Development of New Data Acquisition System for Nearby Supernova Bursts at Super-Kamiokande

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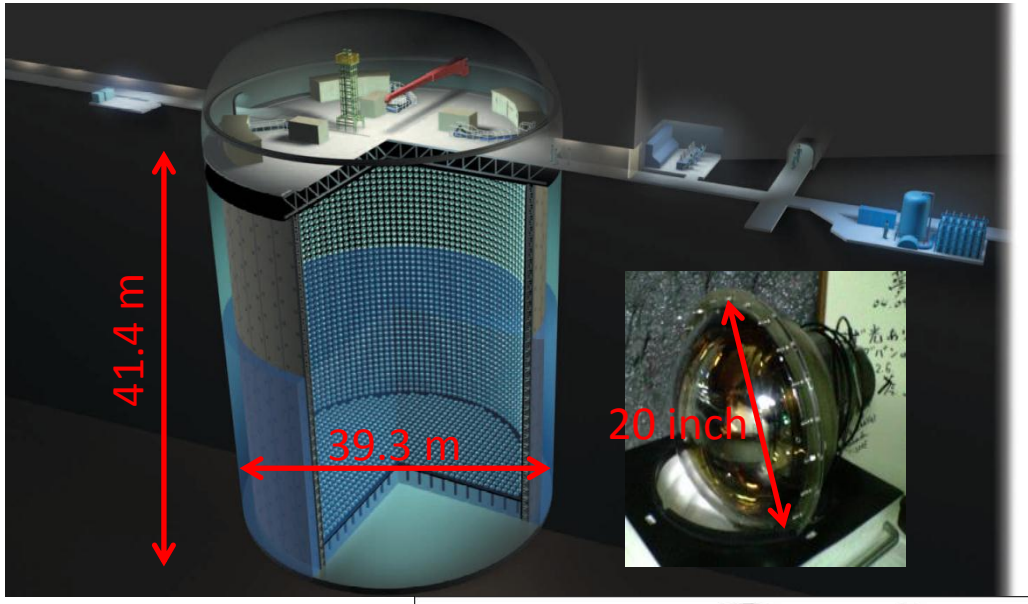
Introduction

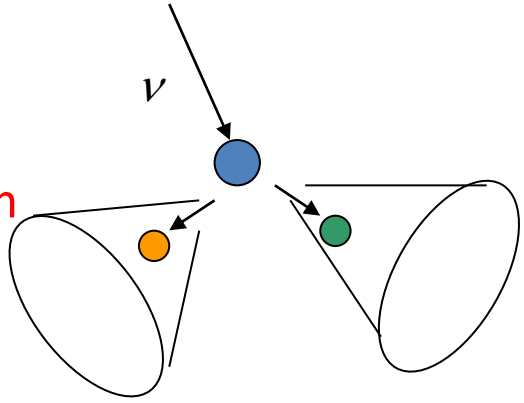
- Observational study of supernova explosion (SN) is important for understanding the mechanism of SN in detail.
  - Observation of SN through neutrino provides unique opportunity.
  - Super-Kamiokande (SK) is able to detect large number of SN neutrino events, which should reveal detailed mechanism of explosion.

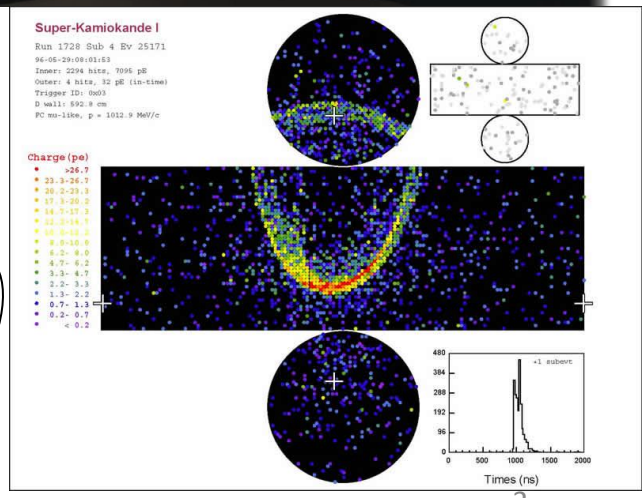
- Nearby supernovae (within the Galaxy) are being awaited.
  - The nearer SN is, the more neutrino events are detected.
  - Can we really handle such a large number of neutrino events?

Super-Kamiokande Detector

- Super-Kamiokande (SK) is a ring imaging water Cherenkov detector
  - 13,000 photomultiplier tubes (PMTs) equipped in 50,000 tons of water tank
- Physics Topics of SK
  - Atmospheric neutrino oscillation: Δm_{23}, θ_{23}
  - Solar neutrino oscillation: Δm_{12}, θ_{12}
  - Neutrino beam from accelerator (T2K): search for θ_{13}
  - Search for neutrinos from supernovae (burst or diffused)
  - Search for proton decay

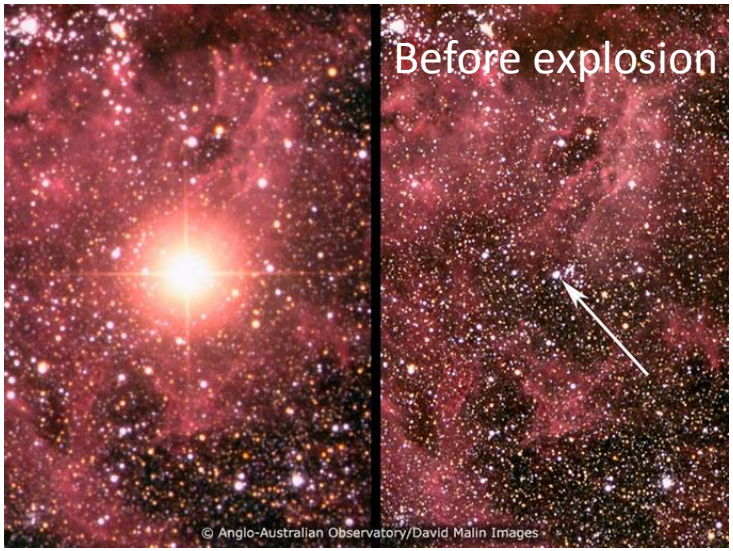


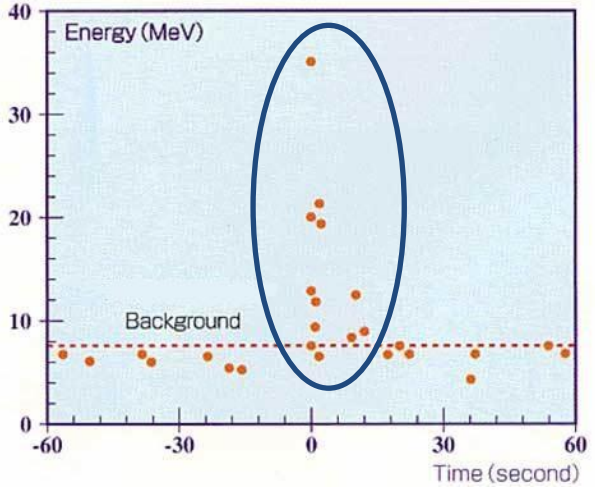




Neutrino Astronomy

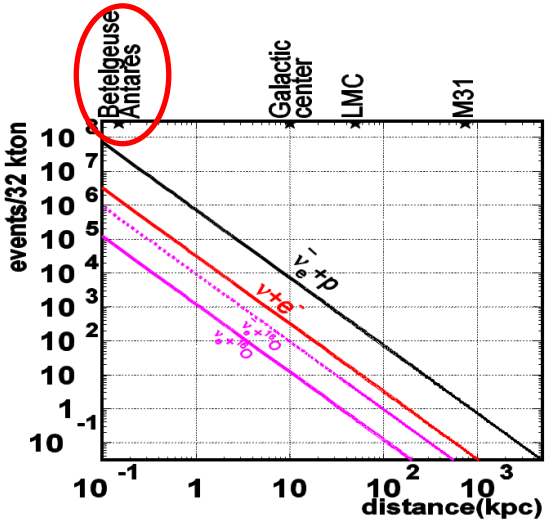
- Supernova Explosion (SN)
  - Collapse of a massive star
  - Release enormous amount of energy
    - Primarily (> 99%) in the form of neutrino
    - In just 10 seconds
- SN1987A
  - On February 23, 1987, SN occurred in Large Magellanic Clouds.
  - Kamiokande observed 11 events of neutrinos from SN.
- SN is expected to occur inside the Galaxy once every 10 to 50 years.
  - If a SN occurs at the center of the Galaxy, SK expects to detect about 10k neutrino events.

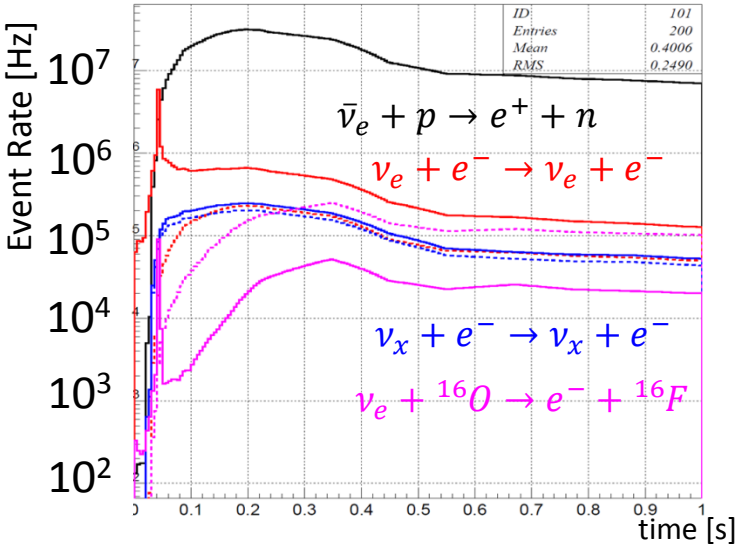




Nearby Supernova

- In June 2009, it was reported that the size of Betelgeuse (α Orionis) decreased by 15% over past 15 years.
  - C. H. Townes *et al.* 2009, *ApJ*, **697**, L127
- If a SN burst occurs at 500 ly from the earth, the total number of events in 10 s at SK reaches 30M and the maximum event rate exceeds 30 MHz.
  - Candidates
    - Betelgeuse: 640 ly
    - Antares: 550 ly





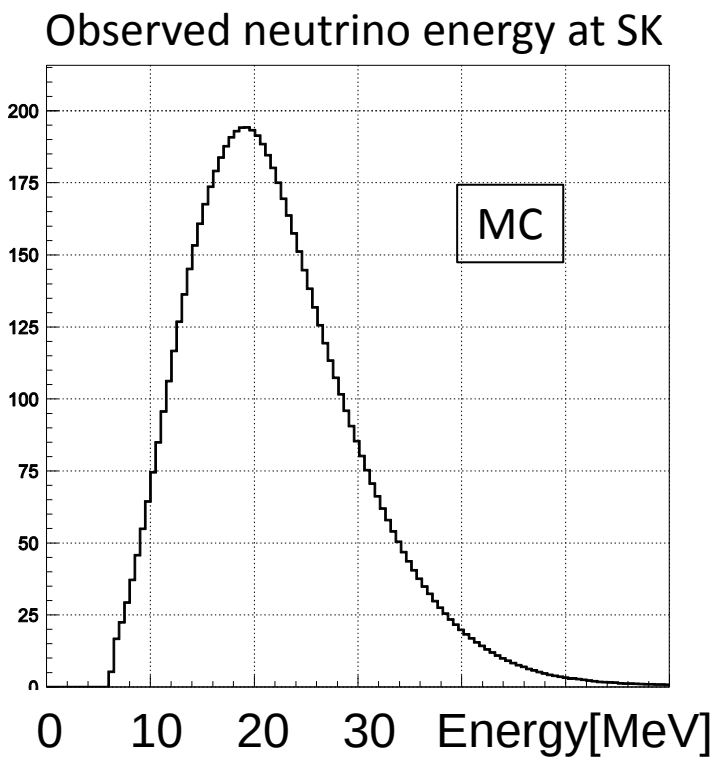
Current DAQ Capability

- SK DAQ system was renewed in 2008.
  - Larger charge dynamic range
  - Lower power consumption
  - High speed data transfer
- Current DAQ can process up to 6M events/10 s without losing data.
  - Bottleneck is mainly disk access.
  - Corresponds to ~1300 ly SN.
  - For 500-ly SN, only first 20% of data can be recorded.

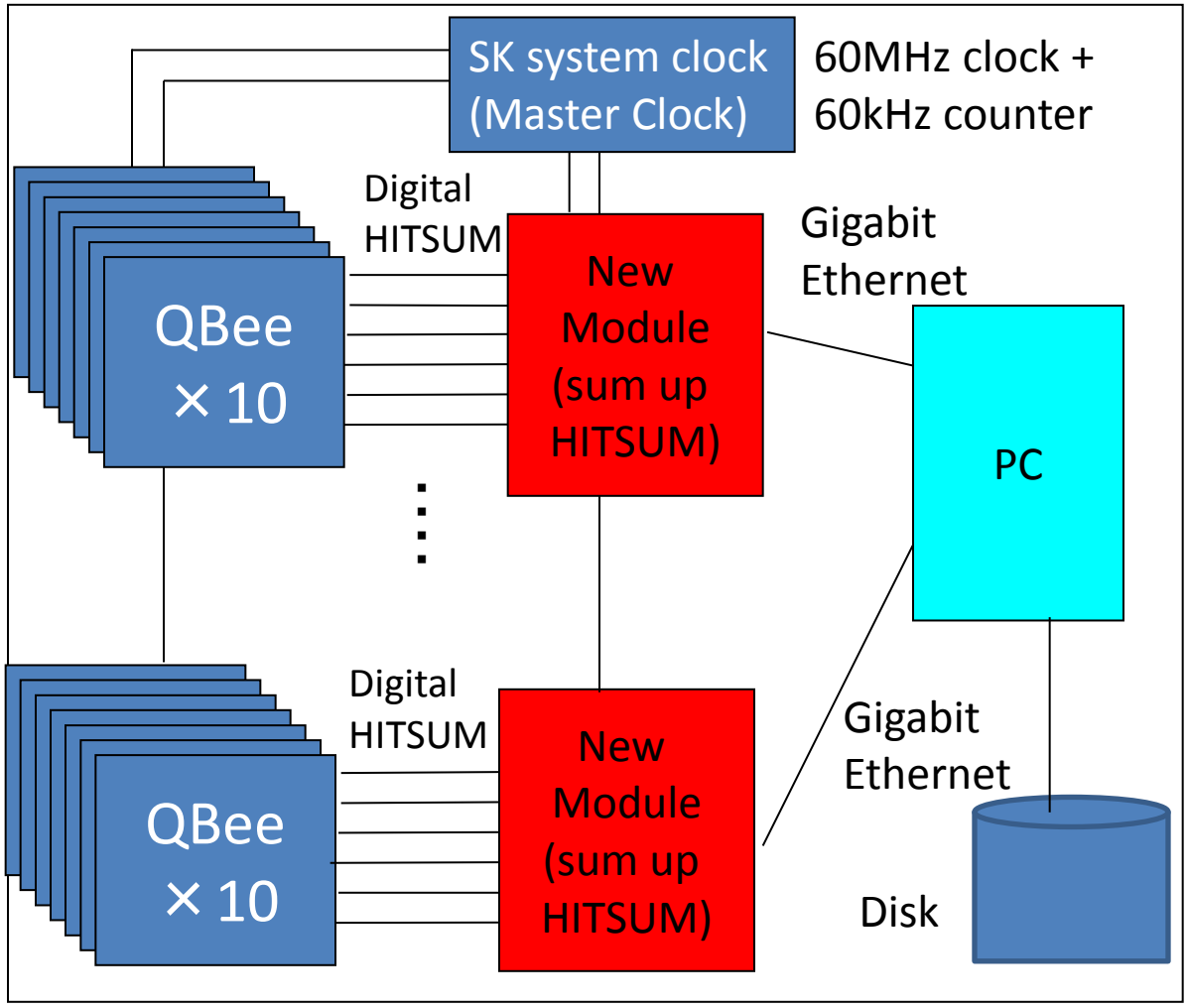
- Implemented prescale (= 100) for such high event rate.
  - Inputting veto trigger into frontend electronics board to reduce data size for main DAQ system
  - Can avoid large dead time
  - Not enough to understand SN structure.

New DAQ System

- Need new DAQ system in parallel to the current system for the SN burst study.
- Requirements for new system:
  - Independent from current online DAQ system
  - Stable against event rate
- Utilize number of hit PMTs
  - Since energy distribution of SN neutrino is narrow, we can estimate the number of neutrinos from number of hits.



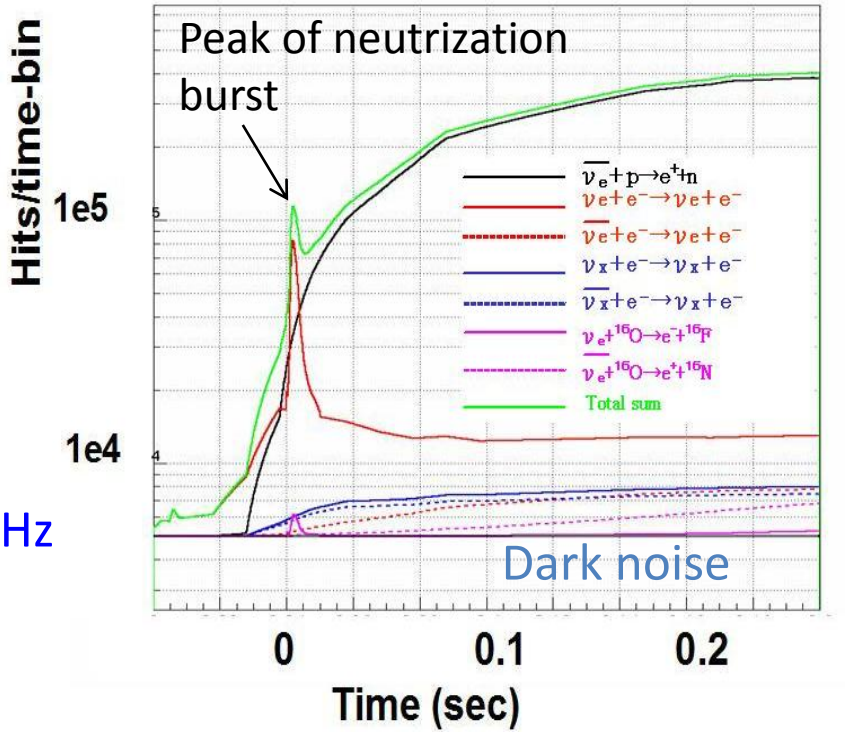
Schematic View of New DAQ



- Digital HITSUM
  - Frontend electronics board (QBee) has an output of number of hit PMTs.
  - Provided in 60 MHz
- New module
  - Sums up HITSUMs from 10 boards.
  - Summed-up numbers are read out by PC through Gigabit Ethernet and written to disk.

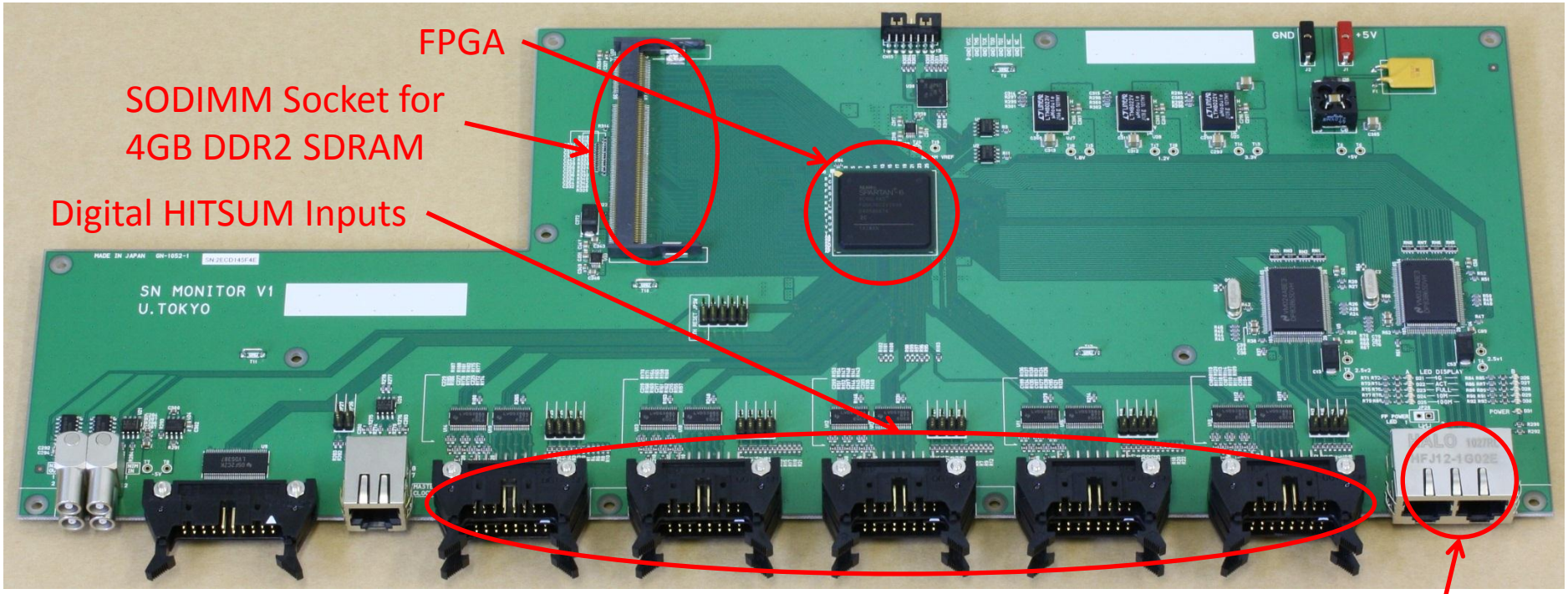
Time Resolution

Time resolution [MHz]	Fluctuation of dark noise [hit/time bin]
60	±0.83
0.1	±22
0.06	±26
0.01	±71



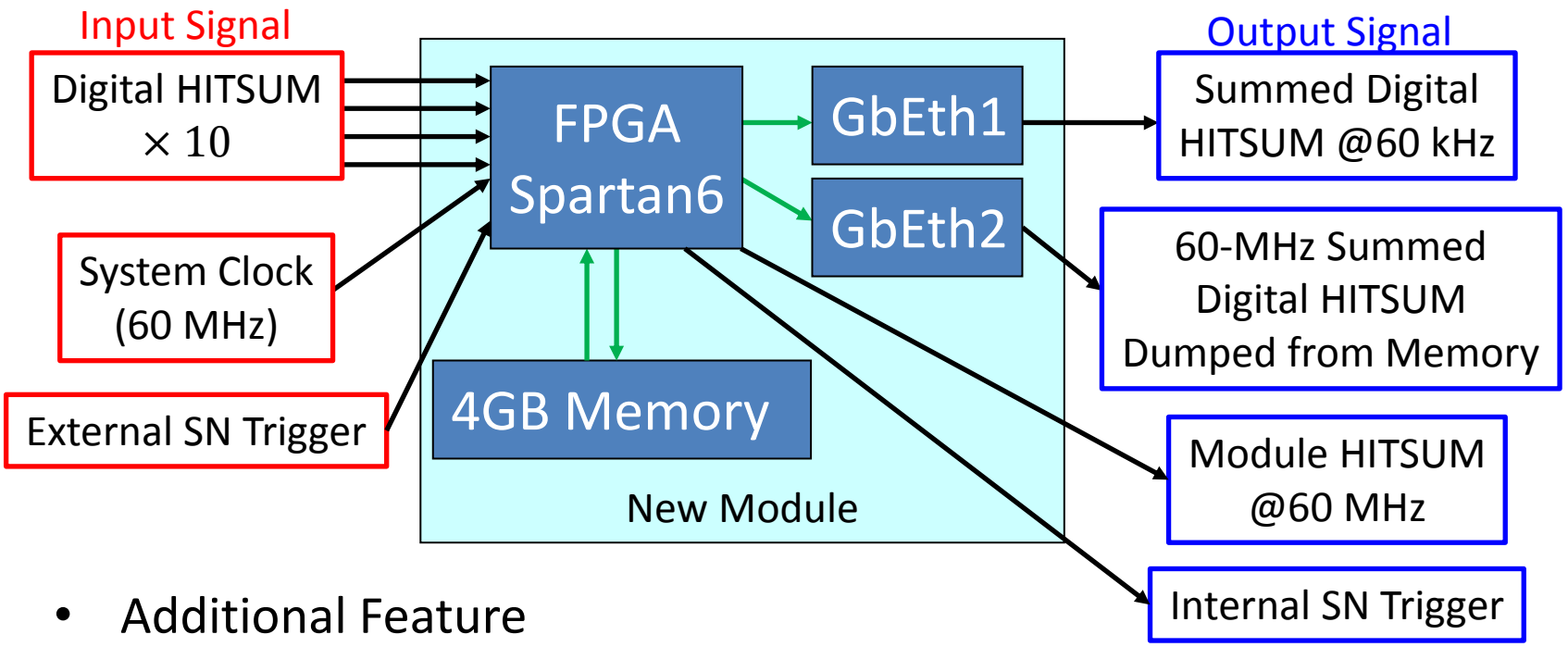
- Data size problem
  - Recording sum of HITSUMs at 60 MHz corresponds to ~500 TB/day.
    - Cf. Current SK DAQ: ~720 GB/day
  - Need reduction of data size
- Lower the time resolution to reduce data size
  - Sensitivity to the peak of neutrization burst should be kept.
  - Keep good significance for ~120 hits/event signal.
  - We chose 60 kHz.
    - $S/\sigma_{BG} \gtrsim 4$, data size ~ 500 GB/day.

Prototype of New Module



- A prototype of the new DAQ module was made.
  - Collect Digital HITSUMs from 10 frontend electronics boards and sum them up
  - Continue summing for 1k cycles (60 MHz → 60 KHz)
  - Output summation information through Gigabit Ethernet
  - Utilize Field-Programmable Gate Array (FPGA) for digital signal processing.

Block Diagram of New Module



- Additional Feature
  - 4 GB RAM to store 60-MHz summed HITSUM information for 1 minute
    - Obtain maximal time resolution around supernova trigger
    - Dump data on memory through another Gigabit Ethernet port
  - Supernova trigger can be generated inside the module, or input from the other system.

Status and Plan

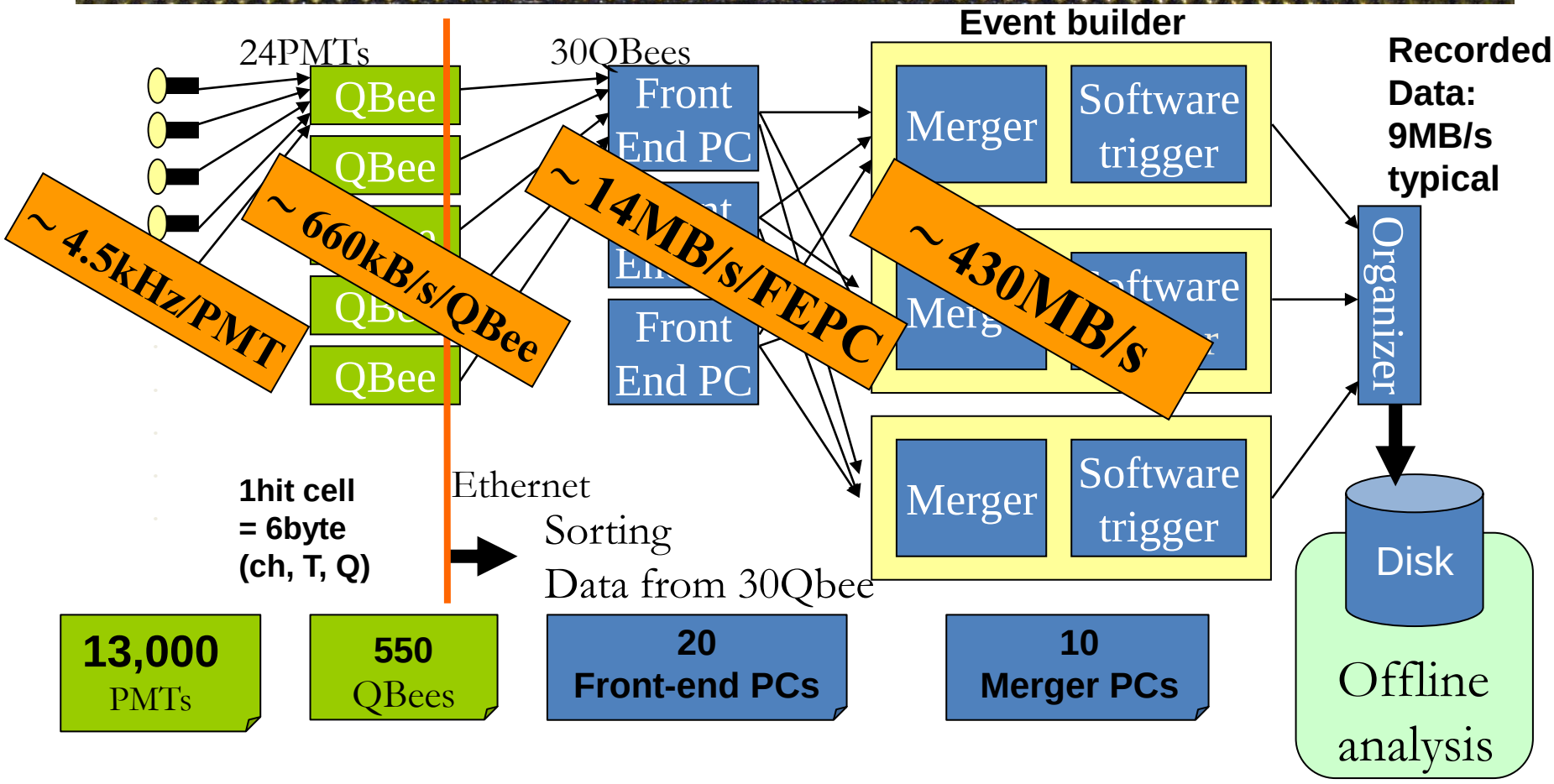
- Test with prototype module at test bench is ongoing.
  - Basic test for the module functionality
  - Debug of the FPGA program (firmware)
- Revision of the module is underway.
  - Correction for the malfunctioning part
  - Addition of functionalities that we overlooked
- Test of the module with the current DAQ system is planned in this summer.
  - Start mass production of the module after this test
- Deployment will be completed in this Japanese fiscal year (by next March).

Summary

- Super-Kamiokande is preparing for the nearby supernova neutrino burst.
  - Current data acquisition system can catch up with SN at 1300 ly or further.
  - New system is under development for the nearer SN.
    - This new system has always the same data size, i.e., stable against the neutrino event rate.
    - Deployment will be completed in this Japanese fiscal year.
  - Hope that nearby supernova burst won't occur before new system is ready…

BACK UP

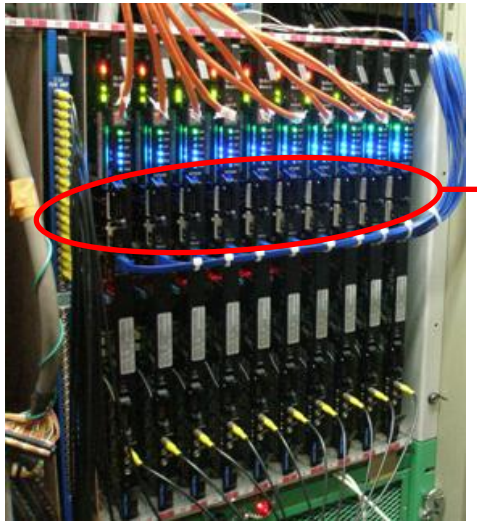
SK Online System

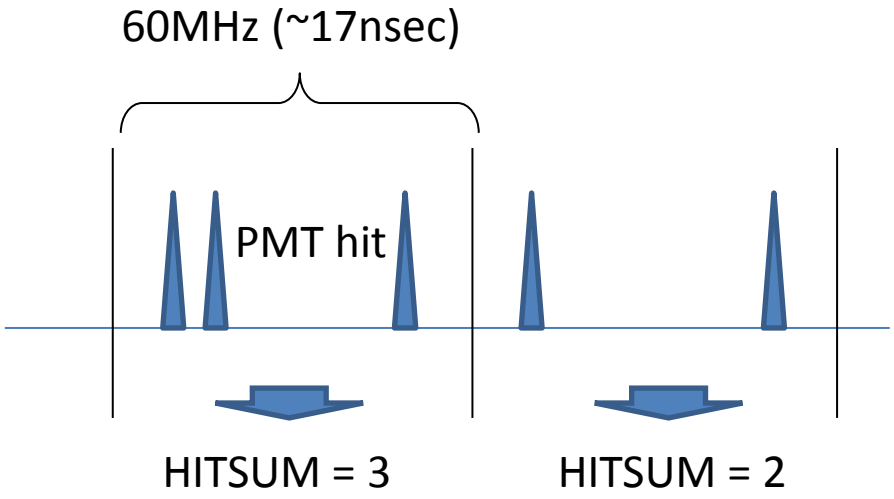


- LINUX Multi-threaded software is running on Online PCs equipped with 4 CPU cores.
- From electronics to offline disk, data is transferred using TCP/IP protocol, with commercial Ethernet network equipment.

Digital HITSUM

- Each frontend electronics module (QBee) is connected to 24 PMTs.
  - Every 60 MHz time period, QBee outputs number of PMT hits (0 to 24) through a dedicated port.
    - This digital signal is continuously output independently from the main data flow.

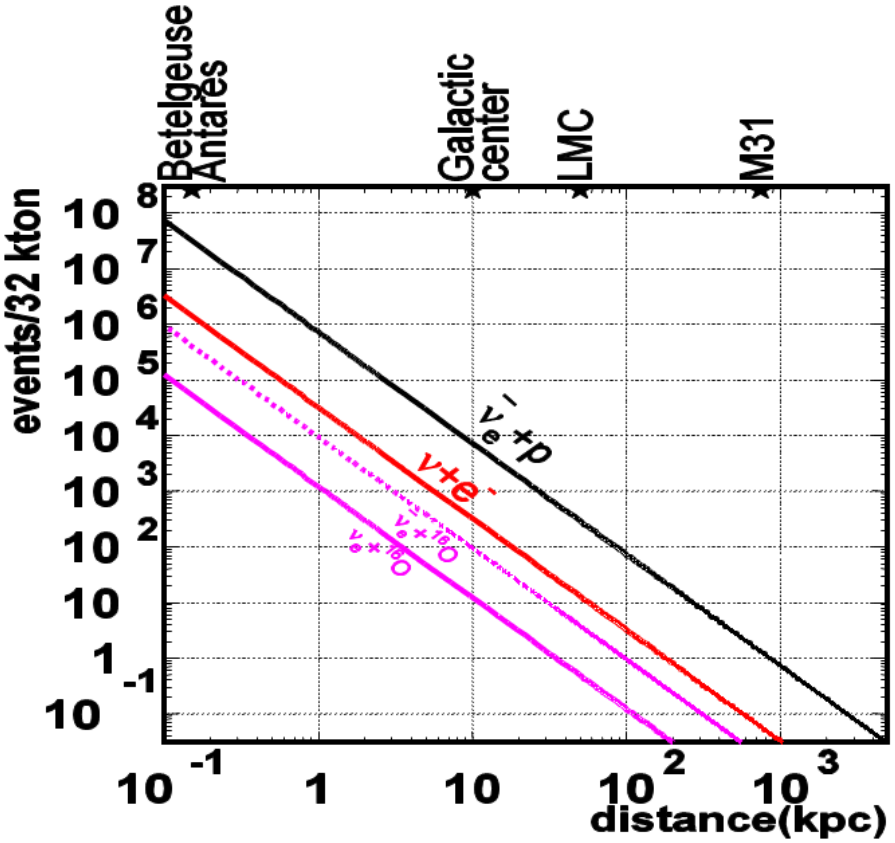




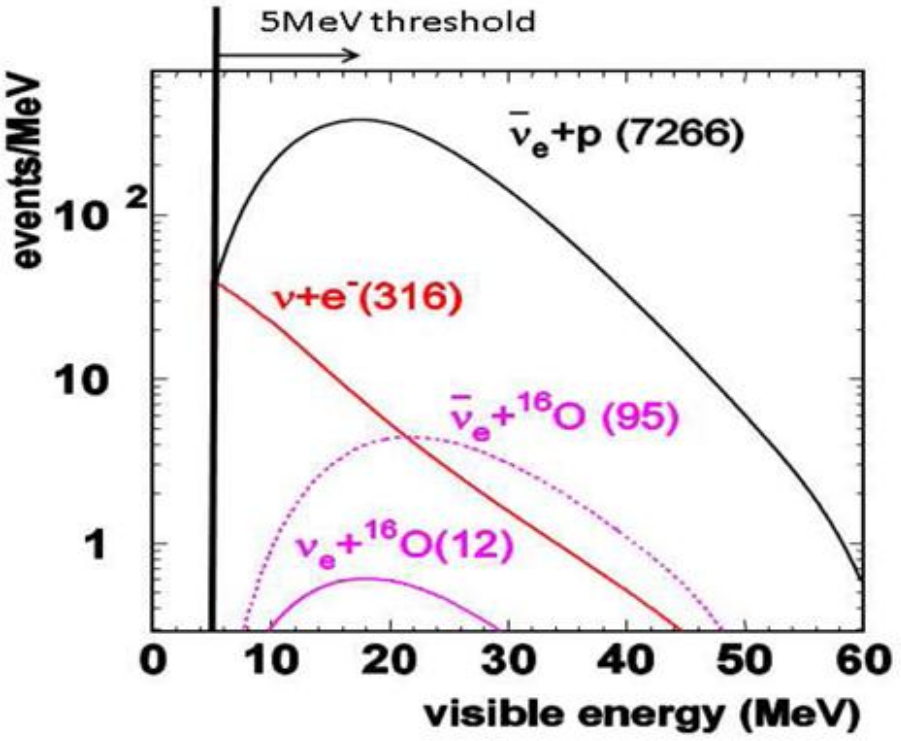
Neutrinos from Supernova

Expected number of events at SK

(T. Totani, K. Sato, H. E. Dalhed, and J. R. Wilson 1998, *ApJ*, **496**, 216)



Expected energy distribution at SK for 10-kpc supernova



Signal Sensitivity

- Number of hits for a SN neutrino event is estimated to be around

$$6 \text{ hits/eV} \times 20 \text{ eV} = 120 \text{ hits}$$

  - Confirmed with the LINAC electron data
- Dominant background is the continuous dark noise hits.
  - 4,500 Hz/PMT, i.e., 0.83 hits/16 ns

Time Resolution [MHz]	Estimated Number of Dark Noise hits [hits/bin]
60	0.83 ± 0.9
10	5 ± 2.2
1	50 ± 7.1
0.1	500 ± 22
0.06	830 ± 26
0.01	5000 ± 71

Test Bench for Prototype

Master Clock

Event number

VME trg32

1. Count up event number and send to Master Clock module

2. Receive event number and send 60MHz clock and encoded event number via RJ45, LVDS level

Encoded event number
60MHz system clock
(LVDS level)

Prototype Board

3. Decode event number and send it via Ethernet

Event number
via Ethernet

Client PC (Linux)

4. Receive event number and read out

Current SN ν Detectors

Number of events expected for 10 kpc		Directionality
Baksan (1980-)	330 ton liquid scintillator ~100 $\nu_e p \rightarrow e^+ n$ events.	No
LVD (1992-)	1000 ton liquid scintillator. 840 counters 1.5m^3 each. 4 MeV thres., ~50% eff. for tagging decayed signal. ~300 $\nu_e p \rightarrow e^+ n$ events.	No
Super-K (1996-)	32,000 tons of water target. ~7300 $\nu_e p \rightarrow e^+ n$, ~300 $\nu e \rightarrow \nu e$ scattering events.	Yes
KamLAND (2002-)	1000 ton liquid scintillator, single volume. ~300 $\nu_e p$, several 10 CC on ^{12}C, ~60 NC γ, ~300 $\nu p \rightarrow \nu p$	No
ICECUBE (2005-)	Gigaton ice target. By coherent increase of PMT single rates. High precision time structure measurement.	No
BOREXINO (2007-)	300 ton liquid scintillator, single volume. ~100 $\nu_e p$, ~10 CC on ^{12}C, ~20 NC γ, ~100 $\nu p \rightarrow \nu p$	No
HALO (2010-)	SNO ^{3}He neutron detectors with 76 ton lead target. ~40 events expected.	No