# Status and physics potential of the JUNO experiment

Frédéric Perrot

On behalf of the JUNO collaboration

*CENBG / IN2P3 / University of Bordeaux*

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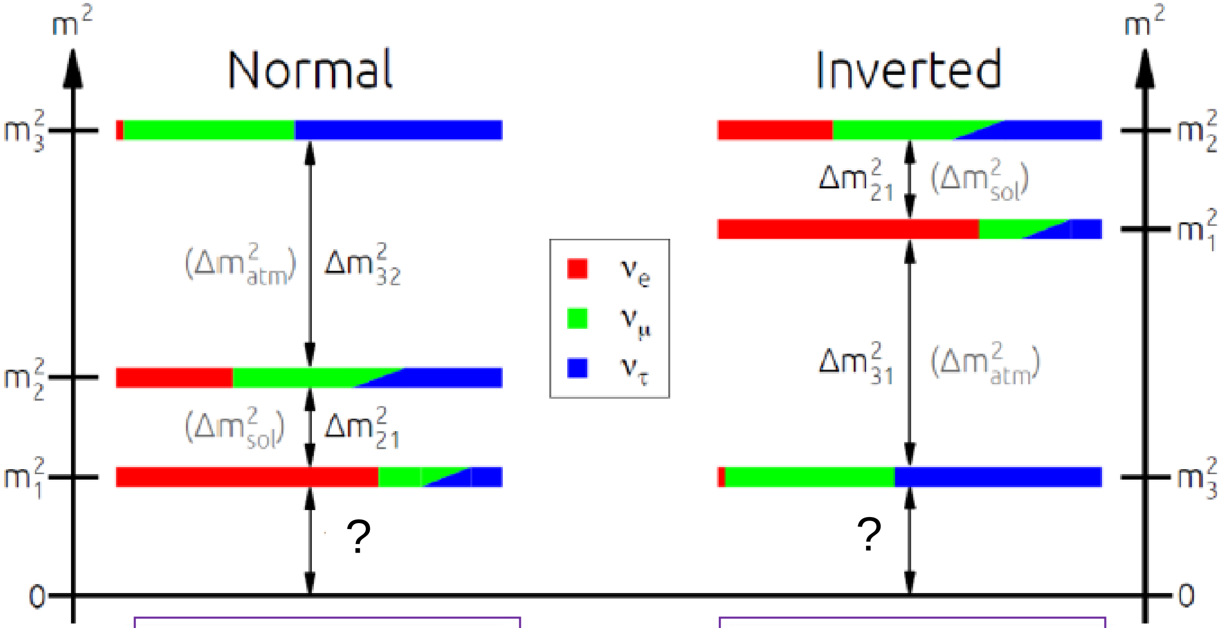
# Neutrino mass hierarchy

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$\Delta m^2_{21} = 7.5 \times 10^{-5} eV^2$$

$$\left|\Delta m^2_{31}\right| = 2.4 \times 10^{-3} eV^2$$

Sign and absolute value of $\Delta m^2_{31}$ depend on mass hierarchy



$m_1 < m_2 < m_3$

$m_3 < m_2 < m_1$

Measuring the neutrino mass hierarchy enables the study of further unknown parameters in neutrino physics :

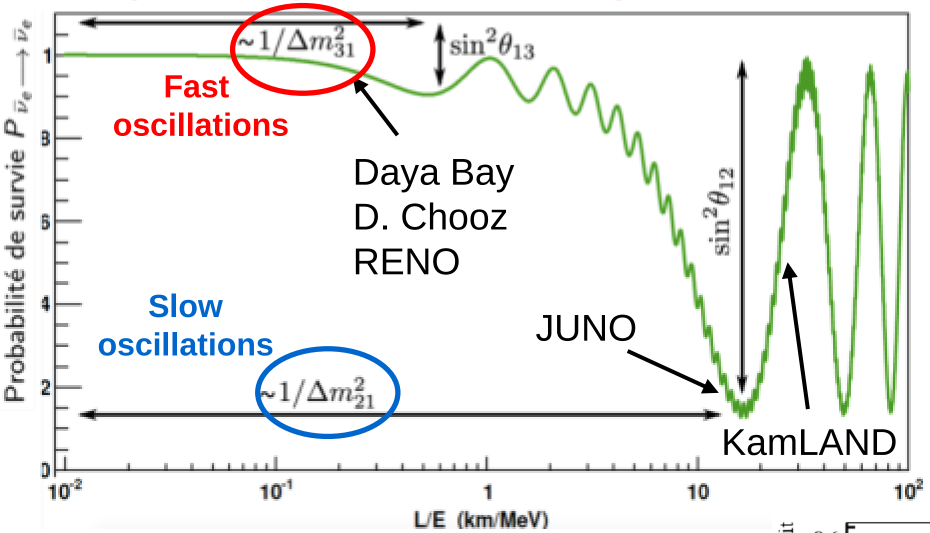
- ✓ Resolving $\delta_{CP}$
- ✓ Octant of $\theta_{23}$
- ✓ Parameter space for 0νββ decay

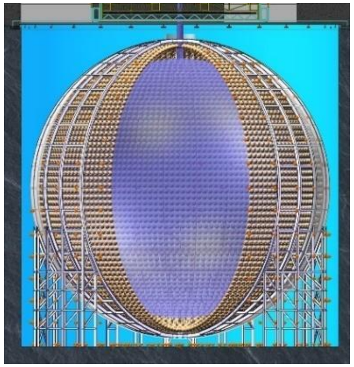
# Reactor electron antineutrinos oscillations

Electron antineutrino survival probability:

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \boxed{\sin^2 2\theta_{13}\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} - \sin^2 2\theta_{13}\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}} - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}}$$

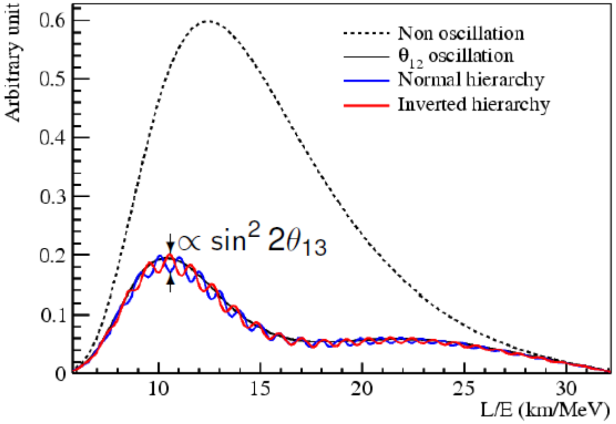
Nuclear reactors
(~$10^{21}$ ν/s/GW$_e$)





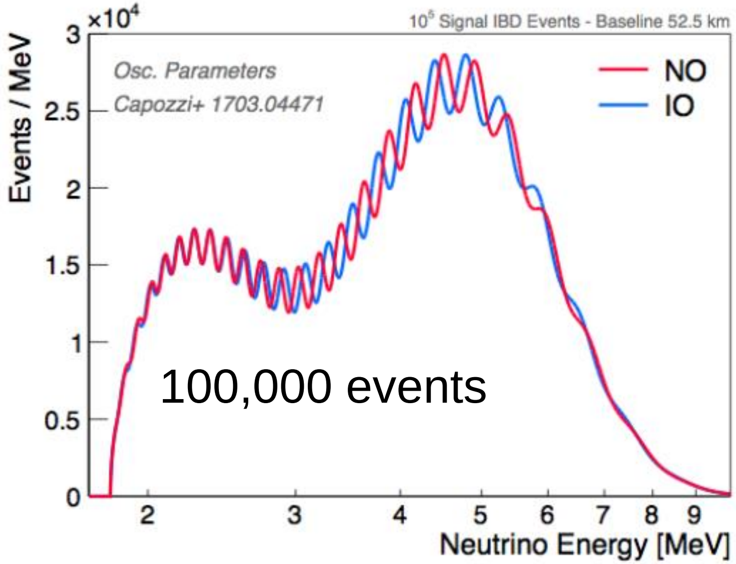
Neutrino detector

- Mass hierarchy is measurable only because $\theta_{13}$ is 'large' → way to determine NH/IH using reactor neutrinos by measuring the interference between $\Delta m^2_{31}$ and $\Delta m^2_{32}$
- Best L/E ratio for maximum interference is ~10 km/MeV, i.e. ~50-60 km distance for reactor antineutrinos energy



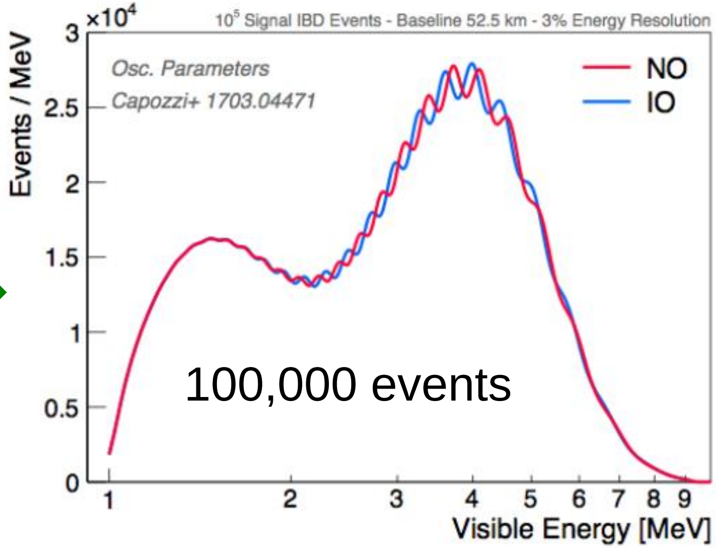
# JUNO MH sensitivity

Ideal oscillated antineutrino spectrum

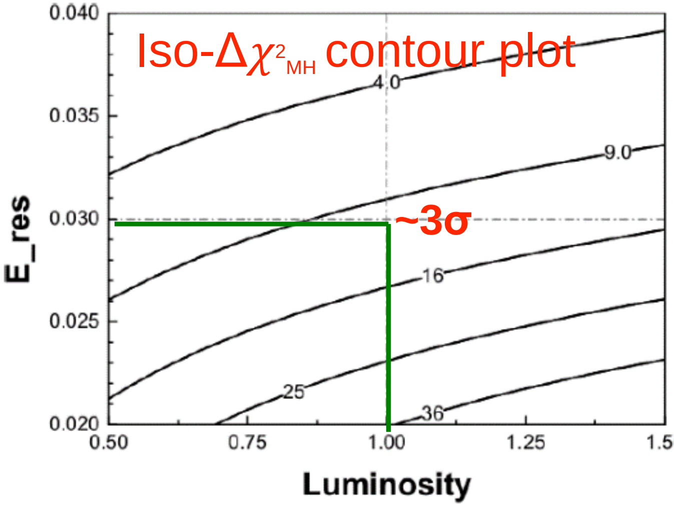


100,000 events

Visible energy spectrum + 3%/√E(MeV) $E_{res}$



100,000 events



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

~3σ

*JUNO collaboration, J. Phys. G 43 (2016) no.3, 030401*

To distinguish between NO/IO at 3σ, one needs:

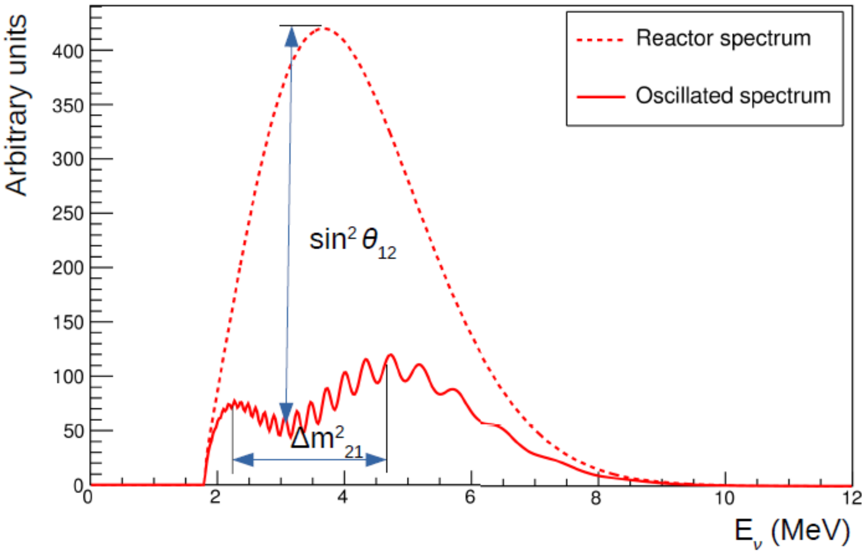
- ✓ at least 100,000 events (nominal luminosity)
- ✓ an energy resolution of 3%/√E(MeV)
- ✓ baseline ~53 km with core dispersion <0.5 km

+ an energy scale uncertainty below 1%

**→ impose the size and the performances of the JUNO experiment**

# Neutrino oscillation parameters with JUNO

- Advantage of JUNO for mass hierarchy determination: no matter effect and not sensitive to CP phase
- JUNO will be the first experiment ever built able to measure simultaneously the fast ($\Delta m^2_{31}$) and slow ($\Delta m^2_{21}$) oscillations along multiple oscillation periods
- Measurement of 3 parameters at a subpercent precision level, especially the solar oscillation parameters ($\Delta m^2_{21}$ and $\sin^2(2\theta_{12})$) in order to solve the tension between solar $\nu_e$ and KamLAND results



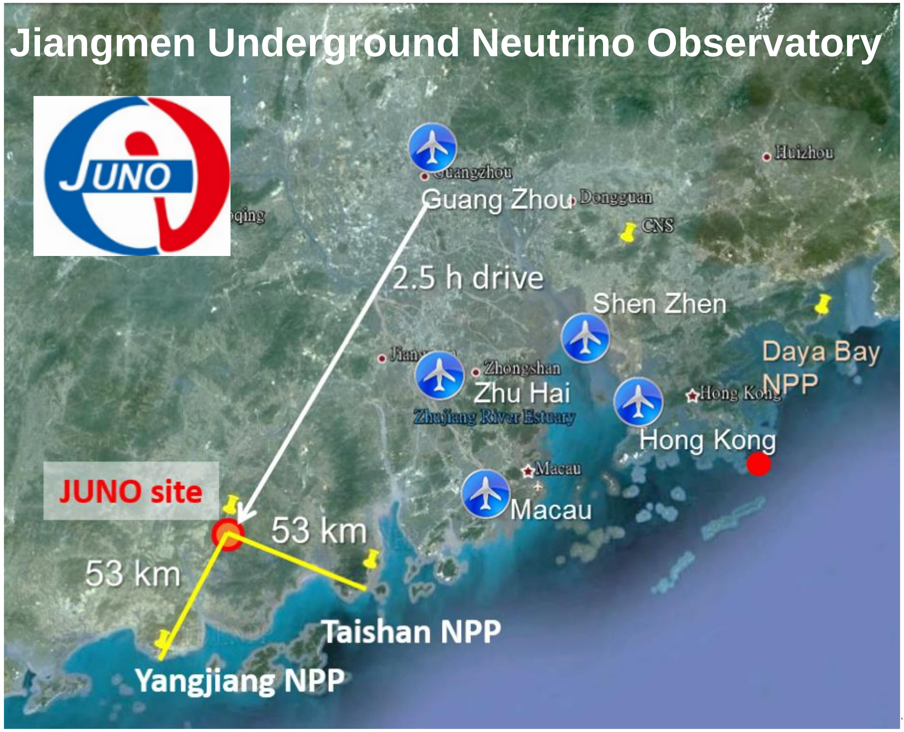
| Oscillation parameters | Current precision at 1σ level * | JUNO only** |
|---|---|---|
| $\lvert\Delta m_{31}{}^2\rvert$ | ~1.6% | ~0.5% |
| $\Delta m_{21}{}^2$ | ~2.3% | ~0.6% |
| $\sin^2(2\theta_{12})$ | ~5.8% | ~0.7% |
| Mass hierarchy | N/A | 3-4 σ |
| $\sin^2(\theta_{13})$ | ~3.9% | ~15% |

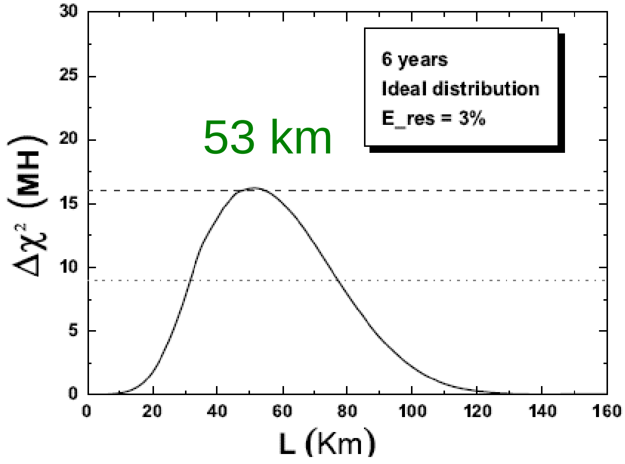
* *M. Tanabashi et al. (PDG), Phys. Rev. D 98, 030001 (2018).*

** *JUNO collaboration, J. Phys. G 43 (2016) no.3, 030401*

→ will help to probe the unitarity of the PMNS matrix at ~1% level

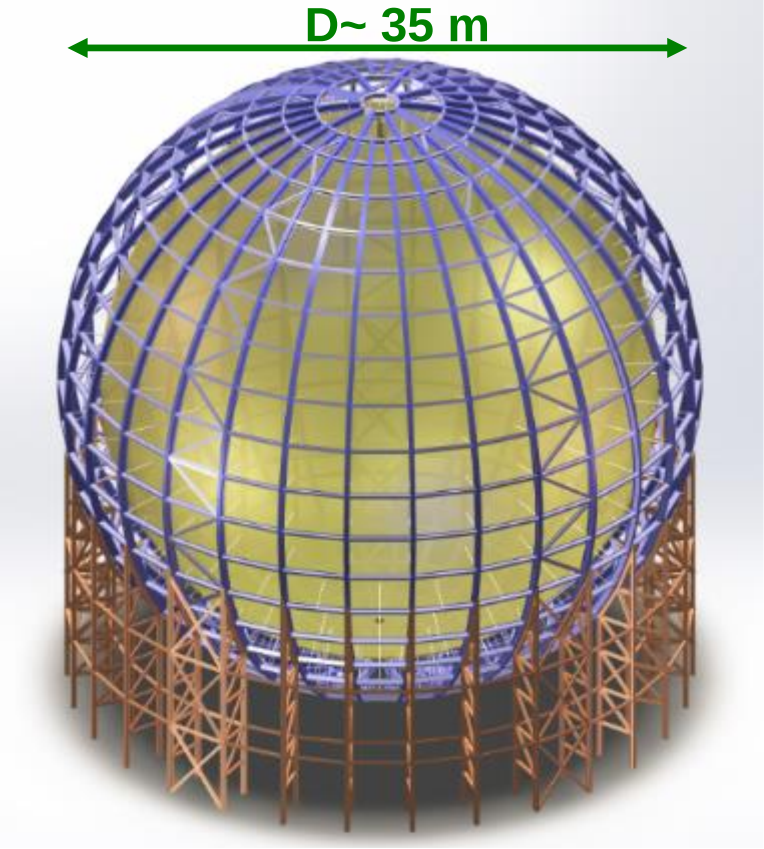
# JUNO location





- ✓ JUNO located at Jiangmen city, Guangdong province
- ✓ Equidistant from two powerful nuclear power plants (Yangjiang and Taishan) at 53 km for MH determination with 26.6 $GW_{th}$ available in 2020
- ✓ 700 m overburden

# JUNO detector: size and concept



- 100,000 events required in 6 years of data taking at 53 km distance

→ 20 ktons of target detector needed (liquid scintillator) in a sphere of ~35 m diameter

- Energy resolution of 3%/√E(MeV)

→ high LS transparency + very high photodetection coverage (~78%)
→ 1200 p.e. with 18,000 20-inch PMTs

**JUNO will be the largest liquid scintillator detector ever built !**

| **Experiment** | **Daya Bay** | **Borexino** | **KamLAND** | **JUNO** |
|---|---|---|---|---|
| LS mass (tons) | 20 /detector | ~300 | ~1,000 | 20,000 |
| Nb of collected p.e. per MeV | ~160 | ~500 | ~250 | ~1200 |
| Energy resolution @ 1 MeV | ~7.5% | ~5% | ~6% | ~3% |

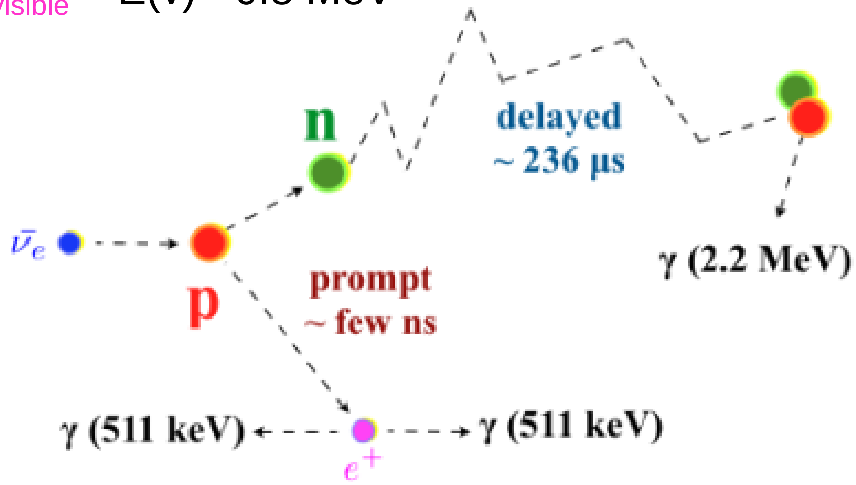
# Electron antineutrino detection

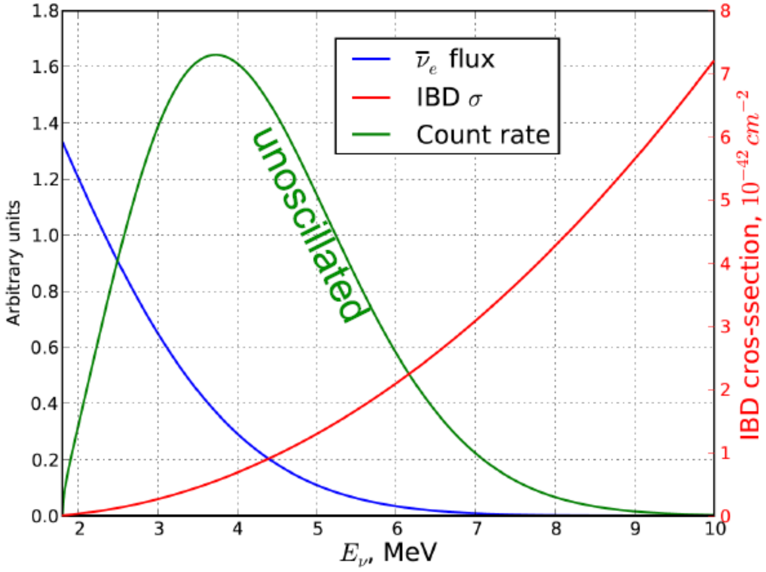
- Electron antineutrinos detected by Inverse Beta Decay (IBD) :

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

Energy threshold: E(ν)>1.8 MeV

$E_{visible}$ = E(ν) - 0.8 MeV





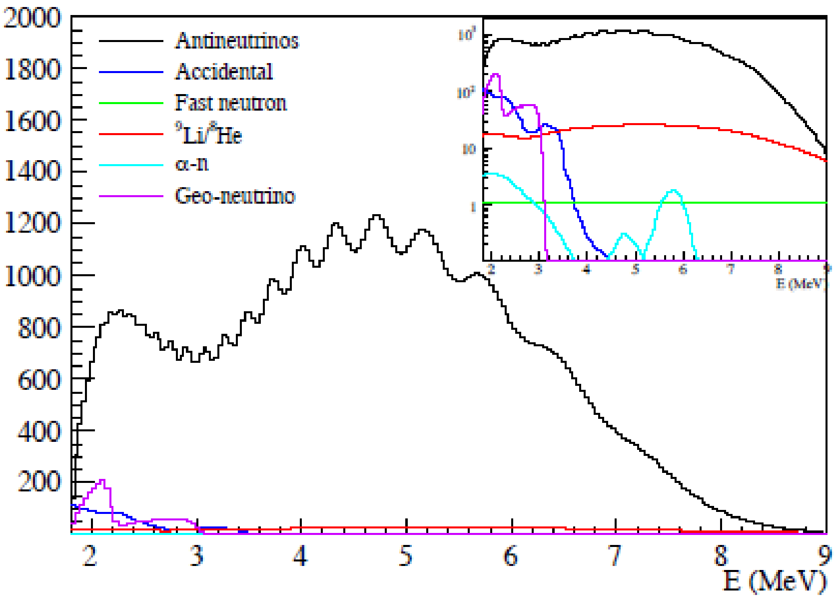
**Neutrino signature :**

– Prompt signal from $e^+$: ionization+annihilation in 2γ (1-10 MeV) → visible energy

– Delayed signal from neutron: capture on $^1$H (2.2 MeV)

– Time correlation < 1 ms

# Signal and backgrounds



- Visible energy of oscillated spectrum from reactor antineutrinos in JUNO
- Energy spectrum contribution from the main 5 backgrounds (correlated and uncorrelated backgrounds)

→ backgrounds need to be under control by design and by active/passive cuts

R<17.2 m

$E_{vis}$>0.7 MeV

ΔT < 1 ms

ΔR < 1.5 m

Veto system

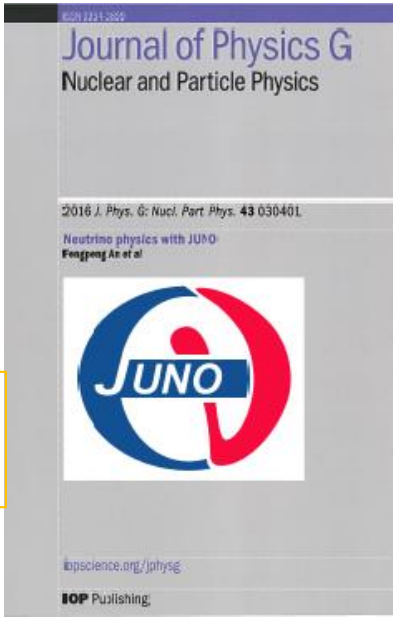
| Selection | IBD efficiency | IBD | Geo-$\nu$s | Accidental | $^{9}$Li/$^{8}$He | Fast $n$ | $(\alpha, n)$ |
|---|---|---|---|---|---|---|---|
| - | - | 83 | 1.5 | $\sim 5.7 \times 10^4$ | 84 | - | - |
| Fiducial volume | 91.8% | 76 | 1.4 | 410 | 77 | 0.1 | 0.05 |
| Energy cut | 97.8% | 73 | 1.3 | | 71 | | |
| Time cut | 99.1% | | | | | | |
| Vertex cut | 98.7% | | | 1.1 | | | |
| Muon veto | 83% | 60 | 1.1 | 0.9 | 1.6 | | |
| Combined | 73% | 60* | 3.8 | | | | |

** At a nominal power of 36 GWth (26.6 GWh in 2020)*

→ after selection cuts: 60 neutrino events/day and 3.8 background events/day

# JUNO non-reactor neutrino physics

“Neutrino Physics with JUNO,” J. Phys. G
**43** (2016) no.3, 030401



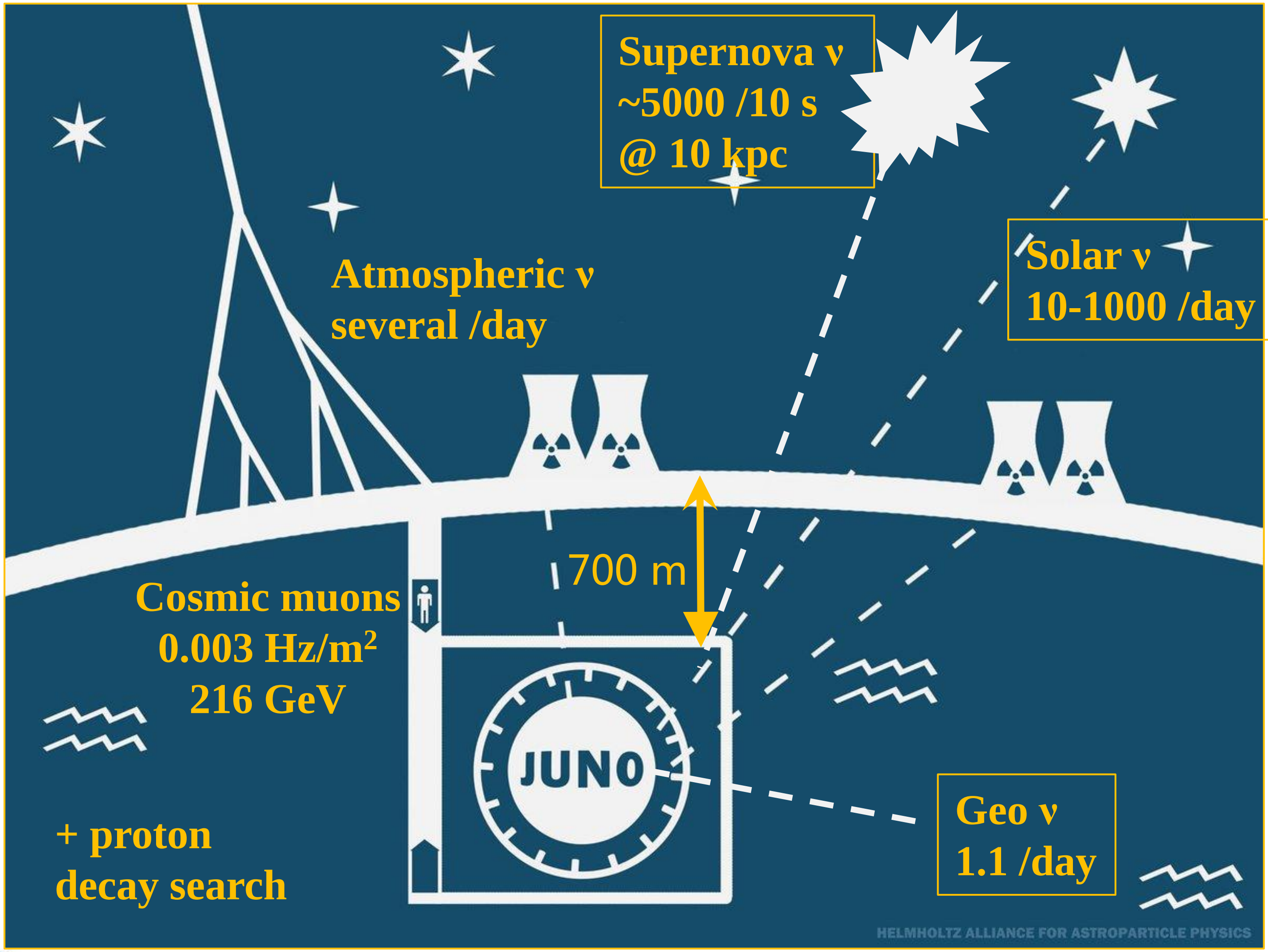
Journal of Physics G
Nuclear and Particle Physics

2016 *J. Phys. G: Nucl. Part. Phys.* **43** 030401

Neutrino physics with JUNO
Fengpeng An et al

iopscience.org/jphysg

**IOP** Publishing



**Supernova ν**
**~5000 /10 s**
**@ 10 kpc**

**Atmospheric ν**
**several /day**

**Solar ν**
**10-1000 /day**

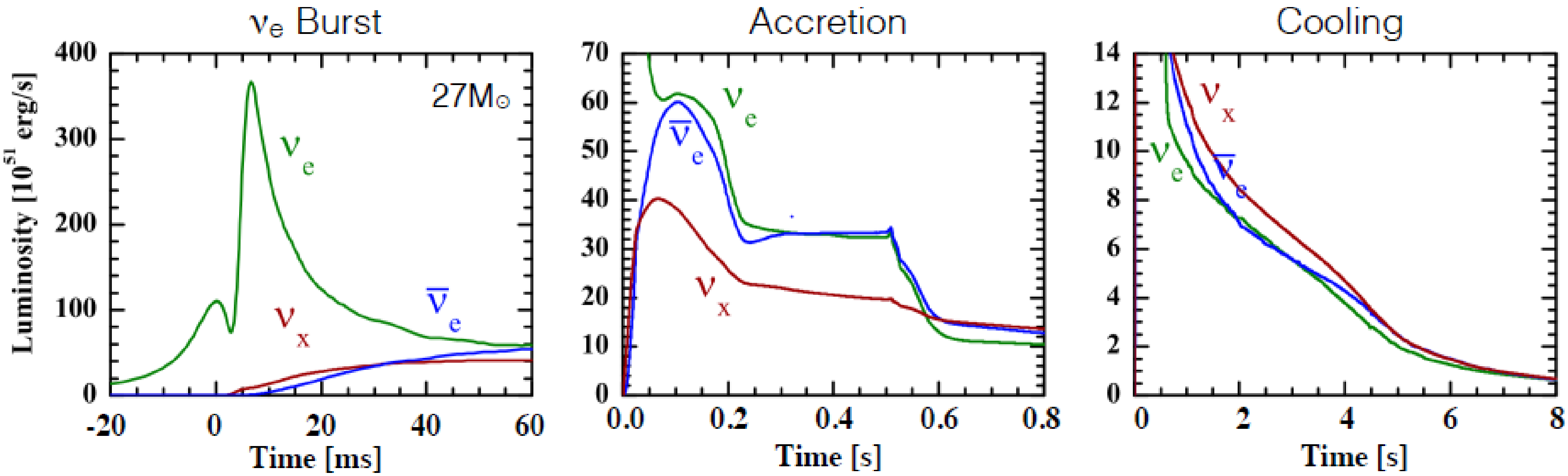
**Cosmic muons**
**0.003 Hz/m$^2$**
**216 GeV**

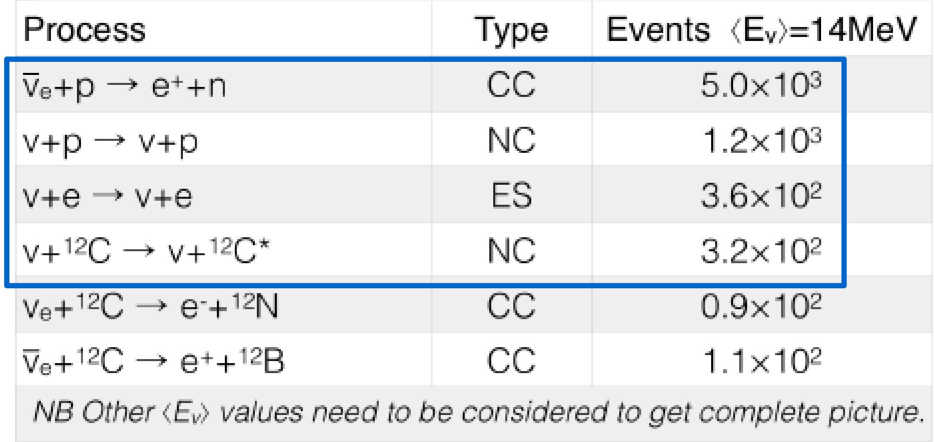
**Geo ν**
**1.1 /day**

**+ proton**
**decay search**

# Supernova neutrinos with JUNO

- 99% of energy released in neutrinos and antineutrinos of all flavors in Supernova neutrino burst
- opportunity to observe with JUNO the 3 phases in order to better understand stellar explosion





| Process | Type | Events ⟨$E_\nu$⟩=14MeV |
|---|---|---|
| $\bar{\nu}_e + p \rightarrow e^+ + n$ | CC | $5.0\times10^3$ |
| $\nu + p \rightarrow \nu + p$ | NC | $1.2\times10^3$ |
| $\nu + e \rightarrow \nu + e$ | ES | $3.6\times10^2$ |
| $\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$ | NC | $3.2\times10^2$ |
| $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$ | CC | $0.9\times10^2$ |
| $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$ | CC | $1.1\times10^2$ |

*NB Other ⟨$E_\nu$⟩ values need to be considered to get complete picture.*

- ~5,000 IBD & ~2000 ν events expected from a typical SN at 10 kpc distance in JUNO

→ background is not a serious concern at this rate of events in only 10 s

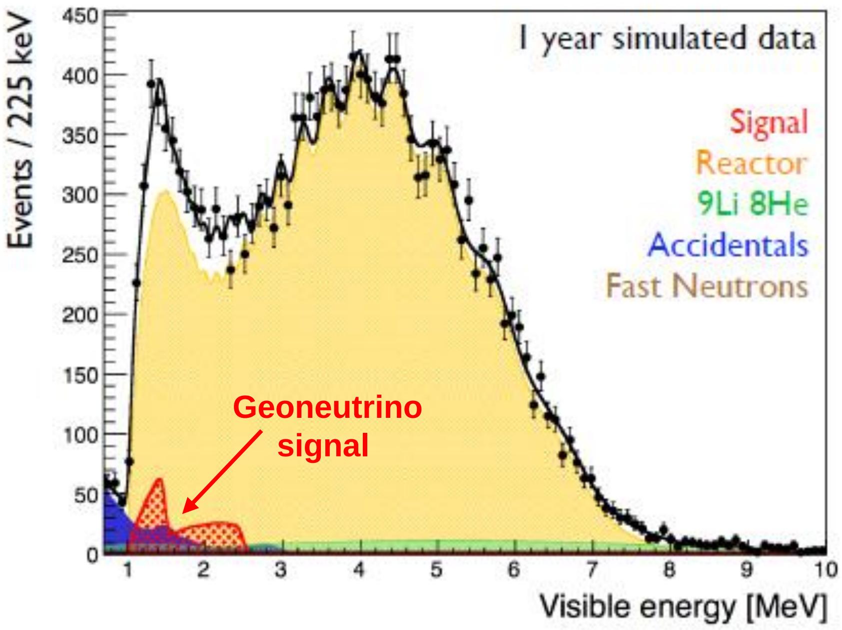
- Opportunity to be able to handle Betelgeuse (0.2 kpc) resulting in a challenging 10 MHz trigger rate acceptance !

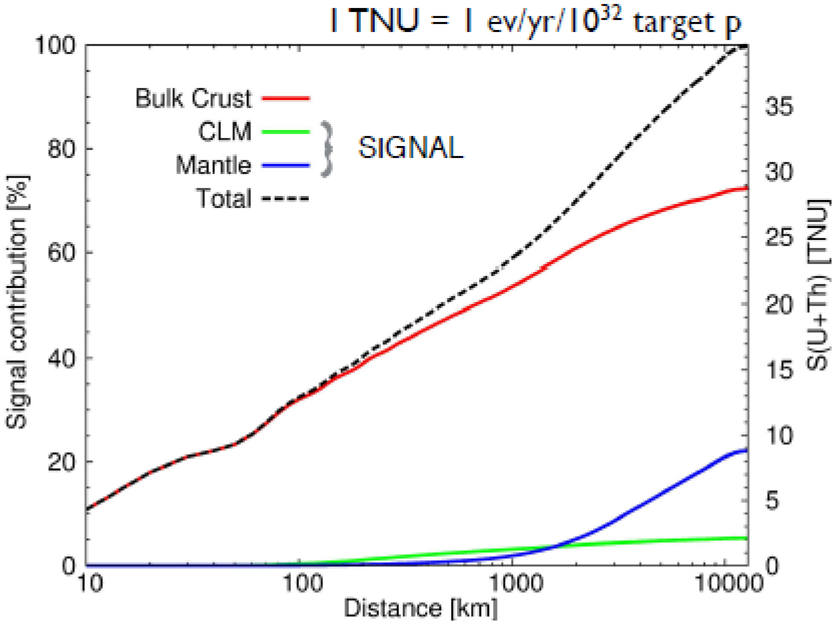
# Geo-neutrinos with JUNO

Earth's surface heat flow 46±3 TW but the fraction of this power coming from primordial or radiogenic origins is unknown. It questions our understanding of :

- composition of the Earth (chondritic meteorites that formed our Planet)
- energy needed to drive plate tectonics
- power source of the geodynamo, which powers the magnetosphere

→ antineutrinos coming from the $^{238}$U and $^{232}$Th decay chains can shed light.





→ JUNO will observe more geoneutrinos (~400) than all the current experiments combined in less than 1 year of data taking !!

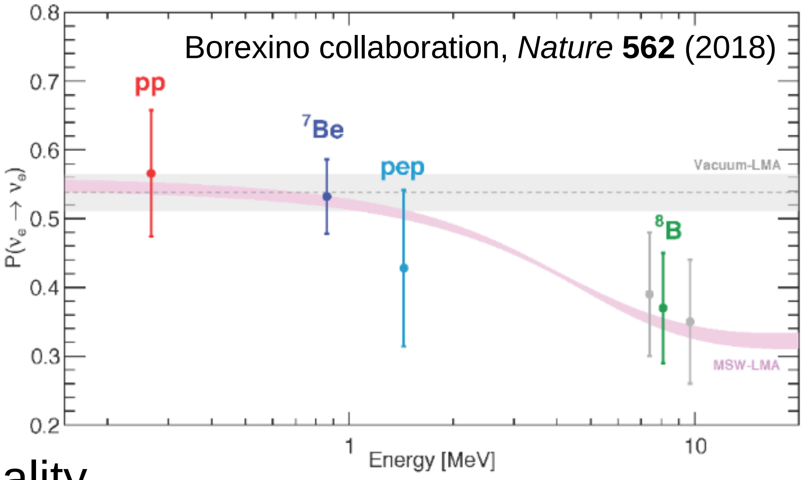
# Solar neutrinos with JUNO

- Goal: new measurement of $^7$Be and $^8$B neutrino fluxes via Elastic Scattering (ES):

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

→ to investigate MSW effect: transition between vacuum and matter dominated regimes

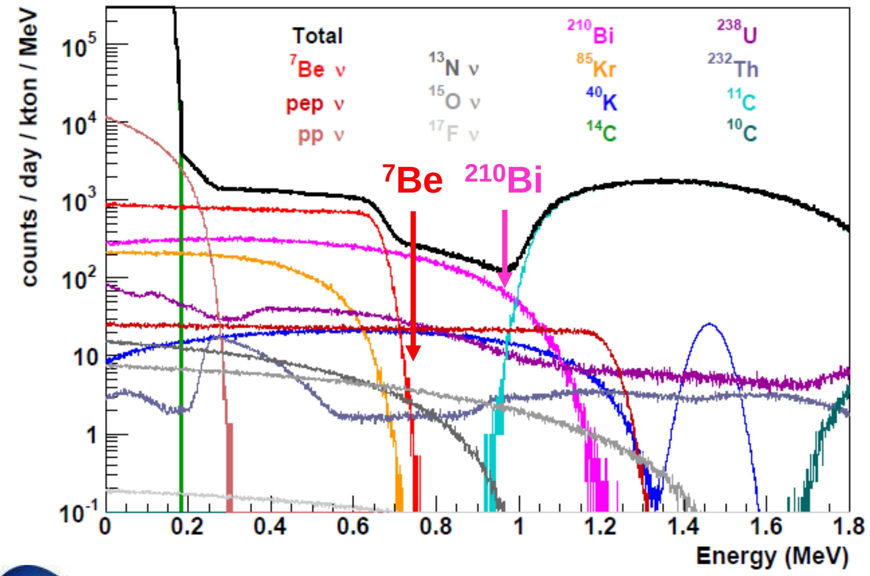
→ to help constrain solar metallicity composition


Borexino collaboration, *Nature* **562** (2018)

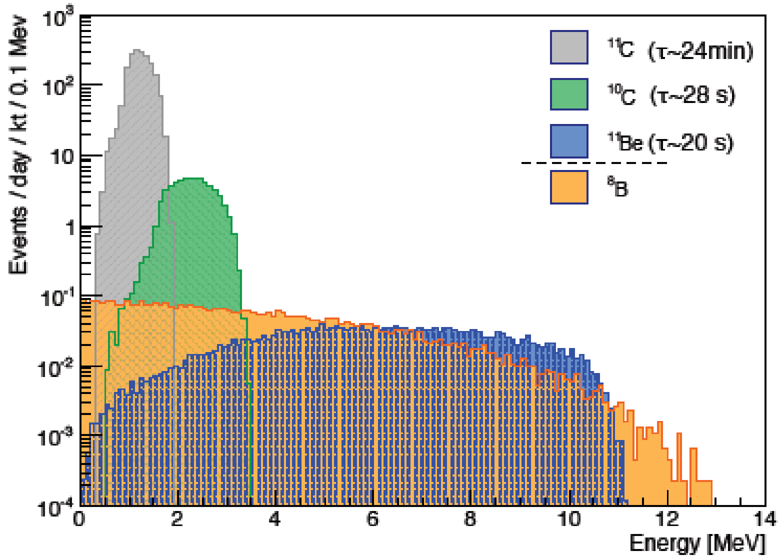
- ES will give single events without any directionality

→ radiopurity (for $^7$Be) and cosmogenic veto ($^8$B) capabilities are the main challenges

***Ideal radiopurity of LS in JUNO***

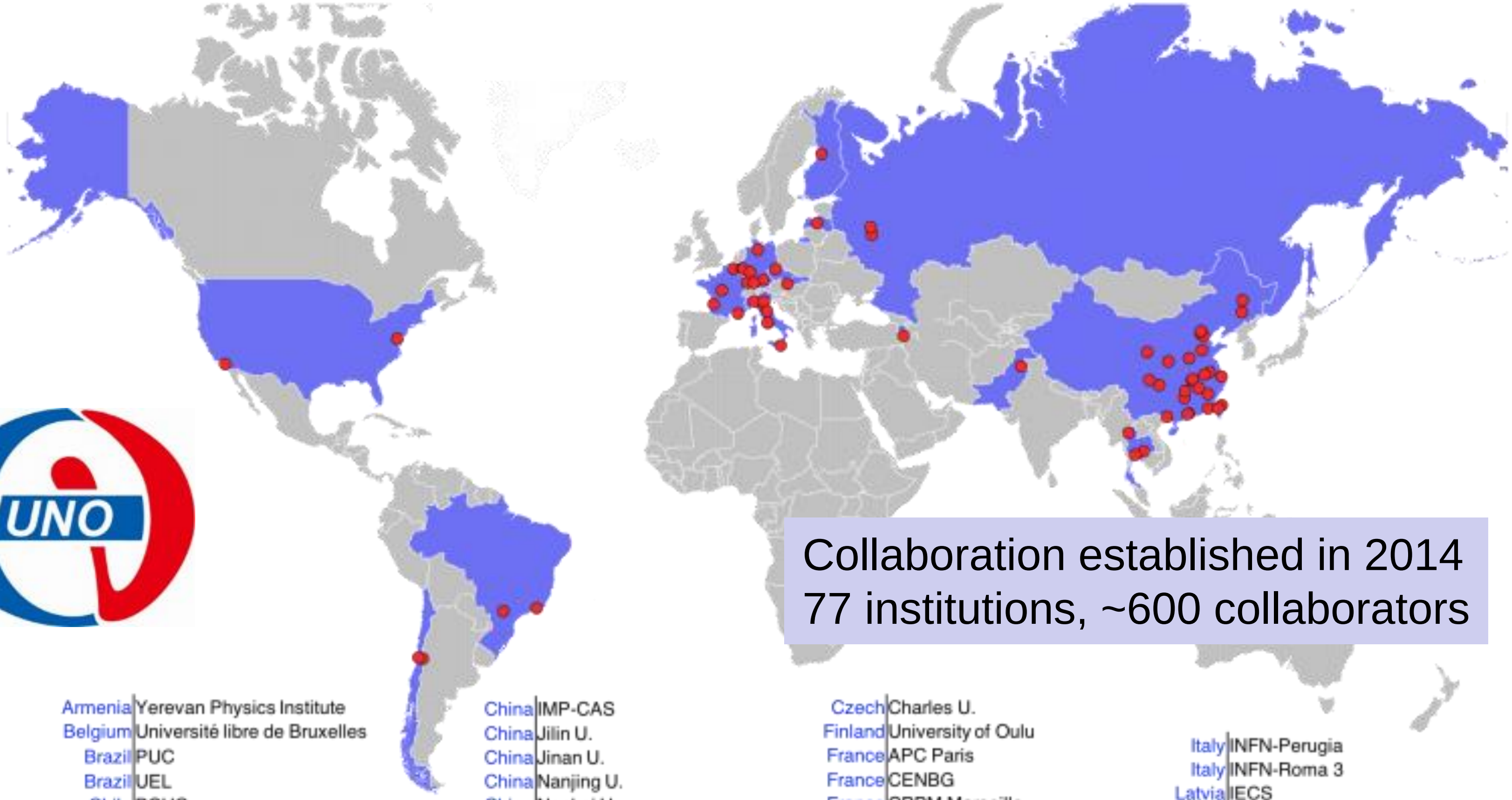


***$^8$B energy spectrum with cosmogenic isotopes***


J.Phys. G43 (2016) no.3, 030401

# Status of the JUNO project

# The JUNO collaboration

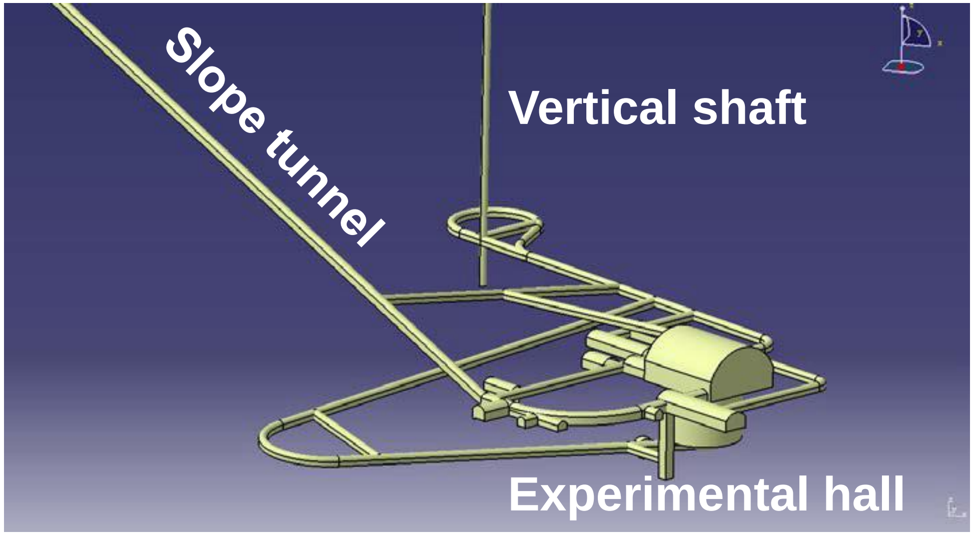


Collaboration established in 2014
77 institutions, ~600 collaborators

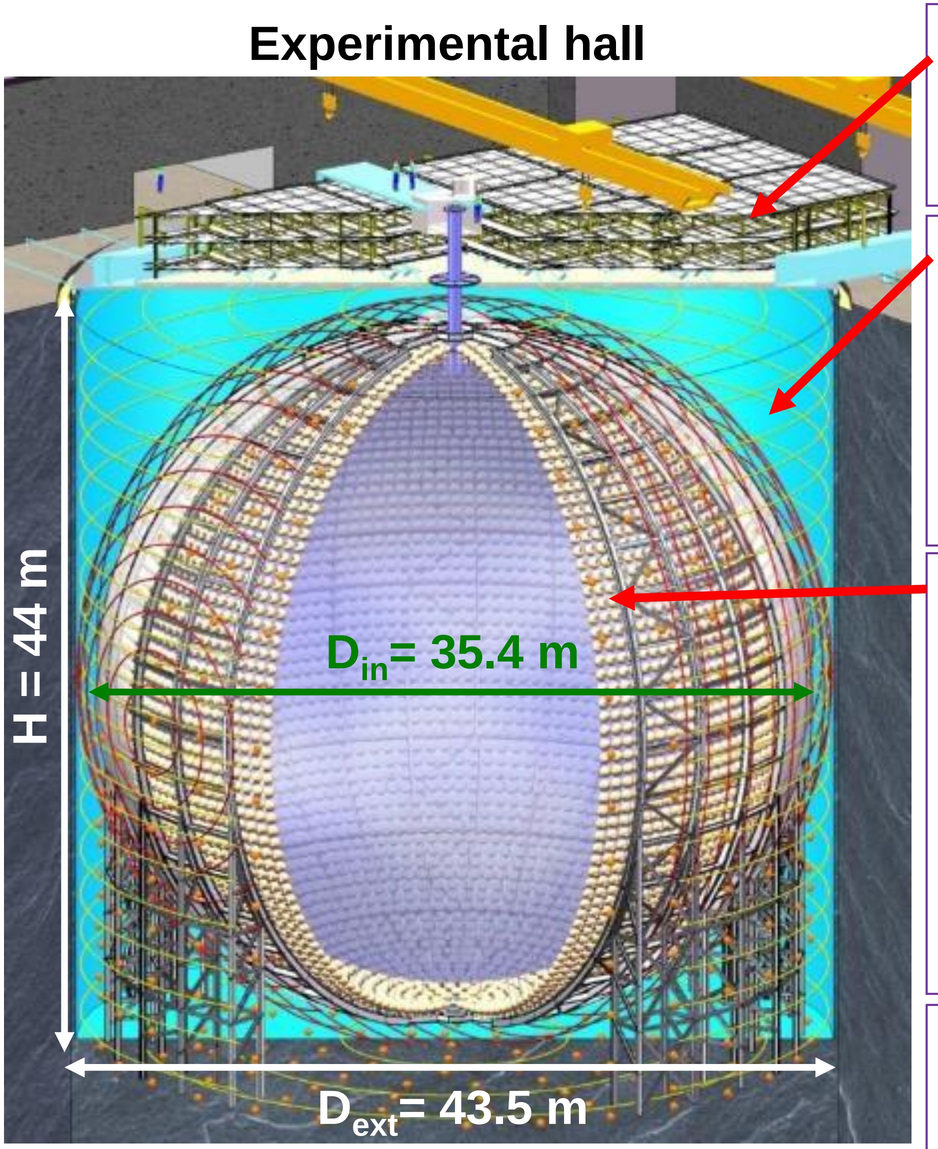
| | |
|---|---|
| Armenia | Yerevan Physics Institute |
| Belgium | Université libre de Bruxelles |
| Brazil | PUC |
| Brazil | UEL |
| Chile | PCUC |
| Chile | UTFSM |
| China | BISEE |
| China | Beijing Normal U. |
| China | CAGS |
| China | ChongQing University |
| China | CIAE |
| China | CUG |
| China | DGUT |
| China | ECUST |
| China | ECUT |
| China | Guangxi U. |
| China | Harbin Institute of Technology |
| China | IGG |
| China | IGGCAS |
| China | IHEP |
| China | IMP-CAS |
| China | Jilin U. |
| China | Jinan U. |
| China | Nanjing U. |
| China | Nankai U. |
| China | NCEPU |
| China | NUDT |
| China | Peking U. |
| China | Shandong U. |
| China | Shanghai JT U. |
| 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 | Zhengzhou U. |
| Czech | Charles U. |
| Finland | University of Oulu |
| France | APC Paris |
| France | CENBG |
| 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 |
| Latvia | IECS |
| 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 | NARIT |
| Thailand | PPRLCU |
| Thailand | SUT |
| USA | UMD1 |
| USA | UMD2 |
| USA | UCI |

# Civil construction

**Surface buildings**



# JUNO overall detector design



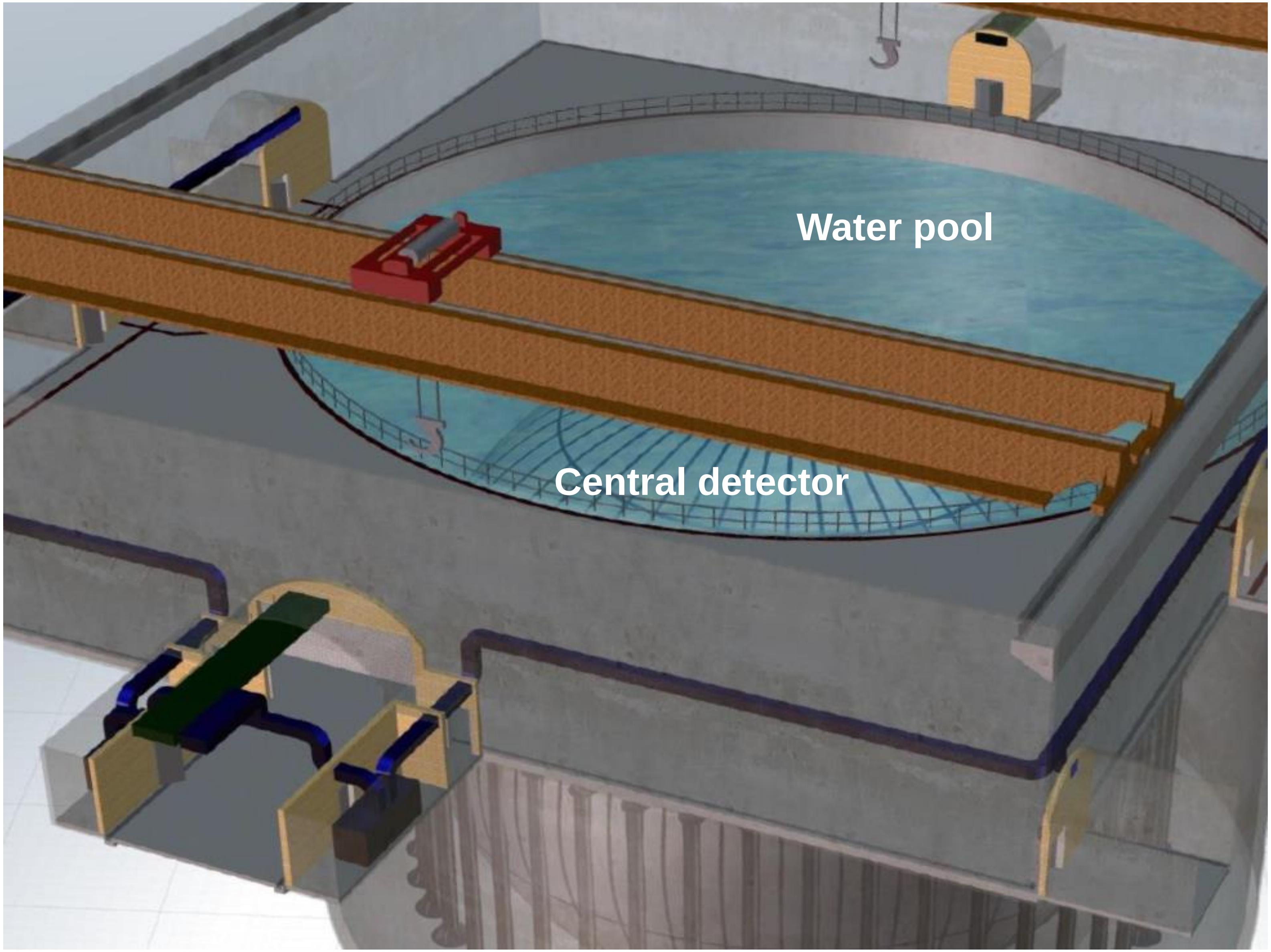
**Top Tracker** for very precise muon tracking
- 3-layers of plastic scintillators
- Reuse of OPERA’s Target Tracker

**Water Cherenkov muon veto**
- 35 ktons of ultrapure water
- 2,000 20-inch PMTs
- Muon detection efficiency > 95%
- Radon control → less than 0.2 Bq/$m^3$

**Central detector** :
- Acrylic sphere filled with 20 ktons of LS
- PMTs immerged in water buffer and fixed on a stainless steel truss:
  - 17,000 20-inch PMTs
  - 25,000 3-inch PMTs
- 78% photocoverage

**Compensation coils**
- Earth‘s magnetic field <10%
- Necessary for 20”PMTs

# JUNO overall detector design



# JUNO liquid scintillator

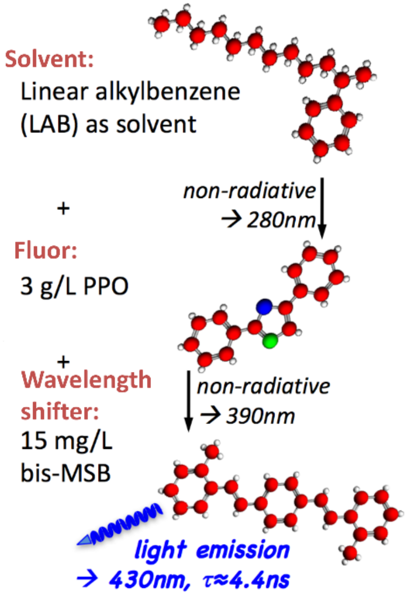
## JUNO LS requirements for $3\%/\sqrt{E(\mathrm{MeV})}$ $E_{res}$

- High light yield: $10^4$ photons/MeV
- High transparency: attenuation length >20m@430nm
- Good radiopurity for $\bar{\nu}_e$ physics: $^{238}$U<$10^{-15}$ g/g, $^{232}$Th<$10^{-15}$ g/g, $^{40}$K<$10^{-16}$ g/g

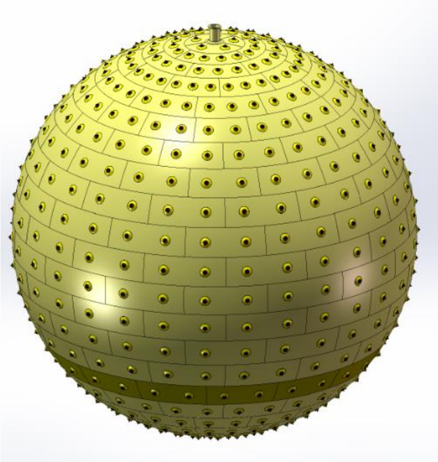
## LS Purification pilot plant

- Under operation at Daya Bay
- Distillation, $Al_2O_3$ column purification, filtration, water extraction, gas stripping
- Attenuation lenght >25 m after filling (measured)
- Optimizing LS recipes (LAB+2.5 g PPO+1-3 mg/L bis-MSB) and studying radio-impurities
- Same plant to be scaled for JUNO

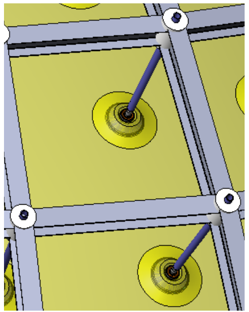
**OSIRIS detector design study** for monitoring the LS radiopurity at a level of $10^{-16}$ g/g in $^{238}$U during JUNO filling



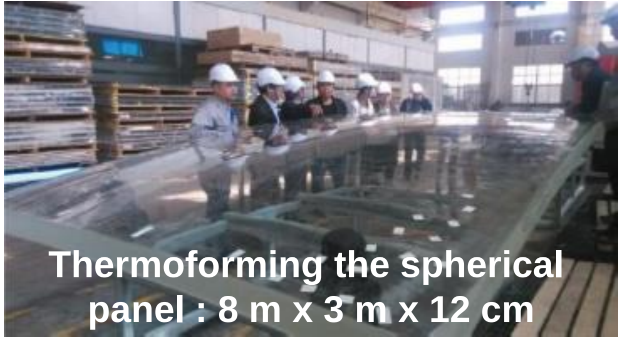
# JUNO acrylic and CD prototype



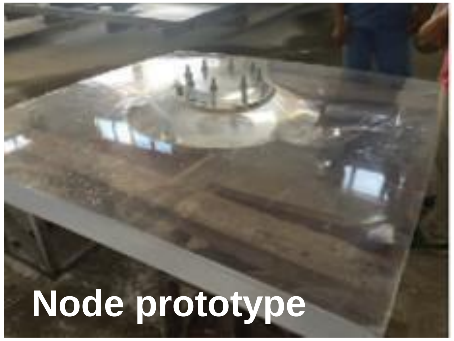
- Central Detector will be built from acrylic panels with 12 cm thickness : about 260 panels with a total weight of ~600 tons



- Several requirements have been defined :
  - Max stress control on acrylic < 3.5 Mpa
  - Max pulling load for acrylic node ~ 8 tons
  - Break at load for acrylic node ~ 100 tons
  - Radiopurity of the acrylic & quality test control



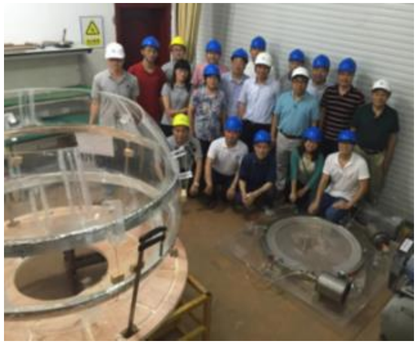
**Thermoforming the spherical panel : 8 m x 3 m x 12 cm**



**Node prototype**

**Tensile testing**

- A JUNO 1:12 prototype has been successfully built at IHEP !

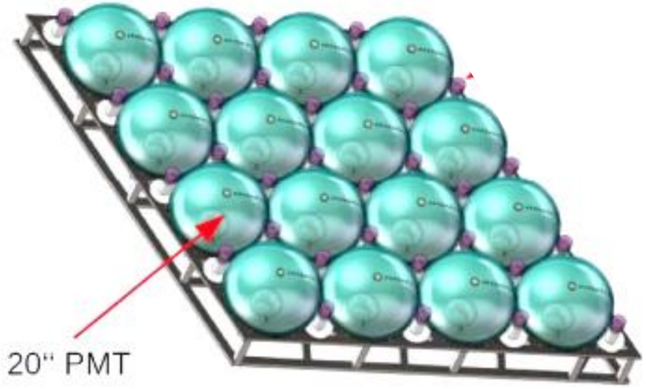


**JUNO prototype**

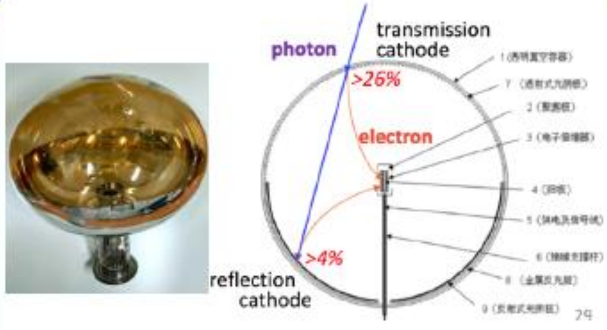
# Large PMT system

- JUNO will use large 20-inch PMTs as its main photodetection system

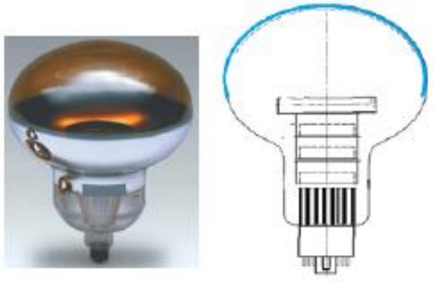
Tight arrangement with a photocoverage of ~75%



2 complementary (and new!) technologies:



Microchannel plate (MCP)-PMTs



Dynode-PMTs

- ✓ 15,000 MCP-PMTs from NNVT
- ✓ 5,000 dynode PMTs from Hamamatsu
- ✓ In production since 2016
- ✓ ~10,000 produced and >5,000 tested
- ✓ Recent 10% improvement of PDE efficiency for MCP-PMT (27→30%)
- ✓ JUNO PMTs equipped with implosion protection cover

| **Characteristics** | **unit** | **MCP-PMT (NNVT)** | **R12860 (Hamamatsu)** |
|---|---|---|---|
| Detection Efficiency (QE*CE) | % | 27% | 27% |
| 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<br>232Th:50<br>40K: 20 | 238U:400<br>232Th:400<br>40K: 40 |

# Small PMT system

- JUNO will also have to control the non-stochastic term of the energy resolution at an unprecedented level below (<1%)

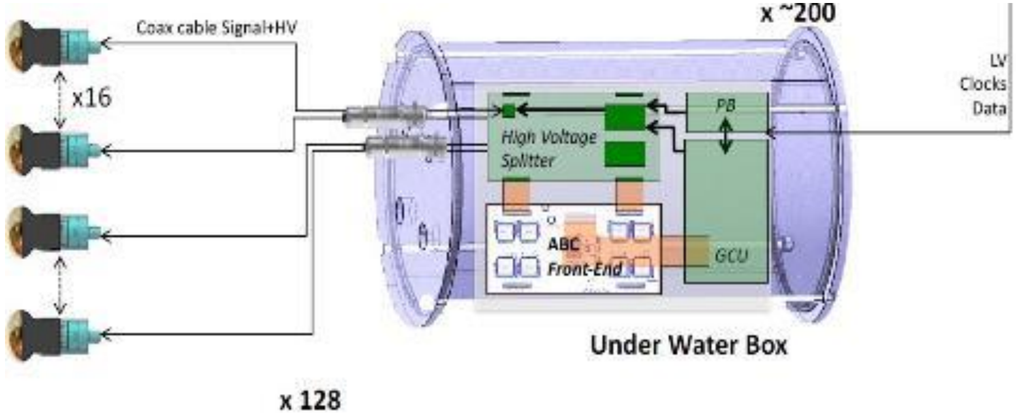
$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{\mathrm{stoch}}}{E} + \sigma^2_{\mathrm{non-stoch}}}$$

~3% (1200 p.e.) <1% never achieved !

→ JUNO will use 3-inch PMTs as a complementary photodetection system in photon-counting mode with :

- ✓ a better control of systematics (stereo-calorimetry)
- ✓ an increased dynamic range (for muons,…)
- ✓ a nice complementary physics potential (precise measurements of $\Delta m^2_{21}$ and $\sin^2(2\theta_{12})$, Supernova neutrinos with unbiased energy and rate meas.)

Custom design for JUNO

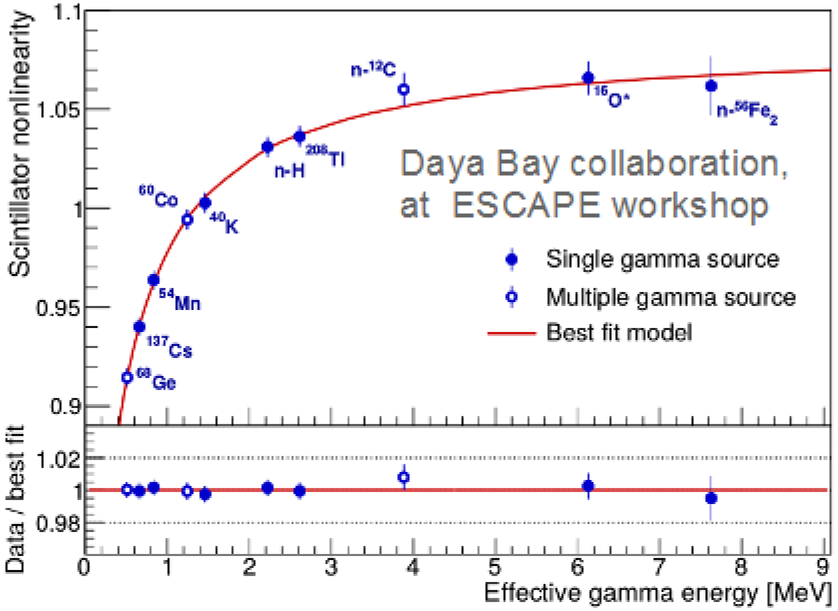


- ✓ 25,000 PMTs from HZC company
- ✓ Production started in Jan. 2018
- ✓ Already 9,000 accepted in Oct. 18 !
- ✓ 128 PMTs connected to one under water electronics box in order to reduce the number of channels

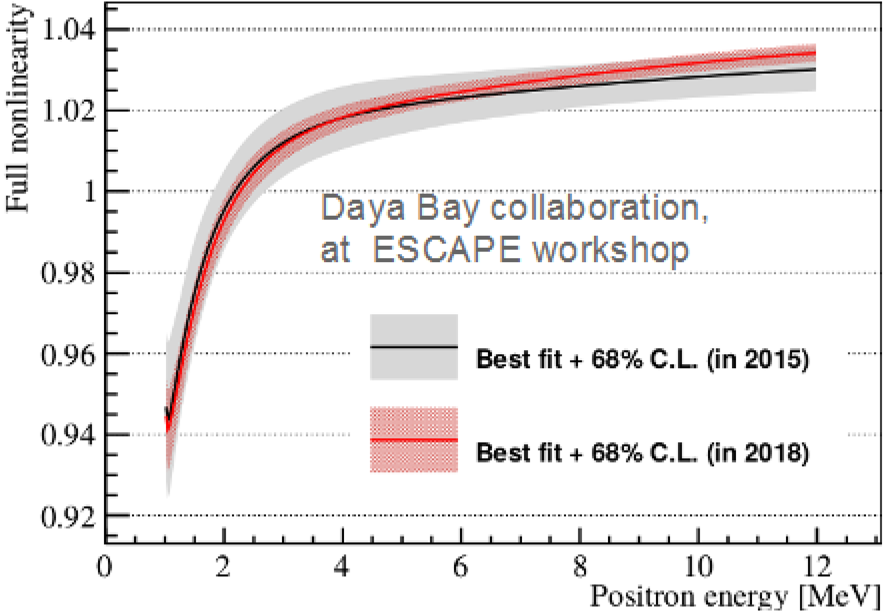
# Control of the energy scale uncertainty

- The JUNO challenge is to keep energy scale uncertainty below 1%

**New results from ESCAPE workshop (June 2018)**



Daya Bay collaboration, Phys. Rev. D 95, 072006 (2017)



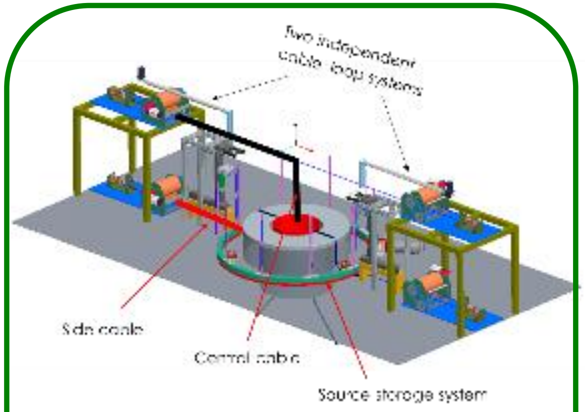
- Other experiments already achieved 1% accuracy (Daya Bay ~0.5%, Double Chooz 0.74%, Borexino <1% (at low energies), KamLAND 1.4%)

→ JUNO with an unprecedent size needs a accurate energy calibration strategy

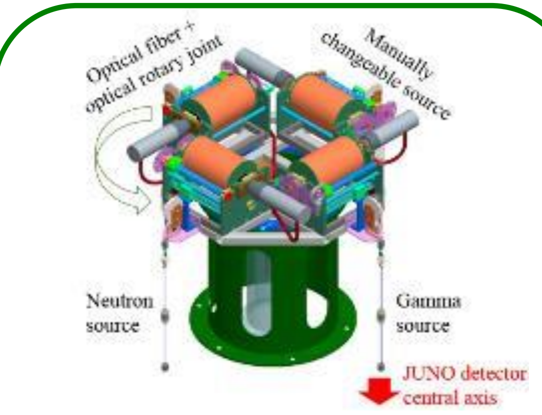
# JUNO calibration strategy

- The JUNO challenge is to keep energy scale uncertainty below 1%

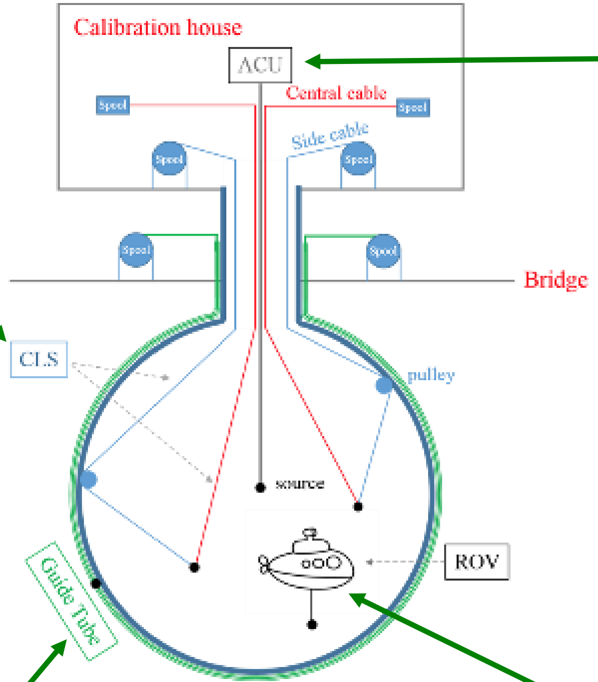
5 complementary calibration systems under development using e$^-$, e$^+$, γ and n sources

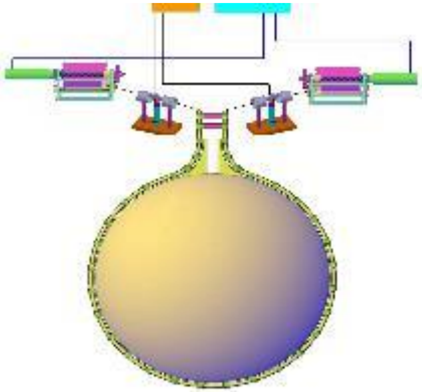


**Cable Loop System (CLS)**
**2D plane inside the vessel**

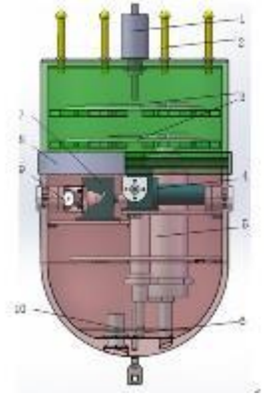


**Automatic calibration unit (ACU)**
**1D along detector z-axis**





**Guide Tube (GT)**
**2D around outer surface vessel**



**Remotely Operated Vehicle (ROV)**
**3D anywhere in the vessel**

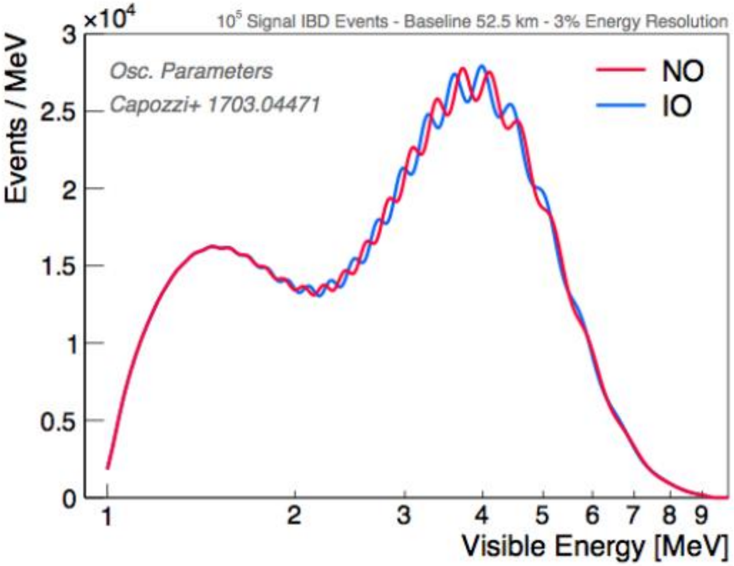
**+ Laser fiber system**
**1D like, fixed position on PMT**

# Reactor shape uncertainties

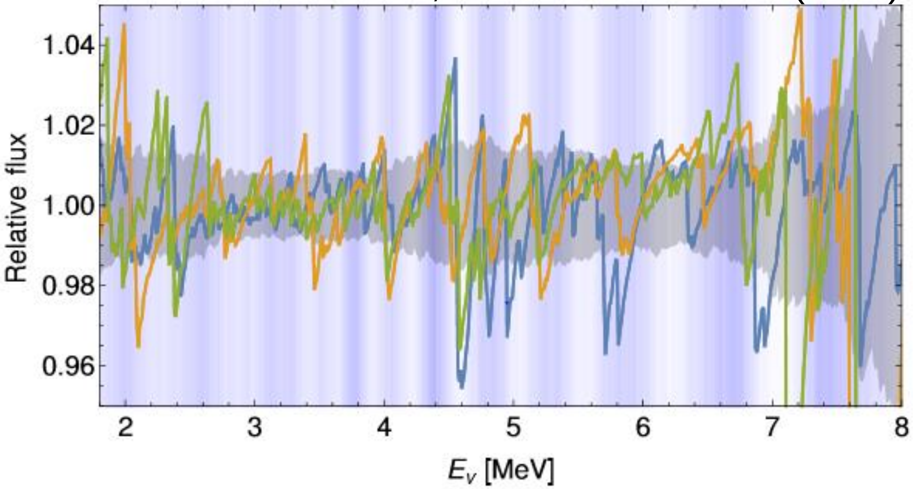
- ✓ “Standard” reactor shape uncertainties have minor impact on the MH sensitivity
- ✓ But reactor spectrum might show micro-structures

*(see A.A.Sonzogni et al. arXiv:1710.00092, D.A. Dwyer & T.J. Langford, Phys. Rev. Lett. 114,012502 (2015))*

- ✓ These micro-structures degrade the MH sensitivity by mimicking periodic oscillation pattern



D.V. Forero et al, arXiv:1710.07378v1 (2017)



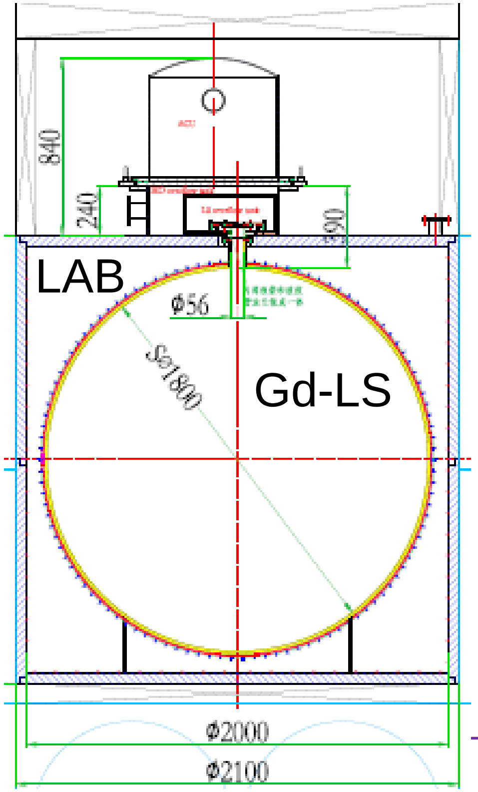
*Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)*

**→ reference detector needed for JUNO**

# JUNO-TAO

Taishan Antineutrino Observatory (TAO) has several physics motivation :

- Precisely measure the 4-6 MeV bump and the fine structure of reactor antineutrino spectrum with unprecedented energy resolution.
- Provide a benchmark for investigation of nuclear database
- Measure antineutrino spectra from $^{235}$U and $^{239}$Pu after combined with other reactor neutrino experiment.
- Search for sterile neutrino with good vertex reconstruction capability



**JUNO-TAO detector design**

- 1 ton fiducial volume Gd-LS detector at 30 m from core

→ **30 times JUNO event rate**

- Full coverage 10 m$^2$ SiPM with 50% PDE operated at -50°C

→ **energy resolution of 1.7%/$\sqrt{E}$(MeV)**

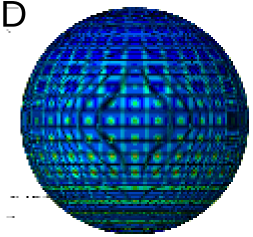
- R&D in progress

→ **welcome new collaborators !**

# Milestones and Schedule

2014:
- International collaboration established
- Start civil construction

2015:
- PMT production line setup
- CD parts R&D

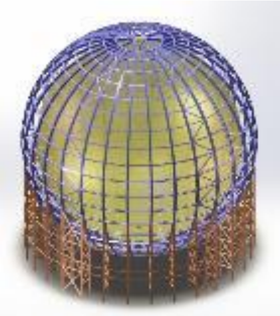


2016:
- Start PMT production
- Start CD parts production

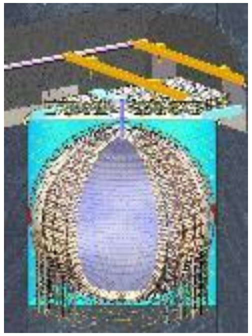
2017:
- Start PMT testing
- TT arrived

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!



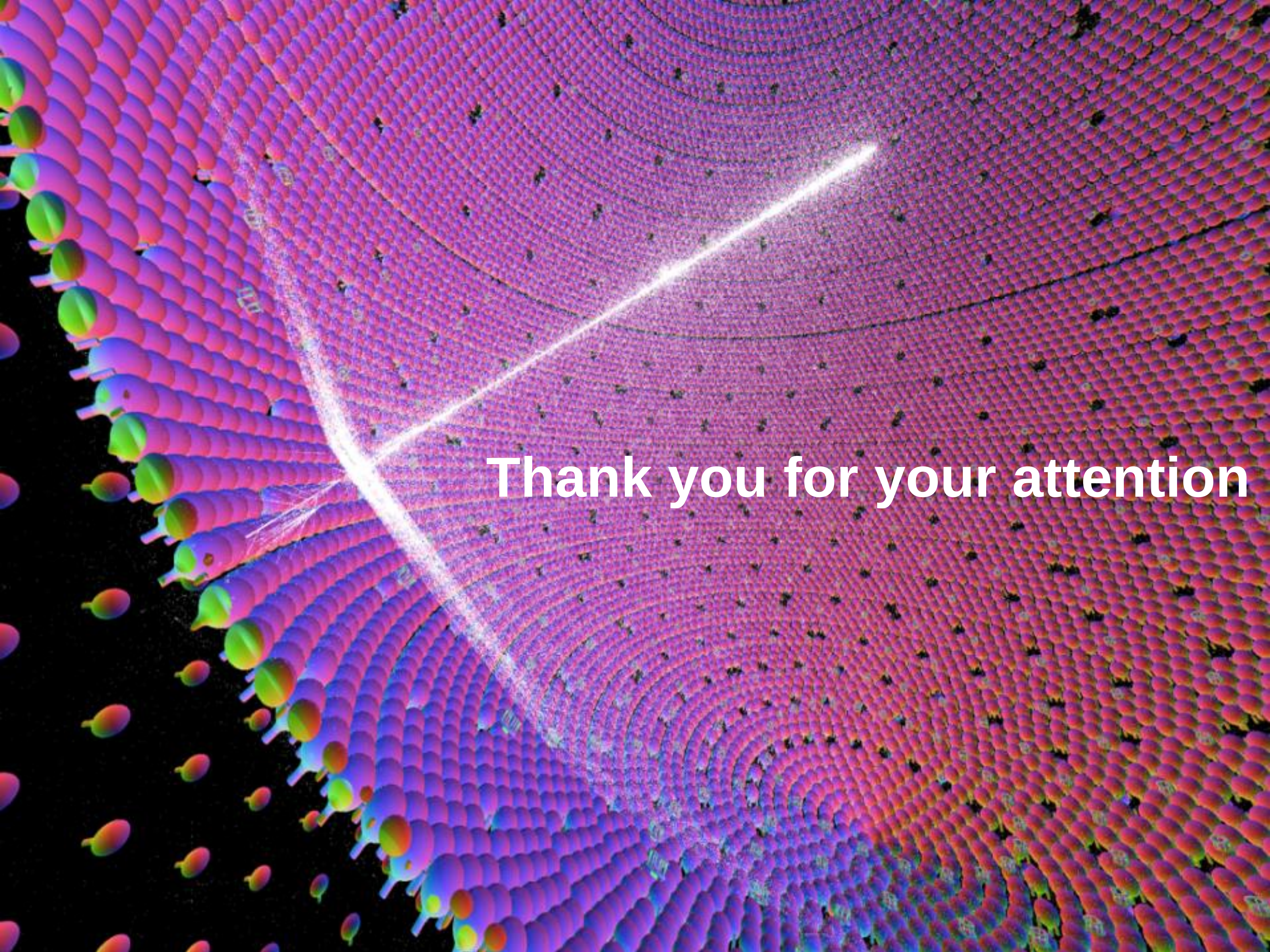
# Summary and conclusions

- JUNO is a next generation experiment with a rich programme in neutrino physics and astrophysics

- Thanks to a large size (20 ktons, 35 m) and an unprecedent energy resolution of 3%/√E(MeV), JUNO will address many neutrino features:
  - ✓ Mass hierarchy determination at 3σ level with JUNO only
  - ✓ First simultaneous measurement of 4 oscillation paramaters along multiple oscillation periods
  - ✓ Precise oscillation parameter measurement below 1% level for $\Delta m^2_{21}$, $\sin^2(2\theta_{12})$ and $\Delta m^2_{31}$
  - ✓ Other exciting neutrino physics : Supernova neutrinos, geoneutrinos and solar neutrinos (and proton decay search)

- Need a precise understanding of the detector response and energy scale
  - ✓ 2 systems of photodetection (LPMT+SPMT) for a stereo calorimetry
  - ✓ JUNO energy calibration strategy with complementary systems
  - ✓ TAO reference detector looking at fine structures in reactor energy spectrum

- Project well along the realization path and expected data taking in 2021 !



# Thank you for your attention