Scintillators
&
PMT

Korea Univ. Lee Jong-won

Detector?

Invisible

Visible

Conversion

&

Amplification

Charged particle

Scintillator
Energy -> Photon (**Scintillation**)

PMT, MPPC,..
Photon -> Electron (**Photoelectric effect**)
Amplification (~1e7)

Electric Signal

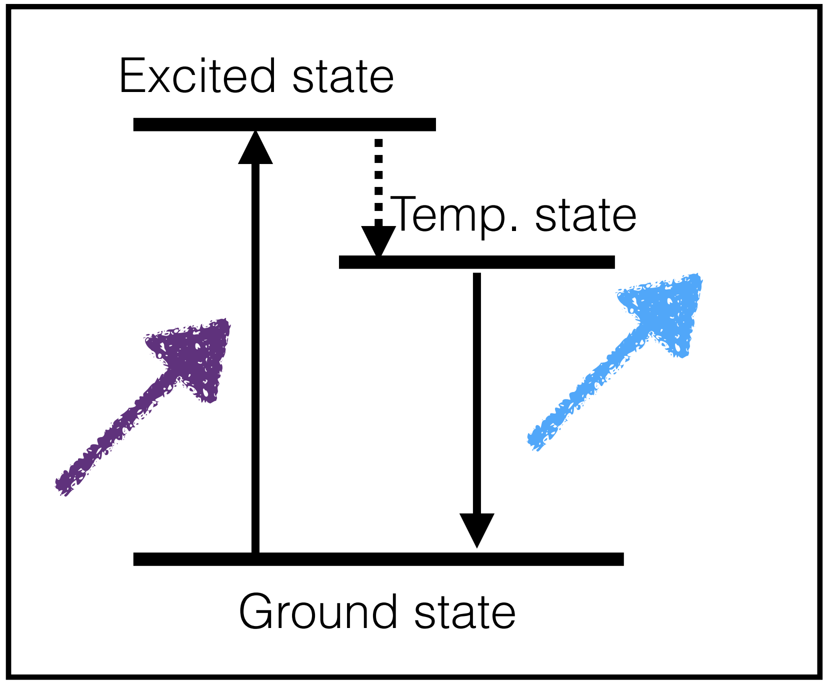


Figure 2-4: Box-and-grid type

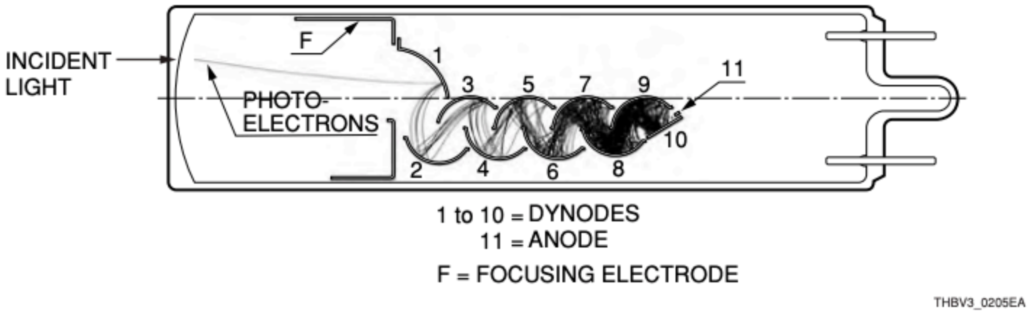
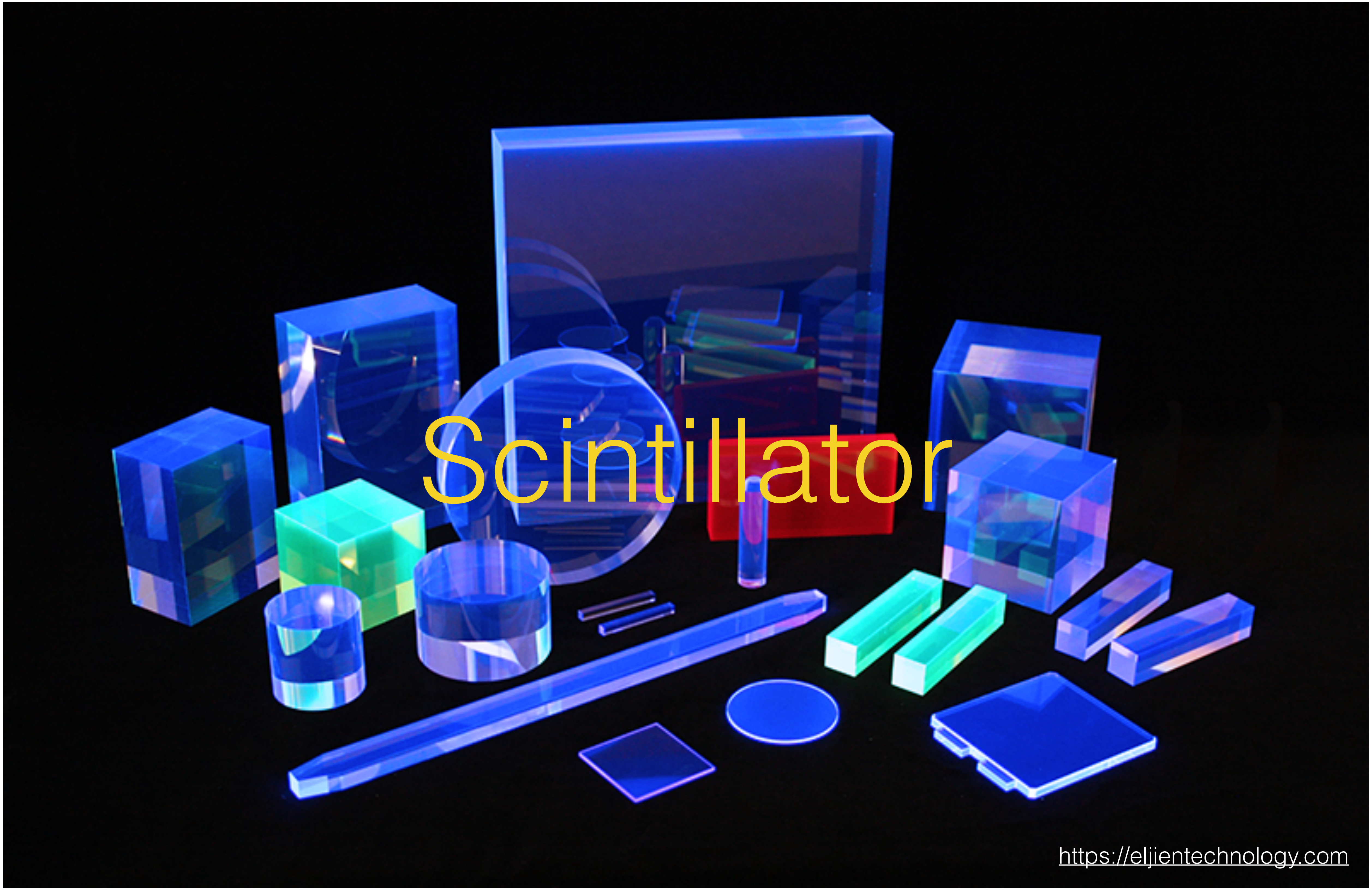


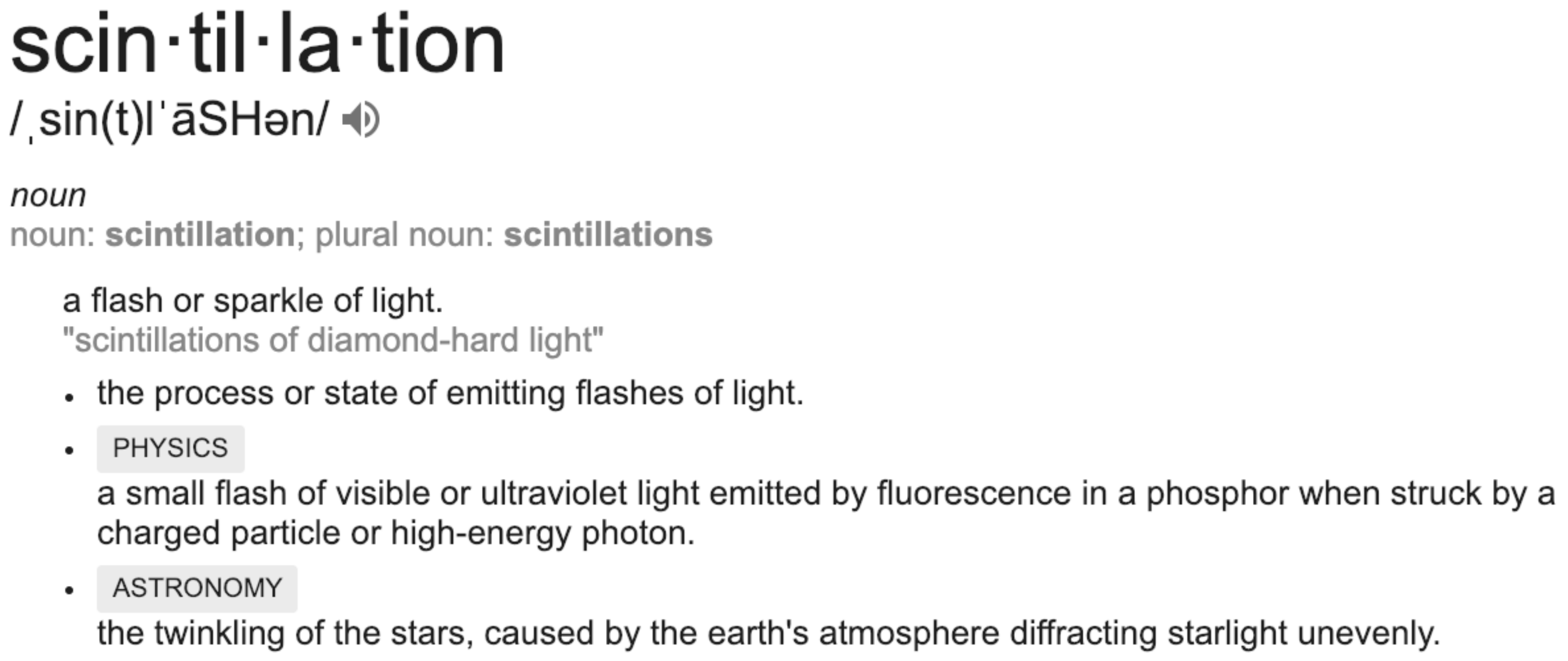
Figure 2-5: Linear-focused type

Backup slides



Scintillator

https://eljientechnology.com



scin·til·la·tion

/ˌsin(t)lˈāSHən/

noun

noun: **scintillation**; plural noun: **scintillations**

a flash or sparkle of light.

"scintillations of diamond-hard light"

- the process or state of emitting flashes of light.
- PHYSICS

  a small flash of visible or ultraviolet light emitted by fluorescence in a phosphor when struck by a charged particle or high-energy photon.
- ASTRONOMY

  the twinkling of the stars, caused by the earth's atmosphere diffracting starlight unevenly.

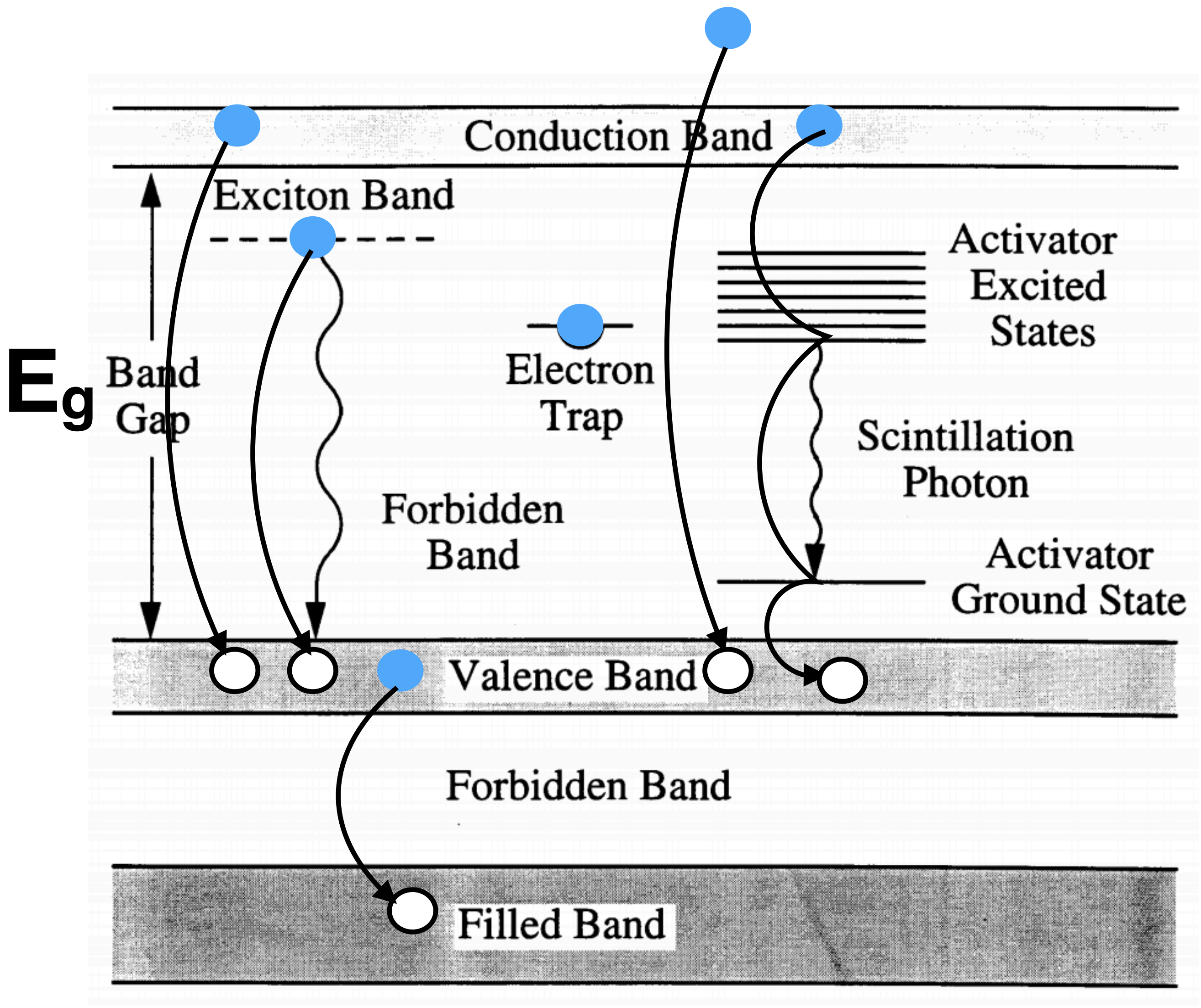
Types of Scintillator

- **Inorganic scintillator**
  - Crystal (CsI, NaI, $PbWO_4$,…)
  - High Z atoms
  - **High density** (3-8 g/cm^3)
    - Short radiation length
  - **High light yield**
    - 10-100 k photon/MeV
    - Good energy resolution
    - Standard : NaI(Tl)
  - ns - μs decay time
  - **Expensive**
  - Hygroscopic (difficult to handle)
  - Temp. dep. in Light yield (~%/°C)
  - **Strong for Rad. damage**
  - EM calorimetery, Medical imaging

- **Gas scintillator**
  - **nitrogen + noble gases**
- **Glass scintillator**
  - **boron silicates**

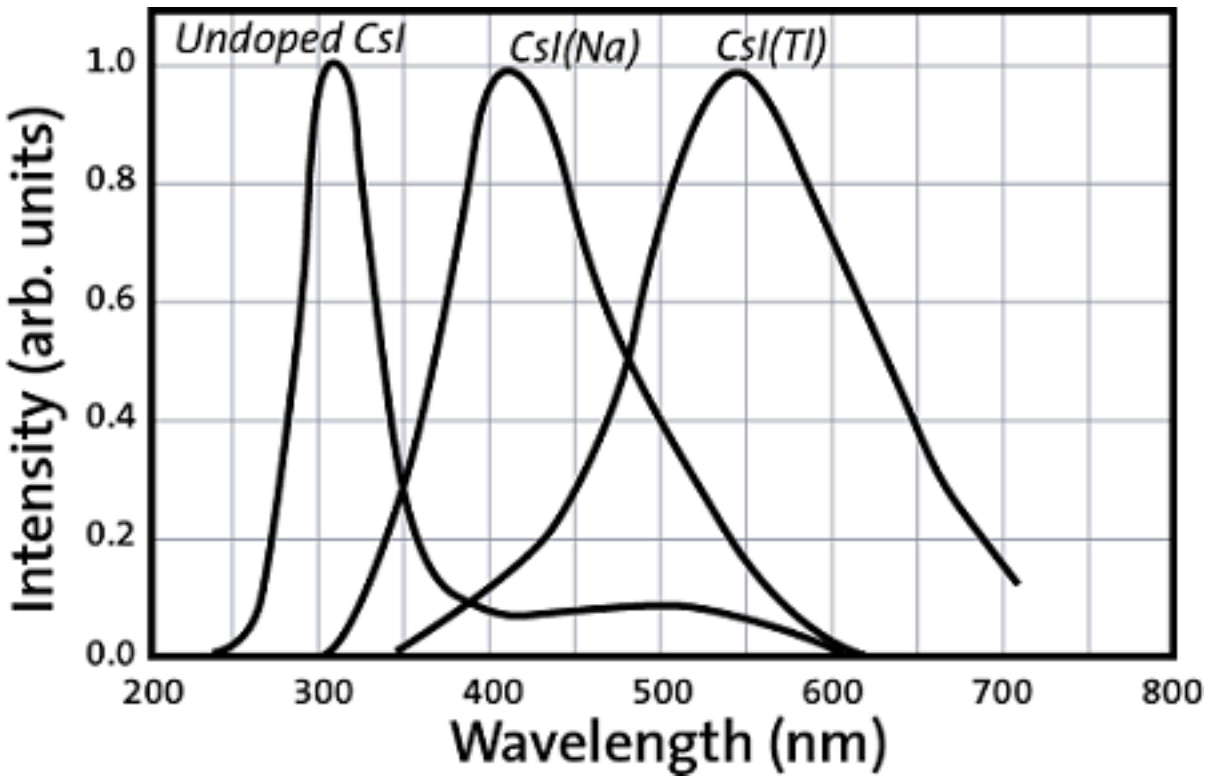
- **Organic scintillator**
  - Crystal, Plastic, Liquid type
  - Low Z (C, H) & density (1-2 g/cm^3)
    - Insensitive for gamma
  - Low light yield
    - 1-10 k photon/MeV
    - Standard : antracene
  - **Fast decay time**
    - ~ ns
    - Good timing resolution
  - **Cheap**
  - Easy to handle (& Manufacture)
  - Temp. indep. (-60 ~ 20 °C)
  - Weak for Rad. damage
  - Tracker, TOF, Trigger, Charged veto, Sampling calorimeter (HCAL)

Inorganic Scintillator - Scintillation



Luminescence mechanism

- Free electron
- Electrons in conduction band
- **Electrons in exciton band**
- **Activator ion**
- **Electrons in electron trap**
  - Defects & Impurities
  - Reduces LY, delays emission

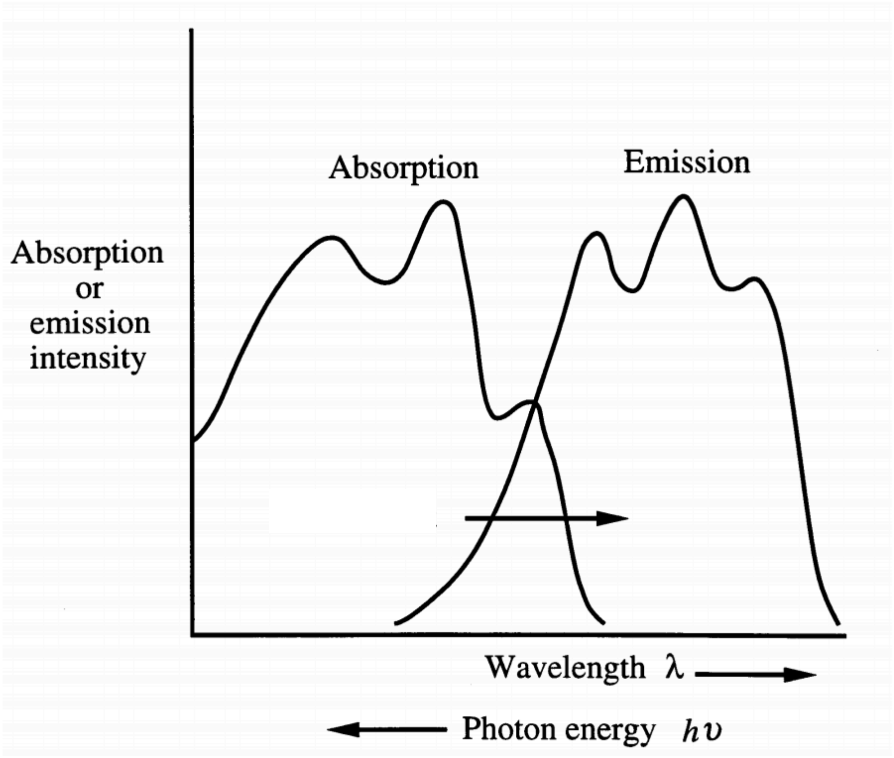


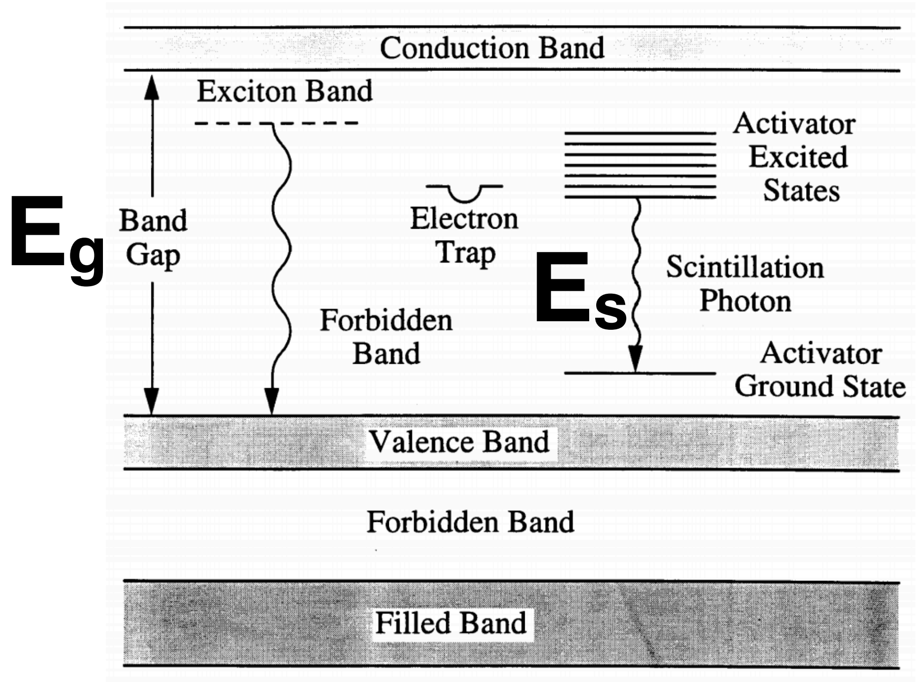
	CsI (pure)	CsI(Na)	CsI(Tl)
LY (N/keV)	2	54	41
Decay Time	6/30 ns	1 µs	630 ns

State of electrons

- $E_e > E_{ion}$: Free
- $E_e > E_g$: Conduction band
- $E_e < E_g$: form Exciton with hole

Inorganic Scintillator -Emission/Absortion



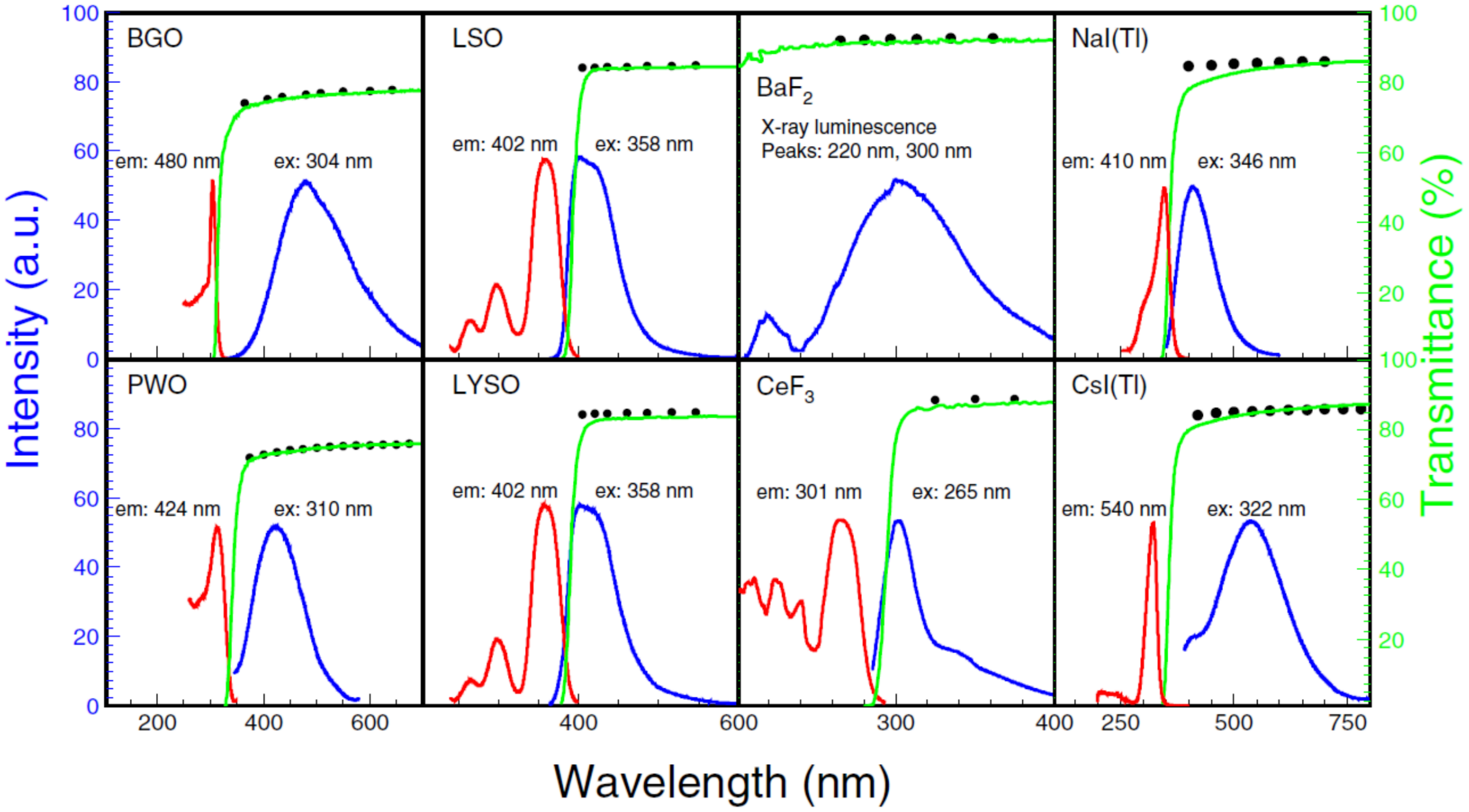


$$E_g > E_s$$

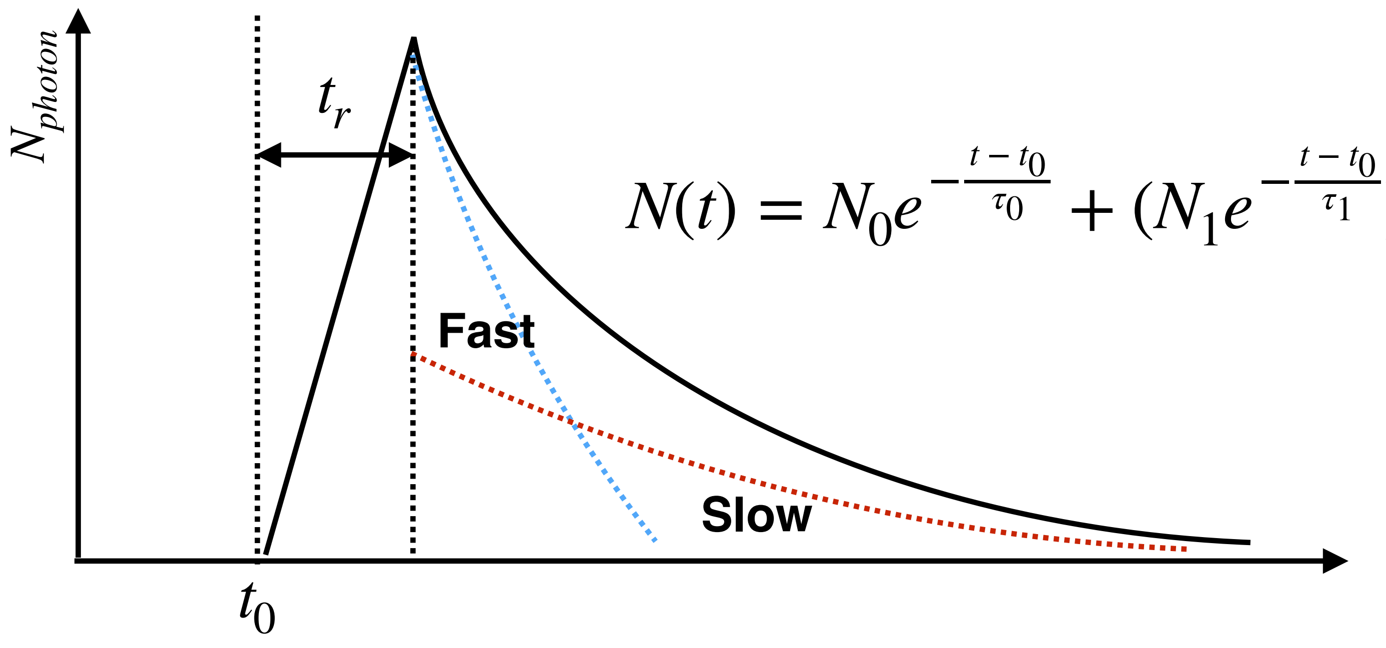
Conditions for good scintillator

- Transfarency for own emission light
- High light yield
- Linear response
- Fast decay time
- Easy to handle

Inorganic Scintillator Absorption and Emission spectra & Transmission



Inorganic Scintillator - photon emission timing



$$N(t) = N_0 e^{-\frac{t-t_0}{\tau_0}} + (N_1 e^{-\frac{t-t_0}{\tau_1}})$$

t_r : Rising time, effected by mobility of electron

τ_0, τ_1 : Decay time const., effected by decay mode

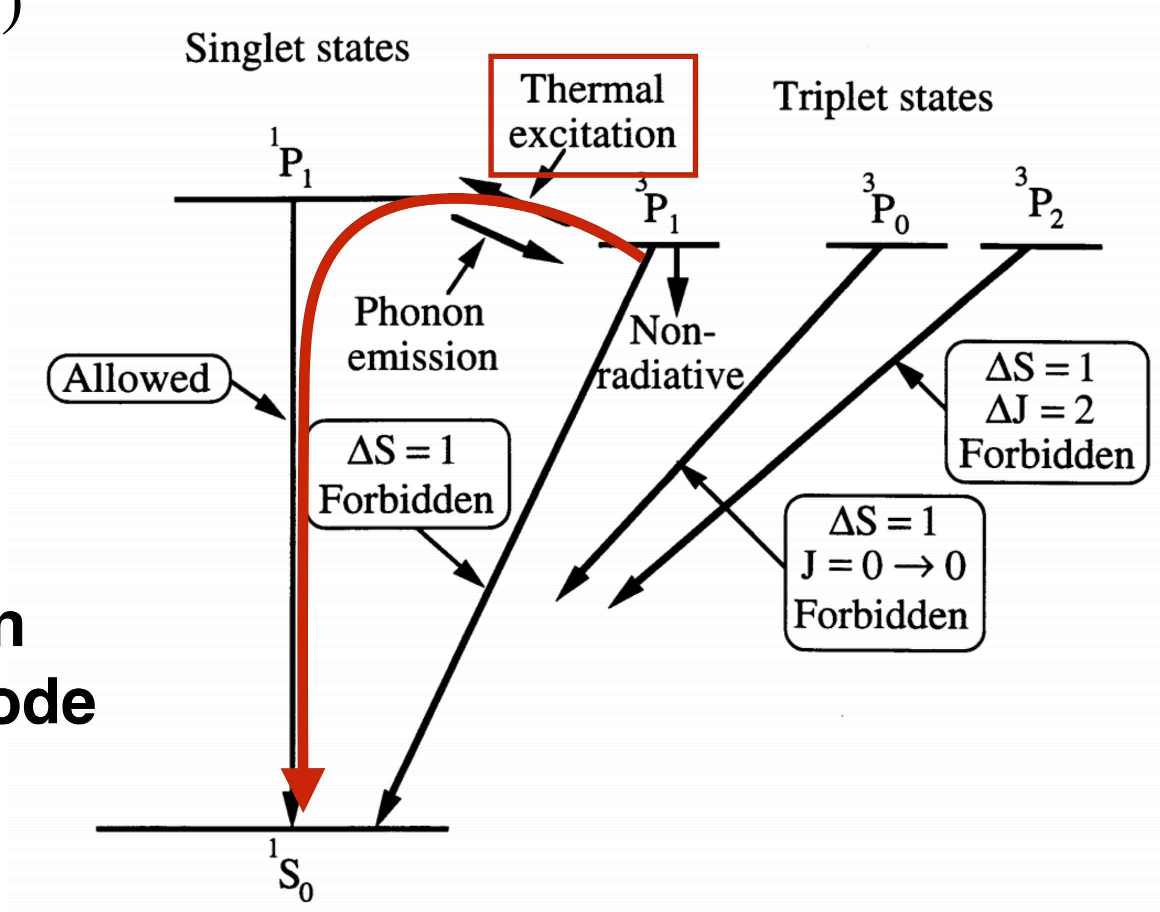
Photon emission example : NaI(Tl)

cooled NaI: h^+ + e- → exciton → phonons + photon

NaI(Tl): $h^+ + Tl^+ \rightarrow$ Tl2+ $\quad e^- + Tl^{2+} \rightarrow (Tl^+)^*$

$e^- + Tl^+ \rightarrow Tl^0 \quad h^+ + Tl^0 \rightarrow (Tl^+)^*$

$(Tl^+)^* \rightarrow Tl^+$ + phonons + photon



Several activator (Tl,Bi) has forbidden state transition
-> Slow decay time

Inorganic Scintillator - Light yield

$$LY(n\,.ph\,./MeV) = N_{e-h}SQ = \frac{10^6}{\beta E_g}SQ$$

- N_{e-h} :Number of e-h pairs
- E_g : band gab energy
- β : Ionization energy conv. eff. (2-7)
- S : Carrier transfer eff. (material dep.)
- Q : q.e. of luminescent center (activator,exciton,…)

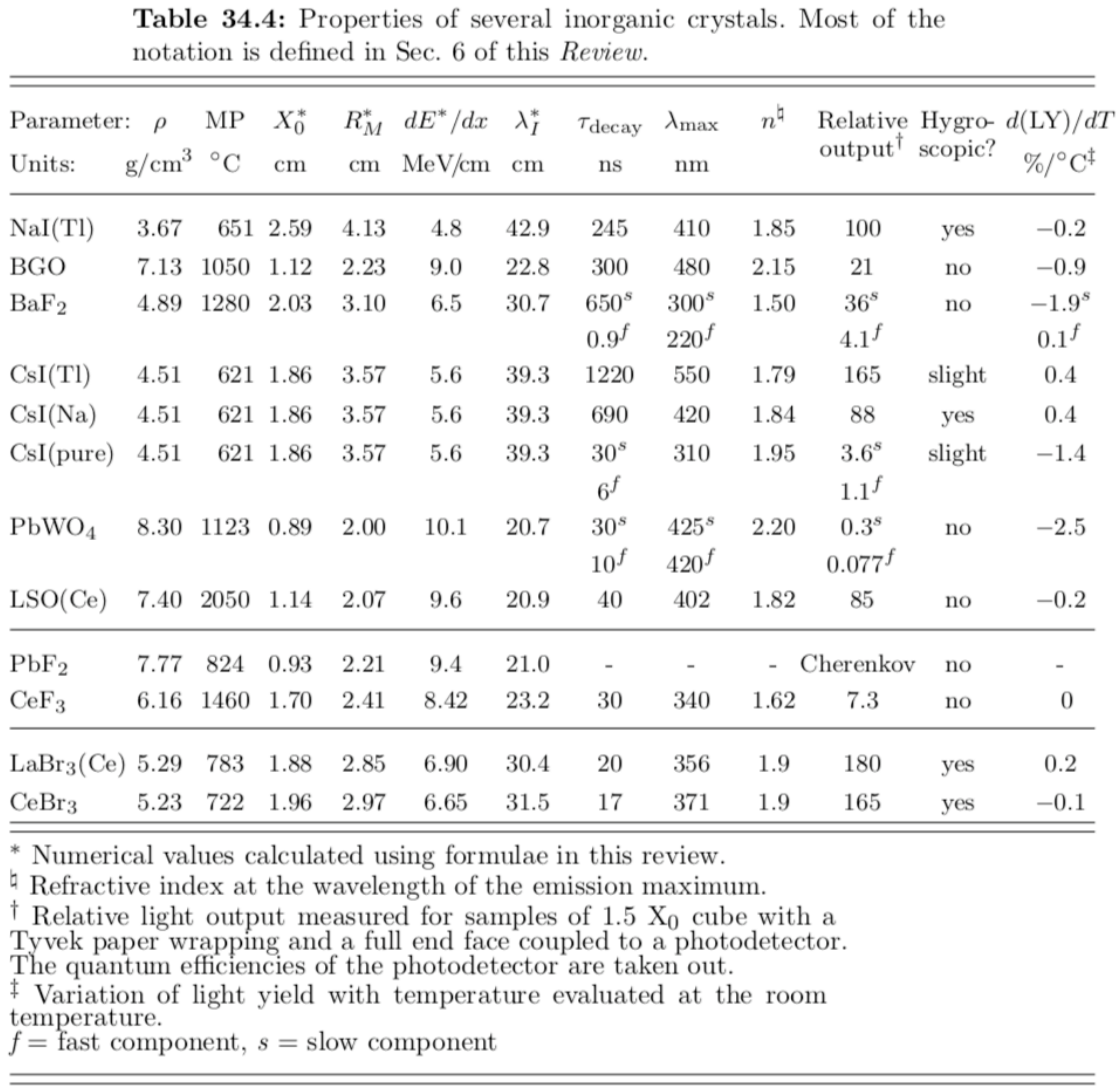


Table 34.4: Properties of several inorganic crystals. Most of the notation is defined in Sec. 6 of this *Review*.

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	$\lambda_{\max}$	$n^\natural$	Relative output†	Hygro- scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(Na)	4.51	621	1.86	3.57	5.6	39.3	690	420	1.84	88	yes	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	310	1.95	3.6^s	slight	−1.4
							6^f			1.1^f		
$PbWO_4$	8.30	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
PbF_2	7.77	824	0.93	2.21	9.4	21.0	-	-	-	Cherenkov	no	-
CeF_3	6.16	1460	1.70	2.41	8.42	23.2	30	340	1.62	7.3	no	0
$LaBr_3$(Ce)	5.29	783	1.88	2.85	6.90	30.4	20	356	1.9	180	yes	0.2
$CeBr_3$	5.23	722	1.96	2.97	6.65	31.5	17	371	1.9	165	yes	−0.1

* Numerical values calculated using formulae in this review.

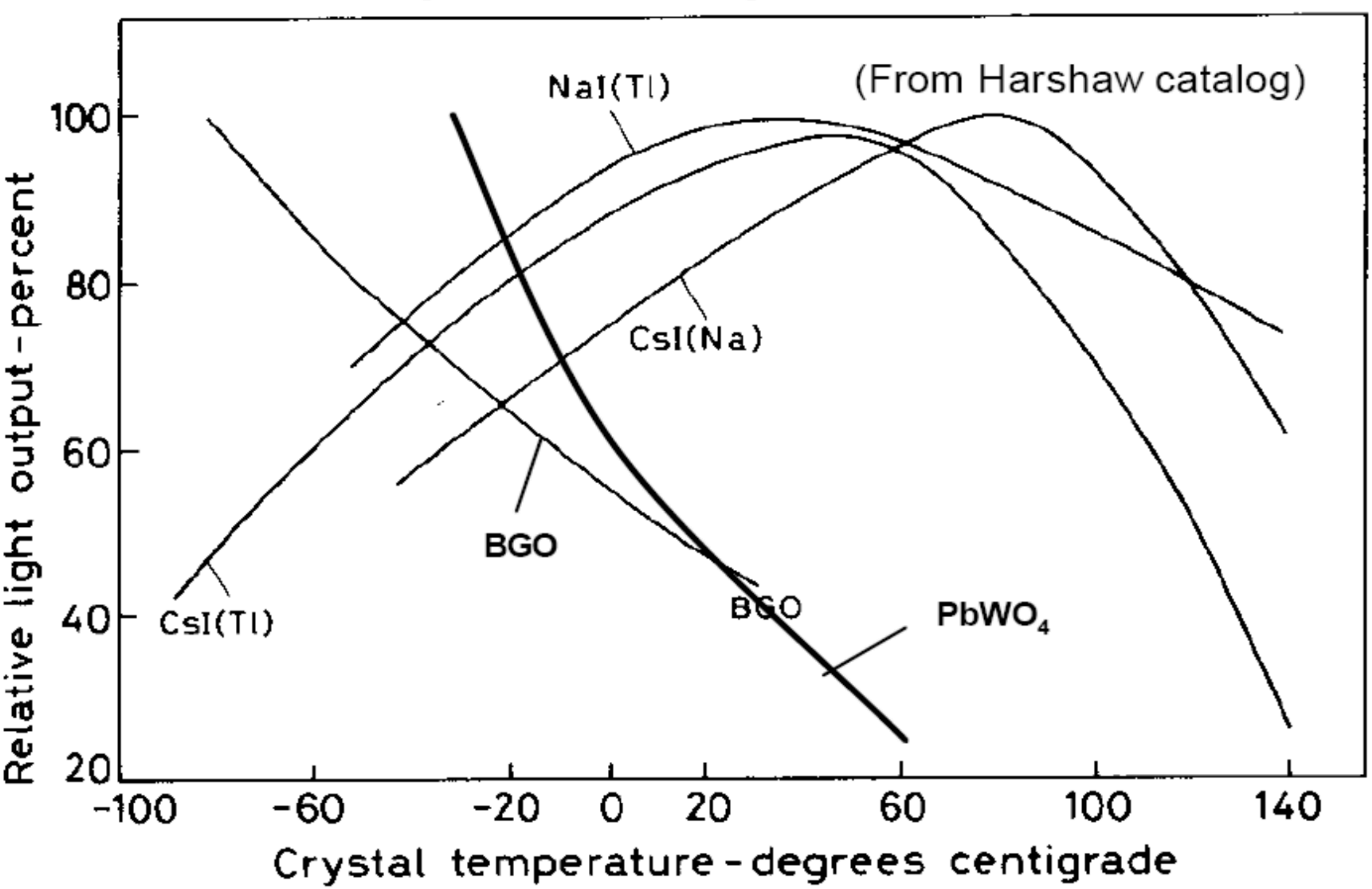
♮ Refractive index at the wavelength of the emission maximum.

† Relative light output measured for samples of 1.5 X_0 cube with a Tyvek paper wrapping and a full end face coupled to a photodetector. The quantum efficiencies of the photodetector are taken out.

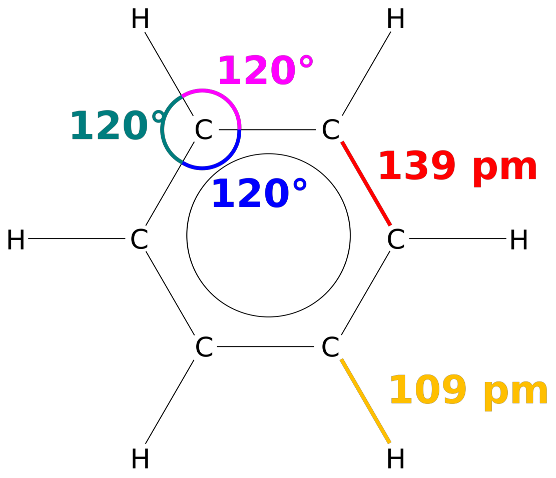
‡ Variation of light yield with temperature evaluated at the room temperature.

f = fast component, s = slow component

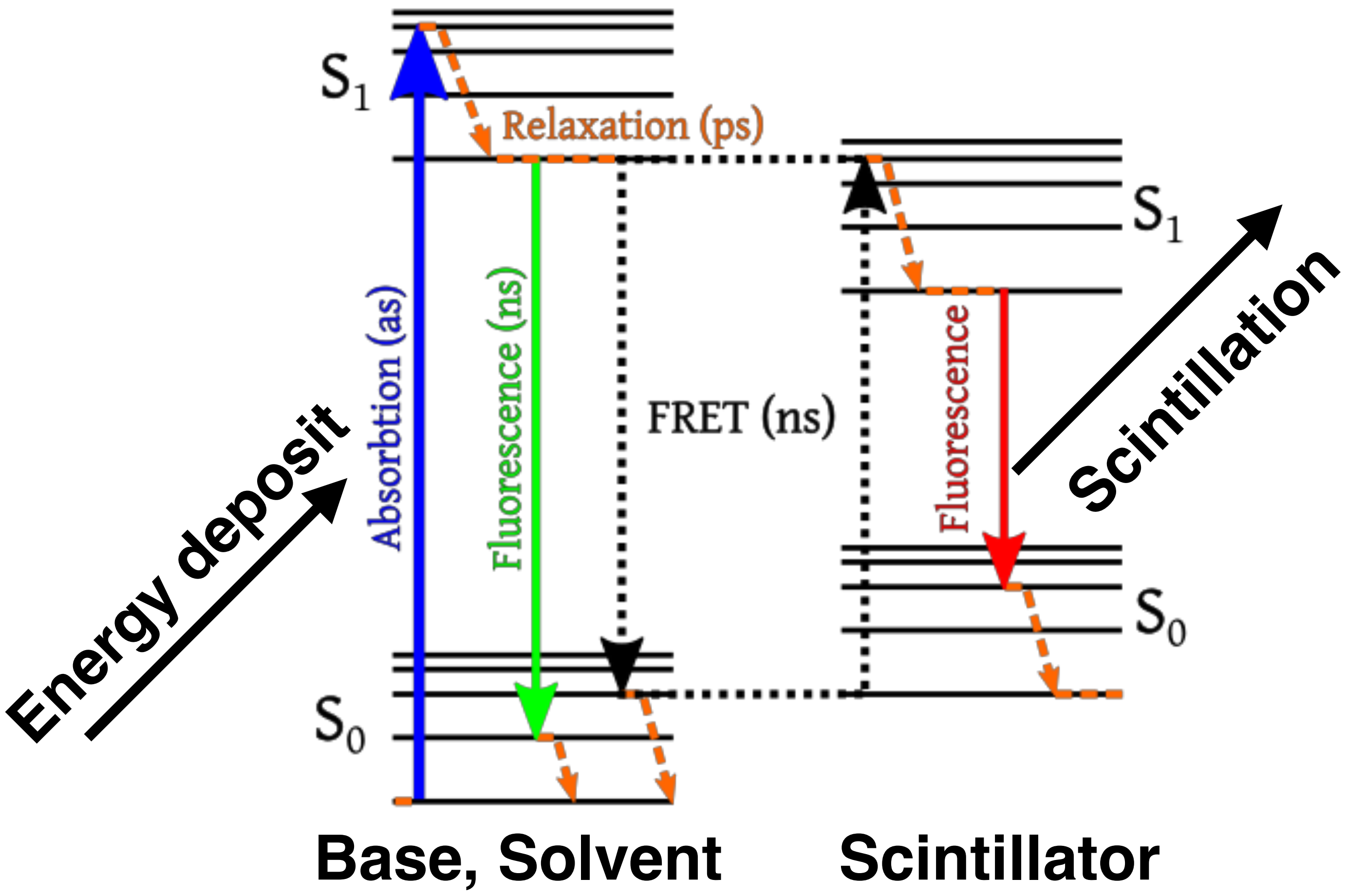
Inorganic Scintillator - Light yield temp. dep.



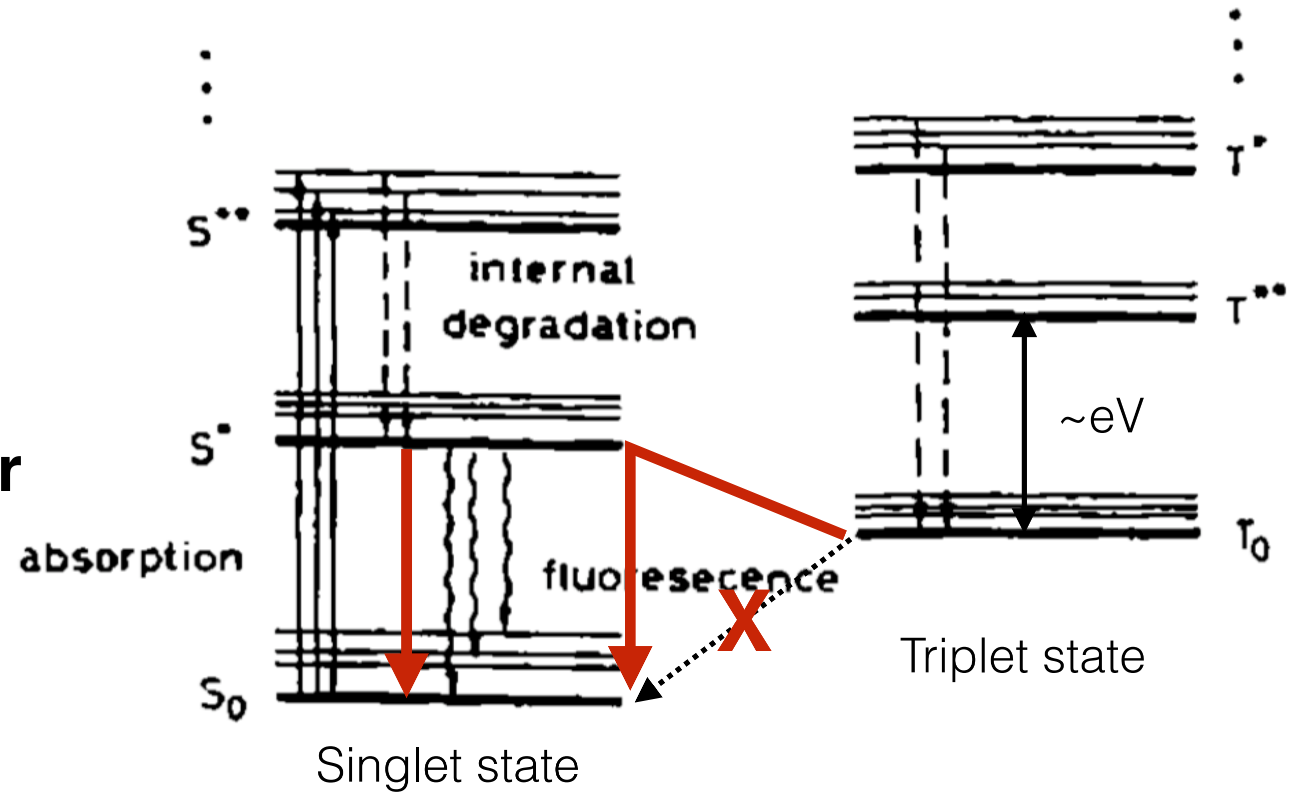
Organic Scintillator - Scintillation



Förster resonance energy transfer
Energy flows in organic scintillator



Energy structure of pi-molecular orbital



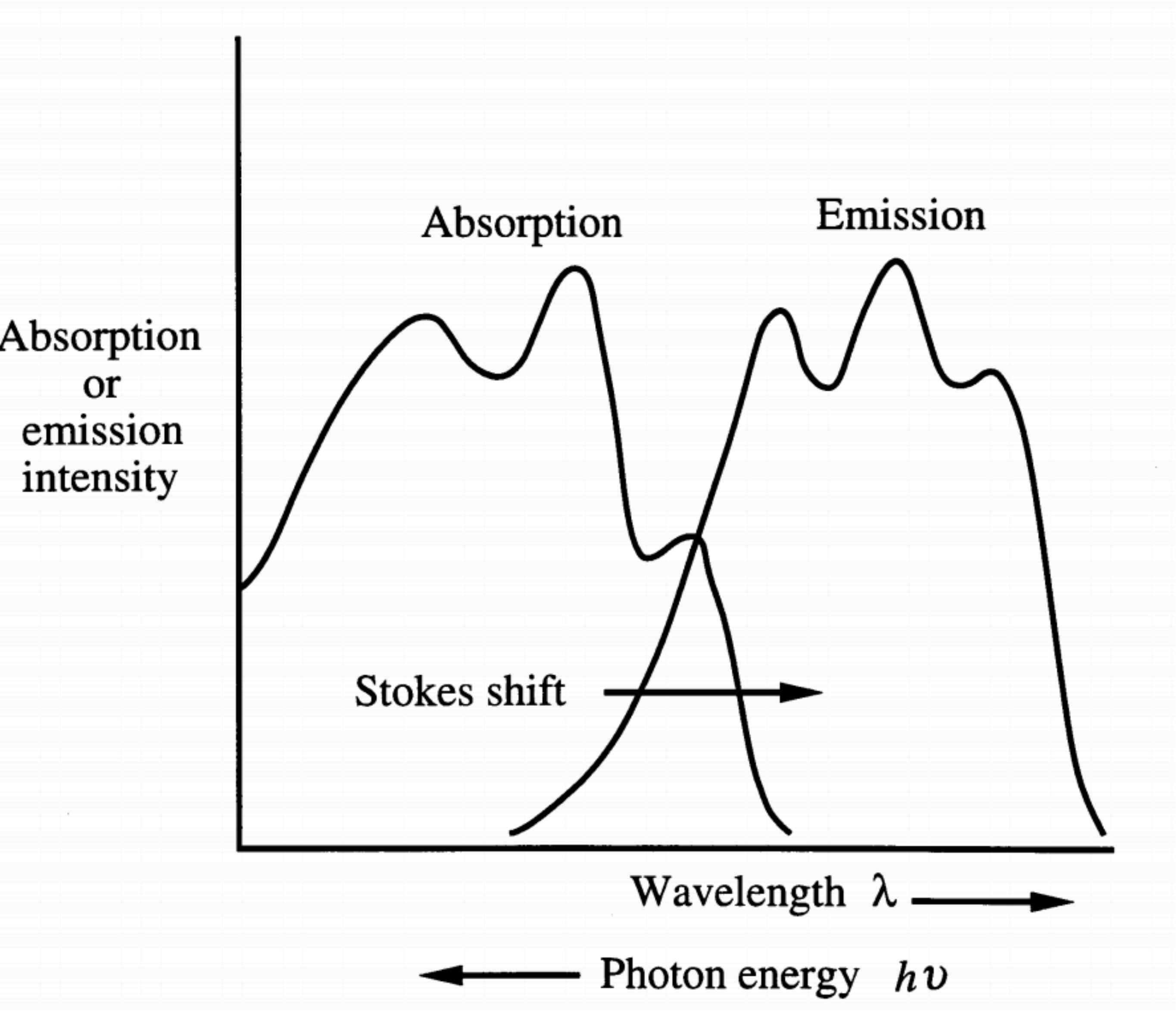
Fast : $S^* \rightarrow S_0 + \gamma$

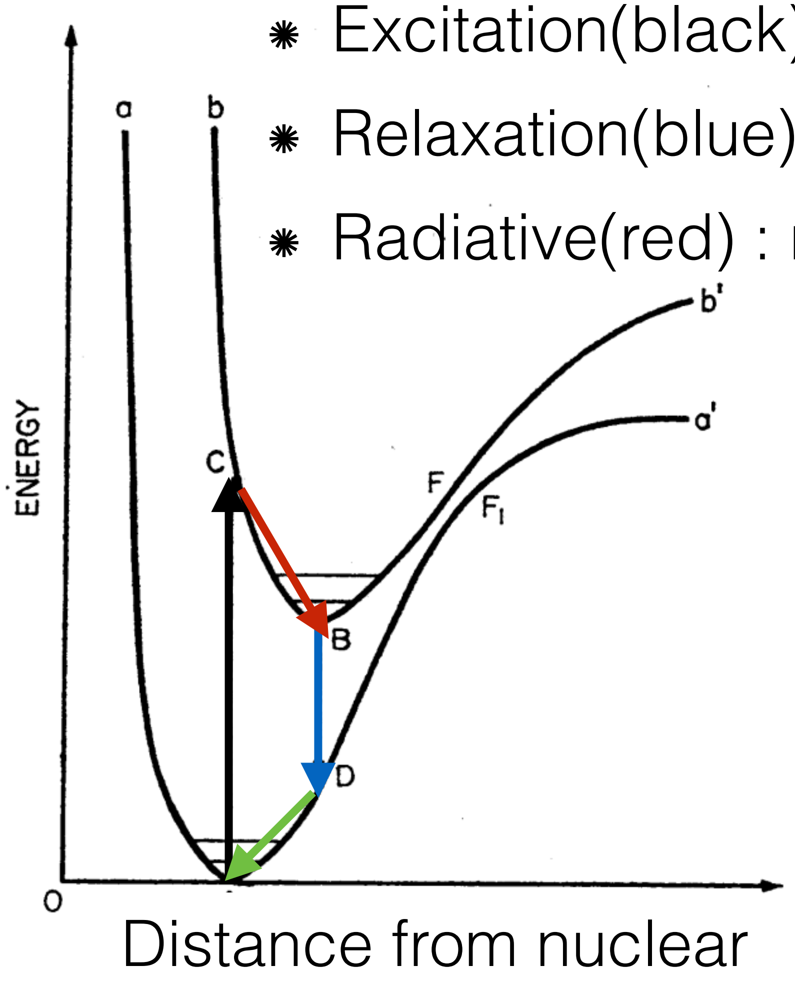
Slow : $T_0 + T_0 \rightarrow S^* + S_0 + \text{phonons}$

↳ $S^* \rightarrow S_0 + \gamma$

$$N(t) = N_0 e^{-\frac{t-t_0}{\tau_0}} + N_1 e^{-\frac{t-t_0}{\tau_1}}, \tau_1 > \tau_0$$

Organic Scintillator -Emission/Absortion





- ⁕ Excitation(black) : fs
- ⁕ Relaxation(blue) : ps
- ⁕ Radiative(red) : ns

Frank-Condon Principle

⁕Excitation <u>into</u> higher vibrational state

⁕De-excitation <u>from</u> lowest vibrational state

Organic Scintillator - Light yield

Ideal Scintillator : Number of photon ~ Deposit energy

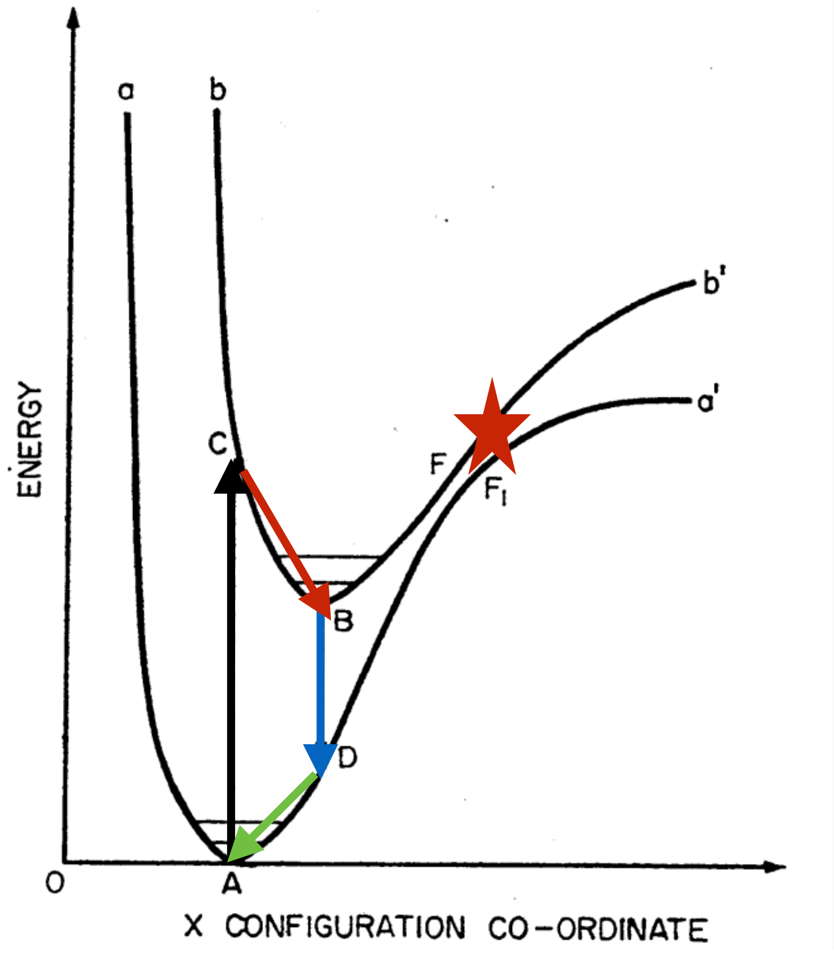
$$\xcancel{\frac{dL}{dx} = S\frac{dE}{dx}}$$

Birk's law

$$\frac{dL}{dx} = S\frac{\frac{dE}{dx}}{1 + k_B\frac{dE}{dx} + \ldots}$$

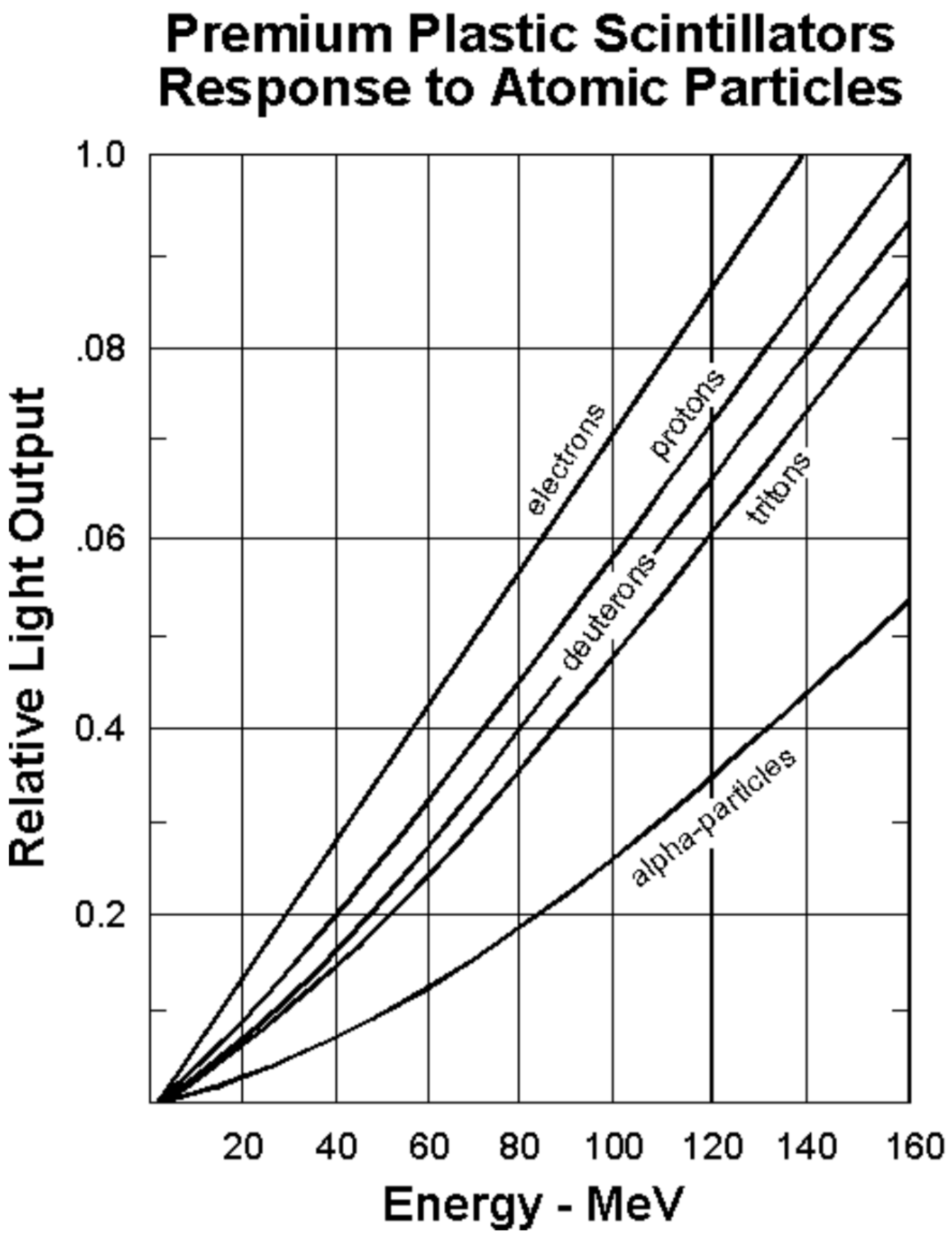
k_B : 0.126 mm/MeV for PS,
1.26~2.07 mm/MeV for PVT

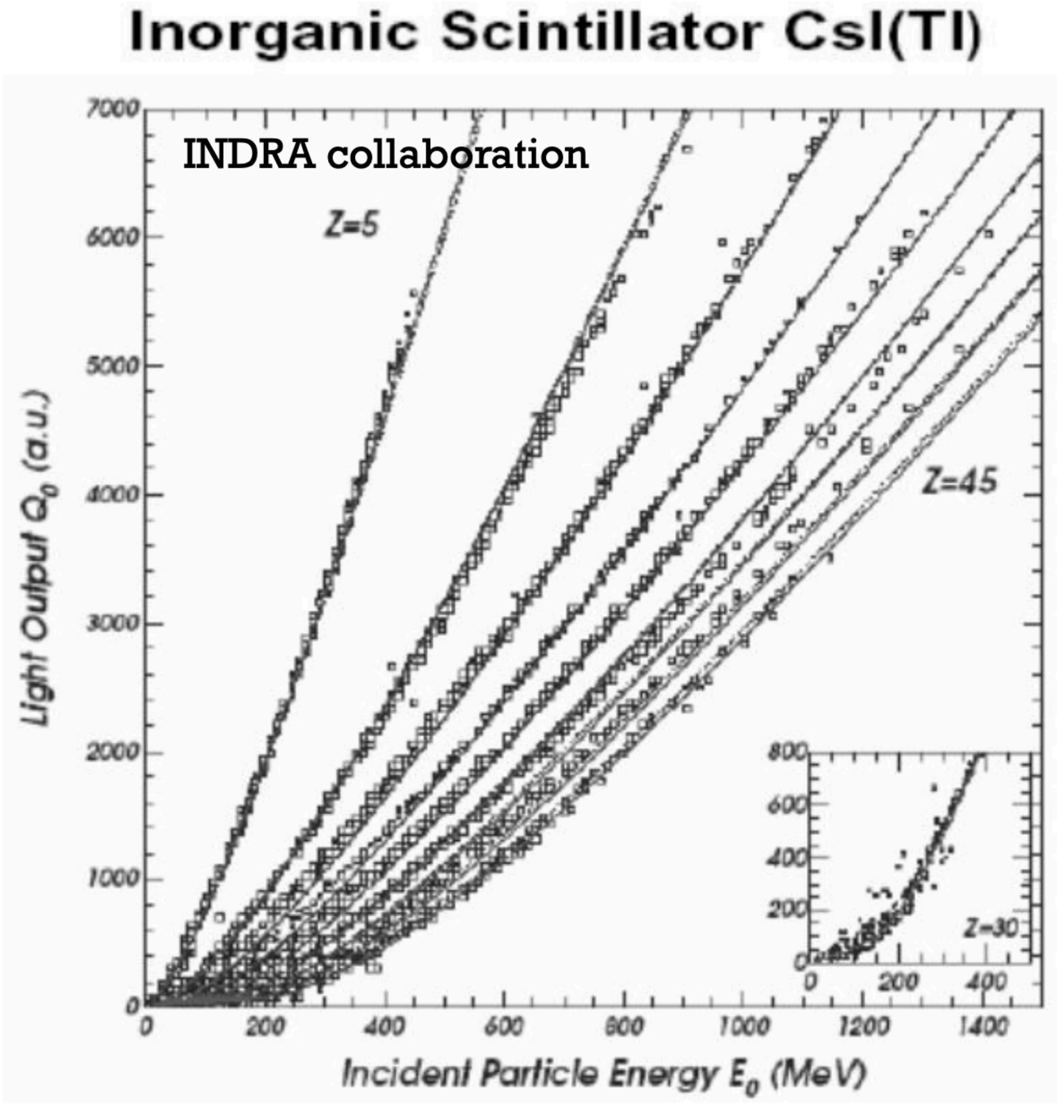
High dE/dx (Low energy charged particle)
->High excitation density
-> Quenching (Luminosity loss)



Organic Scintillator -Light yield-Birk's law

CsI(Tl)-Inorganic





Organic Scintillator
-PSD(Pulse shape discrimination)

High ionization density

↓

Increase T* state density

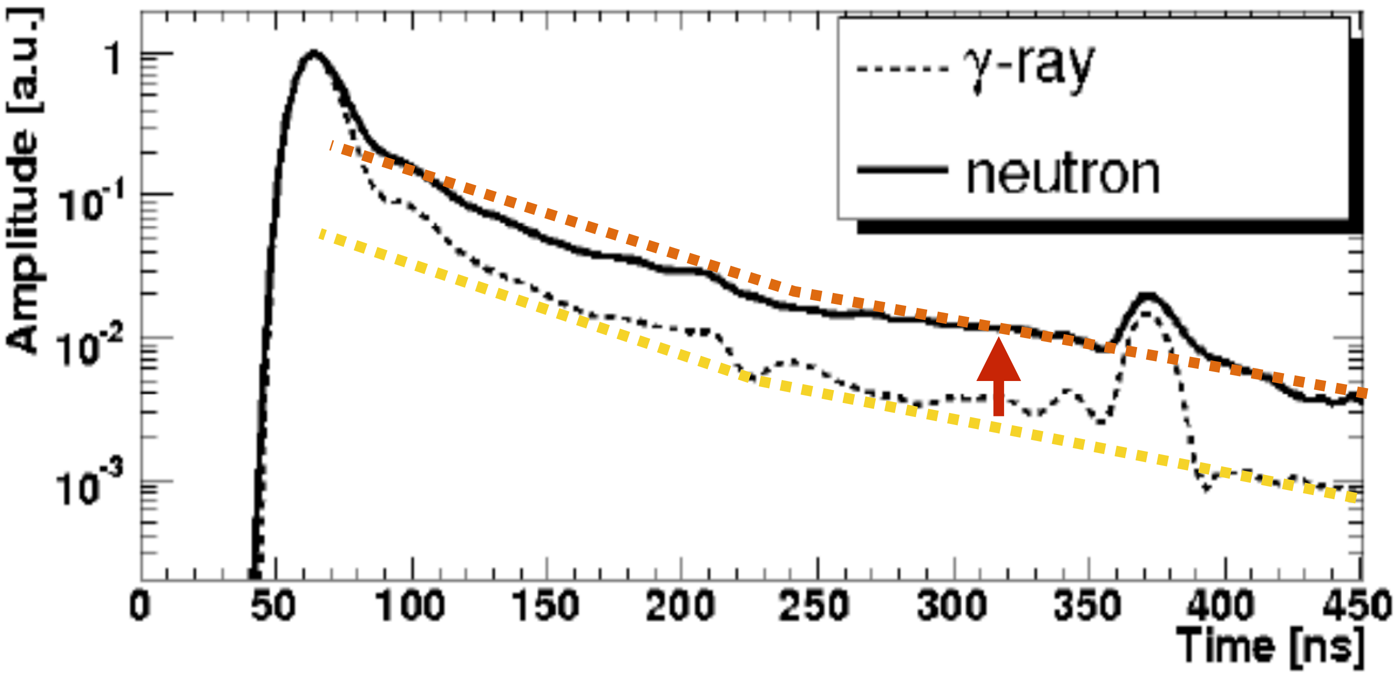
↓

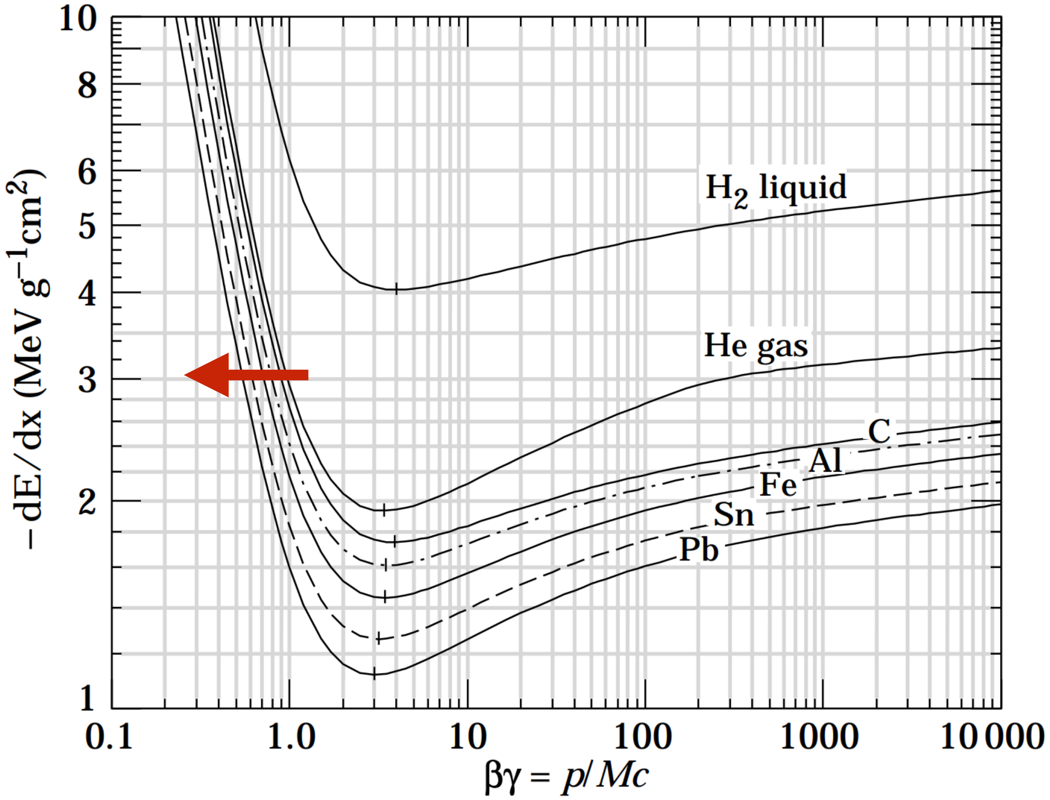
Increase slow component

↓

Waveform of
heavy & charged & low E particle
changes from gamma's

Pulse shapes in BC501A

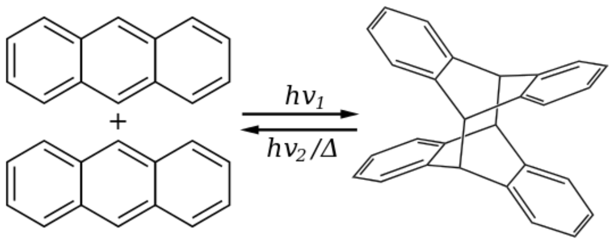




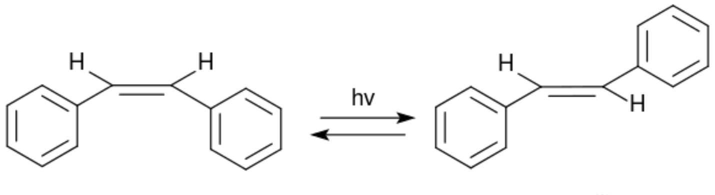
Organic Scintillator - Types

Organic crystal

anthracene



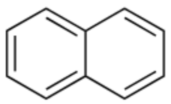
trans-stilbene



cis-stilbene

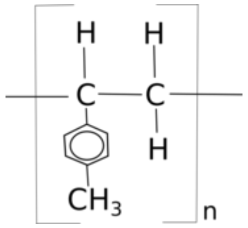
trans-stilbene

naphthalene

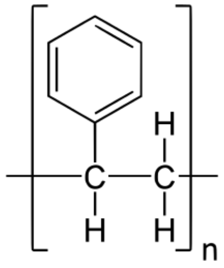


√Plastic

PVT



PS

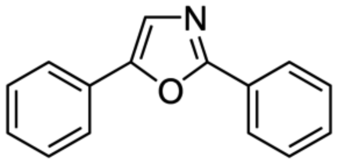


polyphenylbenzene,

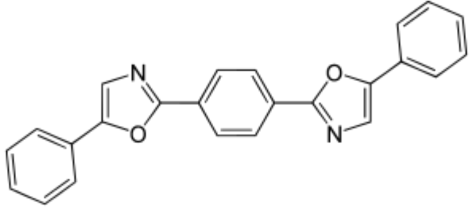
…

p-Terphenyl

2,5-Diphenyloxazole

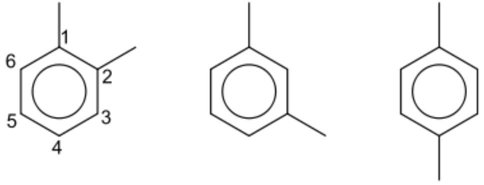


POPOP



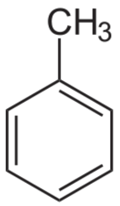
√Liquid

zylene



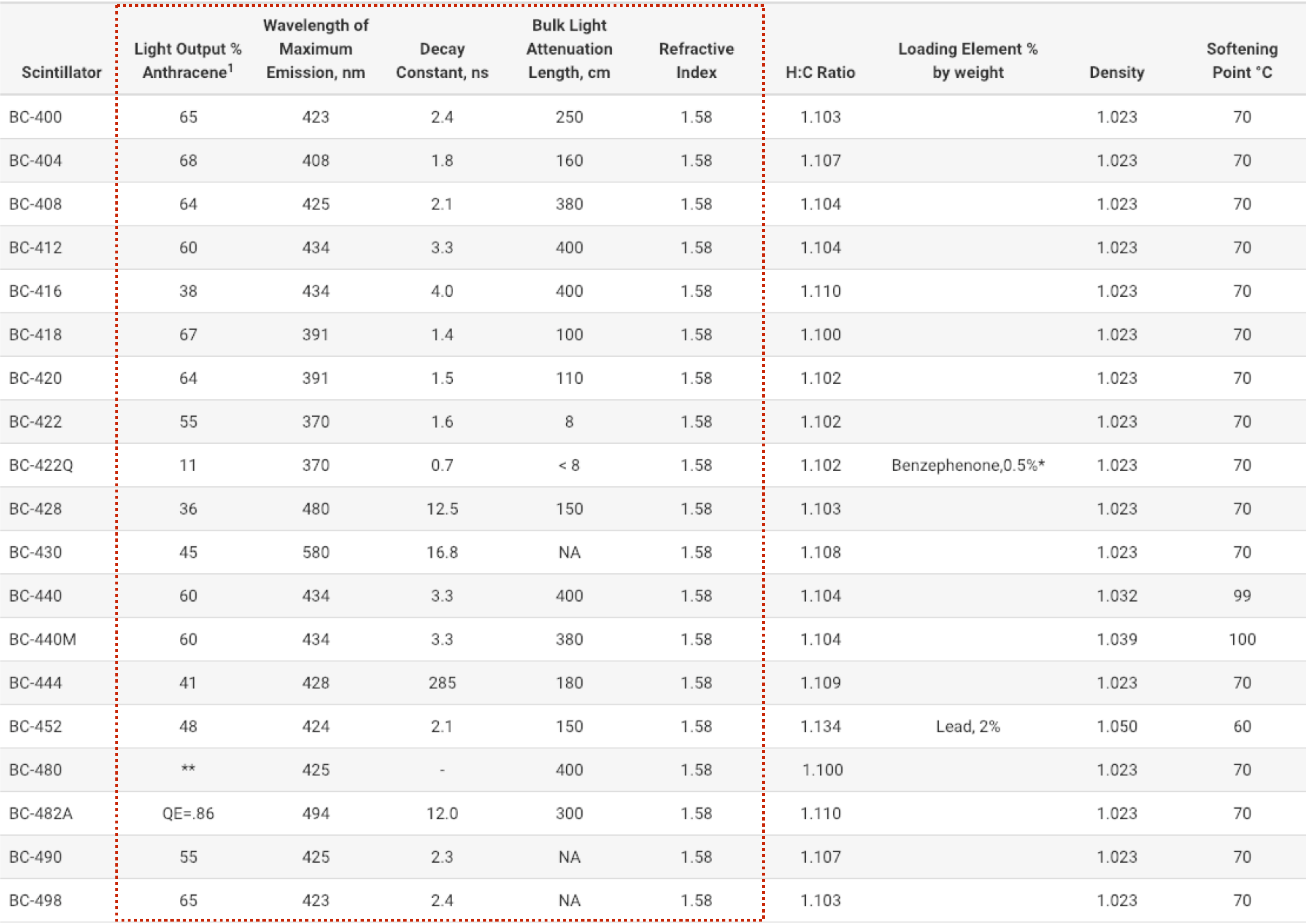
1,2-dimethylbenzene (*ortho*-xylene) 1,3-dimethylbenzene (*meta*-xylene) 1,4-dimethylbenzene (*para*-xylene)

toluene



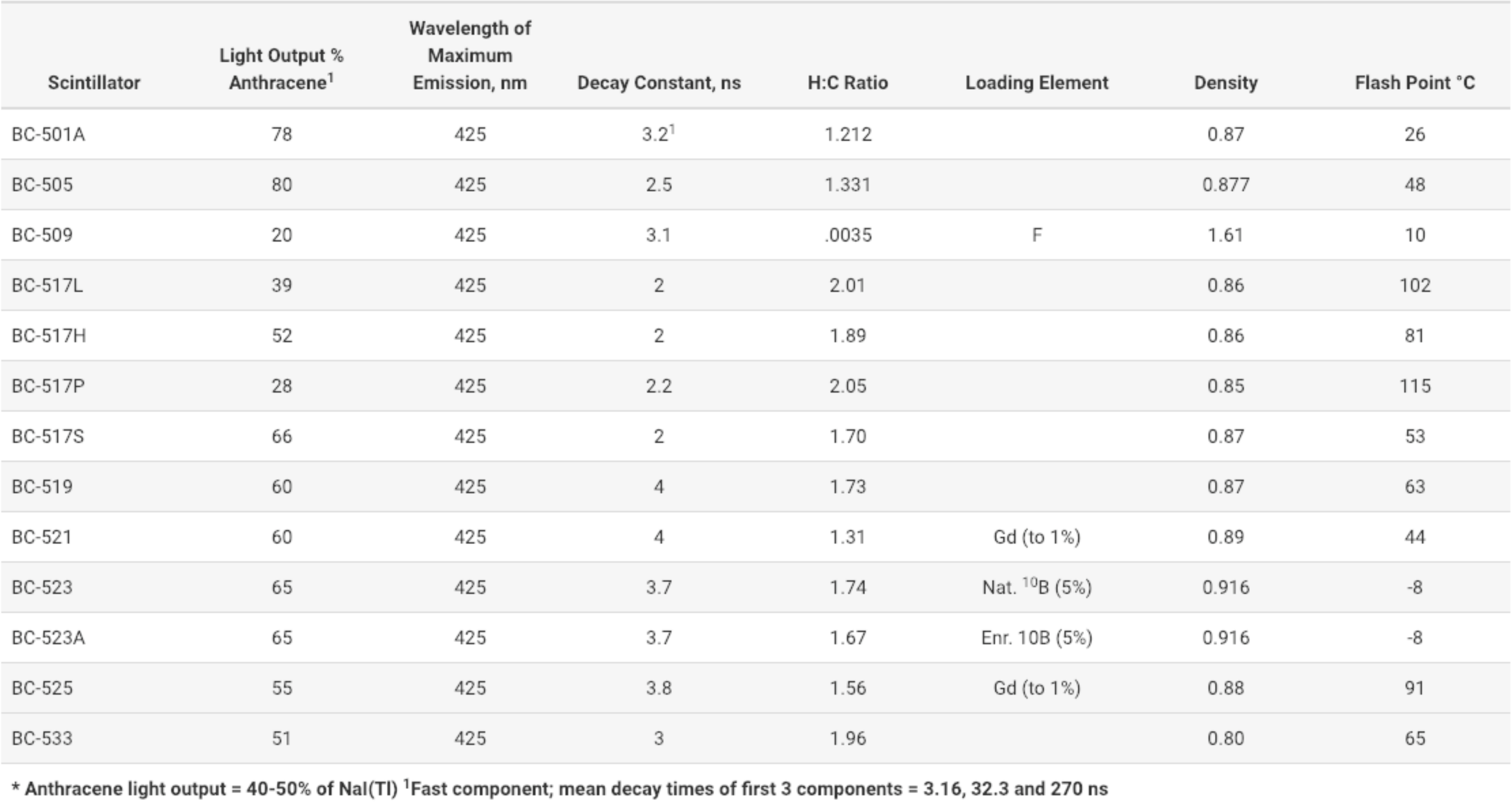
benzene,
phenylcyclohexane,
…..

Organic scintillator-plastic scintillator



Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, ns	Bulk Light Attenuation Length, cm	Refractive Index	H:C Ratio	Loading Element % by weight	Density	Softening Point °C
BC-400	65	423	2.4	250	1.58	1.103		1.023	70
BC-404	68	408	1.8	160	1.58	1.107		1.023	70
BC-408	64	425	2.1	380	1.58	1.104		1.023	70
BC-412	60	434	3.3	400	1.58	1.104		1.023	70
BC-416	38	434	4.0	400	1.58	1.110		1.023	70
BC-418	67	391	1.4	100	1.58	1.100		1.023	70
BC-420	64	391	1.5	110	1.58	1.102		1.023	70
BC-422	55	370	1.6	8	1.58	1.102		1.023	70
BC-422Q	11	370	0.7	< 8	1.58	1.102	Benzephenone,0.5%*	1.023	70
BC-428	36	480	12.5	150	1.58	1.103		1.023	70
BC-430	45	580	16.8	NA	1.58	1.108		1.023	70
BC-440	60	434	3.3	400	1.58	1.104		1.032	99
BC-440M	60	434	3.3	380	1.58	1.104		1.039	100
BC-444	41	428	285	180	1.58	1.109		1.023	70
BC-452	48	424	2.1	150	1.58	1.134	Lead, 2%	1.050	60
BC-480	**	425	-	400	1.58	1.100		1.023	70
BC-482A	QE=.86	494	12.0	300	1.58	1.110		1.023	70
BC-490	55	425	2.3	NA	1.58	1.107		1.023	70
BC-498	65	423	2.4	NA	1.58	1.103		1.023	70

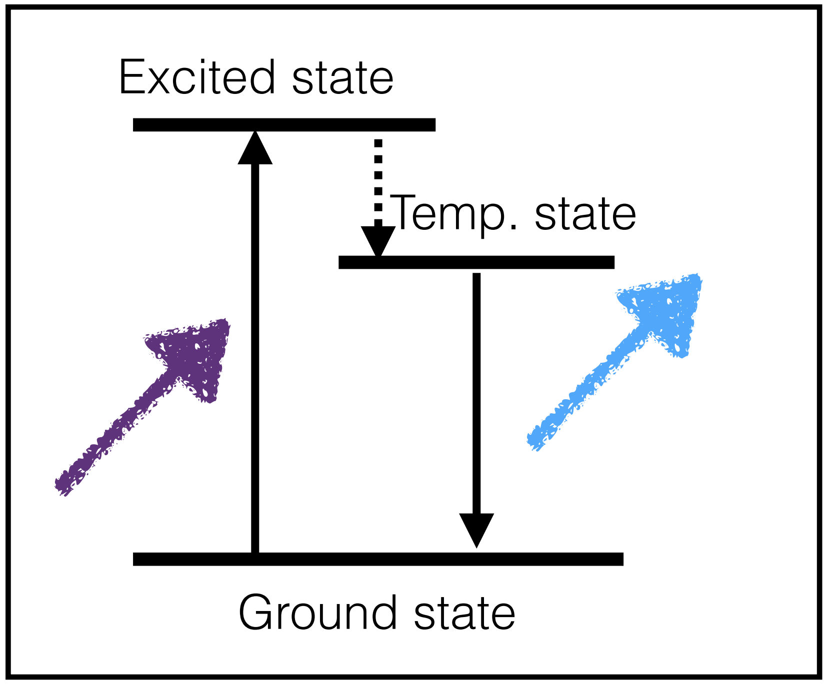
Organic scintillator-liguid scintillator



Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, ns	H:C Ratio	Loading Element	Density	Flash Point °C
BC-501A	78	425	3.2[1]	1.212		0.87	26
BC-505	80	425	2.5	1.331		0.877	48
BC-509	20	425	3.1	.0035	F	1.61	10
BC-517L	39	425	2	2.01		0.86	102
BC-517H	52	425	2	1.89		0.86	81
BC-517P	28	425	2.2	2.05		0.85	115
BC-517S	66	425	2	1.70		0.87	53
BC-519	60	425	4	1.73		0.87	63
BC-521	60	425	4	1.31	Gd (to 1%)	0.89	44
BC-523	65	425	3.7	1.74	Nat. ^{10}B (5%)	0.916	-8
BC-523A	65	425	3.7	1.67	Enr. 10B (5%)	0.916	-8
BC-525	55	425	3.8	1.56	Gd (to 1%)	0.88	91
BC-533	51	425	3	1.96		0.80	65

*** Anthracene light output = 40-50% of NaI(Tl) [1]Fast component; mean decay times of first 3 components = 3.16, 32.3 and 270 ns**

Properties of scintillators



Wavelength of scintillation light ?

수소의 특성X선 에너지 : 13.7 eV

h : 6.625 e-34 Js
c : 2.99 e8 m/s
E : 13.7 eV

$$\longrightarrow \lambda = \frac{hc}{E}$$

145 nm

(Visible/UV 경계 : 390 nm)
(인체적외선 : ~ 9 μm)

Redberg Formula

$$\frac{1}{\lambda} = RZ^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

>>Scintillation light 는 eV 레벨

Energy resolution

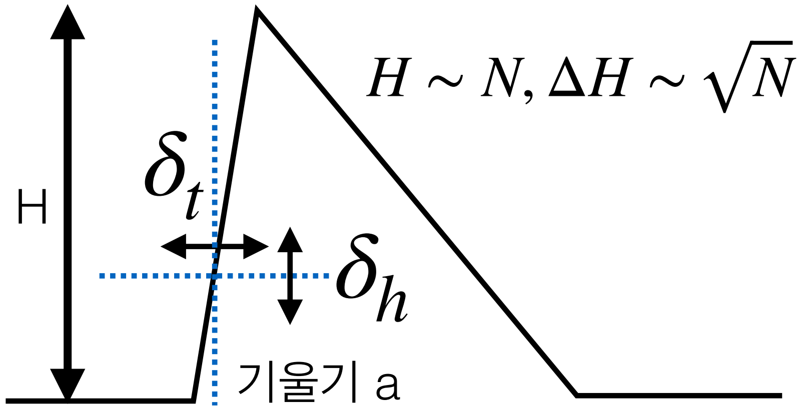
$$\boxed{\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N}}$$

N : 발생한 광자수

+ Systematic & noise

$$\boxed{\frac{\Delta E}{E} = \alpha \oplus \frac{\beta}{\sqrt{E}} \oplus \frac{\gamma}{E}}$$

Timing resolution



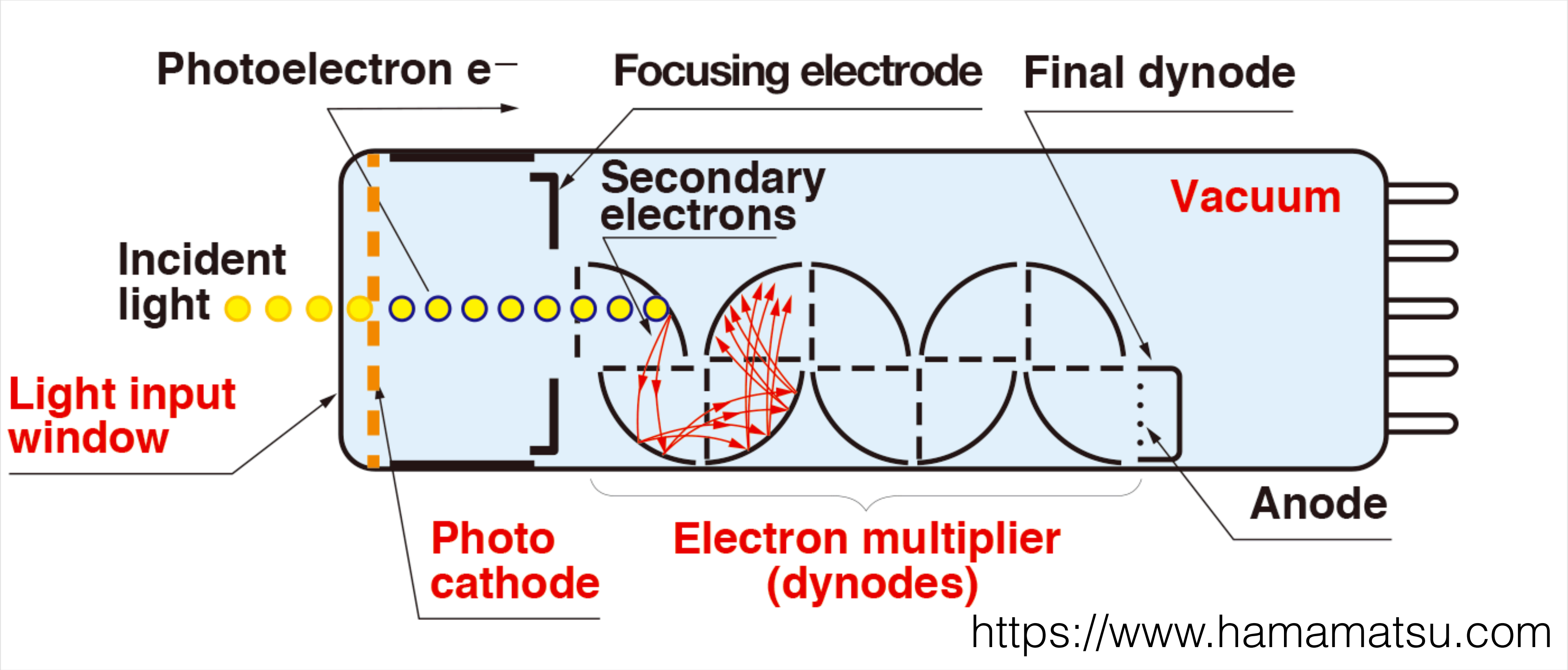
$$a \propto \frac{H}{t_{rise}}$$

$$\delta_h = \underset{\uparrow\,\text{fraction}}{a}\Delta H \oplus \underset{\uparrow\,\text{Noise}}{b}$$

$$\delta_t = \delta_h / a \propto \frac{\alpha}{\sqrt{N}} \oplus \frac{\beta}{N}$$

$$\boxed{\Delta t = \underset{\uparrow\,\text{Intrinsic}}{\alpha} \oplus \frac{\beta}{\underset{\uparrow\,\text{Statistical}}{\sqrt{N}}} \oplus \frac{\gamma}{\underset{\uparrow\,\text{Noise}}{N}}}$$

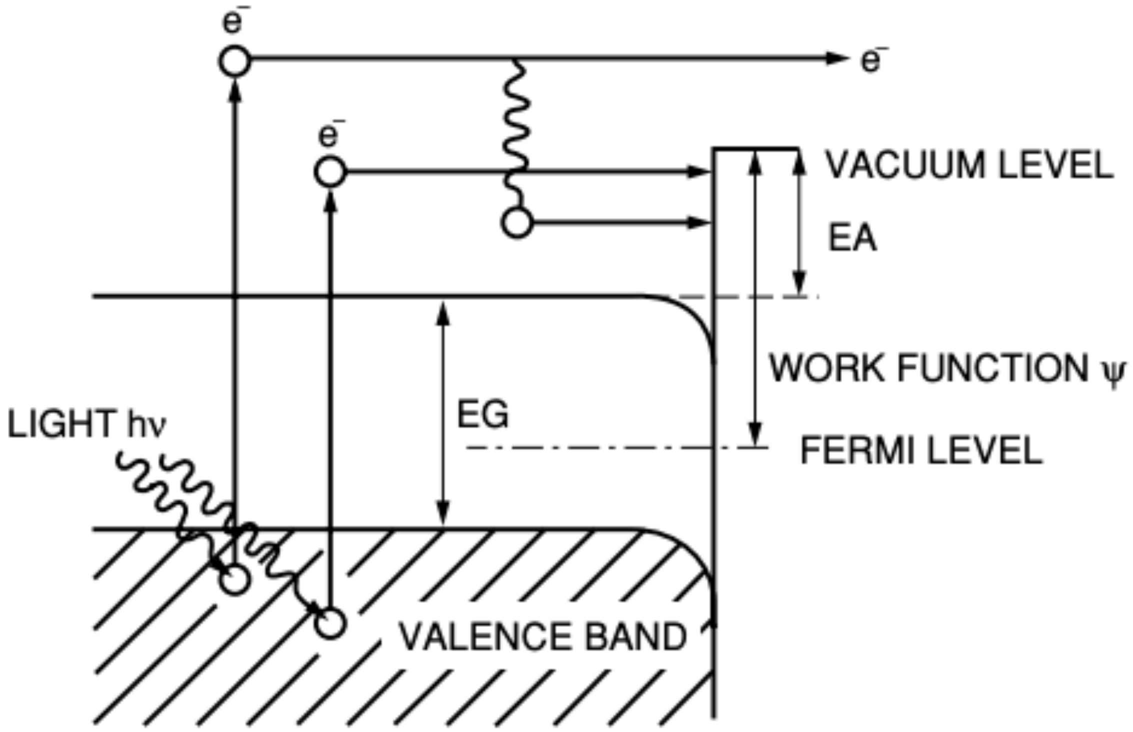
PMT



https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf

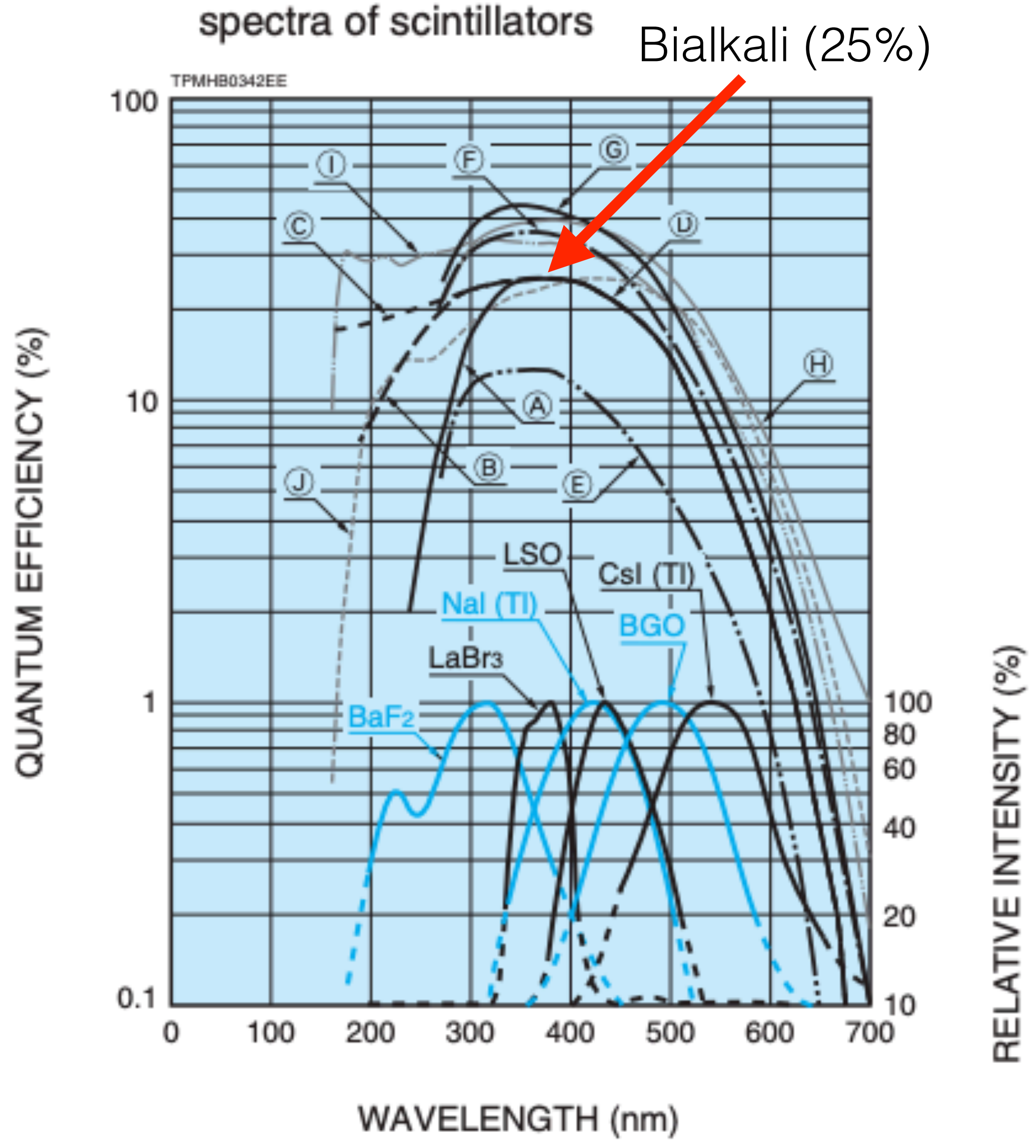
Cathod material

$$Q.E. = \frac{Number\ of\ photoelectronics}{Number\ of\ Photons}$$



Work functions (eV)	
Sb	4.55-4.7
Rb	2.261
Cs	1.95
K	2.29
Ga	4.32
As	3.75
In	4.09

Figure 34: Typical spectral response and emission spectra of scintillators



Ⓐ: Bialkali Photocathode (Borosilicate Glass)
Ⓑ: Bialkali Photocathode (UV Glass)
Ⓒ: Bialkali Photocathode (Silica Glass)
Ⓓ: Bialkali Photocathode
Ⓔ: High Temp. Bialkali Photocathode
Ⓕ: Super Bialkali
Ⓖ: Ultra Bialkali
Ⓗ: Extended Green Bialkali
Ⓘ: Low Temp. (down to -110 °C) Bialkali Photocathode
Ⓙ: Low Temp. (down to -186 °C) Bialkali Photocathode

www.Hamamatsu.com

Window material & dinodes

Window material	
Borosilicate glass	300 nm ~
UV-transmitting	185 nm ~
Silica glass	160 nm ~

Select glass type by budget and required performance

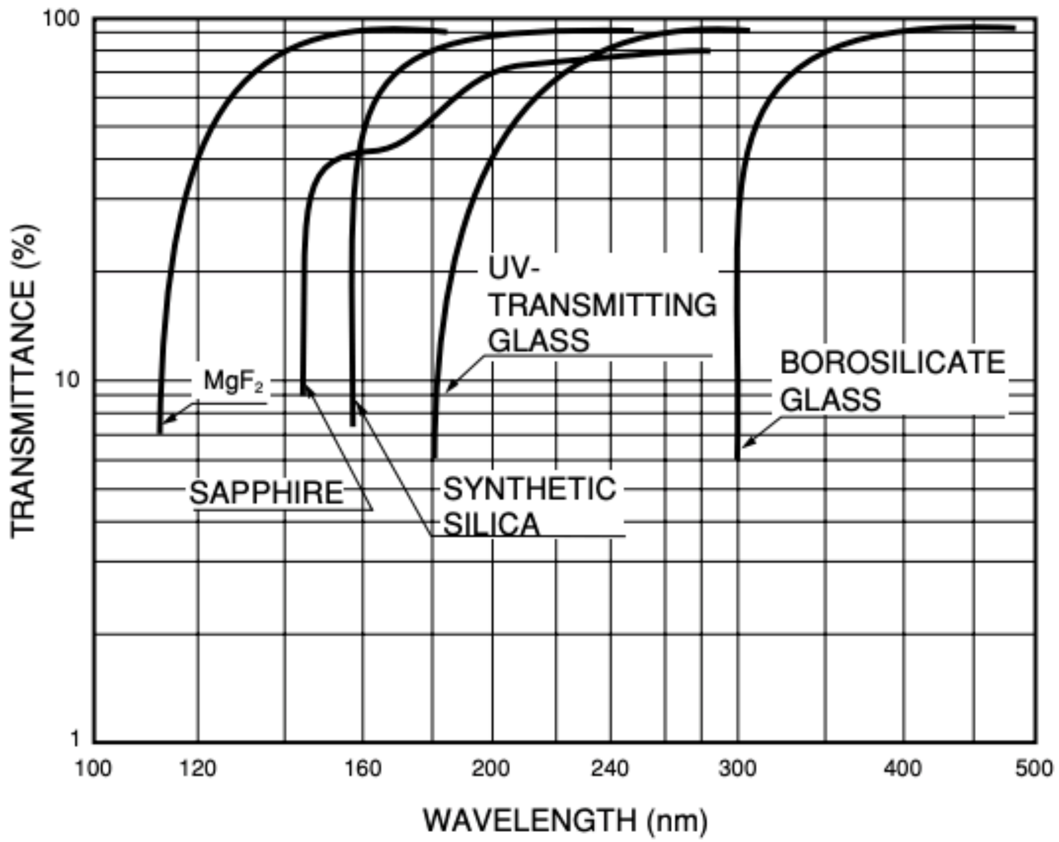


Figure 4-5: Spectral transmittance of window materials

Figure 2-4: Box-and-grid type

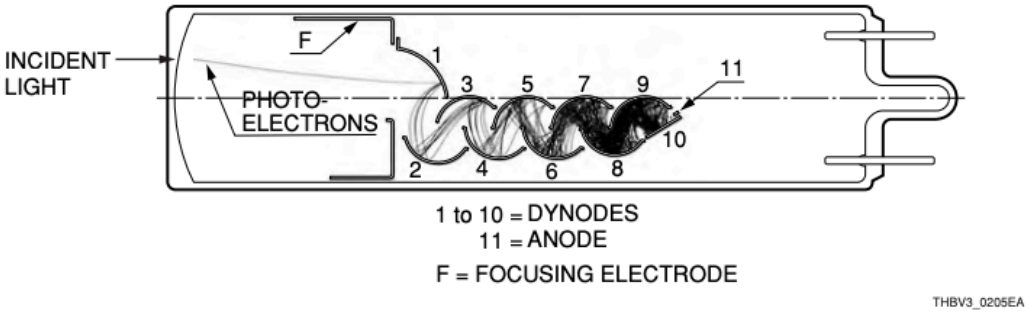


Figure 2-5: Linear-focused type

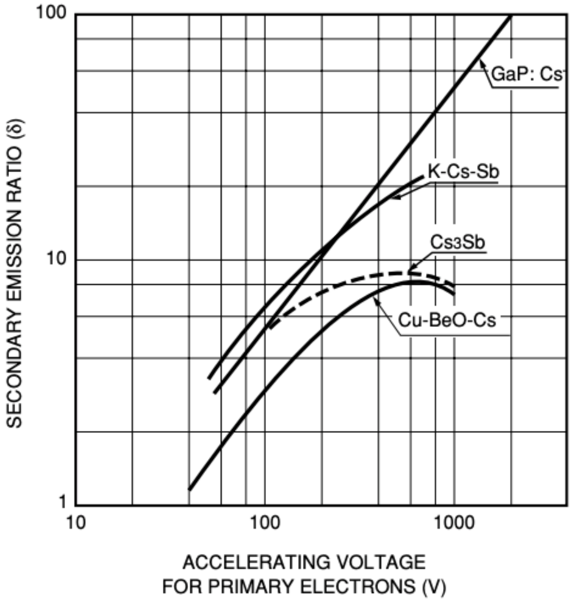


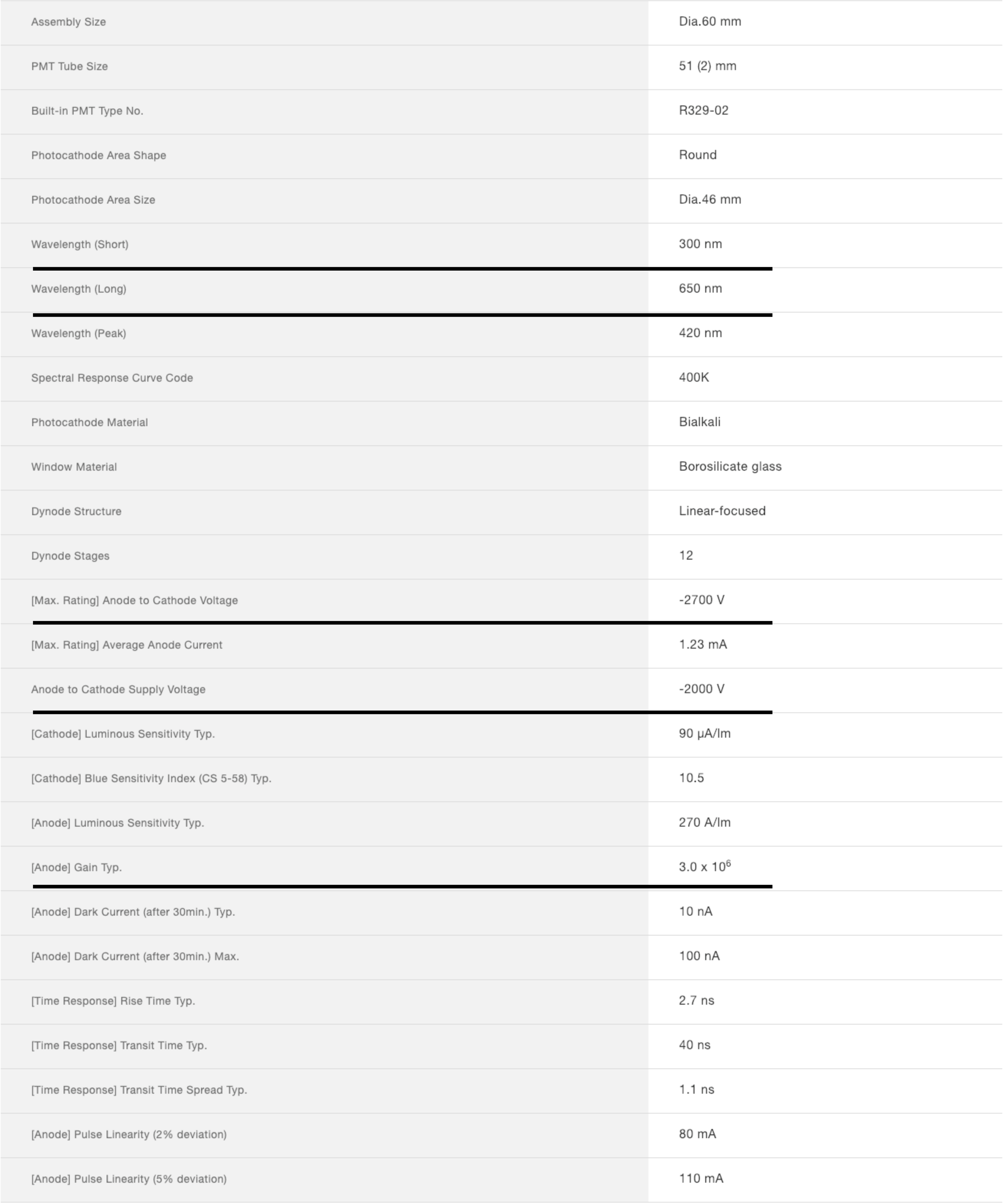
Figure 2-7: Secondary emission ratio δ

PMT gain (G(V)) := Number of electrons in single photon signal

$$G(V) \sim \delta(V)^n, \text{n : number of dinode stages}$$

H7195 : n = 12, V= ~200V, delta(v)=~3.5 => 3e6

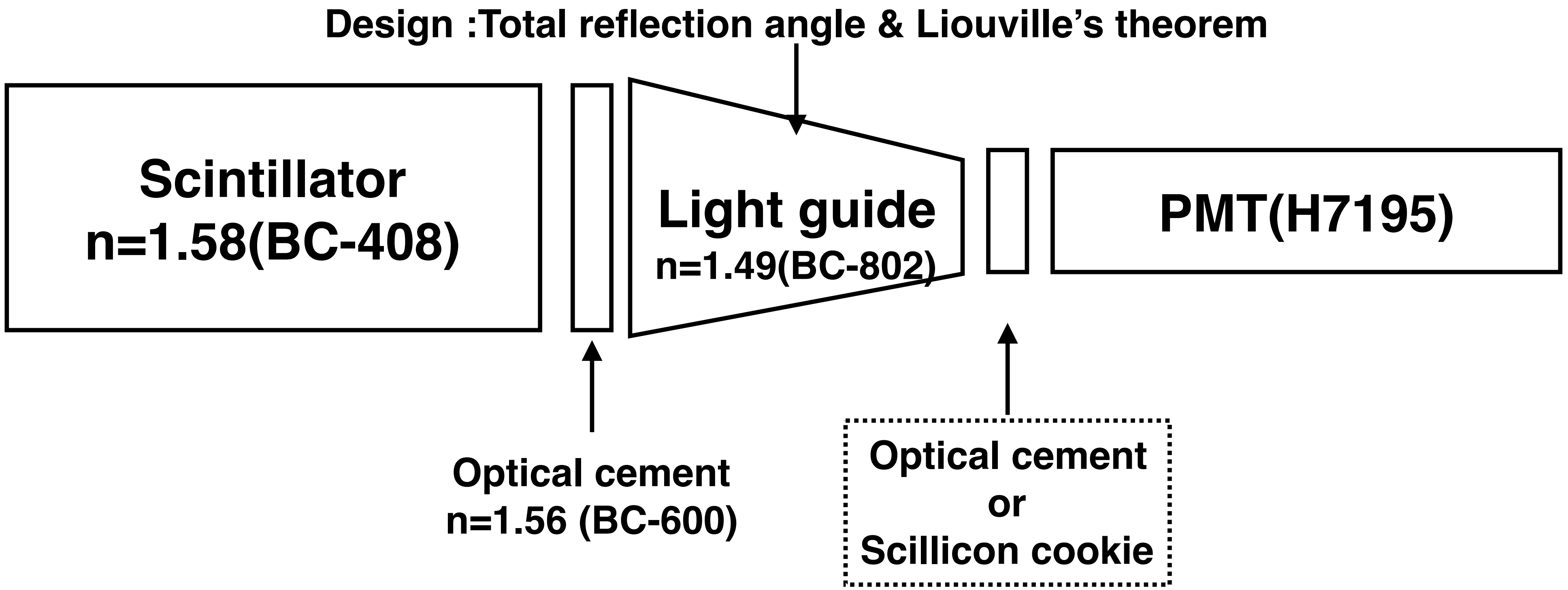
H7195 data sheet



Assembly Size	Dia.60 mm
PMT Tube Size	51 (2) mm
Built-in PMT Type No.	R329-02
Photocathode Area Shape	Round
Photocathode Area Size	Dia.46 mm
Wavelength (Short)	300 nm
Wavelength (Long)	650 nm
Wavelength (Peak)	420 nm
Spectral Response Curve Code	400K
Photocathode Material	Bialkali
Window Material	Borosilicate glass
Dynode Structure	Linear-focused
Dynode Stages	12
[Max. Rating] Anode to Cathode Voltage	-2700 V
[Max. Rating] Average Anode Current	1.23 mA
Anode to Cathode Supply Voltage	-2000 V
[Cathode] Luminous Sensitivity Typ.	90 μA/lm
[Cathode] Blue Sensitivity Index (CS 5-58) Typ.	10.5
[Anode] Luminous Sensitivity Typ.	270 A/lm
[Anode] Gain Typ.	3.0 x 10^6
[Anode] Dark Current (after 30min.) Typ.	10 nA
[Anode] Dark Current (after 30min.) Max.	100 nA
[Time Response] Rise Time Typ.	2.7 ns
[Time Response] Transit Time Typ.	40 ns
[Time Response] Transit Time Spread Typ.	1.1 ns
[Anode] Pulse Linearity (2% deviation)	80 mA
[Anode] Pulse Linearity (5% deviation)	110 mA

Detector Assembly

Optics



Design :Total reflection angle & Liouville's theorem

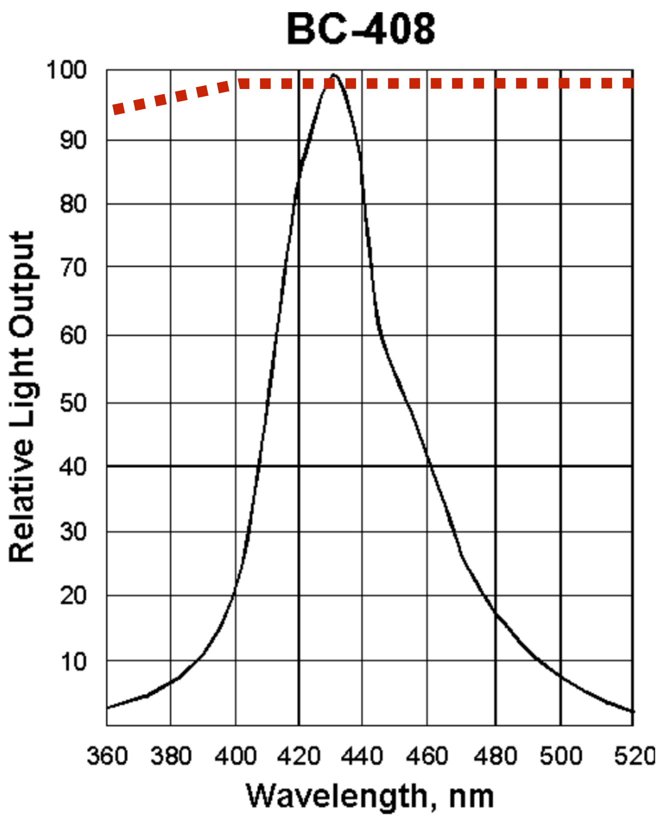
Scintillator
n=1.58(BC-408)

Light guide
n=1.49(BC-802)

PMT(H7195)

Optical cement
n=1.56 (BC-600)

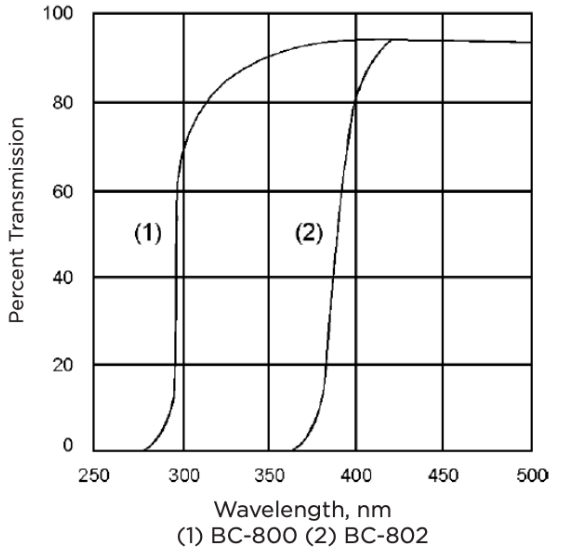
Optical cement
or
Scillicon cookie



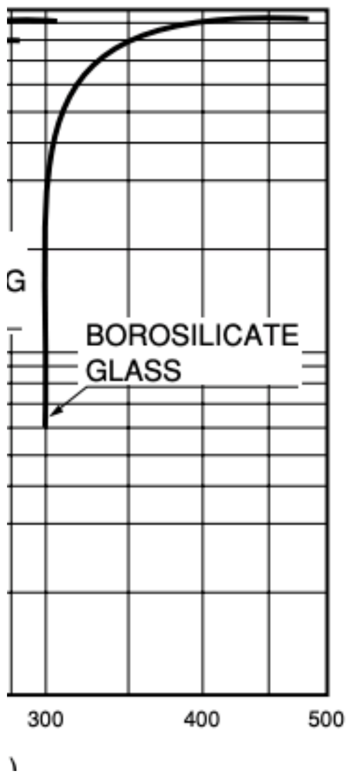
BC-600
(125 μm)

Wavelength	Transmission
above 400nm	>98%
340nm - 400nm	>95%
308nm - 340nm	>90%

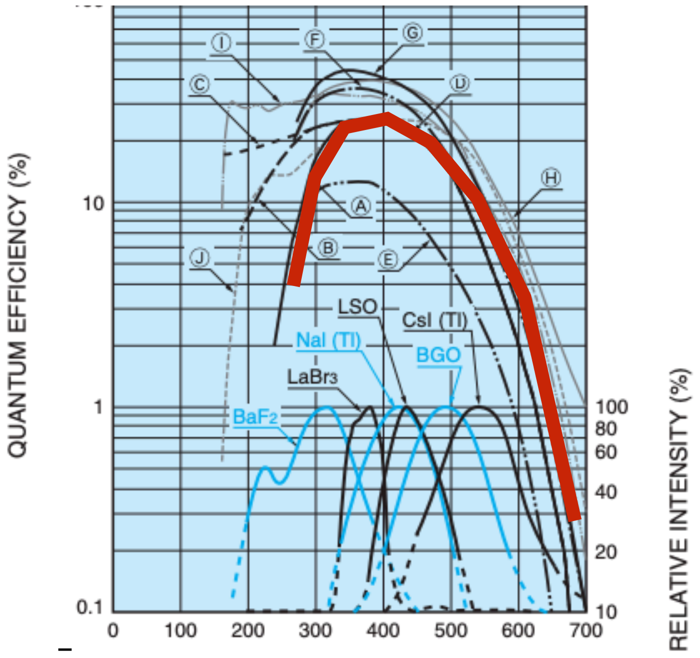
Transmittance of 2.54 cm thick Acrylic –



PMT window
BORO. glass



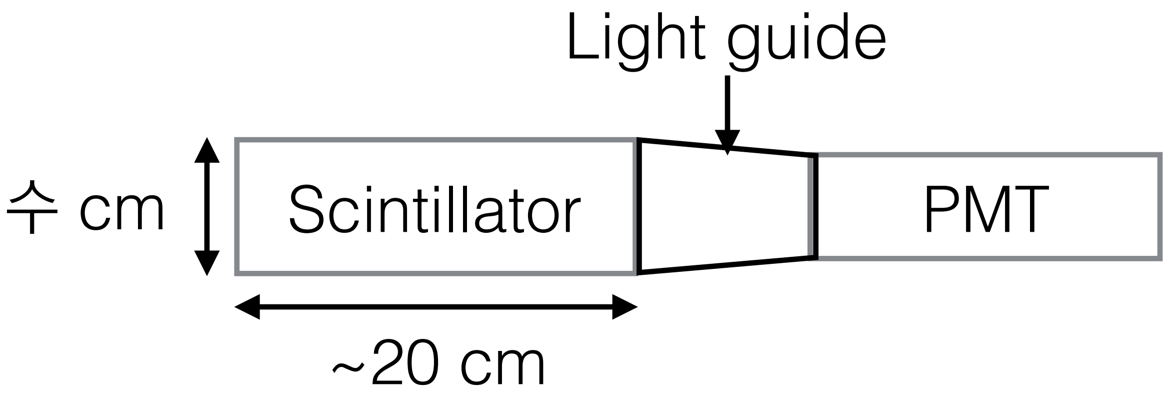
PMT Cathod
Q.E.



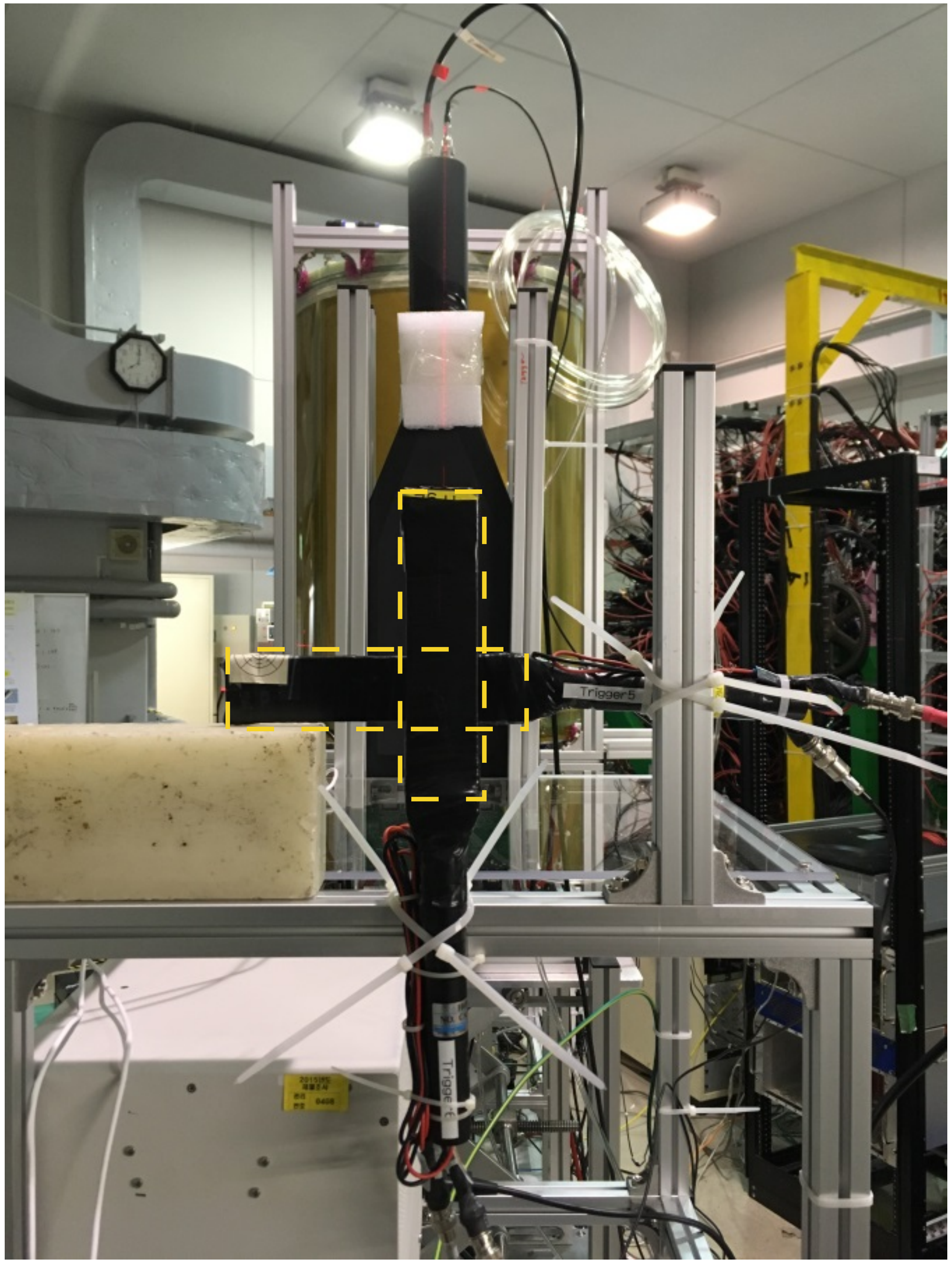
Application

1. Trigger counter
2. Tracker
3. Calorimeter

Trigger counter

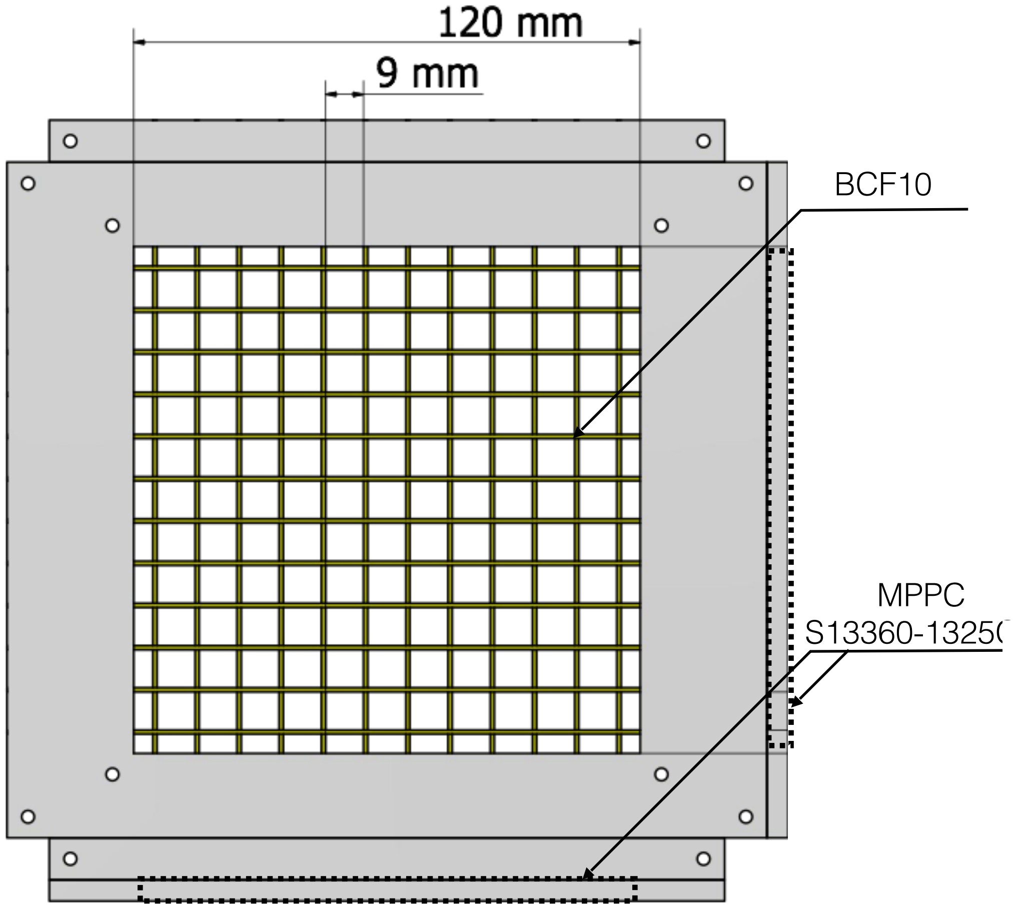


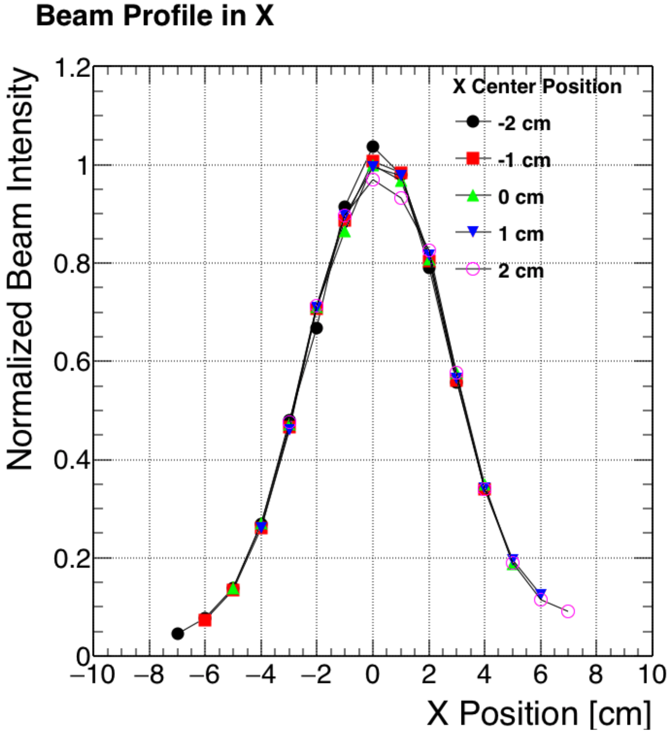
Speed of light in scintillator: ~ 20 cm/ns
Coincidence of two detector
-> 3 x 3 cm^2 detection area
->time zitter <200 ps

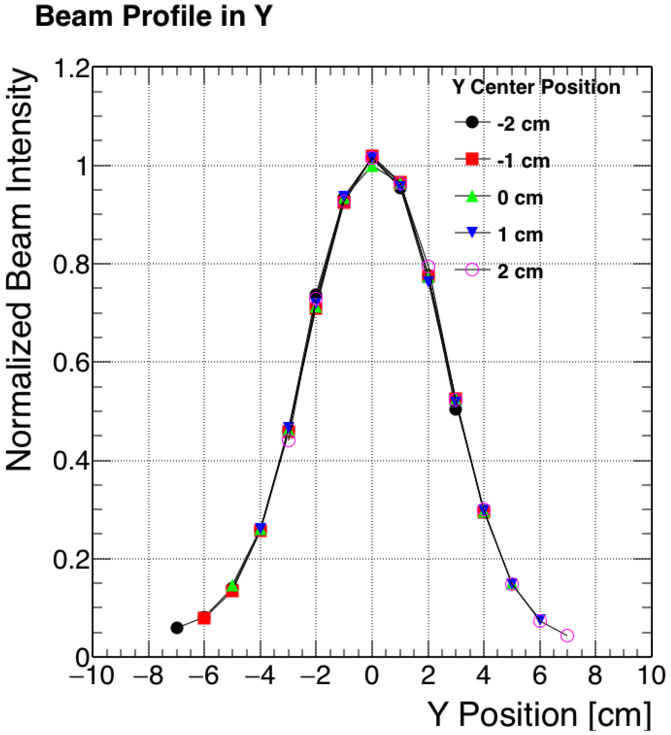


Beam profiler

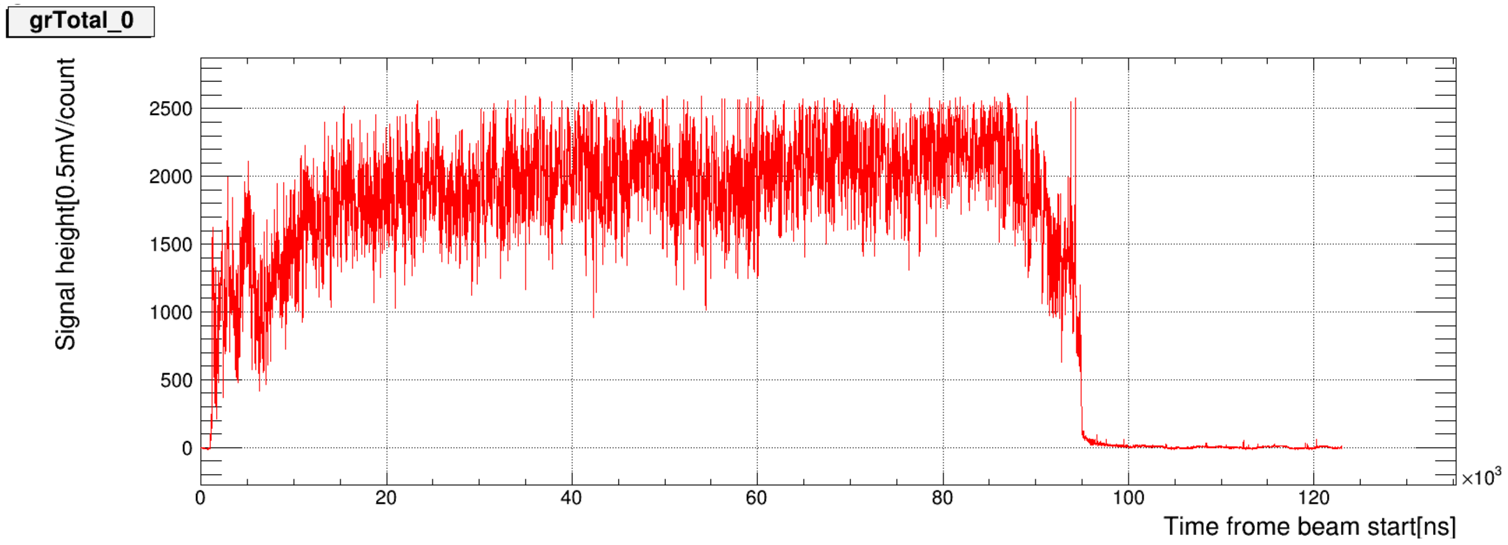
Simple beam profile monitor
(scintillation fiber + MPPC)

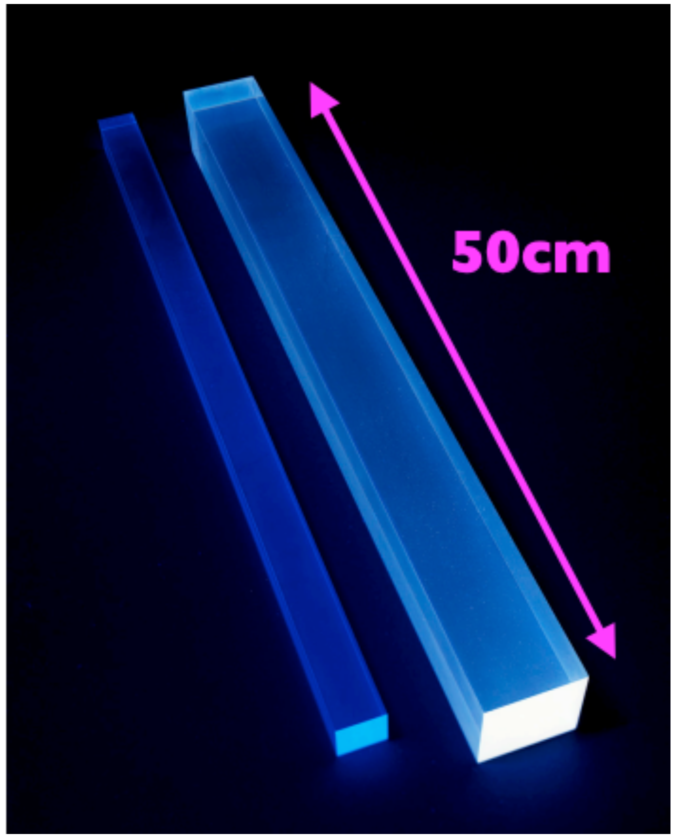


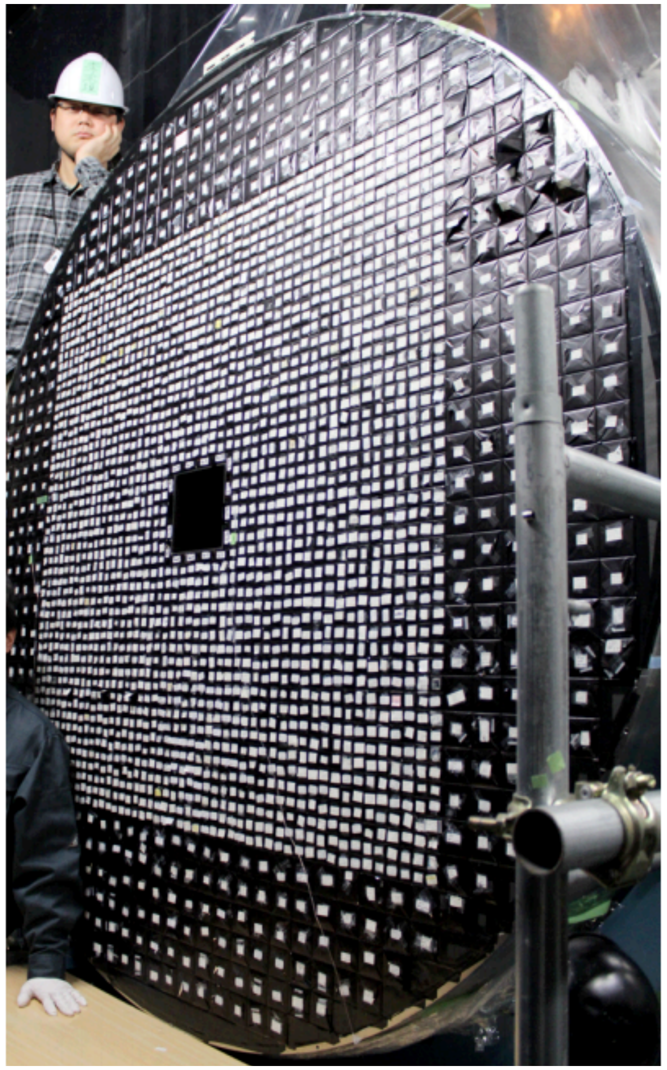

Beam Profile in X

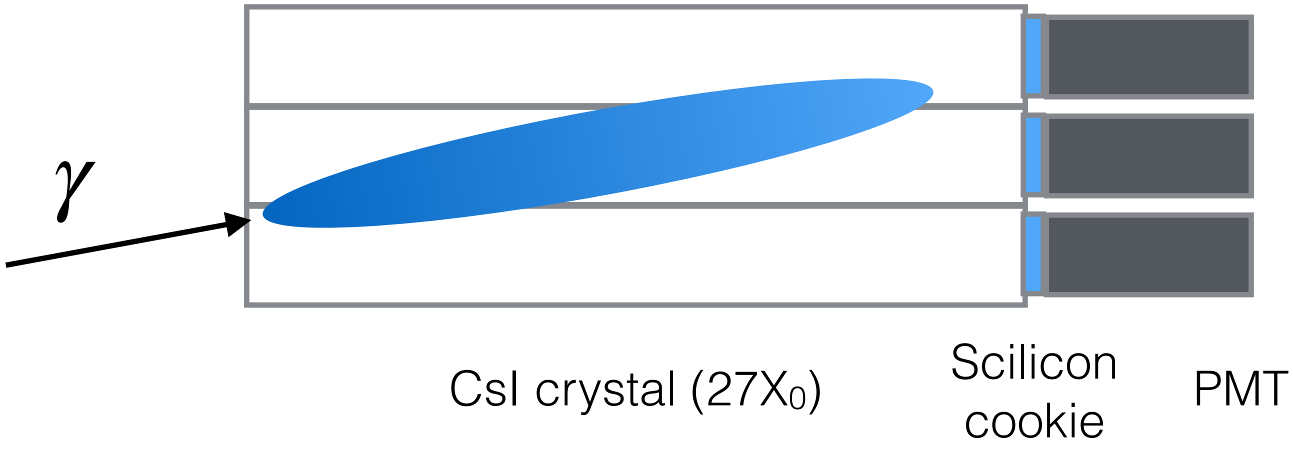

Beam Profile in Y

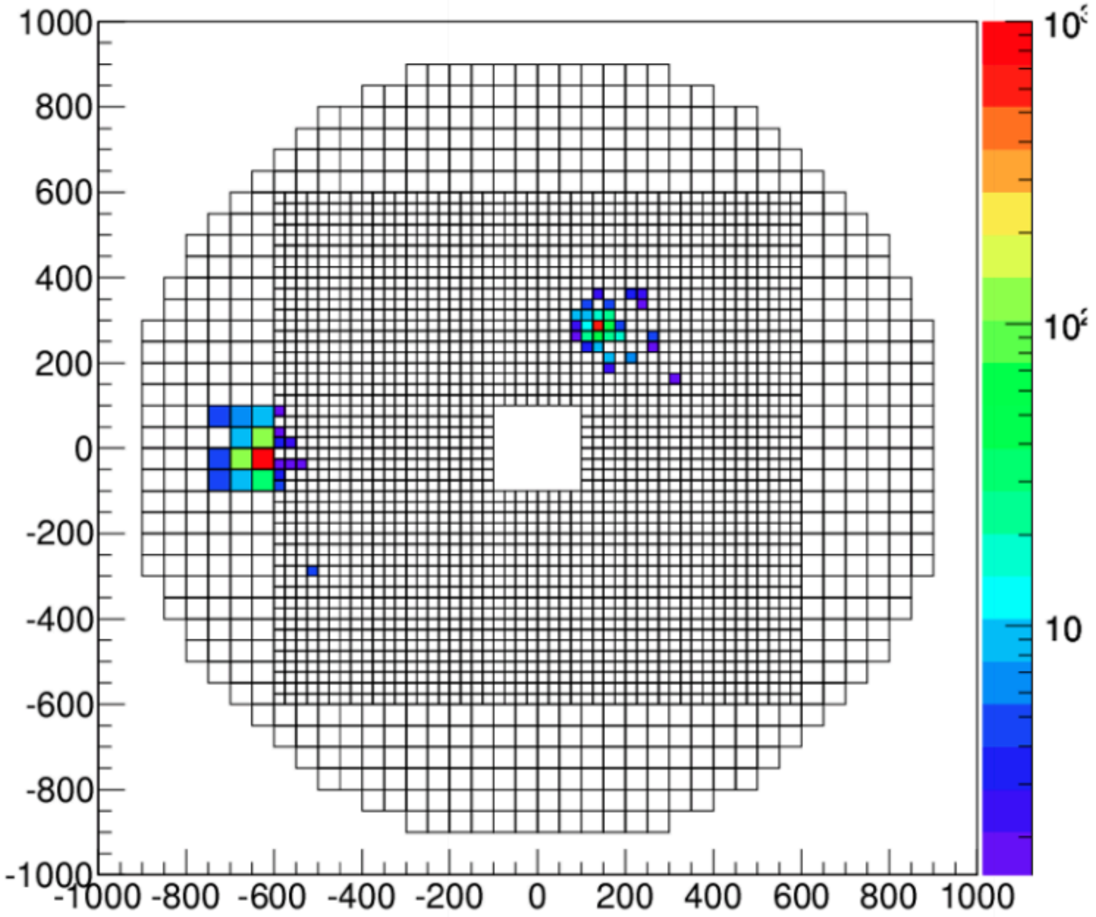
Beam time structure









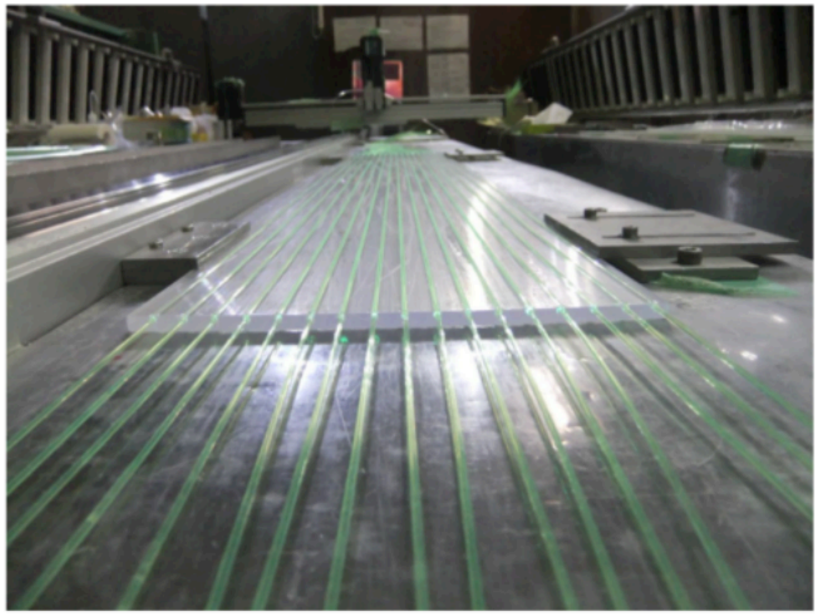


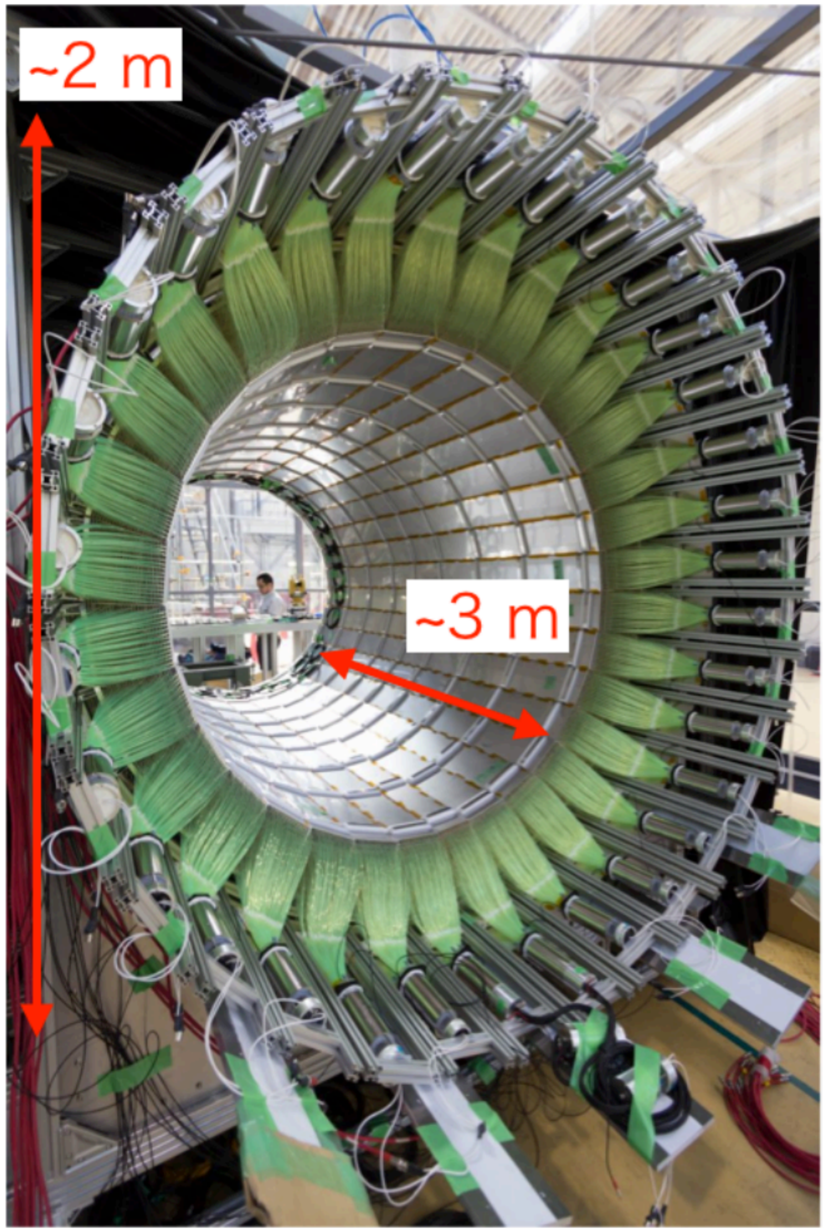
CsI L.Y. : 14 ph./MeV

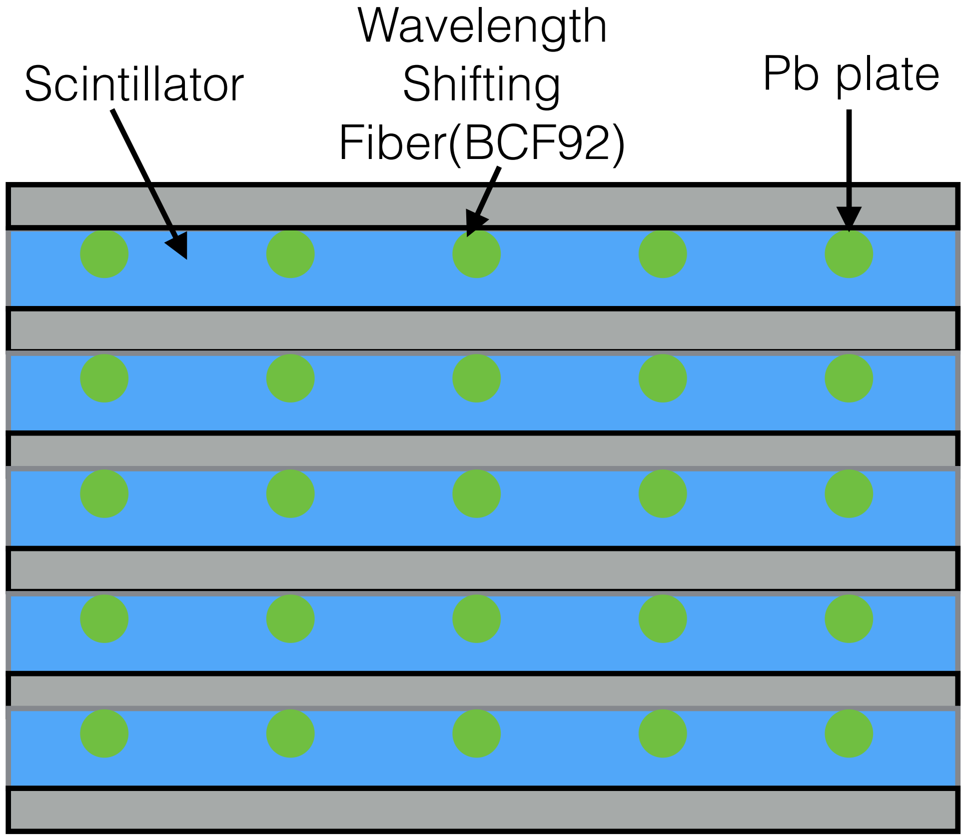
Temperatuere : keeps in ±1°C

Placed in vacuum or Air of humidity < 20%

Veto detector for KOTO experiment

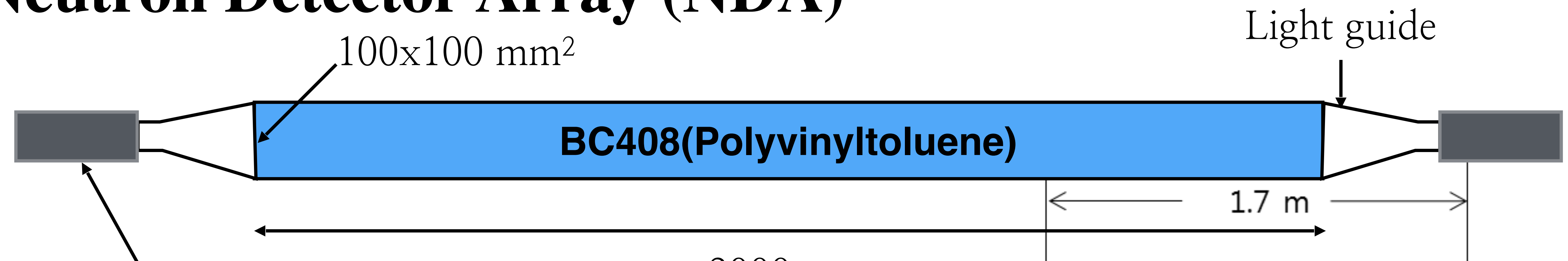


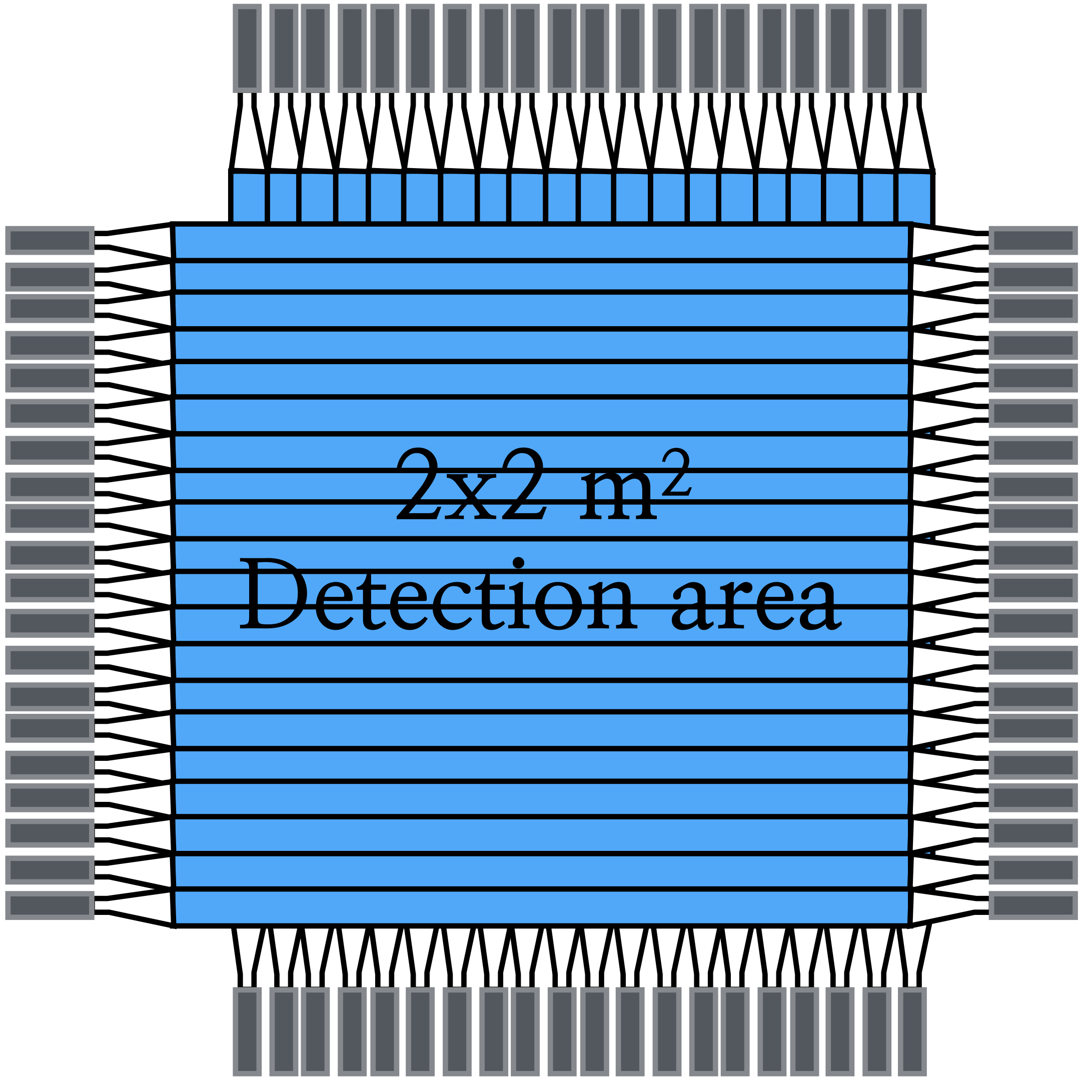


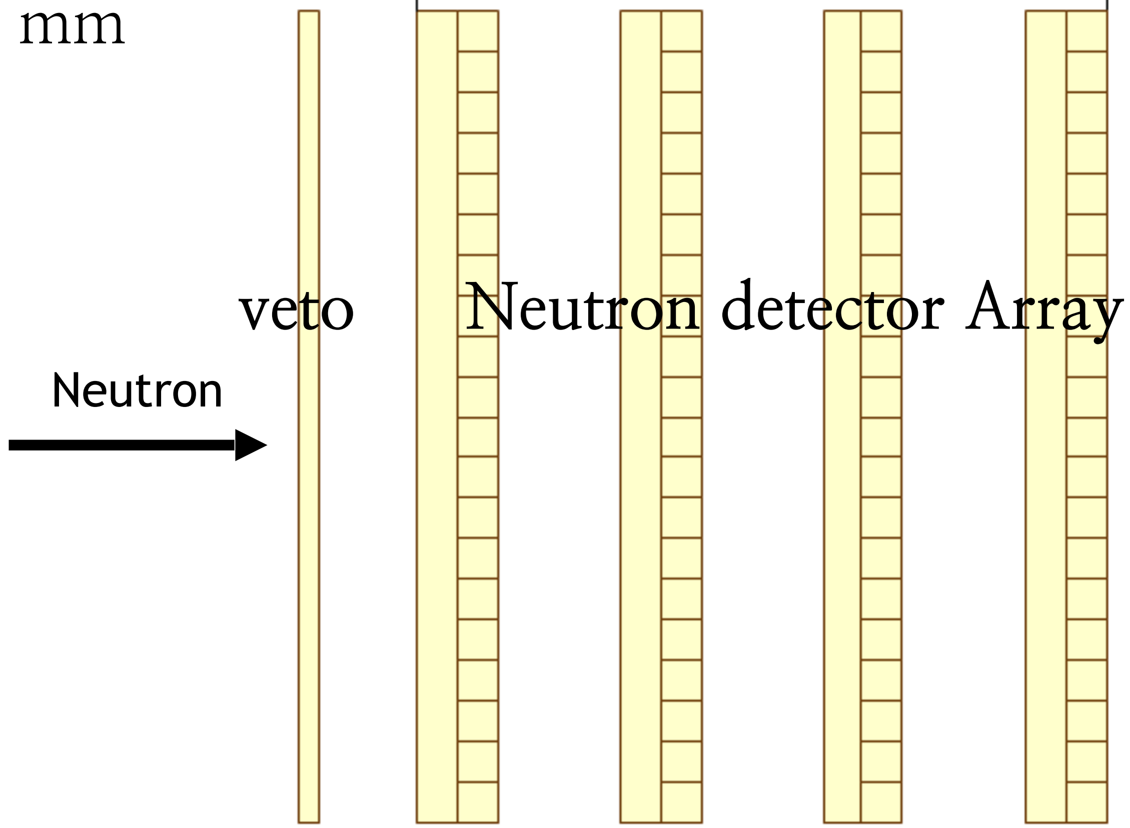


Neutron detector construction

Neutron Detector Array (NDA)







Specipication

-Complete information of neutron

Energy & Momentum from TOF and hit position

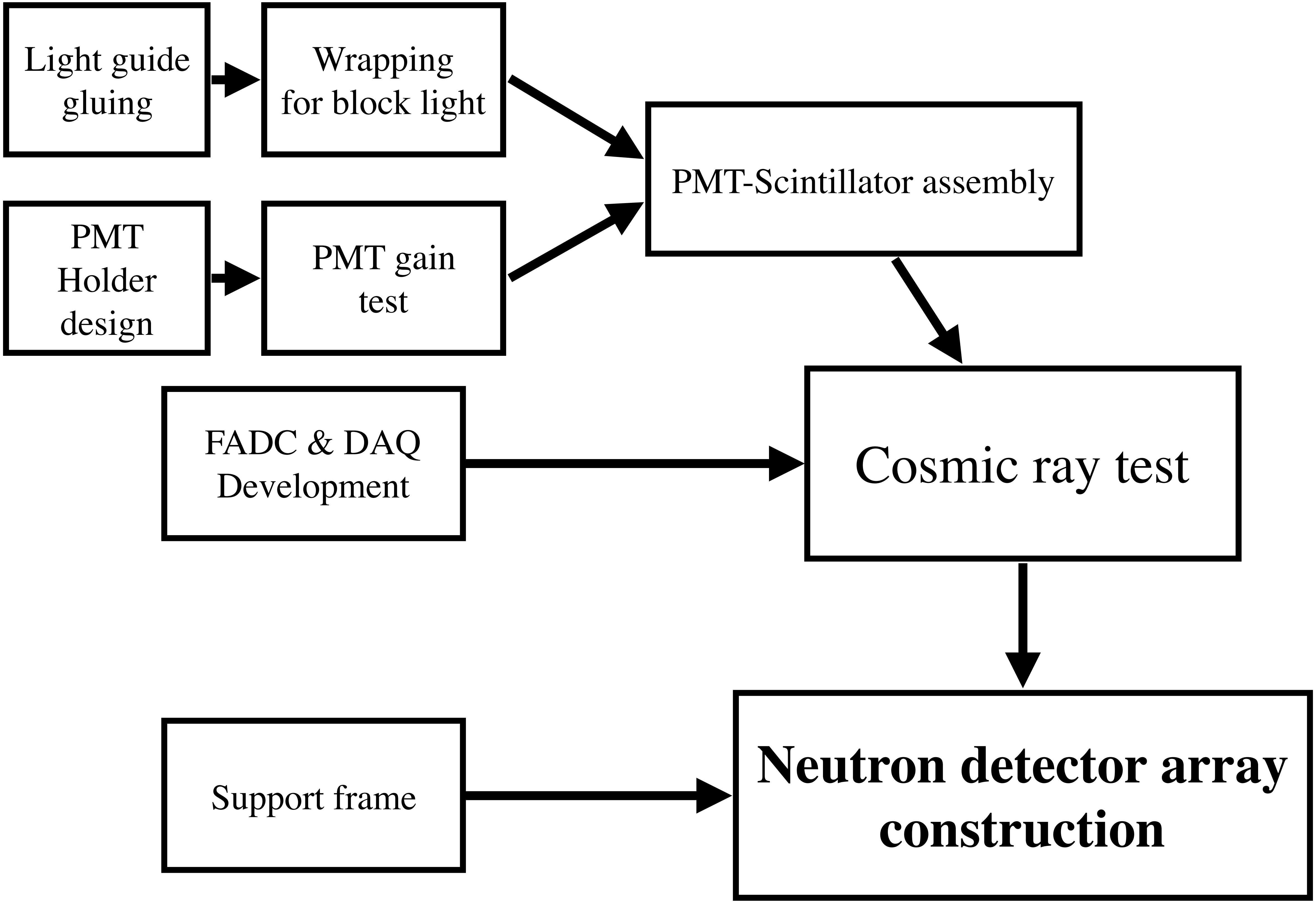
-Readout electronics

- **500 MHz FADC (Notice)**

-Dimension

- **2 x 2 m² detection area (~0.0014 sr)**
- **Thickness : 20 cm / stage, 4 stages in total**
- **180 modules / 360 channels**

Neutron detector array construction - Flow



Light guide gluing

Wrapping for block light

PMT Holder design

PMT gain test

PMT-Scintillator assembly

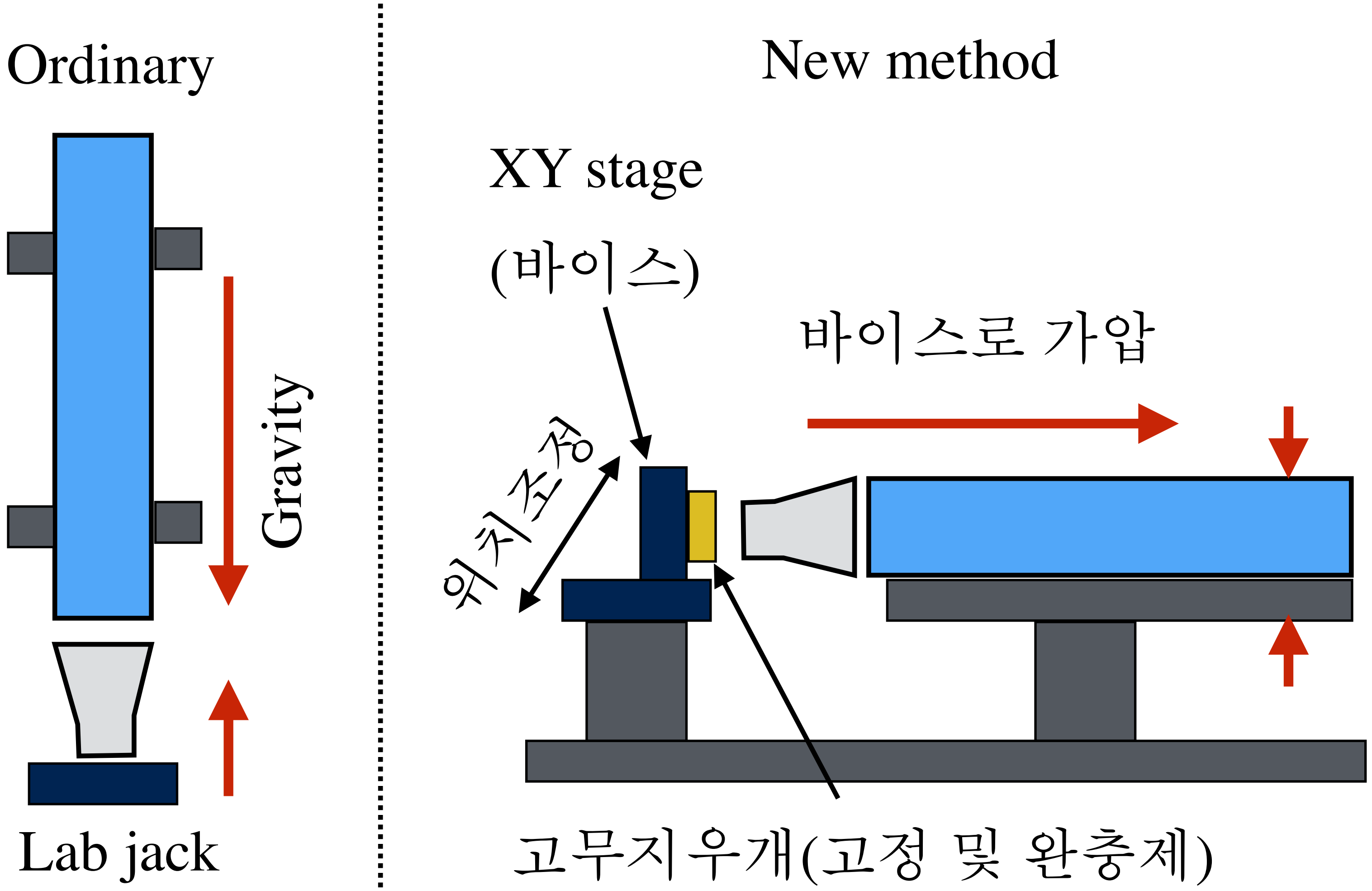
FADC & DAQ Development

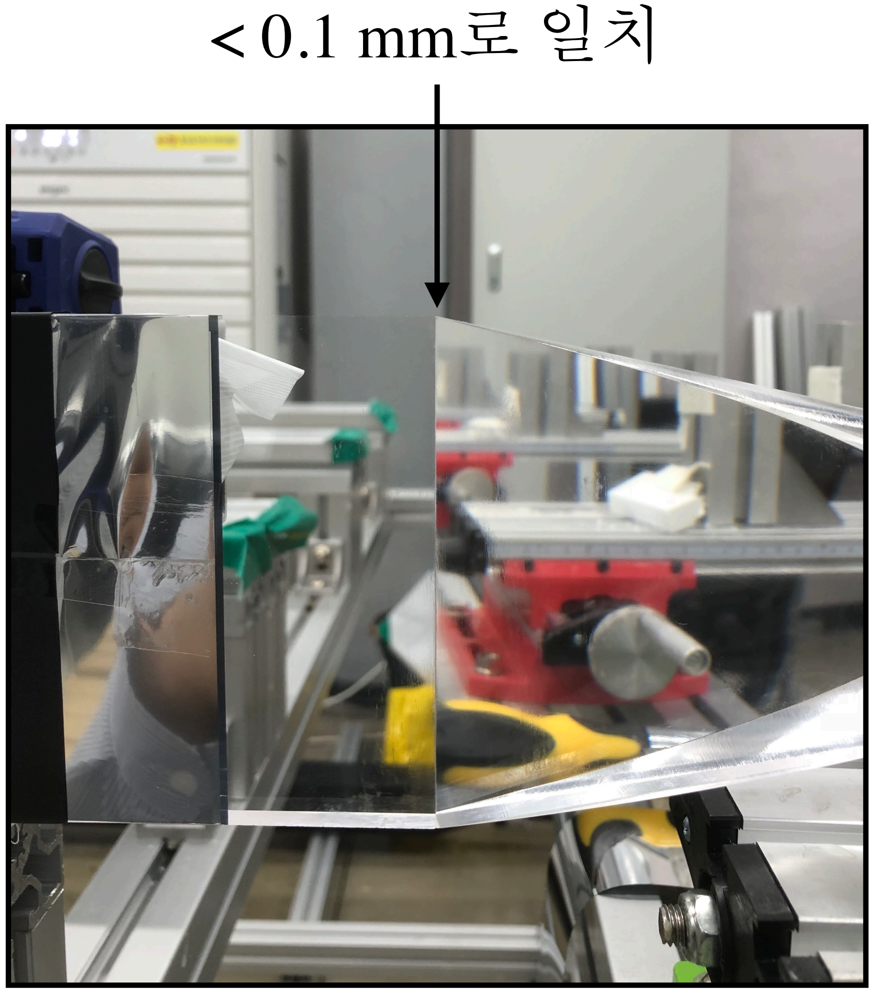
Cosmic ray test

Support frame

Neutron detector array construction

Light guide gluing (1)



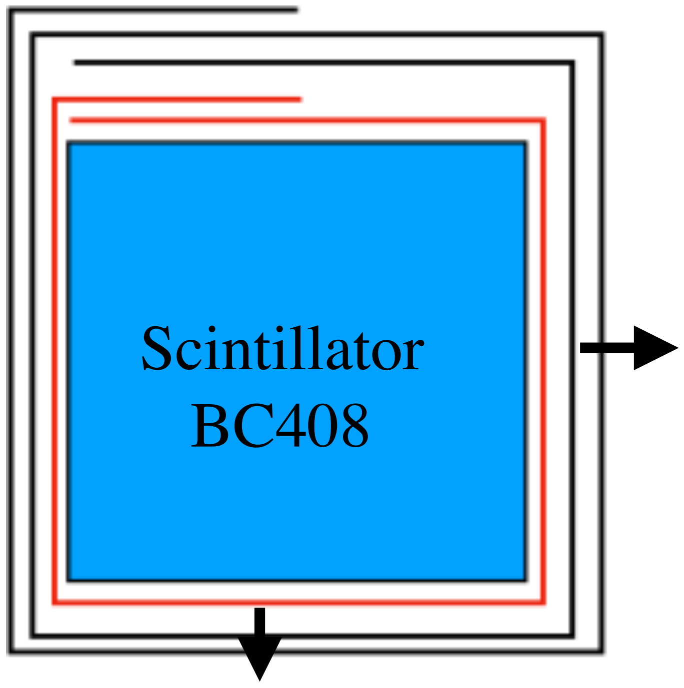


기존방식 : 섬광플라스틱 본체를 수직으로 고정하고 밑에서 라이트가이드를 랩잭으로 올리면서 접합. 문제점 : 완전히 굳을 때(3일)까지 이동불가. 접합면의 상태확인 어려움. 중량물(20kg) 조정의 위험성

신규방식 : 섬광플라스틱 본체를 수평대에 고정하고 측면에서 바이스를 이용하여 압력을 가하여 접착. UV curing glue 사용으로 대기시간 단축 (3-4시간). 접합면의 상태확인용이. 접착면 조정이 용이.

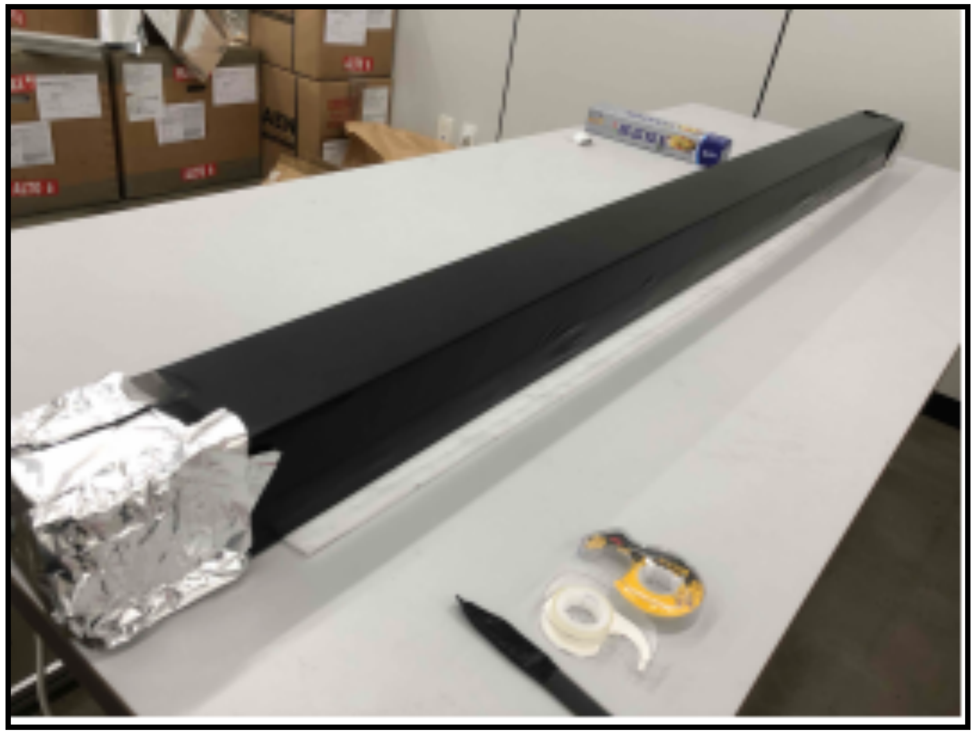
Light guide gluing (2)

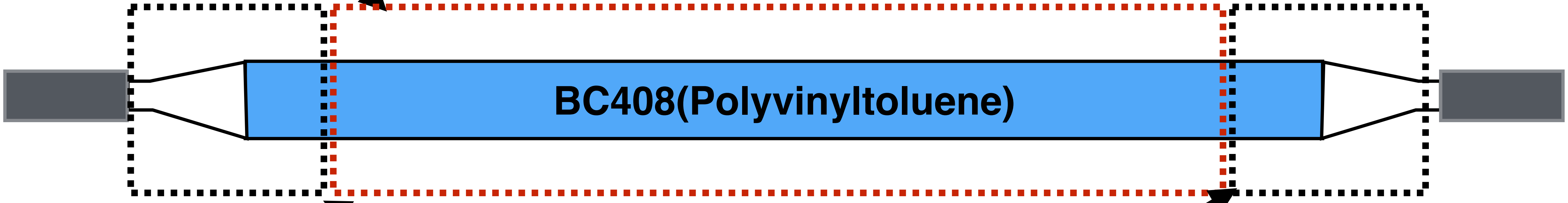
Scintillator Wrapping



Black sheet, ミツビシアグリ
100 μm

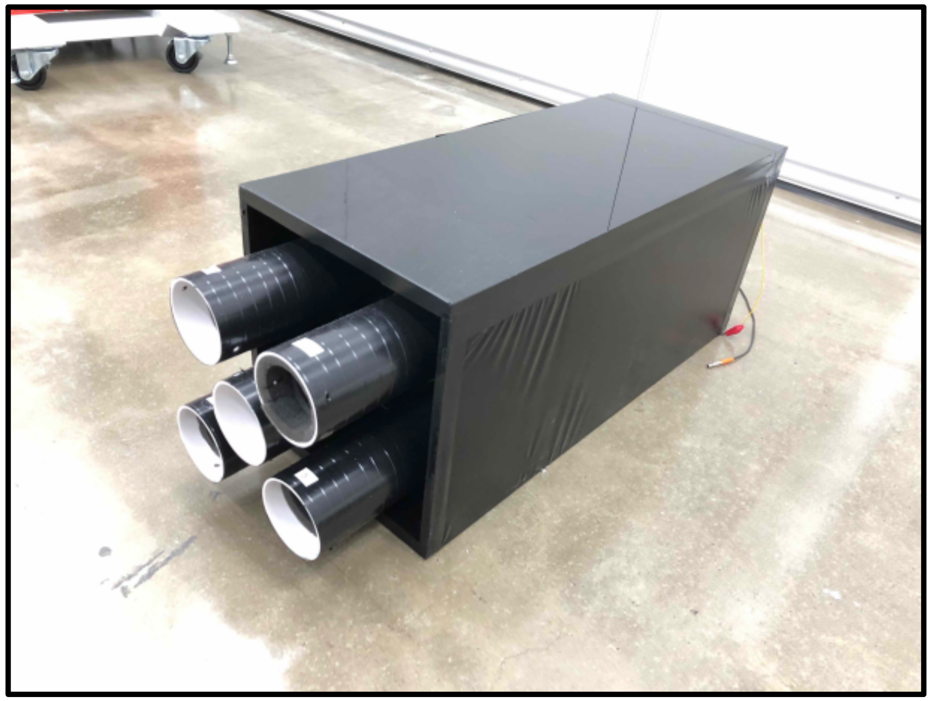
TOREI, Al mylar, 20 um



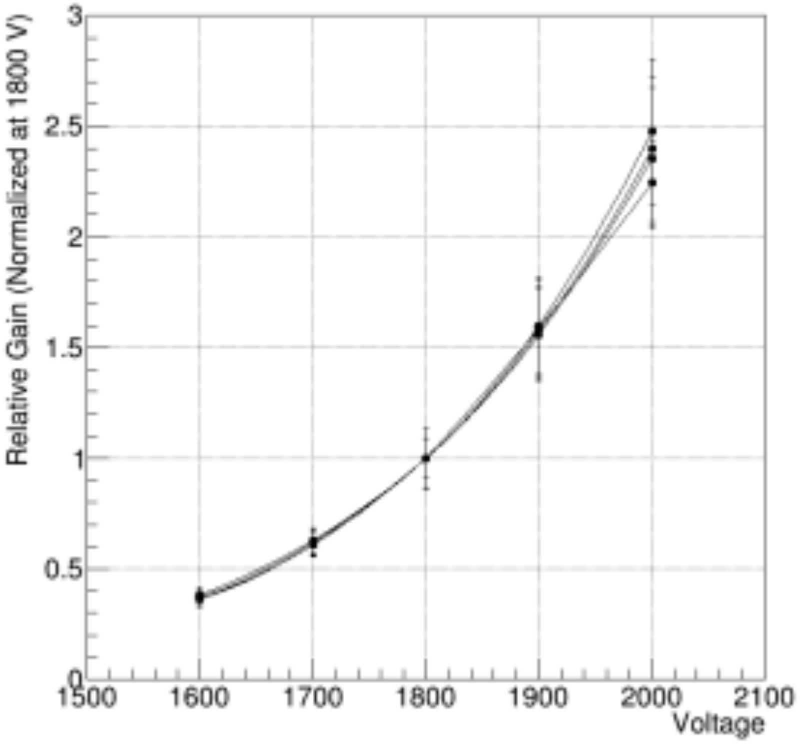


Wrapping with
Al mylar & 3M super 33/88

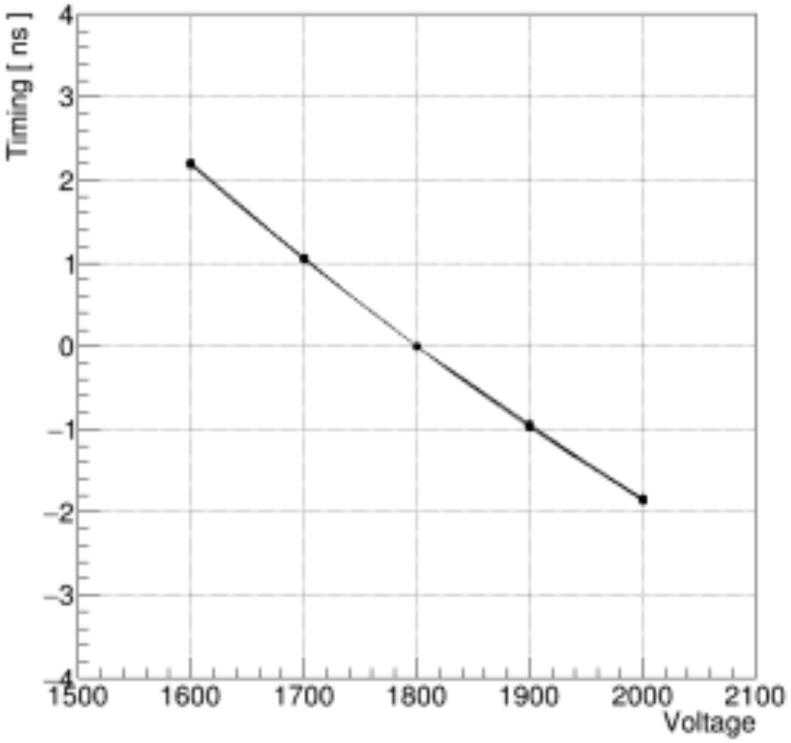
PMT gain measurement



Gain vs Volt



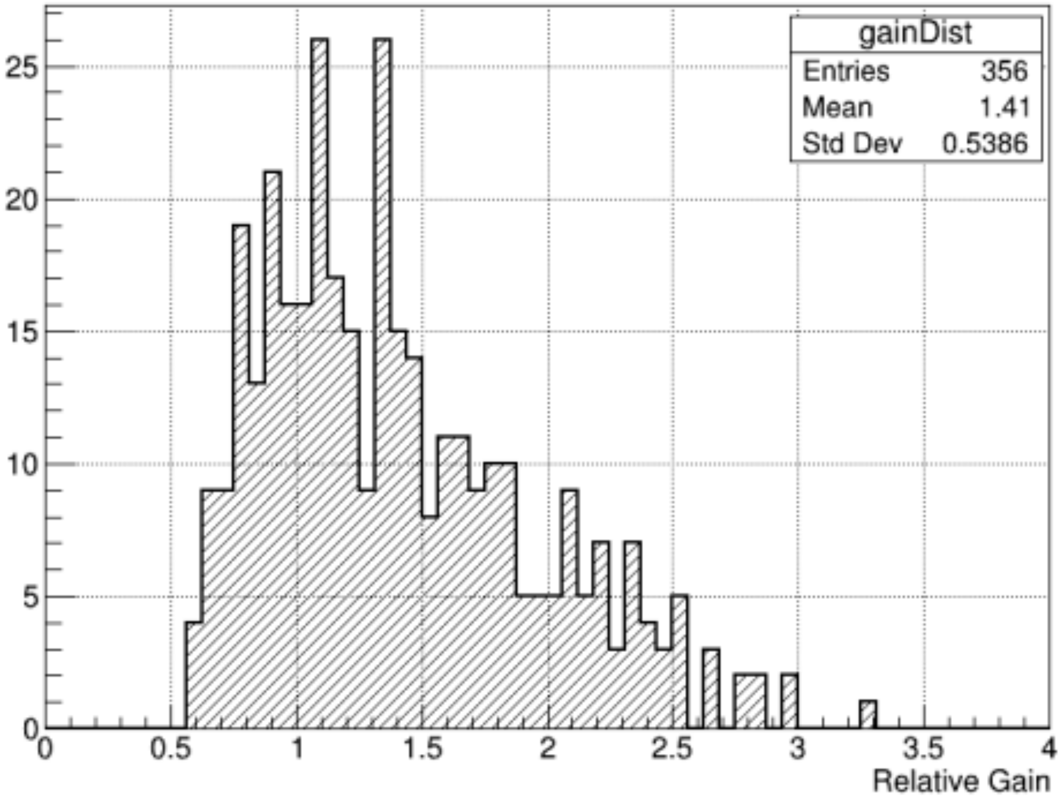
Timing vs Volt



Relative gain measurement

1. Center slot : Base PMT (1800 V applied)
2. 4 slots : Changed by measurements
3. Applied voltage : 1600 V - 2000 V (by 100 V)
4. Gain changed 0.5 to .24 by changing voltages

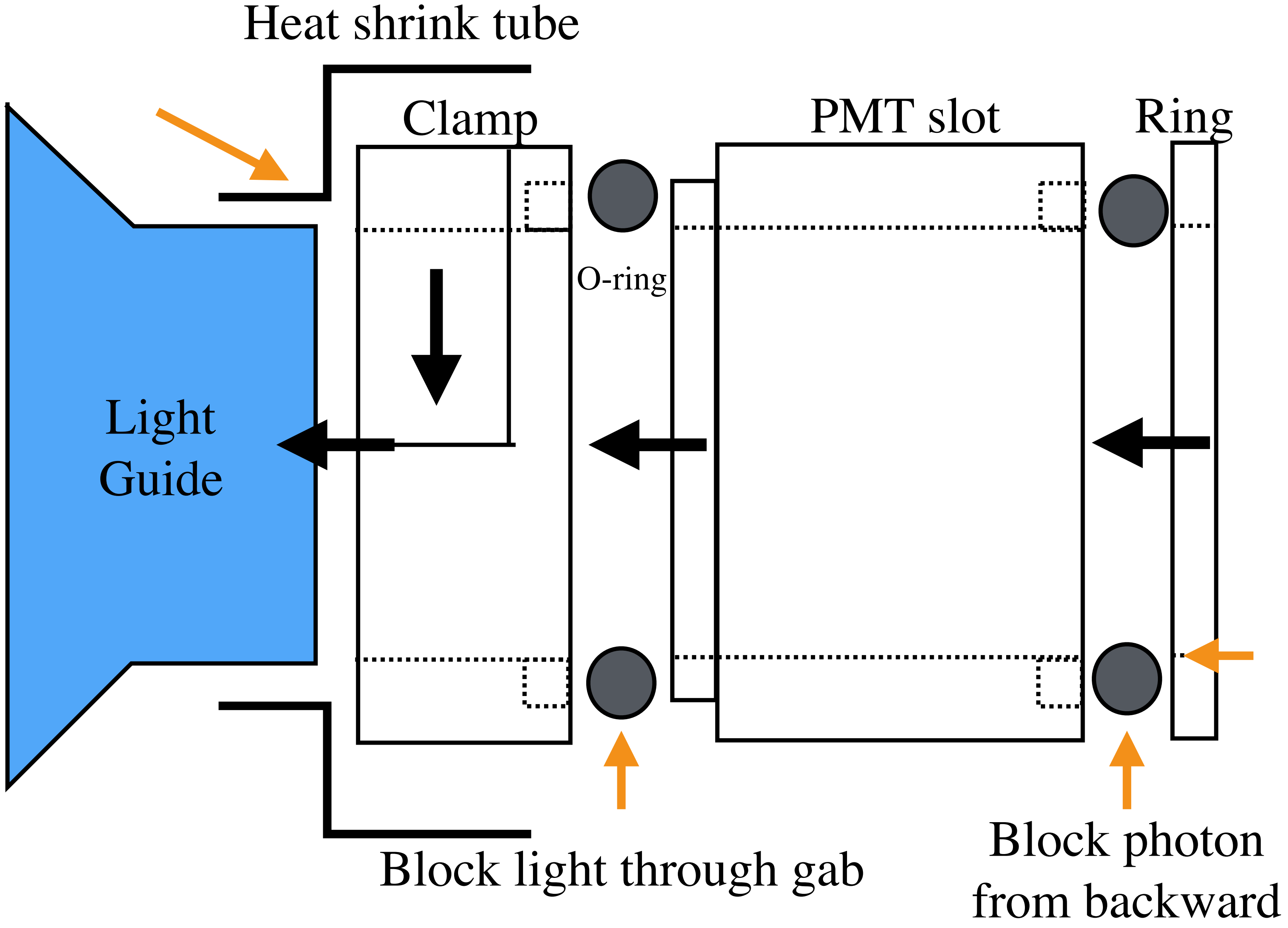
Gain Distribution

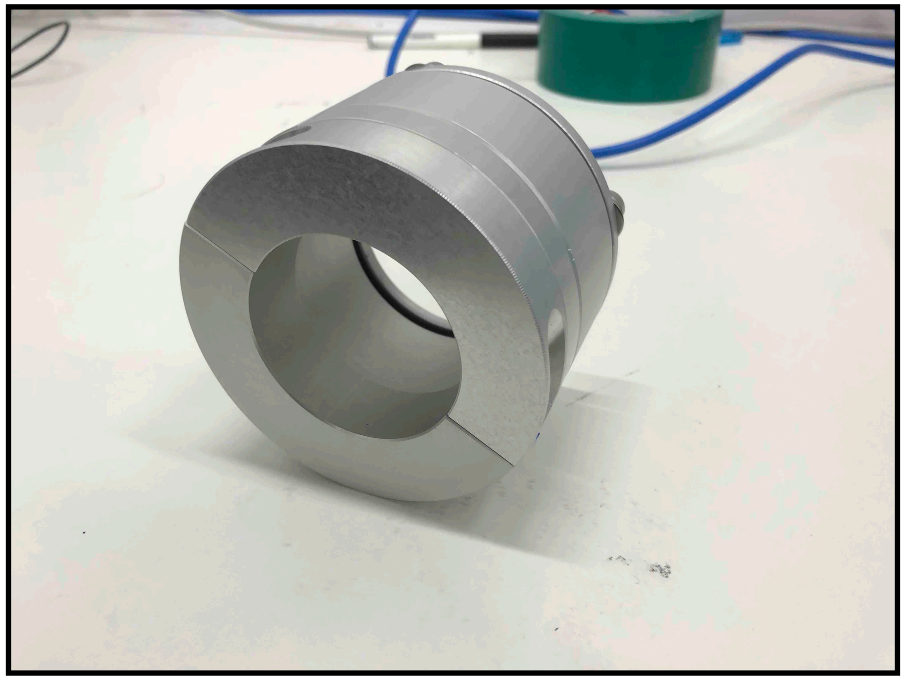


PMT holder design

Requirements

- Replacable
- No gluing
- Fasten PMT and Light guide
- No light leackage

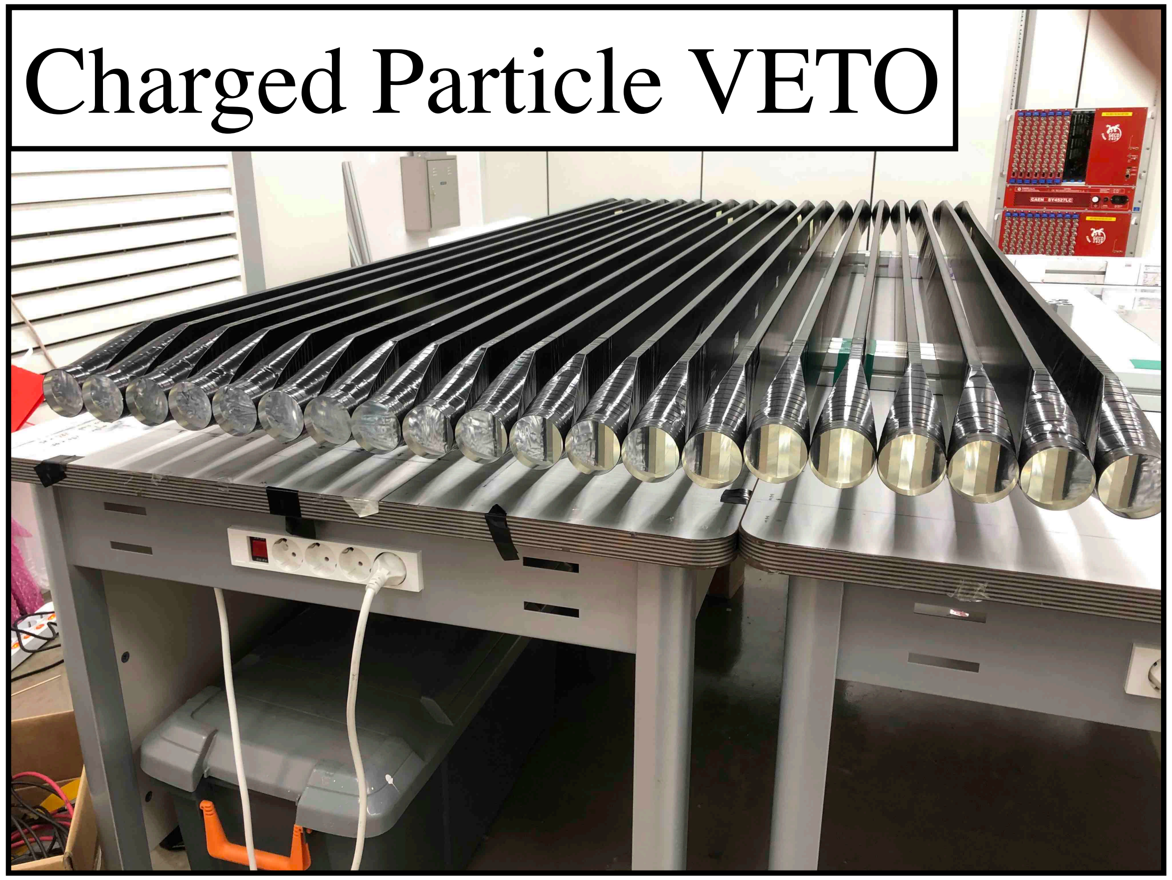




Decide place

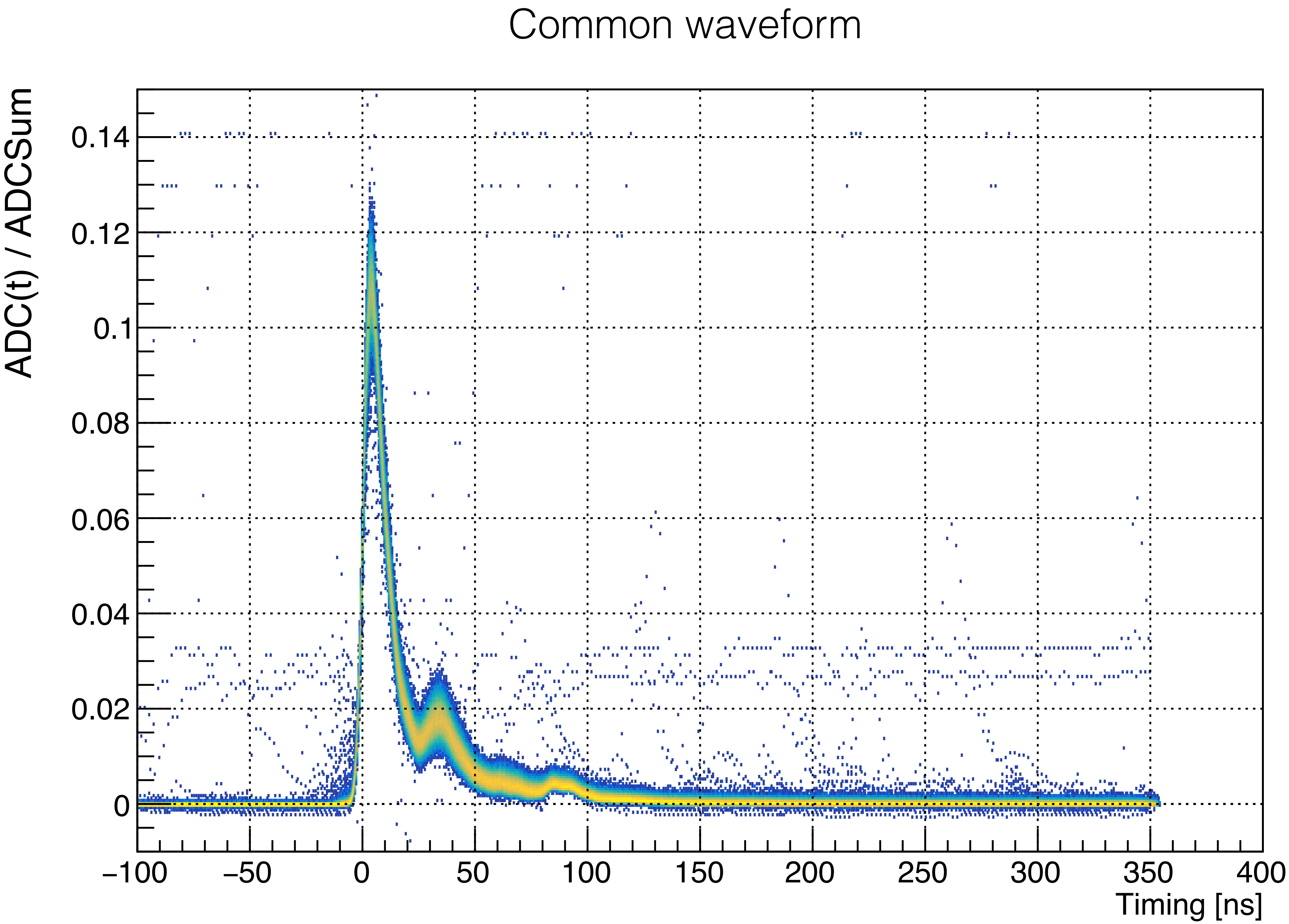

NDA


Layer 1,2


Charged Particle VETO


Layer 3,4

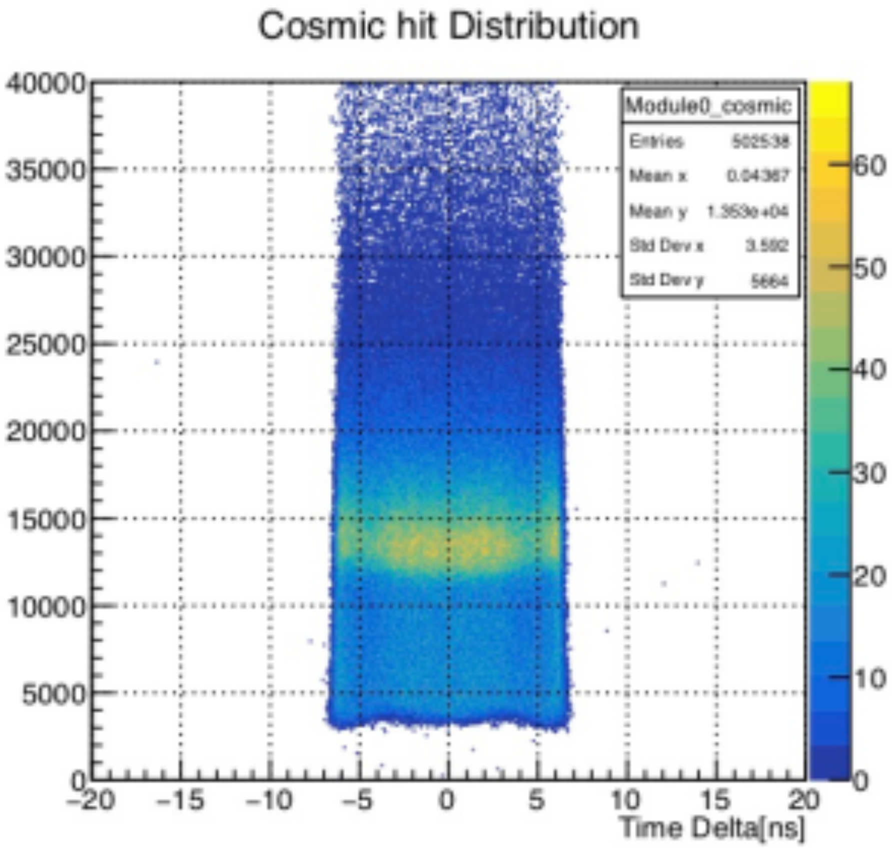
Cosmic ray data

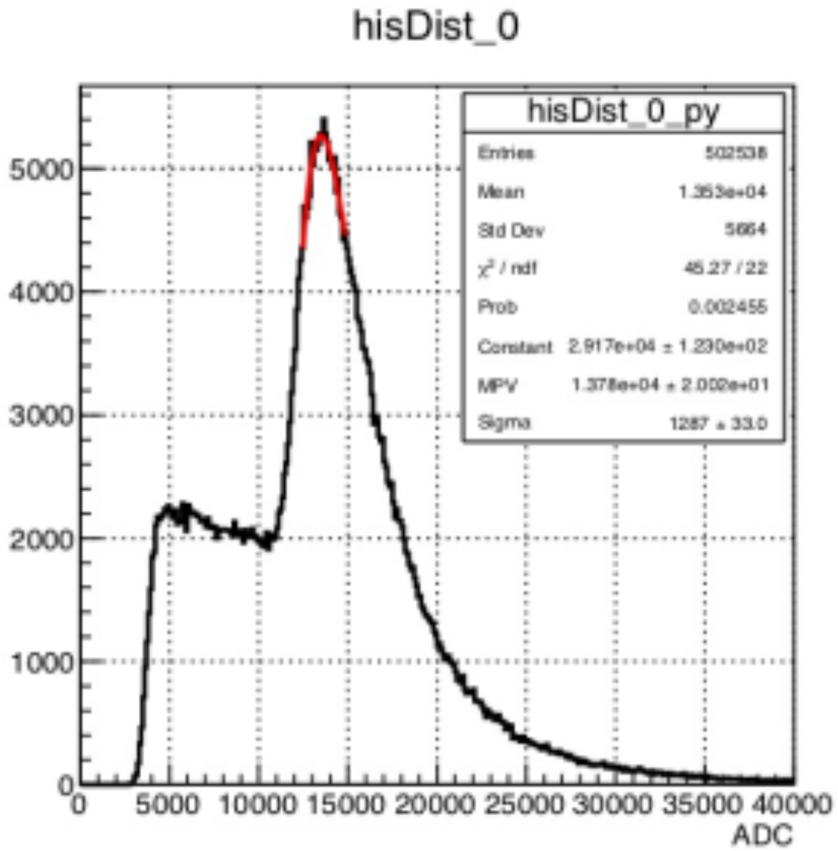


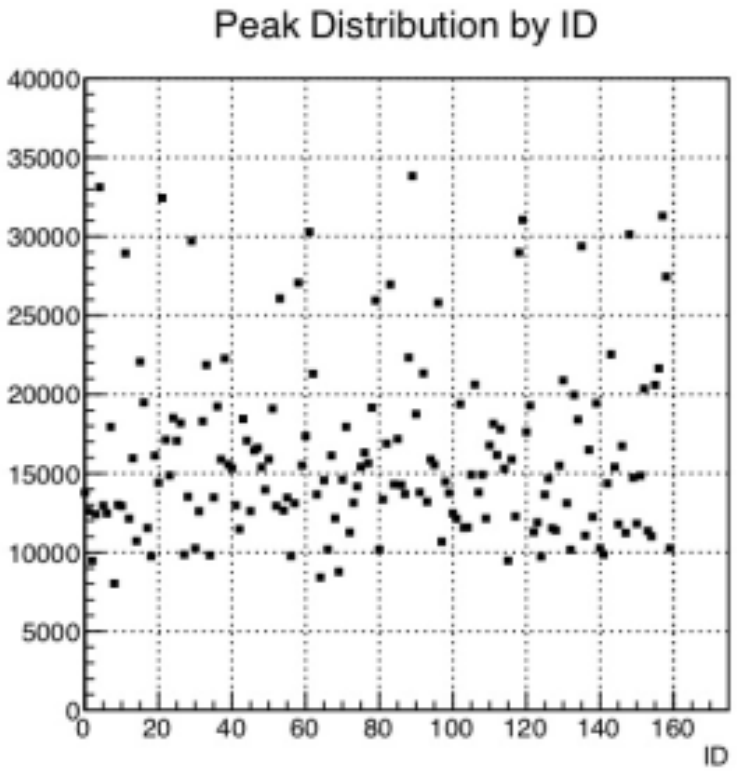
Convert to timing and energy

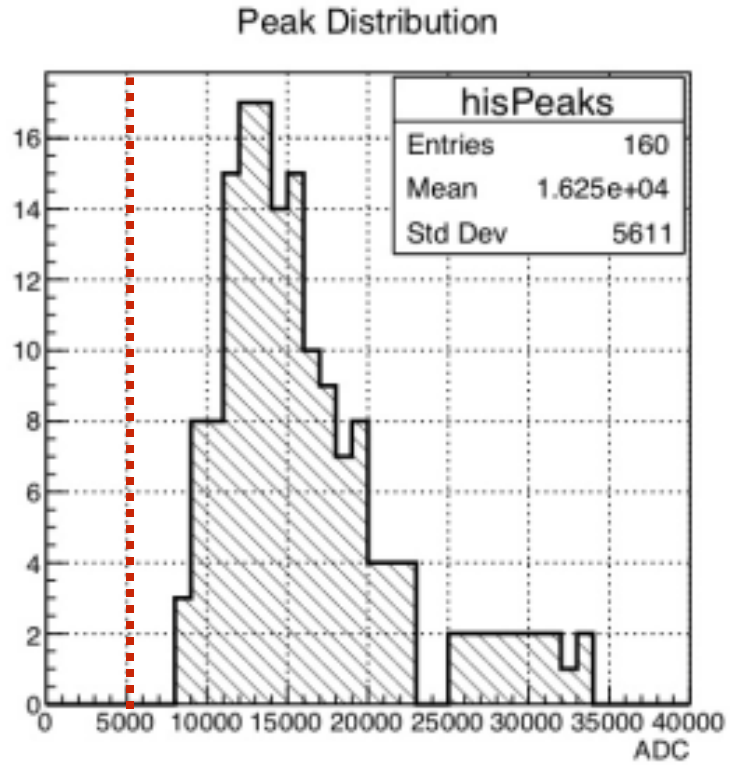
Cosmic ray measurement

40 Modules / measurement
= Same size with 1 layer





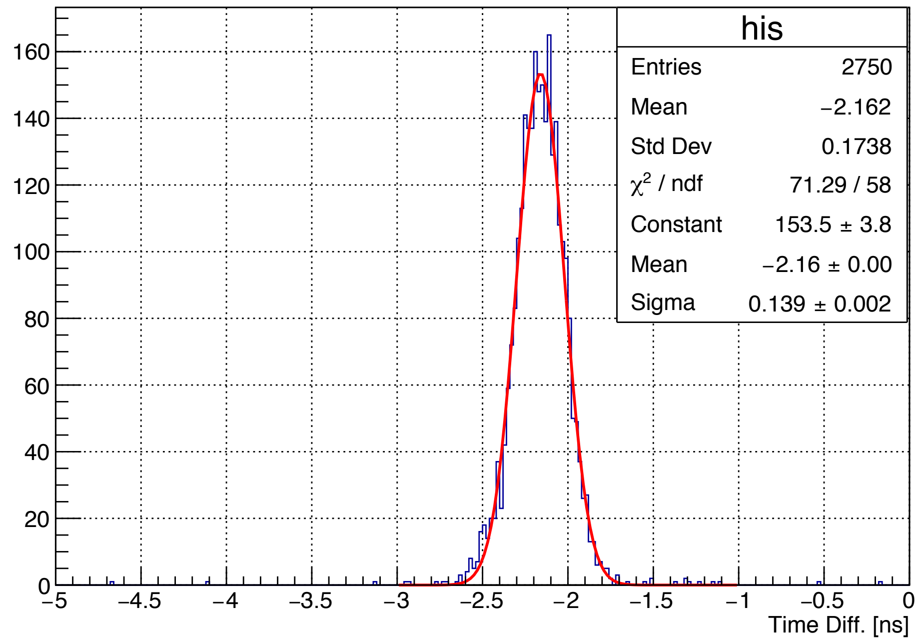




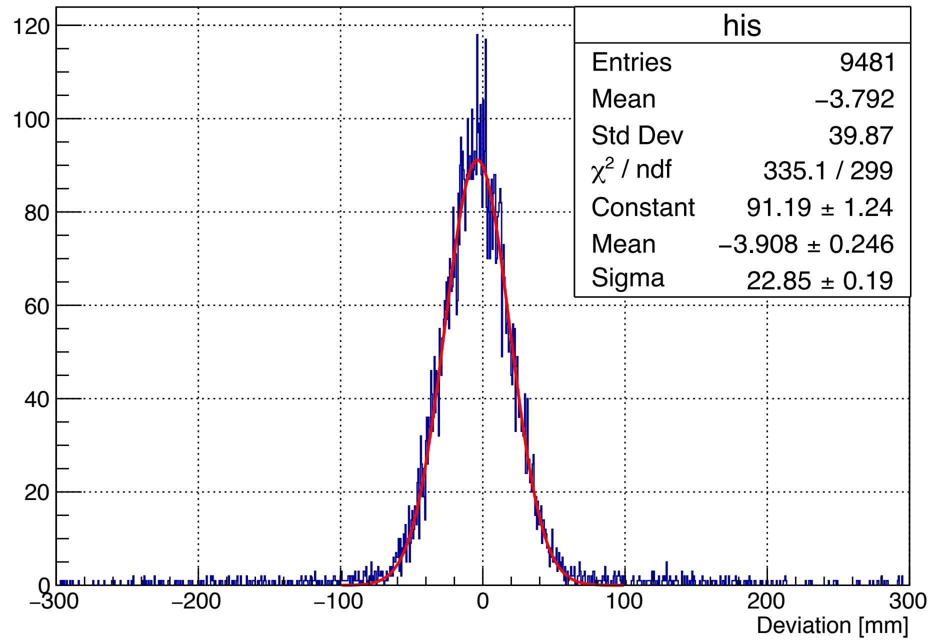
Outputs of all modules were satisfied requirements (>5000).

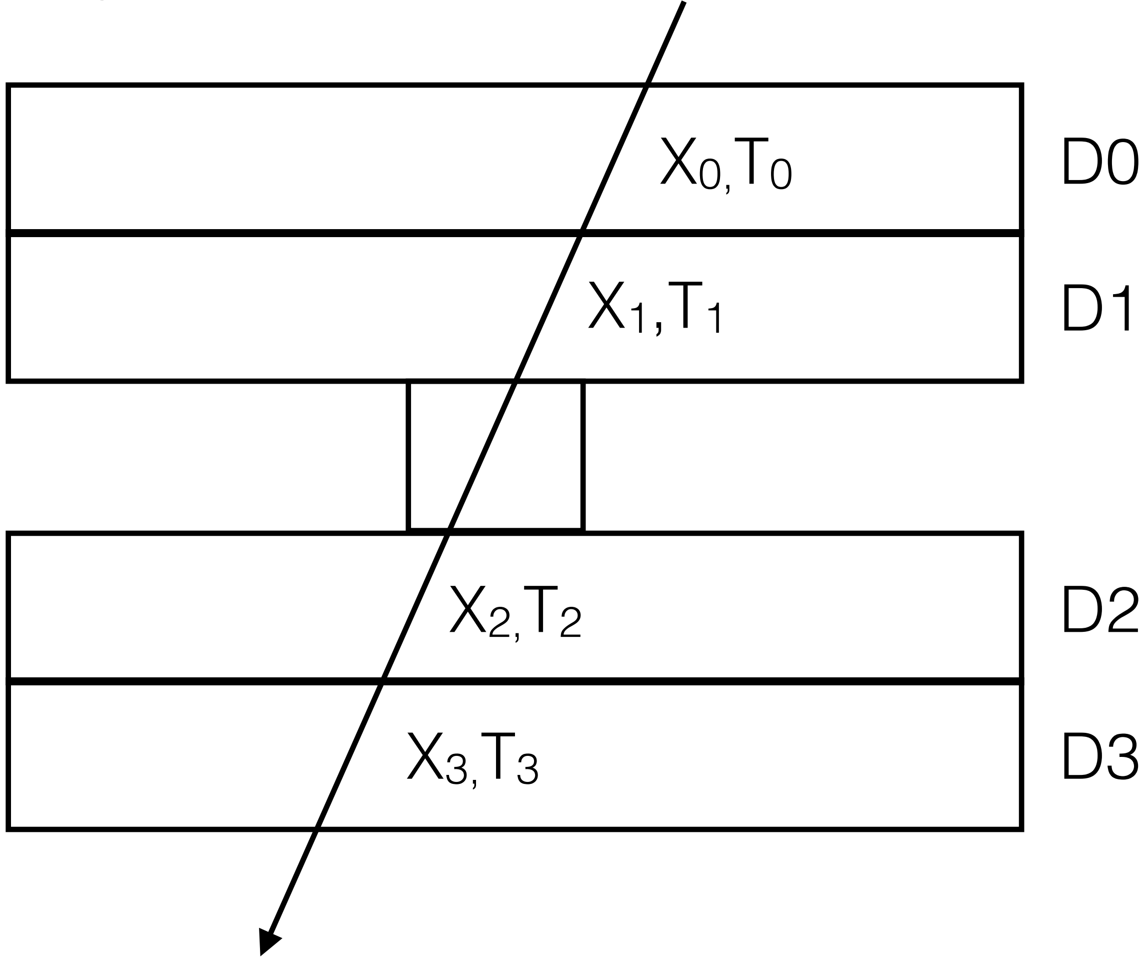
Cosmic ray data

Timing resolution



Position resolution





$$T_{res} = \underbrace{(T_0 - T_3)/4}_{\text{expected}} - \underbrace{(T_2 - T_3)}_{\text{Measured}}$$

$$X_{res} = (X_0 - X_3)/4 - (X_2 - X_3)$$

Resolution (sigma)
timing : 139 ps
position : 22.85 mm

References

Book
http://tesla.phys.columbia.edu:8080/eka/William_R_Leo_Techniques_for_nuclear_and_partic.pdf

Detector
http://www-physics.lbl.gov/~spieler/physics_198_notes
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.98.030001

Scintillator
scintillator.lbl.gov
https://www.crystals.saint-gobain.com/products/organic-scintillation-materials

PMT
https://www.hamamatsu.com/jp/en/our-company/business-domain/electron-tube-division/related-documents.html
https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf

Photo diodes
https://www.hamamatsu.com/jp/en/our-company/business-domain/solid-state-division/related-documents.html