Super-Kamiokande triggering system

Guillaume Pronost

Kamioka Observatory, ICRR, University of Tokyo

4th Hardware Camp for Fast and Low-Light Detection, March 6th 2025

Super-Kamiokande

The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France/Japan

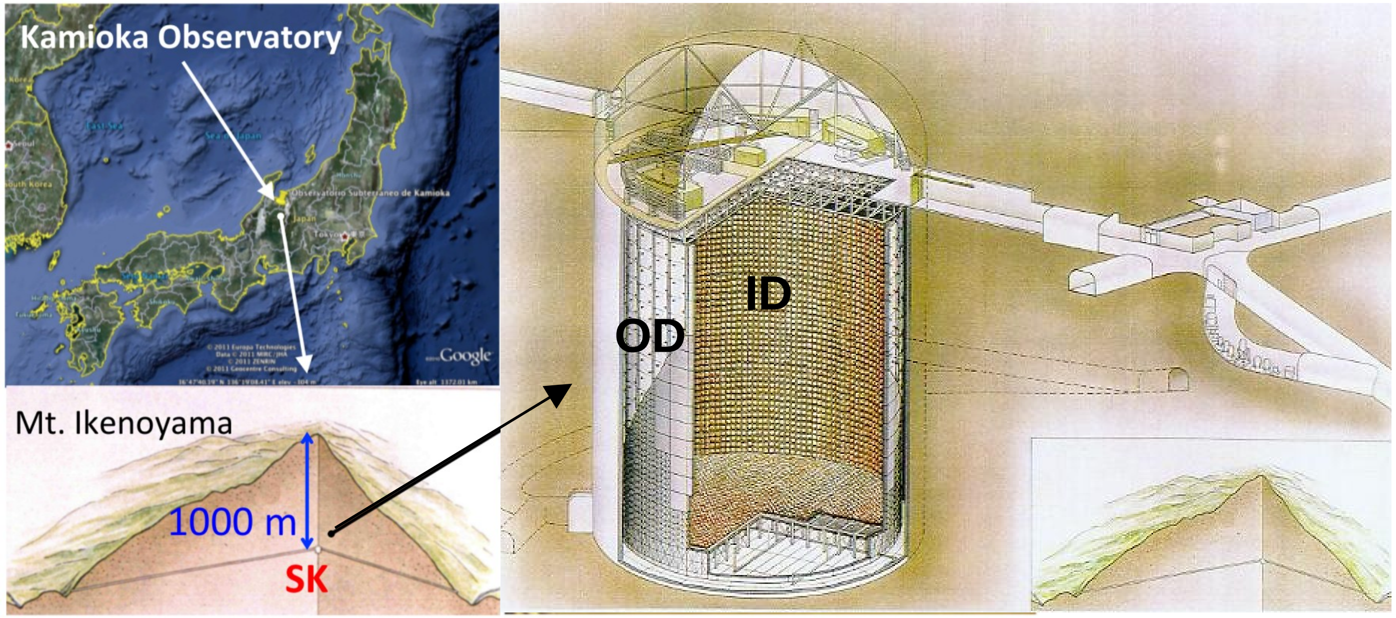
INFN Bari, Italyl
NFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Nihon University, Japan
Okayama University, Japan

Osaka Electro-Communication Univ.,Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~230 collaborators from 53 institutes in 11 countries

Super-Kamiokande

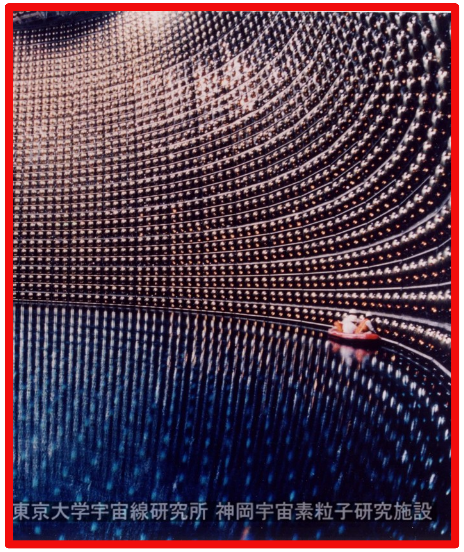
- **World leading** Water Cherenkov detector located in the Kamioka Mine (Japan)

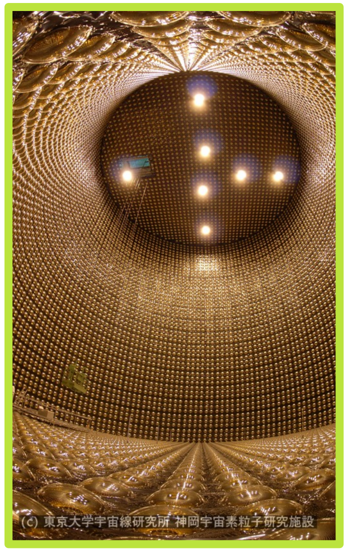


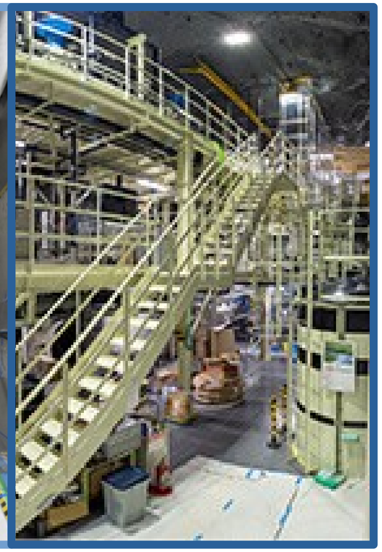
- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-VII is running

- The detector is filled with 50ktons of **gadolinium**-loaded water.
- Gadolinium was loaded at 0.01% in the water in Summer 2020, and the concentration was further increased to 0.03% in May 2022. Calibration was completed and the detector is running stably since then.
- **Physics targets**: Neutrino Oscillations (Solar Neutrino, Atmospheric Neutrinos, T2K beam), Nucleon decay, Astrophysics (Supernova burst, Diffuse Supernova Neutrino Background, etc.)

Super-Kamiokande phases





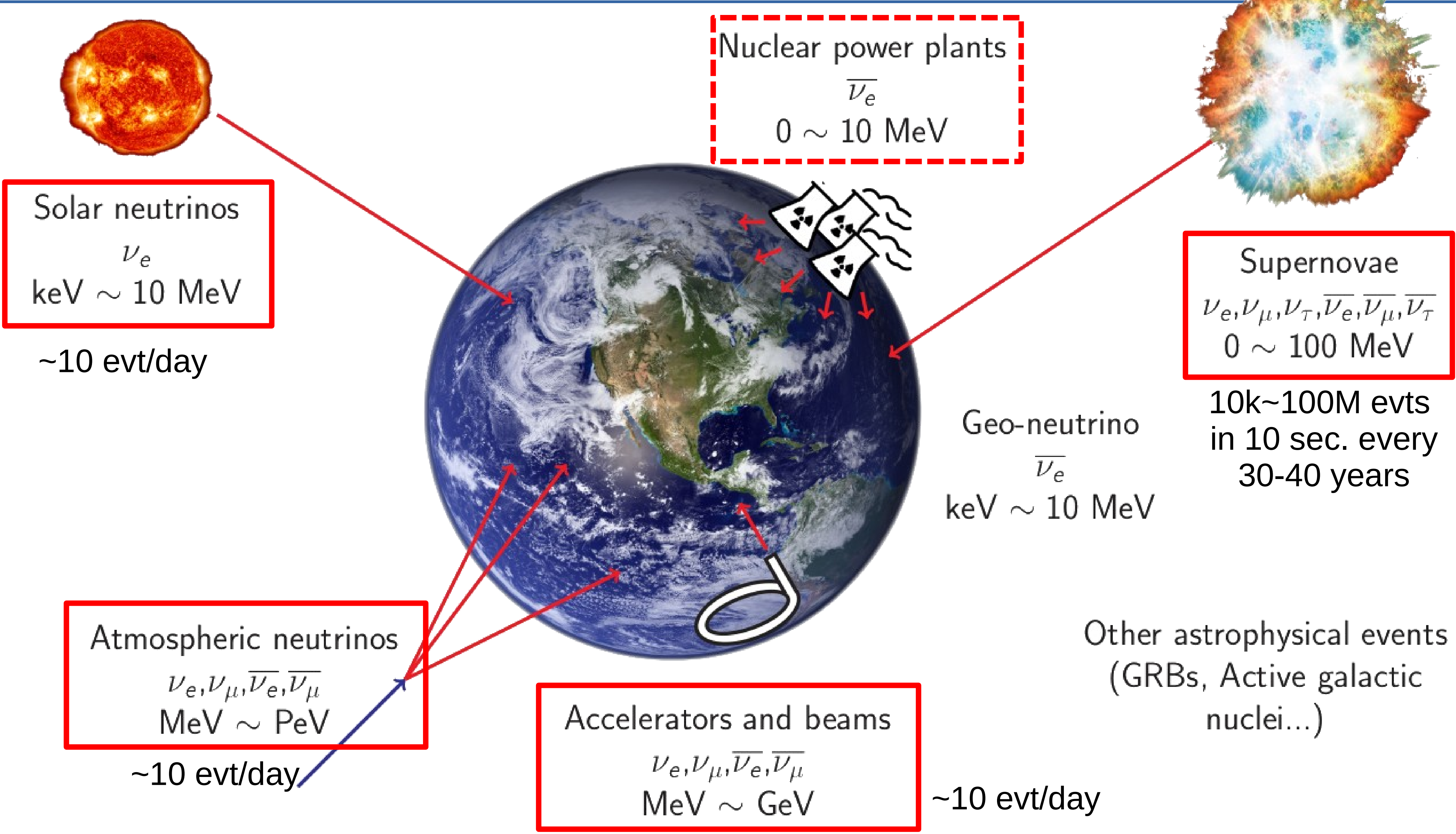


1996	2002	2006	2008	2019	2020	2022
SK-I	SK-II	SK-III	SK-IV	SK-V	SK-VI	SK-VII
40% P.C.	19% P.C.	40% P.C.	New electronics		0.01%	0.03%

SK-Gd (2020 →)

Neutron tagging (2008 →)

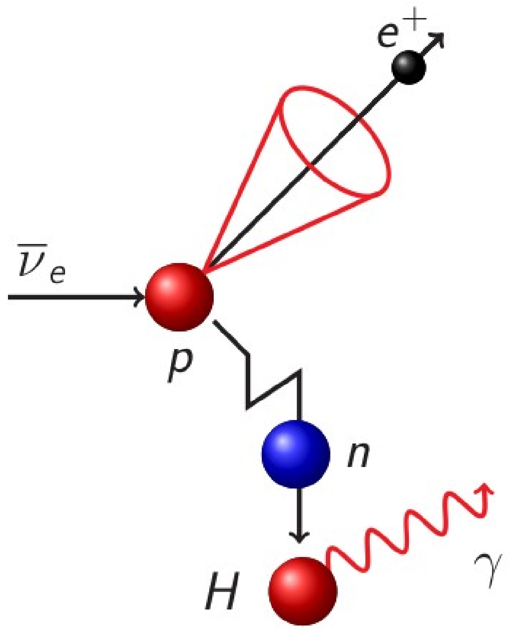
Neutrino sources in Super-Kamiokande



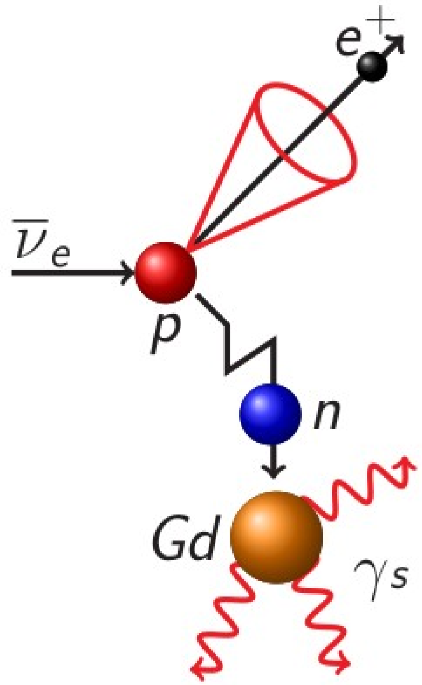
- Super-Kamiokande is looking for a vast range of neutrino source with various energy range and rate. $\rightarrow$ We need a flexible triggering system to handle all of them

Why Gadolinium?

- Gadolinium is the **stable nucleus with the highest neutron capture cross-section** on Earth. The gadolinium-neutron capture produced a gamma cascade with a total energy of ~8 MeV, allowing to detect and reconstruct the neutron capture.
- This is specially useful to tag Inverse Beta Decay interactions



Hydrogen-neutron capture:
single 2.2 MeV gamma
→ Large accidental background
→ Vertex reconstruction difficult



Gadolinium-neutron capture:
Gamma cascade at ~8 MeV
→ Lower background
→ Vertex reconstruction possible

Interactions in SK

Cherenkov light

- Cherenkov light is emitted when a charged particle travel through a medium at a greater speed than the speed of light in this medium. It has a wavelength close to blue ~ ultraviolet.
- For relativistic charged particle in water, the cherenkov angle is θ_c ~42 degree:

  $\cos\theta_c = 1 / (n * \beta)$

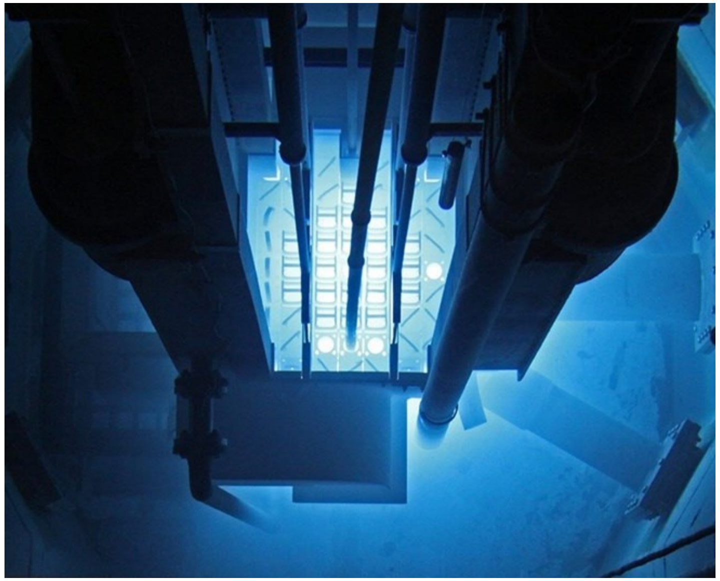
  relativistic: $\beta \sim 1 \rightarrow \cos\theta_c \sim 1/n$

  $n_{water} \sim 1.33 \rightarrow \theta_c$ ~42 degree
- The number of photon emitted is ~340 photons/cm

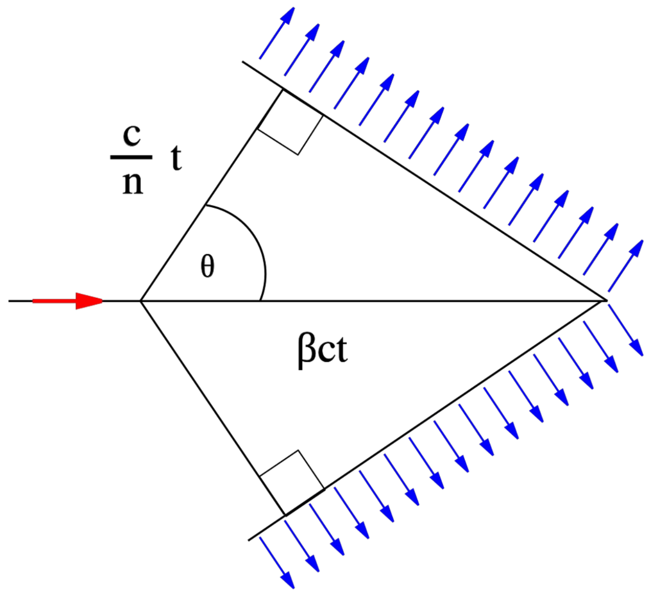
$$\frac{d^2 N_{photon}}{d\lambda dL} = \frac{2p\alpha Z^2}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right)$$

Sensitive wavelength of PMT: 300 ~ 600nm
Cherenkov angle θ=42 degrees, Z (charge) =1

Taking into account the PMT coverage, PMT quantum efficiency, etc. the number of photon detected is much smaller



University of Massachusetts Lowell Radiation Laboratory

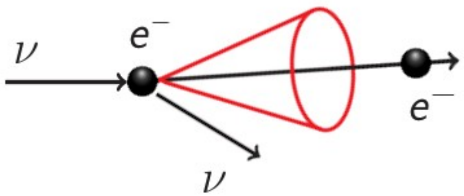


Images from wikipedia

Neutrino interactions

- Neutrino are neutral particle and don't emit Cherenkov light by themselves.
- Charged particles produced by neutrino interaction are the ones producing the Cherenkov light

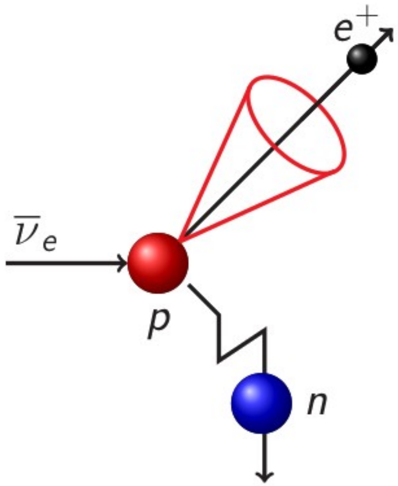
Neutrino-electron interaction:



Electron scattering

Neutrino/antineutrino interacts with the electrons orbiting a nucleus and eject one. The electron keeps the neutrino direction

Neutrino-nucleus interaction:

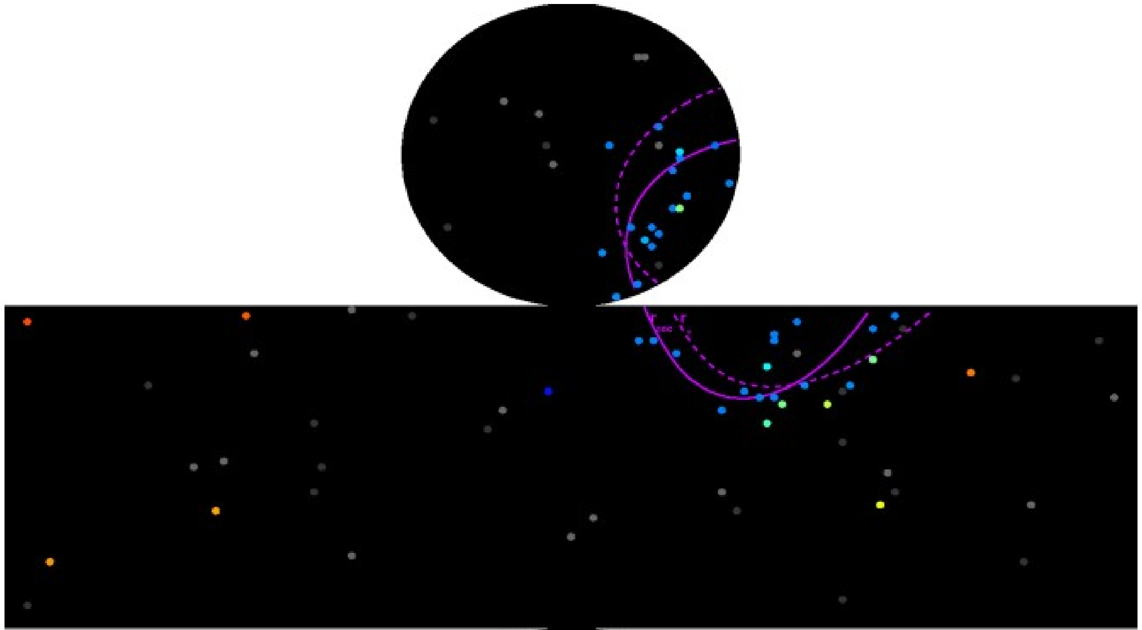


Charged current
(ex) Inverse Beta decay

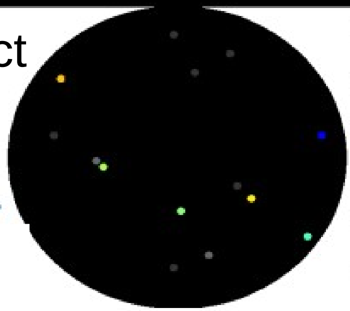
Neutrino/antineutrino interacts with the nucleus, producing multiple its charged leptons and other particle depending on the energy deposited.

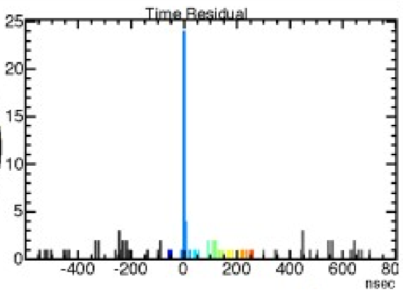
Solar neutrinos

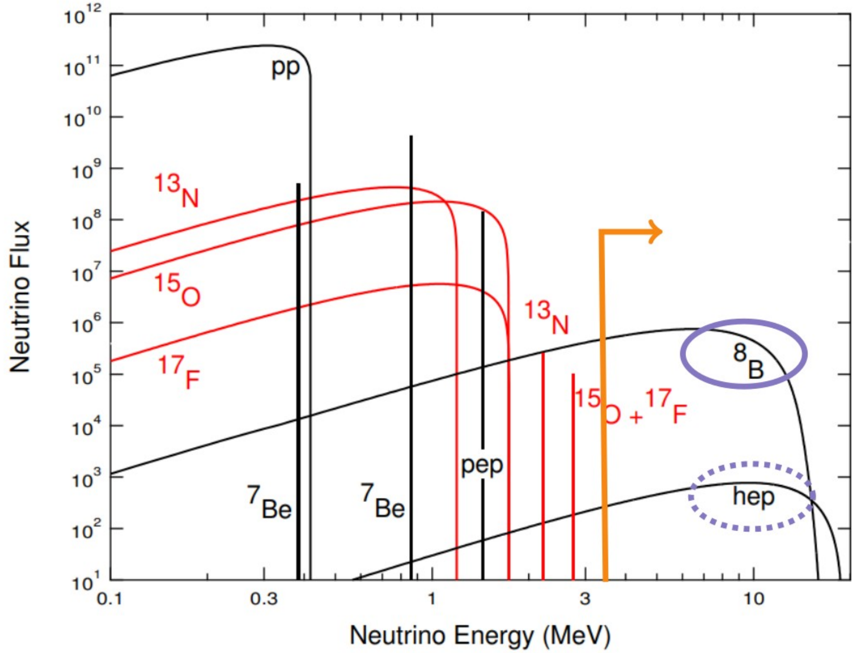
- Produced by fusion reaction within the sun
- ~10 events per day
- Super-Kamiokande can detect Solar neutrino in 5 ~ 15 MeV



25 ~ 100 PMTs detect light (including reflection)



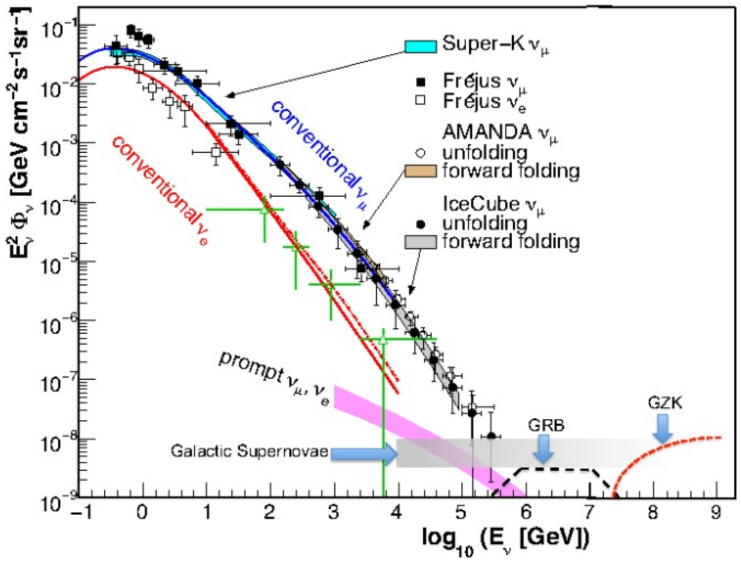


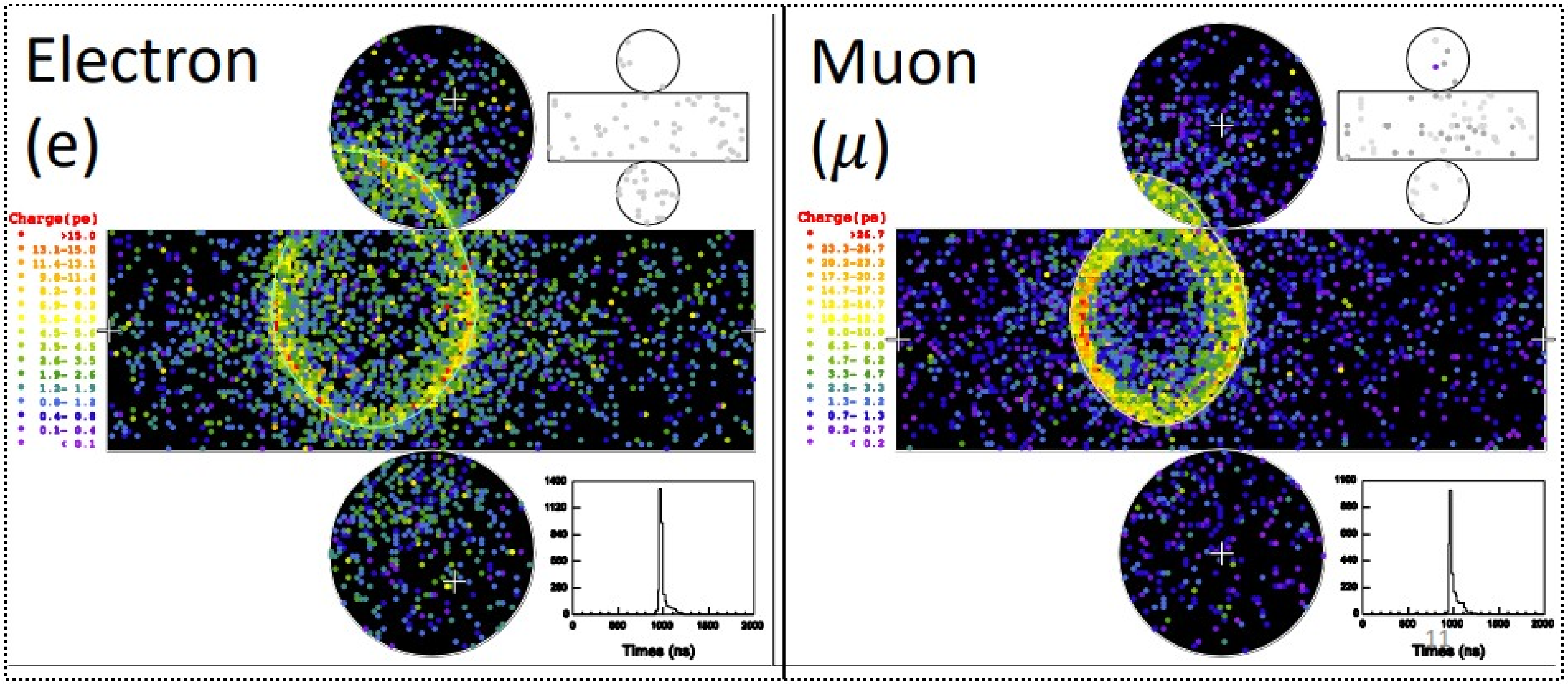


pronost@km.icrr.u-tokyo.ac.jp

Atmospheric neutrinos

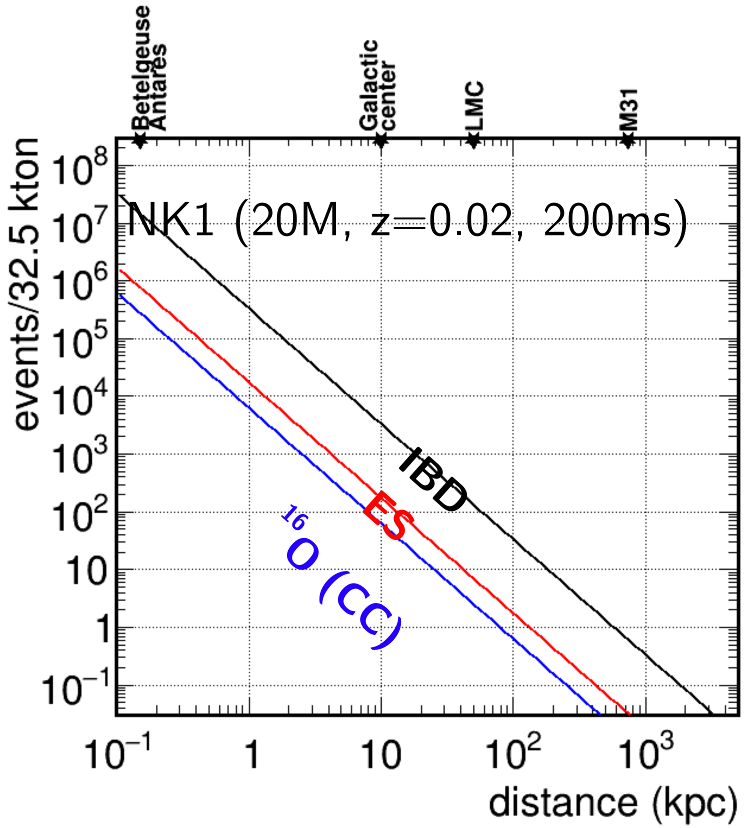
- Produced by cosmic ray interaction in the atmosphere
- $\sim$10 events per day
- Large energy range allowing very energetic neutrino-nucleus interaction.
- Electron and muon (and tau) produce different patterns

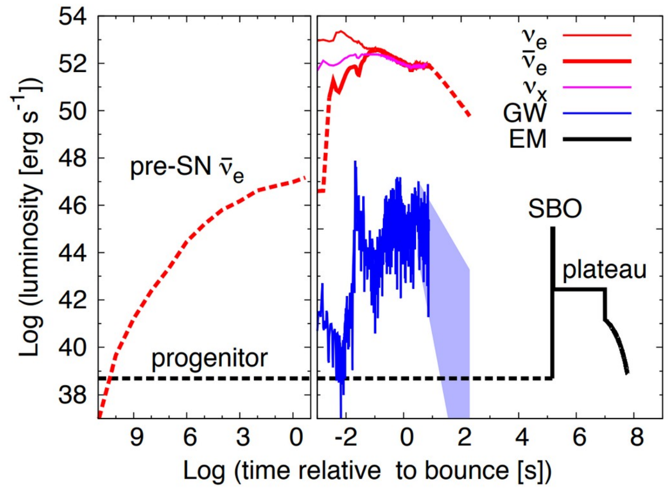




Supernova neutrinos

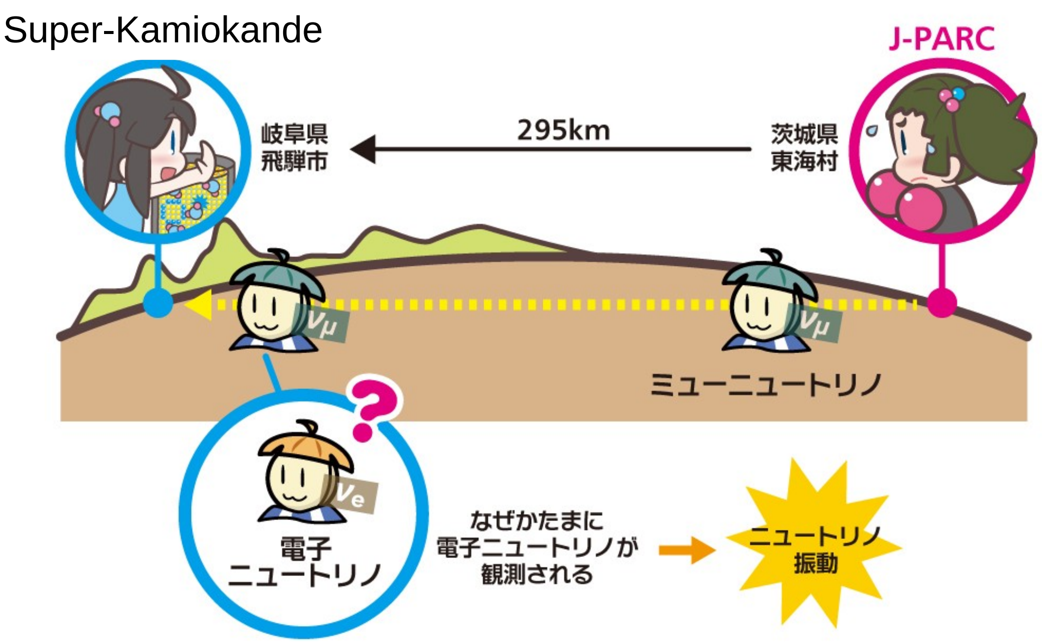
- Rare event (once every 30~40 years depending on the model)
- 99% of the energy released by supernova come as a neutrino flux
- Can induce a massive burst of neutrino interaction in 10 sec if the supernova is close enough:
  - 10~100M events if Betelgeuse becomes a SN
  - ~10k events for a SN at the galactic center
  - ~50 events for a SN at LMC
- DAQ system needs to be able to handle such massive amount of data.

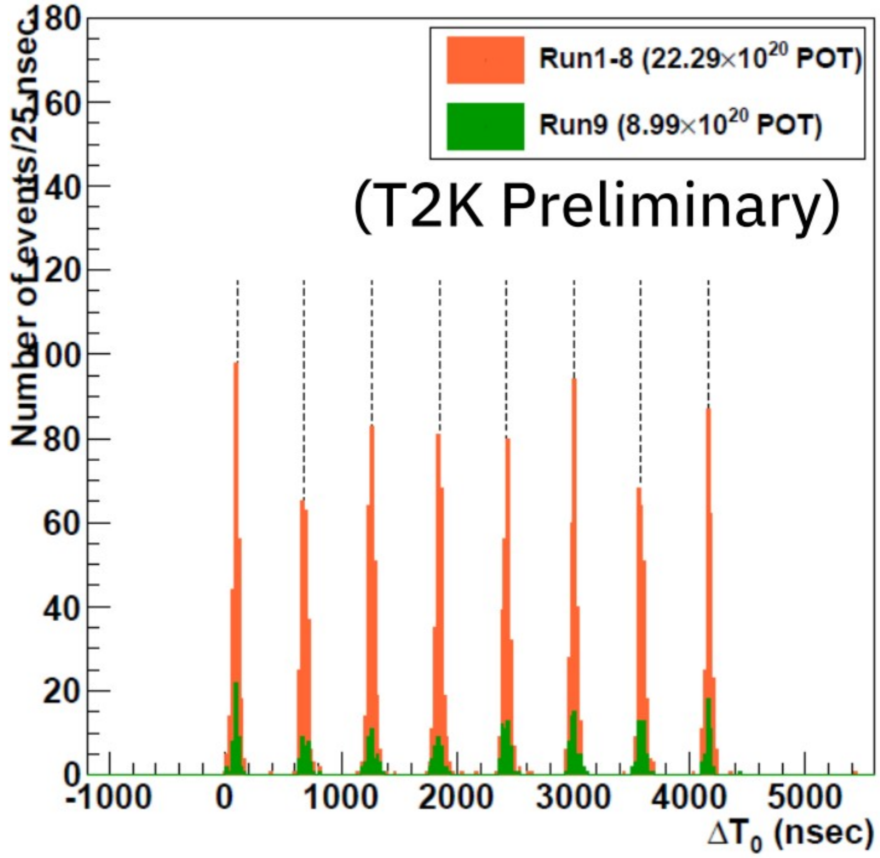




Accelerator neutrinos

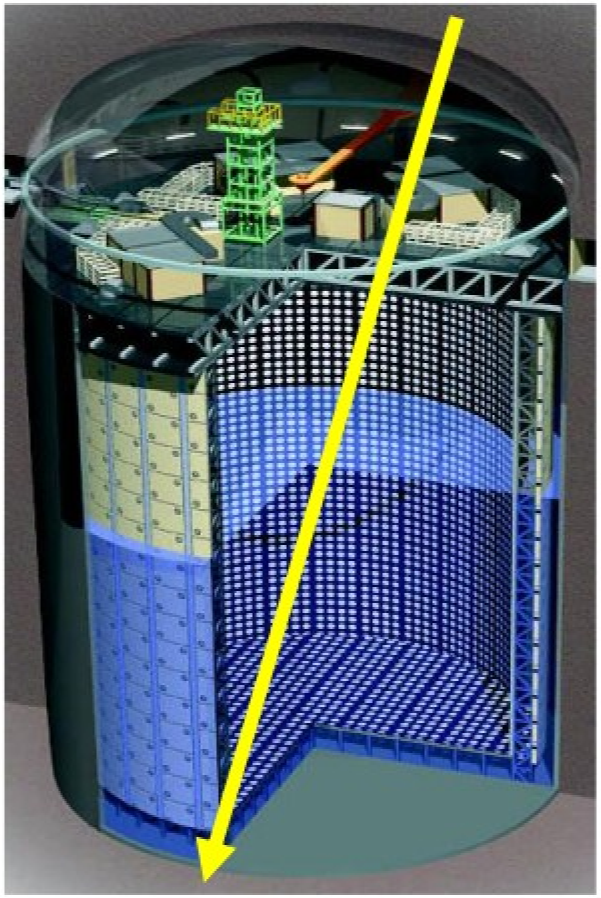
- Neutrino (ν_μ and $\bar{\nu}_\mu$) are generated at J-PARC in the direction of Super-Kamiokande
- Energy of 200~1200 MeV, ~10 events per day during beamtime

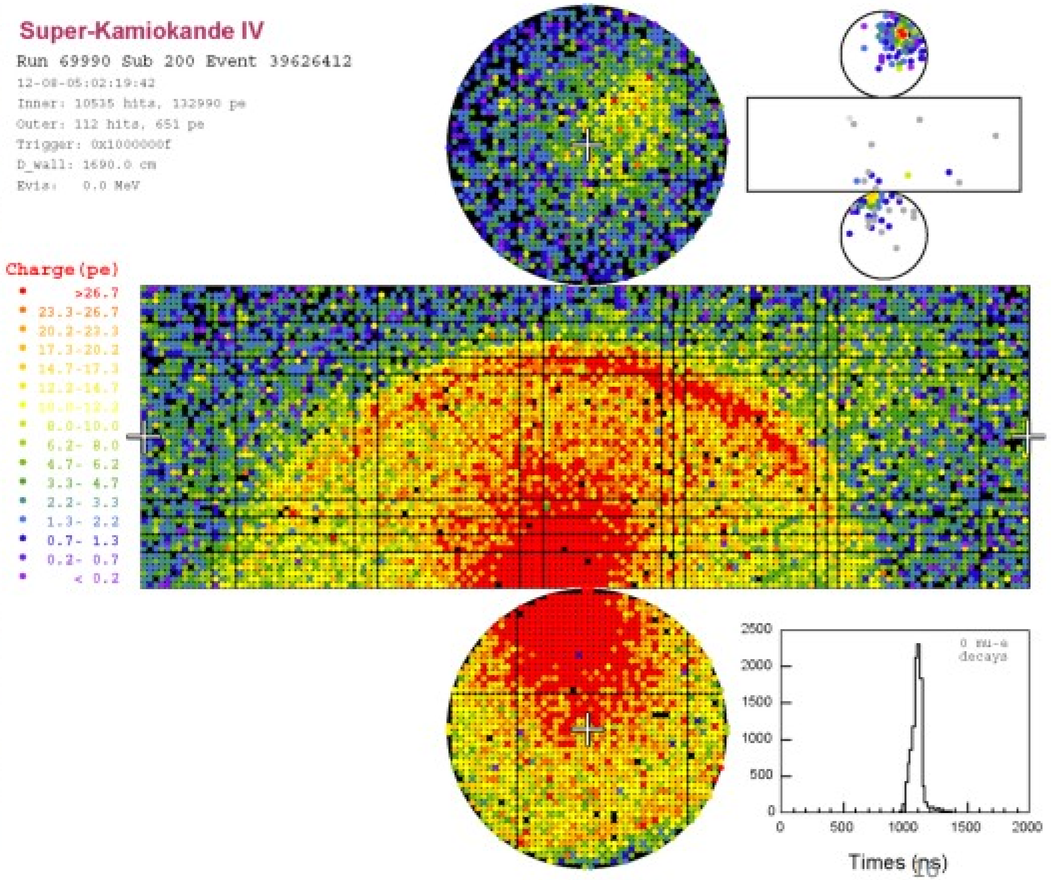




Background: cosmic muons

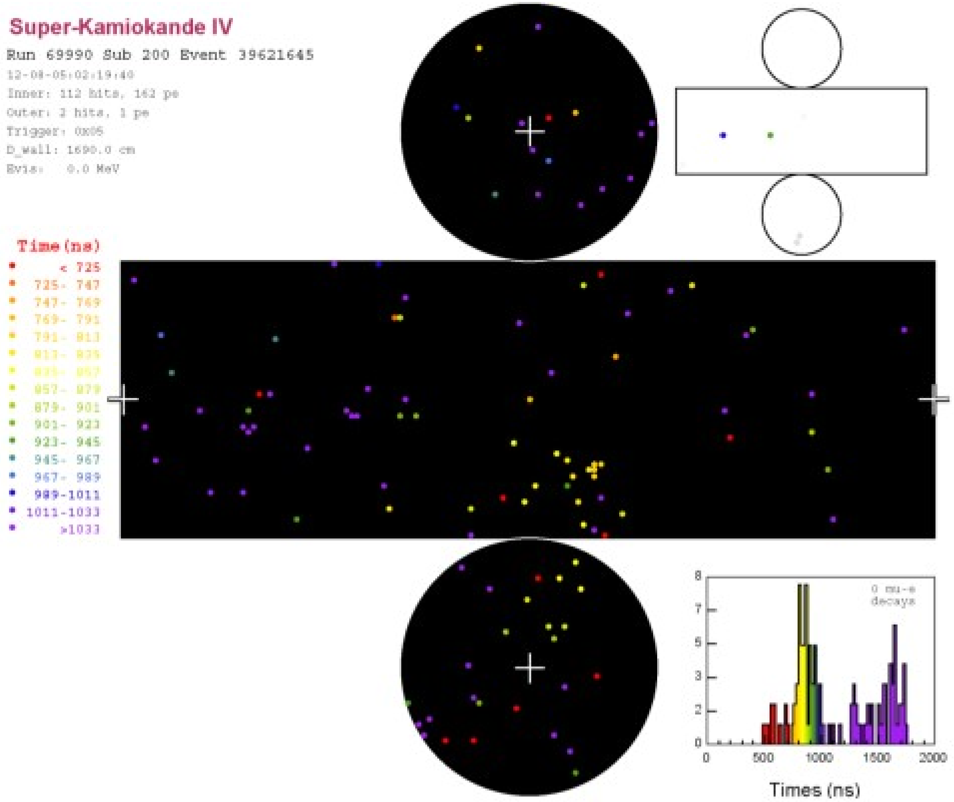
- Produced by cosmic ray interactions in the atmosphere
- Generate background events on their track in the detector
- 2~3 event per seconds





Background: radioactivity

- Radioactivity from detector materials (radon, thallium, etc.), activation from muon interaction, etc.
- Low energy
- ~21k events per seconds (with current settings)



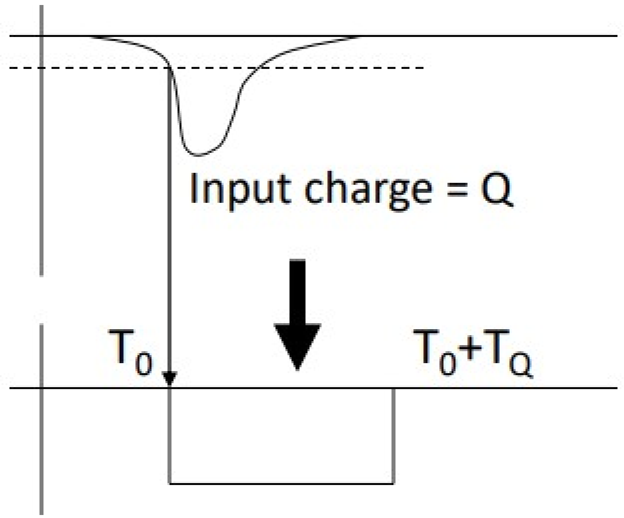
Electronics and Data Acquisition system

General view

- In order to define the electronics and data acquisition system (DAQ) we needed in Super-Kamiokande, we had to define what we are looking to measure and how we should do it.
- What do we measure?
  - Charge from PMT (i.e. number of photons)
  - Timing from PMT (i.e. photon arrival timing)
- What do we need?
  - Self gating signal digitizer (recording time and charge)
  - Accurate clock synchronisation system across 10k PMTs (Synchronisation Clock + counter)
  - GPS
  - A system running 24h 7 days, as we don't know when neutrino interact in the detector → Stable software and hardware

PMT signal digitization

- We use QTC (charge to time converter) with multi-hit contineous readout TDC (Atlas Muon TDC or AMT).
- QTC converts charge to digital signal whose width is linear to the input charge



T_0 : Timing of the input analog signal

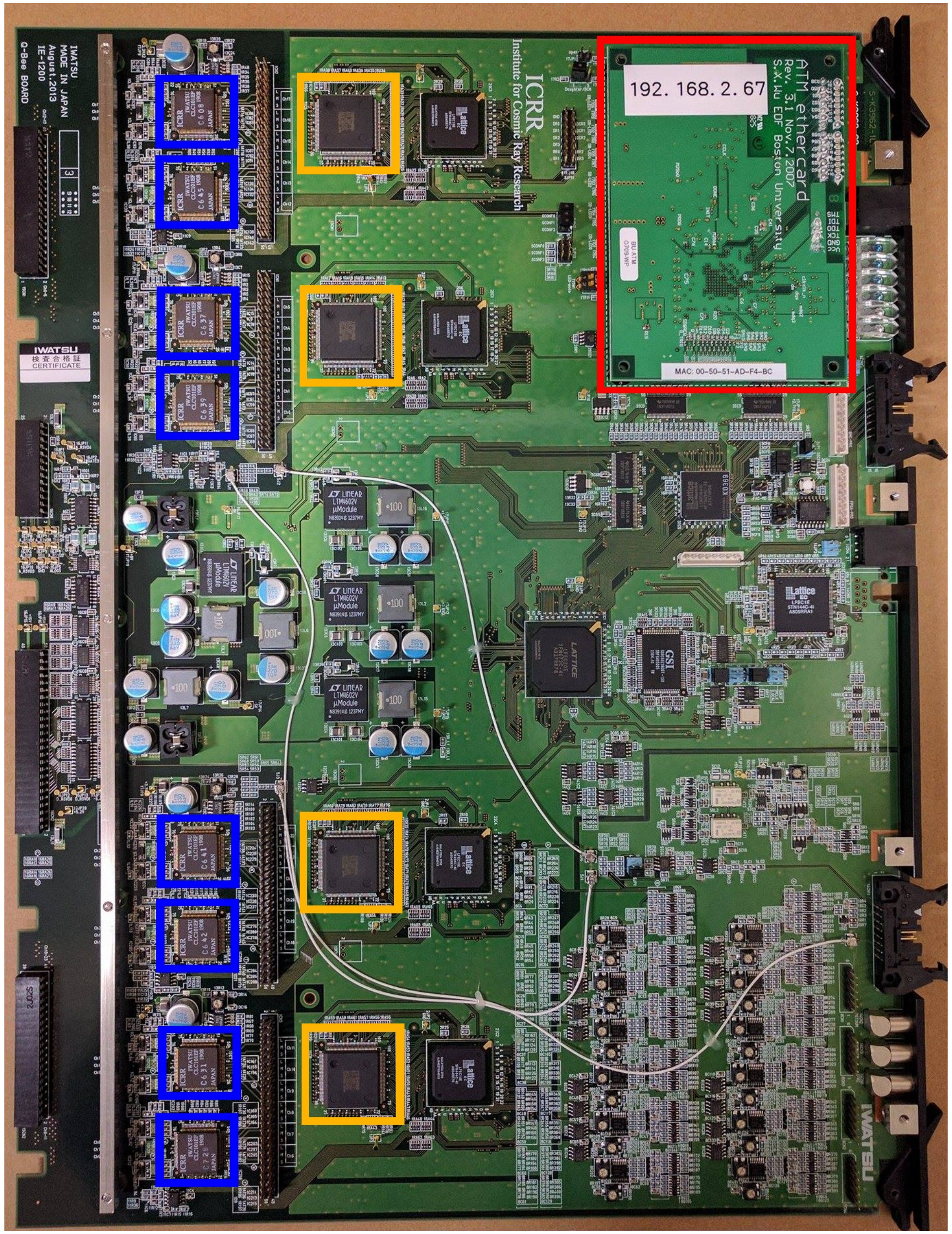
T_Q : Width of the signal linear to the input charge Q

Figure from Hayato-san

- Note: there are small deadtime between each hit integration window so it's not fully "dead-time free"
- QTC converts charge to digital signal whose width is linear to the input charge
- All PMT signals are digitized and readout on computers

Digitizer module: QBEE

- Takes 24 PMT signal, 60kHz clock, and Trigger count as input.
- Nominal speed: ~750kB/s/board
  Maximum speed: ~10MB/s/board
- Built-in discriminator: ¼ PE (~0.3 MeV)
- Processing speed: ~1 µsec/Hit
- High sensibility for single PE
- Charge response resolution:
  RMS: ~0.05 PE ($<$ 25 PE)
- Timing response:
  RMS: 0.3 ns (1 PE)
  0.2 ns ($>$ 5 PE)
- Wide charge dynamic range: 0.1 ~ 1250 PE



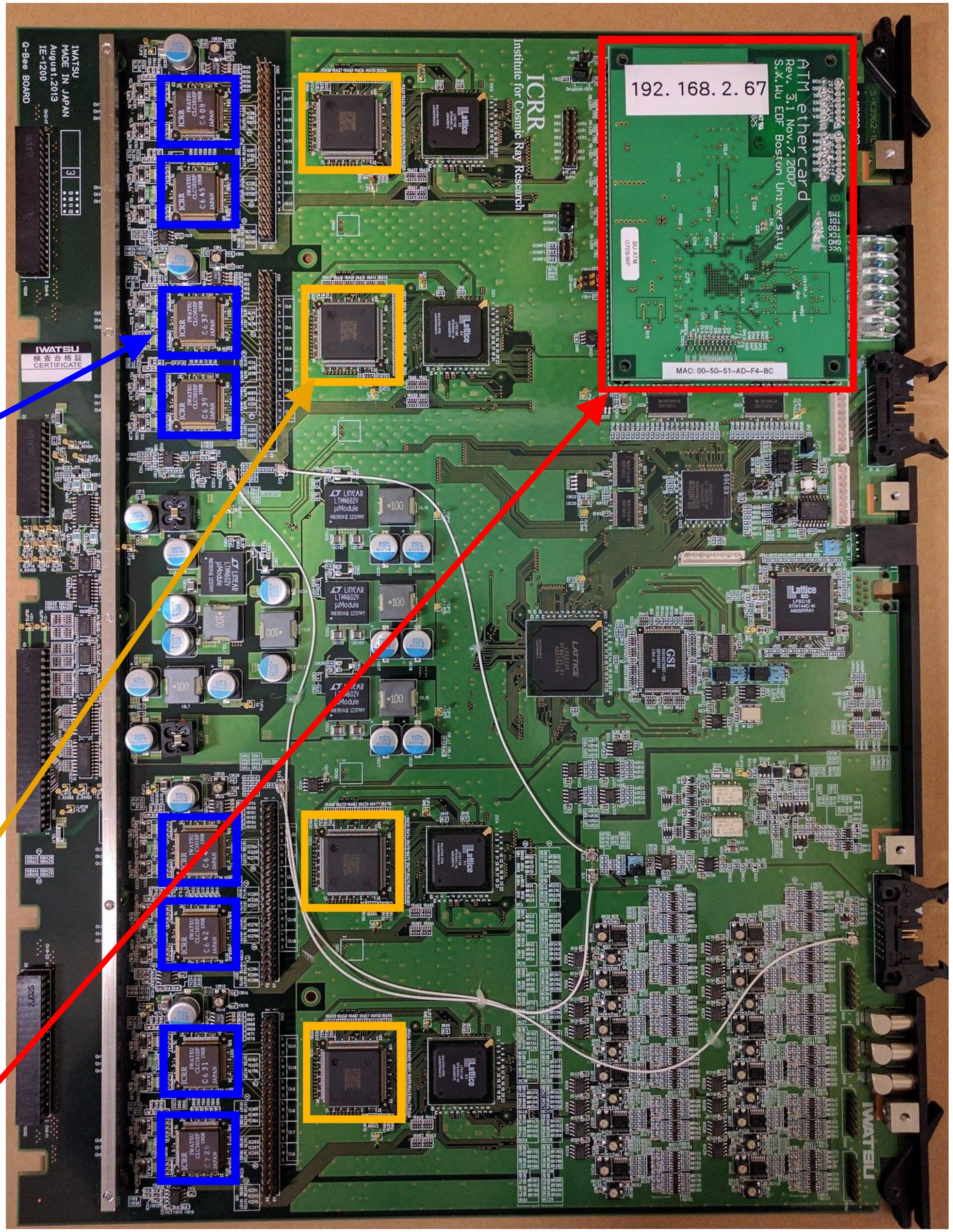
Digitizer module: QBEE

- Takes 24 PMT signal, 60kHz clock, and Trigger count as input.
- Nominal speed: ~750kB/s/board
  Maximum speed: ~10MB/s/board

Custom QTC circuits (high-speed charge-to-time converter IWATSU CLC1101) allowing individual threshold definition for each PMTs at high rate signal processing ($>$ 1 MHz) with 3 channels.

Integrated multi-hit time to digital converters and field-programmable gate arrays.

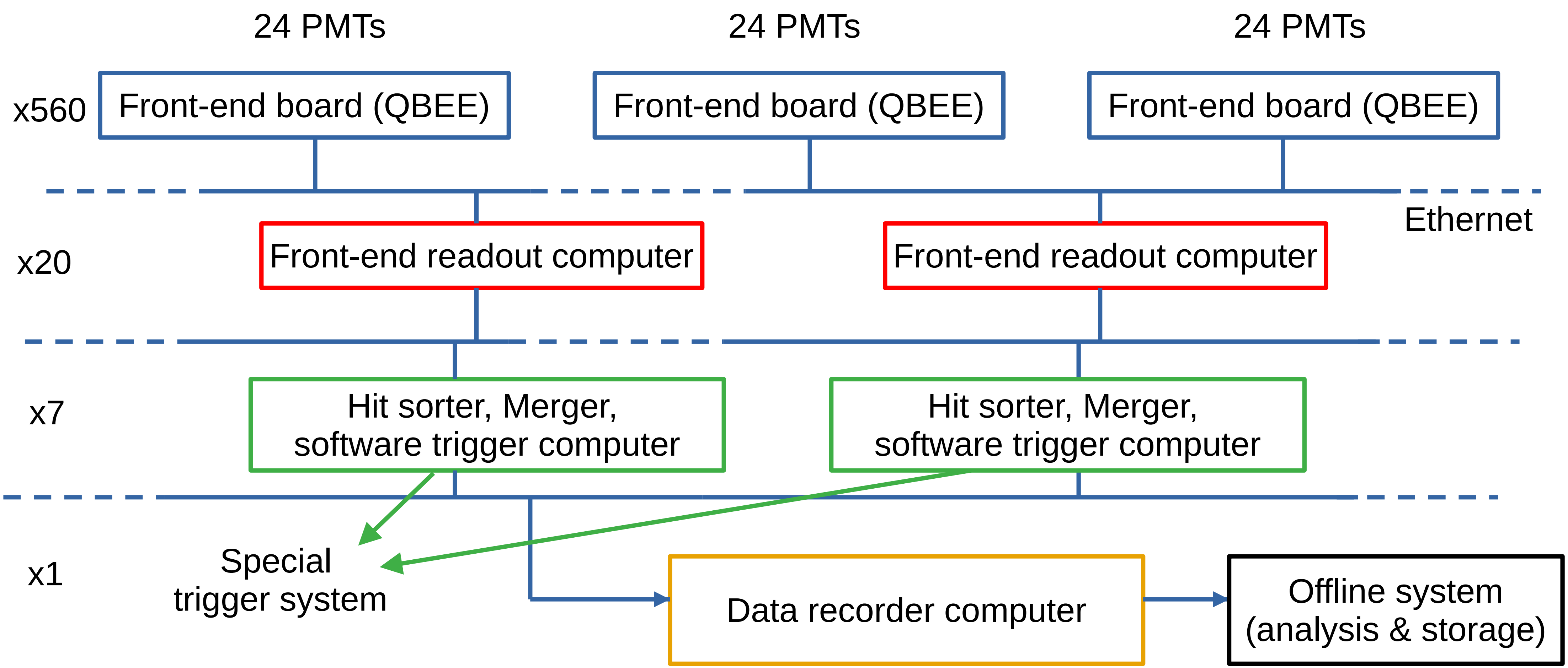
Allows external readout via ethernet connection (100Mbs / 12.5 MBs).



pronost@km.icrr.u-tokyo.ac.jp

Data Acquisition system

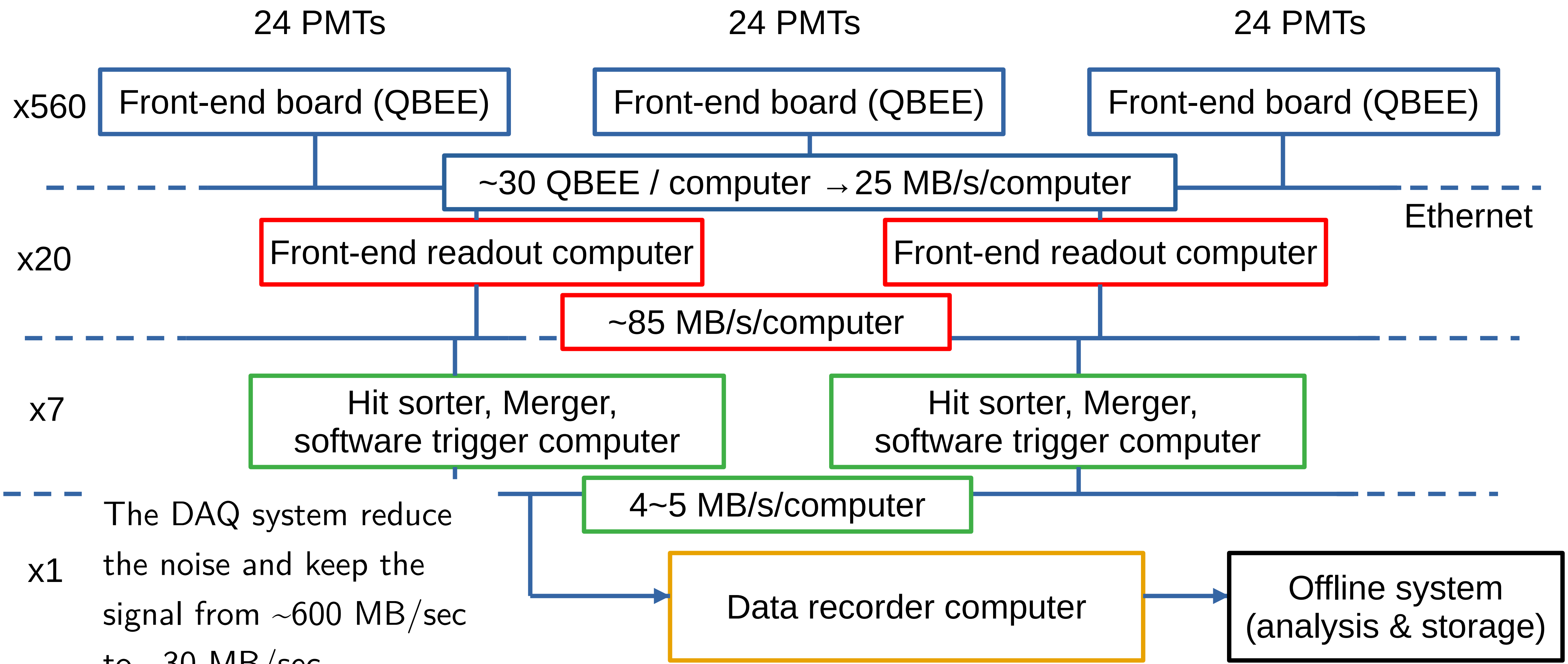
- After recording all digitized hits from PMTs (including dark noise) we process them on computer to apply a "software" trigger, which will define our events.
- We are processing about 600 MB/sec with 11k PMTs in ID and 2k PMTs in OD (assuming ~5 kHz darknoise and 6 bytes/Hit).



pronost@km.icrr.u-tokyo.ac.jp

Data Acquisition system

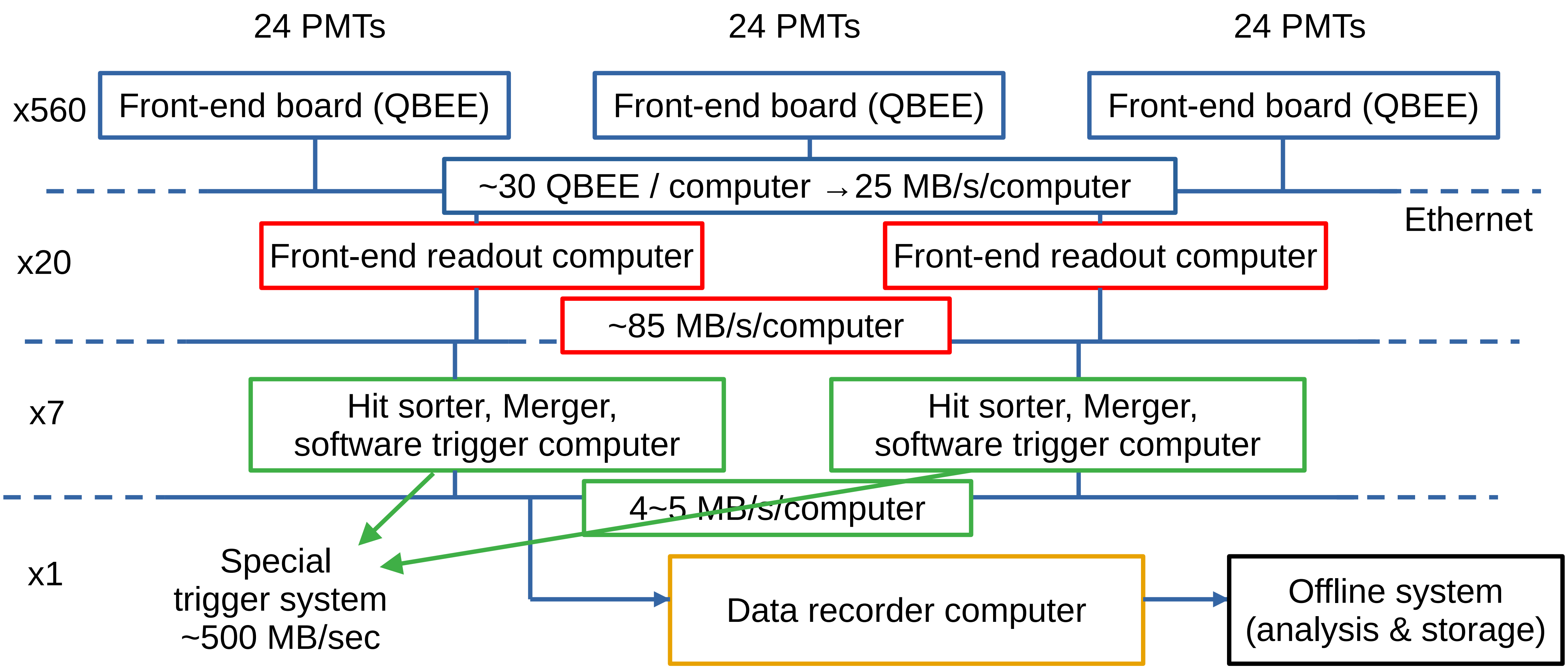
- After recording all digitized hits from PMTs (including dark noise) we process them on computer to apply a "software" trigger, which will define our events.
- We are processing about 600 MB/sec with 11k PMTs in ID and 2k PMTs in OD (assuming ~5 kHz darknoise and 6 bytes/Hit).



The DAQ system reduce the noise and keep the signal from ~600 MB/sec to ~30 MB/sec

Data Acquisition system

- After recording all digitized hits from PMTs (including dark noise) we process them on computer to apply a "software" trigger, which will define our events.
- We are processing about 600 MB/sec with 11k PMTs in ID and 2k PMTs in OD (assuming ~5 kHz darknoise and 6 bytes/Hit).



pronost@km.icrr.u-tokyo.ac.jp

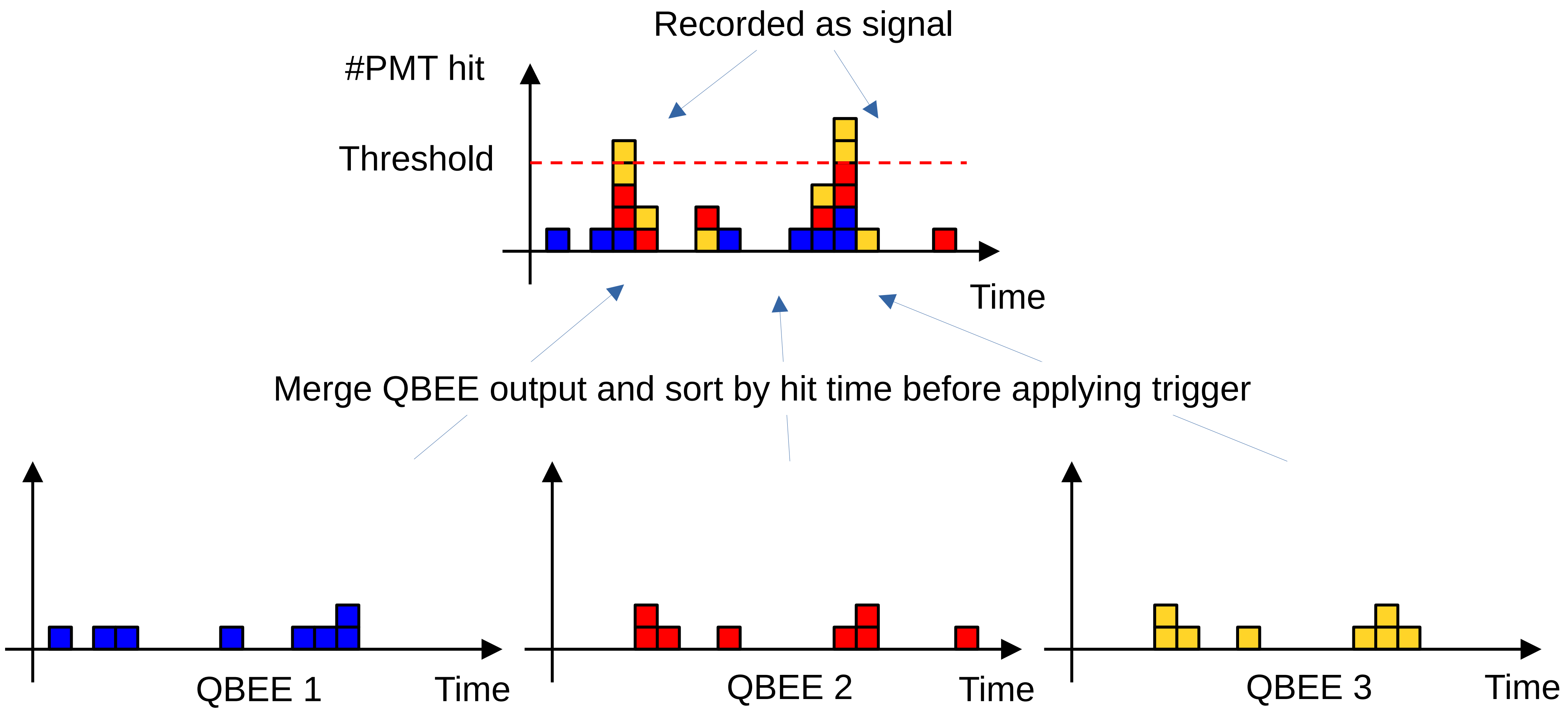
Triggering

Super-Kamiokande triggering

- In Super-Kamiokande we are considering different type of triggers:
  - Simple majority triggers for neutrino events, proton-decay events, etc.
  - External trigger (from T2K or from some calibration sources)
  - Background and dark noise are mostly going to affect the simple majority triggers

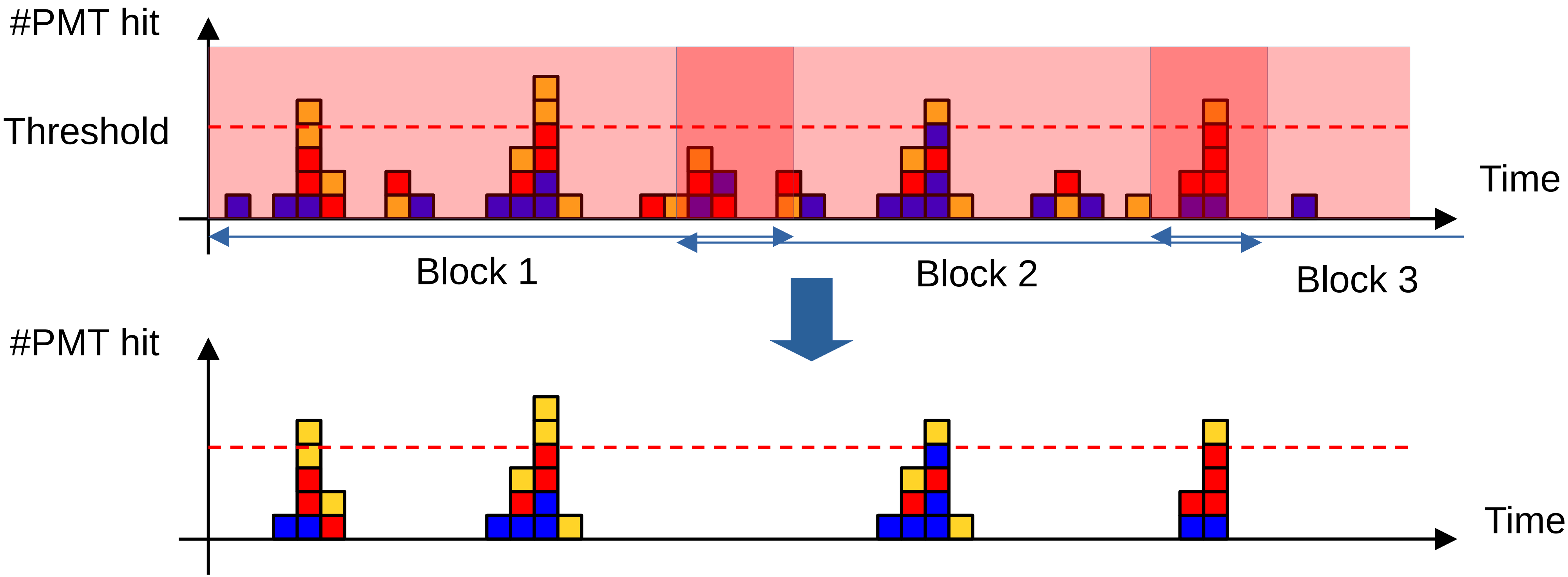
Majority trigger I

- Cherenkov light emission is fast ~200ns, signal can be identified if multiple PMTs produce signal within ~200ns.
- We can set a threshold on the number of PMT hit to select only signal with an high enough energy and to reduce background (radioactivity, dark noise)



Majority trigger II

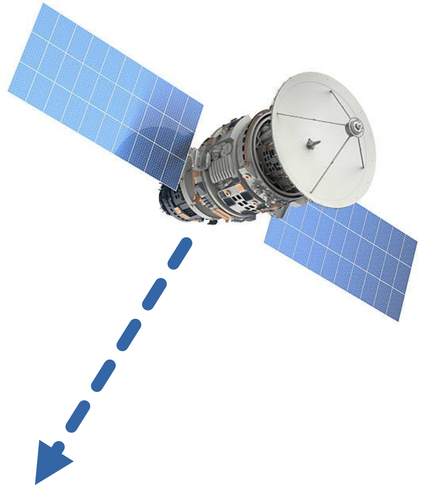
- It's not possible to handle all the data with just one CPU core
  $\rightarrow$ We need to process the data on multiple CPU core.
- However, we don't know when an event happens, so we must to do some overlap in the distributed data to ensure we are not missing any event.
- If an event happen within the overlap region, we will keep only one by checking for overlapping event before storage.

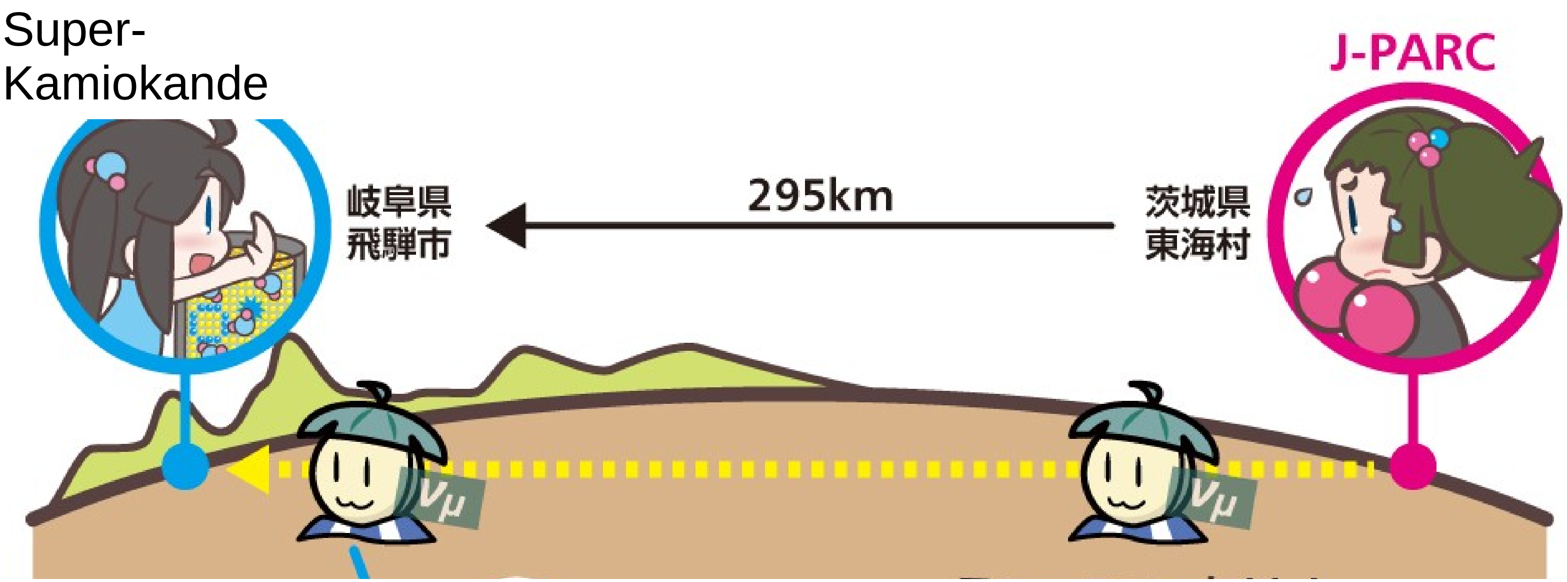


1 block correspond to ~20 ms (1280 HW triggers), the overlap is ~1ms (64 HW triggers)

Accelerator beam trigger

- During beam time, J-PARC produces neutrino every few seconds
  (beam width ∼4 µsec)
- We record the production time at J-PARC using GPS and send the timestamp to Super-Kamiokande via L2VPN (∼10 ms)
- The neutrino arrive at Super-Kamiokande in ∼1 ms
- Data in SK is kept for few seconds with GPS time recorded.
  After arrival of the J-PARC GPS time, the data -500 µsecto 500 µsec around the production time is flagged with a T2K trigger.





Calibration source triggers

- In order to calibrate the detector, we are using different type of calibration source in Super-Kamiokande:
  - Standard radioactive source for which we don't know the timing of the event
  - Controlled sources (light generator, particle accelerator) for which we know the timing of the events
- For trigger, we consider these two cases separatly:
  - Standard radioactive source events are triggered using the usal majority triggers.
  - Controlled sources events are triggered using an external signal, which is feed to one of our QBEE (called the "trigger QBEE") where each channel is associated with a specific trigger and one "hit" (signal) on this channel cause the trigger to be initialised

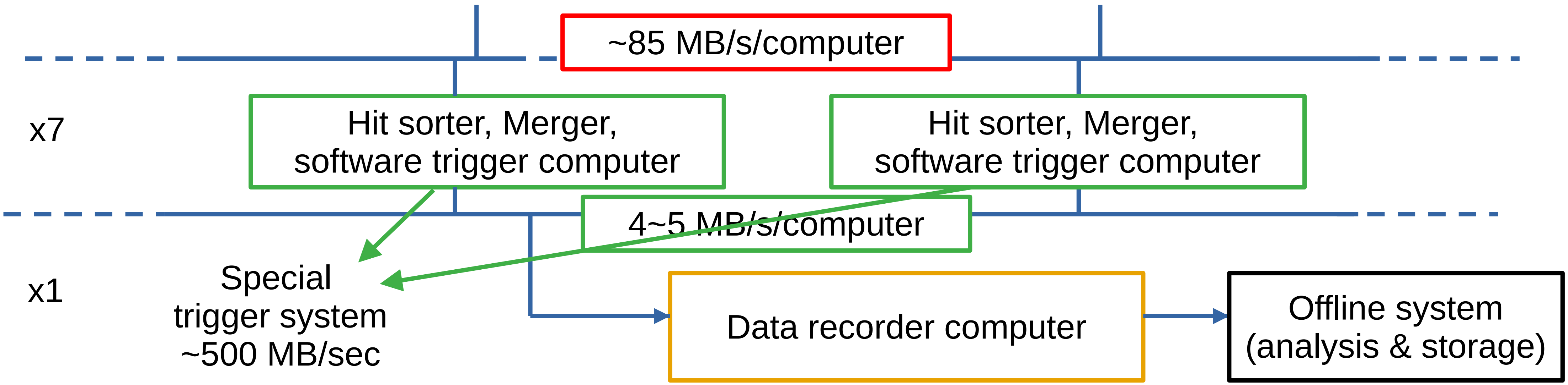
 pronost@km.icrr.u-tokyo.ac.jp

Trigger "gates"

- Each trigger in Super-Kamiokande have "gates", defining which range of PMT hits are stored.
  - For very low energy events ($<$5 MeV), we store $\sim$1.5 µsec around the trigger time (-0.5 to $+$1.0 µsec)
  - For normal events ($>$5 MeV), we store $\sim$40 µsec around the trigger time (-5.0 to $+$35 µsec)
  - As we saw earlier, for T2K trigger, we store 1ms around the trigger time (-500 to $+$500 µsec)
  - Dedicated calibration also have gate defined (mostly similar to normal events) but the trigger time "0" can be shifted with respect to the triggering hit time in order to take into account delay due to cable length difference.
- We also have an special "neutron trigger" which extend the trigger gate of a normal event to $+$535 µsec if its energy is above $\sim$8 MeV.

Intelligent trigger for very low energy events

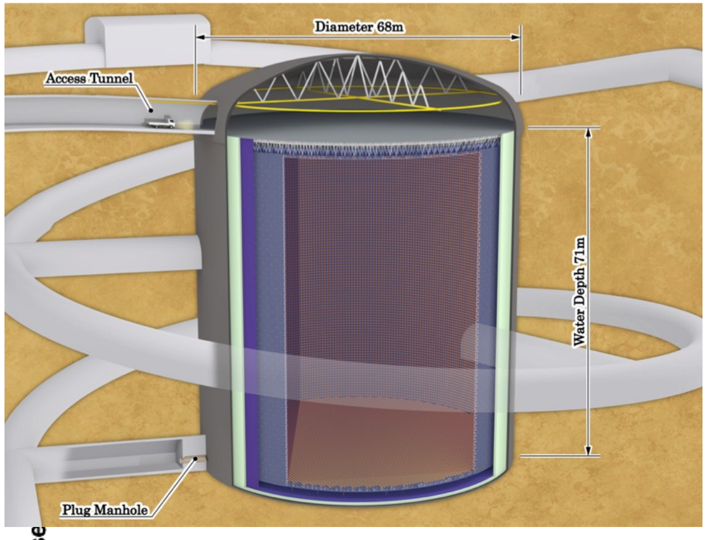
- One limitation of the majority trigger is that we can't lower the threshold too low, as this dramatically increase the dark noise and low-energy radioactivity events
- At 3.5 MeV the trigger rate reach 20kHz and it's difficult to lower further the threshold.
- We have developed an "intelligent trigger" for very low energy events, called "WIT" which is running in parallel to the normal trigger system.
- WIT looks for low energy activity and reconstruct vertex from them in order to reject events too close from the detector walls (as these events are mostly low-energy radioactivity events).

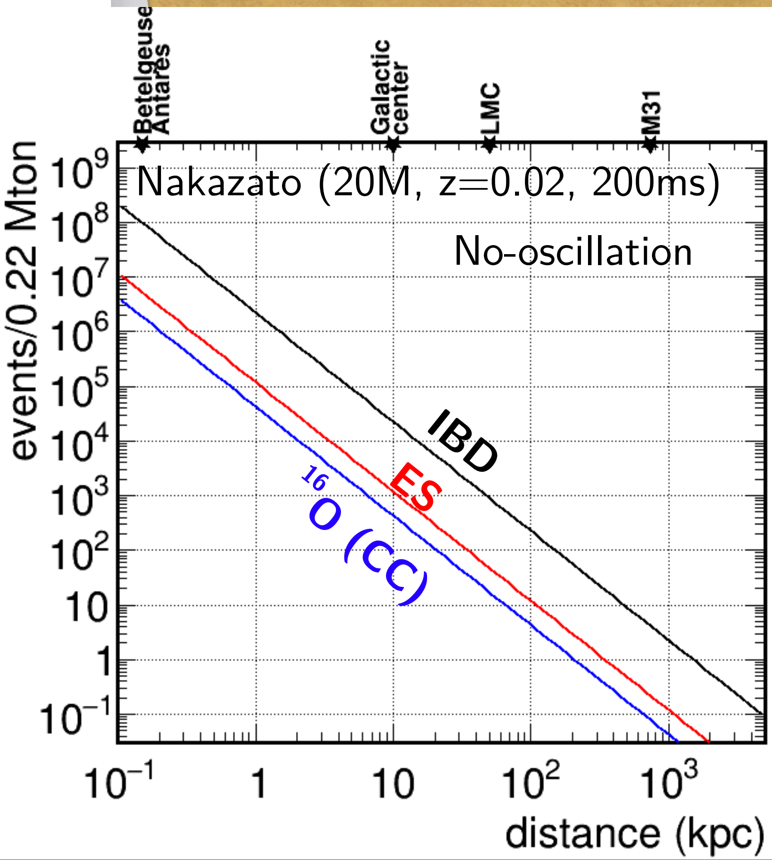


Hyper-Kamiokande

Challenges for Hyper-Kamiokande

- Hyper-Kamiokande is the successor of Super-Kamiokande. It's currently under-construction and is expected to start data taking in 2027. It will be x5 larger than Super-Kamiokande (260 ktons) with a fiducial volume x7 larger than Super-Kamiokande.
- One challenge for the data taking in Hyper-Kamiokande is what would happen in case of a supernova event, as the amount of data to be stored and analyse quickly will be x7 larger than in SK. Some system are being developed to ensure all the data is stored, but how this data would be analysis quickly is not yet fully defined.
- Other potential: newer computer and framework can allow more "intelligent" DAQ system





Summary

Summary

- In Super-Kamiokande, our electronics records all PMT signal above the discriminator threshold, including dark noise.
- All this data is then read on a computer and a "software" trigger is applied to define events, reduce the amount of data, and finally store the triggered events.
- We have different type of triggers:
  - Majority triggers (based on the number of hits)
  - T2K trigger (using GPS signal from J-PARC)
  - Calibration trigger (using external signal on a "trigger QBEE" to trigger the event)
  - Intelligent trigger with event reconstruction for very low energy events
- The data is then also processed on offline computer immediately after being available to further remove the noise events and reduce the disk space usage.

Backup

Realtime supernova monitoring in Super-Kamiokande