AN ONLINE FOLLOW-UP SYSTEM FOR GRAVITATIONAL WAVES IN SUPER-KAMIOKANDE

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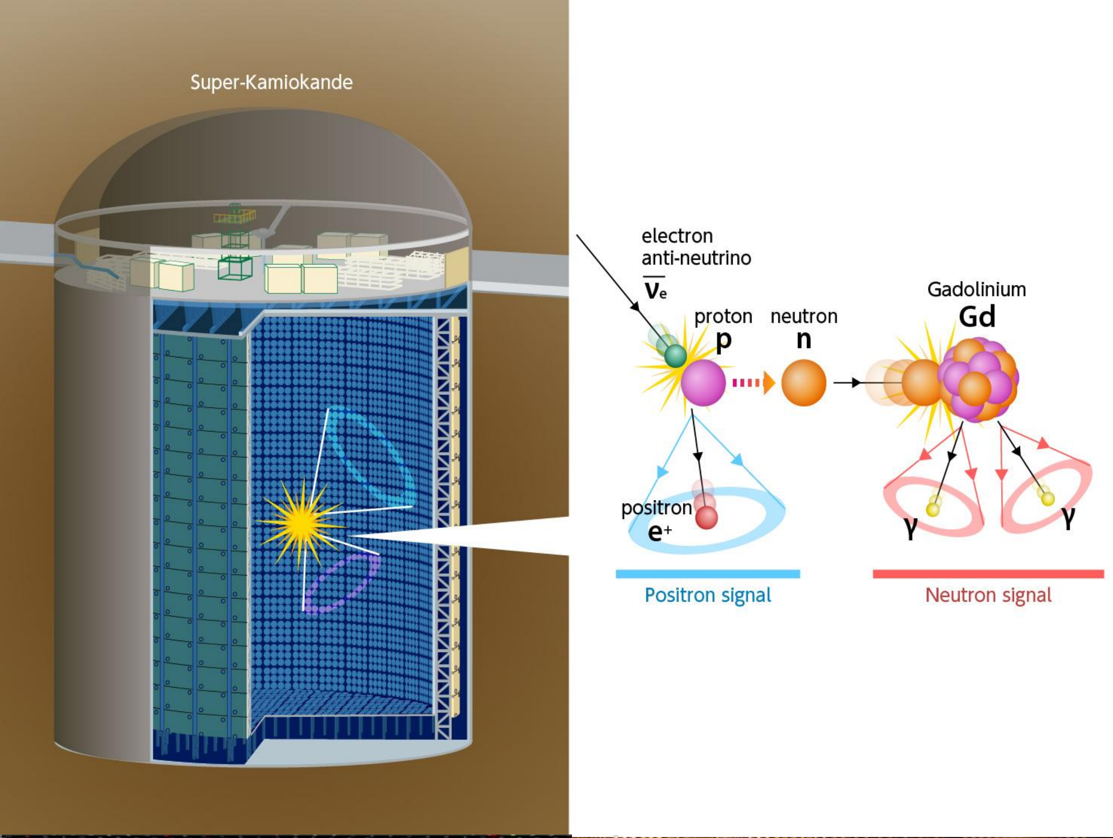
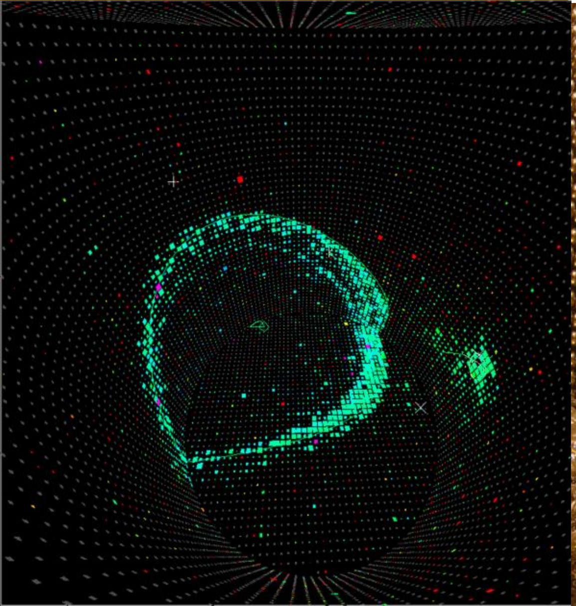
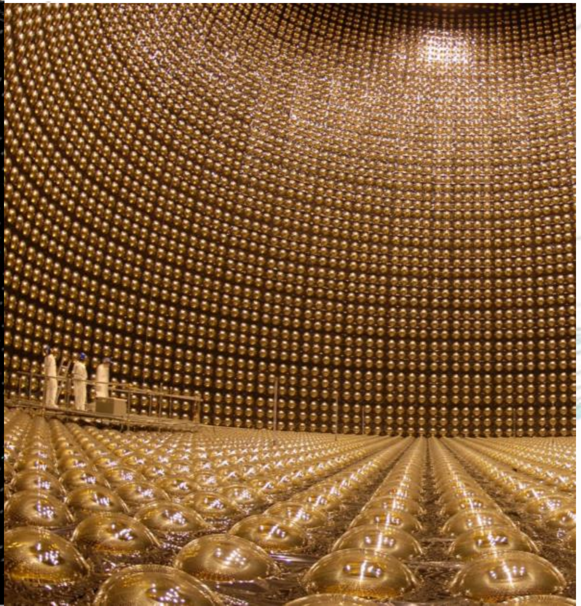
OUTLINE

1. Super-Kamiokande
2. Neutrinos and gravitational waves
3. Online GW follow-up system in Super-Kamiokande
4. Preliminary results of the analysis on the GW-O4a catalogue
5. Prospects and summary

SUPER-KAMIOKANDE







SUPER-KAMIOKANDE

■ Detector

- Located at Kamioka, Japan.
- 50 kton of ultra pure water tank.
- 20-inch PMTs, 11,129 for ID.
- 22.5 kton for analysis fiducial volume.
- Water Cherenkov light technique → Energy, direction, particle identification.
- Since 2020 SK-Gd → Gadolinium loading to improve neutron capture
- Currently running with 0.03% gadolinium by mass

■ Physics target

- Atmospheric neutrino
- Astrophysical neutrino: solar, transient sources, supernova neutrinos, Diffuse Supernova Neutrino Background (DSNB)
- Proton decay
- Reactor neutrinos
- Accelerator Neutrinos (far detector of T2K experiment)

CLASSIFICATION OF EVENTS IN SUPER-KAMIOKANDE

LOW-ENERGY EVENTS (LE)

$E_\nu \sim 3.5 - 100$ MeV

FULLY CONTAINED EVENTS (FC)

$E_\nu \sim 0.1 - 10$ GeV

$\Delta\theta \sim 10^\circ\text{-}100^\circ$

PARTIALLY CONTAINED EVENTS (PC)

$E_\nu \sim 0.1 - 100$ GeV

$\Delta\theta \sim 10^\circ$

UPGOING MUONS (UPMU)

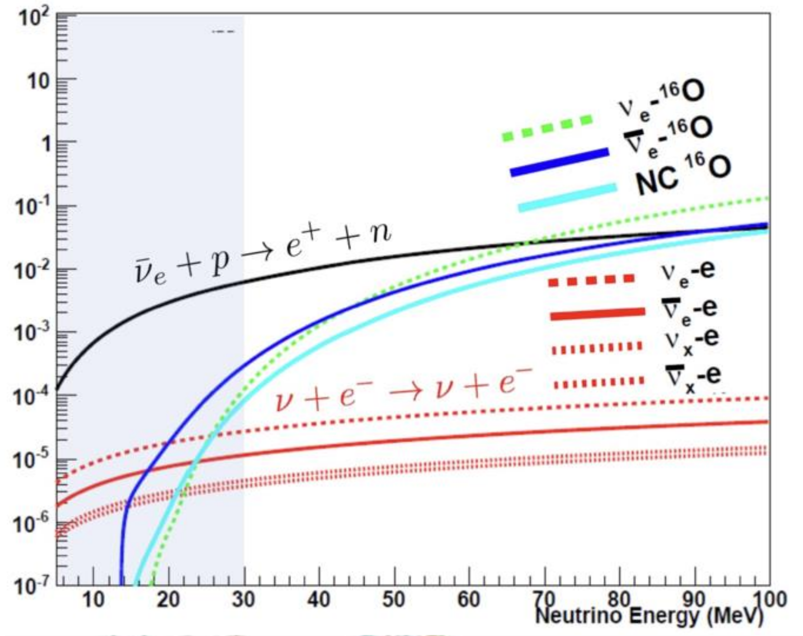
$E_\nu \sim 1.6 - 10^3$ GeV

$\Delta\theta \sim 1^\circ\text{-}10^\circ$

INCREASING ENERGY

LOW ENERGY EVENTS

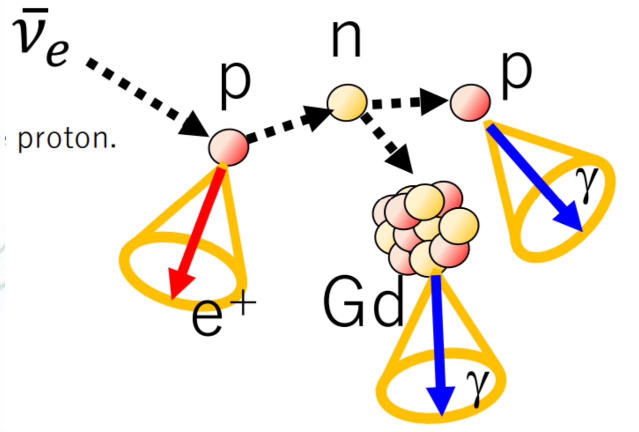
In the MeV energy range, the two main neutrino interactions in water Cherenkov detectors are:



LE neutrino interactions cross section

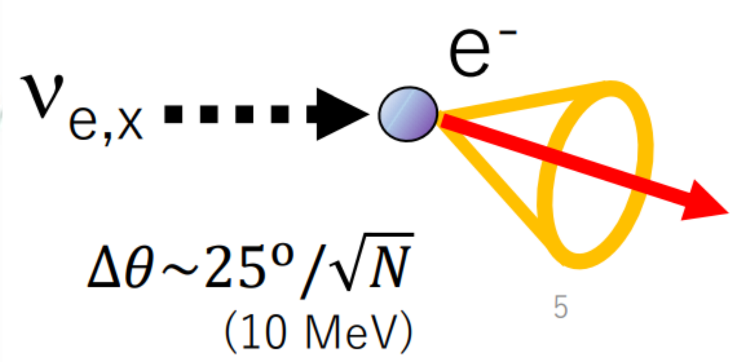
Inverse beta decay (IBD)

DSNB Selection → Looking for $\bar{\nu}_e$



Electron scattering (IBD)

Solar Neutrino Selection → Looking for ν_e



With low energy events produced via Inverse Beta Decay (IBD), we can't extract the information about neutrino direction, while via electron scattering it is possible.

▷ Separating ES from IBD allows to improve the direction pointing accuracy of the detector;
▷ In SK-Gd phase we can enhances the tagging of IBD events thanks to the characteristic delayed coincidence between the IBD's positron emission and delayed neutron capture

NEUTRINOS AND GRAVITATIONAL WAVES

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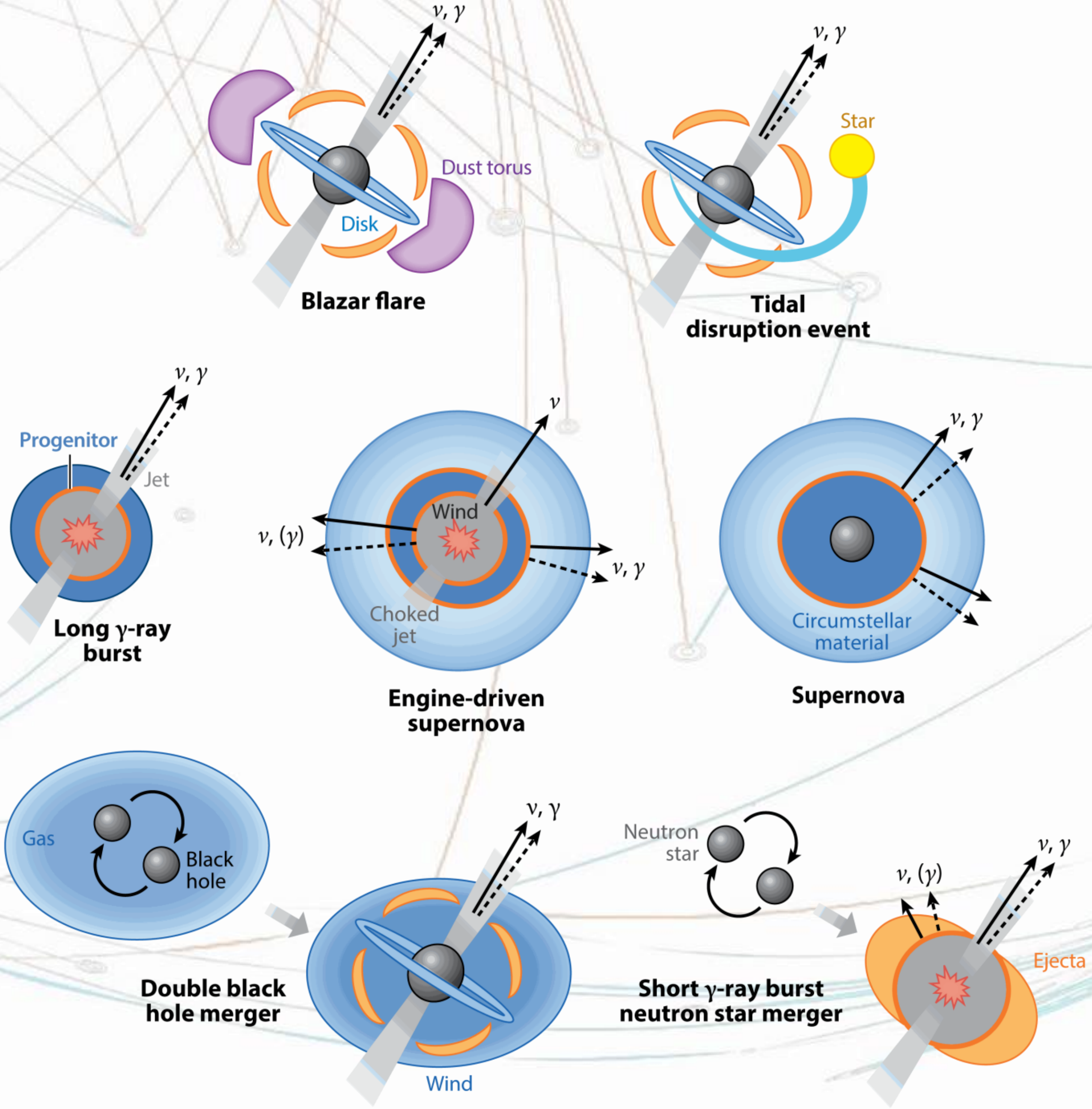
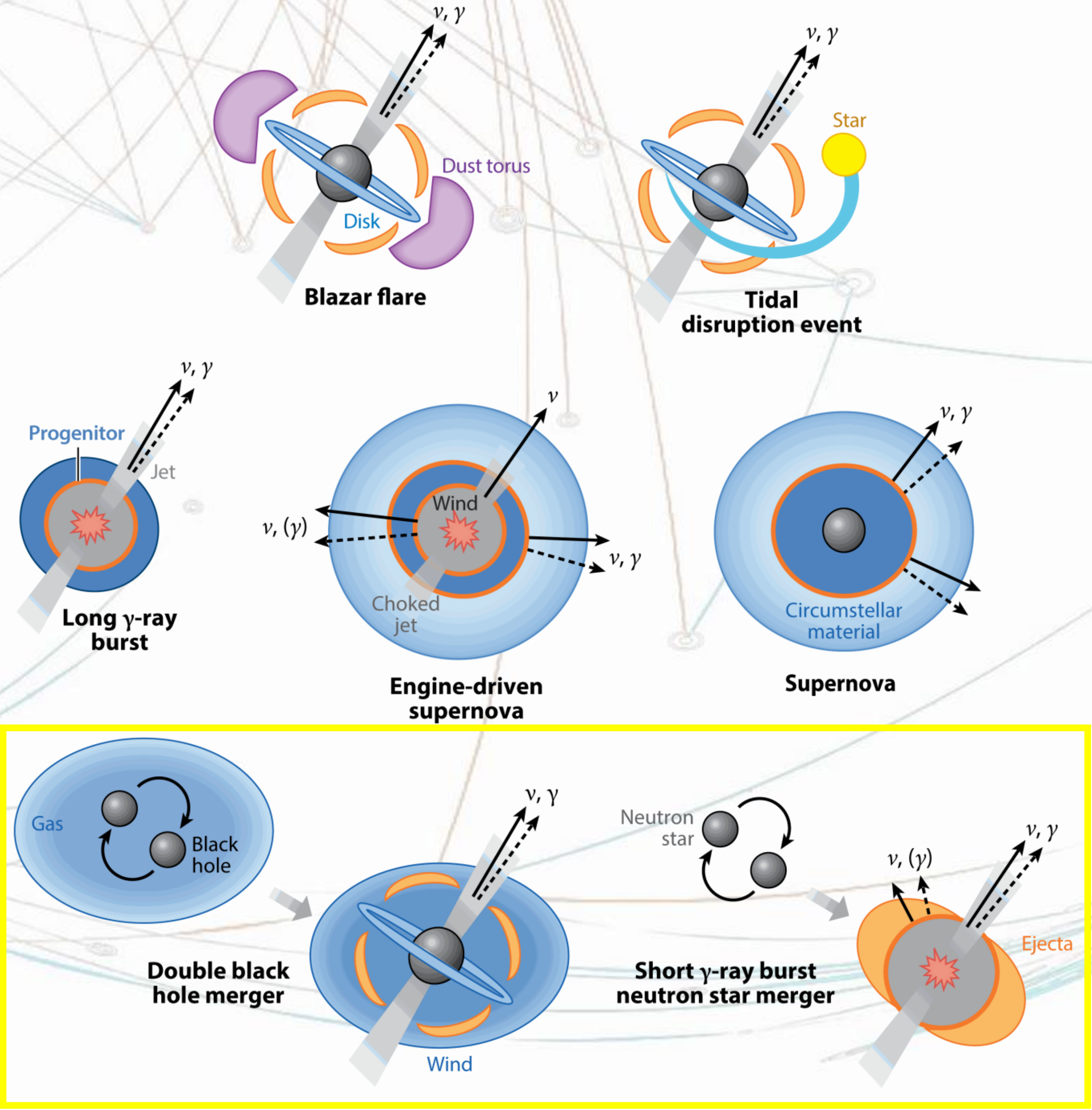


Murase K, Bartos I. 2019.
Annu. Rev. Nucl. Part. Sci. 69:477–506

There are several possible sources for gravitational waves and neutrinos.

Models predict that both low- (>MeV) and high- (>100 GeV) energy neutrino emissions are expected in these scenarios.

NEUTRINOS AND GRAVITATIONAL WAVES



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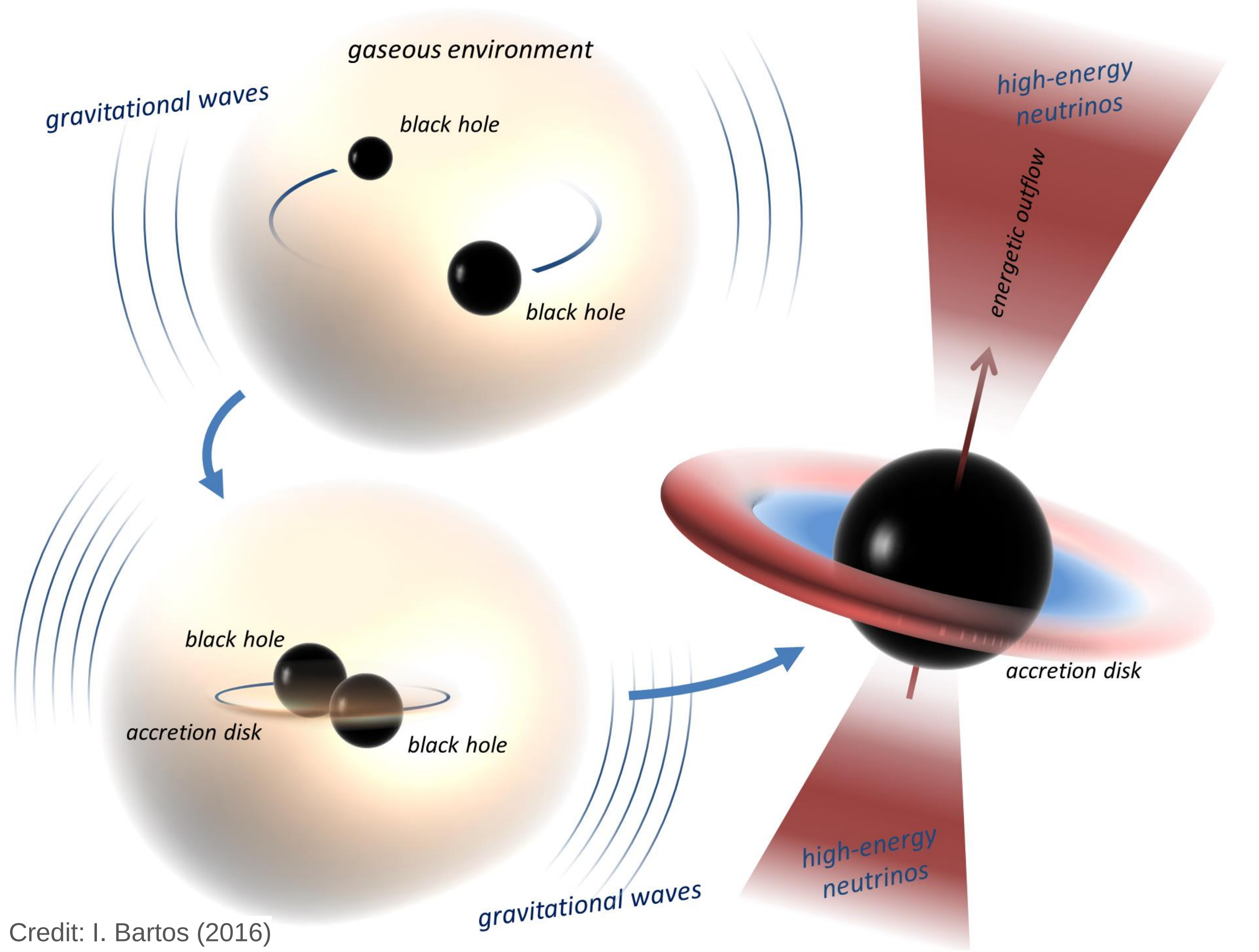
There are several possible sources for gravitational waves and neutrinos.

Models predict that both low- (>MeV) and high- (>GeV) energy neutrino emissions are expected in these scenarios.

In this work, only models of sources which can currently be detected by GW experiments are considered.

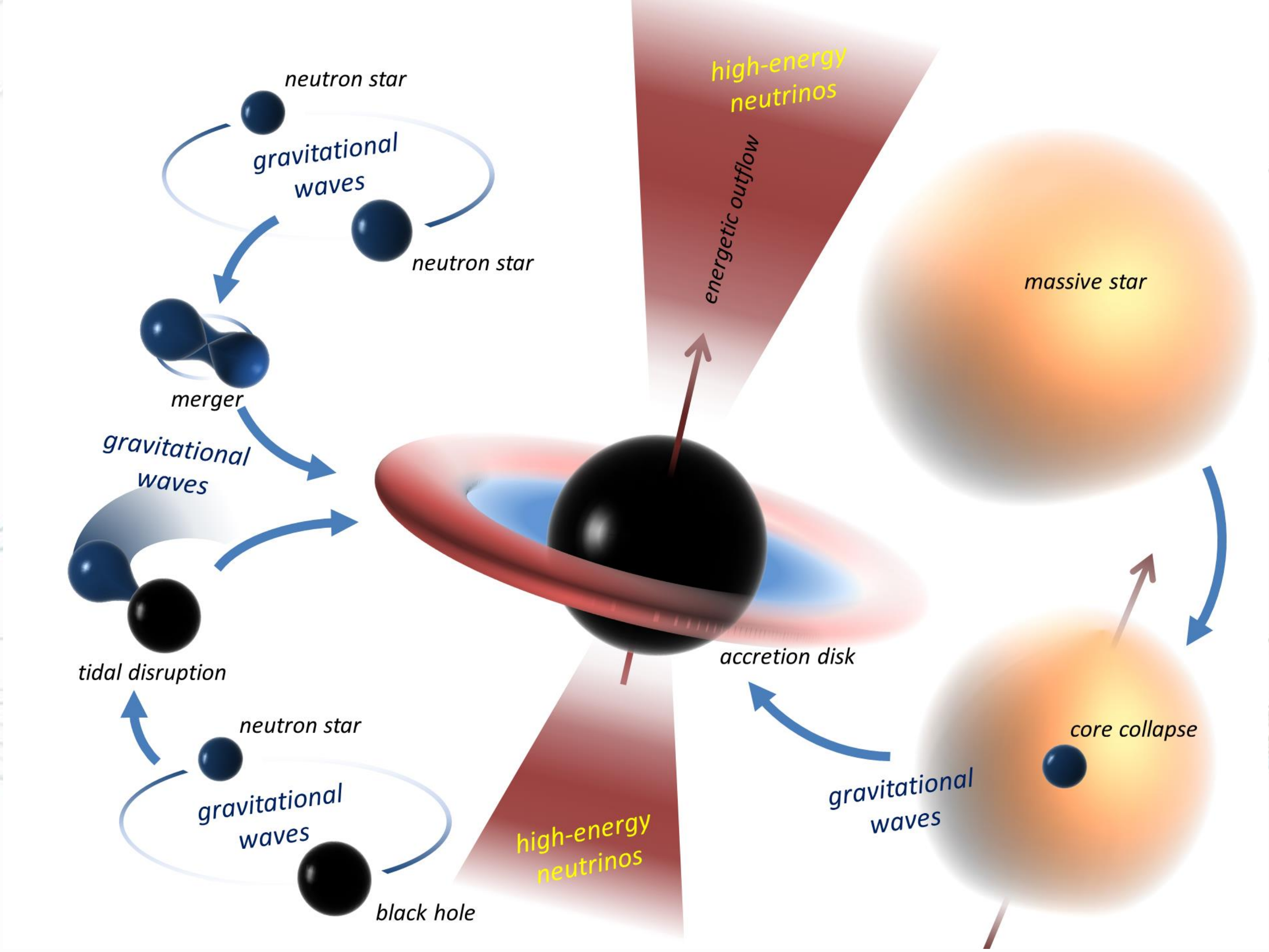
HIGH ENERGY NEUTRINO EMISSION FROM BBH MERGER



Credit: I. Bartos (2016)

- ➢ BBH mergers in a dense environments could produce high energy neutrinos via energetic particles that leaves the BBH environment during accretion.
- ➢ Currently, neutrino brightness within this scenario is not well constrained.

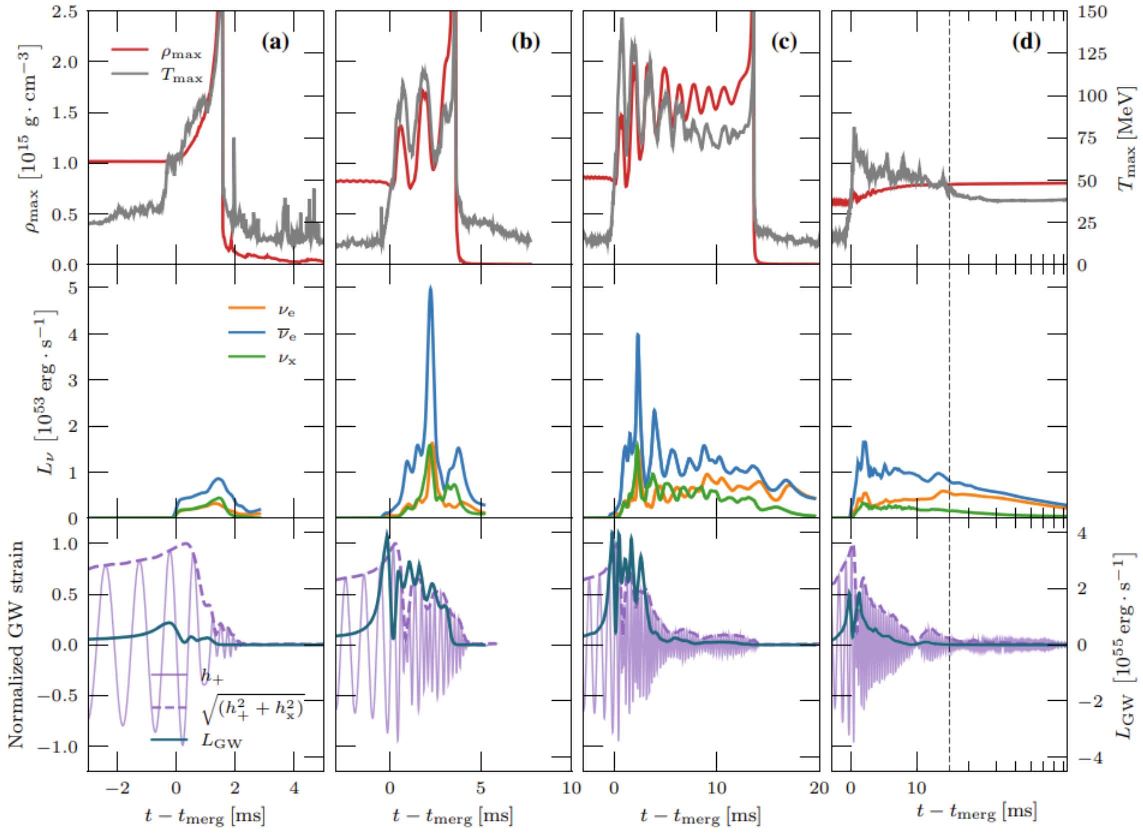
HIGH ENERGY NEUTRINO EMISSION FROM BNS MERGER

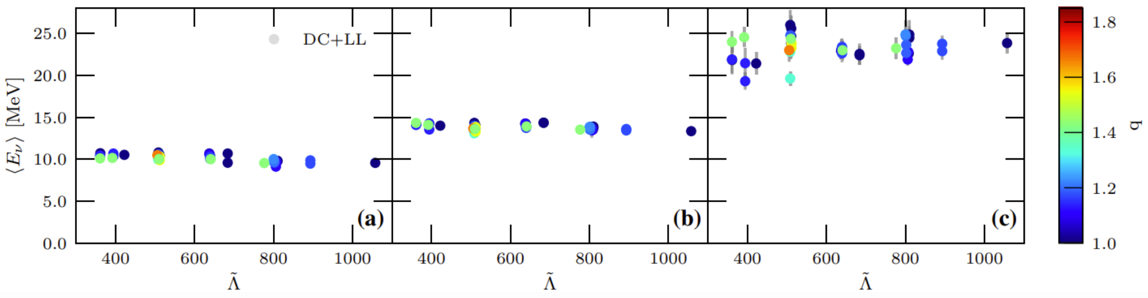


Credit: I. Bartos/Based on arXiv:1212.2289

- ➢ Connection between NS and short GRBs have been already established (see e.g. GW170817).
- ➢ Short GRBs may be also important sources of high-energy neutrinos.
- ➢ In a neutron rich environment, the collision of relativistic protons with slower neutrons also could produce GeV neutrinos.
- ➢ Based on Baret et al., a conservative coincidence time window for GW and HEN is [-500 s, 500 s].

LOW ENERGY NEUTRINO EMISSION FROM BNS MERGER





10.1140/epja/s10050-022-00743-5

Thermal neutrinos (MeVs) are also expected to be emitted during BNS mergers. Models implement different parameters: progenitor masses, EoS, life of remnants…

…But most of them seem to agree on some points:

- All flavors of neutrinos are expected although $\bar{\nu}_e$ are characterized by higher luminosity;
- Most of the emission is expected within few milliseconds from the GW emission;
- Luminosity reach a peak > 10^{53} erg/s;
- Energy ranges from ~5 MeV to 30 MeV;

GW ONLINE FOLLOW-UP SYSTEM

GW ONLINE FOLLOW-UP SYSTEM → WHY ?

- Detecting coincident neutrinos from compact objects merger would allow better understanding of the mechanisms behind them.

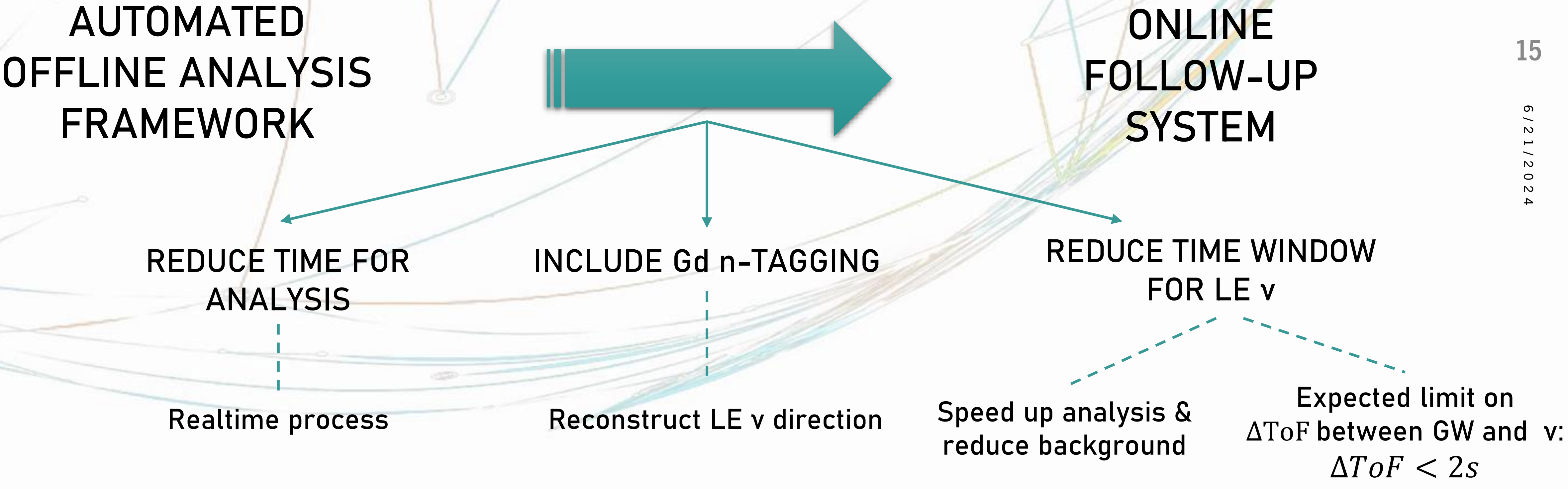
- In the past, several offline search for neutrino counterparts for GW events have been performed in Super-Kamiokande (e.g. 10.3847/2041-8205/830/1/L11, 10.3847/2041-8213/aabaca, 10.3847/1538-4357/ac0d5a).

- A joint observation of GWs and neutrinos is yet to be observed.

- Furthermore, an online GW follow-up system for neutrinos would allow to improve the localization in the sky of a single GW event, increasing the chance for a pointing observatory (e.g. EM follow-up telescopes) to observe a third correlated signal.

GW ONLINE FOLLOW-UP SYSTEM – HOW?

The automated framework for the offline analysis is ready and tested. It employs an analysis similar to that implemented in 10.3847/1538-4357/ac0d5a.



AUTOMATED OFFLINE ANALYSIS FRAMEWORK

ONLINE FOLLOW-UP SYSTEM

REDUCE TIME FOR ANALYSIS

Realtime process

INCLUDE Gd n-TAGGING

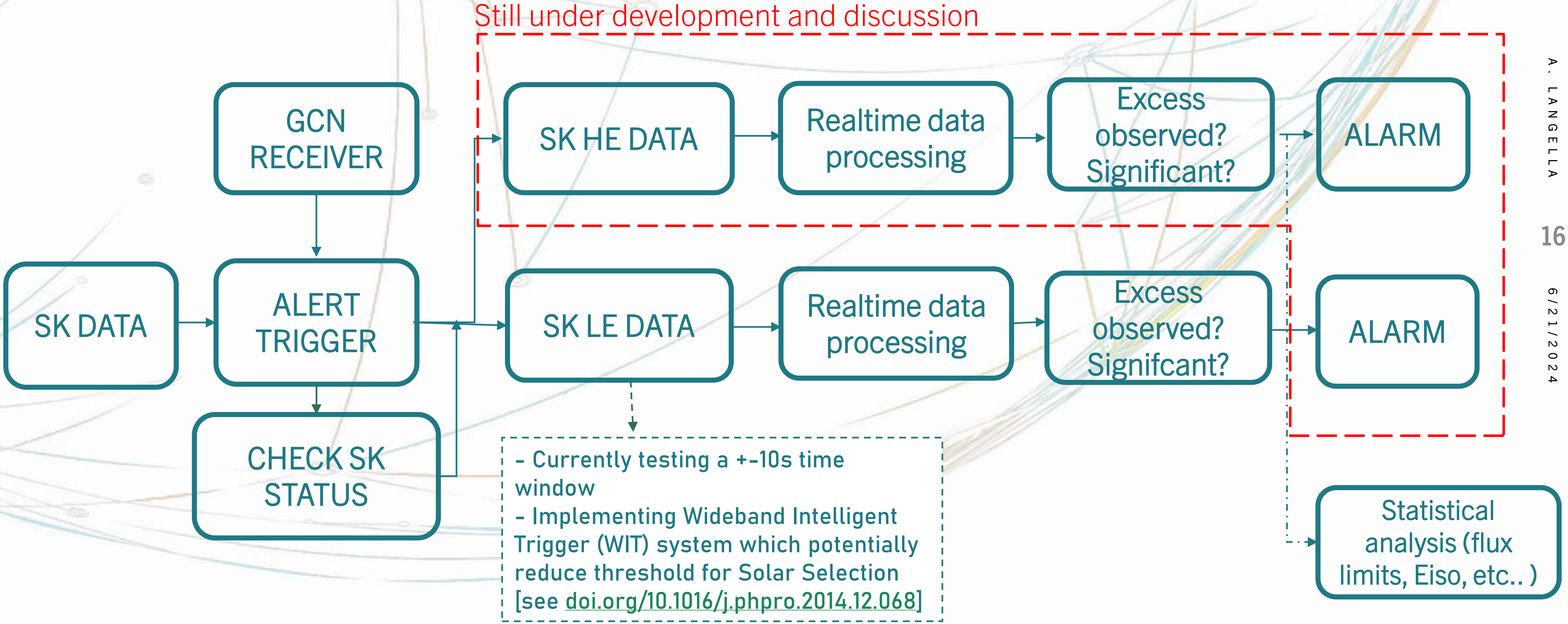
Reconstruct LE ν direction

REDUCE TIME WINDOW FOR LE ν

Speed up analysis & reduce background

Expected limit on ΔToF between GW and ν: $\Delta ToF < 2s$

SCHEME OF THE ONLINE FOLLOW-UP SYSTEM



Still under development and discussion

GCN RECEIVER

SK DATA

ALERT TRIGGER

CHECK SK STATUS

SK HE DATA

Realtime data processing

Excess observed? Significant?

ALARM

SK LE DATA

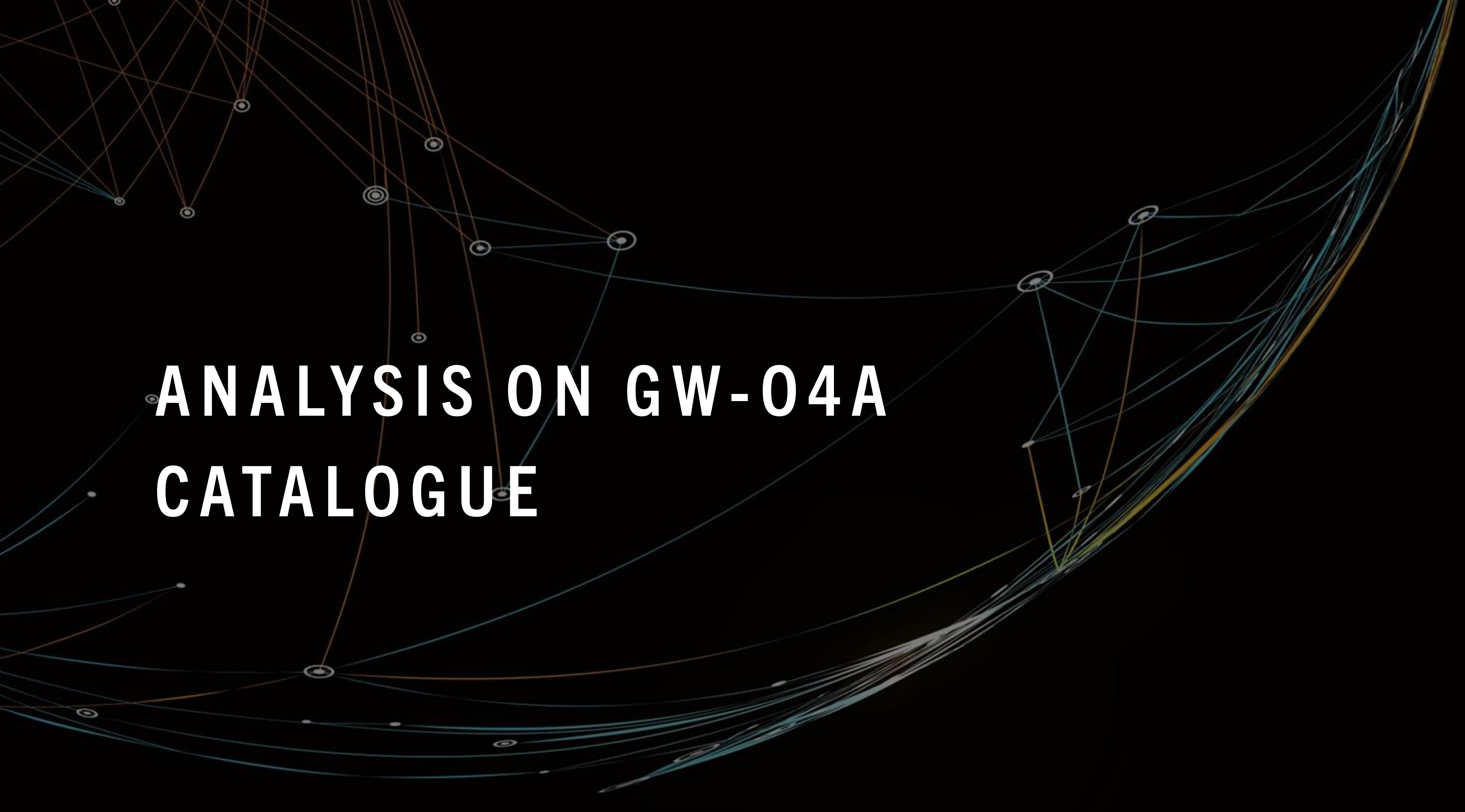
Realtime data processing

Excess observed? Signifcant?

ALARM

Statistical analysis (flux limits, Eiso, etc..)

- Currently testing a +-10s time window
- Implementing Wideband Intelligent Trigger (WIT) system which potentially reduce threshold for Solar Selection [see doi.org/10.1016/j.phpro.2014.12.068]

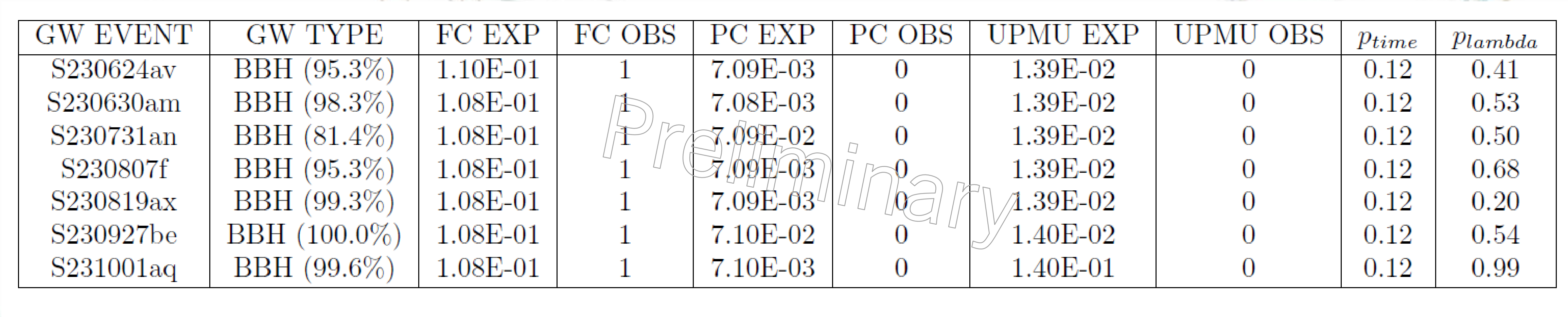


ANALYSIS ON GW-O4A CATALOGUE

GW-O4A JOINT SEARCH ANALYSIS - INTRODUCTION

- The automated offline analysis framework was tested searching for SK counterpart of the population of the first period of GW-O4 catalogue (O4a).
- Only significant GW events from the GraceDB database (https://gracedb.ligo.org/) have been selected.
- Due to SK coil failure, we opted to consider a reduced catalogue of GW events, from May 24th 2023 to October 20th 2023.
- During this period, 56 significant GW have been observed. Two of them were likely associate with NSBH mergers, the other with BBH mergers.
- Five different samples have been considered for this analysis: FC, PC, UPMU, solar sample, DSNB sample (without n-tagging).
- Same time window has been considered for all samples → $[t_{GW}-500s, t_{GW}+500s]$

RESULTS – HE SAMPLES

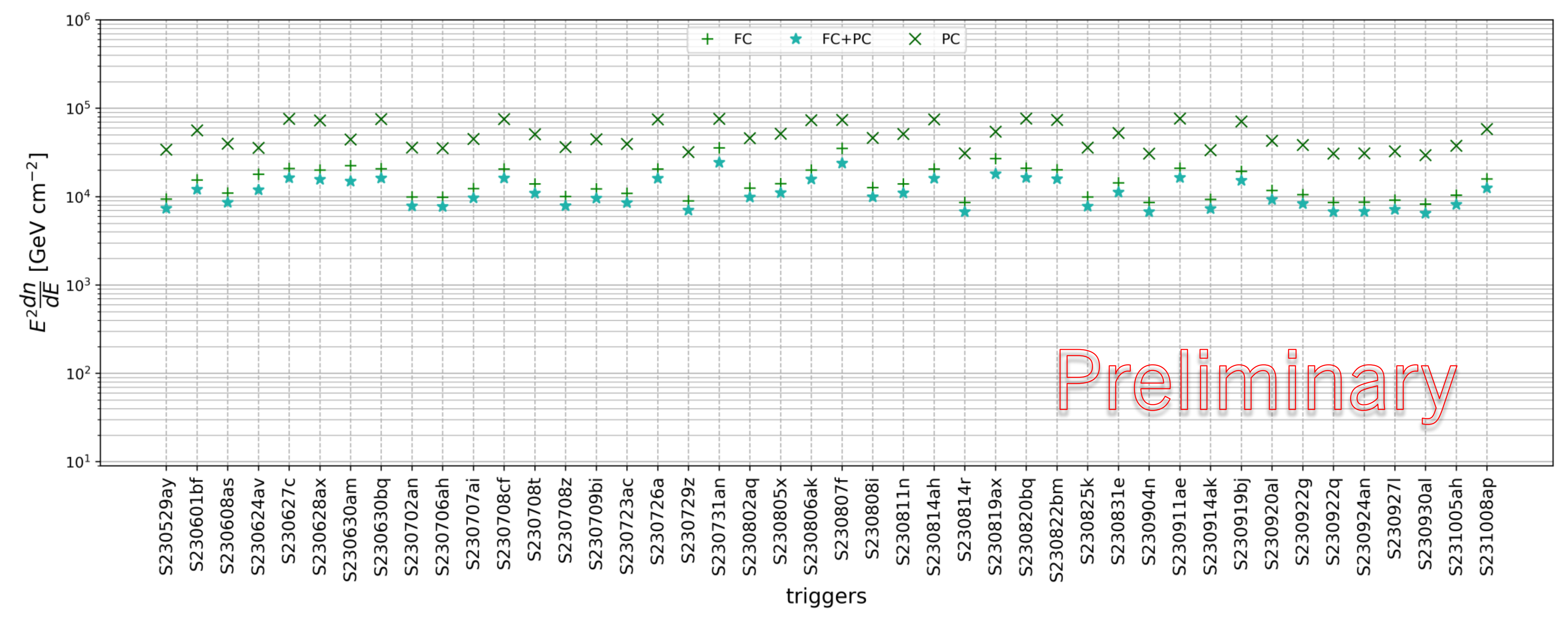


GW EVENT	GW TYPE	FC EXP	FC OBS	PC EXP	PC OBS	UPMU EXP	UPMU OBS	p_{time}	p_{lambda}
S230624av	BBH (95.3%)	1.10E-01	1	7.09E-03	0	1.39E-02	0	0.12	0.41
S230630am	BBH (98.3%)	1.08E-01	1	7.08E-03	0	1.39E-02	0	0.12	0.53
S230731an	BBH (81.4%)	1.08E-01	1	7.09E-02	0	1.39E-02	0	0.12	0.50
S230807f	BBH (95.3%)	1.08E-01	1	7.09E-03	0	1.39E-02	0	0.12	0.68
S230819ax	BBH (99.3%)	1.08E-01	1	7.09E-03	0	1.39E-02	0	0.12	0.20
S230927be	BBH (100.0%)	1.08E-01	1	7.10E-02	0	1.40E-02	0	0.12	0.54
S231001aq	BBH (99.6%)	1.08E-01	1	7.10E-03	0	1.40E-01	0	0.12	0.99

- ❖ A constant background is assumed.
- ❖ Only GW events where N_{OBS} > BKG_{EXP} are shown.

→ No significant excess is observed

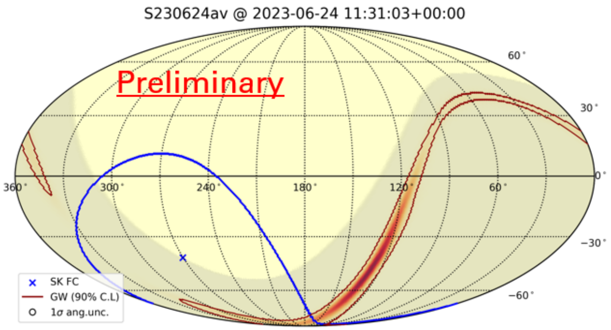
RESULTS – FLUX UPPER LIMITS FOR HE SAMPLES



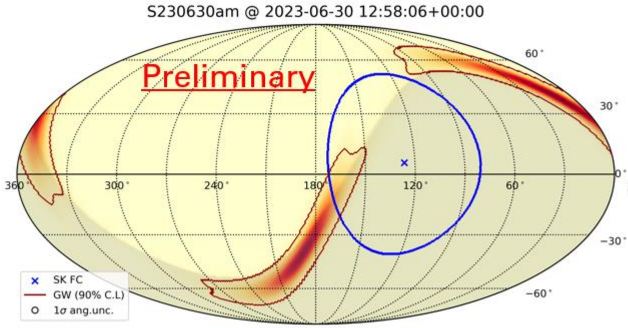
Obtained 90% C.L. upper limits on E^2dn/dE for all neutrino flavors and for the different GW triggers. A E^{-2} spectrum has been considered. Only FC, PC and FC+PC samples are considered. UPMU limits not officialized yet.

RESULTS – SKY MAPS

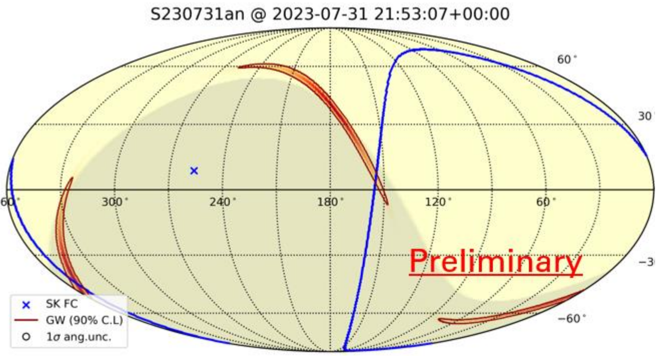
S230624av



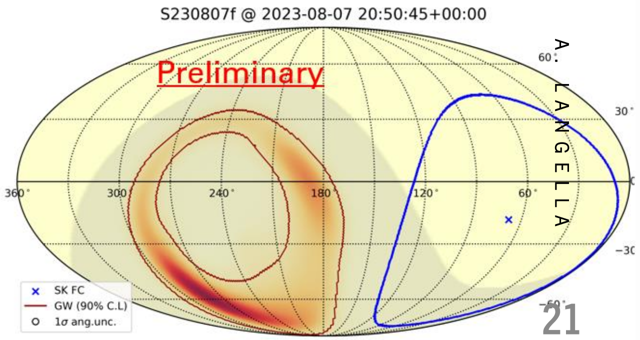
S230630am



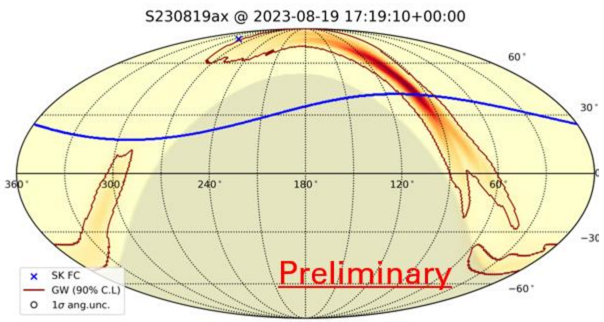
S230731an



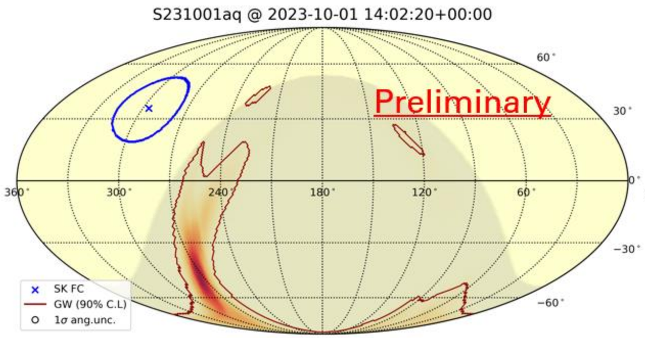
S230807f



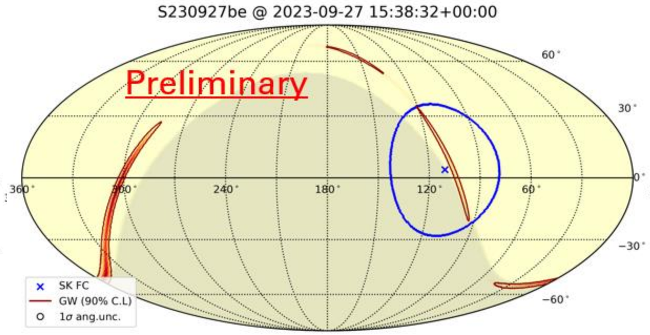
S230819ax



S231001aq



S230927be



Skymaps in equatorial coordinates

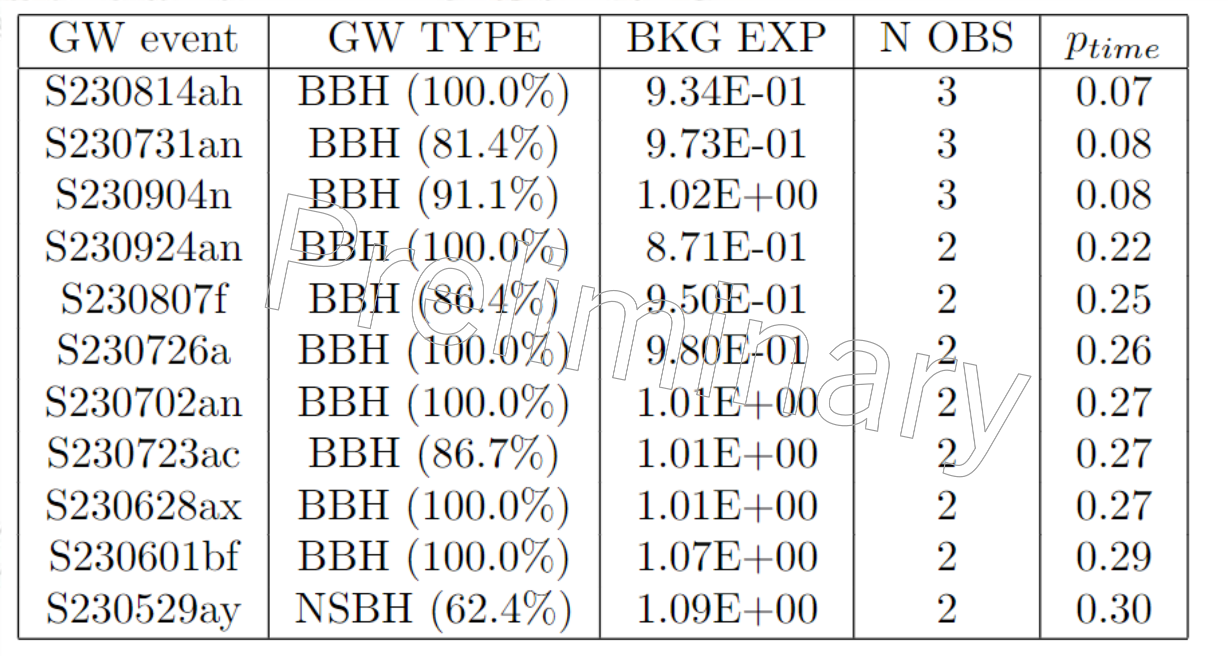
Red: GW localization and 90% contour

Blue: SK FC events with 1 angular uncertainty

Green: SK UPMU events.

Shaded area: SK upmu sky coverage.

RESULTS – LE (SOLAR) SAMPLES



GW event	GW TYPE	BKG EXP	N OBS	p_{time}
S230814ah	BBH (100.0%)	9.34E-01	3	0.07
S230731an	BBH (81.4%)	9.73E-01	3	0.08
S230904n	BBH (91.1%)	1.02E+00	3	0.08
S230924an	BBH (100.0%)	8.71E-01	2	0.22
S230807f	BBH (86.4%)	9.50E-01	2	0.25
S230726a	BBH (100.0%)	9.80E-01	2	0.26
S230702an	BBH (100.0%)	1.01E+00	2	0.27
S230723ac	BBH (86.7%)	1.01E+00	2	0.27
S230628ax	BBH (100.0%)	1.01E+00	2	0.27
S230601bf	BBH (100.0%)	1.07E+00	2	0.29
S230529ay	NSBH (62.4%)	1.09E+00	2	0.30

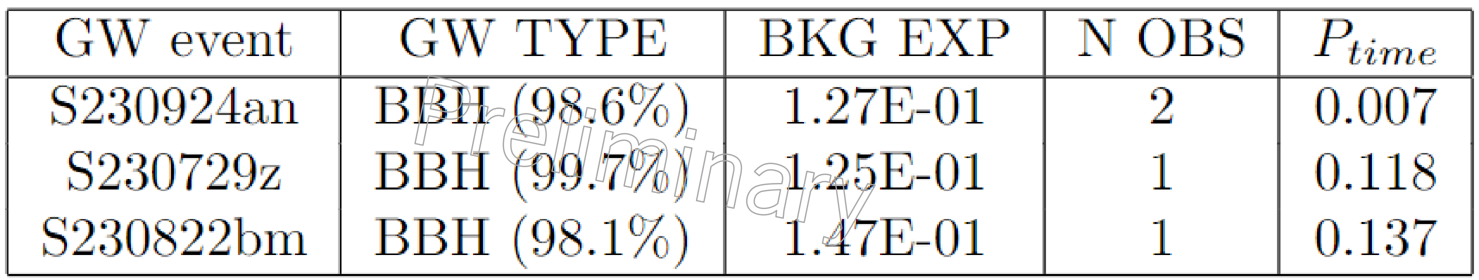
- 6 MeV < E < 8 MeV

- For LE samples the average rate shows some fluctuations, so the number of expected events are calculated taking into account the average rate of +-4 days around GW trigger time (excluding the search time window) and the livetime of each time window.

- Only GW events where N_{OBS} > BKG_{EXP} are shown.

→ No significant excess is observed

RESULTS – LE (DSNB) SAMPLES

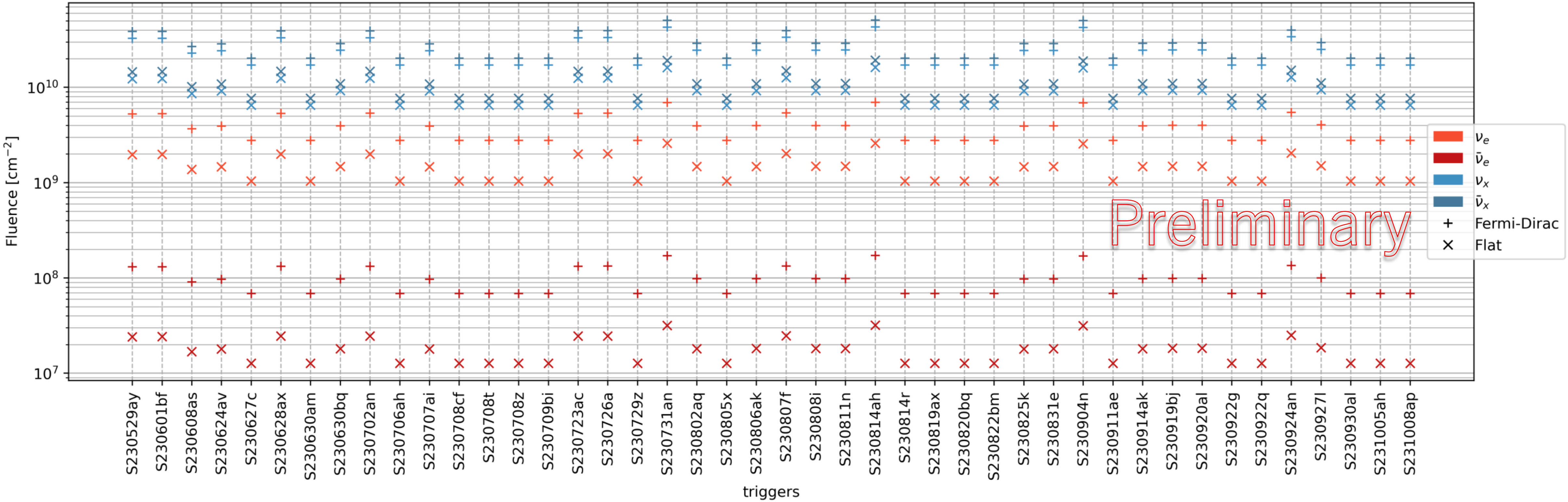


GW event	GW TYPE	BKG EXP	N OBS	P_{time}
S230924an	BBH (98.6%)	1.27E-01	2	0.007
S230729z	BBH (99.7%)	1.25E-01	1	0.118
S230822bm	BBH (98.1%)	1.47E-01	1	0.137

- ❖ 8 MeV < E < 20 MeV
- ❖ For LE samples the average rate shows some fluctuations, so the number of expected events are calculated taking into account the average rate of +-4 days around GW trigger time (excluding the search time window) and the livetime of each time window.
- ❖ Only GW events where $N_{OBS} > BKG_{EXP}$ are shown.
- ❖ Although S230924an is characterized by a low p-value, to assess the significance of this p-value (0.007), a false positive rate was calculated. The p-value become not significant when adjusted to account the FPR.

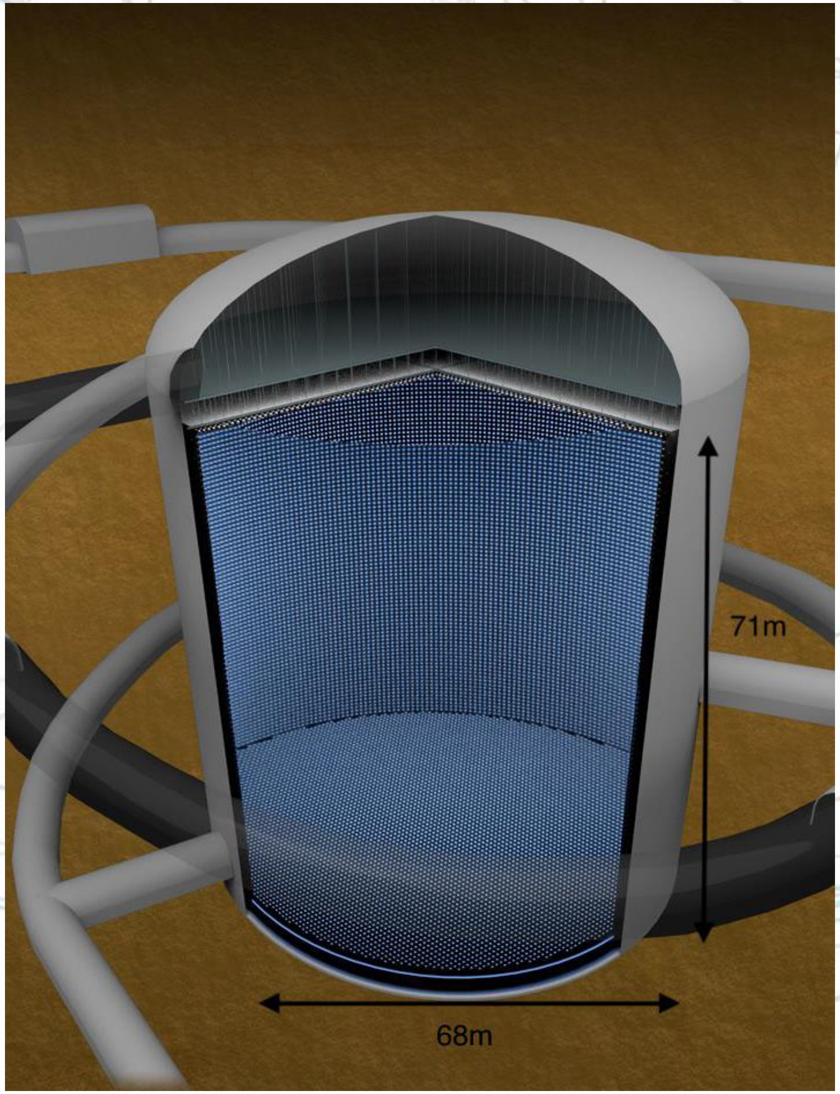
→ No significant excess is observed

RESULTS –FLUENCE LIMITS FOR LE (SOLAR) SAMPLES



Obtained 90% C.L. upper limits on the fluence for all neutrino flavors and for the different GW triggers, using the solar sample. Both Fermi-Dirac and flat spectrum are considered.

PROSPECTS: HYPER-KAMIOKANDE



Hyper-Kamiokande (Hyper-K) is to be the next generation of large-scale water Cherenkov detectors. While adopting successful strategies used in Super-Kamiokande and T2K, main improvements will be:

- Larger detector (x8 SK) for increased statistics
- Improved photo-sensors for better efficiency
- Higher intensity beam and updated/new near detector for accelerator neutrino part

Construction began in may 2021 and data taking will start in 2027 (concurrently with O5 run)

→ Given the bigger volume an increased number of events are expected to be observed
→ Improved photosensors and techinques can lead to a better suppression of background
→ Higher sensitivity to astrophyisical neutrinos

SUMMARY

- Super-Kamiokande is a water Cherenkov detector located in Japan and running since 1996. It serves several physics purposes, such as the study of neutrino properties via atmospheric, solar, reactor and accelerator neutrinos , proton decay, as well as the observation of astrophysical neutrino sources.

- In Super-Kamiokande a framework to perform a coincidence search with GW has been developed and used to search for neutrino counterparts in the GWTC-3 catalogue (see 10.3847/1538-4357/ac0d5a)

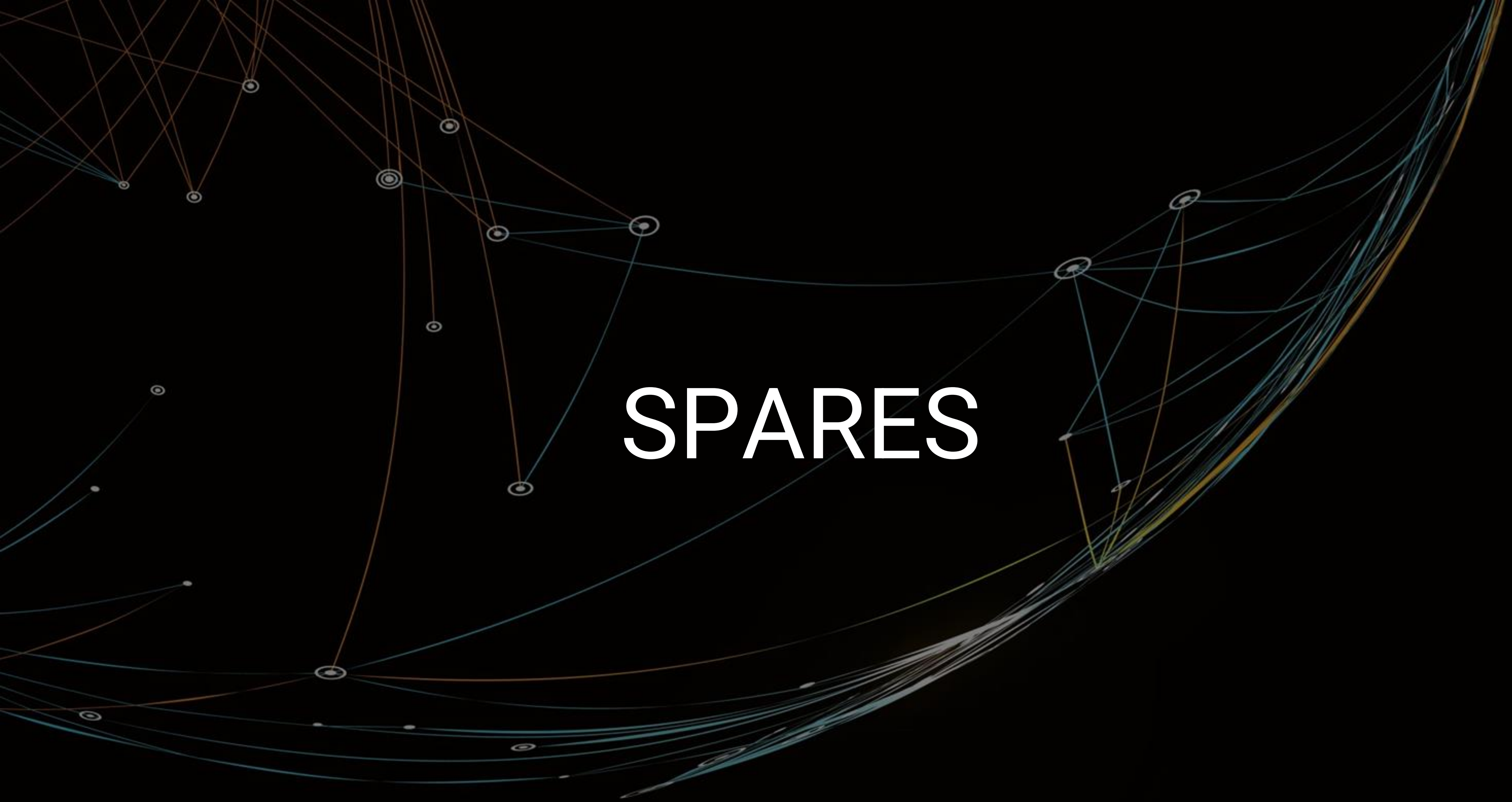
- A new framework, based on the previous one, has been used to search for coincidences with the first period of O4 run (May to October 2023).

- Out of all the 56 sources analysed, no significant excess has been observed.

- A GW realtime follow up system in Super-Kamiokande would allow to better undestard the mechanism behind compact objects merger and to better localize the sources. Super-Kamiokande would in particular allow to enlarge the energy sensitivity to the MeV range.

- The framework is currently under test and a a faster real-time system is under development.

The Super-Kamiokande Collaboration



SPARES

GW-O4A REDUCED CATALOGUE

ID	EventTime_UT	GWtype	Distance
S230529ay	2023-05-29 18:15:00+00:00	NSBH (62.4%)	197.2 +/- 62.1 Mpc
S230601bf	2023-06-01 22:41:34+00:00	BBH (100.0%)	3565.0 +/- 1260.2 Mpc
S230605o	2023-06-05 06:53:43+00:00	BBH (98.8%)	1067.1 +/- 332.8 Mpc
S230606d	2023-06-06 00:43:05+00:00	BBH (99.9%)	1817.8 +/- 557.5 Mpc
S230608as	2023-06-08 20:50:47+00:00	BBH (100.0%)	3446.5 +/- 1079.4 Mpc
S230609u	2023-06-09 06:49:58+00:00	BBH (96.1%)	3389.6 +/- 1124.9 Mpc
S230624av	2023-06-24 11:31:03+00:00	BBH (95.3%)	2124.4 +/- 682.0 Mpc
S230627c	2023-06-27 01:53:37+00:00	NSBH (49.2%)	291.0 +/- 64.1 Mpc
S230628ax	2023-06-28 23:12:00+00:00	BBH (100.0%)	2047.0 +/- 585.1 Mpc
S230630am	2023-06-30 12:58:06+00:00	BBH (98.3%)	5336.2 +/- 2001.3 Mpc
S230630bq	2023-06-30 23:45:32+00:00	BBH (96.8%)	998.8 +/- 285.7 Mpc
S230702an	2023-07-02 18:54:53+00:00	BBH (100.0%)	2427.9 +/- 848.9 Mpc
S230704f	2023-07-04 02:12:11+00:00	BBH (99.7%)	2965.0 +/- 978.1 Mpc
S230706ah	2023-07-06 10:43:33+00:00	BBH (97.3%)	2143.4 +/- 684.3 Mpc
S230707ai	2023-07-07 12:40:47+00:00	BBH (95.1%)	4073.7 +/- 1484.6 Mpc
S230708cf	2023-07-08 23:09:35+00:00	BBH (98.9%)	3335.7 +/- 1075.5 Mpc
S230708t	2023-07-08 05:37:05+00:00	BBH (97.3%)	3010.0 +/- 987.8 Mpc
S230708z	2023-07-08 07:18:59+00:00	BBH (95.4%)	4646.9 +/- 1695.5 Mpc
S230709bi	2023-07-09 12:27:27+00:00	BBH (99.7%)	5008.6 +/- 1547.1 Mpc
S230723ac	2023-07-23 10:18:34+00:00	BBH (86.7%)	1550.7 +/- 436.0 Mpc
S230726a	2023-07-26 00:29:40+00:00	BBH (100.0%)	2131.9 +/- 713.7 Mpc
S230729z	2023-07-29 08:23:17+00:00	BBH (99.7%)	1494.7 +/- 444.5 Mpc
S230731an	2023-07-31 21:53:07+00:00	BBH (81.4%)	1001.1 +/- 241.6 Mpc
S230802aq	2023-08-02 11:33:59+00:00	BBH (90.3%)	444.1 +/- 156.4 Mpc
S230805x	2023-08-05 03:42:49+00:00	BBH (100.0%)	3304.7 +/- 1112.7 Mpc
S230806ak	2023-08-06 20:40:41+00:00	BBH (99.7%)	5423.1 +/- 1862.2 Mpc
S230807f	2023-08-07 20:50:45+00:00	BBH (86.4%)	6817.7 +/- 2379.4 Mpc
S230808i	2023-08-08 04:03:46+00:00	Unmodeled	-

ID	EventTime_UT	GWtype	Distance
S230811n	2023-08-11 03:21:16+00:00	BBH (100.0%)	1904.8 +/- 672.5 Mpc
S230814ah	2023-08-14 23:09:01+00:00	BBH (100.0%)	329.6 +/- 104.8 Mpc
S230814r	2023-08-14 06:19:20+00:00	BBH (93.2%)	3788.4 +/- 1415.6 Mpc
S230819ax	2023-08-19 17:19:10+00:00	BBH (99.3%)	4216.3 +/- 1645.0 Mpc
S230820bq	2023-08-20 21:25:15+00:00	BBH (95.8%)	3599.9 +/- 1436.9 Mpc
S230822bm	2023-08-22 23:03:37+00:00	BBH (98.1%)	5154.3 +/- 1771.5 Mpc
S230824r	2023-08-24 03:30:47+00:00	BBH (100.0%)	4713.7 +/- 1348.4 Mpc
S230825k	2023-08-25 04:13:34+00:00	BBH (99.8%)	5282.9 +/- 2117.4 Mpc
S230831e	2023-08-31 01:54:14+00:00	BBH (98.5%)	4899.9 +/- 2126.1 Mpc
S230904n	2023-09-04 05:10:13+00:00	BBH (91.1%)	1095.2 +/- 326.7 Mpc
S230911ae	2023-09-11 19:53:24+00:00	BBH (100.0%)	1757.8 +/- 588.2 Mpc
S230914ak	2023-09-14 11:14:01+00:00	BBH (99.2%)	2676.1 +/- 827.4 Mpc
S230919bj	2023-09-19 21:57:12+00:00	BBH (100.0%)	1703.0 +/- 471.4 Mpc
S230920al	2023-09-20 07:11:24+00:00	BBH (100.0%)	3163.6 +/- 923.4 Mpc
S230922g	2023-09-22 02:03:44+00:00	BBH (100.0%)	1863.9 +/- 472.9 Mpc
S230922q	2023-09-22 04:06:58+00:00	BBH (100.0%)	6653.3 +/- 2347.8 Mpc
S230924an	2023-09-24 12:44:53+00:00	BBH (100.0%)	2233.3 +/- 617.1 Mpc
S230927be	2023-09-27 15:38:32+00:00	BBH (100.0%)	1058.8 +/- 289.1 Mpc
S230927l	2023-09-27 04:37:29+00:00	BBH (97.6%)	2965.8 +/- 1041.3 Mpc
S230928cb	2023-09-28 21:58:27+00:00	BBH (100.0%)	4059.9 +/- 1553.0 Mpc
S230930al	2023-09-30 11:07:30+00:00	BBH (99.4%)	4902.3 +/- 1671.3 Mpc
S231001aq	2023-10-01 14:02:20+00:00	BBH (99.6%)	4424.6 +/- 1945.6 Mpc
S231005ah	2023-10-05 09:15:49+00:00	BBH (99.8%)	4122.8 +/- 1302.1 Mpc
S231005j	2023-10-05 02:10:30+00:00	BBH (97.8%)	6416.8 +/- 2245.6 Mpc
S231008ap	2023-10-08 14:25:21+00:00	BBH (99.9%)	3531.4 +/- 1319.8 Mpc
S231014r	2023-10-14 04:05:32+00:00	BBH (99.2%)	2857.0 +/- 903.0 Mpc
S231020ba	2023-10-20 14:29:47+00:00	BBH (91.2%)	1167.5 +/- 360.7 Mpc
S231020bw	2023-10-20 18:05:09+00:00	BBH (100.0%)	2620.2 +/- 693.7 Mpc

OFFLINE FOLLOW UP STRATEGY

- ✓ Define a ±500 s centered on GW time.
- ✓ Search for events within this time window, in the five SK samples (solar, DSNB, FC, PC, UPMU).
- ✓ Compare observation with expected background.
- ✓ Compute eventual signal significance. Two approaches have been used to determine the signal significance if N>=1 is observed.:
  1. Evaluate a p-value considering only the time correlation between GW and neutrinos (p_{time}) by Poissonian counting
  2. Evaluating a p-value that takes into account also the localization of both neutrino and GW (defined by a map probability distribution) using a test statistics TS that correlates both time and direction information (only for HE samples)
- ✓ Extract neutrino flux upper limits.
  1. For the HE samples, a E^{-2} spectrum has been considered.
  2. For the LE samples, both Fermi-Dirac (with a mean energy of 20 MeV) and flat spectrum were considered.

Statistical Analysis - significance (1)

Two approaches have been used to determine the signal significance if N>=1 is observed.

1. Evaluate the p-value considering only the time correlation between GW and neutrinos (p_{time}):

$$p = \sum_{k=\sum_s N_s}^{\infty} \mathrm{Poisson}(k, \sum_s n_B^s)$$

2. Lambda method → Taking into account the localization of both neutrino and GW by defining a test statistics TS such that:

$$TS = \max_{\vec{x}_S} [\Lambda(\vec{x}_S)]$$

where

$$\Lambda(\vec{x}_S) = 2\ln\left[\frac{\mathcal{L}_\nu(\widehat{n_S}, \widehat{\gamma}; \vec{x}_S)}{\mathcal{L}_\nu(n_S = 0; \vec{x}_S)}\right] + 2\ln w_L(\vec{x}_S)$$

Best fit position in the sky

GW map probability distribution

Statistical Analysis - significance (2)

We can then compute a p-value, which quantifies how likely the observation is compatible with the background-only hypothesis. For a given gravitational wave event, this can be obtained in two steps:

1. Compute TS background distribution using randomised neutrinos (random energy, direction and time) and the fixed GW sky map $P_{GW}(TS)$

2. Compute the observed TS_{data} and compare to the background distribution:

$$p = \int_{TS_{\mathrm{data}}}^{\infty} P_{\mathrm{bkg}}(TS)\,\mathrm{d}TS$$

Statistical Analysis - HE sample flux limits (1)

We want to take into account the fact that the GW isn't can't be univocally localised, it's position is described by a probability map, thus we define the following likelihood based on Poisson statistics and weighted by GW map probability:

$$\mathcal{L}(\phi_0; n_B, N) = \int \frac{(c(\Omega)\phi_0 + n_B)^N}{N!} e^{-(c(\Omega)\phi_0 + n_B)} \mathcal{P}_{\mathrm{GW}}(\Omega) d\Omega$$

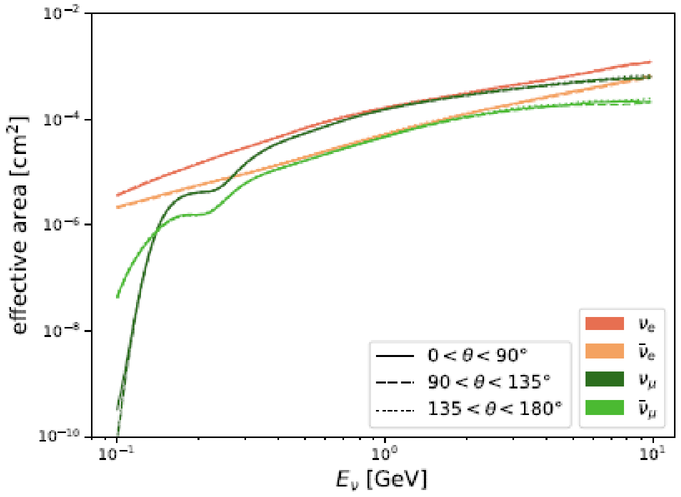
where c(Ω) is the conversion factor from $E^2 dn/dE$ to number of events, n_B is the expected background, N is the observed number of events and $P_{GW}(\Omega)$ is the GW localisation.

Then by solving:

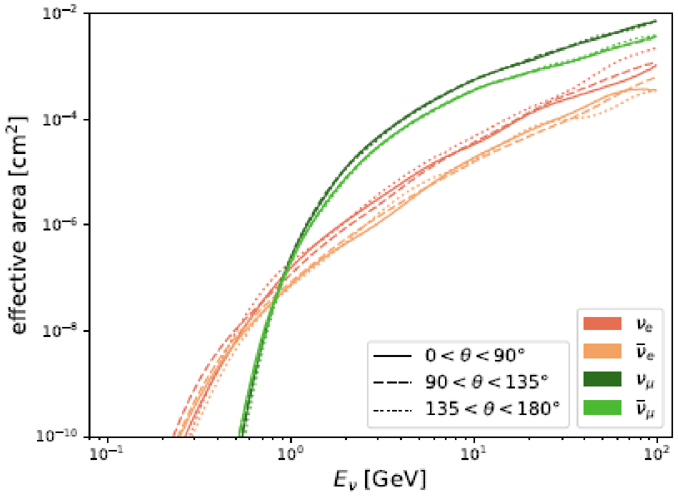
$$\int_0^{\phi^{0,\mathrm{up}}} \mathcal{L}(\phi_0) d\phi_0 = 0.90$$

we obtain the 90% CL upper limit.

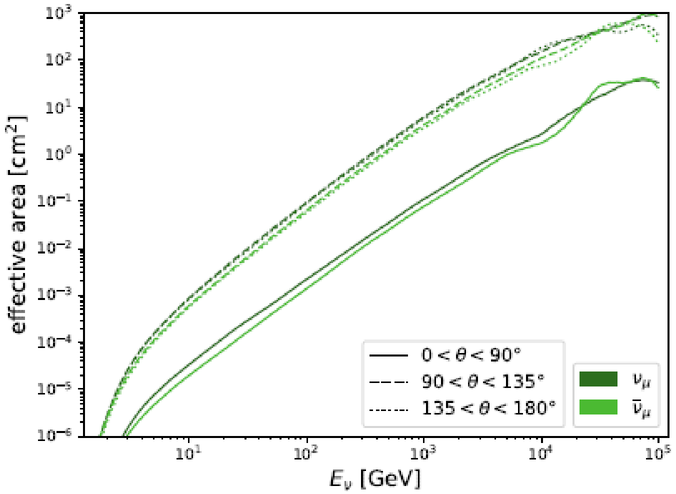
Super-Kamiokande effective area



(a) FC



(b) PC



(c) UPMU

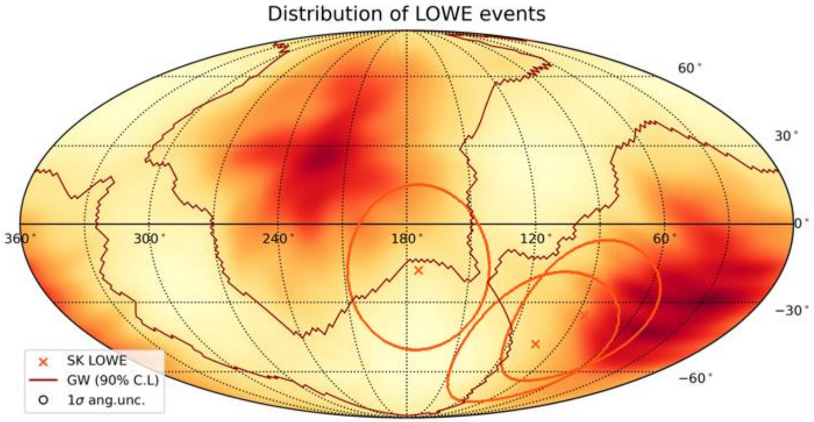
Statistical Analysis - LE sample flux limits (1)

For LE sample, we didn't extract a clear incoming neutrino direction, thus only time correlation is considered. Fluence limits are then simply calculated as:

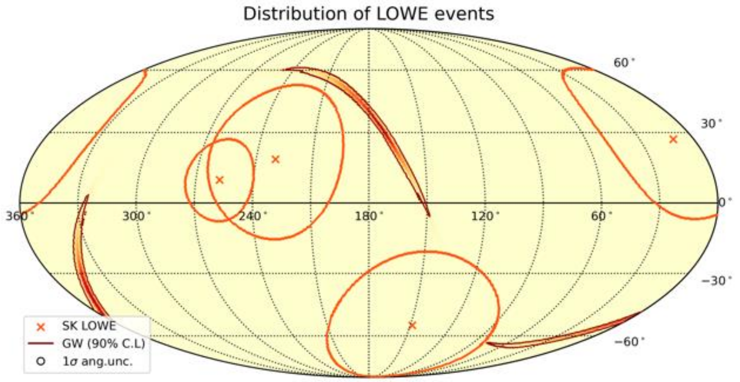
$$\Phi_{90} = \frac{\overbrace{N_{90}}^{\text{90\% C.L. limit on neutrino events}}}{\underbrace{N_T}_{\text{Number of targerts}} \int \underbrace{\lambda(E_\nu)}_{\text{Number density}} \underbrace{\sigma(E_\nu)}_{\text{Cross section}} \underbrace{R(E_e, E_{\text{vis}})}_{\text{Detector response}} \underbrace{\epsilon(E_{\text{vis}})}_{\text{Efficiency}} \, \mathrm{d}E_\nu}$$

RESULTS – LE SKY MAPS

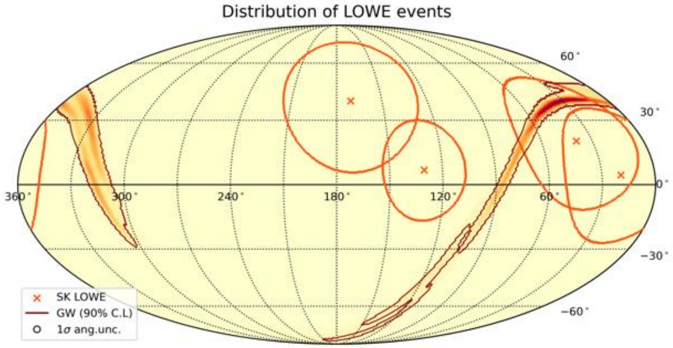
S230814ah (solar sample)



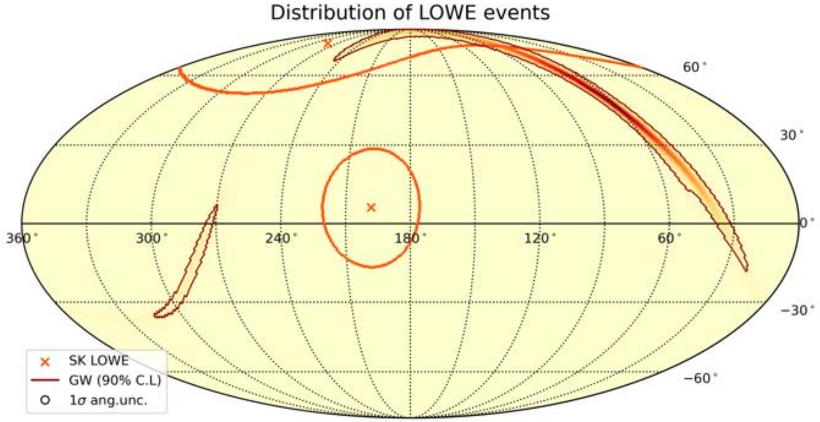
S230731an (solar sample)



S230904n (solar sample)

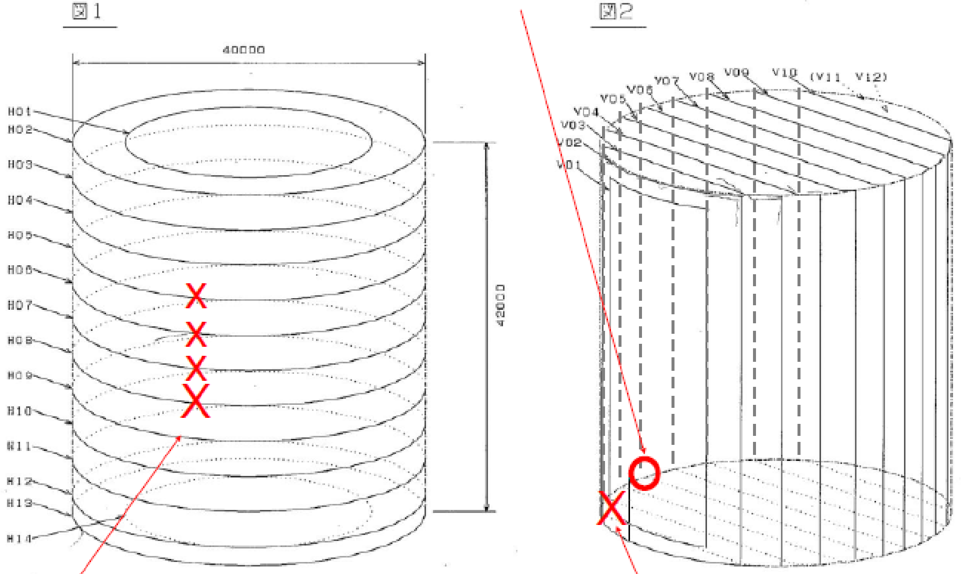


S230924an (DSNB sample)



SK's geomagnetic compensation coil problems and countermeasures

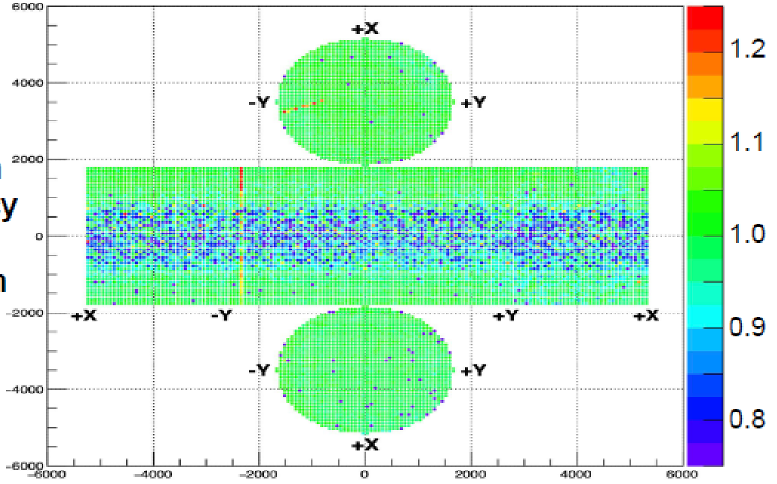
V06 disconnected on Oct.25, 2023.
Damaged sub-cable was bypassed on Dec.1, 2023. [recovered]



H09 disconnected on Dec.8, 2023.
Due to power supply configuration, H06, H07, and H08 are also off.

V01 disconnected on Nov.15, 2023.
V01 was bypassed from the power supply on Dec.2, 2023.

PMT photoelectron collection efficiency ratio, comparing May 2024 condition to nominal



- SK geomagnetic compensation coil cables have failed in three locations.
- At two of locations, part of the coil was successfully bypassed to restore functionality. The other location is entirely underwater, resulting in the entire cable group being turned off.
- A 10-20% decrease in collection efficiency is observed for about 20% of PMTs in the barrel.
- Efficiency for detecting neutron capture on Gd has also decreased by about 3%.
- The physics impact can be compensated by calibration and simulation.
- The likely cause is corrosion of wire connections due to ionized water seeping in under heat shrink insulation.
- SK plans to install six new horizontal coils in summer 2024 to restore the geomagnetic field cancellation.