

Radiogenic background control strategy for the JUNO experiment

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On behalf of the JUNO collaboration



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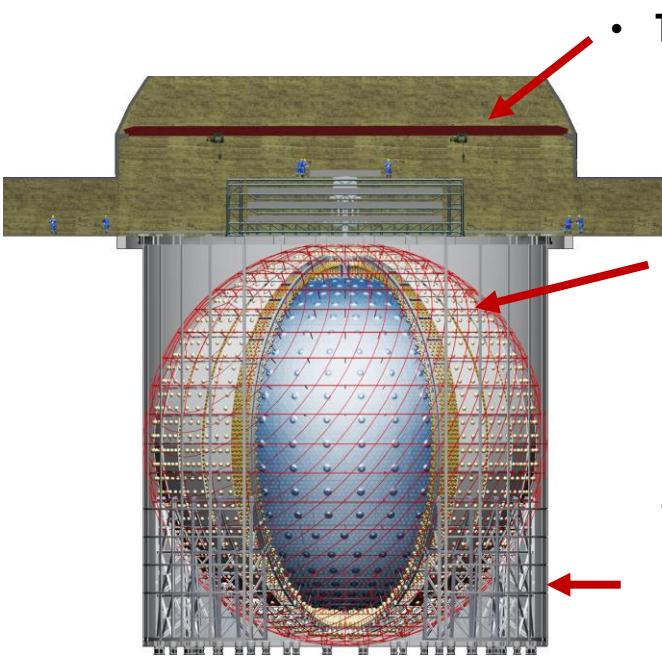
The JUNO experiment – Jiangmen Underground Neutrino Observatory

Main physics goal

- Determination of the **neutrino mass ordering** by measuring reactor antineutrinos
- Measuring oscillation parameter with a precision < 0.5 % (θ_{12} , Δm_{21}^2 , Δm_{31}^2)

JUNO features

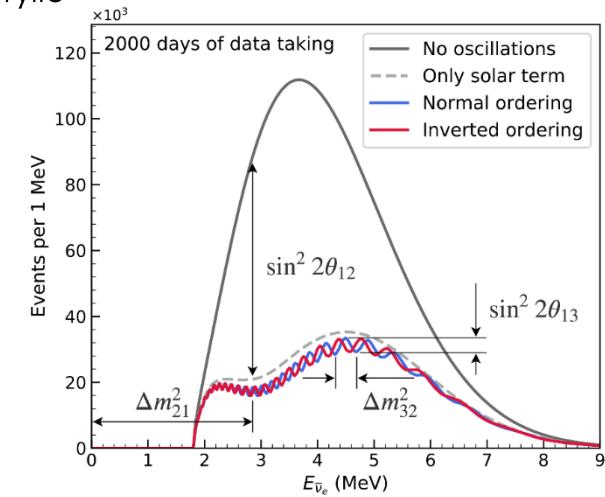
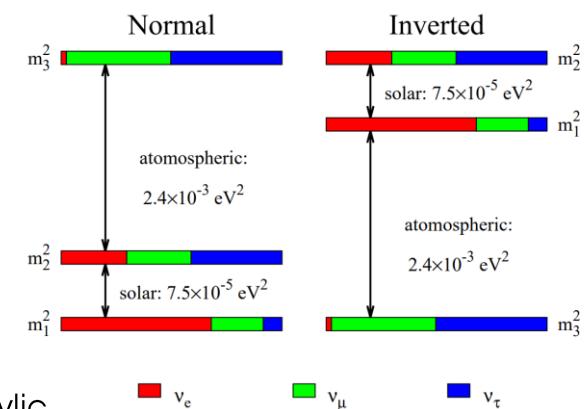
- The biggest LS-based neutrino detector
- Largest PMT coverage ever built
- Excellent energy resolution (3% @ 1 MeV)



- Top Tracker (muon veto)**
- Central detector:**
 - ~ 20 000 t of liquid scintillator in acrylic vessel
 - 17612 large PMTs (20-inch)
 - 25600 small PMTs (3-inch)
 - ~ 78% PMT coverage
 - Earth magnetic field shielding coil
- Water Cherenkov Detector (muon veto):**
 - 2400 20-inch PMTs
 - 35 000 t ultra-pure water
 - Muon detection efficiency > 99%

Broad physics program:

- Solar and supernova neutrinos
- Atmospheric neutrinos
- Geo-neutrinos
- Supernova neutrinos
- ...



JUNO site and construction

JUNO is under construction in the Guangdong province, in China, at 53 km from two nuclear power plants in order to maximize the sensitivity to the mass ordering.



- ✓ Large PMTs and small PMTs production completed
- ✓ LPMTs completely tested
- Acrylic panel production in progress
- Electronics production in progress
- Civil construction in progress

The detector construction
will be completed in 2023



Signal and background

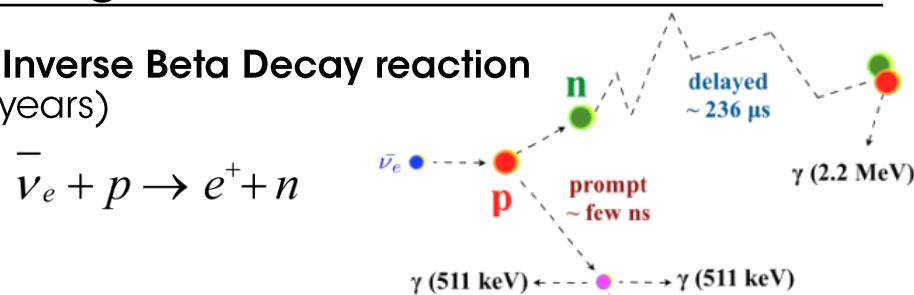
JUNO is designed to detect reactor antineutrinos via **Inverse Beta Decay reaction**
 Expected number of signal events: 60 cpd ($> 10^5 / 6 \text{ years}$)

Inverse Beta Decay (IBD) signals:

- Prompt signal from positron ionization and annihilation
- Delayed signal from neutron capture on ^1H (2.2 MeV γ)

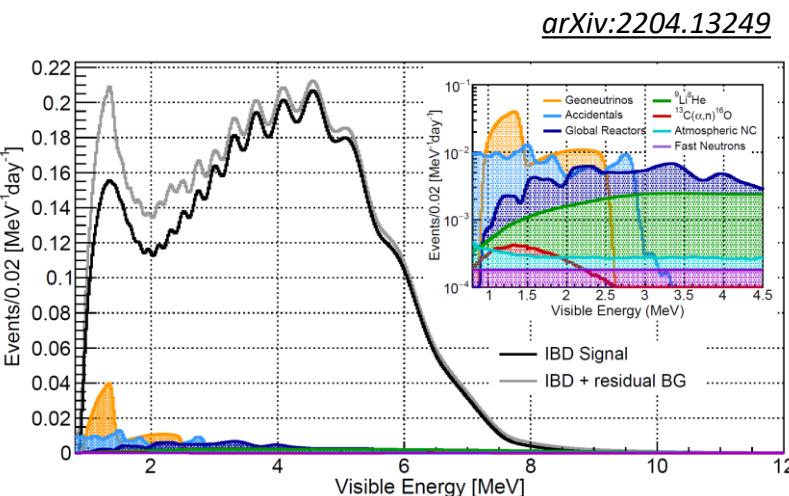
Criteria for IBD identification:

- Prompt signal: $0.7 < E_p < 12 \text{ MeV}$
- Delayed signal: $1.9 < E_d < 2.5 \text{ MeV}$
- Time coincidence $< 1 \text{ ms}$
- Distance between prompt-delay signal vertexes $< 1.5 \text{ m}$



Main background sources for IBDs

- Accidental background from natural radioactivity in materials
- Cosmogenic nuclei ($^9\text{Li}/^8\text{He}$)
- Fast neutrons and (α, n) reactions
- Geo-neutrinos
- Cosmic muons



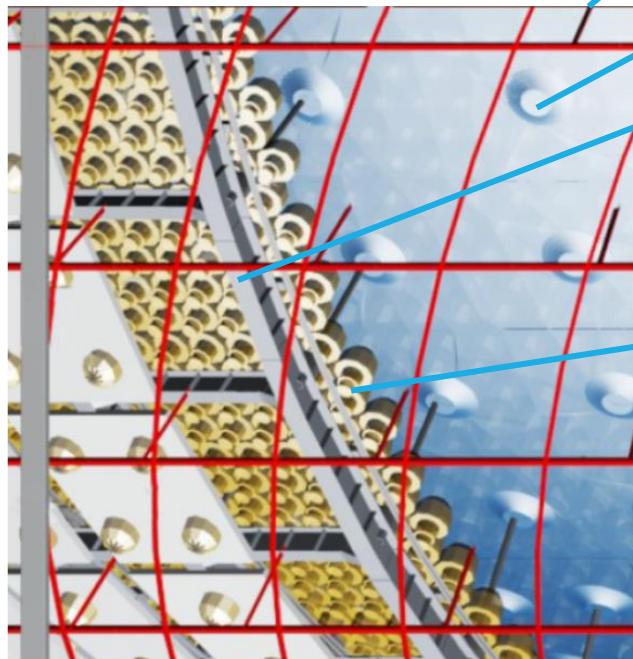
Source	Geo vs	World reactors	Accidentals	$^9\text{Li}/^8\text{He}$	Atm vs	Fast n	(α, n)
Rate	1,2	1,0	0,8	0,8	0,16	0,1	0,05

Single trigger count rate from natural radioactivity in materials must be below **10 Hz** in the liquid scintillator fiducial volume ($R < 17.2 \text{ m}$)

Need for **careful material selection**, surface cleanliness, radon emanation control and dust control.

Radiopurity requirements

All materials must be selected according to their intrinsic low concentration of natural radioactive nuclides.



The radiopurity requirements are less stringent as the distance from the LS increases

Material	Mass (t)	Radius (m)	^{238}U (ppb)	^{232}Th (ppb)	^{40}K (ppb)	$^{210}\text{Pb}/^{222}\text{Rn}$	^{60}Co (mBq/kg)
Liquid scintillator							
LS reactor	2000	0-17.7	10^{-6}	10^{-6}	10^{-7}	10^{-13} ppb	
LS solar			10^{-8}	10^{-8}	10^{-9}	10^{-15} ppb	
Acrylic vessel	580	17.7-17.8	0.001	0.001	0.001		
Acrylic nodes	28.5	17.8-17.9	0.001	0.001	0.001		
Calibration parts	0.04			1.5	4.5	0.02	
SS structure							
truss	1000	20.0-20.05	1	3	0.2		20
bars	65	17.9-20.0	0.2	0.6	0.02		1.5
LPMT glass							
NNTV	84.5	19.2-19.8	200	120	4		
Hamamatsu	33.5	19.2-19.8	400	400	40		
veto (NNTV)	16.0	20.2-20.8	200	120	4		
LPMT cover							
acrylic	110	19.2-19.4	0.003	0.01	0.01		
SS	150	19.4-19.8	0.4	2.5	0.12		
LPMT readout							
divider	0.6	19.8-19.9	3000	5000	100		
potting	24.5	19.7-19.9	70	50	4		
UWB	100	20.1-20.4	50	200	5		20
SPMT glass	2.6	19.3-19.4	400	400	200		
SPMT readout							
divider	0.15	19.4	3000	10000	200		
potting	5.1	19.4-19.5	100	50	20		
UWB	11	20.1-20.4	50	200	5		20
Water	35000	17.8-21.8				10 mBq/m ³	
Rock			10000	30000	5000		

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Measurement techniques

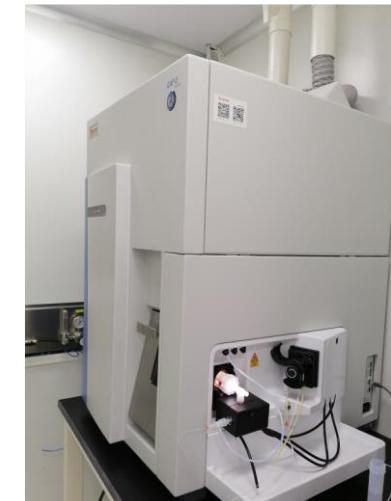
The most suitable techniques for measuring the radioactive contamination of materials depend on different factors



- Live-time of the radionuclides
- Nature and phase of the sample matrix
- Distribution of the contamination

HPGe gamma spectroscopy	<ul style="list-style-type: none">• Short-lived gamma emitters• All matrices can be measured• High mass samples
Neutron activation analysis	<ul style="list-style-type: none">• Long-lived nuclides (especially U, Th and K)• All non activable matrices can be measured• Small mass sample
ICP mass spectrometry	<ul style="list-style-type: none">• Long-lived and stable nuclides (except K)• Almost only aqueous matrices• Small mass sample
Dedicated system for LS	

ICP-MS



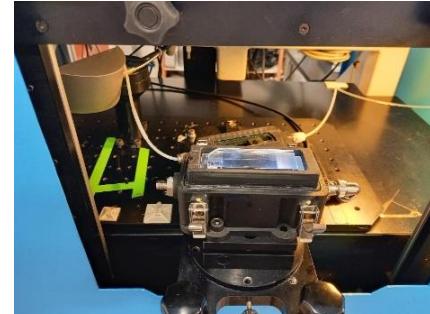
HPGe



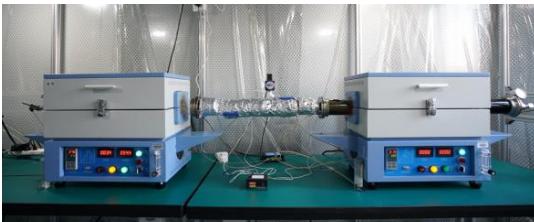
NAA



Laser ablation ICP-MS



Furnace for acrylic ICP-MS



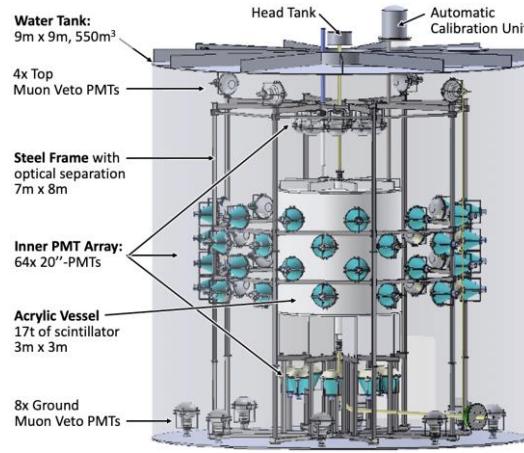
Liquid scintillator

LS is most critical component: $U, Th < 1 \text{ ppq}$, $K < 0.1 \text{ ppq}$ for IBD

- Recirculation impossible for JUNO
 - The requirement must be achieved from the beginning
- Dedicated systems and techniques for LS/LAB validation

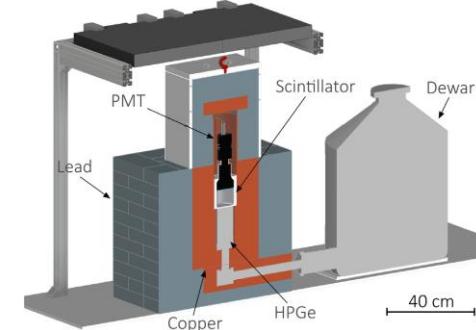
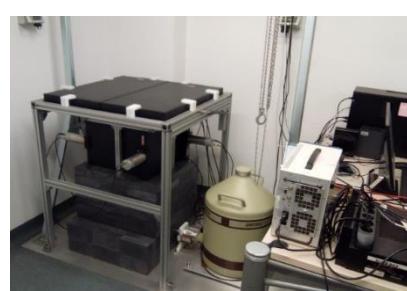
Purification steps:

1. Filtration on Al_2O_3
2. Distillation
3. Water extraction
4. Gas stripping
5. Filling



The LS will be measured with a dedicated detector (OSIRIS) before entering in the acrylic vessel.

- Few days to reach $1 \times 10^{-15} \text{ g/g}$ on U/Th (Bi-Po)
- Drawbacks:
 - Sensitive only to the low part of the U and Th decay chain
 - Able to measure the LS only at the end of the four purification steps



Possible complementary method to measure LAB before each purification step and on smaller samples.

@ Milano-Bicocca (Italy): beta-gamma coincidence detector + delayed coincidence technique + NAA to achieve the required sensitivities for LAB

Acrylic vessel

Acrylic requirements: U, Th, K < 1 ppt

- Mass production started
- Controlled production, cleaning and polishing procedure
 - Bulk measurements at IHEP by ICP-MS, at INFN-Milano by NAA and LNGS with HPGe
 - Surface measurement at LP2i by laser ablation ICP-MS
- All requirements are satisfied

NAA measurements

1. Sample laser cutting
2. Cleaning
3. Activation @ TRIGA reactor
4. HPGe measurement



Sample	Mass (g)	40K (ppt)	238U (ppt)	232Th (ppt)
S0201	41.4	0,09±0,02	<0,17	<0,13
S1001 S0301	42.0	0,38±0,04	<0,24	<0,71
S0701-3000	26.7	0,07±0,02	<0,4	<0,7
S0701-2000	26.7	0,14±0,04	<0,3	<0,5

NAA - Acrylic mass production

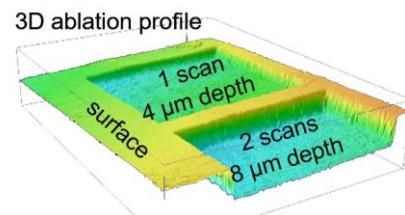
ICP-MS measurements

- ICP-MS for acrylic @ IHEP
Widely used for mass production control
- Laser ablation ICP-MS @ LP2i
Information about surface contaminations

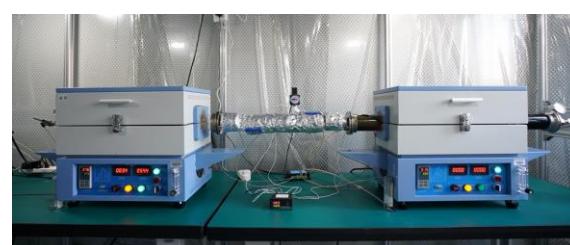
Sample mass: 13,6 kg
Detector: GeMPI2
Time: ~ 48 d

HPGe measurement @LNGS
(courtesy of dr. M. Laubenstein)

	Activity [mBq/kg]	Concentration [g/g]
232Th		
228Ra	<0,062	< 1.5·10 ⁻¹¹
228Th	<0,058	< 1.4·10 ⁻¹¹
238U		
234Th	<2,6	< 2.1·10 ⁻¹⁰
234mPa	<1,1	< 8.7·10 ⁻¹¹
226Ra	<0,045	< 3.6·10 ⁻¹²
235U	<0,074	< 1.3·10 ⁻¹⁰
40K	<0,31	< 1.0·10 ⁻¹⁰
137Cs	<0,031	



Laser ablation ICP-MS



ICP-MS - Acrylic mass production

Main external components screening by HPGe

PMTs

- Production completed
- All requirements are satisfied for both Large PMTs and Small PMTs

Requirements:

PMTs	238U (Bq/kg)	232Th (Bq/kg)	40K (Bq/kg)
LPMTs NNVT	2,5	0,5	1
LPMTs Hamam.	5	1,6	10,5
SPMTs	5	1,6	50

Sample	238U (Bq/kg)	232Th (Bq/kg)	40K (Bq/kg)
Sept 2019	1,80±0,17	1,55±0,11	32±2

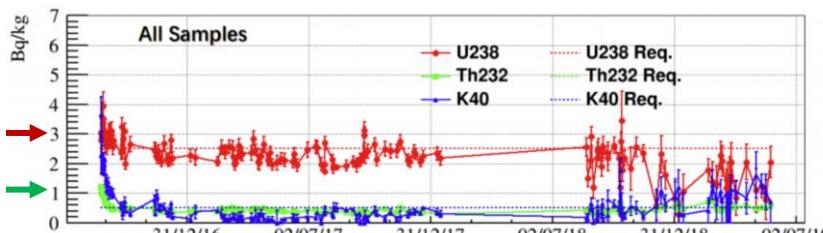
Small PMTs control measurement

Stainless steel

- Production completed
- Installation will be completed this month
- All requirements are satisfied

Requirements:

238U (mBg/kg)	232Th (mBg/kg)	40K (mBg/kg)
2,5	2,4	5,3



NNVT Large PMT bulb glass mass production control analysis

Sample (Bq/kg)	238U	238U from 226Ra	232Th from 224Th	40K
Glass @ LP2i	4,7±0,3	6,5±0,2	2,3±0,1	1,9±0,3
Glass @ Milano-Bicocca	-	5,4±0,2	1,9±0,1	1,7±0,3

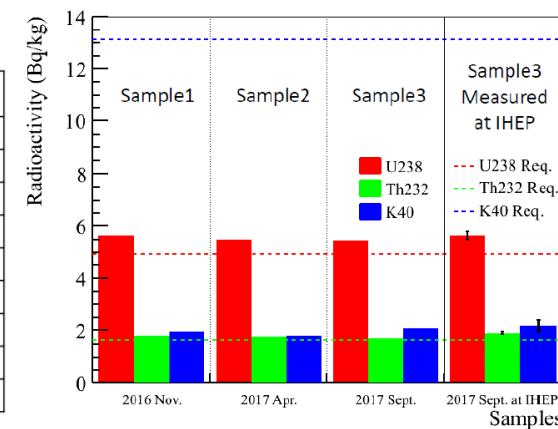


Hamamatsu Large PMT bulb glass control analysis

SS for bars @ LNGS
Sample mass: 3,18 kg
Detector: GeMPI3
Time: ~ 21 d

	Activity [mBq/kg]	Concentration [g/g]
²³² Th		
²²⁸ Ra	0,8±0,3	(2,1±0,8)·10 ⁻¹⁰
²²⁸ Th	0,5±0,2	(1,2±0,6)·10 ⁻¹⁰
²³⁸ U		
²³⁴ Th	<34	<2,8·10 ⁻⁹
^{234m} Pa	<12	<9,8·10 ⁻¹⁰
²²⁶ Ra	0,3±0,1	(3±1)·10 ⁻¹¹
²³⁵ U	<1,1	<2,0·10 ⁻⁹
⁴⁰ K	<2,8	<8,9·10 ⁻¹¹

Hamamatsu Large PMT bulb glass @ Hamamatsu and IHEP



Background Monte Carlo validation

Monte Carlo simulations are required to evaluate the contribution of each detector components to the detector background.

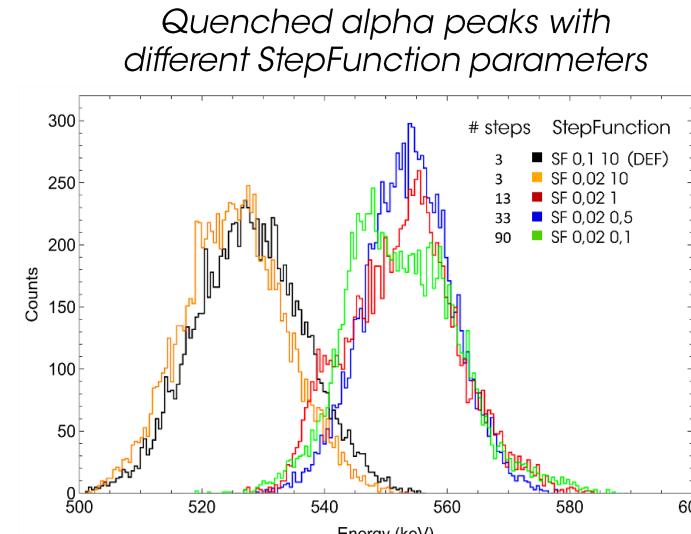
The outcomes of the simulations are used for

Experimental design
Material selection process

MC requirements and characteristics

- The JUNO geometry is reconstructed with the **highest possible accuracy**
- Each component is **uniformly contaminated** with ^{238}U , ^{232}Th , ^{40}K and eventually ^{60}Co and ^{210}Pb
- Two different codes based on Geant4 were used to obtain a cross validation on all components, **SNiPER** (official tool), **ARBY** (INFN-MIB), and a third one **G4-LA** (LP2i) for LAB and acrylic.
- Implementation of the **quenching factor** of LS using the Birks' equation

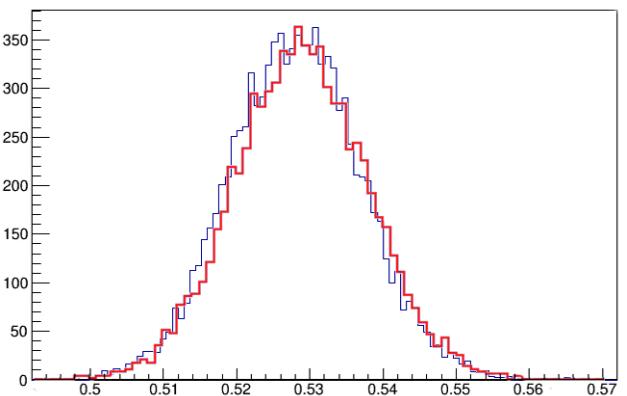
$$E_{scint} = S \cdot \int_0^E \frac{dE}{1 + kB \frac{dE}{dx} + C \left(\frac{dE}{dx} \right)^2}$$



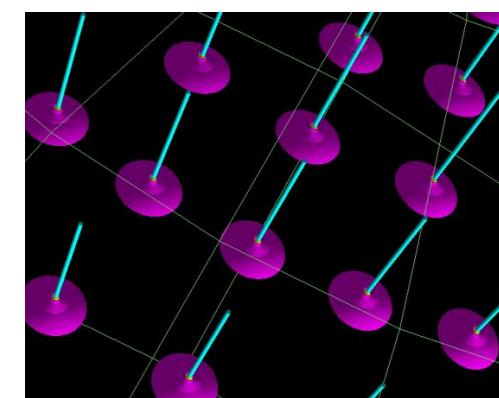
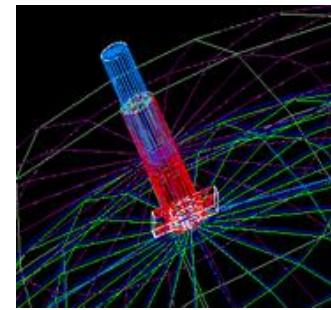
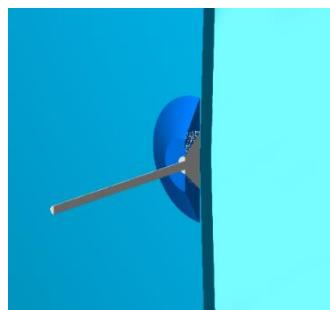
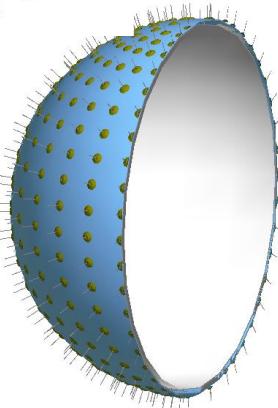
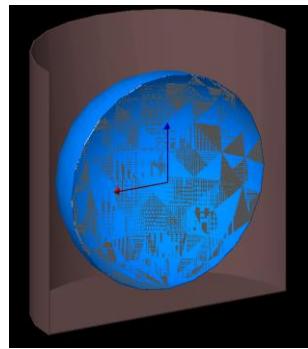
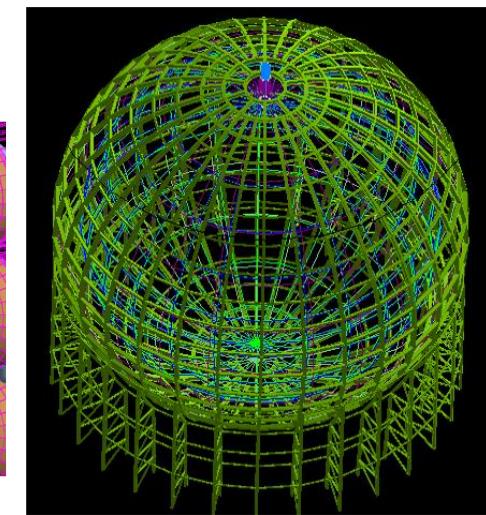
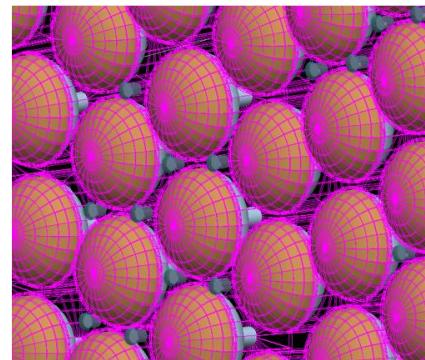
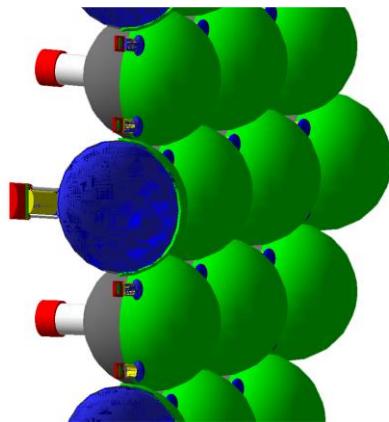
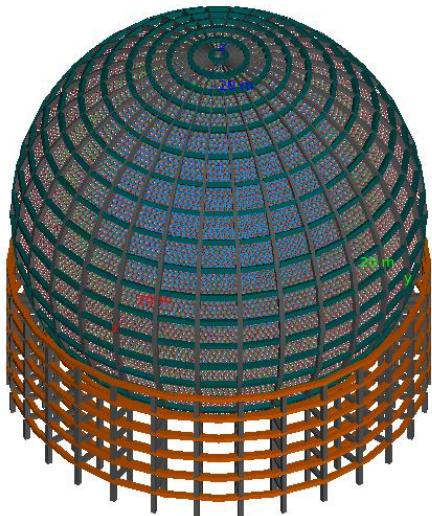
Final Monte Carlo simulation parameters:

- Geant4 version: 10.04.p02
- Physics List: Livermore (default version of G4.10.04.p02)
- Default StepFunction parameters: (0.1, 10um)
- Secondary electron production threshold: 0.1 mm
- Quenching factor for a: $kB = 3,705 \cdot 10^{-3}$; $C = 1,5 \cdot 10^{-6}$
- Quenching factor for b/e: $kB = 6,5 \cdot 10^{-3}$; $C = 1,5 \cdot 10^{-6}$
- Use G4 generator for beta spectra

Quenched alpha peaks comparison (SNiPER-ARBY)



Background Monte Carlo validation: ARBY and SNiPER Models



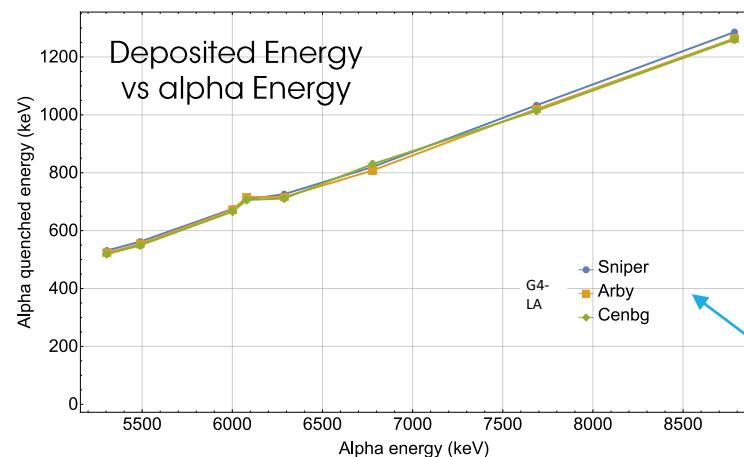
ARBY

SNiPER

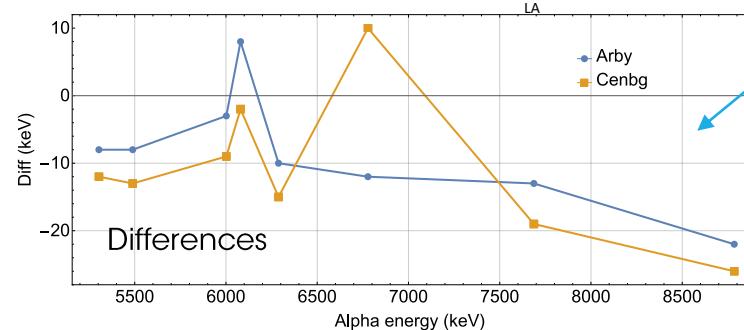
Background Monte Carlo validation: simulations

Simulation setup

- Uniform contamination in the selected volume
- Simulation of the complete decay chain
- No energy resolution applied
- Spectra energy range 0 – 12 MeV
- Spectra binning 10 keV
- Applied QF



MC physics validation



Alpha quenching results

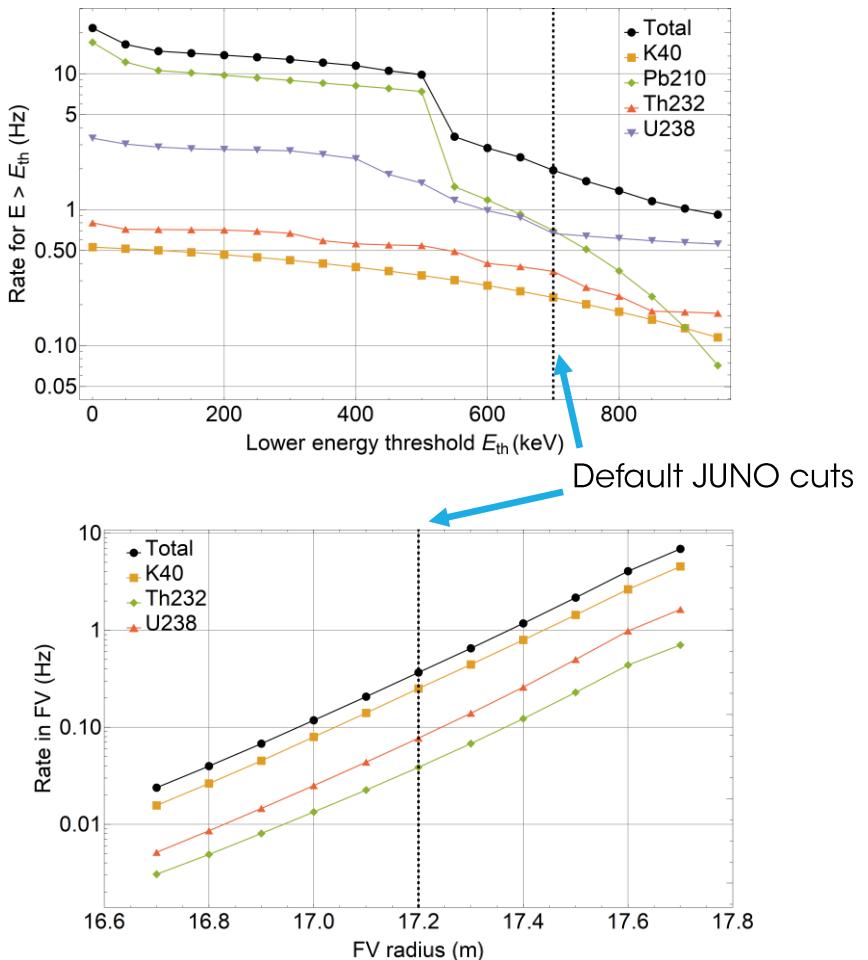
Components simulated by each MC code

Component	SNiPER	ARBY	G4-LA
LS			
Acrylic			
LPMT Glass			
LPMT Acrylic cover			
LPMT SS protection			
LPMT Electronics	Scaled		
SPMT Glass	Scaled		
Nodes & Bars			Low detailed geom
Truss	Scaled		Low detailed geom
Radon			
Rock	MC + Analytic		
Calibration			
Not simulated			

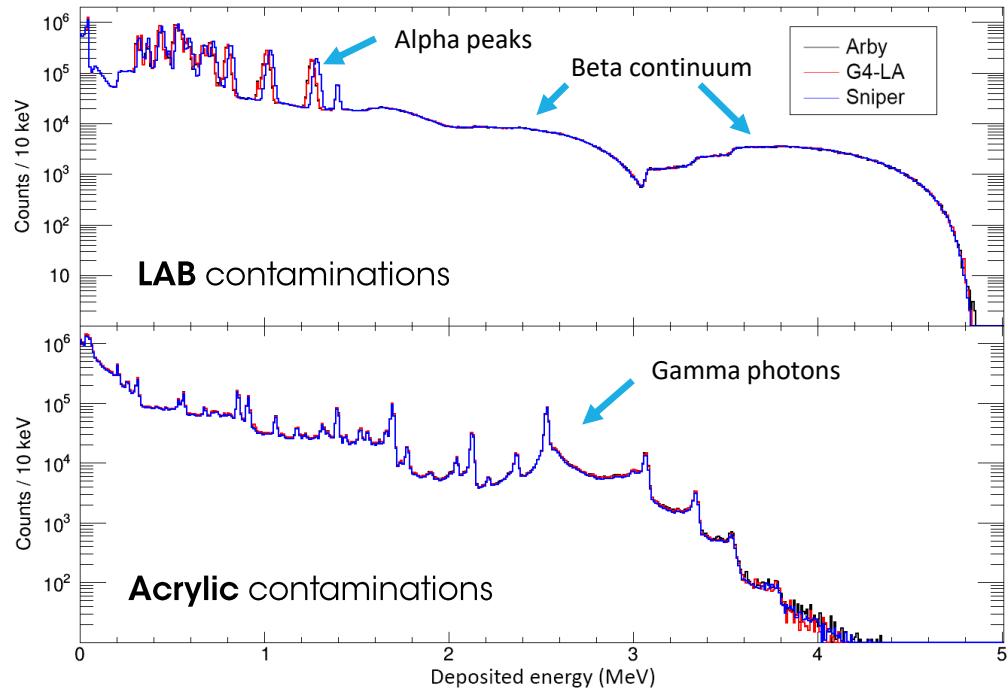
Differences between Sniper and Arby/G4-LA are < 25 keV

Background Monte Carlo validation: results

Background count rates as a function of the lower-level energy threshold and fiducial volume radius cut for LAB contaminations



Deposited energy in the LS fiducial volume ($R < 17.2$ m) from **LAB** and **acrylic** contaminations



Differences between the global rate from the three code are below 2.5% for LAB and acrylic and 7% for all other external components.

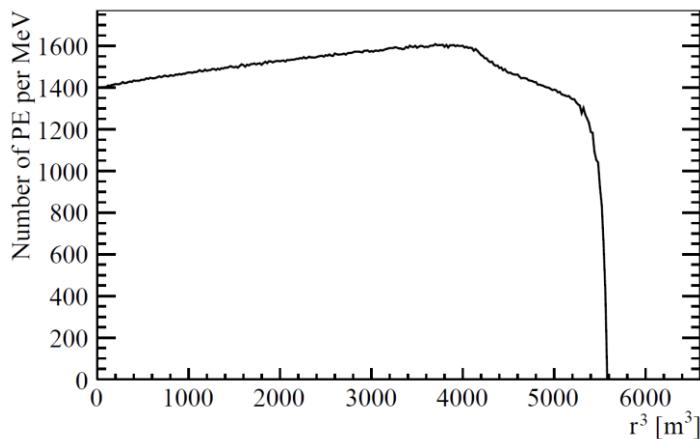
Expected background rate in JUNO

Full event simulation is performed with the SNiPER framework including:

- Energy resolution
- Optical propagation
- Charge conversion
- Non-uniformity of the detector response.



Response of JUNO detector to 1 MeV gamma-ray as a function of the interaction radius



Expected singles rates for JUNO with and without FV cut (17.2 m) and with $E > 0.7$ MeV

Material	Mass (t)	Singles ALL (Hz)	Singles FV (Hz)
LS-reactor	20000	2.5	2.2
Acrylic	610	8.4	0.4
SS structure	1065	15.9	1.1
PMT glass	136.6	26.2	2.8
PMT readout	141.3	3.4	0.3
Other		2.5	0.3
Sum		59	7.2

Conclusions

JUNO is a **massive LS-based** neutrino detector (20 kton) → Expected signal rate in JUNO is **60 IBD per day** → **Natural radioactivity** background overlaps with the signal → **The control of the background sources is crucial**

Measurement for material screening

- Requirements at the limit of available techniques → Development of new techniques and measurement systems
- Different techniques are used based on the sample nature and nuclides (HPGE, NAA, ICP-MS ...)
- Measurement on pre-production samples for screening and production samples for quality control
- All materials comply the JUNO requests

Monte Carlo simulations

- Performed using three different and independent codes (SNiPER, ARBY, C4-LA) to cross-check the results of the official tool (SNiPER)
- Very good agreement has been obtained in central detector: differences are < 2,5 % for LS and 1,6 % for Acrylic total rate
- Good agreement has been obtained also in all external volumes
- The final rate estimation is provided by Sniper simulation considering also the energy resolution, photon propagation, non uniform response and charge conversion

Based on the measured data and Monte Carlo simulation:

- The total expected singles background rate is ~ 7 Hz, lower than the 10 Hz target for IBD analysis channel.

More detail in the paper: Radioactivity control strategy for the JUNO detector. J. High Energ. Phys. 2021, 102 (2021)

Thank you
for your attention

Backup slides

IBS cuts effect on accidental rate

IBD identification cuts uses time
and distance information to
suppress background

$$\Delta t < 1 \text{ ms}$$

$$\Delta x < 1.5 \text{ m}$$

*Rate of a couple of singles events from
radioactive background that satisfies
the signal selection criteria of JUNO*

R_{acc} (cpd)	Fiducial volume radius (m)				
	17.0	17.1	17.2	17.3	17.4
$E_{\text{th}}=0.7 \text{ MeV}$	0.20	0.41	0.89	2.0	4.9
$E_{\text{th}}=0.8 \text{ MeV}$	0.19	0.38	0.83	1.9	4.6
$E_{\text{th}}=0.9 \text{ MeV}$	0.17	0.35	0.78	1.8	4.3

Expected accidental rate
in JUNO detector
To be compare with the
IBD rate of ~ 60 cpd

Improvements could be possible during the running phase of JUNO,
where the default cuts will be tuned to optimize the signal over
background ratio.