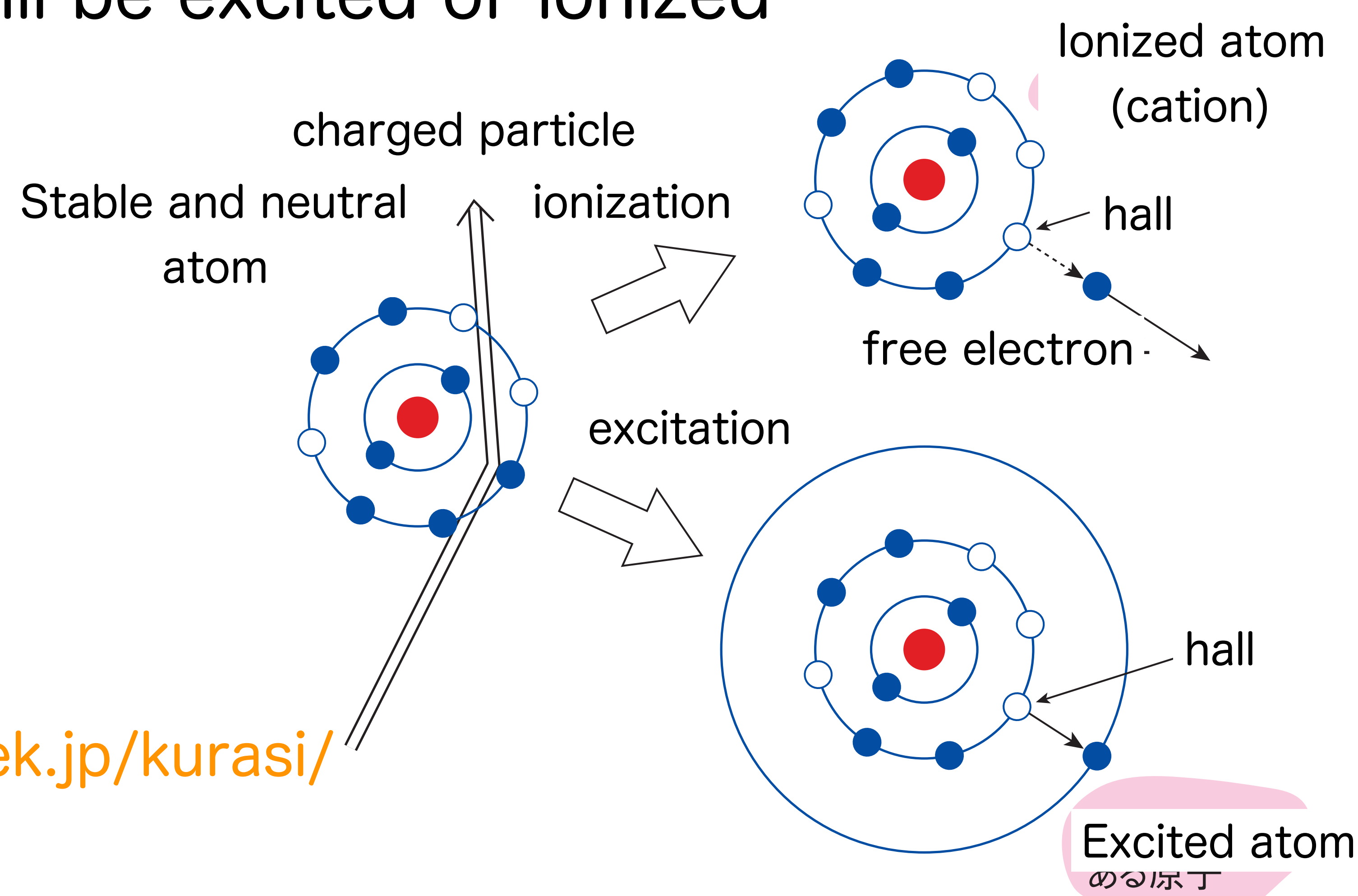
Measurement of a charged particle

How to detect a charged particle

- Please remember “Passage of Radiation through Matter”!
  - The Bethe-Bloch Formula

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

    - The charged particle interacts with an electron in an atom. The atom will be excited or ionized



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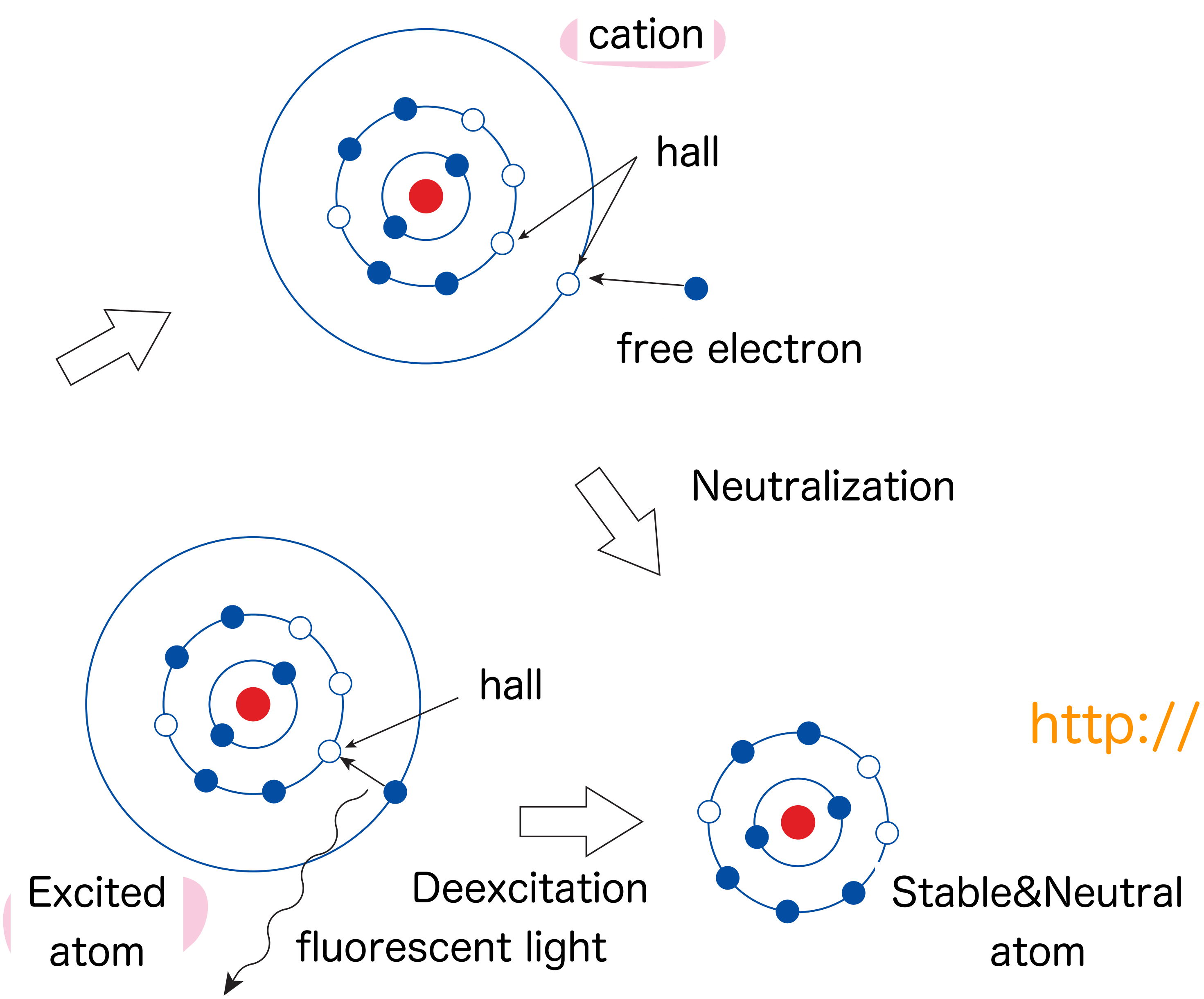
How to detect a charged particle

- Observe
  - the free electron after ionization (or cation)
  - the excited atom



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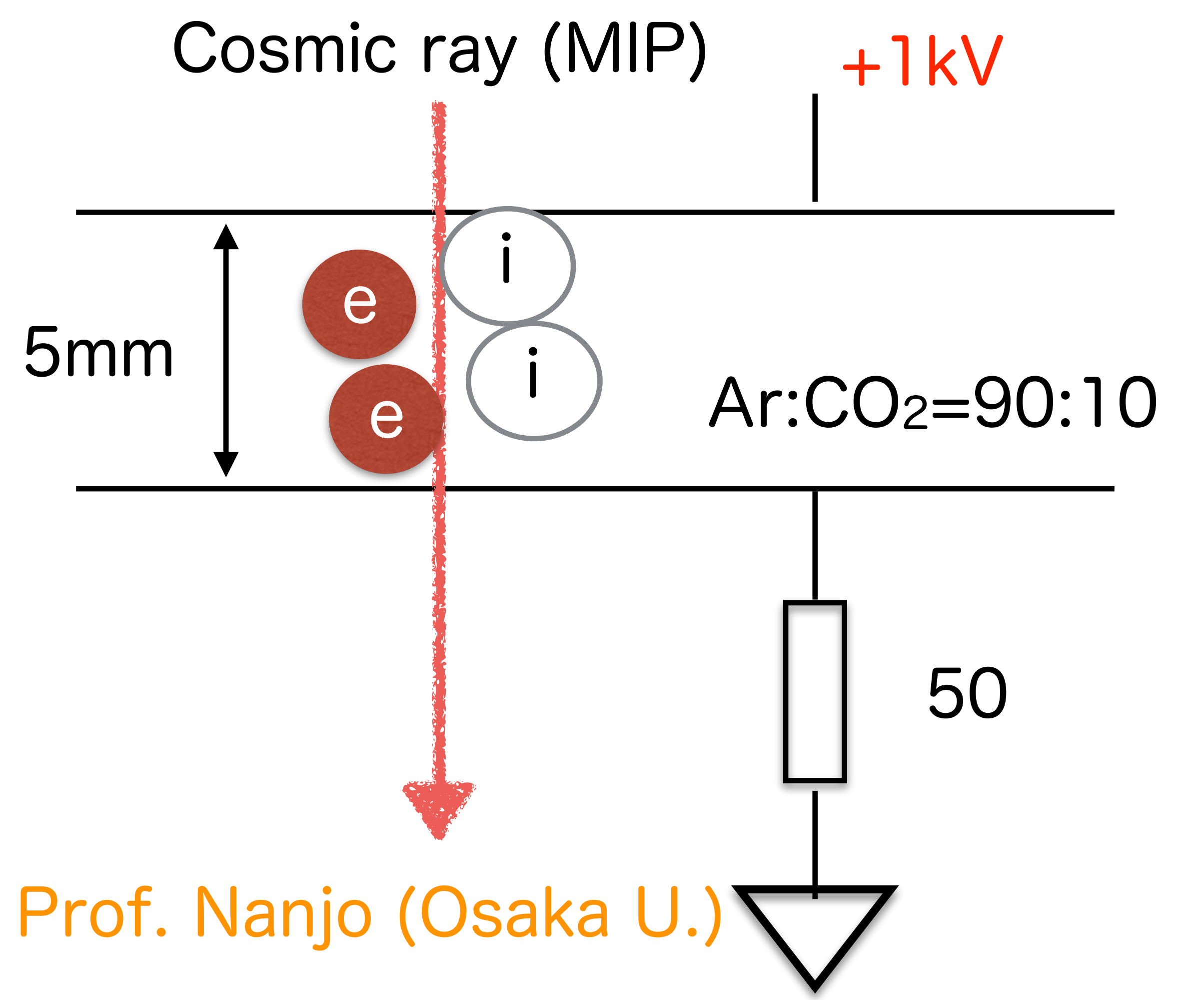
(1) Detection of a free electron (Cation) after Ionization

1. Gaseous Ionization detector with noble gas.
   1. Mean energy for ion-electron pair creation (W value)
      - ~26 eV for Ar (typically ~30 eV)
   2. Catch the electric signal when the electrons move to an electrode
   3. The signal of one electron is too small to be detected
      1. Need an amplification
   4. The amplification depends on the strength of electric field

Table 6.1. Excitation and ionization characteristics of various gases

	Excitation potential [eV]	Ionization potential [eV]	Mean energy for ion-electron pair creation [eV]
H_2	10.8	15.4	37
He	19.8	24.6	41
N_2	8.1	15.5	35
O_2	7.9	12.2	31
Ne	16.6	21.6	36
Ar	11.6	15.8	26
Kr	10.0	14.0	24
Xe	8.4	12.1	22
CO_2	10.0	13.7	33
CH_4		13.1	28
C_4H_{10}		10.8	23



From Prof. Nanjo (Osaka U.)

(1) Detection of a free electron（Cation）after Ionization

[Q1] How much is the energy deposit in 5mm thick gas?

[A1] E〜2MeV/cm × 0.5[cm] × 0.001 [g/cm^2] = 1 keV

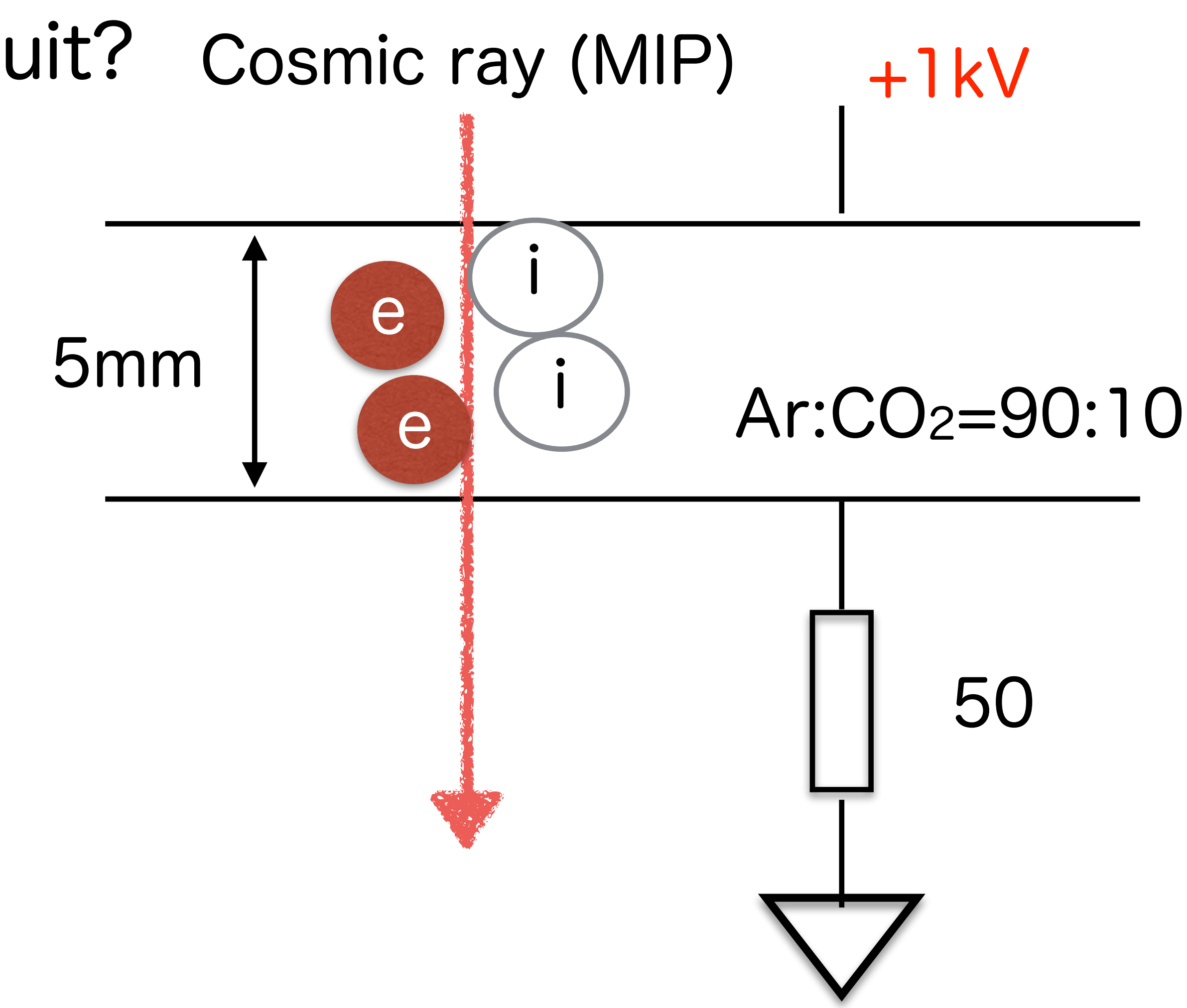
[Q2] How many ion-electron pairs are created?

[A2] E/W = 1000/26 ~ 40 paris

[Q3] How much current flows in the circuit?

The electron drift velocity is assumed

to be 2cm/μs



(1) Detection of a free electron (Cation) after Ionization

[A3]

(1) The electric field moves an electron and an ion to the electrode.

(2) The current flows to the condenser to keep the electric field.

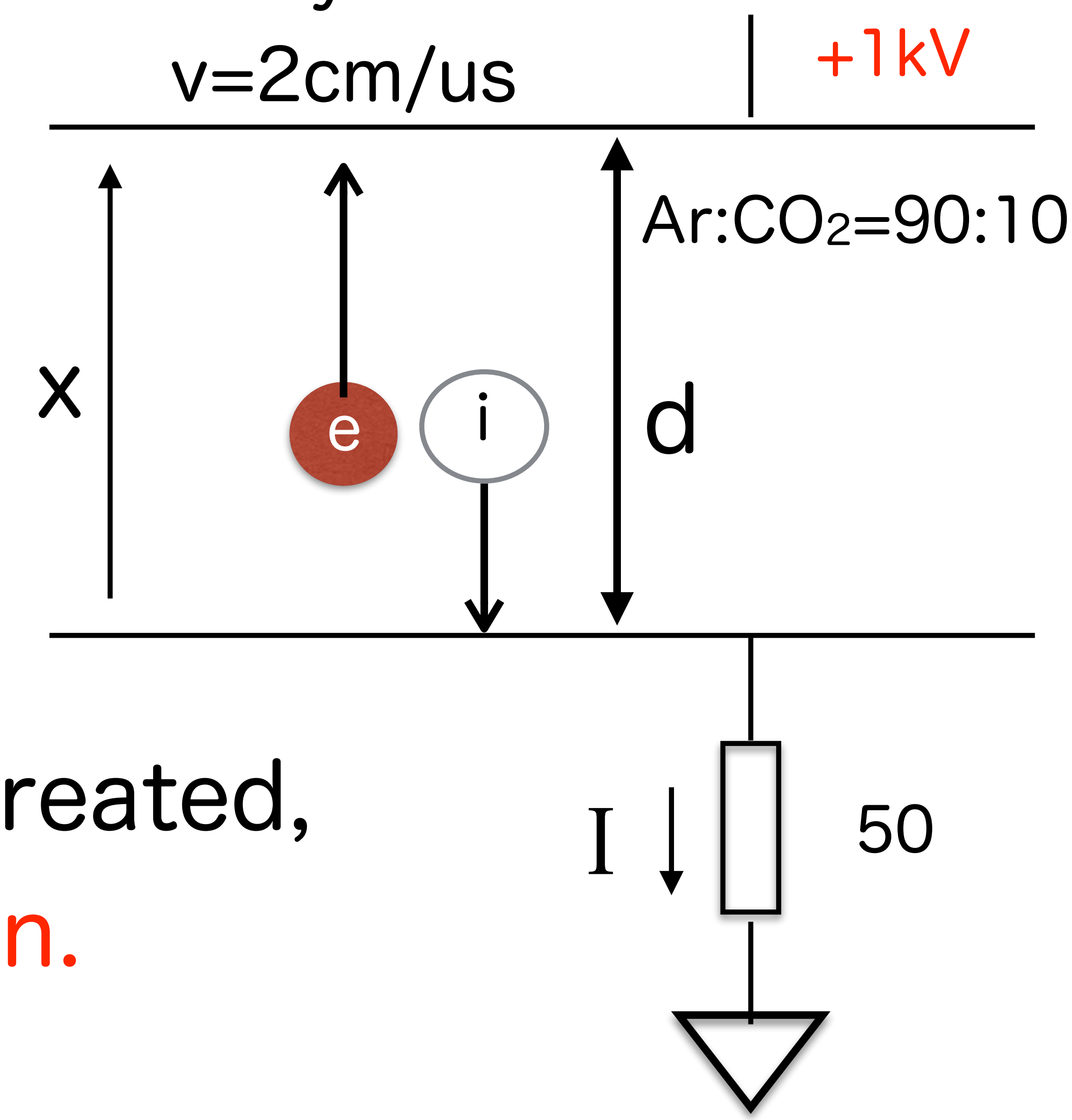
- For a single ion-electron pair,

$$-eE \times dx = V dQ$$

$$I = dQ/dt = -eEv/V = -\frac{ev}{d}$$

I=0.6pA continues for the maximum period of 250ns.

The velocity of electron

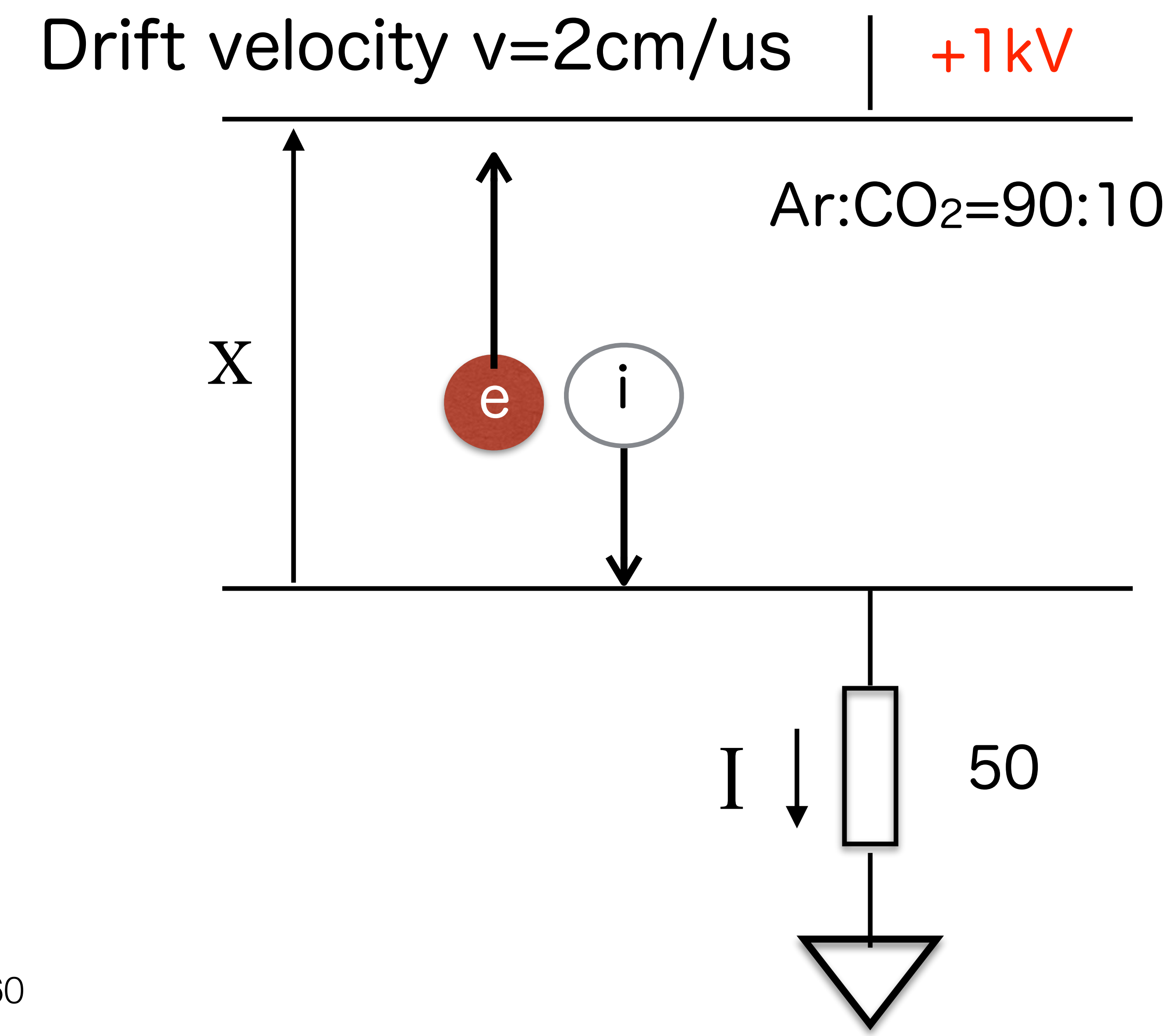


- If 40 ion-electron pairs are created, I=24pA (24×10^{-12}A) is drawn.

(1) Detection of a free electron (Cation) after Ionization

[Remember] The source of current flow is the movement of electric charge!

- [Q] What moves the electric charges?
  - [A] The energy stored in the detector provided by the High-Voltage module.

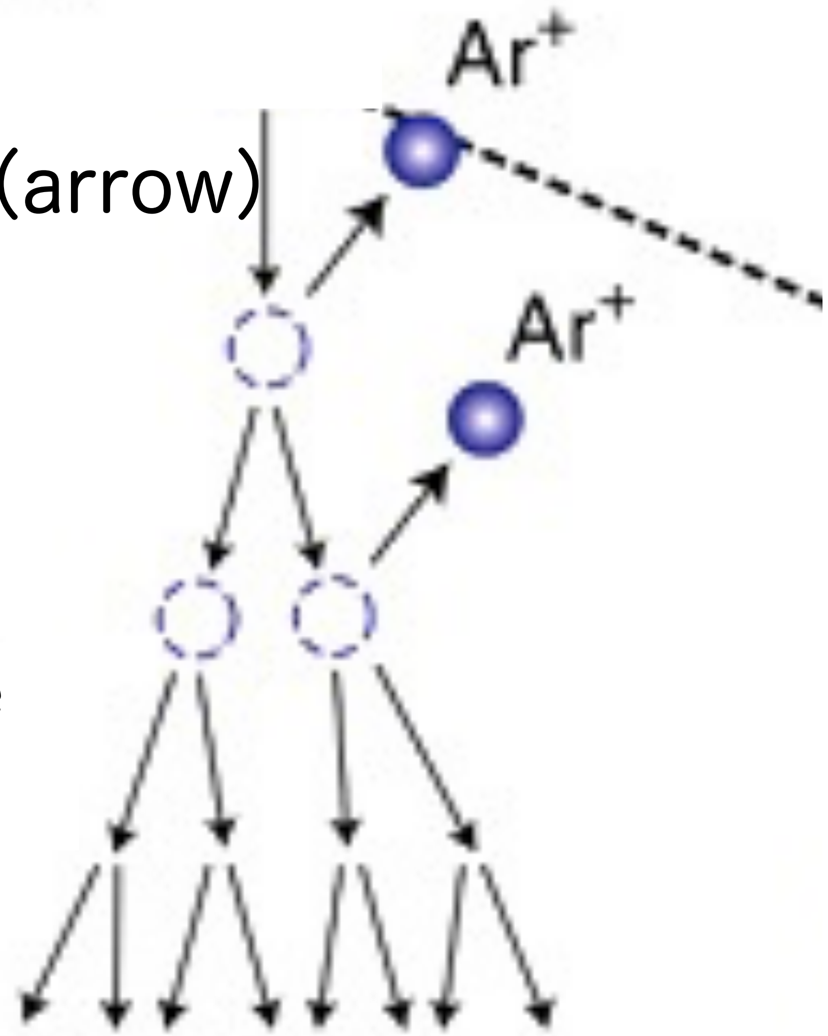


Amplification → Avalanche Multiplication

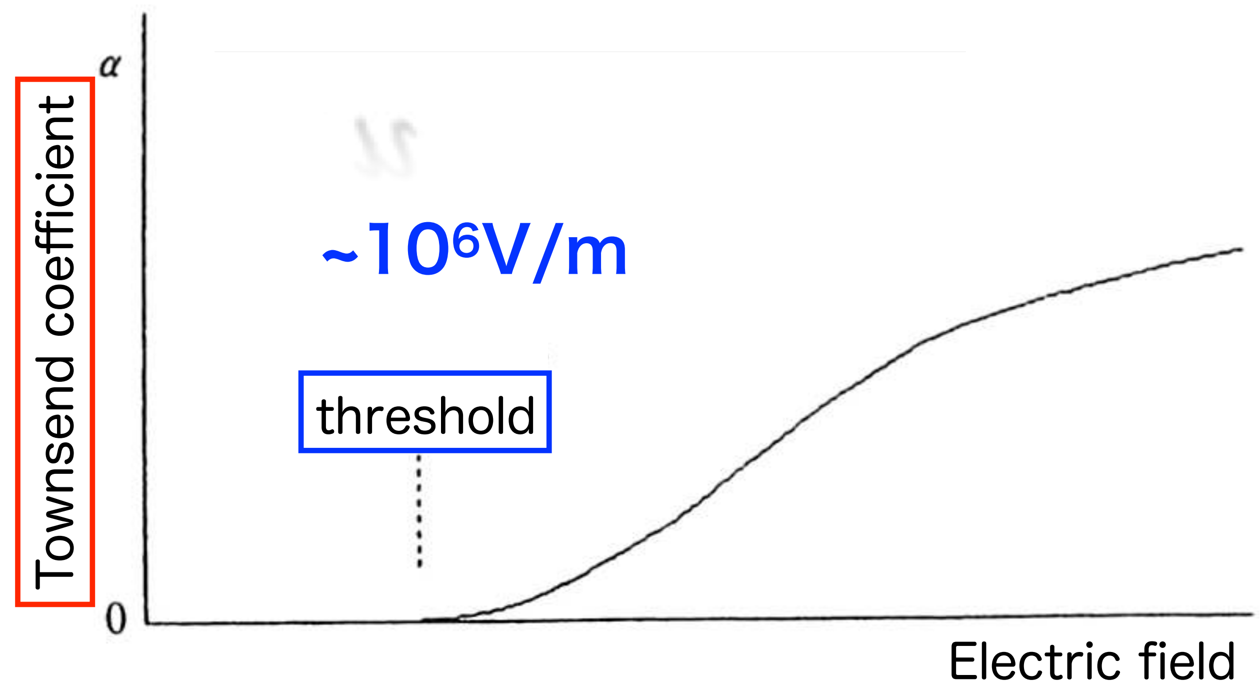
Amplification → Avalanche formation

$$\frac{dn}{n} = \alpha \, dx \qquad (6.1)$$

Electron (arrow)



Avalanche formation



Multiplication in gas

- ～1 : Ionization chamber (no multiplication)
- 10^3～10^5: Proportional counter（The signal is proportional to the number of ion-electron pairs created in the beginning.)
- >10^7: Geiger-Muller counter（The signal size plateaus because of discharge caused by avalanches spread out over all area of the detector. It can be used to count the number of incident particles.)

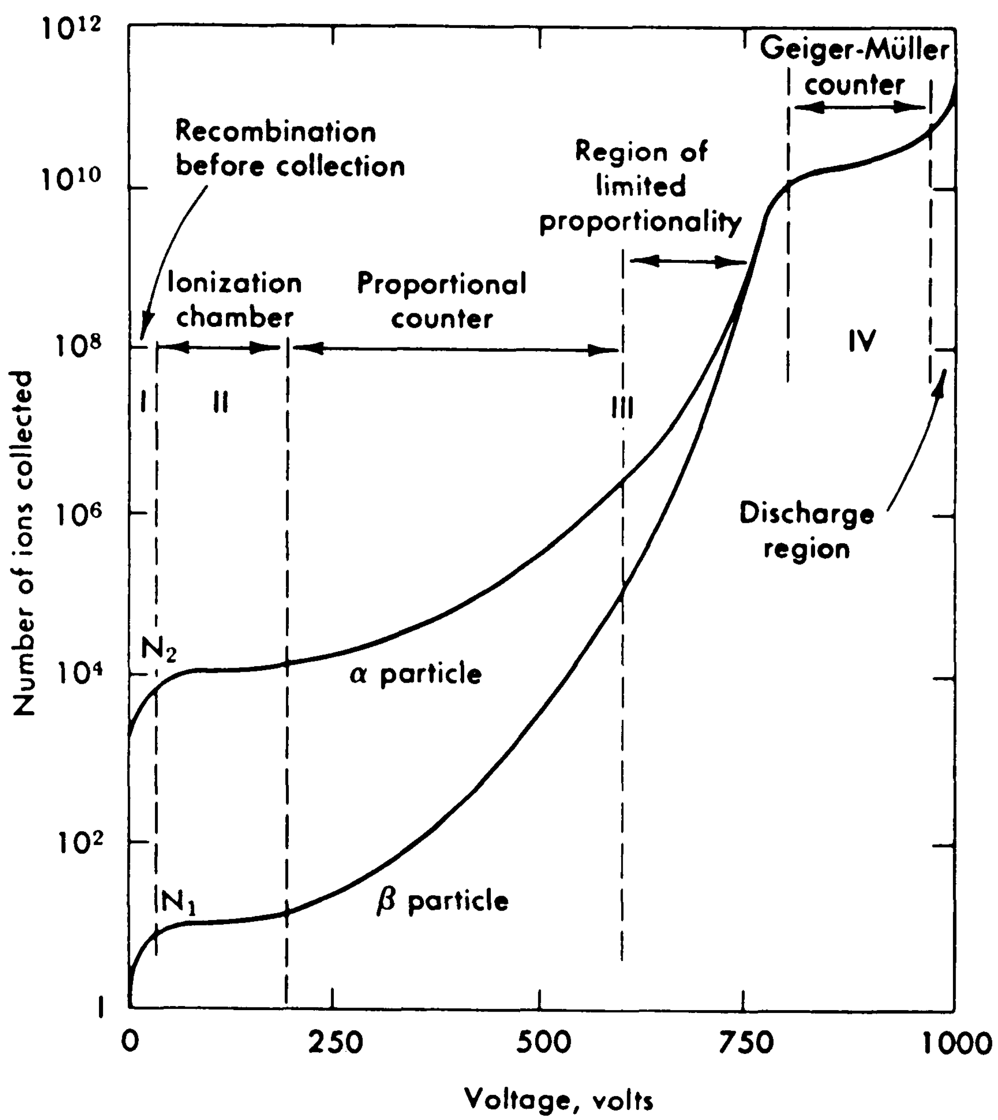


Fig. 6.2. Number of ions collected versus applied voltage in a single wire gas chamber (from *Melissinos* [6.1])

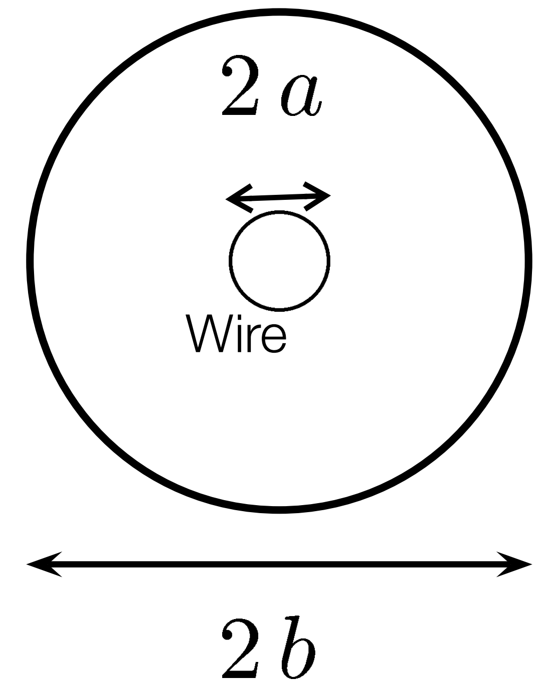
Cylindrical Proportional Counter

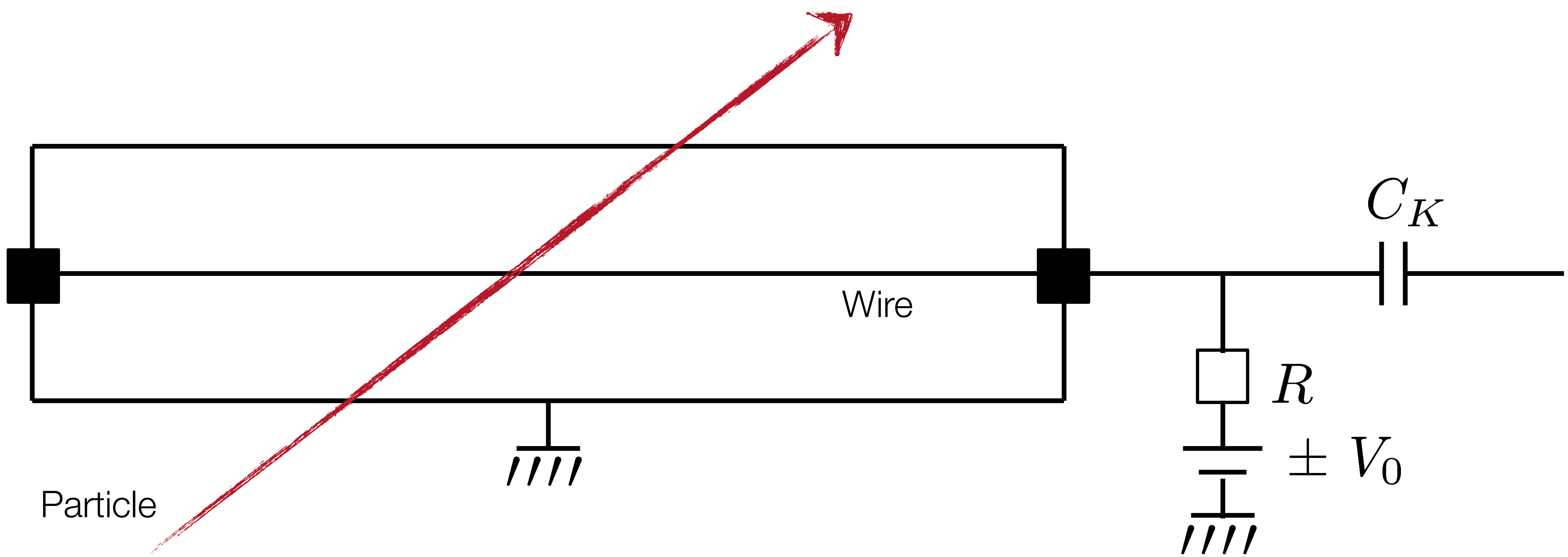
Electric field : $|\vec{E}| = \frac{\lambda}{2\pi\epsilon_0}\frac{1}{r}$

$\lambda = Q/L$ charge density

Voltage : $V_0 = \frac{\lambda}{2\pi\epsilon_0}\ln\frac{b}{a} = \frac{\lambda}{C}$

Capacitance : [unit length] $C = \frac{2\pi\epsilon_0}{\ln\frac{b}{a}}$ [F/m]





by Masaya Ishino (ICEPP, U. of Tokyo)

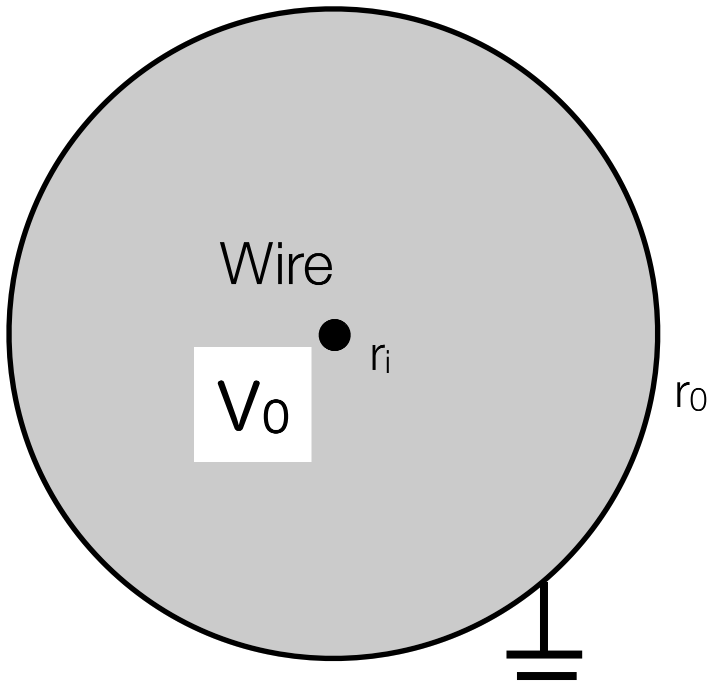
Cylindrical Proportional Counter

Thin wire ⇒ High electric field around the wire

(exercise of Electromagnetism)

$$\mathbf{E} = \frac{Q/L}{2\pi\epsilon_0} \cdot \frac{1}{r}$$

$$V_0 = \int_{r_i}^{r_0} \mathbf{E} \cdot dr = \frac{Q/L}{2\pi\epsilon_0} \cdot ln(\frac{r_0}{r_i}) \longrightarrow \frac{Q/L}{2\pi\epsilon_0} = \frac{V_0}{ln(\frac{r_0}{r_i})}$$



When an electron moves from r_1 to r_2, the energy obtained from the electric field

$$\Delta T_{kin} = e\Delta V = e\int_{r_1}^{r_2} \mathbf{E}(r)dr$$

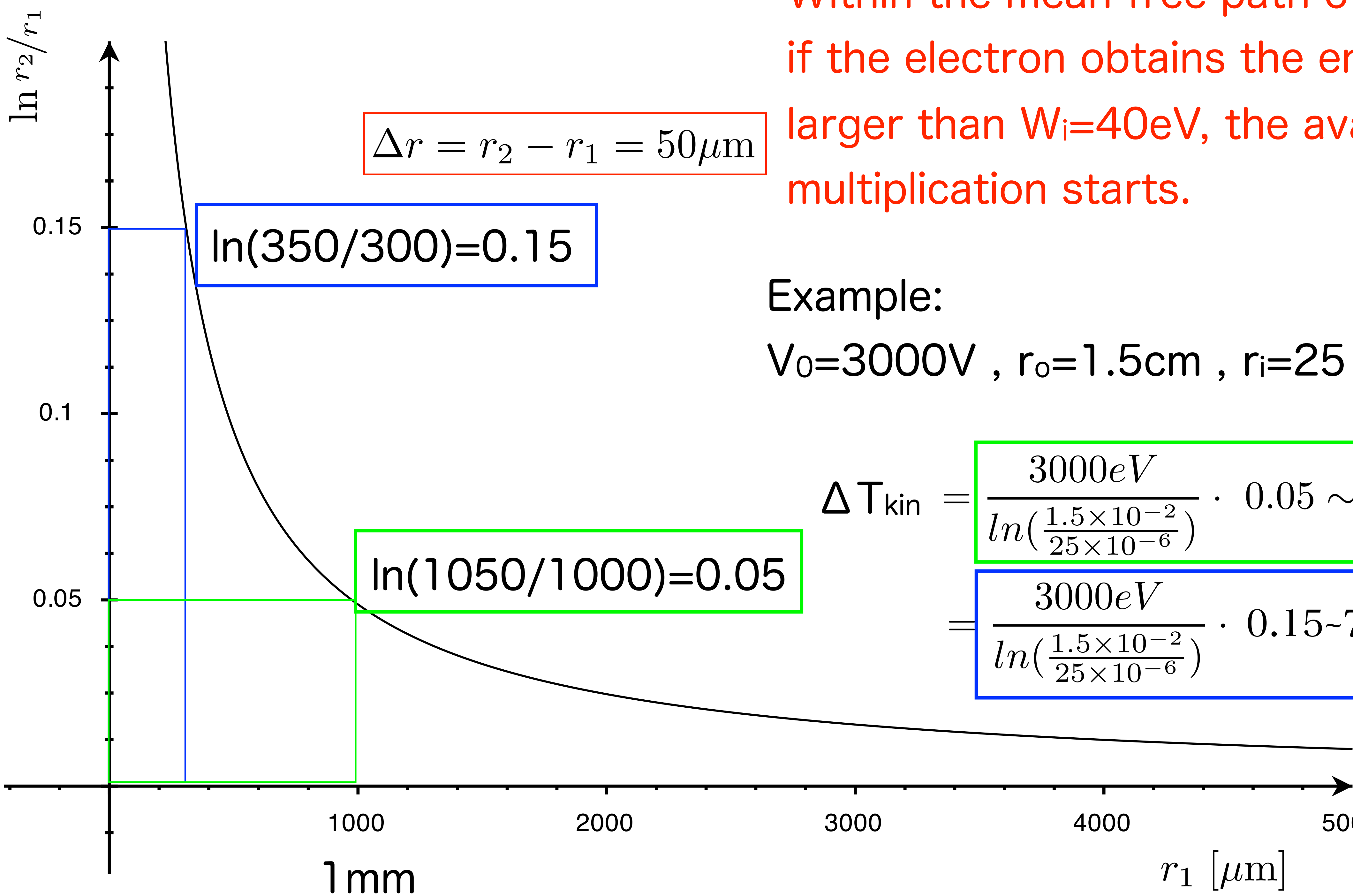
$$= \frac{eV_0}{ln(\frac{r_0}{r_i})} \int_{r_1}^{r_2} \frac{1}{r} dr$$

$$= \frac{eV_0}{ln(\frac{r_0}{r_i})} \cdot ln(\frac{r_2}{r_1})$$

When the energy obtained is bigger than W_i in a short distance than the mean free path. The avalanche multiplication starts

by Masaya Ishino (ICEPP, U. of Tokyo)

Cylindrical Proportional Counter



Within the mean free path of 50μm, if the electron obtains the energy larger than W_i=40eV, the avalanche multiplication starts.

Example:

V_0=3000V , r_o=1.5cm , r_i=25μm

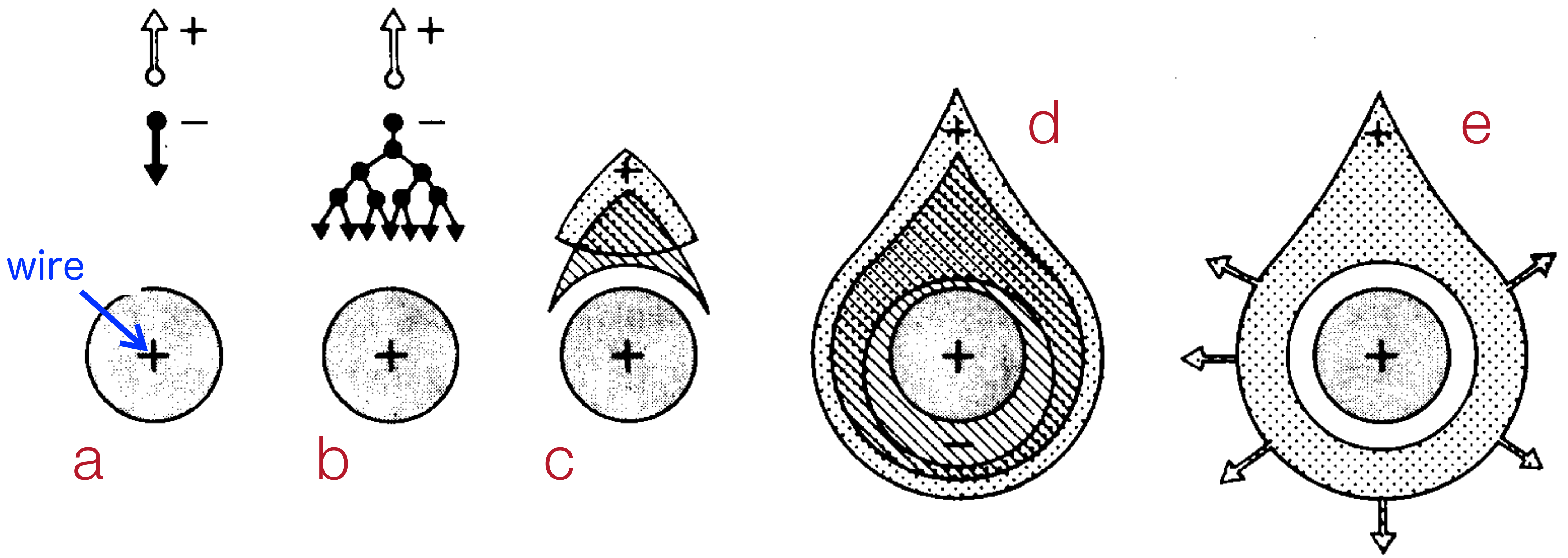
$$\Delta T_{kin} = \frac{3000eV}{ln(\frac{1.5\times10^{-2}}{25\times10^{-6}})} \cdot 0.05 \sim 24eV$$

$$= \frac{3000eV}{ln(\frac{1.5\times10^{-2}}{25\times10^{-6}})} \cdot 0.15\text{~}72\text{eV}$$

When the electron reaches near (~300μm) the wire, the avalanche starts

by Masaya Ishino (ICEPP, U. of Tokyo)

Time evolution of the avalanche



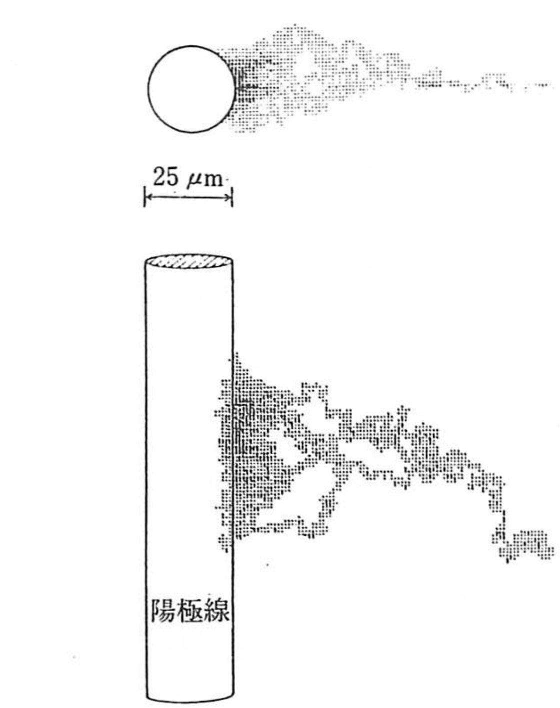


図 6.4 モンテカルロ計算で模擬した 1 個の電子によって誘起された電子なだれの直交 2 方向で示した図．影の部分の濃淡は電子なだれで形成された電子の濃度を示す（Matoba ほか[3] による）

(a)： the electron is forced to the wire

(b)： Near the wire, E is large enough to generate avalanche

(c)： $\mu_{電子} >> \mu_{イオン}$ ⇒ Electrons and Ions are separated

(d)： Surrounding the wire with water-drop shape (Inner: electrons, Outer: ions)

(e)： Electrons are absorbed i the wire within 1ns, while ions are drifting to the wall with 0V.

by Masaya Ishino (ICEPP, U. of Tokyo)

Promotional Counter

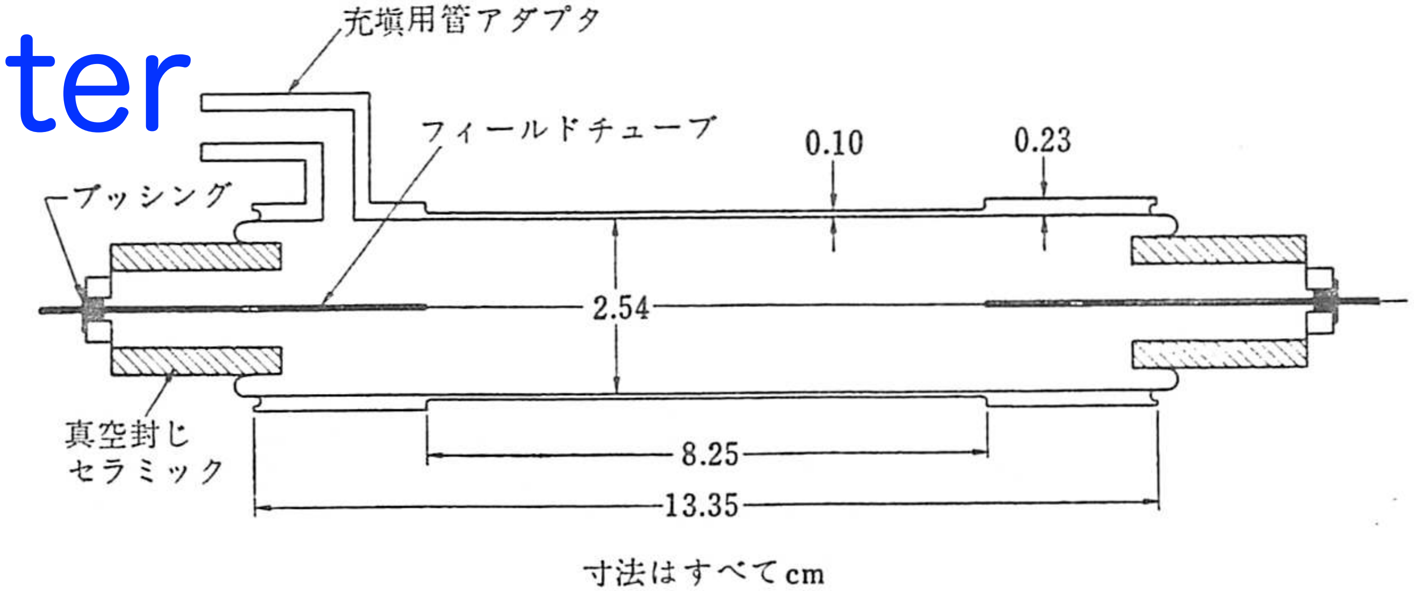
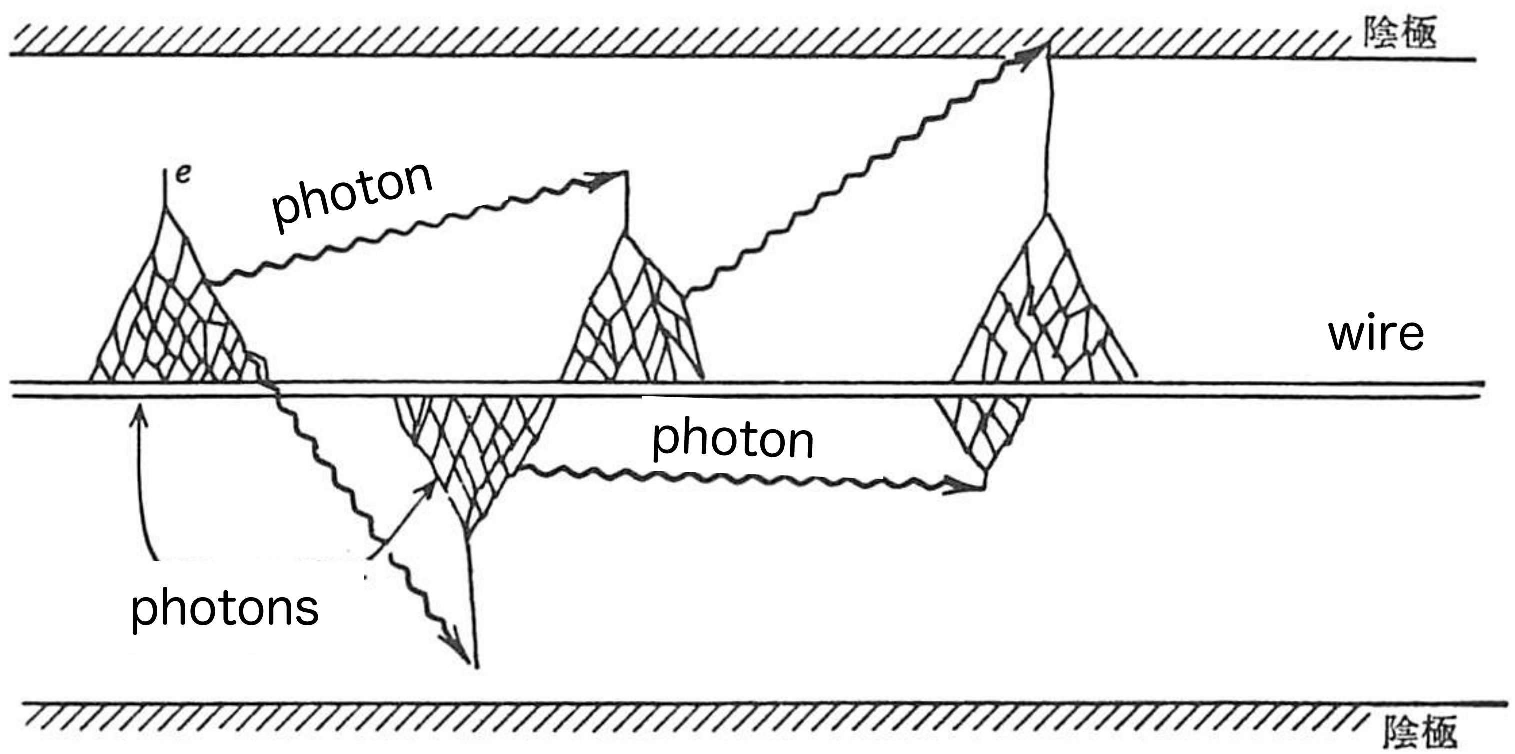


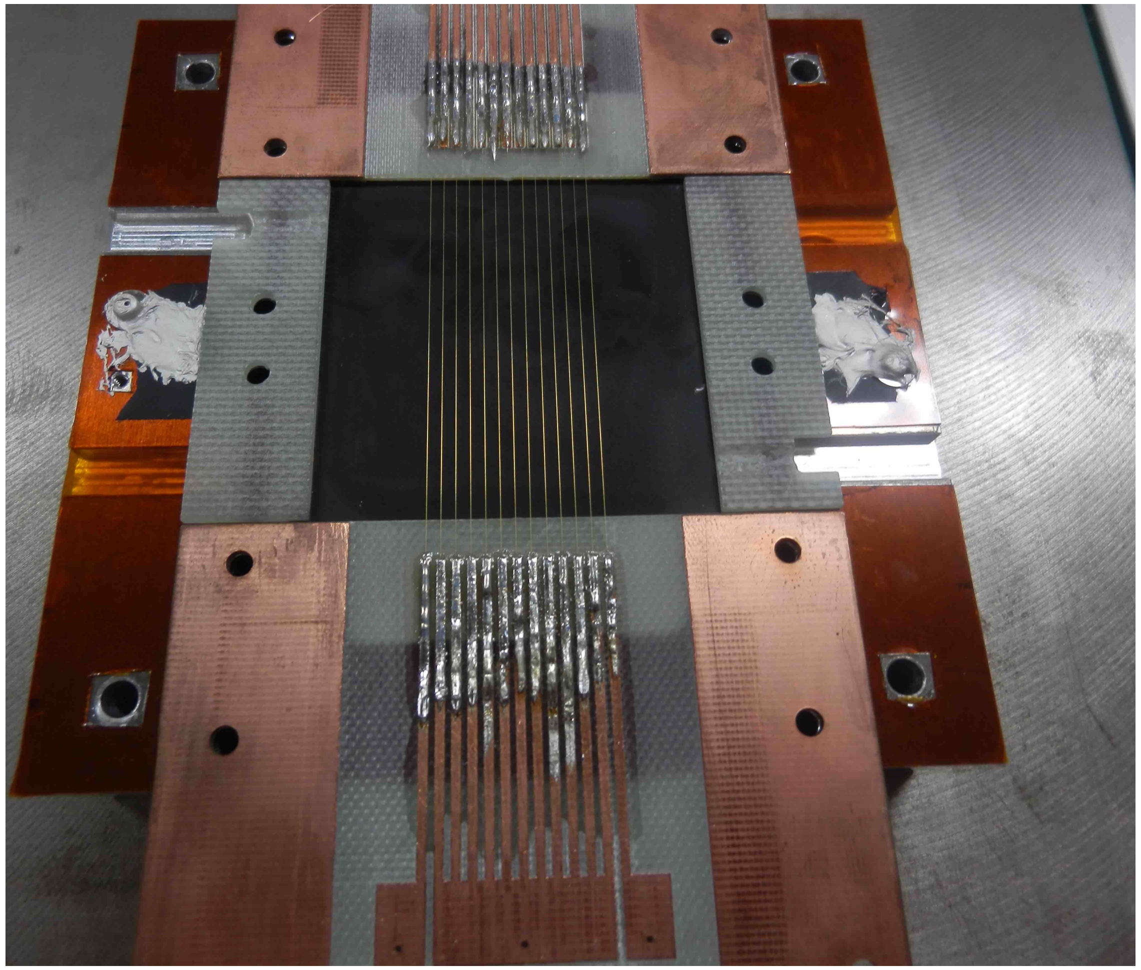
図 6.5　高速中性子検出用特殊比例計数管設計の断面図．陽極は直径 0.025 mm ステンレス鋼線である．フィールドチューブは管の両端で陽極のまわりに取り付けた直径 0.25 mm の注射針である（Bennett and Yule[4] による）

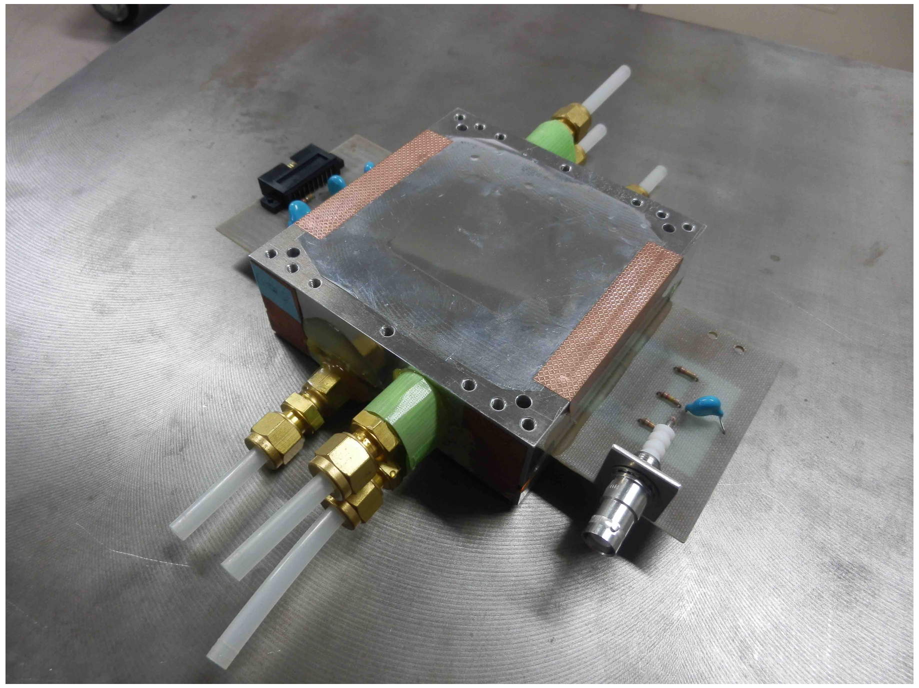
- Typical gas mixture: 90% Ar and 10% CH_4
  - Avoiding the electron captured in the gas (Nobel gas, such as Ar).
    - Oxygen is not good
  - Quencher (such as CH_4) is necessary
    - When the atom is excited, it generates photons which ionize another atom. If the process continues, too much avalanches are produced. To avoid this process, quenching gas is used to absorb photons.
- The selection of gas is not straightforward by considering the drift velocity of electrons as a function of voltage, multiplication, amount of material, possibility of discharge, etc.. You must be an expert.

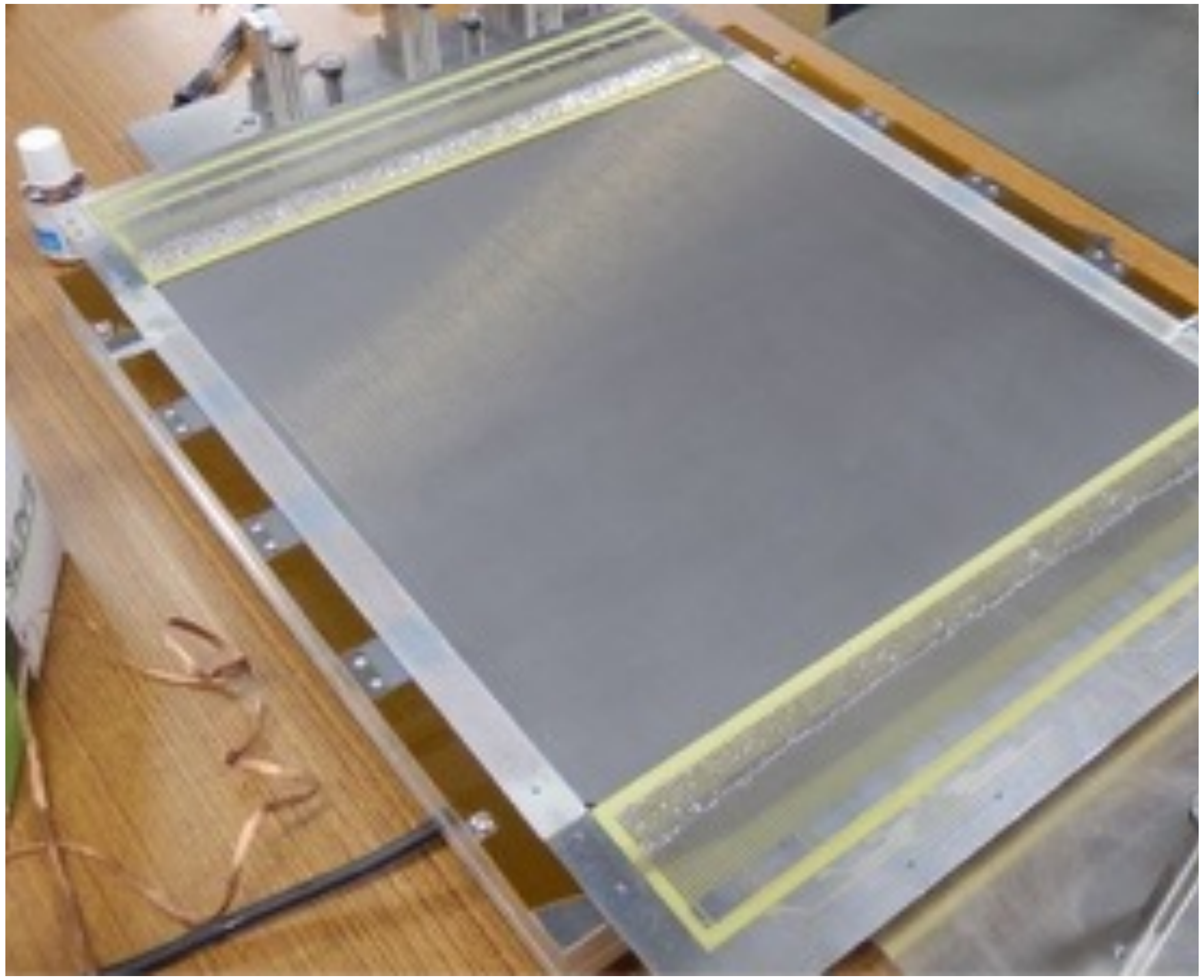
Geiger-Muller counter



- Typical gas: Ar
- with quencher
  - the function of quencher is not same as that used in a promotional counter







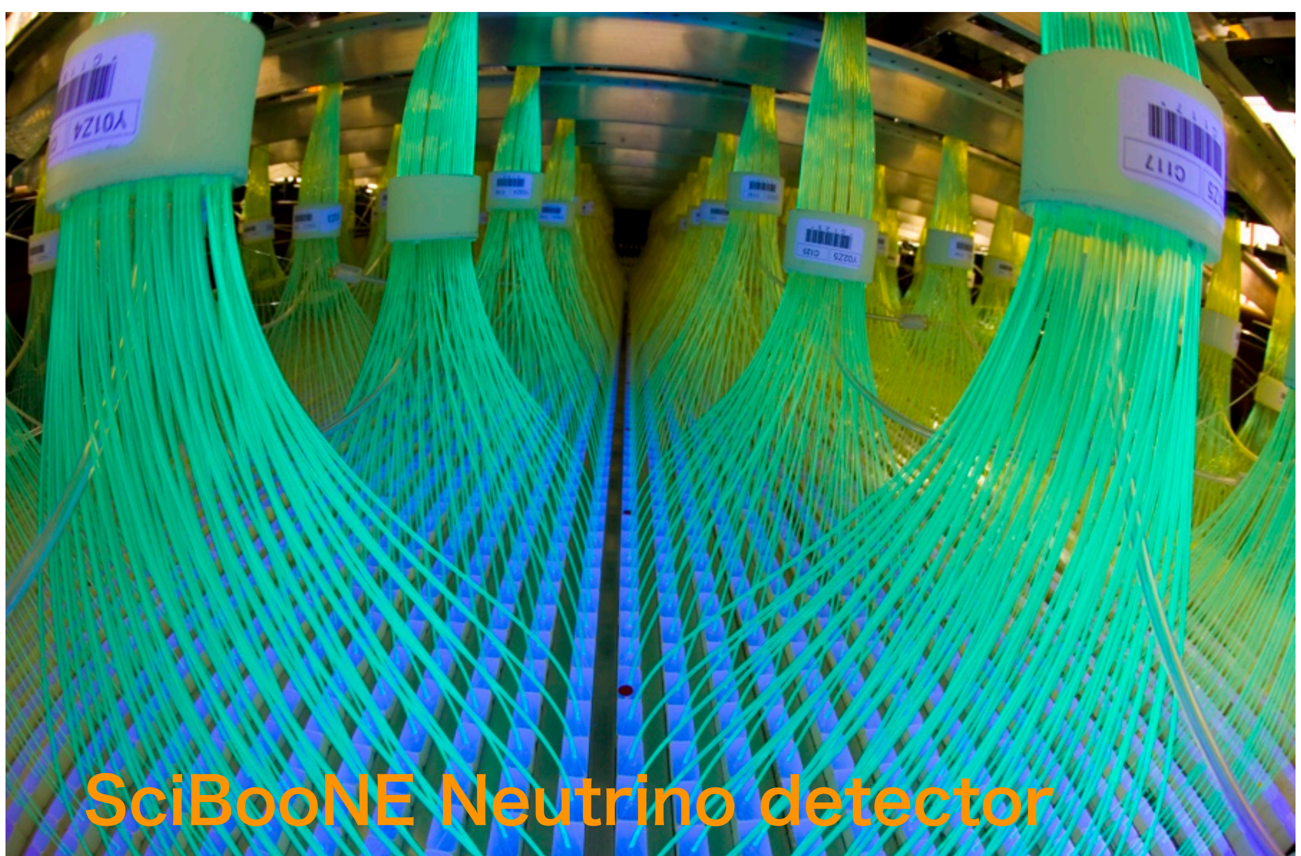
(2) Observation of excited atoms

- Detect photons emitted in deexcitation process of excited atoms (or molecules).
  - Fluorescent light
- The photon produced by radiation is called as a scintillation photon. The material that emits the scintillation photons is called as scintillator.

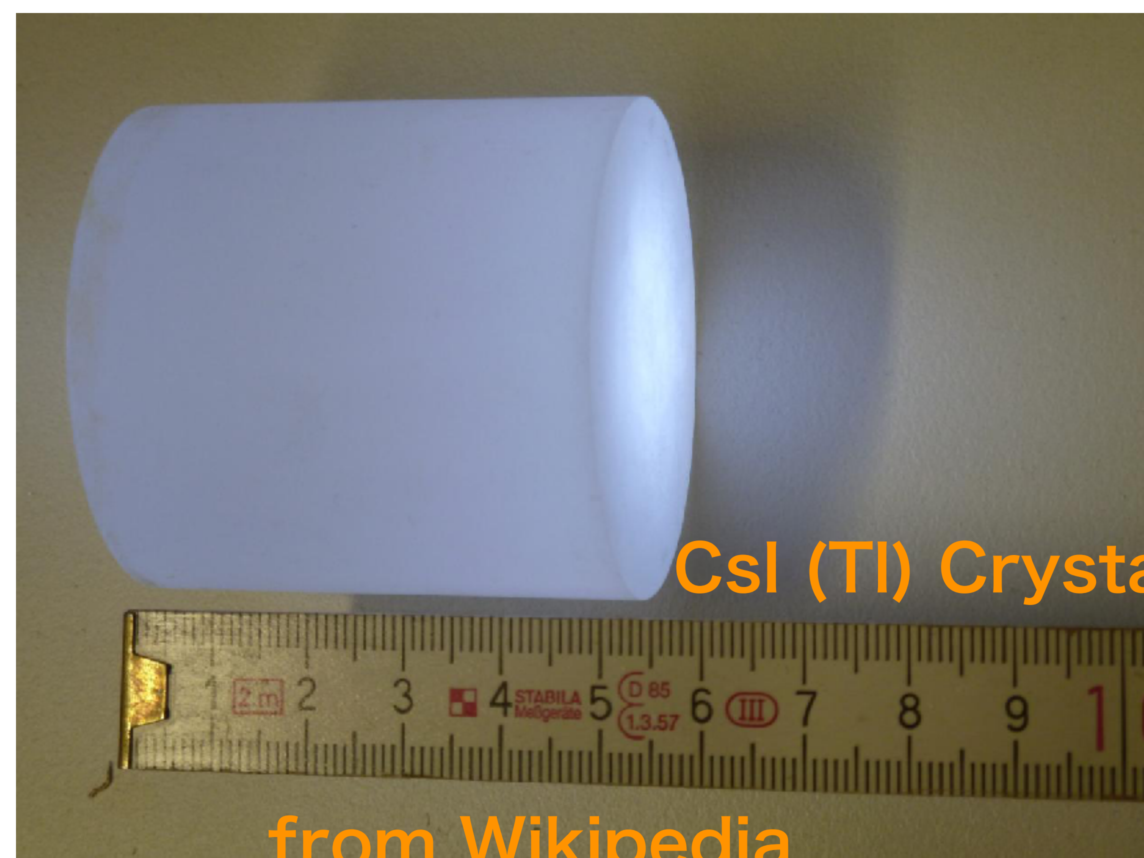
- Characteristics of good scintillators are
  - High efficiency to transform the energy deposit by radiation to scintillation photons (even so, 10% is high)
  - The amount of scintillation photons is proportional to the original energy deposit (linear relation).
  - The material is transparent for scintillation photons.
  - The scintillation photons are produced within a short time period of nsec~μsec (The life time of excited atoms is short).

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.



SciBooNE Neutrino detector



CsI (Tl) Crystal

from Wikipedia

Organic Scintillator

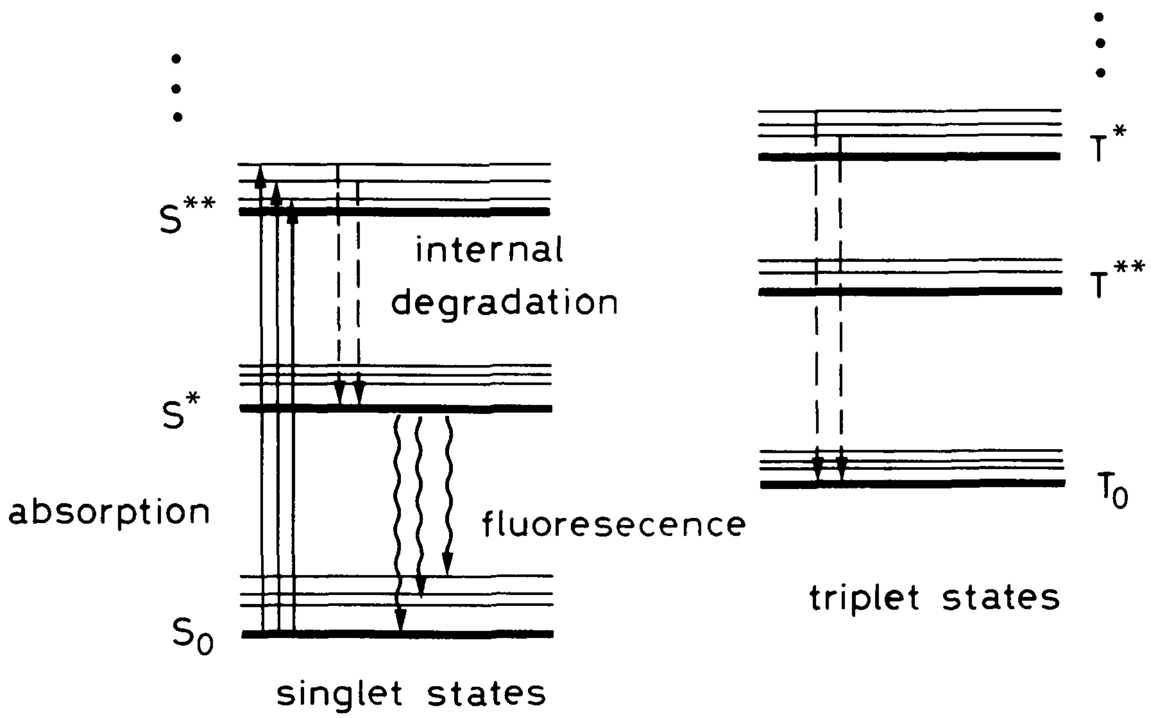


Fig. 7.4. Energy level diagram of an organic scintillator molecule. For clarity, the singlet states (denoted by *S*) are separated from the triplet states (denoted by *T*)

Inorganic Crystal Scintillator

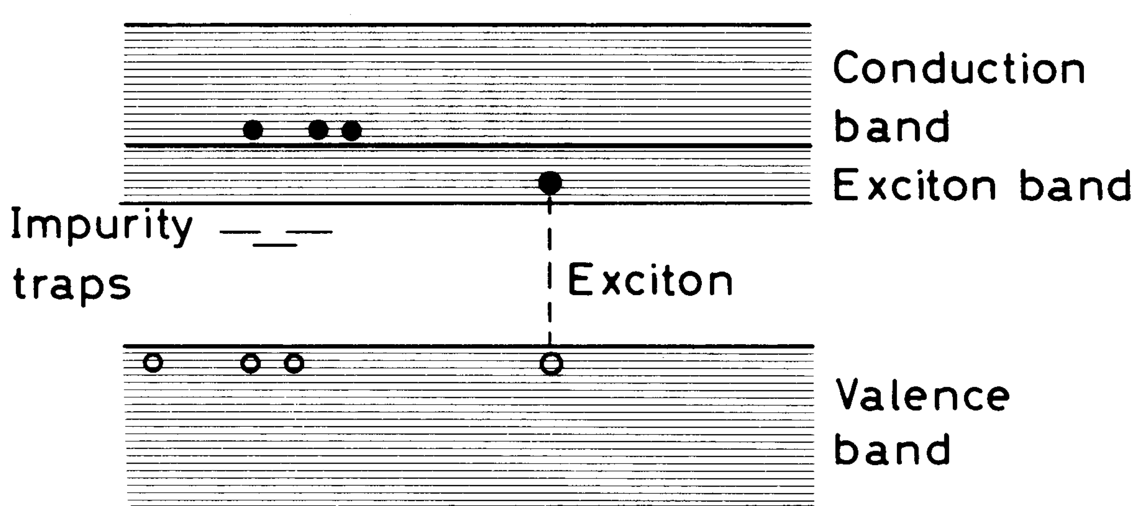
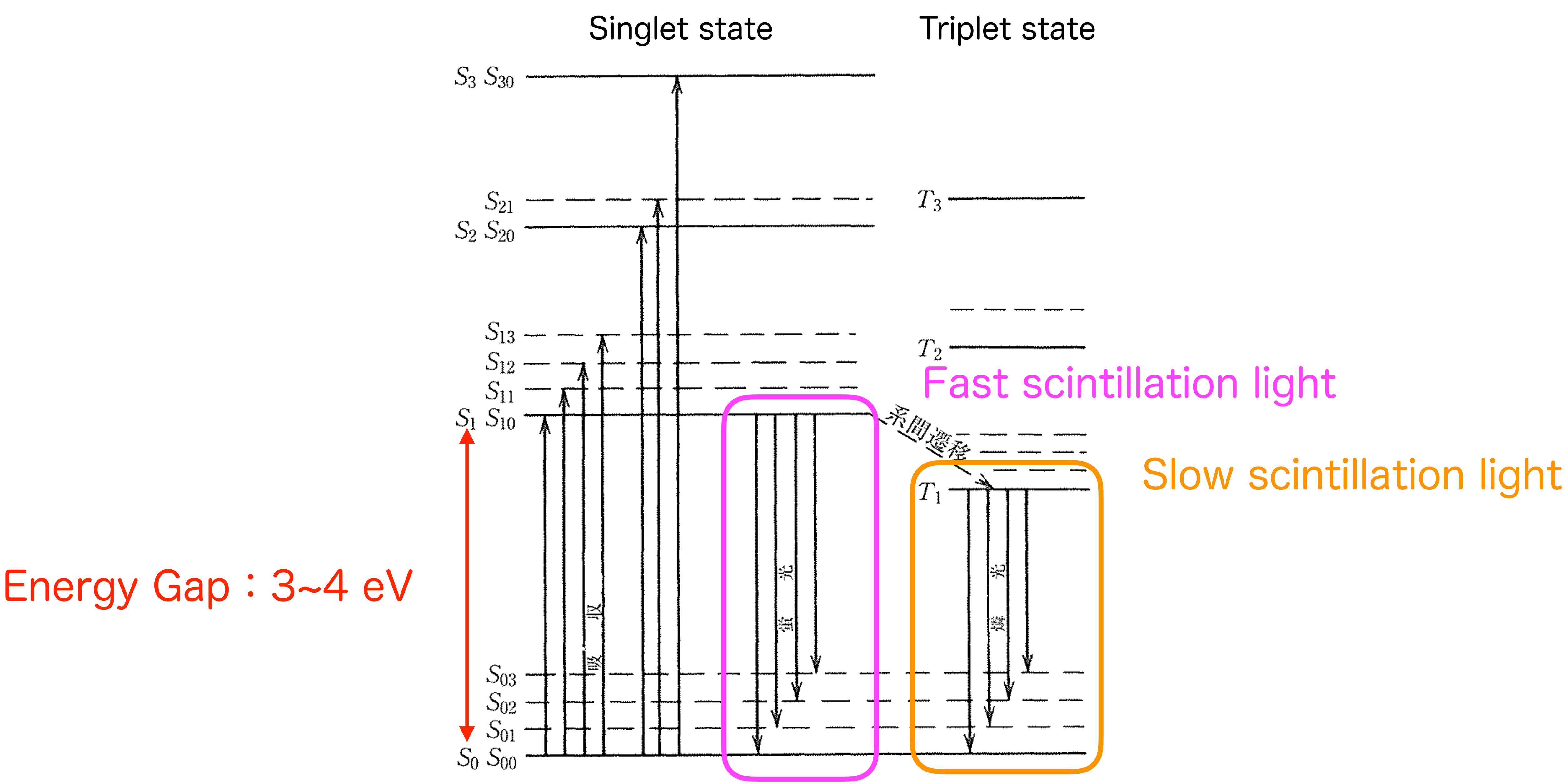


Fig. 7.7. Electronic band structure of inorganic crystals. Besides the formation of free electrons and holes, loosely coupled electron-hole pairs known as excitons are formed. Excitons can migrate through the crystal and be captured by impurity centers

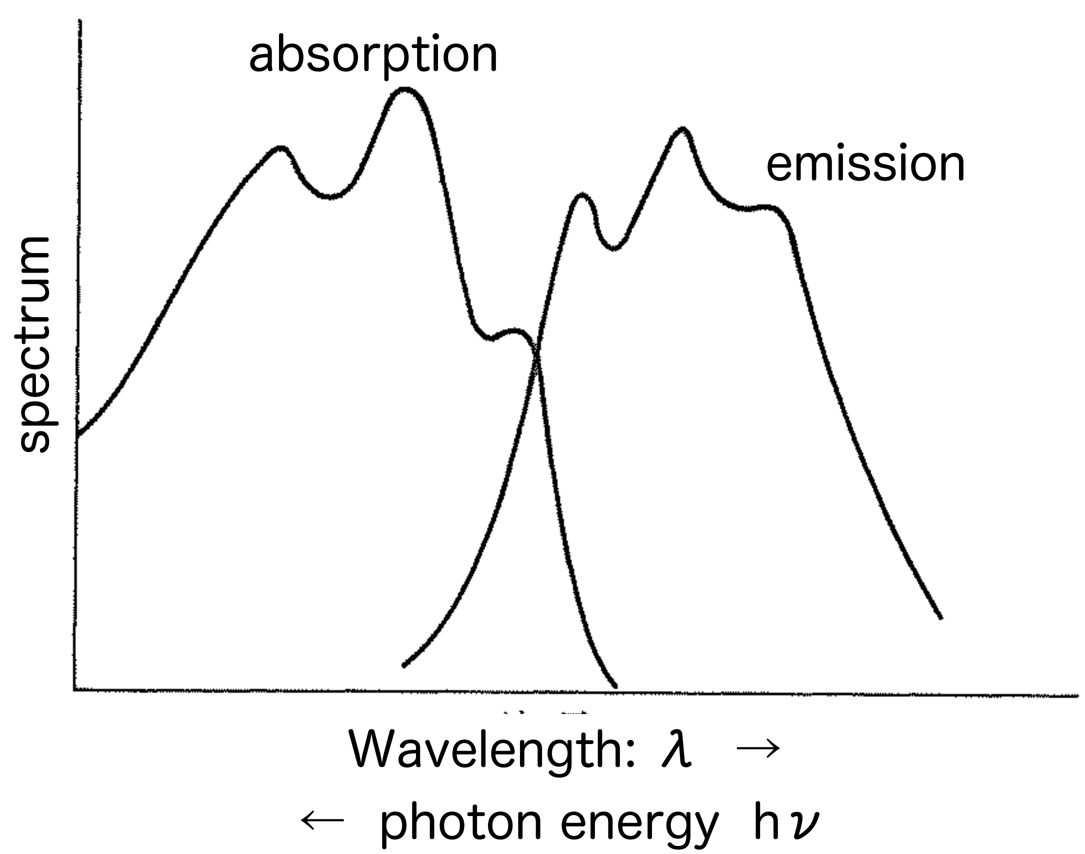
Organic Scintillator

- Organic scintillator
  - The organic scintillators are aromatic hydrocarbon compounds containing linked or condensed benzene-ring structures.



Organic Scintillator

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

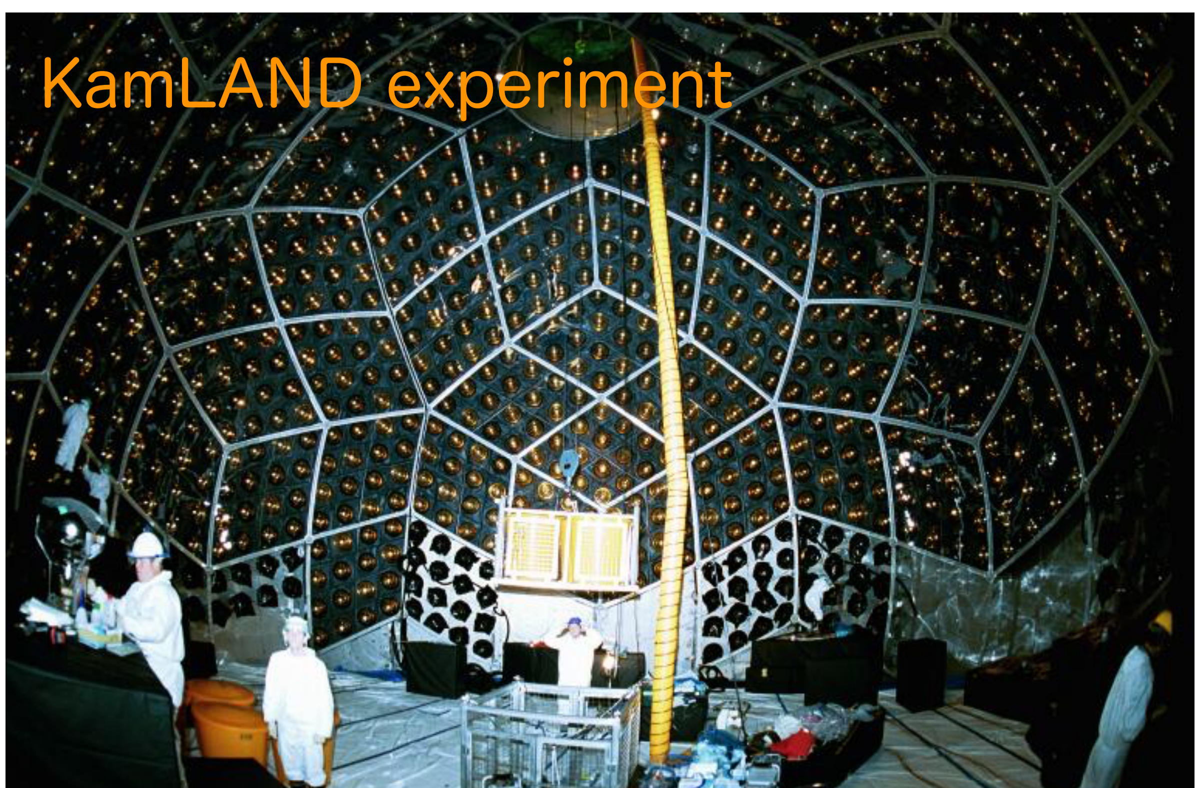


Organic Scintillator

- 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.

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..



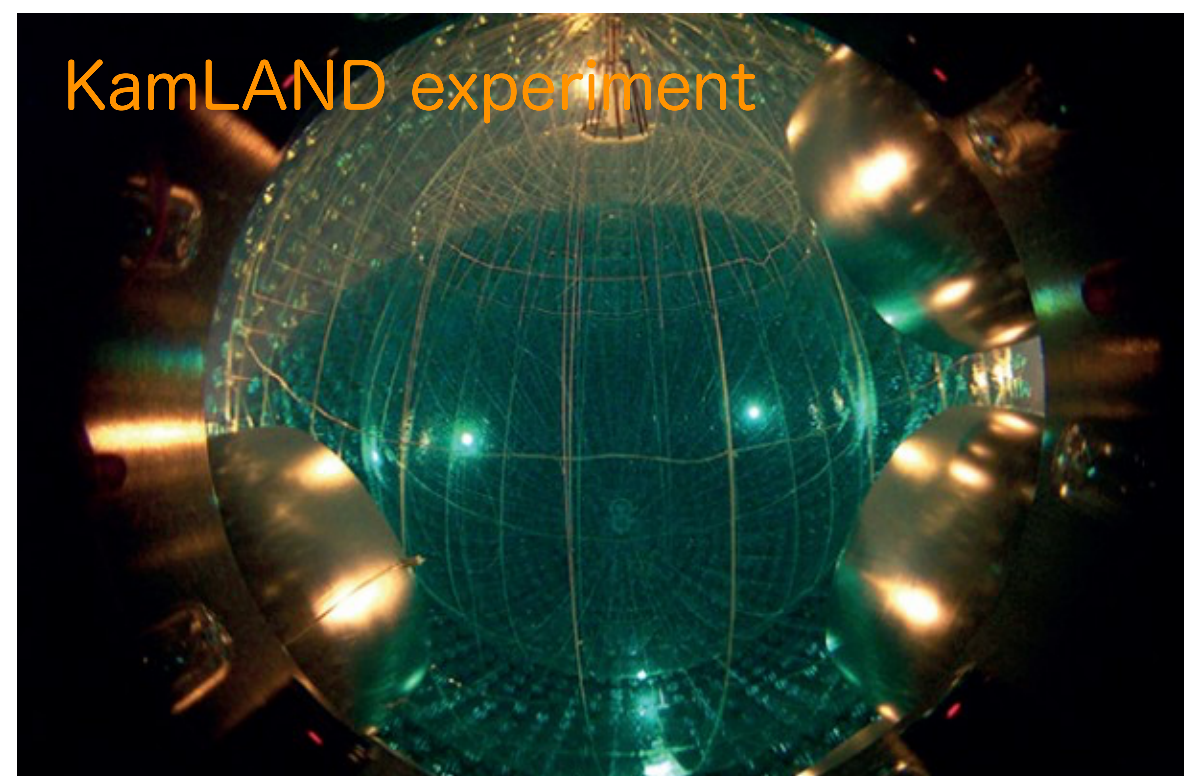


Table 7.1. Physical properties of various commercial scintillators (data from Nuclear Enterprises scintillator catalog [7.1])

	Scintillator	Type	Density	Refractive index	Melting softening or boiling point C[a]	Light output (% Anthracene)	Decay constant, main component [ns]	Wavelength of maximum emission [nm]	Content of loading element (% by wt.)	H/C No. of H atoms/ No. of C atoms	Principal applications
Plastic	NE 102A	Plastic	1.032	1.581	75	65	2.4	423		1.104	γ, α, β, fast n
	NE 104	Plastic	1.032	1.581	75	68	1.9	406		1.100	ultra-fast counting
	NE 104B	Plastic	1.032	1.58	75	59	3.0	406		1.107	with BBQ light guides
	NE 105	Plastic	1.037	1.58	75	46		423		1.098	dosimetry
	NE 110	Plastic	1.032	1.58	75	60	3.3	434		1.104	γ, α, β, fast n etc.
	NE 111A	Plastic	1.032	1.58	75	55	1.6	370		1.103	ultra-fast timing
	NE 114	Plastic	1.032	1.58	75	50	4.0	434		1.109	as for NE 110
	NE 160	Plastic	1.032	1.58	80	59	2.3	423		1.105	use at high temperatures
	Pilot U	Plastic	1.032	1.58	75	67	1.36	391		1.100	ultra fast timing
	Pilot 425	Plastic	1.19	1.49	100			425		1.6	Cherenkov detector
Liquid	NE 213	Liquid	0.874	1.508	141	78	3.7	425		1.213	fast n (P.S.D.)
	NE 216	Liquid	0.885	1.523	141	78	3.5	425		1.171	α, β (internal counting)
	NE 220	Liquid	1.036	1.442	104	65	3.8	425	O 29%	1.669	internal counting, dosimetry
	NE 221	Gel	1.08	1.442	104	55	4	425		1.669	α, β (internal counting)
	NE 224	Liquid	0.877	1.505	169	80	2.6	425		1.330	γ, fast n
	NE 226	Liquid	1.61	1.38	80	20	3.3	430		0	γ, insensitive to n
	NE 228	Liquid	0.71	1.403	99	45		385		2.11	n
	NE 230	Deuterated liquid	0.945	1.50	81	60	3.0	425	D 14.2%	0.984	(D/C) special applications
	NE 232	Deuterated liquid	0.89	1.43	81	60	4	430	D 24.5%	1.96	(D/C) special applications
	NE 233	Liquid	0.874	1.506	117	74	3.7	425		1.118	α, β (internal counting)
	NE 235	Liquid	0.858	1.47	350	40	4	420		2.0	large tanks
	NE 250	Liquid	1.035	1.452	104	50	4	425	O 32%	1.760	internal counting, dosimetry
Loaded liquid	NE 311 & 311A	B loaded liquid	0.91	1.411	85	65	3.8	425	B 5%	1.701	n, β
	NE 313	Gd loaded liquid	0.88	1.506	136	62	4.0	425	Gd 0.5%	1.220	n
	NE 316	Sn loaded liquid	0.93	1.496	148.5	35	4.0	425	Sn 10%	1.411	γ, x-rays
	NE 323	Gd loaded liquid	0.879	1.50	161	60	3.8	425	Gd 0.5%	1.377	n

Response of organic scintillator

- Time response
  - Fast（2~3nsec)
  - The timing shape sometimes depends on the energy deposit (dE/dx). This character is used for Particle Identification. (neutron/γ with liquid scintillator, proton/μ, π in T2K ND280&INGRID)
- Energy Response
  - A dependence of the energy deposit (dE/dx) by the quenching effect.

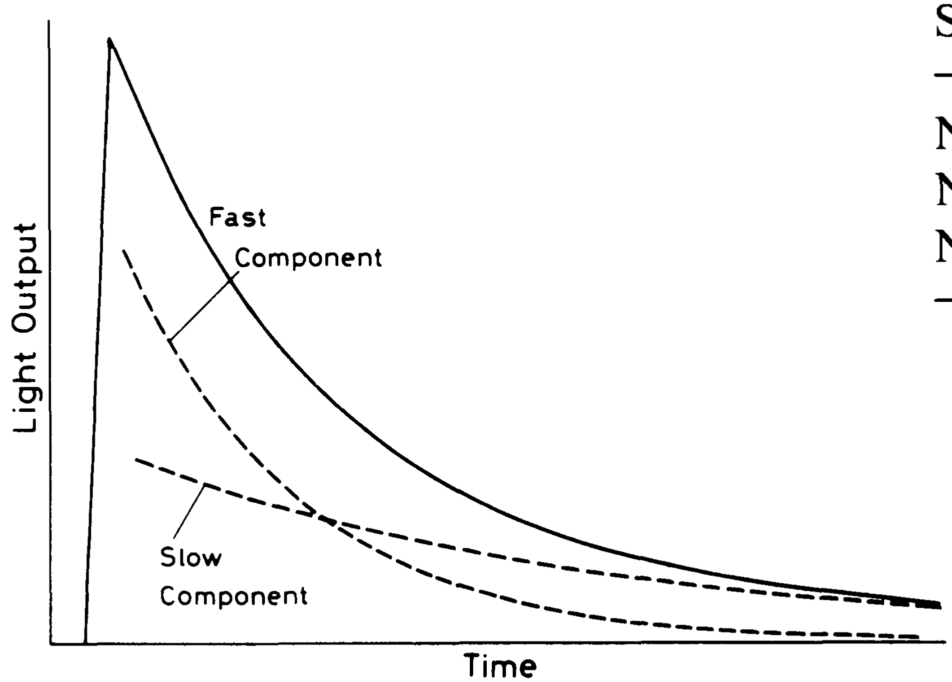


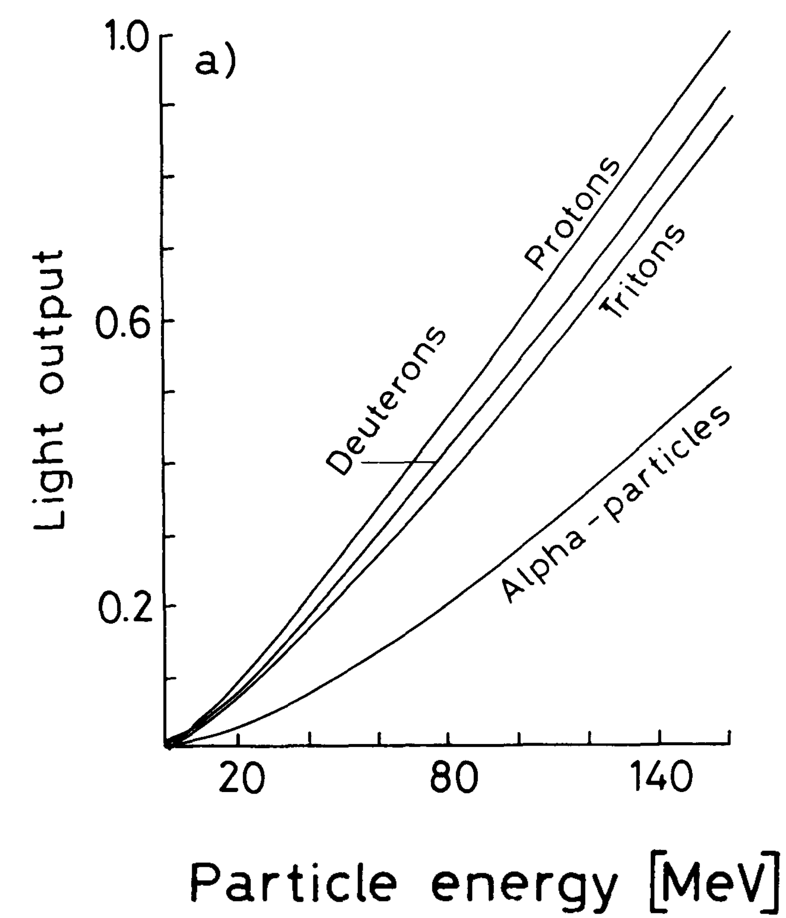
Fig. 7.3. Resolving scintillation light into *fast* (promp (delayed) components. The *solid line* represents the tota curve

Scintillator	σ [ns]	τ [ns]
NE102A	0.7	2.4
NE111	0.2	1.7
Naton 136	0.5	1.87

Table 7.2. Gaussian and exponential parameters for light pulse description from several plastic scintillators (from *Bengston* and *Moszynski* [7.2])

$$\frac{I}{I_0} = f(t) \cdot e^{-t/\tau}$$

f(t): Gaussian with σ_{ET}



(3) Detection of a free electron after Excitation

1. A semiconductor detector is very popular in High energy physics experiments.
   1. Measure the electric signal originated by electron-hole pairs created by energy deposit of a charged particle.
   2. The energy need for an electron-hole pair is small and we can measure many electron-hole pairs.
      - Energy for electron-hole pair creation in semiconductor: ~3 eV
      - Energy for electron-ion pair creation in gas: ~30 eV
      - Energy for scintillation photon：~100 eV

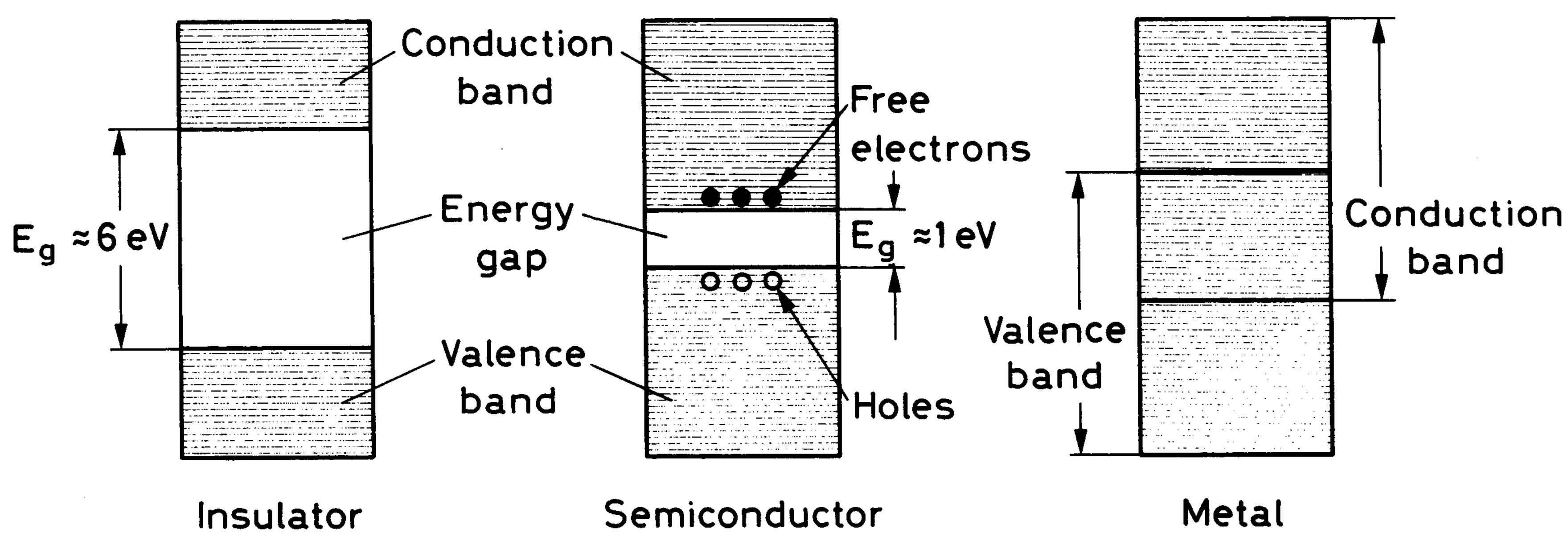


Fig. 10.1. Energy band structure of conductors, insulators and semiconductors

What shall we measure for the charged particle

With the signal of the charged particle, we can measure

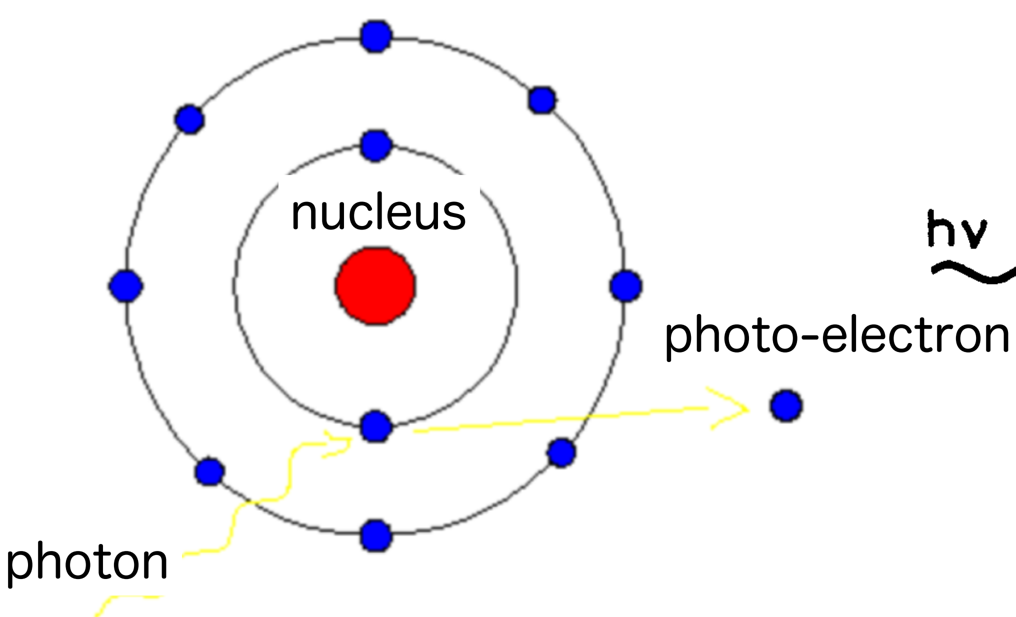
1. position
2. momentum
3. velocity
4. energy

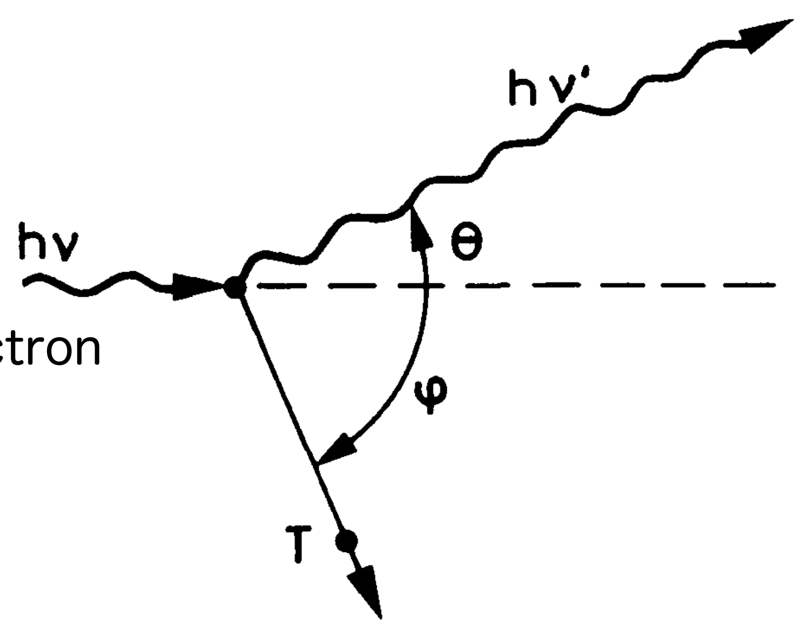
of the particle.

Measurement of a neutral particle (mainly a photon)

How to detect a neutral particle, photon

- Remember the interaction of photons with matters
  - (1) Photoelectric Effect [in low energy]
  - (2) Compton Scattering [in medium energy]
  - (3) Pair production [in high energy]
  - In the interaction, an electron is emitted. We will measure the electron as a signal of photon interaction. We already know how to detect a charged particle.

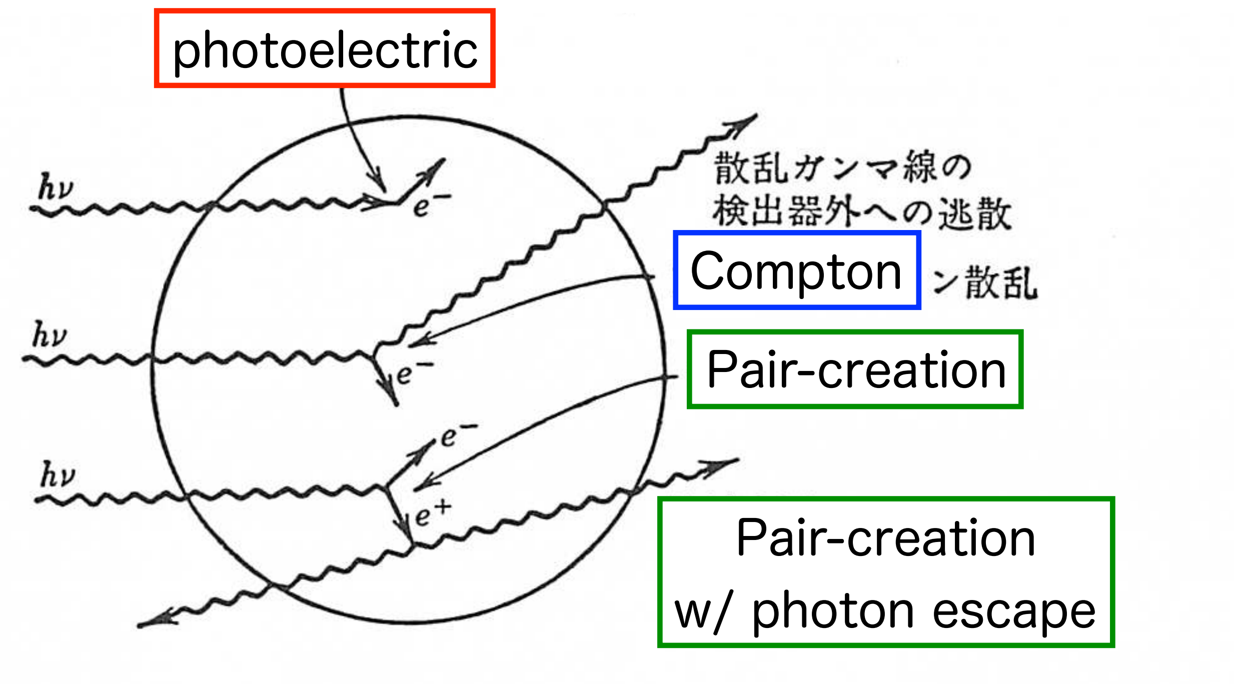


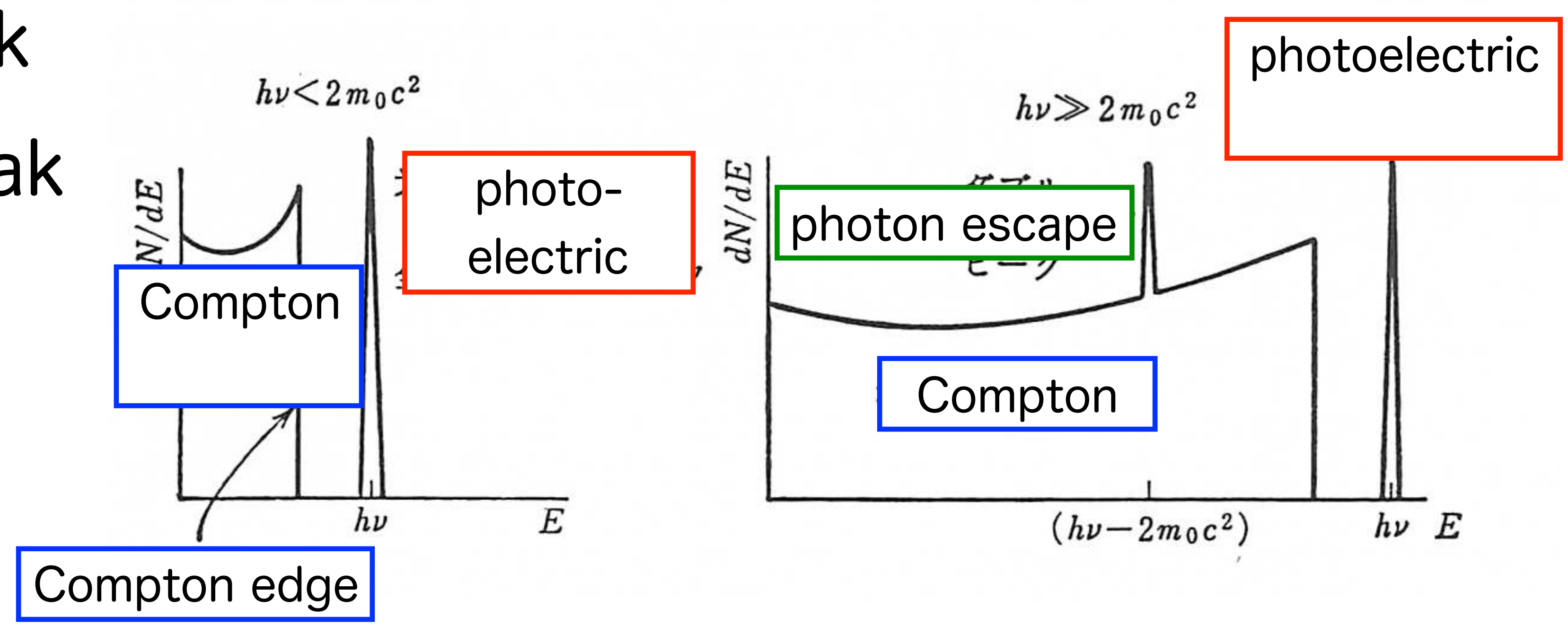


$\gamma + \gamma^* \rightarrow e^+ + e^-$

γ ray spectrum measurement

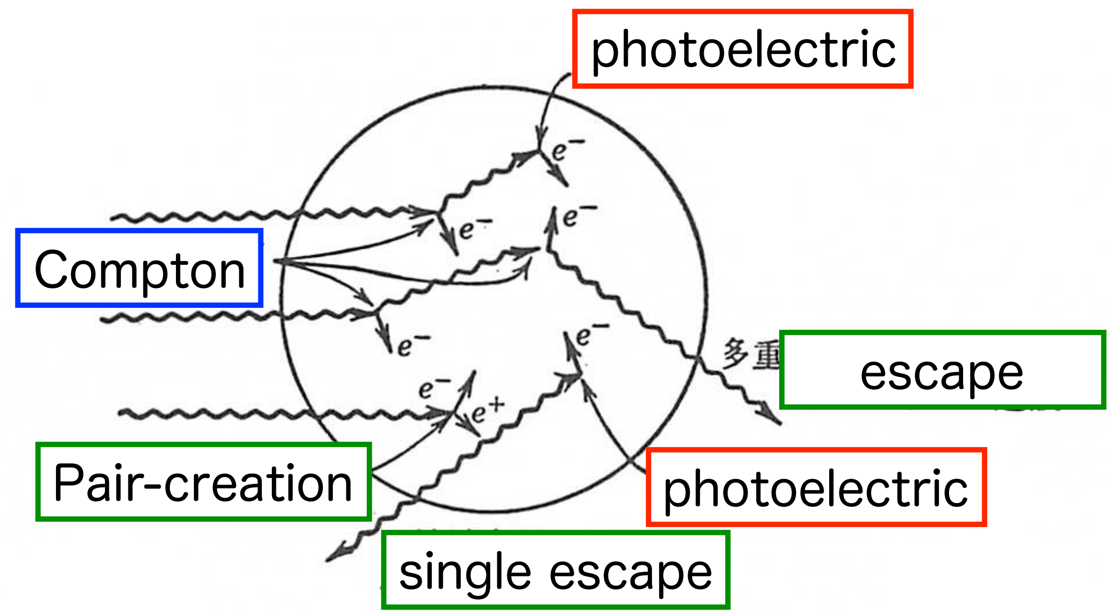
- Signal（Ideal situation)
  - Photoelectric peak
  - Compton spectrum with edge
  - Escape peak of positronium annihilation
    - Single escape peak
    - Double escape peak

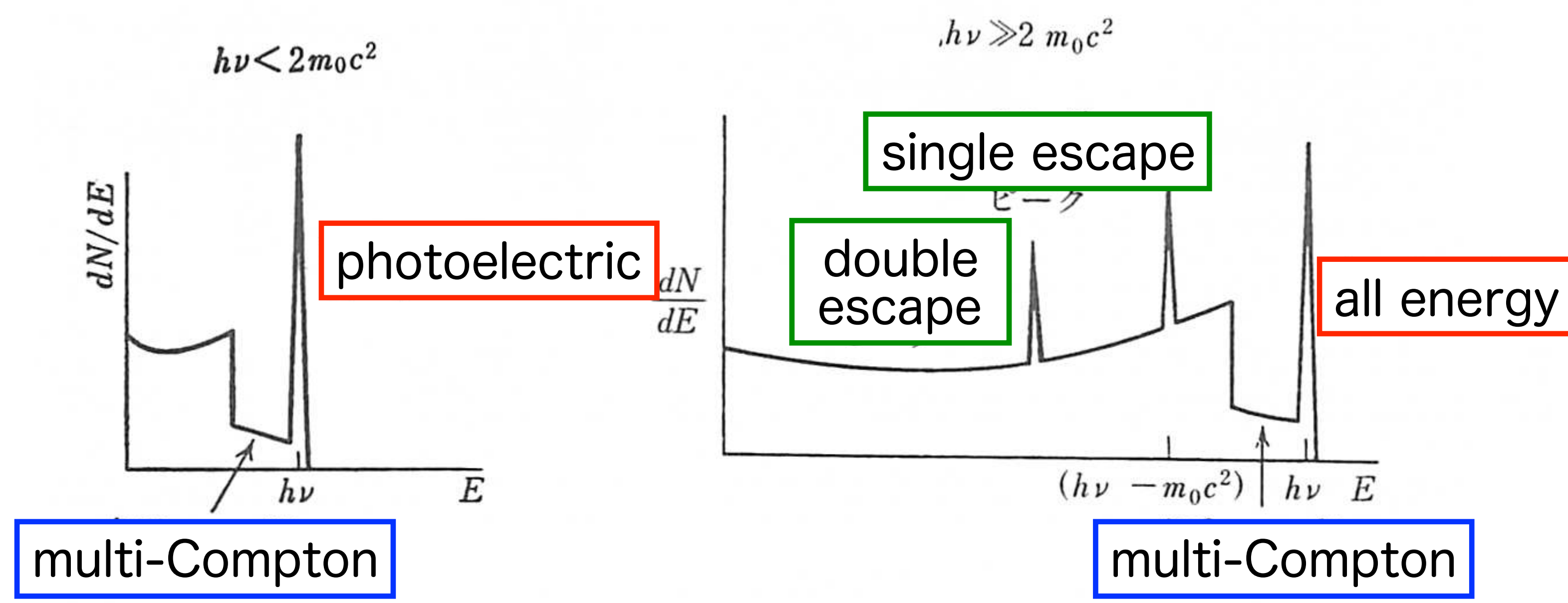




γ ray spectrum measurement

- Signal（Ideal situation)
  - Photoelectric peak
  - Compton spectrum with edge
  - Escape peak of positronium annihilation
    - Single escape peak
    - Double escape peak





How to detect a photon

- First, a photon is interacted, and second, the electron is measured.
- Inorganic crystal scintillator
  - The advantage lies in the greater stopping power due to the higher density and higher atomic number. [Q] Why the higher atomic number?

Atomic number

- Cd: 48
- I: 53
- Cs: 55
- W: 74
- Bi: 83
-

表 8.3 よく用いられる無機シンチレータの特性.

	density	wave-length (nm)	reflection index	decay time (μs)	light yield
アルカリハライド					
NaI (Tl)	3.67	415	1.85	0.23	38,000
CsI (Tl)	4.51	540	1.80	0.68 (64 %) 3.34 (36 %)	65,000
CsI (Na)	4.51	420	1.84	0.46, 4.18	39,000
LiI (Eu)	4.08	470	1.96	1.4	11,000
その他の遅い無機シンチレータ					
BGO	7.13	480	2.15	0.30	8,200
$CdWO_4$	7.90	470	2.3	1.1 (40 %) 14.5 (60 %)	15,000

Scintillation mechanism

- Electronic band structure in crystals: [Example: NaI(Tl)]
    - If a charged particle goes through the crystal, electrons are excited to conduction band from the valence band and the holes are also pair-created. An electron and hole pair is loosely coupled and forms an exciton.
    - It is not efficient that the electrons go back to the valence band with scintillation light. The probability is not high for an electron to meet a hole.
    - By doping impurities, the excitons can migrate through the crystal and be captured by impurity centers. Then, the scintillation lights are emitted.

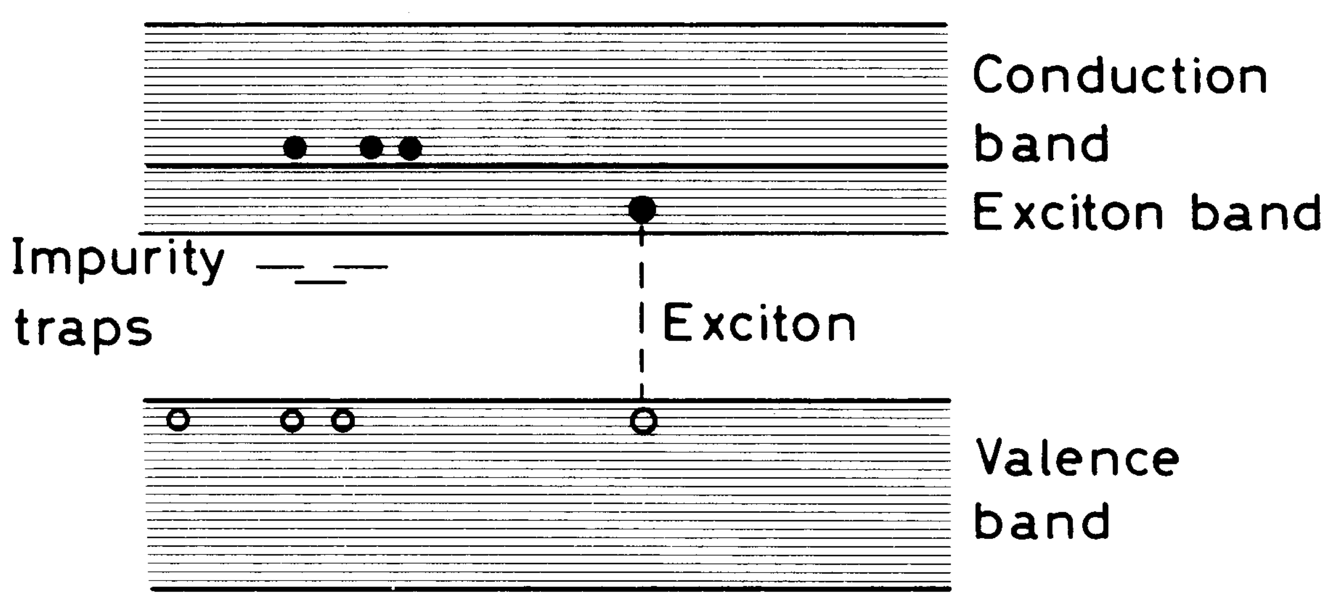


Fig. 7.7. Electronic band structure of inorganic crystals. Besides the formation of free electrons and holes, loosely coupled electron-hole pairs known as excitons are formed. Excitons can migrate through the crystal and be captured by impurity centers

Scintillation mechanism

- Lifetime of the excitation state (typically 30〜500 nsec) is longer than the time when the excitons are captured by impurity centers.
- The wavelength of scintillation lights is in a wider range. We often use the scintillator with visible lights.

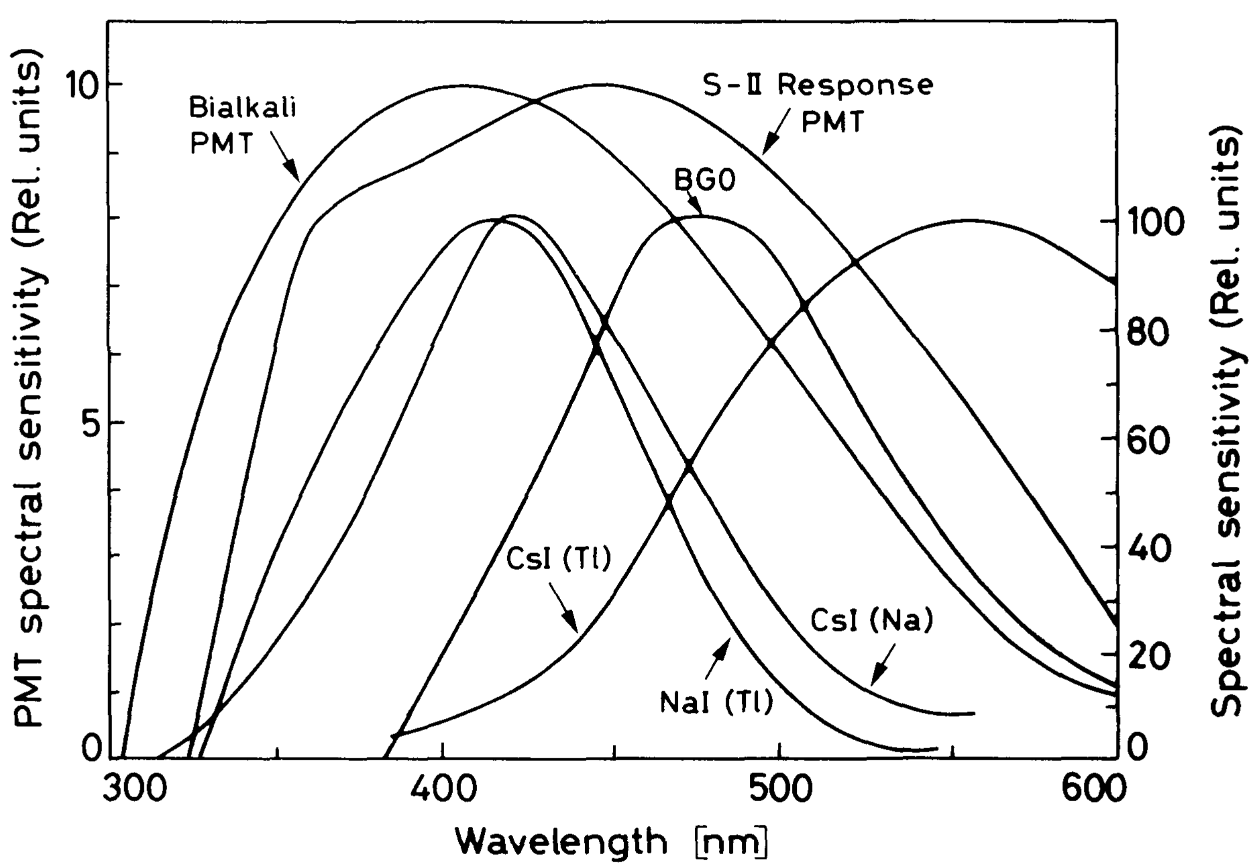
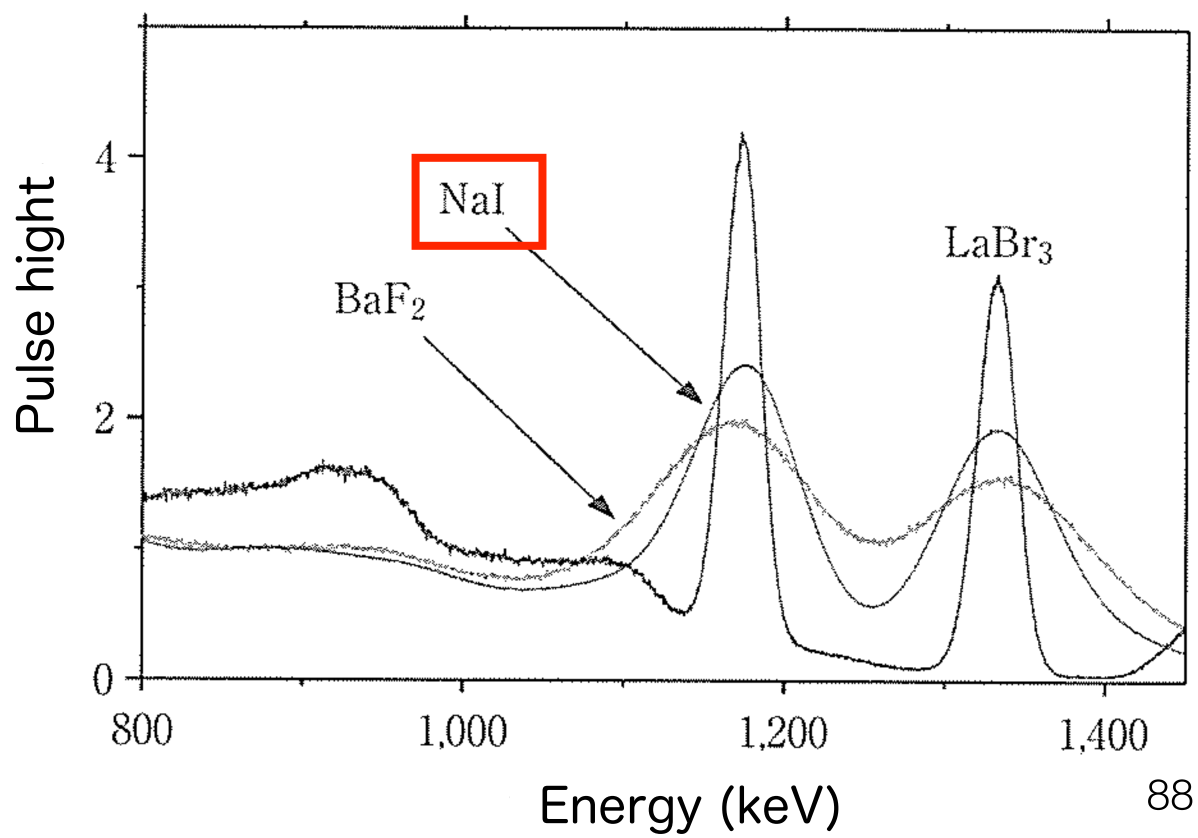


Fig. 7.6. Light emission spectra for different inorganic crystals (from *Harshaw Catalog* [7.3])

Scintillation mechanism

- Light Yield is important. [Example: NaI(Tl)]
  - In the case of 1MeV energy deposit
    - Efficiency of scintillation is typically 12%.
    - The energy of visible light is 3eV.
    - The number of scintillation lights is
      - 1,000,000eV×0.12%÷3eV=40,000
  - Since 1,000,000eV÷40,000 photons=25eV/photon, the energy for one electron-hole pair is 25eV.



The energy resolution depends on the light yield

many kinds of inorganic scintillators

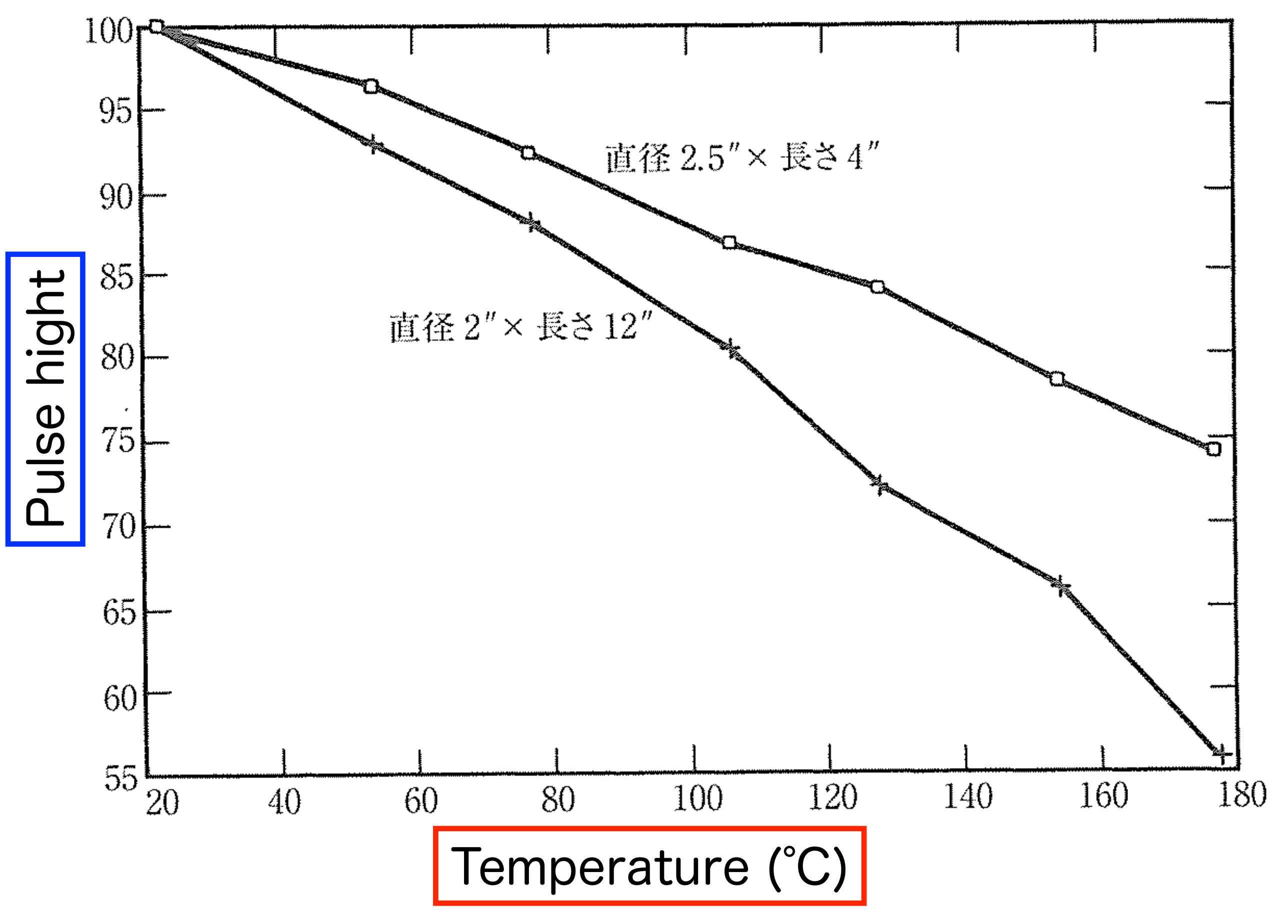
表 8.3 よく用いられる無機シンチレータの特性.

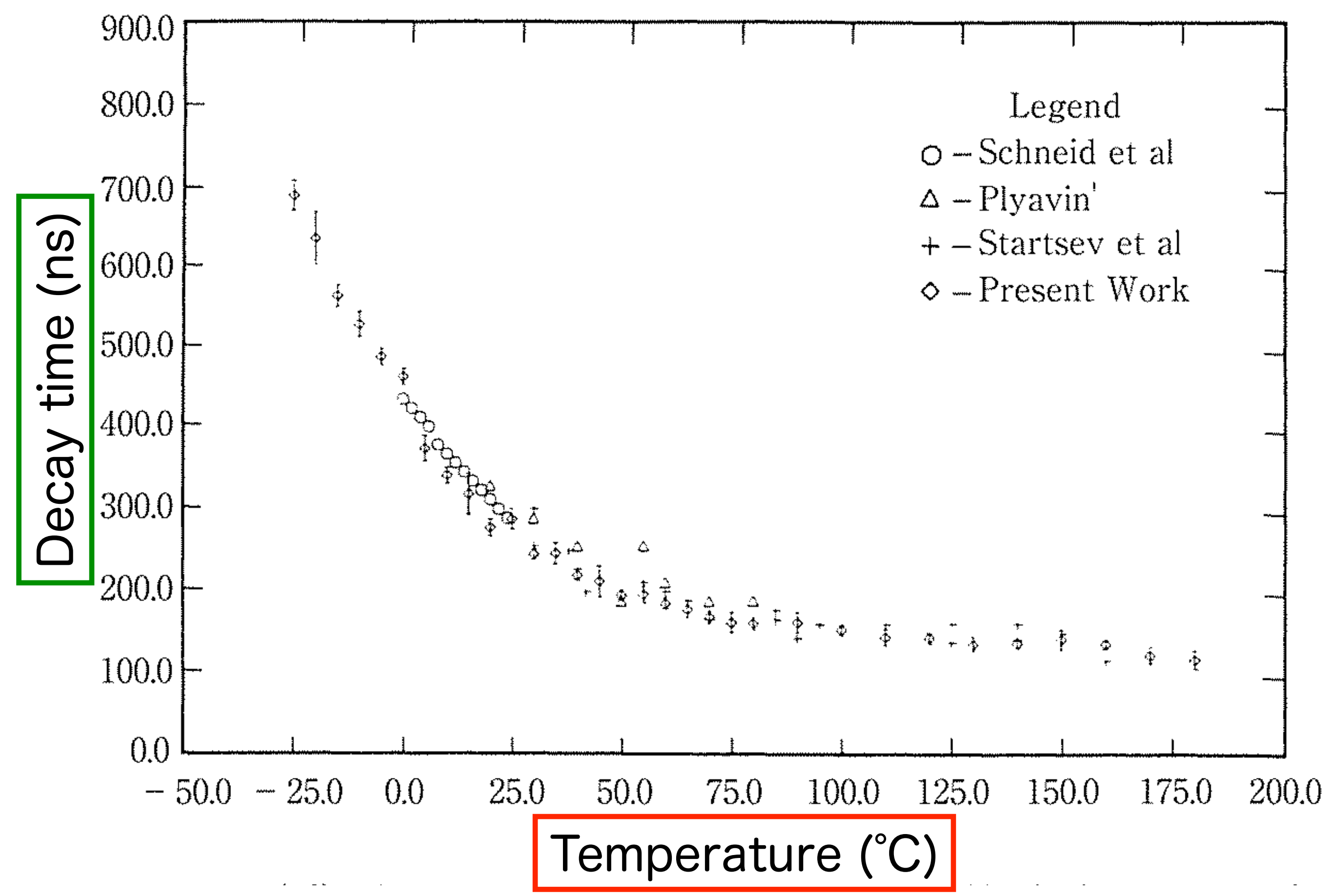
	比重	最高放出波長 (nm)	屈折率	減衰時間 (μs)	絶対発光量 (光子/MeV)	バイアルカリ光電子増倍管による相対的パルス波高	参考文献
アルカリハライド							
NaI (Tl)	3.67	415	1.85	0.23	38,000	1.00	
CsI (Tl)	4.51	540	1.80	0.68 (64 %) 3.34 (36 %)	65,000	0.49	85, 105, 106
CsI (Na)	4.51	420	1.84	0.46, 4.18	39,000	1.10	112
LiI (Eu)	4.08	470	1.96	1.4	11,000	0.23	
その他の遅い無機シンチレータ							
BGO	7.13	480	2.15	0.30	8,200	0.13	
$CdWO_4$	7.90	470	2.3	1.1 (40 %) 14.5 (60 %)	15,000	0.4	119-121
$CaWO_4$	6.1	420	1.94	8	15,000		123
SrI_2 (Eu)	4.6	435		1.2	85,000		125
ZnS (Ag) (多結晶)	4.09	450	2.36	0.2		1.3[a]	
CaF_2 (Eu)	3.19	435	1.47	0.9	24,000	0.5	
活性化物質なしの高速無機シンチレータ							
BaF_2 (高速成分)	4.89	220		0.0006	1,400	na	133-135
BaF_2 (遅発成分)	4.89	310	1.56	0.63	9,500	0.2	133-135
CsI (高速成分)	4.51	305		0.002 (35 %) 0.02 (65 %)	2,000	0.05	140-142
CsI (遅発成分)	4.51	450	1.80	数μsまで多くの成分	多い	多い	141, 142
CeF_3	6.16	310, 340	1.68	0.005, 0.027	4,400	0.04 ~ 0.05	83, 146, 147
Ce 活性化高速無機シンチレータ							
GSO	6.71	440	1.85	0.056 (90 %) 0.4 (10 %)	9,000	0.2	156-160
YAP	5.37	370	1.95	0.027	18,000	0.45	85, 165
YAG	4.56	550	1.82	0.088 (72 %) 0.302 (28 %)	17,000	0.5	85, 167
LSO	7.4	420	1.82	0.047	25,000	0.75	170, 171
YSO	4.54	420		0.070	24,000		152, 153, 155
LuAP	8.4	365	1.94	0.017	17,000	0.3	178, 180, 183
$LaCl_3$ (Ce)	3.79	350		0.028	46,000		212
$LaBr_3$ (Ce)	5.29	380	2.05~2.10	0.026	63,000		212, 218
ガラスシンチレータ							
Ce 活性化 Li ガラス[b]	2.64	400	1.59	0.05 ~ 0.1	3,500	0.09	84, 241
Tb 活性化ガラス[b]	3.03	550	1.5	約3,000 ~ 5,000	約 50,000	na	241
比較用，典型的な有機（プラスチック）シンチレータ							
NE102A	1.03	423	1.58	0.002	10,000	0.25	

a. α 粒子に対する値.
b. 配合により特性は変化，表 15.1 参照.
特記するもの以外は文献[81)82)]より主に引用.

Scintillation mechanism

- Temperature dependence (some energy is transformed to heat)
  - Light yield (Scintillation efficiency) varies.
  - Timing shape (decay time, lifetime of excited state) varies.





Photomultiplier Tube (PMT)

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

https://youtu.be/9EbX0dfWuU4

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

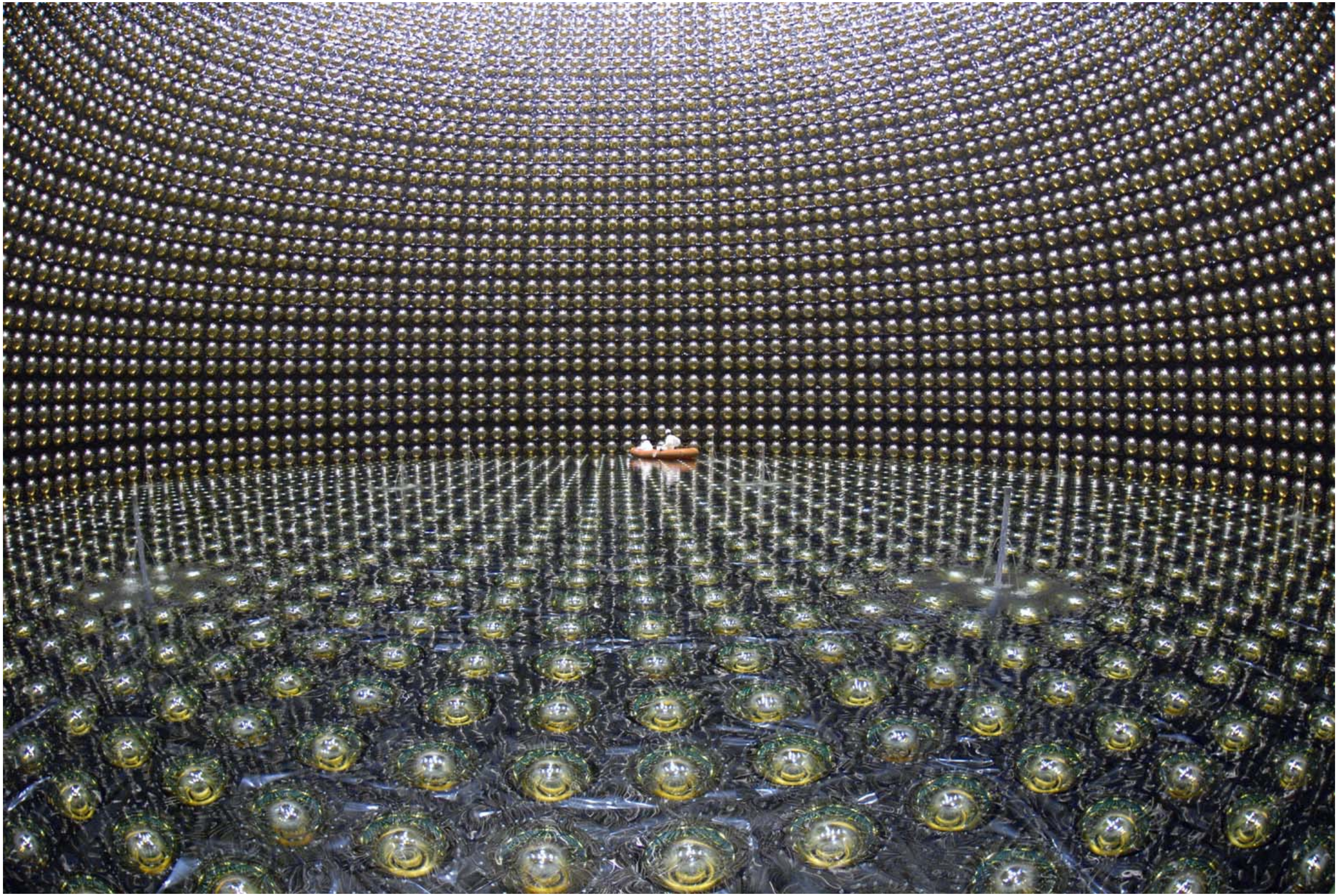
Hamamatsu: No. 1 PMT vendor

Prof. Koshiba with 50 cm PMT

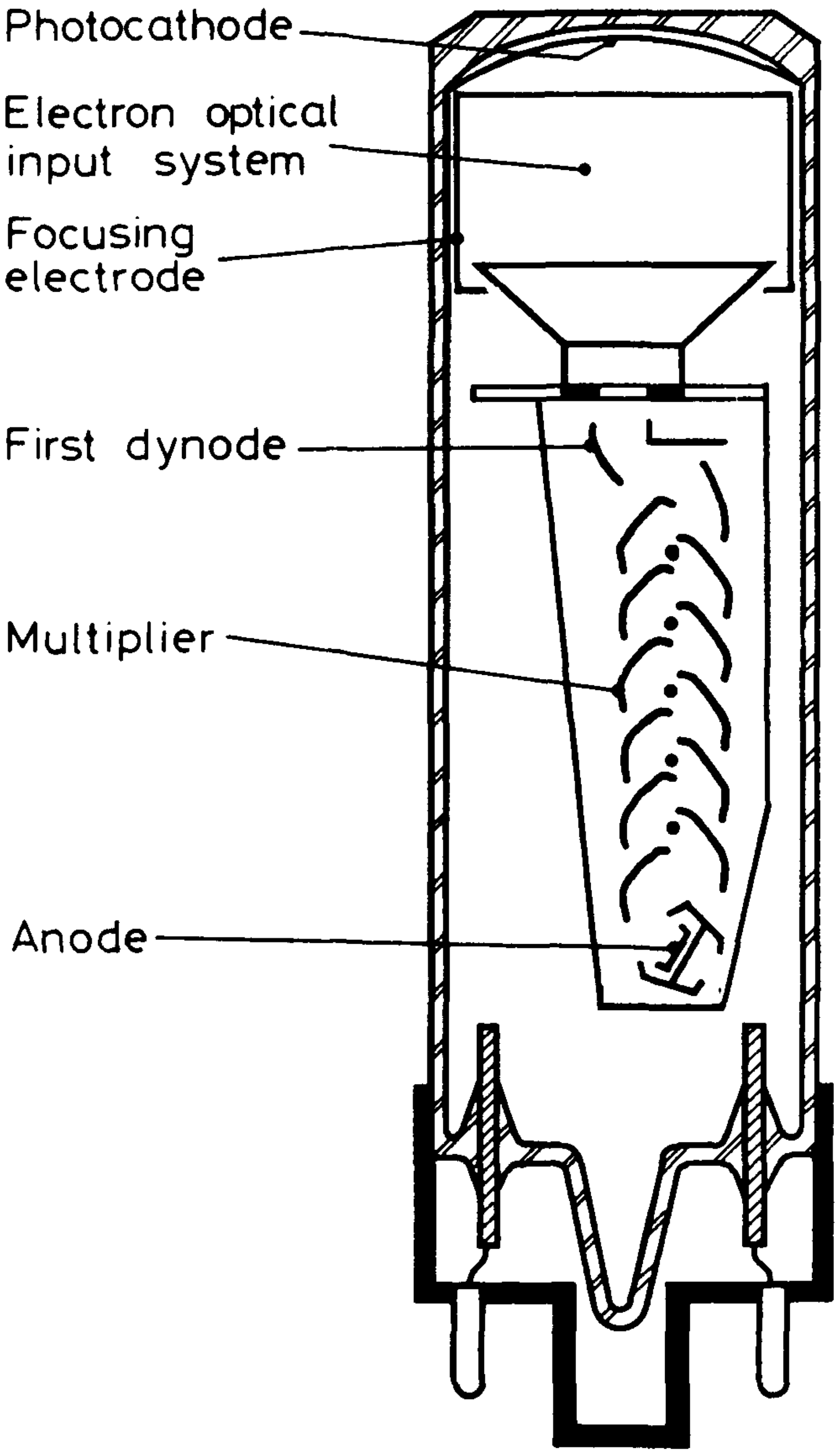
「カミオカンデからスーパーカミオカンデへ」

戸塚　洋二　より

Super-Kamiokande



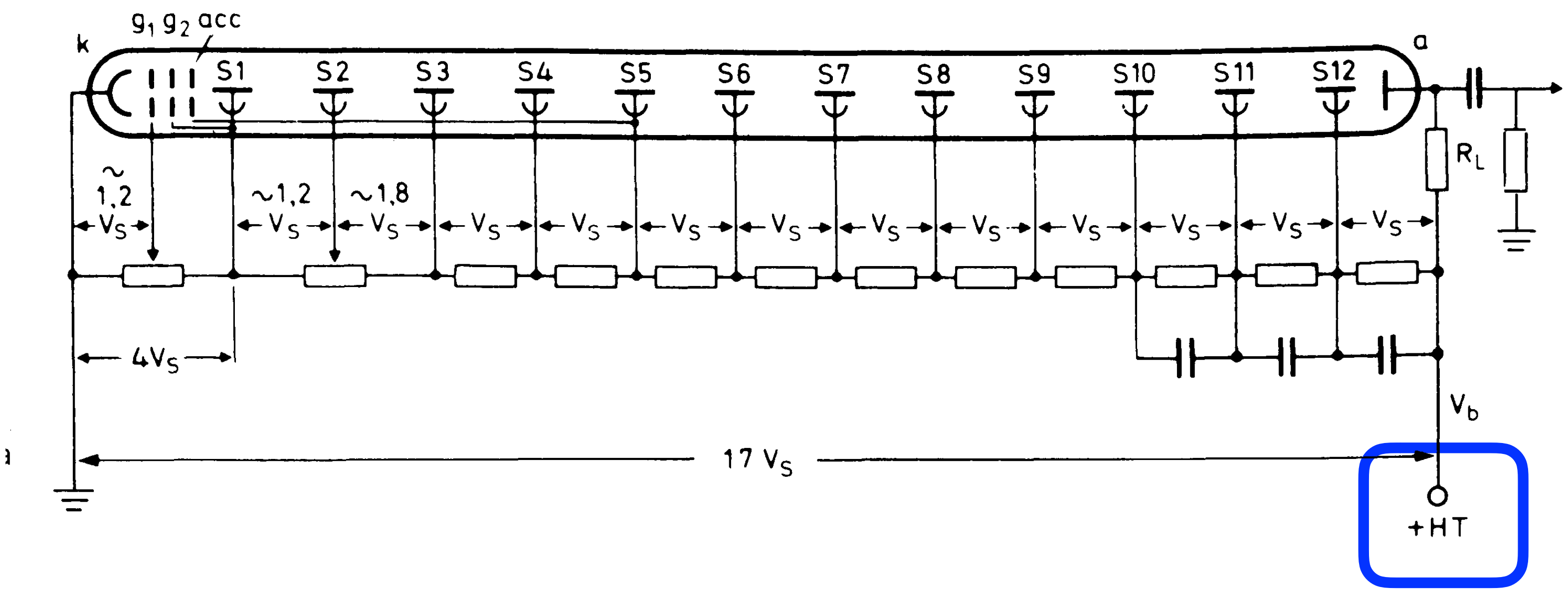
Function of Photomultiplier



- 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.

Photomultiplier voltage divider

- High Voltage (HV) divider (Base): Voltage of 1000~2000V is applied. Positive HV type, and the negative HV type exist.



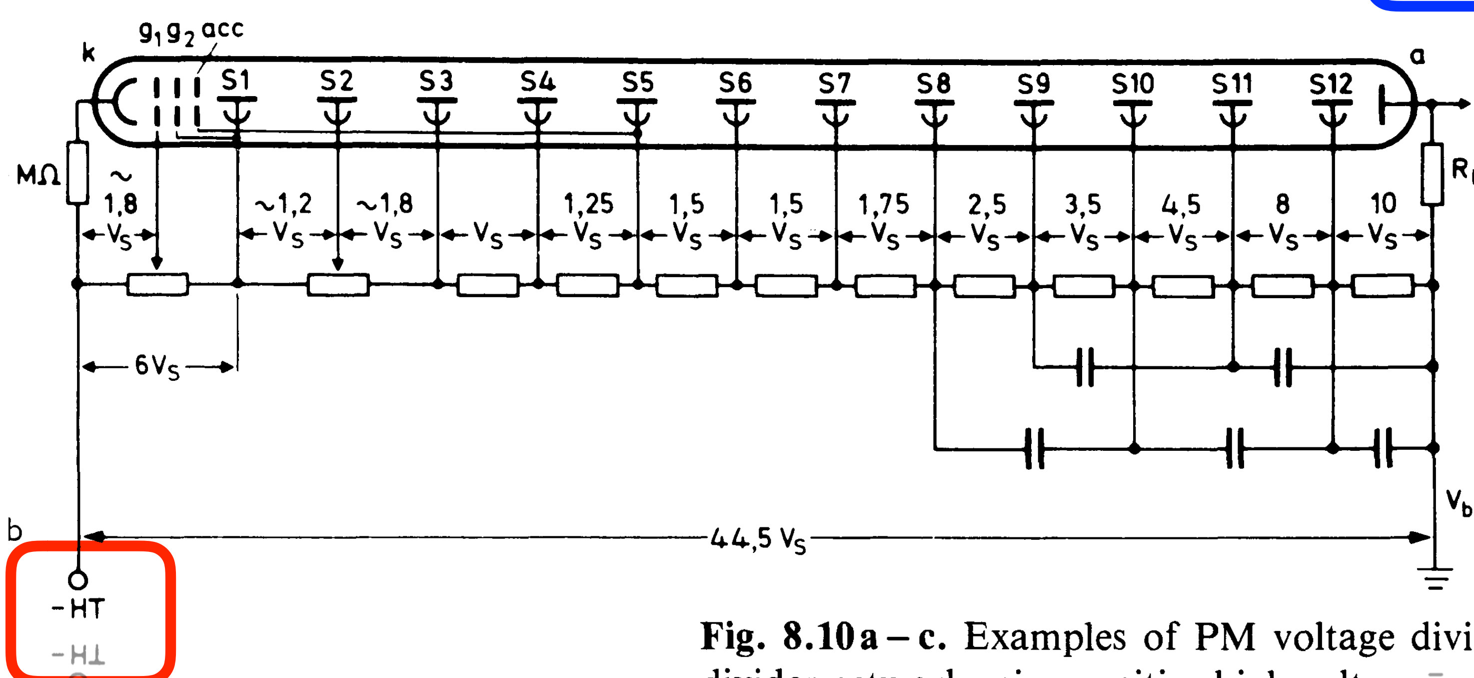
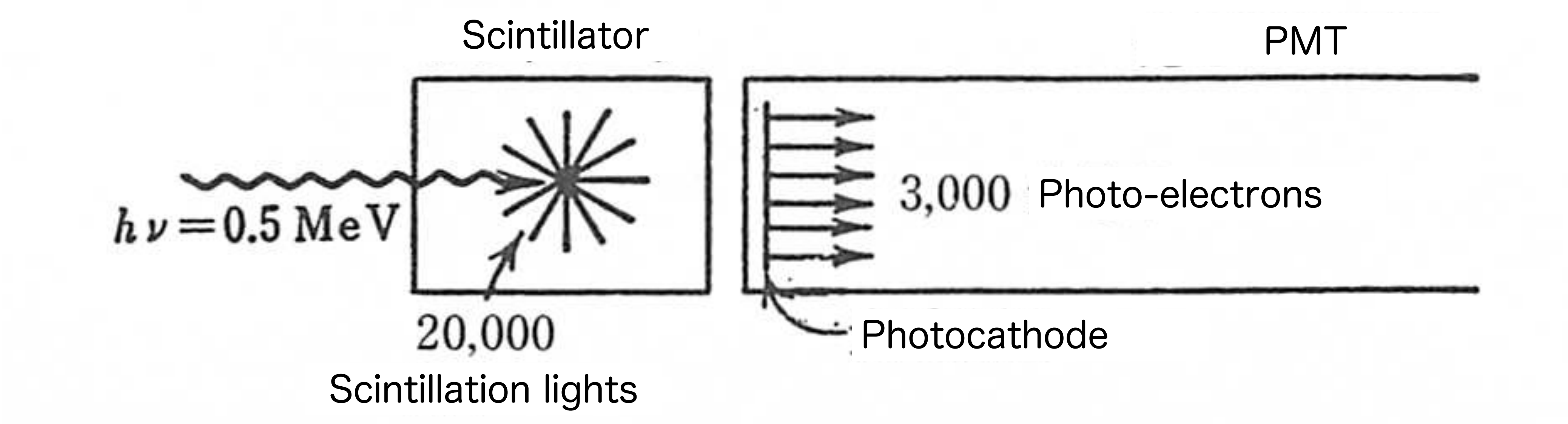


Fig. 8.10 a – c. Examples of PM voltage divider networks (after examples from *Philips Catalog* [8.7]: **(a)** divider network using positive high voltage; note the AC coupling capacitor at the anode, **(b)** a network using negative high voltage and decoupling capacitors for maintaining the voltages between the last few dynodes,

The number of photons (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
    - $\sqrt{(3000)} \div 3000 = 0.018$ (1.8%)

Semiconductor photon detector

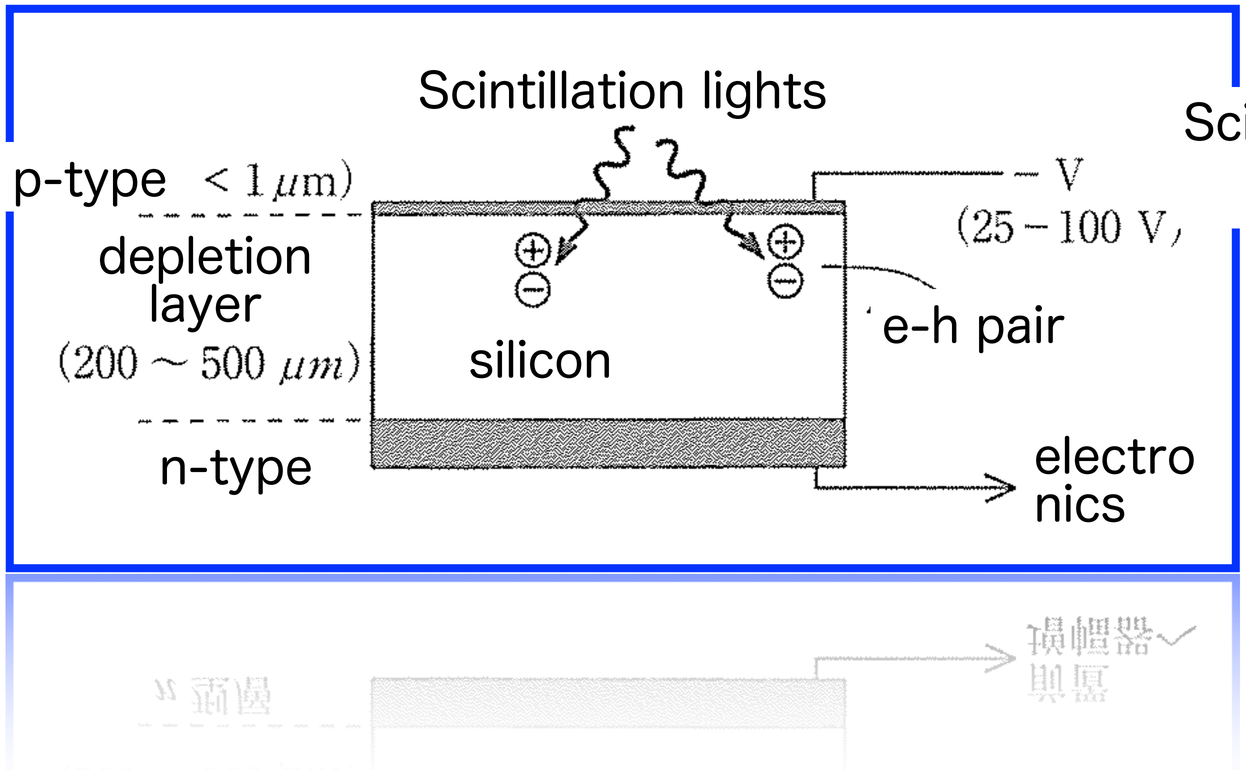
Hamamatsu HP: “What is MPPC?”

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

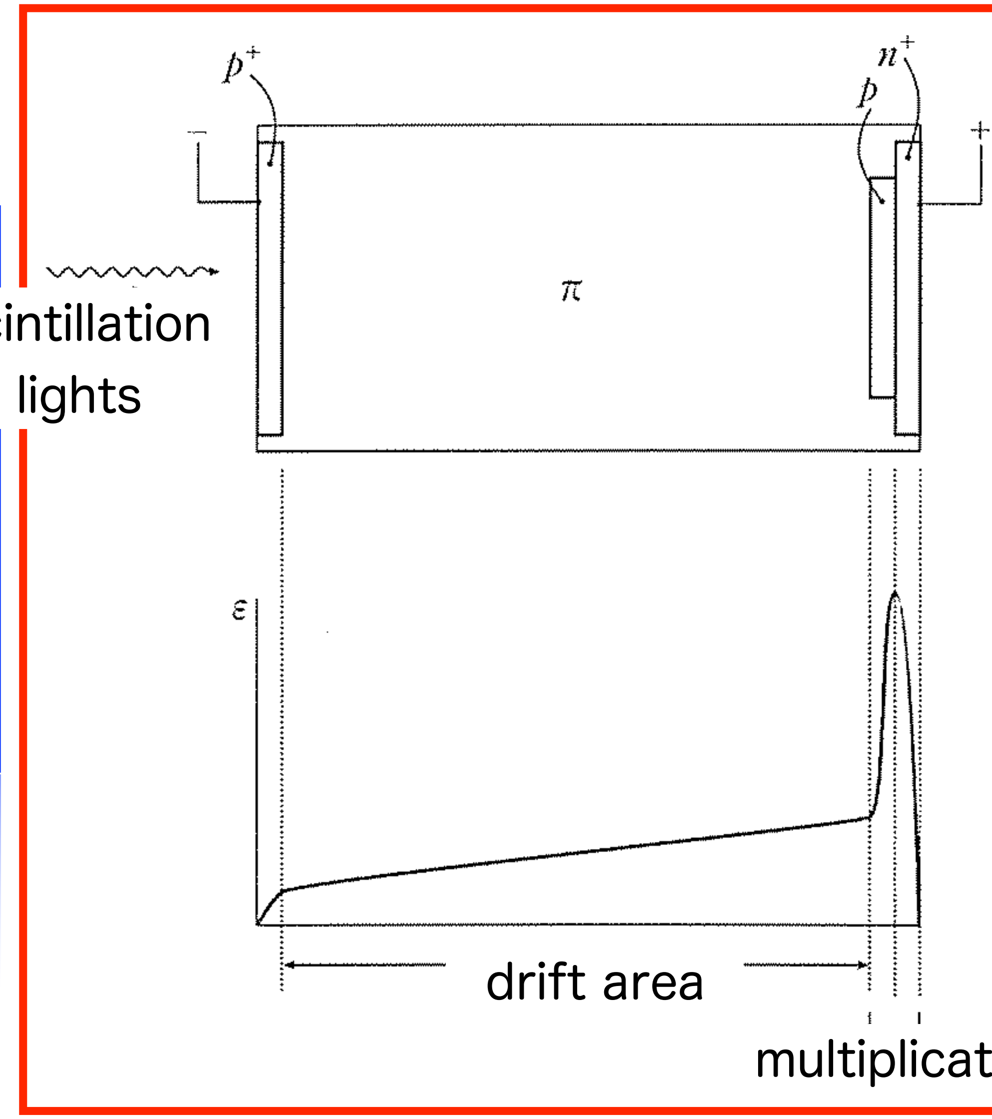
	PD	APD	MPPC	PMT
	Photo-diode	Avalanche photo-diode	Multi-channel Giger mode photo-diode	Photomultiplire tube
gain	1	10^2	$\sim 10^6$	$\sim 10^7$
sensitivity	low	medium	high	high
Voltage applied	5V	100~500 V	30~60 V	800~1000V
Sensitive area	small	small	small-medium	large
Electronics	complicated	complicated	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	○	○	○	×

Semiconductor photon detector

PD



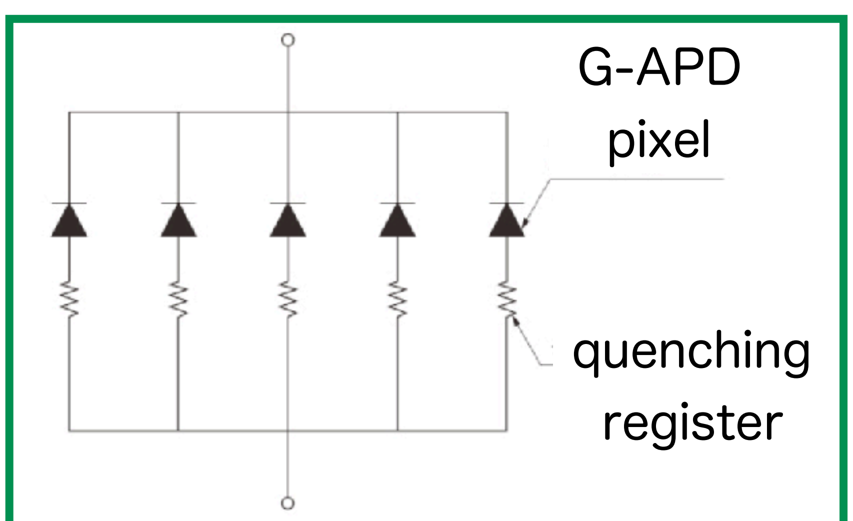
APD



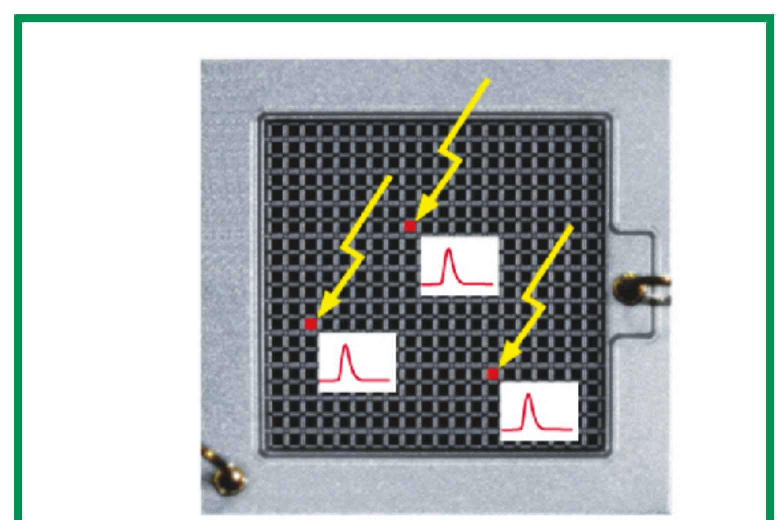
構造

MPPCによるフォトンカウンティングのイメージ

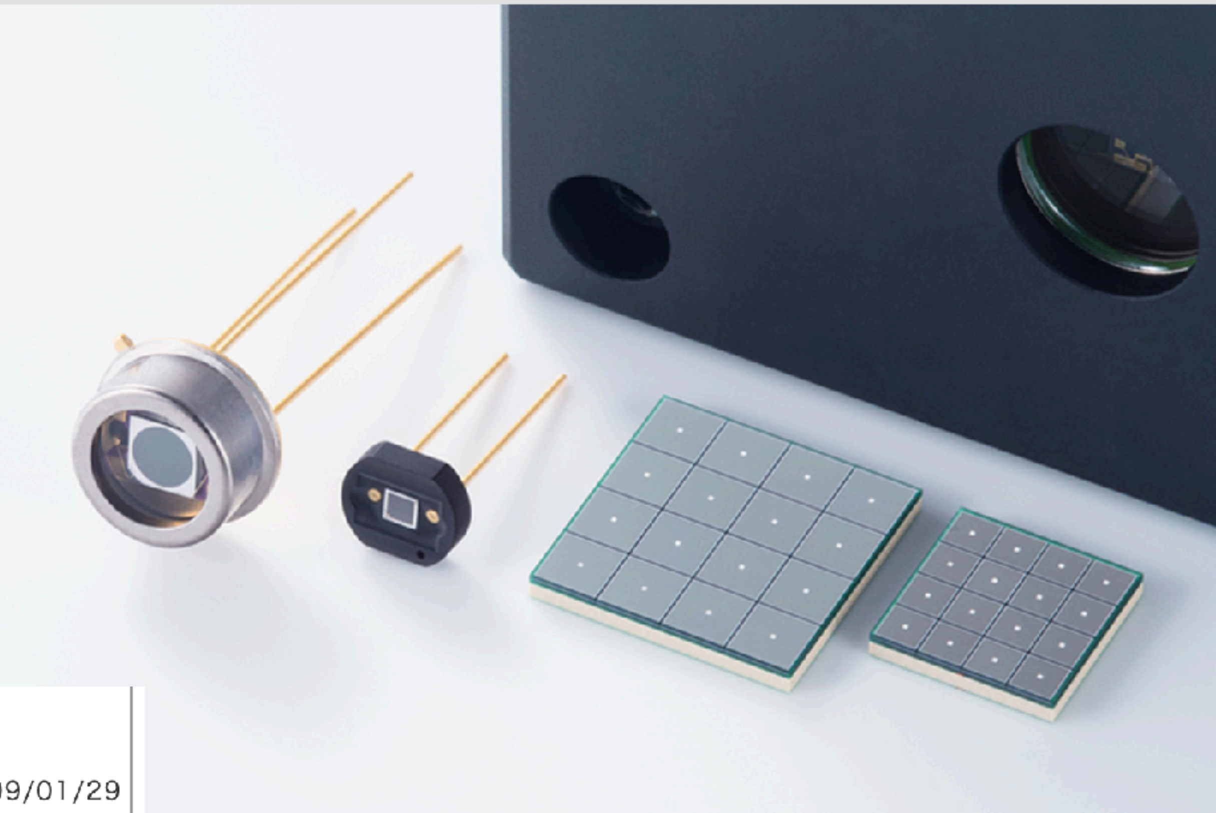
MPPC



MPPC

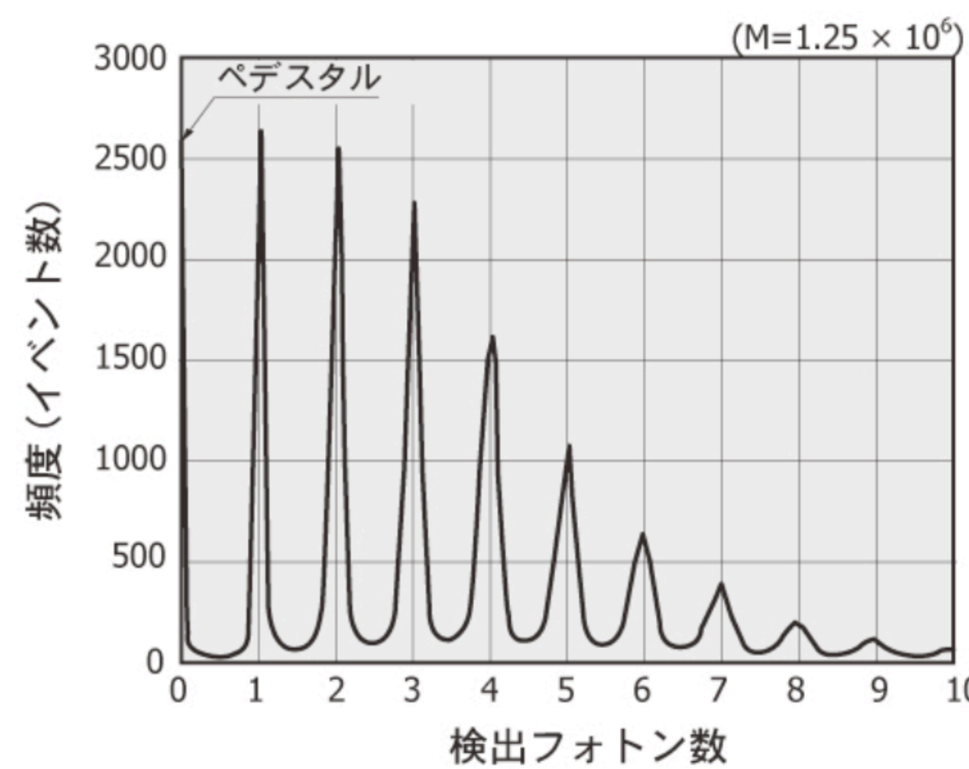


MPPC (SiPM)



Japanese (many master thesis, but one English)
https://www-he.scphys.kyoto-u.ac.jp/theses

2008	大谷 将士	T2K長基線ニュートリノ振動実験ニュートリノビームモニター INGRIDの製作と性能評価	2009/01/29
	河崎 直樹	K^{O}TO実験のためのNeutron Collar Counterのdesignおよび開発	
	永井 直樹	T2K実験において用いられる半導体検出器MPPCの大量測定	
	増田 孝彦	K^{O}TO実験に用いる低消費電力型光電子増倍管ベースの開発	
2007	川向 裕之	T2K長基線ニュートリノ振動実験ニュートリノビームモニター INGRIDに用いるシンチレーター及び光子検出器MPPCの性能評価	2008/01/31
	久保 一	NUMIビームラインを用いたT2K実験ミューオンモニターの長期試験 (FNAL T968実験)	
	黒澤 陽一	長基線ニュートリノ振動実験T2Kの電磁ホーンの調整位置/電流モニタ・制御系の開発研究	
	五味 慎一	半導体光検出器MPPCの性能評価システムの構築	
	塩見 公志	E14実験におけるバックグラウンド事象についての研究	
2006	田口 誠	Development of Multi-Pixel Photon Counters and readout electronics	2007/01/31
	松岡 広大	T2K長基線ニュートリノ振動実験ミューオンモニターの開発	
2005	江澤 孝介	ガンマ線に対して高い位置分解能を持ったシンチレーション検出器の開発	2006/02/01
	栗本 佳典	T2K実験におけるニュートリノビームモニターの開発	
	中島 康博	中性K中間子稀崩壊探索実験のためのエアロジェルを用いた光子検出器の開発	
	信原 岳	新型光検出器MPPCの開発	



Semiconductor detector

- What is semiconductor?
  - Semiconductors have the intermediate remittances between metals and insulators. They are crystalline materials with covalent bonding; silicon and germanium.

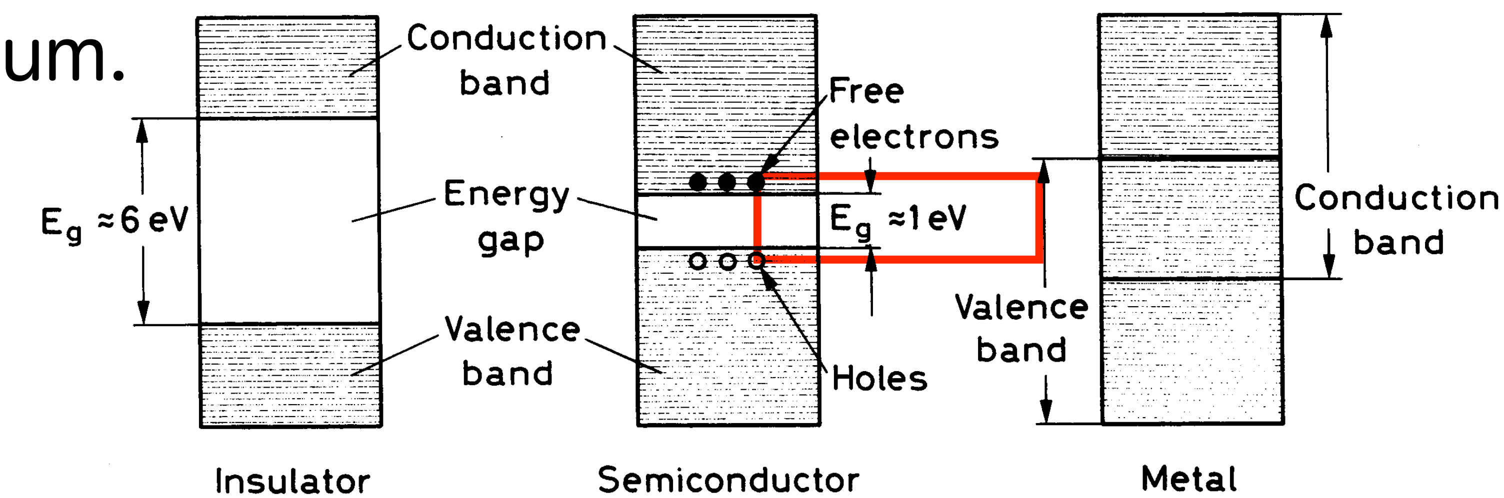


Fig. 10.1. Energy band structure of conductors, insulators and semiconductors

- Very good energy resolution
- Doped semiconductors

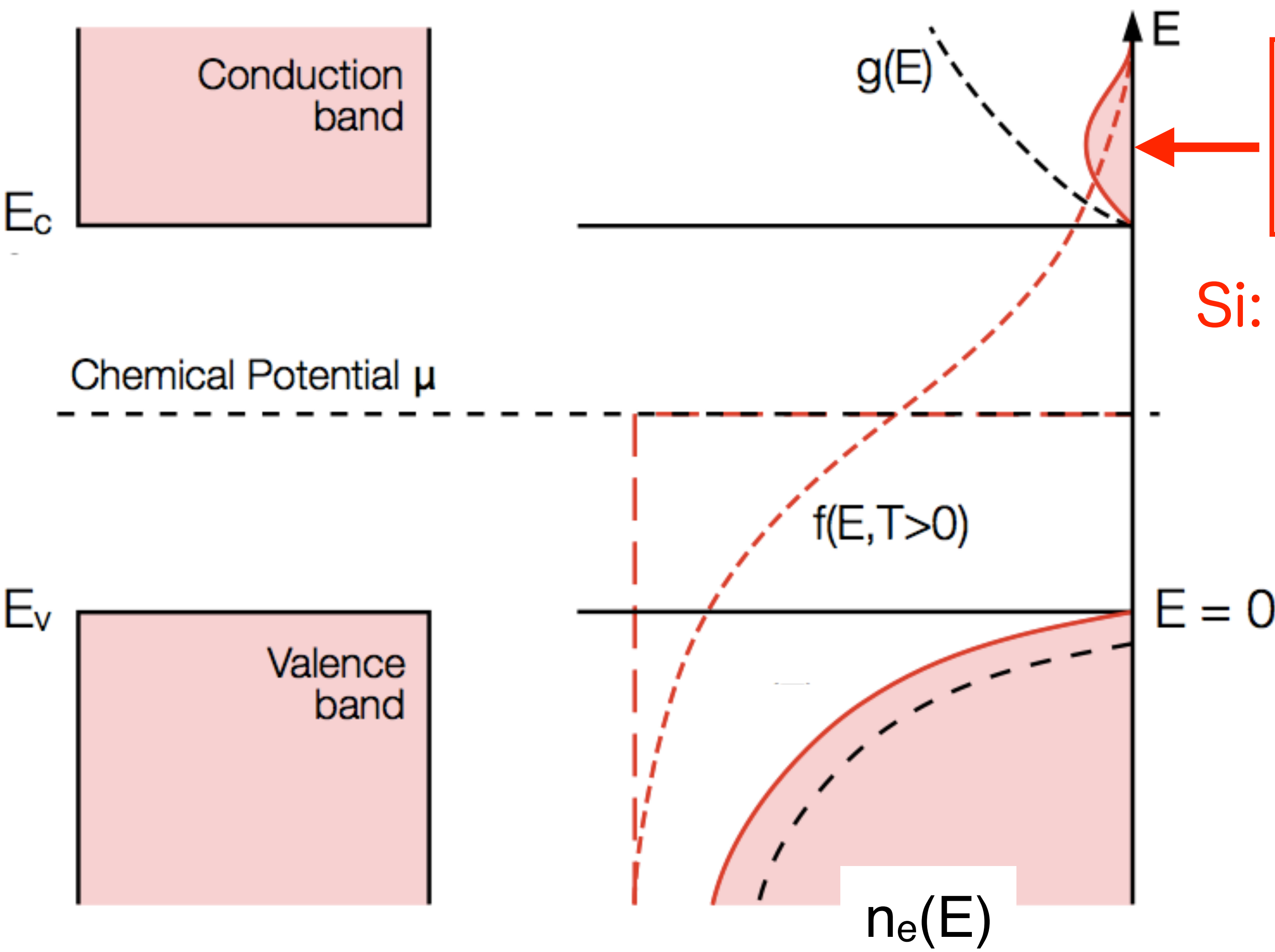
(1) n-type

- The impurity atom (P, As, Sb, ..) has five valence electrons, an extra electron is left.

(2) p-type

- The impurity atom (Al, B, Ga, In, ···) has three valence electrons (one less valence electrons), there is an excess of holes.

The number of electrons in the conduction band



$$n = \frac{\sqrt{\pi}}{2}\frac{(2m_e k_B T)^{\frac{3}{2}}}{2\pi^2\hbar^3}\cdot e^{-(E_C-\mu)/k_B T}$$

Si: ~10^{10} electrons, Ge: ~10^{13} electrons n-type

p-type

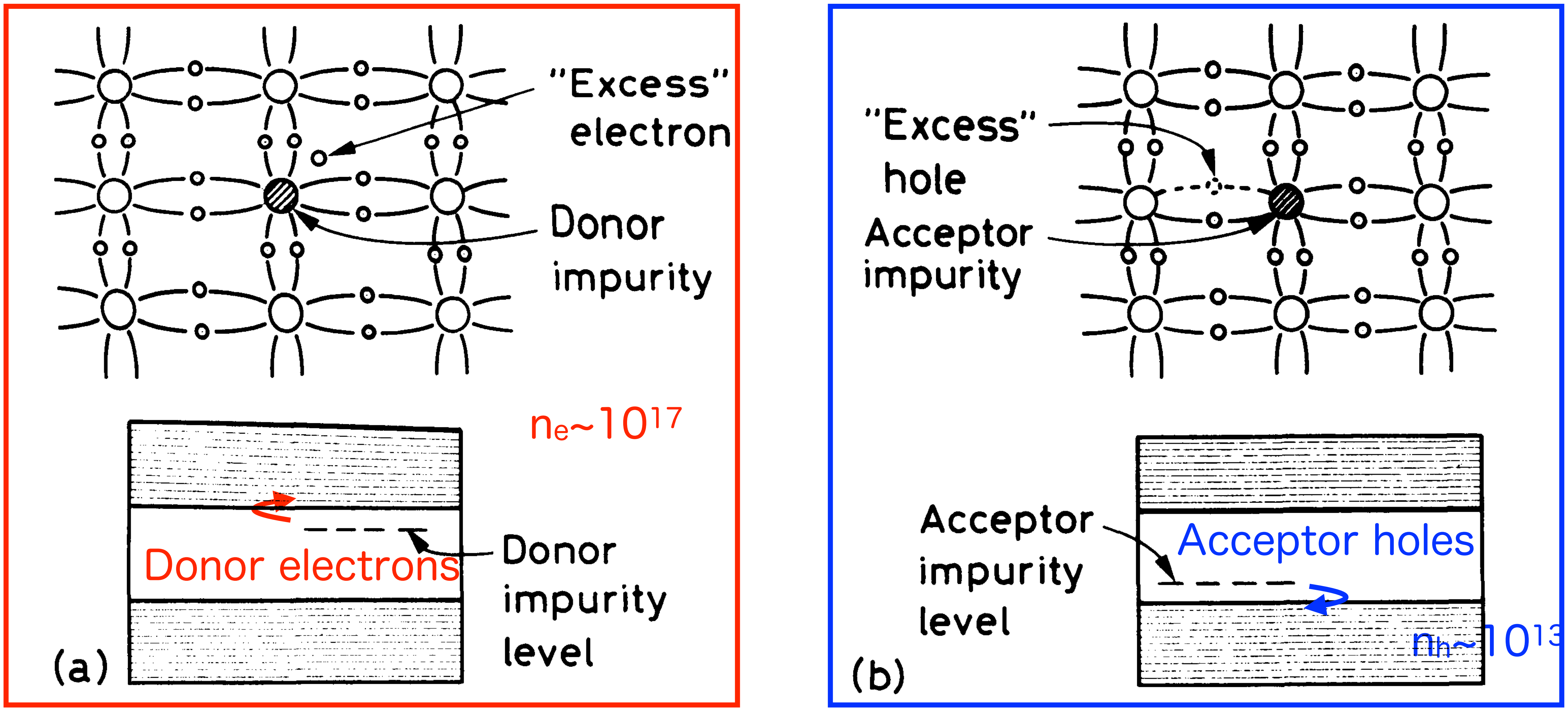


Fig. 10.4. (a) Addition of donor impurities to form n-type semiconductor materials. The impurities add *excess* electrons to the crystal and create donor impurity levels in the energy gap. **(b)** Addition of acceptor impurities to create p-type material. Acceptor impurities create an *excess* of holes and impurity levels close to the valence band

The np Semiconductor Junction

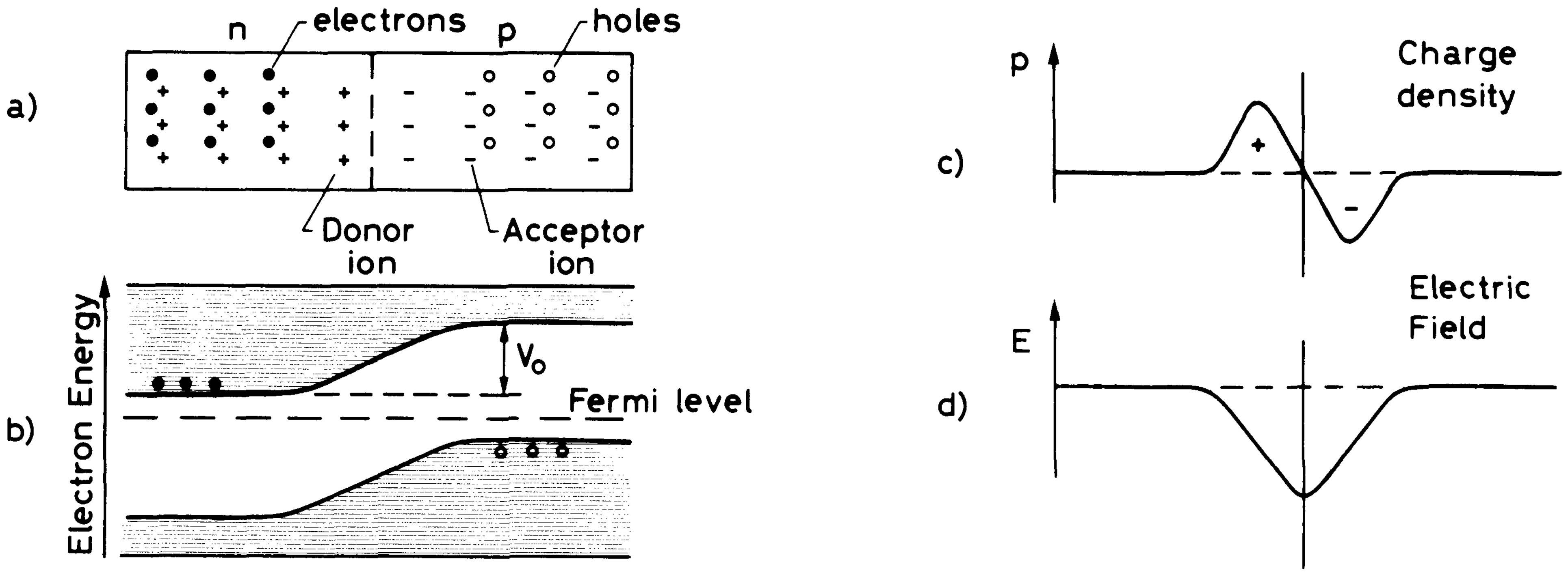
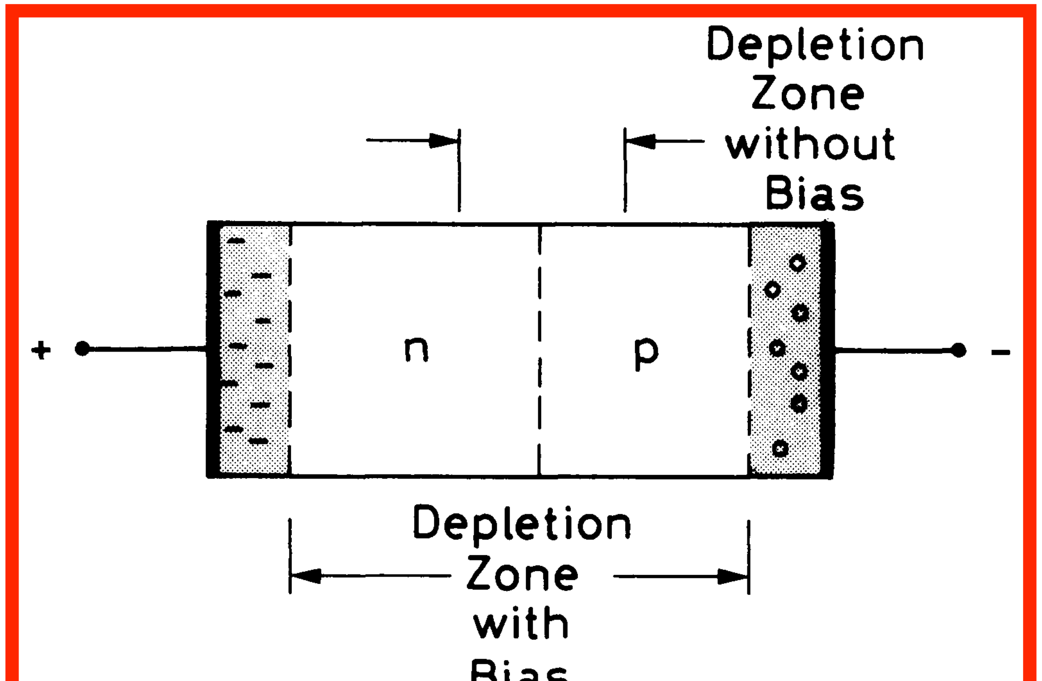


Fig. 10.5. **(a)** Schematic diagram of an np junction, **(b)** diagram of *electron* energy levels showing creation of a contact potential V_0, **(c)** charge density, **(d)** electric field intensity

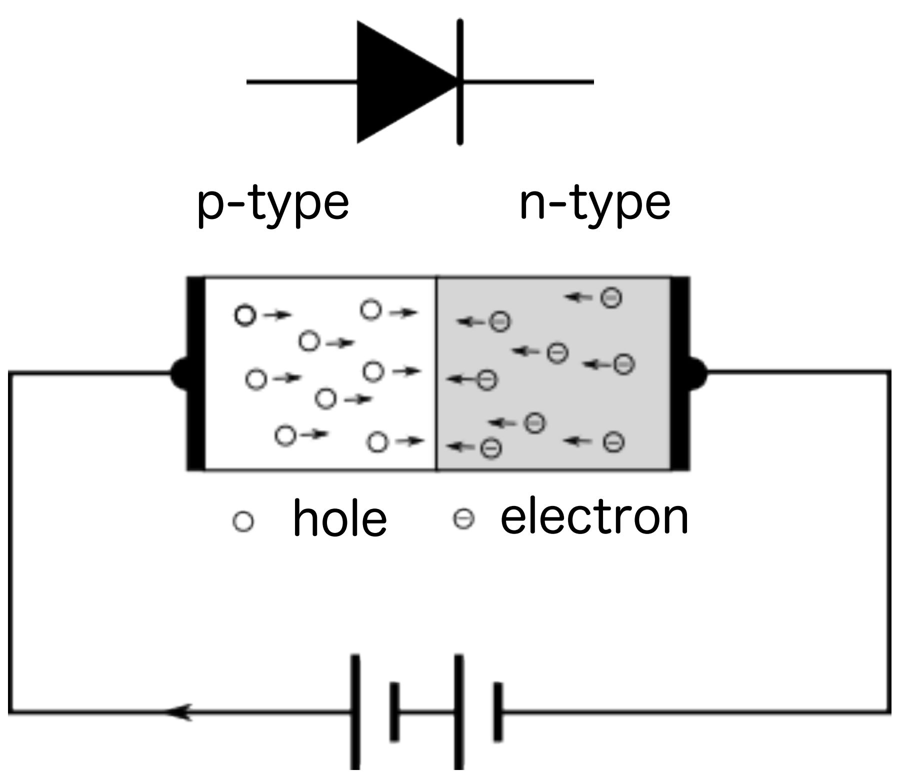
Reversed bias applied



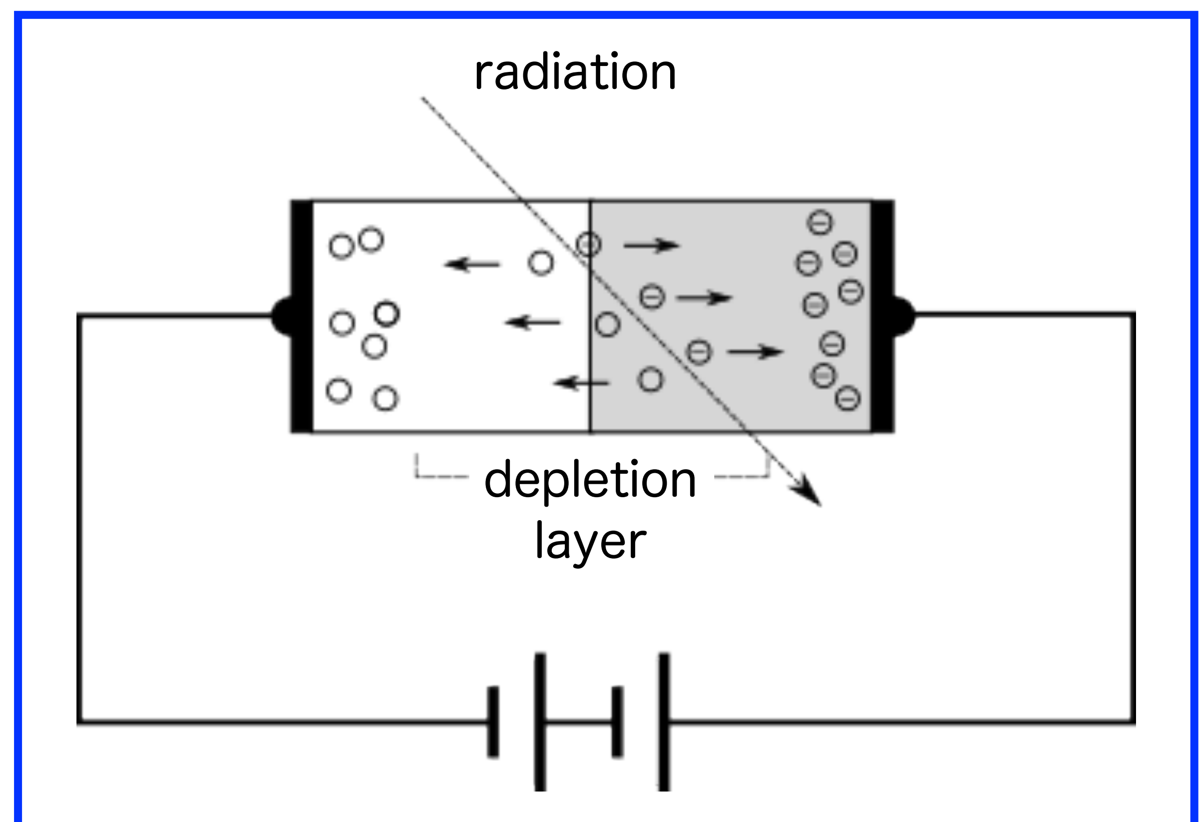
Semiconductor (The np junction and Depletion depth w/ reversed bias)

- http://www.x-ray.co.jp/mame.html

Normal Bias



Reverse bias for radiation detector



Ge γ ray semiconductor detector

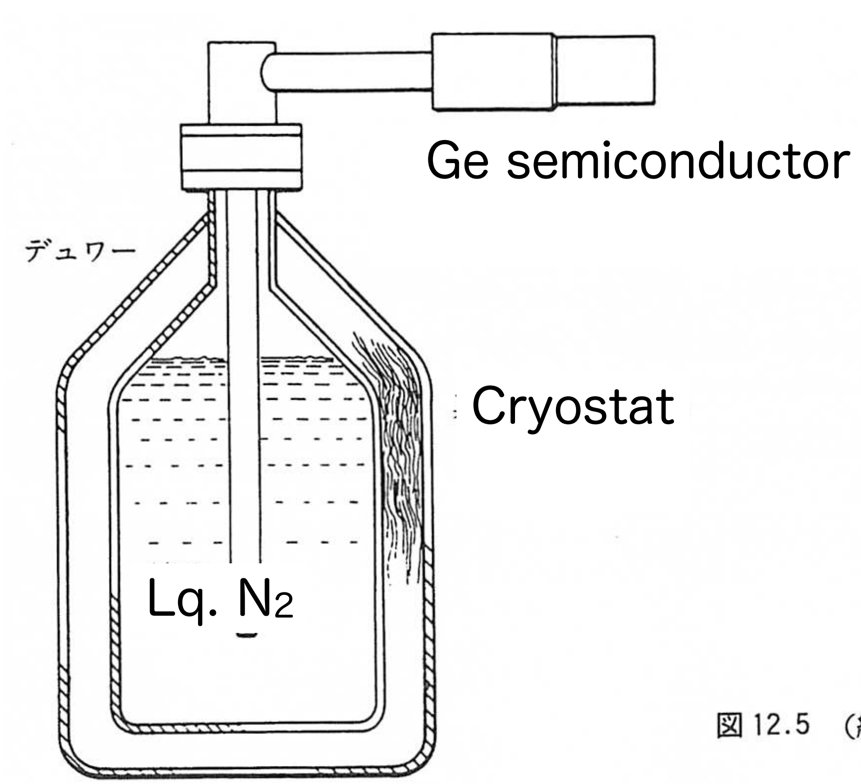
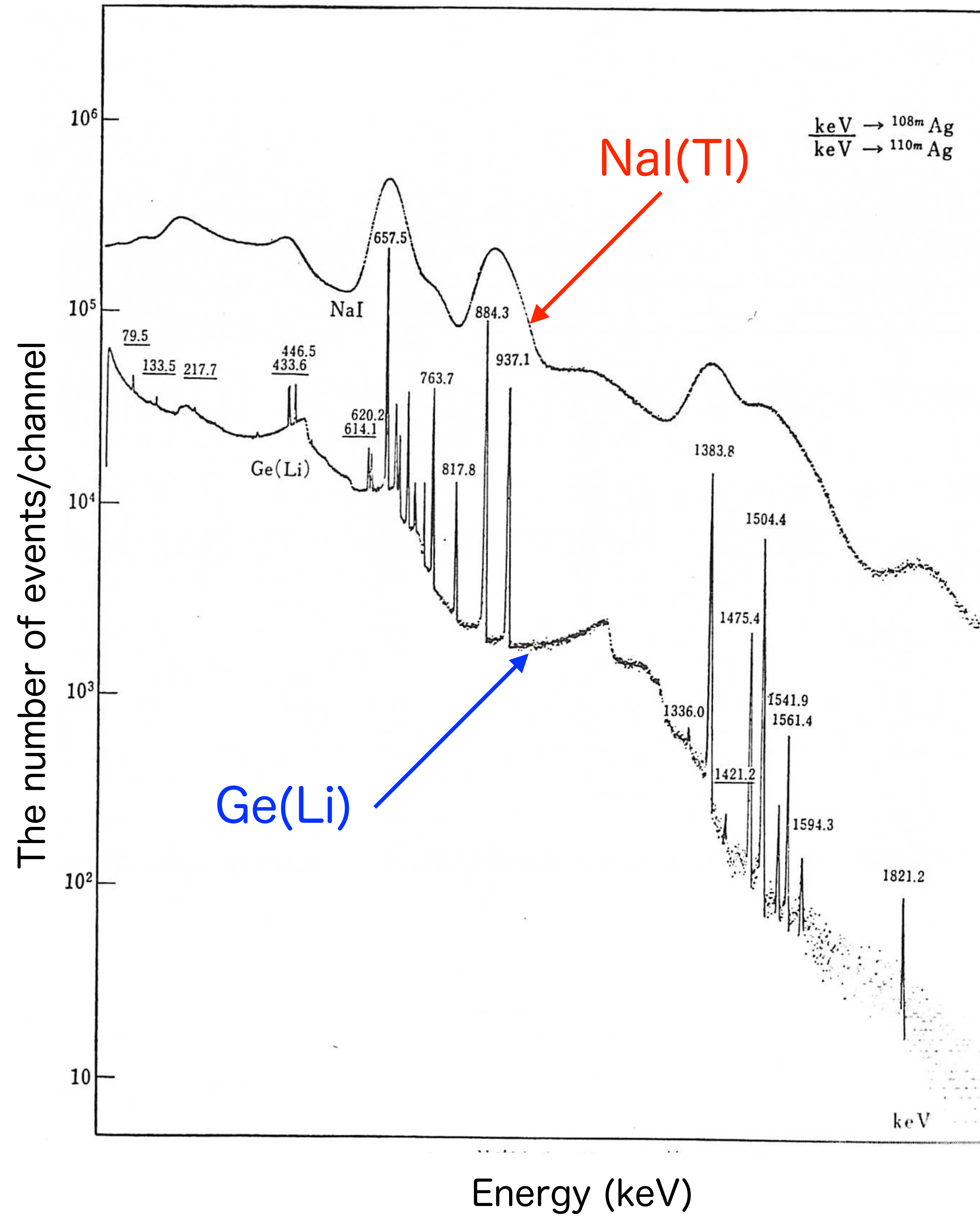


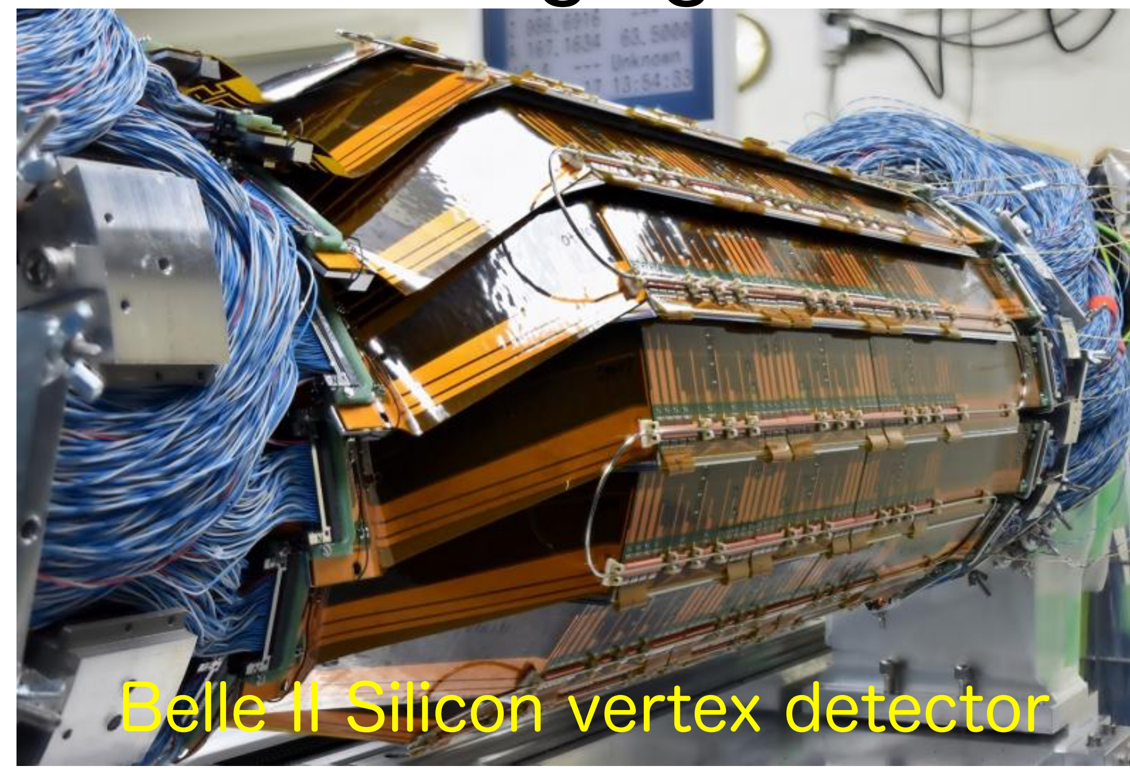
図 12.5 （続き）

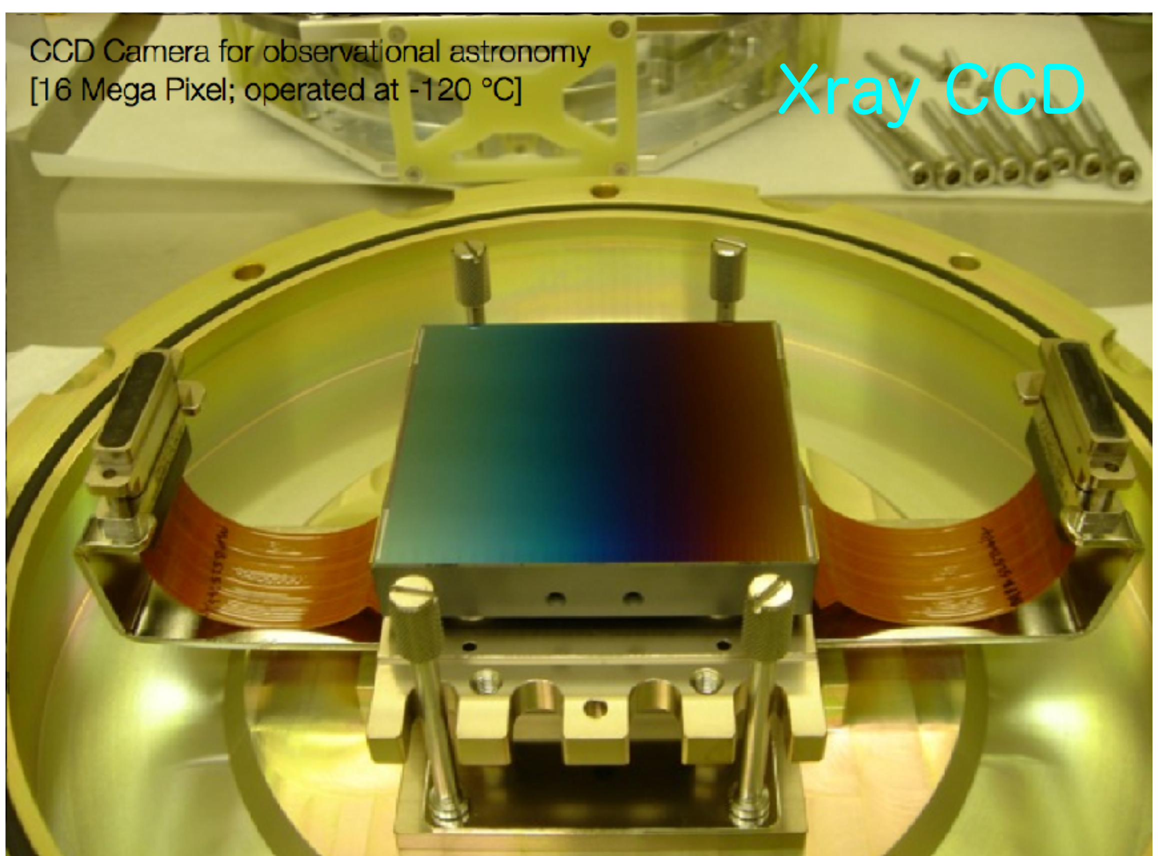
Germanium semiconductor detector

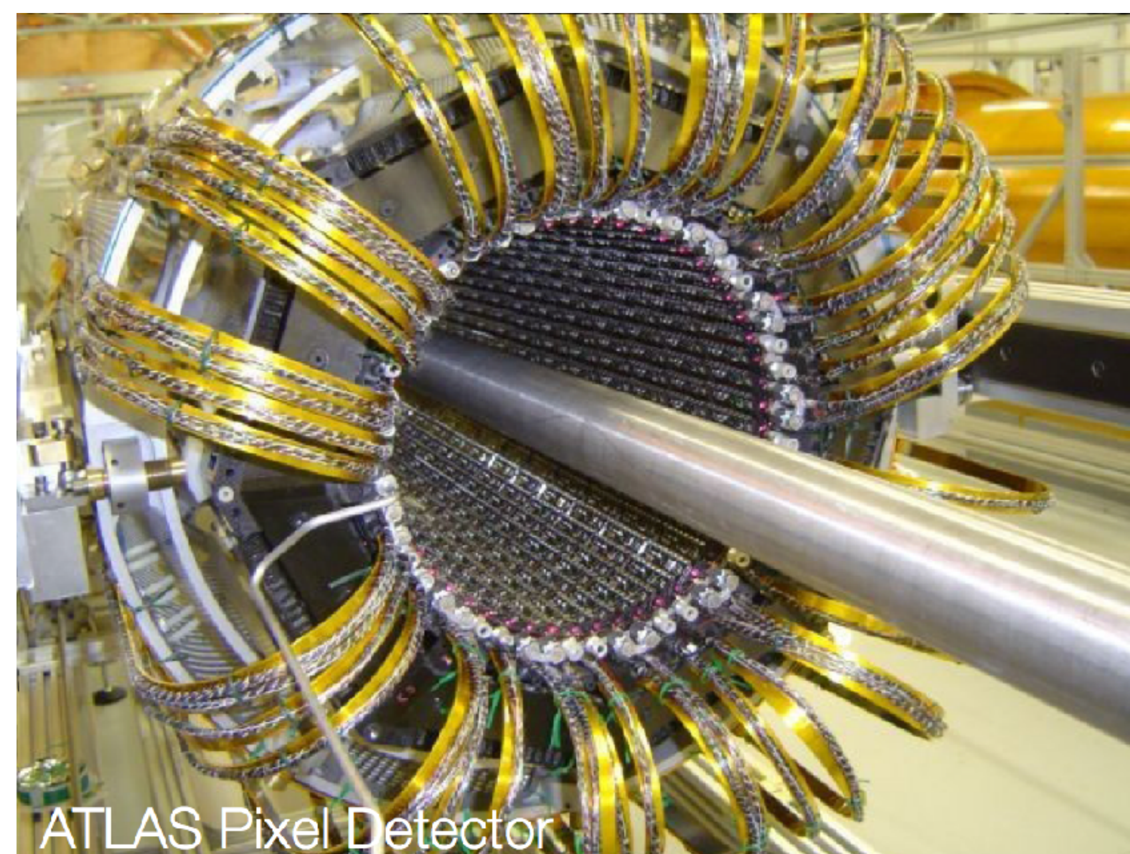


Semiconductor detectors

- Semiconductor detectors for vertex and imaging
  - Vertex detector
    - Strip structure
    - Pixel structure
  - X ray CCD

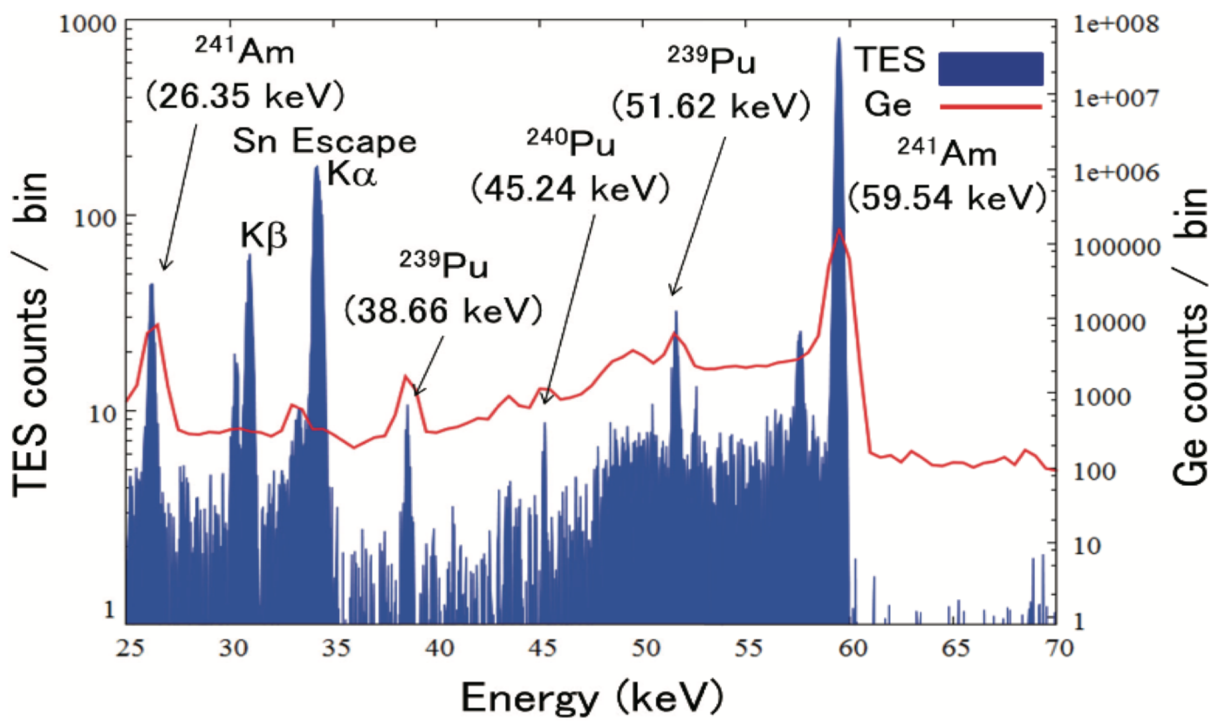


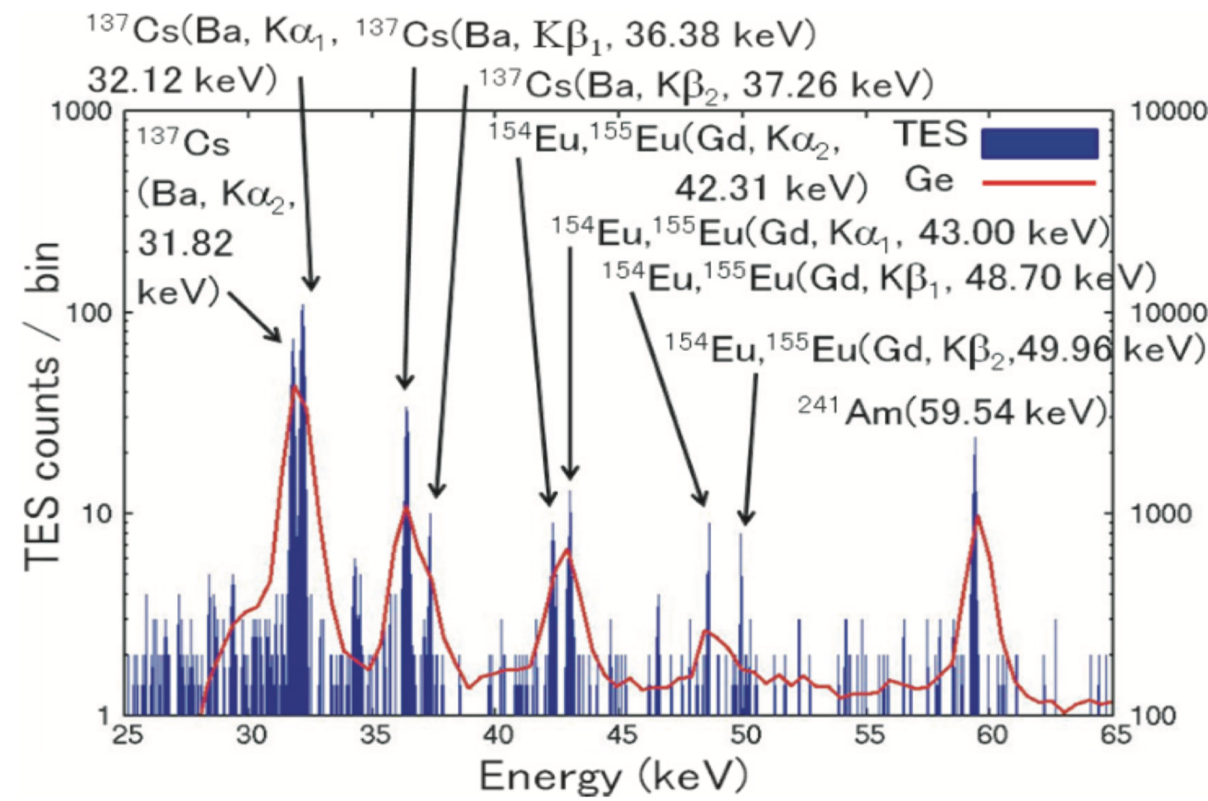




Superconducting detector（Ultimate detector?)

Superconductor Semiconductor

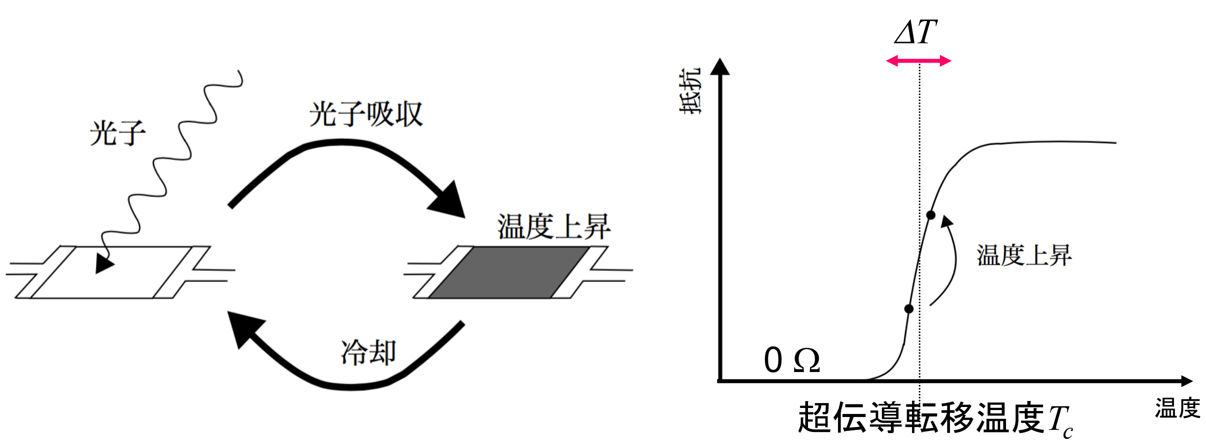




by Prof. Osamu Tajima

Transition edge sensor (TES)

photon測定:ミリ波からガンマ線まで



光子のエネルギー∝温度上昇

→TESの抵抗変化

106

Open-It：計測システム研究会2017

http://openit.kek.jp/workshop/2017/dsys/main

「可視光用超伝導転移端センサーの開発」

服部香里（産総研）

Advantage & Disadvantage of Semiconductor (Superconducting) Detector

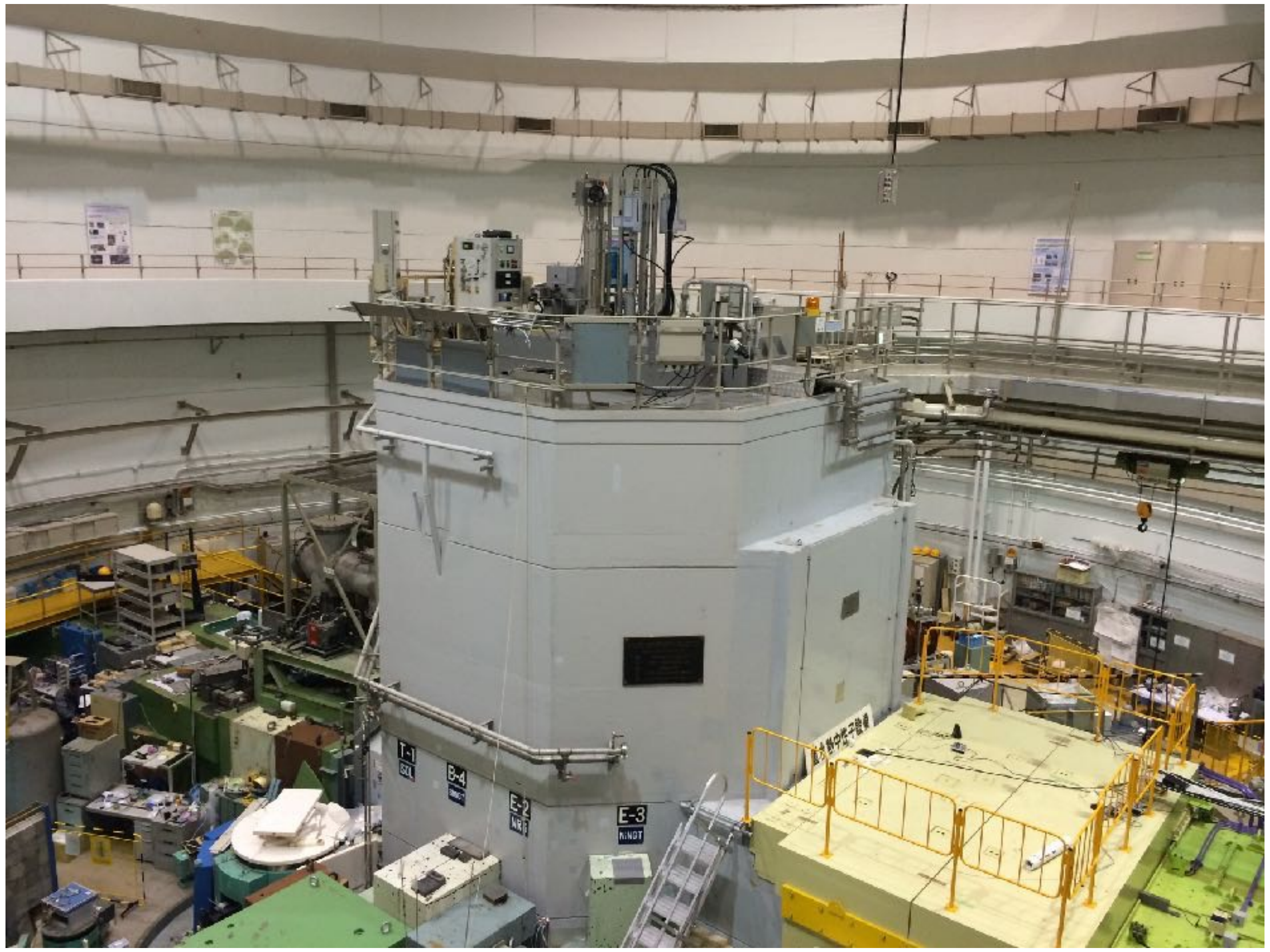
- Good points
  - Excellent Energy resolution
  - Precise position resolution
- Weak points
  - Expensive
  - not easy to make a large detector
  - Only experts can produce
  - Experts knowledge is requested even for operation
    - A superconducting detector is operated only in very low temperature.
  - The data size is often huge because of fine segmentation.

Measurements of particles -other type of detectors-

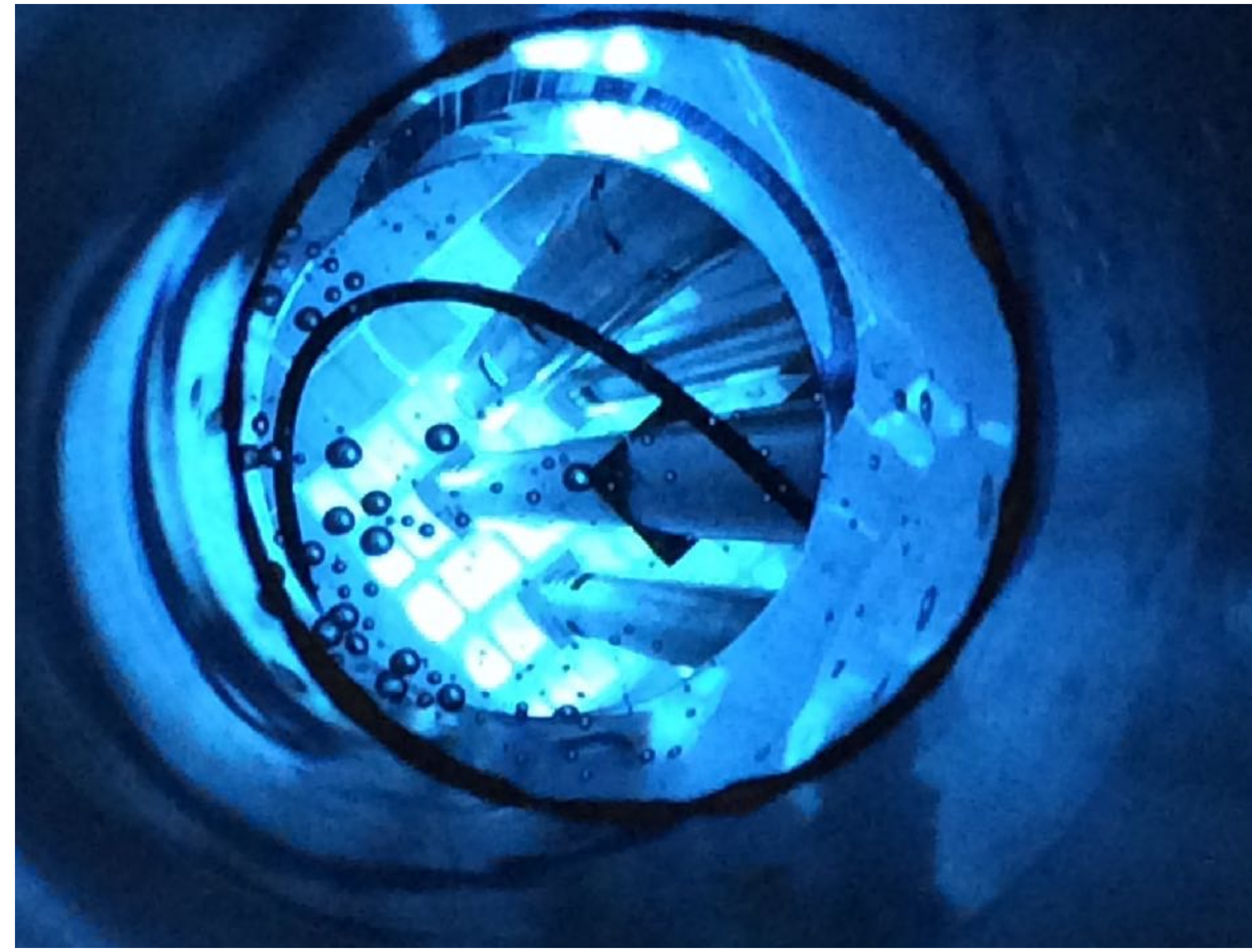
6. Measurements of particles

1. Cherenkov Detector
2. Transition Radiation Detector
3. TPC: Time Projection Chamber
4. Nuclear Emulsion
5. Nobel liquid detector

Cherenkov light



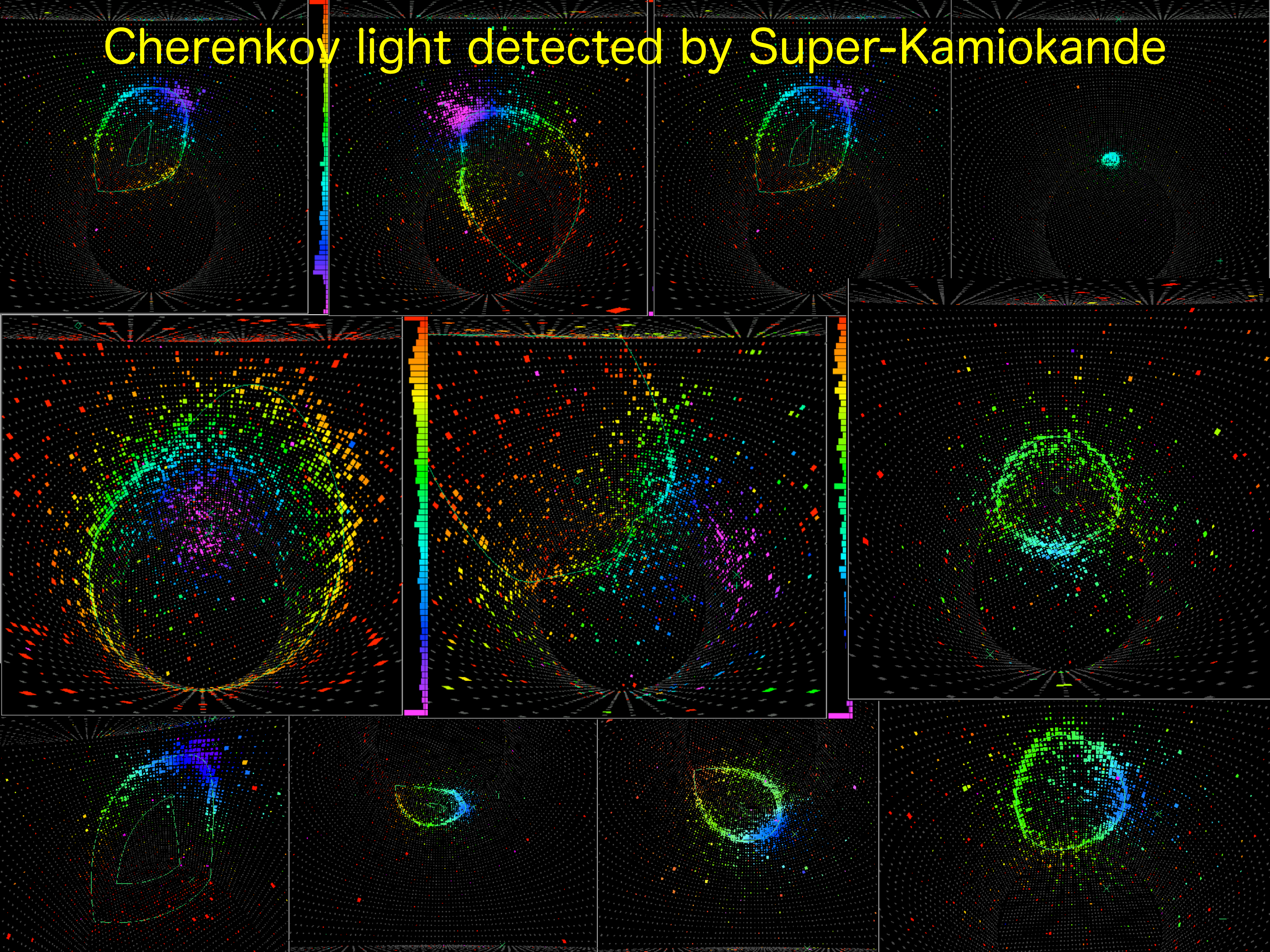
Kyoto U. Nuclear Reactor



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).

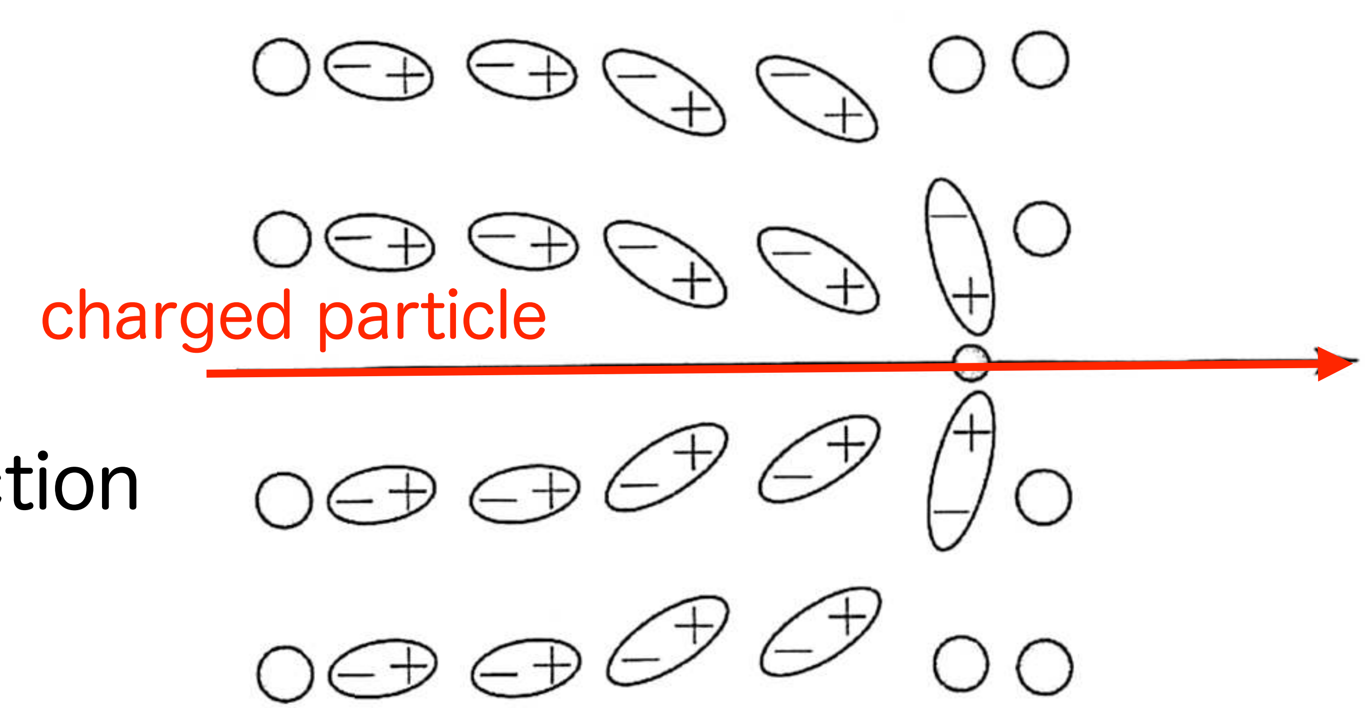
Cherenkov light detected by Super-Kamiokande



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 $v = \beta c > c/n \Rightarrow \beta n > 1$
  - Is is discovered by Cherenkov (the Soviet Union) in 1937.

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



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

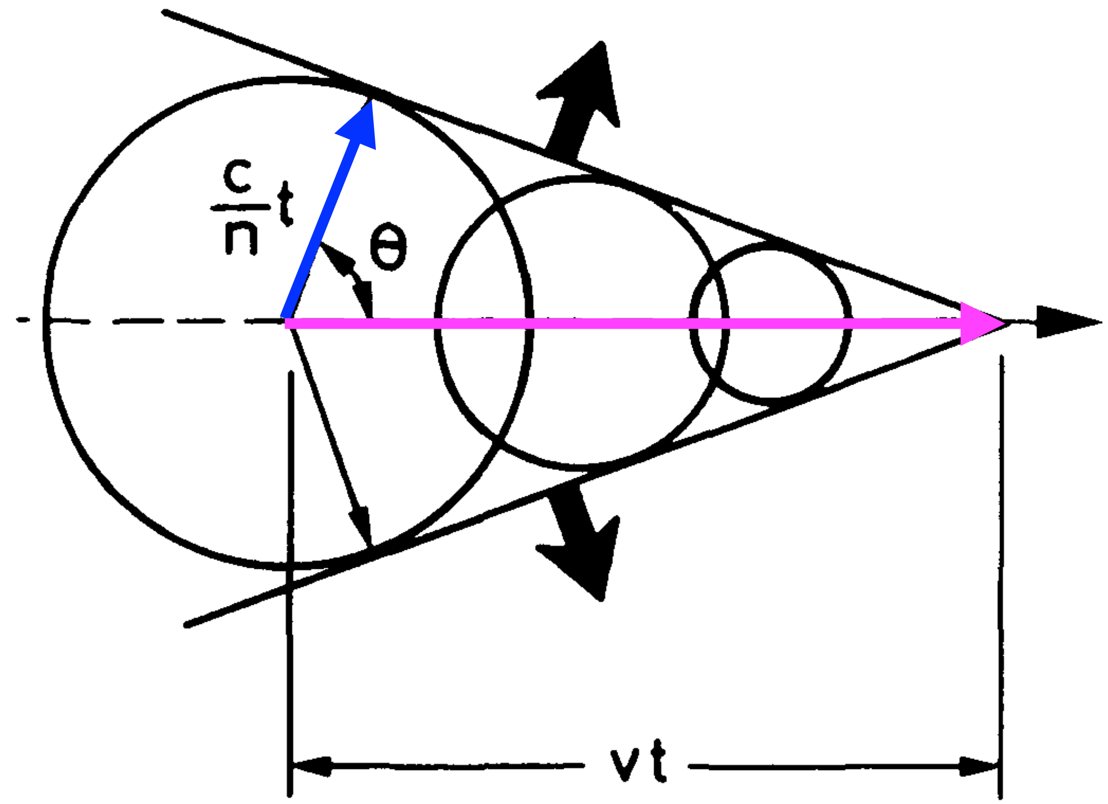


Fig. 2.9. Cherenkov radiation: an electromagnetic shock wave is formed when the particle travels faster than the speed of light in the same medium

Characteristic of Cherenkov radiation

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

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

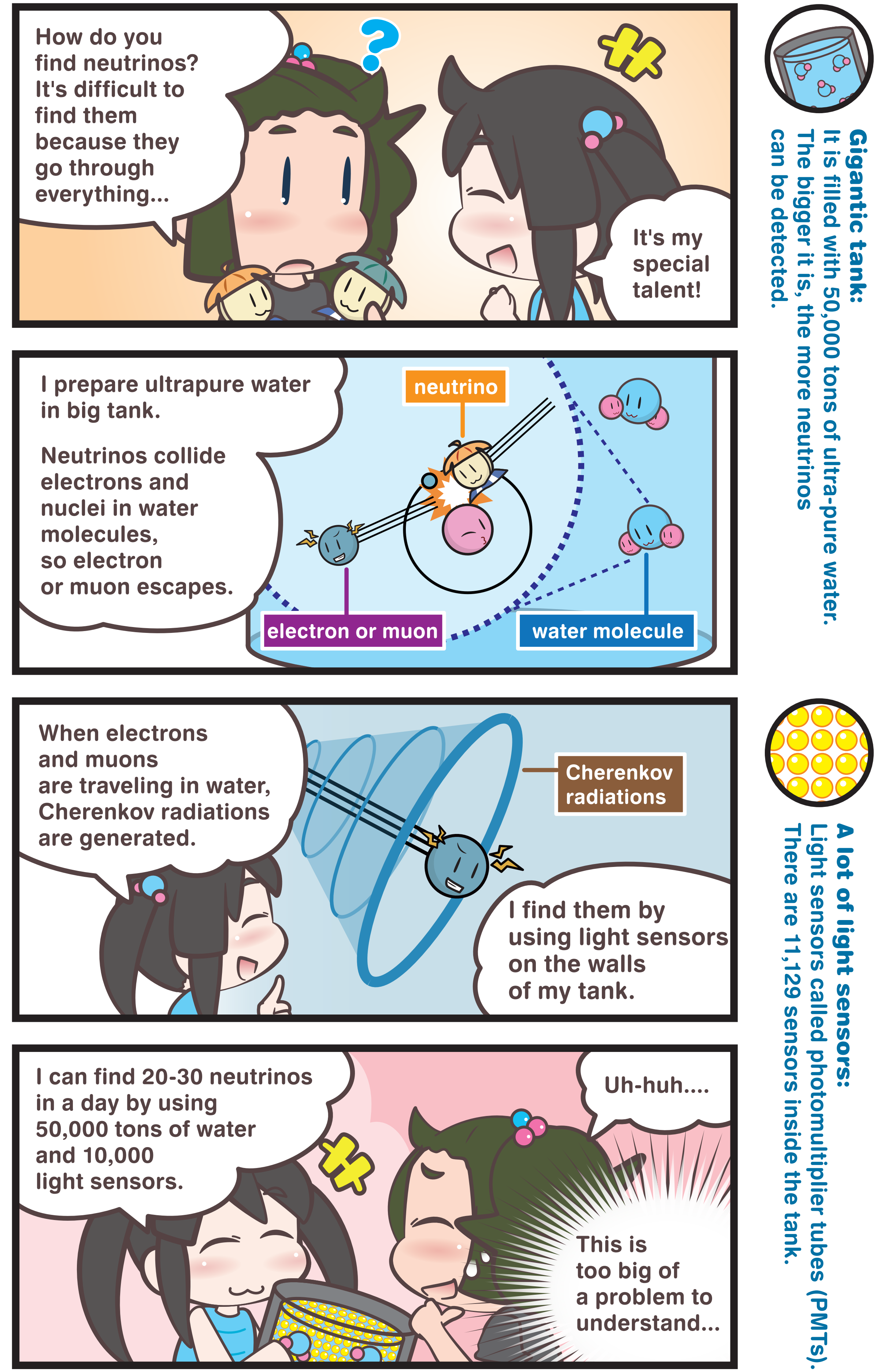
2. Very fast (Prompt radiation)
3. (Disadvantage) The light yield is small. The fraction of energy transforming to the radiation is only 0.1% or so. (Ref. It is ~10% for scintillation)
    - [Q] How many Cherenkov photons are detected in Super-Kamiokande for an 10 MeV electron.
4. The Cherenkov photons 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.

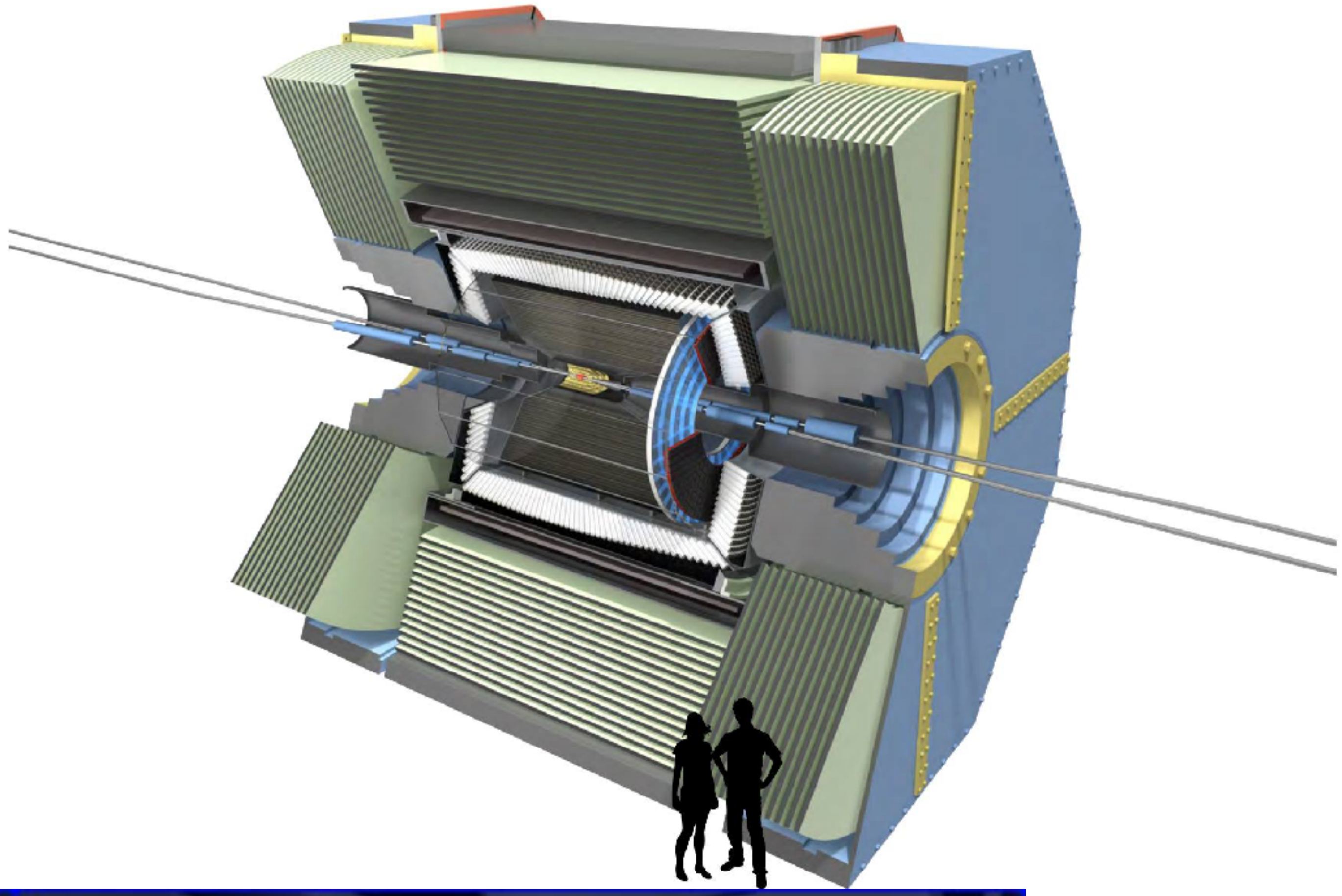
Material medium for Cherenkov

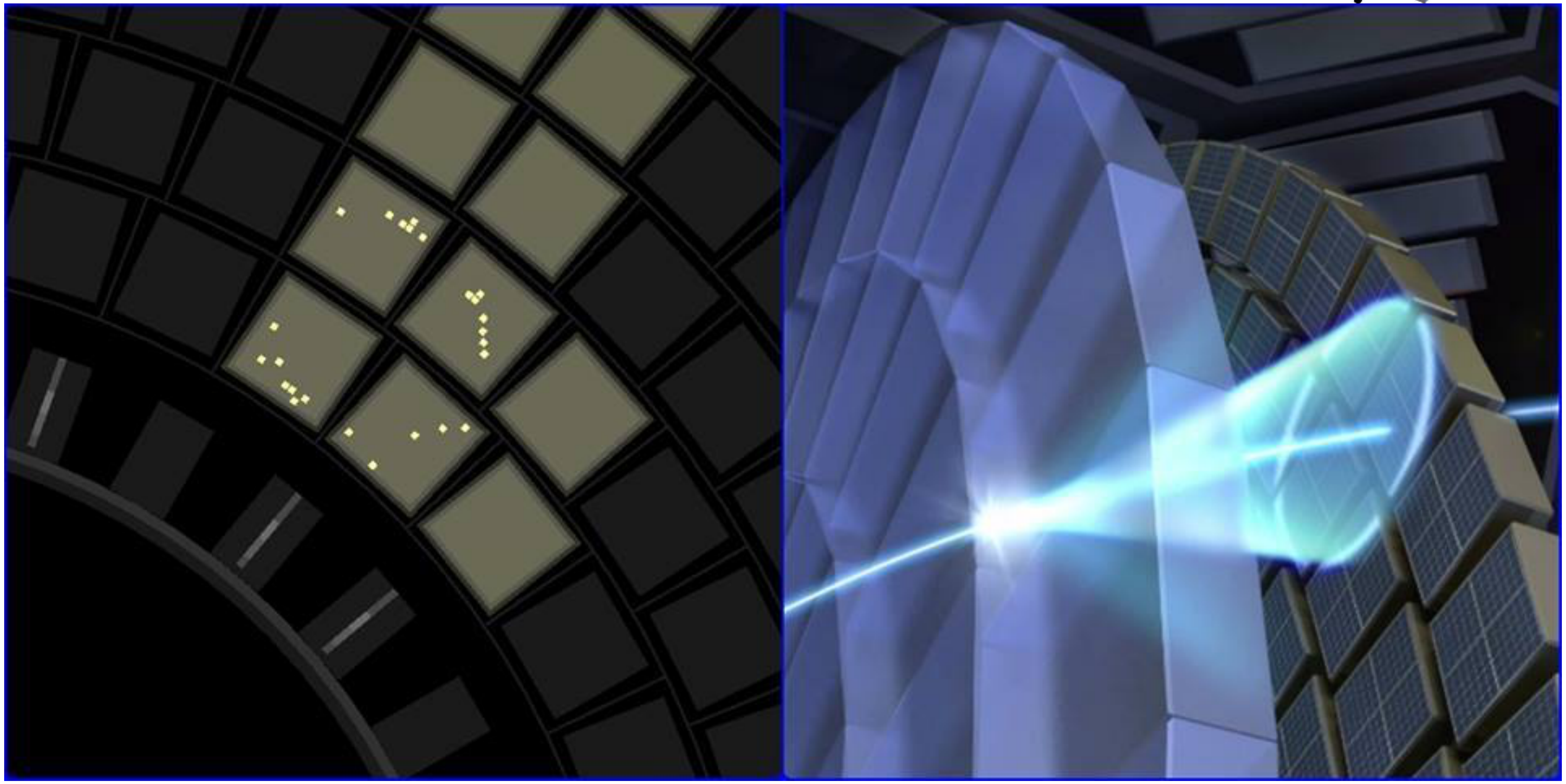
	n-1	β threshold
Diamond	1.42	0.41
glass	0.46~0.75	0.57~0.68
scintillator	0.58	0.63
Water	0.33	0.75
Silica aerogel	0.025~0.075	0.93~0.976
CO_2 gas	4.3×10^{-4}	0.9996
He gas	3.3×10^{-5}	0.99997

How to find Neutrino



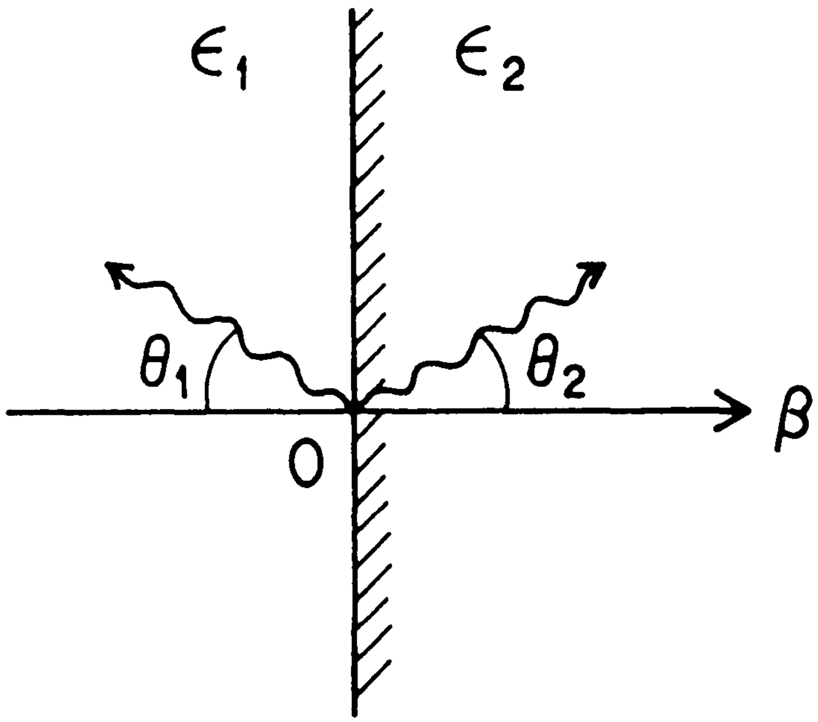
Belle II
Aerogel Ring Image Cherenkov Counter (ARICH)





Transition Radiation

- If a high energy charged particle passes through inhomogeneous media, such as a boundary between two different media (with different dielectric properties), the radiation called “Transition Radiation” is emitted.
  - The radiation of X ray (visible light) is emitted to the very forward (backward) direction of the charged particle.
  - The transition radiation photons are emitted with the angle $\theta = 1/\gamma$ to form a cone shape to the direction of the charged particle moving.



RADIOISOTOPES,47,383(1998)

TRD: Transition Radiation Detector

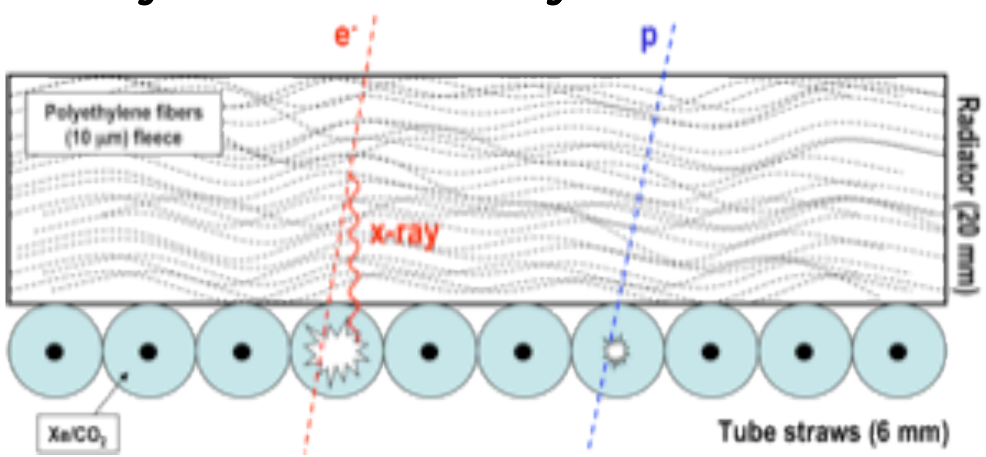
- Total energy of Transition Radiation W is proportional to γ.
  - It is used to identify the particle species with $\beta \sim 1$ (>GeV energy region)
  - X ray is emitted by an electron with >1GeV

$$W = \frac{1}{3}\alpha\hbar\omega_{\rm p}\gamma$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{mc^2} :$$

$$\omega_{\rm p} = \sqrt{\frac{N_{\rm e}e^2}{\varepsilon_0 m_{\rm e}}} :$$

Plasma frequency

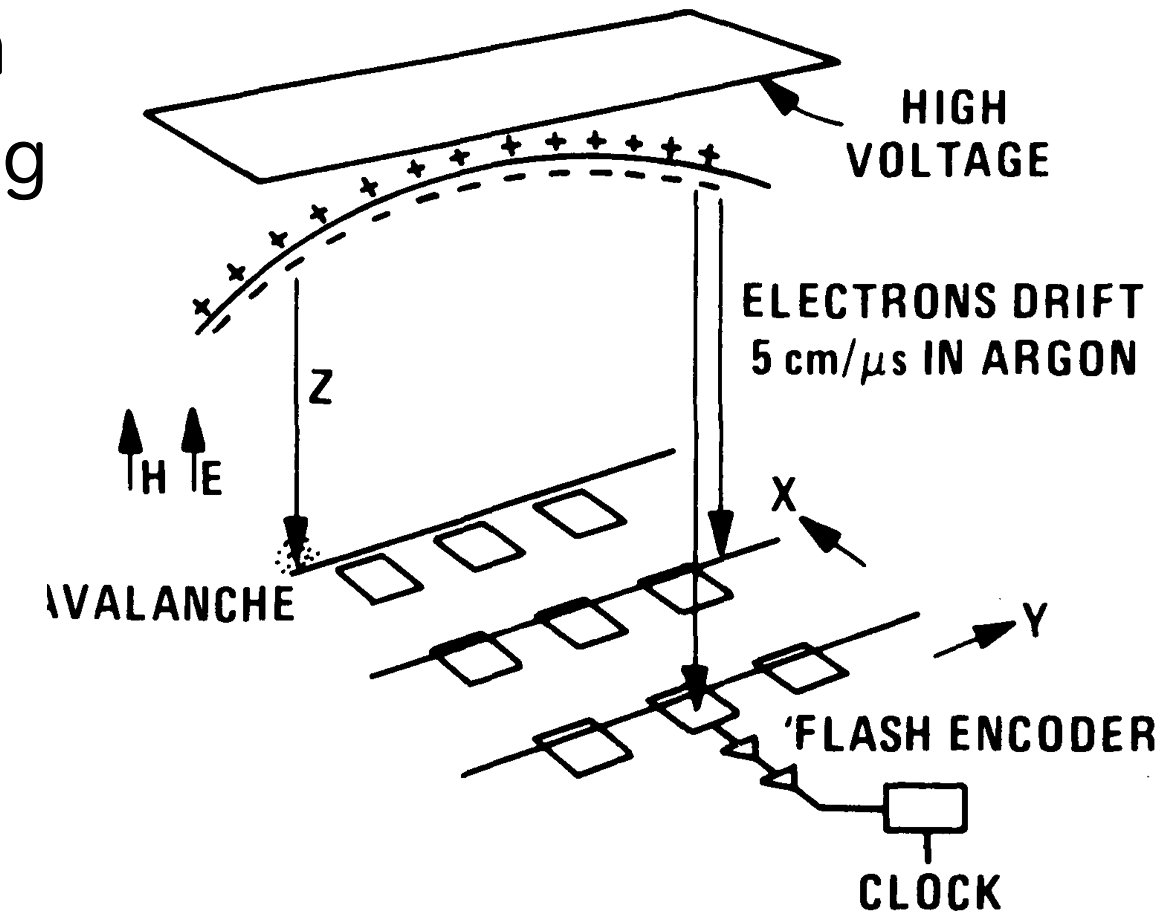


https://youtu.be/GOJsccquXNQ

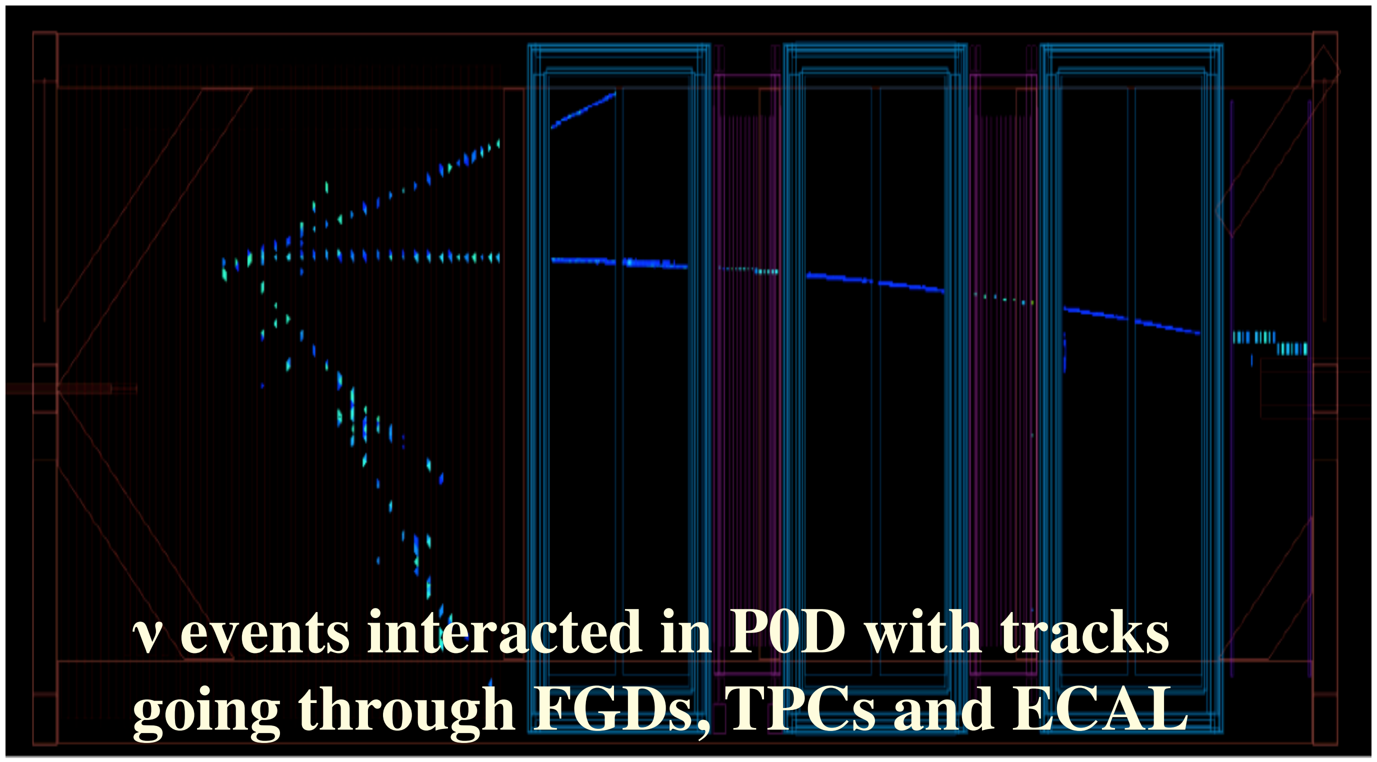
AMS HP

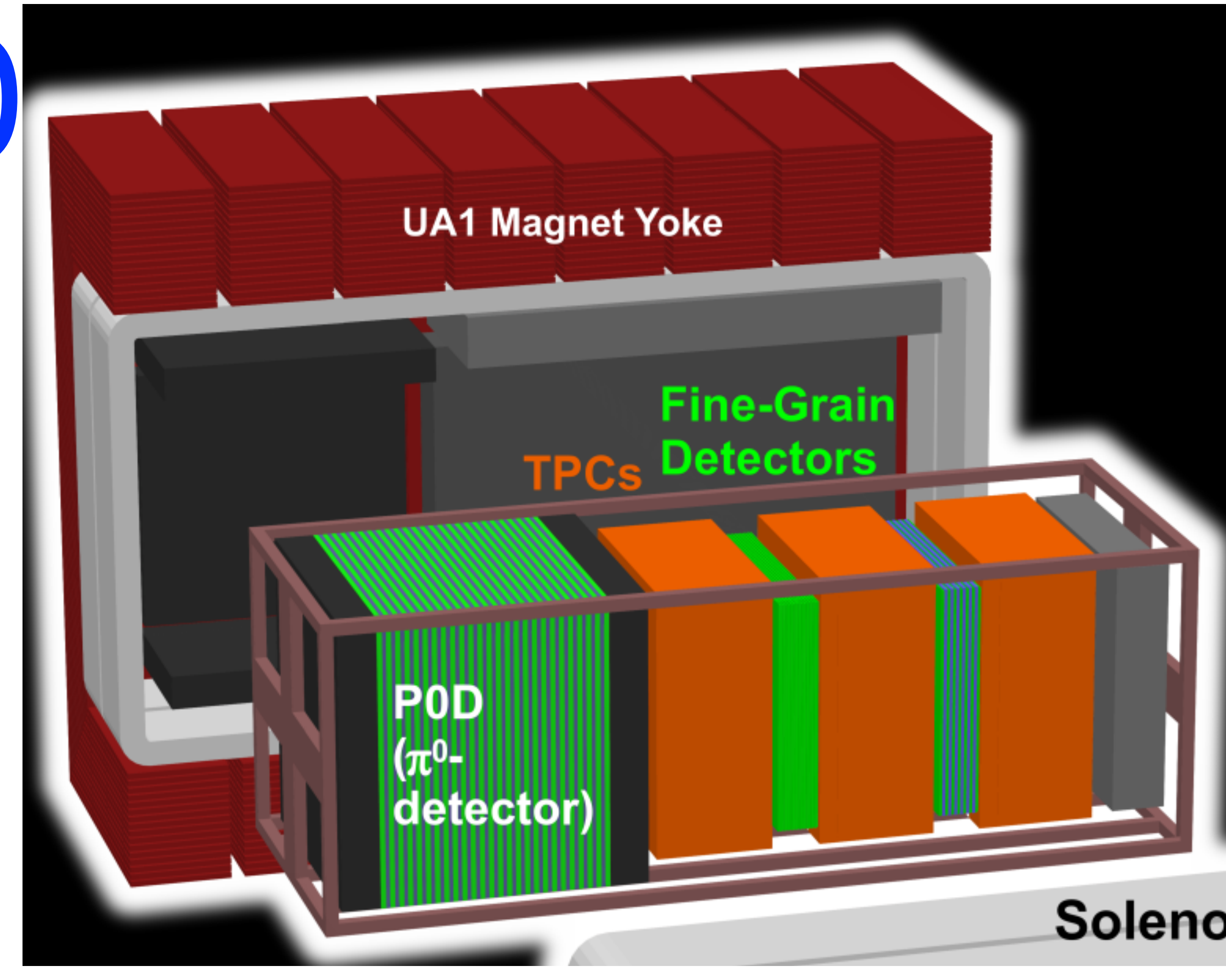
TPC: Time Projection Chamber

- A three-dimensional tracking detector capable of providing information on many points of a particle track along with information on the specific energy loss, dE/dx, of the particle.
- The TPC makes use of ideas from both the MWPC and drift chamber.
  - Two dimensions by hit positions
  - One dimension by drift time of electrons.



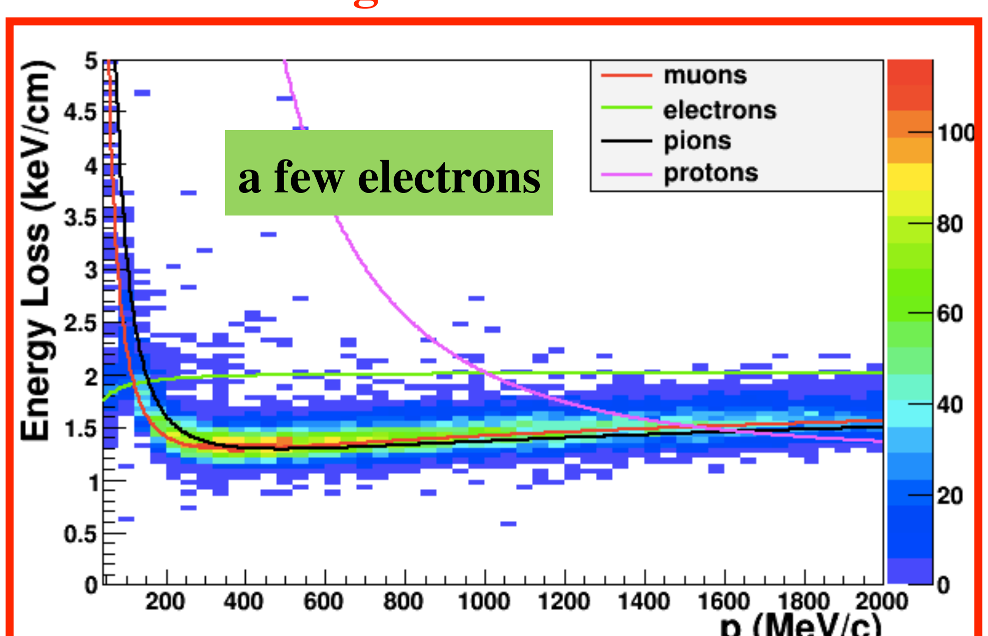
TPC : T2K ND280



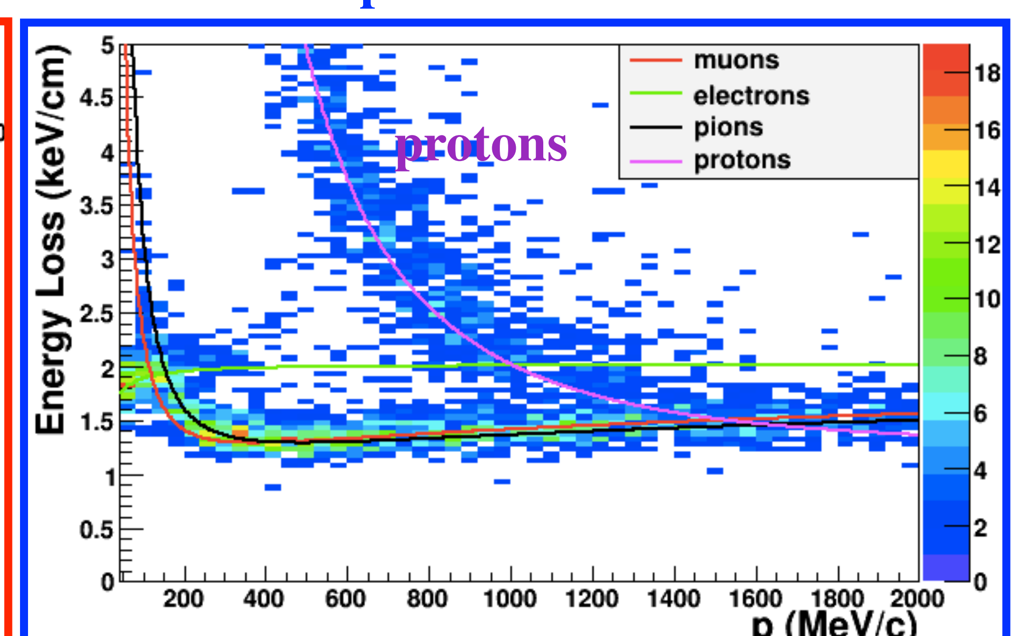


TPC PID

negative track

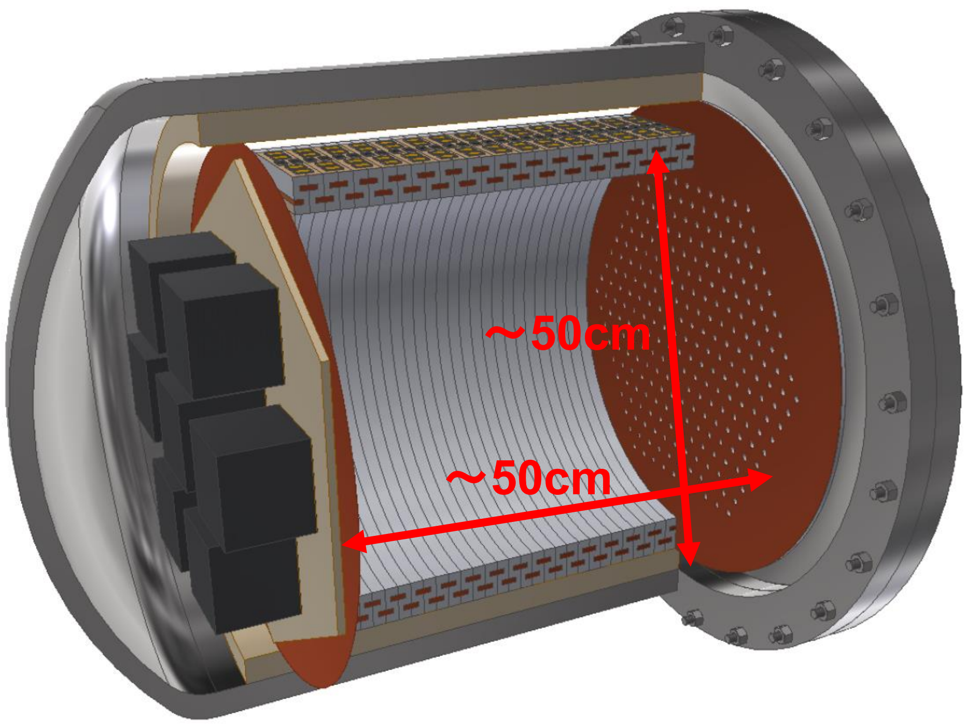


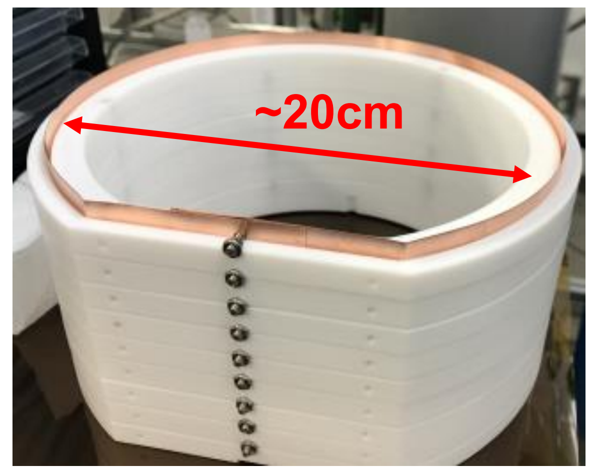
positive track

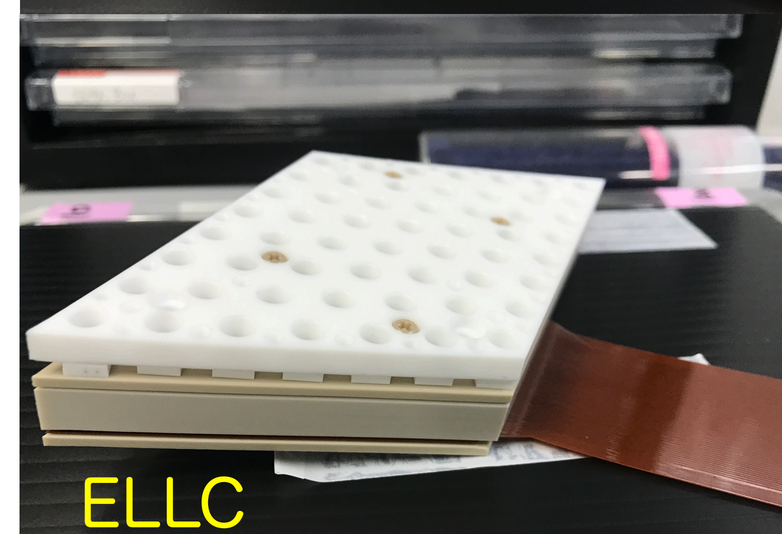


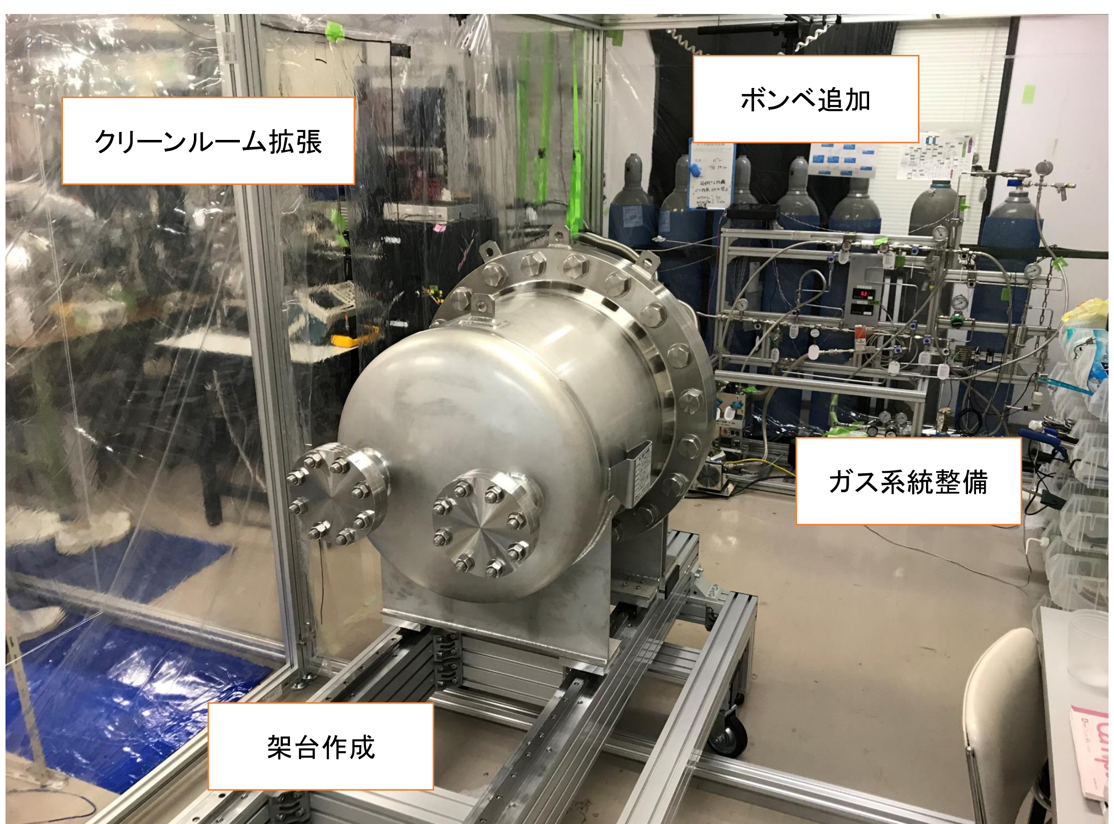
TPC：AXEL detector

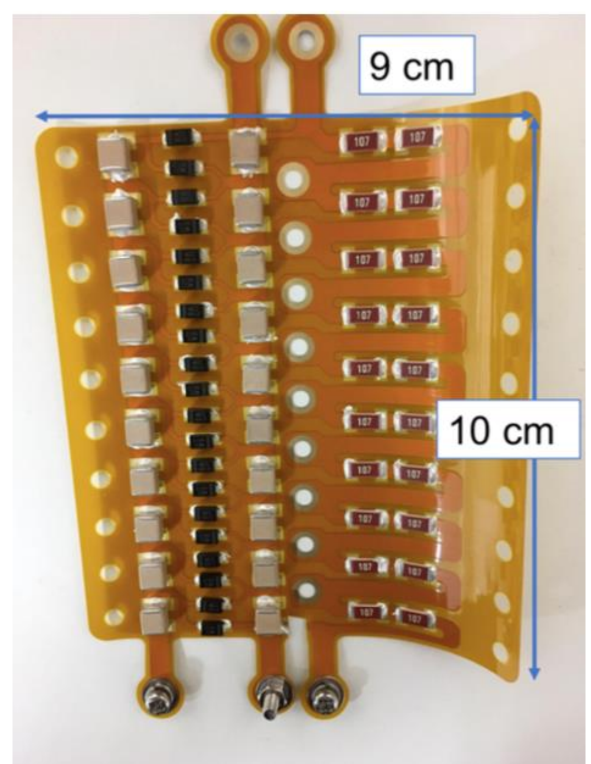
https://www-he.scphys.kyoto-u.ac.jp/research/Neutrino/AXEL/index.html





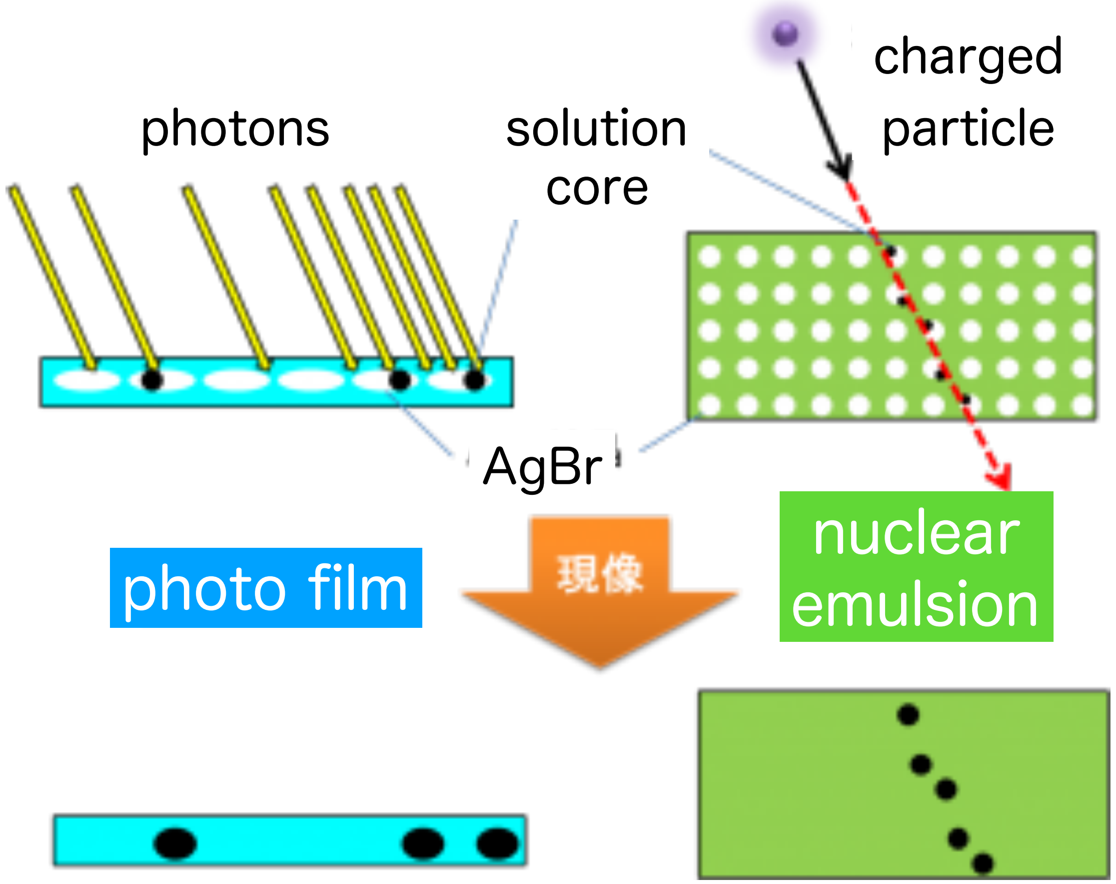






Nuclear Emulsion (a kind of Photo film)

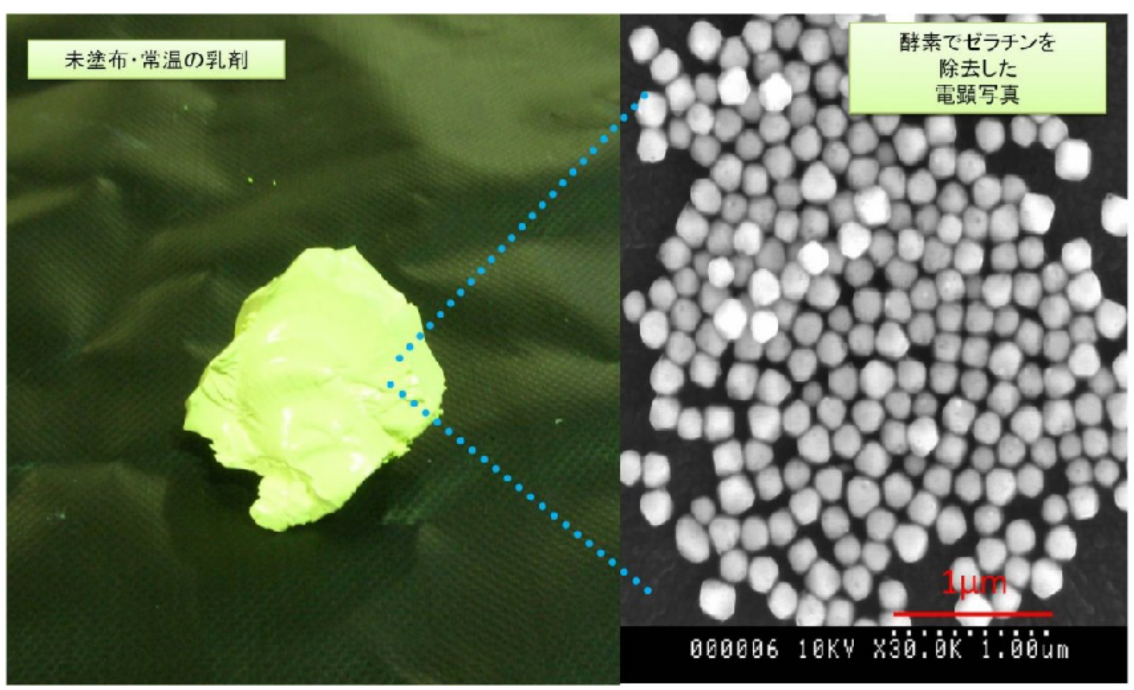
- A simple equipment to measure the radiation. It has a long history.
  - In 1896, Becquerel discovered radioactivity by observing blackened Photo film
- It is still the high-end equipment by which the most precise position and the most precise tracking are realized. (Week point: no timing information).
- Once a AgBr crystal absorb a photon, AgBr is decomposed and the region with Ag becomes black.



Nagoya Uni. F-lab
http://flab.phys.nagoya-u.ac.jp/2011/tech/nuclear_emulsion/

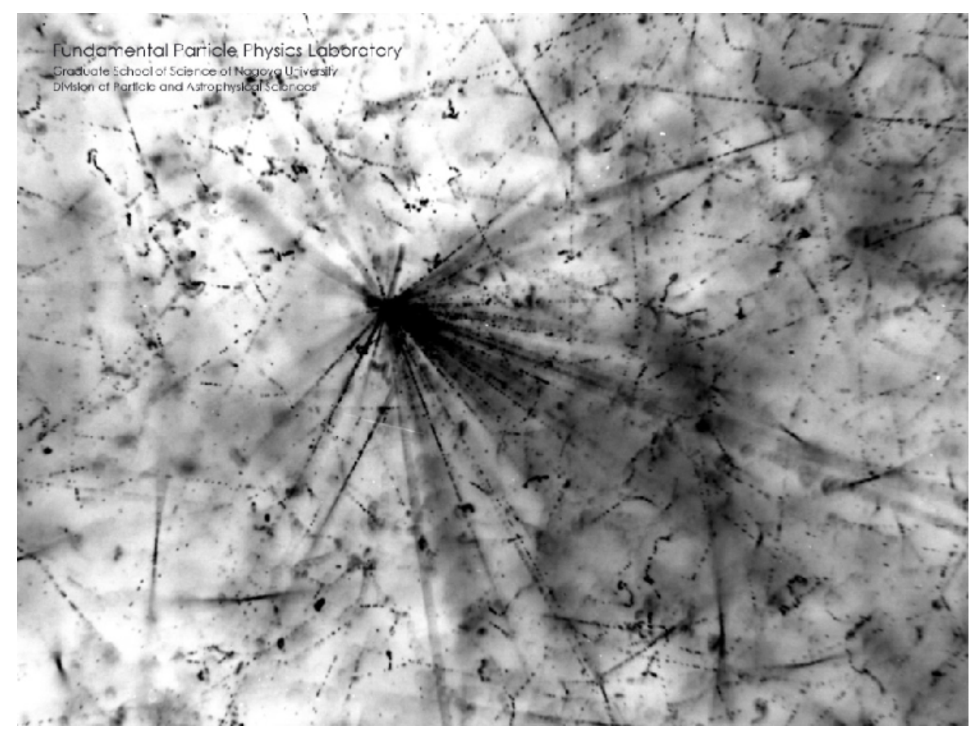
Nuclear Emulsion

- Since the AgBr crystal particle is about 200nm size, the precision of track position better than 1 μm is possible. (Today, the most precise tracking device).
- No electric power is necessary, and we can just put the films where we like.
  - After the exposure, the development of the films is necessary.
- The image on the film can be scanned and recorded as digital data (image).
- No timing information (integrate all activities [tracks])
  - [Hybrid system] The emulsion is sometimes used together with other detector of good timing and moderate tracking (position) capability.



Crystal of AgBr

Negoya Univ. F-Lab

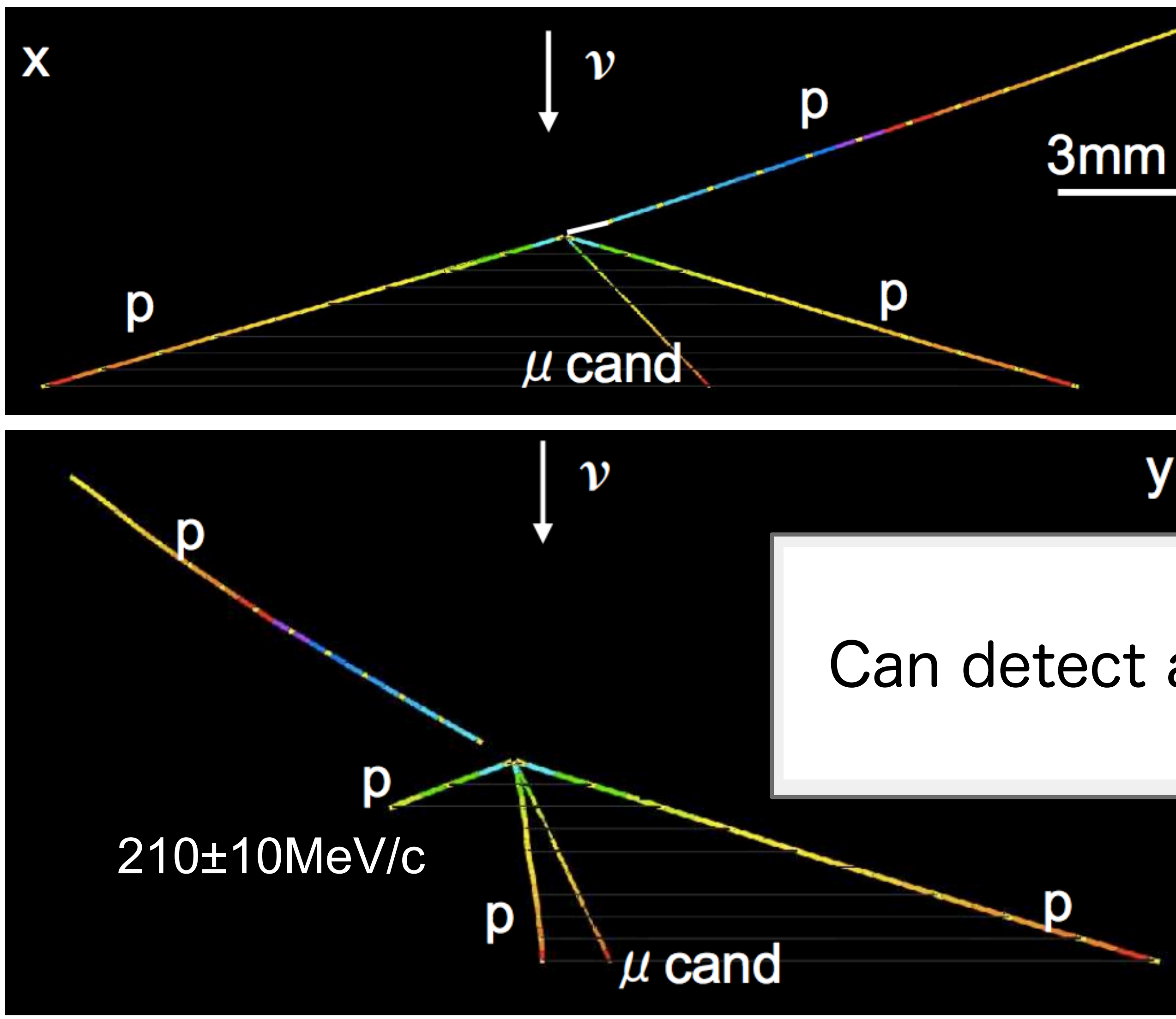


Cosmic ray interaction recorded in the emulsion film

Nuclear Emulsion for a neutrino experiment

J-PARC NINJA Experiment

Precise measurement of neutrino interactions
with nuclear emulsions

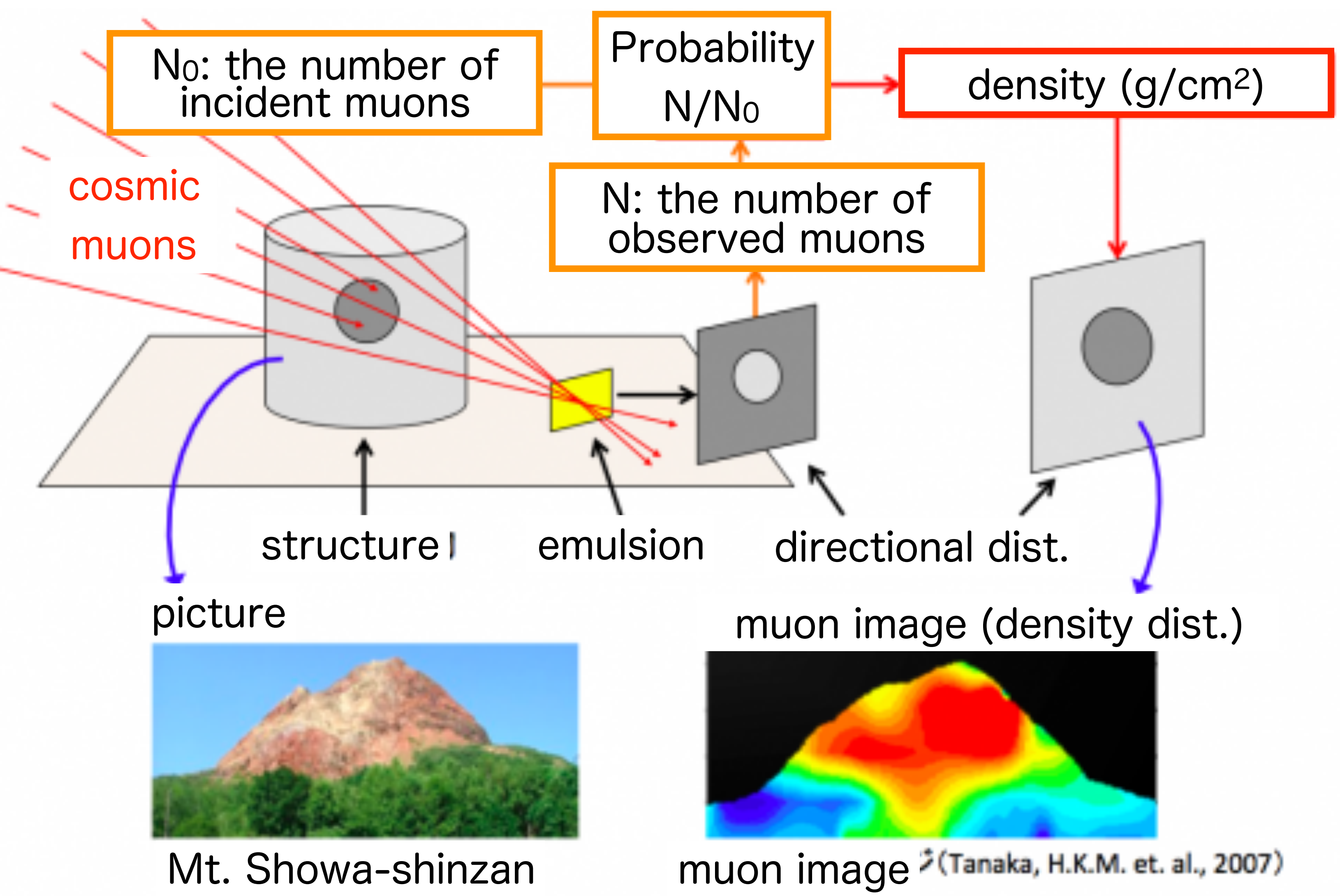


Can detect a very short track

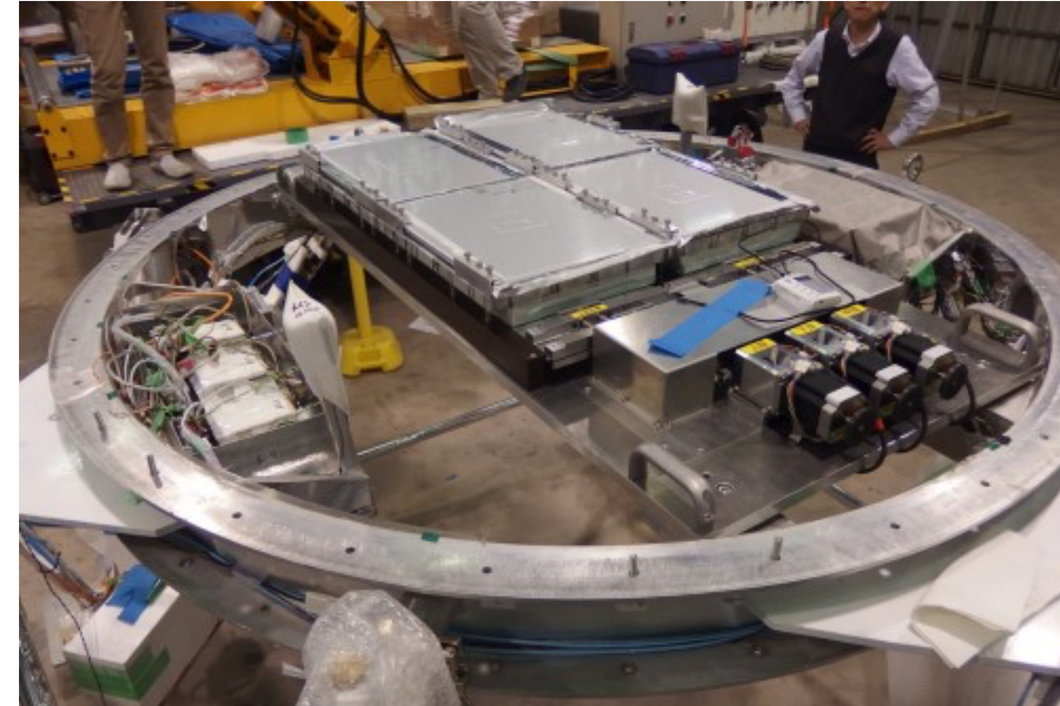
by A. Hiramoto (Kyoto University)

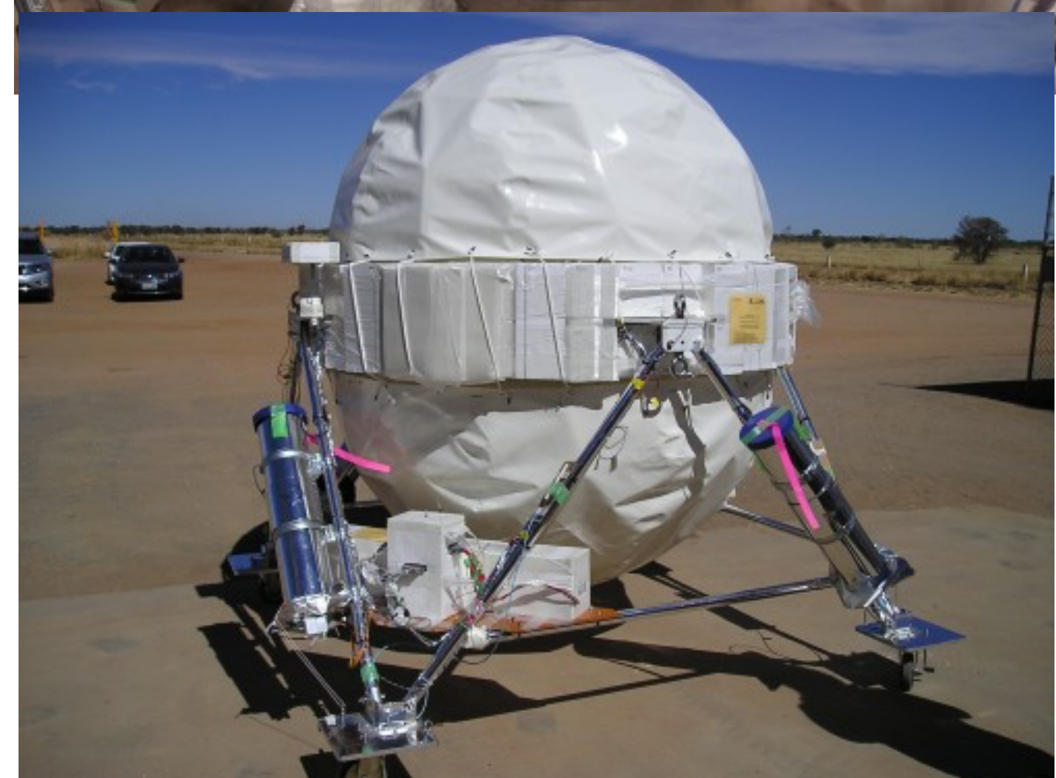
Application of Emulsion

- Cosmic Ray Muon Radiography
  - Inside a volcano, Pyramid, etc..
- Precision Cosmic ray experiment



Nagoya Univ. F-Lab





http://www.aip.nagoya-u.ac.jp/en/public/nu_research/highlights/detail/0004155.html

Highlights

Physicists at Nagoya University discover a huge void in Giza's Great Pyramid by cosmic-ray imaging

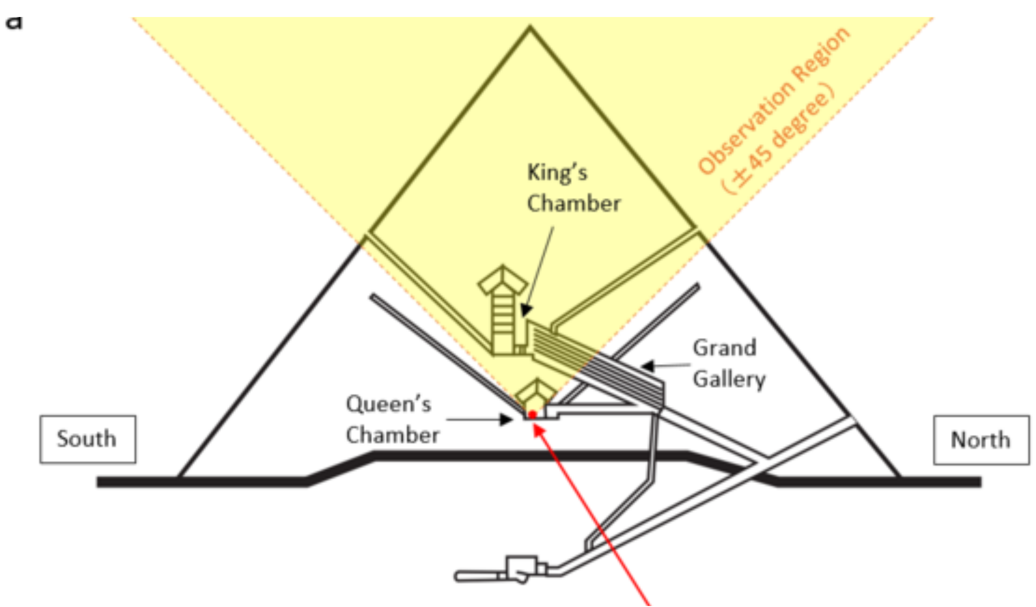
Read in Japanese ツイート いいね！ 2017/11/22

Institute of Materials and Systems for Sustainability / Institute of Advanced Research

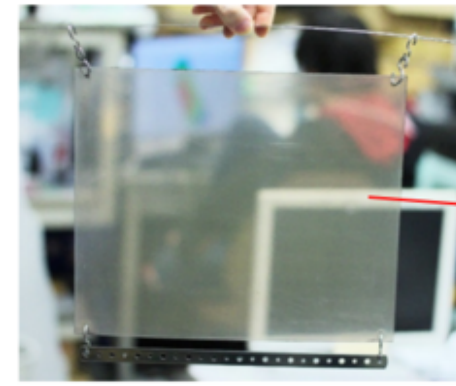
Designated Associate Professor Kunihiro Morishima

Figure1. Khufu Pyramid at Giza © Kunihiro Morishima

a



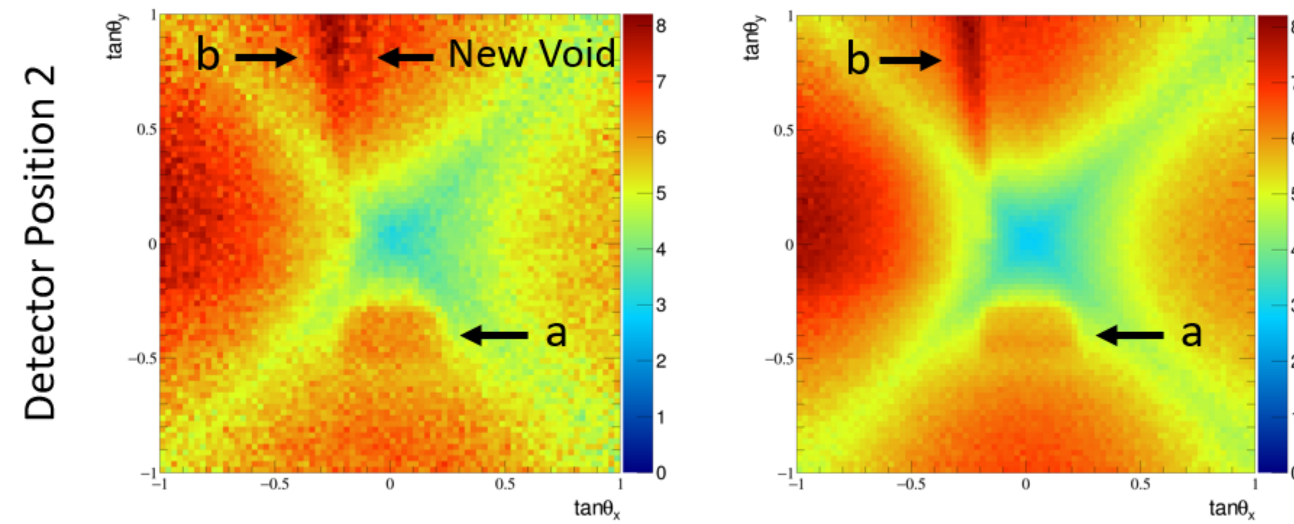
b



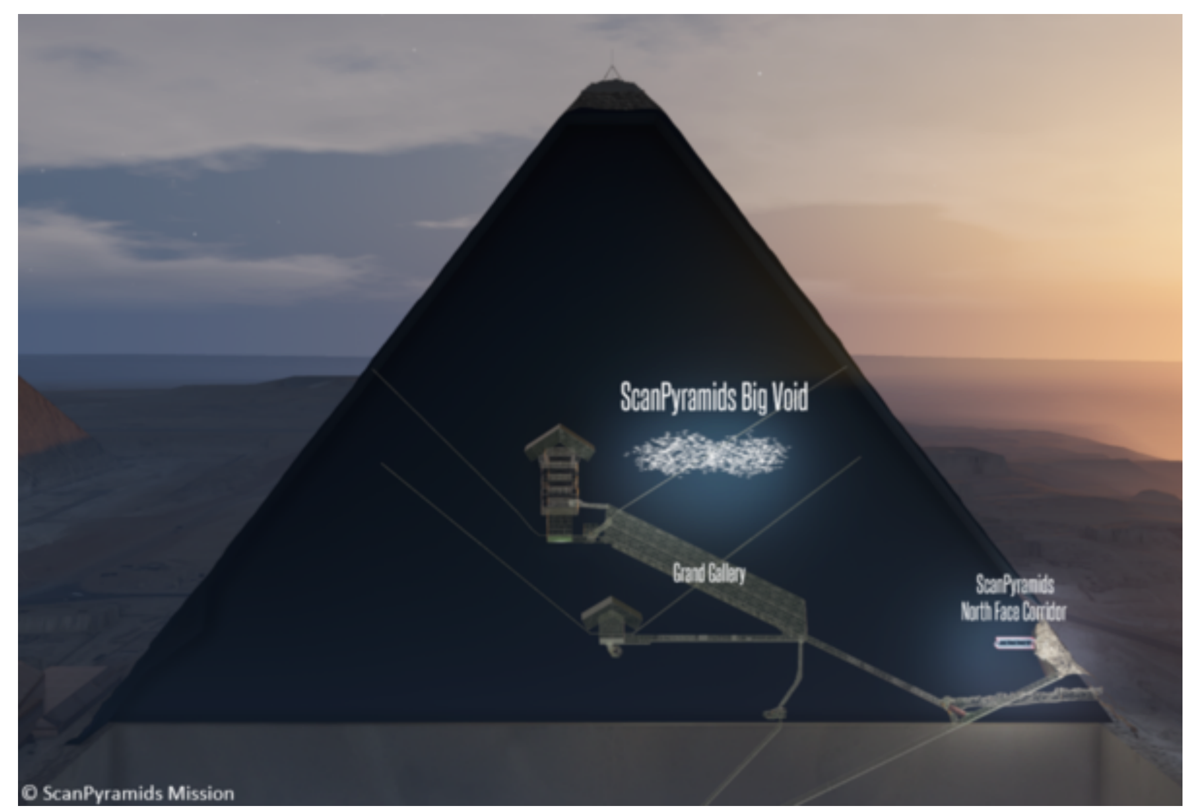
Nuclear emulsion film

c

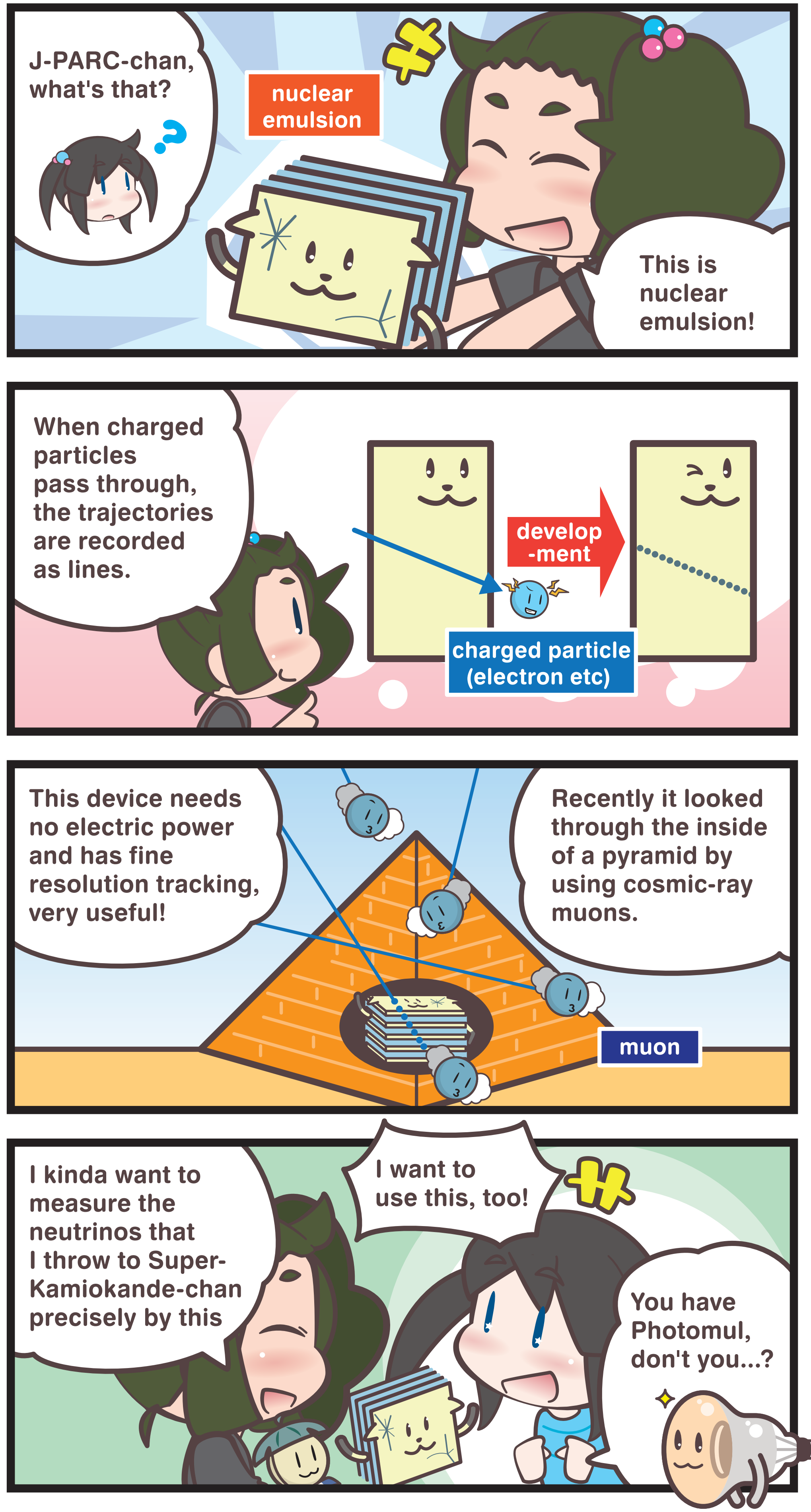
Detectors installed in the Queen's Chamber

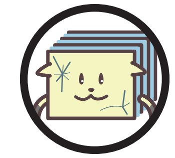


a : King's Chamber, b : Grand Gallery



Emulsion as popular trend device





Nuclear emulsion:
A kind of particle detector, same principle as photographic films, has been used for fundamental particle observations from the dawn of particle physics.

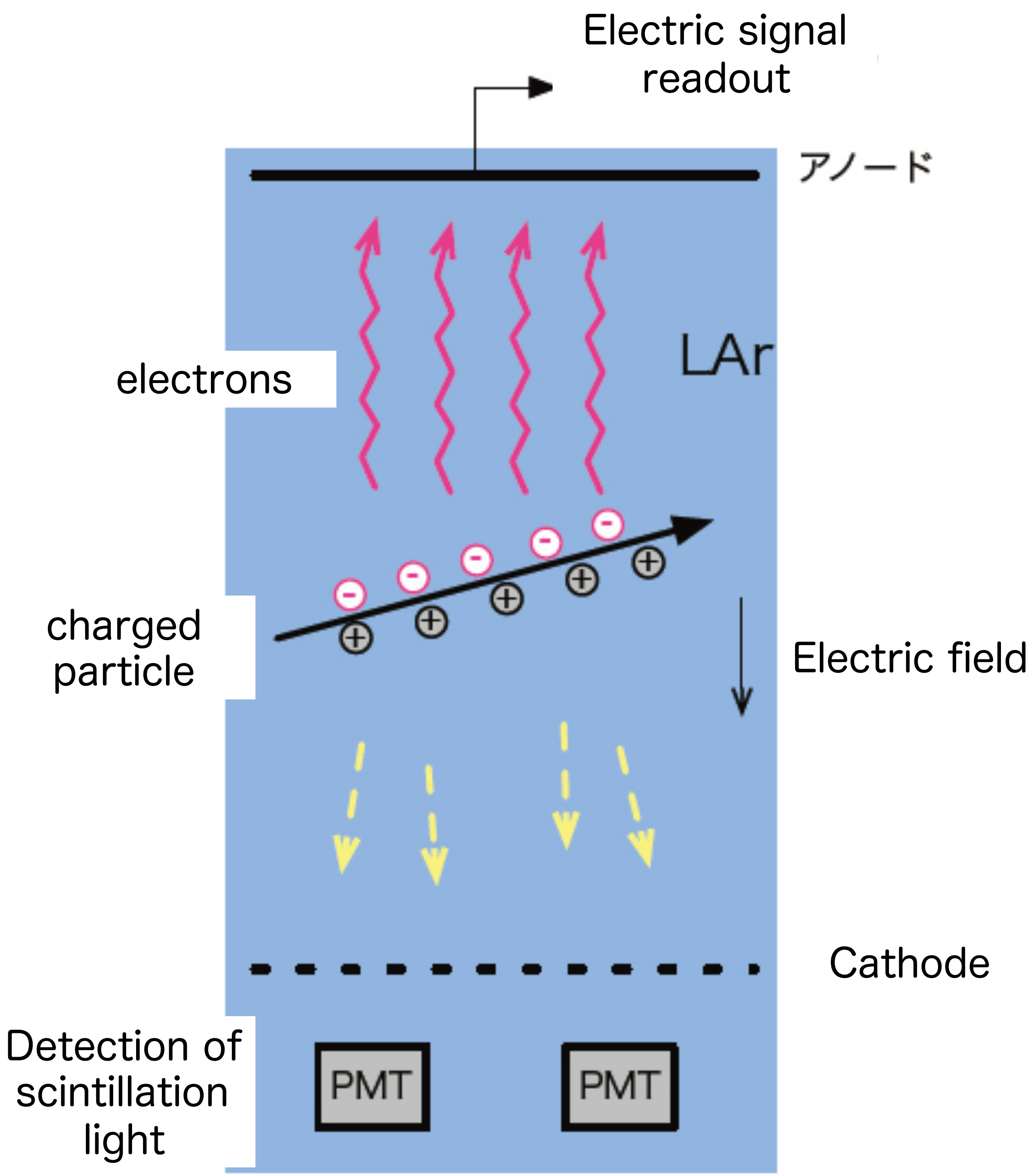
J-PARC-chan and emulsion:
NINJA experiment is planned to precisely measure neutrinos produced by J-PARC-chan.

Nobel Liquid detector

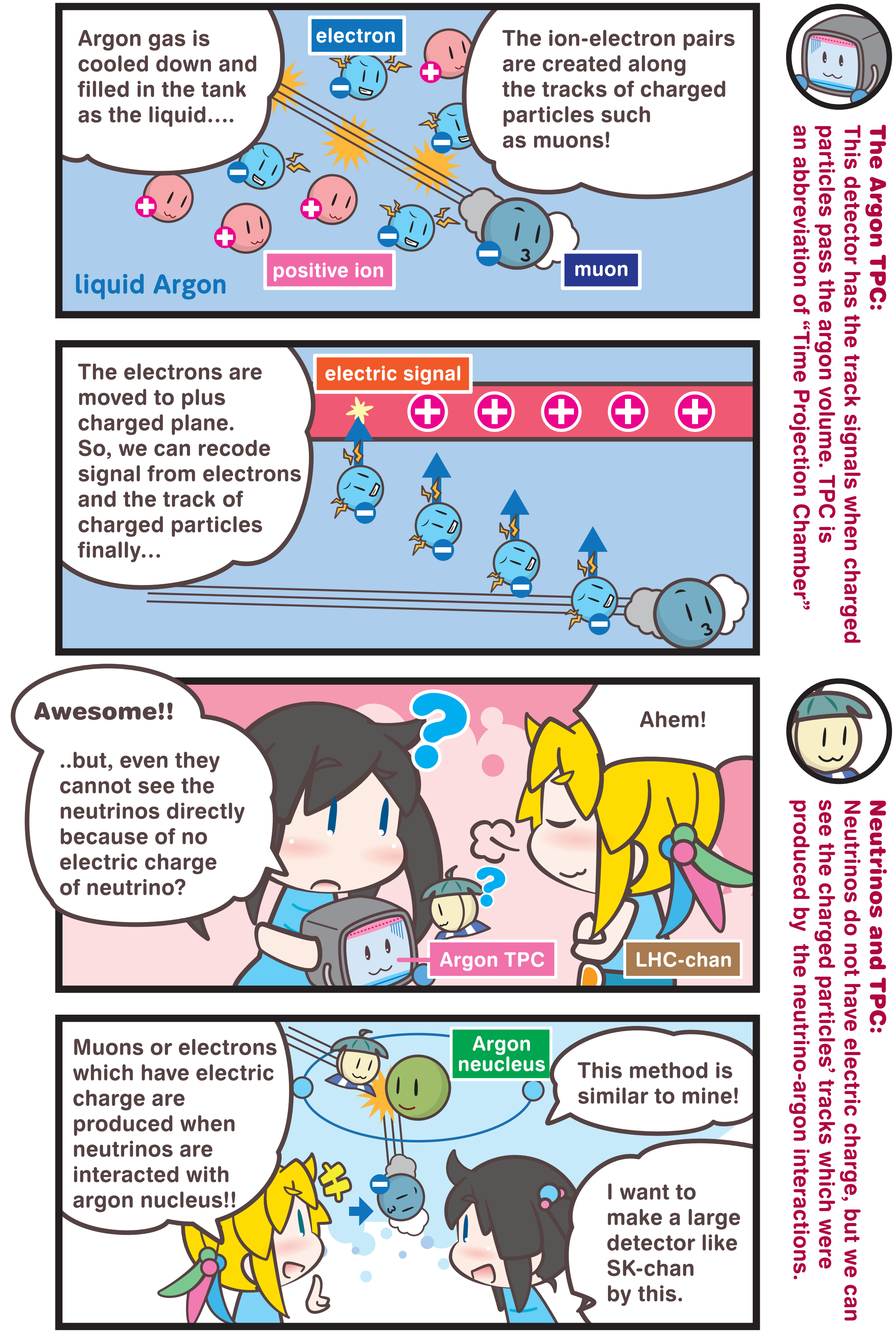
- Instead of gas phase, liquid phase of the material is used for a radiation measurement
- Advantage：　The density is 1000 times higher.
    - The high interaction probability for rare events (neutrinos, dark matter, etc..)
    - More electrons per unit length (1000 times more than gas). No amplification may be necessary.
- Disadvantage
    - No avalanche (no amplification) occurs in liquid.
    - The density of impurity may be 1000 times more. The long drift length of electrons with lower impurity is the key to operate this kind of detector.

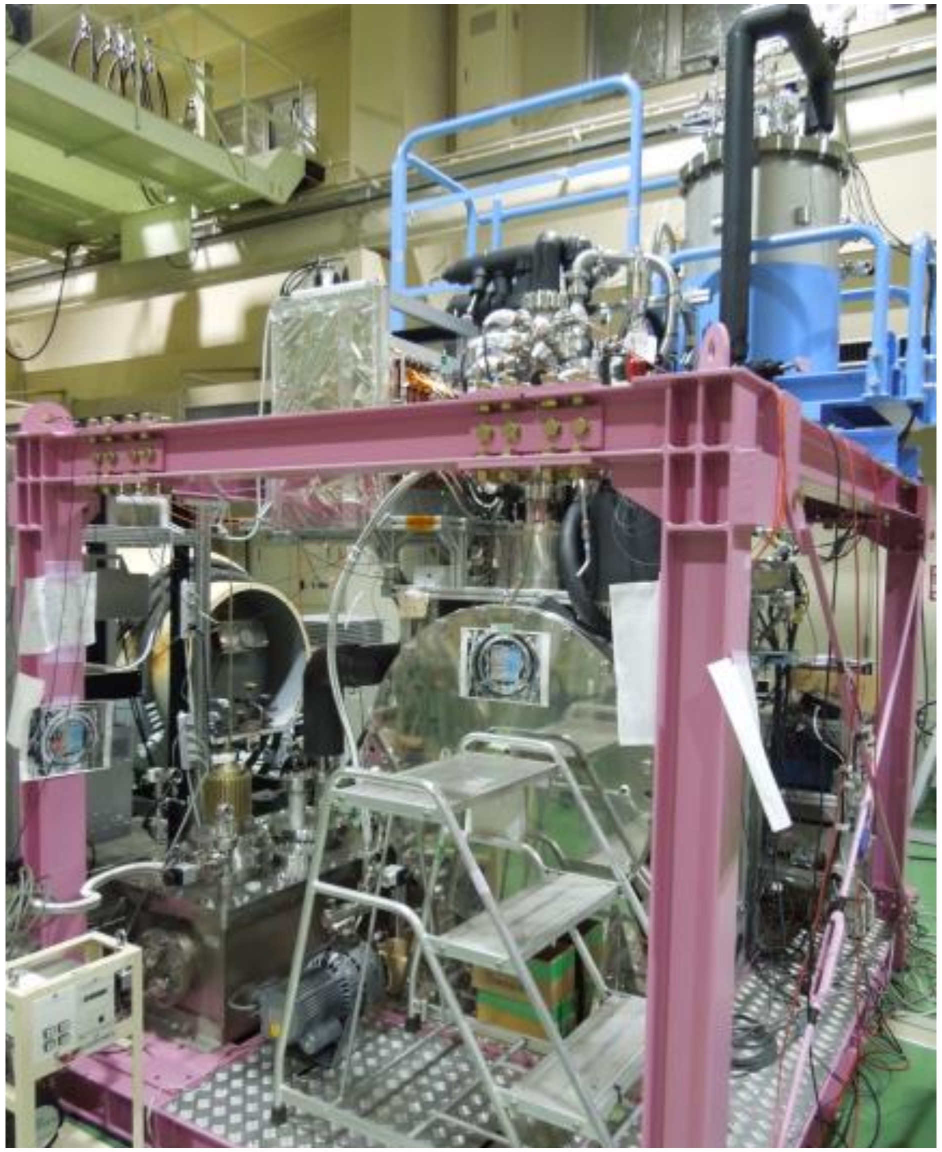
	Z	$\left(\frac{g}{cm^3}\right)$	Boiling point	W(eV/ion&e pair) expect	W(eV/ion&e pair) measure
Lq. Ar	18	1.41	87 K	23.3	23.6
Lq. Kr	36	2.15	120 K	19.5	
Lq. Xe	54	3.52	166 K	15.4	15.6
			融点		
Solid Ar	18	1.62	84 K		

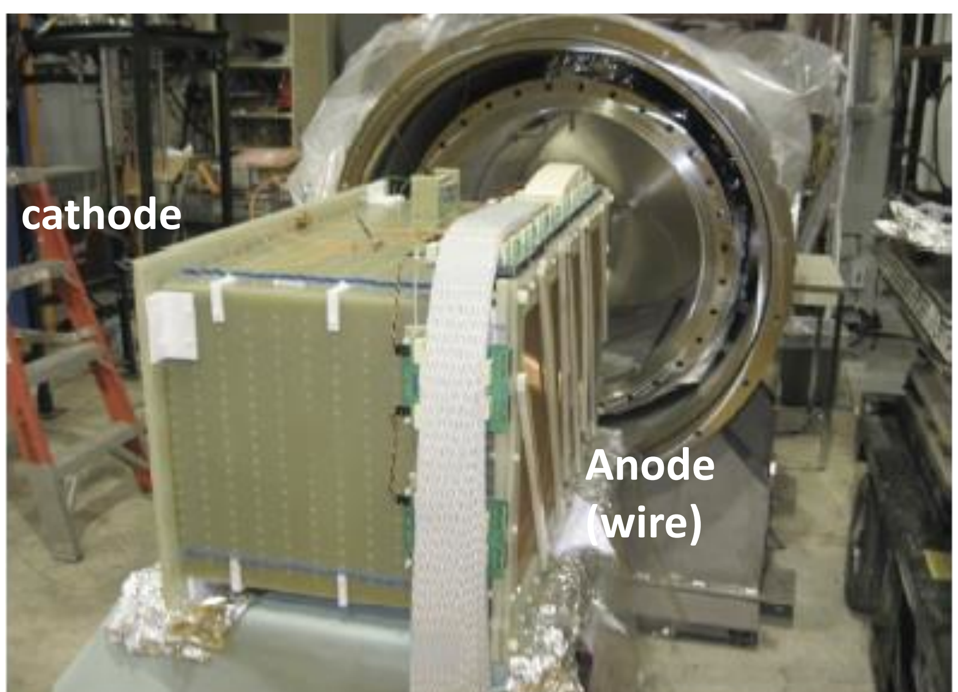
Liquid Ar TPC

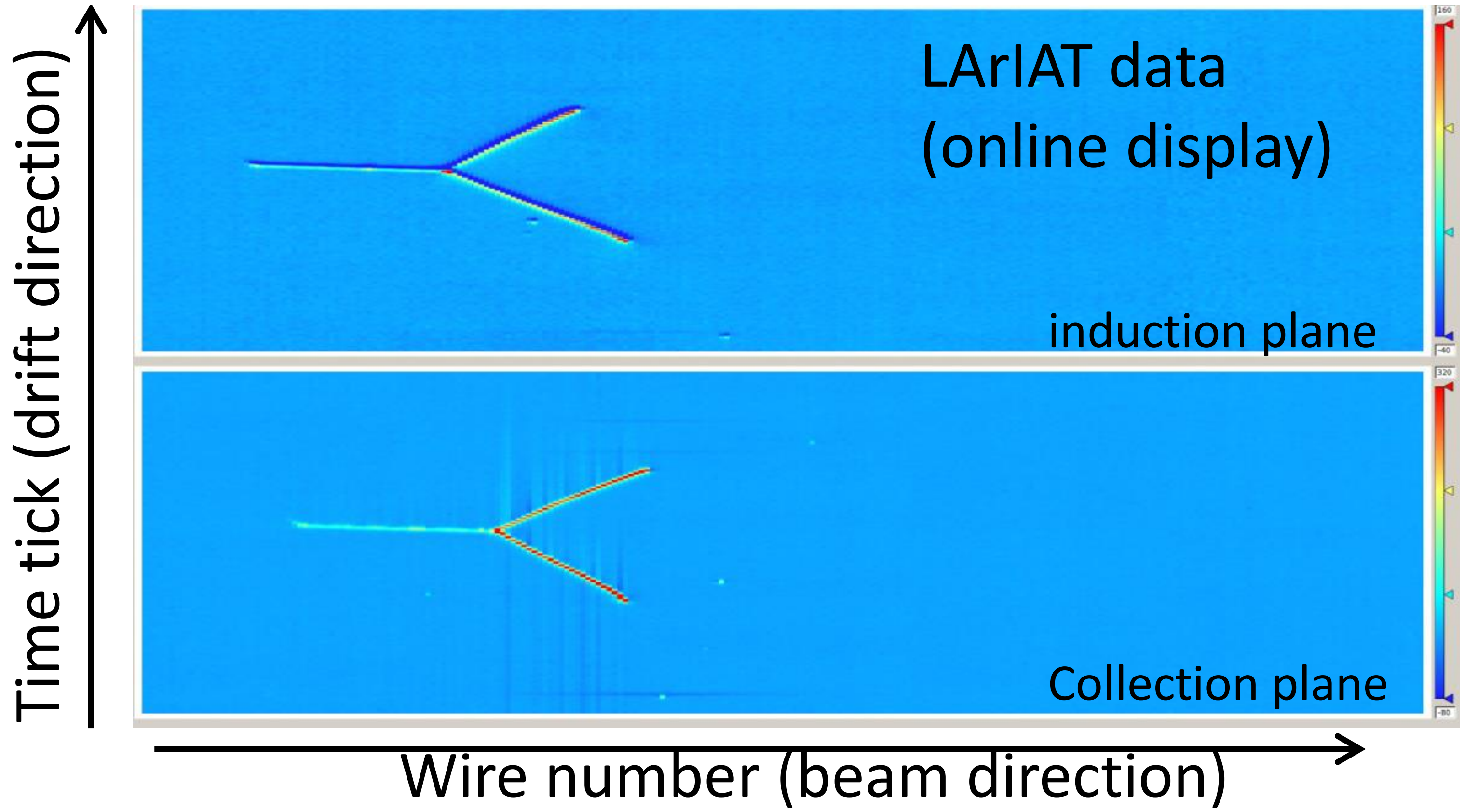


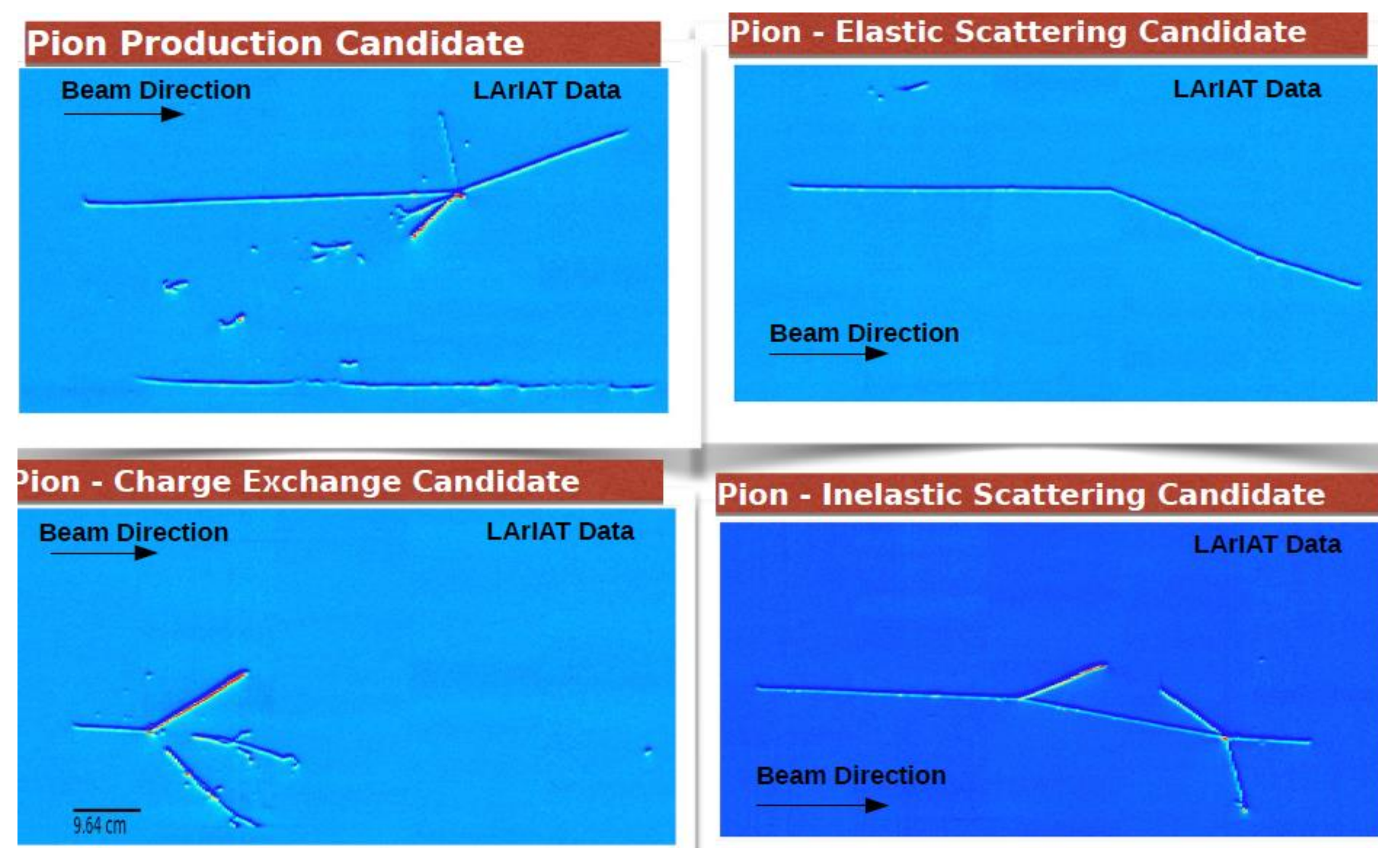
Even neutrinos are seen?











by T. Maruyama