Trigger system at Super-K
(How we record data at SK)

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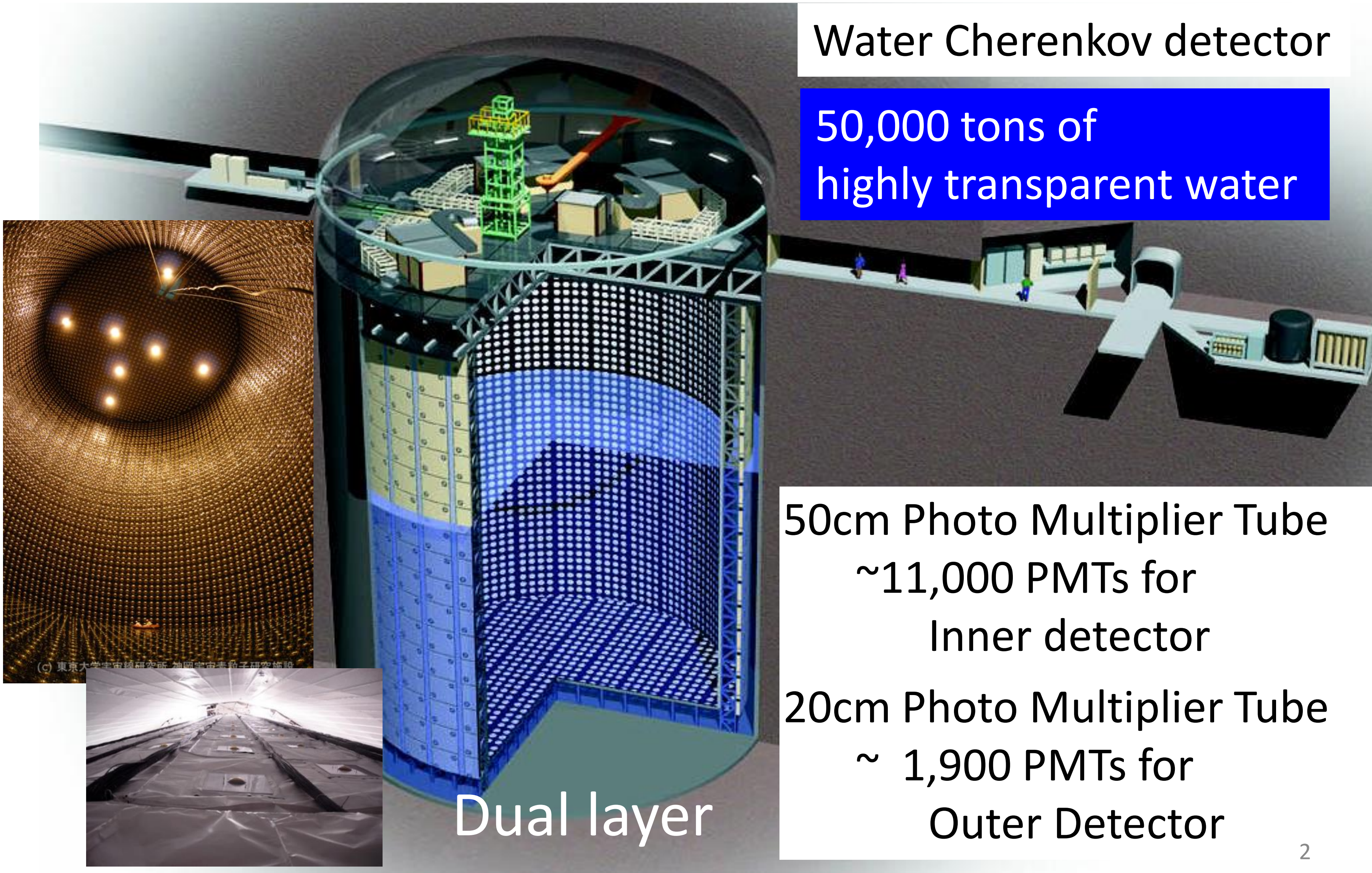
Super-Kamiokande

Ring imaging Water Cherenkov detector



Water Cherenkov detector

50,000 tons of
highly transparent water

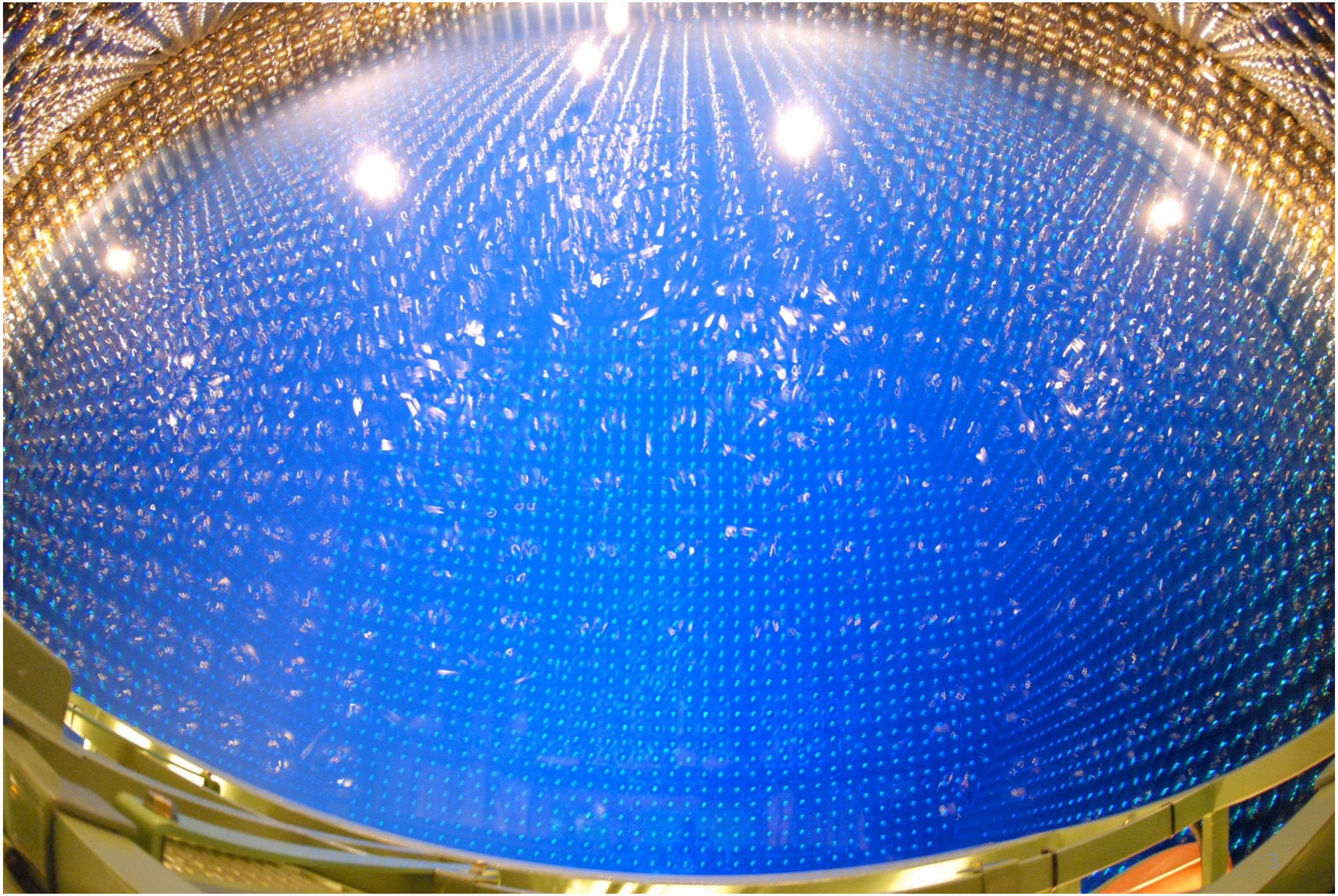
50cm Photo Multiplier Tube
~11,000 PMTs for
Inner detector

20cm Photo Multiplier Tube
~ 1,900 PMTs for
Outer Detector

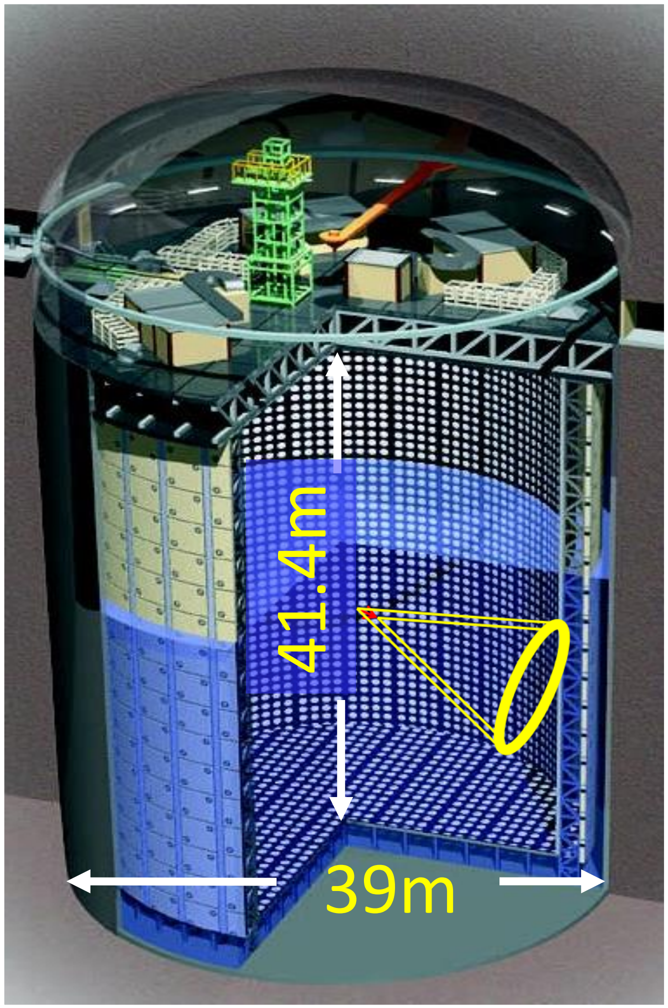
Dual layer

Super-Kamiokande

Ring imaging Water Cherenkov detector



Super-Kamiokande
Ring imaging Water Cherenkov detector



Inner detector photo coverage 40%
(except for SK II)

Pure water phases

Super–Kamiokande I (Apr. 1996 to Jul. 2001)
Super–Kamiokande II (Oct. 2002 to Oct. 2005)
(half density)
Super–Kamiokande III (Jul. 2006 to Aug. 2008)
Super–Kamiokande IV (Sep. 2008 to May 2018)
Super–Kamiokande V (Jan. 2019 to Jul. 2020)

Gadolinium loaded phases (SK–Gd)

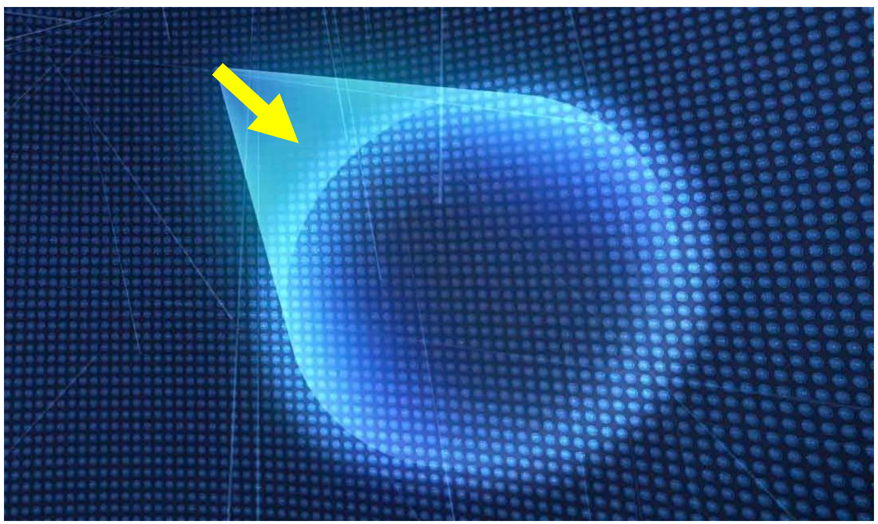
Super–Kamiokande VI (Jul. 2020 to May 2022)
with 0.01% Gd.
Super–Kamiokande VII (Jul. 2022 ～)
with 0.03% Gd.

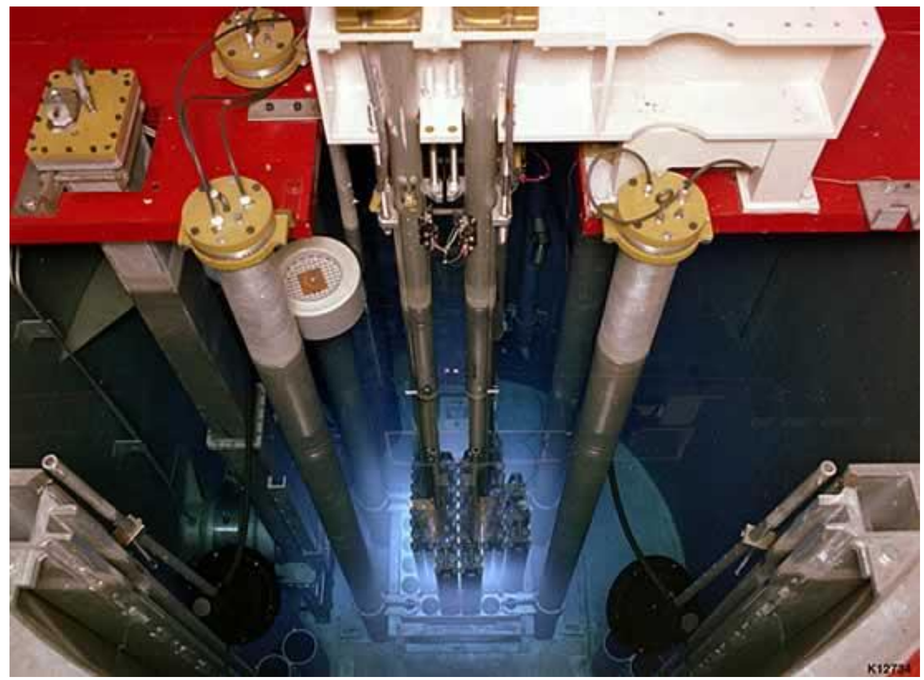
Super-Kamiokande
Ring imaging Water Cherenkov detector

Cherenkov light

- Emitted when the speed of the charged particle is faster than the speed of the light in the medium.
- Relativistic charged particle in water

$\theta_c \sim 42\ degree$





Neutron Radiography Reactor, Hot Fuels Examination Facility, Idaho National Laboratory.

- Color (wavelength)
  Blue ~ Ultra-violet

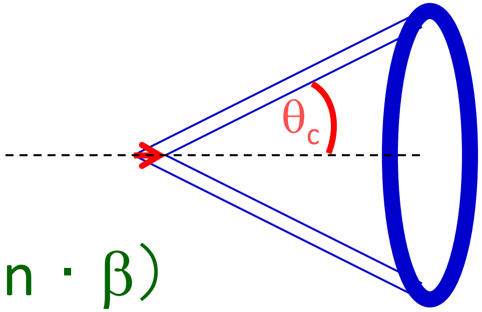
Super-Kamiokande
Ring imaging Water Cherenkov detector

Cherenkov light

emission : if $n \cdot \beta > 1$

n : refractive index

$\beta = p / E$



direction : $\cos\theta_c = 1/(n \cdot \beta)$

$n_{water} \sim 1.33$ ➜ $\theta_c \sim 42$ degree.

# of emitted Cherenkov photons

➜ ~ 340 photons / 1cm

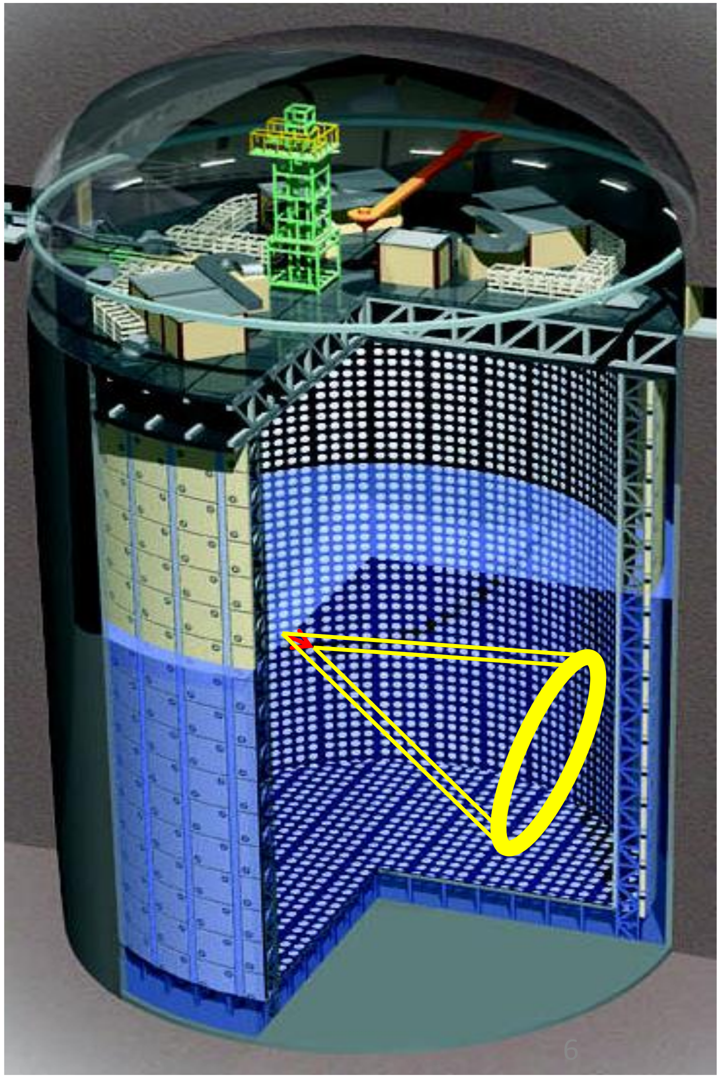
$$\frac{d^2 N_{photon}}{d\lambda dL} = \frac{2 p \alpha Z^2}{\lambda^2}\left(1 - \frac{1}{n^2 \beta^2}\right)$$

Sensitive wavelength of PMT: 300 ~ 600nm

Cherenkov angle θ=42 degrees, Z (charge) =1

Detected # of photons used are much smaller.

PMT quantum efficiencies, PMT coverage, light absorption in the water etc..

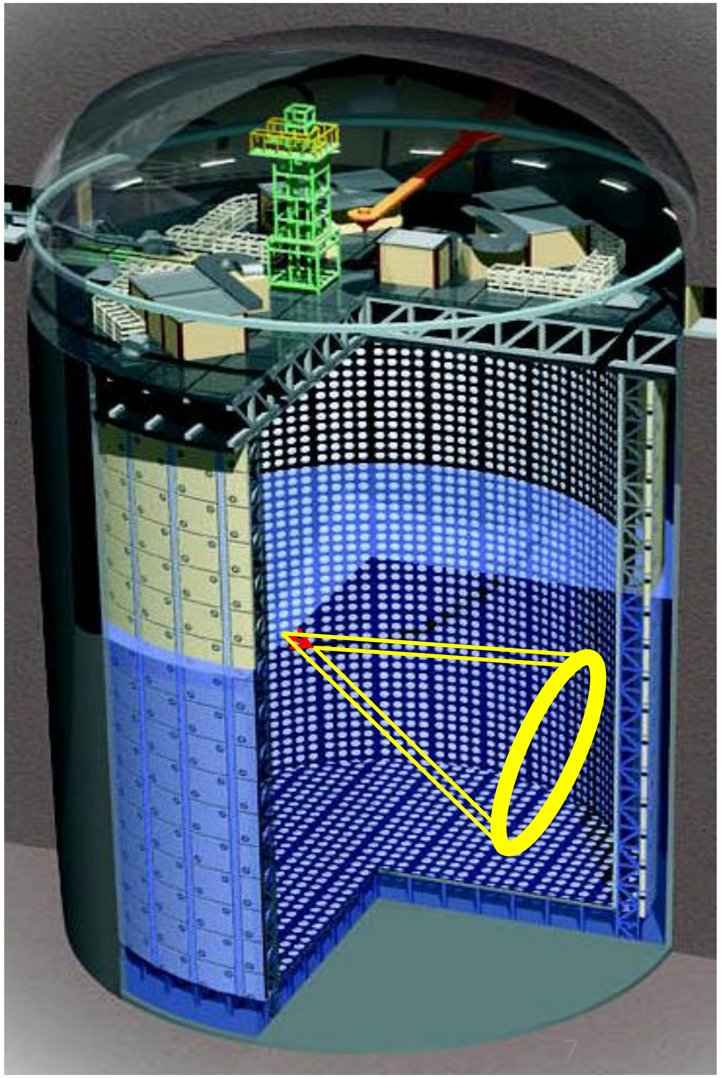


Super-Kamiokande
Ring imaging Water Cherenkov detector

- # of the charged particles & photons
  ~ # of rings
- Momentum (~energy) of a particle
  $\propto$ # of photons
- Generated position of the particles
- Direction of a particle
- Type of the particle

  Reconstructed using the
  arrival timings and
  geometrical distributions
  of the Cherenkov light.

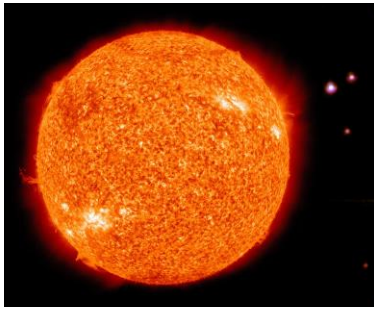
- Wide energy coverage
  a few MeV to TeV



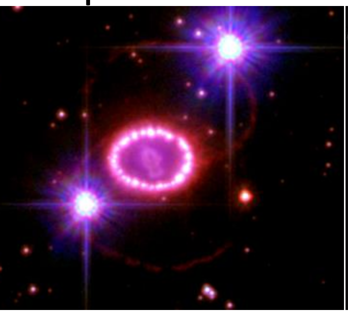
Super-Kamiokande

Physics targets

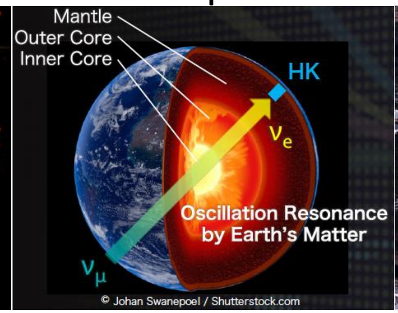
Solar neutrinos



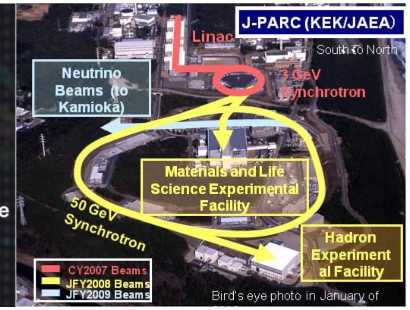
Supernova ν



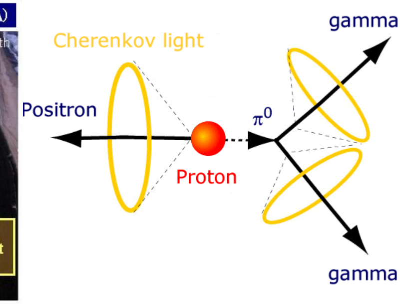
Atmospheric ν



Accelerator ν



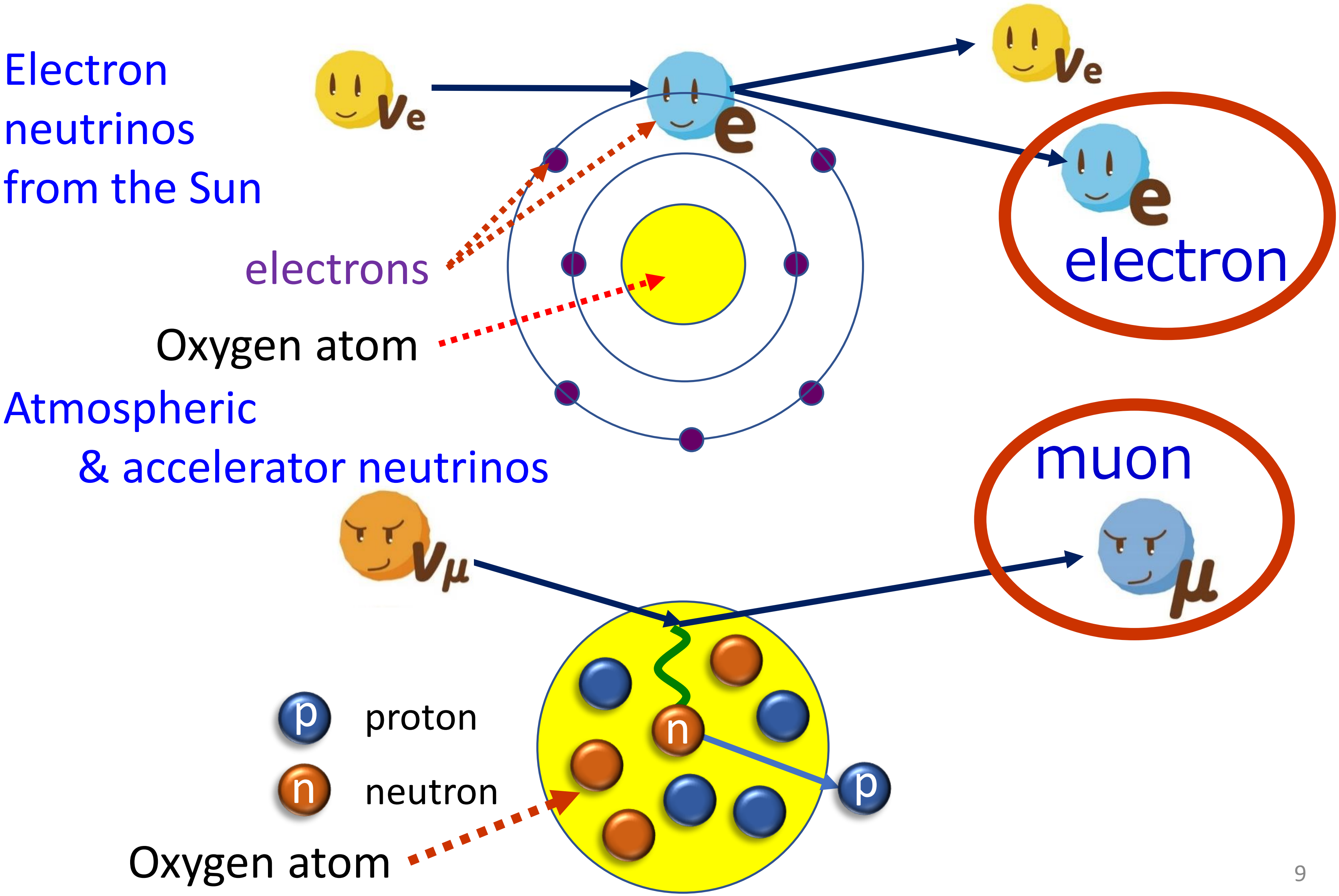
Proton decay



Target	Energy range	Expected rate
Solar neutrinos	3.5 ~ 15 MeV	~10 events/everyday
Atmospheric neutrinos	100 MeV ~ TeV + 2.2 MeV γ	~10 events/everyday
Accelerator neutrinos (From J-PARC)	100 MeV ~ 30 GeV + 2.2 MeV γ	~15 events/day (During the beamtime)
Supernova neutrinos (Galactic)	Typically < 30MeV	~10k events in 10 sec. Every 30 ~ 50 years
Supernova neutrinos (Nearby)	Typically < 30 MeV	~ 100M events in 10 sec. Within ~10000 years?
Proton decay	30MeV (200MeV/c μ) ~ GeV + 2.2 MeV γ	Very rare

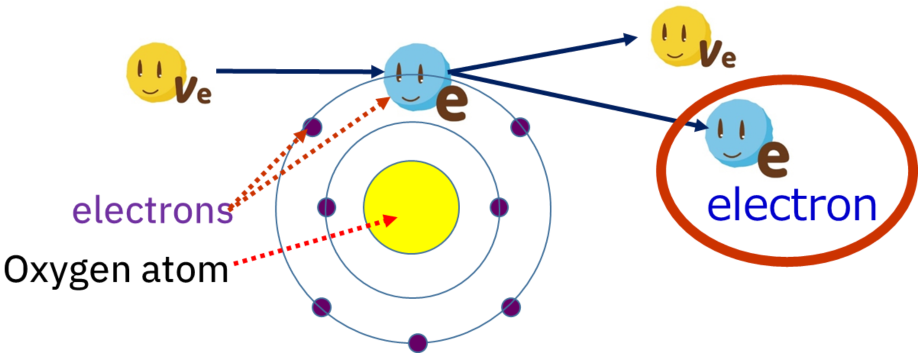
Super-Kamiokande

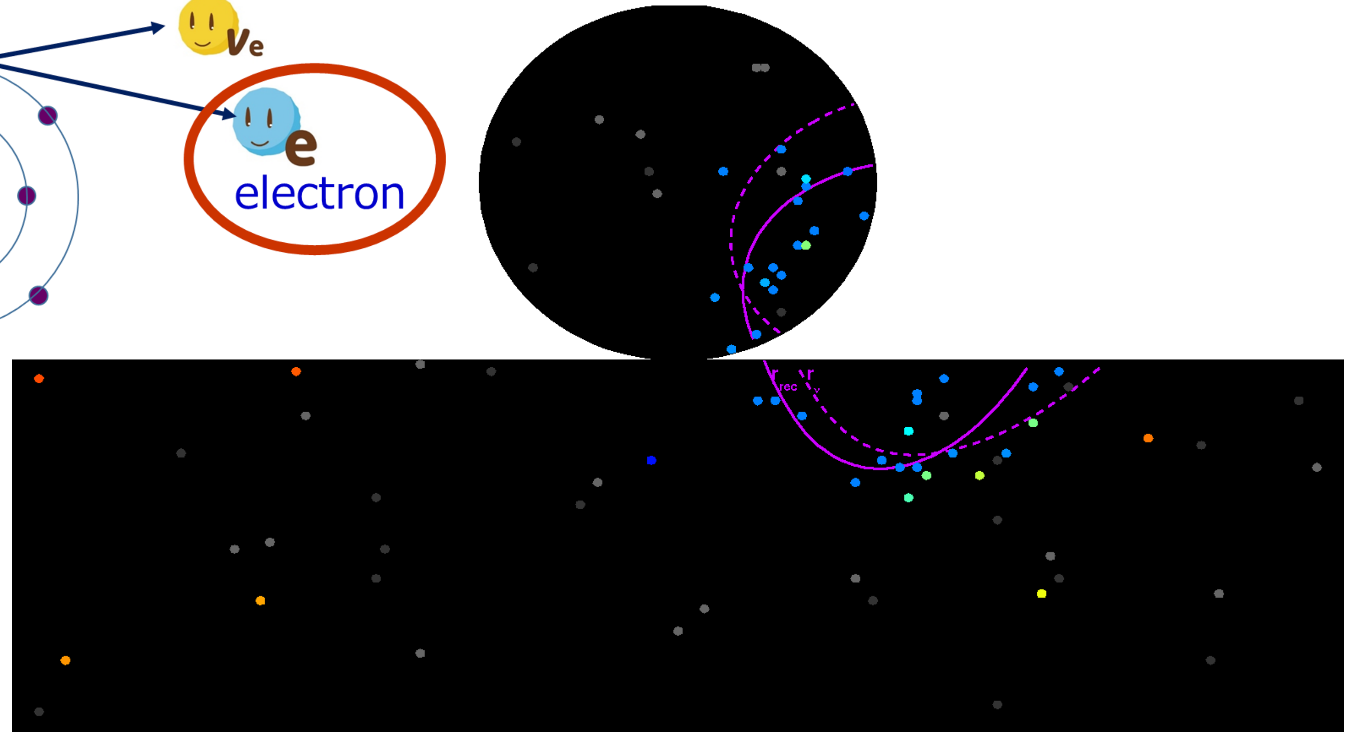
Ring imaging Water Cherenkov detector

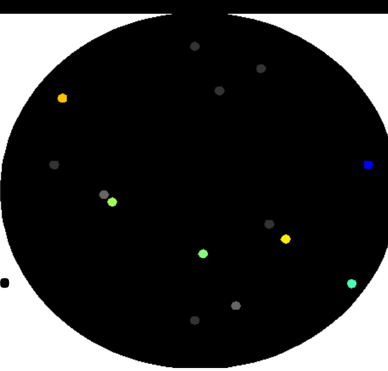


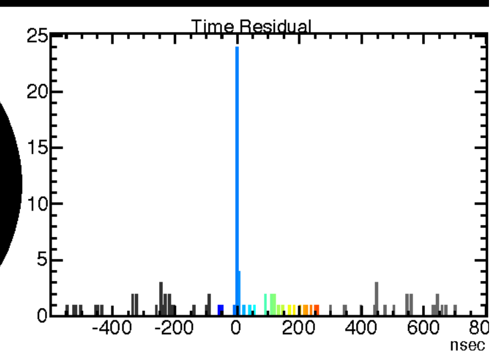
Super-Kamiokande

Solar neutrino ~ 10 events / day









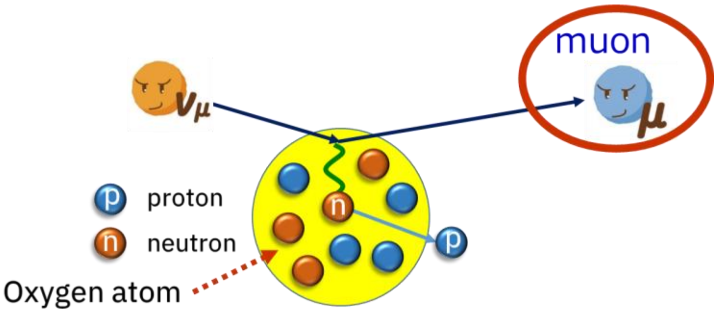
Energy (SK) 4 ~ 15 MeV

25 ~ 100 PMTs detect light.

Super-Kamiokande

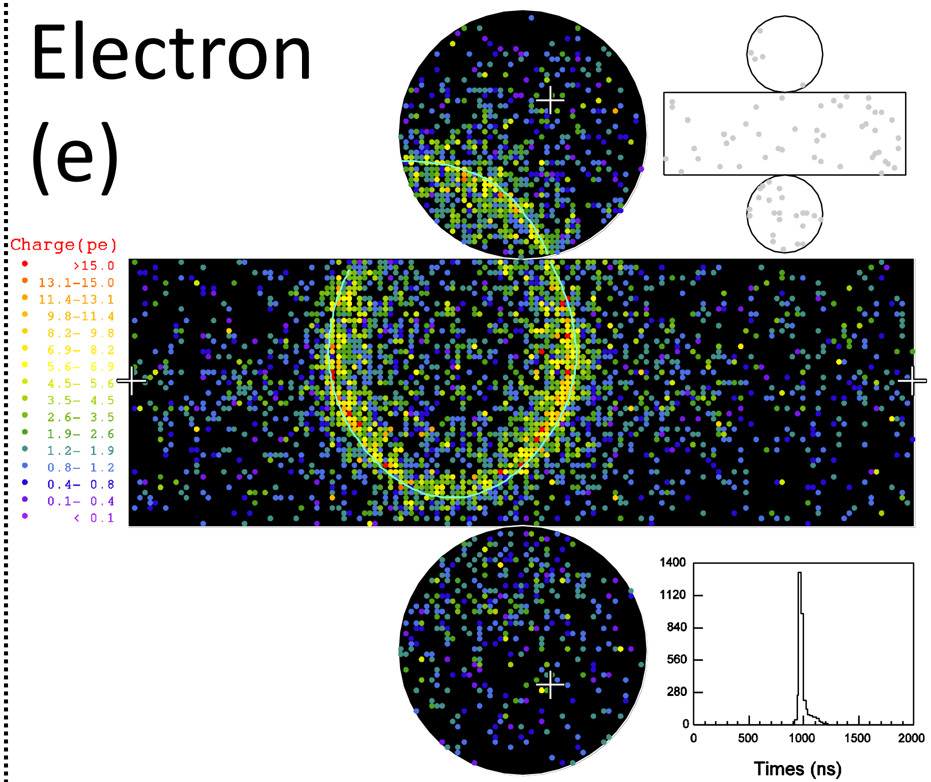
Atmospheric neutrino events ~ 12 events / day

(A few hundreds of MeV ~ TeV)

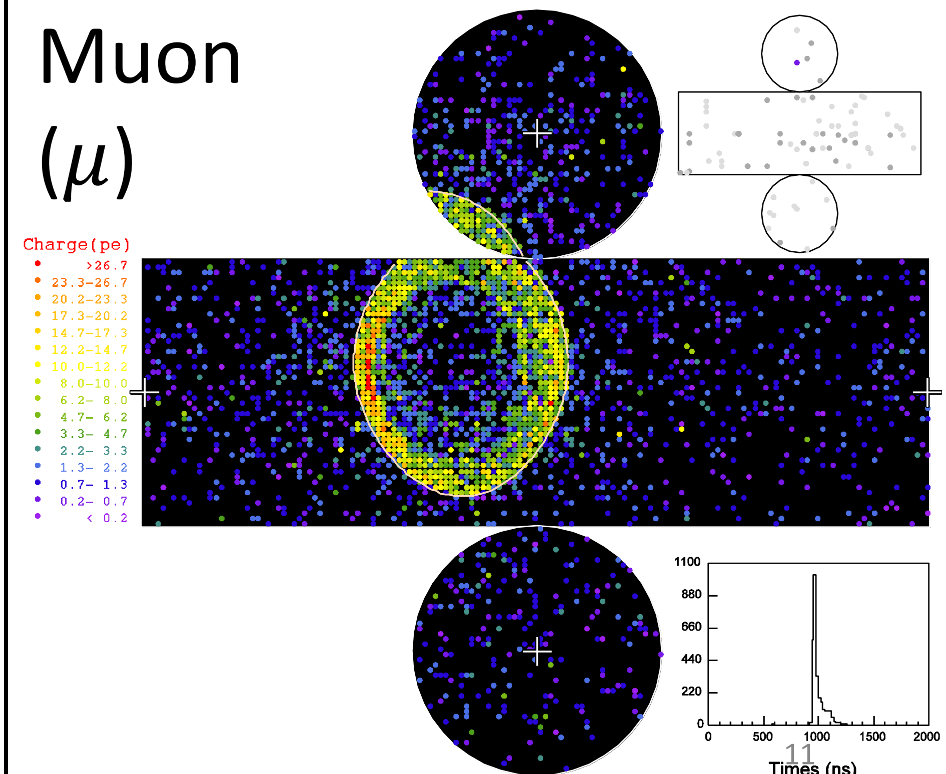


Electron and muon produces different patterns

Electron (e)



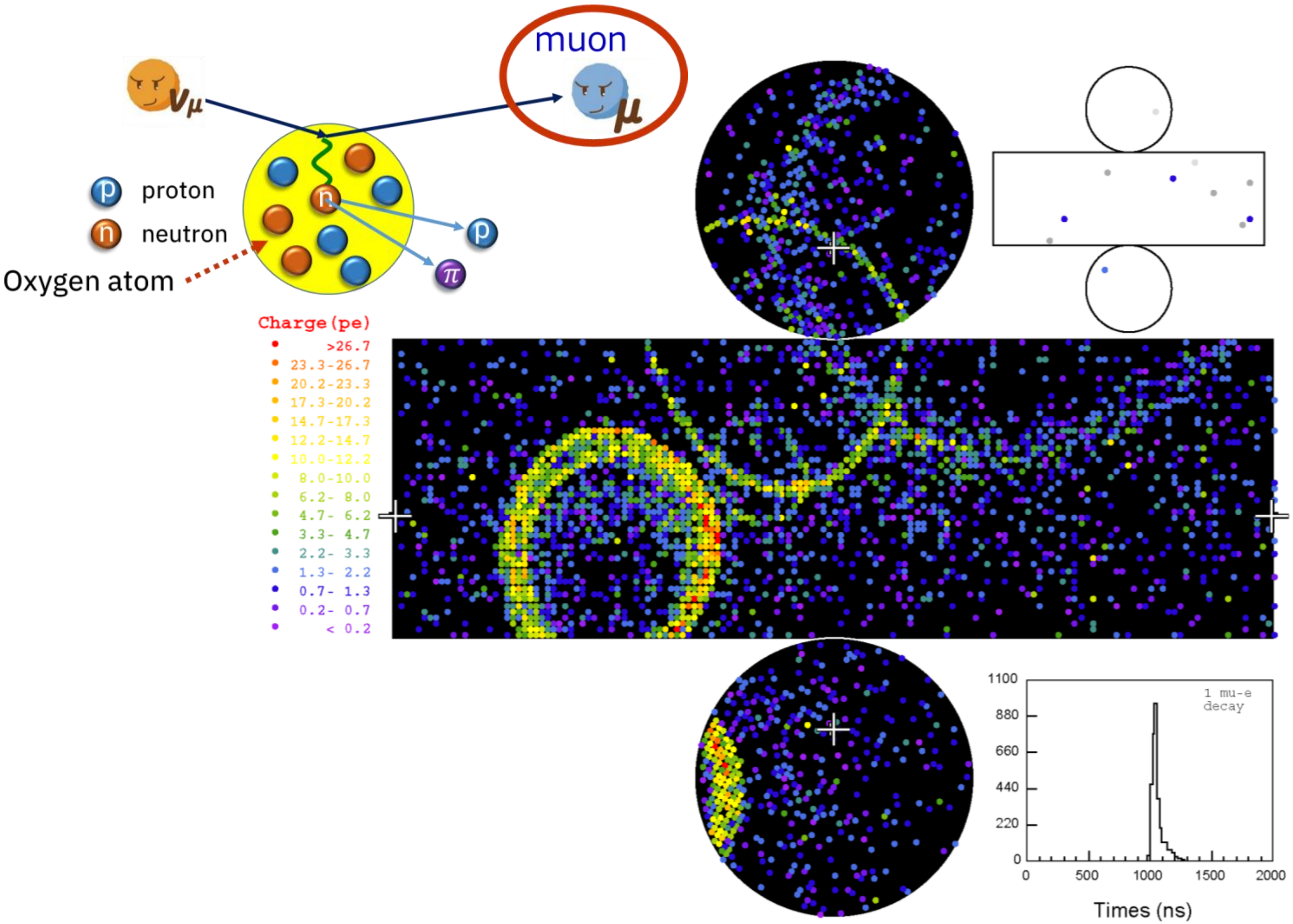
Muon (μ)



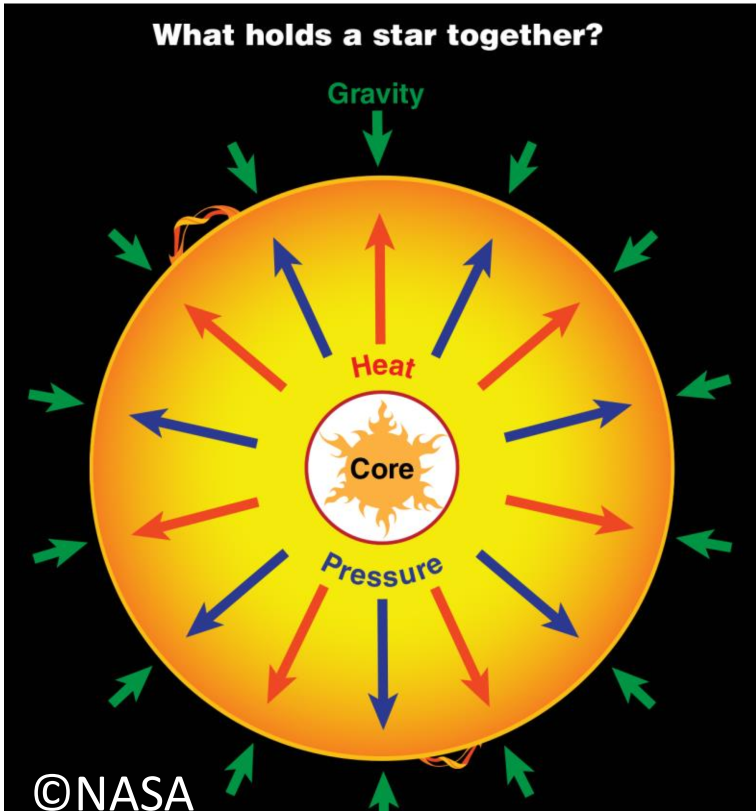
Super-Kamiokande

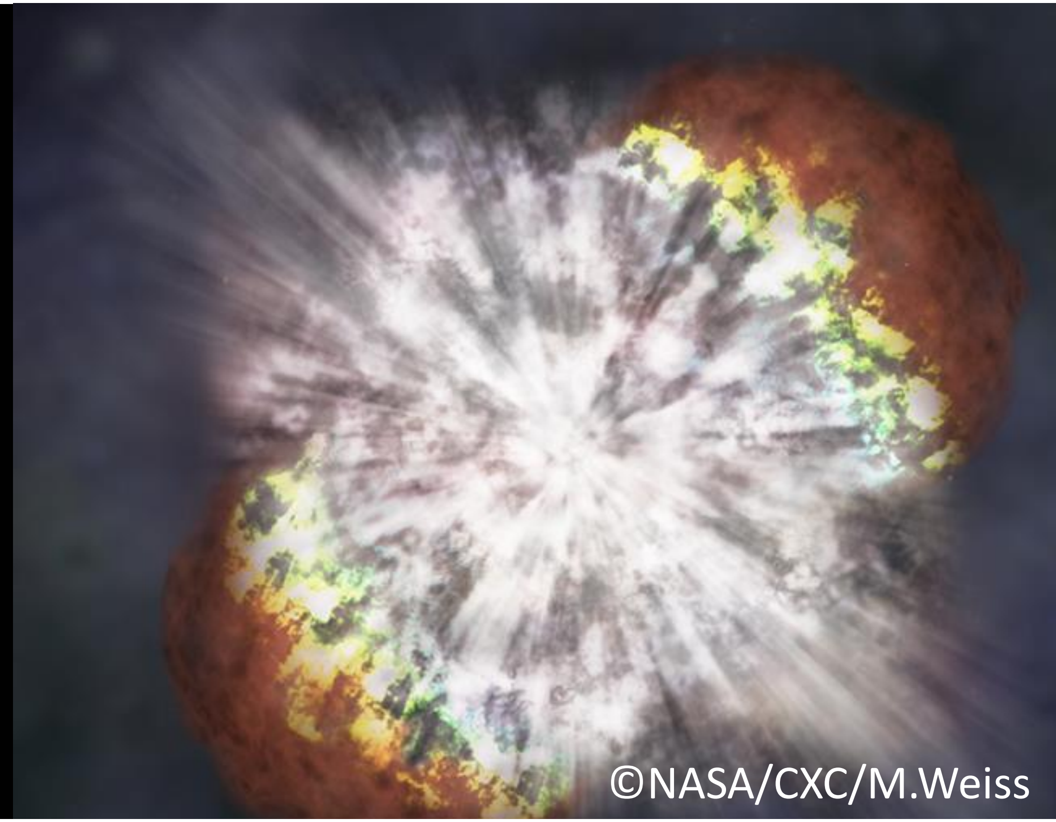
Atmospheric neutrino events ~ 12 events / day

Sometimes, multiple rings (particles) observed.



Super-Kamiokande
Supernova bust neutrinos





~99% of energy from Supernova is released as neutrinos.

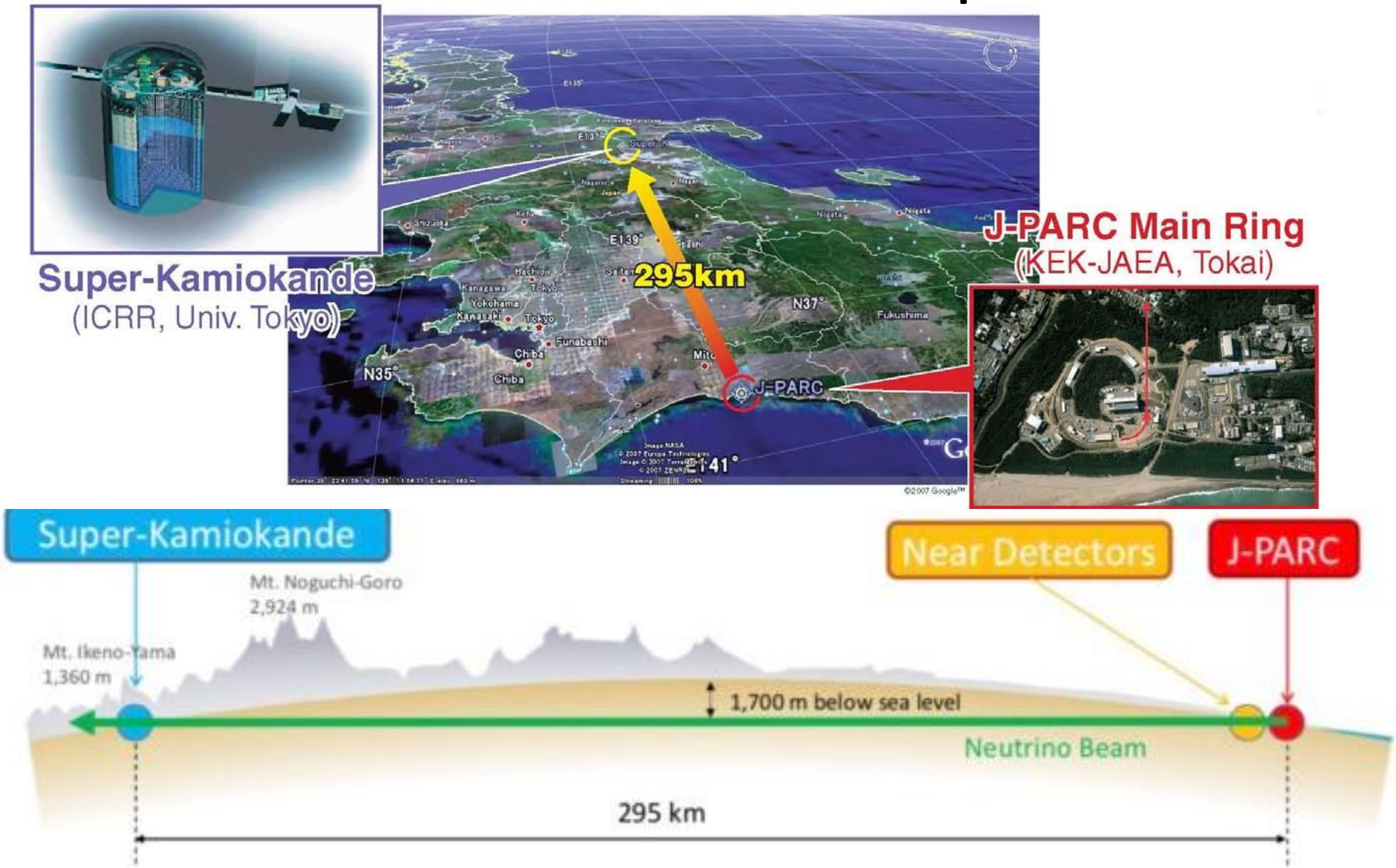
From a supernova at the galactic center (~10kpC ~ 32,600 ly)

~10,000 events are expected in just 10 seconds.

If Betelgeuse becomes supernova, **10M ~ 100M** events are expected.

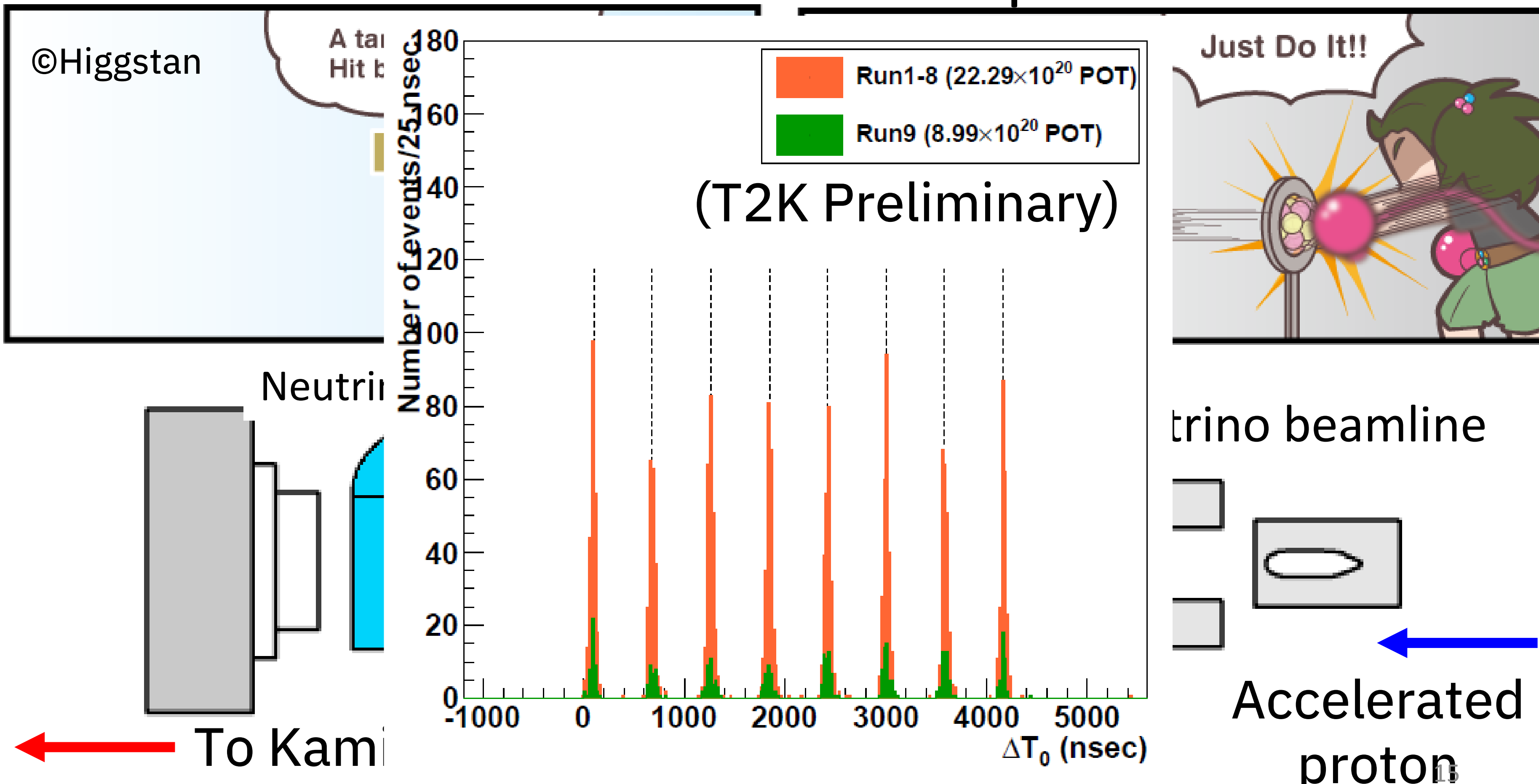
Super-Kamiokande
Accelerator neutrinos

Generate muon neutrinos (ν_μ and $\overline{\nu_\mu}$) at J-PARC in the direction of Super-Kamiokande.



Super-Kamiokande
Accelerator neutrinos

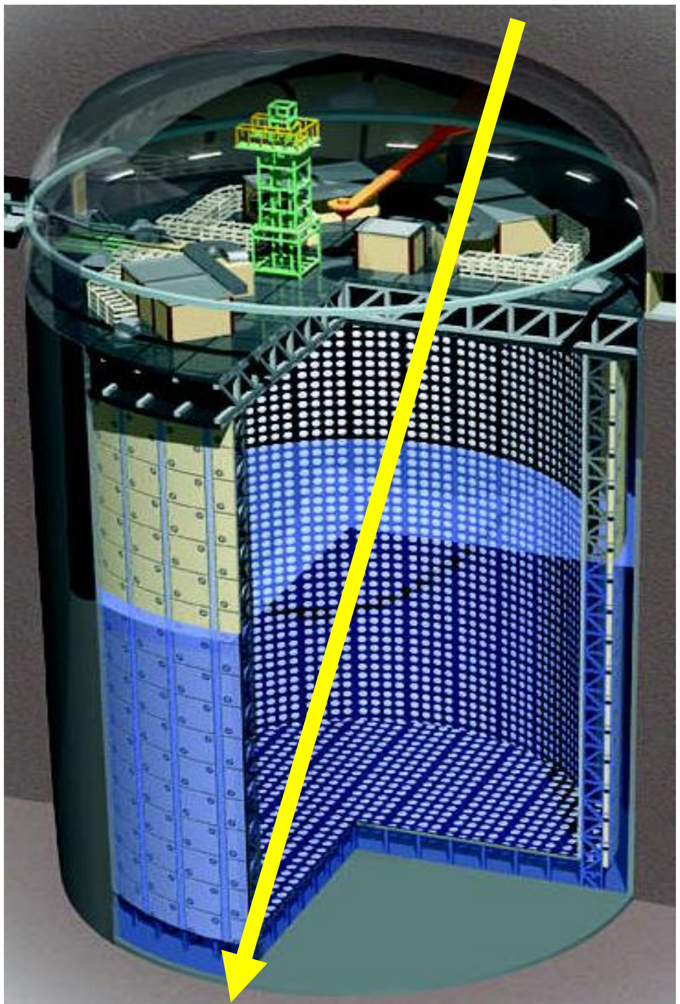
Generate muon neutrinos (ν_μ and $\overline{\nu_\mu}$) at J-PARC in the direction of Super-Kamiokande.

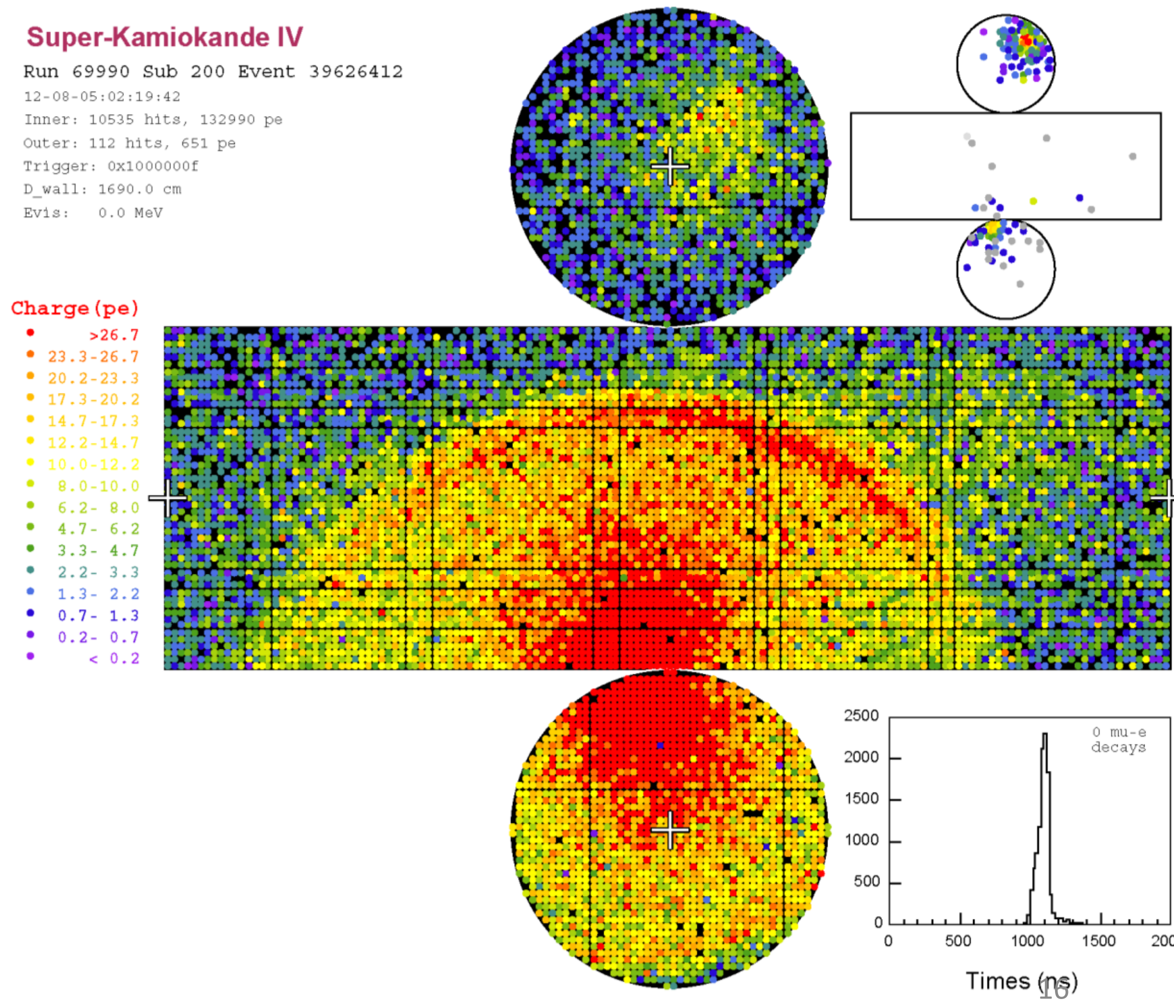


Super-Kamiokande

Background events :Cosmic ray muons

2 ~ 3 events / second





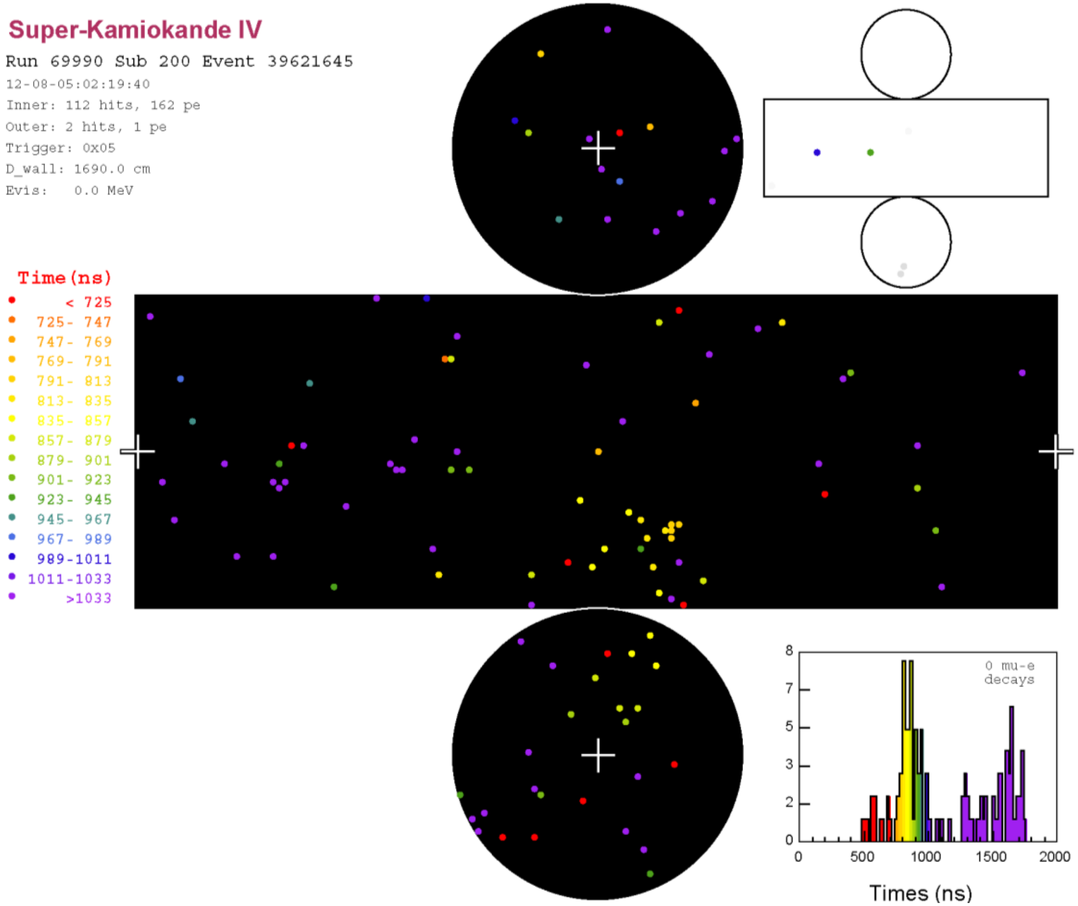
Super-Kamiokande

Background events :radio activities

Radon in the water etc..

~20,000 events / second

(with current setting.)



Super-Kamiokande
Electronics and data acquisition system

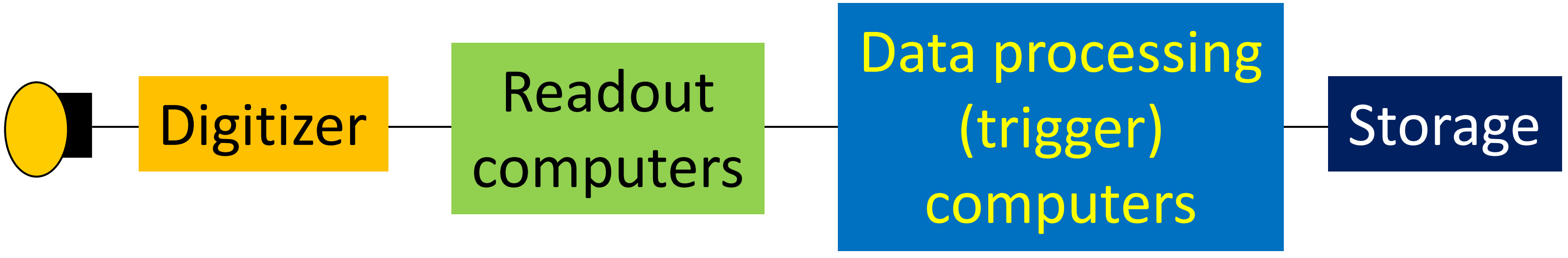
What we want to measure? (necessary functionalities)

Measure the charge and the timing from PMT.

= Number of photons and their arrival timings.

What we need?

- Self gating signal digitizer (Charge + Timing)
- Accurate clock synchronization system
  (Synchronization Clock + Counter)
- GPS



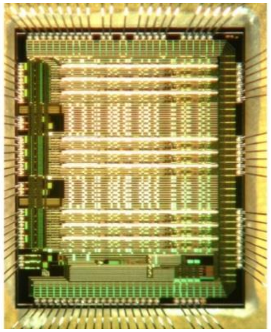
We don’t know when neutrinos interacts in the detector.

24 hours 7 days operation

Stable hardware and software

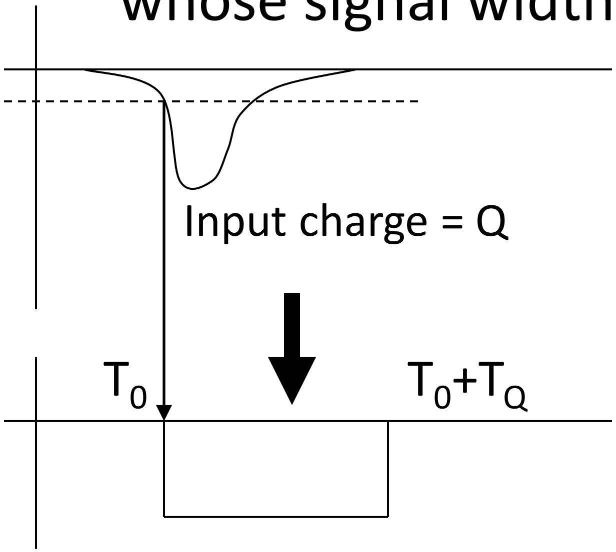
Super-Kamiokande
PMT signal digitization

Charge to time converter
(ASIC developed for SK
by ICRR and IWATSU)



Use QTC (charge to time converter)
with multi-hit continuous readout TDC (AMT)

QTC converts charge to the digital signal
whose signal 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

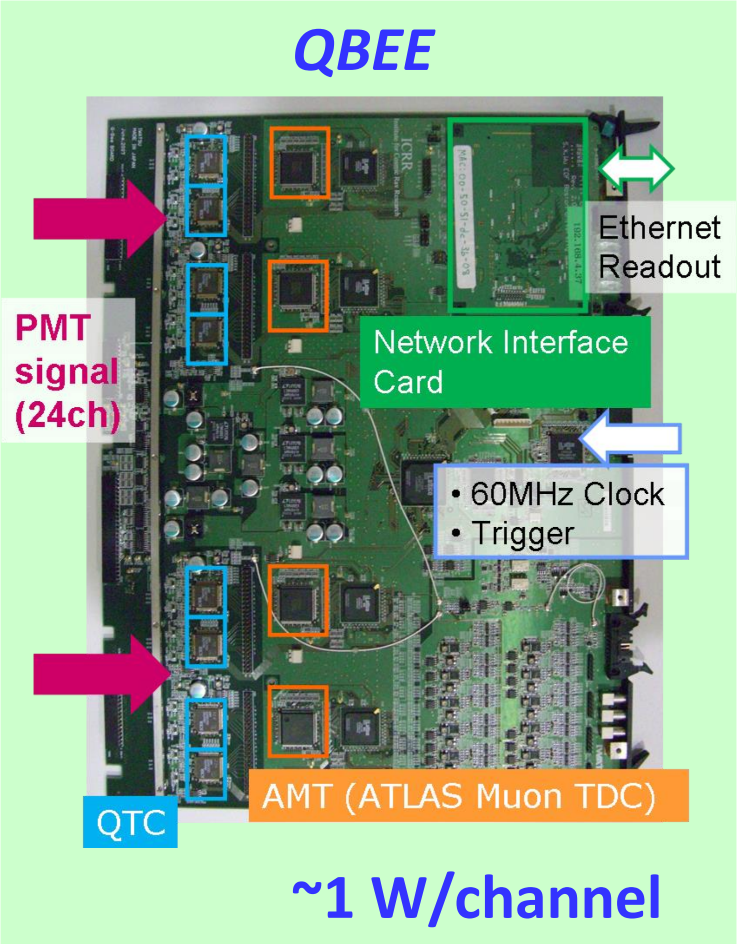
Usually, there are small dead-time after each hit (integration gate)
and thus, it is not completely "dead-time" free.

- Digitize all the hits from all PMTs
  and readout everything using the computers

Super-Kamiokande
Digitizer module (QBEE)

Performance of QTC for SK

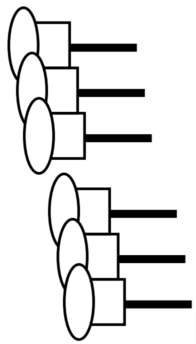
- Built-in Discriminator
  ¼ p.e. (~ 0.3 mV)
- Processing Speed
  ~1usec/HIT
- High Sensitivity for single p.e.
- Charge Response
  RMS Resolution:
  ~ 0.05p.e. (<25p.e.)
- Timing Respons
  0.3ns (1p.e.⇔ -3mV) (RMS)
  0.2ns (>5p.e.)
- Wide Charge Dynamic Range
  0.1 ~ 1250p.e. (0.2~2500pC)



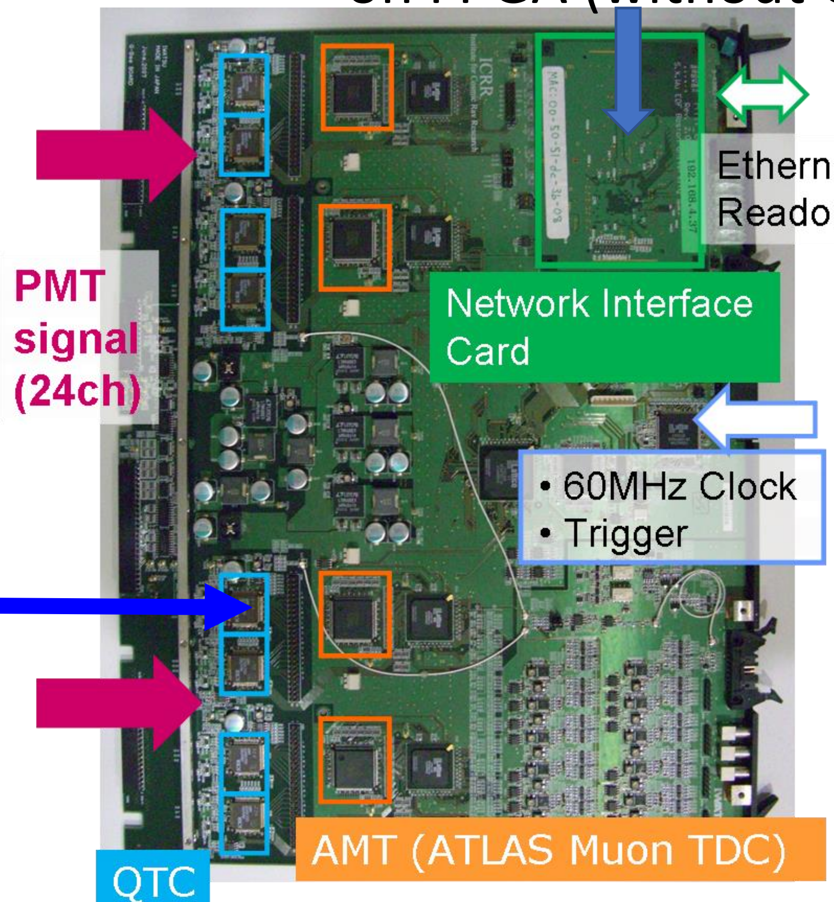
Super-Kamiokande
Charge and timing digitizer module

SiTCP : TCP/IP implemented on FPGA (without CPU)

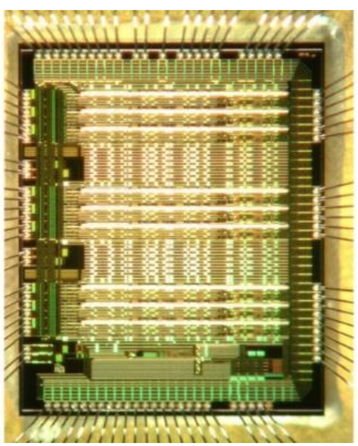
PMTs



x24



Fast Ethernet



Charge to time converter (QTC)
(ASIC developed for SK
by ICRR and IWATSU)

Nominal ~750kB/s/board
Maximum ~10MB/s/board

Super-Kamiokande
DAQ system (software trigger system)

Record all the hits from PMTs including dark noise.

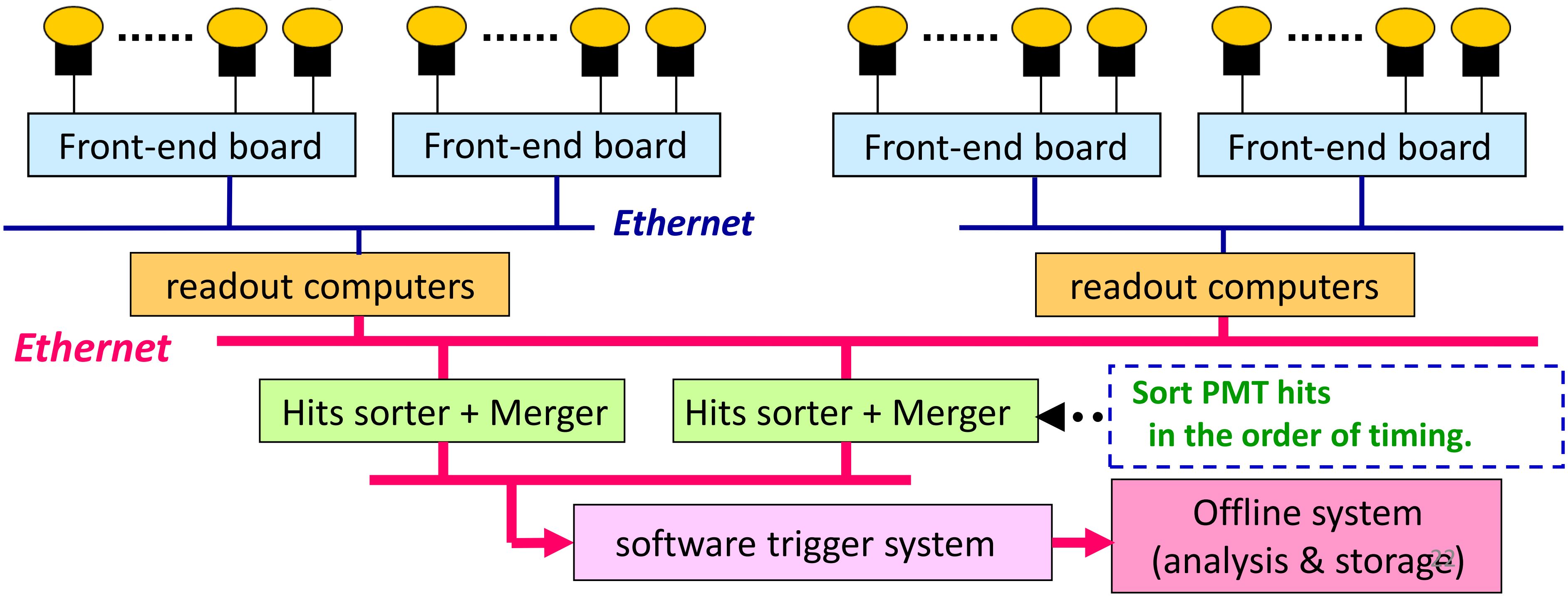
Then, apply the "software" trigger and define an event.

Assuming nominal dark rate (~5kHz) and

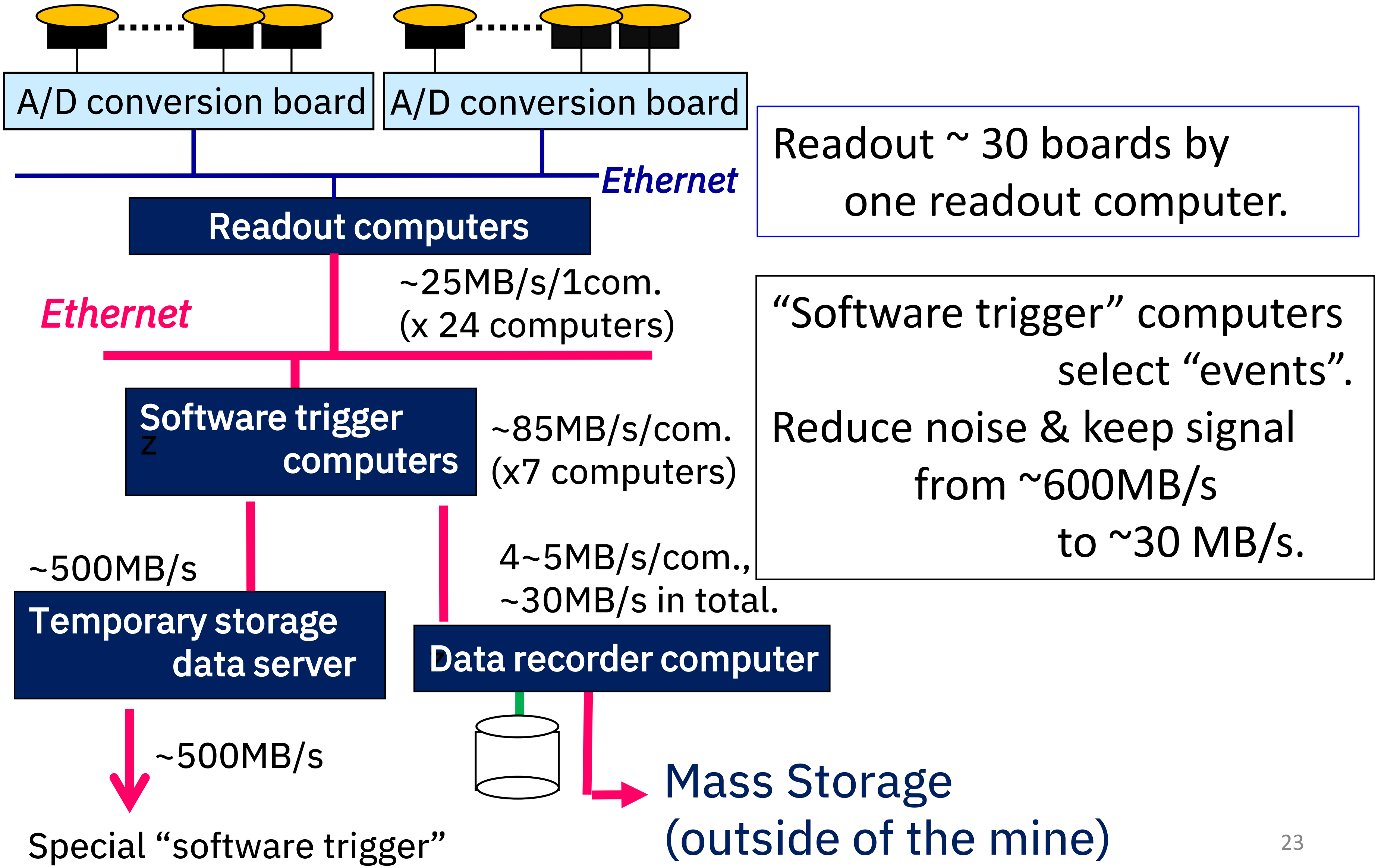
data size of 6bytes/PMT hit

~600MB/sec for a detector with 11k ID +2k OD PMTs.

Schematic diagram



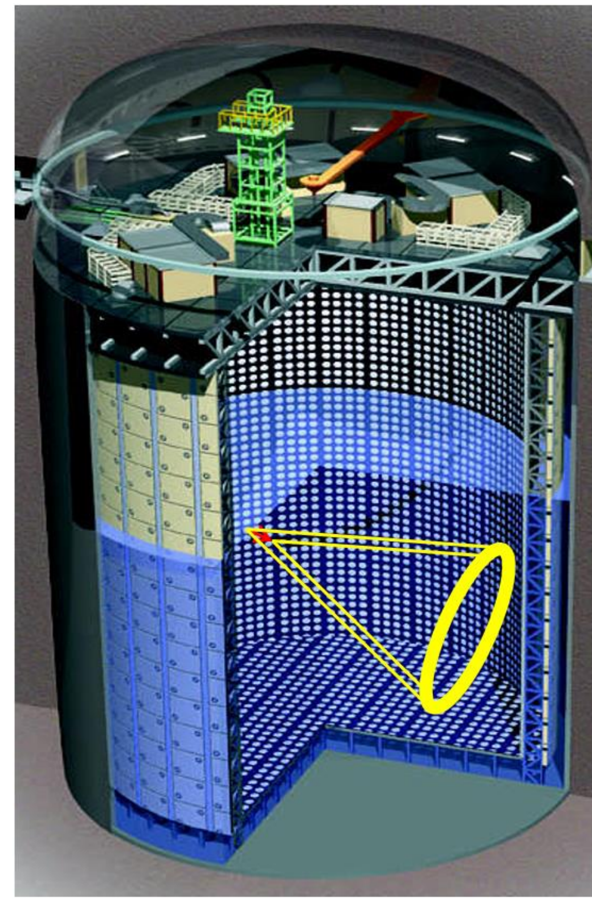
Super-Kamiokande
DAQ system (incl. software trigger system)



Super-Kamiokande
Triggers

What we want to record
- Neutrino events
- Proton decay events
- T2K neutrino beam events
  (Minimum bias)
- Calibration source events
  - Light injector (laser lights)
  - Radioactive sources
    (NiCf, AmBe, DT gen.)
  - LINAC (electron source)

Background
- Radioactivity
  - in the water and the detector material
- PMT dark noise

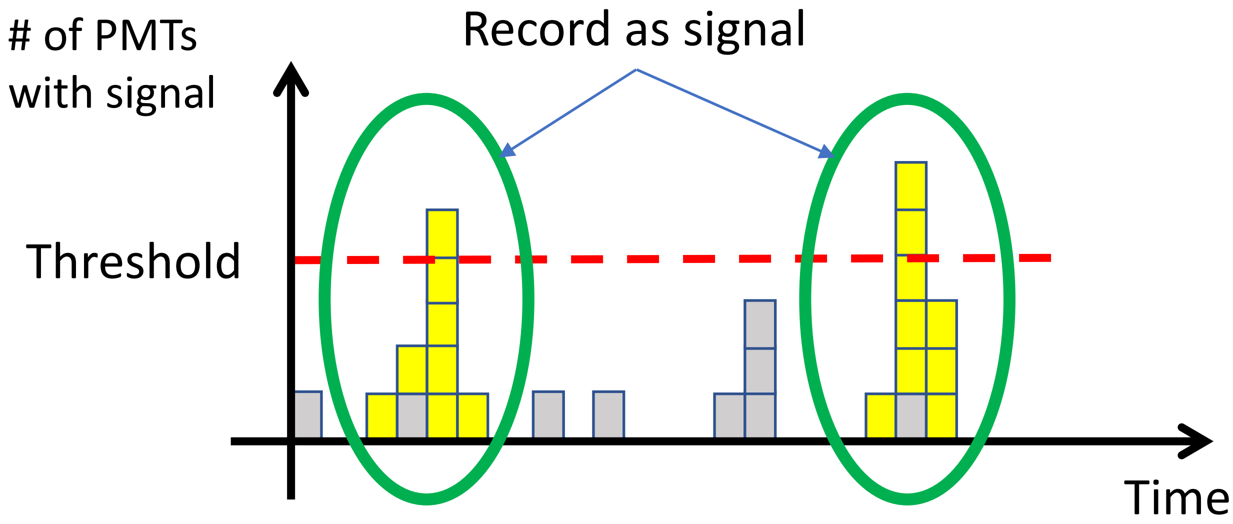


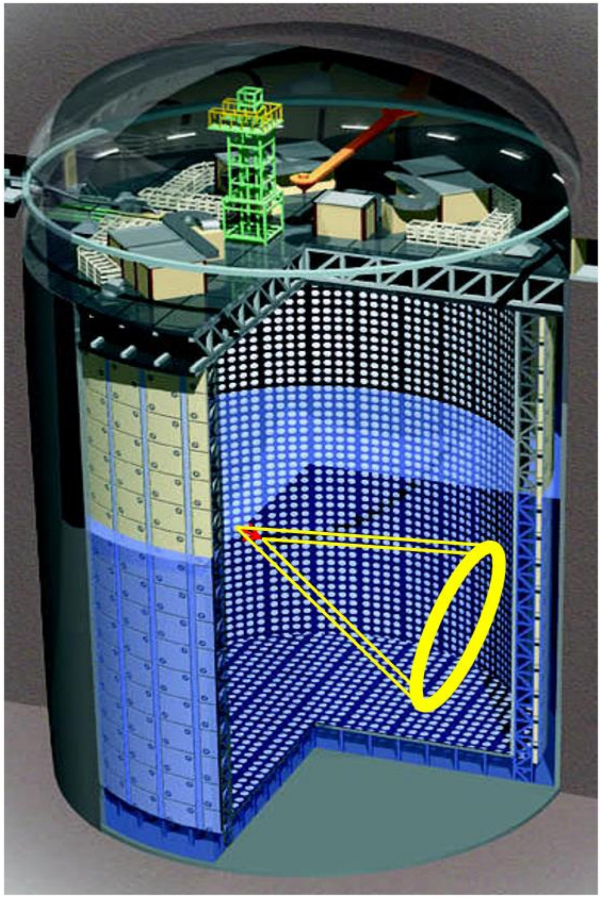
Super-Kamiokande

Trigger #1; Simple majority trigger

Signal Cherenkov light emission occurs
in a short period of time, a few ~ 200 ns.

Noise Continuous (~5kHz/PMT)
Radio activities in the detector



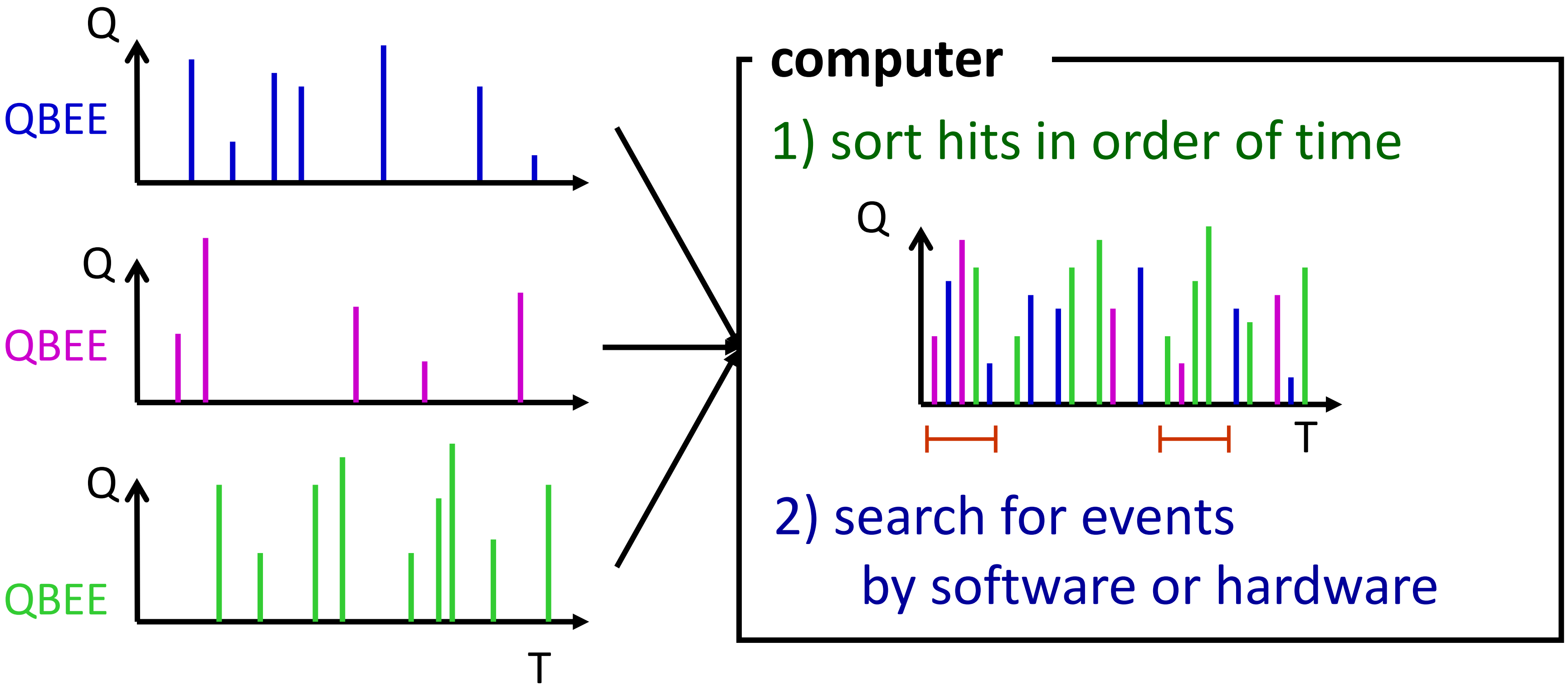


Signal could be identified
when multiple PMTs
produce signals within ~200ns.

Super-Kamiokande

Trigger #1; Simple majority trigger

Record all the hits from PMTs including dark noise.



Possible to change the gate width of each event category

- Shorter gate width for low energy events
- Longer for higher energy to contain decay electron
- Use GPS information for the accelerator beam etc..

Super-Kamiokande

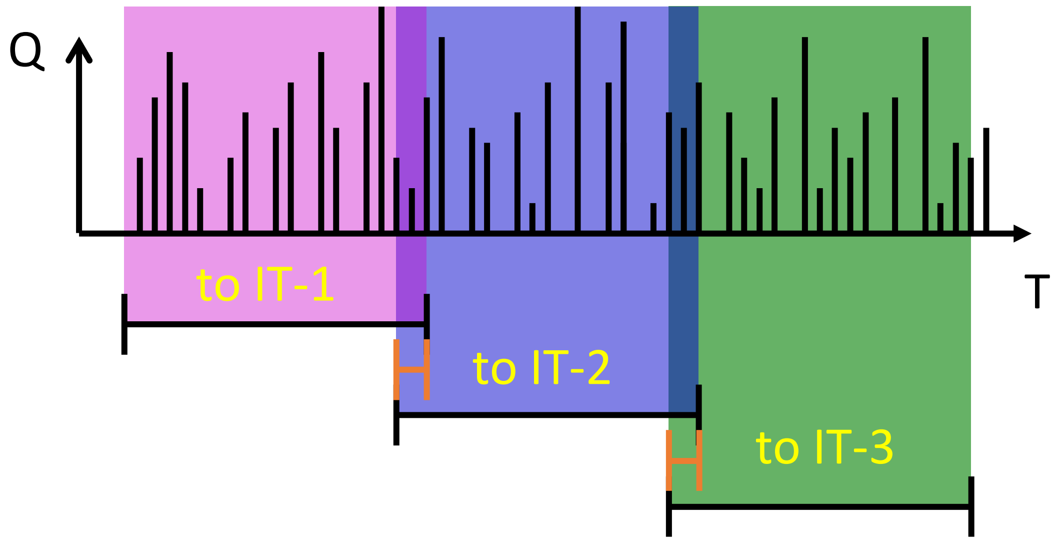
Trigger #1; Simple majority trigger

It is not possible to handle all the data by one CPU core.

Need to process the data using multiple CPU cores.

But we don't know when an event happens.

There must be some overlaps in distributing the data.



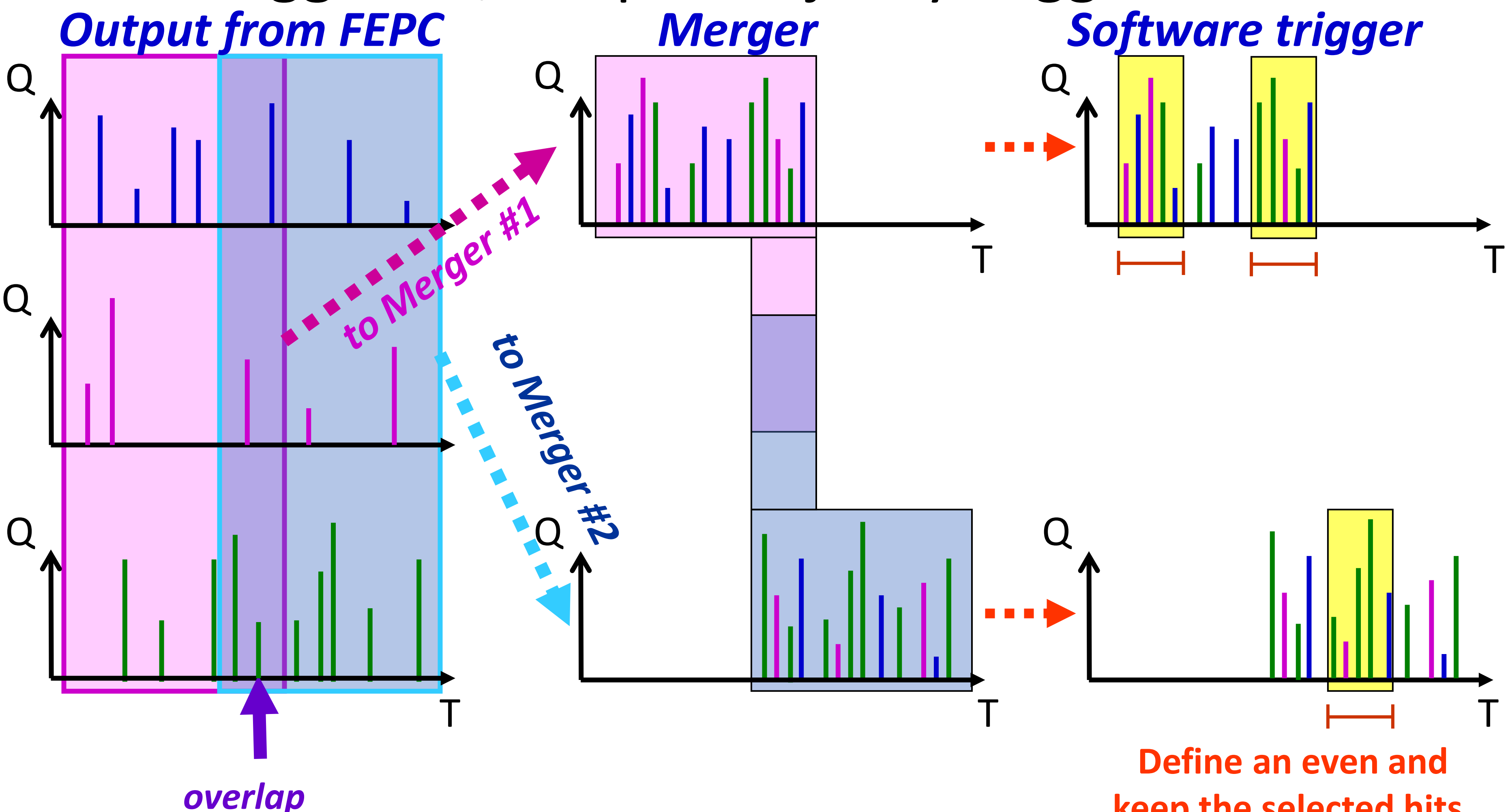
But same event will be produced

if an event occurred in the overlap region.

Reject overlapping events before storing the events.

Super-Kamiokande

Trigger #1; Simple majority trigger



1 segment corresponds to **~20ms** (1280 HW triggers)

1 overlapping period corresponds to**~ 1ms** (64 HW triggers)

Define an even and keep the selected hits.

Event selection criteria

- **# of hits within 200ns**
- **Neutrino beam timing**

Super-Kamiokande

Trigger #2; Accelerator neutrino beam trigger

Accelerator produces neutrino every few sec.

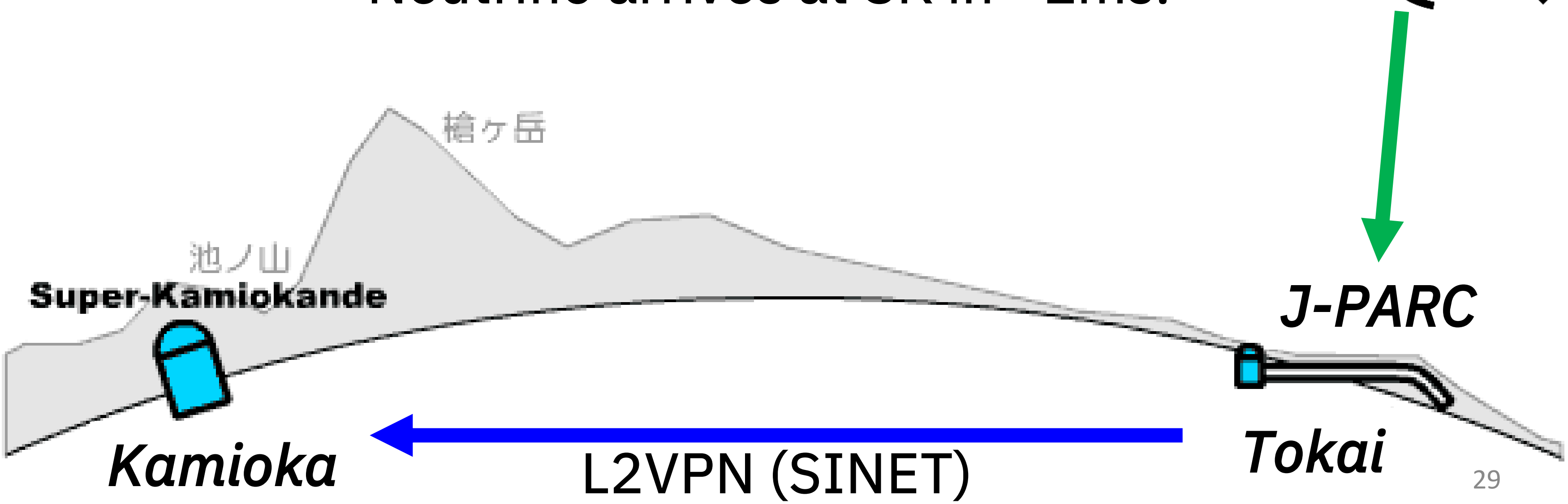
(beam width ~4 micro seconds.)

Record the neutrino production time with GPS.

Send information via L2VPN. (Typically ~10ms.)

Distance = 295km

Neutrino arrives at SK in ~1ms.

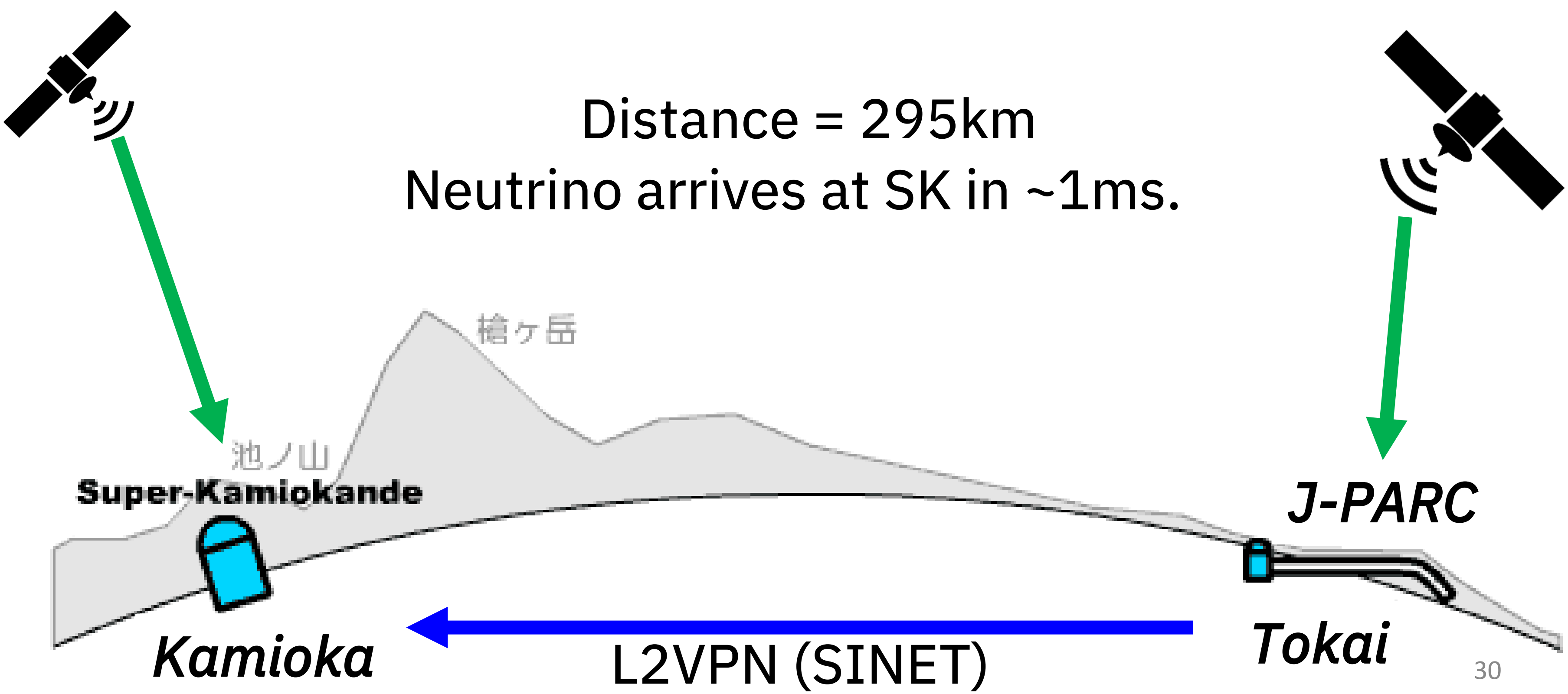


Super-Kamiokande

Trigger #2; Accelerator neutrino beam trigger

In SK, keep all the data for several seconds.
GPS data is always recorded @ SK, also.
Record the data around the beam arrival timing,
from $-500\mu s$ to $+500\mu s$.

Distance = 295km
Neutrino arrives at SK in ~1ms.



Super-Kamiokande

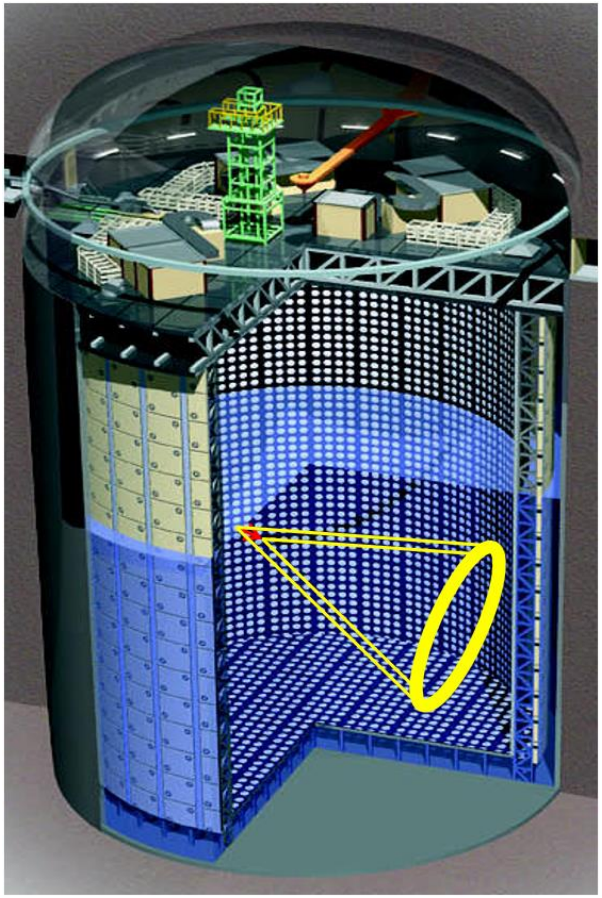
Trigger #3; Calibration source triggers

Signal Cherenkov light emission (radioactive sources)
Injected light (light source)

Triggers

a) Known timing (light injector etc.)
Light injection timing is fed to one of the QBEES, called "trigger QBEE." When one of the channels of the "trigger QBEE" has the hits (detected external signal), software trigger records the data.

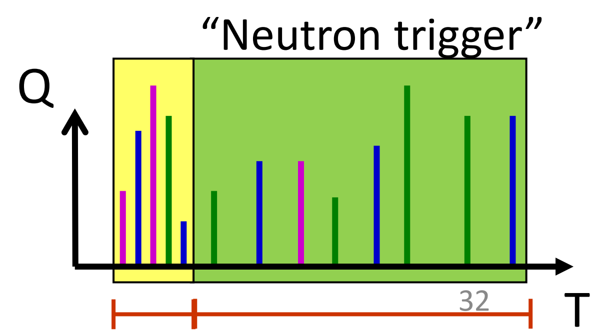
b) Unknown timing (Radioactive sources)
Record the "events" using the usual majority trigger.



Super-Kamiokande
Some notes on the trigger

Events have different "gate widths" for different triggers.

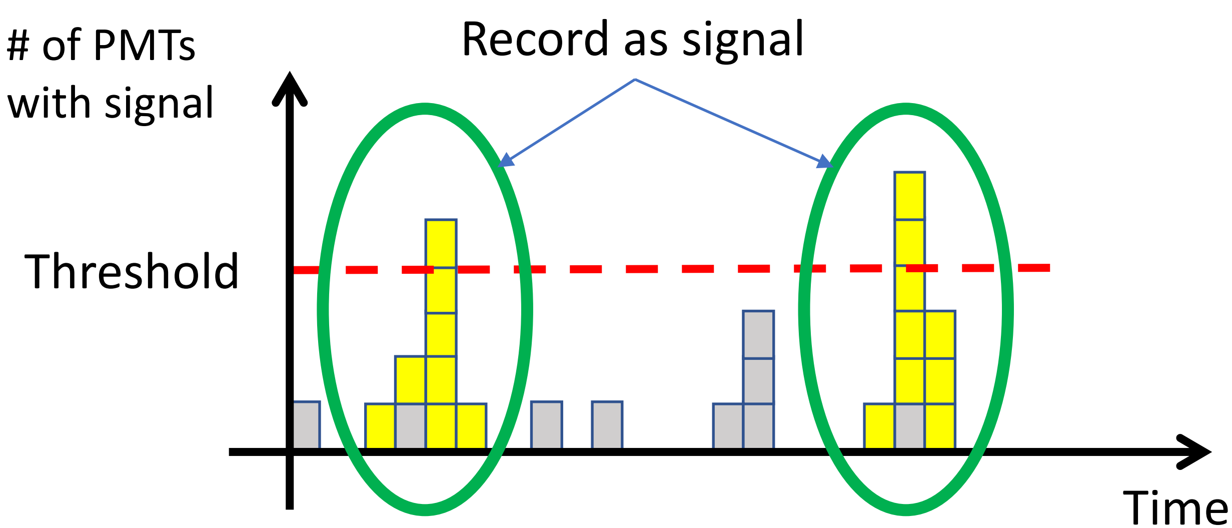
1) Event gate width of the very low energy events (< ~5MeV) is set to 1.5 us. (-0.5 to 1.0 us)
2) Event gate width of the normal events (>5MeV) is set to 40 us (-5 to 35 us).
3) Event gate width for T2K is 1 ms (-500 to 500 us).
4) Special "neutron trigger" is issued when there is an event with the energy higher than ~8MeV. This effectively extends the gate width from 40 us to 540 us (+35 to +535 us).



Super-Kamiokande
Limitation of the “majority” (NHIT) trigger

The trigger rate increased drastically if we lowered the threshold.
“Low energy gamma from radio activities + dark noise”

If we lower the threshold below ~3.5 MeV,
trigger rate becomes much higher than 20kHz and
it is not possible to record the data.



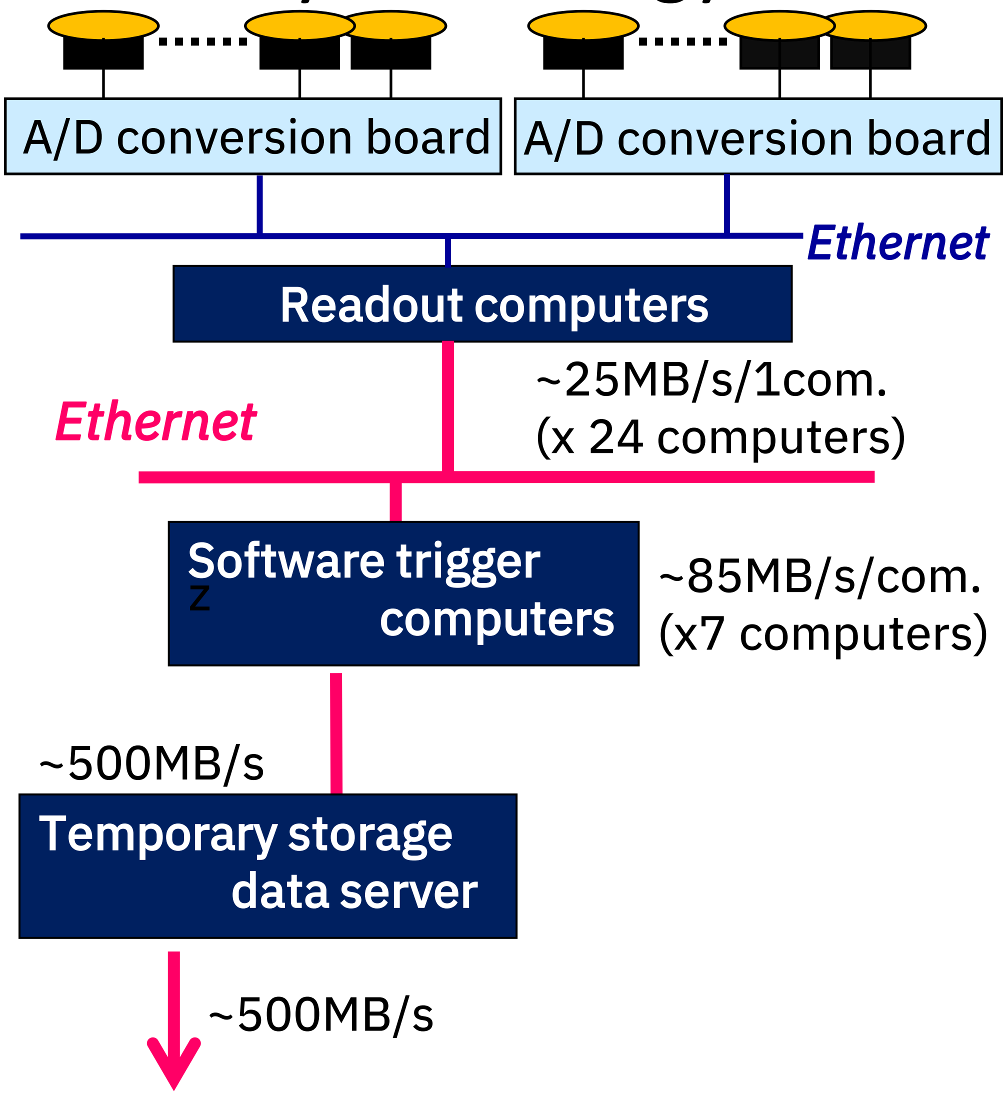
Super-Kamiokande

Intelligent trigger for very low energy events

Special "intelligent" trigger for very low energy events, called "WIT" is running in parallel to the normal trigger system.

WIT searches for the small activities and reconstruct vertex.

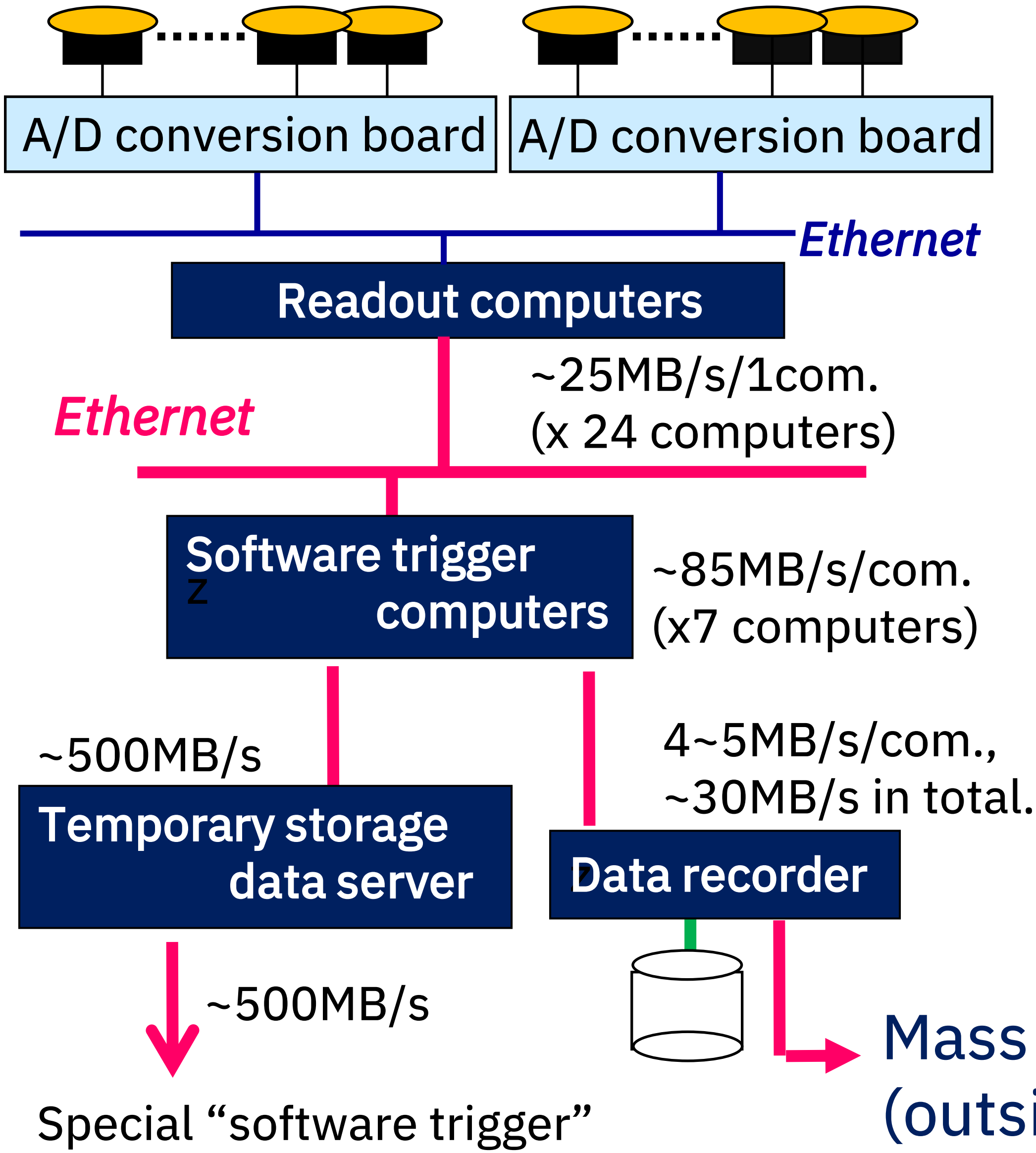
Noise events tend to occur in the surrounding region of the tank.
Reject "noise-like" events.



Special "intelligent" trigger

Super-Kamiokande

Intelligent trigger for noise rejection



Most of the "low energy" events are not signal.
(Radio activities with noise)
No need to keep "noises."

Apply event reconstruction using the offline computer system and reject "noise-like" events as soon as the data are transferred to the offline computer system.
(Noise-like events are removed.)

Summary

Super-Kamiokande electronics records all the PMT signal above the discriminator threshold, including the dark noise.

The DAQ system reads out all the PMT hits, applies the "software trigger" to define the events, and records the data.

There are several types of triggers,

Majority trigger (# of hits trigger),
T2K trigger (GPS timing trigger),
Calibration trigger (external signal), and
Intelligent trigger with event reconstruction
for the very low-energy events.

The data is also "selected" as soon as the data are transferred.
to the offline computing system to reject noise events.