Photon propagation in scintillation detectors

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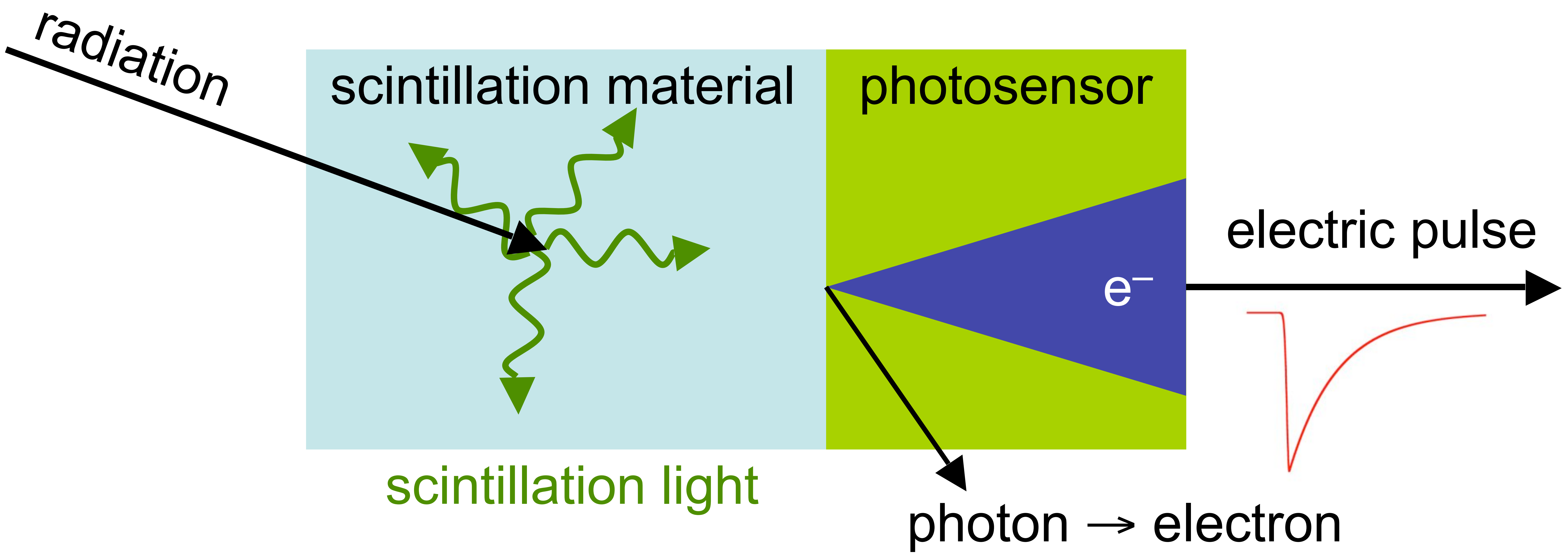
Scintillation detectors



Major steps

1. Energy deposition by ionising radiation
2. Conversion of energy to scintillation photons
3. Transport of photons to a photodetector
4. Photon to electrical signal

1. Inorganic scintillators
   (high light o/p, slow response~10-1000ns)
   Ex. NaI, CsI, BaF_2

2. Organic scintillators
   (low light o/p, fast response ~a few ns)
   Ex. Liquid scintillator, plastic scintillator

Plastic scintillators and applications

- Fast response time (~nanoseconds)
- Can be moulded into any desired form
- Rugged nature
- Relatively cheap, hence affordable for large area requirements

Plastic scintillators are used in high energy, cosmic ray and nuclear physics experiments

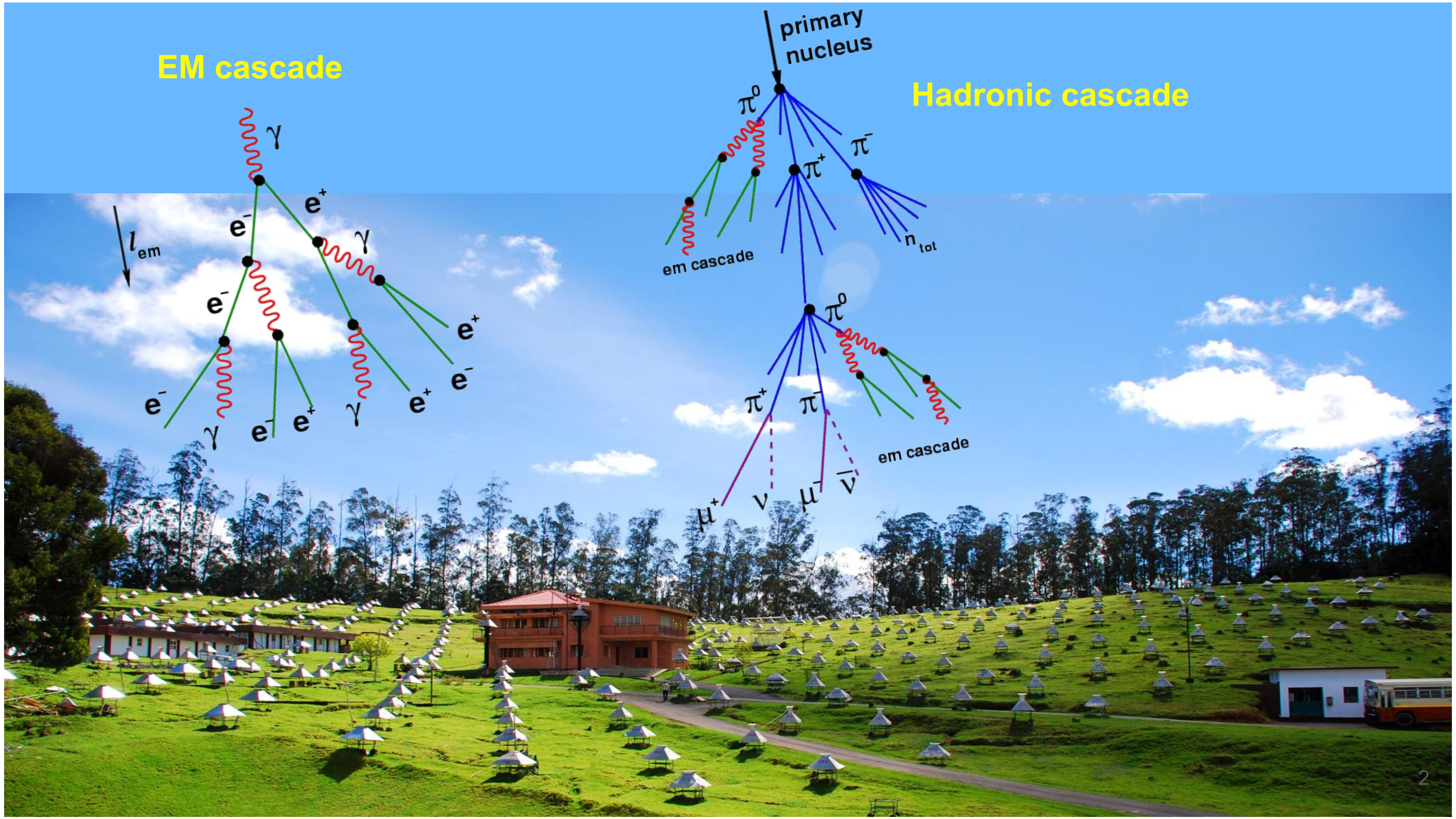
Space based detectors

Radiation portal monitors

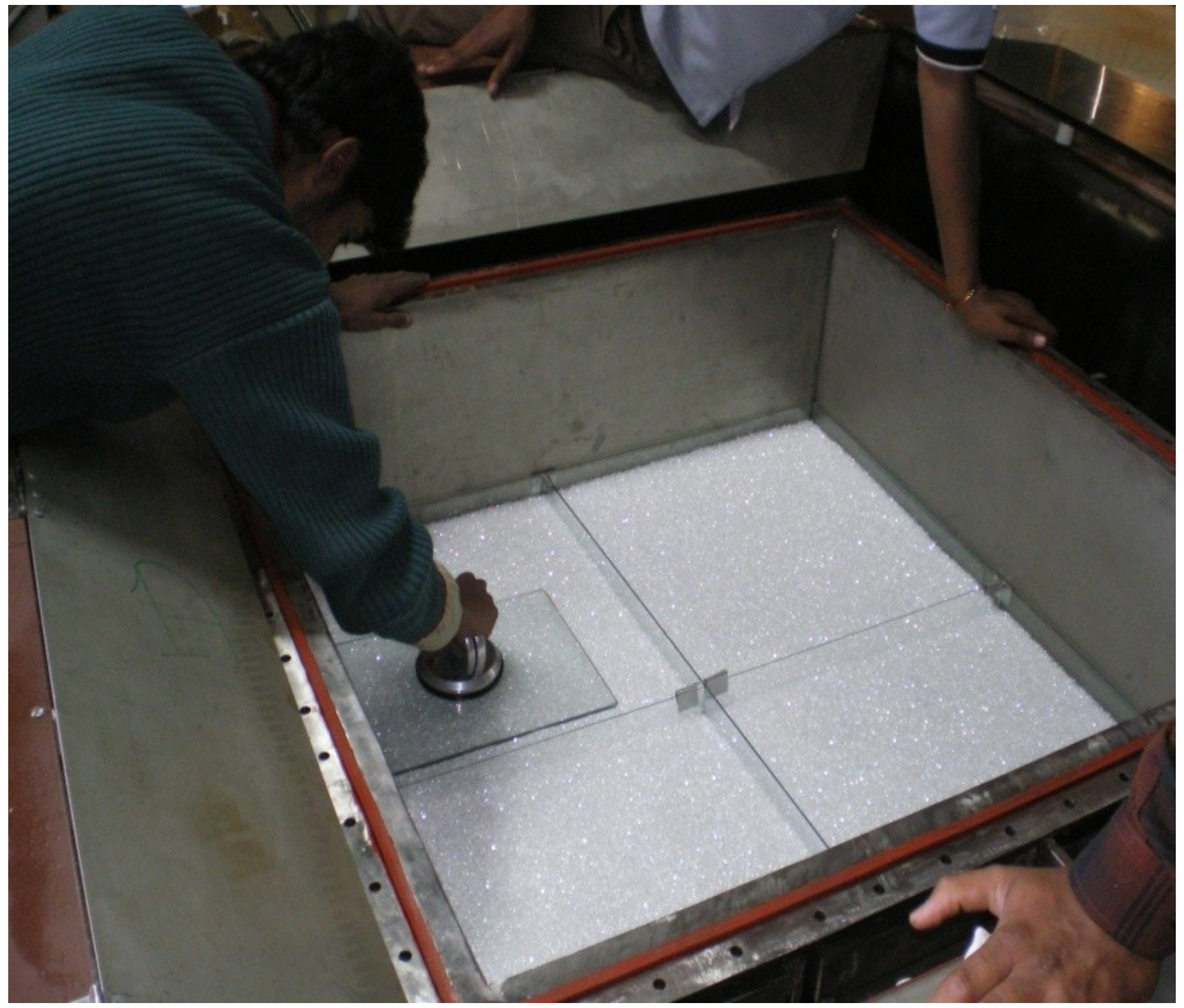
Muon tomography

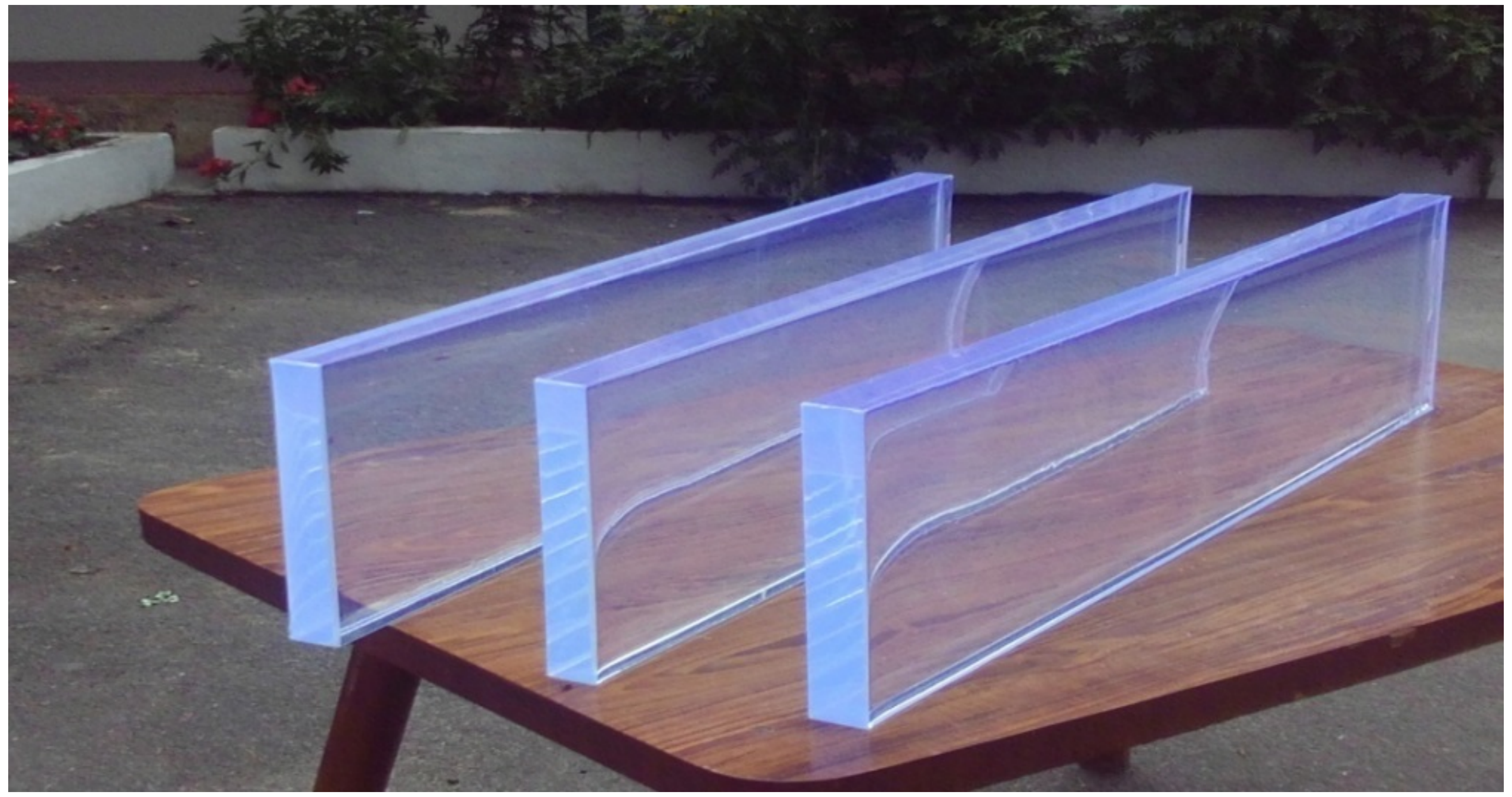
The GRAPES-3 Experiment at Ooty

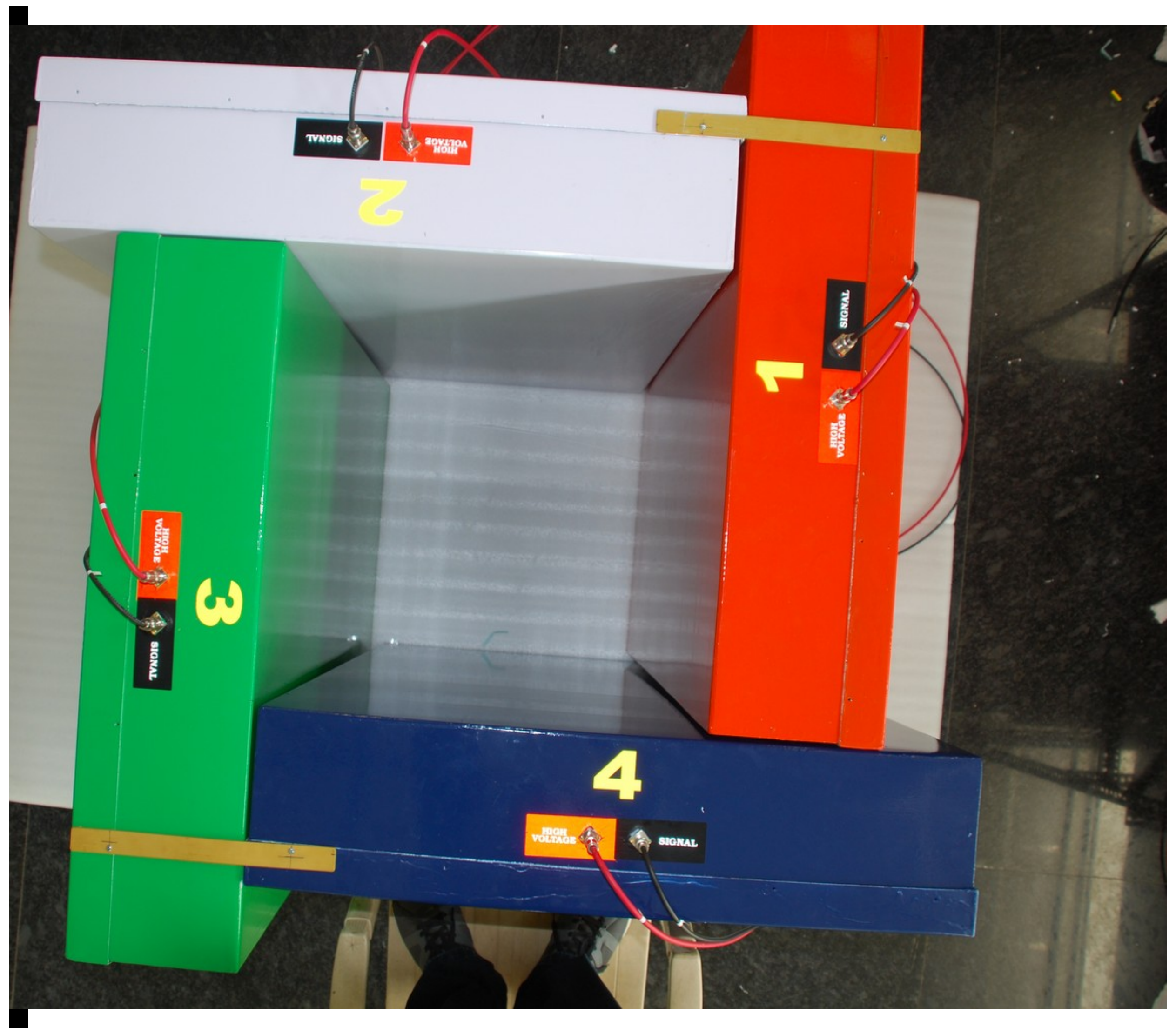
- 400 plastic scintillator detectors (1 m^2 area) with 8 m inter-separation spread over 25,000m^2
- 560 m^2 muon telescope consisting 3712 proportional counters (6m x 0.1m x 0.1m)
- Records EAS events per day = 3 x 10^6, median energy = 15 TeV



R&D of plastic scintillators at CRL







Radiation monitor for BARC

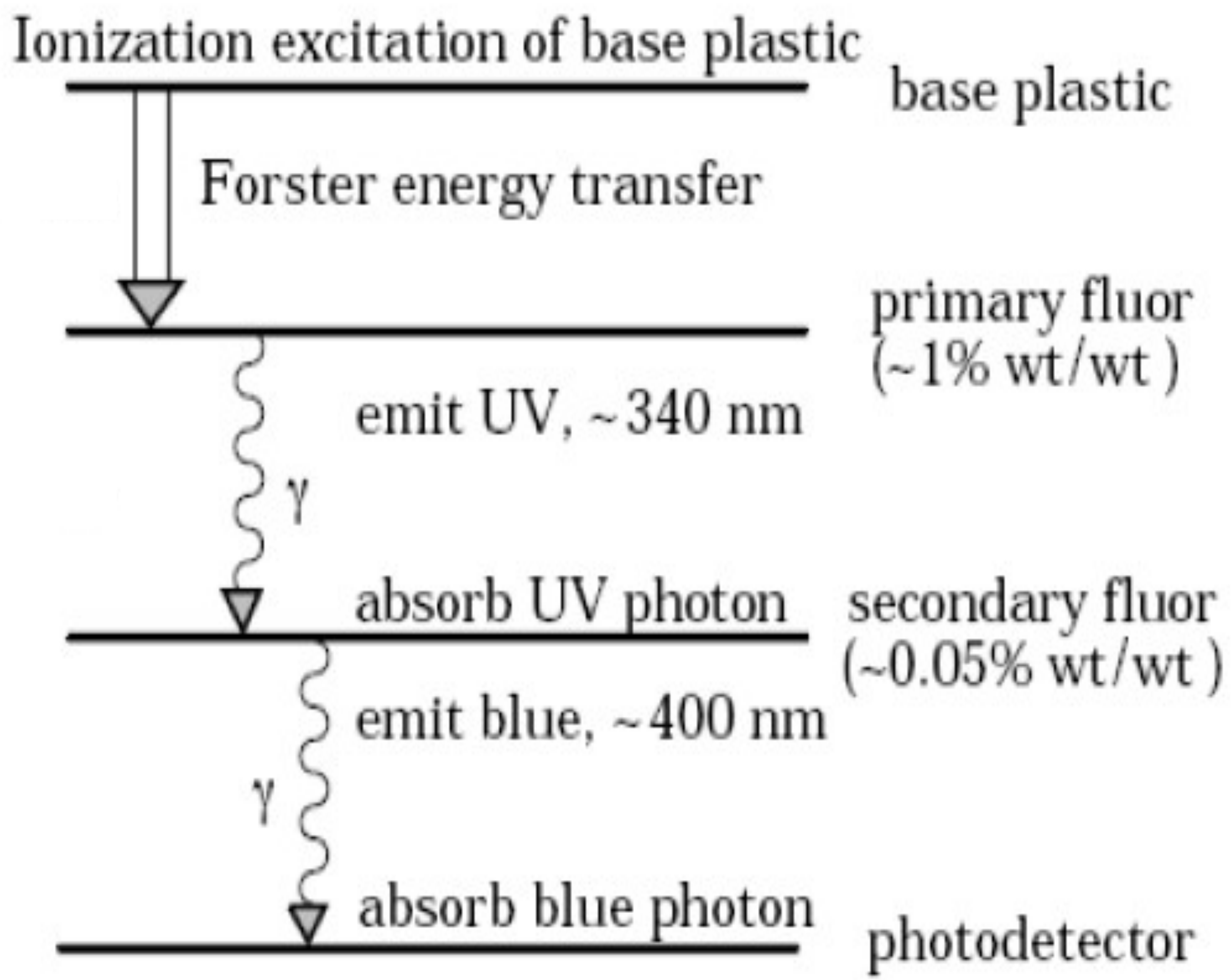
Decay Time= 1.6 ns Light Output = 85% Bicron (54% anthracene)

Timing 25% faster Atten. Length λ= 100cm Cost ~30% of Bicron

Max Size 100cmX100cm Total > 2000

CERN, Osaka, IUAC Delhi, Bose, VECC, BARC, ECIL, Utkal U., Dayalbag Edu. Inst, IISER Pune

Scintillation mechanism



Polyvinyltoluene, Polystyrene

p-Terphenyl

POPOP

PMT, SiPM

Scintillation mechanism

Scintillator molecules have various electronics states (S_0, S_1, S_2,...) and vibrational states (S_{00}, S_{01}, S_{02}, ..., S_{10}, S_{11}, S_{12},.............)

Spacing between electronics states is 3 to 4 eV and spacing between vibrational states is about 0.15 eV.

At room temperature, average energy is about 0.025 eV. All molecules are in the S_{00} state.

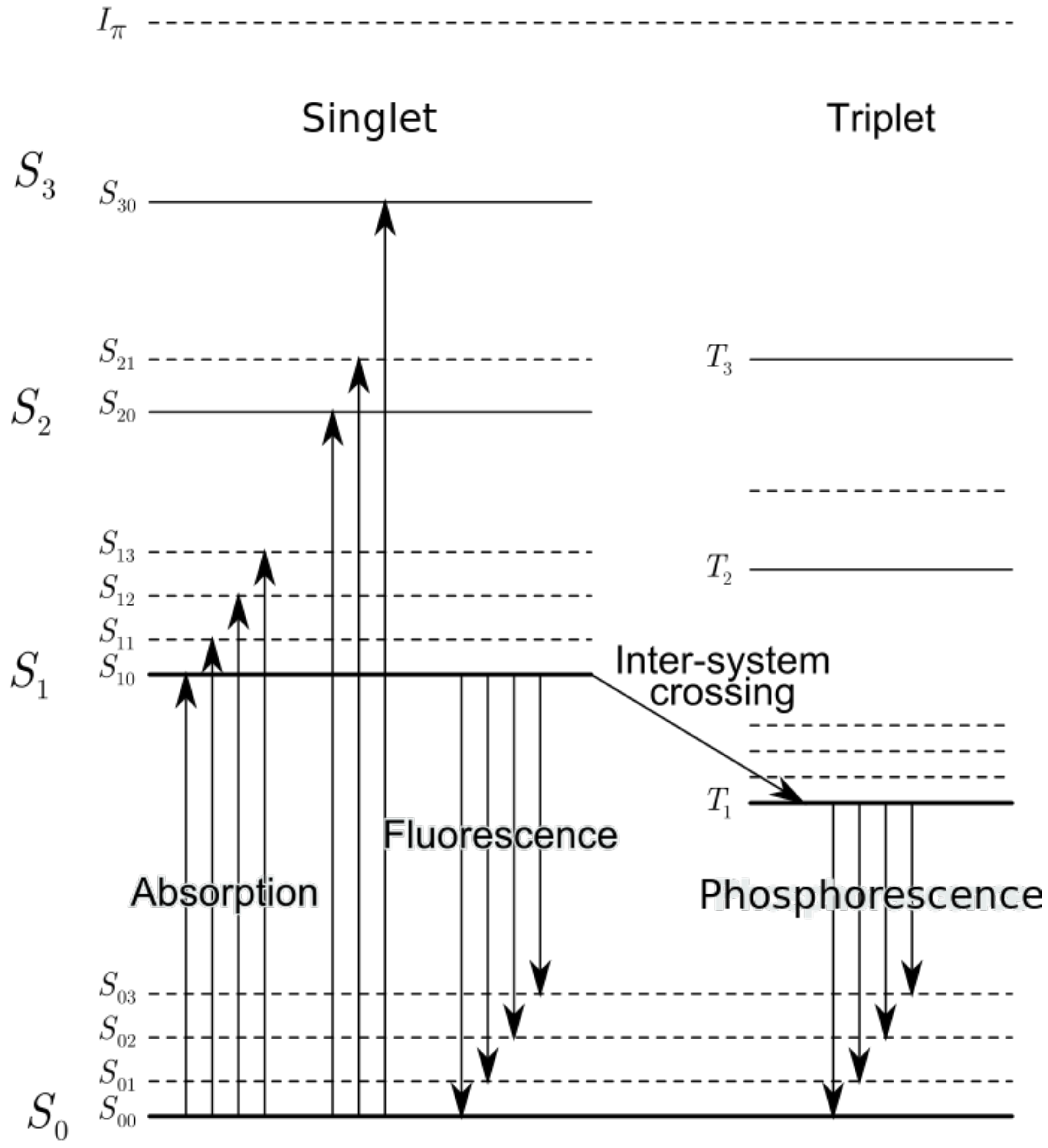
When charged particle passes through the scintillator, kinetic energy is absorbed by the molecules and electrons are excited to upper levels.

Higher states deexcites to quickly (pico seconds) to S_1 state through radiation loss transitions.

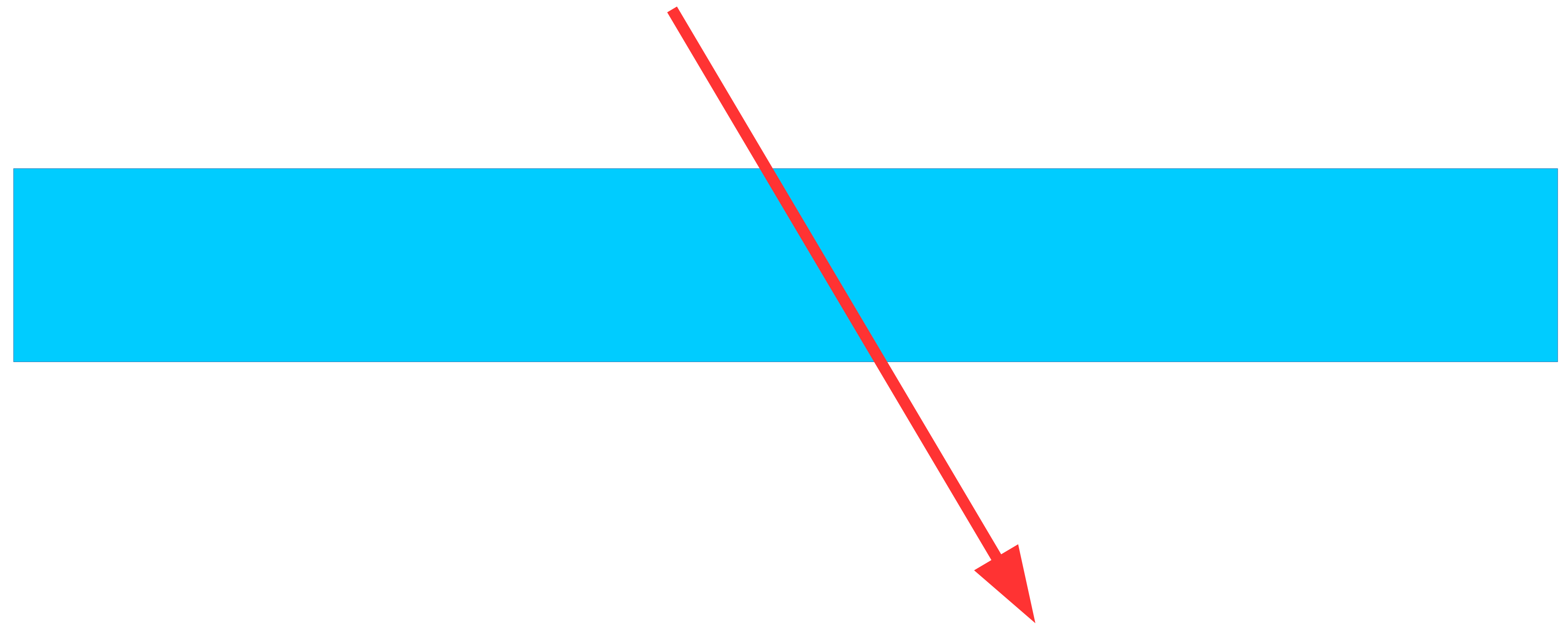
Transition from S_{10} to ground state produces scintillation light. The process is called fluorescence.

Fluorescence intensity at time t is

$$I = I_0 e^{-t/\tau}, \quad \tau \text{ is few nano seconds}$$



Energy loss in scintillator and conversion to photons



Mean energy loss by ionizing particle like muon in scintillator of thickness 1 cm is **2 MeV**

Scintillation photons are produced isotropically along the track of the particle.

Energy loss to photon conversion: 1 photon (3 eV) per 100 eV energy

Number of photon produced per cm is typcially 20,000

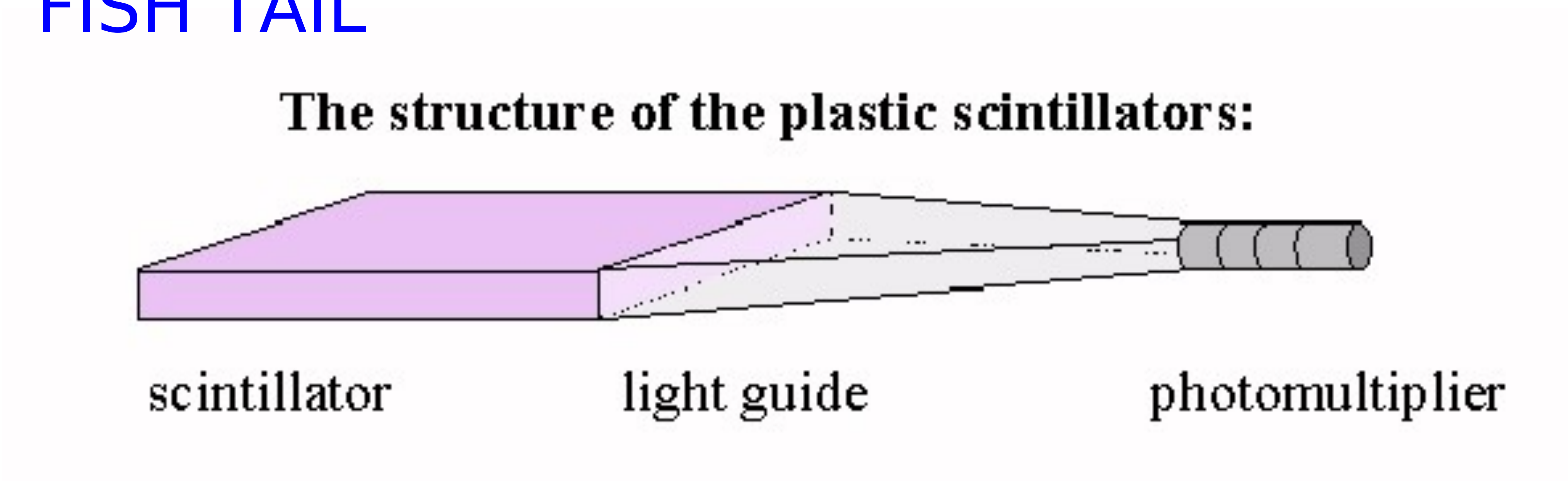
It is important to efficiently transport the photons to a photodetector which converts photons to a measurable electrical signal

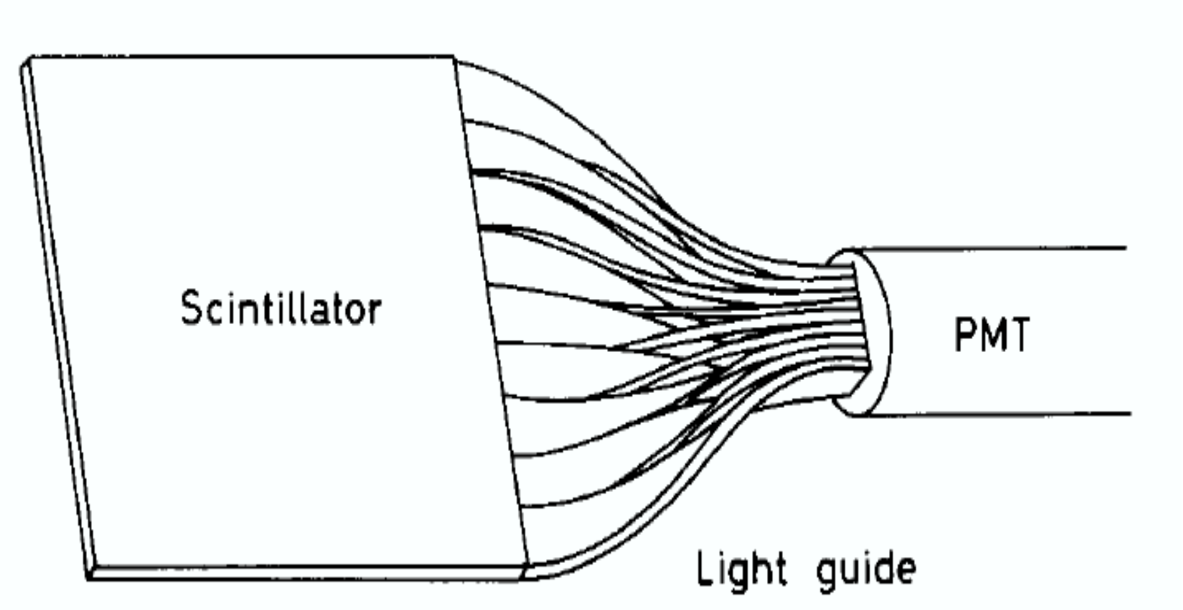
Light guides

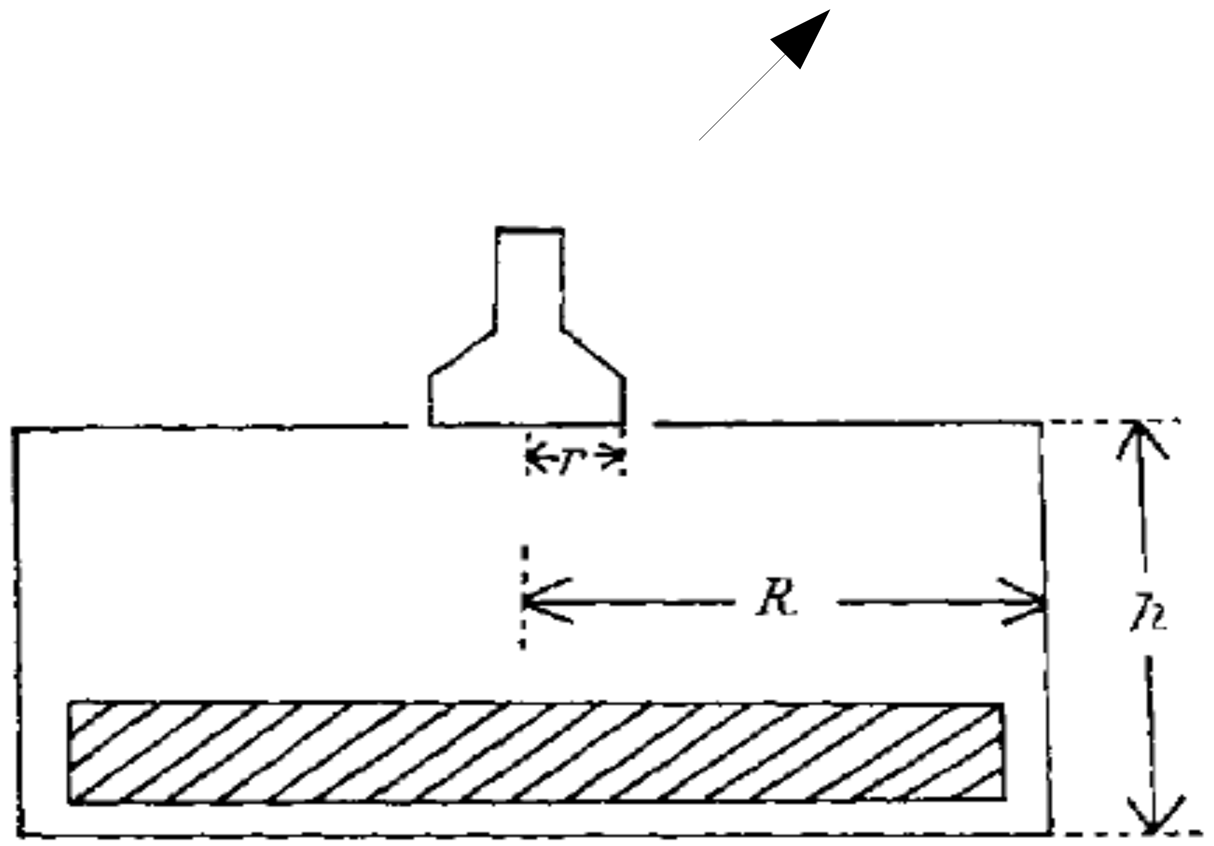
Scintillation light comes out from all surfaces
.....Needs to be navigated to photodetector

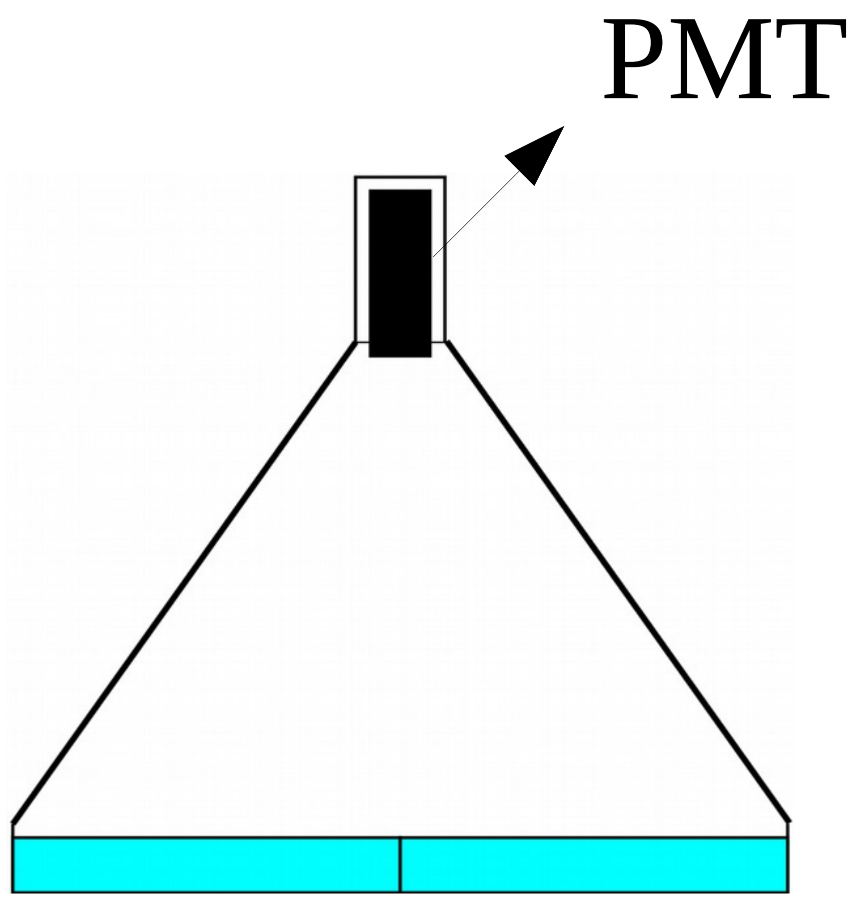
ADIABATIC GUIDE

FISH TAIL



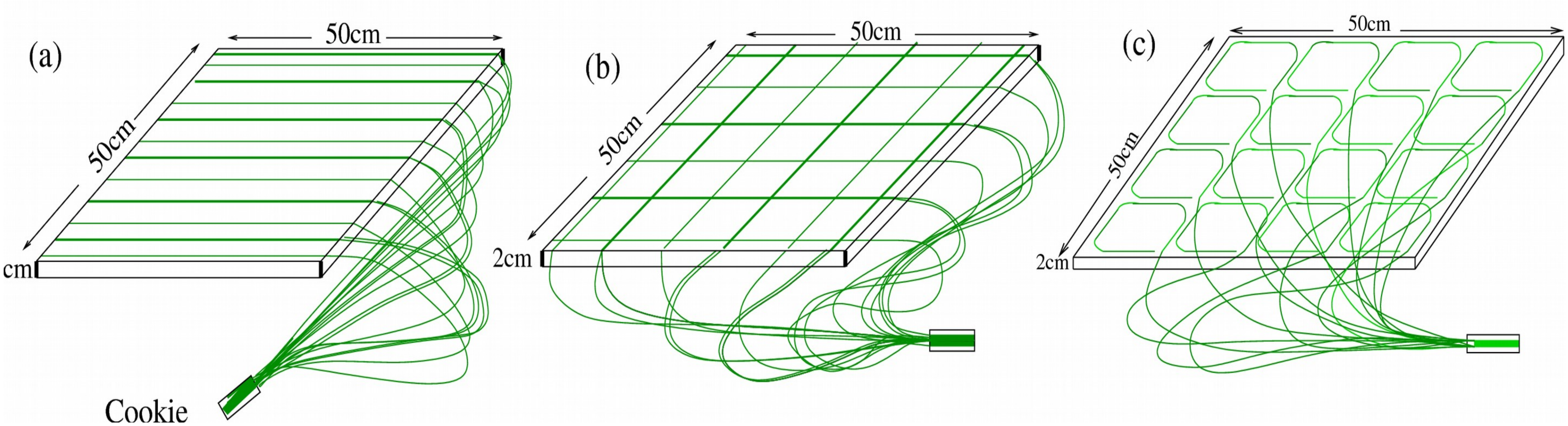






Wavelength shifting fiber readout

Uniform collection and efficient transport of light from scintillator to photodetector



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Monte Carlo code G3sim for simulation of plastic scintillator detectors with wavelength shifter fiber readout

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A detailed description of a compact Monte Carlo simulation code "G3sim" for studying the performance of a plastic scintillator detector with wavelength shifter (WLS) fiber readout is presented. G3sim was developed for optimizing the design of new scintillator detectors used in the GRAPES-3 extensive air shower experiment. Propagation of the blue photons produced by the passage of relativistic charged particles in the scintillator is treated by incorporating the absorption, total internal, and diffuse reflections. Capture of blue photons by the WLS fibers and subsequent re-emission of longer wavelength green photons is appropriately treated. The trapping and propagation of green photons inside the WLS fiber is treated using the laws of optics for meridional and skew rays. Propagation time of each photon is taken into account for the generation of the electrical signal at the photomultiplier. A comparison of the results from G3sim with the performance of a prototype scintillator detector showed an excellent agreement between the simulated and measured properties. The simulation results can be parametrized in terms of exponential functions providing a deeper insight into the functioning of these versatile detectors. G3sim can be used to aid the design and optimize the performance of scintillator detectors prior to actual fabrication that may result in a considerable saving of time, labor, and money spent. [http://dx.doi.org/10.1063/1.3698089]

G3sim code

A realistic photon propagation simulation code written in C++ (~1400 lines)

1: Generation and propagation of muons

$$\frac{dN_\mu}{d\Omega} \propto \cos^2\theta.$$

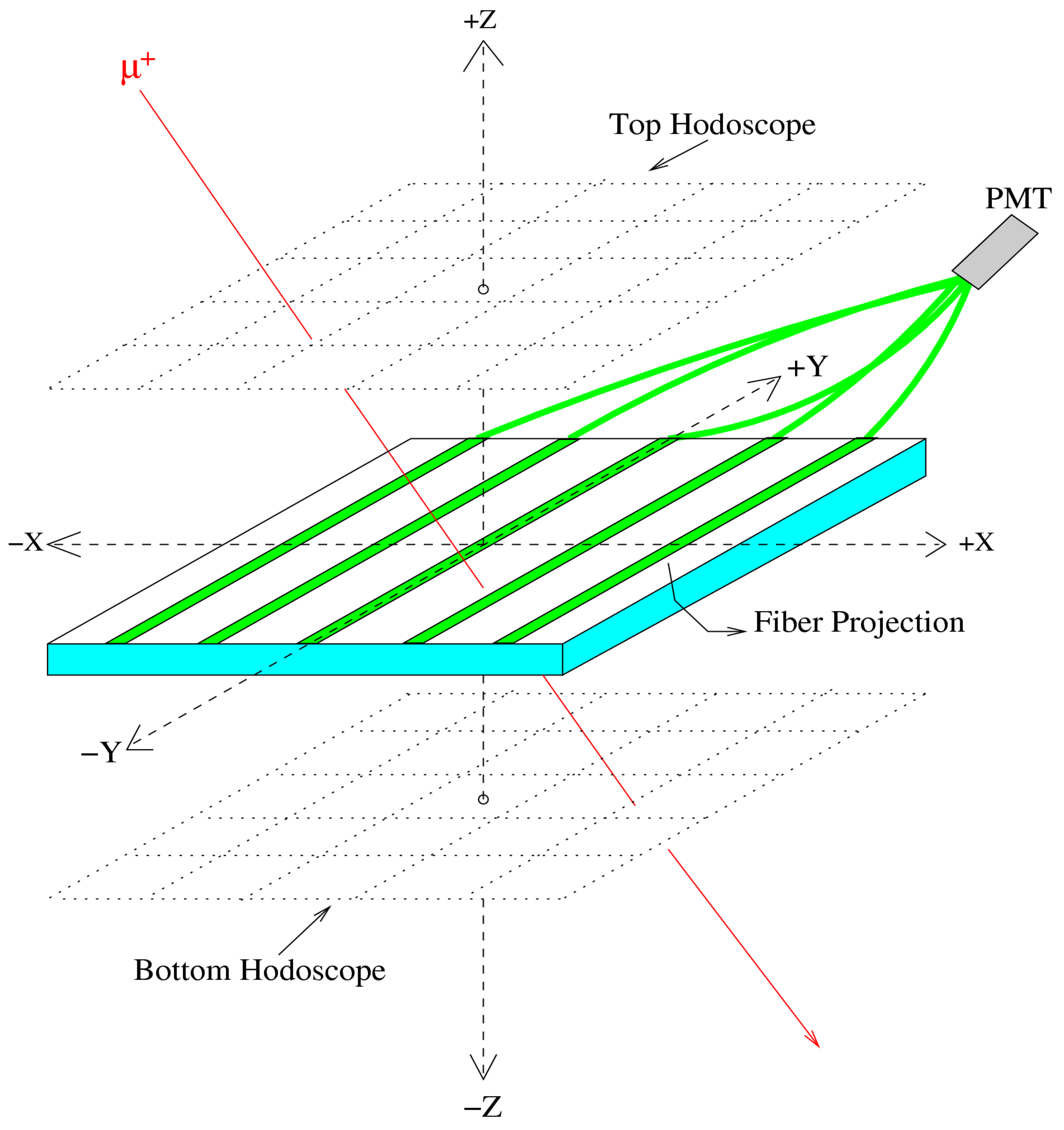
2: Energy loss (dE/dX) calculation using Landau distribution

3: Generation of photons in scintillator.

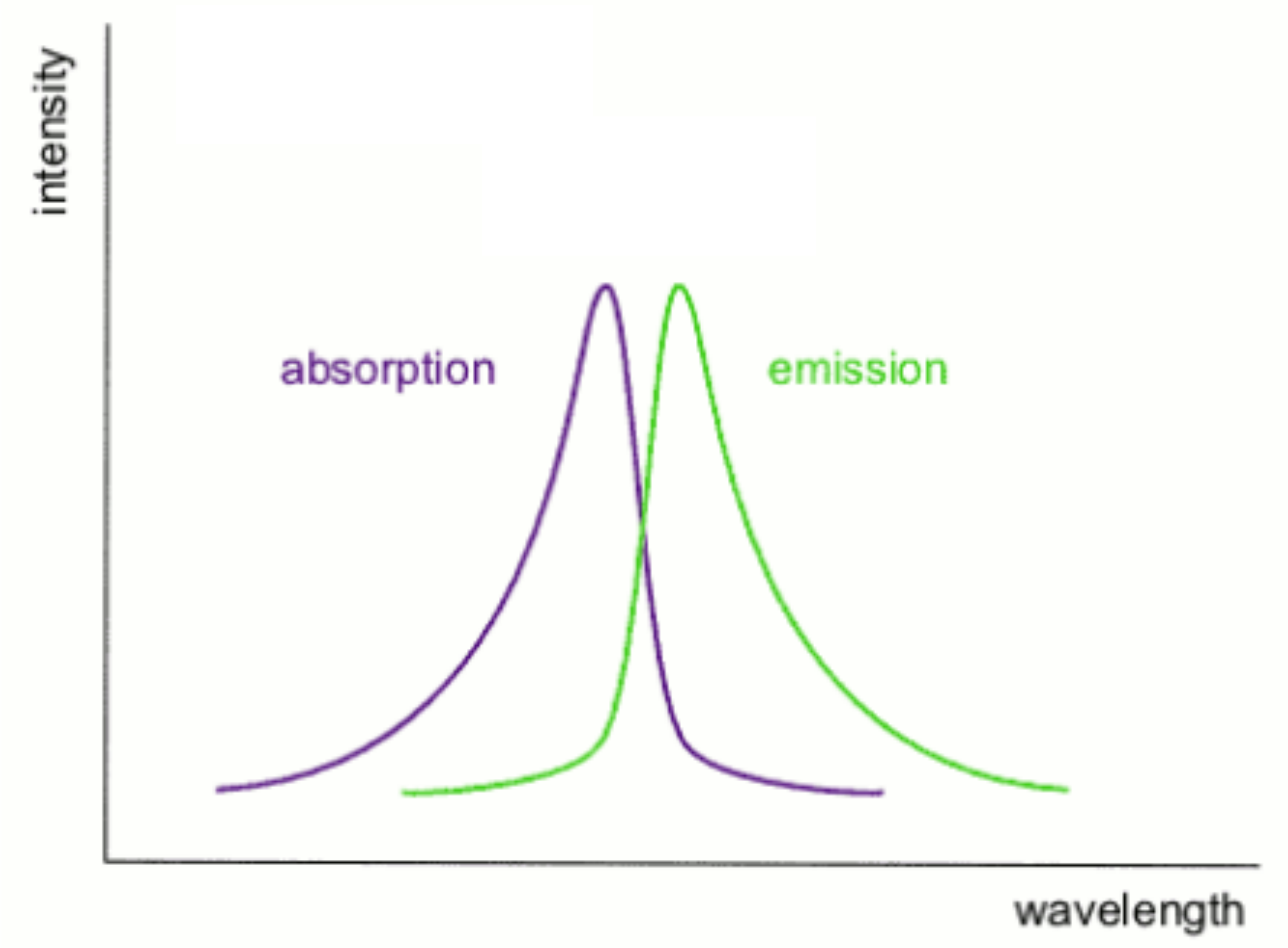
4: Propagation of photons in scintillator using basic laws of reflection and considering attenuation loss and loss due to imperfect surface

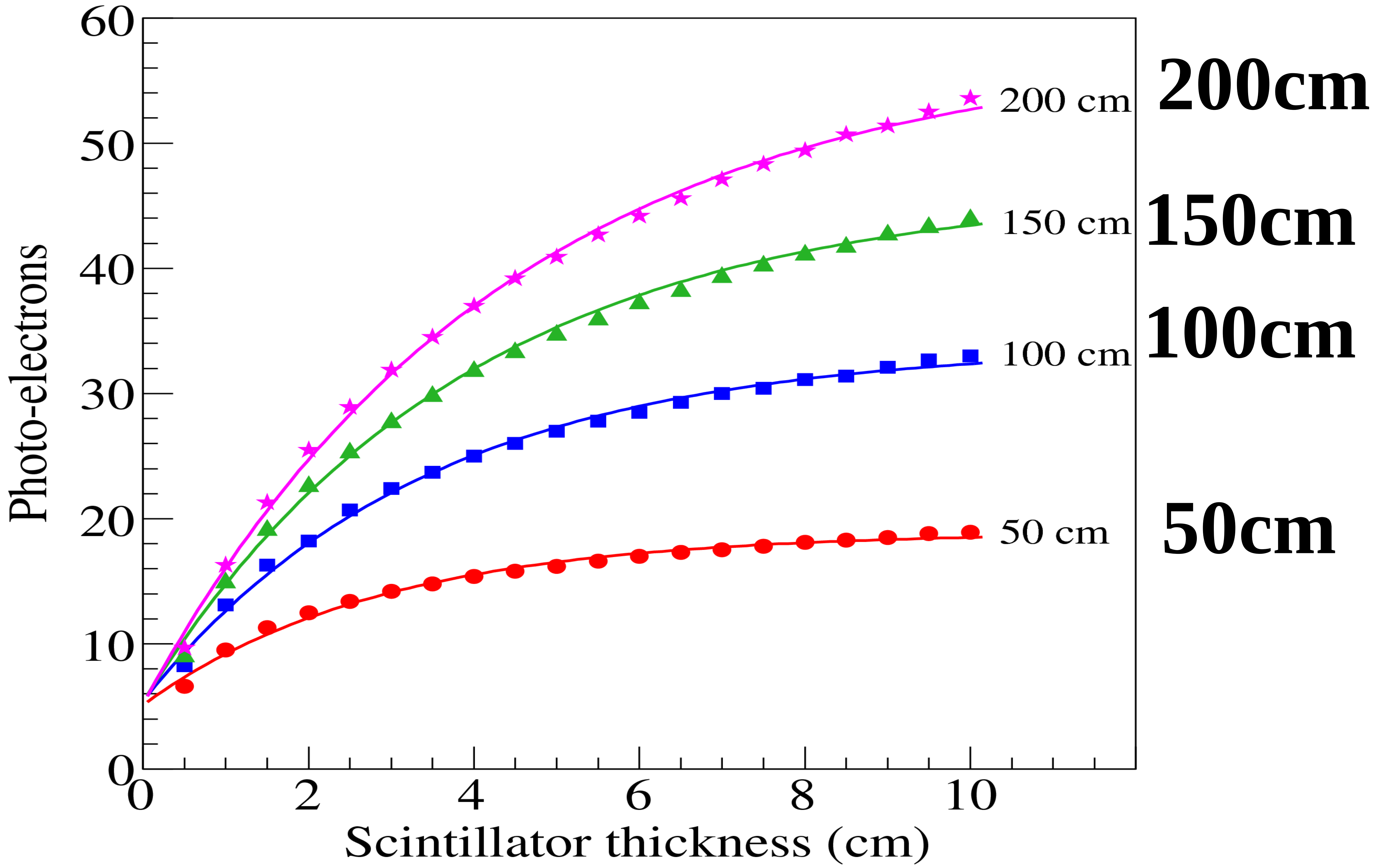
5: Capture, trapping and propagation of photons in WLS fiber considering meridional and skew ray modes

6: Convolution of PMT responses.



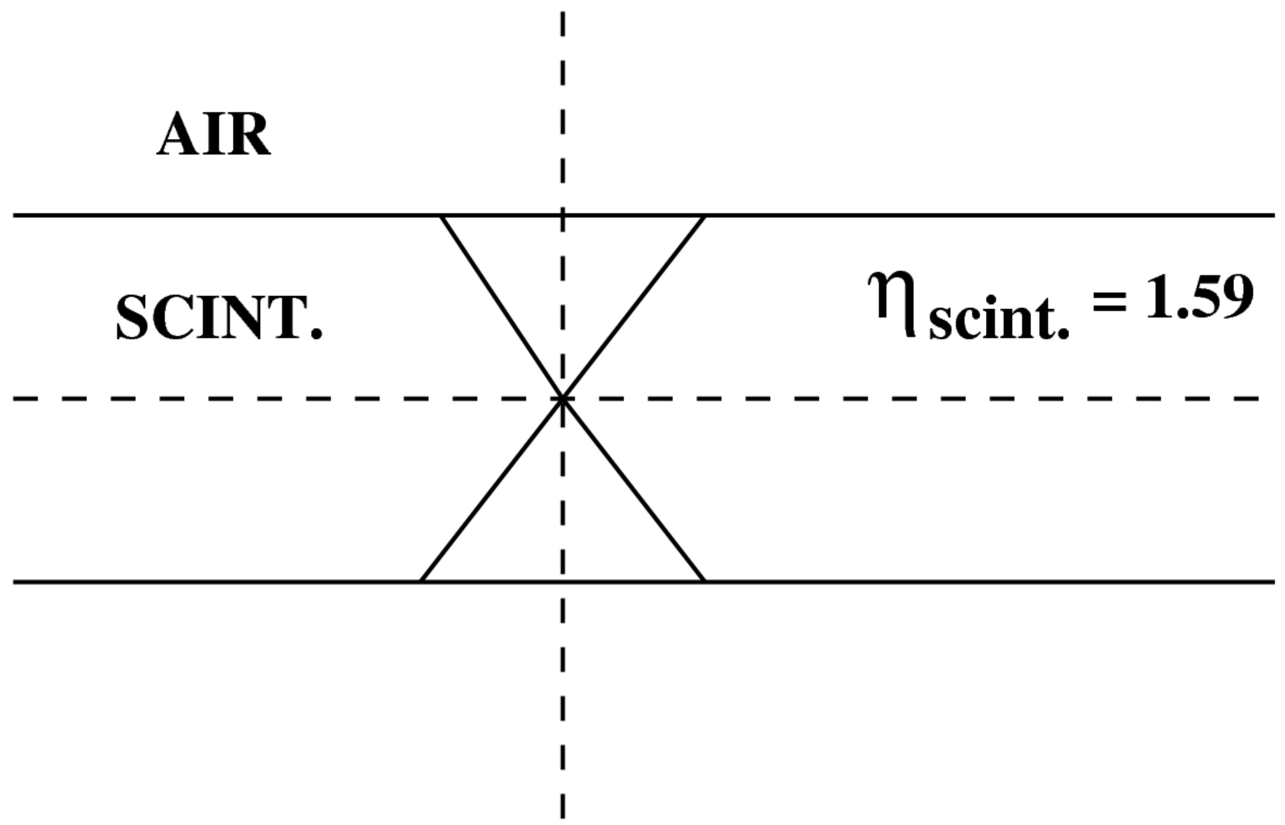
Attenuation due to self absorption



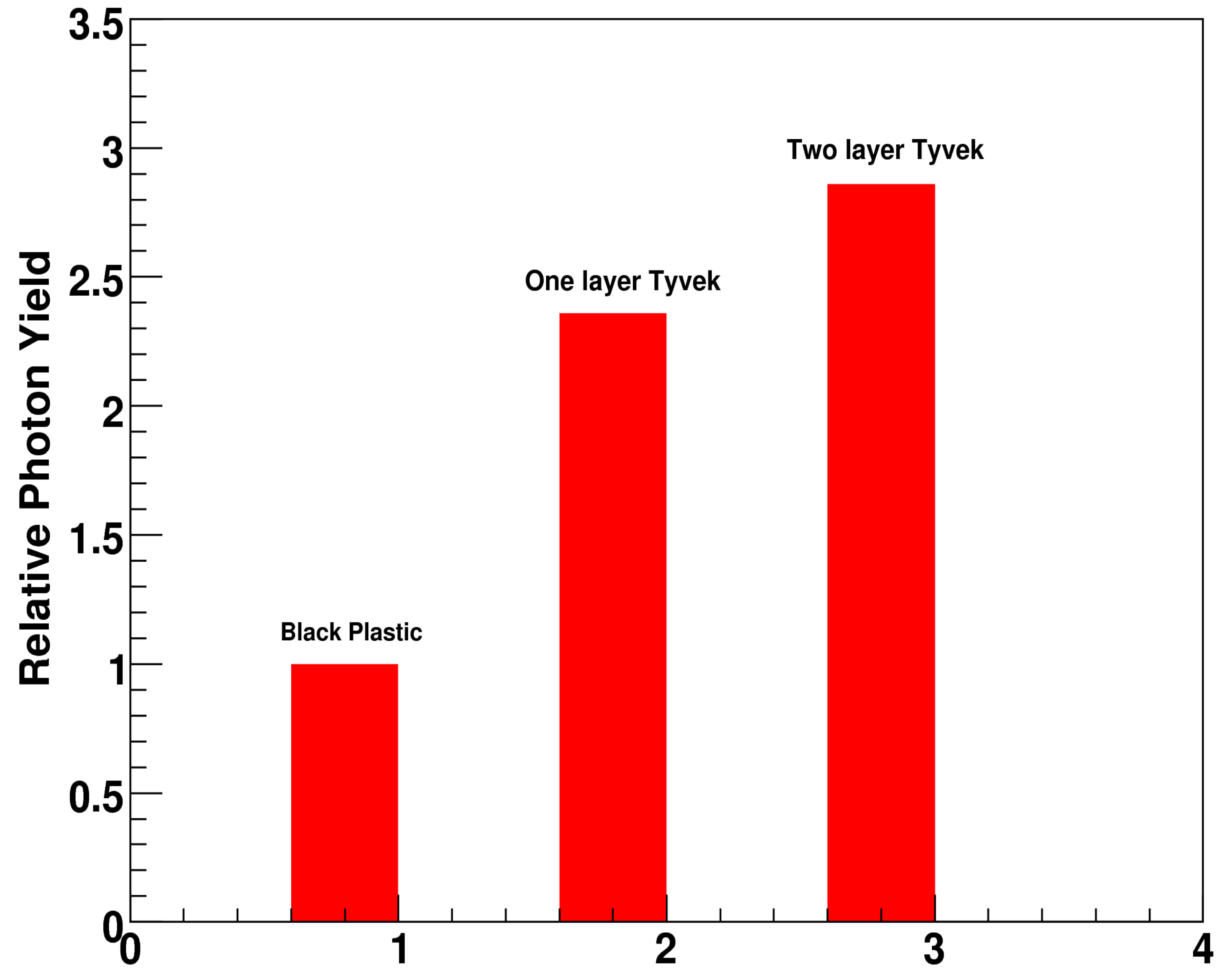


Reflectors

Reflectors play a very significant role to enhance the light collection



Escape fraction ~ 70%



Specular Reflection: Reflected angle is equal to incident angle ($\theta_i = \theta_r$)

Aluminum foil (Reflectivity ~ 90%)

Diffuse Reflection: Reflected angle is independent of incident angle

Tyvek has good strength and resistant to degradation (Reflectivity ~ 90%)

$$\frac{dI}{d\theta} \propto \cos\theta.$$

Wave-length shifting fibers

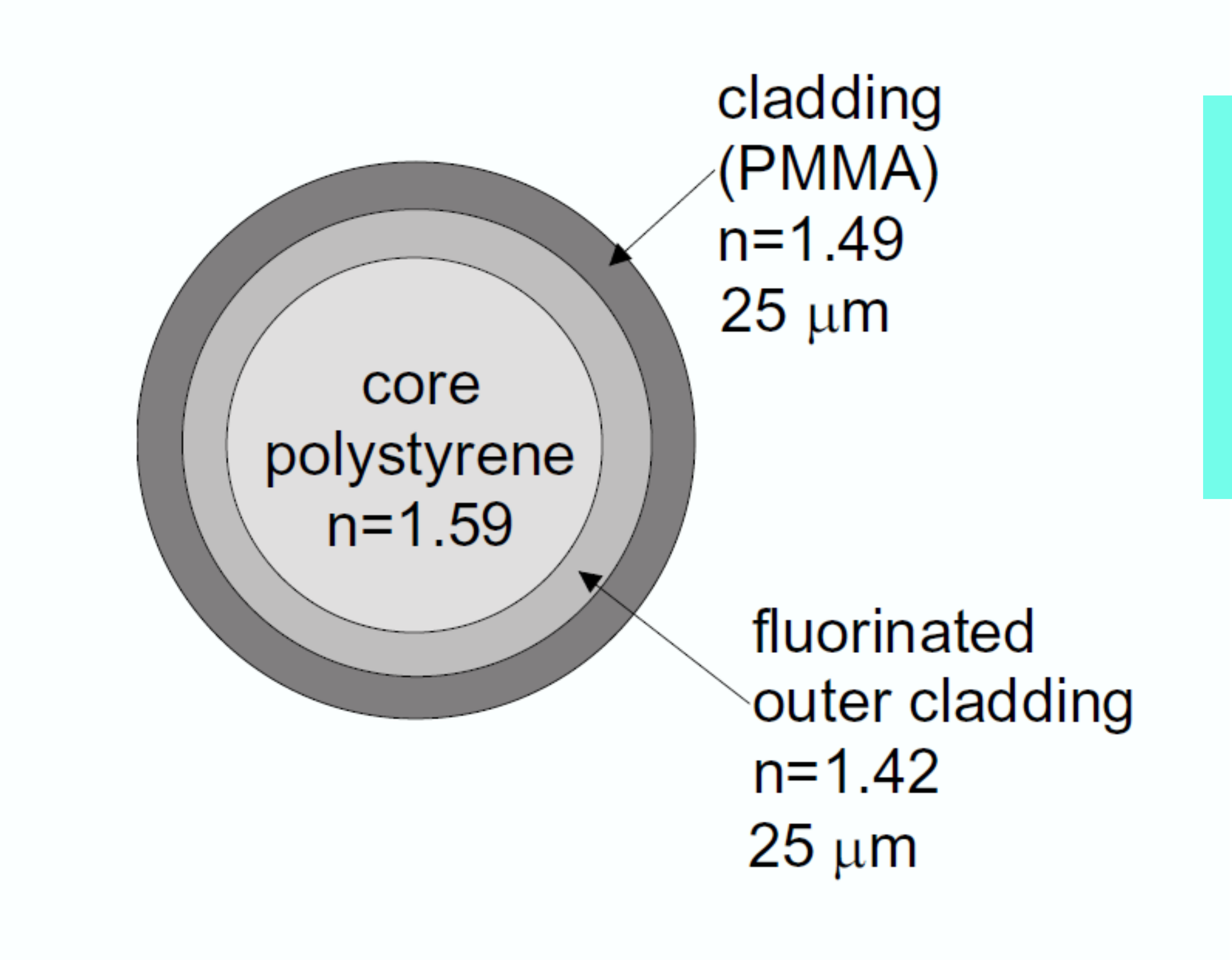
Absorption wavelength of WLS fiber matches with scintillator emission wavelength (blue, ~420 nm).

Emission of WLS fiber is at longer wavelength (green, ~495 nm).

Reduced self-absorption results longer attenuation for WLS fiber

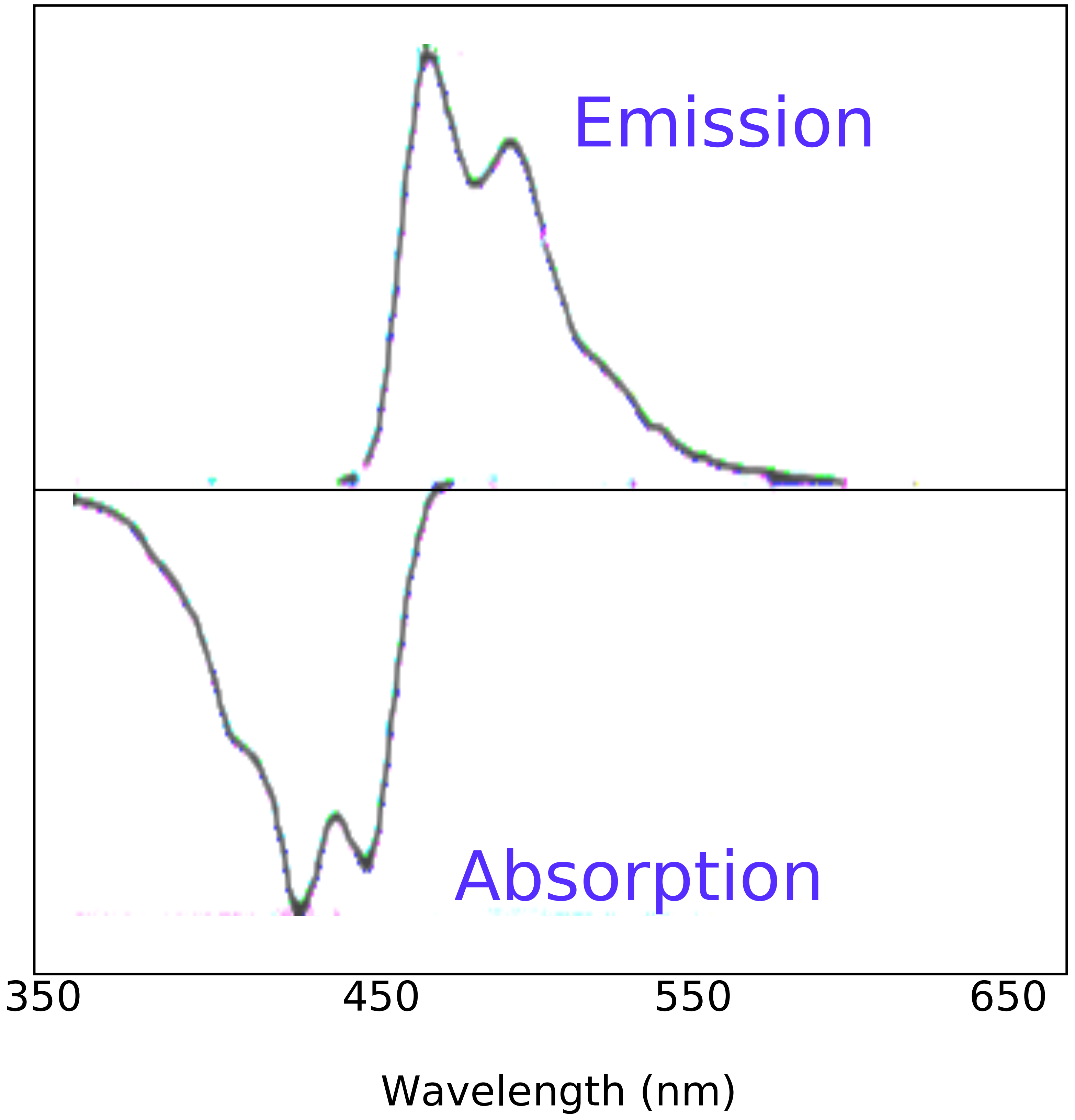
Attenuation length of scintillator ~1 m

Attenuation length of WLS fiber (Y-11 Kuraray) ~3.5 m

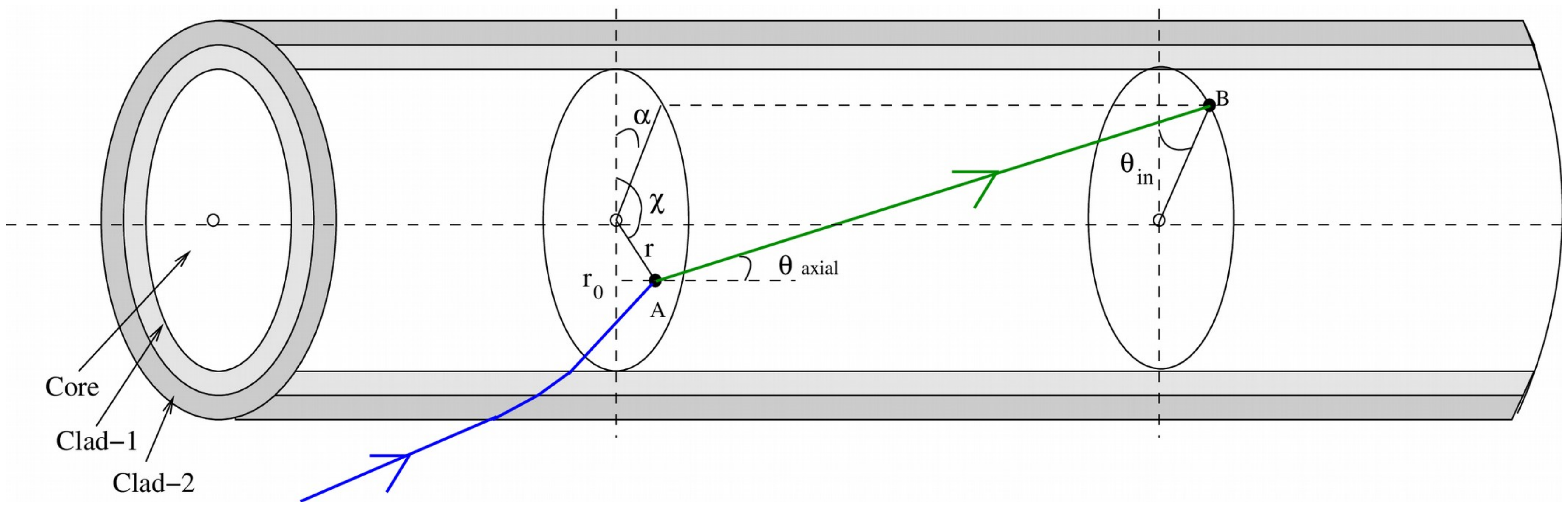


Trapping efficiency

single-clad fiber	~3.1%
double-clad fiber	~5.3%



Photon Trapping in Fiber



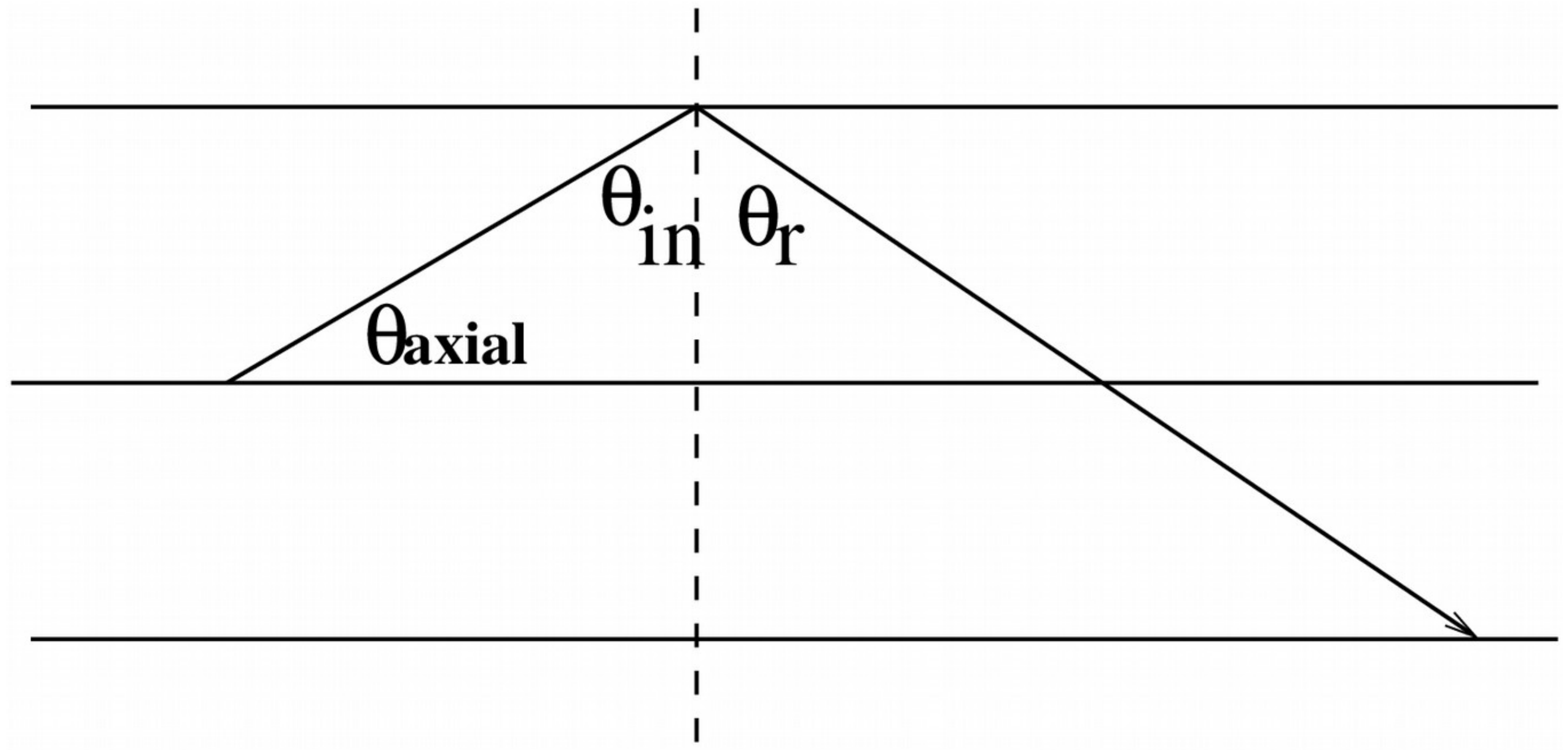
Core: 0.94mm
Refractive index = 1.59

Inner clad: 0.03mm
Refractive index = 1.49

Outer clad: 0.03mm
Refractive index = 1.42

Meridional rays

Incident, normal and reflected ray lie in the same plane



$$\cos(\theta_{in}) = \sin(\theta_{axial})$$

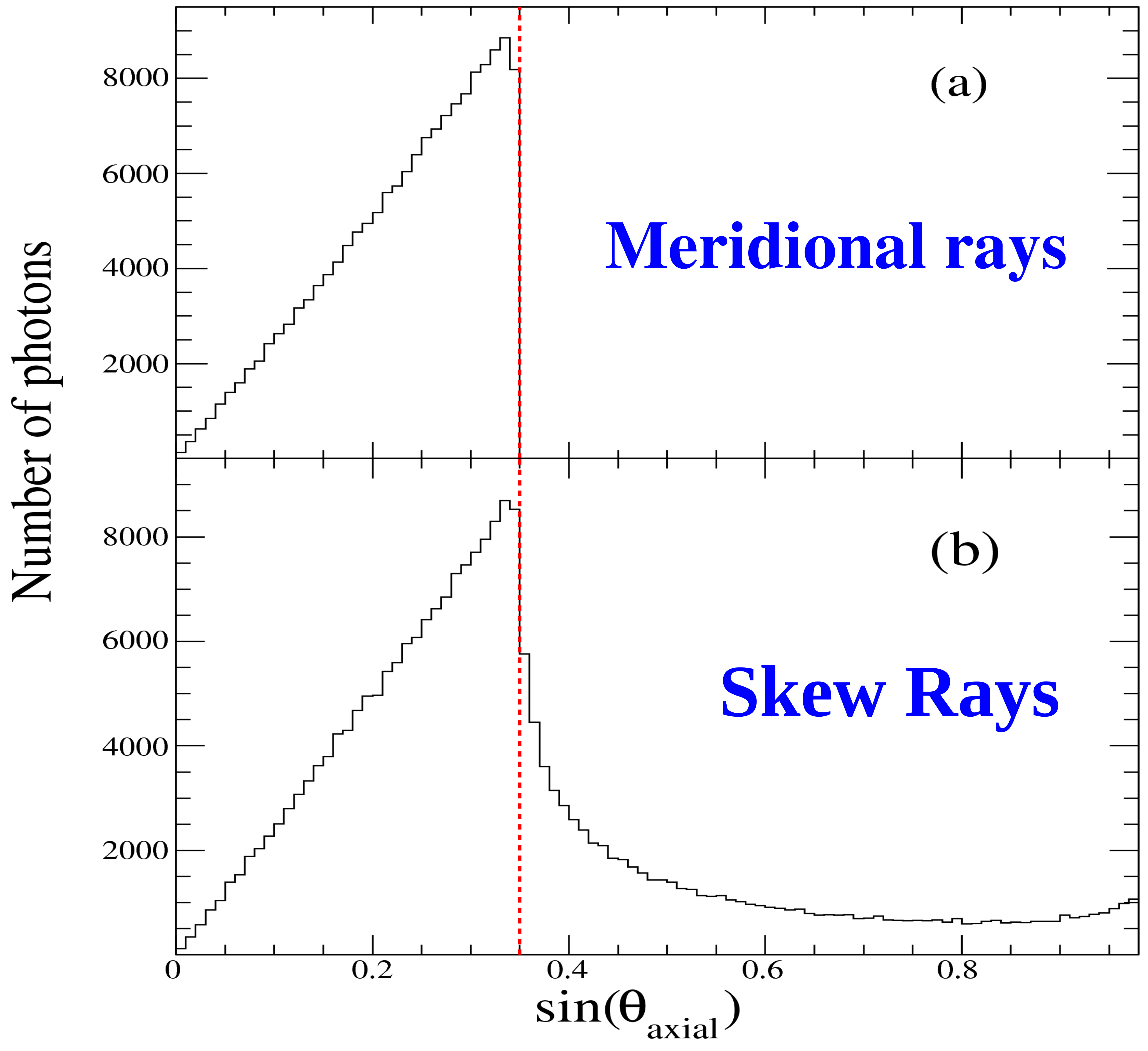
Skew Rays

do not lie in the same plane

$$\sin(\theta_{axial}) = \cos(\theta_{in})\left\{1 + \left(\frac{r/r_0 \sin(\chi - \alpha)}{1 - r/r_0 \cos(\chi - \alpha)}\right)^2\right\}^1$$

P.K. Mohanty et al. Rev. Sci. Instrum. 83 (2012) 043301.

Axial angle distribution of trapped photons



Trapping Efficiency of meridional rays = 3.2 %

With inclusion of skew rays, trapping efficiency = 4.8%

Losses in Fiber

Self absorption loss : Attenuation length for Kuraray double clad fiber = 350 cm

Loss from the imperfect surface:

Total internal reflectivity $R = 0.9999$

For 1 meter long and 1mm diameter fiber, number of reflections $N \sim 500$

Survival probability = $R^N = 0.95$

G3sim input parameters

TABLE I. Simulation parameters.

Photon conversion	100 eV
Maximum reflections	150
Scintillator ETIR	0.93
Tyvek reflectivity	0.90
Fiber reflectivity	0.9999
Path-length step	0.01 cm
λ_{scint}	100 cm
λ_{WLS}	350 cm
η_{scint}	1.59
η_{core}	1.59
η_{clad-1}	1.49
η_{clad-2}	1.42
η_{air}	1.00
Min, Max (X Y Z)	-25 25 -25 25 -1 1 cm

Photon statistics (50 cm x 50 cm x 2 cm)

TABLE II. Photon statistics.

Produced in scintillator	46 000	
Escaped from scintillator	11 500	
Absorbed in scintillator	30 000	
Entered WLS fiber	4500	→ 10%
Escaped from WLS fiber	3850	
Trapped in WLS fiber	650	
Absorbed in WLS fiber	450	
Arrived at the PMT	200	→ 0.4%

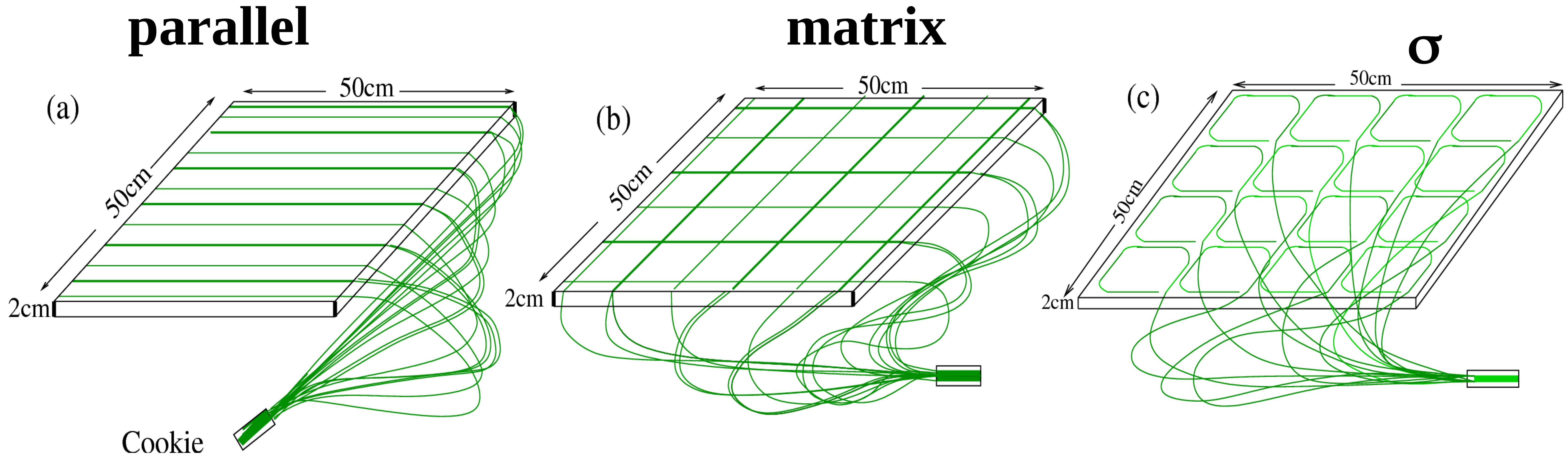
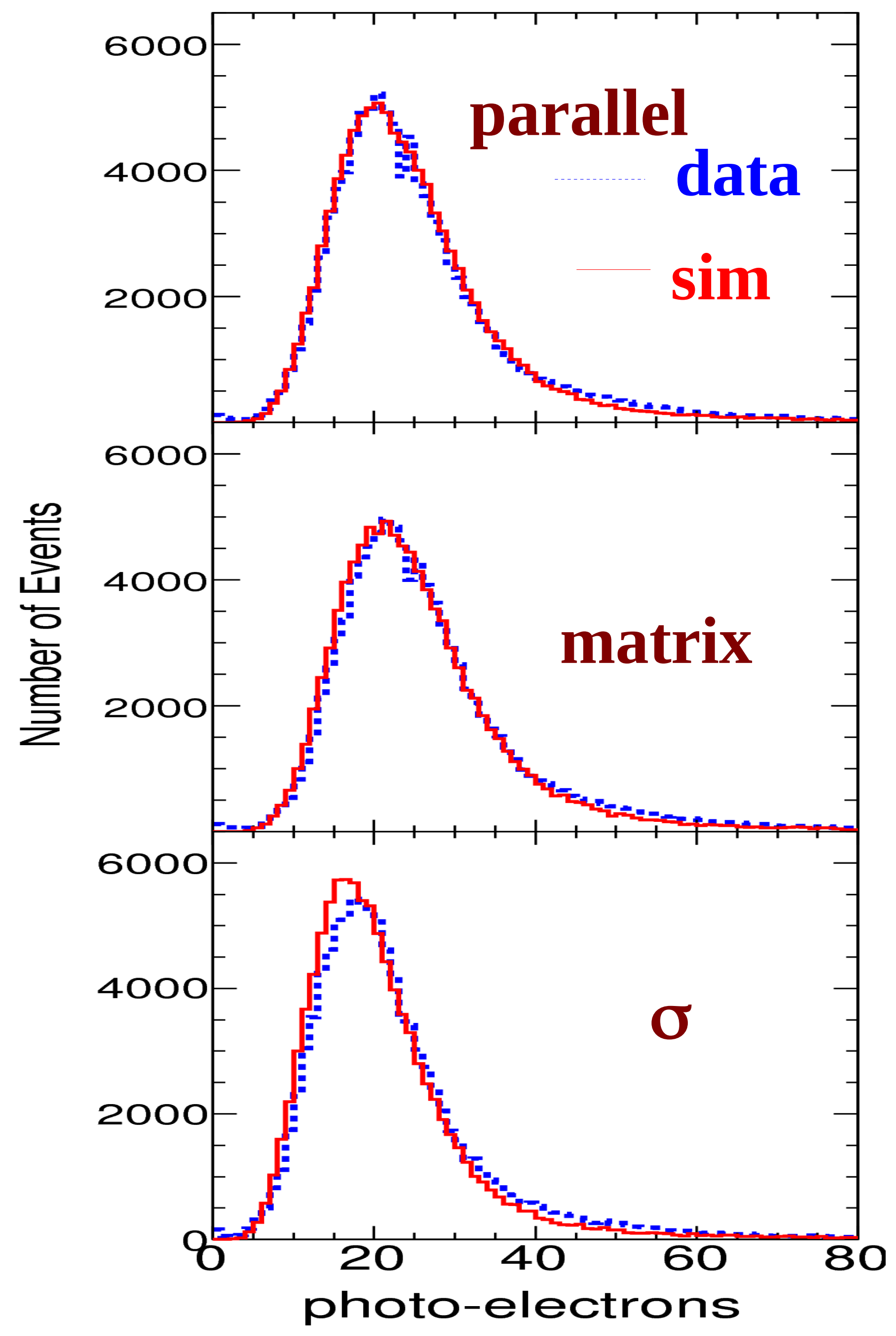
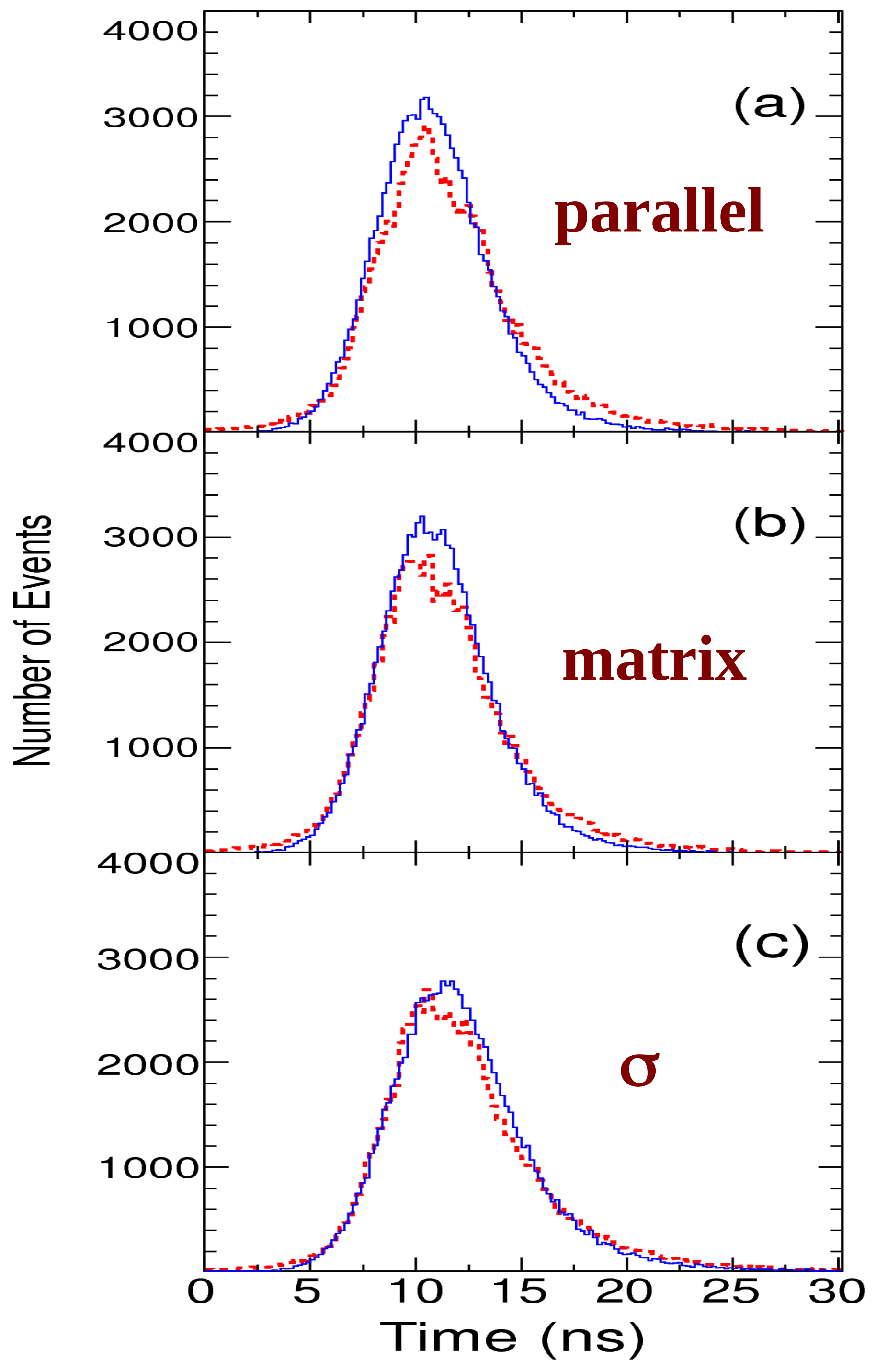


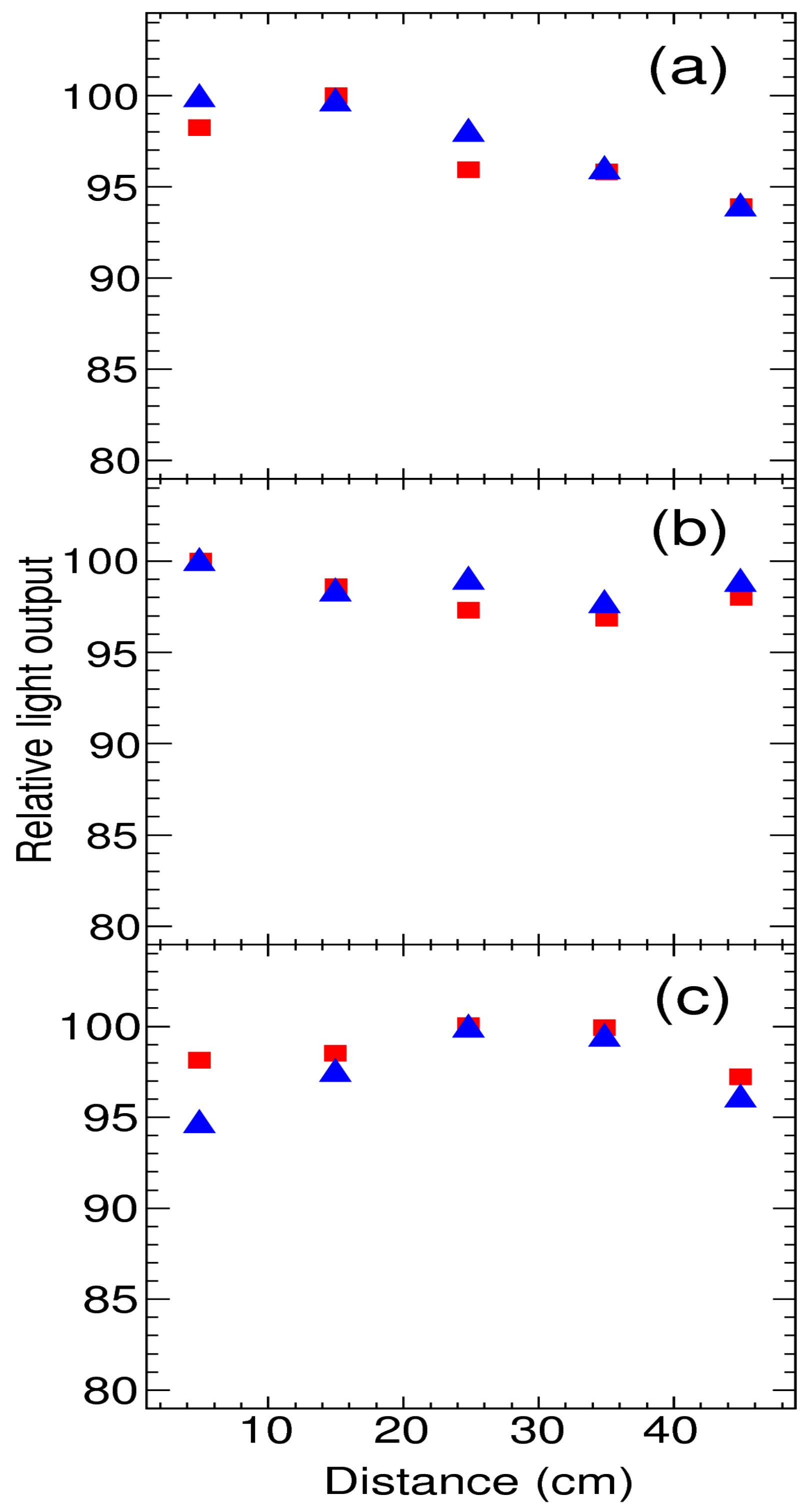
Photo-electron Yield



Time Response



Uniformity



Summary of groove comparisons

Photo-electron yield

Groove	Fiber-length(cm)	Photo-electrons
Parallel	900	20.5
Matrix	900	21.7
σ	656	17.9

RMS non-uniformity (%)

Groove	Experiment	Monte Carlo
Parallel	2.7	2.0
Matrix	2.1	1.6
σ	3.5	3.3

Time Response (ns)

Groove	Experiment	Monte Carlo
Parallel	2.5	2.3
Matrix	2.4	2.3
σ	2.4	2.4

Conclusion

photo-electron yield is proportional to the length of fibers in the groove and other responses are found be independent of design.

Parallel groove design selected for final configuration because of ease in fabrication

THANK YOU