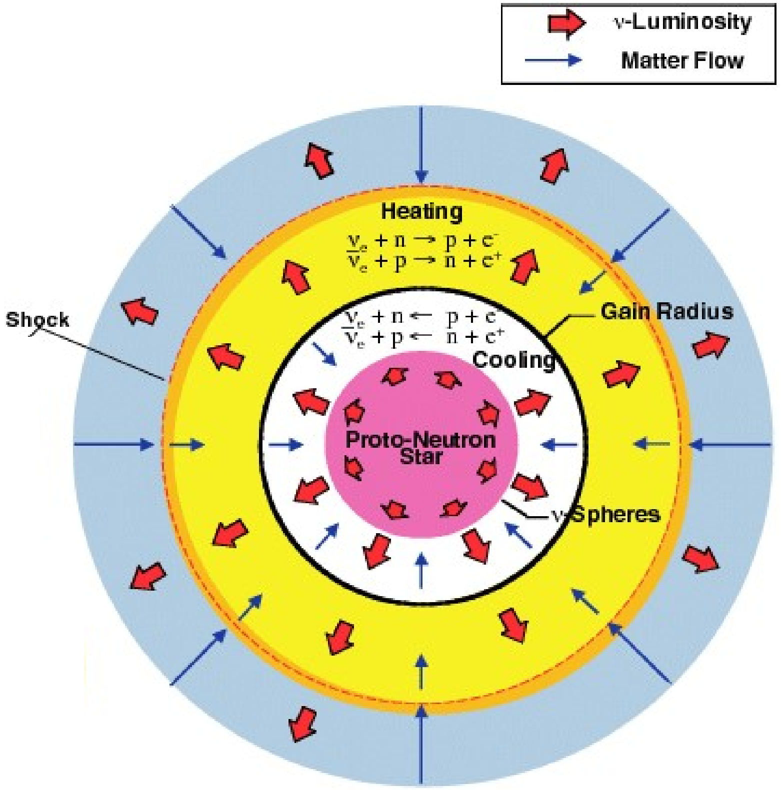
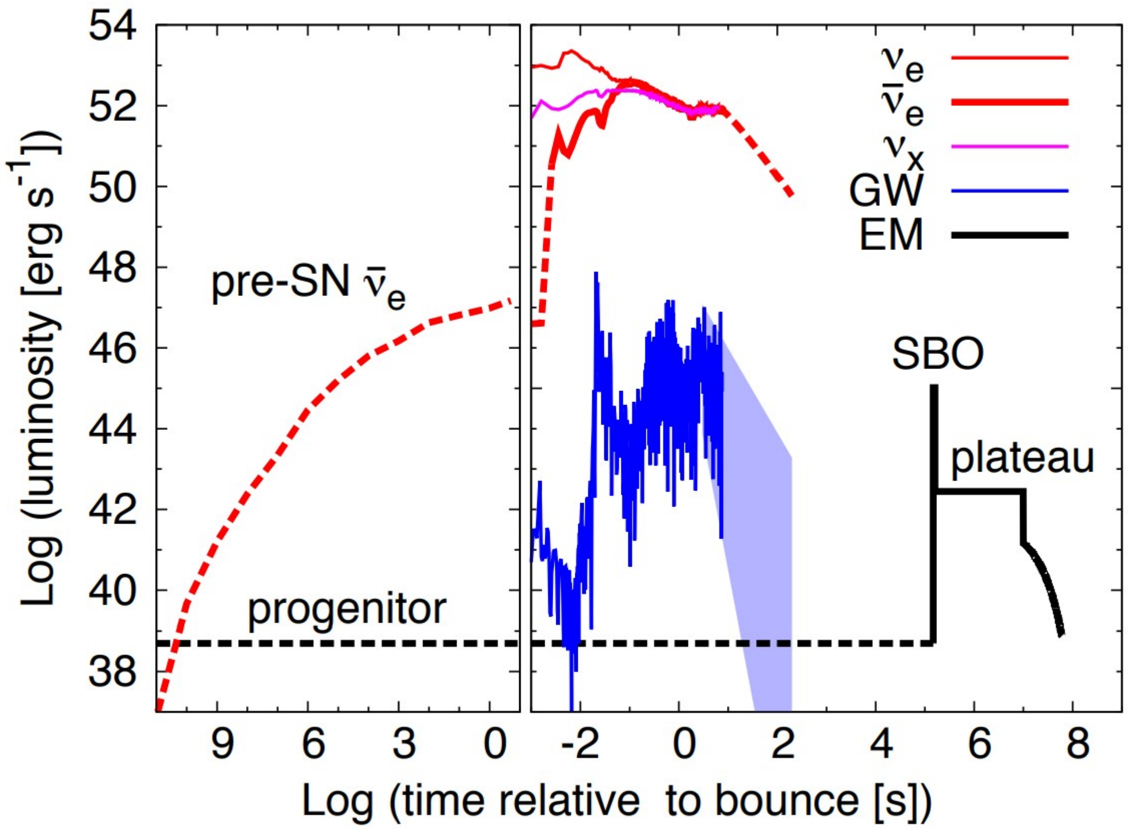
Super-Kamiokande Supernova monitoring: a trigger for multi-messenger analysis

Guillaume Pronost (Kamioka Observatory, ICRR, University of Tokyo)

Introduction

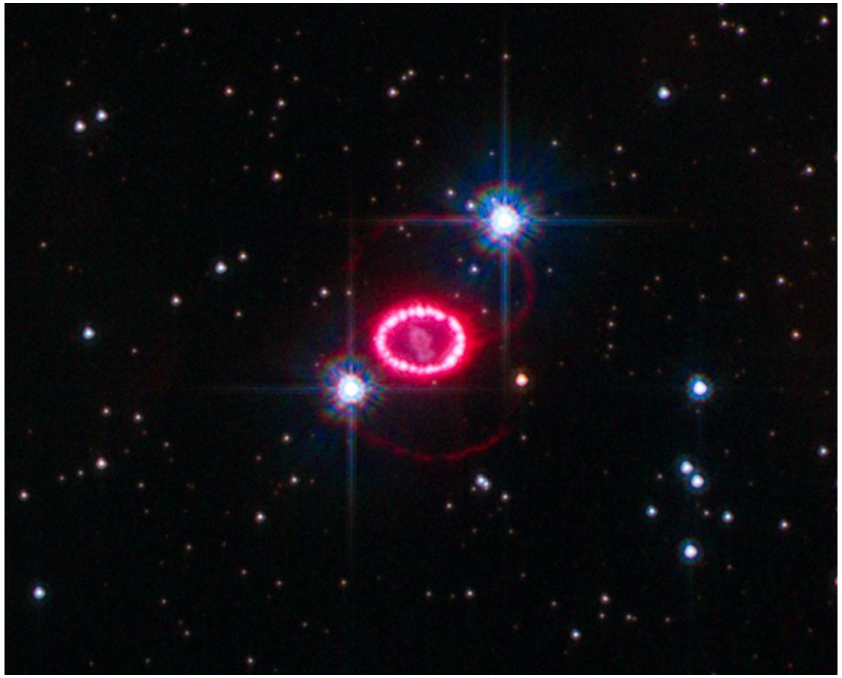
Core-Collapse Supernovae



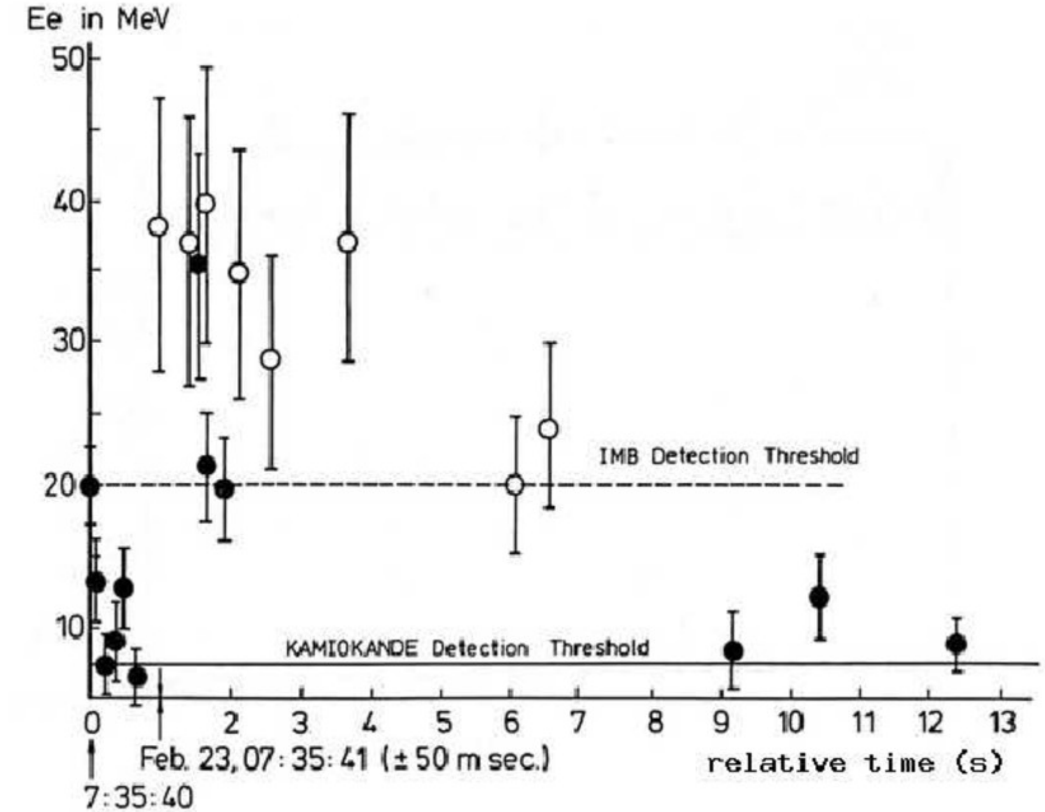


- Massive stars (8+ M$_\odot$) can end their life as core-collapse supernovae (or Type II SN), a cataclysmic implosion giving birth to a neutron stars or a black hole (failed supernova).
- 99% of the Core-Collapse Supernova's energy is released through neutrino. These neutrino can reach Earth few minutes to several hours before the electromagnetic waves. $\rightarrow$ Neutrino detectors can give an alert to telescopes for them to look at the electromagnetic breakout light.

Core-Collapse Supernova Neutrinos



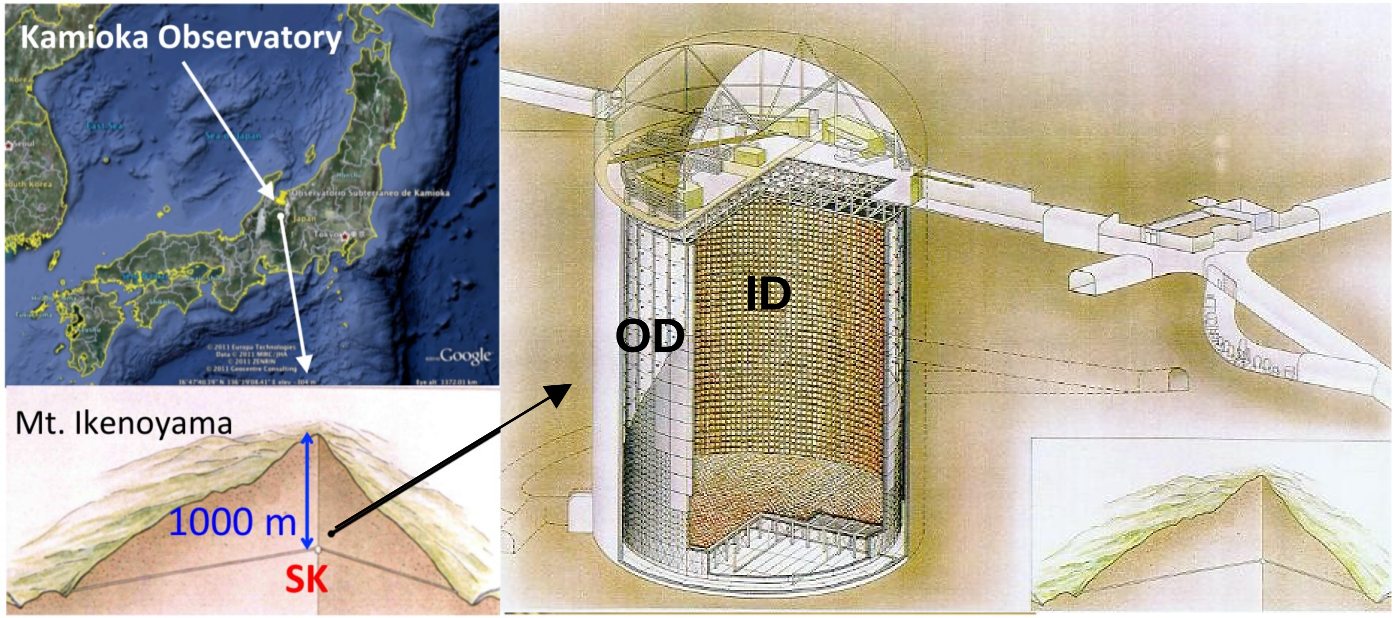
SN1987A remnant



- 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)

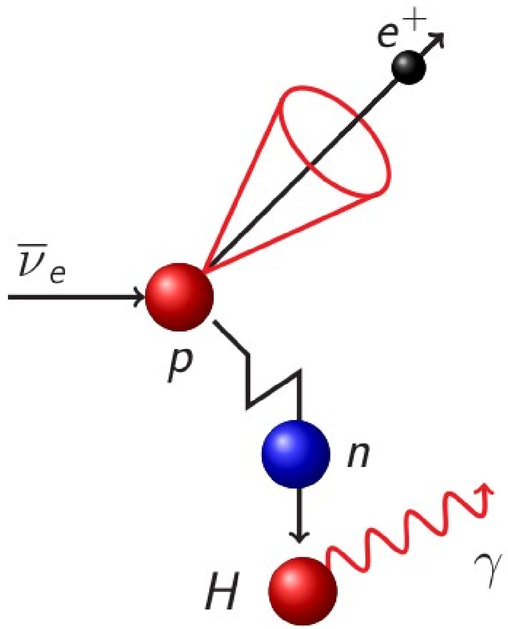


- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-VII is running

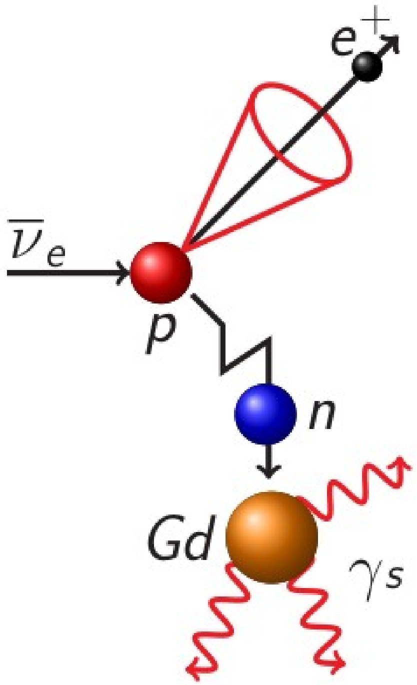
- The detector is filled with 50ktons of **gadolinium**-loaded water.
- Gadolinium was loaded at 0.01% in the water in Summer 2020, and the concentration was further increased to 0.03% in May 2022. Calibration was completed and the detector is running stably since then.
- **Physics targets**: Neutrino 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

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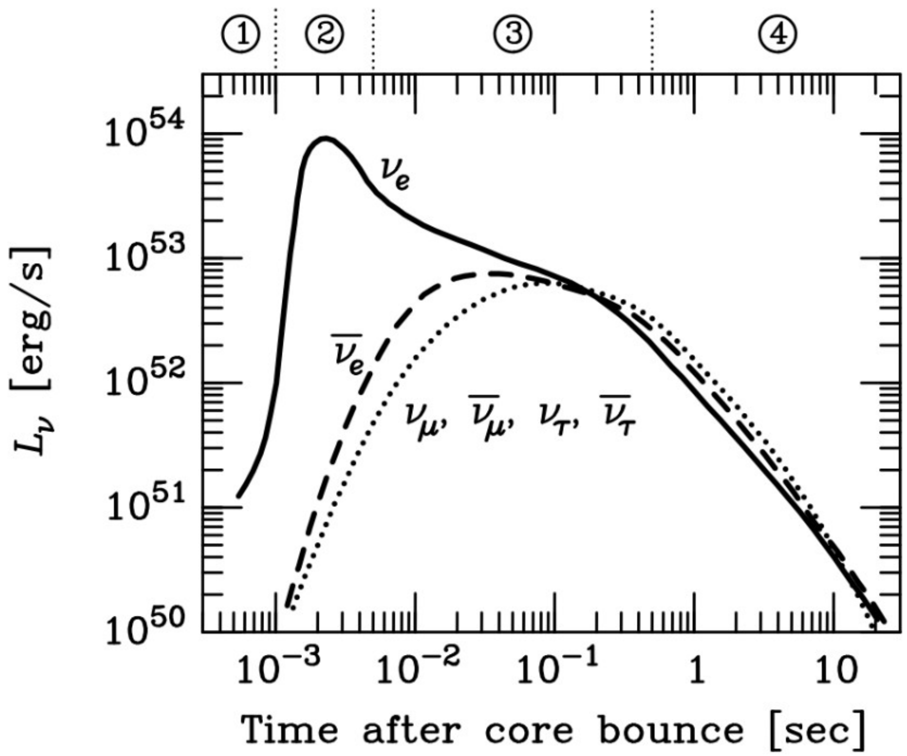
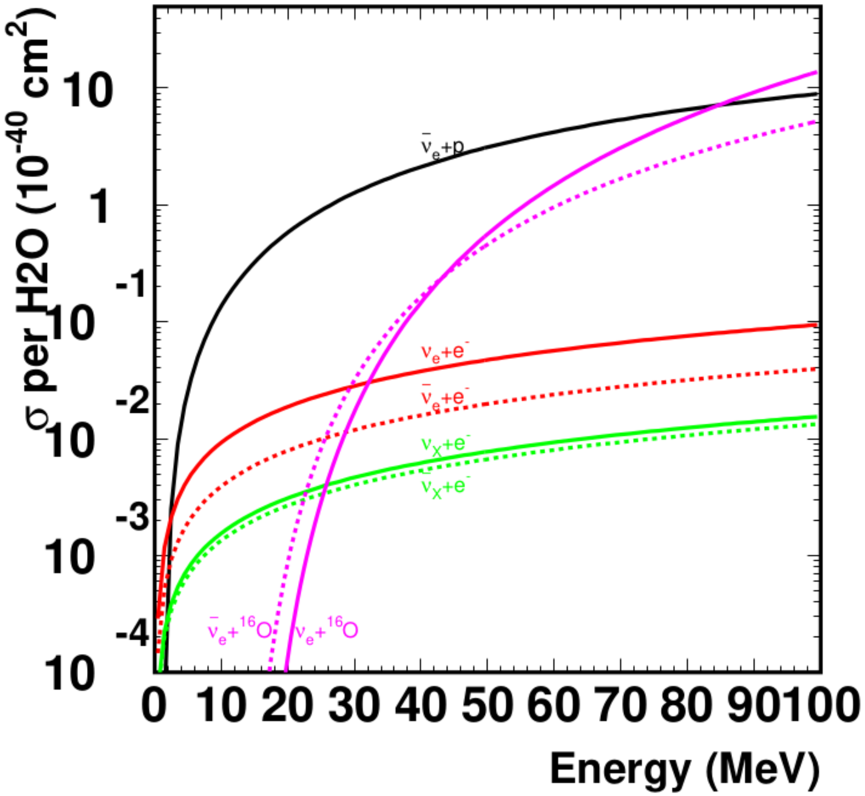
Core-Collapse Supernova Burst

- 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 $\overline{\nu}$



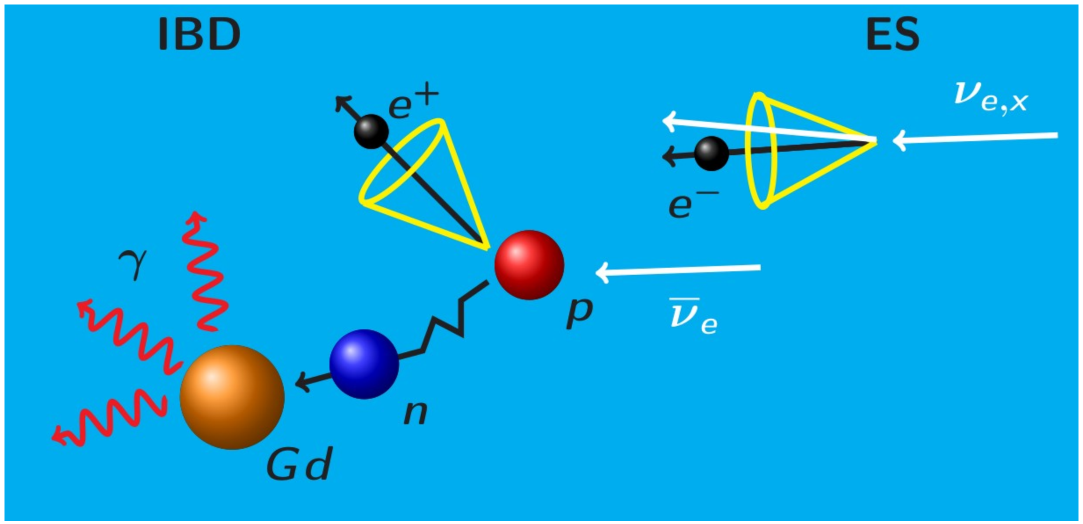
Supernova Neutrinos in Water Cherenkov Detectors

- 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) $\rightarrow \sim$90% of the interactions
  - **Electron Scattering interactions** (ES) $\rightarrow \sim$5% of the interactions



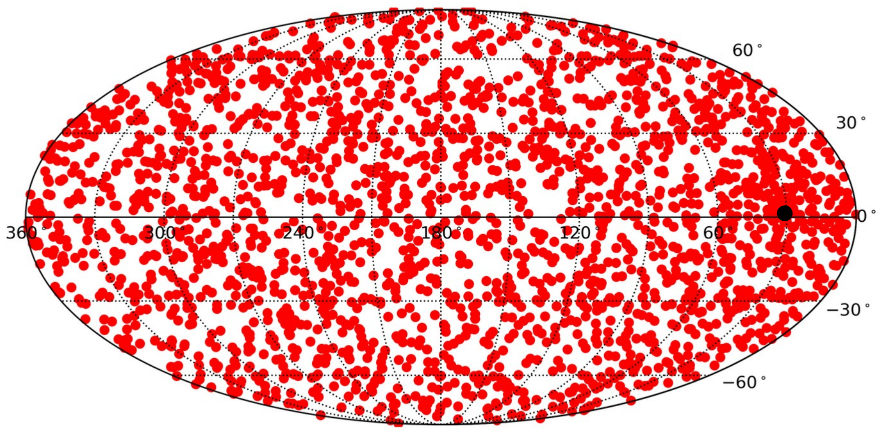
Keep the neutrino direction information

- ^{16}O interactions (CC and NC) $\rightarrow \sim$5% of the interactions

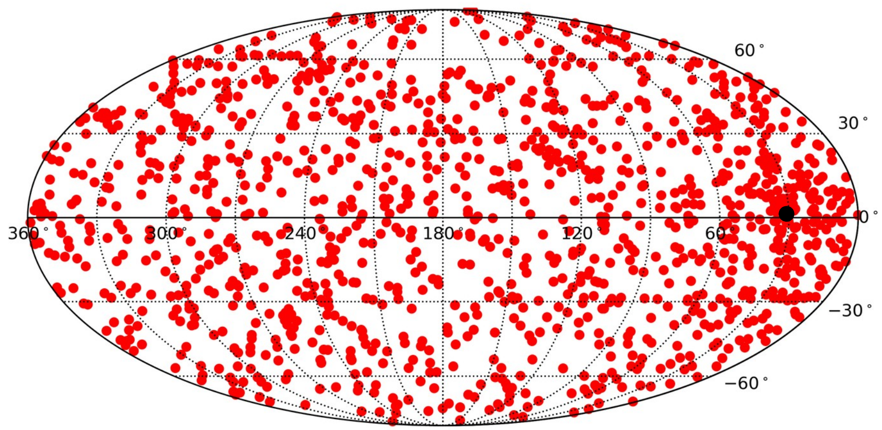


Using Gd-n to separate IBD and ES

- 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.



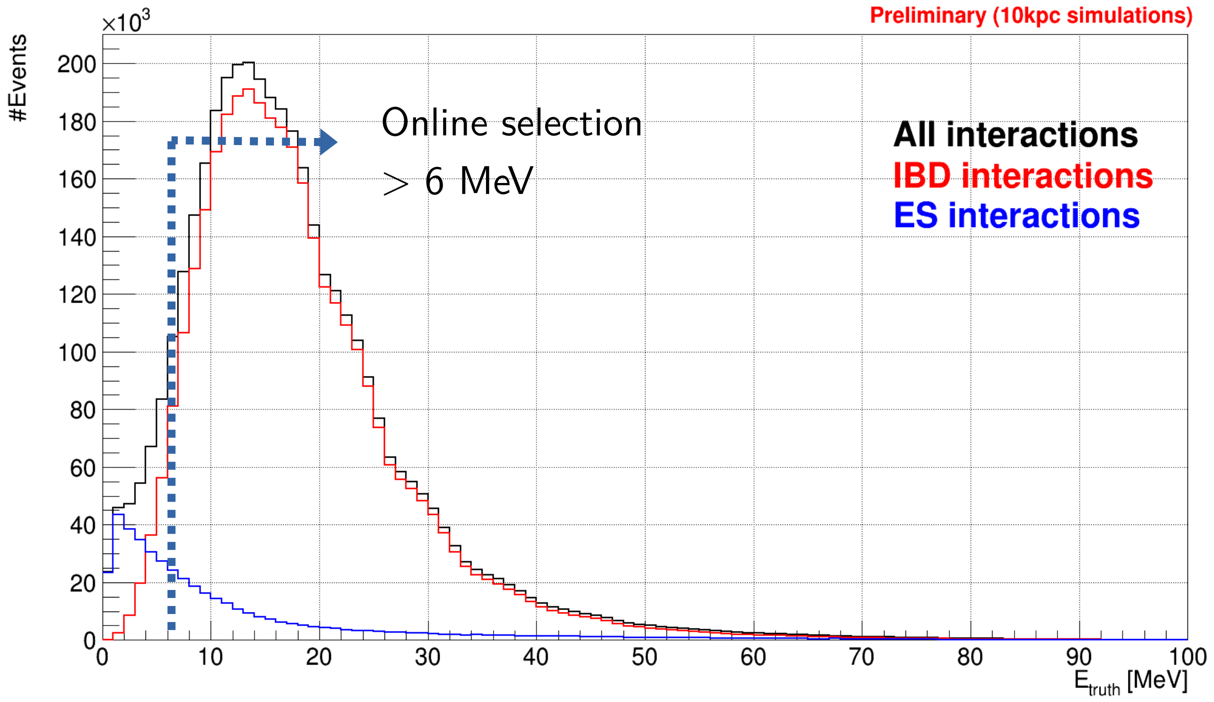
SN burst events w/o IBD tagging
(10kpc simulation w/o Gd)



SN burst events w/ ~50% 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

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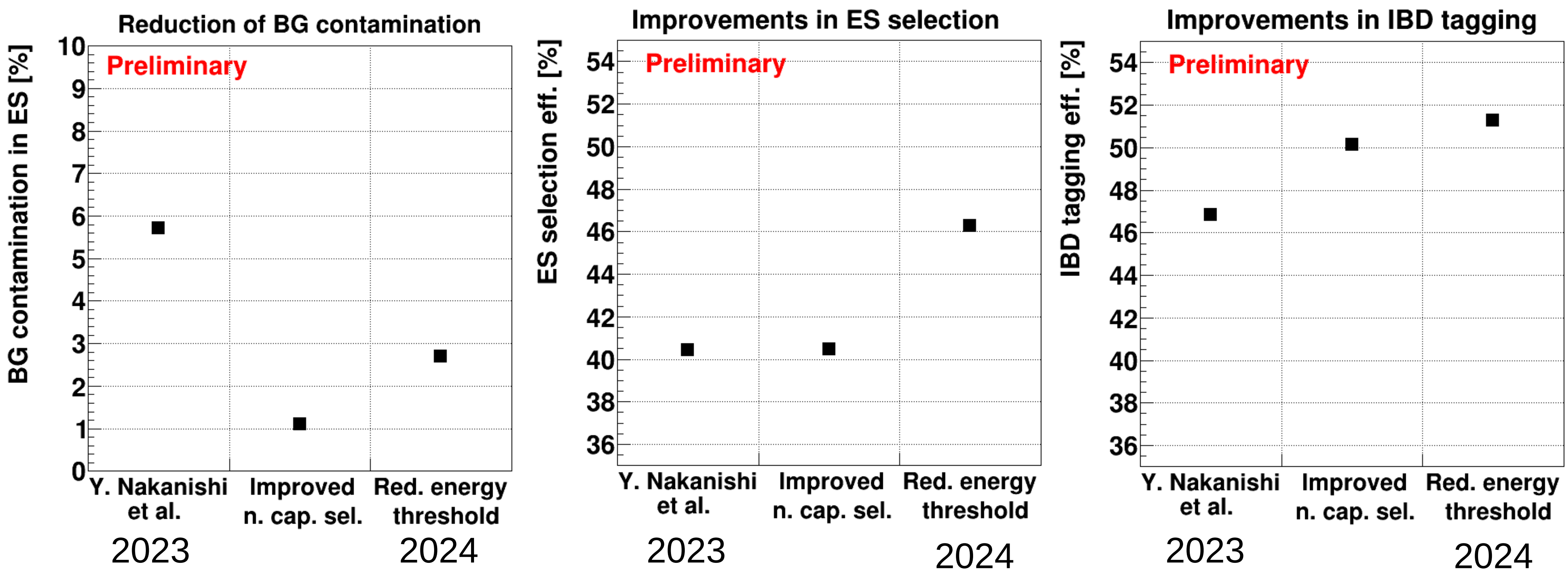
Realtime analysis

- 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)

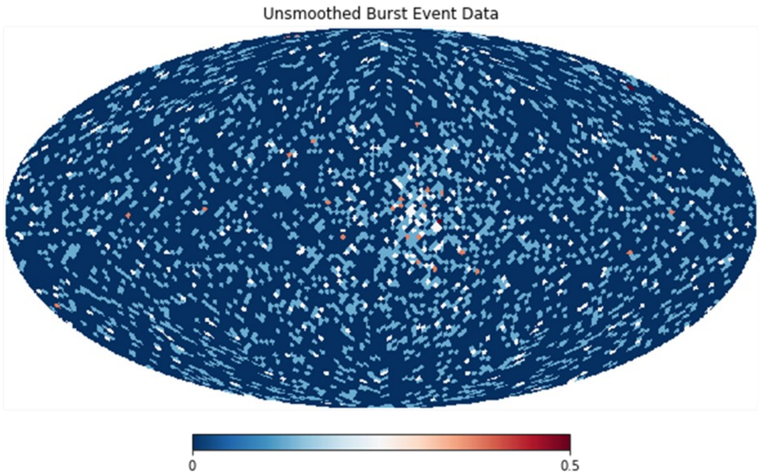
  → ~**51.3% IBD interactions are tagged**



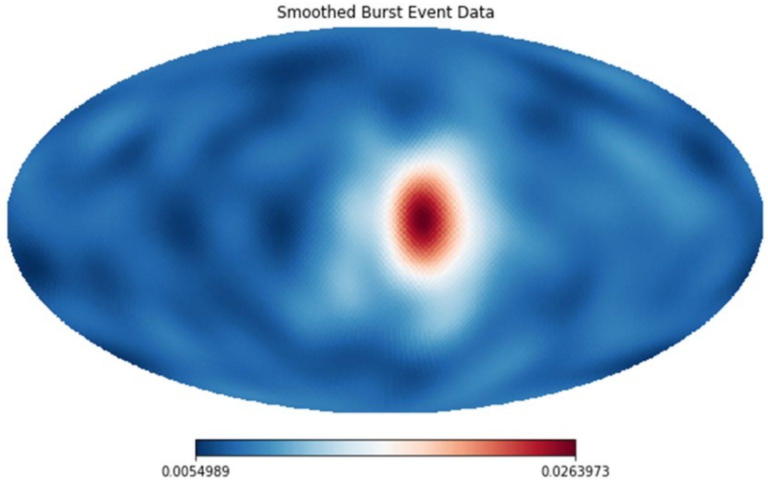
SN direction fitter improvement

- In 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

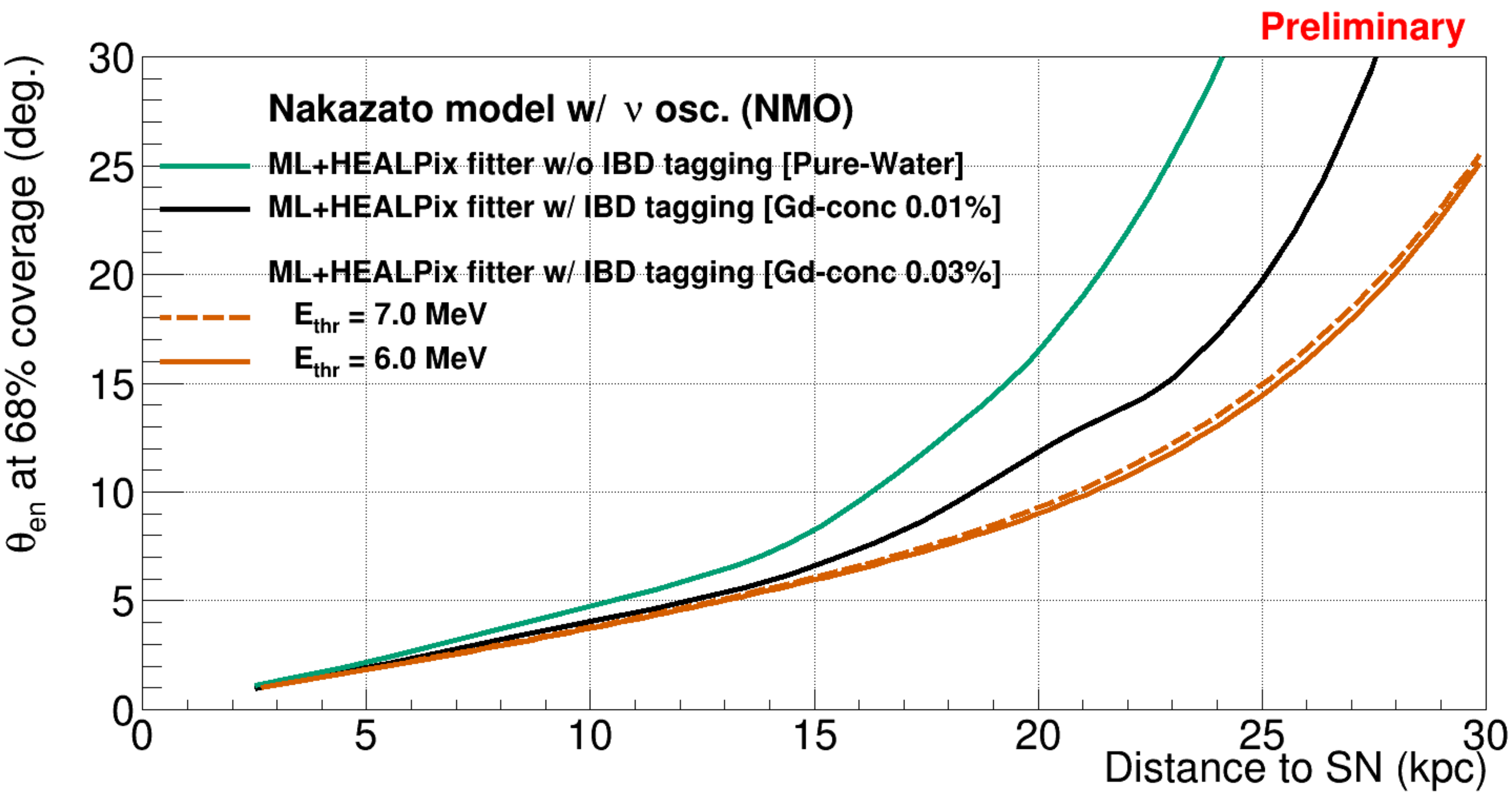


Gaussian Smoothed, σ = 0.15 rad.



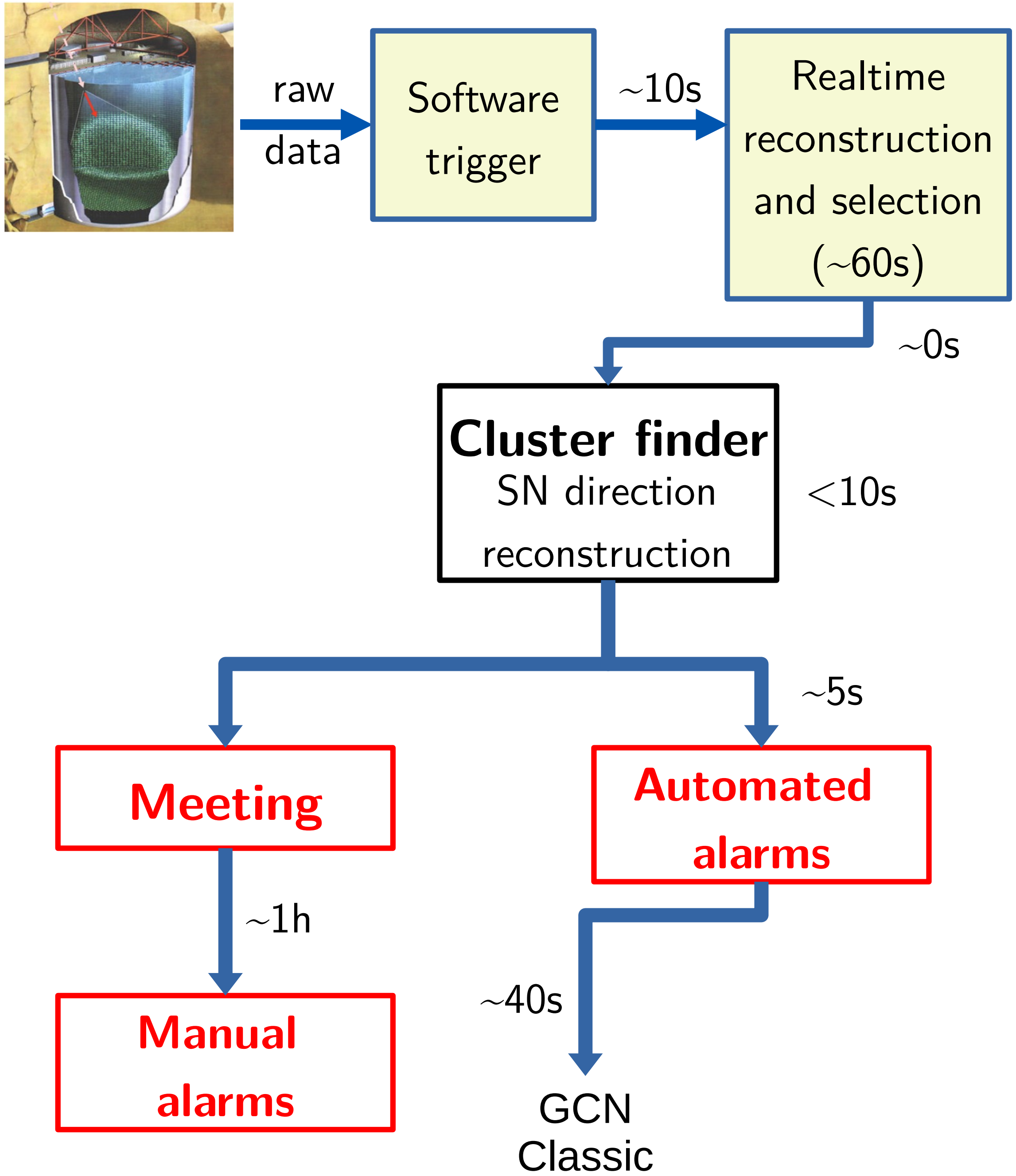
Realtime angular resolution

- In 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).



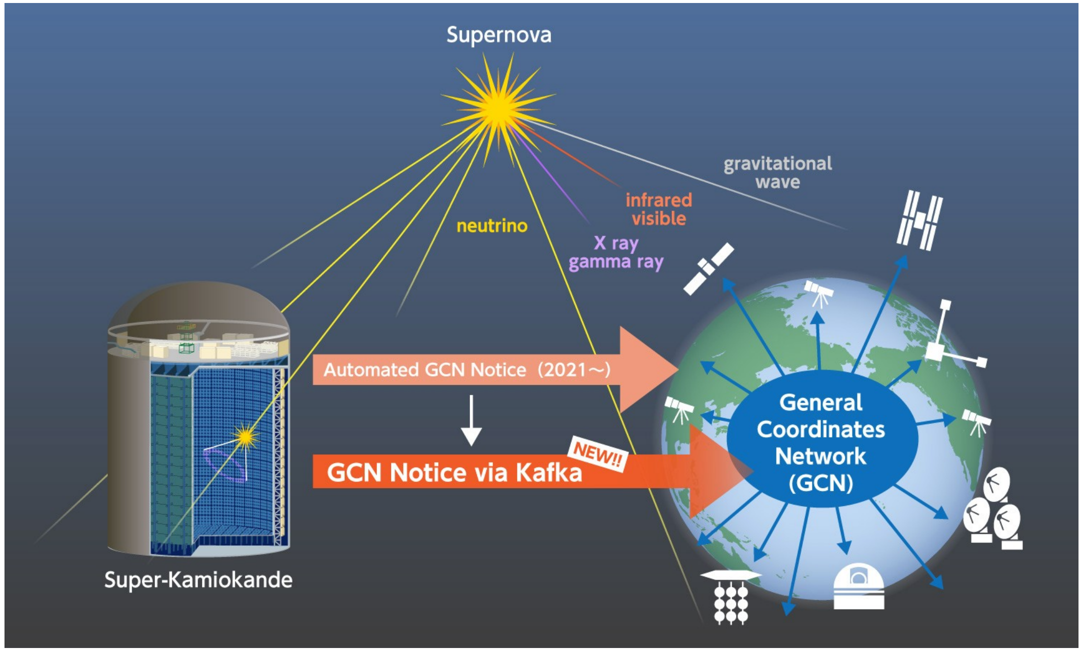
Alarm release: speed is critical

- Depending on the SN progenitor, the time difference between the neutrino burst and the electromagnetic burst can be rather small. (~minutes in case of Wolf-Rayet stars)
  - Fast alarm release is critical
  - Fast followup is also critical
- Automated alarm, through GCN (classic) were introduced in December 2021.
  - The alarm is send by mail, adding ~40 seconds delay before it reach subscribers
  - Alarm format was in machine readable format, difficult to update.



GCN Kafka upgrade

- On August 27th, we upgraded our alarm system to send alarm through GCN Kafka:
  - Much faster delivery: ~1sec
  - Flexible format (JSON)
    → Easy to update if we want to add new information
  - **GCN classic is still supported, but please consider switching to GCN Kafka to receive our alarms**
- We are investigating the possibility to send alarm earlier than currently (before the burst is fully processed) and update it afterhand thanks to the new alarm structure → critical for close SNe with large number of events

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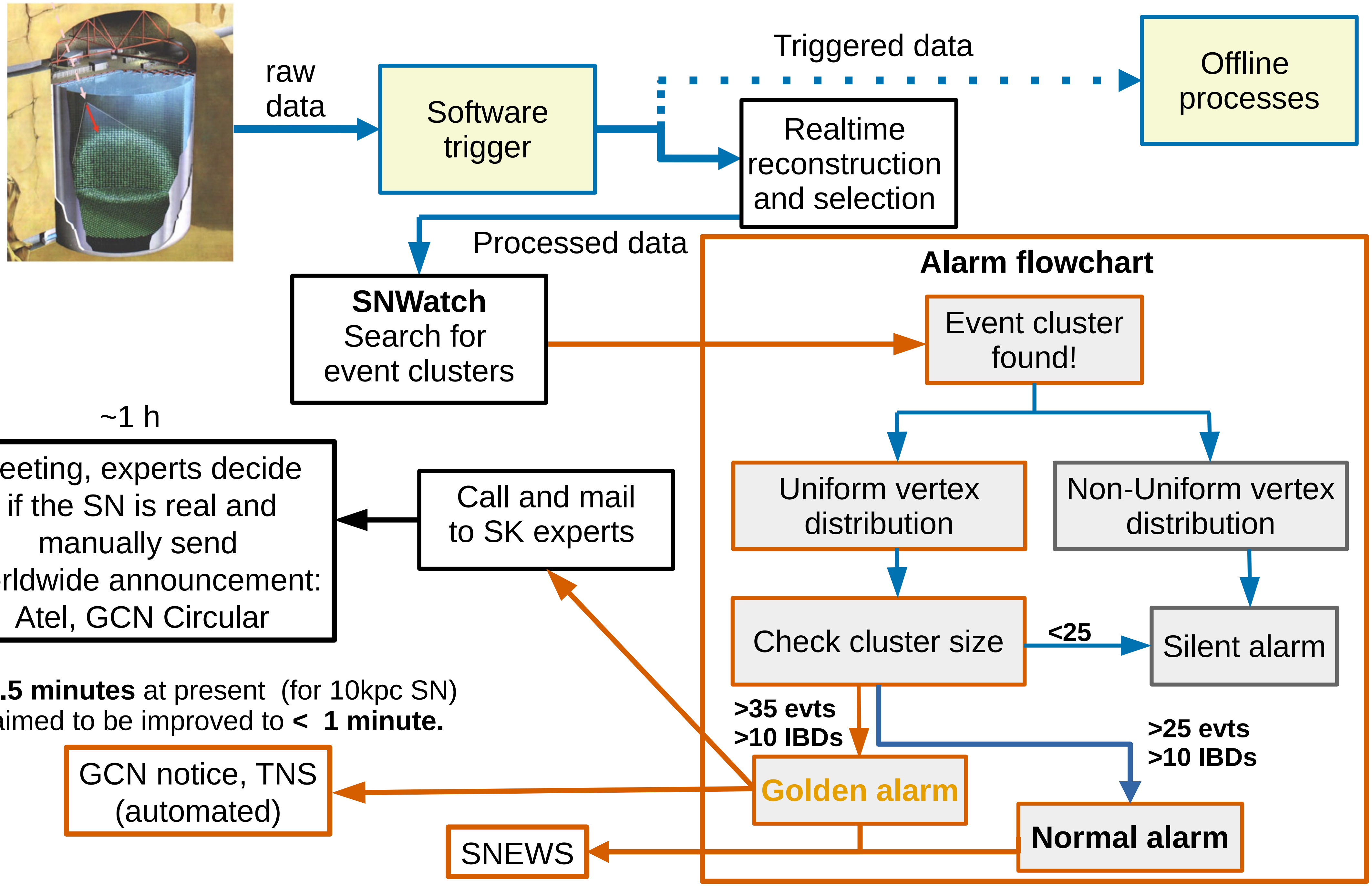
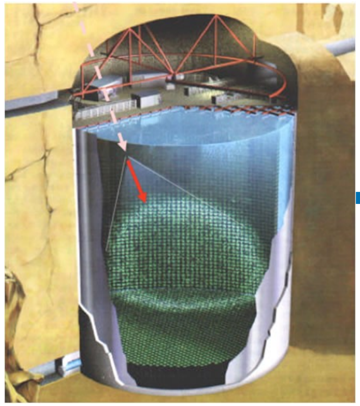
Realtime supernova monitoring in Super-Kamiokande



Realtime supernova monitoring in Super-Kamiokande



raw data

Software trigger

Triggered data

Offline processes

Realtime reconstruction and selection

Processed data

SNWatch Search for event clusters

Alarm flowchart

Event cluster found!

Uniform vertex distribution

Non-Uniform vertex distribution

Check cluster size

<25

Silent alarm

Call and mail to SK experts

~1 h

Meeting, experts decide if the SN is real and manually send worldwide announcement: Atel, GCN Circular

~1.5 minutes at present (for 10kpc SN) aimed to be improved to **< 1 minute.**

GCN notice, TNS (automated)

Transient Name Server (IAU) notices are now automated!

SNEWS

GCN Kafka upgrade

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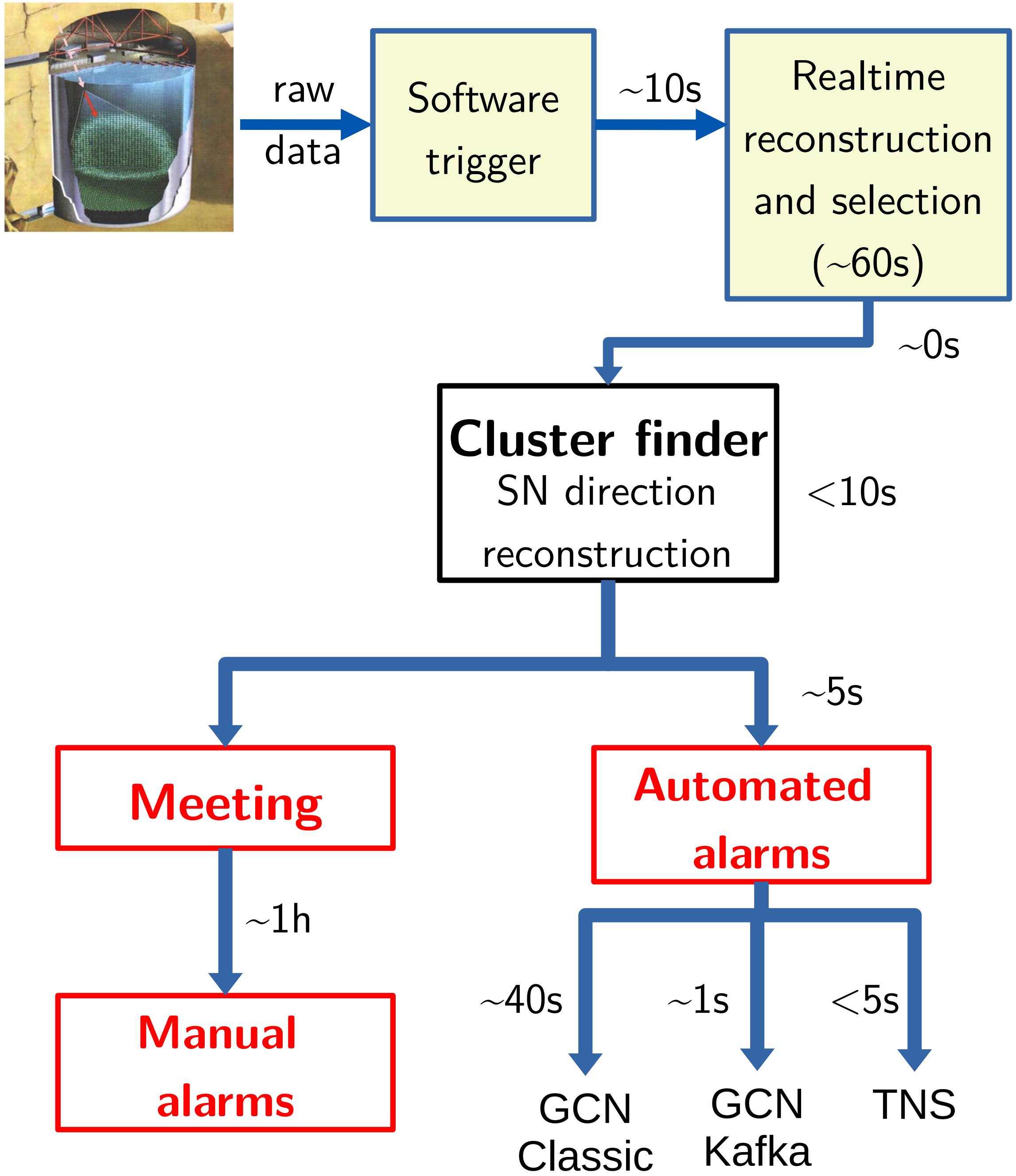
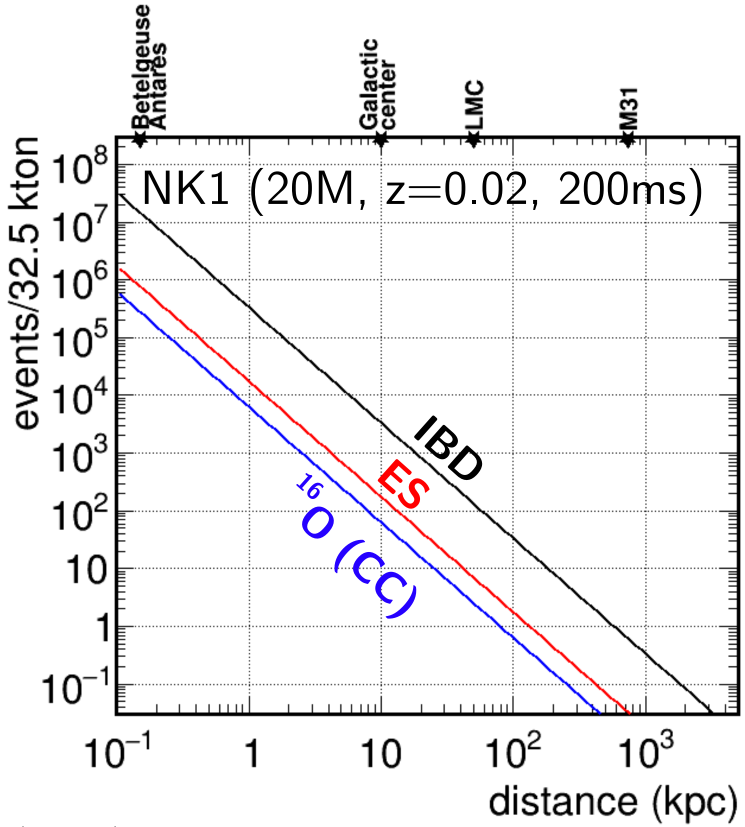
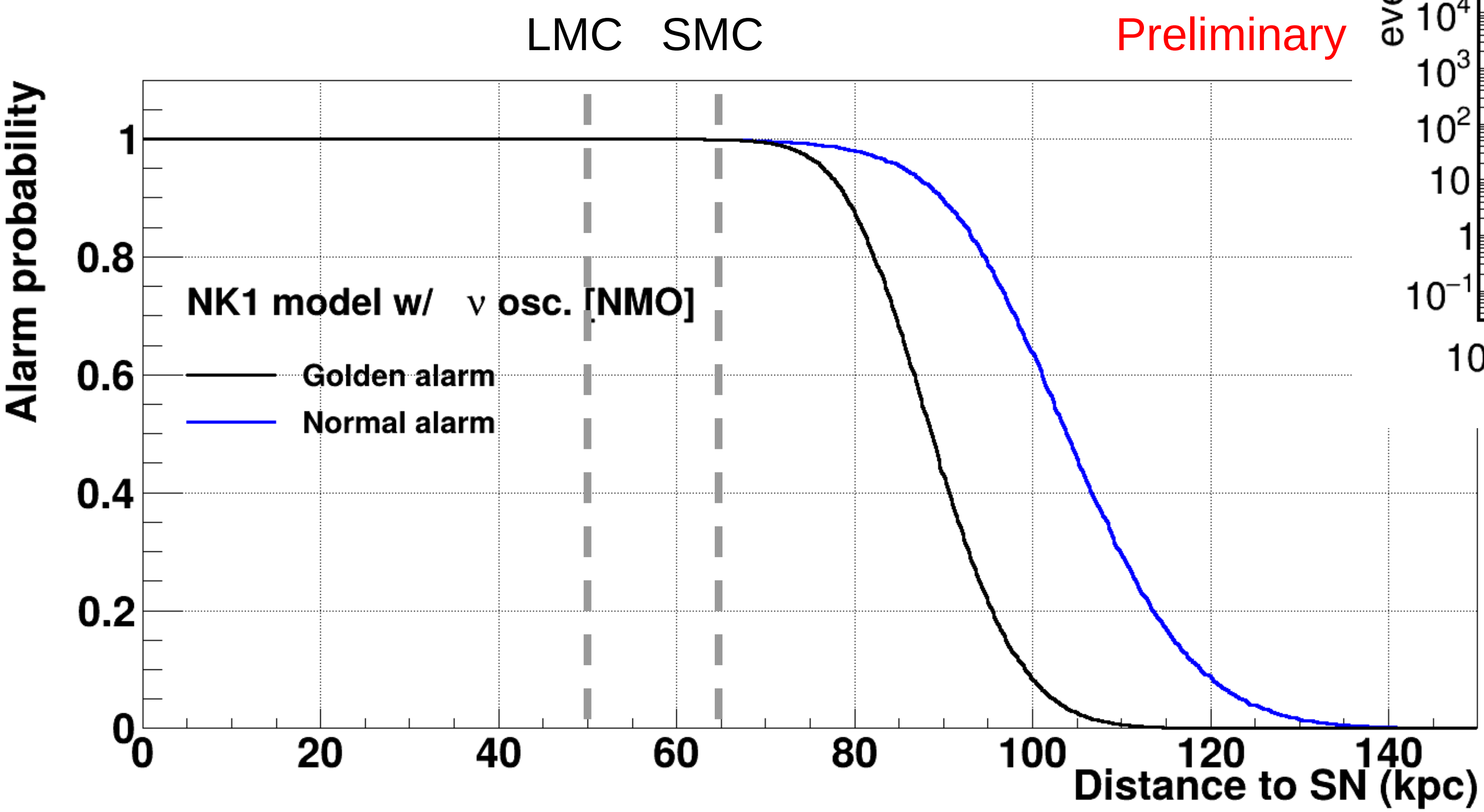


Supernova alarm in Super-Kamiokande

- 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 by Golden alarm (~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
    - Tomoe Gozen, a telescope in Japan operated by the Institute of Astronomy (University of Tokyo)
  - Discussion on-going with other telescopes (XRISM, OISTER, etc.)
  - 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!

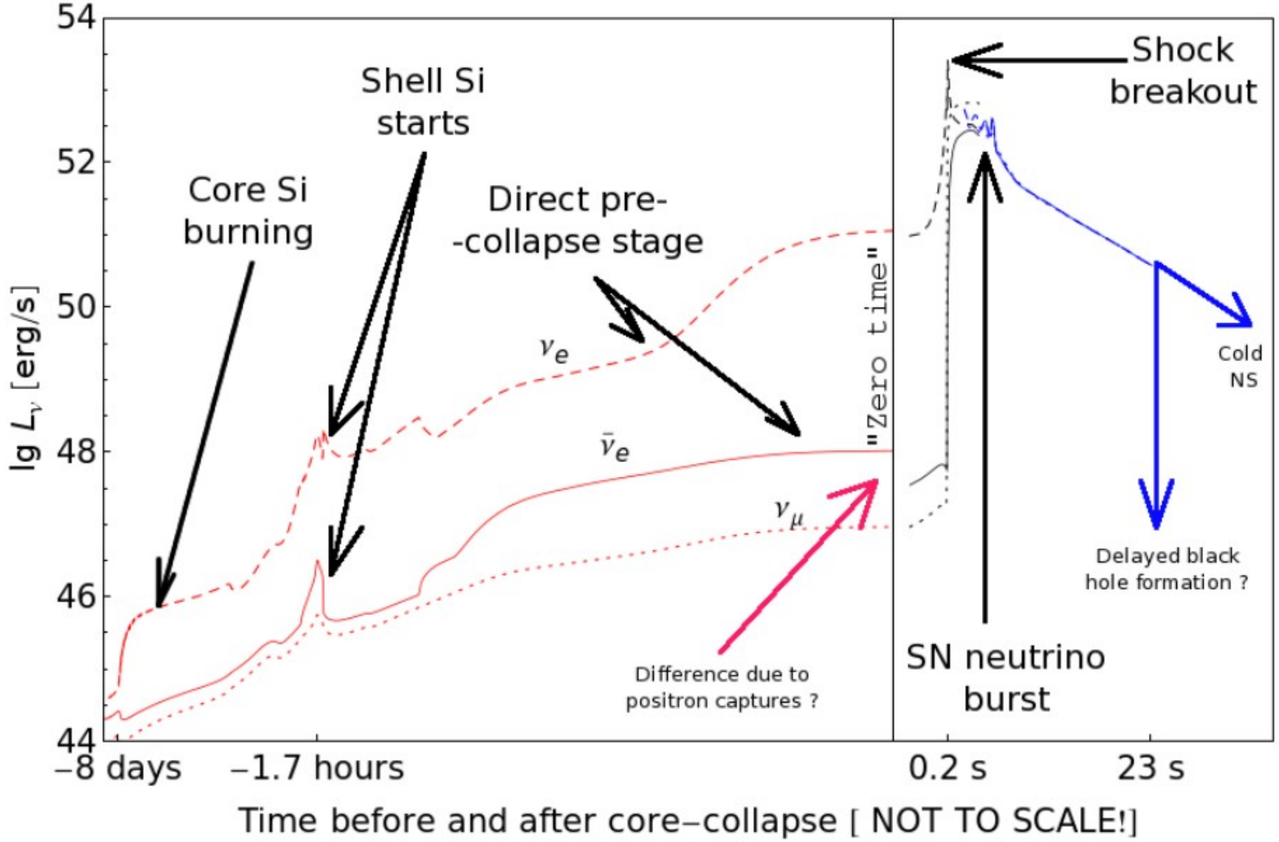
Pre-Supernova neutrinos

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 $\sim 10^{5}\ L_\odot$)

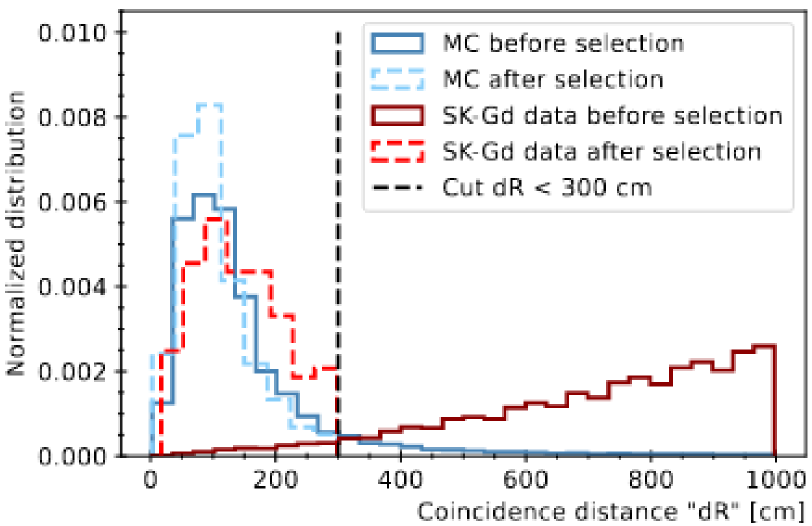
$$e^- + e^+ \rightarrow \nu_x + \overline{\nu}_x$$

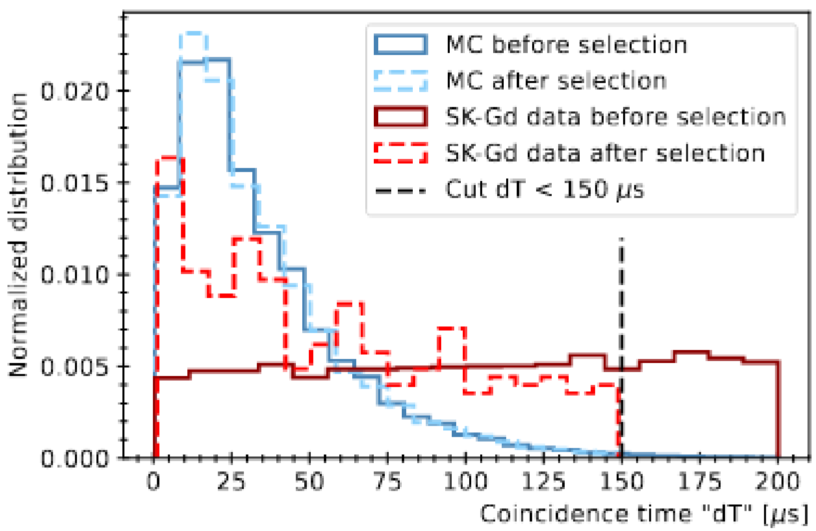
- During the Si-layer burning ($\sim$few days before the core-collapse), the average neutrino energy is above the IBD threshold (1.8 MeV), allowing a potential detection.



Pre-Supernova Neutrinos analysis

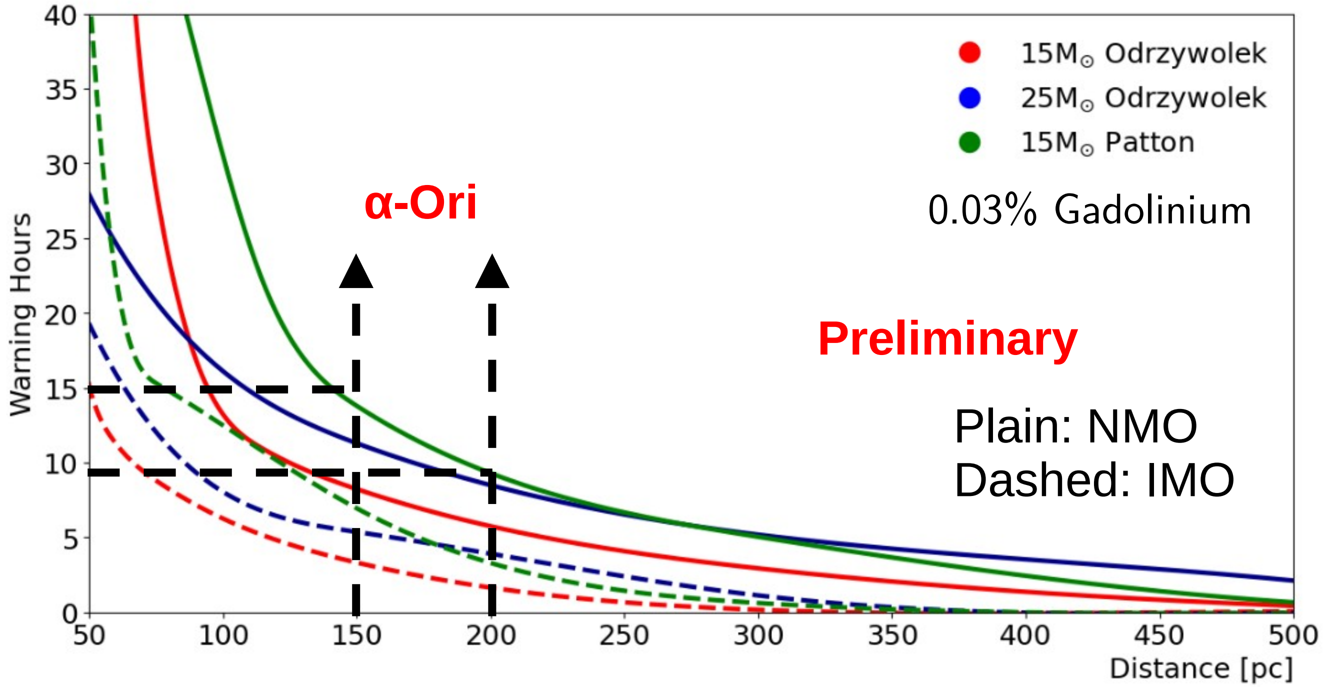
- The pre-supernova neutrino analysis in Super-K is an **online** analysis
  $\rightarrow$ We need to be fast in order to release alarm as soon as possible.
- Several analysis methods are used:
  - Two Boost Decision Trees are used in order to perform fast selection: One to perform a pre-selection of 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 ~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/



Summary

Summary

- Super-Kamiokande aims to ready for the potential detection of the next gallactic supernova. Such detection would allow to trigger a multi-messenger observation of the cataclysmic event.
- Speed and precision are critical, with fast alarm release, in order to allow fast follow-up:
  - 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
- MoUs with several telescopes in order to ensure follow-up and smooth potential Target on Observation request needs.
- Pre-supernova neutrino observation can allow to postpone calibration or down-time if the chance of a SN burst is high:
  - Potential detection **few hours** before the CCSN within 500 pc
  - Public alarm is available, combining data from Super-Kamiokande and KamLAND

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Backup

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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
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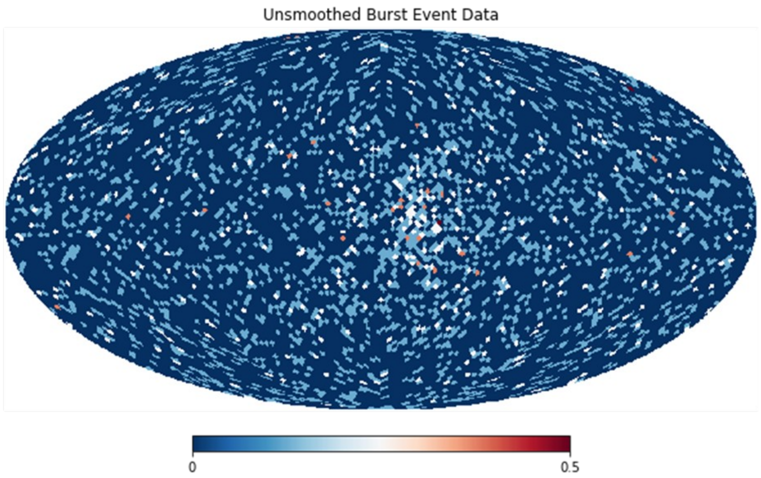
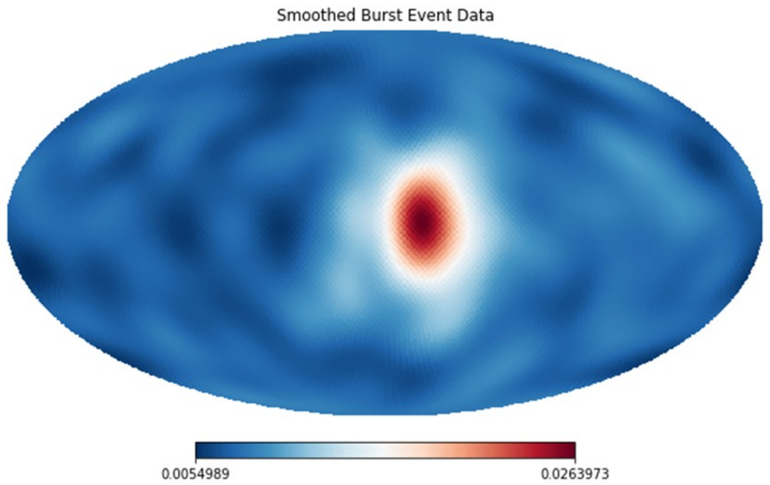
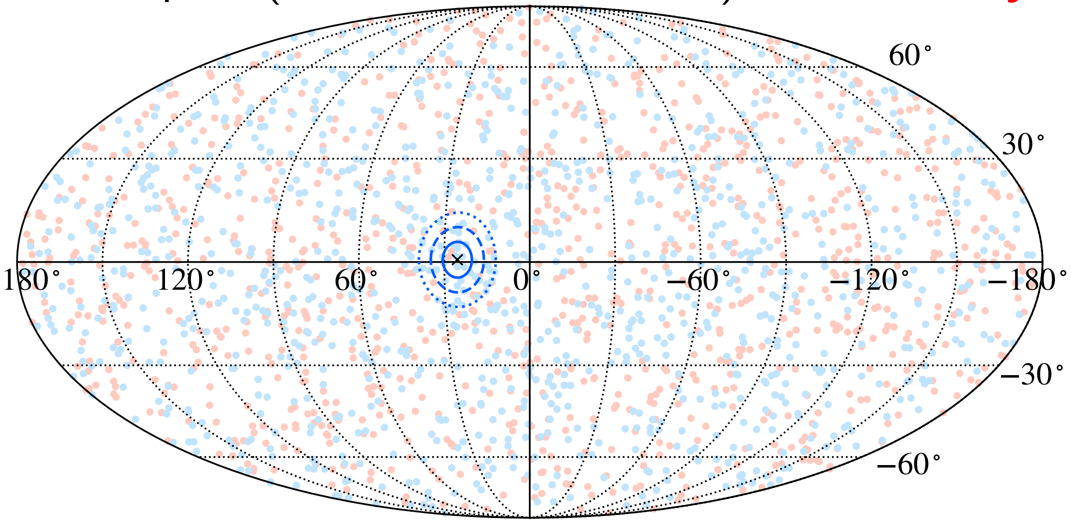


Gaussian Smoothed, σ = 0.15 rad.

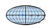


Realtime angular resolution with other models

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***

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Realtime angular resolution with other models

Nakazato (ML fitter: $4.01 \pm 0.13^\circ$) **Preliminary**

Fischer (ML fitter: $6.07 \pm 0.19^\circ$) **Preliminary**

Mori (ML fitter: $4.55 \pm 0.14^\circ$) **Preliminary**

Tamborra (ML fitter: $5.09 \pm 0.16^\circ$) **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

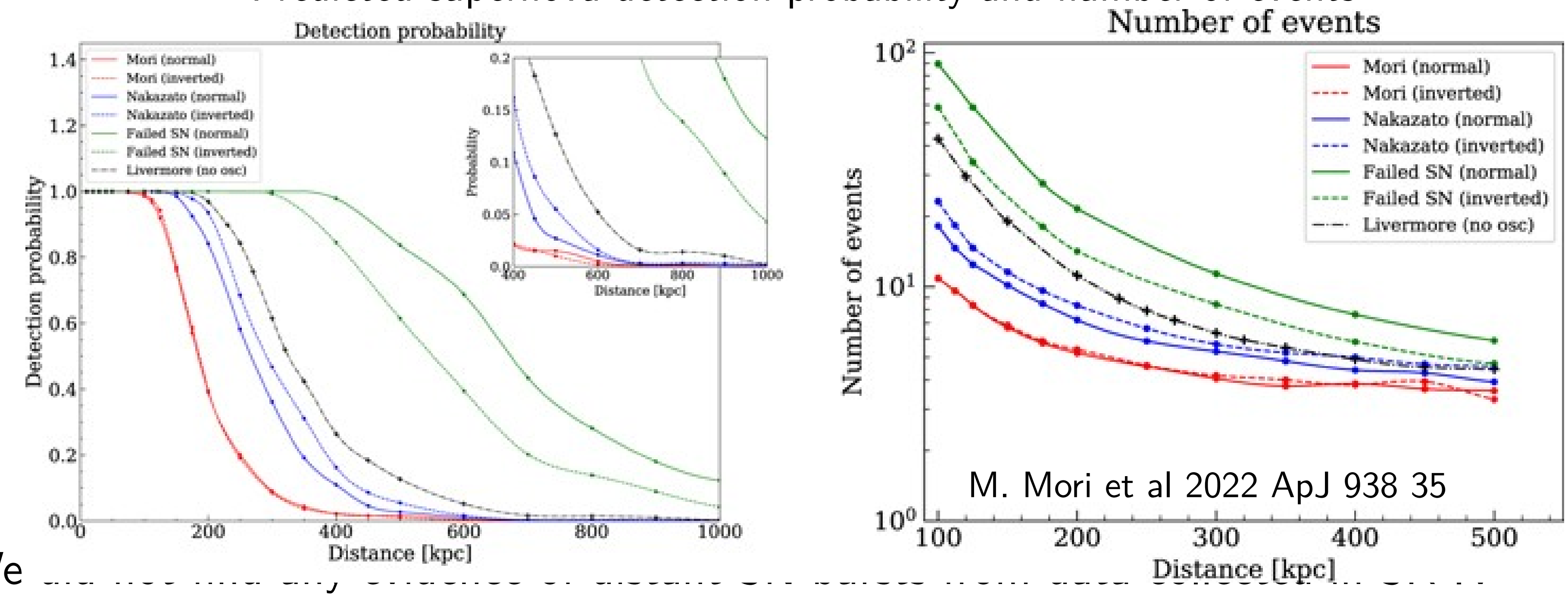
Reference [1] Totani, T., et al. *ApJ* 496.1 (1998): 216
[2] Nakazato, K., et al. *ApJS* 205.1 (2013): 2
[3] Mori, M., et al. *PTEP* 2021.2 (2021): 023E01
[4] Hüdepohl, L., et al. *PhRvL* 104.25 (2010): 251101
[5] Fischer, T., et al. *A&A* 517 (2010): A80
[6] Tamborra et al. *PRD* 90.4 (2014): 045032.

*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.

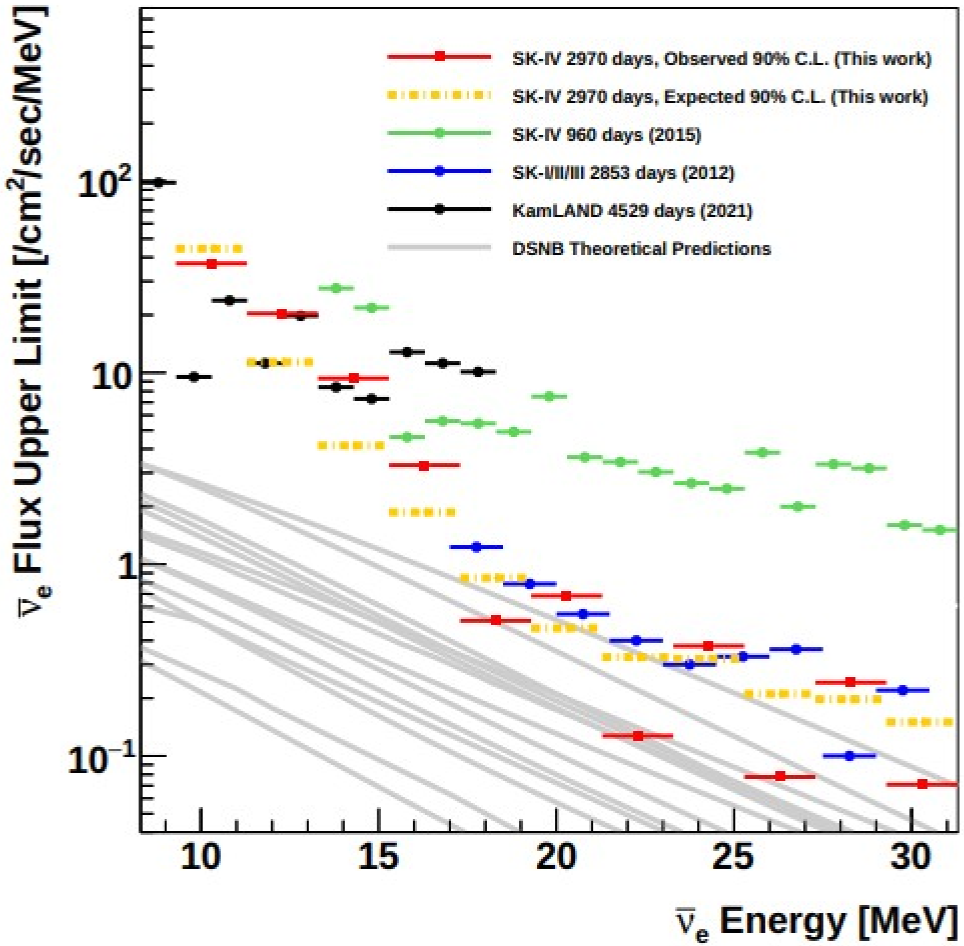
Predicted supernova detection probability and number of events

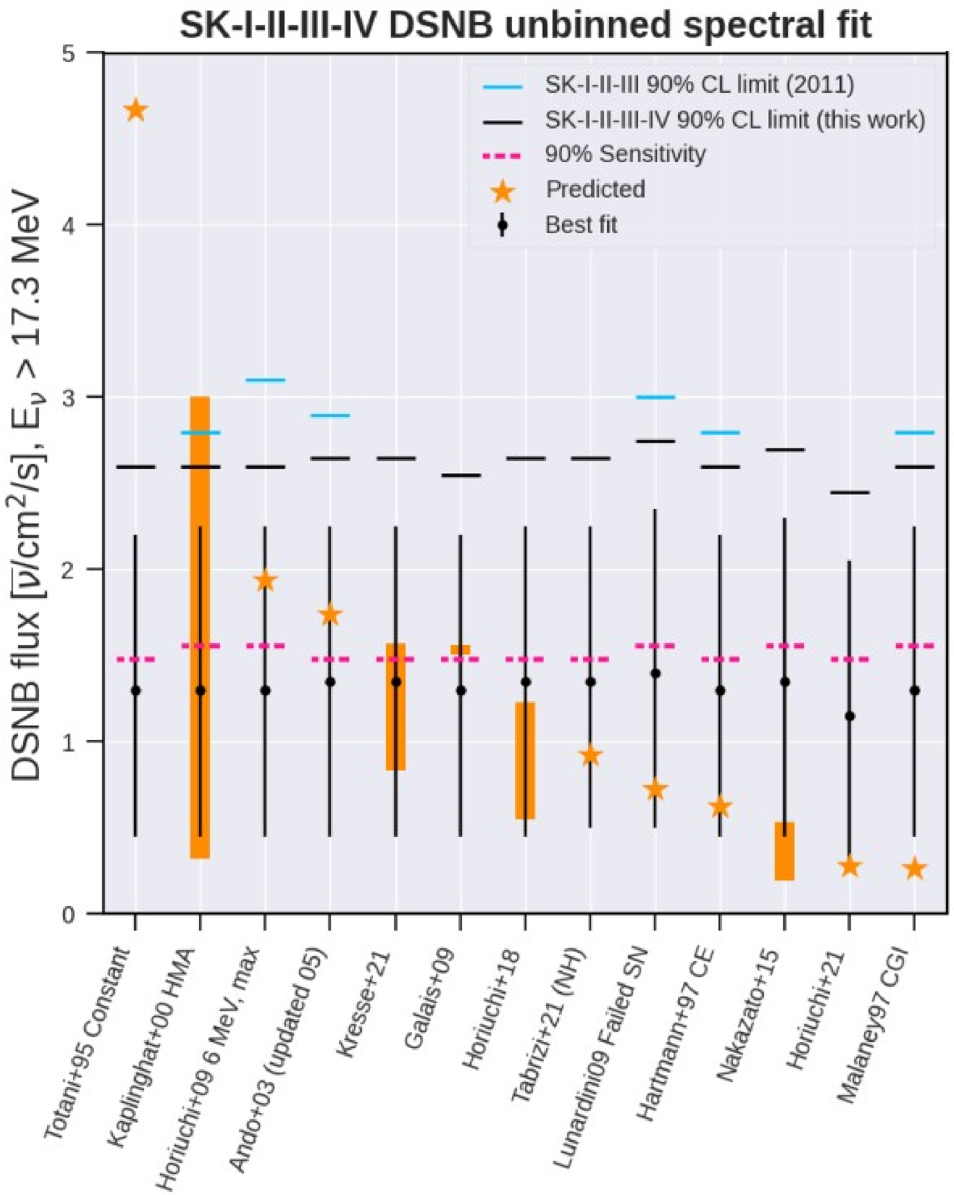


- We
(2008~2018), allowing to define the following upper limits:
→ $<$ **0.29 yr^{-1}** supernovae out to 100 kpc (300 kpc for failed supernovae)
- Coincidence with SN2023ixf was also investigated, but no significant signal was observed (ATEL 16070, GCN circular 33916)

Diffuse Supernova Neutrino Background limits

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





Results for SK-IV (without Gd)