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Supernova burst monitoring in Super-Kamiokande

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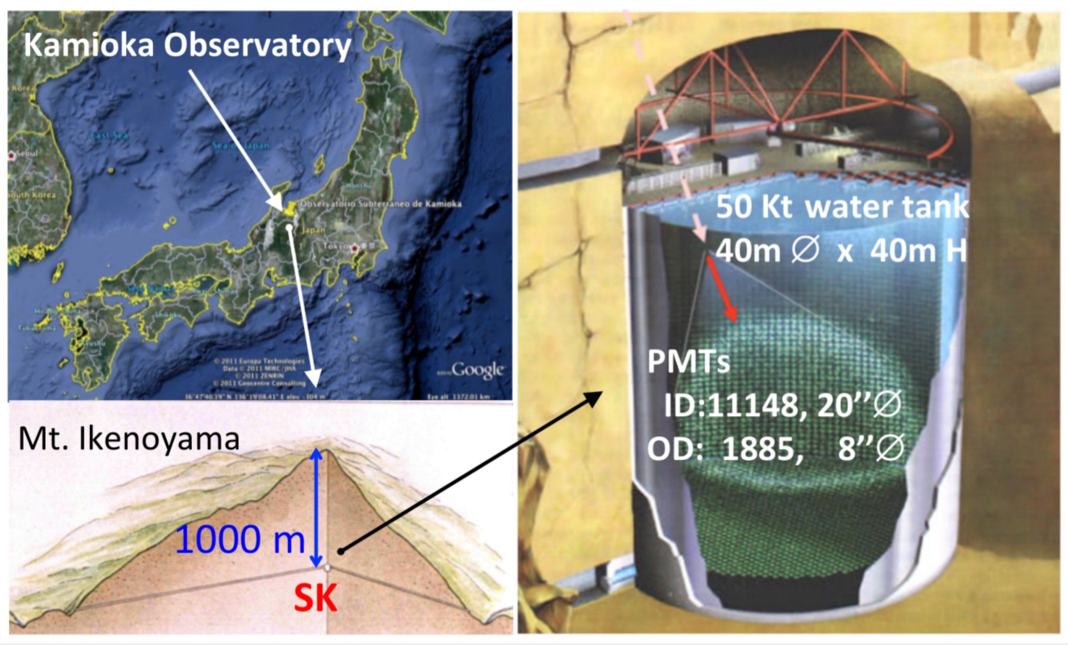
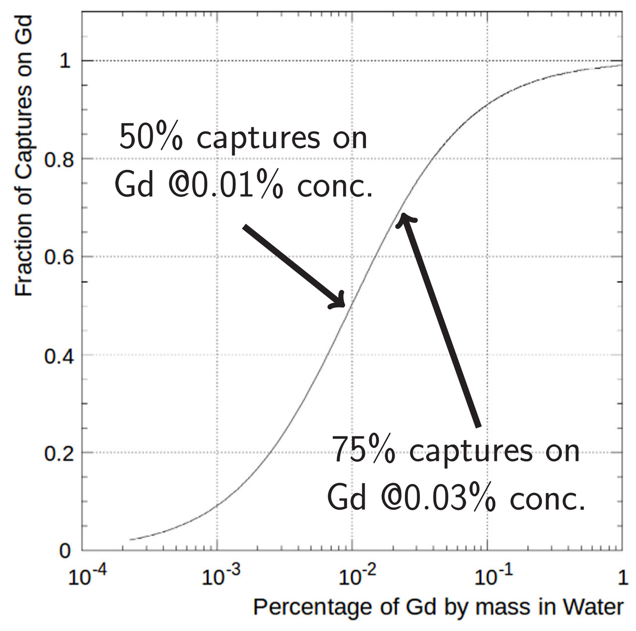
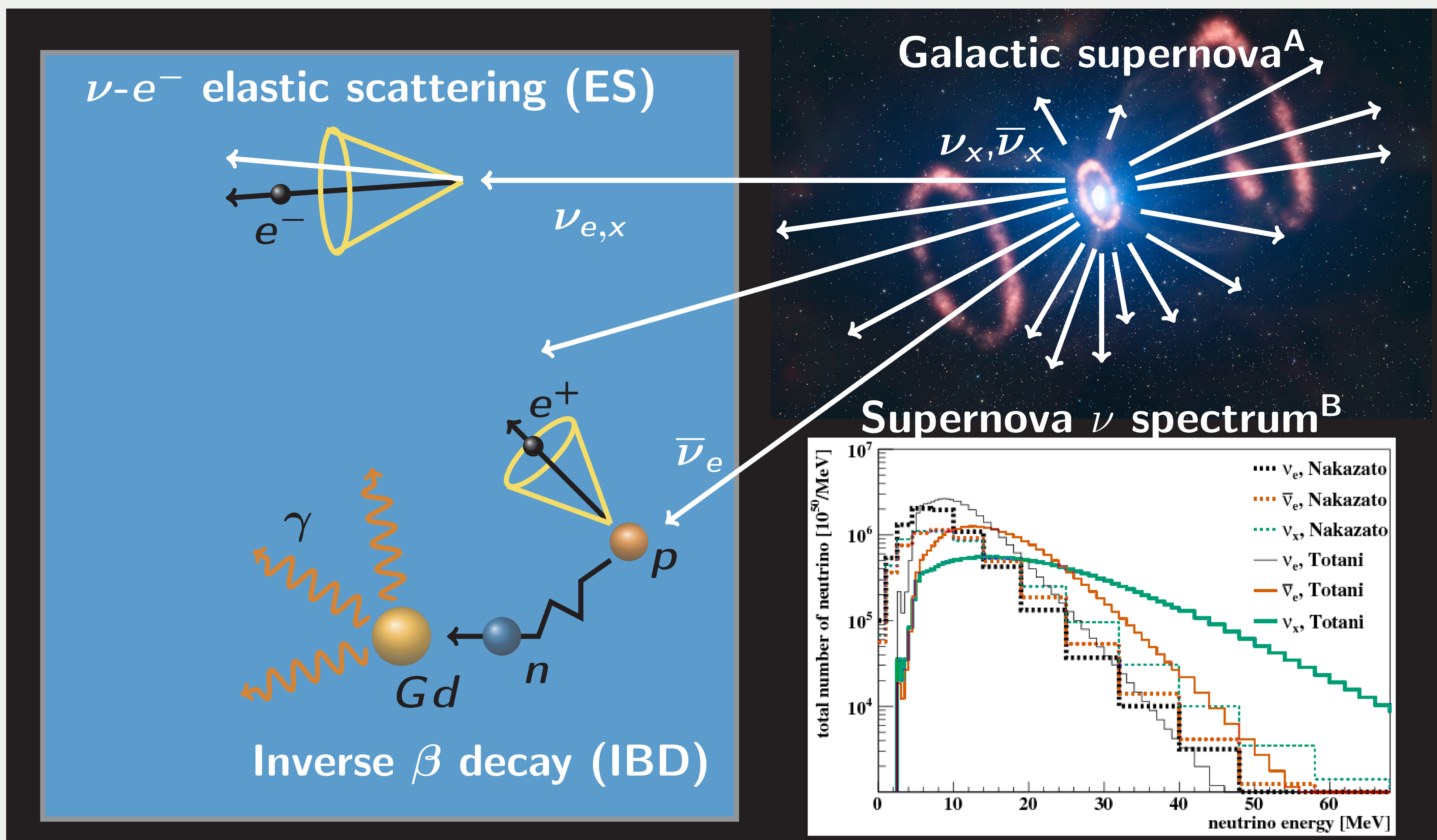
1 Context: Super-Kamiokande experiment

- Super-Kamiokande (SK) is a neutrino experiment located in the Kamioka mine, about 1 km under Mt. Ike (Ikenoyama), in Kamioka-cho (Japan).
- 50 ktons water Čerenkov detector, operated since 1996.
- Gadolinium (Gd) was loaded in the water at a concentration of 0.01% in 2020, and increased to 0.03% in 2022. This allows to improve the detectability of neutron capture, as Gd has the highest neutron capture cross-section among stable nuclei on Earth.
- The main goal of the gadolinium loading is to reduce the background (BG) affecting the Diffuse Supernova Neutrinos Background detection using the delayed coincidence of the inverse β decay reaction (IBD).
- The improved detectability of the neutron is also useful for the detection of supernova ν burst.







- IBD: $\sim$ **90%** of SN ν interactions in the detector. **Delayed coincidence.**
- ES: $\sim$ **5%** of SN ν interactions in the detector. **Keep ν's direction.**

With the presence of gadolinium in the detector, we can tag IBD interactions. Thanks to this **two main improvements can be achieved**:
→ The ES interactions keep the SN direction information, by improving the separation between ES and IBD events, we can **improve the SN direction reconstruction accuracy**.
→ The IBD delayed coincidence allows the selection of a quasi BG-free sample, giving **a clear signature of a SN burst.**

2 Context: Supernova neutrino bursts

- Since SN1987A [1] we know core-collapse SN produce a large number of neutrinos. $\sim$ 99% of the SN energy is carried away by neutrinos. If the SN is close enough, this burst of neutrinos can be detected on Earth.
- The ν burst is produced few minutes to several hours before the electromagnetic signal, **its detection could give an early warning to astronomers**.

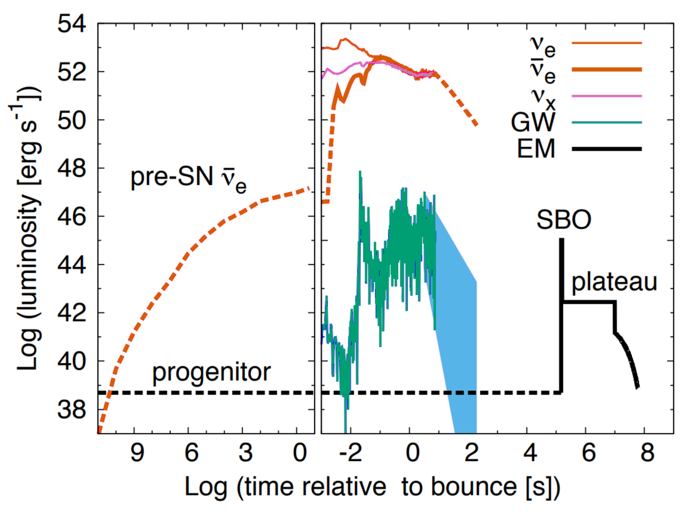
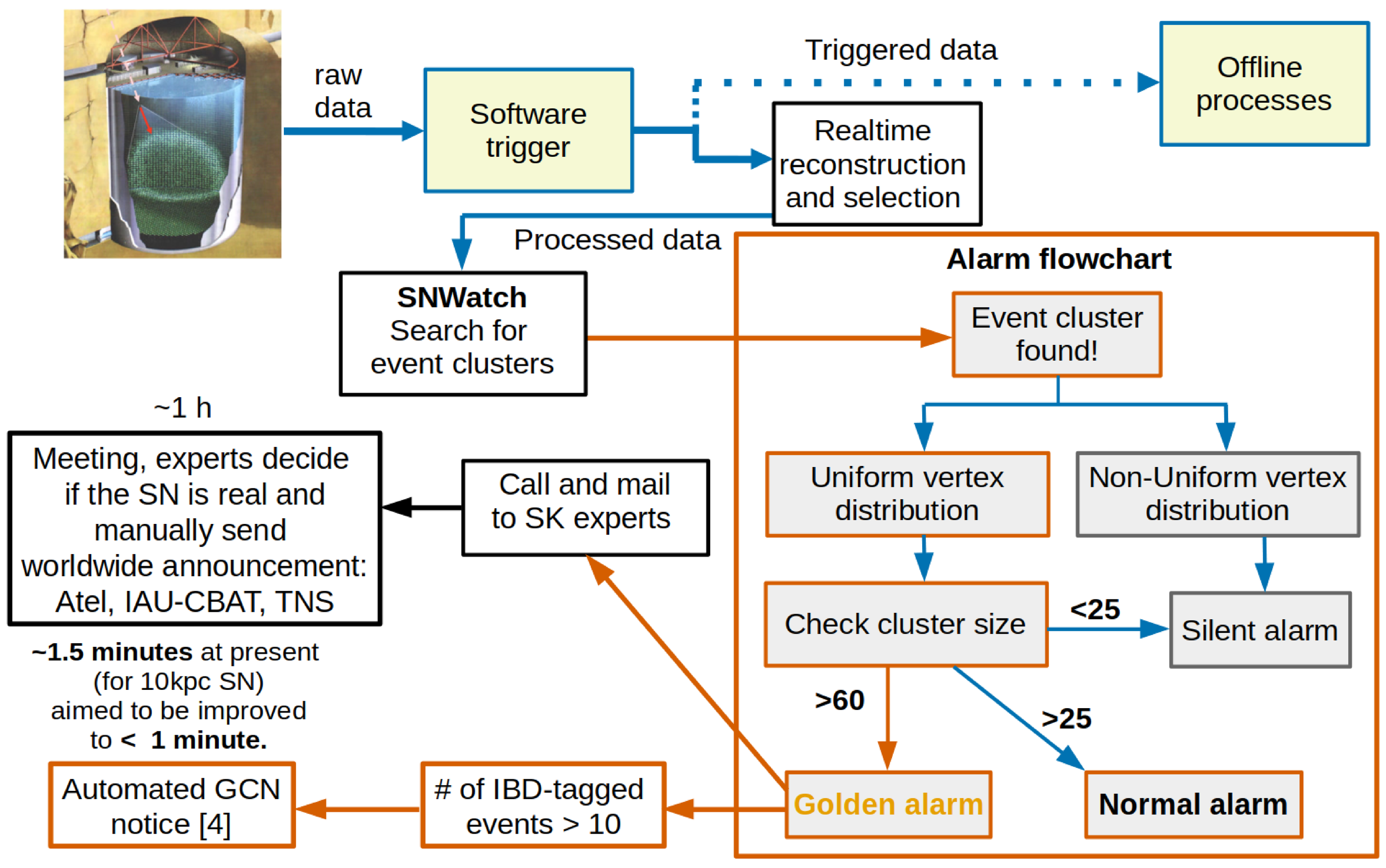


Figure from [2]

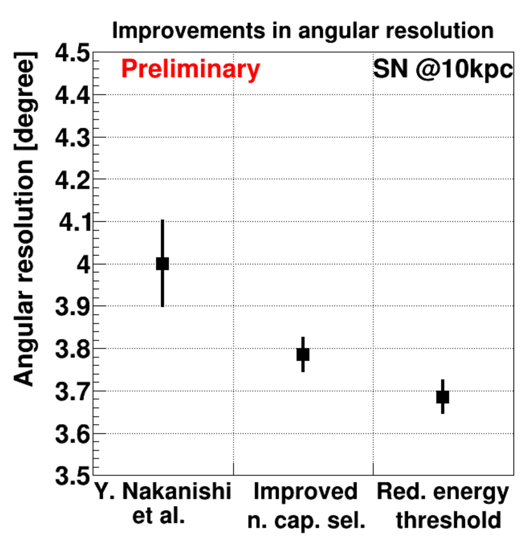
- In order to give such early warning, the neutrino experiment needs to:
  → Reconstruct the direction of the supernova
  → Release the alarm in a short amount of time ($\sim$minutes)
- In SK, with the Gd loading, we managed to improve the precision of the supernova direction reconstruction, as well as to the alarm release delay.

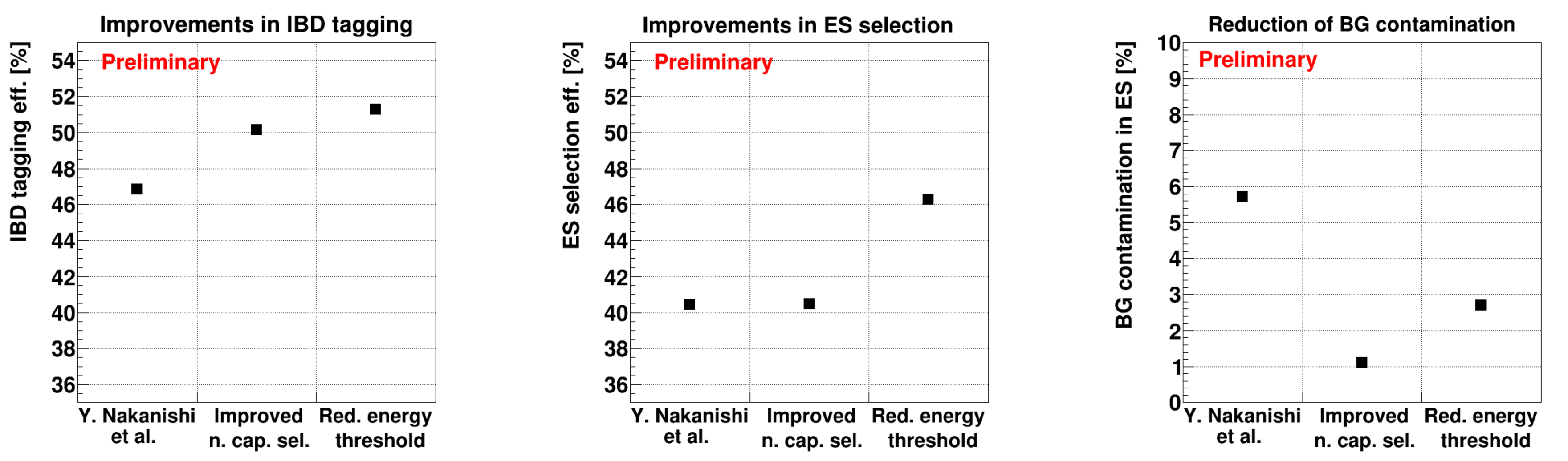
3 Supernova burst monitoring in SK



4 Recent analysis improvements

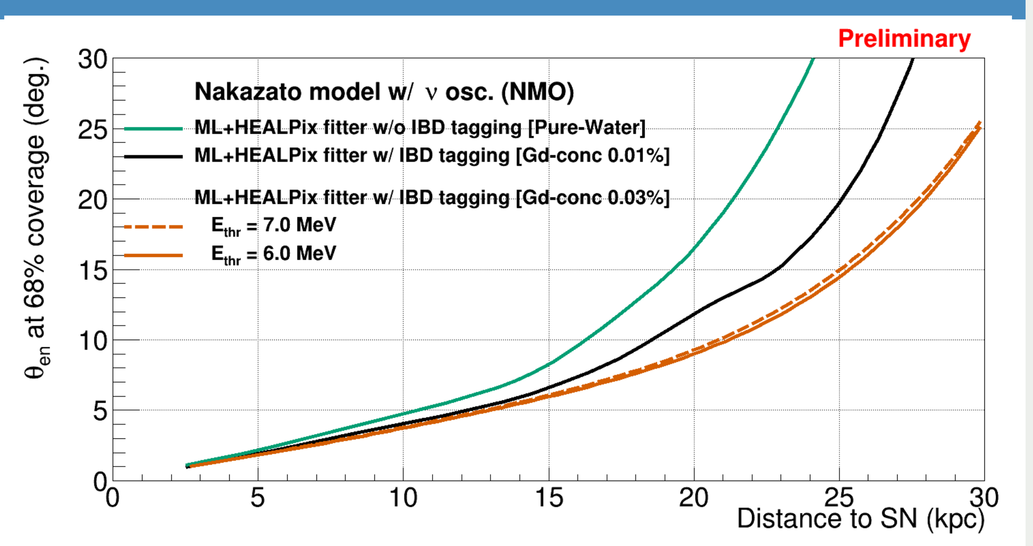
- Several improvements have been implemented in the SNWatch online analysis since [3]:
- The IBD tagging algorithm was reworked, allowing a better neutron capture event selection.
  → reduction of the neutron capture event contamination in the selection.
- Reduction of the analysis energy threshold, allowing to improve the selection of ES events.
- Positive impact on the reconstructed SN direction's angular resolution.

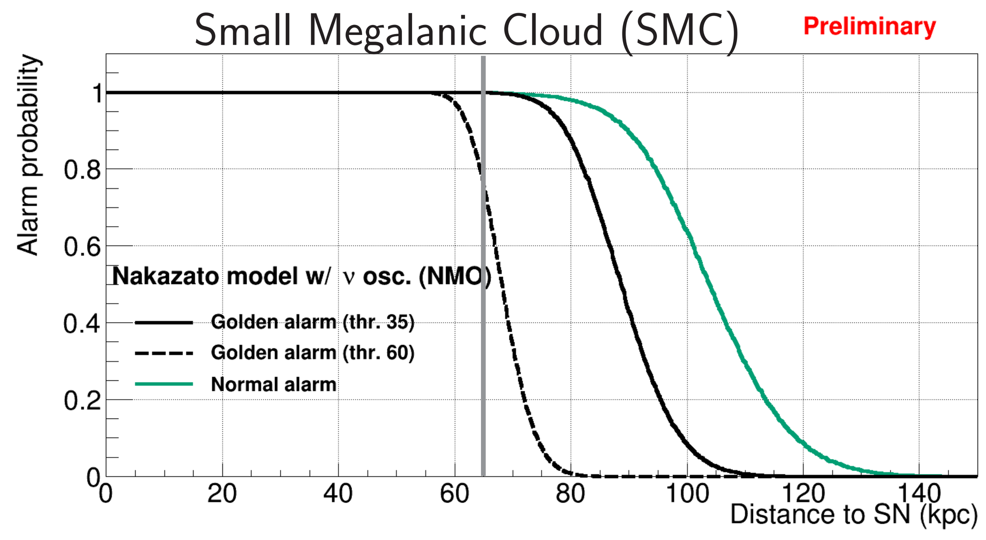




5 Supernova monitoring performances

- We implemented in summer 2023 a new fitter (HEALPix+ML) allowing fast reconstruction of the SN direction (see Poster #575)
- Resolution @10kpc:
  $3.78 \pm 0.04°$ ($E_{thr} = 7$ MeV)
  $3.68 \pm 0.04°$ ($E_{thr} = 6$ MeV)
- Golden alarm threshold will be reduced to 35 events, allowing full coverage of the SMC 75.38% → 99.81% @65kpc





Figures made assuming Nakazato model and Normal Mass Ordering (NMO) ($20M_{sun}$, $r_{revival}$ = 200ms, Z=0.02)

6 Summary / Key points

- Super-Kamiokande is ready to detect the next galactic/nearby supernova with a **range up to the SMC**
- The direction reconstruction has a **resolution of $3.68 \pm 0.04°$ @10kpc**
- Detection alarm can be send **within 1.5 minutes after the burst arrival**. We are working to improve this, aiming to reach < 1 minute

[A] 1987A picture from © ESO/Luis Calcada
[B] from XMASS Collaboration (K. Abe et al.) Astropart.Phys. 89 (2017) 51-56
[1] K. S. Hirata et al., PRD 38 (1988), 448
[2] K. Nakamura et al., Mon. Not. Roy. Astron. Soc. 461 (2016)
[3] Super-Kamiokande Collaboration (Y. Kashiwagi et al.), Accepted by ApJ, arXiv:2403.06760
[4] https://gcn.nasa.gov/missions/sksn

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