Search for neutron invisible decay modes at JUNO

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On behalf of JUNO Collaboration

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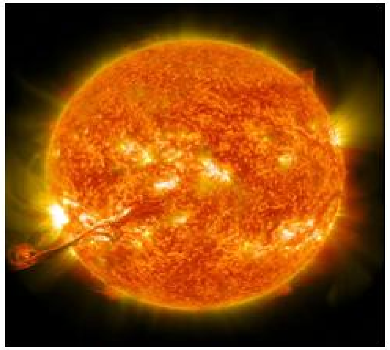
Outline

- *Introduction*
- *Signal*
- *Background*
- *Summary and Outlook*

◆ **Jiangmen Underground Neutrino Observatory (JUNO)**, a **multi-purpose** neutrino experiment

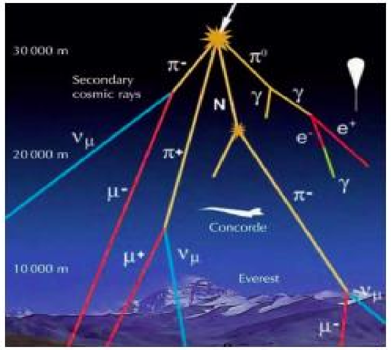
$\sim 50/\mathrm{day}$

Reactor neutrino



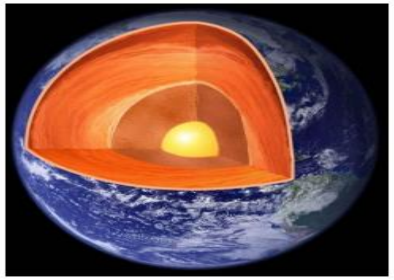
$\mathcal{O}(1000)/\mathrm{day}$

Solar neutrino



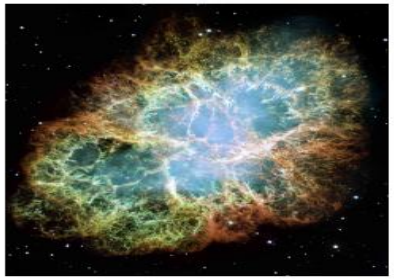
~ 10 - $20/\mathrm{day}$

Atmospheric neutrino



~ 1 - $2/\mathrm{day}$

Geoneutrino



CCSN @10kpc : $\mathcal{O}(1000)/\mathrm{s}$

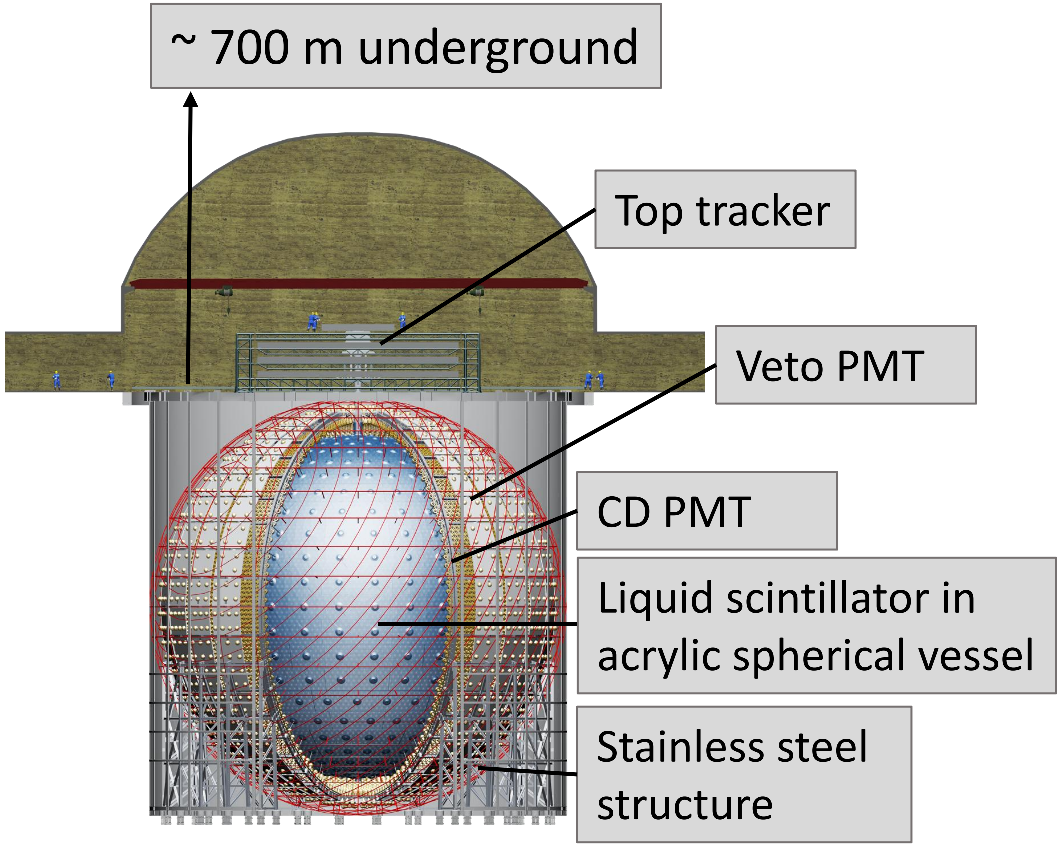
DSNB: few/year

Supernova neutrino

New Physics

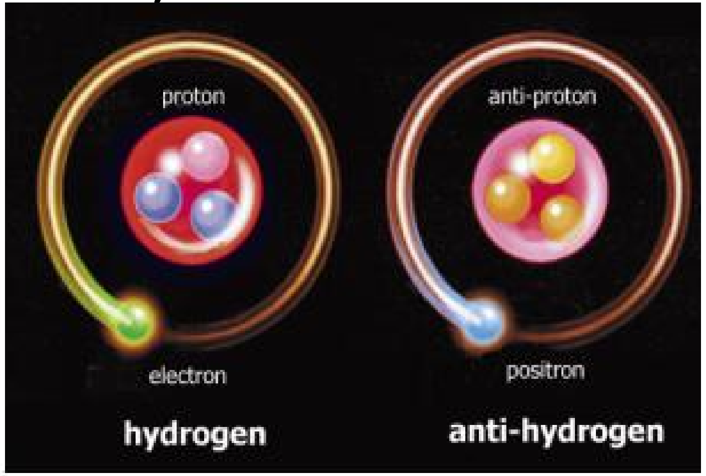
↑

Nucleon decay etc. (Focus of this talk)



Introduction— Why and what neutron invisible decay?

- **Matter-antimatter is asymmetric in universe**
  - ***Conservation* of *baryon number (B):*** accidental global symmetry in SM
  - ***B* violation: key step** to explain this asymmetry
    - Predicted by various Grand Unified Theories
    - No process violating ***B*** has been observed
  - **Nucleon decay : a direct observation** of *B* violation

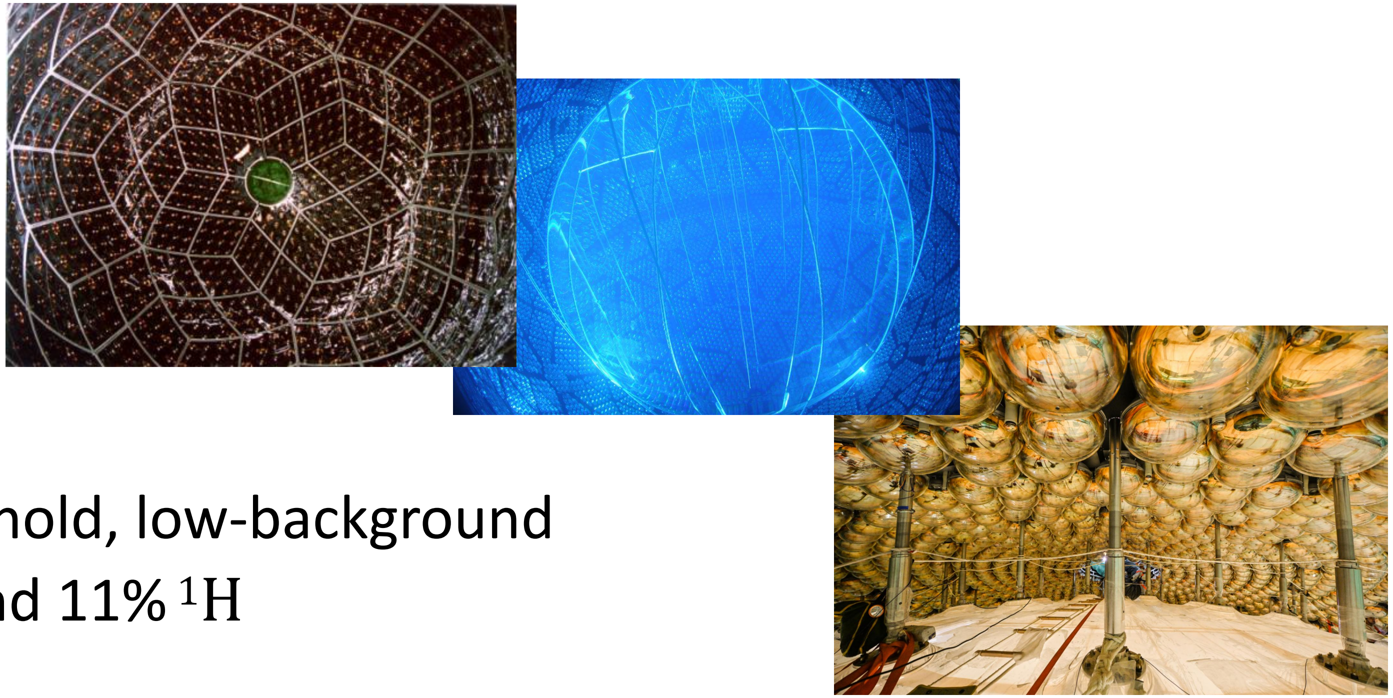


- **Neutron's invisible decay**
  - $n \rightarrow$ neutrinos, beyond-Standard-Model particles

    J. Heeck and V. Takhistov PhysRevD.101.015005 (2020)
  - Nuclear de-excitation emission searches
    - strictest model-independent limits
  - Two invisible decay modes of bounded neutron
    - $\boldsymbol{n \rightarrow inv}$, $\boldsymbol{nn \rightarrow inv}$ ★

Introduction— Current searches

- KamLAND (LS)
  - ^{12}C in liquid scintillator
- SNO+ (water phase)
  - ^{16}O water H_2O
- JUNO
  - large LS detector **20 kt** , low-threshold, low-background
  - Mass fraction: **88% C (99% ^{12}C)** and 11% ^{1}H



Experiment	$\tau(n \to inv) 90\% \, C.L.$	$\tau(nn \to inv) \, 90\% \, C.L.$	reference
Borexino	-	$> 4.9 \times 10^{25} y$	*Nucl.Phys.B.Proc.Suppl. 118(2003) 499-499*
SNO+	$\mathbf{> 9.0 \times 10^{29} y}$	$> 1.5 \times 10^{28} y$	*Phys.Rev.D 105 (2022) 11, 112012*
KamLAND	$> 5.8 \times 10^{29} y$	$\mathbf{> 1.4 \times 10^{30} y}$	*PRL 96, 101802 (2006)*

Introduction— How to search for at JUNO ?

- Bounded neutrons in **^{12}C** : two invisible decay modes
  - $\boldsymbol{n \rightarrow inv}$ ($\mathbf{^{12}C \rightarrow {}^{11}C^*}$)
  - $\boldsymbol{nn \rightarrow inv}$ ($\mathbf{^{12}C \rightarrow {}^{10}C^*}$)
  - Detect de-excitation products of $^{11}\mathrm{C}^*$, $^{10}\mathrm{C}^*$ in LS to search for this signal
- Consider **four** deexcitation modes (form a **triple coincidence signal** in the LS detector)

Prompt(1st)
- Proton recoil by neutron
- Neutron inelastic scattering with $\mathbf{^{12}C}$
- γ (3.35 MeV) and proton (0.922 MeV)

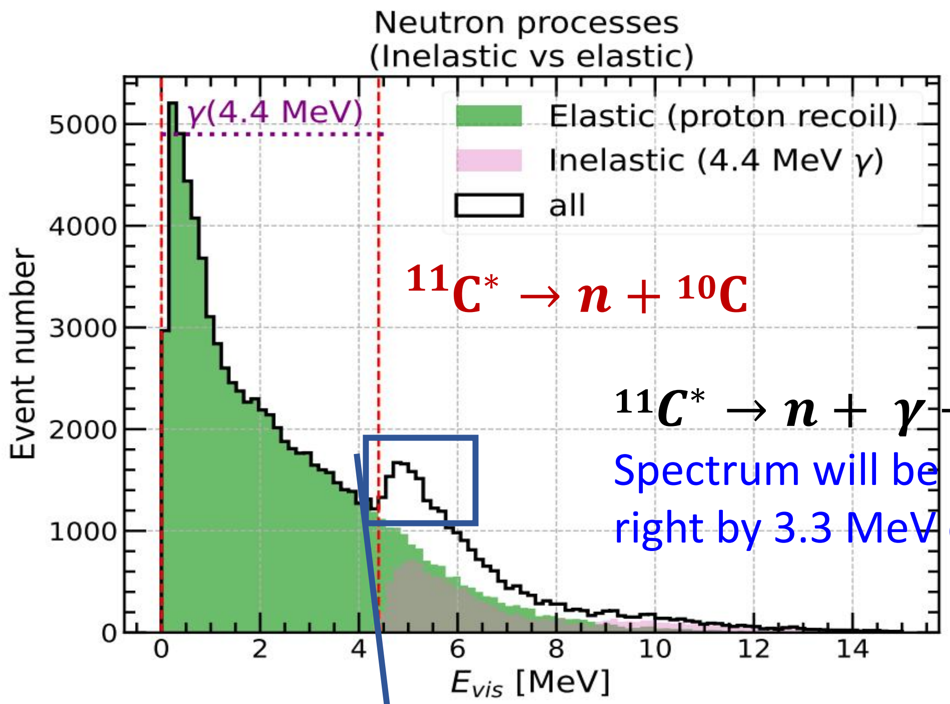
Delayed(2nd)
- Neutron capture (220 μs, 2.2 MeV)

$^{11}\mathrm{C}^* \rightarrow n + {}^{10}\mathrm{C}$	$(Br_{n1} = 3.0\%)$	$\boldsymbol{n \rightarrow inv}$
$^{11}\mathrm{C}^* \rightarrow n + \gamma + {}^{10}\mathrm{C}$	$(Br_{n1} = 2.8\%)$	
$^{10}\mathrm{C}^* \rightarrow n + {}^{9}\mathrm{C}$	$(Br_{nn1} = 6.2\%)$	$\boldsymbol{nn \rightarrow inv}$
$^{10}\mathrm{C}^* \rightarrow n + p + {}^{8}\mathrm{B}$	$(Br_{nn1} = 6.0\%)$	

Decay (3rd)
- β^+ decay of $\mathbf{^{10}C}$ ($\boldsymbol{\tau}$: 27.8 s), $\mathbf{^{9}C}$ ($\boldsymbol{\tau}$: 0.18 s), $\mathbf{^{8}B}$ ($\boldsymbol{\tau}$: 1.1 s)

Yuri Kamyshkov, Edwin Kolbe PRD 67, 076007 (2003)

Neutron interactions in LS: elastic and inelastic

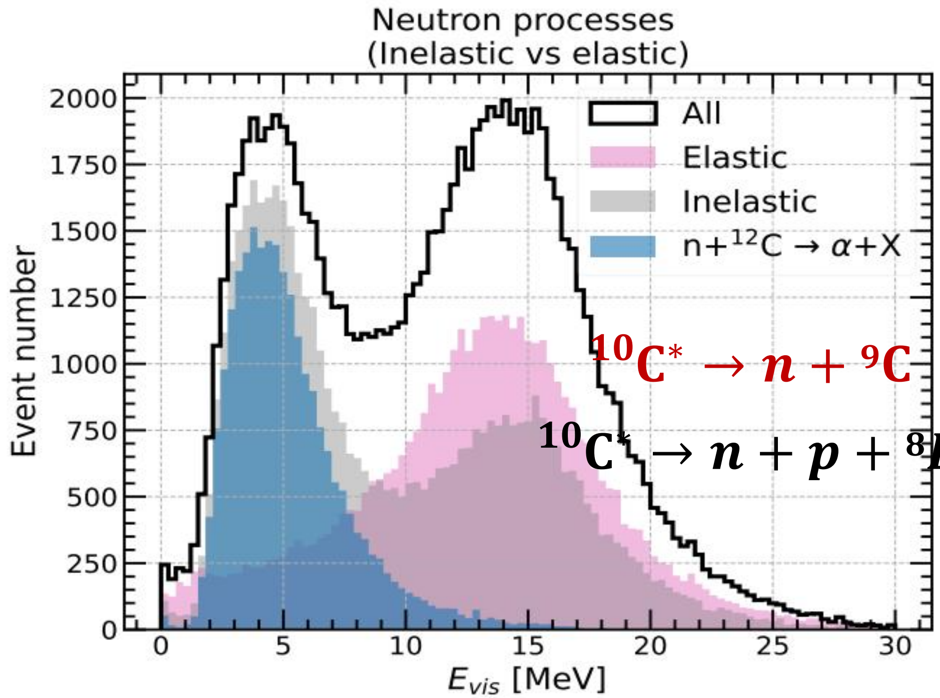


$^{11}C^* \rightarrow n + {}^{10}C$

$^{11}C^* \rightarrow n + \gamma + {}^{10}C$

Spectrum will be shifted right by 3.3 MeV due to γ

Neutron inelastic scattering with ^{12}C



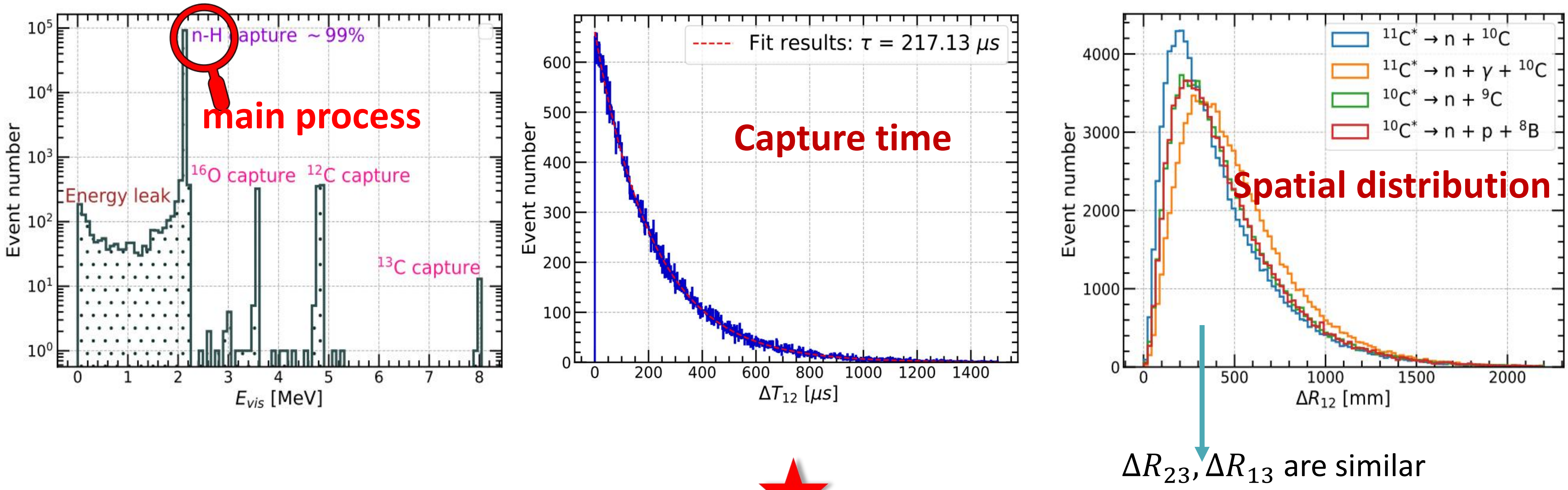
$^{10}C^* \rightarrow n + {}^{9}C$

$^{10}C^* \rightarrow n + p + {}^{8}B$ is similar

Main inelastic process: $n + {}^{12}C \rightarrow \alpha + X$

- **Elastic** (proton recoil) and **inelastic** processes contribute to the **prompt** energy spectrum
- γ produced in inelastic process deposits 4.4 MeV

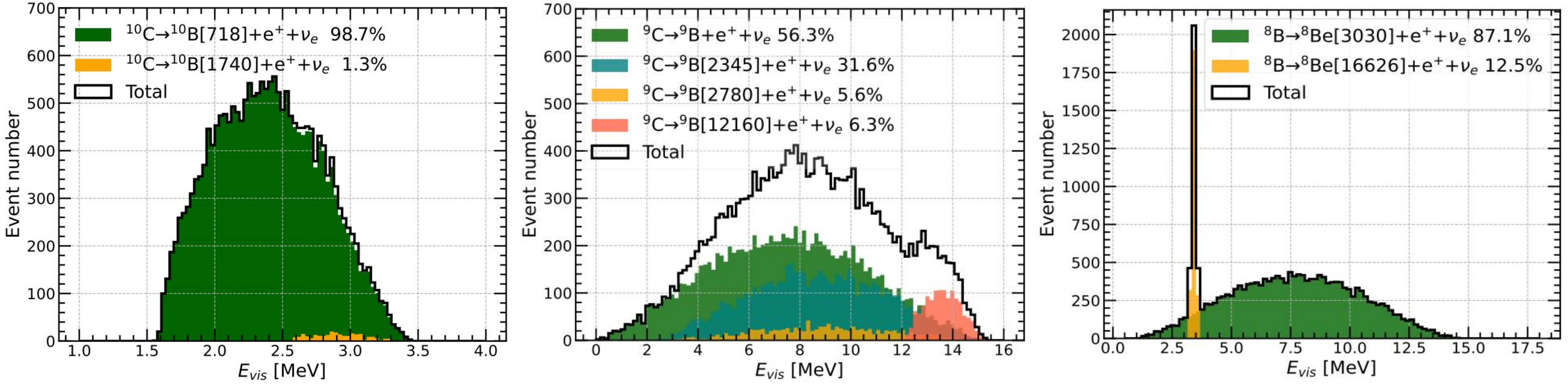
Signal— Characteristics of Delayed signal



- **Neutron-capture** contributes to **delayed energy** spectrum, **average capture time ~ 220 μs**
- **Distances** between signals are mostly **< 1.5 m**

Signal— Characteristics of Decay signal

◆ β^+ decay of daughter nuclei ^{10}C, ^{9}C, ^{8}B



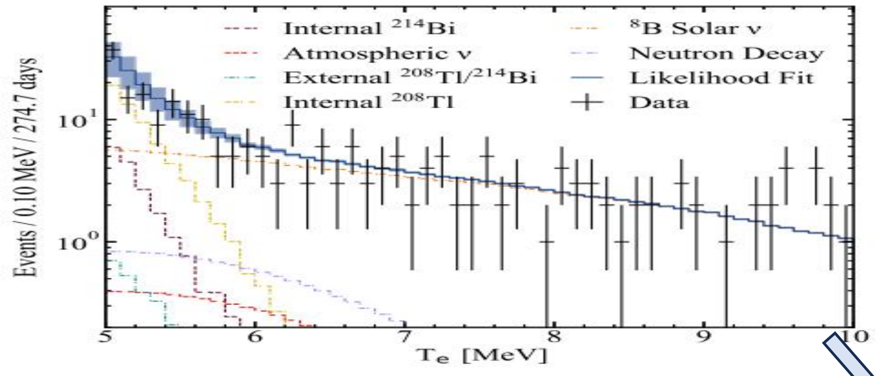
- The **decay energy** spectrum consists of β^+ decay ★
  - ~ 98.7 % ^{10}C will decay into the first excited state of ^{10}B
  - $^{9}C \to ^{9}B[12160\ kev] + e^+ + \nu_e$ results in a small bulge of ^{9}C energy distribution
  - Narrow peak of ^{8}B channel: ^{8}Be[16626] subsequently decays into two α particles

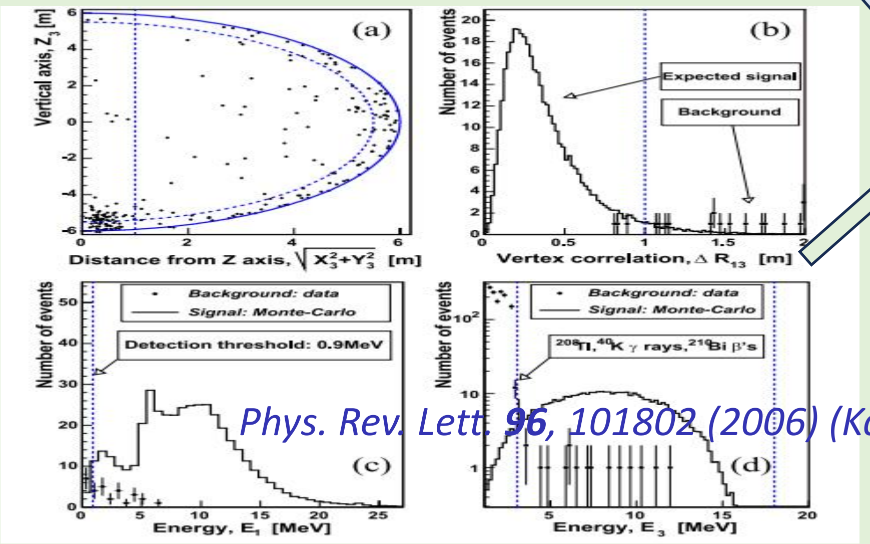
Review of SNO+ and KamLAND

Phys.Rev.D 105 (2022) 11, 112012 (SNO+)

Observable	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
R (m) max	5.1	5.1	5.1	5.1	5.4	5.2
Z (m) [min, max]	[-6.0, 1.5]	[-6.0, 1.5]	[-6.0, 1.5]	[-3.1, 1.9]	[-6.0, 2.0]	[-6.0, 3.0]
Livetime (days)	5.0	14.6	30.2	28.9	11.2	184.8

Optimized fiducial volume and livetime for each of the included datasets.





Phys. Rev. Lett. **96**, 101802 (2006) (KamLAND)

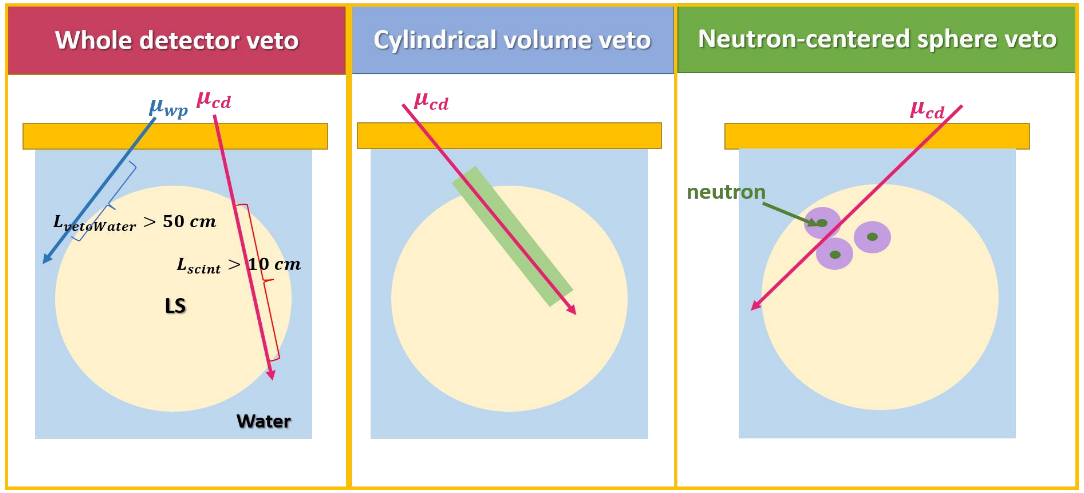
*: derived from left two papers

		SNO+	KamLAND
Life time limit		$\tau\ (n \to inv) > 9.0 \times 10^{29} y$	$\tau\ (nn \to inv) > 1.4 \times 10^{30} y$
Fiducial volume		--	5.5 m
Target mass		~ 0.9 kt	~ 0.5 kt
$Br.\boldsymbol{\epsilon_n}$	$Br1.\boldsymbol{\epsilon_{nn1}}$	Average ~ 0.26*	~ 0.04*
	$Br2.\boldsymbol{\epsilon_{nn2}}$		~ 0.04*
Target neutron number/pairs		$\mathbf{1.2 \times 10^{32}}$	$\mathbf{2.3 \times 10^{31}}$
Expected backgrounds ($yr^{-1} kton^{-1}$)		~ 200*	~ 0.02*
Dominant background combination		^{8}B solar ν Atmospheric ν	IBD + singles ^{9}Li + singles …

JUNO: LS detector
Similar to KamLAND's signal and background

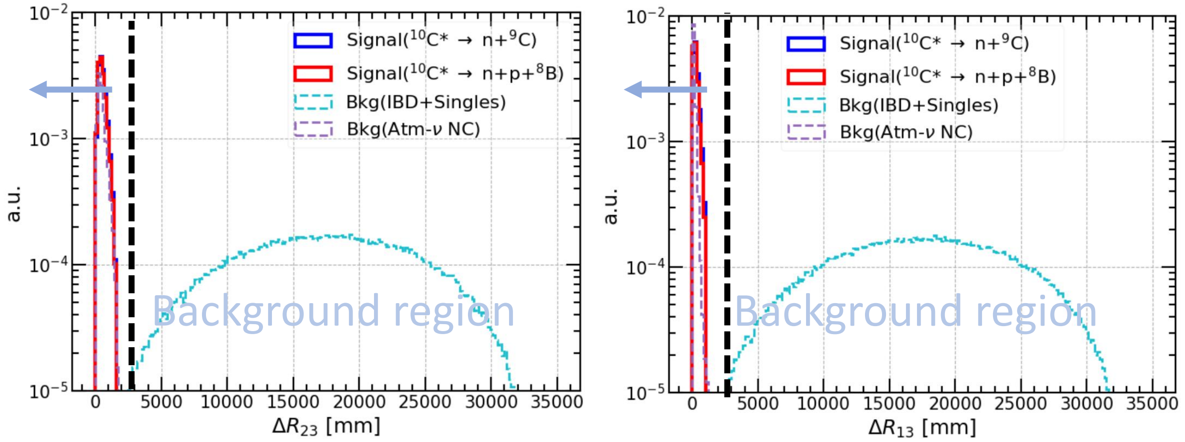
Signal— Strategies and results of signal selection

- **Design Muon veto strategies** to reduce isotopes from cosmic muons



- **Results** of event selection
  - **Acceptable** signal efficiency
  - **Possible** to **search** for neutron invisible decay

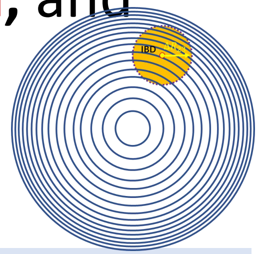
- **Event selection** based on signal characteristics



Summary of event selection				
	$n \rightarrow inv$		$nn \rightarrow inv$	
Muon veto				
Fiducial volume	$r < 16.7$ m		$r < 16.7$ m	
Selection criteria	$\Delta T_{12} < 1$ ms $\Delta T_{23} \in [0.002, 100]$ s $\Delta R_{12} < 1.5$ m $\Delta R_{23} < 1.5$ m $\Delta R_{13} < 1.0$ m $E_1 \in [0.7, 12]$ MeV $E_2 \in [1.9, 2.5]$ MeV $E_3 \in [1.5, 3.5]$ MeV		$\Delta T_{12} < 1$ ms $\Delta T_{23} \in [0.002, 3.0]$ s $\Delta R_{12} < 1.5$ m $\Delta R_{23} < 1.5$ m $\Delta R_{13} < 1.0$ m $E_1 \in [0.7, 30]$ MeV $E_2 \in [1.9, 2.5]$ MeV $E_3 \in [3.0, 16]$ MeV	
Multiplicity cut				
Total efficiency (%)	$^{11}C^* \rightarrow n + {}^{10}C$	$^{11}C^* \rightarrow n + \gamma + {}^{10}C$	$^{10}C^* \rightarrow n + {}^{9}C$	$^{10}C^* \rightarrow n + p + {}^{8}B$
	35.6 ± 0.2	43.6 ± 0.2	53.9 ± 0.3	49.1 ± 0.3

Background— How to estimate backgrounds

- **Background sources** (**5** categories):
  - **IBD**(Inverse Beta decay), **isotope from cosmic muons**, **radioactivity**, **fast neutron**, and **$Atm - v$ NC** (atmospheric neutrino neutral current)



- **Estimate the background** as completely as possible by using two methods

Method I (Toy MC)

- **Random sampling** ⟹ spatial distributions between independent backgrounds which may contribute to background
- **Estimation formula**

$$R_{triple} = R_1 \cdot (1 - e^{-R_2 \cdot P_{12} \cdot \Delta T_{12}}) \cdot (1 - e^{-R_2 \cdot P_{23,31} \cdot \Delta T_{23}})$$

Method II (numerical calculation)

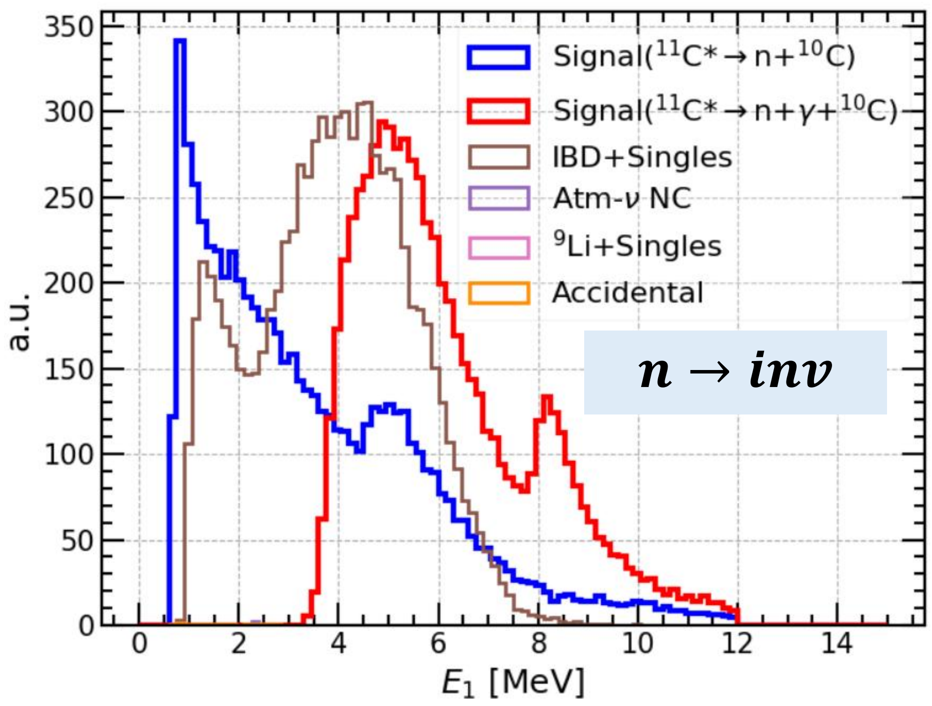
- **Divide** sphere into concentric shells of the same volume
- Assume the IBD and Singles distributed **uniformly in each shell**
- **Estimation formula**

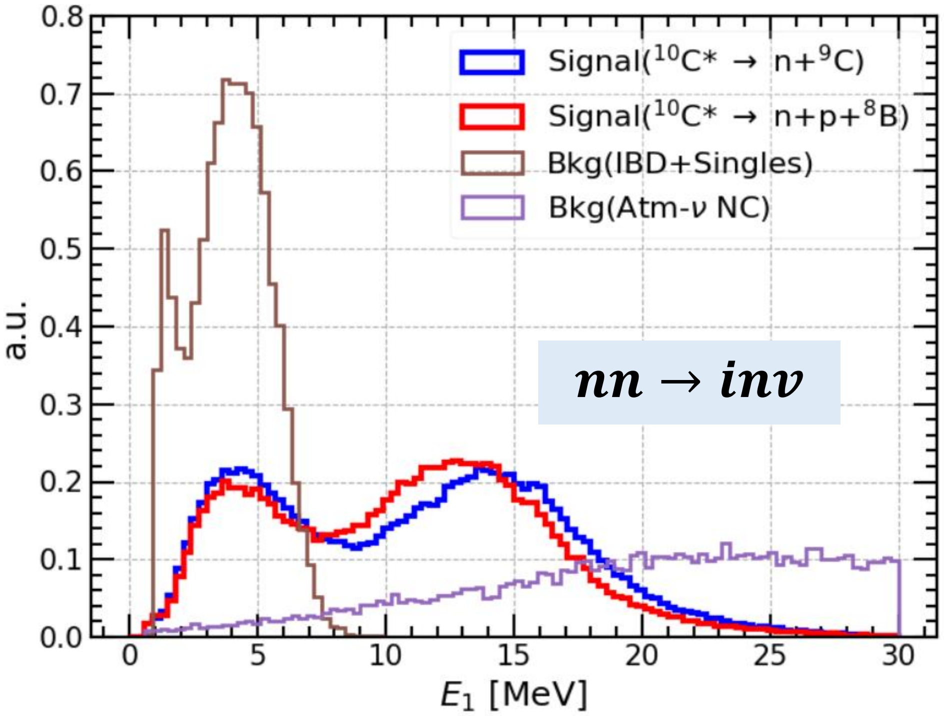
$$Rate = \sum_{i=1}^{n} R_i^{IBD} (1 - e^{-\sum_{j=1}^{n} R_j^{singles} \Delta T_{23}}) P_{\Delta R_{13}}$$

Results from two methods: **Consistent!**

Background— Results of backgrounds estimation

After event selection (exposure 10 years)

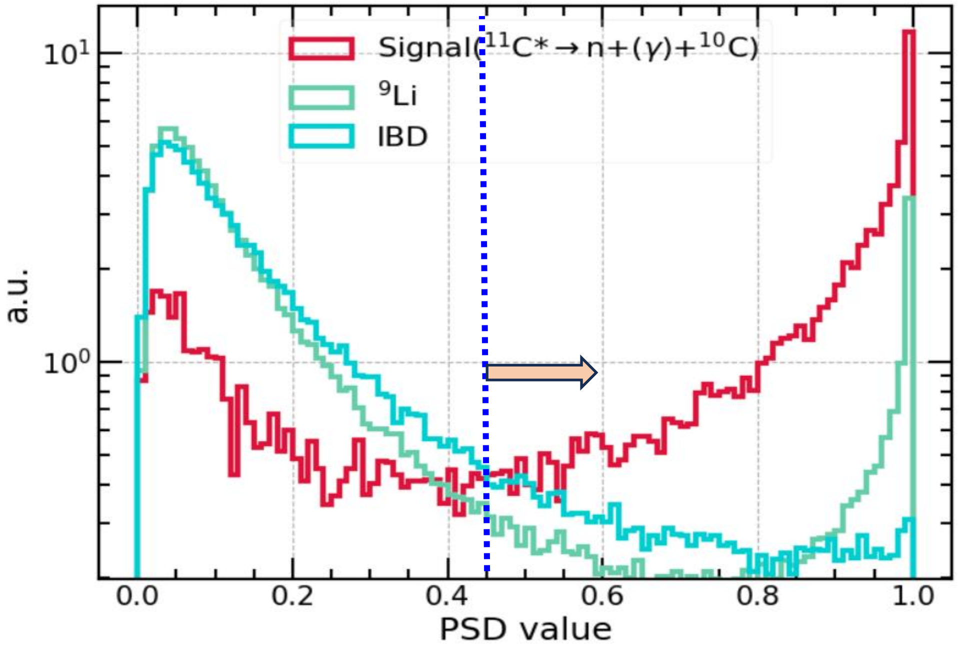


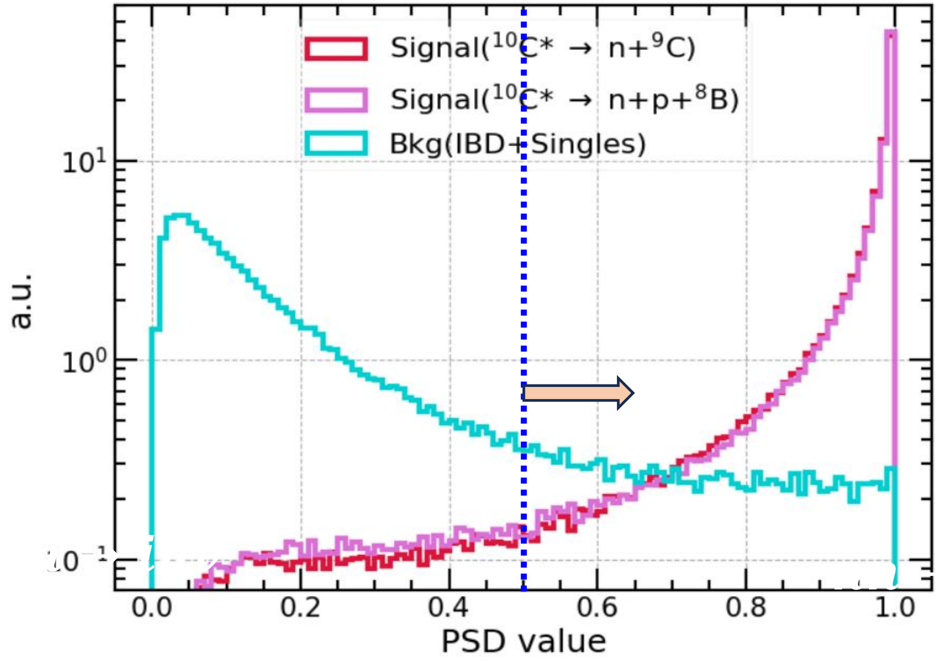


- **Triple backgrounds** from **coincidence** between 5 background sources
- **IBD + singles** is the **dominant** background
- **Too many** backgrounds for $n \rightarrow inv/nn \rightarrow inv$, Need to **suppress** ! **How ?**

Background— How to suppress background

- Backgrounds: **too many**, need to **suppress (Machine Learning)**!
  - Use Pulse Shape Discrimination (**PSD**) and Multi-Variate-Analysis (**MVA**) to **suppress**
  - **PSD (MLP)**
    - **Particle's emission photon time are different**

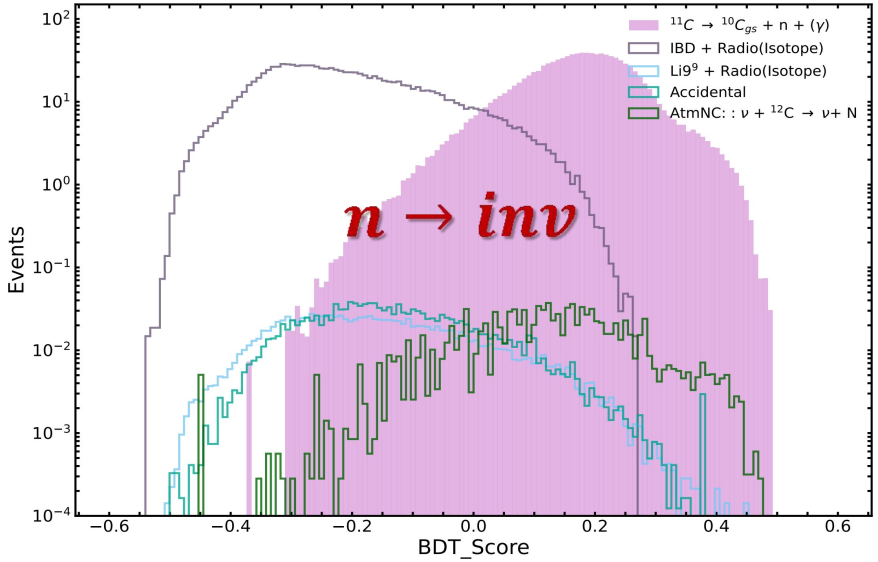


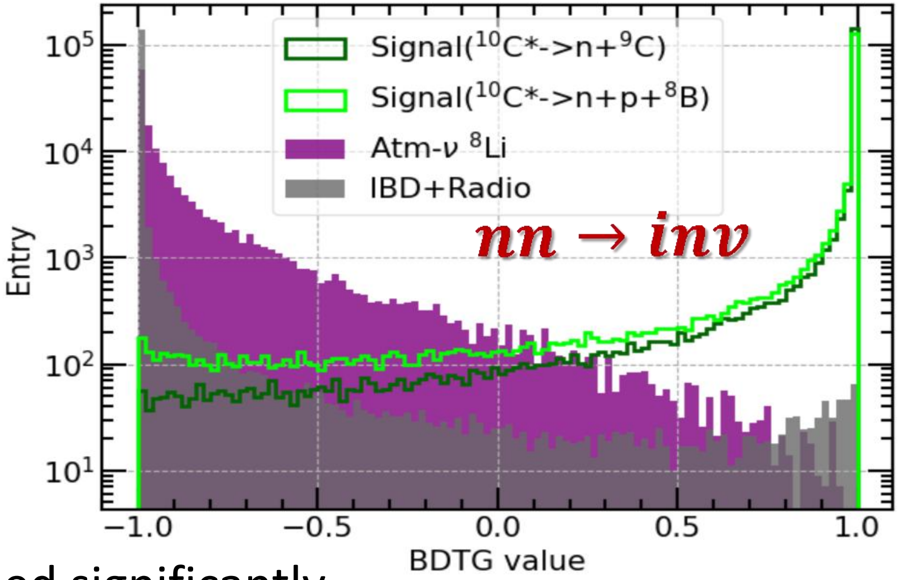


- Choose a PSD value (blue dash line)
- IBD-related backgrounds significantly suppressed, ~ 80 % of them can be removed

Multi-Variate-Analysis (MVA)— BDT/BDTG

- Use Multi-Variate-Analysis (MVA) to **further suppress** backgrounds
  - Combine **multidimensional** features of signals to distinguish signal and backgrounds
  - For $n \rightarrow inv$ / $nn \rightarrow inv$
    - Consider dominant bkgs, use basic features: E_1, E_2, E_3, ΔR_{12}, ΔR_{23}, ΔR_{13}





- From above plots, backgrounds can be suppressed significantly
- Combine **PSD + MVA**, ~ a factor of 100 reduction for the background of $n \rightarrow inv$, ~ a factor of 10 reduction for the background of $nn \rightarrow inv$

Summary and Outlook

- Designed **muon veto** strategies to reduce isotopes from cosmic muons
- **More** target neutron number/pairs
- Signal efficiencies are **acceptable**
- Lower backgrounds than SNO+, comparable backgrounds with KamLAND
- Introducing ML to suppress backgrounds
  - Before ML, $\frac{\epsilon_{sig}}{\sqrt{bkg_{tot}}}$: ~ 0.01 ($n \to inv$), ~ 0.2 ($nn \to inv$)
  - After ML, $\frac{\epsilon_{sig}}{\sqrt{bkg_{tot}}}$: ~ 0.06 ($n \to inv$), ~ 0.6 ($nn \to inv$)

	SNO+	KamLAND	JUNO	
Life time limit	$\tau\ (n \to inv) > 9.0 \times 10^{29} y$	$\tau\ (nn \to inv) > 1.4 \times 10^{30} y$	$n \to inv$	$nn \to inv$
Fiducial volume cut	--	< 5.5 m	< 16.7 m	
Target mass	~ 0.9 kt H_2O	~ 0.5 kt LS	16.8 kt LS	
Target neutron number/pairs	1.2×10^{32}	2.3×10^{31}	1.5×10^{33}	7.4×10^{32}
$Br. \epsilon_n$ / $Br1. \epsilon_{nn1}$	~ 0.26	~ 0.04	~ 0.023	~ 0.03
$Br2. \epsilon_{nn2}$		~ 0.04		~ 0.03
Expected backgrounds ($yr^{-1} kton^{-1}$)	~ 200	~ 0.02	~ 7.4	~ 0.03
$N \cdot Br. \epsilon_{sig}/\sqrt{bkg}$	2.3×10^{30}	1.8×10^{31}	3.1×10^{30}	6.3×10^{31}
Dominant background combination	^{8}B solar ν Atmospheric ν	IBD + singles ^{9}Li + singles …	IBD + singles ^{9}Li + singles …	

JUNO has a great potential to search for invisible neutron decays!

Thank you for your attention!

Backup

Signal

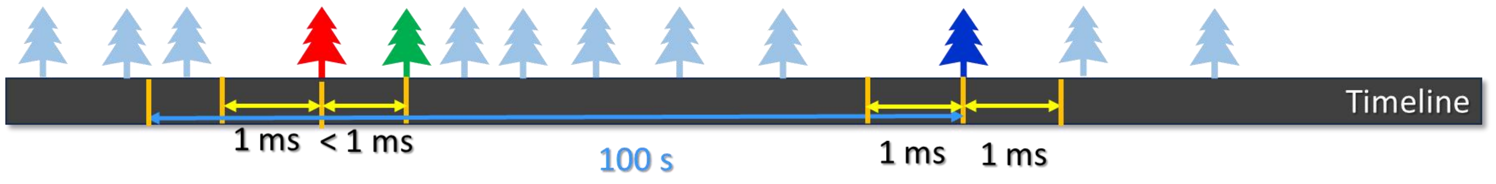
Prompt(1st)
- Proton recoil by neutron
- Neutron inelastic scattering with ^{12}**C**
- γ (3.35 MeV) and proton (0.922 MeV)

Delayed(2nd)
- Neutron capture (220 μs, 2.2 MeV)

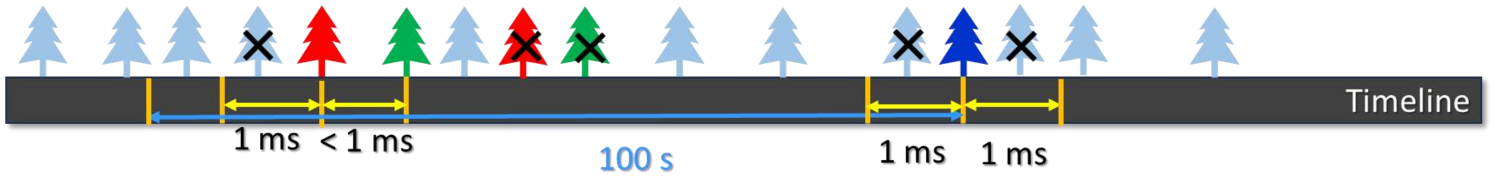
$$^{11}\mathrm{C}^* \rightarrow n + {}^{10}\mathrm{C} \quad (Br_{n1} = 3.0\%)$$
$$^{11}\mathrm{C}^* \rightarrow n + \gamma + {}^{10}\mathrm{C} \quad (Br_{n1} = 2.8\%)$$
$$^{10}\mathrm{C}^* \rightarrow n + {}^{9}\mathrm{C} \quad (Br_{nn1} = 6.2\%)$$
$$^{10}\mathrm{C}^* \rightarrow n + p + {}^{8}\mathrm{B} \quad (Br_{nn1} = 6.0\%)$$

Decay (3rd)
- β^+ decay of ^{10}**C** (**τ**: 27.8 s), ^{9}**C** (**τ**: 0.18 s), ^{8}**B** (**τ**: 1.1 s)

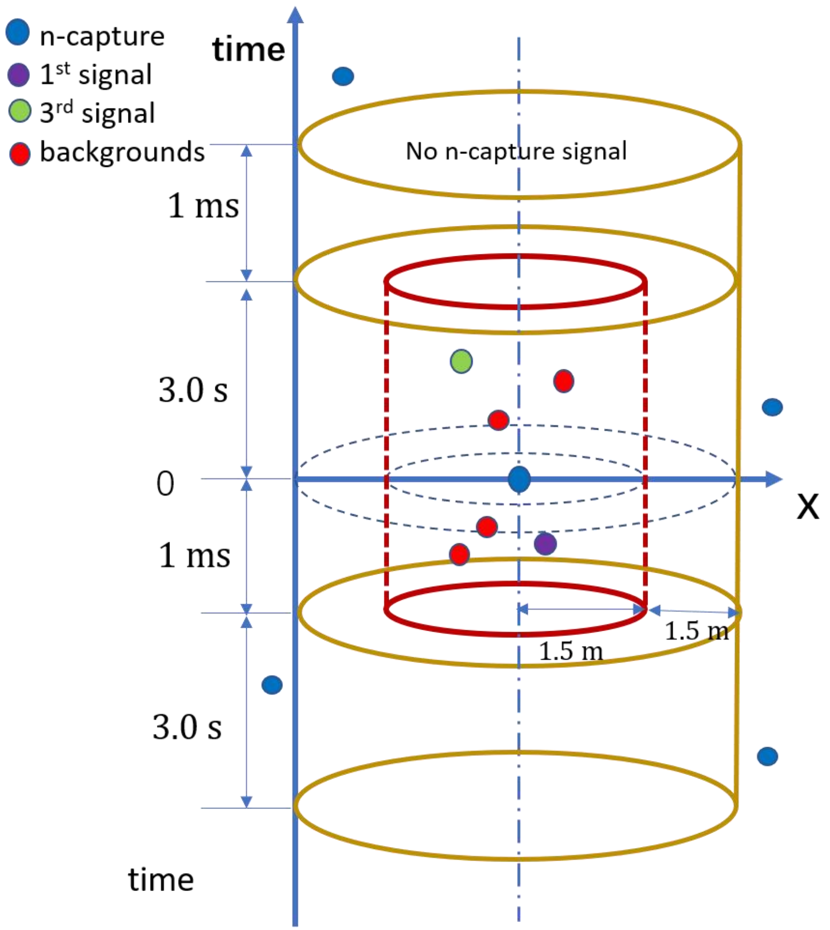
Multiplicity cut



This is a **true** triple invisible decay signal

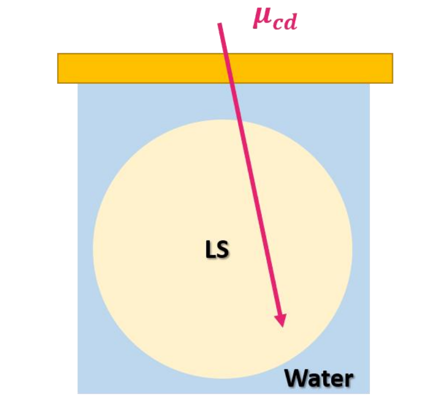


These triggers should not appear at **X** positions on the timeline. **This is a false triple invisible decay signal**



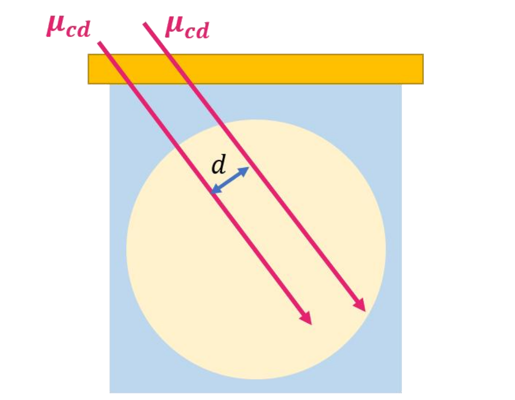
Muon veto strategies

One μ_{cd}



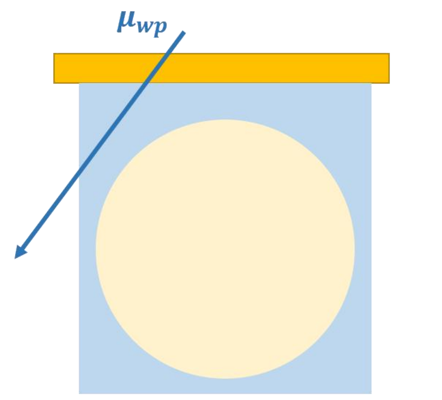
- Cylindrical volume veto (2 m, 2 s)
- Whole detector veto 3 ms
- Neutron-centered sphere veto (3 m, 30 s)/(3 m, 10 s) around 3 ms spallation neutron

Two μ_{cd}

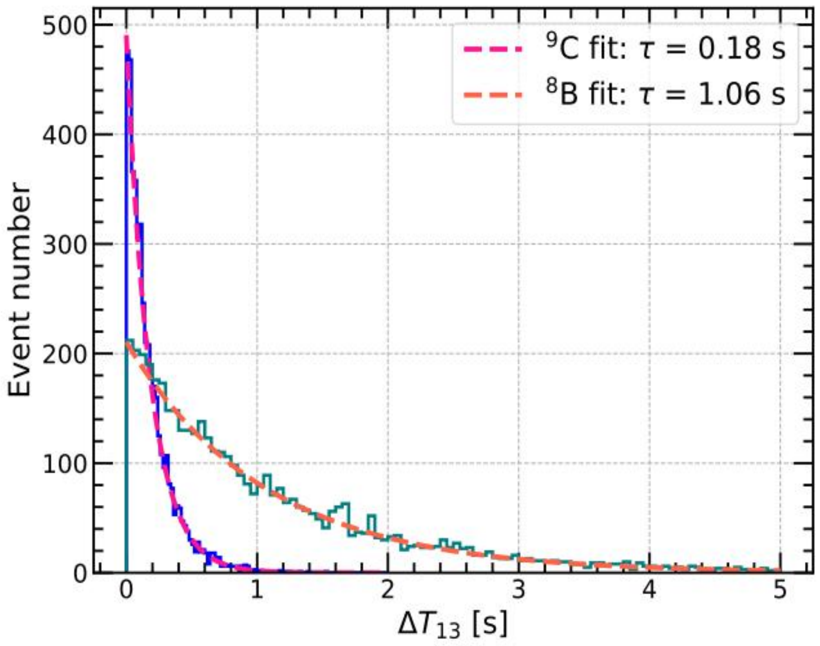


- $d < 3.0\ m$
  - Cylindrical volume veto(3.5 m, 5 s)
- $d > 3.0\ m$
  - Each μ_{cd} Cylindrical volume veto(2 m, 2 s)
- Whole detector veto 3 ms
- Neutron-centered sphere veto (3 m, 30 s)/(3 m, 10 s) around 3 ms spallation neutron

μ_{wp}



- Whole detector veto 3 ms
- Neutron-centered sphere veto (3 m, 30 s)/(3 m, 10 s) around 3 ms spallation neutron



PSD

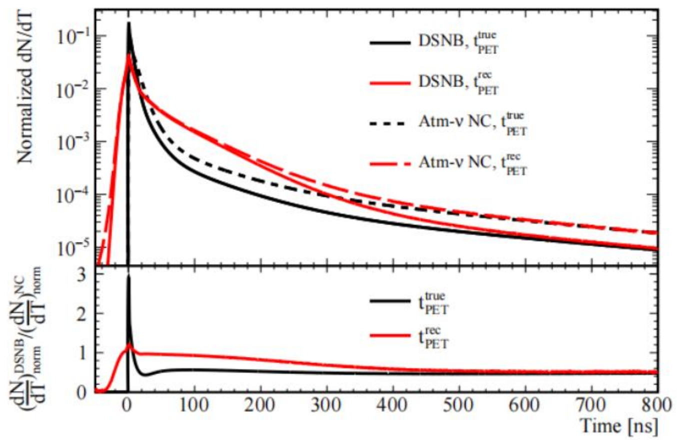


Figure 5. The averaged true (black) and reconstructed (red) profiles of the photon emission time (PET) are illustrated for both the DSNB signal (solid) and NC background (dashed). The upper panel is shown for the normalized time profiles and the lower panel for the relative ratios of the DSNB signal and NC background.

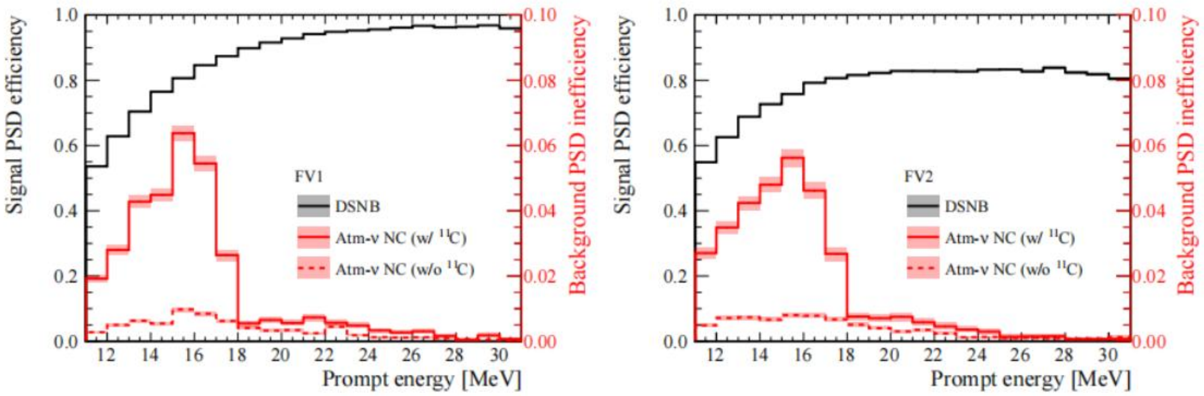


Figure 6. PSD efficiencies as functions of the prompt energy with the BDT method. The left and right panels are shown for the signal and background efficiencies in the regions of FV1 and FV2. The black solid lines are for the signal efficiency after the PSD cut, and the red lines are for the background inefficiencies of the atmospheric ν NC backgrounds with (solid) and without (dashed) ^{11}C. The shadowed bands are shown for the statistical uncertainty of simulated data samples.

Angel Abusleme et al JCAP10(2022)033