Supernova neutrino searches in Super-Kamiokande

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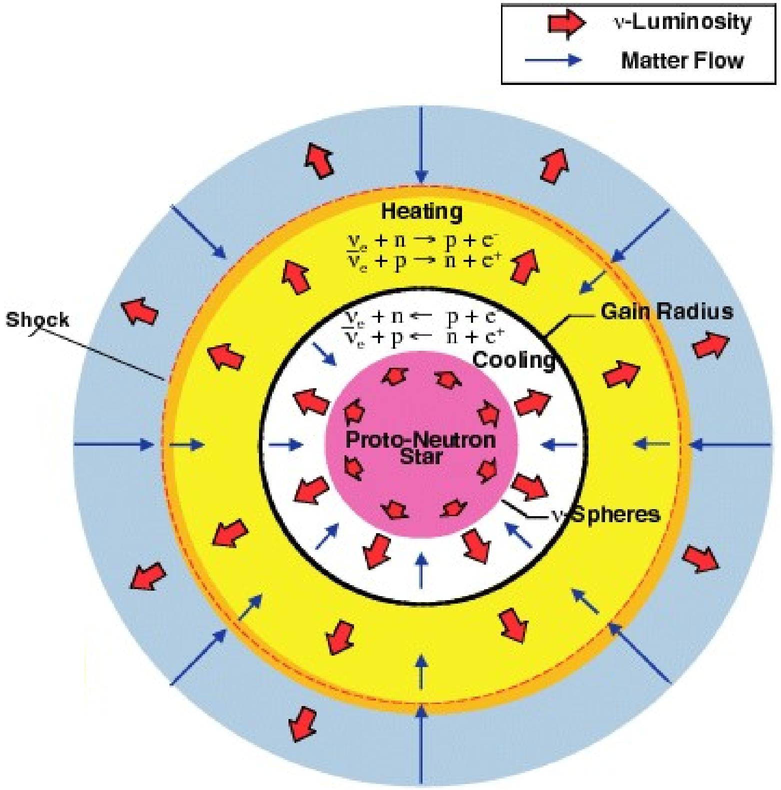
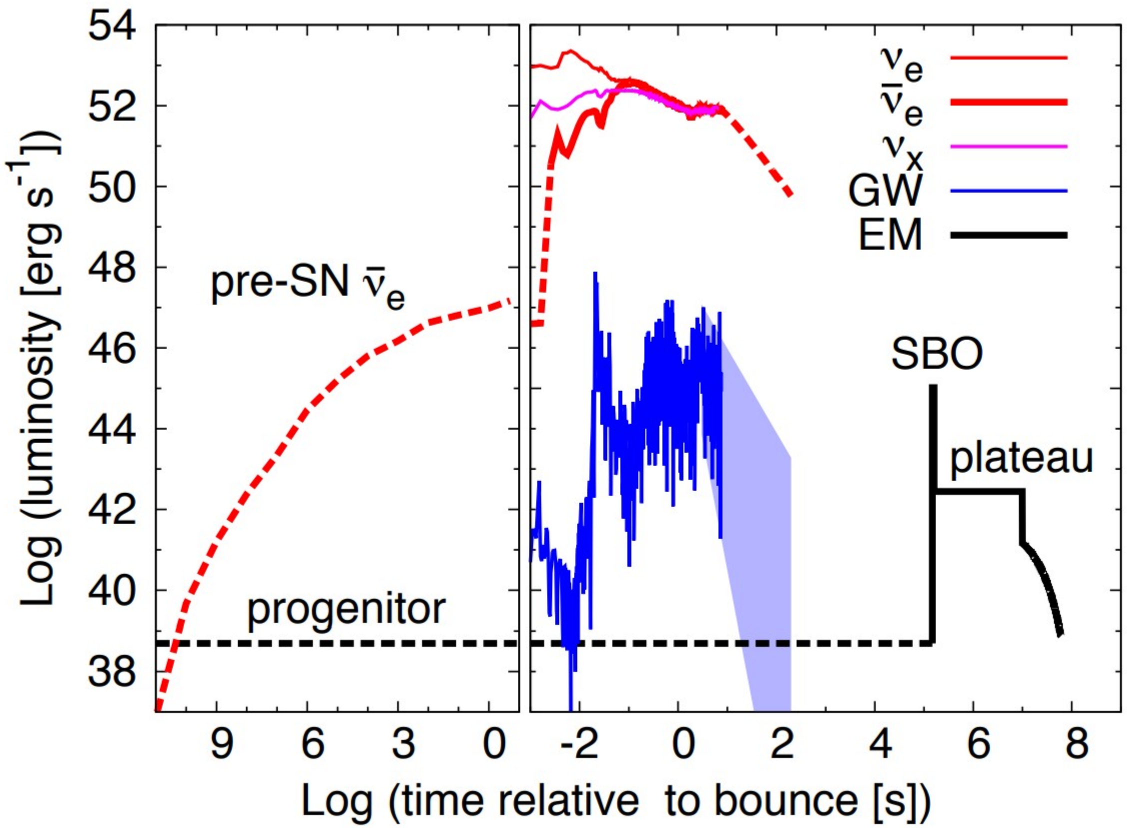
Introduction

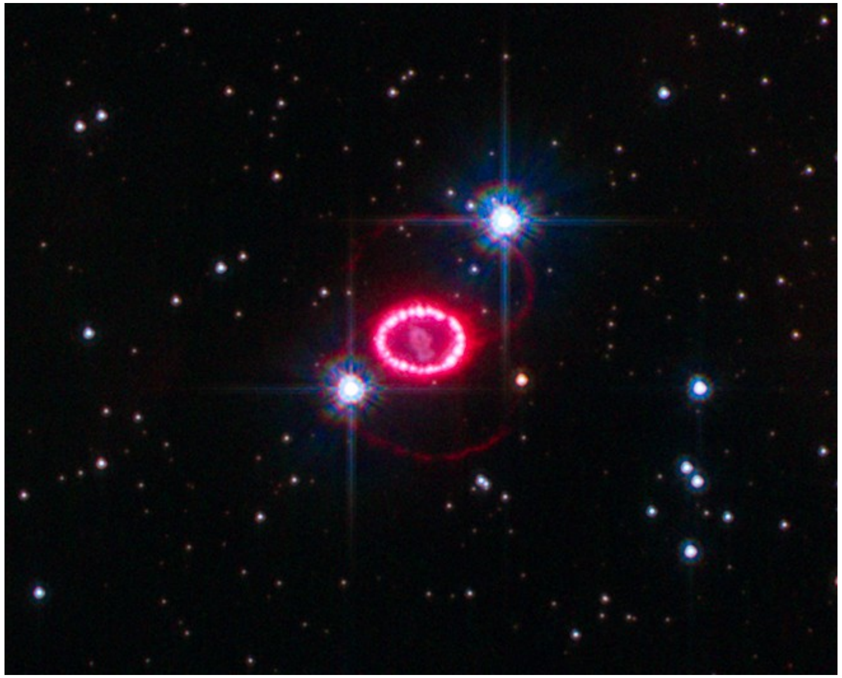
Core-Collapse Supernovae



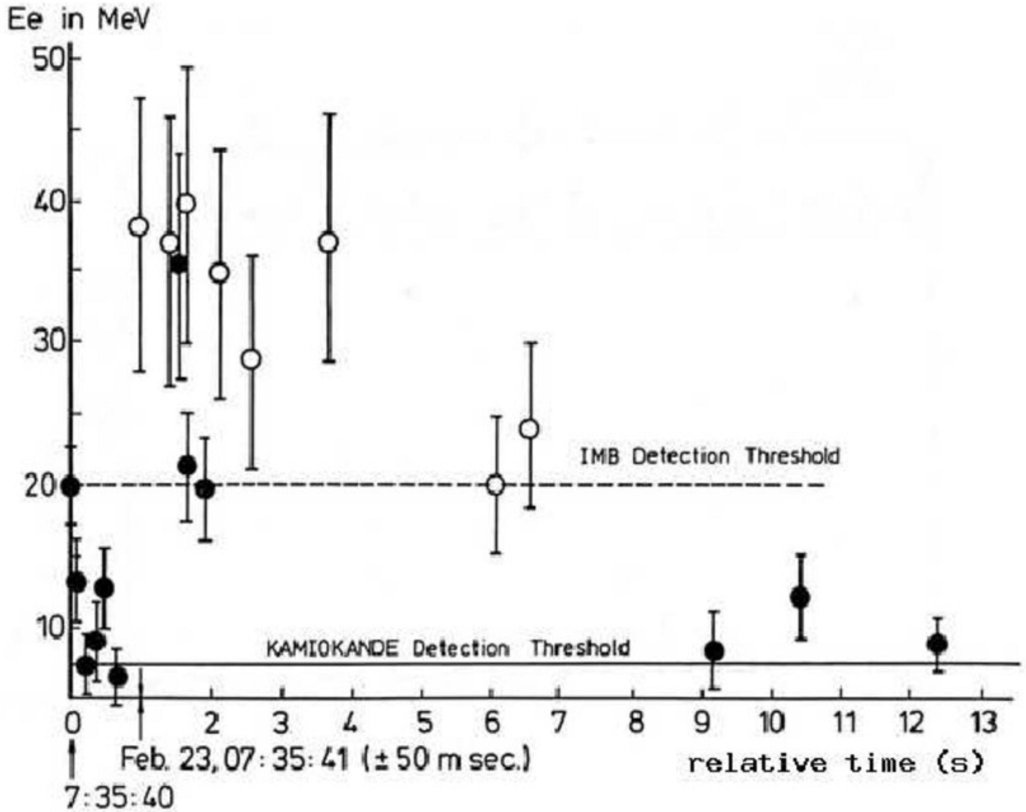


- Massive stars (8+ $M_\odot$) can end their life as core-collapse supernovae (or Type II SN), a cataclysmic implosion giving birth to a neutron stars or a black hole (failed supernova).
- 99% of the Core-Collapse Supernova's energy is released through neutrino

Core-Collapse Supernova Neutrinos



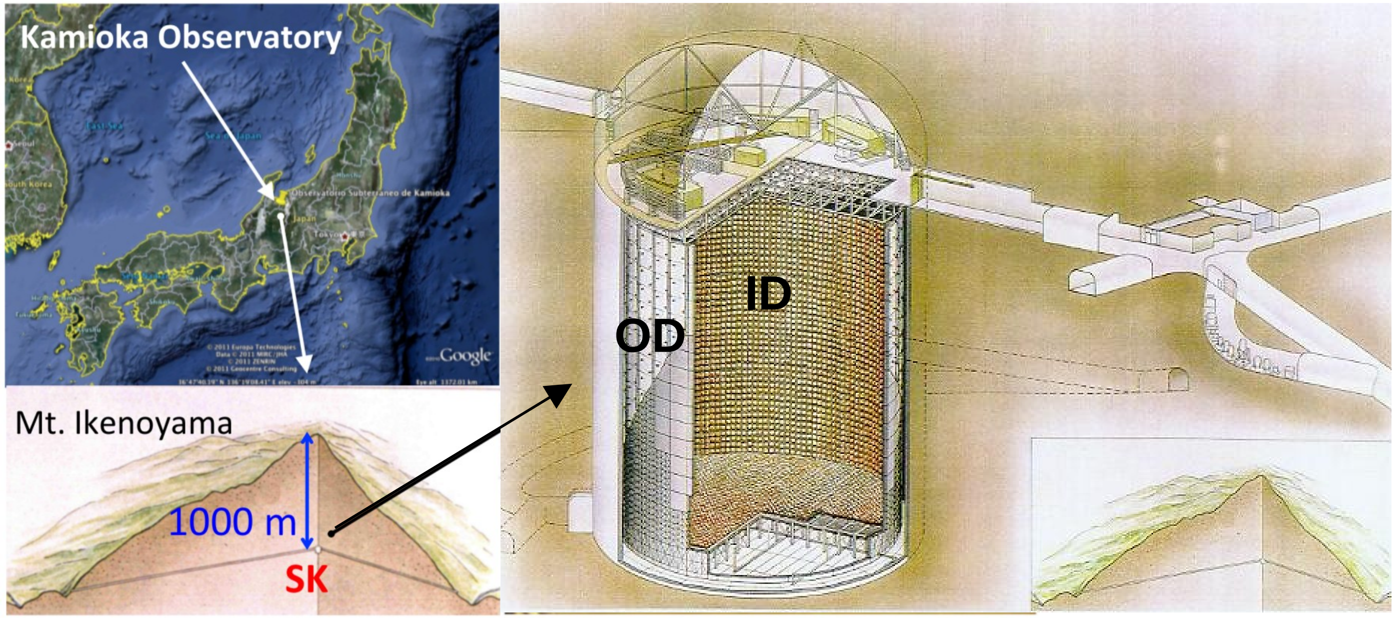
SN1987A remnant



- SN1987A is so far the only supernova (SN) for which neutrinos were detected (by Kamiokande-II, IMB, and Baksan), this demonstrated the production of neutrino during core-collapse supernovae and trigger the wait for the next one.
- In Super-Kamiokande, we are looking forward the next core-collapse supernova, but are also looking for other neutrinos linked to supernovae.

Super-Kamiokande

- **World leading** Water Cherenkov detector located in the Kamioka Mine (Japan)

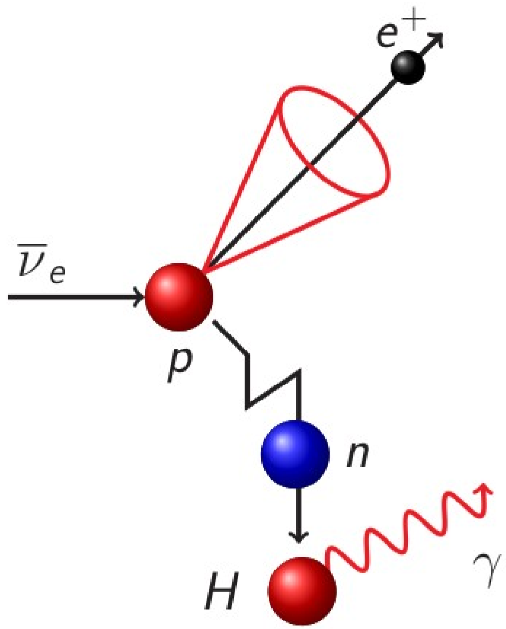


- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-VII is running

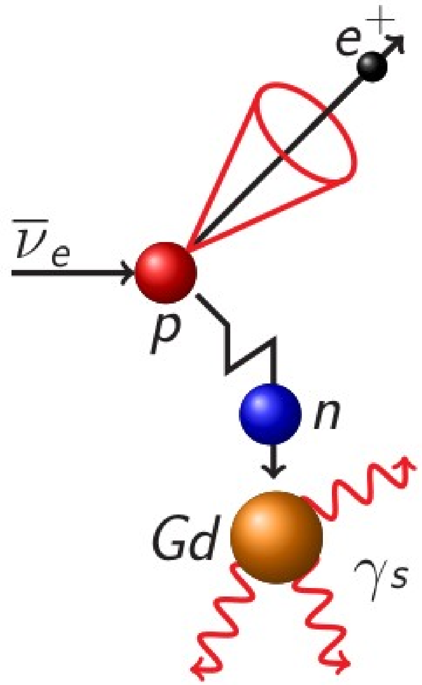
- The detector is filled with 50ktons of **gadolinium**-loaded water.
- Gadolinium was loaded at 0.01% in the water in Summer 2020, and the concentration was further increased to 0.03% in May 2022. Calibration was completed and the detector is running stably since then.
- **Physics targets**: Neutrino Oscillations (Solar Neutrino, Atmospheric Neutrinos, T2K beam), Nucleon decay, Astrophysics (**Supernova burst**, Diffuse Supernova Neutrino Background, etc.)

Why Gadolinium?

- Gadolinium is the **stable nucleus with the highest neutron capture cross-section** on Earth. The gadolinium-neutron capture produced a gamma cascade with a total energy of ~8 MeV, allowing to detect and reconstruct the neutron capture.
- This is specially useful to tag Inverse Beta Decay interactions



Hydrogen-neutron capture:
single 2.2 MeV gamma
→ Large accidental background
→ Vertex reconstruction difficult



Gadolinium-neutron capture:
Gamma cascade at ~8 MeV
→ Lower background
→ Vertex reconstruction possible

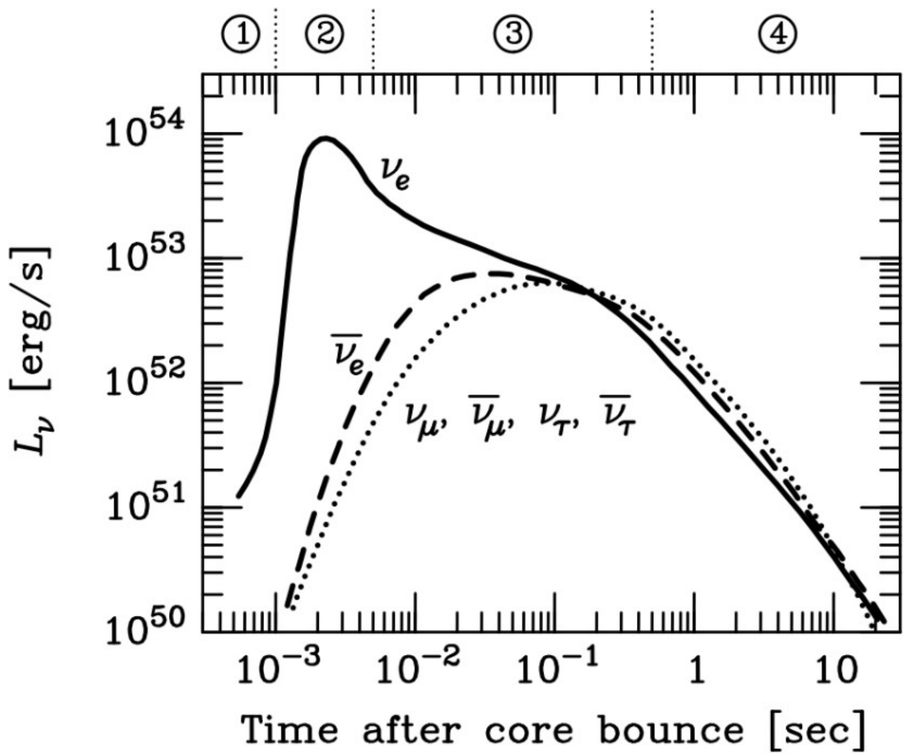
Core-Collapse Supernova neutrinos

References:

- G. Pronost, Neutrino 2024 Supernova monitoring poster
- Y. Kashiwagi et al. (SK collaboration), accepted at ApJ

Core-Collapse Supernova Burst

- After the finishing burning its fuel, massive stars can collapse on themselves, as the heat pressure is not enough to compensate the gravitionnal force.
  - Higher energy gamma rays are produced, decomposing the Fe nuclei into He and free neutrons through photo-disintegration.
  - High matter density triggers a **neutronization** process, producing ν_e through electron-capture on protons (1)
  - High density of ν_e leads ν_e to have continuous interactions with e^- (2)
    $\rightarrow$ Build up of a degenerate ν sea, producing all 6 flavors of ν and $\bar{\nu}$

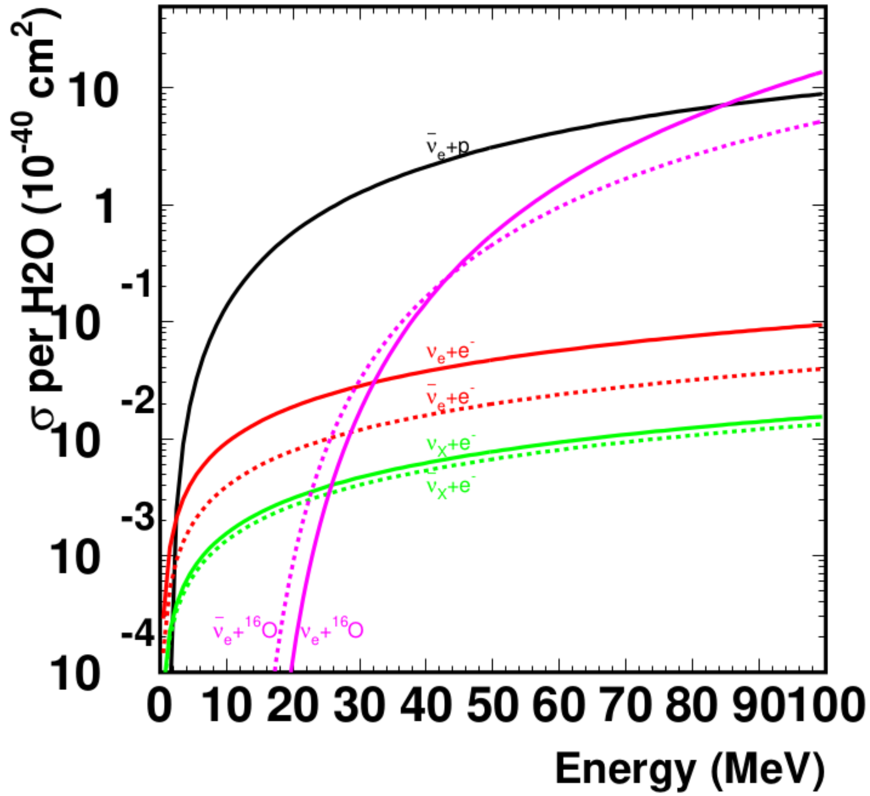


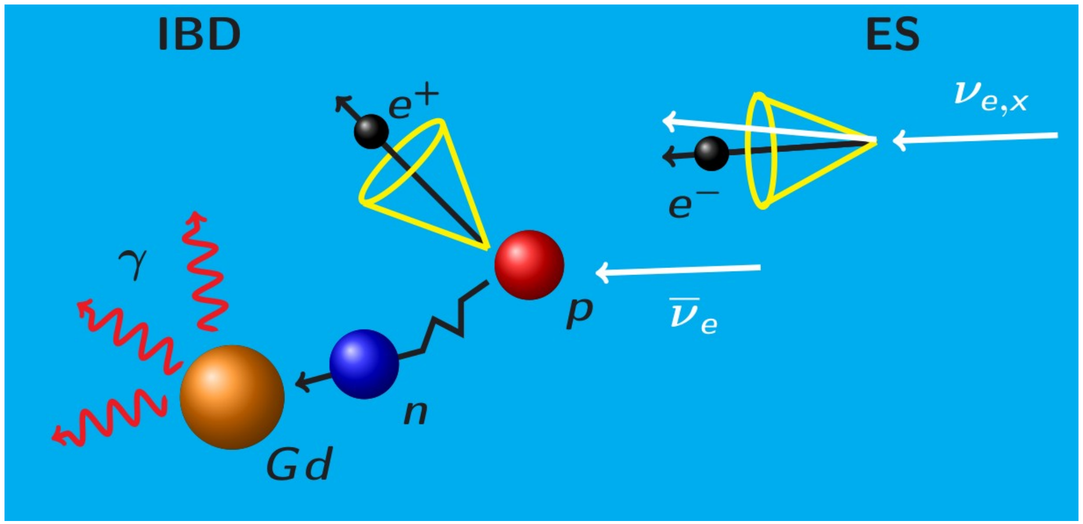
Supernova Neutrinos in Water Cherenkov Detectors

- Even if all neutrino and antineutrinos flavours are produced during the core-collapse supernova, due to interaction cross-sections, we are sensitive only to a few of them.
- In case of Water Cherenkov detector, the main interactions expected are:
  - ▷ **Inverse Beta Decay reaction** (IBD)
    → ~90% of the interactions
  - ▷ **Electron Scattering interactions** (ES)
    → ~5% of the interactions

Keep the neutrino direction information

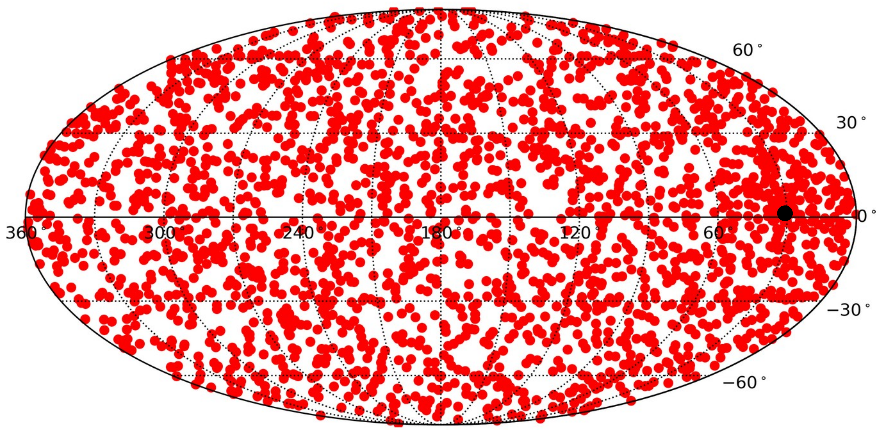
- ▷ ^{16}O interactions (CC and NC)
  → ~5% of the interactions



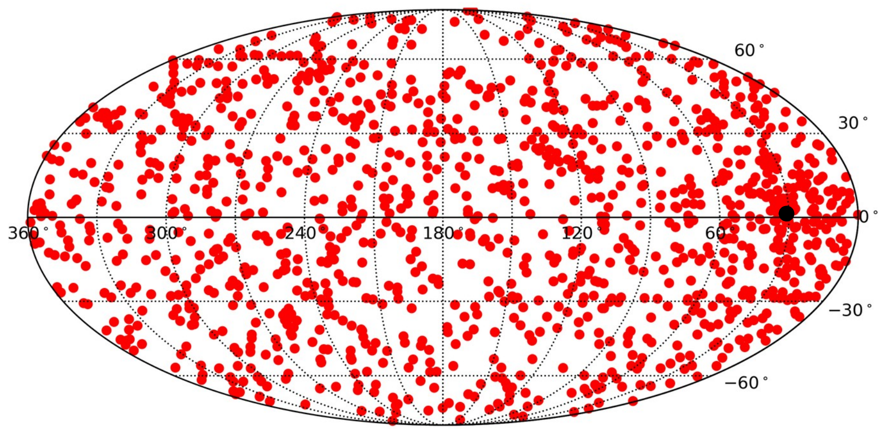


Using Gd-n to separate IBD and ES

- Water cherenkov detector can **extract the direction** of the SN from the ES interactions
  - **Separating ES** from **IBD** allows to **improve** the **SN direction pointing** accuracy of the detector
  - We can use the characteristic **delayed coincidence** between the IBD's positron emission and delayed neutron capture to **tag IBD events**.
    $\rightarrow$ Gd enhance the detectability of the neutron capture.



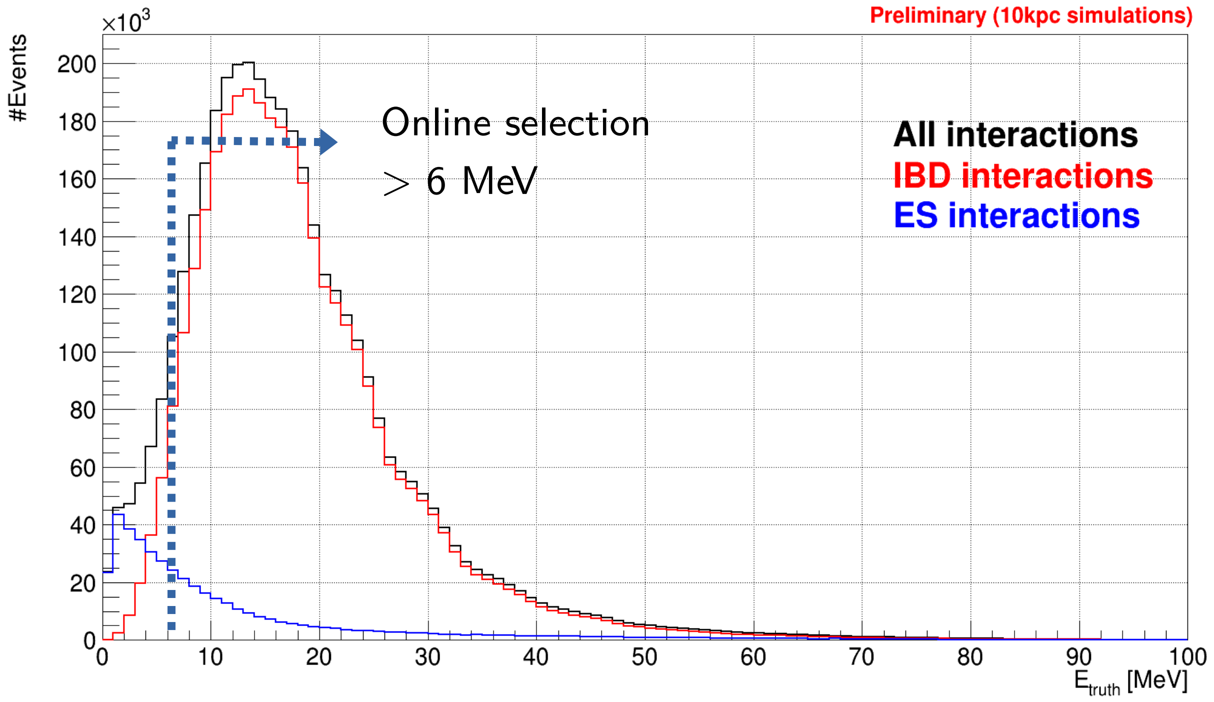
SN burst events w/o IBD tagging
(10kpc simulation w/o Gd)



SN burst events w/ 49.7% IBD events tagged/removed
(10kpc simulation with 0.03% Gd)

Realtime analysis

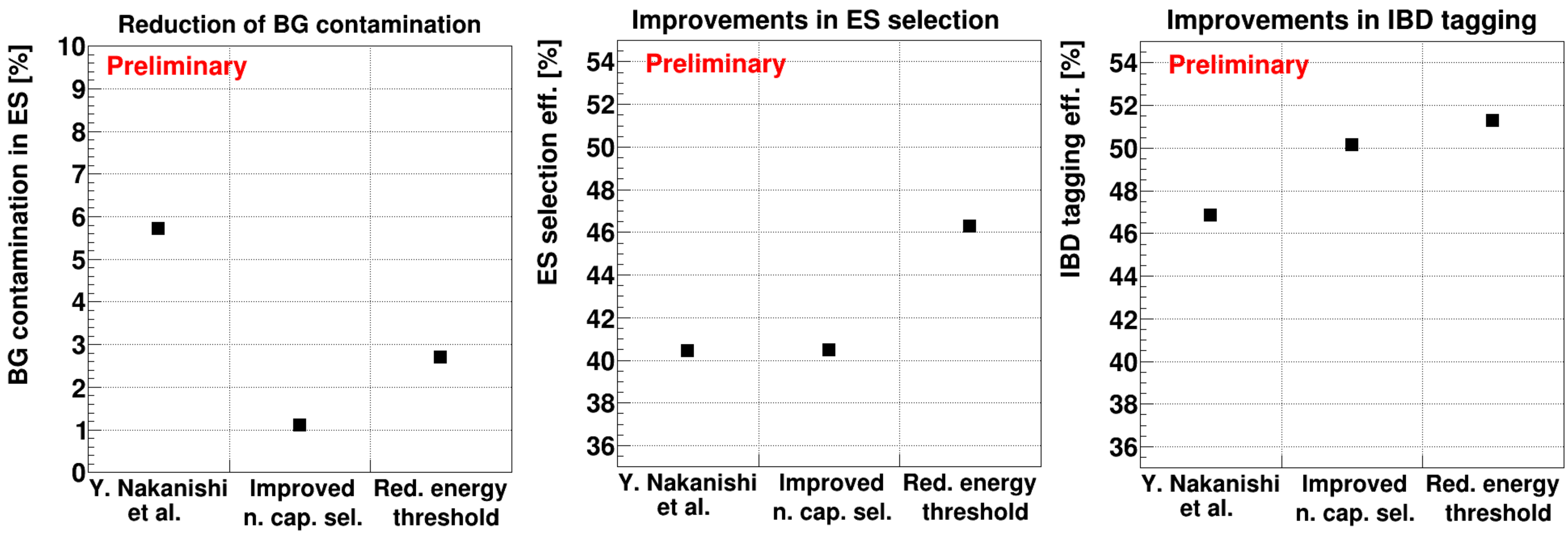
- The SN burst monitoring analysis is a **cut based online** analysis.
  Hard cuts are applied to remove any potential noise, leading to lower efficiencies compared to the full potential of Super-Kamiokande. Offline (and slower) analysis reach better performances.



1000 MC simulations

Realtime analysis

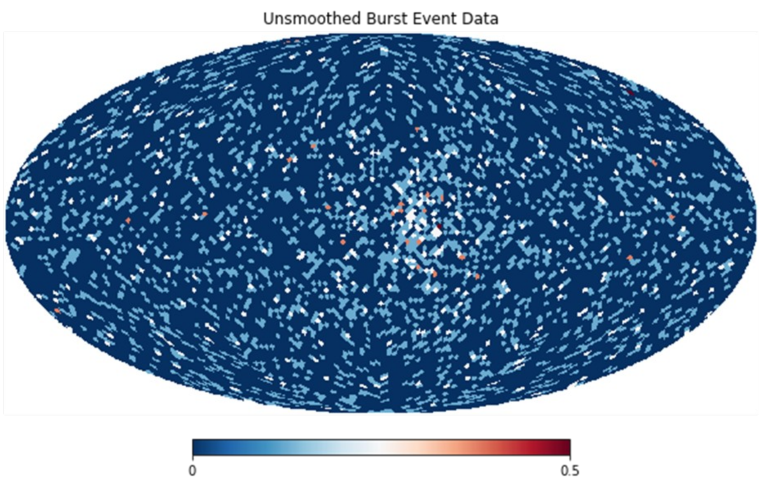
- Recent analysis improvements allowed to reduce the background contamination
- Realtime selection efficiencies (assuming Nakazato model, NMO):
  - ~45.5% of the ES interactions
  - ~91.2% of the IBD's positron interactions
  - ~56.3% of the IBD's neutron capture interactions (with 0.03% Gd)
    → ~**51.3% IBD interactions are tagged**



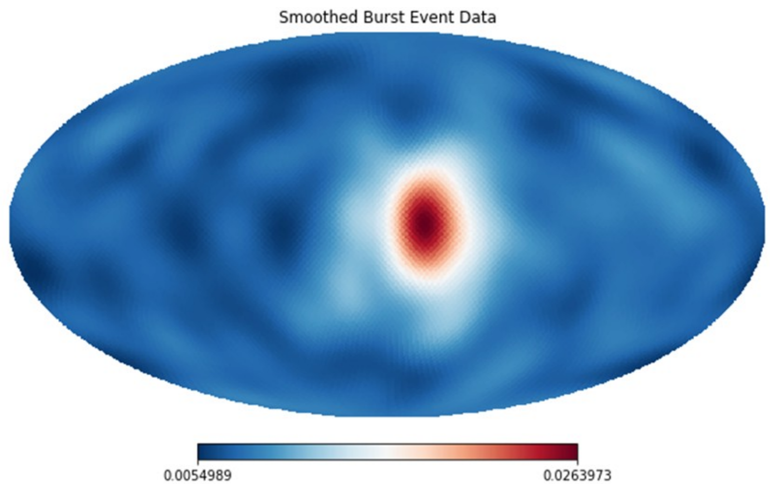
SN direction fitter improvement

- Last year (June 2023) we deployed a new fitter (Maximum Likelihood + HEALPix) to improve the speed and the efficiency of our Supernova direction reconstruction.
- **HEALPix** based fitter (**H**ierarchical **E**qual **A**rea iso**L**atitude **Pix**elation of a sphere):
  - A sphere of the sky is made and divided in pixels of equal area
  - The pixels are populated with the projection of each event's reconstructed direction on the sphere.
  - The sphere is then smoothed with a gaussian function
  - The pixel with the maximum number of events is then selected as the SN direction

Nside = 32, Npix = 12,288



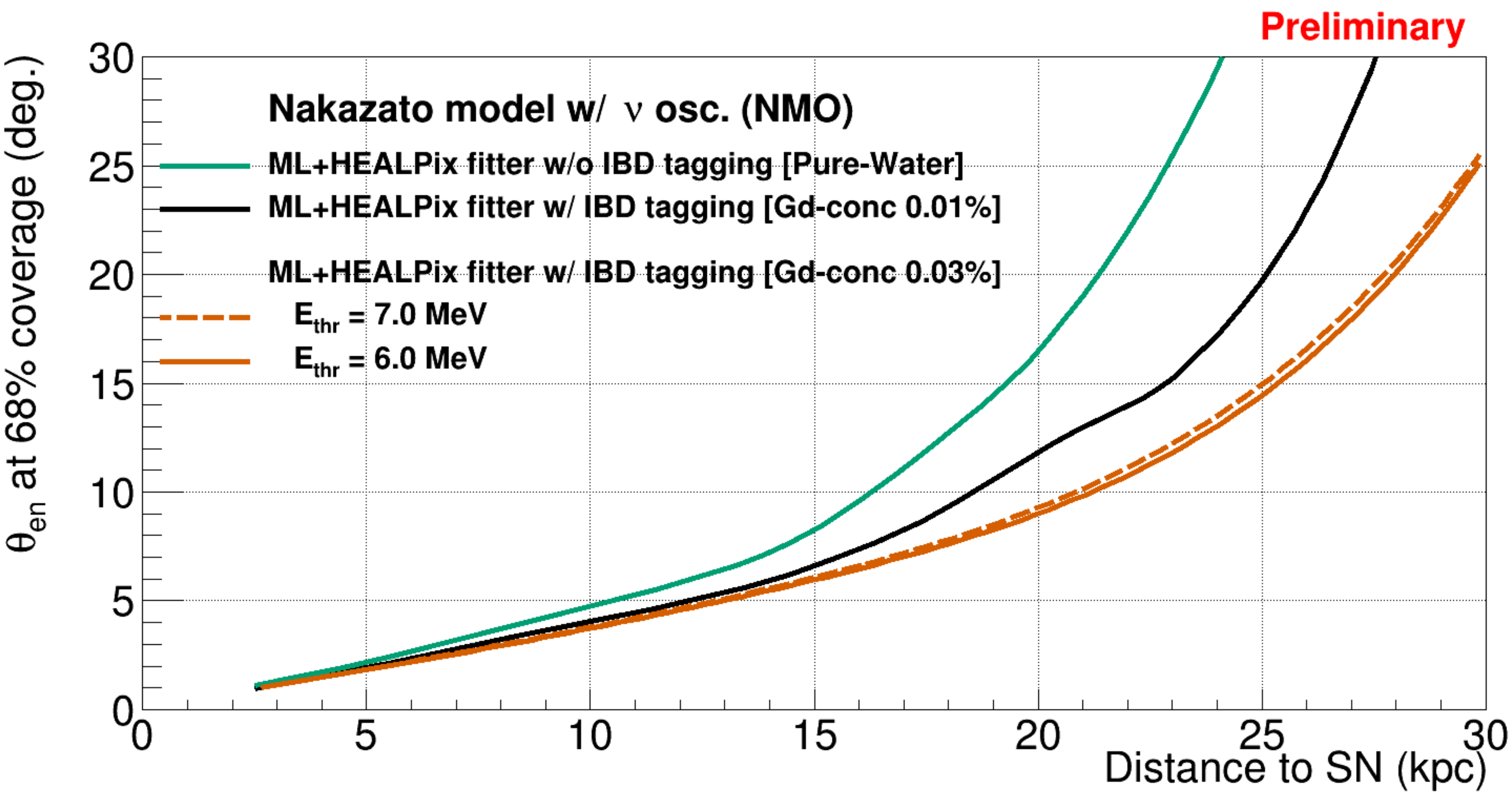
Gaussian Smoothed, $\sigma = 0.15$ rad.



 pronost@km.icrr.u-tokyo.ac.jp

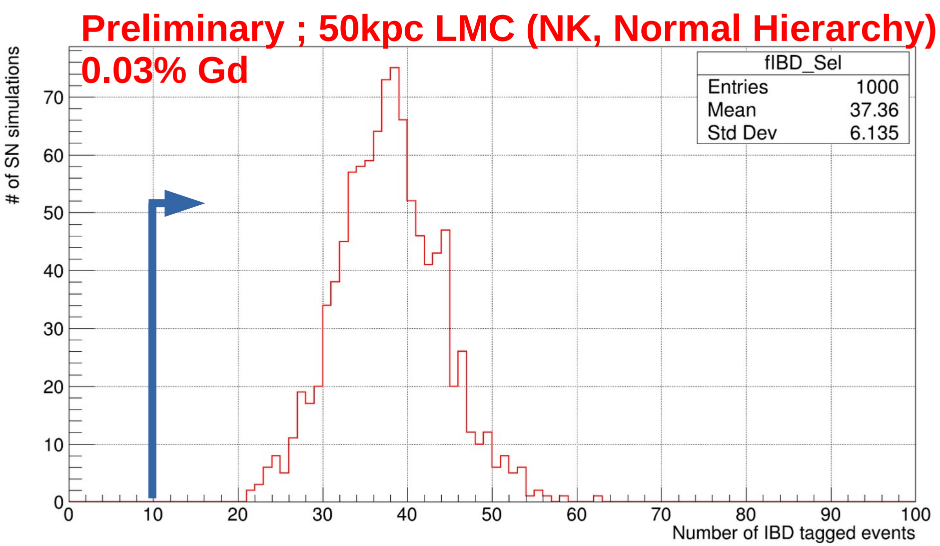
Realtime angular resolution

- This month (June 2023) we deployed a new fitter (Maximum Likelihood + HEALPix) to improve the speed and the efficiency of our Supernova direction reconstruction.
- With 0.03% Gd, our last realtime direction pointing accuracy is $3.68 \pm 0.04°$ at 10 kpc (Nakazato model, 6 MeV threshold). This reconstruction alone is achieved **in less than 10 seconds** (with respect to 1.5~2 minutes before).

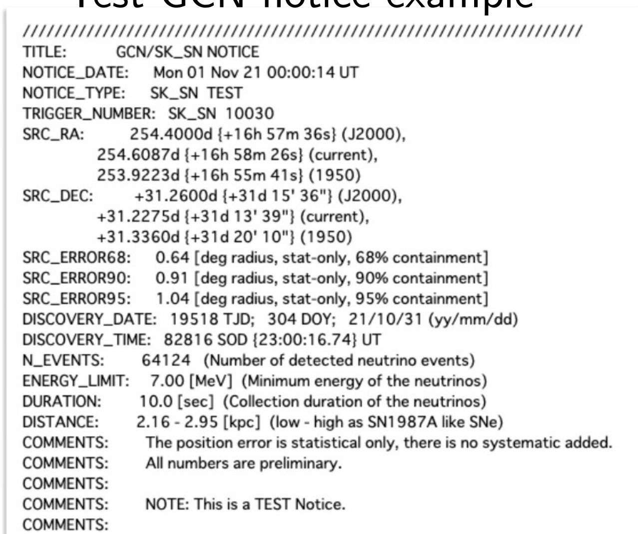


Automated SN alarm: GCN

- In case of a burst of events matching our criteria (isotropic distribution and more than 35 good events) Super-Kamiokande will send an alarm. Since December 13th 2021, this alarm is automated:
  - If the number of IBD tagged events is > 10, an automated **GCN notice** will be distributed.
  - This GCN notice is currently send by mail, which induces some delay to distribute it.
  - GCN itself has been upgraded ("Kafka") recently, with an unified schema, and a new distribution method which we are implementing. This upgrade will reduce the delay for the GCN notice distribution to less than 1 second.



Test GCN notice example

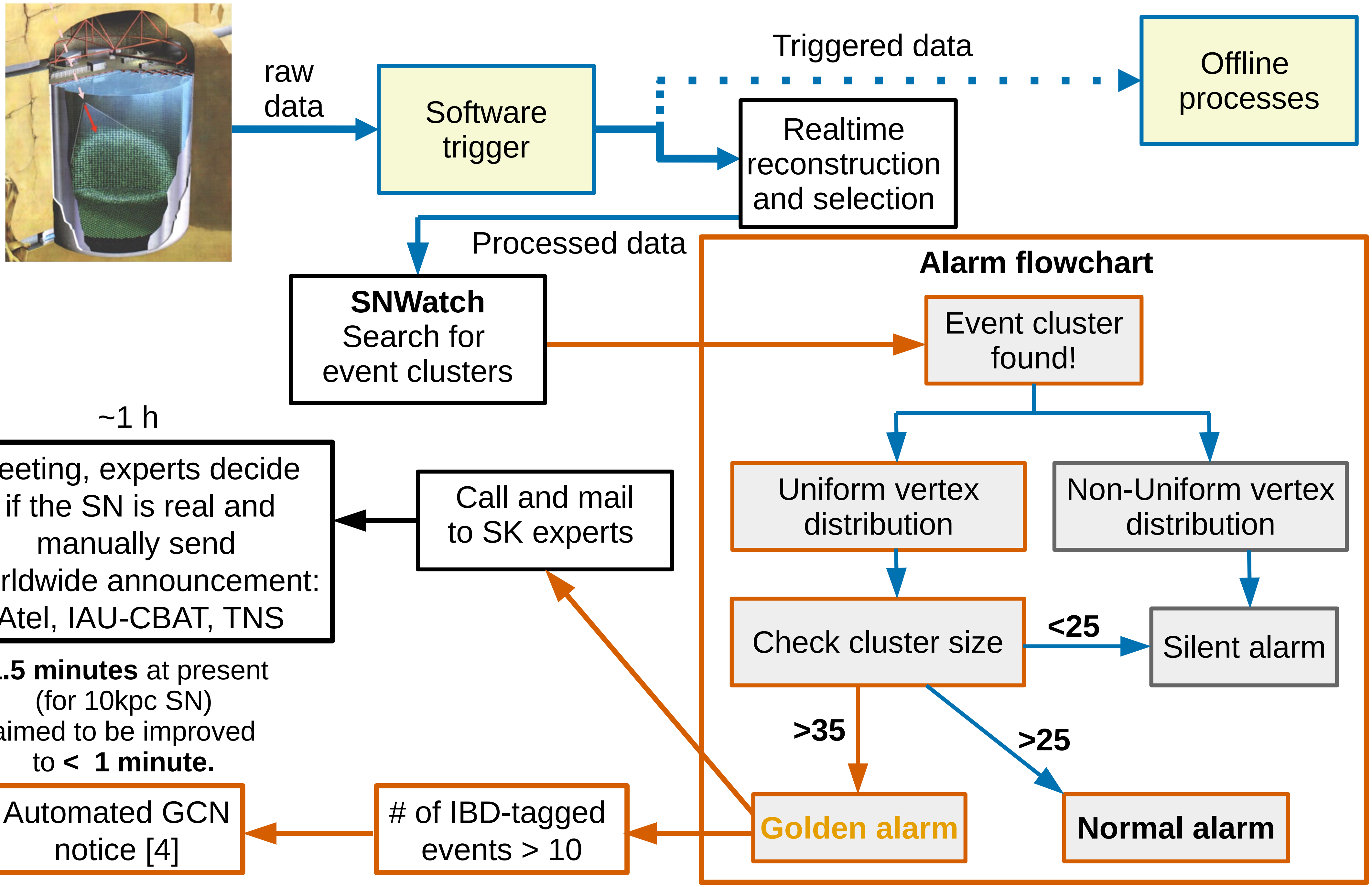


```
////////////////////////////////////////////////////////////////////
TITLE:           GCN/SK_SN NOTICE
NOTICE_DATE:     Mon 01 Nov 21 00:00:14 UT
NOTICE_TYPE:     SK_SN TEST
TRIGGER_NUMBER:  SK_SN 10030
SRC_RA:          254.4000d {+16h 57m 36s} (J2000),
                 254.6087d {+16h 58m 26s} (current),
                 253.9223d {+16h 55m 41s} (1950)
SRC_DEC:         +31.2600d {+31d 15' 36"} (J2000),
                 +31.2275d {+31d 13' 39"} (current),
                 +31.3360d {+31d 20' 10"} (1950)
SRC_ERROR68:     0.64 [deg radius, stat-only, 68% containment]
SRC_ERROR90:     0.91 [deg radius, stat-only, 90% containment]
SRC_ERROR95:     1.04 [deg radius, stat-only, 95% containment]
DISCOVERY_DATE:  19518 TJD;  304 DOY;  21/10/31 (yy/mm/dd)
DISCOVERY_TIME:  82816 SOD {23:00:16.74} UT
N_EVENTS:        64124  (Number of detected neutrino events)
ENERGY_LIMIT:    7.00 [MeV]  (Minimum energy of the neutrinos)
DURATION:        10.0 [sec]  (Collection duration of the neutrinos)
DISTANCE:        2.16 - 2.95 [kpc]  (low - high as SN1987A like SNe)
COMMENTS:        The position error is statistical only, there is no systematic added.
COMMENTS:        All numbers are preliminary.
COMMENTS:
COMMENTS:        NOTE: This is a TEST Notice.
COMMENTS:
```

Note: this structure will change with the unified schema

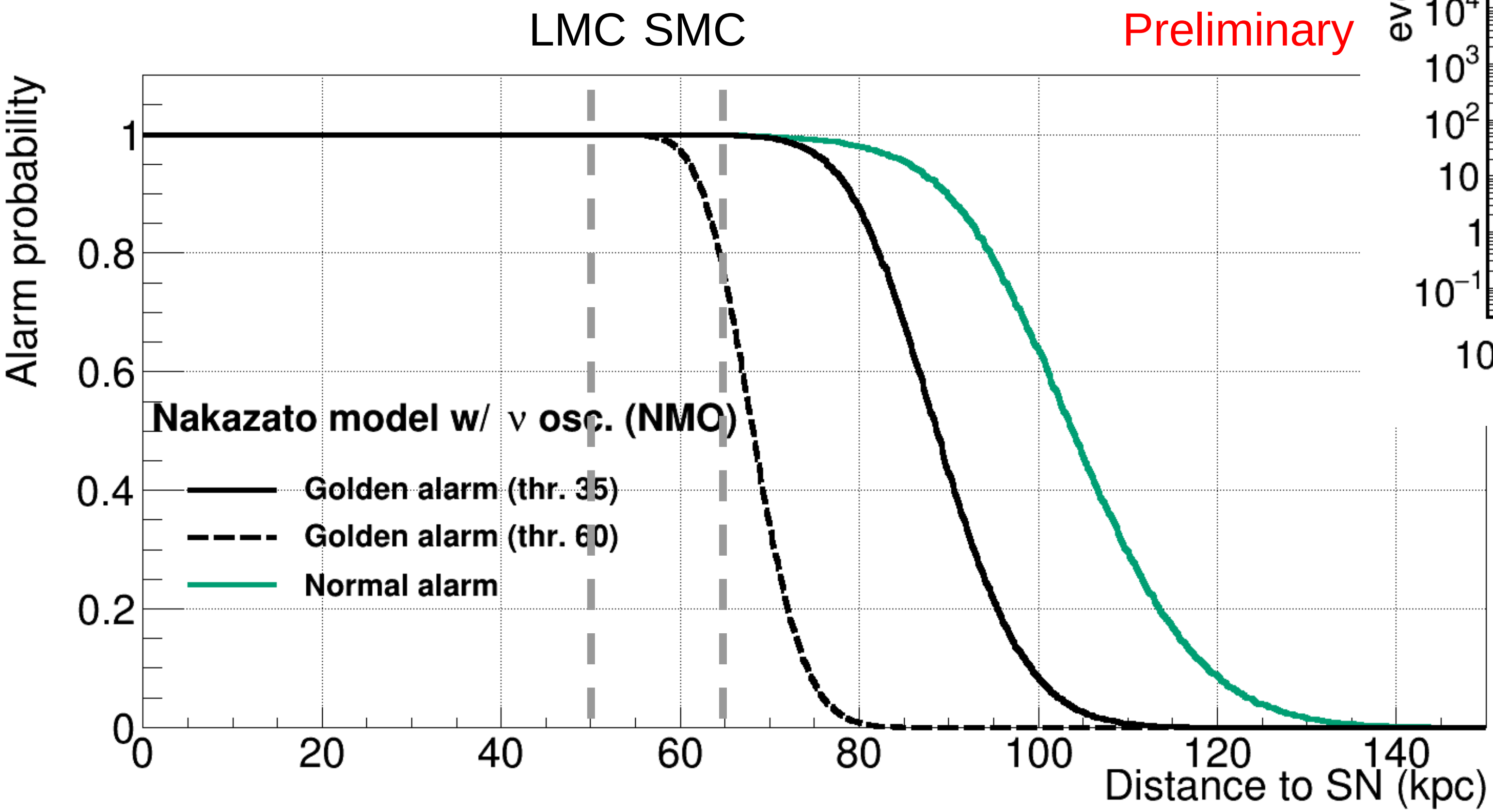
 pronost@km.icrr.u-tokyo.ac.jp

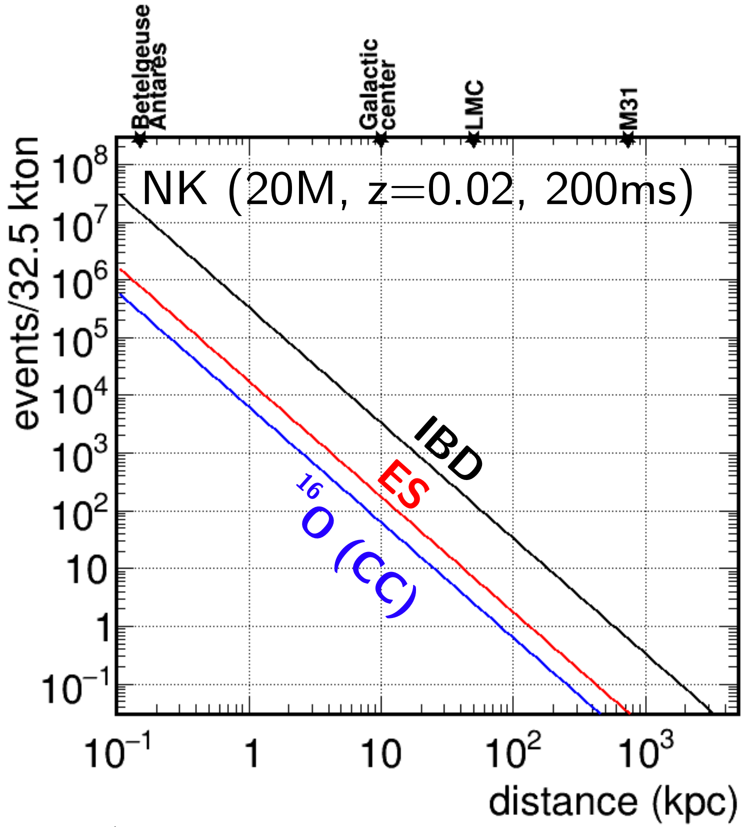
Realtime supernova monitoring in Super-Kamiokande



Supernova alarm in Super-Kamiokande

- In case of supernova, SK would detect a burst of events for SN happening up to >100kpc (depending on the models assumed), and send Golden alarms (automated) and Normal alarms (non-automated)
  - LMC is covered by Golden alarm
  - SMC is covered also now by Golden alarm ($\sim$99.81% probability @65kpc with thr. 35)





Co-operation with telescopes

- If (when) Super-Kamiokande send a supernova alarm to the world, we hope some telescopes will be able to look for it in order to observe the first instants of the supernova burst.
  - In order to increase the probability our alarm will be used, to maximise the change to have combined neutrino-optical observations of SN in the Milky Way, we are made a MoU with the **A**ll-**S**ky **A**utomated **S**urvey for **S**uper**N**ovae Collaboration (ASAS-SN), a network of 20 telescopes located around the globe
  - Discussion on-going with another telescope in Japan (Tomoe Gozen)

- If any other telescope collaborations or consortia are interested in making a direct, minimum latency connection with Super-Kamiokande's supernova alarm, please contact us!

Pre-Supernova neutrinos

References:

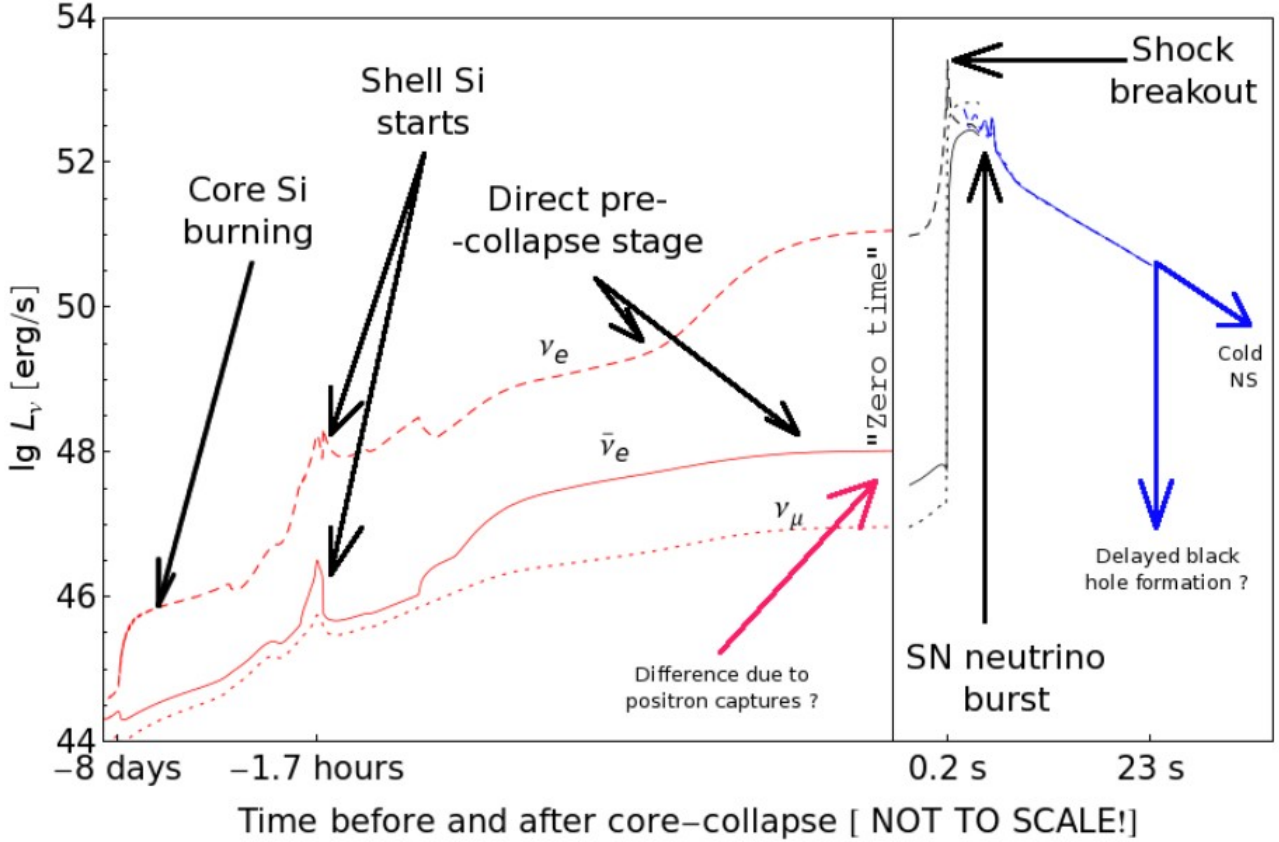
- L.N. Machado, Neutrino 2024 DSNB poster
- L.N. Machado et al. (SK collaboration), ApJ, Vol. 935, 1 (2022)

Pre-Supernova Neutrinos

- During the last stages of its life, massive stars burn their C, O, Ne, and Si layers. This burning produce a neutrino flux which can reach a luminosity of $\sim 10^{12}\ L_\odot$ (whereas the photon luminosity is $\sim 10^{5}\ L_\odot$)

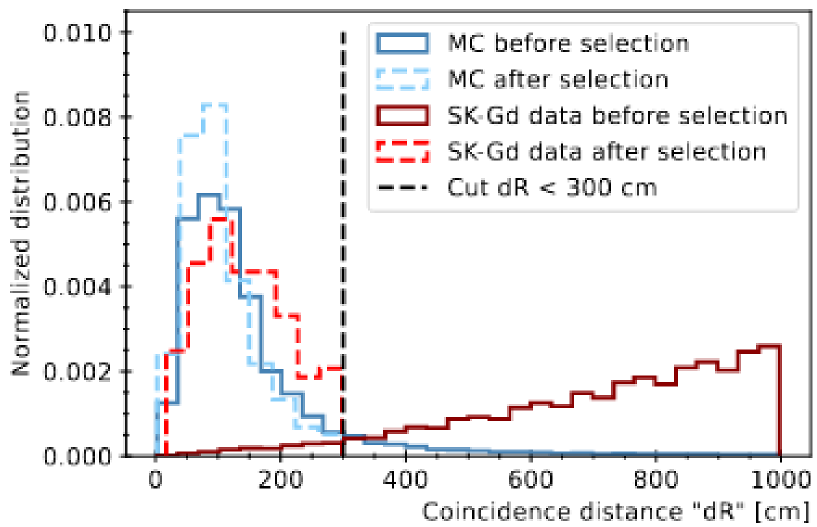
$$e^- + e^+ \rightarrow \nu_x + \overline{\nu}_x$$

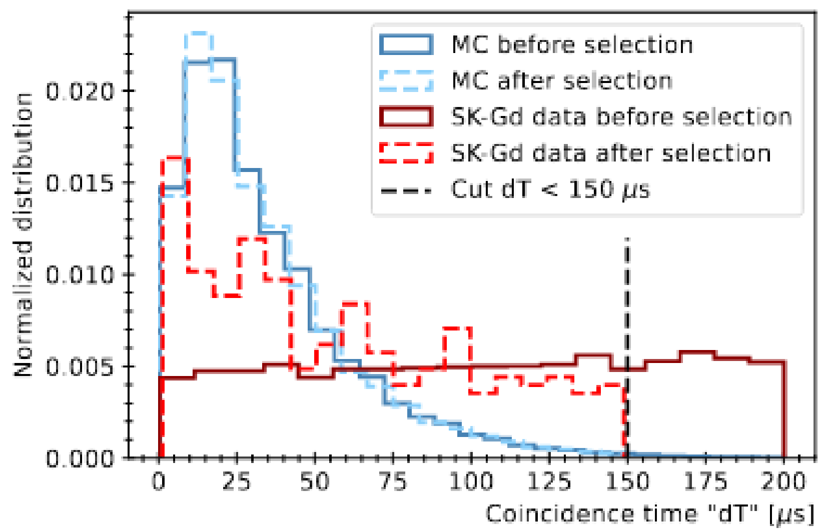
- During the Si-layer burning (~few days before the core-collapse), the average neutrino energy is above the IBD threshold (1.8 MeV), allowing a potential detection.



Pre-Supernova Neutrinos analysis

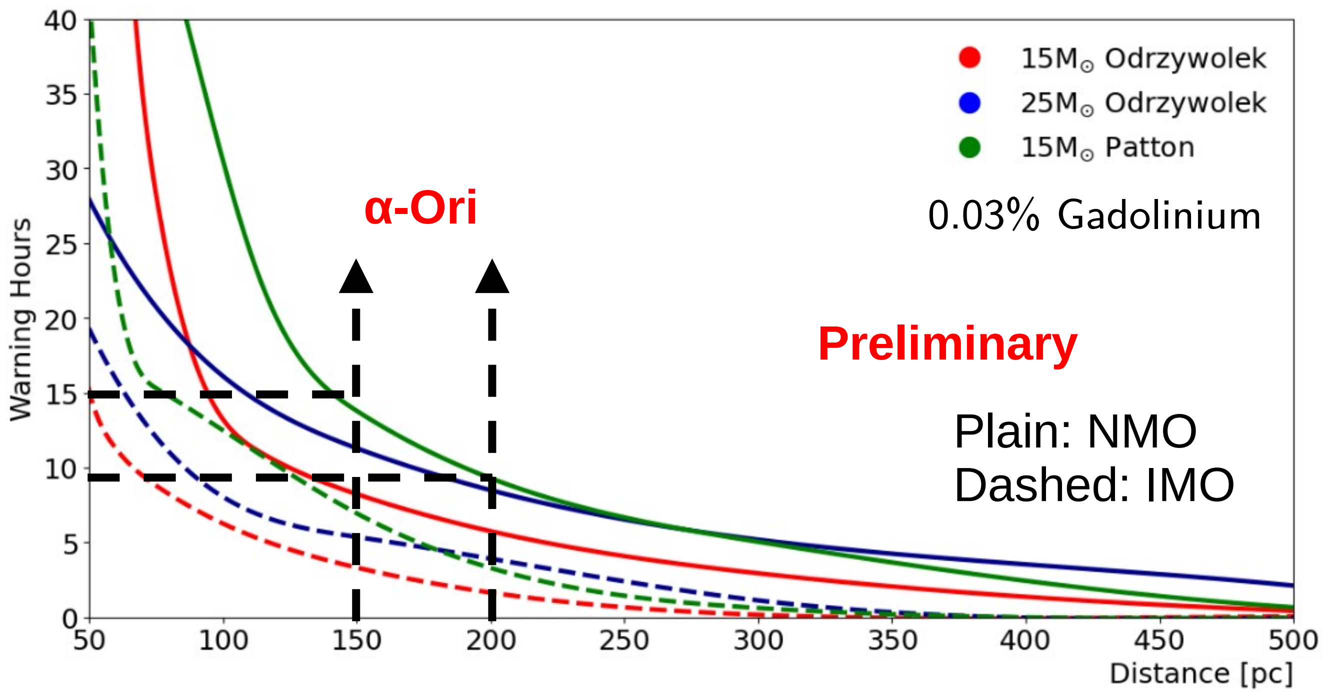
- The pre-supernova neutrino analysis in Super-K is an **online** analysis
  $\rightarrow$ We need to be fast in order to release alarm as soon as possible.
- Several analysis methods are used:
  - Two Boost Decision Trees are used in order to perform fast selection: One to perform a pre-selection of IBD candidates from the online data sample. The second one is used to perform the final selection.
  - Spatial and time correlation cut in order to separation IBD signal from background.
- This analysis has an IBD selection efficiency of $\sim$24.9%





Pre-Supernova Neutrinos alarm

- If pre-SN neutrinos are detected, announcing an up-coming SN, this information can be used by neutrino experiment to postpone maintenance / down-time of the detector
- From this online analysis, we can trigger a public alarm if the IBD rate significence is at least 4σ (an internal alarm is trigger if the significance reached 3σ).
- Betelgeuse (α-Ori) → warning 10∼15 hours before the core-collapse (NMO)
- Combined alarm between SK and KamLAND: https://www.lowbg.org/presnalarm/

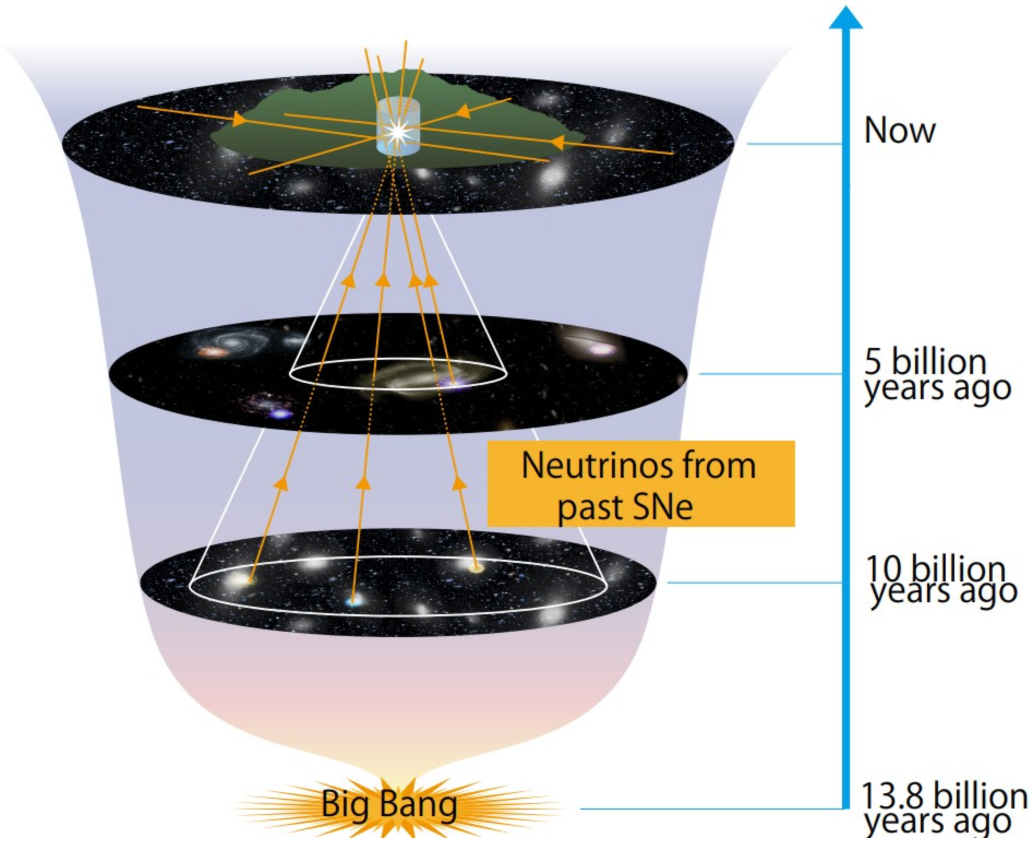


Waiting for the next Supernova?

- With a theoretical rate of ~1 every 30 years, the next galactic supernova can be expected within the next few decades.
- However, there were ~O(10^{19}) SNe since the Big Bang

$$\sim 10^{11} \text{ stars/galaxy} \times \sim 10^{11} \text{ galaxies} \times 0.3\% \text{ (chance to become SN)}$$

- We could look at these neutrinos produced by **past Supernovae**



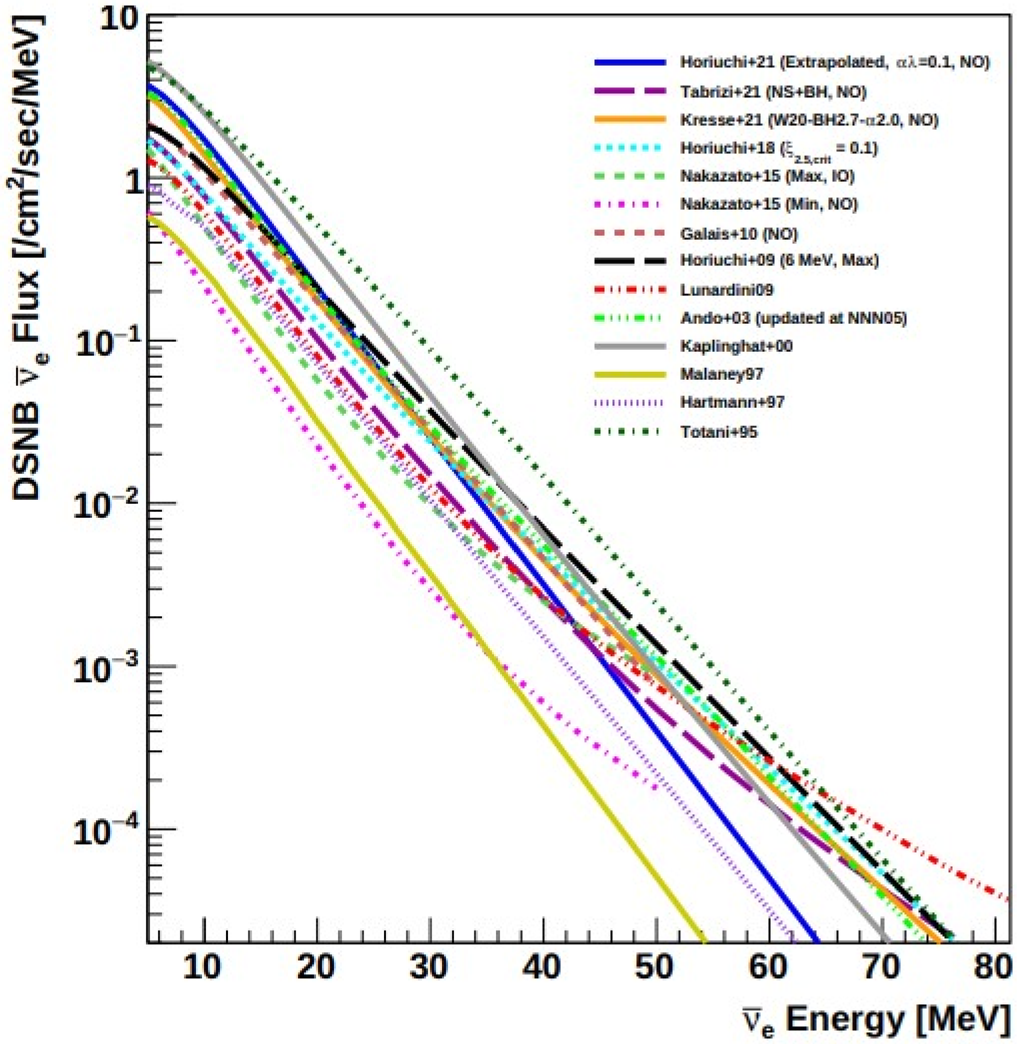
Diffuse Supernova Neutrino Background

References:

- A. Santos et al., Neutrino 2024 DSNB poster
- M. Harada, Neutron 2024 DSNB review
- K. Abe et al. (SK collaboration), Phys. Rev. D 104, 122002 (2021)

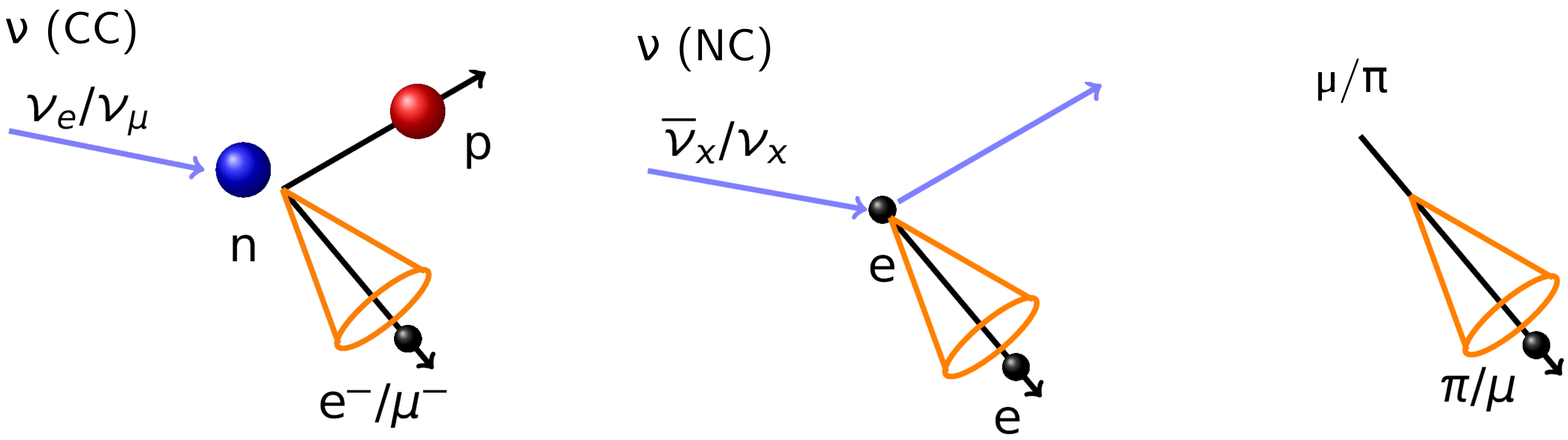
Diffuse Supernova Neutrino Background

- Predicted in 1984 by L. M. Krauss, S. L. Glashow and D. N. Schramm
  Nature 310, 191 (1984)
- DSNB can provide information regarding the history of SN and flux characteristics:
  - CCSN rate
  - Failed CCSN rate (Black Hole formation rate)
  - Binary star formation effect
  - Typical CCSN neutrino spectrum
  - Neutrino oscillation inside the star, neutrino decay, other NSI
- "Low" neutrino flux expected:
  0.13 event/kton/yr
  (only electron antineutrino are expected to be detected, through IBD reactions)



DSNB backgrounds

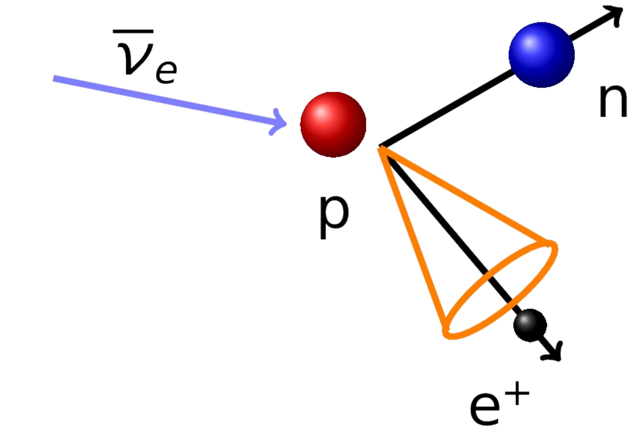
- Expected DSNB signal is the Inverse Beta Decay reaction
  $\rightarrow$ Tagging the neutron capture can help separating signal from background producing 0 or multiple neutrons.
  - SK-IV $\rightarrow$ Neutron tagging with H-n (pure-water period)
  - SK-VI $\rightarrow$ Neutron tagging with 0.01% Gd
  - SK-VII $\rightarrow$ Neutron tagging with 0.03% Gd
- Reduction of ν CC, ν NC, μ and π BGs



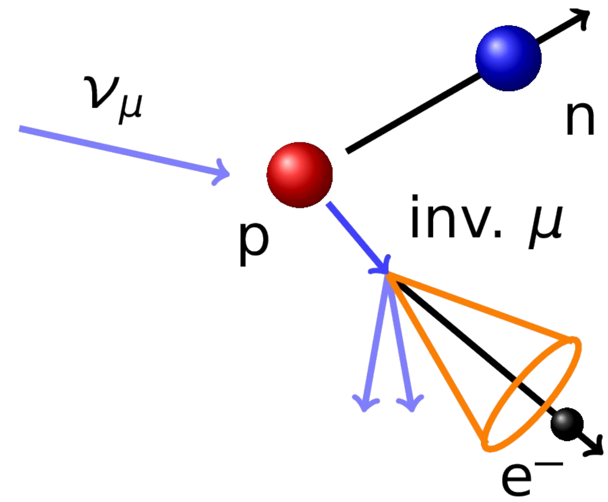
DSNB backgrounds with neutron tagging

- With neutron-tagging, the dominant background picture change:

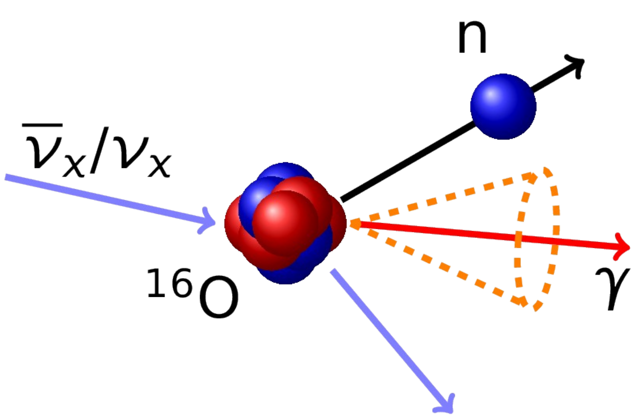
Atm. / reactor $\bar{\nu}_e$ (CC)



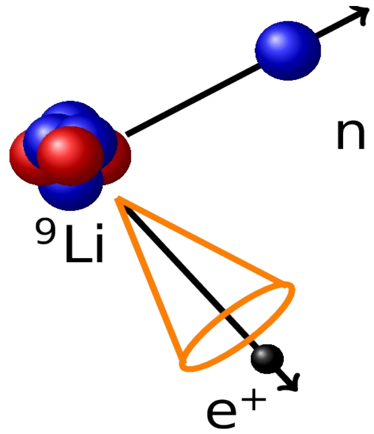
Atm. ν (CC)



Atm. ν (NCQE)

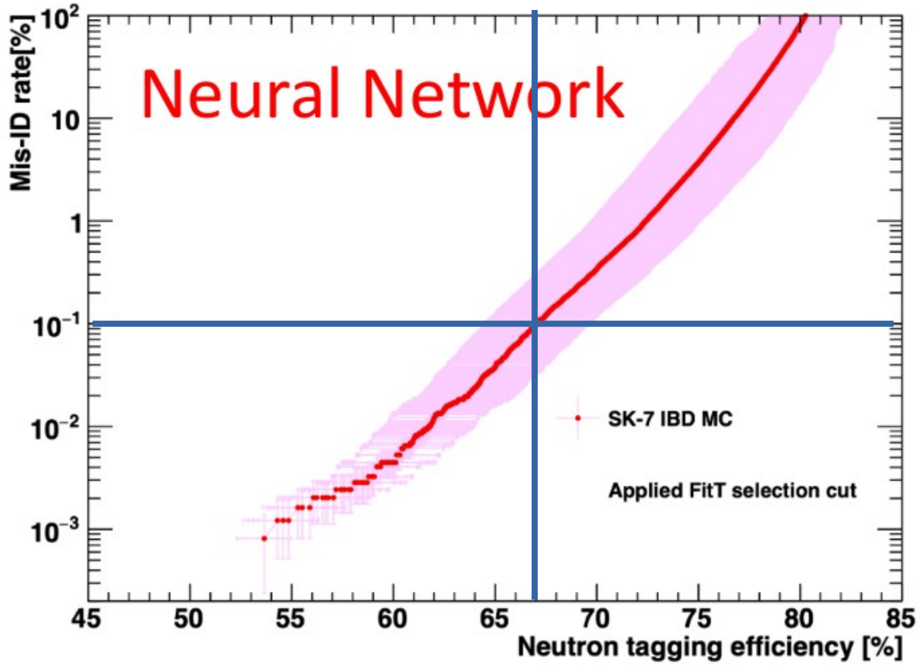


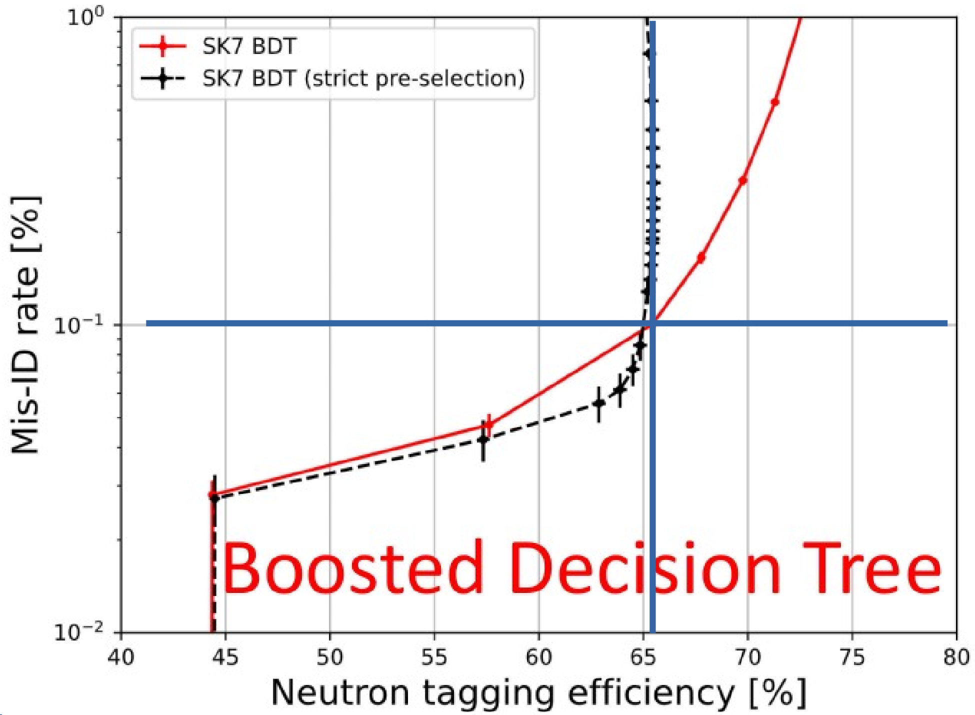
^{9}Li (spallation)



DSNB signal selection

- In SK-VI and SK-VII several improvements on the BG reduction and signal selection:
  - 2 independent neutron tagging methods (NN, BDT)
    >60% signal selection efficiency
    (previously: 35.6% in Gd analysis, 10∼30% in pure water)





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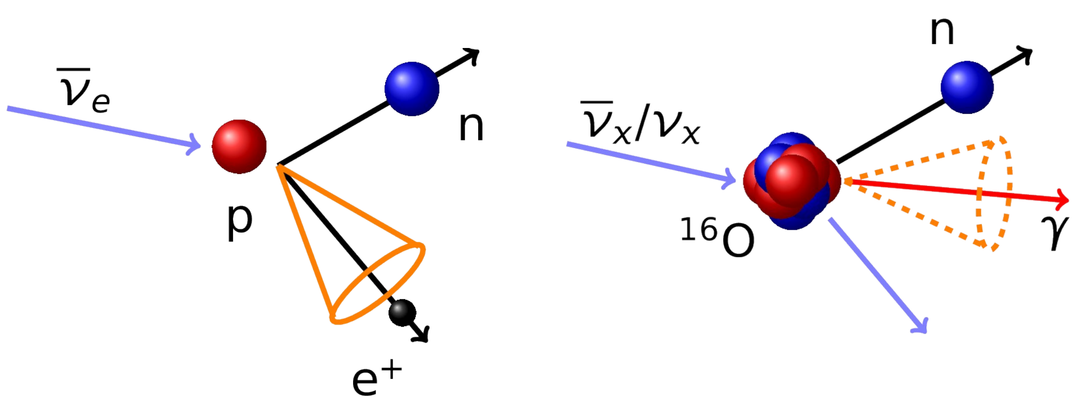
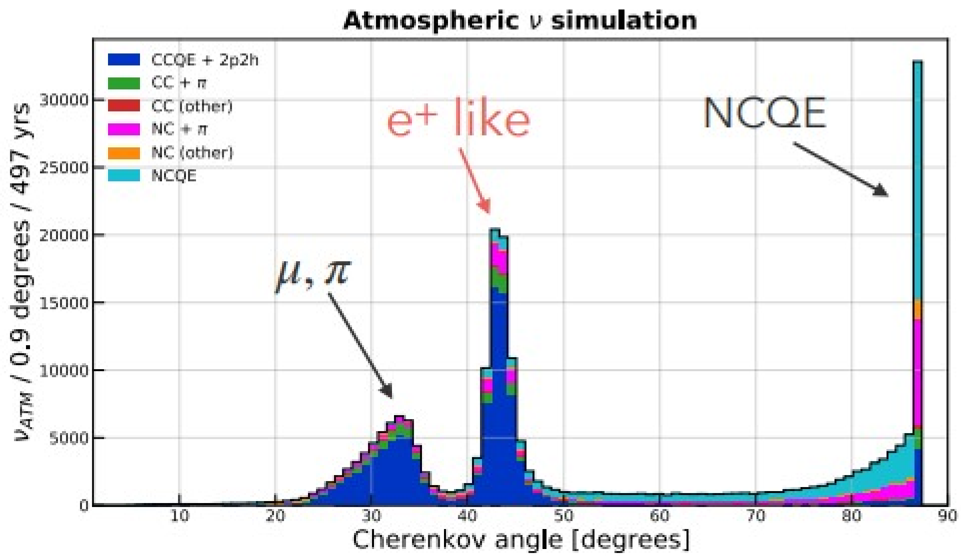
  - Reduction of ~90% of NCQE, using light cone characteristics (multivariate analysis)





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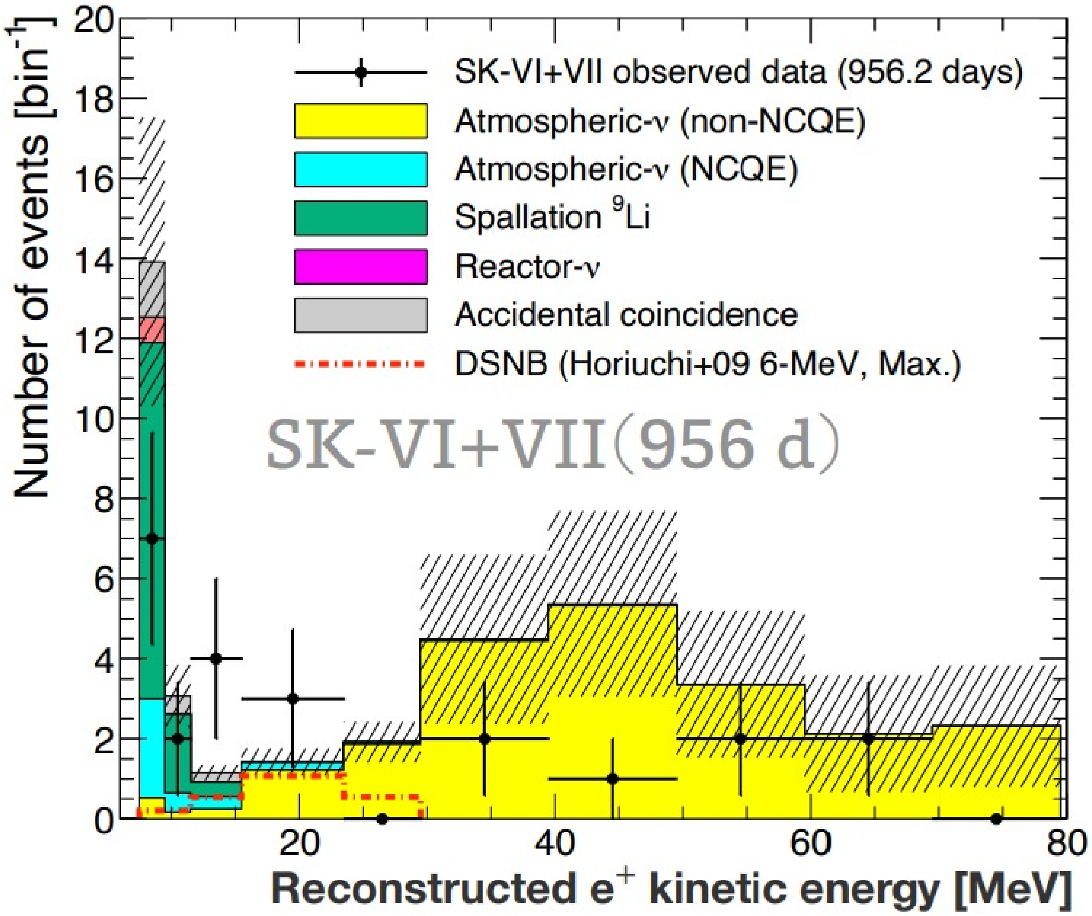
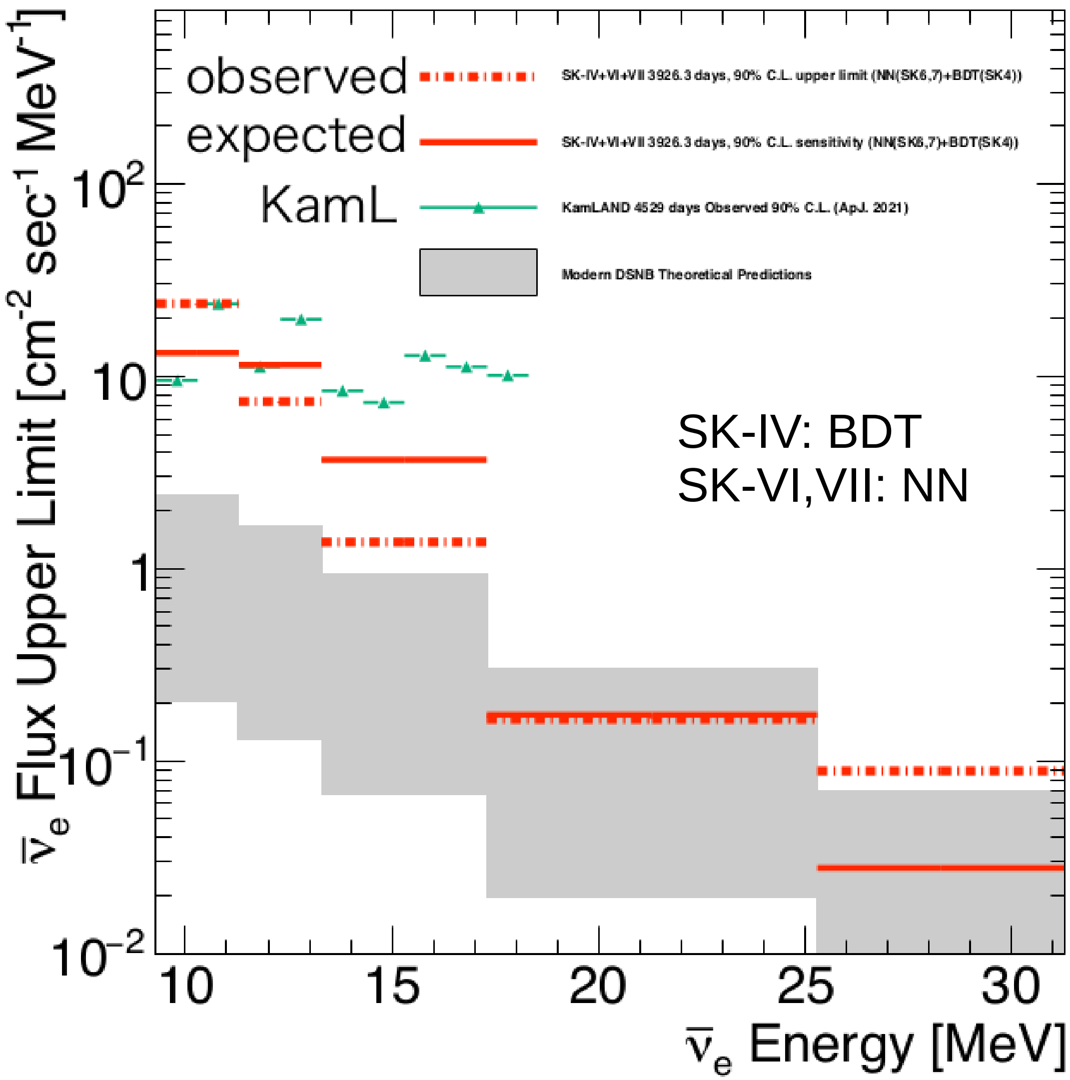
  - 2 independent neutron tagging methods (NN, BDT) >60% signal selection efficiency (previously: 35.6% in Gd analysis, 10~30% in pure water)
  - Reduction of ~90% of NCQE, using light cone characteristics (multivariate analysis)
- No obvious excess, but maybe a hint (min. p-value=0.04)



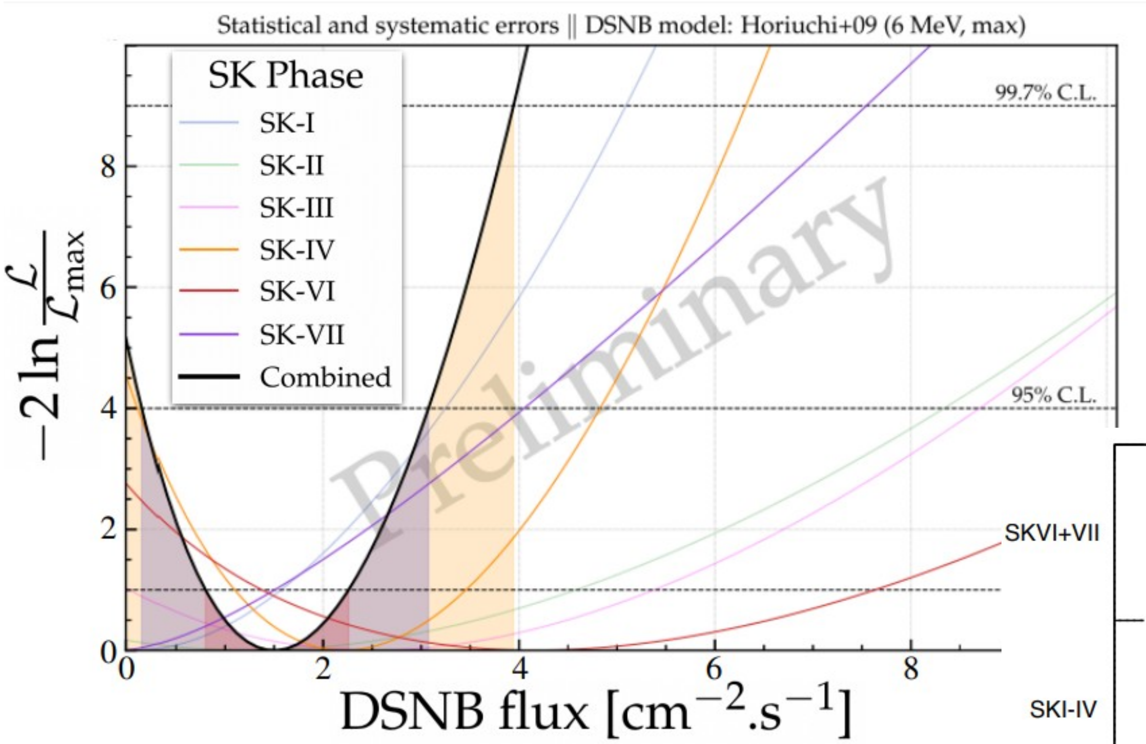
DSNB new limits

- New tightest limit using SK-IV, VI, and VIII combined results

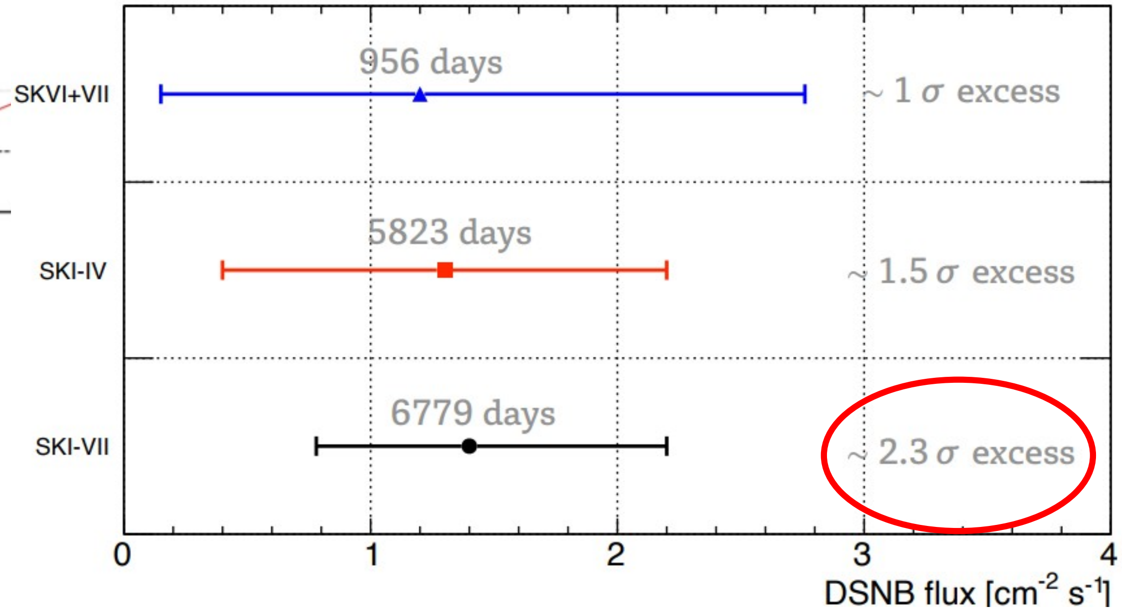


Significance

- Spectrum fitting analysis for the full SK periods (pure-water + Gd) combined
- Energy threshold at >17.3 MeV (to remove spallation in pure-water phases)



Best fit: $1.4^{+0.8}_{-0.6}$ cm^{-2}.s^{-1}



Summary

Summary

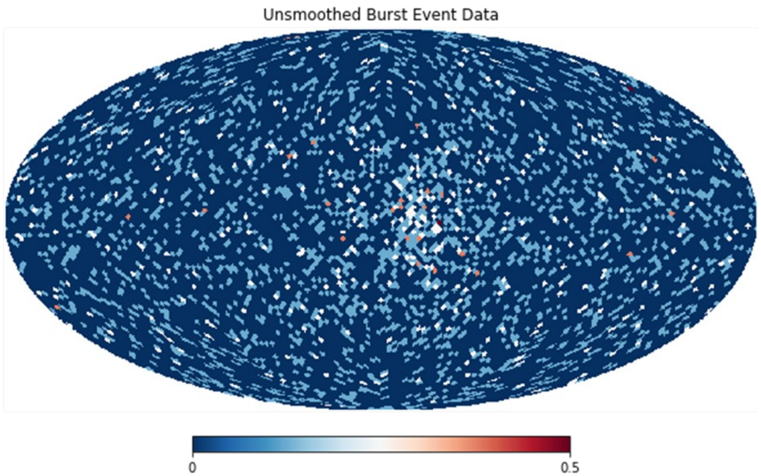
- Super-Kamiokande supernova program cover neutrino production from all the phase of the CCSN: pre-supernova Si-burning neutrinos, CCSN neutrino burst, and the diffuse background resulting from the SNe since the Big Bang.
- **Supernova burst:**
  - Supernova direction reconstructed with a resolution of **3.68±0.04°** at 10 kpc (assuming Nakazato model, NMO)
  - Automated alarm through GCN notice **within 1.5 minutes** after the neutrino burst
- **Pre-supernova neutrino:**
  - Potential detection **few hours** before the CCSN within 500 pc
  - Public alarm is available, combining data from Super-Kamiokande and KamLAND
- **Diffuse Supernova Neutrino Background:**
  - Analysis was improved for the last Gd-loaded periods
  - **2.3σ** tension from non-DSNB hypothesis $\rightarrow$ potential detection in the next decade?

Backup

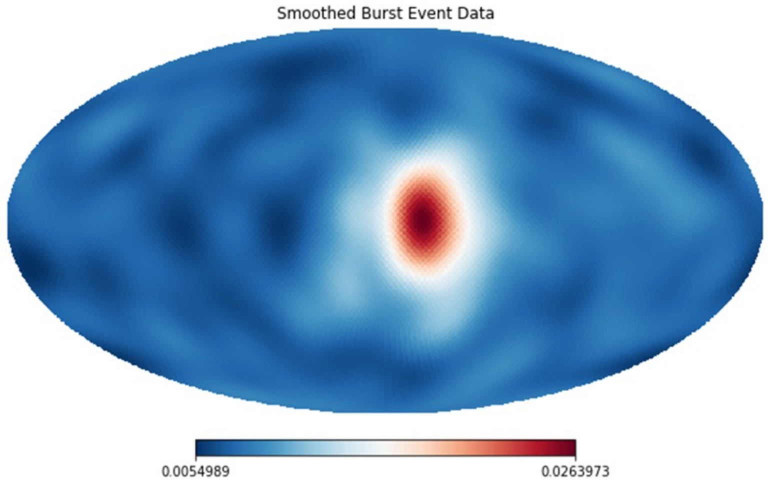
SN direction fitter improvement investigations

- **HEALPix** based fitter (**H**ierarchical **E**qual **A**rea iso**L**atitude **Pix**elation of a sphere):
  - A sphere of the sky is made and divided in pixels of equal area
  - The pixels are populated with the projection of each event's reconstructed direction on the sphere.
  - The sphere is then smoothed with a gaussian function
  - The pixel with the maximum number of events is then selected as the SN direction

Nside = 32, Npix = 12,288

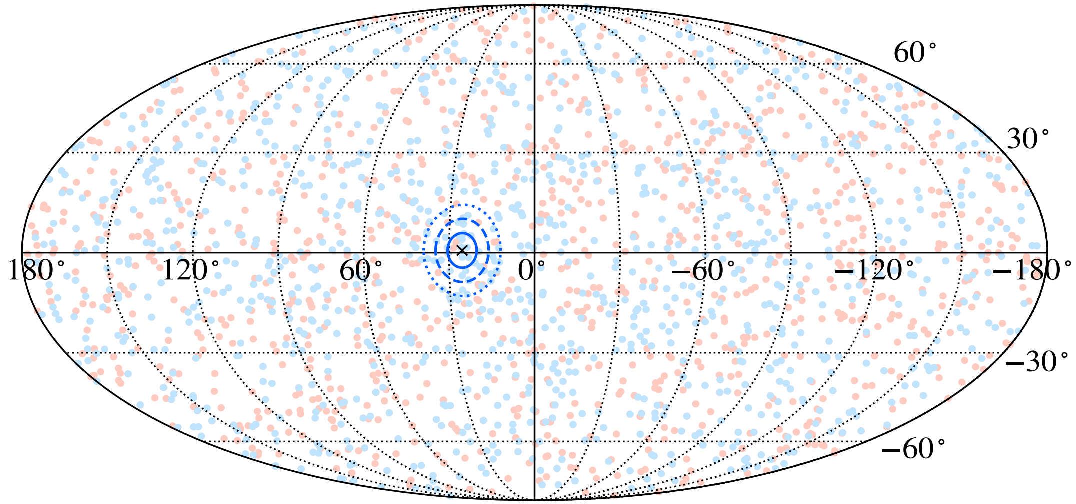


Gaussian Smoothed, σ = 0.15 rad.

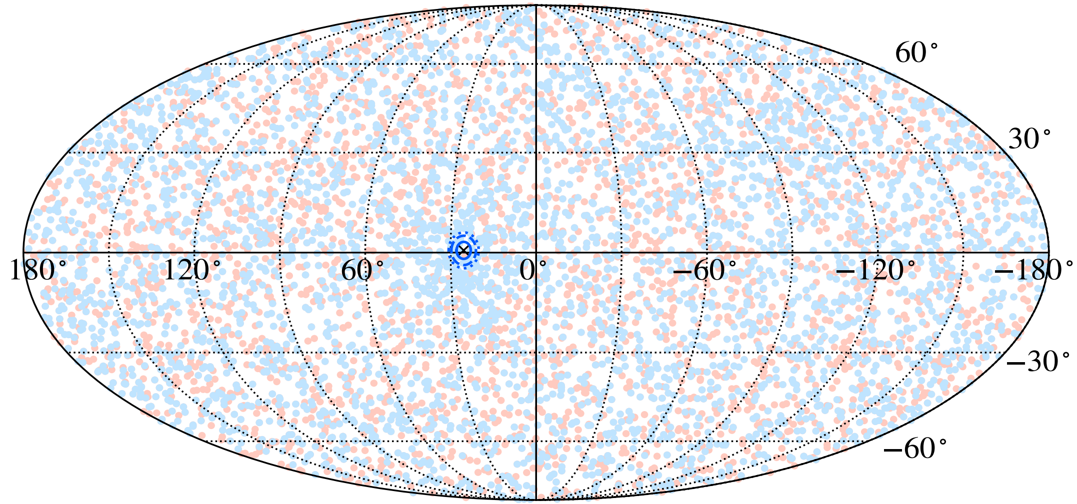


Realtime angular resolution with other models

Hudelpohl (ML fitter: 5.11±0.16°) **Preliminary**



Wilson (ML fitter: 2.51±0.08°) **Preliminary**



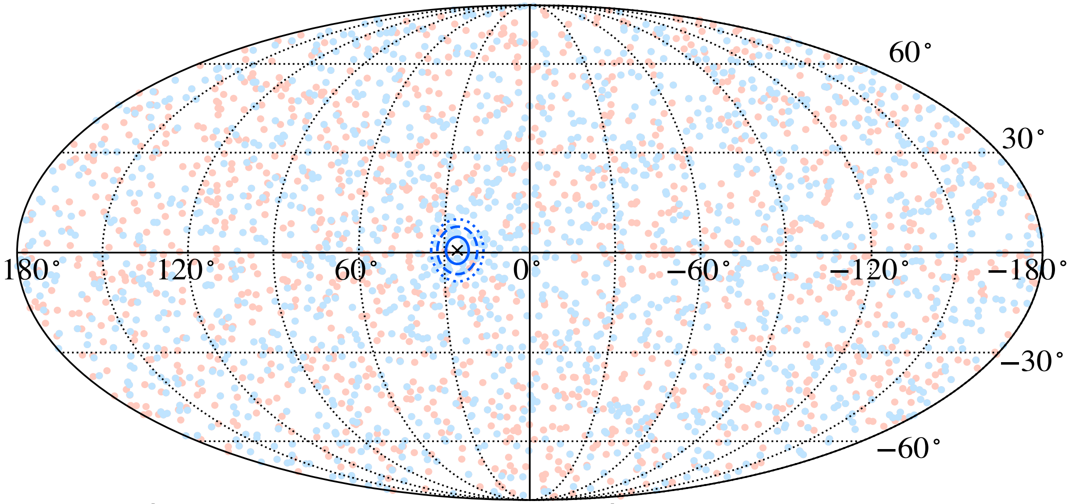
All models are with NMO

Summary of Supernova models. Core bounce occurs at 0 s.

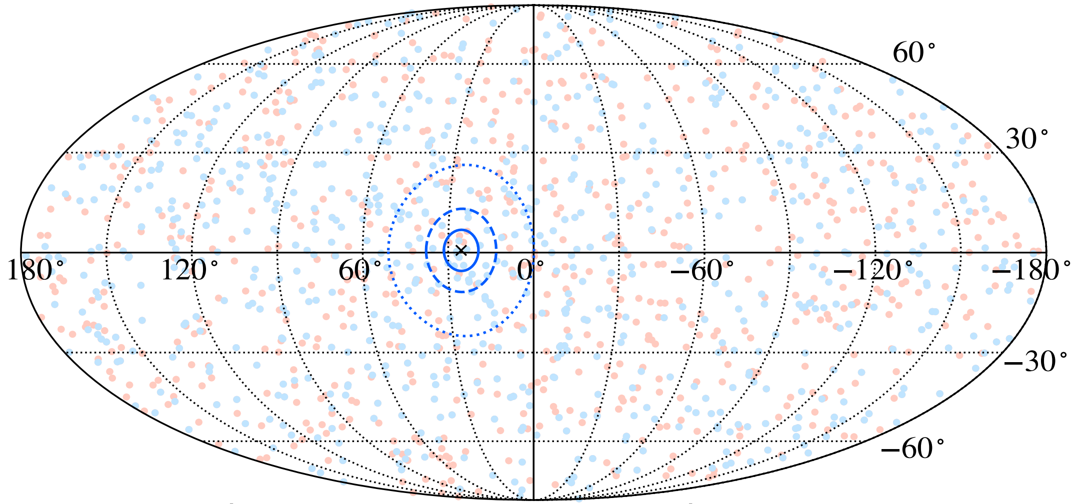
Model Name	Wilson[1]	Nakazato[2]	Mori[3]	Hüdelpohl[4]	Fischer[5]	Tamborra[6]
Dimension	1D	1D	1D	1D	1D	3D
progenitor mass [$M_\odot$]	20	20	9.6	8.8	8.8	27
start time [s]	0.03	-0.05	-0.256	-0.02	0.0	0.011
duration [s]	14.96	20.05	19.95	8.98	6.10	0.54
Equation of State	-	Shen*	DD2**	Shen*	Shen*	LS***

Realtime angular resolution with other models

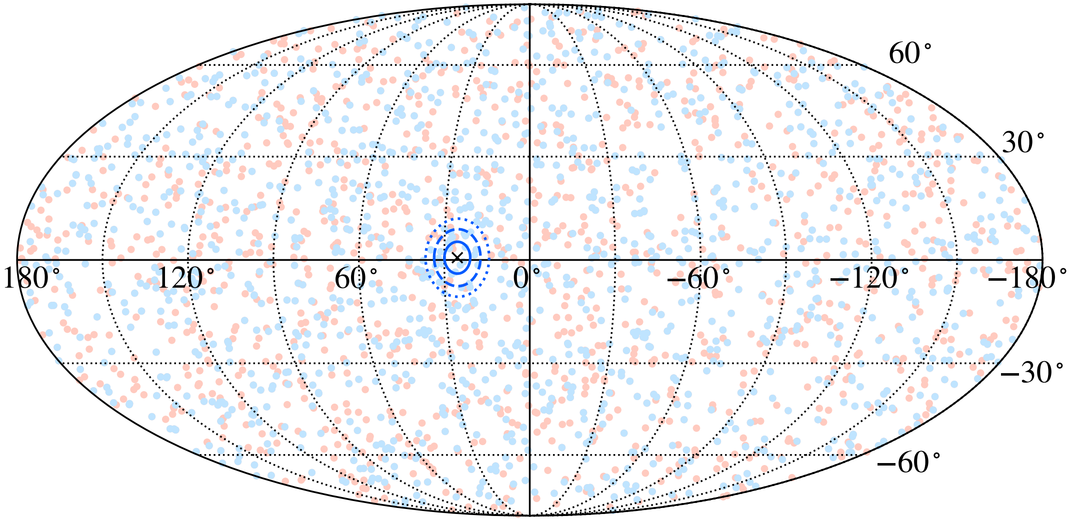
Nakazato (ML fitter: 4.01±0.13°) **Preliminary**



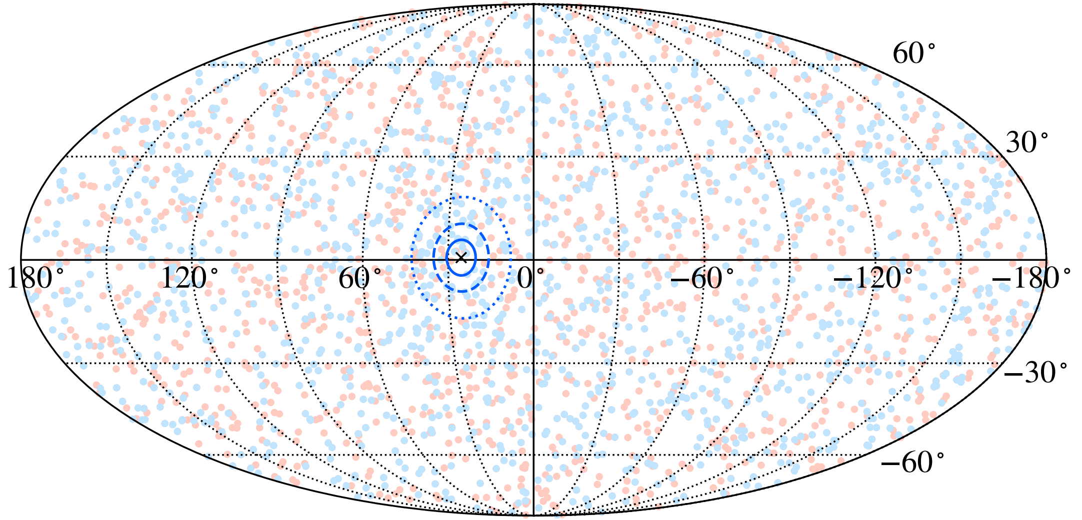
Fischer (ML fitter: 6.07±0.19°) **Preliminary**



Mori (ML fitter: 4.55±0.14°) **Preliminary**



Tamborra (ML fitter: 5.09±0.16°) **Preliminary**



All models are with NMO

- Performances with the previous Maximum Likelihood (ML) fitter. New fitter (ML+ HEALPix) performances are equivalent with a much faster processing.

Realtime angular resolution with other models

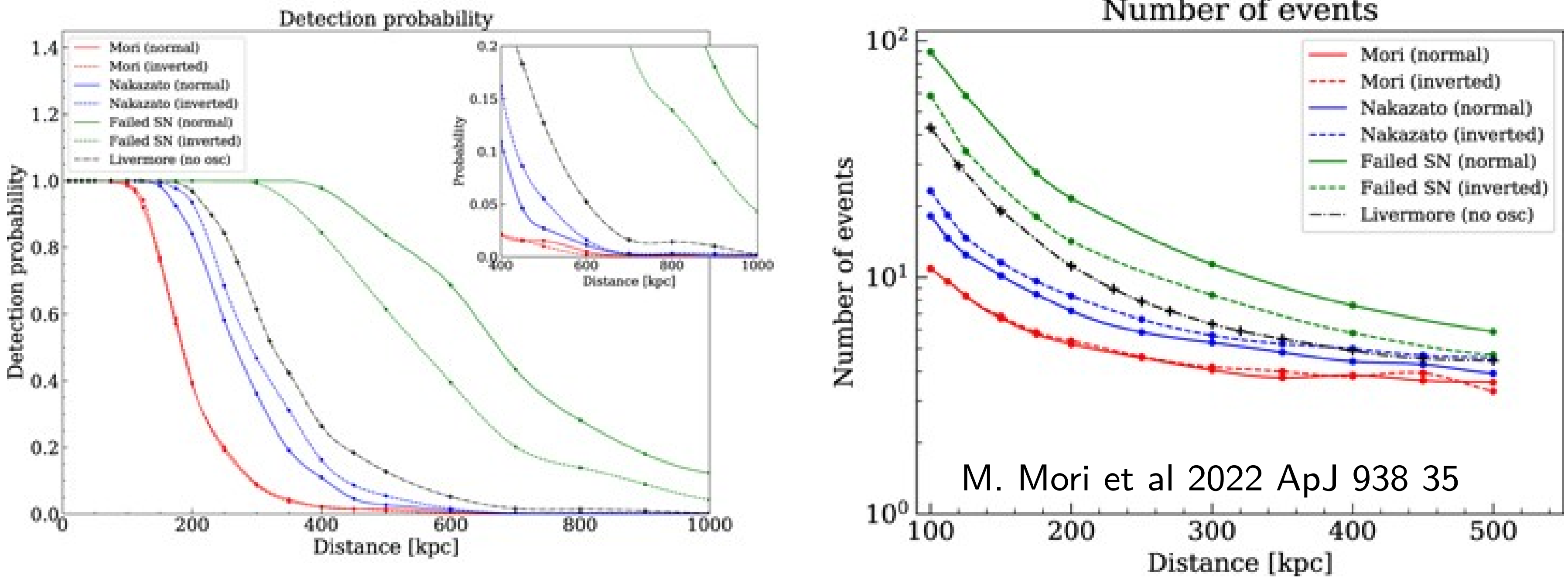
Reference [1] Totani, T., et al. *ApJ* 496.1 (1998): 216
[2] Nakazato, K., et al. *ApJS* 205.1 (2013): 2
[3] Mori, M., et al. *PTEP* 2021.2 (2021): 023E01
[4] Hüdepohl, L., et al. *PhRvL* 104.25 (2010): 251101
[5] Fischer, T., et al. *A&A* 517 (2010): A80
[6] Tamborra et al. *PRD* 90.4 (2014): 045032.

*Shen, et al. *Nucl. Phys. A* **637** (1998) 435–450.
Shen, et al. *PTEP* **100** (1998) 1013–1031.
Mori *et al.*, *PTEP* **2021 (2021) 023E01
***Lattimer & Swesty, *Nucl. Phys. A* **535** (1991) 331–376.

Offline Supernova search

- In case of supernovae (and failed supernovae) farther away than the SMC, our online monitoring system may missed them. We also perform offline supernova search in our data.

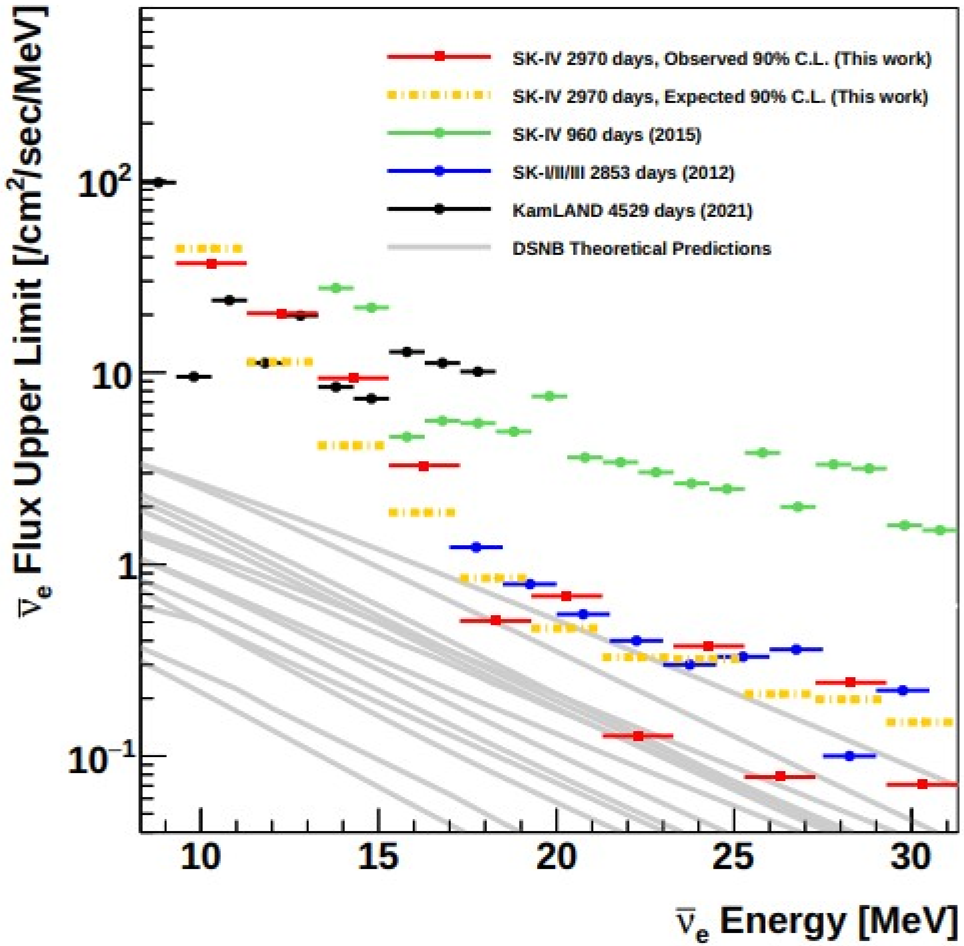
Predicted supernova detection probability and number of events

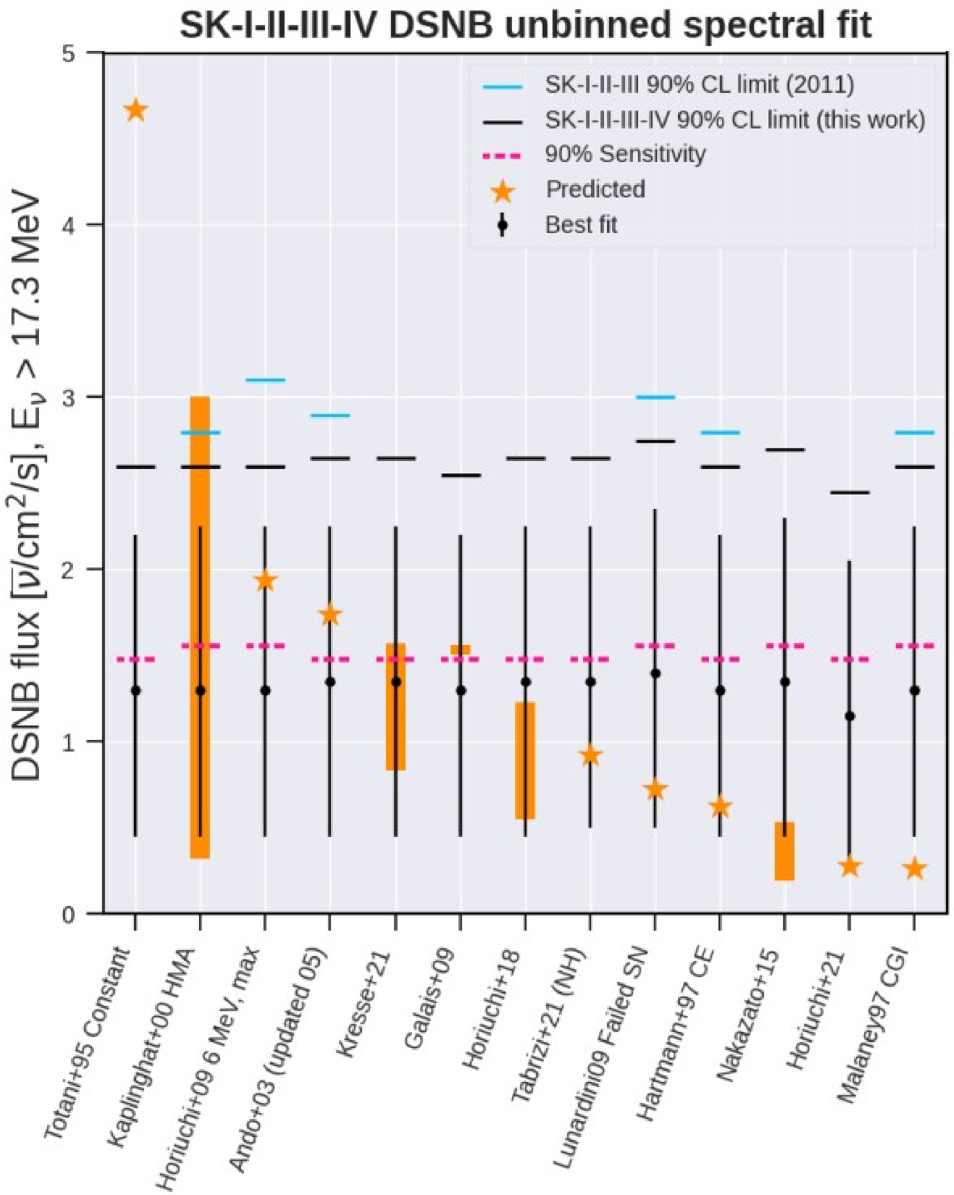


- We did not find any evidence of distant SN bursts from data collected in SK-IV (2008~2018), allowing to define the following upper limits:
  $\rightarrow$ $<$ **0.29 yr^{-1}** supernovae out to 100 kpc (300 kpc for failed supernovae)
- Coincidence with SN2023ixf was also investigated, but no significant signal was observed (ATEL 16070, GCN circular 33916)

Diffuse Supernova Neutrino Background limits

- Best limits are held by Super-Kamiokande which disfavoured several optimistic models





Results for SK-IV (without Gd)