Search for GRB neutrinos at SK (and HK)

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2022.3.25

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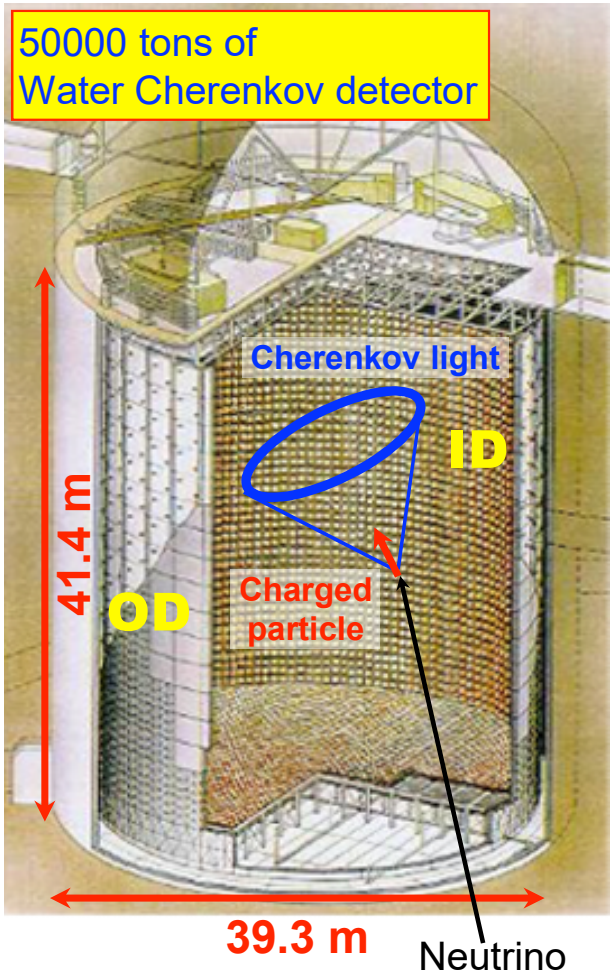
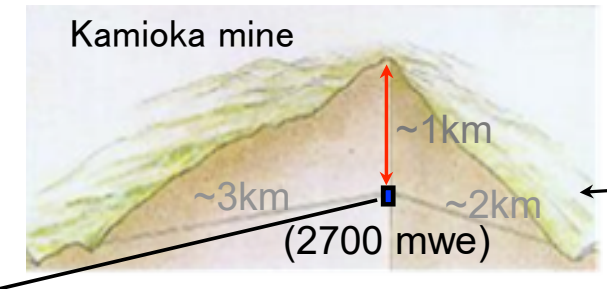
Super-Kamiokande detector

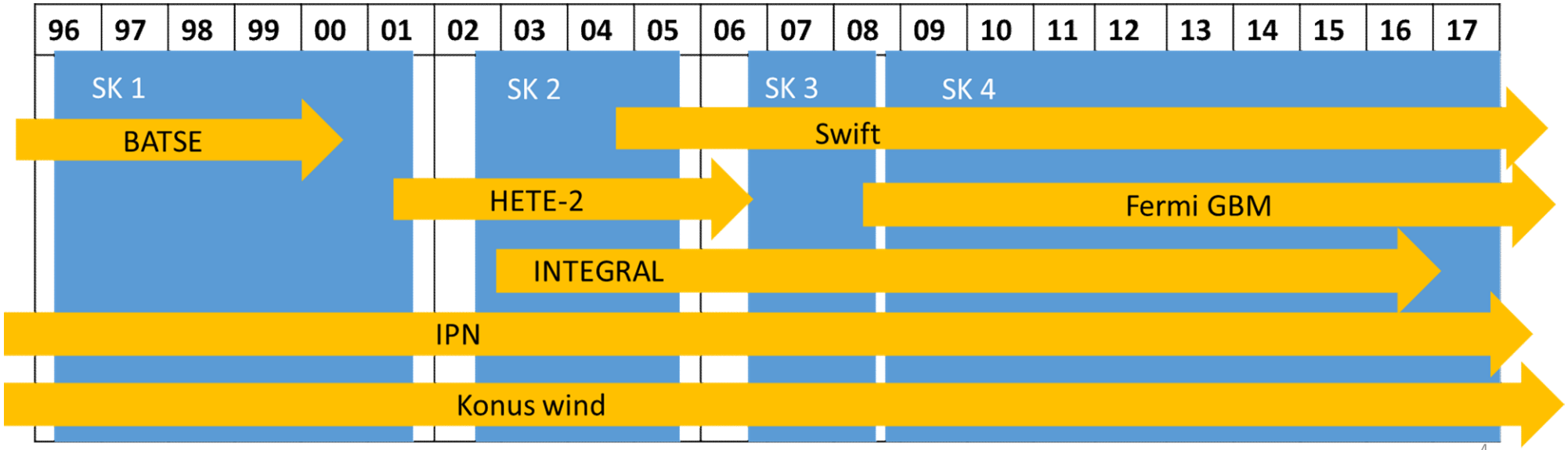




Phase	Period	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%) (coverage)	4.5
SK-IV	2008.9 ~2018.6	22.5 (>5.5MeV) 16.5 (4.5<E<5.5) 8.9 (<4.5MeV)		3.5 (Kin. energy)

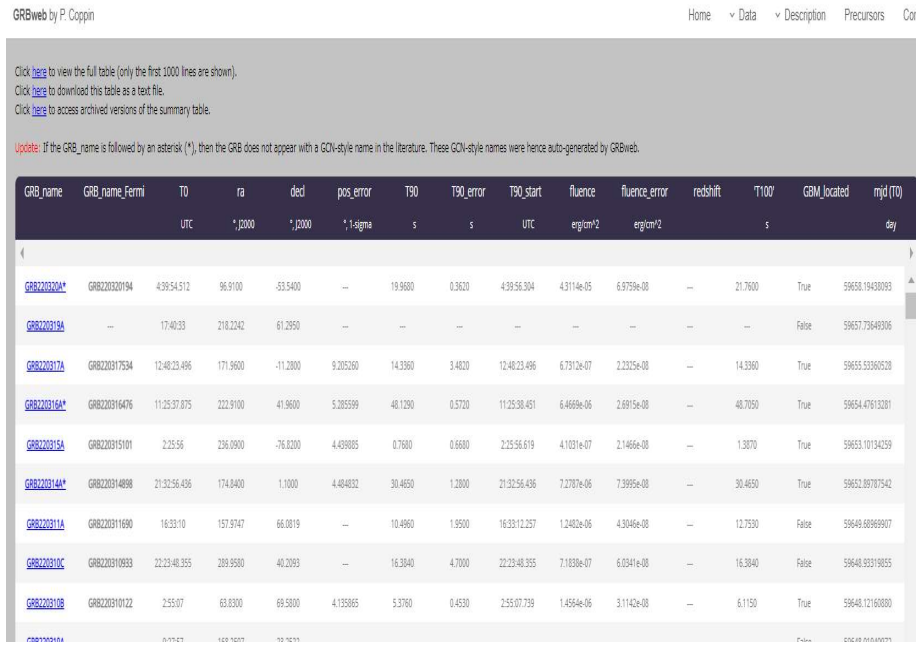
GRB observations and SK operation

- More and faster information from satellite observations
  - Help (under)ground based follow up observations
  - Include : host galaxy, afterglow light curve
    - We can perform more detailed analysis
      fluence limit for long GRBs and short GRBs
- Gamma-Ray Candidate Network (GCN) is available to get such information



GRB data base

- GCN database prepared by ICECUBE group
  →GRB web (all event, 2008-)
  (Thanks to M.Tanka san for his advice)
- Analys period：2008/12/7-2017/3/31
  - Total 2208 GRB in SK physics runs
  - Duration (t90) is available
    2136 GRBs (323 short/ 1813 long)
  - GRB start/stop time are available
    2194GRBs



https://user-web.icecube.wisc.edu/~grbweb_public/Summary_table.html

Analysis overview (MeV neutrino search)

Raw data (SK 4 period)

Apply calibration constant
Apply event reconstruction

First reduction

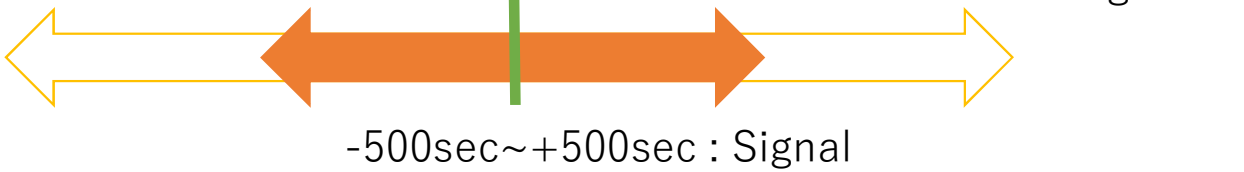
Cut noise events

Second reduction

Cut physics background

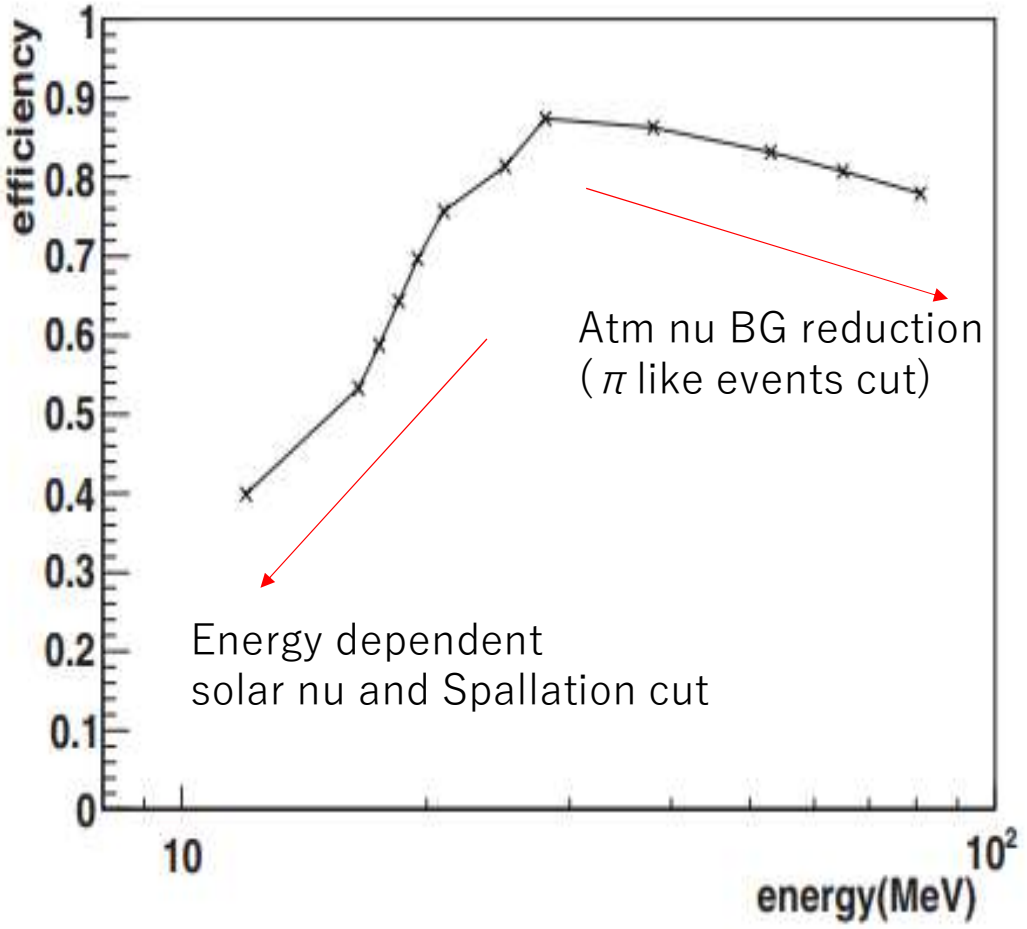
Select events around GRB

- For individual GRB
  - Fixed time window
    +-500sec window
  - Variable time window
    Use GRB start/stop time of the database
- Stacked analysis
  - Sum up all events around all GRBs
    - Check statistical excess from background



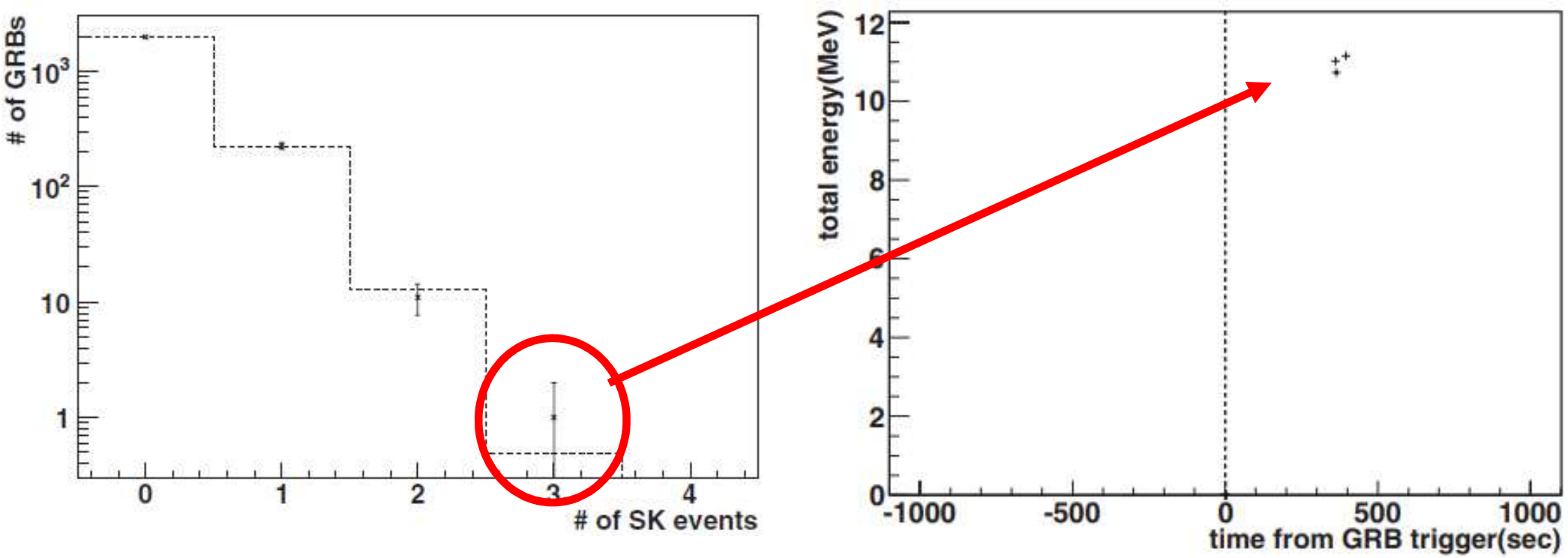
Summary of reduction

- First reductions
  - FV cut and other noise cuts
    - ~70% efficiency
- Second reductions
  - Solar nu BG (~ 20MeV)
    - Cut solar direcition
  - Spallation BG (~ 20MeV)
    - Check correlation with all muons within 30sec
  - Atmospheric nu BG (higher energy)
    - Pion / muon like events
      - Hit pattern
    - Events with sub events
      - Hit pattern and hit timing



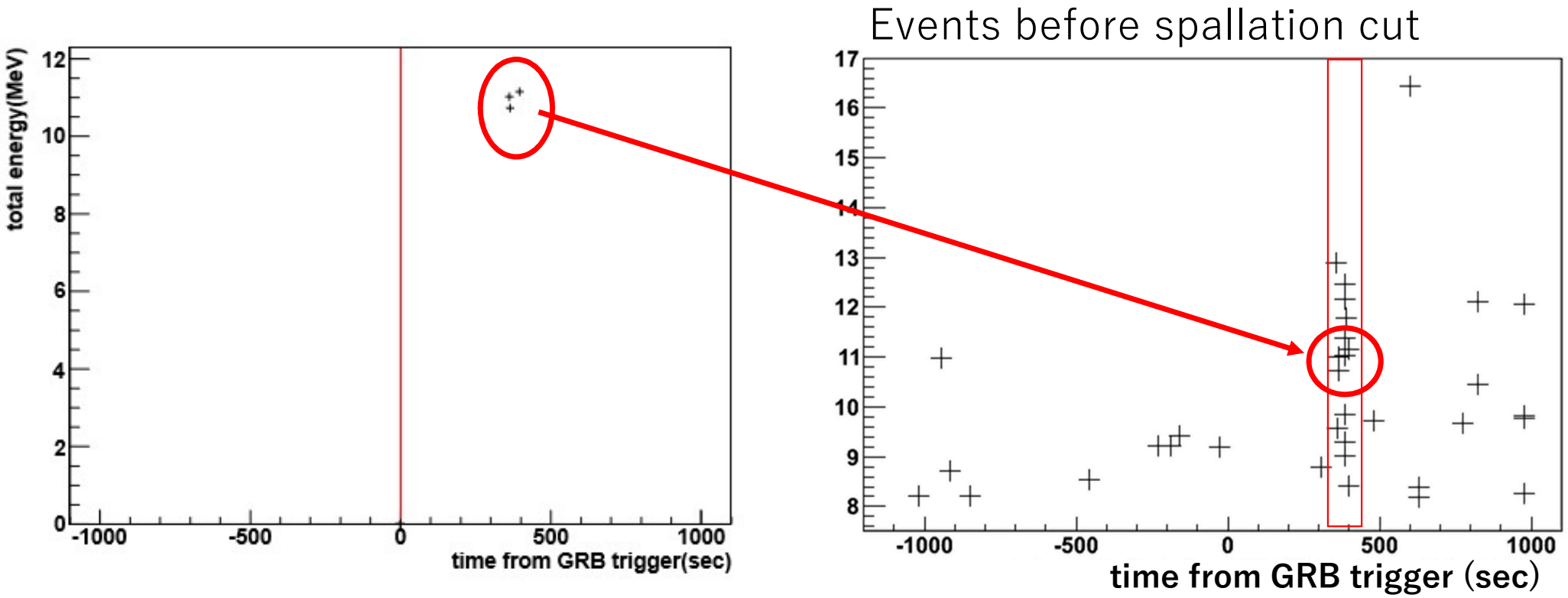
Fixed time window analysis

- Check ±500 sec around individual GRB



Background rate is obtained from the sideband (±1000 sec) : 0.114 event/1000sec
Number of observed SK events agree with the Poisson distribution of BG rate

3 events due to spallation products…

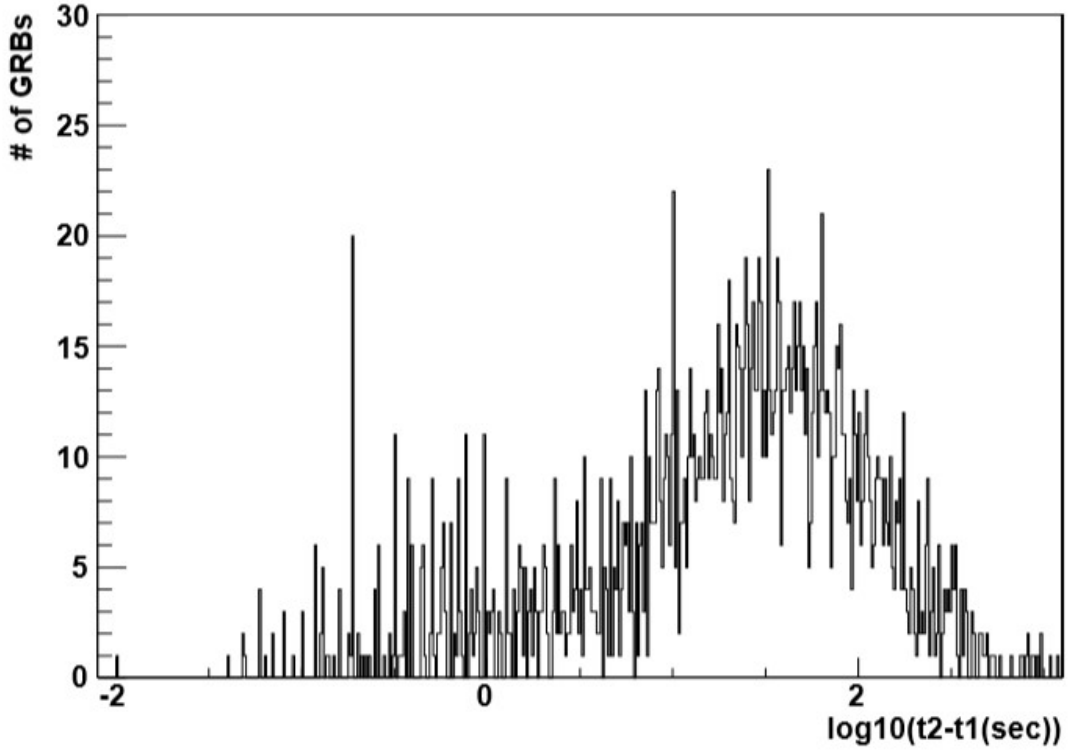


We also confirmed that positional correlation with the parent muons

Variable timing window analysis

The length of search time window is different for each GRBs

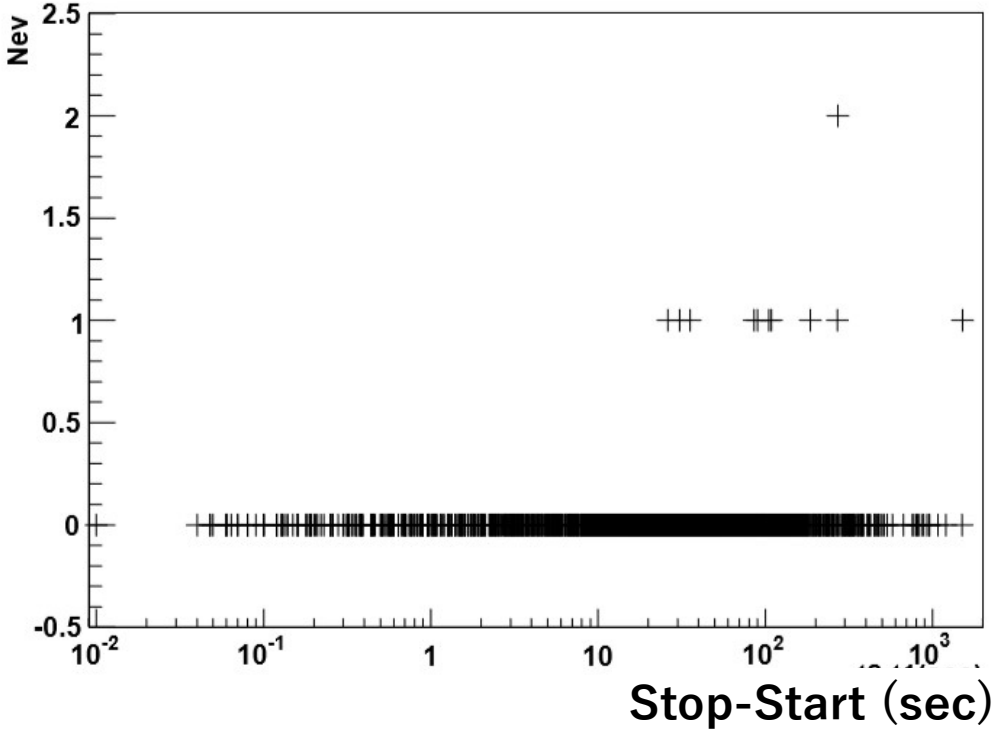
- GRB's start time and stop time is available
  - 2194 GRBs
- Start (t_s) and stop (t_e) time:
  - O(0.1sec) to O(1000 sec)
  - Let' search events within the time window



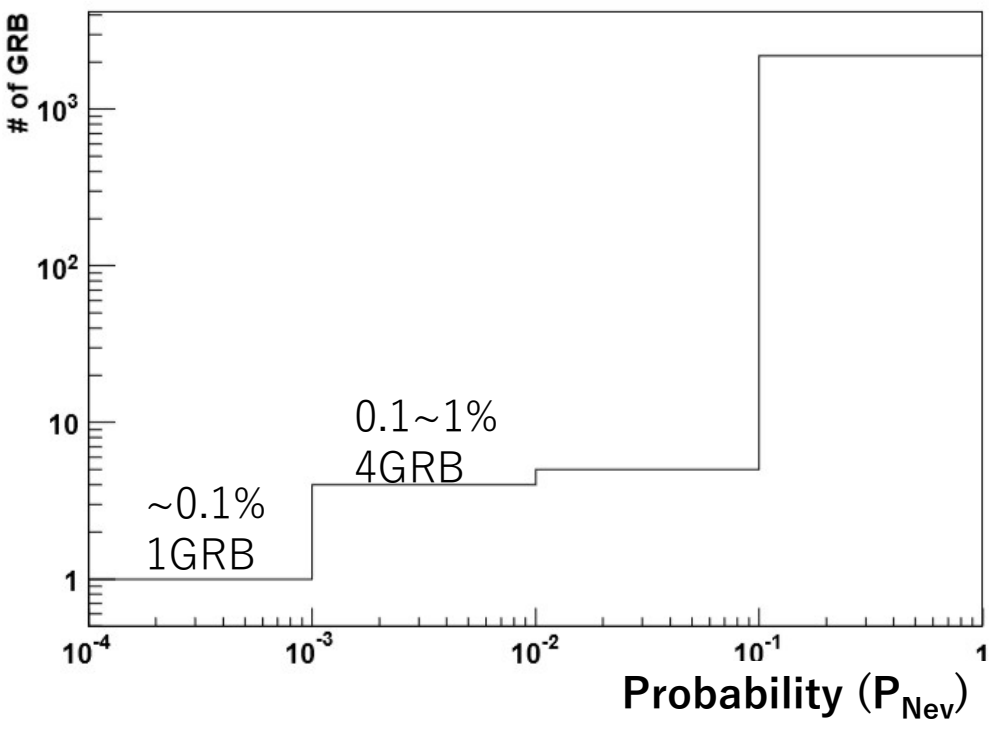
Log10 (t_e-t_s) (sec)

Events in the individual time window

Number of candidate events (Nev) for each GRB



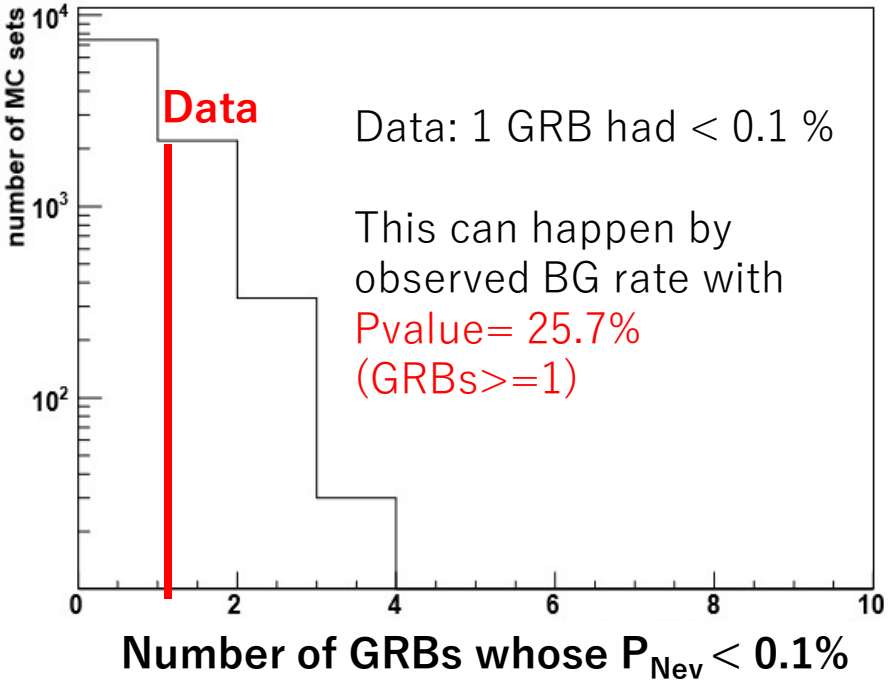
Distribution of probability (P_{Nev})※
to observe Nev for each GRB

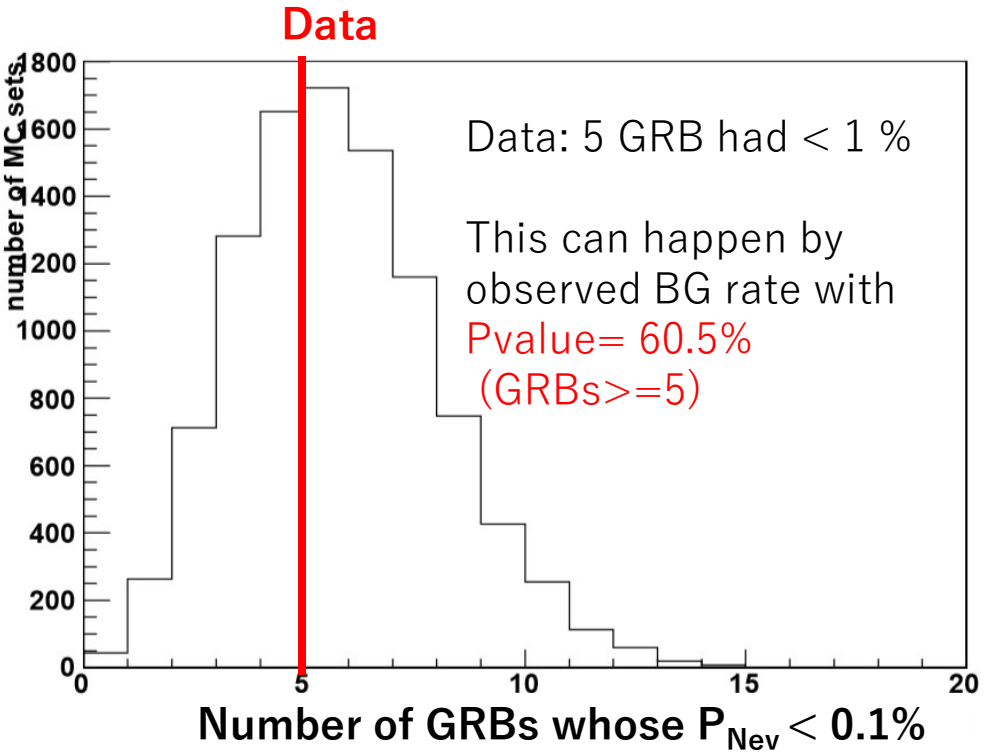


※ P_{Nev} : N_{ev} events to be observed in $(t_e - t_s)$ sec with a Poisson distribution of the average background rate of 0.114 events per 1000 s.

Statistical test with toy MC

- From the observed BG rate, we have simulated 10000 sets of 2194 GRBs (with real t_e-t_s) and checked P_{Nev} as it's done for data

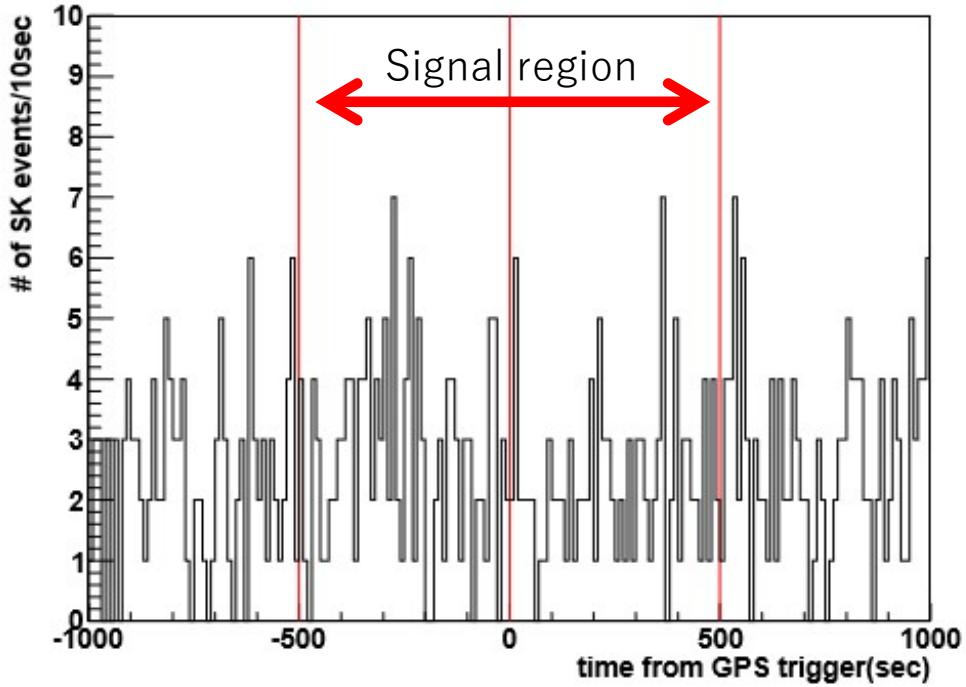


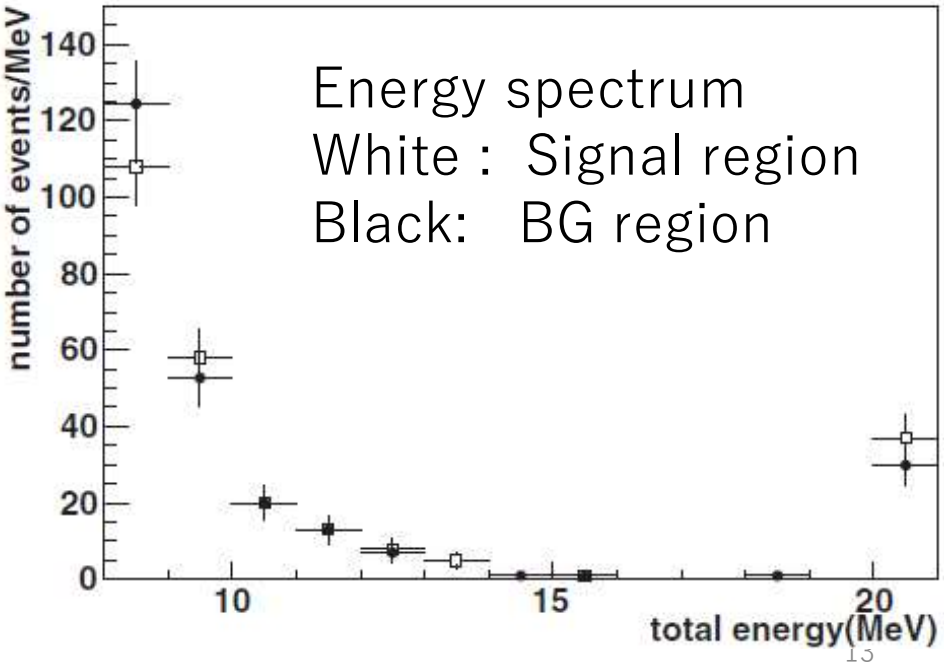


Therefore, the result (previous page) is not statistically significant.

Stacked data analysis

- Sum neutrino candidate events for all 2208 GRB
  - Signal window +/- 500 sec of GRB timing
  - Background window +/- 1000 sec (500 sec out side of signal window)



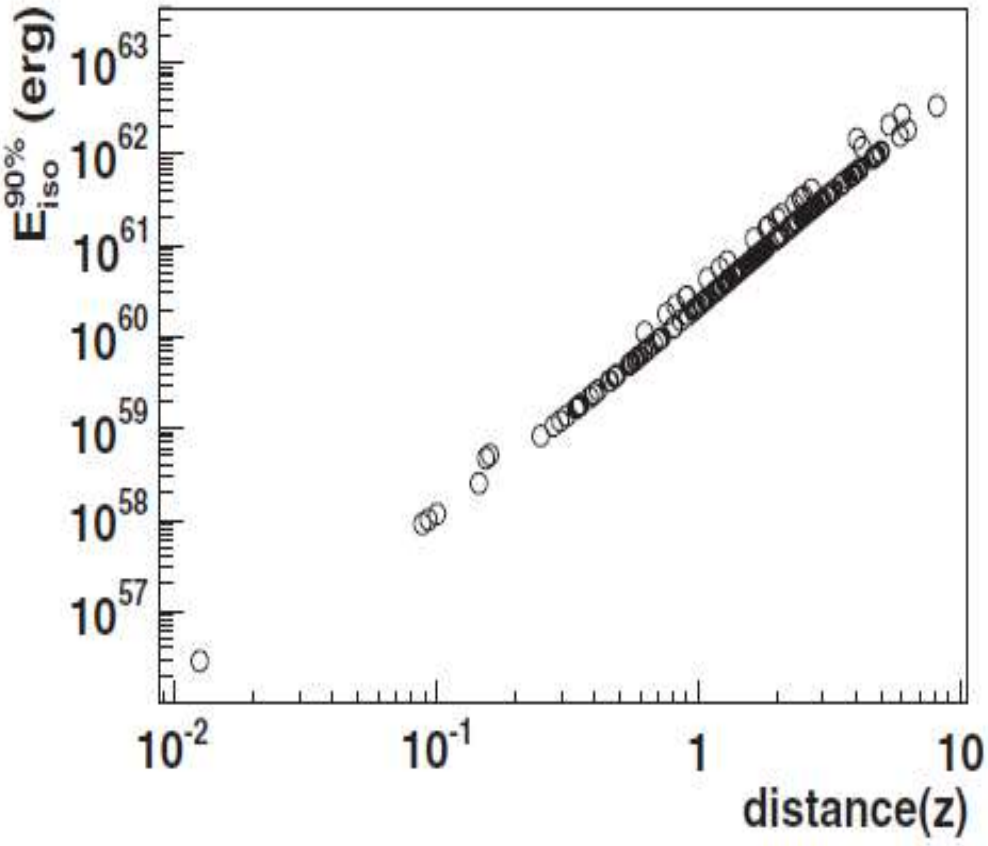


Fluence upper limit

Total fluence $< 1.12 \times 10^{8}$ cm^{-2}/2208GRBs
$=$ **5.07×10^{4} cm^{-2}/GRB**

- 8MeV to 100 MeV
- Assuming a flat spectrum at GRB

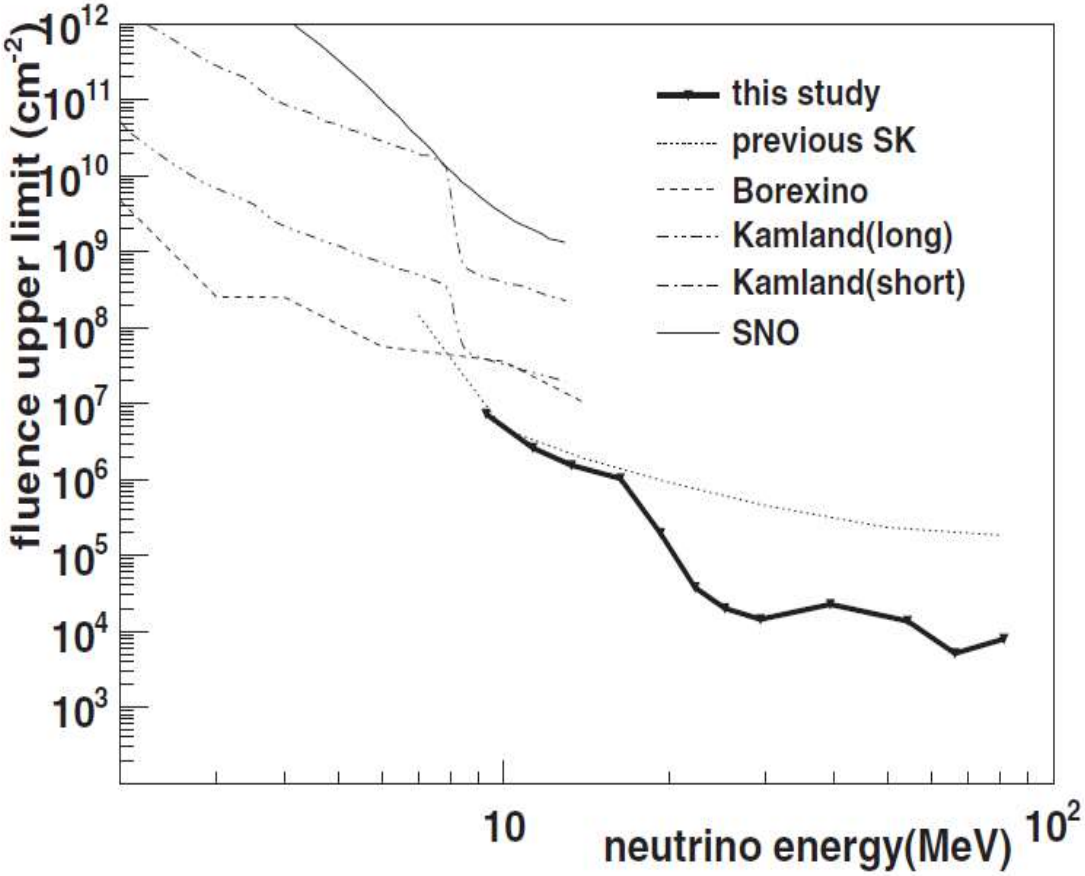
- For 189 GRBs, distance is available in the database.
  - Limits on the total energy carried away from the source by neutrinos can be calculated.
  - Assuming neutrino emission at the source is isotropic



Fluence vs. energy

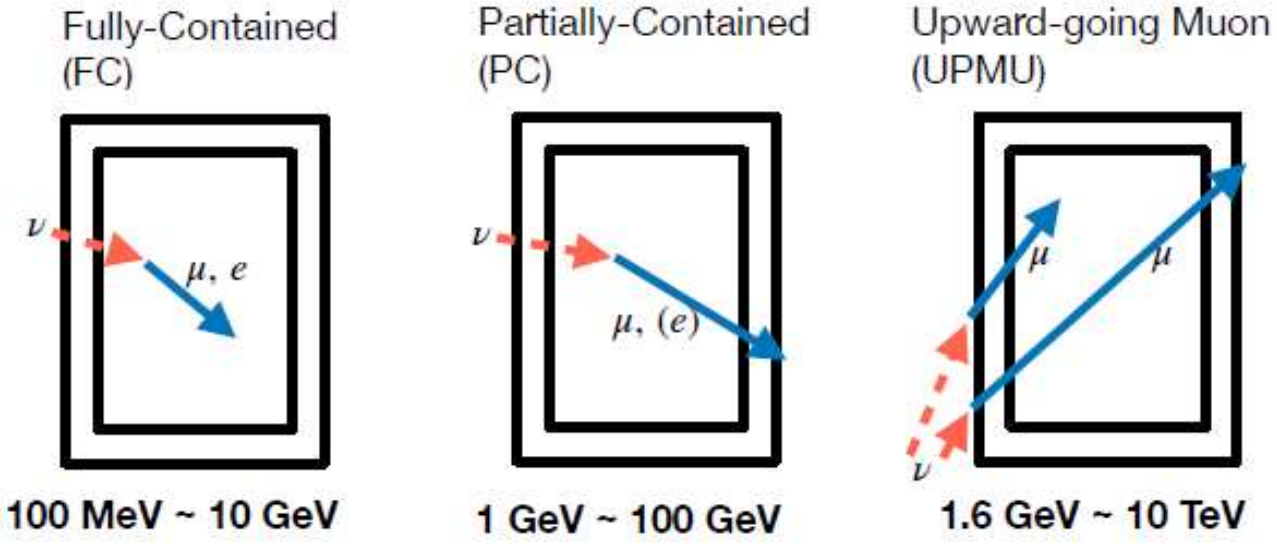
- Fluence limit per GRB is calculated as a function of energy.
- For each energy point(E), the number of candidate events with energy $\pm 3\sigma_E$ around the point is counted.

- Limits for short and long GRBs are also calculated in the paper.



Higher energy GRB neutrino search

- Search of 100 MeV – 10 TeV using data from SK1-4 (more than 20year).
- Use GRBweb
  - 3864 GRBs found during the period
- The correlation between nu direction and event direction is strong.
  - Look for events within 15 degree to GRB direction
- We have 3 categories depending on neutrino energy



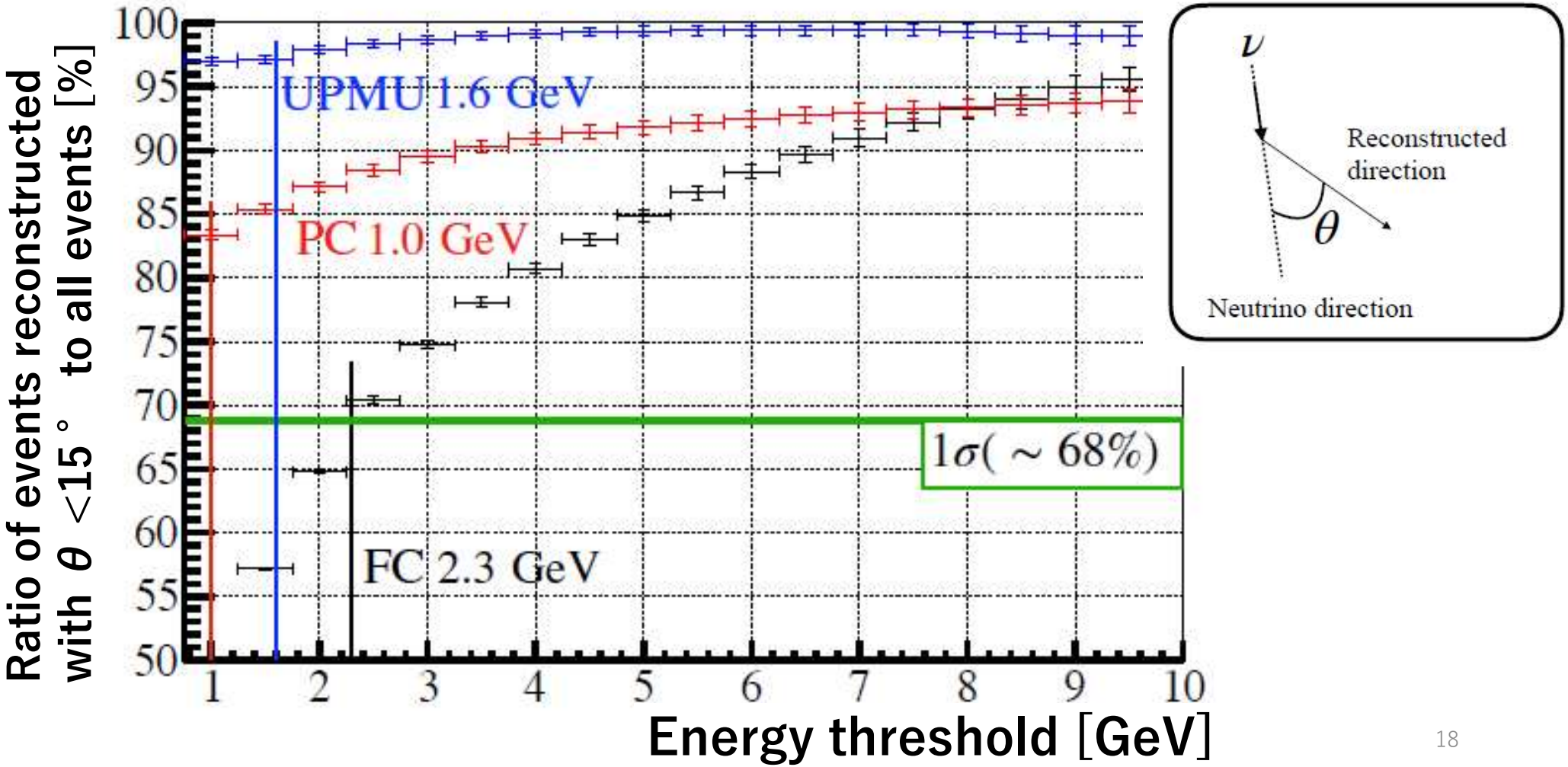
Atm. nu background estimation

At high energy, atmospheric neutrino BG is dominant BG source.

Data and MC shows good agreement

Event rate [$\times 10^{-5}$/sec]	Data	MC
FC	9.44±0.05	9.43
PC	0.72±0.02	0.74
UPMU	1.60±0.04	1.57

Energy threshold for each category



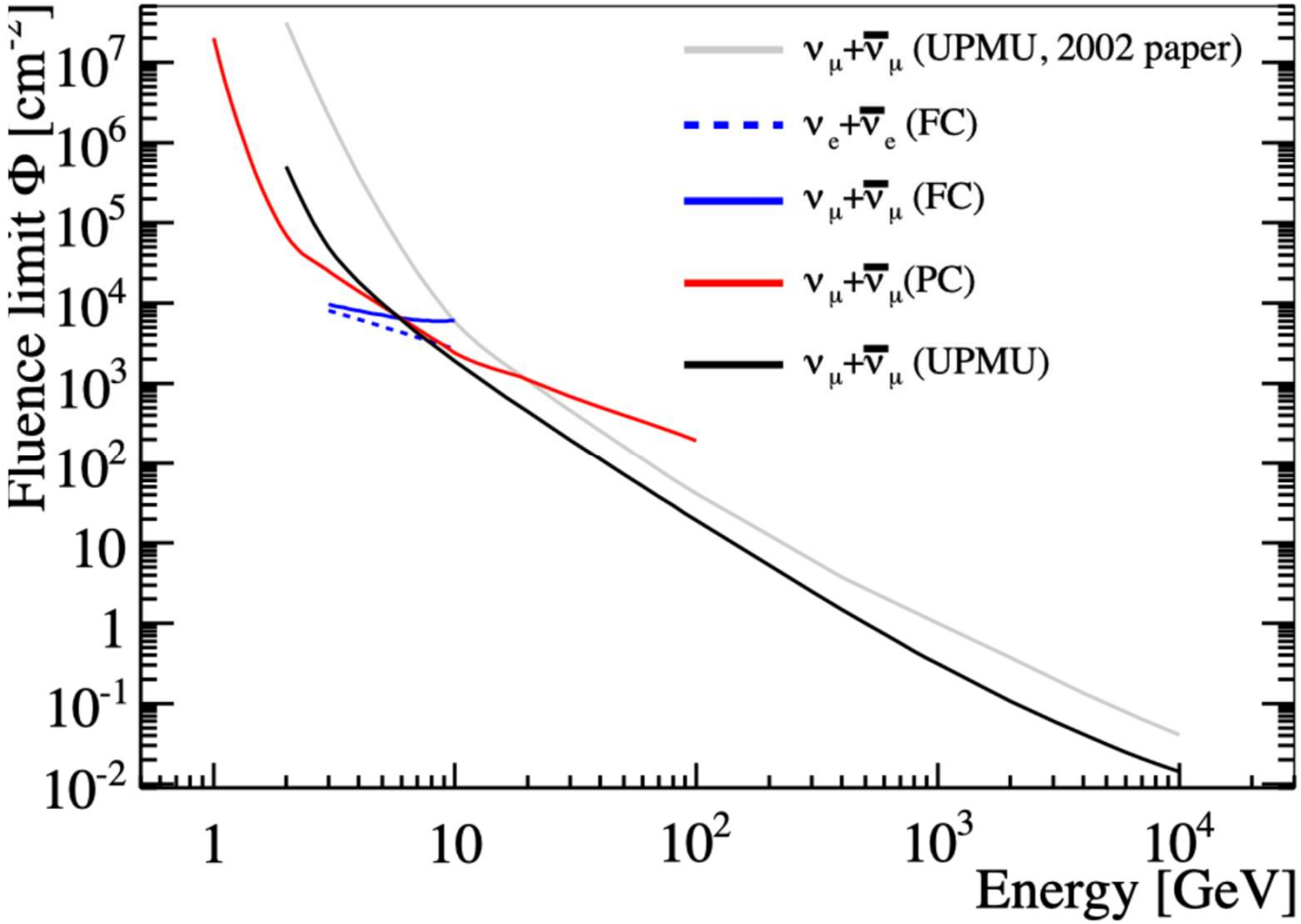
Results:

- Count number of candidates with
  - ±500 sec of GRB time
  - Difference between the reconstructed direction and GRB direction < 15°
  - （Only for UPMU）z direction of GRB ＜ 0
- No significance observed

	# of GRBs	Data	Expected BG
FC	3737	2±1.4	0.77
PC	3737	0	0.48
UPMU	1737	1±1.0	0.76

90% C.L. fluence upper limit

Preliminary



Assuming flat spectrum from GRB

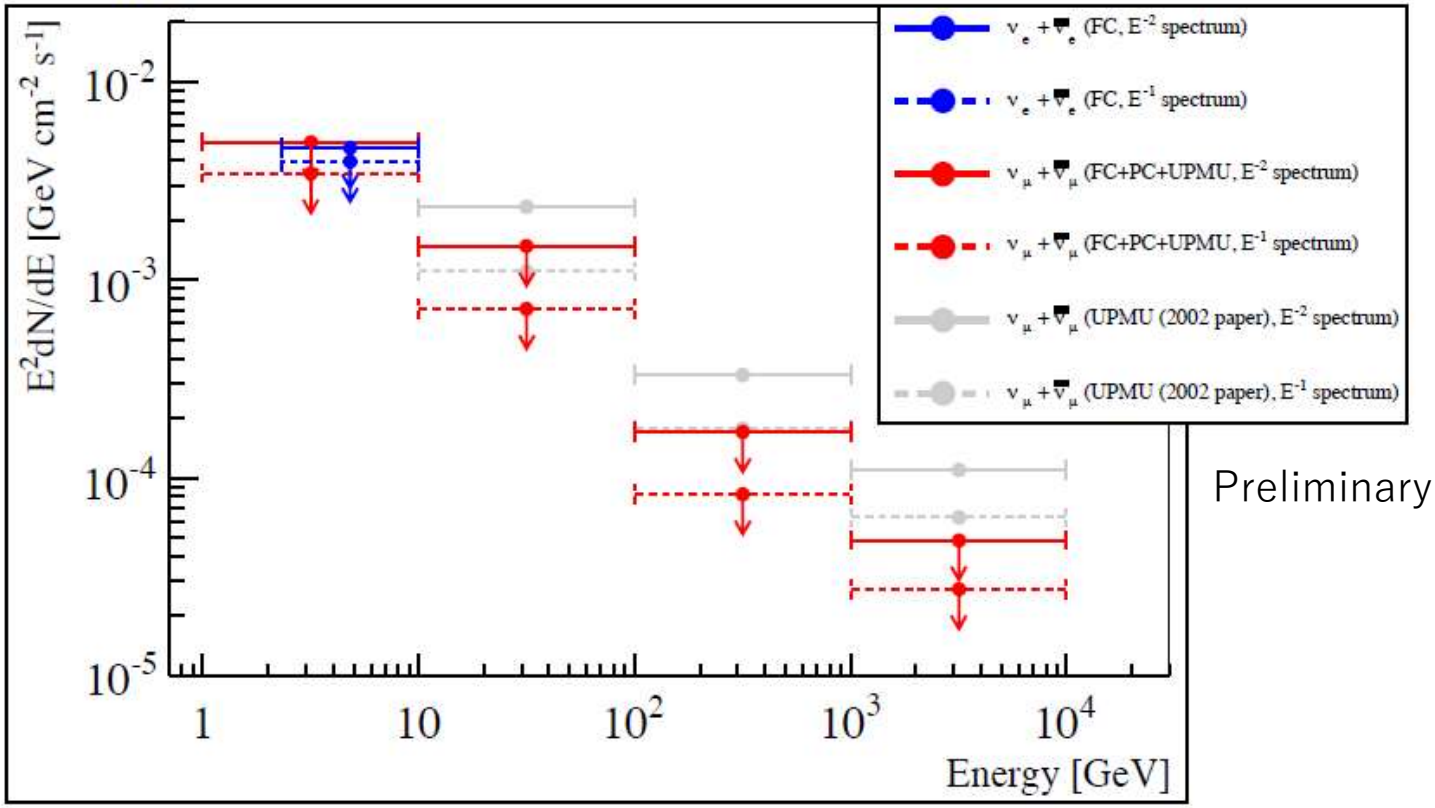
90% C.L. energy flux upper limit with E^{-2} (or E^{-1}) spectrum

Fluence

$$\Phi = \frac{\left[\int_{E_{min}}^{E_{max}} \frac{\lambda(E_\nu)}{\Phi_{ind}(E_\nu)} dE_\nu\right]^{-1}}{nGRB} \ [\mathrm{cm}^{-2}]$$

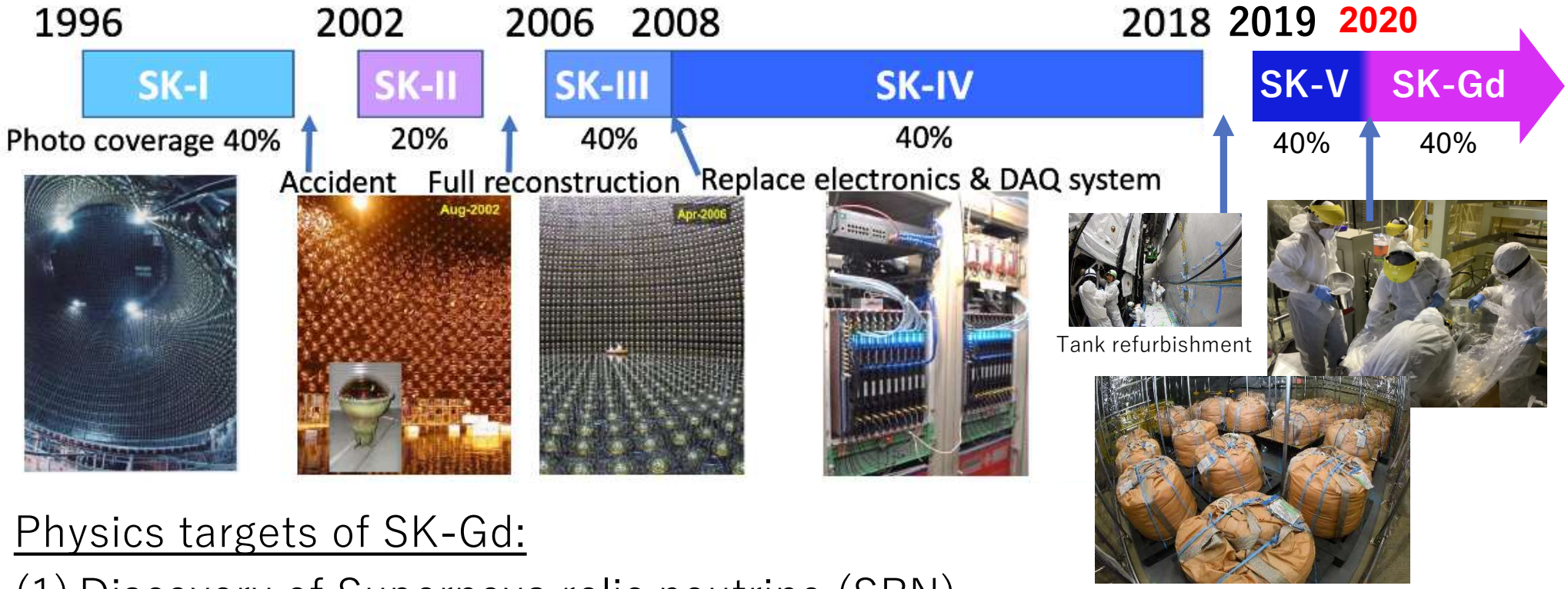
Energy flux

$$E^2 \frac{d\Phi}{dE} [\mathrm{GeV\ cm^{-2}\ s^{-1}}] = E_c^2 \frac{\Phi}{E_{Max} - E_{min}} \times \frac{1}{T_{Ave}}$$



Preliminary

Super-Kamiokande Gd project just started



Physics targets of SK-Gd:

(1) Discovery of Supernova relic neutrino (SRN)

(2) Galactic supernovae (pointing accuracy, and Si-burning ν)

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

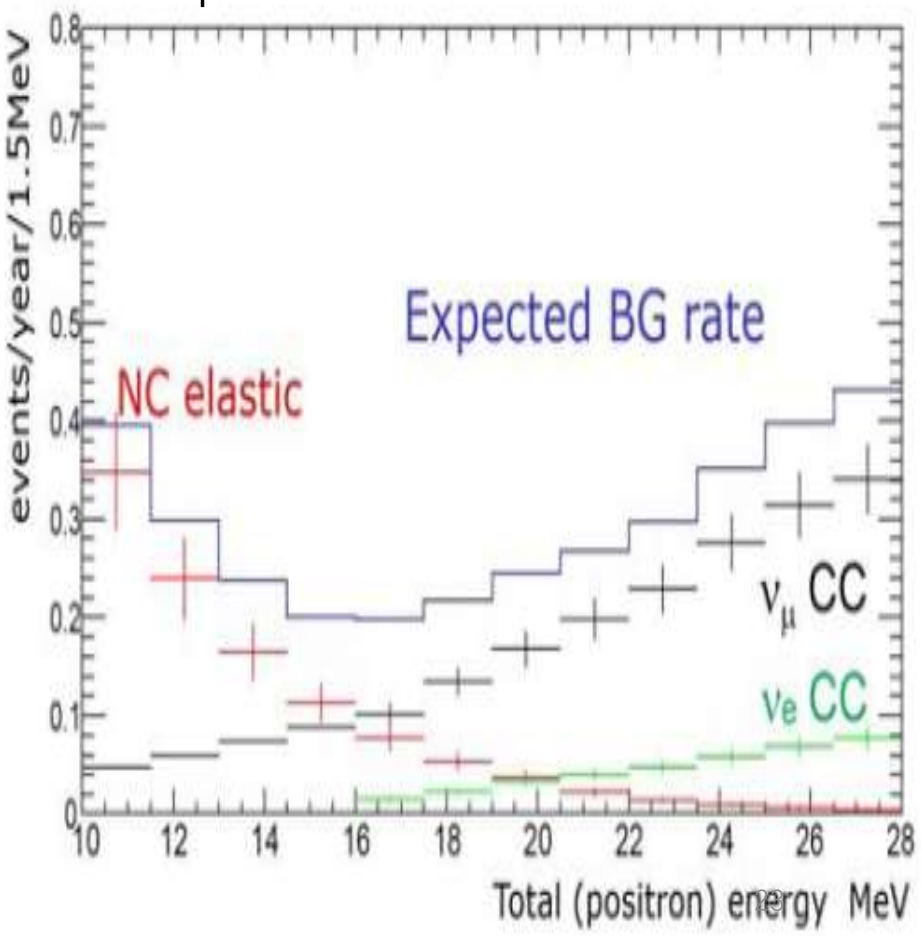
(4) Neutrino/anti-neutrino discrimination

Prospect of SK-Gd (MeV ν search)

- Below 15 MeV:
  - Dominant BG is spallation product
  - With IBD tag, only Li9 will remain.
    - ~ 2 events/year is expected
- Above 15 MeV:
  - Dominant BG is atmospheric nu
  - With IBD tag, ~1/4 of current BG

- Expected sensitivity after 10 years observation with SK-Gd.
  Improvement from current limit
  - Below 15 MeV : ~ 1/6
  - Above 15 MeV : ~ 1/2

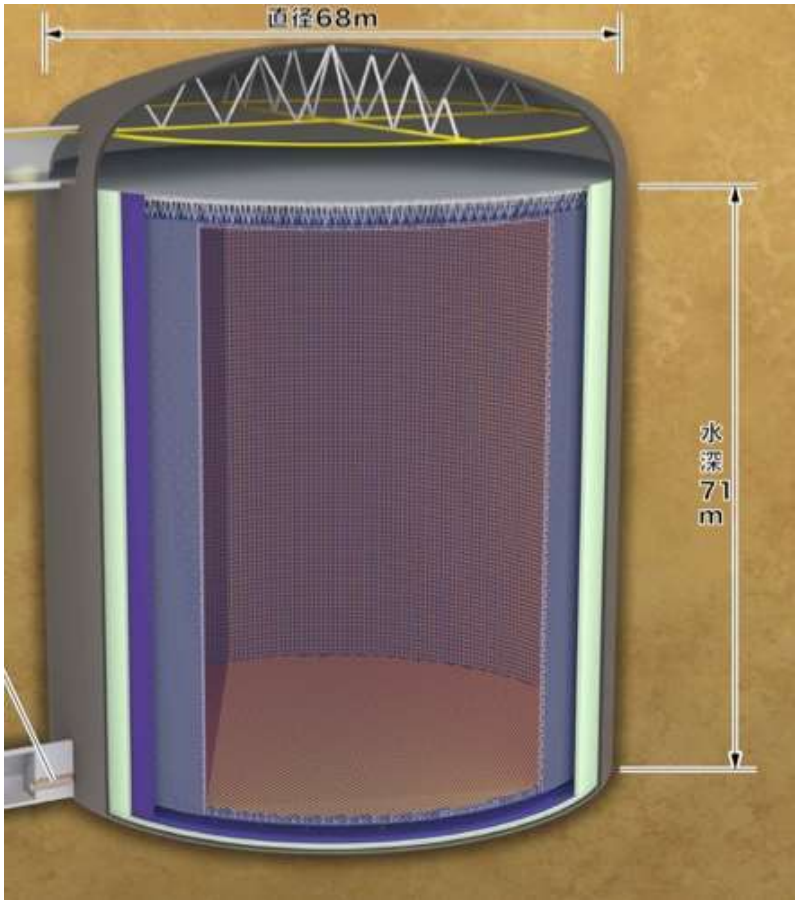
Expected BG rate at SK-Gd



Hyper-Kamiokande

- Target ：SK×8
- Below 15 MeV:
  - Overburden ~ 600m (SK:1000m)
  - Spallation product density~SK×3
    - Spallation BG : ～SK×8×3
    - See more detail for HK design report https://arxiv.org/pdf/1805.04163.pdf
- Above 15 MeV:
  - Atmospheric BG : ~SK×8
- Expected sensitivity after 10 years observation with HK

  Improvement from current limit
  - Below 15 MeV : ~$\sqrt{8\times3}$/8 ~60%
  - Above 15 MeV : ~ $\sqrt{8}$/8~35%



Fiducial volume ：~ SK ×8

Summary

- GRB search with SK.
  - O(10MeV) ; No significant signal found
  - O(100MeV-10TeV); No significant signal found
  - Improved upper limits are obtained.

- Future prospect
  - SK-Gd: Spallation BG will be reduced a lot.
  - HK: Large improvement especially at higher energy region.