Physique des neutrinos auprès des réacteurs

Cécile Jollet on behalf of IN2P3 JUNO group

Physics with JUNO

CNRS/IN2P3 2020 Prospect on Neutrino Physics

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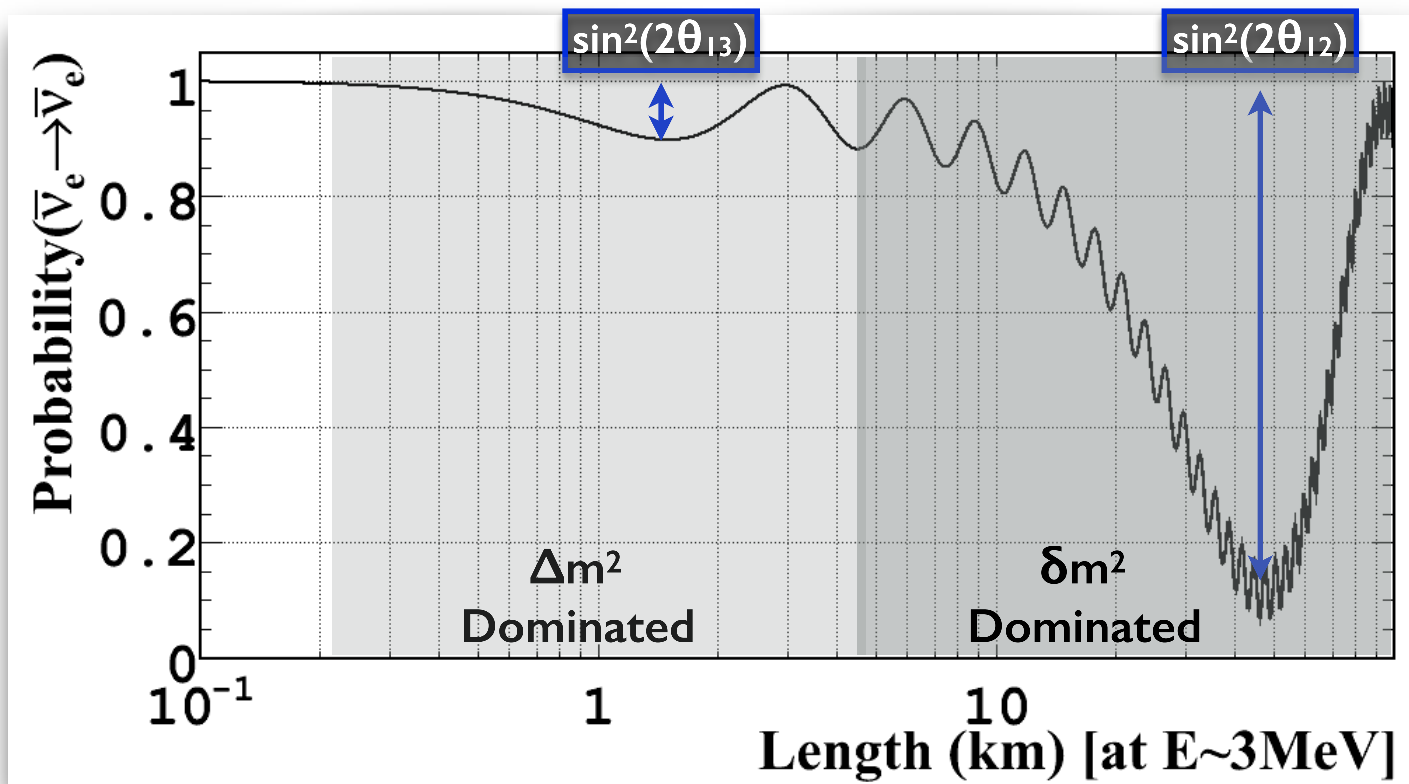
Neutrino physics at reactor

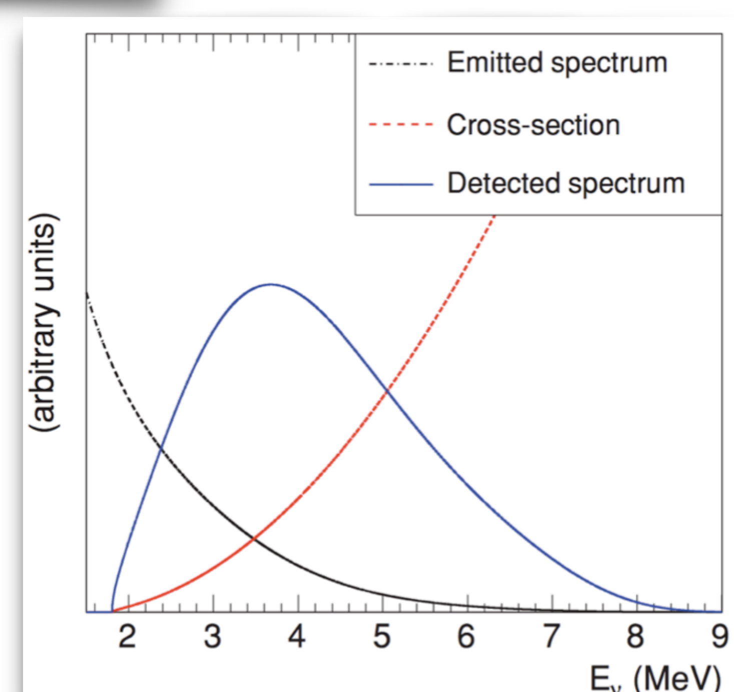
- Reactor oscillation experiments aim at the measurement of oscillation parameters (θ_{13}, θ_{12}, and mass splitting) through the observation of $\overline{\nu}_e \rightarrow \overline{\nu}_e$ transition according to the oscillation probability.



- Neutrino reactor experiments are insensitive to the δ-CP phase helping for a clean measurements of parameters.

- The neutrinos are observed via Inverse Beta Decay (IBD) allowing a two-fold coincidence for a clean signal.

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

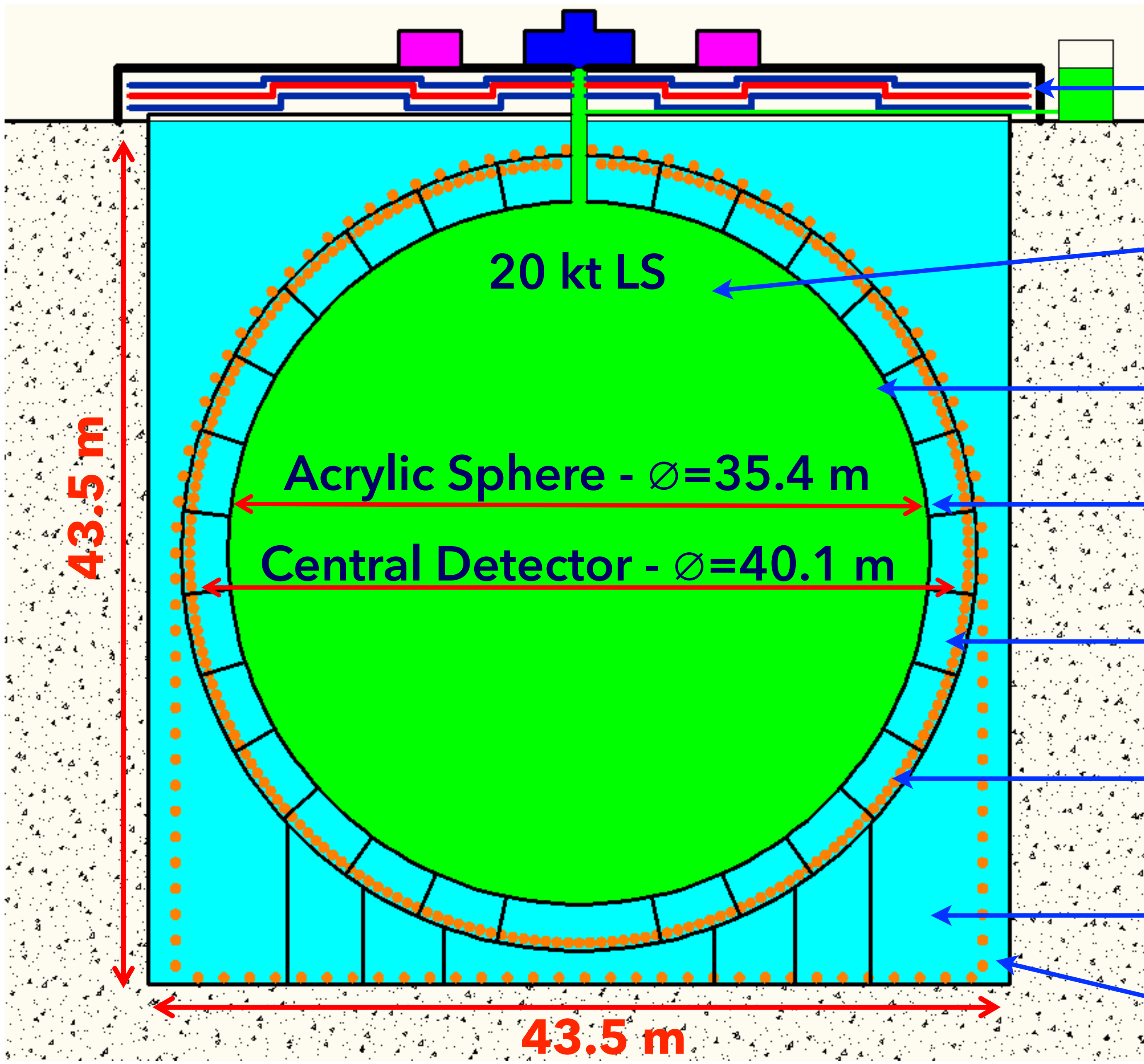


JUNO experiment

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

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	**Operation**	**Planned**	**Planned**	**Operation**	**Operation / Pending**
Power	**17.4 GW**	**17.4 GW**	**17.4 GW**	**17.4 GW**	**9.2 + 9.2 GW**

JUNO detector design



Top muon veto (Top Tracker): plastic scintillator strips

LS: 20 kton LAB based

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

Buffer: water

PMTs: 17000 20" PMTs + 25600 3" PMTs **(SPMT)** for a ~77.8% coverage

Buffer/PMT support: Stainless steel structure

Water Cherenkov veto: 20 kton water

PMTs: 2000 20" veto PMTs

✳ in red: strong contribution of IN2P3: Top Tracker and SPMT system

JUNO collaboration

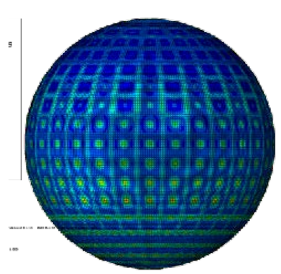
- 77 institution members from 17 countries for 632 collaborators.

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		

TimeLine

2014:

- International collaboration established
- Start civil construction



2015:

- PMT production line setup
- CD parts R&D

2016:

- Start PMT production
- Start CD parts production

2017:

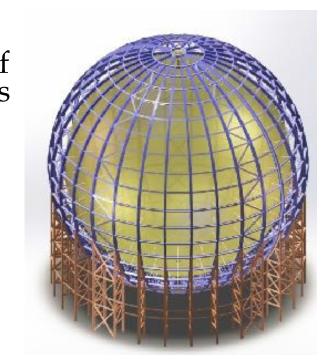
- Start PMT testing
- TT arrived

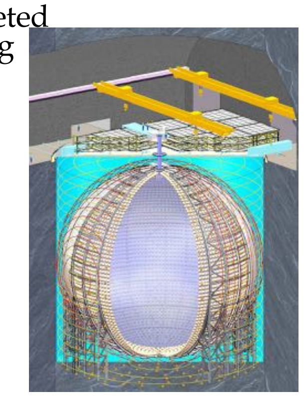
2018:

- PMT potting
- starts Delivery of surface buildings
- Start production of acrylic sphere

2019-2020:

- Electronics production starts
- Civil work and lab preparation Completed
- Detector constructing

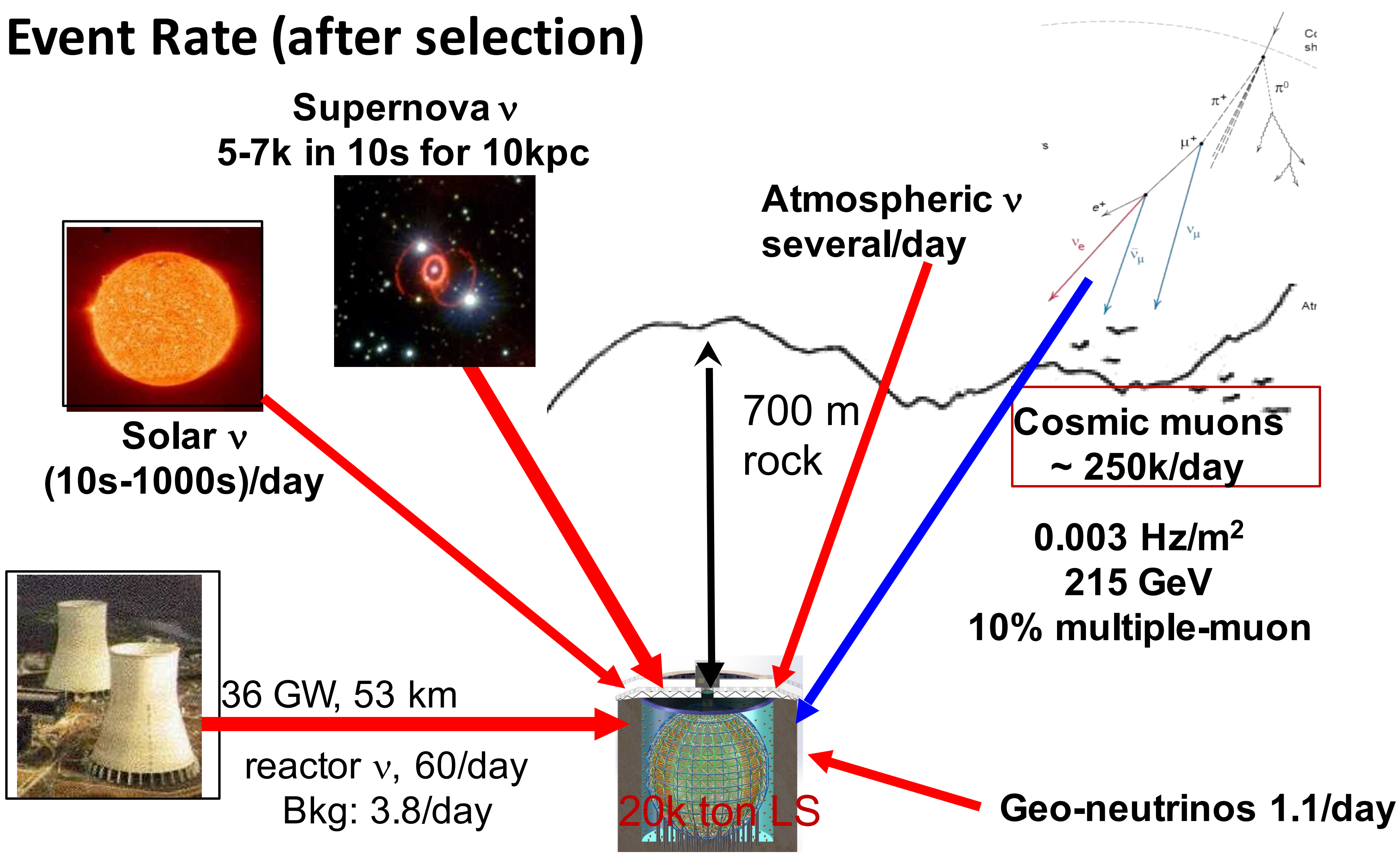




2021:

- Detector ready for Data taking!

Physics possibilities of JUNO

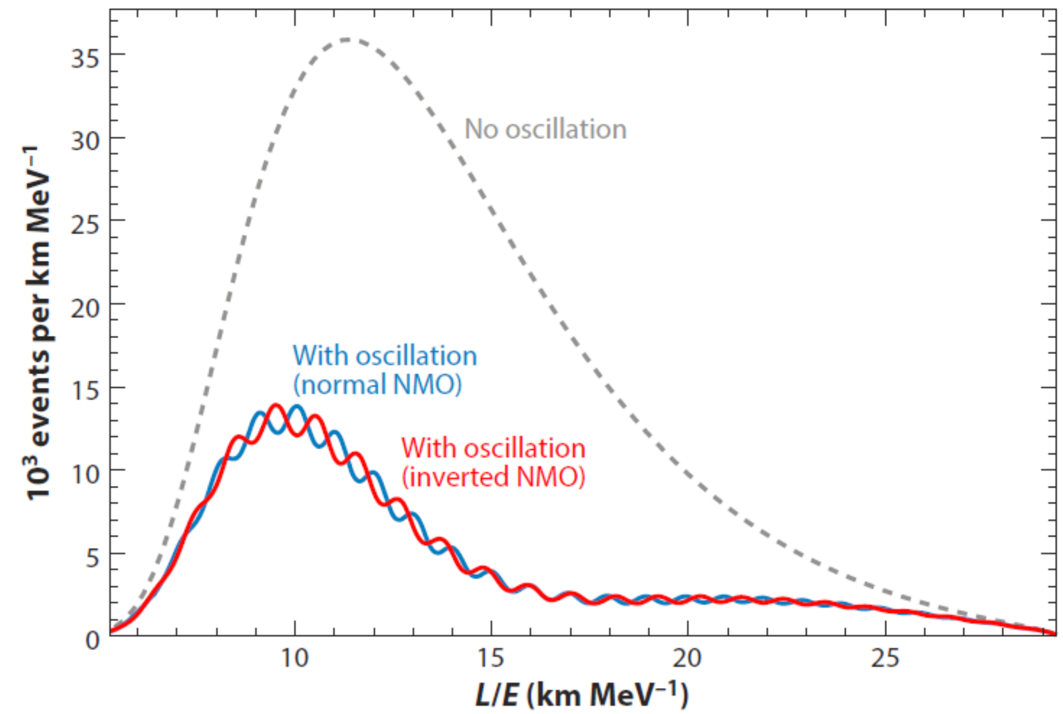


- Many neutrinos sources can be observed and studied.
- Additional physics studies (proton decay, sterile neutrinos, exotic searches).
- All the physics program is detailed in « Neutrino Physics with JUNO » **J.Phys. G43 (2016)no.3, 030401**

Mass hierarchy determination

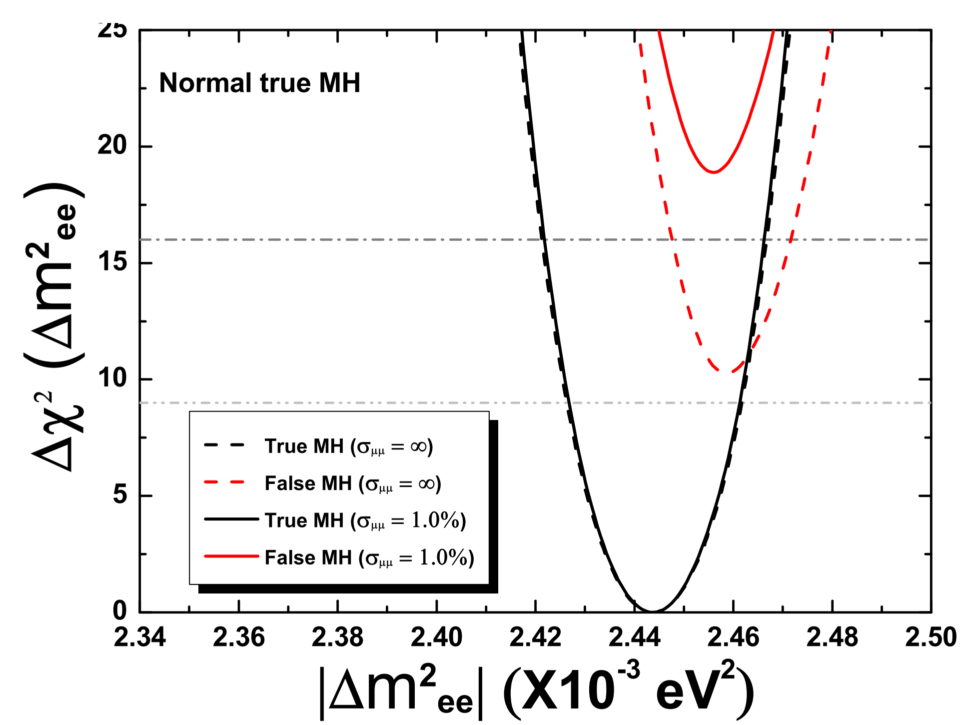
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

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



- We can perform a relative measurement (no constraint on Δm^2_{31}, **$\Delta\chi^2>9$**) or an absolute measurement (**$\Delta\chi^2>16$**) accounting for constraints from external experiments in particular on $\Delta m^2_{\mu\mu}$ (from long baseline experiment).

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

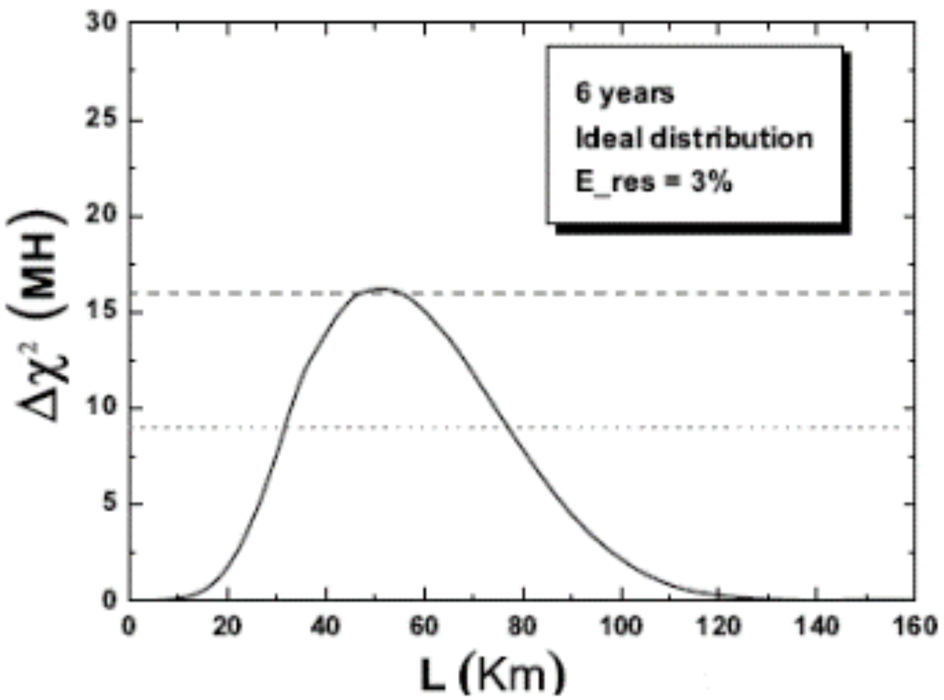


$$
\begin{aligned}
\Delta m^2_{\mu\mu} &\simeq \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \sin 2\theta_{12}\sin\theta_{13}\tan\theta_{23}\cos\delta\Delta m^2_{21} \\
\Delta m^2_{ee} &\simeq \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}
\end{aligned}
$$

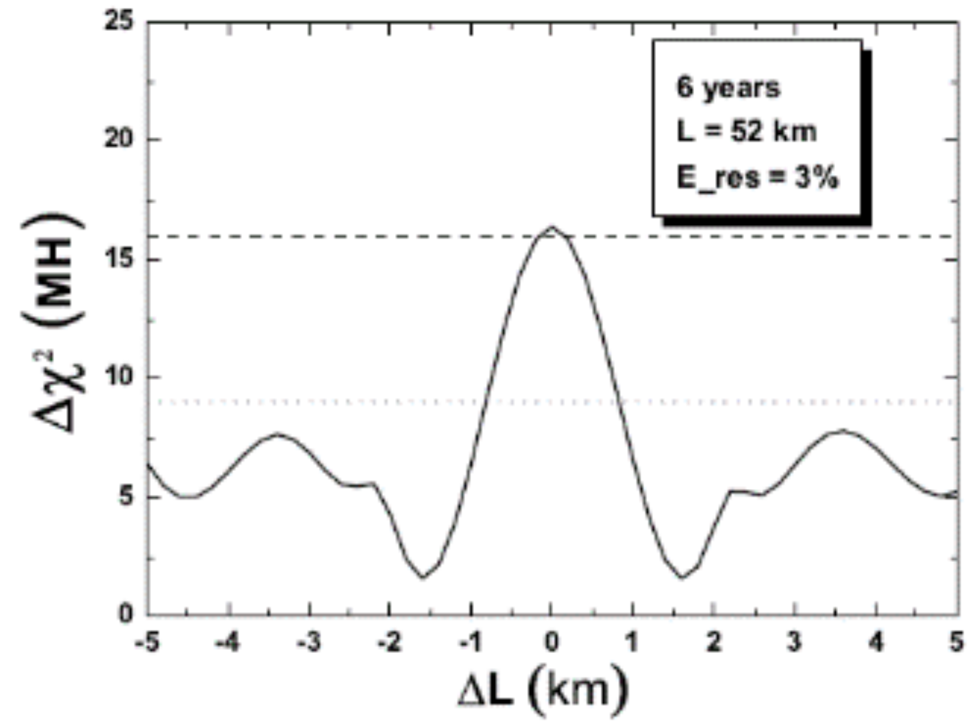
- Clean measurement since it does not rely on δ_{CP} and θ_{23}.
- Several conditions on baseline and energy resolution are necessary to perform such a measurement.

Requirements for mass hierarchy determination

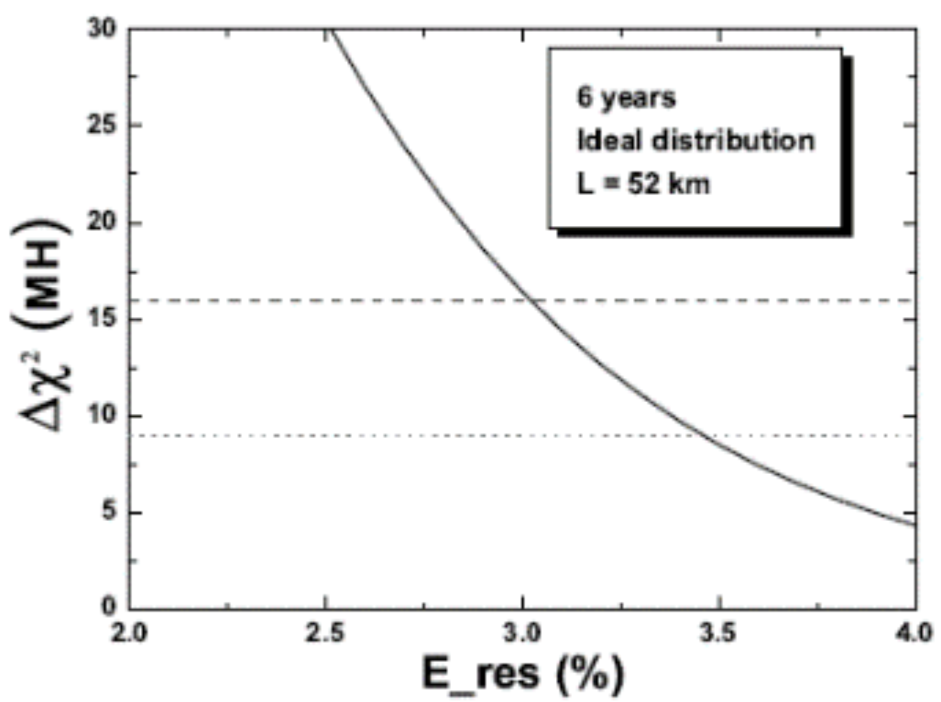
Specific baseline: 45-60 km



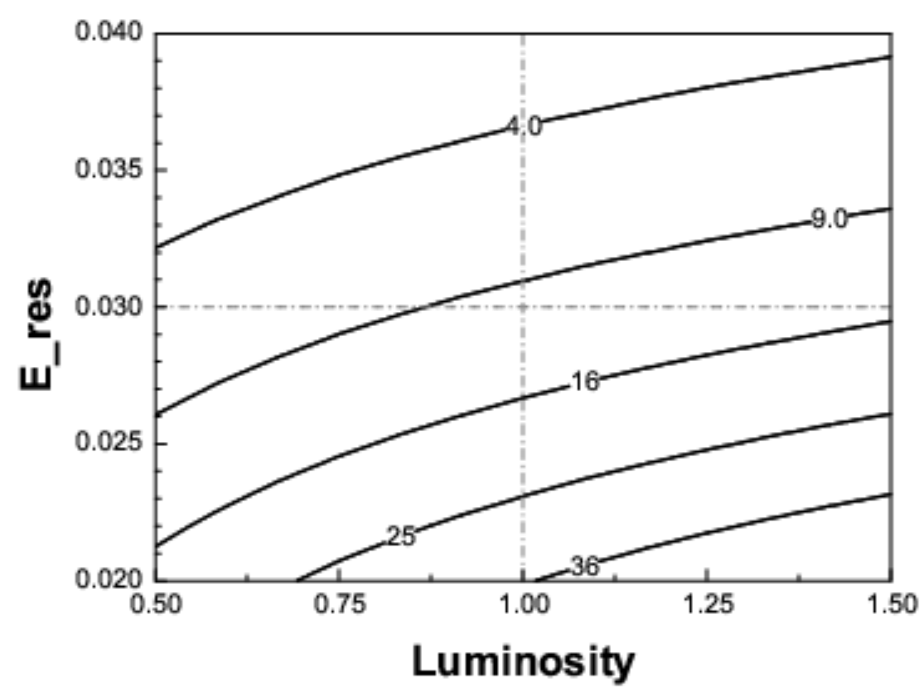
Equal baselines: difference to reactor cores less than 500 meters



Energy resolution: 3% at 1 MeV



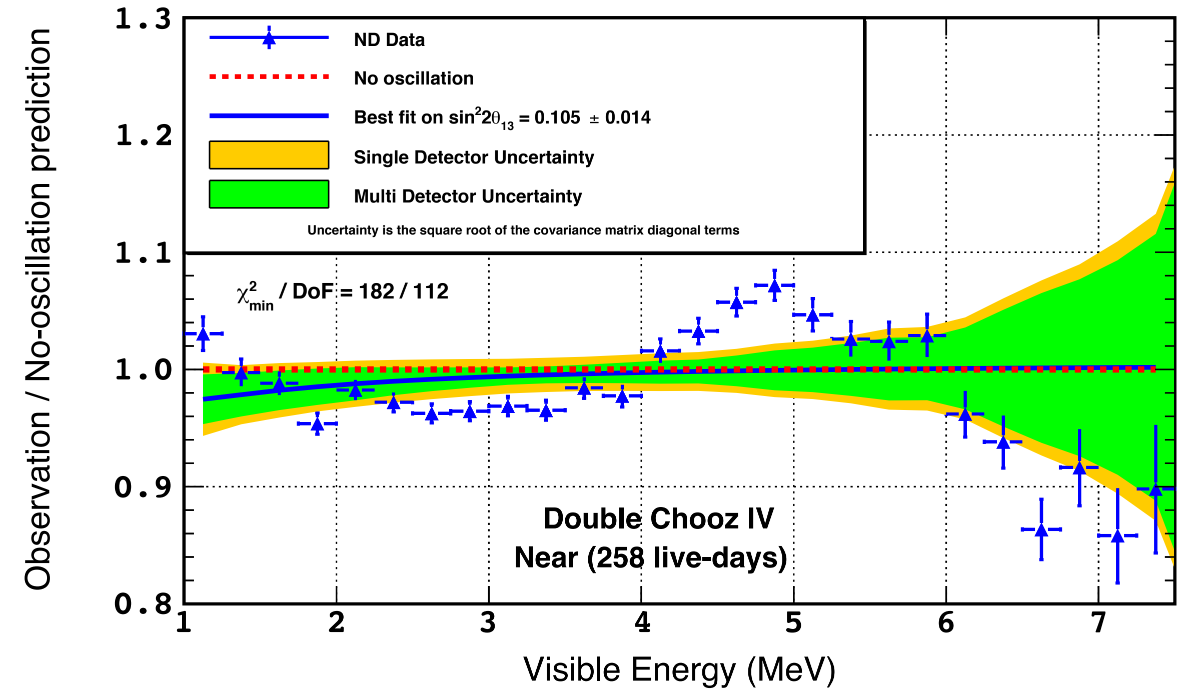
Statistics. 100 kevents=20 kton×35 GW×6 years



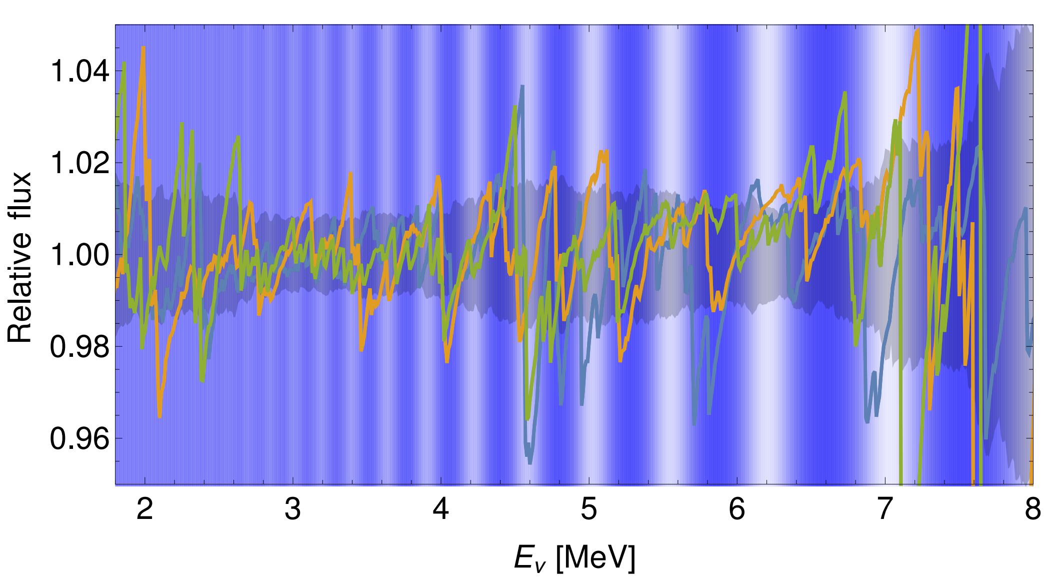
- Additional requirements?

Implications of the reactor shape uncertainty

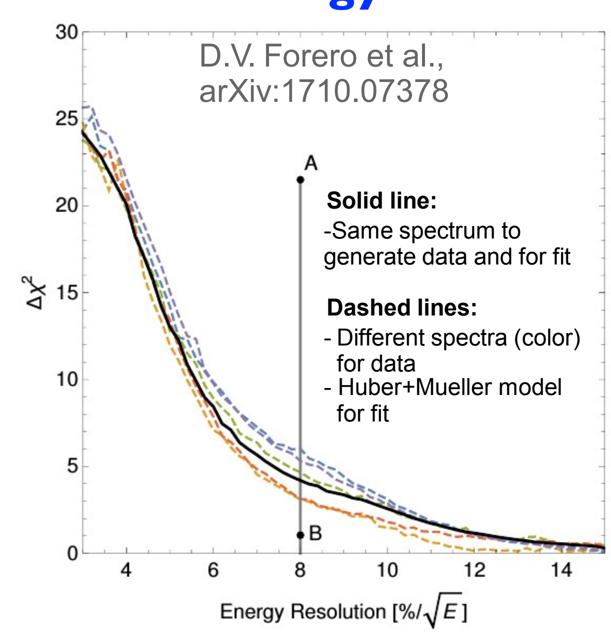
- We know from reactor experiments that the neutrino spectrum is not perfectly understood.
- Observation of a bump at ~ 5 MeV not explained theoretically.
- This bump has minor impact on the mass hierarchy sensitivity…**but reactor spectrum might show micro-structures** that can mimic periodic oscillation pattern.
- To assure a good $\Delta\chi^2$ determination, the energy resolution of the reference spectrum is important.



Anti-neutrino synthetic spectra



$\Delta\chi^2$ as a function of the near detector energy resolution



Need to know the reference spectrum with an energy resolution at least similar to the JUNO one.

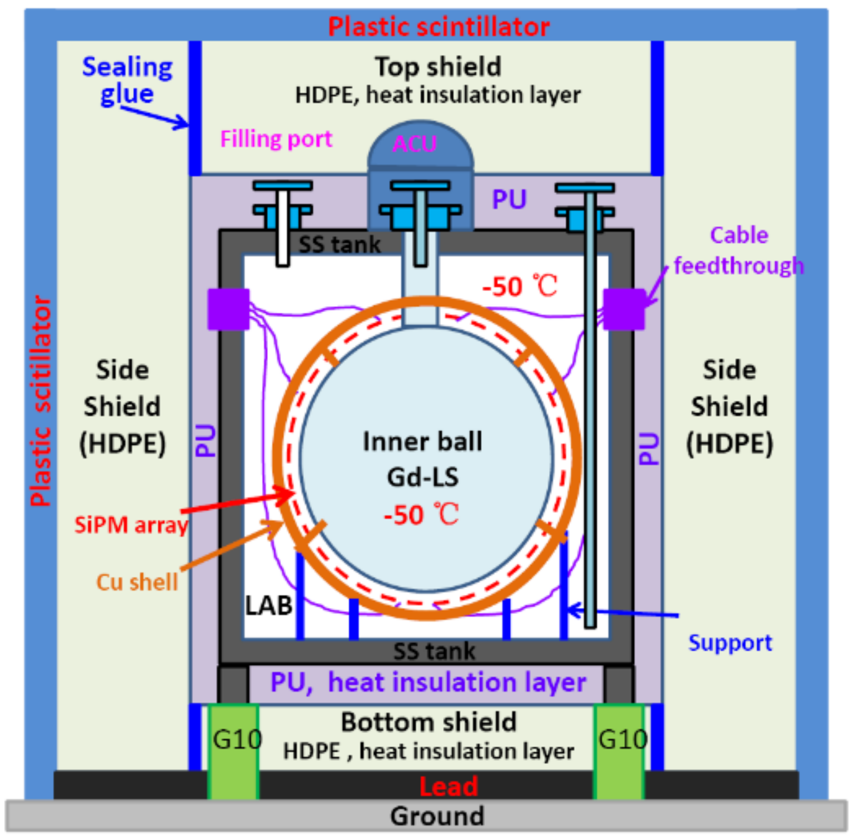
Near/reference detector: TAO

- **Taishan Antineutrino Observatory (TAO)**, a ton-level, high energy resolution LS detector at 30 meters from the core, a satellite experiment of JUNO.

- Measure reactor neutrino spectrum with sub-percent energy resolution.
  - model-independent reference spectrum for JUNO.
  - a benchmark for investigation of the nuclear database.

- Ton-level Liquid Scintillator (Gd-LS)
- Full coverage of SiPM.
- Operate at -50°C (SiPM darknoise).
- 4500 p.e./MeV

- Taishan Nuclear Power Plant, 30-35 m from a 4.6 GW_{th} core.
- 2000 IBD/day
- Online in 2021.



- IN2P3 not involved in this detector phase.

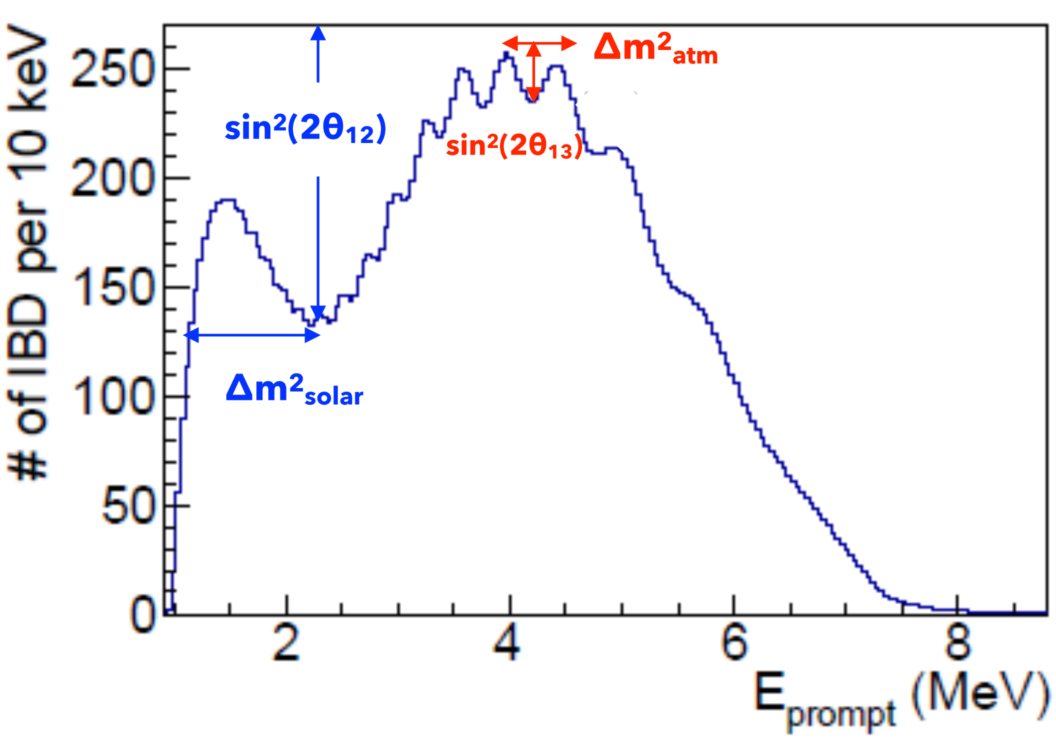
Precision measurements

- The current precision on the oscillation parameters is:

	Δm^2_{21}	$\|\Delta m^2_{31}\|$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	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%

- By measuring the energy spectrum, JUNO will be sensitive to solar parameters and mass hierarchy.
- Precision measurements essential to test consistency of neutrino oscillation framework.

Energy spectrum for 100k IBD



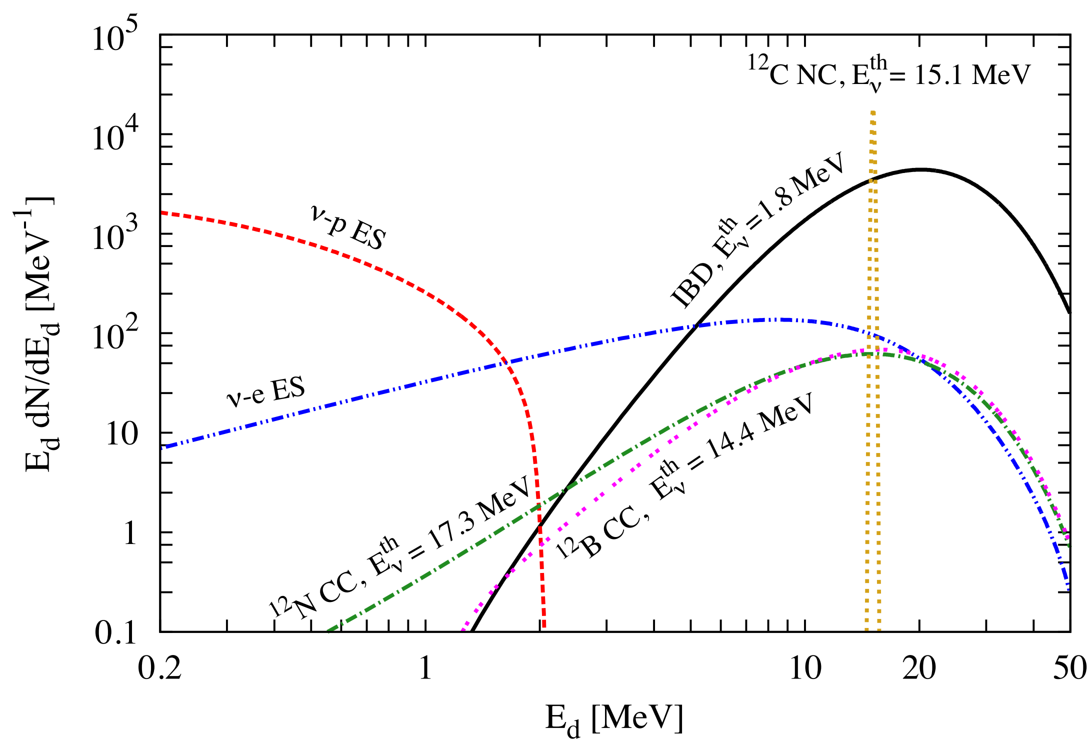
Precision that can achieve JUNO

	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\|\Delta m^2_{ee}\|$	0.27%	0.31%	0.31%	0.35%	0.44%

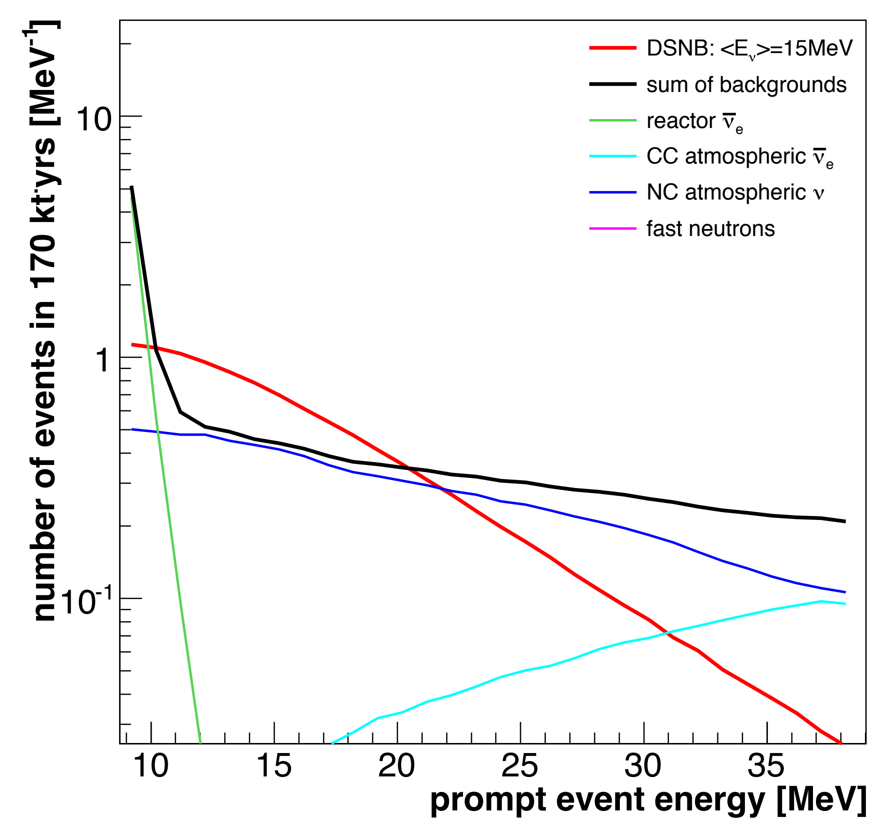
Table 3-2: Precision of $\sin^2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$ from the nominal setup to those including additional systematic uncertainties. The systematics are added one by one from left to right.

Supernova neutrinos

- **Galactic core-collapse supernova neutrinos (CCSN):** 1 SN is expected during the operation time of JUNO
  - Determination of flavor content, energy spectrum and time evolution.
  - Low energy threshold: ~0.2 MeV
  - Golden channel: IBD, ~5000 events for SN@10 kpc
  - information about ν_x thanks to ν-p ES channel.
- JUNO is part of the SNEWS project (Supernova Neutrino in the Multi-messenger Era). The IN2P3 is very well positioned to study these multi-messenger events (LIGO-VIRGO HESS, CTA, JUNO, KM3NET).

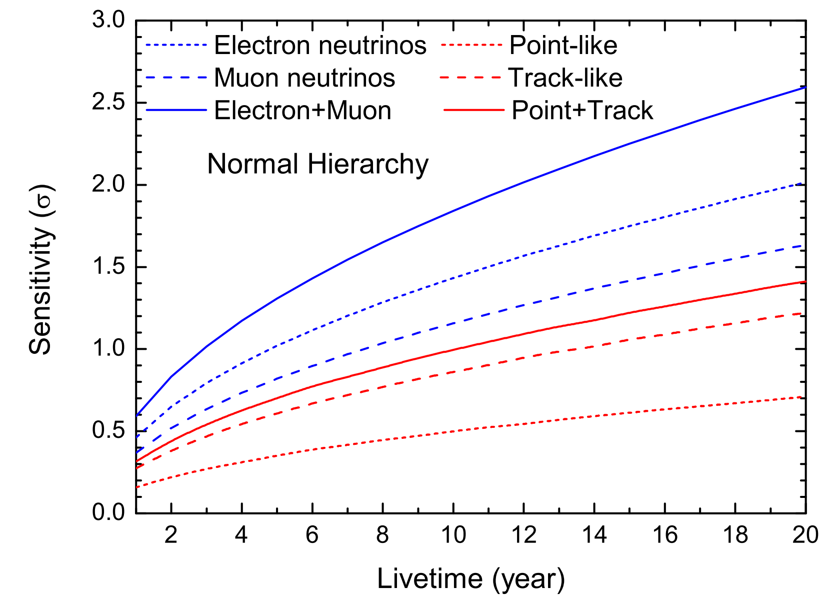


- **Diffuse Supernova Neutrino Background (DSNB):** integrated neutrino flux from all past core-collapse events.
  - Expected detection of ~3σ after 10 years.
  - Leading constraint if DSNB is not observed (the upper limit on the flux above 17.3 MeV would be ~0.2 $cm^{-2}s^{-1}$ after 10 years).



Solar and atmospheric neutrinos

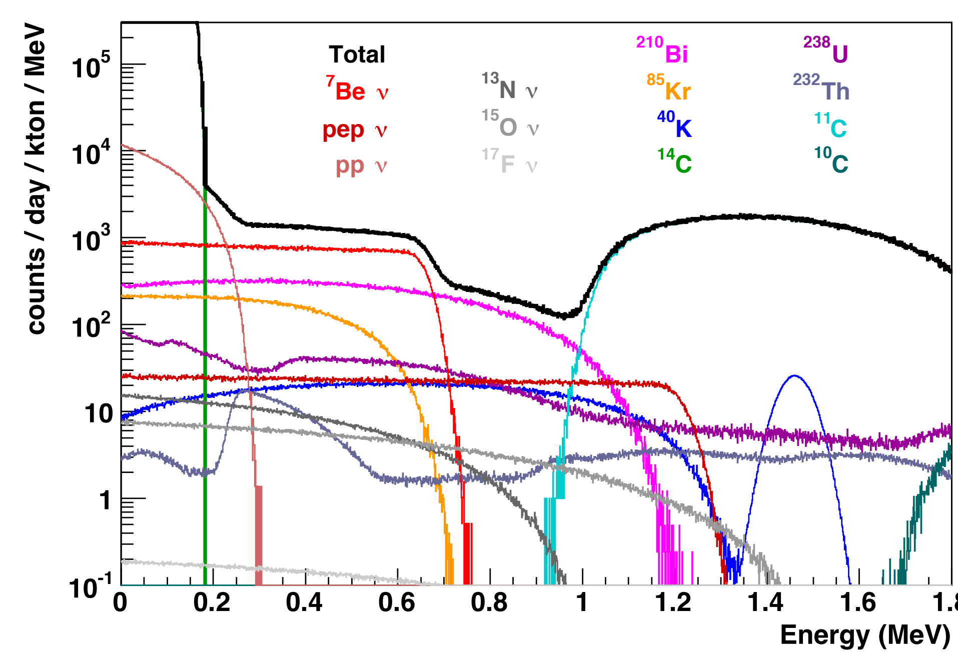
- **Atmospheric neutrinos:**
  - Additional measurement of mass hierarchy with matter effects.
  - Sensitivity to θ_{23} (the wrong θ_{23} octant could be ruled out at 1.8σ (0.9σ) for the true normal (inverted) hierarchy and θ_{23} =35°).
  - CP violation sensitivity given by the [100-300] MeV energy range.
  - Combined studies of oscillation from different sources.



- **Solar neutrinos:**
  - Independent measurement of ^{7}Be flux.
  - New low-threshold (2 MeV) ^{8}B measurement.
  - Two different radio purity requirements for the solar phase.

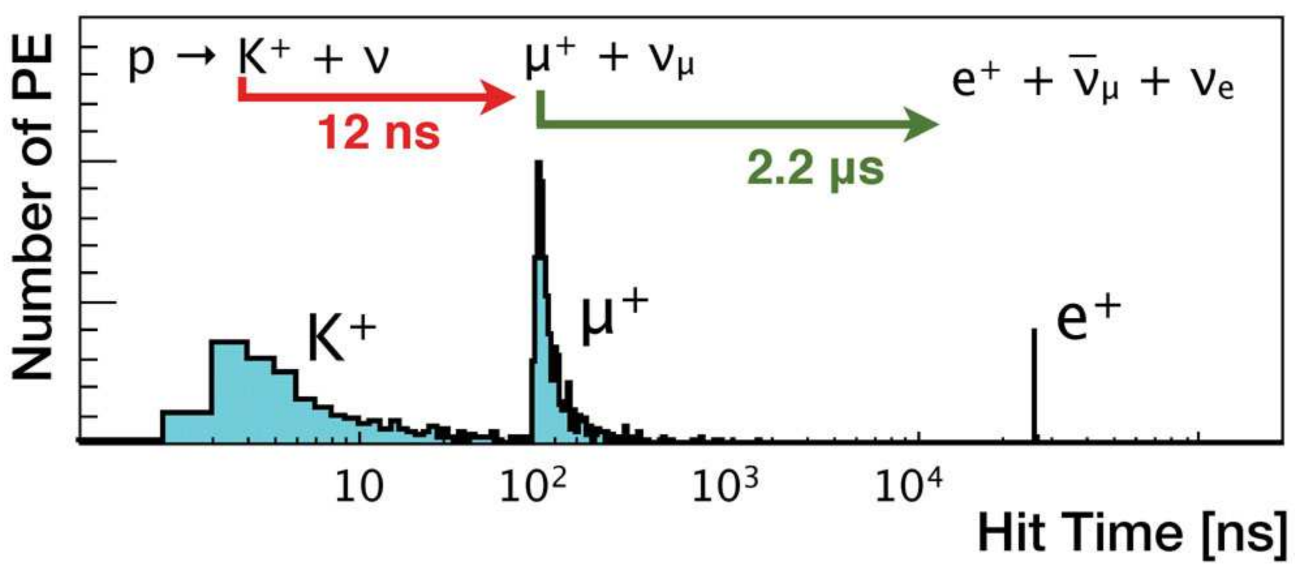
Internal radiopurity requirements		
	baseline **S/B=1/3**	ideal **S/B=2/1**
^{210}Pb	5×10^{-24} [g/g]	1×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]	100 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{232}Th	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{40}K	1×10^{-17} [g/g]	1×10^{-18} [g/g]
^{14}C	1×10^{-17} [g/g]	1×10^{-18} [g/g]
Cosmogenic background rates [counts/day/kton]		
^{11}C	1860	
^{10}C	35	
Solar neutrino signal rates [counts/day/kton]		
pp ν	1378	
^{7}Be ν	517	
pep ν	28	
^{8}B ν	4.5	
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1	

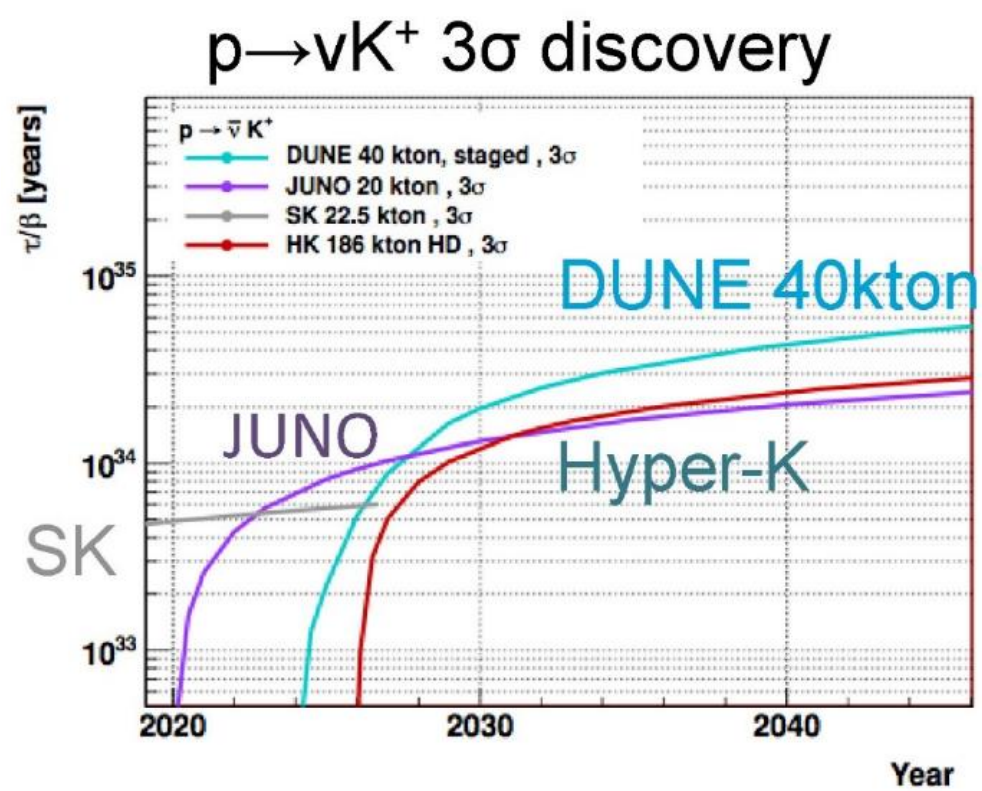
ν_x+e$^-$→ν_x+e$^-$ channel
(ideal radiopurity assumption)



Proton decay

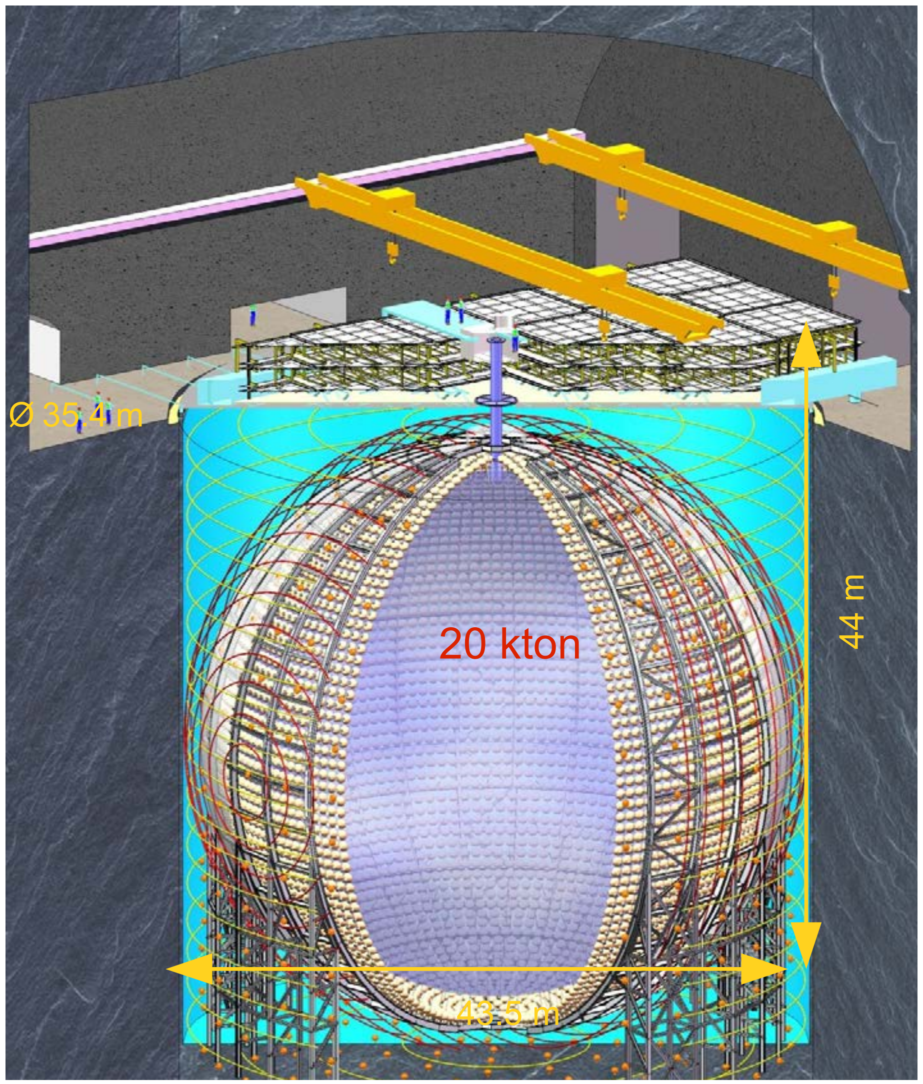
- Competitive sensitivity to proton decay searches exploiting the $p \rightarrow \bar{\nu} + K^+$
  - clear identification: 3 signals in coincidence
  - background from atmospheric neutrinos.
- After 10 years of data taking, JUNO will be sensitive to $\tau \sim 2\times10^{34}$ years.

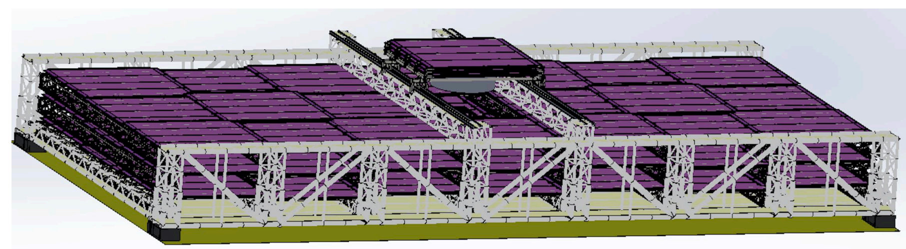


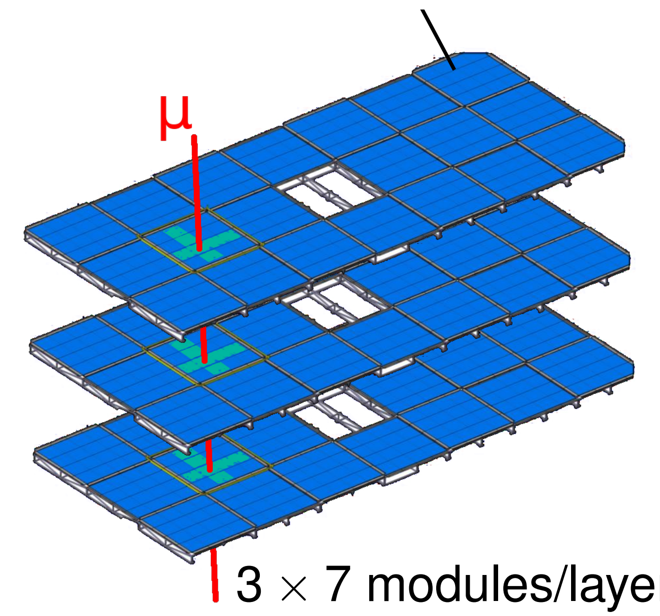


Top Tracker

- Use of the 62 walls of the Target Tracker of OPERA.
- 3 layers of plastic scintillator for a coverage of 60% above Water Cerenkov detector.



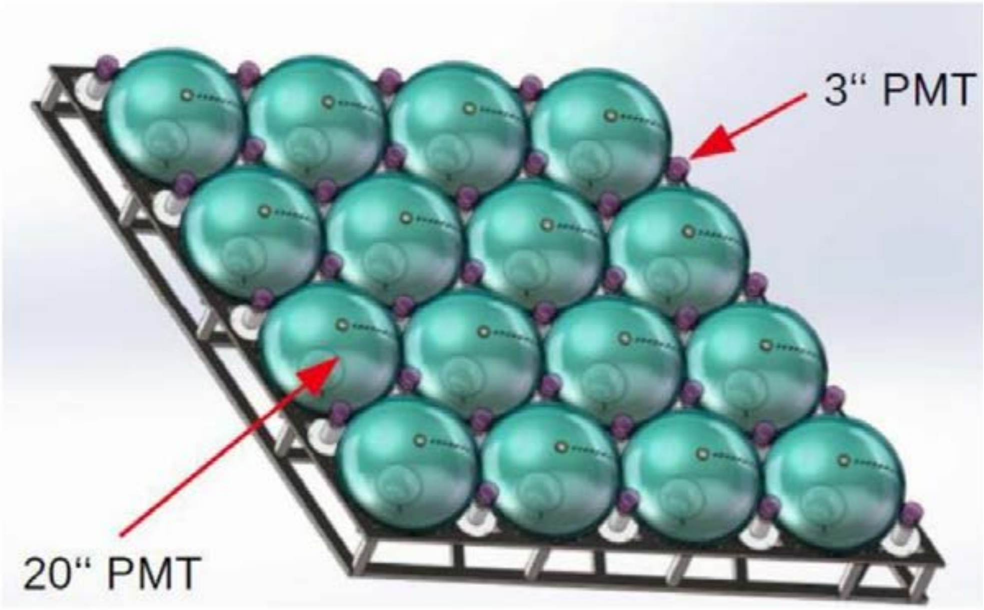




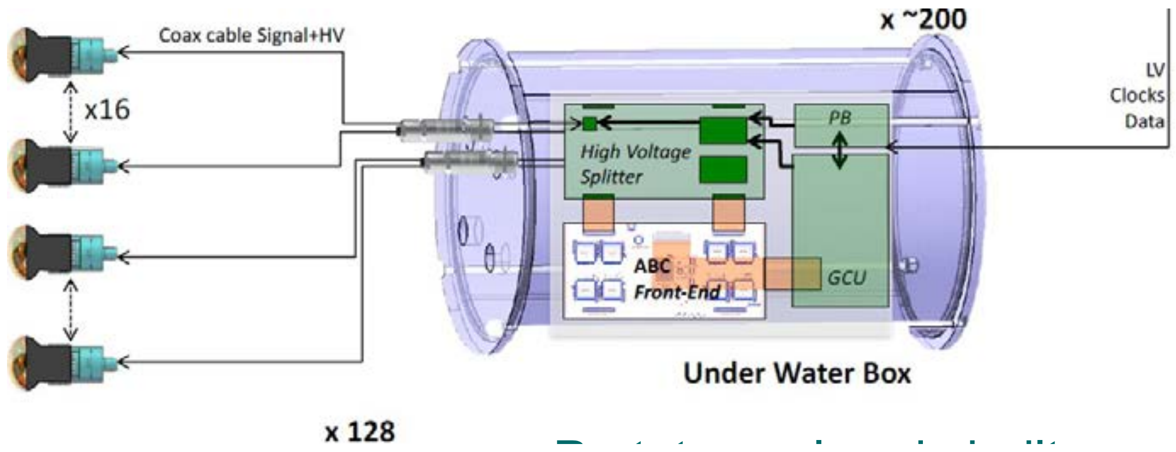
- **The TT will permit a precise μ reconstruction:**
  - Tune the reconstruction of the muons in the central detector.
  - Optimize the muon veto (IBD inefficiency/cosmogenic background reduction).
  - Improve the definition of stopping muons.

Small Photomultipliers

- Installation of 25600 additional 3” photomultipliers (Small PMTs) to the 17000 20” photomultipliers of the Central Detector.



200 boxes × 128 PMTs



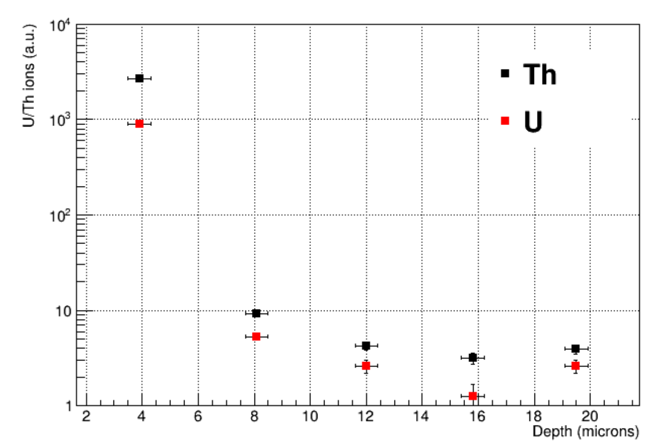
- **The 3” photomultipliers will run in photon counting:**
  - Calibration of non-linear response of large PMTs (energy resolution).
  - Increased the dynamic range (helps with large signal such as muons or supernovae).
- **Good TTS of about 2-3 ns:**
  - Hit time profile reconstruction for particle identification.
  - Improve muon reconstruction.
- Complementary system for the measurement of the solar parameters.

Other ongoing contributions

- **Computing**
  - Software installed at CC@Lyon.
  - Contributing to defining the distributed computing framework: transfer data to Europe and distributed analysis.

- **Analysis/Simulation**
  - Preparation of the tools for the TT and Small photomultipliers analysis.
  - Ortho-positronium and $^{9}Li/^{8}He$ generators for a better description of signal and backgrounds.
  - Sensitivity studies: mass hierarchy, solar parameters.

- **Radiopurity**
  - Photomultipliers radiopurity: γ spectrometry and radon emanation measurements.
  - Radon diffusion across the liner.
  - Acrylic radiopurity: cartography of the U/Th contaminations in the sample.



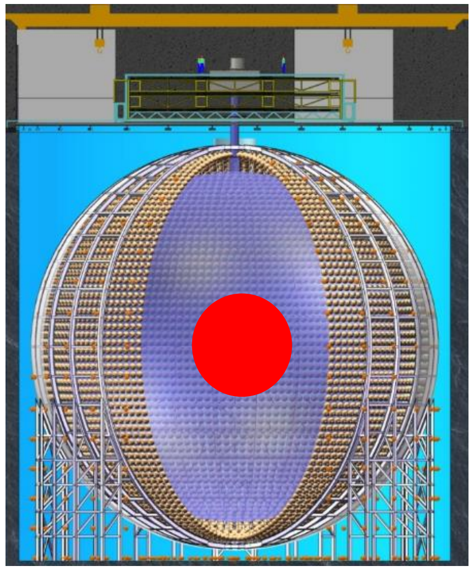
Far future: double beta decay

- Second phase of the experiment after mass hierarchy determination …. after 2030.
- Insertion into the central detector of a balloon filled with enriched (^{136}Xe) xenon gaz dissolved in an ultra-pure LS.
- Advantage of JUNO: good energy resolution (1.9%σ at ^{136}Xe $Q_{\beta\beta}$) and powerful shielding thanks to its large volume.

Number of events in the ROI (110 keV)

summary of backgrounds in $0\nu\beta\beta$ ROI [ROI·(ton ^{136}Xe)·yr]$^{-1}$	
$2\nu\beta\beta$	0.2
^{8}B solar ν	0.7
cosmogenic background	
^{10}C	0.053
^{6}He	0.063
^{8}Li	0.016
^{12}B	3.8×10^{-4}
others ($Z \leqslant 6$)	0.01
^{137}Xe	0.07
internal LS radio-purity (10^{-17} g/g)	
^{214}Bi (^{238}U chain)	0.003
^{208}Tl (^{232}Th chain)	—
^{212}Bi (^{232}Th chain)	0.03
external contamination	
^{214}Bi (Rn daughter)	0.2
total	1.35

- ^{136}Xe loaded LS in balloon
- ^{130}Te doped LS (other option)



- Assuming 5 tons of fiducial ^{136}Xe target mass and 5 years live time, a sensitivity of $T_{1/2}$ ($m_{\beta\beta}$) of ~5.6×10^{27} years (8-22 meV) can be achieved at 90% C.L.

Conclusions

- The JUNO experiment will provide vast opportunities with its large mass and unprecedented energy resolution.
- The sensitivity on the neutrino mass hierarchy after 6 years of data taking will be:
    - about 3σ and can reach more than 4σ with 1% constraint on $\Delta m^2_{\mu\mu}$.
- Sub-percent measurement on $\sin^2\theta_{12}$, Δm^2_{12}, Δm^2_{ee}.
- The institute is well engaged in the project being responsible of two parts of the detector: Top Tracker and Small Photomultipliers.
- Heavy implication on the technical side will move towards analysis once systems installed.
- These 2 systems are of primordial importance for the analysis of the JUNO vast program (muon reconstruction, backgrounds, energy resolution).
- Interest from IN2P3 physicists in a wide range of topics reachable by JUNO: neutrino oscillations, Supernova, nuclear measurements, and potentially $\beta\beta0\nu$ in the future.