PONTIFICIA
UNIVERSIDAD
CATÓLICA
DE CHILE

JUNO: Next Generation Reactor Neutrino Experiment

Yury Malyshkin on behalf of the JUNO collaboration

HEP2016, Valparaiso,
January 9, 2016

Neutrino Flavor Mixing

3 flavor eigenstates:

$|\nu_e\rangle,\ |\nu_\mu\rangle,\ |\nu_\tau\rangle$

3 mass eigenstates:

$|\nu_1\rangle,\ |\nu_2\rangle,\ |\nu_3\rangle$

They mix:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

The mixing matrix can be expressed as following:

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

$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$

$P_\nu = \mathrm{Diag}\{e^{i\rho}e^{i\sigma}, 1\}$ – Majorana phase matrix

Transition probability

Neutrino mixing leads to oscillation between different flavors:

$$P_{\alpha\to\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

or

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha i} U^*_{\beta j}) \sin^2(\frac{\Delta m^2_{ij} L}{4E})$$

$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha i} U^*_{\beta j}) \sin(\frac{\Delta m^2_{ij} L}{2E})$$

where $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$

Example: $\overline{\nu}_e$ Survival Probability

Using the 'sin' and 'cos' parametrization electron anti-neutrino survival probability formula can be written as:

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \underbrace{\frac{\Delta m_{21}^2 L}{4E}} - \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \underbrace{\frac{\Delta m_{31}^2 L}{4E}} + s_{12}^2 \sin^2 \underbrace{\frac{\Delta m_{32}^2 L}{4E}} \right]$$

oscillation phases
in *L/E* space

'Frequencies' of oscillations:

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

$$\Delta m_{31}^2 \simeq \Delta m_{32}^2 \equiv m_3^2 - m_2^2$$

'Amplitudes' of oscillations are driven by mixing angles θ_{12} and θ_{13}

Neutrino Oscillations Parameters

In the standard 3-flavor framework there 6 independent parameters:

Parameter	Value		Uncertainty
	NH	IH	
$\sin^2 2\theta_{12}$	0.846		2.5%
$\sin^2 2\theta_{13}$	0.084		6%
θ_{23}	~45º		octant is unknown
Δm^2_{21}	$7.54 \cdot 10^{-5}$ eV^2		2.3%
$\lvert\Delta m^2_{31}\rvert$	$2.47 \cdot 10^{-3}$ eV^2	$2.42 \cdot 10^{-3}$ eV^2	2.5%, sign is unknown
δ	?	?	preference to ~270º

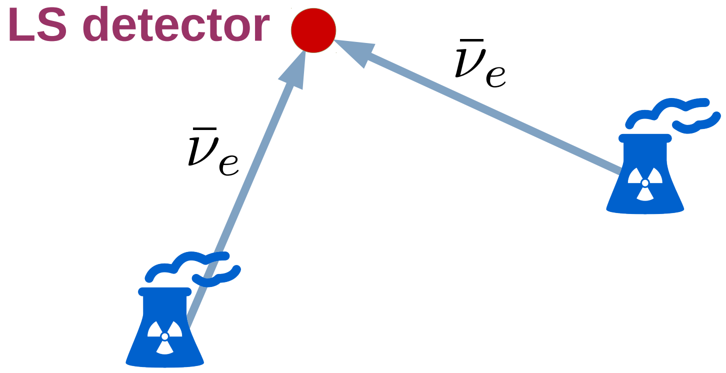
JUNO

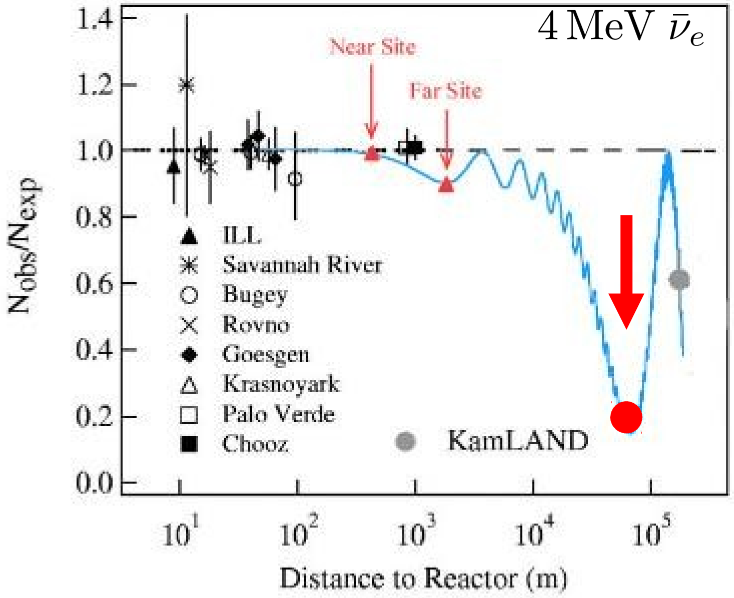
← **<1%**

← **<1%**

← **sign**

JUNO Layout





- **Source:** 6+4 reactors (Yangjiang and Taishan NPP, under construction)
- **Baseline:** 53 km
- **Detection channel:** inverse β-decay

  $$\bar{\nu}_e + p \rightarrow e^+ + n$$
- **Target:** single volume 20-kt liquid scintillator
- **Detection technique:** system of photomultiplier tubes (PMTs) (17k 20" PMTs + 17-35k 3" PMTs)
- **Overburden:** 700 m

JUNO Location

N 22°07’05”, E 112°31’05”
Jinji town, Kaiping city,
Jiangmen city, Guangdong province

Neutrino Detection

Reactor neutrinos will be detected, like in Daya Bay and other reactor antineutrino experiments, through the inverse beta-decay (IBD) reaction and subsequent neutron capture:

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

$$\tau \simeq 200\mu\text{sec} \longrightarrow n + p \to d + \gamma$$

Then neutrino energy:

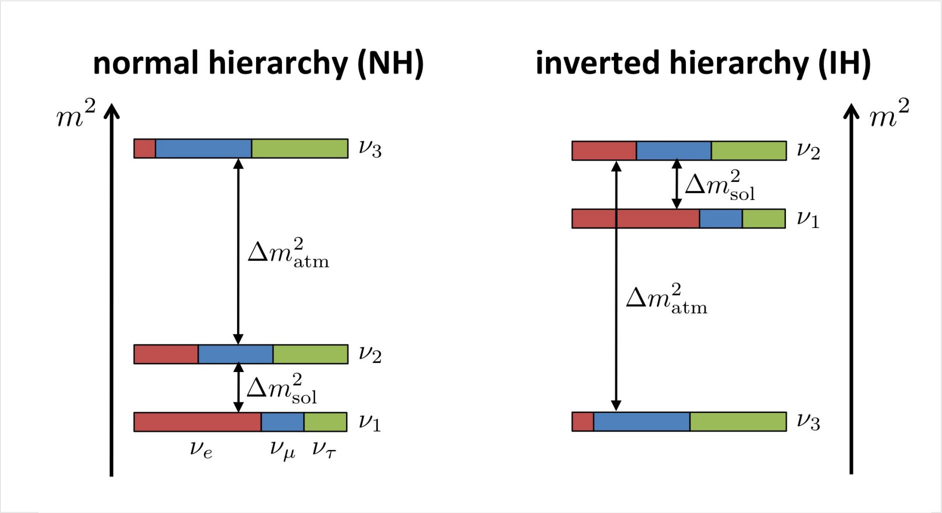
$$E_{\bar{\nu}_e} \cong E_{e^+} + \underbrace{E_n}_{\text{30-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV}}$$

Goals

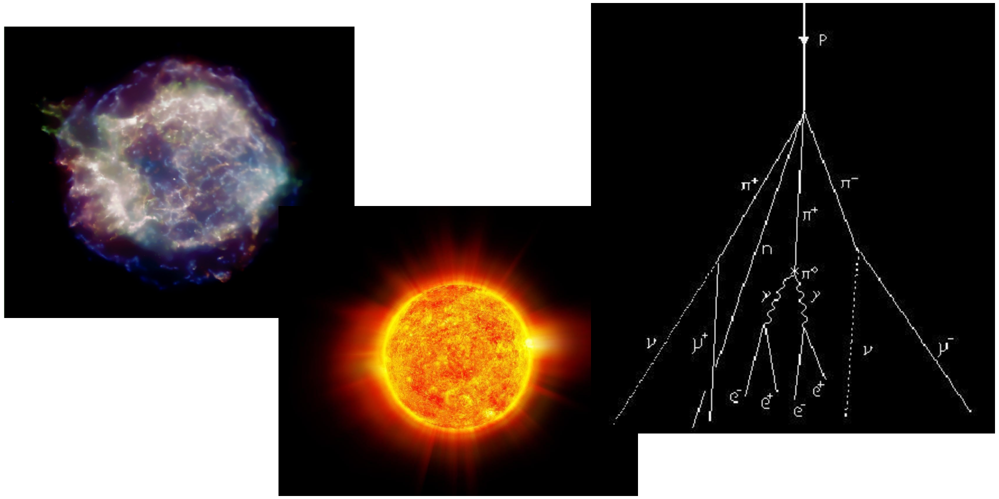
- **Mass hierarchy** (main goal)
- <1% precision of
  - **$\sin^2\theta_{12}$,**
  - **Δm^2_{ee}**
  - **Δm^2_{21}**

helps to check unitarity of the PMNS matrix:

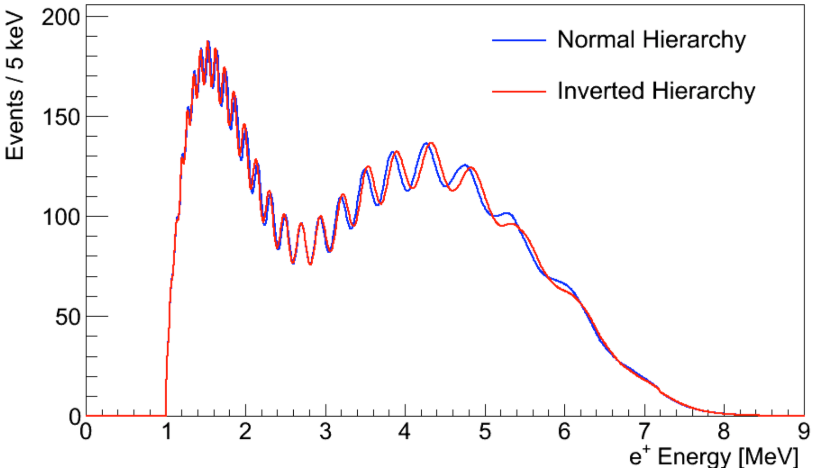
$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 \overset{?}{=} 1$$

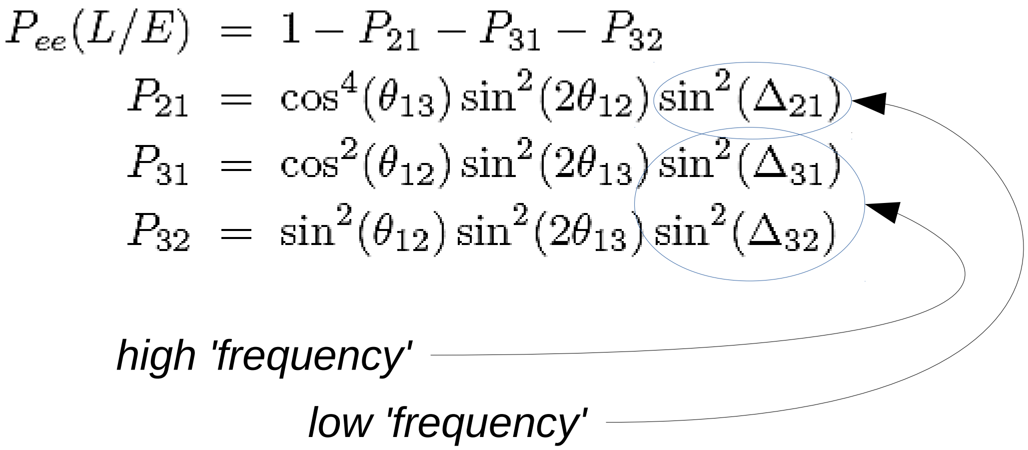


- Other aspects:
  - Supernova neutrinos
  - Diffused supernova neutrinos
  - Solar neutrinos
  - Atmospheric neutrinos
  - Geo-neutrinos
  - Proton decay ($p \rightarrow K^+ + \bar{\nu}$):
    $\tau > 1.9 \times 10^{34}$ yr (90% C.L.)



Method of resolving MH



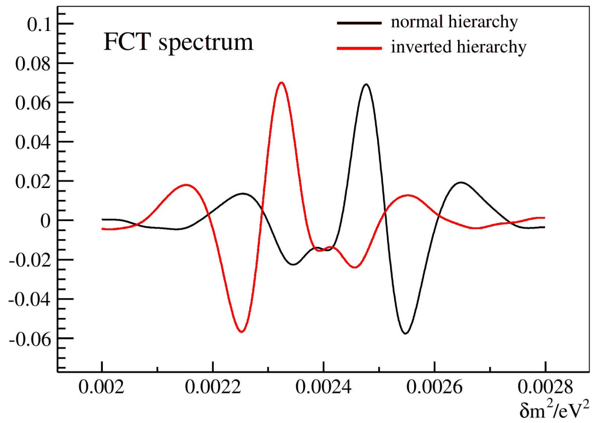


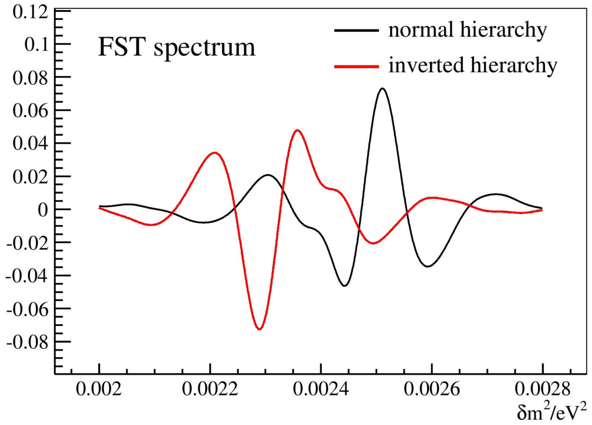
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

high 'frequency'

low 'frequency'

Fourier transformation:





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

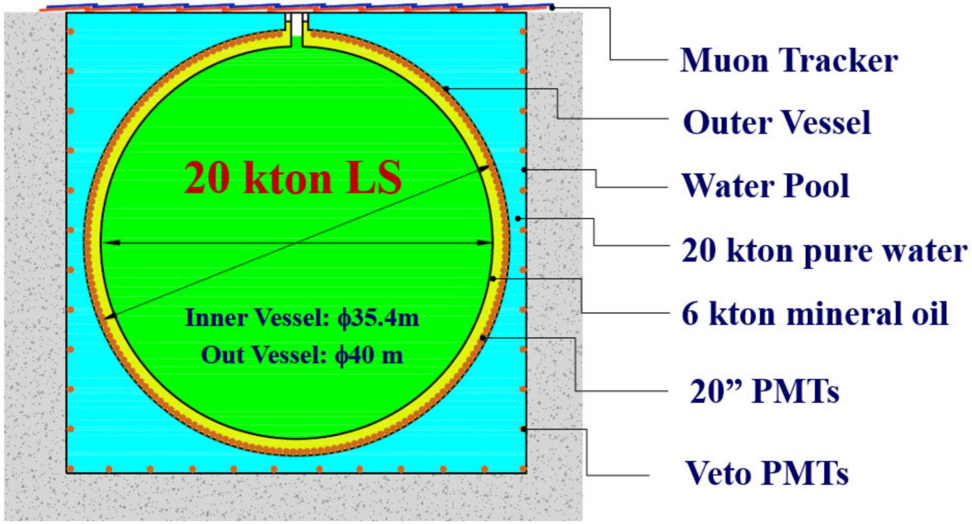
$$\mathrm{FST}(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t)\mathrm{d}t$$

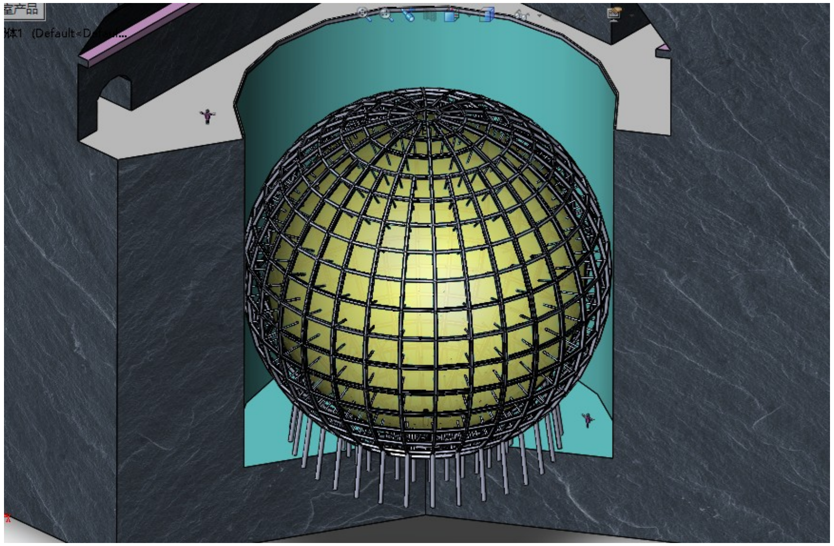
$$\omega = 2.54 \times \Delta m^2_{ij} \;\; - \;\; \text{frequency}$$

$$t = L/E : \; [L/E_{max}, L/E_{min}]$$

Detector design

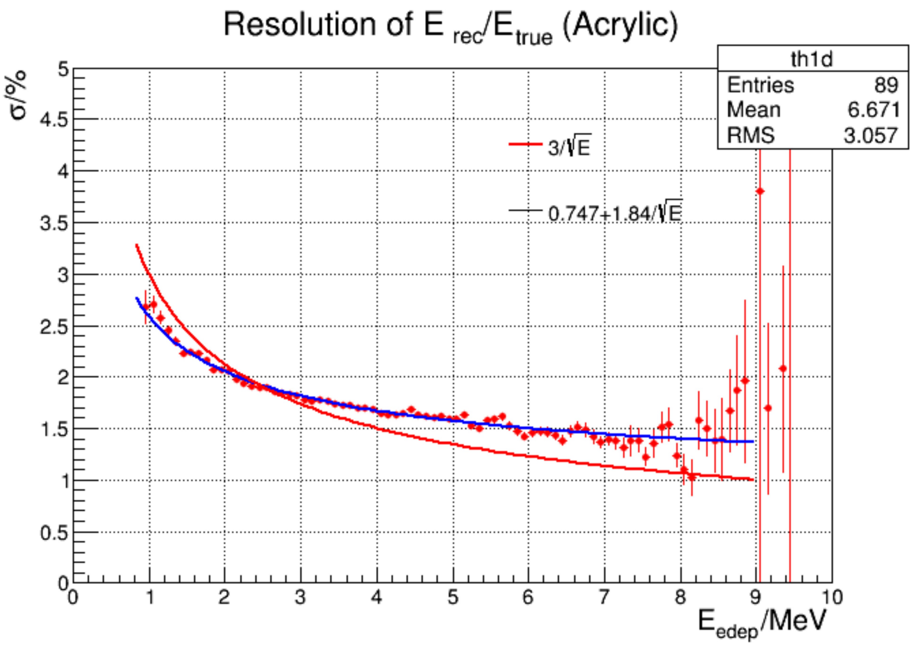
- **Liquid scintillator central detector**
  - Big mass (20 kt)
  - High purity (>20 m att. length)
  - High luminosity (1200 p.e/MeV)
- **PMTs**
  - 17k 20" **+** 17-35k 3" (optional)
  - High photo-cathode coverage (75-80%)
  - High detection efficiency (QE 35%)
- ***μ* veto** (0.0031 Hz/m^2)
  - Top tracker (plastic scintillator)
  - Water Cherenkov with 2k PMTs





How to reach 3% energy resolution

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



Noise

- keep the noise as low as possible (clean materials and quiet PMTs)

Photon statistics

- high light yield scintillator
- high photocathode coverage
- high detection efficiency PMTs

Energy leakage

Non-uniformity

- keep detector as uniform is possible (spherical geometry)

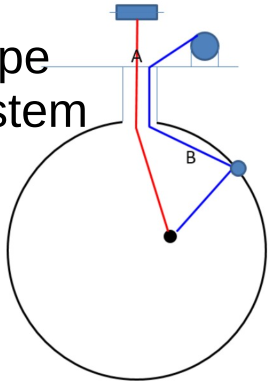
JUNO – an ambitious project

	Daya Bay	BOREXINO	KamLAND	**RENO-50**	**JUNO**
Target Mass	20t	~300t	**~1kt**	**~18kt**	**~20kt**
PE Collection	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	**>1000 PE/MeV**	**~1200 PE/MeV**
Photocathode Coverage	~12%	**~34%**	**~34%**	**~67%**	**~80%**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**3%/√E**	**3%/√E**
Energy Calibration	~1.5%	**~1%**	~2%	**?**	**<1%**

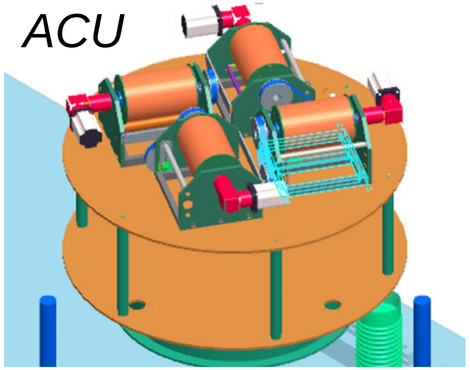
Calibration: < 1% energy scale unc.

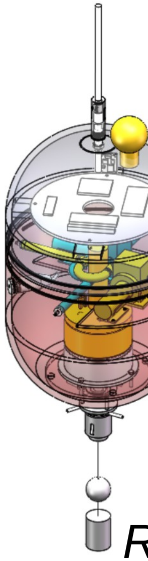
- Automated calibration unit (ACU) – vertical scan
- Rope system – off-center access
- Remotely operated under-liquid-scintillator vehicles (ROV) – 4*π* coverage
- A pelletron system which can provide mono-energetic positron beams
- Guide tubes along the surface – boundary effects
- A diffuse system that can introduce short-lived radioactive isotopes into the central detector.

Rope system



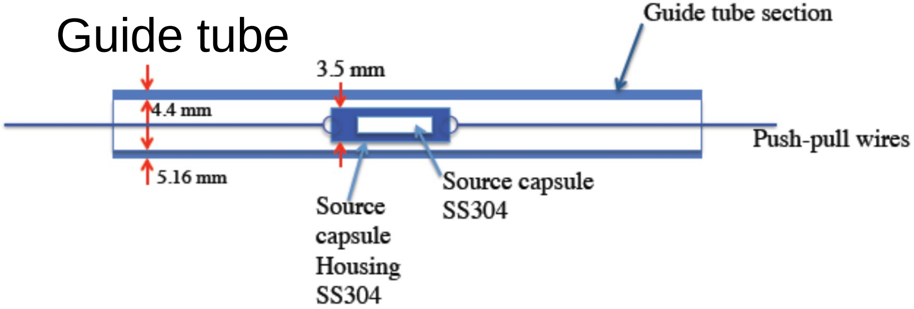
ACU





ROV

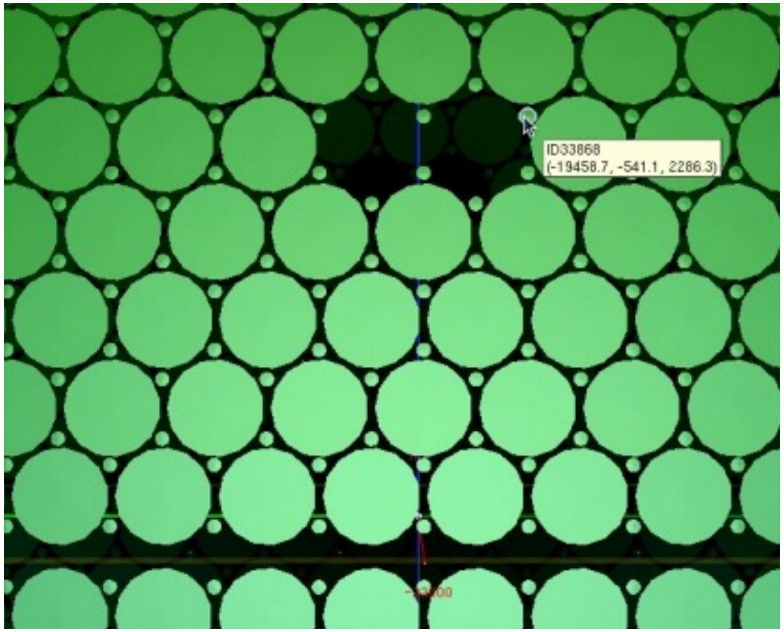
Guide tube



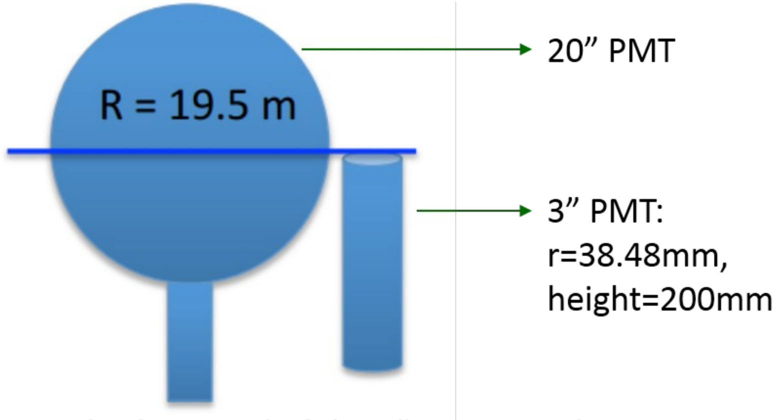
PMT system (LPMT+SPMT)

Two subsystems:

Large PMTs (20") + Small PMTs (3")



SPMTs are in the gaps between LPMTs



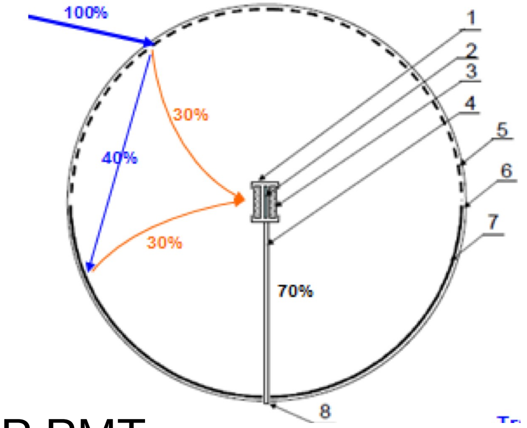
The front end of the 3” PMT is in the same plane as the equatorial plane of 20” PMT

LPMT and SPMT complement each other

Large PMTs

Major photo-cathode coverage (75-80%) – the most statistics

Requirements:
- quantum efficiency 30% @ 420 nm, 35% @ 390 nm
- Low noise
- Several ns time characteristics
- …



MCP PMT

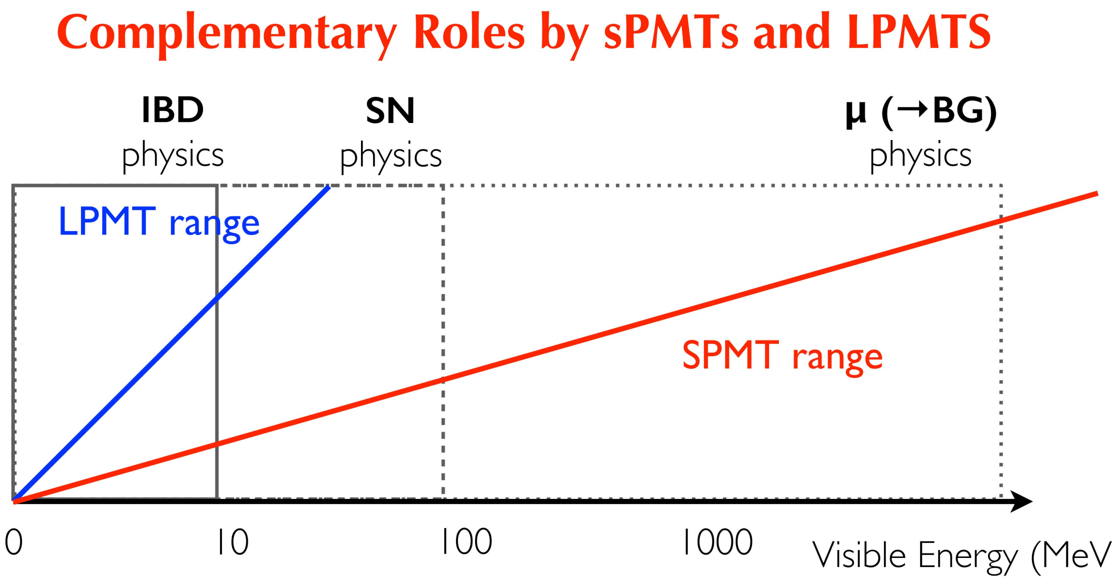
Two options:

1. Micro-channel plate (MCP) PMT – **a new 4π design**
2. New Hamamatsu SBA high QE PMTs

Small PMTs

Advantages:

- Faster time response (< 1 ns)
- Less noisy
- Higher QExCE
- Cheaper than large PMTs

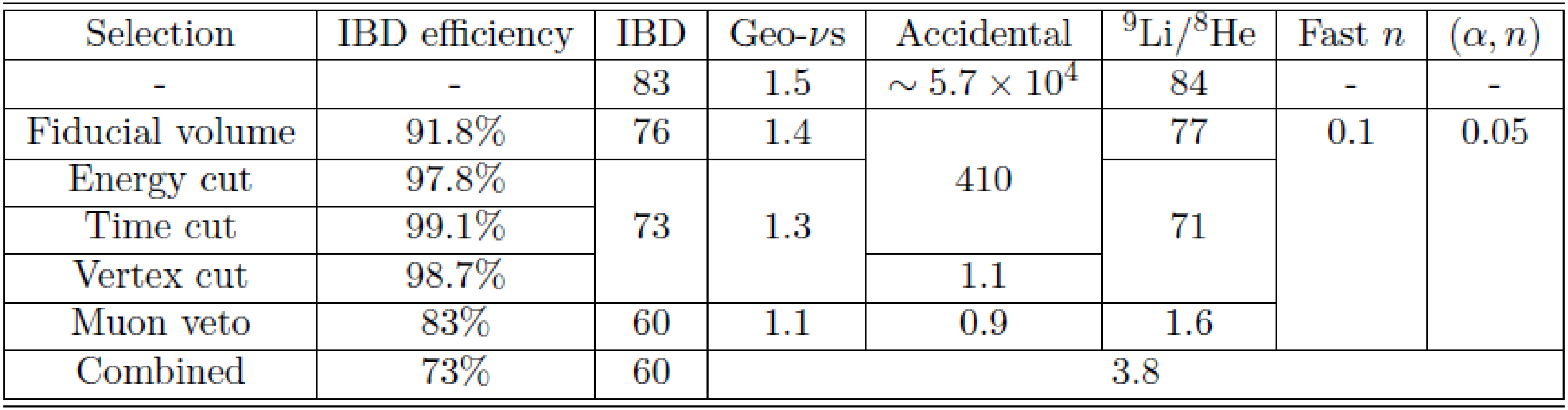


Improvements in comparison with only LPMT system:

- Better muon reconstruction in the central detector
- Increase of dynamic range
- Avoid high rate pile-ups in case of a near supernova
- No negative effects on the main LPMT system

Selection cuts

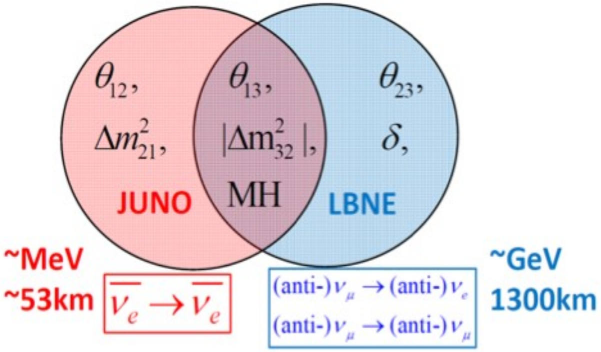
Allow to suppress backgrounds rejecting only a small fraction of the signal:

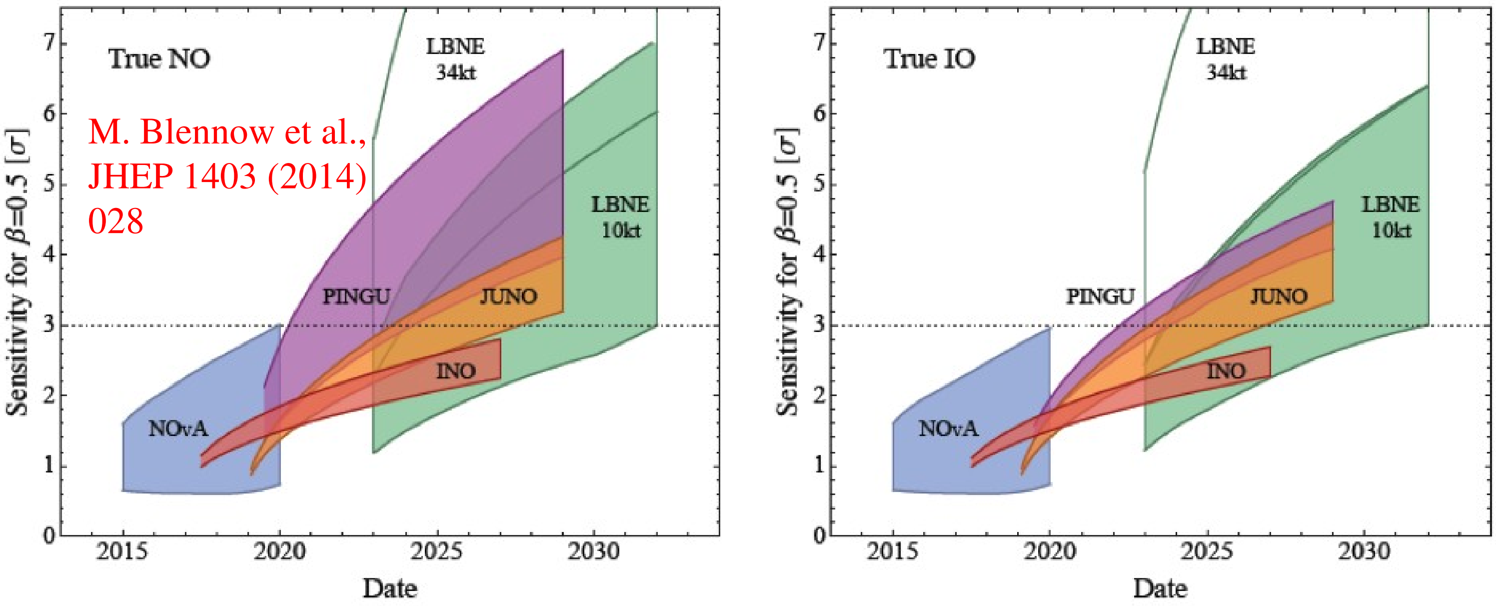


Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

Synergy with other experiments

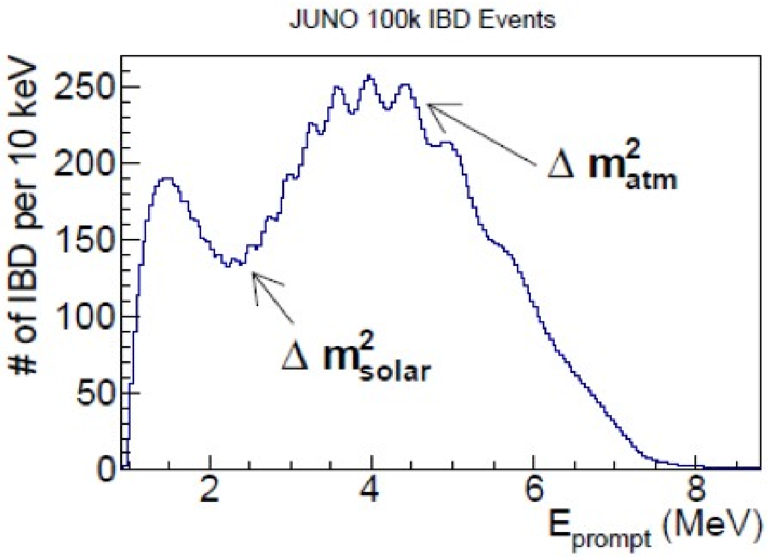
- Atmospheric (INO, PINGU, Hyper-K) and accelerator experiments (NOvA, LBNF/DUNE) all utilize the matter effect to determine the neutrino mass hierarchy.
- JUNO uses a completely different method, from the frequency difference between Δm^2_{32} and Δm^2_{31} through precision measurement of the oscillation frequency.
- The JUNO measurement is independent of θ_{23}, δ_{CP} and the matter effect.




M. Blennow et al., JHEP 1403 (2014) 028

Synergy with other experiments

- Precision measurement of oscillation parameters



	JUNO	DUNE
$\sin^2 2\theta_{12}$	0.7%	
Δm^2_{21}	0.6%	
$\lvert\Delta m^2_{32}\rvert$	0.5%	0.3%
MH	3-4σ*	>5σ
$\sin^2 2\theta_{13}$	14%**	3%
$\sin^2\theta_{23}$		3%
δ_{CP}		10°

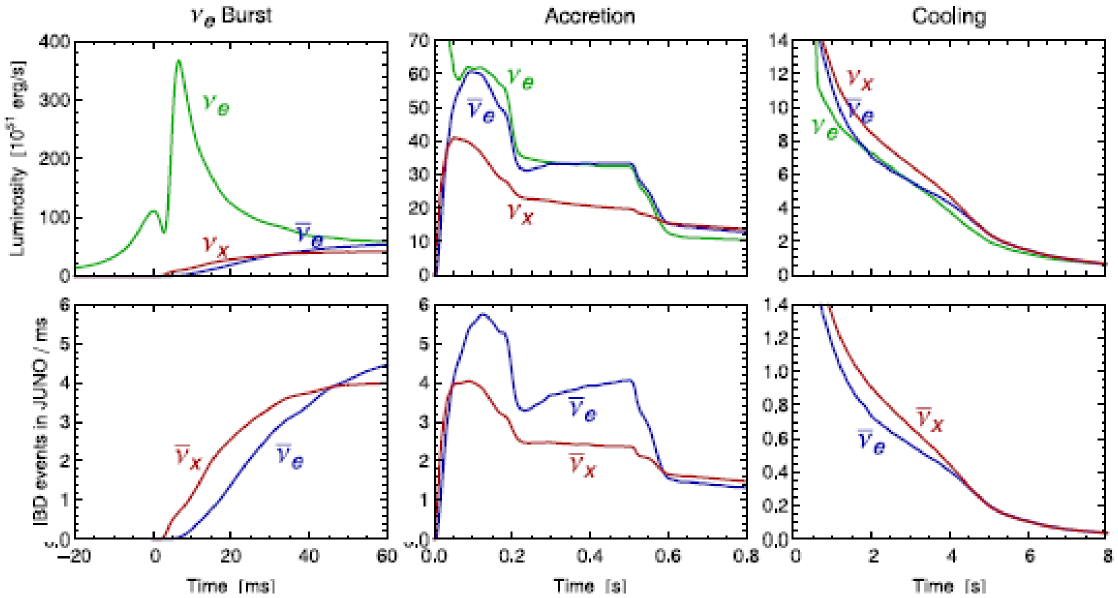
* 4σ requires 1% $\lvert\Delta m^2_{uu}\rvert$ ** Daya Bay reaches 3%

- First experiment to simultaneously observe “solar” and “atmospheric” oscillations
- First experiment to observe more than two cycles of neutrino oscillations
- Complementary to long-baseline accelerator program
- Probing the unitarity of U_{PMNS} to sub-percent level.

Supernova neutrinos

- Large amount of events:
  ~10^4 @ 10 kpc
- Short time:
  ~10 seconds
- Separate detection of ν_e, $\bar{\nu}_e$ and $(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\bar{\nu}_e + p \to e^+ + n$	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
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

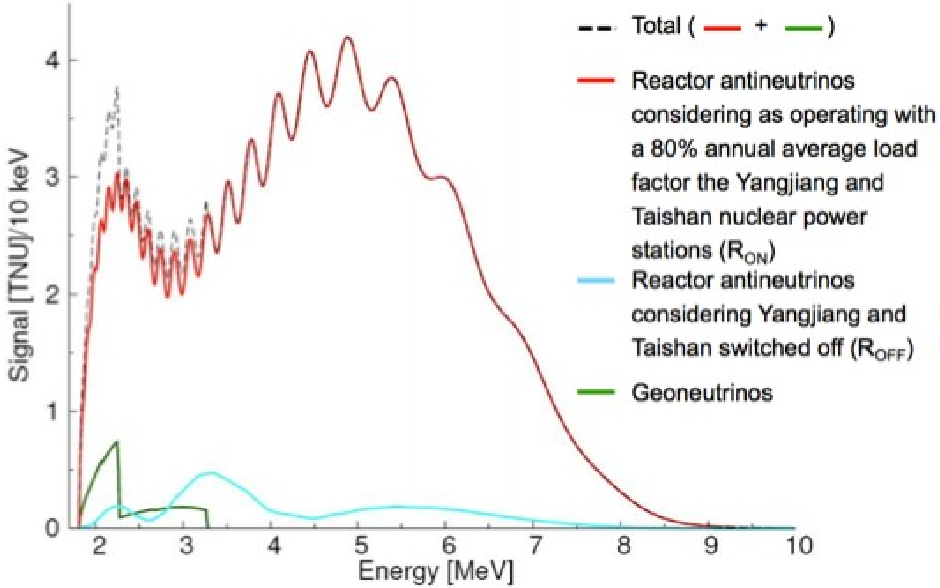


Physical outcomes:

- ν mass: < 0.83±0.24 eV
  at 95% CL [arXiv:1412.7418]
- Locating the SN: ~9°
- Pre-SN ν (> 1 day)
- SN nucleosynthesis via ν_x spectra
- Collective ν oscillation
- Mass hierarchy

Geoneutrinos

- Current results
  - KamLAND: 30±7 TNU [*PRD 88 (2013) 033001*]
  - Borexino: 38.8±12.2 TNU [*PLB 722 (2013) 295*]
    (Statistics dominant)
- Desire to reach an error of 3 TNU
- JUNO: x20 statistics
  - Huge reactor neutrino backgrounds
  - Need accurate reactor spectra



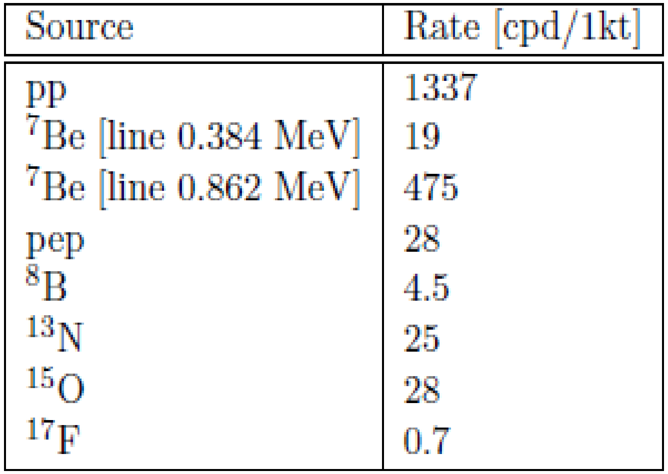
[V. Strati et al., Progress in Earth and Planetary Science 2, 1-7, (2015)]

Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$	18.2 ± 9.1
Accidental coincidences	401 ± 4

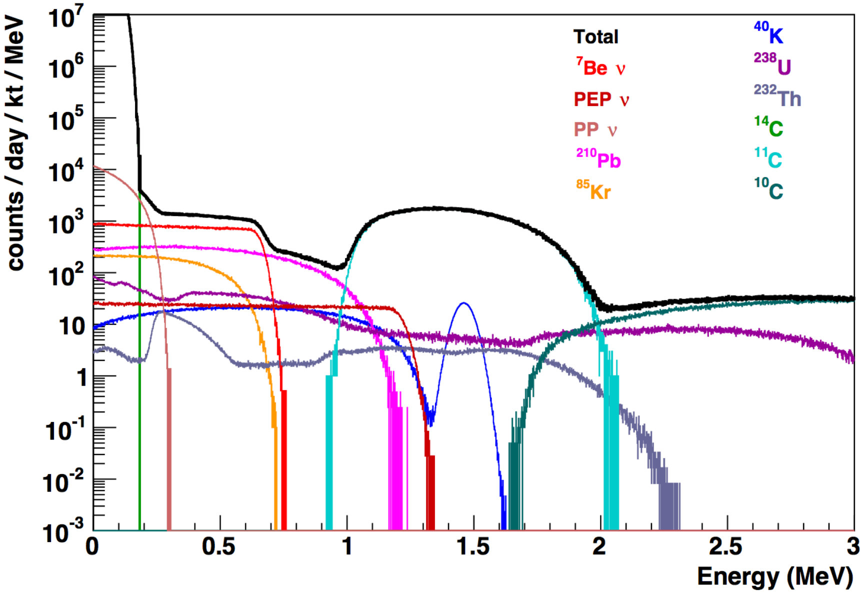
[arXiv:1510.01523]

Solar neutrinos

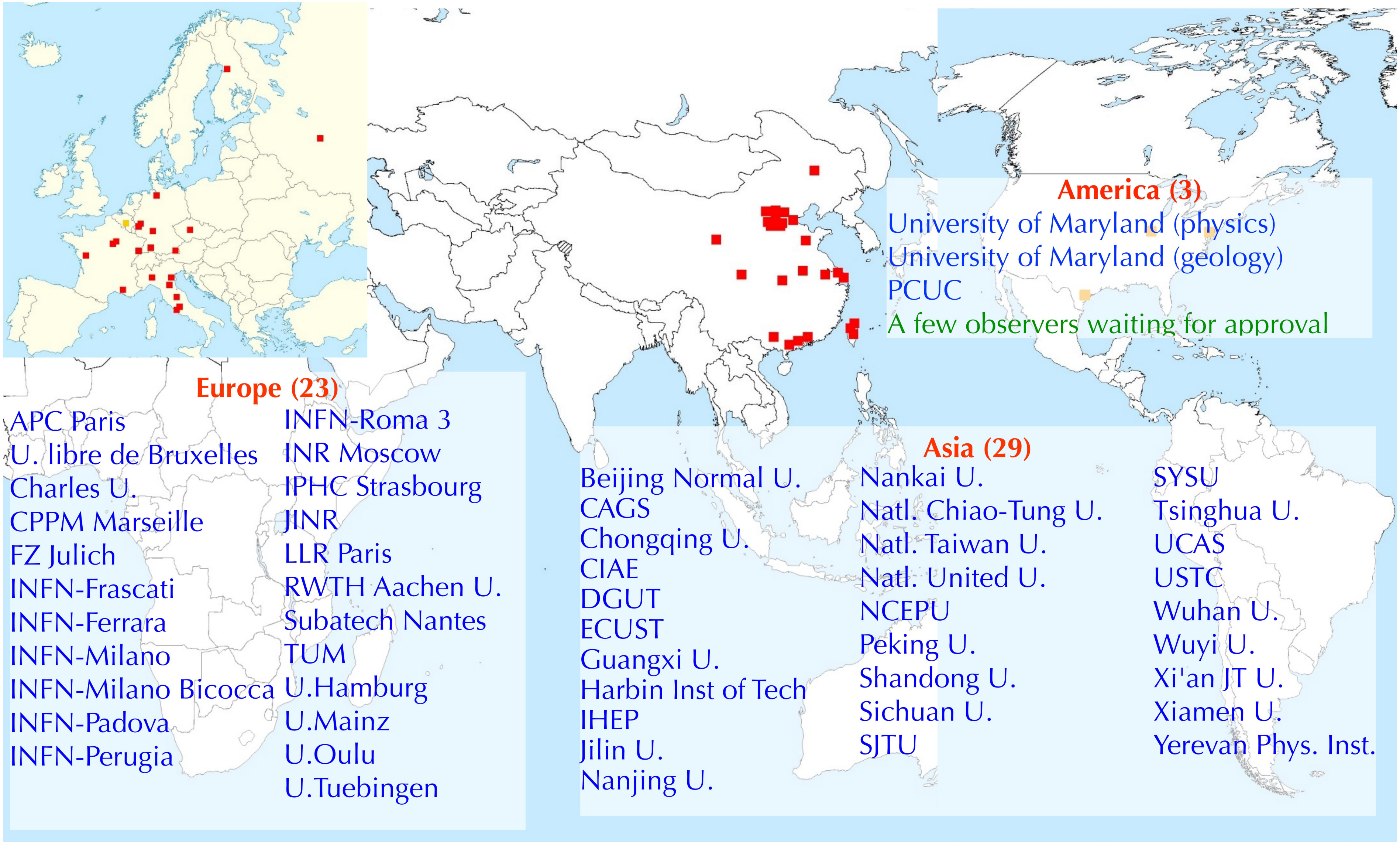
- Detection of solar neutrinos of all flavors through electron scattering
- Low level of intrinsic background is required
- Better understanding solar model:
  - Metallicity (discrimination of high and low Z version of the Solar Model)
  - ^{7}Be and ^{8}Be spectra



Source	Rate [cpd/1kt]
pp	1337
^{7}Be [line 0.384 MeV]	19
^{7}Be [line 0.862 MeV]	475
pep	28
^{8}B	4.5
^{13}N	25
^{15}O	28
^{17}F	0.7



Collaboration



America (3)

University of Maryland (physics)
University of Maryland (geology)
PCUC
A few observers waiting for approval

Europe (23)

APC Paris
U. libre de Bruxelles
Charles U.
CPPM Marseille
FZ Julich
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Milano Bicocca
INFN-Padova
INFN-Perugia
INFN-Roma 3
INR Moscow
IPHC Strasbourg
JINR
LLR Paris
RWTH Aachen U.
Subatech Nantes
TUM
U.Hamburg
U.Mainz
U.Oulu
U.Tuebingen

Asia (29)

Beijing Normal U.
CAGS
Chongqing U.
CIAE
DGUT
ECUST
Guangxi U.
Harbin Inst of Tech
IHEP
Jilin U.
Nanjing U.
Nankai U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
NCEPU
Peking U.
Shandong U.
Sichuan U.
SJTU
SYSU
Tsinghua U.
UCAS
USTC
Wuhan U.
Wuyi U.
Xi'an JT U.
Xiamen U.
Yerevan Phys. Inst.

Schedule

2013 – Funding approved

2014 – Collaboration officially formed

now

2015-2017 – Civil construction

2016-2017 – Detector component production

2016-2019 – PMT production

2018-2019 – Detector assembly and installation

2020 – Filling

2020 – Start of data taking

Summary

Detector of new generation

- Single volume 20-kt liquid scintillator
- High transparency: 20 m attenuation length
- High luminosity: 1200 p.e./MeV
- 3% energy resolution
- < 1% energy scale uncertainty

Rich physics program:

- Resolving mass hierarchy
- < 1% precision measurements of $\sin^2\theta_{12}$, Δm^2_{ee} and Δm^2_{21}
- SN, solar, atmospheric, geo-neutrinos and other physics

Start of data taking – 2020