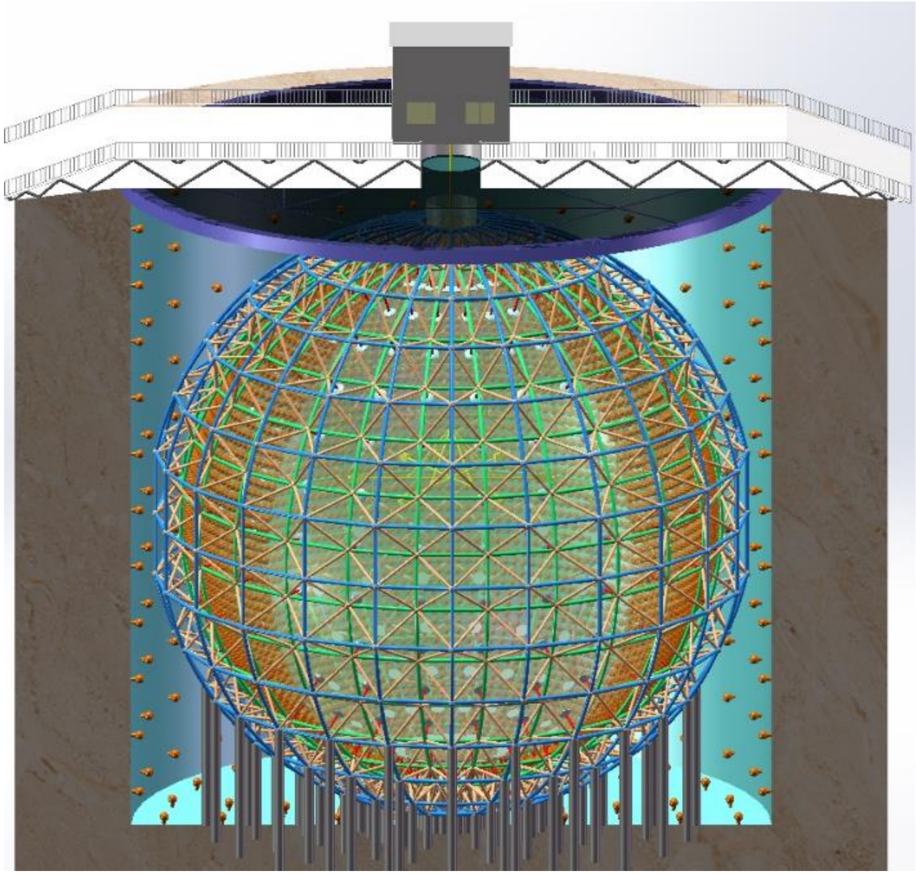
Seminari di Gruppo II

spazio dedicato alle attività finanziate @ Bicocca dalla
Commisione Scientifica Nazionale II dell'INFN

JUNO:
il più grande osservatorio sotterraneo di neutrini al mondo

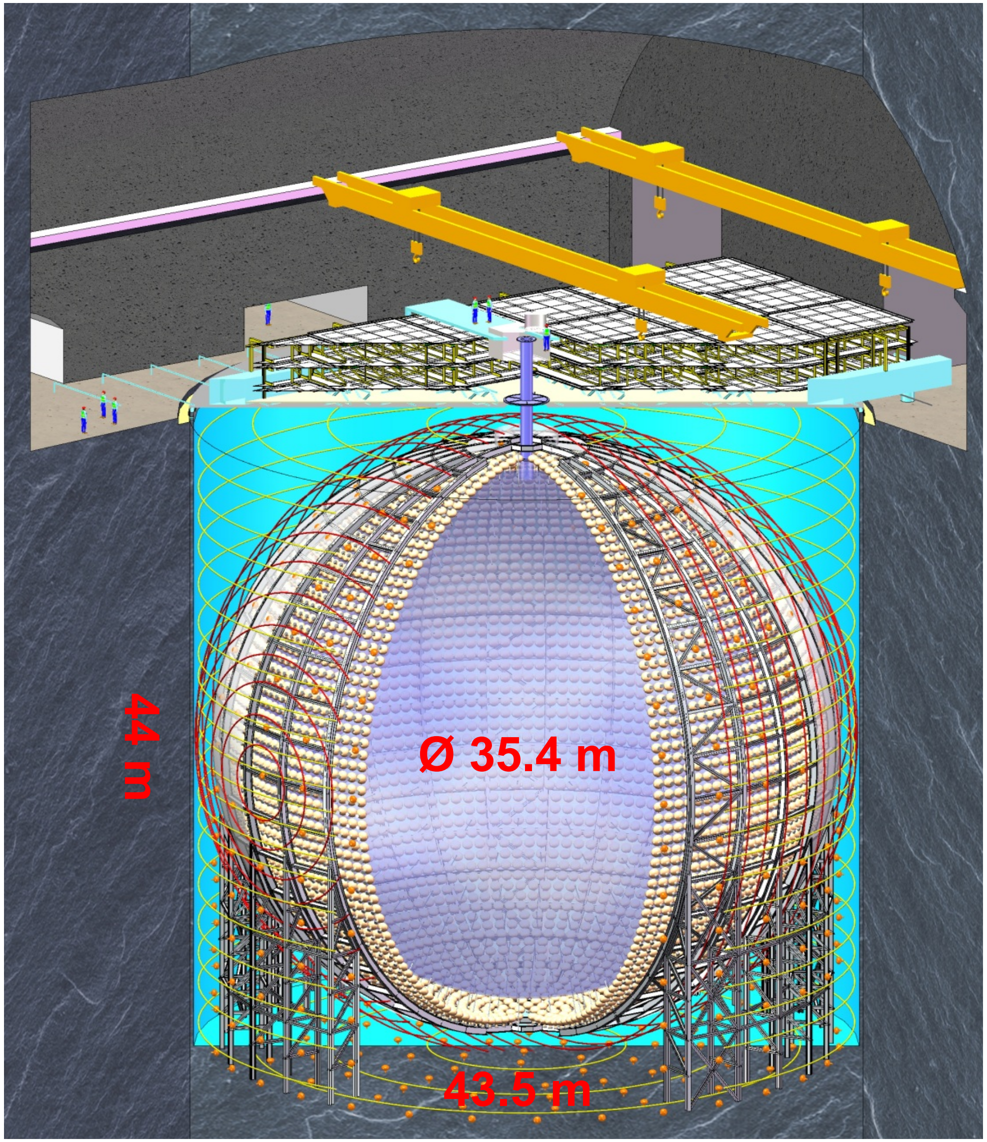


Monica Sisti
Davide Chiesa
Massimiliano Nastasi

INFN & Università Milano-Bicocca

L'esperimento JUNO

Obiettivo scientifico primario:
determinare l'ordinamento delle masse dei neutrini (ν)

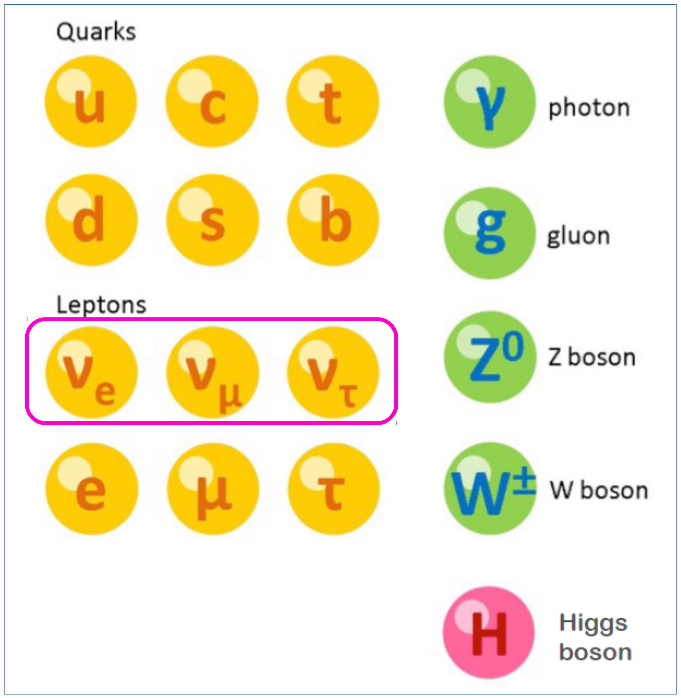


***J**iangmen **U**nderground **N**eutrino **O**bservatory*

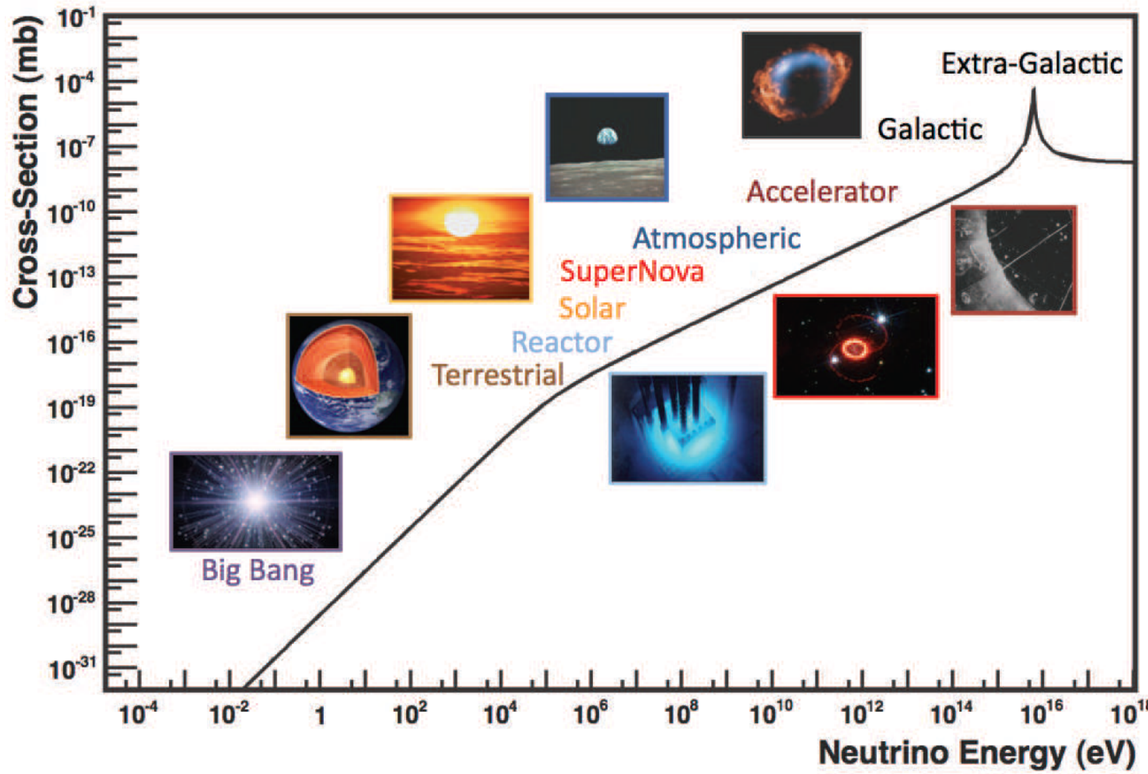
Massive: ~20 kton Liquid Scintillator (LS)
Underground: ~700 m overburden
High resolution: 3% / √E (MeV)
Energy scale precision: < 1%

I neutrini

Le particelle elementari



Leggerissimi, velocissimi, quasi inafferrabili: i neutrini sono ovunque nell'universo!



Studiare i ν è difficile ma importante: sono messaggeri dell'Universo!

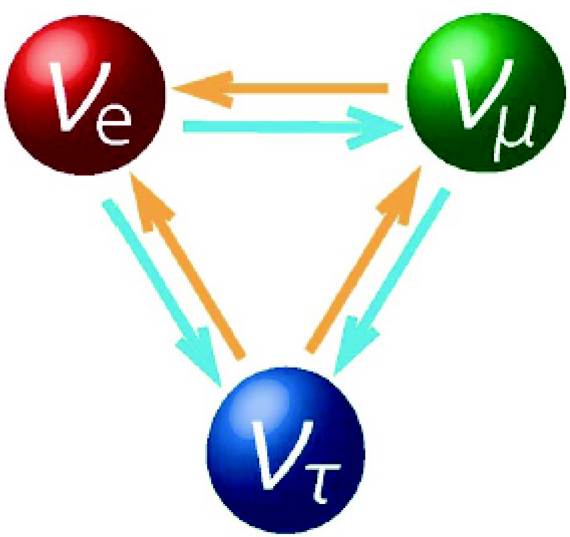
Solo rarissimamente qualche neutrino si “ferma” nella materia e produce un segnale osservabile con strumenti molto sofisticati.

I neutrini oscillano

Ad oggi conosciamo tre tipi di neutrino:
elettronico, muonico, tauonico,
detti anche “sapori”

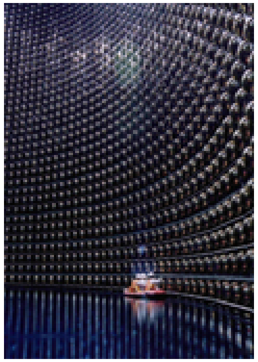
Secondo il Modello Standard, i neutrini sono particelle prive di massa
➡ oggi sappiamo che non è così

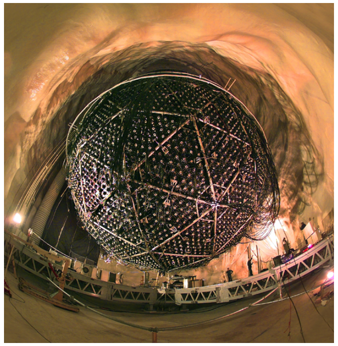
I neutrini si trasformano ciclicamente l'uno nell'altro:
questo fenomeno è possibile solo se **i neutrini hanno massa non nulla** (seppur molto piccola)



“Oscillazioni” di neutrino

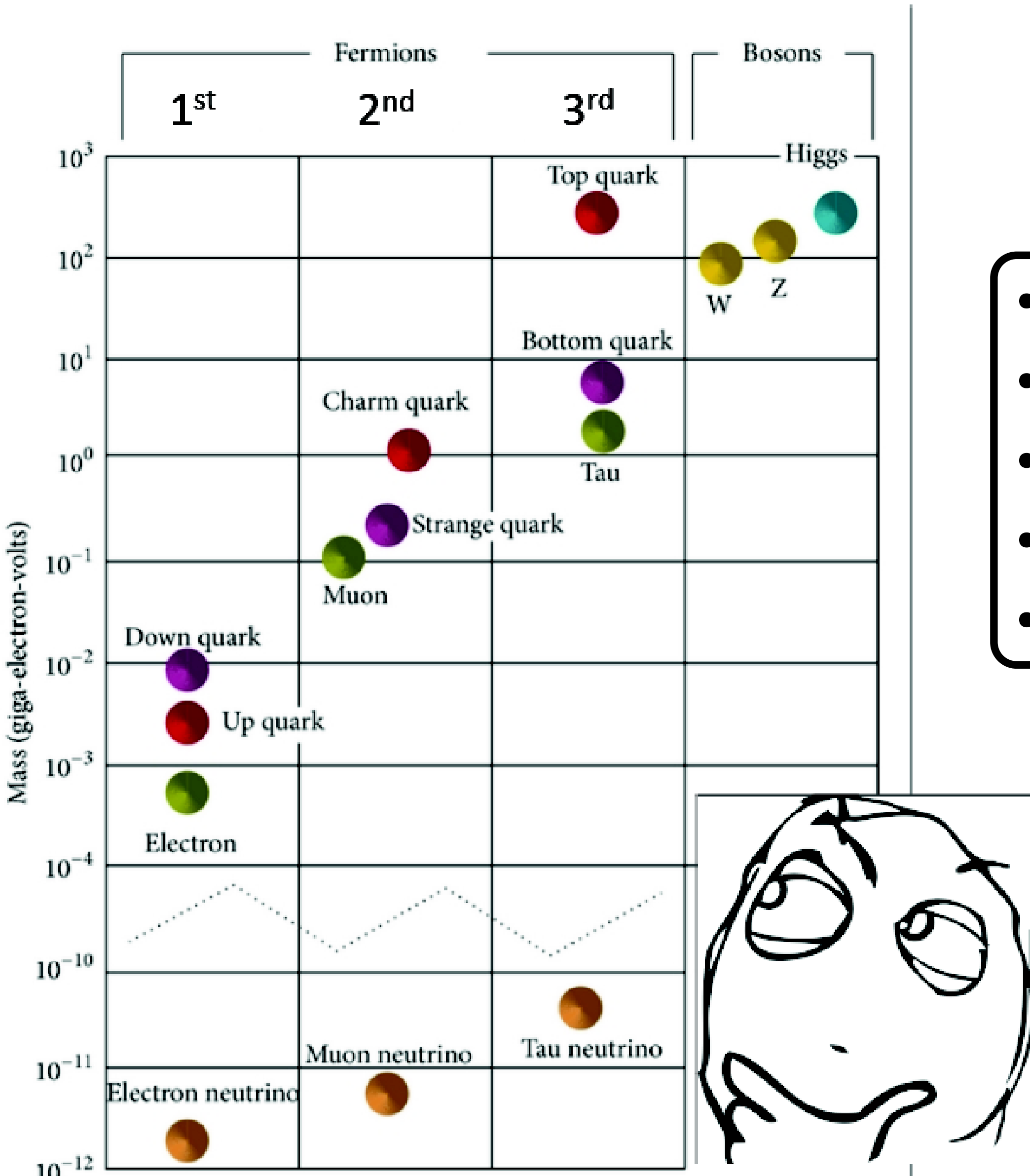
scoperte sperimentalmente negli anni 1998-2002 (premio Nobel 2015)


SuperKamiokande

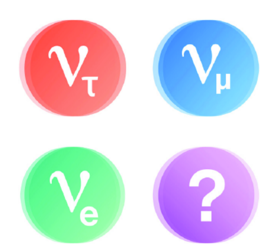

SNO

I misteri dei neutrini

Le proprietà dei neutrini sono la chiave per avvicinarci alla piena comprensione del nostro Universo



- Quanto pesano i neutrini?
- Qual è il ν più leggero?
- Quanti sono i sapori di neutrino?
- Neutrini ed anti-neutrini coincidono?
- I ν violano le simmetrie della fisica?



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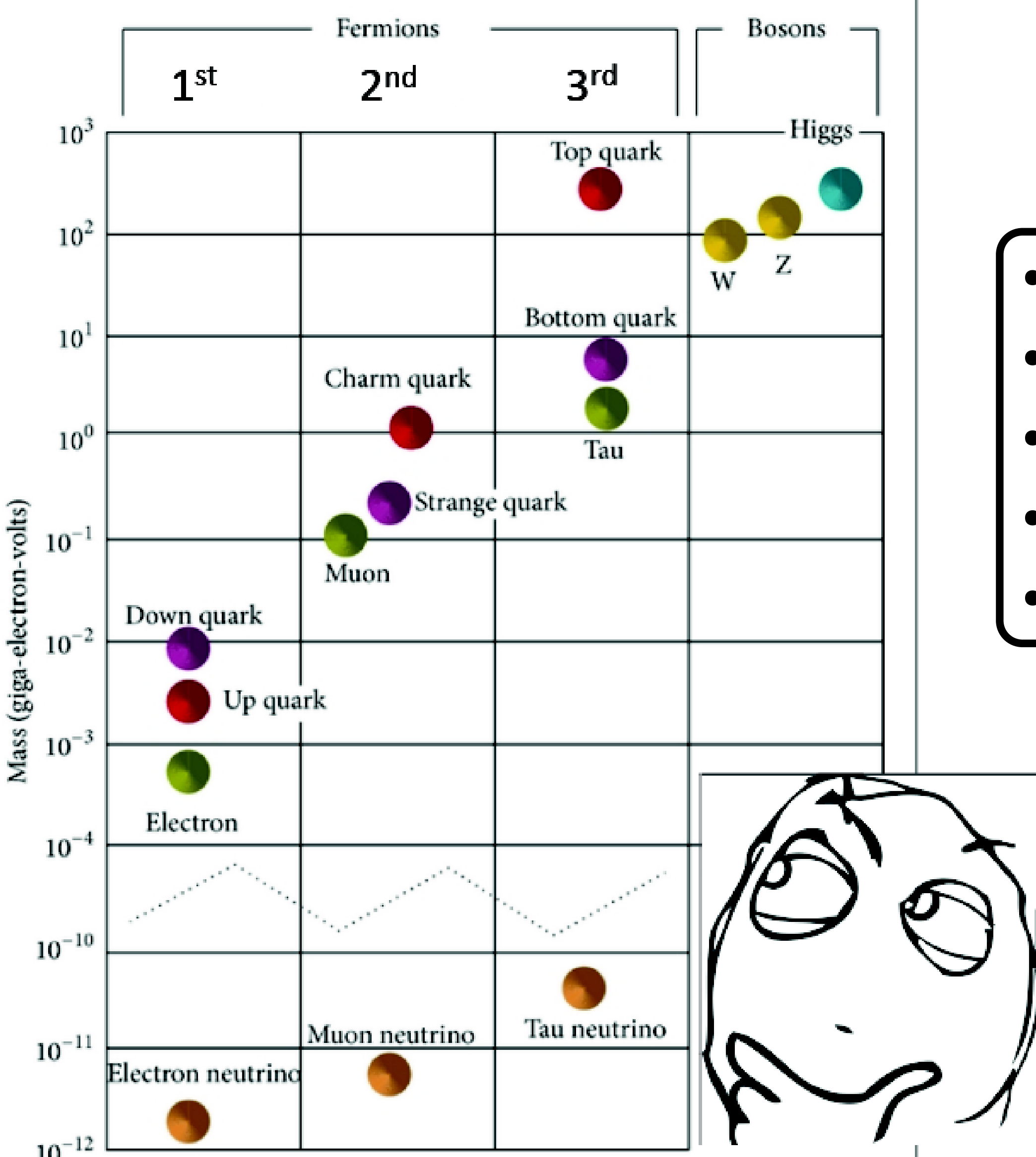

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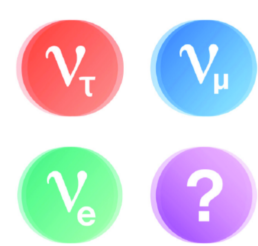
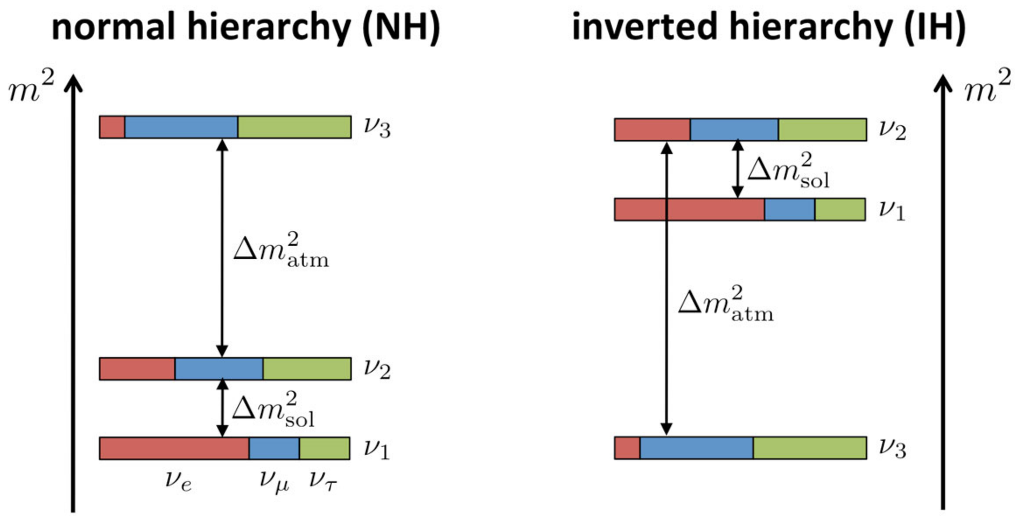


La questione dell'ordinamento delle masse dei ν



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

$\Delta m_{21}^2 \approx 7.5 \times 10^{-5}\ eV^2$

$|\Delta m_{32}^2| \approx 2.5 \times 10^{-3}\ eV^2$

NH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

IH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

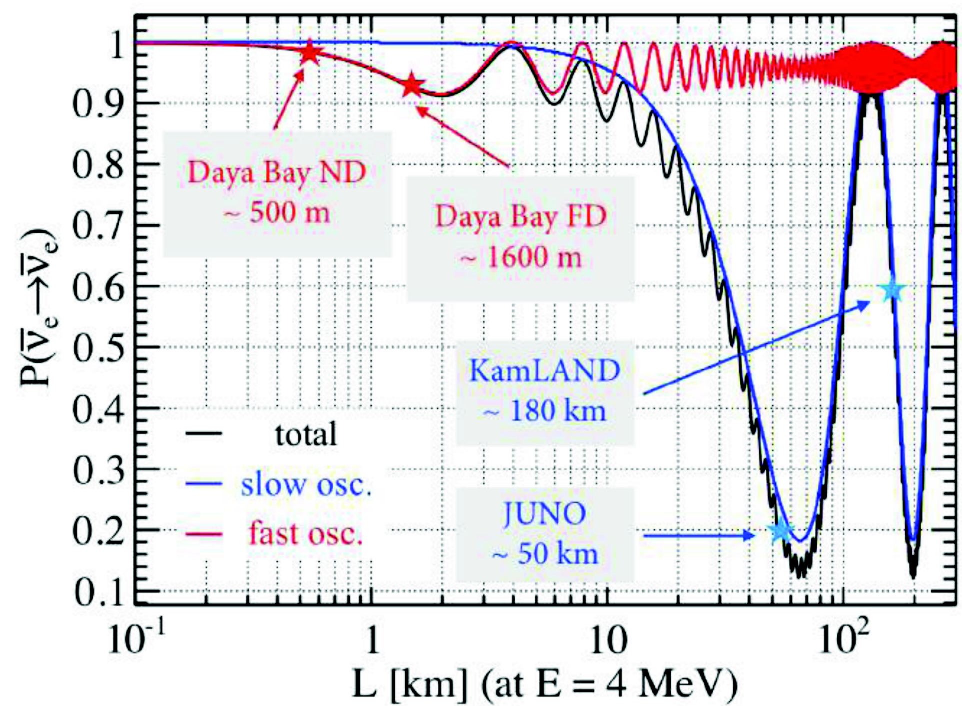
La misura dell'ordinamento delle masse dei ν (νMO) può essere effettuata sfruttando le oscillazioni degli antineutrini emessi dai reattori nucleari

Probabilità di sopravvivenza dell'anti-ν elettronico:

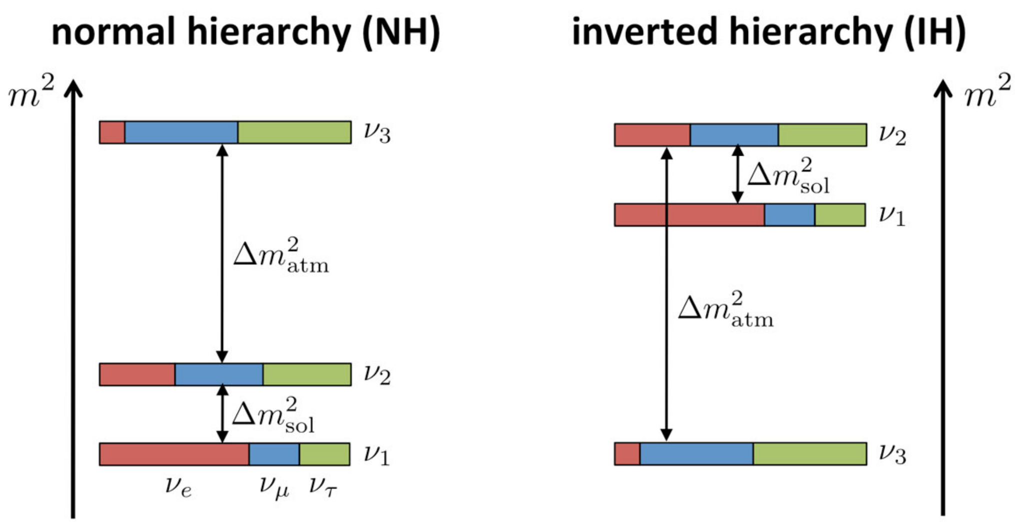
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\vartheta_{13}\sin^2 2\vartheta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E} + $$
$$- \sin^2 2\vartheta_{13}\left(\cos^2\vartheta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\vartheta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)$$

Solar (slow)

Atmospheric (fast)



La questione dell'ordinamento delle masse dei ν



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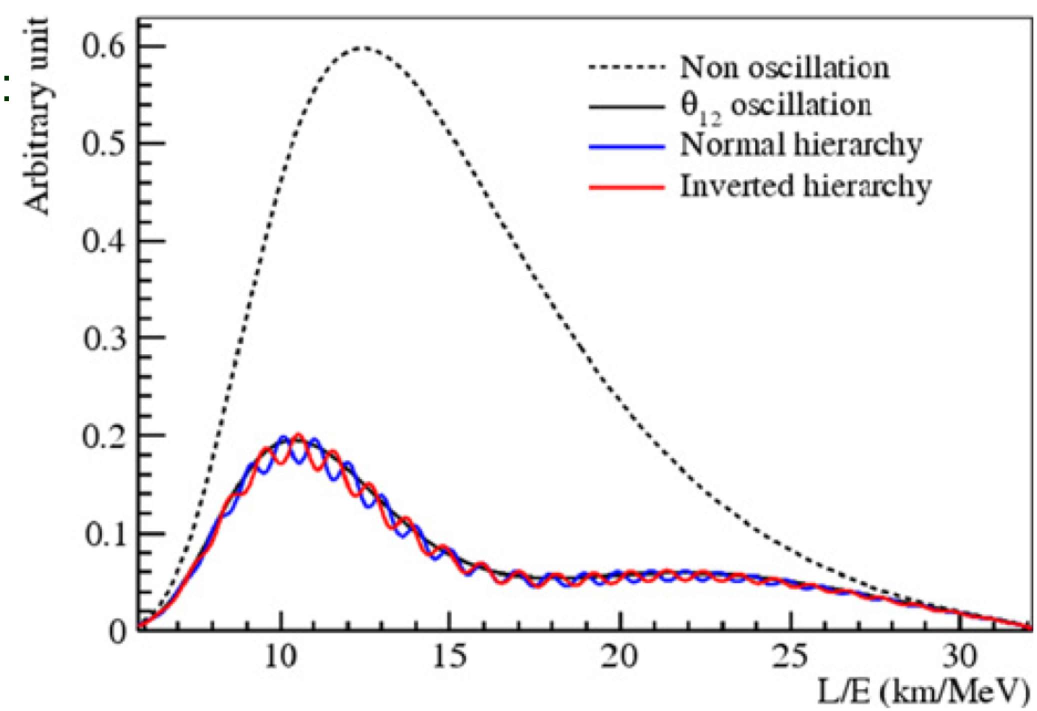
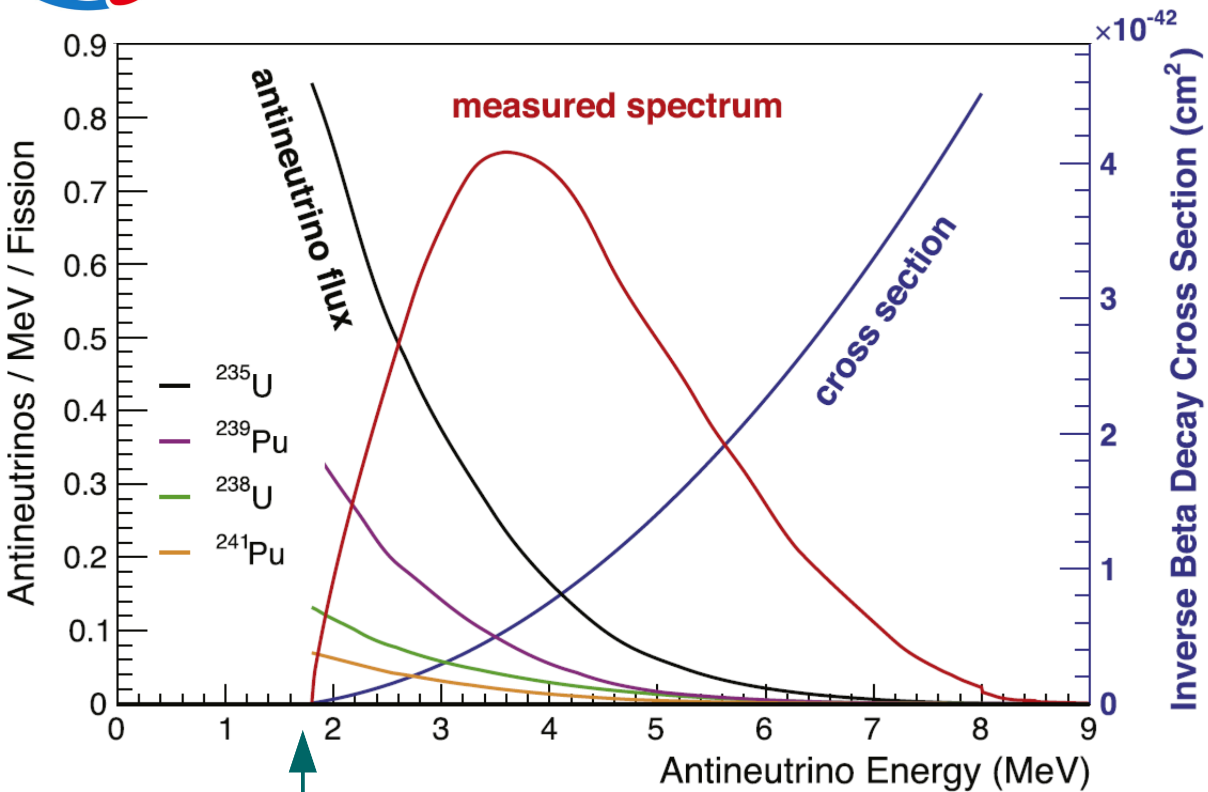
$\Delta m_{21}^2 / \Delta m_{32}^2$ ~3%
è la risoluzione energetica richiesta!



Reactor antineutrino detection

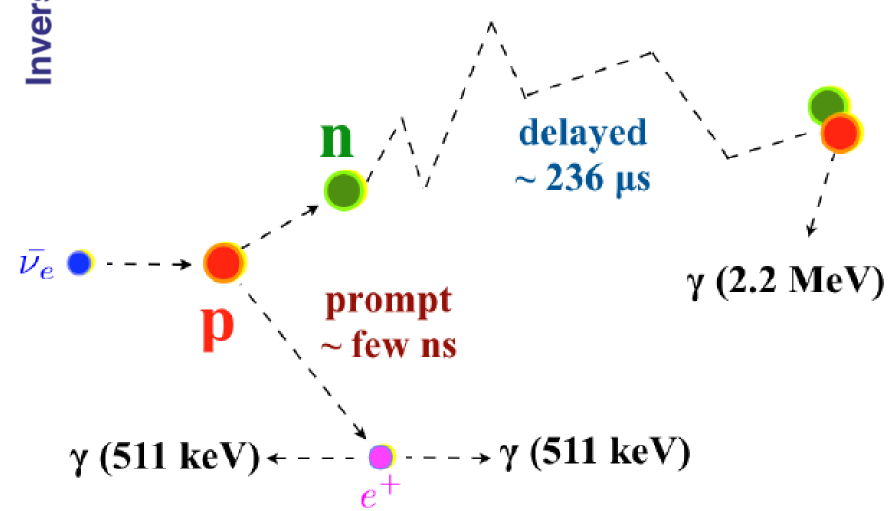


Energy threshold: 1.8 MeV

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

Antineutrinos from reactors

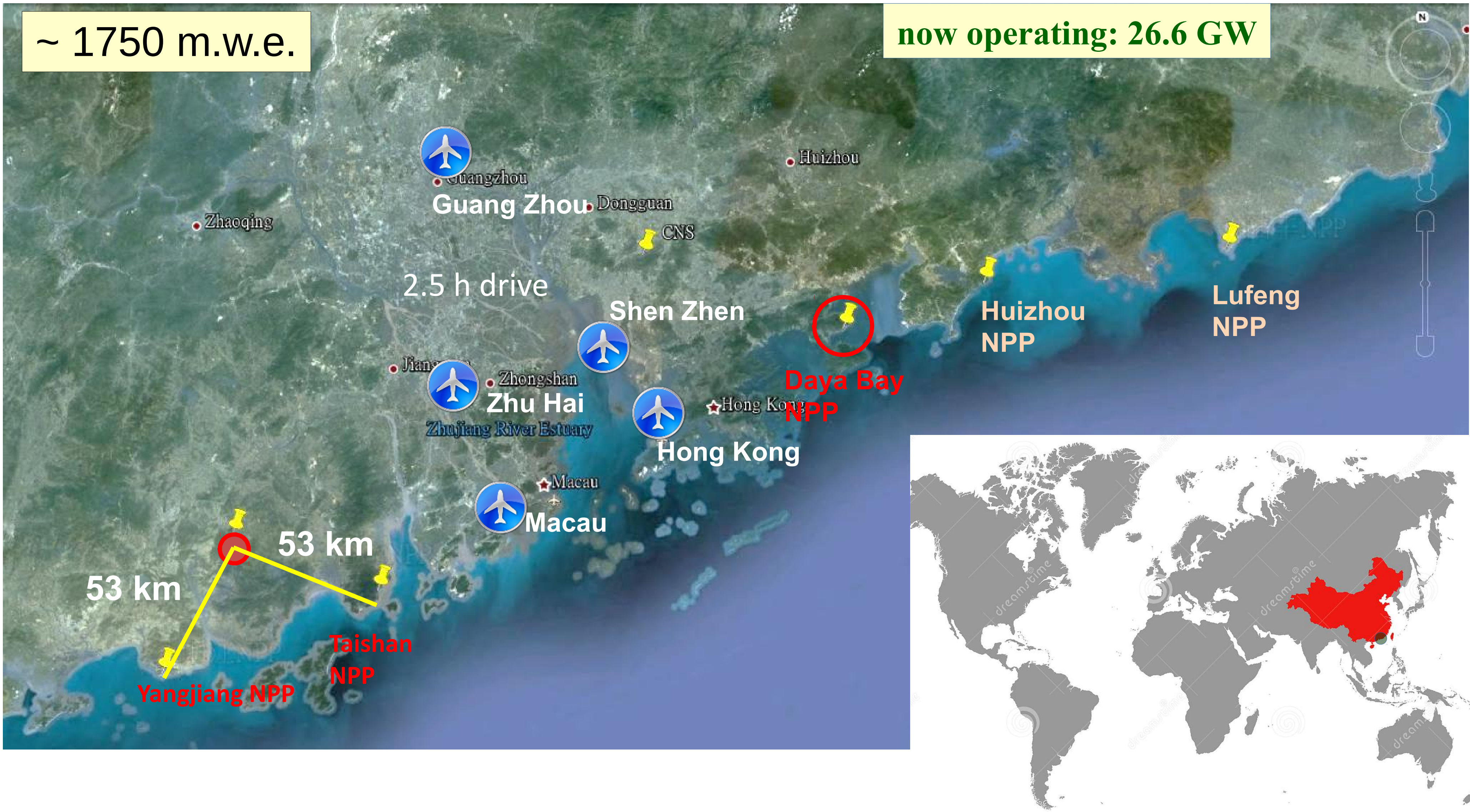
INVERSE BETA DECAY (IBD) reaction on the scintillator:



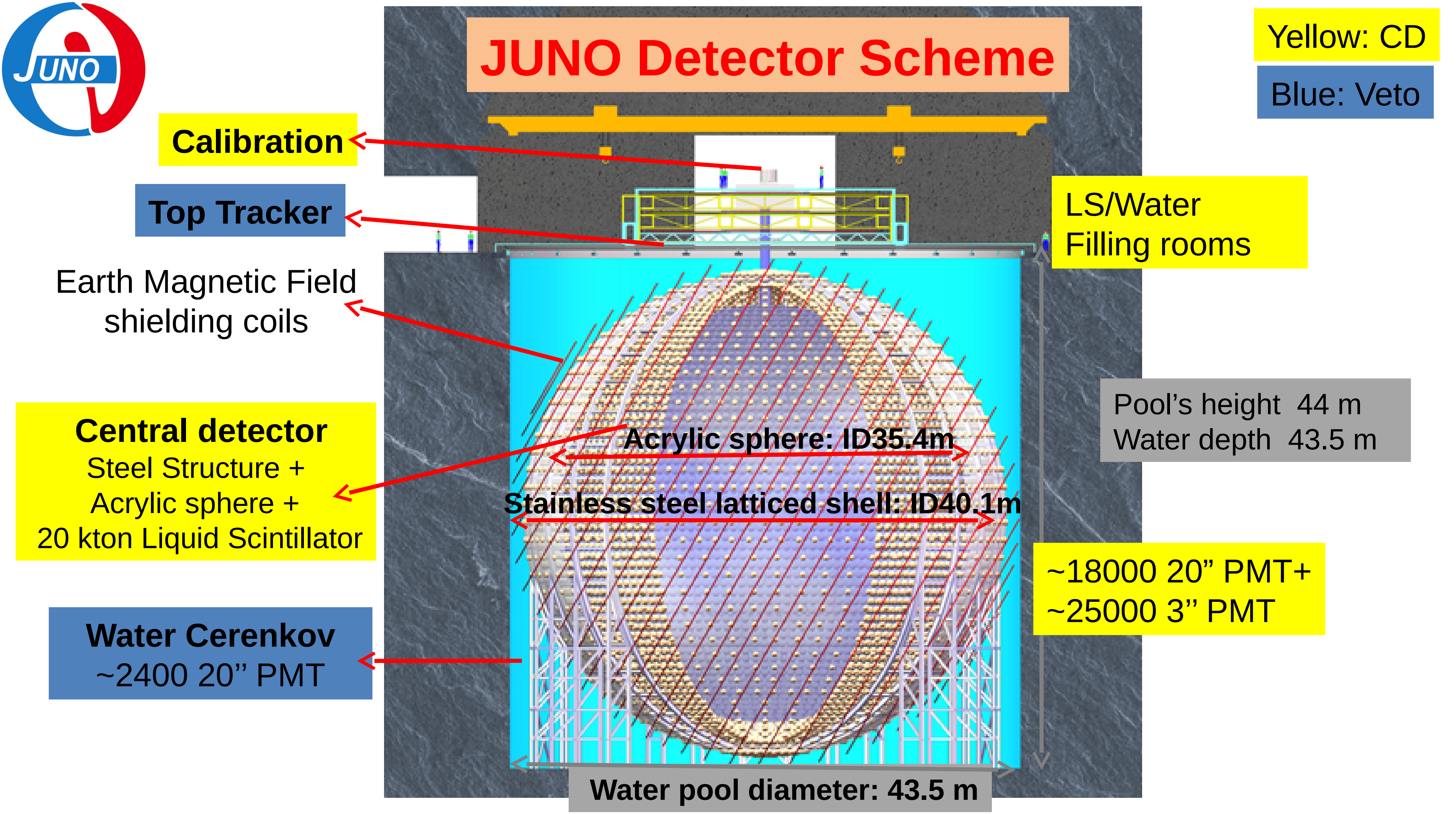
- E_{vis} (e+) ≃ E ($\bar{\nu}_e$) – 0.8 MeV
- Time coincidence between prompt and delayed signals to reject uncorrelated background

JUNO location

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Operational	Operational / Planned
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	9.2 GW / 18.4 GW

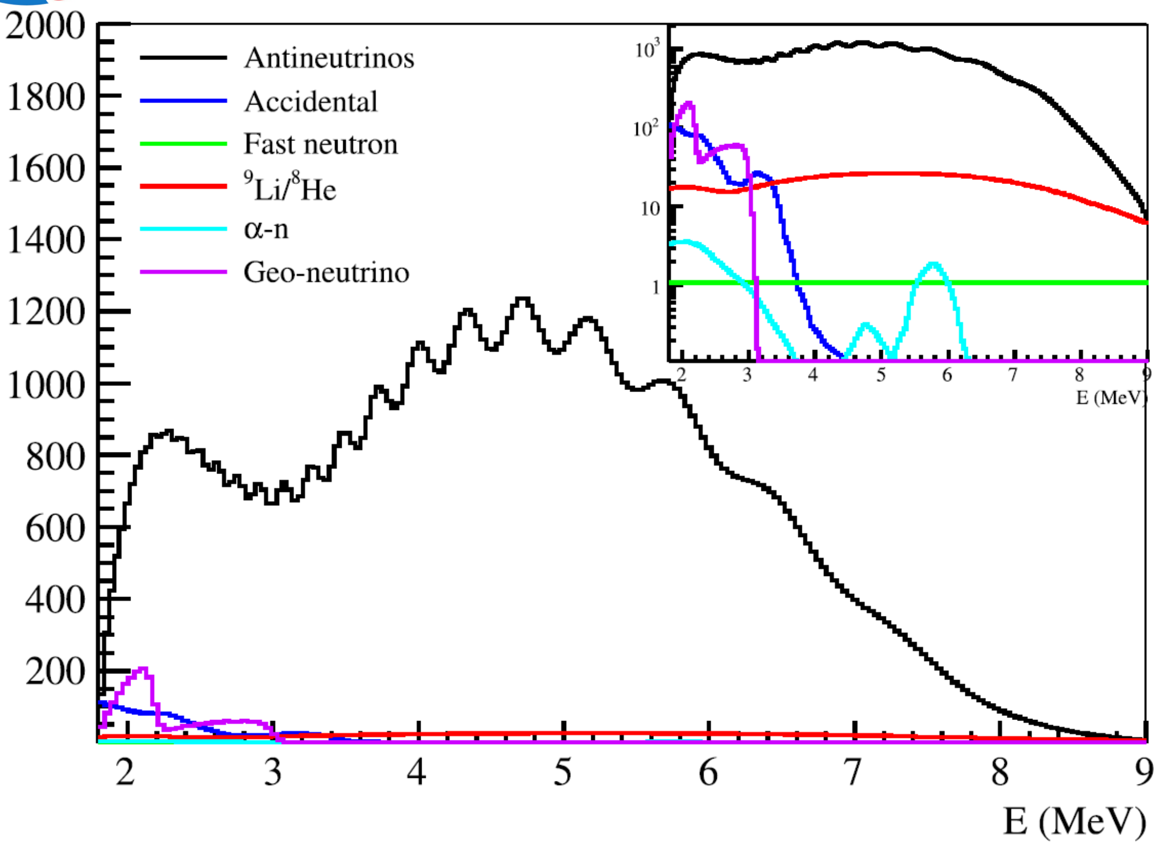


JUNO Detector Scheme



Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	~80%
Energy resolution	~7.5%/√E	~5%/√E	~6%/√E	~3%/√E
Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	~ 1200 p.e. / MeV

Quanti eventi IBD ci aspettiamo in JUNO?



Main background sources:

- **Natural radioactivity**
- **Cosmogenic isotopes in LS**
- **Fast neutrons**
- **Muons**

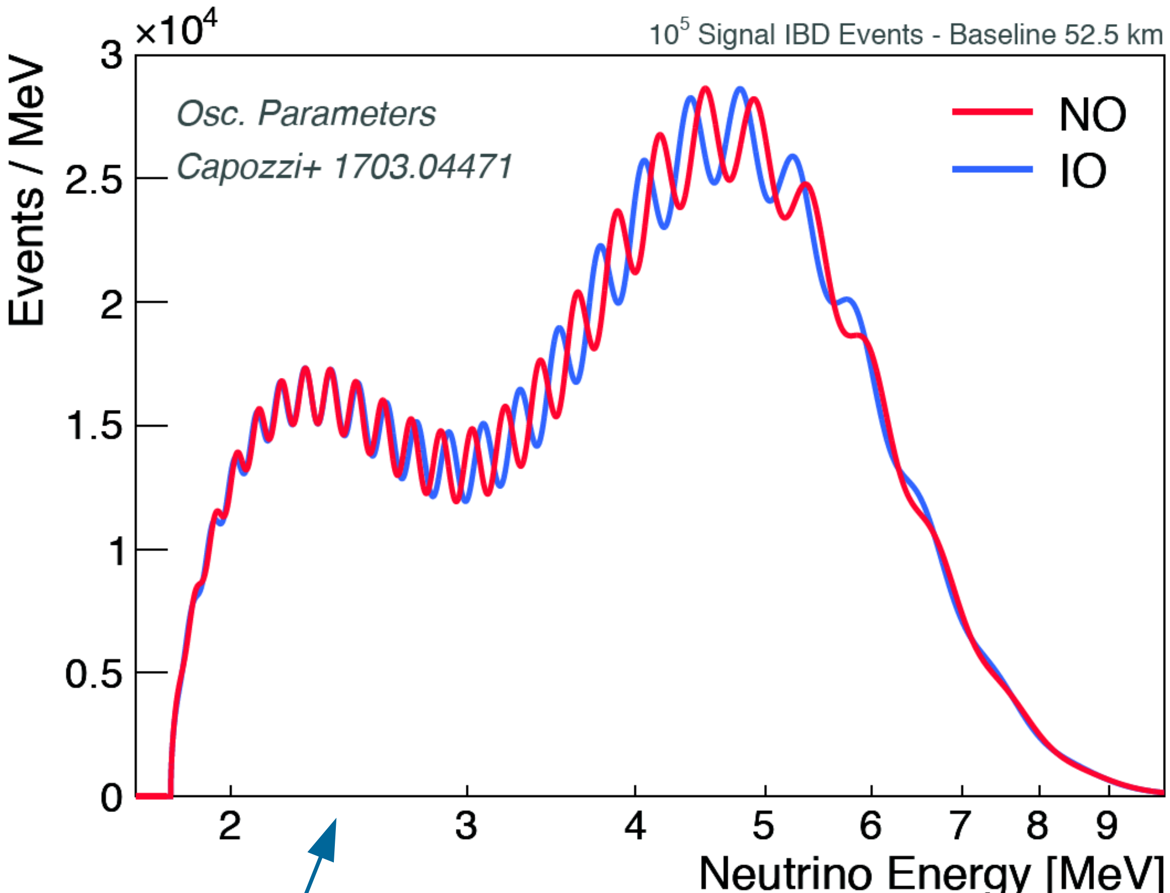
Total Background to Signal ratio (B/S): ~6.3%

From JUNO Yellow Book: Accidental singles rate ~ 7.6 Hz, neutron-like signals ~ 8%

Criteri di selezione

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		

Le sfide del rivelatore JUNO



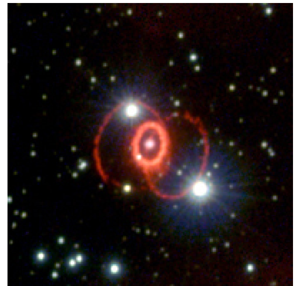
Ideal case for 20 kton × 6 y exposure

- Energy resolution < 3% / $\sqrt{E[MeV]}$
- Energy scale uncertainty < 1%
- Reactor baseline variation < 0.5 km
- Large statistics: 100k IBD in 6 y
- **Low radioactive background**
- **Systematics control**

JUNO: a neutrino underground observatory

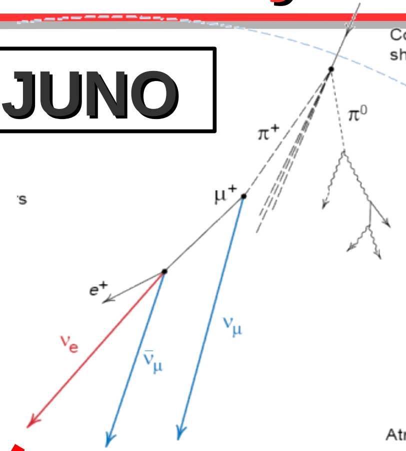
Neutrino Rates at JUNO

Supernova ν
~ 5k in 10s for 10kpc



Solar ν
(10s-1000s)/day

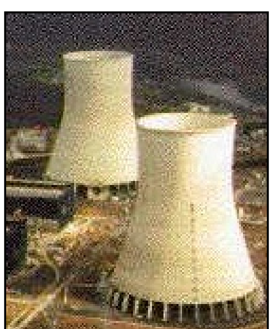
Atmospheric ν
several/day



700 m

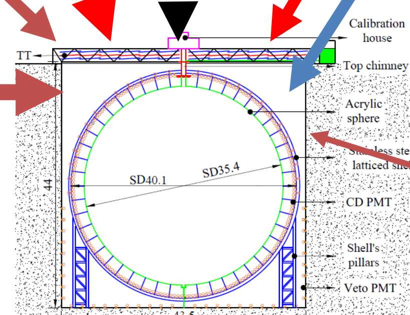
Cosmic muons
~ 250k/day

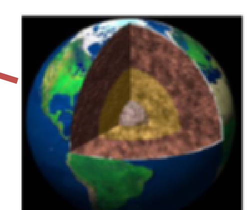
0.003 Hz/m², 215 GeV
10% multiple-muon



36 GW, 53 km

Reactor ν
~ 80/day





Geo-ν
1-2/day

The JUNO collaboration

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	Italy	INFN-Ferrara
Chile	UTFSM	China	U. of South China	Italy	INFN-Milano
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano Bicocca
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Padova
China	CAGS	China	Xi'an JT U.	Italy	INFN-Perugia
China	ChongQing University	China	Xiamen University	Italy	INFN-Roma 3
China	CIAE	China	Zhengzhou U.	Latvia	IECS
China	DGUT	China	NUDT	Pakistan	PINSTECH (PAEC)
China	ECUST	China	CUG-Beijing	Russia	INR Moscow
China	Guangxi U.	China	ECUT-Nanchang City	Russia	JINR
China	Harbin Institute of Technology	Czech R.	Charles University	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	LAL Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	CENBG Bordeaux	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	CPPM Marseille	Taiwan-China	National United U.
China	Nankai U.	France	IPHC Strasbourg	Thailand	NARIT
China	NCEPU	France	Subatech Nantes	Thailand	PPRLCU
China	Pekin U.	Germany	FZJ-ZEA	Thailand	SUT
China	Shandong U.	Germany	RWTH Aachen U.	USA	UMD1
China	Shanghai JT U.	Germany	TUM	USA	UMD2
China	IGG-Beijing	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Wuhan	Germany	FZJ-IKP		

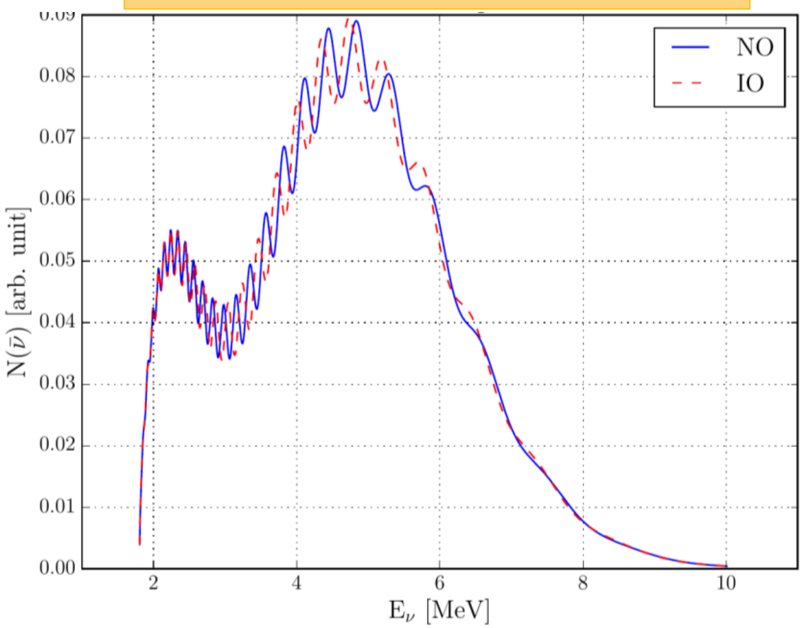
77 members
from
17 countries
for a total of
632 collaborators

DATA TAKING START: 2022

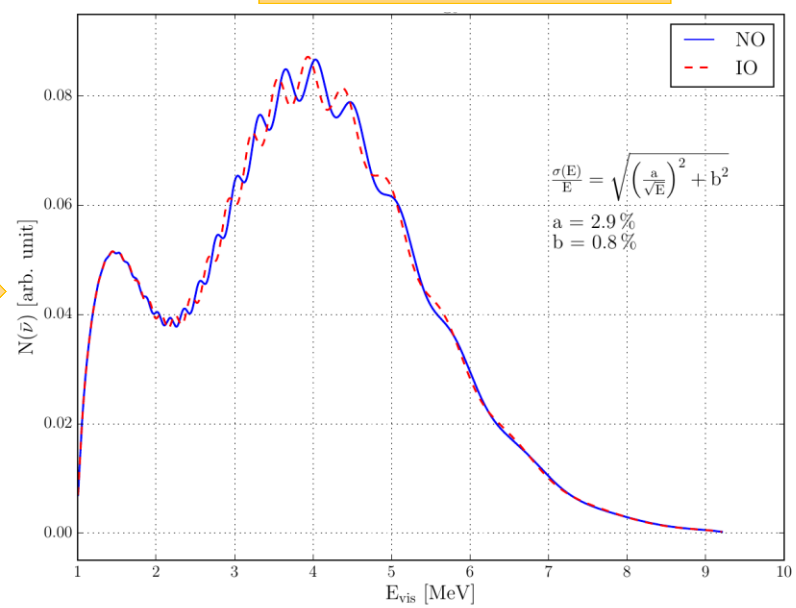
JUNO analysis for neutrino mass ordering

- JUNO analysis for neutrino mass ordering assessment relies on the measurement of a (relatively) small phase difference in the oscillation pattern.
- Experimentally, we need high statistics and good energy resolution…

INFINITE RESOLUTION (IDEAL)



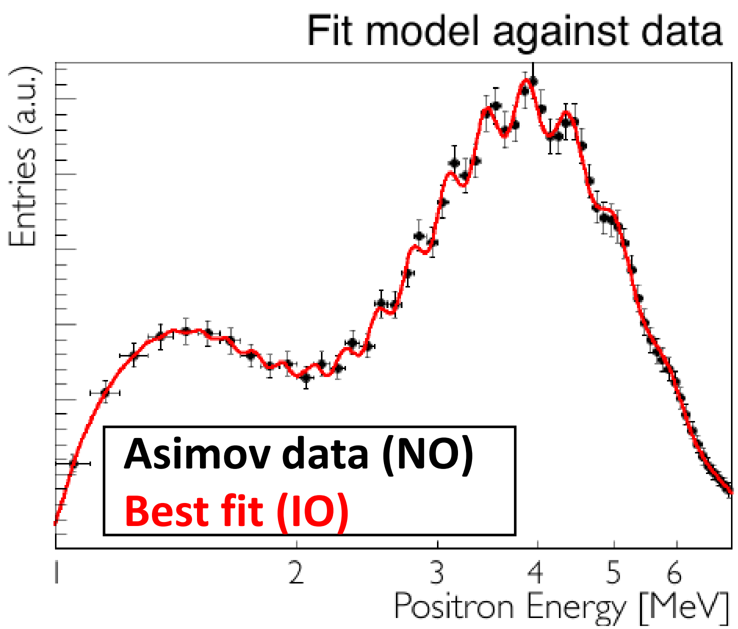
REAL RESOLUTION

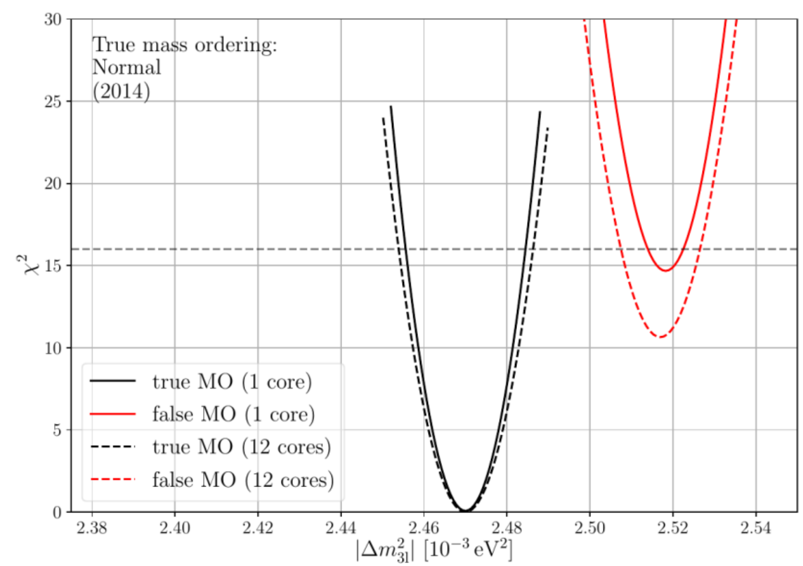


… but these are not the only key ingredients!!!

JUNO analysis for neutrino mass ordering

- To determine the neutrino mass ordering a χ^2 function is minimized to fit the predicted $\overline{\nu_e}$ spectrum to the experimental data in both scenarios: inverted ordering (IO) and normal ordering (NO).
- The $\Delta\chi^2$ between NO and IO fit results provides the experimental sensitivity for neutrino mass ordering measurement.



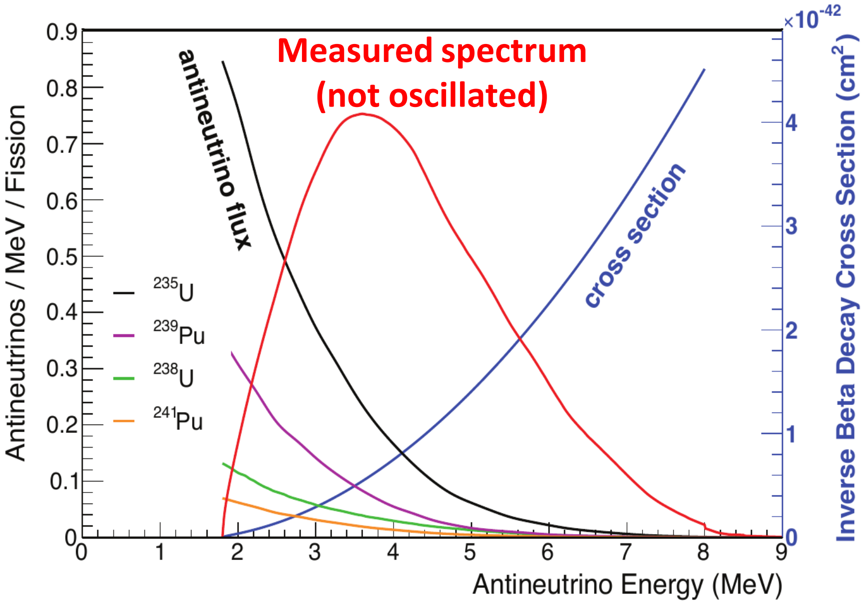


⇨ Uncertainties on the predicted $\overline{\nu_e}$ spectrum cannot be neglected!

Reactor antineutrino flux

…its uncertainty is not negligible!

- It's the starting point to build the expected $\overline{\nu_e}$ spectrum.
- $\overline{\nu_e}$ are emitted from β-decays of fission fragments.
- > 99% of reactor $\overline{\nu_e}$ emissions come from fissions of four main isotopes: ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U.



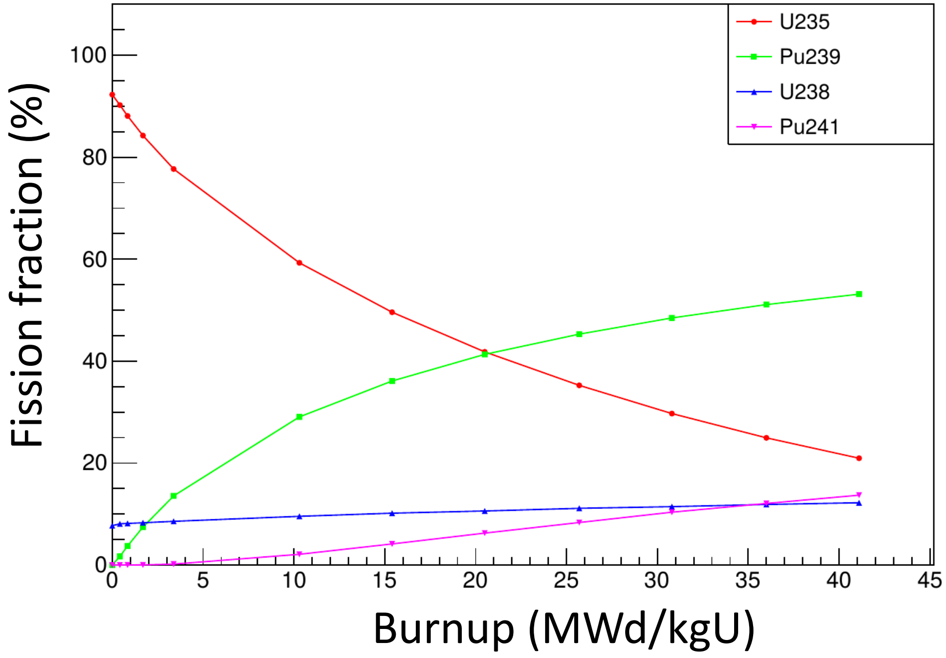
- If one knows the fission rates of each isotope (f_i) and the $\overline{\nu_e}$ energy spectrum of each isotope ($S_i(E_\nu)$), the $\overline{\nu_e}$ flux is simply obtained as:

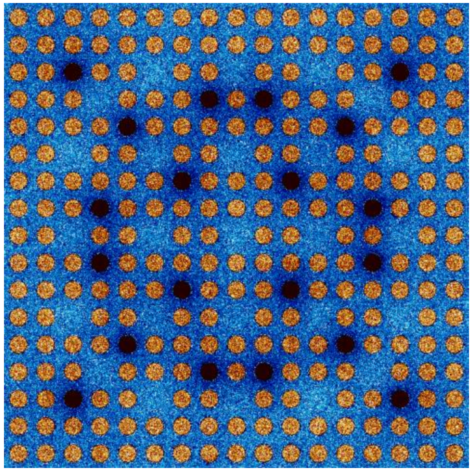
$$S(E_\nu) = \sum_i f_i S_i(E_\nu)$$

⇨ We need to know f_i and $S_i(E_\nu)$ with high accuracy and precision!

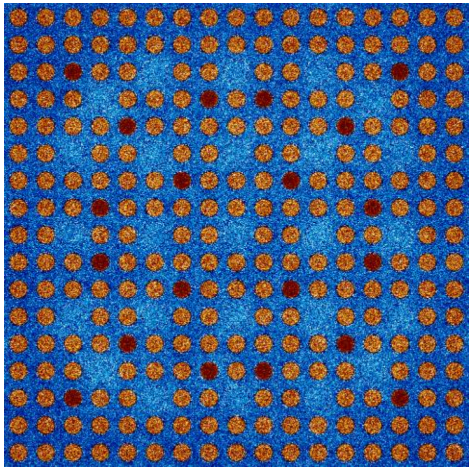
Nuclear reactor simulations

- Nuclear reactors are very complex systems evolving in time and the emitted $\bar{\nu}_e$ flux depends on fuel evolution (burnup), which in turn depends on reactor neutronics and thermal distribution.
- Simulations are used to determine fission rates f_i as function of time and their uncertainty.





Fresh fuel assembly



Fuel assembly after burnup

Estimation of $\overline{\nu_e}$ spectra ($S_i(E_\nu)$)

"β^- conversion" method

- In the 1980s, foils of fissile isotopes were exposed to the neutron flux of ILL reactor.
- The cumulative β^- spectra of fission products were measured.
- Inversion to the $\overline{\nu_e}$ spectra by fitting a set of 30 virtual β branches to the measured β^- spectra.

Expected to carry an uncertainty of 2-3%, but…

"Ab initio" method

- Direct estimation of $\overline{\nu_e}$ spectra based on nuclear databases (fission yields, β-decay spectra):

  > 1000 daughter isotopes

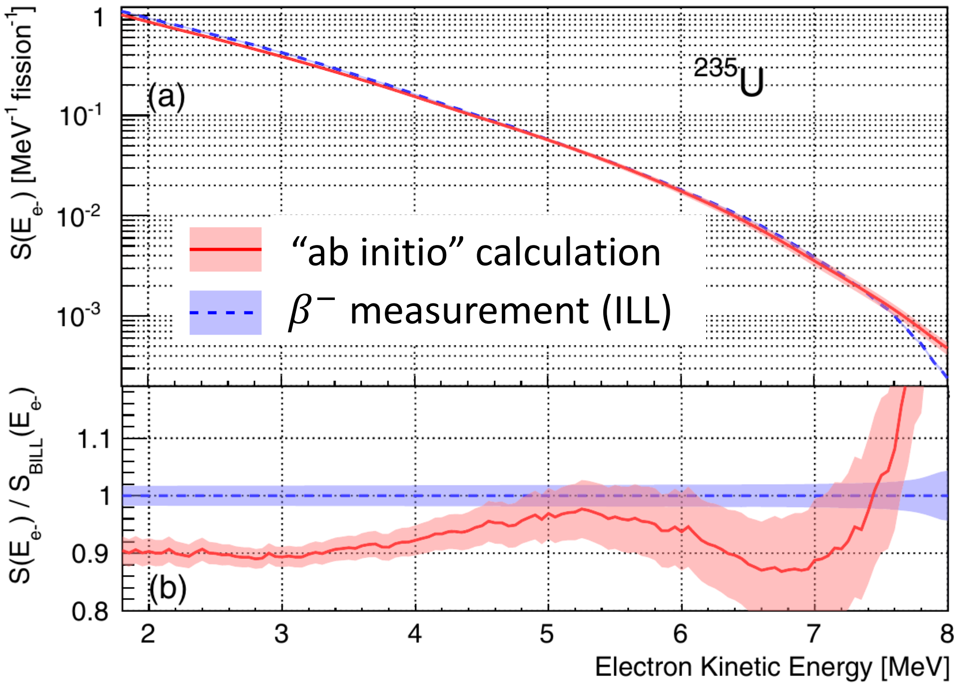
  > 6000 unique β-decays

- Such approach is challenging due to:
  - missing data
  - biased branching fractions
  - shape corrections to β-decay spectra (allowed/forbidden decays)

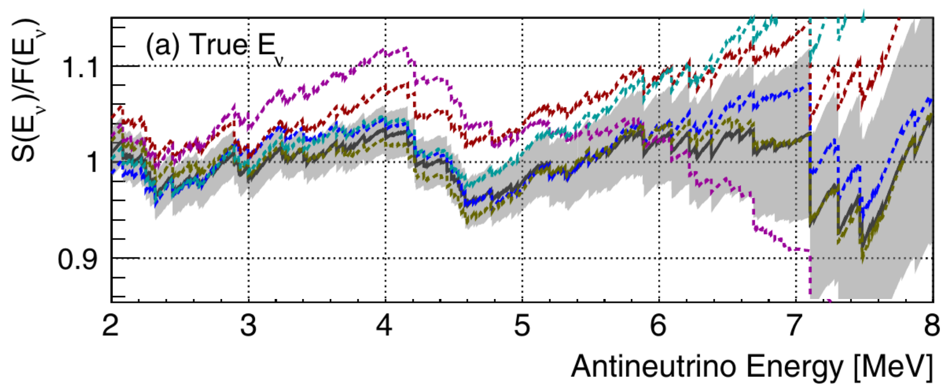
Uncertainty is ~10%

Estimation of $\overline{\nu_e}$ spectra ($S_i(E_\nu)$)

PRL 114, 012502 (2015)



- Comparison between "ab initio" nuclear calculation and measurement of β^- spectrum from ^{235}U fissions at ILL.

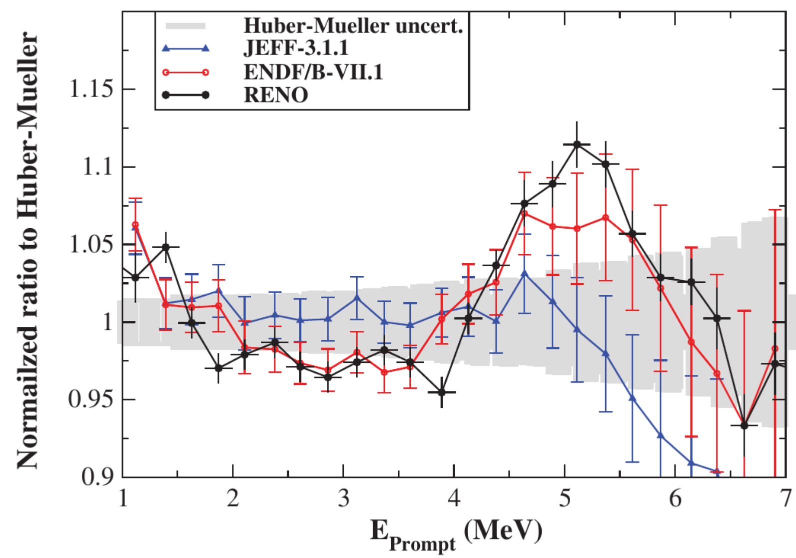


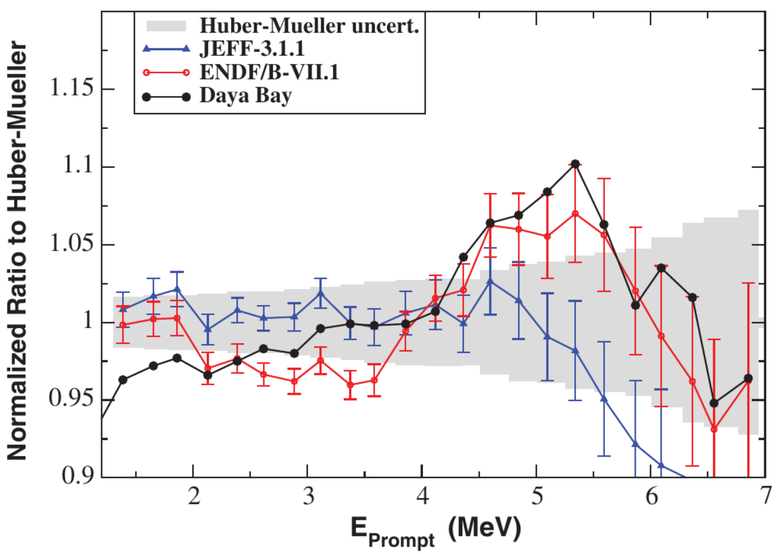
- "Ab initio" $\overline{\nu_e}$ spectrum divided by a smooth approximation (β^- conversion).
- Discontinuities are caused by the Coulomb correction to the spectra of prominent beta decays.
- Random variation of fission yields and branching fractions can alter the particular pattern (dashed colored lines).

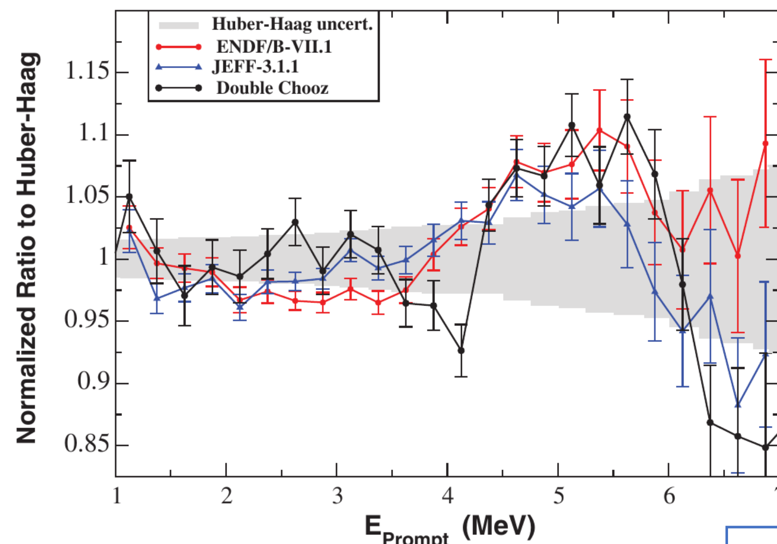
Comparison with experimental data

- Short-baseline experiments (RENO, Daya Bay and Double Chooz) measured the $\overline{\nu_e}$ spectrum with *near* detectors.
- By comparing the experimental data with the $\overline{\nu_e}$ spectrum predicted using the "β^- conversion" method, a significant discrepancy is found.

PRD 92, 033015 (2015)



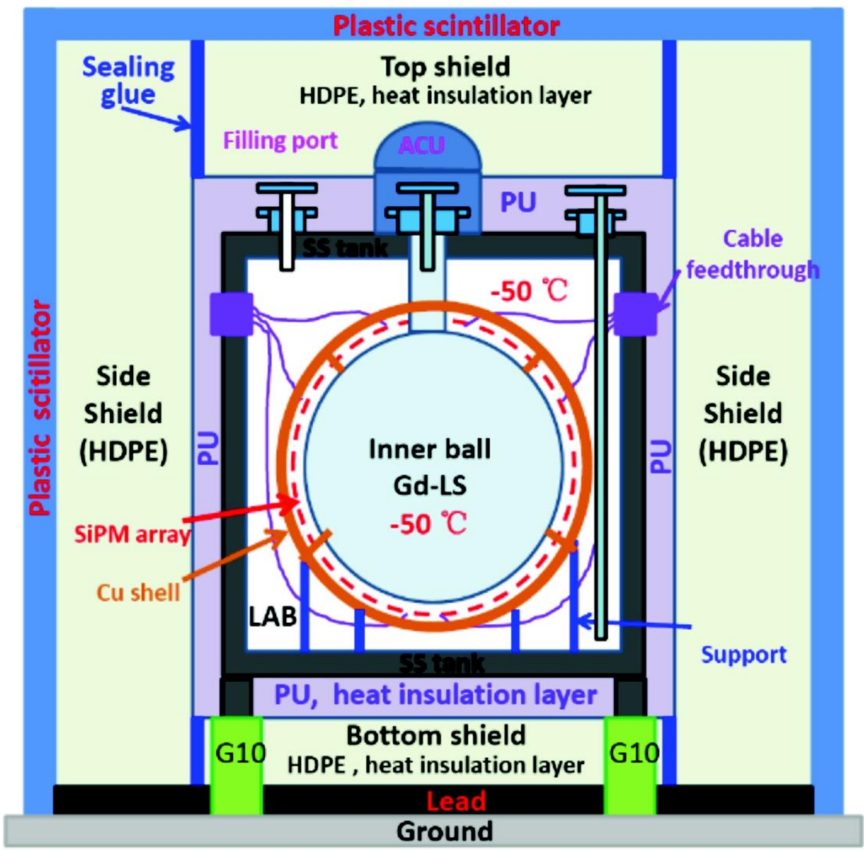




The TAO detector

The JUNO collaboration is building the **T**aishan **A**ntineutrino **O**bservatory (**TAO**) with the aim of:

- measuring the not oscillated $\bar{\nu_e}$ reactor spectrum with unprecedented energy resolution: $\sim 1.5\%$ at 1 MeV.
- providing a model-independent reference $\bar{\nu_e}$ spectrum for JUNO.



- ❑ 2.6 ton Gd-LS in a spherical vessel at -50°C:
  - 1-ton Fiducial Volume, 4000 $\bar{\nu_e}$'s/day
  - 10 m^2 SiPM of 50% PDE
- ❑ Laboratory in a basement at -10 m
- ❑ 30-35 m from Taishan core (4.6 GW$_{th}$)
- ❑ Planned to be online in 2021

From Inner to Outside:

- Gd-LS inner ball surrounded by SiPM array
- Cryogenic vessel
- 1.5 m water or High-Density PE shielding
- Muon veto

Work in progress @ MiB

1. Evaluation of uncertainties affecting fission rates (f_i) using nuclear reactor simulations (Serpent & MURE Monte Carlo codes).
2. Development of analysis tools to:
   - evaluate the impact of $\overline{\nu_e}$ reactor spectrum uncertainties in neutrino mass ordering analysis;
   - exploit the TAO measured spectrum for reducing the impact of model uncertainties.

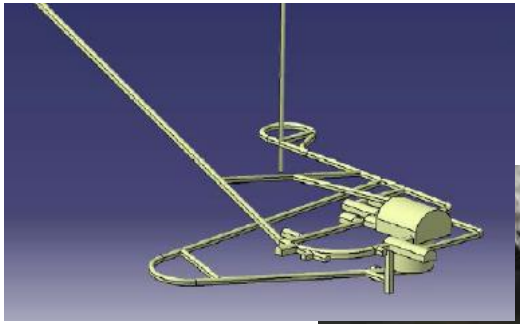
POSSIBLE FUTURE ANALYSIS

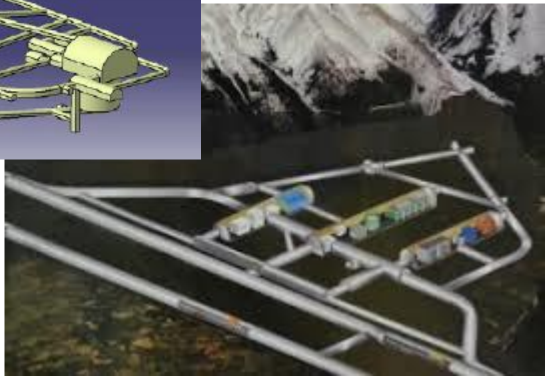
Development of a background model for JUNO, to analyze solar neutrino signal.

Il problema del fondo ambientale

In molti degli **esperimenti di fisica del neutrino** la possibilità di studiare eventi rari è fortemente influenzato dai conteggi di **fondo (eventi indesiderati)** presenti nella zona di interesse dello spettro energetico

↓





Tecniche di riduzione del fondo

- Laboratori sotterranei
- Sistemi di veto
- Criteri di selezione degli eventi
- **Selezione dei materiali** → **La radio purezza dei materiali** è una condizione fondamentale per la riuscita dell'esperimento

JUNO: ***il più grande osservatorio sotterraneo di neutrini al mondo***

JUNO - sorgenti del fondo radioattivo

Nuclei di origine cosmogenica

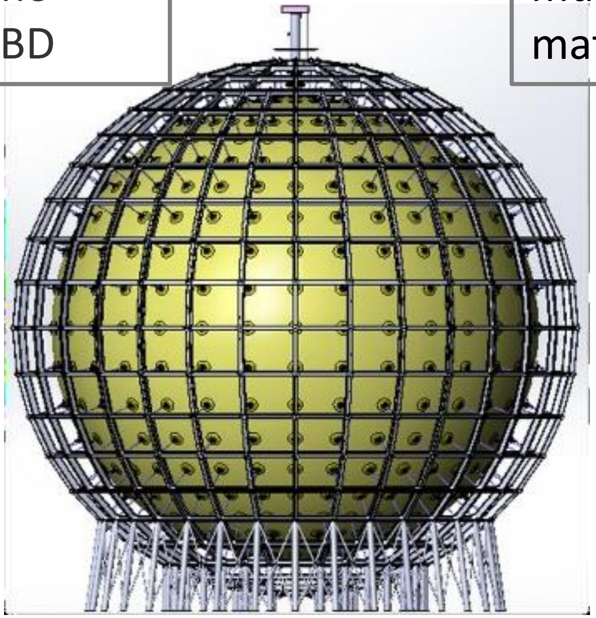
I decadimenti β–n prodotti da ^{9}Li and ^{8}He possono emulare le reazioni IBD

Neutroni Veloci

Neutroni possono essere prodotti dall’interazione dei muoni nelle rocce e nei materiali del rivelatore

Reazioni (α,n)

Le particelle alfa prodotte dai decadimenti di U e Th possono reagire con ^{13}C nel LS



Geo-neutrini

Prodotti dai decadimenti radioattivi di ^{232}Th e ^{238}U presenti nella Terra

Coincidenze accidentali

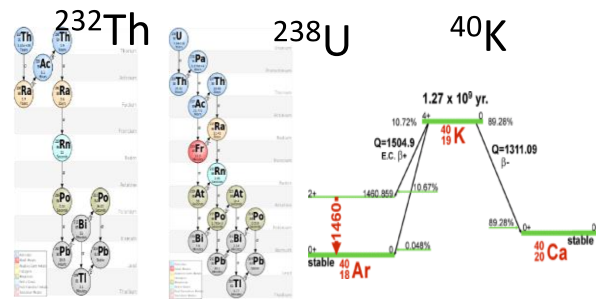
Eventi generati dalla radioattività U/Th/K contenuta nei materiali del rivelatore

Radioattività naturale

Le contaminazioni radioattive naturali nei materiali del rivelatore possono generare **coincidenze accidentali**

↓

Lo spettro energetico si **sovrappone al segnale** cercato (IDB) $\bar{\nu} + p \rightarrow e^{+} + n$

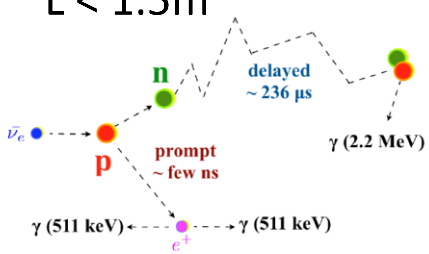


Isotopi gassosi: ^{222}Rn, ^{39}Ar
Antropogenici: ^{60}Co, ^{85}Kr

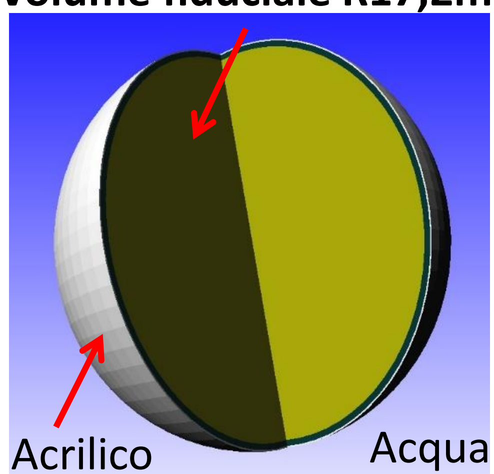
Soppressione del fondo accidentale

Criteri di selezione

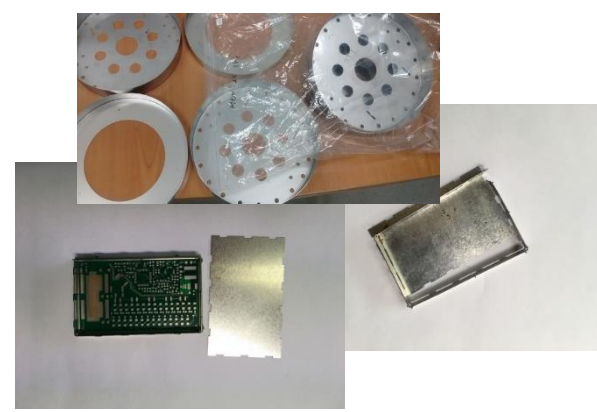
0.7 < Ep < 12 MeV
1.9 < Ed < 2.5 MeV
ΔT < 1 ms
L < 1.5m



Volume fiduciale R17,2m



Selezione dei materiali

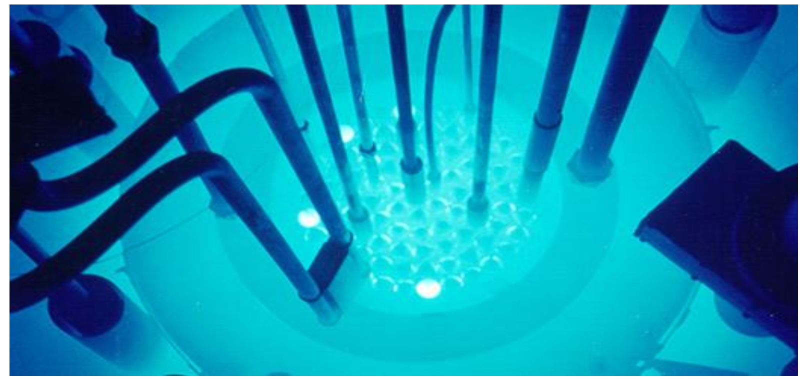


La cassetta degli attrezzi

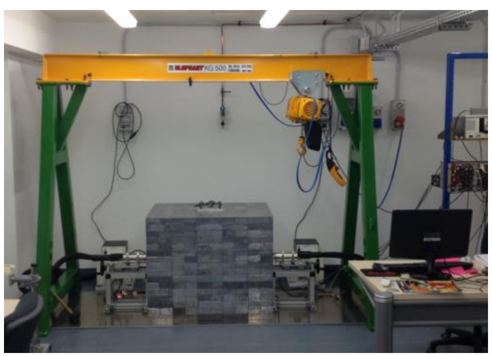
Selezione dei materiali consiste nel misurare e individuare i materiali con il minor contenuto di contaminanti radioattivi (U/Th/K) adatti ad essere utilizzati nell'esperimento

Misure a basso fondo

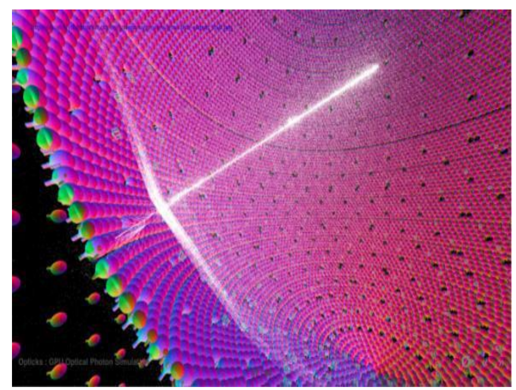
Neutron Activation Analisys



Misure in coincidenza

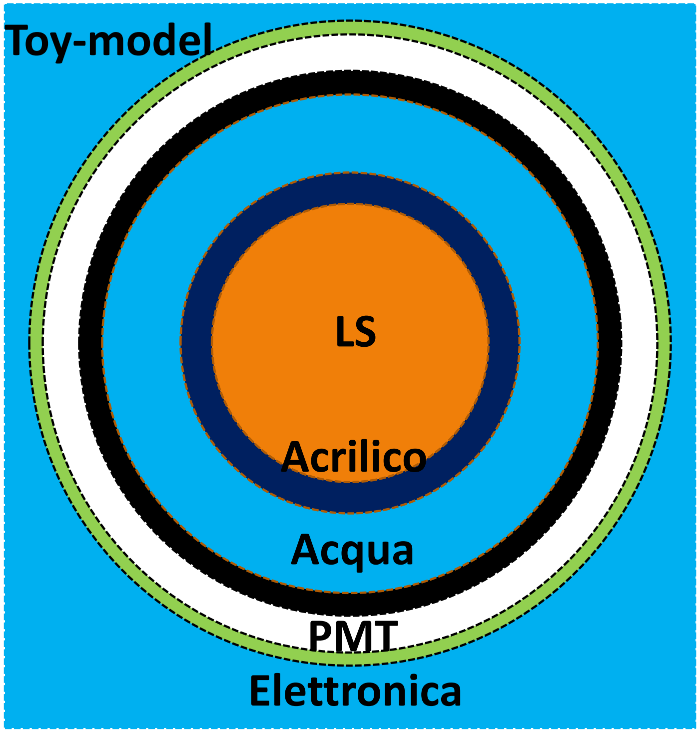


Software MC



Le richieste di radio purezza

Le valutazioni del rateo di conteggi attesi è stimato sulle conoscenze acquisite in precedenti esperimenti di fisica del neutrino (assumendo FV R < 17.2 m & E > 0.7 MeV):



Materiale	Massa	238U g/g	232Th g/g	40K g/g	Single Hz
LS	20kt	$<10^{-15}$	$<10^{-15}$	$<10^{-16}$	1,75
Acrilico	566t	$<10^{-12}$	$<10^{-12}$	$<10^{-12}$	0,37
SS truss	1000t	$<1\cdot10^{-12}$	$<5\cdot10^{-12}$	$<0{,}2\cdot10^{-12}$	0,06
PMT 20”	177.4t	$<4\cdot10^{-7}$	$<4\cdot10^{-7}$	$<0{,}4\cdot10^{-7}$	1,04
PMT 3”	3.1t	$<4\cdot10^{-7}$	$<4\cdot10^{-7}$	$<0{,}2\cdot10^{-7}$	0,07
Elettronica	2.85t	$<1\cdot10^{-6}$	$<4\cdot10^{-6}$	$<0{,}1\cdot10^{-7}$	0,09
Rocce		$<10\cdot10^{-6}$	$<30\cdot10^{-6}$	$<5\cdot10^{-7}$	0,98

Per I neutrino solari la radiopurezza deve essere due ordini di grandezza inferiore

Valutare una concentrazione pari a **$1\cdot10^{-15}$ g/g** è equivalente a stimare un **rapporto in massa** tra:

e 9000 x

Stazza: 220.000t

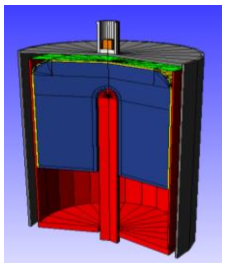
Misure di spettroscopia gamma a bassa radioattività

Scelta del rivelatore

↓

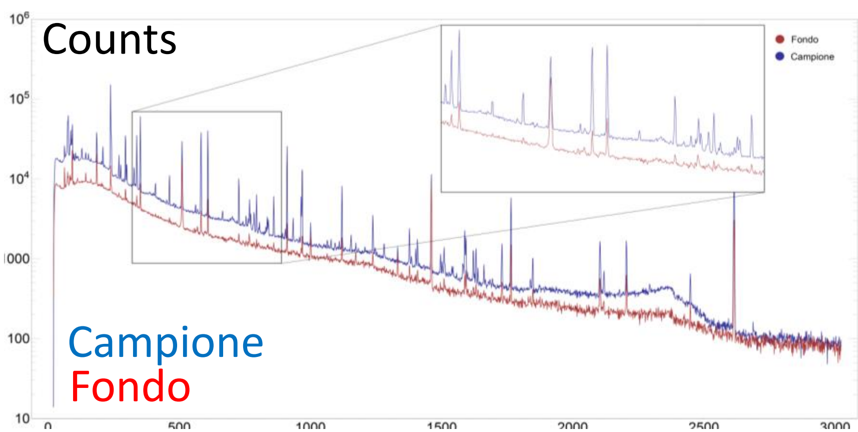
Preaparazione del campione

↓



Ottimizzazione dei parametri

↓



keV

$$A\left[\frac{Bq}{kg}\right]=\frac{C_{Camp}-C_{Fondo}}{T\cdot m\cdot BR\cdot \varepsilon_{abs}}$$

Sensibilità: $<10^{-9} g/g$

Rivelatori HPGe

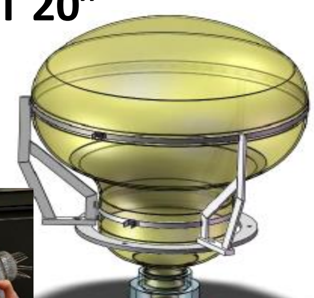
- Range: ~keV ÷ 3600keV
- Risoluzione Energetica <2keV
- Volumi sensibili
- Geometrie: coassiali, planari, well

Tecniche di riduzione del fondo

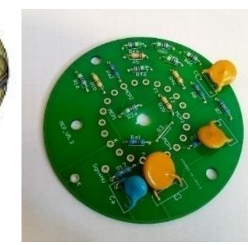
Laboratori sotterranei
Selezione materiali
Elettronica remotizzata
Schermature

JUNO

PMT 20"



Elettronica



Vetro

JUNO: ***il più grande osservatorio sotterraneo di neutrini al mondo***

Neutron Activation Analysis (NAA)

Il processo di attivazione neutronica consiste nella produzione di isotopi instabili attraverso l'assorbimento di neutroni da parte dei nuclei presenti nel campione

Esposizione del campione al flusso di neutroni

TRIGA Mark II (250 kW) - Pavia

^{232}**Th** (n, γ) ^{233}Th → ^{233}Pa

^{238}**U** (n, γ) ^{239}U → ^{239}Np

^{41}**K** (n, γ) ^{42}K

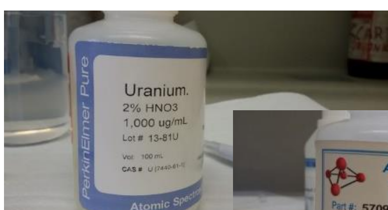
HPGe- detector

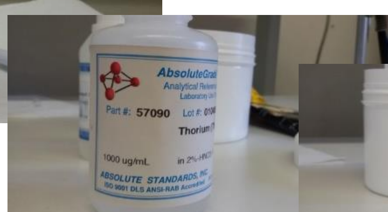
Estrazione del campione irraggiato e **misura** della radiazione gamma indotta

Sensibilità: $<10^{-12} g/g$

Determinazione della quantità di elemento precursore($^{A}_{Z}X$)

Uranio





Torio

Potassio

Acrilico

Post-Irraggiamento

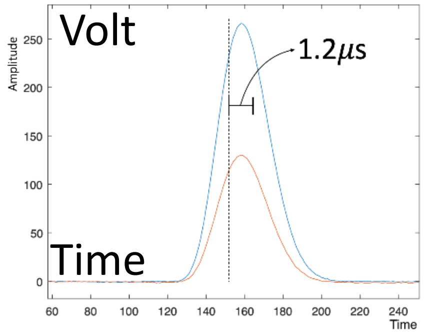
JUNO: ***il più grande osservatorio sotterraneo di neutrini al mondo***

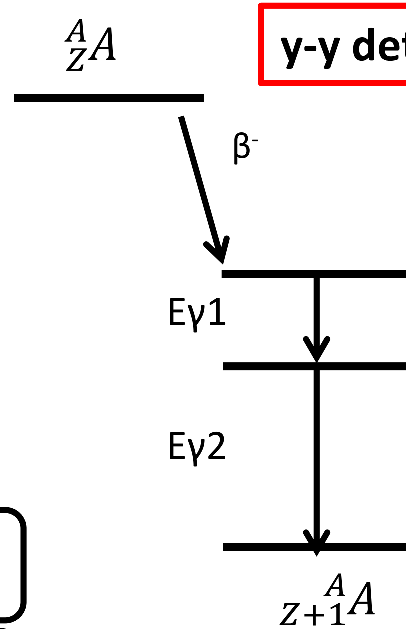
Sviluppo di sistemi di misura operanti in coincidenza

Riduzione fondo ambientale mediante **tecniche attive**

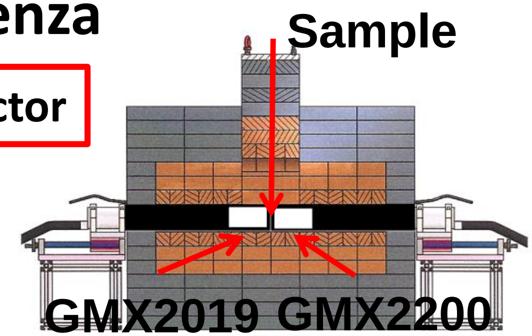
Veto - μ

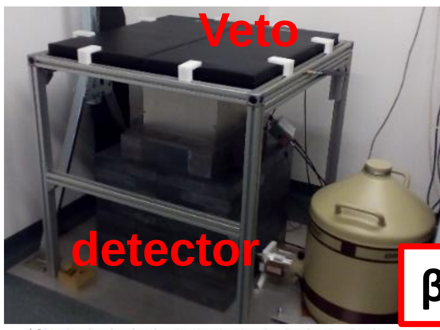
Coincidenza-temporale



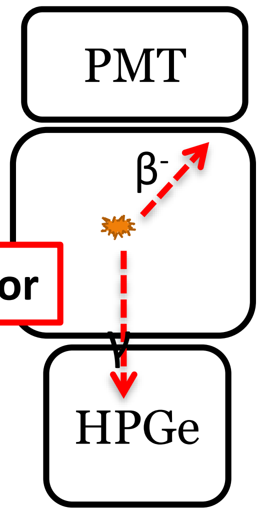


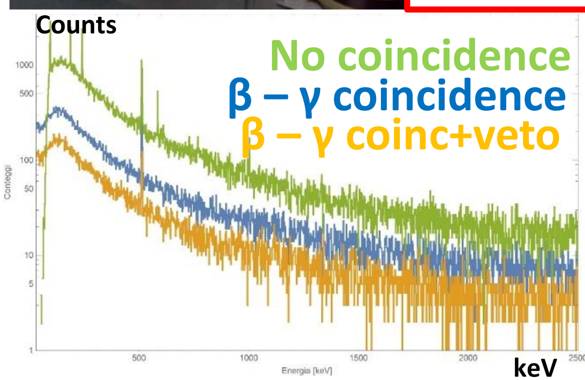
γ-γ detector





β-γ detector



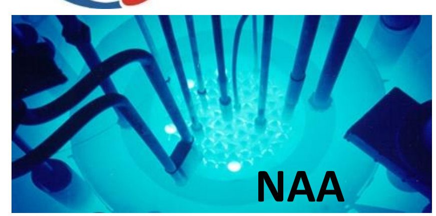


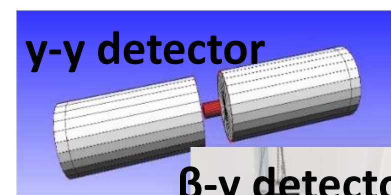
<6·10^{-14}*g/g per U*

<3·10^{-13}*g/g per Th*

Misura del Liquido Scintillante

Richieste <10^{-15}*g/g (U/Th/K)*





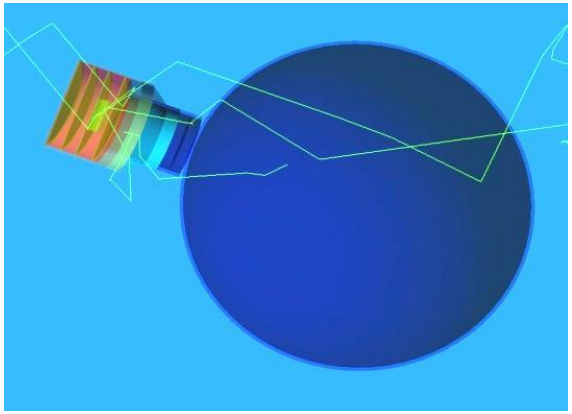
$${}^{A}_{Z}X + \mathrm{n} \longrightarrow {}^{A+1}_{Z+1}Y + \gamma_{cascate}$$

β-

JUNO: ***il più grande osservatorio sotterraneo di neutrini al mondo***

Simulazioni MonteCarlo

Nel corso degli anni il Gruppo di ricerca di Milano-Bicocca ha sviluppato un tool di simulazioni MC: **ARBY**



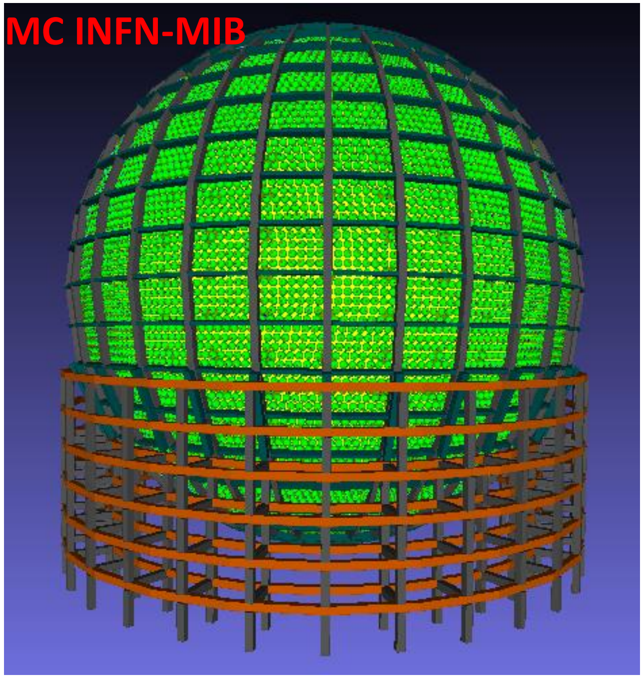
Le **misure sperimentali** forniscono informazione riguardo la contaminazione dei materiali che costituiscono i componenti dell'esperimento

↓

Ricostruzione al simulatore con la maggiore precisione possibile della **geometria dell'esperimento**

↓

Singles[Hz]= A[Bq/kg]·M[kg]·ε



JUNO: ***il più grande osservatorio sotterraneo di neutrini al mondo***

Prossimi passi:

Misure di screening → Verifica del processo di produzione delle lastre di Acrilico

Misure ad alta sensibilità → Incremento della sensibilità mediante processi di radiochimica

Software MC

Completamento dell’intera geometria del rivelatore

Interconfronto con il MC dei colleghi cinesi (SNIPER)

→ Background budget

The JUNO collaboration

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	Italy	INFN-Ferrara
Chile	UTFSM	China	U. of South China	Italy	INFN-Milano
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano Bicocca
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Pad[illegible]
China	CAGS	China	Xi'an JT U.	Italy	[illegible]
China	ChongQing University	China	Xiamen University	Italy	[illegible]
China	CIAE	China	Zhengzhou U.	[illegible]	[illegible]
China	DGUT	China	NUDT	[illegible]	[illegible]
China	ECUST	China	[illegible]	[illegible]	[illegible]
China	Guangxi U.	[illegible]	[illegible]	[illegible]	[illegible]
China	Harbin Institute of Technolog[illegible]	[illegible]	[illegible]	[illegible]	MSU
China	IHEP	[illegible]	[illegible]	[illegible]ovakia	FMPICU
China	Jilin U	[illegible]	[illegible]	Taiwan-China	National Chiao-Tung U.
China	[illegible]	[illegible]	[illegible] Bordeaux	Taiwan-China	National Taiwan U.
[illegible]	[illegible]	[illegible]	CPPM Marseille	Taiwan-China	National United U.
[illegible]	[illegible]	France	IPHC Strasbourg	Thailand	NARIT
[illegible]	[illegible]	France	Subatech Nantes	Thailand	PPRLCU
[illegible]	[illegible]	Germany	FZJ-ZEA	Thailand	SUT
[illegible]	[illegible]andong U.	Germany	RWTH Aachen U.	USA	UMD1
[illegible]	Shanghai JT U.	Germany	TUM	USA	UMD2
China	IGG-Beijing	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Wuhan	Germany	FZJ-IKP		

77 members
from
17 countries
for a total of
632 collaborators

GRAZIE PER L'ATTENZIONE!

BACK UP SLIDES

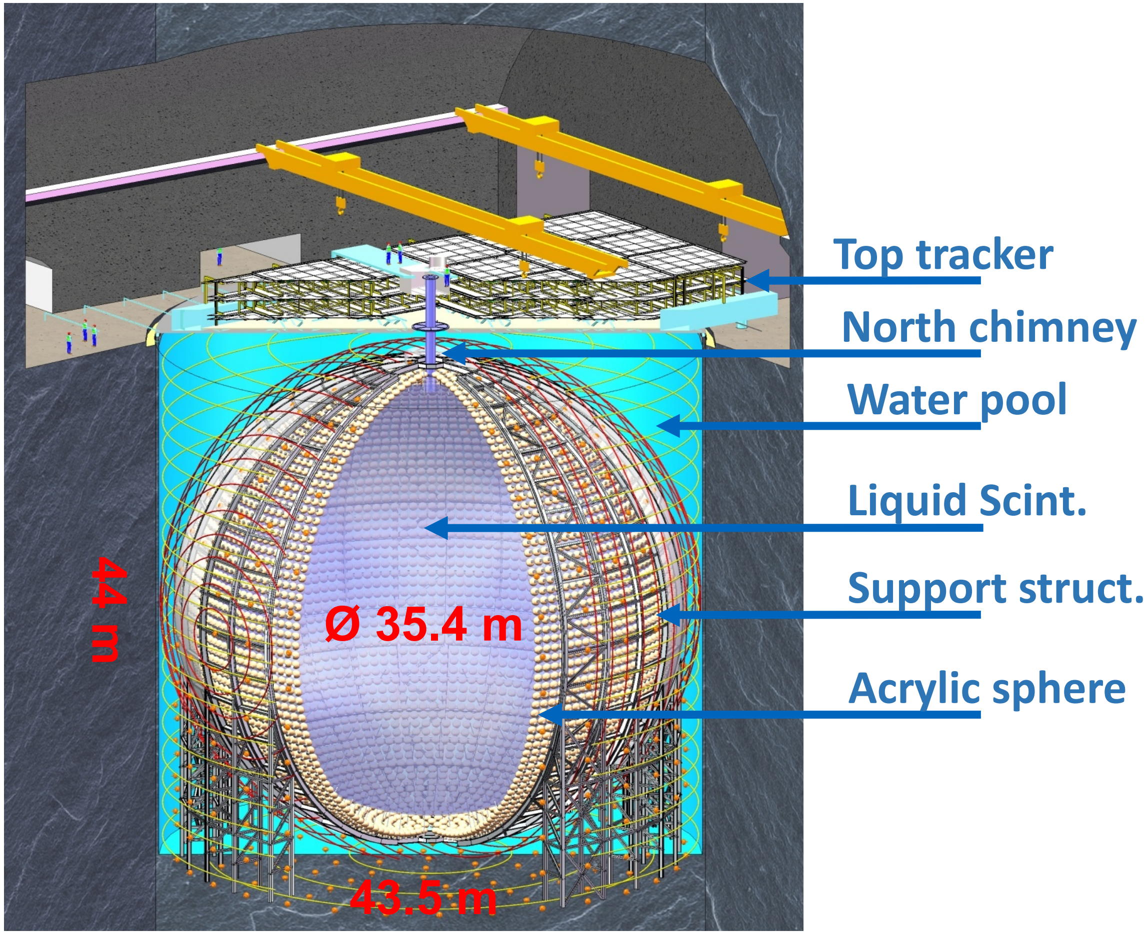
Overall detector design

Central detector:
- Acrylic sphere with liquid scintillator
- 17571 large PMTs (20-inch)
- 25600 small PMTs (3-inch)
- > 75% PMT coverage
- PMTs in water buffer

Water Cerenkov muon veto:
- 2400 20” PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%
- Radon control → less than 0.2 Bq/m^3

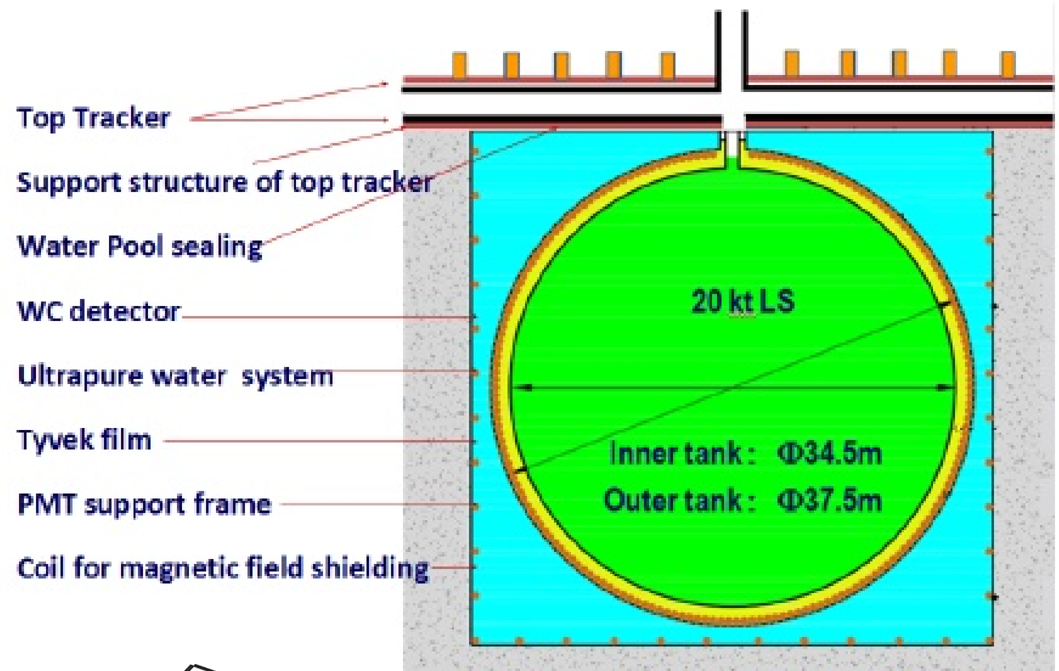
Compensation coils:
- Earth magnetic field <10%
- Necessary for 20” PMTs

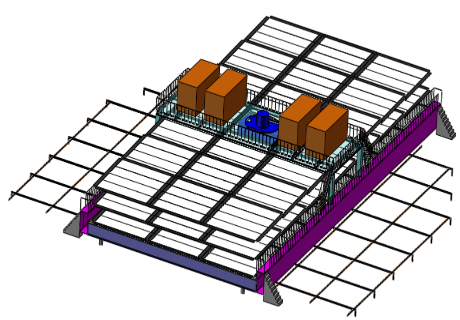
Top tracker:
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top of the water pool

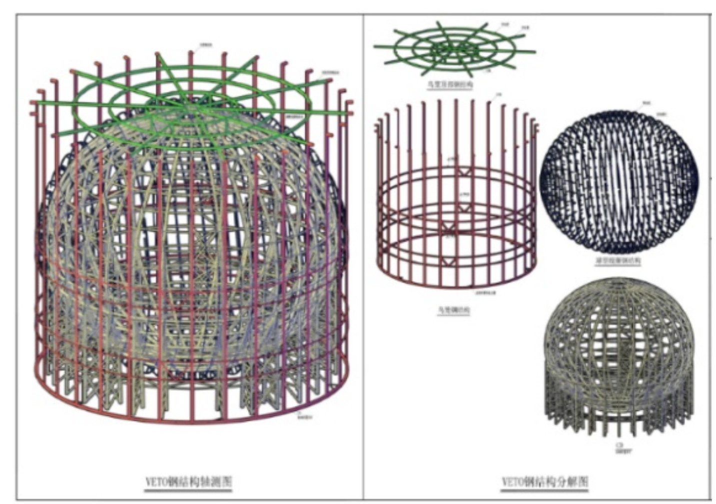


Veto

- **Tasks:**
  - Shield rock-related backgrounds
  - Tag & reconstruct cosmic-rays tracks
- **Detector:**
  - Top tracker: refurbished OPERA scintillators
  - Water Cerenkov detector
- **Pool lining: HDPE**
- **Earth magnetic field compensation coil**



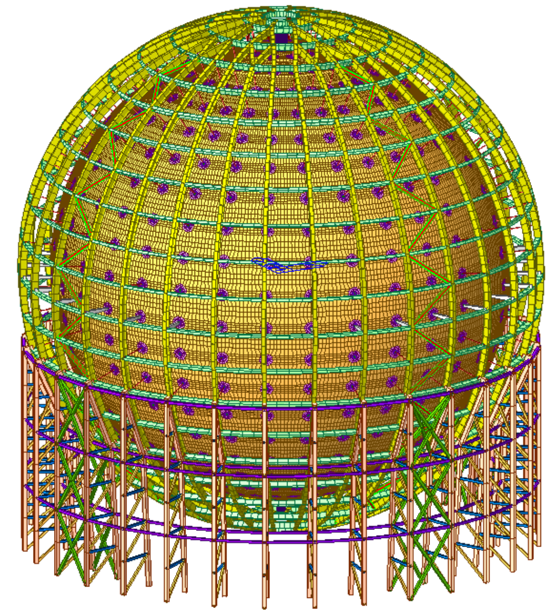




Central Detector: Steel Truss & Acrylic Sphere

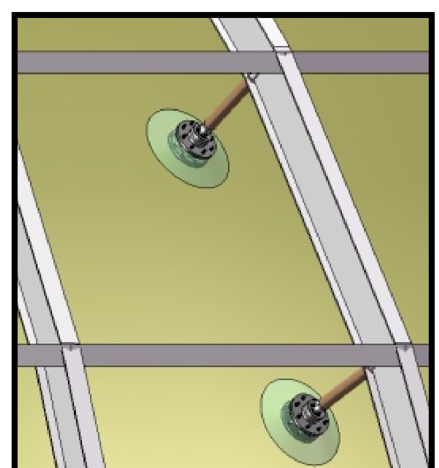
- Stainless steel structure to hold the acrylic sphere and to anchor the PMTs
  - ▶ Supporting bar to hold the acrylic tank
  - ▶ Stress of the acrylic < 3.5 MPa everywhere

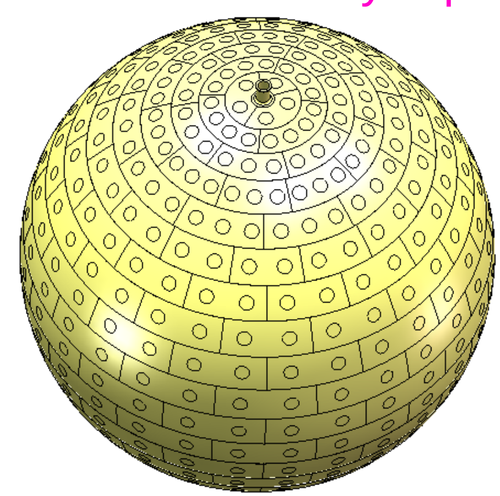
- Main issues:
  - ▶ Mechanical precision for 3 mm PMT clearance
  - ▶ Thermal expansion matching: 21°C ± 1°C
  - ▶ Earthquake and liquid-solid coupling
  - ▶ Acrylic transparency > 96%
  - ▶ Radiopurity U/Th/K: Acrylic $\prec$ 1 ppt, Steel $\lesssim$ ppb



More than 200 Acrylic panels

Panel size: 3 m × 8 m × 120 mm



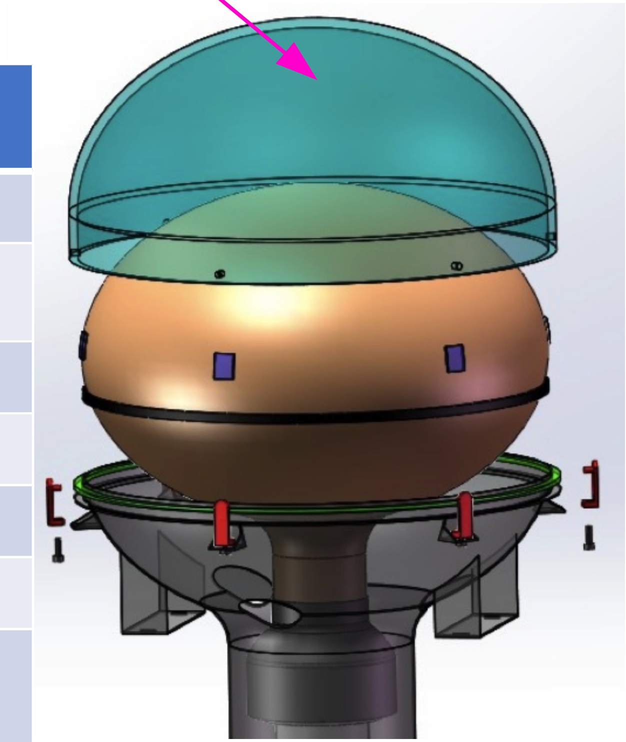


Acrylic panel mass production started

Large PMT array

- 15000 MCP-PMTs from NNVT (Northern Night Vision Technology)
- 5000 dynode PMTs from Hamamatsu (R12860 HQE)
- 17571 PMTs will read out the scintillation light of the Central Detector
- In production since 2016
- PMT testing:
  - Finished for dynode PMTs
  - ~10000 of 15000 MCP-PMTs already tested

Specifications	Unit	MCP-PMT (NNVT)	R12860 Hamamatsu HQE
Det. Efficiency (QE*CE)	%	26.9% (**new Type: 30.1%**)	28.1%
Peak to Valley of SPE		3.5, (>2.8)	3, (>2.5)
TTS on the top point	ns	12, (<15)	**2.7, (<3.5)**
Rise time / Fall Time	ns	RT~2, FT~12	RT~5, FT~9
Anode Dark Count	kHz	20, (<30)	10, (<50)
After Pulse Rate	%	1, (<2)	10, (<15)
Radioactivity (glass)	ppb	**^{238}U: 200** **^{232}Th: 120** **^{40}K: 4**	^{238}U: 400 ^{232}Th: 400 ^{40}K: 40

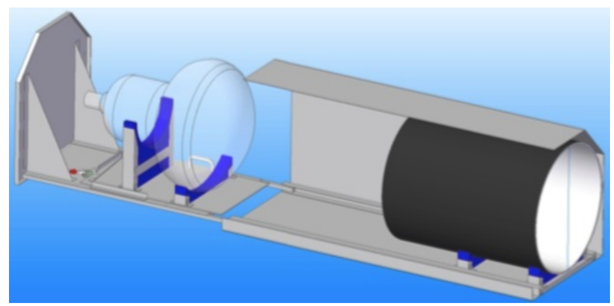


Large PMT testing facility

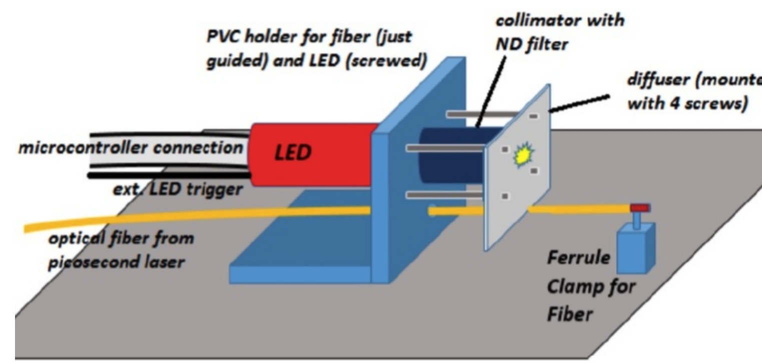
PMT Testing Containers (all PMTs):

- Capacity: 36 (-5) PMTs per Container
- Relative PDE Measurement
  - 1 fixed & 4 rotating reference PMTs
- Four containiers
  - 1 & 2 operational
  - 3 & 4 commissioned
- Magnetic shielding: 10% EMF
- Climate control systems
- Two light sources:
  - stabilized LED
  - Picosecond-Laser

Two testing containers in Zhongshan (Pan-Asia)



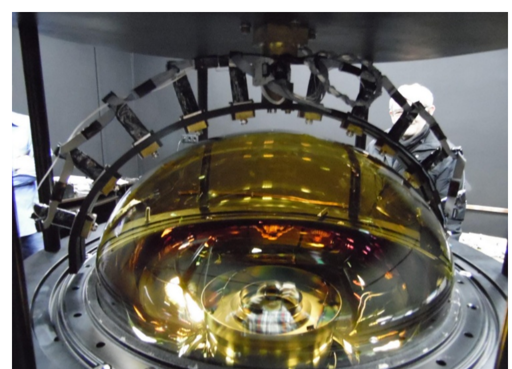
PMT test box with PMT holder



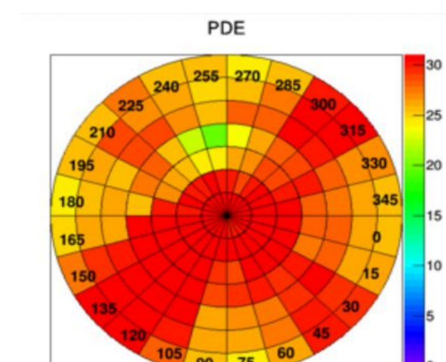
Light sources used in the testing containers

Scanning Station (5-10% of PMTs):

- Provide non-uniformity measurement of PMT parameters
- Study dependence of PMT performance on magnetic field
- Provide a tool for precise PMT studies and cross calibration



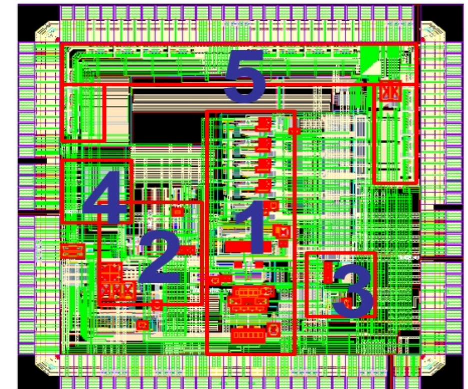
PMT in the scanning station



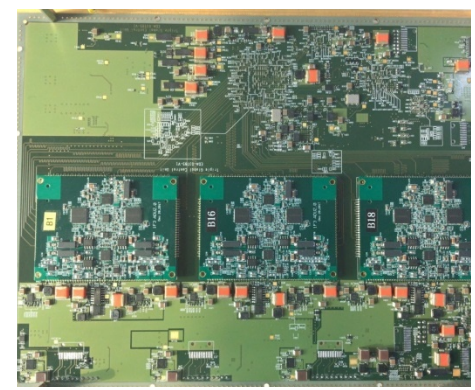
PDE differences (photocathode)

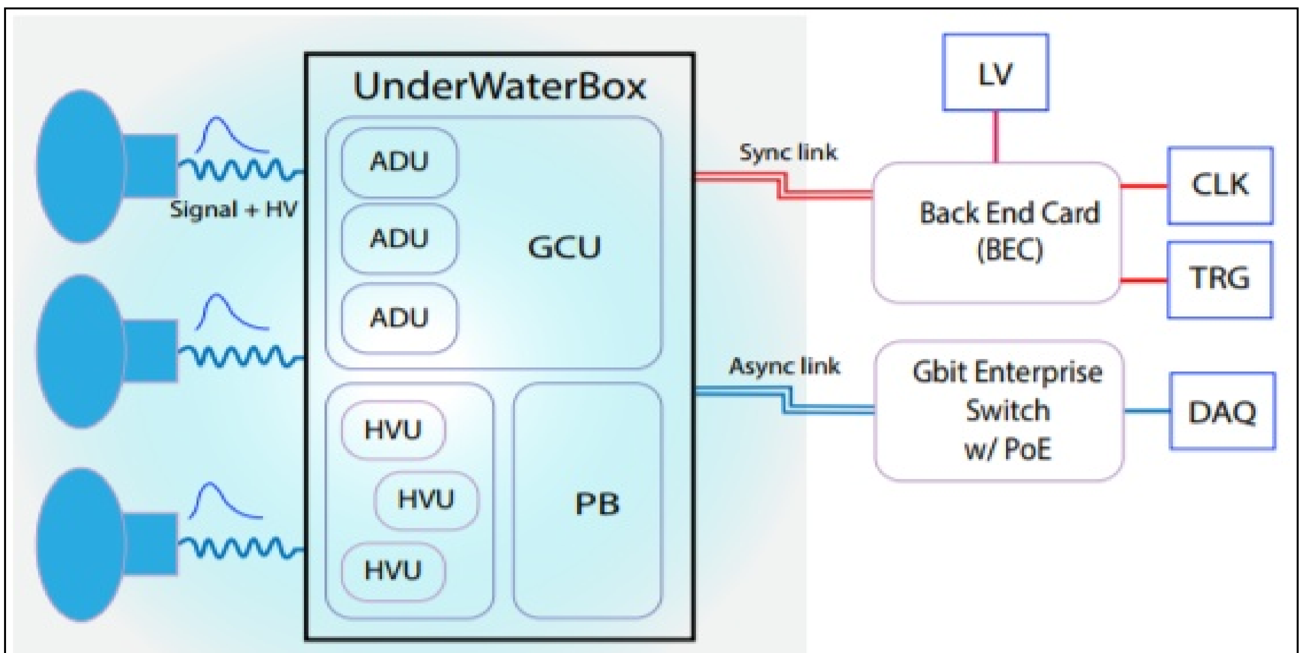
Electronics

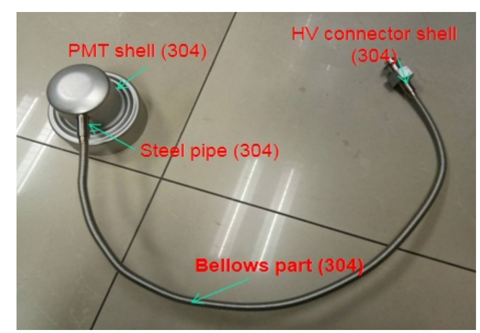
- 20000 ch. for LPMT & 100 m cable needed
- Dynamic range: 1- 4000 PE
- Noise: < 10% @ 1 PE
- Resolution: 10%@1 PE, 1%@100 PE
- Failure rate: < 0.5%/6 years
- Final solution: 1 GHz sampling FADC in a small box (×3 ch.) in water; all cables in corrugated pipes



芯片版图







Small PMT array

Double calorimetry

Always in photon counting mode

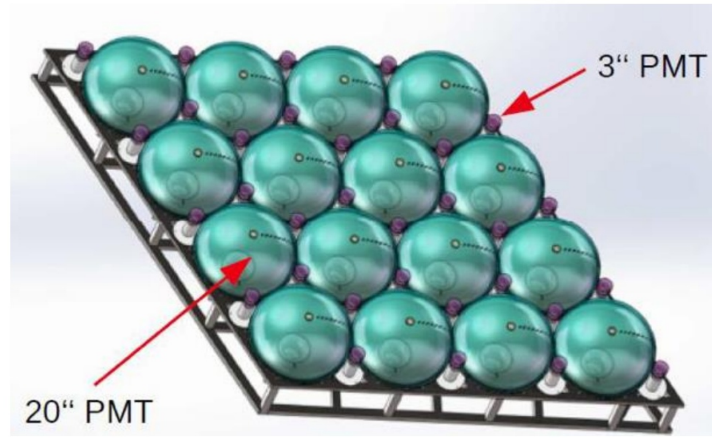
Less non-linearity: calibration of large PMT array

Better dynamic range for high energy signals

Higher granularity of the CD

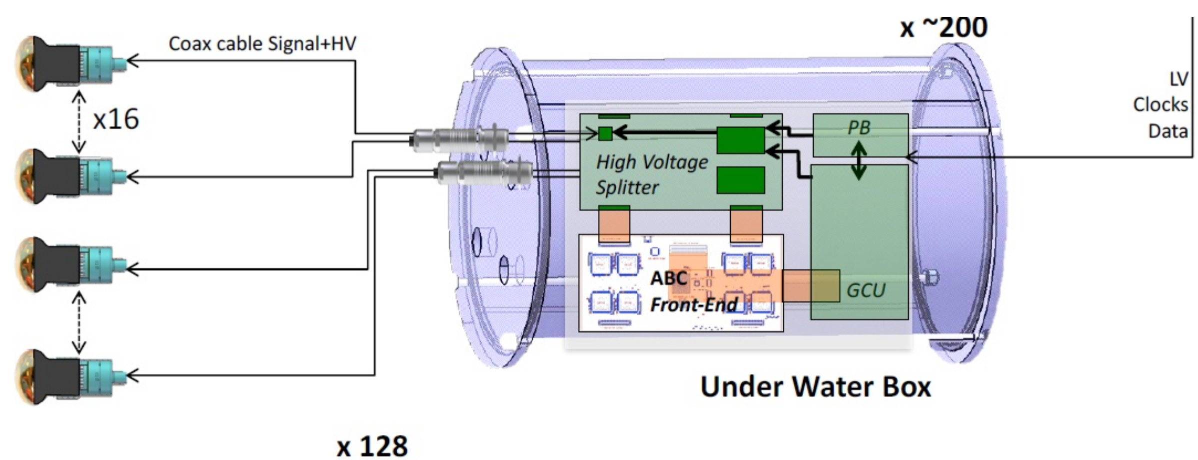
25600 PMTs in the Central Detector
- **2.5% coverage**
- Provided by HZC Photonics (Hainan, PR China)

Can effectively help in:
- Muon tracking (+ shower muon calorimetry)
- **Supernova readout**
- Solar oscillation parameter measurement



Arrangement of large and small PMTs

~ 200 boxes × 128 PMTs



Under water box provides supply for 128 PMTs
(Prototype already built and successfully tested!)

Liquid Scintillator

Purification of LAB in 4 Steps:

- **Al_2O_3 filtration column:** improvement of **optical properties**
- **Distillation:** removal of **heavy metals**, improvement of transparency
- **Water Extraction (underground):** removal of **radio isotopes** from uranium and thorium chains and furthermore of ^{40}**K**
- **Steam / Nitrogen Stripping (underground):** removal of **gaseous impurities** like Ar, Kr and Rn

Optical Requirements:

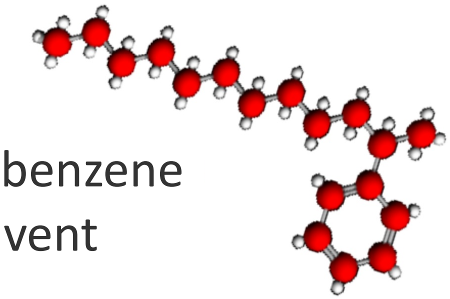
Light output: **~10.000 Photons / MeV**
→ **~1200 p.e. / MeV**
Attenuation length: **> 20 m @ 430 nm**

Required Radiopurity:

Reactor neutrinos:
^{238}U / ^{232}Th < 10^{-15} g/g, ^{40}K < 10^{-16} g/g, ^{210}Pb < 10^{-22} g/g, ^{14}C < 10^{-17} g/g

Solar neutrinos:
^{238}U / ^{232}Th < 10^{-17} g/g, ^{40}K < 10^{-18} g/g, ^{210}Pb < 10^{-24} g/g, ^{14}C < 10^{-18} g/g

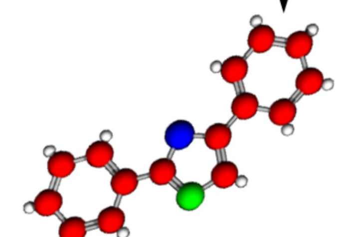
Solvent:
Linear alkylbenzene (LAB) as solvent



+

non-radiative → 280nm

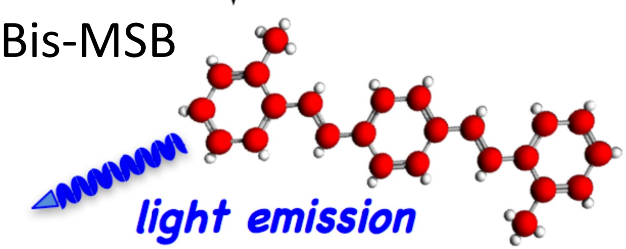
Scintillation Fluor:
2.5 g/l PPO



+

non-radiative → 390nm

Wavelength Shifter:
3 mg/l Bis-MSB



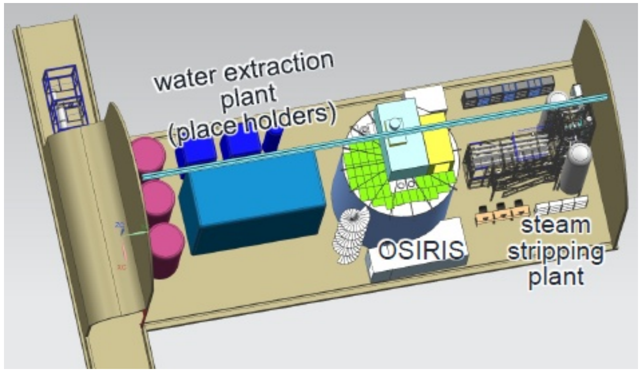
light emission → 430nm, τ≈4.4ns

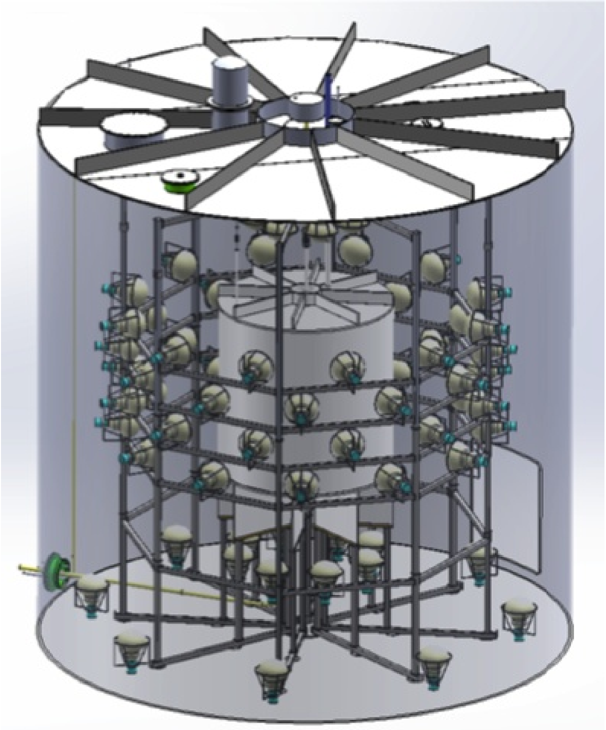
OSIRIS

Online Scintillator Internal Radioactivity Investigation System

Liquid Scintillator purity monitor:

Detect radioactive contaminated scintillator **after purification** but **before putting** it into the acrylic vessel!





Exploit fast coincidences in the ^{238}U and ^{232}Th chains

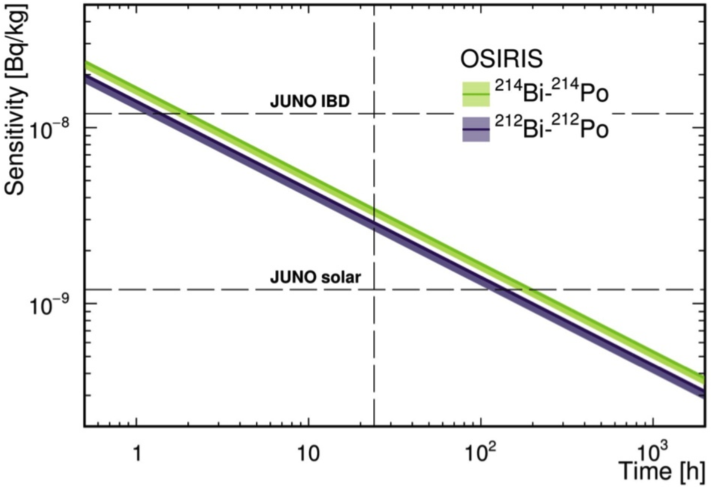
18 ton LS volume ($Ø$=3 m, H=3 m)

Instrumentation:

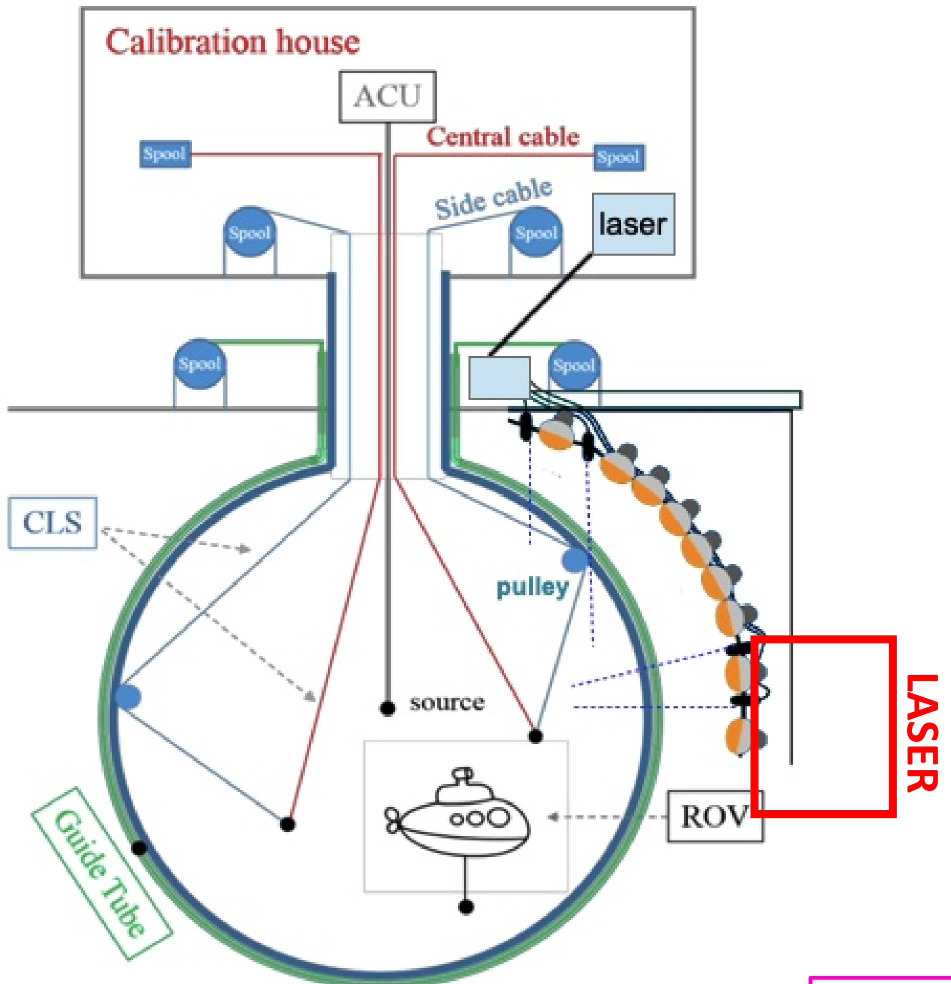
68x 20" PMTs for the scintillator
12x 20" PMTs for the myon veto

Expected radiopurity level sensitivity (Simulation):

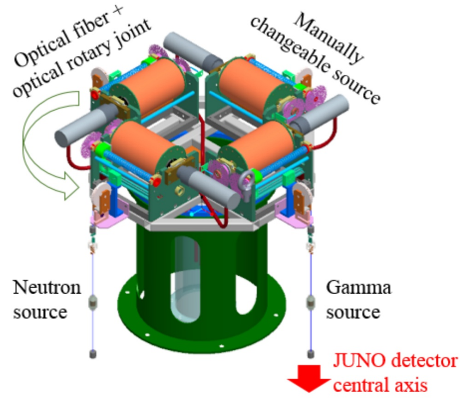
JUNO IBD limit within a few hours
JUNO solar limit possible



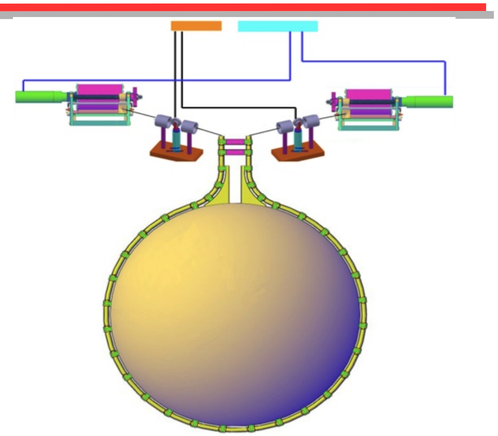
Calibration system



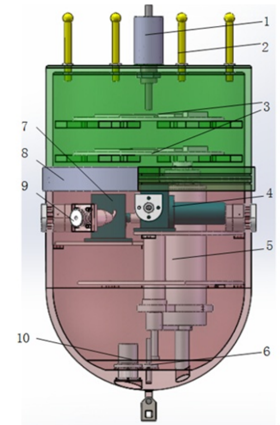
Overview of JUNO's Calibration Systems
(including laser calibration system)



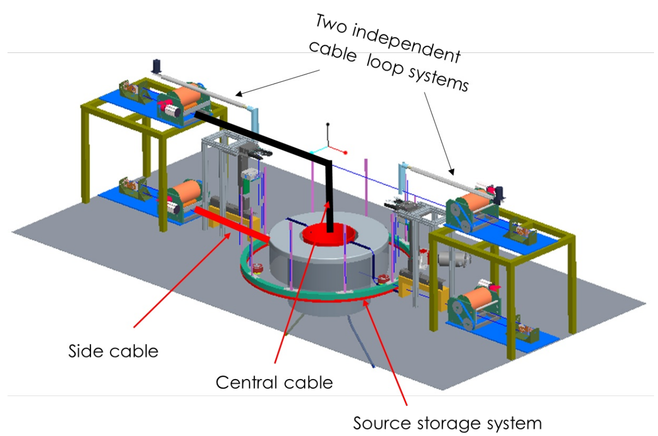
ACU (Automatic Calibration Unit)



Guide Tube System



ROV
(Remotely Operated Vehicle)

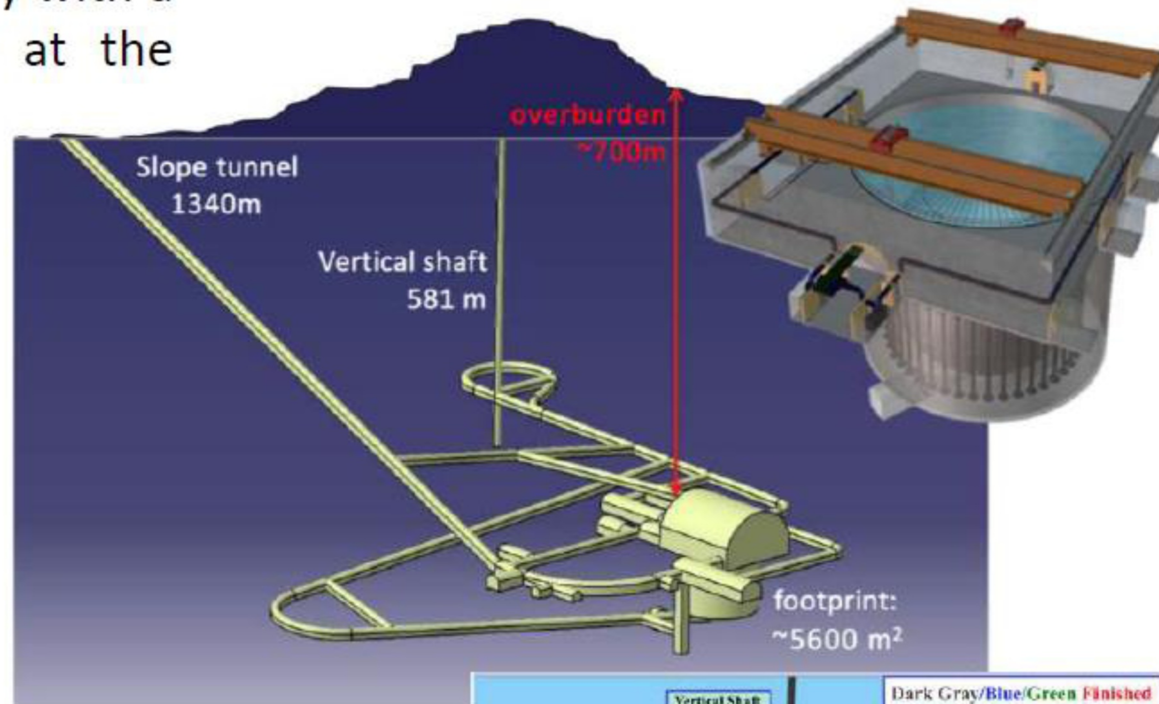


Cable Loop System

Strategy:
- Many sources (LS non-linearity)
- Tunable photon source (electronics non-linearity)
- Many locations (detector non-uniformity)

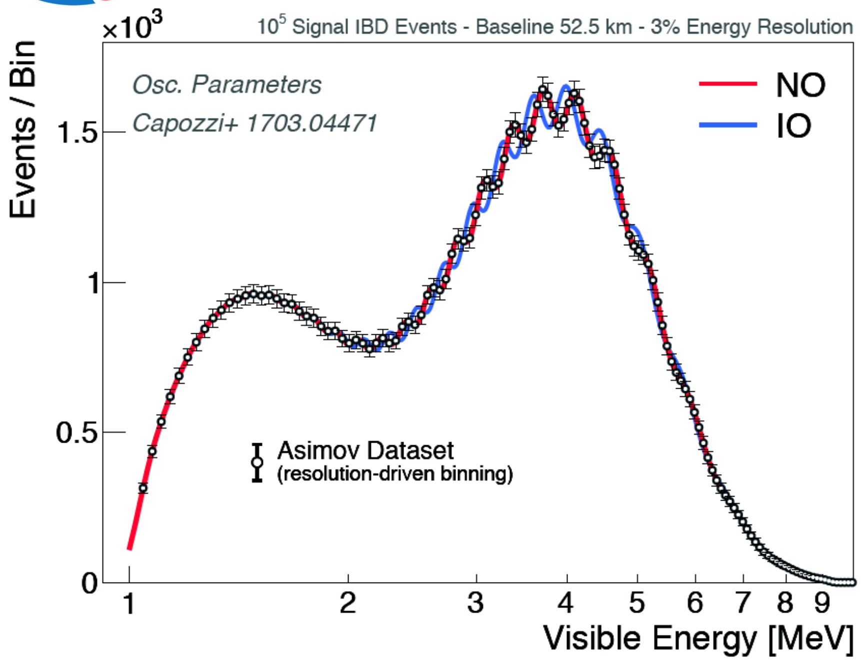
Civil construction

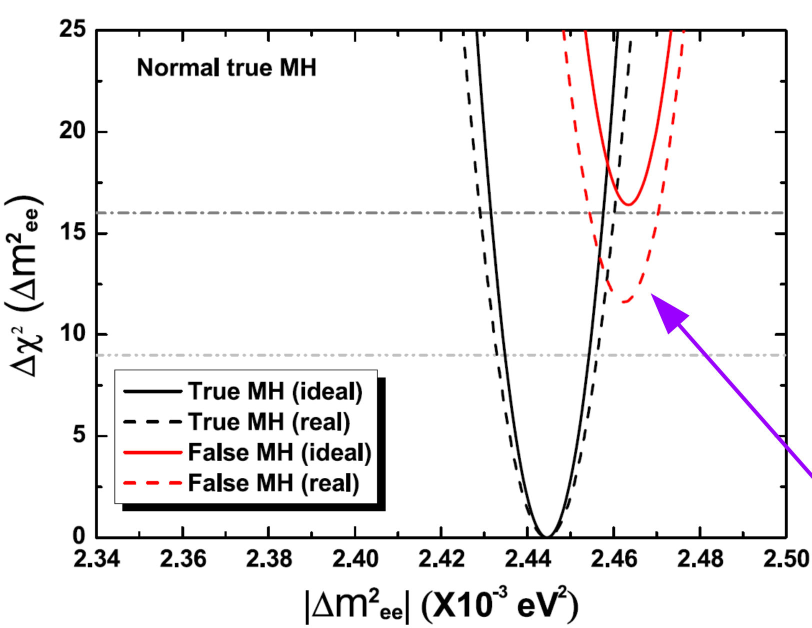
Since 2015 a new underground laboratory with a 700 m overburden and infrastructure at the surface is under construction



Vertical shaft and slope tunnel completed

Sensitivity of νMO determination





Fit data against both models

Systematics induced by:

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

Sensitivity estimation

Assume NH as true MH, and fit the spectrum with false and true MH cases respectively, to get:

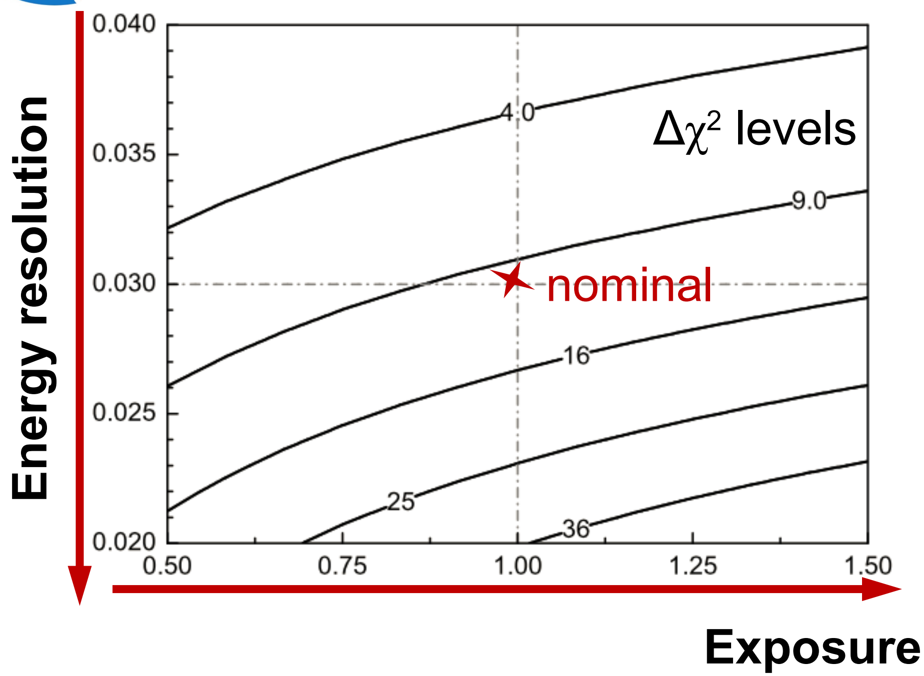
$\Delta\chi^2 = \chi^2(\text{false}) - \chi^2(\text{true})$

$$\chi^2_{\text{REA}} = \sum_{i=1}^{N_{\text{bin}}} \frac{[M_i - T_i(1 + \sum_k \alpha_{ik}\epsilon_k)]^2}{M_i} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2}$$

$$\Delta\chi^2_{\text{MH}} = |\chi^2_{\text{min}}(\text{N}) - \chi^2_{\text{min}}(\text{I})|$$

degradation due to real reactor core distribution

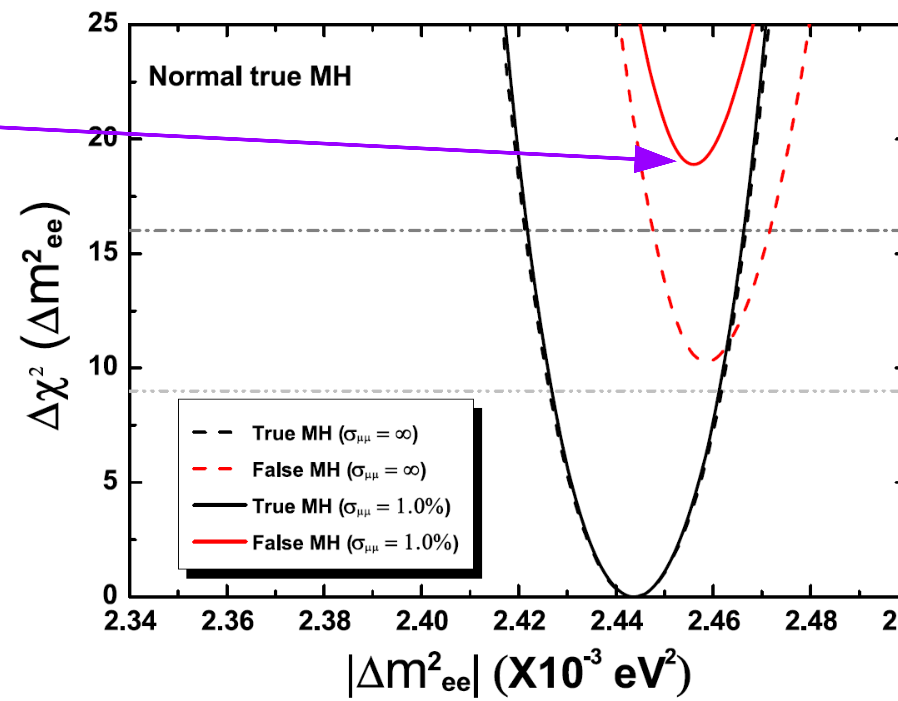
JUNO sensitivity (6 years of data)



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

1) Daya Bay & Huizhou reactors
2) Background to Signal

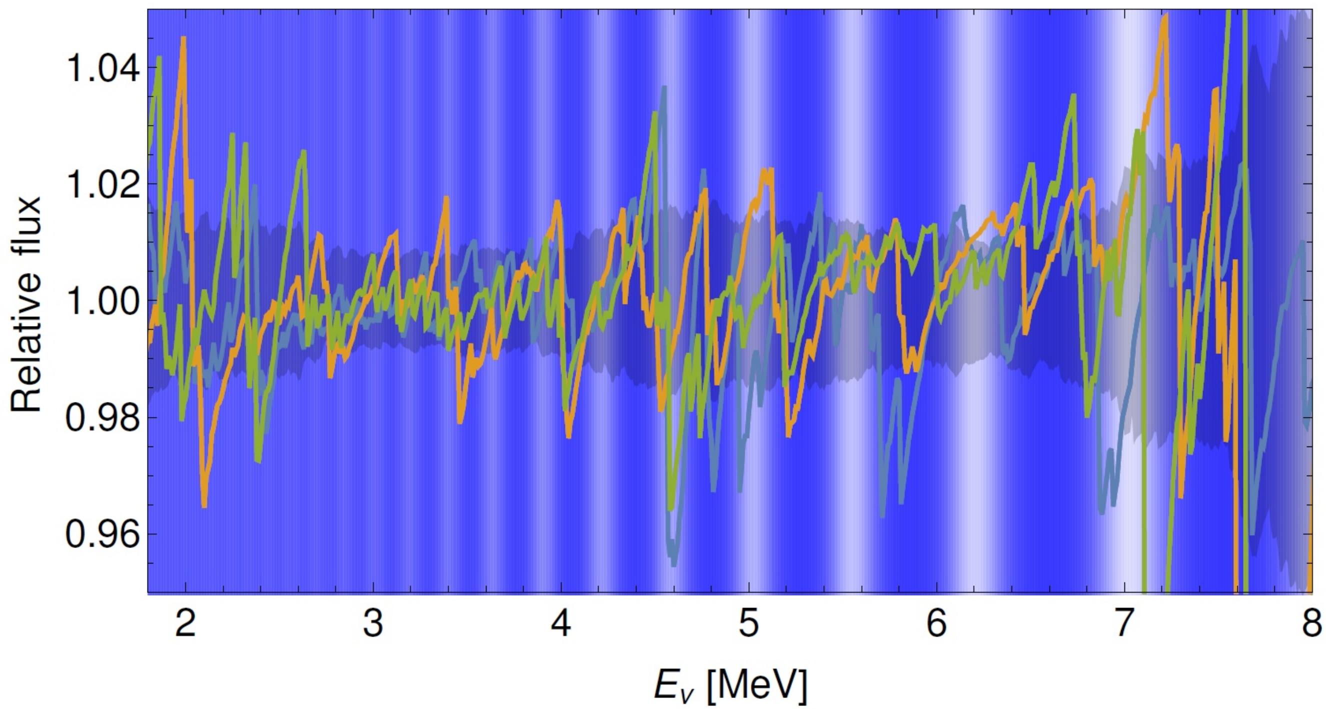
Sensitivity improvement from $\Delta m^2_{\mu\mu}$



- $\nu_\mu \to \nu_e$ (appearance) channel can also determine the NMO
- T2K+NOvA precision assumed ~ 1%
- Combining T2K+NOvA (both disappearance and appearance) with JUNO: sensitivity improves to 4σ to 5σ or better

Substructures in the reactor spectrum

- Large scale fine structures constrained by Daya Bay experiment
- **A known fine structure does not hurt JUNO MH determination**
  ⇒ Tested with multiple spectra with fine local structure from ab initio calculation (PRL 114:012502, 2015) → no major effect on JUNO sensitivity
- **Unknown fine structure might have a larger impact**



Relative difference of 3 synthetic spectra to ILL data (Huber-Muller model)

arXiv:1710.07378

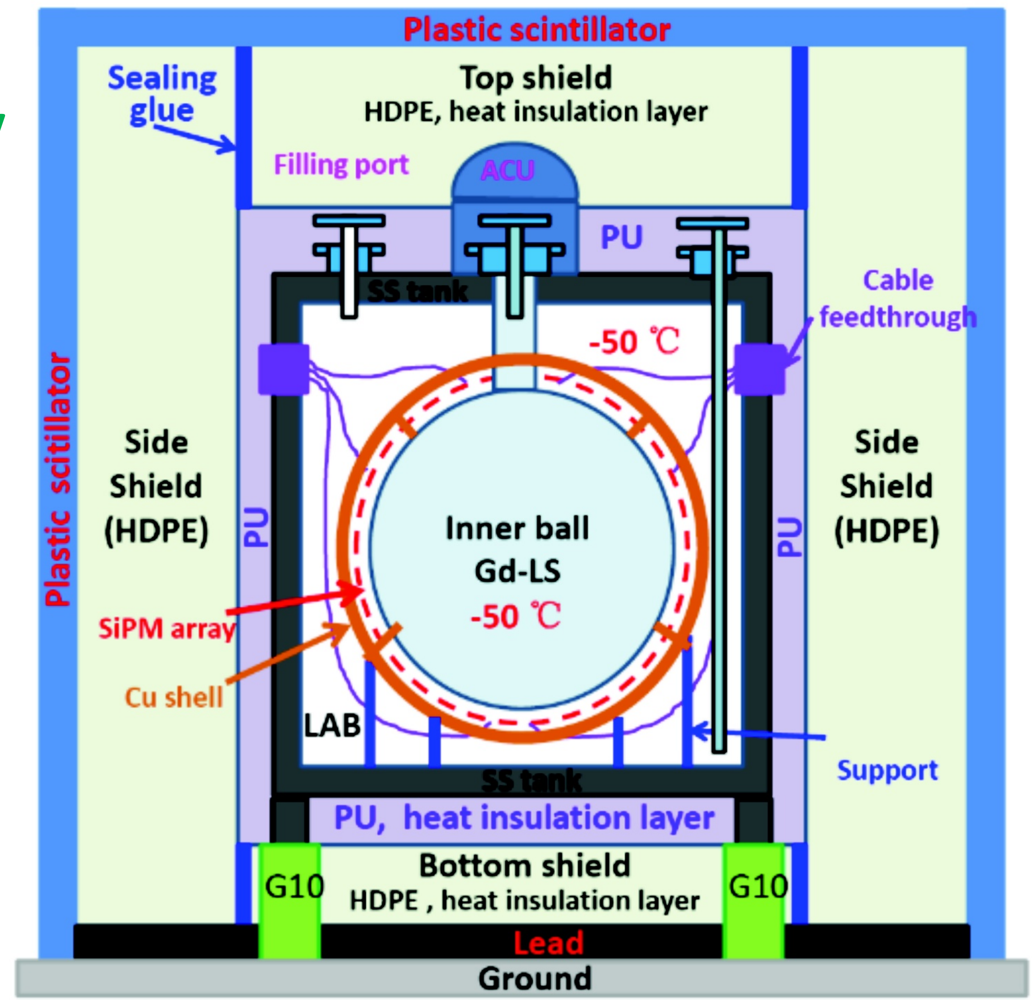
Fine structure depends on the ab-initio calculation using nuclear database and can not be precisely determined.

JUNO-TAO

Taishan Antineutrino Observatory (TAO), a satellite exp. of JUNO.

Measure reactor neutrino spectrum with unprecedented E resolution: ~1.5% / $\sqrt{E}$ [MeV]
Provide model-independent reference spectrum for JUNO

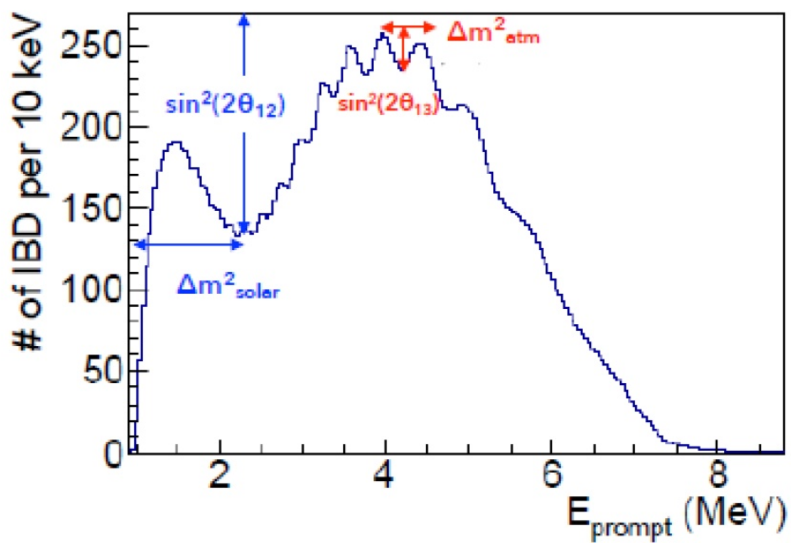
- **2.6 ton Gd-LS in a spherical vessel**
  - **1-ton Fiducial Volume, 4000 ν's/day**
  - **10 m² SiPM of 50% PDE**
- **Operate at -50°C**
- **From Inner to Outside**
  - **Gd-LS working at -50°C**
  - **SiPM and support**
  - **Cryogenic vessel**
  - **1~1.5 m water or HDPE shielding**
  - **Muon veto**
  - **Laboratory in a basement at -10 m,**
- **30-35 m from Taishan core (4.6 GW_{th})**
- **Plan to be online in 2021**



Precision measurement of oscillation parameters

Current precision

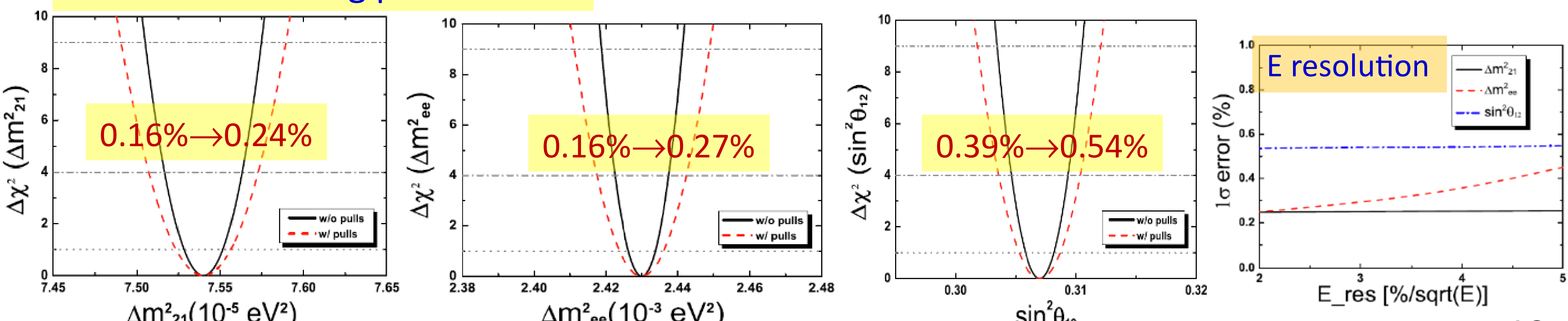
	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%



	Statistics	+BG, +1% bin-to-bin +1% EScale , +1% EnonL
$\sin^2\theta_{12}$	0.54%	**0.67%**
Δm^2_{21}	0.24%	**0.59%**
Δm^2_{ee}	0.27%	**0.44%**

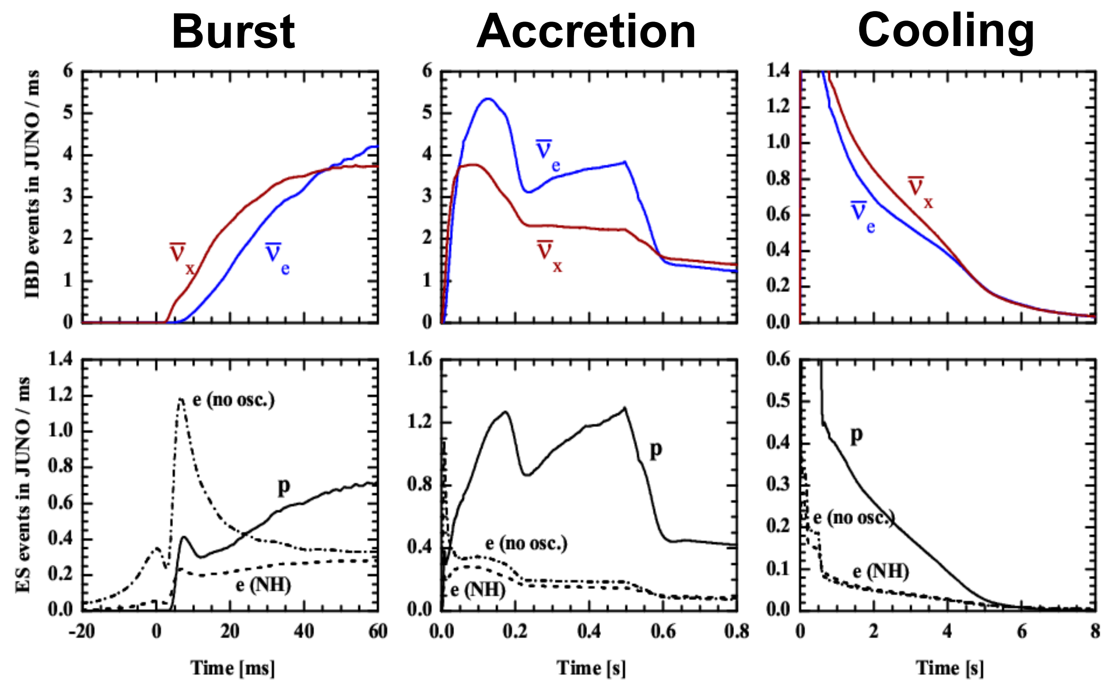
Probing the unitarity of U_{PMNS} to ~1%

Correlation among parameters:



Supernova (SN) burst neutrinos

- Core collapse SN emits 99% of energy in form of ν
- Galactic core-collapse SN rate: ~ 3 per century
- JUNO will be able to observe the 3 SN phases from core-collapses happening in our own Galaxy and its satellites
- JUNO will be able to make a real time detection of SN bursts and take part in international SN alert, e.g. SNEWS



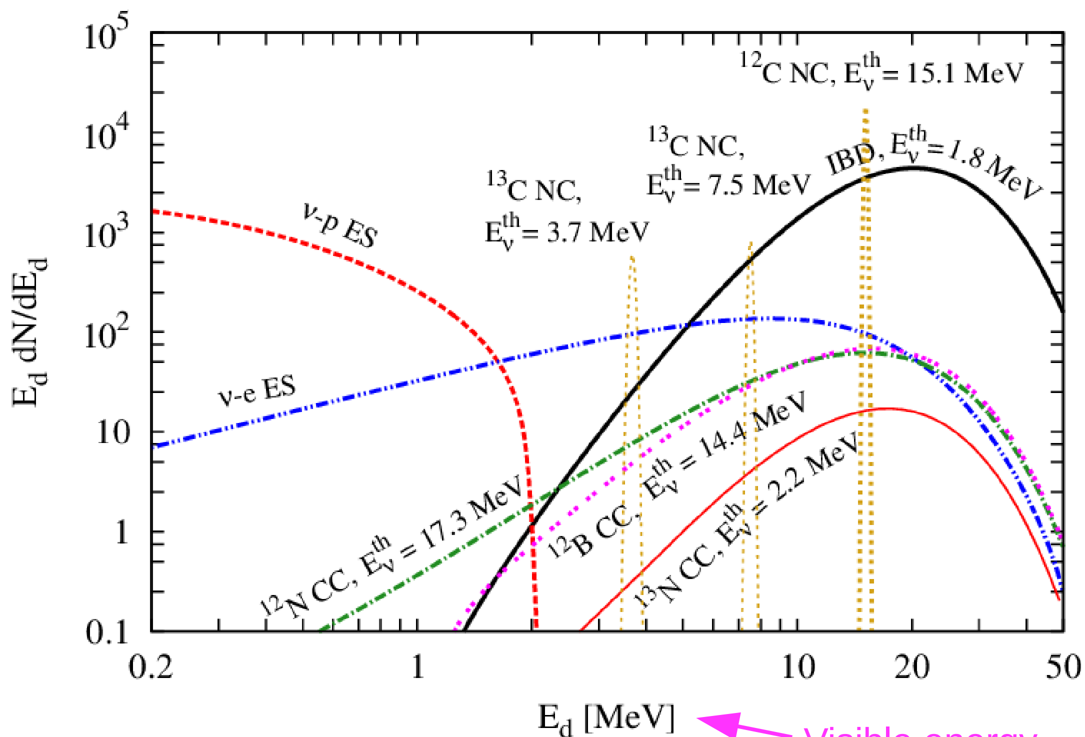
Detection channels in JUNO

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

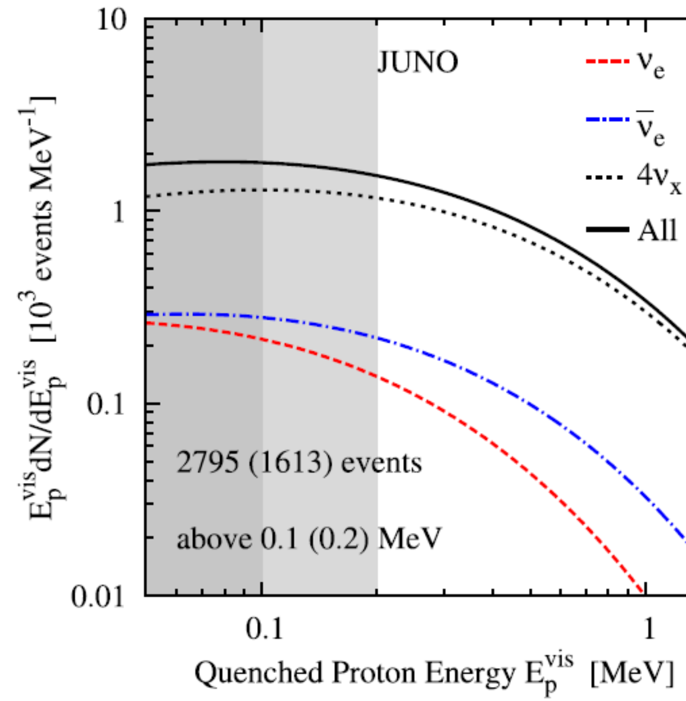
IBD main detection channel: ~5000 events from a SN at a distance of 10 kpc

Supernova (SN) burst neutrinos

The measurement is almost background free, since SN burst ν lasts for ~10 s



Visible energy

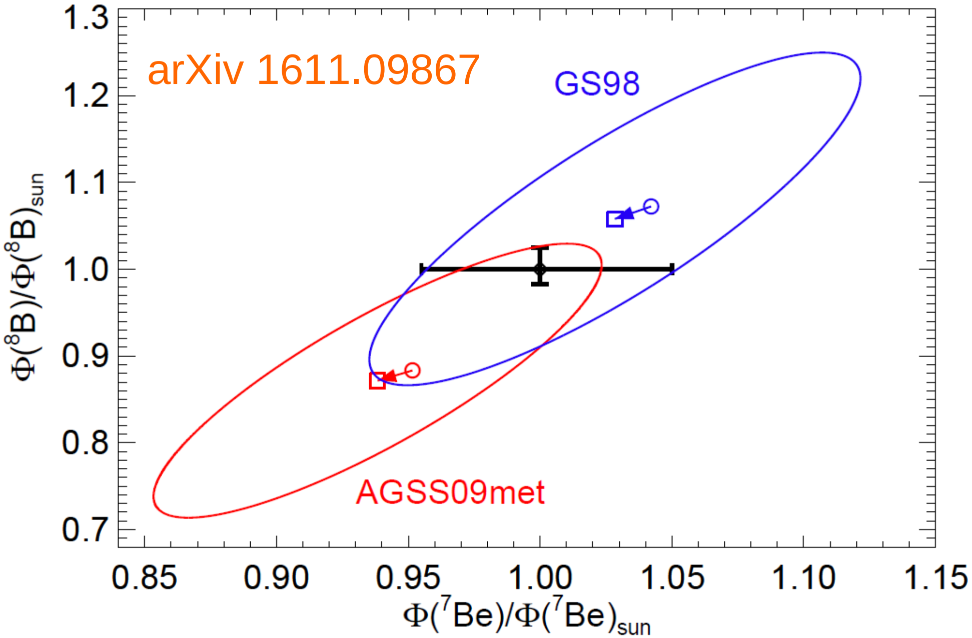


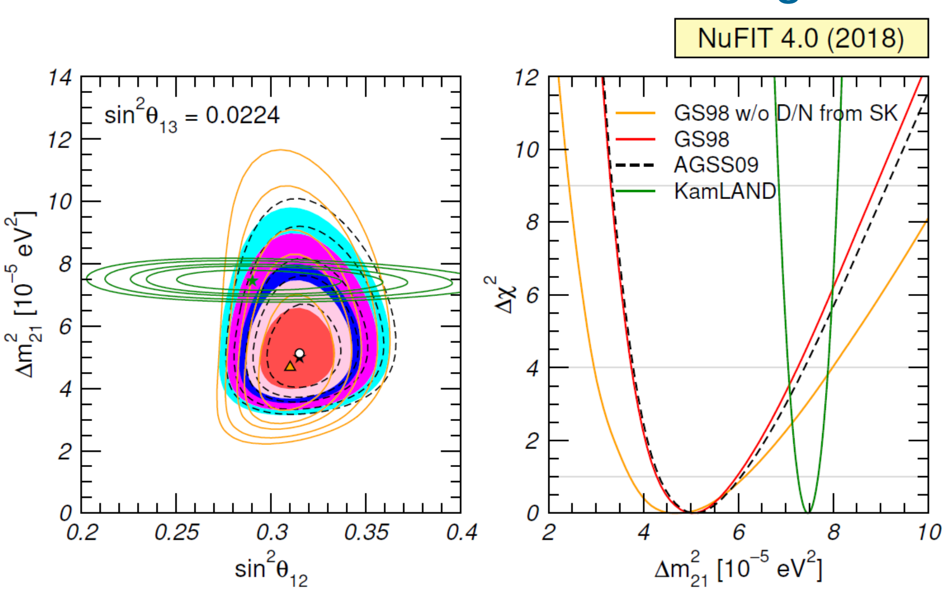
- Full flavor detection and low energy threshold, ~0.2 MeV in LS
- pES is a promising channel, which can provide more informations with respect to other type of detectors (e.g. WC, Lar-TPC)
- Pulse Shape Discrimination (PSD) to distinguish between eES and pES

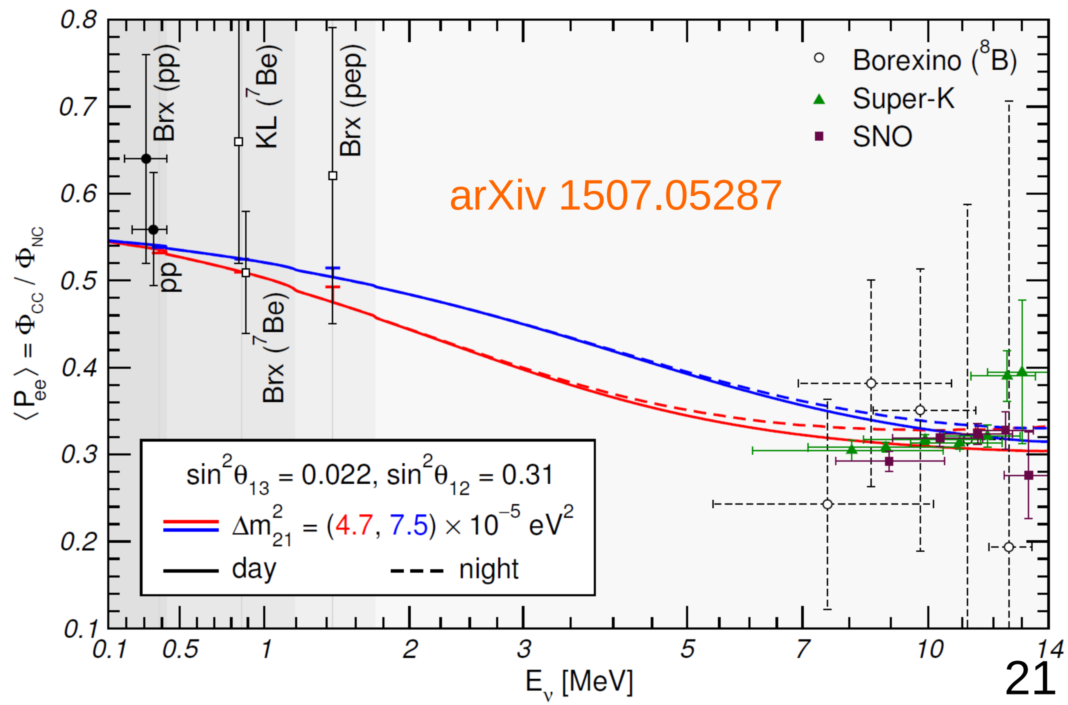
Solar neutrinos

Open issues to be investigated by JUNO:

- Better determination of the oscillation parameters, to test the mild tension between solar and reactor data
- Solution to the solar metallicity problem by improving the accuracy on ^{7}Be and ^{8}B fluxes
- Analysis of the energy dependence of the ν_e survival probability (up-turn in ^{8}B spectrum) to study the transition from vacuum to matter dominated regions







Solar neutrinos

Main detection channel: elastic scattering

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$

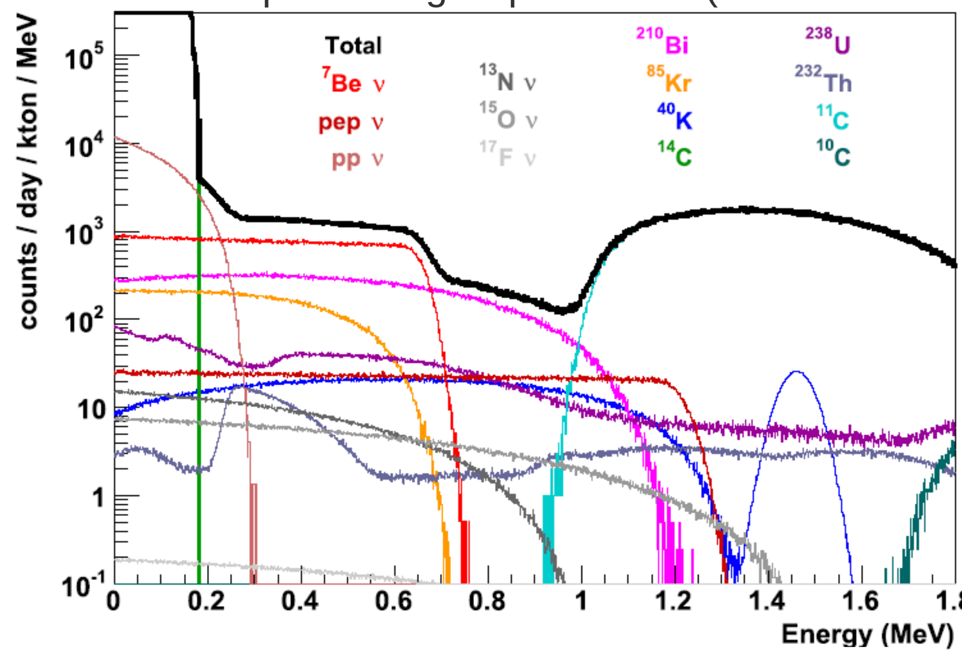
Radioactive background is a severe challenge

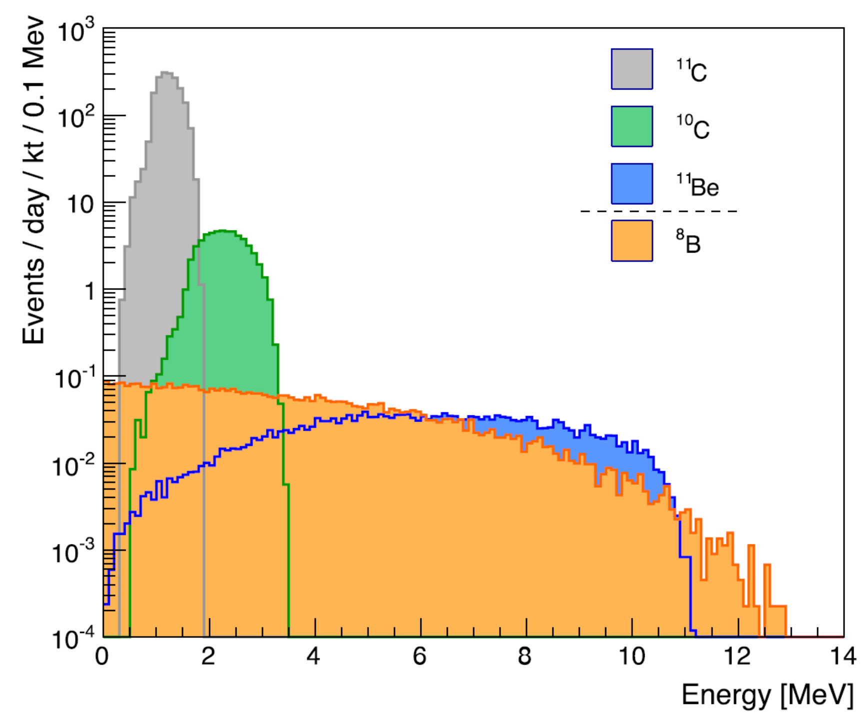
→ required internal radiopurity of LS:
10^{-15} g/g U/Th, 10^{-16} g/g K baseline
10^{-17} g/g U/Th, 10^{-18} g/g K solar phase
→ better muon veto approach

Three main observables:

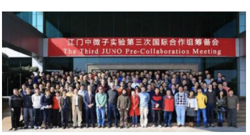
- Electron kinetic energy spectrum
- Day-night asymmetry
- ν_e - ^{13}C charged-current channel (E_{th}~2.2 MeV) [for the first time]

with solar phase bkg requirements (see JUNO-YB)





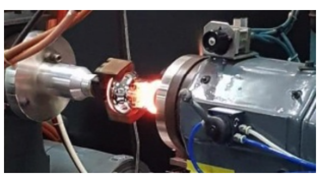
Schedule and milestones



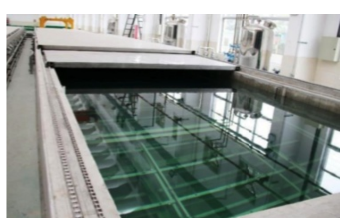
2014

- Int. Collaboration established!

2015



- PMT production line setup
- Start civil construction
- CD parts R&D



2016

- Start PMT production
- Start CD parts production

2017

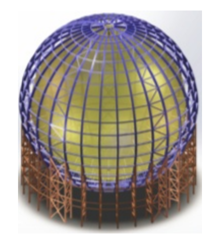
- Start PMT testing
- Top Tracker arrived!
- Daya Bay LS tests

2018

- PMT potting start
- Delivery of surface buildings
- Start production of acrylic sphere
- OSIRIS was funded
- TAO working group formed

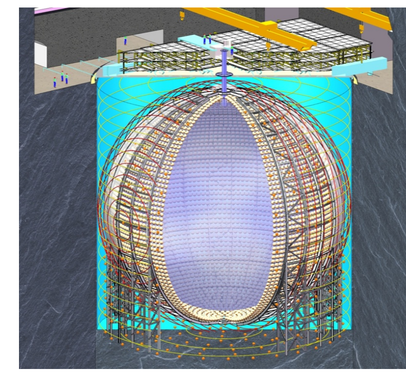
2019-20

- Electronics production starts
- Civil work and lab preparation completed
- Detector construction



2021

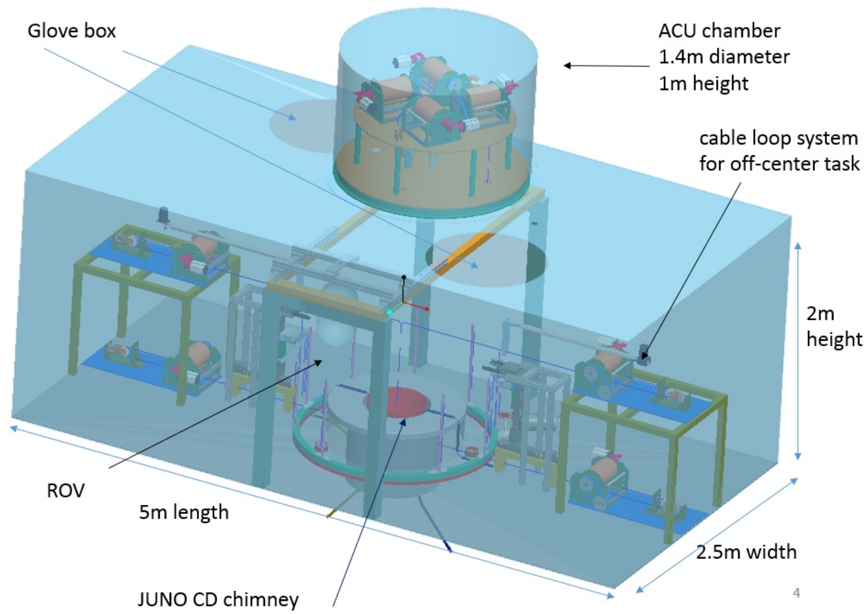
- Detector filled & comissioned
- TAO ready
- Detector ready

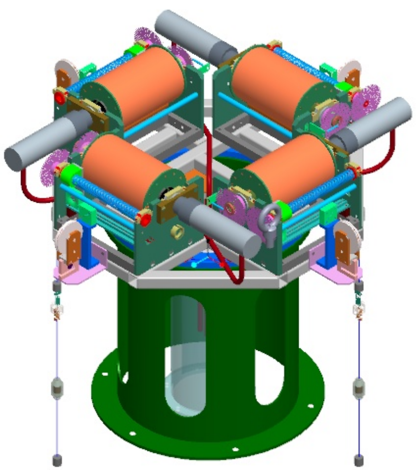


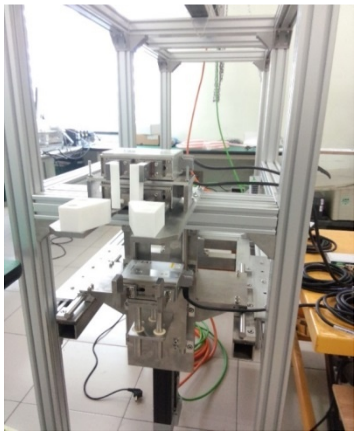
Data Taking

Calibration system

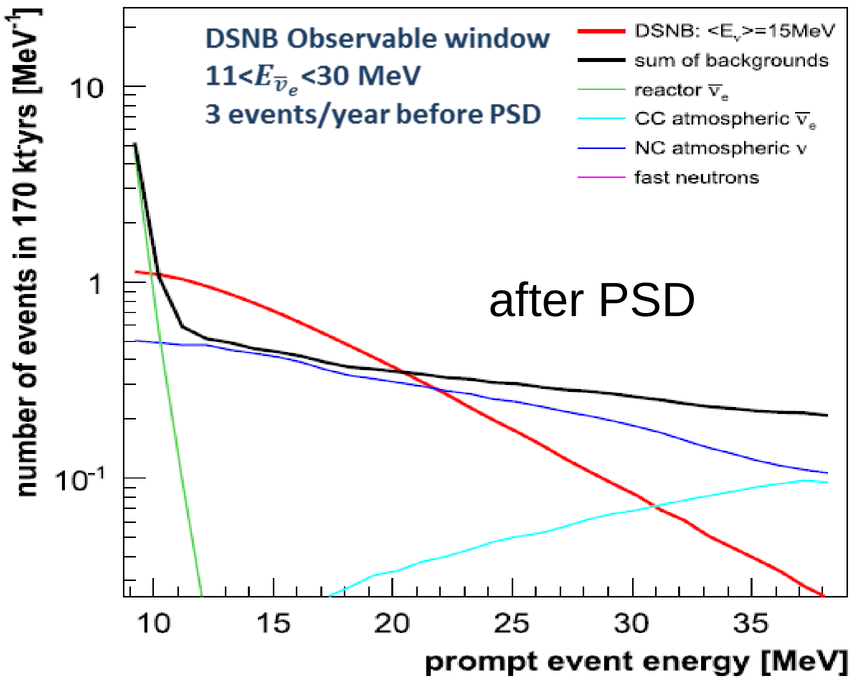
- **Main method**
  - ⇨ Routinely Source into LS by
    - ✓ ACU: at central axis
    - ✓ rope loop: a plane
  - ⇨ Source into Guided tube
  - ⇨ "sub-marine": anywhere in the LS
- **Choice of sources & location scan**
  - ⇨ Simulation shows that the response map of the detector can be obtained
- **R&D on key technical issues**
  - ⇨ Source deployment
  - ⇨ Source locating system

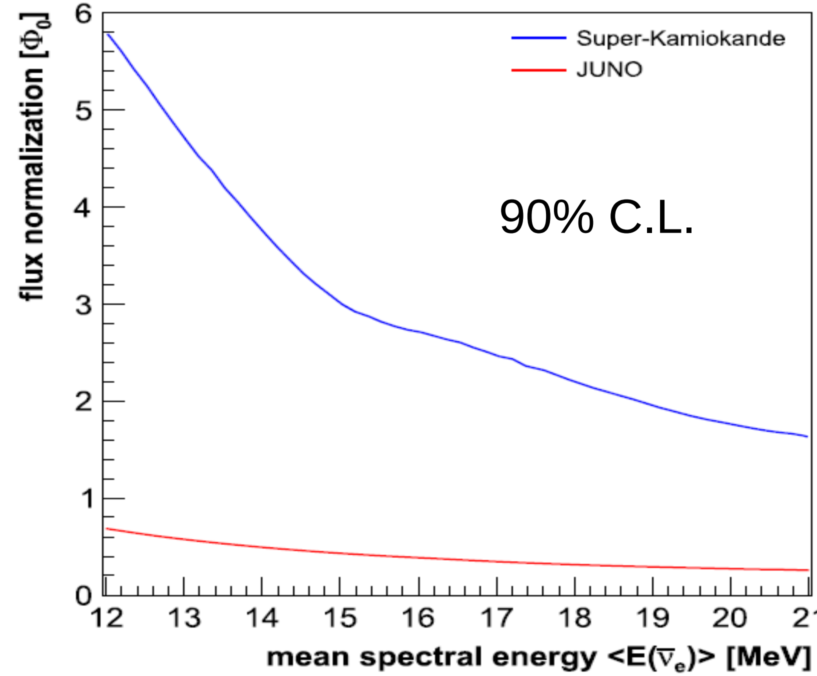






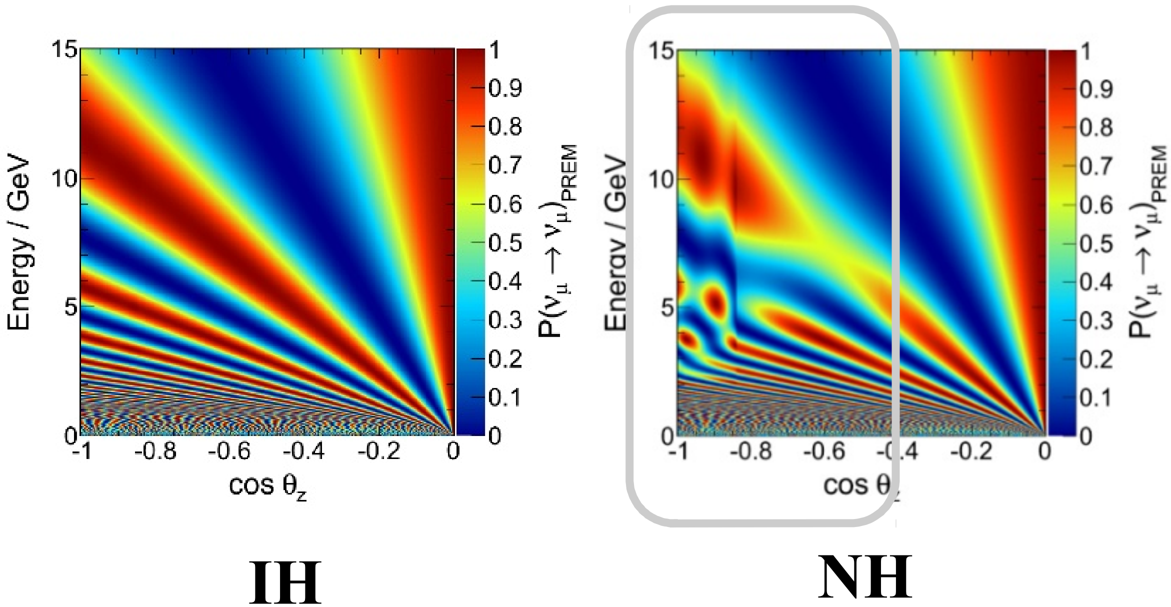
Diffused Supernova ν background (DSNB)



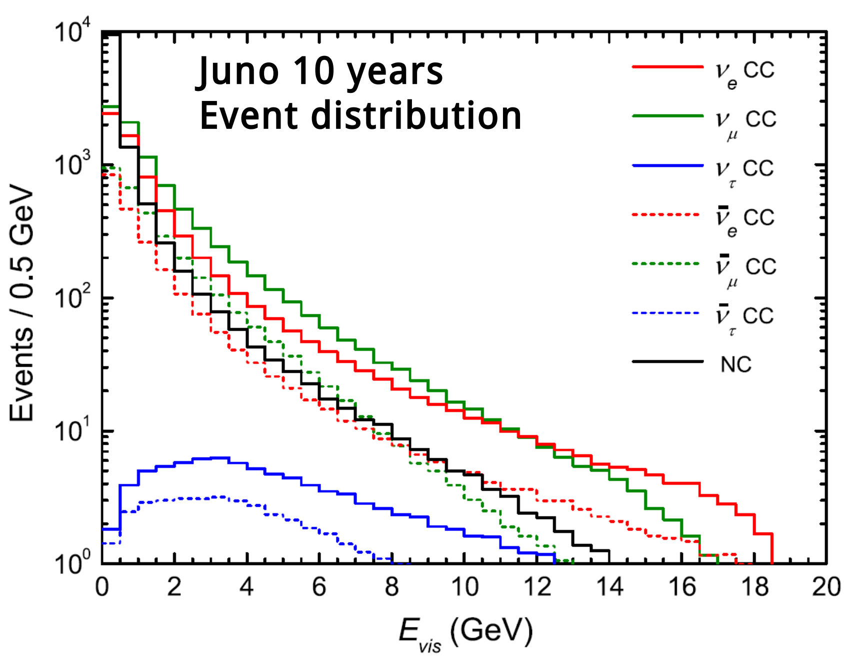


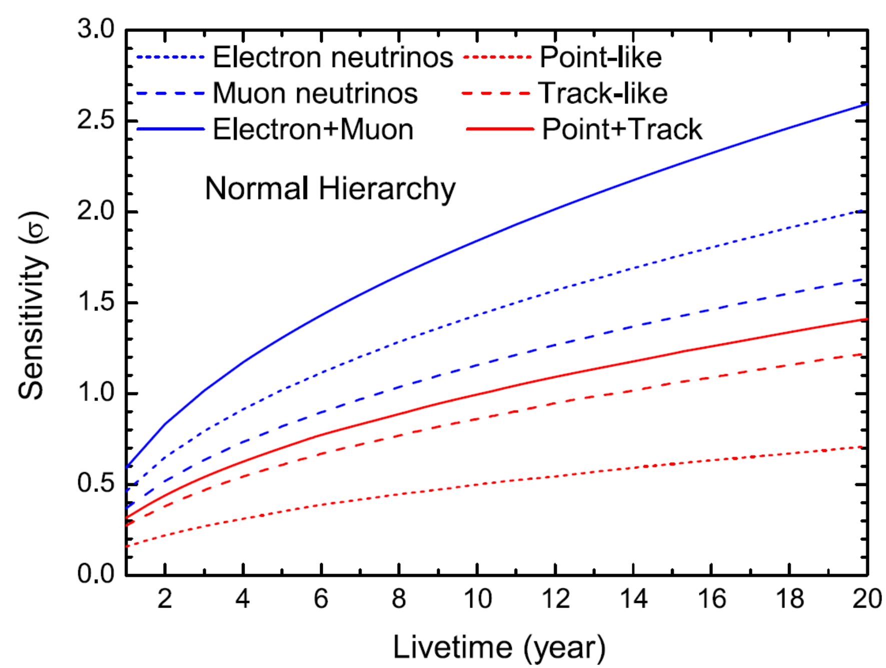
- DSNB rate: approx. **10 core collapse/sec** in the visible universe
- Provide information of star formation rate, emission from average CCSNe and BHs.
- **Pulse Shape Discrimination** to suppress background, mainly **atmospheric neutrinos**
- The expected **detection significance is ~3σ** after 10 years of data taking in JUNO, with ~15 MeV, background systematic uncertainty ~20%

Atmospheric neutrinos



- **Sensitive to MH and θ_{23}**
- MH determination via matter effect
- Complementary to MH with reactor neutrinos
- 1-2 σ for 10 years data taking
- θ_{23} accuracy of 6 deg

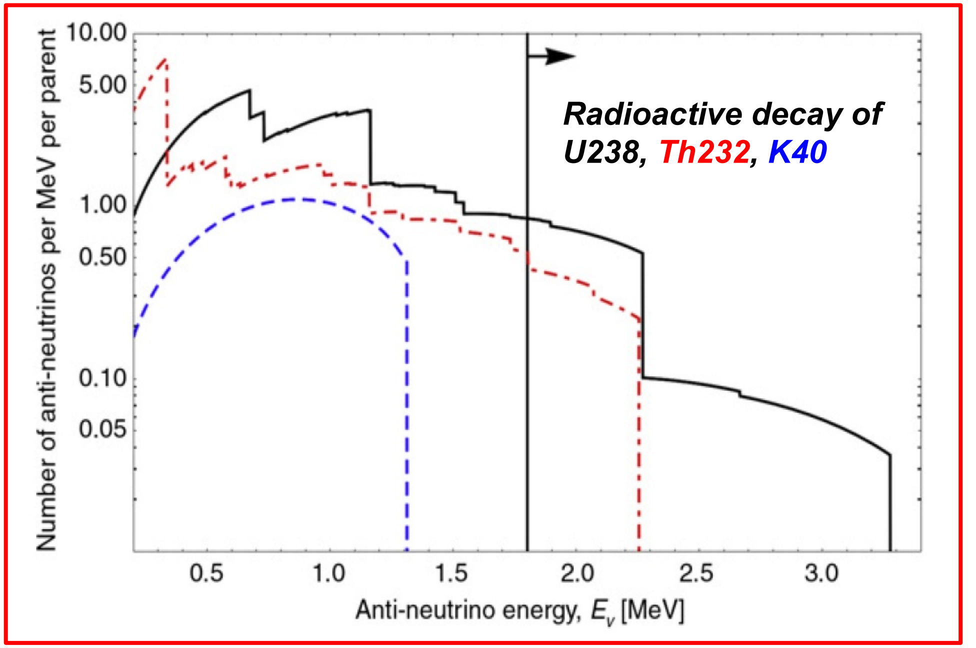




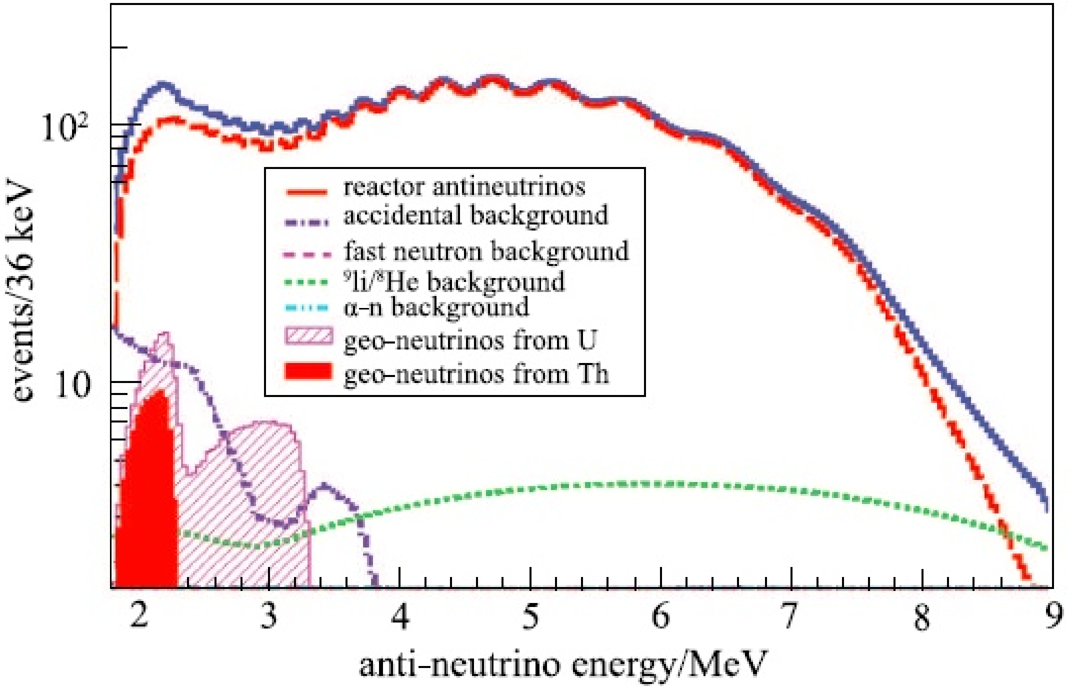
Geo-neutrinos

Geo-ν as a tool to explore the composition of the Earth and to estimate the amount of radiogenic power driving the Earth's engine

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\beta^- + 6\bar{\nu}_e$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\beta^- + 4\bar{\nu}_e$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \beta^- + \bar{\nu}_e$$



Detection channel: IBD



- Expected 400-500 IBD/y, larger than all accumulated geo-ν events before
- Challenge: reactor-ν background, ~40 times larger
- Precision will go from 13% (1 year) to 5% (10 years)
- Measure U/Th ratio at percent level
- Interdisciplinary team of physicists and geologists at work to develop a local refined crust model (required to get information on the mantle)

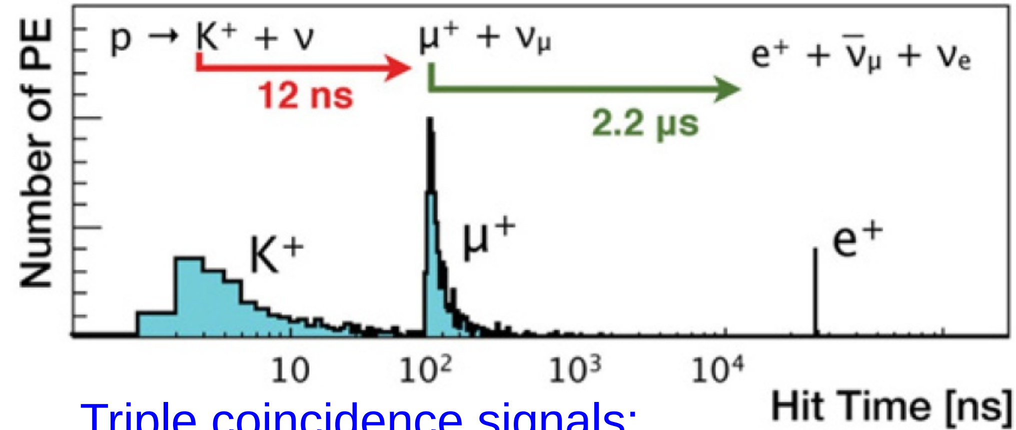
Proton decay

- Two possible decay channels:

$p \rightarrow \pi^0 + e^+$ (favored by GUT)

$\boldsymbol{p \rightarrow K^+ + \upsilon}$ (favored by SUSY)

- Current best limits set by the Super-Kamiokande experiment
- Kaon is invisible in a water Cherenkov detector
- JUNO will focus on the K decay mode to take advantage of the LS technique



Triple coincidence signals:

1st: $T_{K^+} = 105$ MeV $\rightarrow \tau_{K^+} = 12.38$ ns

2nd: $T_{\mu^+} = 152$ MeV$/E_{\pi^+\pi^0} = 494$ MeV

3rd: $2.2\mu s \rightarrow$ Michel electron