Towards the discovery of the Diffuse Supernova Neutrino Background

Les Rencontres de Noirmoutier

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- Core-collapse supernovae (CCSNe) are among the most cataclysmic phenomena in the Universe and essential elements of the dynamics of the cosmos
- Death of massive stars ($M \geq 8\ M_\odot$), where $\sim$ 99% of the binding energy (10^{53} erg) is released via the emission of neutrinos and antineutrinos of all flavors ($\sim$ 10 MeV)
- Underlying mechanism still poorly understood and requires knowledge of the core of the collapsing star
- 10^{58} neutrinos emitted in a burst $\Rightarrow$ carry unique and unambiguous information about this core

Credit: NASA, ESA, CSAn, STScI, T. Temin (Princeton University)

Crab Nebula in IR by JWST six-light-year-wide expanding remnant of SN1054

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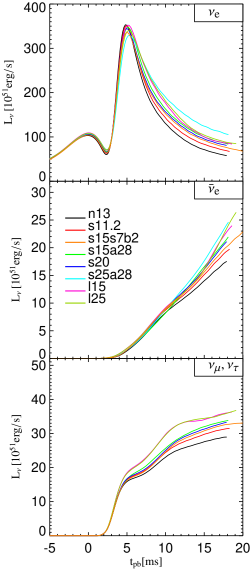
Phys. Rev. D 71, 063003 (2005)



Progenitor star between 11.2 and 25 $M_\odot$

Supernovae physics

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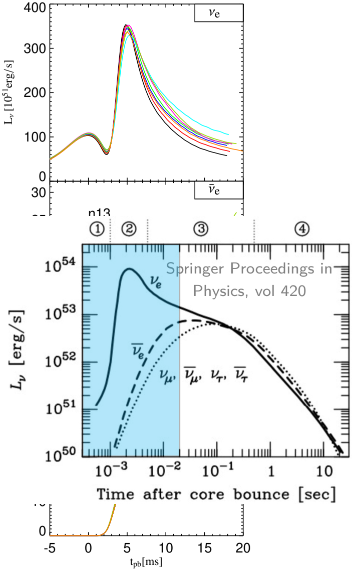
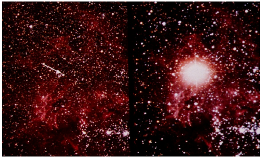


Springer Proceedings in Physics, vol 420

Progenitor star between 11.2 and 25 $M_\odot$

- So far, only SN1987a in LMC (50 kpc) has been detected by neutrino experiments, all current detectors ready to detect one nearby
- If burst happens in the galatic center $\Rightarrow \sim 8000$ neutrinos in Super-Kamiokande... but only few times per century in our galaxy



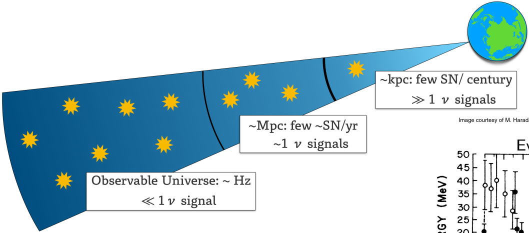
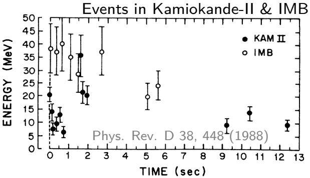


Image courtesy of M. Harada

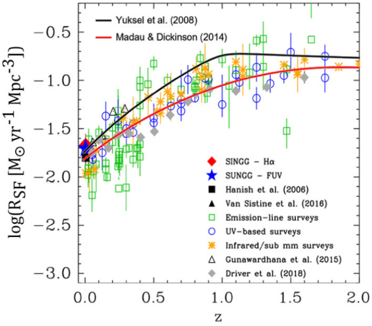


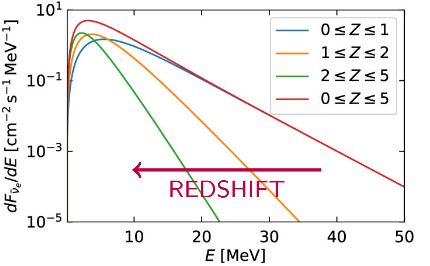
$\Rightarrow$ quest for the Diffuse Supernova Neutrino Background (DSNB)

The Diffuse Supernova Neutrino Background

- Composed by neutrinos of all past SN of all flavors whose energies have been redshifted when propagating to the Earth ⇒ information not only on the SN neutrino emission process but also star formation and Universe expansion history

$$\frac{d\phi_{\mathrm{DSNB}}}{dE} = \iint R_{SN}(z, M) \left[\frac{dF\left(E\left(1+z\right), M\right)}{dM}\right] \left|c\frac{dt}{dz}\right| dzdM$$



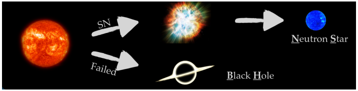


Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10

- Normalisation mostly determined by SN rate, related to cosmic star formation rate

- Shape depends on many parameters :
  - fraction of BH-forming SN,
  - effective neutrino energies (core temperature),
  - the expansion of the Universe
  - neutrino oscillation inside the star (dense matter),
  - neutrino mass-hierarchy,
  - neutrino decay and other NSI

- Rich physics program depending on the precision on the DSNB spectrum measurement



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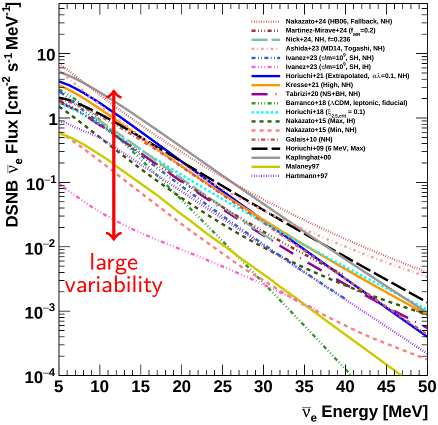
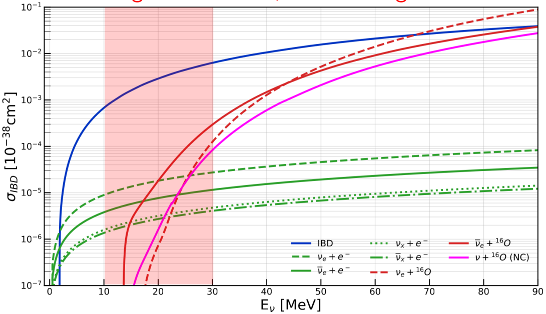
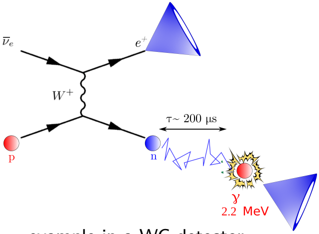


DSNB detection

- Usual detection channel : inverse β-decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$
- Searched at $\mathcal{O}(10)$ MeV, bounded by reactor + spallation background at lower energy and atmospheric neutrinos at higher energies
- In order to disentangle signal from backgrounds, neutron detection in coincidence with the positron is mandatory

region of interest, IBD has largest cross-section





example in a WC detector

- w/ current detectors
  - Liquid scintillator (LS) : **KamLAND** (1 kt), **Borexino** ($\mathcal{O}$(100) t)
  - Water Cherenkov (WC) : **Super-Kamiokande** (22.5 kt), SNO (0.7 kt)
  - Gd-loaded WC detectors : SK-Gd $\Rightarrow$ **SK-VI** discussed later
- Next generation experiments for DSNB detection
  - WC : Hyper-Kamiokande
  - LS : JUNO

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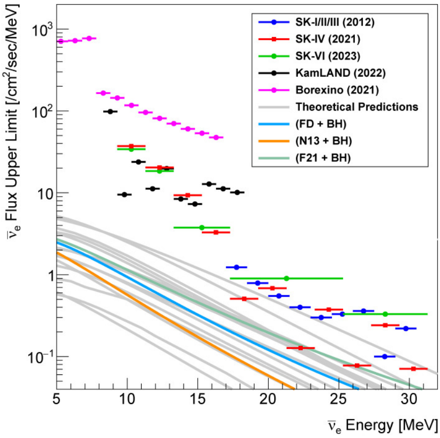

Highlight of recent search and prospects

- w/ current detectors
  - Liquid scintillator (LS) :
    KamLAND (1 kt),
    Borexino ($\mathcal{O}(100)$ t)
  - Water Cherenkov (WC) :
    Super-Kamiokande (22.5 kt),
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  - Gd-loaded WC detectors : SK-Gd
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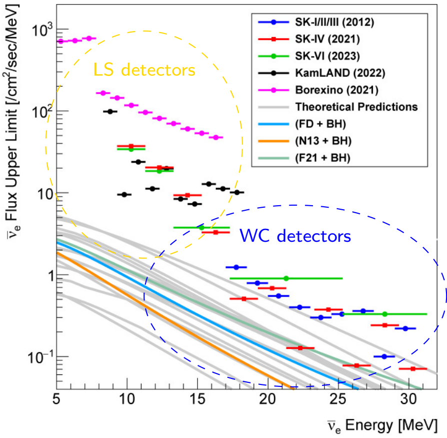

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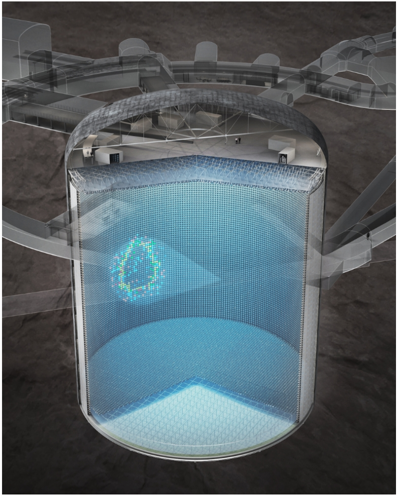
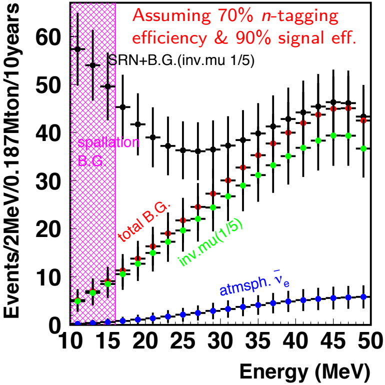
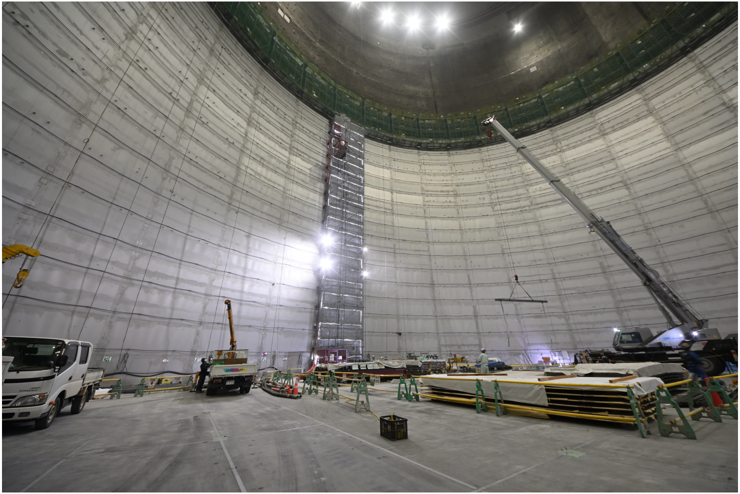


- 258 kton WC detector @ Kamioka, Japan
- Will start data taking in 2028
- Expected $> 4\sigma$ in 10 years due to its large volume and upgraded phototubes ($\times 2$ eff.)



arXiv:1805.04163 [physics.ins-det]

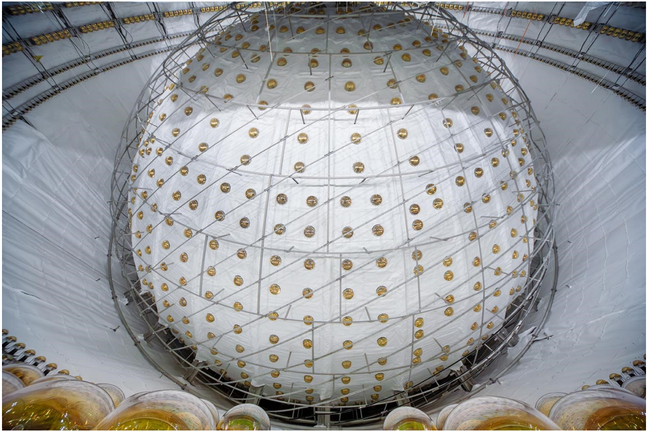
Future experiments - Hyper-Kamiokande (cont'd)



Construction for the 19th and 20th lift of the barrel section on April 22, 2026

Future experiments - JUNO

Liquid Scintillator detector @ Jiangmen, China $\Rightarrow$ started data taking since Aug. 2025

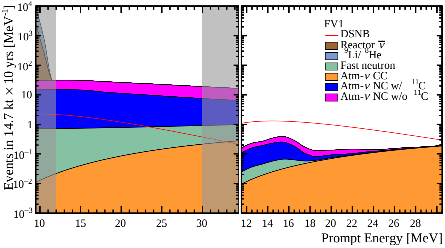


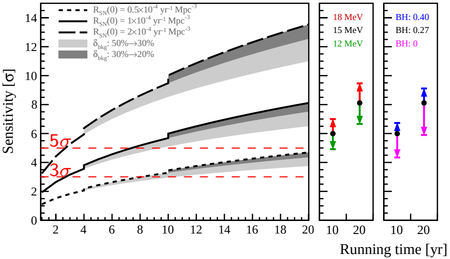
see talk by B. Viaud on Tuesday

Key factors: 700 m underground *i.e.* 1800 m.w.e., 17 kton LS fiducial mass for DNSB, LY $\sim 1345\,\mathrm{p.e./MeV}$ can reach very low energies, excellent energy resolution $\sim 3\%/\sqrt{E(\mathrm{MeV})}$

- Assuming 80% signal efficiency and effective background reduction using muon veto and PSD method $\Rightarrow$ S/B ~ 3.5
- 3σ within 3 years or $> 5\sigma$ within 10 years for reference DNSB model (solid curve / black dots)
- Higher SN rates, larger SN energies, and greater black hole fractions enhance discovery potential
- 3σ sensitivity is achievable in 10 years even for pessimistic DSNB models

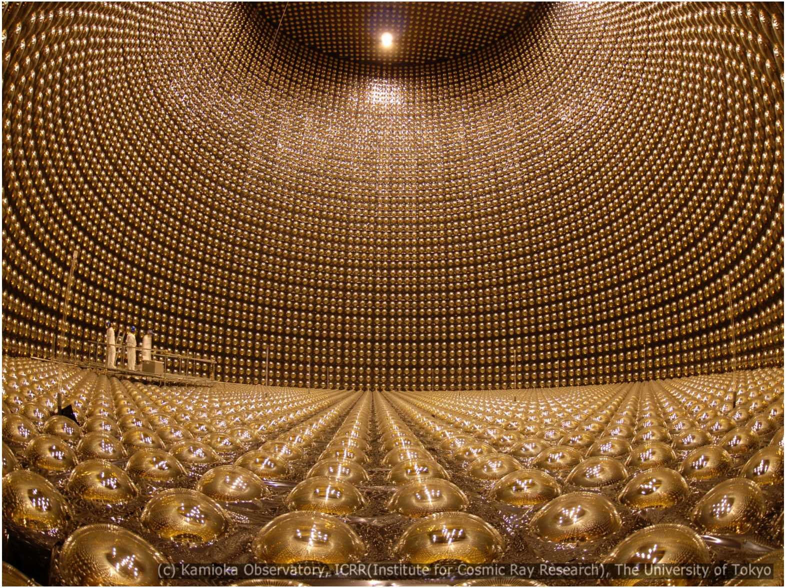
Pinched Fermi-Dirac





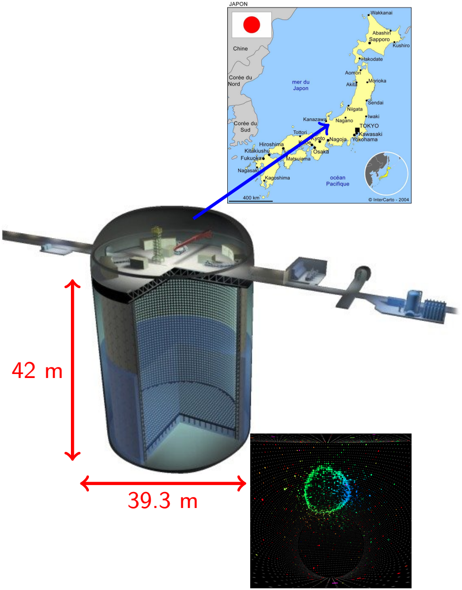
JCAP 10 (2022) 033

Latest Super-Kamiokande results with Gd



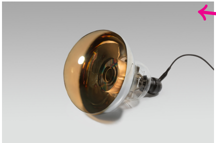
- 50 kton water Cherenkov detector (currently doped with Gd)
- Located in Kamioka, Japan, under Mt. Ikenoyama : 1 km rock overburden (2.7 km water equivalent)
- Optically divided into an inner detector (ID) with a fiducial volume of 22.5 kton and an outer detector (OD), instrumented with
  - ID : $\sim$ 11000 inward facing large 20"-PMTs, 40% photo-coverage
  - OD : 1885 8"-PMTs primarily used as veto

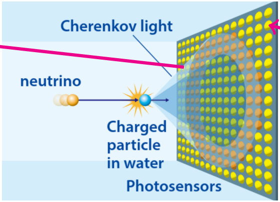
Running for 30 years
and still has a lot to teach !

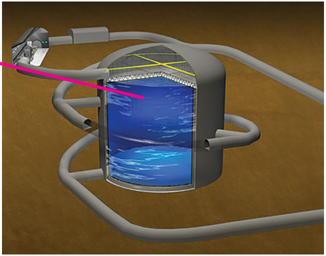


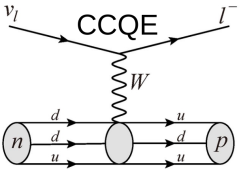
Neutrino detection with water Cherenkov detectors

PhotoMultiplier Tube (PMT)



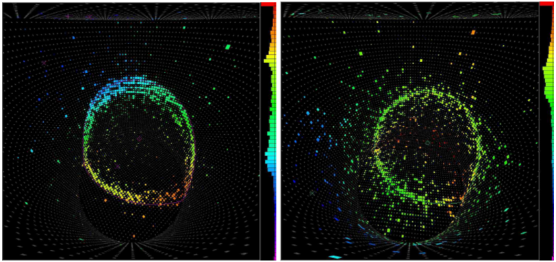






Muon

Electron



courtesy of SK collaboration

Neutrino detection with water Cherenkov detectors

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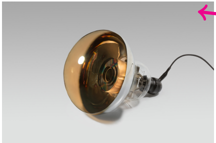
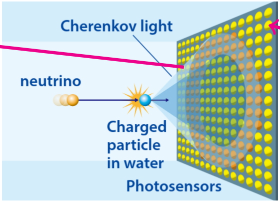
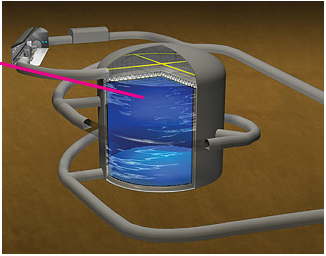
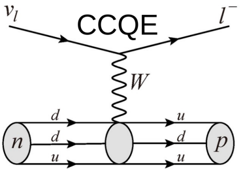
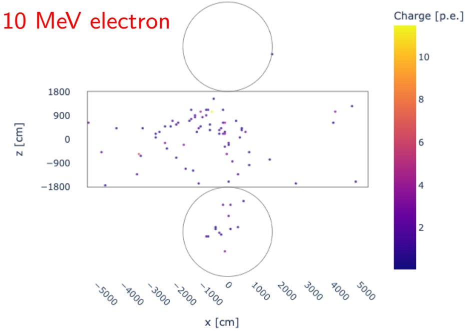










Detector phases

- SK experiment has collected data during 8 phases

Phase	Period	Event
SK-I	1996.4 to 2001.7	Start of the experiment
SK-II	2002.10 to 2005.10	20% photo-coverage after accident
SK-III	2006.7 to 2008.8	Full photo-coverage (40%) restored
SK-IV	2008.9 to 2018.5	Upgraded electronics
SK-V	2019.1 to 2020.8	Detector upgraded for Gd-loading
SK-VI	2020.8 to 2022.6	0.01% Gd-doping
SK-VII	2022.6 to 2023.12	0.03% Gd-doping
SK-VIII	since 2023.12	0.03% Gd-doping

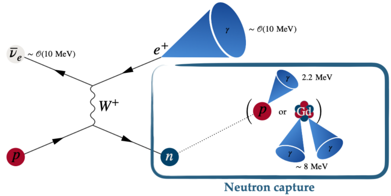
Phys. Rev. D104, 122002 (2021)

Astrophys.J.Lett. 951 (2023) 2, L27

arXiv:2511.02222v1, accepted by ApJ.
→ discussed today

- Highly versatile multi-purpose experiment in the MeV - TeV range : solar & atmospheric neutrinos, supernovae neutrinos, DSNB, neutrino astrophysics, proton-decay, dark matter, beam neutrino (T2K)

- Regarding the search for the DNSB, neutron tagging is only possible since SK-IV period with its upgraded electronics



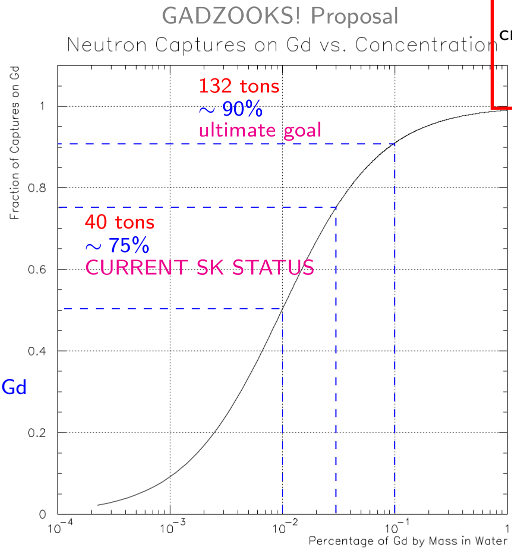
Motivations

- Improve neutron detection at SK, in SK-IV neutron tagging possible but inefficient
- Dissolve Gd sulfate in water to enhance neutron signal : very high neutron capture cross-section of 49.7 kb ($\sigma_H = 0.33\,\mathrm{b}$) + 8 MeV photon cascade

Upgrade process

- 2002: first proof of concept
- 2009: small scale prototype detector started (EGADS)
- 2018: SK detector refurbishment (SK-V)
- 2020: SK detector w/ 0.01% Gd (SK-VI)
- 2022: SK detector w/ 0.03% Gd (SK-VII, currently running)
- SK detector w/ 0.1% Gd?

Gd thermal neutron cross section : 49.7 kb
($\sigma_H = 0.33$ b)
8 MeV γ cascade



13.2 tons of
$Gd_2(SO_4)_3 8H_2O$
in 50 ktons water
~ 50% capture on Gd
August 2020

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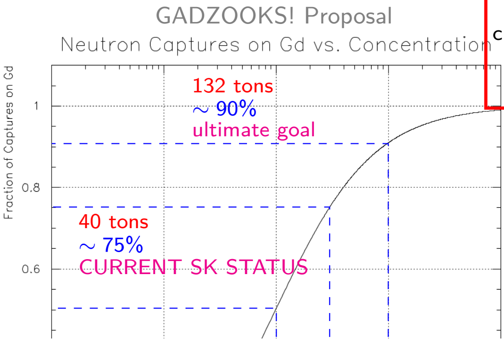

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PoS ICHEP2020 (2021) 164

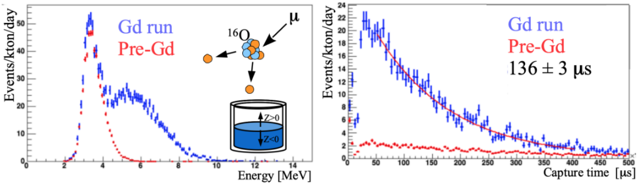
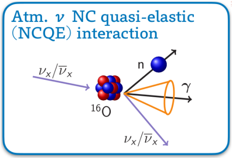


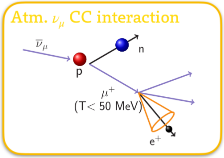
Figure 5: Reconstructed energy for spallation neutrons candidates for runs with and without Gd in the lower region of the detector (left) and capture time of the neutron candidates (right).

Background sources

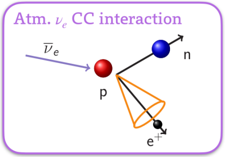
1. **Atmospheric neutrinos**
   - NCQE interactions (inducing nuclear γ ray) is the main atm. ν background $\lesssim$ 20 MeV
   - at higher energies $\gtrsim$ 30 MeV CCQE interactions and π production dominate, mostly Michel-e^- from invisible μ/π decay (up $\sim$ 50 MeV)
   - ν_e/ν_μ CC can be largely reduced using neutron tagging
   - $\bar{\nu}_e$ CCQE are irreducible $\Rightarrow$ sets the analysis upper threshold



2. **Cosmic ray muon spallation**
   - 2700 mwe $\Rightarrow$ $\sim$ 2 Hz of muon in SK inducing spallation of ^{16}O
   - misidentification of decays of produced radioactive isotopes as IBD
   - below 20 MeV spallation events are 10^6 times higher than DSNB events
   - drastically reduced by neutron tagging apart from βn emitters and accidental coincidence



3. **Reactor neutrinos**
   - Irreducible, overwhelm DSNB events $\lesssim$ 8 MeV $\Rightarrow$ sets the analysis lower threshold



4. **Solar neutrinos**
   - ν_e from the *pp* chain (^{8}B & *hep*) up to $\sim$ 20 MeV
   - easily removed using neutron tagging and directional cuts using θ_{Sun}

Data Quality

Remove poorly reconstructed events, Rn events, events with OD activity

↓

Spallation Background

Remove long-lived, high-energy, spallation isotopes (^{8}Li, ^{8}B, ^{9}Li, ^{9}C) remove events near "neutron clouds"

↓

Atmospheric Background

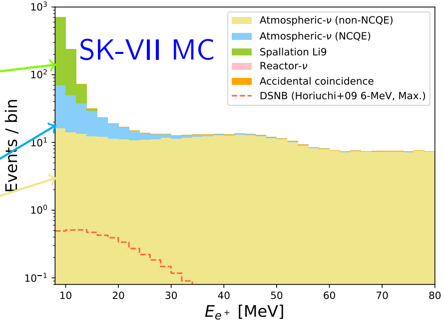
Remove multi-cone prompt events remove μ/π events

↓

Neutron Tagging

[2 different ML algorithms BDT/NN]

no reduction applied



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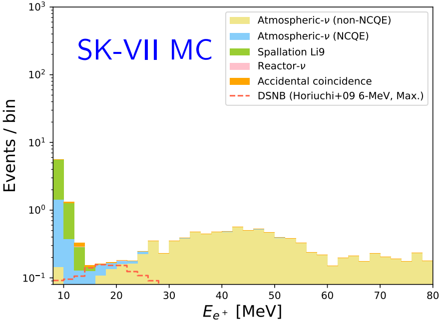
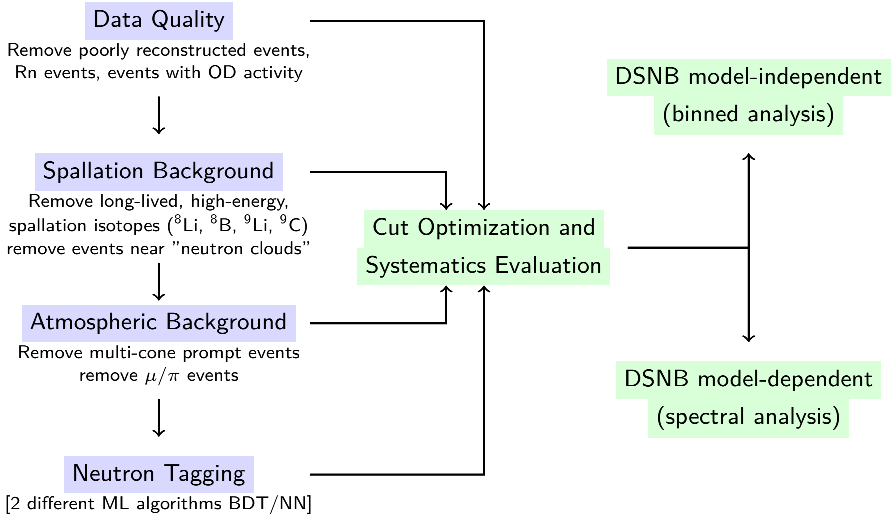
[2 different ML algorithms BDT/NN]

all reductions applied

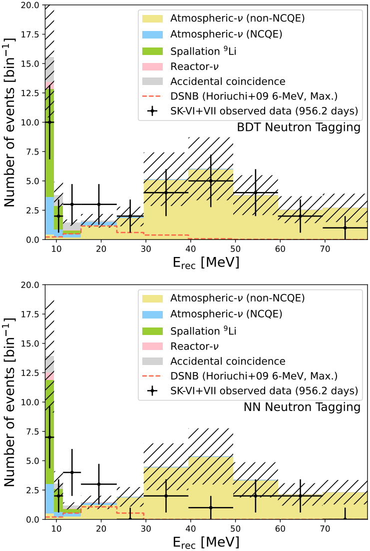


Super-Kamiokande DSNB analysis - Reduction steps

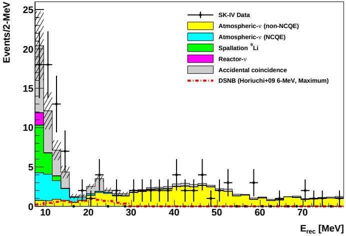


Binned analysis - SK-Gd & SK-IV energy spectra

arXiv:2511.02222v1, accepted by ApJ.



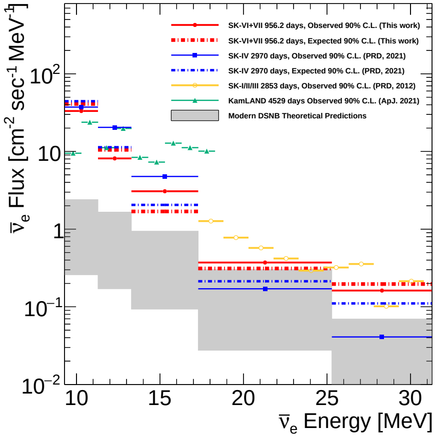
SK-IV w/ BDT neutron tagging



Phys. Rev. D104, 122002 (2021)

← huge reduction of NCQE background

arXiv:2511.02222v1, accepted by ApJ.



Model independent analysis

Only use $N_n = 1$ events

World stringent sensitivity

- $CLs \equiv p_{S+BG}/(1 - p_{BG})$ upper limits are conservative by construction

$$\phi_{90} = \frac{N_{90}}{\sigma_{\text{IBD}}\, T\, \epsilon_{\text{IBD}}\, N_p\, \Delta E}$$

- Limits are highly similar in the various energy bins for BDT / NN analysis
- Differences are driven either by neutron tagging technique and/or the evaluation of accidental coincidences
- This result takes into account the correlation between SK phases due to the same backgrounds and their predicted levels per bin
- In the near future, expect appreciable sensitivity to a wide variety of models...

Spectral fitting analysis - Fit procedure

- Fit the number of observed events $(N_s, \vec{N}_b)$ that maximizes the following extended likelihood :

$$\mathcal{L}\left(\text{data} \,|\, N_s, \vec{N}_b, \vec{\varepsilon}\right) = \mathcal{L}(\vec{\varepsilon_0}|\vec{\varepsilon}) \times e^{-\sum_{j\in s+b} N_j} \times \prod_{i=1}^{N_{\text{data}}} \sum_{j\in s+b} N_j \cdot \text{PDF}_j\left(E^i, \theta_C^i, N^i_{\text{tagged }n} \,|\, \vec{\varepsilon}\right)$$

with 3 regions in θ_C and 2 regions in $N_{\text{tagged }n}$

	Sideband $20^\circ < \theta_C < 38^\circ$	Signal region $38^\circ < \theta_C < 53^\circ$	Sideband $78^\circ < \theta_C < 90^\circ$	
$N_{\text{tagged}} \neq 1$				Non IBD-like events
$N_{\text{tagged}} = 1$				IBD-like events
	Mostly μ/π events	Signal & bkg (spall., decay-e, atm CC)	Mostly NCQE	

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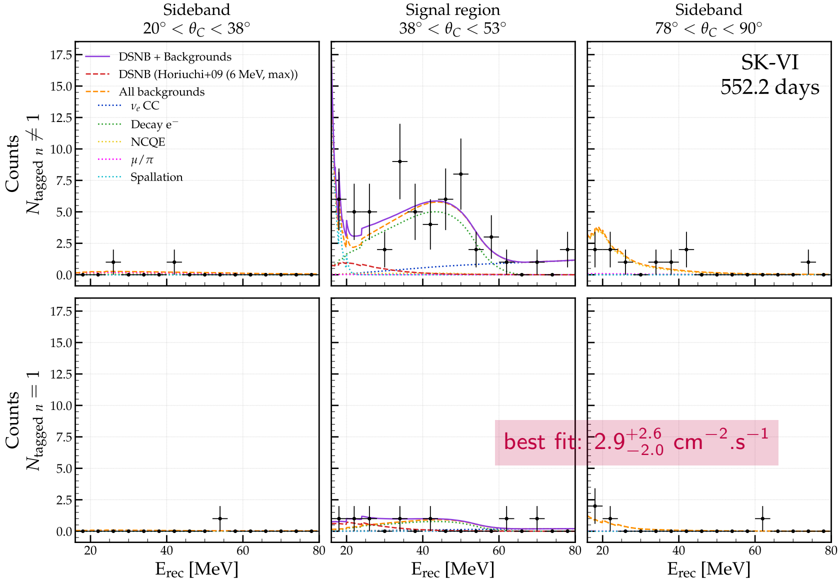
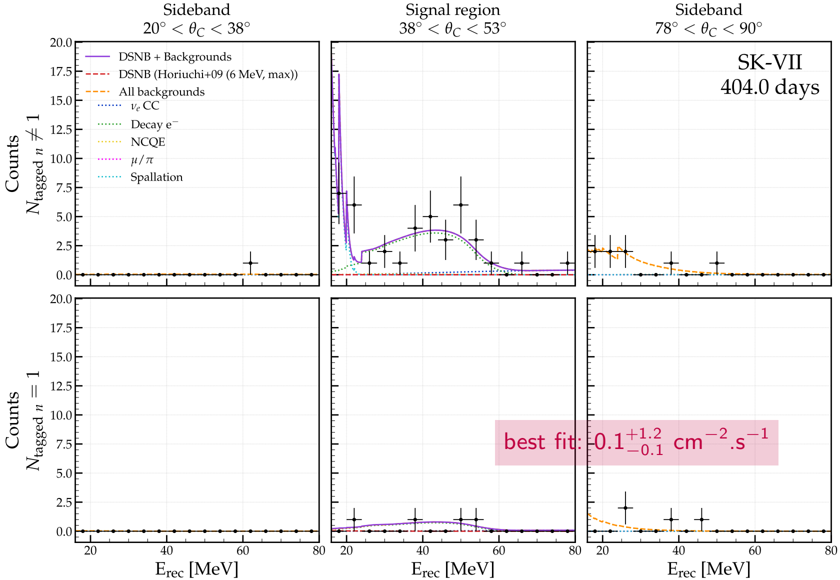
Spectral fitting analysis - SK-VI best fit (NN Neutron Tagging)



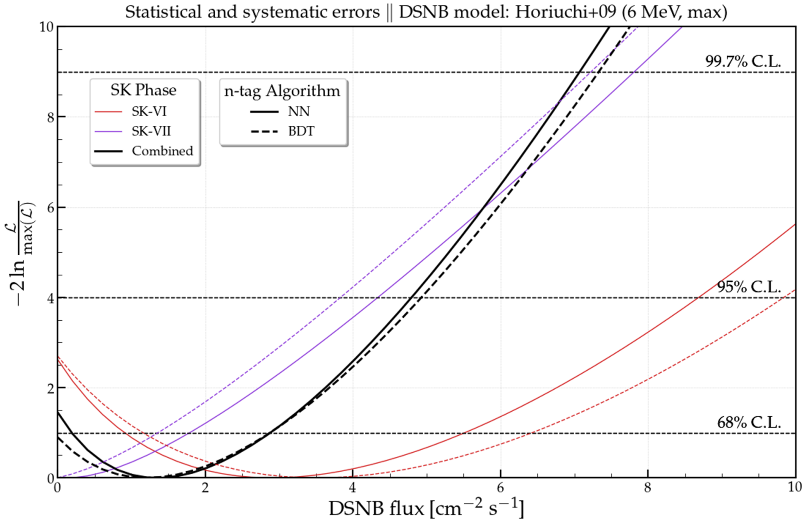
arXiv:2511.02222v1, accepted by ApJ.

Spectral fitting analysis - SK-VII best fit (NN Neutron Tagging)



arXiv:2511.02222v1, accepted by ApJ.

Spectral fitting analysis - SK-Gd profile likelihood



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Summary and perspectives

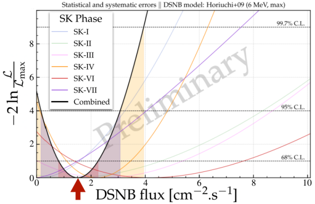
- DSNB flux carries valuable information about not only the supernova neutrino flux, but also the history of star formation, cosmic-expansion and neutrino properties
- Worldwide neutrino detectors sensitive to $\mathcal{O}(10)$ MeV running and foreseen to observe the DSNB
- Super-Kamiokande experiment published first results for the SK-Gd era in 2023
- @ Neutrino 2024, SK preliminarily showed the phase-combined result among SK-I/II/III/IV/VI/VII, 6779 days (5823 d of pure-water / 956 d of Gd-water), indicating 2.3σ excess from null-hypothesis

Tension from zero assumption

Spectral-fitting analysis

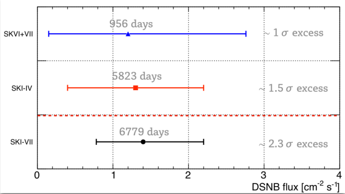
Spectrum fitting analysis to extract significance

- Total 6779 days of SK (5823 d pure-water and 956 d Gd-water) combined
- Analysis threshold: $E_\nu > 17.3$ MeV
- Suppress uncertainty of background prediction by fitting both $N_n=1$, $N_n \neq 1$



Best fit: 1.4

(Rogly, poster 79)



Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is $\mathbf{1.4^{+0.8}_{-0.6}}$ **cm^{-2} s^{-1}** for $E_\nu > 17.3$ MeV

➡ **exhibit ~2.3 σ excess!!**

17

Slide taken from M. Harada, Review of DSNB, NEUTRINO 2024 @ Milan, Italy

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- Results that I showed today only concerns SK-Gd data
- Additional data: 379 days of pure-water and 700 days of Gd-water ($\sim$ 2000 d pure-water equiv.) + improved analysis + combination previous data to be released @ Neutrino 2026

Stay tuned!