Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO

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On behalf of the JUNO collaboration

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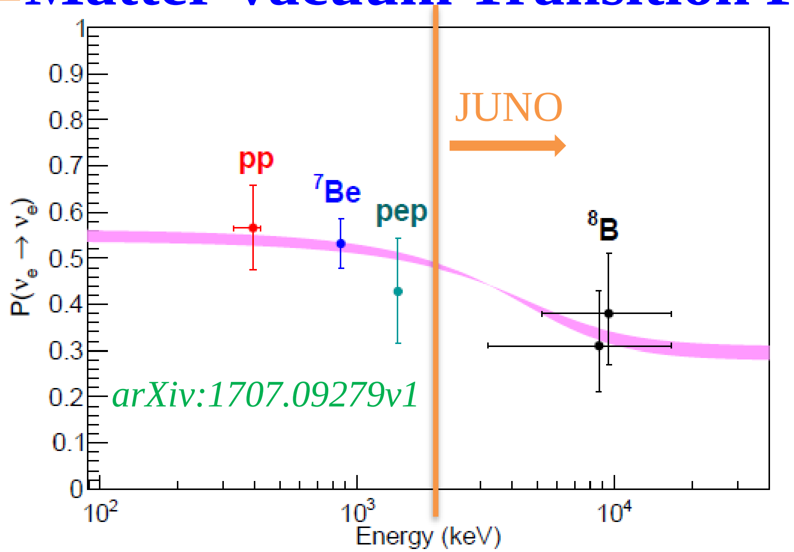
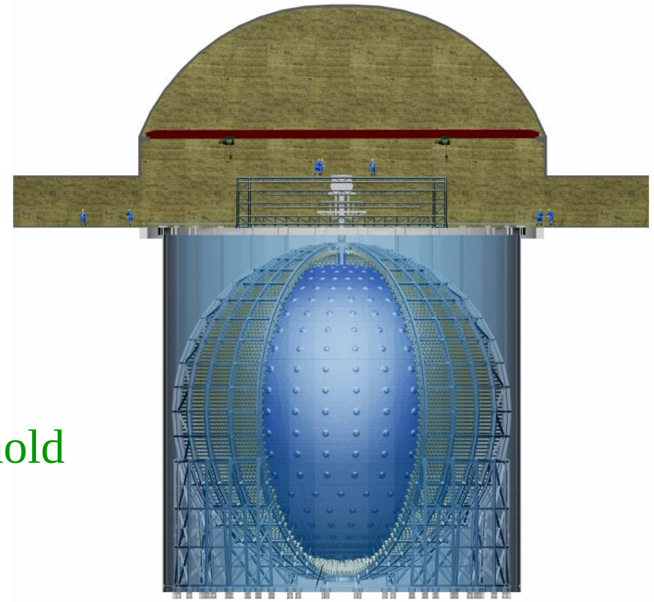
Physics potentials for low threshold ^{8}B neutrinos @JUNO

Matter-vacuum Transition Phase (E > 2 MeV)



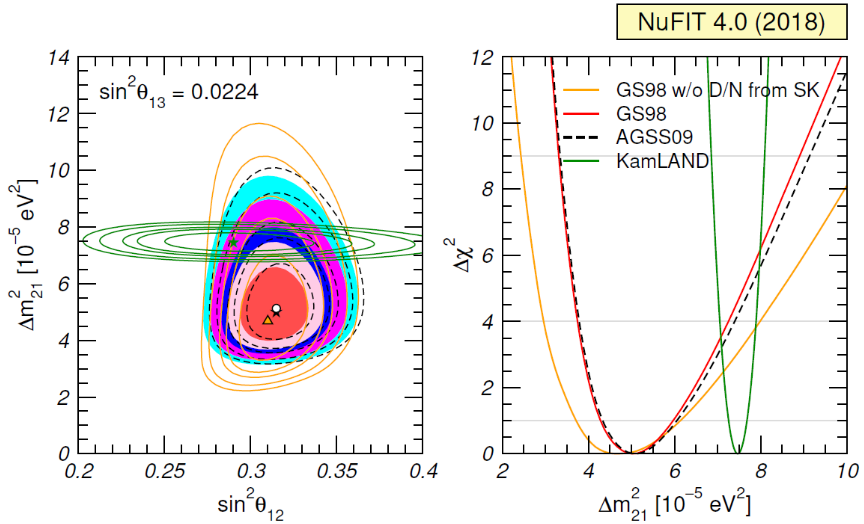
JUNO detector



20 kt LS, 3%/$\sqrt{E}$ energy resolution

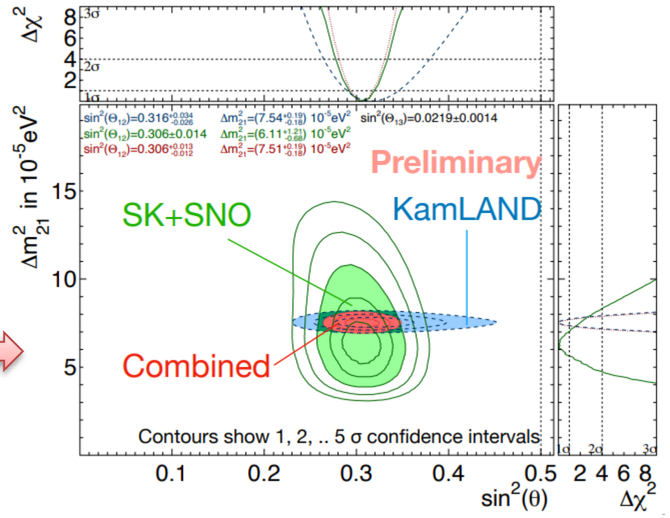
- ✓ Afford excellent self-shielding
- ✓ Comparable statistics to Super-K
- ✓ Expected 2 MeV detection threshold

Solar & reactor measurement in Δm^2_{21} using one single detector



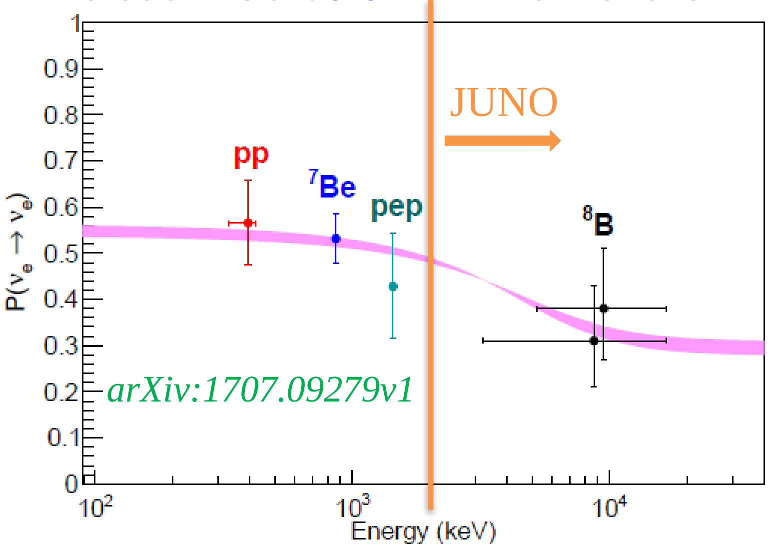
2.2 σ (2018) -> 1.4 σ (2020)

SK results @ Neutrino2020



Physics potentials for low threshold ^{8}B neutrinos @JUNO

Matter-vacuum Transition Phase



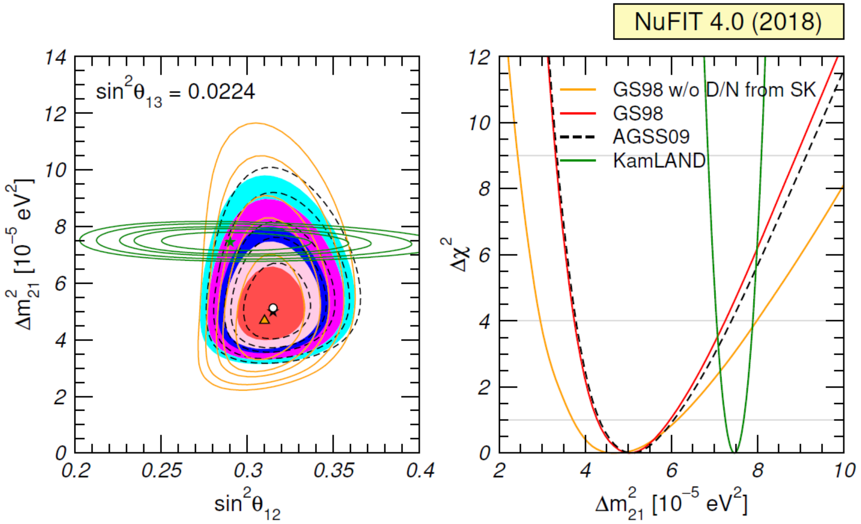
Two main observables:

- ✓ ES channel (ν+e → ν+e): E_{vis} > 2 MeV
- ✓ Day-night asymmetry

Challenge: Cosmogenic & Radioactivity

- ✓ LS radioactivity: 10^{-17} g/g (solar phase)
- ✓ Optimized fiducial volume
- ✓ Better muon veto approach

Solar & reactor measurement in Δm^2_{21} using one single detector



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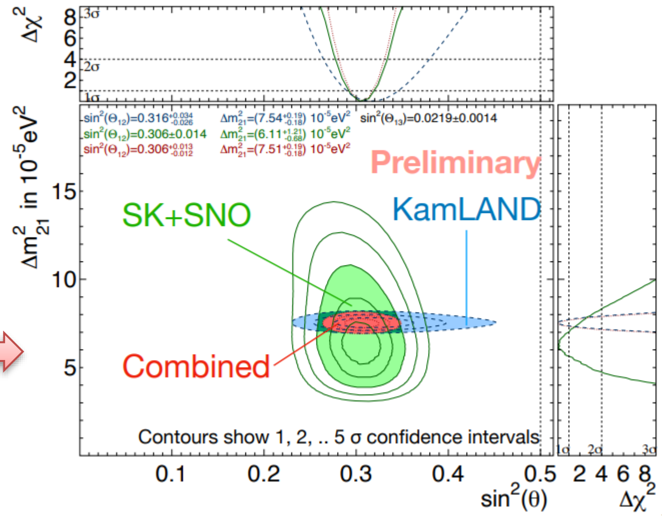
SK results @ Neutrino2020



Prediction

Neutrino flux and spectrum

- **Flux:** $(5.25 \pm 0.20) \times 10^6$ /cm^2/s from SNO NC measurement *(Phys.Rev.C* 88 (2013) 025501)
- **Spectra:** http://www.sns.ias.edu/~jnb

ES signal in JUNO LS

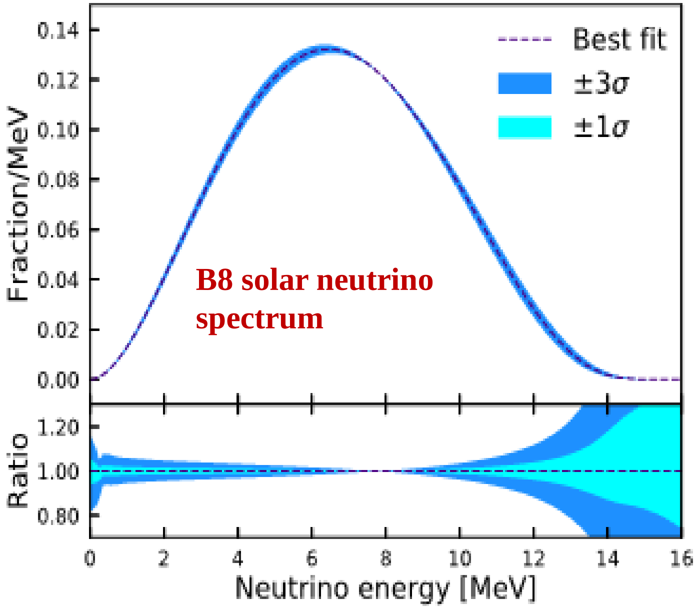
Rate $[cpd/kt]$	(0, 16) MeV		(2, 16) MeV	
	Day	Night	Day	Night
Δm^2_{21}=4.8×10^{-5}eV^2	2.05	2.10	1.36	1.40
Δm^2_{21}=7.5×10^{-5}eV^2	2.17	2.19	1.44	1.46

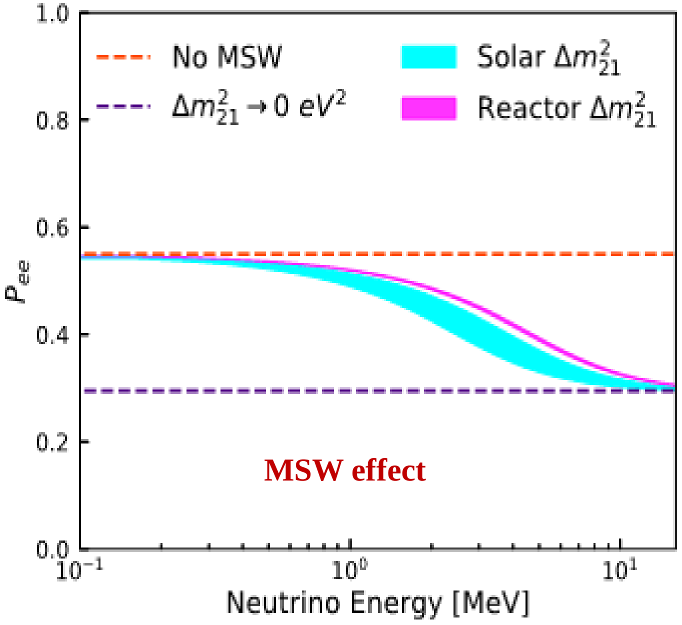
Detection

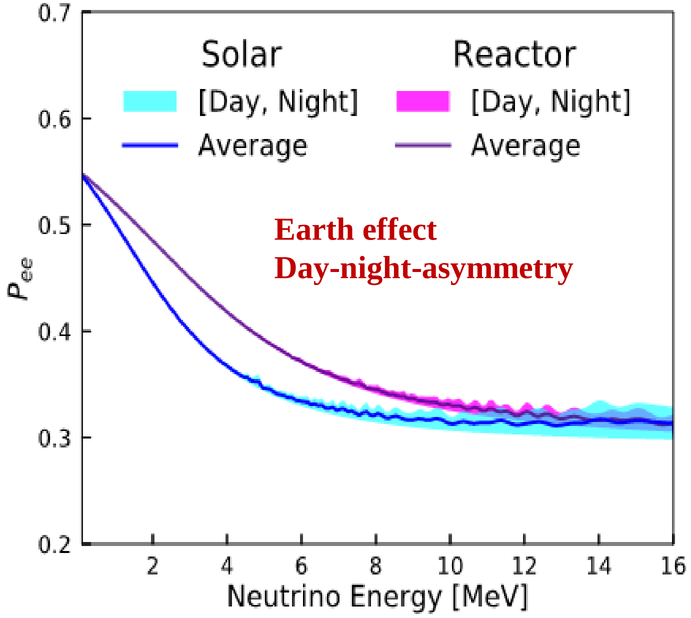
In this talk

- **Main channel:** ν-e ES $\nu_\alpha + e^- \to \nu_\alpha + e^-$
- **Other channel:** ν_e–^{13}C CC $\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}$

  ν–^{13}C NC $\nu + {}^{13}\mathrm{C} \to \nu + {}^{13}\mathrm{C} + \gamma$

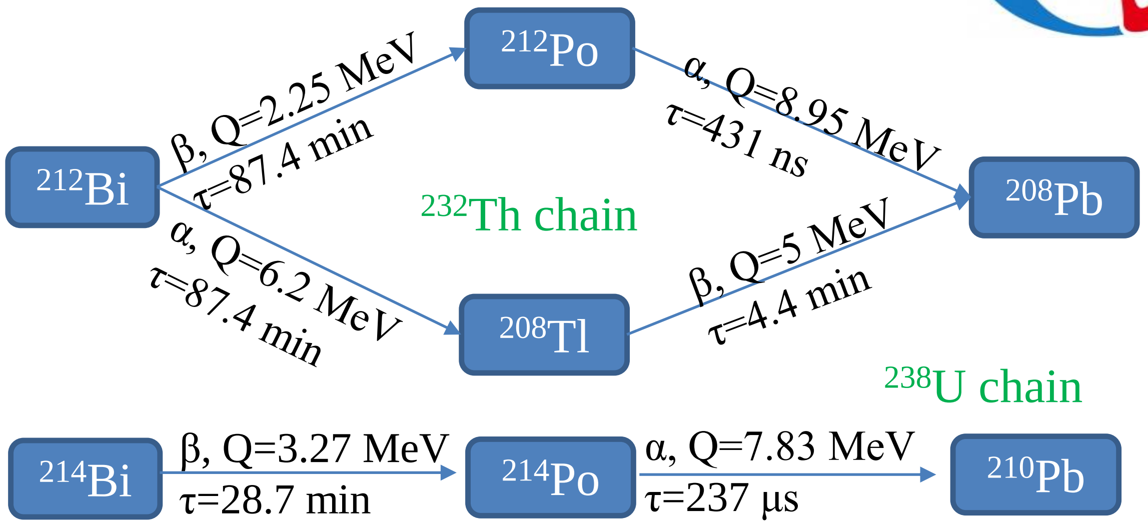




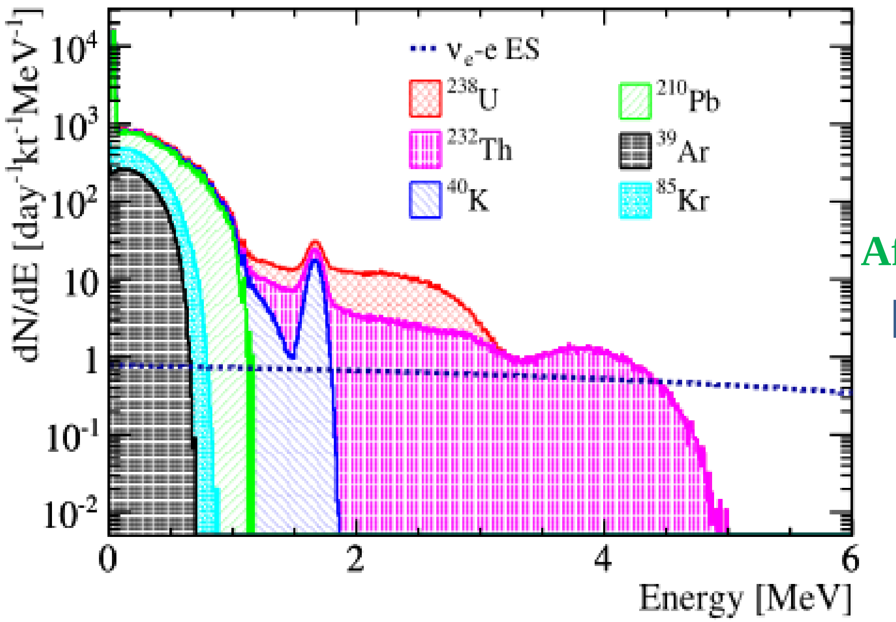


Internal background

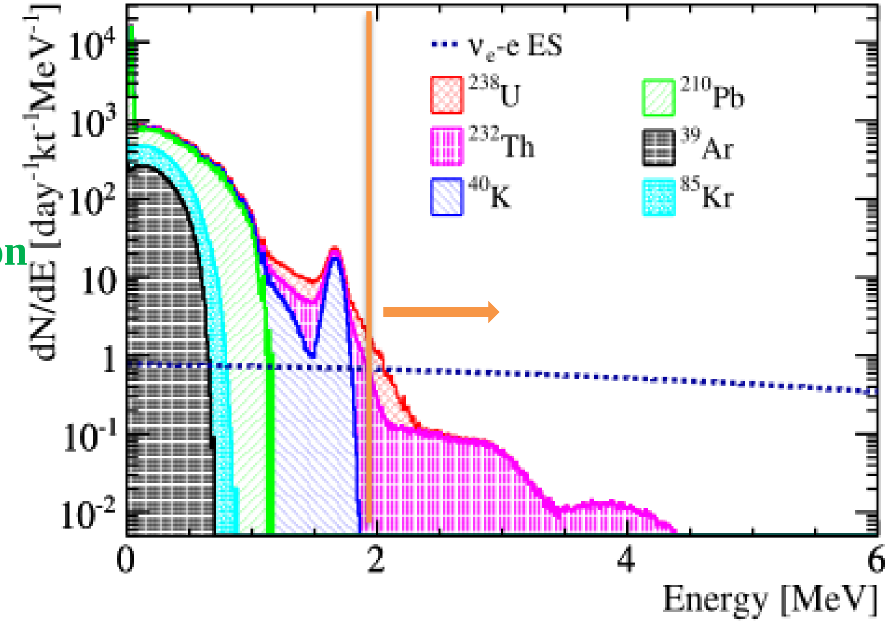
- ~2 MeV threshold achievable
  - ✓ ^{210}Bi, ^{40}K are not easy to be removed.
  - ✓ Alpha energy after quenching is < 2 MeV
  - ✓ ^{214}Bi, ^{212}Bi and ^{208}Tl decays can be removed by cascade decays.
    - Well discrimination on α/β with PMT shape information



^{238}U: 10^{-17} g/g
^{232}Th: 10^{-17} g/g
^{40}K: 10^{-18} g/g
^{210}Pb: 10^{-24} g/g
^{14}C: 10^{-17} g/g
^{39}Ar/^{85}Kr: 1uBq/m^3
^{210}Po: 2600 cpd/kt



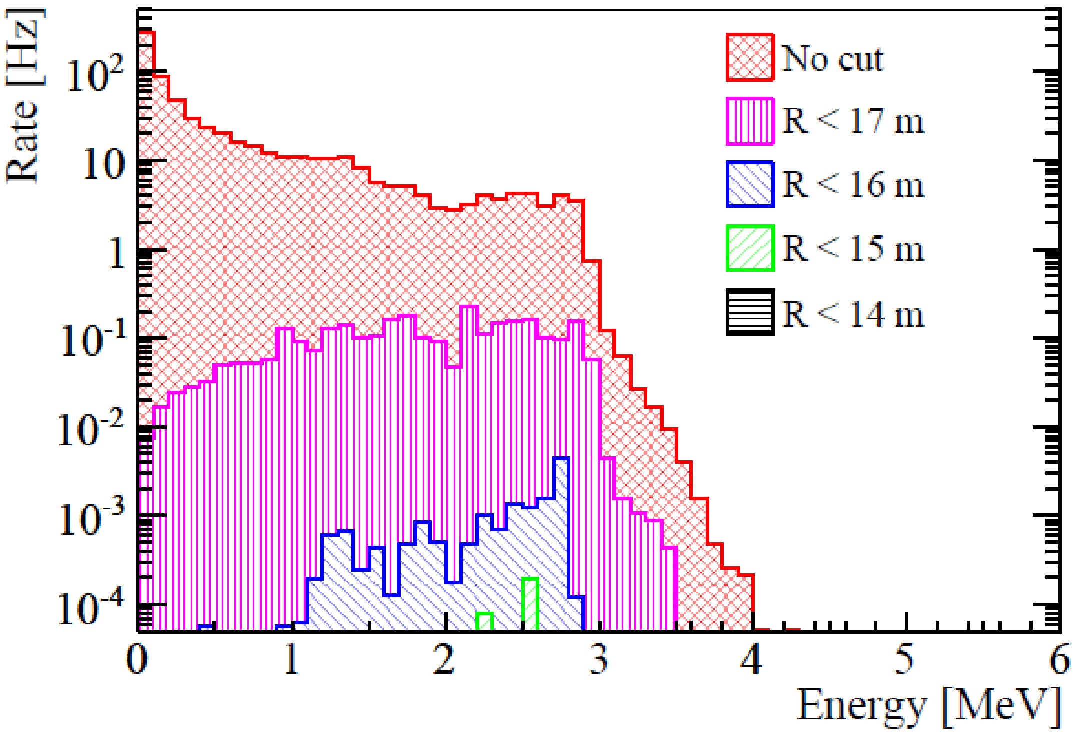
After reduction



External radioactivity

External radioactivity

Main materials	Measurement (U/Th)	Information
Acrylic	< 1 ppt	Measured by NAA (LRT2019) and ICP-MS (arXiv2011.06817)
Stainless steel	< 1 ppb	Same supplier with Daya Bay
PMT glass	~200 ppb	Ref: NIMA 898 (2018) 67–71
Water	Radon < 0.1 Bq/m^3	Ref: RDTM (2018) 2:48
Rock	10~30 ppm	4 m water and 5 mm HDPE shielding, negligible



External neutron captures

- ✓ High energy gamma: neutron captures on iron, PMT glass and acrylic
- ✓ Residual: < 0.001 cpd with R < 16.5 m

Final optimized fiducial volume cut

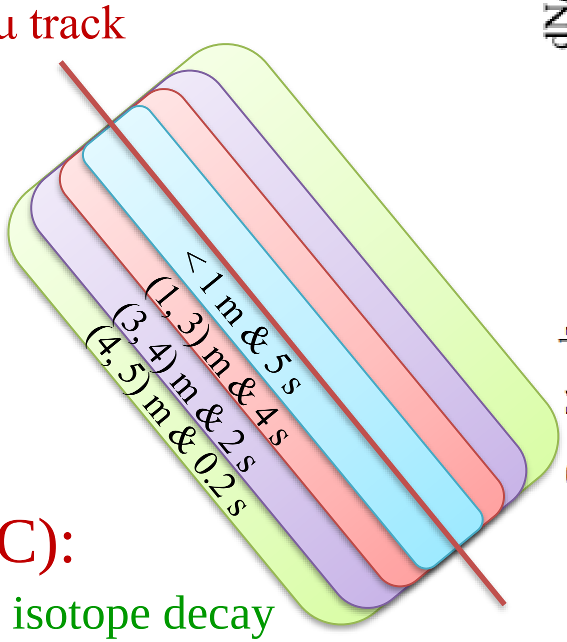
	R < 16.5 m	R < 15 m	R < 13 m
Energy (MeV)	> 5	(3, 5)	(2, 3)
Target mass (kt)	16.2	12.2	7.9

- ✓ With about 5 m self-shielding, ^{208}Tl decays from external materials are negligible.

Long-lived cosmogenic isotopes

Muon rate

Overburden	Muon flux	$<E_\mu>$	R_μ in LS	R_μ in water
~700 m	0.004 Hz/m^2	207 GeV	3.6 Hz	10 Hz



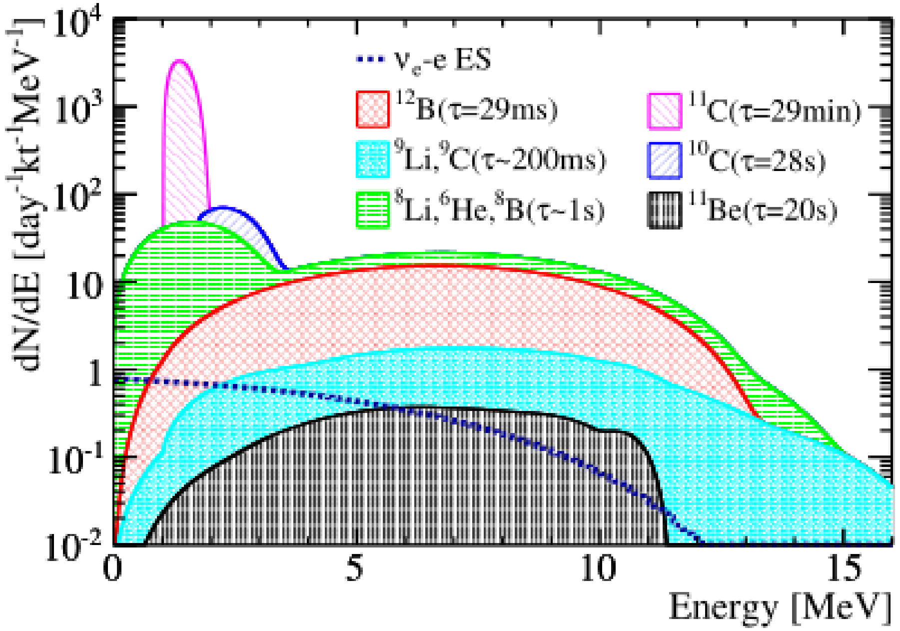
Optimized veto strategy

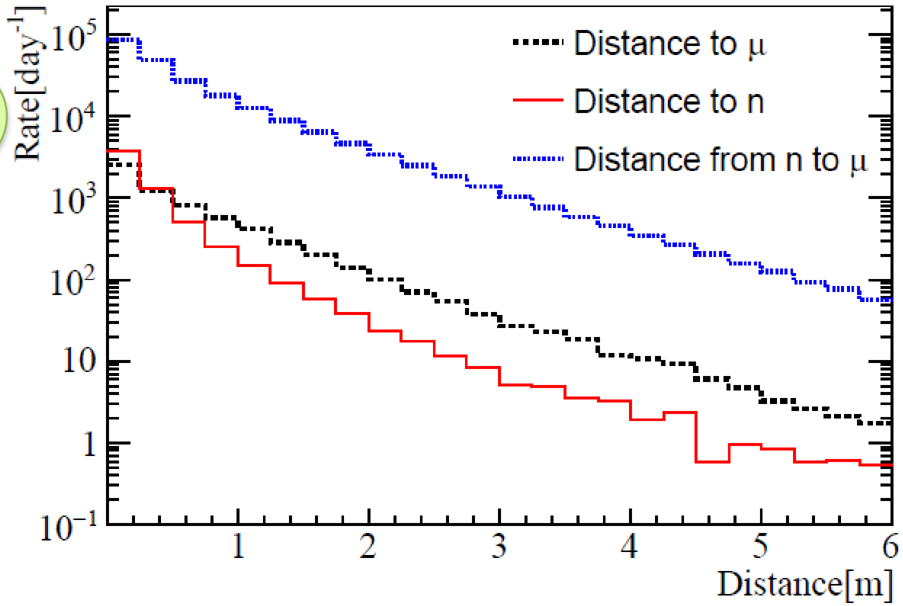
✓Muon veto:

- Whole detector veto for non-track μ
- Cylinder veto around μ track
  - The nearer distance, the longer veto time
- Dead time: ~44%

✓Three-Fold Coincidence cut (TFC):

- TFC: Muon, spallation neutron capture, isotope decay
- TFC fractions: > 90%
- Spherical veto around spallation neutron
- Dead time ~4%

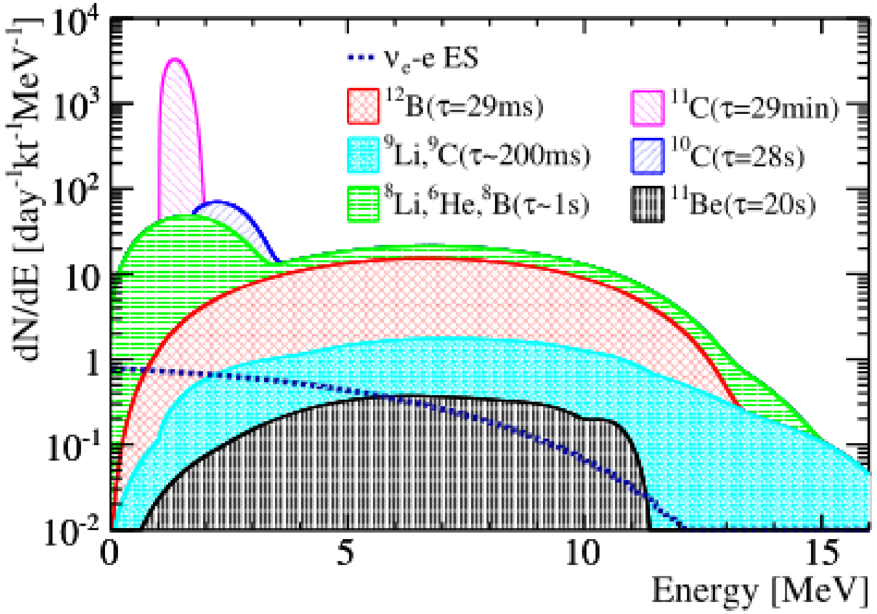




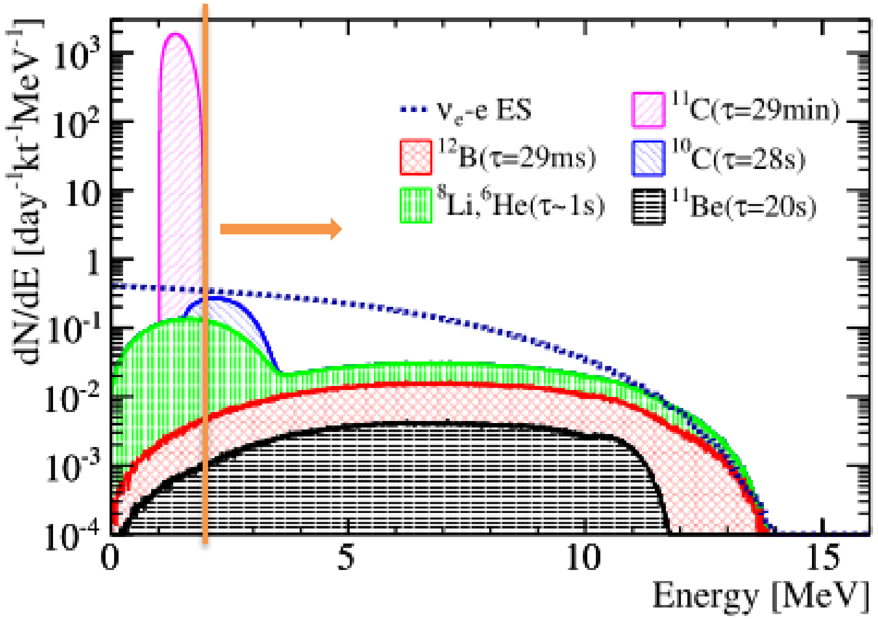
Long-lived cosmogenic isotopes

Spectrum

Yield in LS is scaled from measurement by Borexino and KamLAND



After reduction



Systematics

Systematic uncertainty	^{12}B	^{8}Li	^{6}He	^{10}C	^{11}Be
livetime (τ)	29.1ms	1.21 s	1.16s	27.8 s	19.9s
KamLAND [47]	—	3.3%	—	—	10.8%
JUNO	1%	1~3%	1~3%	5~10%	5~10%

✓ The actual isotope yields, distance distributions, and TFC fractions will be measured *in-situ* in future.

Summary of background and signal

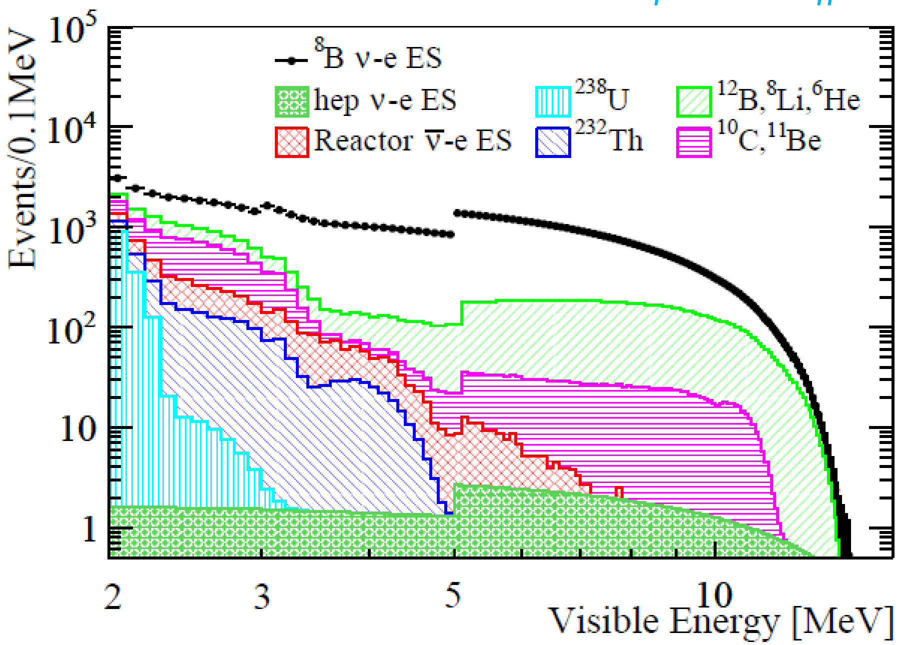
^{8}B signal efficiency

- ✓ Muon veto efficiency: 52%
- ✓ (3, 5) MeV: 52% (muon veto) * 80% (^{212}Bi-^{208}Tl cut)

Other systematics

- ✓ FV cut: 1%, refer to Borexino
  (Phys. Rev. D, 101(6):062001, 2020).
- ✓ Detector energy scale: 0.3%, refer to Daya Bay
  (Nucl. Instrum. Meth. A, 940:230-242, 2019.)

The discontinuities at 3 MeV and 5 MeV come from the different FV cut.



$\Delta m^{2\star}_{21} = 4.8 \times 10^{-5}$ eV^2, and $\Delta m^{2\dagger}_{21} = 7.5 \times 10^{-5}$ eV^2

cpd/kt	FV	^{8}B signal eff.	^{12}B	^{8}Li	^{10}C	^{6}He	^{11}Be	^{238}U	^{232}Th	$\bar{\nu}$-e ES	Total bkg.	Signal rate at $\Delta m^{2\star}_{21}$	Signal rate at $\Delta m^{2\dagger}_{21}$
(2, 3) MeV	7.9 kt	~51%	0.005	0.006	0.141	0.084	0.002	0.050	0.050	0.049	0.39	0.32	0.30
(3, 5) MeV	12.2 kt	~41%	0.013	0.018	0.014	0.008	0.005	0	0.012	0.016	0.09	0.42	0.39
(5, 16) MeV	16.2 kt	~52%	0.065	0.085	0	0	0.023	0	0	0.002	0.17	0.61	0.59
Syst. error	1%	<1%	3%	10%	3%	10%	1%	1%	2%				

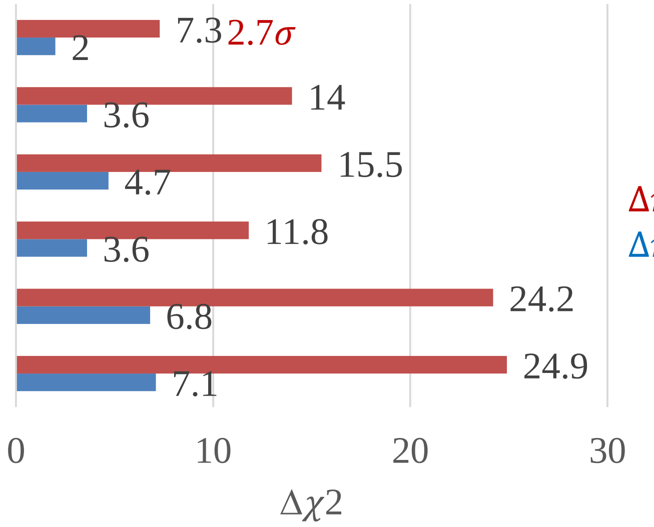
Background after reduction, and muon veto efficiency corrected .

Spectrum distortion test

Systematics

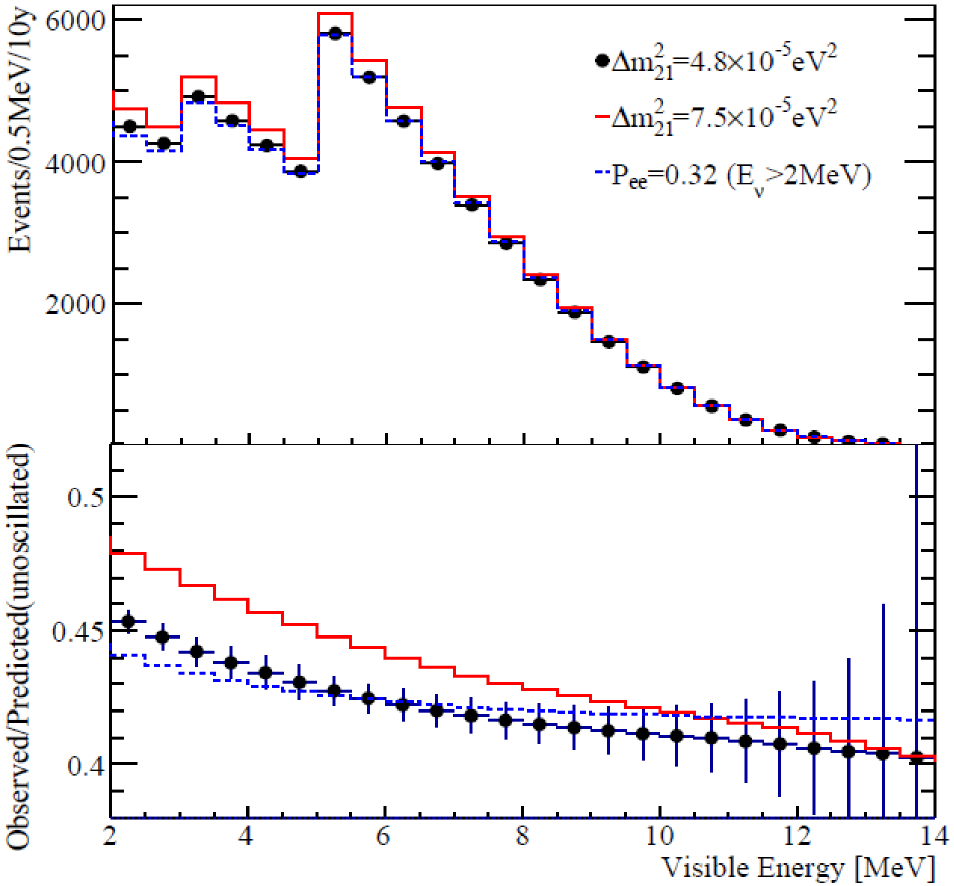
	Notation	Value	Reference
Detection efficiency	σ_d	1%	Borexino [23]
Detector energy scale	σ_e	0.3%	Daya Bay [35], Double Chooz [65]
The ^{8}B ν flux	σ_f	3.8%	SNO [25]
The ^{8}B ν spectrum shape	σ_s	1	Bahcall [26]
The j^{th} background	σ_b^j	Table 4	This study

Energy-independent hypothesis: *flat P_{ee} for E > 2 MeV*



10 y exposure

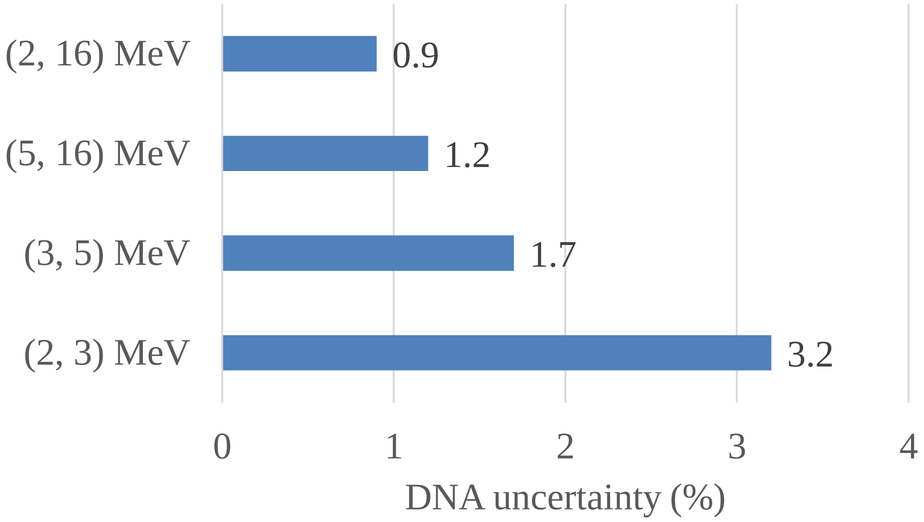
Δm^2_{21} = 7.5×10^{-5} eV^2
Δm^2_{21} = 4.8×10^{-5} eV^2

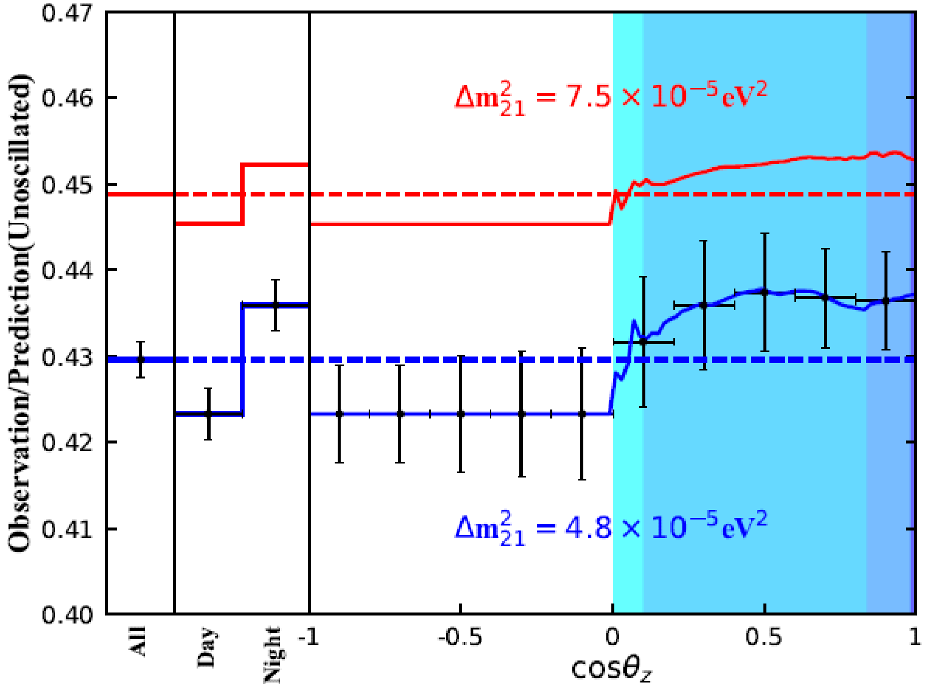


✓ This hypothesis is rejected at 2.7 σ with large Δm^2_{21}, and the statistic-only sensitivity can reach 5 σ.

Sensitivity on Day-Night-Asymmetry

- **Day-night-asymmetry** $DNA = \frac{R_D - R_N}{(R_N + R_D)/2}$
  - ✓ R_N, R_D are background-subtracted signal rates during the Day ($\cos\theta_z < 0$) and Night ($\cos\theta_z > 0$)
- **Sensitivity (10 years data)**
  - ✓ Most systematics are cancelled, statistics dominate





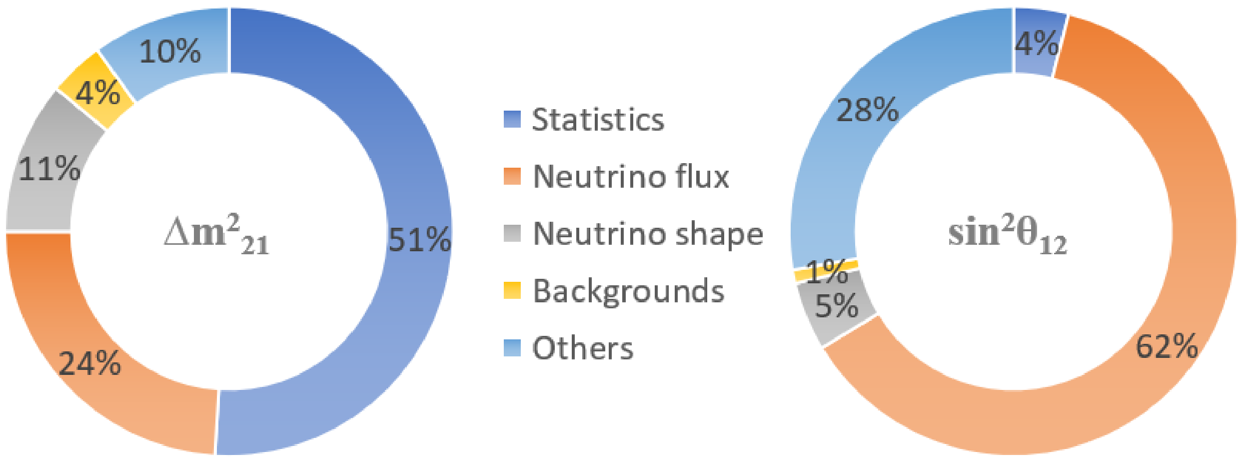
Day/Night asymmetry: *Super-K results @ Neutrino2020*

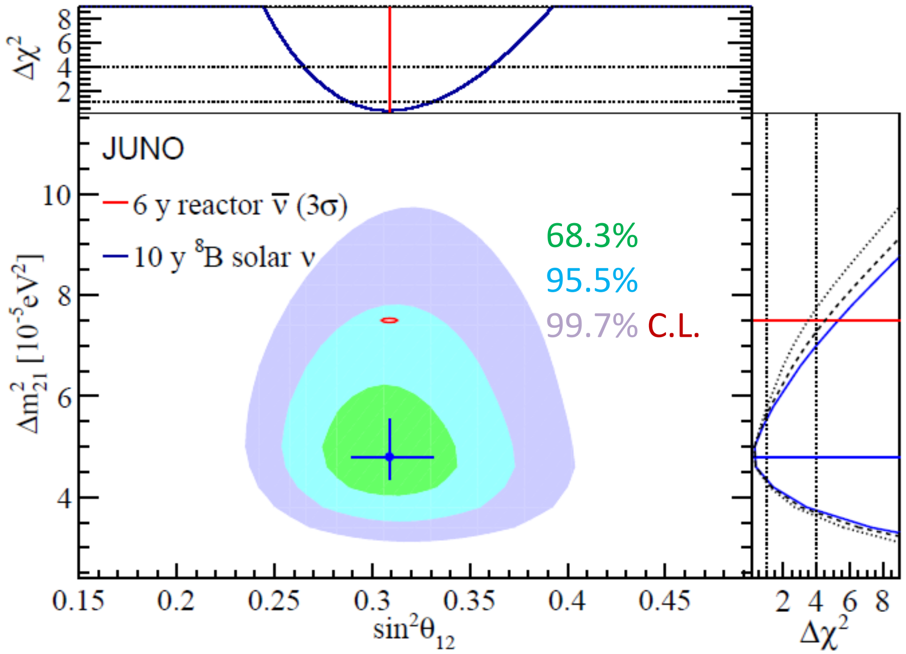
$A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\,\% \rightarrow A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$

✓ JUNO will reach SK 20y uncertainty (1.1%) in less than ten years due to the better S/B ratio.

Measurement of oscillation parameters

χ^2 fitting with both energy and sun-detector angle





- ✓ Statistics/flux dominate the uncertainty of Δm^2_{21}/ $sin^2\theta_{12}$
- ✓ the discrimination on Δm^2_{21} from 4.8×10^{-5} eV^2 to 7.5×10^{-5} eV^2 can reach 2σ.

Discussion on worse conditions

- ✓ ^{210}Po reach Phase I of Borexino (10^4 cpd/kt), ^{208}Tl could not be reduced. Dashed line in the right panel
- ✓ ^{238}U/^{232}Th ~ 10^{-15} g/g, E_{vis} > 5 MeV. Dotted line in the right panel

Summary of this study

- **Detailed study on background reduction**
  - ✓ **Internal radioactivity**: Bi-Po, Bi-Tl cascade decay
  - ✓ **External radioactivity**: optimized FV for different energy region
  - ✓ **Muon veto strategy:** muon track & TFC

- **Physics potential of detecting ^{8}B solar neutrinos at JUNO (10 years data)**
  - ✓ Signal 60,000, background 30,000, E_{th} ~ 2 MeV
  - ✓ The elimination of flat P_{ee}: $\geq 2\sigma$ for the large Δm^2_{21}(7.5×10^{-5} eV^2)
  - ✓ Day-Night-Asy: 0.9%, better than Super-K's latest result 1.1%
  - ✓ Solar & reactor measurement in Δm^2_{21} with one single detector
    - the discrimination on Δm^2_{21} from 4.8×10^{-5} eV^2 to 7.5×10^{-5} eV^2 can reach 2σ.
  - ✓ Collaboration paper published at *CPC Vol. 45, No.2 (2021)*

Thanks for your attention!

Back up

Internal background

■Strategy for Background reduction

✓ With correlation cuts (time, position, energy) most of ^{214}Bi, ^{212}Bi and ^{208}Tl decays can be removed

	^{214}Bi-^{214}Po-^{210}Pb	^{212}Bi-^{212}Po-^{208}Pb	^{212}Bi-^{208}Tl-^{208}Pb
Prompt signal	Beta (2, 3.5) MeV	Beta (2, 3.5) MeV	Alpha (0.5, 0.7) MeV
Delayed signal	Alpha (0.85, 1.05) MeV	Alpha (0.85, 1.05) MeV	Beta (3, 5) MeV
Time & position correlation	2 ms & 2 m	5 μs & 2 m	22 min & 1 m

Visible energy

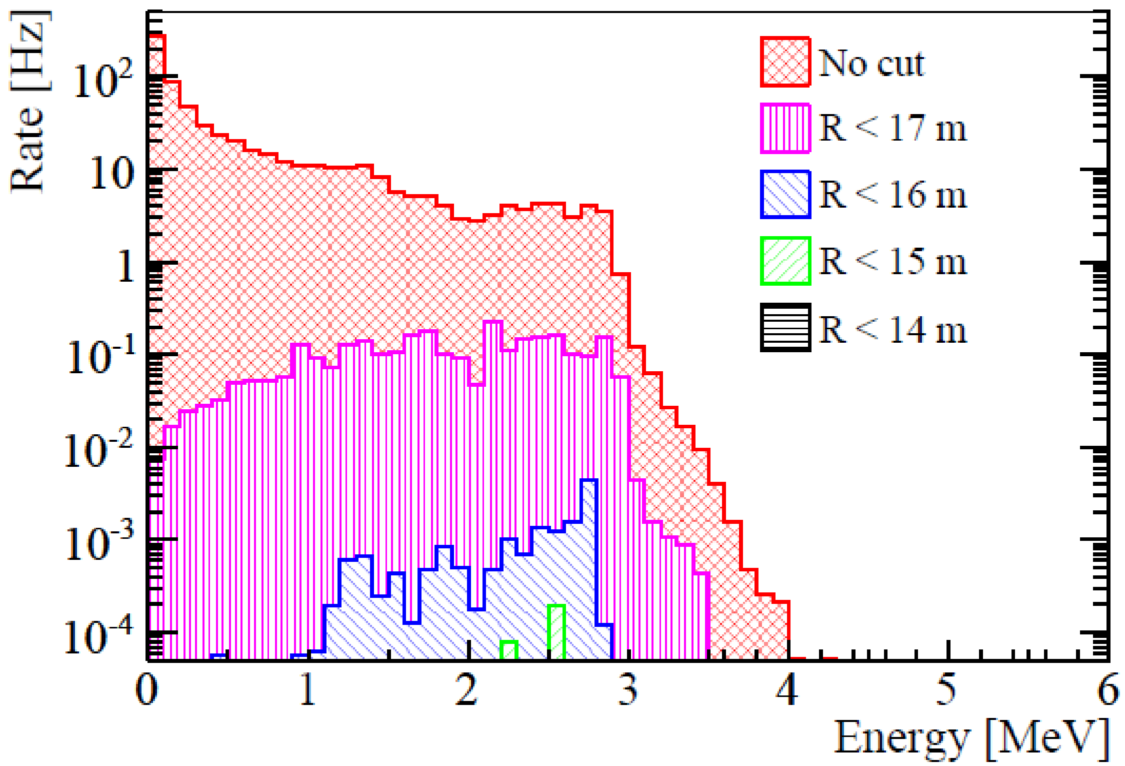
Isotopes in the ^{238}U and ^{232}Th decay chains with decay energies larger than 2 MeV

Isotope	Decay mode	Decay energy	τ	Daughter	Daughter's τ	Removal eff.	Removed signal
^{214}Bi	β^-	3.27 MeV	28.7 min	^{214}Po	237 μs	>99.5%	<1%
^{212}Bi	β^-: 64%	2.25 MeV	87.4 min	^{212}Po	431 ns	93%	~0
^{212}Bi	α: 36%	6.21 MeV	87.4 min	^{208}Tl	4.4 min	N/A	N/A
^{208}Tl	β^-	5.00 MeV	4.4 min	^{208}Pb	Stable	99%	20%
$^{234}Pa^m$	β^-	2.27 MeV	1.7 min	^{234}U	245500 years	N/A	N/A
^{228}Ac	β^-	2.13 MeV	8.9 h	^{228}Th	1.9 years	N/A	N/A

External radioactivity and neutron captures

External radioactivity

- ✓ Simulation is done with JUNO offline software
- ✓ Contribution from rock is negligible with at least 4 m water and 5 mm HDPE liner shielding
- ✓ **Effectively removed by the fiducial volume (FV) cut**



External neutron captures

- ✓ High energy gamma: neutron captures on iron, PMT glass and acrylic

Unit: cpd	R<17.7 m	R<17 m	R<16 m	R<15 m	R<14 m
Acrylic	1.3e-5	1.53e-7	2.7e-9	5.57e-11	0
Node	3.52e-5	8.9e-7	5.1e-8	4.1e-9	4.3e-10
Bar	9.8e-5	2.6e-6	1.8e-7	1.2e-8	2.7e-9
PMT glass	2.5e-2	1.8e-4	7.2e-6	0	0
Total	0.025	1.9e-4	7.5e-6	1.6e-8	3.1e-9

- ✓ **PMT glass dominates the contribution, but can be effectively remove with R < 16.5 m FV cut**

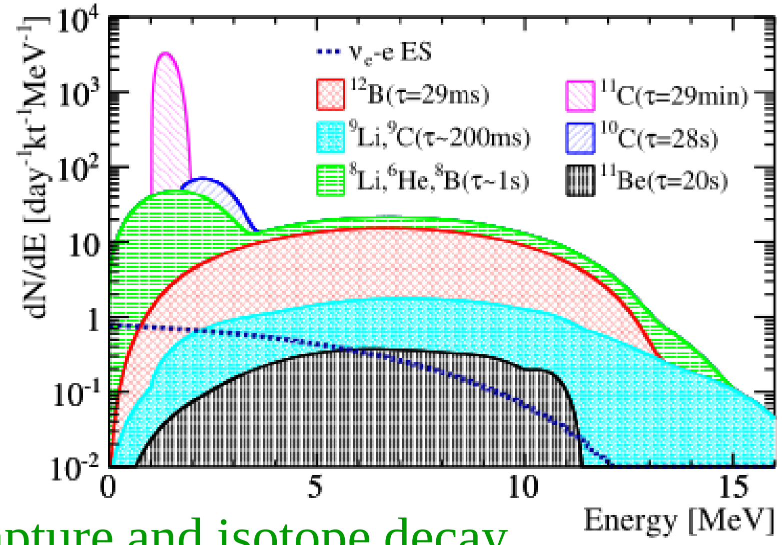
Final optimized fiducial volume cut

	R < 16.5 m	R < 15 m	R < 13 m
Energy (MeV)	> 5	(3, 5)	(2, 3)
Target mass (kt)	16.2	12.2	7.9

Long-lived cosmogenic isotopes

Muon rate

- With ~700 m overburden, muon flux is 0.004 Hz/m^2 with an average energy of 207 GeV.
- About 3.6/10 Hz muons passing through the LS/water



Yield

- Three-Fold Coincidence cut (TFC) among muon, spallation neutron capture and isotope decay

Used in this study

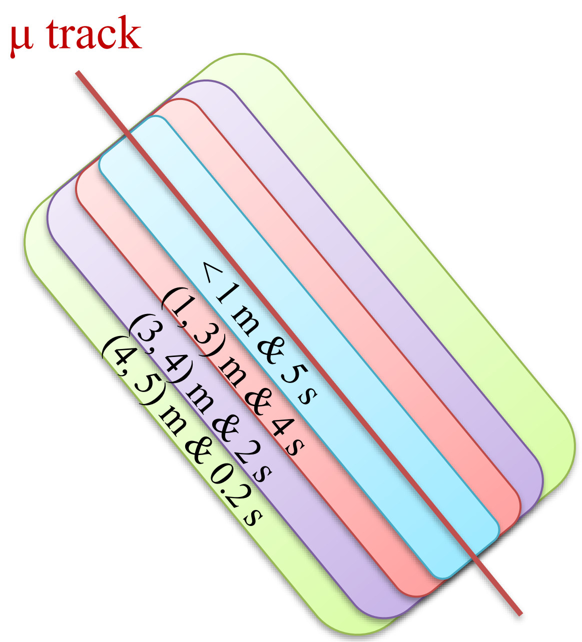
Isotope	Decay mode	Decay energy (MeV)	τ	Yield in LS (/day)		TFC fraction
				Geant4 simulation	Scaled	
^{12}B	β^-	13.4	29.1 ms	1059	2282	90%
^{9}Li	β^-: 50%	13.6	257.2 ms	68	117	96%
^{9}C	β^+	16.5	182.5 ms	21	160	>99%
^{8}Li	$\beta^- + \alpha$	16.0	1.21 s	725	649	94%
^{6}He	β^-	3.5	1.16 s	526	2185	95%
^{8}B	$\beta^+ + \alpha$	~18	1.11 s	35	447	>99%
^{10}C	β^+	3.6	27.8 s	816	878	>99%
^{11}Be	β^-	11.5	19.9 s	9	59	96%
^{11}C	β^+	1.98	29.4 min	11811	46065	98%

Scaled: scale from measurement by Borexino and KamLAND

Long-lived cosmogenic isotopes

Optimized veto strategy

	For reconstructed track	Strategy	Dead time
Whole detector veto	w/ track	Veto 2 ms	44%
	w/o track	Veto 1 s	
Cylindrical volume veto (*d*: distance between candidate to muon track)	w/ track	Veto d < 1 m for 5 s Veto 1 m < d < 3 m for 4 s Veto 3 m < d < 4 m for 2 s Veto 4 m < d < 5 m for 0.2 s	
TFC veto		Veto 2 m spherical volume around neutron for 160 s	4%



Differential cross section of ν_e *and* $\nu_{\mu\tau}$

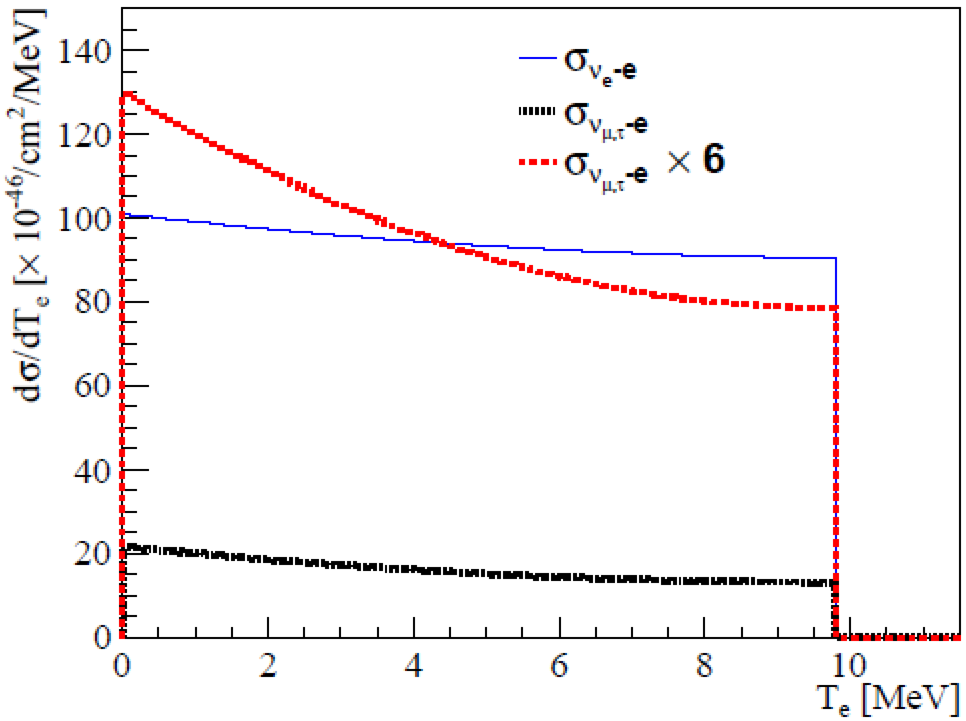


Figure 4: Differential cross section of $\nu_e - e$ (blue) and $\nu_{\mu,\tau} - e$ (black) elastic scattering for a 10 MeV neutrino. The stronger energy dependence of the $\nu_{\mu,\tau} - e$ cross section, as illustrated in red, produces another smooth upturn in the visible electron spectrum compared to the case of no $\nu_{\mu,\tau}$ appearance.