SUPER-KAMIOKANDE RESULTS AND PREDICTIONS ON SUPERNOVA NEUTRINO

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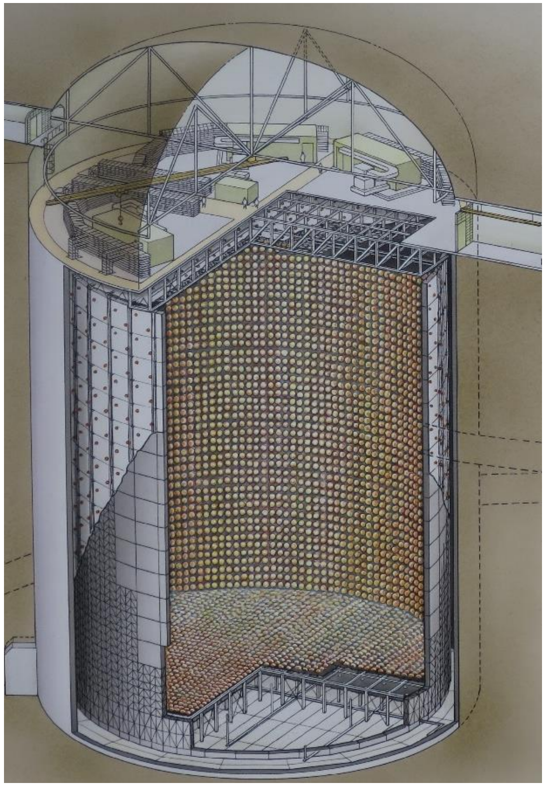
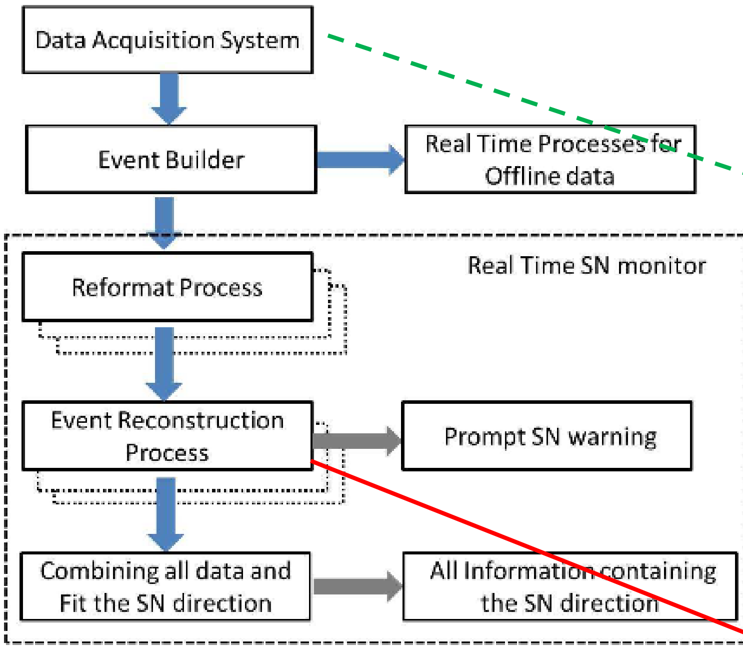
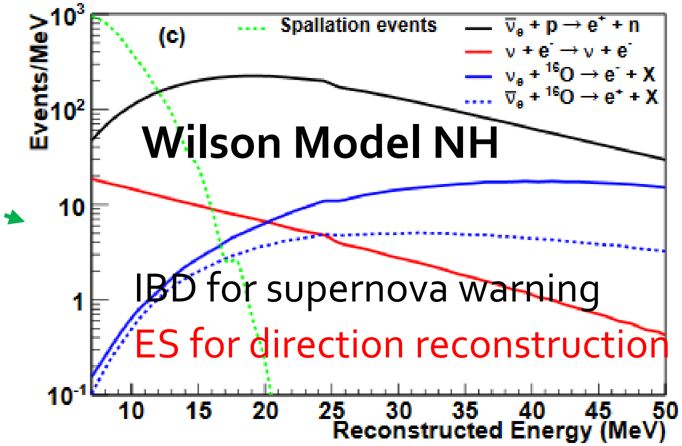
Super-Kamiokande
A Water-Cerenkov Detector

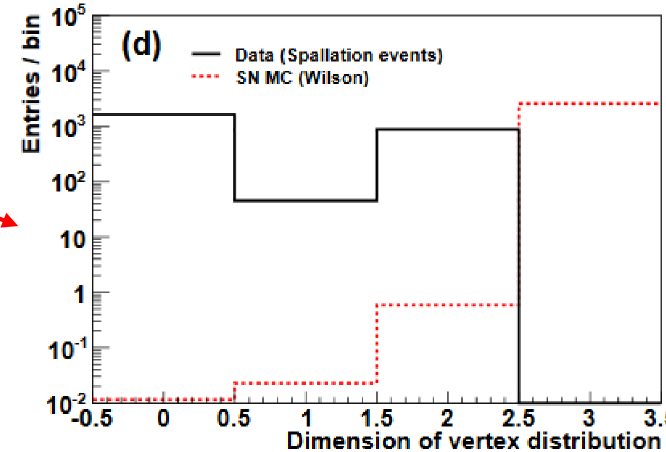
- Detector:
  39.3 m × 41.4 m pure water
  ID: 32.5 kT; Fiducial: 22.5 kT
- PMT Coverage: ∼40%
- Water Cerenkov:
  $E_{thr}\left(e^{+/-}\right) \approx 0.77\ \text{MeV}$
  $E_{thr}\left(\mu^{+/-}\right) \approx 157\ \text{MeV}$
- Direction:
  reconstruct from Cerenkov ring
- Water Transparency:
  ∼ 120 m by decay electron



Real-Time Burst Monitor



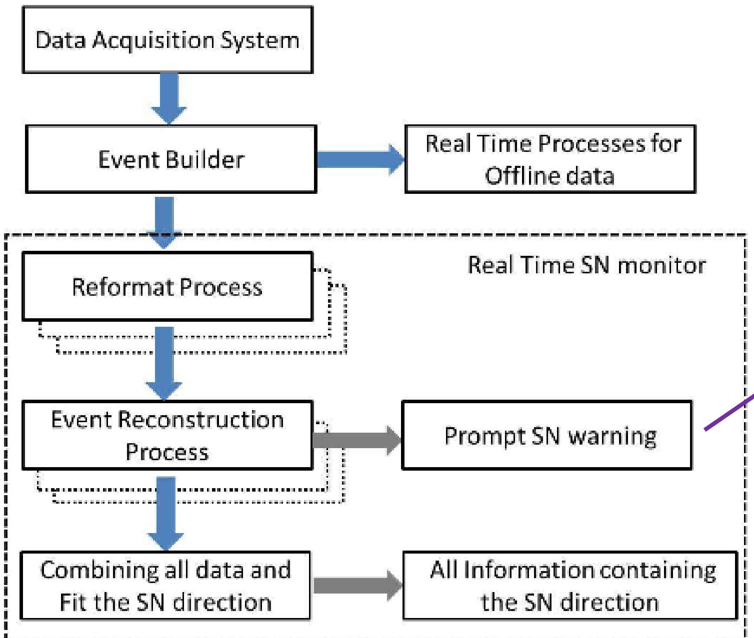


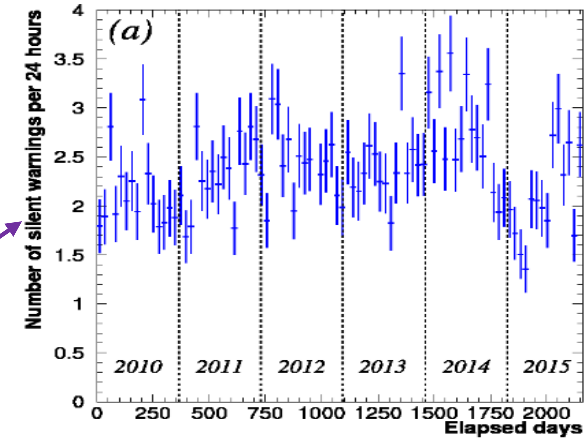


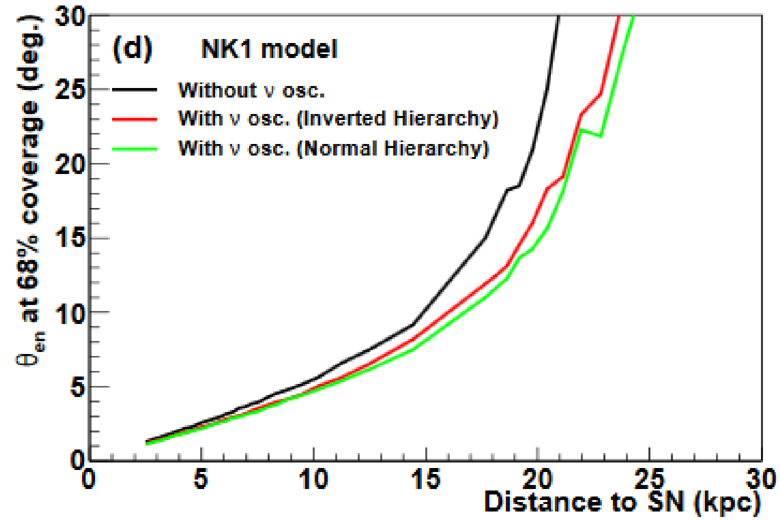
5,200 (2,200) for the Wilson (NK1) model at 10 kpc (No oscillation)

With SuperK-Gd, acc bkg will drop!!!

Real-Time Burst Monitor



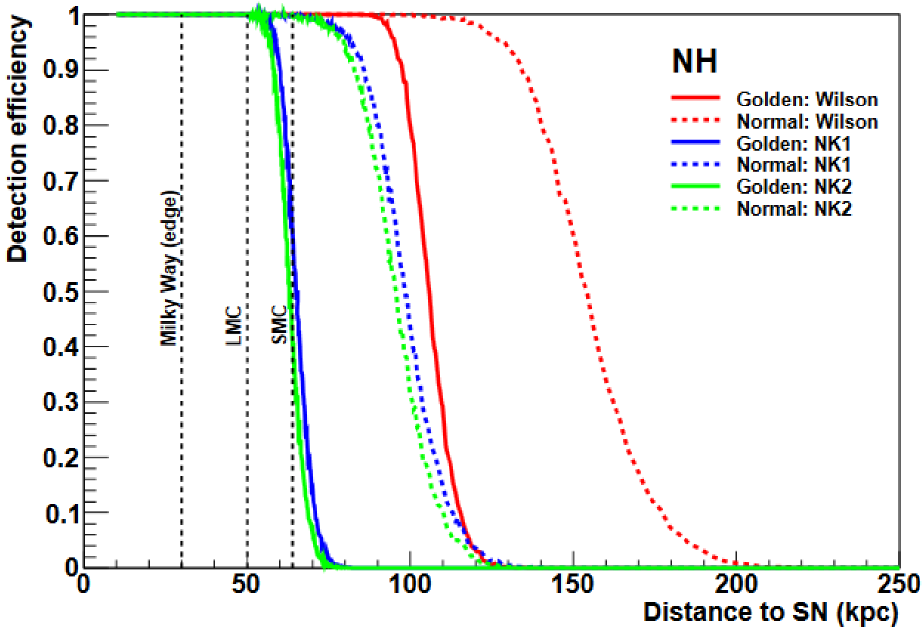




Silent warning: 2 / day

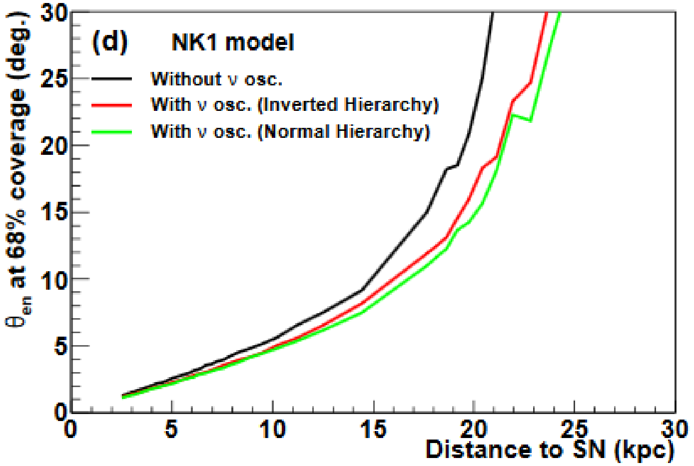
The ONLY detector that enables SN **direction reconstruction** using neutrinos.

Real-Time Burst Monitor



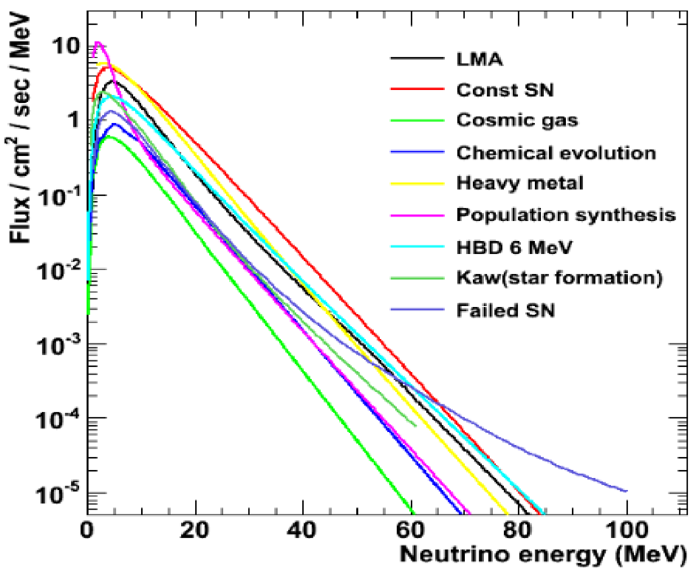
Golden: 100% efficiency

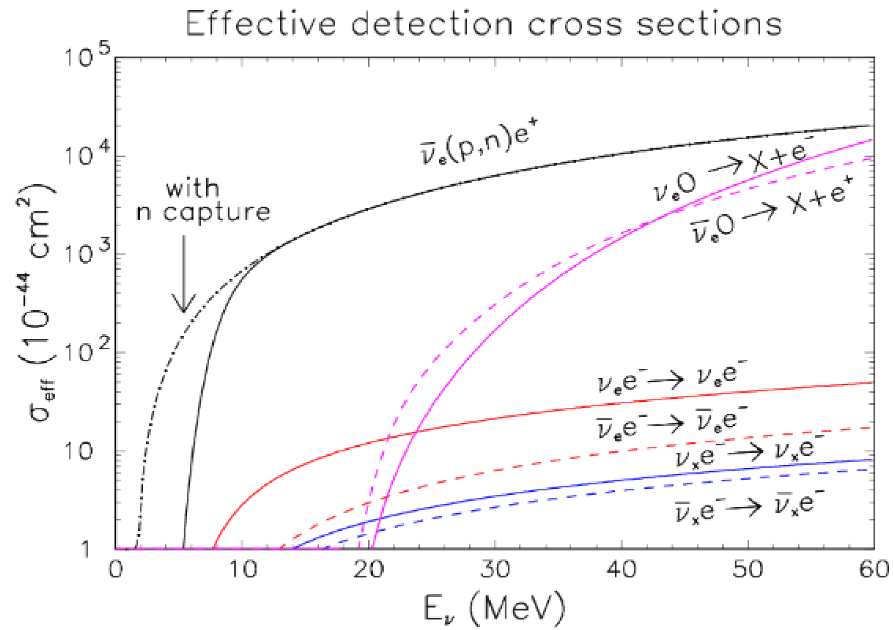
Fast warning to the world within one hour.



Pointing accuracy 3.1~3.8° at 68.2% coverage for the Wilson model at 10 kpc.

Supernova Relic Neutrino





- Inverse Beta Decay

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

An SRN (or Diffused Supernova Neutrino Background, DSNB) detector should detect the positron (and gamma).

- Neutron Capture

$$n + p \rightarrow He + \gamma$$

- ☐ H Capture $\tau \approx 200\ \mu s$ $E_\gamma = 2.2$ MeV
- ☐ Gd Capture $\tau \approx 30\ \mu s$ $E_\gamma \approx 8.0$ MeV

Neutrino Background

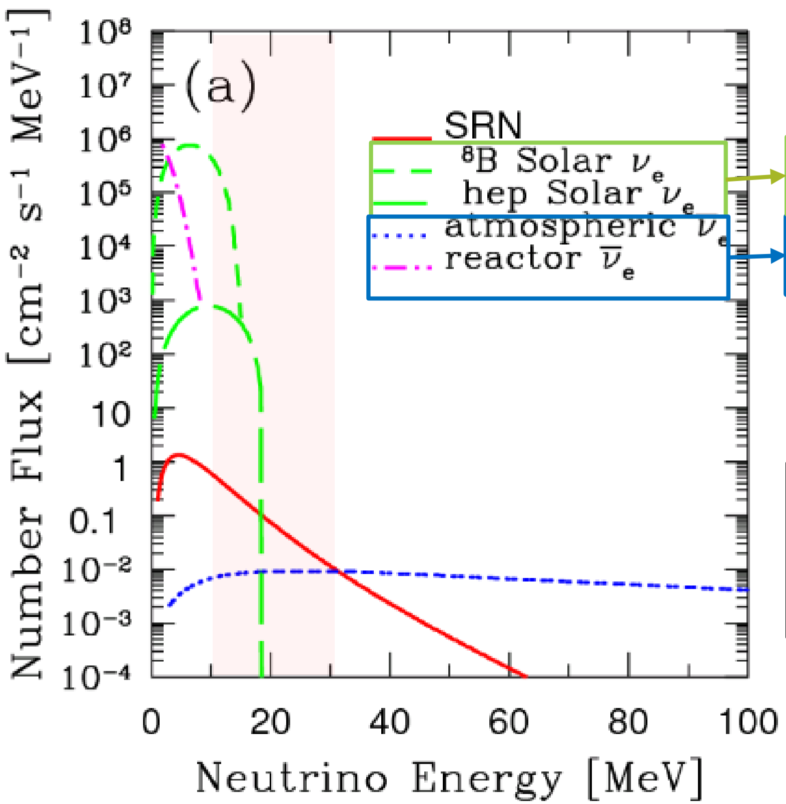


Figure 1.3 The expected neutrino sources at SK site[19].

Solar angle cut

Irreducible

This bkg can be removed by **neutron tagging** (which is simple for many materials but difficult for pure water…)

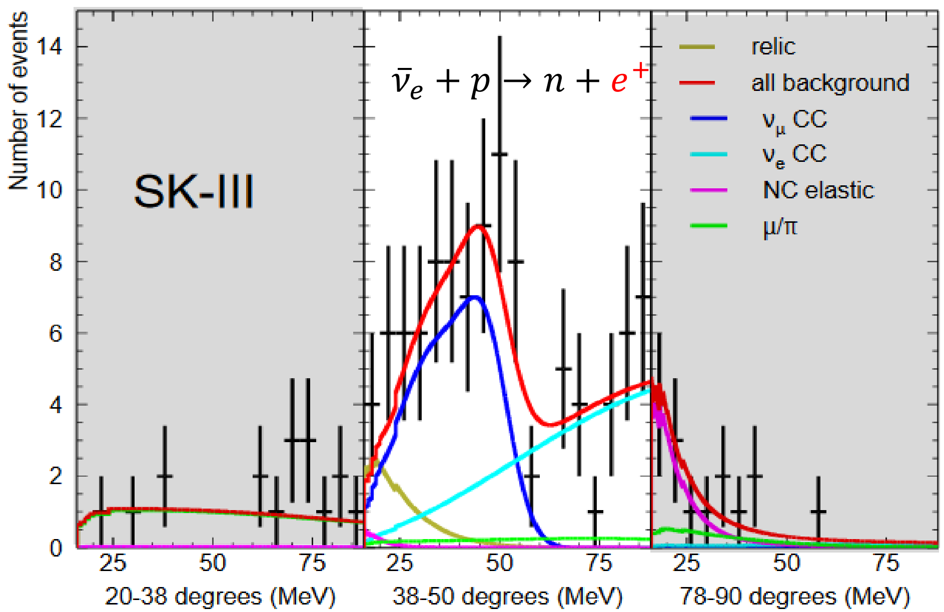
Atmospheric neutrino dominate the bkg for $E > 30$ MeV

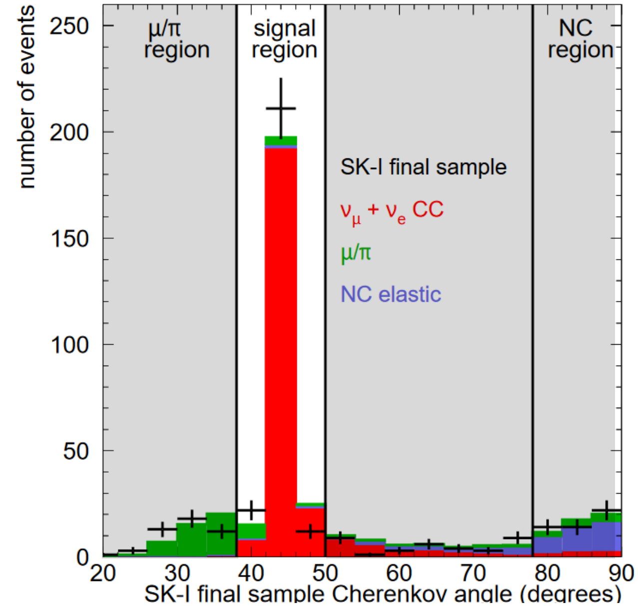
Reactor neutrino dominate the bkg for $E < 10$ MeV

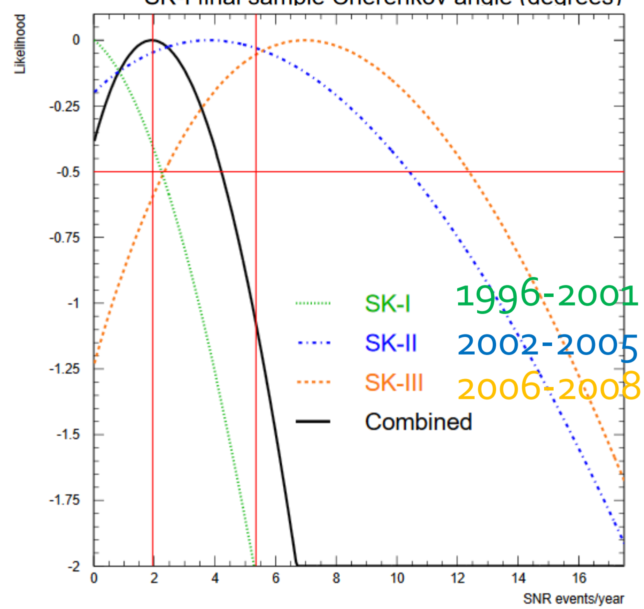
Non-neutrino bkg discussed in following slides.

Golden Energy Window: 10~30 MeV

Method 1
Spectrum Analysis







- 16MeV(Spallation)~85MeV(Atmospheric)
- N/C removed by Cerenkov cut

SK1~Sk3 combined best fit: 2 events/year

Method 1 Spectrum Analysis Constrain on SRN Model

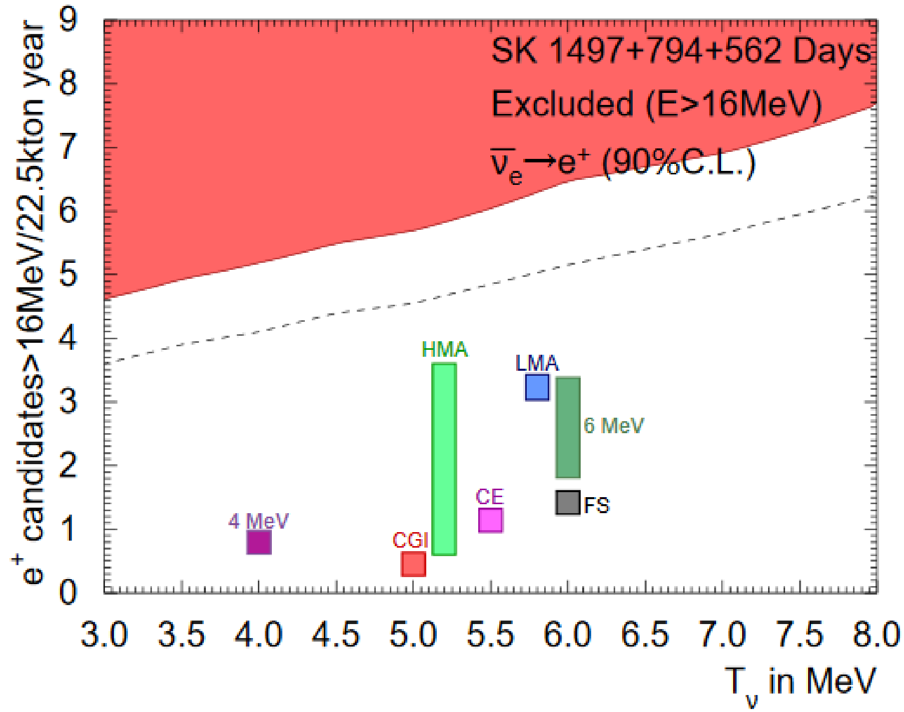
$$\frac{d\phi}{dE_\nu}(E_\nu) = \int_0^\infty \left[(1+z)\varphi[E_\nu(1+z)]\right]\left[R_{SN}(z)\right]\left[\left|\frac{c\,dt}{dz}\right|dz\right] \qquad R_{SN} \simeq \frac{R_{SF}(z)}{143 M_\odot}$$

$$\varphi(E_\nu) = E_{\bar{\nu}_e,tot}\frac{120}{7\pi^4}\frac{E_\nu^2}{T^4}\frac{1}{e^{E_\nu/T}+1}$$

2 free parameters:

- ☐ Neutrino temperature
- ☐ Average luminosity

CGI: Cosmic Gas Infall
HMA: Heavy Metal Abundance
CE: Chemical Evolution
FS: Failed Supernova
4/6 MeV: neutrino temperature



Method 2: Neutron Tagging

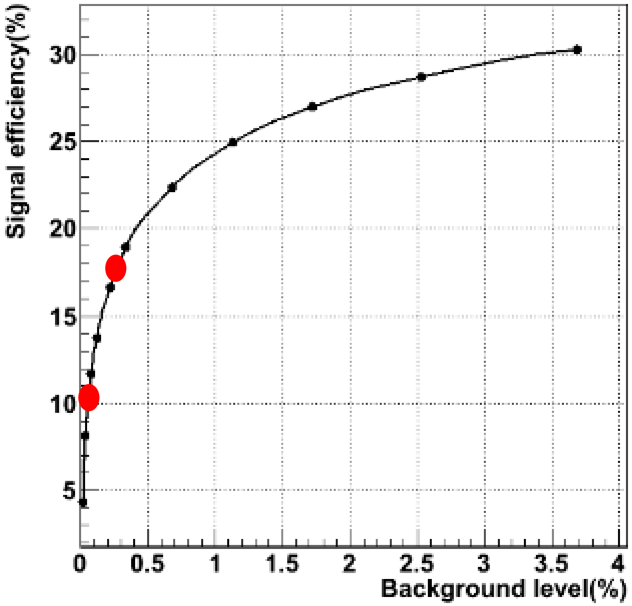
SK4 employed QBEE to lower the hardware trigger threshold, enabling neutron tagging.

Pretty difficult for water due to the low light yield.

Tagging Efficiency:

$E_\nu < 14.3$ MeV $\sim 10\%$

$E_\nu > 14.3$ MeV $\sim 18\%$



- Neutron Capture

$$n + p \rightarrow He + \gamma$$

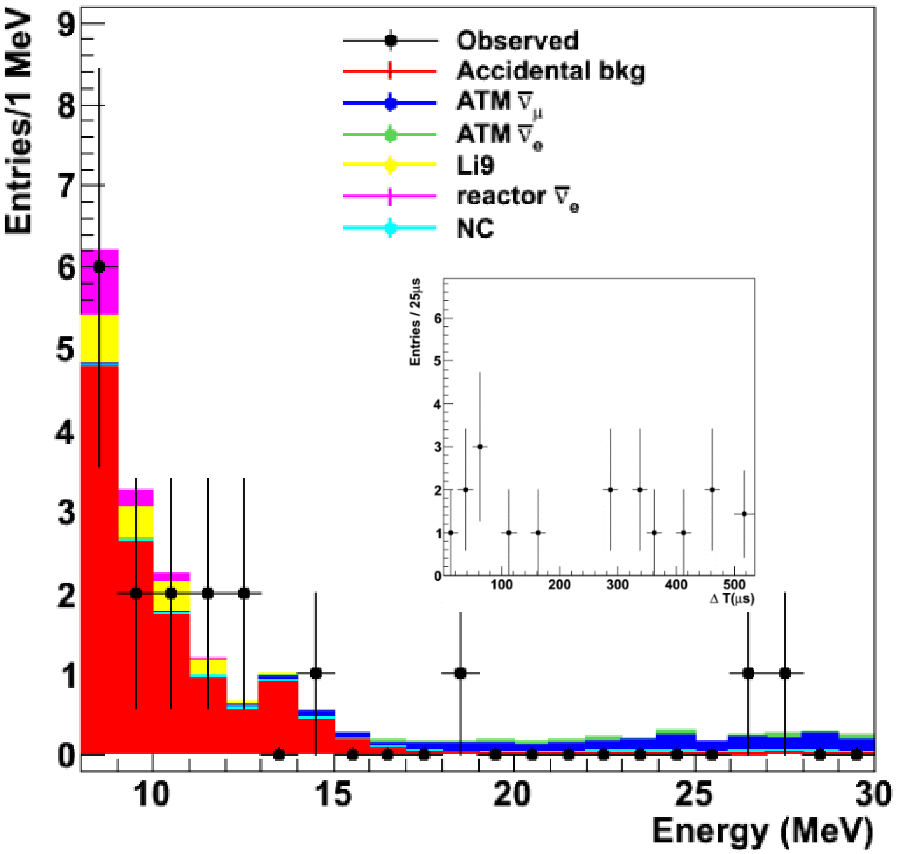
☐ **H Capture** $\tau \approx 200\ \mu s$ $E_\gamma = 2.2$ MeV

Method 2: Neutron Tagging

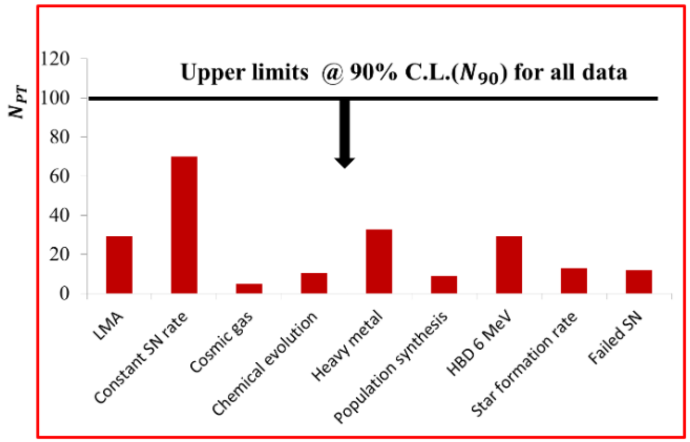
Spallation induced accidental bkg reduced by 4 orders of magnitude, expanding the energy range to < 10 MeV.

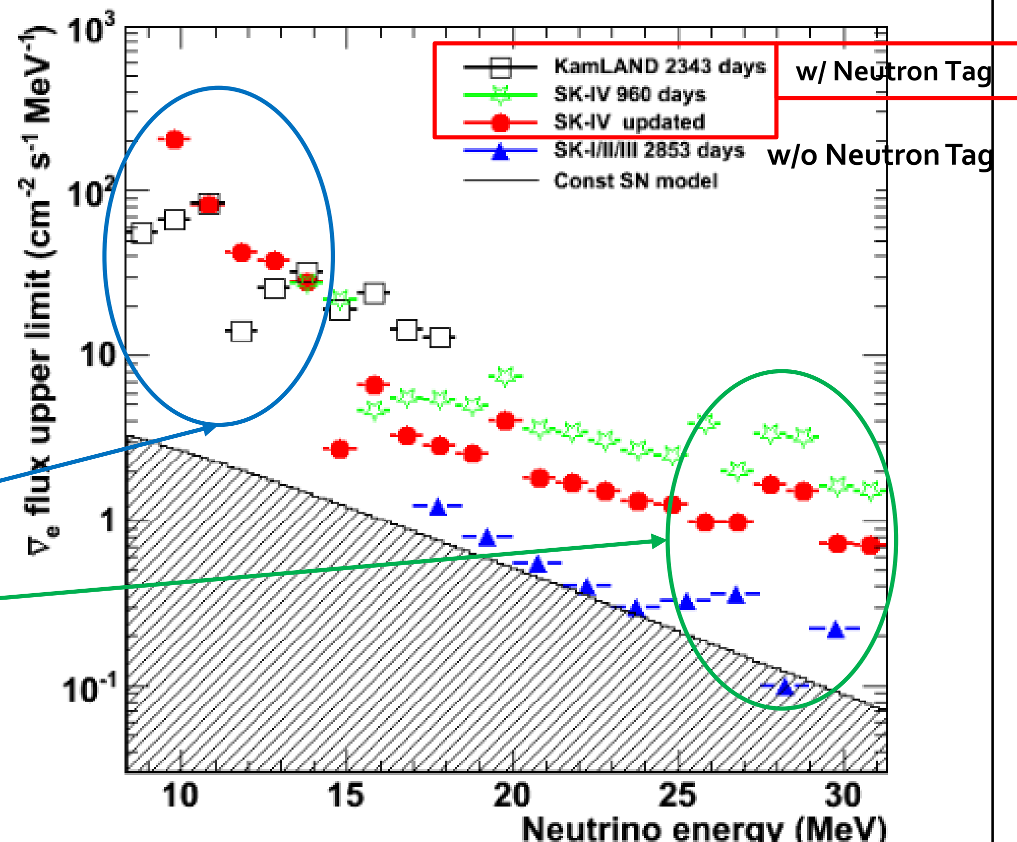
Exclude the possible SRN candidates in spectrum analysis for the vacancy of neutron.

Low efficiency → Low Statistics → Unable to lower the upper limit for SRN.



Method 2 Neutron Tagging Constrain on SRN Model





Accidental dominant

Atmosphere dominant

- No significant signal observed.

Future Analysis before SK-Gd

- Combined spectrum analysis for SK 1-4
  - doubled statistics
- Neutron tagging optimizing
- Data selection optimizing
  - Spallation analysis

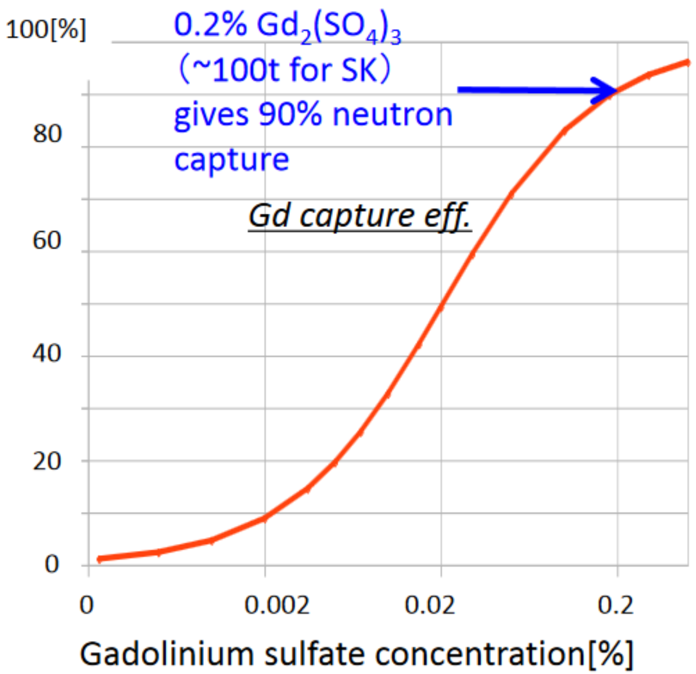
SuperK-Gd Project

Approved!
2015/11

Large photon energy from neutron capture →Higher neutron tagging efficiency (10% → 90%)

Shorter lifetime → Further discrimination between bkg and correlated $e^+ + \gamma' s$ signal.

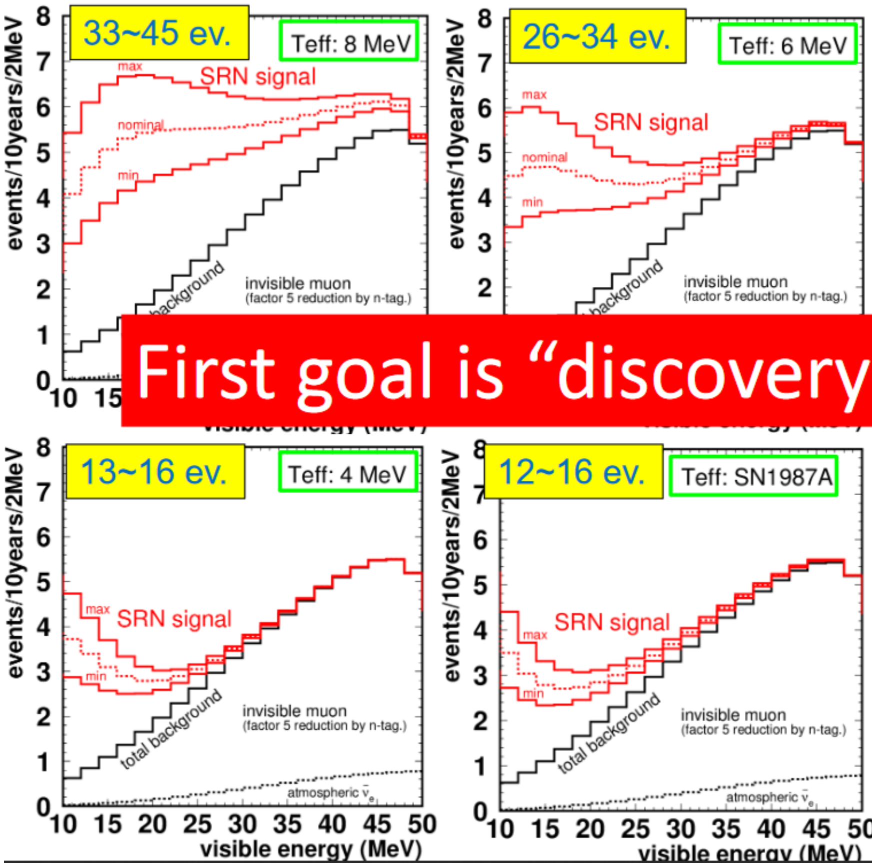
Expected time of refurbishment
2018



- Neutron Capture
  $n + Gd \rightarrow Gd + \gamma' s$ □ Gd Capture $\tau \approx 30\ \mu s$ $E_\gamma \approx 8.0$ MeV

Expected Signal & Bkg

SRN: Expected signal and background in SK-Gd 10yr



Expect number of events in 10 years in E_{total} =10-30 MeV

Assuming

Capture efficiency of 90% and Gd gamma ... of ... is 35% of the SK-IV invisible muon BG.

Min/nominal/Max are due to uncertainties in astronomy.

Background: ~18 ev.

SRN flux from Horiuchi et al. PRD, 79, 083013 (2009)

13

First goal is "discovery" of SRN

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@JPARC

More than 5σ of discovery for HBD 6 MeV within 10 yr (2028).

Conclusion

- Real-time Monitor
  - pointing accuracy 3.1~3.8° at 68.2% coverage for the Wilson model at 10 kpc.
- SRN
  - upperlimit has not touched most of the predictions yet
  - main bkg for Super-K is spallation induced accidental
- SuperK-Gd
  - much higher neutron tagging efficiency
  - significant improvement expected (discovery???)

Paper List

- Real-Time Supernova Neutrino Burst Monitor at Super-Kamiokande,
  The Super-Kamiokande Collaboration,
  arXiv: 1601.04778
- Supernova Relic Neutrino Search with Neutron Tagging at Super-Kamiokande-IV,
  The Super-Kamiokande Collaboration,
  Astropart. Phys. 60, 41 (2015), arXiv:1311.3738
- Supernova relic neutrino search at super-Kamiokande.
  The Super-Kamiokande Collaboration,
  Phys. Rev. D 85, 052007 (2012)
- Search for Supernova Neutrino Bursts at Super-Kamiokande
  The Super-Kamiokande Collaboration, Astrophys J. 669 (2007) 519,
  astro-ph/arxiv:0706.2283
- Search for Supernova Relic Neutrinos at Super-Kamiokande
  The Super-Kamiokande collaboration,
  Phys. Rev. Lett 90, 061101 (2003); hep-ex/0209028

Discussion on JUNO

- Large statistics:
  - 20 kT (17 kT FV)
- Energy & vertex resolution:
  - High light yield scintillator & coverage & QE & long attenuation length
- Accidental suppression:
  - Neutron tagging
- Atmosphere NC separation:
  - …PSD? (How to distinguish the neutron faked prompt signal?)
- Expand energy range:
  - No (reactor neutrino background below ~10 MeV)
- Burst supernova direction
  - 9° ? (vertex reconstruction for e^+ & γ)