Search for neutrinos in Super-Kamiokande associated with gravitational wave events

2018 July 9th (Mon)

ICNFP2018 & Workshop on Frontiers in Gravitation, Astrophysics and Cosmology

@Kolymbari, Crete Greece

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(Kamioka Observatory, ICRR, The University of Tokyo)

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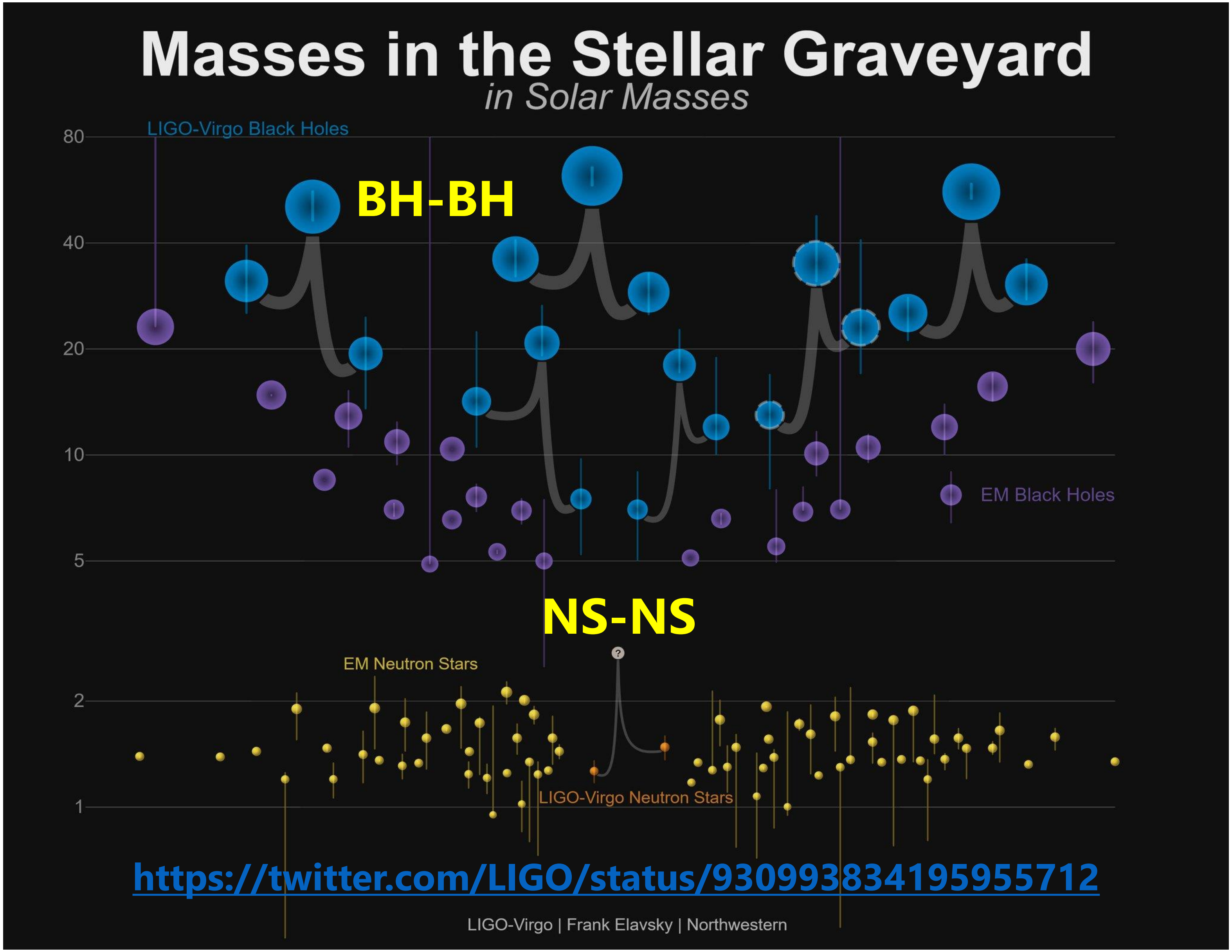
Observation of gravitational wave events



https://twitter.com/LIGO/status/930993834195955712

Motivation of this study

■ Era of multi-messenger

- LIGO-Vergo detected the gravitational wave events in 2015.
  → GW150914, GW151226….
- Many efforts of astronomical counterparts.

■ Experimental search for neutrinos

- No significant neutrino signal has been observed yet.
- Test astrophysical mechanisms of neutrino emission.
- **New physics** if the coincidence of neutrino signal is observed.

Experiment	keV	MeV	GeV	TeV	PeV	EeV
Borexino			250 keV~15 MeV			
KamLAND			1.8 MeV~111 MeV			
Super-Kamiokande			3.5 MeV~100 PeV			
ANTARES				100 GeV~100 PeV		
IceCube				100 GeV~100 PeV		
Pierre Auger			100 PeV~25 PeV			

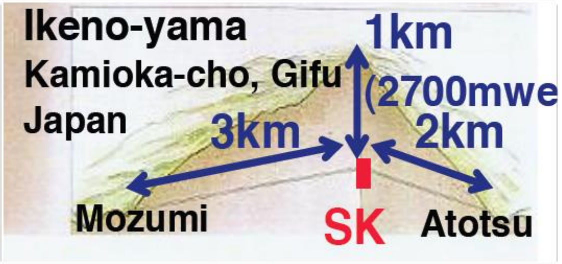
Super-Kamiokande

Super-Kamiokande collaboration

~165 people
45 institutes, 9 countries

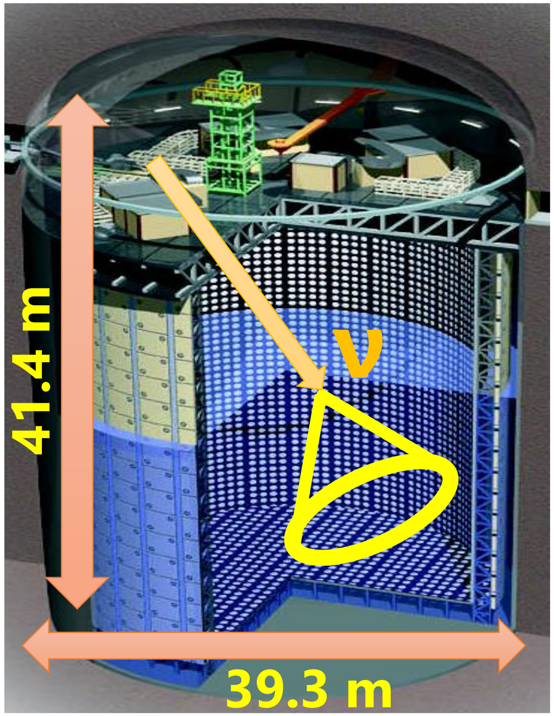
Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
Imperial College London, UK
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
The University of Winnipeg, Canada
Yokohama National University, Japan

Super-Kamiokande (SK)



■ 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.
- Long term operation since 1996 (~22 yrs).



■ Physics target

- Atmospheric neutrino
- Astrophysical neutrino (solar, supernova)
- Proton decay
- Long base line neutrino (T2K)
- Dark matter search etc…

Solar ν 3.5-20 MeV | Supernova ν 20-100 MeV | Atmospheric ν and proton decay ~100 MeV GeV TeV PeV

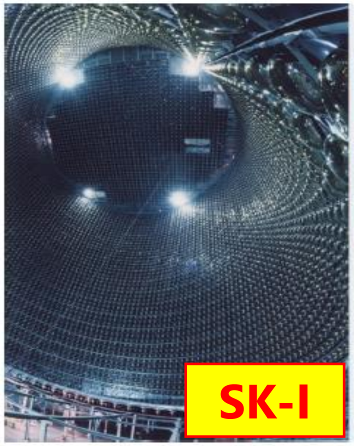
History of Super-Kamiokande

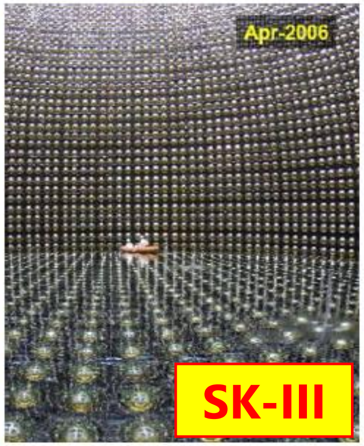
■ Brief history and current status

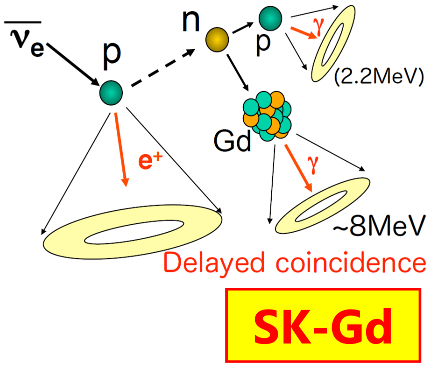
- SK-I started on 1996 April and SK-IV ended on 2018 May.
- Total live time is more than **5,500 days**.
- Refurbishment works **toward SK-Gd** have started since May 31st.

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
SK-I						SK-II				SK-III		SK-IV											SK-Gd	
PMT 11,146 (40%*)						5,182 (19%*)				11,129 (40%*)														
4.5 MeV**						6.5 MeV**				4.0 MeV**			3.5 MeV**											

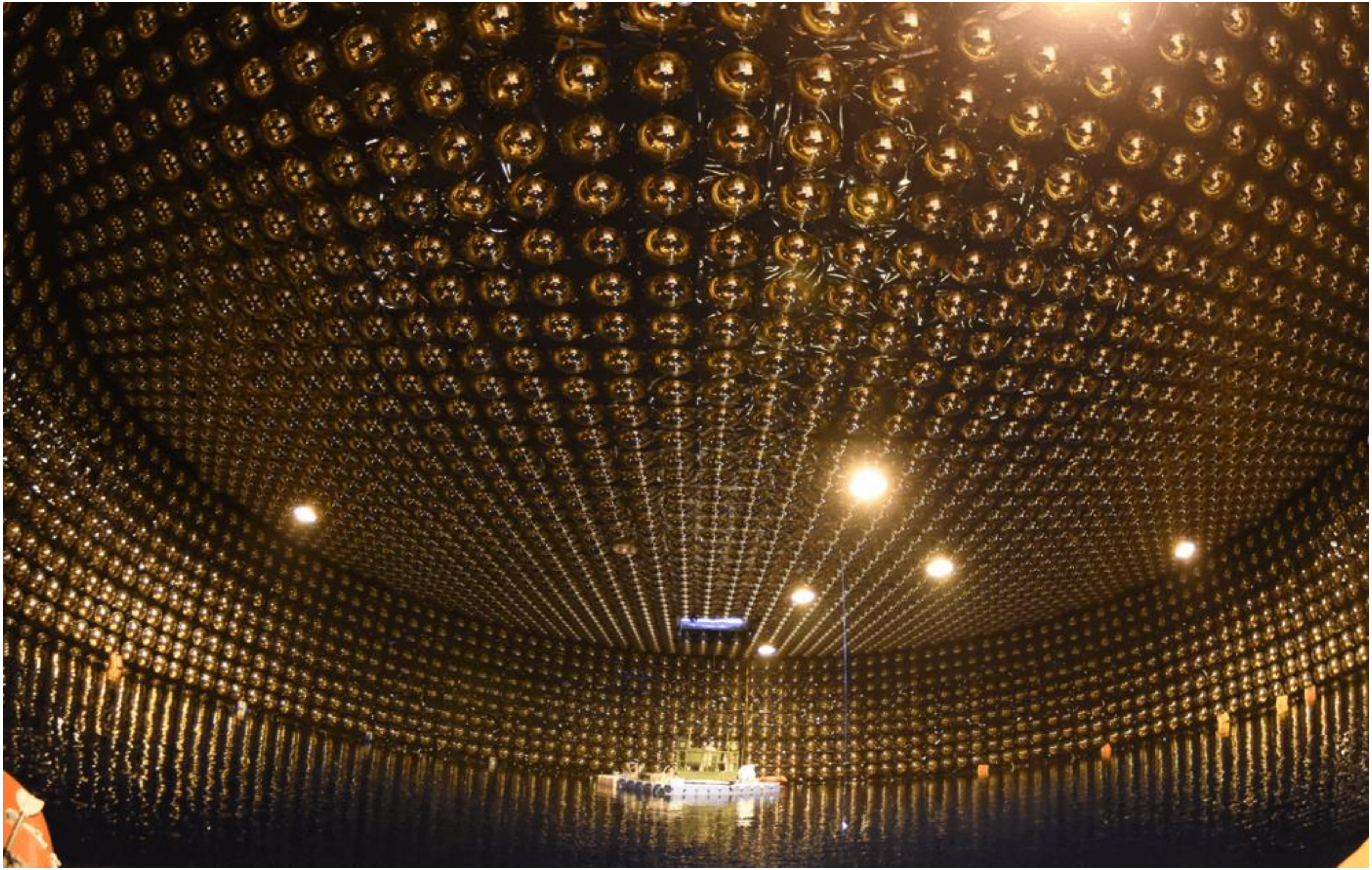
* Photo coverage [%], ** Recoil electron kinetic energy [MeV].







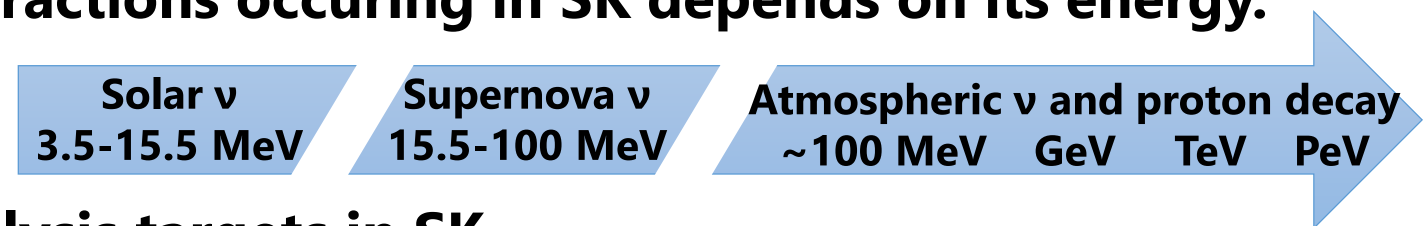
Inside of the detector



Neutrino analysis in SK

■ Analysis targets in SK

- SK has sensitivity to a **wide** neutrino energy range:
  → From multi-MeV region to 100 PeV.
- Interactions occuring in SK depends on its energy.

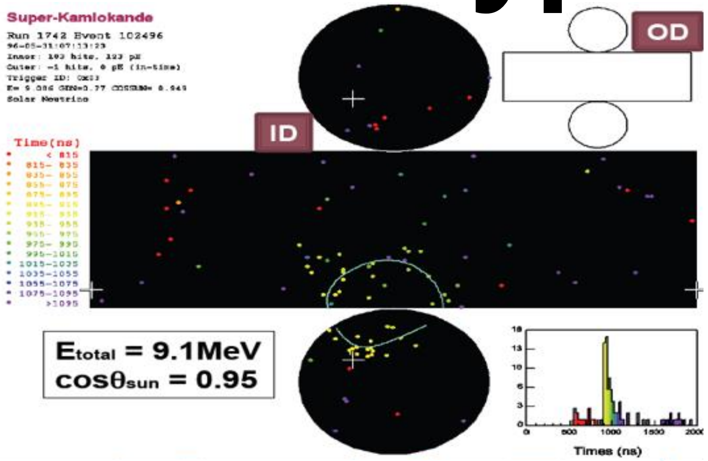


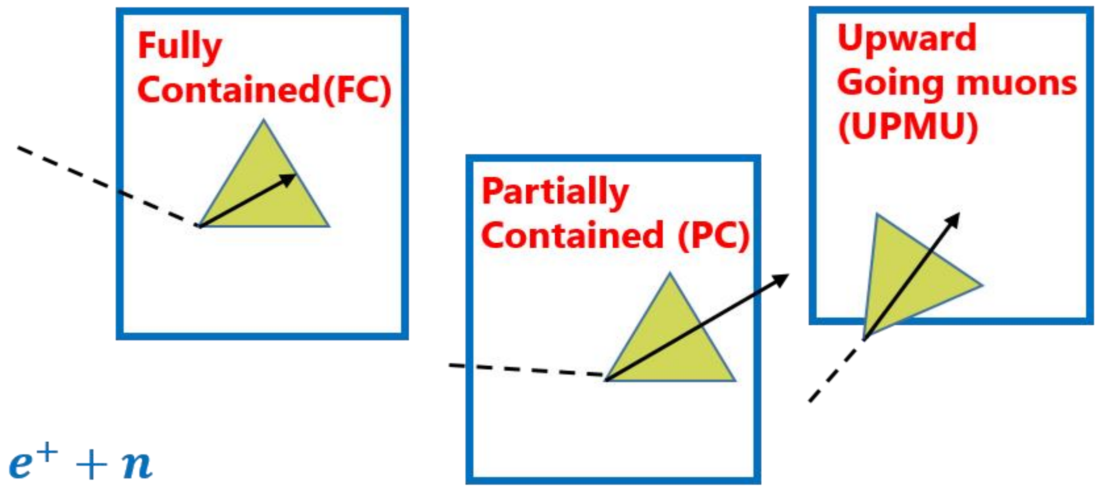
■ Analysis targets in SK

- **3 analysis samples** are available according to its energy.
  → Difference of topology of event in SK.

Sample name	Energy range	Specific category
Low energy	3.5-15.5 MeV	Solar neutrino
	15.5-100 MeV	Relic neutrino
High energy	100 MeV – 100 PeV	Fully Contained (FC) Partially Contained (PC) Up-going muon (UPMU)

Typical event in SK

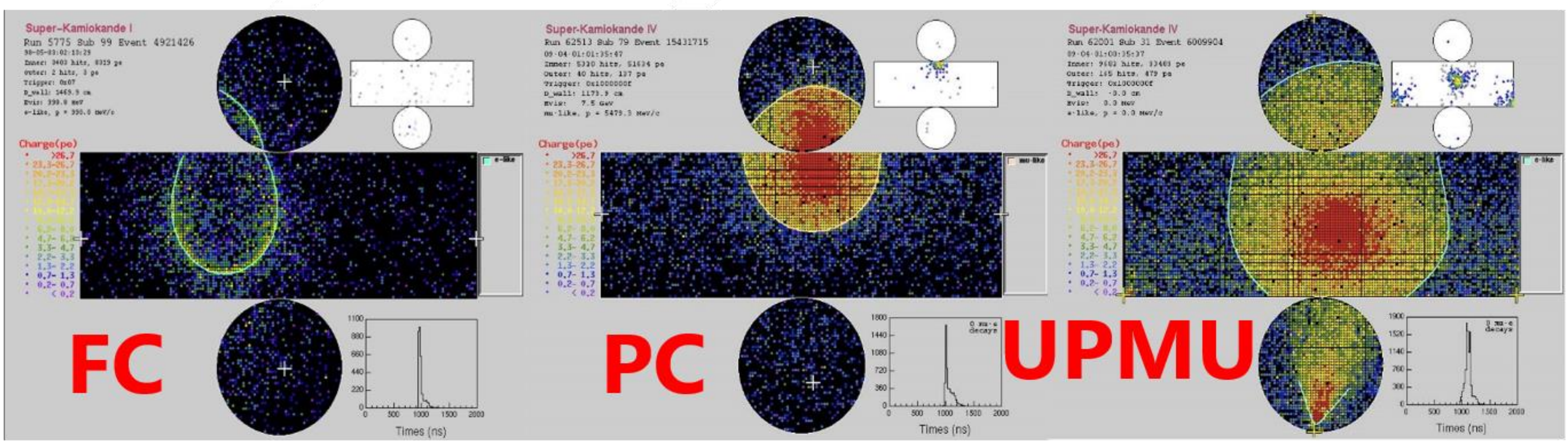




$\nu_x + e^- \rightarrow \nu_x + e^-$ $\overline{\nu_e} + p^+ \rightarrow e^+ + n$

Angular resolution ~23°@10 MeV ~15°@1 GeV

Solar ν 3.5-15.5 MeV | Supernova relic ν 15.5-100 MeV | Atmospheric ν and so on: 100 MeV, GeV, TeV, PeV



BH-BH merger (GW150914 & GW151226)

Search for ν from BH-BH merger

■ Observation of BH-BH merger

GW150914: Phys. Rev. Lett. 118, 061102 (2016)
GW151226: Phys. Rev. Lett. 116, 241103 (2016)
Fermi: Astrophys. J. Lett. 826, L6 (2016)

- No counterpart except for Fermi-LAT.

GW event	Time [UTC]	Astronomical counterpart
GW150914	9:50:45	Fermi-LAT ~0.4 second later
GW151226	3:38:53	---

■ Theoretical models

- No theory of neutrino generation associated with BH-BH merger.
  → Possibility of high energy ν emission from relativistic jet when accretion disk is formed around source.

Nature 340, 126 (1989)
Astrophys. J. 405, 273 (1993)

■ Data acquisition status in SK

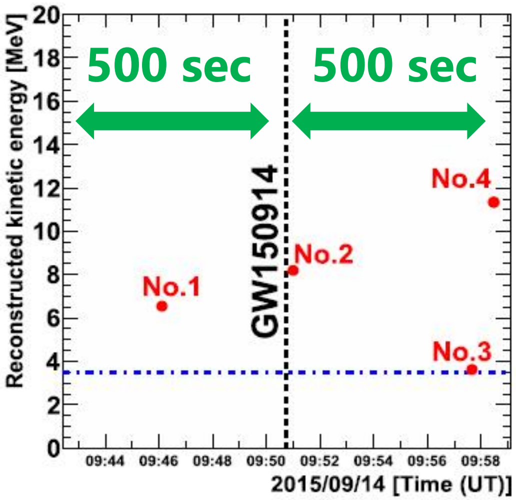
- Physics data-taking was operated at the time when both mergers.
- Searching for neutrino-like event within ±500 seconds.

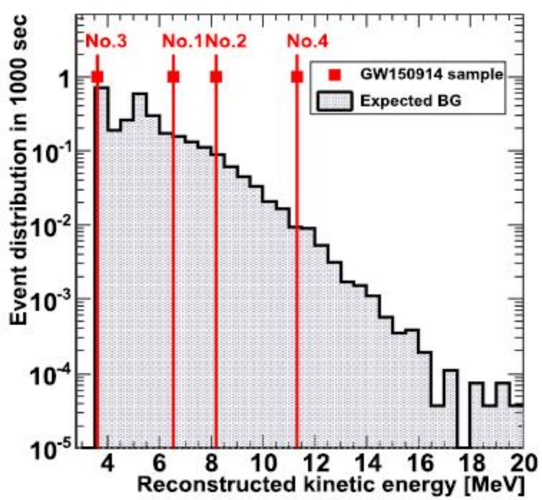
Neutrino signal in SK (BH-BH)

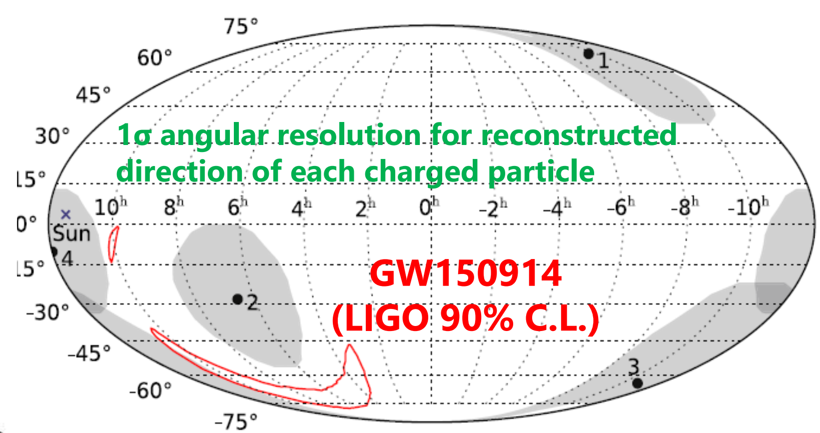
■ GW150914

- **4 events** remain below 15.5 MeV (in solar sample).
  No.1 & 2: Spallation event (Next page)
  No.3: Radon daughter event
  No.4: Solar neutrino event
- 4 or more events passing the reduction cuts → **33.0%**.

Expected BG:
2.90±0.01 event/1000 sec



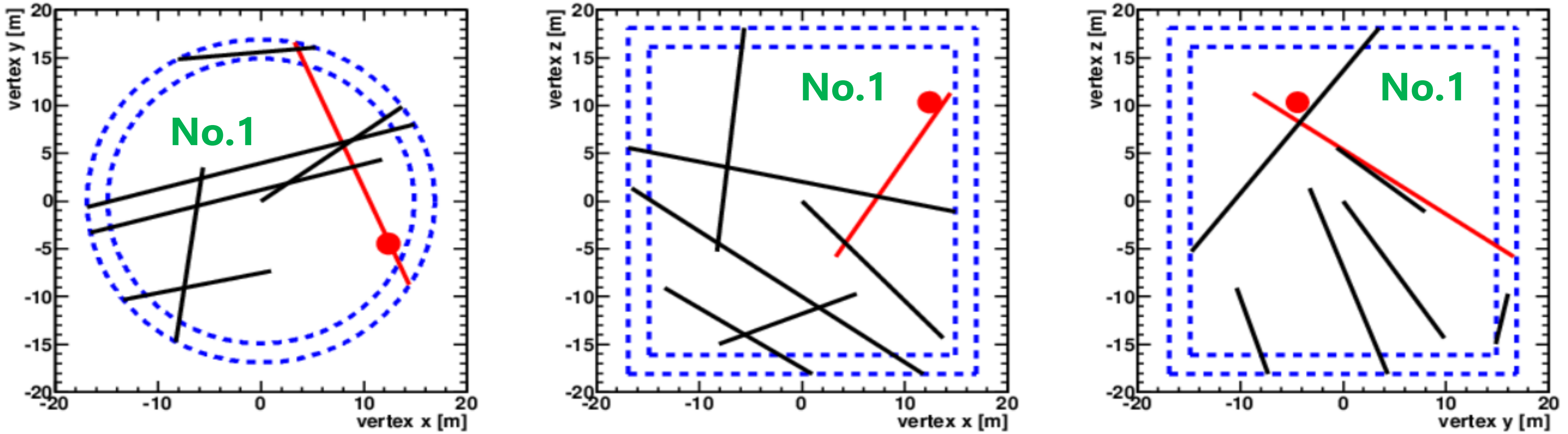




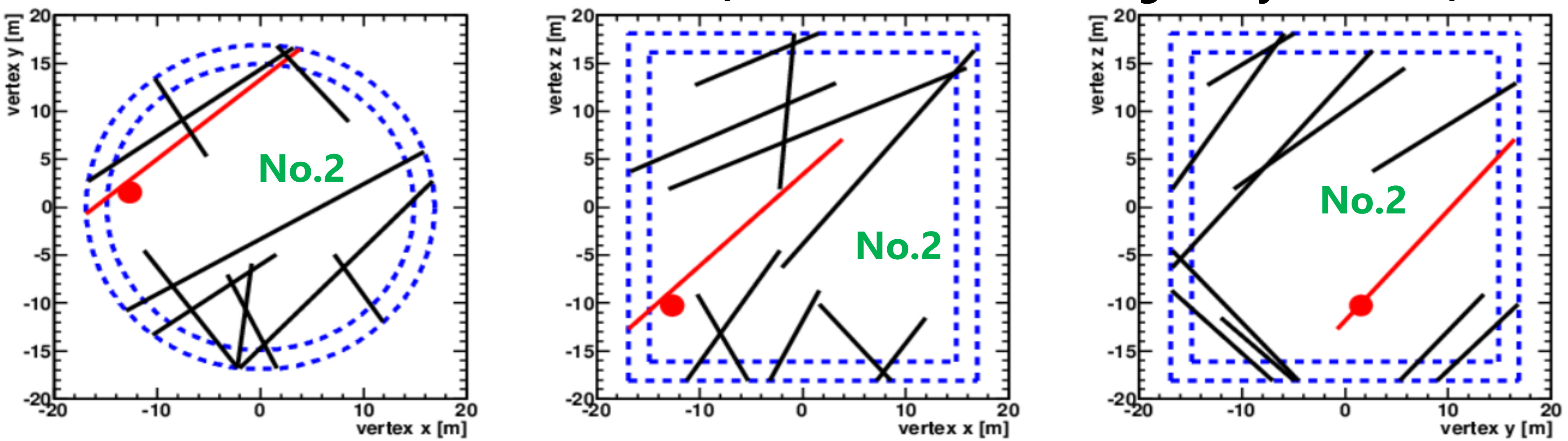
■ GW151226

- **No event** is found around GW151226 in SK.
- 0 events passing the reduction cuts → **5.5%**.

Event No.1 & 2 (spallation BG)



Time difference between the event and preceding muon
No.1 → 10.77 sec, No.2 → 17.38 sec. (^{16}N BG since it has long decay constant)



Fluence limits for BH-BH (MeV region)

■ Assumption of energy spectrum

- No reason for power spectrum
  → **index 0 (flat)** is used.

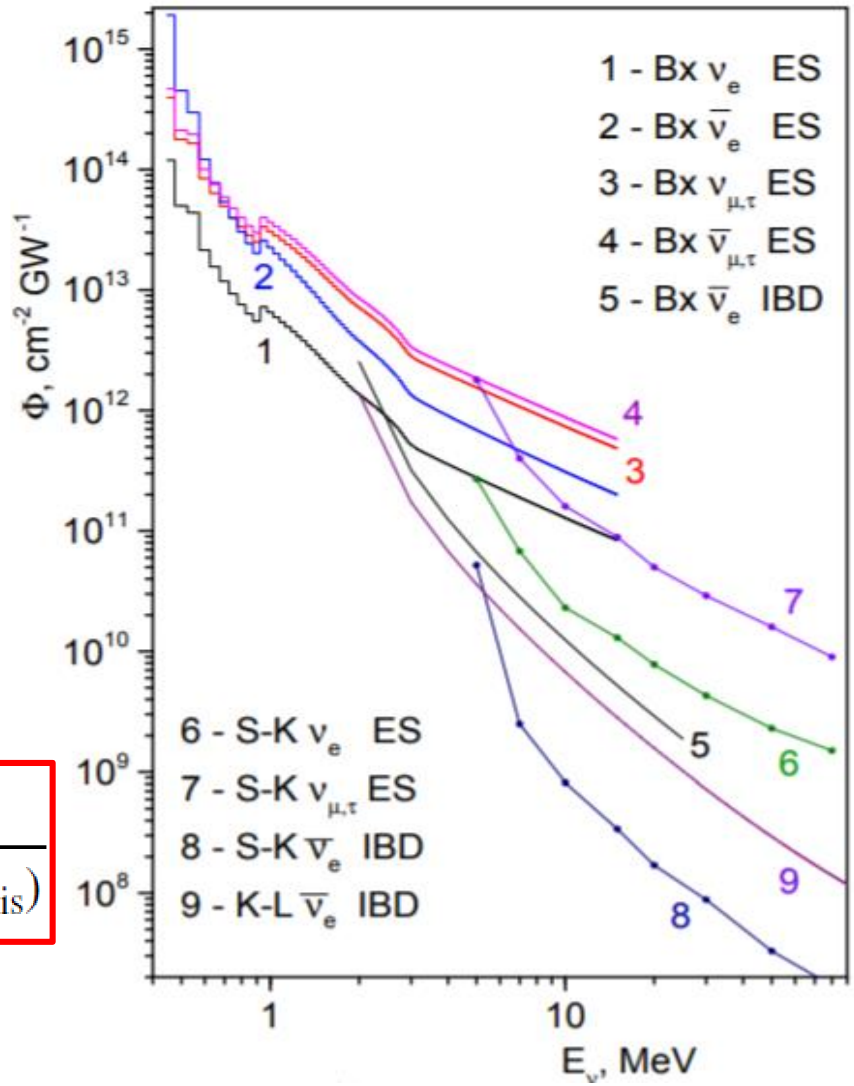
■ Fluence calculation

- Energy range: Solar+Relic sample.
  → 3.5 MeV – 100 MeV.
- Considering:
  (1) Target (N_T)
  (2) Cross section (σ)
  (3) Detector response (*R*)
  (4) Reduction efficiency (*ε*)

$$\Phi_{\rm lowe} = \frac{N_{90}}{N_T \int dE_\nu \lambda(E_\nu) \sigma(E_\nu) R(E_e, E_{\rm vis}) \epsilon(E_{\rm vis})}$$

- Best limit above ~5 MeV.

Astrophys. J. 850, 21 (2017)



Fluence limits for BH-BH (Above 100 MeV)

■ Fluence limit for high energy sample

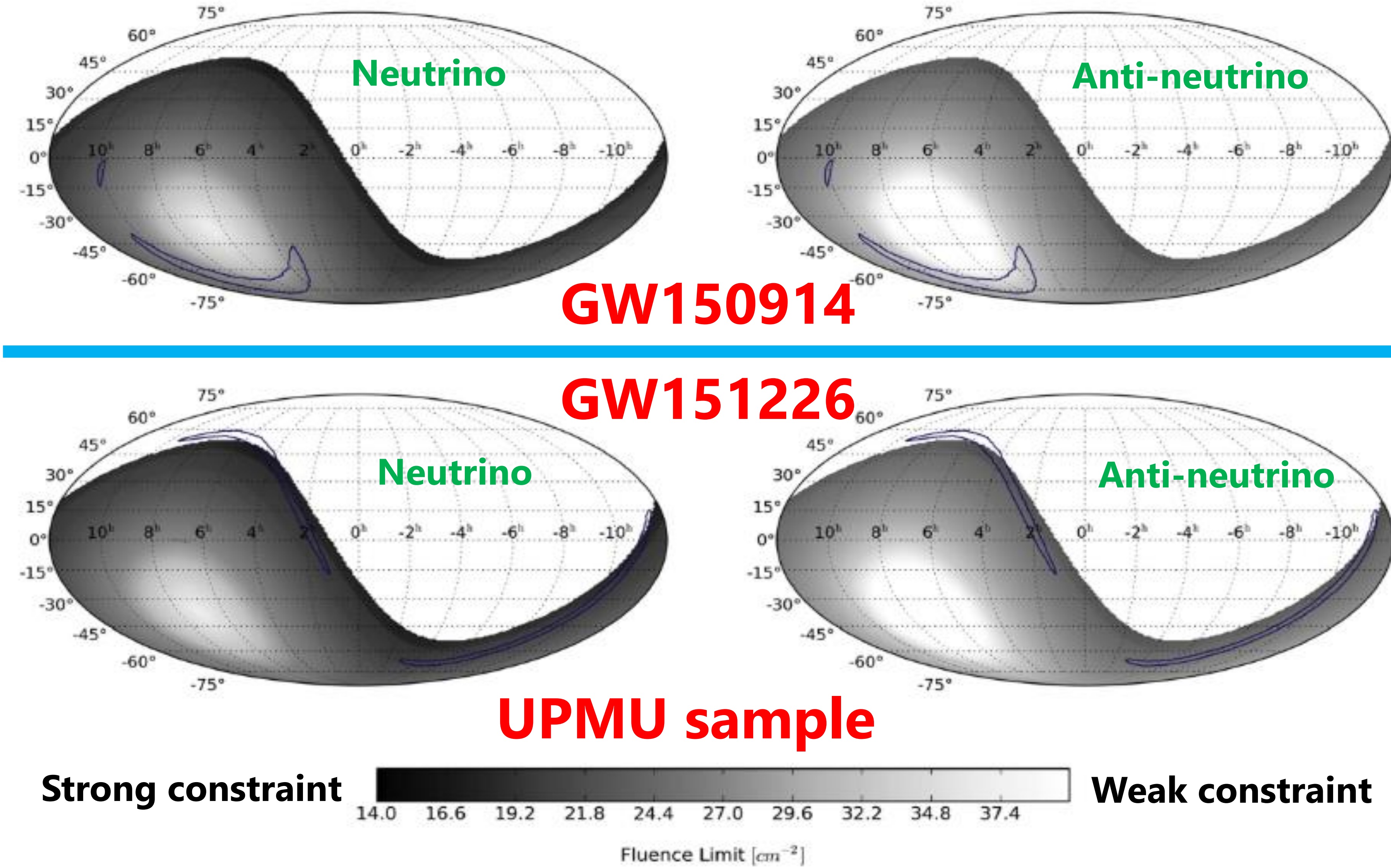
- Assumption of energy spectrum: power spectrum with index -2.
- FC+PC sample: basically same as low energy sample
- UPMU sample: Zenith angle dependence *Aeff(z)*
  Shadow effect of the earth *S(z,E)*

Sample	Energy range	Fluence calculation
FC+PC	100 MeV- 10 GeV	$\Phi_{\mathrm{FC,PC}} = \frac{N_{90}}{N_T \int dE_\nu \sigma(E_\nu) \epsilon(E_\nu) \lambda(E_\nu^{-2})}$
UPMU	1.6 GeV-100 PeV	$\Phi_{\mathrm{UPMU}} = \frac{N_{90}}{A_{\mathrm{eff}}(z) \int dE_\nu P(E_\nu) S(z, E_\nu) \lambda(E_\nu^{-2})}$

	GW150914 Φ_ν (cm^{-2})	GW151226 Φ_ν(cm^{-2})	Combined Φ_ν (cm^{-2})
	From FC+PC only		
ν_μ	5.6×10^4	5.6×10^4	2.8×10^4
$\bar{\nu}_\mu$	1.3×10^5	1.3×10^5	6.5×10^4
ν_e	4.8×10^4	4.8×10^4	2.4×10^4
$\bar{\nu}_e$	1.2×10^5	1.2×10^5	6.0×10^4
	From UPMU only		
ν_μ	14–37	14–37	...
$\bar{\nu}_\mu$	19–50	19–50	...

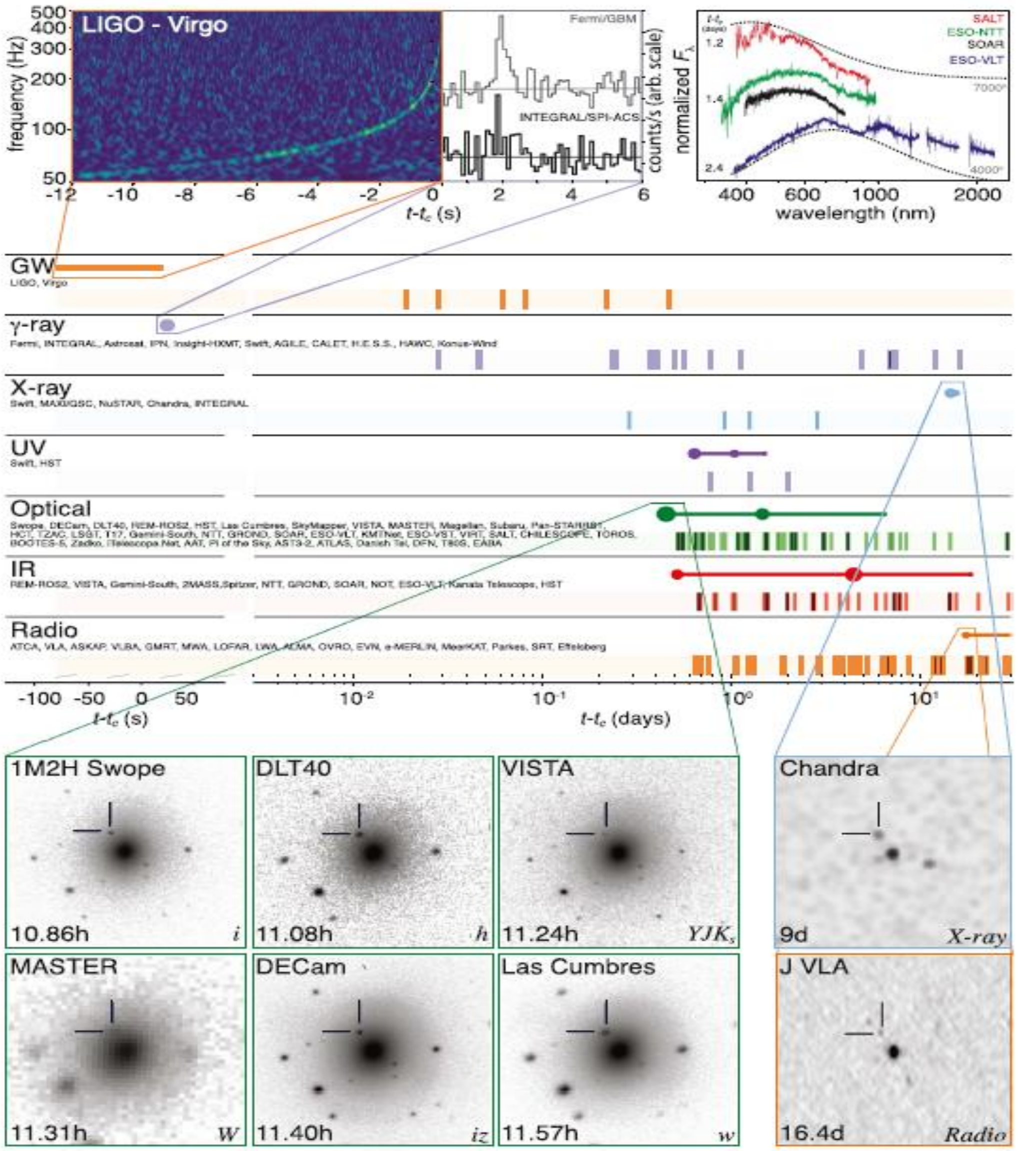
Fluence limits for BH-BH (Above 100 MeV)

■ Fluence limit for high energy sample



NS-NS merger

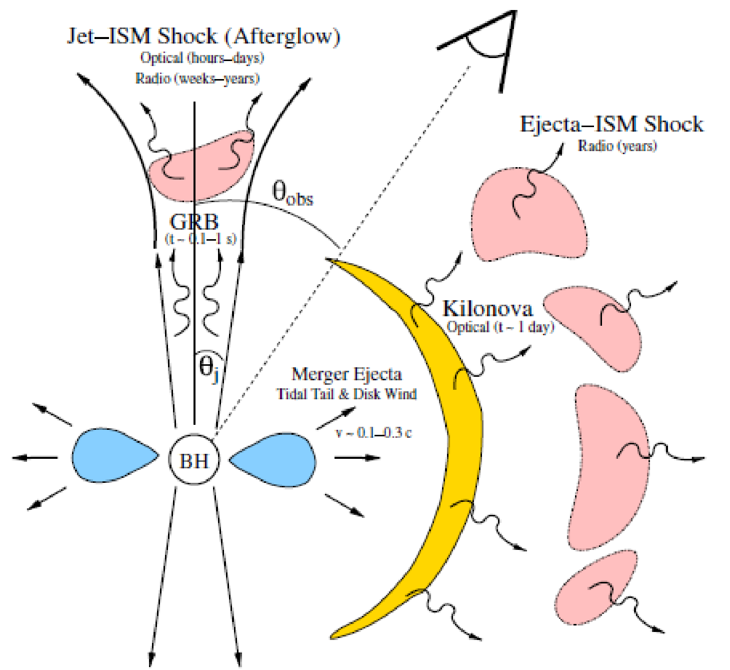
Search for ν from NS-NS merger



GW170817: Astrophys. J. Lett. 848, L12 (2017)

■ GW170817 (GRB170817A)

- **Binary neutron star merger**
- Radiation energy
  → 4.5×10^{52} erg.
- Multi-messenger detection
  → **Short gamma-ray burst**
  kilonova/micronova

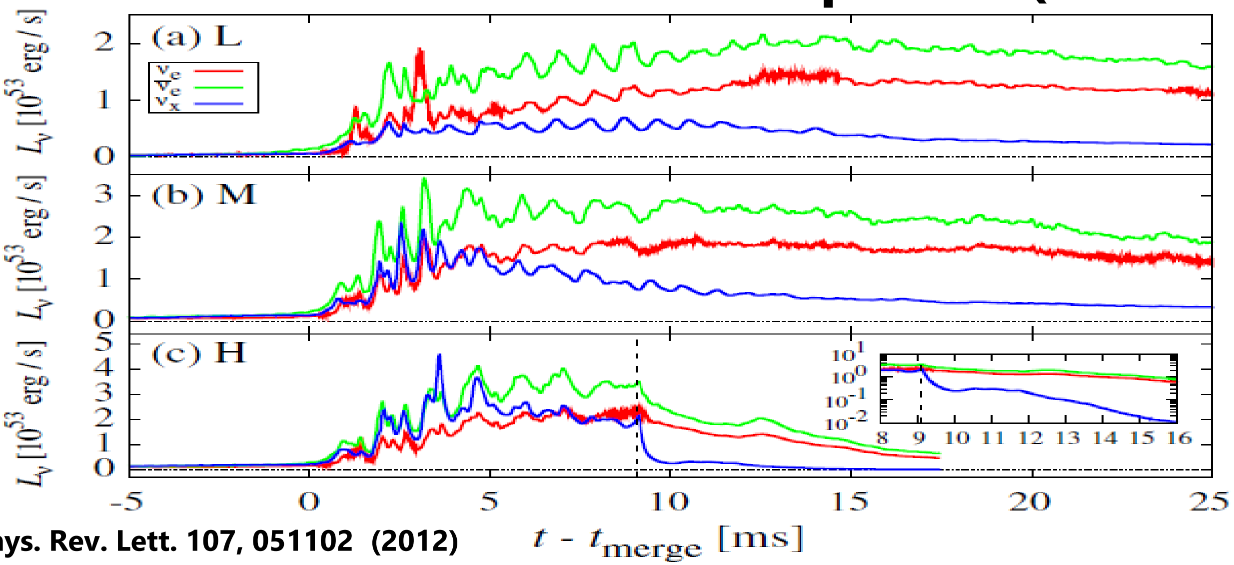


GW170817: Astrophys. J. 746, 48 (2012)

Search for ν from NS-NS merger

■ Models of neutrino emission

- Many models of neutrino emission are proposed.
  → High energy ν (10^{14} eV) in relativistic ejecta.
  → Similar mechanism as for core-collapse SN (simulation base).



Phys. Rev. Lett. 107, 051102 (2012)

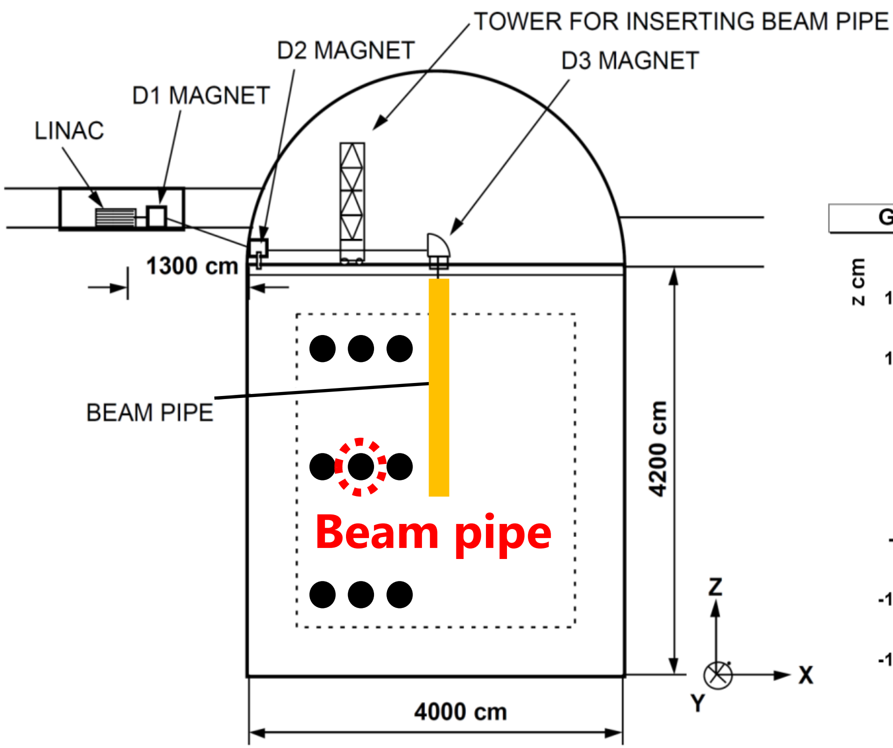
■ Data acquisition status in SK

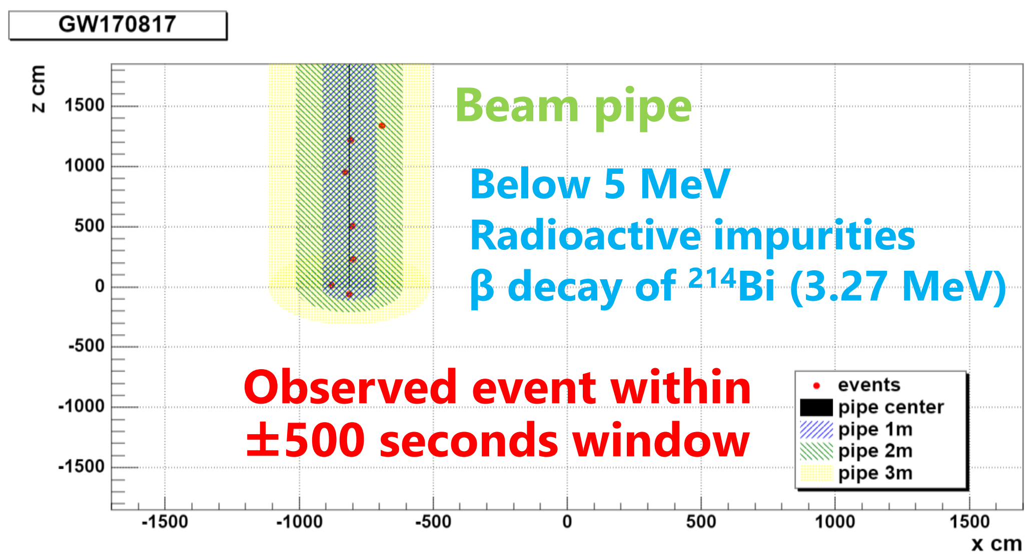
- Searching for neutrino-like event **within ±500 seconds**.
→ Fortunately, data-taking was operated at the time of merger.
→ However, we had taken **LINAC calibrations** from Aug 3rd to 22nd.
- **14-day time window** relevant for longer-lived emission process.

Neutrino signal (NS-NS) in ±500s

■ GW170817 (±500 seconds)

- **No event** is found in all samples in ±500 seconds.
  → 7 events are found on the surface of the LINAC beam pipe.
  Just after extending the beam pipe (No beam).
  → They are removed by the calibration source cut (2m).



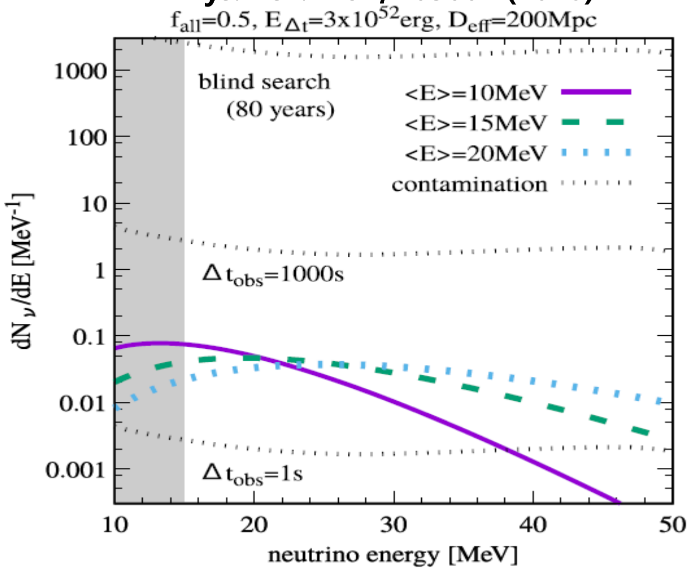


Fluence limits in ±500s

■ Fluence of GW170817 (±500 seconds)

- Same method used in BH-BH merger.
- Expected neutrino energy spectrum is simulated in case of BNS merger.
  → Newly analyze Fermi-Dirac spectrum in low energy sample.

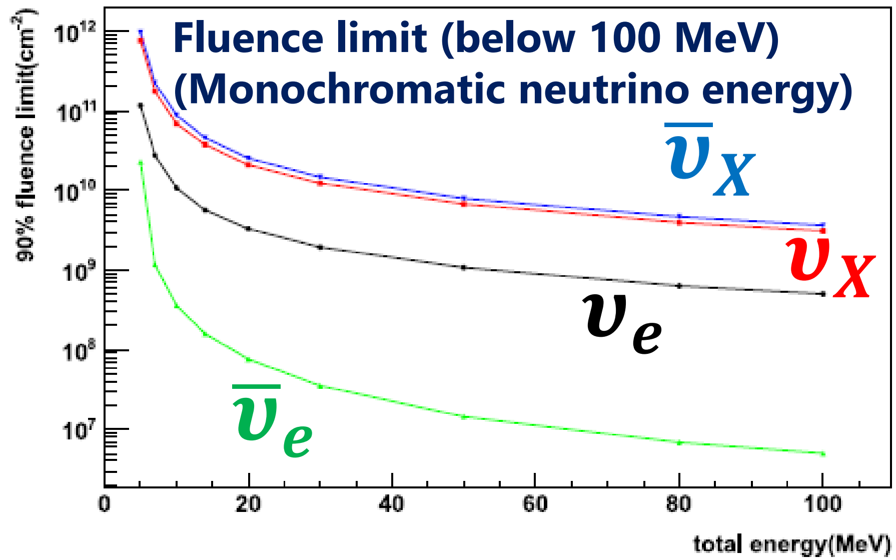
Phys. Rev. D 97, 103001 (2018)



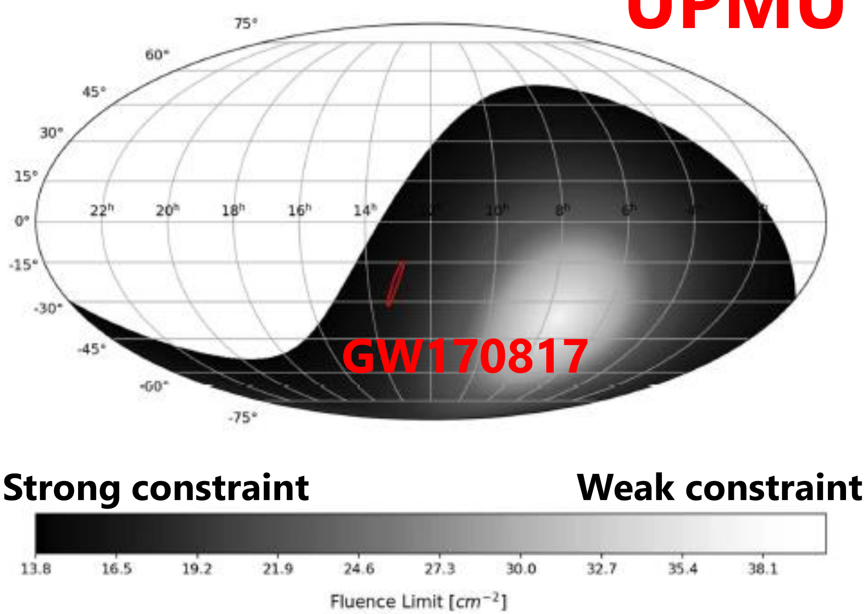
Sample	Energy range	Energy spectrum	Fluence calculation
LOWE	3.5 MeV 100 MeV	Flat (index 0) Fermi-Dirac (E_{ave}=20 MeV)	$\Phi_{lowe} = \frac{N_{90}}{N_T \int dE_\nu \lambda(E_\nu)\sigma(E_\nu)R(E_e, E_{vis})\epsilon(E_{vis})}$
FC+PC	100 MeV 10 GeV	Index -2	$\Phi_{FC,PC} = \frac{N_{90}}{N_T \int dE_\nu \sigma(E_\nu)\epsilon(E_\nu)\lambda(E_\nu^{-2})}$
UPMU	1.6 GeV 100 PeV	Index -2	$\Phi_{UPMU} = \frac{N_{90}}{A_{eff}(z) \int dE_\nu P(E_\nu)S(z, E_\nu)\lambda(E_\nu^{-2})}$

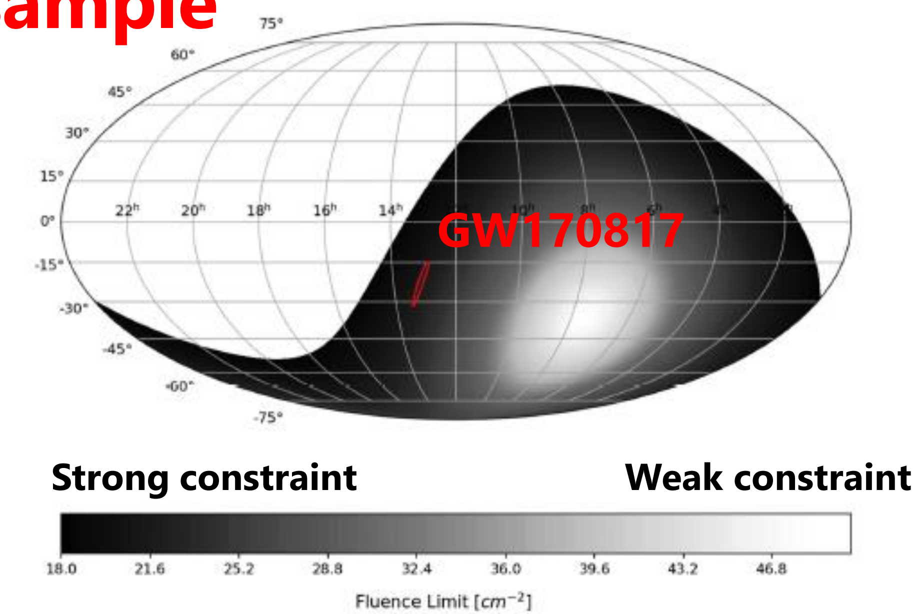
Fluence limits in ±500s

GW170817 Φ_ν (cm^{-2})		
	from FC+PC only	from UPMU only
ν_μ	5.6×10^4	$16.0^{+0.7}_{-0.6}$
$\bar{\nu}_\mu$	1.3×10^5	$21.3^{+1.1}_{-0.8}$
ν_e	4.8×10^4	...
$\bar{\nu}_e$	1.2×10^5	...
	from low-energy only flat spectrum	Fermi–Dirac with $E_{ave} = 20$ MeV
$\bar{\nu}_e$	1.2×10^7	6.6×10^7
ν_e	1.0×10^9	3.4×10^9
$\bar{\nu}_x$	7.5×10^9	2.6×10^{10}
ν_x	6.3×10^9	2.1×10^{10}



UPMU sample





Observed events in following 14 days

■ Following 14-day time window

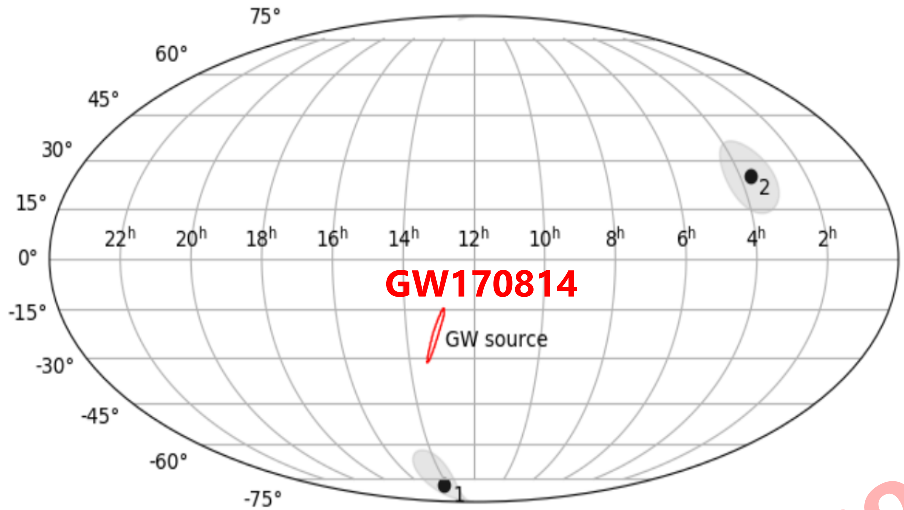
- Due to the calibration, solar sample has large background.
  → Many radioactive impurities in SK pure water.
- Other samples are checked.
  → No significant neutrino signal over the background is observed.

Sample	Livetime	Observed [event/livetime]	Expected [event/livetime]
Solar	After LINAC calibration	Many radioactive impurities	--
Relic	9.15	2±1.41	$(1.93\pm0.08)\times10^{-3}$
FC	11.30	76±8.72	91.44±0.57
PC	11.30	8±2.83	7.35±0.23
UPMU	11.30	13±3.61	16.05±0.23
UPMU (<5°)*	11.30	0	$(6.11\pm0.04)\times10^{-2}$

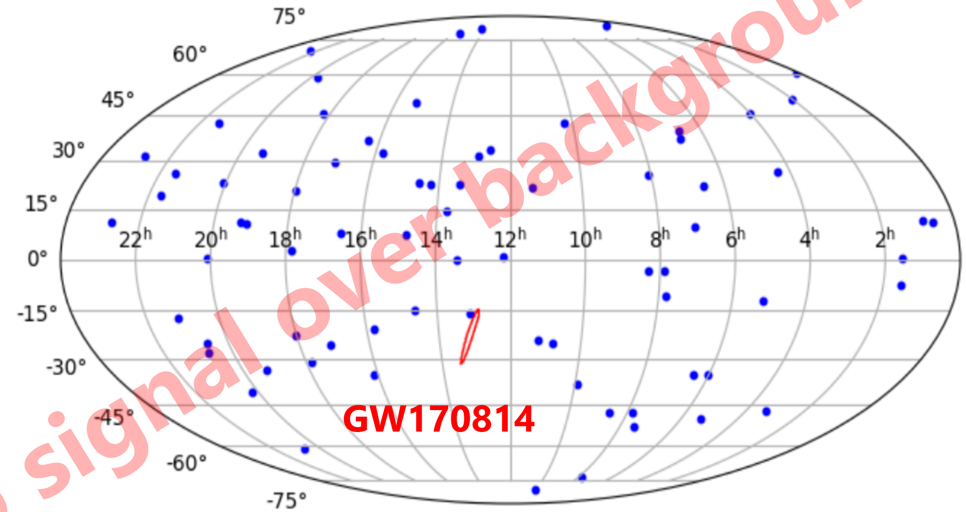
(*)The UPMU events are higher in energy than the other topologies and therefore the detected lepton points back to the incoming neutrino with more accuracy, allowing for a smaller search cone.
See detail: Astrophys. J. Lett. 850 (2017) 116.

Following 14 days for all sky

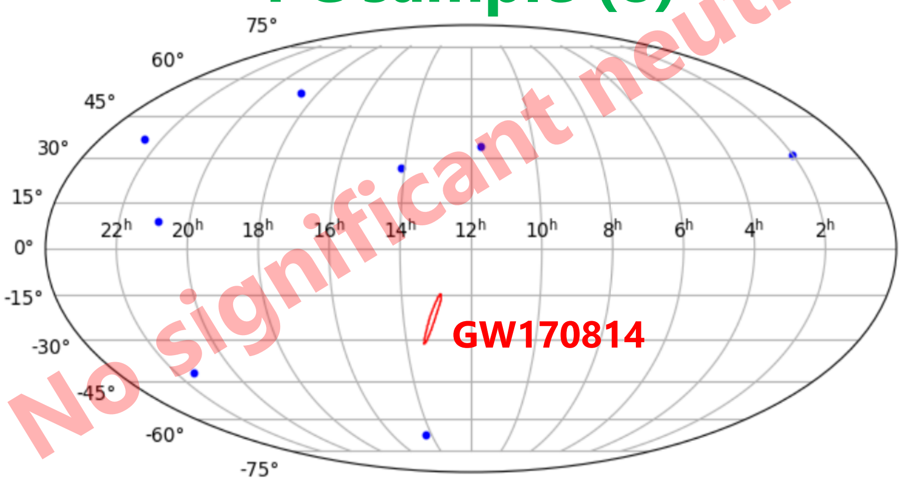
Relic sample (2)



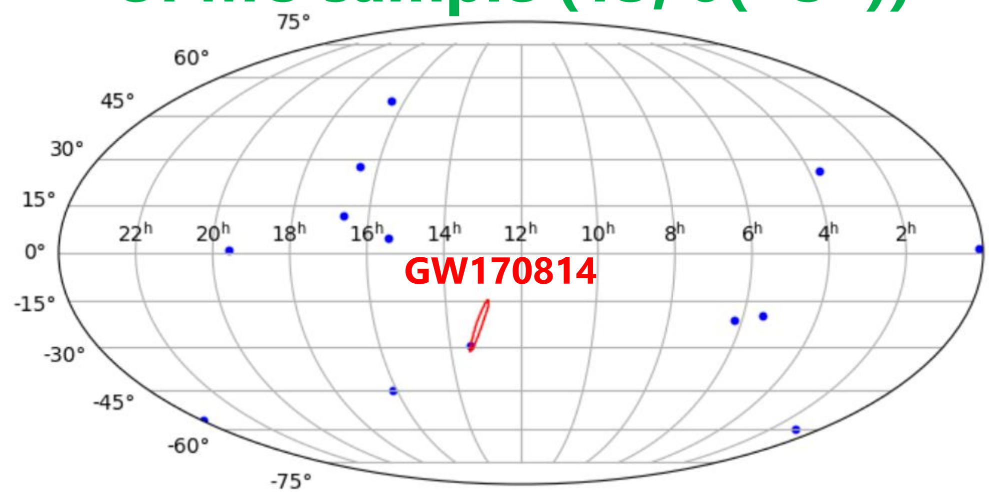
FC sample (76)



PC sample (8)



UPMU sample (13, 0(<5°))



No significant neutrino signal over background

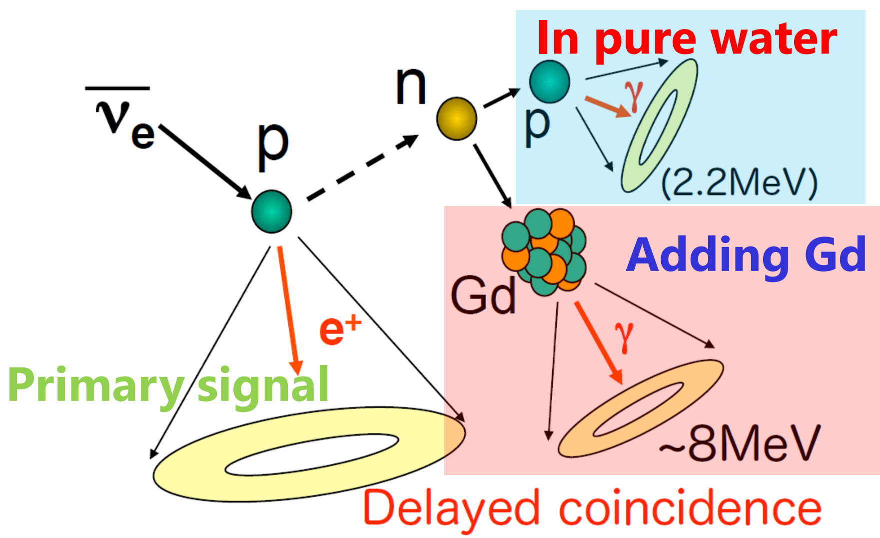
Future prospects and summary

Future prospects

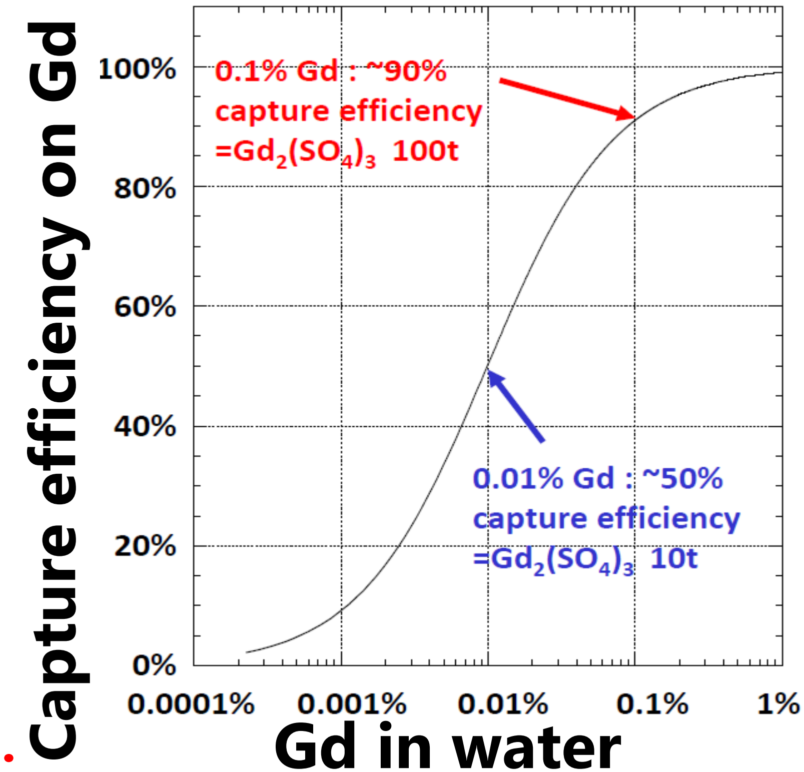
■ SK-Gd project

- Current SK observation is not enough to distinguish $\nu_e/\overline{\nu}_e$.
- Adding Gd enhances the detection efficiency of $\overline{\nu}_e + p \rightarrow e^+ + n$.
  → Delayed coincidence technique by neutron tagging.
- More precise measurement of neutrino flux is expected.

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



Time difference: ~30 μsec, Vertex : ~50 cm.



Summary

■ Era of Multi-messenger

- The observation of the gravitational wave events opens new window for understanding our universe.
- Multi-messenger astrophysics has been started.

■ Super-Kamiokande

- Multi-purpose detector.
- Chance to search for neutrino from Multi-MeV to PeV region.

■ GW150814 & GW151226

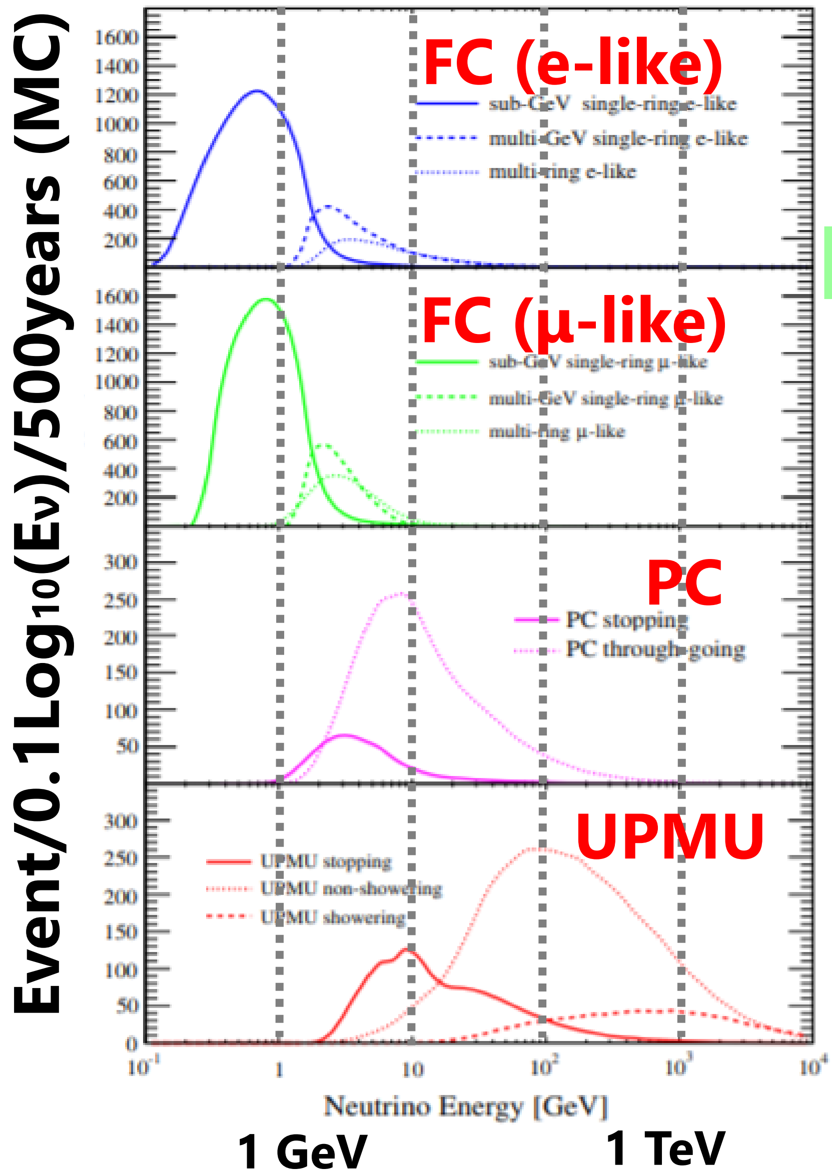
- 4 events remain within ±500 seconds (consistent with BG).
- Set the 90% neutrino fluence limits for both merge events.

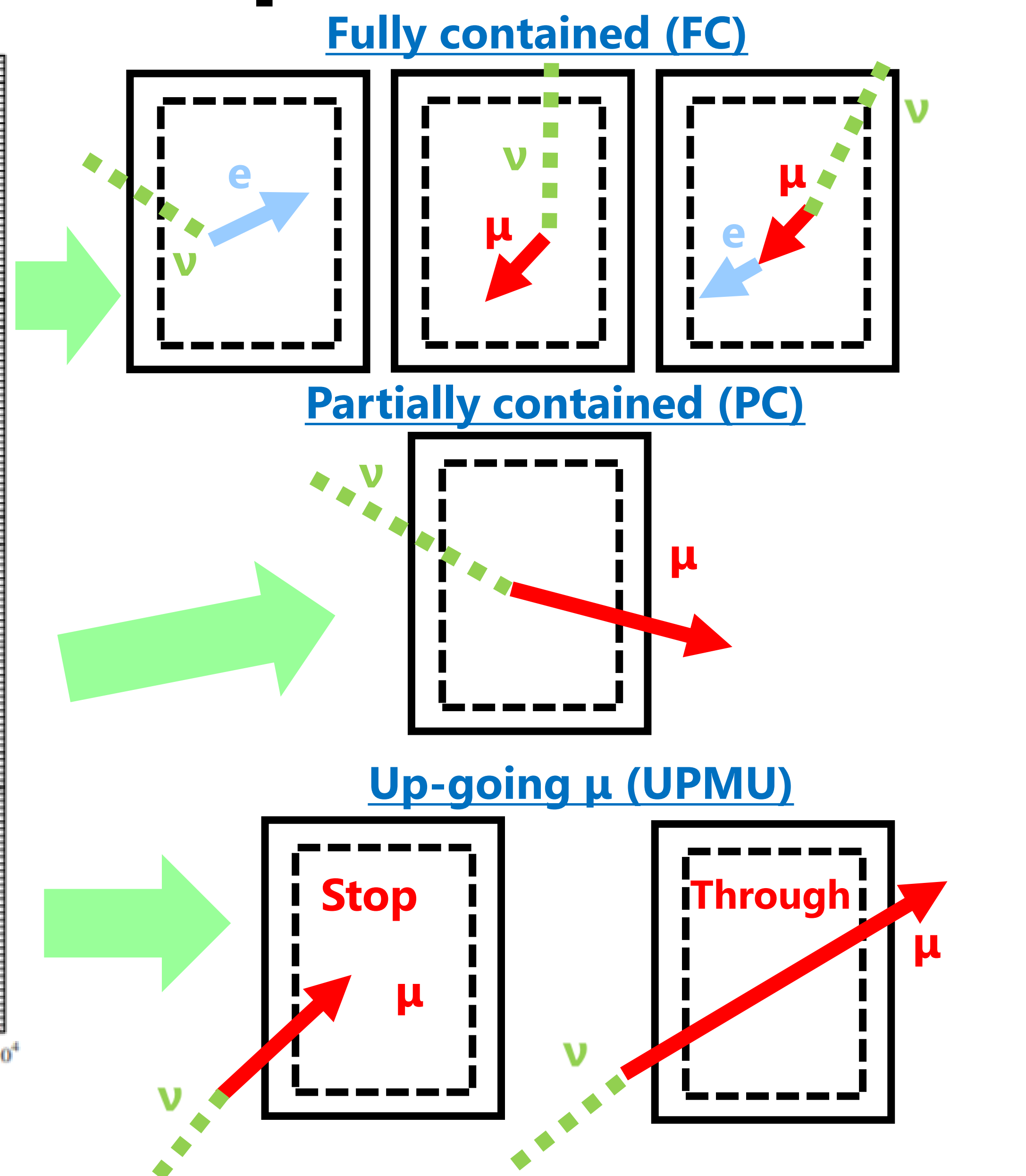
■ GW170817

- No events remain within ±500 seconds.
- No significant signal over BG is observed in following 14 days.
- Set the 90% neutrino fluence limits for GW170817.

Back up slides

Topologies of atmospheric ν events





Spallation products in SK

Isotope	$\tau_{1/2}$ [sec]	decay mode	Kinetic Energy [MeV]
$^{8}_{2}\mathrm{He}$	0.119	β^- β^-n	$9.67 + 0.98(\gamma)$ 16%
$^{8}_{3}\mathrm{Li}$	0.838	β^-	~ 13
$^{8}_{3}\mathrm{B}$	0.77	β^+	13.9
$^{9}_{3}\mathrm{Li}$	0.178	β^- β^-n	13.6(50.5%) ($\sim$ 50%)
$^{9}_{6}\mathrm{C}$	0.127	β^+n	$3 \sim 15$
$^{11}_{3}\mathrm{Li}$	0.0085	β^- β^-n	$16 \sim 20(\sim 50\%)$ $\sim 16(\sim 50\%)$
$^{11}_{4}\mathrm{Be}$	13.8	β^-	11.51(54.7%) $9.41 + 2.1(\gamma)(31.4\%)$
$^{11}_{4}\mathrm{Be}$	13.8	β^-	11.71
$^{12}_{5}\mathrm{B}$	0.0236	β^-	13.37
$^{12}_{7}\mathrm{N}$	0.0110	β^+	16.32
$^{13}_{5}\mathrm{B}$	0.0174	β^-	13.44
$^{13}_{8}\mathrm{O}$	0.086	β^+	13.2 or 16.7
$^{14}_{5}\mathrm{B}$	0.0138	β^-	$14.55 + 6.09(\gamma)$
$^{15}_{6}\mathrm{C}$	2.449	β^-	9.77(36.8%) $4.47 + 5.30(\gamma)$
$^{16}_{6}\mathrm{C}$	0.747	β^-n	~ 4
$^{16}_{7}\mathrm{N}$	7.13	β^-	10.42(28.0%) $4.29 + 6.13(\gamma)(66.2\%)$

LINAC calibration