Summary of resent updates for SN burst detection at SK

M.Ikeda
(U Tokyo, ICRR)

For Super-Kamioiande Collaboration
@ 10th SN workshop (Okayama Univ.)

Contents:

Super-K experiment

1000m underground = 2600 m.w.e

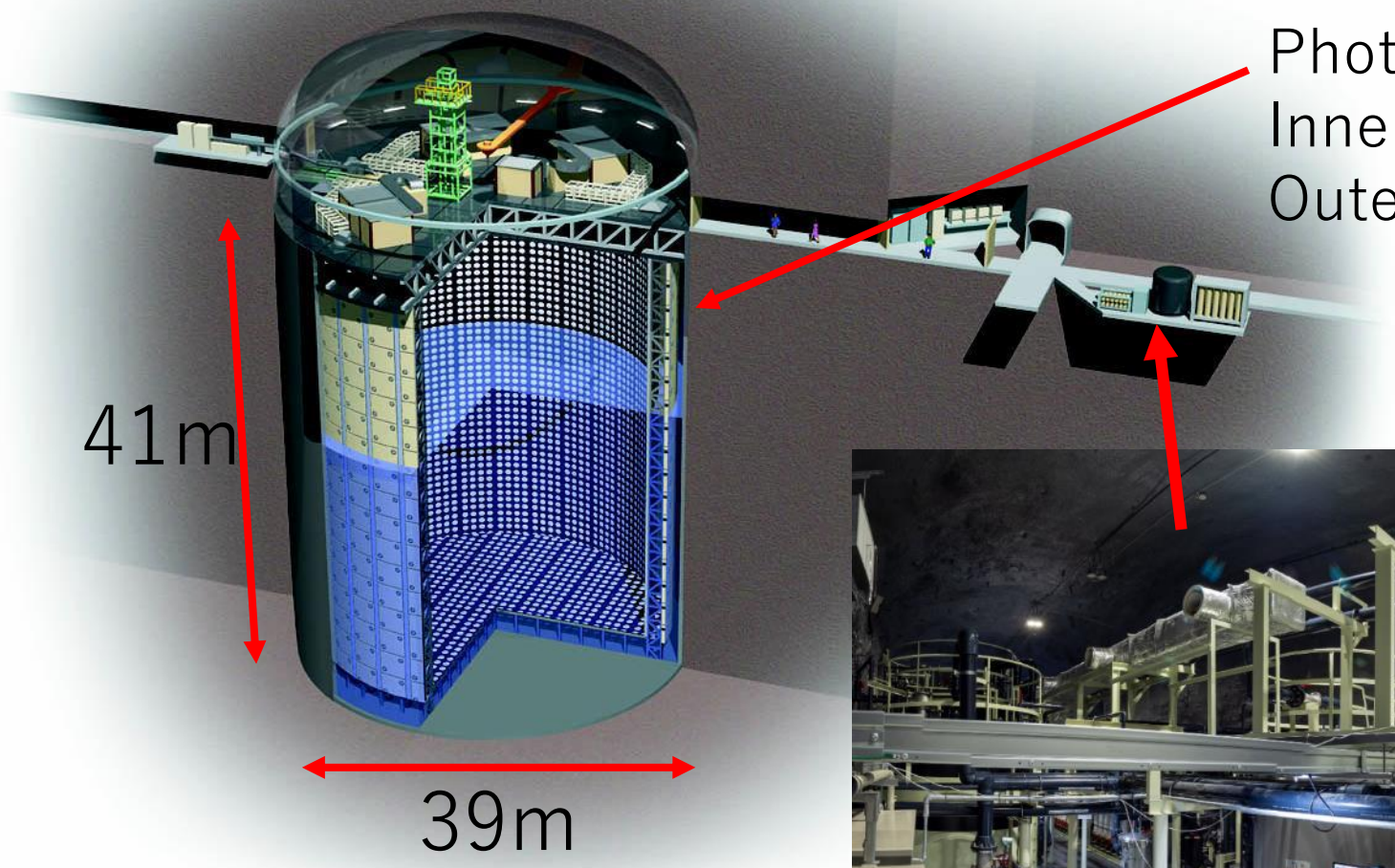


Photo sensors :
Inner detector: 11129 20inch PMTs
Outer detector: 1885 8inch PMTs

Gd water system room

SK-Gd project

Dissolving Gd to enhance detection capability of neutrons from ν interactions

Phys.Rev.Lett. 93 (2004) 171101

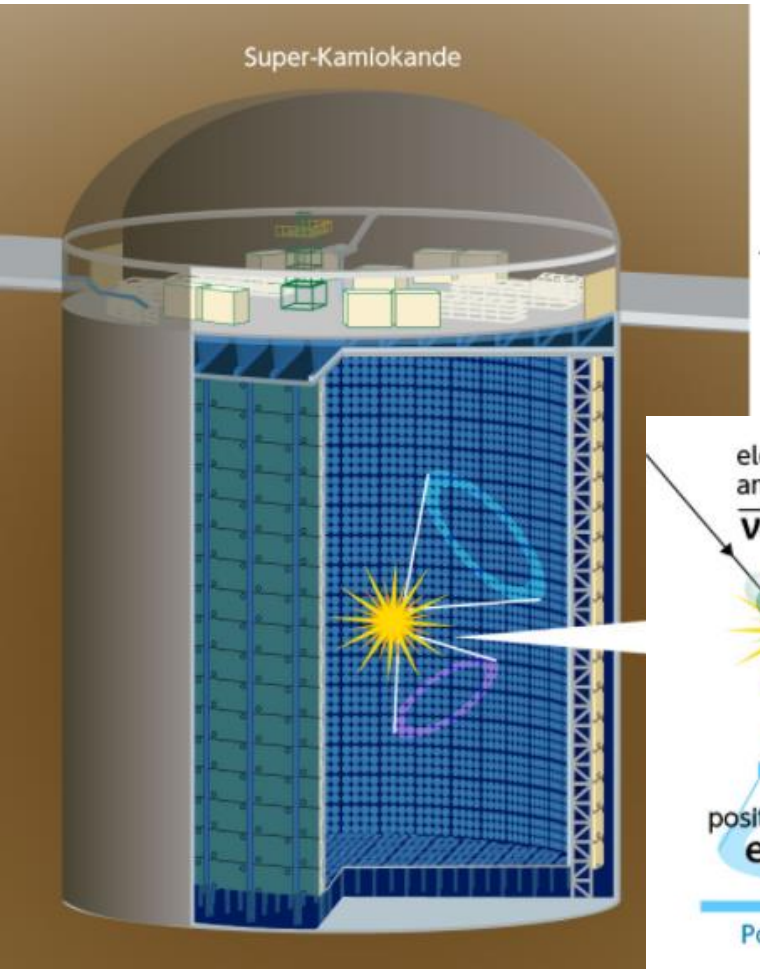
Physics targets:

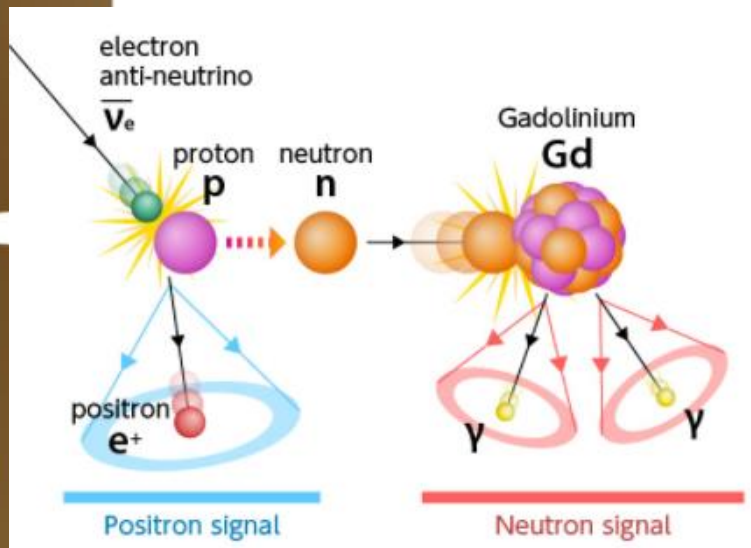
(1) Discovery of Supernova relic neutrino (or DSNB)

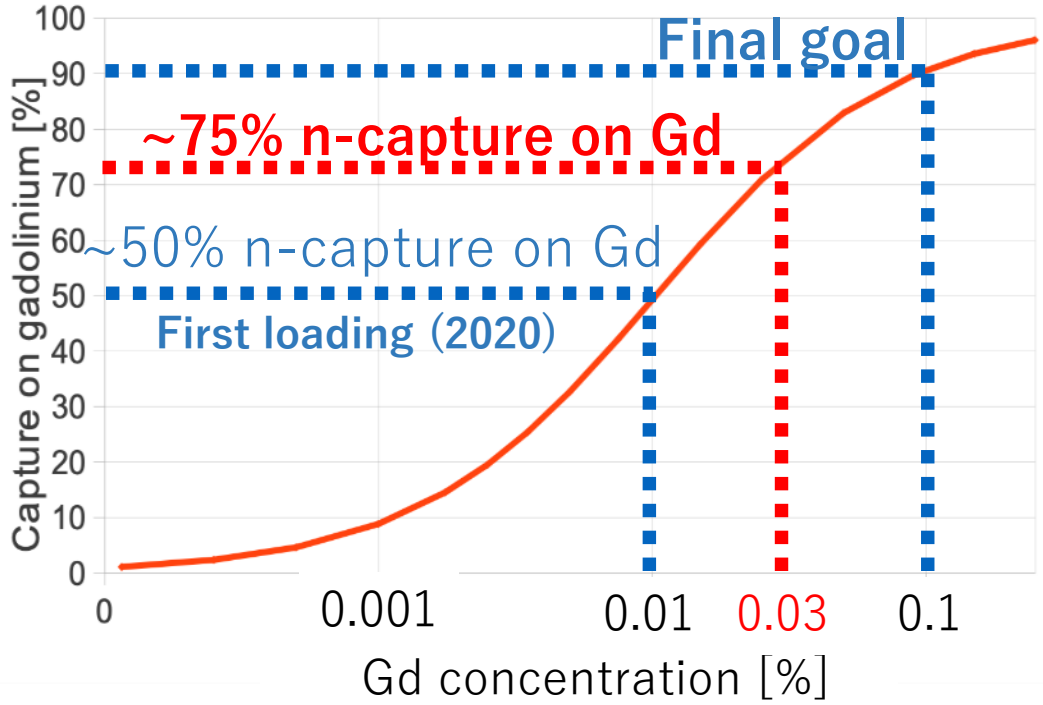
(2) Galactic supernovae (pointing accuracy, and pre-SN ν)

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

(4) Neutrino/anti-neutrino discrimination



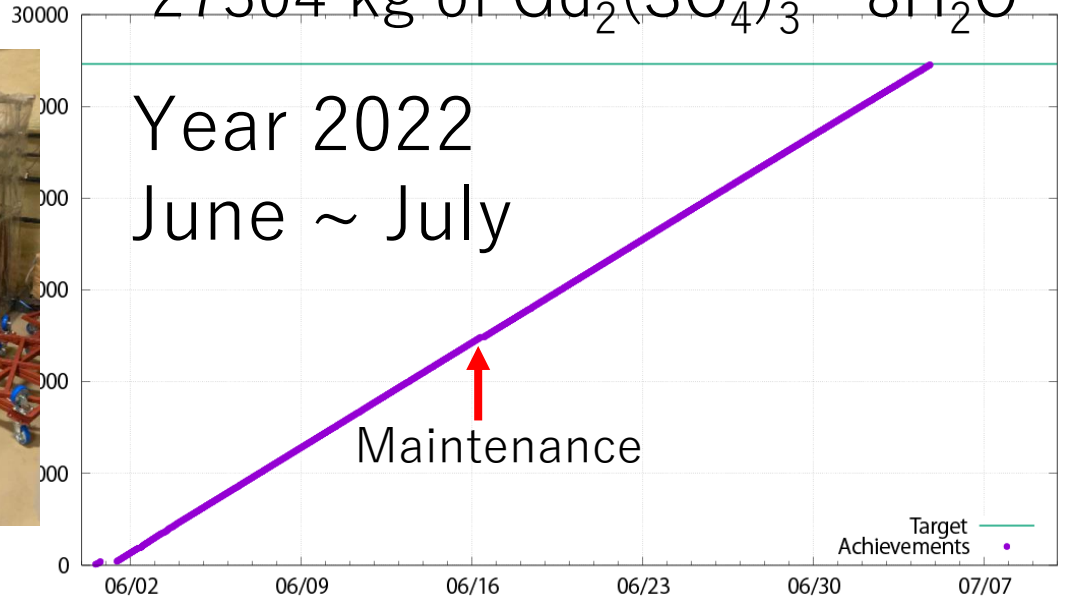




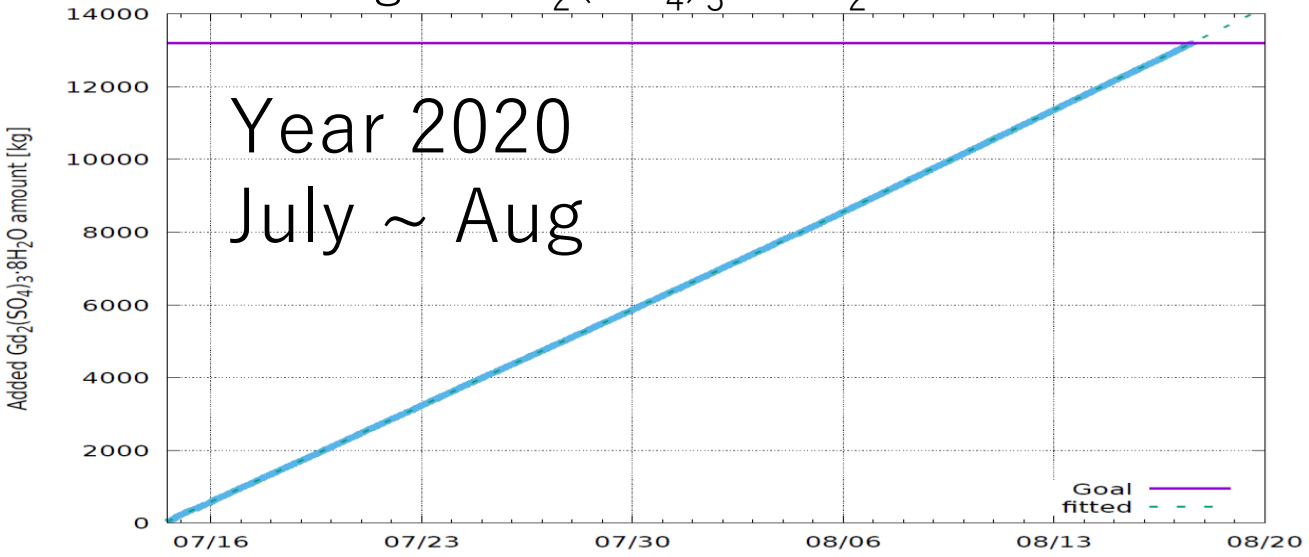
Gd loading in 2020 and 2022

Beginning of the dissolving work in 2022

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



12884 kg of $Gd_2(SO_4)_3 \cdot 8H_2O$



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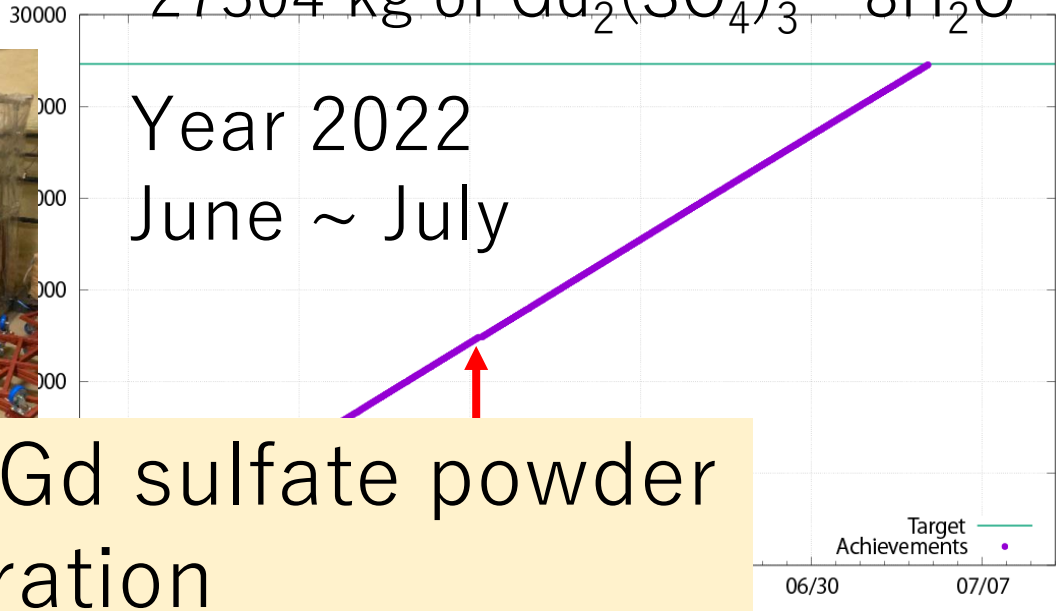
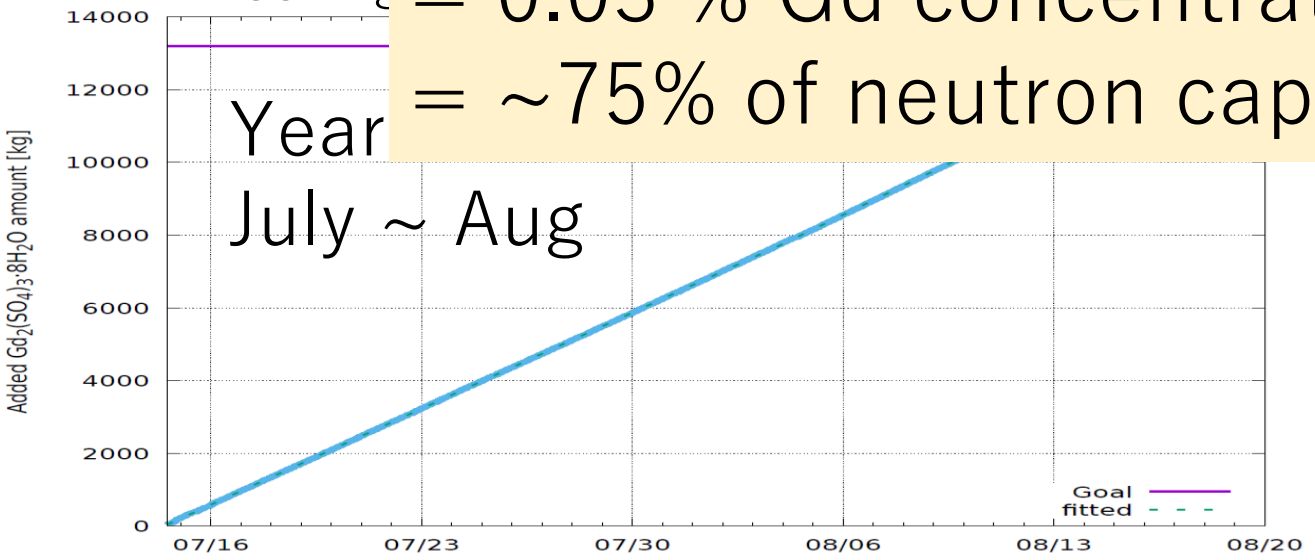


In total : ~40 tons of Gd sulfate powder
= 0.03 % Gd concentration
= ~75% of neutron capture by Gd

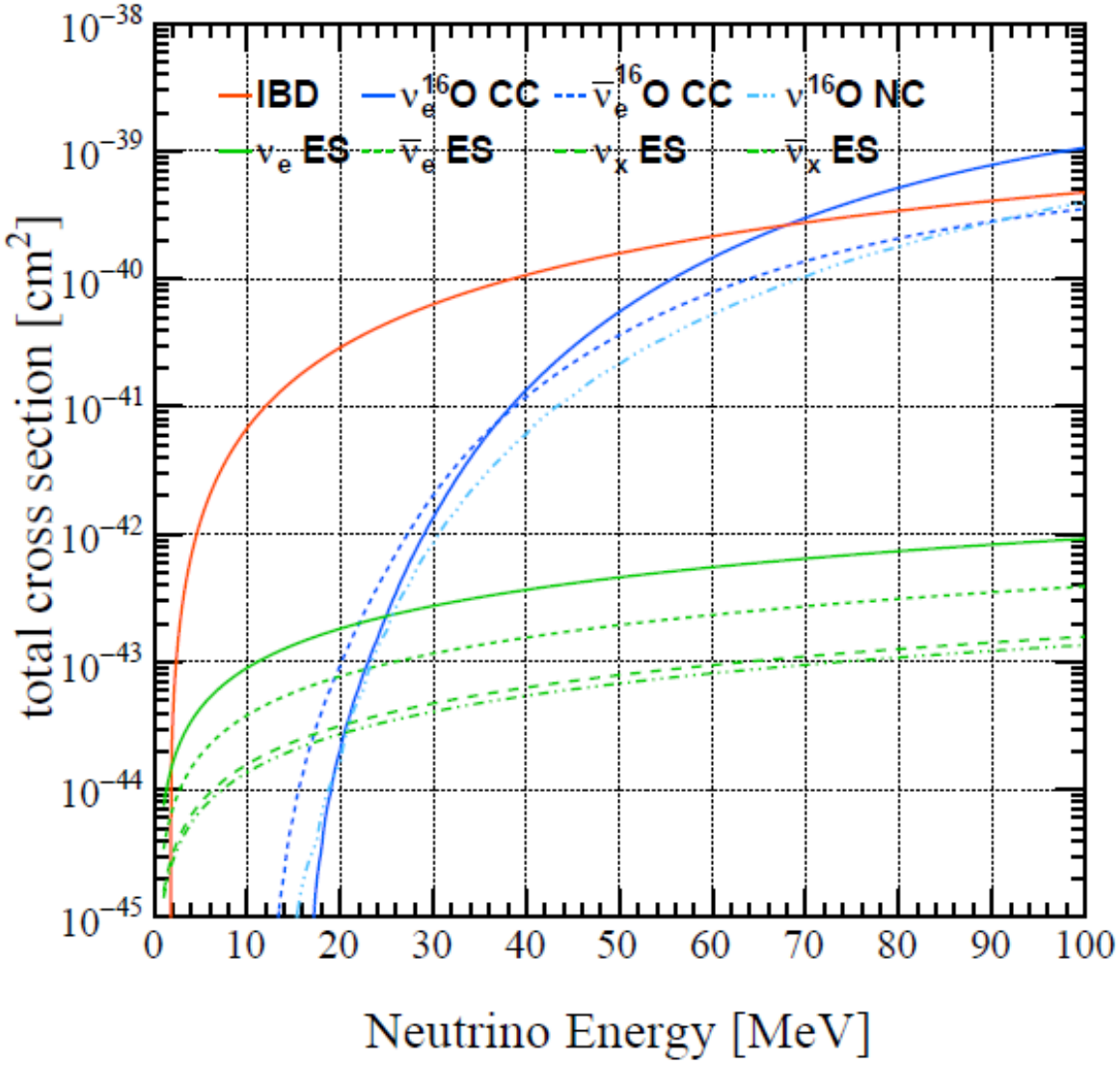
12884 kg



Detection of SN burst neutrinos

- Inverse Beta Decay (IBD)
  - ~90% of the expected interactions
- Electron Scattering (ES)
  - ~5% of the expected interactions
  - Keep the neutrino direction information
- 16O interactions (CC and NC)
  - ~5% of the expected interactions

Nakanishi san



Detection of SN burst neutrinos

B.Pointon

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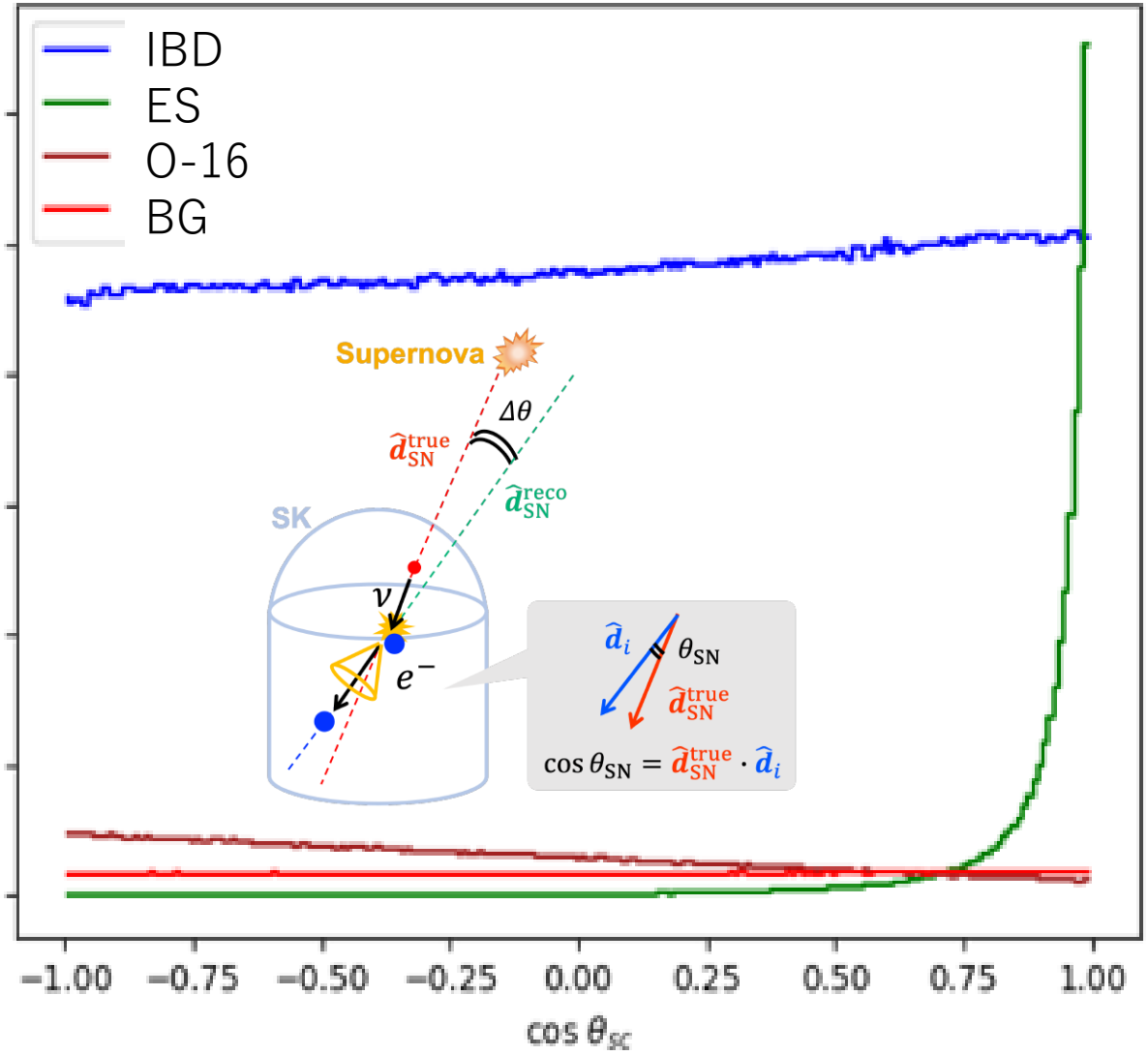


Supernova monitor at SK (Snwatch)

raw data

Software trigger

Triggered data

Offline processes

Realtime reconstruction

Processed data

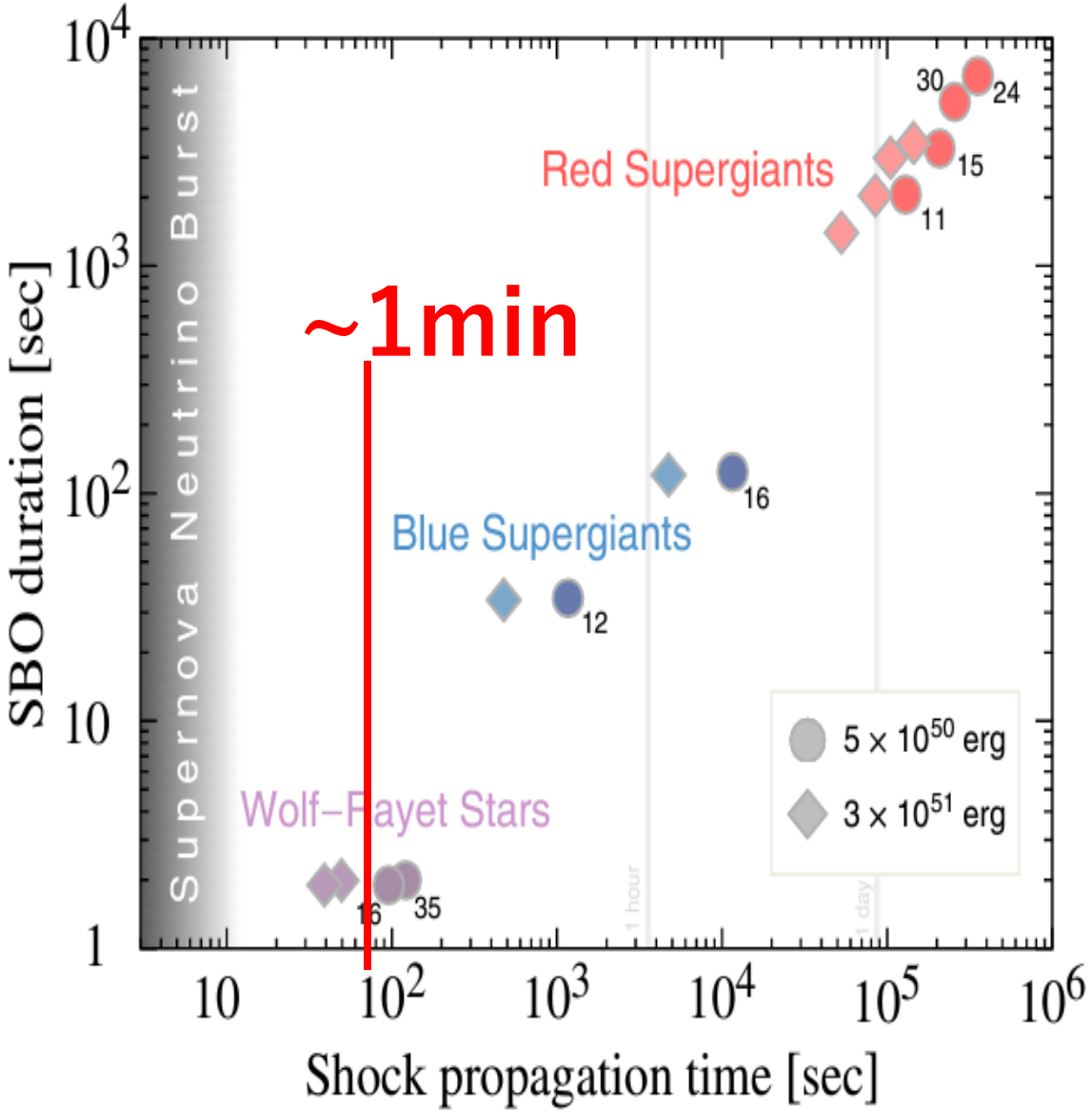
SNWatch
Search for event clusters

Alarm

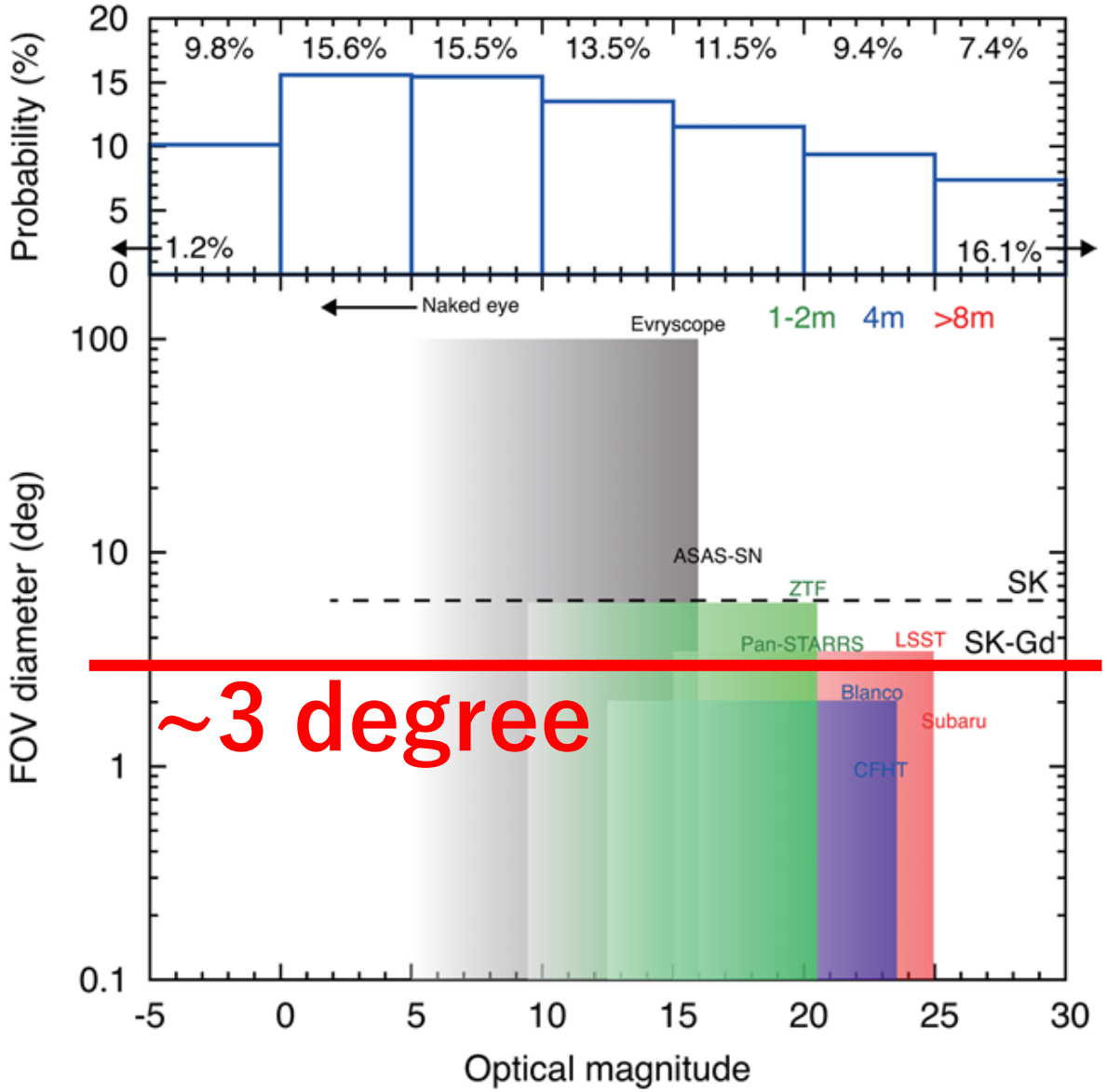
Fast analysis:
- vertex reconstruction
- direction reconstruction
- energy reconstruction
- **Inverse Beta Decay candidates selection**

Our requirement

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



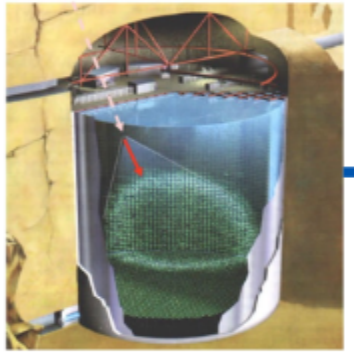
K.Nakamura et al. MNRAS461,3296–3313(2016)



Resent improvements of SN detection

- GCN Notice
  - G.Pronost (ILANCE/U Tokyo) et al.
- Study of SK performance for SN models
  - Kashiwagi san's (ICRR) talk at Last SN work shop
- SN direction fitter improvement
  - B.Pointon (UBTIT/TRIUMF) et al.
- Offline analysis
  - Nakanishi san (Okayama)
- Pre SN
  - SK+Kamland: Saito san (Tohoku)
- New DAQ system for very close SN
  - Mori san (NAOJ)

Automatic alert to GCN notice



raw data

Software trigger

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Realtime reconstruction

Processed data

Alarm flowchart

SNWatch

Search for event clusters

Event cluster found!

Uniform vertex distribution

Non-Uniform vertex distribution

Check cluster size

<25

Silent alarm

> 35

>25

Golden alarm

Normal alarm

~1 h

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

Call and mail to SK experts

~3.5 minutes at present (for 10kpc SN) aimed to be improved to **< 1 minute.**

# of IBD-tagged events > 10

Automated GCN notice

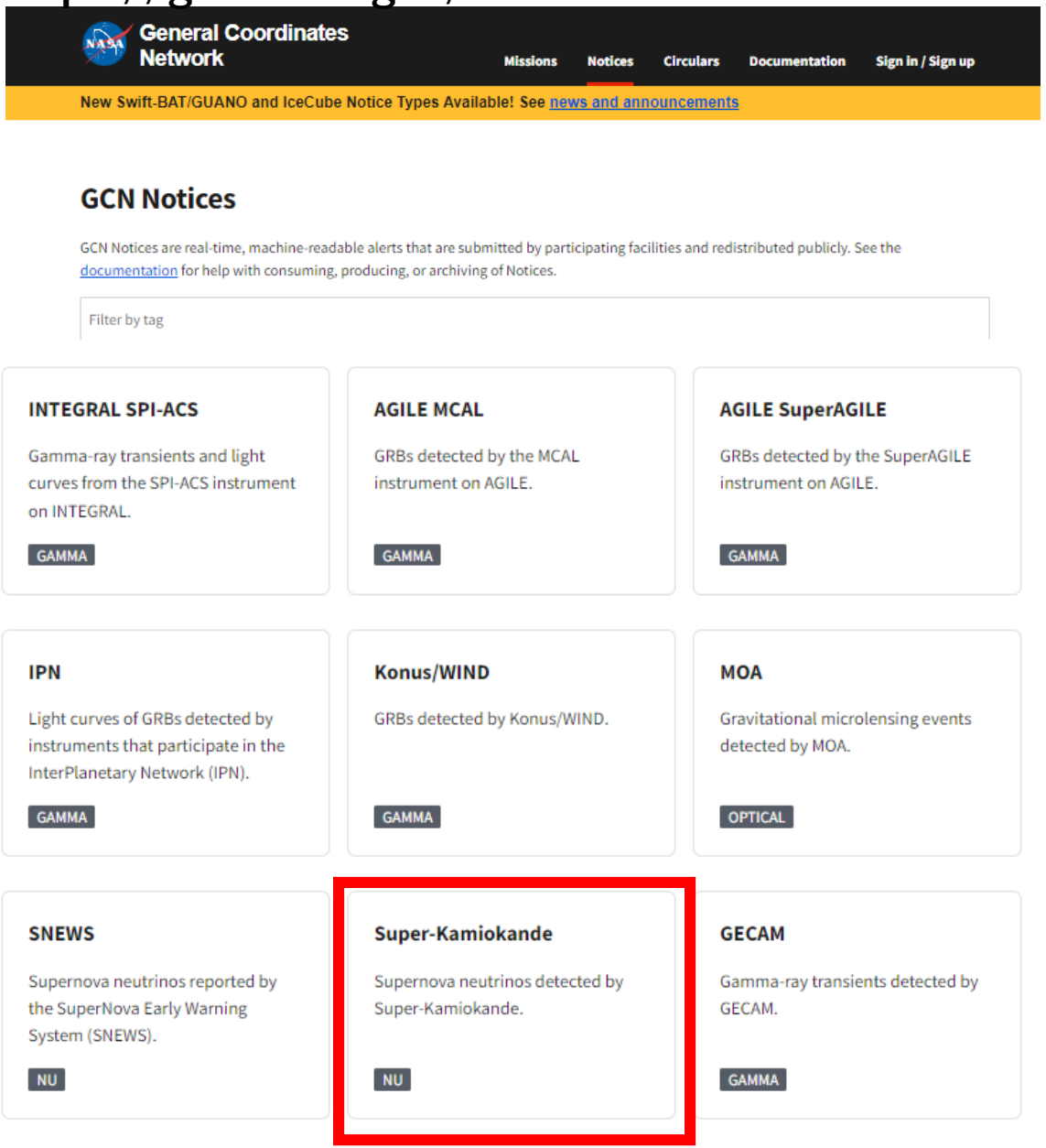
Automatic GCN Notice

Alarm probability
= Can make **automatic alarm**
if we observe significant number of n-tagged IBD events.

Automatic alarm:
GCN notice will be distributed automatically
~ few min after the observation.

Previously, it took ~1hour
after expert checks

https://gcn.nasa.gov/notices



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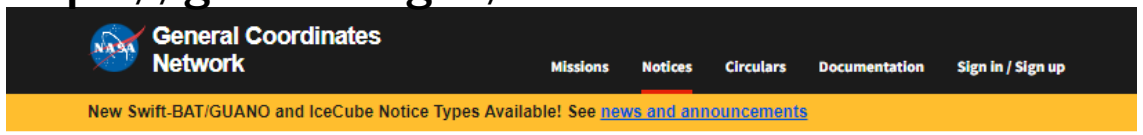


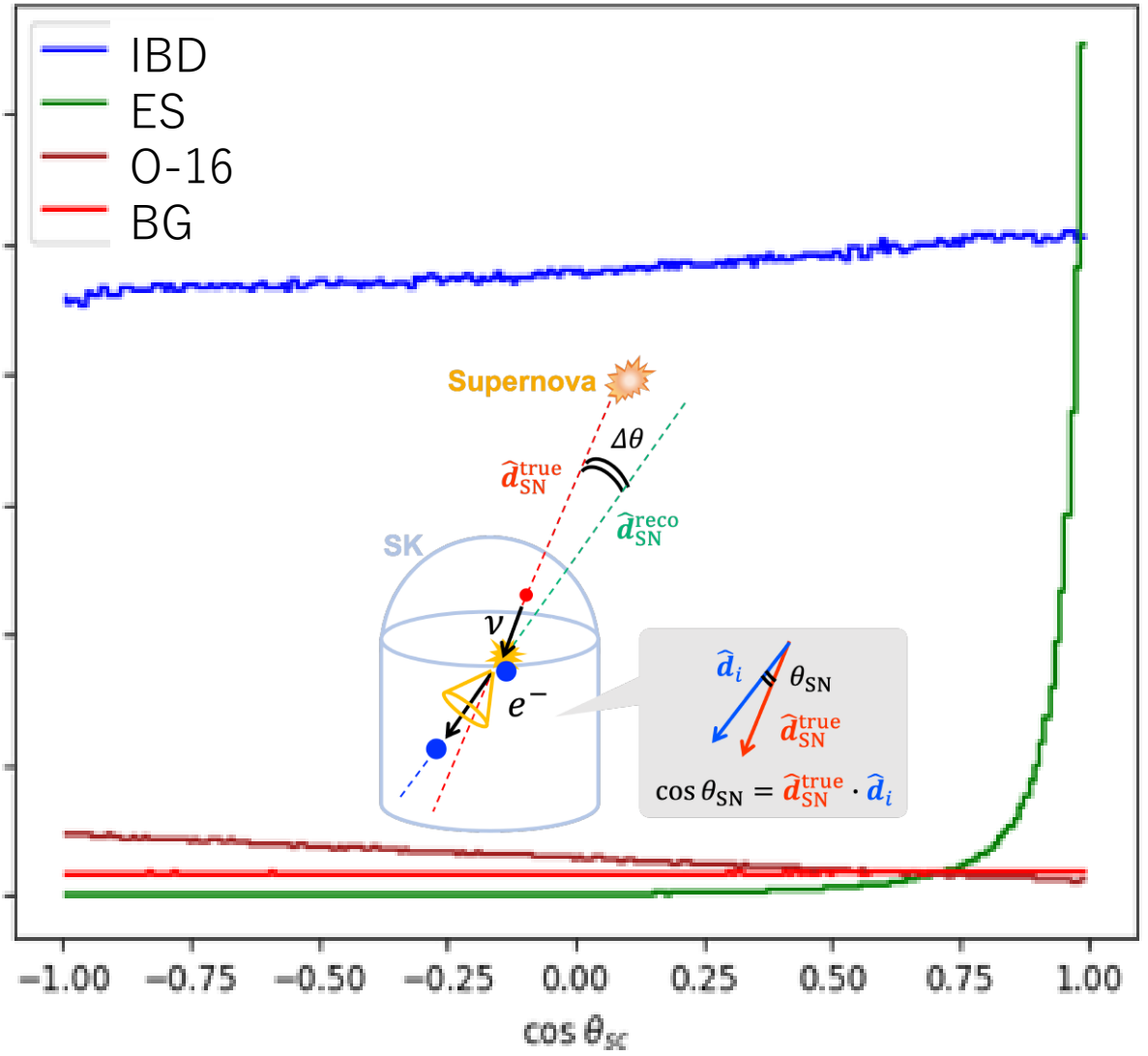
GCN Notices

```
////////////////////////////////////////////////////////////////////////
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:
```

Direction fitter using Gd signals

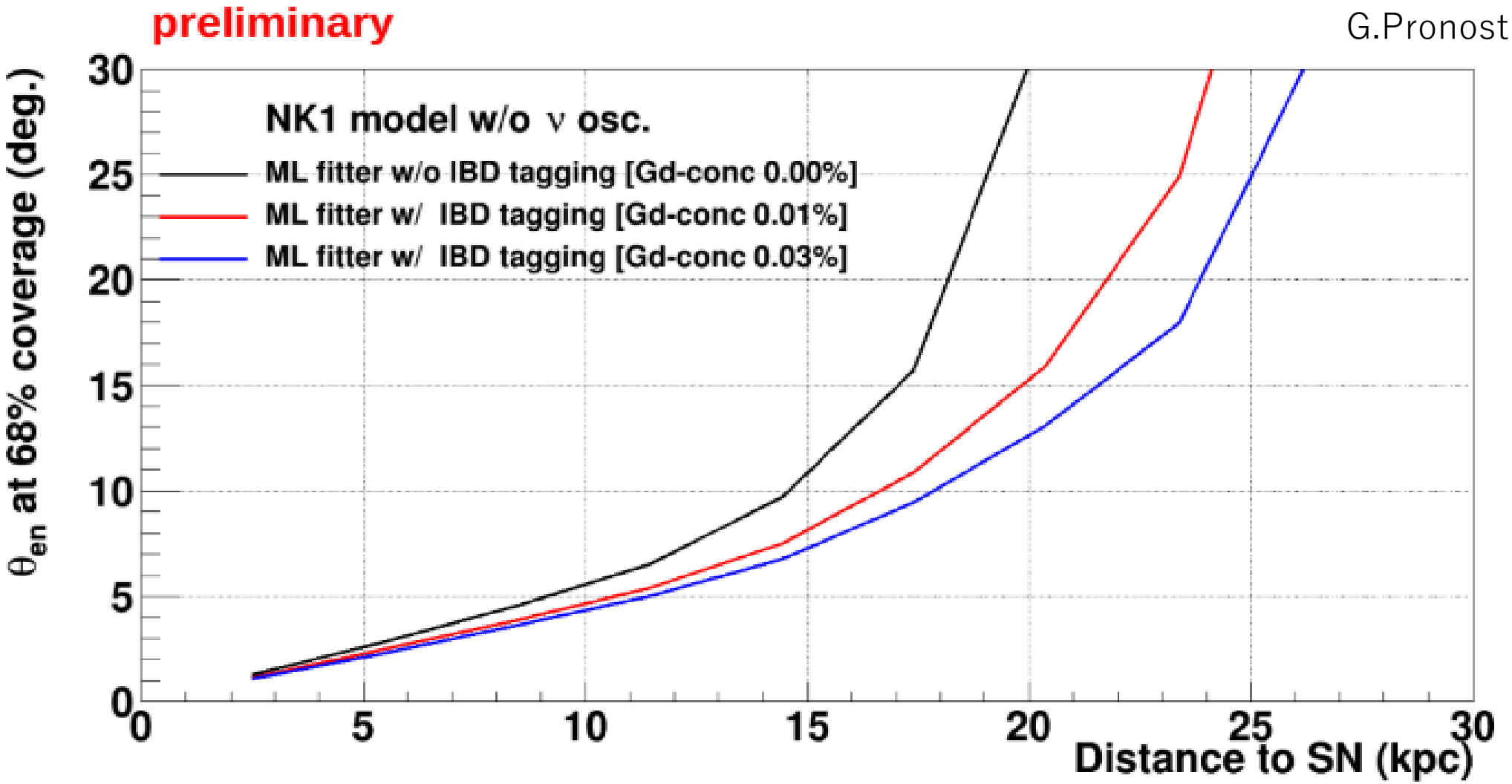
B.Pointon

- Now, SK can tag IBD event with Gd
  - N-tag eff:
    - N-Capture eff ×Tagging eff ~ 50%
    - Trying to improve more
- >10kpc, the statistics is very important.
- We should not just treat IBD events as background of ES
  - IBD also has slight directionality
- Solution:
  - If IBD like (= tagged by Gd signal)
    - Use IBD pdf (Blue)
  - If ES like
    - Set weight for IBD pdf as N-tag eff



Improvement by introducing Gd

SN pointing accuracy



Performance of SK for SN models

Result

Pointing Accuracy at 1 σ [°]

Wilson

NMO	IMO
2.51±0.08	2.81±0.09

Nakazato

NMO	IMO
4.01±0.13	4.27±0.14

Mori

NMO	IMO
4.55±0.14	4.55±0.14

Hüdelpohl

NMO	IMO
5.11±0.16	5.01±0.16

Fischer

NMO	IMO
6.07±0.19	6.93±0.22

Tamborra

NMO	IMO
5.09±0.16	4.67±0.15

- For SN at 10 kpc: 3-7°
- 3° accuracy is achieved in Wilson model (SK-Gd's goal)

ES/IBD Ratio

Wilson

NMO	IMO
0.035±0.003	0.028±0.002

Nakazato

NMO	IMO
0.040±0.004	0.033±0.003

Mori

NMO	IMO
0.037±0.004	0.034±0.004

Hüdelpohl

NMO	IMO
0.036±0..004	0.036±0.004

Fischer

NMO	IMO
0.040±0.006	0.033±0.005

Tamborra

NMO	IMO
0.028±0.004	0.038±0.005

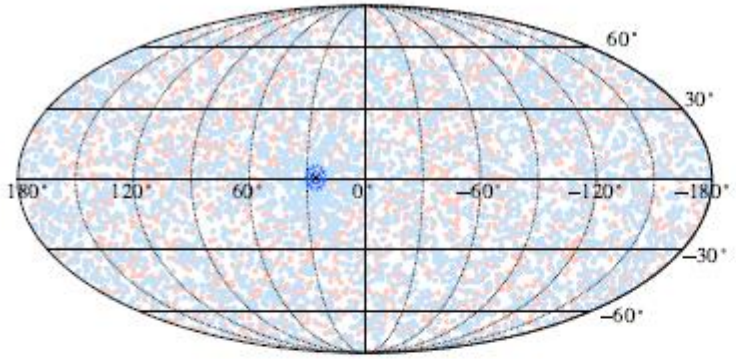
- Better pointing accuracy with Higher ES/IBD ratio.

https://www.lowbg.org/ugap/ws/sn2023/slides/Kashiwagi.pdf

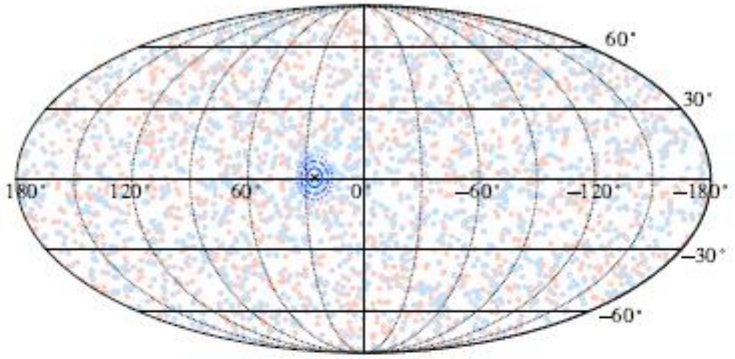
Pointing accuracy for different models

Blue : ES like, Red: IBD like

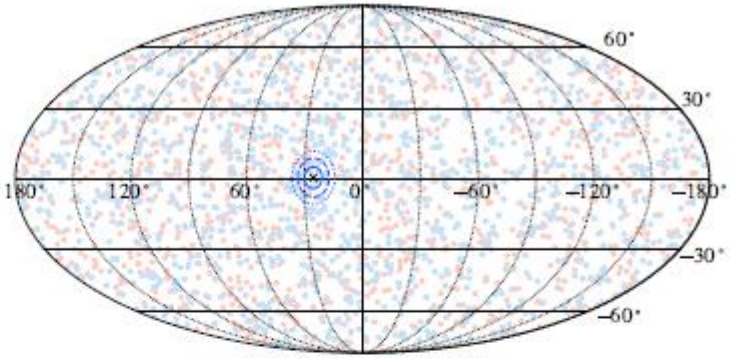
Y.Kashiwagi



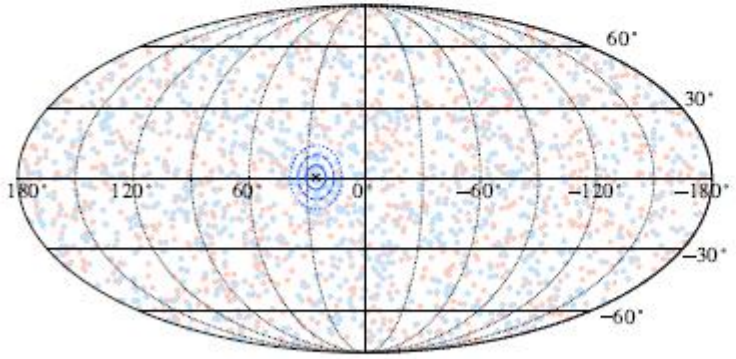
(a) the Wilson model



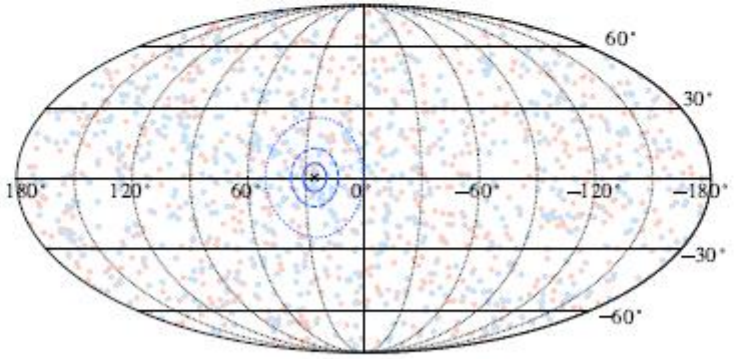
(b) the Nakazato model



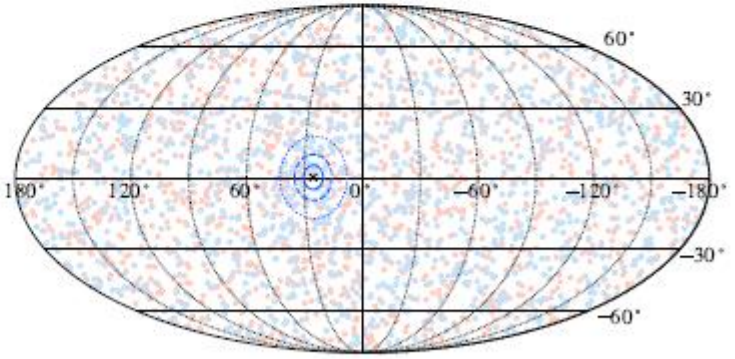
(c) the Mori model



(d) the Hüdepohl model



(e) the Fischer model

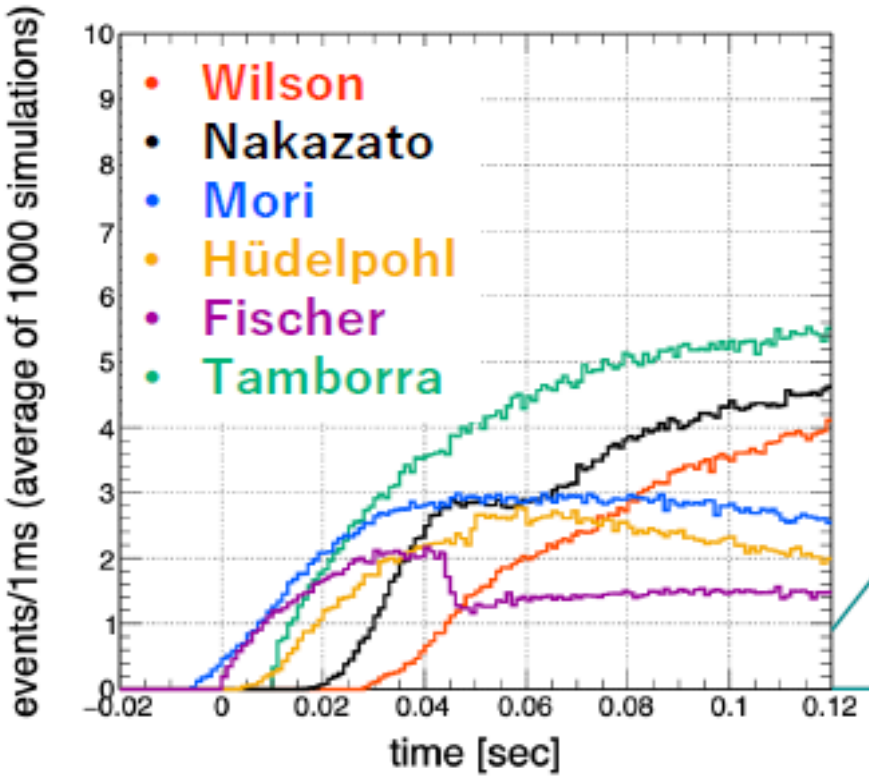


(f) the Tamborra model

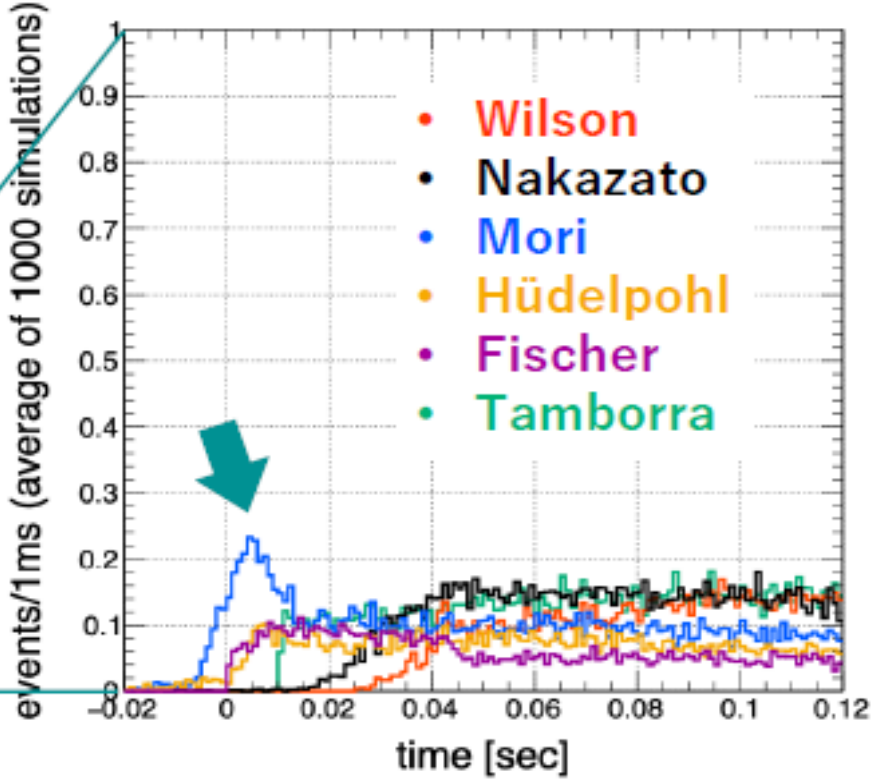
Performance of SK for SN models

- We are about submitting a new paper about SK performance to various SN models

IBD



ES



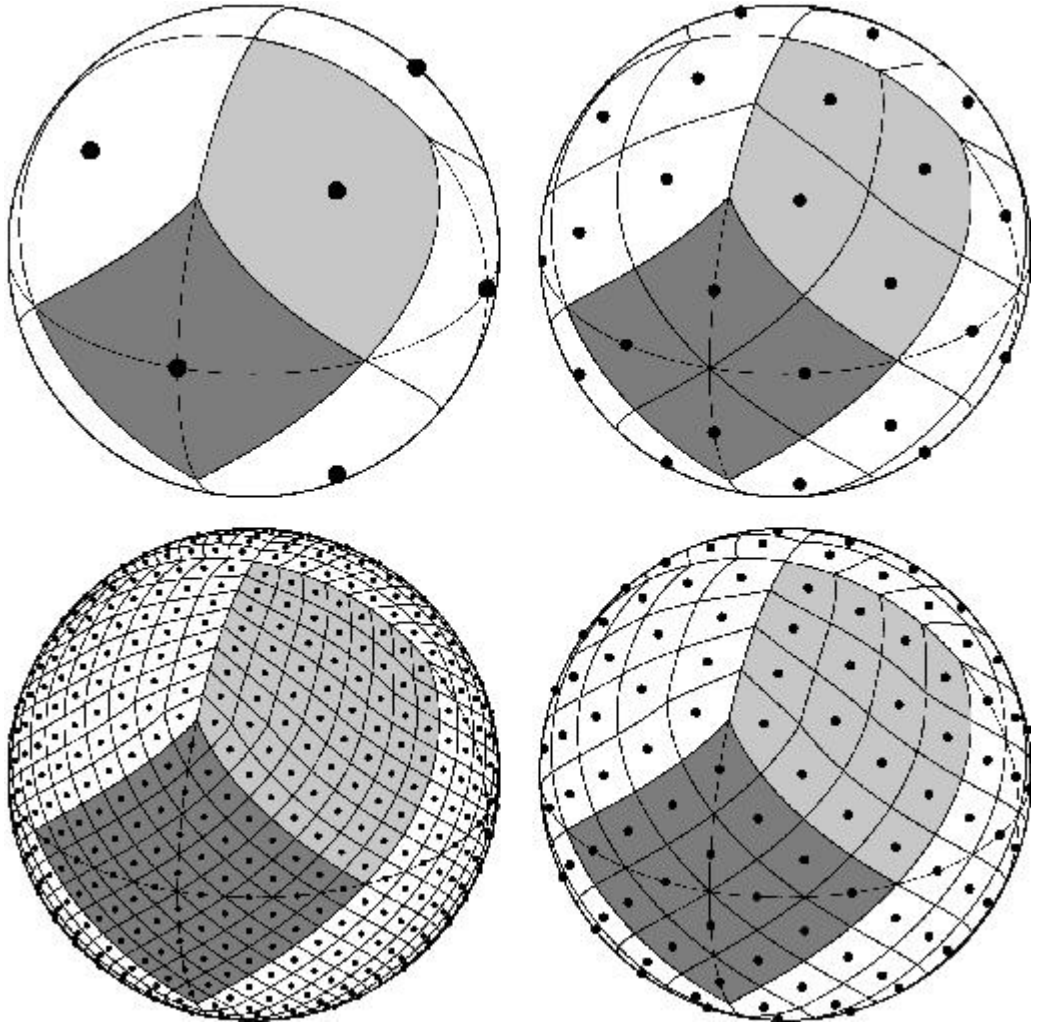
Difference in time structure can be used in model discrimination

- Neutronization burst feature appeared as an ES event peak in Mori Model
  - possibly detectable for a closer SN

https://www.lowbg.org/ugap/ws/sn2023/slides/Kashiwagi.pdf

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 in to vectors
  - To implement them, Phython is used since it has many useful packages



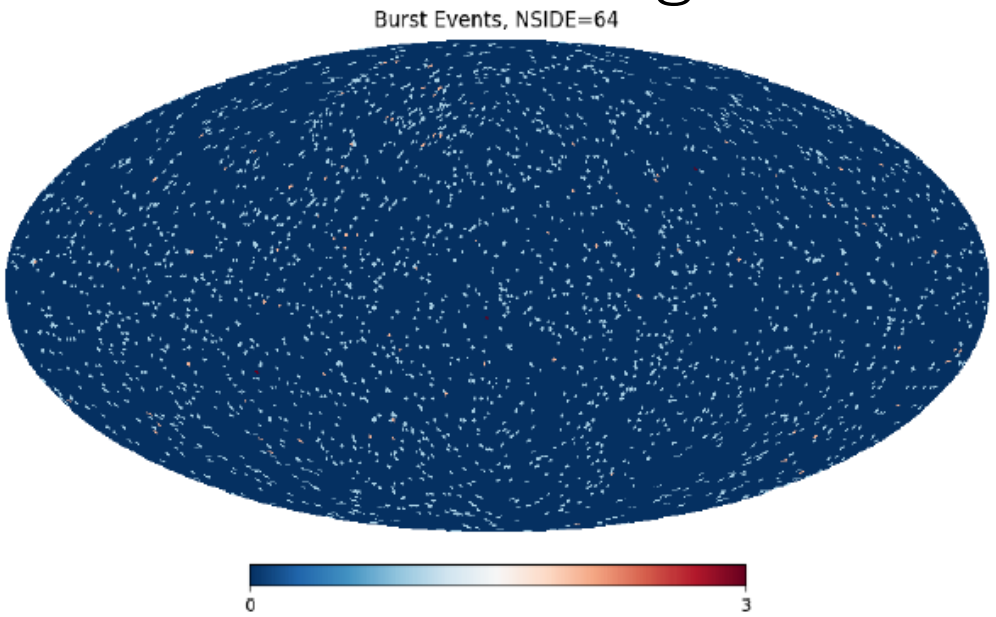
https://healpix.sourceforge.io/

HEALPix fitter

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

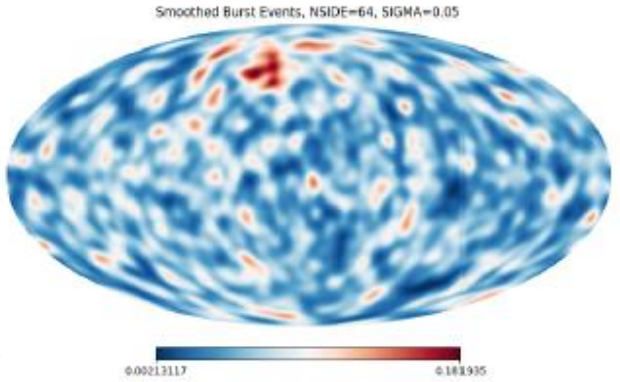
B.Pointon

No smearing

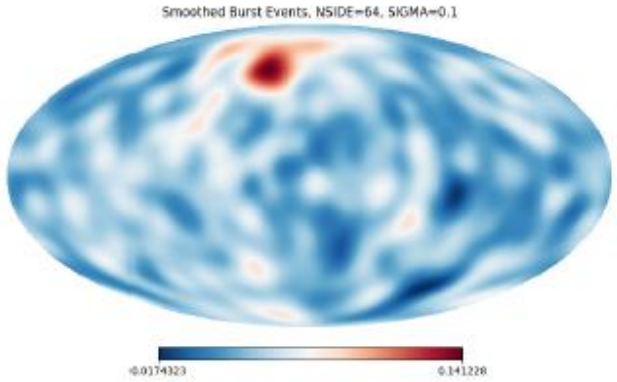


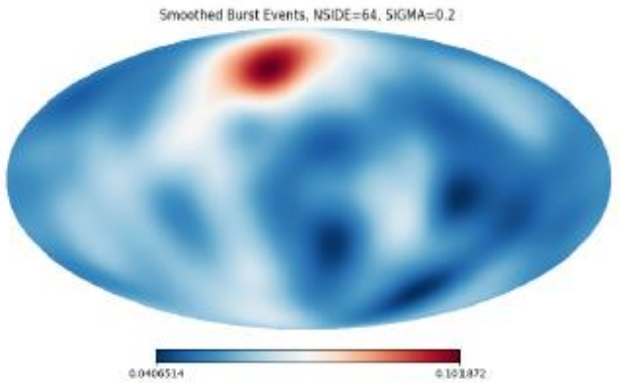
Number of pixels : 49152

Smearing width: 0.05rad

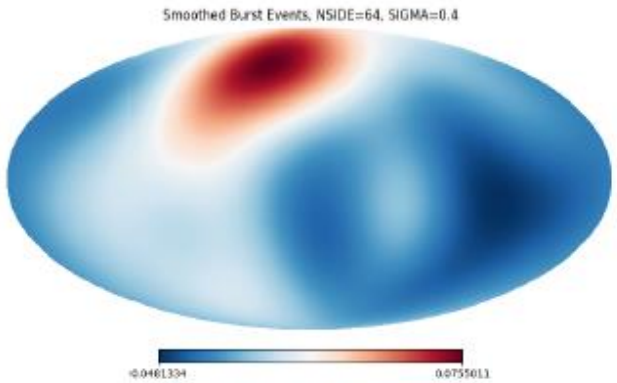


Smearing width: 0.1rad





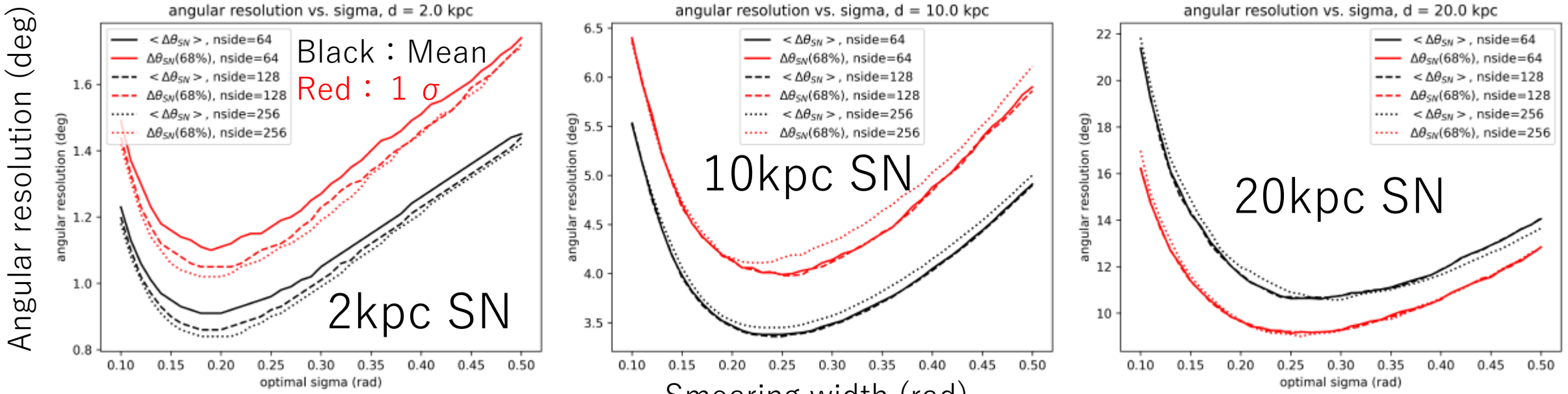
Smearing width: 0.2rad



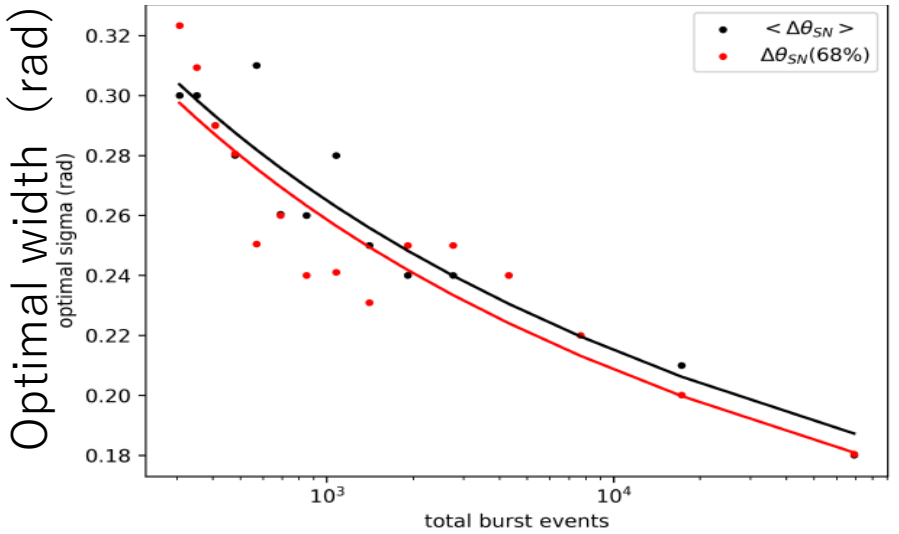
Smearing width: 0.4rad

Set best parameters for HP fitter

B.Pointon



NSIDE	# of Pixels	Angular Res (deg)	Pixel Area (deg^2)
8	768	7.3	53.7
16	3072	3.7	13.4
32	12,288	1.8	3.4
64	49,152	0.92	0.84
128	196,608	0.45	0.21
256	786,432	0.23	0.052



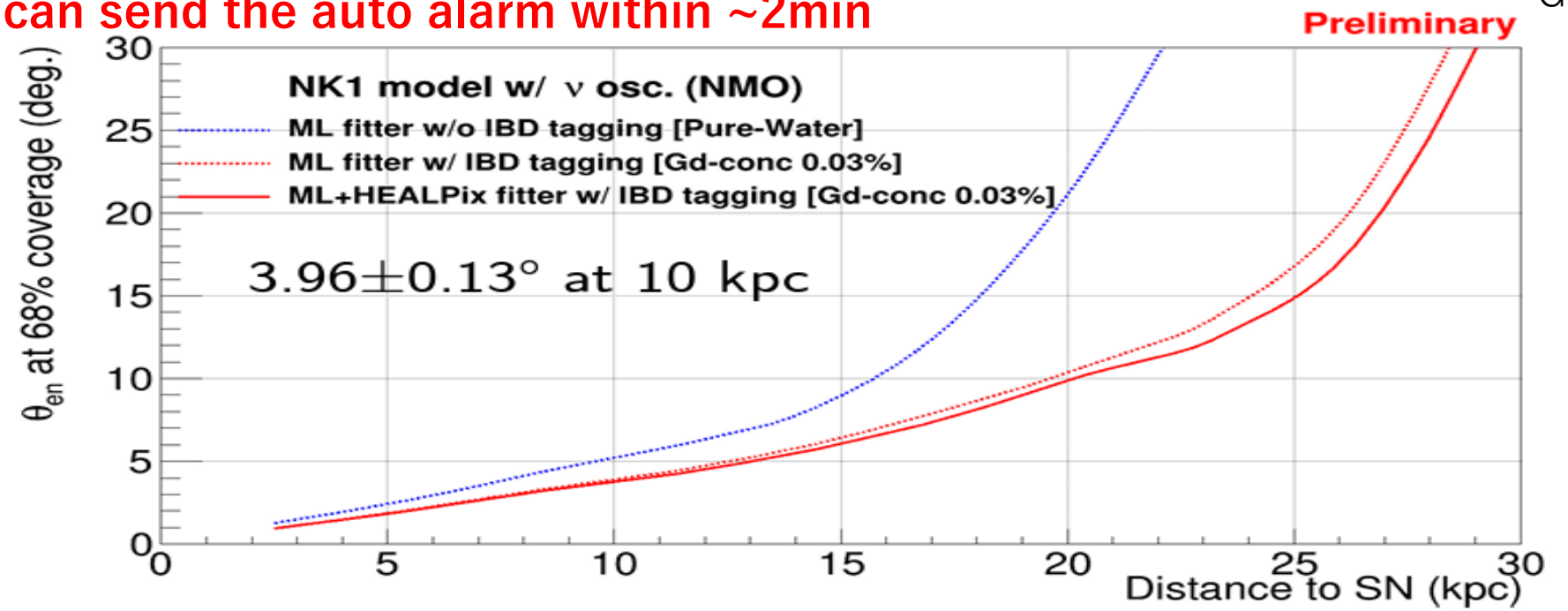
Great improve!

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

Including data processing and reconstruction,
we can send the auto alarm within ~2min

G.Pronost



Summary

- SK Gd status:
  - 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
  - Study of SK performance for SN models
    - Now we have tools to compare models and data quickly!
      SN direction accuracy : 3-6 degree (depending on models)
  - SN direction fitter improvement
    - HP fitter and new ML fitter enable to send auto alerm within 2min.