An analytic technique for the estimation of the light yield of a scintillation detector

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Introduction

- ***Scintillation detectors*** are used in all fields of physics and for many purposes (calorimetry, triggering purposes, particle identification, ...)
- A typical scintillation detector is constituted by a *scintillating material* contained in a *reflective box* that is observed by a system of ***Photo Sensitive Devices*** (PSDs)
- In many cases they allow to perform calorimetric measurements since their output signal is often proportional to the deposited energy
- *The constant ratio between the signal* (usually in charge) *and the deposited energy* is the **light yield** (LY) and is measured in *(photo-) electrons/keV*
- LY deeply influences the design of a scintillation detector since it *fixes the scale of the intensity of the output signal*
- The layout of the detector needs to be optimized in order to match as well as possible the LY with the characteristics (energy, Linear Energy Transfer, . . .) of the *incoming radiation* and of the *electronic read-out chain*
- Traditionally LY is evaluated by means of ***Monte Carlo simulations*** => precise results BUT need programming and running codes that invoke the propagation of millions of photons AND cumbersome in an optimization process
- In this work ***an alternative and completely analytic approach for the estimation of the LY of simple detectors is presented*** => FAST and ROBUST results AND *explicit dependence on optical parameters* makes this technique particularly suitable for optimization processes.

Light Yield of a scintillation detector

LY can be factorized as:

$$\boxed{LY = N_\gamma \bullet \varepsilon_{PSD} \bullet \varepsilon_{opt}}$$

Where:

- ✓ $\boldsymbol{N_\gamma}$ is the *photon yield* of the scintillator => *number of photons produced per unit of deposited energy by a certain radiation*
- ✓ $\boldsymbol{\varepsilon_{PSD}}$ is the *conversion efficiency of the PSDs* => *the efficiency of the PSD system in converting photons into signal (photo-electrons)*
- ✓ $\boldsymbol{\varepsilon_{opt}}$ is the *optical efficiency* => *the fraction of the originally produced photons that manages to cross the windows of the PSDs*

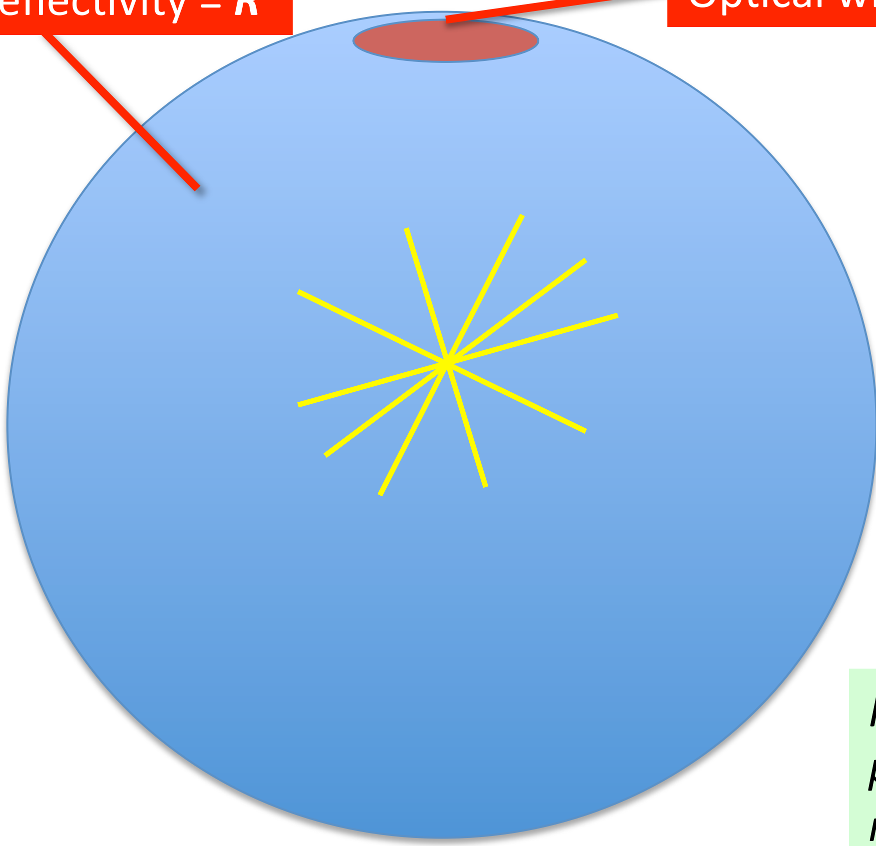
N_γ and ε_{PSD} in the majority of the cases are precisely known. On the other side **ε_{opt} is typically unknown and needs to be estimated.**

Recursivity of light propagation (think to a sphere...)

The propagation of photons inside a scintillation detector is an *intrinsically recursive process*.

Reflectivity = ***R***

Optical window – photcatodic coverage = ***f***



A photon produced in a **random point inside the sphere** with a random direction when reaches the boundary surface has an *average probability **f** to be detected*

And a probability ***R(1-f)*** to be sent back into the chamber

*Reflected photons has again a detection probability equal to **f** and a probability to be reflected equal to **R(1 – f)** when hit the boundary surface for the second time*

The same situation will repeat again ***identical to itself after any reflection.***

...let's generalize a little bit (I)

- Consider a ***general scintillation detector*** and assume that the ***process is recursive***
- It can be divided into a *series of subsequent and indistinguishable steps* and *it is possible to define two quantities:*
  - ✓ ***α*** *is the average probability per step that a photon is detected*
  - ✓ ***β*** *is the average probability per step that a photon is regenerated, that is the probability that it is not lost (detected or absorbed) and that some physical process randomizes again its direction (reflection for instance)*
  - ✓ *α and β are constant for all the steps (recursivity of the process)*
  - ✓ $\alpha \leq 1$ and $\beta < 1$
- **Detection and regeneration probabilities after n steps are easily calculated:**

	detection probability	regeneration probability
step 0	α	β
step 1	$\alpha\beta$	β^2
step 2	$\alpha\beta^2$	β^3
$\ldots$	$\ldots$	$\ldots$
step n	$\alpha\beta^n$	β^n

…let's generalize a little bit (II)

$$\boxed{\varepsilon_{opt} = \sum \alpha\beta^n = \frac{\alpha}{1-\beta}}$$

For the *spherical scintillator* (and one can safely extend ***to scintillators of regular shapes***) this means that:

$$\boxed{\varepsilon_{opt} = \frac{f}{1-R(1-f)}}$$

$\alpha = f$

$\beta = R(1-f)$

If the optical window has *transmissivity* T_w and *reflectivity* R_w:

$$\boxed{\varepsilon_{opt} = \frac{T_w f}{1-R(1-f)-R_w f}}$$

$\alpha = T_w f$

$\beta = R(1-f) + R_w f$

Including Rayleigh scattering and absorption

Define: $$\boxed{\frac{1}{\tilde{\lambda}} = \frac{1}{\lambda_R} + \frac{1}{\lambda_A}}$$

λ_R -> Rayleigh scattering length
λ_A -> absorption length

and: $\boxed{U_{RA}}$

probability that a photon reaches the end of the step, as defined in absence of scattering/ absorption, without interactions

It is possible to define:

Photon regenerated by reflections

Photon regenerated by scattering

$$\alpha = U_{RA}\alpha_0$$

$$\beta = U_{RA}\beta_0 + (1 - U_{RA})\frac{\tilde{\lambda}}{\lambda_R}$$

with α_0 and β_0 detection and regeneration probabilities in absence of scattering and absorption

Including Rayleigh scattering and absorption (II)

After little algebra one finds:

$$\boxed{\varepsilon_{opt} = \frac{\alpha_0}{Q - \beta_0}}$$

α_0 and β_0 detection and regeneration probability in absence of scattering and absorption

With:

$$\boxed{Q = \frac{1 - (1 - U_{RA})\dfrac{\tilde{\lambda}}{\lambda_R}}{U_{RA}}}$$

This factor takes into account all the effects of scattering and absorption

For our simple detector, under reasonable hypotheses, one obtains:

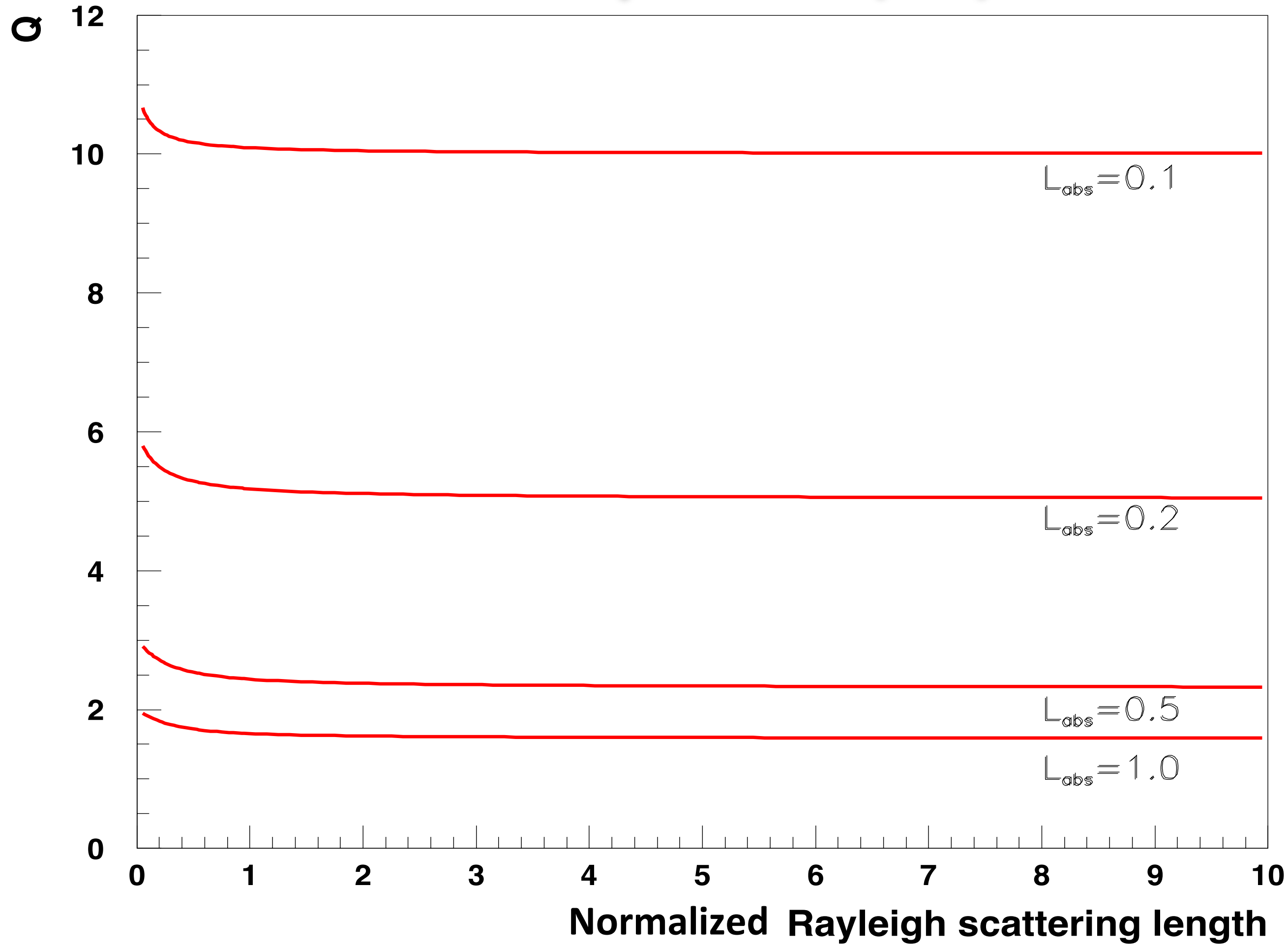
$$\boxed{U_{RA} = \frac{\tilde{\lambda}}{\tilde{L}}\left(1 - e^{-\tilde{L}/\tilde{\lambda}}\right)}$$

with:

$$\boxed{\tilde{L} = 6\frac{V}{S}}$$

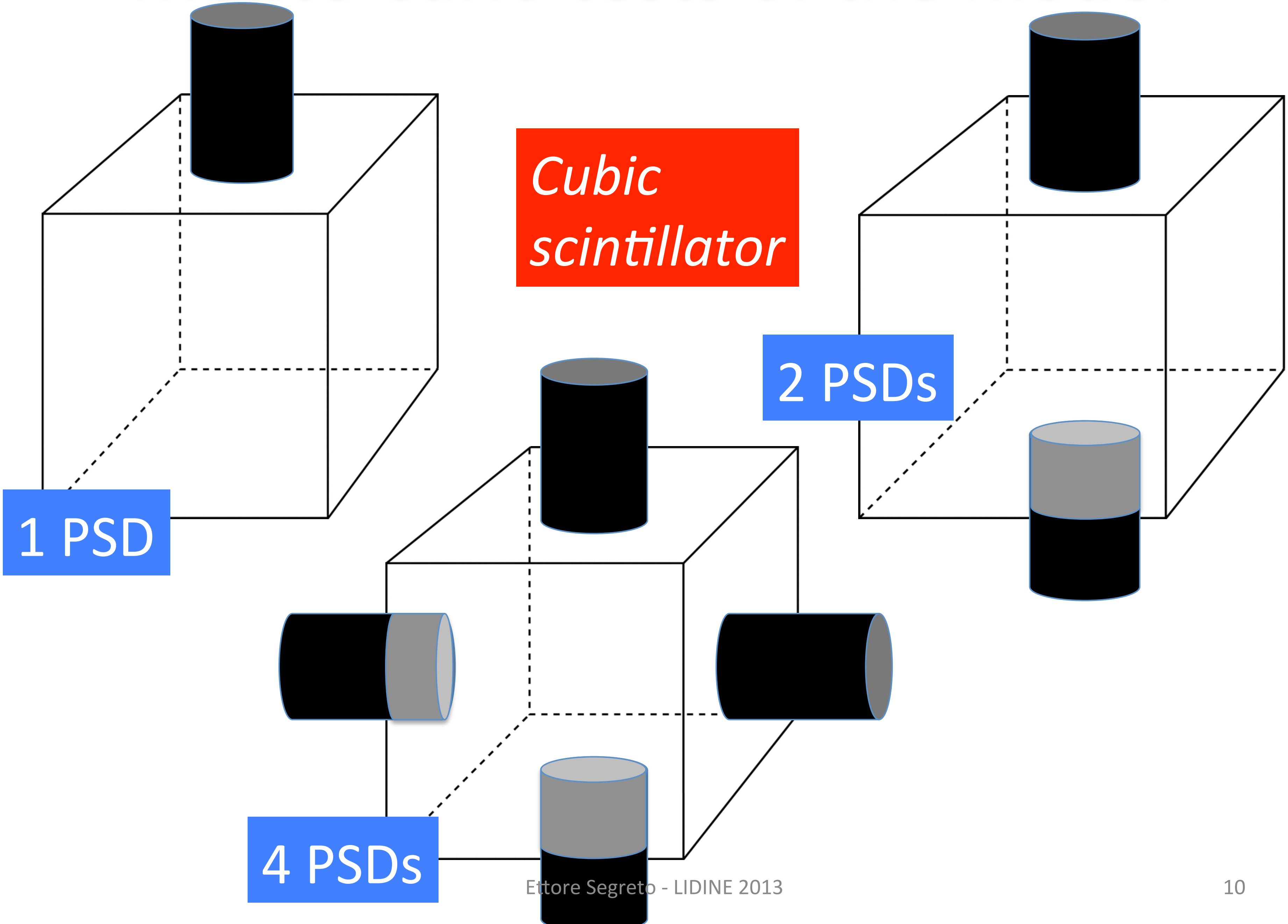
It is the characteristic linear dimension of the detector

Including Rayleigh scattering and absorption (III)



Q is only weakly dependent on the normalized Rayleigh scattering length and visible effects can be seen only when it is smaller than one. The dependence on the (normalized) absorption length is much stronger and for L_{abs} = 1 the term Q is already near to 2

Monte Carlo tests of the model



Monte Carlo tests of the model (I)

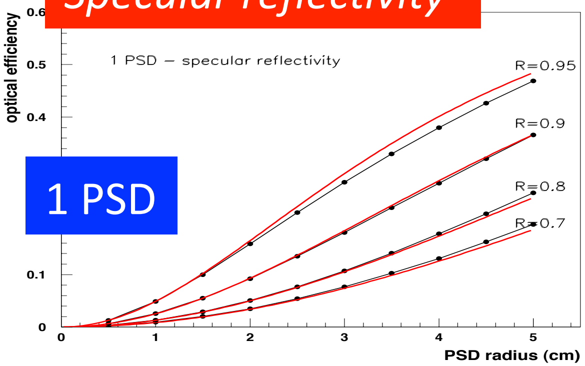
- The predictions of this simple *toy model* have been compared with the results of **Monte Carlo simulations of specific scintillation detectors**
- A **cubic scintillator** is considered *(good degree of symmetry but not a sphere)*
- The cube is assumed to have a side of length ***L = 10 cm*** and is observed by ***one*** (***two*** or ***four***) PSD(s) with circular flat window(s)
- The *reflectivity* of the window is set at $\boldsymbol{R_w = 0.3}$ and the *transmissivity* at $\boldsymbol{T_w = 0.5}$
- The *reflectivity* ***R*** of the *internal non active surface* is varied ***between 0.70 and 0.95***
- The ***radius of the PSD*** window is varied between ***0.5cm and 5.0cm***
- The *optical efficiency of the detector*, $\boldsymbol{\varepsilon_{opt}}$, for any given configuration of the parameters is evaluated by randomly extracting a point inside the cube and generating *a huge number of photons (10^5)* with direction uniformly distributed in space. This procedure is *repeated for 10^5 times* and each time the fraction N_{det} *of photons transmitted across the PSD window is stored*
- The average fraction of detected photons is determined by fitting the distribution of N_{det} with a *Gaussian function* and taking its central value.

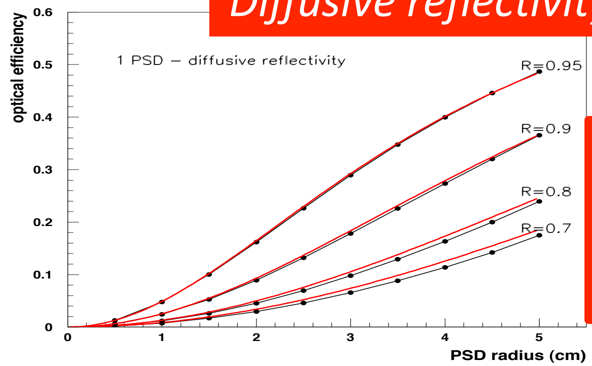
Monte Carlo tests of the model (II)

Specular reflectivity

Diffusive reflectivity

1 PSD

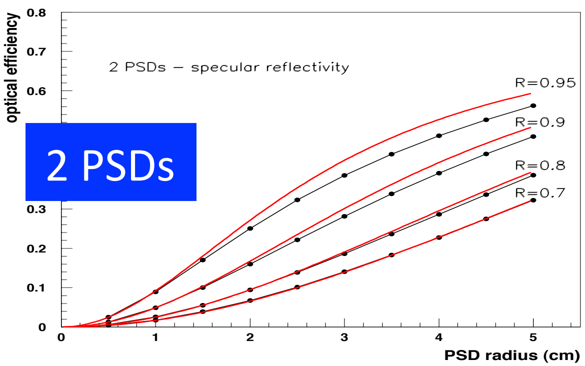


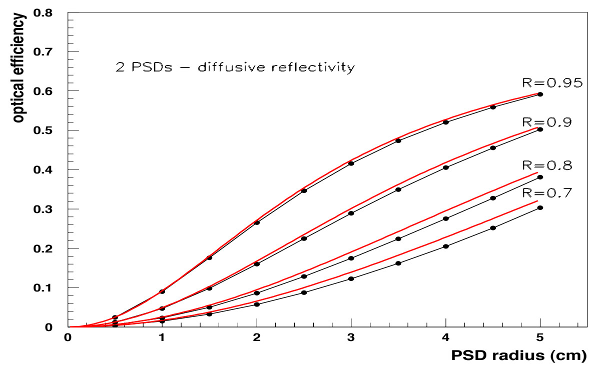


RED LINES :

$$\varepsilon_{opt} = \frac{T_w f}{1 - R(1-f) - R_w f}$$

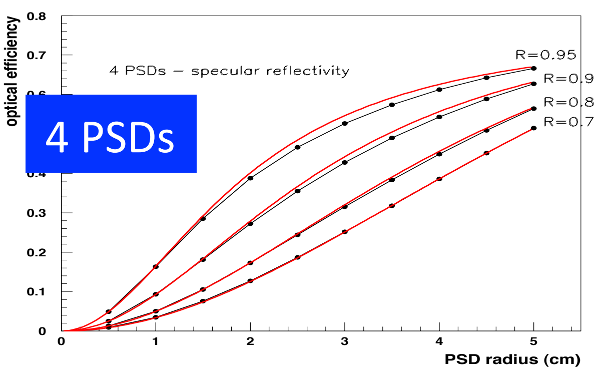
2 PSDs

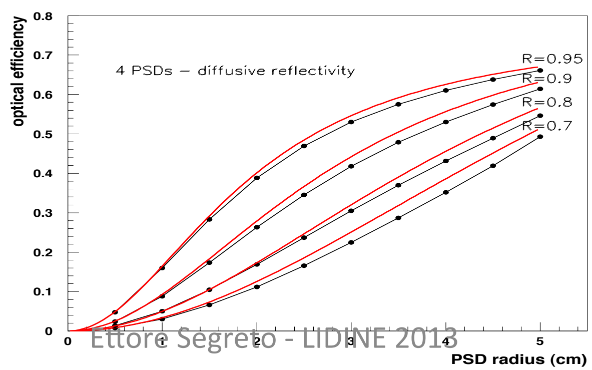




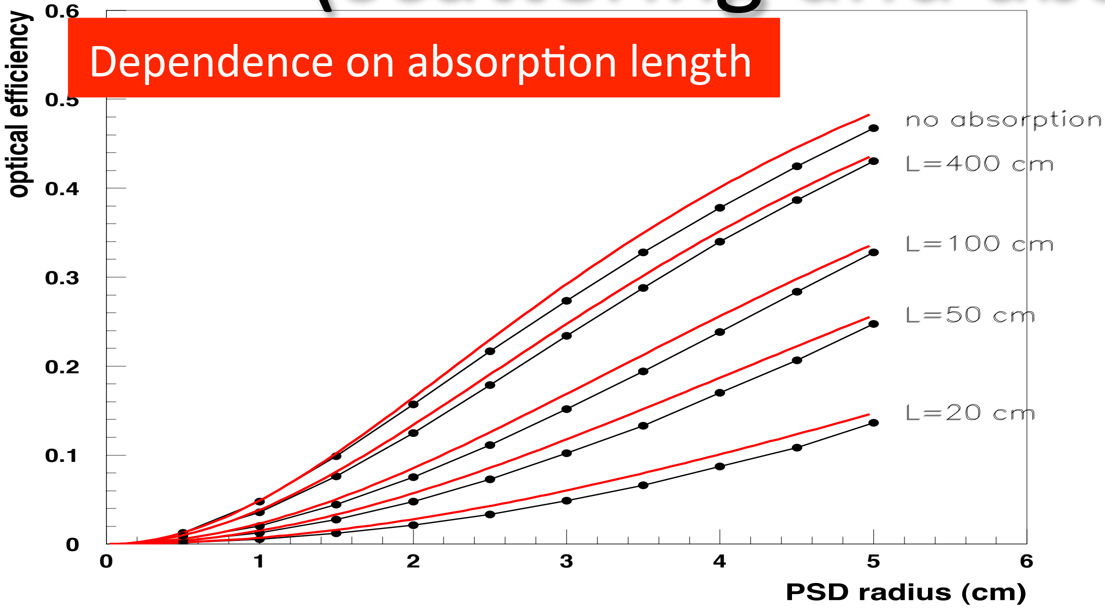
In the case of 2 (4) PSDs the formula is calculated with respect to one PSD. R is the average reflectivity of inactive surfaces and other PSDs' windows. The total efficiency is 2 (4) times the single PSD efficiency

4 PSDs

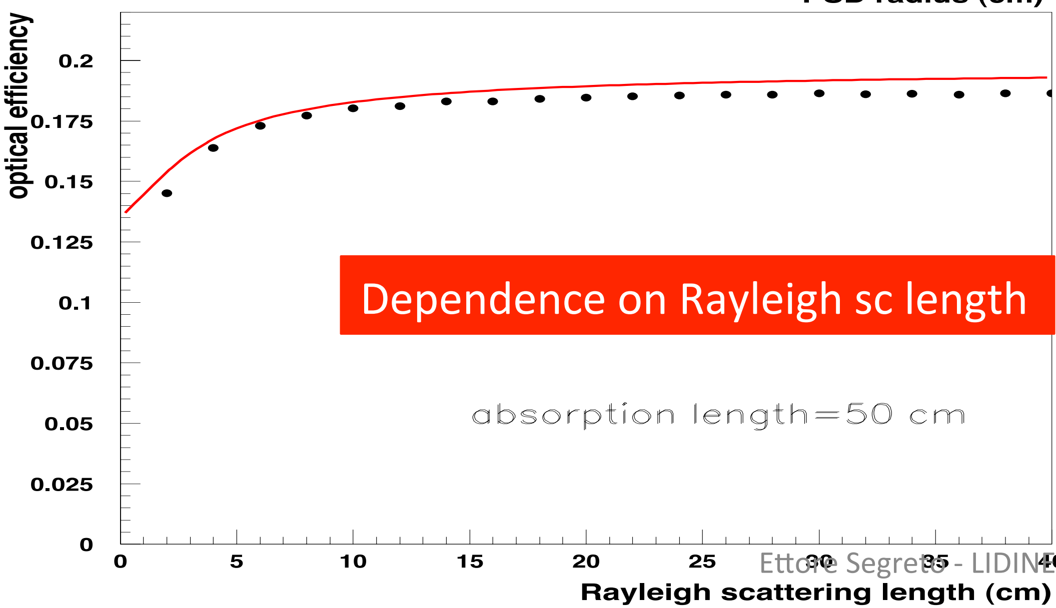




Monte Carlo tests of the model (scattering and absorption)



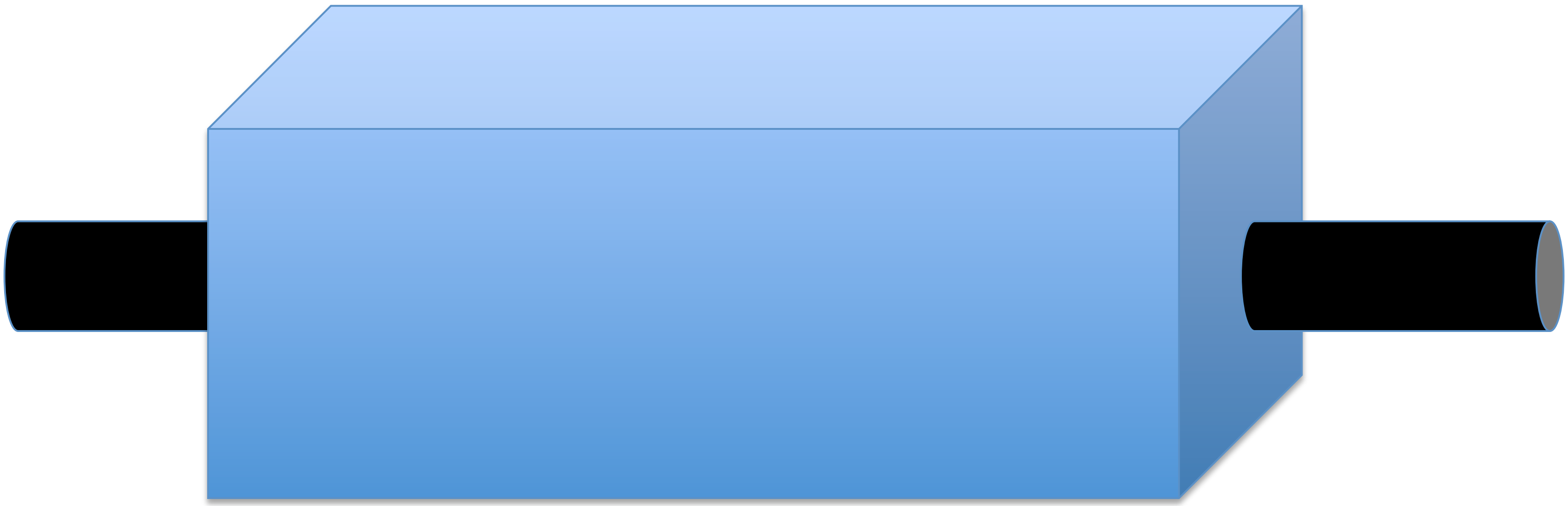
1 PSD
Specular reflectivity
R = 0.95
Rayleigh scattering = 10 cm



1 PSD
PSD radius = 4 cm
Specular reflectivity
R = 0.95
Absorption length = 50 cm

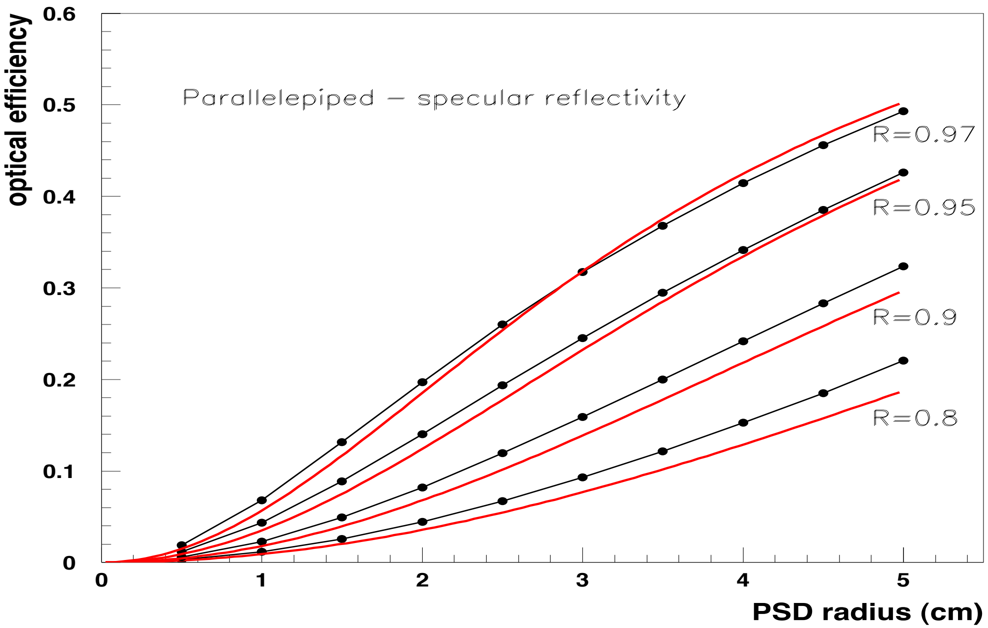
$$U_{RA} = \frac{\tilde{\lambda}}{\tilde{L}}\left(1 - e^{-\tilde{L}/\tilde{\lambda}}\right)$$

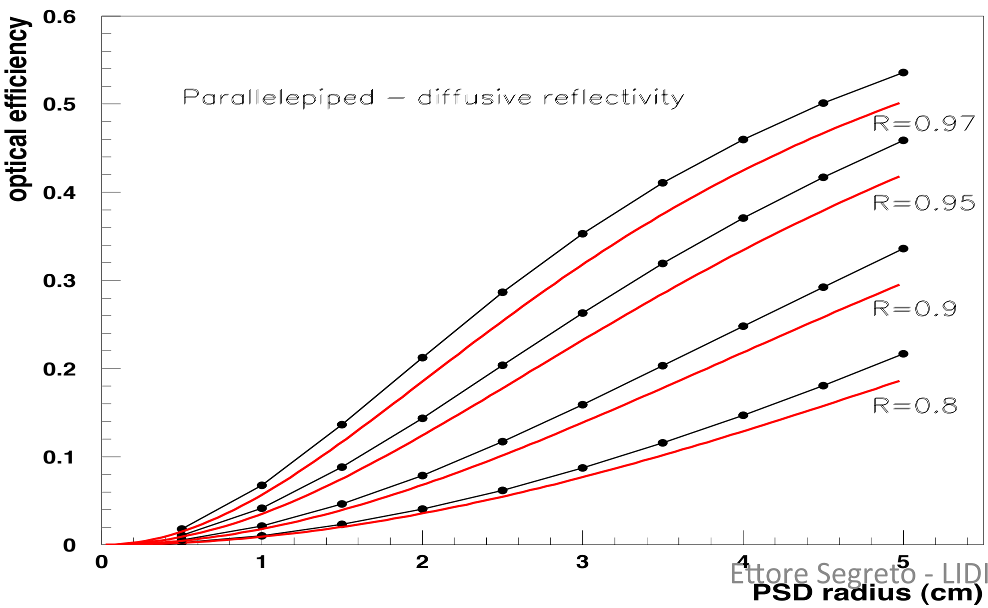
Monte Carlo tests of the model: Parallelepiped



- ✓ Parallelepiped 10 cm × 10 cm × 30 cm (l × w × h).
- ✓ 2 PSDs on the opposite faces
- ✓ Windows' reflectivity is set at 0.3 and transmissivity at 0.5 (as for the cubic scintillator)

Parallelepiped (cont.)





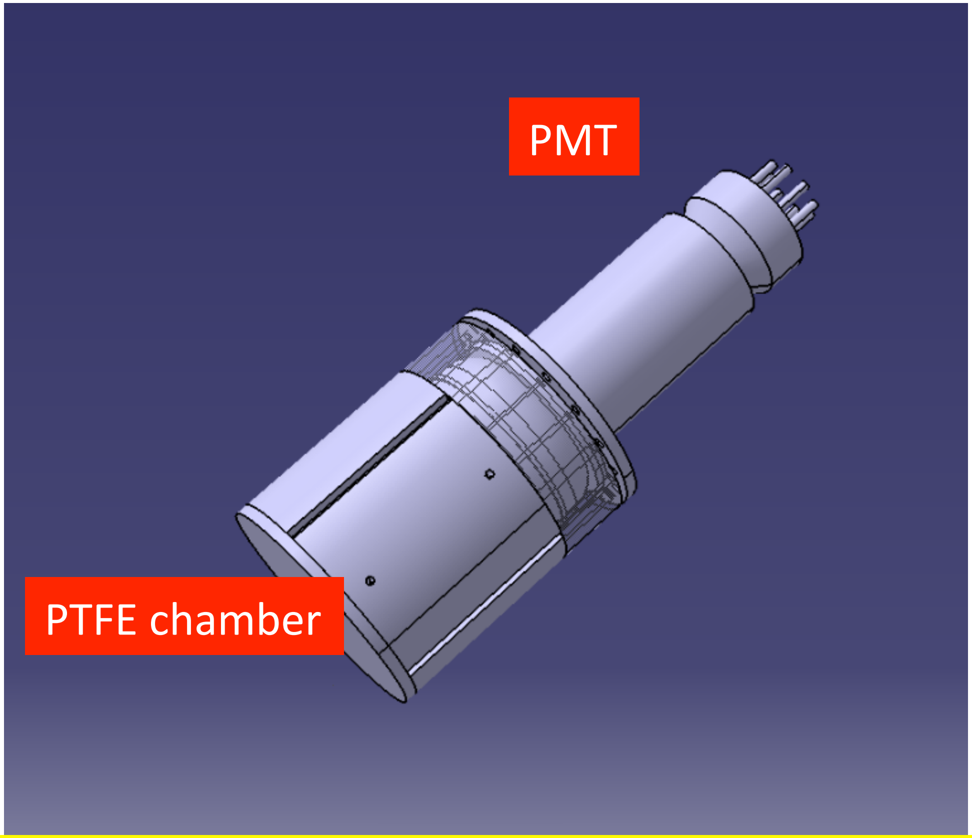
RED LINES :

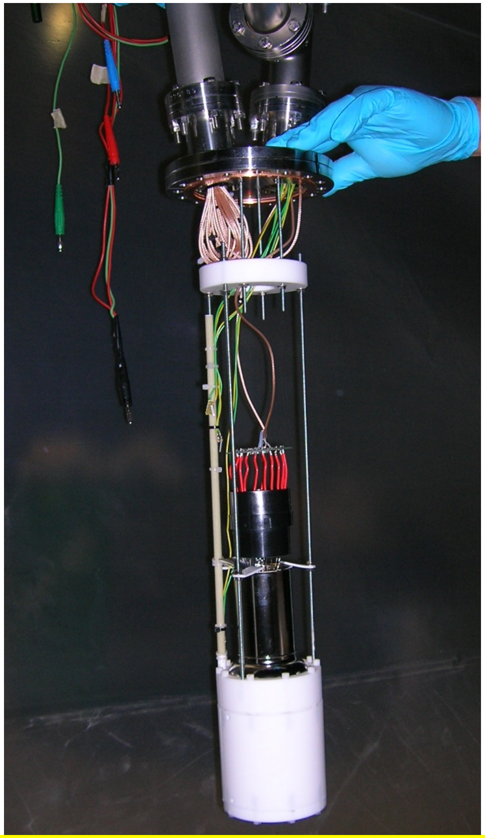
$$\varepsilon_{opt} = \frac{T_w f}{1 - R(1-f) - R_w f}$$

Extremely asymmetric detector

- ✓ Surprisingly good agreement between MC simulation and model outcomes
- ✓ For specular reflectivity, above 0.9, discrepancies at the level of few percent are found
- ✓ In all other cases they are of the order of 10%.

LY estimation of a real detector





LAr scintillation chamber - PTFE cell (h = 9.0 cm and φ = 8.4 cm) - observed by a single 3" photomultiplier (Hamamatsu R11065)
Internal surface of the cell completely covered with a reflective foil deposited with Tetra Phenyl Butadiene.

WARP Collaboration, *Demonstration and comparison of photomultiplier tubes at liquid Argon temperature*, 2012 JINST 7 P01016 [arXiv:1108.5584].

LY estimation of a real detector (I)

Parameters used for LY estimation

photon yield	$N_\gamma = 40$ photons/keV [11]
photocathodic coverage	$f = 13\%$
transmissivity of PMT window	$T_w = 0.94$ [12]
reflectivity of PMT window	$R_w = 0$
conversion efficiency of PMT	$\varepsilon_{PSD} = 28\%$
no absorption of VUV photons	$Q_{VUV} = 1$
no absorption of visible photons	$Q_{vis} = 1$
conversion efficiency of passive surface	$\varepsilon_{WLS} = 1$ [13]
conversion efficiency of PMT window (no shifter)	$\varepsilon_{wls} = 0.$
reflectivity of passive surface (reflector+TPB)	$R = 0.95$ [14]

LAr is assumed to be pure => no absorption (Q = 1)

Photons converted on the walls

$$LY_{estimated} = N_\gamma \varepsilon_{PSD} \varepsilon_{WLS}(1-f)\frac{T_w f}{1-R(1-f)} = 6.9\frac{phel}{keV}$$

$$LY_{measured} = 7\frac{phel}{keV} \pm 5\%$$

Conclusions

- A toy-model for the estimation of LY of a scintillation detector based on very simple hypotheses
- Easy to take into account effects related to Rayleigh scattering and absorption
- Model benchmarked with MC simulations of specific detectors => accuracy better than 10%
- Model applied to the estimation of the light yield of a real liquid Argon scintillation detector and a value of 6.9 phel/keV has been found => measured value 7.0 phel/keV ± 5%.
- Article published on *Journal of Instrumentation*:
  '*An analytic technique for the estimation of the light yield of a scintillation detector*', E. Segreto, *2012 JINST 7 P05008*