Status of JUNO

(Jiangmen Underground Neutrino Observatory)

future neutrino oscillation experiment

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on behalf of Daya Bay Collaboration

Neutrino mixing

flavor eigenstates

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

mass eigenstates

Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

Atmospheric
$\theta_{23} = 45°$

Reactor
$\theta_{13} = 9°$

Solar
$\theta_{12} \approx 34°$

Majorana
$0\nu\beta\beta$

Neutrino mass hierarchy

Is ν_3 mass eigenstate heavier or lighter than ν_1 and ν_2?

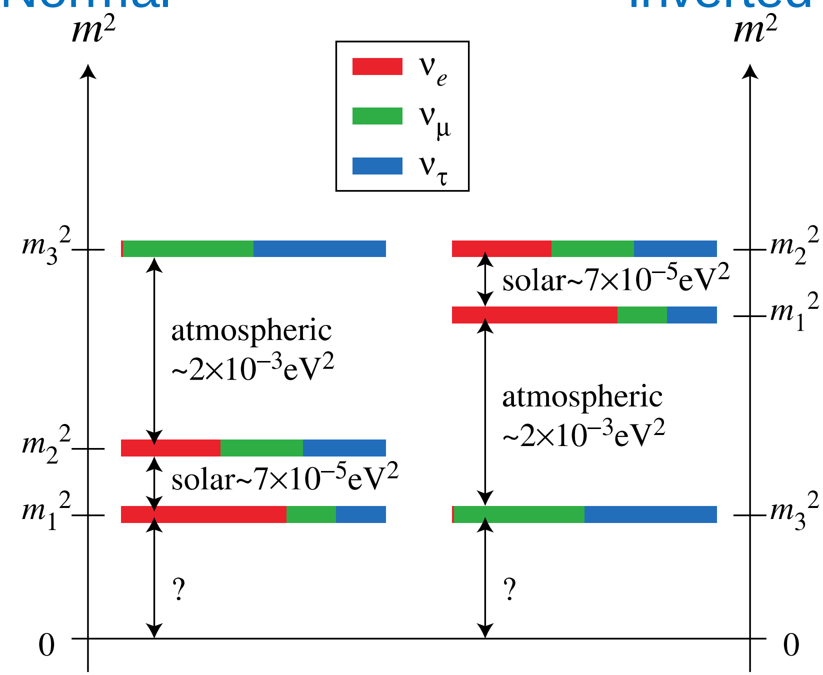
The mass hierarchy can impact on many important processes in particle physics, astrophysics and cosmology.

E.g. in case of the inverted mass hierarchy the $0\nu2\beta$-decay could be observed in the next generation experiments proving Majorana (excluding Dirac) nature of the neutrinos.

We want to know

$m_3 < m_{1,2}$ or $m_3 < m_{1,2}$

Normal Inverted



We know

$$\Delta m^2_{21} << |\Delta m^2_{32}| \approx |\Delta m^2_{31}|$$

$$\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

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

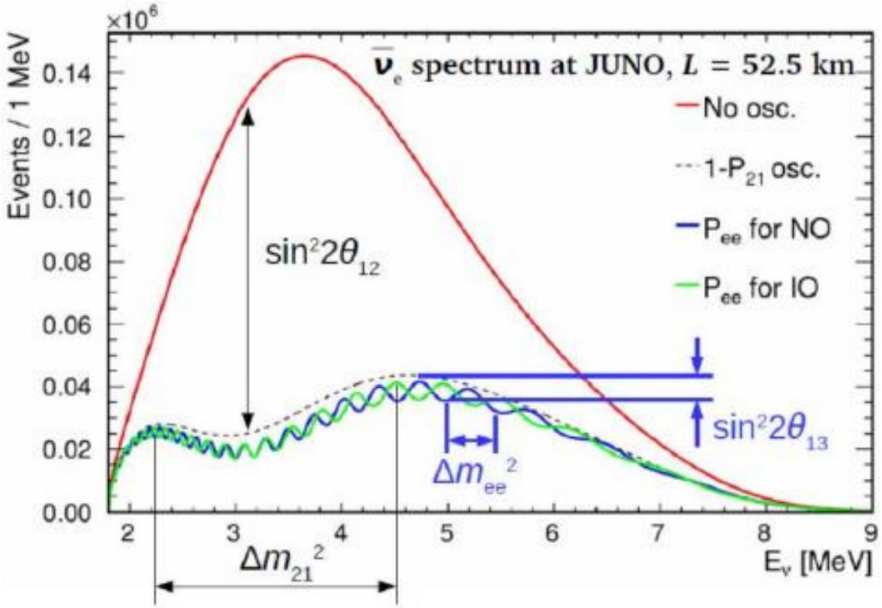
JUNO physics measurements

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \left(\cos^2\theta_{12} \sin^2 \Delta_{31} + \sin^2\theta_{12} \sin^2 \Delta_{32}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

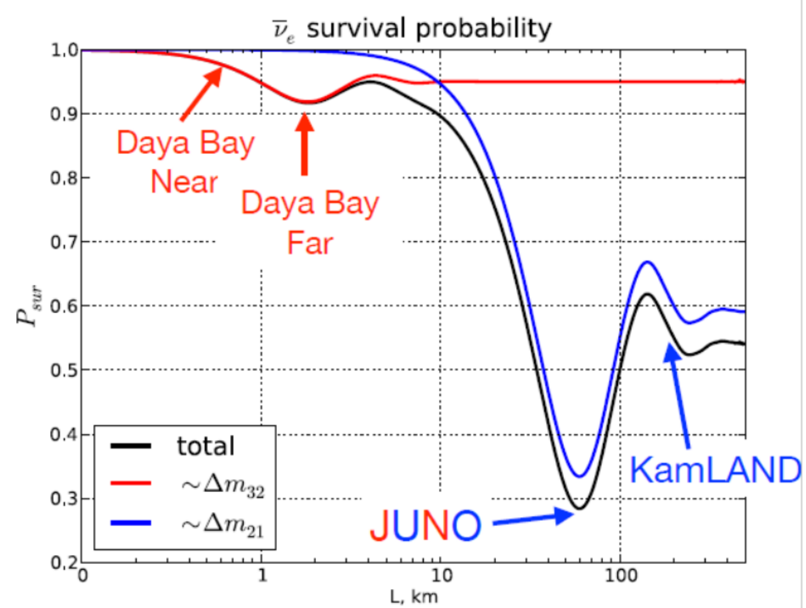
$$\approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee} - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \qquad \Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

Measurement of the antineutrino spectrum allows to determine precisely four oscillation parameters:

$\sin^2 2\theta_{12}$ Δm^2_{21} $\sin^2 2\theta_{13}$ $|\Delta m^2_{ee}|$



Measurement is the most sensitive in the location of the maximal oscillation effect.

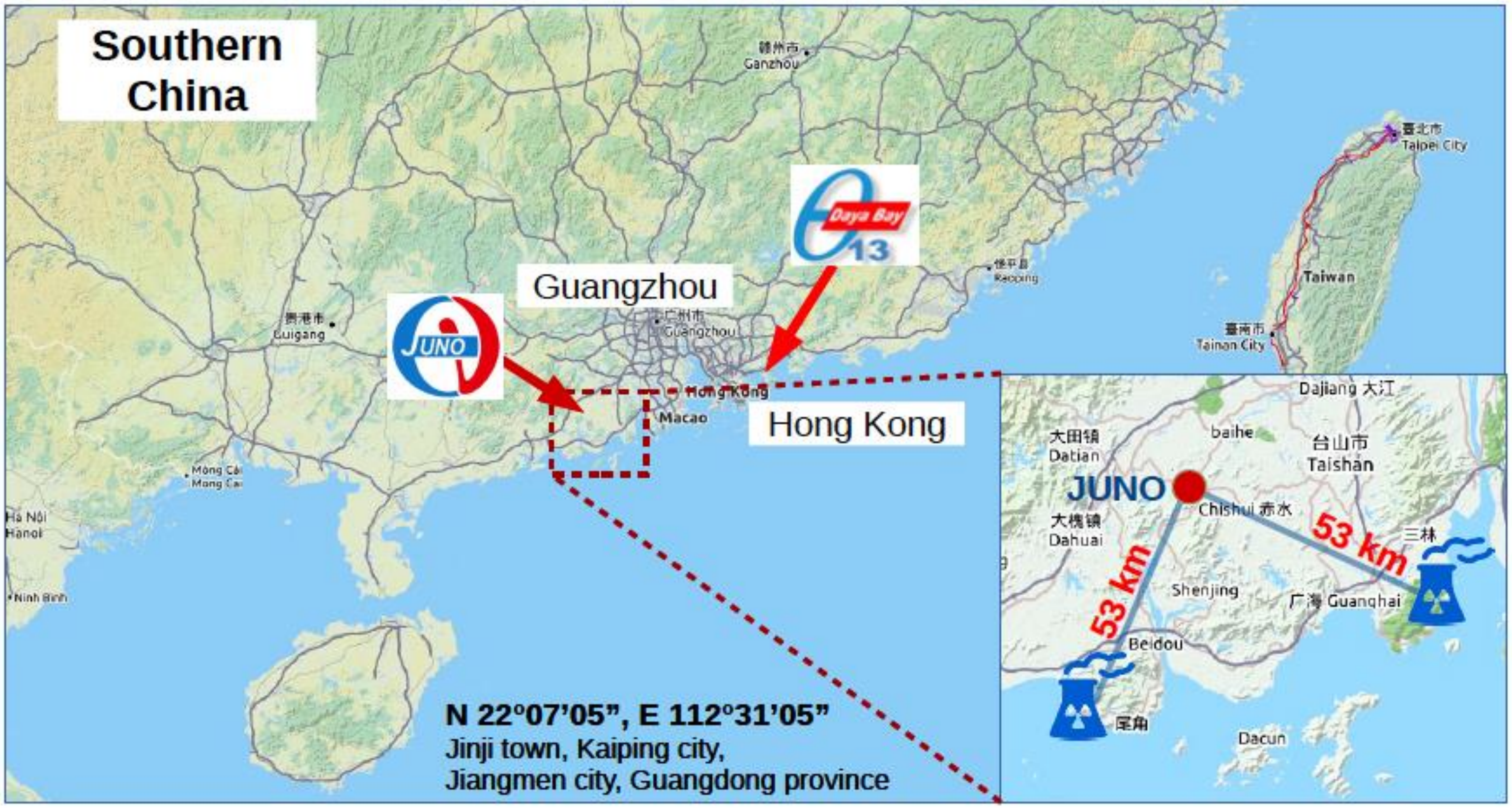


A good energy resolution and statistics is necessary to distinguish between the normal and inverted neutrino mass hierarchies.

JUNO Experiment

- Jiangmen Underground Neutrino Observatory
- a multi-purpose neutrino experiment,
- approved in Feb. 2013,
- ~ 300 M$,
- data taking: ~2020.

- Neutrino source: 10 nuclear reactors (Yangjiang+Taishan: 26.6-35.7 GWth),
- baseline: 53 km,
- overburden: ~700 m.

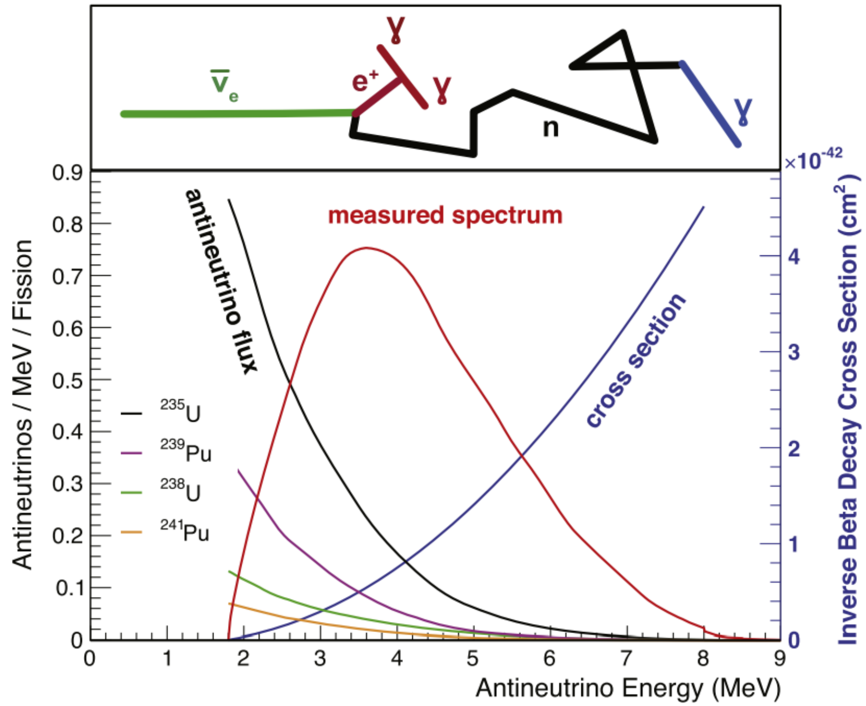


Detection of $\bar{\nu}_e$

Inverse beta-decay in LAB liquid scintillator:

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

$\hookrightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV})$ (t~240 μs)



$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8$ MeV (threshold)

$E_{prompt} = T_{e+} + 2m_e$ (annihilation gammas)

$E_{\bar{\nu}} \approx E_{prompt} + 0.8$ MeV

How to reach the requested energy resolution
(Mass Hierarchy)

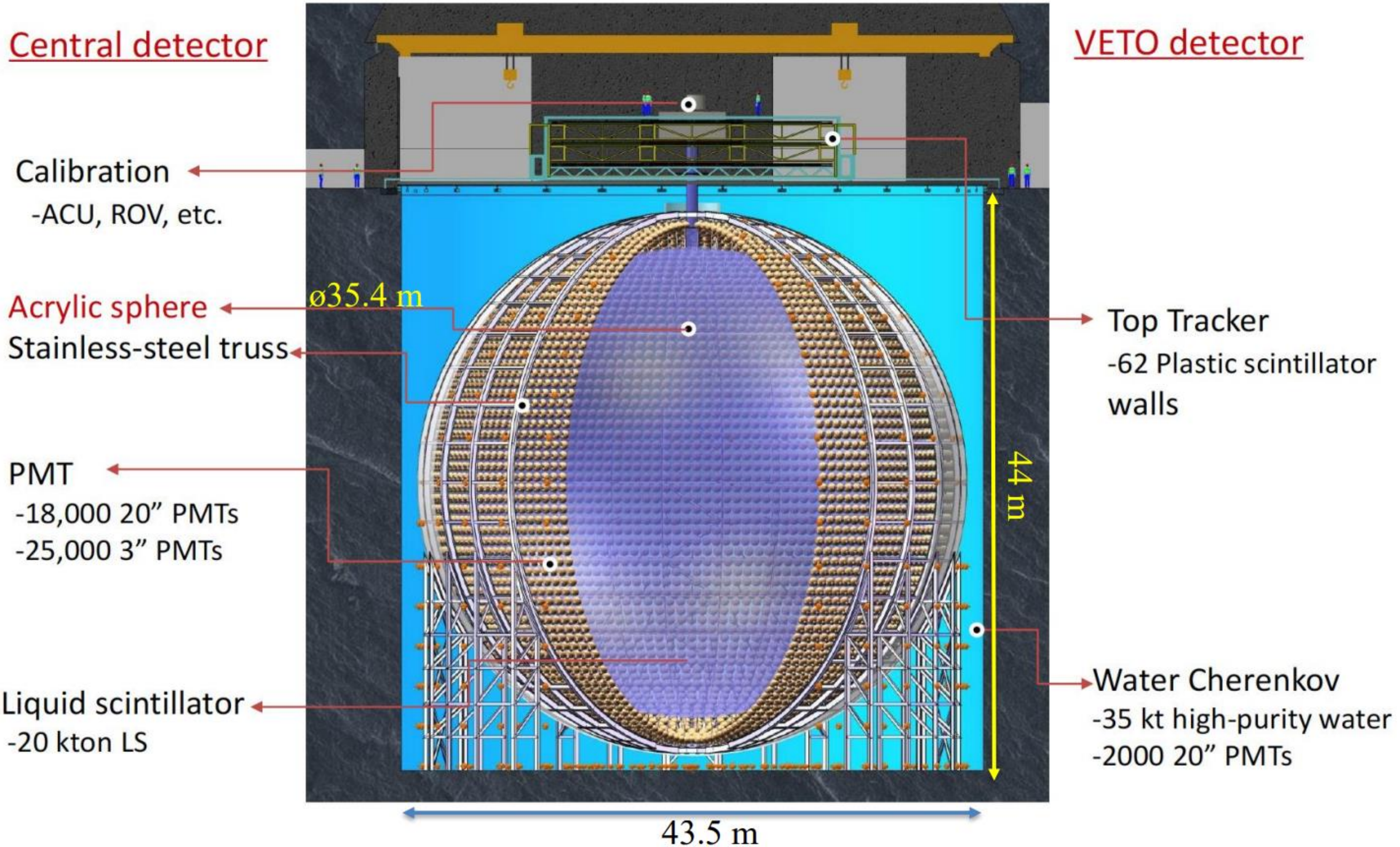
	KamLAND	BOREXINO	Daya Bay	JUNO
Target Mass	1 kton	300 ton	8x20 ton	20 kton
PE Collection (PE/MeV)	250	500	160	1200
Photocathode Coverage	34%	34%	12%	80%
Energy Resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Energy Calibration	2%	1%	1.5%	<1%

JUNO will be the largest liquid scintillator detector and with the best energy resolution in the world.

JUNO detector

Central detector: 20 kton active mass LAB scintillator, PMTs coverage > 75%, energy resolution 3%@1 MeV.

Detector overburden: ~700 m of granite.



Veto system

Top tracker (TT):

- Re-using the Target Tracker walls of the OPERA experiment;
- Total number is 62 and cover half of the top area;
- 3 TT layers spaced by 1.7 m, each layer have x,y readout;
- A solid bridge support the TT and its mechanical structure;
- Perform a precise muon tracking and provide valuable information for cosmic muon induced Li9/He8 study.

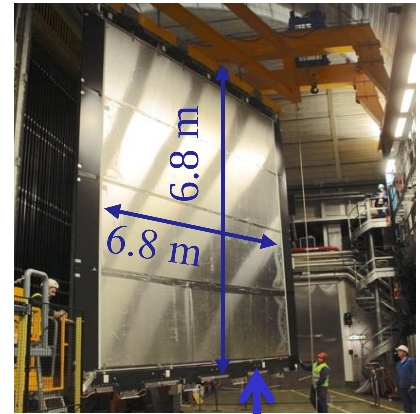
Water Cherenkov detector:

- ~2000 20” MCP-PMTs used for veto system;
- Detector efficiency is expected to be >95%;
- Fast neutron background ~0.1/day.

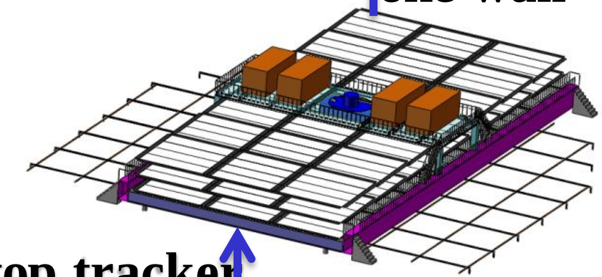
Compensation coils system used for earth magnet field shielding to keep PMT performance.

Water system:

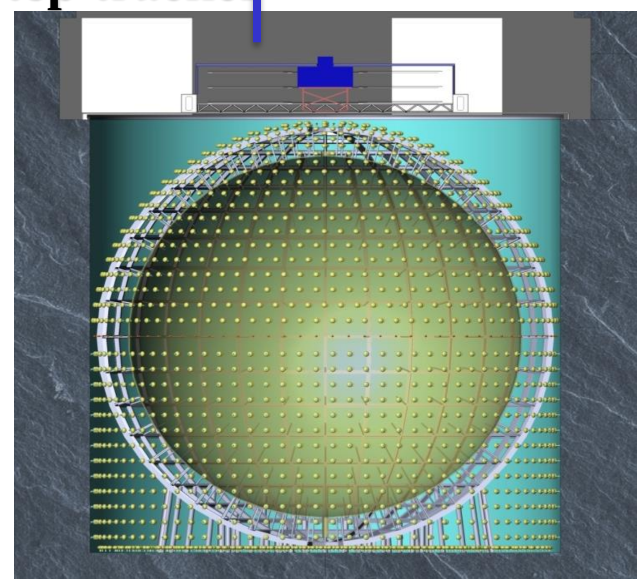
- Employ a circulation/polishing water system;
- Keep a good water quality -including radon control.



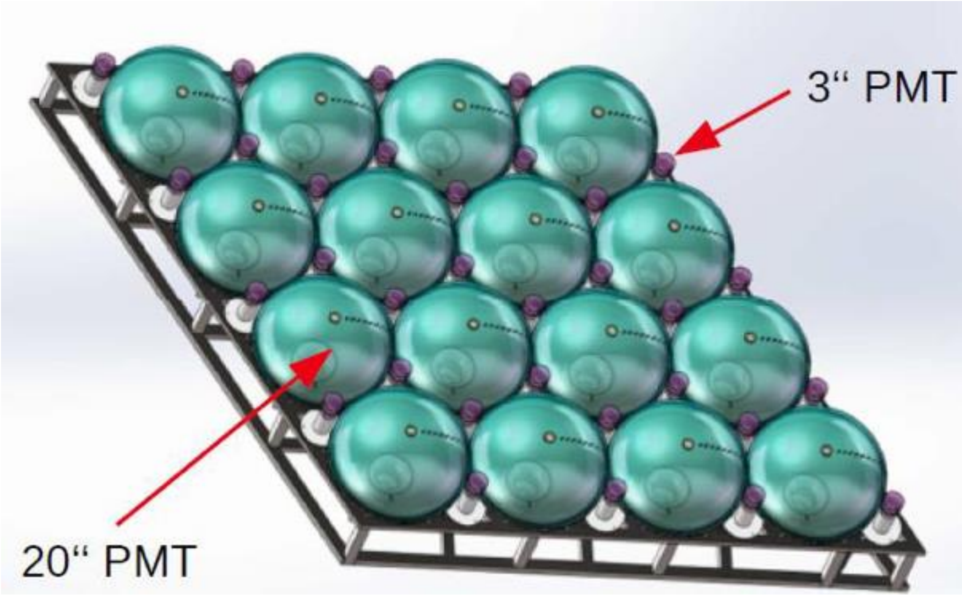
one wall



top tracker



Central detector PMT systems



Design goal: 1.2 k p.e. / MeV

Requirements:

- High optical coverage (~ 78%)
- High photon detection efficiency
- Acceptable noise / radio purity levels
- Acceptable time resolution (event reconstruction)
- Broad dynamic range

JUNO will have two independent calorimetry PMT systems:

18 k large 20" PMTs

- 75% coverage
- Stochastic term: 3% / sqrt(E/MeV)
- Slower + worse p.e. resolution
- High dark noise

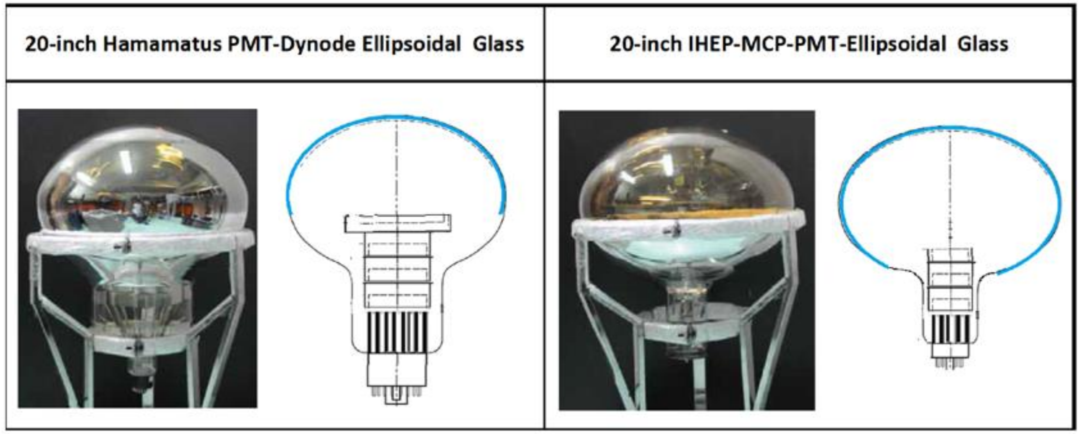
25 k small 3" PMTs

- 3% coverage
- Stochastic term: 14% / sqrt(E)
- Faster + better p.e. resolution
- Low dark noise

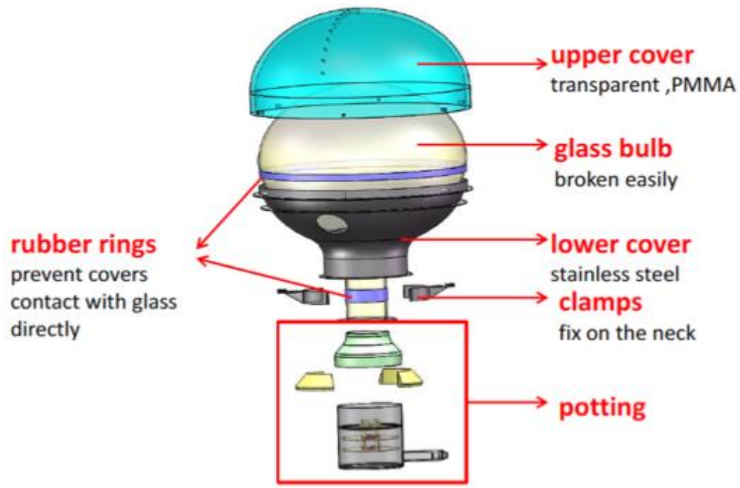
20" PMTs

Contracts were signed in 2015

- 15k MCP-PMT (75%) from NNVT
- 5k Dynode PMT (25%) from Hamamatsu

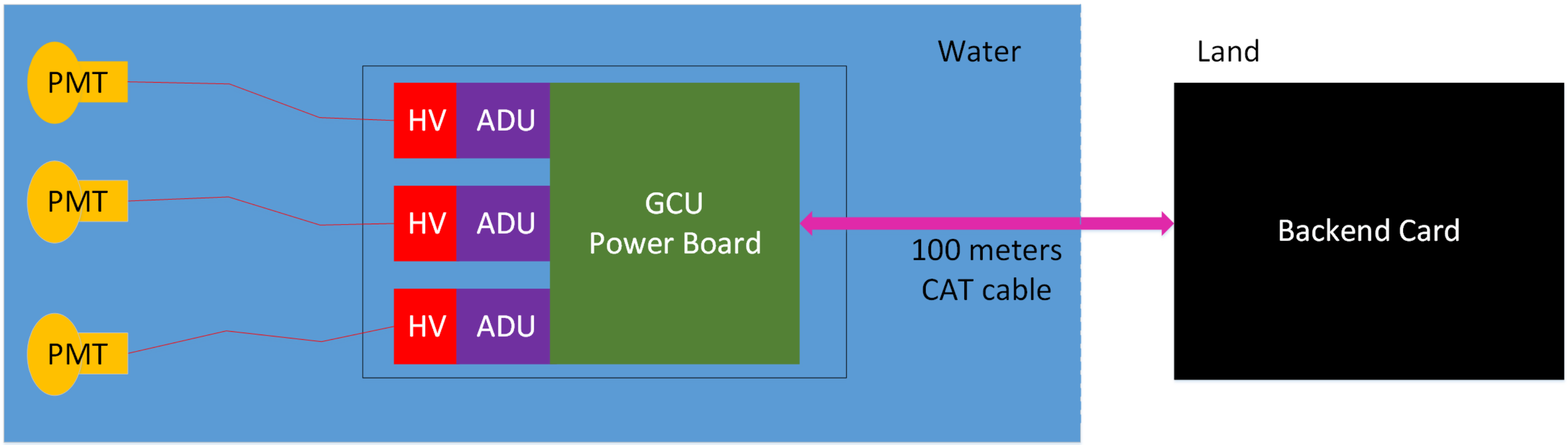


Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE*area)	%	27%, > 24%	27%, > 24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5, F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

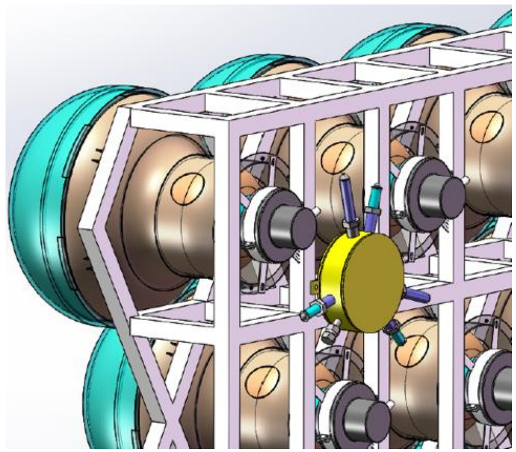


20” PMTs – electronics

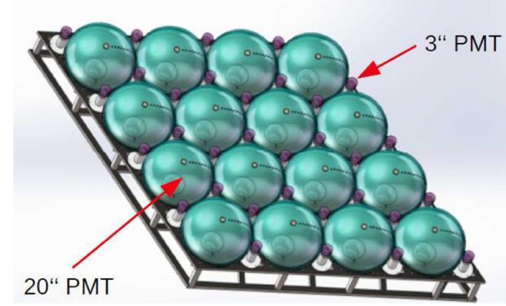
1F3 scheme



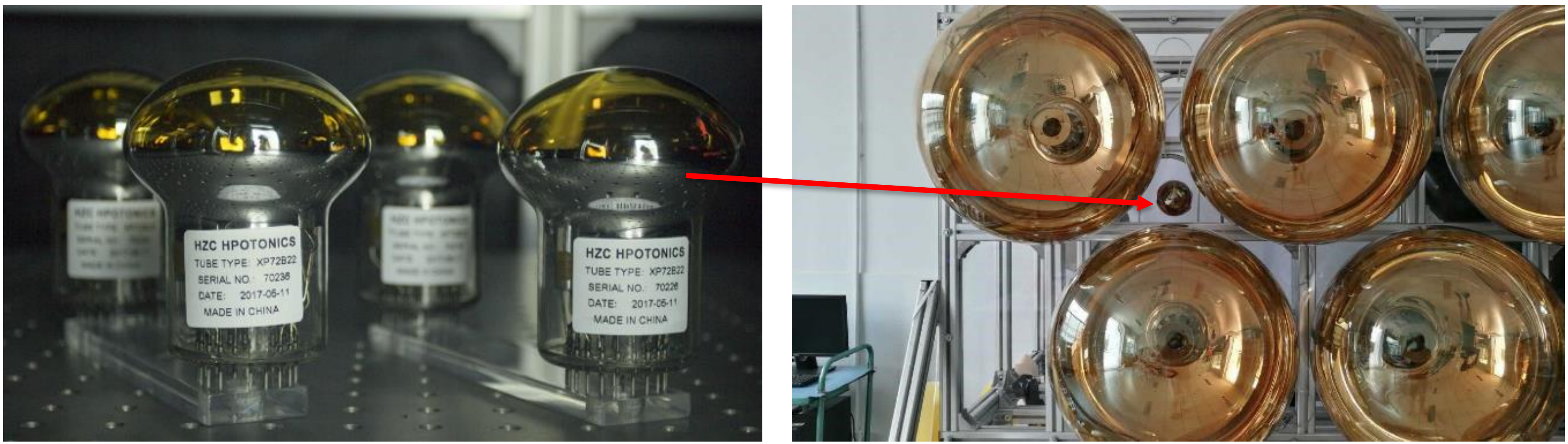
- PMT: photomultiplier tubes
- HV: High Voltage units
- ADU: Analog to Digital Unit
- GCU: Global Control Unit
- CAT cable: Category 5e cable
- High reliability needed
- Severe constraints by power consumption



3" PMTs

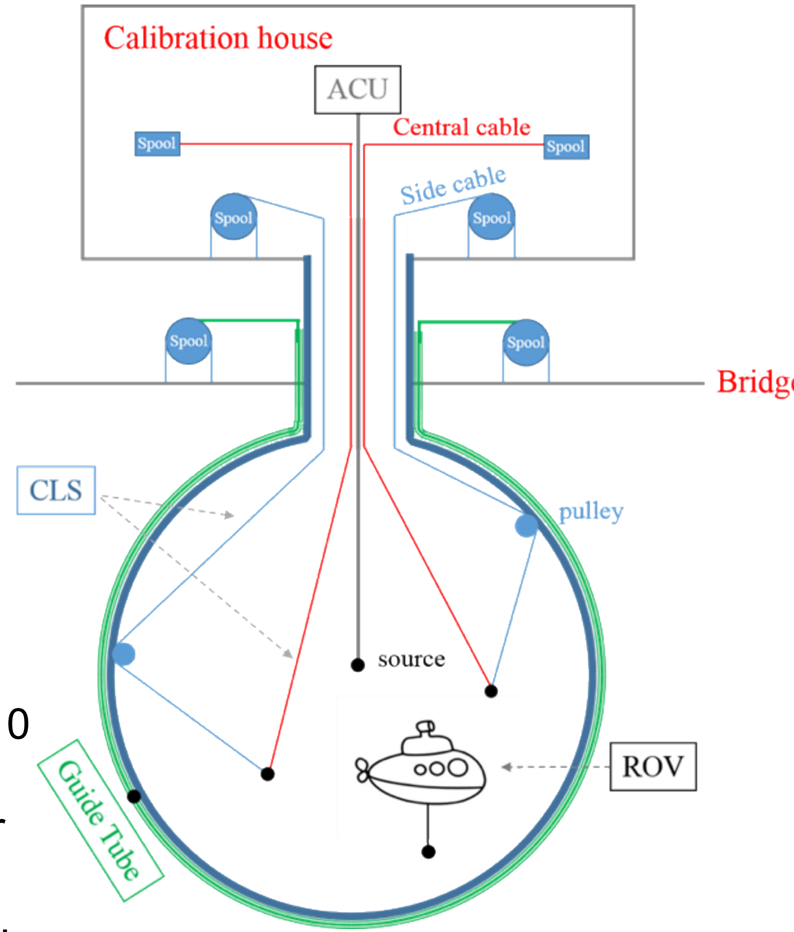


- 25000 3” PMTs, contracted to HZC (China)
- Together with the 20” PMTs as a double calorimetry
  - Increase photon statistics by ~2.5%
  - Energy measurement via “photon counting”, better control of systematics
  - muon tracking, supernova detection …
- Production is expected to start early 2018



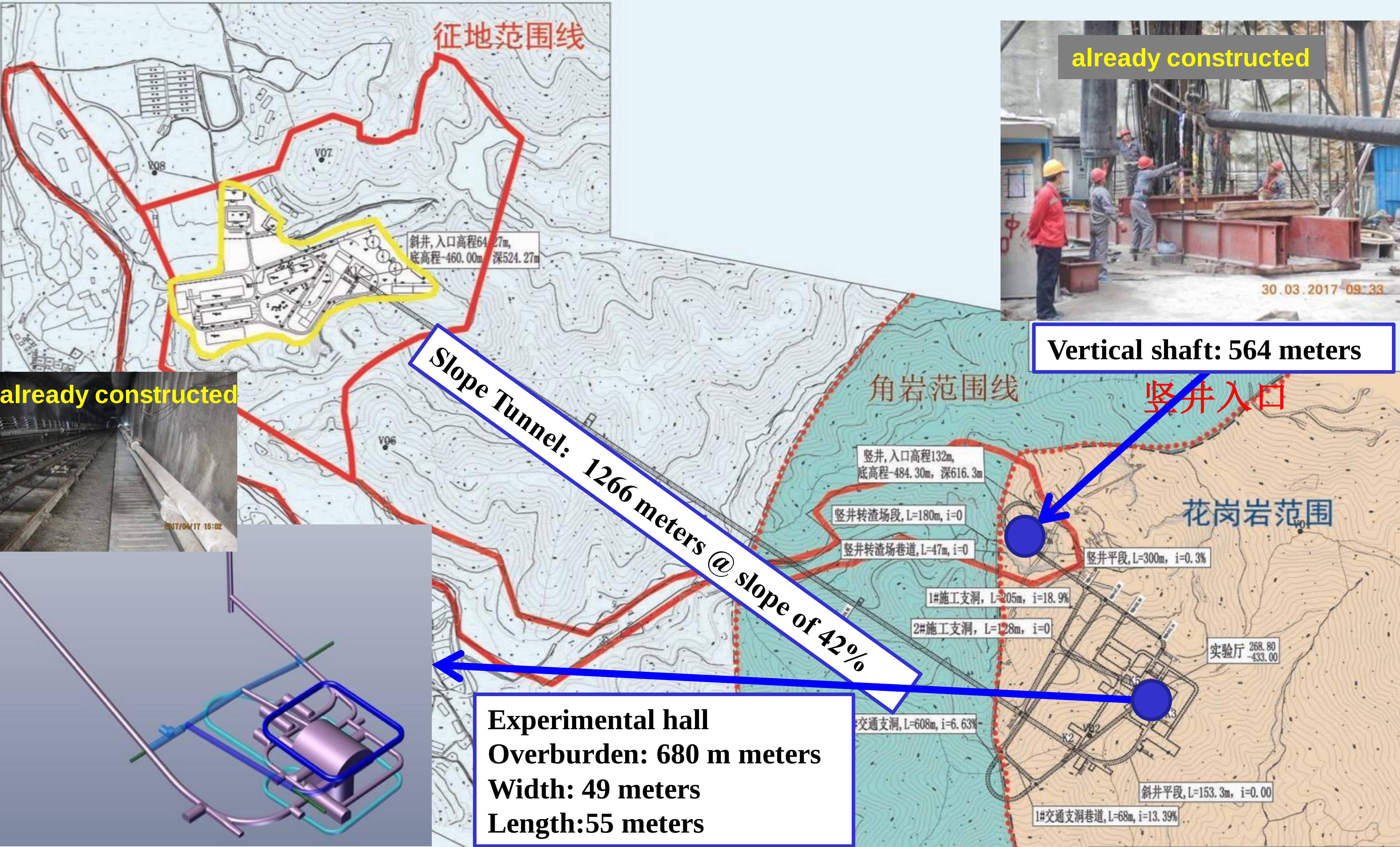
Calibration

- The goal:
  - Overall energy resolution: ≤ 3%/√E/MeV
  - Energy scale uncertainty: <1%
- Radioactive sources:
  - gamma： ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs
  - positrons： ^{22}Na, ^{68}Ge
  - neutrons： ^{241}Am-Be, ^{241}Am- ^{13}C or ^{241}Pu- ^{13}C, ^{252}Cf
- Four complementary calibration systems
  - 1-D: Automatic Calibration Unit (ACU) → for central axis scan (sub-cm positioning),
  - 2-D:
    - Cable Loop System (CLS) → scan vertical planes (10 cm precision),
    - Guide Tube Calibration System (GTCS) → CD outer surface scan (already tested),
  - 3-D: Remotely Operated under-LS Vehicle (ROV) → whole detector scan (first version tested)



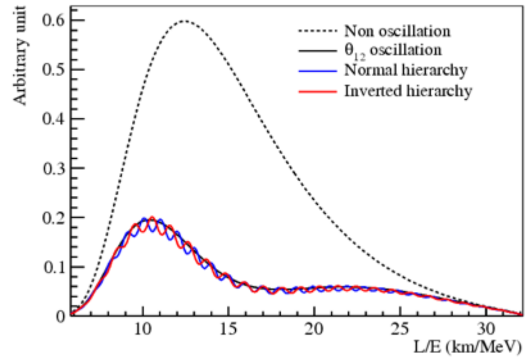
Experimental site

JUNO civil construction

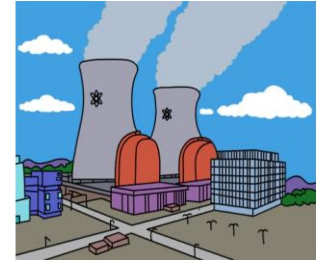


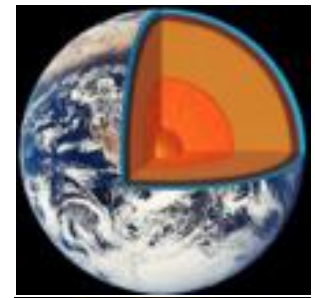
JUNO Physics Program

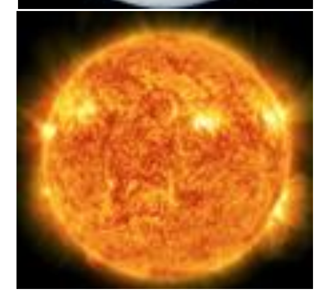
Neutrino Physics with JUNO,
J. Phys. G 43, 030401 (2016)

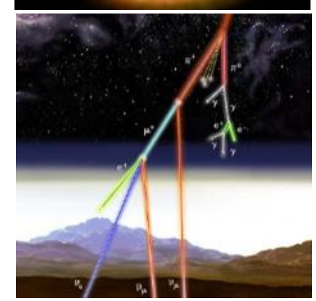


- Reactor neutrinos
  - Mass Hierarchy
    - needed energy resolution ~3% @ 1 MeV,
    - energy scale uncertainty <1%
  - Precision measurements of oscillation parameters
- Supernovae neutrinos
- Geoneutrinos
- Solar neutrinos
- Atmospheric neutrinos
- Exotic searches









JUNO schedule

2014: International collaboration established

- start civil construction

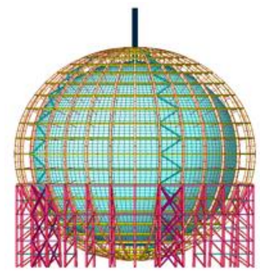
2015: PMT production line manufacturing

2016: Start PMT and detector production

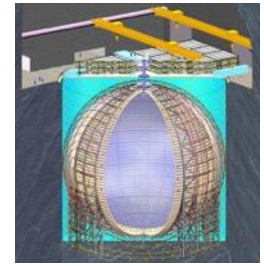
2017: Start PMT testing

2018: PMT potting

2019: Start building central detector and LS filling



beginning of next decade: start data taking



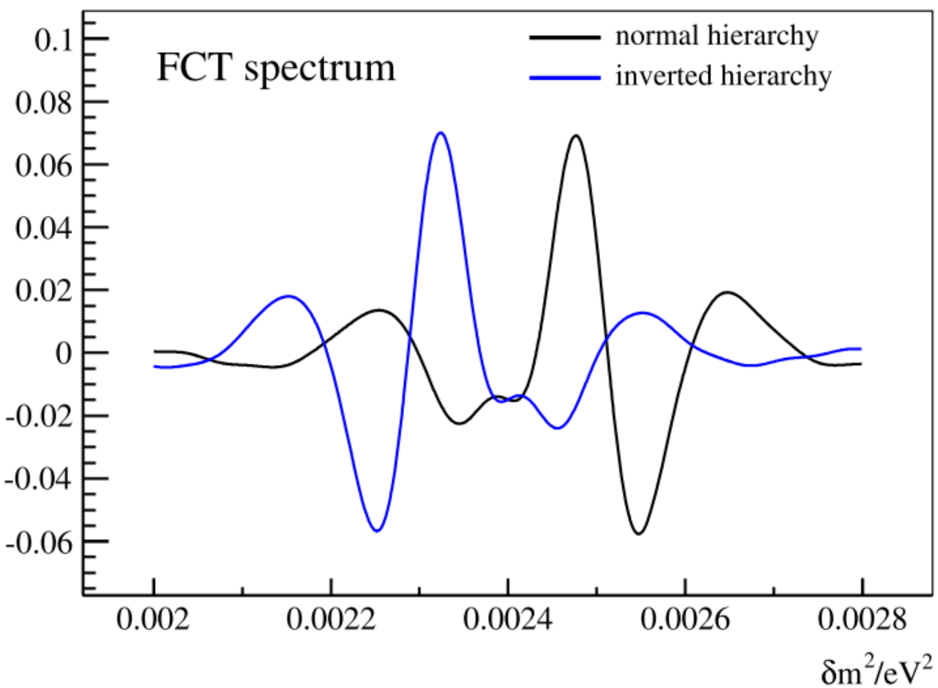
JUNO Collaboration

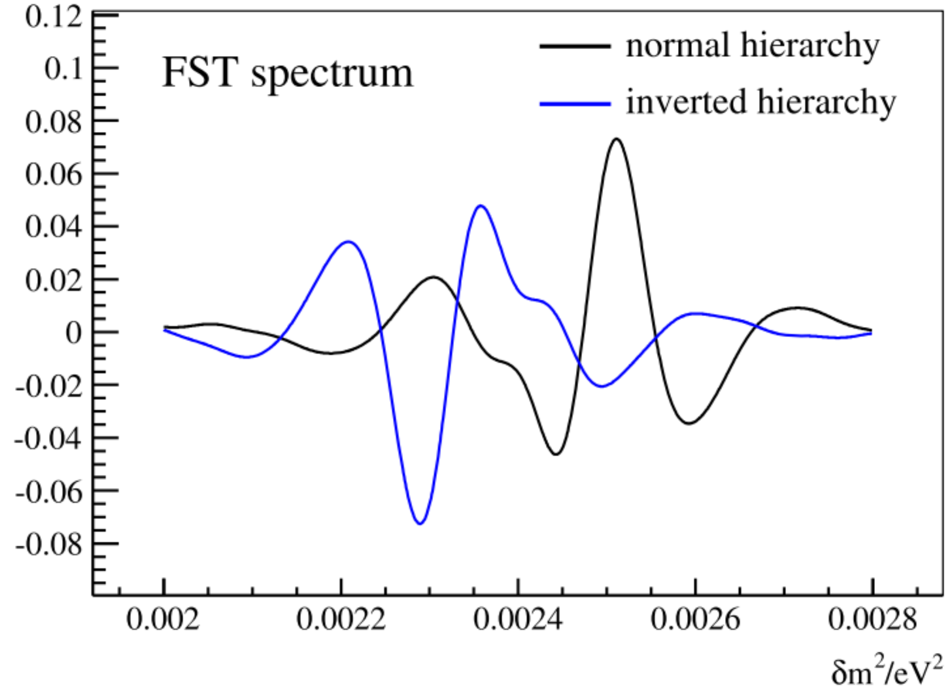
Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	IHEP
China	Jilin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

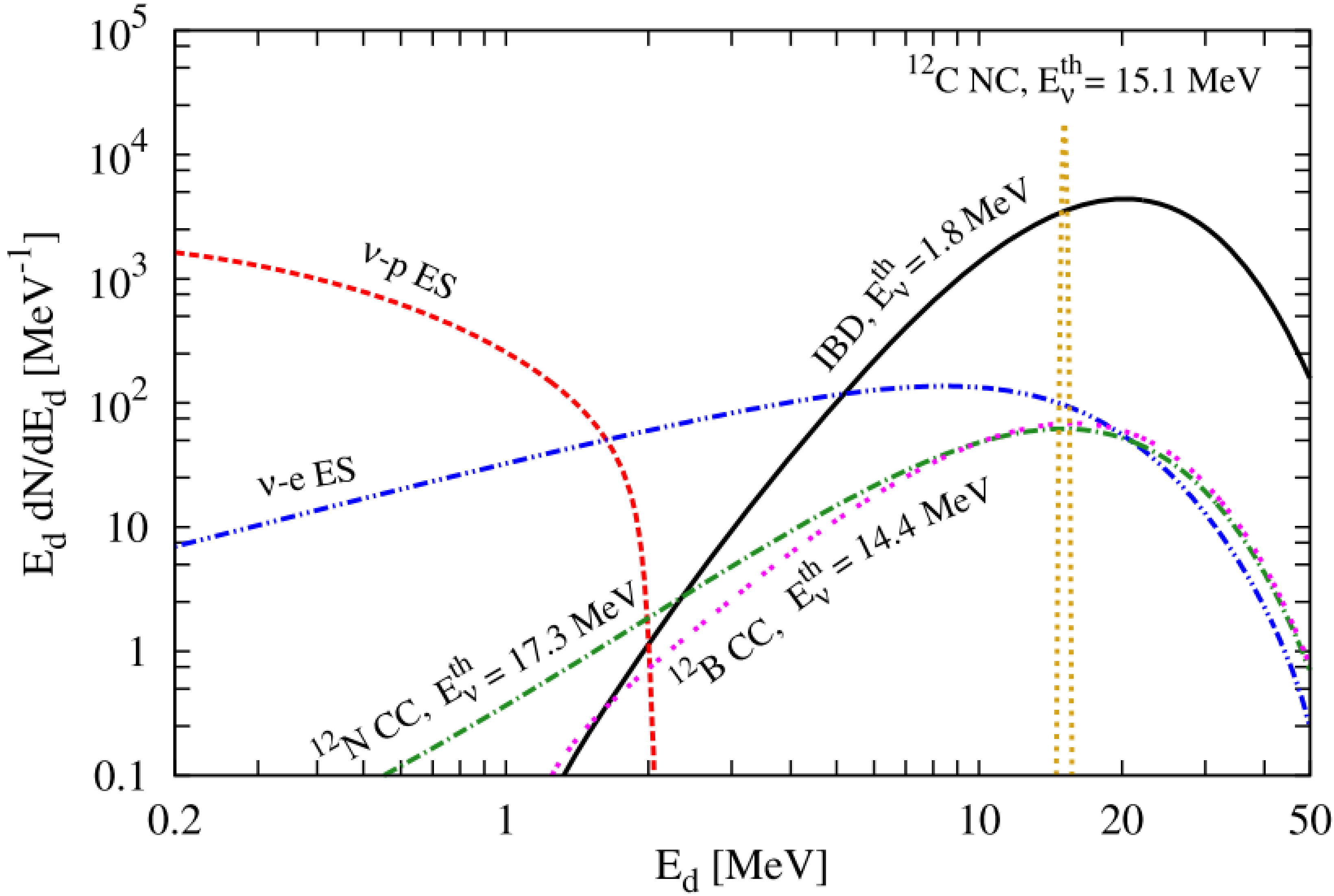
Conclusions

- JUNO Collaboration since 2014
  - 71 institutes from 16 countries
- High energy resolution is needed mainly for MH determination
  - ✓ High quality liquid scintillator
  - ✓ High detection efficiency PMTs
  - ✓ More than 75% photocathode coverage
  - ✓ Extensive calibration program
- Construction of the underground lab ongoing
- PMTs already purchased and tests already started
- The detector design is now finalised, installation by 2019
- Data taking beginning of next decade

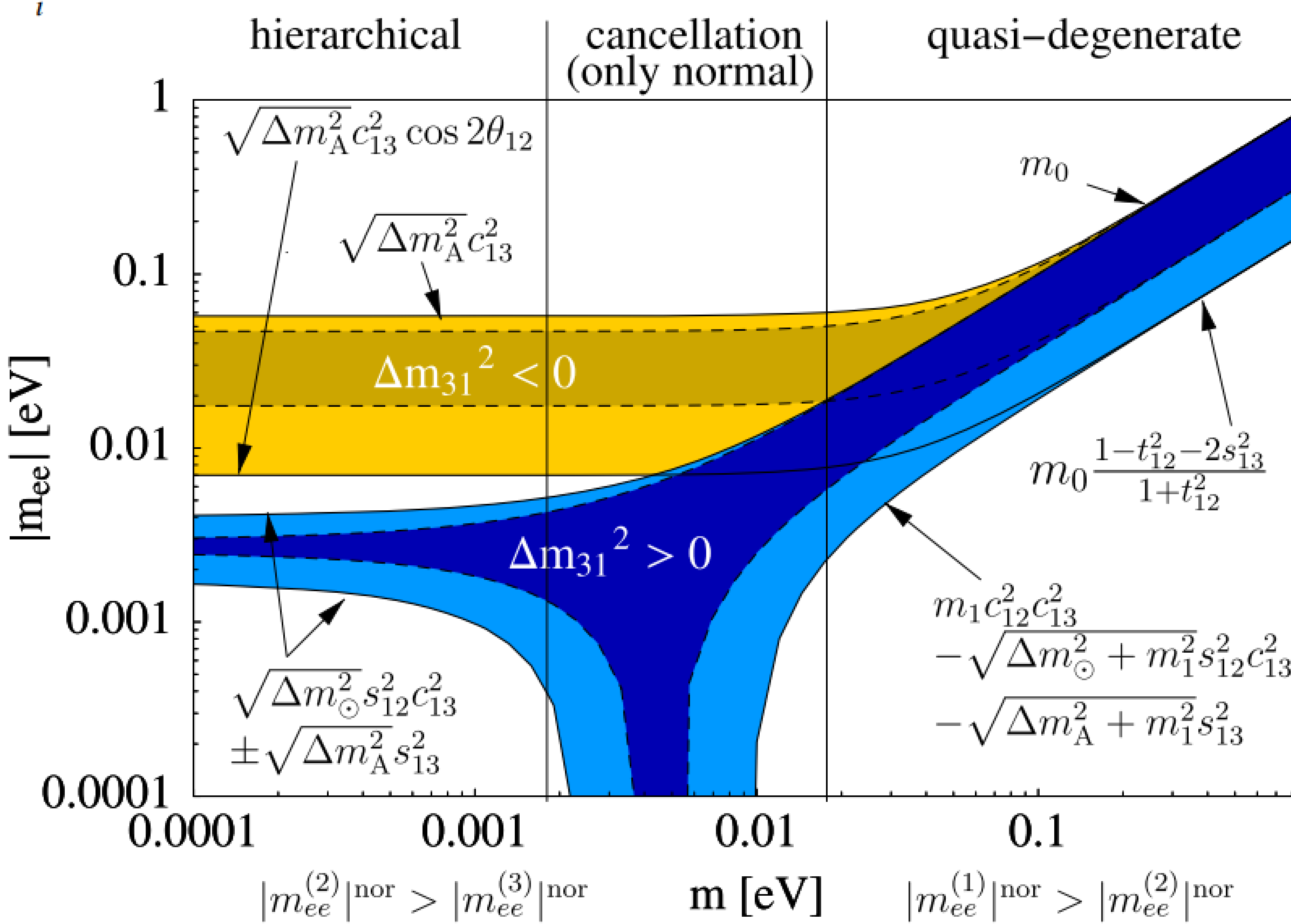
Backup

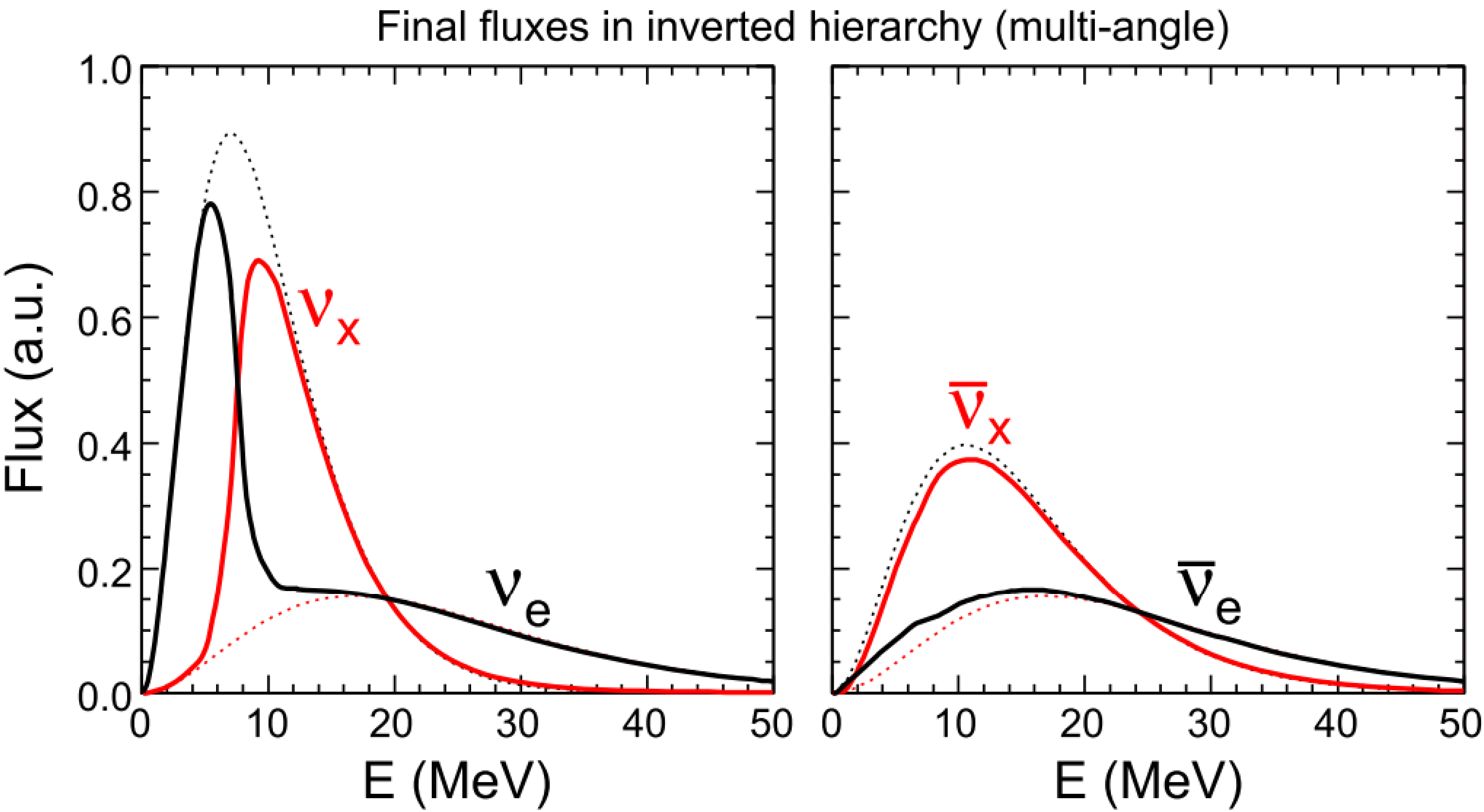

FCT spectrum
normal hierarchy
inverted hierarchy
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0.002
0.0022
0.0024
0.0026
0.0028
δm²/eV²


FST spectrum
normal hierarchy
inverted hierarchy
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0.002
0.0022
0.0024
0.0026
0.0028
δm²/eV²

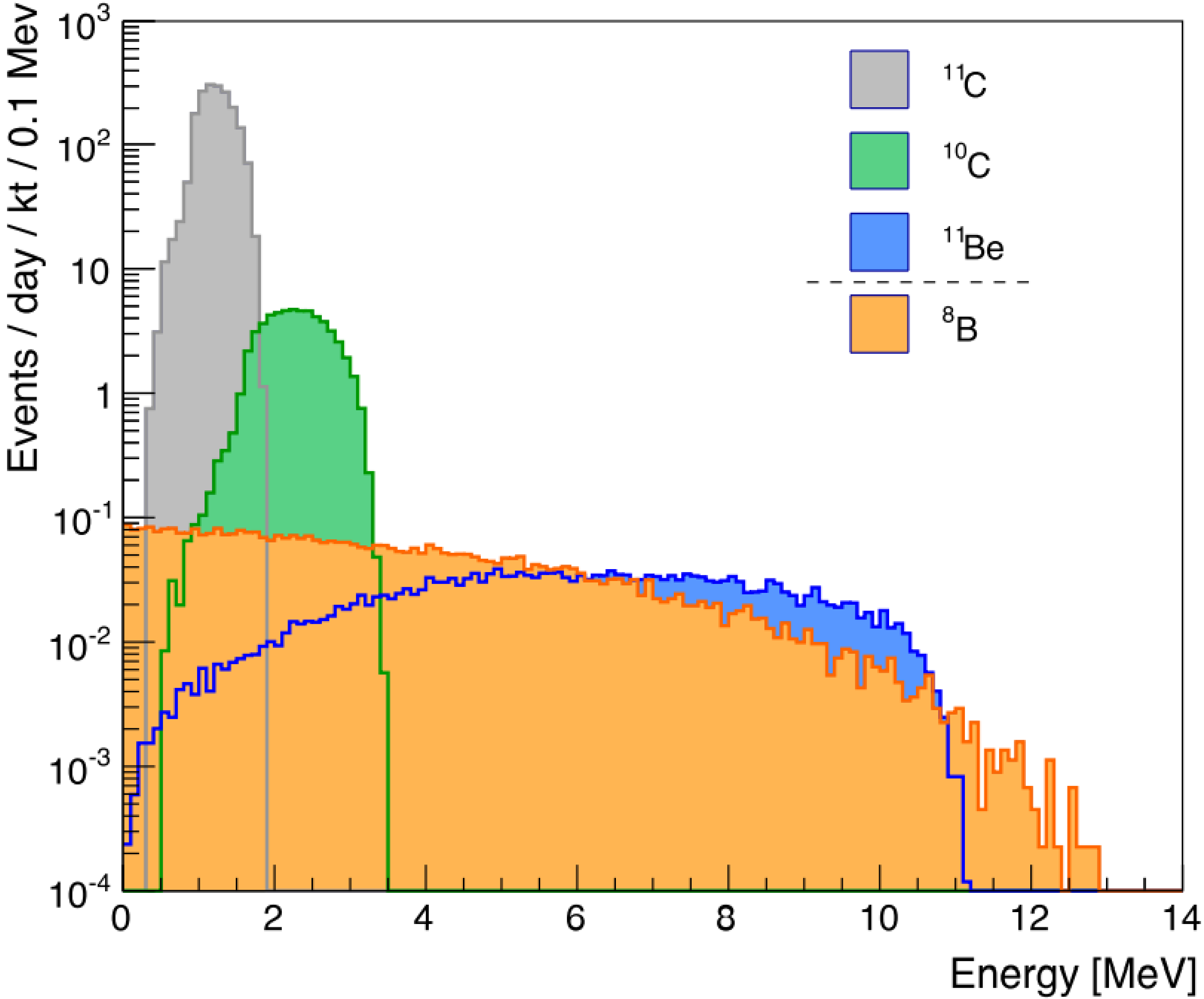

^{12}C NC, E_ν^{th}= 15.1 MeV
IBD, E_ν^{th}=1.8 MeV
ν-p ES
ν-e ES
^{12}N CC, E_ν^{th} = 17.3 MeV
^{12}B CC, E_ν^{th} = 14.4 MeV
E_d dN/dE_d [MeV^{-1}]
E_d [MeV]
10^5
10^4
10^3
10^2
10
1
0.1
0.2
1
10
20
50

$$\langle m \rangle_{ee} \equiv \sum_i \left(m_i U_{ei}^2 \right)$$

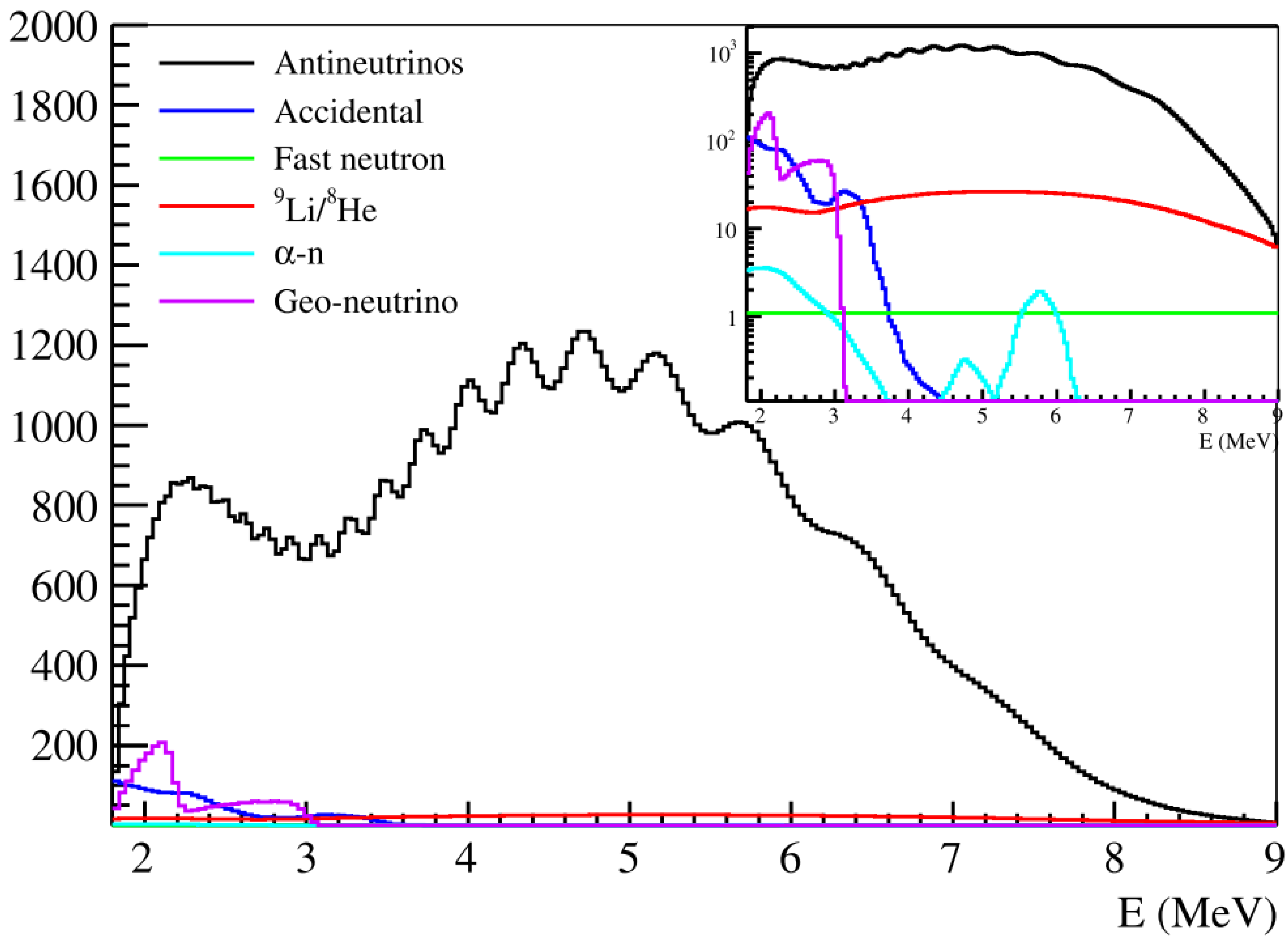




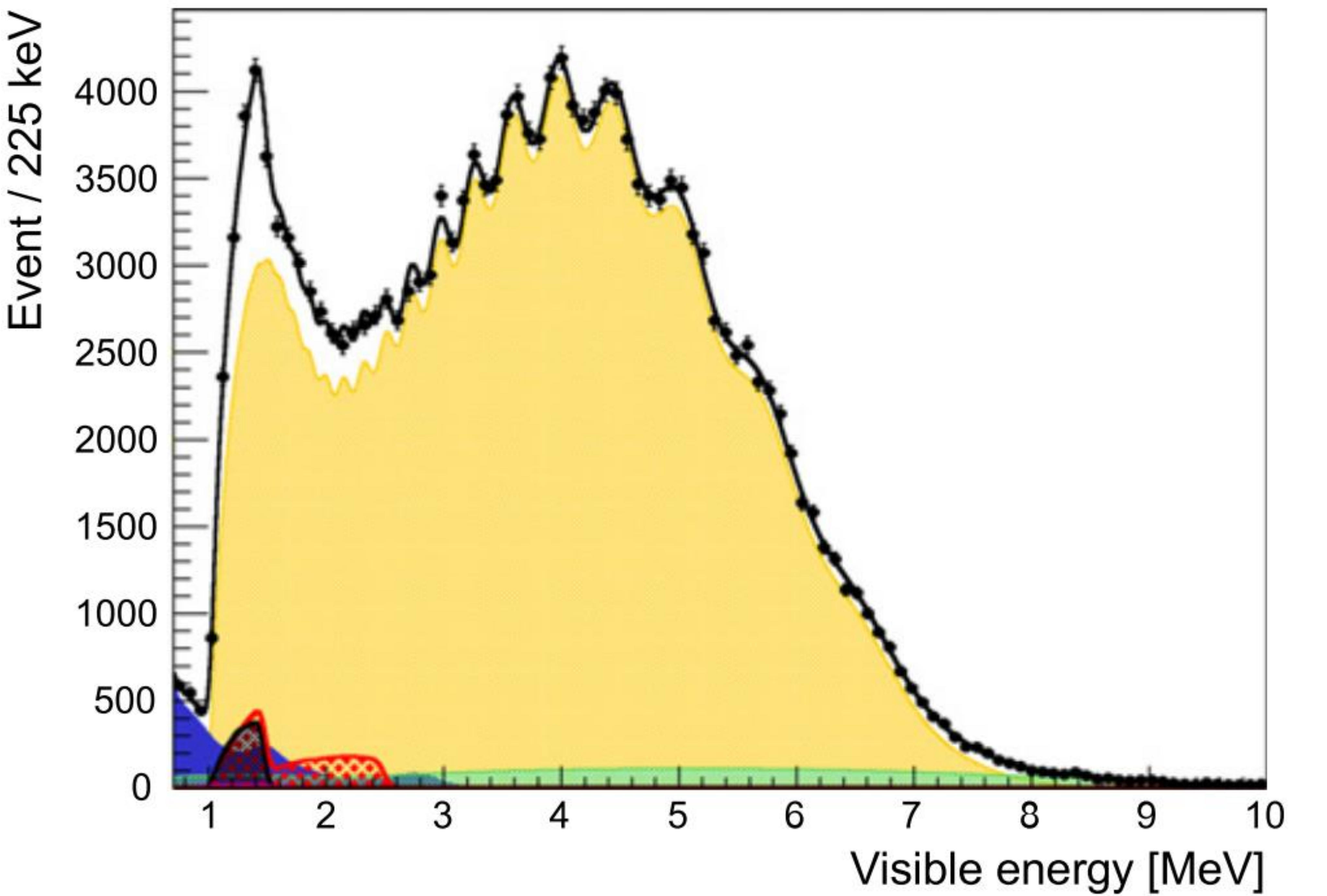
Final fluxes in inverted hierarchy (multi-angle)
Flux (a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
E (MeV)
ν_x
ν_e
$\bar{\nu}_x$
$\bar{\nu}_e$



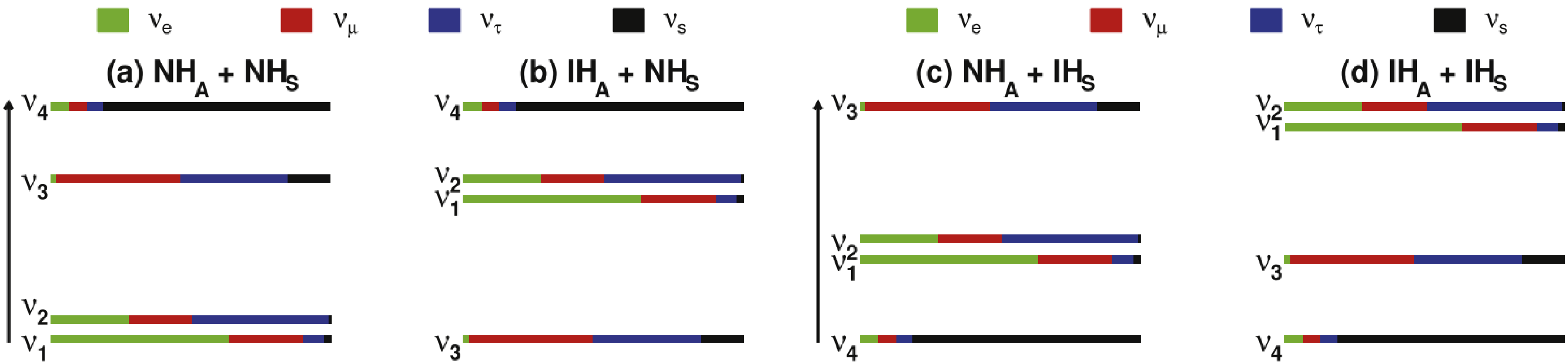
Events / day / kt / 0.1 Mev
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
12
14
Energy [MeV]
^{11}C
^{10}C
^{11}Be
^{8}B



Antineutrinos
Accidental
Fast neutron
⁹Li/⁸He
α-n
Geo-neutrino
2000
1800
1600
1400
1200
1000
800
600
400
200
2
3
4
5
6
7
8
9
E (MeV)

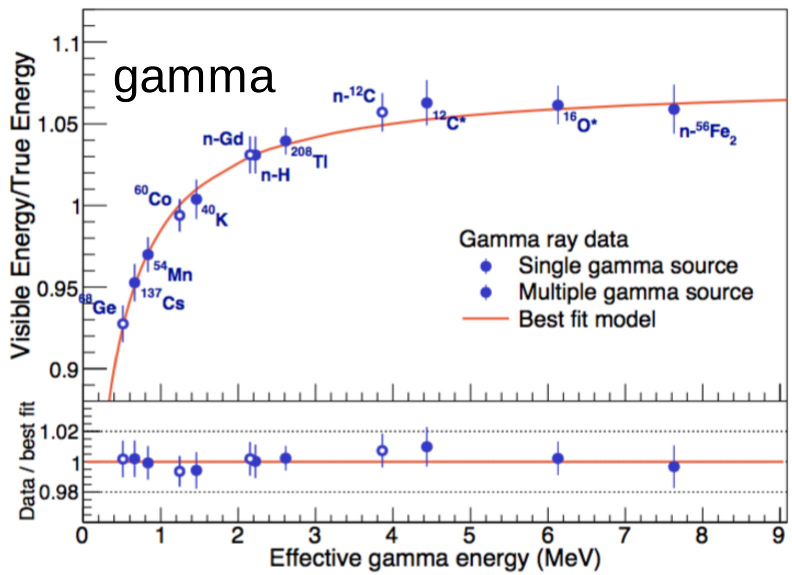


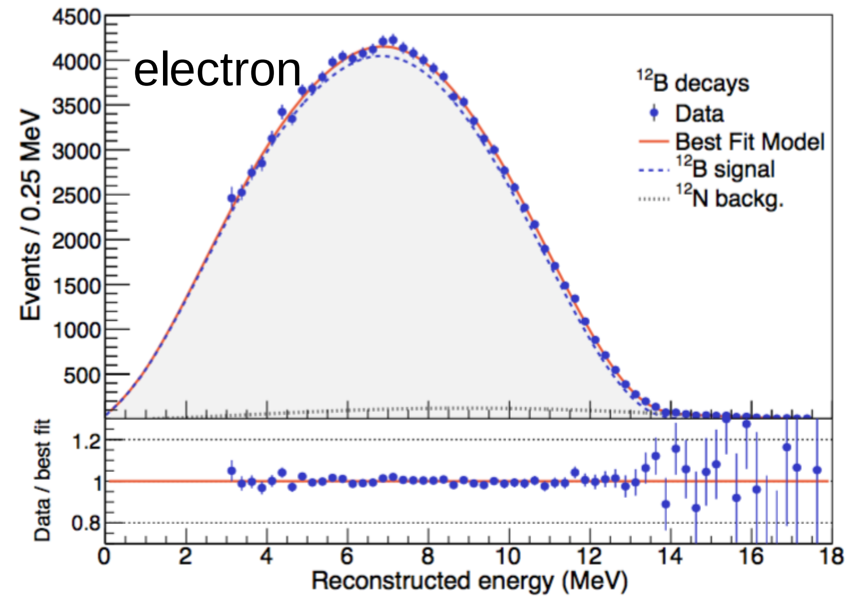
Event / 225 keV
4000
3500
3000
2500
2000
1500
1000
500
0
1
2
3
4
5
6
7
8
9
10
Visible energy [MeV]

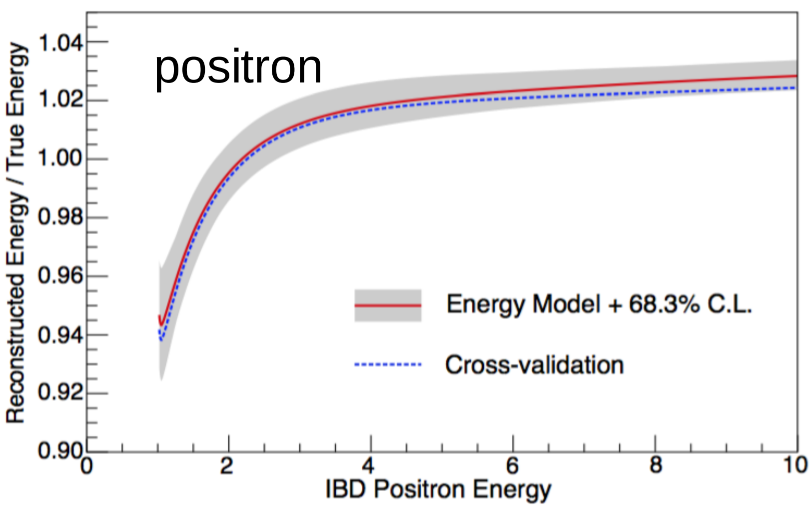


ν_e
ν_μ
ν_τ
ν_s
(a) $NH_A + NH_S$
(b) $IH_A + NH_S$
(c) $NH_A + IH_S$
(d) $IH_A + IH_S$
ν_4
ν_3
ν_2
ν_1

Energy non-linearity calibration

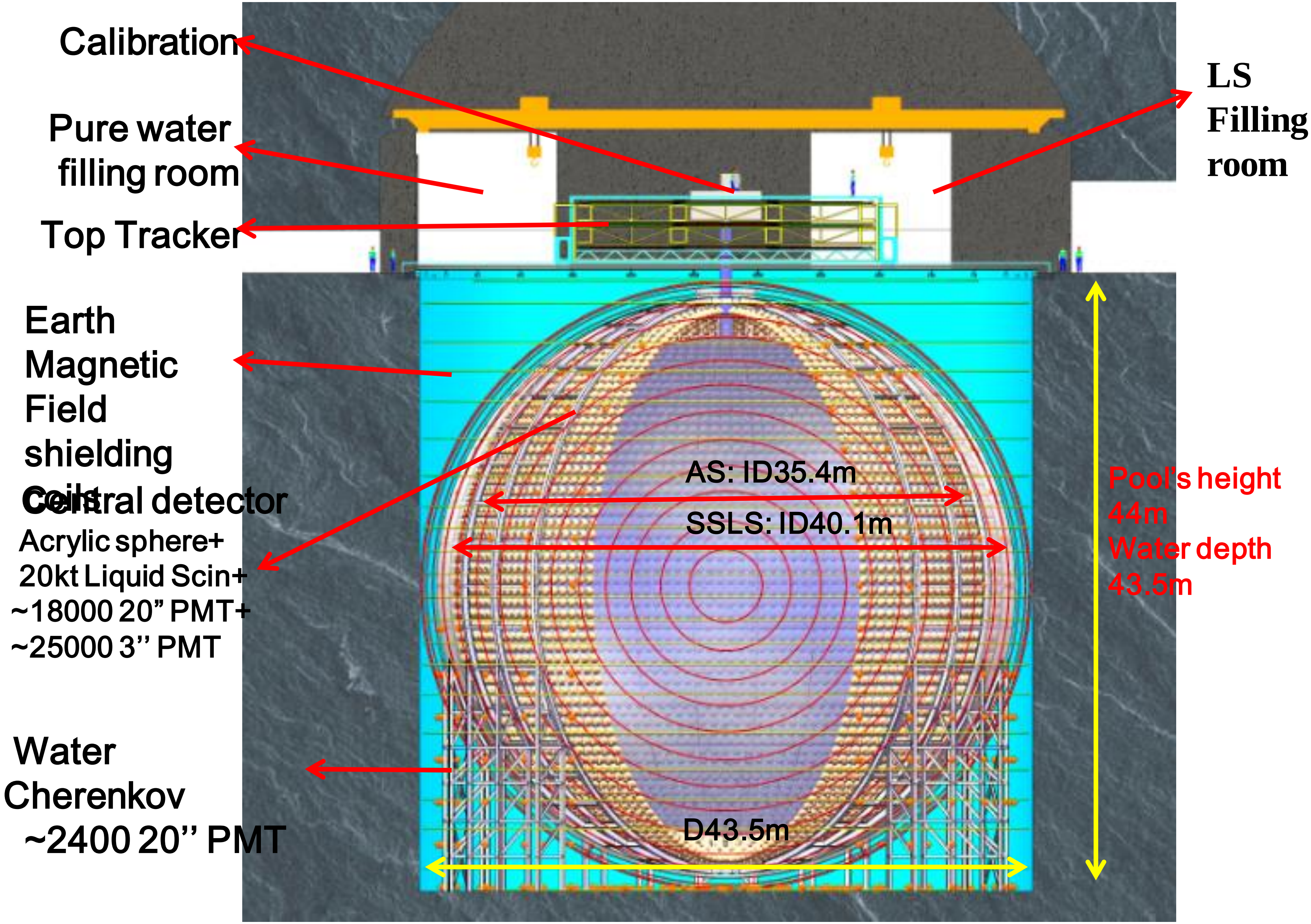






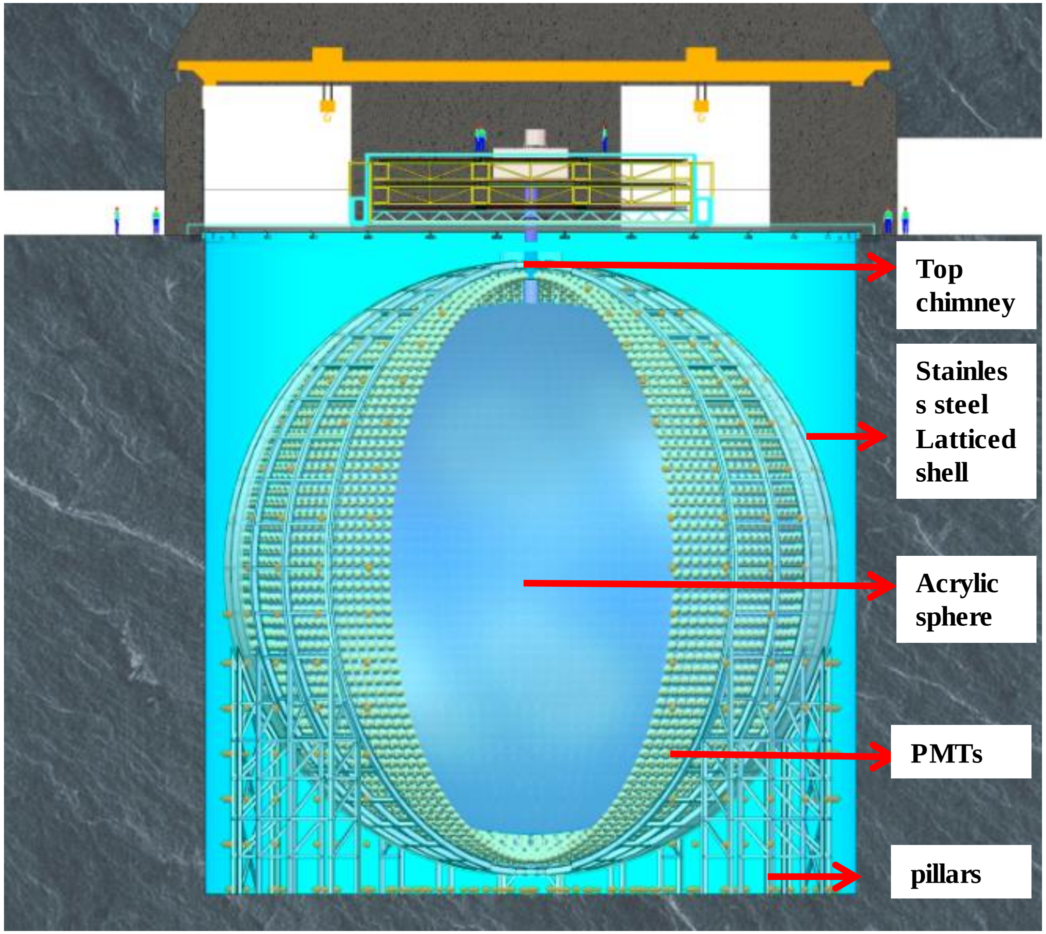
- Two major sources of non-linearity:
  - Scintillator response
  - Readout electronics
- Energy model for positron is derived from measured gamma and electron responses using simulation.

~1% uncertainty (correlated among detectors)

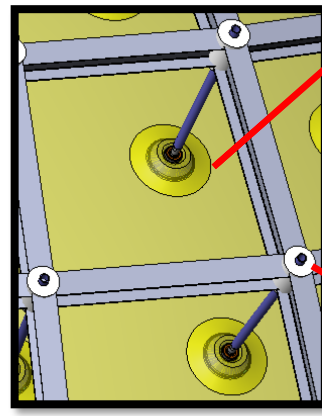


AS: Acrylic sphere; SSLS: stainless steel latticed shell

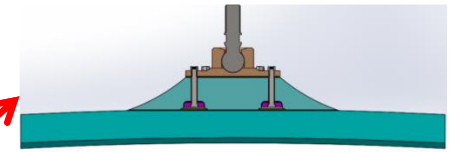
Central detector



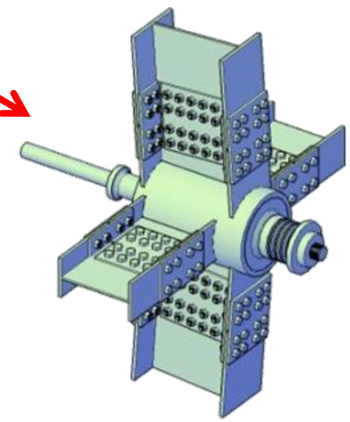
Acrylic sphere supported by stainless steel shell



Connection bars



Acrylic node



steel node

Other system of CD: filling system

Veto System

Top Tracker

- Re-using the OPERA's Target Tracker (plastic scintillators)
- Three (x-y) layers to ensure good muon tracking (3 muons/s)
- Muon rejection studies
- Cosmogenic background study (^{9}Li, ^{8}He)
- Arrived in China in July

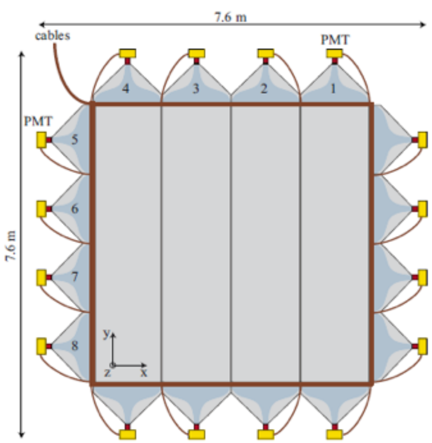
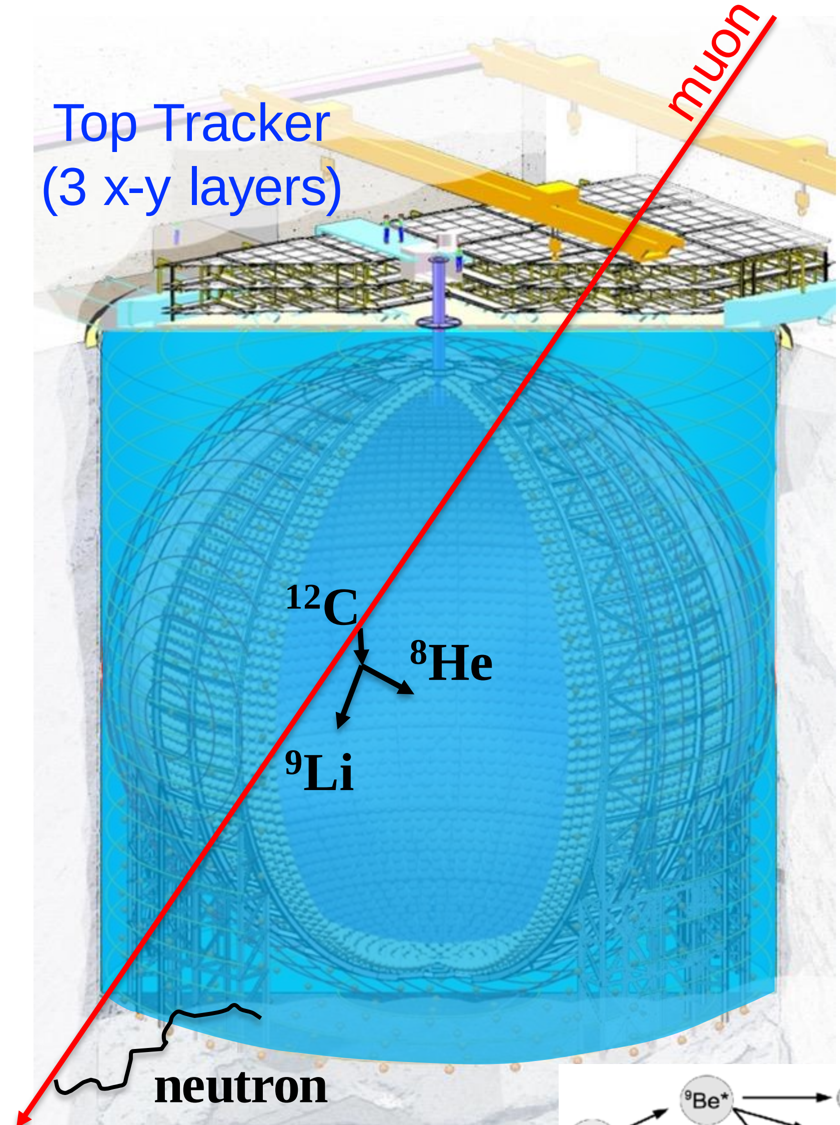
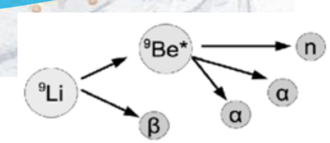


Fig. 3. Schematic view of a plastic scintillator strip wall.





alparaiso