Super-Kamiokande's Supernova monitoring

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on behalf of the Super-Kamiokande Collaboration

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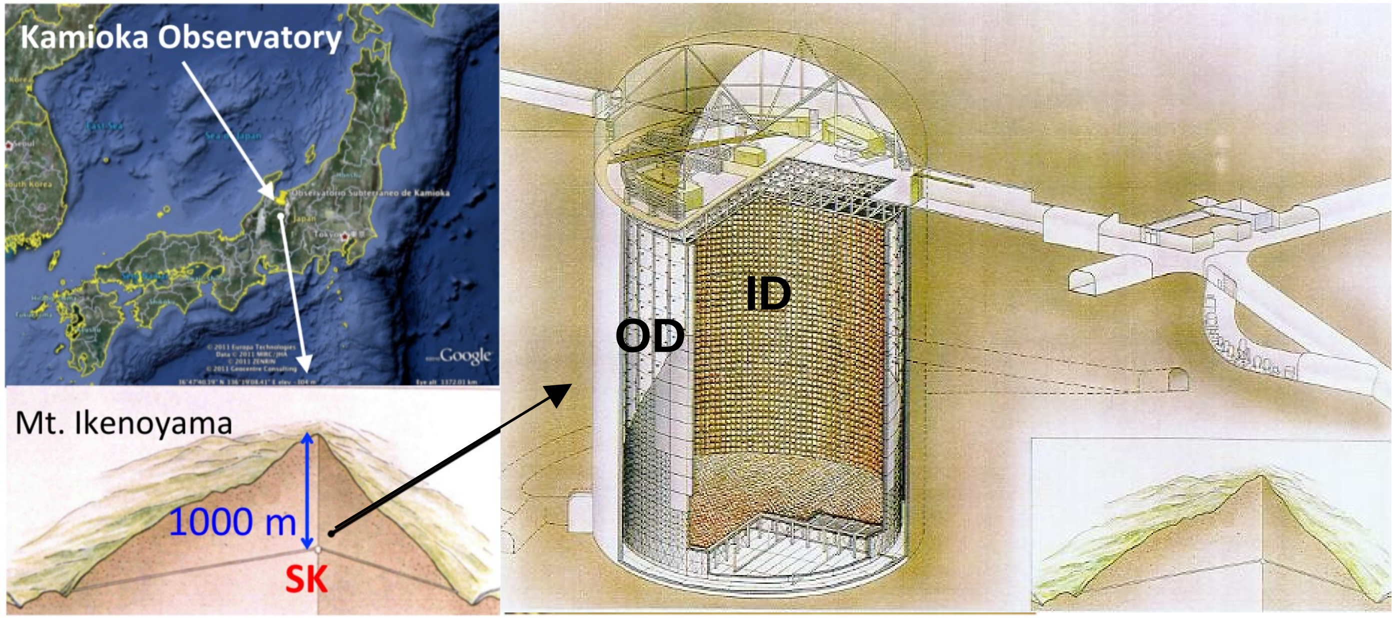
Super-Kamiokande

- **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

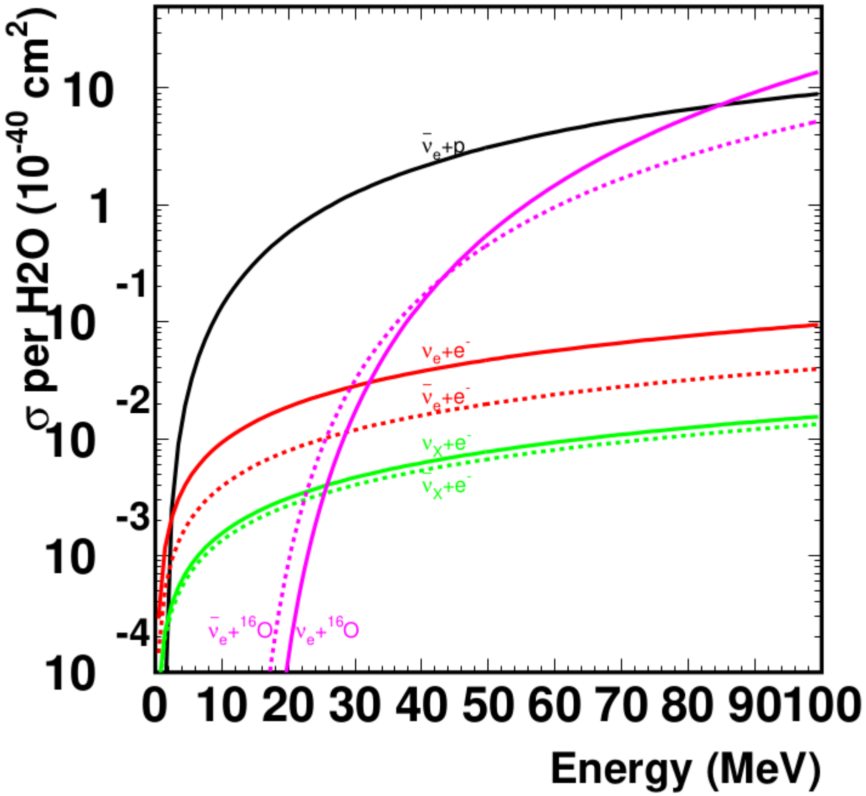
- The detector is filled with 50ktons of **gadolinium**-loaded water.
- Gadolinium was loaded at 0.01% in the water in Summer 2020, and the concentration was further increased to 0.03% in May 2022. Calibration was completed and the detector is running stably since then.
- **Physics targets**: Neutrino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

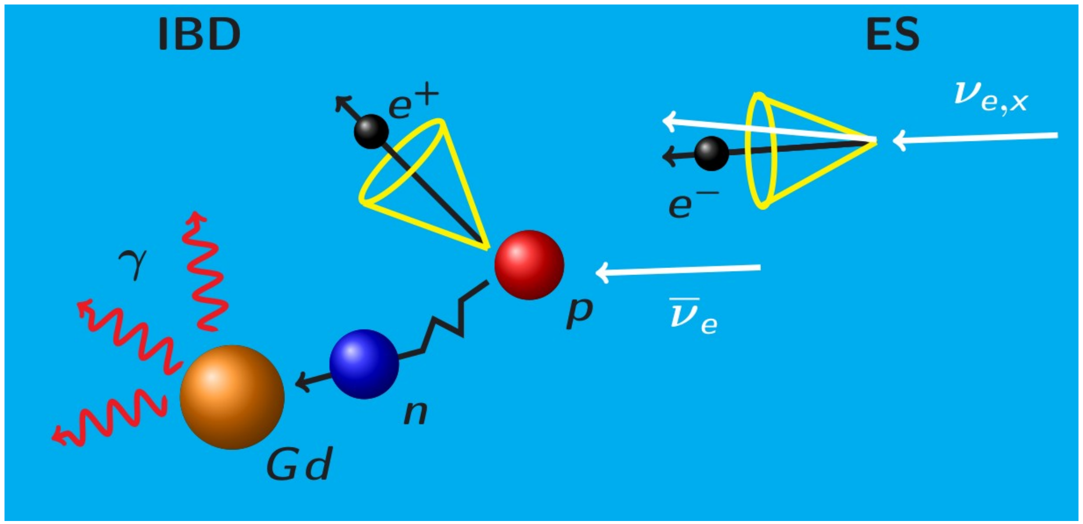
Supernova Neutrinos in Water Cherenkov Detectors

- 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

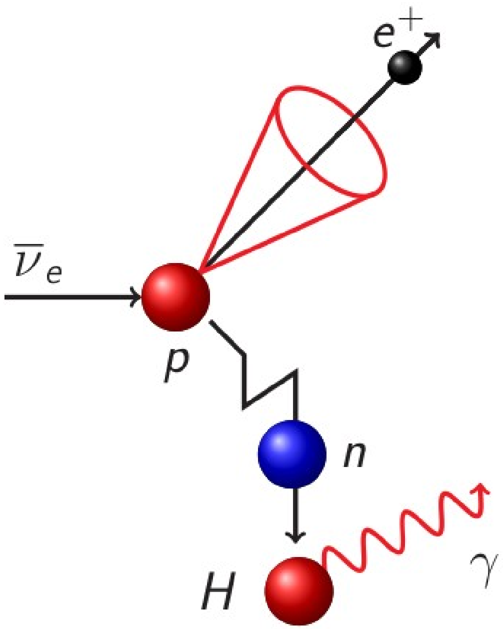
  - ^{16}O interactions (CC and NC)
    $\rightarrow$ $\sim$5% of the interactions



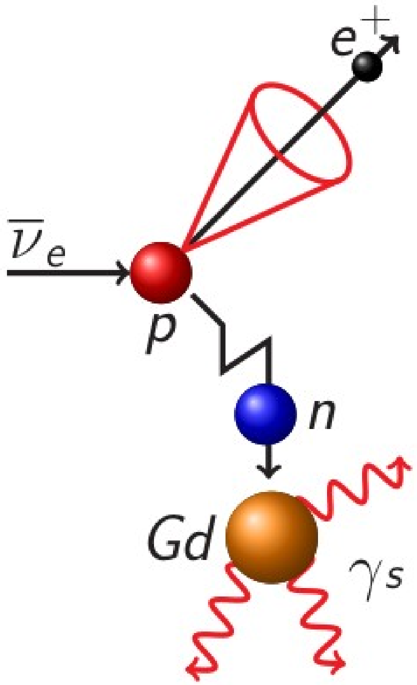


Why Gadolinium?

- 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



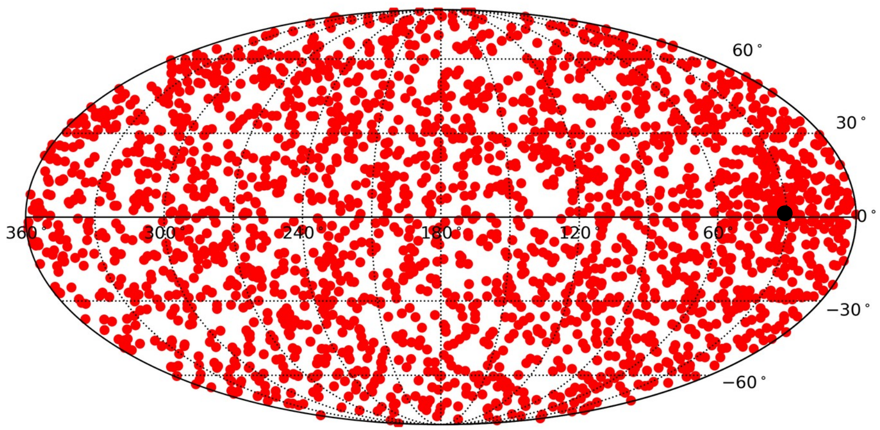
Hydrogen-neutron capture:
single 2.2 MeV gamma
→ Large accidental background
→ Vertex reconstruction difficult



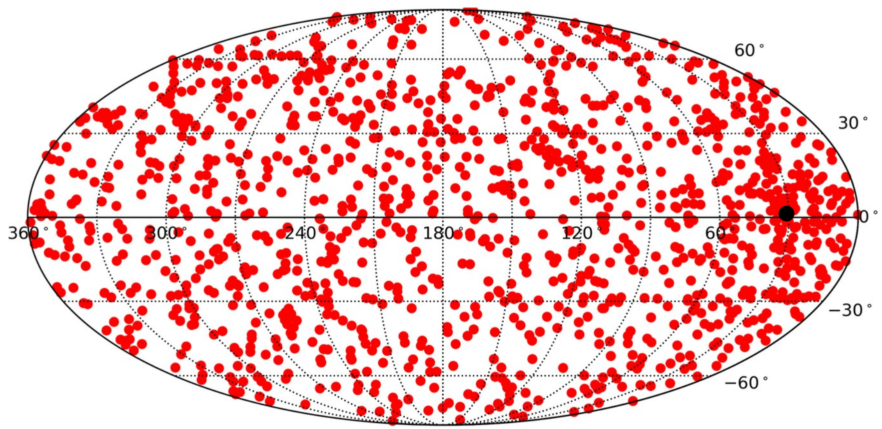
Gadolinium-neutron capture:
Gamma cascade at ~8 MeV
→ Lower background
→ Vertex reconstruction possible

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)

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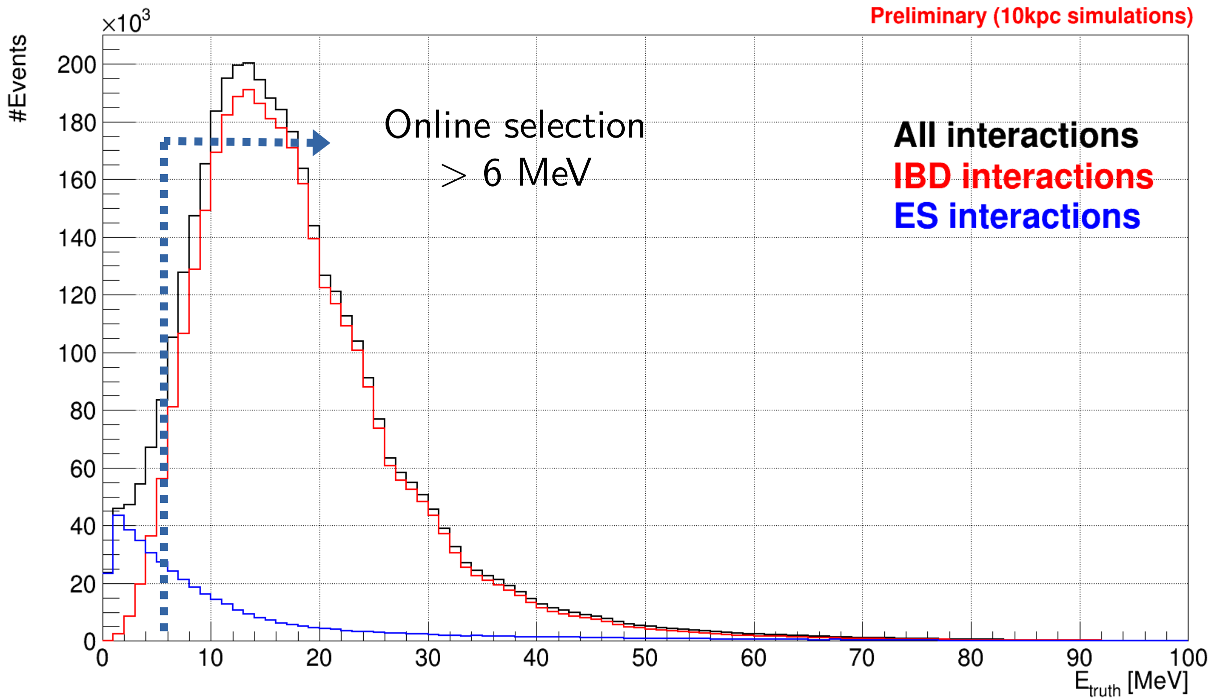
Realtime analysis

- The Supernova 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.
  $\rightarrow$ Having a low energy threshold allows to collect more ES interaction, but leads to increase BG contamination

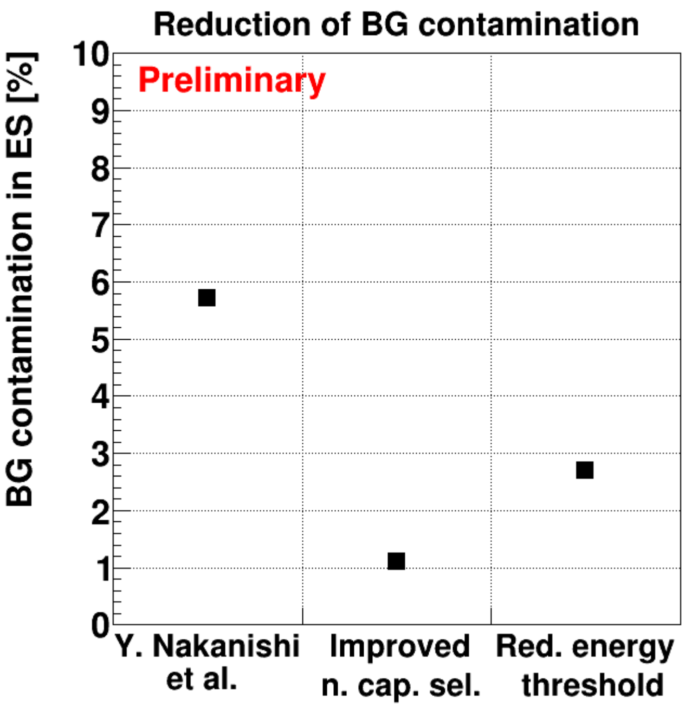


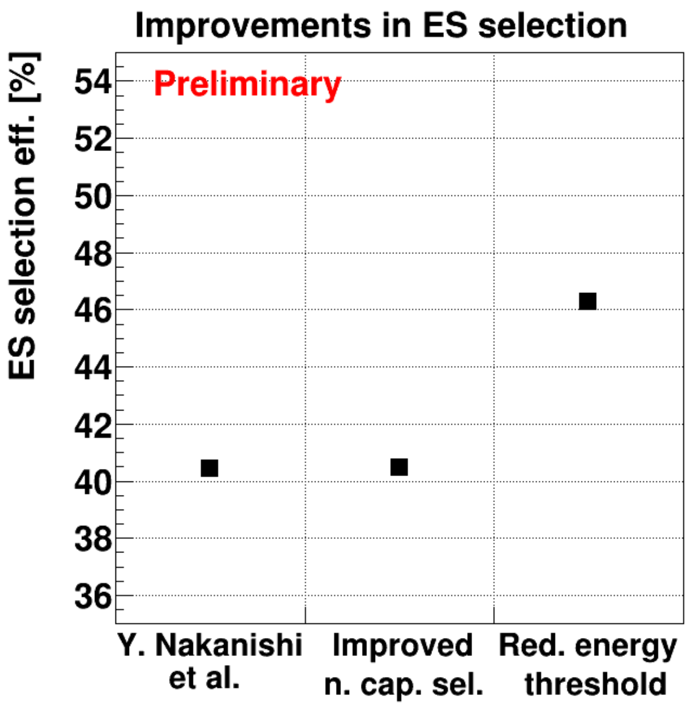
1000 MC simulations

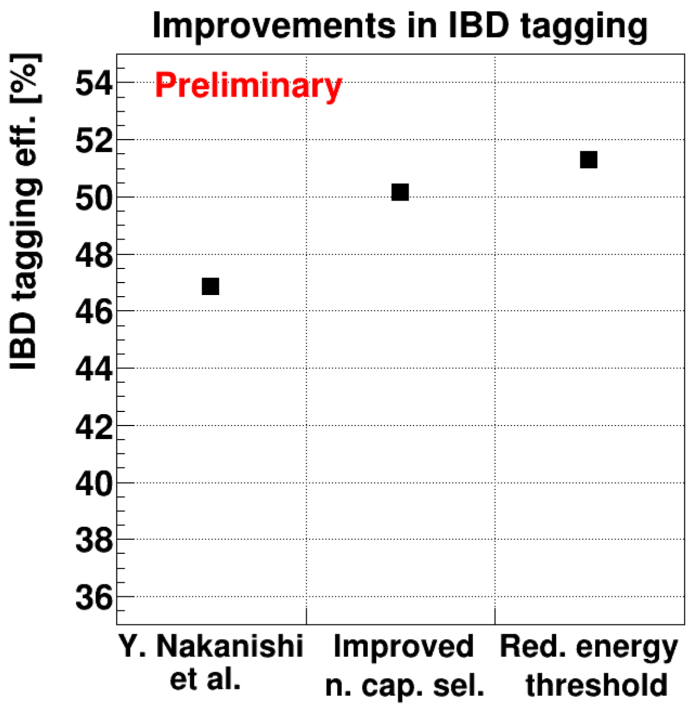
Realtime analysis

- Improvement on the IBD tagging algorithms reduced the BG contamination, allowing to reduce the energy threshold from 7 to 6 MeV for a BG contamination of 2.70±0.01%
- Improvement on the IBD and ES interaction selection efficiency (Nakazato model, NMO):
  - ~45.5% of the ES interactions (**+5.8%**)
  - ~91.2% of the IBD's positron interactions (**+1.7%**)
  - ~56.3% of the IBD's neutron capture interactions (with 0.03% Gd) (**+1.9%**)

  → ~**51.3% IBD interactions are tagged (+4.4%)**

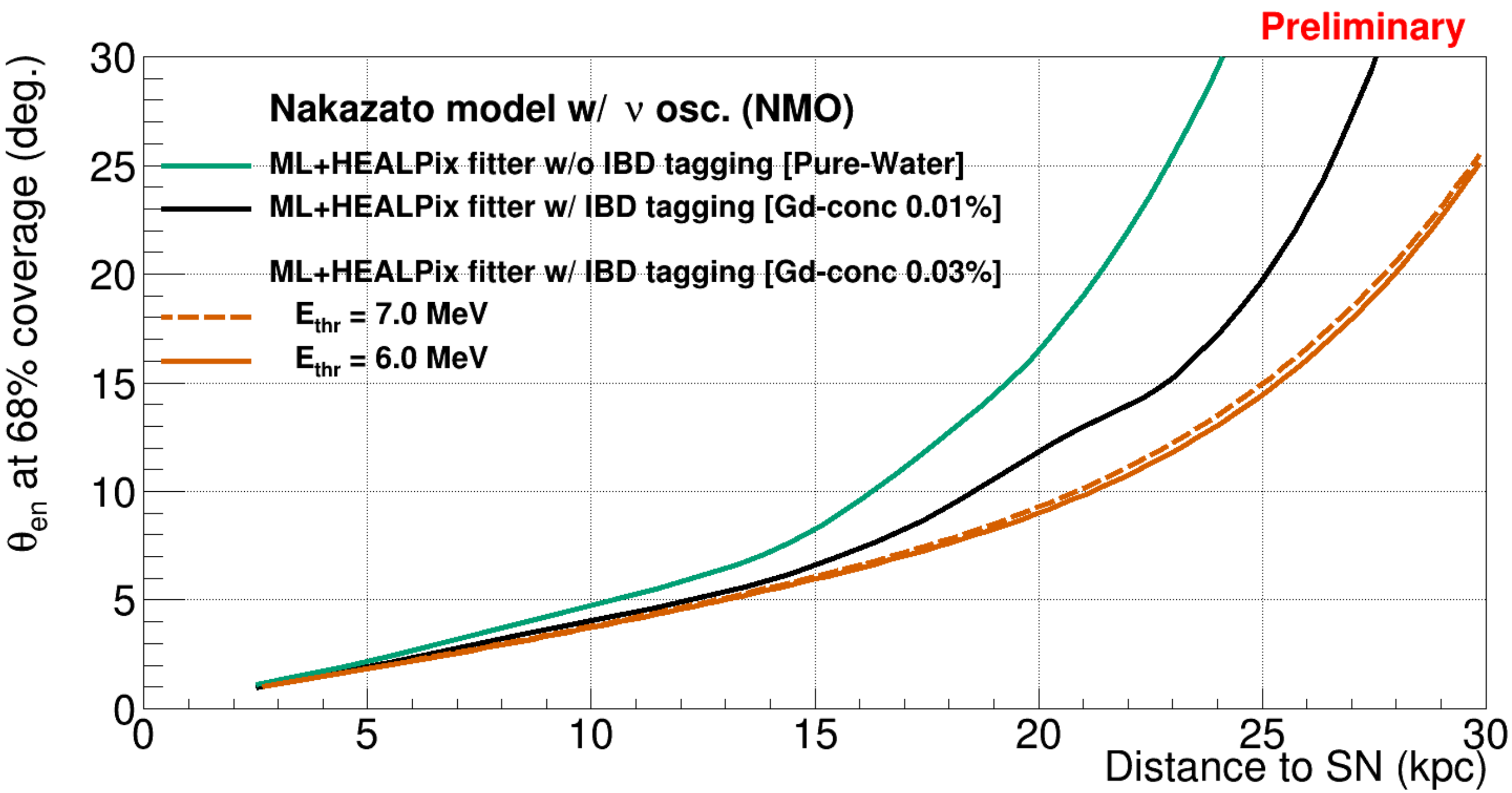






Realtime angular resolution

- Selection improvement led to better angular resolution:
  - With 0.03% Gd, our last realtime direction pointing accuracy is 3.68±0.04° at 10 kpc (Nakazato model, 6 MeV threshold) (0.30° improvement).



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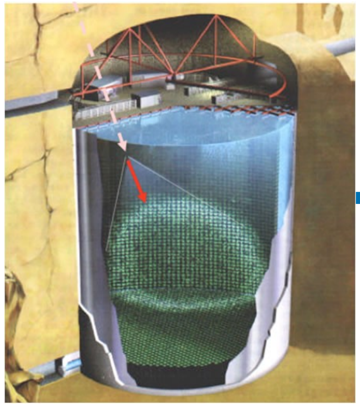
Realtime supernova monitoring in Super-Kamiokande



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

>35

>25

Golden alarm

Normal alarm

\# of IBD-tagged events > 10

Automated GCN notice

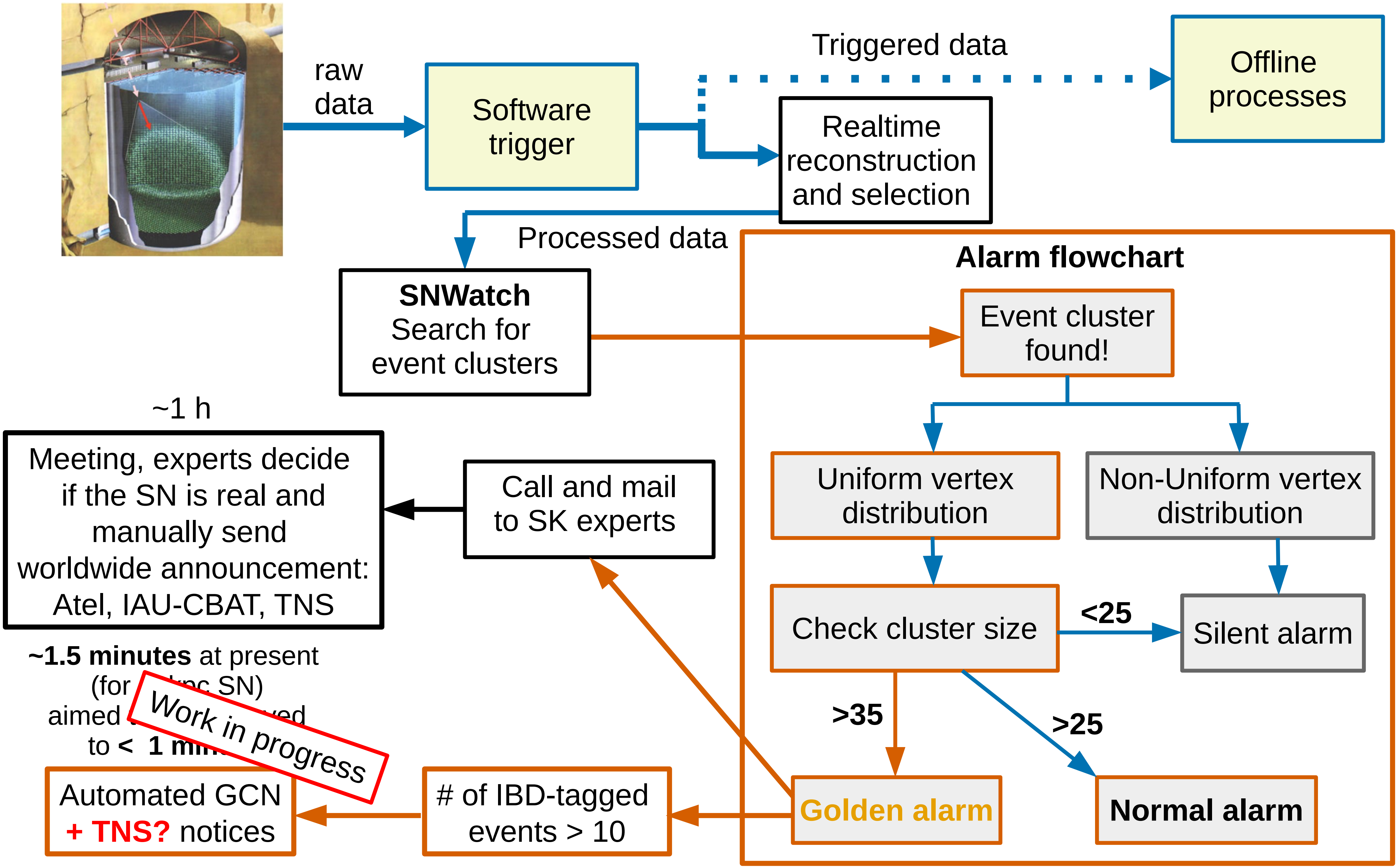
Call and mail to SK experts

~1 h

Meeting, experts decide if the SN is real and manually send worldwide announcement: Atel, IAU-CBAT, TNS

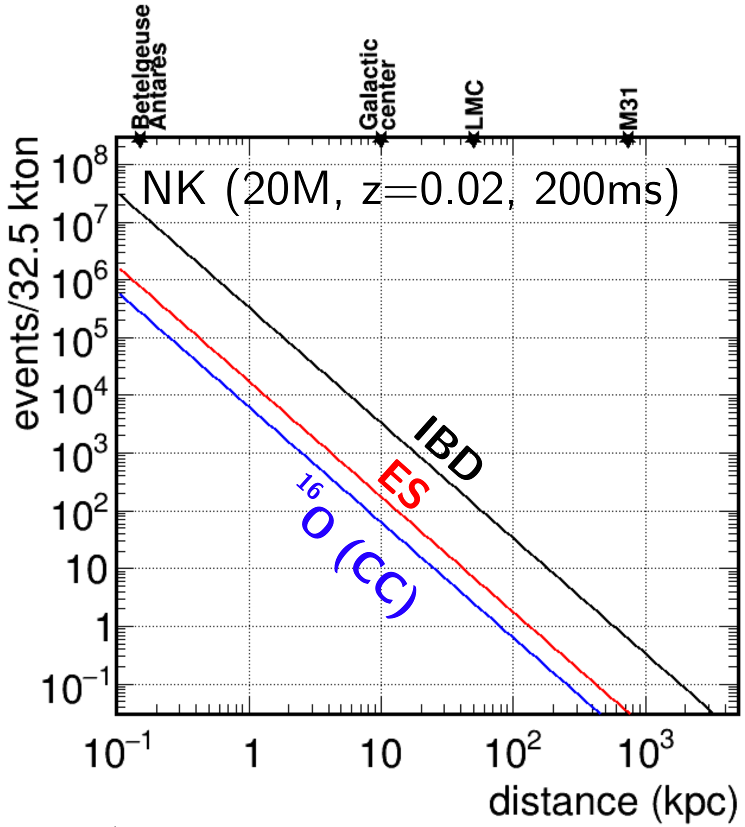
~1.5 minutes at present (for 10kpc SN) aimed to be improved to **< 1 minute.**

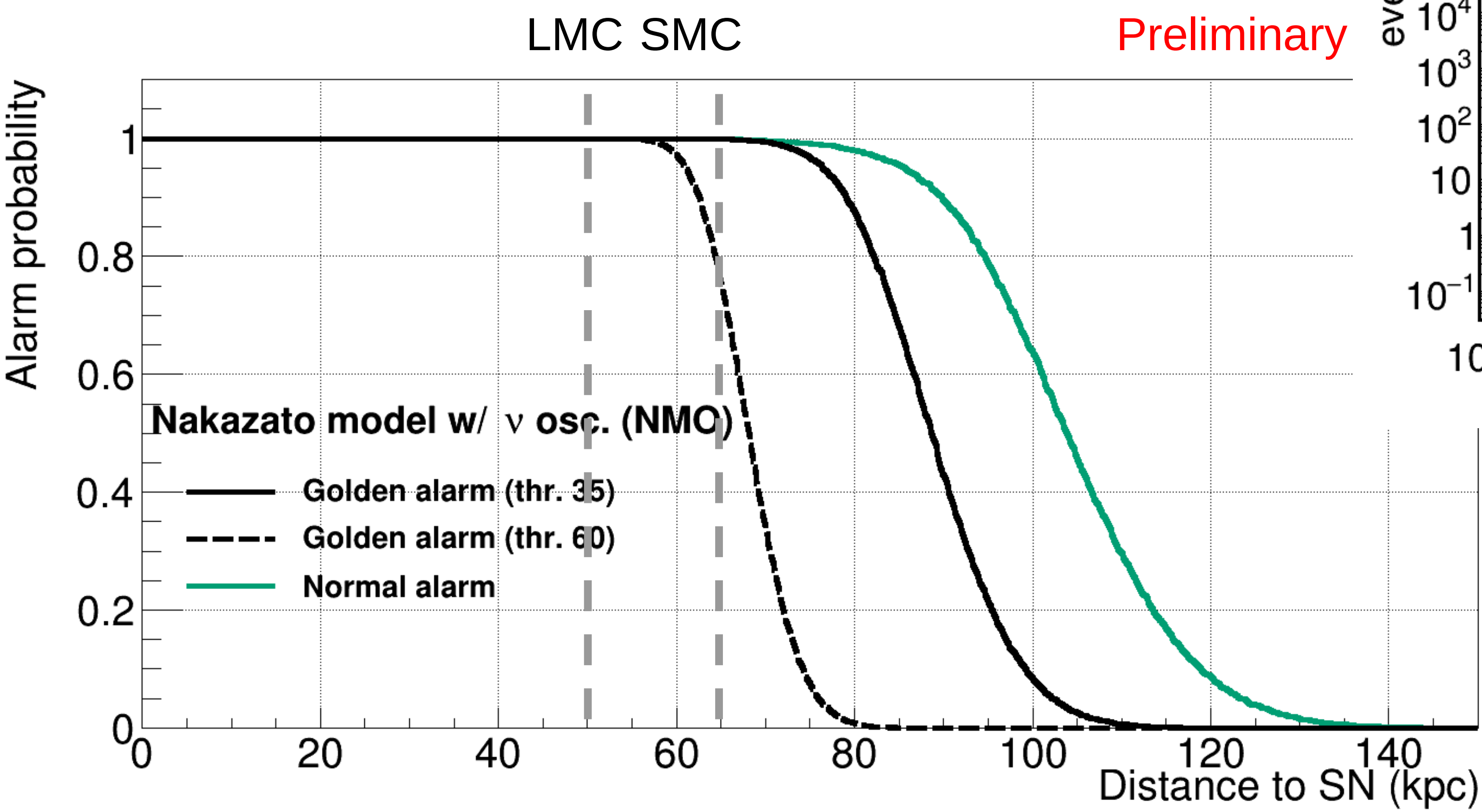
Realtime supernova monitoring in Super-Kamiokande



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**)



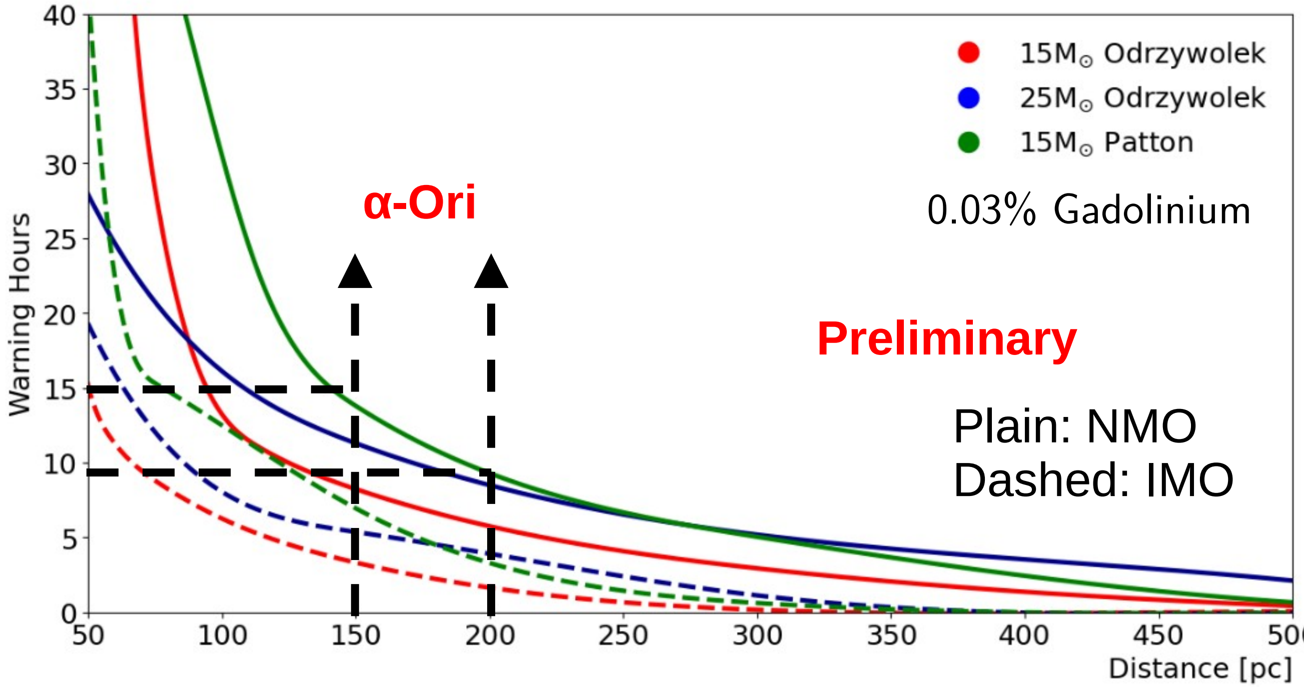


Pre-supernovae neutrinos

- Before the core-collapse, supernova progenitors starts burning 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 $\sim 10^{5}\ L_\odot$) *[Astropart.Phys. 21 (2004) 303-313)]*

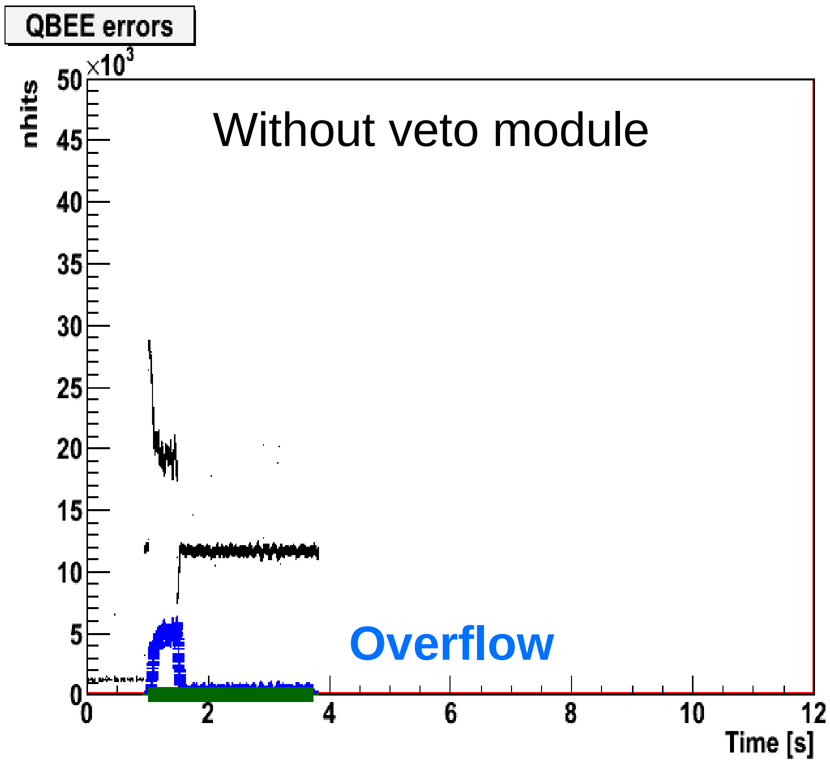
$$e^- + e^+ \rightarrow \nu_x + \bar{\nu}_x$$

- 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 in Super-Kamiokande and the release of a pre-supernova alarm.
- For Betelgeuse (α-Ori) we can send a warning 10~15 hours before the core-collapse (NMO).
- This pre-supernova warning alarm can allow detectors to avoid/postpone maintenance or down time few hours before a supernova.
- A combined alarm between Super-Kamiokande and KamLAND is available: https://www.lowbg.org/presnalarm/

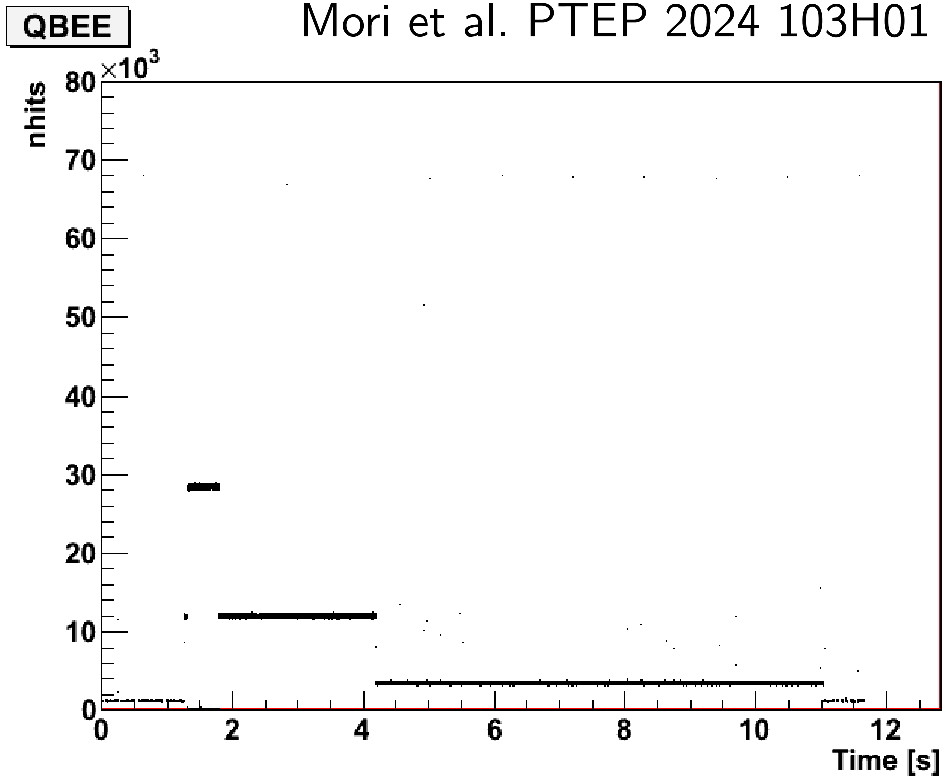


Close supernova detection

- In case of very close supernova bursts, the amount of neutrino interactions may be too high for the Super-Kamiokande electronics system, causing overflow.
  - We have developed two modules to prevent this issue
    - A “SN module” which records number of PMT hits overtime
    - A “veto module” which prescales the number of PMT hits to prevent overflow, enabled when a pre-SN alert is detected



Mori et al. PTEP 2024 103H01



Figures from Mori-san

Co-operation with telescopes

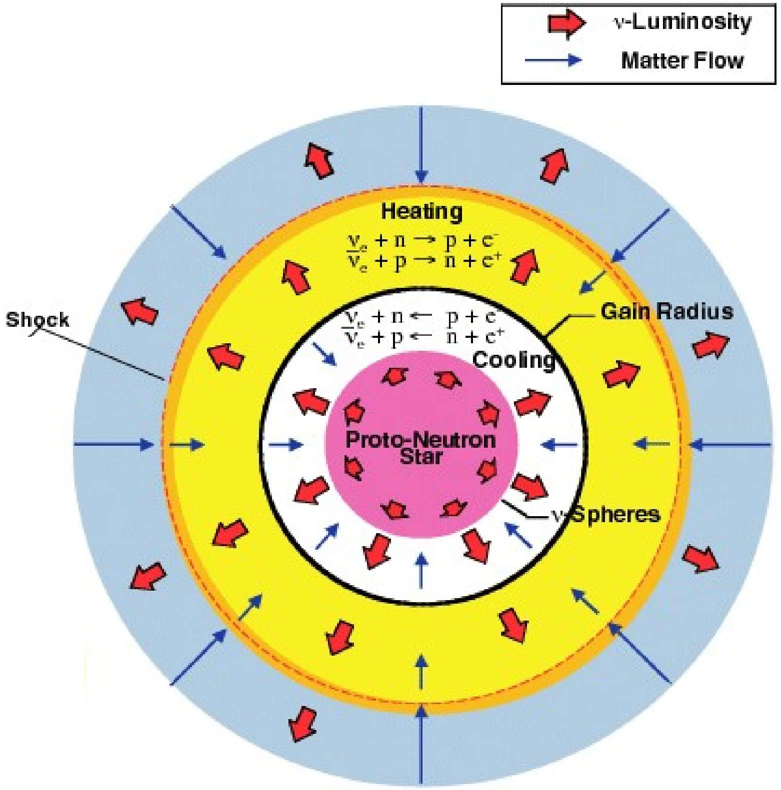
- If (when) Super-Kamiokande send a supernova alarm to the world, we hope some telescopes will be able to look for it in order to observe the first instants of the supernova burst.
  - We made a MoU with the **A**ll-**S**ky **A**utomated **S**urvey for **S**uper**N**ovae Collaboration (ASAS-SN), a network of 20 telescopes located around the globe
  - We alos made a MoU with **Tomo-e Gozen**, allowing us to send them low significance alarms for training purpose
- 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!

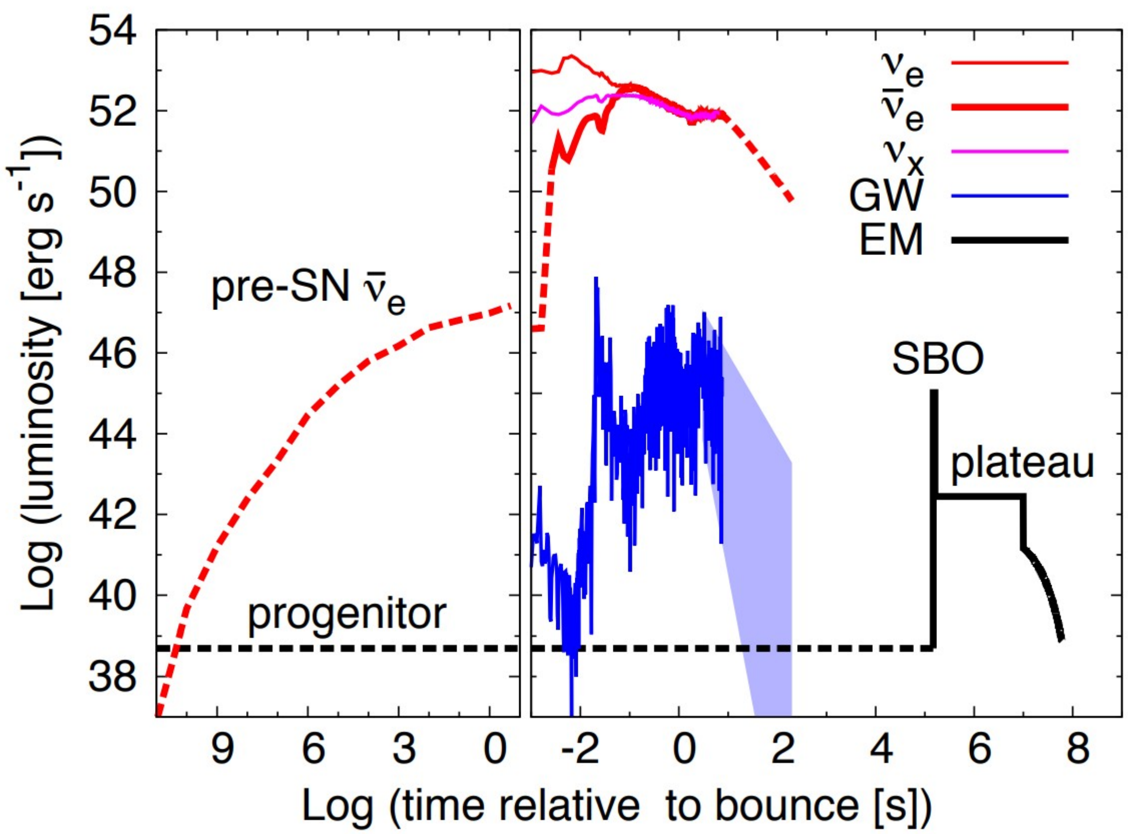
Summary

- Super-Kamiokande is continuously monitoring the detector events to probe any burst of events indicating a supernova.
  - Selection algorithm improvements allowed to reduce our energy threshold while keeping good BG rejection level, improving our selection efficiencies
  - 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.
  - Using pre-SN neutrino, Super-Kamiokande may be able to detect a close SN (<100pc) 10~15h before the core collapse. For such close SN, custom hardware modules allow to handle and smooth the rate of events in the detector, preventing our electronics to be overflowed.
- We are making cooperation agreement with some telescopes, in order to ensure our supernova alarms will be followed to observe the first instants of the supernova burst.
  - MoU with **A**ll-**S**ky **A**utomated **S**urvey for **S**uper**N**ovae Collaboration (ASAS-SN)
  - MoU with Tomo-e Gozen, to send them low significance alarms for training purpose
  - Discussion on-going with other telescopes.

Backup

Core-Collapse Supernovae

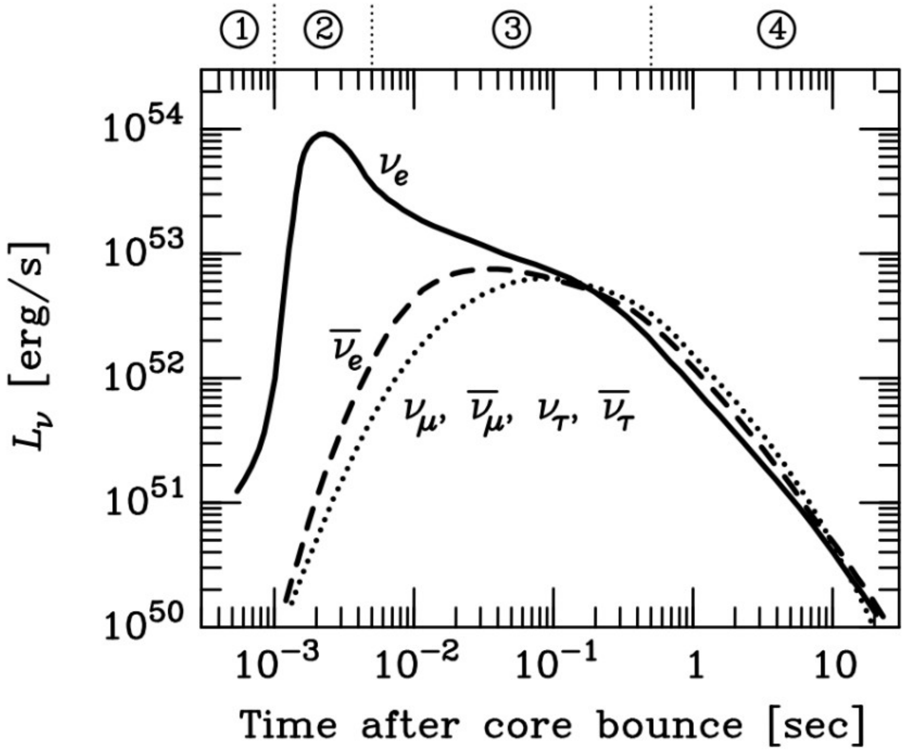




- Massive stars (8+ $M_\odot$) can end their life as core-collapse supernovae (or Type II SN), a cataclysmic implosion giving birth to a neutron stars or a black hole (failed supernova).
- 99% of the Core-Collapse Supernova's energy is released through neutrino

Core-Collapse Supernova Burst

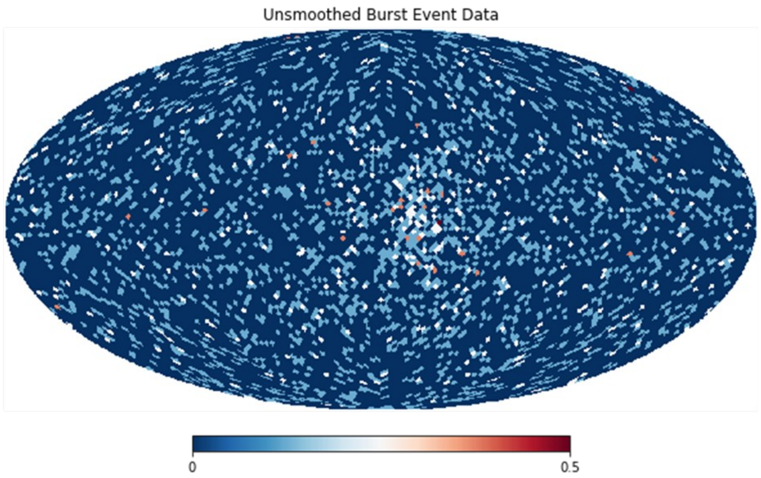
- After the finishing burning its fuel, massive stars can collapse on themselves, as the heat pressure is not enough to compensate the gravitionnal force.
  - Higher energy gamma rays are produced, decomposing the Fe nuclei into He and free neutrons through photo-disintegration.
  - High matter density 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 $\overline{\nu}$



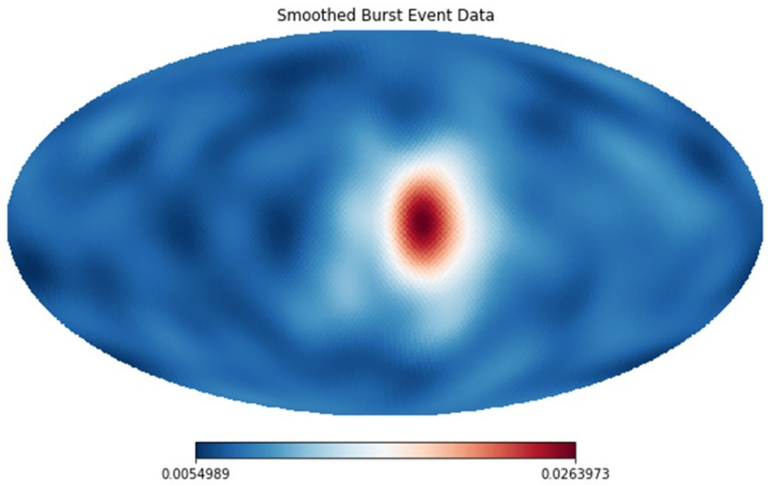
SN direction fitter improvement investigations

- **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

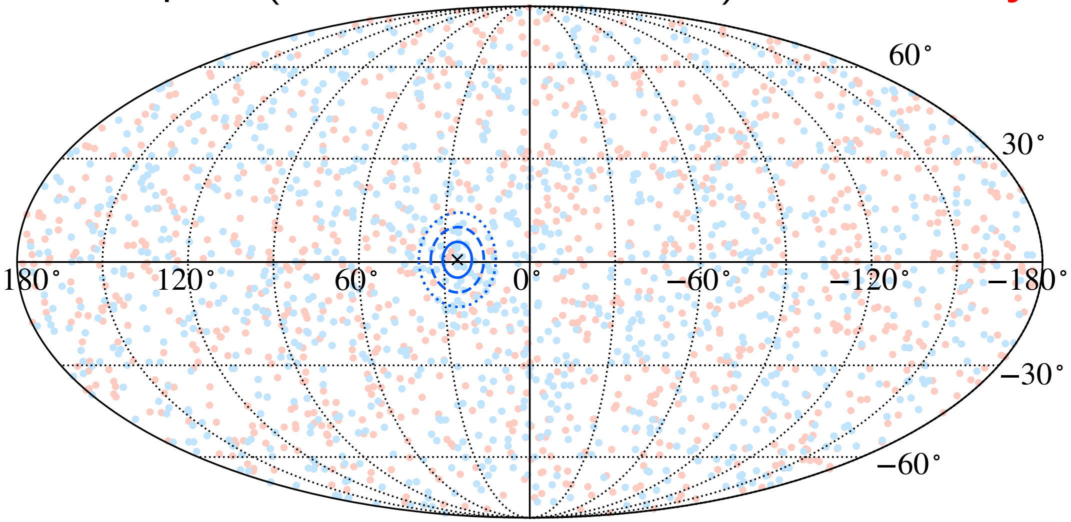


Gaussian Smoothed, σ = 0.15 rad.

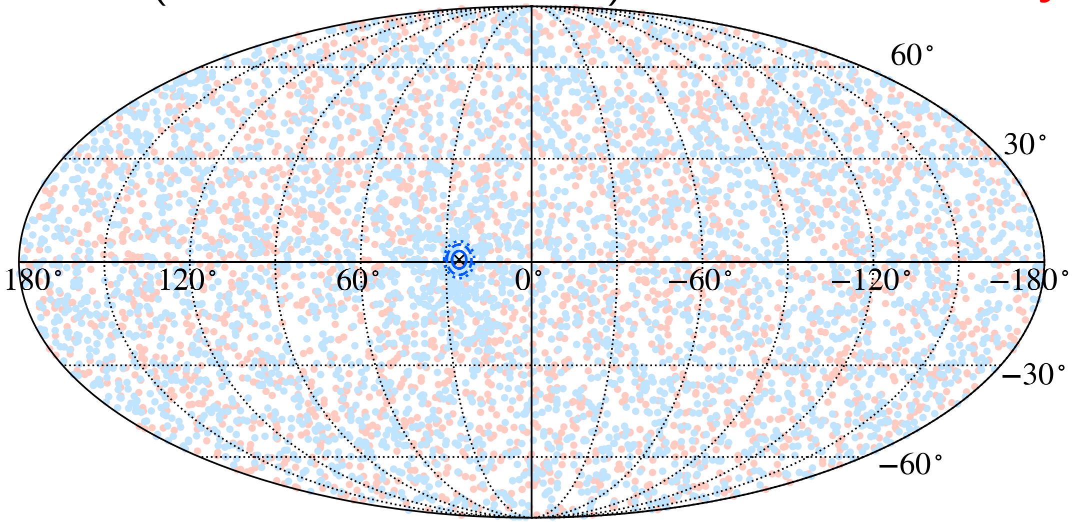


Realtime angular resolution with other models

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***

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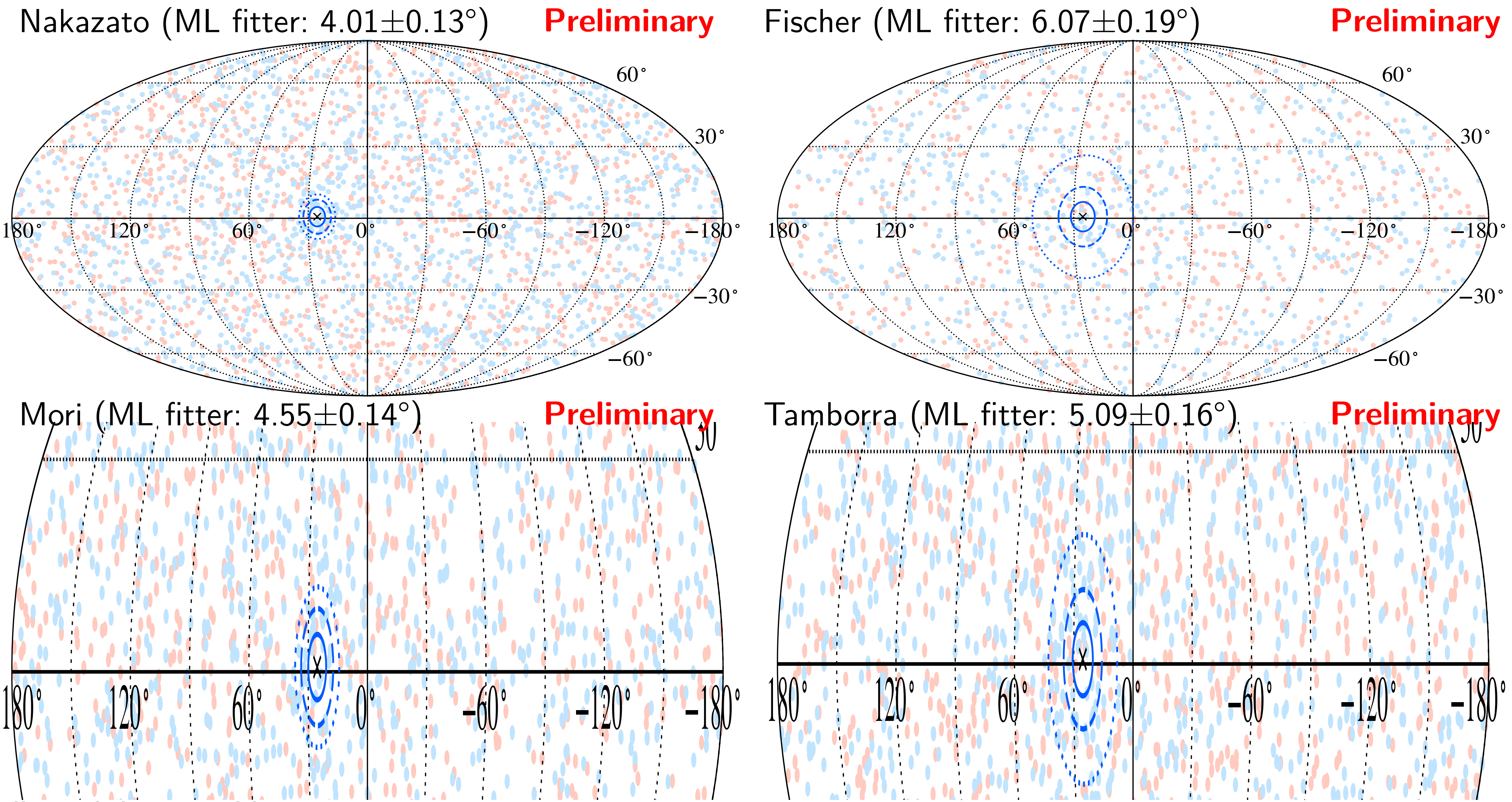
Realtime angular resolution with other models



All models are with NMO

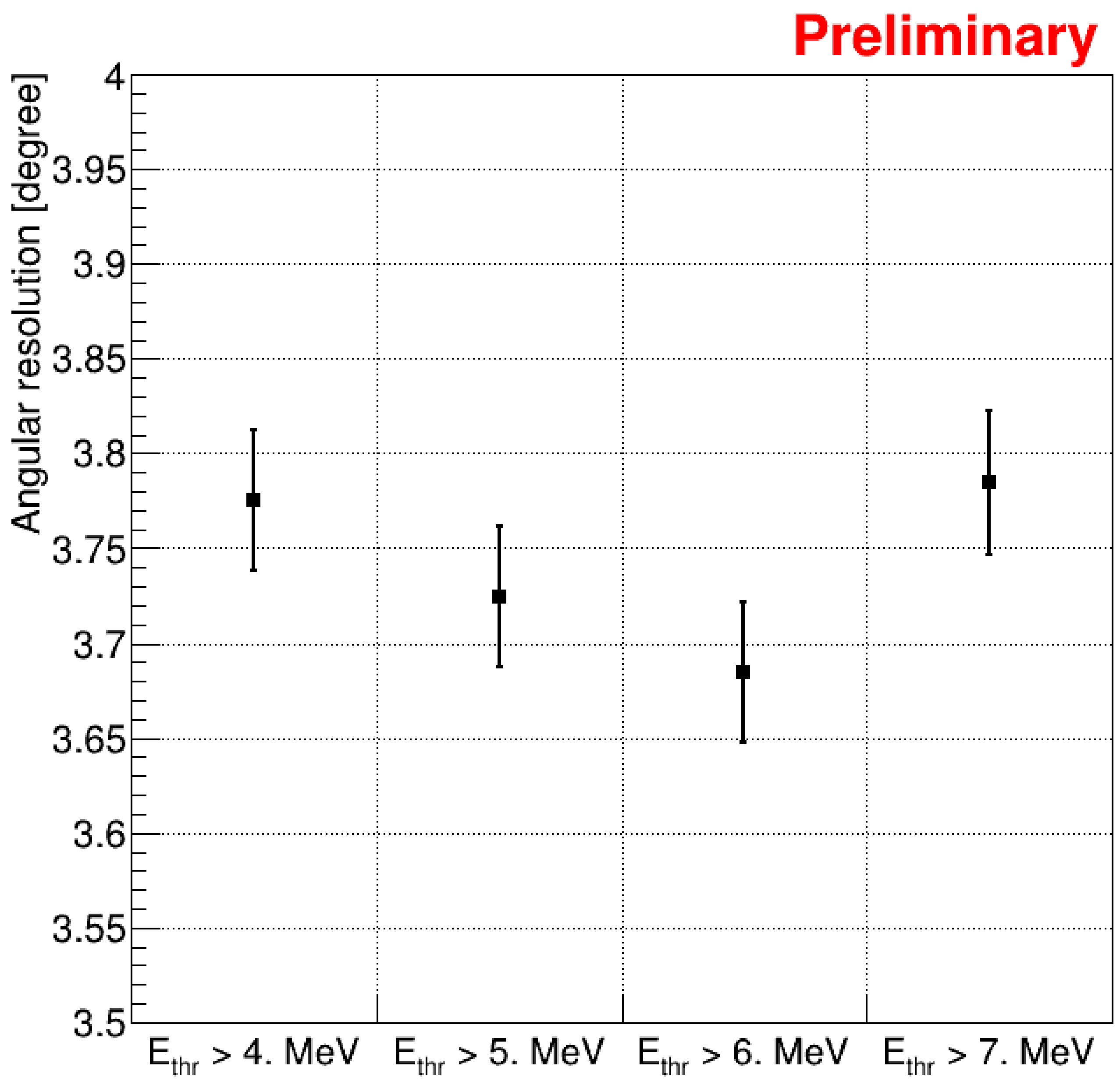
- Performances with the previous Maximum Likelihood (ML) fitter. New fitter (ML+ HEALPix) performances are equivalent with a much faster processing.

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.

Angular resolution as function of energy threshold



Low alarm

- This internal alarm is shared with some telescopes following an MoU
- We can have a $\sim$50% coverage for SN up to 150 kpc for the following cuts:
  - Cluster with dimension 3 (volumic) or 2 (area), with high enough likelihood ($>$400)
  - $+$ Number of events (after muon events excluded) > 9
  - $+$ Number of tagged IBD (after muon events excluded) > 5
- Our current sample of false alarms doesn't pass these criteria