on behalf of the JUNO collaboration

Status and physics of the JUNO experiment

Seminar at Petersburg Nuclear Physics Institute

Smirnov Mikhail

21.01.2020

Questions in neutrino physics

Neutrino nature – Dirac or Majorana

Octant puzzle for θ_{23}

Absolute value of neutrino mass

Unitarity of the mixing matrix

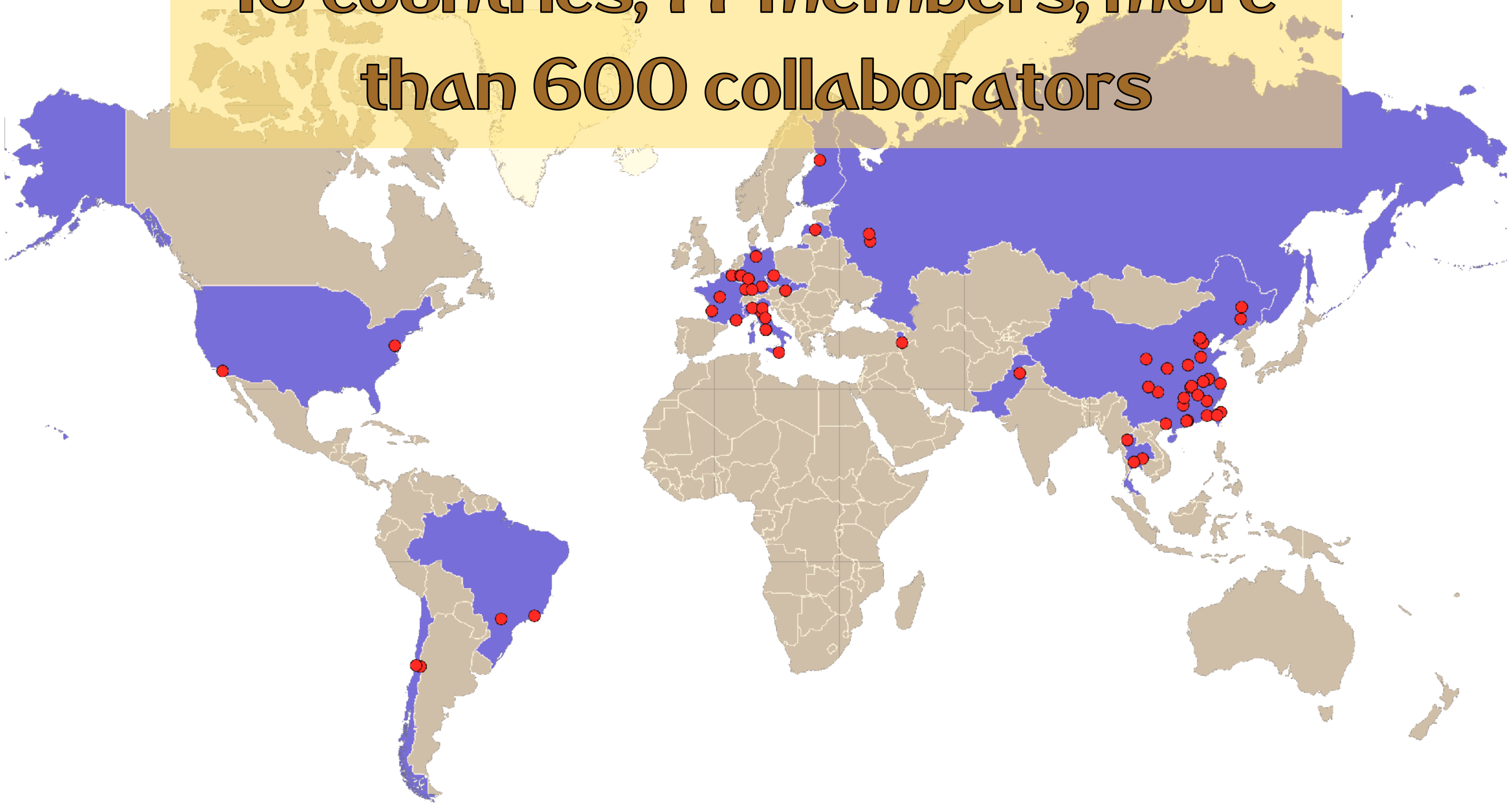
Dirac CP-phase

Mass ordering – normal or inverted

Majorana CP-phases

JUNO collaboration

16 countries, 77 members, more than 600 collaborators

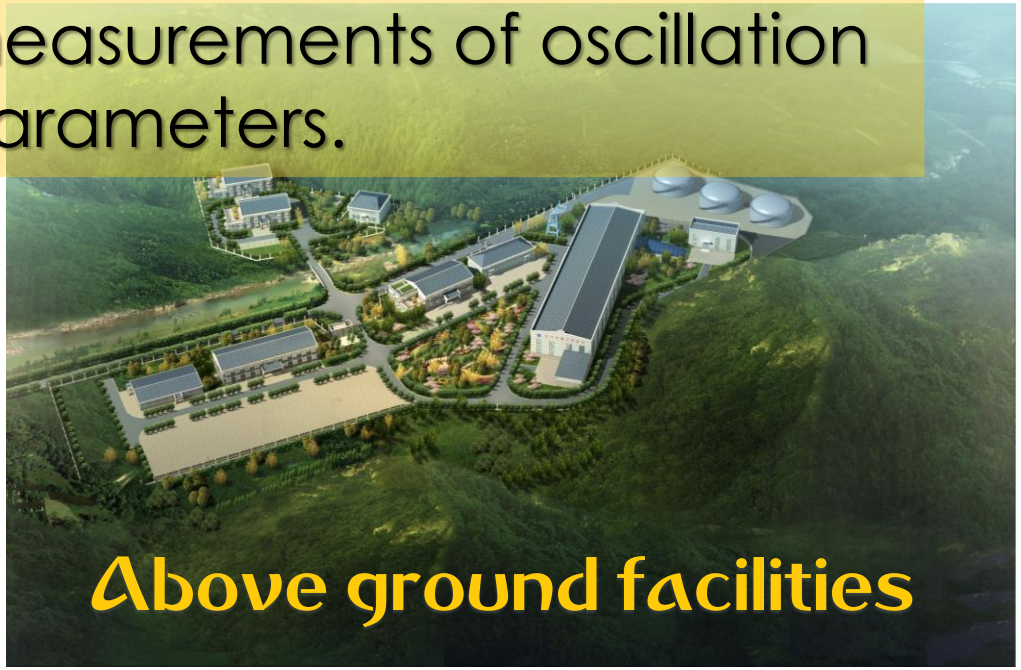


Armenia	1
Belgium	1
Brazil	2
Chile	2
China	34
Czech Republic	1
Finland	1
France	5
Germany	7
Italy	8
Latvia	1
Pakistan	1
Russia	3
Slovakia	1
Taiwan-China	3
Thailand	2
USA	3

JUNO – Jiangmen Underground Neutrino Observatory

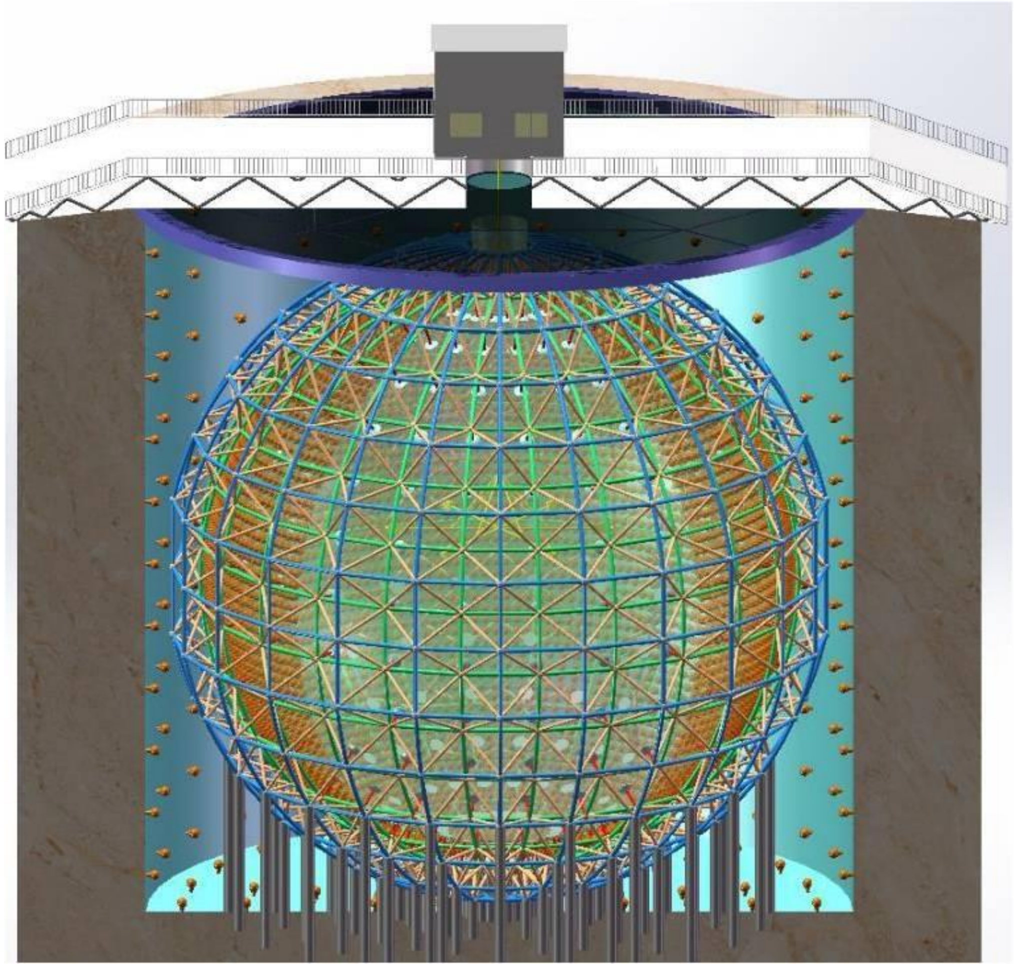
NPP	Power, GW	Status
Taishan	9.2/18.4	Operational
Yangjiang	17.4	Operational

20 kt liquid scintillator (LS) spherical detector. Main goals are mass hierarchy determination and precise measurements of oscillation parameters.



Detector design + veto

JUNO – the largest LS in the world!



Central detector

- Acrylic sphere with diameter 35.4 m
- LS as a target material with mass 20 kt
- PMTs 17.6k 20'' and 25k 3''
- 78% PMT photo coverage
- Energy resolution 3%@1 MeV ~1200 p.e.

Muon water Cherenkov Veto

- Diameter of water pool 43.5 m
- Mass of purified water 35 kt
- 2k 20'' PMTs inside

Top tracker

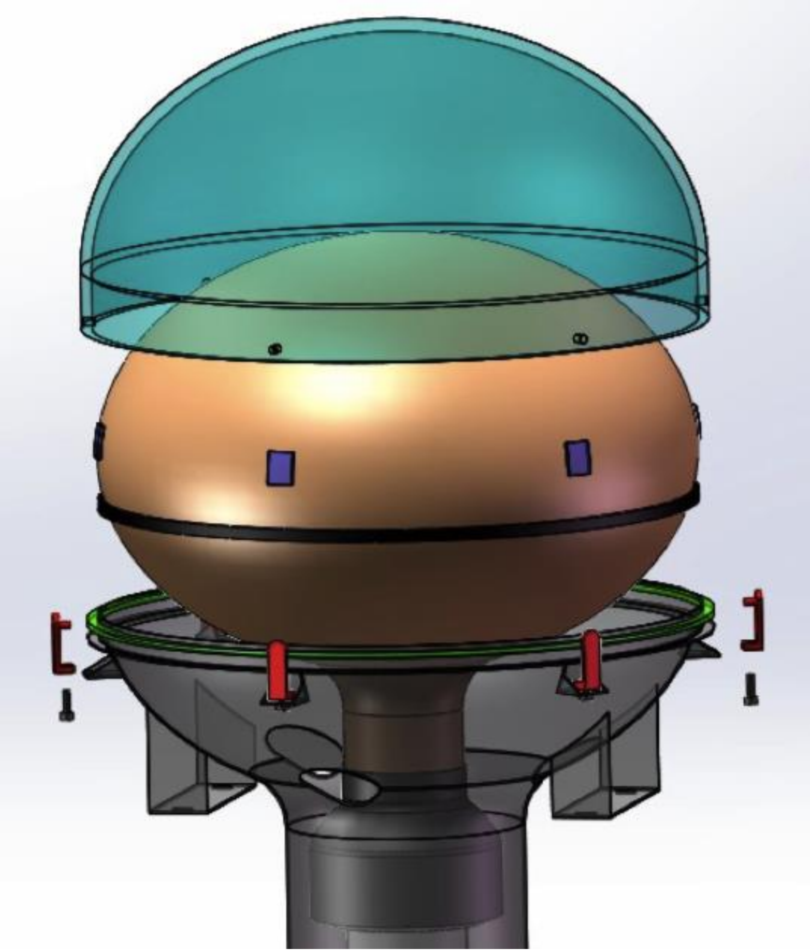
- Three layers of plastic scintillator
- Precise muon tracking

arXiv:1508.07166

Large PMT array

- 15000 MCP-PMTs from NNVT (Northern Night Vision Technology)
- 5000 dynode PMTs from Hamamatsu (R12860 HQE)
- 17571 PMTs will read out the scintillation light of the Central Detector
- In production since 2016
- PMT testing:
  - Finished for dynode PMTs
  - ~10000 of 15000 MCP-PMTs already tested

Specifications	Unit	MCP-PMT (NNVT)	R12860 Hamamatsu HQE
Det. Efficiency (QE*CE)	%	28.3% (**new Type: 30.1%**)	28.1%
Peak to Valley 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	RT~2, FT~12	RT~5, FT~9
Anode Dark Count	kHz	20, (<30)	10, (<50)
After Pulse Rate	%	1, (<2)	10, (<15)
Radioactivity (glass)	ppb	**^{238}U: 50 ^{232}Th: 50 ^{40}K: 20**	^{238}U: 400 ^{232}Th: 400 ^{40}K: 40



Double calorimetry

Energy resolution

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

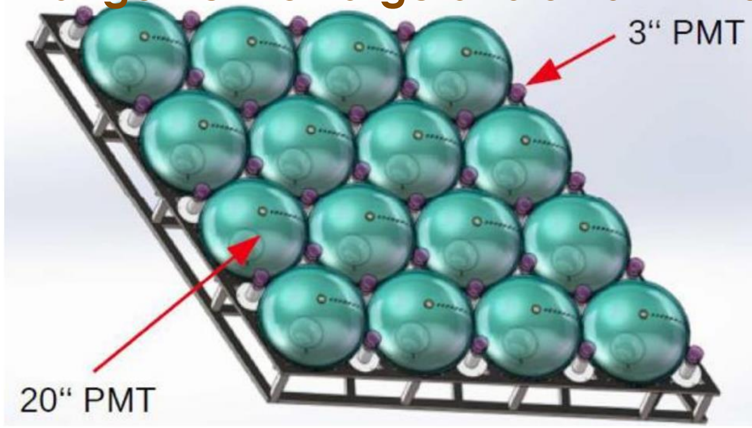
stochastic term: depends on photostatistics

non-stochastic term: residual issues (stability, uniformity, linearity) after calibration

LPMTs use charge integration and provide info about stochastic term

SPMTs use photon counting and provide info about non-stochastic term

Arrangement of large and small PMTs



JUNO custom design: XP72B22

QE 24%, Peak / Valley 3.0, TTS 2-5 ns

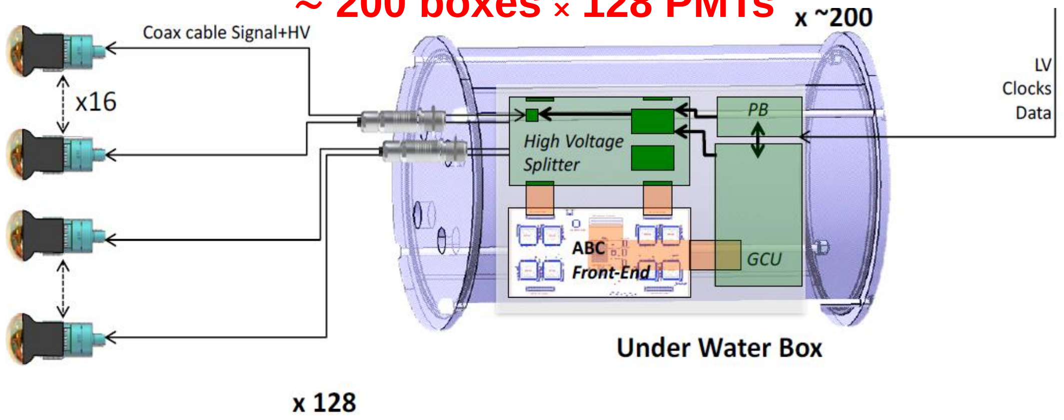
25600 PMTs in the Central Detector

- **2.5% photocoverage**
- Provided by HZC Photonics (Hainan, PR China)

Can effectively help in:

- Muon tracking (+ shower muon calorimetry)
- Supernova measurements
- Independent measurement of solar oscillation parameters

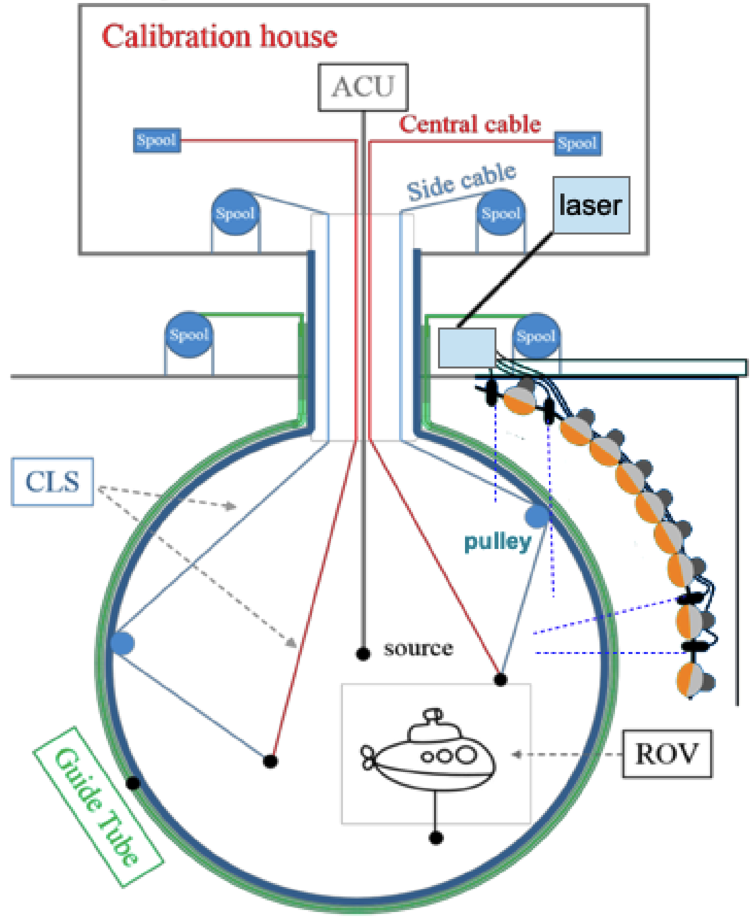
~ 200 boxes × 128 PMTs



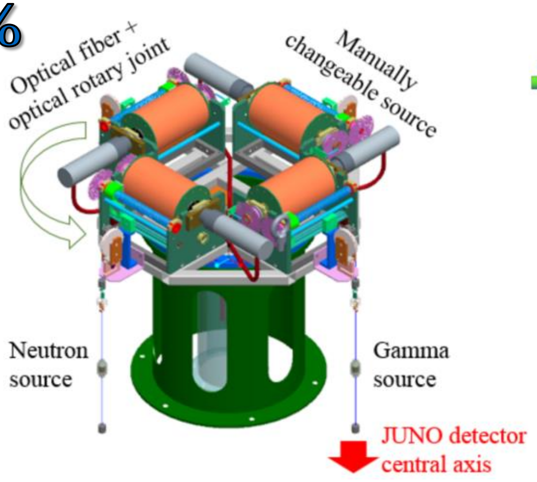
Under water box provides supply for 128 PMTs
(Prototype has already built and successfully tested!)

Calibration systems

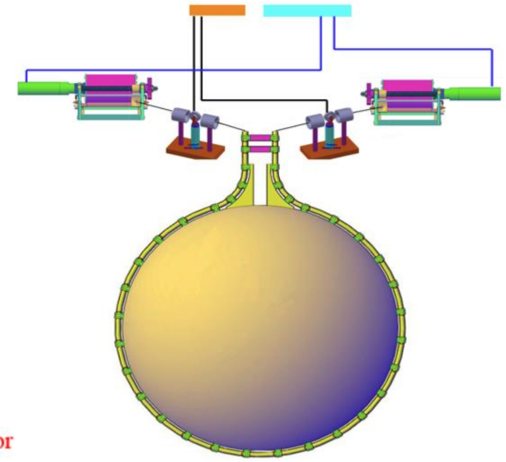
Energy scale error less than 1%

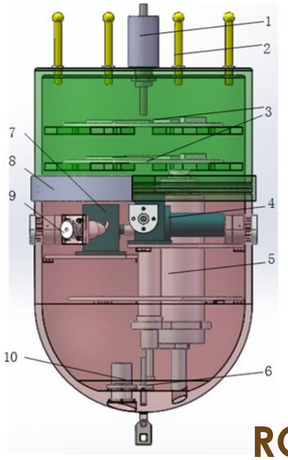


Overview of JUNO's Calibration Systems
(including laser calibration system)

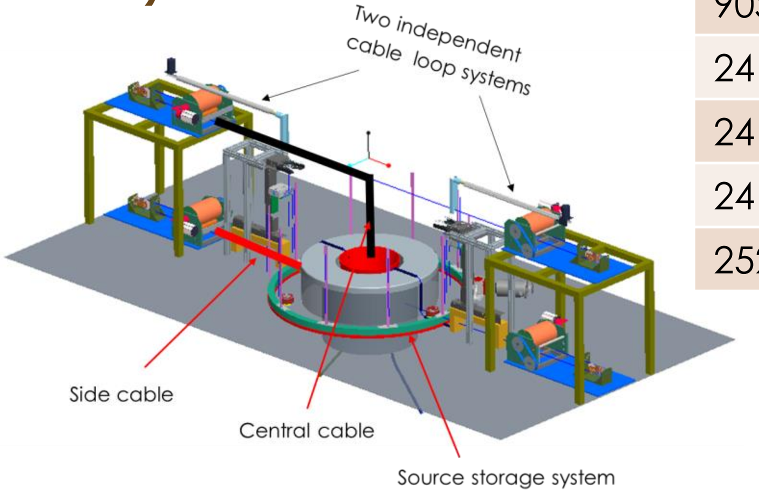


ACU (Automatic Calibration Unit)


Guide Tube System



ROV
(Remotely Operated Vehicle)



Cable Loop System

source	type
40K	γ, e⁻
54Mn	γ
60Co	γ
137Cs	γ
22Na	e⁺
68Ge	e⁺
90Sr	e⁻
241Am-Be	n, γ
241Am-C	n, γ
241Pu-C	n, γ
252Cf	n, γ

Liquid scintillator for JUNO

Requirements for LS

- Low background: $^{238}U < 10^{-15}$ g/g, $^{232}Th < 10^{-15}$ g/g, $^{40}K < 10^{-17}$ g/g
- High light yield: 10^4 PE/MeV
- High transparency: Attenuation length > 20 m for 430 nm

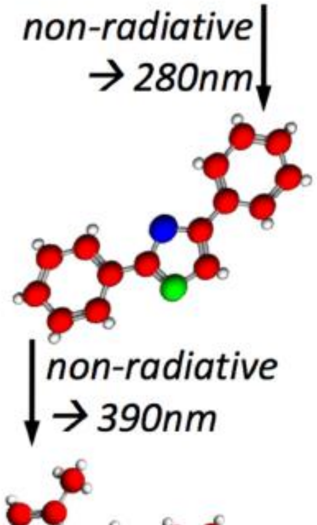
Purification pilot plant

- Distillation: Remove heavy metal and improve transparency
- Al_2O_3 column purification: Remove impurity
- Water extraction: Remove U/Th/K
- Gas stripping: Remove Ar/Kr/Rn
- Use one DayaBay AD for R&D
- 222Rn suppression > 94%

Solvent:
Linear alkylbenzene (LAB) as solvent

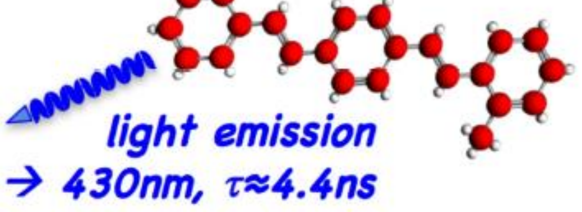
+

Fluor:
2.5 g/l PPO

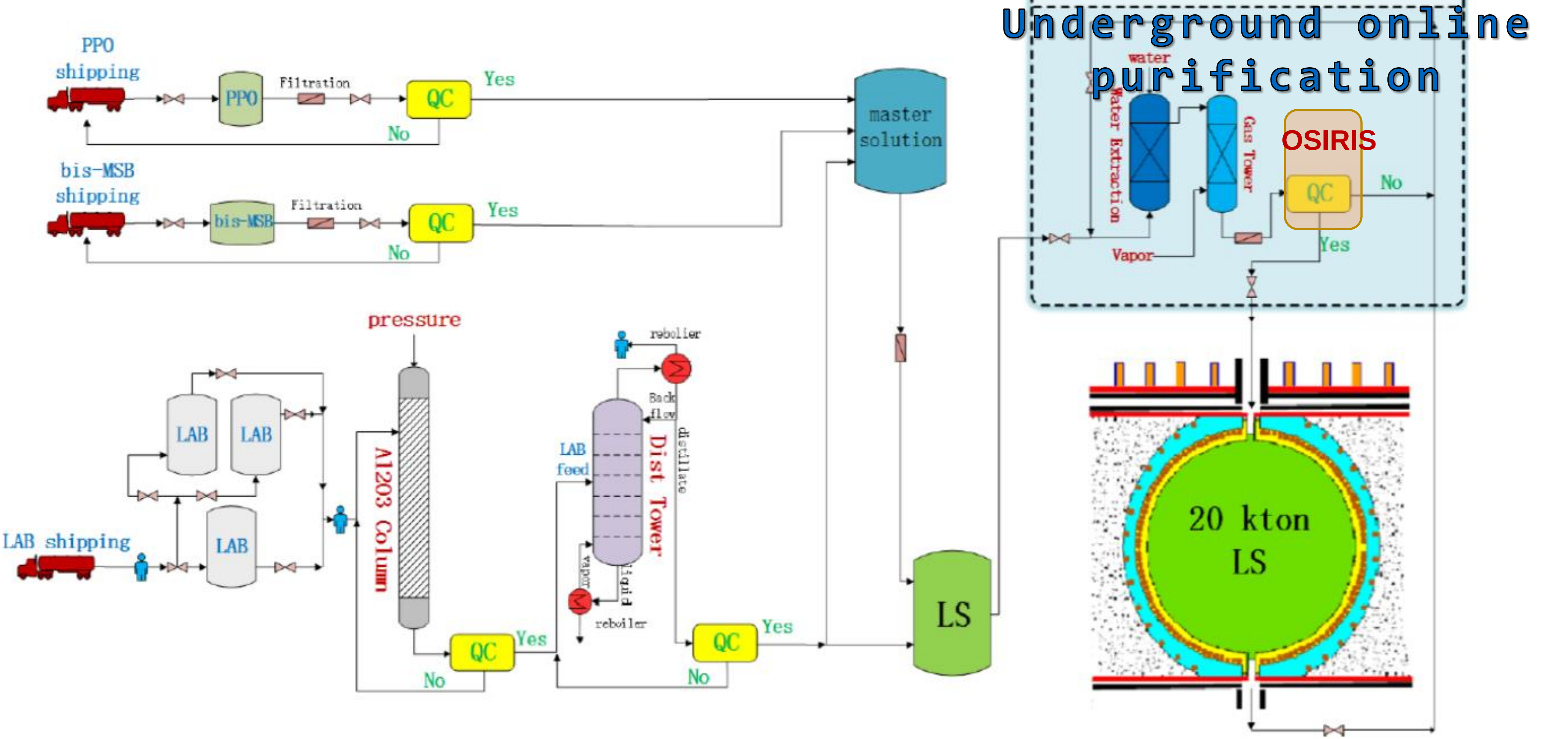


+

Wavelength Shifter:
3 mg/l Bis-MSB



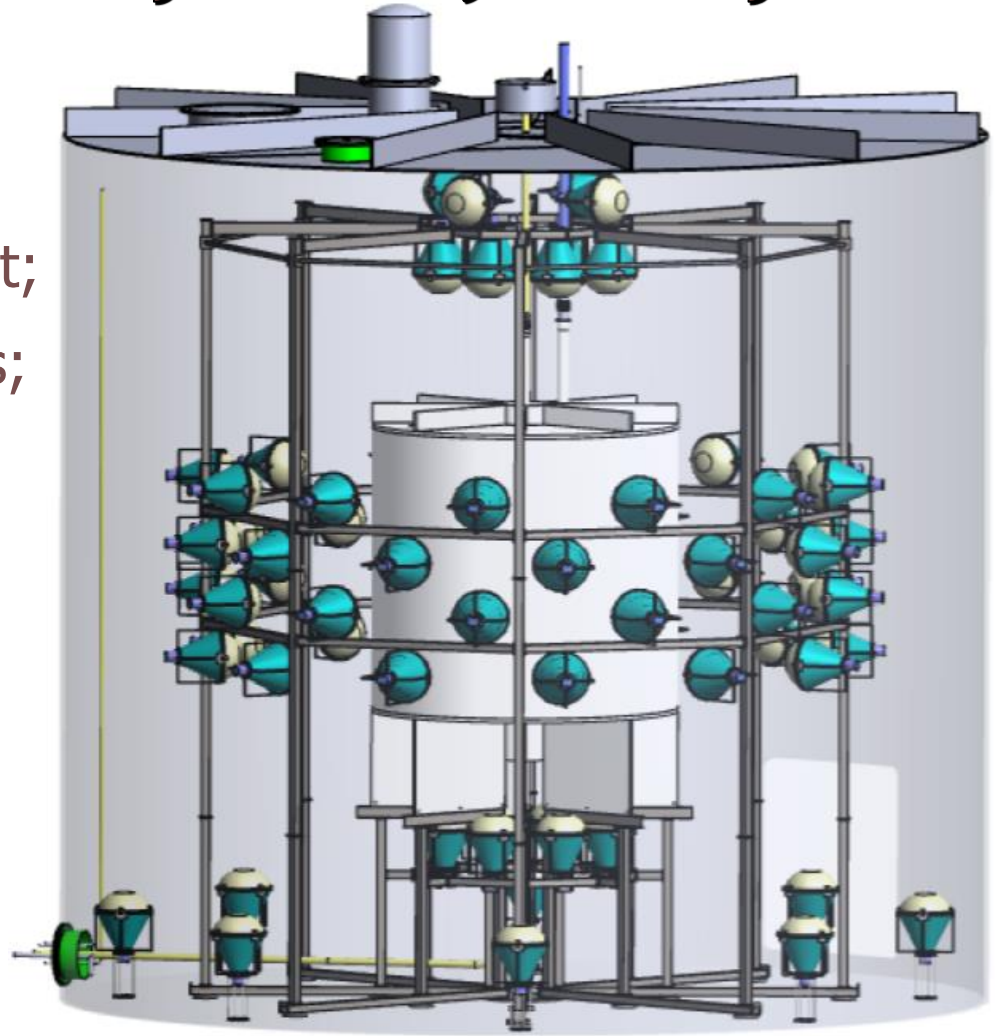
LS purification scheme



OSIRIS

OSIRIS - Online Scintillator Internal Radioactivity Investigation System

- Measure the radioactive contamination of LS before filling into JUNO detector;
- Sensitivity: IBD requirements within 10 h measurement;
- Sensitivity: solar neutrinos within 5 days measurements;
- Measure ~19 t LS per day;
- Detector:
  - Diameter 3 m, height 3 m acrylic tank;
  - 2.5 m water shielding;
  - 81 20″ PMTs for photon detection;
  - 12 20″ PMTs inside water pool for veto.



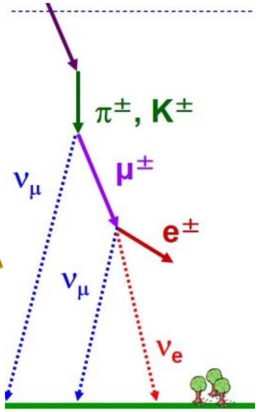
Neutrino physics with JUNO

Solar Neutrino
~10k per day

Supernova
Neutrino (burst)
~5k in 10 s for
10 kpc

Diffuse
Supernova
Neutrino
~3 per year

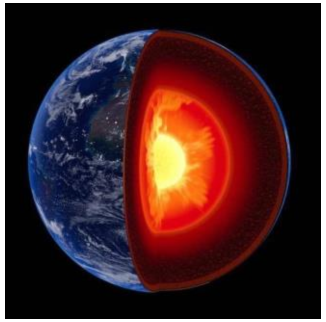
Atmospheric Neutrino
several per day



Cosmic-rays
~250k per day

Reactor Neutrino
~60 per day

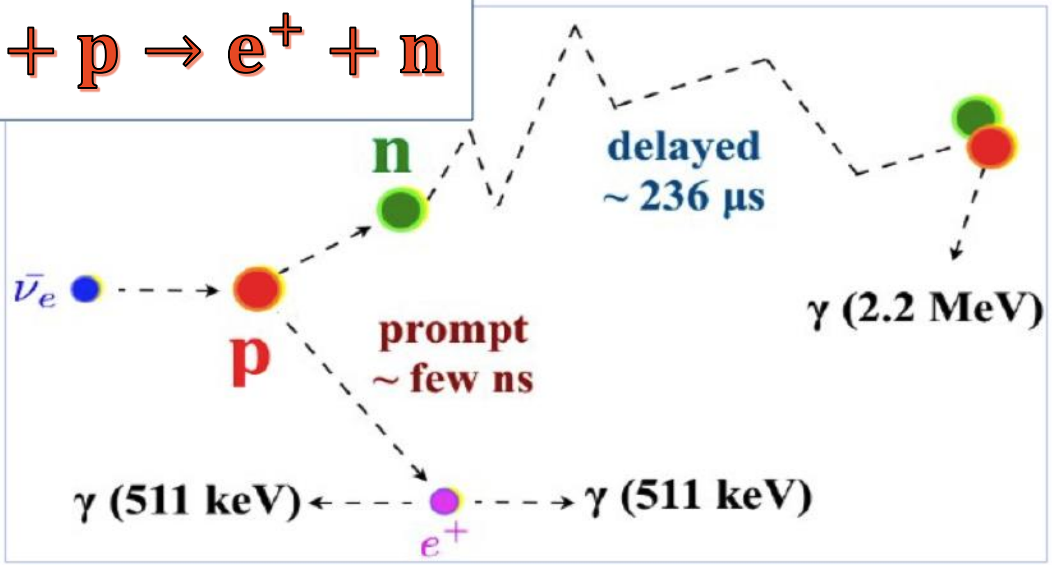
Geo-Neutrino
~1 per day

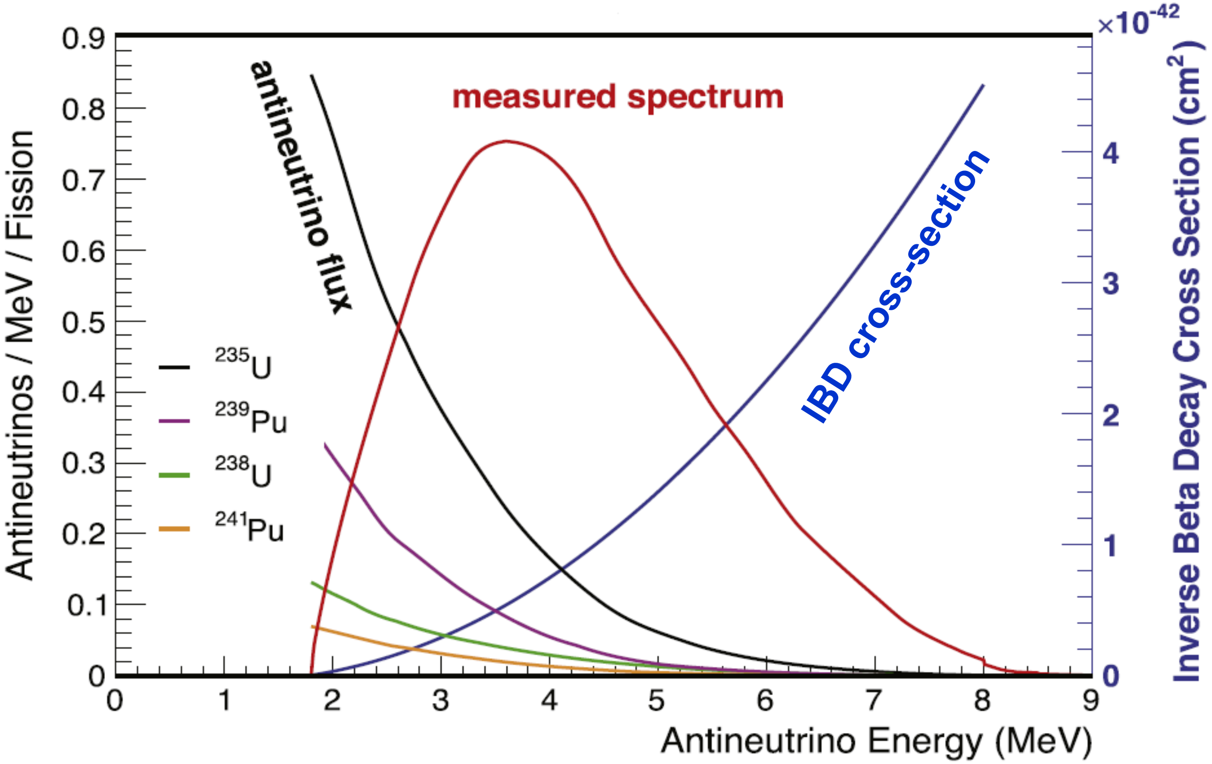


Proton Decay

Inverse beta-decay reaction

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



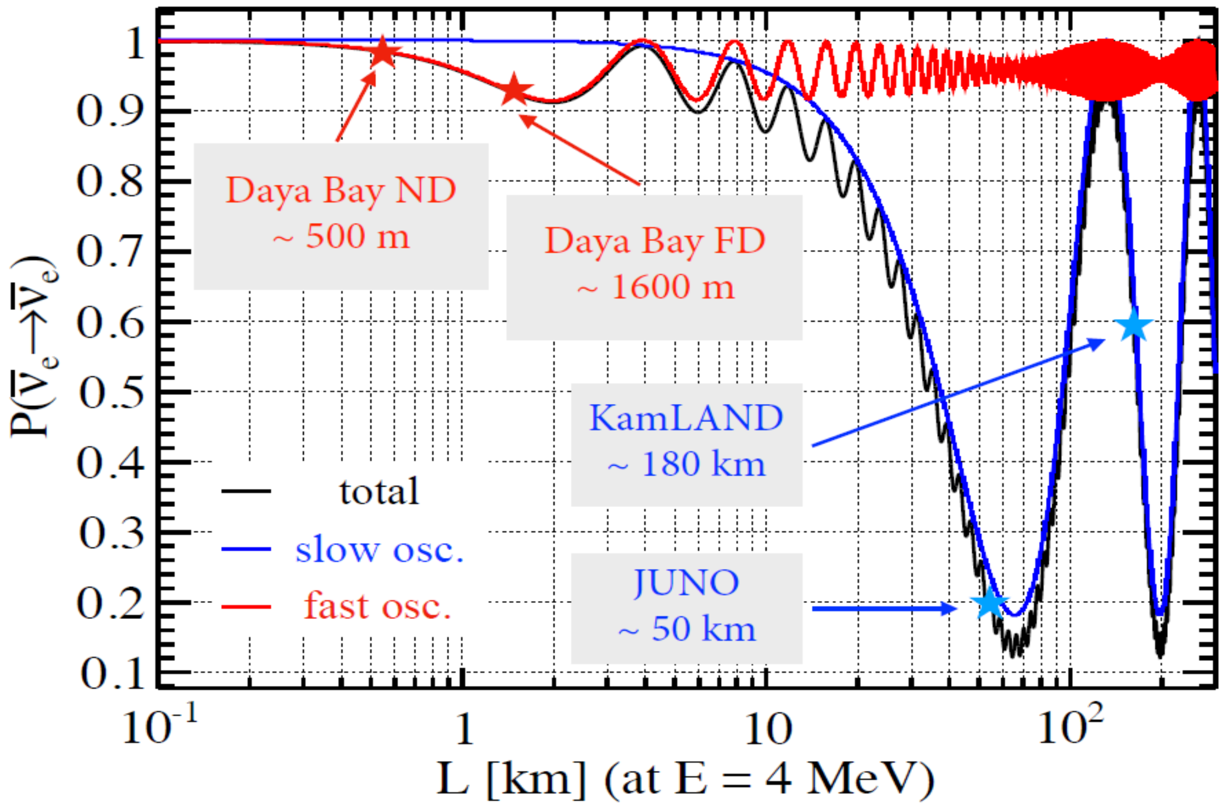


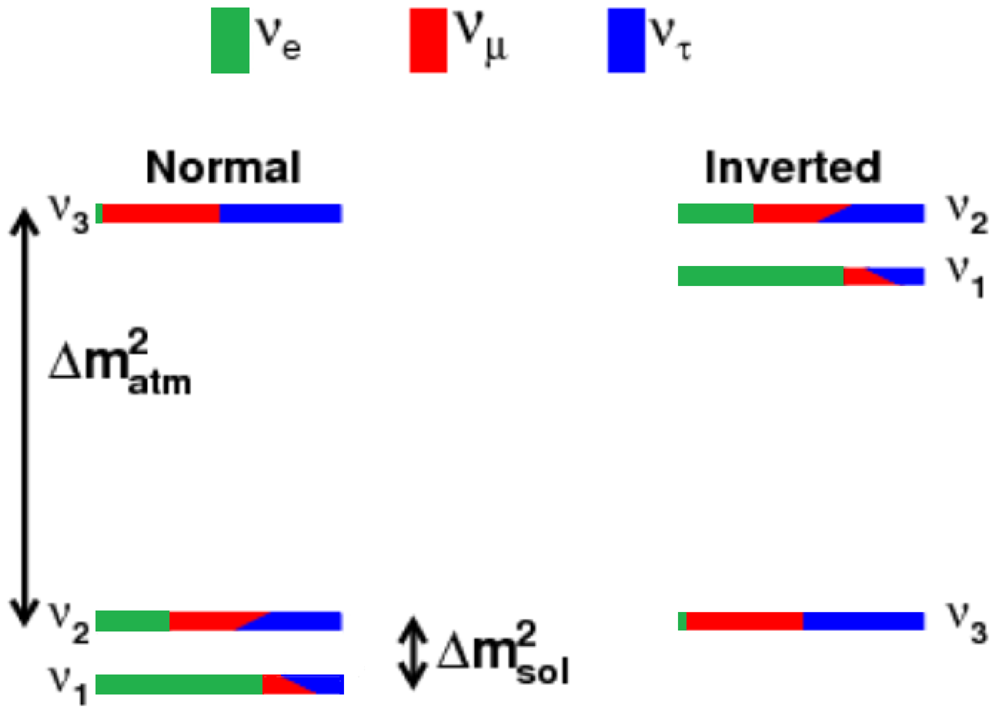
IBD is golden reaction of neutrino physics

- Higher cross-section than other channels
- Signature is a coincidence of prompt and delay signals
- Positron energy carries information about antineutrino energy
- Threshold is 1.8 MeV

survival probability

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





NH : $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

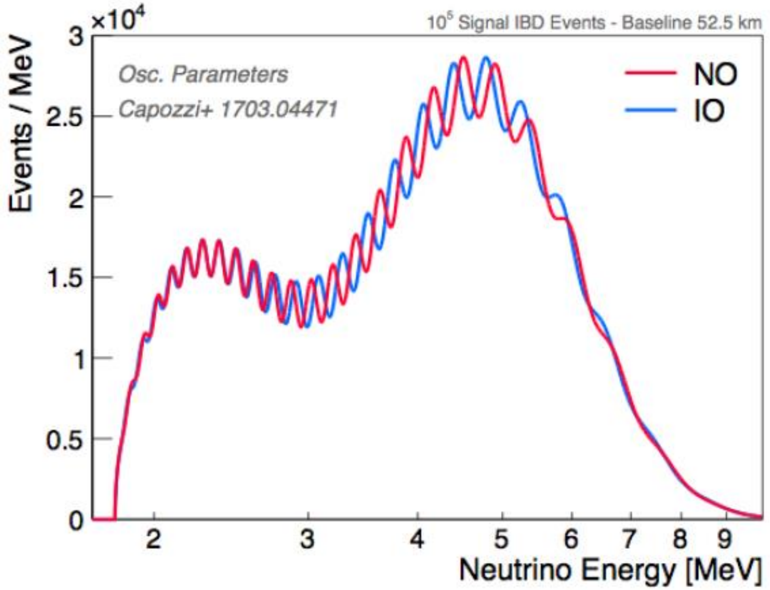
IH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$

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

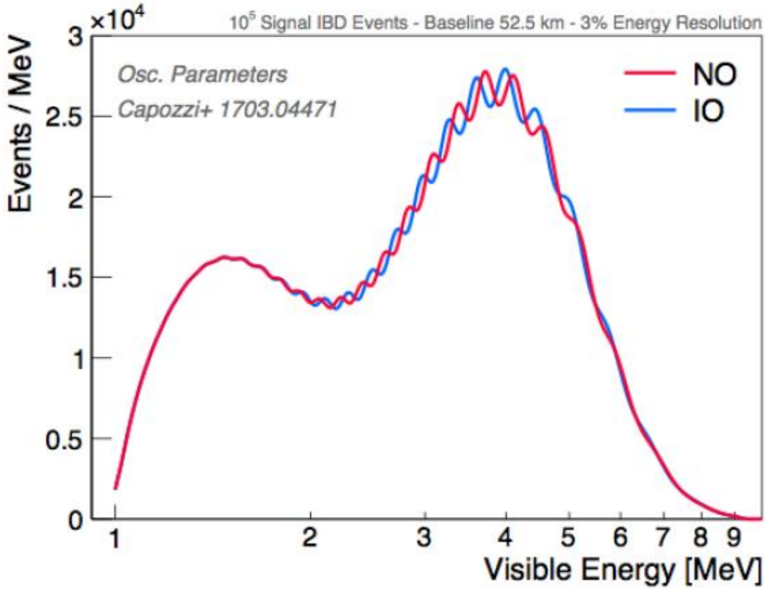
S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRD78, 071302 (2008)
L. Zhan, PRD78:111103, 2008, PRD79:073007, 2009
J. Learned et al., arXiv:0810.2580
Y.F Li et al, PRD 88, 013008 (2013)

Difficulties

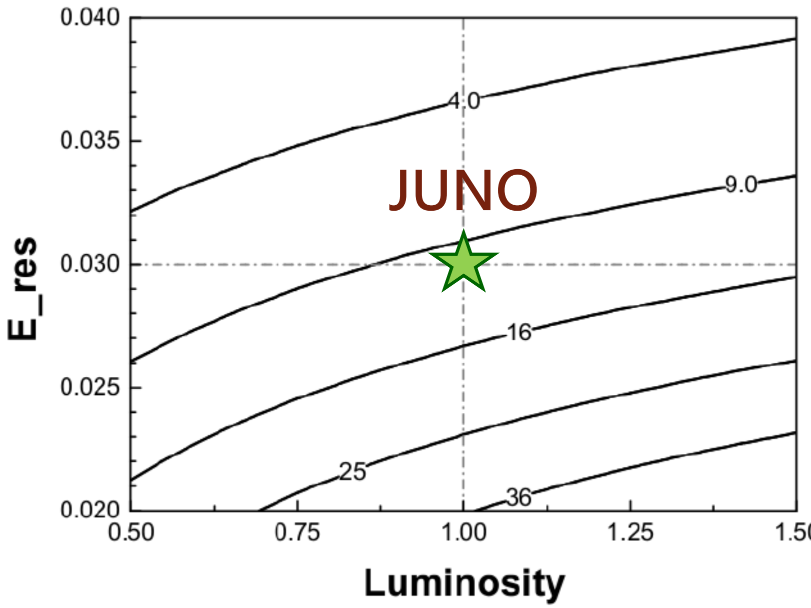
Ideal neutrino spectrum



Measured spectrum + energy resolution 3%@1 MeV



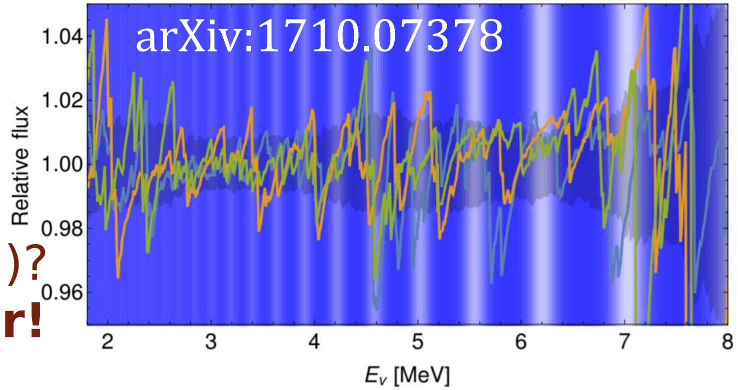
Chi-square map

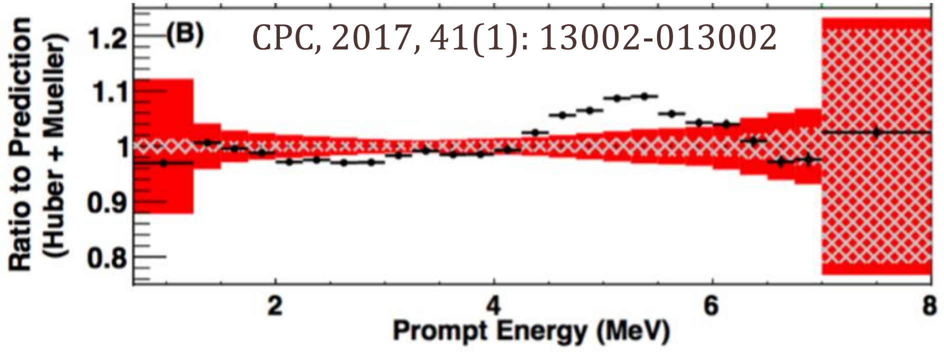


More detailed information about reactor spectrum is needed.

- 5 MeV bump?
- Fine structure (may affect to MH)?

It requires a reference detector!





TAO detector

JUNO TAO

Taishan **A**ntineutrino **O**bservatory

High precision measurement of reactor spectrum:

- Provide model-independent reference for JUNO
- Possible improvement of nuclear databases
- Investigate the reactor spectrum anomaly (5 MeV bump)
- 30 × JUNO statistics

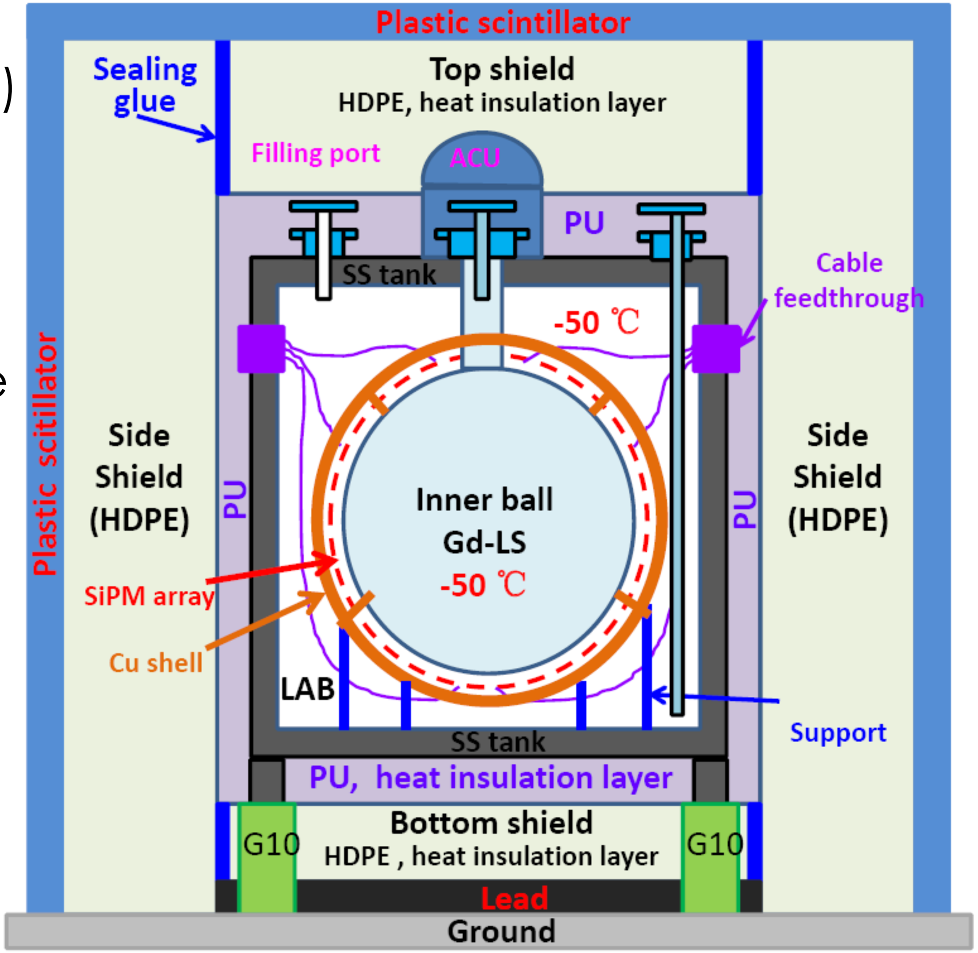
TAO Design Features:

- **2.6 ton Gd-LS** as target material (1 ton fiducial target)
- Detector placed at **30 m distance** from one reactor core
- 10 m^2 **SiPM**, with **50% PDE**, **Coverage: ~94-96%**
- SiPMs and LS **cooled down to -50 °C** (reduce noize from SiPM)

Expected Performance:

- **~ 4500 p.e. / MeV** collected charge
- Energy Resolution: ~ **1.7% @ 1 MeV, < 1.0% above 3 MeV**

Planned to be online in early 2021!



Neutrino mass ordering

Expected background

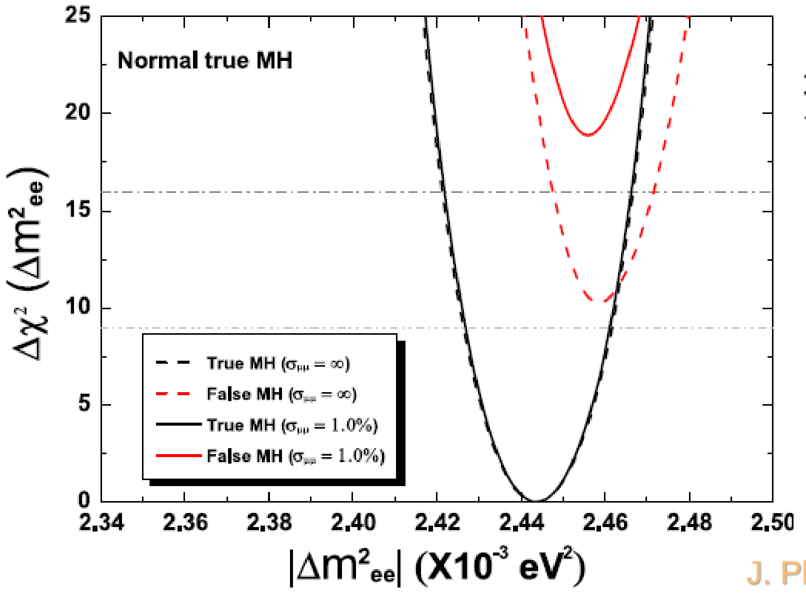
Event type	Rate (per day)	Rate uncertainty (relative)	Shape uncertainty
IBD candidates	60	—	—
Geo-νs	1.1	30%	5%
Accidental signals	0.9	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li–^{8}He	1.6	20%	10%
^{13}C $(\alpha, n)^{16}$O	0.05	50%	50%

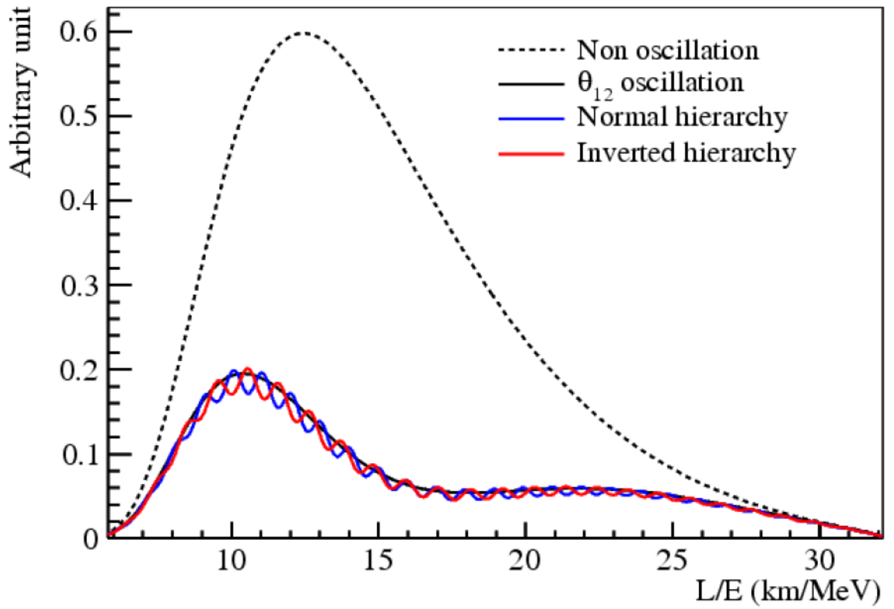
Requirements for setup:

- Energy resolution < 3%@1 MeV
- Energy scale uncertainty < 1%
- Reactor baseline variation < 0.5 km
- Large statistics: 100k IBD in 6 years

	Size	$\Delta\chi^2_{MO}$
Ideal	52.5 km	+16
Core distr.	Real	-3
DYB & HZ	Real	-1.7
Spectral Shape	1%	-1
B/S (rate)	6.3%	-0.6
B/S (shape)	0.4%	-0.1
$\lvert\Delta m^2_{\mu\mu}\rvert$ T2K&Nova	1%	+(4-12)

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



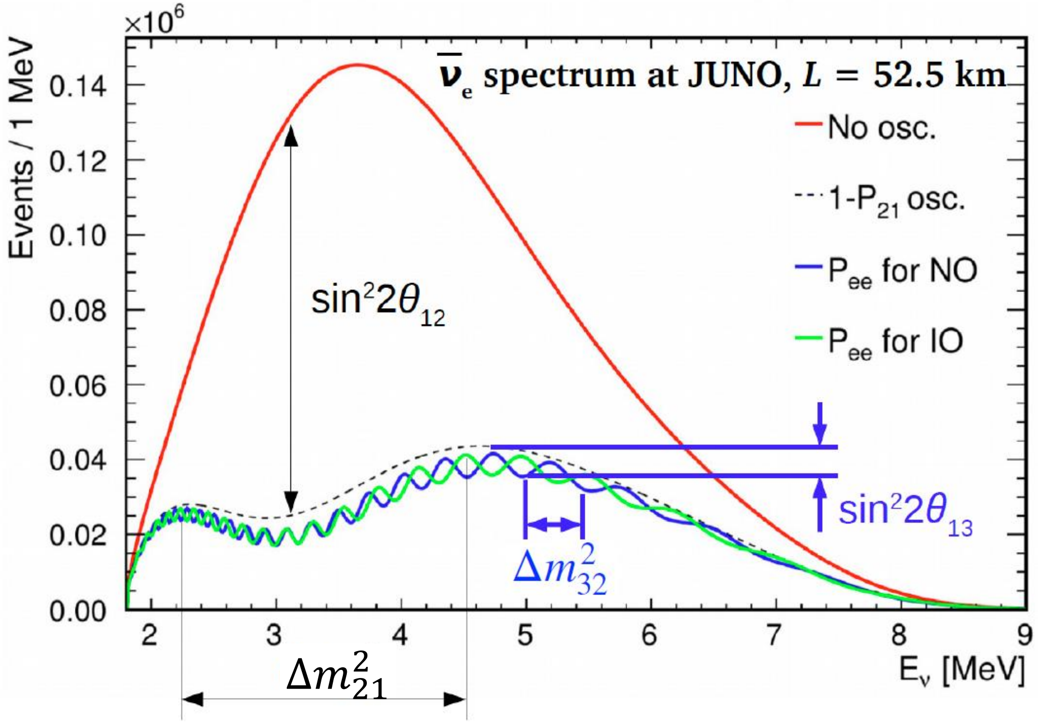


J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401

Precise measurements

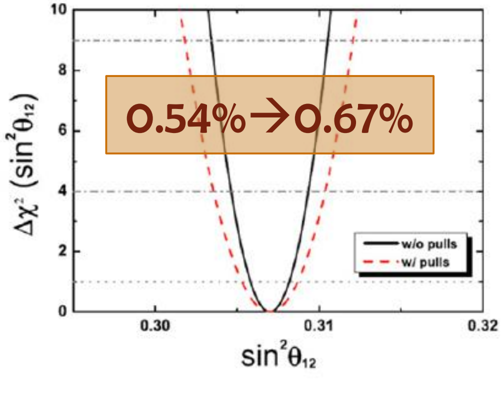
Oscillation physics with JUNO:

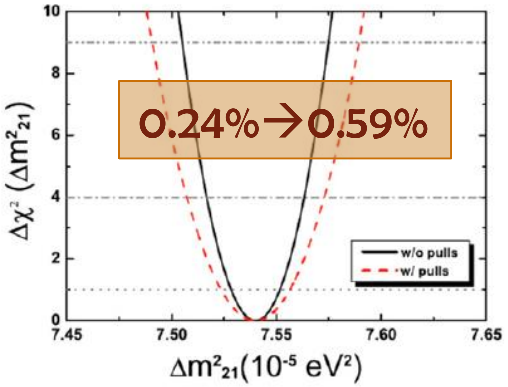
- Independent from CP-violation
- Tiny influence from matter effect
- Insensitive to θ_{23} and octant problem
- Sensitive to $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{32}$
- For θ_{13} precision is worse than current best fit result

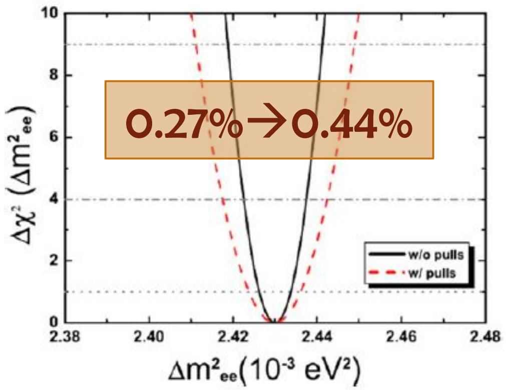


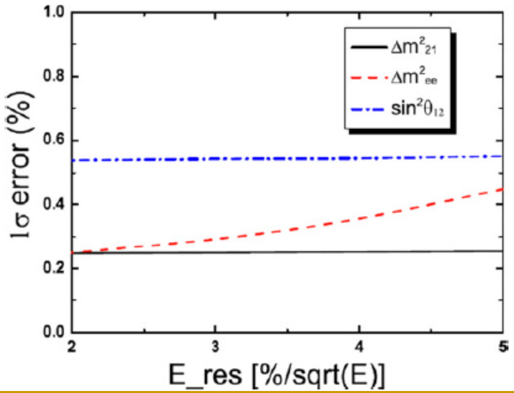
Current status

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%





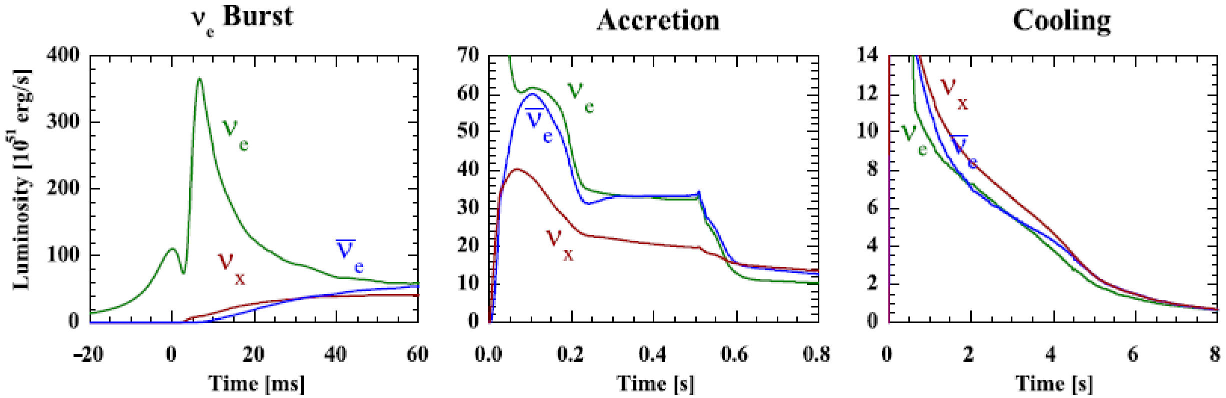




Supernova neutrinos and JUNO

Expected number of burst-type events at 10 kpc

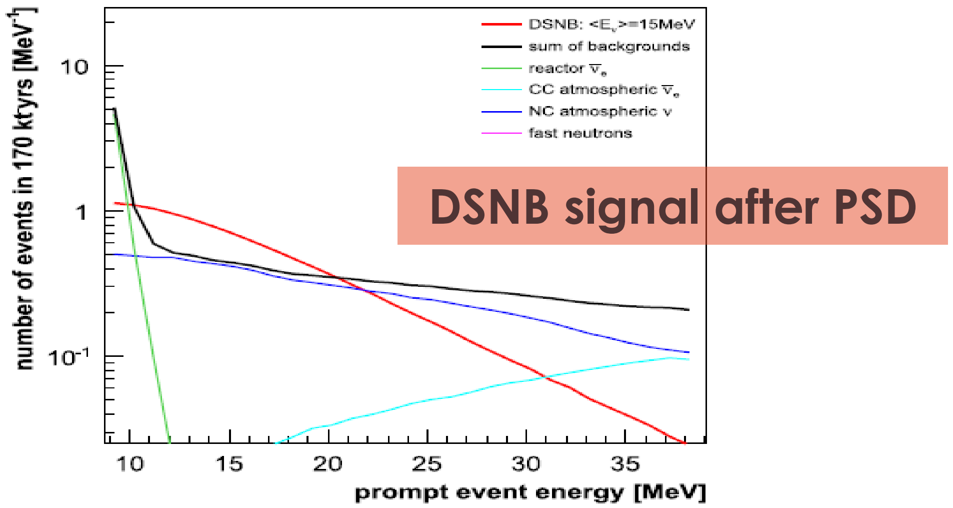
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2



JUNO is able to determine flavor content, energy spectrum and time evolution of SN burst-type neutrinos

DSNB rate after 10 years fiducial volume 17 kt

Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\overline{\nu}_e} \rangle = 12$ MeV	13	$\varepsilon_\nu = 50\%$	7
	$\langle E_{\overline{\nu}_e} \rangle = 15$ MeV	23		12
	$\langle E_{\overline{\nu}_e} \rangle = 18$ MeV	33		16
	$\langle E_{\overline{\nu}_e} \rangle = 21$ MeV	39		19
Background	reactor $\overline{\nu}_e$	0.3	$\varepsilon_\nu = 50\%$	0.13
	atm. CC	1.3	$\varepsilon_\nu = 50\%$	0.7
	atm. NC	6×10^2	$\varepsilon_{NC} = 1.1\%$	6.2
	fast neutrons	11	$\varepsilon_{FN} = 1.3\%$	0.14
	Σ			7.1



J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401

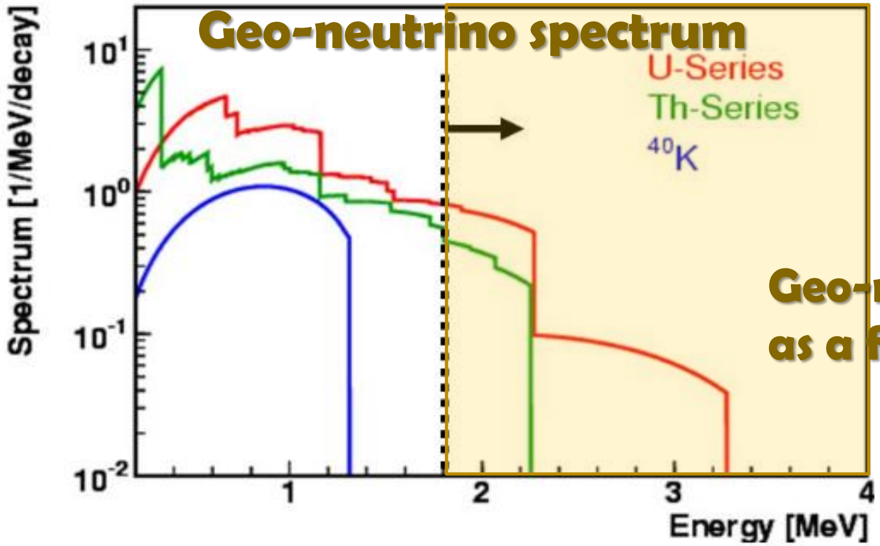
Geo-neutrino signal

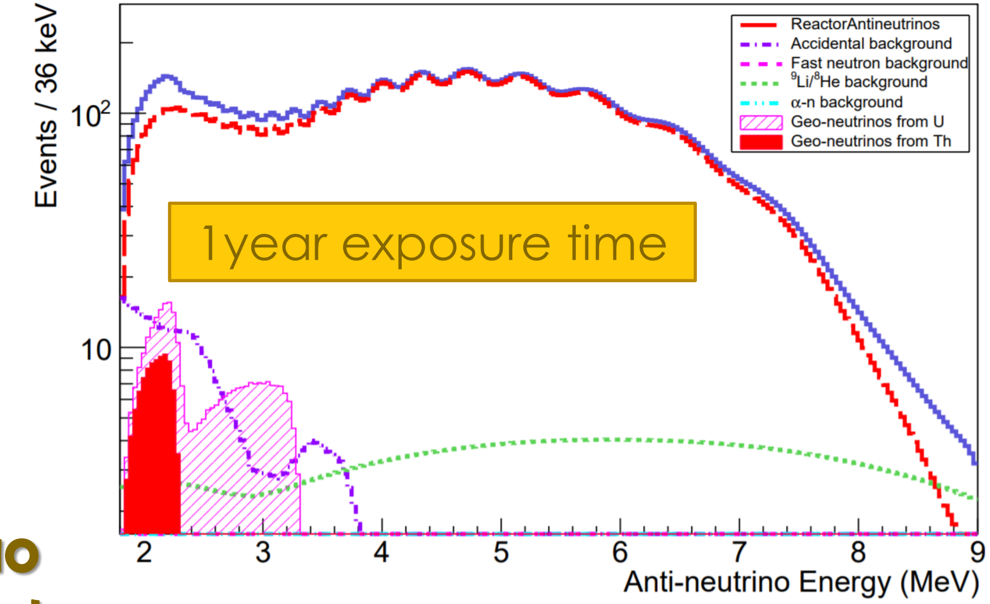
$$^{238}\mathrm{U} \rightarrow\ ^{206}\mathrm{Pb} + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow\ ^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow\ ^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.3\ \mathrm{MeV}$$

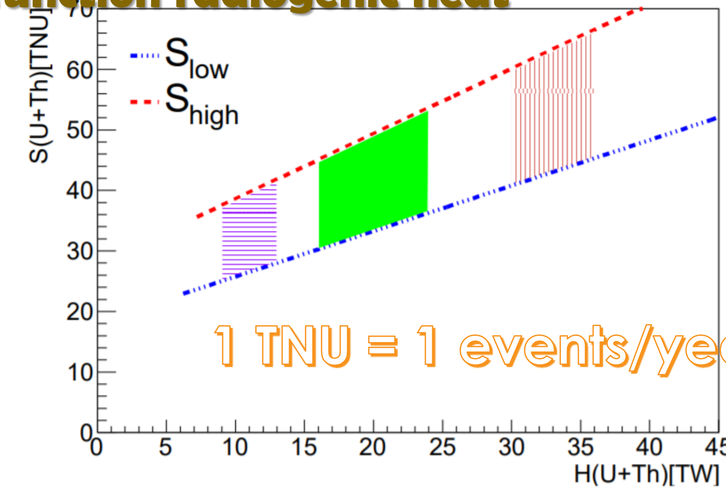
Geo-neutrino spectrum



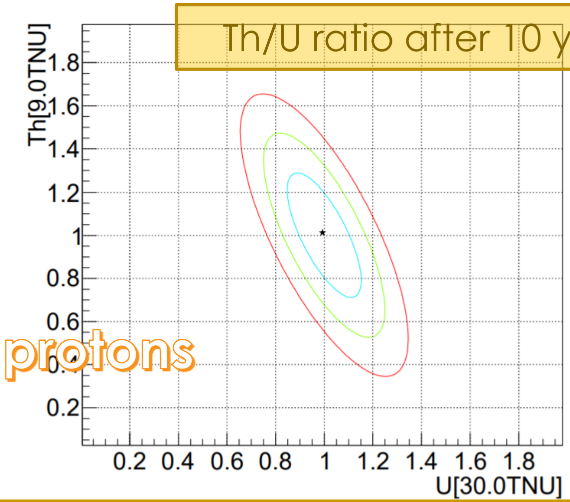


1year exposure time

Geo-neutrino signal at JUNO as a function radiogenic heat



Th/U ratio after 10 years



1 TNU = 1 events/year/10^{32} protons

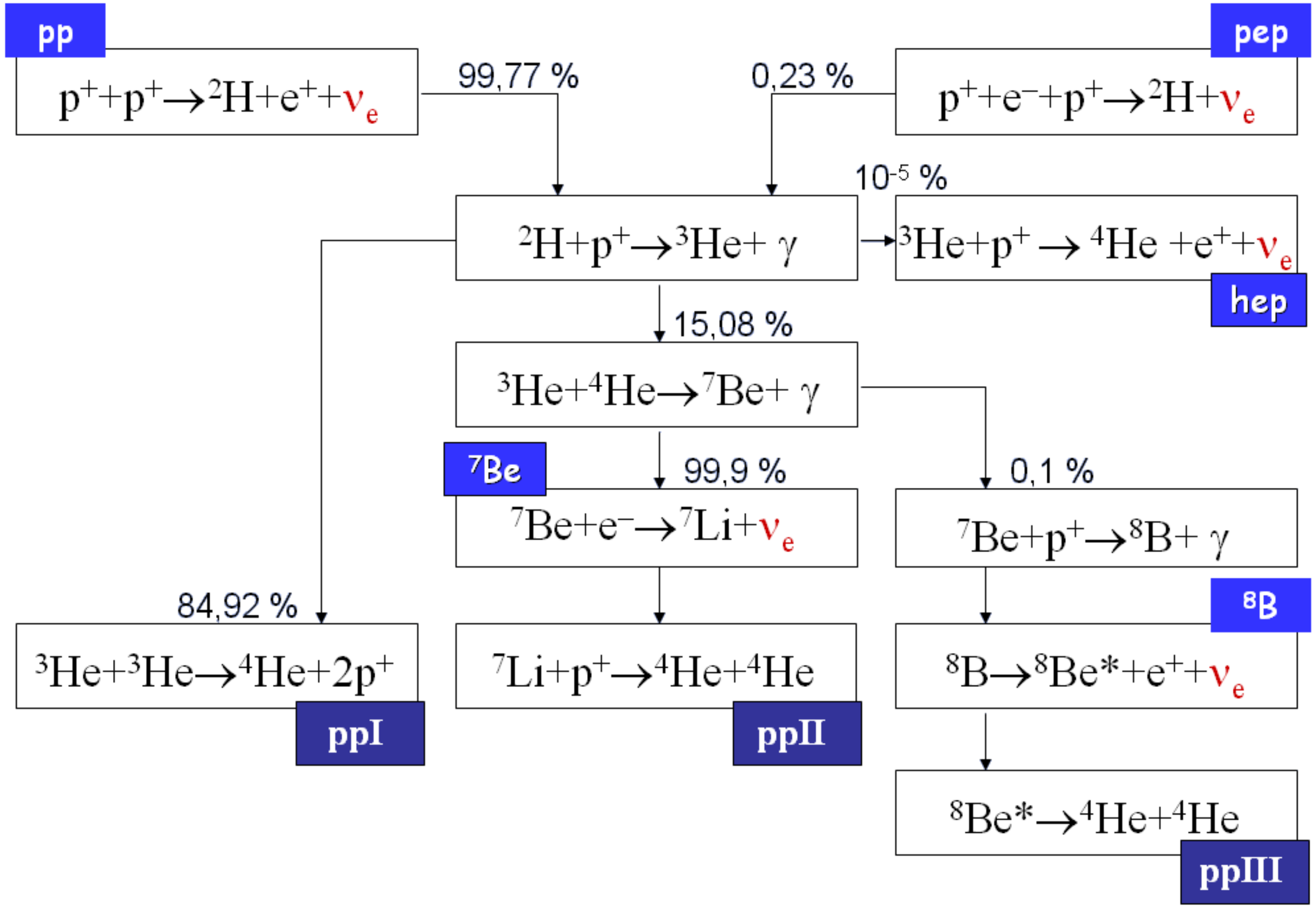
Uncertainty for U/Th flux after 10 years:

- U: 11%
- Th: 24%

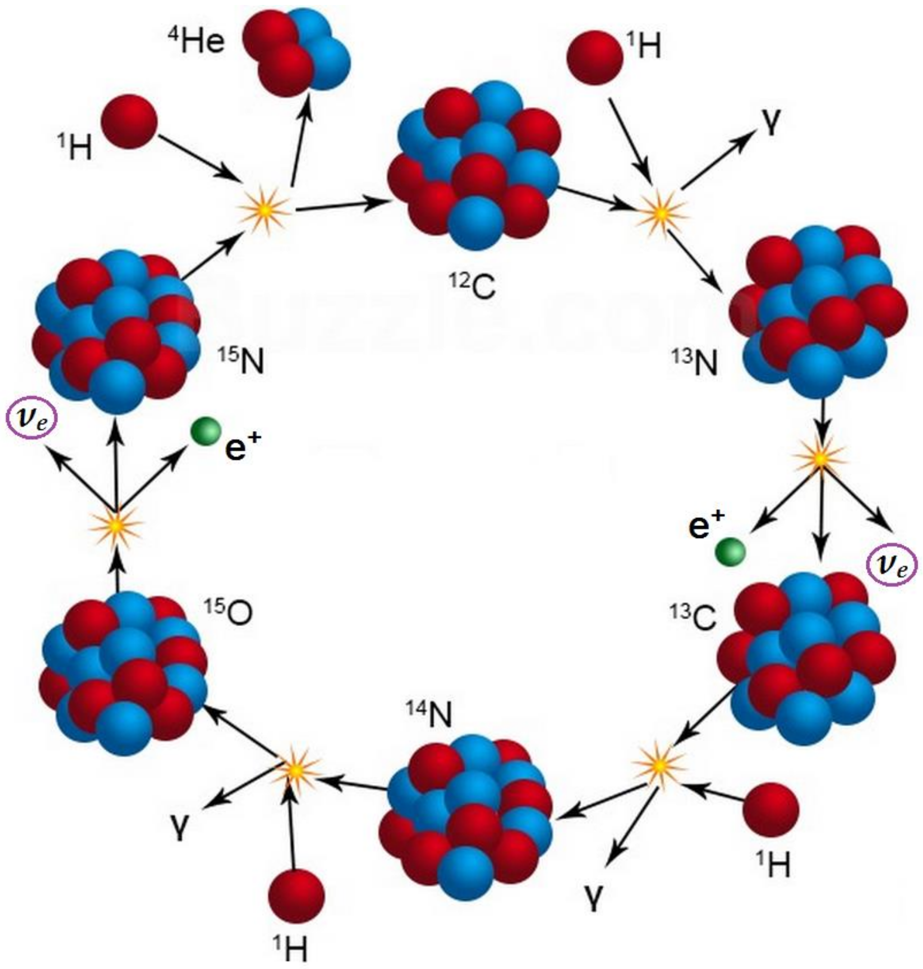
Chin.Phys. C40 (2016) 033003

Solar neutrinos production

Proton-proton cycle

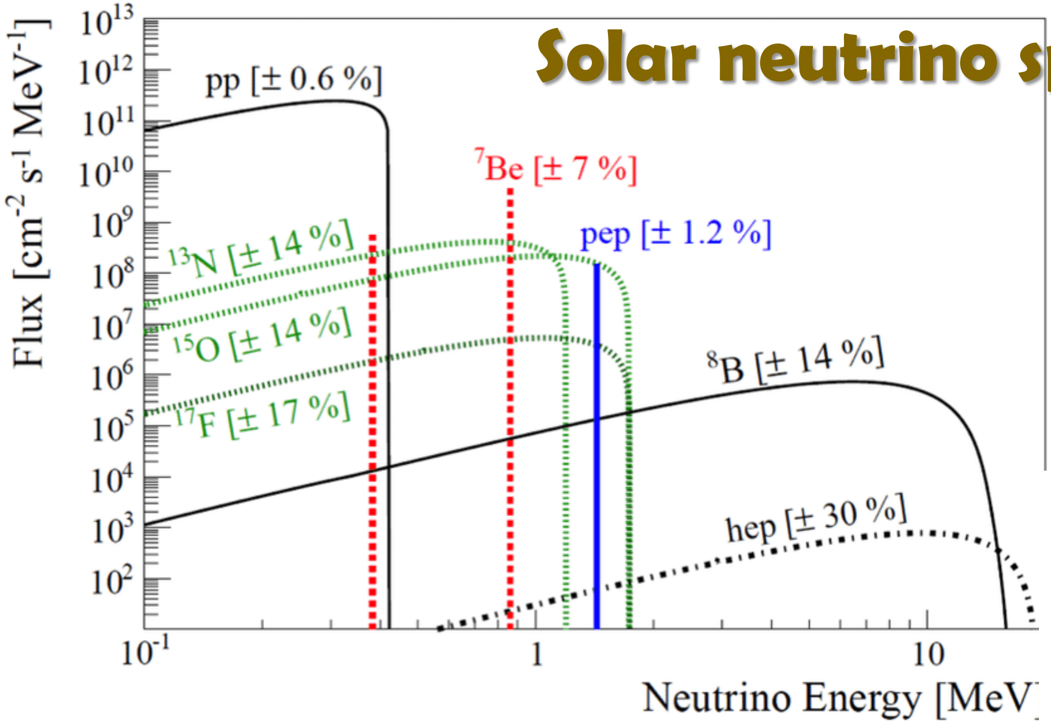


CNO-I cycle



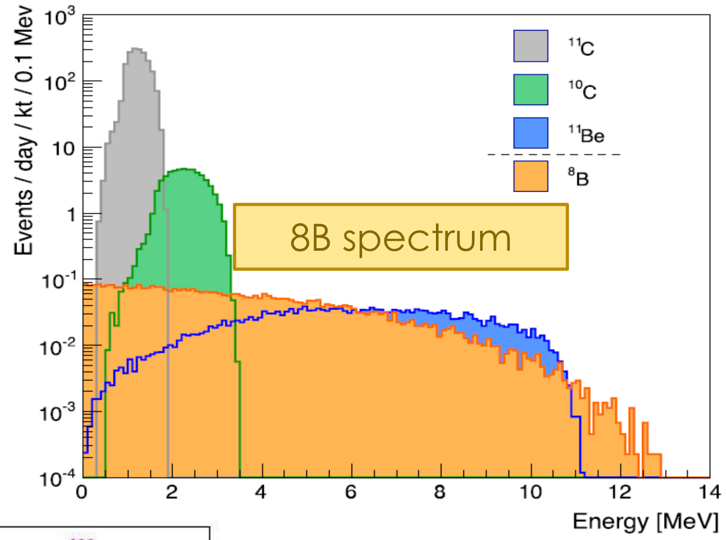
Solar neutrinos

Solar neutrino spectrum

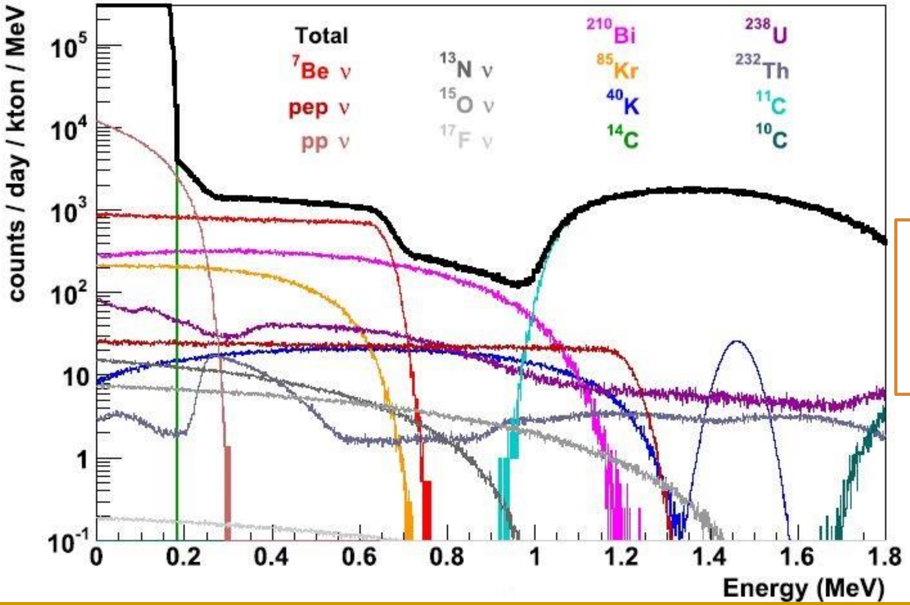


Solar neutrino signal rates (counts/day/kton)

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



Ideal radiopurity of LS



Any antineutrinos from the Sun?

Sterile neutrinos

Unexplained neutrino anomalies

- "Gallium anomaly" solar neutrino experiments GALLEX&SAGE
- Beam experiments LSND&MiniBooNE
- Reactor antineutrino anomaly (RAA)

Extended mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \mathrm{U}[4 \times 4] \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Simple solution – additional eV scale sterile neutrino!

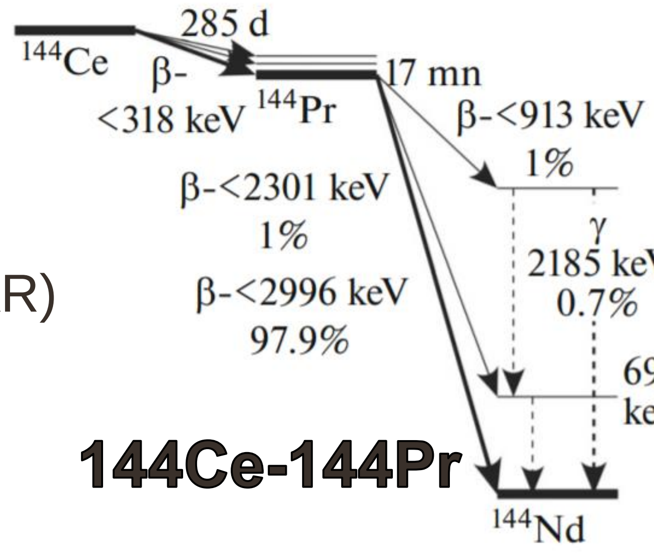
Disappearance channel:

$$P_{\alpha\alpha} \approx 1 - 4|U_{\alpha 4}|^2 \cdot (1 - |U_{\alpha 4}|^2)\sin^2\left(1.27\Delta m^2_{41} \cdot \frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

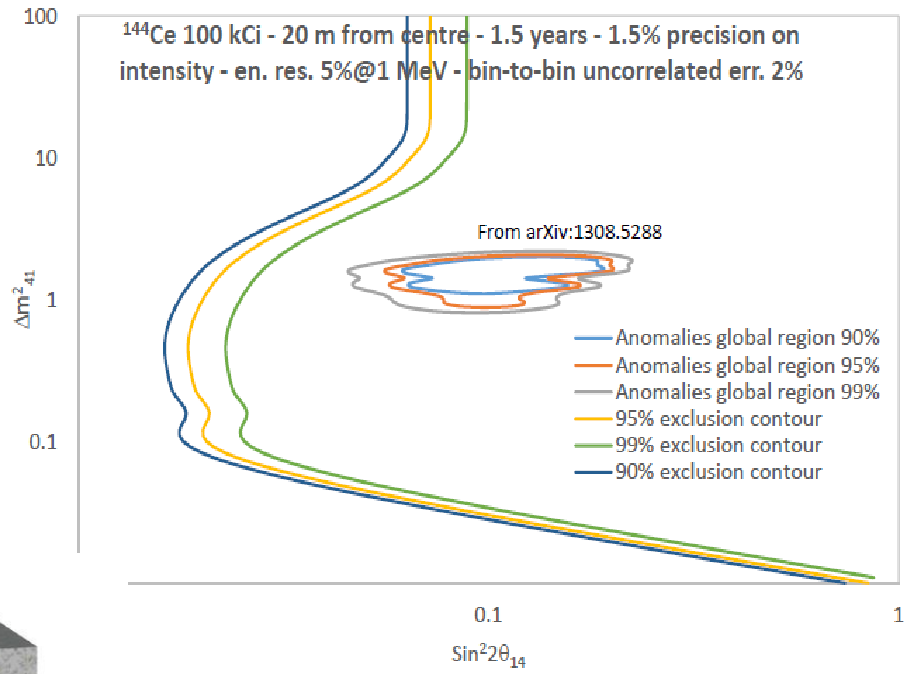
Sterile neutrinos – proposals

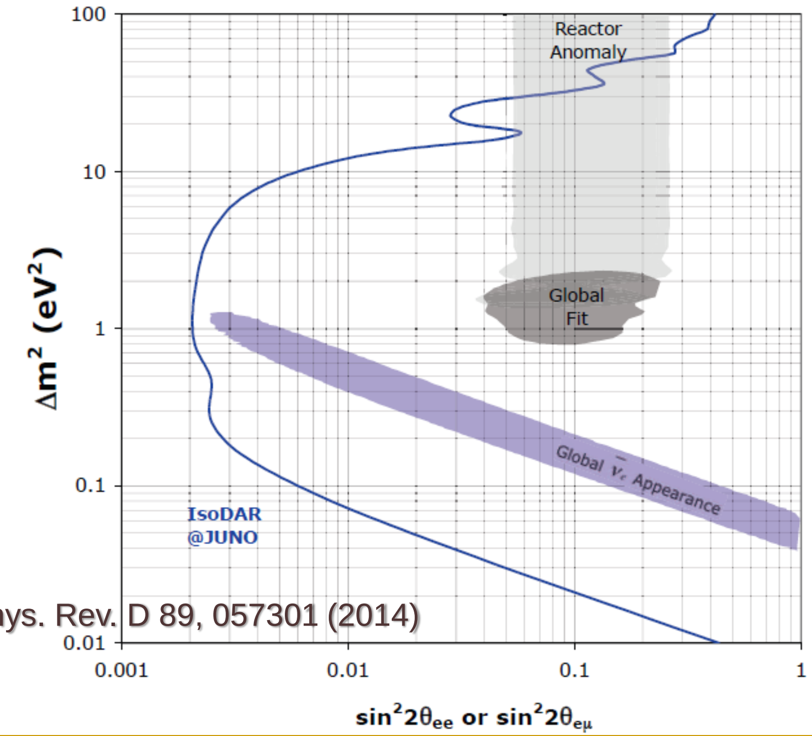
Radioactive sources:

Neutrino emitters: 37Ar, 51Cr
Antineutrino emitters: 144Ce-144Pr, 106Ru-106Rh, 90Sr-90Y, 8Li (IsoDAR)

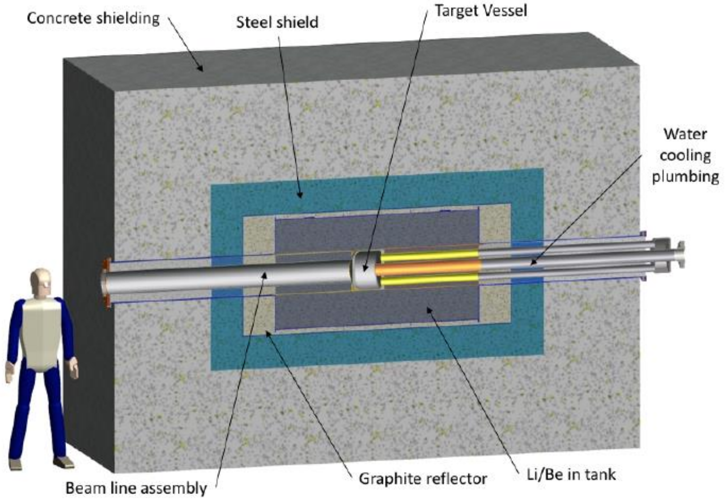


144Ce-144Pr





Phys. Rev. D 89, 057301 (2014)



8Li (IsoDAR)

- cyclotron 10 mA, 600 kW
- 5 m distance to the edge
- 5 years running
- $2.7 \cdot 10^7$ IBD events

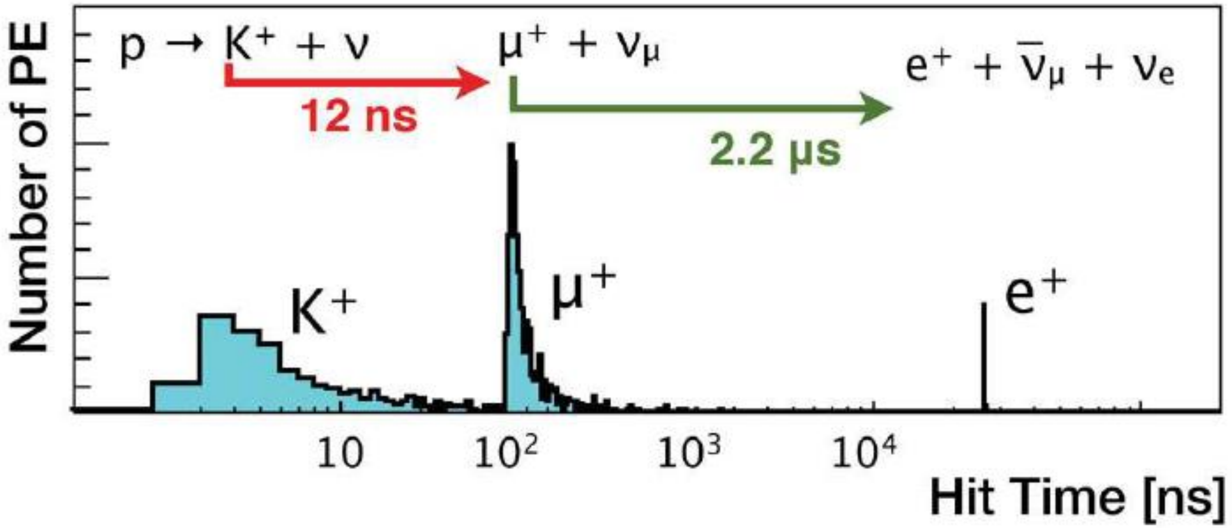
Proton decay

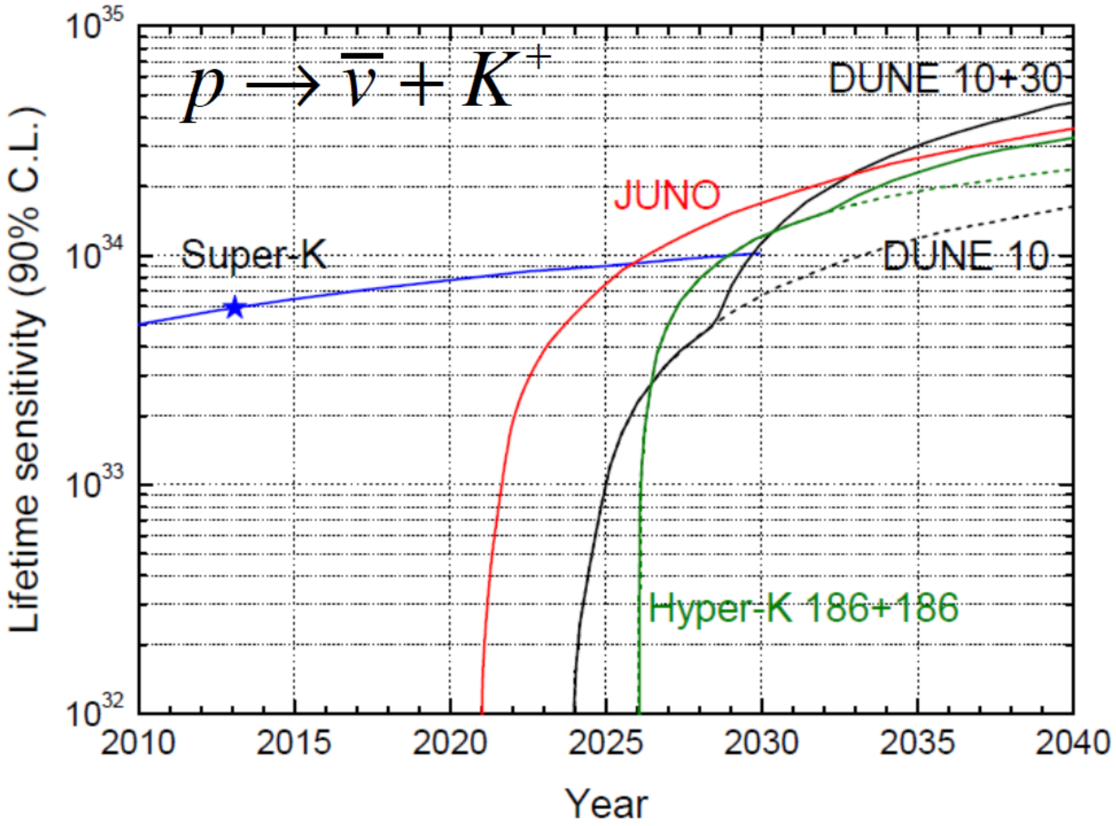
The most promising channels:

$p \to \pi^0 + e^+$ (from GUT)

$p \to \bar{\nu} + K^+$ (from SUSY)

Signature is triple coincidence





Upper limit after 10 years
$1.9 \cdot 10^{34}$ years 90% C.L.
based on LENA

Schedule

2014
- International collaboration established!

2015
- PMT production line setup
- Start civil construction
- CD parts R&D

2016
- Start PMT production
- Start CD parts production

2017
- Start PMT testing
- Top Tracker arrived!
- Daya Bay LS tests

2018
- Delivery of surface buildings
- Start production of acrylic sphere
- OSIRIS was funded
- TAO group formed

2019-20
- Electronics production starts
- Civil work and lab preparation completed
- Detector construction

2021
- Detector filled & comissioned
- TAO ready
- Detector ready

DATA TAKING!!!

THANK YOU FOR ATTENTION!!!

The 15th JUNO Collaboration Meeting   January 13-17, 2020, Guangxi University, Nanning

BACKUP

- Reactor ν oscillation

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

- Daya Bay's 2-ν approximation

$$P_{\rm sur} \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

  – In the standard 3-ν framew $\sin^2\Delta_{ee} \equiv \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$

- The Δm^2_{ee} definition is irrelevant to JUNO, since the 2-ν approximation is not valid. Δm^2_{31} and Δm^2_{32} should always be used.
- Detailed information is in *arXiv:1905.03840*