The Jiangmen Underground Neutrino Observatory

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The 4th Geo-neutrino Joint Meeting

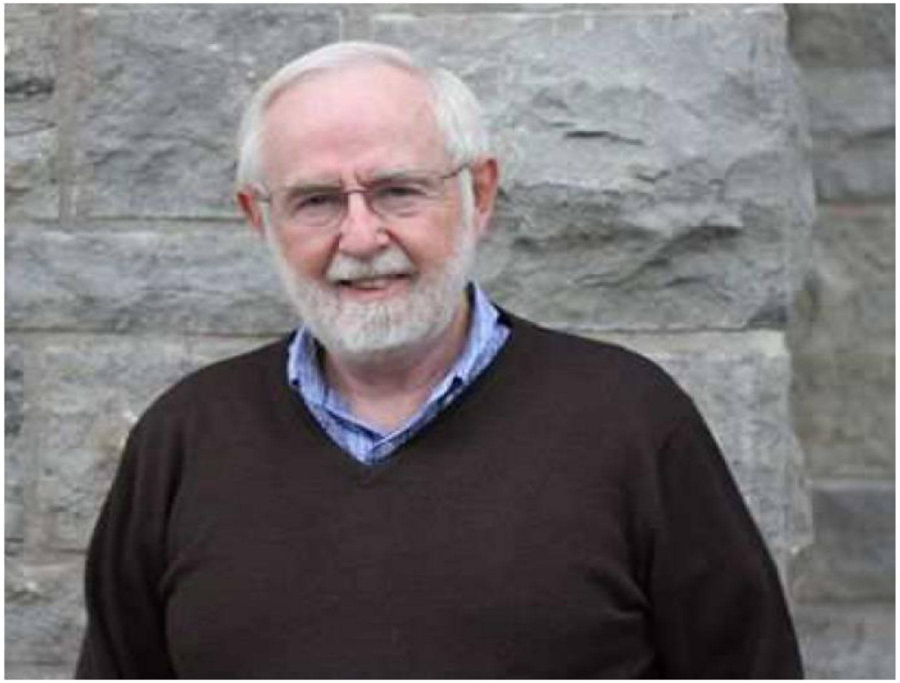
Discovery of Neutrino Oscillations

1998: Oscillations of atmospheric neutrinos observed by the Super-Kamiokande experiment

Takaaki Kajita
2015 Physics Nobel Prize

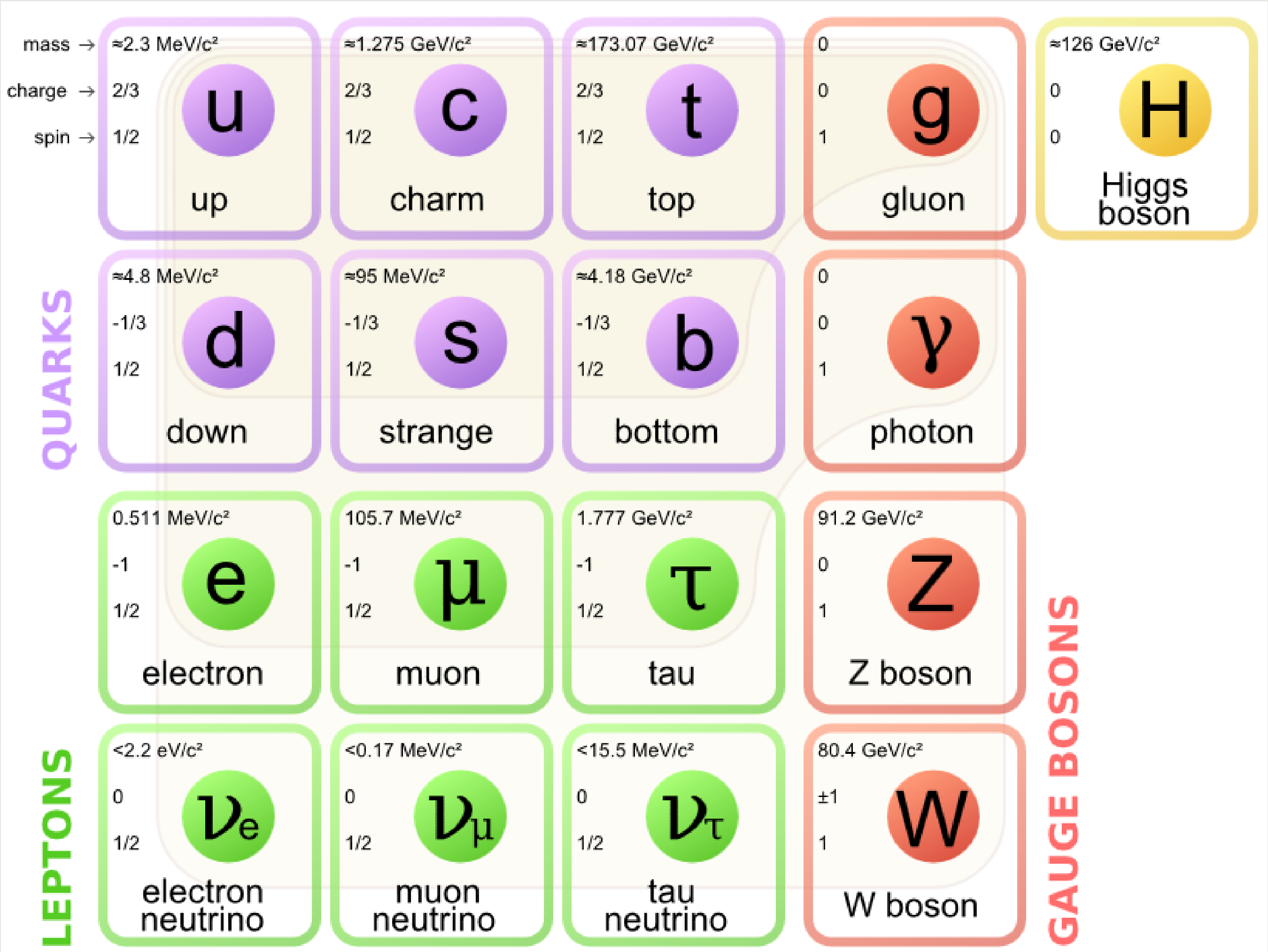
2002: Oscillations of solar neutrinos observed by the SNO experiment

Arthur B. McDonald
2015 Physics Nobel Prize



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Standard Model



Standard Model of Elementary Particles:

a) Three generations of quarks and leptons

b) Gauge bosons as force carriers:

strong interaction (8 gluons)

Weak interaction (W & Z)

Electromagnetic interaction (γ)

Gravitation (Graviton?)

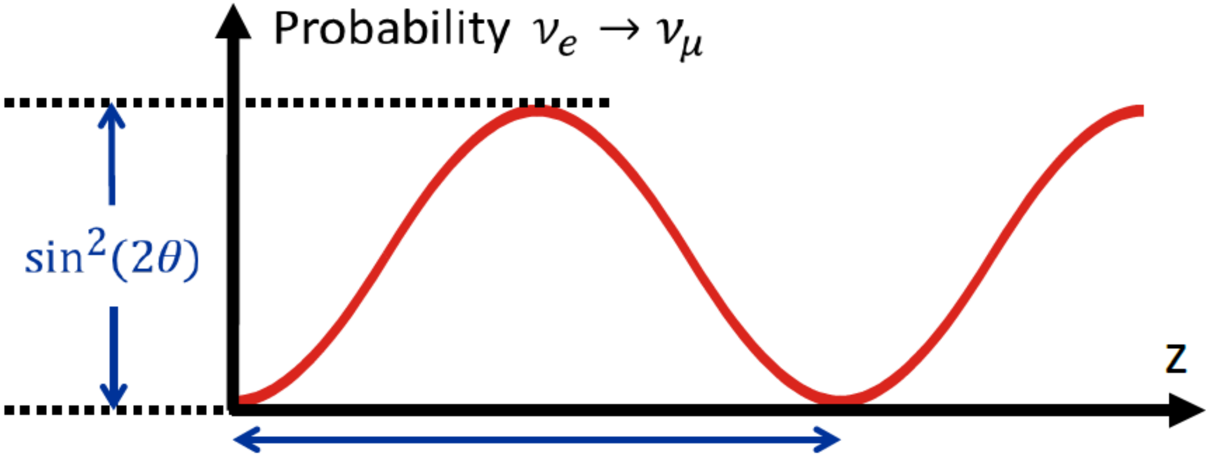
Massive neutrinos are already the Physics beyond the Standard Model

Neutrino Oscillation Theory

Two-flavor mixing $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

Pontecorvo, 1957; Maki, Nakagawa, Sakata, 1962

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



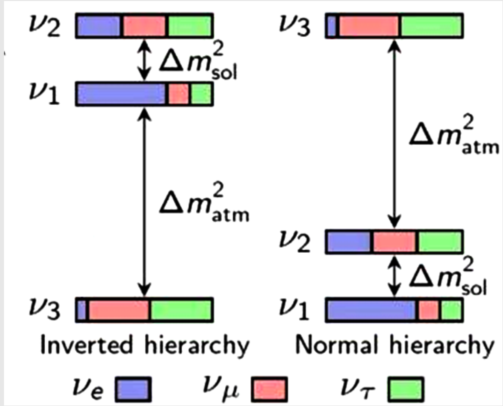
Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\ \text{m}\ \frac{E}{\text{MeV}} \left(\frac{\text{eV}}{\delta m}\right)^2$

Bruno Pontecorvo (1913–1993) Invented ν oscillations

Neutrino Oscillations: quantum phenomena of massive neutrinos at the macroscopic distances

Neutrino Oscillation Parameters

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



$2.4 \cdot 10^{-3} \mathrm{eV}^2$

$7.5 \cdot 10^{-5} \mathrm{eV}^2$

- **3 mixing angles**
- **1 CP phase**
- **2 mass-squared differences**

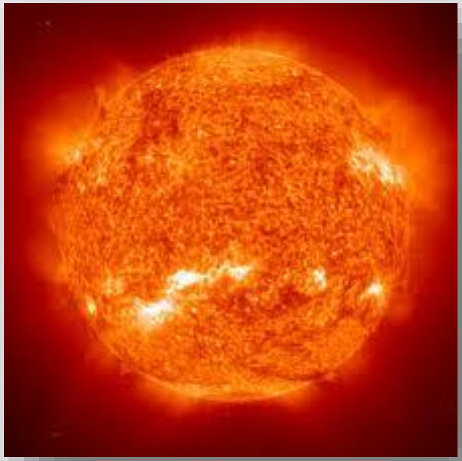
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45°$
Atmospheric
Accelerator

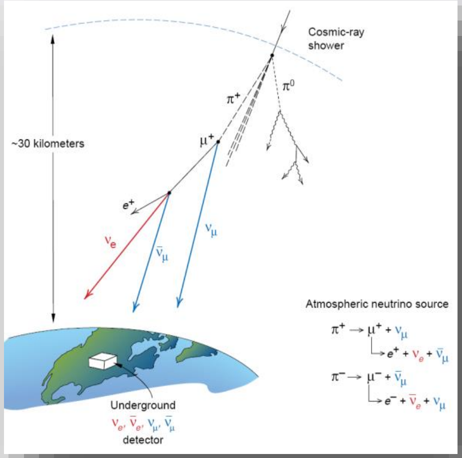
$\theta_{13} \sim 9°$
Reactor
Accelerator

$\theta_{12} \sim 34°$
Solar
Reactor

Neutrino sources



θ_{12} Δm^2_{21}

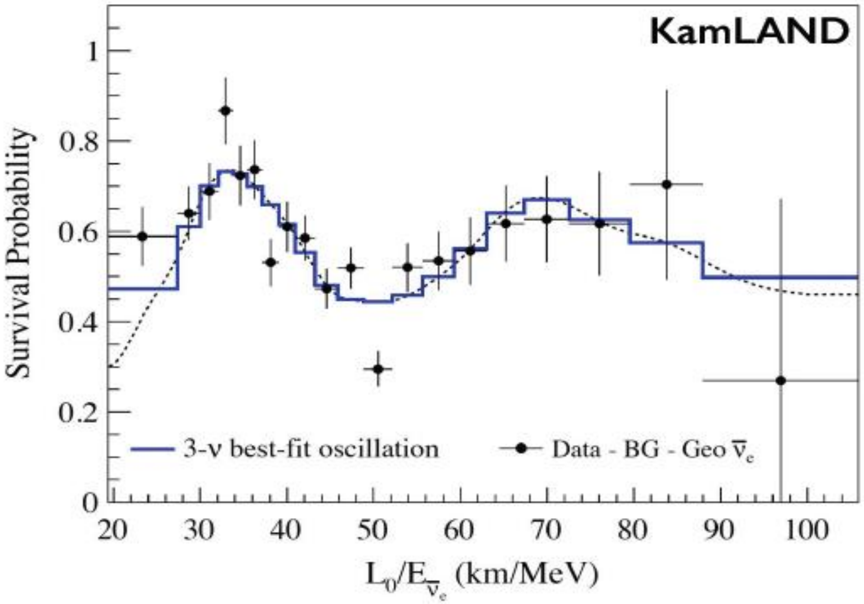


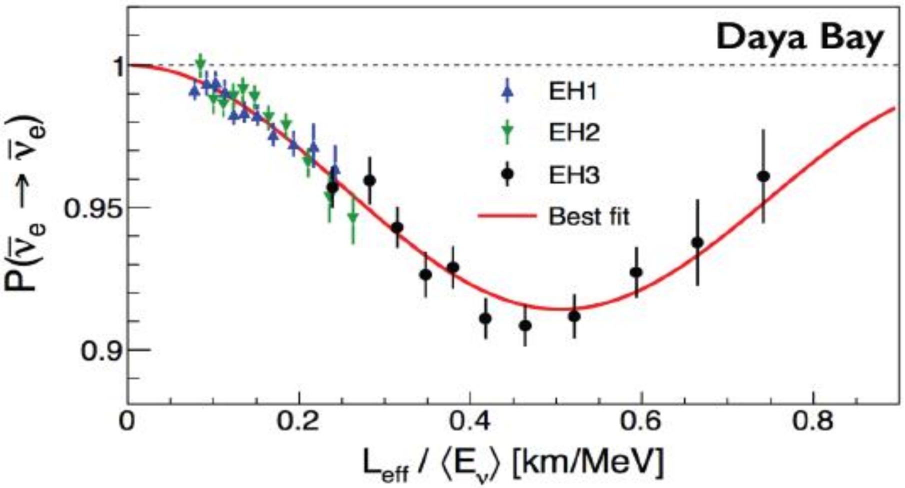
θ_{23} Δm^2_{32}

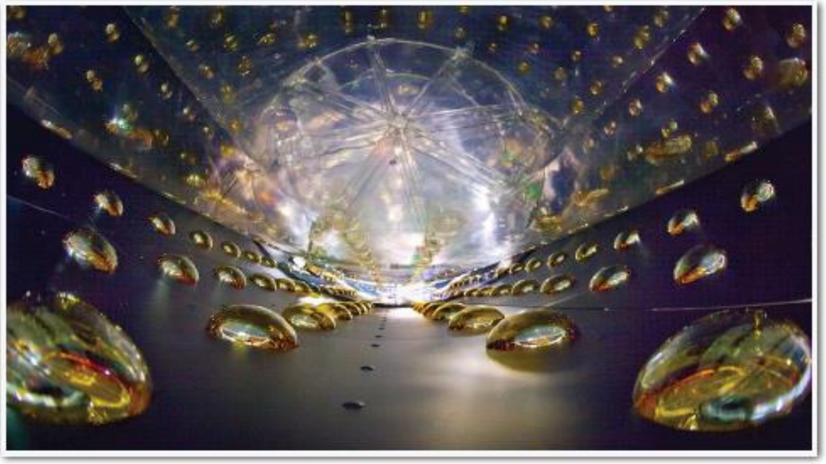
θ_{23} Δm^2_{32} θ_{13} δ

θ_{13} Δm^2_{31} θ_{12} Δm^2_{21}

Neutrinos DO oscillate



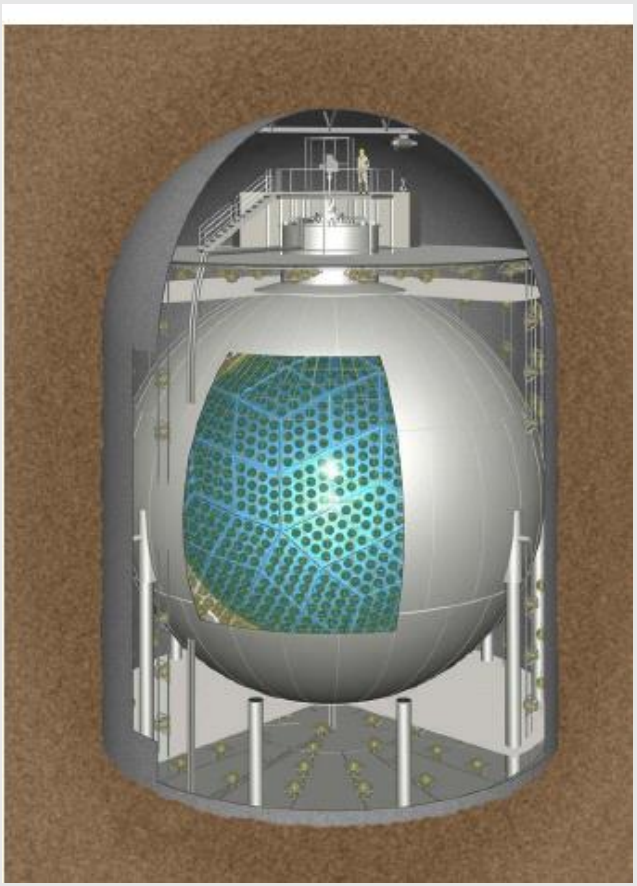




Observation of geo-neutrinos

First observed in 2005 by KamLAND, then in 2010 by Borexino

KamLAND, Japan (1kt)

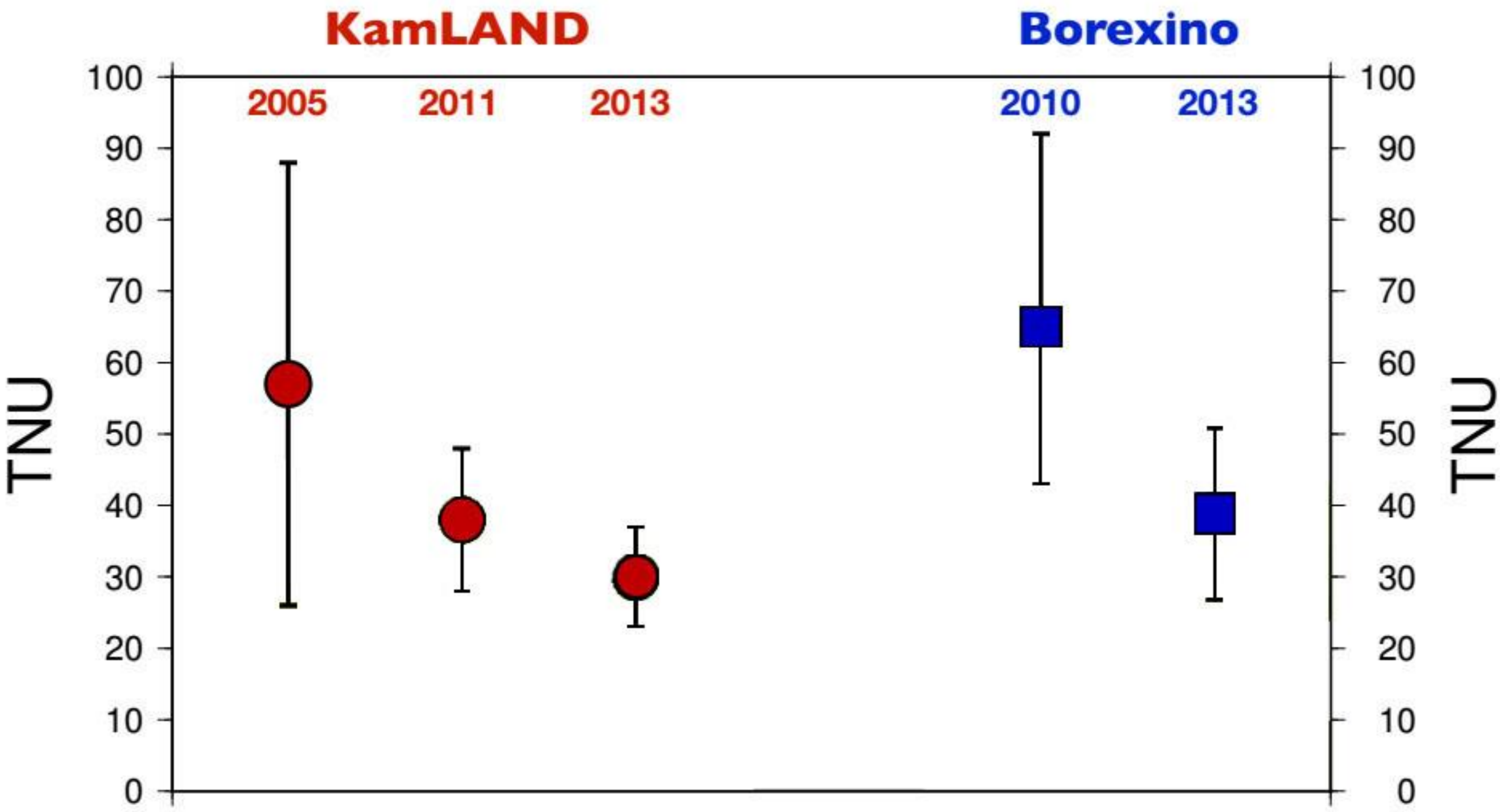


~1 event/30 days

Borexino, Italy (0.6kt)

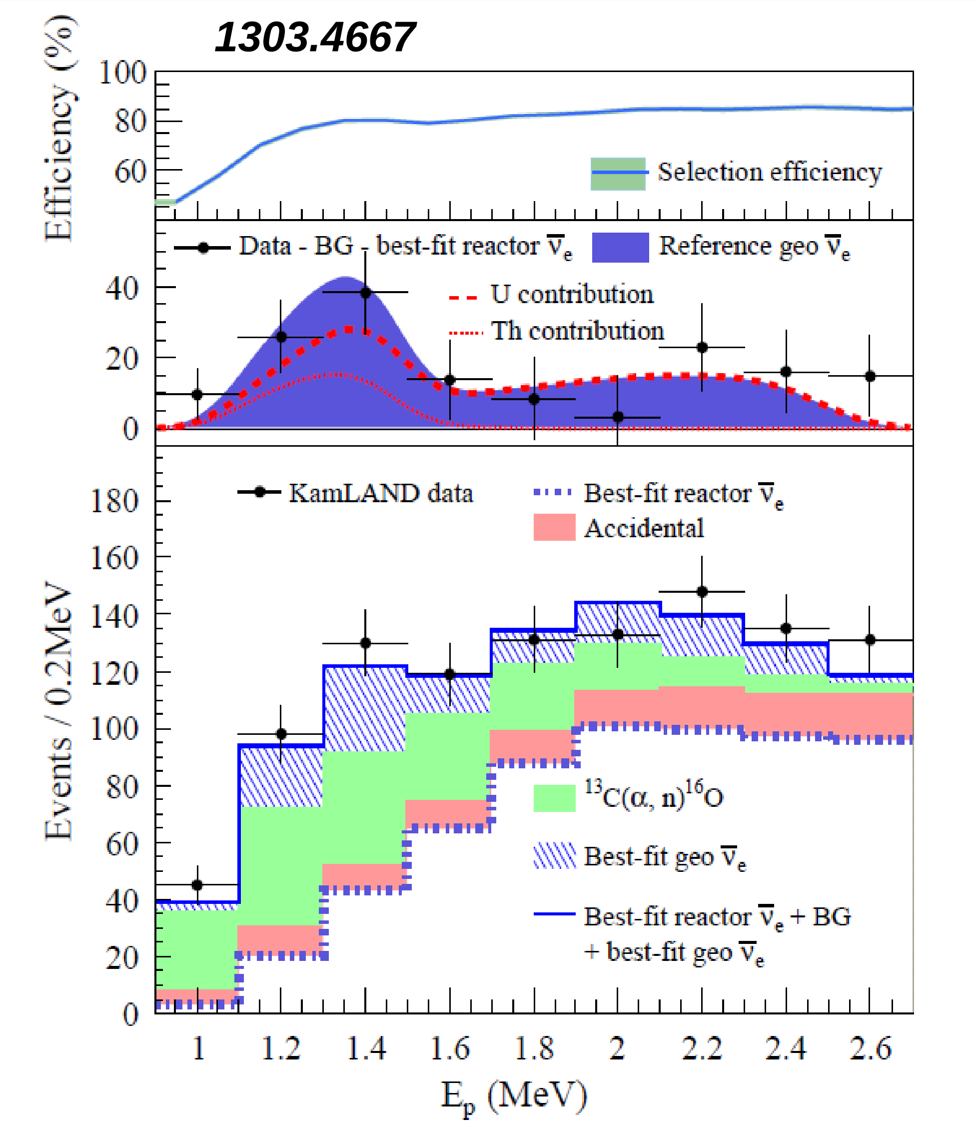
~1 event/70 days

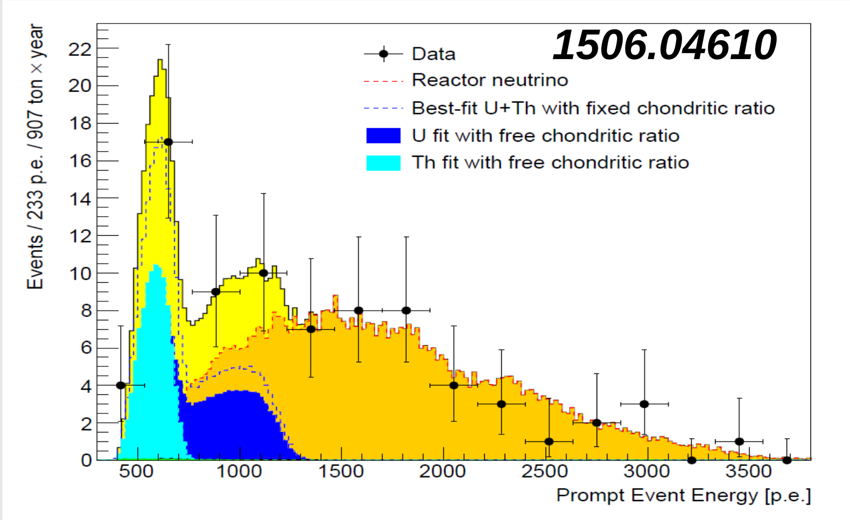
Current experimental status

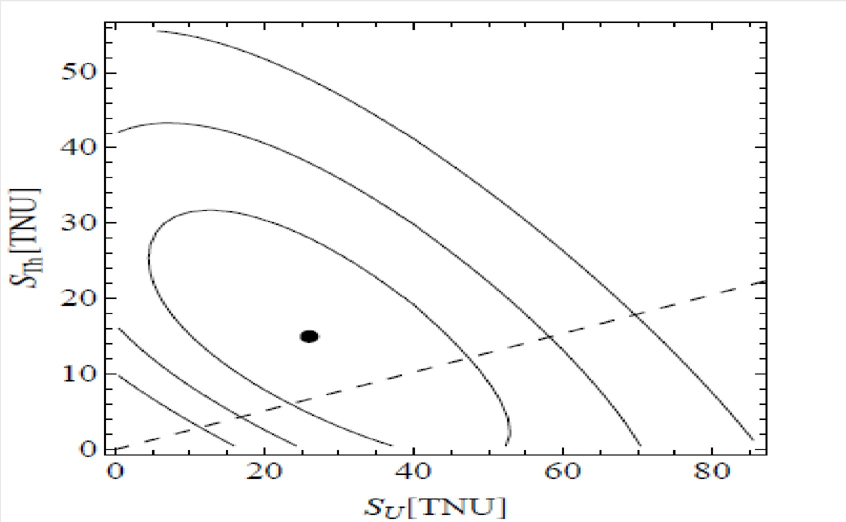


TNU: **one event per 10^{32} free protons (a kiloton) per year**

Spectral information: U v.s. Th





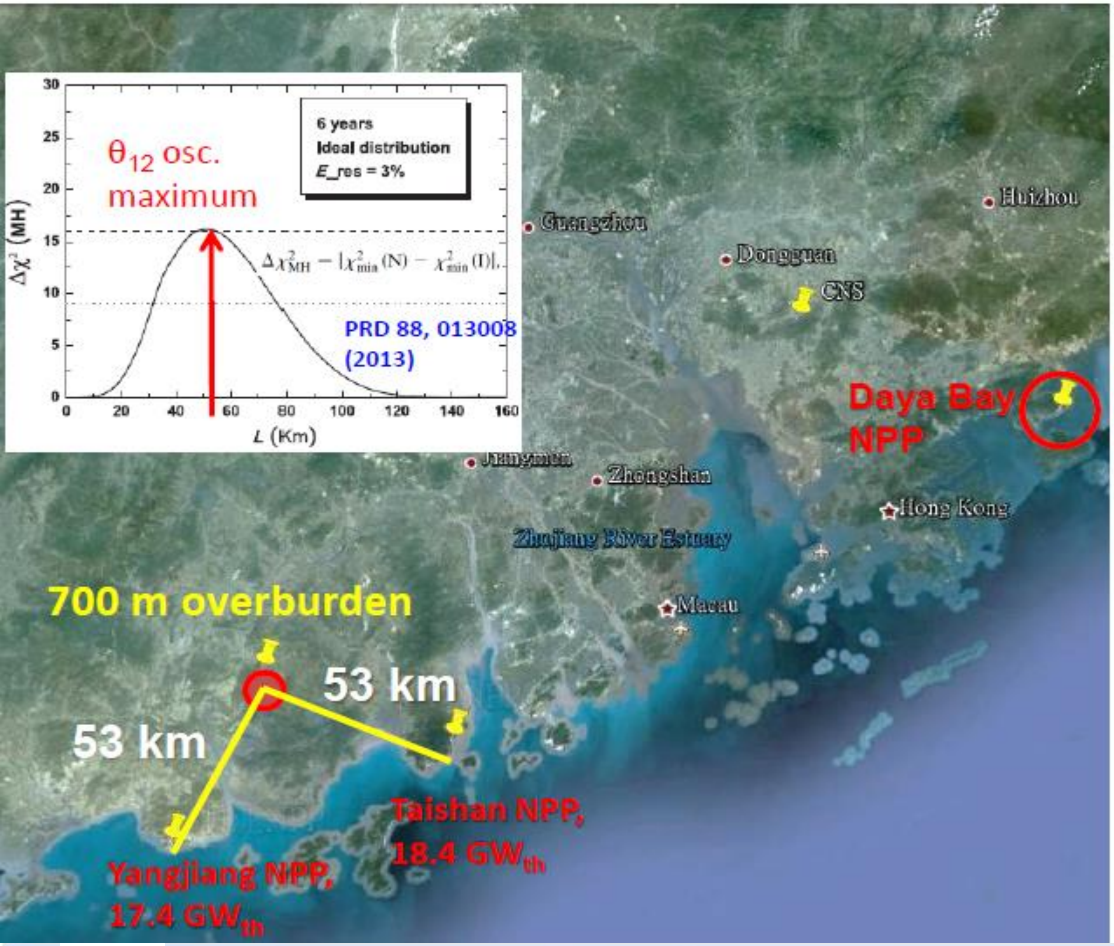


Spectral information helps in the U & Th seperation.

JUNO Experiment

- Jiangmen Underground Neutrino Observatory
  - 20 kton LS detector, $3\%/\sqrt{E}$ energy resolution
- A multiple-purpose neutrino experiment

J. Phys. G 43: 030401 (2016) (arXiv:1507.05613)



- Rich Physics
  - Reactor neutrinos: Mass hierarchy & Precision measurement of mixing parameters
  - Supernova neutrinos
  - Geo-neutrinos
  - Solar neutrinos
  - Sterile neutrinos
  - Atmospheric neutrinos
  - Exotic searches

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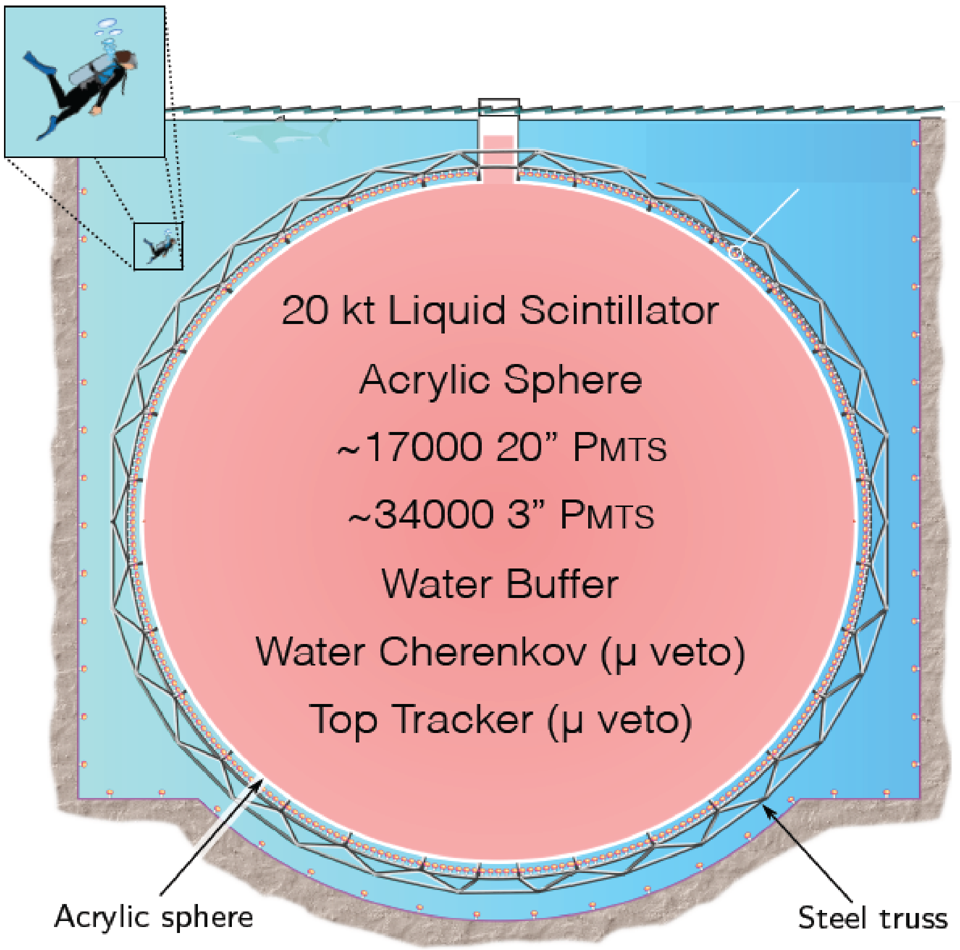
JUNO detector concept

Liquid Scintillator (Anti)neutrino Detector

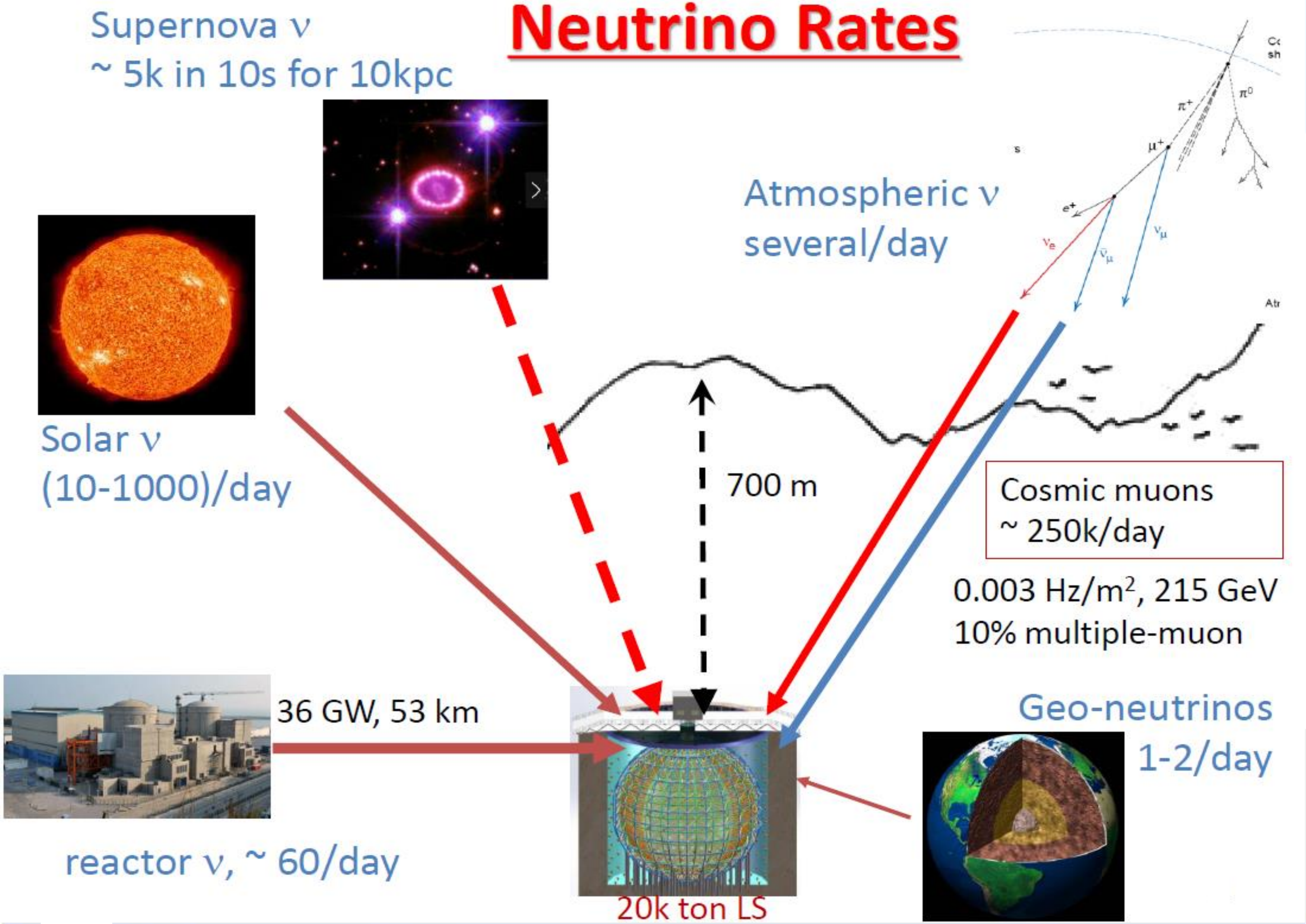


2 Key parameters:

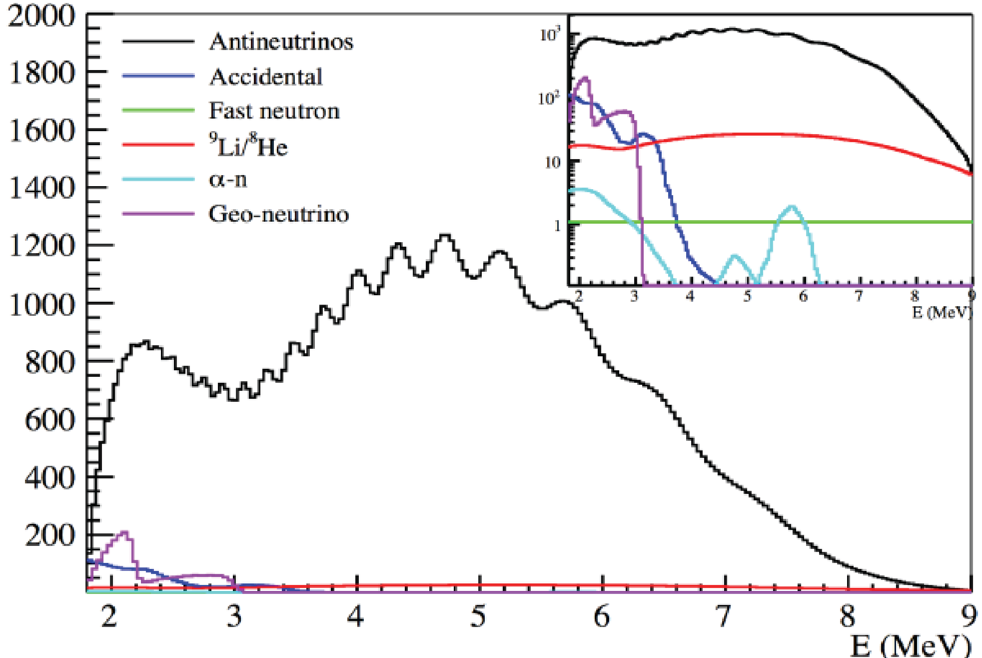
LARGE & PRECISE

	DETECTOR TARGET MASS	RESOLUTION
KamLAND	1000 t	6%/√E
Double Chooz	8 t	8%/√E
RENO	16 t	8%/√E
Daya Bay	20 t	8%/√E
Borexino	300 t	5%/√E
JUNO	20000 t	3%/√E

Neutrino Rates



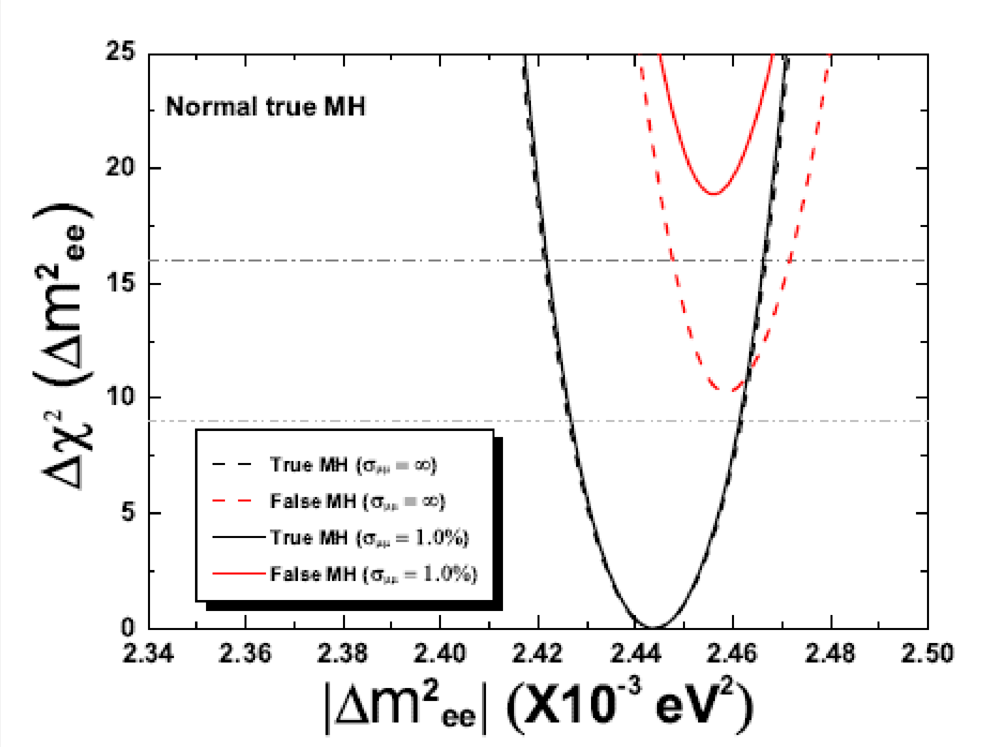
Event rate and spectra of antineutrinos



Event Rate per 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				

Mass hierarchy and precision measurement



	Current	JUNO
Δm^2_{12}	3%	0.59%
Δm^2_{23}	5%	0.44%
$\sin^2\theta_{12}$	6%	0.67%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	14% → 4%	~ 15%

New physics searches: Check the unitary of mixing matrix to ~1%

MH sensitivity with 6 years' data of JUNO (PRD88, 013008 (2013))

- **Ideal case: 4σ** with relative measurement, **5σ** with absolute Δm^2 measurement
- **Taking into account the spread of reactor cores, uncertainties from energy non-linearity, etc. 3σ** with relative measurement, **4σ** with absolute Δm^2 measurement

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Detector overview

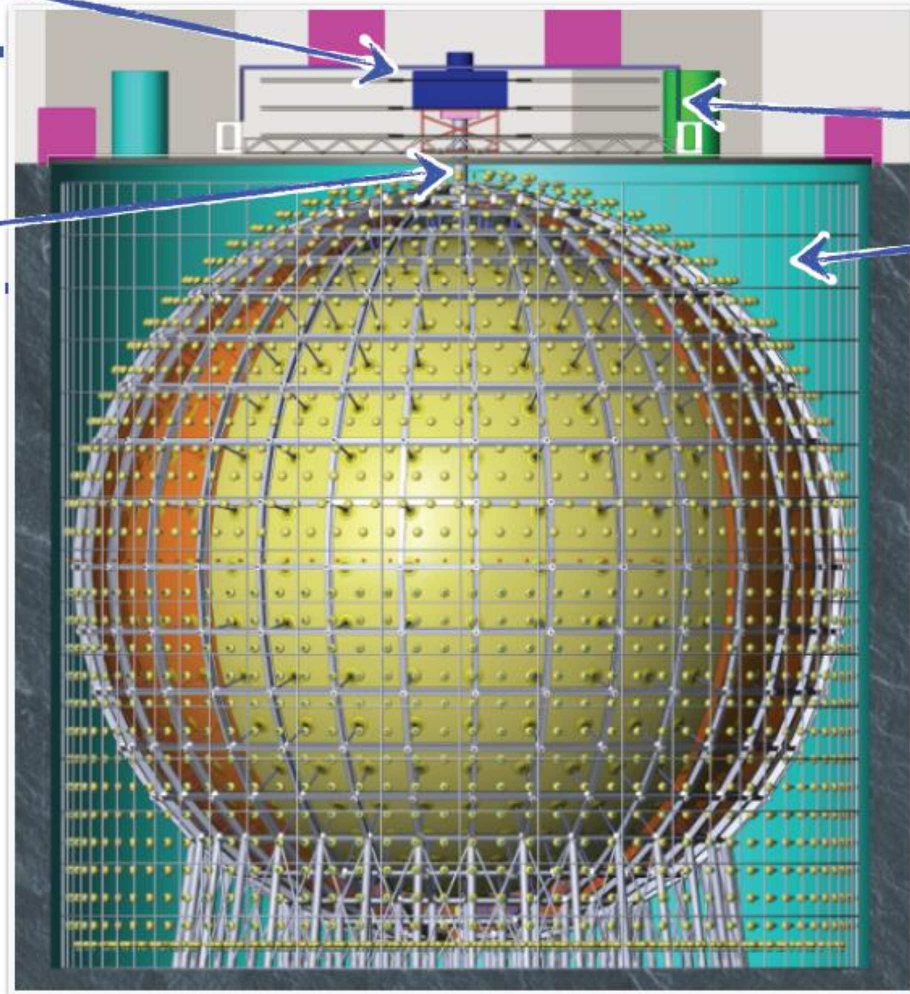
Calibration Room

Muon Veto

Chimney

Top Tracker

Water Pool



Central Detector

Steel Truss

Holding PMTs

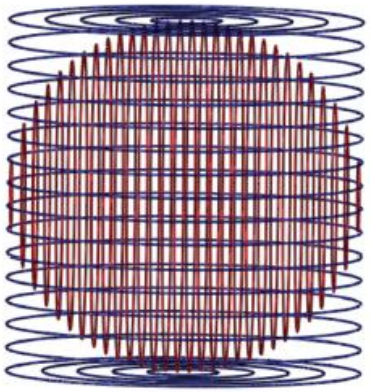
~17000 x 20"

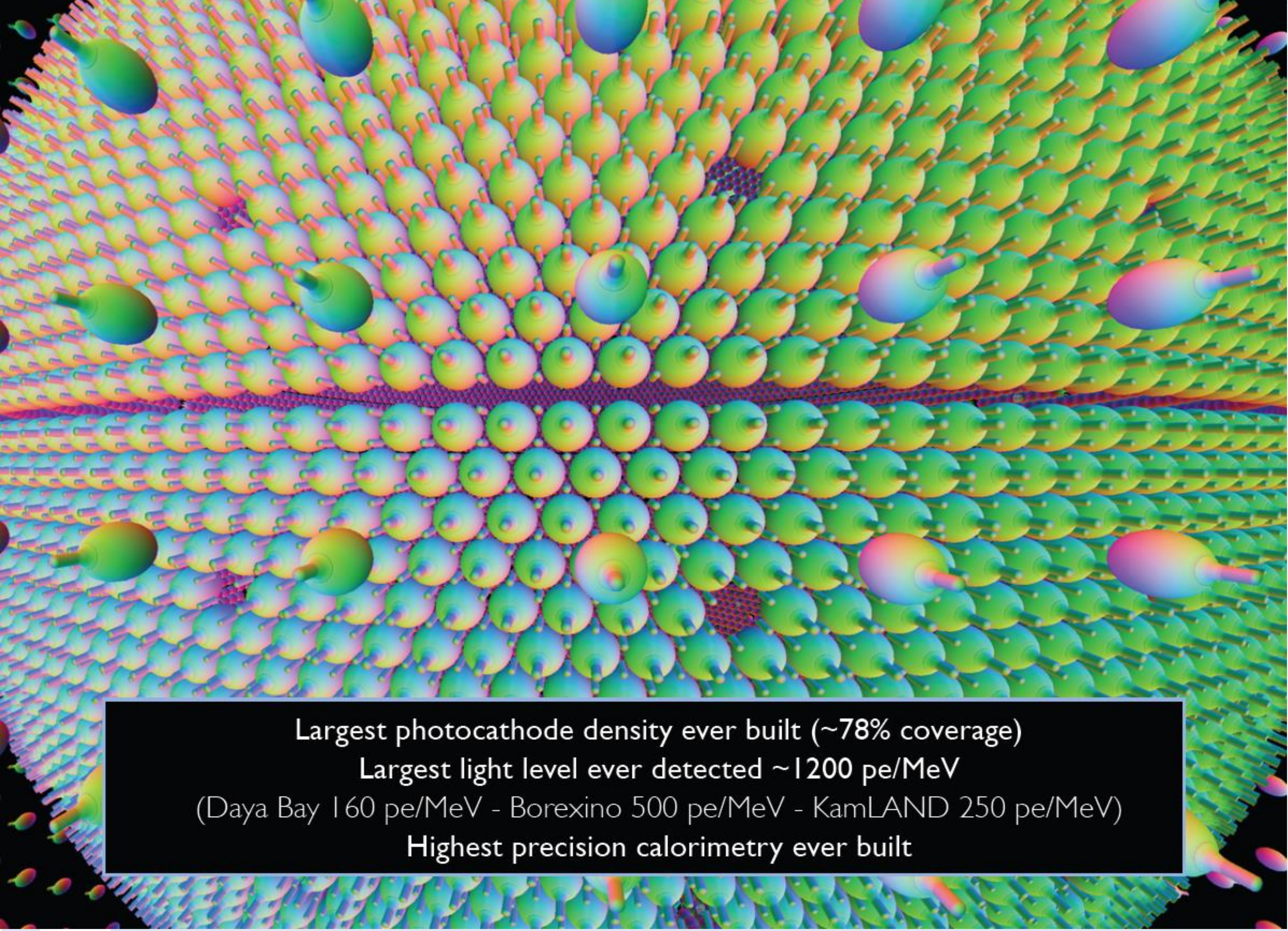
~34000 x 3"

Acrylic Sphere

filled with LS

Magnetic Field Compensating Coil





Largest photocathode density ever built (~78% coverage)
Largest light level ever detected ~1200 pe/MeV
(Daya Bay 160 pe/MeV - Borexino 500 pe/MeV - KamLAND 250 pe/MeV)
Highest precision calorimetry ever built

20-inch PMT

Large PMTs: 20", 78% coverage - 30% quantum efficiency at 420 nm

Meant for calorimetry

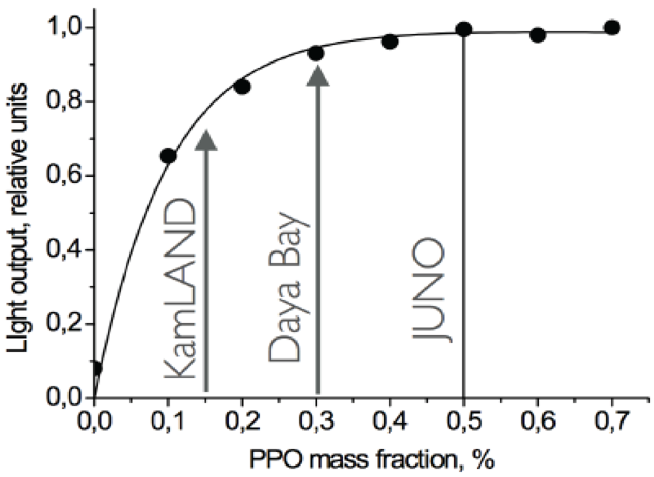
2 different producers NNVC (China)15000 units & Hamamatsu (Japan) 5000 units

Characteristics	unit	MCP-PMT (IHEP)	R12860 (Hamamatsu)	
Electron Multiplier	–	MCP	Dynode	
Photocathode mode	–	reflection+transmission	transmission	
Quantum Efficiency (400 nm)	%	26 (T), 30 (T+R)	30 (T)	Resolution
Relativity Detection Efficiency	%	~110%	~100%	Resolution
P/V of SPE		>3	>3	Reconstruction
TTS on the top point	ns	~12	~3	Vertex
Rise time/Fall time	ns	R~2, F~10	R~7, F~17	
Anode Dark Count	Hz	~30K	~30K	Trigger
After Pulse Time Distribution	μs	4.5	4, 17	
After Pulse Rate	%	3	10	
Glass	–	Low-Potassium Glass	Hario-32	Background

Liquid Scintillator

20 kton Liquid Scintillator

- Cocktail: LAB + PPO + bisMSB (no Gd Loading)
- Increase light yield
  - Fluor concentration optimisation ongoing
- Increase transparency
  - Improve the production process of raw solvent (LAB)
  - onsite purification
- Reduce radioactivity
  - no Gd Loading
  - K/U/Th contamination < 10^{-15} g/g



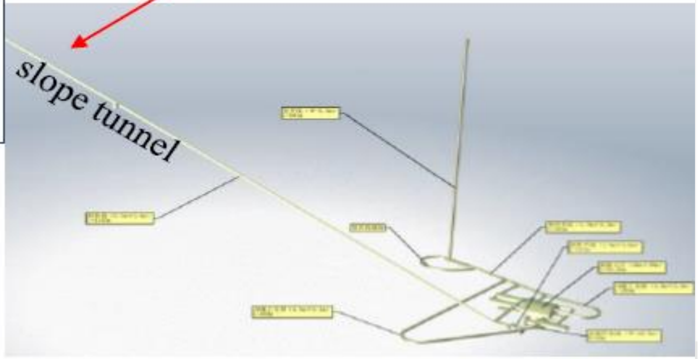
LAB	Attenuation Length [m] at 430nm
RAW	14.2
Vacuum Distillation	19.5
SiO_2 Column	18.6
Al2O3 Column	25

Progress and Plan

- Decided Central Detector Scheme: 2015.07
- Finished PMT bidding: 2015.12 (production: 2016-2019)

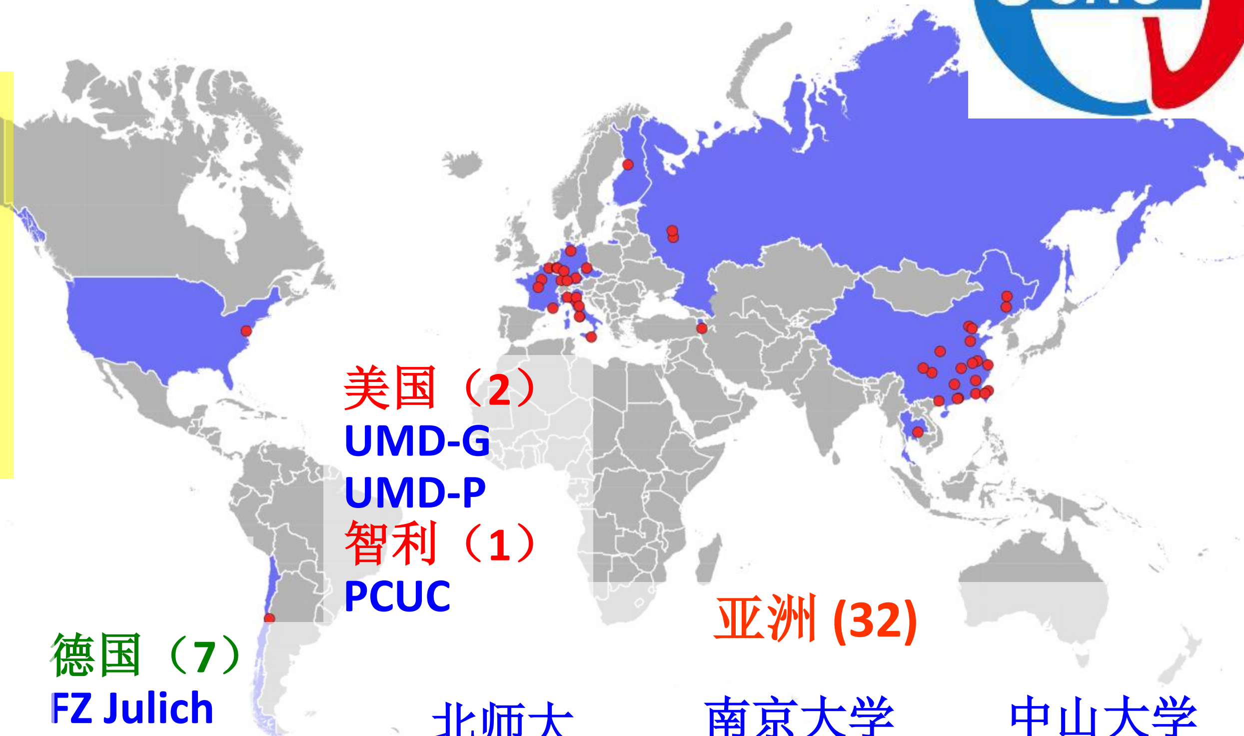
- Finish the engineering design of detector structure: 2016.07
- Bidding for acrylic production: end of 2016

- Civil construction: 2015-2017
- Detector component production: 2016-2017
- Build detector onsite: 2018-2019
- PMT installation, Veto, cleaning, filling : 2019-2020
- Data taking : 2020



江门国际合作组

国际合作组：12个国家和地区，62个单位，成员 400人
高能所 ~120
国内大学 ~130
欧洲 ~150



美国（2）
UMD-G
UMD-P
智利（1）
PCUC

欧洲 (27)

法国（5）
APC Paris
CPPM Marseille
IPHC Strasbourg
LLR Paris
Subatech Nantes
芬兰（1）
U Oulu
俄罗斯（3）
JINR
INR Moscow
Moscow Stat

意大利（8）
INFN-Catania
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-MilanoB
INFN-Padova
INFN-Perugia
INFN-Roma 3
捷克（1）
Charles U

德国（7）
FZ Julich
RWTH Aachen
TUM
U Hamburg
U Mainz
U Tuebingen
比利时（1）
ULB
亚美尼亚（1）
YPI

亚洲 (32)

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原子能院
东莞理工
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广西大学
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泰国（1）
SUT

The terrestrial mater effects and precise density profile

Motivation

(1) The mass hierarchy and at JUNO needs very precise measurement of the oscillation behavior.

(2) The neutrino trajectories are mostly in matter, which contribute ~1% of the oscillation.

(3) We need a relative precise knowledge of the density profile along the neutrino path:

straight lines from the reactor cores to the detector

Current assumptions

(1) All the neutrino trajectories are in matter
(neglect the small parts in vacuum)

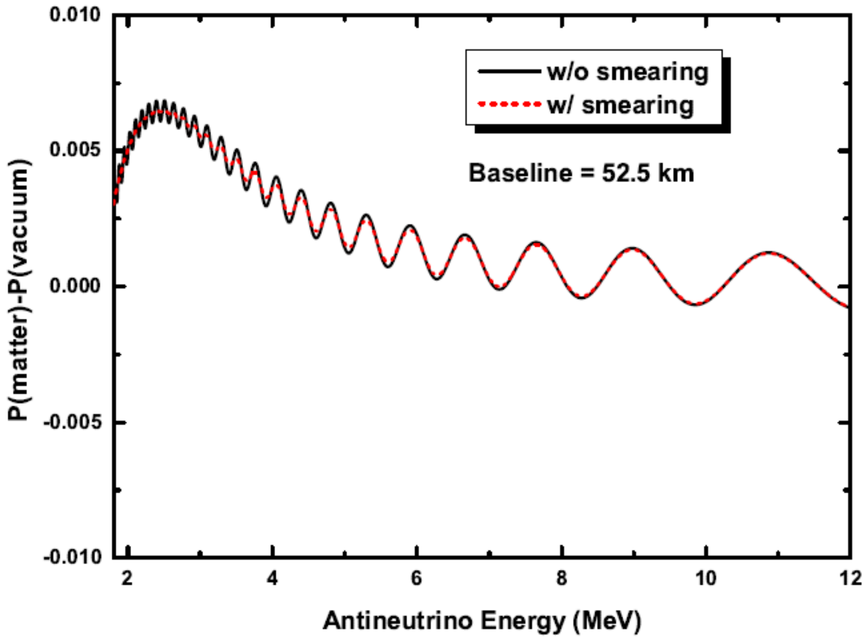
(2) Matter density is constant

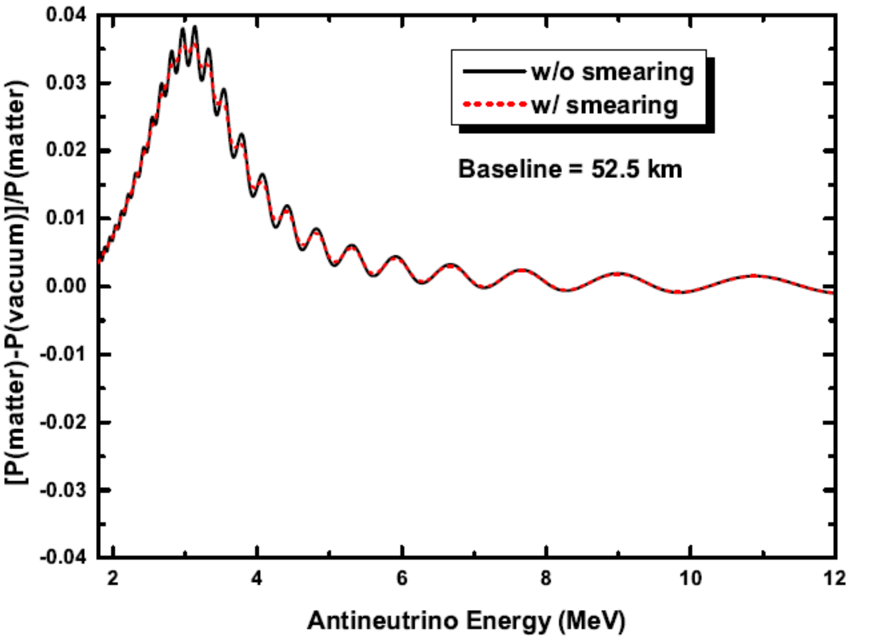
(may have variations)

(3) Matter density is 2.6 g/cm^3

(may be smaller)

Numerical estimates





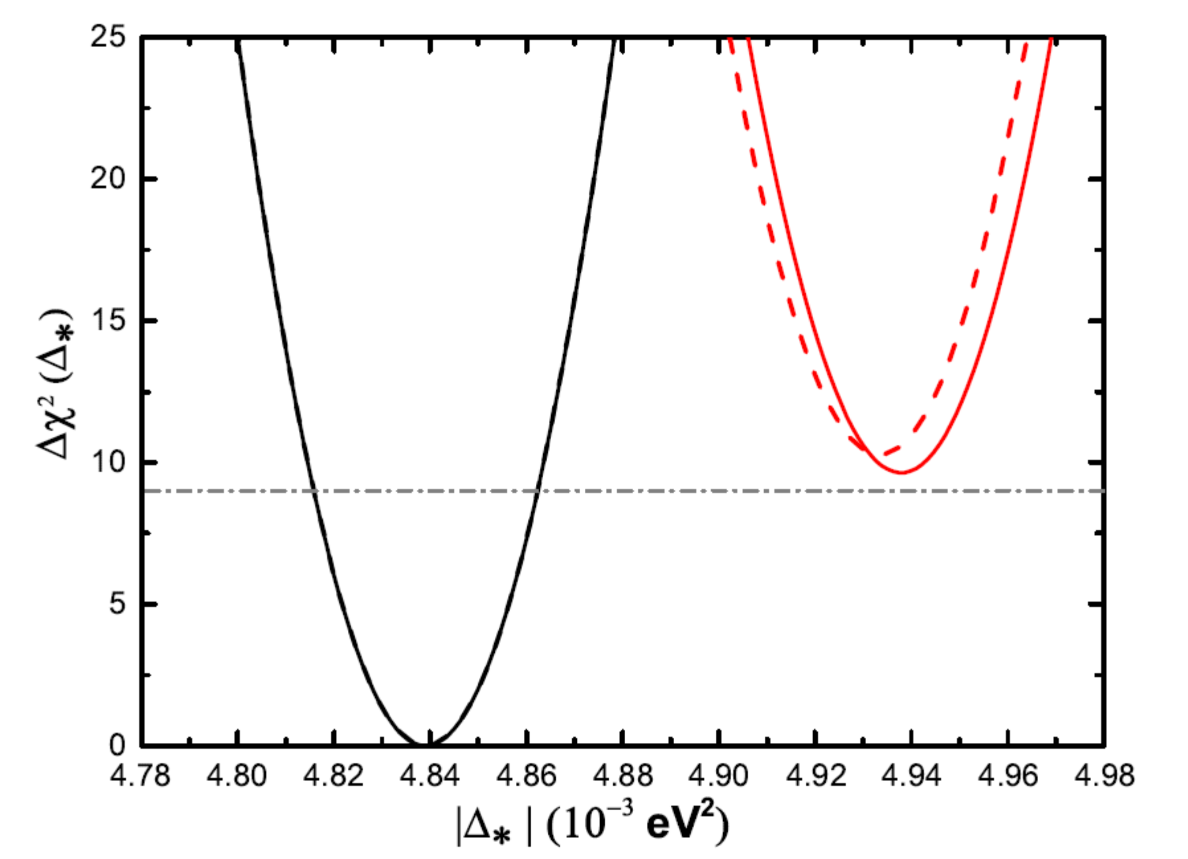
The largest correction is 0.7% (absolute) and 4% (relative)

Dominate contributions are for the solar parameters.

Large residual solar oscillations + small wiggles

Mass hierarchy

With six years of running, the $\Delta\chi^2$ of mass ordering measurements will reduce from 10.28 (vacuum) to 9.64 (matter).



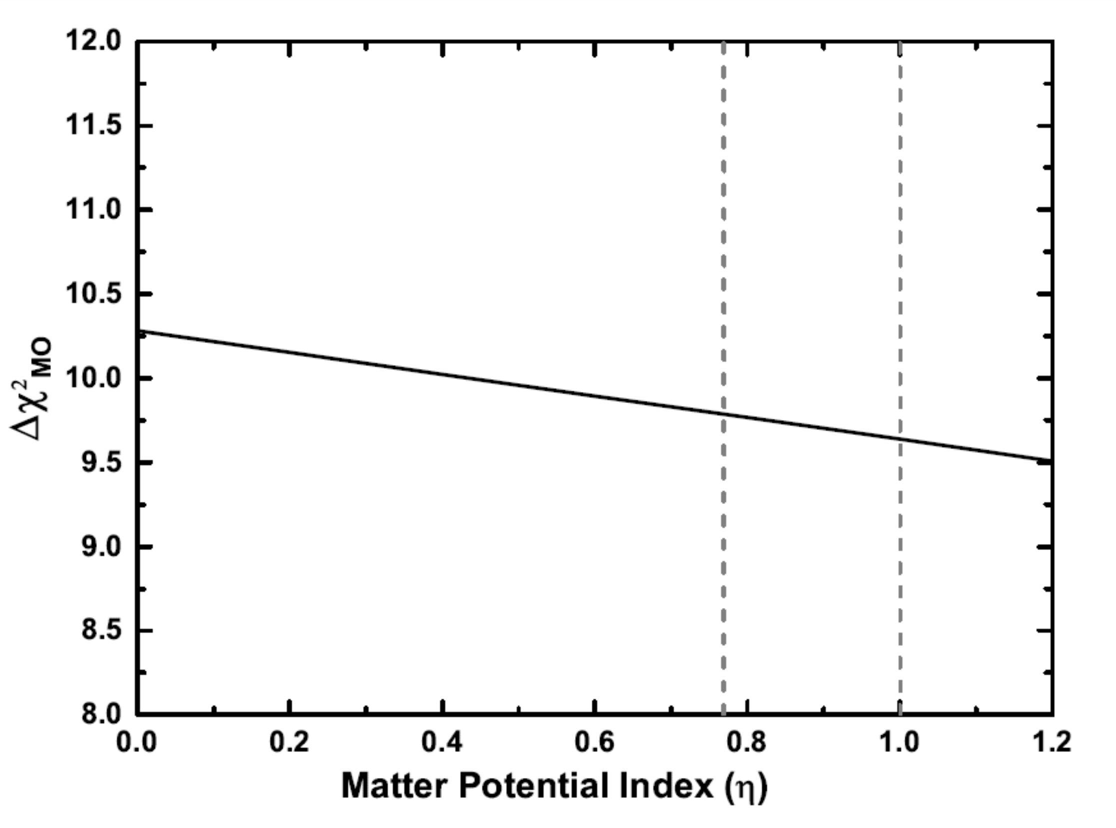
(1) Possible reason for the reduction is from the suppression of theta(12).

(2) Increase of Δ_{21} will compensate parts of the reduction.

(3) A reduction of 0.6 is comparable to other systematic uncertainties.

Variations of matter density

The baseline from reactors to the detector is only ~50 km, the neutrino trajectories are expected to include a large proportion of the sedimentary layer.



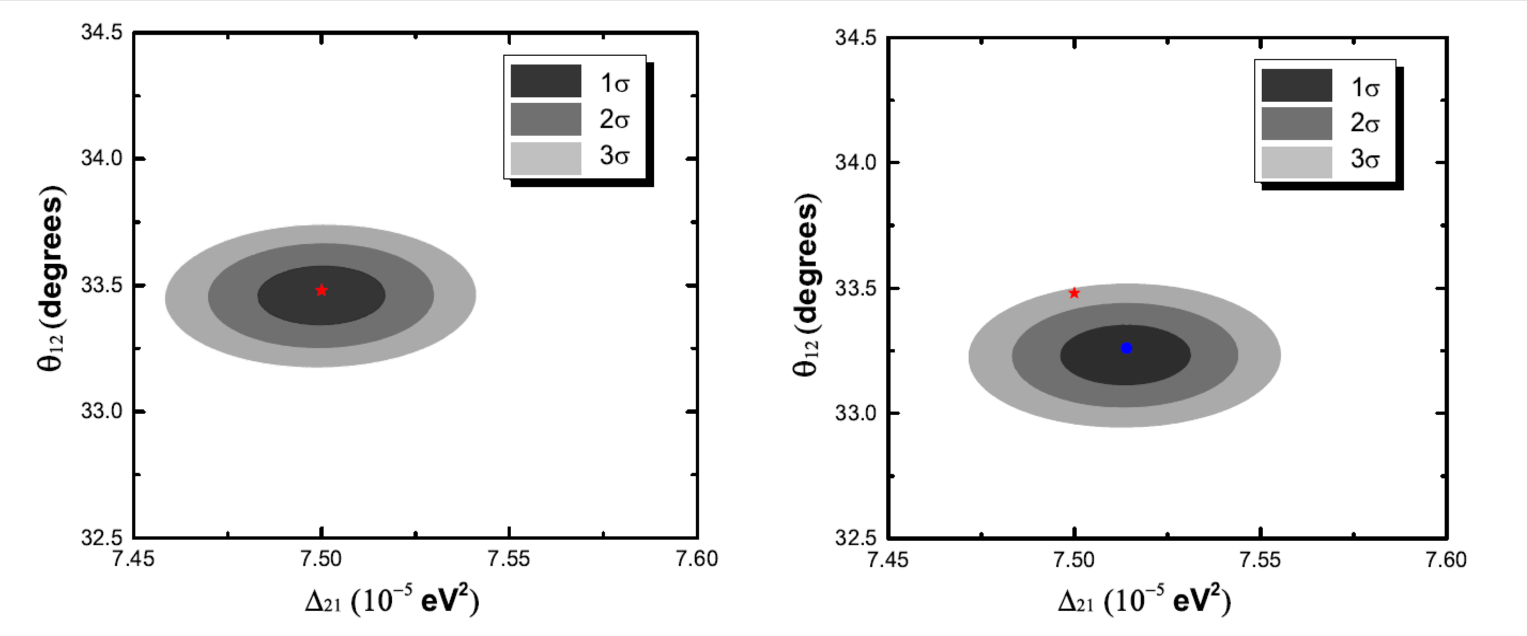
The matter density could be smaller than the typical assumed 2.6 g/cm^3 of the crust.

The reduction would be from 10.28 to 9.79 if 2.0 g/cm^3 is taken.

Precision measurement

Assume matter density of 2.6 g/cm^3 in the measurements:

left(w/ matter effects), right (w/o matter effects)



(1) Including matter effects, the fitted values are identical to the true values, with the precision of 0.58% and 0.23% (they are 0.54% and 0.24% in vacuum); with additional systematics as the Yellow Book, they are 0.72% and 0.60% (0.67% and 0.59% in vacuum).

(2) Without matter effects, the fitted values will shift by 1σ - 2σ.

What we need for the inputs?

Previous assumptions:

(1) All the neutrino trajectories are in matter:

How large is the neutrino path in vacuum?

(2) Matter density is constant

What is the variation of the density along the path?

(3) Matter density is 2.6 g/cm^3

What is the real density values?

To what accuracy? 10% (baseline)

Summary

JUNO is a multi-purpose neutrino experiment, which is planed to resolve the neutrino mass hierarchy using reactor antineutrinos.

Geo-neutrino is one of the most important targets in the JUNO program, which will be beneficial to both the neutrino physicists and geo scientists.

The progress is very good, and data taking by ~2020.

Welcome to JUNO
@Kaiping, Jiangmen

Thanks

Backup

JUNO Yellow Book: 1507.05613

Neutrino Physics with JUNO

arXiv:1507.05613v1

Abstract

The Jiangmen Underground Neutrino Observatory (JUNO), a 20 kton multi-purpose underground liquid scintillator detector, was recently proposed with the determination of the neutrino mass hierarchy as a primary physics goal. The excellent energy resolution and the large fiducial volume anticipated for the JUNO detector offer exciting opportunities for addressing many important topics in neutrino and astro-particle physics. In this document, we present the physics motivations and the anticipated performance of the JUNO detector for various proposed measurements.

a) Reactor antineutrino physics:

Mass hierarchy, precision measurement, search for new physics

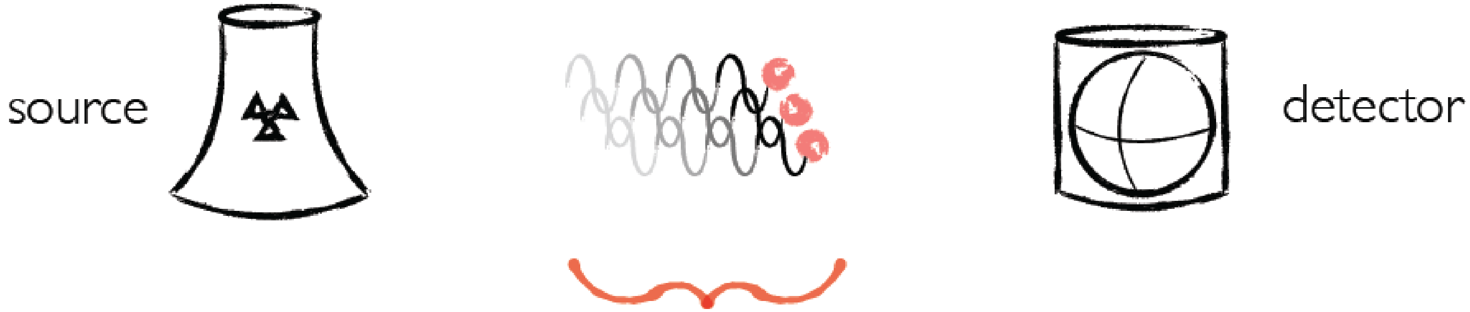
b) Astrophysical neutrinos:

supernova burst neutrinos, DSNB, solar neutrinos, geo-neutrinos

c) Search for High energy events:

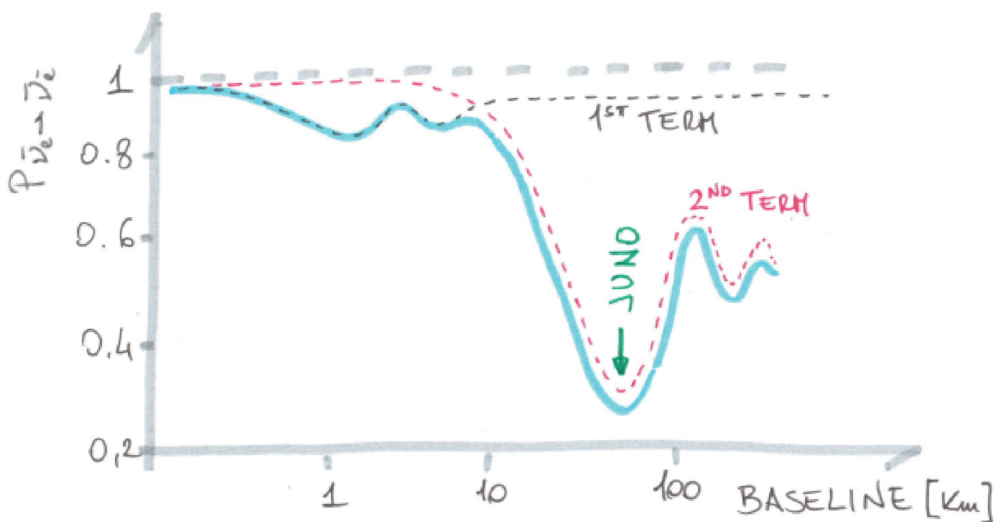
atmospheric neutrinos, nucleon decays, indirect dark matter search

Antineutrinos from Reactor (Propagation)



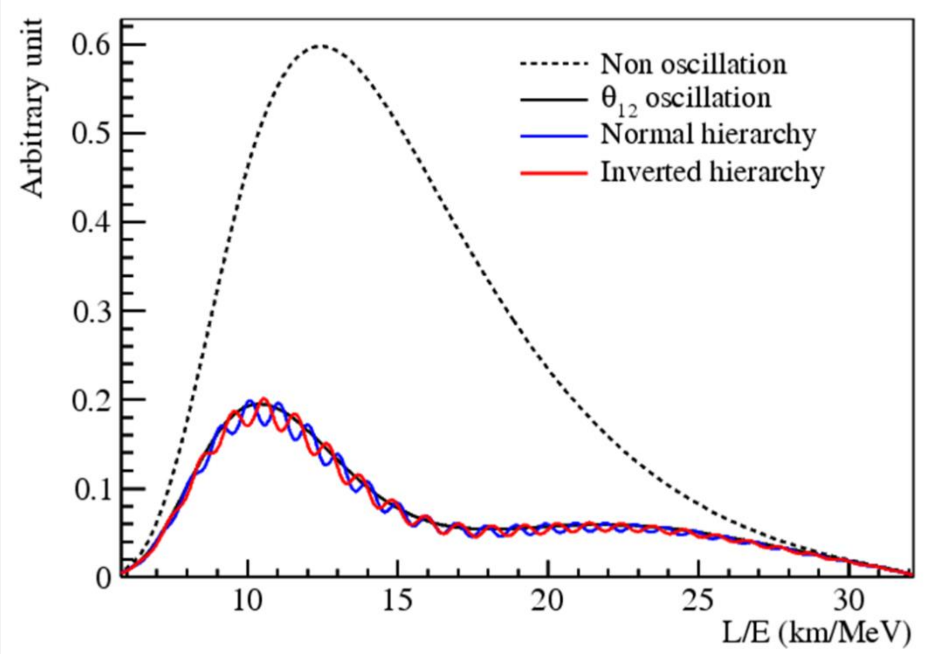
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\vartheta_{13} \, \sin^2\left(\cos^2\vartheta_{12} \, \sin^2\Delta_{31} + \sin^2\vartheta_{12} \, \sin^2\Delta_{32}\right)$$

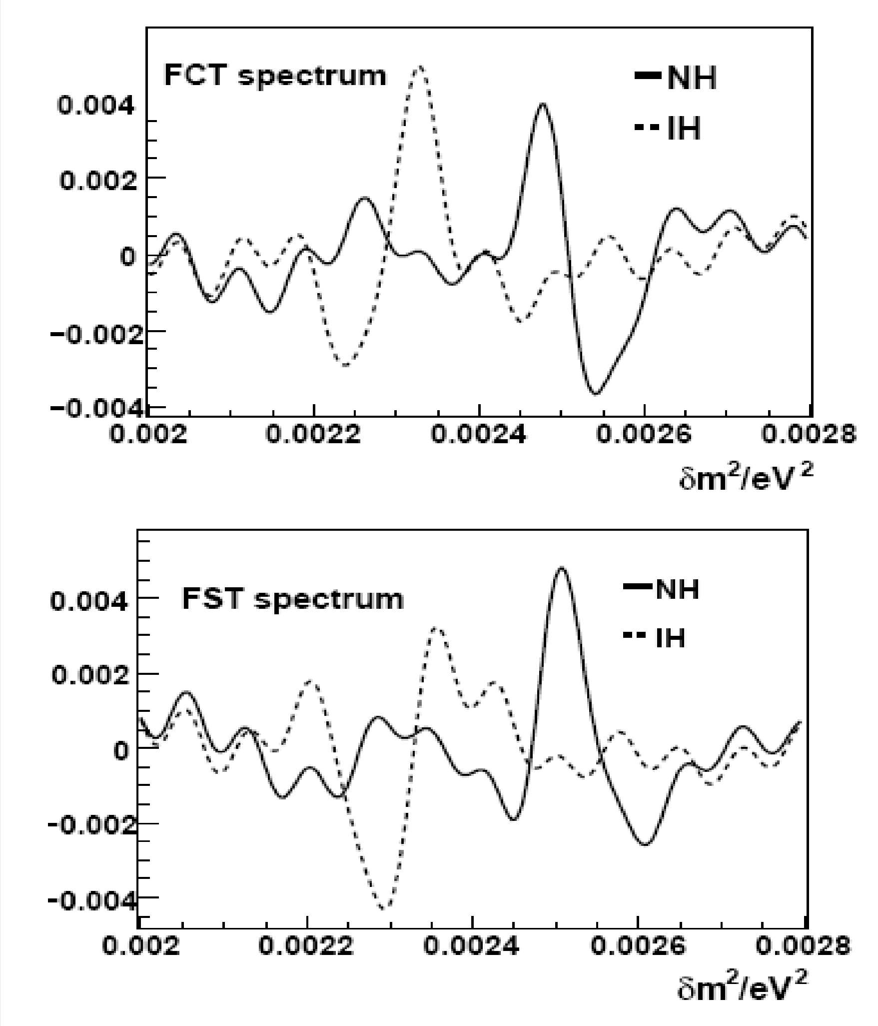
$$- \sin^2 2\vartheta_{12} \, \cos^4\vartheta_{13} \, \sin^2\Delta_{21}$$



$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

Spectral information





How the interference happens?

Fourier transform to L/E spectrum:

L/E spectrum←→Δm^2 spectrum(oscillation frequency)

J. Learned *et. al.* hep-ex/0612022

L. Zhan *et. al*. 0807.3203

Supernova burst neutrinos

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	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	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	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	6.0×10^1	1.1×10^2	1.6×10^2

- **For a SN@10 kpc, JUNO will register about ~5000 events from inverse beta decay (IBD), ~2000 events from all-flavor elastic neutrino-proton scattering (>0.2 MeV).**

  High statistics, different flavors, good energy resolution

- **particle physics:**

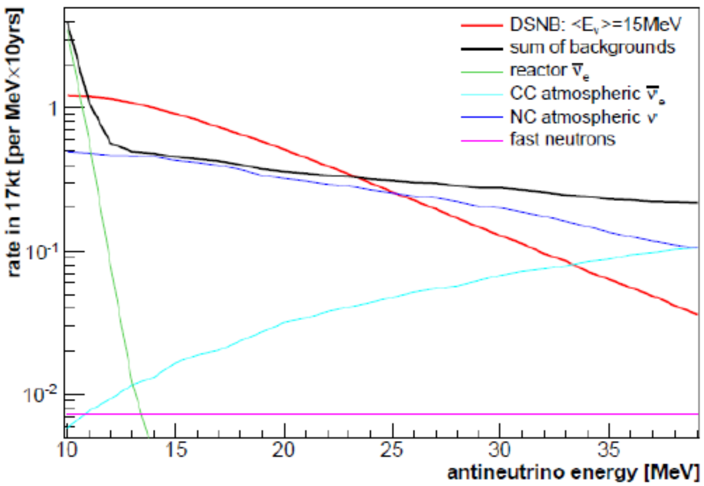
  a) neutrino mass scale: 0.7 eV@95% C.L. [10 kpc]

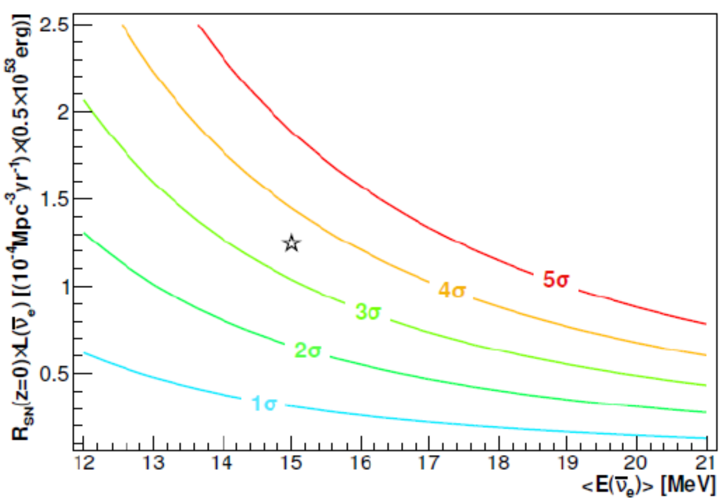
- **astrophysics:**

  b) precision of SN parameters (luminosity & ave. energy):

  nu_e_bar: 1%, nu_x: 5%, nu_e: 10%

Diffuse Supernova Neutrino Background





- DSNB: Past core-collapse events
  - ⇨ Cosmic star-formation rate
  - ⇨ Core-collapse neutrino spectrum
  - ⇨ Rate of failed SNe

Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e}\rangle = 12\,\mathrm{MeV}$	12.2	$\varepsilon_\nu = 50\,\%$	6.1
	$\langle E_{\bar{\nu}_e}\rangle = 15\,\mathrm{MeV}$	25.4		12.7
	$\langle E_{\bar{\nu}_e}\rangle = 18\,\mathrm{MeV}$	42.4		21.2
	$\langle E_{\bar{\nu}_e}\rangle = 21\,\mathrm{MeV}$	61.2		30.8
Background	reactor $\bar{\nu}_e$	1.6	$\varepsilon_\nu = 50\,\%$	0.8
	atm. CC	1.5	$\varepsilon_\nu = 50\,\%$	0.8
	atm. NC	716	$\varepsilon_{\mathrm{NC}} = 1.1\,\%$	7.5
	fast neutrons	12	$\varepsilon_{\mathrm{FN}} = 1.3\,\%$	0.15
	Σ			9.2

10 Years' sensitivity

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e}\rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21 MeV	$6.9\,\sigma$	$7.3\,\sigma$	$6.2\,\sigma$	$6.4\,\sigma$

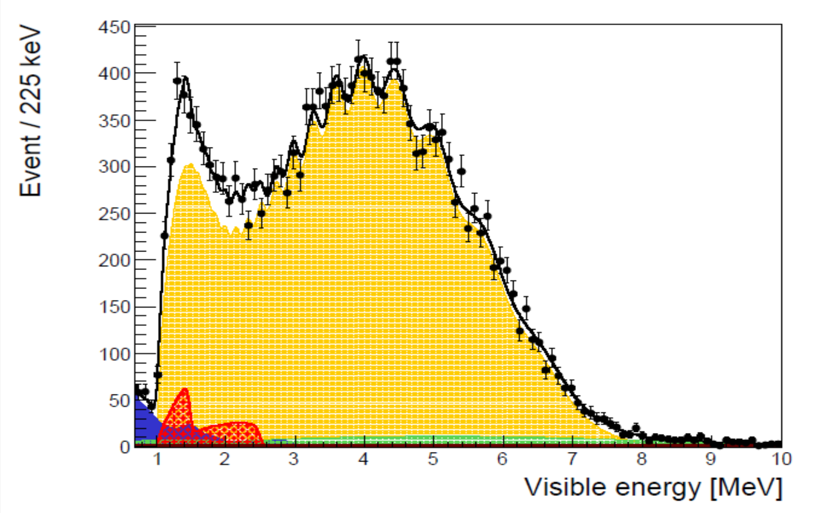
Geo-neutrinos

(1) Current measurements: statistics dominates

KamLAND: 30±7 TNU & Borexino: 38.8±12.2 TNU

(2) JUNO: 40 TNU, with ×20 statistics, but huge reactor backgrounds

Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	36.5 ± 36.5
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4



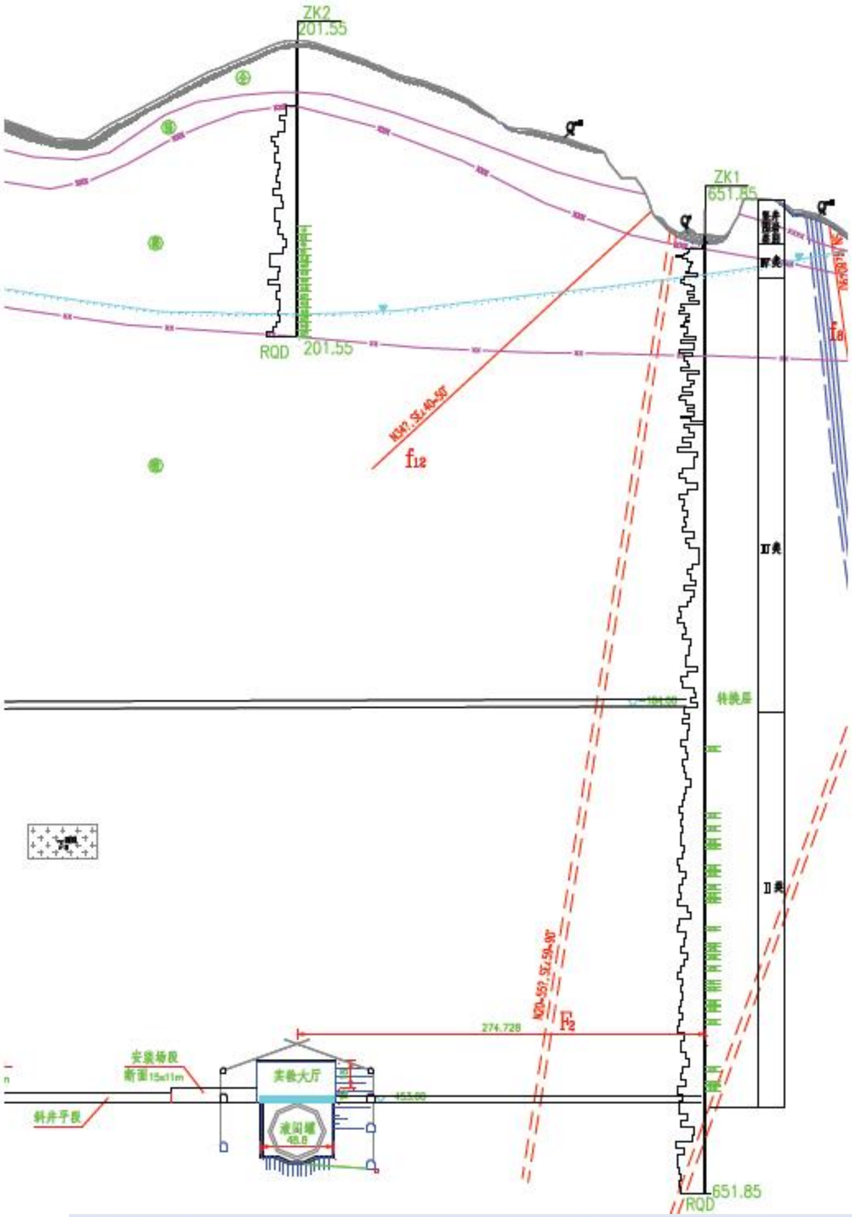
(3) accurate reactor spectra: a precision of 3 TNU (10 years) to test geophysical models.

(4) accurate local crust geology study: separate the mantle signals

Schedule

- **2013**: Complete conceptual design. Complete civil design and bidding
- **2014**: Start civil construction. Complete prototyping (PMT & detector). International collaboration established
- **2015**: PMT production line manufacturing
- **2016**: Start PMT production. Start detector production or bidding
- **2017**: Complete civil construction. Start detector construction and assembly
- **2018**: Start LS production
- **2019**: Complete detector assembly, installation and LS filling
- **2020**: Start data taking

Overburden



720 m Rock Overburden (1900 mwe)

611 m vertical shaft (digging…)