SK/HKでの超新星爆発モニター開発とマルチメッセンジャー観測

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@Kashiwa, ICRR
高エネルギー現象で探る宇宙の多様性Ⅳ

Contents

- SK Gd status
- Improvements of SN burst detection
  - SN direction fitter improvement
  - Automatic GCN Notice
- Very close SN detection
- Multi-Messenger Observation
- Hyper-K status
  - Construction
  - Sensitivity to supernovae
- Summary

Super-K experiment

1000m underground = 2600 m.w.e

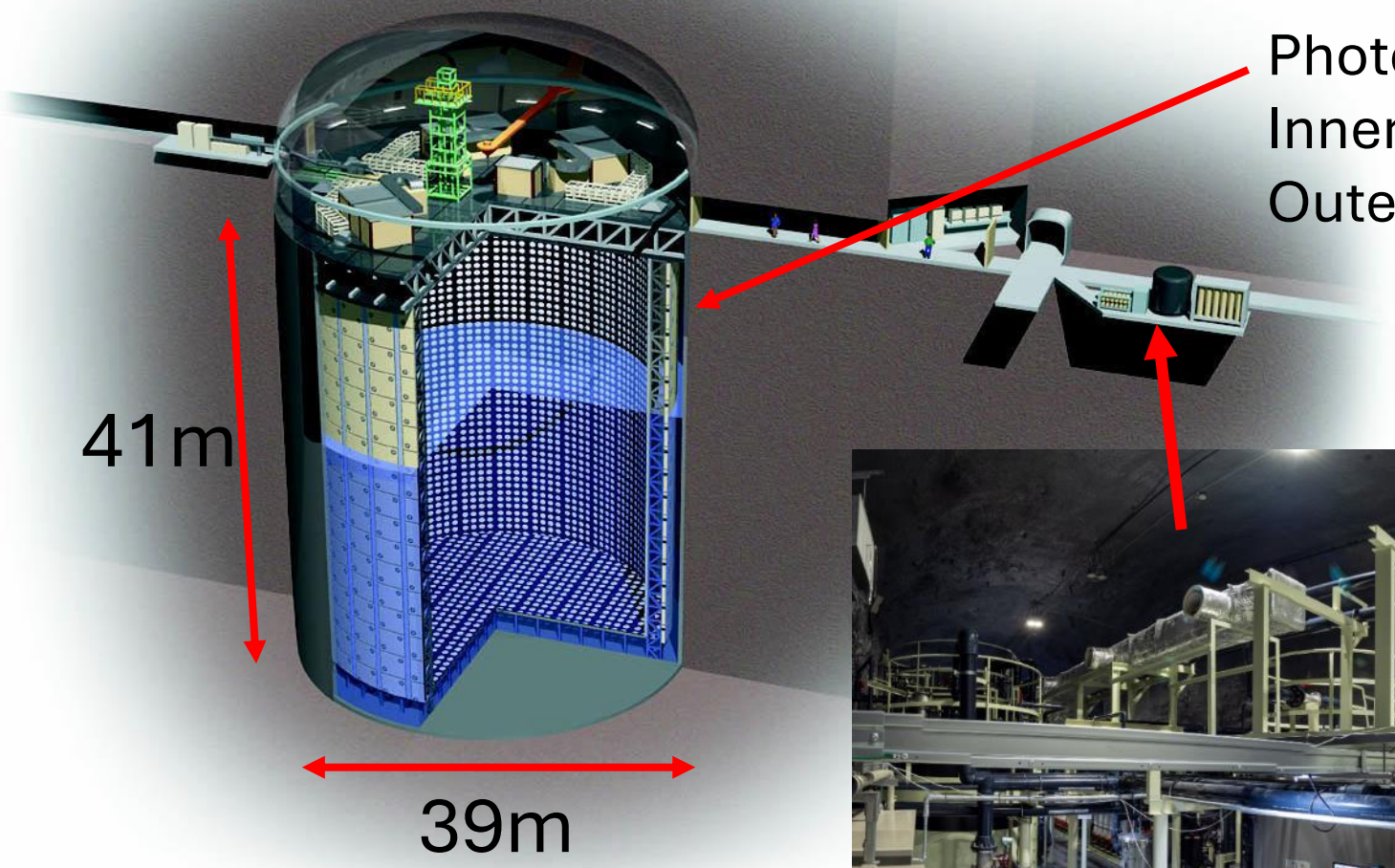


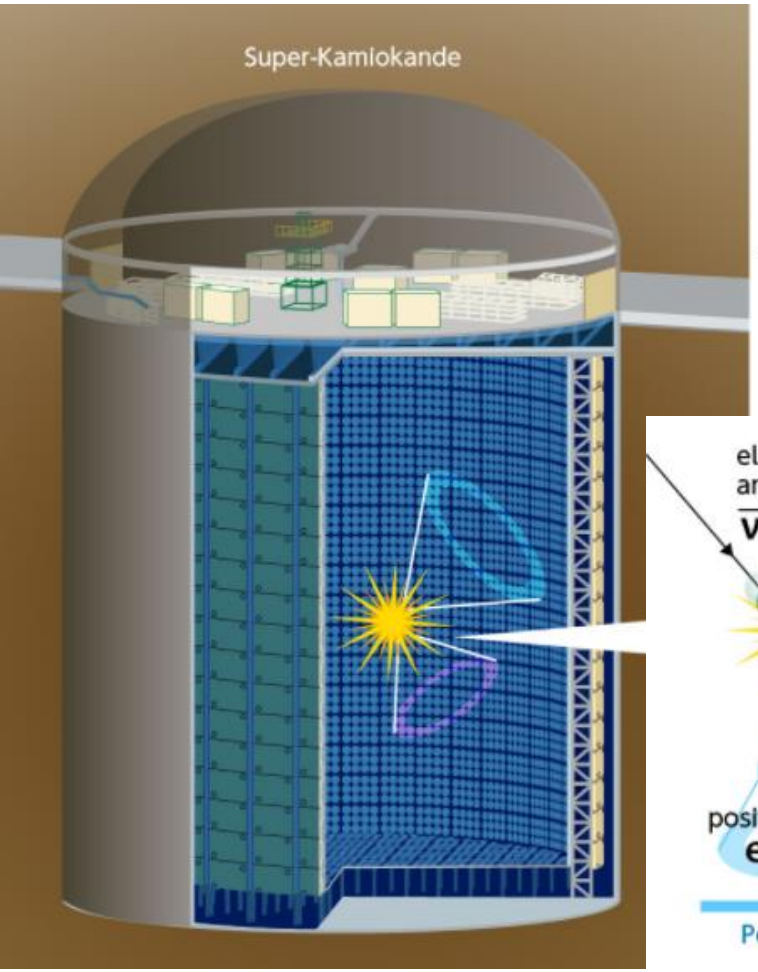
Photo sensors :
Inner detector: 11129 20inch PMTs
Outer detector: 1885 8inch PMTs

Gd water system room

SK-Gd project

Dissolving Gd to enhance detection capability of neutrons from ν interactions

Phys.Rev.Lett. 93 (2004) 171101



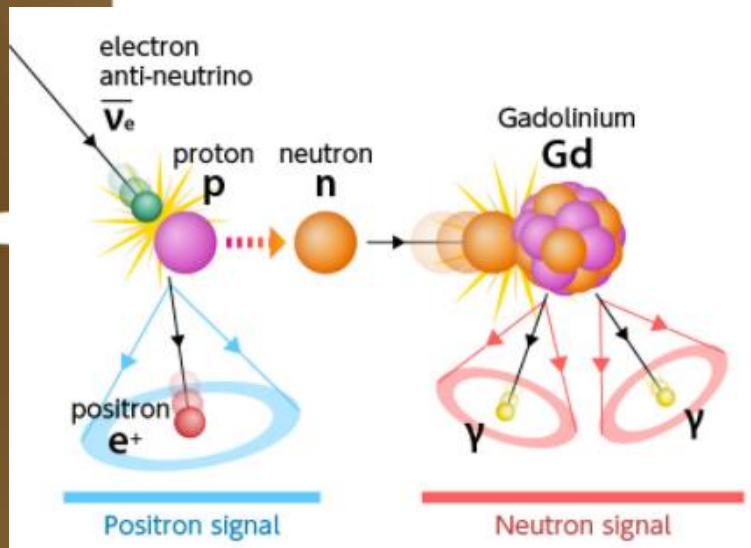
Physics targets:

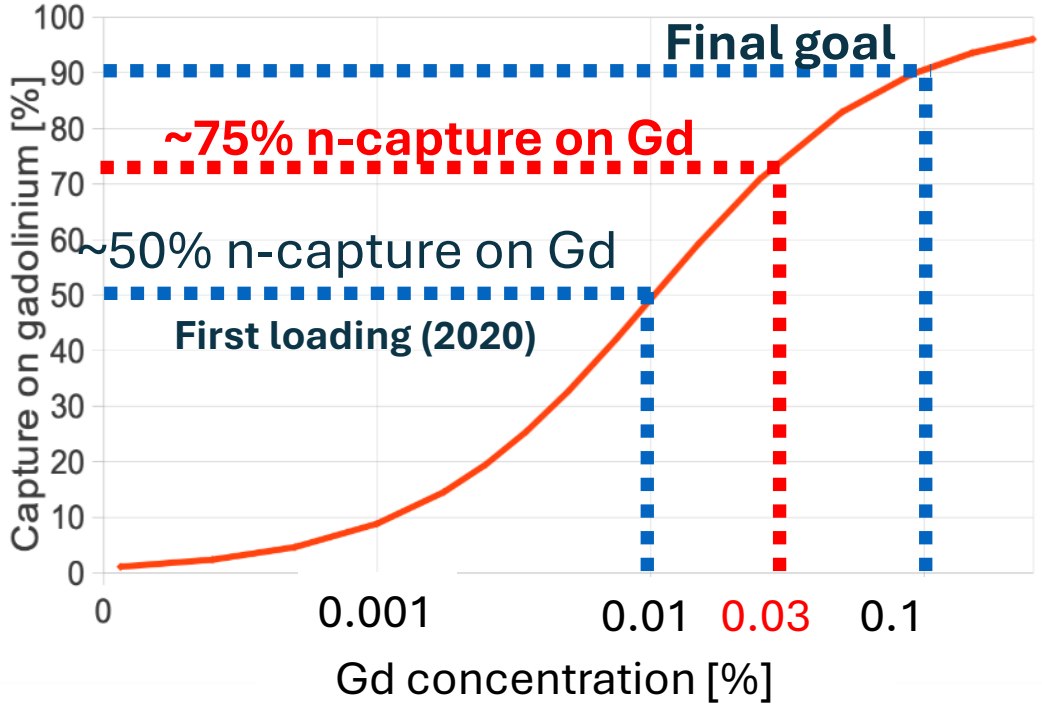
(1) Discovery of Supernova relic neutrino (or DSNB)

(2) Galactic supernovae (pointing accuracy, and pre-SNν)

(3) Reduction of BG for proton decay, solar ν, or reactor ν

(4) Neutrino/anti-neutrino discrimination

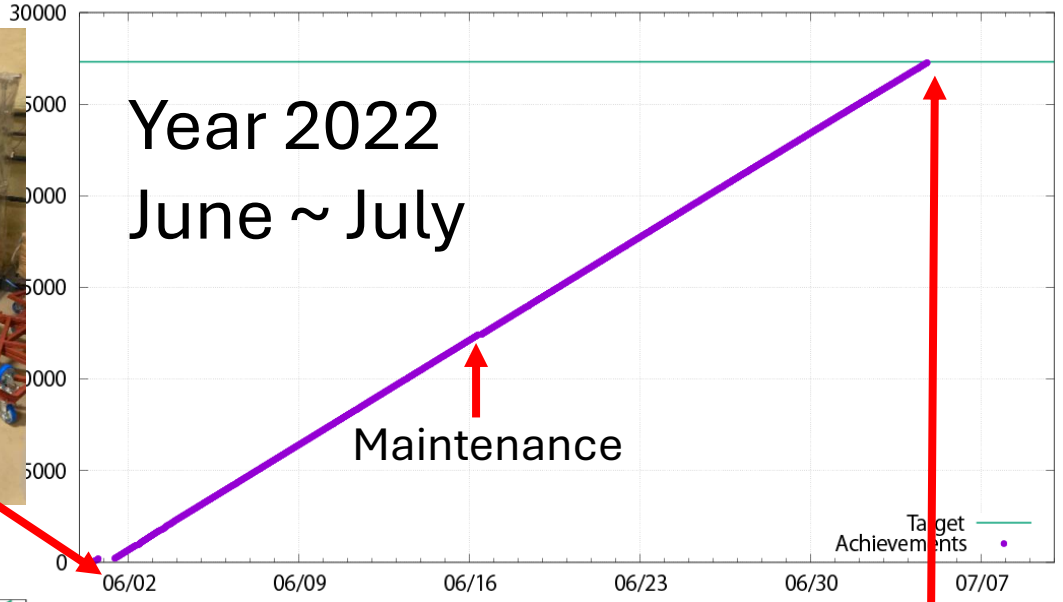


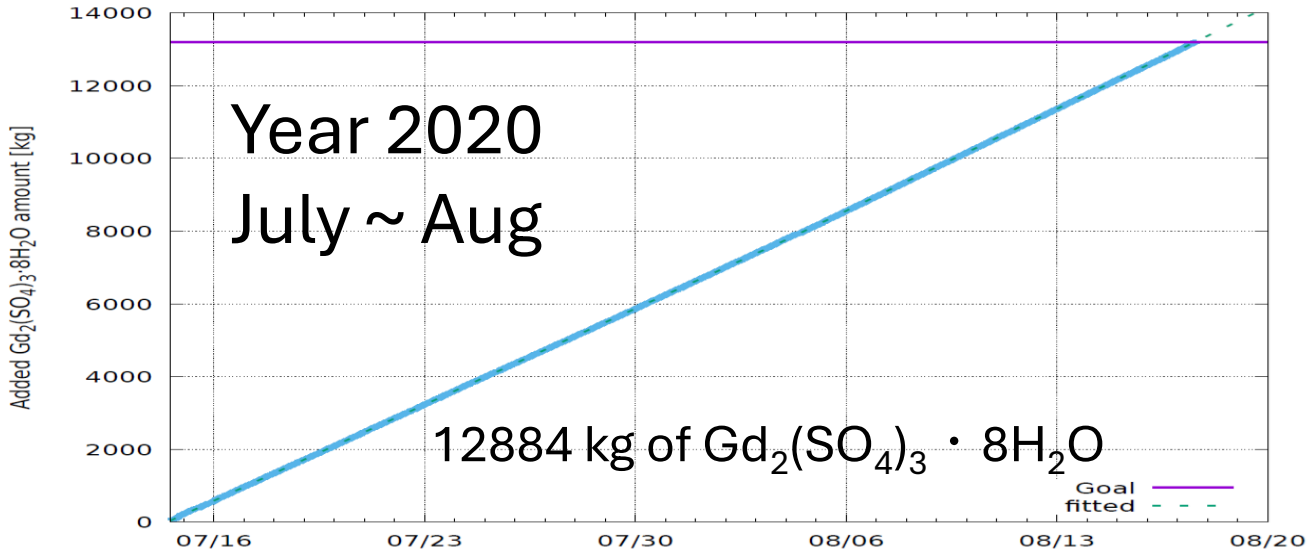


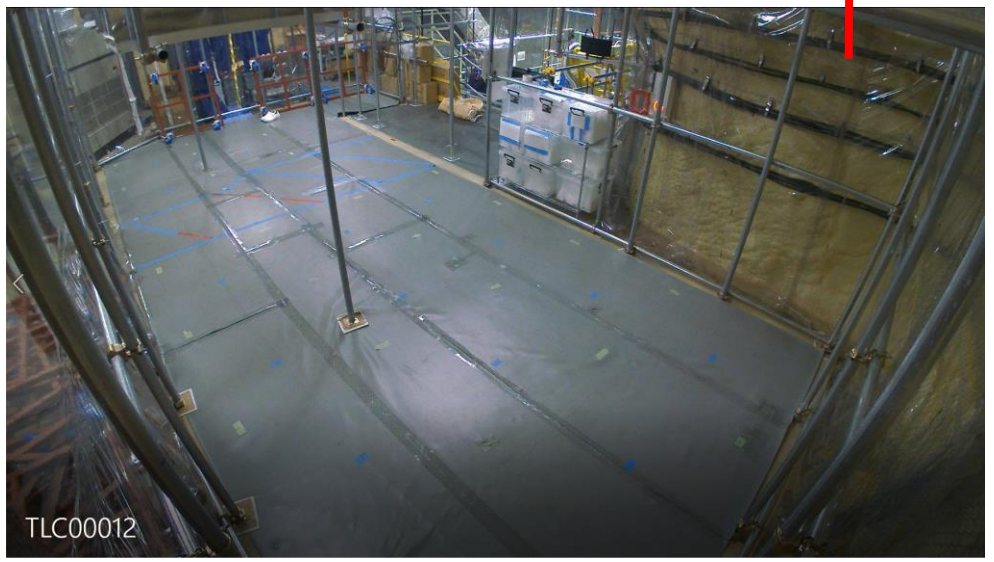
Gd loading in 2020 and 2022

Beginning of the dissolving work in 2022

27304 kg of $Gd_2(SO_4)_3 \cdot 8H_2O$







Gd loading in 2020 and 2022

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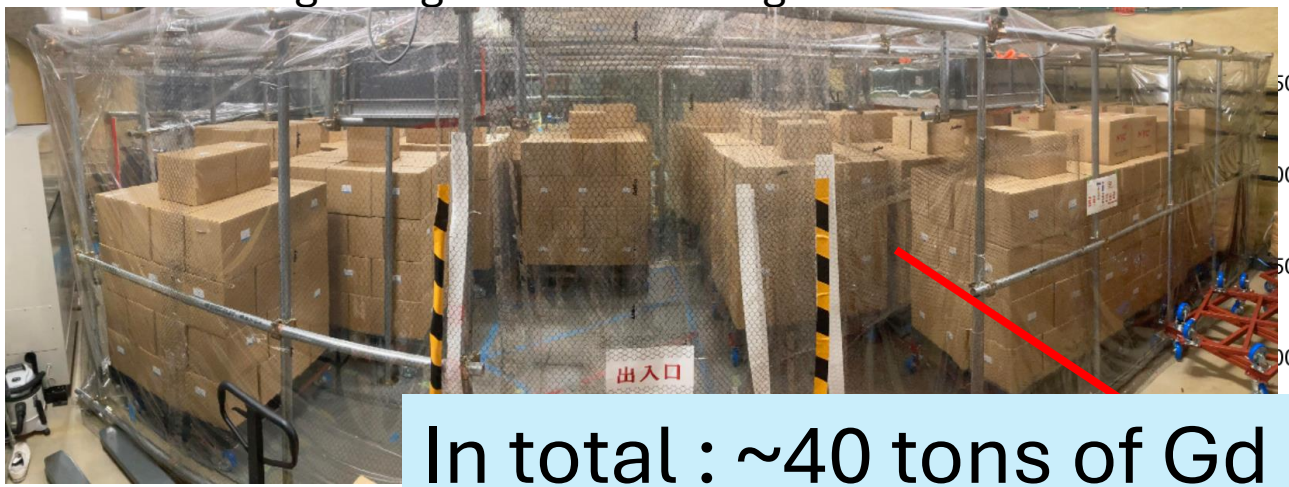
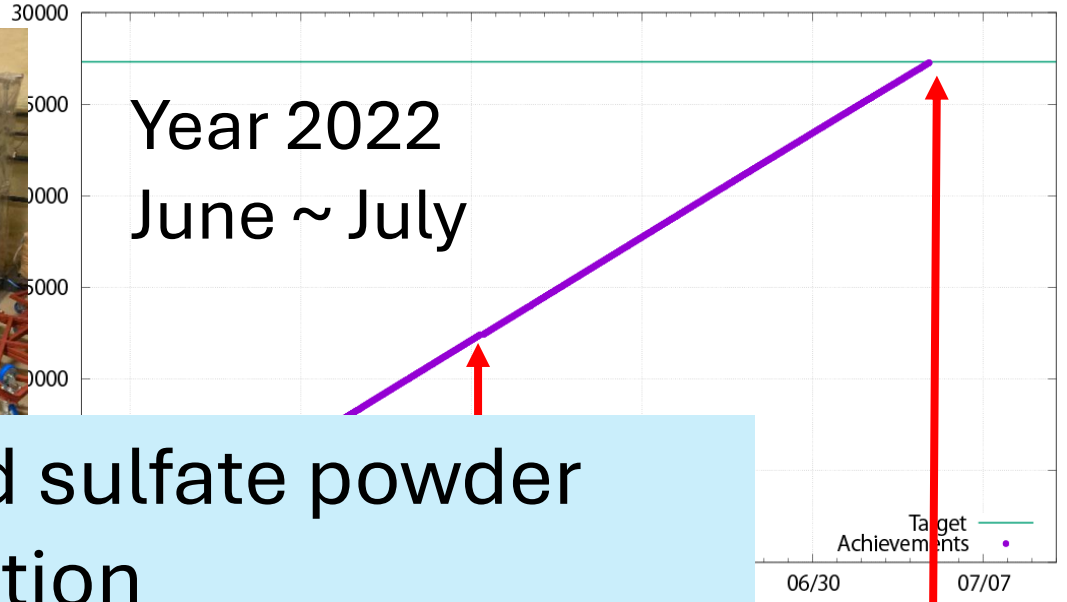
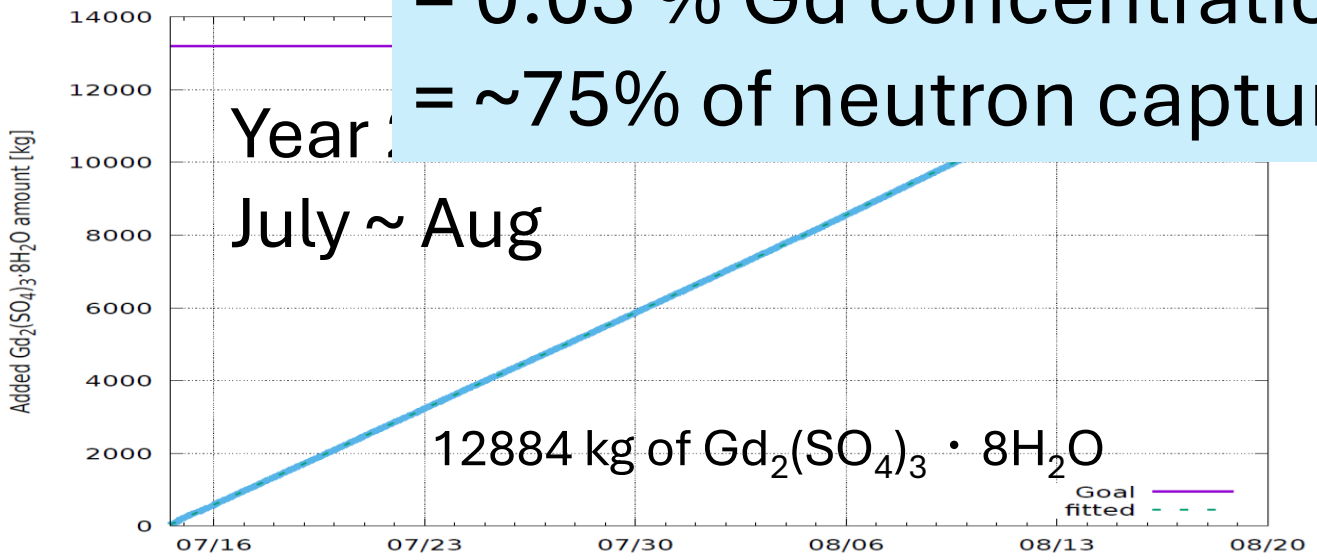
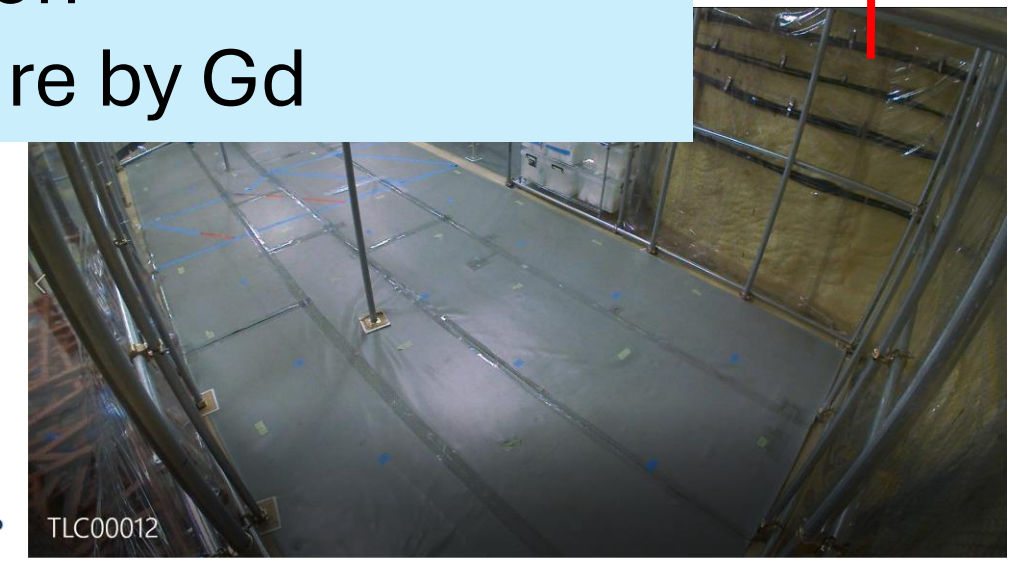




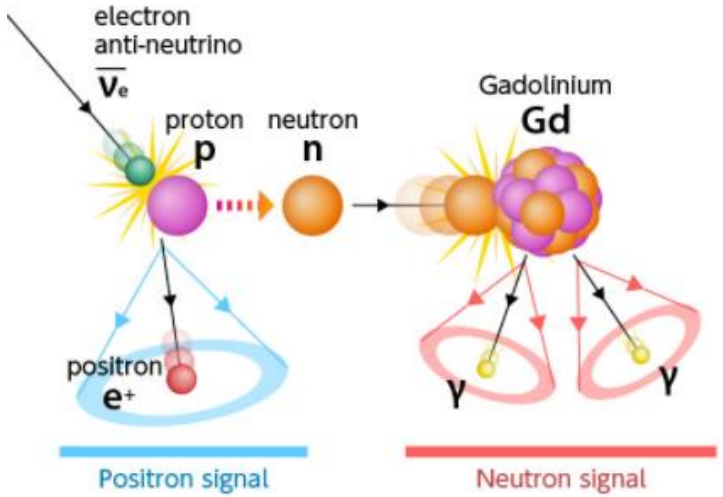
27304 k

In total : ~40 tons of Gd sulfate powder
= 0.03 % Gd concentration
= ~75% of neutron capture by Gd

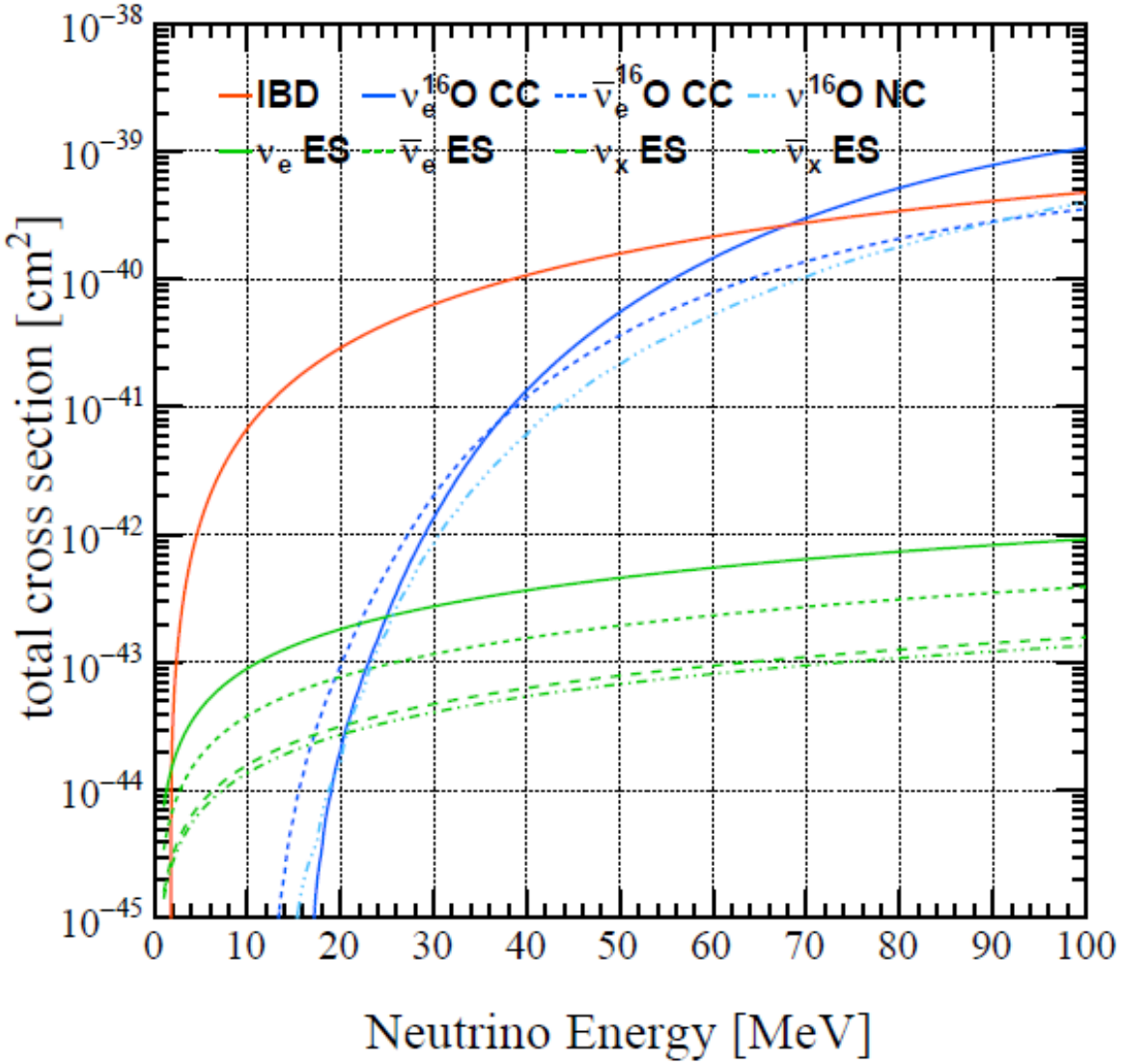




SK・HK：Neutrino interactions of SN neutrinos



- Inverse beta decay (IBD)
  - ~90% of total interactions
- Elastic scattering (ES)
  - ~5% of total interactons
  - Keep the neutrino direction
- 16O (CC and NC)
  - ~5%



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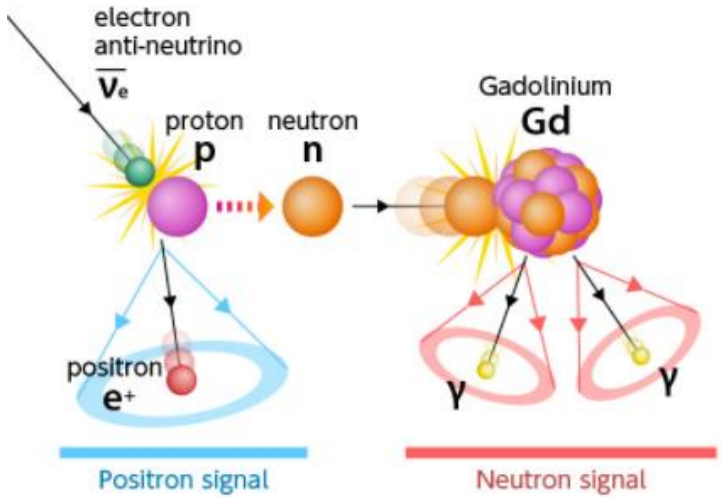

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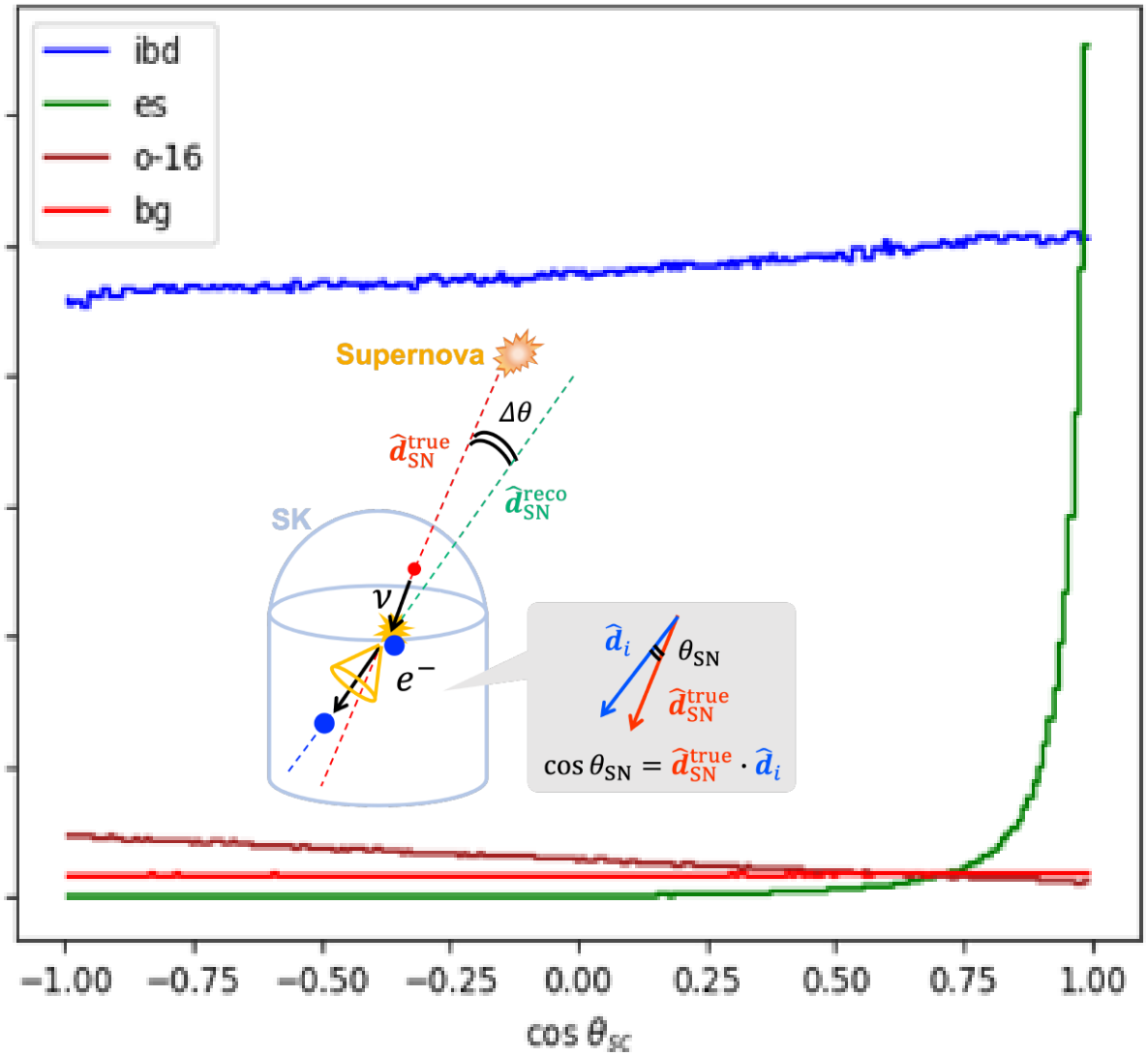
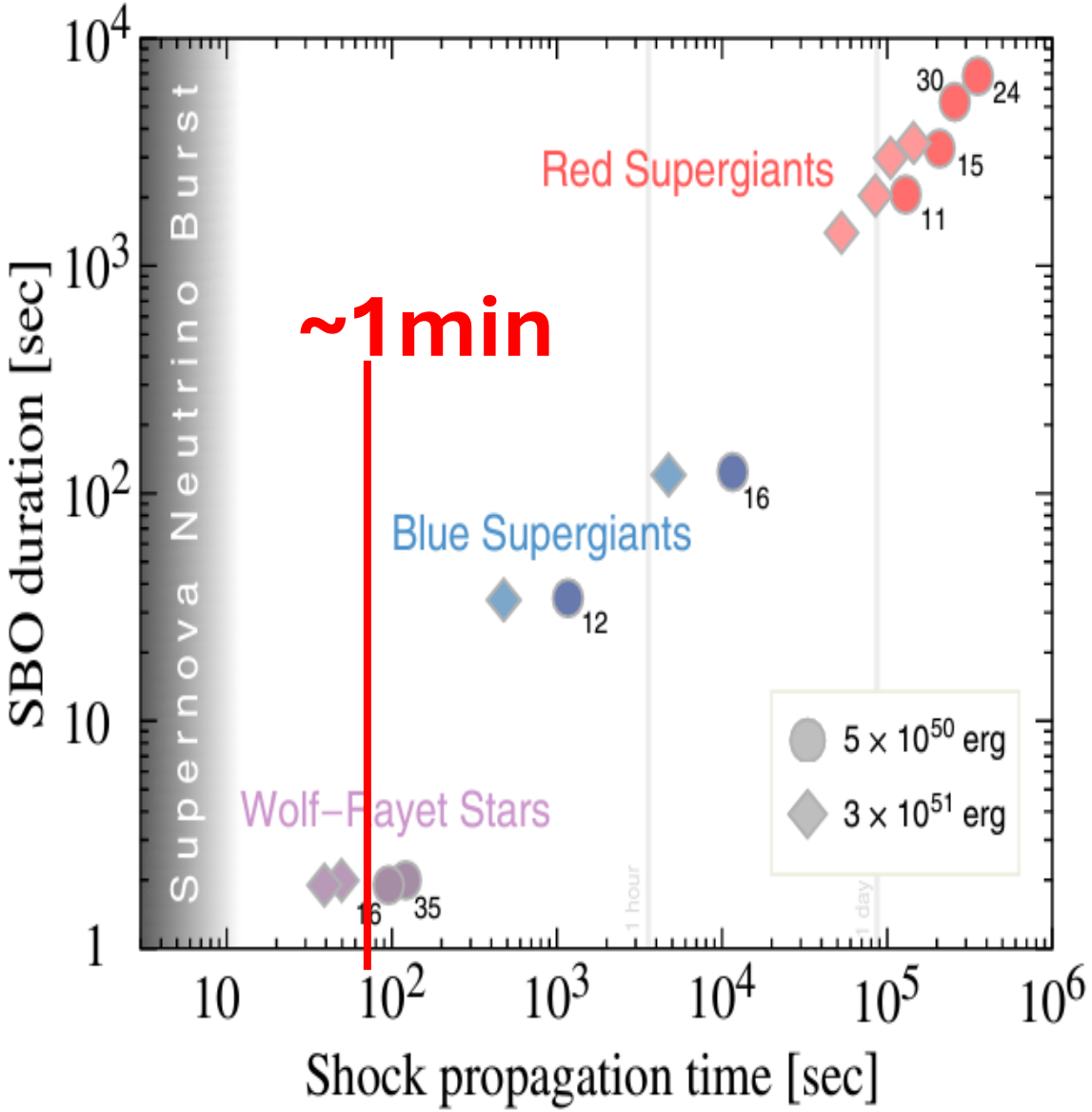
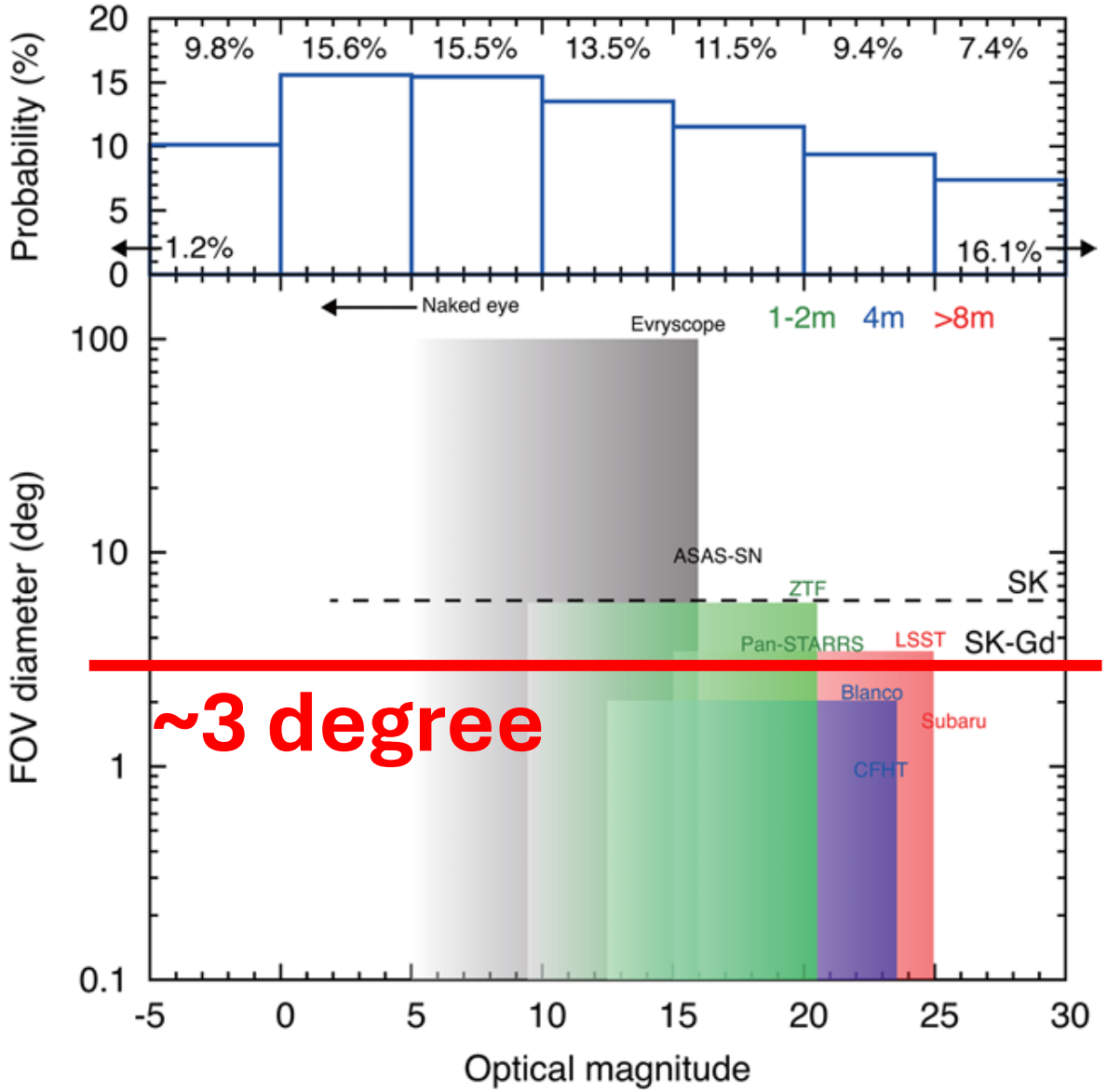


Requirement of SN burst monitor

Kistler, M., Haxton, W., & Yuksel, H. 2013, Astrophys. J. 778;81, 9pp,



K.Nakamura et al. MNRAS461,3296–3313(2016)



Improvement of SN observation at SK-Gd

- Update of SN direction pointing accuracy and latency （Time between the observation and issuing an alert）
  - New method of SN direction calculation
    - Resolution improvement using Gd signals
    - Fast calculation of SN direction
  - Automatic GCN Notice
- Very close (~100pc) SN detection
  - Monitor of Pre-SN neutrinos
  - New DAQ system to avoid DAQ errors during very high rate signal

Latency improvement

Observation（in case of 10kpc SN）

Data transfer~1min

Length of subrun is ~1 min

Event reconstruction~1min

Obtain energy, vertex position, and direction for each event

SN direction fitter~10min → New method
Better resolution
Faster! ~few sec

Have a meeting among experts and confirm signals ~30min → Auto GCNNotice ~ sec

SN Golden alert (Originally ~1h) → Current latency : ~ few min

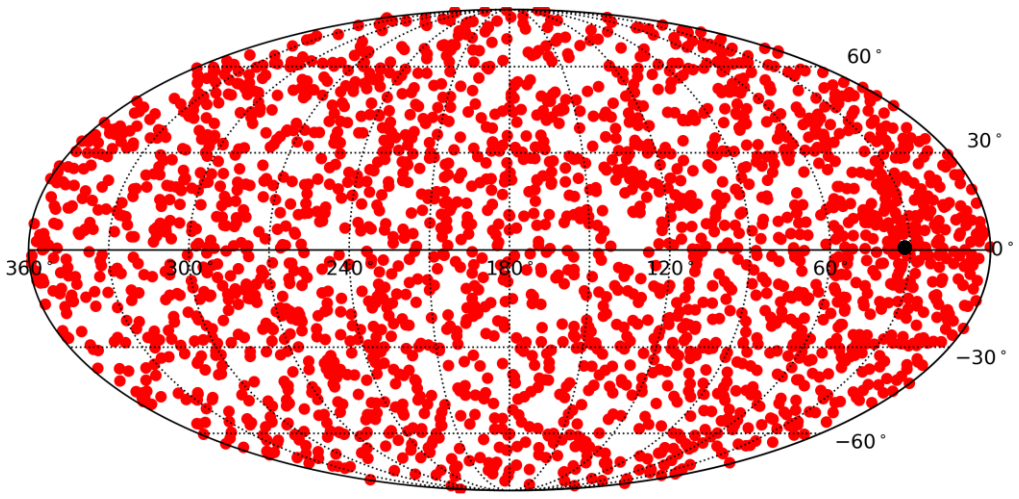
Improvement of SN direction fitter

- **Separation of ES/IBD →Better resolution of SN pointing**
- By using Gd signals we can separate ES/IBD
  → SK-Gd can have better resolution!

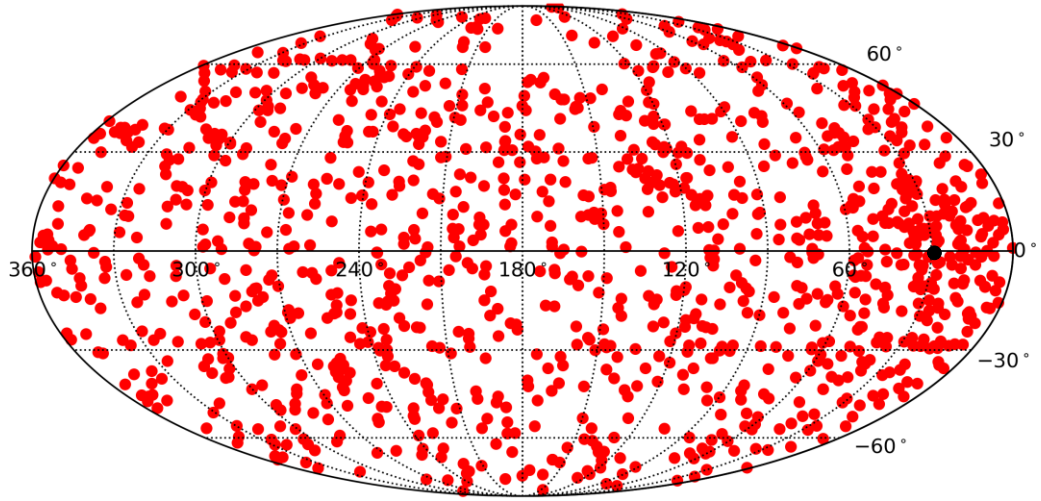
Skymap of each event direction

Example of ES and IBD separation

10 kpc SN (Nakazato Model)



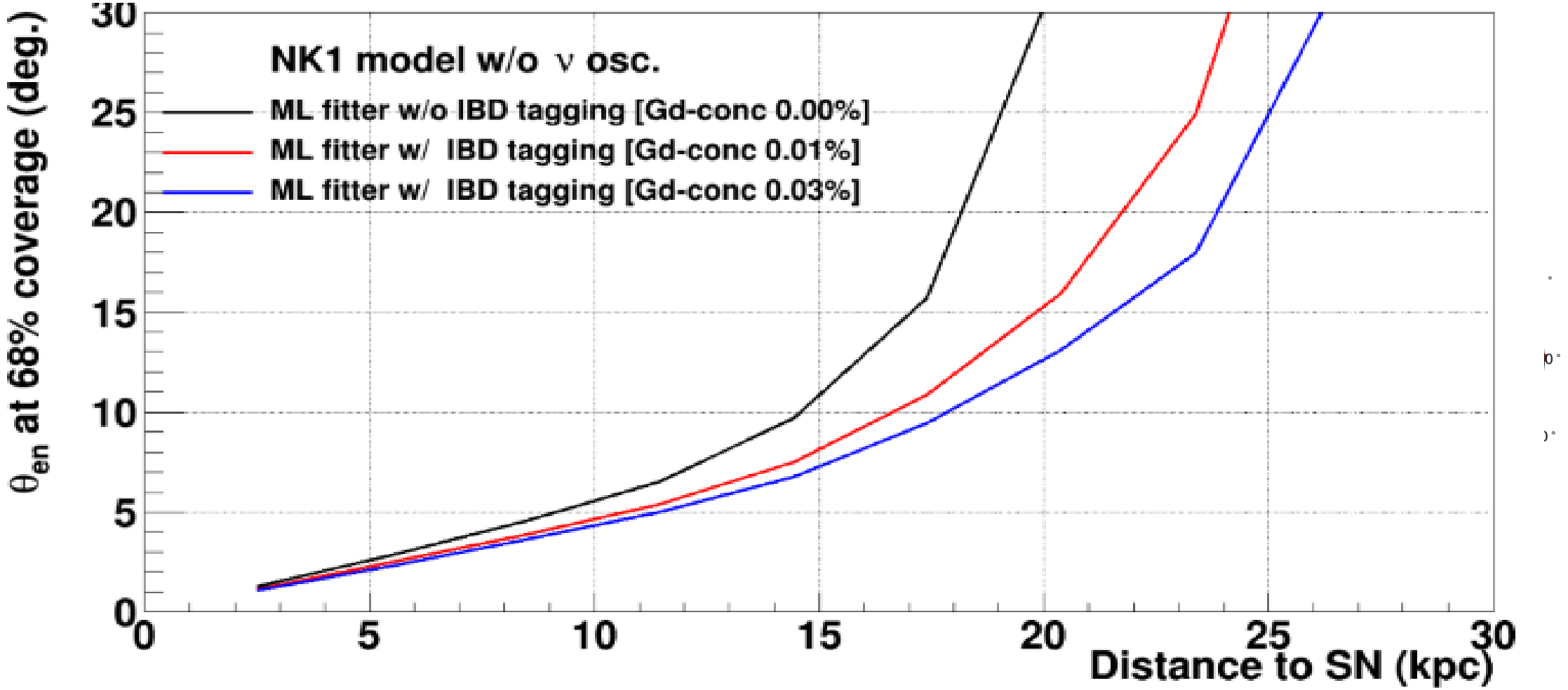
Without IBD tagging



With IBG tagging of 49.7% efficiency

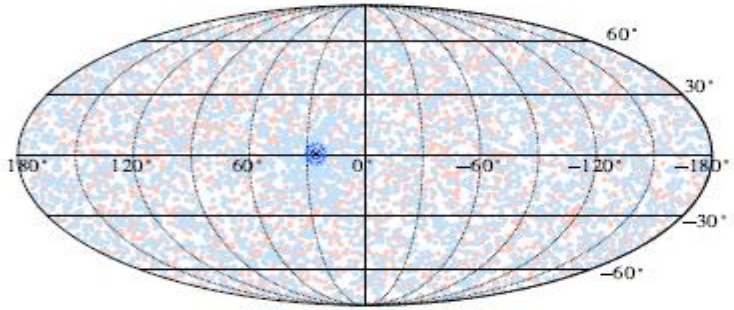
Improvement of SN direction fitter

- **Separation of ES/IBD →Better resolution of SN pointing**
- By using Gd signals we can separate ES/IBD
  → SK-Gd can have better resolution!

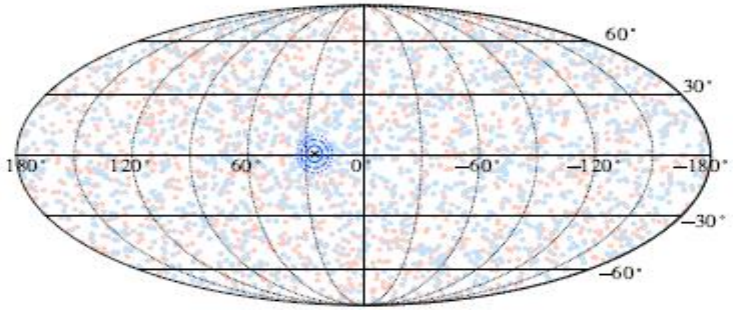


Evaluation with various SN models

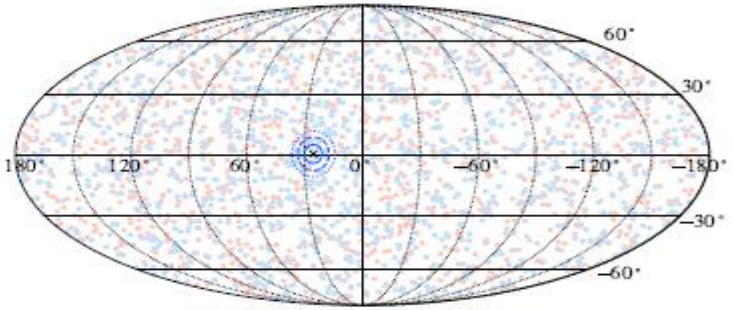
Blue : ES like, Red: IBD like



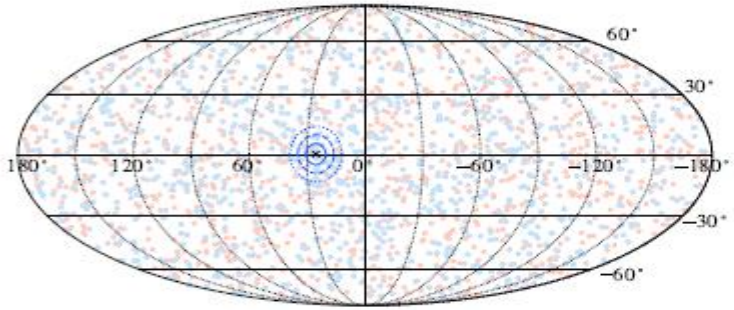
(a) the Wilson model



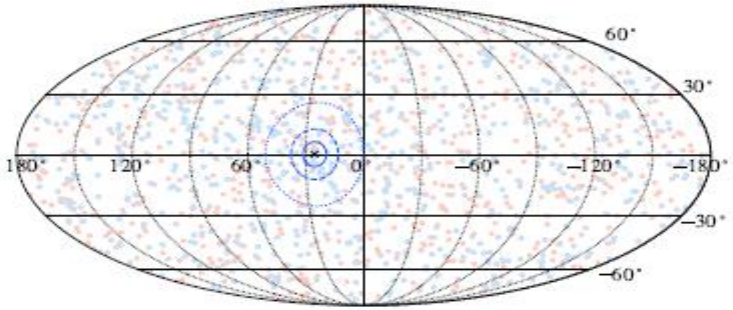
(b) the Nakazato model



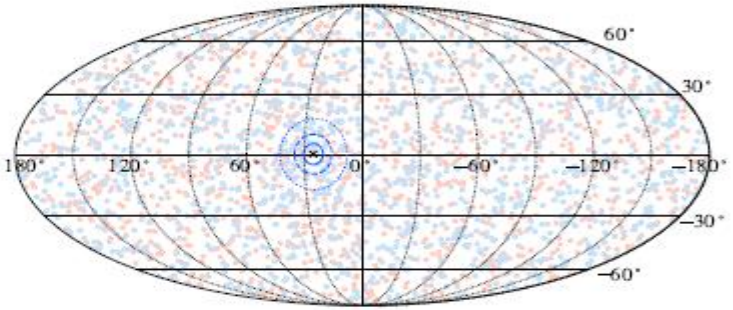
(c) the Mori model



(d) the Hüdepohl model



(e) the Fischer model



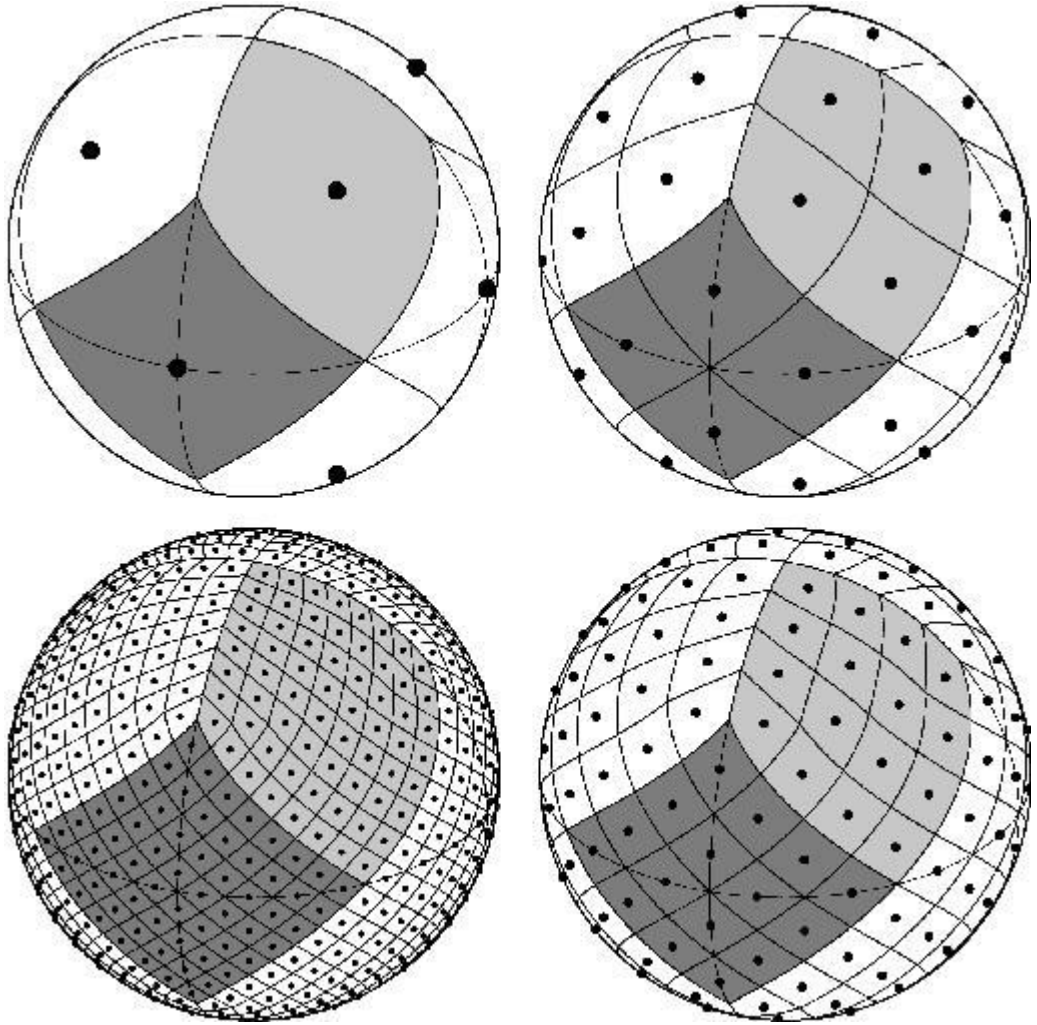
(f) the Tamborra model

Achieved 3-7 degree resolution for 10kpc SN

*** For Wilson model, we have achieved 3 degree resolution**

Faster and more accurate

- Original fitter has 2 steps;
  - Initial grid search
  - Maximum Likelihood fit
- In both steps, we needed many loops which runs all burst events to get difference between a trial SN direction and each event direction.
  - Takes ~ 5min for 10kpc burst
- New fitter
  - Grid search -> HEALPix spheres
  - Event loops -> put them into vectors
  - To implement them, Phython is used since it has many useful packages

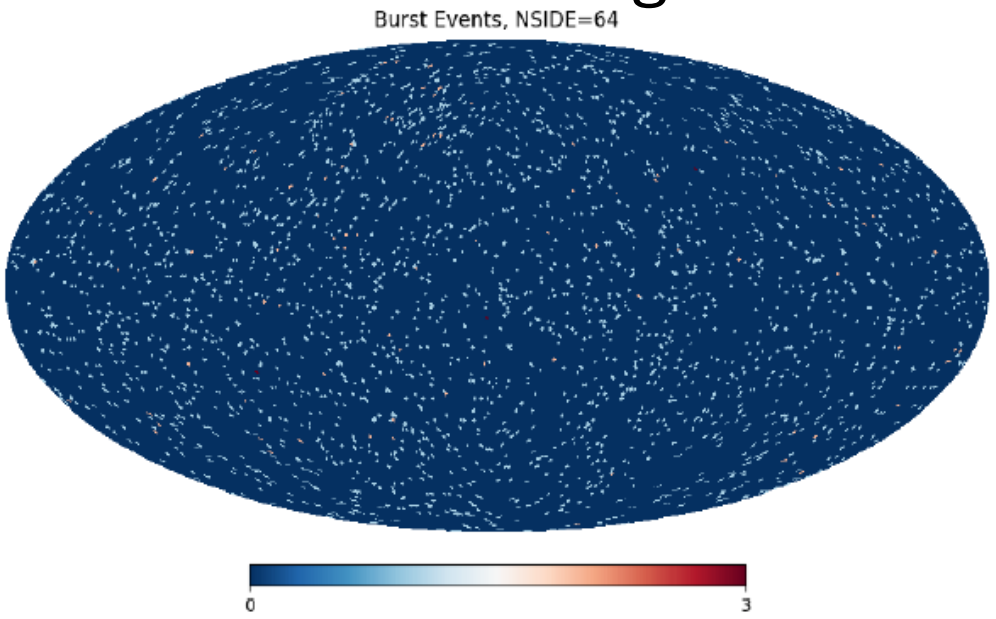


https://healpix.sourceforge.io/

New direction fitter using HEALPix

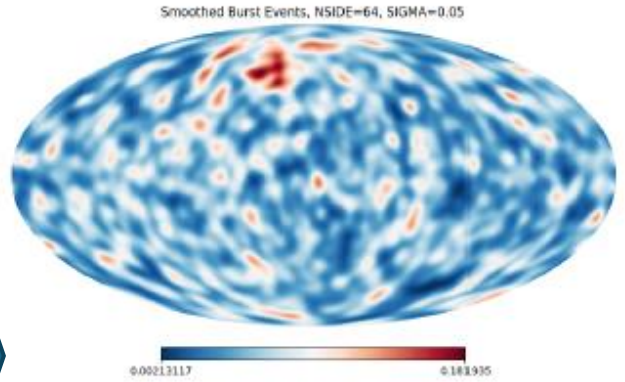
- Very simple!
  - Plot event direction to HEALPix sphere with Gaussian smearing
  - Find a pixel with maximum content

No smearing

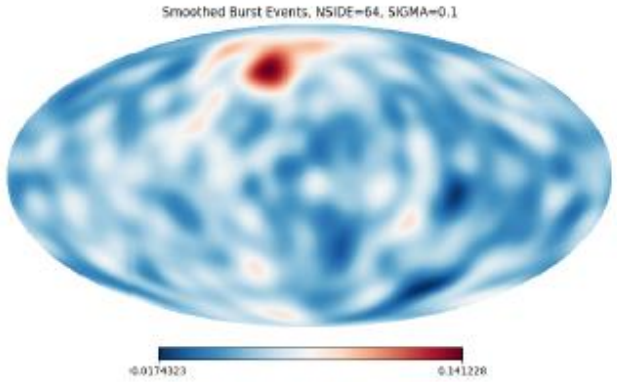


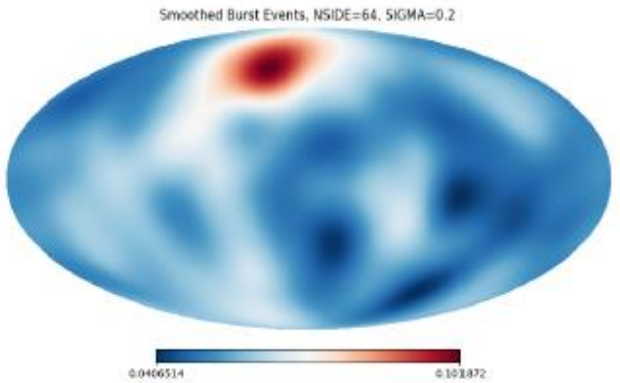
Number of pixels : 49152

Smearing width: 0.05rad

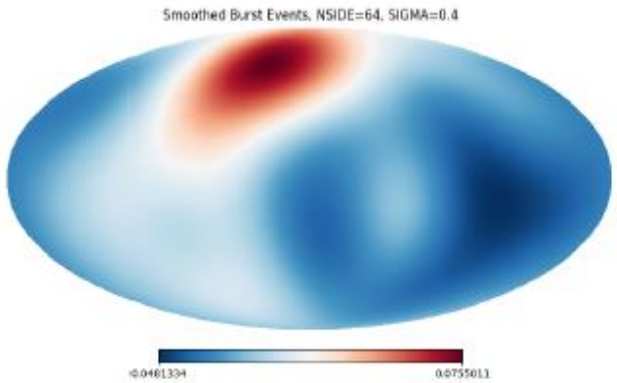


Smearing width: 0.1rad





Smearing width: 0.2rad

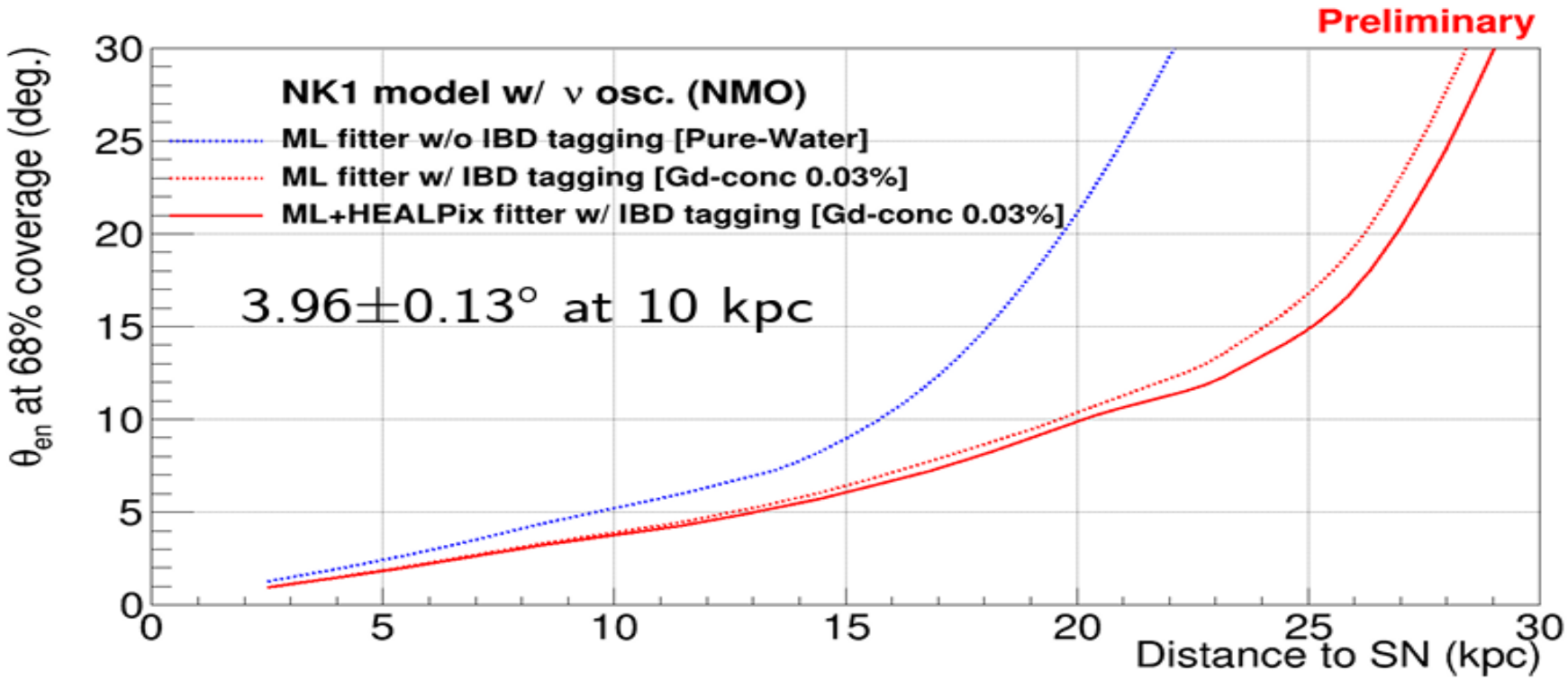


Smearing width: 0.4rad

Great improve!

Paper in preparation

method	Direction Reconstruction Times (sec) 3000 events	10,000 events	60,000 events
ML-fitter (2021)	~300	~600	~1320
HP-fitter	0.36	0.36	0.35
ML-fitter (2022)	1.00	2.21	11.12



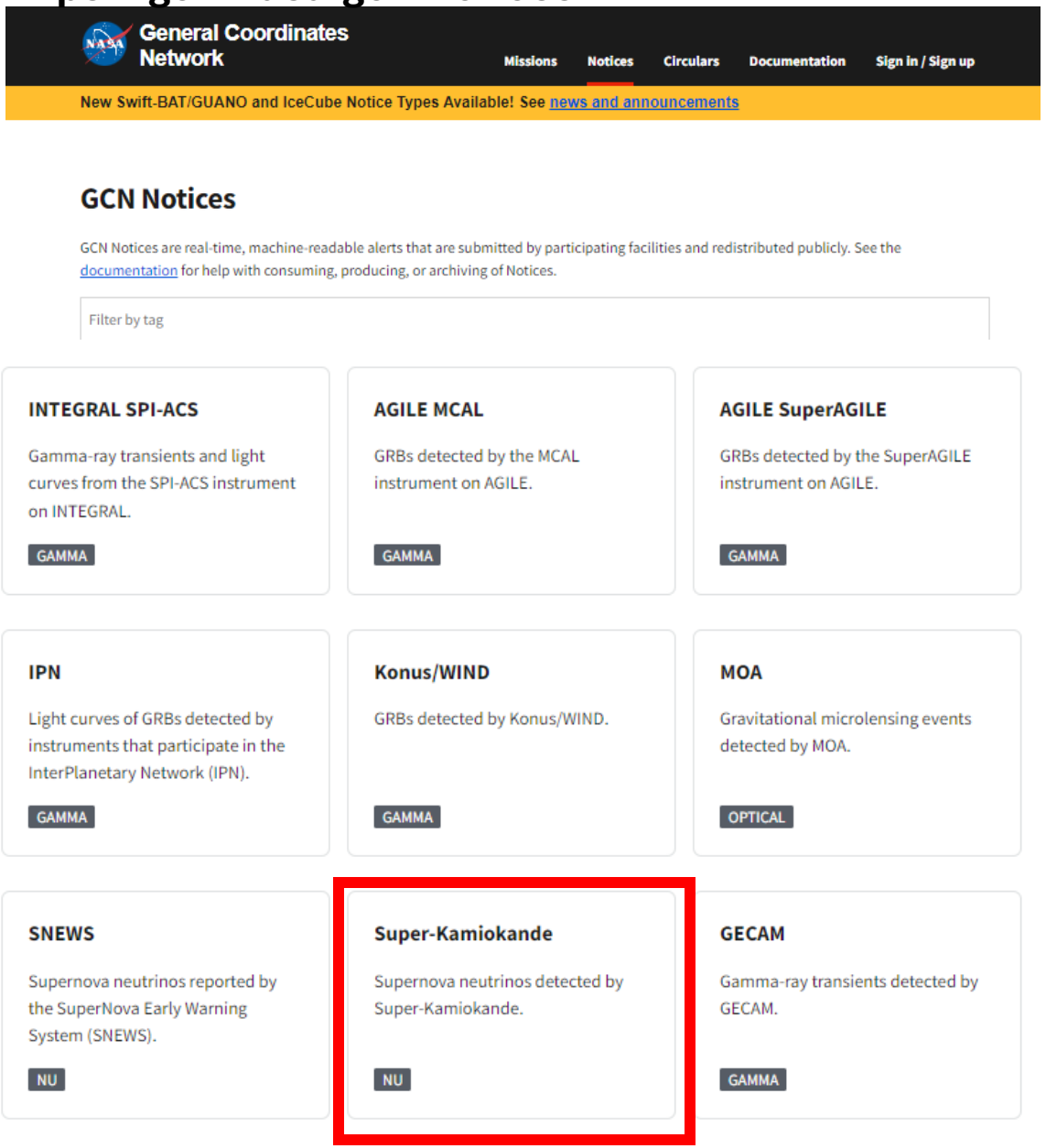
Automatic GCN Notice

Real SN signals :
IBD interaction ~90％
Cosmic spallation background
Less neutron compared to real SN

We can reject most of backgrounds by applying :
# of IBD tagged events > 10 events

We are now able to skip human checks before sending an SN alert

https://gcn.nasa.gov/notices

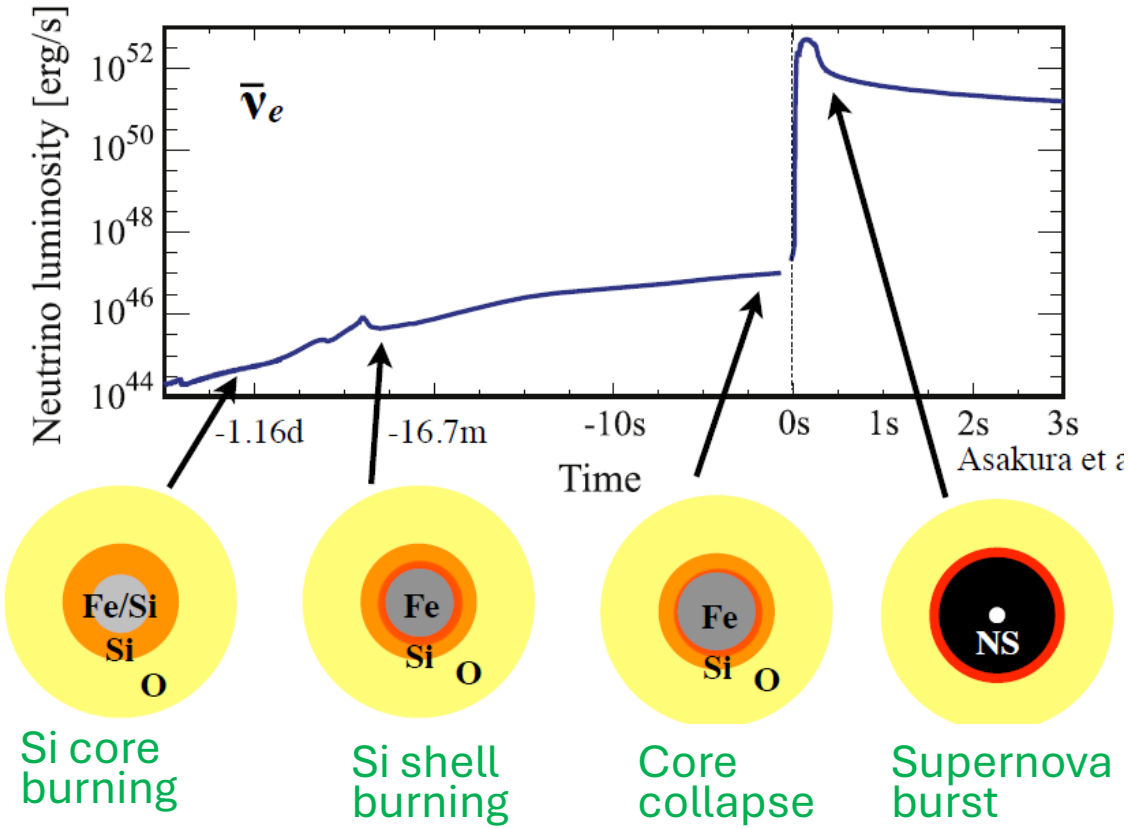


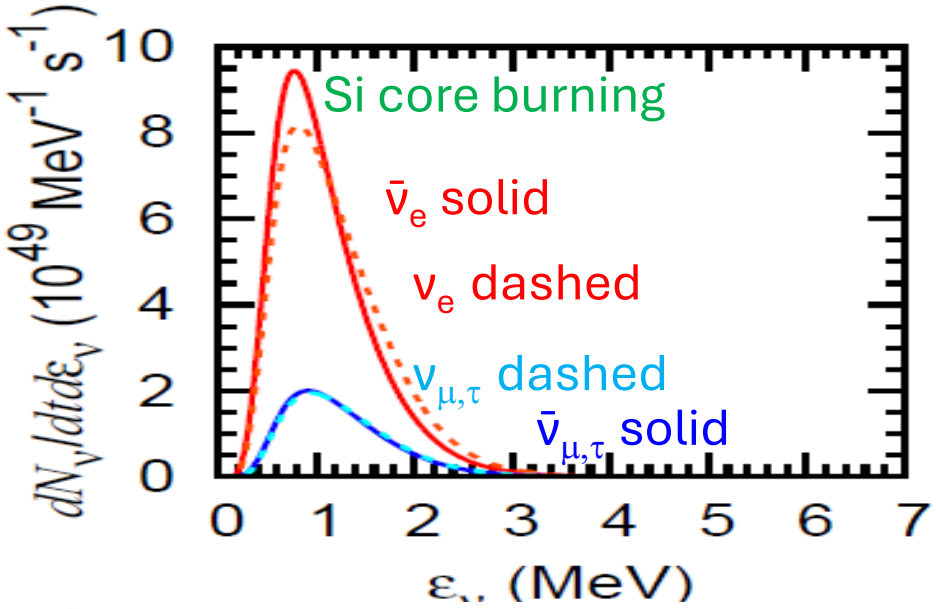
Please register the GCN/SK_SN Notice

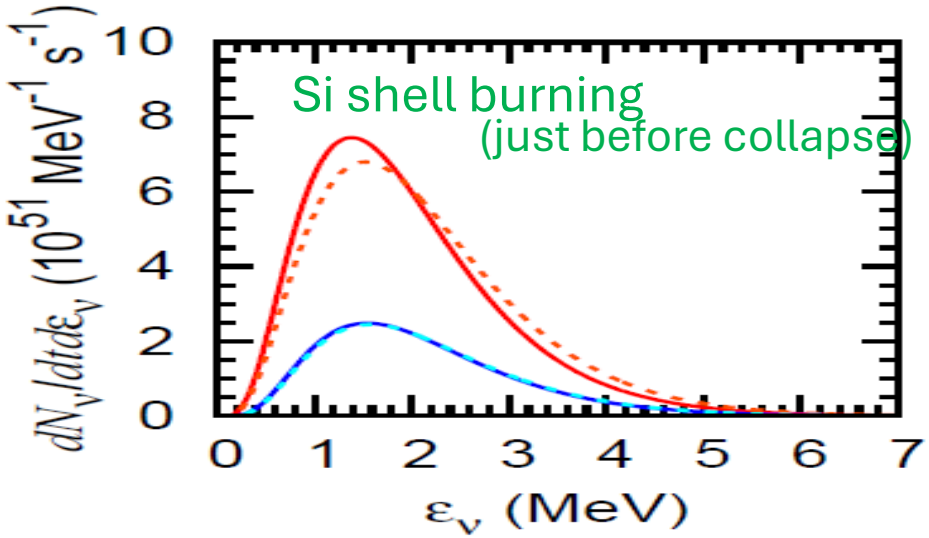
Pre-SN neutrinos from very close SN (~100pc)

A.Odrzywolek, M.Misiaszek, M.Kutschera, AIP Conf. Proc. 944, 109(2007)
T. Yoshida et al., Phys. Rev. D93 (2016) no.12, 123012.

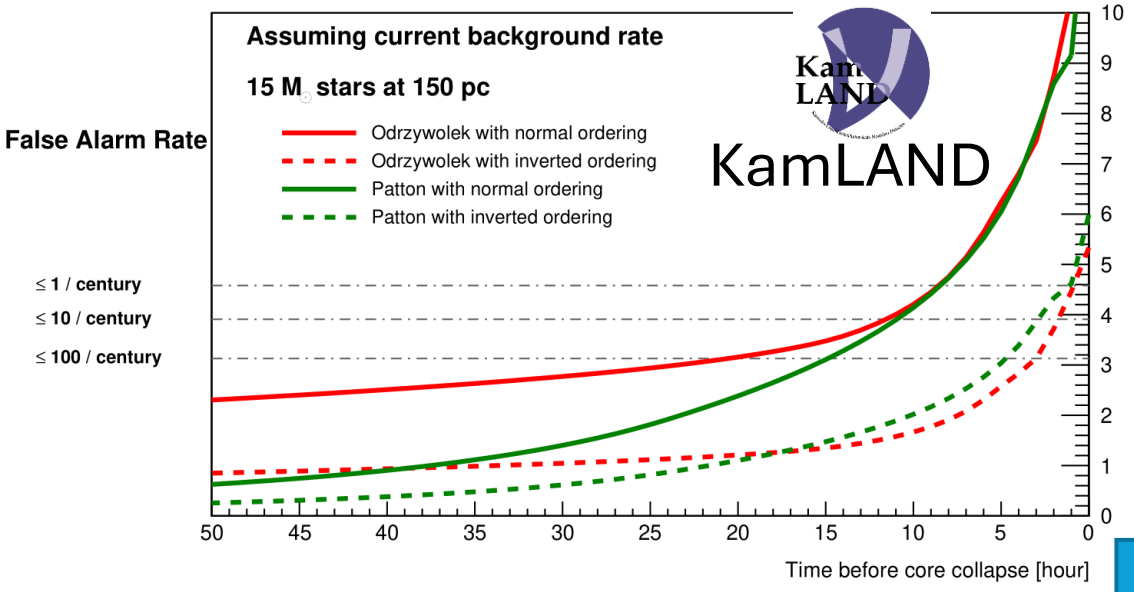
Burning phases of $15M_{sun}$

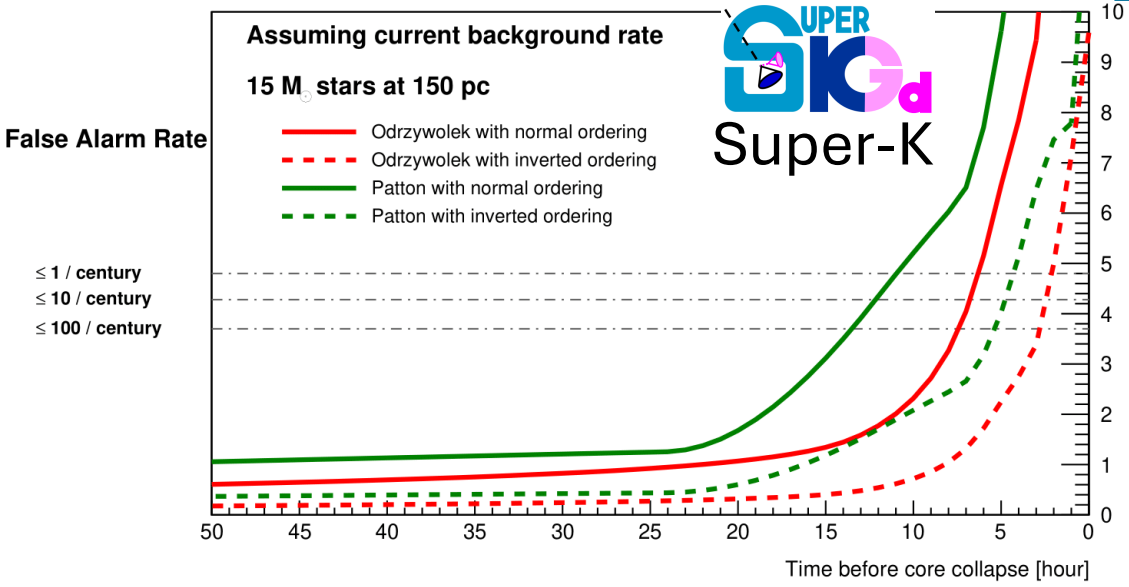




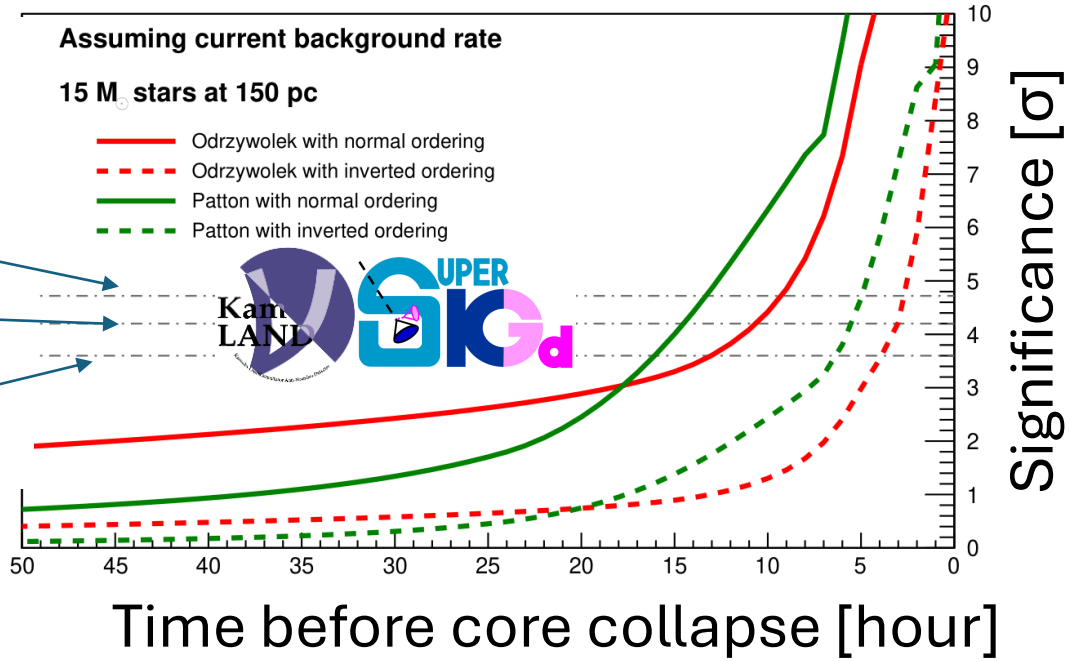


KL, SK, (KL+SK) sensitivity



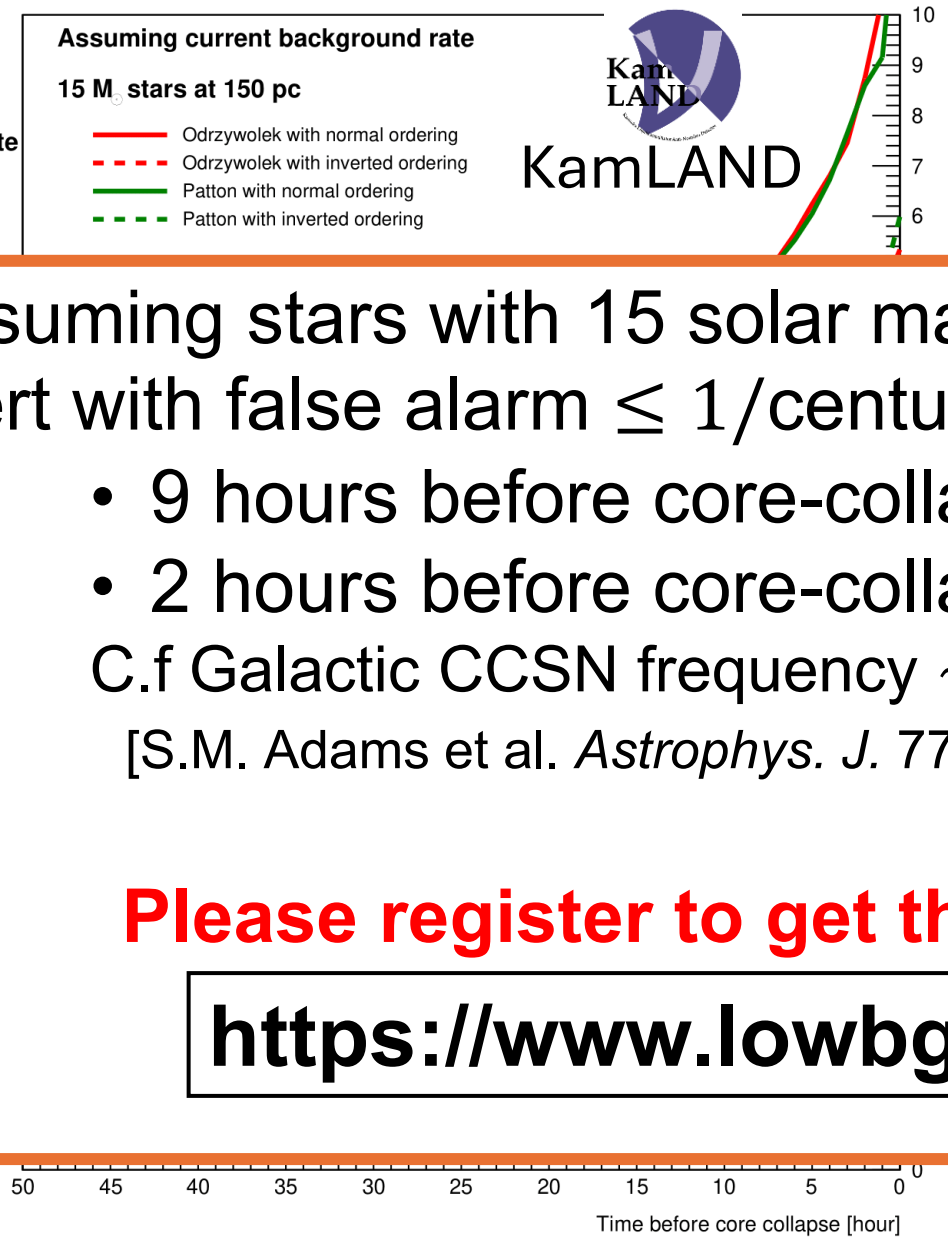


False Alarm Rate
1/100年
1/10年
1/1年



- KamLAND can resolve a signal early because of low background rate.
- Super-K's large size help increasing significance.
- **Combined**: Taking advantages from KL & SK

KL, SK, (KL+SK) sensitivity



Assuming stars with 15 solar mass at 150 pc (Betelgeuse)

Alert with false alarm ≤ 1/century can be issued：

- 9 hours before core-collapse, for all models with NMO
- 2 hours before core-collapse, for all models with IMO

C.f Galactic CCSN frequency ~ 3.2 per century

[S.M. Adams et al. *Astrophys. J.* 778 (2013)]

Please register to get the alert from our system

https://www.lowbg.org/presnalarm/

SK

New DAQ system to avoid errors for very close SN

- In case of Betelgeuse (~100pc) , we can expect tens of million events at SK
  - Maximum trigger rate will be tens MHz

DAQ might have trouble!

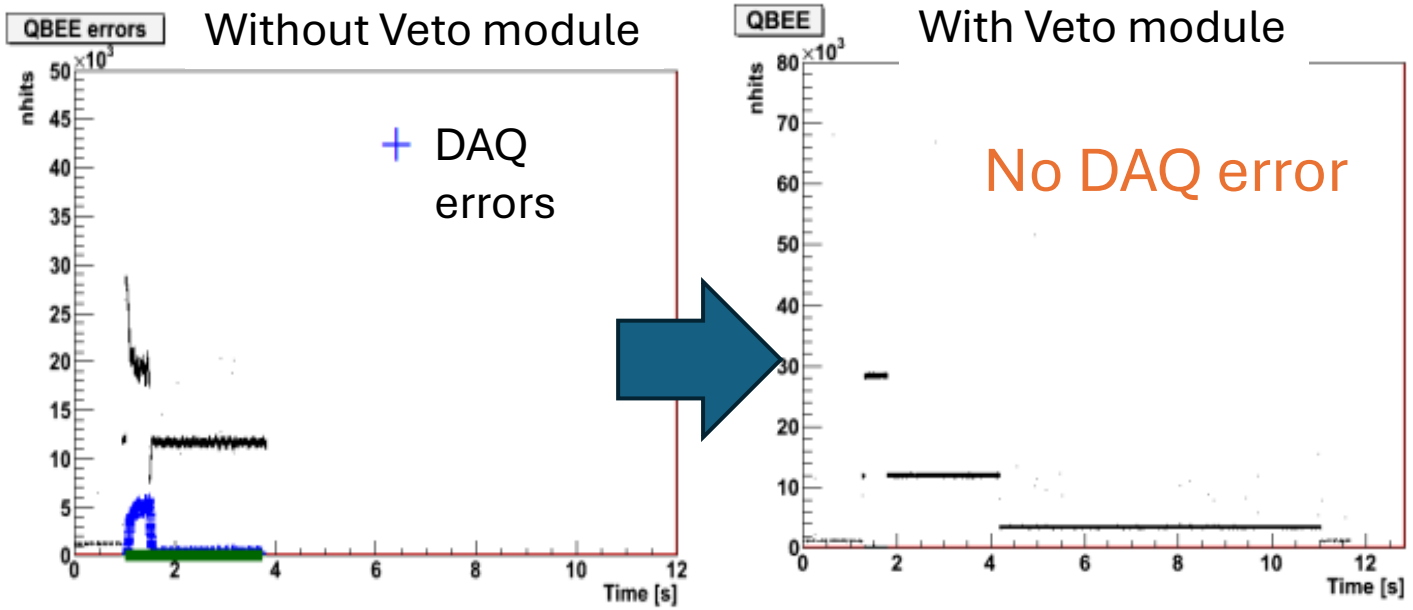
- Development of new DAQ system
  - SN module :
    Independent from the main DAQ
    detect SN using only hit information
  - Veto module:
    Using SN module signal,
    reduce the event rate by pre-scaling triggers depending on the SN size.

- **DAQ will not hang up with tens of MHz event rate!**

Mori et al. Prog. Theor. Exp. Phys. 2024, 103H01

Newly developed VETO module

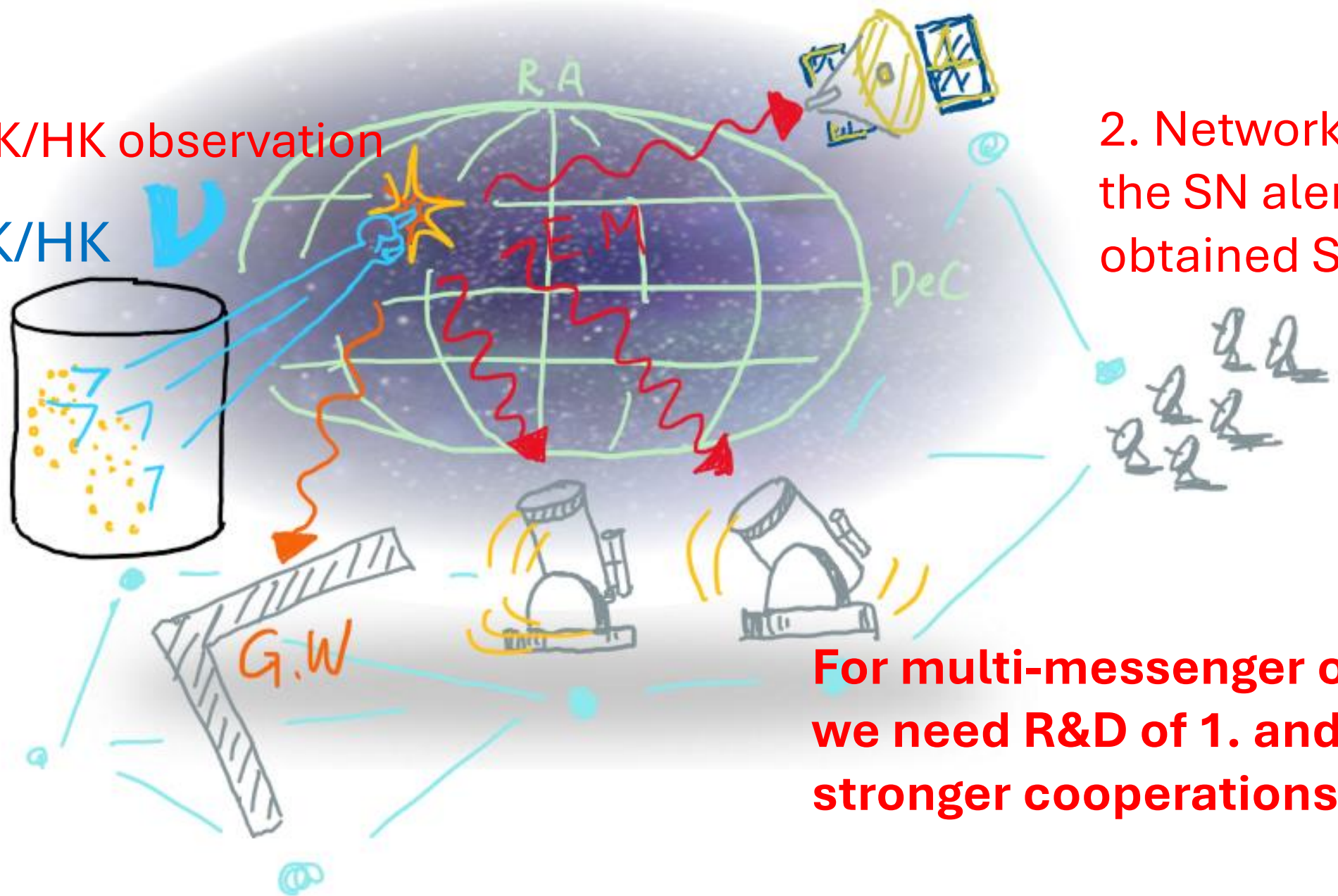
Laser Diode test to simulate SN burst signals at SK tank



Burst time ~ 10sec

For Multi-Messenger Observation of SN

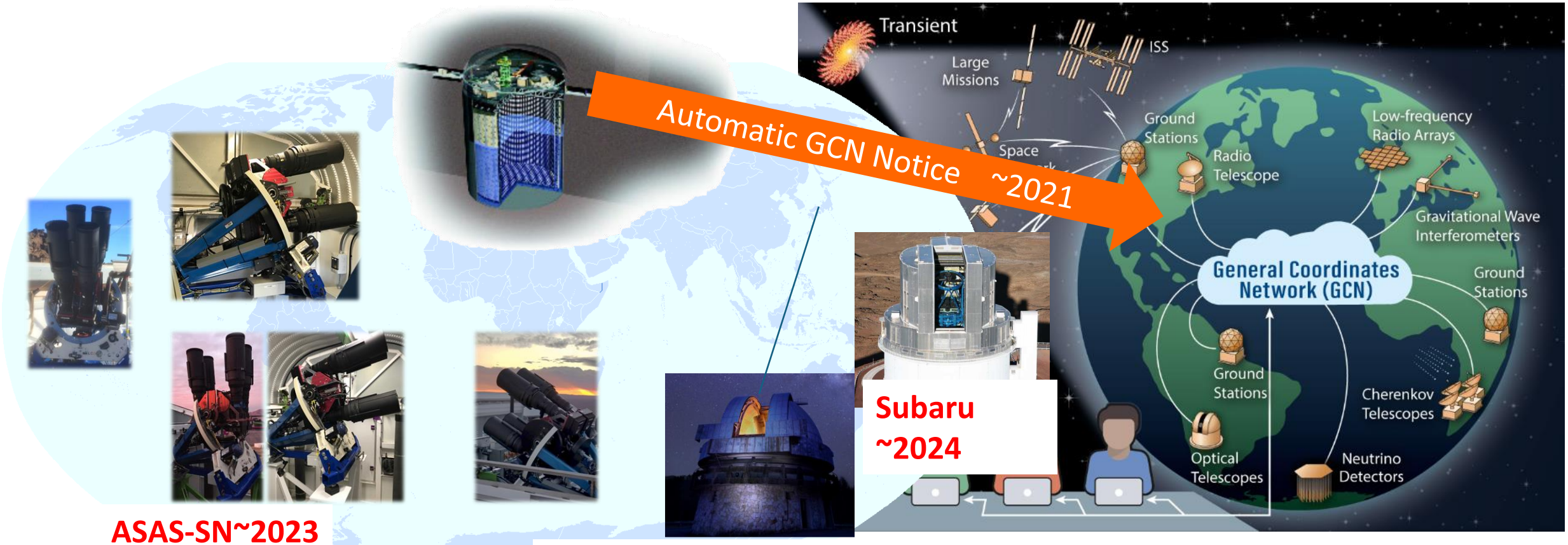
1. SK/HK observation



2. Network to share the SN alert including obtained SN direction

For multi-messenger observation, we need R&D of 1. and 2. with stronger cooperations.

Cooperation with optical telescopes



Actual latency is from a neutrino observation to set telescopes in the direction

We will continue to strengthen our cooperations

With Xray telescopes

Slide from Uchida san(Kyoto U)

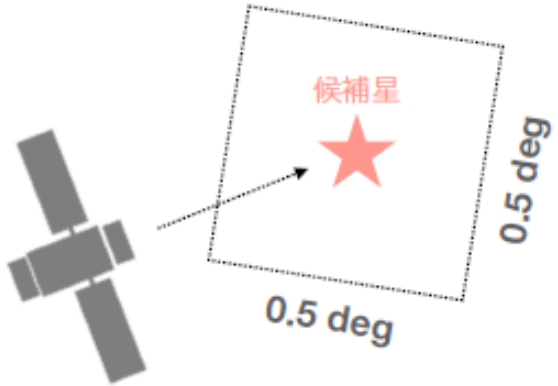
Discusstion has just started!

XRISM 2023~

Chronos 2030年代

0.1 kpc

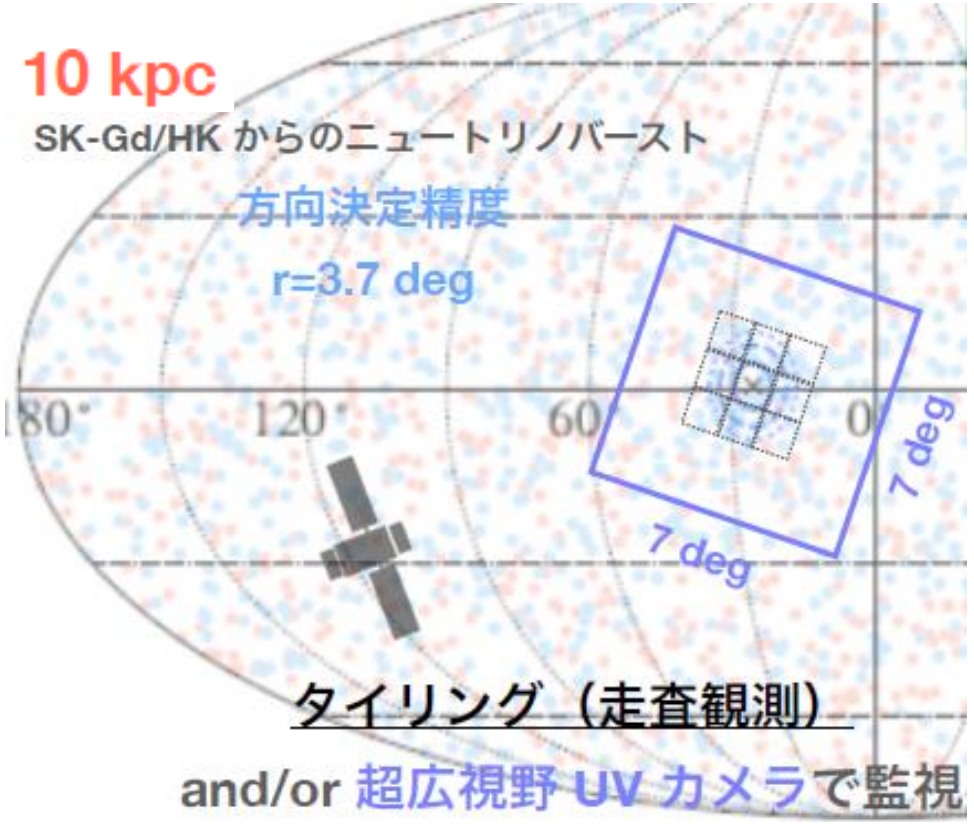
KamLAND/SK からの Si 燃焼前兆ニュートリノ



ポインティング観測

10 kpc

SK-Gd/HK からのニュートリノバースト



タイリング（走査観測）

and/or 超広視野 UV カメラで監視

遠方（> 10 kpc）で起きた場合は広視野モニタが有効。

XRISM: Xtend (0.5 deg × 0.5 deg)

Chronos: X線カメラ (0.5 deg × 0.5 deg) + UV カメラ (7 deg × 7 deg)

超新星に限らず、マルチメッセンジャー天体の初期放射には紫外線が使える。

広視野の紫外線モニタが有効。Chronos には搭載予定。

More cooperation needed!

So far, we are making effort to make partnership between SK and each telescope

Now we need more cooperation between telescopes to share information during SN observation

Hyper Kamiokande

- Upgrade of Super-Kamiokande (SK)
  - 260 kton pure **water Cherenkov** detector
  - **~8.4 times larger** fiducial volume
- Construction started in 2020, operation from 2027~
- Main physics targets:
  Neutrino oscillation, proton decay, neutrino astronomy (supernova etc.)

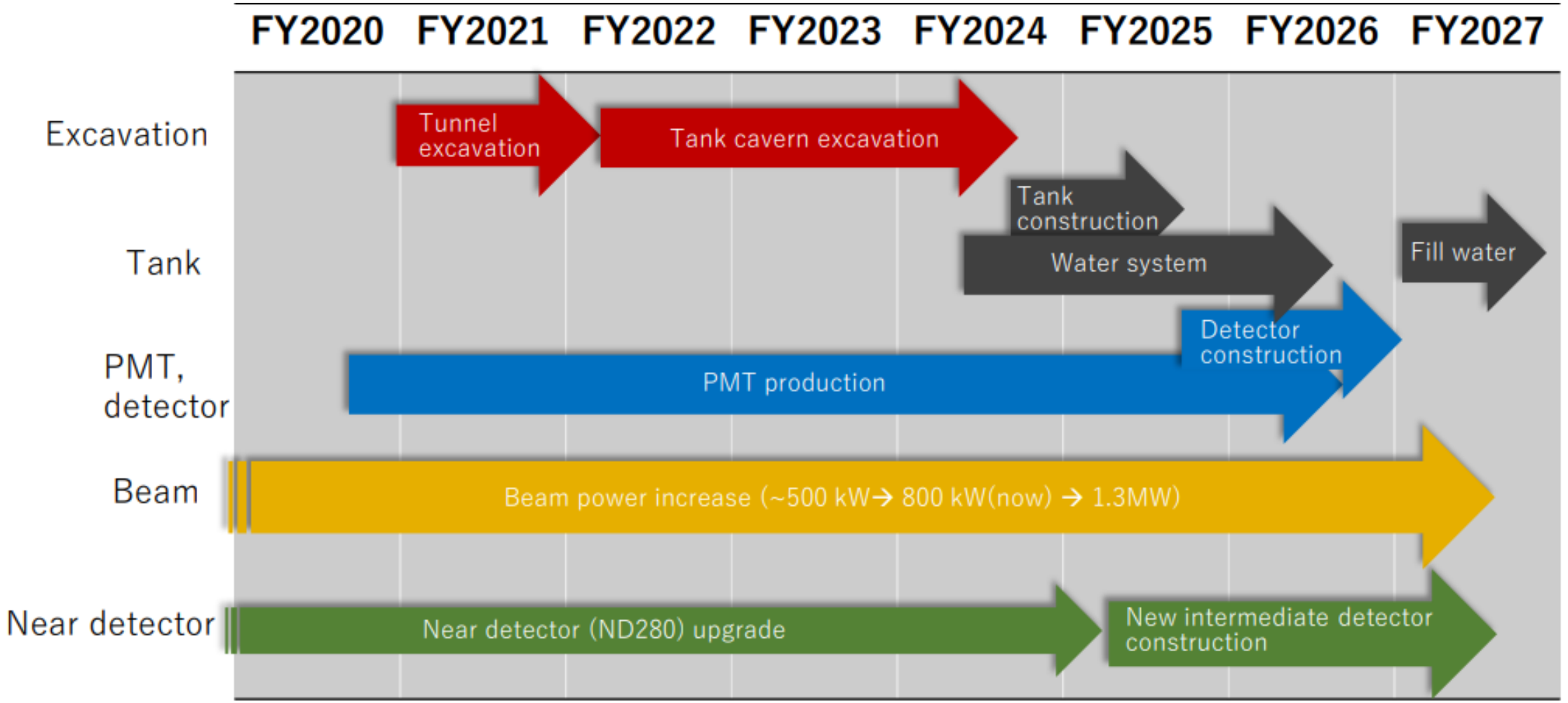
Kamiokande
(1983~1996)
3 kton

Super-Kamiokande (1996~)
50 kton, 40% PMT coverage

Hyper-Kamiokande (2027~)
260 kton, 20% PMT coverage

Construction schedule

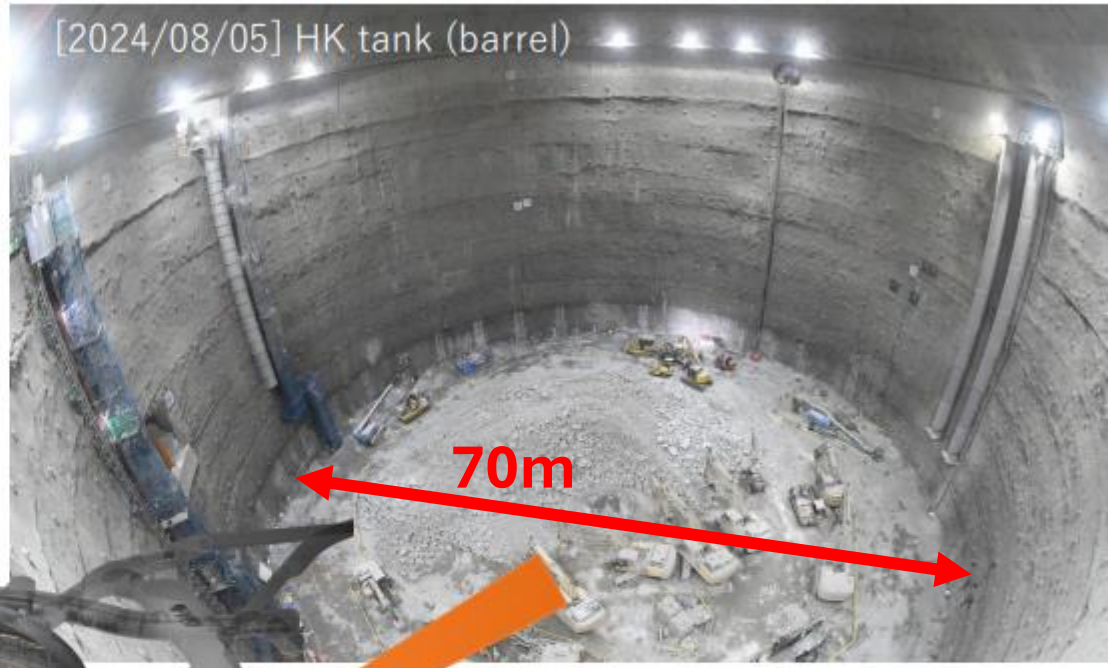
- We will start observation in 2027.
  - Now we are very final stage of the excavation and preparation of the tank and water system construction



Construction schedule

- We will start observation in 2027.
  - Now we are very final stage of the excavation and preparation of the tank and water system construction

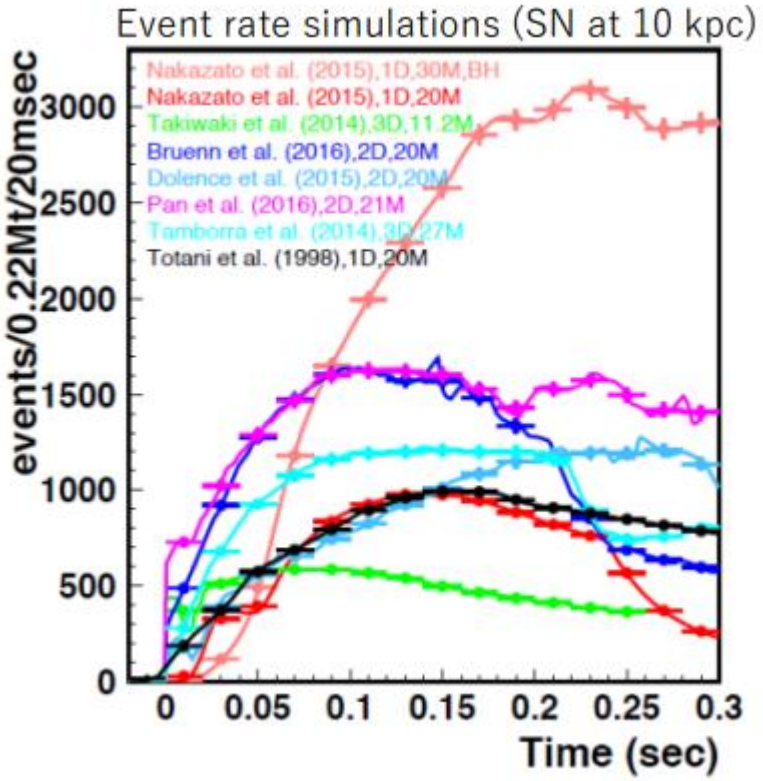
Water system room

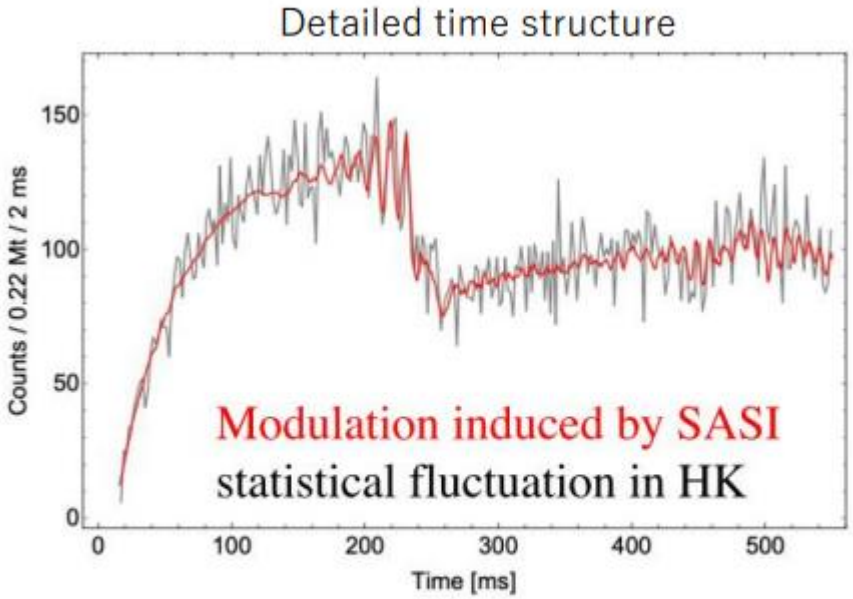


Main detector tank

SN burst observation with Hyper-K

- Large statistics：Can access to ~1 Mpc(Andromeda galaxy)
  - 20000~70000 events will be detected at 10 kpc SN
  - 1 degree pointing accuracy!
  - Distinguish explosion models from rate, energy variation in time





Summary

- SK Gd
  - Start observation with 0.03% Gd since 2022
- Many improvements of SN burst detection
  - Automatic GCN Notice has been installed
    - You can resister SK_SN notice
  - SN direction fitter improvement
    - SN direction accuracy : 3-6 degree (depending on models)
    - HP fitter and new ML fitter enable to send auto alert within 2min.
- Very close SN
  - Pre-SN neutrino monitor is now available
  - No DAQ trouble thanks to the new triggering system.
- Multi-Messenger Observation
  - Cooperations between other telescopes are getting stronger
- Hyper-K
  - Will start data taking in 2027. Excavation will finish soon. Then start the tank construction.
  - Thanks to the large statistics, we can achieve 1degree SN pointing accuracy