Detecting Supernova neutrino bursts in Super-Kamiokande

Guillaume Pronost, on behalf of the Super-Kamiokande collaboration

ILANCE, CNRS - The University of Tokyo

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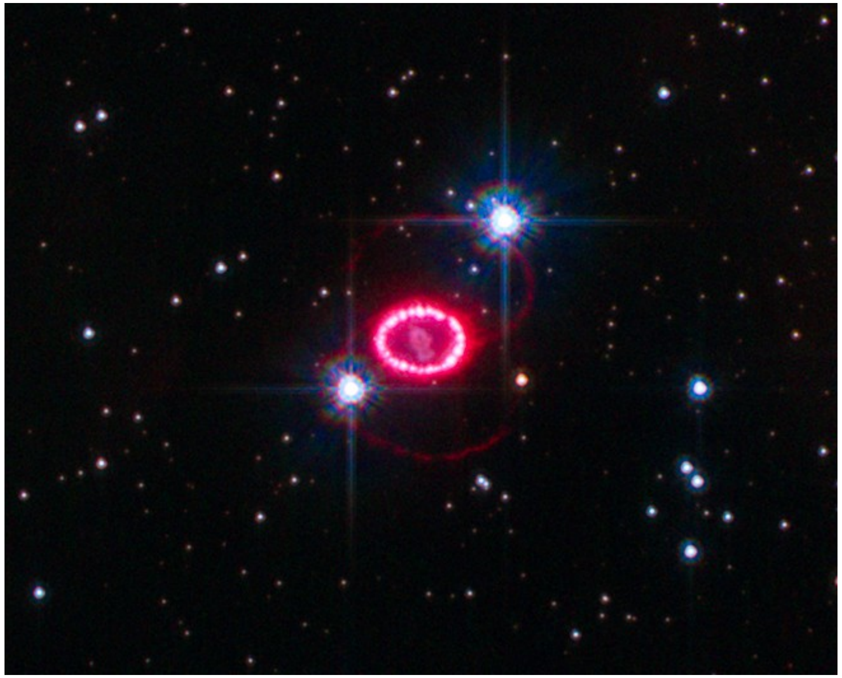
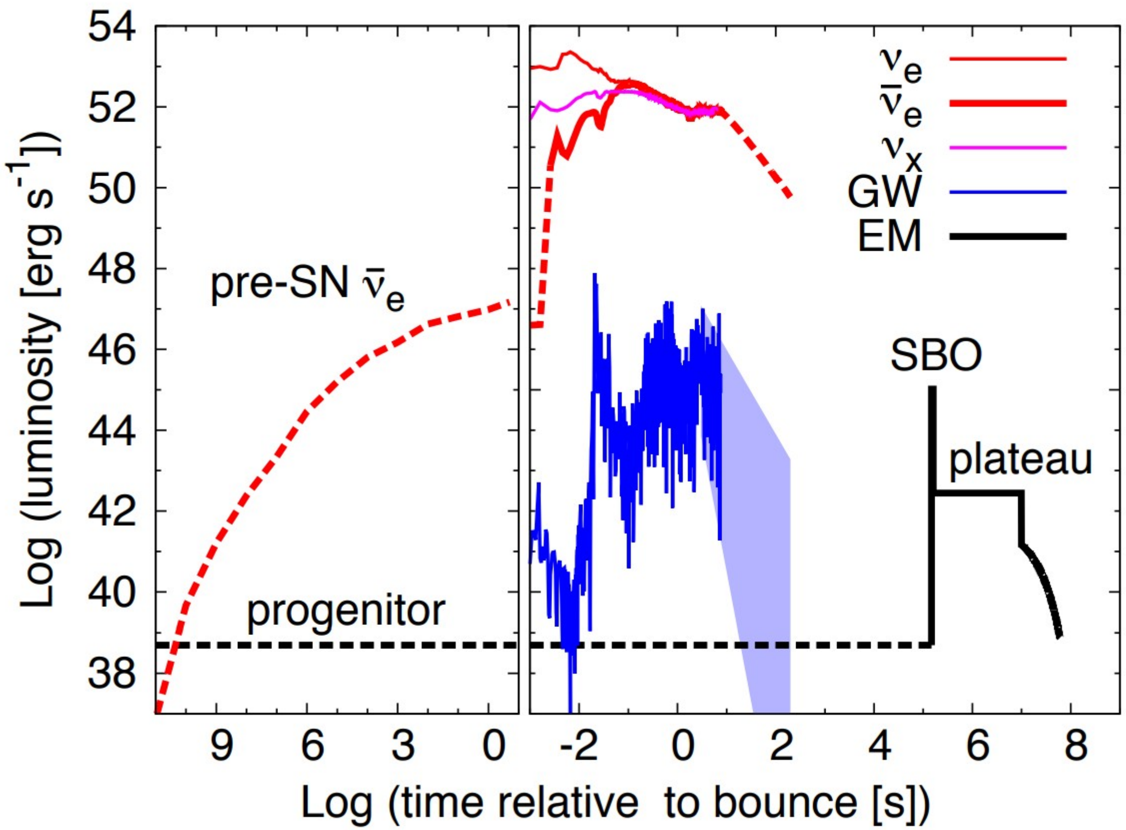
Core-Collapse Supernova Neutrinos



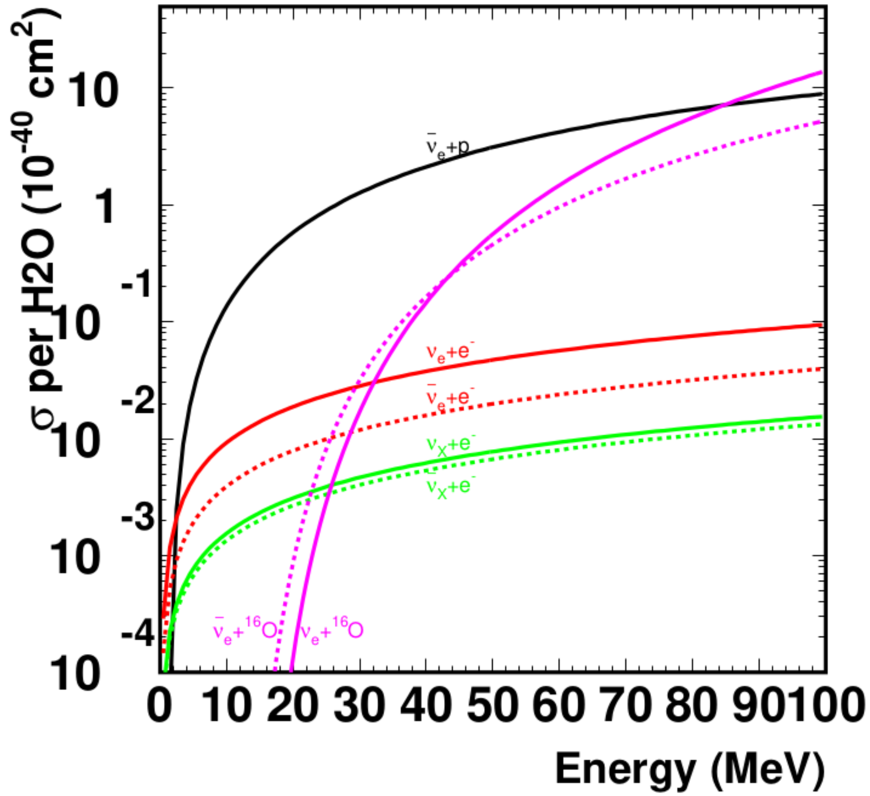
SN1987A remnant

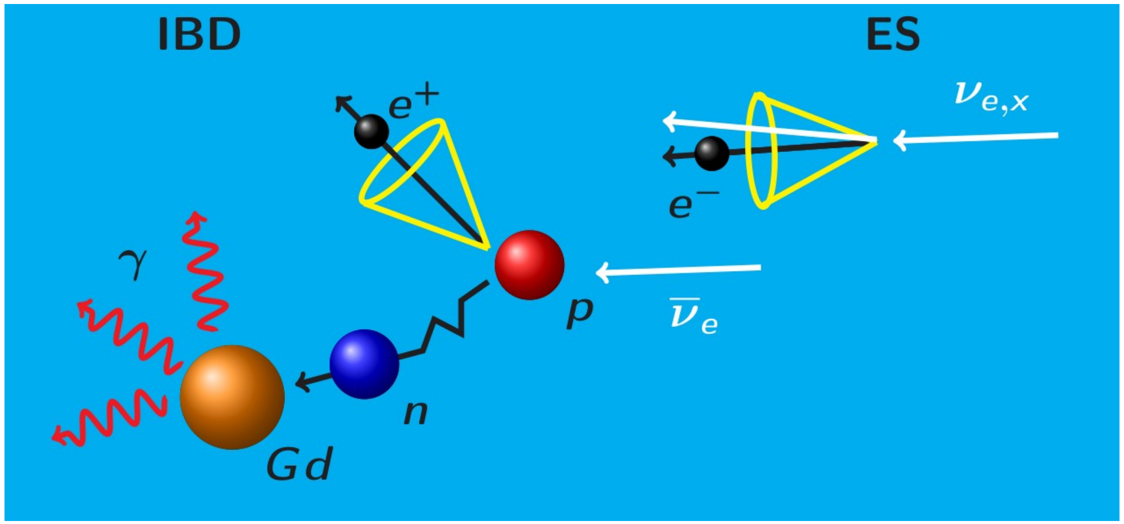


- Since 1987A supernova (SN), we know that in case of supernova a burst of neutrino is expected to be produced few minutes to several hours before the stellar explosion.
- If the SN is close enough, we can detect this burst on Earth and give an early warning to astronomers looking for the light from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

Supernova Neutrinos in Water Cherenkov Detectors

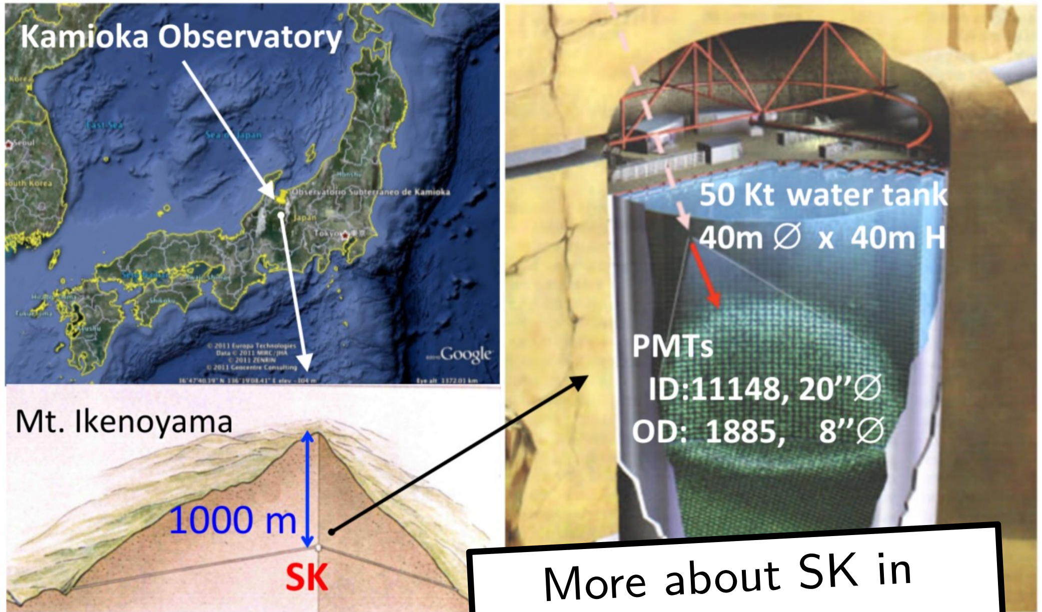
- The SN neutrino burst is composed of (roughly) similar amount of neutrino and antineutrino of each flavours. However, due to cross-sections, the number of detected neutrino interaction will be different.
- In case of Water Cherenkov detector, the main interactions expected are:
  - Inverse Beta Decay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



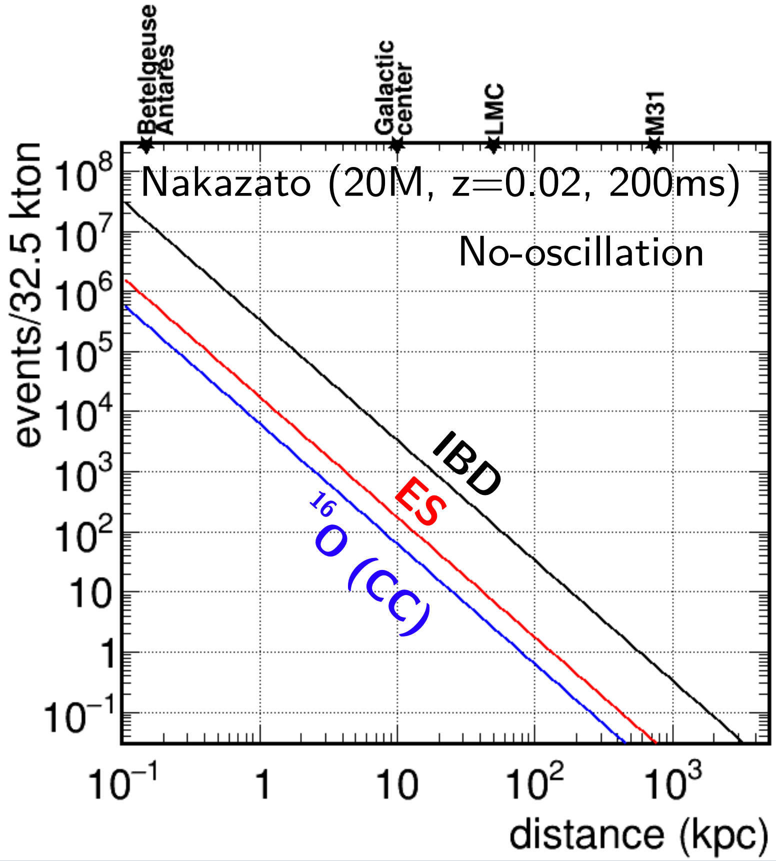


Supernova Neutrino in Super-Kamiokande

- Super-Kamiokande (SK) is a Water Cherenkov detector located in Kamioka, Japan, operating for ~25 years.
- The detector is filled with 50ktons of gadolinium-loaded water. We increased the Gd concentration from 0.01% to 0.03% in May 2022. Calibration was completed and the detector is running stably since then.
- In case of supernova, SK would detect a burst of events for SN happening up to >100kpc (depending on the models assumed).

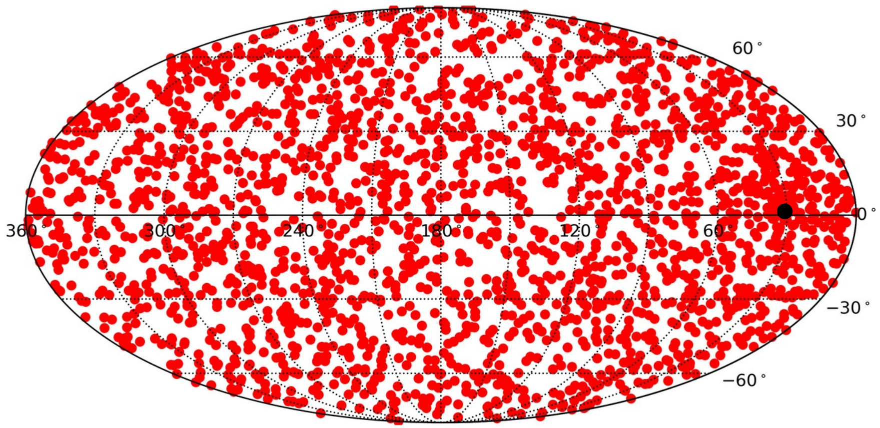


More about SK in Thomas Mueller's talk!

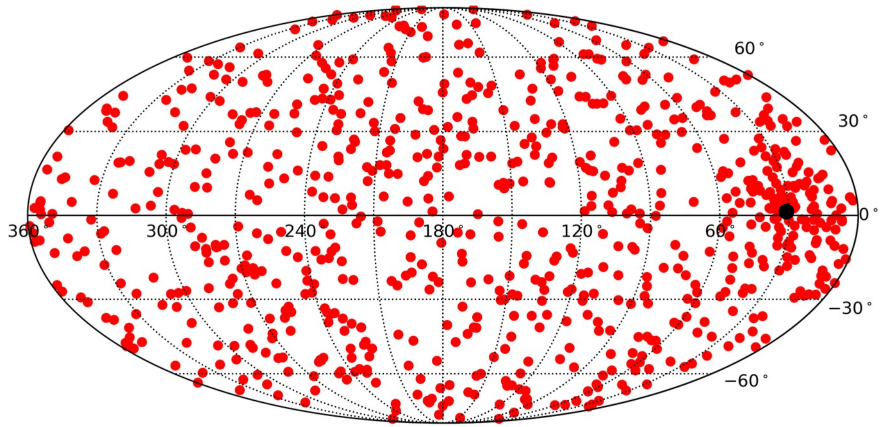


Using Gd-n to separate IBD and ES

- 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.

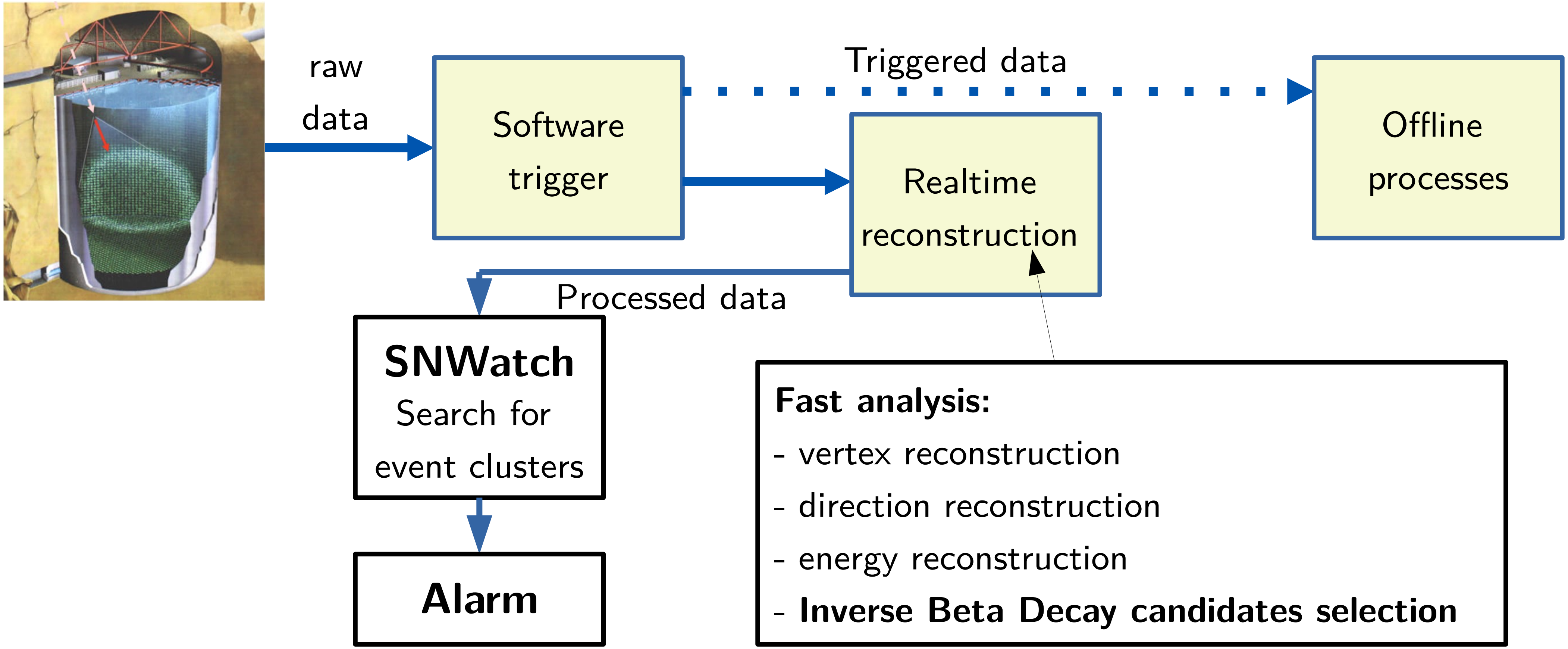


SN burst events w/o IBD tagging
(10kpc simulation)



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

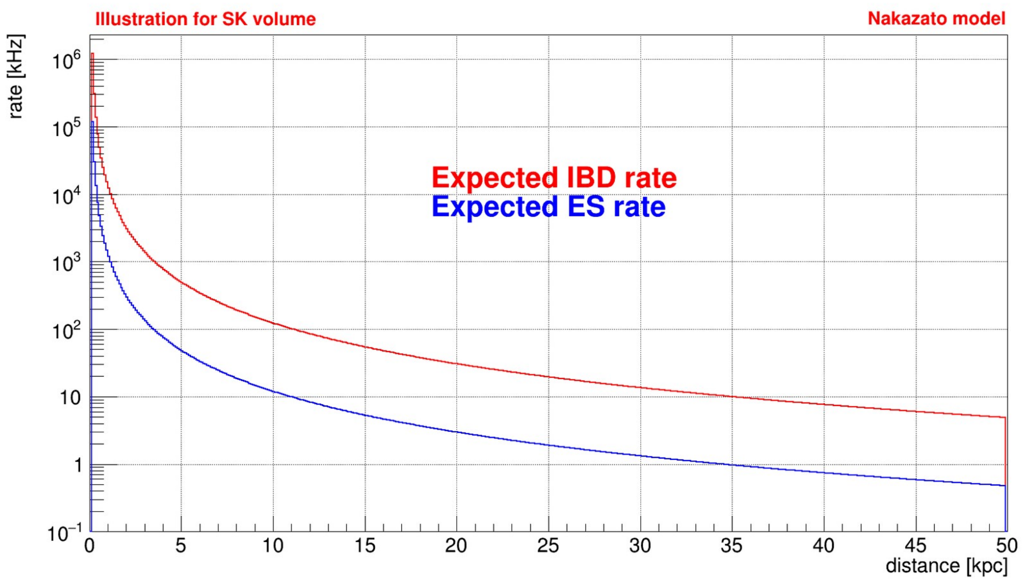
Realtime supernova monitoring

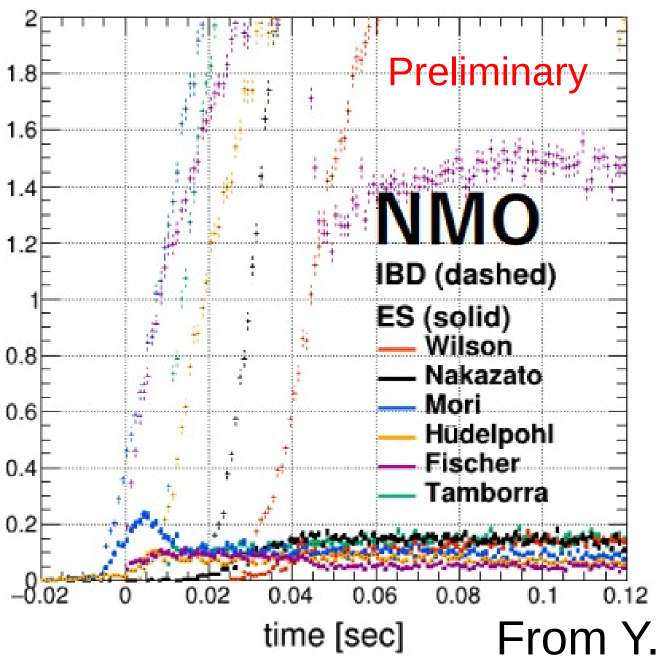


SK shifters are keeping watch to ensure these online processes are always running

Supernova simulations

- In order to study the capability of our realtime monitoring system, we need realistic supernova data. As SN are rare, we need to rely on supernova neutrino burst simulation.
  - In SK, we developed realistic supernova simulations taking into account the potential overlap between the various neutrino primary and secondary interactions in the detector. → These simulations allow to study the impact of the increased interaction rate on our reconstruction algorithms for close SNs.
- We also implemented several SN models in these simulations in order to study their differences, and test if SN models could be separated based on a SN burst observation in Super-Kamiokande (paper in preparation)

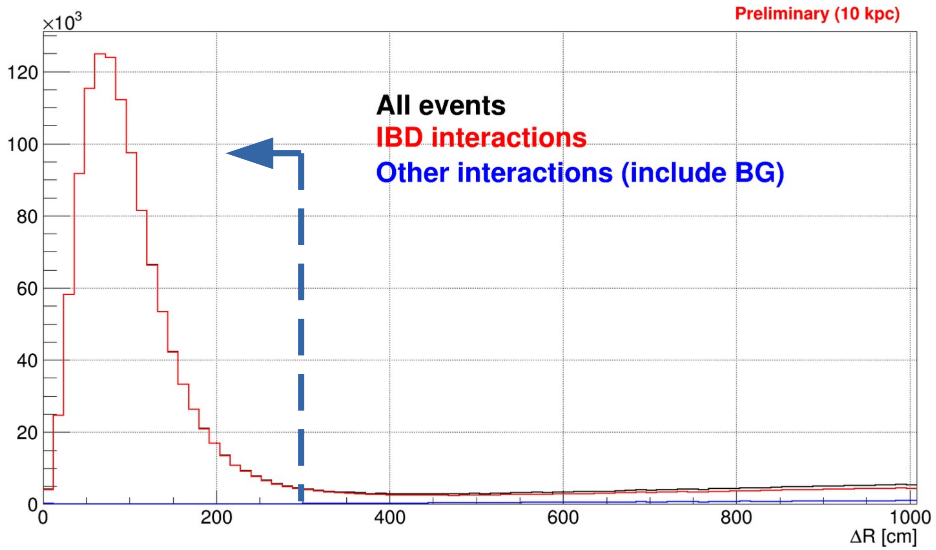




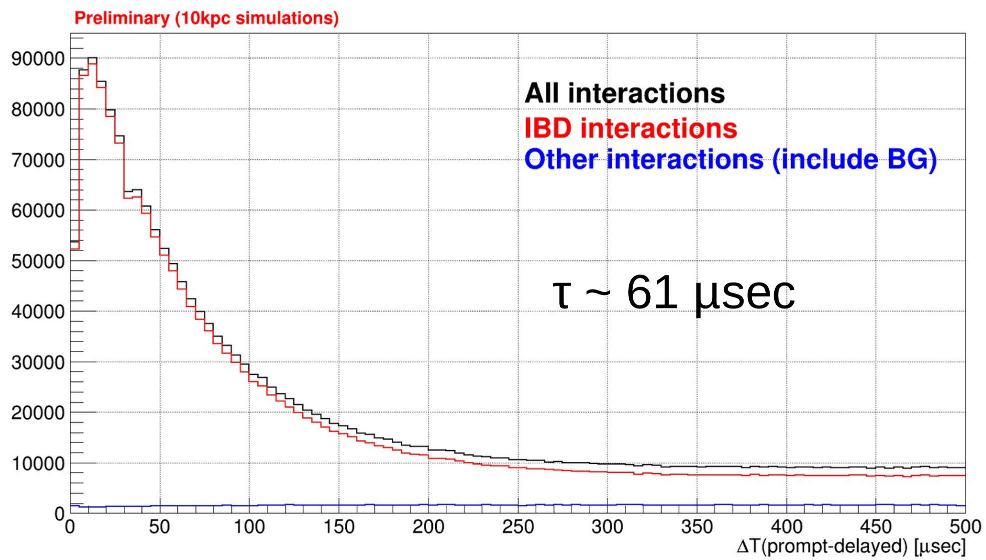
From Y. Kashiwagi

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 ~**46% IBD** events with the current Gd loading (65% if scaled to 0.1% Gd loading). It is designed to be simple and fast, for online use.



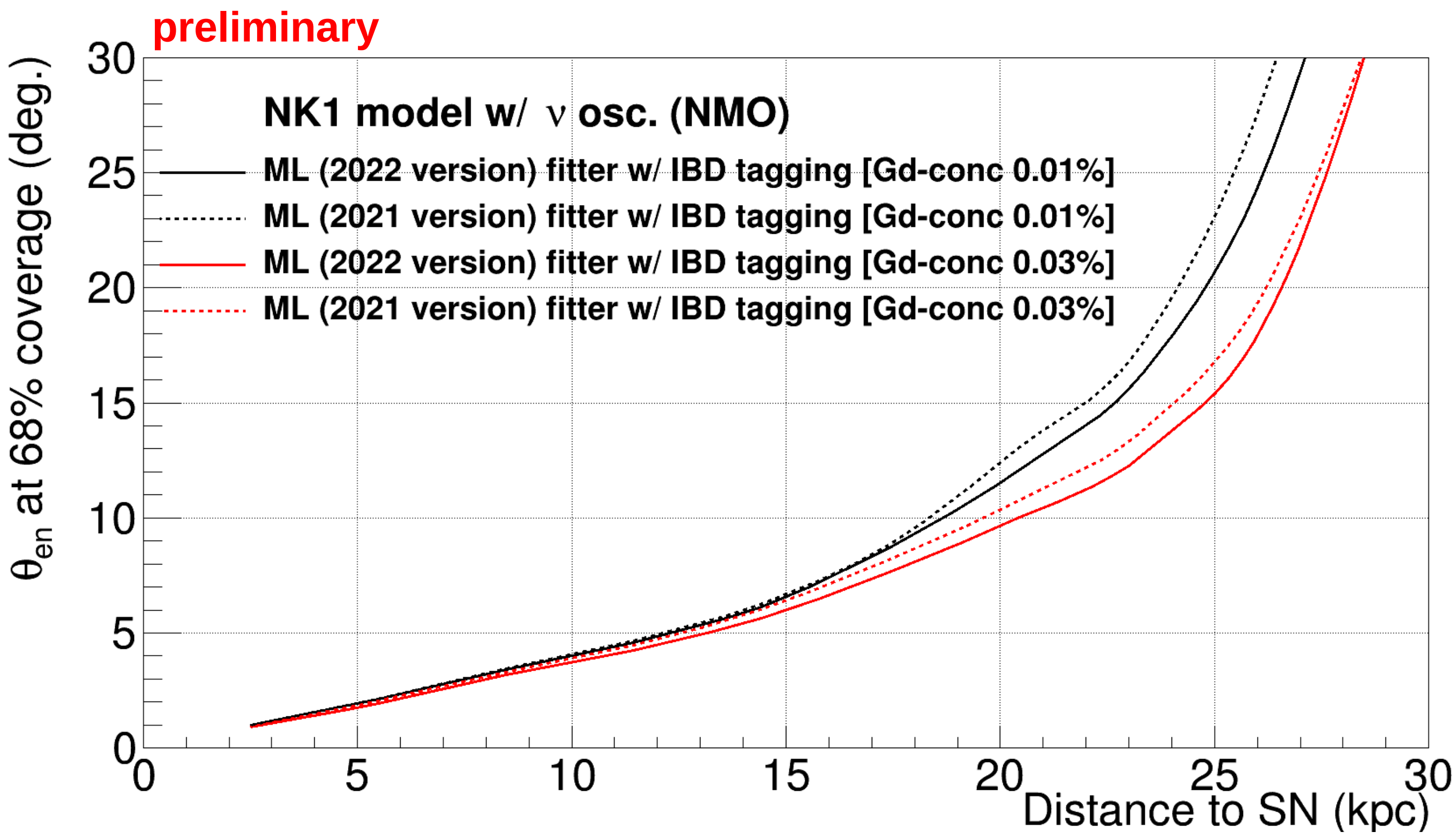
1000 MC simulations



1000 MC simulations

Supernova direction reconstruction

- With 0.03% Gd (46% IBD tagging efficiency), the supernova direction pointing accuracy is improved by 0.35 degree at 10 kpc with respect to the previous 0.01% Gd loading (33% IBD tagging efficiency).
- The supernova direction reconstruction is the slowest process with the SK realtime SN monitoring system. We are developing a new version (2022), preliminary results show a reduction of the processing time from ~2 minutes (with 2021 version) to <10 seconds for 10kpc SN.



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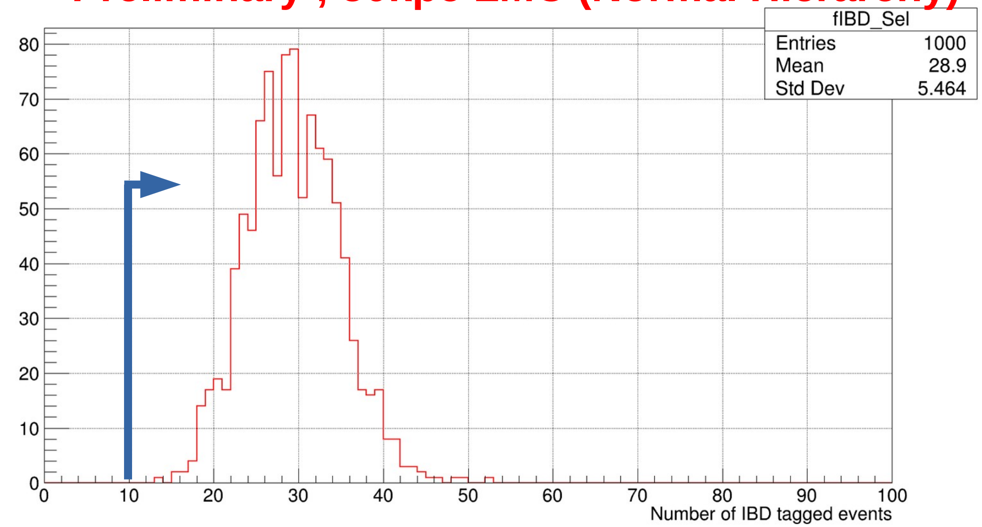
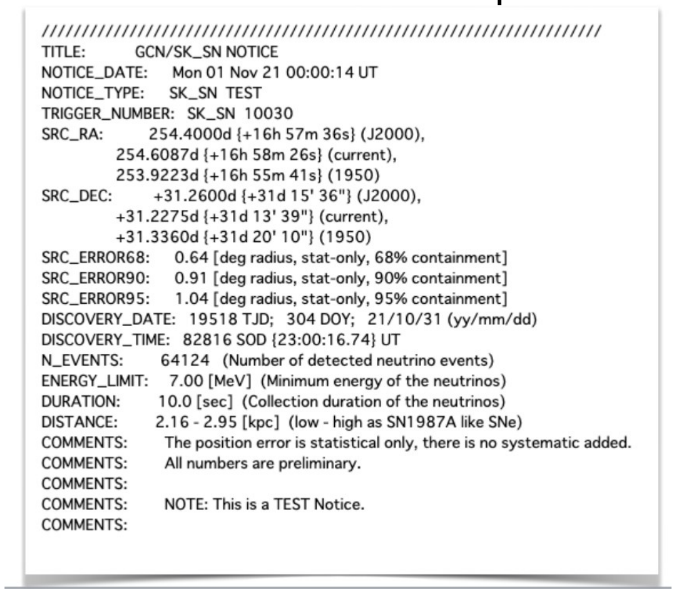
Automated SN alarm: GCN

- Since December 13th 2021, we have 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.
    This criteria was selected to ensure a full coverage of the Milky Way and its main satellite galaxies (up to LMC)
  - Due to the system latency, the alarm takes in average $\sim$10 seconds to be send to GCN and GCN takes $\sim$1 min to distributed it. $\rightarrow$ Potential possible improvement with direct connection to GCN or with the upcoming GCN Kafka upgrade

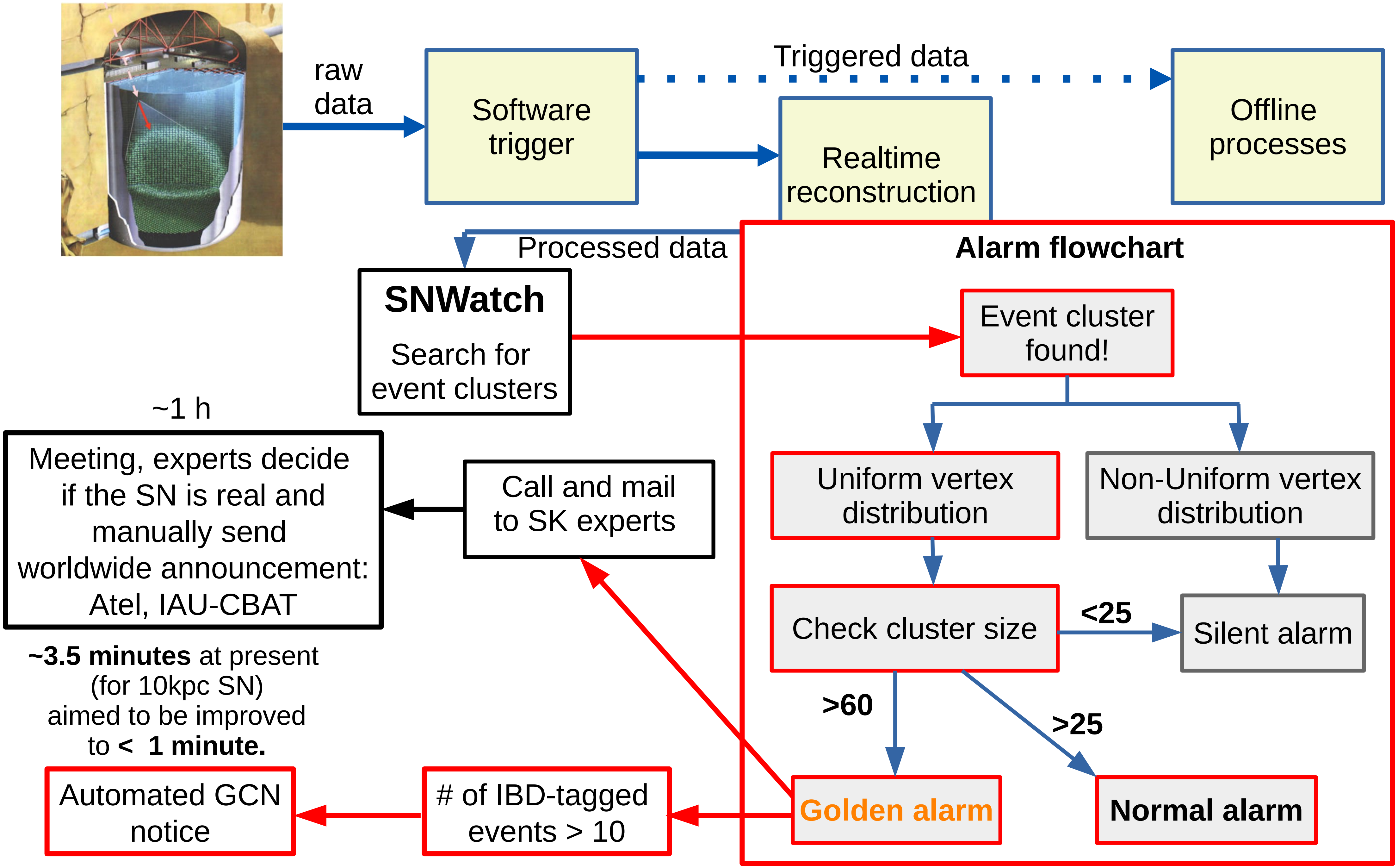
Preliminary ; 50kpc LMC (Normal Hierarchy)



Test GCN notice example

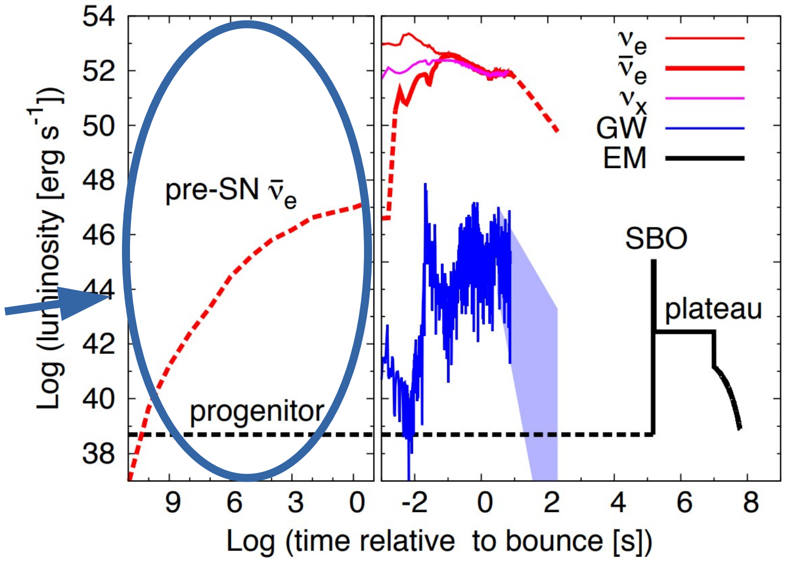

```
//////////////////////////////////////////////////////////////////////
TITLE:           GCN/SK_SN NOTICE
NOTICE_DATE:     Mon 01 Nov 21 00:00:14 UT
NOTICE_TYPE:     SK_SN  TEST
TRIGGER_NUMBER:  SK_SN  10030
SRC_RA:          254.4000d {+16h 57m 36s} (J2000),
                 254.6087d {+16h 58m 26s} (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:
```

Realtime supernova monitoring in Super-Kamiokande

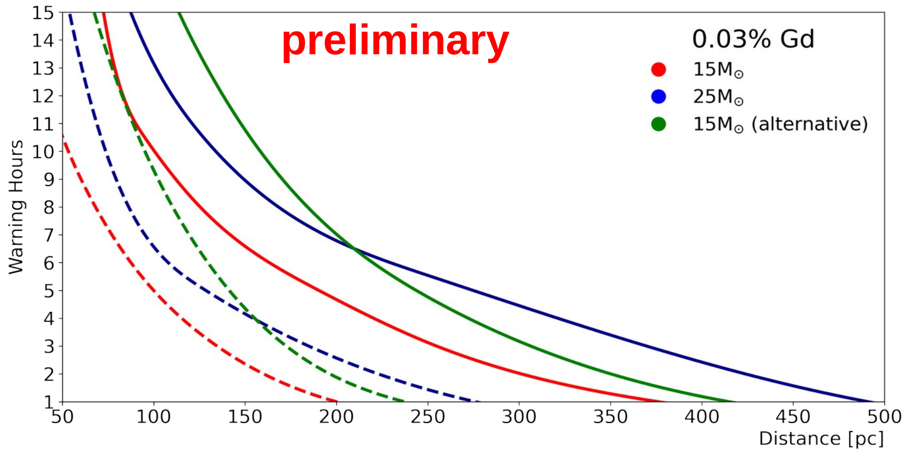


Pre-Supernova Neutrinos

- 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 developed an alarm system to probe these pre-SN neutrinos for close progenitors
- In May 2022, the Super-Kamiokande collaboration signed a MOU with the KamLAND collaboration to combine our alarm systems in order improve their performances.



Plot from L. Machado

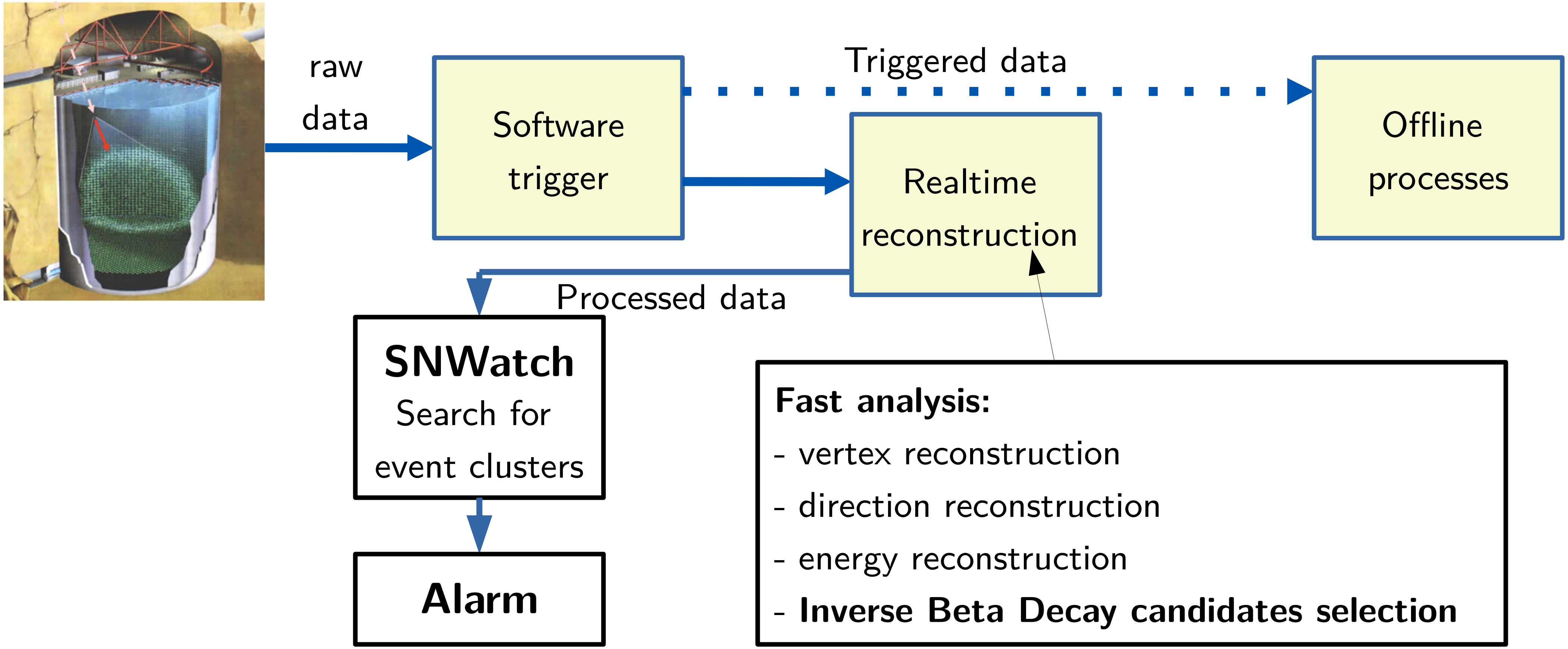
See more about pre-SN neutrinos in Zhuojun poster (n31) "Joint Pre-Supernova Neutrino Monitor with Super-Kamiokande and KamLAND"

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, our realtime IBD tagging algorithm allow us to tag ∼46% of the IBD events, providing both a clear SN signal with low BG contamination, as well as a mean to separate the IBD interactions from the ES interactions in order to increase the accuracy of the Supernova direction reconstruction.
  - Speed being critical for a realtime supernova monitoring, we are improving the efficiency of our monitoring system with the goal to reach less than 1 minute between the SN burst and the alarm for 10 kpc SN. Past years progresses allow us to be at ∼3.5 minutes currently, with promising potential for further processing time reduction in a close future.
  - SK and KamLAND are now collaborating for a joint pre-SN neutrino monitoring system (See Zhuojun poster for more details)

Backup

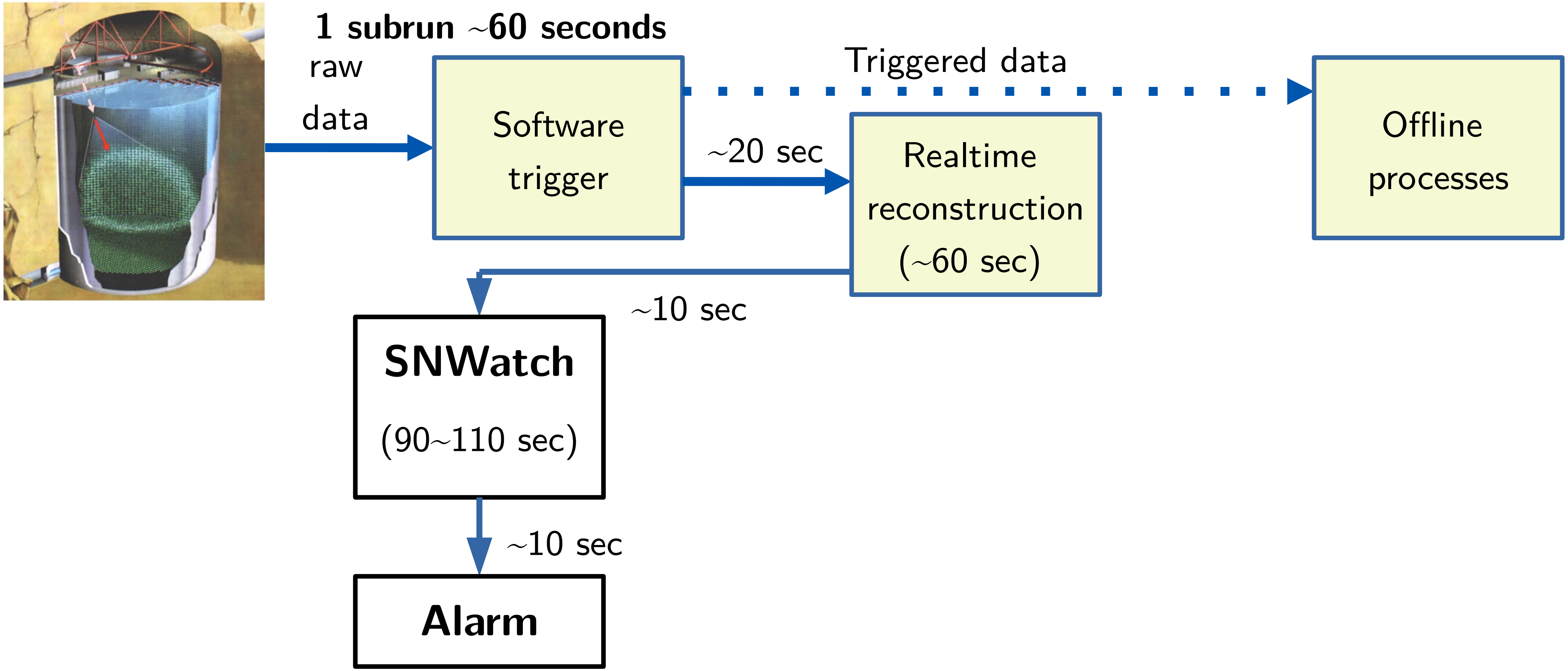
Realtime supernova monitoring



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

From the SN burst events in the detector to the alarm to the community, **speed is critical!**
For Wolf-Rayet stars it can takes only **few minutes** between the neutrino burst and the electromagnetic burst

Realtime supernova monitoring speed



- For a 10 kpc SN case, the main processes of the supernova monitoring (realtime reconstruction and SNWatch) takes 2~3 minutes. To which we need to add the latency between each progress which take in average ~40 sec. Leading to 2.5~3.5 minutes between the end of the subrun with the SN burst and the alarm.
- We are continuously working to reduce this processing time.

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Alarm release time

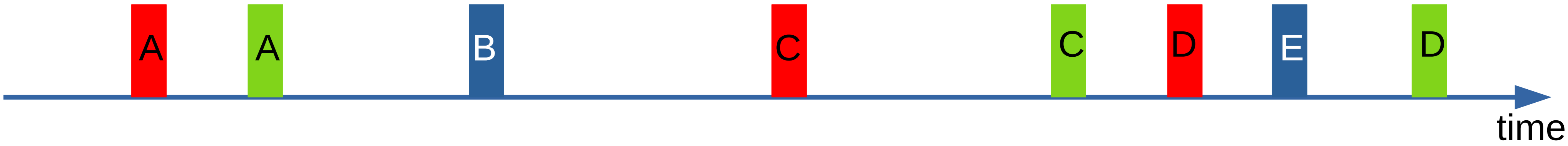
- For Supernova monitoring distributing **fast alarm** is **critical** to allow astronomers to observe the SN burst light.
- Up to recently, it was taking a long time for SK to release an alarm, this long processing time coming from:
  - Event reconstruction ~1 min for 10 kpc SN
  - Supernova direction reconstruction ~2 min for 10 kpc SN
  - Experts meeting to take decision to release an alarm and send the alarm.
    → 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.
- Automated alarm system was then needed.

Realistic SN simulation

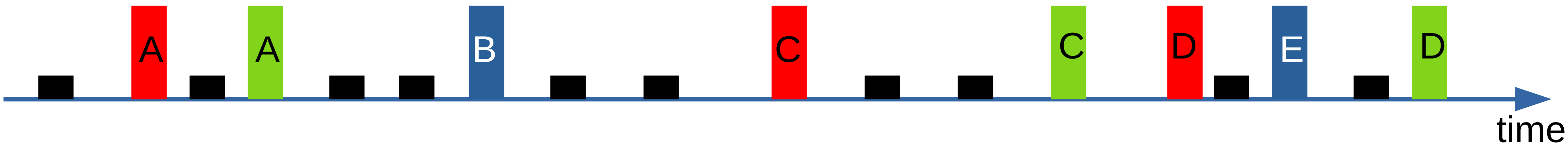
- In order to solve this issue, we developed realistic SN simulations: we simulate separately each interactions (IBD, ES, etc.) and merge the simulated interaction

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

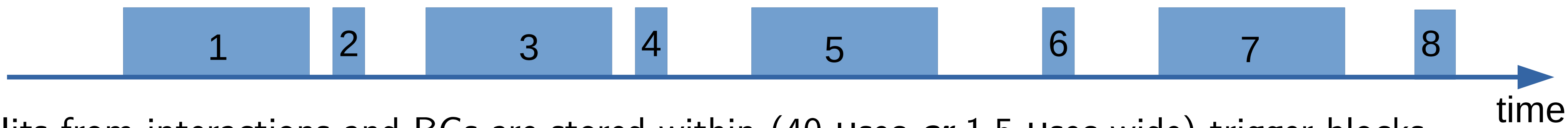
2) Merge the simulated interaction following the SN time profile:



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



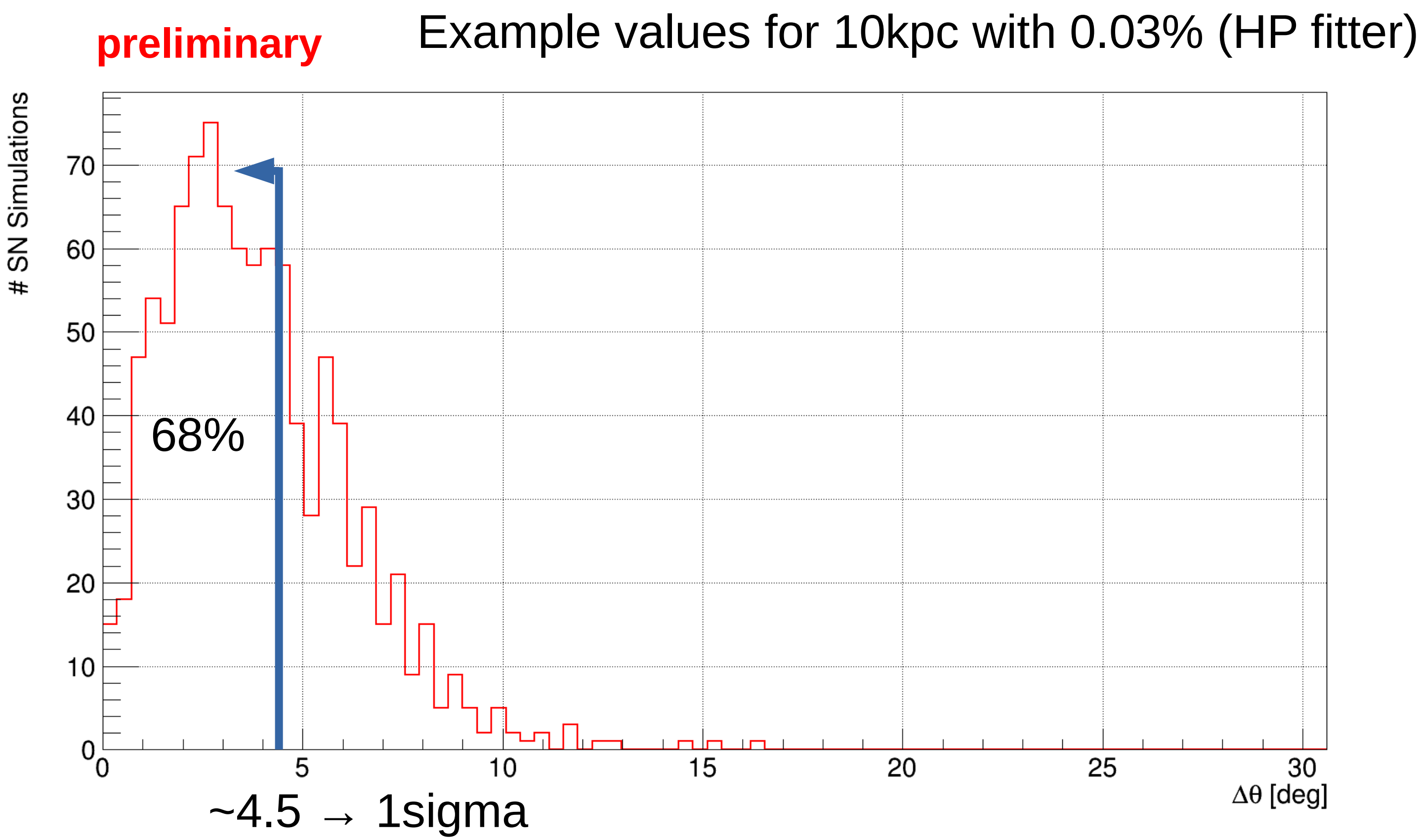
4) Apply the trigger simulation (software trigger): → Realistic output of the SK detector



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

Pointing accuracy calculation

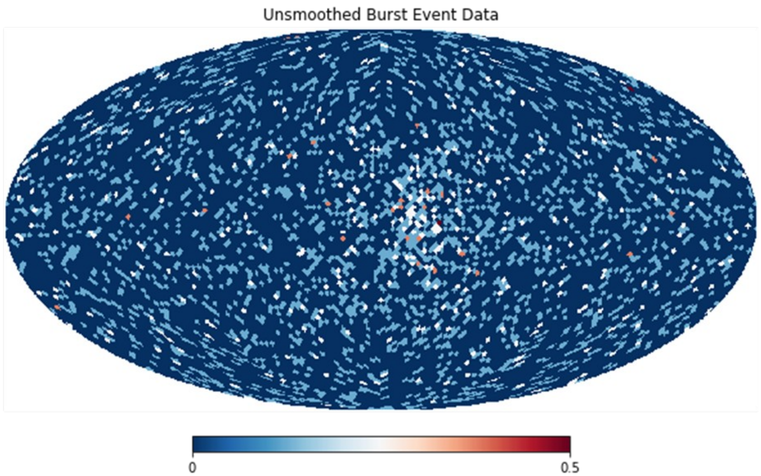
- In order to calculate the pointing accuracy we plot the value of the angle difference between the true SN direction and the reconstructed SN direction for each SN simulation.
- The value below which the integral of the histogram is 68% is the 1sigma angular resolution:



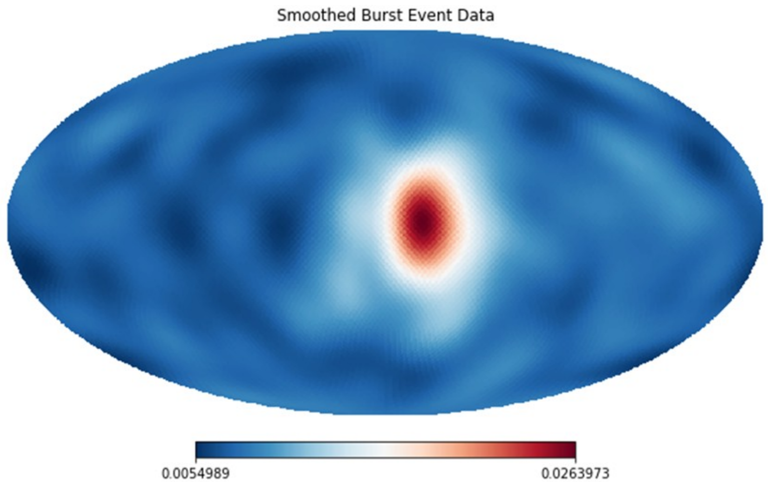
SN direction fitter improvement investigations

- **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
- Preliminary results: Fast processing (∼sec) for equivalent angular resolution when compared with the current Maximum Likelihood fitter.

Nside = 32, Npix = 12,288



Gaussian Smoothed, σ = 0.15 rad.



Figures from Barry Pointon (British Columbia Institute of Technology)

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SN direction fitter improvement investigations

- In previous JPS meetings, we reported investigation on **HEAPix** (**H**ierarchical **E**qual **A**rea iso**L**atitude **Pix**elation of a sphere) based fitter, giving fast results with an equivalent angular resolution from our current fitter.
- The main drawback of this fitter was the difficulty to get a model independent angular resolution.
- We developed a vectorised version (2022 version) of our initial Maximum-Likelihood fitter using HEALPix as a pre-fitter, in order to get fast results and keep the capability to provide a model independent angular resolution. $\rightarrow$ Give similar results (better for longer distance) than the non-vectorised version (2021 version)

Gaussian Smoothed, σ = 0.15 rad.

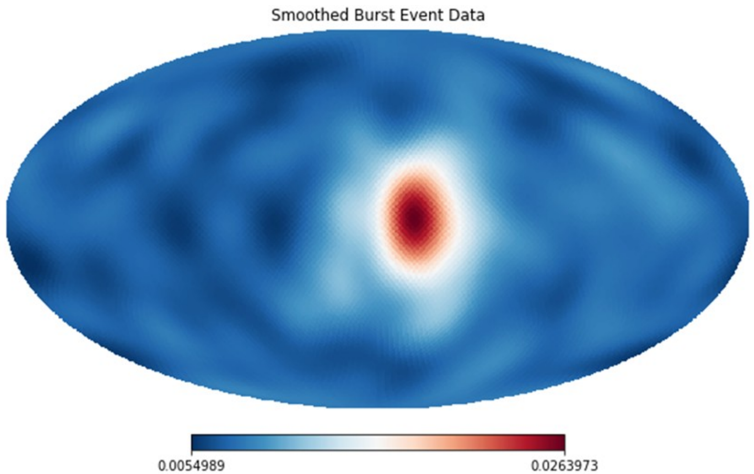
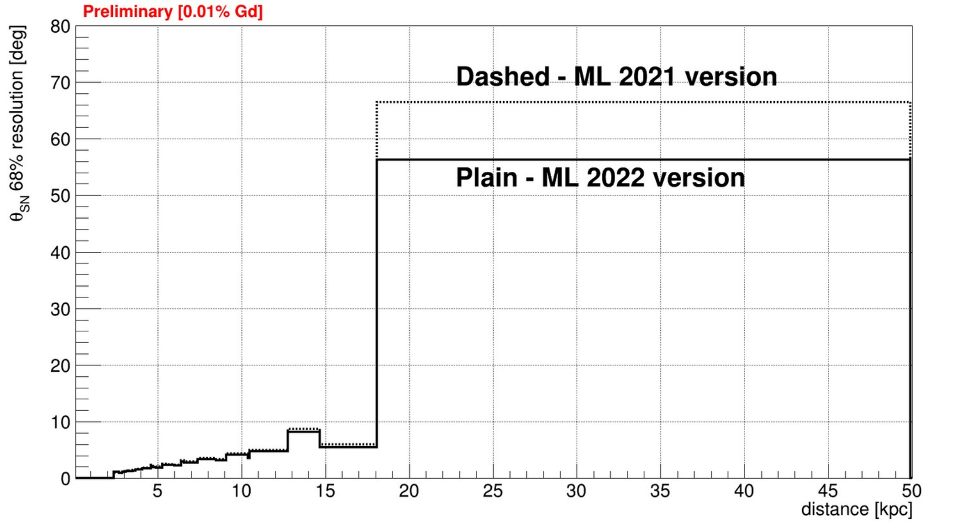


Figure from Barry Pointon

Model independent resolution (15x15 matrix)



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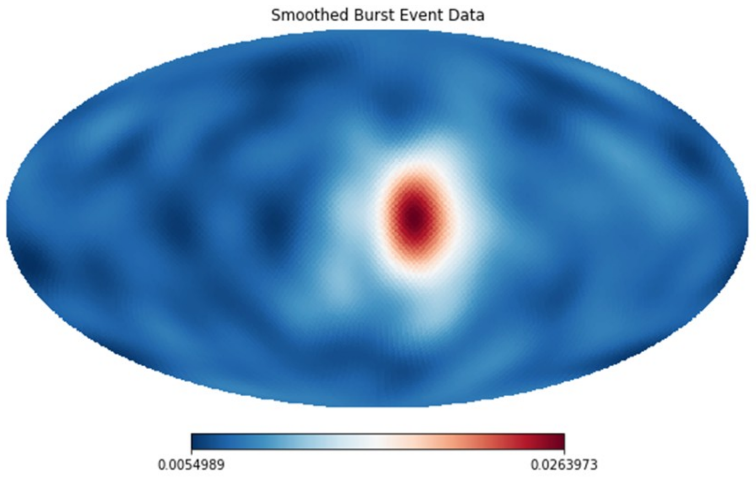

Figure from Barry Pointon

Model independent resolution (15x15 matrix)