The JUNO experiment

Jiangmen Underground Neutrino Observatory

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On behalf of the JUNO collaboration

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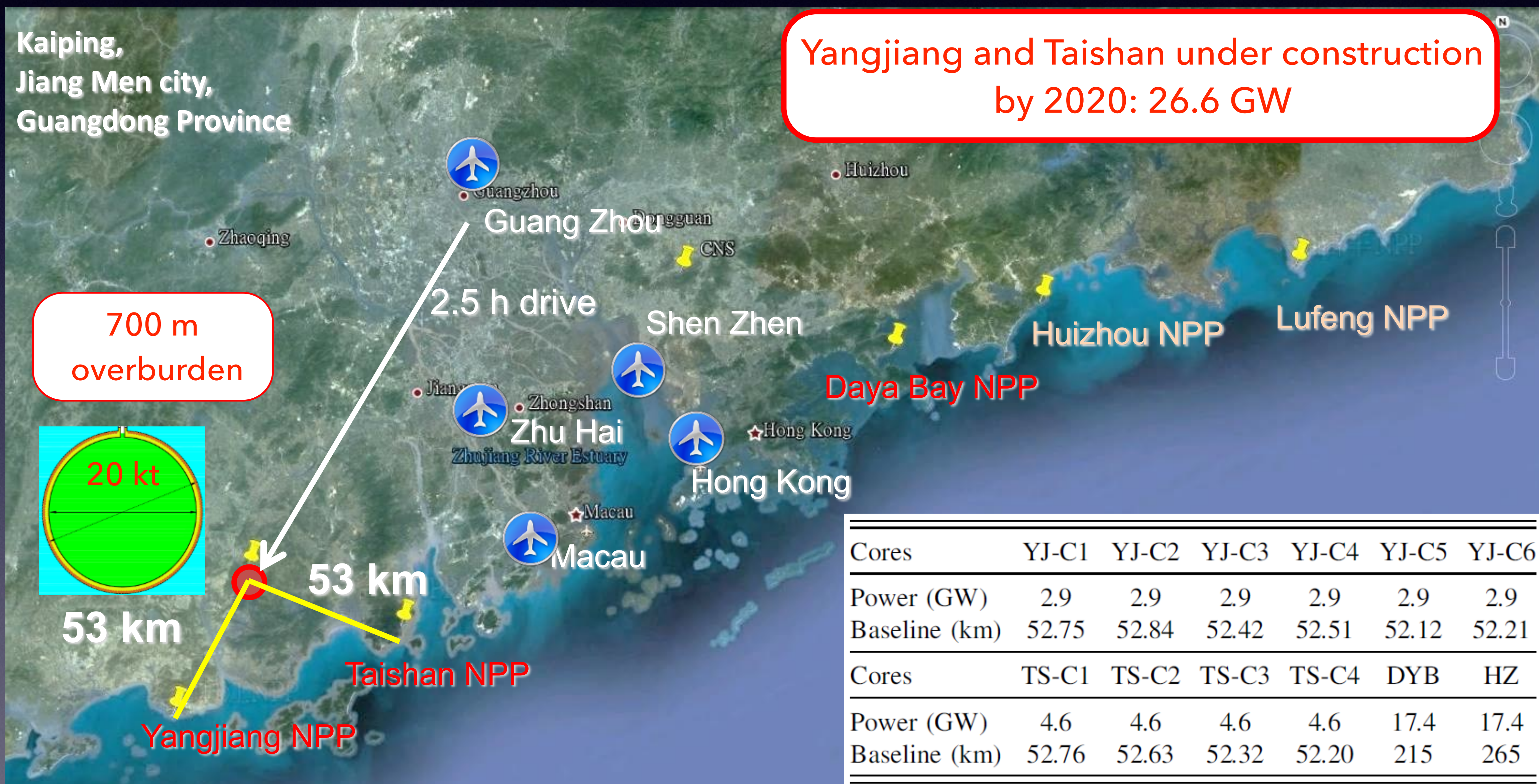
JUNO experiment

- JUNO is a « medium-baseline » (53 km) reactor neutrino experiment.
- JUNO will be the largest Liquid scintillator detector ever built (20 ktonnes).



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

Introduction

- The neutrino mixing matrix can be parameterized as:

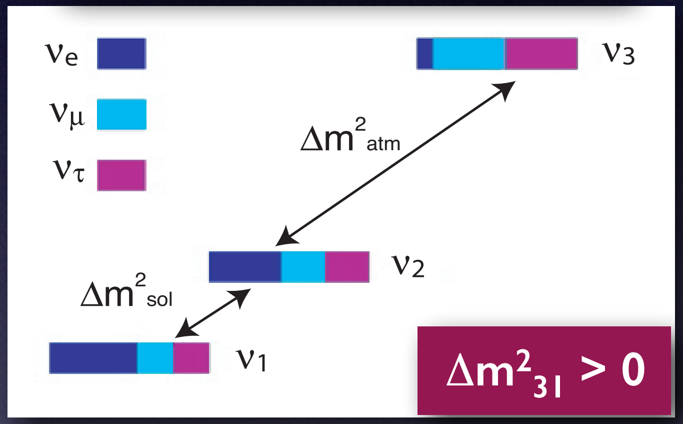
Atmospheric — Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\xi_1/2} & 0 & 0 \\ 0 & e^{i\xi_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

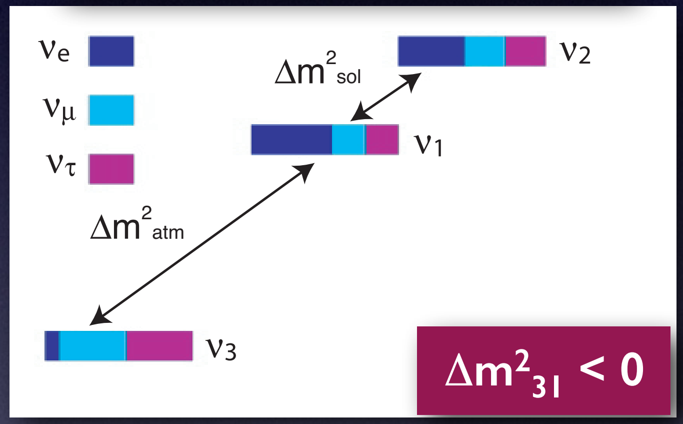
$s_{ij} = \sin(\theta_{ij})$
$c_{ij} = \cos(\theta_{ij})$
$\delta = \mathrm{CP\ phase}$
$\xi_1, \xi_2 = \mathrm{Majorana\ phases}$

- The non-zero value of θ_{13} opens the way for the measurement of the CP violation phase in the leptonic sector.
- An additional goal for next generation neutrino experiment is the mass hierarchy determination.

Normal Hierarchy (N.H.)



Inverted Hierarchy (I.H.)



- The electron antineutrino survival probability in vacuum can be written as:

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

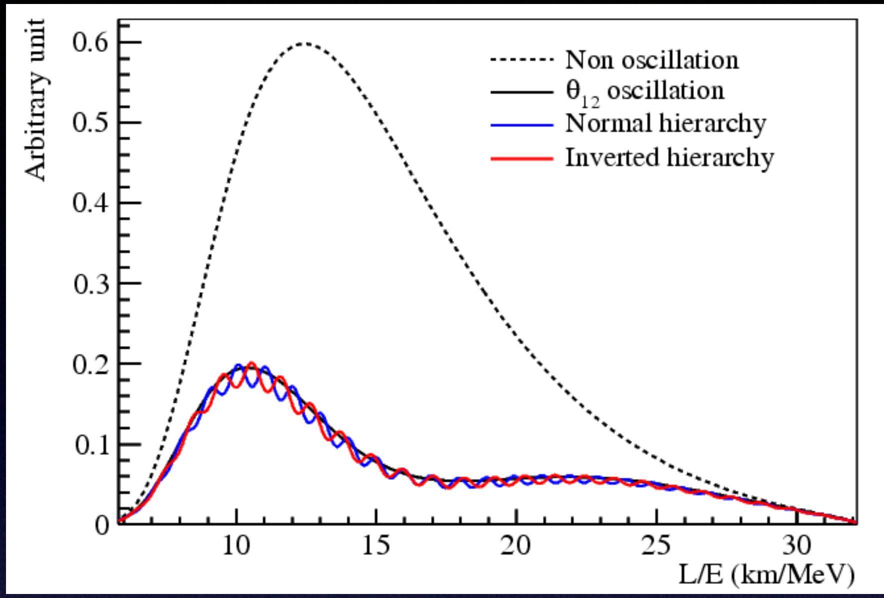
- According to the mass hierarchy, one oscillation frequency ω is larger than the other:

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH:}\ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \qquad \omega P_{31} > \omega P_{32} \\ \mathrm{IH:}\ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \qquad \omega P_{31} < \omega P_{32} \end{aligned}$$

Mass hierarchy determination for reactor antineutrinos

- The spectral distortion contains the MH information, thus the sensitivity is obtained constructing a χ^2 function. The discriminator of the MH is defined as:

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



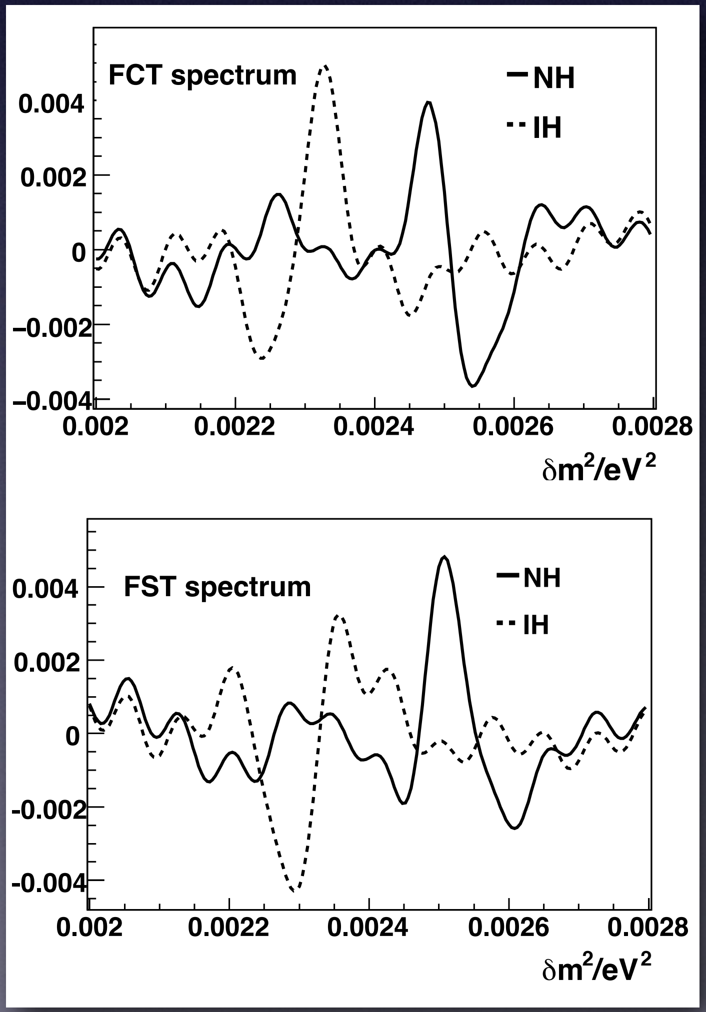
- Moreover, Fourier analysis can be applied to the reconstructed energy spectrum to discriminate between the two hierarchies.

$$FST(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t){\rm d}t$$

$$FCT(\omega) = \int_{t_{min}}^{t_{max}} F(t)\cos(\omega t){\rm d}t$$

with the frequency: $\omega = 2.54 \times \Delta m^2_{ij}$

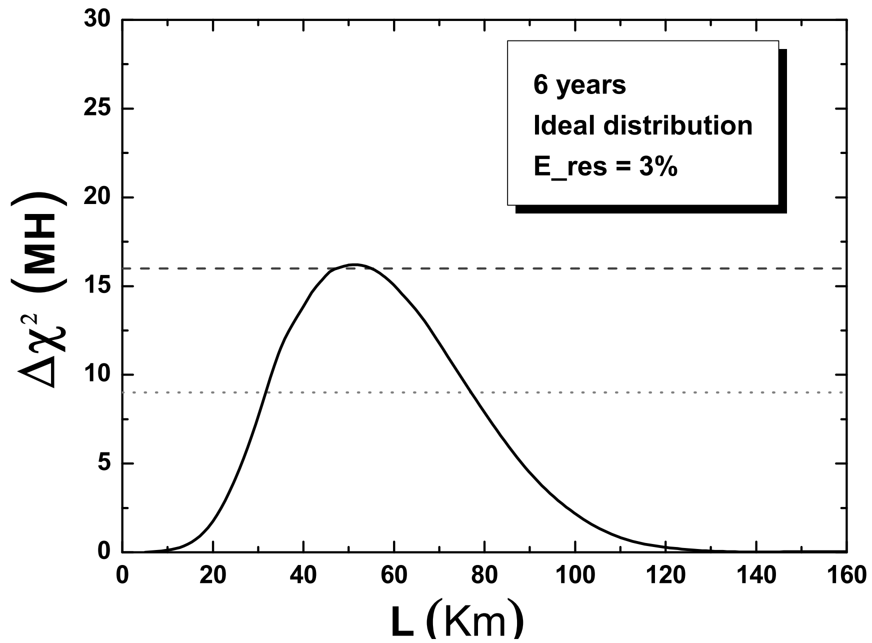
and $t = L/E$

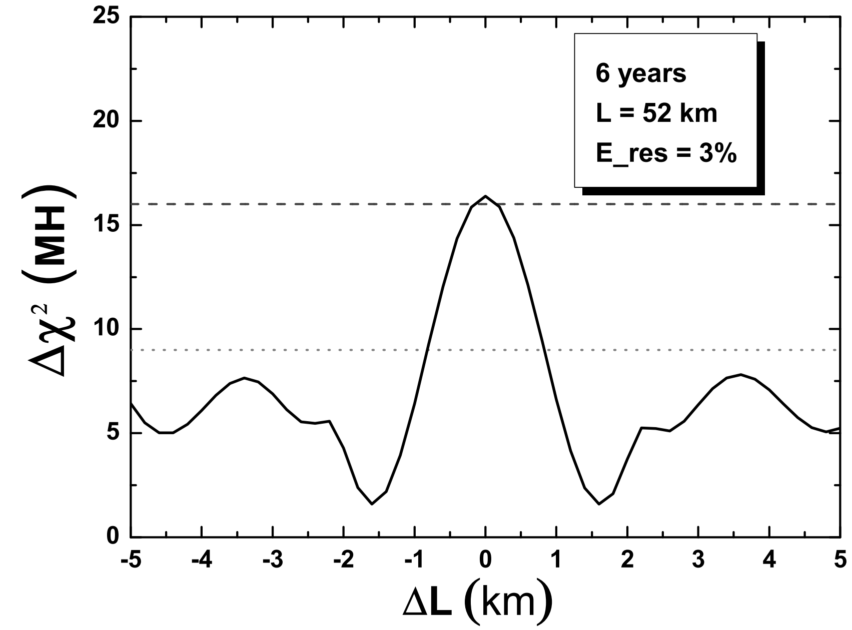


Mass hierarchy sensitivity

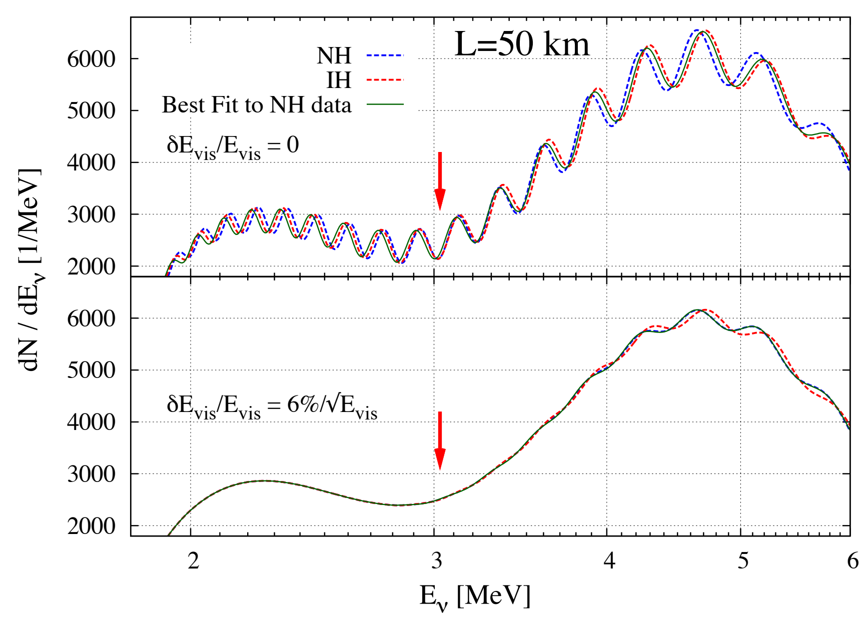
- Two critical parameters have to be optimized: the baseline and the energy resolution.

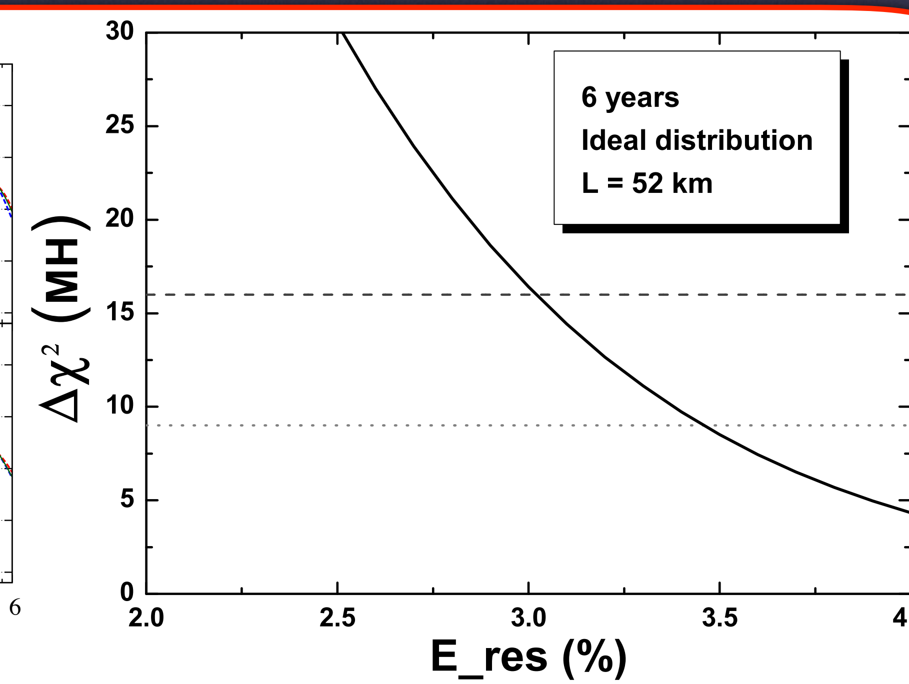
The **baseline** is optimized to **53 km** with a difference to reactor cores of less than 500 m.





The **energy resolution** (photo-electron statistics) is a critical parameter in the achievable sensitivity. The goal is to achieve **$3\%/\sqrt{E[MeV]}$**.





Mass hierarchy sensitivity

- Taking into account the true baseline and **3% energy resolution at 1 MeV**, JUNO can achieve a relative measurement (no constraint on Δm^2_{31} or Δm^2_{32}) of **$\Delta\chi^2$>9 for 100 kIBDs** (20 kton×35 GW×6 years).

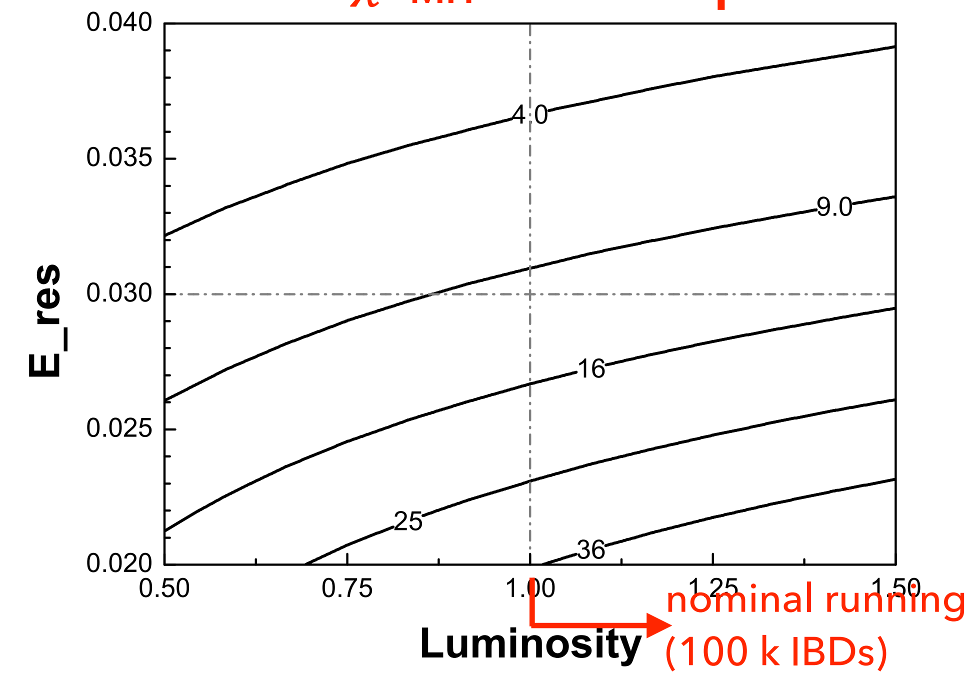
- JUNO can also perform an absolute measurement accounting for constraints from external experiments in particular on $\Delta m^2_{\mu\mu}$ from long baseline experiments.

$$\Delta m^2_{\mu\mu} \simeq \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \sin 2\theta_{12}\sin\theta_{13}\tan\theta_{23}\cos\delta\Delta m^2_{21}$$
$$\Delta m^2_{ee} \simeq \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

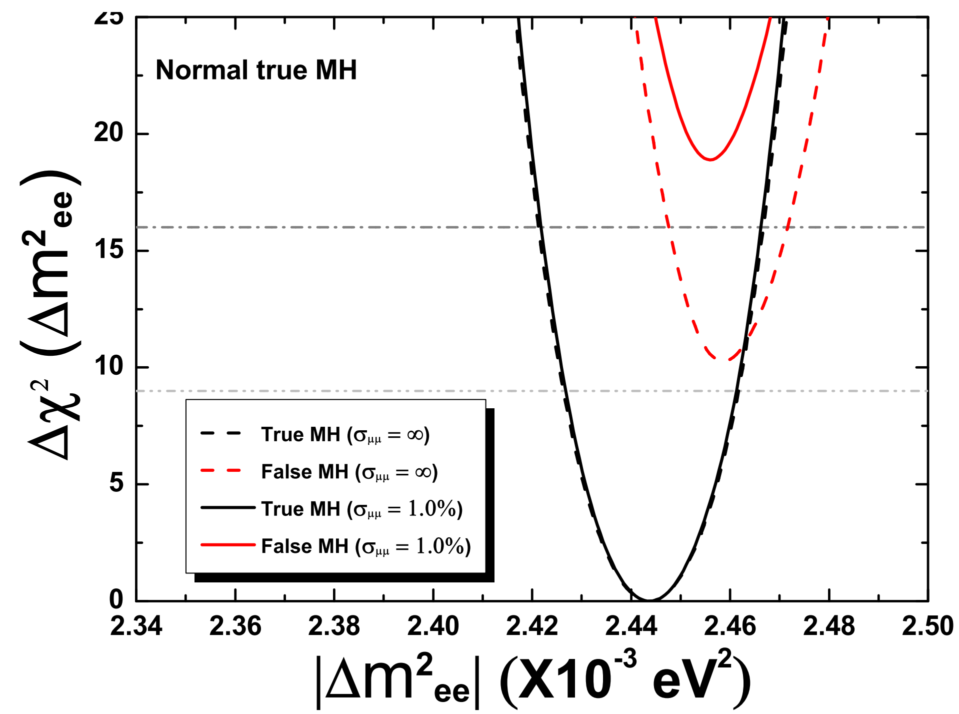
Relative measurement: $\Delta\chi^2$>9

Absolute measurement: $\Delta\chi^2$>16

iso-$\Delta\chi^2_{MH}$ contour plot

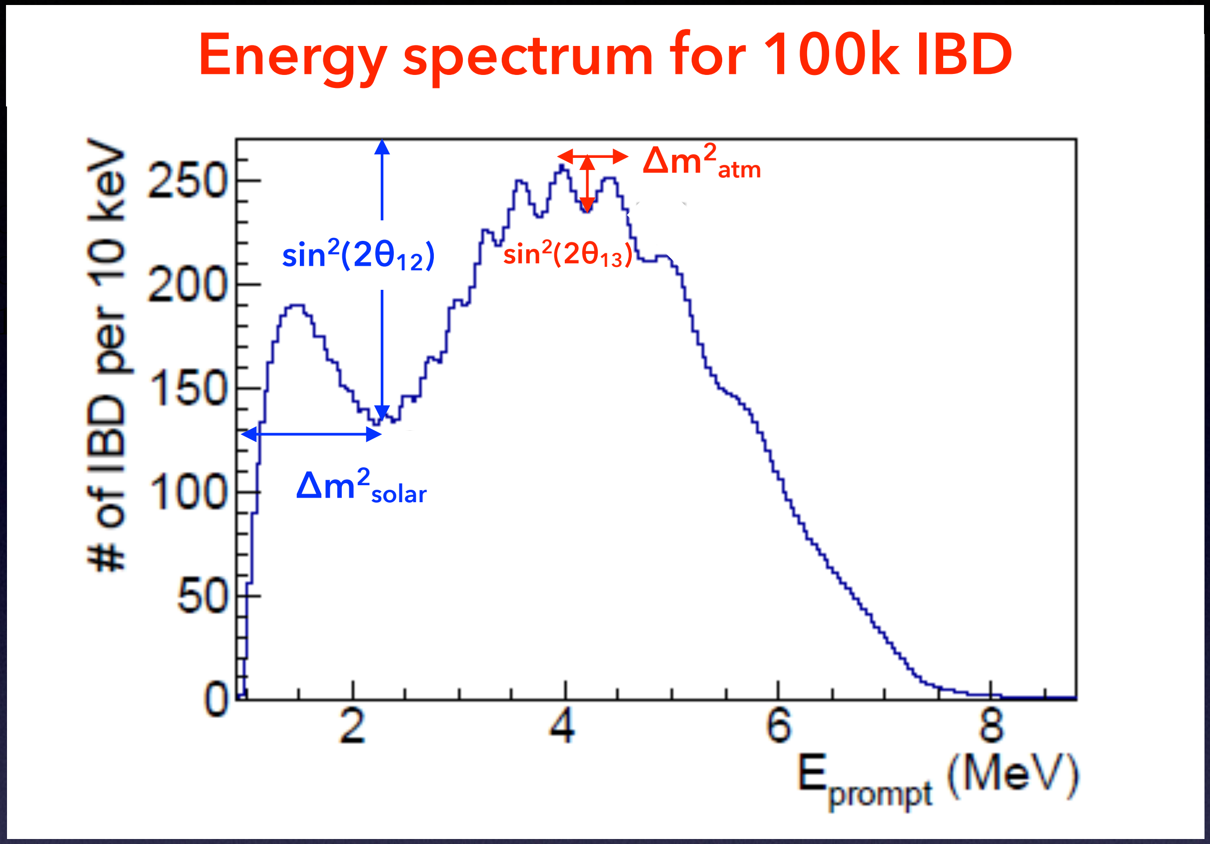


Sensitivity for 100 k IBDs
(20 kton×35 GW×6 years).



Physics program of a large LS detector at 53 km from nuclear cores

- Mass hierarchy determination by measuring the energy spectrum. Advantage of JUNO: no matter effect and no sensitive to CP phase.
- Measurement of Δm^2_{12} and θ_{12} with the highest precision ever reached.
- These precision measurements will permit to probe the unitarity of U_{PMNS} up to ~1%.



	Current precision	JUNO goal
$\sin^2 2\theta_{12}$	6 %	0.7 %
Δm^2_{12}	3 %	0.6 %
$\lvert\Delta m^2_{32}\rvert$	5 %	0.5 %
MH	N/A	3-4σ
$\sin^2 2\theta_{13}$	3 %	15 %

Additional Physics reach

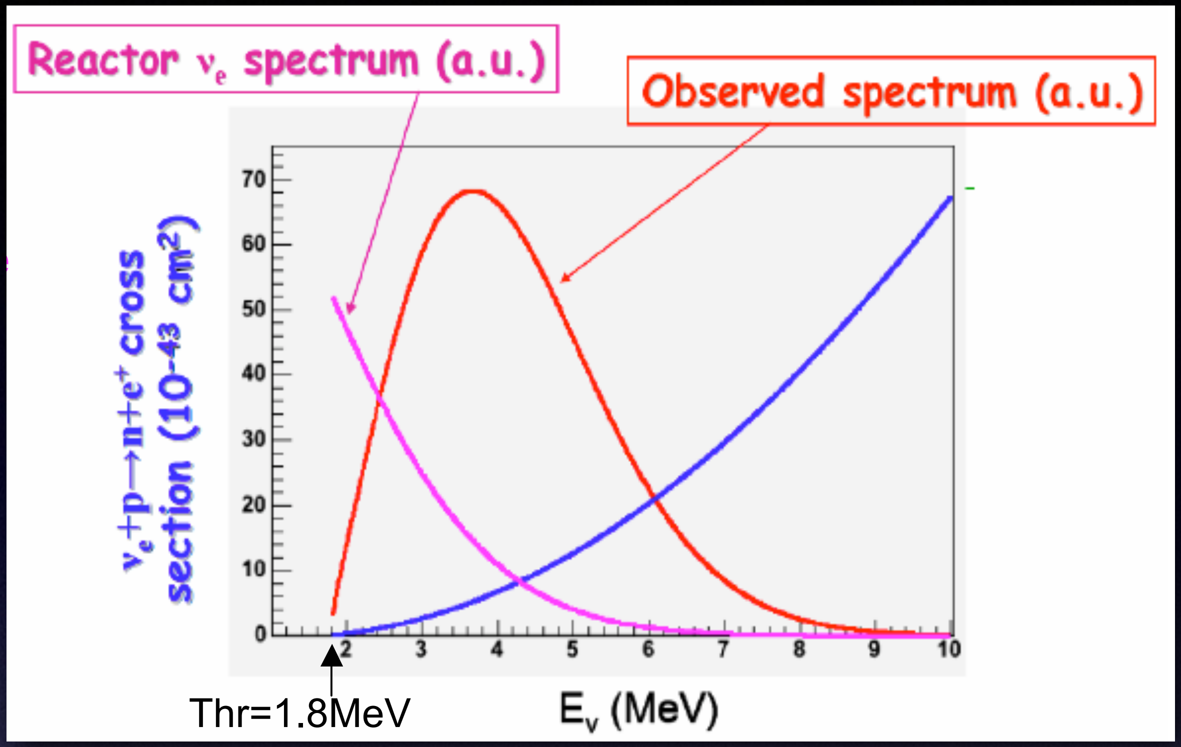
- High statistics supernova neutrino observation: about 5000 IBD events and 2000 events from other channels are expected for a SN explosion at 10 kpc.
- Geo-neutrino observation: about 2 events per day expected.
- Proton decay, solar and atmospheric neutrinos.

Neutrino detection

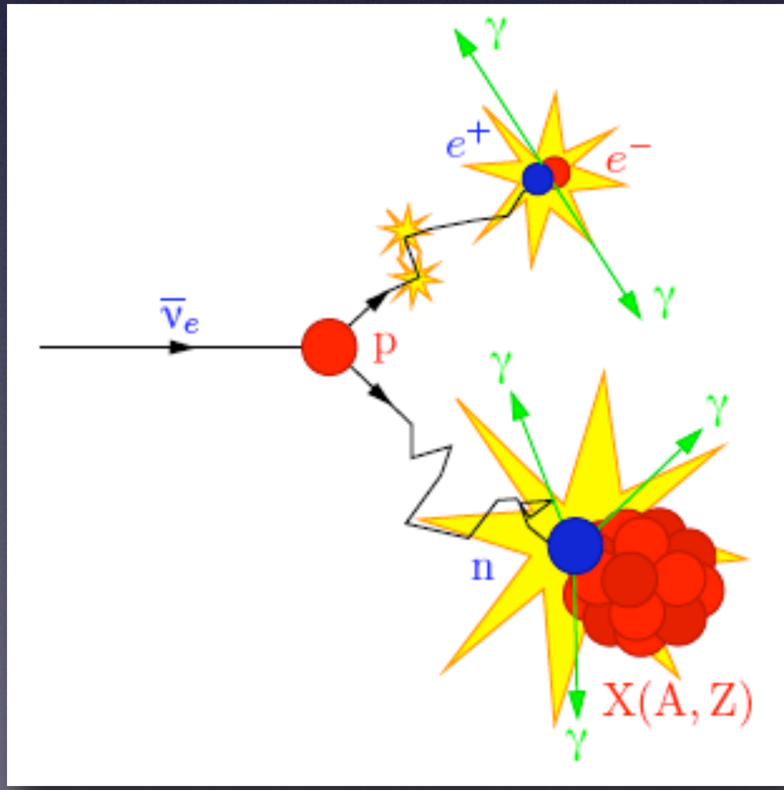
- Neutrinos are observed via Inverse Beta Decay (IBD):

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

- The energy spectrum is a convolution of flux and cross section (threshold at 1.8 MeV).

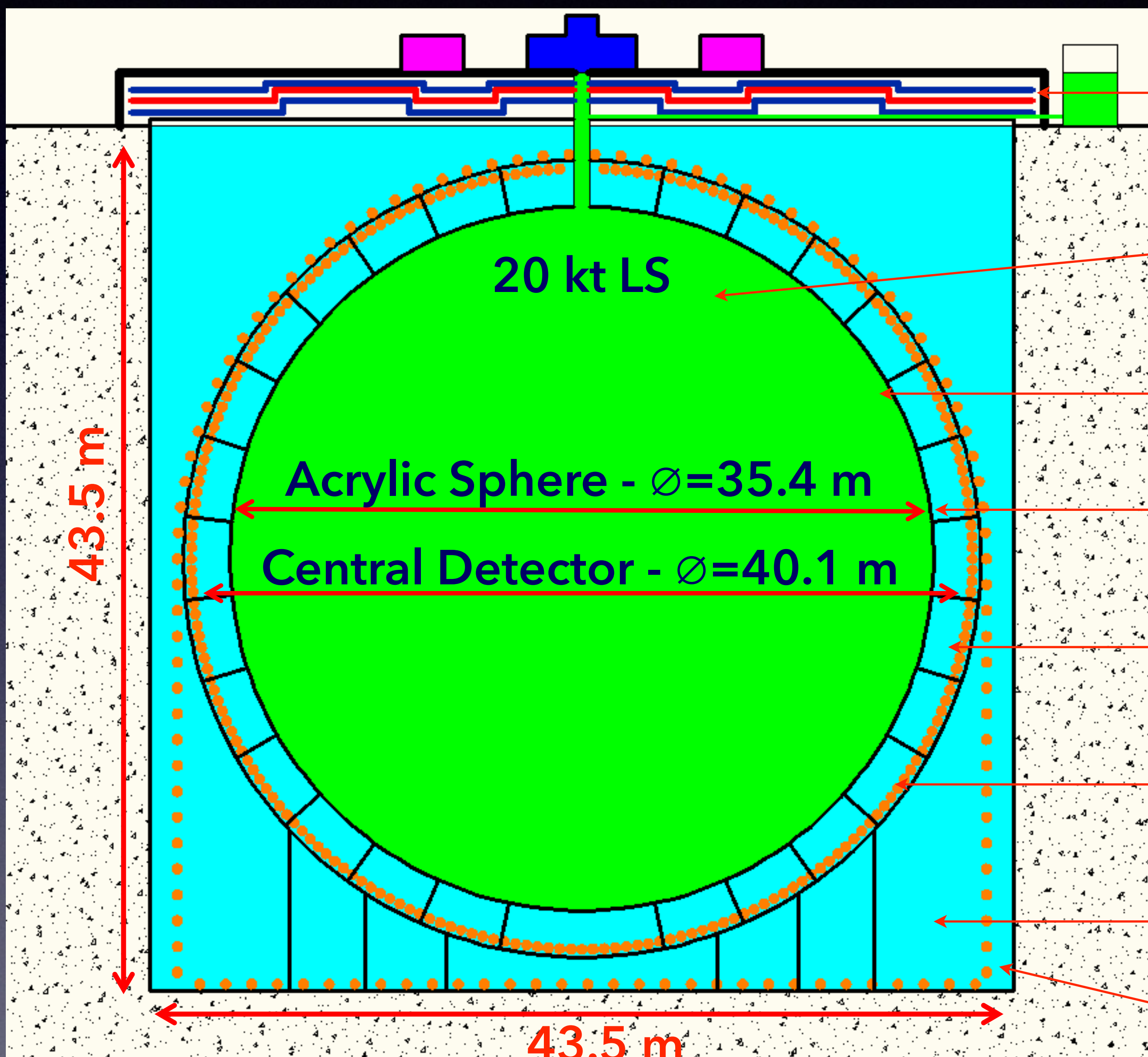


- The signal signature is given by:
  - Prompt photons from e^+ ionisation and annihilation (1-8 MeV).
  - Delayed photons from n capture on Hydrogen (2.2 MeV).
  - Time (Δt~200 μs) correlation.



Detector design

- The experiment consists of a very large 20 kton liquid scintillator detector.



Top muon veto: plastic scintillator strips

LS: 20 kton LAB based

LS container: acrylic. The maximum stress should be <35 MPa.

Buffer: water

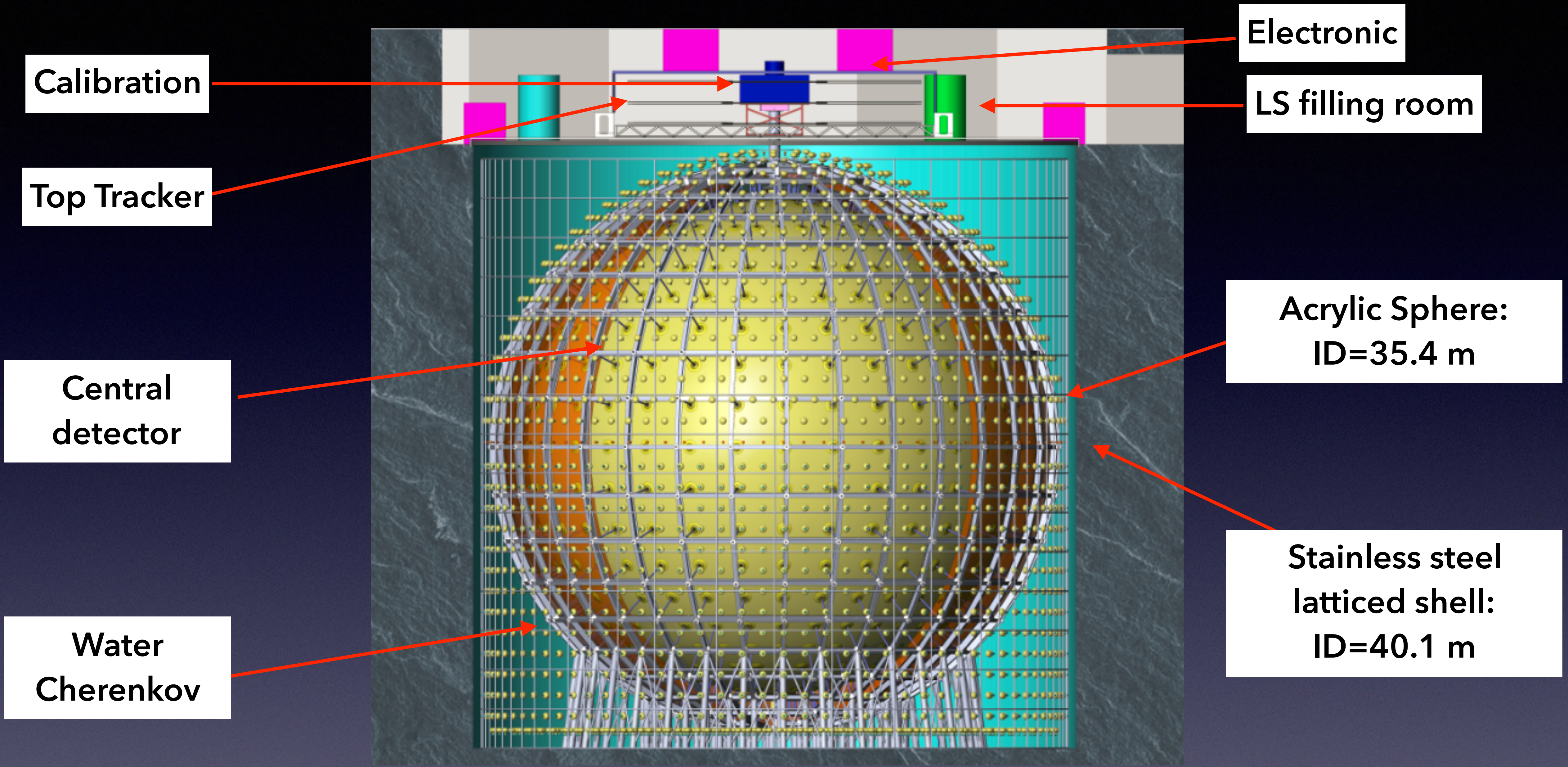
PMTs: 17000 20″ PMTs + 34000 3″ PMTS for a ~77.8% coverage

Buffer/PMT support: Stainless steel structure

Water Cherenkov veto: 20 kton water

PMTs: 2000 20″ veto PMTs

Challenge of the JUNO detector



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

The energy resolution requirement

- Given the energy resolution requirements of 3%/√(E), such a large detector would require particular attention to the scintillator attenuation length and on the detected p.e.

- To reach 1200 p.e./MeV, we should achieved a high light yield and transparency:
  - High light yield scintillator.
  - High photocathode coverage.
  - High detection efficiency of PMTs.
- The response of the detector should be uniform (spherical geometry).
- The PMTS should be clean and have a low dark current.

$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Energy leakage +non-uniformity

photon statistics

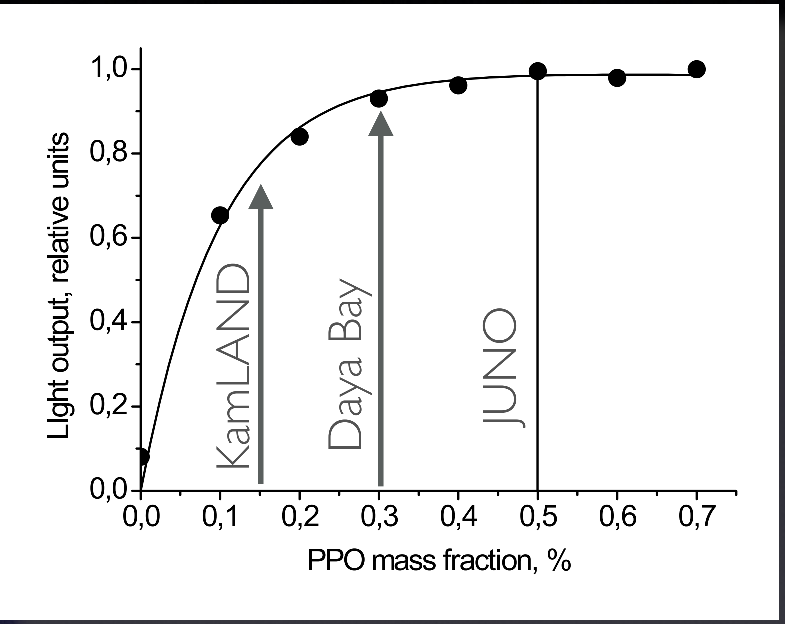
noise

- Moreover, the energy scale requires calibration at the sub-percent level and it can be achieved with a comprehensive calibration program (cable loop system, remotely operated vehicle, guide tube) to address both the non-uniformity and non-linearity in the detector energy response.

Central detector: liquid scintillator

20 kton of LS with high transparency and low background should be produced for a 6 years running experiment.

- The chosen LS is a LAB+PPO+bisMSB (no Gd loading).
- Increase of the light yield: optimisation of fluor concentration.
- Increase of the transparency:
  - Good raw solvent LAB (improve production process).
  - Onsite handling/purification.
- Reduce radioactivity:
  - No Gd loading.
  - Intrinsic single rates <3 Hz above 0.7 MeV
  - ^{40}K/U/Th $<10^{-15}$ g/g.



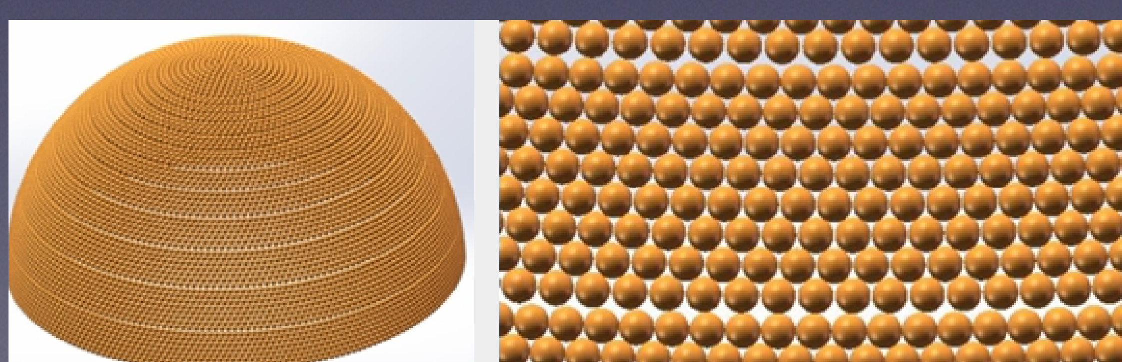
LAB	Attenuation length (m) at 430 nm
RAW	14.2
Vacuum distillation	19.5
SiO_2 column	18.6
Al_2O_3 column	25

Central detector: PMTs

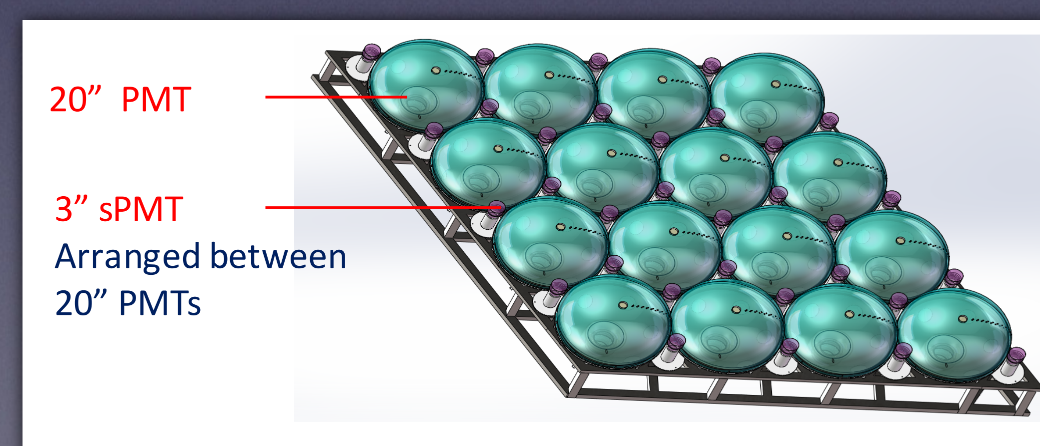
- Two sub-systems to increase the dynamic range and to improve the muon reconstruction in the central detector:
  - **Large PMTs**: 20'', 75-80% coverage and 30% quantum efficiency at 420 nm. The high QE 20'' PMTs are under development:
    - 15000 Micro Channel Plate PMT (MCP- PMT) using a 4π collection.
    - 5000 New Hamamatsu SBA High QE PMTs.
  - **Small PMTs**: 3'' and faster time response. The idea is to have~34000 SPMTS (2 SPMTs for every LPMT).

PMT arrangement

Super layer arrangement method:
77.8% coverage



SPMTs are in the gap between LPMTs.



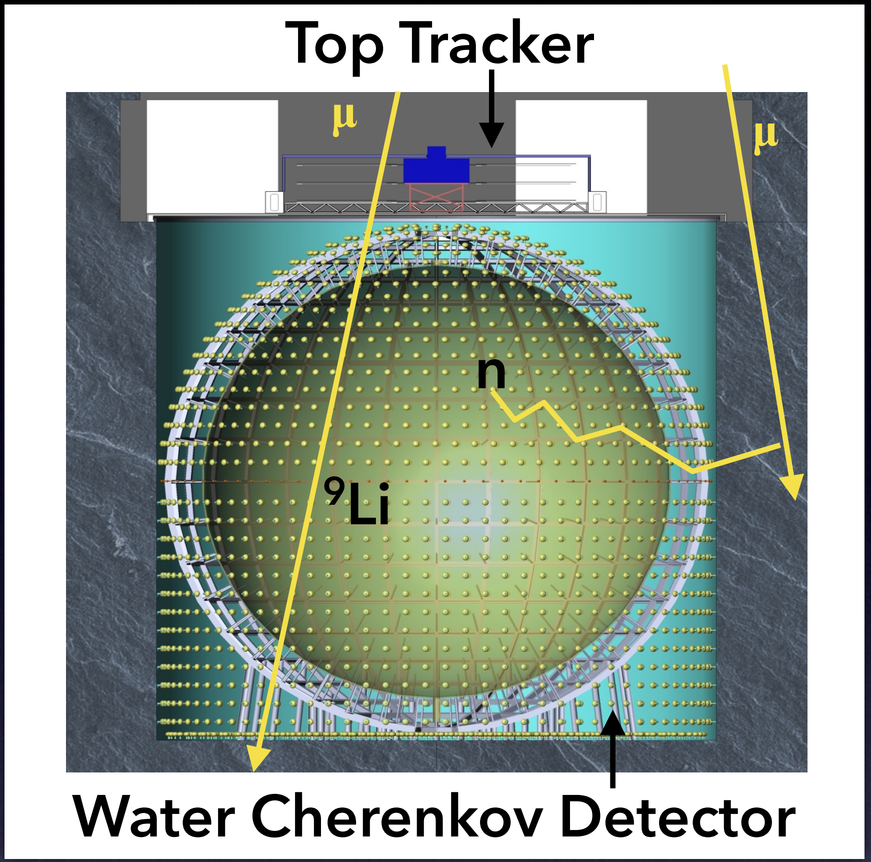
Central detector: PMTs

- Characteristics of the PMTs (15000 MPC-PMT and 5000 Dynode PMT).

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)
Relativity Detection Efficiency	%	~110%	~100%
P/V of SPE		>3	>3
TTS on the top point	ns	~12	~3
Rise time/Fall time	ns	R~2, F~10	R~7, F~17
Anode Dark Count	Hz	~30k	~30k
After Pulse Time Distribution	μs	4.5	4, 17
After Pulse Rate	%	3	10
Glass	–	Low-Potassium Glass	Hario-32

Veto

- The veto will be critical to reduce all sources of background.
  - Cosmogenic isotopes rejection: good reconstruction of muon tracks and 1.2 s veto around them.
  - Neutrons rejection: passive shielding and possible tagging when multiple proton recoils are detected.
  - Gamma rejection: passive shielding.
- To achieve the desired background reduction two sub-detectors are used: a water Cherenkov veto and a Top Tracker veto.



Water Cherenkov

- Water pool containing the central detector.
- 20 kton ultra pure water.
- 2000 20'' PMTs.

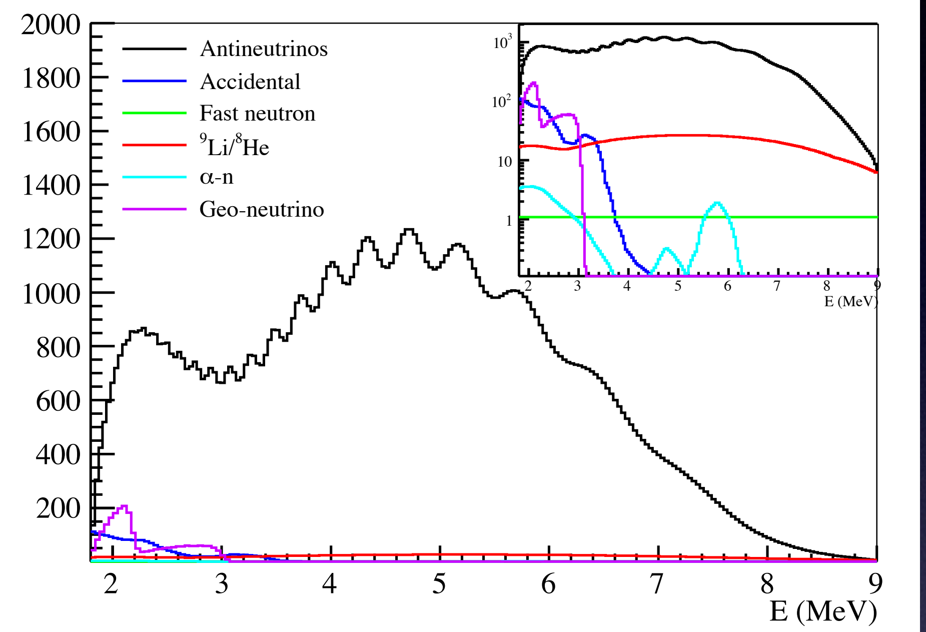
Top Tracker

- OPERA Target Tracker (plastic scintillator strips) will be used on top of the detector.
- It will permit to validate the muon tracking of the central detector.
- Cosmogenic background studies.

Selection cuts

Applying the different selection cuts, the signal rate will be 60 events/day and the background will be 3.8 events/day.

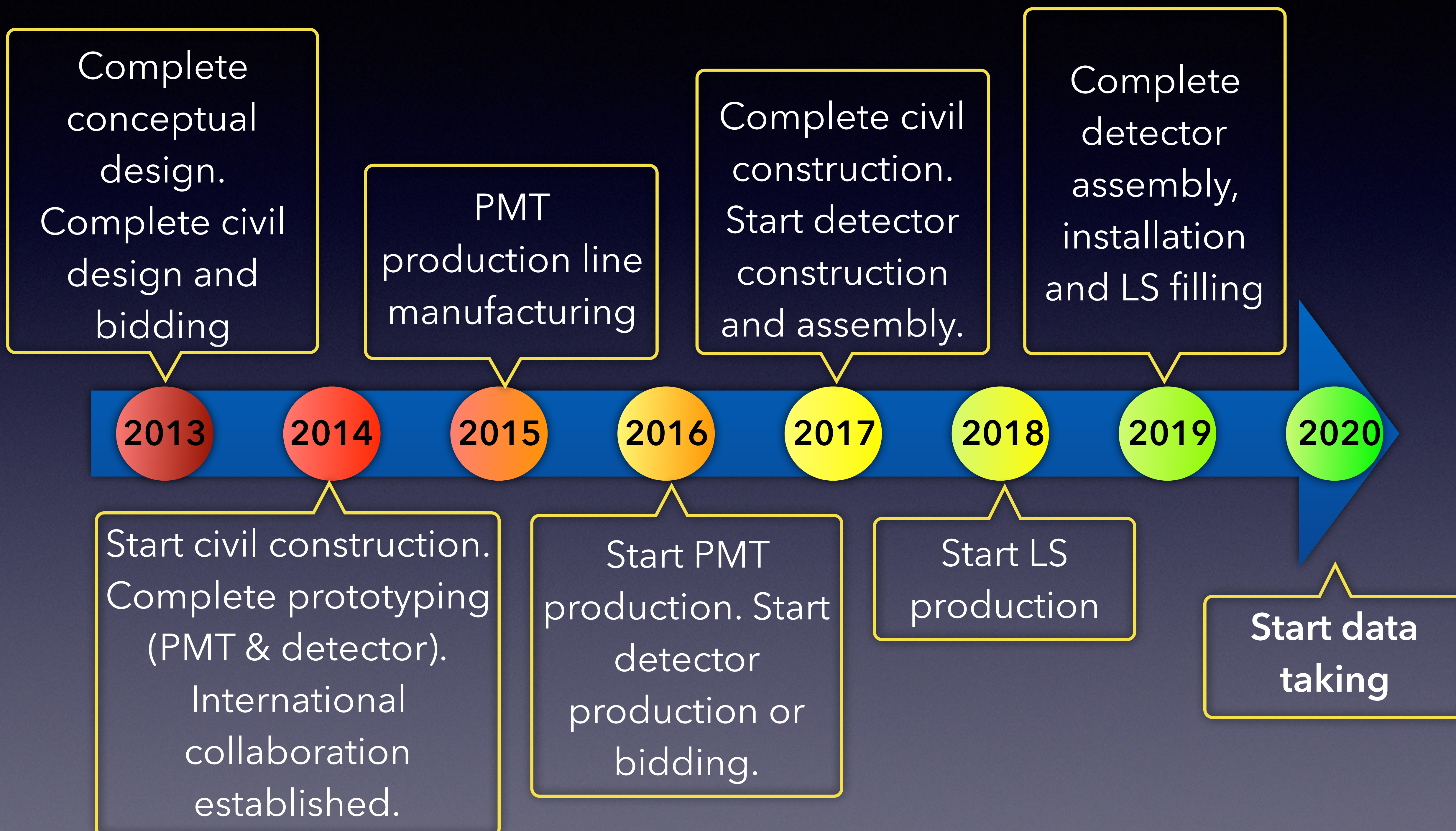
Antineutrino signal spectra and five kinds of main background



Efficiency, signal and background rates after each selection criterion

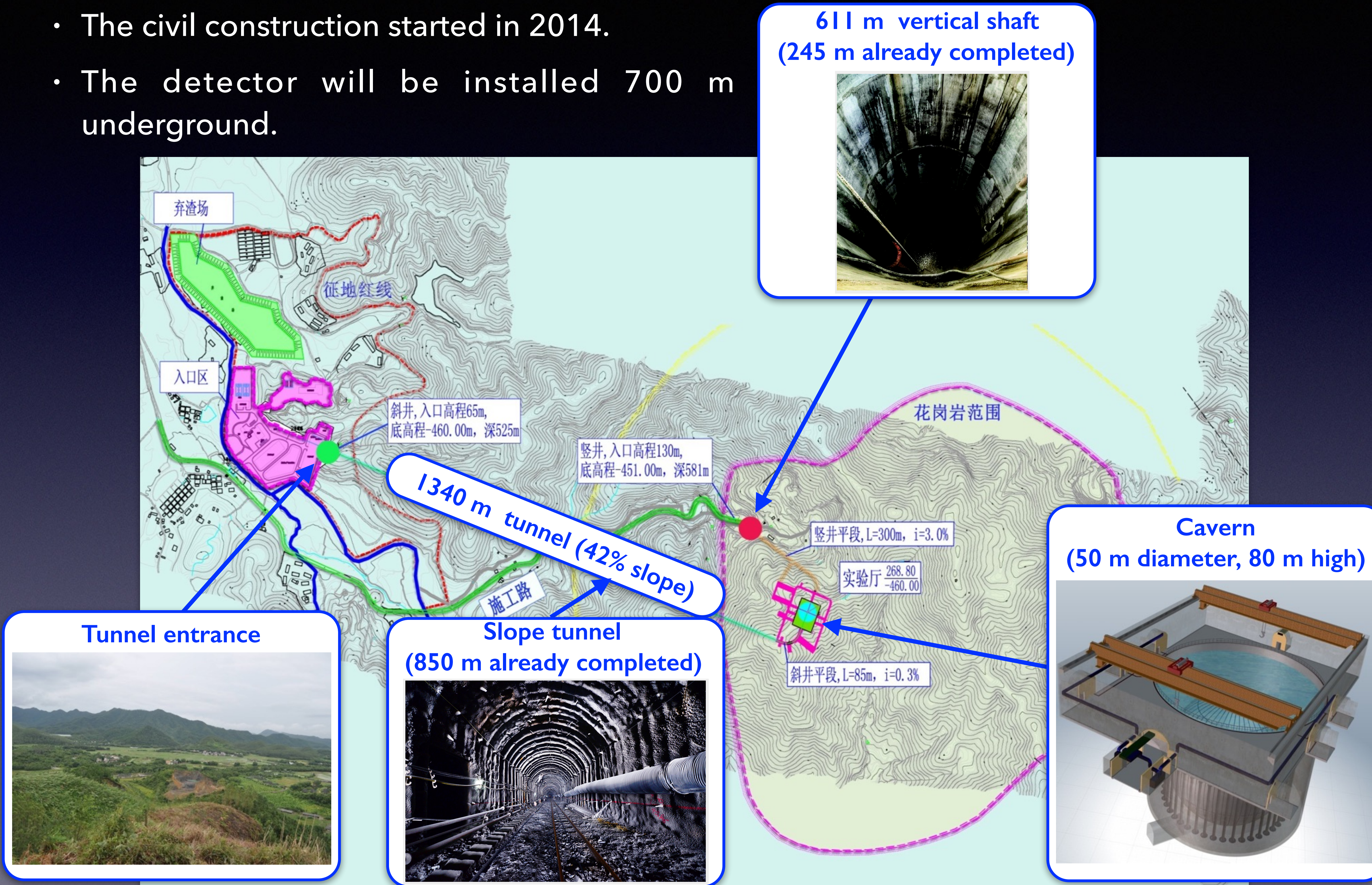
<table>
<tr><th>Selection</th><th>IBD efficiency</th><th>IBD</th><th>Geo-νs</th><th>Accidental</th><th>^{9}Li/^{8}He</th><th>Fast n</th><th>(α, n)</th></tr>
<tr><td>-</td><td>-</td><td>83</td><td>1.5</td><td>$\sim 5.7 \times 10^{4}$</td><td>84</td><td>-</td><td>-</td></tr>
<tr><td>Fiducial volume</td><td>91.8%</td><td>76</td><td>1.4</td><td rowspan="3">410</td><td>77</td><td rowspan="5">0.1</td><td rowspan="5">0.05</td></tr>
<tr><td>Energy cut</td><td>97.8%</td><td rowspan="3">73</td><td rowspan="3">1.3</td><td rowspan="3">71</td></tr>
<tr><td>Time cut</td><td>99.1%</td></tr>
<tr><td>Vertex cut</td><td>98.7%</td><td>1.1</td></tr>
<tr><td>Muon veto</td><td>83%</td><td>60</td><td>1.1</td><td>0.9</td><td>1.6</td></tr>
<tr><td>Combined</td><td>73%</td><td>60</td><td colspan="5">3.8</td></tr>
</table>

Overall schedule of JUNO

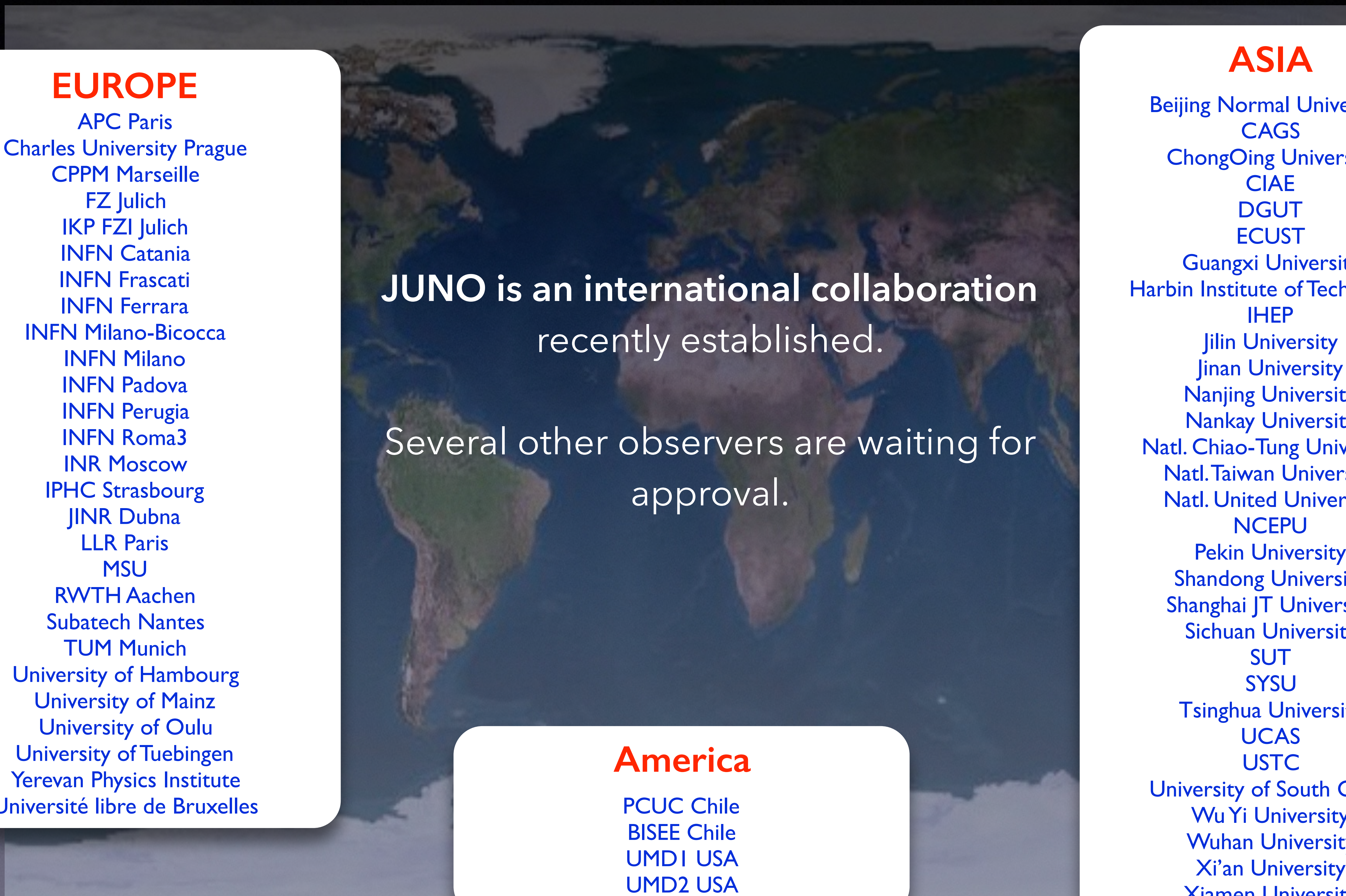


Civil construction

- The civil construction started in 2014.
- The detector will be installed 700 m underground.



JUNO collaboration



EUROPE

APC Paris
Charles University Prague
CPPM Marseille
FZ Julich
IKP FZI Julich
INFN Catania
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LLR Paris
MSU
RWTH Aachen
Subatech Nantes
TUM Munich
University of Hambourg
University of Mainz
University of Oulu
University of Tuebingen
Yerevan Physics Institute
Université libre de Bruxelles

JUNO is an international collaboration recently established.

Several other observers are waiting for approval.

America

PCUC Chile
BISEE Chile
UMD1 USA
UMD2 USA

ASIA

Beijing Normal University
CAGS
ChongOing University
CIAE
DGUT
ECUST
Guangxi University
Harbin Institute of Technology
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Sichuan University
SUT
SYSU
Tsinghua University
UCAS
USTC
University of South China
Wu Yi University
Wuhan University
Xi'an University
Xiamen University

Conclusions

- The JUNO experiment was approved in February 2013 and the international collaboration was established in July 2014.
- The civil construction has started and the laboratory should be ready end of next year.
- JUNO is an unprecedented large (20 kton) and high precision calorimetry liquid scintillator requiring high transparency (20 m attenuation length), high light collection (1200 p.e./MeV) to reach a 3% energy resolution at 1 MeV.
- JUNO has a rich physics program starting in 2020.
- In 6 years a sensitivity of $\Delta\chi^2$>9 (relative measurement) and $\Delta\chi^2$>16 (absolute measurement with $\sigma_{\mu\mu}$=1%) could be reached on the mass hierarchy discrimination.