#### Multi-messenger astronomy in Super-Kamiokande

H. Menjo (Nagoya Univ.) For SK collaboration





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# Super-Kamiokande

Cherenkov light measurement of neutrino interactions using 50,000 t Pure Water



## History of "Kamiokande"



ENERGY (MeV

10

Improvement of neutron detection efficiency

#### **Multi-messenger for Transient events**

- Alert publication
  - Supernova World-best sensitivity
    - 100% efficiency for events in our galaxy
    - Latency of alert from neutrino burst: ~10min ( $\rightarrow$  1min)
- Follow-up observation
  - Coincidence event search with the events
    - GRBs
    - Blazar TXS0506+056 (IceCube)
    - Solar flares
    - GW <u>GW150914+GW151226</u>, <u>GW170817</u> <u>GW in O3a</u> 01 02

**On-time analysis** 

**Off-line** 



#### Follow-up "observation" by SK

- Operation 🗠
  - $\square$  24 hour operation (only ~5% dead time)
  - $4\pi$  acceptance ( $2\pi$  for Up-going muon)

#### SK available for all transient events !!

SK do not need to have a special operation when an alert was received. Only analyze the data corresponding to the event time.

 $\Leftrightarrow$  Telescopes: Pointing, Weather condition, Moon ....

- Statistics (
- - Very small effective area
    - ~  $10^{-4}$  cm<sup>2</sup> @ E<sub>v</sub> = 1 GeV
    - ~ 10 cm<sup>2</sup> @ E<sub>v</sub> = 1 TeV

- Difficult to enlarge detector
- Reduce background

### **Event Categolies**



## Transient follow-up system

- 1. Receive a GW alert (Notice) via NASA-GCN.
- 2. Wait until realtime reduction data becomes available.
- 3. Process the analysis
  - Search the event in the time window (GW: ±500 sec)
  - P-value estimation



# Coincidence event search with GW in O3a

The Astrophysical Journal, Volume 918, Number 2 (2021), <u>arXiv:2104.09196</u>

#### **GW events: GWTC-2**

- Third GW operation (O3) from April 2019 to March 2020  $\rightarrow 56 \text{ alerts published via GCN notice}$
- GWTC-2 covers the first half of O3 (April September)
  → 39 confirmed events including some new events from the realtime alerts

For each GW, we have:

- time of the event
- sky localisation
- estimated distance
- estimated masses of the two objects
- can be roughly classified based on masses  $(m < 3 M_{\odot} = NS, m > 3 M_{\odot} = BH)$



#### **Coincident event search**

- Search window: ±500 sec on GW event time
- Search neutrino candidate events in four samples

Low-energy sample: Comparing the result with the expected background

High-energy sample: Check the reconstructed neutrino direction and GW event localization (GW skymap)

Low-energy sample	FC	<b>High-energy sample</b> PC	s UPMU
Standard solar/SRN selection + 7 MeV energy threshold to ensure stable bkg rate	Standard atmospheric selection		
expected background = 0.729 in 1000 seconds	0.112	0.007	0.016

### Nevents in each GW event



#### **Event direction and GW skymap**



### Significance of each event

 Define the test statistics for separating signal (GW location) and background (uniform) and compute p value



#### GW190602\_175927



The most significant GW+ $\nu$  coincidence is for GW190602\_175927: p = 0.22%

Considering the number of trials (N = 36 follow-ups), we get a **post-trial** p-value:

P = 7.8%

#### No significant event was found in this search

#### Flux limit

Compute the flux upper limit at the observation site.
 assumed the neutrino spectrum of E<sup>-2</sup>



#### Eiso limit

 E<sub>iso</sub>: Total energy of neutrino emission at the source assuming isotropic emission.



#### Prospects of realtime followup by SK

- The realtime process was established in GW-O3.
  - New process to minimize the process time is under development.
  - Defining the procedure to publish the results
- Followup program was under discussion:
  - □ GW-O4: ~1 event per day
  - □ GRB: ~1 event per day
  - High-energy neutrino event by IceCube
  - Novae
  - Solar flare Any suggestions are welcome !!

## Summary

- Searched the neutrino events coincident with 39 GW events in GWTC-2.
  - □ The observed events are equivalent to backgrounds.
  - Flux and Eiso upper limited was estimated for each events and total for each GW event categories.
- SK realtime system for follow-up is basically ready for any type of alerts in GCN notice
  - Improvement of process time from ~ 1 day to one hour
  - Define the filter of events for GW in O4 and GRB