The Diffuse Supernova Neutrino Background in Super-Kamiokande

Sonia El Hedri, for the Super-Kamiokande collaboration

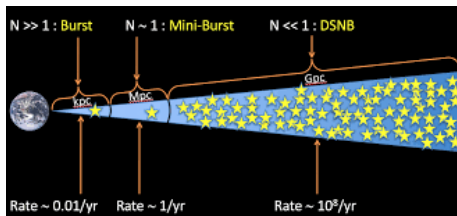ICHEP 2020

July 30, 2020

The Diffuse Supernova Neutrino Background

Neutrino flux from all distant core-collapse supernovae
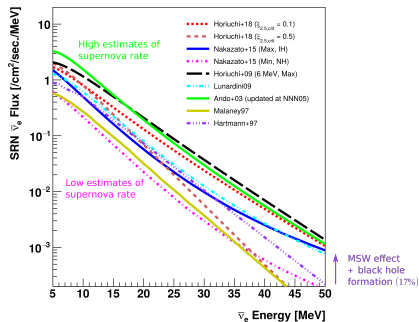
2-3 galactic supernovae/century
1 SN/s in the observable Universe

J. Beacom

Y. Ashida

$$\Phi(E) = \frac{c}{H_0} \int_0^{z_{max}} R_{\mathsf{SN}}(z) \, F_\nu[E(1+z)] \frac{\mathrm{d}z}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

- Aggregate properties of core-collapse supernovae
- All flavors of neutrinos, redshifted
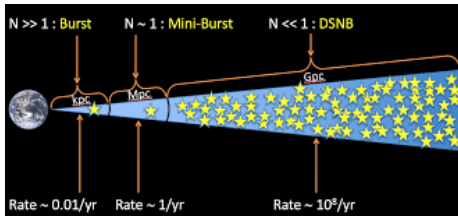- Elusive low energy signal

The Diffuse Supernova Neutrino Background

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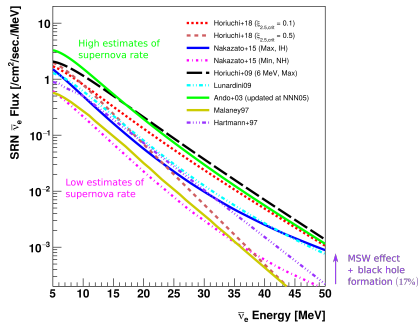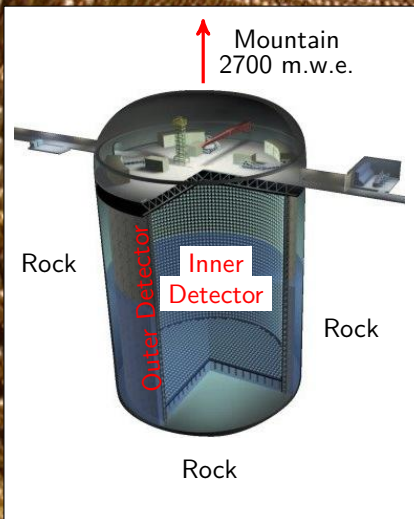1 SN/s in the observable Universe

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$$\Phi = \int \begin{bmatrix} \nu \text{ emission} \\ \text{(black hole} \\ \text{fraction)} \end{bmatrix} \otimes \begin{bmatrix} \text{Star} \\ \text{formation} \end{bmatrix} \otimes \begin{bmatrix} \text{Universe} \\ \text{expansion} \end{bmatrix}$$

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Super-Kamiokande: A cheat sheet

- Kamioka Mine, Japan
- 50 kton Water Cherenkov detector
- Water constantly recirculated and purified
- 11129 Inner Detector PMTs
  50 cm, 3 ns resolution
- Energy coverage
  4 MeV to ~TeV
- Currently in phase VI, doping with
  Gadolinium just started!
- Current study: phase IV
  longest data-taking period (2008-2017)
  2790.1 live days
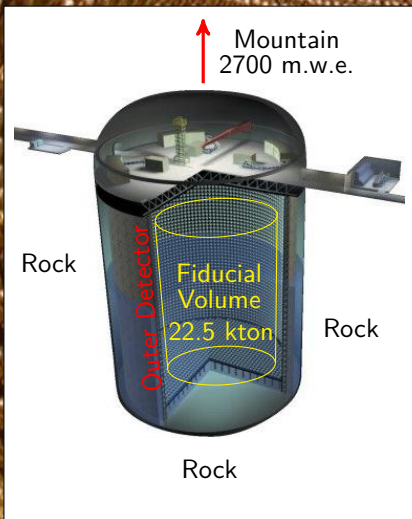
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The DSNB in Super-Kamiokande
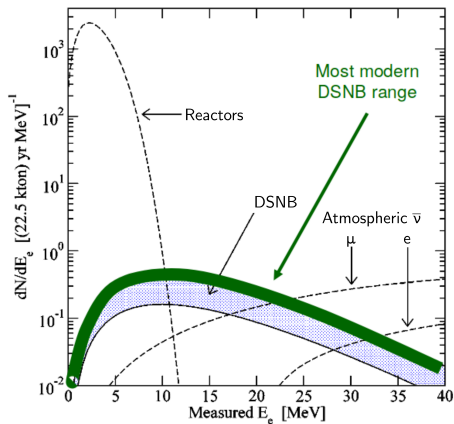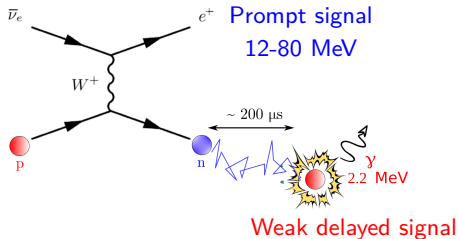
Detecting antineutrinos via Inverse Beta Decay (IBD)

[Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004]

- 5-20 events/year – Energy range 12-80 MeV
- Need to characterize spallation and atmospheric backgrounds and **identify the neutrons**

The DSNB in Super-Kamiokande

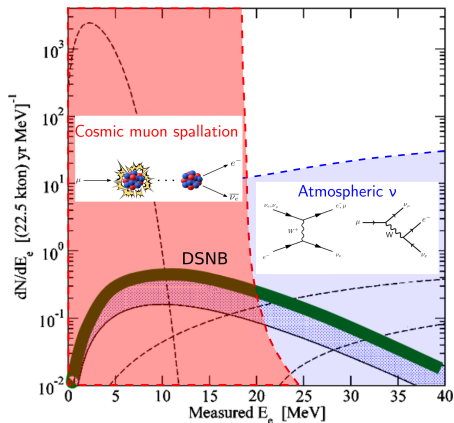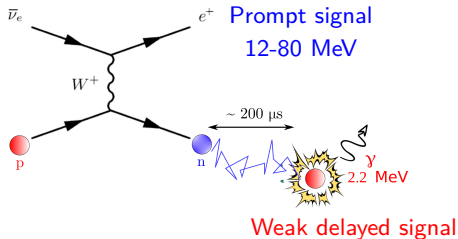Detecting antineutrinos via Inverse Beta Decay (IBD)

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The three pillars of the DSNB analysis

After basic noise reduction cuts:

I - Spallation cuts

- Remove radioactive isotopes produced by cosmic muons

II - Atmospheric background reduction/characterization

- Remove atmospheric signals with pions/muons/gammas
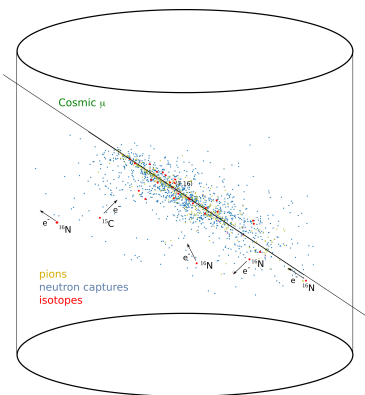- Estimate spectral shapes of low energy atmospheric neutrinos

III - Neutron tagging

- Possible only since SK-IV
- Identify neutron capture signal in water

Spallation backgrounds

Radioactivity induced by cosmic muon spallation in water
See talk by L. Bernard, 29/07

- About one muon every two minutes causes spallation in SK
- Needs to be reduced by $\mathcal{O}(10^4)$
- Main signatures
  - $> 99\%$ β decays: $A \to e^{\pm} + \nu$
  - $< 1\%$ IBD-like (^{9}Li): $A \to e^{\pm} + n$
- Isotopes' half-lives up to 13 s
  $\Rightarrow$ correlations over large time scales!
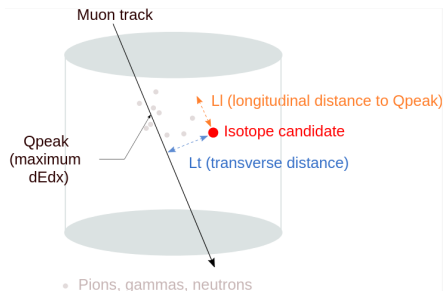- No existing simulation in WC detectors

Reduction strategy:
- Identify isotope clusters and neutrons from muon showers
- Investigate correlations between muons and candidate events

Spallation: hunting for correlations

Pair each candidate event with muons up to 30 s before
Investigate correlations using a likelihood analysis

Observables

- Δt, L_t, L_l: distance and time difference
- resQ: charge deposited by the muon in addition to minimum ionization
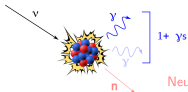
Extracting distributions
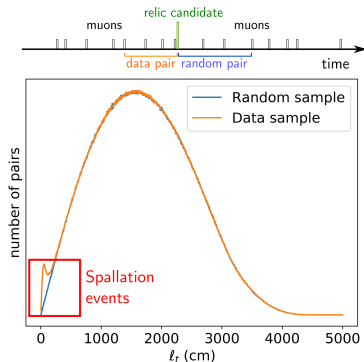
Final performance: $> 90\%$ background rejection ($> 99\%$ on ^{9}Li)
40-90% signal efficiency (depending on reconstructed energy)
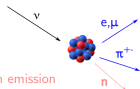
Evaluating and reducing atmospheric neutrinos

Interaction types

Neutral Current (NC)   Charged Current (CC) ν_e, ν_μ

Neutron emission (rare process)

Light patterns in SK

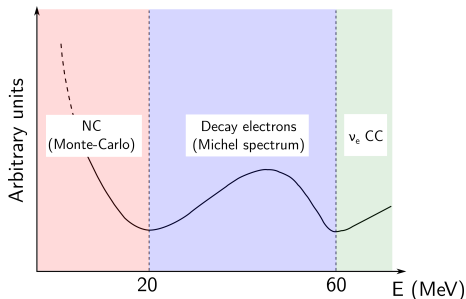Energetic photon(s)   Energetic μ/π Electrons (μ/π decays, CC ν_e)

Large Cherenkov angle

Small Cherenkov angle
Specific light pattern
Double signal if decay

Irreducible background

Atmospheric backgrounds after cuts

Arbitrary units

NC (Monte-Carlo)

Decay electrons (Michel spectrum)

ν_e CC

20   60   E (MeV)

- Categories: NC and μ/π (reducible), ν_e CC and decay electrons (irreducible).
- For NC and μ/π: high efficiency cuts on the Cherenkov light pattern.

Estimating normalization and spectral shapes:

- $\mathcal{O}(100\%)$ uncertainties on rates and spectral shapes below 100 MeV except for decay electrons (measured Michel spectrum from stopping muons).
- Strategies: Use T2K to estimate cross-sections and efficiencies (NC backgrounds), or use sidebands in energy and Cherenkov angle.
  [Y. Ashida, Ph D. thesis (2019)]

Selecting neutrons: a needle in a haystack

Neutron capture occurs **near the positron vertex**
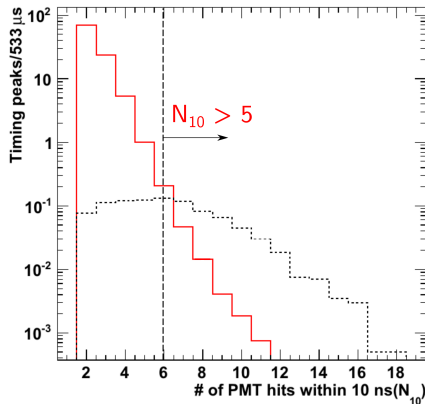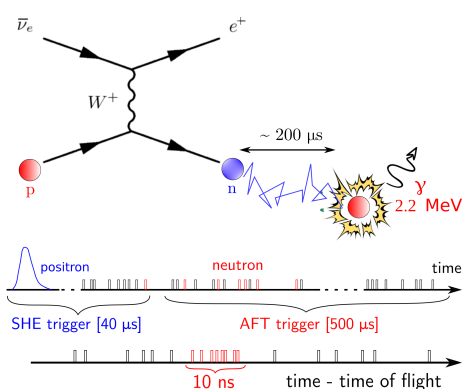

- New in SK-IV: "AFT" trigger window after the positron window
- Sensitivity to dark noise: inject random trigger data into MC simulation (SKDetSim – GEANT3) for cut optimization.
- Preselection: define **candidate neutron peaks** with $N_{10} > 5$

Selecting neutrons: final step

Use a Boosted Decision Tree (BDT) to tag neutron candidates.

Neutron tagging performance

Very preliminary

Overall efficiencies
for our analysis
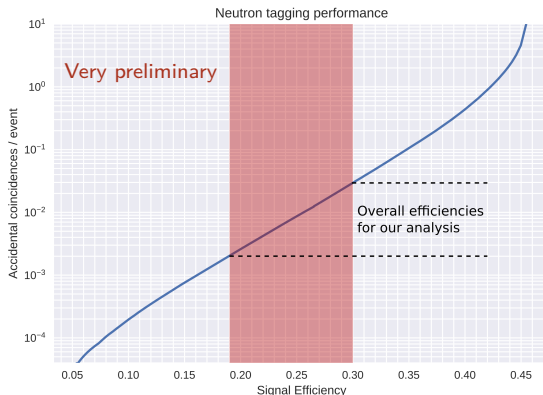
- **Final performance**: $0.3 - 3\%$ background acceptance
  $18 - 30\%$ signal efficiency.
- Expect considerable performance enhancement after Gadolinium doping [see next talk by Lluis Marti Magro].

Analysis procedures

Supernova model-independent analysis

- Low energy analysis: $12 - 30$ MeV reconstructed positron energy
- Atmospheric CC: estimate by fitting Michel spectrum in $[30, 50]$ MeV
- Atmospheric NC: estimate using T2K data $\Rightarrow$ define 3 large energy bins
  50% uncertainties for NC backgrounds – 30% uncertainties for CC
- Bin-by-bin cut optimization and limit calculation

Spectral analysis

- Fit observed energy spectrum by DSNB $+$ atmospheric spectra
- Need to eliminate spallation $+$ solar backgrounds
  $\Rightarrow [16, 80]$ MeV energy range
- Atmospheric spectral shapes: use sidebands in Cherenkov angle for NC and μ/π. Assume $\mathcal{O}(100\%)$ uncertainties on normalizations and shapes **except for Michel spectrum**.

Supernova model-independent analysis

No excess observed – Significantly improved exclusion bounds at low energy
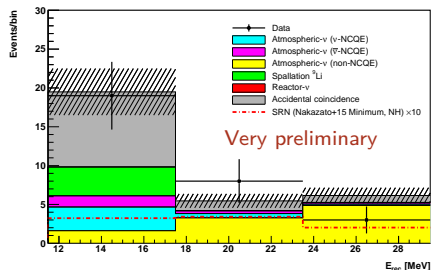

Search Results & Integrated SRN Electron Antineutrino Flux [/cm²/sec.]

E_ν region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	9.48	1.35	0.82
SK-IV 2970 days (Observed)	9.08	2.22	0.35
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Ando+03 (updated at NNN05)	2.652	0.796	0.261

- Neutron tagging allowed to bring the analysis threshold from 16 to 12 MeV (limit set by reactor neutrinos and atmospheric backgrounds)
- Current limits within a factor of a few of optimistic DSNB scenarios.
- SK-Gd will probe a significant fraction of the DSNB parameter space
- Even with Gd, important uncertainties from NC γ emission and neutron multiplicity

Spectral analysis

Combination of SK-I to IV for the Ando (optimistic) model
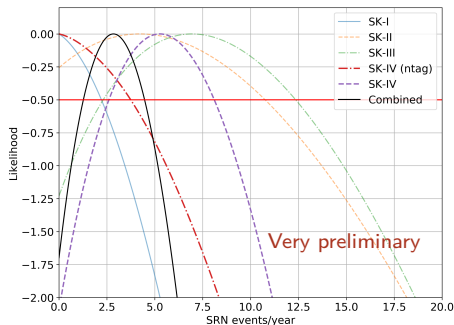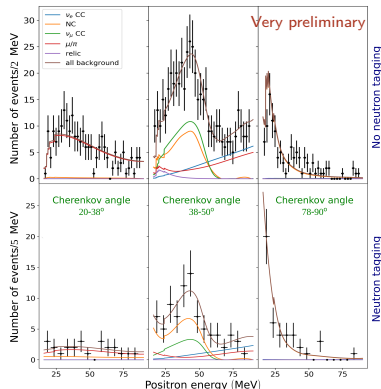
- Slight excess at low energy without neutron tagging
- Current 90% C.L. limits on the Ando model flux (1.7 cm^{-2}/s):

SK-IV (no neutron tagging) :	$\Phi_{90} = 4.9$ cm^{-2}/s
SK-IV (neutron tagging):	$\Phi_{90} = 3.8$ cm^{-2}/s
Combined (22.5×2853 kton.day) :	$\Phi_{90} = 2.7$ cm^{-2}/s

Conclusion

- First analysis of the diffuse supernova neutrino background with the full SK-IV dataset **and neutron tagging capabilities**.

- The most optimistic DSNB models are tantilizingly close...maybe a discovery in Super-K Gd?

- One lesson to remember: atmospheric NC backgrounds will need to be fully characterized in other experiments, such as the Intermediate Water Cherenkov Detector projet in Hyper-Kamiokande.

Stay tuned for the near and far future!

Thank you for your attention