Supernova neutrino detection in Super-Kamiokande and Hyper-Kamiokande

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Synergies at new frontiers at Gamma-rays, Neutrinos and Gravitational Waves, March 24th 2022

科研費
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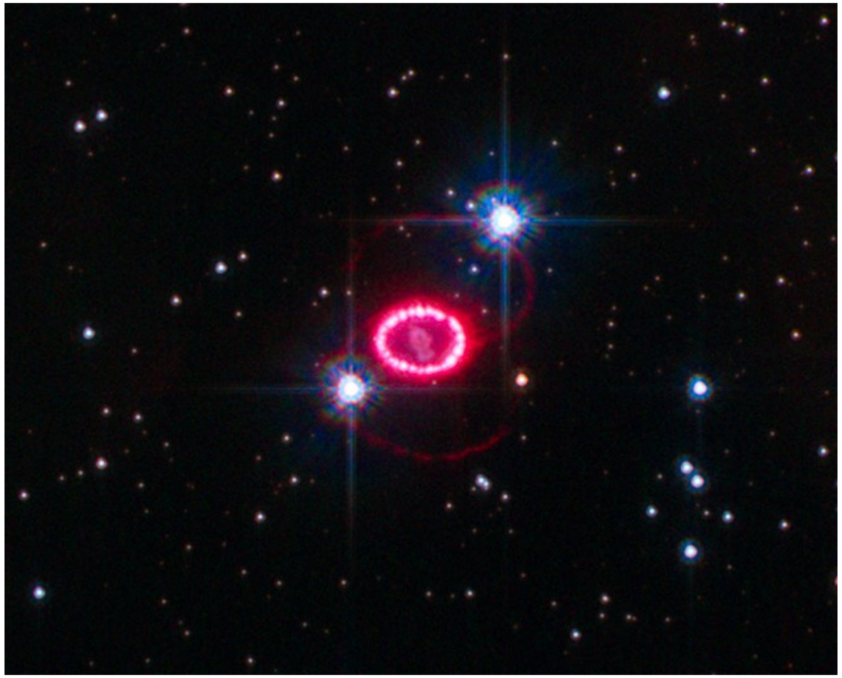
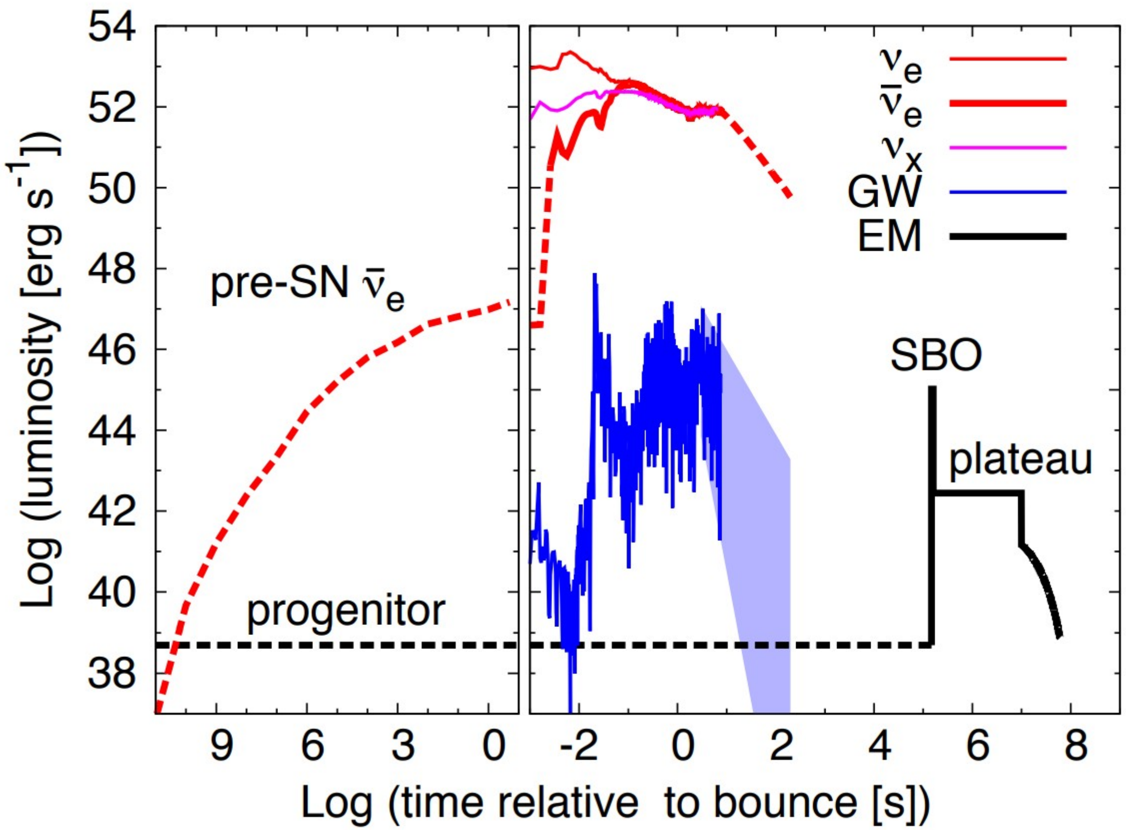
(Supported by KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas JP17H06365)

Core-Collapse Supernova Neutrinos



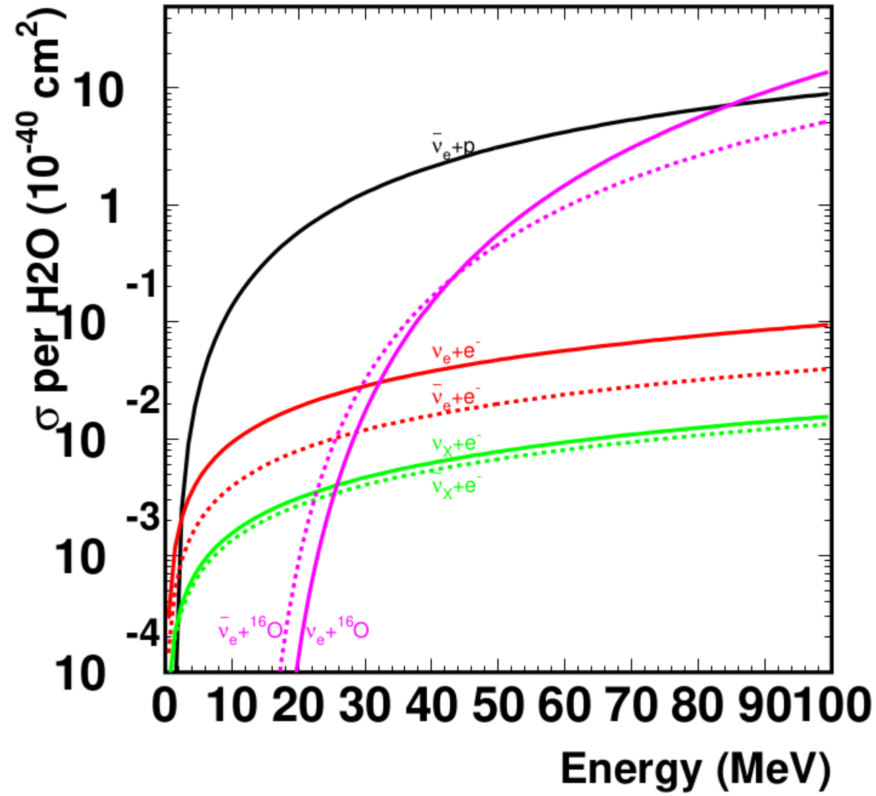
SN1987A remnant

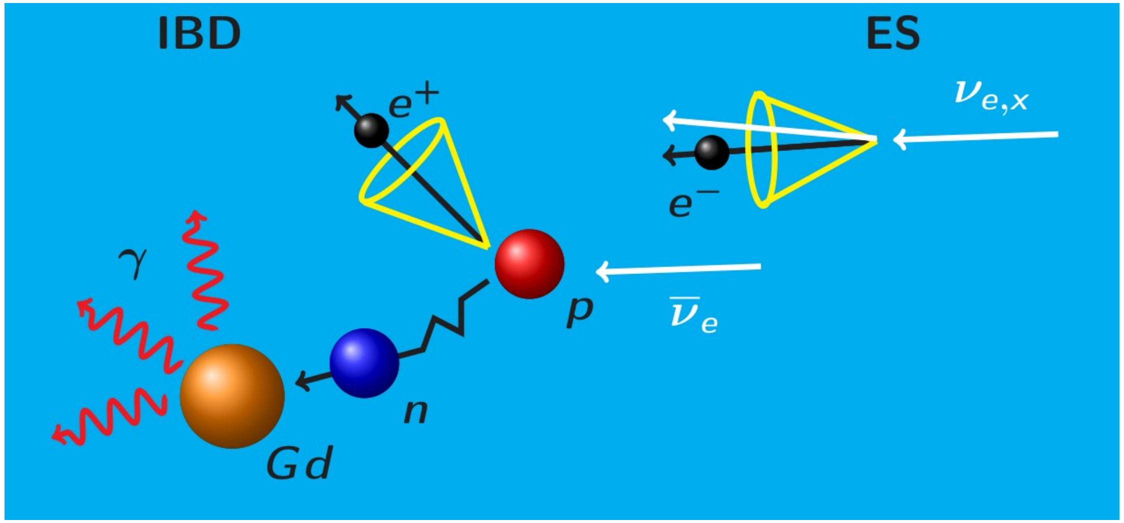


- Since 1987A supernova (SN), we know that in case of supernova a burst of neutrino is expected to be produced few minutes to several hours before the stellar explosion.
- If the SN is close enough, we can detect this burst on Earth and give an early warning to astronomers looking for the light from the stellar explosion.

Supernova Neutrinos in Water Cherenkov Detectors

- The SN neutrino burst is composed of (roughly) similar amount of neutrino and antineutrino of each flavours. However, due to cross-sections, the number of detected neutrino interaction will be different.
- In case of Water Cherenkov detector, the main interactions expected are:
  - Inverse Beta Decay reaction (IBD)
    $\rightarrow \sim$90% of the expected interactions
  - Electron Scattering interactions (ES)
    $\rightarrow \sim$5% of the expected interactions
    Keep the neutrino direction information
  - ^{16}O interactions (CC and NC)
    $\rightarrow \sim$5% of the expected interactions

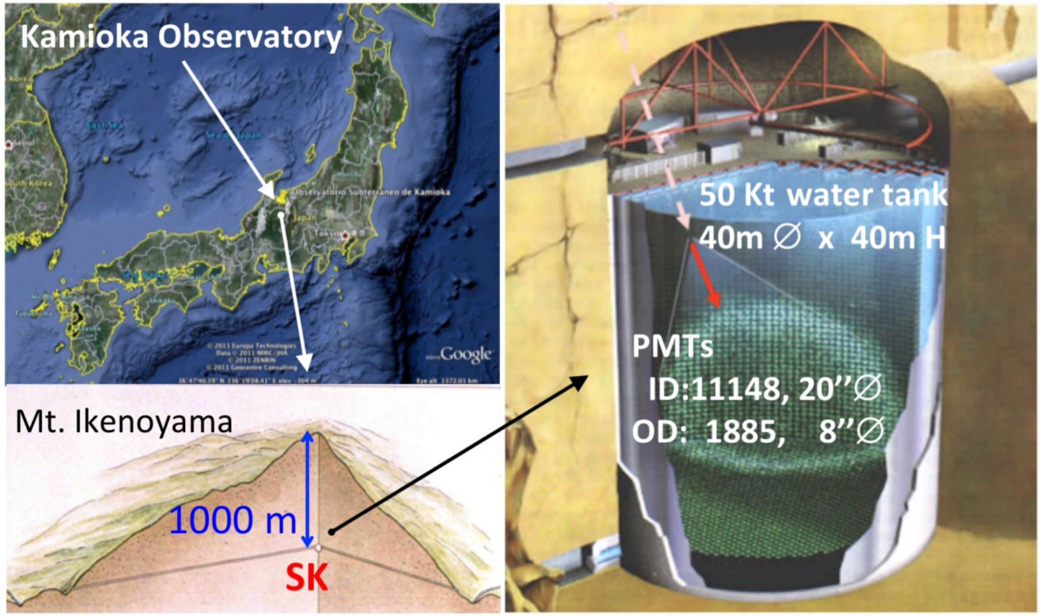


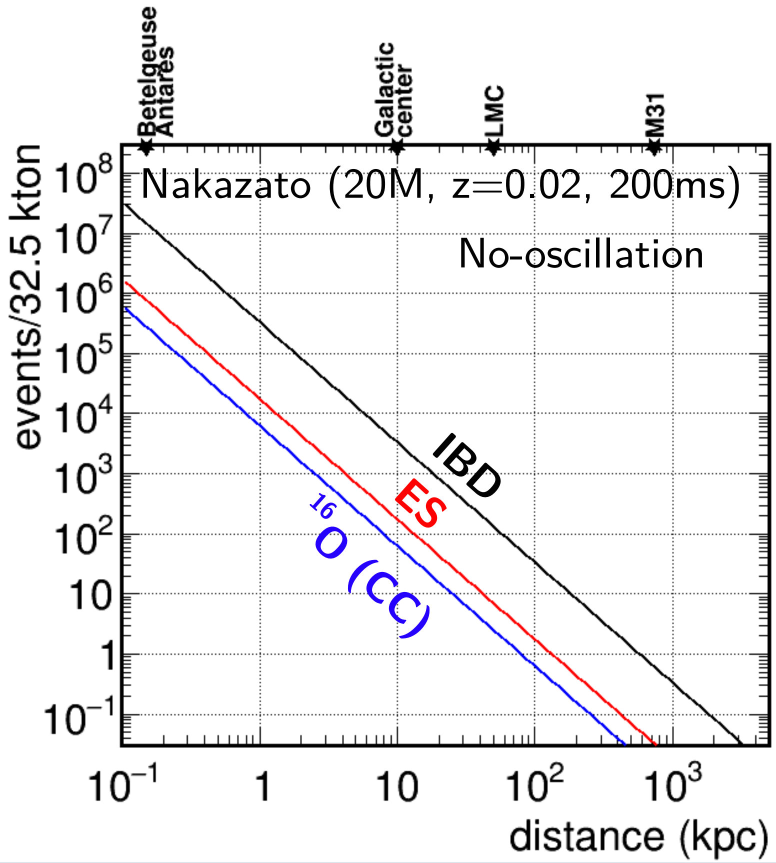


Supernova Neutrino in Super-Kamiokande

Supernova Neutrino in Super-Kamiokande

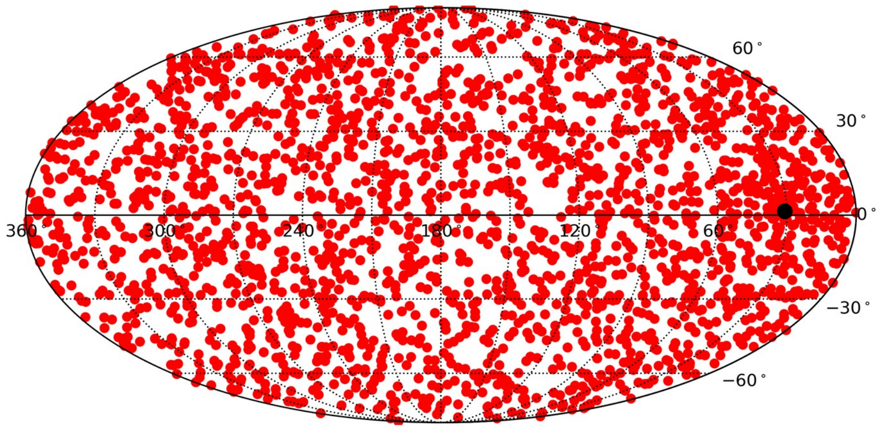
- Super-Kamiokande (SK) is a Water Cherenkov detector located in Kamioka, Japan, operating for ~25 years.
- The detector is filled with 50ktons of water, loaded with 0.01% of gadolinium (Gd) since summer 2020 to improve the detection of neutron produced during (anti)neutrino interactions.
- In case of supernova, SK would detect a burst of events for SN happening up to $>$100kpc (depending on the models assumed).



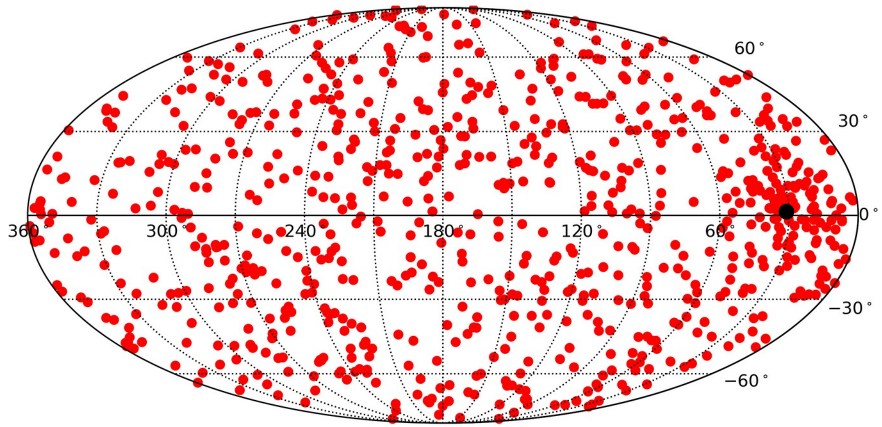


Using Gd-n to separate IBD and ES

- 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.

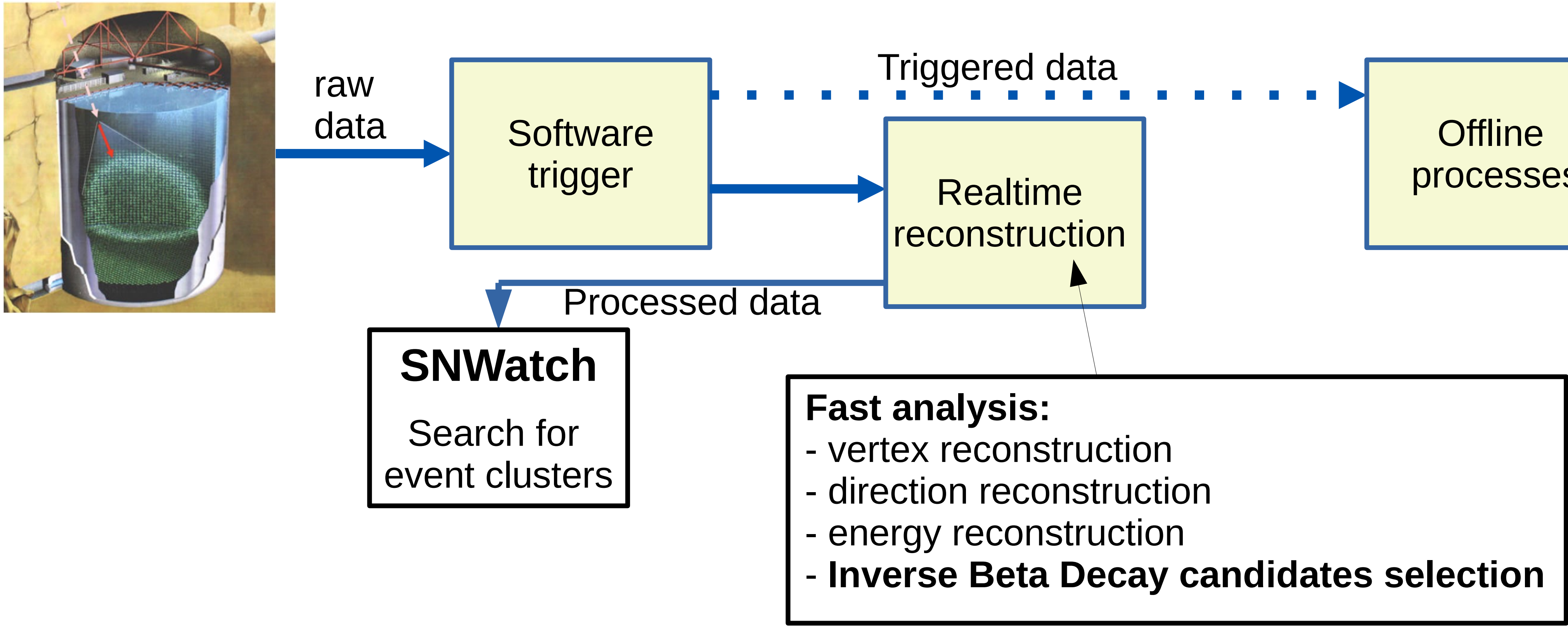


SN burst events w/o IBD tagging
(10kpc simulation)



SN burst events w/ 72% IBD events tagged/removed
(10kpc simulation)
$\rightarrow$ **Our goal**
(Expected with 0.1% Gd, goal of SK-Gd)

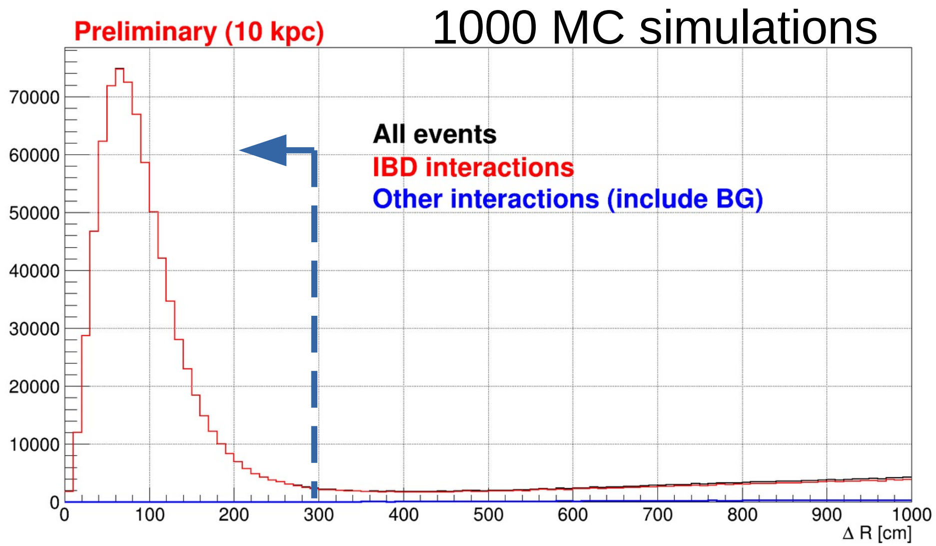
Realtime supernova monitoring in Super-Kamiokande

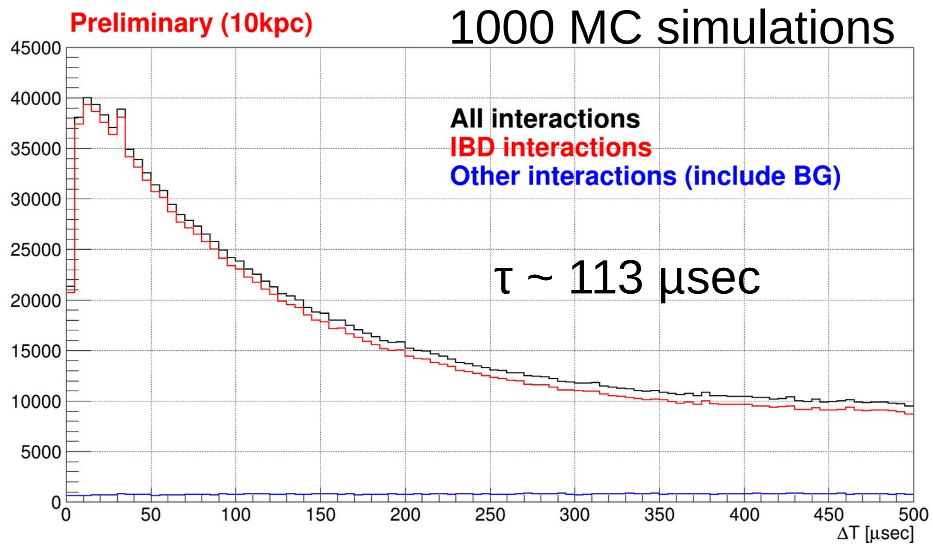


SK shifters are keeping watch to ensure these online processes are always running

IBD selection

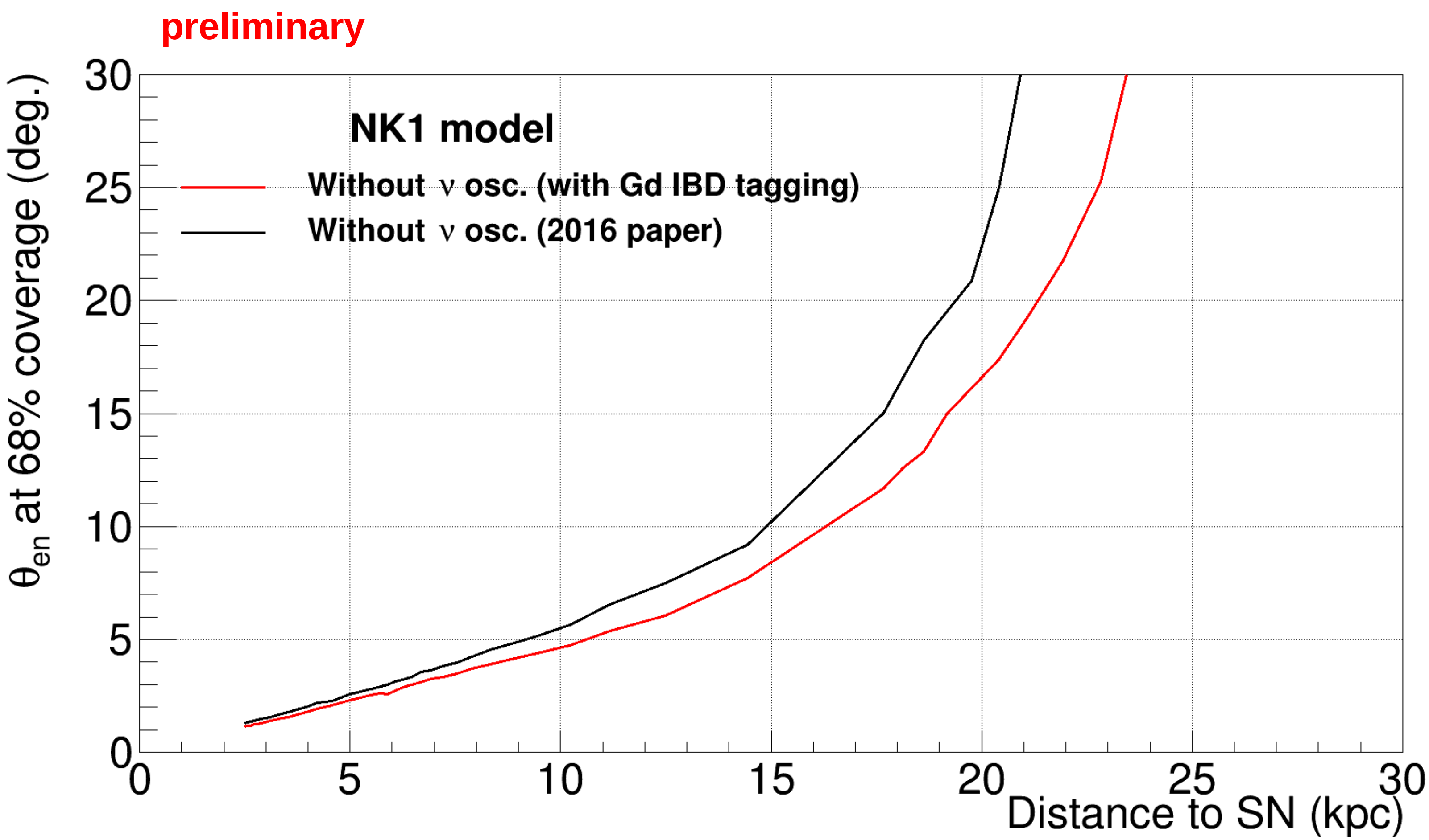
- From the sample of reconstructed events, we separate **"prompt-like"** candidates (events with $E > 7$ MeV) and **"delayed-like"** candidates (events with $E < 7$ MeV). Time and space correlation between "prompt-like" and "delayed-like" candidates allow to build an IBD candidates selection:
  - Positions and time of **each** prompt candidates are compared with those of **each** delayed candidates. Pair of events with $\Delta T < 500$ µsec, and $\Delta R < 300$ cm, are selected as IBD candidates.
- This selection algorithm allows tagging ~**33% IBD** events with the current Gd loading (65% if scaled to 0.1% Gd loading).





Pointing accuracy with IBD tagging

- With 33% IBD tagging efficiency, the supernova direction pointing accuracy is improved by 10∼30% between 2.5 and 25 kpc (0.6 degree improvement at 10 kpc)



Super-Kamiokande: Alarm release time (I)

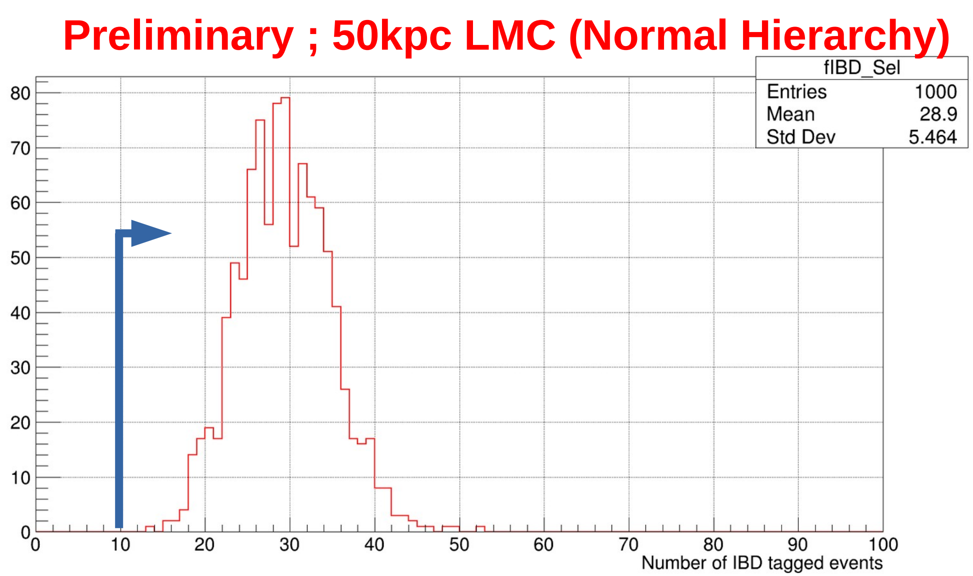
- For Supernova monitoring distributing **fast alarm** is **critical** to allow astronomers to observe the SN burst light.
- Up to recently, it was taking a long time for SK to release an alarm, this long processing time coming from:
  - Event reconstruction ~3 min for 10 kpc SN (~10 min for 3 kpc SN)
  - Supernova direction reconstruction ~5 min for 10 kpc SN (~10 min for 3 kpc)
  - Experts meeting to take decision to release an alarm and send the alarm.
    $\rightarrow$ In average ~1h was needed to send the alarm
- For some stars (ex: Wolf-Rayet stars) in case of supernova, the delay between the neutrino burst and the light is only few minutes. Faster processing time is then needed.
- Super-Kamiokande SNWatch team is currently working on improving this processing time.

Super-Kamiokande: Alarm release time (II)

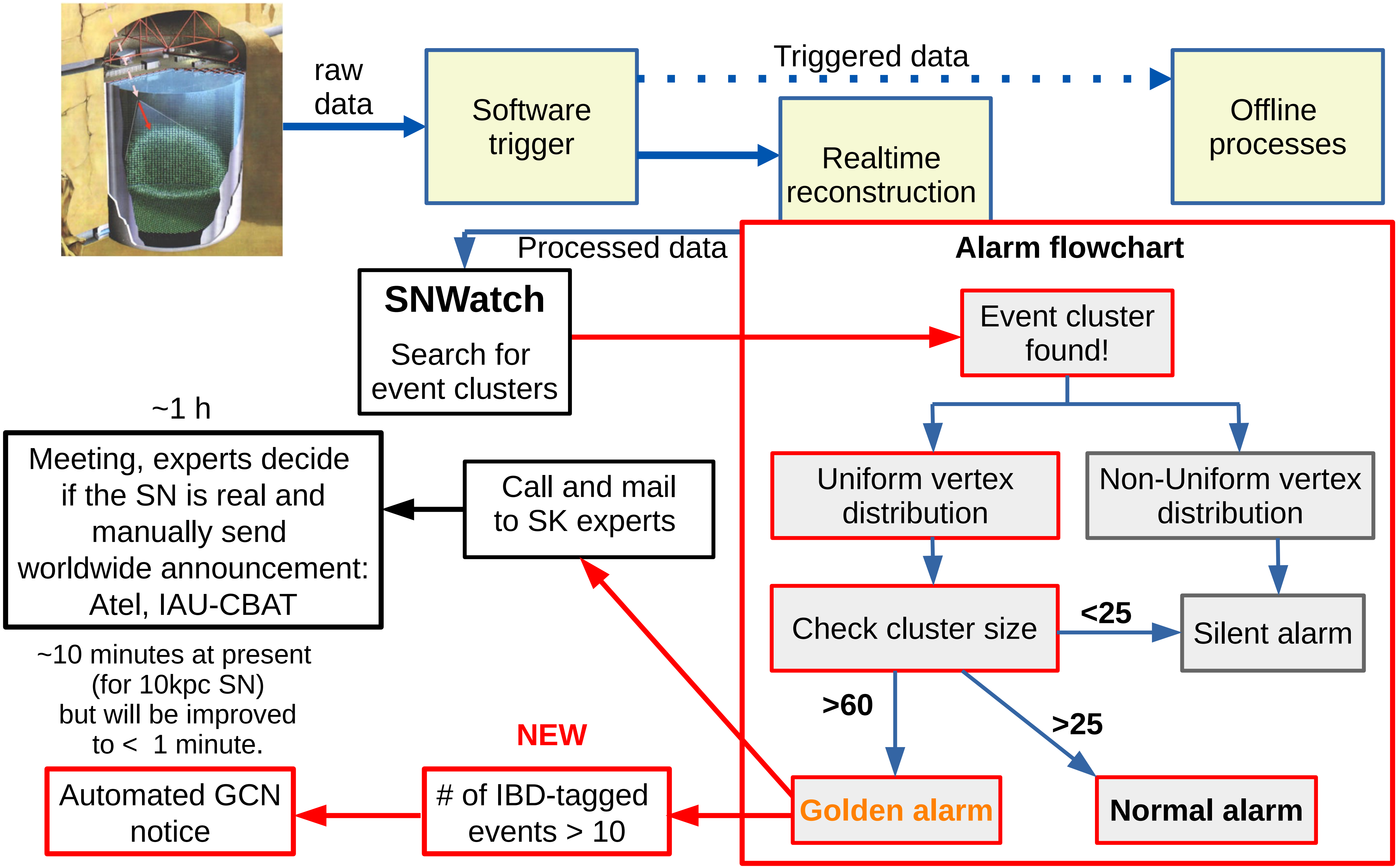
- Thanks to software and algorithm upgrades SNWatch processing time is going to be largely improved:
  - Event reconstruction: Improved by using multi-threading
    $\rightarrow$ <1 min for 10 kpc SN (~5 min for 3 kpc SN)
  - Supernova direction reconstruction: Under investigation, promising results
    $\rightarrow$ ***Preliminary*** results indicate ~2 sec for 10 kpc SN (<5 sec for any SN)
  - Alarm release: automated alarm shortly after the SN direction reconstruction (see next slide)
    $\rightarrow$ Alarm could be released in about 1 minute following the SN burst (Preliminary)

Super-Kamiokande: Automated alarm

- With the implementation of the IBD tagging algorithm, we now have an unfalsifiable signal for SN burst: IBD tagging has a low BG contamination, and any burst of IBD uniformly distributed in the detector will be a clear SN signal.
- Thanks to this, we are confident the burst signals passing our selection criteria will be true supernovae and can be automatically distributed to the astronomer community.
- Since December 13th 2021, we activated an automated GCN notice process in SNWatch:
  - If SNWatch detects a SN burst passing our selection criteria: uniform event distribution in the detector, and cluster size $>$ threshold. It will automatically distribute a **GCN notice** if the number of IBD tagged events is > 10.
  - The 10 IBD threshold was selected in to ensure a full coverage of the Milky Way and its main satellite galaxies (up to LMC).

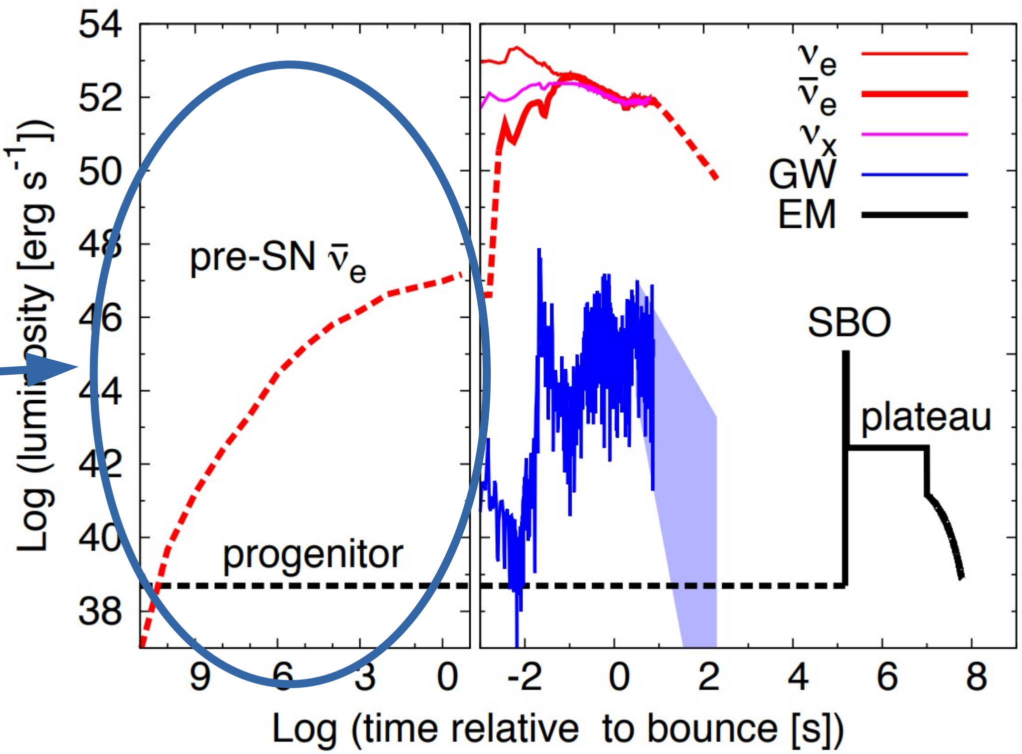


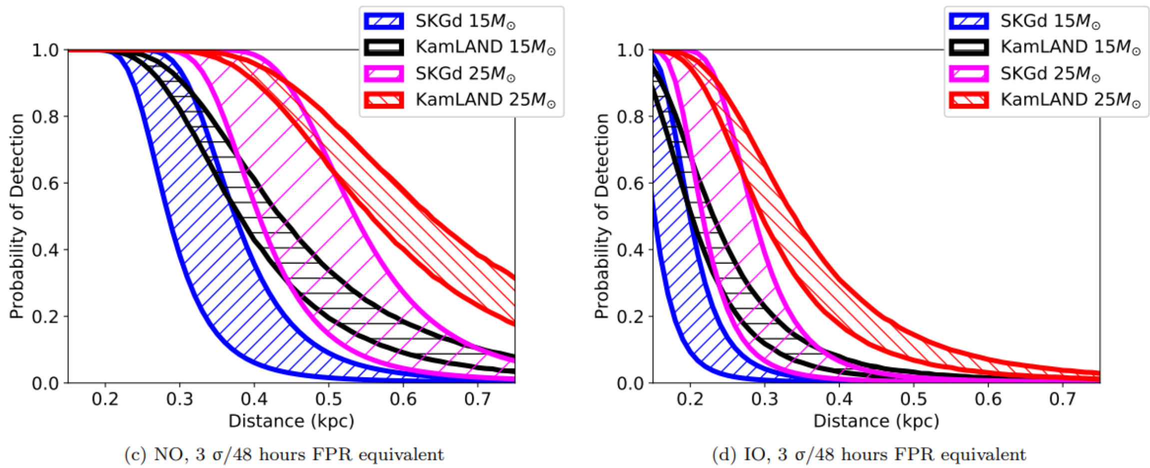
Realtime supernova monitoring in Super-Kamiokande



Pre-Supernova Neutrinos

- Before the core-collapse SN, the star start to produce a flux of electron antineutrino as the metal-layers (C, Ne, O, Si) are burned.
- From the Si-layer these electron antineutrinos average energy is above the IBD threshold and they then can be detected in a water Cherenkov detector if the star is close enough.
- SK is developing a system to monitor these pre-SN neutrino in order to send ar alert if the rate is above a certain threshold.
- We are preparing a paper on this alarm system and updated sensibilities





(c) NO, 3 σ/48 hours FPR equivalent
(d) IO, 3 σ/48 hours FPR equivalent

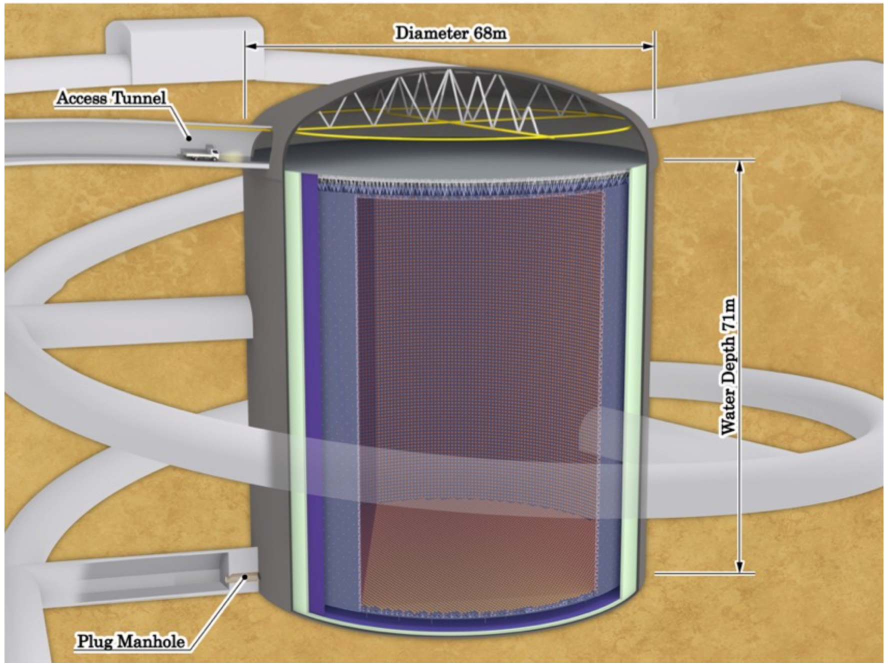
Sensibility at 0.1% Gd loading. Odrzywolek model
C. Simpson et al. Ap.J. 885(2019):133

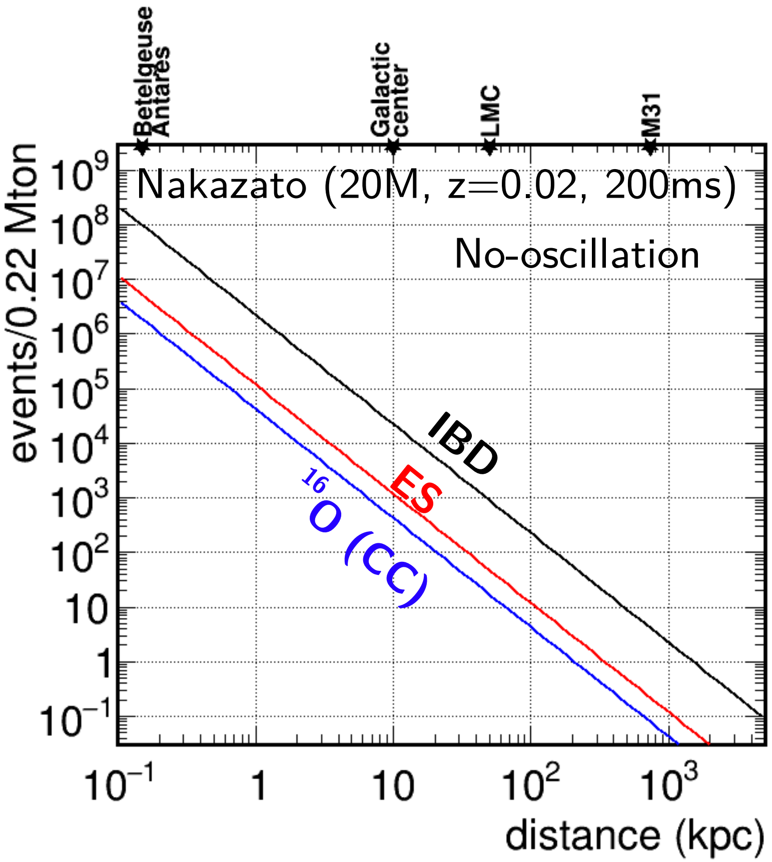
Supernova Neutrino in Hyper-Kamiokande

Supernova Neutrino in Hyper-Kamiokande

- Hyper-Kamiokande (HK) is Super-Kamiokande's future successor. It will be a water Čherenkov detector filled with 260 ktons of pure water (~x5 SK).
- Tunnel and cavern excavation are on-going, the detector is expected to start in 2027.
- HK will be able to cover the full Milky Way and its satellite galaxies, and could cover M31 (Andromeda) depending on the models (and neutrino mass ordering)

  Thanks to its larger inner detector volume (~x7 SK) would detect a much larger amount of events in case of close galactic SN.





Supernova Neutrino in Hyper-Kamiokande (II)

- With the large statistics HK will collect in case of Supernova burst detector, model discrimination could be performed using the observed event times and energies.
- Studies show HK will allow to identify the supernova models that best match the observed burst and so exclude some class of models.

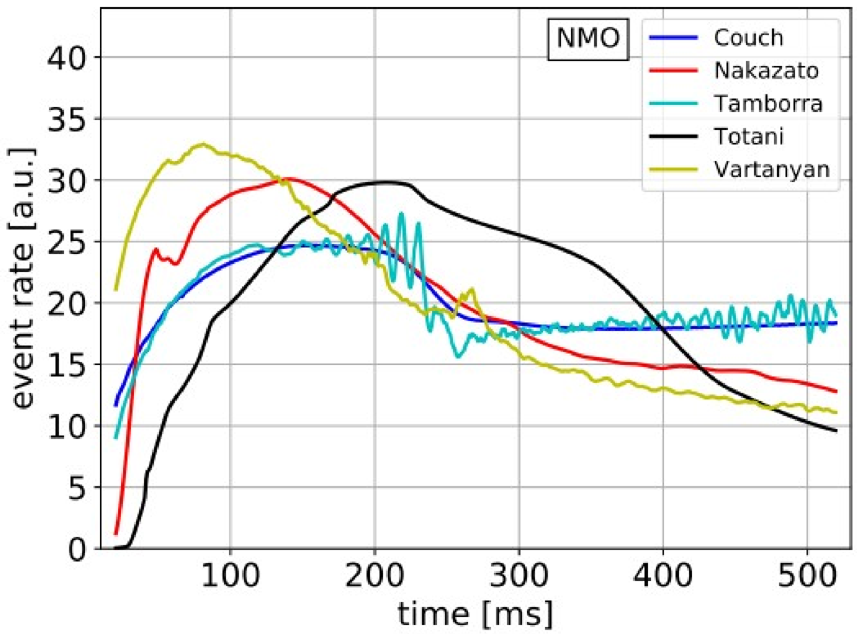
True Model (rows) vs. Reconstructed Model (columns):

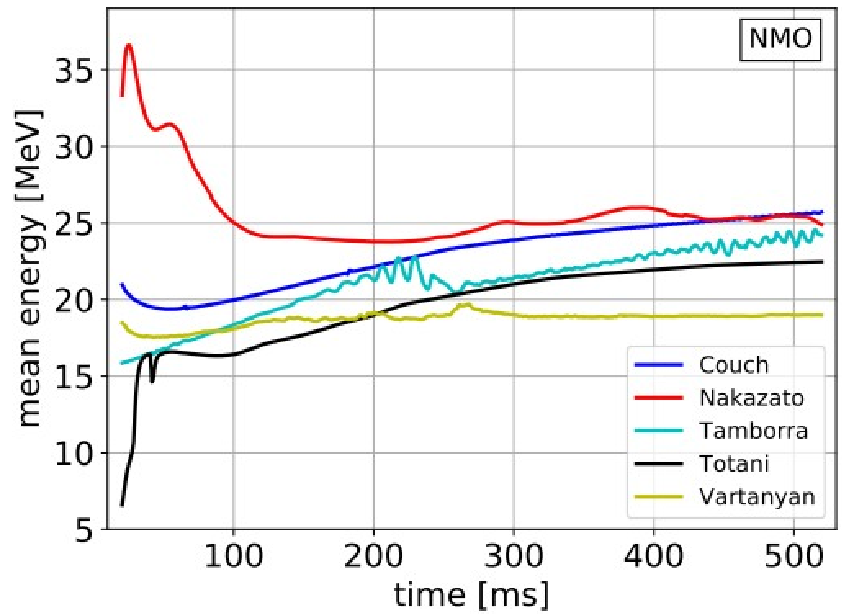
Normal	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	**98.2**	0.2	1.6	0.0	0.0
Nakazato	0.1	**99.9**	0.0	0.0	0.0
Tamborra	1.6	0.0	**98.0**	0.2	0.2
Totani	0.0	0.0	0.0	**100.0**	0.0
Vartanyan	0.0	0.0	0.0	0.0	**100.0**

True Model (rows) vs. Reconstructed Model (columns):

Inverted	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	**99.9**	0.1	0.0	0.0	0.0
Nakazato	0.0	**100.0**	0.0	0.0	0.0
Tamborra	0.0	0.0	**97.4**	0.1	2.5
Totani	0.0	0.0	0.0	**100.0**	0.0
Vartanyan	0.0	0.0	0.8	0.0	**99.2**

Results for 300 events detected → 56~59 kpc





K. Abe et al., ApJ 916 15

Summary

- Super-Kamiokande is continuously monitoring the detector events to probe any burst indicating a supernova.
  - Recent progress has been done on the angular resolution of the reconstructed supernova direction allowing to improve the SN pointing accuracy by **0.6 deg at 10 kpc** (Nakazato model) with Gd-n IBD tagging.
  - Thanks to the **automated GCN notice system** implementation, the delay before sending an alarm to astronomers has been reduced to ~10 minutes for 10kpc SN and we expect to reduce to ~1 minute within this year.
- Hyper-Kamiokande is expected to start in 2027
  - Large statistics expected in case of galactic supernova.
  - Hyper-Kamiokande supernova monitoring system is under development to handle such high rate and provide fast alarm.
  - Hyper-Kamiokande could identify the supernova models that best match the observed neutrino burst, thus allowing to exclude some class of models.

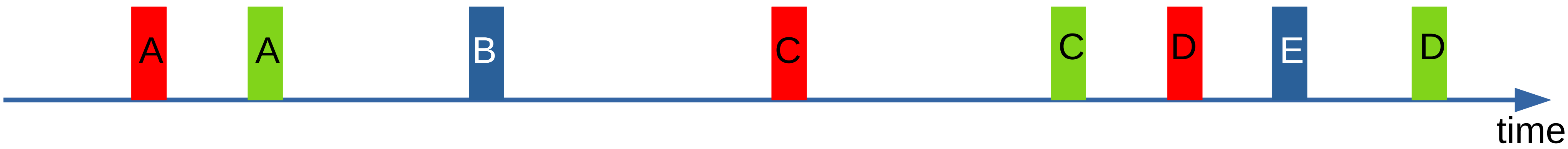
Backup

Realistic SN simulation

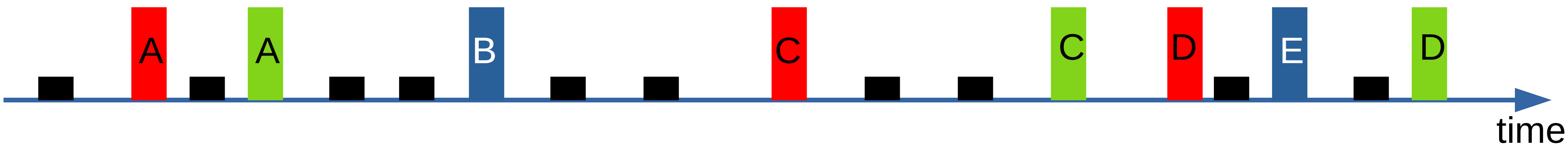
- In order to solve this issue, we developed realistic SN simulations: we simulate separately each interactions (IBD, ES, etc.) and merge the simulated interaction

1) Simulate each interactions without dark noise or background (BG):

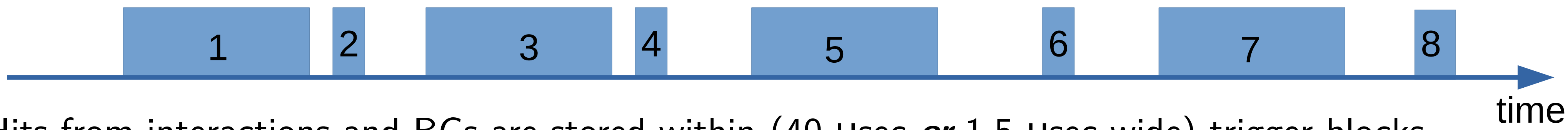
2) Merge the simulated interaction following the SN time profile:



3) Add BG from real SK data (sampled from a random trigger):



4) Apply the trigger simulation (software trigger): → Realistic output of the SK detector



Hits from interactions and BGs are stored within (40 µsec ***or*** 1.5 µsec wide) trigger blocks