Super-Kamiokande sensitivity to SN

SNνD 2023@LNGS

International conference on Supernova Neutrino Detection

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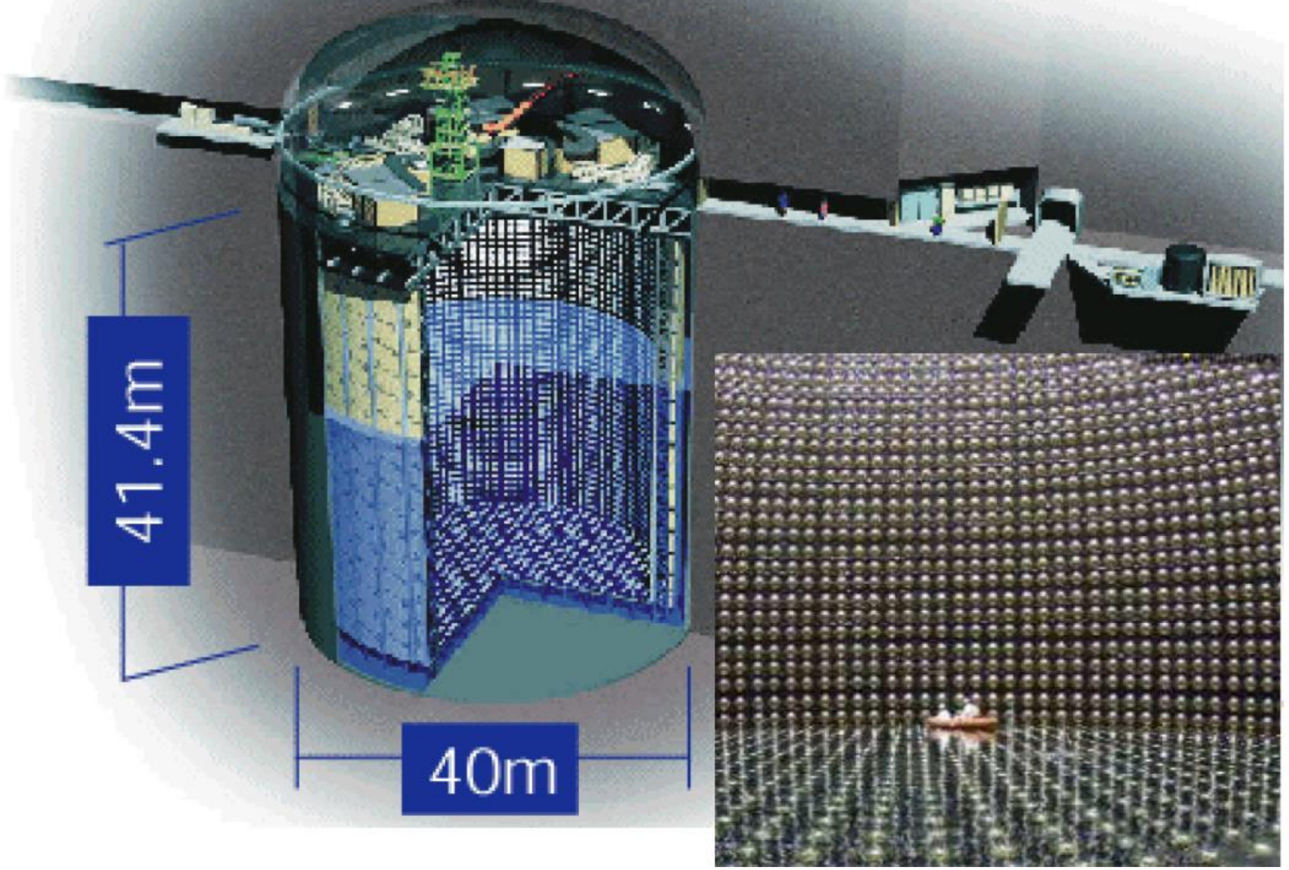
for the Super-Kamiokande collaboration

Searches for neutrinos from core-collapse supernovae

Searches for neutrinos from core-collapse supernova explosions with several procedures and approaches are being conducted at Super-Kamiokande.

- Individual core-collapse supernova bursts
  - (1) Real-Time Monitor
    - Supernova alert system
    - Pre-supernova alert system
  - (2) Distant burst search
- (3) Diffuse supernova neutrino background (DSNB)
  - Most stringent limits was set and some optimistic models were surveyed.

Super-Kamiokande (SK) detector



- The world leading water Cherenkov detector located in Kamioka mine (36° 25’ N, 137° 18’ E).
- 50 kton water (22.5 kton fiducial, 2m from the walls of the inner detector)
- 1,000 m (2,700 m w.e.) underground
- 11,129 20-inch PMTs in inner detector (ID)
- 1,885 8-inch PMTs in outer detector (OD)
- ~ 4.0 MeV energy (total) threshold

Many physics targets:

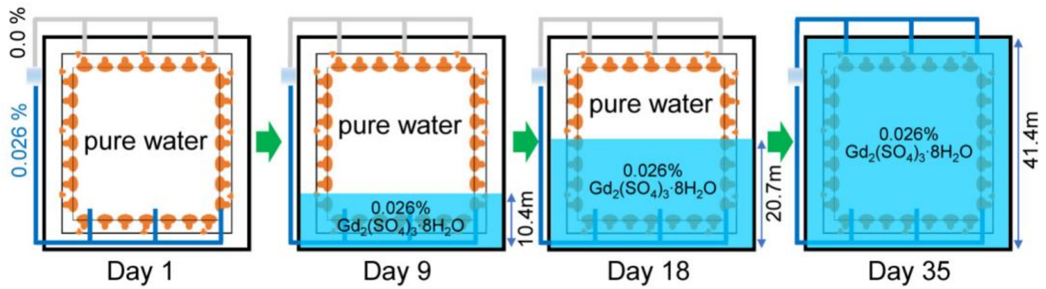
- Neutrino oscillation: atmospheric ν, solar ν, T2K beam
- Nucleon decay
- **Astrophysics**: **Supernova burst**, **Diffuse supernova neutrino background**

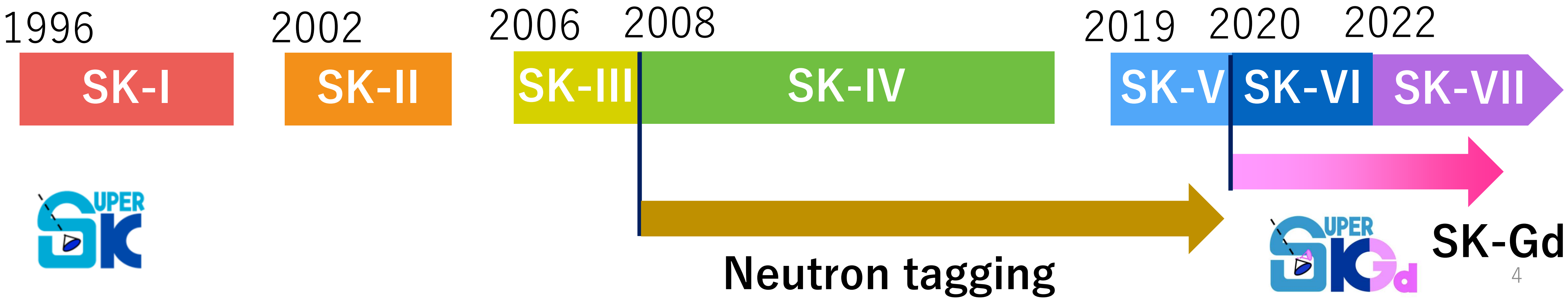
  WIMP search, monopole search, etc.

History of SK

- **SK-I**: 1996~2001: 40% photo coverage.
- **SK-II**: 2002~2005: 19% photo coverage due to accident.
- **SK-III**: 2006~2008: recover to 40% photo coverage.
- **SK-IV**: 2008~2018: analysis by neutron tagging started owing to upgraded front-end electronics.
- **SK-V**: 2019~2020: final pure-water phase before Gd loading.

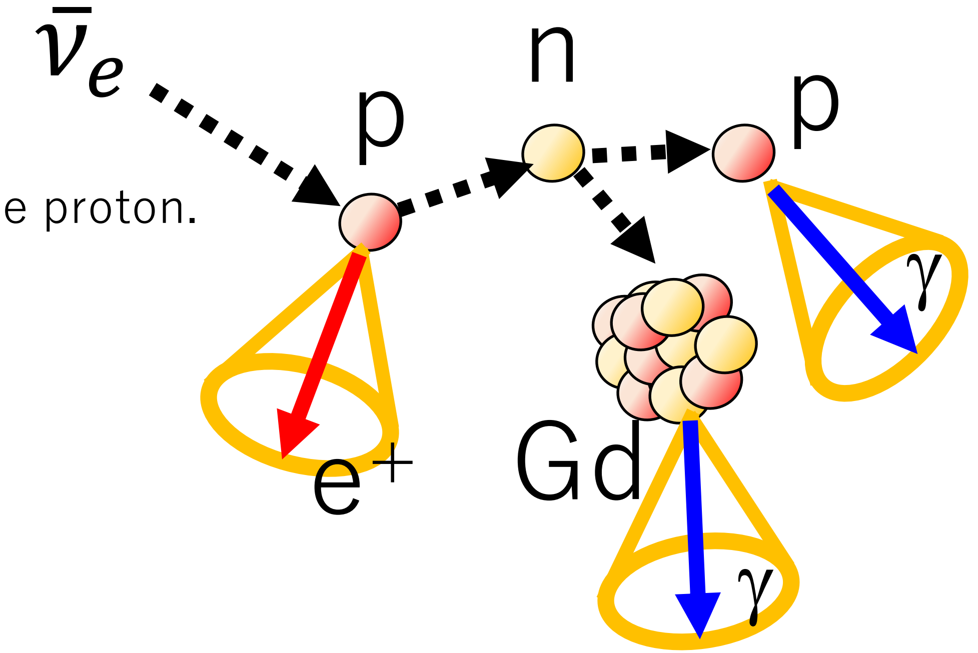
- **SK-VI**: 2020/Sep.~2022/Jun.: Gd 0.01 wt%
- **SK-VII**: 2022/Jun.~ : Gd 0.03 wt%





Main interactions for supernova ν in SK-Gd

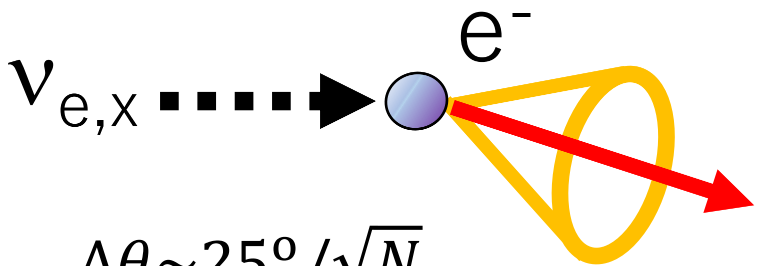
- Inverse beta decay (IBD) $\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$



  - Dominant in water Cherenkov detector owing to lots of free proton.
  - $\bar{\nu}$ energy is obtained from the e+ energy.
    $E_e \sim E_\nu - (m_n - m_p) \sim E_\nu - 1.3$ MeV, $E_\nu > 1.86$ MeV
  - Neutron tagging using delayed coincidence.
    $n + p \rightarrow d + \gamma$ (2.2 MeV),
    $n + Gd \rightarrow Gd + \gamma$ (total ~8 MeV)

- Elastic scattering $\boxed{\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-}$

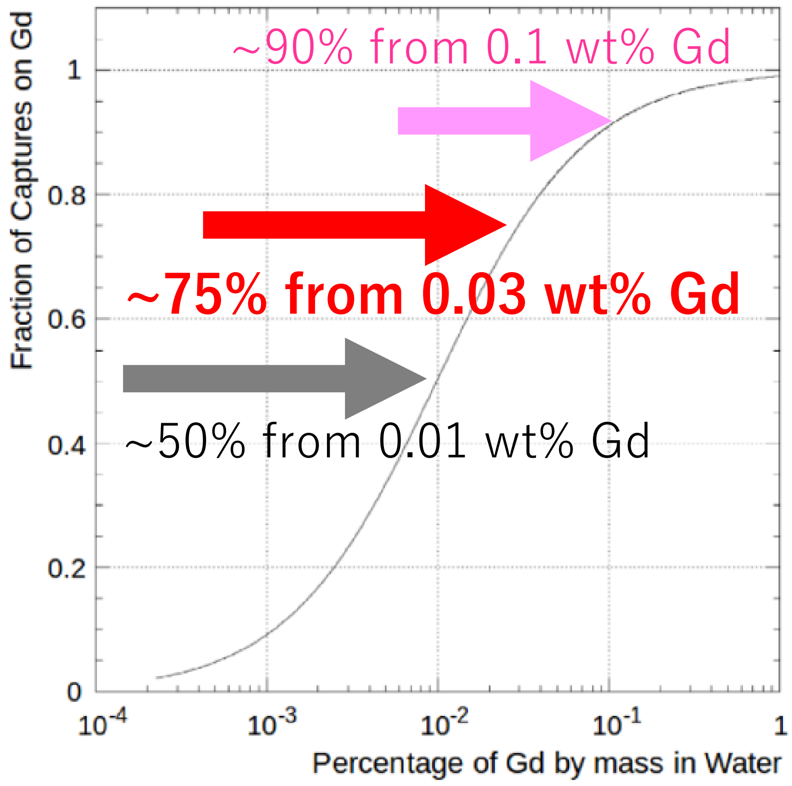
  - All neutrinos are sensitive.
    The cross section for ν_e is larger than others because of CC effect.
  - Good directionality.
  - Only recoil electron energy is measurable (not ν energy).



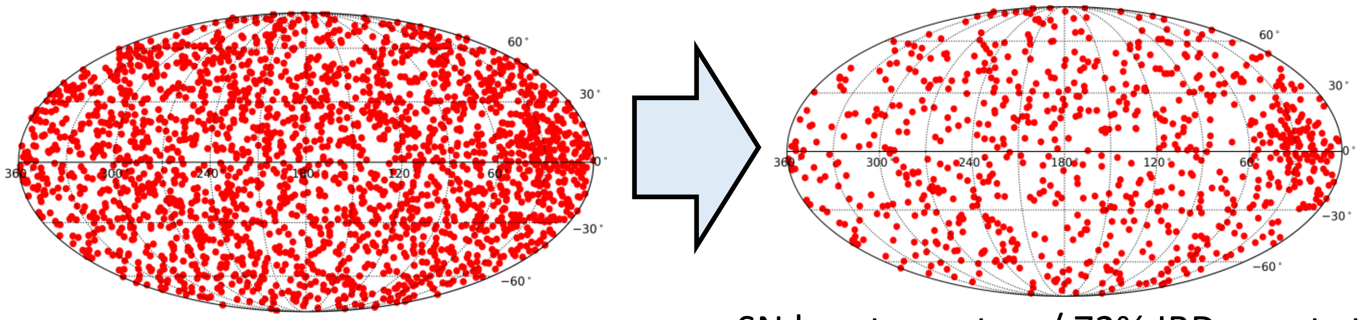
$\Delta\theta \sim 25^o/\sqrt{N}$
(10 MeV)

Neutron tagging in SK-Gd

- Detection efficiency for IBD is improved by tagging thermal neutrons.
- Neutron capture on hydrogen emits a single 2.2 MeV γ-ray resulting in Compton electrons with energy close to or below the Cherenkov threshold, while neutron capture on Gd emits easily detectable γ-ray cascades of about 8 MeV.



- **1st phase of SK-Gd (SK-VI)** with a loading of 0.01 wt% Gd had ~50% of the neutron capture on Gd. The capture time was ~115 μs evaluated Am/Be calibratiotn.
- **Current phase (SK-VII)** with a loading of 0.03 wt% Gd has ~75% capture on Gd. The capture time is ~62 μs.
- **Ultimate goal** with a loading of 0.1 wt% Gd has ~90% capture on Gd.



Tagged IBD events are removed

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)

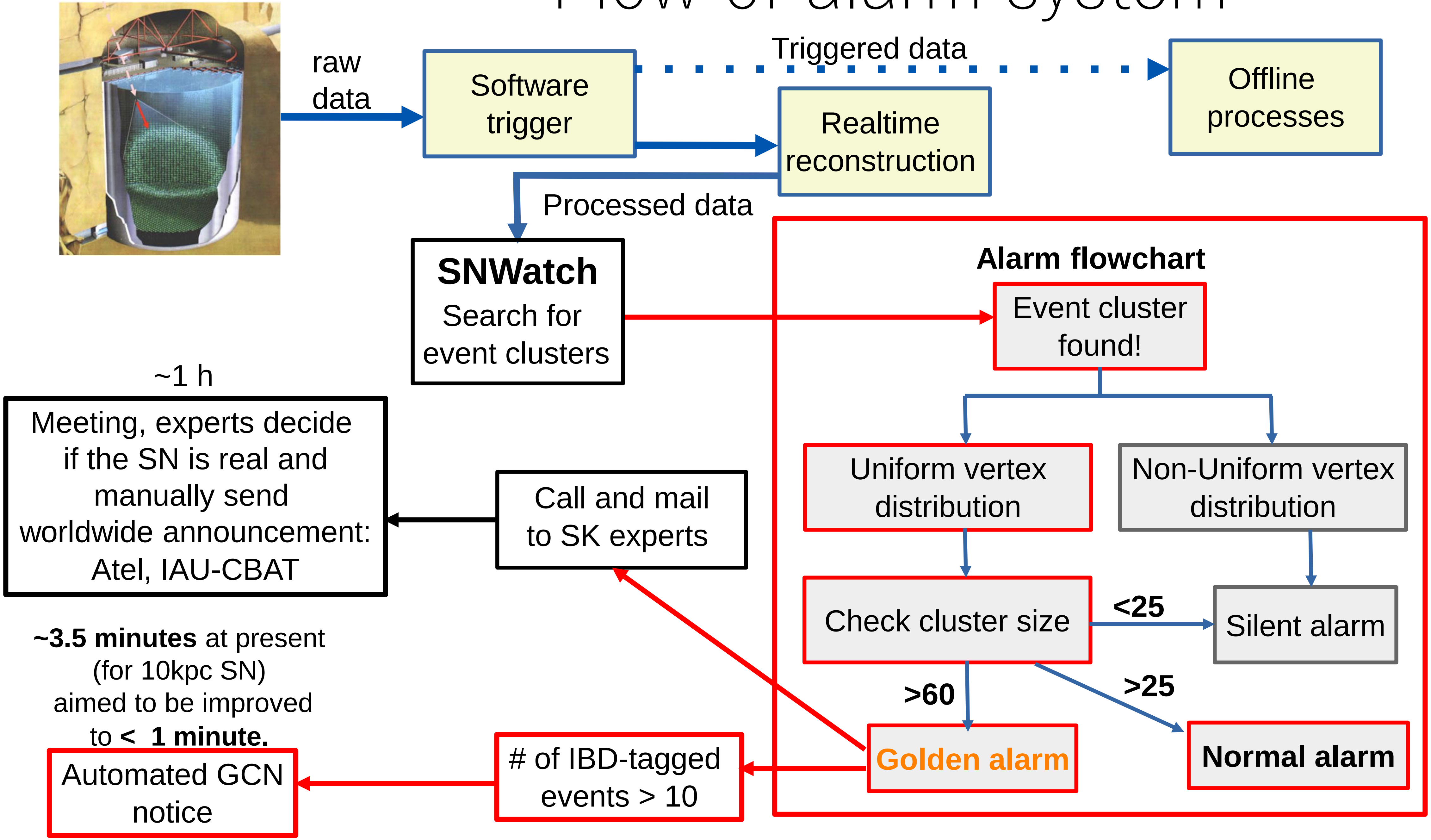
(1) Real-time monitor for supernova burst

- Fast broadcasting of detection by neutrinos is important for multi-messenger astronomy.
  - Neutrinos are expected to come earlier (tens of minutes ~ tens of hours) than light.
  - Direction information is also important to guide optical instruments toward the SN explosion.

- SK is suitable for that purpose
  - World's largest water Cherenkov detector with enough low energy threshold.
    - O(1000) events are detected in ~10 sec for SN near the galactic center (10 kpc).
  - Direction is determined.
    - 3~7 degrees accuracy for 10 kpc SN from elastic scattering (~3% fraction) by removing IBD events with neutron tagging.

  - After upgrade to SK-Gd, detection capability for pre-supernova signal has been improved.

Flow of alarm system



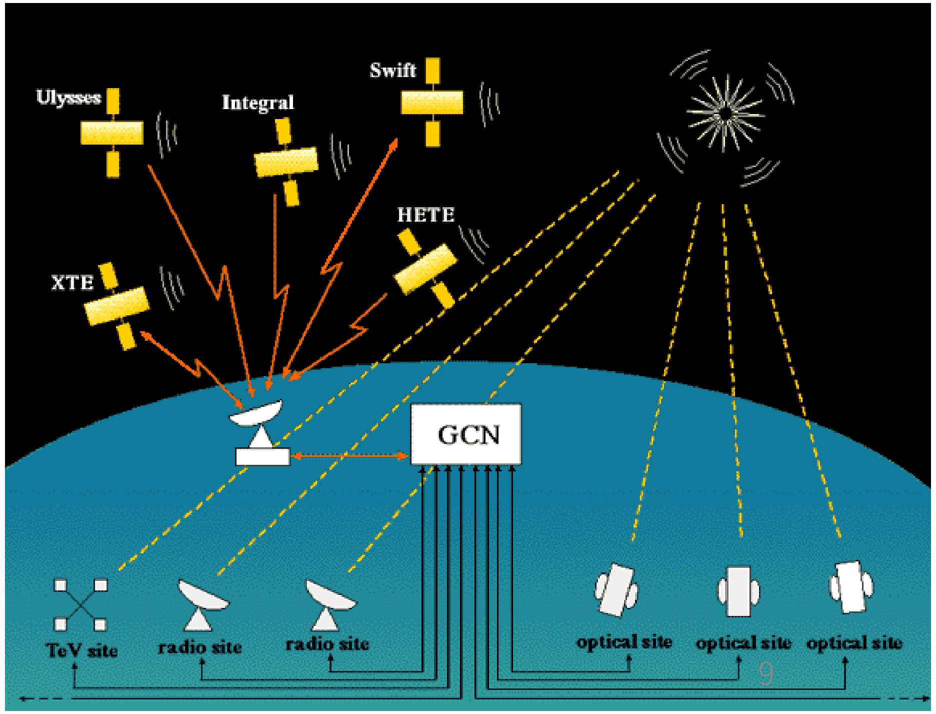
Automated GCN Notice

- Since Dec. 13th 2021, we have an automated General Coordinate Network (GCN) Notice process in real-time monitor system:
  - If golden alarm is issued and number of IBD tagged events in cluster is larger than 10, an alarm will be automatically published. Due to the system latency, the alarm takes in average ~10 seconds to be send to GCN and GCN takes ~1 minutes to distribute it.
    → It will be improved soon to ~1 sec for GCN distribution with GCN kafka upgrade.
  - If golden alarm has smaller number of IBD tagged events (<10), expert's check will be taken within 1 hour.
  - A dummy (test) alarm is published for a test every month (on the first day of the month).

Test GCN notice example

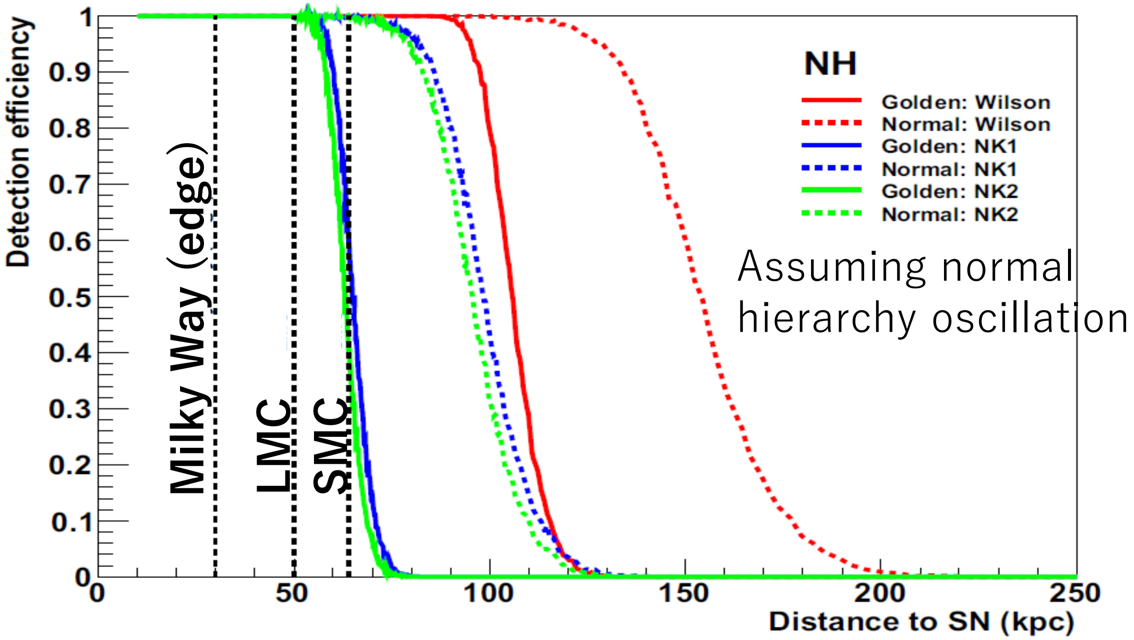
```
////////////////////////////////////////////////////////////////////////////
TITLE:            GCN/SK_SN NOTICE
NOTICE_DATE:      Mon 01 Nov 21 00:00:14 UT
NOTICE_TYPE:      SK_SN  TEST
TRIGGER_NUMBER:   SK_SN  10030
SRC_RA:           254.4000d {+16h 57m 36s} (J2000),
                  254.6087d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

https://gcn.gsfc.nasa.gov/



Detection efficiency and pointing accuracy

- 100% detection efficiencies for various models are estimated for following targets:
  - LMC (50 kpc) by golden alarm
  - SMC (62 kpc) by normal alarm

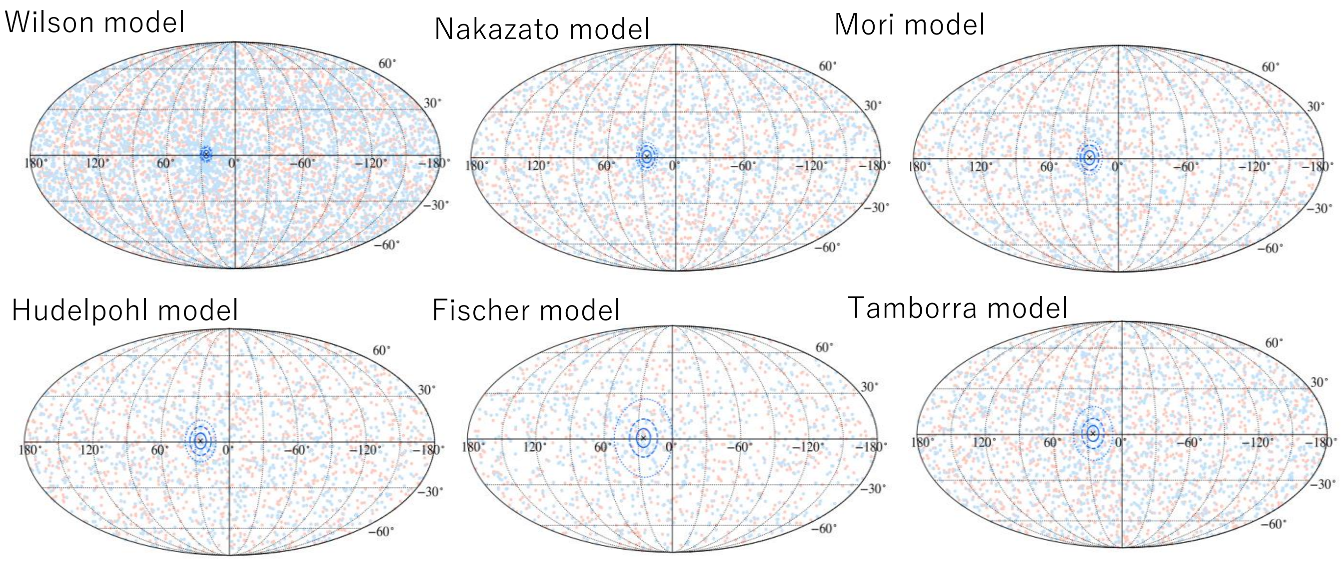


- **Wilson model** : *T. Totani, et al., Astrophys. J. 496 (1998) 216.*
- Nakazato (NK) model : *K. Nakazato, et al., Astrophys. J. Suppl. 205 (2013) 2.*
  - **NK1**: M = 20 solar mass, t_{revive} = 200 ms, Z = 0.02
  - **NK2**: M = 13 solar mass, t_{revive} = 100 ms, Z = 0.004

  (M: progenitor mass, t_{revive}: shock revival time, Z: metallicity)

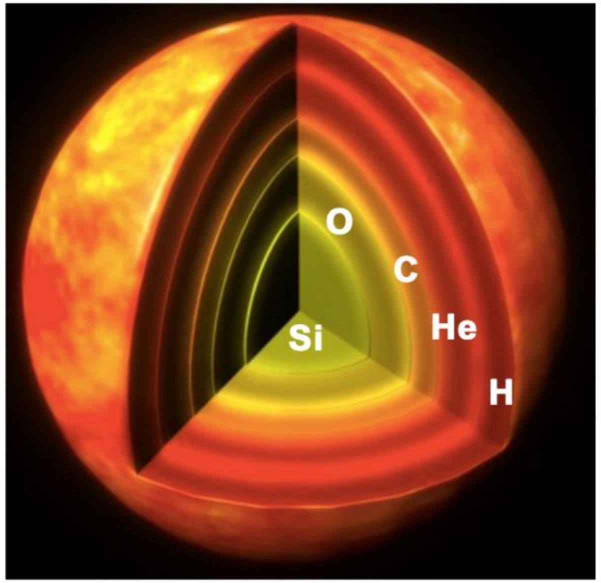
Astropart. Phys. 81 (2016) 39-48

- Detailed MC study showed that the direction pointing accuracy is 3-7 degrees at 10 kpc with IBD tagging (Gd 0.03 wt%) among several models and neutrino oscillation assumption.

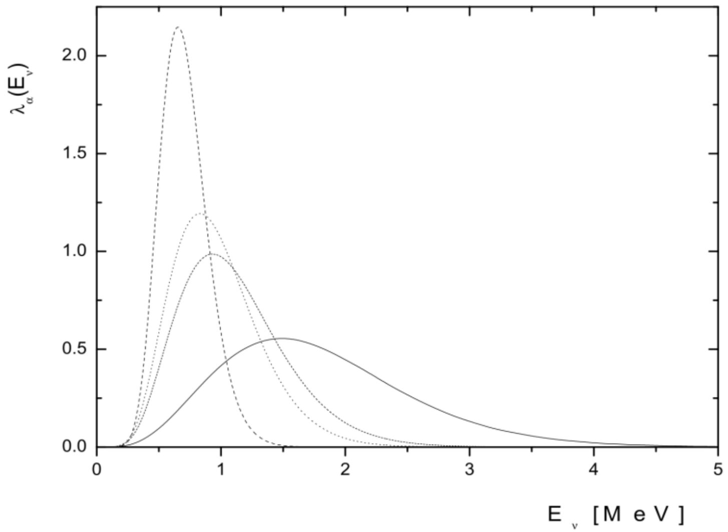


10 kpc SN (NMO). Reconstructed SN position from tagged IBD events (light red) and not tagged IBD events (light blue). Pointing accuracy of 1σ, 2σ, and 3σ are shown in solid, dashed, and dotted contours in blue, respectively.

Pre-supernova neutrinos



- Prior to cores collapsing, fusion of heavy nuclei and ignition of carbon burning start as neutrino-cooled stars. They proceed with nuclear fusion of He, C, O, Ne, and Si. Neutrino luminosity reaches $\sim 10^{12}\ L_\odot$, while the photon luminosity is $\sim 10^{5}\ L_\odot$.
- The final stage of the neutrino-cooled stars are called **pre-supernova stars.**
- Main process contributing to the neutrino emission:
  $\mathbf{e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x \quad (x = e, \mu, \tau)}$
- In the Si-burning stage at $\sim 3 \times 10^9$ K, $\bar{\nu}_e$ ($\sim 1/3$ of the $\bar{\nu}$ flux) can exceed the energy threshold of IBD reaction.
  Odrzywolek et al. (Astropart. Phys. 21 (2004) 303-313)



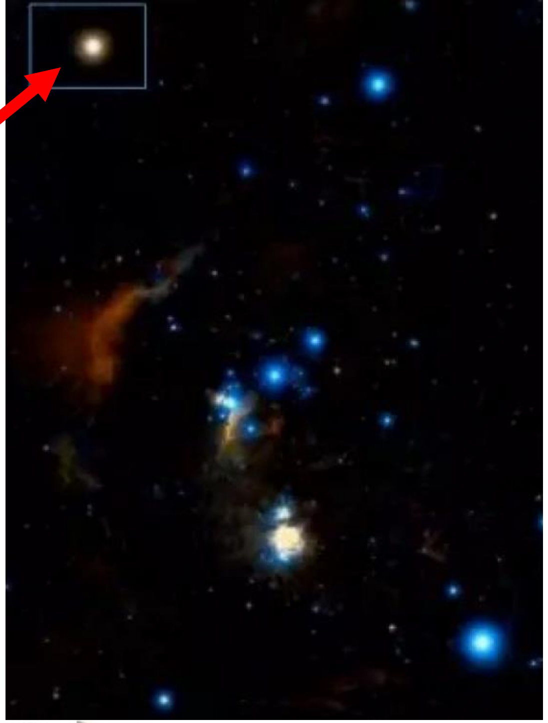
Pre-supernova $\bar{\nu}_e$ spectrum for a 20 $M_\odot$ star.
Astropart. Phys. 21 (2004) 303-313

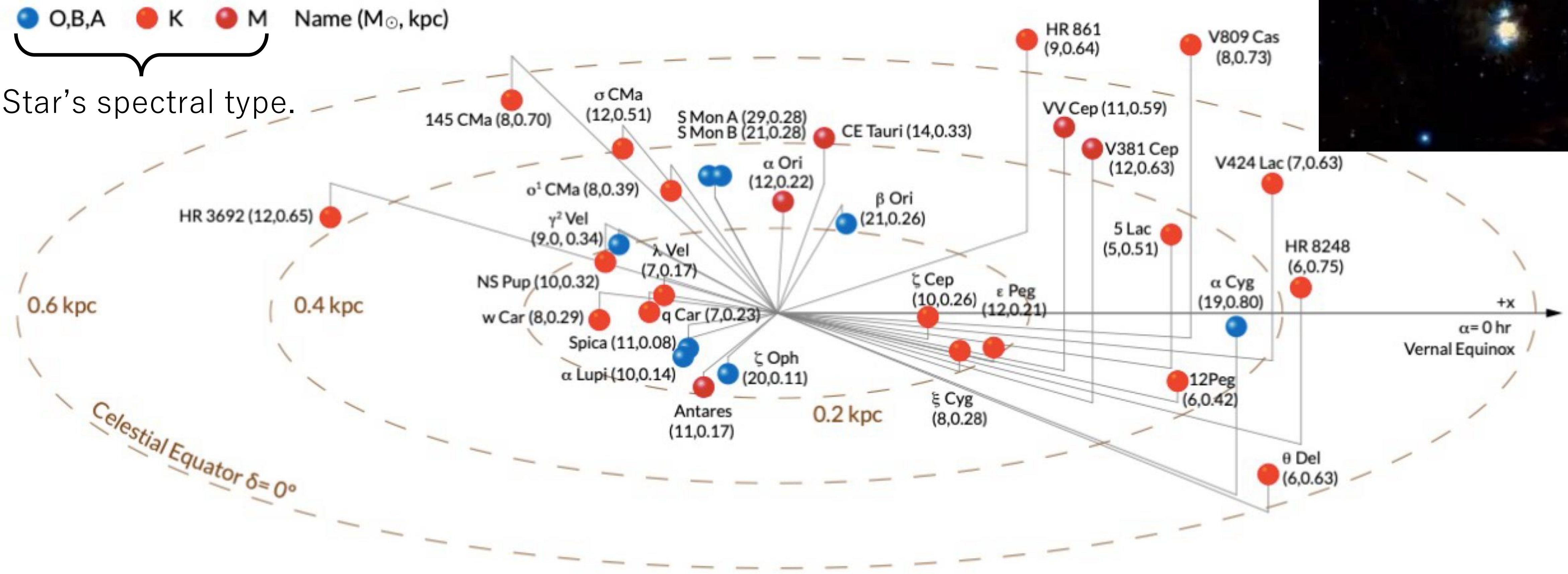
Burning stage	Duration	Average ν energy
C	300 years	0.71 MeV
Ne	140 days	0.99 MeV
O	180 days	1.13 MeV
Si	2 days	1.85 MeV

Approximate duration and average ν_e energy emitted by pair-annihilation in burning stages for a 20 $M_\odot$ star.

Pre-supernova candidates

- α-Ori is the best candidate (~15 $M_{\odot}$ and ~220 pc).

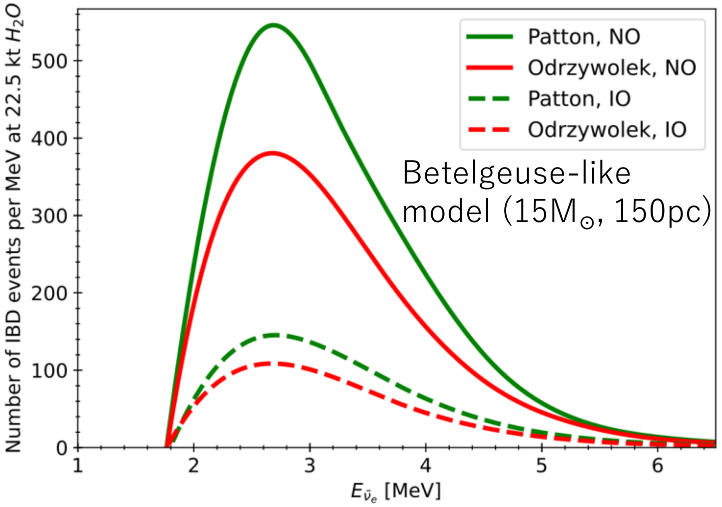




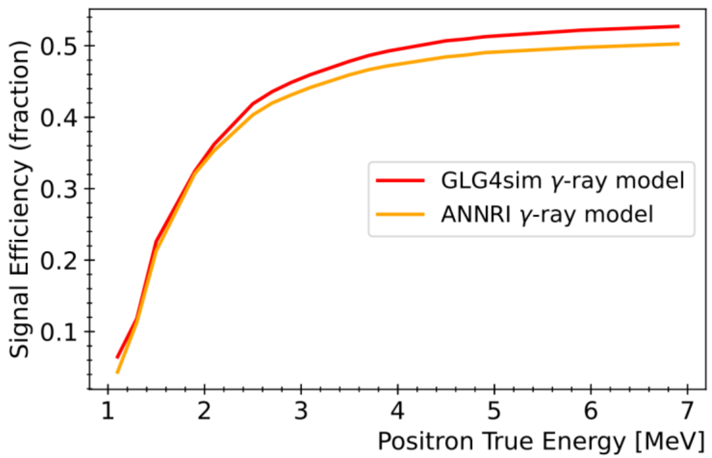
Mukhopadhyay, et al., 2020 Apj. 899 153

Expected signal and real data

Calculated # of pre-supernova IBD interactions in the 22.5 kt SK FV

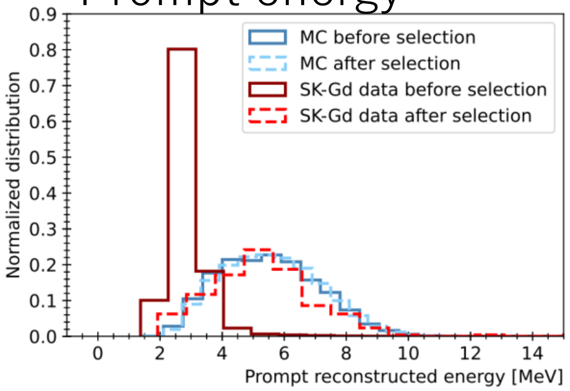


Selection efficiency as a function of e+ true energy

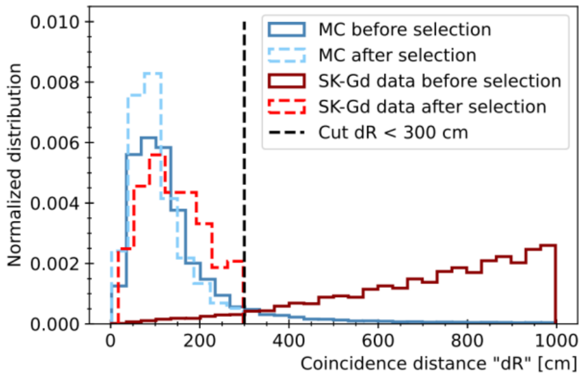


- Expected number of IBD interactions in SK for Betelgeuse-like pre-supernova models during final 10 hours (upper left).
- IBD pre-supernova events are selected not only by reconstructed position and time but also a machine learning technique (Boosted Decision Trees).
- Selection efficiency as a function of e+ true energy simulated with GEANT4 based MC assuming 2 models for neutron capture on Gd (upper right).

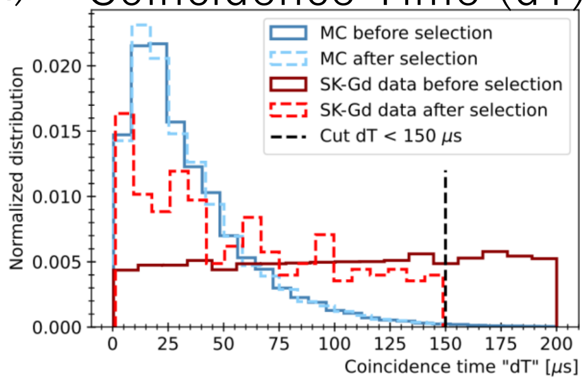
Prompt energy



Coincidence distance (dR)



Coincidence Time (dT)



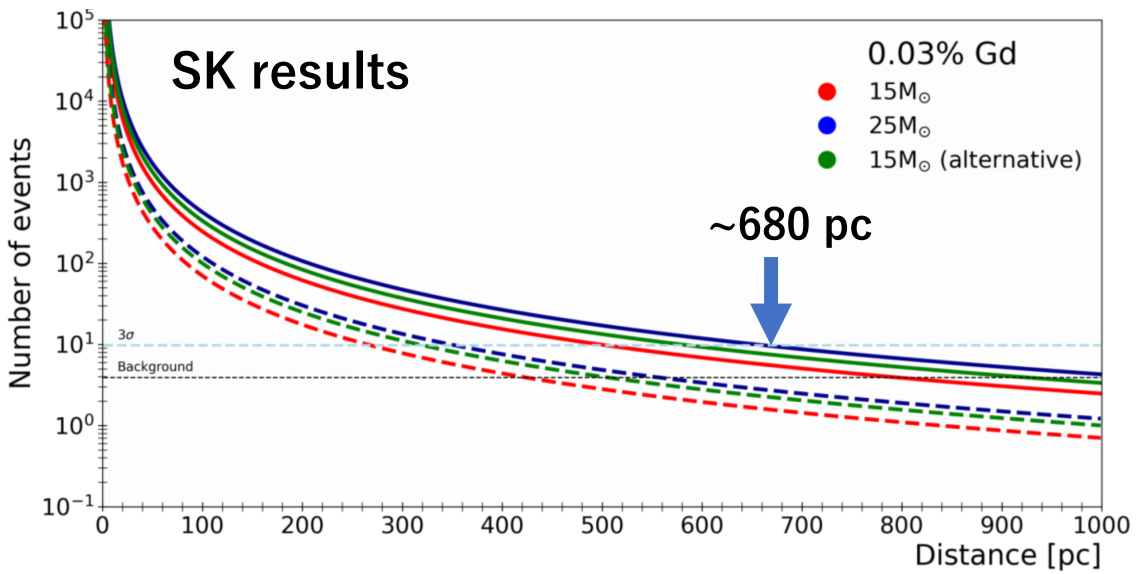
- Distributions of signal and SK-Gd real data before and after event selection.
- The area of each distribution is normalized to 1.

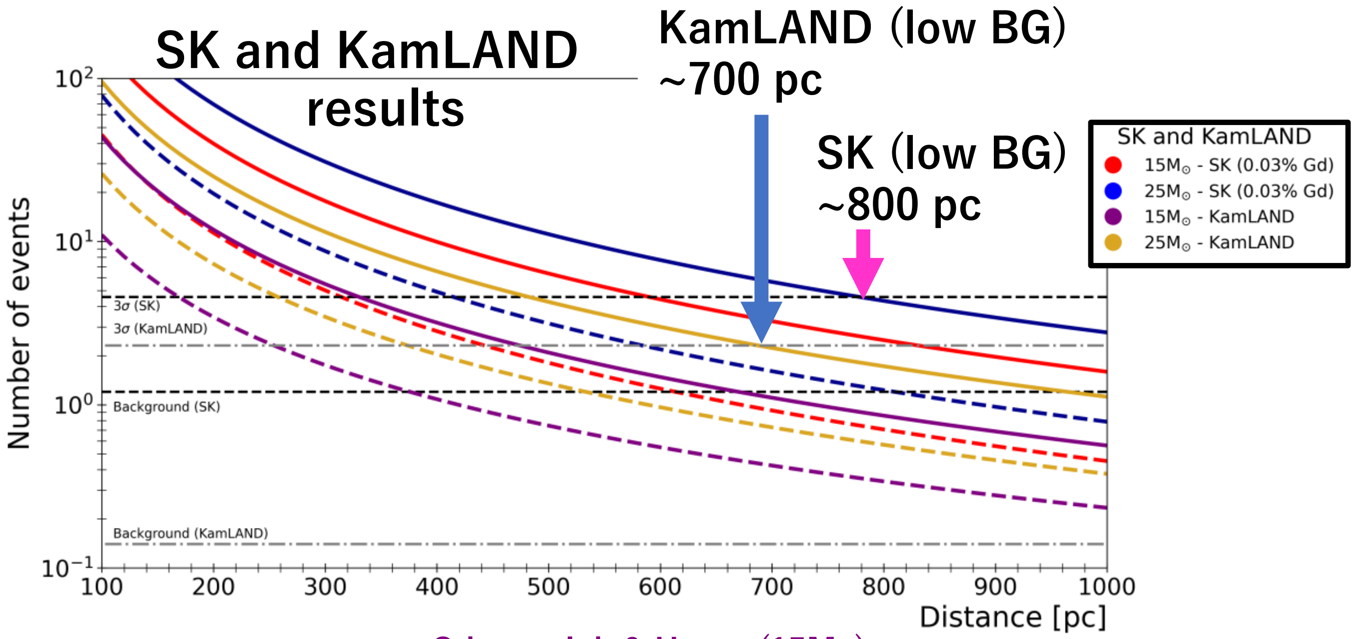
Astrophysical Journal, 935, 40 (2022)

Note: above results obtained from SK-VI (0.01 wt% Gd) are slightly different from latest situation (SK-VII 0.03 wt% Gd).

Sensitivities

- Expected number of IBD events in SK (0.03 wt% Gd)
  - Integrated over 8 hours preceding the core-collapse.





- **Odrzywolek & Heger ($15M_\odot$)**: *Odrzywolek, A., & Heger, A. 2010, Acta Phys. Polon. B, 41, 1611.*
- **Odrzywolek & Heger ($25M_\odot$)**: same as above.
- **Patton ($15M_\odot$)** : *Patton, et al., Astrophysical Journal, 851, 6..*

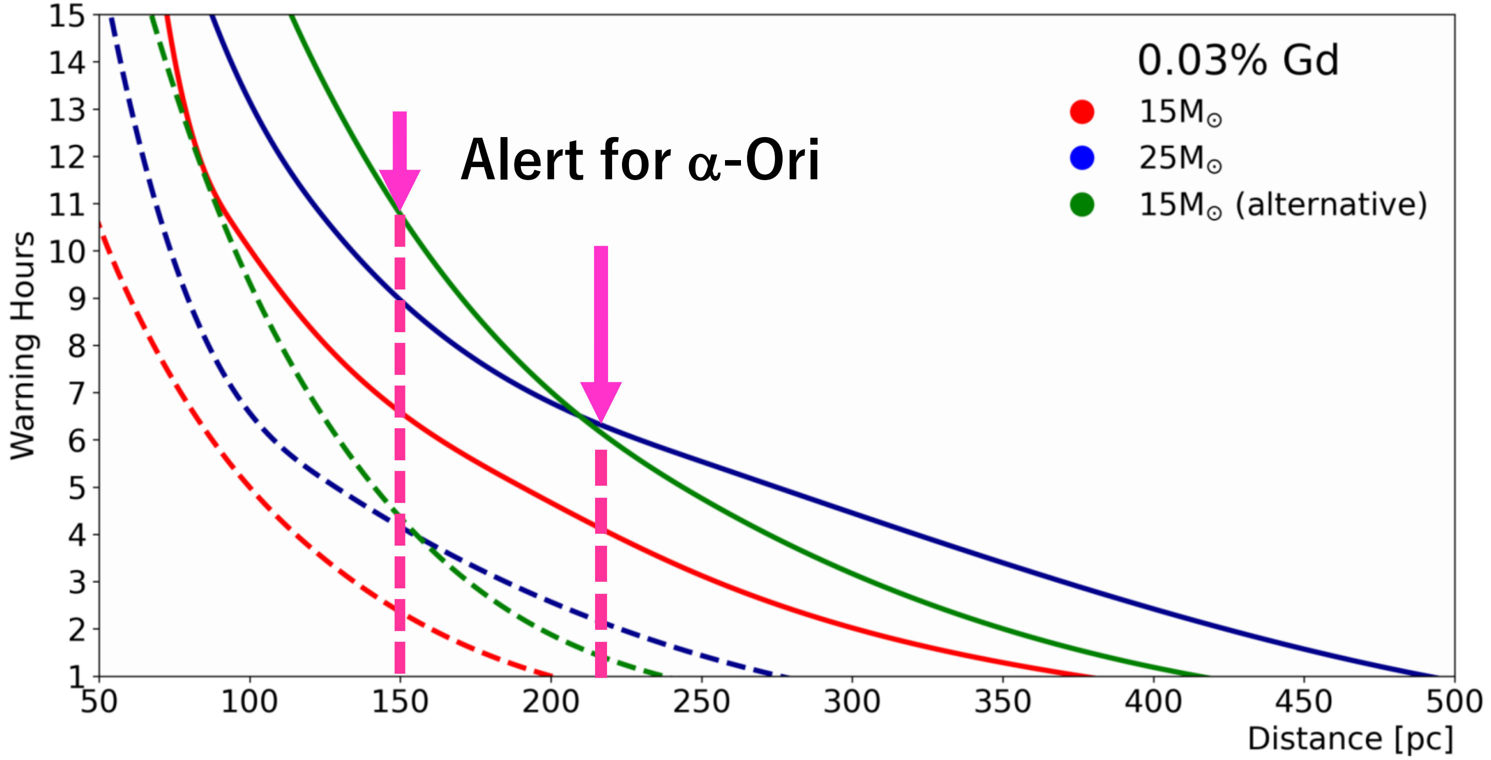
- **Odrzywolek & Heger ($15M_\odot$)**
- **Odrzywolek & Heger ($25M_\odot$)**

Astrophysical Journal, 935, 40 (2022)

- (**Left**) SK can perform 3σ observation of pre-supernova neutrinos for stars up to ~680 pc away from Earth. It has been updated from Astrophysical Journal, 935, 40 (2022) considering latest situation of SK-VII.
- (**Right**) Comparison between SK and KamLAND. In KamLAND, integrated time is optimized to 48 hours. It is taken from Astrophysical Journal, 935, 40 (2022). In both of experiment, low level of BG (all Japanese reactors turned off).

Alert system capability

Expected warning time as function of distance for 3σ detection by alert system



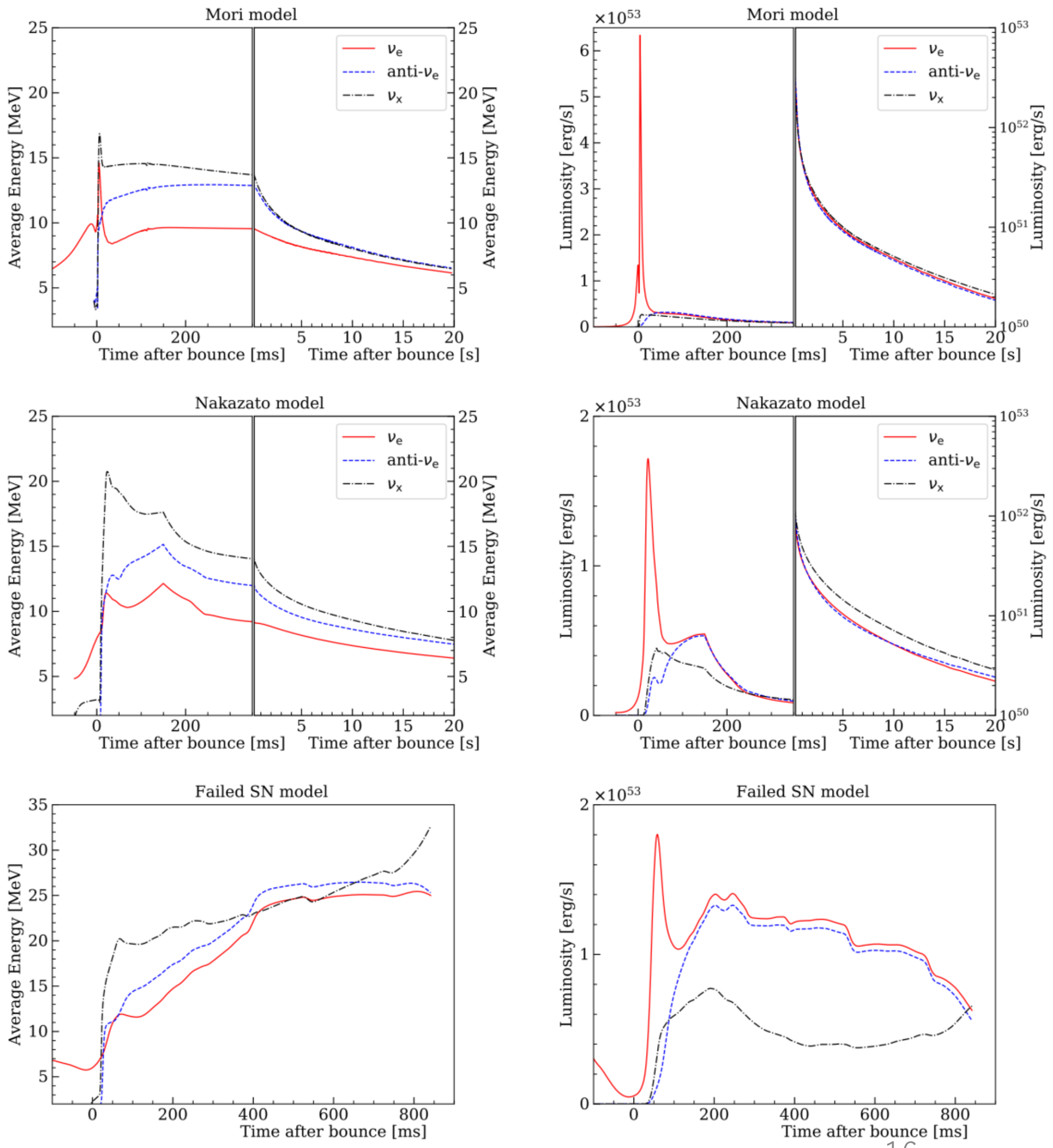
Astrophysical Journal, 935, 40 (2022)

- Real-time alert system has been implemented to SK on Oct. 22nd 2021.
- In the case of α-Ori (Betelgeuse) with optimistic parameters, SK would produce alerts up to ~11 hours before the core-collapse supernova.
  (mass and distance for α-Ori have uncertainties, but they are highly correlated: 150 pc for 15$M_\odot$ and 220 pc for 25$M_\odot$. The combination of 150 pc and 15 $M_\odot$ gives most optimistic one.)

(2) Offline search for distant supernovae

- It focuses on detecting more distant supernovae using offline approach.
- Cluster of events in specified time window were searched:
  - ≧2 events in 0.5 sec window
  - ≧2 events in 2 sec window
  - ≧4 events in 10 sec window

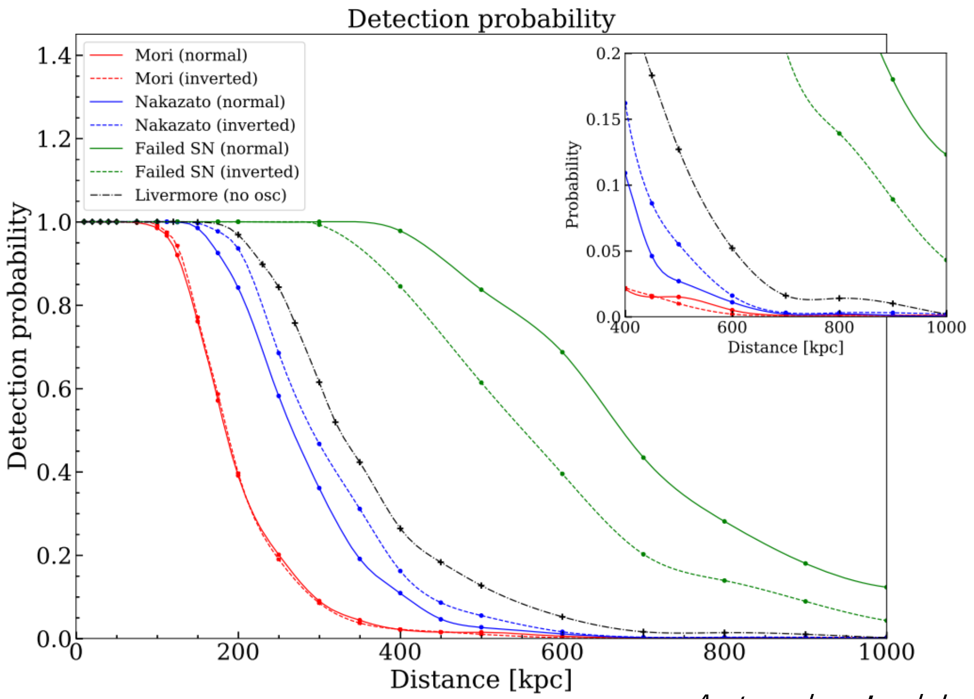
- Most serious background comes from muon-induced spallation. But, these events are highly correlated with the timing and path of their preceding muons and can be removed using well established algorithms.

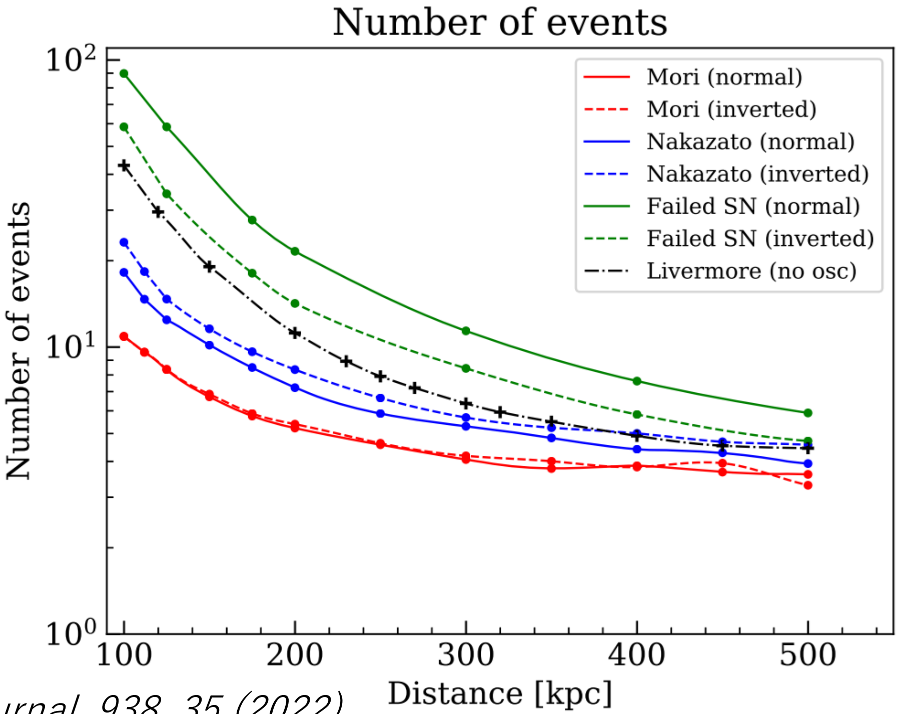


Astrophysical Journal, 938, 35 (2022)

Offline search for distant supernovae

- Predicted detection probability (left) and number of events detected in a cluster (right) as a function of distance.





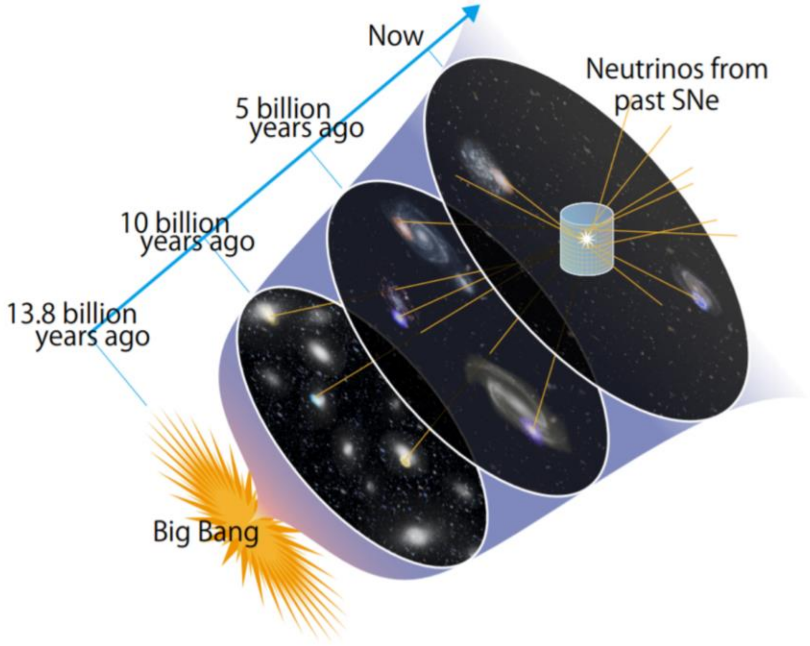
Astrophysical Journal, 938, 35 (2022)

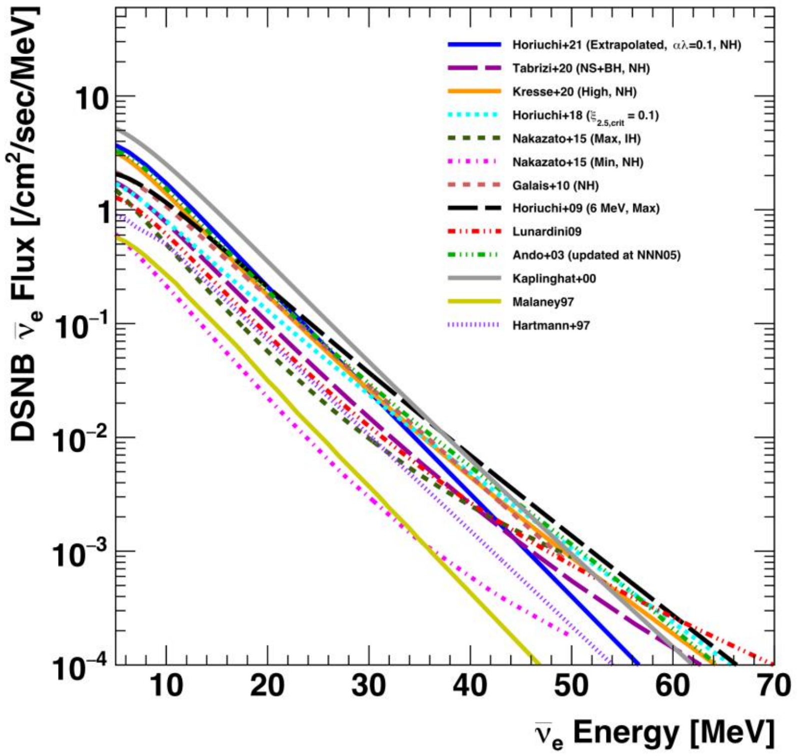
- **Mori model**: *Mori et al., 2020, PTEP, 023E01*
- **Nakazato** and - **Failed SN model**: *Nakazato et al., 2013, ApJS, 205, 2*
- **Livermore model**: *Totani et al., 1998, ApJ, 496, 216*

- No evidence of distant SN bursts was found from data collected in SK-IV (2008~2018):
  - The upper limit of 0.29 yr^{-1} out to 100 kpc at 90% C.L. was set.
  - For SN that fail to explode and collapse directly to black hole, the limit reached to 300 kpc.

(3) DSNB search

- Although SK has enough sensitivity for detection of supernova bursts occurring in or around our galaxy, no burst was detected since it began observations in 1996 because they are extremely rare (a few times per century in our galaxy).
- Another channel for detection of neutrinos from supernova is diffuse supernova neutrino background (DSNB)
- DSNB: accumulated flux of the neutrinos from all past core-collapse supernova bursts.

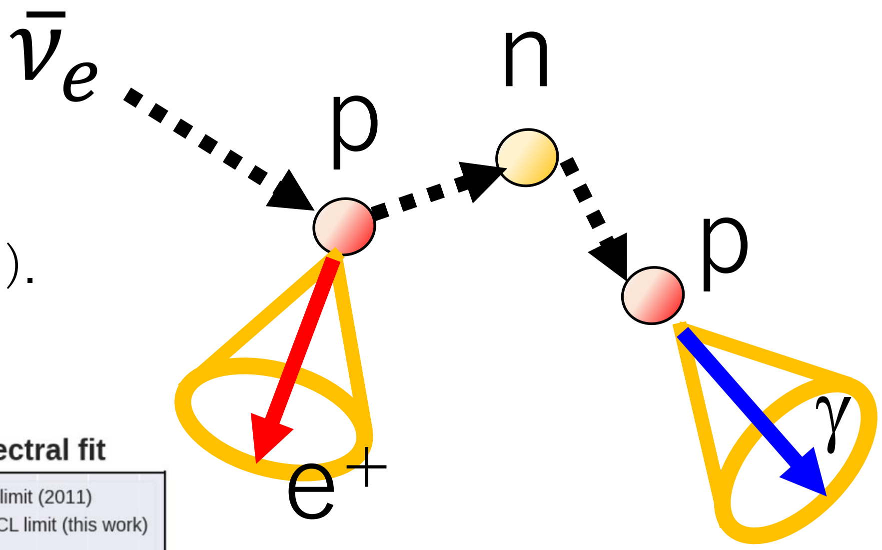




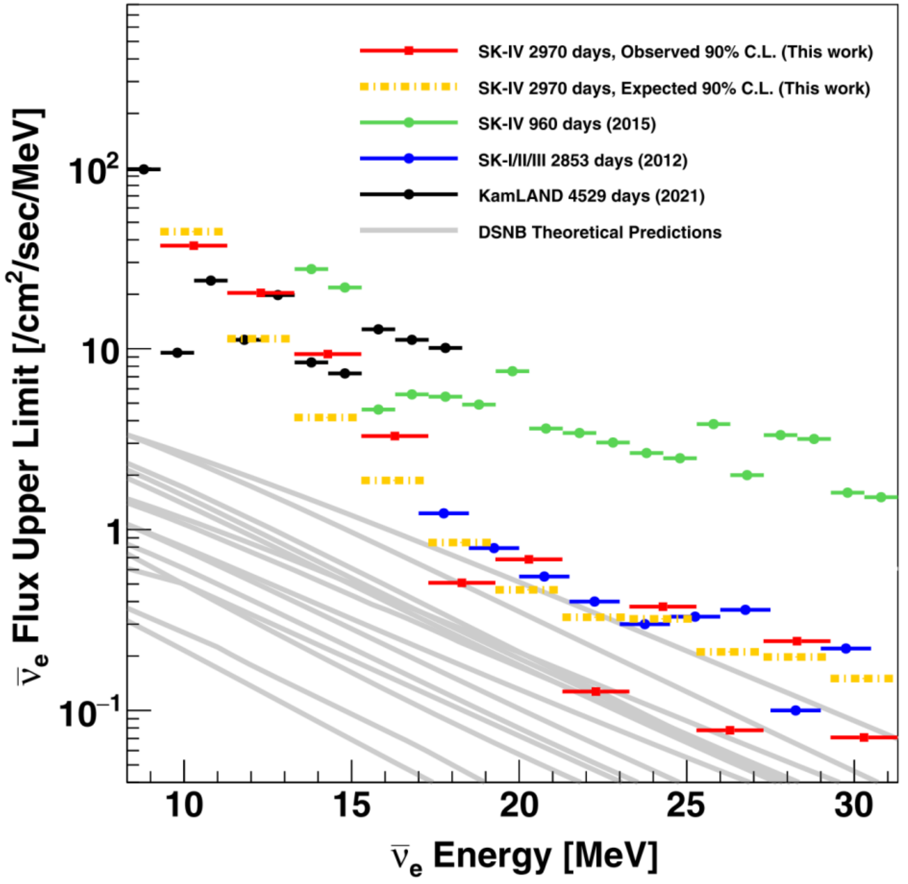
Phys. Rev. D 104, 122002 (2021)

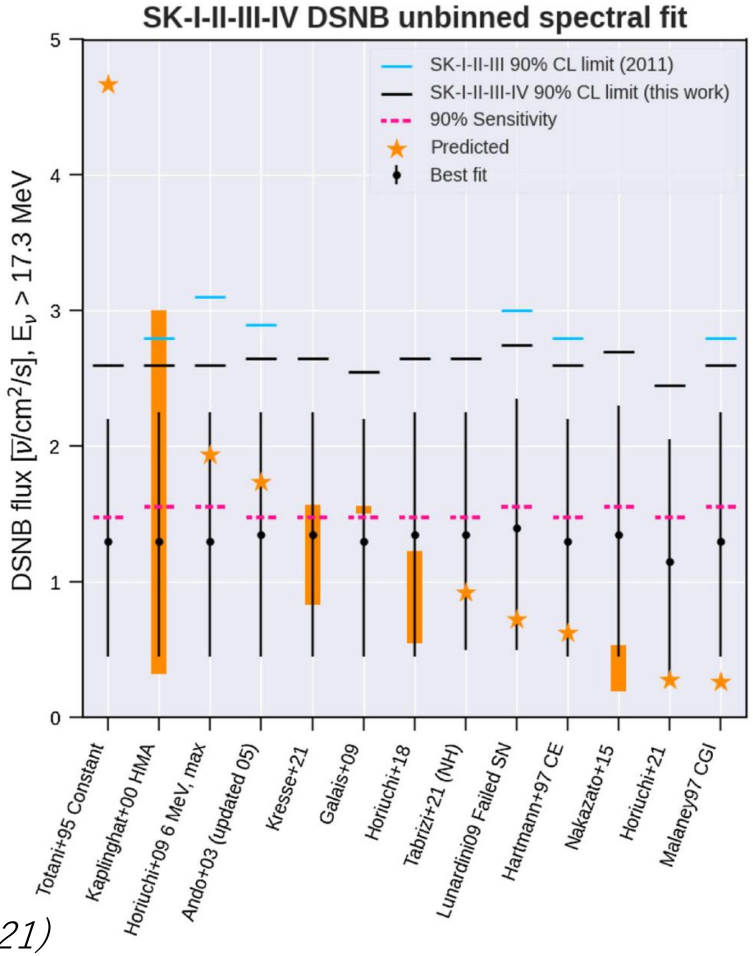
Expected DSNB flux is affected by various parameters and various theoretical models are proposed.

DSNB search in SK



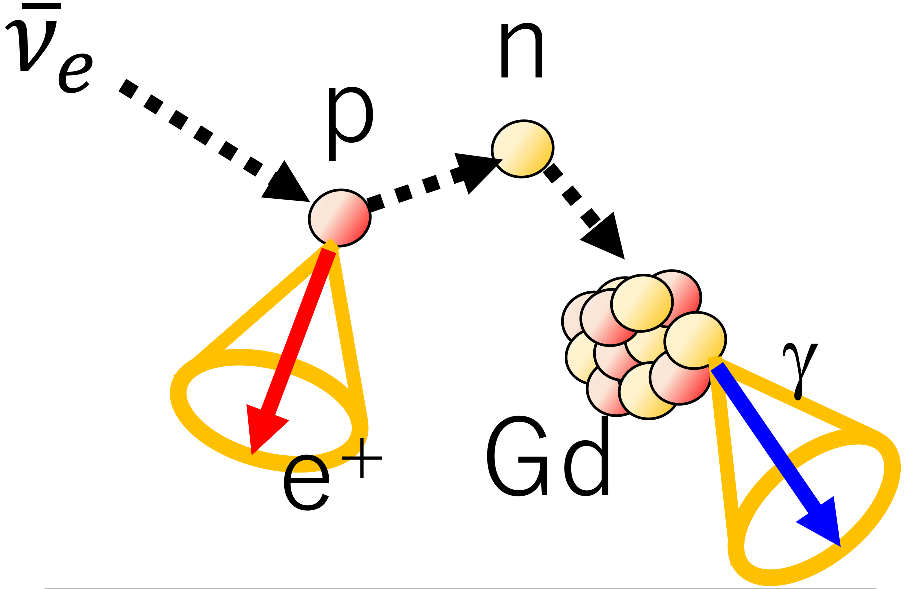
- Most stringent limit was set by SK (*Phys. Rev. D 104, 122002 (2021)*). from neutron capture on proton.
- Some optimistic models were surveyed.





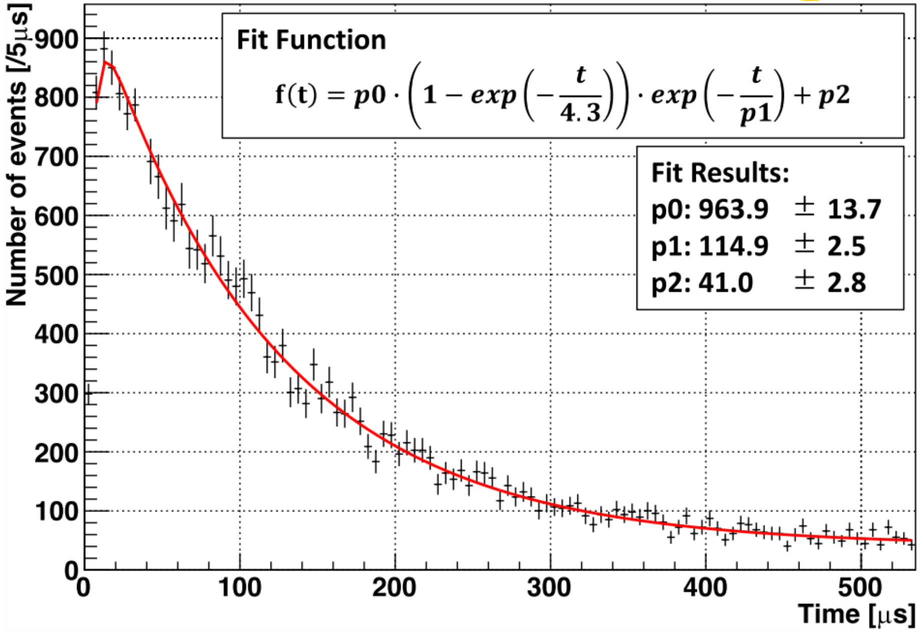
Phys. Rev. D 104, 122002 (2021)

DSNB search in SK-Gd



DSNB search with neutron capture on Gd was performed.

- Data set: SK-VI
  - From Aug. 2020 to Jun. 2022 (552.2 live days)
  - Search range: 7.5–29.5 MeV
- Gd concentration: 0.011 wt%
  - Fraction of neutron capture on Gd: ~50%
  - Time constant: ~115 μs
- Background reduction:
  - Muon spallation products (9Li).
  - Atmospheric neutrinos from NCQE and non-NCQE interaction.
  - Reactor neutrinos.
  - Accidental coincidence.

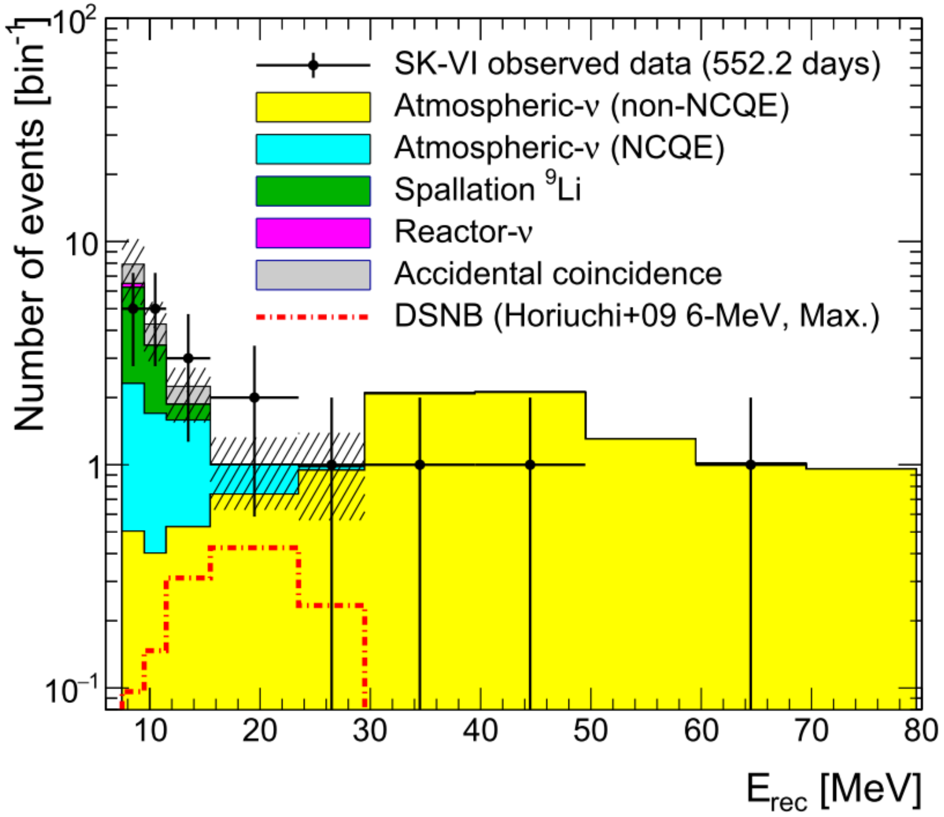


Time distribution of neutron capture event candidates measured with Am/Be source.

NIM A 1027 (2022) 166248

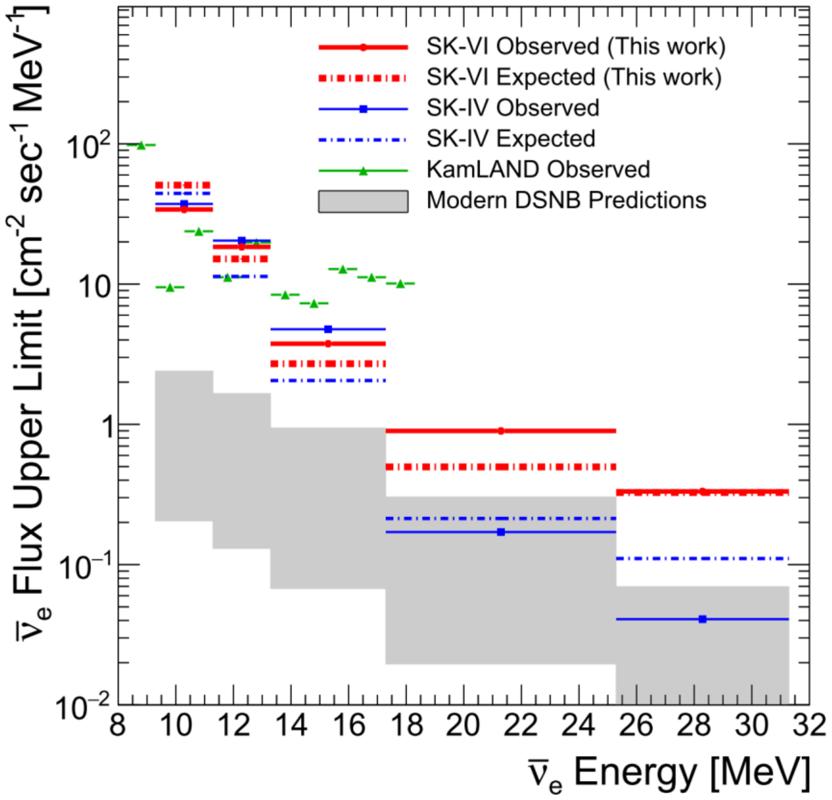
First results for DSNB search in SK-Gd

- 16 events remain within the signal region between 7.5 and 29.5 MeV.
- They were consistent with BG estimation.



M. Harada et al., arXiv:2305.05135

- Differential upper limit was extracted.



→ It was comparable with SK-IV 10 years results.

Summary

- Individual core-collapse supernova bursts
  - (1) Real-Time Monitor
    - **Supernova alert system**: 100% detection efficiencies for various models are estimated for LMC (50 kpc) by golden alarm and SMC (62 kpc) by normal alarm.
      Alert time and direction pointing accuracy have been improved owing to identification of IBD events from enhanced neutron tagging.
      Automated alert to GCN Notice has been implemented. Current lead time is 3.5 minutes, being improved to less than one minuets.
    - **Pre-supernova alert system**: It has been implemented in SK on Oct. 22nd 2021.
      In the case of Betelgeuse with optimistic parameters, alert would be issued up to ~11 hours before the core-collapse explosion.
  - (2) **Distant burst search**:
    - The upper limit of 0.29 yr^{-1} out to 100 kpc at 90% C.L. was obtained.

- (3) **Search for DSNB**
  - Most stringent limits was set and some optimistic models were surveyed before Gd loading.
  - Results from first 552 days of SK-Gd data was comparable with SK-IV (no Gd) 10 years results owing to enhanced neutron tagging .