Super-Kamiokande Supernova monitoring

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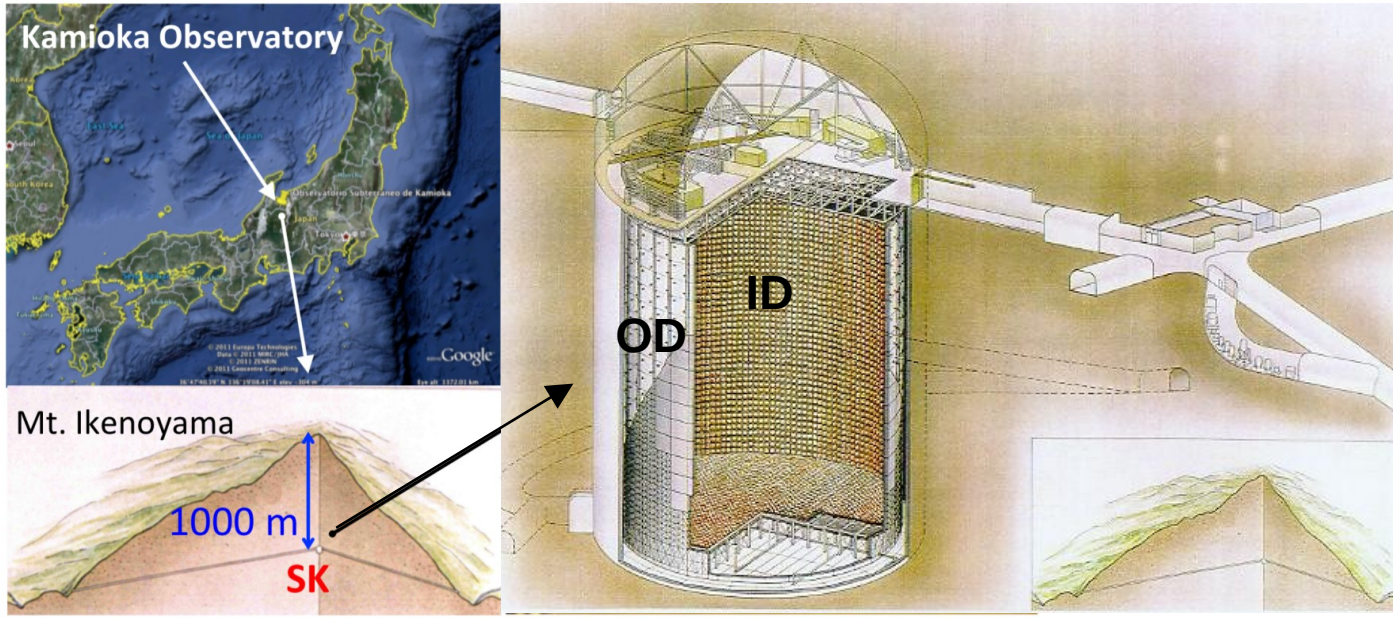
Super-Kamiokande

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

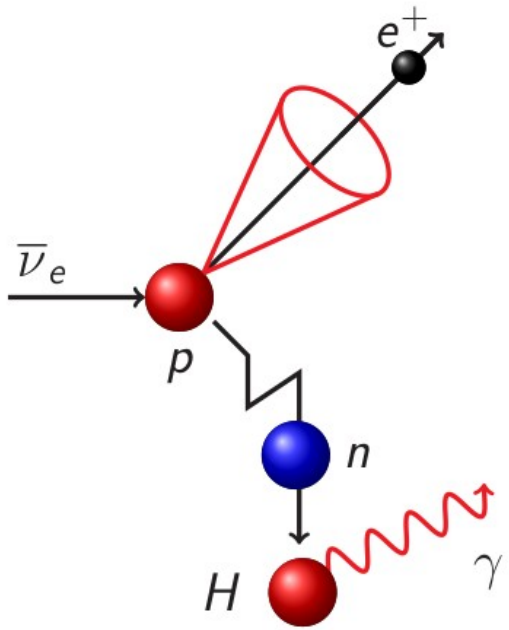


- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-VII is running

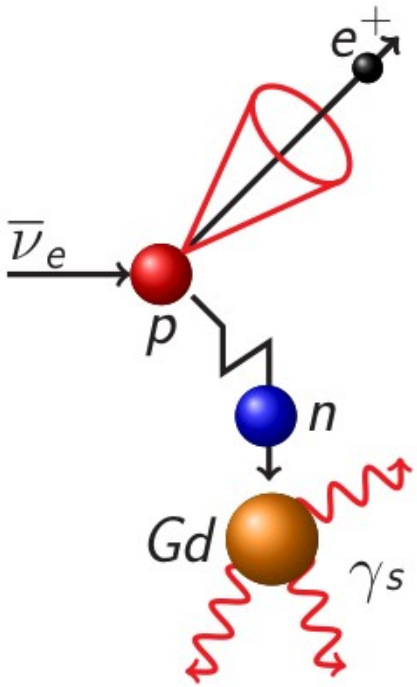
- The detector is filled with 50ktons of **gadolinium**-loaded water.
- Gadolinium was loaded at 0.01% in the water in Summer 2020, and the concentration was further increased to 0.03% in May 2022. Calibration was completed and the detector is running stably since then.
- **Physics targets**: Neutrino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



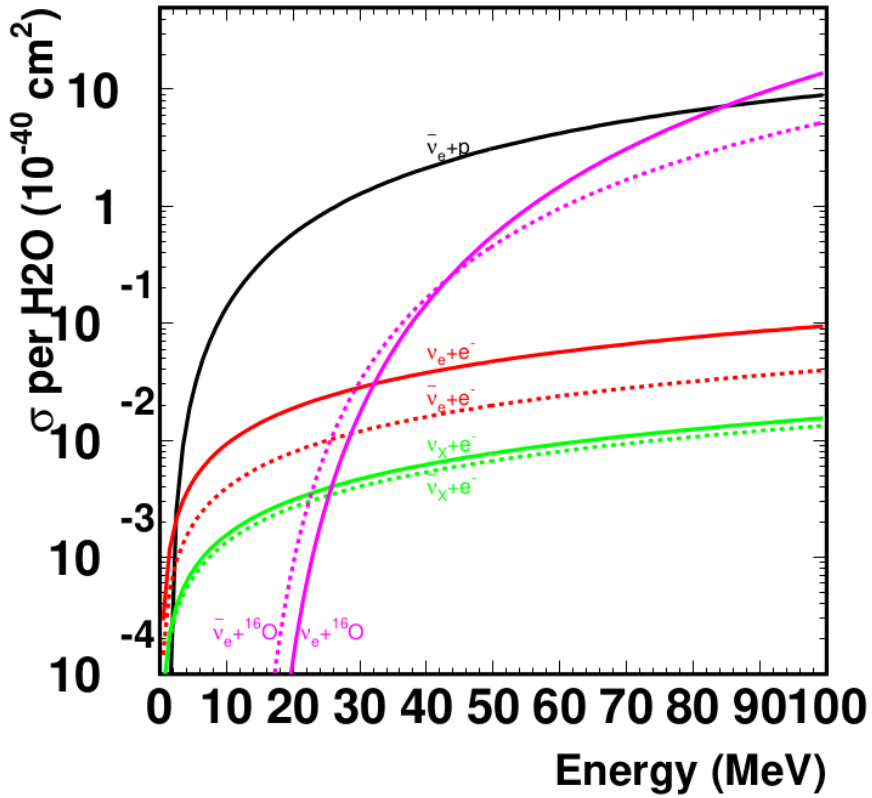
Hydrogen-neutron capture:
single 2.2 MeV gamma
→ Large accidental background
→ Vertex reconstruction difficult

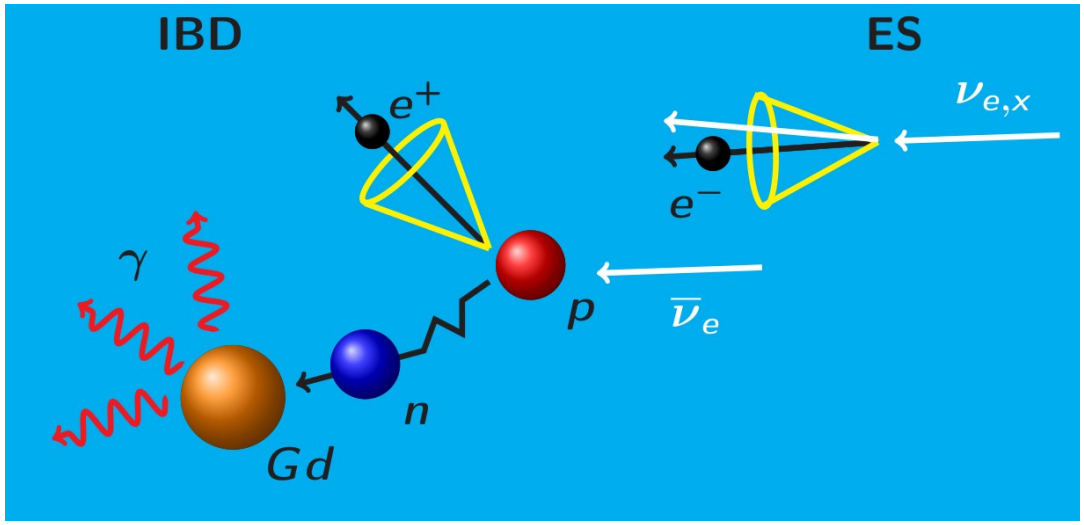


Gadolinium-neutron capture:
Gamma cascade at ~8 MeV
→ Lower background
→ Vertex reconstruction possible

Supernova Neutrinos in Water Cherenkov Detectors

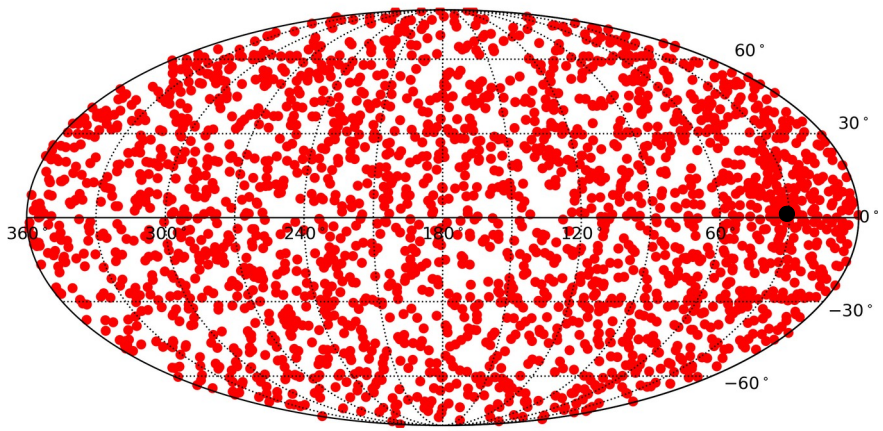
- All neutrino and antineutrinos flavours are ~evenly produced during the core-collapse supernova.
  However, due to interaction cross-sections, we are sensitive only to a few of them.
- In case of Water Cherenkov detector, the main interactions expected are:
  - **Inverse Beta Decay reaction** (IBD)
    → ~90% of the interactions
  - **Electron Scattering interactions** (ES)
    → ~5% of the interactions
    Keep the neutrino direction info.
  - ^{16}O interactions (CC and NC)
    → ~5% of the interactions



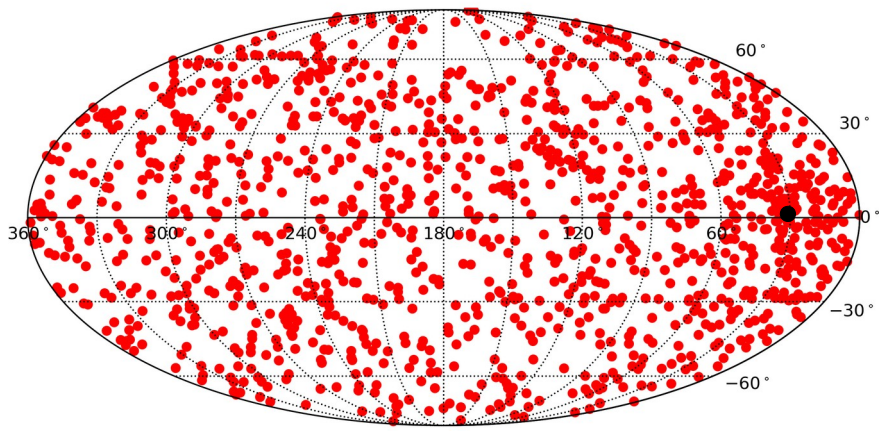


Using Gd-n to separate IBD and ES

- 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.



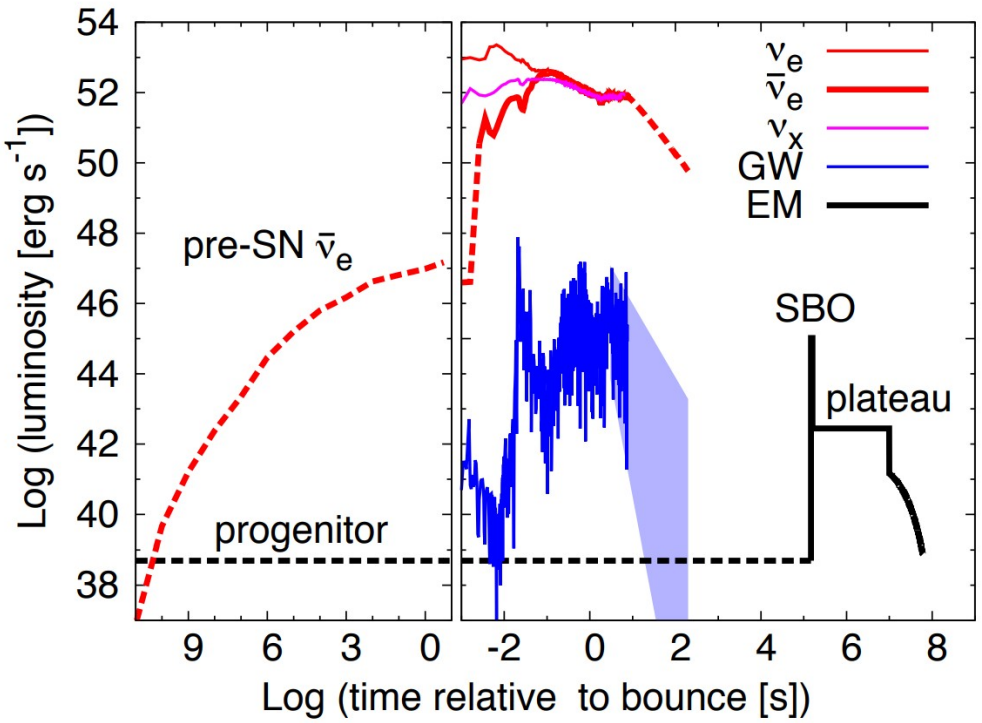
SN burst events w/o IBD tagging
(10kpc simulation w/o Gd)



SN burst events w/ ~50% IBD events tagged/removed
(10kpc simulation with 0.03% Gd)

Monitoring strategy

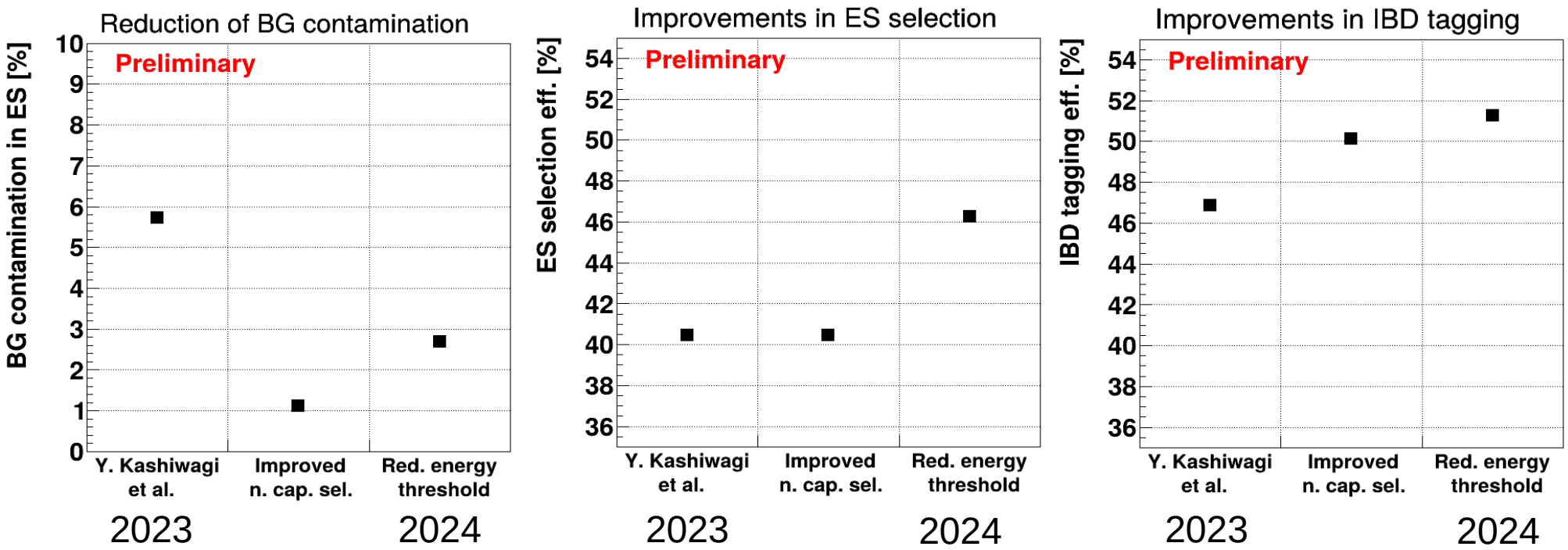
- Depending on the SN progenitor, the time difference between the neutrino burst and the electromagnetic burst can be rather small. (~minutes in case of Wolf-Rayet stars)
  - We need to release fast and reliable alarms
- Super-K strategy for supernova monitoring consists in:
  - **Low dead time** (let's not miss the next supernova)
  - **Release alarm quickly**, ~1 minute (allow telescope to not miss the breakout light)
  - Reliable alarm with meaningful information:
    - **Supernova estimated direction**
    - **Supernova estimated distance**



Analysis details

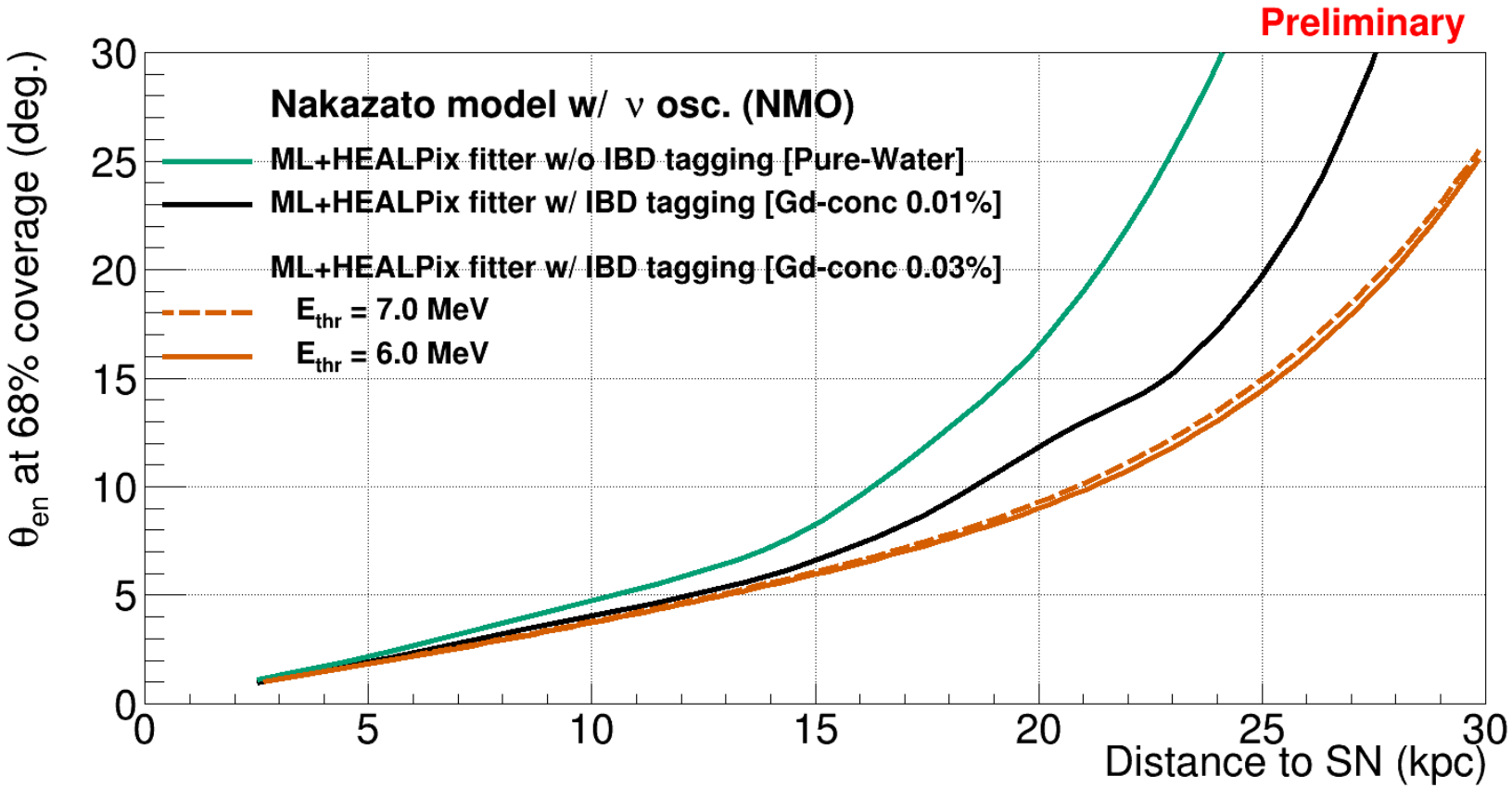
- Our supernova analysis is a cut-based realtime analysis, meaning we have lower performance that what we could achieve with longer analysis duration.
- Realtime selection efficiencies (assuming Nakazato model, 2002, NMO):
  - ~45.5% of the ES interactions
  - ~91.2% of the IBD's positron interactions
  - ~56.3% of the IBD's neutron capture interactions (with 0.03% Gd)

    → ~**51.3% IBD interactions are tagged** *(recently improved to ~52%, work-in-progres)*



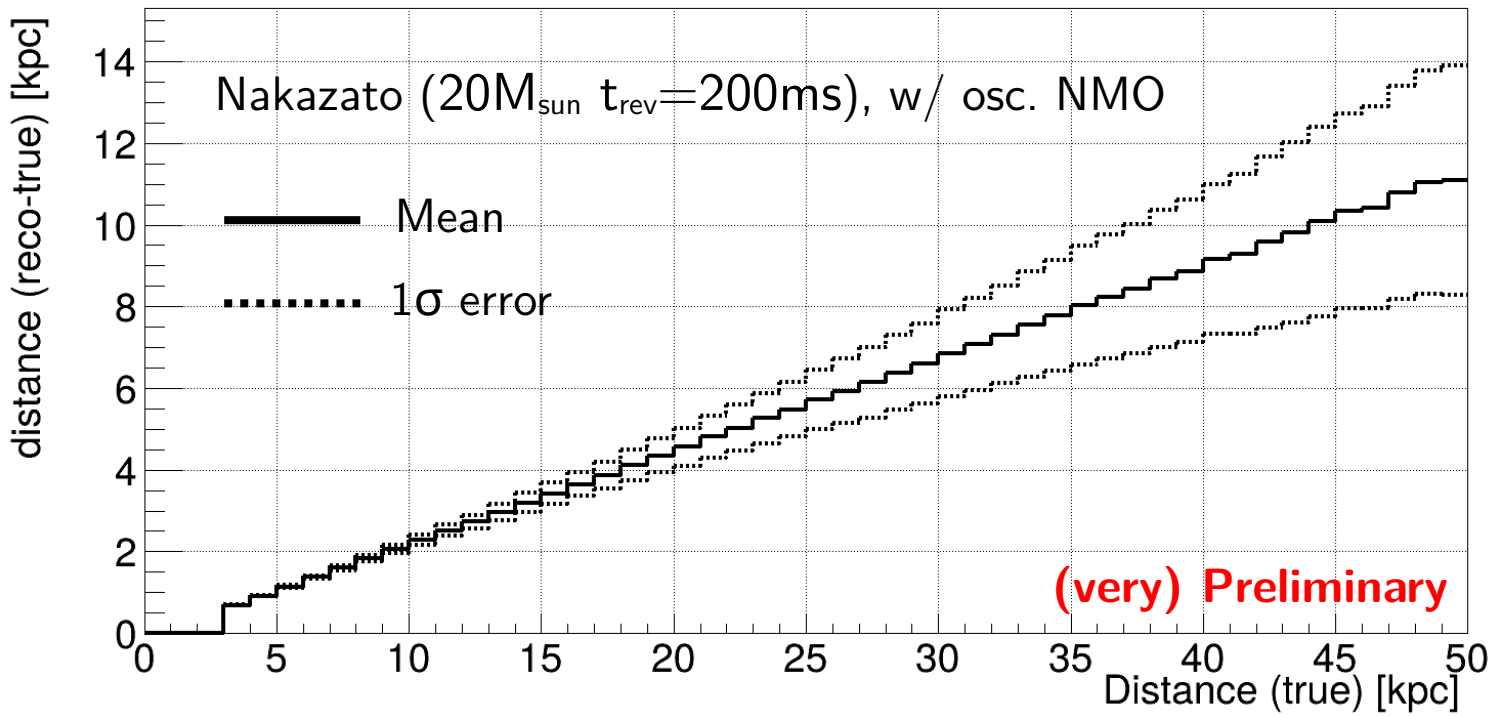
Realtime angular resolution

- 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±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).



Distance estimation

- More recent works have been on-going on improving our distance estimation.
- Current method is to use SN1987A as reference and scale with the observed number of events.
  → ~20% bias + ~6% error this method (Nakazato $20M_{sun}$ t_{rev}=200ms model)
  Precision vary largely depending on the model (e.g. with Fisher 8M ~81% uncertainty)



Distance estimation: alternative exploration (WIP)

- Alternative to our current method are being investigated:
  - Suwa et al. (2025) ApJ 980 117
    $\rightarrow$ Use event rate during SN cooling time
    - Note: require dedicated models with extended duration to simulate the events. Direct application on simulation using model without extended cooling duration give quite bad results (as expected)
  - Kachelrieß et al. (2005) Phys.Rev. D71 063003 M.
    $\rightarrow$ Use event rate during neutronization peak / beginning of the burst
    - Note: we need to define a reference for this method (e.g. Nakazato $20M_{sun}$ 200ms?)
    - One difficulty is how to identify the beginning of the burst in online (start, wideness) $\rightarrow$ work in progress
- Which method to use depends also on what is the need from telescopes regarding the precision of the measurement.
  $\rightarrow$ **We are looking forward your inputs**

Distance estimation: alternative exploration (WIP)

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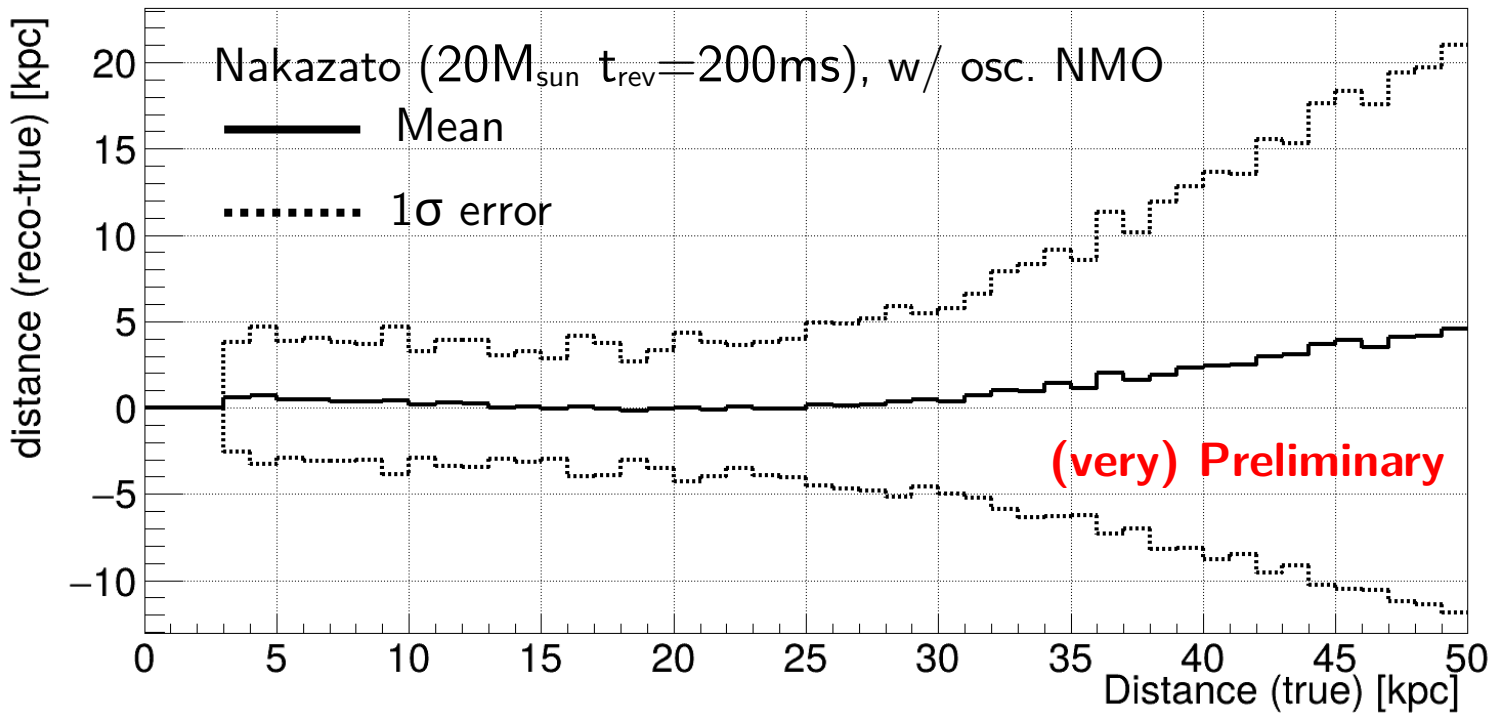
  - Suwa et al. (2025) ApJ 980 117

    → Use event rate during SN cooling time
    - Note: require dedicated models with extended duration to simulate the events. Direct application on model without extended cooling duration give quite bad results as expected
    - Ex. with Nakazato $20M_{sun}$ t_{rev}=200ms model (not extended): ~35% error at 10kpc

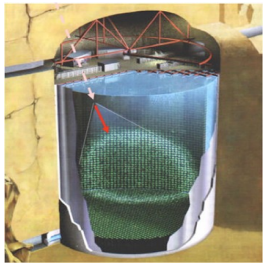


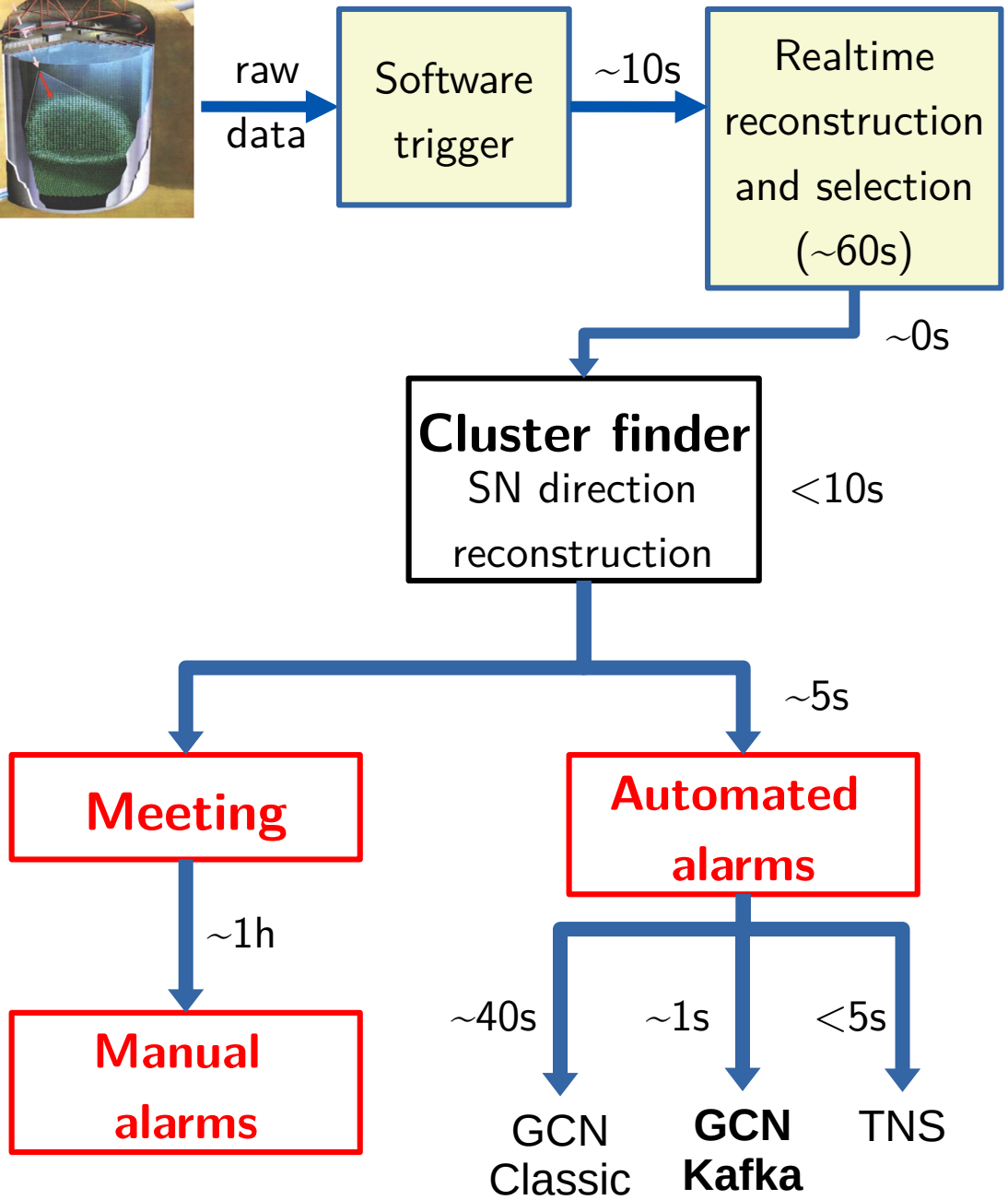
Distance estimation: timeline

- Alternative distance estimation will continue to be studied.
  - Several models are going to be tested (simulation is on-going):
    - Nakazato ($20M_{sun}$ t_{rev}=200ms) → default model in SK
    - Nakazato (spectob Hmax + $20M_{sun}$ t_{rev}=300ms) → long cooling simulation
    - Nakazato (spectob Hmin + $20M_{sun}$ t_{rev}=300ms) → long cooling simulation
    - Nakazato (spectob Lmax + $20M_{sun}$ t_{rev}=300ms) → long cooling simulation
    - Nakazato (spectob Lmin + $20M_{sun}$ t_{rev}=300ms) → long cooling simulation
    - Fischer (8M)
    - Hudelpohl
    - Mori (z9p6)
    - Tamborra (27M)
    - Wilson
  - Plan is to complete simulation by the end of the month and get results approved at the next Super-K collaboration meeting (in May)

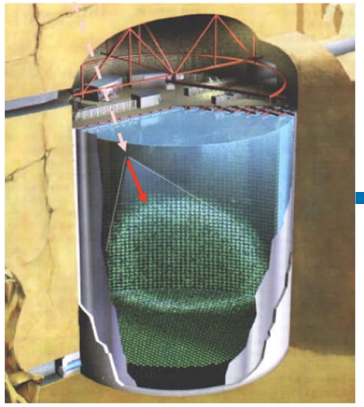
Alarm release: speed is critical

- 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
- We have been working to automatise our alarms to reduce time lags.
- We are investigating the possibility to send alarm earlier (before the burst is fully processed) and update information afterward using GCN Kafka follow-up feature
  $\rightarrow$ critical for close SNe with large number of events





Realtime supernova monitoring in Super-Kamiokande



raw data → Software trigger → Realtime reconstruction and selection

Triggered data → Offline processes

Processed data → **SNWatch** Search for event clusters

Alarm flowchart

- Event cluster found!
- Uniform vertex distribution → Check cluster size
- Non-Uniform vertex distribution → Silent alarm
- Check cluster size: <25 → Silent alarm
- Check cluster size: >35 evts, >10 IBDs → Golden alarm
- Check cluster size: >25 evts, >10 IBDs → Normal alarm

Golden alarm → GCN notice, TNS (automated)

Golden alarm / Normal alarm → SNEWS

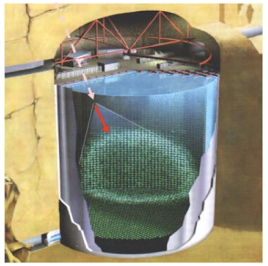
Call and mail to SK experts → Meeting, experts decide if the SN is real and manually send worldwide announcement: Atel, GCN Circular

~1 h

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

Alarm release: speed is critical → or not?

- Even if fast release is critical, we may have some more time.
  - If the star is not a Wolf-Rayet star → hours before the first light
  - Some telescope will not be ready immediately (e.g. wait for night)
- We are now working on a "slow" alarm → Will be a follow-up of the "fast" alarm using GCN Kafka features
- Automated analysis with reduced energy threshold and extended time windows in order to improve performance on direction and distance accuracy → Work in progress



Co-operation with telescopes

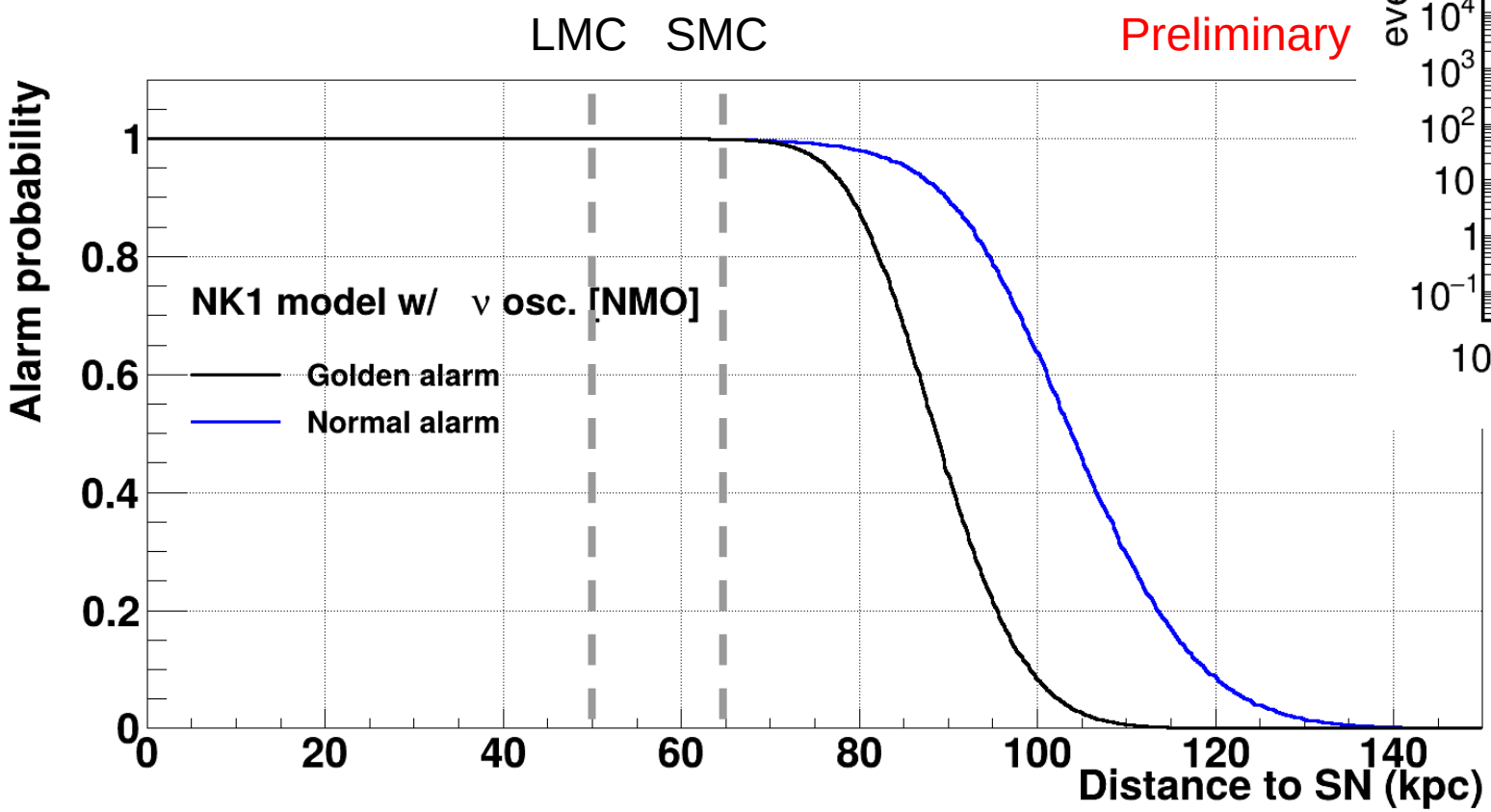
- If (when) Super-Kamiokande send a supernova alarm to the world, we hope some telescopes will be able to look for it in order to observe the first instants of the supernova burst.
  - In order to increase the probability our alarm will be used, to maximise the change to have combined neutrino-optical 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, RUBIN)
  - 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!

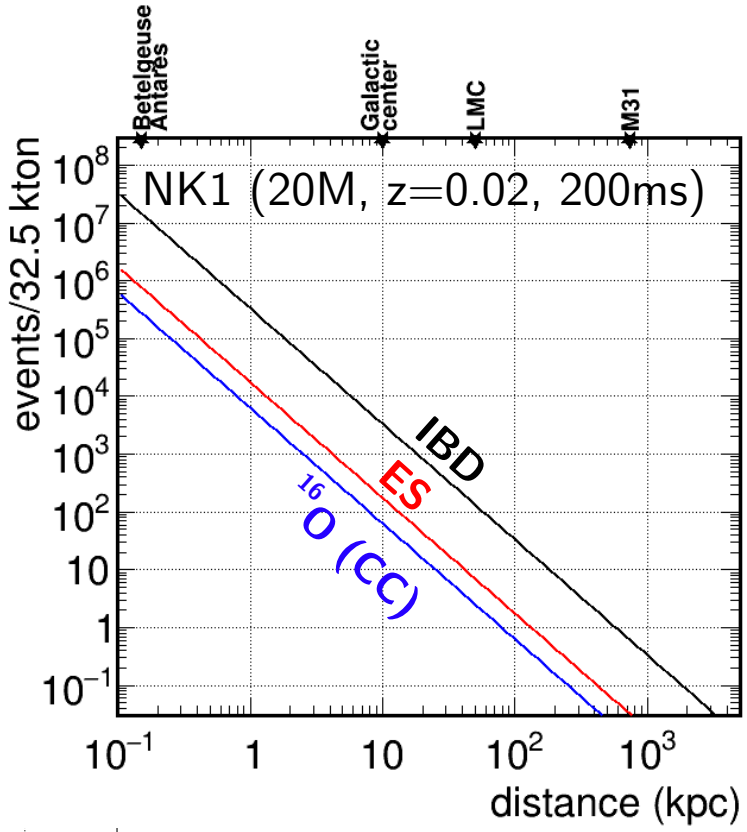
Summary

- 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)
  - Distance estimated with ~26% uncertainty (Nakazato model, NMO)
  - Automated alarm through GCN notice (Kafka) **within 1.5 minutes** after the neutrino burst
- Work-in-progress in order to provide:
  - Better distance estimation
  - "Slower" alarm (10m~1 h after burst detection) to provide improved distance and direction estimation
- MoUs with several telescopes in order to ensure follow-up and smooth potential Target on Observation request needs.

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)



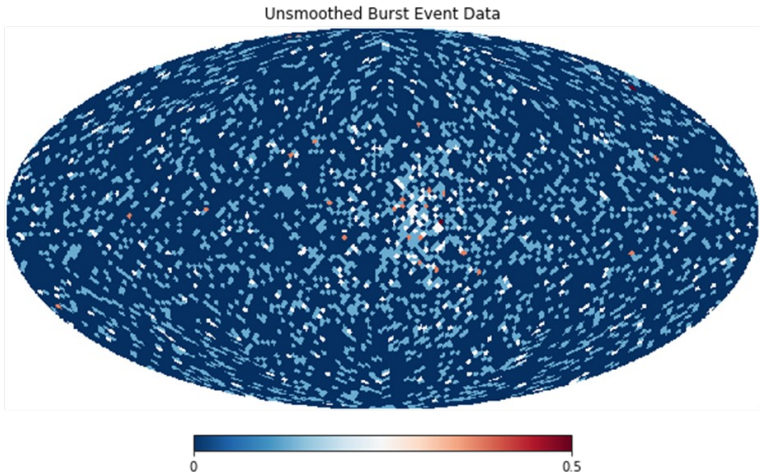
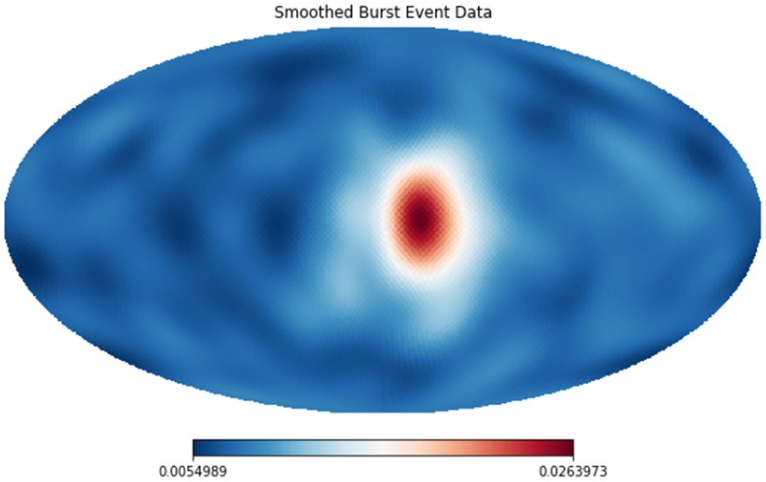


Backup

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.