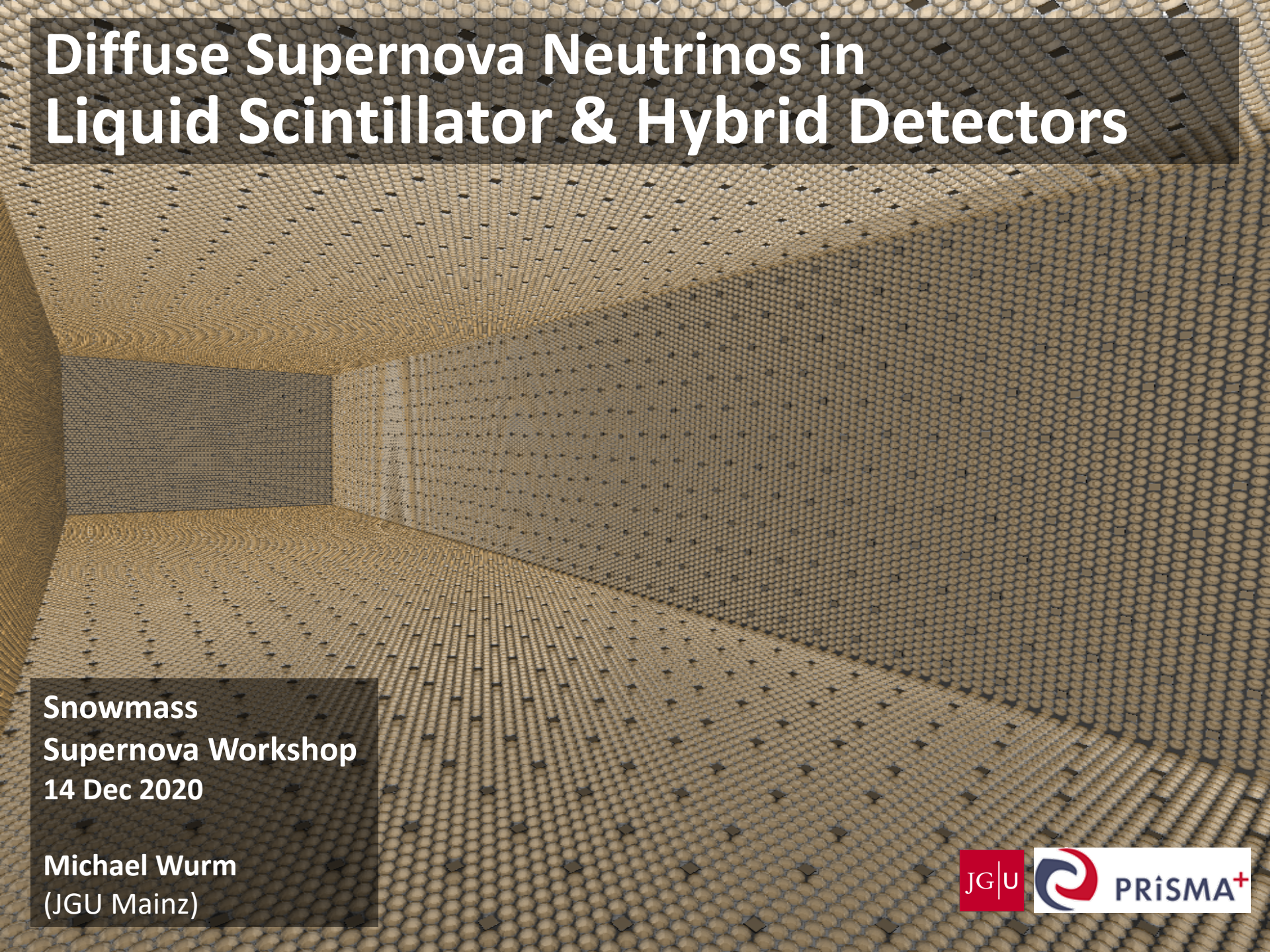
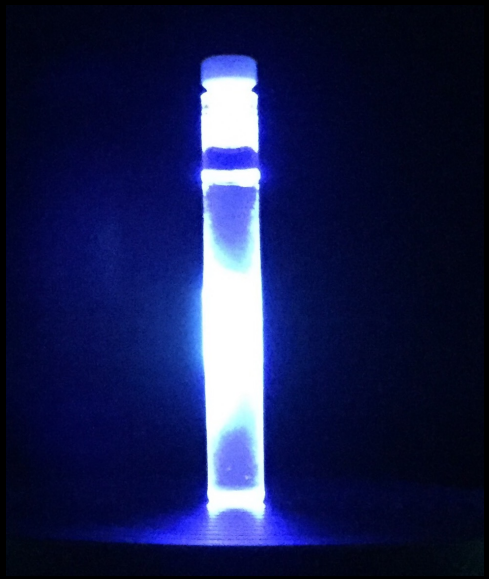
Diffuse Supernova Neutrinos in Liquid Scintillator & Hybrid Detectors



Snowmass Supernova Workshop
14 Dec 2020

Michael Wurm
(JGU Mainz)

DSNB detection in Liquid Scintillator



when compared to water+Gd detectors:

Virtues

- high light yield
  → very efficient neutron tag
  → high detection efficiency (~90%)
- background discrimination by pulse-shaping: electron-muon, positron-hadron

Disadvantages

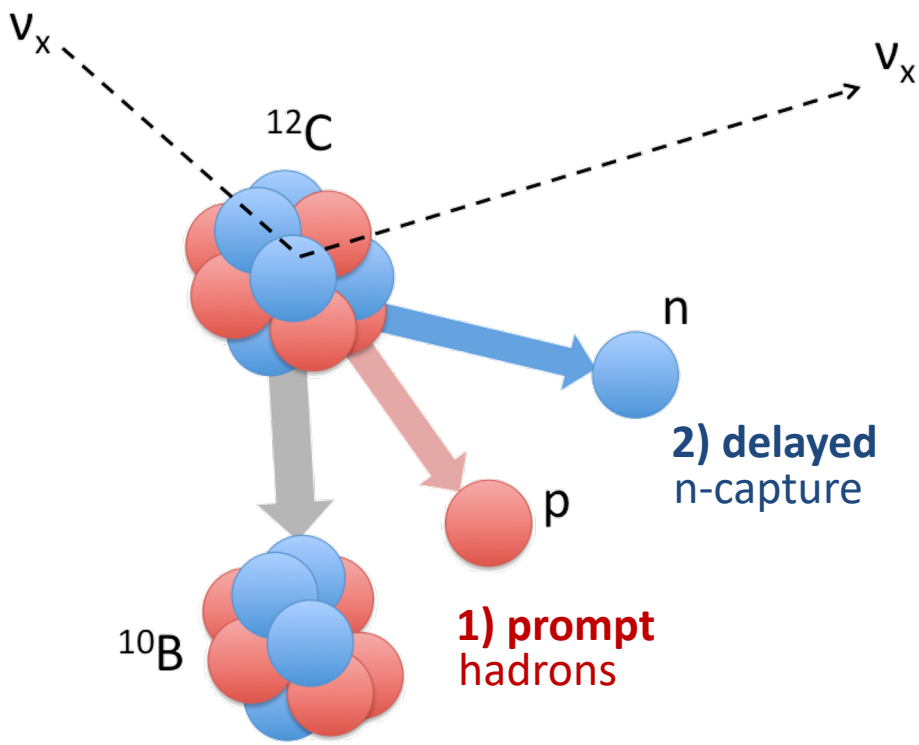
- scintillation signal from atmospheric neutrino NC interactions → **important background!**

Atmospheric neutrino NC background

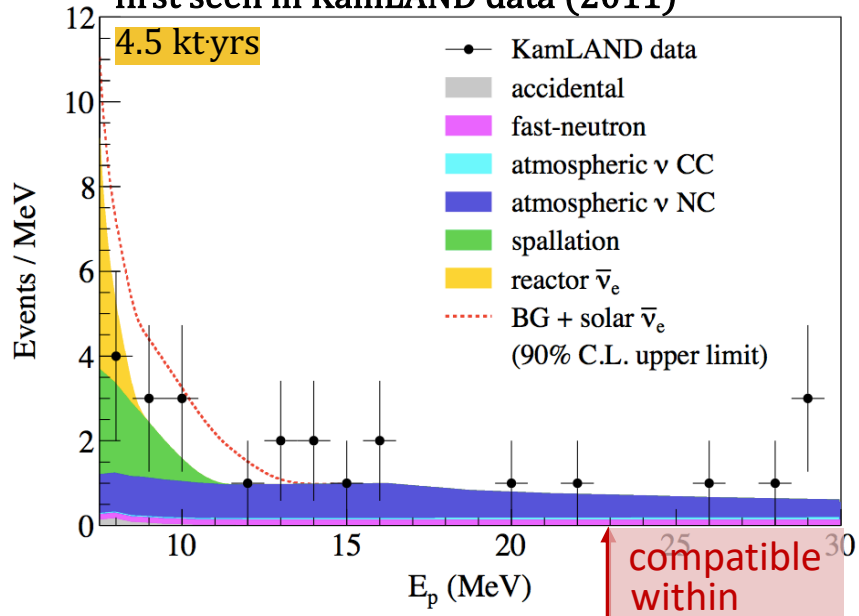
BG specific to scintillation detectors:
nucleons/nuclear fragments in final state produce (low) scintillation light + neutrons

→ **can be confused with prompt of IBD**

KamLAND: 5 (kt·yr)$^{-1}$ vs. SK: 0.4 (kt·yr)$^{-1}$

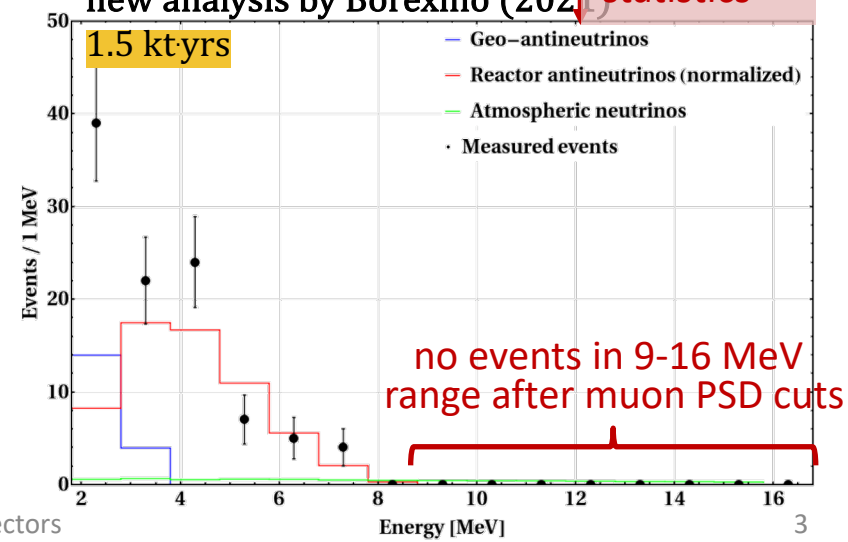


first seen in KamLAND data (2011)



compatible within statistics

new analysis by Borexino (2021)



no events in 9-16 MeV range after muon PSD cuts

Signal & Background Predictions for JUNO

Energy window

ca. 10-30 MeV

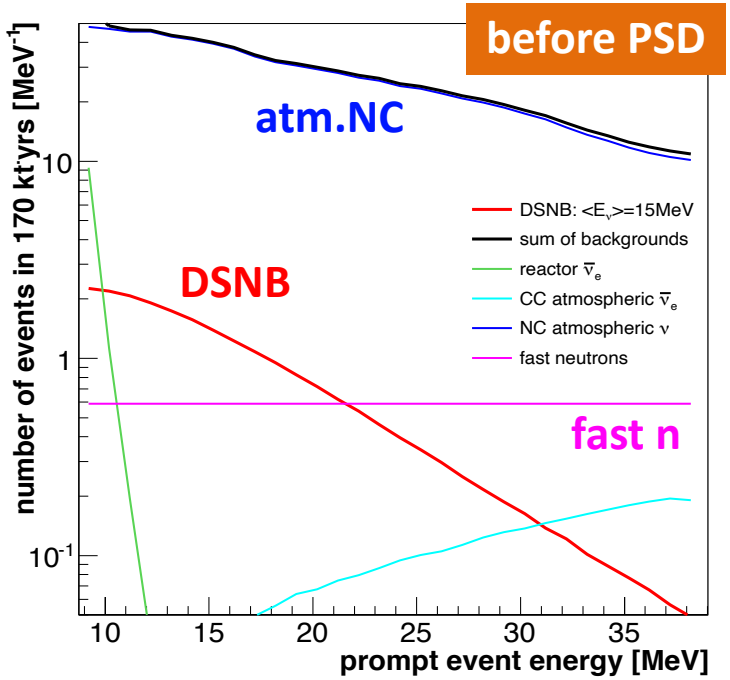
Event Rate

IBD: 2-4 yr^{-1}

BG (w/o PSD)

atm. NC: 60 yr^{-1}

fast n's: 1 yr^{-1}



JUNO key parameters

- total mass: 20,000 tons
- p.e. yield: >1100 pe/MeV
- radiopurity: $<10^{-(16\div17)}$ U/Th
- depth: ~1,800 mwe

Measuring program

- JUNO offers signal statistics similar to SK+Gd but at much larger background level

Signal & Background Predictions for JUNO

Energy window

ca. 10-30 MeV

Event Rate

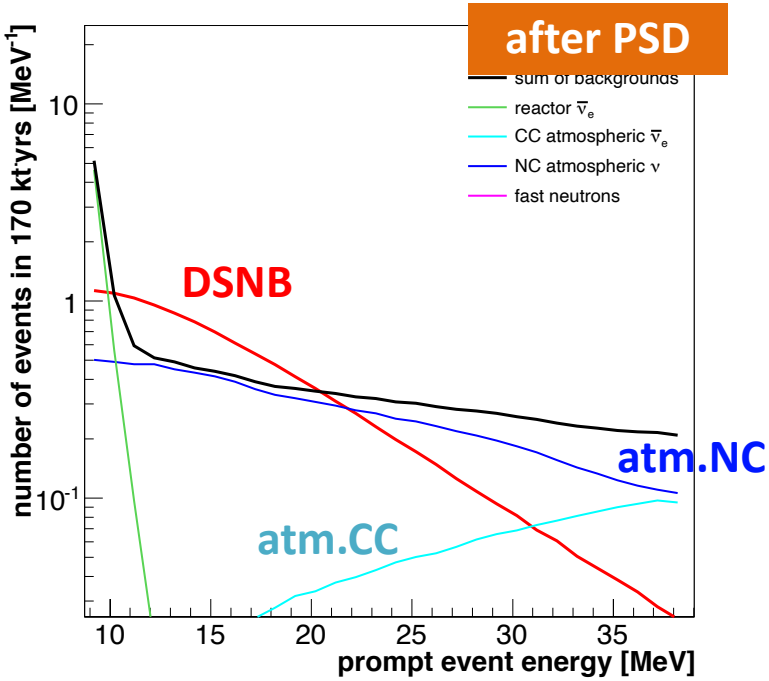
(ε~0.5)

IBD: 1-2 yr^{-1}

BG (w/ PSD)

atm. NC: 0.6 yr^{-1}

fast n's: 10^{-2} yr^{-1}



JUNO key parameters

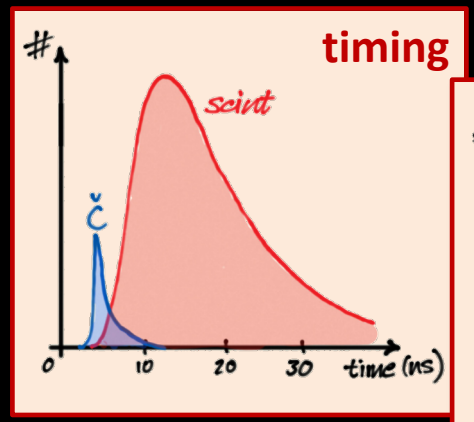
- total mass: 20,000 tons
- p.e. yield: >1100 pe/MeV
- radiopurity: $<10^{-(16\div17)}$ U/Th
- depth: ~1,800 mwe

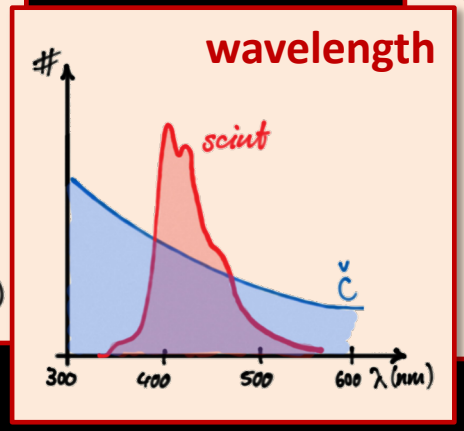
Measuring program

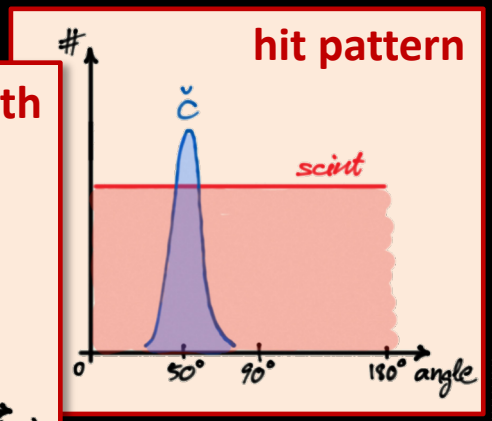
- JUNO offers signal statistics similar to SK+Gd but at much larger background level
- efficient pulse shape discrimination is key, residual atm. NC BG rate determined with ^{11}C tag

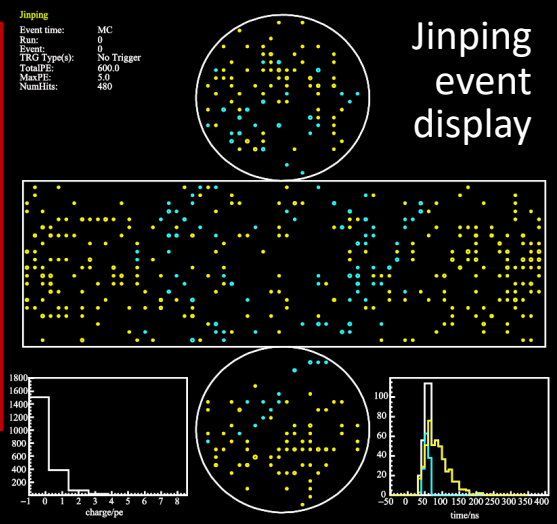
→ **expected sensitivity: ~3σ in 10 yrs**

Hybrid Cherenkov/Scintillation Detectors









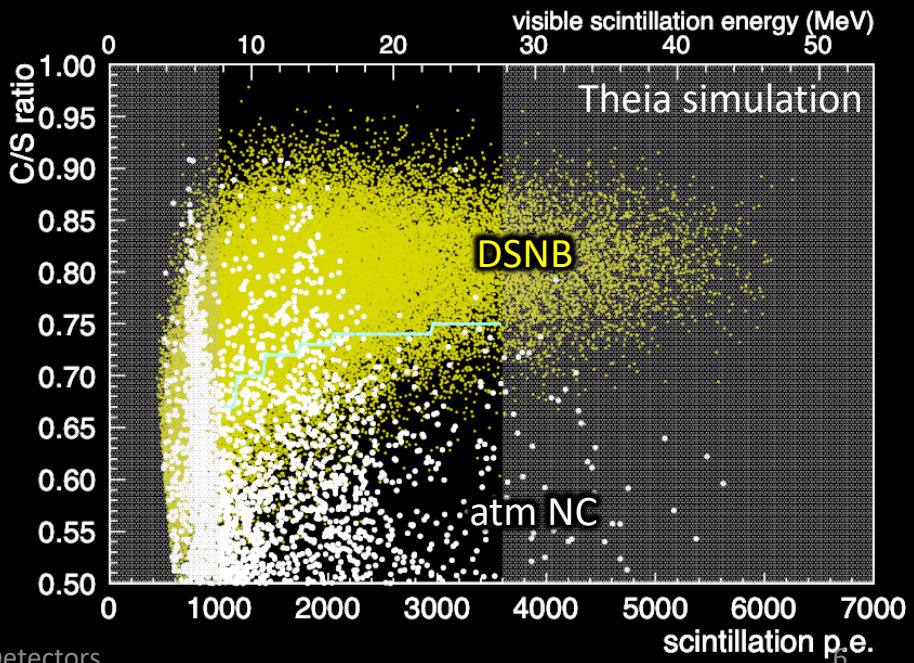
Jinping event display

Basic ingredients for hybrid C/S detection:

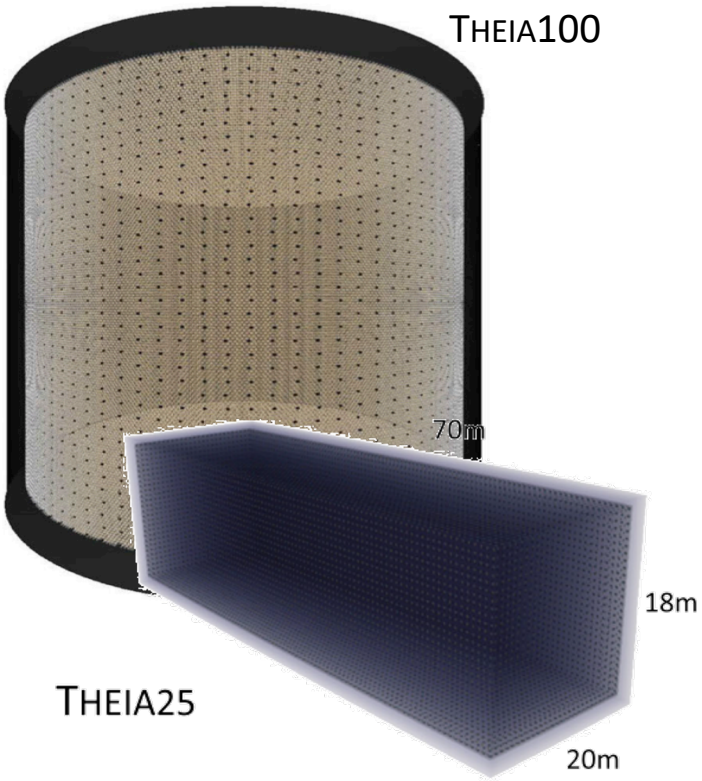
- scintillator sufficiently transparent to let the Cherenkov light reach the light sensors
- light sensors permitting C/S discrimination (ns-PMTs, LAPPDs, dichroicons)

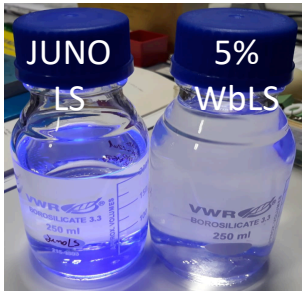
Advantages:

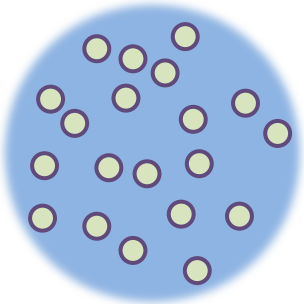
- potent background discrimination based on Cherenkov/scintillation ratio
- possibility for detailed study of atm. NC BG

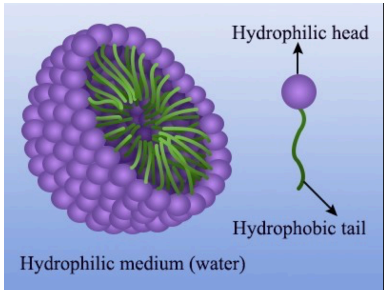


Theia









WbLS mycels (nm-scale)

Water-based Liquid Scintillator

- water + surfactant + LAB (10%) + fluor
- great transparency, cheap → large detector
- fast scintillation → sub-ns photo sensors

Specific discrimination tags

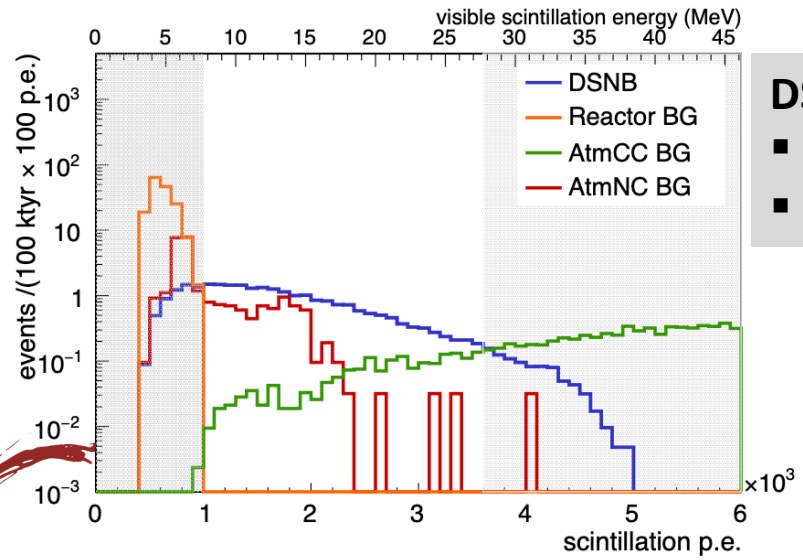
- Cherenkov/scintillation ratio → high C/S ratio
- Cherenkov ring multiplicity → single-ring events
- delayed decays of final-state nuclei → ^{15}O (BR 49%)

Theia25 key parameters

- fiducial mass: 12,000 tons
- p.e. yield: ~30 pe/MeV
- radiopurity: 10^{-15} g/g U/Th
- depth: 4,800 mwe

Expected performance:
→ signal efficiency: >80%
→ background residual: <1.3%

Theia's DSNB Sensitivity

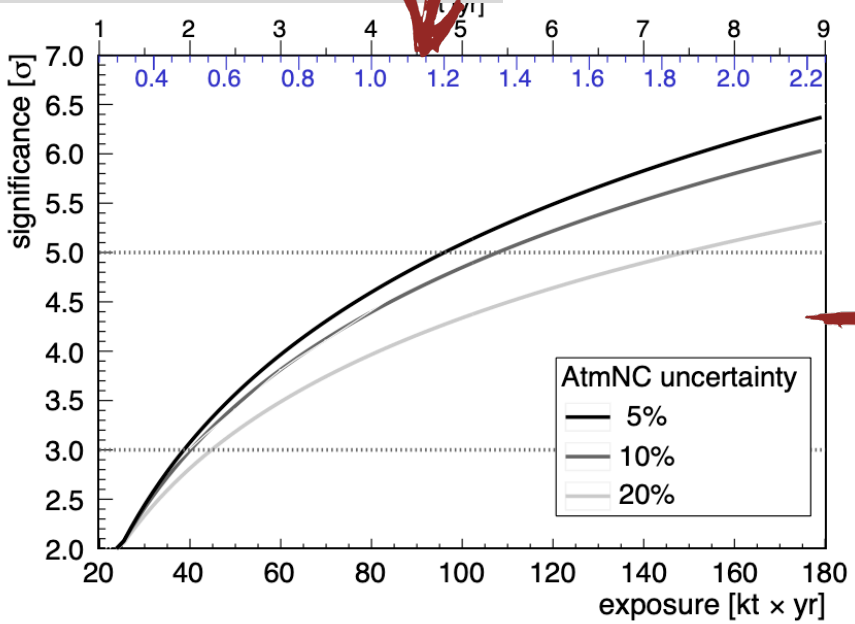


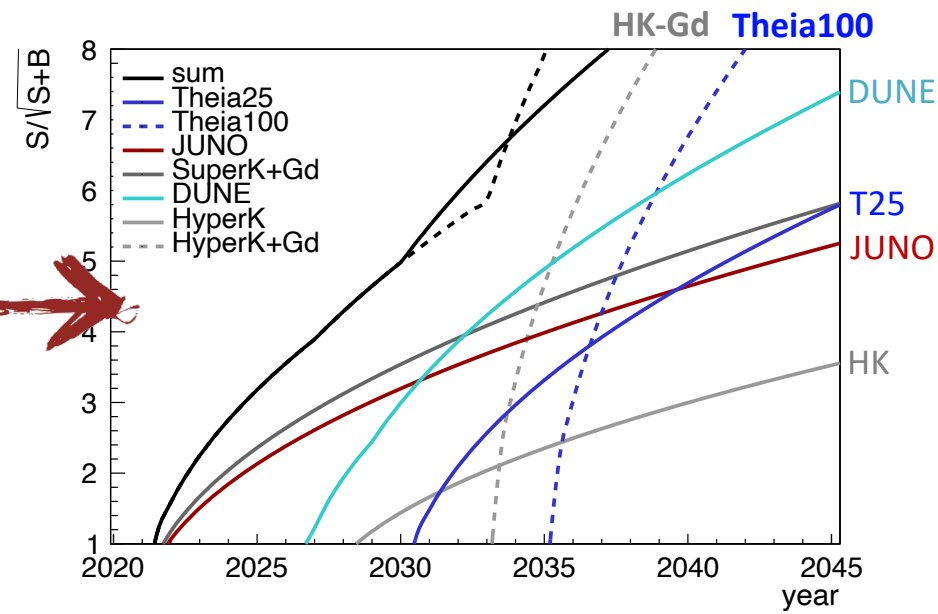
DSNB spectrum (after cuts)

- DSNB rate: 20 in 100 kt·yrs
- S/B ratio: 3.7

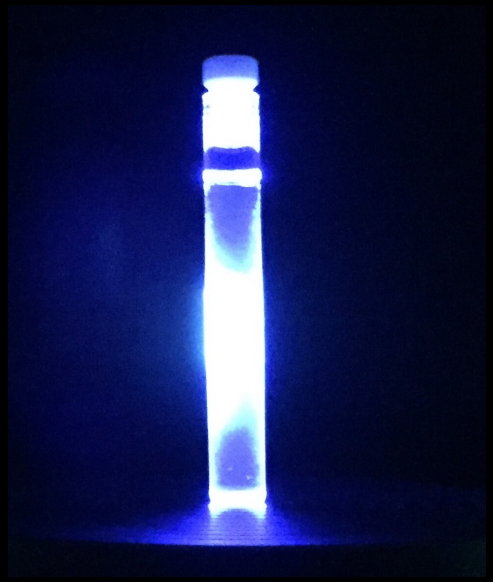
DSNB sensitivity (5σ)

- Theia25: after 6 years
- Theia100: after 1.5 yrs





Conclusions



- despite the atmospheric NC background, liquid scintillator detectors feature excellent sensitivity to the DSNB
- JUNO expected to arrive at 3σ after 10 years
- hybrid detectors offer considerable discovery potential based on excellent BG discrimination
- Theia: 5σ measurement in 125 kt·yrs
- detailed cross-detector background studies will be needed to maximize sensitivity
- ultimate goal: DSNB spectroscopy
  → input from all large detectors required!

Thank you!

JG|U

- KamLAND Coll., A study of extraterrestrial antineutrino sources with the KamLAND detector, Astrophys.J. 745 (2012) 193, arXiv:1105.3516
- Borexino Coll., *Search for low-energy neutrinos from astrophysical sources with Borexino*, Astropart.Phys. 125 (2021) 102509, arXiv:1909.02422
- JUNO Coll., *Neutrino Physics with JUNO*, J.Phys.G 43 (2016) 3, 030401, arXiv:1507.05613
- M. Askins et al., *THEIA: an advanced optical neutrino detector*, Eur. Phys. J. C 80 (2020) 5, 416, arXiv:1911.03501
- J. Sawatzki, M. Wurm, D. Kresse, *Detecting the Diffuse Supernova Neutrino Background in the future Water-based Liquid Scintillator Detector Theia*, accepted by PRD (2020), arXiv:2007.14705
- Hanyu Wei et al., *Discovery potential for supernova relic neutrinos with slow liquid scintillator detectors*, Phys.Lett.B 769 (2017) 255-261, arXiv:1607.01671

Backup Slides

Delayed decays in organic LS

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Several of the spallation isotopes produced are not stable:

Reaction channel	Branching ratio	
(1) $\nu_x + {}^{12}C \rightarrow \nu_x + n + {}^{11}C$	38.8 %	→ *taggable*
(2) $\nu_x + {}^{12}C \rightarrow \nu_x + p + n + {}^{10}B$	20.4 %	→ *stable*
(3) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + n + {}^{9}Be$	15.9 %	→ *stable*
(4) $\nu_x + {}^{12}C \rightarrow \nu_x + p + d + n + {}^{8}Be$	7.1 %	→ *too fast*
(5) $\nu_x + {}^{12}C \rightarrow \nu_x + \alpha + p + n + {}^{6}Li$	6.6 %	→ *stable*
(6) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + d + n + {}^{7}Li$	1.3 %	→ *stable*
(7) $\nu_x + {}^{12}C \rightarrow \nu_x + 3p + 2n + {}^{7}Li$	1.2 %	→ *stable*
(8) $\nu_x + {}^{12}C \rightarrow \nu_x + d + n + {}^{9}B$	1.2 %	→ *too fast*
(9) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + t + n + {}^{6}Li$	1.1 %	→ *stable*
(10) $\nu_x + {}^{12}C \rightarrow \nu_x + \alpha + n + {}^{7}Be$	1.1 %	→ *too slow*
(11) $\nu_x + {}^{12}C \rightarrow \nu_x + 3p + n + {}^{8}Li$	1.1 %	→ *taggable*
other reaction channels	4.2 %	

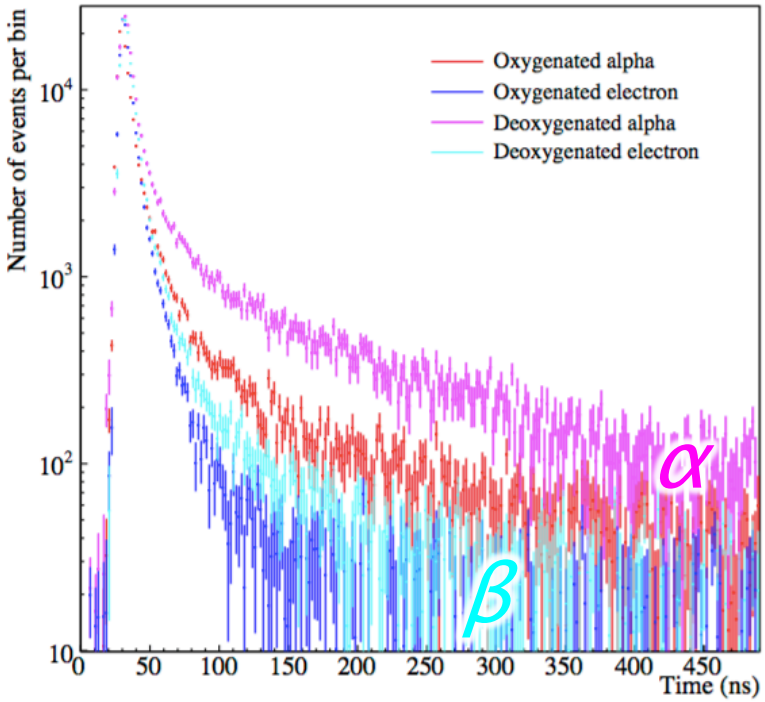
→ potentially allows to tag about 40% of the NC background events

→ remaining amount is still several times the DNSB signal

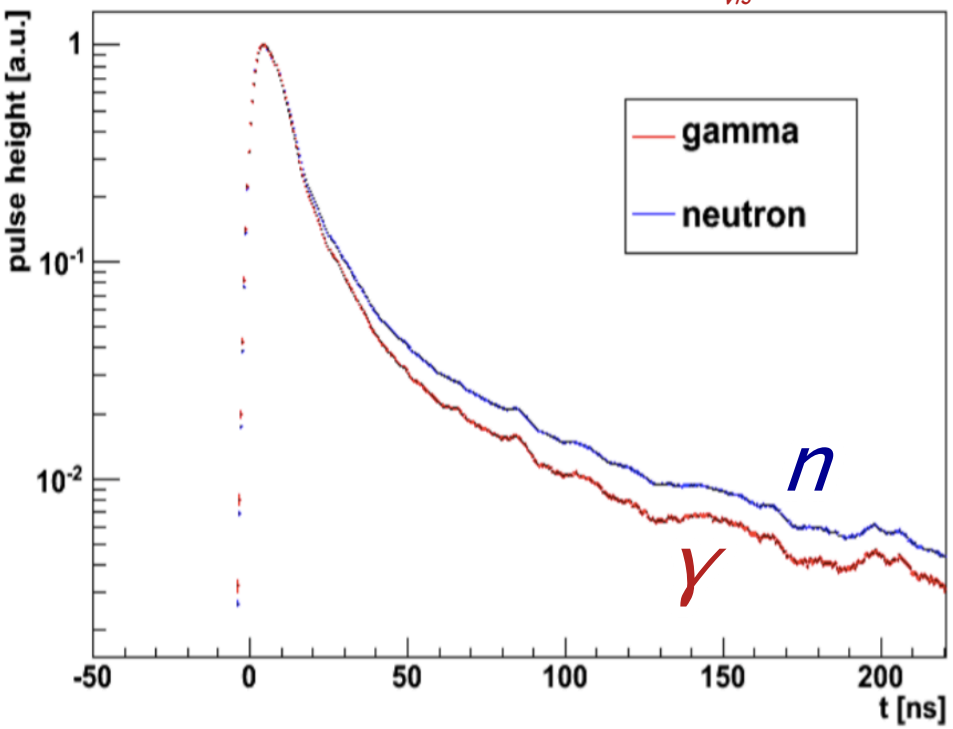
Pulse Shape measurements for JUNO

Pulse shapes in linear alkyl-benzene (LAB) were studied for SNO, LENA and JUNO:
→ scintillator composition: LAB + 2-3 g/l PPO (+ 20mg/l bis-MSB)

O'Keeffe et al., arXiv:1102.0797



from MLL measurements at TUM: E_{vis}=2-2.5MeV

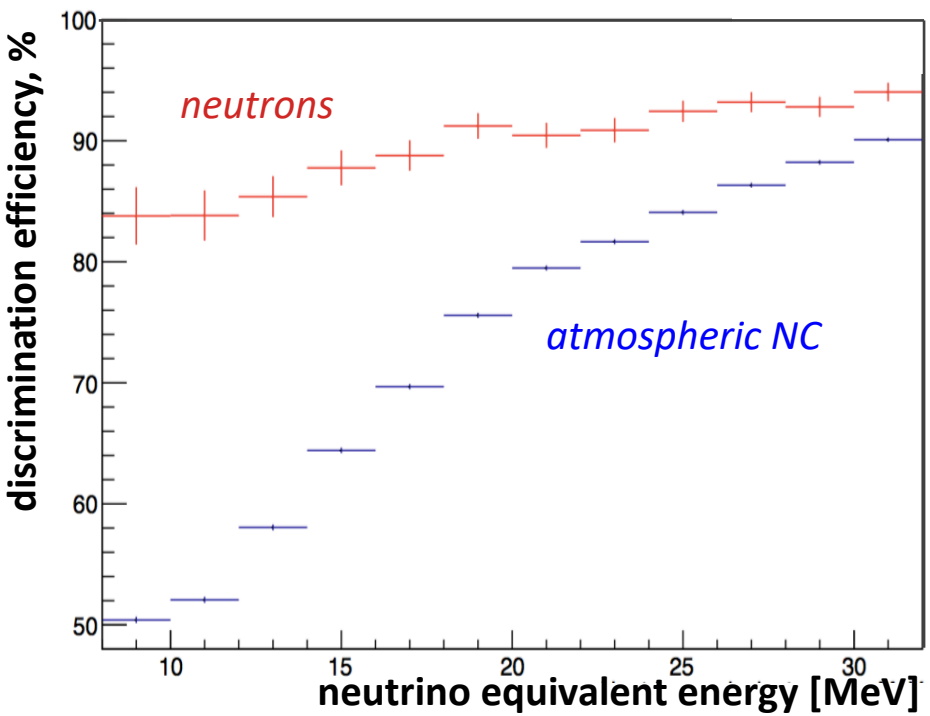


→ excellent particle discrimination properties

Pulse Shape Discrimination for DSNB

PSD to be used not only for **atmospheric NC** but also **fast neutron** background:

PSD discrimination efficiency vs. E_{vis}
DSNB signal acceptance: **95%**



PSD efficiencies vs. signal acceptance

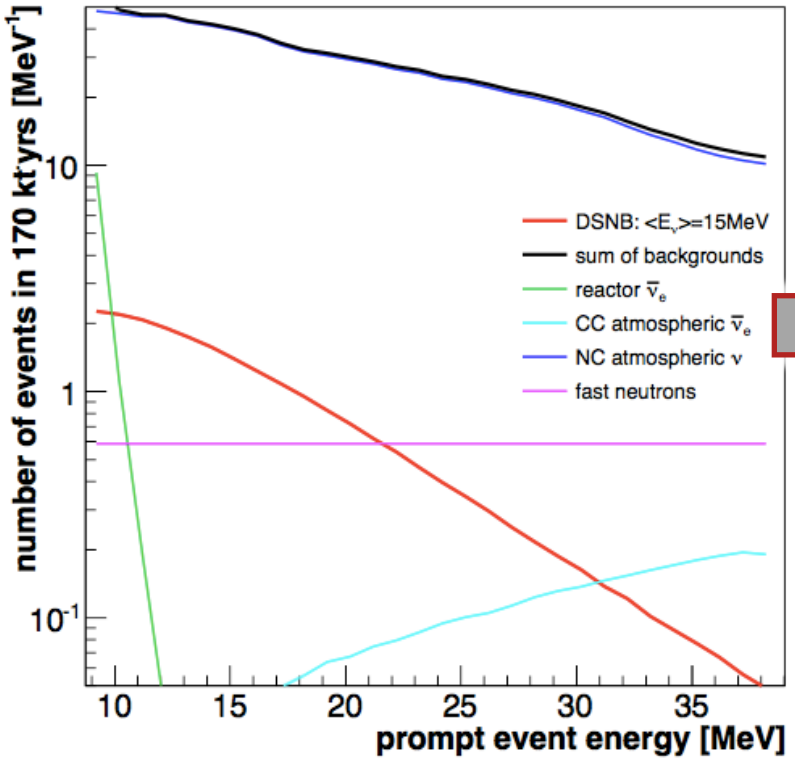
IBD acceptance	FN rejection	NC rejection
95%	84.3%	66.6%
90%	91.8%	87.4%
80%	95.2%	94.8%
55%	97.8%	98.9%
50%	98.1%	99.1%
40%	98.5%	99.3%

→ IBD acceptance has to be reduced to ~50% to obtain sufficient BG rejection

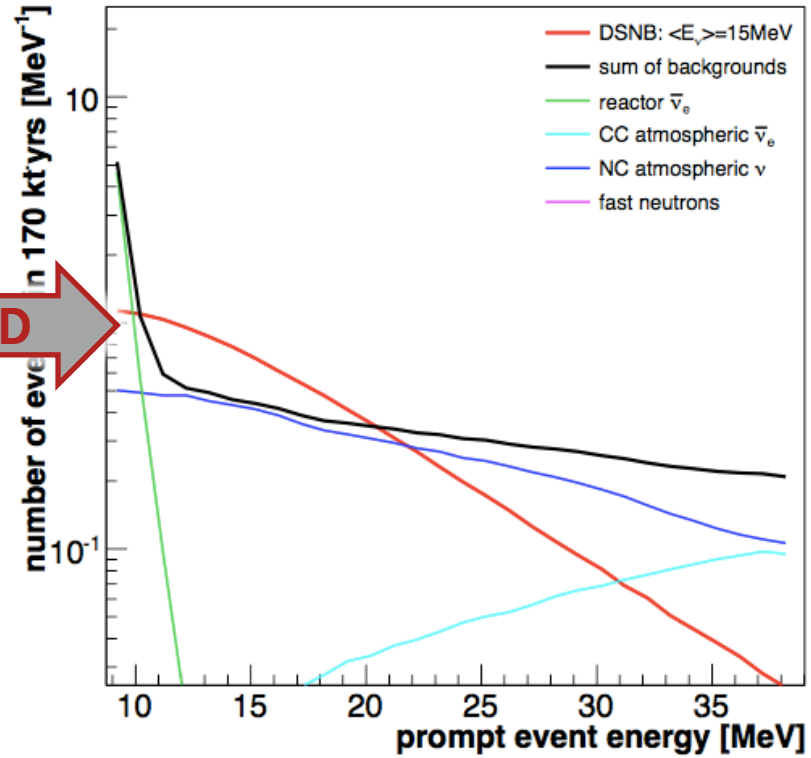
→ fast neutron detection allows to use almost the entire scintillator volume

JUNO backgrounds to DSNB detection

from JUNO Yellow Book



PSD



before PSD:

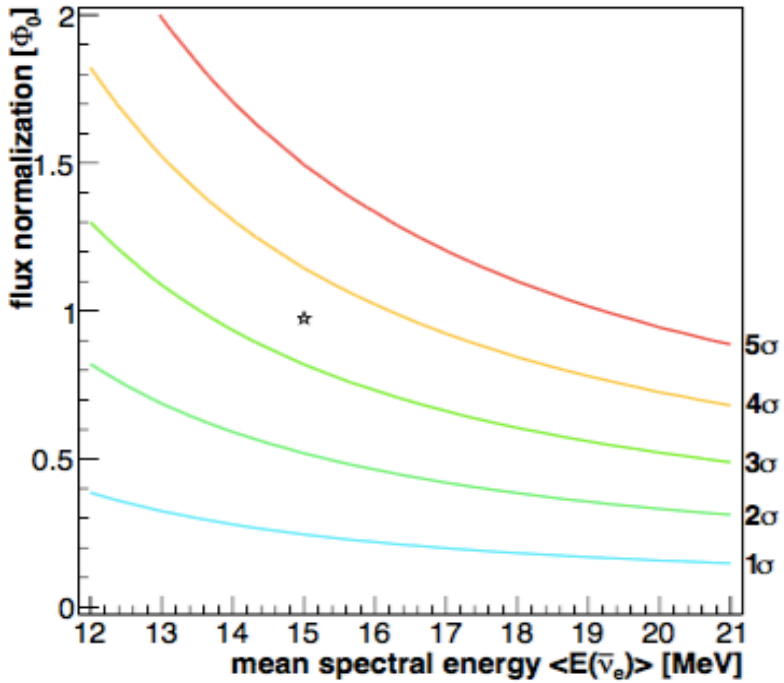
- atmospheric ν NC reactions
- fast neutrons

dominate the DSNB signal

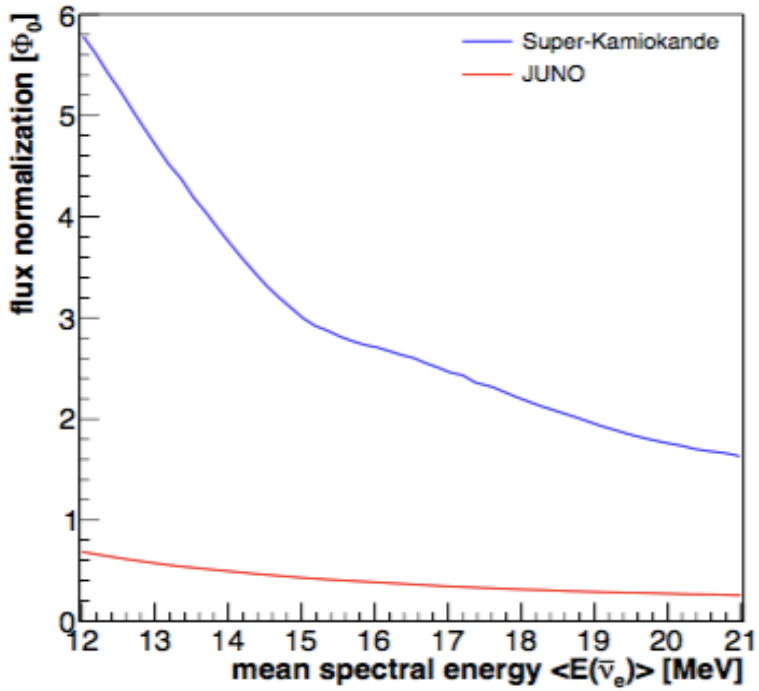
after PSD:

- atm. NC & FN greatly reduced
- reactor & atmospheric IBDs define observation window

DSNB discovery/exclusion in JUNO



from JUNO Yellow Book



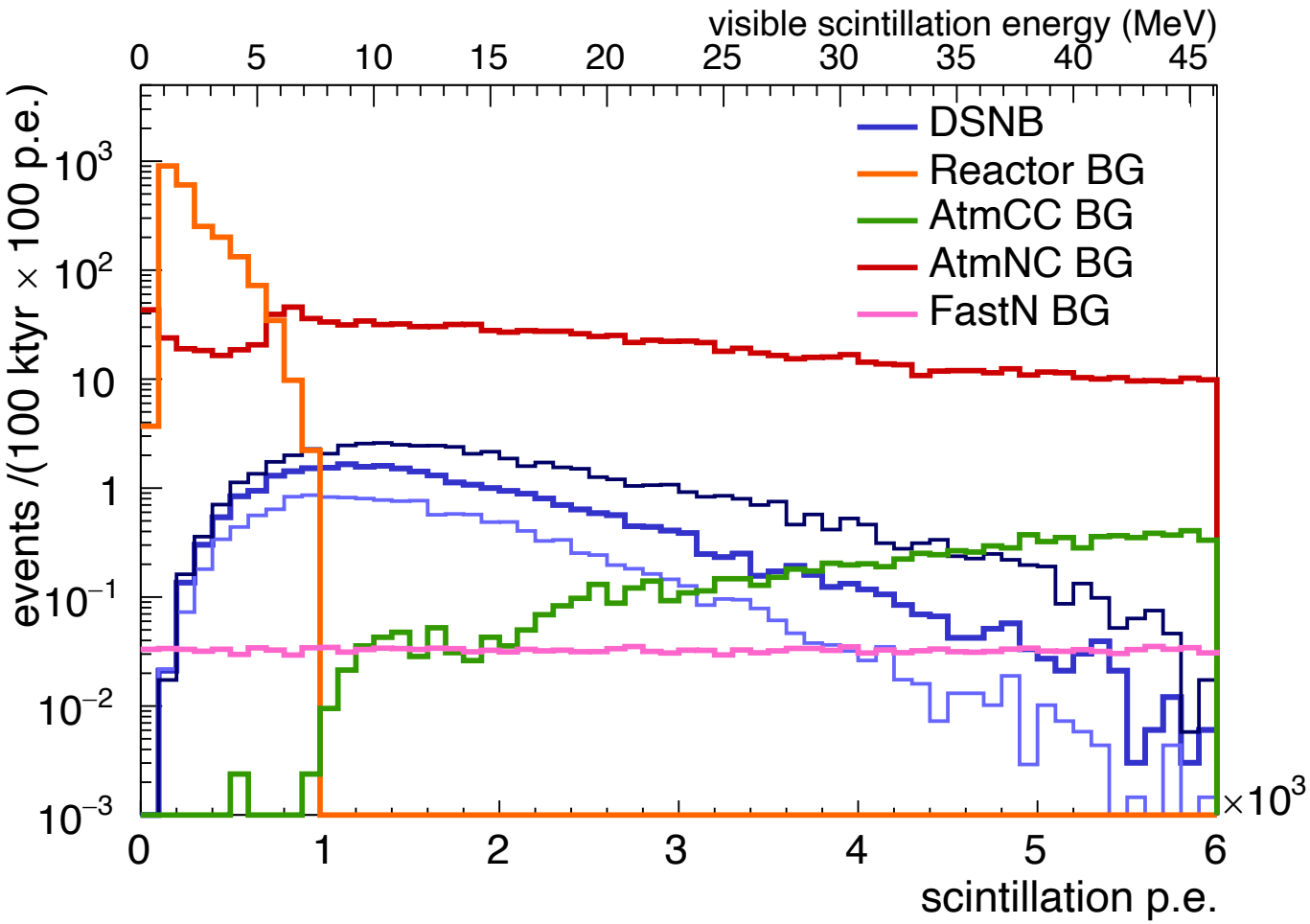
- **Discovery potential**
  - esposure: 17kt x 10 yrs
  - syst. uncertainty on BG: 5%

  → **possibility for evidence of DSNB signal at 3σ level**

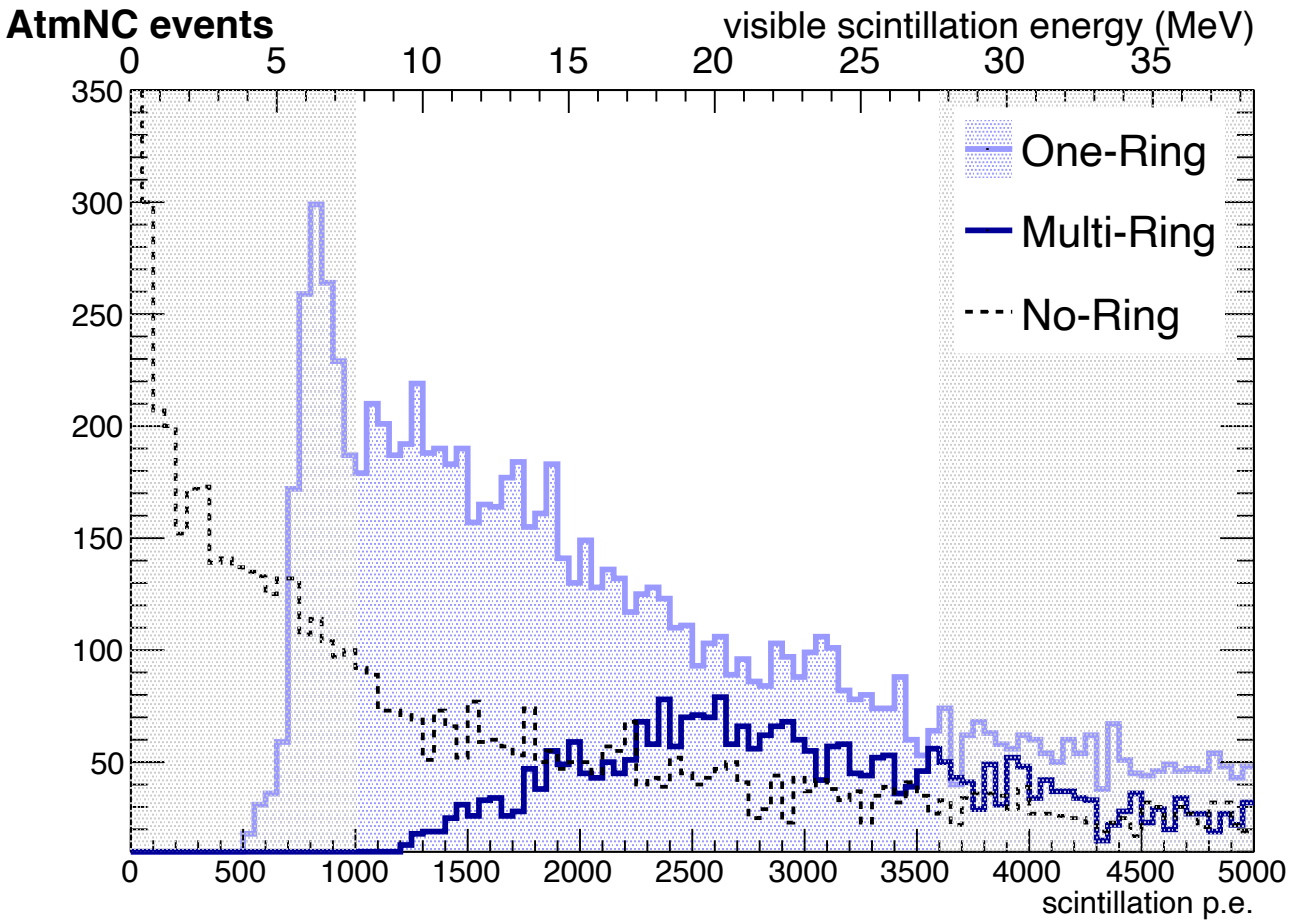
- **Exclusion plot**
  - same assumptions as before
  - only BG prediction detected

  → **significant improvement over current Super-K limit**

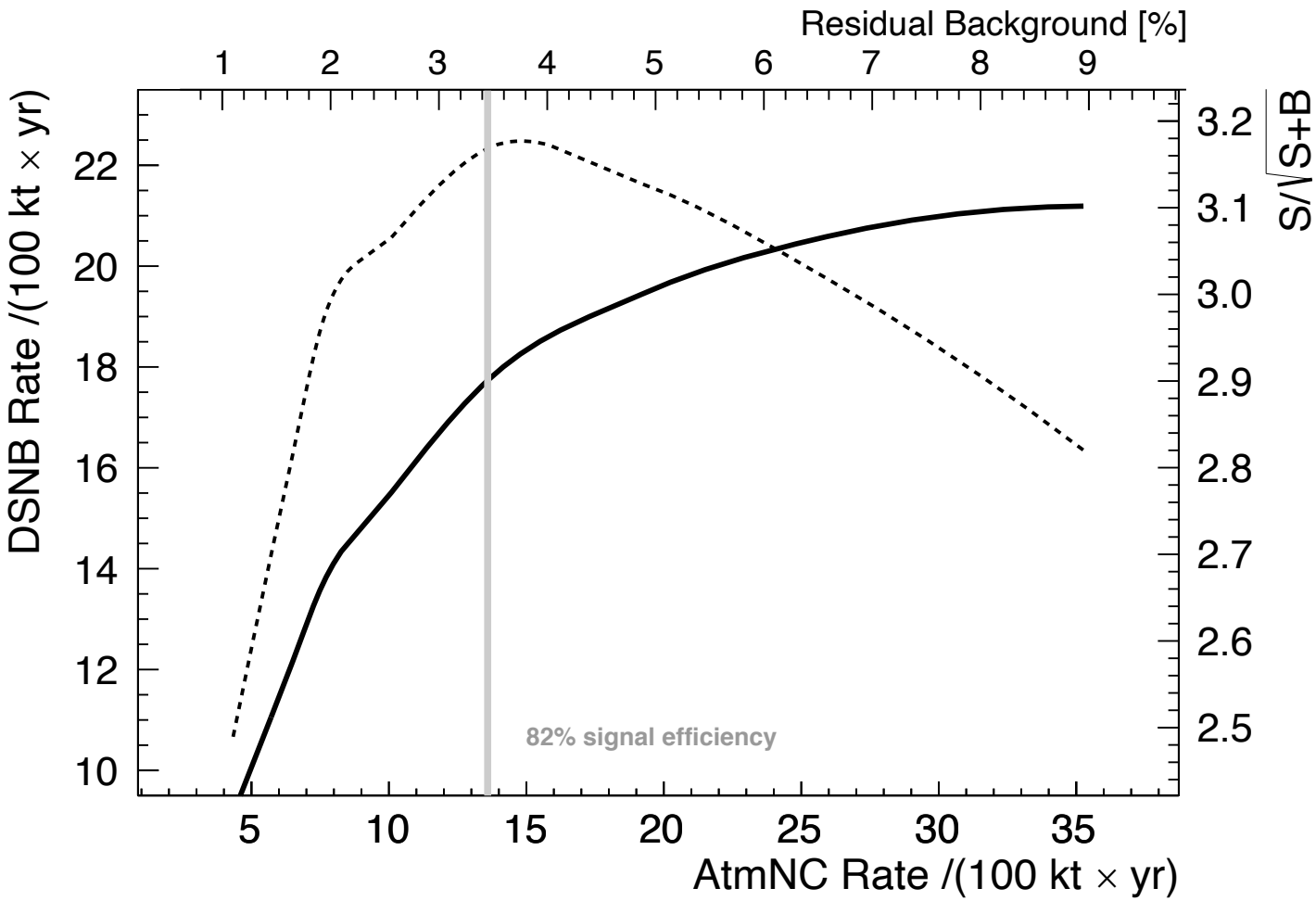
Theia DSNB spectrum before cuts



DSNB Ring Counting



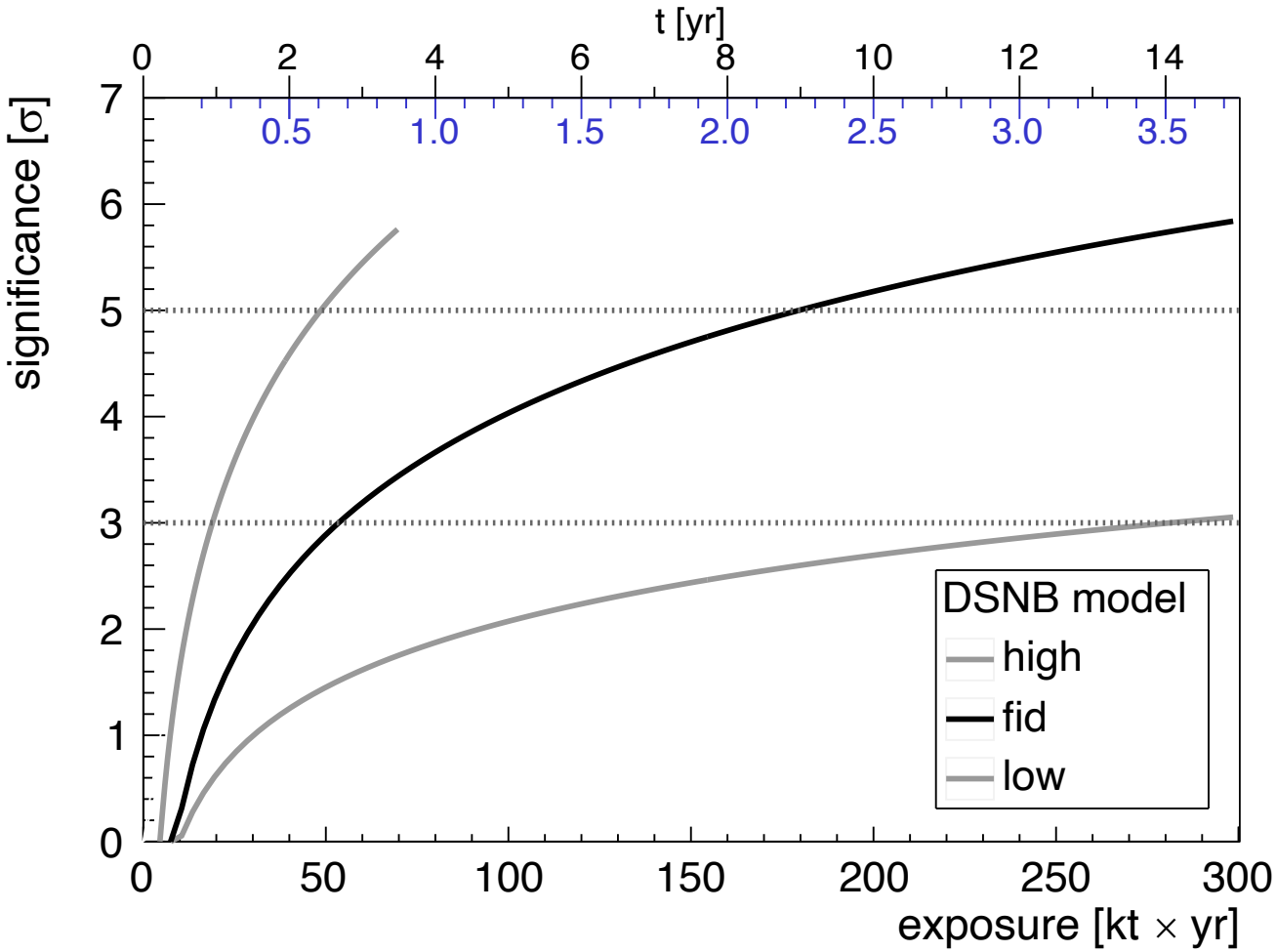
DSNB C/S ratio background rejection



Theia: Delayed decay tags

Reaction channel	Branching Ratio	
(1) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + {}^{15}\mathrm{O}$	45.9%	← taggable
(2) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \mathrm{p} + {}^{14}\mathrm{N}$	19.7%	
(3) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + 2\,\mathrm{p} + {}^{13}\mathrm{C}$	14.7%	
(4) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \mathrm{p} + \mathrm{d} + {}^{12}\mathrm{C}$	9.1%	
(5) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \mathrm{p} + \mathrm{d} + \alpha + {}^{8}\mathrm{Be}$	2.0%	
(6) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + 3\,\mathrm{p} + {}^{12}\mathrm{B}$	1.8%	← taggable
(7) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \alpha + {}^{3}\mathrm{He} + {}^{8}\mathrm{Be}$	1.6%	
(8) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + \mathrm{p} + \alpha + {}^{10}\mathrm{B}$	1.4%	
(9) $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x + \mathrm{n} + 2\,\mathrm{p} + \alpha + {}^{9}\mathrm{Be}$	1.2%	
other reaction channels	2.6%	

Theia sensitivity vs. DSNB model



Theia DSNB Signal and Background Rates

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	100 kt·yrs exposure		
	Before Cuts	Muon Veto	Volume Cut
DSNB signal	30.5	29.9	29.9
Reactor neutrinos	2240	2218	2218
Atmospheric CC	9.0	8.9	8.9
Atmospheric NC	1270	1253	1253
βn-emitters (^{9}Li)	529	–	–
fast neutrons	131 (57)	129 (56)	2 (4)

TABLE II. Rates of DSNB signal and backgrounds at energies below $\sim$46 MeV (6000 p.e.) normalized to a live exposure of 100 kt·yrs. The fast neutron rates displayed in the last row assume a 2.5 m (1.5 m) fiducial volume cut for Theia100 (Theia25).