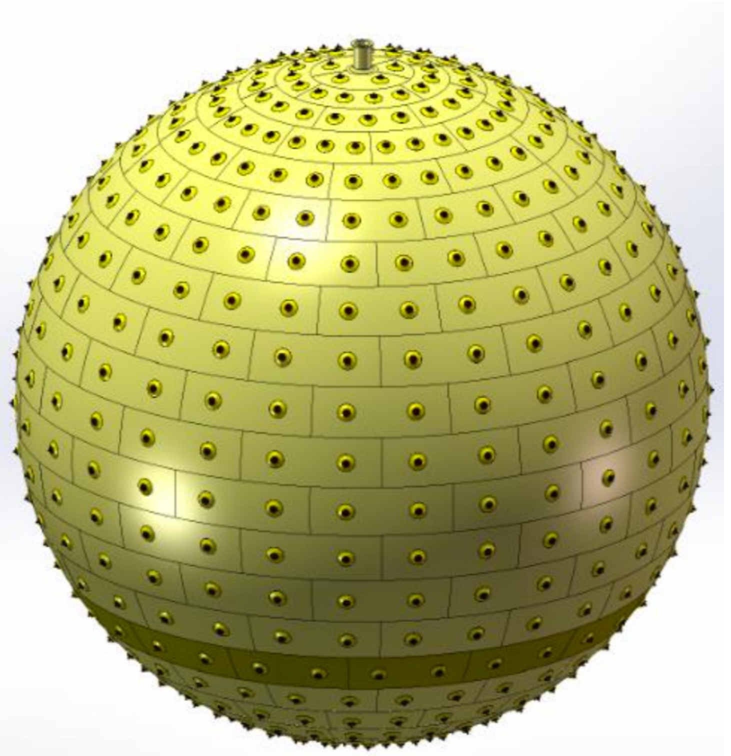
Purification:

- Distillation (remove heavy metals and increase transparency)
- Filtration with Al_2O_3 column purification (remove impurities and increase attenuation length)
- Water extraction (remove U/Th/K)
- Gas stripping (remove Ar/Kr/Rn)

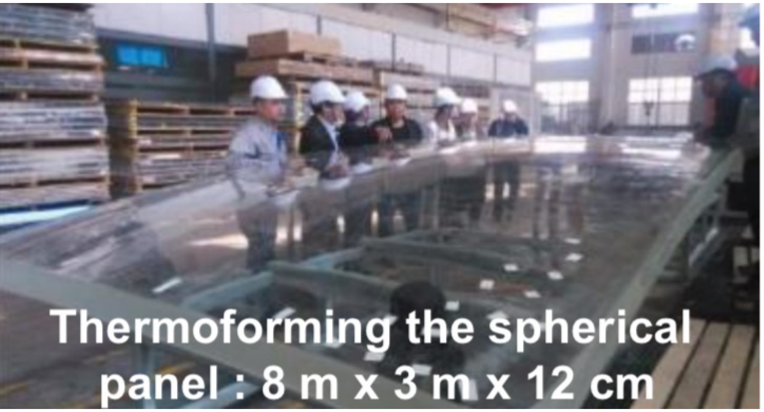
JUNO Acrylic and CD Prototype

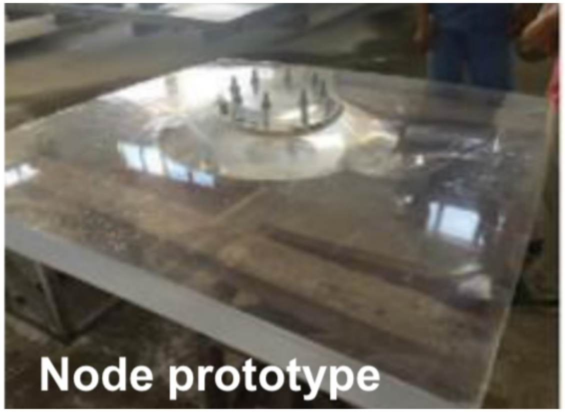
The **Central Detector** is composed by **260 acrylic panels** with 12 cm thickness (total weight of ~600 tons)

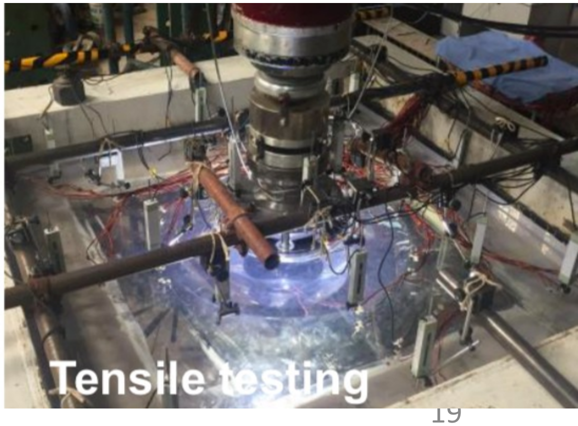




A JUNO 1:12 **prototype** has been successfully built at IHEP !





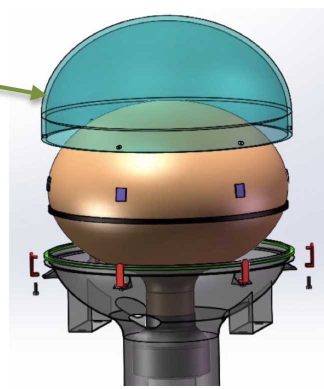


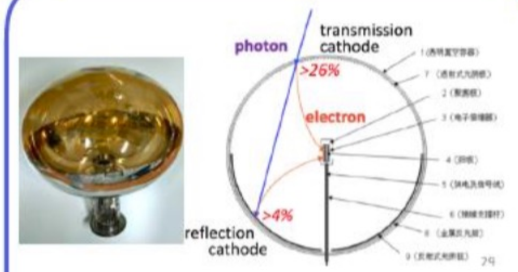
Photodetection System - Large PMT System

JUNO will use **2 types of large 20-inch PMTs** as its main photodetection system

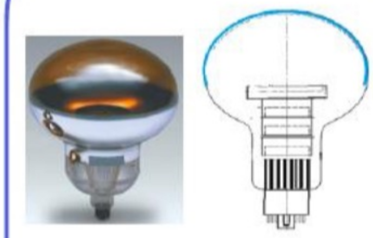
- **15000 MCP-PMTs** from NNVT *(Northern Night Vision Technology)*
- **5000 dynode-PMTs** from Hamamatsu *(R12860 HQE)*

All PMTs are equipped with an implosion protection cover.





Microchannel plate (MCP)-PMTs


Dynode-PMTs

Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection efficiency (QE*CE)	%	27 (increased to 30)	27
P/V of SPE		3.5, >2.8	3, >2.5
TTS on top point	ns	~12, <15	2.7, <3.5
Rise time/Fall time	ns	R~2, F~12	R~5, F~9
After pulse rate	%	1, <2	10, <15
Glas radioactivity	ppb	238U : 50 232Th : 50 40K : 20	238U : 400 232Th : 400 40K : 40

Photodetection System - Small PMT System

JUNO will also have **to control the non-stochastic term** of the energy resolution at an unprecedented level below (<1%)

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$$

JUNO will use also **3-inch PMTs** as a complementary photodetection system in order to

a. improve the control of systematics

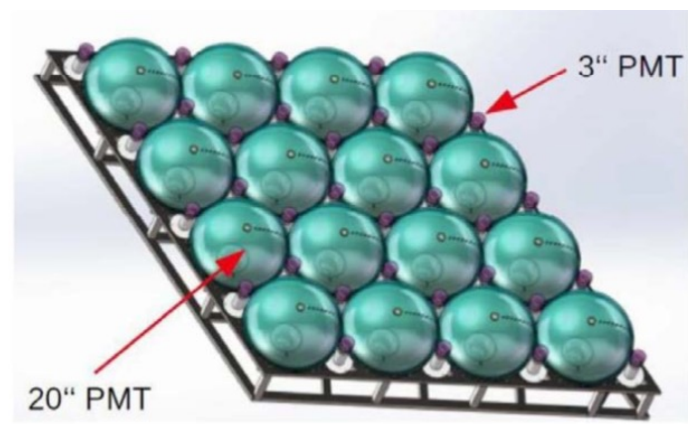
b. increase the dynamic range

   Helps with large signals
   (e.g. muons, supernova)

JUNO custom design: XP72B22
QE 24%, Peak / Valley 3.0, TTS 2-5 ns

Operate in photon-counting mode.

25600 PMTs from HZC Photonics *(Hainan, PR China)* 2.5% coverage



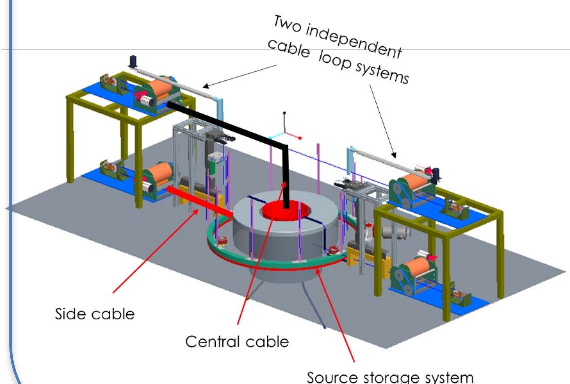
Arrangement of large and small PMTs

Calibration Systems

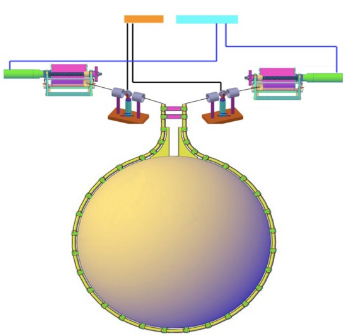
In order to obtain:
- Energy Resolution 3% @ 1MeV
- Energy Scale Uncertainty < 1%

JUNO has developed 4 complementary calibration systems

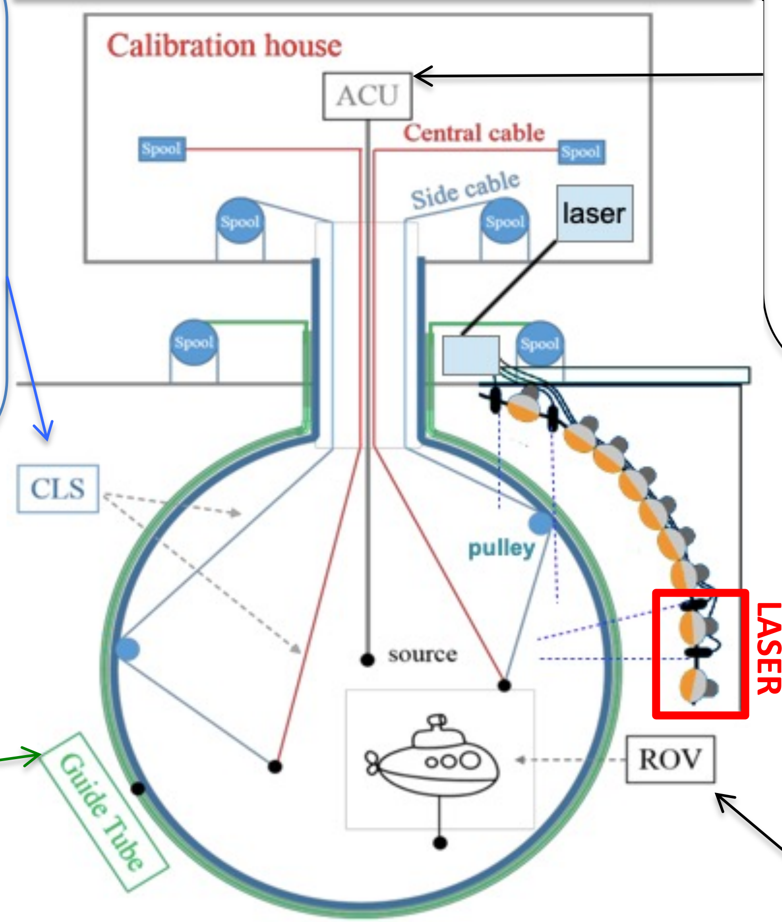
Cable Loop System **CLS**



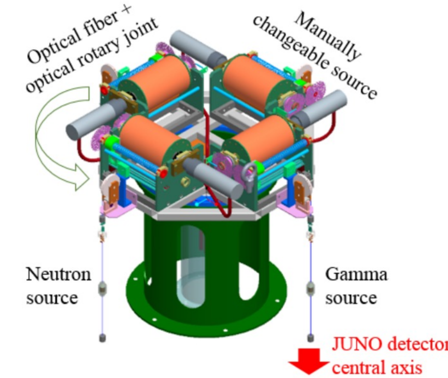
Guide Tube System

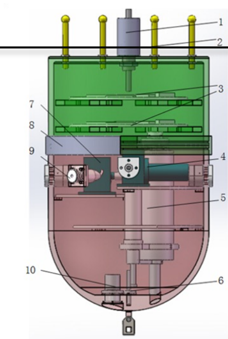


Overview of JUNO's Calibration Systems
(including LASER calibration system)



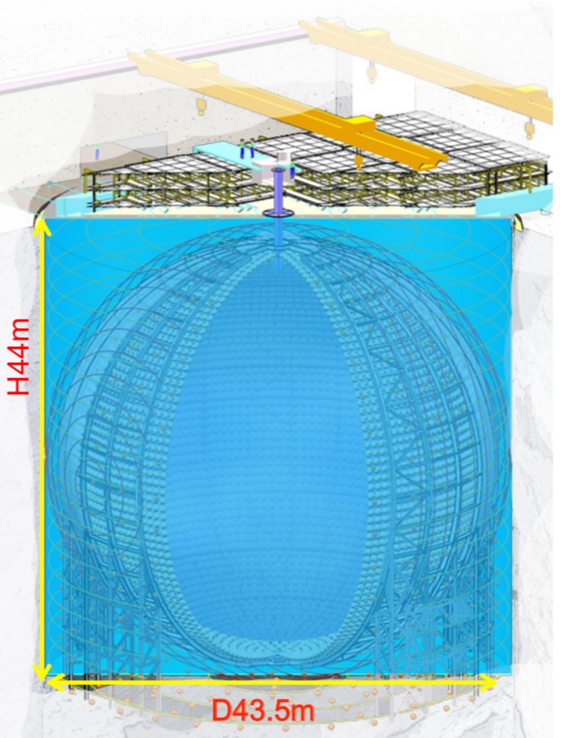
Automatic Calibration Unit
ACU





Remotely Operated Vehicle
ROV

Muon Veto System

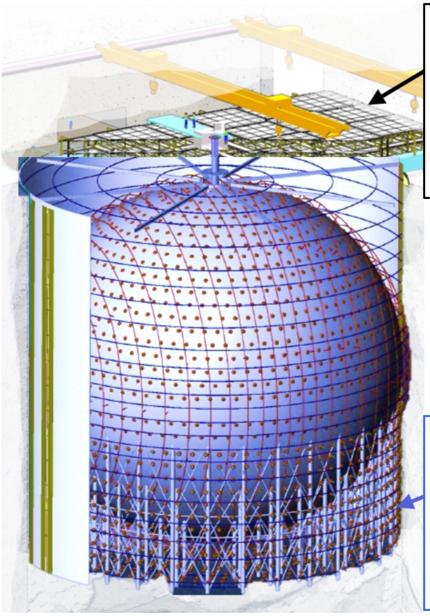


The acrylic sphere will be immersed in a cylindrical water pool containing **35 kton ultrapure water** instrumented with **2400 20-inch PMTs**

Double- purpose:

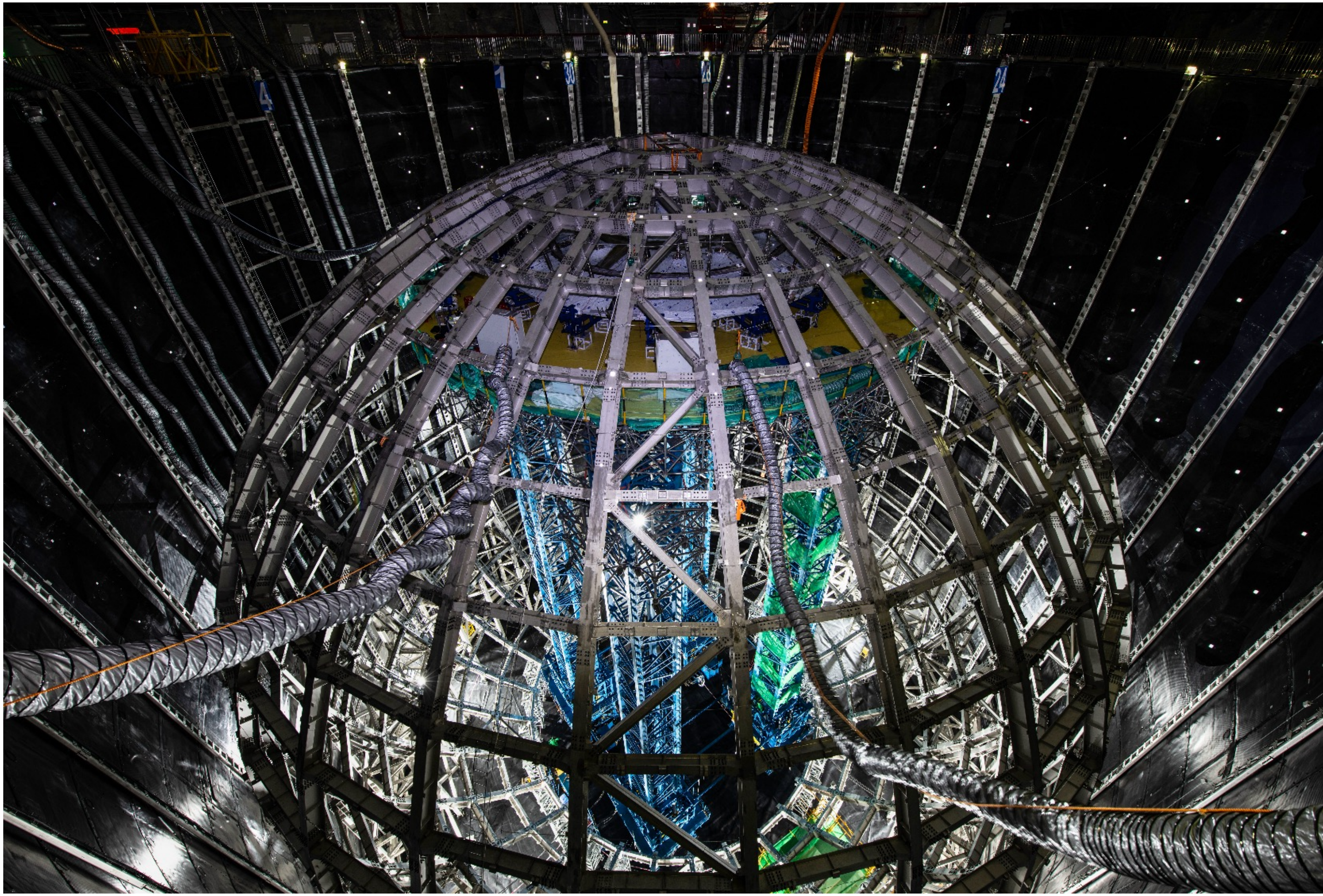
1. Shield central detector against radioactivity from rock and neutrons from cosmic rays
2. Veto cosmic-ray muons *(most backgrounds are of cosmic ray origin)*

Detection efficiency > 95%



The muon veto system will also have a **top tracker** composed by 3-layers of plastic scintillators.

There will also be a **compensation magnetic field** (EMF) shielding system



Real photo of the stainless steel structure inside the water pool. Picture taken on November 2022.

TAO – near JUNO detector

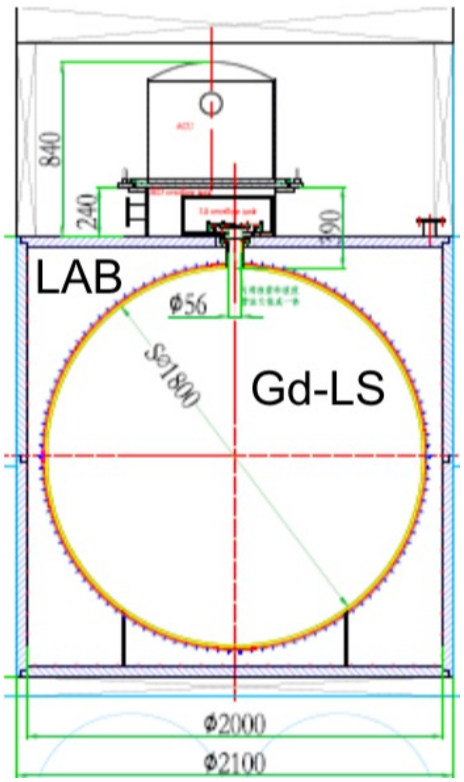
Reactor shape uncertainties

- "Standard" reactor shape uncertainties have minor impact on the MO sensitivity
- But reactor spectrum might have not yet observed micro-structures
- These micro-structures degrade the MO sensitivity by mimicking periodic oscillation pattern

→ reference detector needed for JUNO

Taishan Antineutrino Observatory (TAO) has several physics motivation:

- To measure precisely the 4-6 MeV bump and the fine structure of reactor antineutrino spectrum with unprecedented energy resolution.
- Provide a benchmark for investigation of nuclear database
- Measure antineutrino spectra from ^{235}U and ^{239}Pu
- Search for sterile neutrino with good vertex reconstruction capability

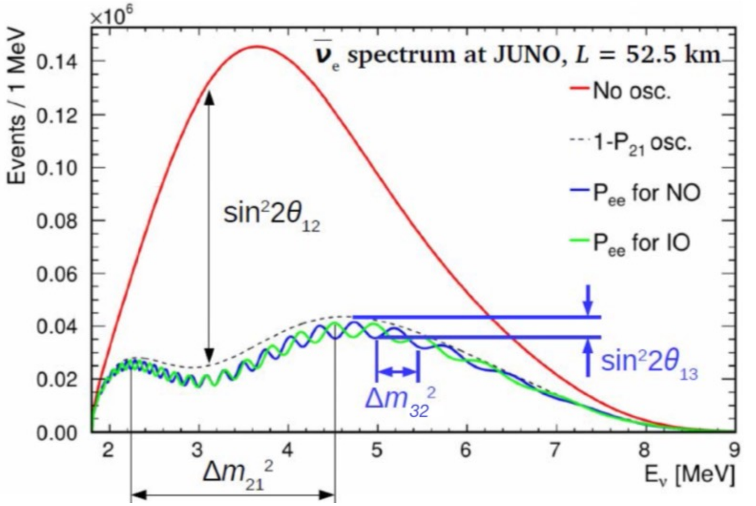


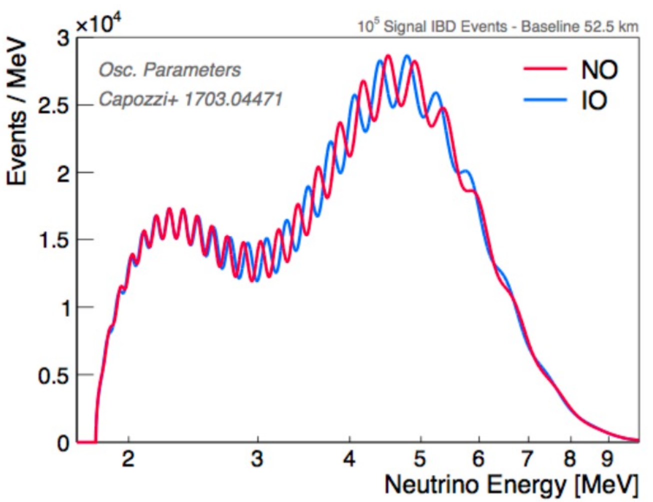
JUNO-TAO detector design

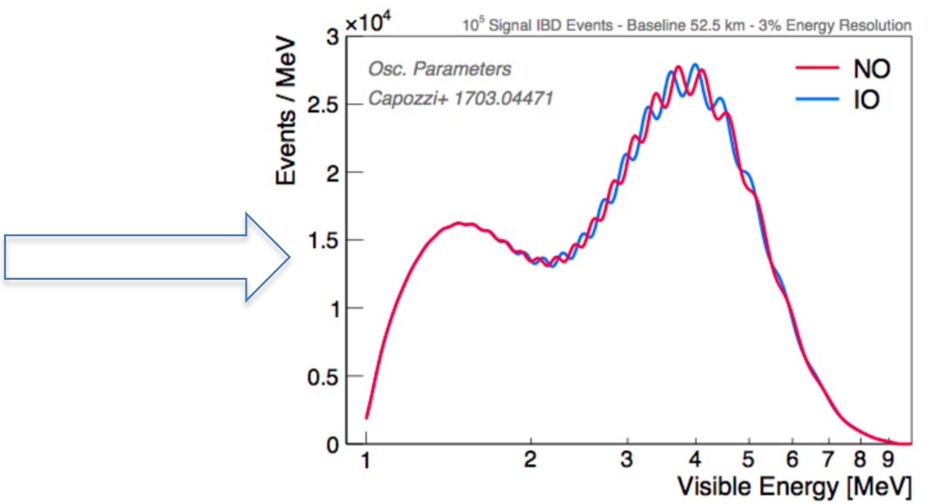
- 1 ton fiducial volume Gd-LS detector at 30 m from core
- Full coverage 10 m^2 SiPM with 50% PDE operated at -50°C
- Energy resolution of **1.7%/√E(MeV)**

To distinguish between **NO**/**IO** **at 3σ**, one needs:

- ✓ at least 100,000 events (nominal luminosity)
- ✓ an energy resolution of 3%/√E(MeV)
- ✓ baseline ~53 km with core dispersion <0.5 km
- ✓ an energy scale uncertainty < 1%



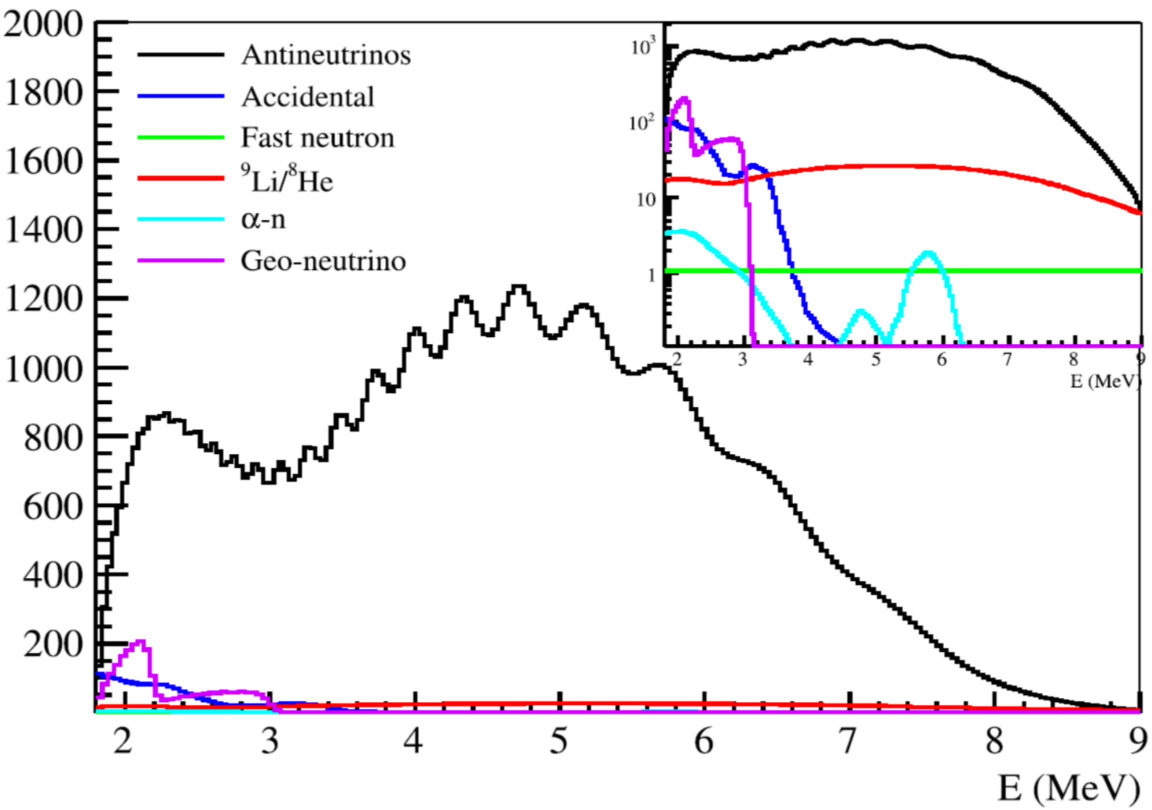




Senza tener conto della Risoluzione Energetica

Risol. En, = 3%/√E(MeV)

Signal vs. Backgrounds



Backgrounds

- **Uncorrelated**

- Accidental: (radioactivity, radioactivity), (radioactivity, cosmogenic isotope), (radioactivity, spallation neutrons)

- **Correlated**

- $^{8}He/^{9}Li$: muon-induced isotopes, $\beta - n$ decays
- Fast neutron: cosmic muons passing surrounded rock, non-tagged
- $^{13}C(\alpha, n)^{16}O$: U/Th-chain radioactivities
- Geo-νs: U/Th antineutrinos from the earth

Signal vs. Backgrounds

Antineutrino selection criteria

- fiducial volume cut r < 17 m;
- prompt energy cut 0.7 MeV $< E_p <$ 12 MeV;
- delayed energy cut 1.9 MeV $< E_d <$ 2.5 MeV;
- time cut between the prompt and delayed signal $\Delta T_{p\text{-}d} <$ 1.0 ms;
- distance cut between the prompt and delayed signal $R_{p\text{-}d} <$ 1.5 m;
- Muon veto.

Rate/day

Selection	IBD efficiency	IBD	Geo-νs	Accidental	$^{9}Li/^{8}He$	Fast n	(α, n)
—	—	83	1.5	$\sim 5.7 \times 10^4$	84	—	—
Fiducial volume	91.8%	76	1.4		77	0.1	0.05
Energy cut	97.8%			410			
Time cut	99.1%	73	1.3		71		
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60			3.8		

BKG/Signal = 3.8/60 = 6%

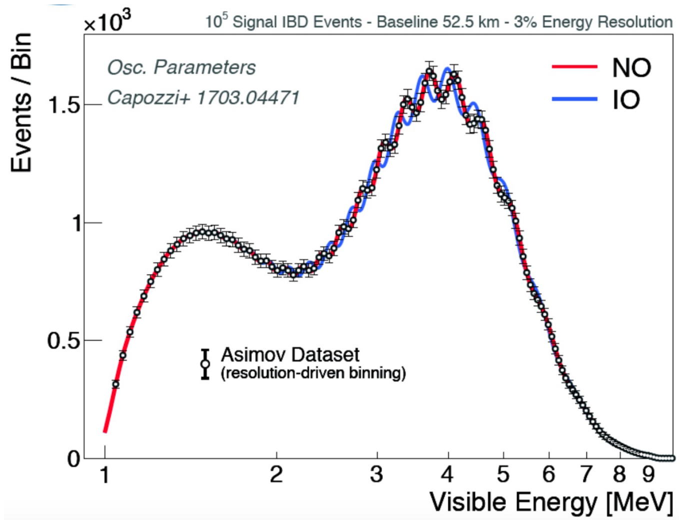
Sensitivity to NMO determination

Sensitivity estimation

In order to determine the NMO we fit data against both models

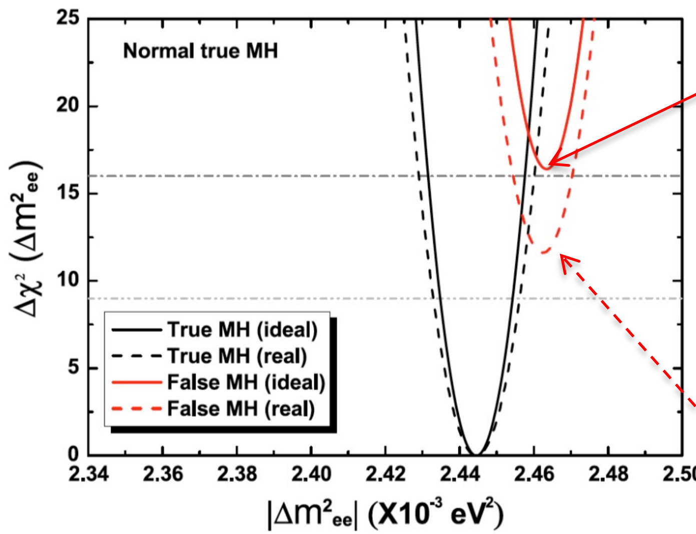
Assume NO as true Mass Ordering, and fit the spectrum with false and true Mass Ordering cases respectively, to get:

$$\Delta\chi^2_{MO} = \left|\chi^2_{min}(N) - \chi^2_{min}(I)\right|$$



Systematics induced by:

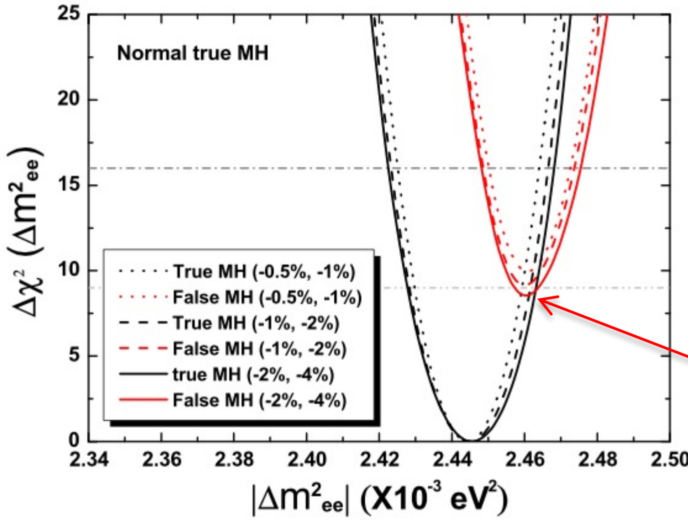
- Distribution of reactor cores
- Energy resolution
- Energy linearity
- ...



	Size	$\Delta\chi^2_{MO}$
Ideal	52.5 km	16
Core distr.	Real	-3
DYB & HZ	Real	-1.7
Reactor (shape)	1%	-1
B/S (rate)	6.3%	-0.6
B/S (shape)	0.4%	-0.1

degradation from real reactor core distribution

Sensitivity to NMO determination



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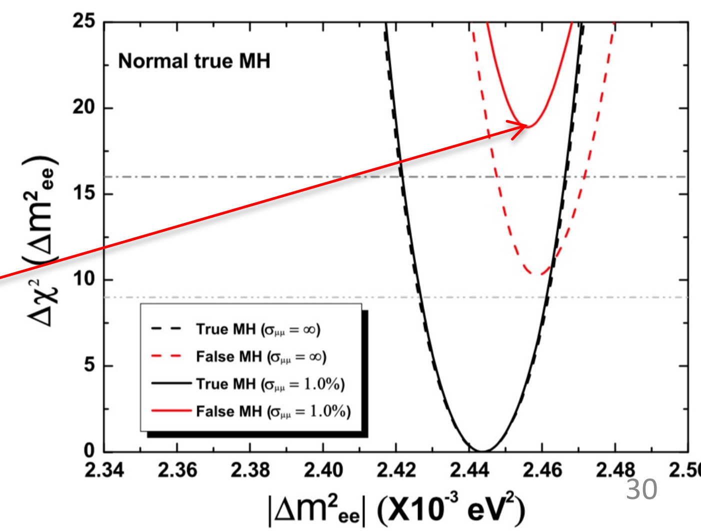
Total degradation: ~9.6

External constraints

Sensitivity can be improved from Δm^2_{atm} from long baseline experiments

if we combine T2K+NOvA (assuming a precision ~1%) with JUNO the sensitivity improves to 4σ.

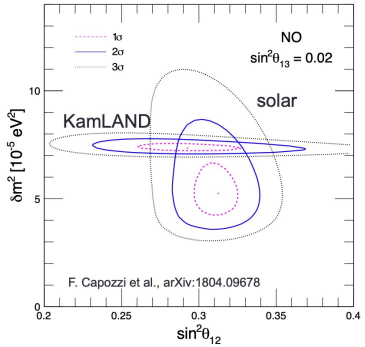


Precision measurement of neutrino oscillation parameters

JUNO will measure the 3 Oscillation parameters at a subpercent precision level

In particular the **solar oscillation parameters** [Δm^2_{21} and $\sin^2(2\theta_{12})$] in order to solve the **tension** between solar ν_e and KamLAND results

Tension between solar ν_e and KamLAND results:



Longstanding tension at 2σ level on best-fit for δm^2 between solar and KamLAND oscillation analysis :

1. CPT invariance?
2. Physics beyond the SM?
3. Subtle unknown effect in present analysis?

Oscillation parameters	Current precision at 1σ level *	JUNO only**
$\lvert\Delta m_{31}^2\rvert$	~1.6%	~0.5%
Δm_{21}^2	~2.3%	~0.6%
$\sin^2(2\theta_{12})$	~5.8%	~0.7%
Mass hierarchy	N/A	3-4 σ
$\sin^2(\theta_{13})$	~3.9%	~15%

* *M. Tanabashi et al. (PDG), Phys. Rev. D 98, 030001 (2018).*

** *JUNO collaboration, J. Phys. G 43 (2016) no.3, 030401*