Physics potential of searching for 0νββ decays in JUNO

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Double Beta France Workshop II

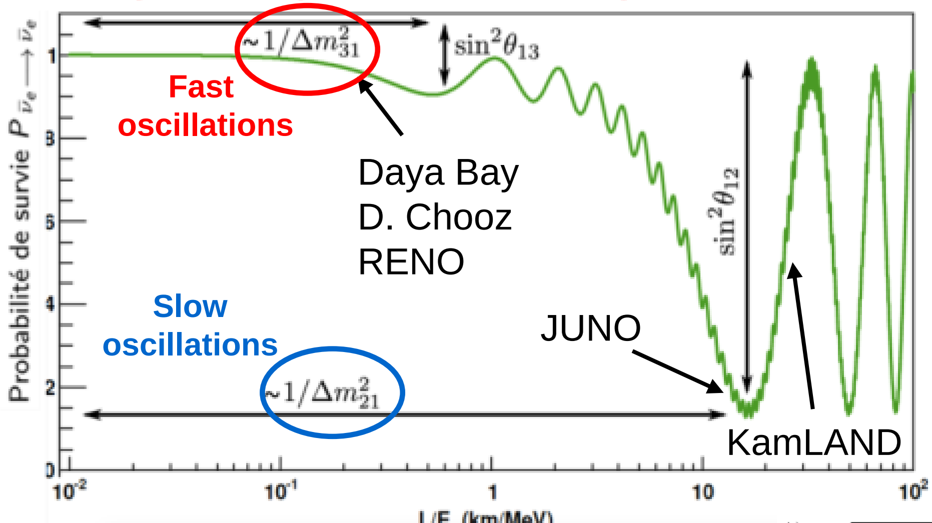
Neutrino physics with JUNO

Reactor electron antineutrinos oscillations

Electron antineutrino survival probability:

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

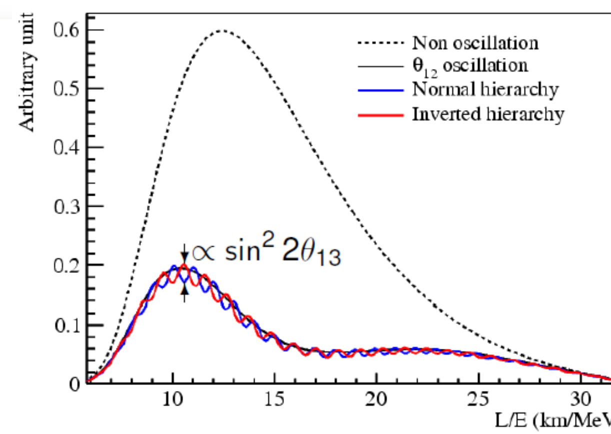
Nuclear reactors ($\sim 10^{21}$ ν/s/GW$_e$)



Neutrino detector

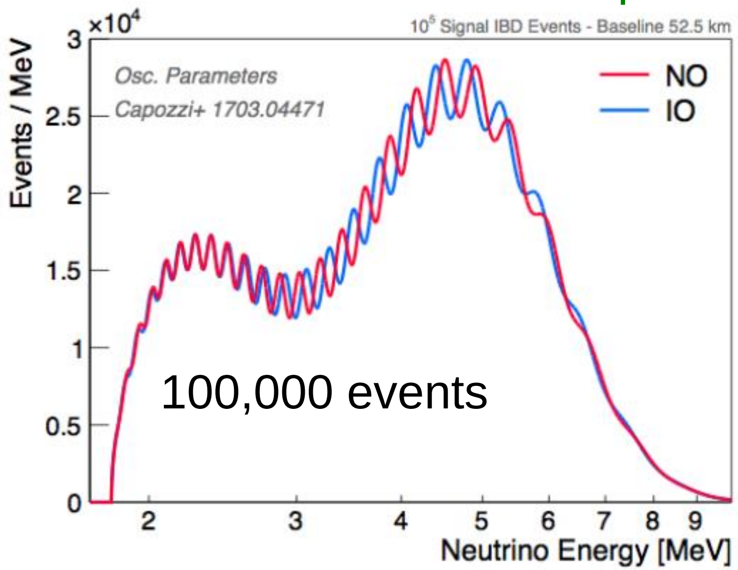
- Mass hierarchy is measurable only because θ_{13} is 'large' → way to determine NH/IH using reactor neutrinos by measuring the interference between Δm^2_{31} and Δm^2_{32}

- Best L/E ratio for maximum interference is ~10 km/MeV, i.e. ~50-60 km distance for reactor antineutrinos energy

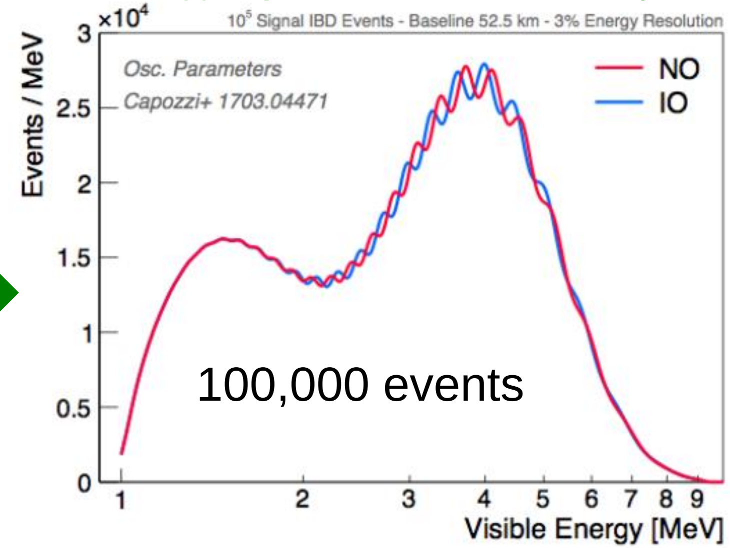


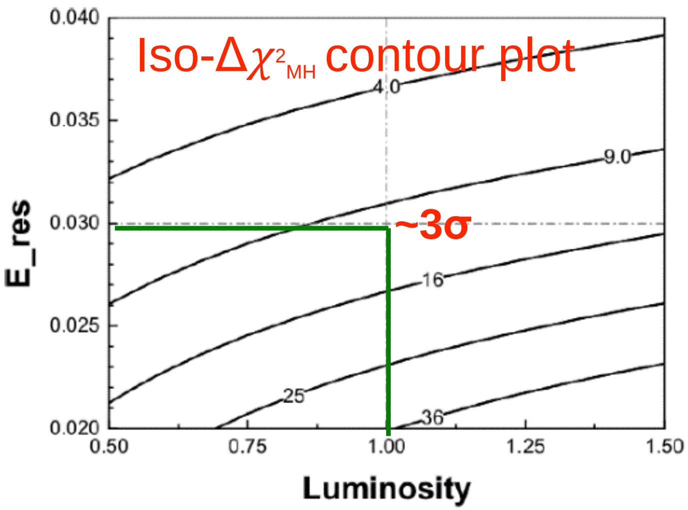
JUNO mass ordering sensitivity

Ideal oscillated antineutrino spectrum



Visible energy spectrum + 3%/√E(MeV)





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

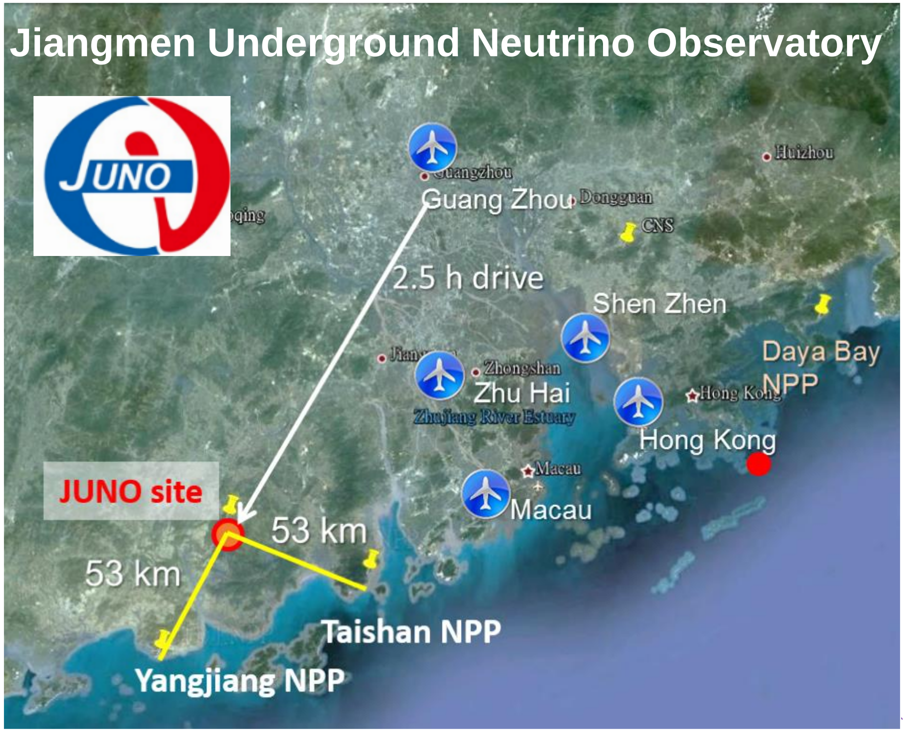
To distinguish between NO/IO at 3σ, one needs:

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

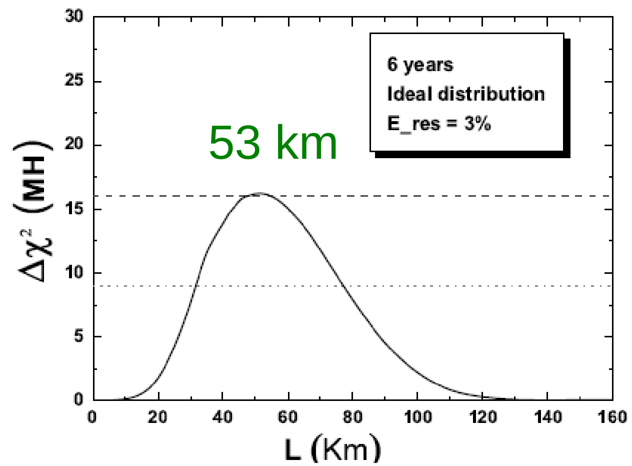
+ an energy scale uncertainty below 1%

→ impose the size and the performances of the JUNO experiment

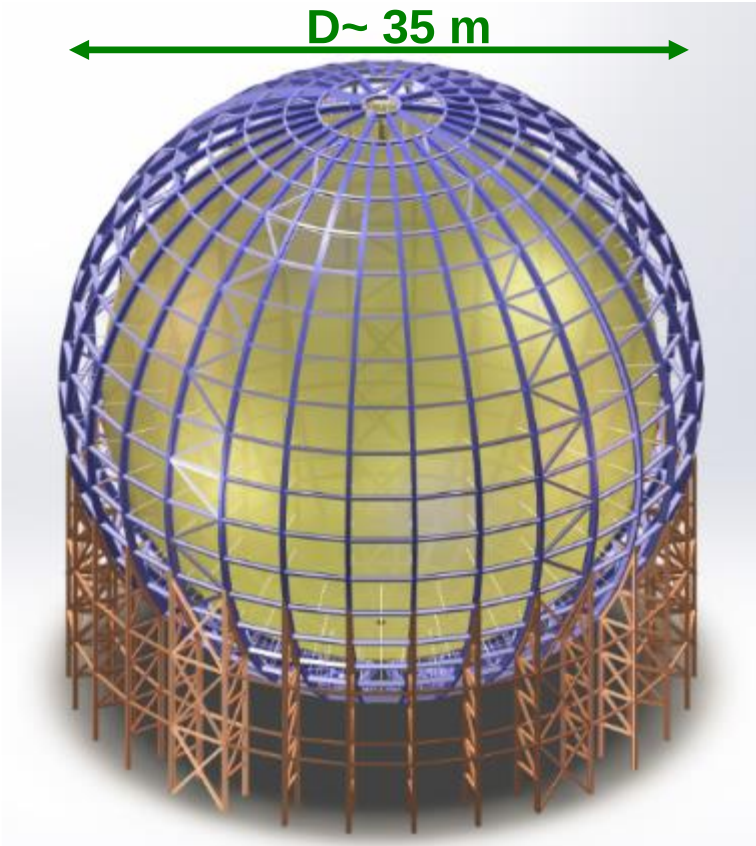
JUNO location



- ✓ JUNO located at Jiangmen city, Guangdong province
- ✓ Equidistant from two powerful nuclear power plants (Yangjiang and Taishan) at 53 km for mass ordering determination with 26.6 GW_{th} available in 2021
- ✓ 700 m overburden (1750 m.w.e.)



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)

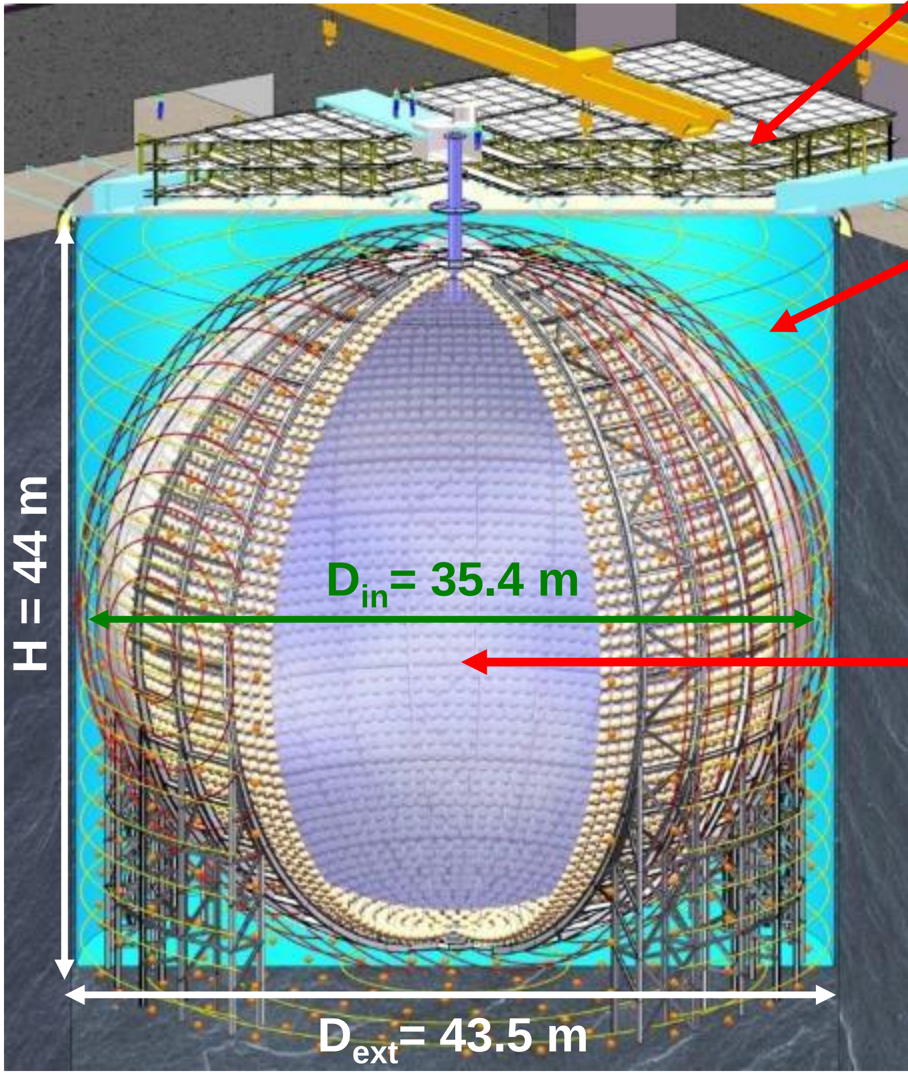
→ high LS transparency + very high photodetection coverage (>75%)
→ >1200 p.e. with 18,000 20-inch PMTs

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%

JUNO overall detector design

Experimental hall



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

IN2P3

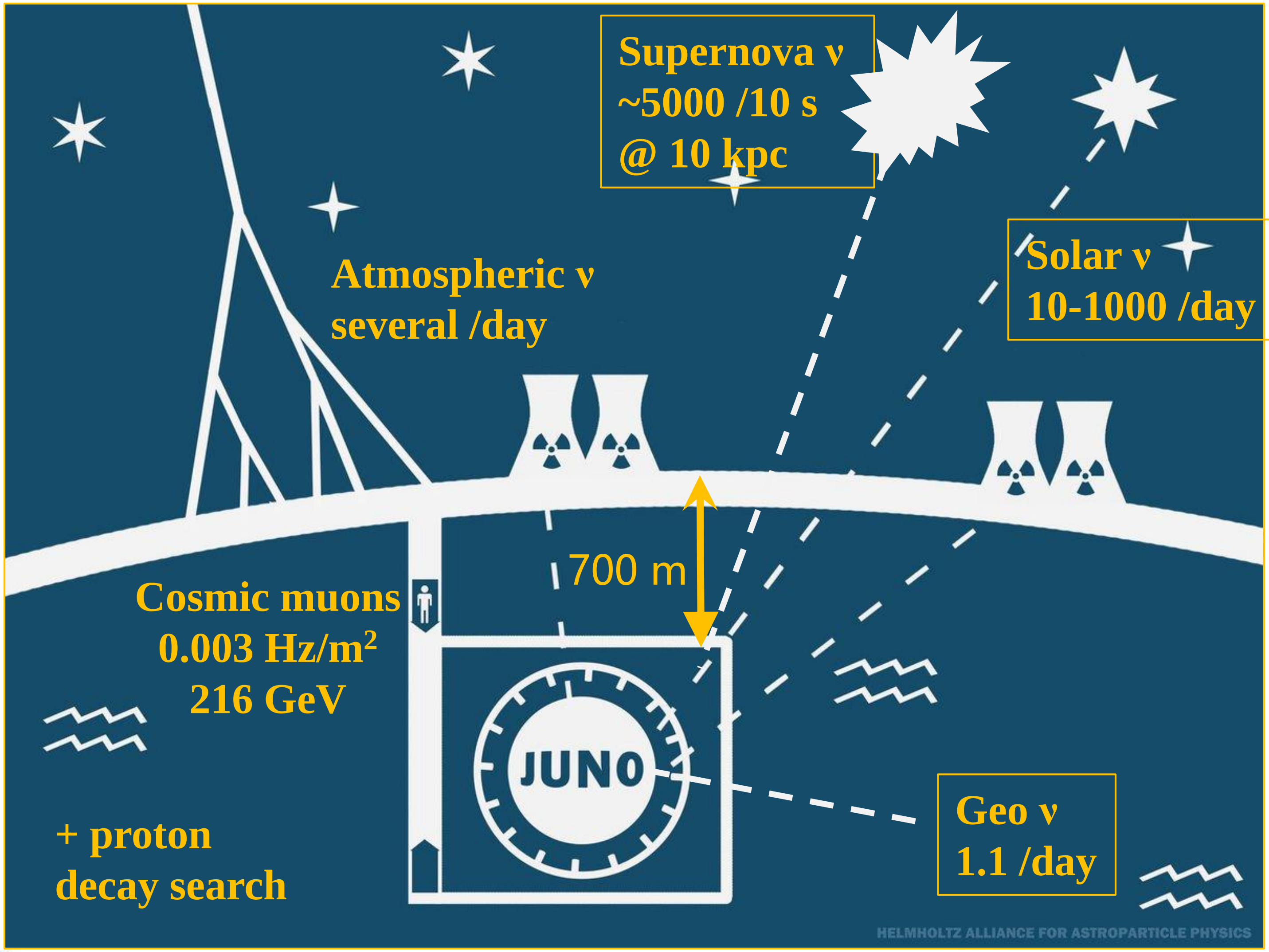
Water Cherenkov muon veto
- 35 ktons of ultrapure water
- 2,000 20-inch PMTs
- Muon detection efficiency > 95%
- Radon control → less than 0.2 Bq/m^3

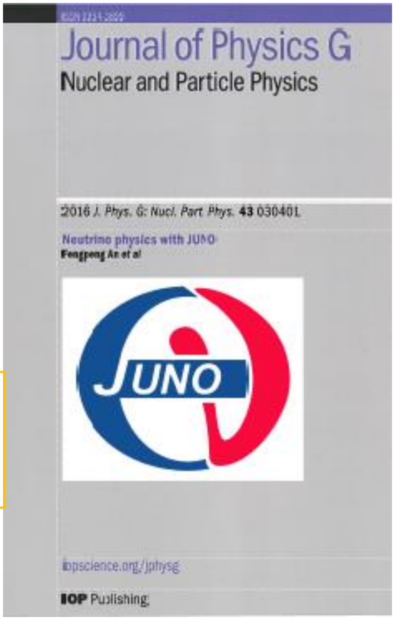
Central detector :
- Acrylic sphere filled with 20 ktons of LS
- PMTs immerged in water buffer and fixed on a stainless steel truss:
  - ~18,000 20-inch PMTs
  - ~26,000 3-inch PMTs
- >75% photocoverage

IN2P3

JUNO non-reactor neutrino physics

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

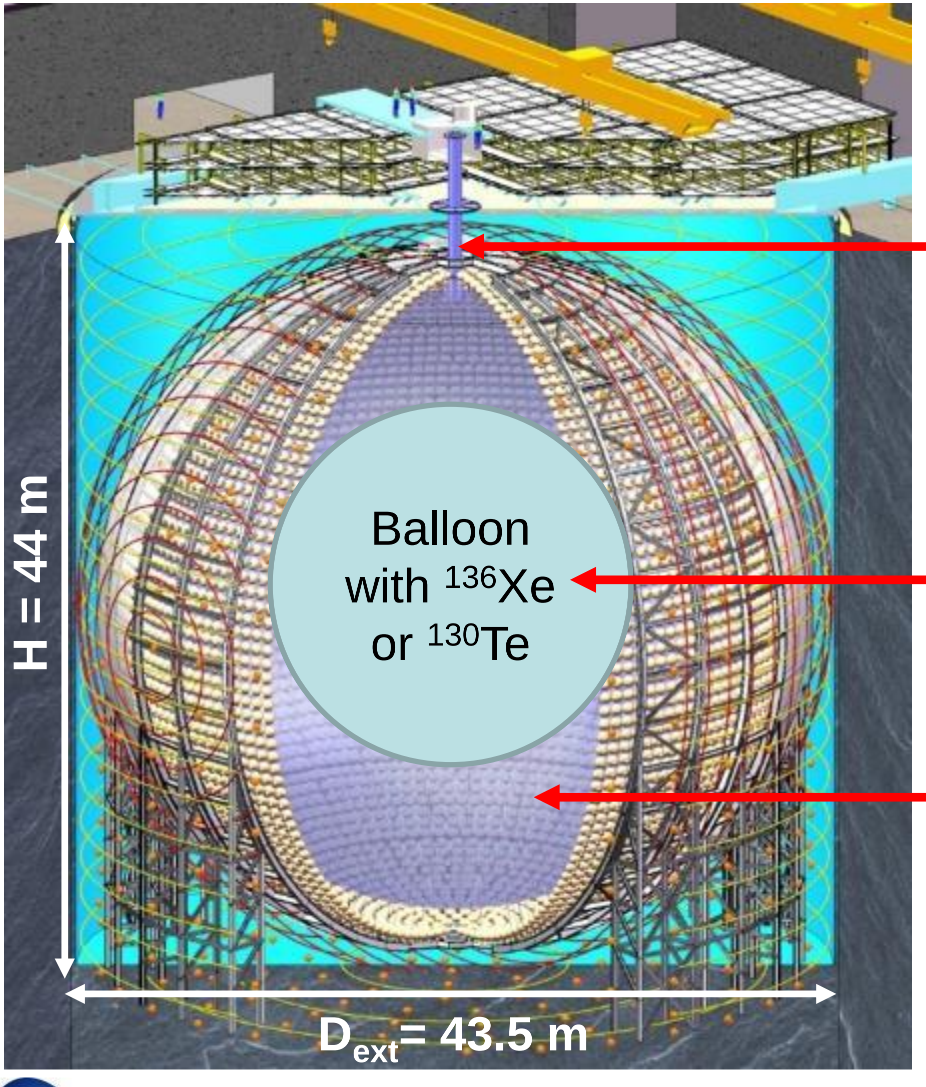




Physics potential for 0νββ searches with JUNO

JUNO conceptual design for 0νββ

- After mass hierarchy phase starting fall 2022, **opportunity to start a neutrinoless double beta phase in JUNO after 2030**



Chimney with a diameter of 80 cm to deploy a balloon in the future

Transparent balloon

- Filled with ultrapure LS
- Enriched ββ isotopes (^{136}Xe or ^{130}Te) dissolved in the LS

External LS

- Acts as an ultrapure active shielding
- 1 m fiducial cut will be sufficient to remove external background

0νββ studies in JUNO Xe-LS

- Sensitivity study published in 2017 with ^{136}Xe ($Q_{\beta\beta}$=2457.8 keV). ^{130}Te is also a good candidate.

Chinese Physics C Vol. 41, No. 5 (2017) 053001

Physics potential of searching for 0νββ decays in JUNO *

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- **Assumptions for JUNO and comparison to KamLAND-Zen**

	KamLAND-Zen	JUNO Xe-LS
energy resolution	$6.6\%/\sqrt{E}$ [10]	$3\%/\sqrt{E}$
	$7.3\%/\sqrt{E}$ [17]	
Xe-doping	2.5% (phase I [10])	5%
	2.9% (phase II [17])	
^{136}Xe enrichment	∼91% [10, 17]	80%
0νββ ROI	(2.3, 2.7) MeV [17]	(2403, 2513) keV
$\varepsilon_{0\nu\beta\beta}$ in ROI	89.9%*	75.8%

*corresponding to $\sigma \sim 7.3\%\sqrt{E}$ resolution

JUNO backgrounds for 0νββ

- **Simulations of all the backgrounds in JUNO**
- **Background index in evt/ROI/(ton ^{136}Xe)/yr**
- **ROI is [2403-2513] keV, i.e. 110 keV**

- **Intrisic 2νββ background** : reduced by the good $3\%/\sqrt{E}$ energy resolution

→ 0.2 evt/ROI/(ton ^{136}Xe)/yr

- **Solar-ν background**: dominated by ν-e scattering signal from ^{8}B solar neutrinos with a continuous spectrum > 10 MeV

→ 0.7 evt/ROI/(ton ^{136}Xe)/yr

Natural radioactivity background

- **Detector components (PMTs, SS structure, acrylic,…):** will be suppressed by a 1 m fiducial cut from the LS edge, sufficient to remove all the gammas from the detector components

- **Internal ^{238}U and ^{232}Th contamination in LS**: concentration of 10^{-17} g/g for U/Th
  - ^{214}Bi (^{238}U) measured by ^{214}BiPo cascade (τ=237 μs) using α/e tagging , timing cut (<2 ms) and spatial cut (<2 m). 99.97 % of the events are rejected

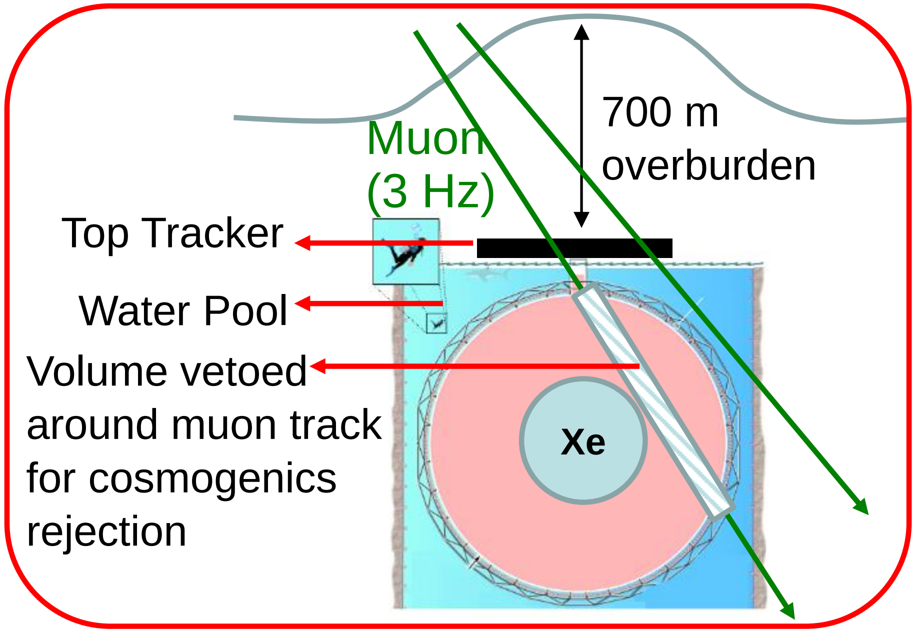
  → <0.003 evt/ROI/(ton ^{136}Xe)/yr
  - ^{212}Bi (^{232}Th) measured by ^{212}BiPo cascade (τ=431 ns) using 1 GHz FADC with PSD approach to disentangle the α/e summed signal with a discrimination efficiency greater than 97.5 %

  → <0.03 evt/ROI/(ton ^{136}Xe)/yr

- **External ^{238}U and ^{232}Th contamination of the balloon** at the sub-ppt level
  - Fiducial volume cut of 1 m from Xe-LS target edge will be sufficient to remove this background

Cosmogenics background

- With a modest overburden of JUNO (700 m overburden, i.e. 1750 m.w.e.), **the rate of muons passing through the JUNO sphere is ~3 Hz**
- Thanks to its large size, it will be able to veto a cylindrical volume along the muon track in order to reduce the muon induced backgrounds



- Main cosmogenics produced by showering processes in LS accompagnied by neutron(s):
  - ^{10}C (19,3 s)
  - ^{6}He (0,807 s)
  - ^{8}Li (0,84 s)
  - *^{12}B (0,02 s)*

Cosmogenics background

- Veto strategies:
  - **Normal muon veto**: track<(R_{Xe}+3) meters + 1.2 s veto time window
  - **Normal muon + neutron identification**: neutron vertex<(R_{Xe}+2) meters + $\Delta t_{\mu\text{-}n}$<1 ms and energy in [2.0-2.4] MeV → any signal within 2 m from neutron-like event and within $t_{n\text{-}\mu}^{veto}$ time window is rejected

- Optimization of the $t_{n\text{-}\mu}^{veto}$ time window for long-lived isotopes like ^{10}C (19.3 s)

	background index^a				
	no veto	μ_{norm} veto	n-associated muon veto		
			$2\ \tau_{^{10}C}$	$4\ \tau_{^{10}C}$	$6\ \tau_{^{10}C}$
efficiency ε_μ	1	0.902	0.879	0.858	0.837
^{10}C	16.4	14.3	1.98	0.27	0.053
^{6}He	4.9	1.69	0.065	0.065	0.063
^{8}Li	1.5	0.54	0.017	0.017	0.016
^{12}B	1.9	0.05	3.8e-4	3.8e-4	3.8e-4
others	0.51	0.17	0.01	0.01	0.01
total bkg	25.2	16.8	2.1	0.36	0.14

- Reduction by a factor ~300 of the ^{10}C background index using a 6xτ(^{10}C) veto window with negligible loss of livetime due to the low production yield of ^{10}C

→ 0.053 evt/ROI/(ton ^{136}Xe)/yr for ^{10}C

^{137}Xe background

- ^{137}Xe is produced by neutrons from muons
- ^{136}Xe(n,γ)^{137}Xe reaction followed by ^{137}Xe β decay provides a triple coincidence signature μ-γ-β to identify and reject such muon-induced background
- The expected ^{137}Xe production rate in JUNO Xe-LS has been scaled from the KamLAND-Zen detector

	KamLAND-Zen	JUNO Xe-LS
R_n in Xe-LS[a]	0.045 [26]	0.073 [2]
n-^{136}Xe fraction	9.5×10^{-4} [10, 29]	1.7×10^{-3}
^{136}Xe(n,γ)^{137}Xe yield[b]	61	98
background index[c]	8.2	2.3

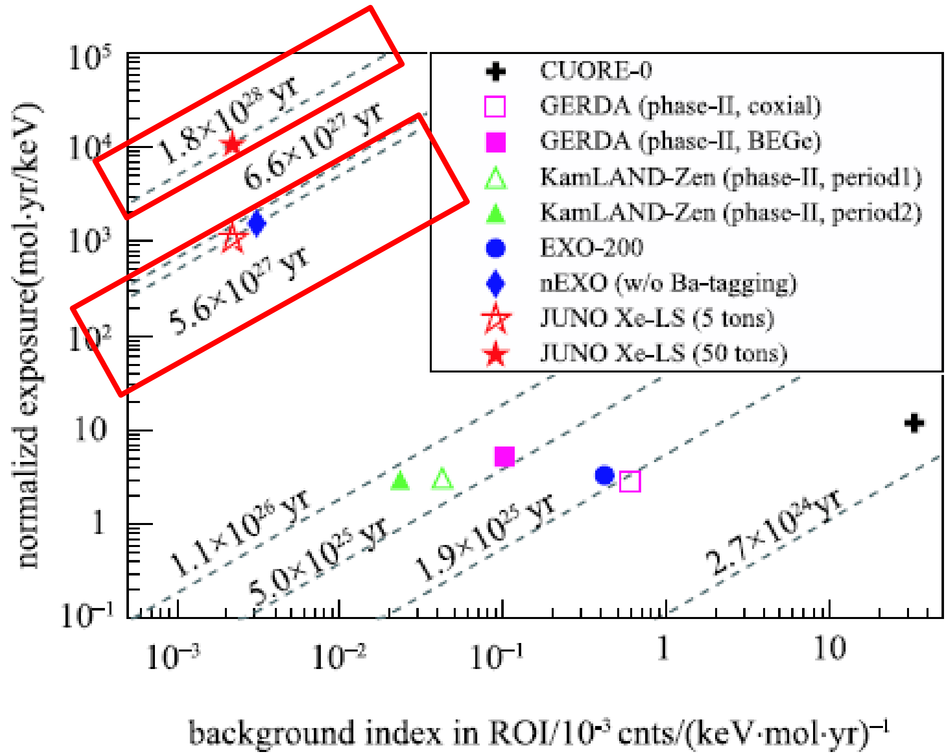
[a] in Hz/(kton Xe-LS) unit
[b] in (ton ^{136}Xe)$^{-1}\cdot$yr^{-1} unit
[c] in ROI$^{-1}\cdot$(ton ^{136}Xe)$^{-1}\cdot$yr^{-1} unit

→ 0.07 evt/ROI/(ton ^{136}Xe)/yr

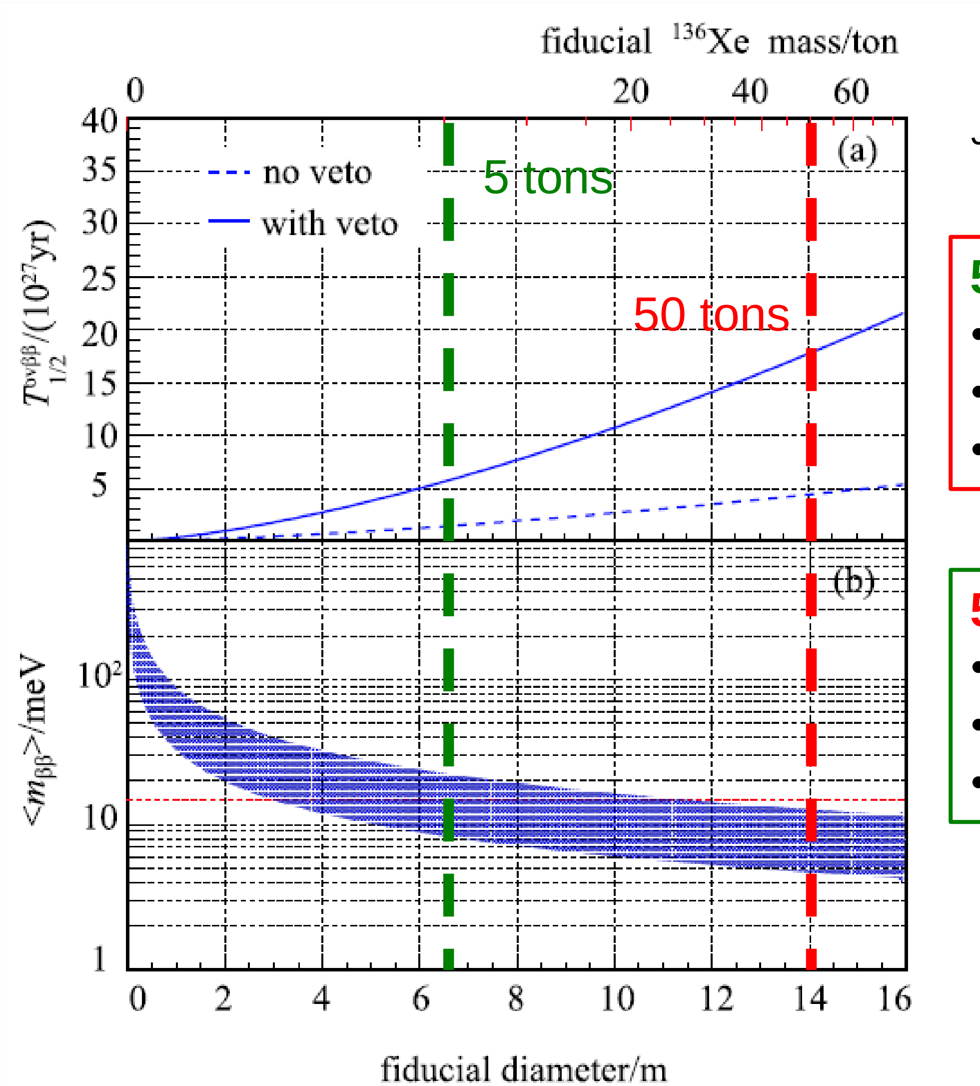
Background summary

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

- Background index comparison



JUNO sensitivity



J. Zhao et al., Chin. Phys. C 41, no.5, 053001 (2017)

5 tons scenario:
- 5 years live time
- $T_{1/2}$~5.6 x 10^{27} y (90% C.L.)
- $m_{\beta\beta}$ ~(8-22 meV)

50 tons scenario:
- 5 years live time
- **$T_{1/2}$~1.8 x 10^{28} y (90% C.L.)**
- **$m_{\beta\beta}$ ~(5-12 meV)**

→ allow to explore the normal neutrino mass ordering region

How to go down to 1 meV sensitivity ?

- If the sensitivity of $m_{\beta\beta}$=1 meV is ultimately realized, the determination of absolute neutrino masses and the constraints on one of two Majorana CP phases are possible. *J. Cao et al., Chin. Phys. C 44, no.3, 031001 (2020)*

- In the next 10 years, a dedicated R&D program in JUNO will focus on the purification and doping of liquid scintillator with a suitable $0\nu\beta\beta$ isotope, as well as on the development of advanced techniques, such as machine learning, for background rejection (especially solar ν and cosmogenics).

- A cost effective technique and a dedicated research facility will be developed during R&D to allow a mass production of enriched isotopes

- $m_{\beta\beta}$=1 meV sensitivity may be reached by JUNO using 250 tons of $0\nu\beta\beta$ isotope in 10 years live time (*Snowmass2021 – LOI)*

- JUNO neutrinoless double beta phase is supposed to start in ~2030

JUNO @IN2P3

- Several IN2P3 laboratories are already involved in the JUNO experiment (CENBG, CPPM, IJCLab, IPHC, Subatech) ~ 10-15 physicists

- Several contributions to the hardware (Top Tracker, SPMT system), to the radiopurity of the detector and to physics simulations

→ very good visibility in the JUNO collaboration

→ Opportunity to contribute to the R&D program on 0νββ phase in the next 10 years in France

Conclusions

- JUNO is a next generation experiment with a rich program in neutrino physics and astrophysics (MO, precise oscillation parameters, supernovae, geoneutrinos,…) thanks to a large size (20 ktons, 35 m) and an unprecedented energy resolution of 3%/√E(MeV)

- In a second phase by 2030, JUNO may become very competitive for the search of 0νββ decay using ^{136}Xe or ^{130}Te isotopes

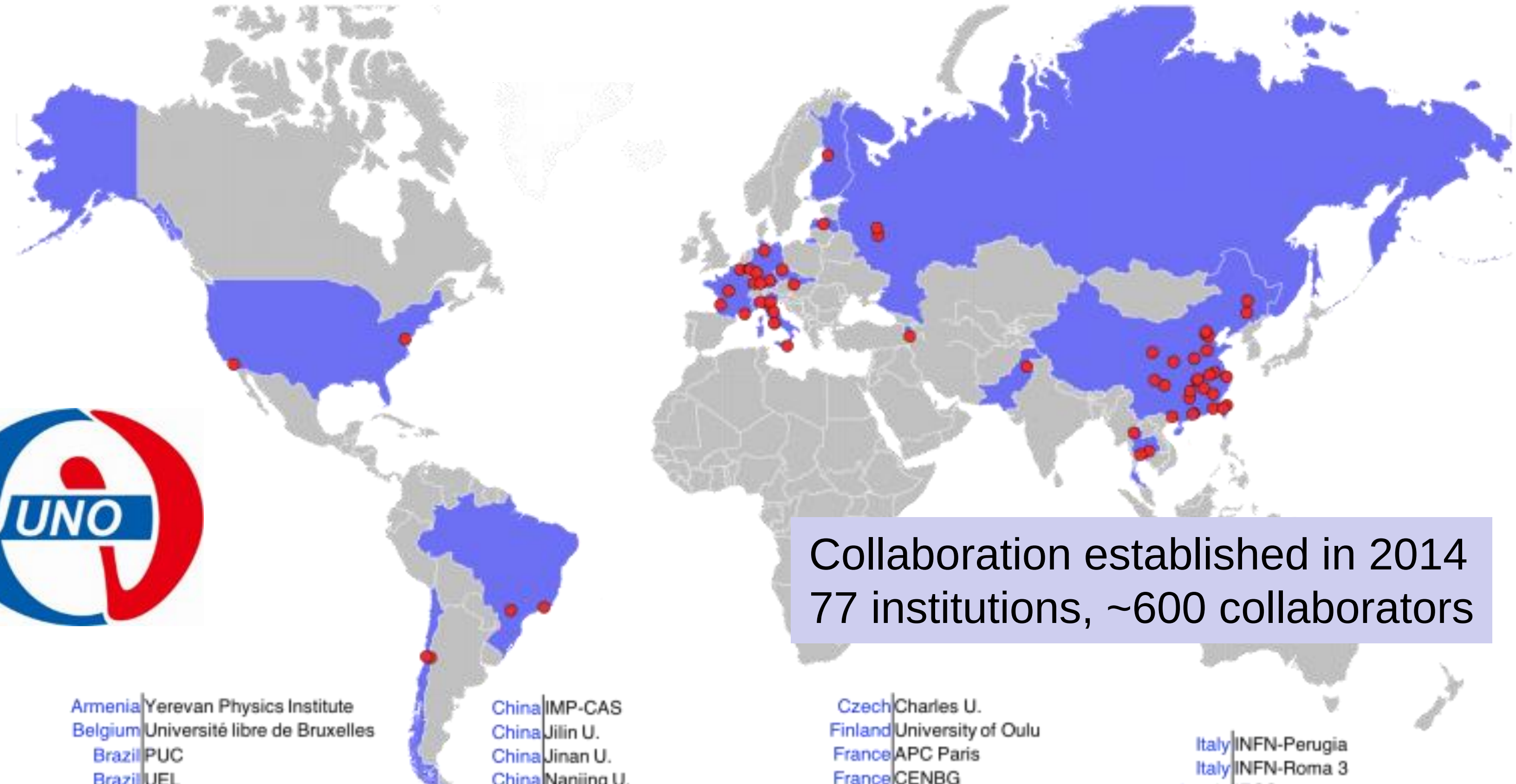
- A preliminary promising simulation study of the backgrounds has been performed to evaluate its sensitivity to 0νββ decays with an effective neutrino mass of 5-10 meV reached with 50 tons of ^{136}Xe and 5 years

- A dedicated R&D is foreseen in the next 10 years to focus on the purification and doping of liquid scintillator as well as on the development of advanced techniques for background rejection in order to reach a $m_{\beta\beta}$= 1 meV effective neutrino mass sensitivity

- Opportunity to contribute to this R&D program in France in the next years

Backup slides

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

Experiments vs sensitivity

experiment	isotope	exposure /(ton·yr)	$\varepsilon_{0\nu\beta\beta}$	B.I.	ROI /keV	90% C.L. limit (L) or sensitivity (S)	
						$T^{0\nu}_{1/2}$, $\times 10^{27}$yr	$m_{\beta\beta}$/meV
current results							
CUORE-0 [37]	^{130}Te (34.17%)	9.8e-3	0.813	58[a]	5.1 FWHM	0.004[b] (L)	270 – 760 (L)
EXO-200 [38]	^{136}Xe (80.6%)	0.1	0.846	1.7[c]	150 (2σ)	0.019 (S)	190 – 450 (L)
GERDA [39]	^{76}Ge (87%)	5e-3[d]	0.51	3.5	10.2 (3σ)	0.04[e] (S)	160 – 260 (L)
(phase-II)		5.8e-3	0.60	0.7	7.7 (3σ)		
KamLAND-Zen [17]	^{136}Xe (90.77%)	∼0.255	—	28.1/yr	400	0.056 (S), 0.092 (L)	61 – 165 (L)[f]
(phase-II)		∼0.249	—	15.5/yr	400		
prospective sensitivities							
EXO-200 phase-II [40]	^{136}Xe	∼0.16 · 3	—	—	—	0.057 (S)	110 – 260 (S)
KamLAND-Zen 800 [17]	^{136}Xe	∼0.8 · ?	—	—	—	—	∼50 (S)
SNO+ phase I [11]	^{130}Te	∼0.8 · 5	—	13.4/yr	—	0.09 (S)	55 – 133 (S)
CUORE [41]	^{130}Te	0.206 · ?	—	10	—	0.095 (S)	50 – 130 (S)
GERDA Phase-II [39]	^{76}Ge	>0.1	—	∼1	—	>0.1 (S)	—
SNO+ Phase II [11]	^{130}Te	∼8.0 · ?	—	—	—	0.7 (S)	19 – 46 (S)
KamLAND2-Zen [42]	^{136}Xe	∼1 · ?	—	—	—	—	∼20 (S)
nEXO [43]	^{136}Xe (90%)	∼5 · 5	—	0.02[g]	58FWHM	6.6 (S)	7 – 22 (S)
JUNO Xe-LS	^{136}Xe (80%)	50 · 5	0.63	0.012	110FWHM	18 (S)	5 – 12 (S)

[a]The quoted B.I. is normalized to the total TeO_2 exposure (35.2 kg yr). The same for CUORE.

[b]This limit is from the combination with the 19.75 kg·yr exposure of ^{130}Te from Cuoricino, while it is 2.7×10^{24} yr for CUORE-0 only.

[c]This quoted B.I. is normalized to the total Xe exposure (123.7 kg yr).

[d]The quoted 5 (5.8) kg·yr exposure is for the total coaxial (BEGe) detectors in GERDA Phase-II.

[e]The limits of $T^{0\nu}_{1/2}$ and $m_{\beta\beta}$ are from the combination of Phase-I and Phase-II. For Phase-I only, it was 2.1×10^{25} yr (90% C. L.).

[f]The quoted limit is from the combination of KamLAND-Zen Phase-I and Phase-II.

Background reduction

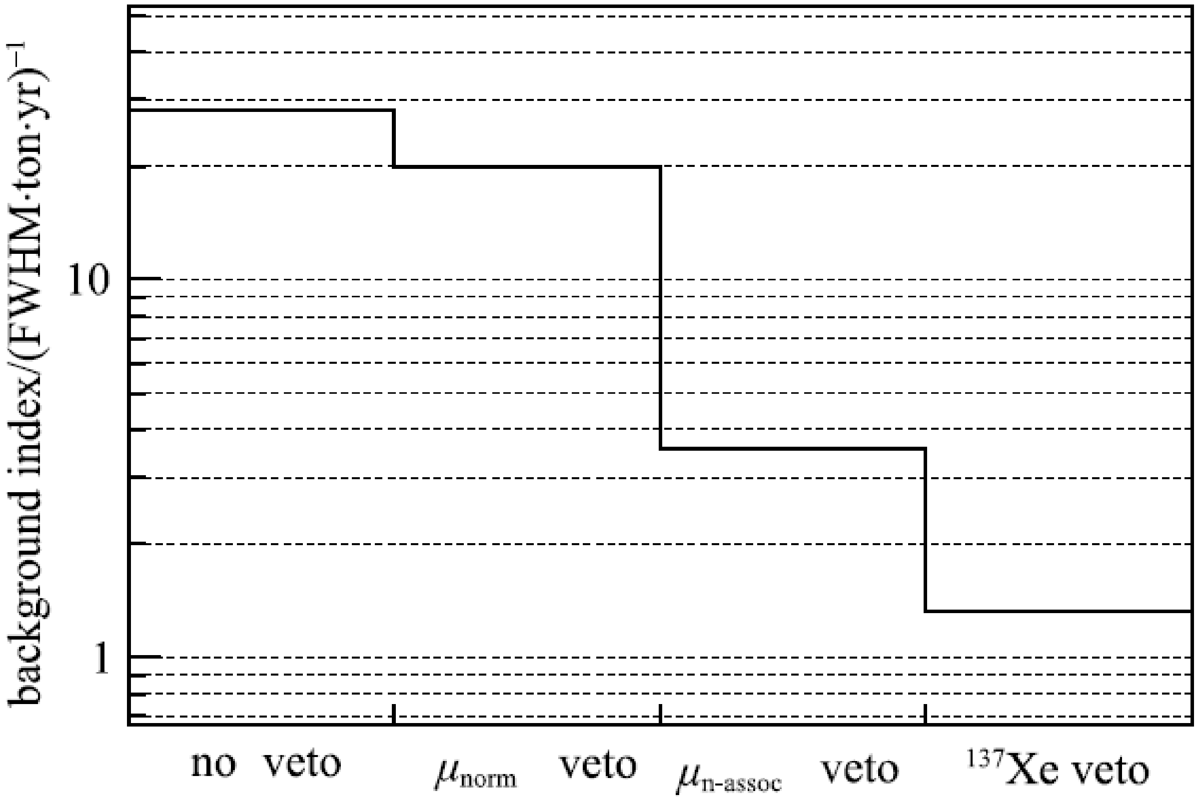


Fig. 1. The reduction of the total background index for different muon veto schemes. The μ_{norm} and $\mu_{\mathrm{n-assoc}}$ refer to the normal muon veto and the neutron-associated muon veto methods, respectively, as described in Section 3.4.