Super-Kamiokande galactic supernova's neutrino burst monitoring

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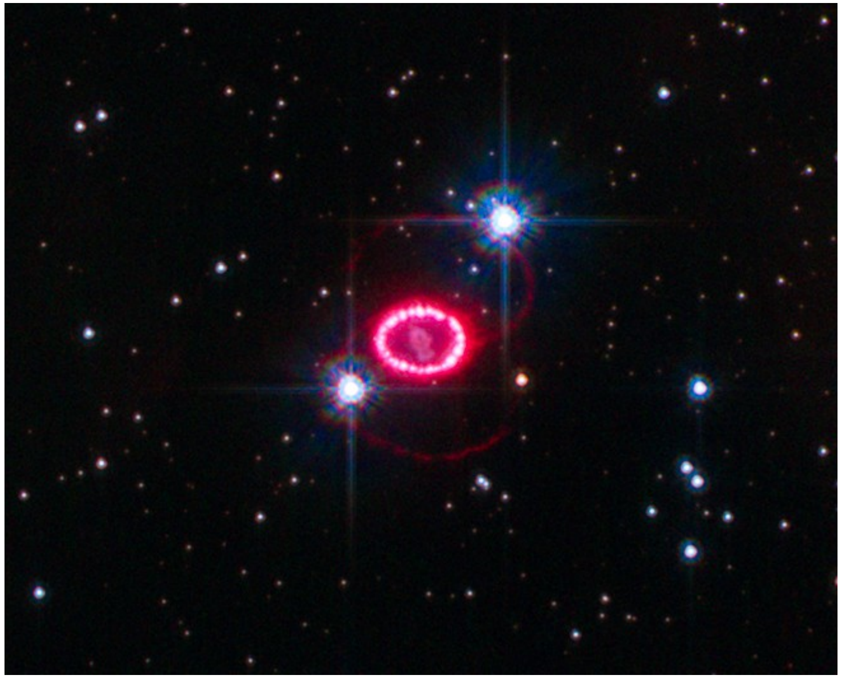
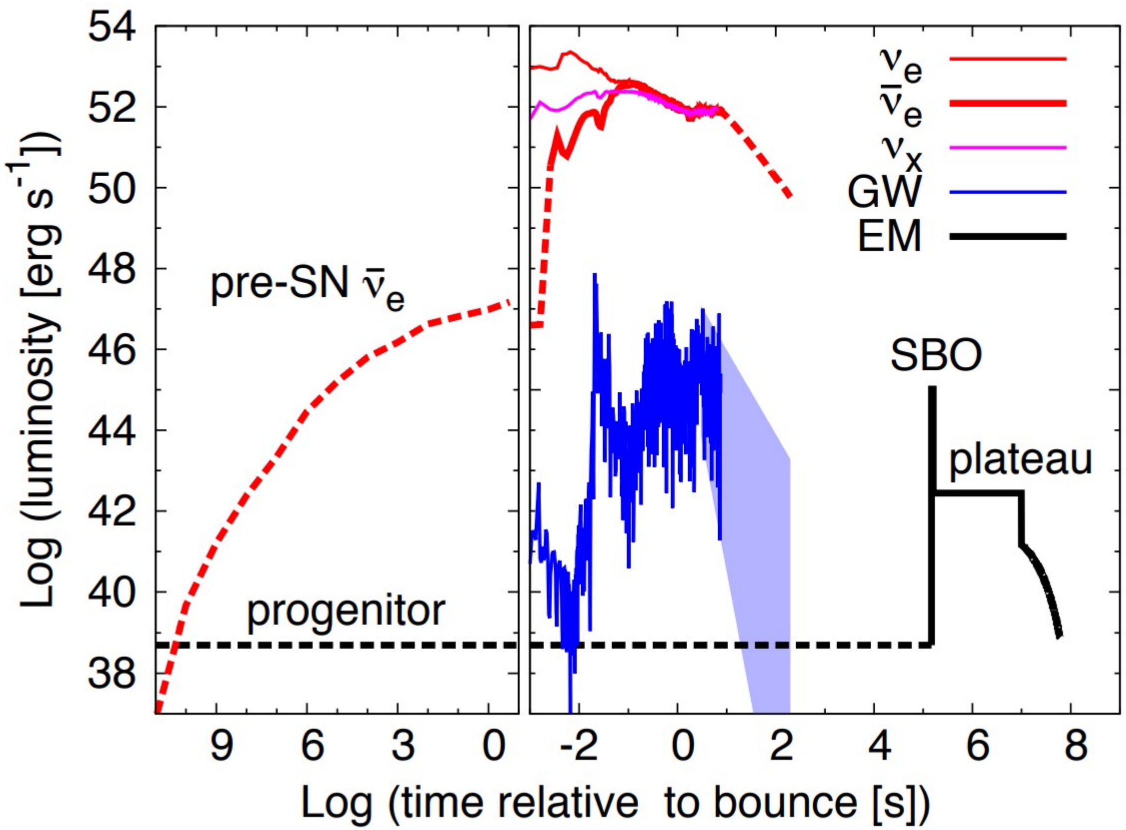
Core-Collapse Supernova Neutrinos



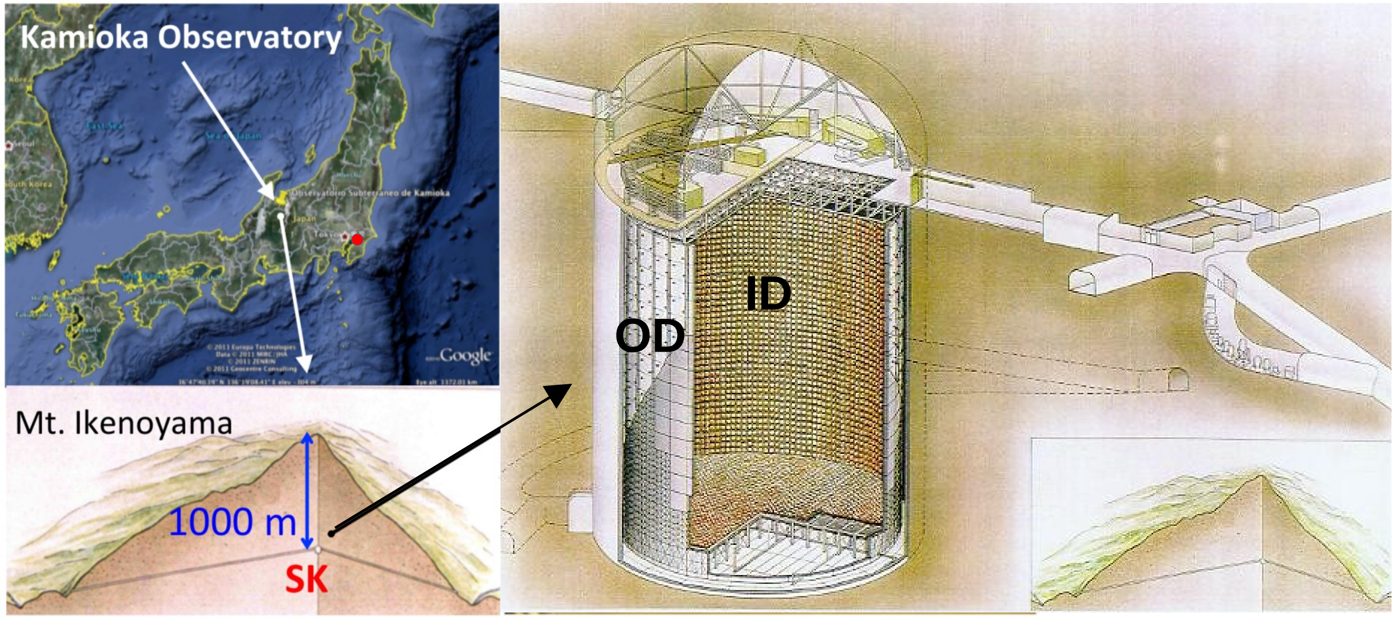
SN1987A remnant



- 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.

Super-Kamiokande

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

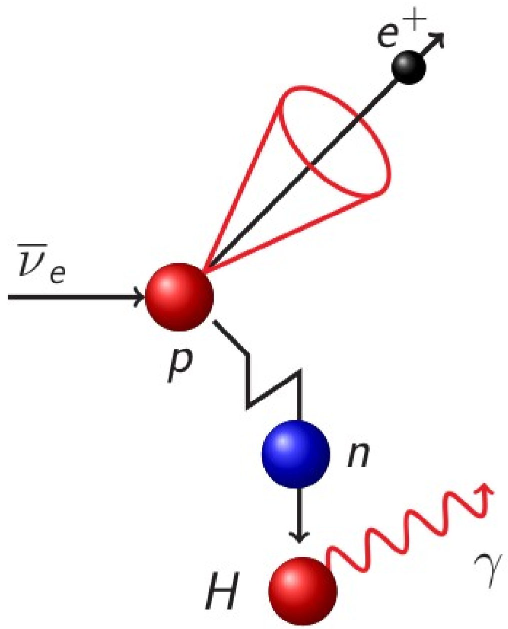


- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-VII is running

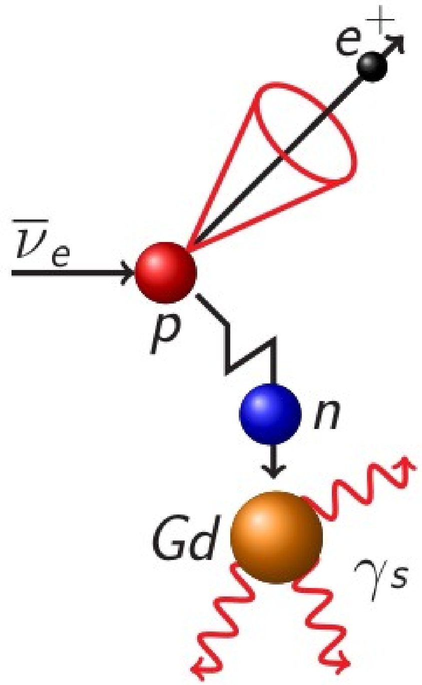
- The detector is filled with 50ktons of **gadolinium**-loaded water.
- Gadolinium was loaded at 0.01% in the water in Summer 2020, and the concentration was further increased to 0.03% in May 2022. Calibration was completed and the detector is running stably since then.
- **Physics targets**: Neutrino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



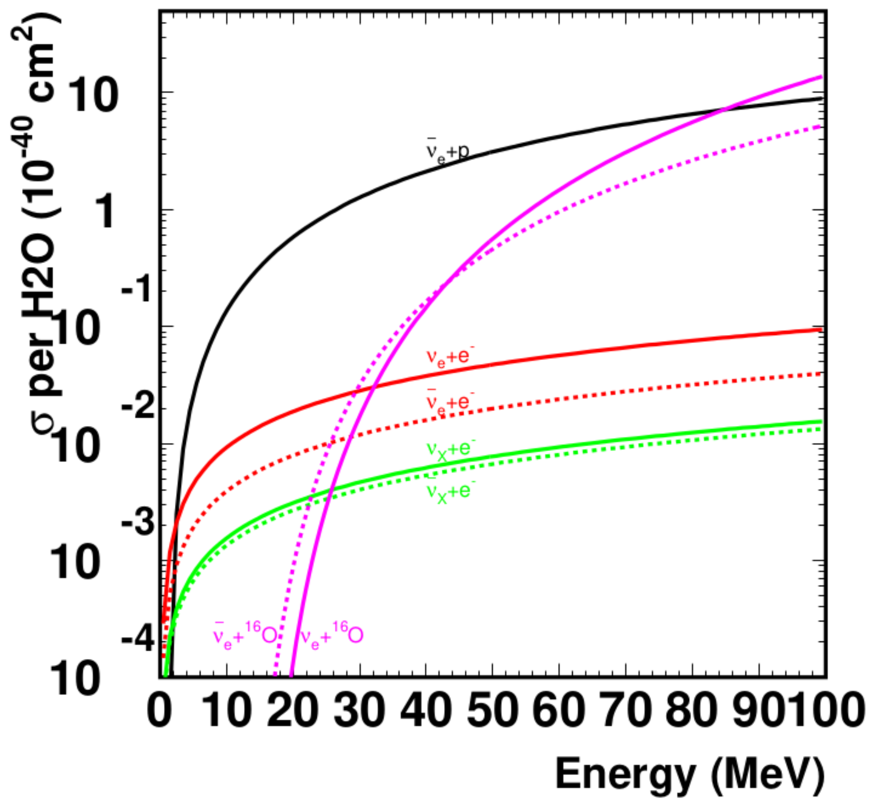
Hydrogen-neutron capture:
single 2.2 MeV gamma
→ Large accidental background
→ Vertex reconstruction difficult

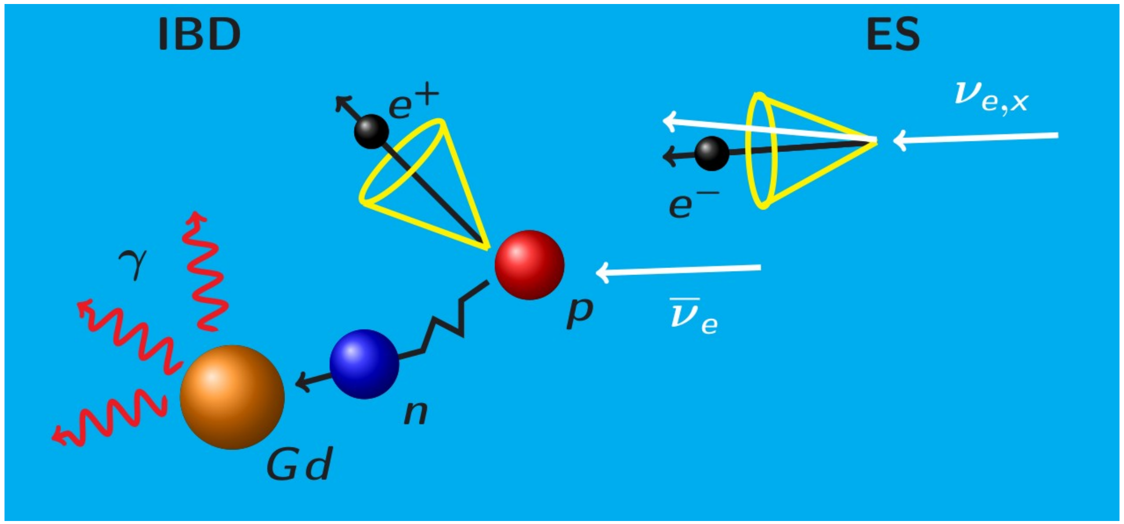


Gadolinium-neutron capture:
Gamma cascade at ~8 MeV
→ Lower background
→ Vertex reconstruction possible

Supernova Neutrinos in Water Cherenkov Detectors

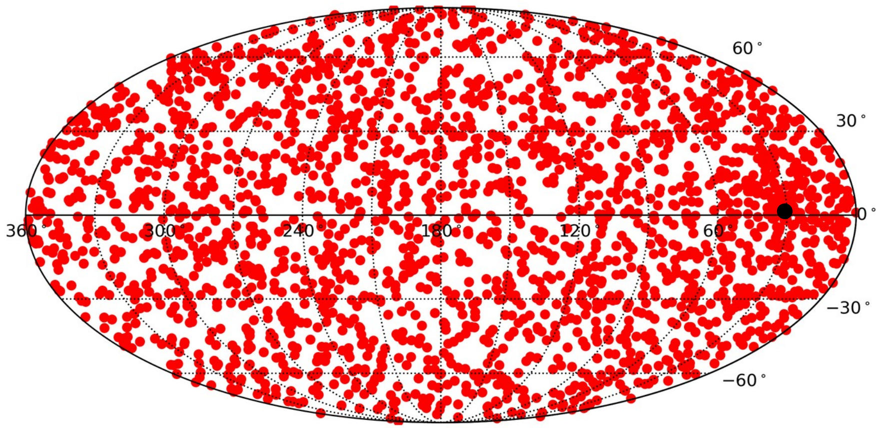
- The SN neutrino burst is composed of (roughly) similar amount of neutrino and antineutrino of each flavours. However, due to cross-sections, the number of detected neutrino interaction will be different.
- In case of Water Cherenkov detector, the main interactions expected are:
  - **Inverse Beta Decay 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



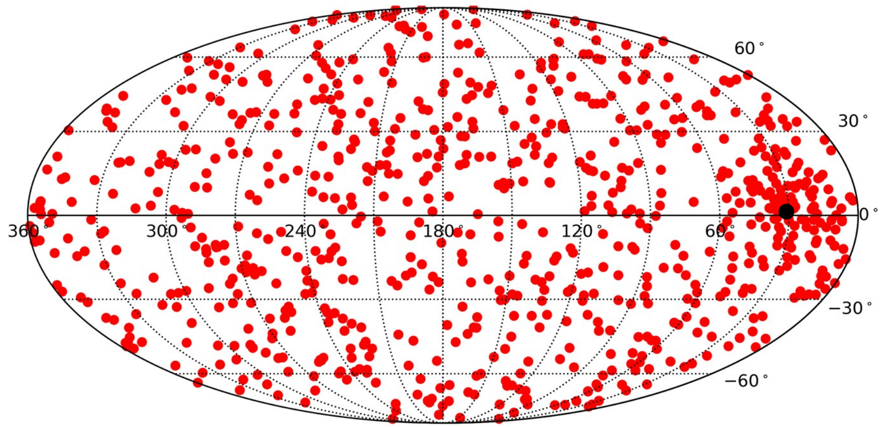


Using Gd-n to separate IBD and ES

- 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.



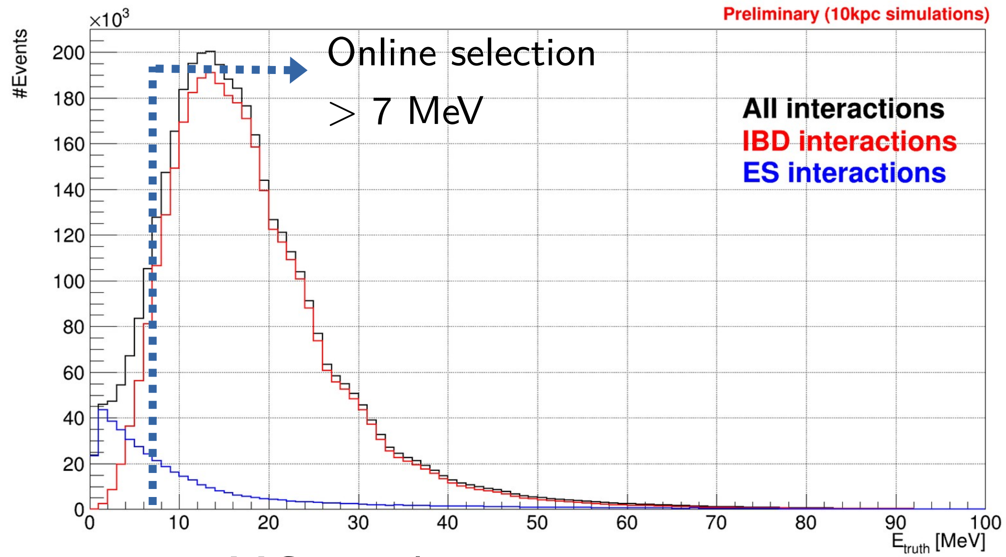
SN burst events w/o IBD tagging
(10kpc simulation)



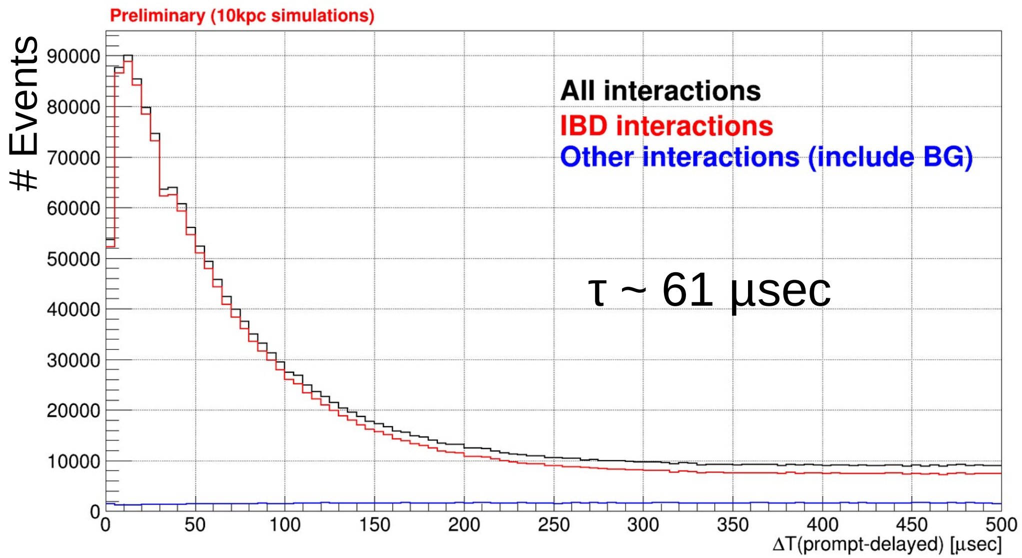
SN burst events w/ 72% IBD events tagged/removed
(10kpc simulation)
(Expected with 0.1% Gd)

Realtime event selection

- In order to monitor event burst within the Super-Kamiokande detector, we are reconstructing and selecting "SN interaction like" events in realtime.
- Realtime selection efficiencies:
  - ▷ ~35.3% of the ES interactions
  - ▷ ~89.5% of the IBD's positron interactions
  - ▷ ~54.4% of the IBD's neutron capture interactions (with 0.03% Gd)
    → **~46% IBD interactions are tagged as IBD**
- These realtime efficiencies are lower than the full performance of Super-Kamiokande as hard cuts are applied to remove any potential noise. Offline (slower) analysis reach better performances.



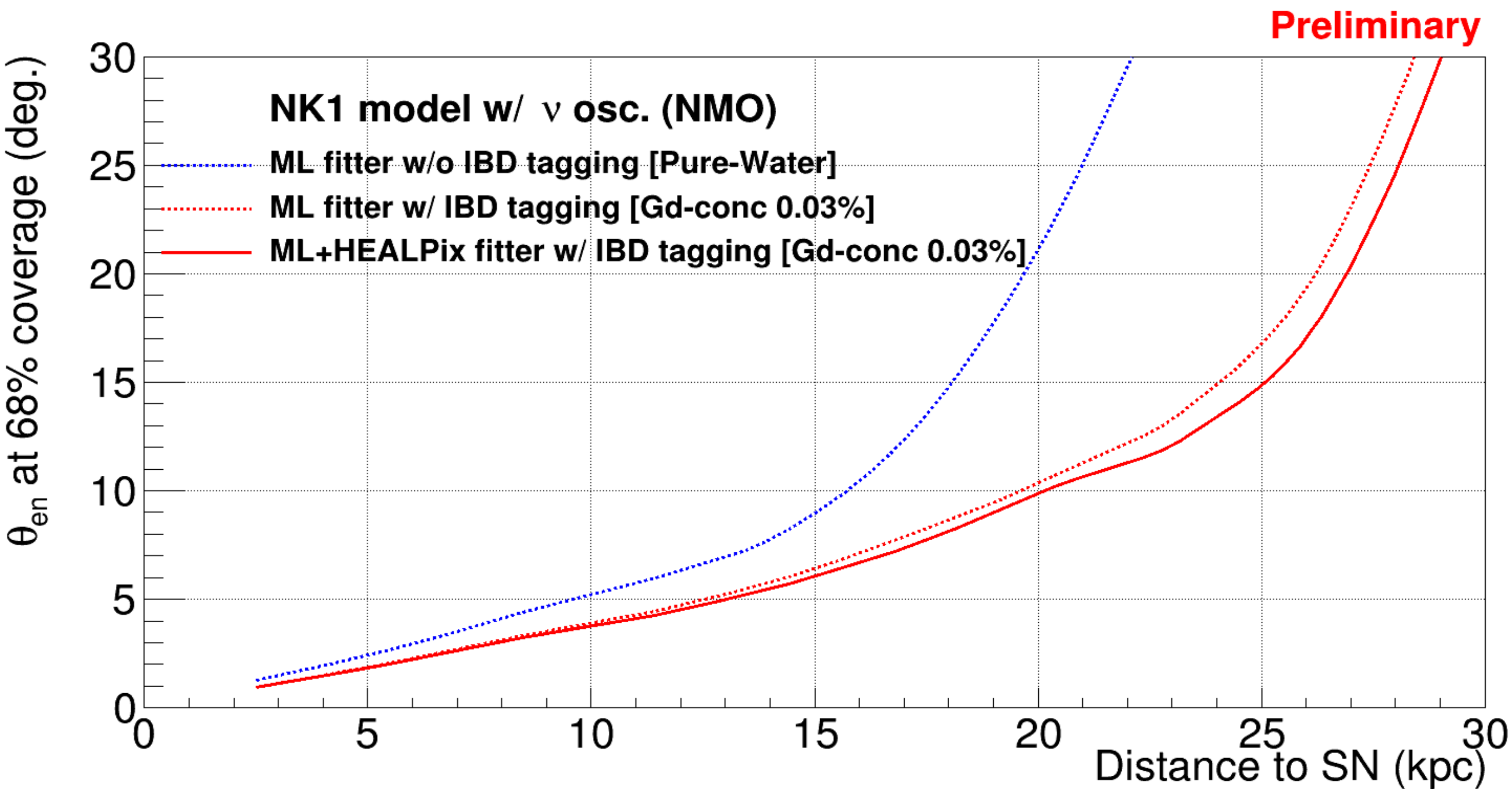
1000 MC simulations



1000 MC simulations

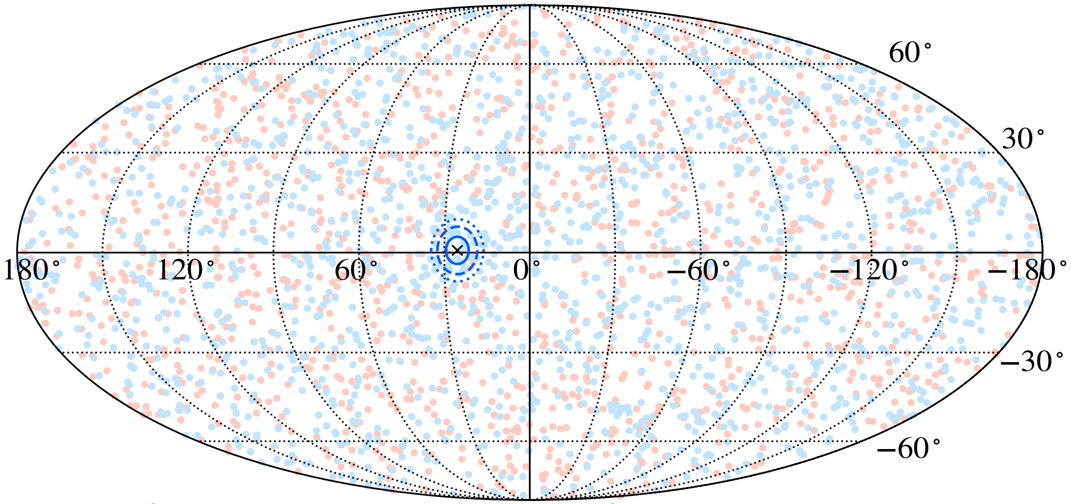
Realtime angular resolution I

- 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 $3.96 \pm 0.13°$ at 10 kpc (Nakazato model). This reconstruction alone is achieved **in less than 10 seconds** (with respect to 1.5~2 minutes before).

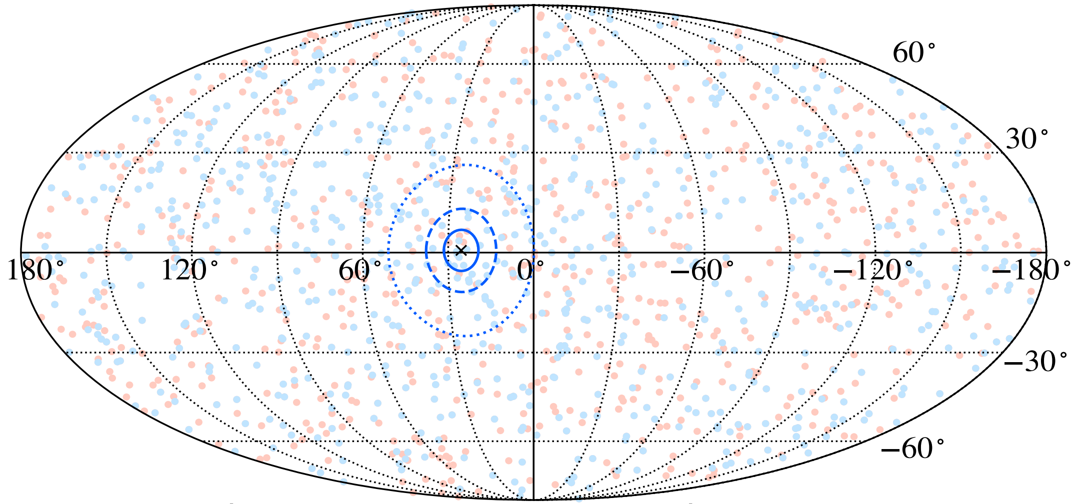


Realtime angular resolution with other models

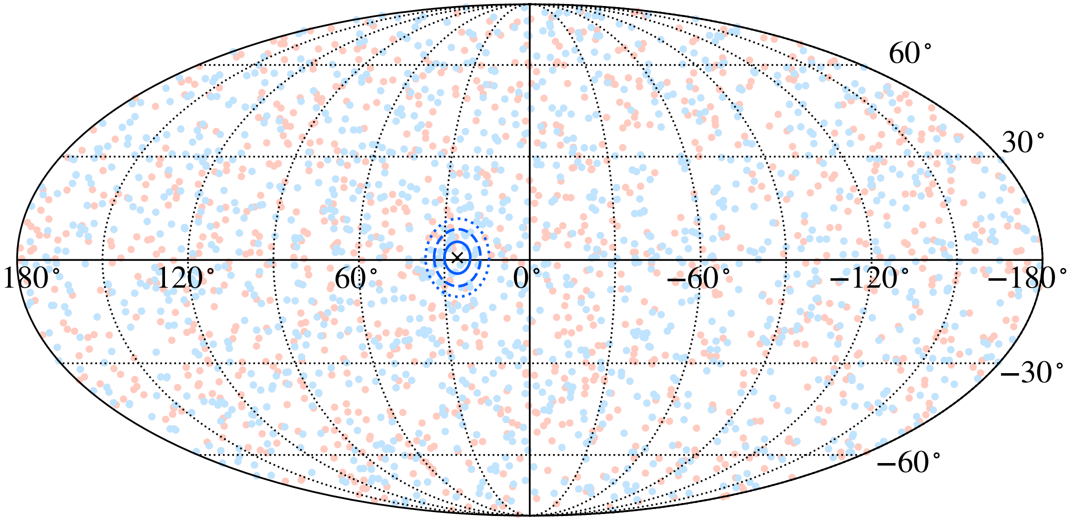
Nakazato (ML fitter: 4.01±0.13°) **Preliminary**



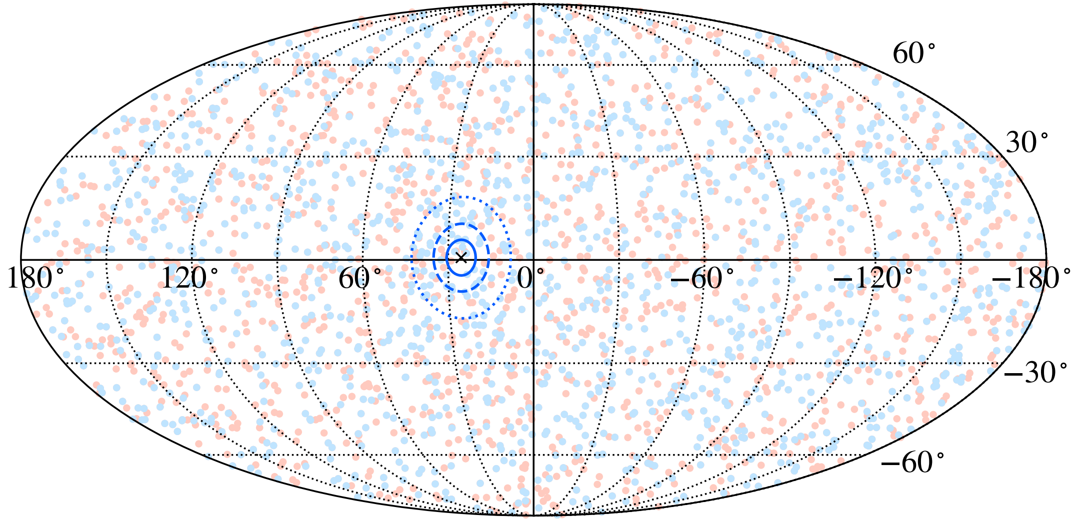
Fischer (ML fitter: 6.07±0.19°) **Preliminary**



Mori (ML fitter: 4.55±0.14°) **Preliminary**



Tamborra (ML fitter: 5.09±0.16°) **Preliminary**



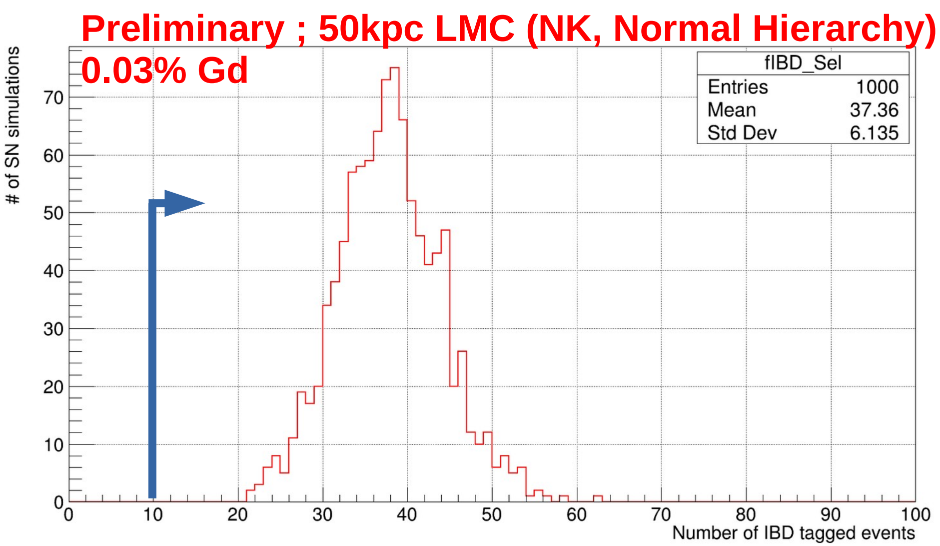
All models are with NMO

Performances with the previous Maximum Likelihood (ML) fitter.

New fitter (ML+ HEALPix) performances are equivalent with a much faster processing.

Automated SN alarm: GCN

- In case of a burst of events matching our criteria (isotropic distribution and more than 60 good events) Super-Kamiokande will send an alarm. Since December 13th 2021, this alarm is automated:
  - If the number of IBD tagged events is > 10, an automated **GCN notice** will be distributed.
  - This GCN notice is currently send by mail, which induces some delay to distribute it.
  - GCN itself is under-going an upgrade ("Kafka") recently, with an unified schema, and a new distribution method which we are implementing. This upgrade will reduce the delay for the GCN notice distribution to less than 1 second.

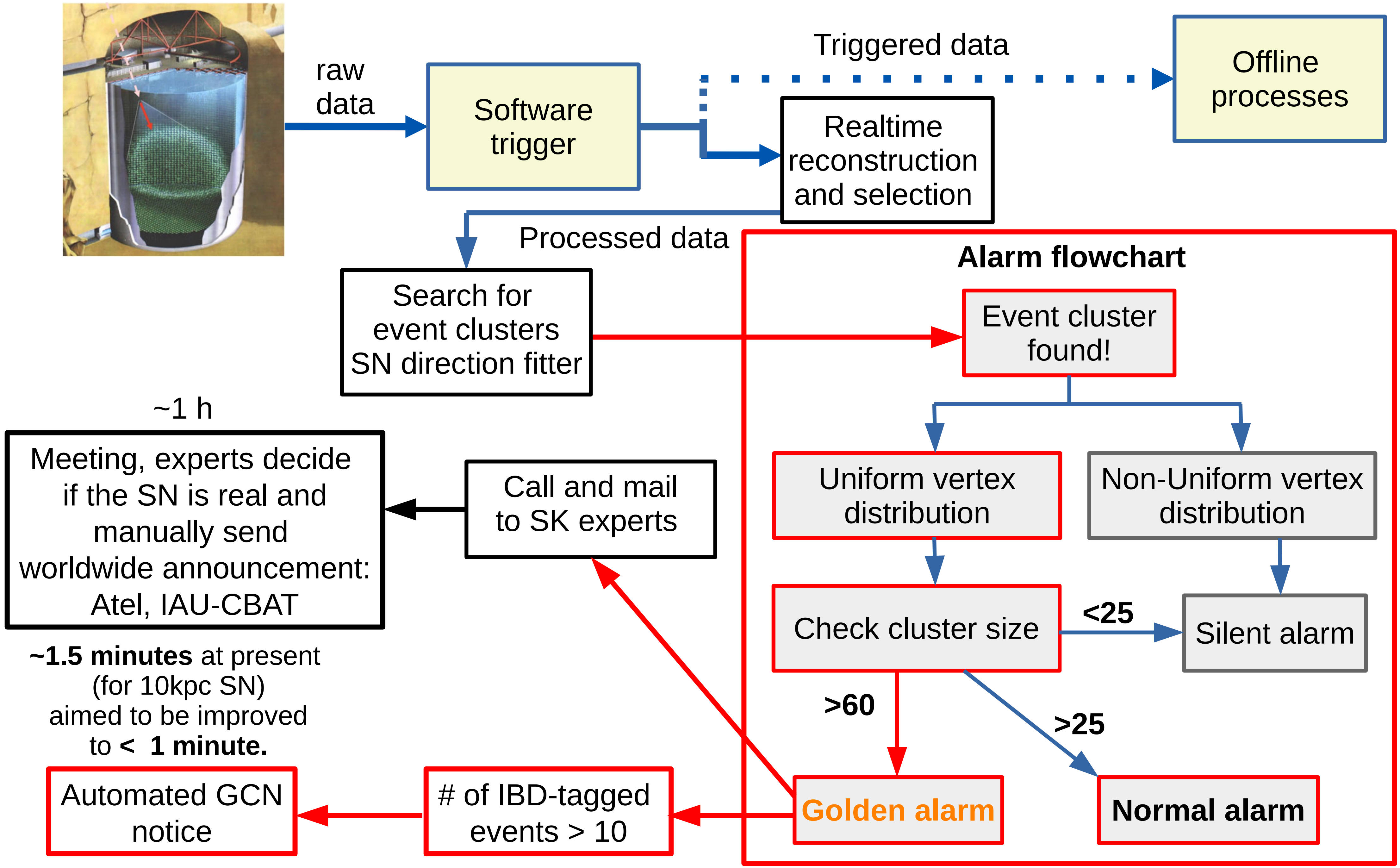


Test GCN notice example

```
/////////////////////////////////////////////////////////////////////////////////
TITLE:           GCN/SK_SN NOTICE
NOTICE_DATE:     Mon 01 Nov 21 00:00:14 UT
NOTICE_TYPE:     SK_SN  TEST
TRIGGER_NUMBER:  SK_SN  10030
SRC_RA:          254.4000d {+16h 57m 36s} (J2000),
                 254.6087d {+16h 58m 26s} (current),
                 253.9223d {+16h 55m 41s} (1950)
SRC_DEC:         +31.2600d {+31d 15' 36"} (J2000),
                 +31.2275d {+31d 13' 39"} (current),
                 +31.3360d {+31d 20' 10"} (1950)
SRC_ERROR68:     0.64 [deg radius, stat-only, 68% containment]
SRC_ERROR90:     0.91 [deg radius, stat-only, 90% containment]
SRC_ERROR95:     1.04 [deg radius, stat-only, 95% containment]
DISCOVERY_DATE:  19518 TJD;  304 DOY;  21/10/31 (yy/mm/dd)
DISCOVERY_TIME:  82816 SOD {23:00:16.74} UT
N_EVENTS:        64124  (Number of detected neutrino events)
ENERGY_LIMIT:    7.00 [MeV]  (Minimum energy of the neutrinos)
DURATION:        10.0 [sec]  (Collection duration of the neutrinos)
DISTANCE:        2.16 - 2.95 [kpc]  (low - high as SN1987A like SNe)
COMMENTS:        The position error is statistical only, there is no systematic added.
COMMENTS:        All numbers are preliminary.
COMMENTS:
COMMENTS:        NOTE: This is a TEST Notice.
COMMENTS:
```

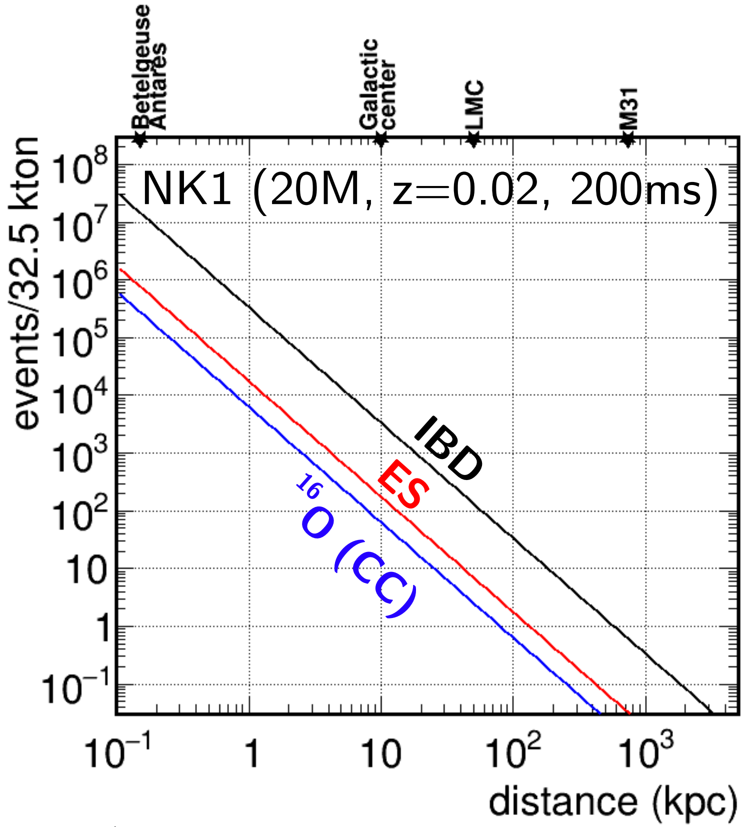
Note: this structure will change with the unified schema

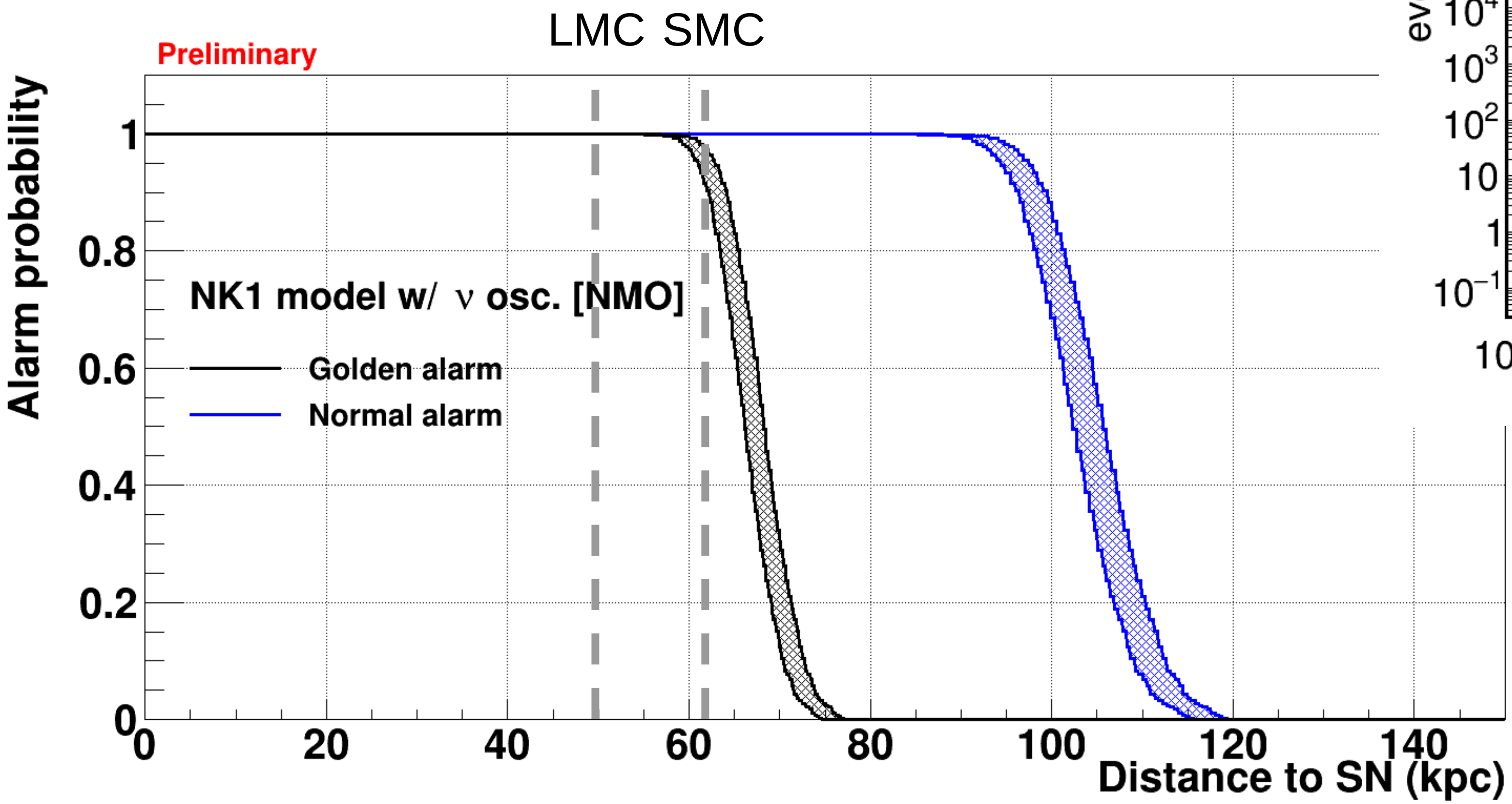
Realtime supernova monitoring in Super-Kamiokande



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 by Normal alarm (∼90% probability for Golden alarm)





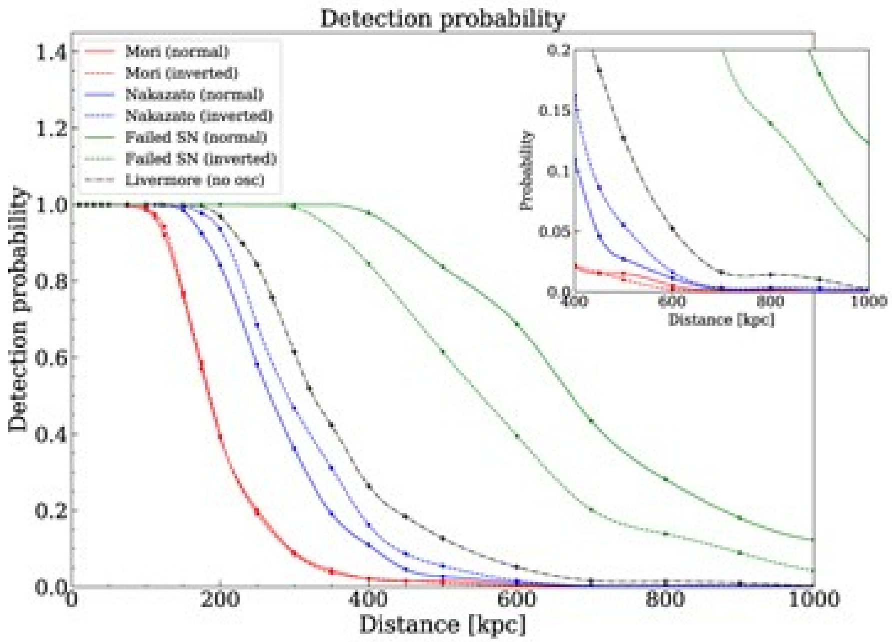
Co-operation with telescopes

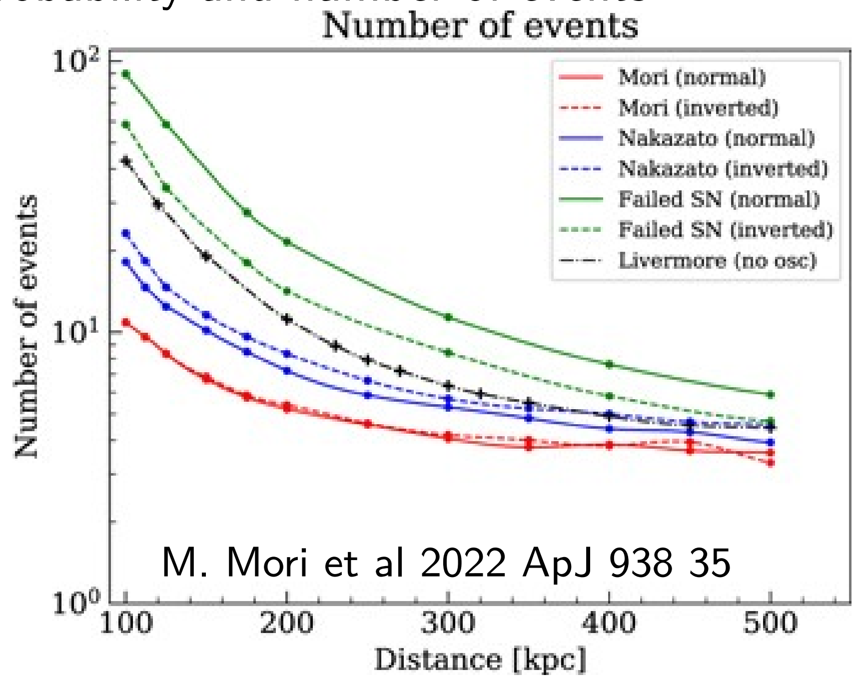
- If (when) Super-Kamiokande send a supernova alarm to the world, we hope some telescopes will be able to look for it in order to observe the first instants of the supernova burst.
  - In order to increase the probability our alarm will be used, to maximise the change to have combined neutrino-optical observations of SN in the Milky Way, we are made a MoU in June 2023 with the **A**ll-**S**ky **A**utomated **S**urvey for **S**uper**N**ovae Collaboration (ASAS-SN), a network of 24 telescopes located around the globe
  - ASAS-SN implemented an automated follow-up of our SK alarm this month
- **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!**

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 did not find any evidence of distant SN bursts from data collected in SK-IV (2008~2018), allowing to define the following upper limits:

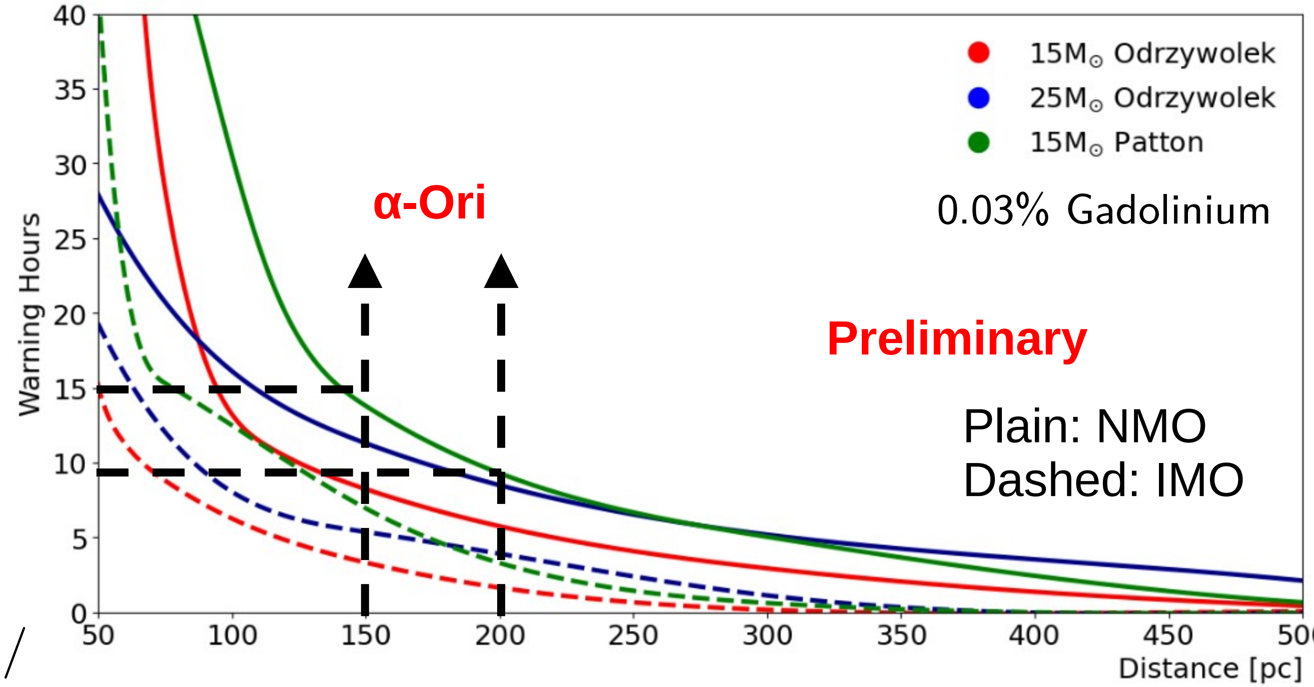
  $\rightarrow$ $<$ **0.29 yr^{-1}** supernovae out to 100 kpc (300 kpc for failed supernovae)
- Coincidence with SN2023ixf was also investigated, but no significant signal was observed (ATEL 16070, GCN circular 33916)

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)]*

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

- 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 now available: https://www.lowbg.org/presnalarm/



Summary

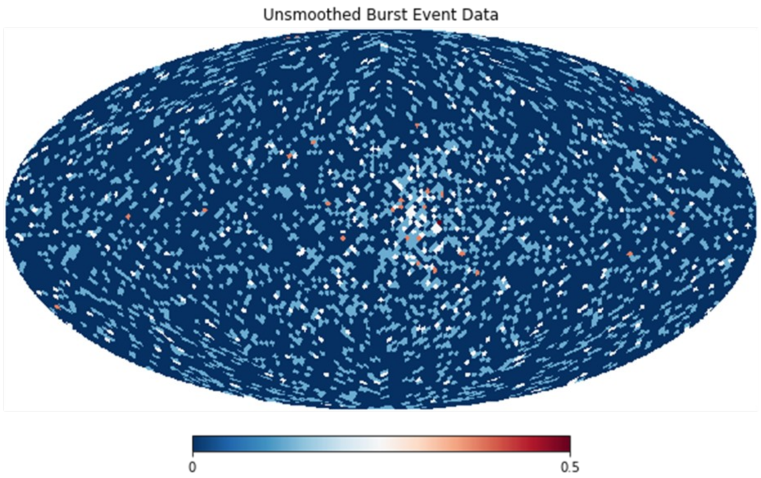
- Super-Kamiokande is continuously monitoring the detector events to probe any burst indicating a supernova.
  - Thanks to the 0.03% Gd loading in the detector water, we are able to tag ~46% of the Inverse Beta Decay events, providing both a clear SN signal with low BG contamination, as well as a mean to increase the accuracy of the SN direction reco.
  - Super-Kamiokande monitoring system can provide a direction with a resolution of **3.96±0.13°** at 10 kpc (assuming Nakazato model, NMO)
  - We are releasing automated alarm through GCN notice **within 1.5 minutes** following the neutrino burst in the detector.
- Pre-supernova neutrino can be detected few hours before the core-collapse in Super-Kamiokande within 500 pc, further improvement can be expected by combining Super-Kamiokande and KamLAND alarms.
- An MoU has been signed between ASAS-SN and Super-Kamiokande in order to maximise our change for neutrino-optical detection of the next galactic supernova. If any other telescope collaborations are interested in making a direct connection with SK's SN alarm, please contact us!

Backup

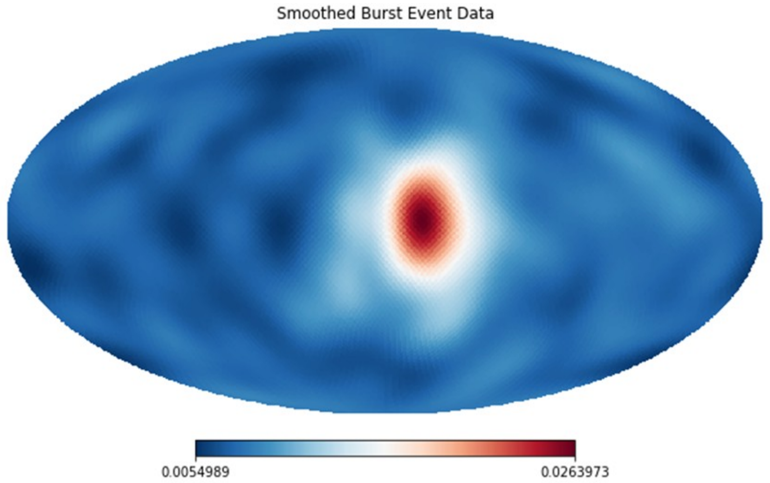
SN direction fitter improvement investigations

- **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

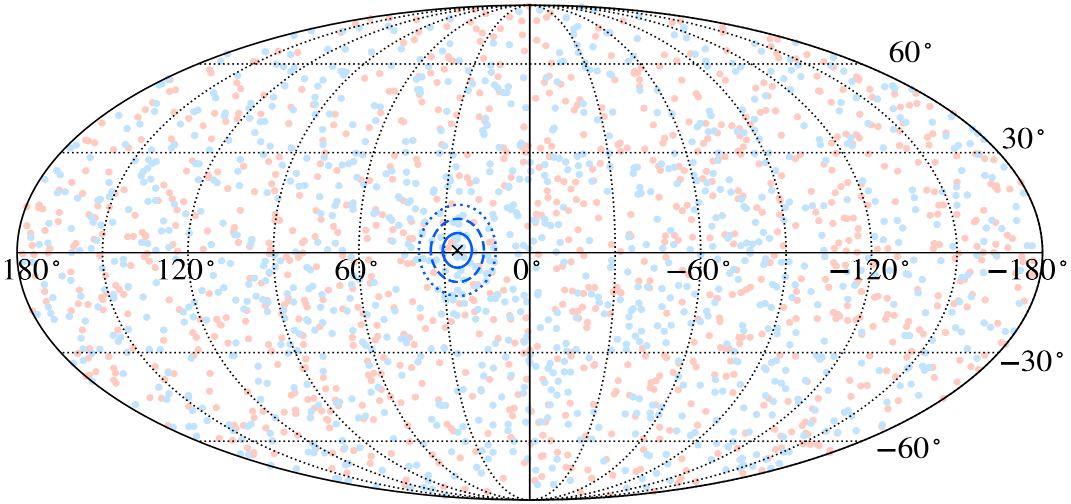


Gaussian Smoothed, σ = 0.15 rad.

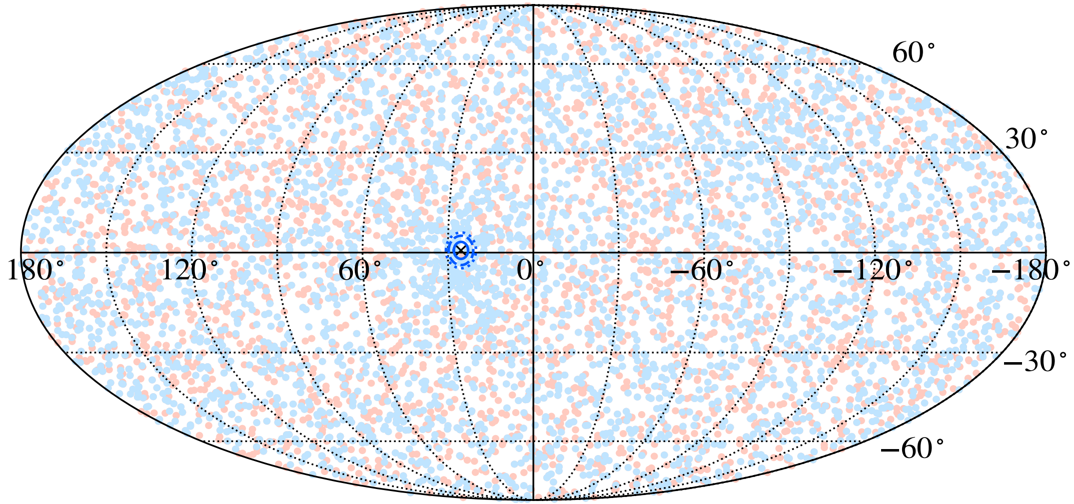


Realtime angular resolution with other models

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***

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.