Search for nucleon decay in JUNO

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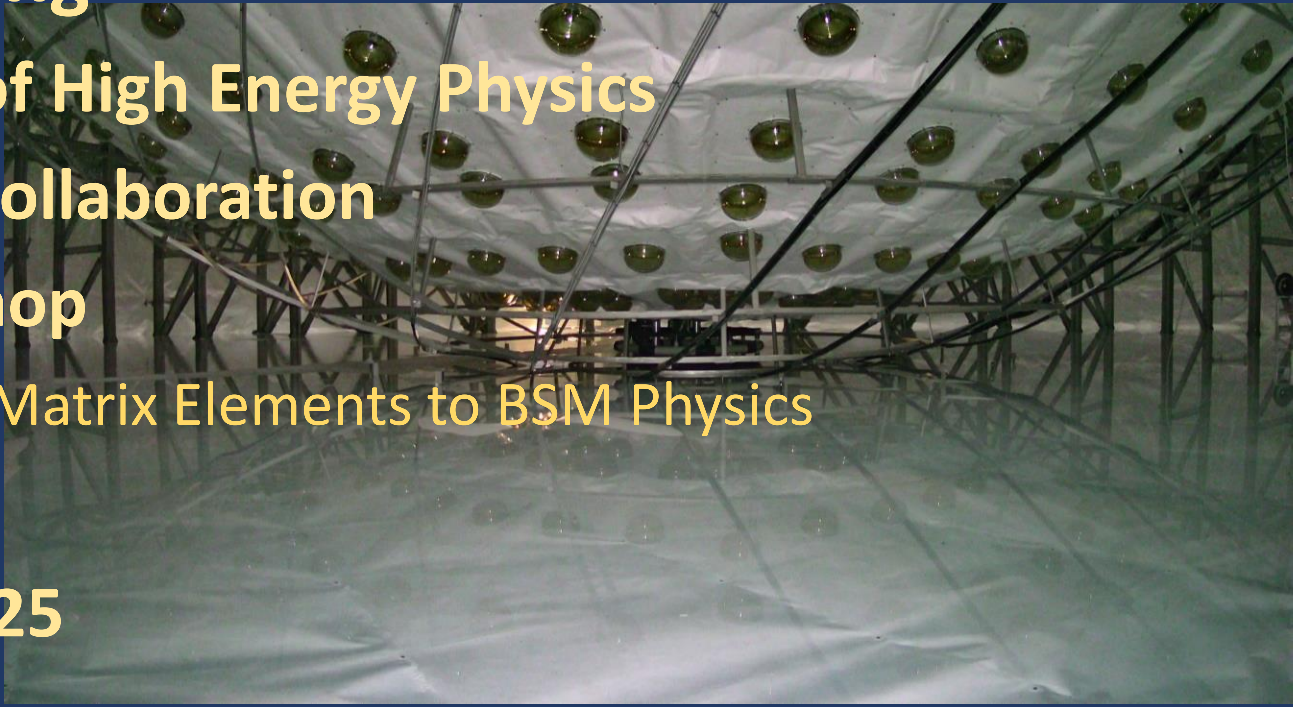
On behalf of JUNO Collaboration

INT workshop

Baryon Number Violation: From Nuclear Matrix Elements to BSM Physics

Jan. 13 2025



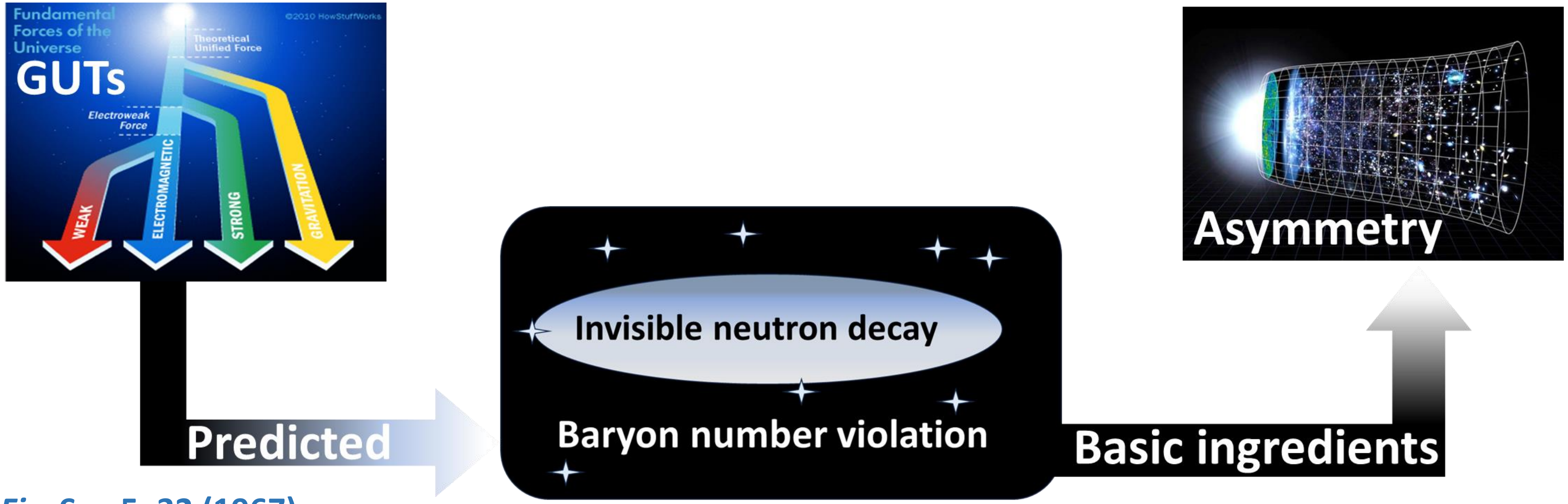
Outline

- Introduction
- JUNO experiment
- Nucleon decay
  - $p \rightarrow \overline{v} + K^{+}$
  - Invisible neutron decay
- Summary

Introduction

Motivation of nucleon decay

- **Matter-antimatter is asymmetric in universe**
  - **Sakharov conditions**
    - ***explain the asymmetry***
    - **Baryon number violation $\Delta B \neq 0$**
    - **C and CP violation**
    - **departure from thermal equilibrium**

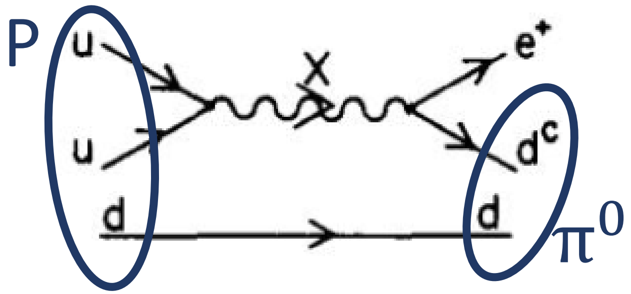


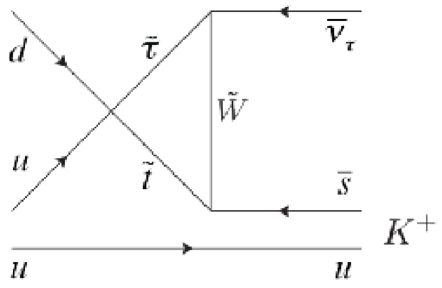
Pisma Zh. Eksp. Teor. Fiz. Ser. 5, 32 (1967)

Nucleon decay in theory

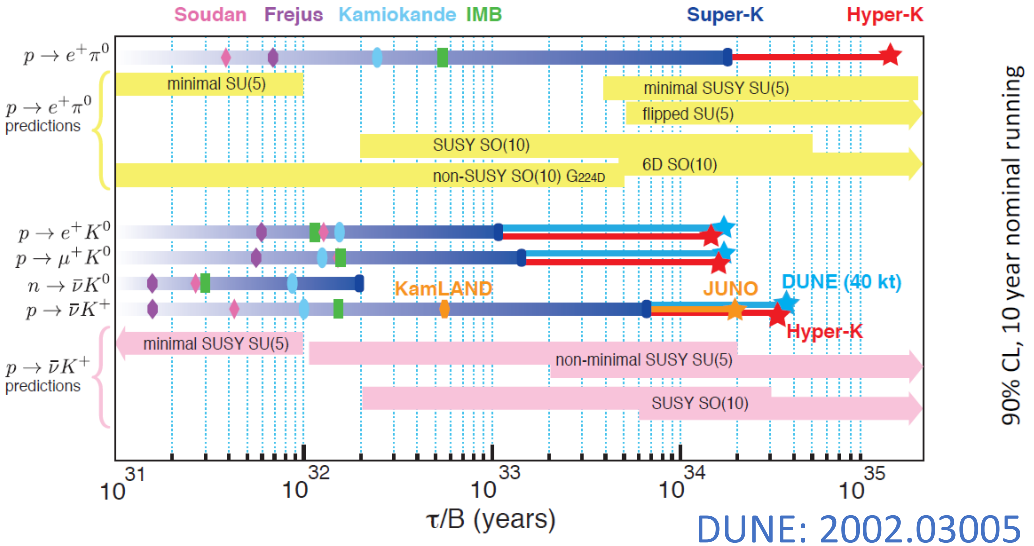
➢GUTs predict instability of nucleon

- Protons can decay into lighter subatomic particles(hypothesis) *Phys. Rept*. 441, 191-317 (2007)
- Examples
  - $p \to e^+ + \pi^0$ **(Non-SUSY GUTs)**
  - $p \to \overline{\nu} + K^+$ **(SUSY GUTs)**





- Invisible neutron decay: neutron decay into **undetected** particles (hypothesis)
- Examples
  - $n \to \text{neutrino}, n \to dark\ fermions$ …
  - *Phys. Rev. D* 67, 075015 (2003).
  - *Phys. Lett. B* 662, 259 (2008).
  - *Phys. Rev. D* 98, 035049 (2018).

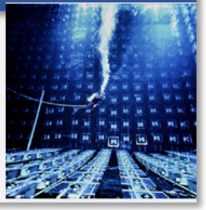


DUNE: 2002.03005

Current searches for proton decay

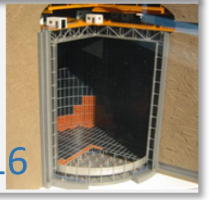
IMB

- 3.3 kton water-Cherenkov detector, 2000 PMTs
- $\tau/B(p \rightarrow e^{+}\,\pi^{0})$> 5.5×10^{32} *years* (1990)
- No proton decay have been found *Phys. Rev. D* **42**, 2974



KamiokaNDE

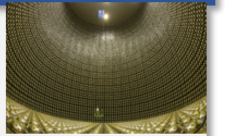
- 0.88 kton water-Cherenkov detector, 948 PMTs
- $\tau/B(p \rightarrow e^{+}\,\pi^{0})$> 2.6×10^{32} *years* (1989)
- No proton decay have been found *Phys. Lett. B* 220 (1989) 308-316



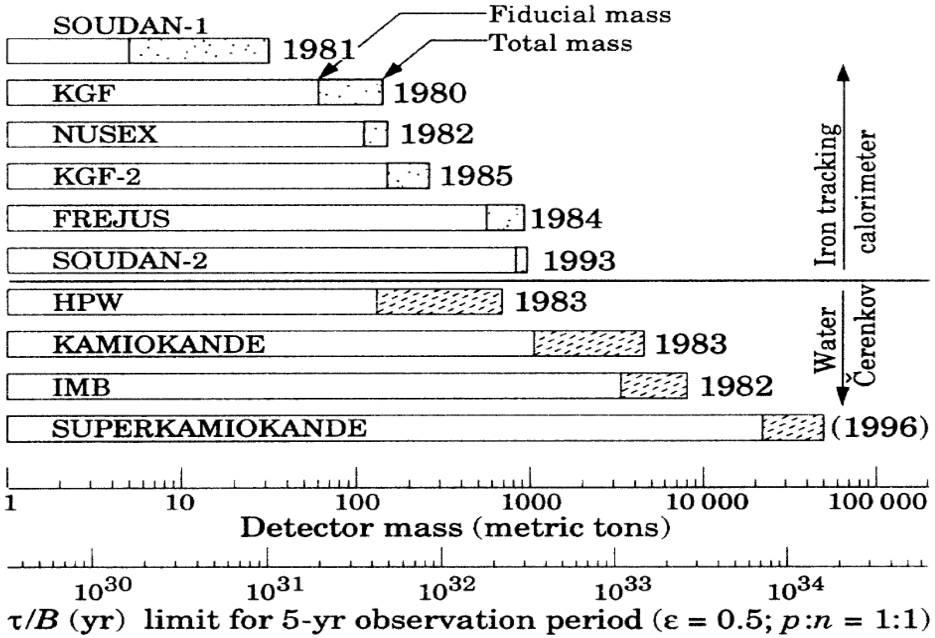
Super-Kamiokande (Super-K)

- 22.5 kton water-Cherenkov detector, 11146 PMTs
- $\tau/B(p \rightarrow e^{+}\,\pi^{0})$> 2.4×10^{34} *years* (2020)
- $\tau/B(p \rightarrow \bar{\nu}\,K^{+})$> 5.9×10^{33} *years* (2014)
- No proton decay have been found

Phys. Rev. D **102**, 112011
Phys. Rev. D 90, 072005



Past searches



Current searches for invisible neutron decay

KamLAND

- 0.5 kton liquid scintillator detector
- $\tau/B(n \rightarrow inv) > 5.8 \times 10^{29} years$ (2006)
- $\tau/B(nn \rightarrow inv) > 1.4 \times 10^{30} years$ (2006)
- No invisible neutron decay have been found

Phys .Rev. Lett. 96 (2006) 101802

SNO+

- 0.9 kton liquid scintillator detcor
- $\tau/B(n \rightarrow inv) > 9.0 \times 10^{29} years$ (2022)
- $\tau/B(nn \rightarrow inv) > 1.5 \times 10^{28} years$ (2022)
- No invisible neutron decay have been found

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

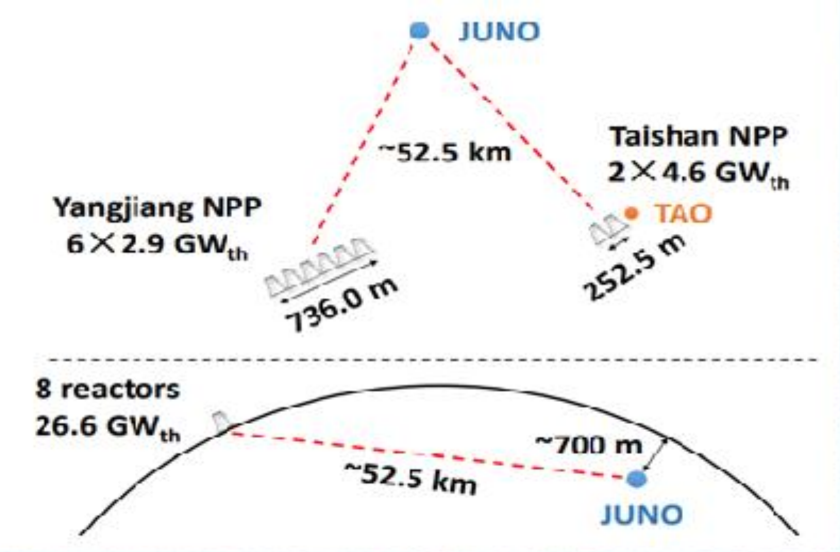
Future Nucleon Decay Experiments

Hyper-K | **DUNE** | **JUNO**

	Hyper-K	DUNE	JUNO
Mass (kton)	258 (186)	4*17 (4*10)	20
Target Nucleus	H2O	Ar40	12% H, 88% C12
Technology	Water Cerenkov	LAr TPC	Liquid Scintillator
Advantages	Large mass and cheap Good particle Identification Good direction resolution	Excellent track reconstruction Excellent particle Identification Good energy resolution	Excellent energy resolution 3% Excellent *E* threshold 0.7MeV
Shortcomings	Cerenkov threshold	Complex FSI for Ar40	Direction information lost

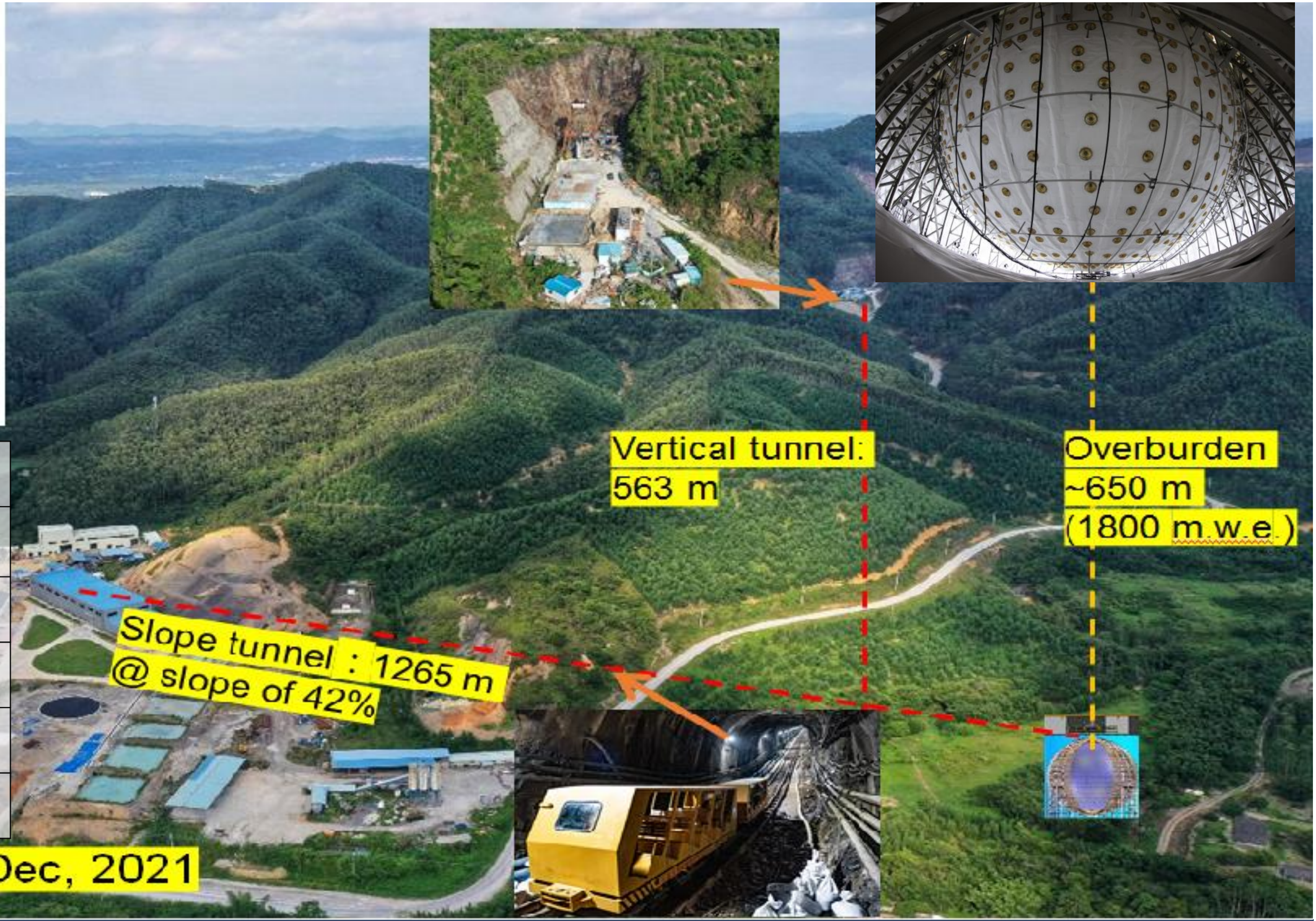
JUNO experiment

JUNO experiment overview



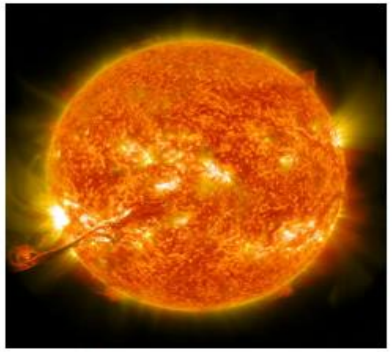
Photon Statistics	1665 p.e./MeV
PMT coverage	77%
LS transparency	> 20 m
Light yield(anthracene)	45%
Detection Eff.(QE×CE)	30%
Target mass	20 kt

Civil construction finished in Dec, 2021

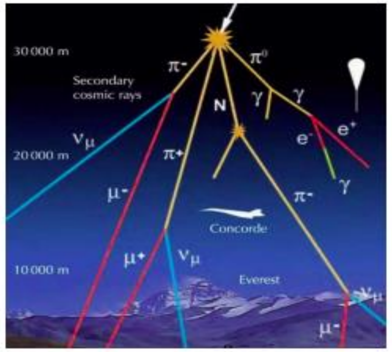


➢**Jiangmen Underground Neutrino Observatory** **(JUNO)**, a **multi-purpose** neutrino experiment

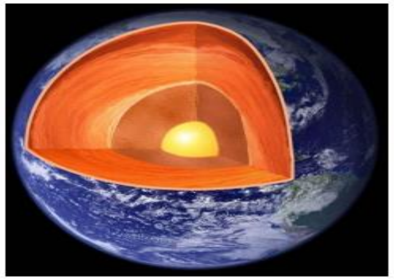
$\sim$ 50/day



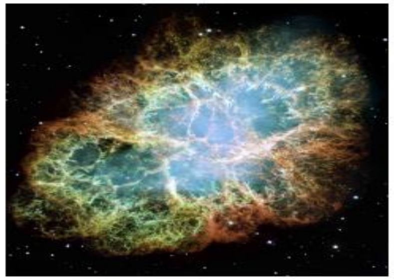
$\mathcal{O}(1000)$/day



$\sim$ 10 - 20/day

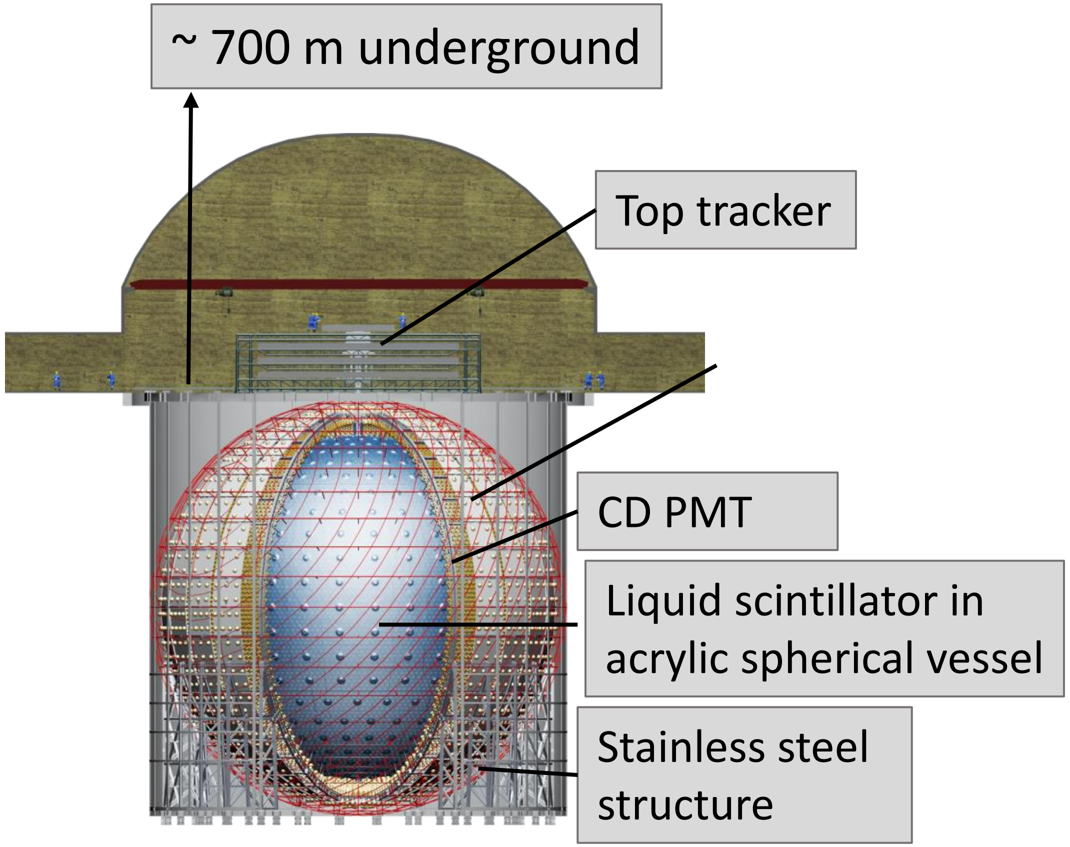


$\sim$ 1 - 2/day



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

New Physics (Nucleon decay...)



F. An et al. [JUNO] J. Phys. G 43, no.3, 030401 (2016)

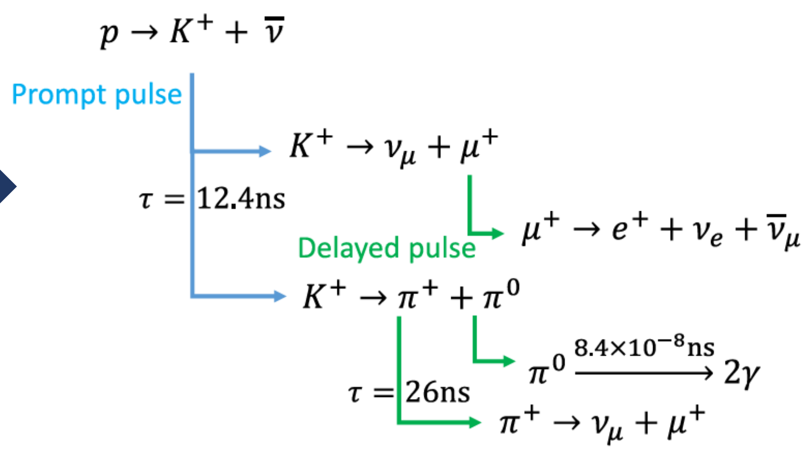
Nucleon decay: $p \to \overline{v} + K^{+}$

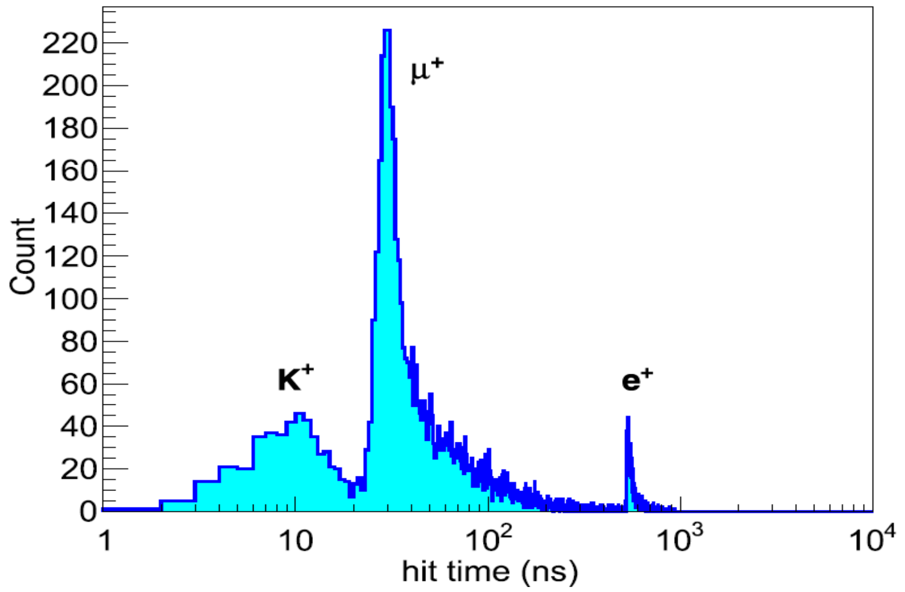
Signal characteristics of $p \to \overline{\nu} + K^+$

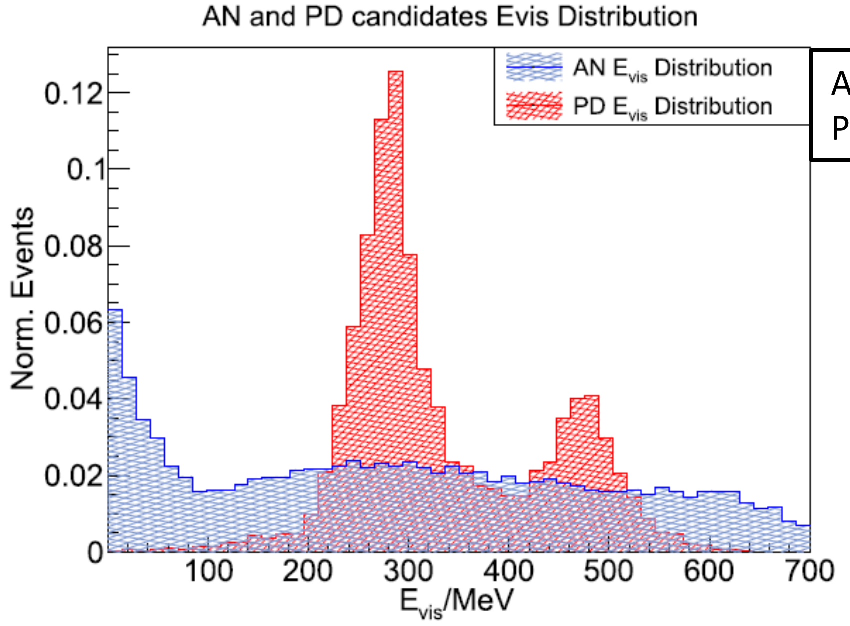
➢ Form triple coincident signals

Decay mode	Branching ratio (%)	Kinetic energy sum (MeV)
$K^+ \to \mu^+\nu_\mu$	63.55 ± 0.11	152
$K^+ \to \pi^+\pi^0$	20.66 ± 0.08	354
$K^+ \to \pi^+\pi^+\pi^-$	5.59 ± 0.04	75
$K^+ \to \pi^0 e^+\nu_e$	5.07 ± 0.04	265–493
$K^+ \to \pi^0\mu^+\nu_\mu$	3.353 ± 0.034	200–388
$K^+ \to \pi^+\pi^0\pi^0$	1.761 ± 0.022	354

Two most dominant channels

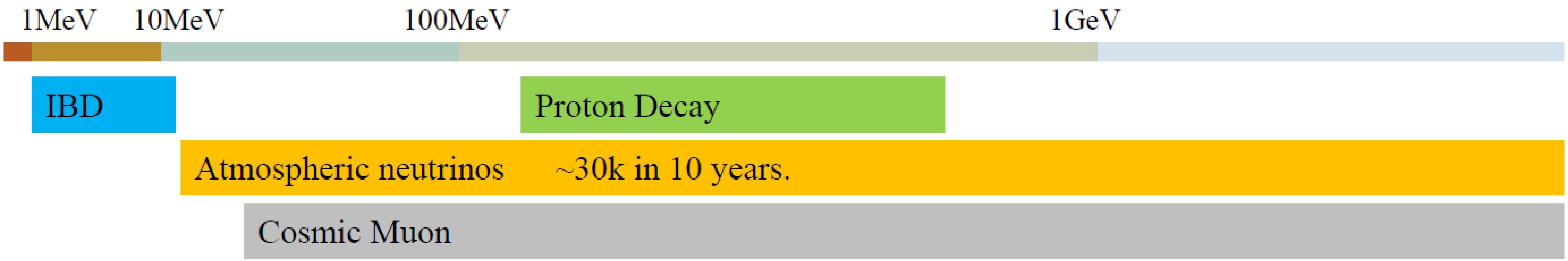






AN: Atmospheric neutrinos
PD: Proton decay

- Most dominant background: Atmospheric neutrinos



Type	Ratio (%)	Ratio with E_{vis} in [100 MeV, 600 MeV](%)	Interaction	Signal characteristics
NCES	20.2	15.8	$\nu + n \to \nu + n$ $\nu + p \to \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \to n + l^+$ $\nu_l + n \to p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \to l^- + p + \pi^+$ $\nu + p \to \nu + n + \pi^+$	Approximate Single Pulse (Second pulse too low)
Kaon Production	1.1	0.2	$\nu_l + n \to l^- + \Lambda + K^+$ $\nu_l + p \to l^- + p + K^+$	Double Pulse

Low energy background

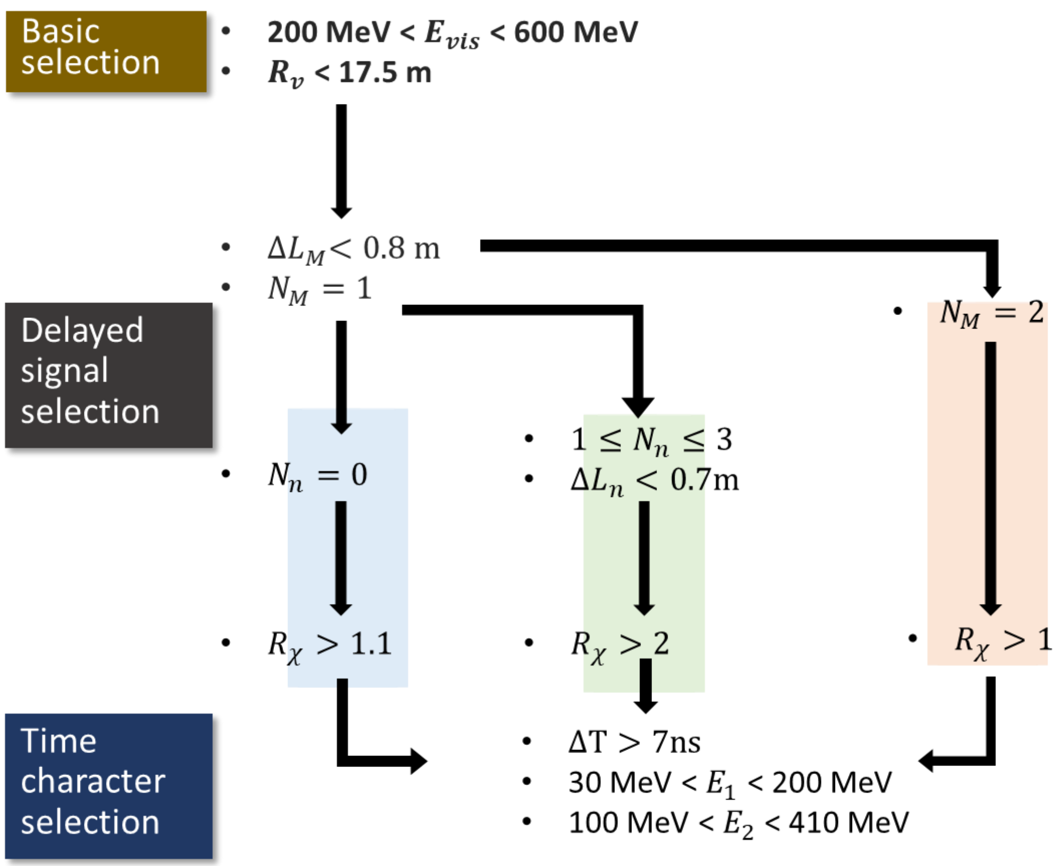
- Removed by energy cut
  - IBD, solar-υ, geo-υ, and low energy atm-υ

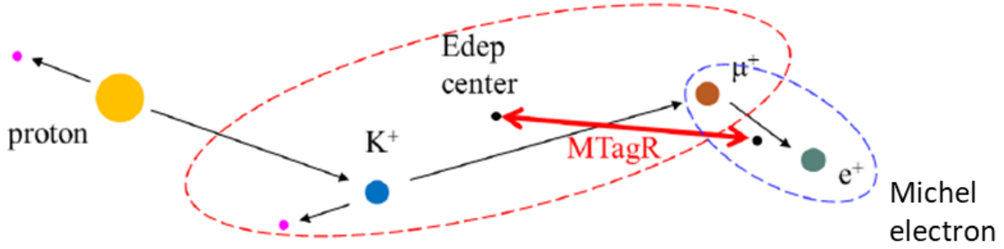
Cosmic Muon

- Removed by muon veto and FV cut

Event selection

➢Selection flow





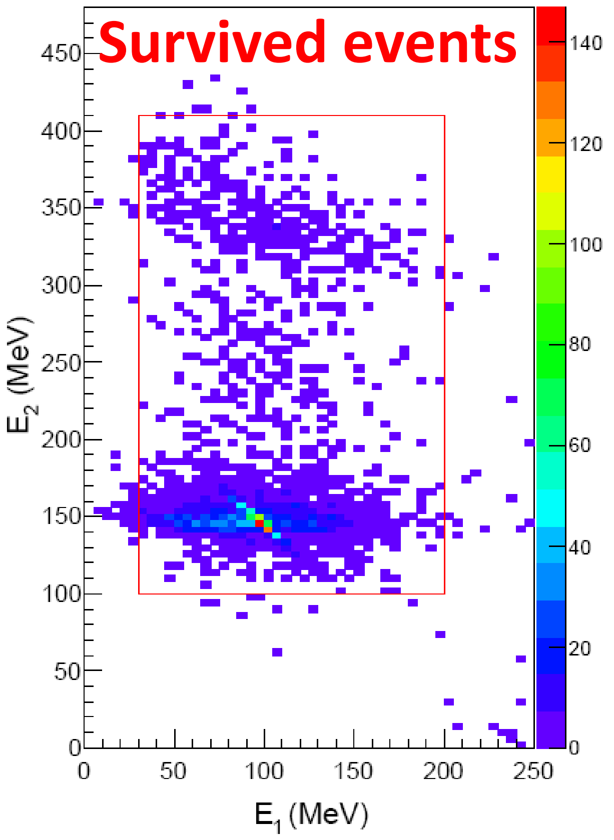
Prompt Edep Center to Michel birth place.

Selection result

Criteria		Survival rate of $p \to \bar{\nu}K^+$ (%) Sample 1	Sample 2	Sample 3	Survival count (fraction) of atmospheric ν Sample 1	Sample 2	Sample 3
basic selection	E_{vis}	94.6			51299 (32.1%)		
	R_V	93.7			47849 (29.9%)		
Delayed signal selection	N_M	74.4		4.4	20739 (13.0%)		1143 (0.7%)
	ΔL_M	67.0		4.4	13796 (8.6%)		994 (0.6%)
	N_n	48.4	17.9	–	5403 (3.4%)	6857 (4.3%)	–
	ΔL_n	–	16.6	–	–	4472 (2.8%)	–
Time character selection	R_χ	45.9	9.0	3.8	4326 (2.7%)	581 (0.4%)	716 (0.4%)
	ΔT	28.3	7.7	2.4	121 (0.07%)	18 (0.01%)	30 (0.02%)
	E_1, E_2	27.4	7.3	2.2	1 (0.0006%)	0	0
Total		36.9			1		

- R_v: Fiducial volume
- N_M: tagged Michel electron number
- ΔL_M: correlated distance to Michel electron
- N_n: tagged neutron number
- ΔL_n: correlated distance to neutron
- R_χ: χ^2 ratio

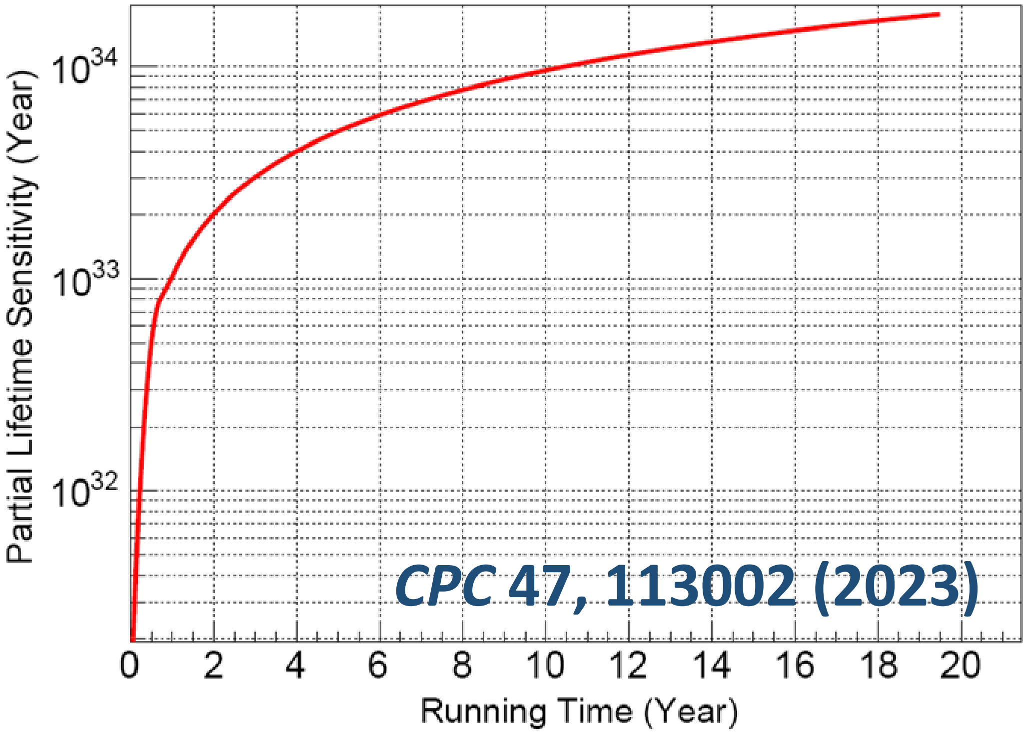
Sensitivity to $p \to \overline{\nu} + K^+$



(a) $p \to \bar{\nu} K^+$ (b) atmospheric ν

Background rate: 0.2/10 yrs

Signal efficiency : 36.9%



$\tau/B(p \to \overline{\nu}\, K^+) > 9.6 \times 10^{33}$ yrs/10 yrs

Best limit: 5.9×10^{33} **yrs from Super-K**

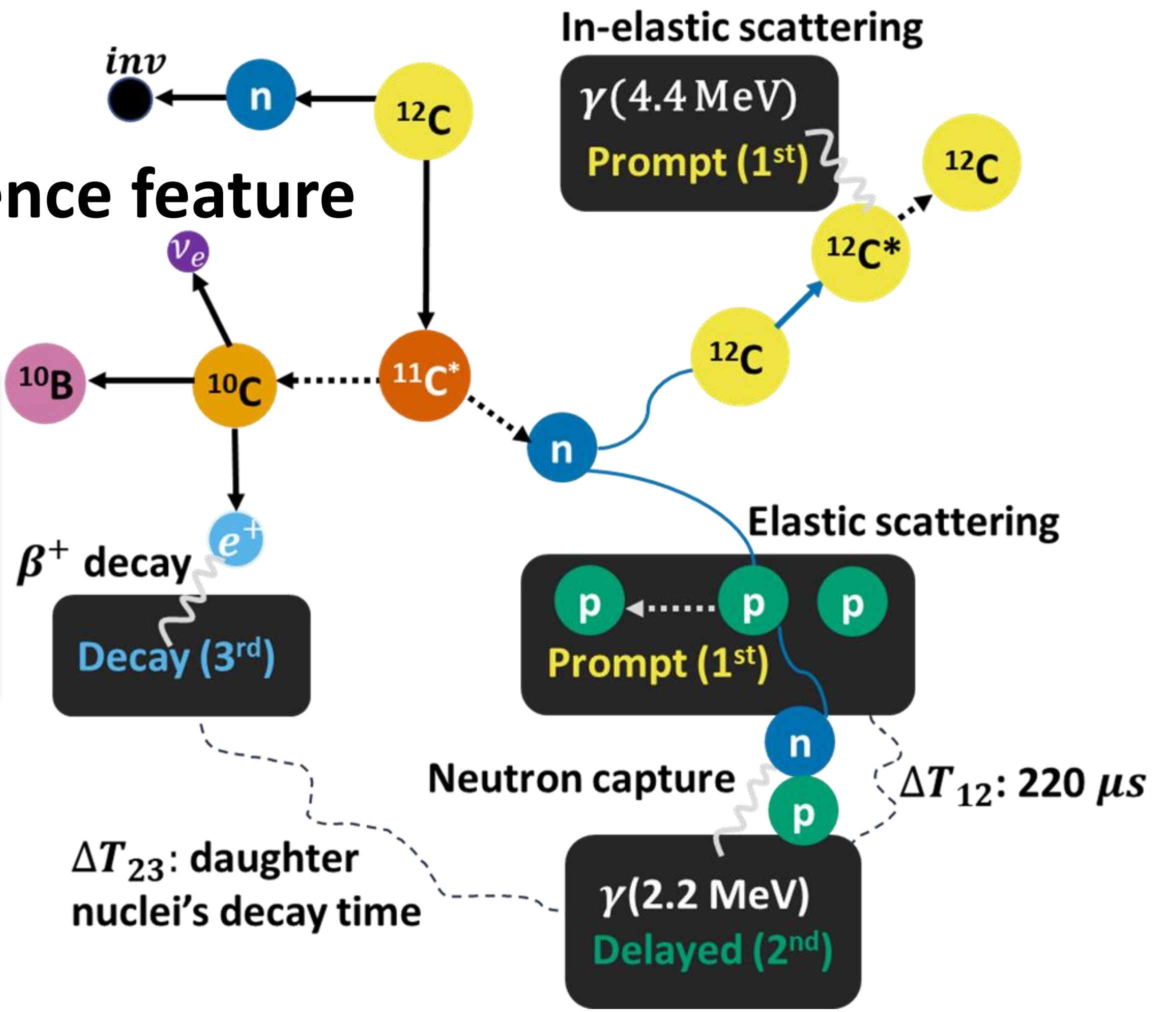
Nucleon decay: invisible neutron decay

Signal characteristic of invisible neutron decay

- **Bounded neutrons in ^{12}C : two invisible decay modes**
  - $n \rightarrow inv$ $(^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{C}^{*})$
  - $nn \rightarrow inv$ $(^{12}\mathrm{C} \rightarrow {}^{10}\mathrm{C}^{*})$
- **De-excitation modes have triple coincidence feature**

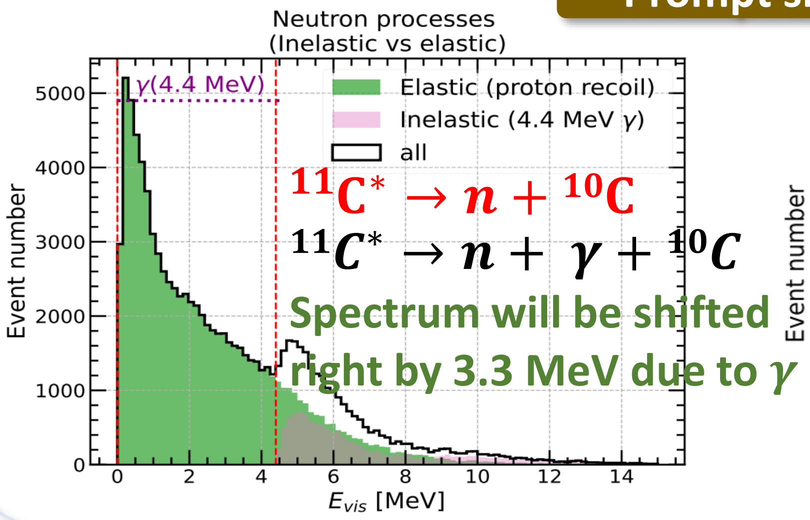
$$^{11}\mathrm{C}^{*} \rightarrow n + {}^{10}\mathrm{C} \quad (Br_{n1} = 3.0\%)$$
$$^{11}\mathrm{C}^{*} \rightarrow n + \gamma + {}^{10}\mathrm{C} \quad (Br_{n2} = 2.8\%)$$
$$^{10}\mathrm{C}^{*} \rightarrow n + {}^{9}\mathrm{C} \quad (Br_{nn1} = 6.2\%)$$
$$^{10}\mathrm{C}^{*} \rightarrow n + p + {}^{8}\mathrm{B} \quad (Br_{nn2} = 6.0\%)$$

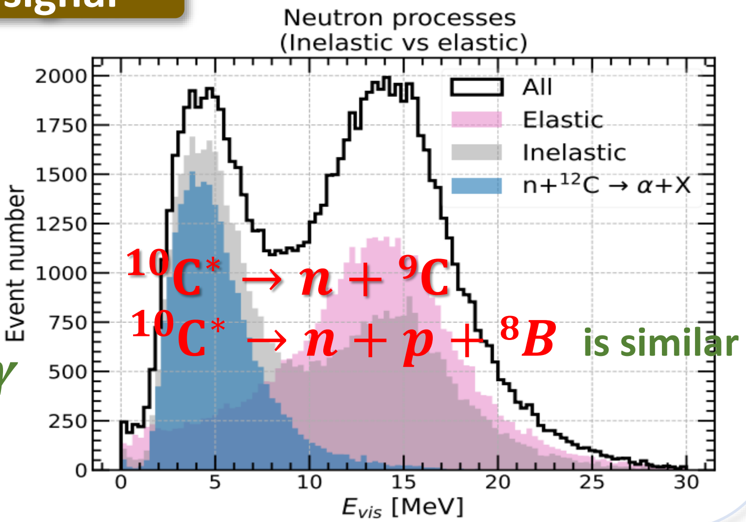
Yuri Kamyshkov, Edwin Kolbe PRD 67, 076007 (2003)



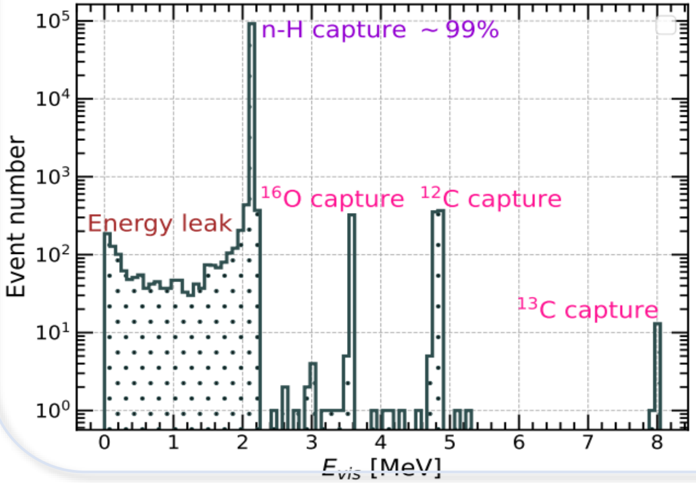
Signal characteristic of signal energy

Prompt signal

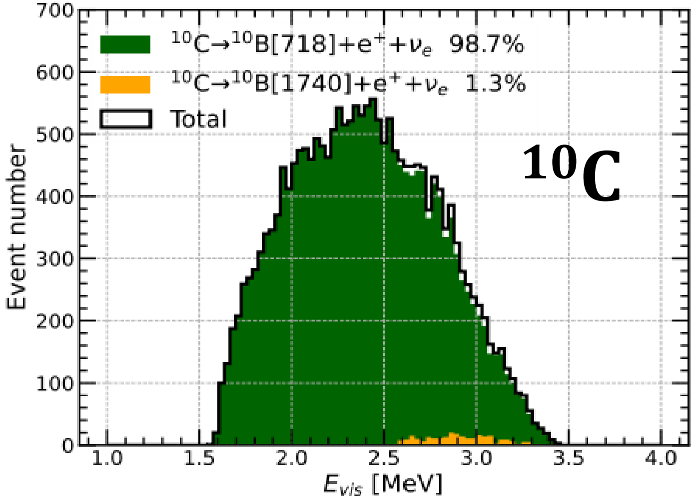


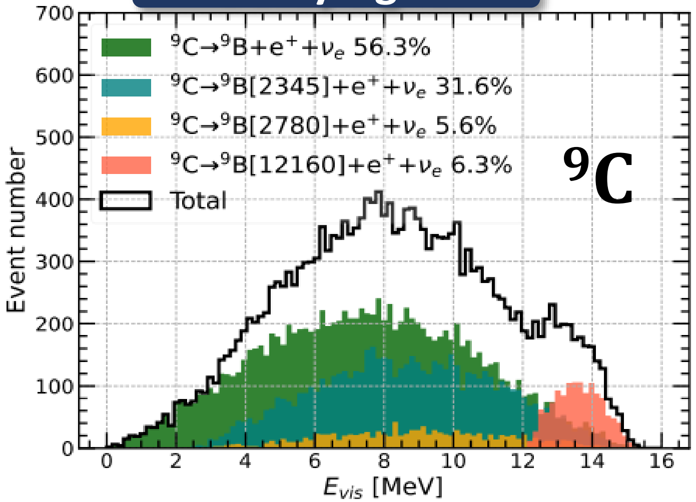


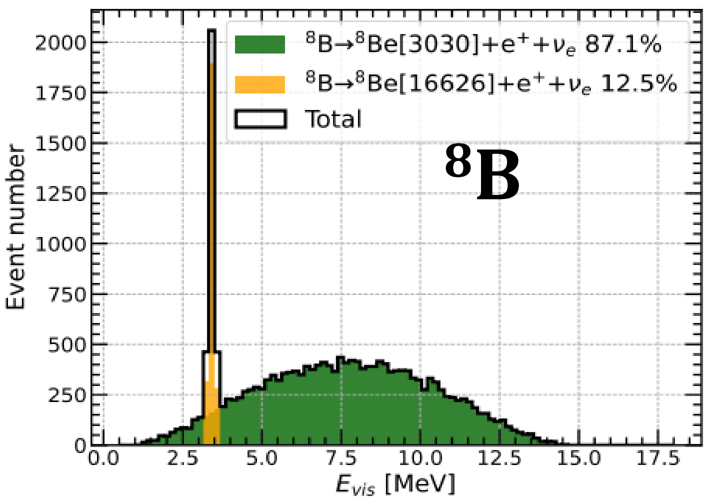
Delayed signal



Decay signal





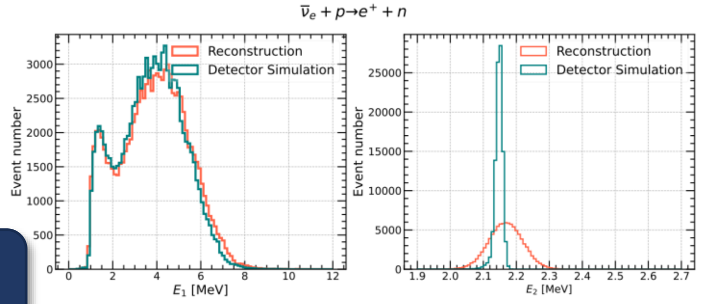


Backgrounds

- Six background **sources**
- **Single**
  - Radioactivity
  - Long-lived isotopes
- **Correlated (Prompt-Delayed)**
  - IBD (Inverse Beta decay)
  - Atm-ν NC (atmospheric neutrino neutral current)
  - Long-lived isotopes (Li9/He8) from cosmic muons
  - Fast neutron
  - Alpha-n
- Triple (Prompt-Delayed-Decay)
  - Atm-ν NC

Single + Single + Single
Correlated + Single

Combination



$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + p + {}^{10}\mathrm{B}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + p + \alpha + {}^{6}\mathrm{Li}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + 2p + {}^{9}\mathrm{Be}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + p + d + {}^{8}\mathrm{Be}\,.$$

$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + {}^{11}\mathrm{C}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + 2n + {}^{10}\mathrm{C}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + 3p + n + {}^{8}\mathrm{Li}$$

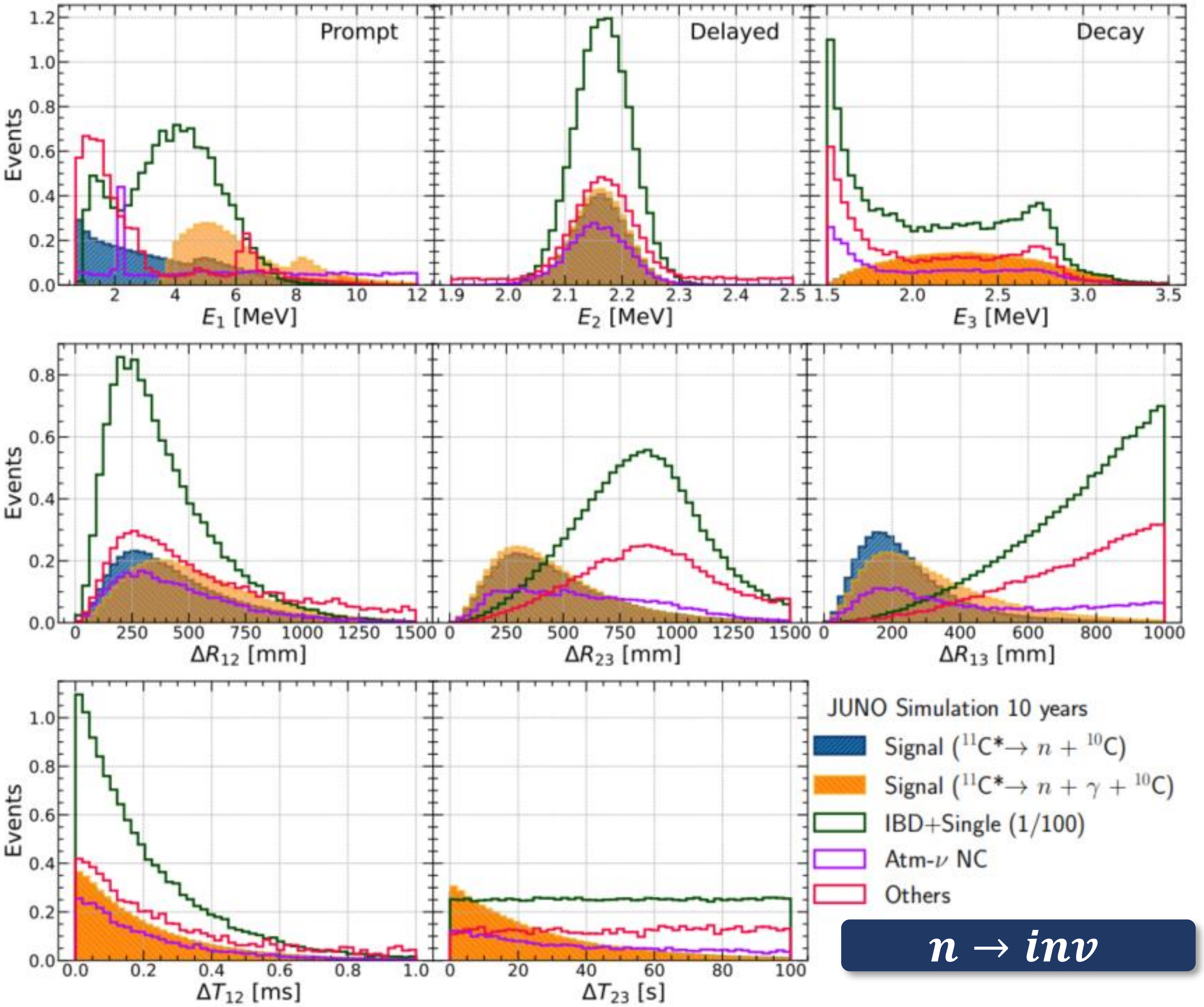
Event selection

➢Consider **10 years** data taking

- **Signal rate**
  - from the final sensitivity result

Selection criteria

Quantity	$n \to inv$	$nn \to inv$
$R_{1,2,3}$ [m]	< 16.7	< 16.7
E_1 [MeV]	0.7-12	0.7-30
E_2 [MeV]	1.9-2.5	1.9-2.5
E_3 [MeV]	1.5-3.5	3.0-16.0
ΔT_{12} [ms]	< 1	< 1
ΔT_{23} [s]	0.002-100	0.002-3.0
ΔR_{12} [m]	< 1.5	< 1.5
ΔR_{23} [m]	< 1.5	< 1.5
ΔR_{13} [m]	< 1.0	< 1.0



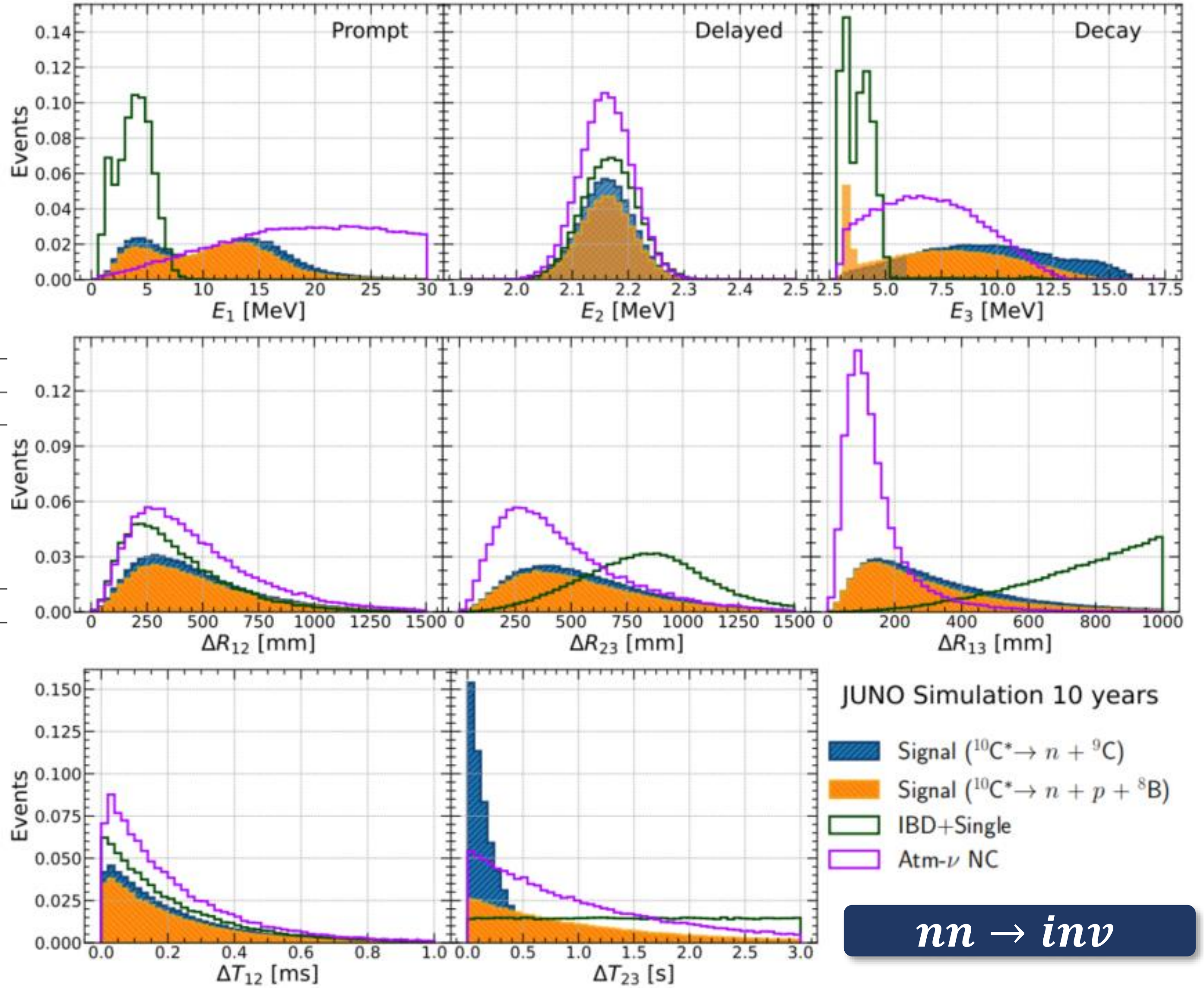
$n \to inv$

Event selection

- Consider **10 years** data taking
  - **Signal rate**
    - from the final sensitivity result

Signal efficiencies

Selection Criterion	$n \to inv$		$nn \to inv$	
	$^{11}C^* \to n + ^{10}C$	$^{11}C^* \to n + \gamma + ^{10}C$	$^{10}C^* \to n + ^{9}C$	$^{10}C^* \to n + p + ^{8}B$
All triple signals	100	100	100	100
Muon Veto	65.7 ± 0.2	65.5 ± 0.2	80.8 ± 0.2	78.3 ± 0.2
Fiducial Volume	83.5 ± 0.4	82.7 ± 0.4	82.9 ± 0.4	83.1 ± 0.4
Event Selection	75.4 ± 0.9	89.7 ± 0.3	89.2 ± 0.3	83.5 ± 0.3
Multiplicity Cut	93.8 ± 0.1	93.8 ± 0.1	$99.9 \pm \mathcal{O}(10^{-4})$	$99.9 \pm \mathcal{O}(10^{-4})$
Combined Selection	38.8 ± 0.5	45.6 ± 0.3	59.7 ± 0.4	54.3 ± 0.4



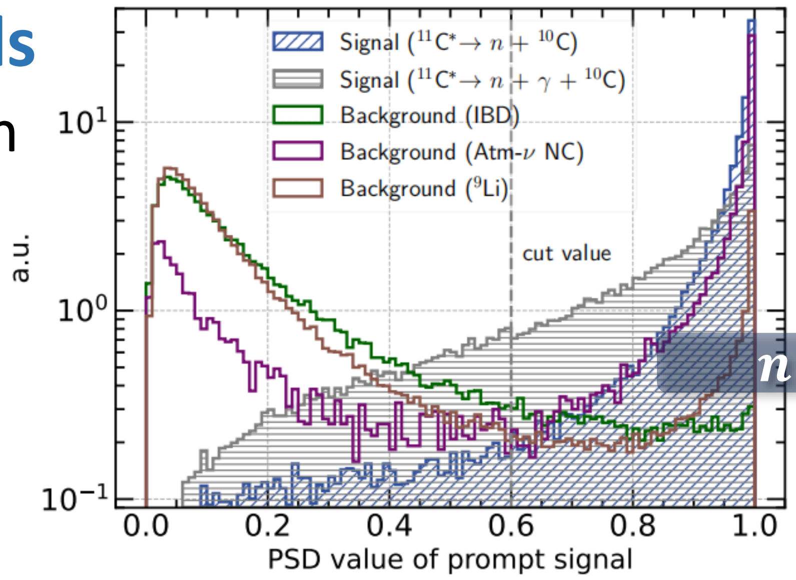
$nn \to inv$

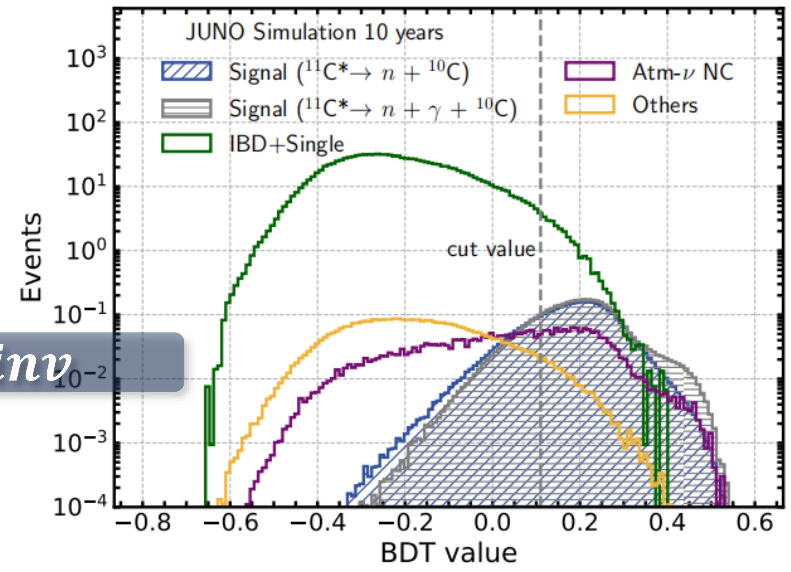
Background suppression

➢Two suppression methods

- **P**ulse **S**hape **D**iscrimination
  - Particle's emission photon time are different
- **M**ulti **V**ariate **A**nalysis
  - Combine multidimensional features

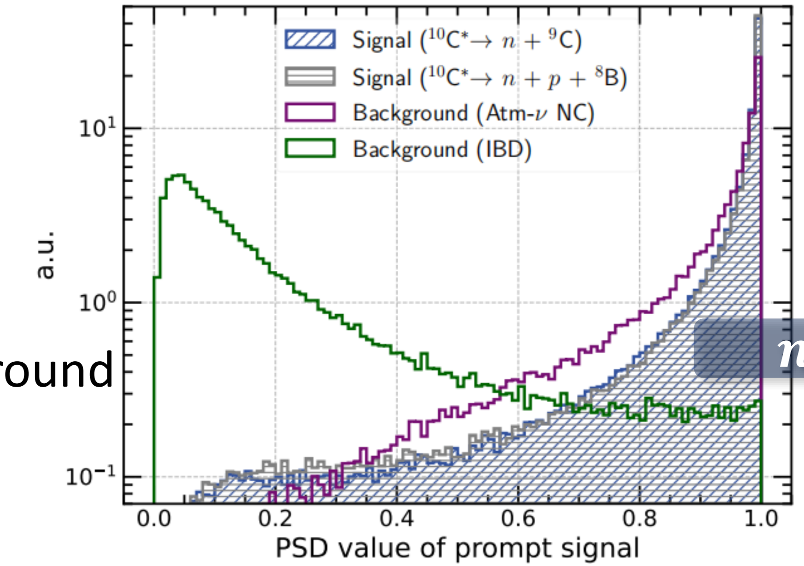
$n \rightarrow inv$

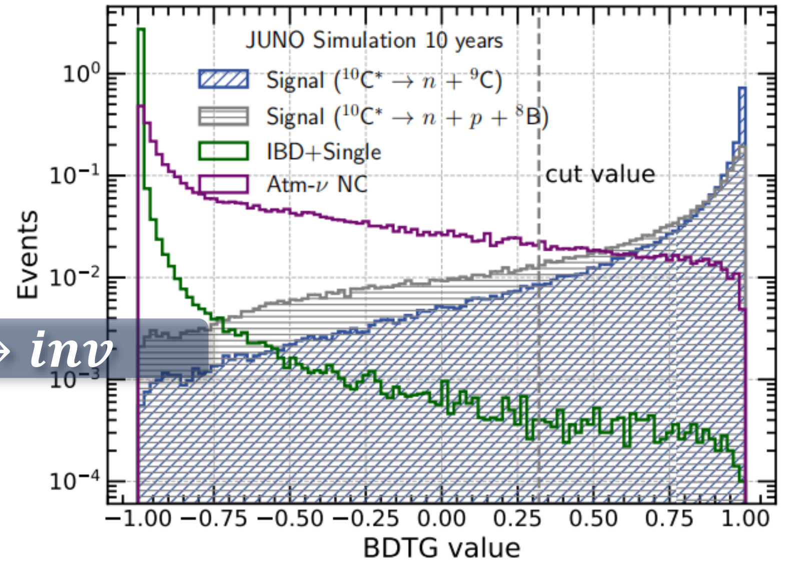




- Both **PSD** and **MVA** have **good** performance
  - Effectively suppress background

$nn \rightarrow inv$





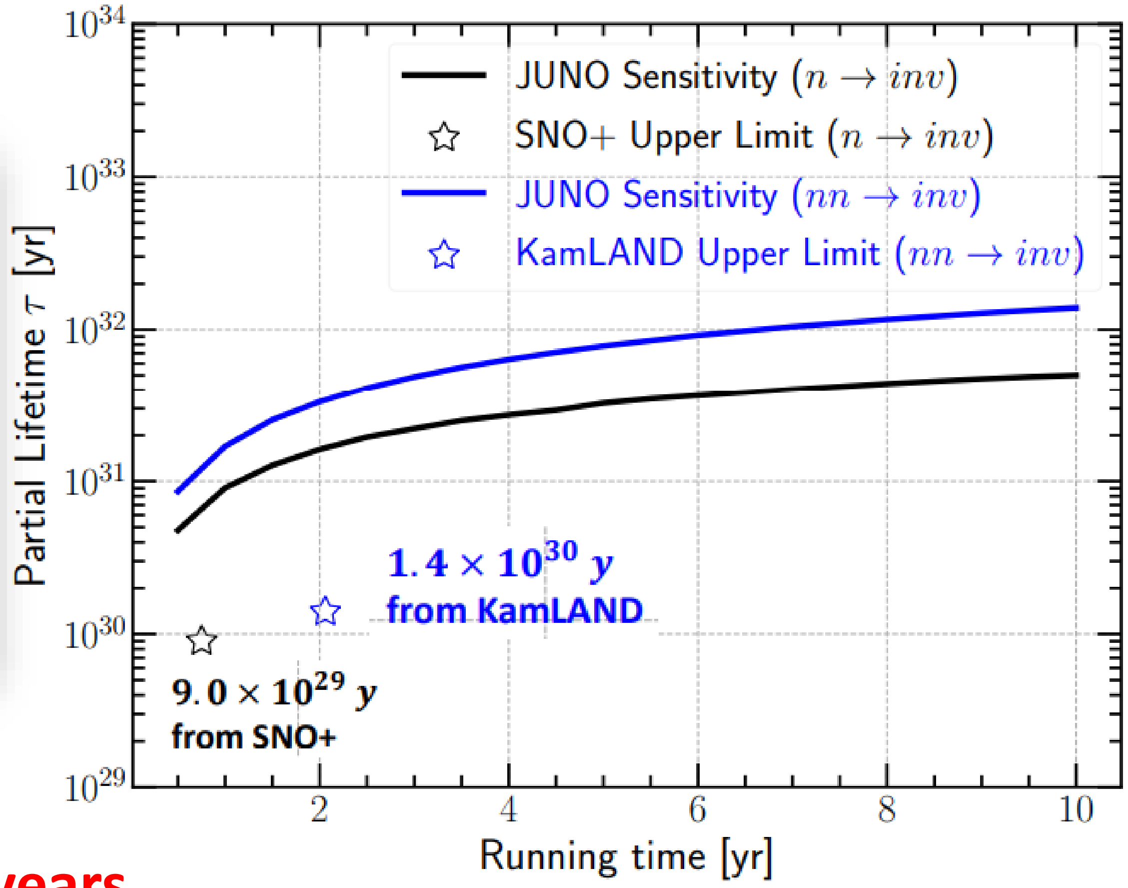
Sensitivity

Summary of Signal and background

Backgrounds (10 years)	$n \to inv$ Basic selection	$n \to inv$ PSD + MVA	$nn \to inv$ Basic selection	$nn \to inv$ PSD + MVA
IBD + Single	1235 ± 50	2.72 ± 0.10	3.01 ± 0.09	0.0110 ± 0.0003
Atm-ν NC	3.0 ± 1.1	0.93 ± 0.67	4.3 ± 3.5	0.55 ± 0.63
$^{13}C(\alpha,n)^{16}O$ + Single	3.4 ± 1.4	0.036 ± 0.013	–	–
$^{9}Li/^{8}He$ + Single	1.55 ± 0.39	0.29 ± 0.17	0.13 ± 0.13	0.13 ± 0.13
Accidental	1.46 ± 0.05	0.095 ± 0.004	–	–
Total	1244 ± 50	4.07 ± 0.68	7.4 ± 3.5	0.69 ± 0.64
Signal efficiency (%)	$n \to inv$ Basic selection	$n \to inv$ PSD + MVA	$nn \to inv$ Basic selection	$nn \to inv$ PSD + MVA
$\epsilon_{n(nn)1}$	35.6 ± 0.2	23.5 ± 0.2	54.0 ± 0.3	48.2 ± 0.3
$\epsilon_{n(nn)2}$	43.6 ± 0.3	30.3 ± 0.3	49.2 ± 0.3	36.3 ± 0.3

$$\tau/B(n \to inv) > 5.0 \times 10^{31} \text{ years},$$
$$\tau/B(nn \to inv) > 1.4 \times 10^{32} \text{ years}.$$

10 years



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An order of magnitude improvement to the current best limits in 2 years data taking

Summary

- **JUNO is a large LS detector**
  - **20 kton LS**
    - 1.45×10^{33} **free protons,** 5.30×10^{33} **bound protons/neutrons**
- **Competitive sensitivities for nucleon decay (some channels)**
  - **Nucleon decay (**JUNO 10-year sensitivity**)**
    - $\tau/B(p \rightarrow \bar{\nu} K^{+}) > 9.6 \times 10^{33}$ **year at 90% C.L.**
    - $\tau/B(n \rightarrow inv) > 5.0 \times 10^{31}$ **year at 90% C.L.**
    - $\tau/B(nn \rightarrow inv) > 1.4 \times 10^{32}$ **year at 90% C.L.**
- **JUNO is during filling stage, overcoming challenges**
- **JUNO has the potential to study nucleon decay and test new physics**

Thank you for your attention!