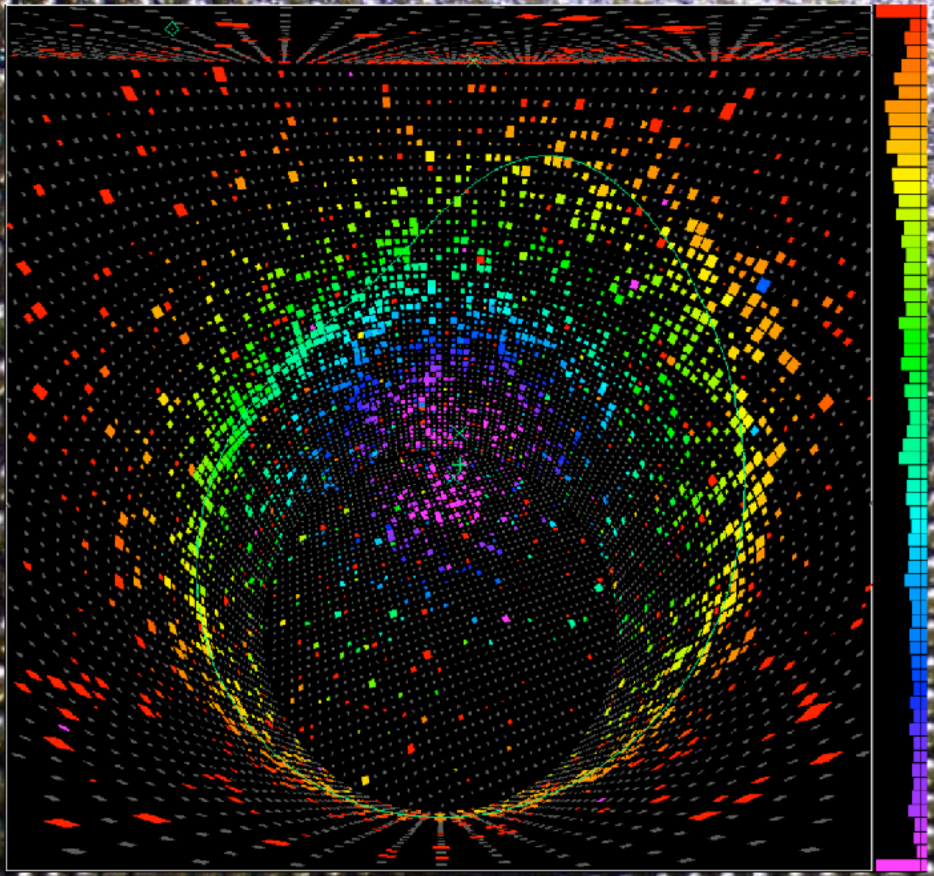


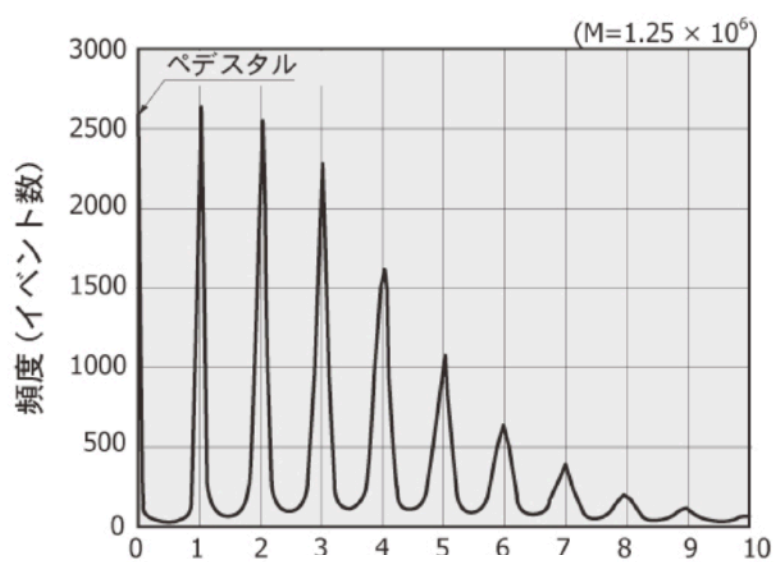
3rd Hardware Camp for Fast and Low-light Detection, March 4th (Mon.), 2024

Photo-detectors in particle physics

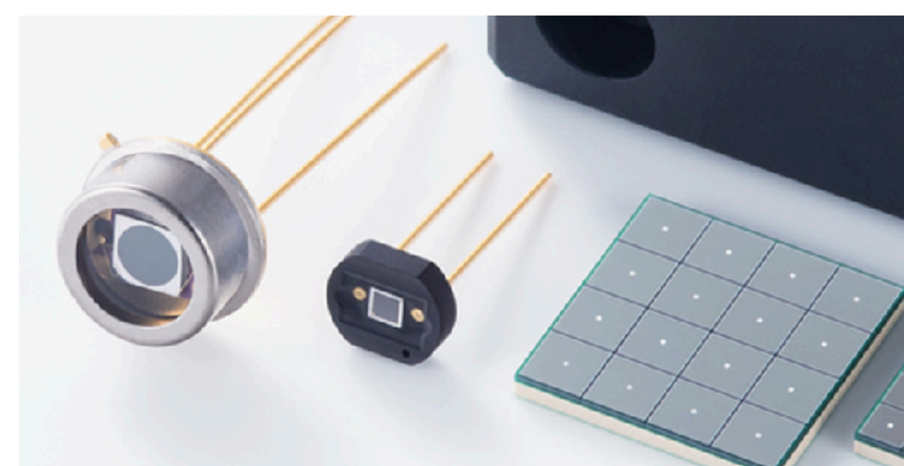
T. Nakaya (Kyoto Univ.)

Fast and Low light detection in particle physics

- Elementary particles
  - Photon, electron, muon, neutrino, and quarks
- How fast
  - $c = 3\times10^{8}$ m/s $= 1/(0.333\times10^{-8})$ m/s $=$ 1m/3.33nsec
  - A photon-detector has the timing resolution of better than 100 psec (0.1 nsec)
- How low
  - 1 photon



#photons



The things is that there are a lot photons reach us even in a blinking of LED

$$E_{photon} = hf \text{ where } h = 6.26 \times 10^{-34} Js$$

The Thorlabs 405nm LED has optical power of 6mW, how many photons emitted in a second ?

$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}[m/s]}{405 \times 10^{-9}[m]} = 7.4 \times 10^{14}[s^{-1}] = 7.4 \times 10^{14}[Hz]$$

Number of photons emitted per second

$$n_{photon} = \frac{6 \times 10^{-3}[W] \times 1[s]}{6.626 \times 10^{-34}[Js] \times 7.4 \times 10^{14}[s^{-1}]} = \boxed{1.2 \times 10^{15}}$$

https://www.thorlabs.co.jp/newgrouppage9.cfm?objectgroup_id=2814

Photomultiplier Tube (PMT)

- An equipment to measure photons
- It often called as PMT (PhotoMulTiplier tube)

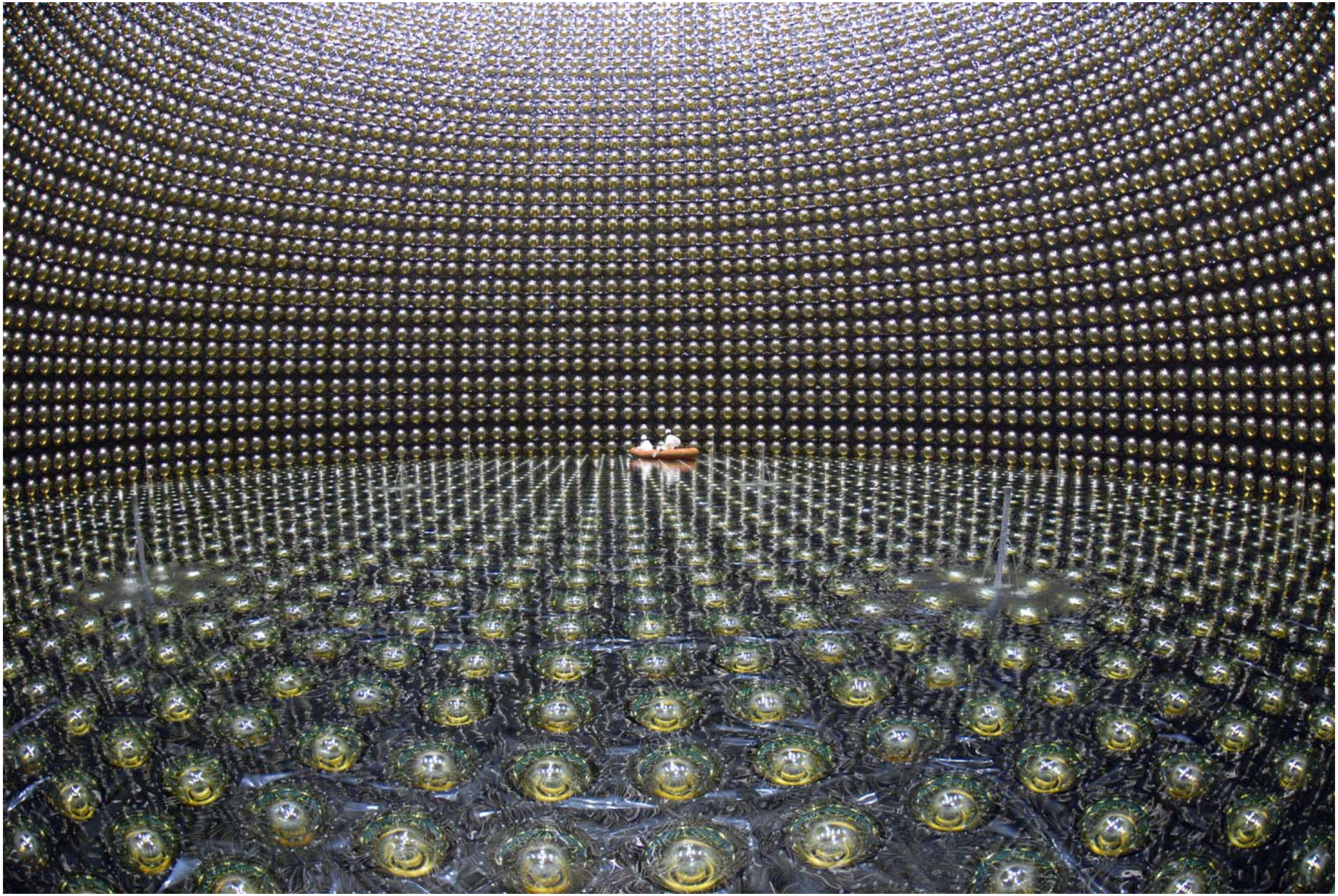
高エネルギー物理学分野への進出 - Foray into High Energy Physics

Hamamatsu: No. 1 PMT vendor

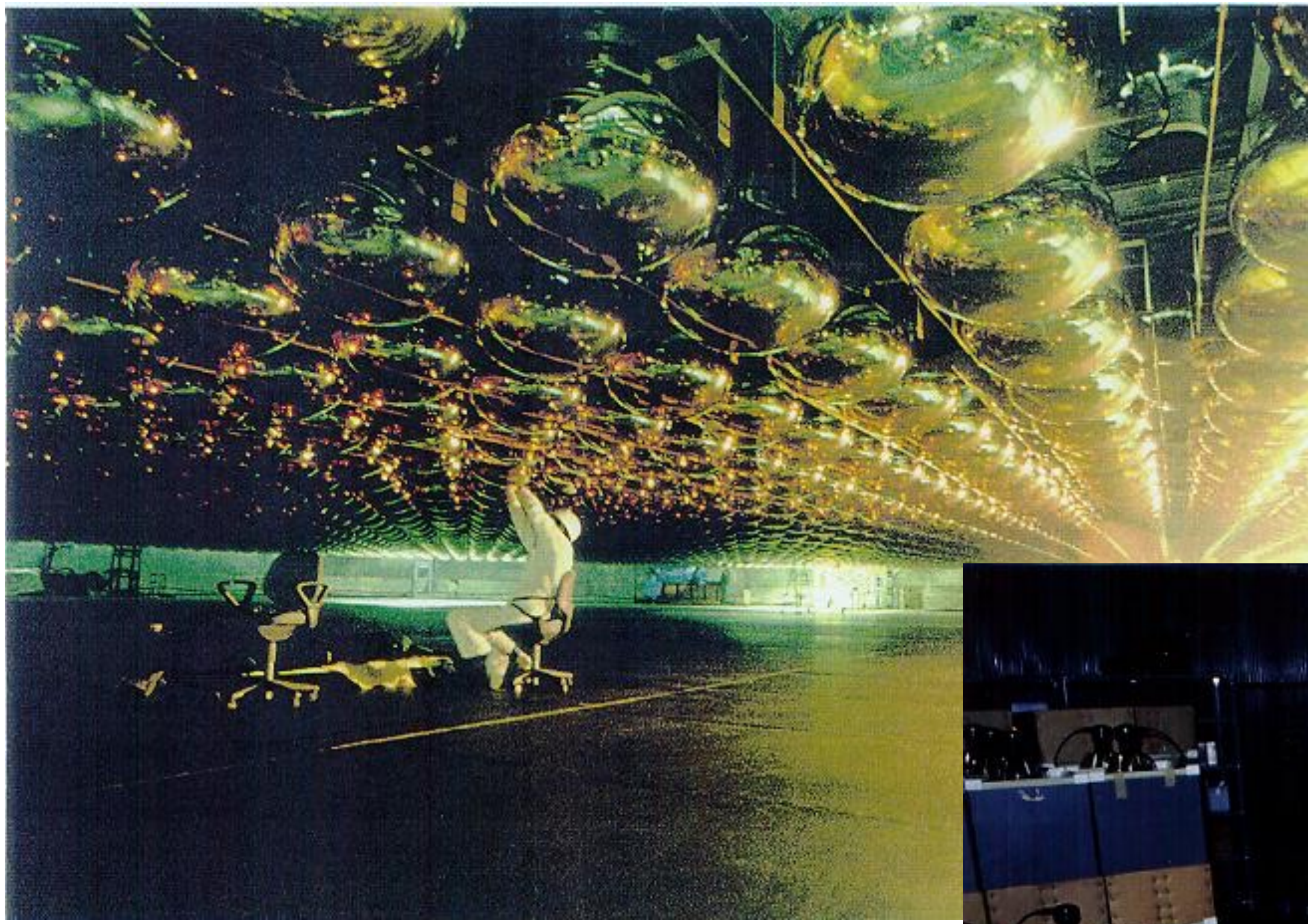
Prof. Koshiba with 50 cm PMT

「カミオカンデからスーパーカミオカンデへ」
戸塚　洋二　より

Super-Kamiokande



Eyes of Super-Kamiokande



50cm PMT

~11,000

Detection Principle

- A neutrino detector
  - Neutrino interactions occurring and being detected in all volume of the detector

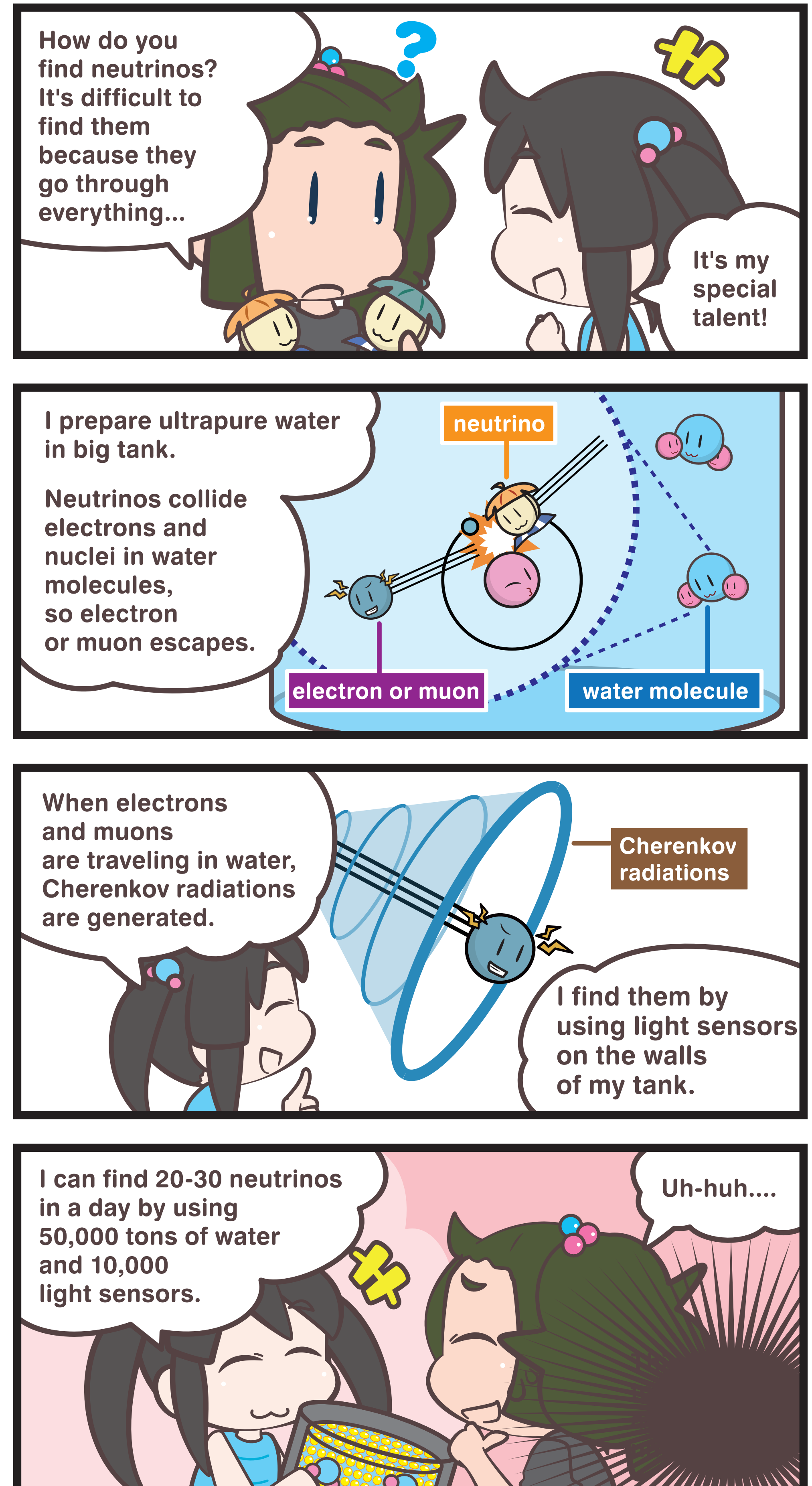
- Features of neutrino detectors
  - Large mass and large active volume
  - Small background
  - Good resolutions in the large volume
    - (Resolution for what?)

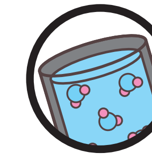
WCD (Water Cherenkov Detector)

- The large mass and large active volume
  - The large mass can be achieved inexpensively by using water.
  - The active volume is realized by detecting Cherenkov radiation in transparent water.
    - Good acceptance for photons of Cherenkov radiation is essential.
- The small background
  - Ultra-pure water is necessary for
    - extremely low radio-active environment
    - transparent material with no loss of light (and images).
- Good resolution in a large volume
  - Good energy resolution
  - Good timing resolution for vertex reconstruction
  - Good imaging resolution for PID and particle counting

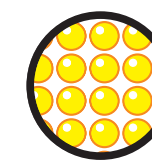
How to find neutrinos

How to find Neutrino



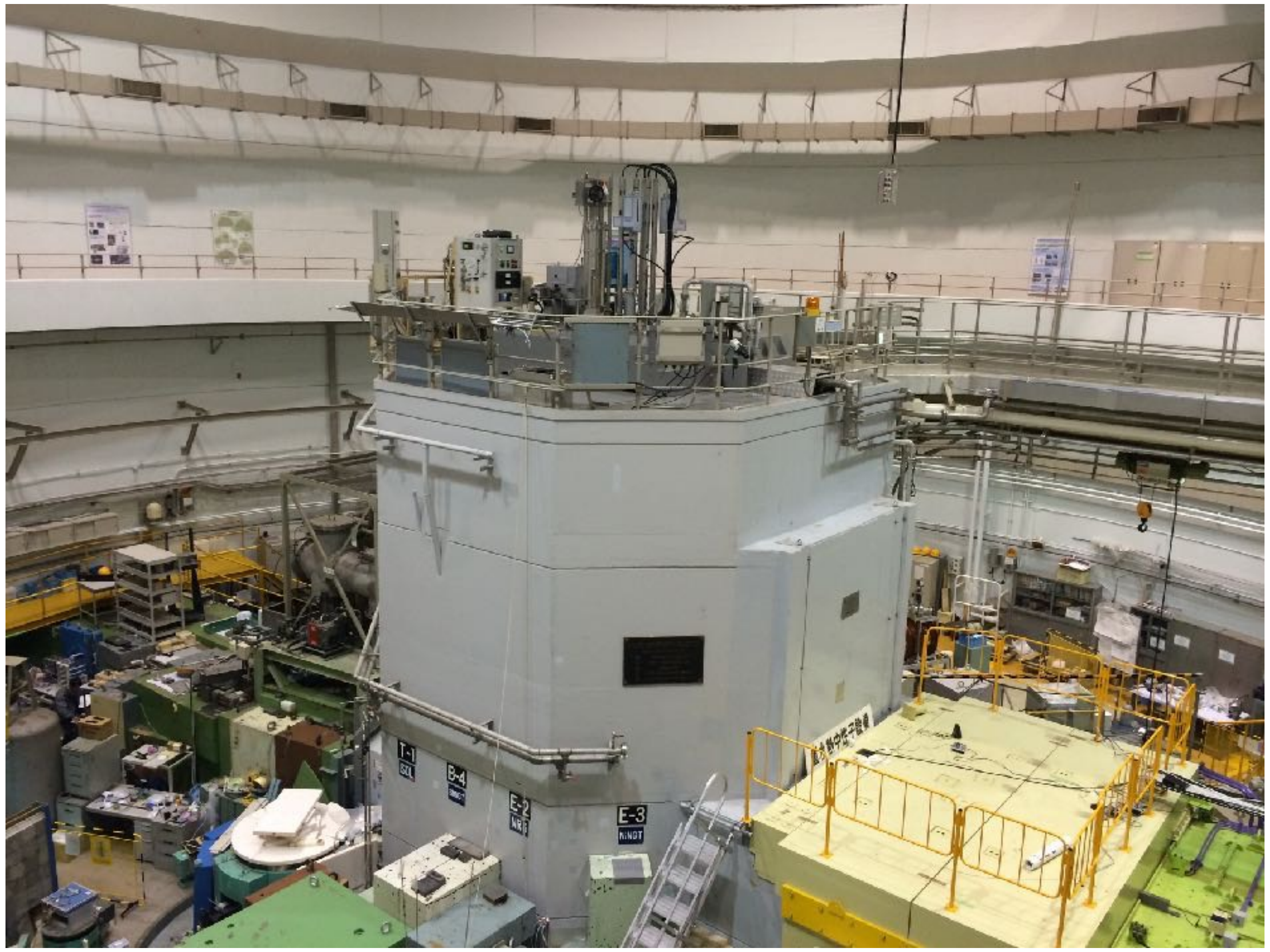


Gigantic tank: It is filled with 50,000 tons of ultra-pure water. The bigger it is, the more neutrinos can be detected.

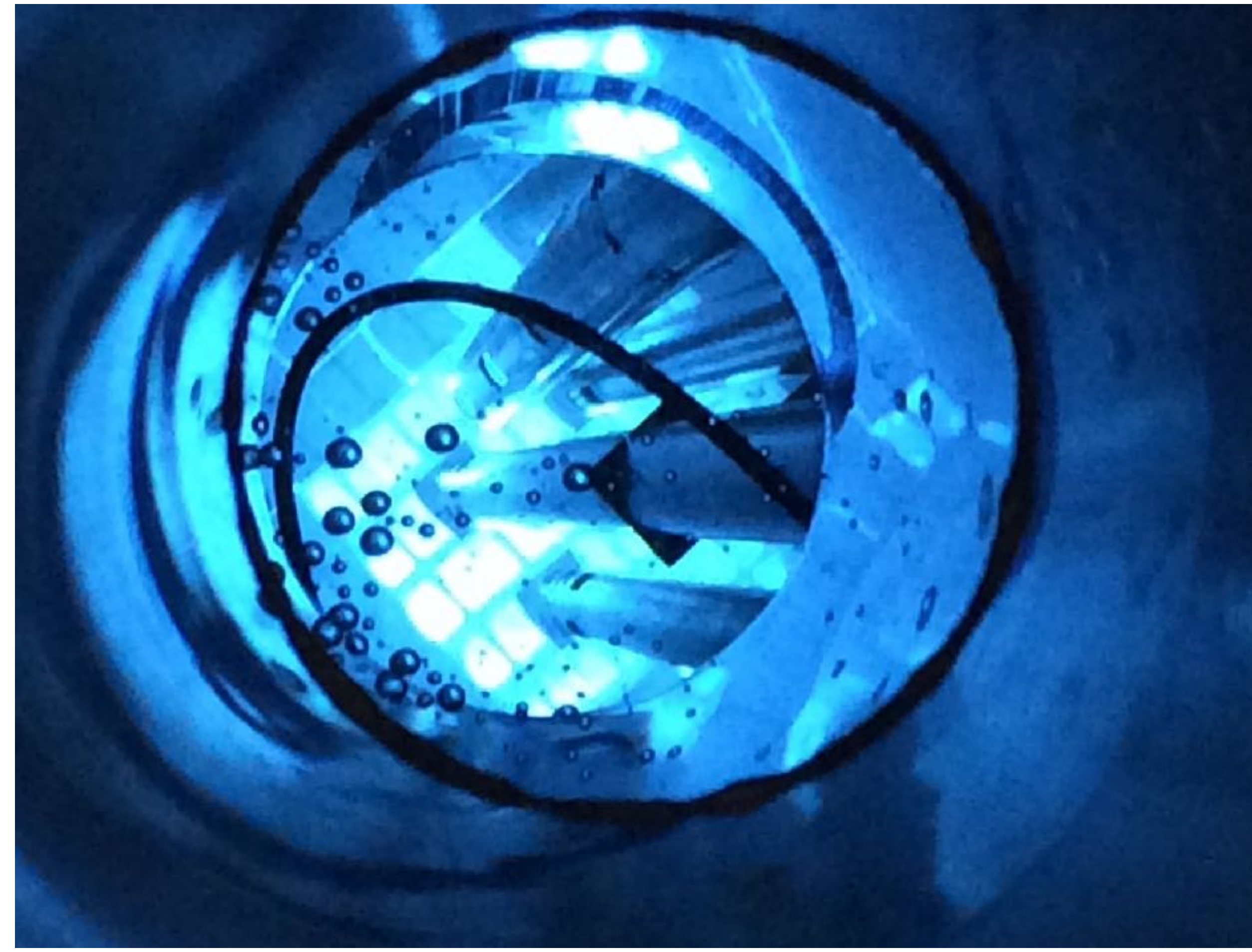


A lot of light sensors: Light sensors called photomultiplier tubes (PMTs). There are 11,129 sensors inside the tank.

Cherenkov light



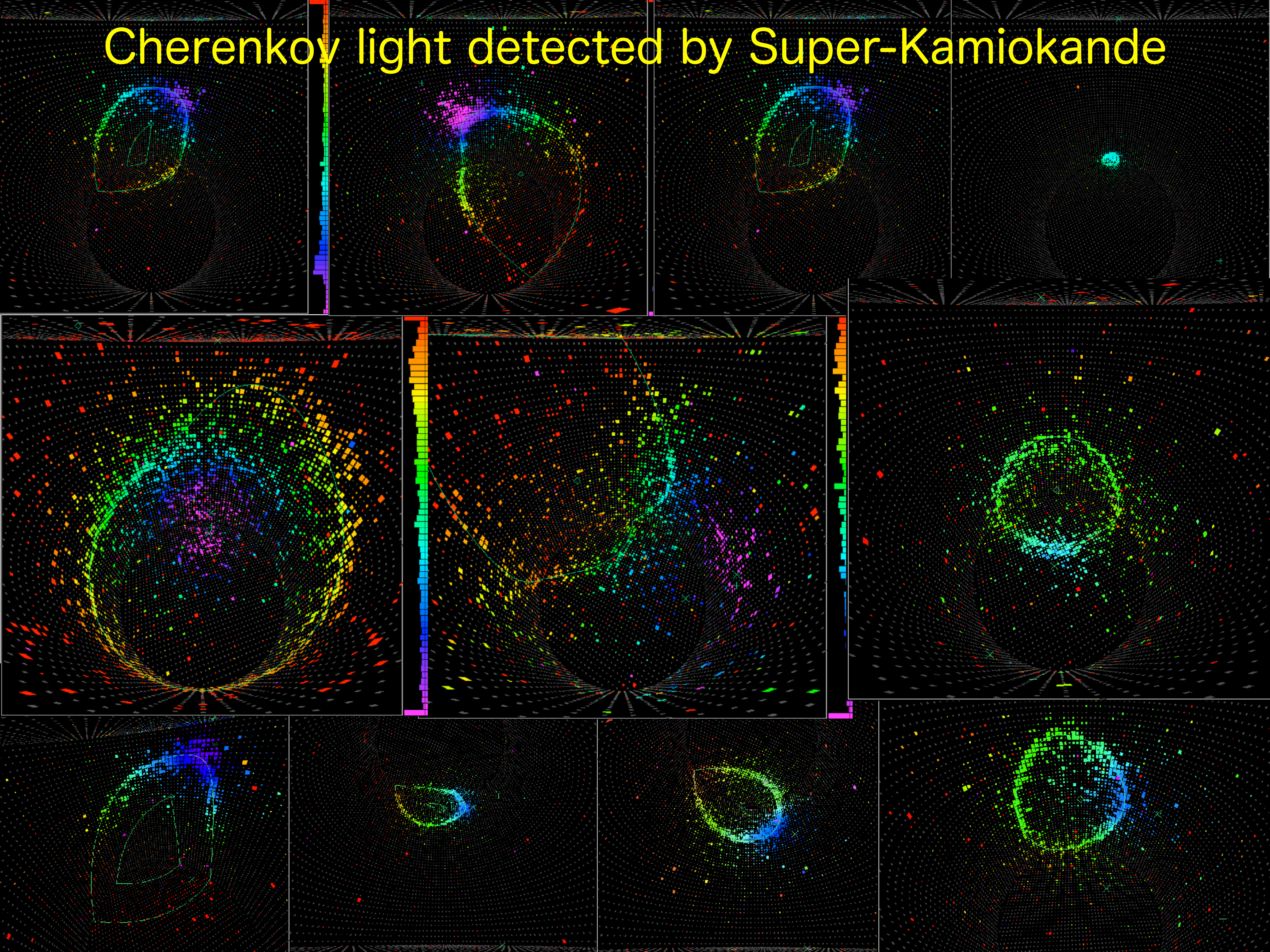
Kyoto U. Nuclear Reactor



Inside of reactor taken by TN in March, 2014

- When we look into the inside of nuclear reactor, we can see blue light (Cherenkov light).

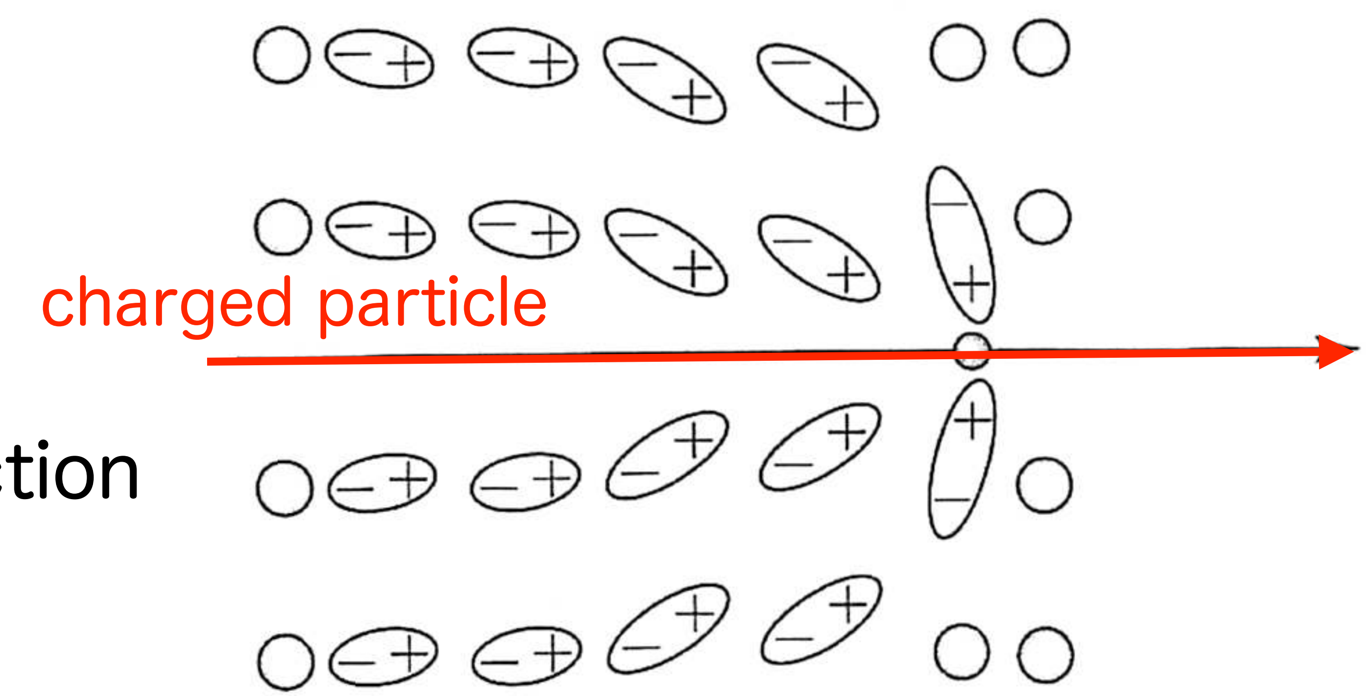
Cherenkov light detected by Super-Kamiokande



Cherenkov light

- Cherenkov radiation arises when a charged particle in a material medium moves faster than the speed of light in the same medium.
  - The condition is $v=\beta c>c/n$ => $\beta n>1$
  - Is is discovered by Cherenkov (the Soviet Union) in 1937.

Microscopic view:
Atoms are polarized in the direction of the charged particle moving.



$$\cos\theta_c = \frac{ct/n}{\beta c t} = \frac{1}{\beta n}$$

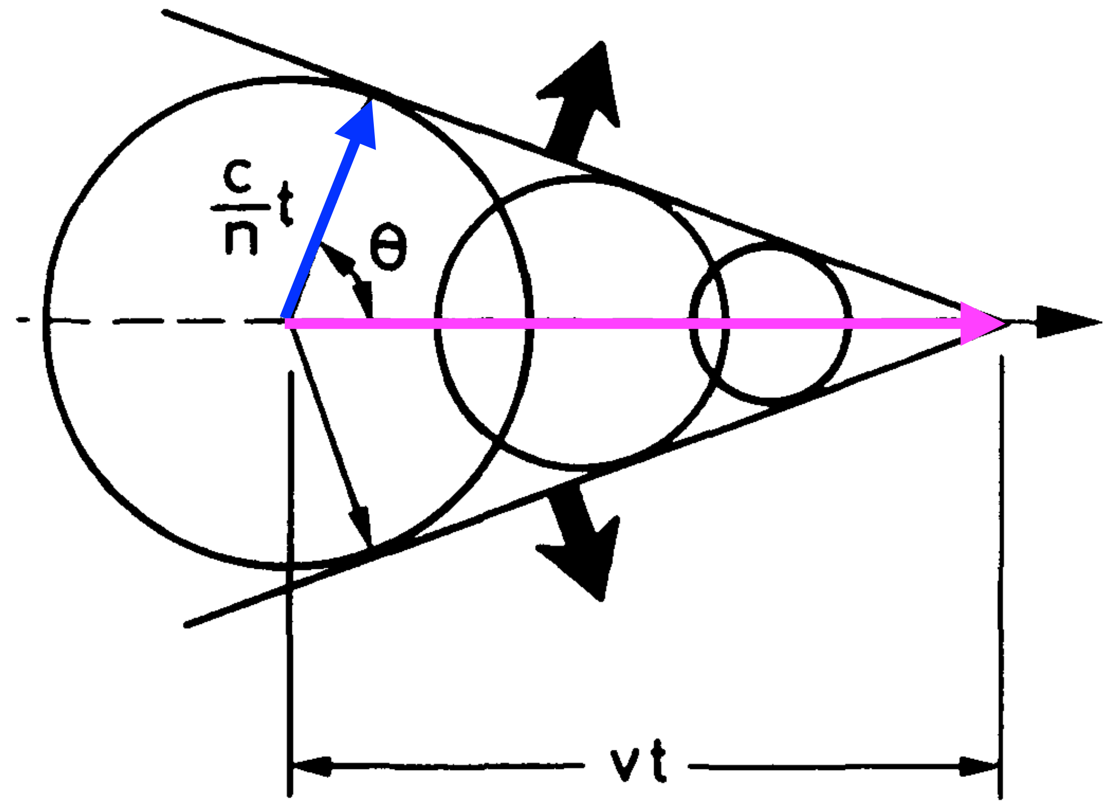


Fig. 2.9. Cherenkov radiation: an electromagnetic shock wave is formed when the particle travels faster than the speed of light in the same medium

Characteristic of Cherenkov radiation

1. There is a threshold on energy (E_{th}) for Cherenkov radiation

$$E_{th} = m_0 c^2 \left\{ -1 + \sqrt{1 + \frac{1}{n^2 - 1}} \right\}$$

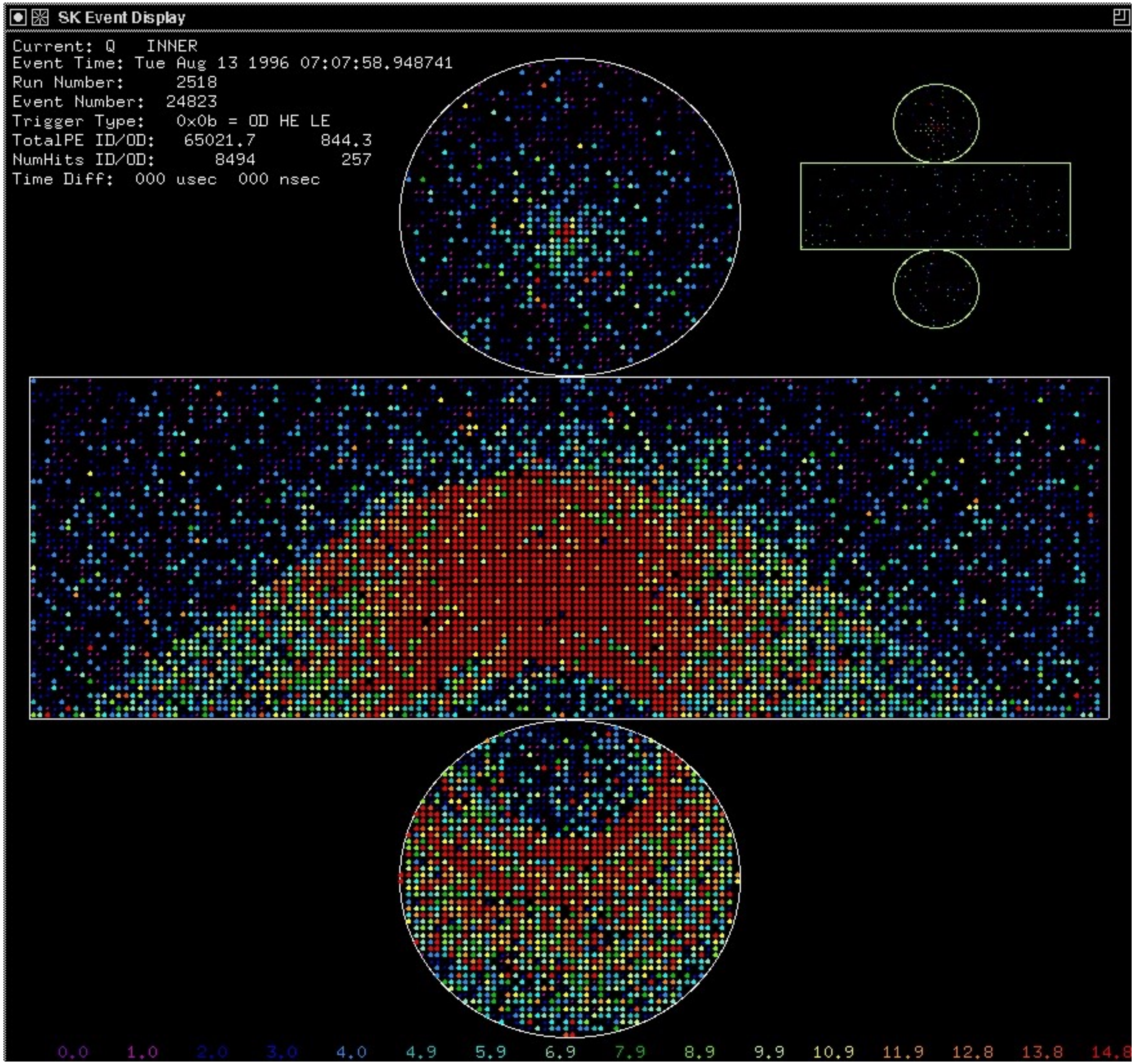
2. Very fast (Prompt radiation)
3. (Disadvantage) The light yield is small. The fraction of energy transforming to the radiation is only 0.1% or so. (Ref. It is ~10% for scintillation)
   - [Q] How many Cherenkov photons are detected in Super-Kamiokande for an 10 MeV electron.
4. The Cherenkov photons are emitted in the direction of the charged particle moving with the angle θ_C to form a cone shape. (Ref. The scintillation lights are emitted isotropic).
5. The Cherenkov yield is proportional to $1/\lambda^2$ (λ: Wavelength of Cherenkov light).

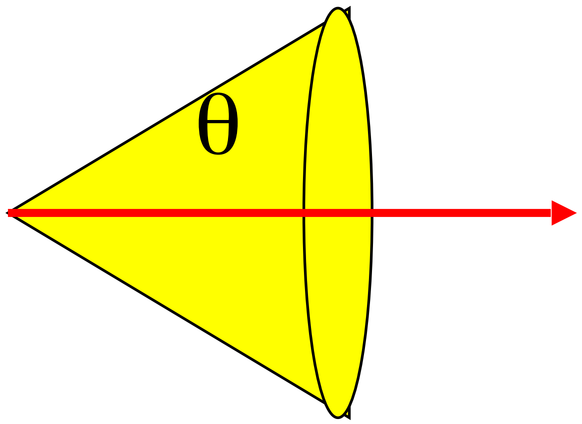
- With the above characters, a Cherenkov detector is often used for particle identification with the momentum threshold. It is also unique that the moving direction is determined.

Material medium for Cherenkov

	n-1	β threshold
Diamond	1.42	0.41
glass	0.46~0.75	0.57~0.68
scintillator	0.58	0.63
Water	0.33	0.75
Silica aerogel	0.025~0.075	0.93~0.976
CO_2 gas	4.3×10^{-4}	0.9996
He gas	3.3×10^{-5}	0.99997

Ring Imaging Water Cherenkov pixel detector



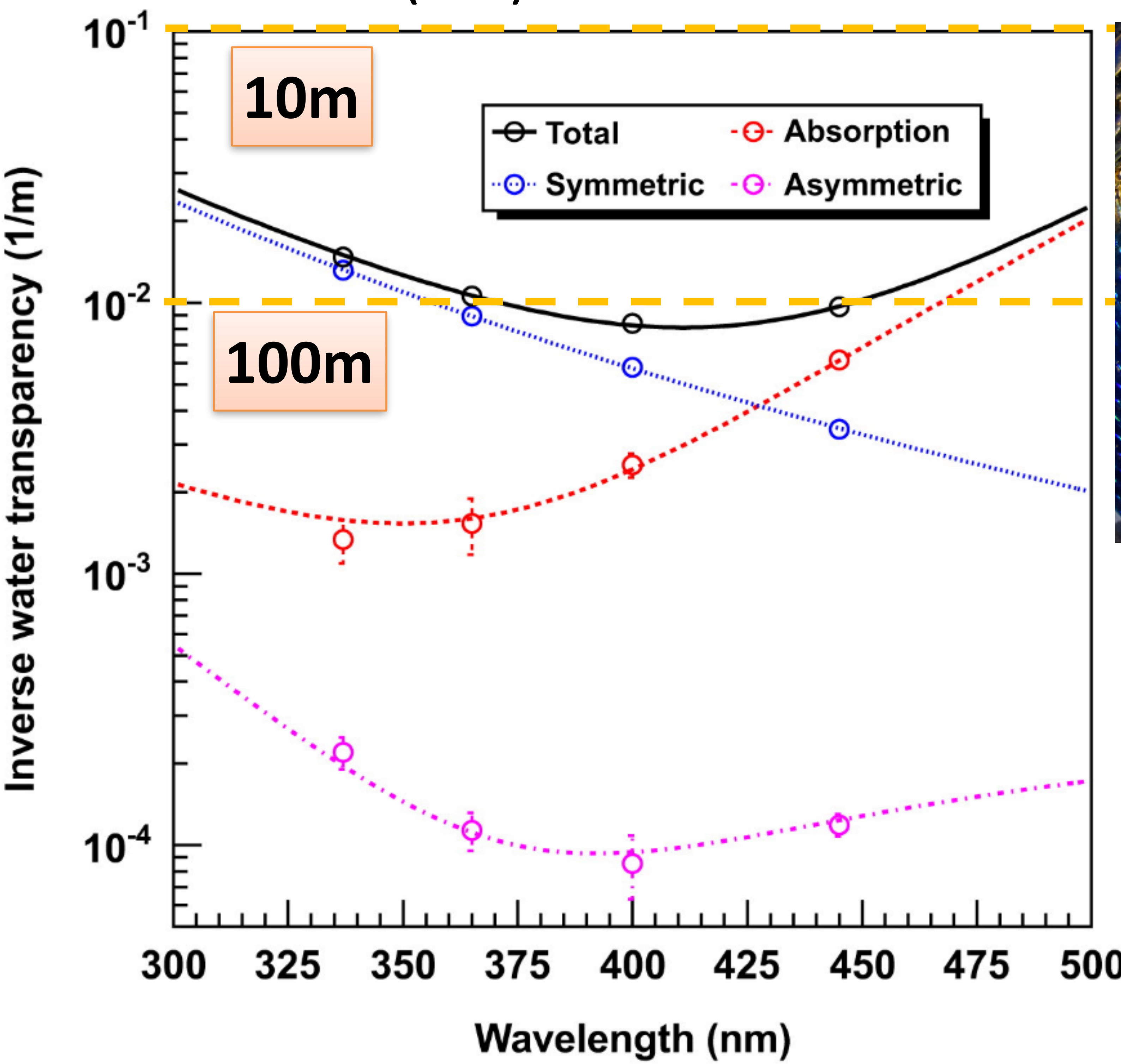


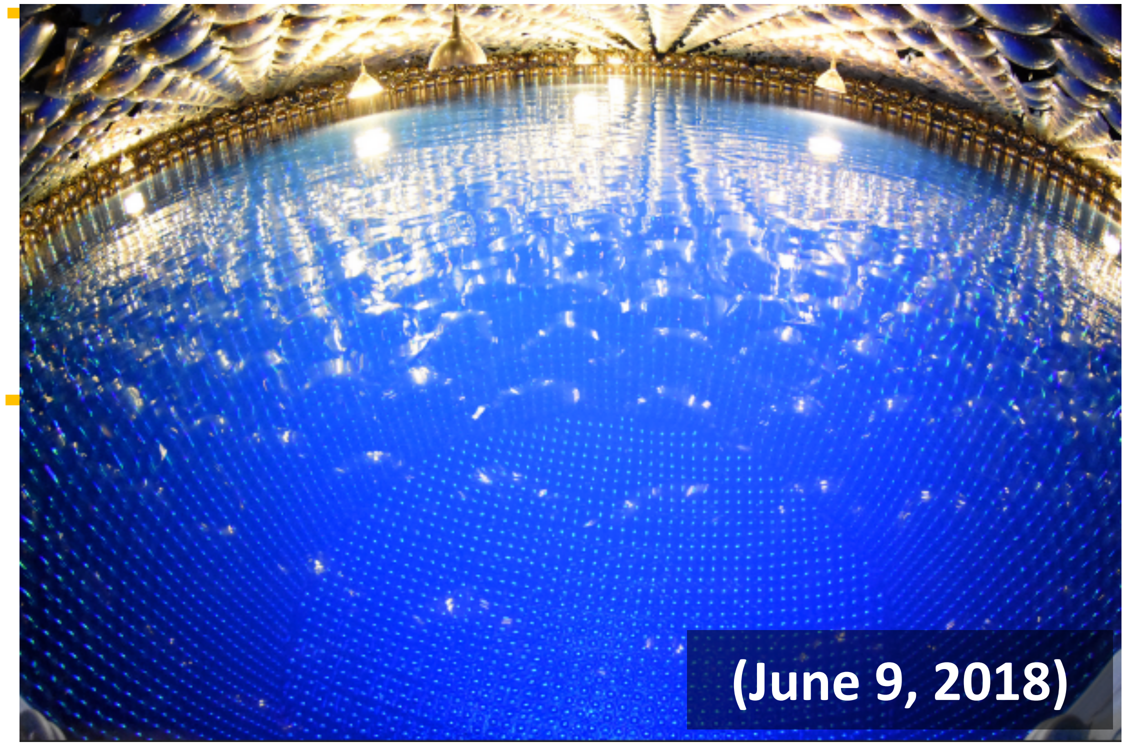
$\beta > 1/n$ ($n=1.33$)

$\cos\theta = 1/n\beta$

Water transparency

NIM A 737 (2014) 253-272





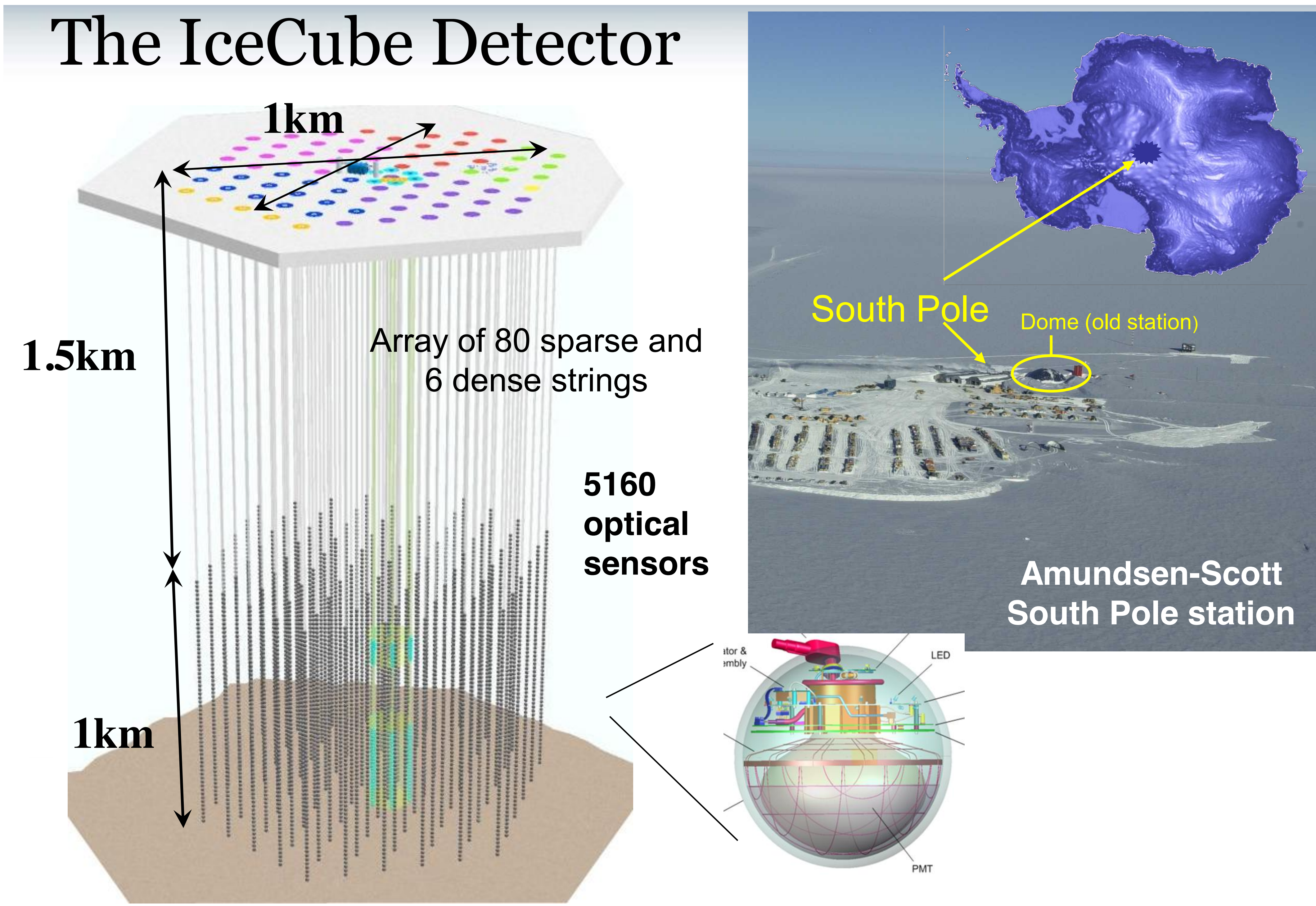
- Around 400 nm region, absorption and scattering are measured in the SK detector with nitrogen & dye lasers.
- Rayleigh scattering, Mie scattering, Absorption are considered
- Absorption in the long wavelength is obtained from R.M.Pope and E.S.Fry, Appl. Opt. 36 (1997) 8710

- Water purification system

https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf

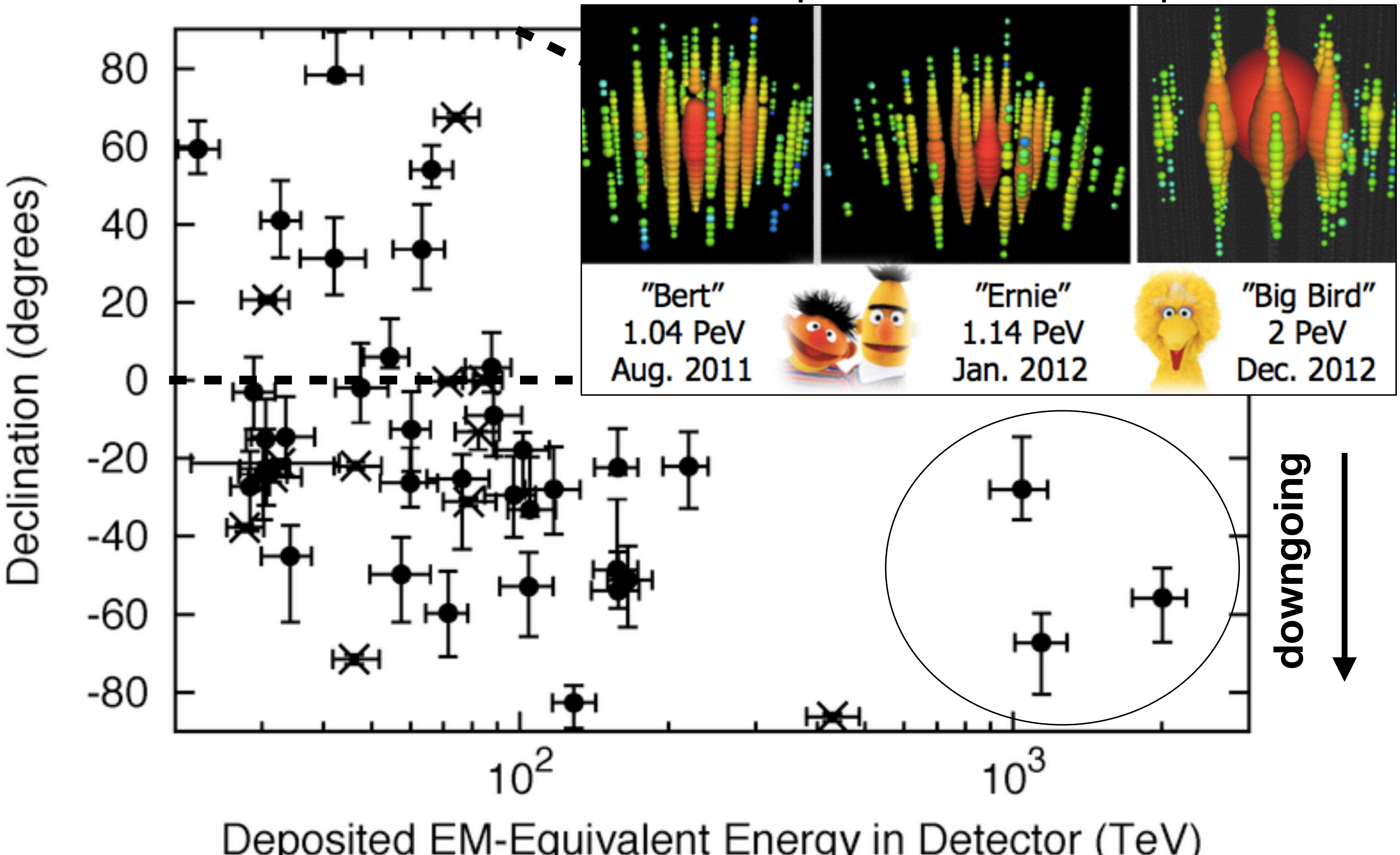
Cosmic Neutrino

- The High Energy Cosmic Neutrinos were first detected in 2012 by IceCube.

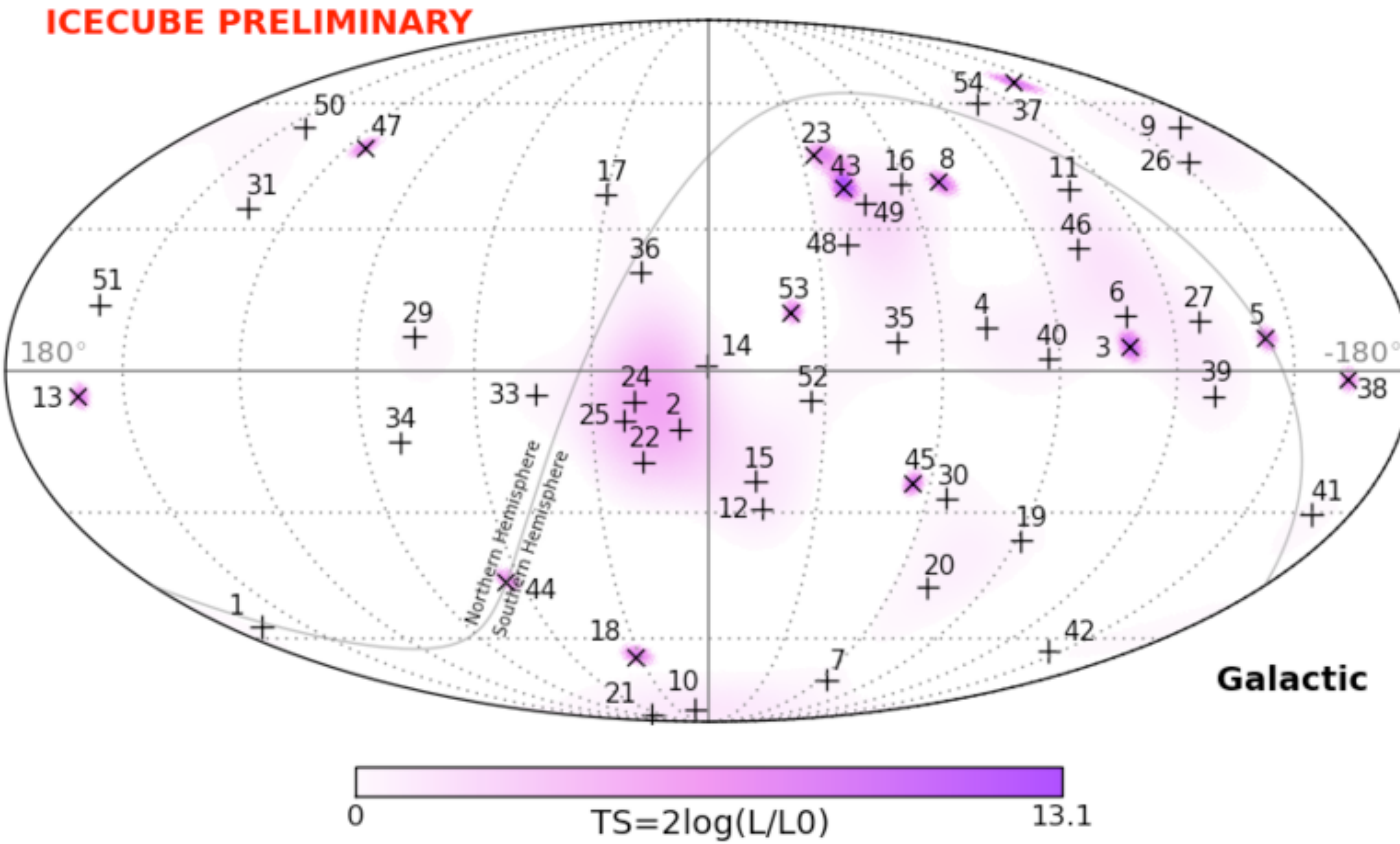


Astrophysical Neutrinos!

54 events observed with 20±6 expected from atmosphere

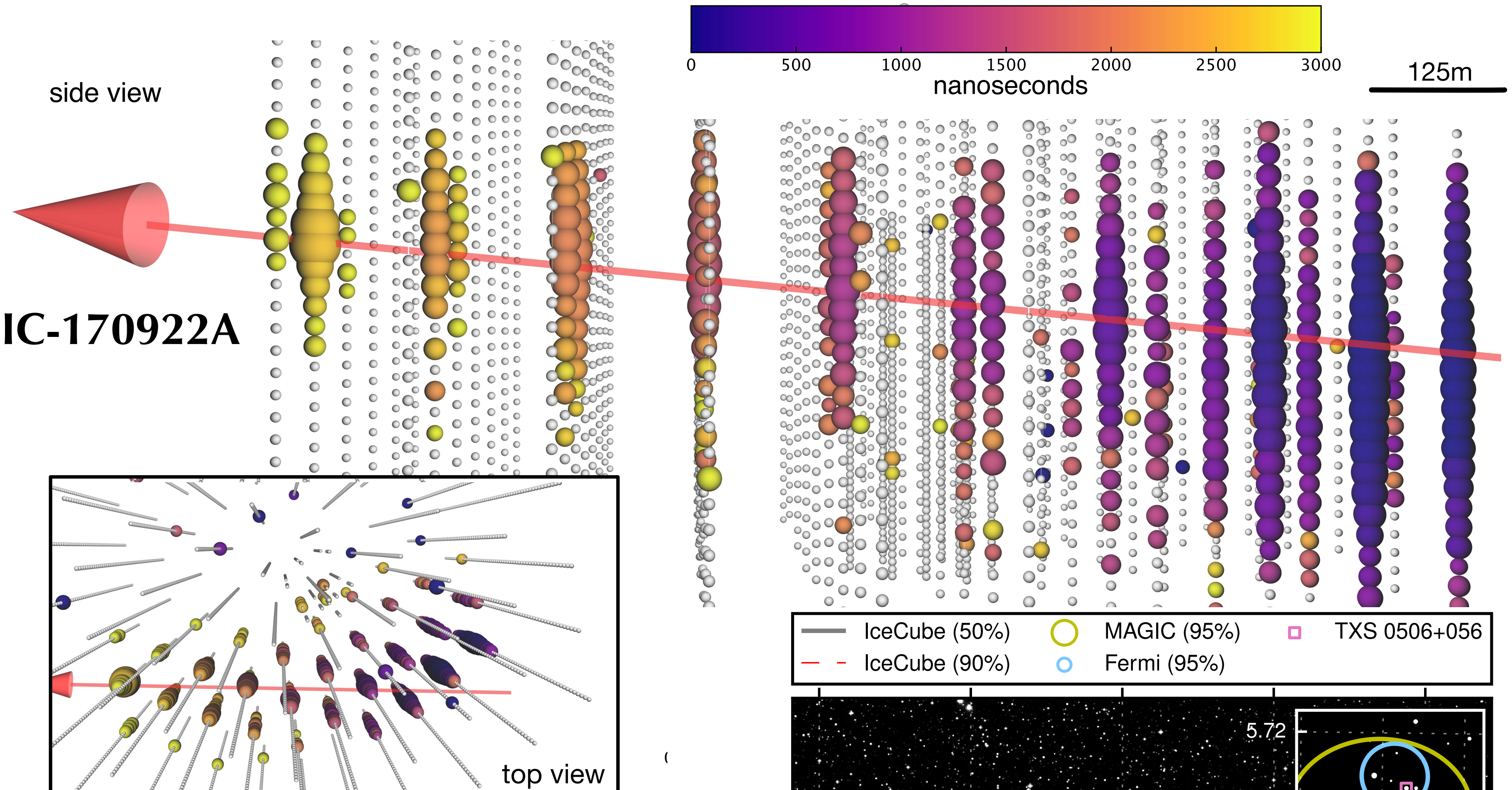


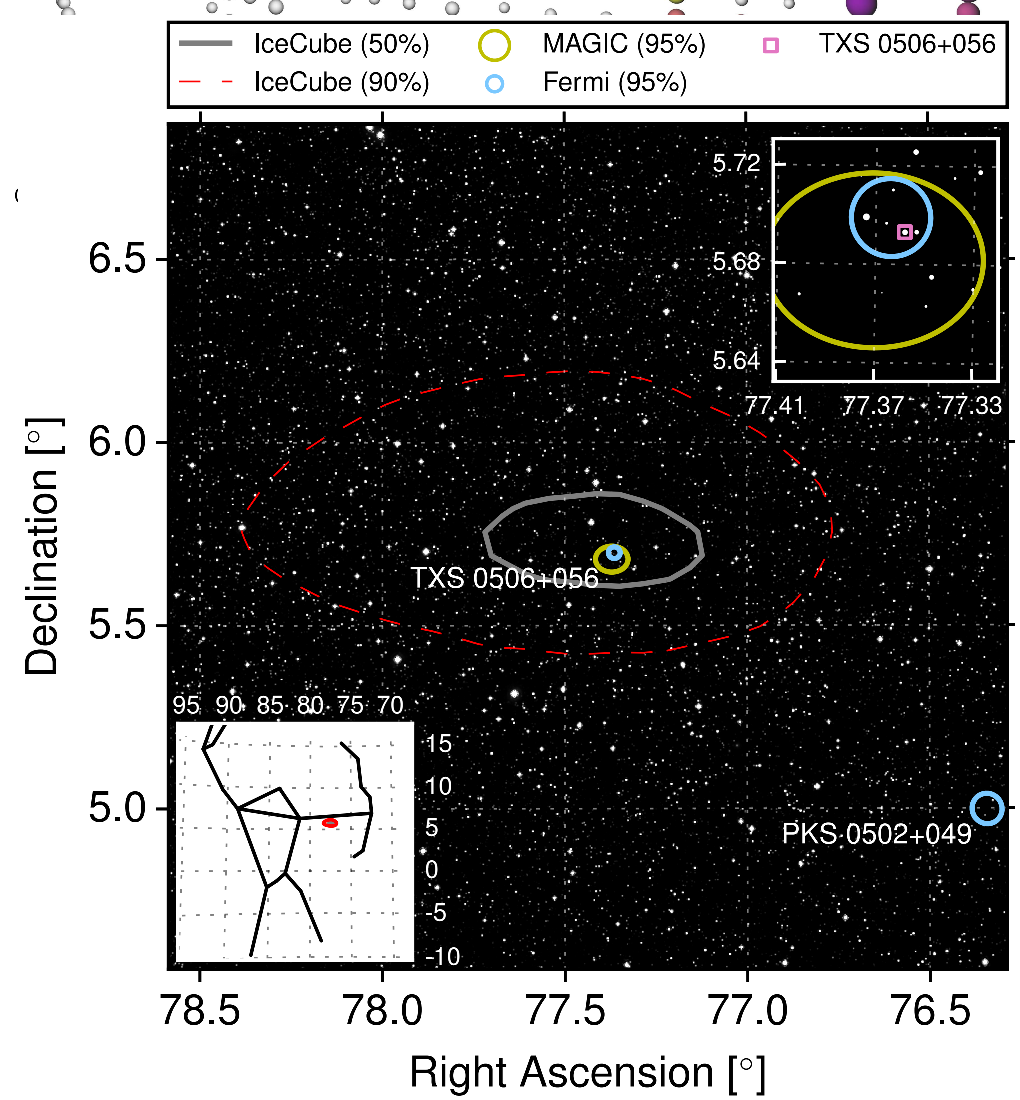
Sky map of 54 High Energy Starting Events



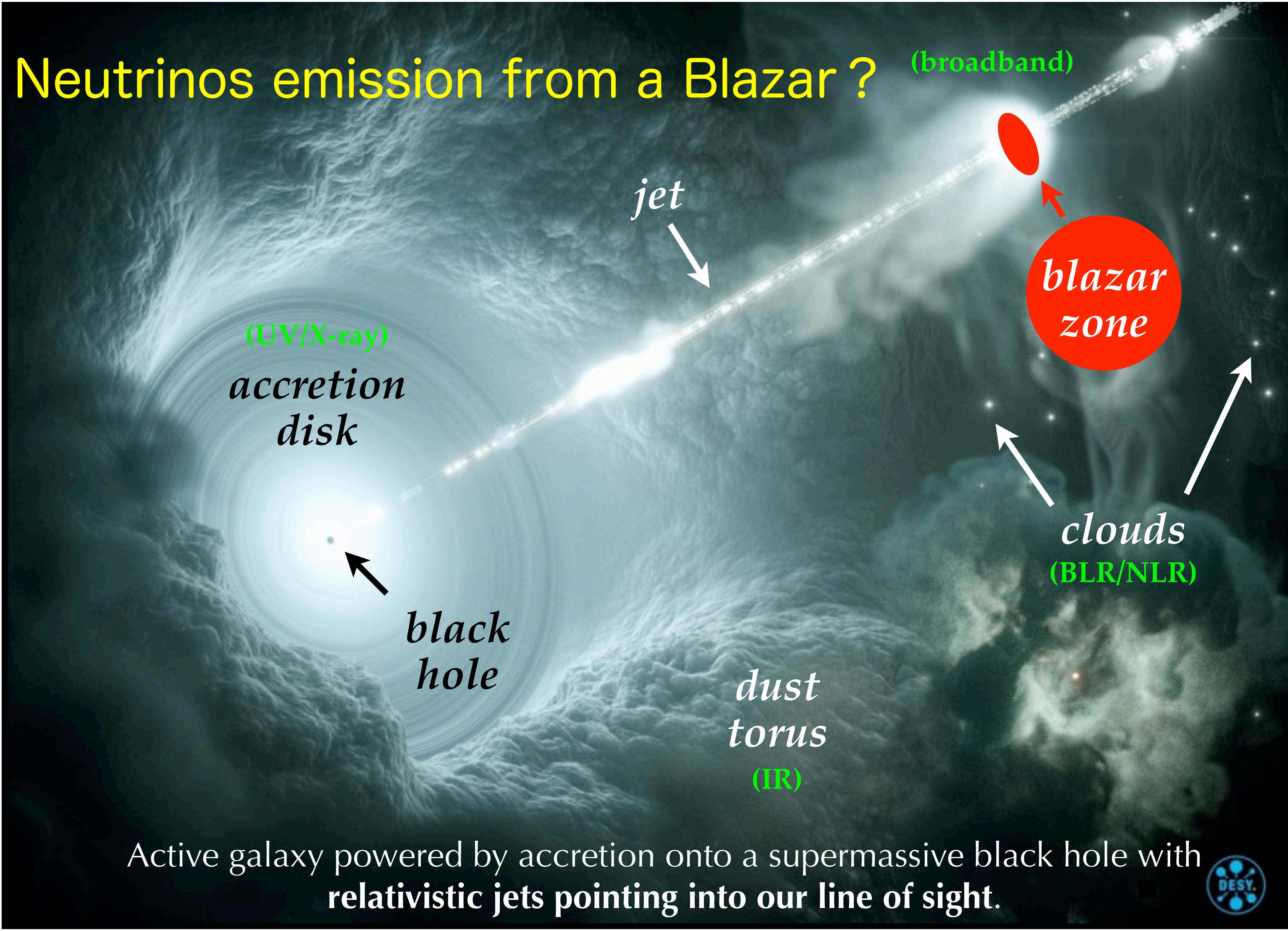
Largely isotropic ⇒ extragalatic origin!

Multi-messager



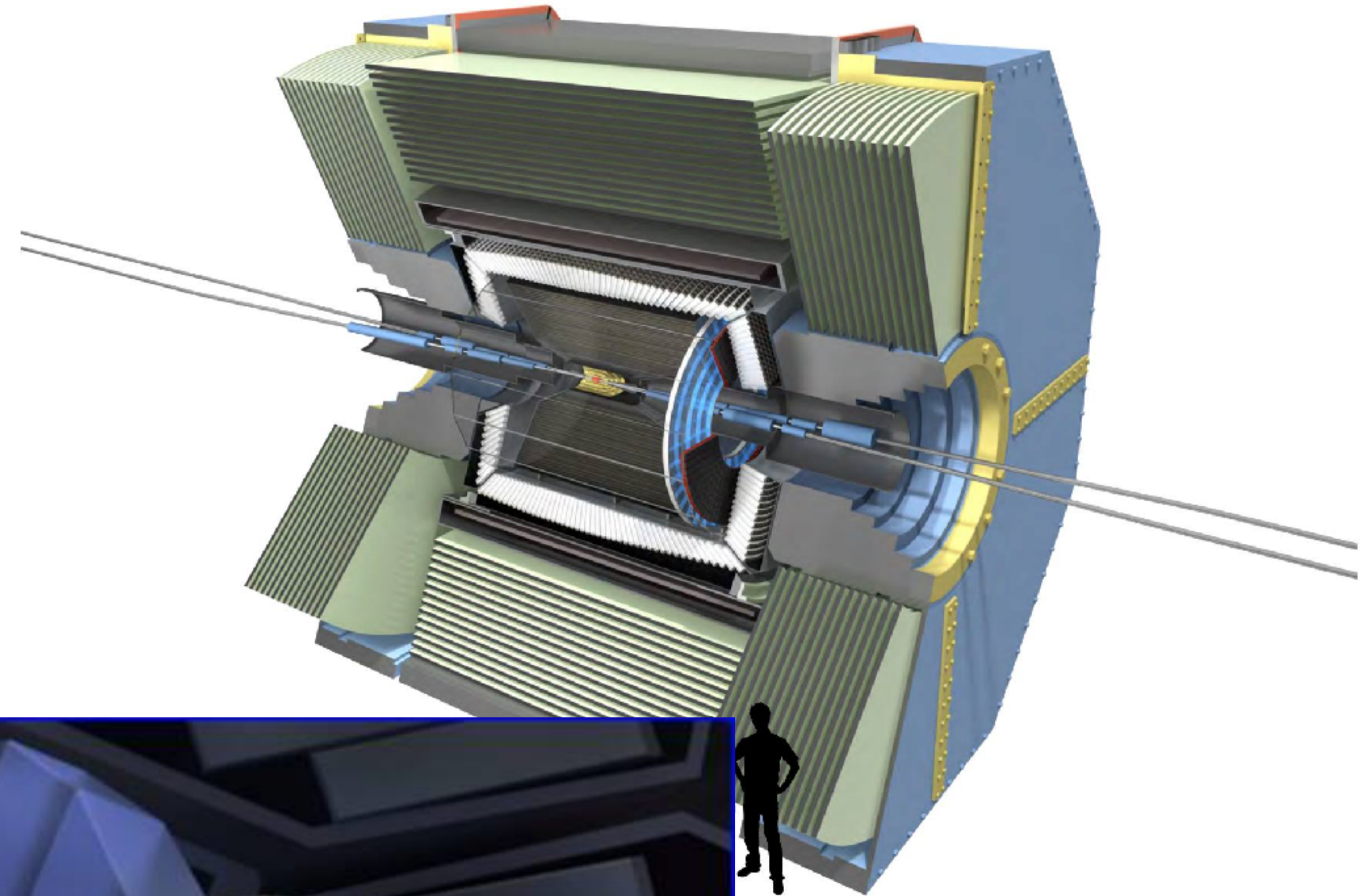


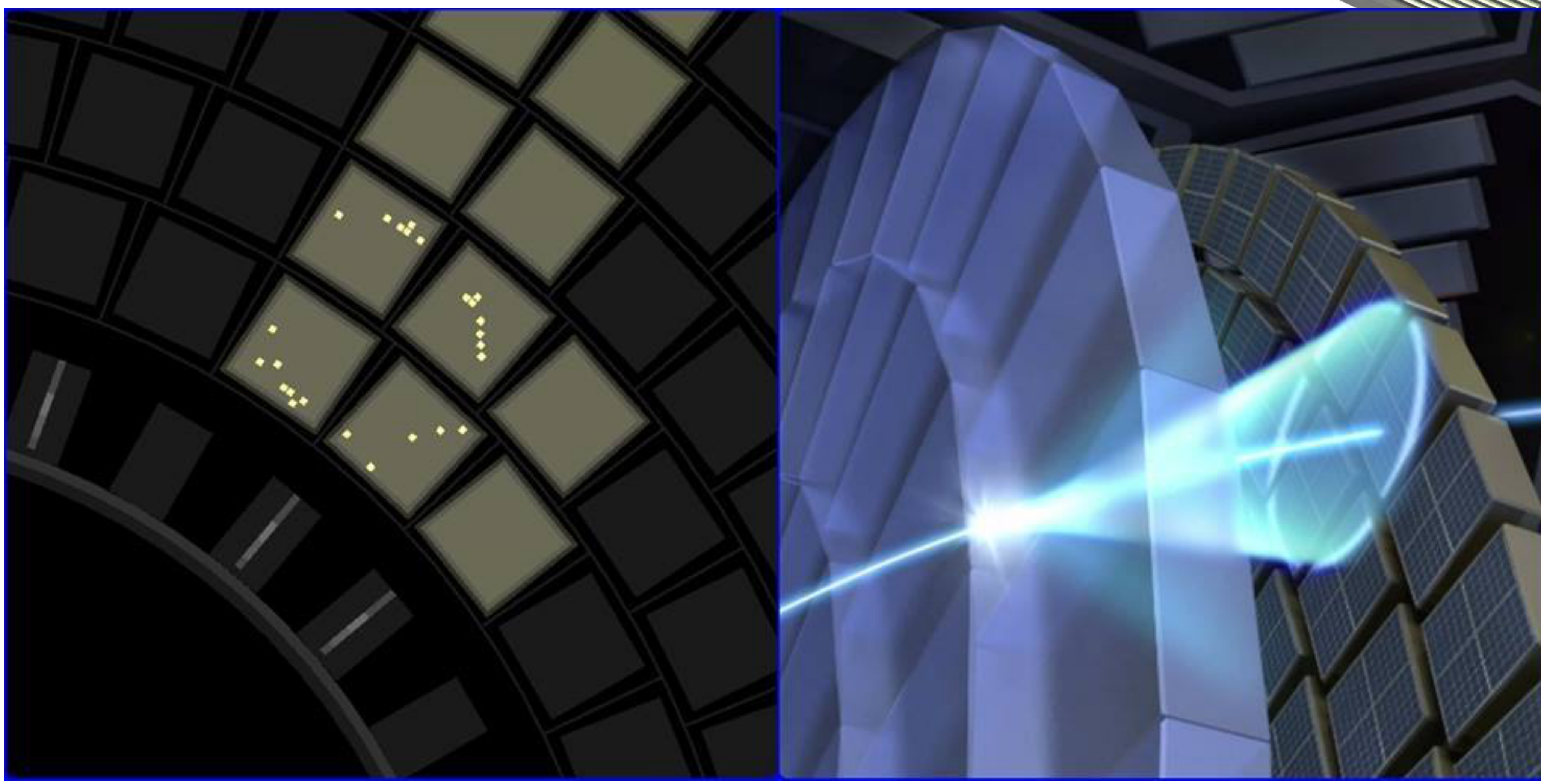
- IC-170922A observed September 22, 2017 had a coincidence with flaring blazar TXS0506+056 (3σ level)



Neutrinos emission from a Blazar ?
(broadband)
jet
blazar zone
(UV/X-ray)
accretion disk
black hole
clouds
(BLR/NLR)
dust torus
(IR)
Active galaxy powered by accretion onto a supermassive black hole with
relativistic jets pointing into our line of sight.

Belle II
Aerogel Ring Image Cherenkov Counter (ARICH)





Multianode Hybrid Photo-detector

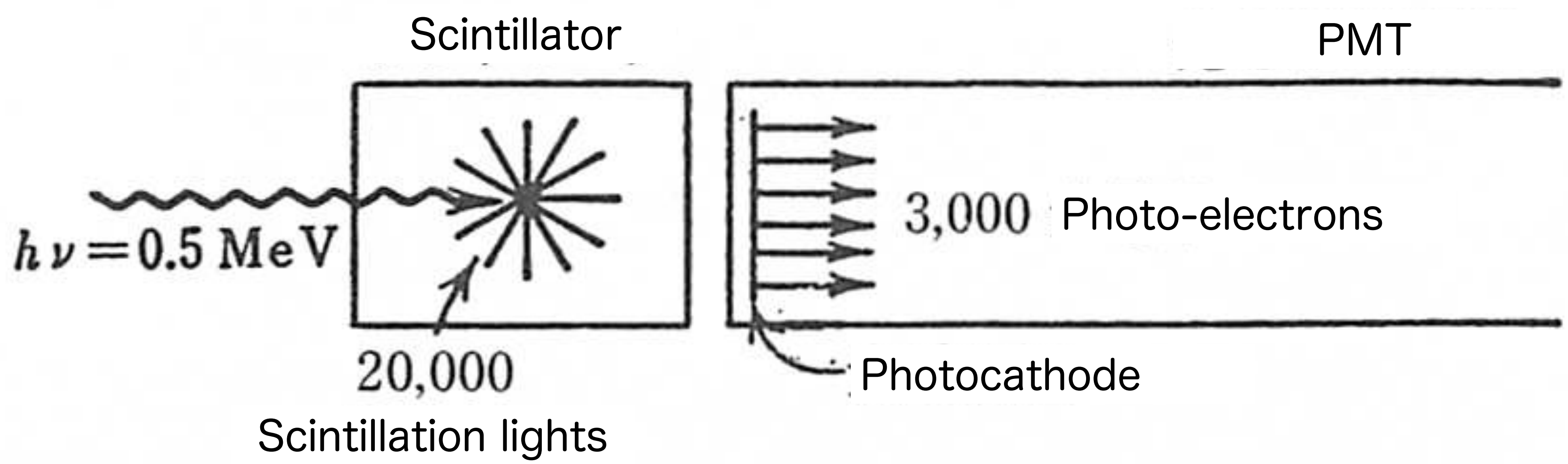
More applications in High Energy experiments

Photo-detector application in High Energy Physics

- Popular application of photo-detectors in High Energy Physics experiments are
  - Calorimeter
    - Measure the energy of particles (especially electrons and photons)
  - Trigger and/or TOF (Time-of-flight) counter
    - Measure the timing of a particle passing the counter

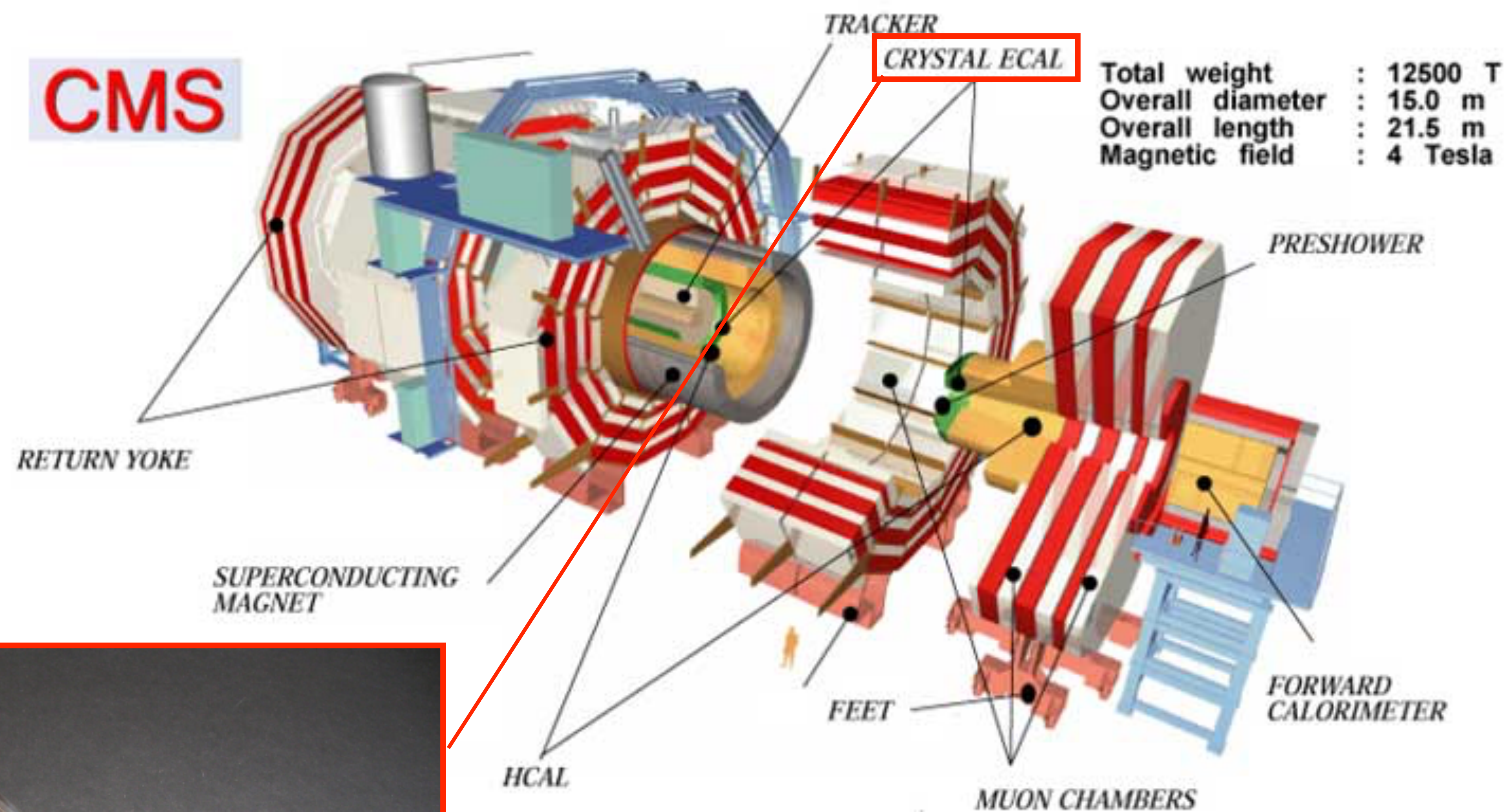
  - Scintillation light detected by a photo-sensor.

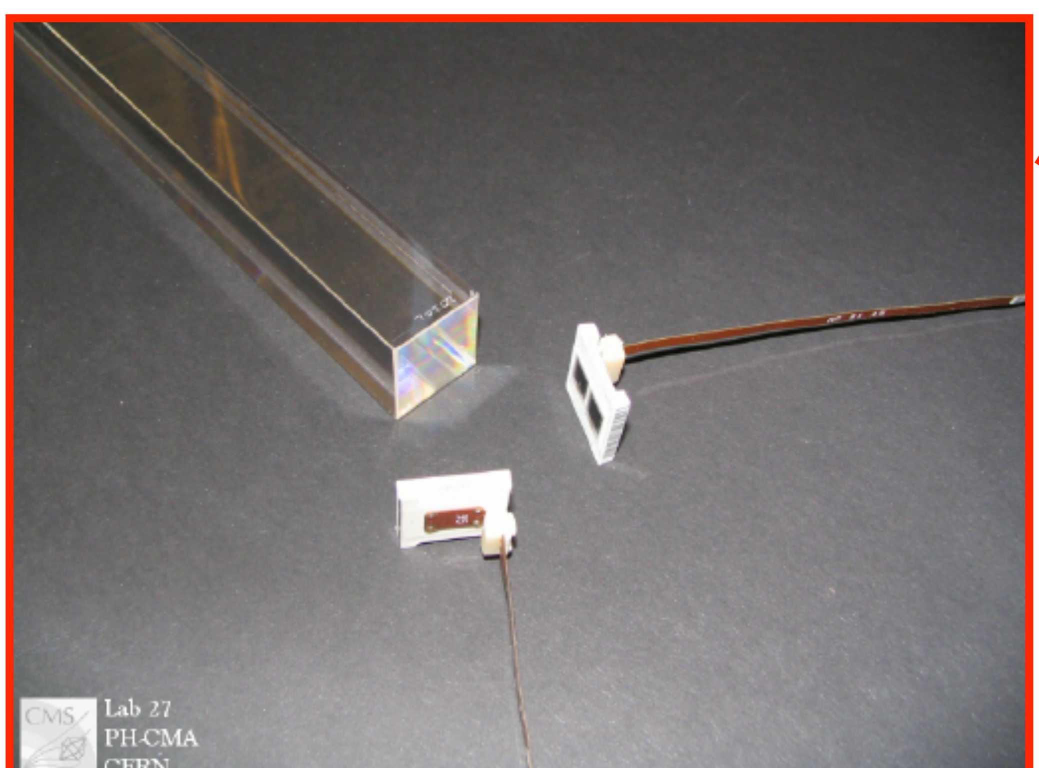
Scintillator + PMT



- Example
  - Incident energy of γ ray: 0.5 MeV
  - The number of scintillation lights: 20,000
  - Quantum efficiency (+light collection in a crystal): 15%
  - Energy resoultion
    - √(3000)÷3000 = 0.018 (1.8%)

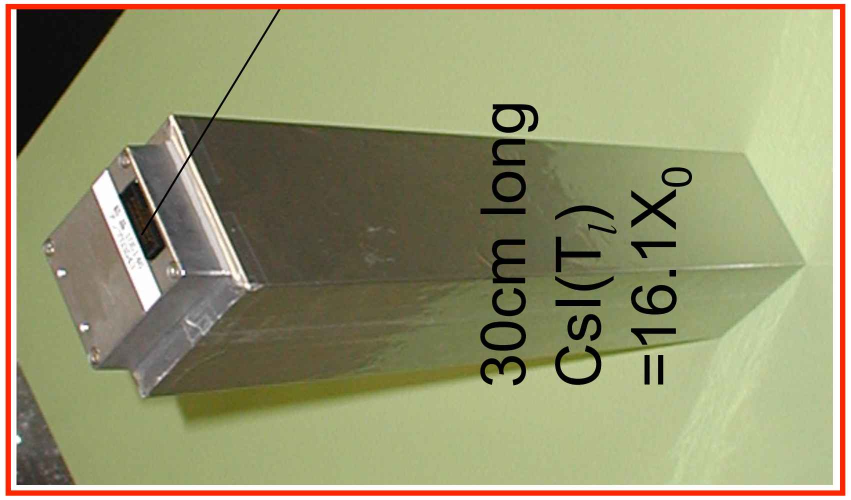
Higgs and New Physics in pp collisions





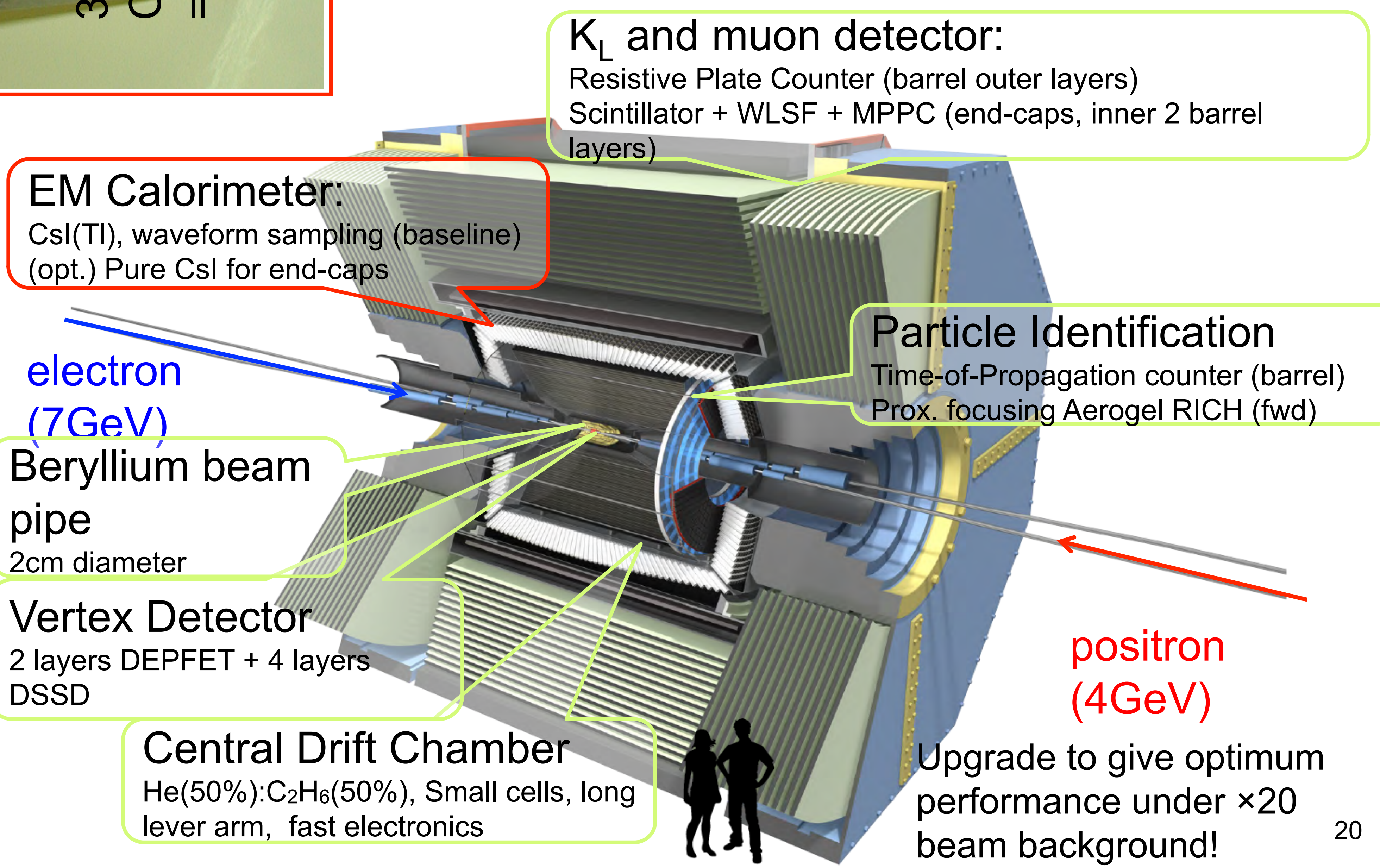
APD (Avalanch-Photo-Diode)

B Physics in e^+e^- collisions



PD (PIN-Photo-Diode)

Belle II Detector



20

Semiconductor photon detector

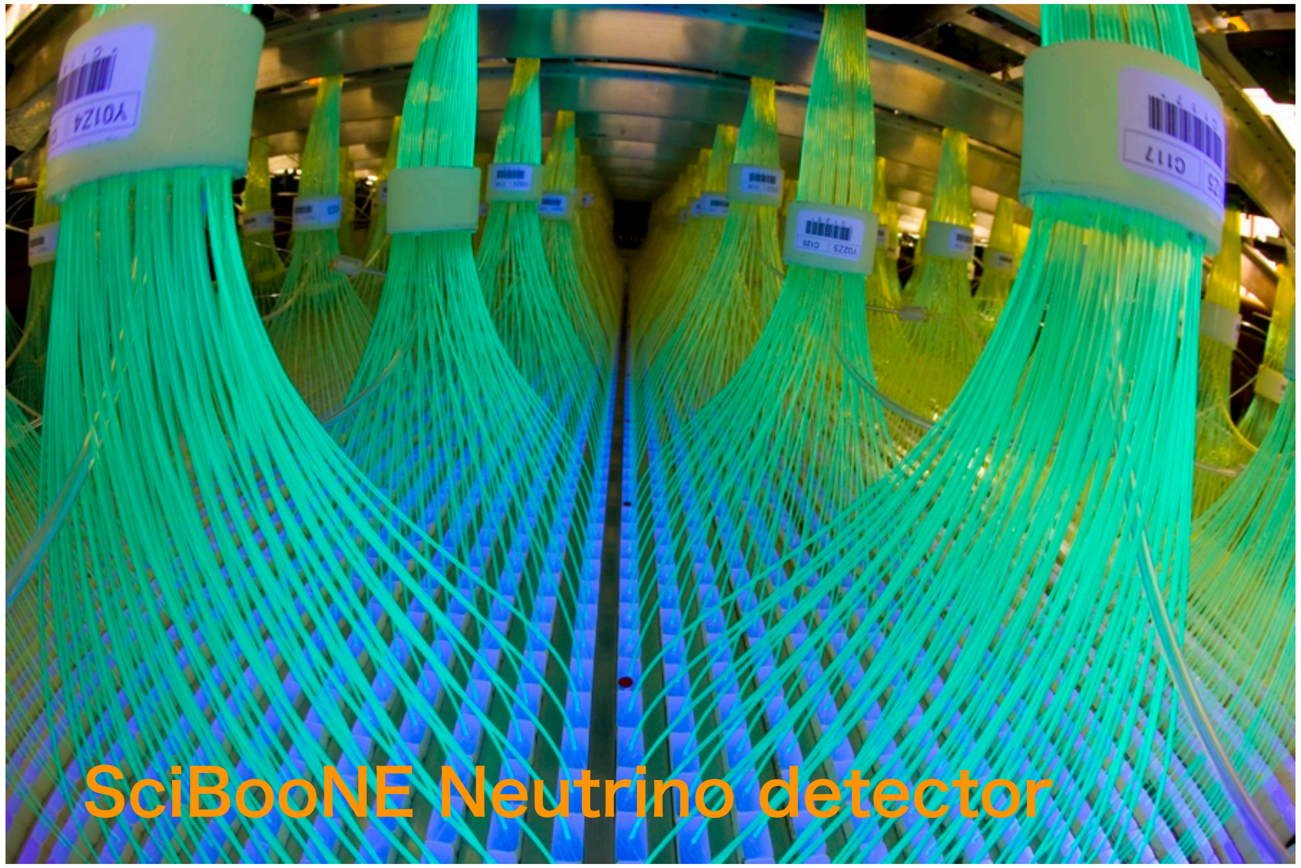
Hamamatsu HP: “What is MPPC?”

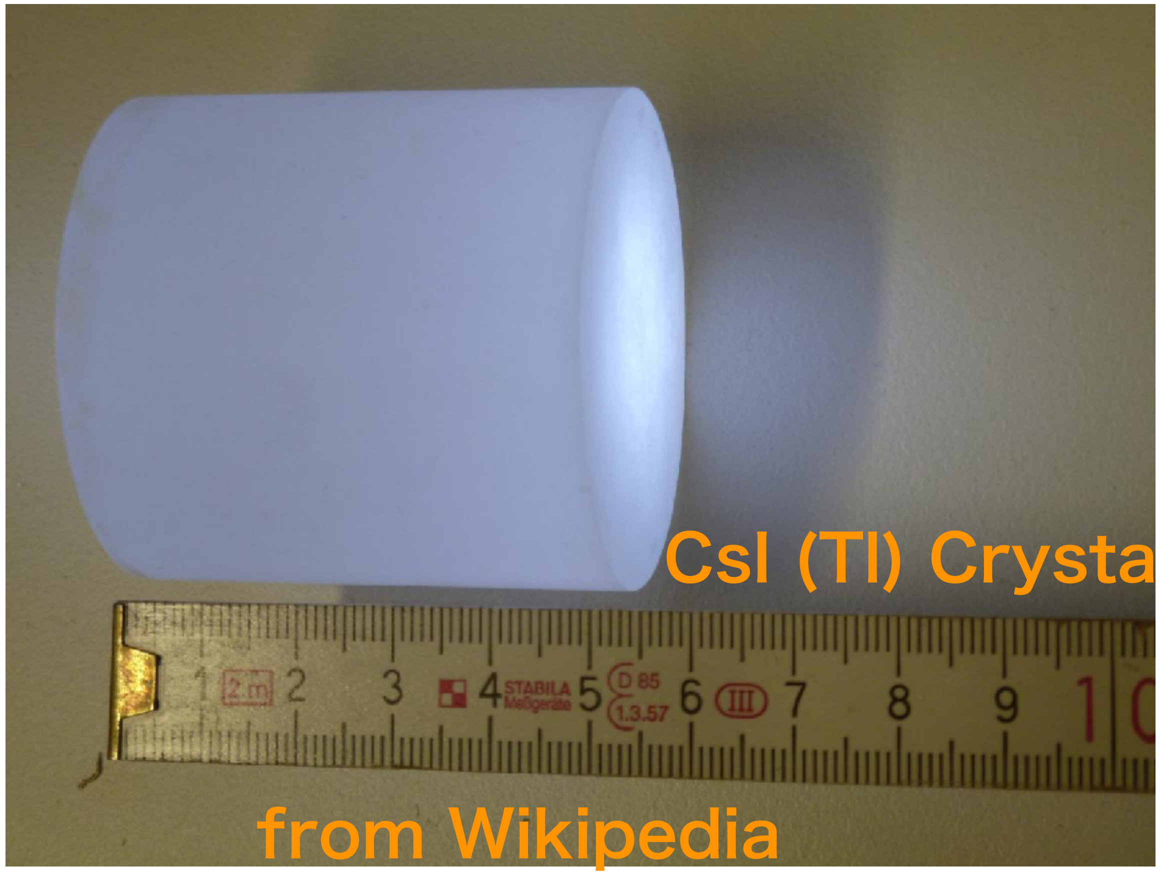
https://www.hamamatsu.com/jp/ja/product/optical-sensors/mppc/what_is_mppc/index.html

	PD	APD	MPPC	PMT
	Photo-diode	Avalanche photo-diode	Multi-channel Giger mode photo-diode	Photomultiplire tube
gain	1	10^2	~10^6	~10^7
sensitivity	low	medium	high	high
Voltage applied	5V	100~500 V	30~60 V	800~1000V
Sensitive area	small	small	small-medium	large
Electronics	complicated	complicated	simple	simple
Noise	low	medium	medium	low
Uniformity	◎	○	◎	○
Fast response	○	○	◎	○
Energy resolution	good	not bad	good	good
Temperature dep.	low	high	medium	high
Outer-light dep.	○	○	○	×
Magneticfield dep.	○	○	○	×
Compact & light	○	○	○	×

Type of scintillators

- Organic Scintillator
  - The scintillation photons are emitted from transitions made by the free valence electrons of the molecules. Scintillation material can be in the states of solid, liquid and gas.
- Inorganic Crystal scintillator
  - The scintillation photons are emitted based on the electron band structure of inorganic crystals.





Organic Scintillator

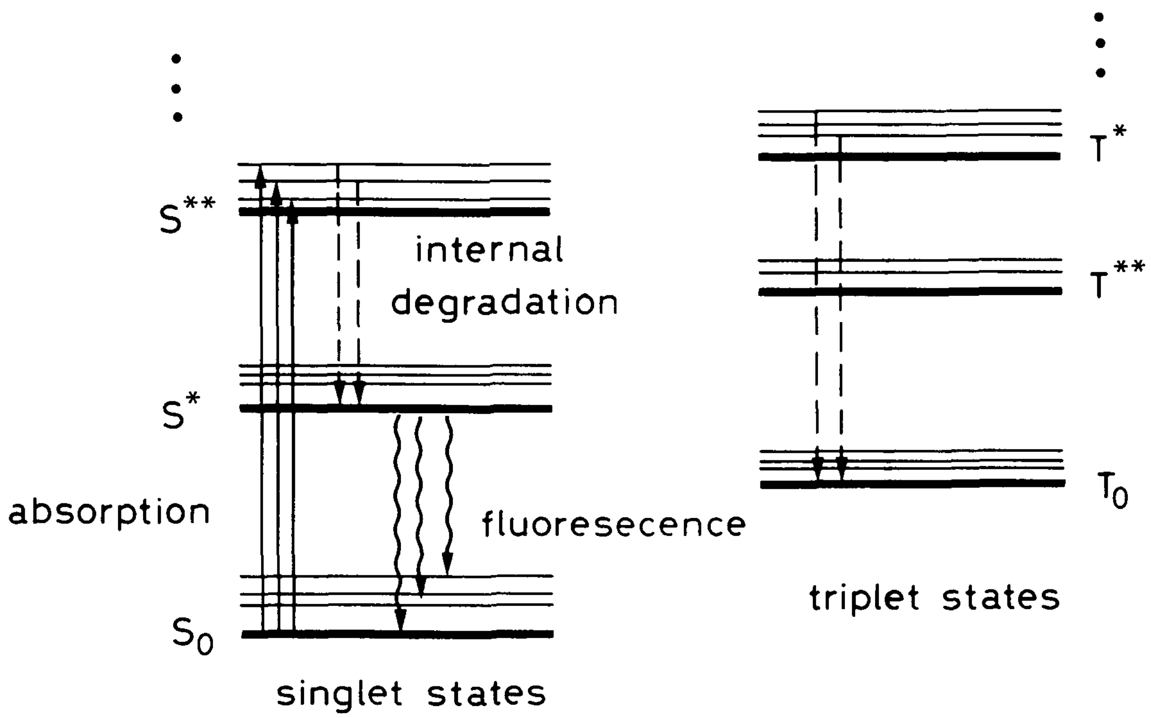


Fig. 7.4. Energy level diagram of an organic scintillator molecule. For clarity, the singlet states (denoted by *S*) are separated from the triplet states (denoted by *T*)

Inorganic Crystal Scintillator

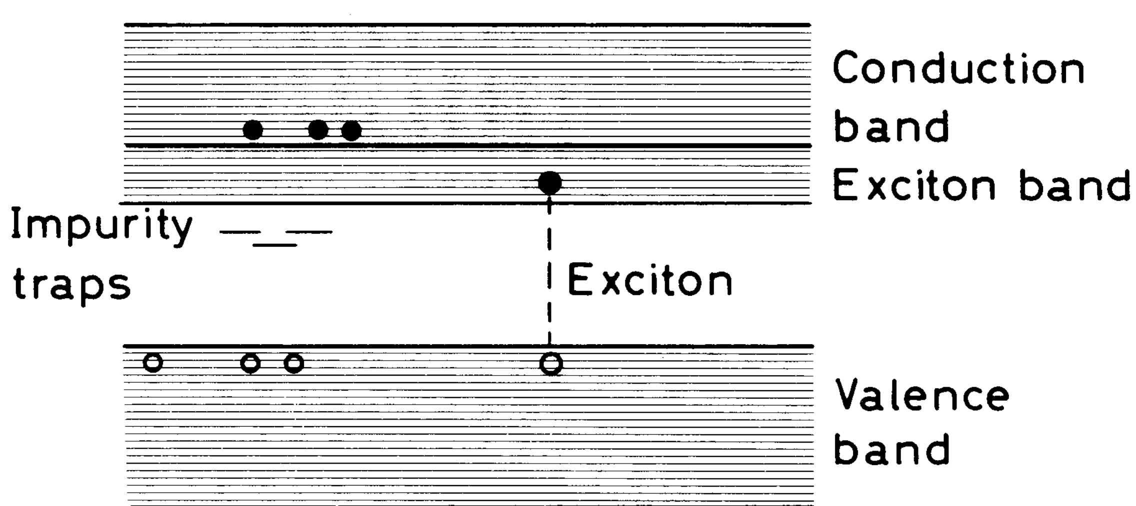
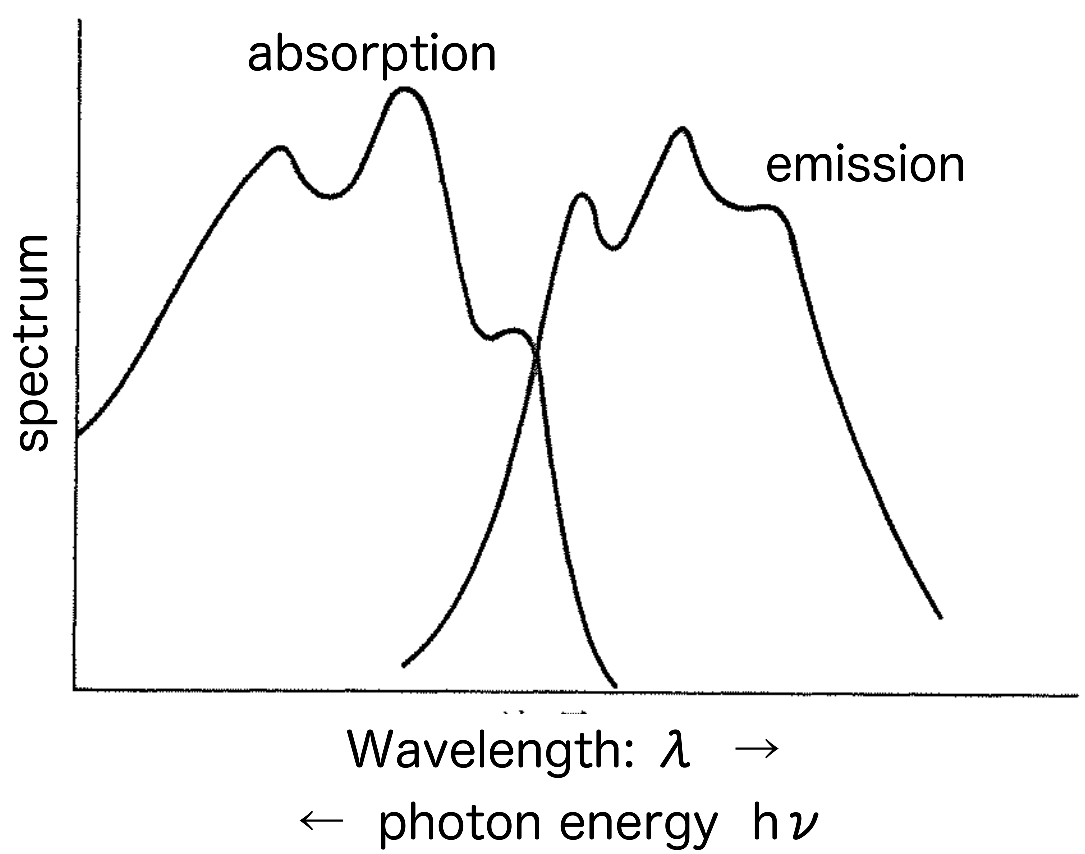


Fig. 7.7. Electronic band structure of inorganic crystals. Besides the formation of free electrons and holes, loosely coupled electron-hole pairs known as excitons are formed. Excitons can migrate through the crystal and be captured by impurity centers

Organic Scintillator

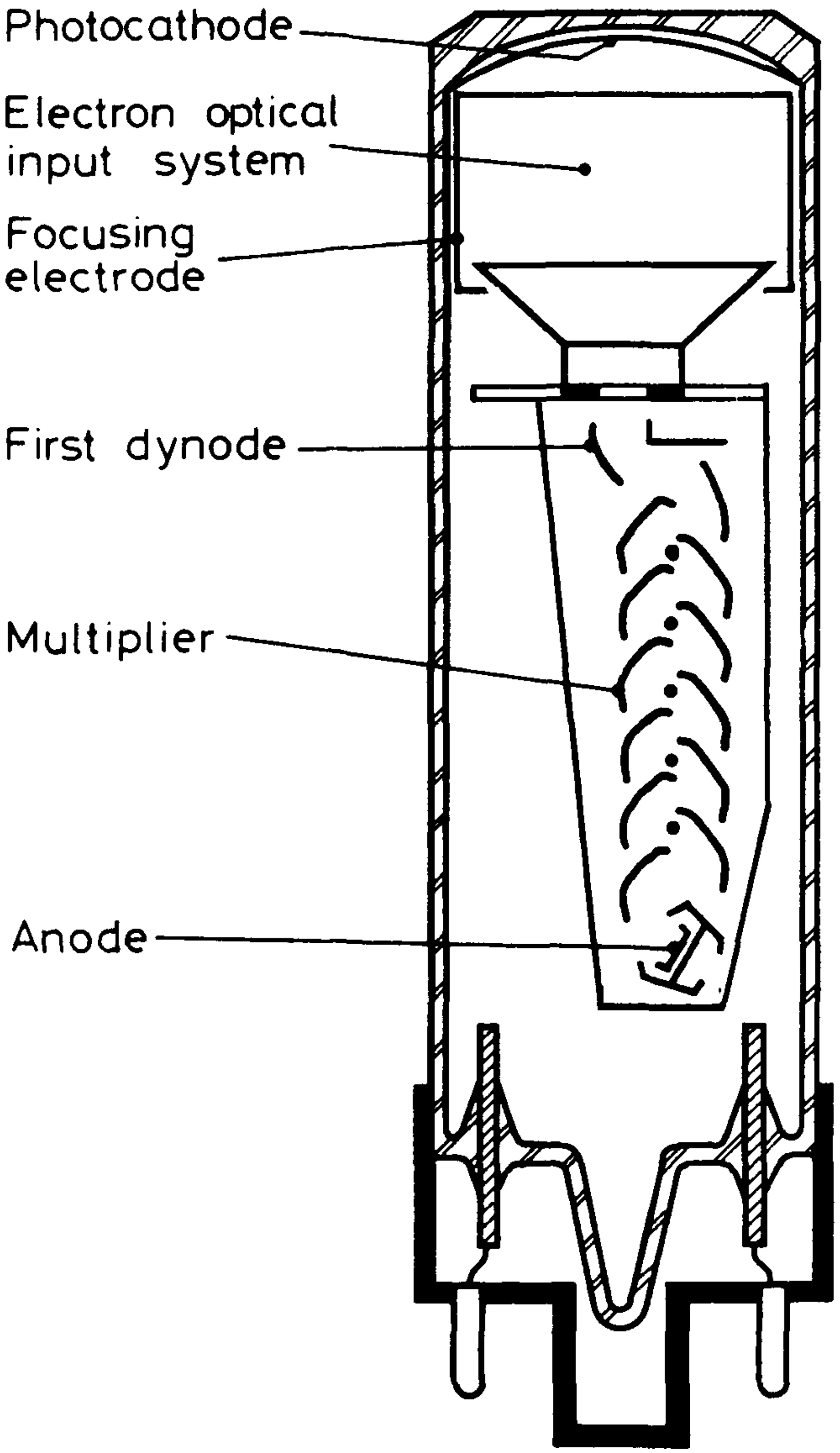
- Scintillation lights are little absorbed（transparent)
- The emission time of scintillation lights (the lifetime of excited states) is fast [2~3 nsec].



Organic Scintillator

- Scintillation efficiency
  - The efficiency is getting low if the excited energy is not used for the emission of lights, but heat. The process is called as quenching. (Example) Quenching occurs in the liquid scintillator with Oxygen.
- Solvent and Solute
  - The ionization energy seems to be absorbed mainly by the solvent (and plastics) and then passed on to the scintillation solute. This transfer is quick and efficient. A typical scintillation solute is PBD, PPO and POPOP.
- Wave Length Shifter
  - The secondary solute such as POPOP is added with the first solute of PBD for its wavelength shifting properties. The primary scintillation photons are absorbed by the secondary solute and emits the photons of longer wavelength that are more transparent and more matched to the sensitivity of photon-sensors.

Function of Photomultiplier

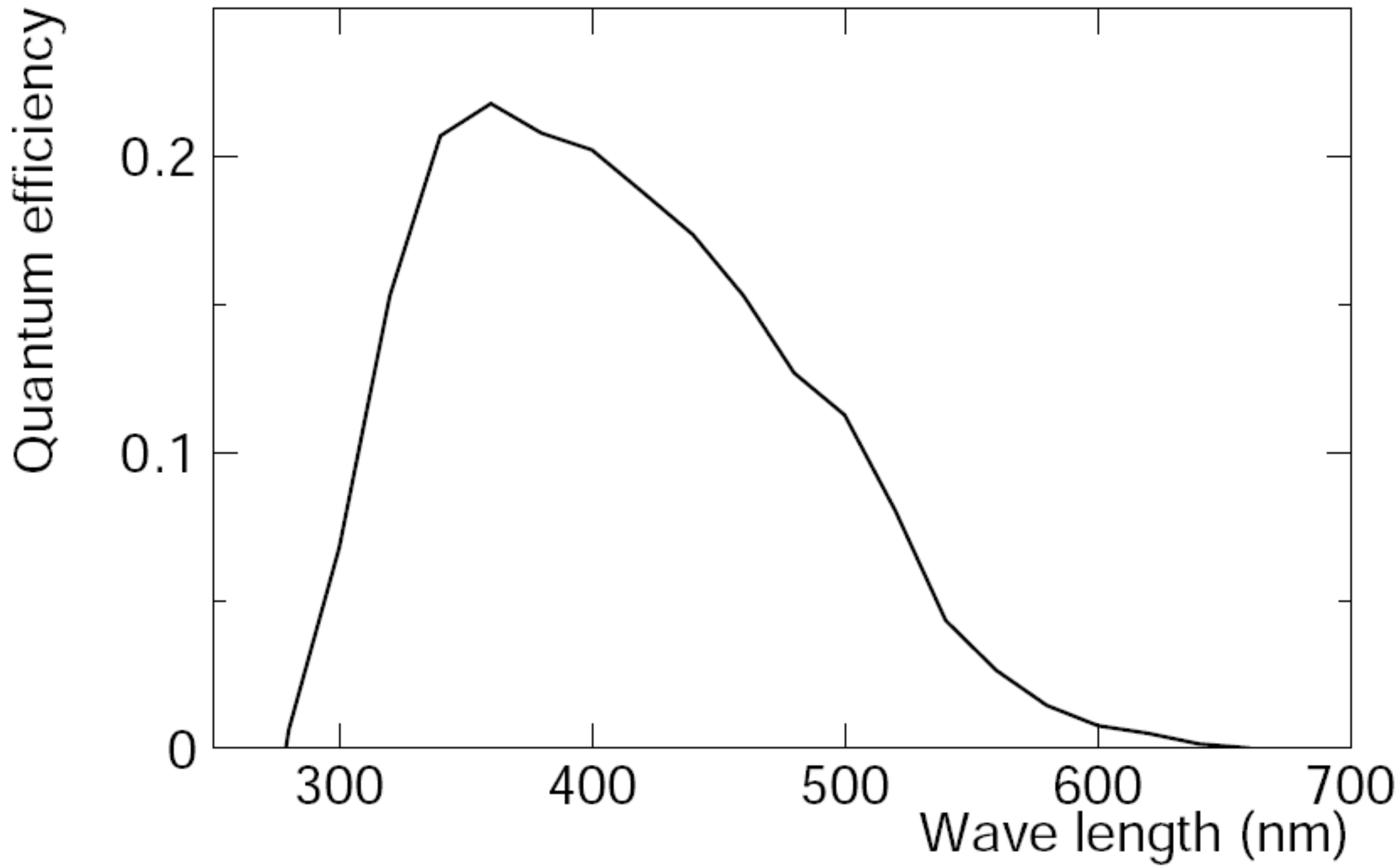


- A photon enters the photocathode, and the photo-electron is emitted by photo-electric effect.
    - Quantum efficiency: 10~30% (typical)
- Inside vacuum
- The first photo-electron is focused into the first dynode.
- Voltage between dynodes is typically 100V or so
- With many dynodes, the number of electrons are multiplicated.
- A typical multiplication factor of one dynode is 2~3, but with 13 dynodes, the multiplication becomes 3^{13}~1,000,000.
- It is readout as an electronic signal.

QE of 20-inch PMT

Quantum Efficiency (QE)

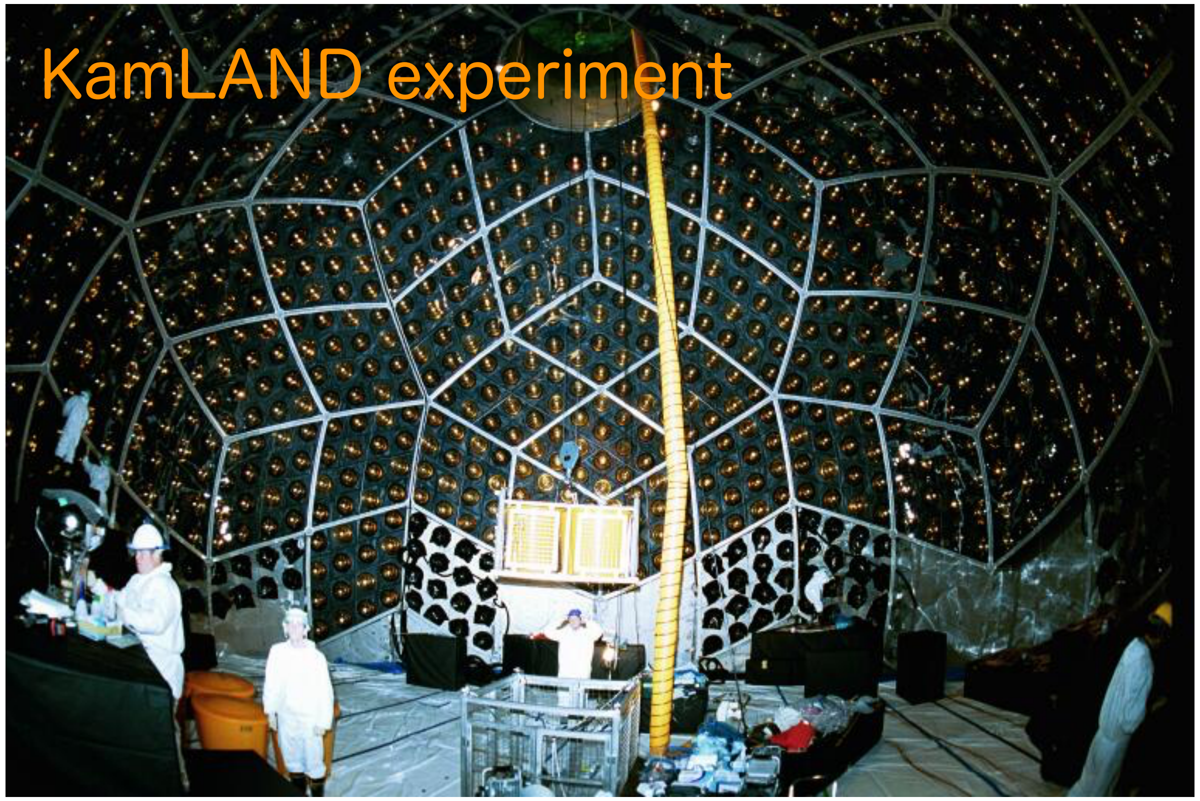
Provided by Hamamatsu Photonics K. K.

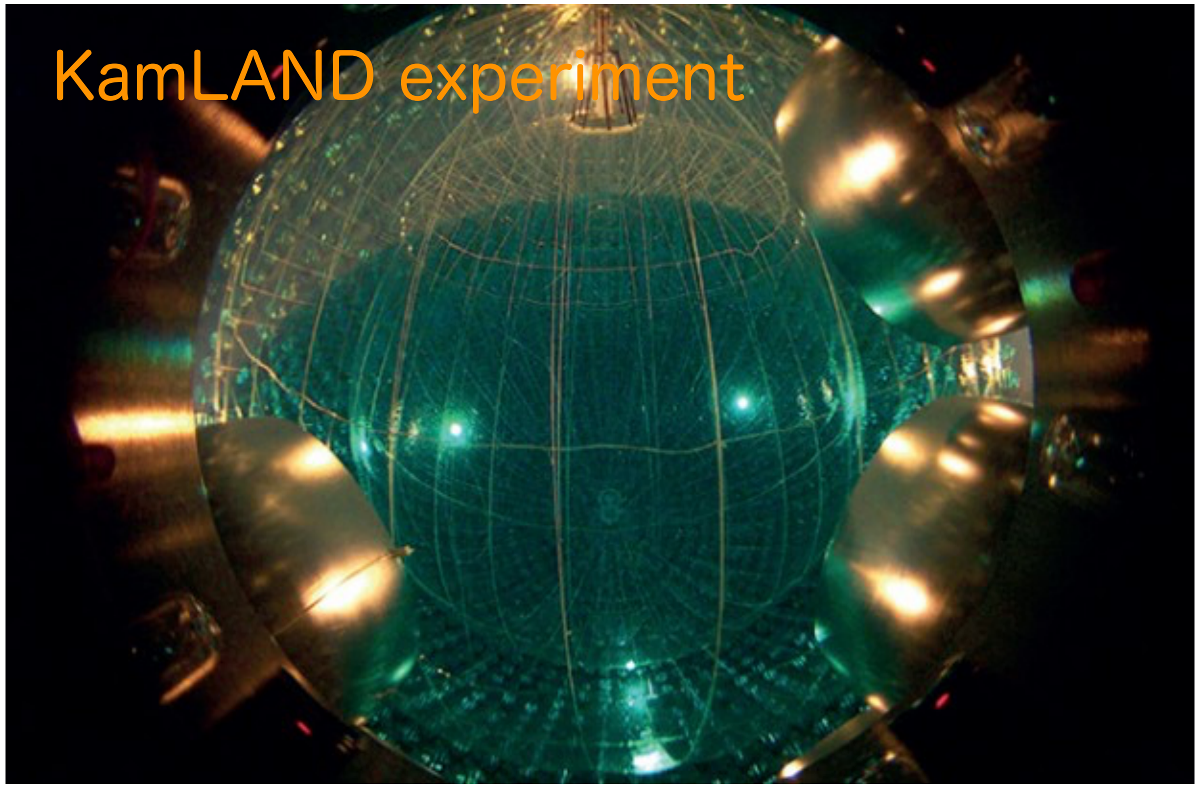


Note: Hyper-K PMT has x2 better QE+Collection eff.

Organic Scintillator

- Organic Crystal Scintillator: Anthracene ($C_{14}H_{10}$), etc..
- Plastic Scintillator
  - Very Flexible shape: Scintillator plate, Scintillator bar (T2K ND280/FGD), Scintillating Fibers (NINJA Tracker), etc..
- Organic Liquid Scintillator
  - KamLAND, Double Chooz, Daya Bay, NOvA, etc..





Summary

- Applications of photo-detector in particle physics experiments are introduced.
  - Neutrino detectors with PMT
    - Cherenkov light detection
  - Scintillator with PMT, MPPC, APD and PD
    - Calorimeter
    - Trigger and TOF counters
  - I skip MPPC and Tracking Neutrino detectors that were covered in the lectures by Dr. Son Cao and Prof. Jennifer Thomas.