DSNB Detection with LiCl Water-based Liquid Scintillator at Jinping

Atmospheric Neutrino Background Rejection and Sensitivity Estimation

Changxu Wei

Tsinghua University

July 2, 2026

What is the DSNB?

- **Diffuse Supernova Neutrino Background**
  - Integrated $\bar{\nu}_e$ flux from **all past core-collapse supernovae**
  - Isotropic, steady cosmic background
  - Visible energy: ∼10–30 MeV
- **Physics potential**
  - Cosmic star formation history
  - Black hole formation fraction
  - Neutrino properties & cosmology
- Energy density ~ 0.01 eV/cm^3 — second only to CMB & EBL
- **Not yet detected** — requires low-background, large exposure

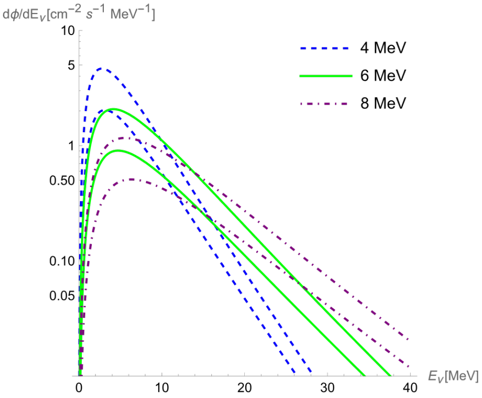


图 1: DSNB flux predictions

How to Detect DSNB: Inverse Beta Decay

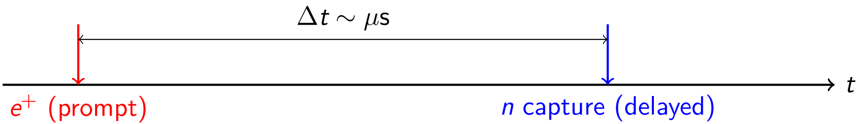
$$\bar{\nu}_e + p- > e^+ + n$$

Prompt signal (e^+)

- Positron kinetic energy + annihilation γ's
- Cherenkov light (if $\beta \approx 1$) + scintillation light
- Visible energy: ~10–30 MeV

Delayed signal (n capture)

- Neutron thermalizes, captured by nucleus
- Characteristic γ emission
- $\Delta t \sim \mu$s (capture-time dependent)



Coincidence of prompt + delayed → **unique IBD signature**

The Core Challenge: How Backgrounds Mimic IBD

DSNB signal = e^+ (prompt) + n (delayed). Anything producing a similar topology is a background.

Atmospheric neutrinos are the dominant background ($\sim 7\times$ DSNB rate):

Background	**Physical Process**	**How it mimics IBD**
Atm. ν CC (decay-e)	ν_μ CC $\rightarrow$ invisible μ; $\mu \rightarrow e$	Decay $e =$ "prompt", possible real n
Atm. NCQE	$\nu + {}^{16}\mathrm{O} \rightarrow \nu + \gamma + n$	De-excitation γ = "prompt", real n
Atm. NC (high-E n)	ν + nucleus $\rightarrow$ recoil p/n	Recoil p scint. = "prompt", real n

Each detector type is "tricked" by different backgrounds. $\rightarrow$ depends on its **intrinsic capabilities**.

Why Each Detector Gets Stuck — and the LiCl Solution

If you lack capability X, you get stuck by backgrounds that need X to reject:

- **Pure water (SK):** no scintillation
  - e^+ and decay-e identical in Cherenkov
  - $\rightarrow$ **decay-e dominates**
- **Gd-water (SK-Gd):** n-tag, no PID
  - γ and e^+ identical in Cherenkov
  - $\rightarrow$ **NCQE dominates**
- **Traditional LS:** no Cherenkov
  - e^+ and recoil p identical in scintillation
  - $\rightarrow$ **NC dominates**

LAB slow LS:

- C/S separation ✓ — backgrounds suppressed
- ^{1}H capture: $\sigma = 0.33$ b, $\tau \sim 200\ \mu$s

LiCl water-based LS:

- C/S separation ✓ + high-σ n capture
- **Disadvantage:** lower free-H density
  - Water base $\rightarrow$ fewer free protons per kt
  - $\rightarrow$ IBD rate lower than pure LS

Trade-off: C/S PID + fast n capture vs. lower free-proton density $\rightarrow$ background suppression compensates for lower IBD rate

Jinping Underground Laboratory (CJPL)

Deepest underground lab worldwide

- 2400 m rock overburden (6720 m.w.e.)
- Cosmic μ flux $\sim 2 \times 10^{-10}$ cm^{-2}s^{-1}
- $\rightarrow$ spallation bg. (^{9}Li etc.) dramatically suppressed
- Distance to nearest reactor ~ 1000 km
- $\rightarrow$ reactor $\bar{\nu}_e$ background low

Detector: 500 m^3 LiCl water solution
$\sim$2800 MCP-PMTs

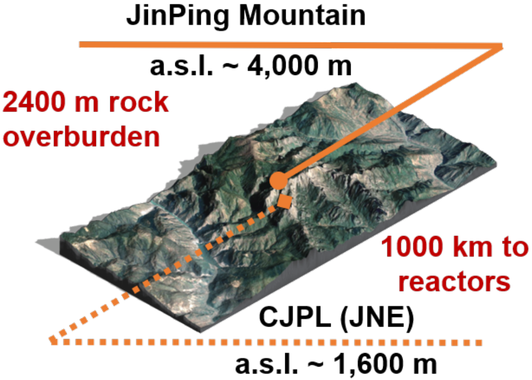


图 2: CJPL Position

LiCl Water-based LS: C/S PID + High-σ n Capture

1. C/S Separation → Particle Identification

Water base → simultaneous Cherenkov (prompt) + Scintillation (slow):

- e^+ ($\beta \approx 1$): **high C/S ratio** Nucleons ($\beta < 1$): **low C/S ratio**

→ Distinguish DSNB signal (e^+) from atm. ν background (nucleons/γ)

2. High-σ Neutron Capture — three channels

Isotope	σ [b]	τ_{cap} [μs]	E_γ [MeV]	Fraction
^{1}H	0.33	∼200	2.23	1.7%
^{35}Cl	**44**	∼5	**8.58**	**30.7%**

Key advantage: ^{35}Cl n capture: $\sigma = 44$ b, $E_\gamma = 8.58$ MeV, $\tau \sim 5$ μs
vs. pure ^{1}H ($\sigma = 0.33$ b, $\tau \sim 200$ μs): $\sigma \uparrow 130\times$, $\tau \downarrow 40\times$

DSNB Signal: Inverse Beta Decay

$\bar{\nu}_e + p \to e^+ + n$

Prompt: e^+ (Cherenkov + scintillation)
Delayed: n capture $\to \gamma$ (scintillation)

DSNB flux model: HBD 6 MeV, $T_\nu = 6$ MeV

- Rate: $\sim$2.2 / (20 kt·yr) before cuts
- Visible energy: 10–30 MeV

Geant4 simulation: e^+ + neutron capture

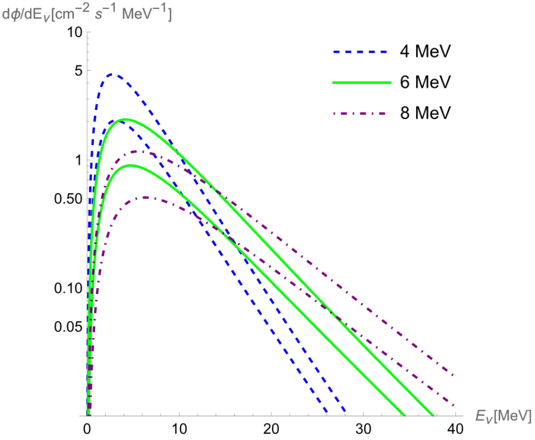


图 4: DSNB flux: integrated $\bar{\nu}_e$ from all past CCSNe

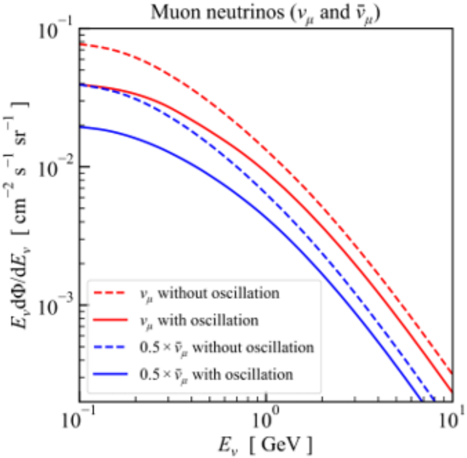
Atmospheric Neutrino Background

GENIE 3.04, $E < 100$ MeV, all nuclei ^{1}H–^{37}Cl

Event rates [/(20 kt·yr)] — flavor $\times$ nuclide:

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	**Total**
H-1	0.52	0.21	1.00	0.61	2.34
H-2	0.00	0.00	0.00	0.00	0.00
Li-6	0.00	0.00	0.04	0.02	0.06
Li-7	0.18	0.07	0.55	0.21	1.01
C-12	0.00	0.00	0.00	0.00	0.00
C-13	0.00	0.00	0.00	0.00	0.00
O-16	1.10	0.40	2.90	1.10	5.50
O-18	0.00	0.00	0.01	0.00	0.01
Cl-35	0.97	0.35	2.50	0.94	4.76
Cl-37	0.33	0.11	0.84	0.27	1.55
Total	3.10	1.15	7.83	3.15	**15.23**

DSNB ∼2.2 vs. atm. ν ∼15.2 → need ∼700× suppression



Jinping Neutrino Experiment: 500-ton Simulation

Detector geometry (Geant4)

- 500 m^3 LiCl water solution
- Tank: $14.5\times12.9\times13.2$ m^3
- $\sim$6400 MCP-PMTs, 8-inch
- Full optical simulation

Simulation chain:

1. GENIE 3.04: ν-nucleus interactions
2. Geant4: particle propagation + optical photons
3. Detector response + electronics
4. MLE reconstruction (electron template)

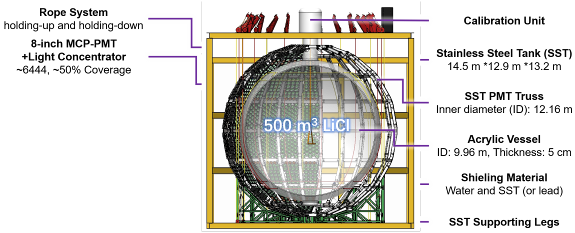


图 6: JNE 500-ton detector simulation geometry

Reconstruction: Maximum Likelihood Method

Likelihood function

$$\mathcal{L} = \prod_i \text{Poisson}(n_i; n_i^{\text{pred}}) \cdot \prod_j \sum_k \frac{n_j^k}{n_j^{\text{pred}}} f^k(t_j^{\text{photon}})$$

5 PE types modeled:

1. Direct Cherenkov
2. Indirect Cherenkov
3. Direct Scintillation
4. Indirect Scintillation
5. Dark noise

$\sigma_E/E = 20.6\%/\sqrt{E}$ Position resolution < 10 cm

Reconstructed parameters (7-D)

- E: energy
- (x, y, z): vertex
- t_0: event time
- (d_θ, d_ϕ): direction

Key point: All events reconstructed with **electron template**

e^+ (DSNB) $\rightarrow$ fits well
Nucleons (atm. ν) $\rightarrow$ fits poorly

$\rightarrow$ basis for fitting-goodness selection

C/S PE Separation: Per-PE Posterior Probability

Per-PE Cherenkov posterior

$$P(C \mid \mathrm{PE}_j) = \frac{n_j^C f_j^C(t_j^{\mathrm{photon}})}{\sum_k n_j^k f_j^k(t_j^{\mathrm{photon}})}$$

- Full time residual + PMT position + direction
- Each PE individually classified as C or S
- Sum per PMT → **CPE** / **SPE**

Important: SPE/CPE reconstruction performed only for events with good e^+ fit

- → rejects poorly-reconstructed events early, saves computation

Selection Framework

Selection flow:

Simulated events
↓
Cut-0: Coincidence (20 μs)
↓
Cut-1: Energy windows
↓
Cut-2: Fitting goodness
↓
SPE/CPE reco. (e^+ model)
↓
Cut-3: Cherenkov ring angle
↓
Cut-4: C/S ratio
↓
DSNB Candidates

Cut-0 & Cut-1

Cut-0: OSTW coincidence

- 20 μs window per trigger, keep fold=2
- $4\tau_{\text{cap}}$ ($\tau \approx 5.17$ μs) $\rightarrow$ $> 98\%$ captures
- Wei2017: 0.2–1000 μs $\rightarrow$ **50$\times$ narrower**

Cut-1a: Prompt energy [10, 30] MeV

- < 10 MeV: reactor $\bar{\nu}_e$ dominant
- > 30 MeV: atm. ν increases

Cut-1b: Delayed energy ($\pm 3\sigma$, three channels)

Isotope	E_{cap} [MeV]	σ [MeV]	Window [MeV]
^{6}Li	0.50	0.15	[0.06, 0.94]
^{1}H	2.23	0.31	[1.30, 3.16]
^{35}Cl	8.58	0.60	[6.78, 10.38]

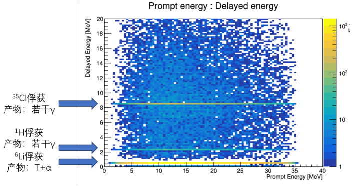


图 7: Prompt (left) and Delayed (right) energy distributions

Cut-2: Fitting Goodness

Concept: Unified **electron model** reconstruction. e^+ (DSNB) $\rightarrow$ fits well $\rightarrow$ low χ^2_P; Nucleons $\rightarrow$ fits poorly.

χ^2_P **definition:** ν_i (expected PE) vs. n_i (observed PE) in each PMT/time window, from fitted $(E, \vec{x}, \vec{d})$:

$$\chi^2_P = 2\sum_i \left(n_i \ln \frac{n_i}{\nu_i} + \nu_i - n_i \right)$$

Selection: $\chi^2_P < 311\, E_{\text{prompt}} + 1212$

DSNB: tight χ^2_P-E correlation. $\nu_\mu/\bar{\nu}_\mu$ CC overwhelmingly fails. $\bar{\nu}_e$ CC (real IBD) fits well — irreducible.

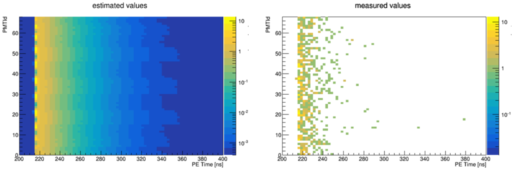


图 8: ν_i (expected) vs. n_i (observed) PE distribution

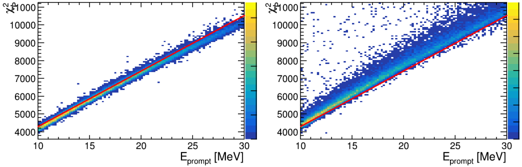


图 9: χ^2_P vs. E: DSNB (left) vs. Atm. ν (right)

Goodness: What Gets Rejected?

Category	Rejection	vs. DelayedE
NC	95.5%	from 27,309 $\rightarrow$ 1,240
$\bar{\nu}_e$ CC	16.5%	from 170 $\rightarrow$ 142
$\nu_\mu/\bar{\nu}_\mu$ **CC**	**99.1%**	**from 588 $\rightarrow$ 5**
Total Atm. ν	95.1%	from 28,067 $\rightarrow$ 1,387

Physics: $\nu_\mu/\bar{\nu}_\mu$ CC produces $\mu^\pm$ + hadronic debris.
Reconstructed with e^+ template $\rightarrow$ poor χ^2_P $\rightarrow$ **99.1% rejected**.
$\bar{\nu}_e$ CC = real IBD $\rightarrow$ excellent fit $\rightarrow$ largely unaffected (irreducible background floor).

Cut-3: Cherenkov Ring Angle

Concept Different particles generate different Cherenkov ring patterns.

- e^+ (DSNB): single Cherenkov cone $\rightarrow$ sharp peak at $\cos\theta \approx 0.7$
- $\mu^\pm$ + hadrons: multiple tracks $\rightarrow$ overlapping rings
- γ (NC): isotropic emission $\rightarrow$ no well-defined ring

$\rightarrow \chi^2_{\text{chev}}$ quantifies ring "cleanliness" by comparing observed vs. expected $\cos\theta$ distribution

Method We apply Cherenkov angle distribution as Cherenkov ring pattern indicator. For each PE tagged as Cherenkov PE, compare $\cos\theta$ with expected e^+ ring template.

$$\chi^2_{\text{chev}} = 2\sum_i \left(n_i \ln \frac{n_i}{\nu_i} + \nu_i - n_i\right)$$

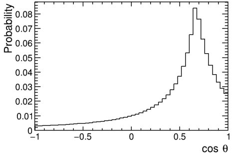


图 10: $\cos\theta_C$ distribution ν_i, calibrated with e^+ simulation

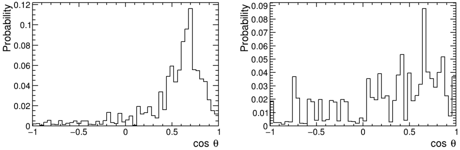
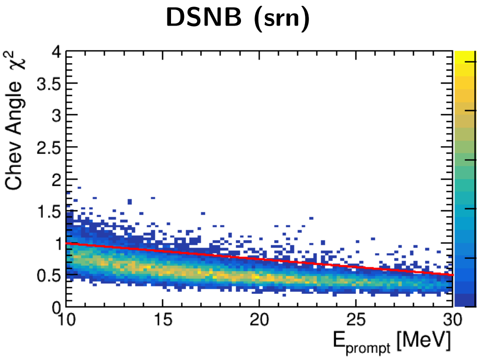
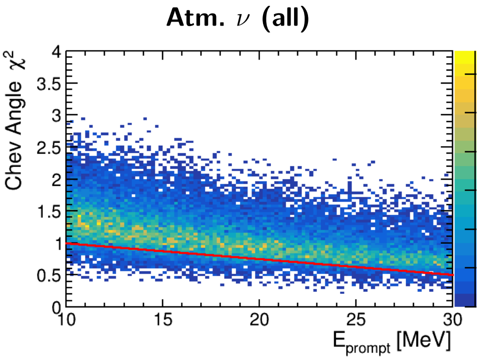


图 11: n_i from a DSNB event vs. n_i from an

Ring Angle by Event Type (Independent Cuts)



Tight, low χ^2_{chev} — clean single ring



Broad, high χ^2_{chev} — multi-ring / isotropic

Ring angle cut independently applied to samples. Clear separation: signal (low χ^2) vs. background (high χ^2).

Ring Angle: What Gets Rejected?

Category	Rejection	vs. DelayedE
NC	91.3%	from 27,309 $\rightarrow$ 2,372
$\bar{\nu}_e$ CC	4.7%	from 170 $\rightarrow$ 162
$\nu_\mu/\bar{\nu}_\mu$ CC	67.7%	from 588 $\rightarrow$ 190
Total Atm. ν	90.3%	from 28,067 $\rightarrow$ 2,724

Physics: NC events produce isotropic multi-γ — no well-defined ring $\rightarrow$ 91.3% rejected. $\bar{\nu}_e$ CC: single e^+ ring $\rightarrow$ passes. $\nu_\mu/\bar{\nu}_\mu$ CC: μ + hadronic activity degrades ring.

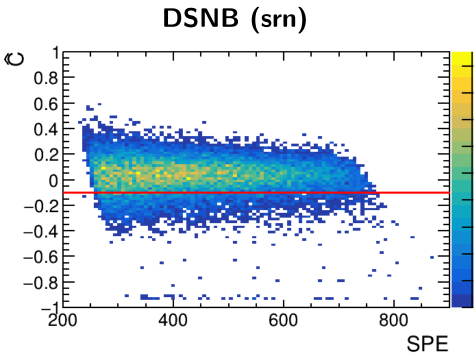
Cut-4: C/S Ratio (CPE vs. SPE)

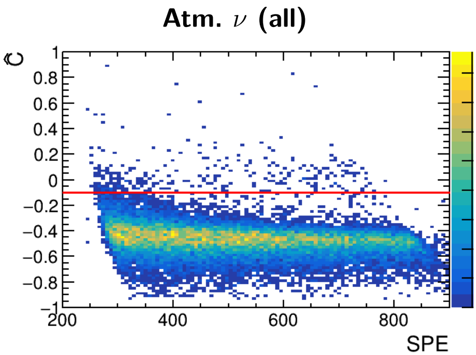
Method: Reconstruct CPE, SPE via e^+ model. Use CPE/SPE ratio to select e^+-like events.

Physics of C/S ratio:

- e^+ ($\beta \approx 1$, $E \sim 10$–30 MeV): well above threshold $\rightarrow$ high CPE/SPE
- Nucleons ($\beta \ll 1$ at same E): below or near threshold $\rightarrow$ low CPE/SPE
- γ: converts to e^+e^- with lower effective energy per particle; same total E yields **less CPE** due to energy sharing + threshold effects

CSR by Event Type (Independent Cuts)





e^+, $\beta \approx 1$ —high CSR, tight cluster

Broad, low CSR —nucleon recoils + γ

CSR cut independently applied to Delayed Energy sample. Nucleons below Cherenkov threshold → intrinsically low CPE.

DSNB eff.: 84.5% **Atm.** ν **eff.:** 1.1%

CSR: What Gets Rejected?

Category	Rejection	vs. Prev. Cut
NC	**99.0%**	**88.5%** (from 2,372 after Angle)
$\bar{\nu}_e$ CC	2.4%	—
$\nu_\mu/\bar{\nu}_\mu$ CC	77.2%	29.5% (from 190 after Angle)
Total Atm. ν	98.0%	79.0% (from 2,724 after Angle)

Physics: NC events lack charged particles above Cherenkov threshold.
Nucleons (p, n) from NC produce scintillation but negligible Cherenkov $\rightarrow$ CPE always low.
CSR cut is the **NC specialist** —removes what Ring Angle couldn't catch.

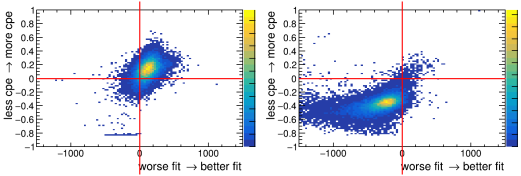
Which Cut Kills Which Background?

Background	Dominant Cut	Rej.
NC	**C/S Ratio (CPE)**	**99.0%**
$\bar{\nu}_e$ CC	(Prompt Energy)	91.3%
$\nu_\mu/\bar{\nu}_\mu$ **CC**	**Fitting Goodness**	**99.1%**
Total Atm. ν	—	99.4%

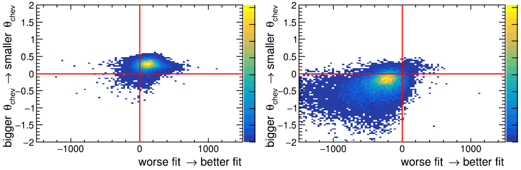
Physical mechanism:

- NC: no charged lepton $\rightarrow$ no Cherenkov $\rightarrow$ CPE cut kills
- $\nu_\mu/\bar{\nu}_\mu$ CC: μ + hadrons $\rightarrow$ poor e^+ fit $\rightarrow$ Goodness kills
- $\bar{\nu}_e$ CC: real IBD $\rightarrow$ irreducible, quality cuts pass

Cuts are complementary in 2D



DSNB (left): tight cluster. Atm. ν (right): broad.



Goodness + chev angle also complementary.

Per-Category Selection Efficiency

Three categories respond to different cuts:

Category	Goodness	Angle	CPE	All 3
NC	4.5%	8.7%	**1.0%**	**0.1%**
$\bar{\nu}_e$ CC	83.5%	**95.3%**	**97.6%**	**81.8%**
$\nu_\mu/\bar{\nu}_\mu$ CC	**0.9%**	32.3%	22.8%	**0.0%**
Total Atm. ν	4.9%	9.7%	2.0%	0.6%

表 1: Efficiency relative to Delayed Energy (= events passing cut / events at DelayedE)

- **NC:** CPE is the killer (only 1.0% survive). NC has no Cherenkov ring.
- $\bar{\nu}_e$ **CC:** All quality cuts mostly pass (81.8% survive). Real IBD → irreducible.
- $\nu_\mu/\bar{\nu}_\mu$ **CC:** Goodness kills 99.1%, combined → **zero** survive ✓

Selection Efficiency

Cut	DSNB Eff.	Atm. ν Eff.
Coincidence (20 μs)	$\sim$100%	28.5%
Prompt Energy [10,30] MeV	$\sim$50%	11.1%
Delayed Energy ($\pm 3\sigma$)	$\sim$50%	7.3%
Fitting Goodness	85.5%	4.7%
Cherenkov Ring Angle	95.37%	9.7%
C/S Ratio (CPE/SPE)	84.5%	2.0%
All cuts	**$\sim$30%**	

Final (per 20 kt·yr):
DSNB $\sim$0.66, Atm. ν $\sim$0.02, **S/B $\sim$ 33**

vs. Wei2017:
bg. 0.64, S/B = 6.4 $\rightarrow$ our bg. $\sim$30$\times$ lower

Towards Discovery Sensitivity

Current status:

- Cuts optimized by **signal-to-background ratio** (S/B)
- Achieved S/B $\sim$33, background $\sim$0.02/(20 kt·yr)
- **But:** sensitivity depends on both S and B — lower free-proton density means lower signal rate

Next step: sensitivity-based optimization

- Trade-off: tighter cuts $\rightarrow$ lower B but also lower S
- Optimal cut = maximizes Poisson significance, not S/B
- Wei2017 (LAB slow LS) as baseline reference

Comparison with LAB Slow LS

Aspect	LAB slow LS	This work (LiCl)
n capture	^{1}H ($\tau \sim 200\ \mu$s)	**^{35}Cl ($\tau \sim 5\ \mu$s)**
Coincidence window	0.2–1000 μs	**0–20 μs**
C/S separation	Temporal cut	**Per-PE posterior**
Bg. classification	CC / NC	**NC / $\bar{\nu}_e$ CC / $\nu_\mu/\bar{\nu}_\mu$ CC**
S/B	∼6	**∼33**
Total bg. [20 kt·yr]	∼0.6	**∼0.02**

Key: ∼30× lower bg. via three-category cuts. Trade-off: lower free-p → lower IBD rate.

Summary

1. **DSNB detection bottleneck = background suppression**
   - Different detectors stuck by different backgrounds
2. **LiCl water-based LS = C/S PID + high-σ n capture**
   - Solves both background rejection and IBD efficiency
3. **Three-category background analysis**
   - NC $\rightarrow$ killed by C/S ratio (99.0%)
   - $\nu_\mu/\bar{\nu}_\mu$ CC $\rightarrow$ killed by fitting goodness (99.1%)
   - $\bar{\nu}_e$ CC (real IBD) $\rightarrow$ irreducible
4. **Final background $\sim$0.02/(20 kt·yr), S/B $\sim$ 33**
   - $\sim$30$\times$ lower background than LAB slow LS
   - Cuts currently S/B-optimized; sensitivity optimization underway

Outlook

Short-term

- **Cut optimization based on discovery sensitivity**
  - Current cuts optimized by S/B; sensitivity-based optimization may improve
  - Explore multi-dimensional cut (simultaneous goodness + angle + CSR)

Medium / Long-term

- Systematic uncertainty evaluation (flux, cross-section, nuclear models)
- **Method transfer to slow liquid scintillator**
  - C/S separation framework applies to any hybrid Cherenkov-scintillation detector
  - Slow LS may offer higher free-proton density while retaining PID
- Combined sensitivity with JUNO, SK-Gd, Hyper-K

References

[1] H. Wei, Z. Wang, S. Chen, *Discovery potential for supernova relic neutrinos with slow liquid scintillator detectors*, Phys. Lett. B **769** (2017) 255–261.

[2] S. Ando et al., *Supernova neutrinos in the multi-messenger era*, PNAS **120** (2023).

[3] K. Abe et al. (Super-Kamiokande Collaboration), *Search for DSNB with 956.2 days of SK-Gd*, arXiv:2511.02222 (2025).

[4] W. Luo et al., *Reconstruction algorithm for a novel Cherenkov scintillation detector*, JINST (2023).

[5] Y. Zhang, S. Chen, **发现超新星遗迹中微子——中微子天文学的下一个里程碑**, **物理** (2023).

Thank you!

Questions & Discussion