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Division of Nuclear Physics and Elementary Particles

PhoSim: A Simulation Package Designed for Macroscopic and Microscopic Studies In the Time-Resolved Optical Tomography

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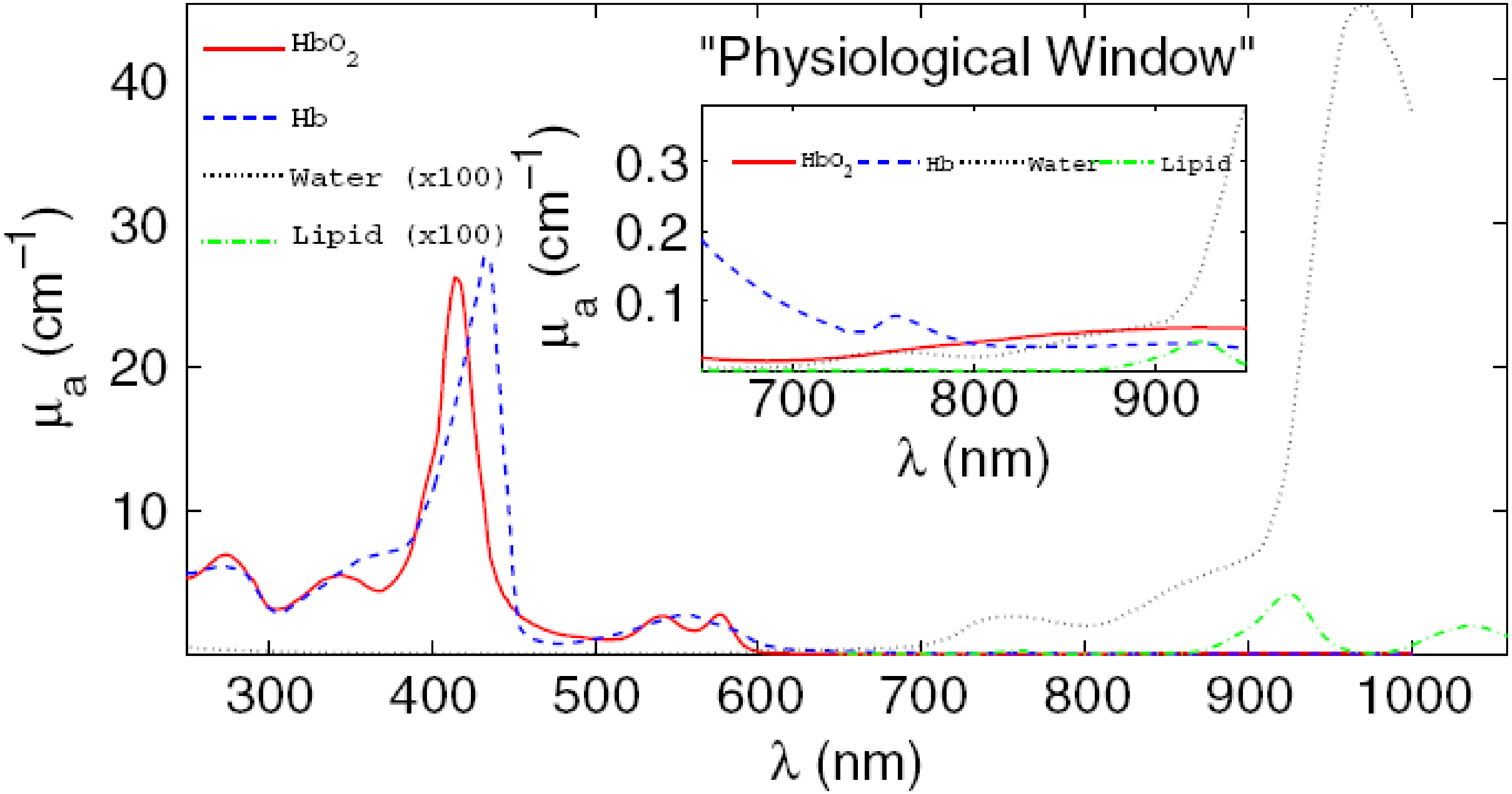
HINPw4 2017, University of Ioannina

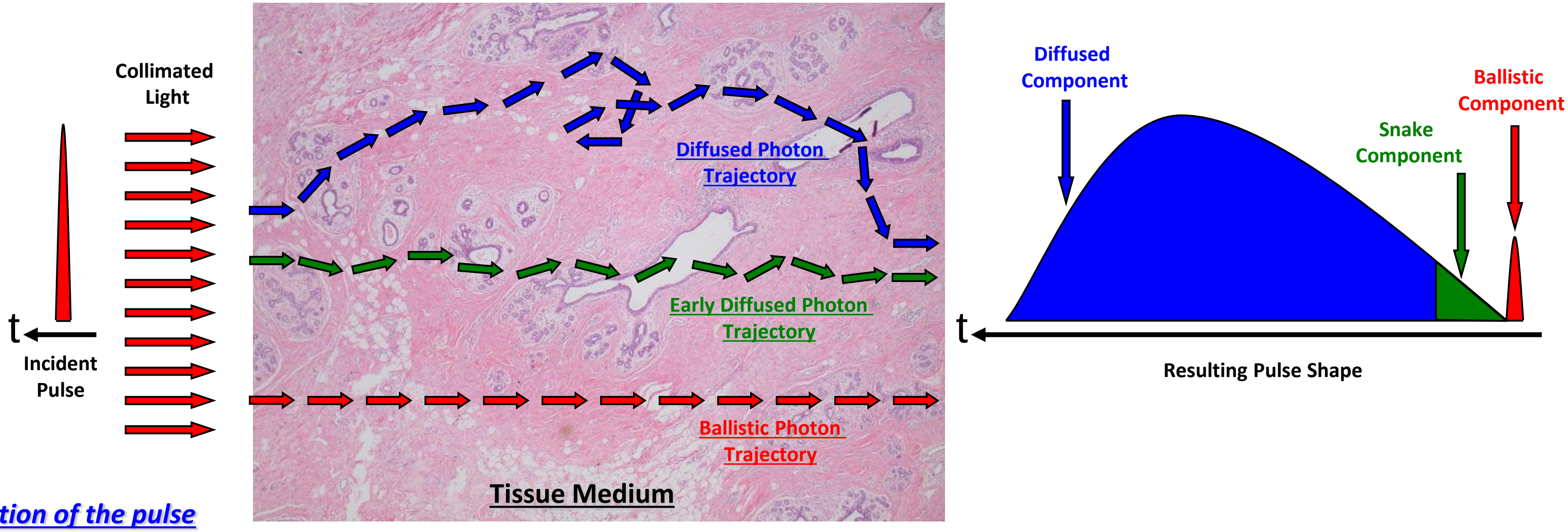
Principle of Optical Imaging

Discovery of the Physiological Window for the light absorption in tissues by Jöbsis (μ_{α}, absorption coefficient)



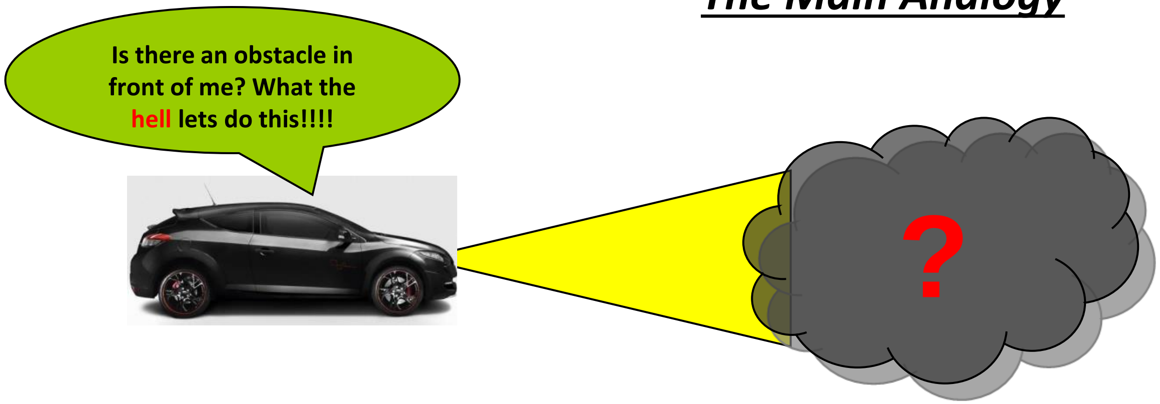
Jobsis, F.F. (1977). *Noninvasive infrared monitoring of cerebral and myocardial sufficiency and circulatory parameters. Science 198, 1264-1267.*

Time-Resolved Photon Propagation



[The duration of the pulse depends on the physical width of the medium under investigation!!!]

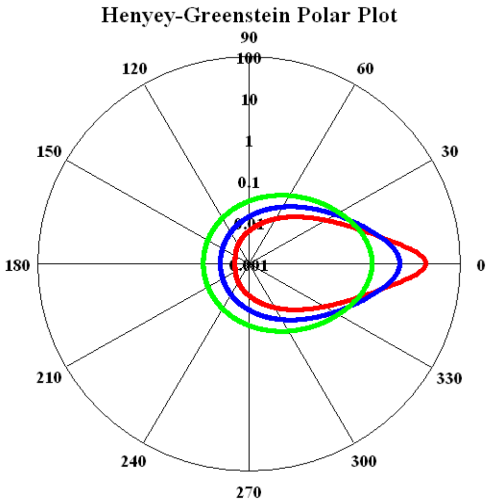
The Main Analogy



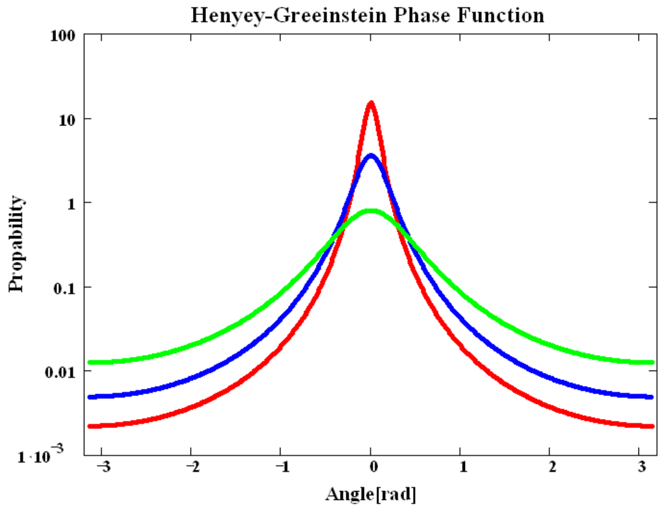
PhoSim an Algorithm Dedicated to TROT Modalities

- ***PhoSim***, *can* resolve the Mie multiple scattering problem by utilizing the Henyey-Greenstein Phase Function.
- This is extremely useful, since it only depends on one parameter g (-1≤g≤1), that represents the average cosine of scattering.

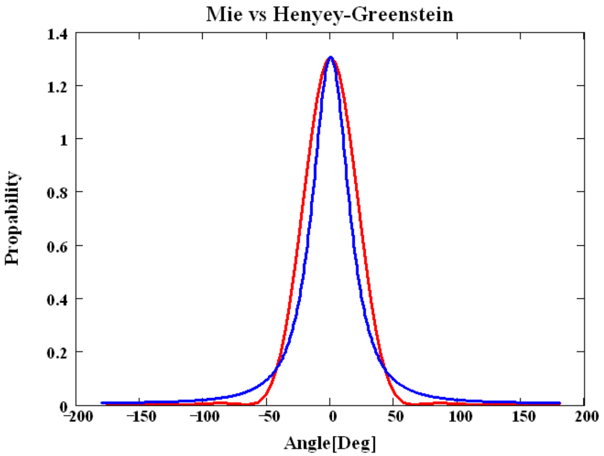
$$P(\theta) = \frac{1}{4\pi} \frac{1-g^2}{\left[1+g^2-2g\cos\theta\right]^{3/2}}$$



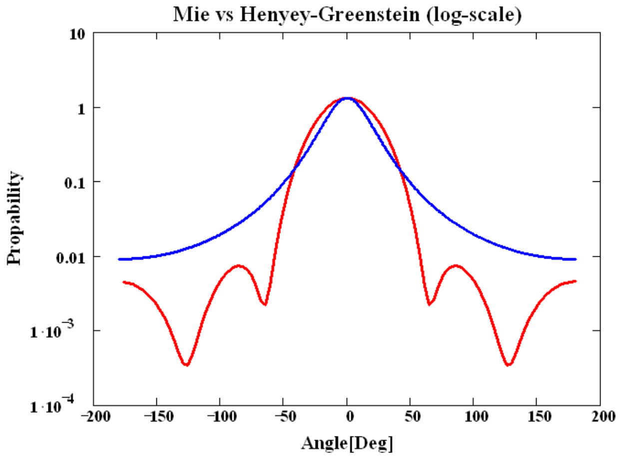
Henyey-Greenstein Polar Plot



Henyey-Greeinstein Phase Function



Mie vs Henyey-Greenstein

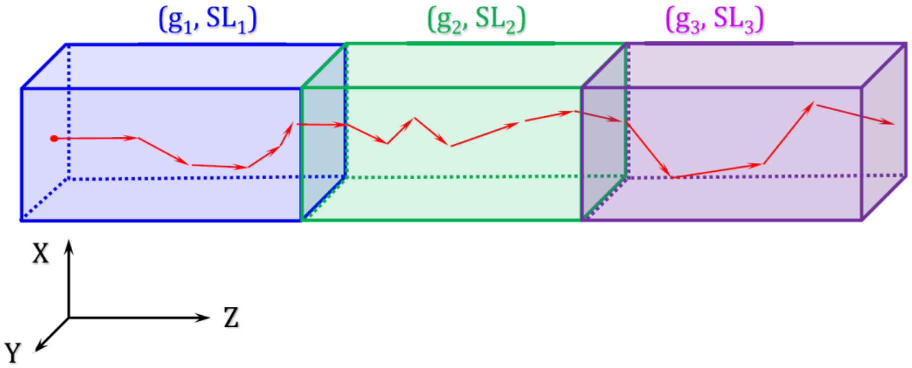


Mie vs Henyey-Greenstein (log-scale)

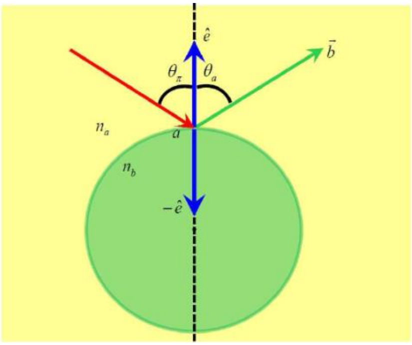
PhoSim's capabilities

- **Creation of multi-layer (tissue) environments:**

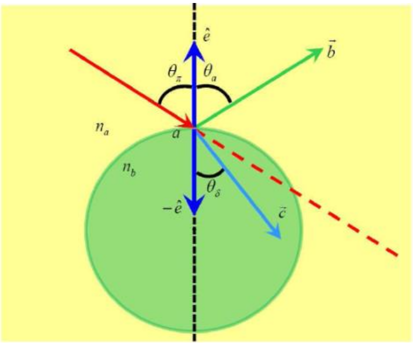
  Variation of the g parameter, the Scattering Length (SL) and the index of refraction n_i for propagation areas.



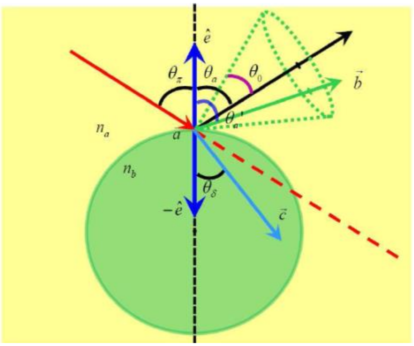
- **Insertion of optical spherical objects:**



Perfect reflectors



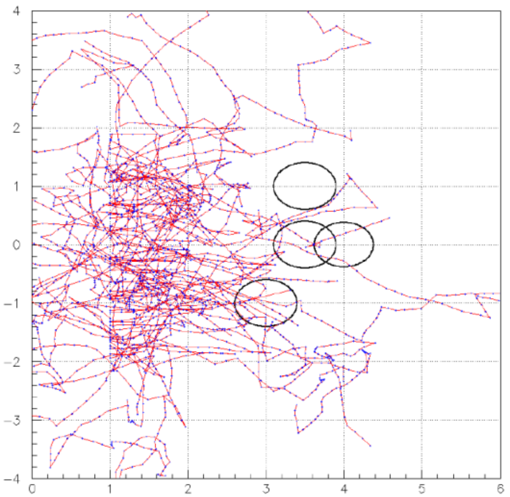
Classical Optical Objects

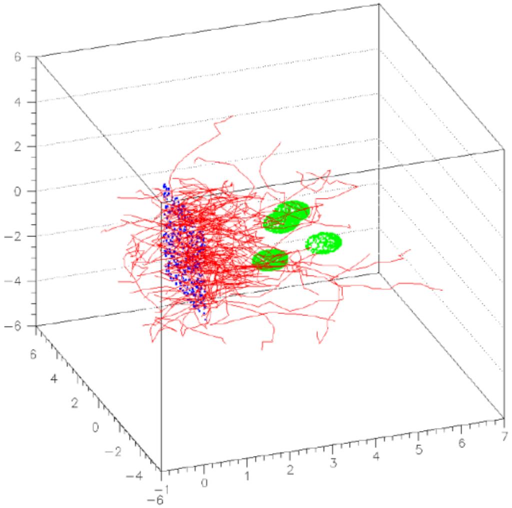


Diffusers

- **Ray-tracing:**

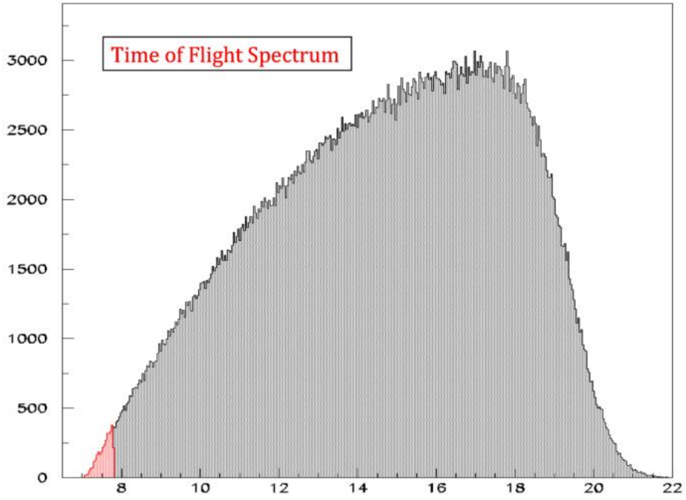
  PhoSim can ray-trace every event throughout the different simulated tissue materials.





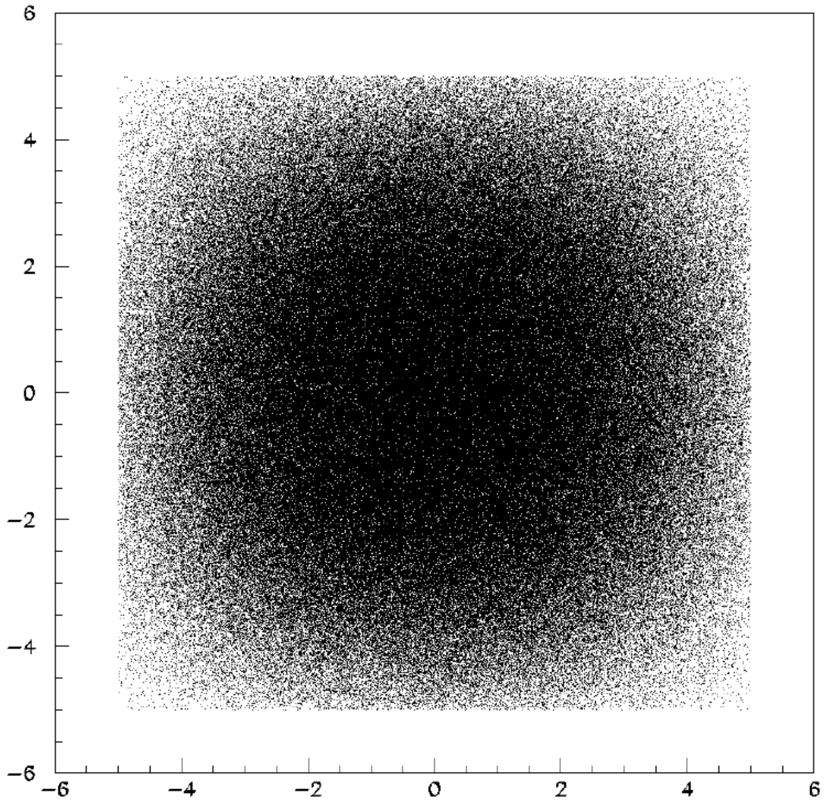
- **Time-of-Flight (ToF) Information:**

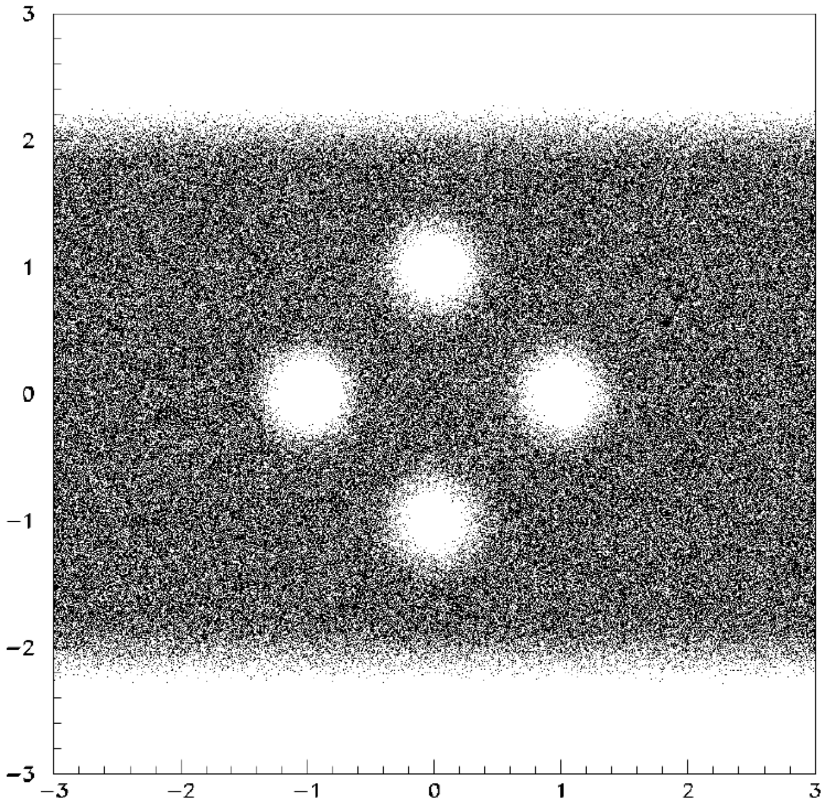
  Calculates the (ToF) for each photon using its optical path segments and the refraction index of the medium.

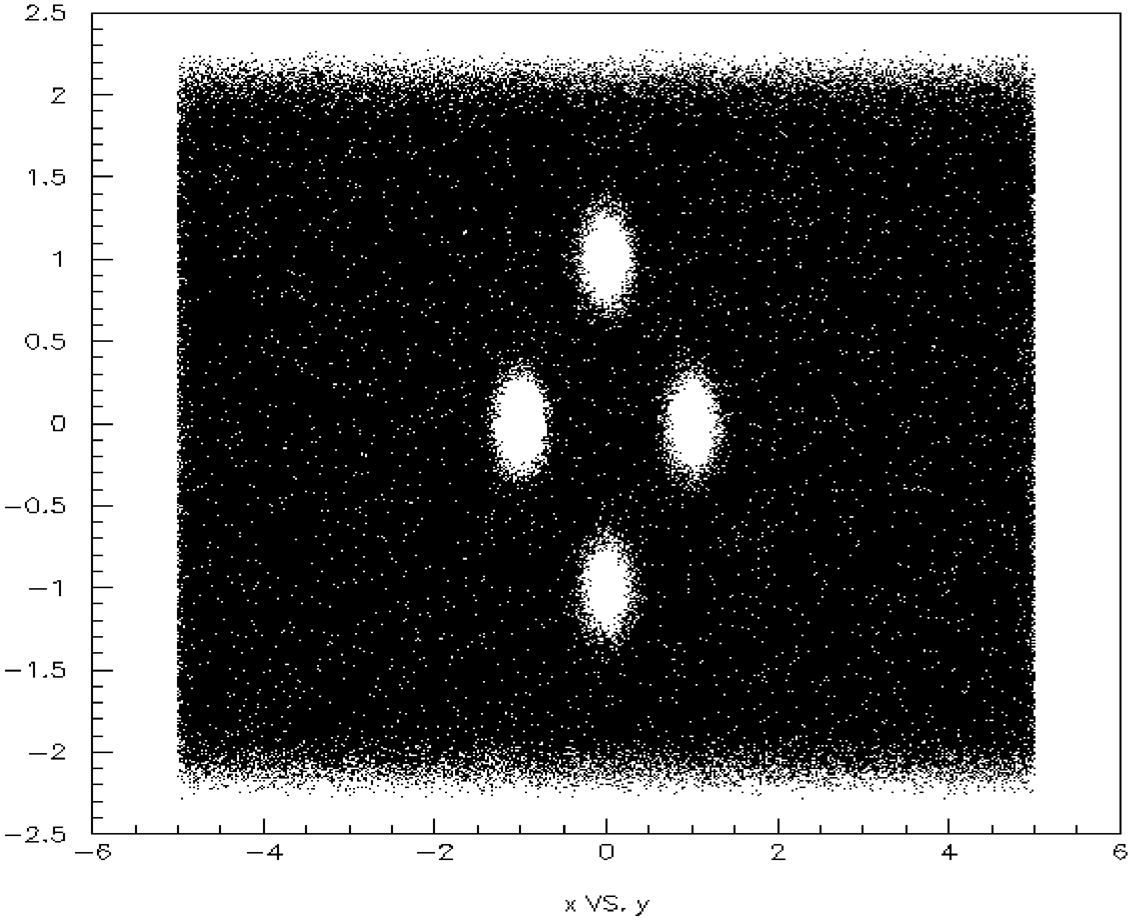


PLANAR IMAGING AND TOMOGRAPHIC CAPABILITIES

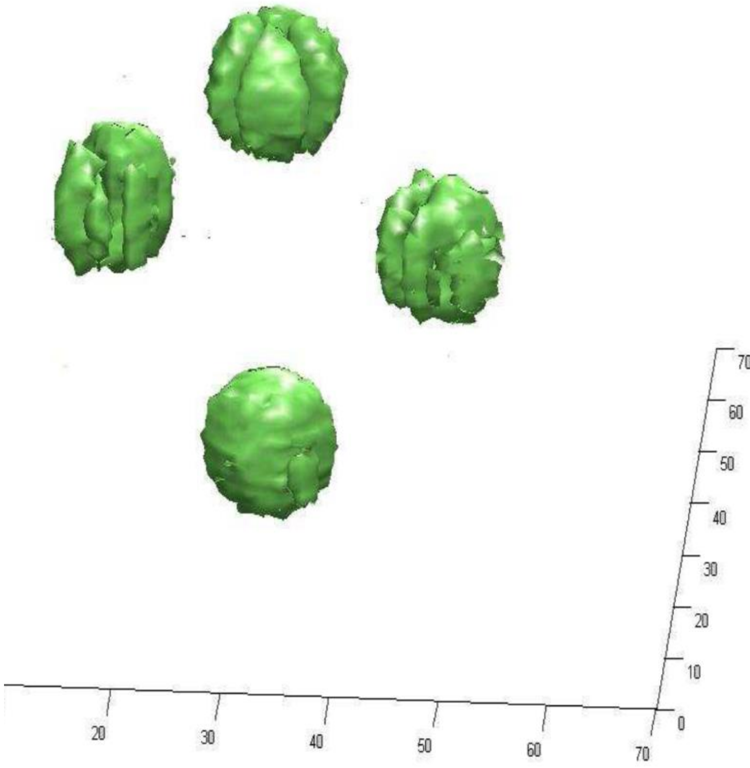
- The Time of Flight information provided for simulated rays allows a proper event filtering on the detected data (planar images).







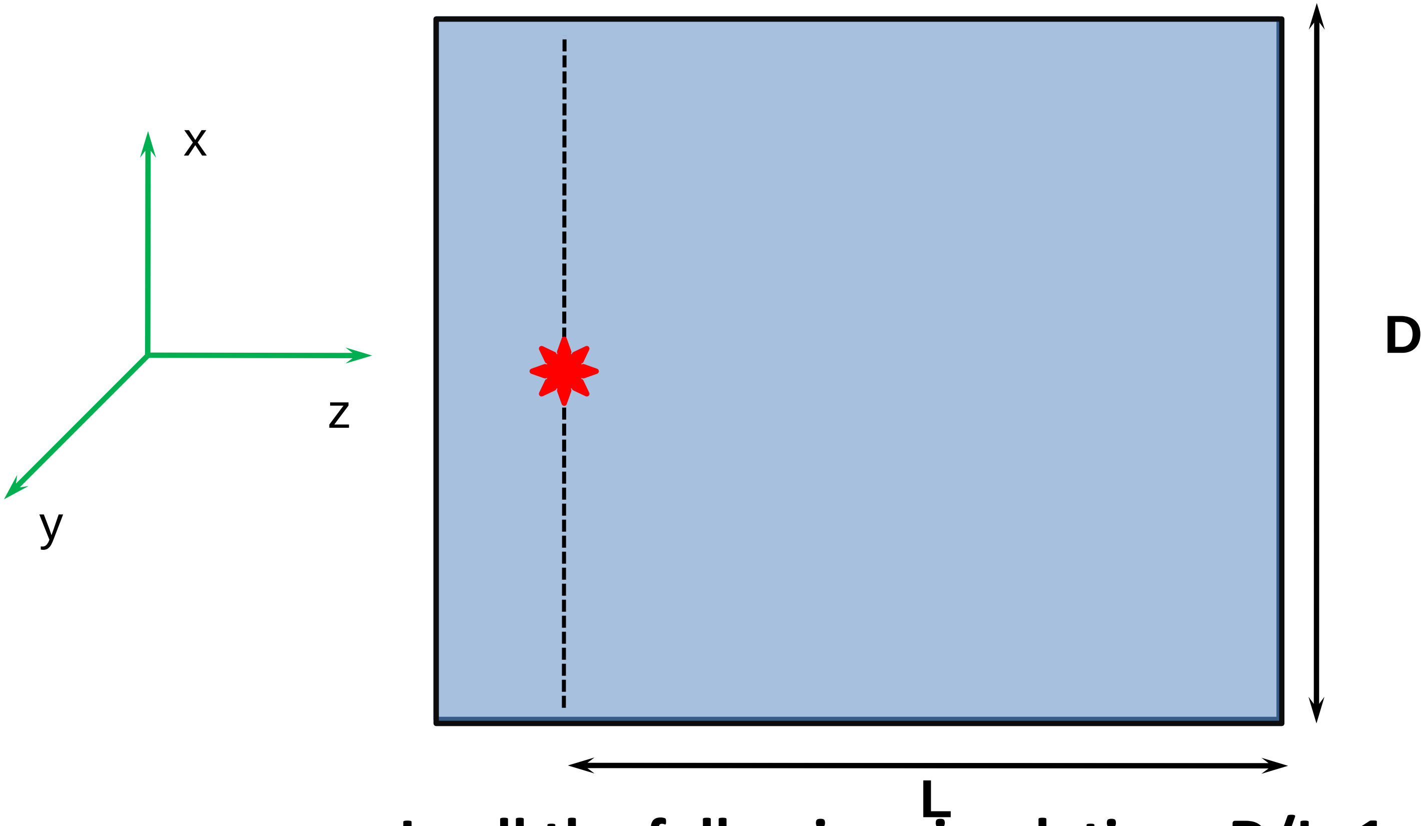
Planar Images



3D Reconstruction

Efficiency Measurements For Point Source

Efficiency = ε = N_{int}/N_{det}



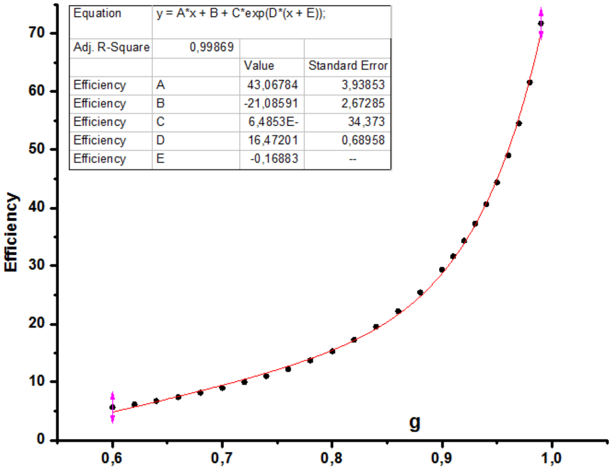
In all the following simulations D/L=1

and the

Total number of photons initiated: 1000000

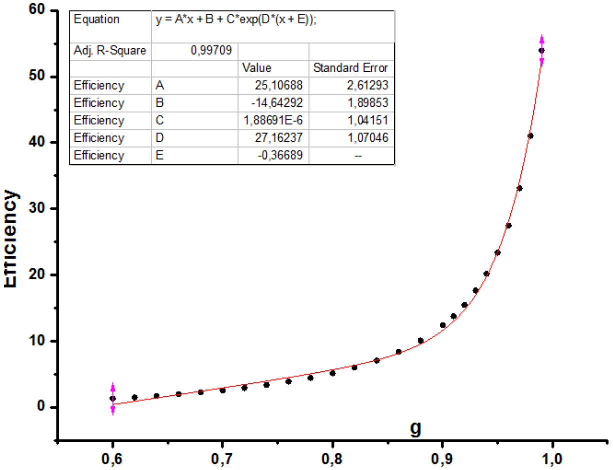
Efficiency vs g-Factor

05 Scatterings



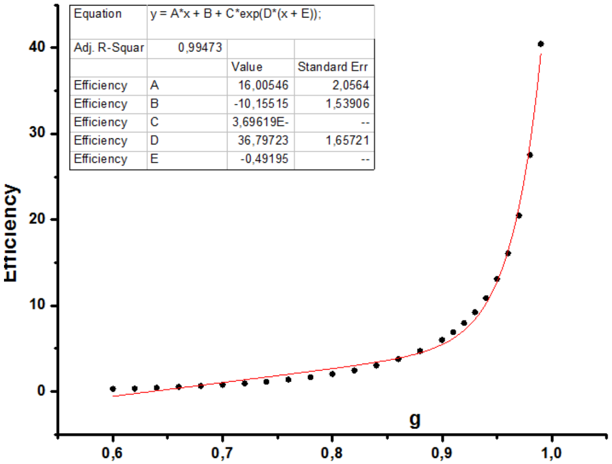
Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99869		
		Value	Standard Error
Efficiency	A	43,06784	3,93853
Efficiency	B	-21,08591	2,67285
Efficiency	C	6,4853E-	34,373
Efficiency	D	16,47201	0,68958
Efficiency	E	-0,16883	--

10 Scatterings



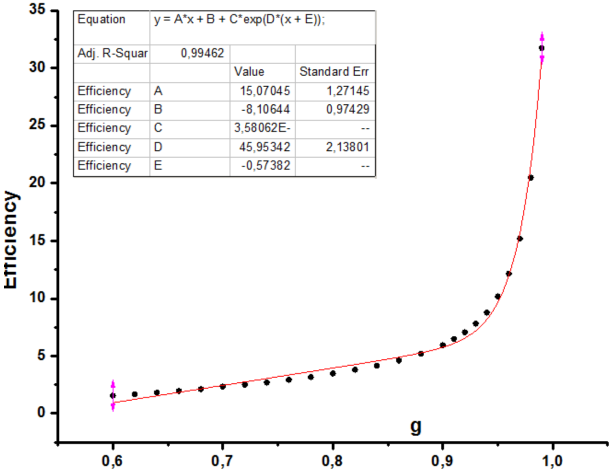
Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99709		
		Value	Standard Error
Efficiency	A	25,10688	2,61293
Efficiency	B	-14,64292	1,89853
Efficiency	C	1,88691E-6	1,04151
Efficiency	D	27,16237	1,07046
Efficiency	E	-0,36689	--

15 Scatterings



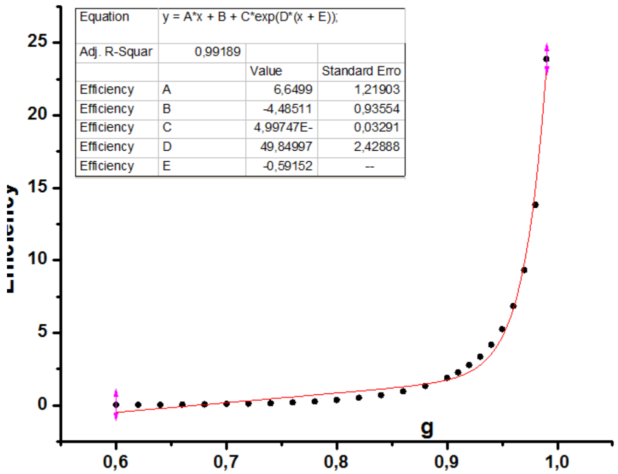
Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Squar	0,99473		
		Value	Standard Err
Efficiency	A	16,00546	2,0564
Efficiency	B	-10,15515	1,53906
Efficiency	C	3,69619E-	--
Efficiency	D	36,79723	1,65721
Efficiency	E	-0,49195	--

20 Scatterings



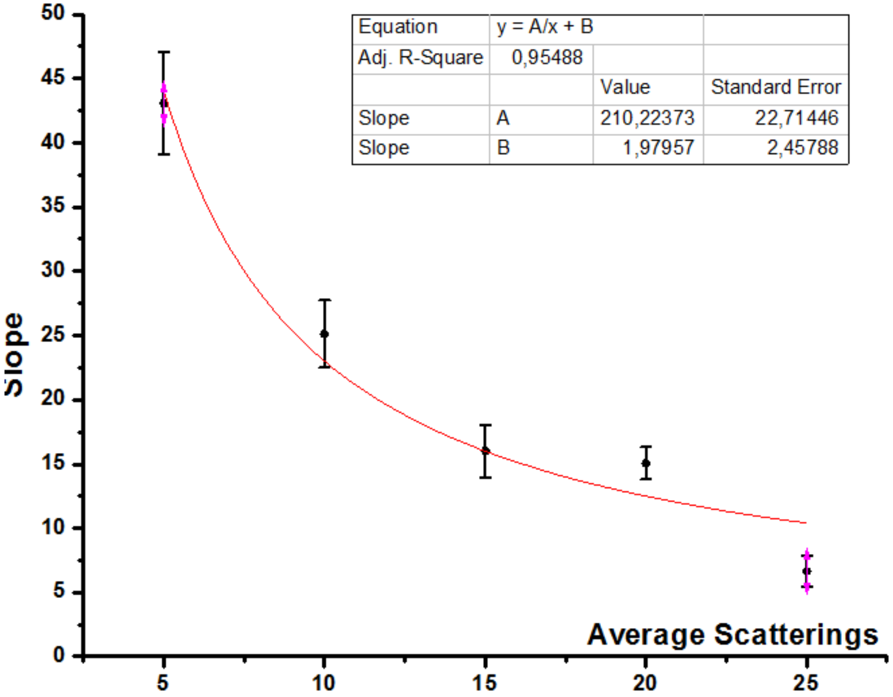
Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Squar	0,99462		
		Value	Standard Err
Efficiency	A	15,07045	1,27145
Efficiency	B	-8,10644	0,97429
Efficiency	C	3,58062E-	--
Efficiency	D	45,95342	2,13801
Efficiency	E	-0,57382	--

25 Scatterings



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Squar	0,99189		
		Value	Standard Erro
Efficiency	A	6,6499	1,21903
Efficiency	B	-4,48511	0,93554
Efficiency	C	4,99747E-	0,03291
Efficiency	D	49,84997	2,42888
Efficiency	E	-0,59152	--

Slope Vs Average Numbers of Scattering

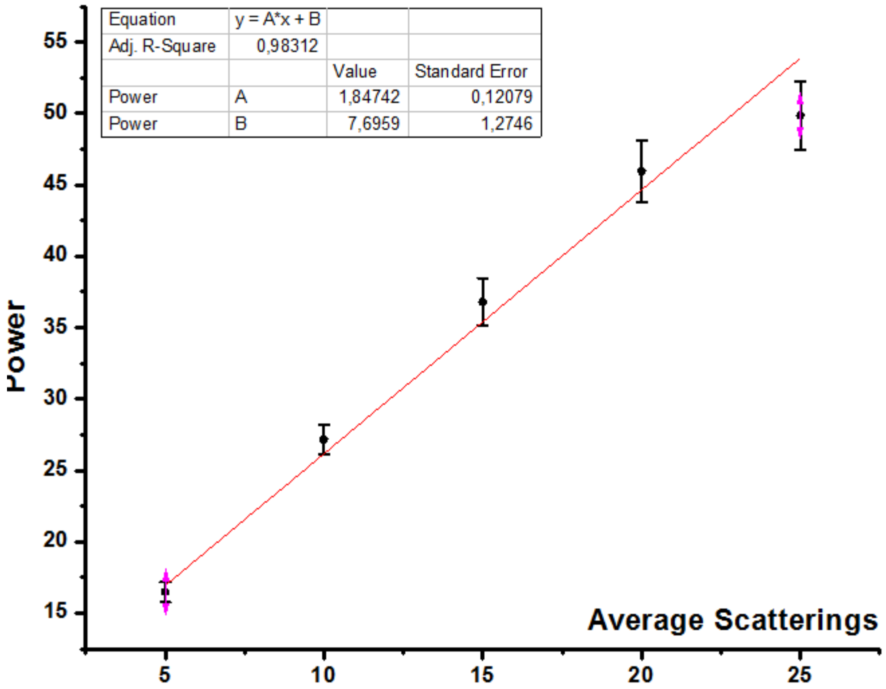


Equation	y = A/x + B		
Adj. R-Square	0,95488		
		Value	Standard Error
Slope	A	210,22373	22,71446
Slope	B	1,97957	2,45788

Slope (**A**) depicted in each of the previous graphical fits vs the Average Number of Scattering.

The best fitting curve in this case was:
y = A/x + B

Power Vs Average Numbers of Scattering



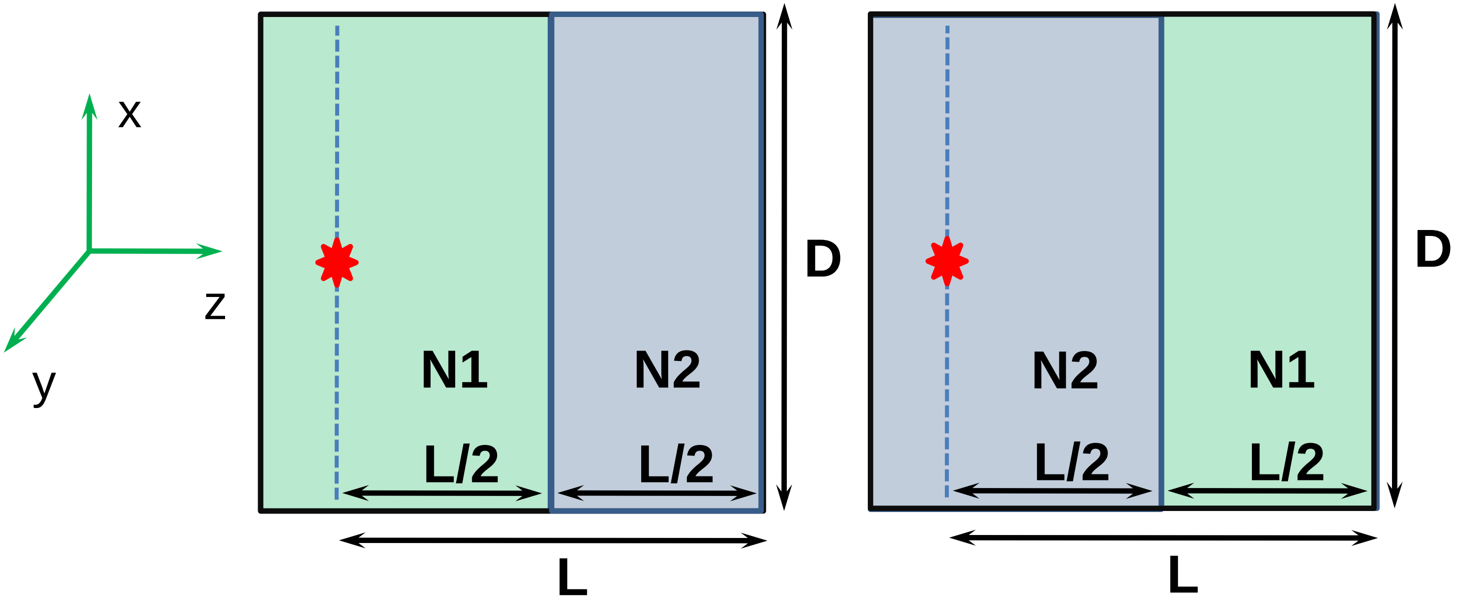
Equation	y = A*x + B		
Adj. R-Square	0,98312		
		Value	Standard Error
Power	A	1,84742	0,12079
Power	B	7,6959	1,2746

Power of the exponential (**D**) depicted in each of the previous graphical fits vs the Average Number of Scattering.

The best fitting curve in this case was a linear equation: **y = Ax + B**

Efficiency Measurements for Two Volumes

- Efficiency calculation of two different materials for the same **g** but for different scattering lengths **SL_1** and **SL_2** .
- For the fist volume the average number of scatterings **N_1** was the 40% of the total ones **N**.
- The efficiency was also calculated when the volumes where commuted as depicted in the following picture.



In all the following simulations D/L=1

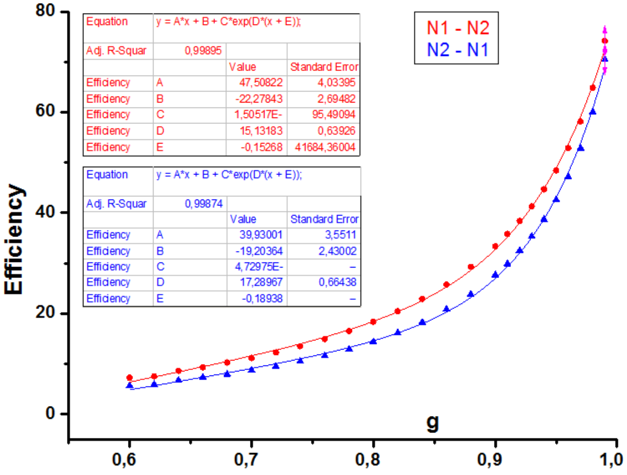
and the

Total number of photons initiated: 1000000

Efficiency vs g-Factor for Interchanged Volumes

Different Scattering Lengths

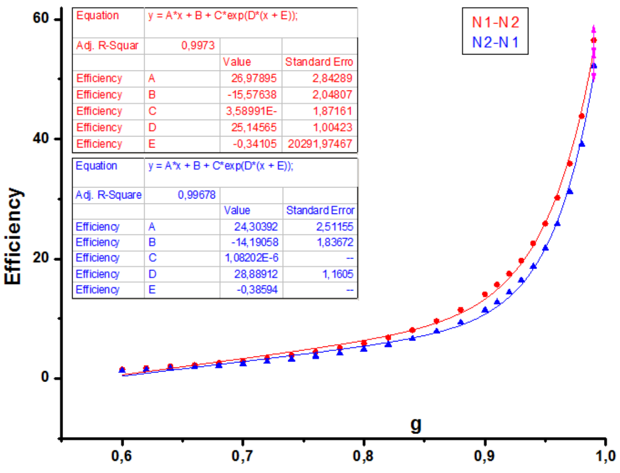
$N_1 = 2 \quad N_2 = 3$



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Squar	0,99895		
		Value	Standard Error
Efficiency	A	47,50822	4,03395
Efficiency	B	-22,27843	2,69482
Efficiency	C	1,50517E-	95,49094
Efficiency	D	15,13183	0,63926
Efficiency	E	-0,15268	41684,36004

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Squar	0,99874		
		Value	Standard Error
Efficiency	A	39,93001	3,5511
Efficiency	B	-19,20364	2,43002
Efficiency	C	4,72975E-	–
Efficiency	D	17,28967	0,66438
Efficiency	E	-0,18938	–

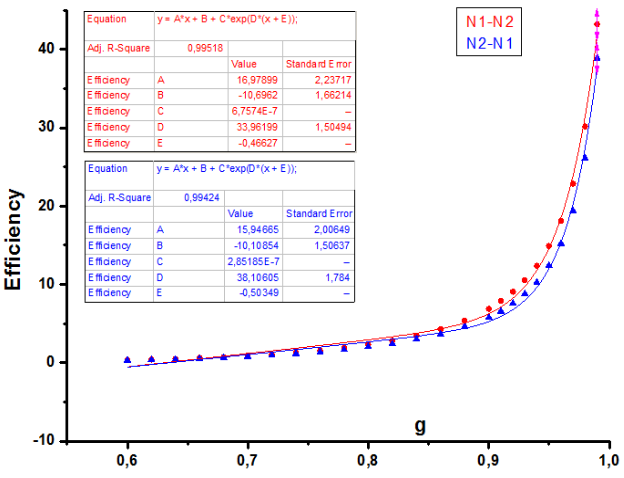
$N_1 = 4 \quad N_2 = 6$



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Squar	0,9973		
		Value	Standard Erro
Efficiency	A	26,97895	2,84289
Efficiency	B	-15,57638	2,04807
Efficiency	C	3,58991E-	1,87161
Efficiency	D	25,14565	1,00423
Efficiency	E	-0,34105	20291,97467

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99678		
		Value	Standard Error
Efficiency	A	24,30392	2,51155
Efficiency	B	-14,19058	1,83672
Efficiency	C	1,08202E-6	--
Efficiency	D	28,88912	1,1605
Efficiency	E	-0,38594	--

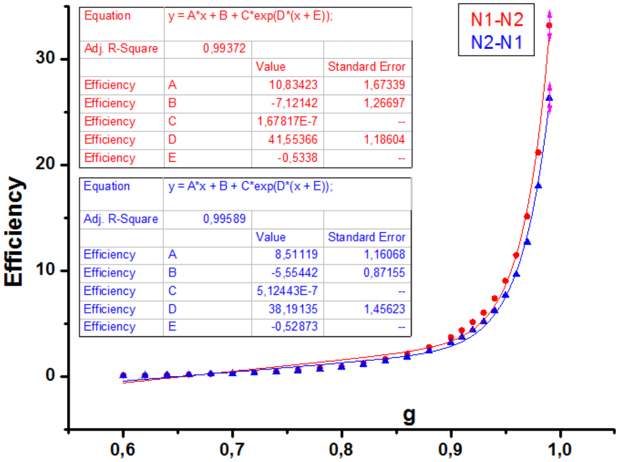
$N_1 = 6 \quad N_2 = 9$



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99518		
		Value	Standard Error
Efficiency	A	16,97899	2,23717
Efficiency	B	-10,6962	1,66214
Efficiency	C	6,7574E-7	–
Efficiency	D	33,96199	1,50494
Efficiency	E	-0,46627	–

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99424		
		Value	Standard Error
Efficiency	A	15,94665	2,00649
Efficiency	B	-10,10854	1,50637
Efficiency	C	2,85185E-7	–
Efficiency	D	38,10605	1,784
Efficiency	E	-0,50349	–

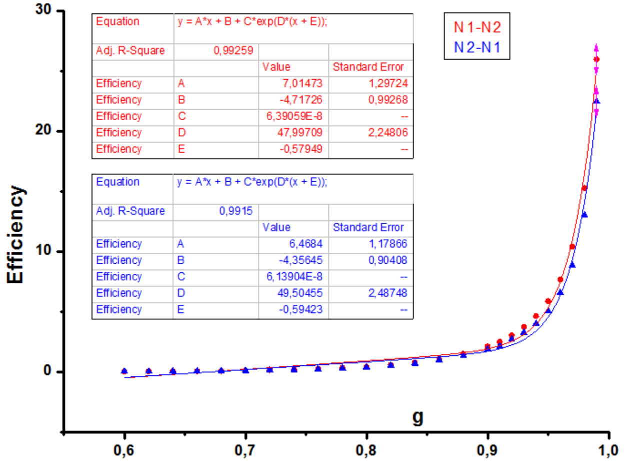
$N_1 = 8 \quad N_2 = 12$



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99372		
		Value	Standard Error
Efficiency	A	10,83423	1,67339
Efficiency	B	-7,12142	1,26697
Efficiency	C	1,67817E-7	--
Efficiency	D	41,55366	1,18604
Efficiency	E	-0,5338	--

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99589		
		Value	Standard Error
Efficiency	A	8,51119	1,16068
Efficiency	B	-5,55442	0,87155
Efficiency	C	5,12443E-7	--
Efficiency	D	38,19135	1,45623
Efficiency	E	-0,52873	--

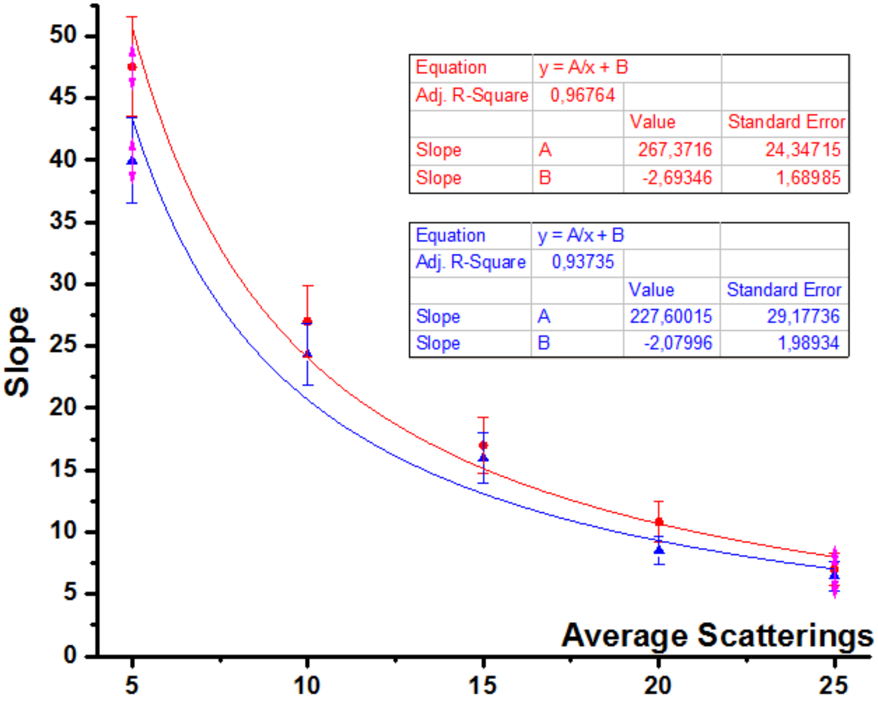
$N_1 = 10 \quad N_2 = 15$



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99259		
		Value	Standard Error
Efficiency	A	7,01473	1,29724
Efficiency	B	-4,71726	0,99268
Efficiency	C	6,39059E-8	--
Efficiency	D	47,99709	2,24806
Efficiency	E	-0,57949	--

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,9915		
		Value	Standard Error
Efficiency	A	6,4684	1,17866
Efficiency	B	-4,35645	0,90408
Efficiency	C	6,13904E-8	--
Efficiency	D	49,50455	2,48748
Efficiency	E	-0,59423	--

Slope Vs Average Numbers of Scattering



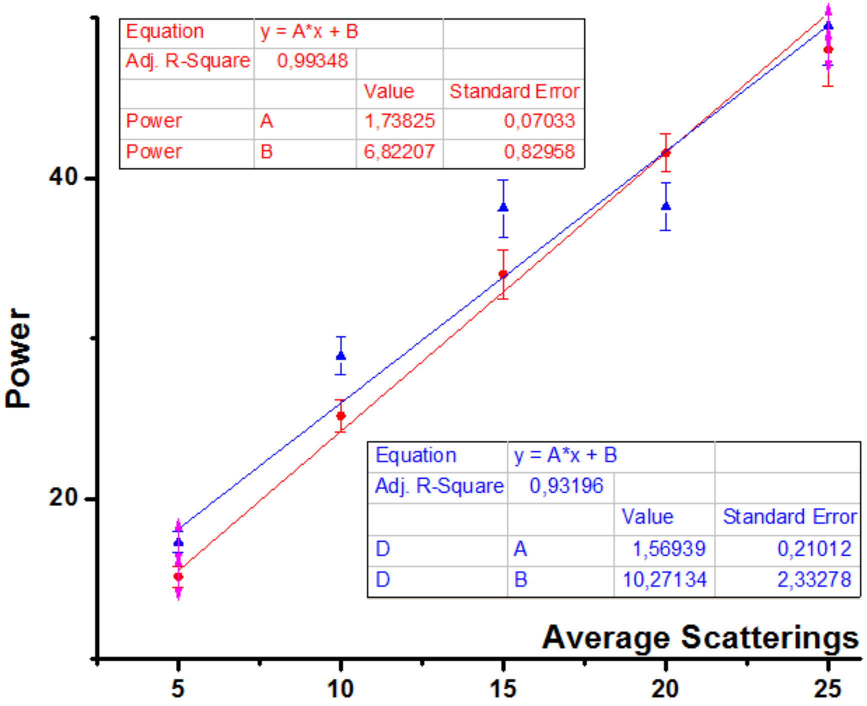
Equation	y = A/x + B		
Adj. R-Square	0,96764		
		Value	Standard Error
Slope	A	267,3716	24,34715
Slope	B	-2,69346	1,68985

Equation	y = A/x + B		
Adj. R-Square	0,93735		
		Value	Standard Error
Slope	A	227,60015	29,17736
Slope	B	-2,07996	1,98934

The best fitting curve in this case was:

y = A/x + B

Power Vs Average Numbers of Scattering



Equation	y = A*x + B		
Adj. R-Square	0,99348		
		Value	Standard Error
Power	A	1,73825	0,07033
Power	B	6,82207	0,82958

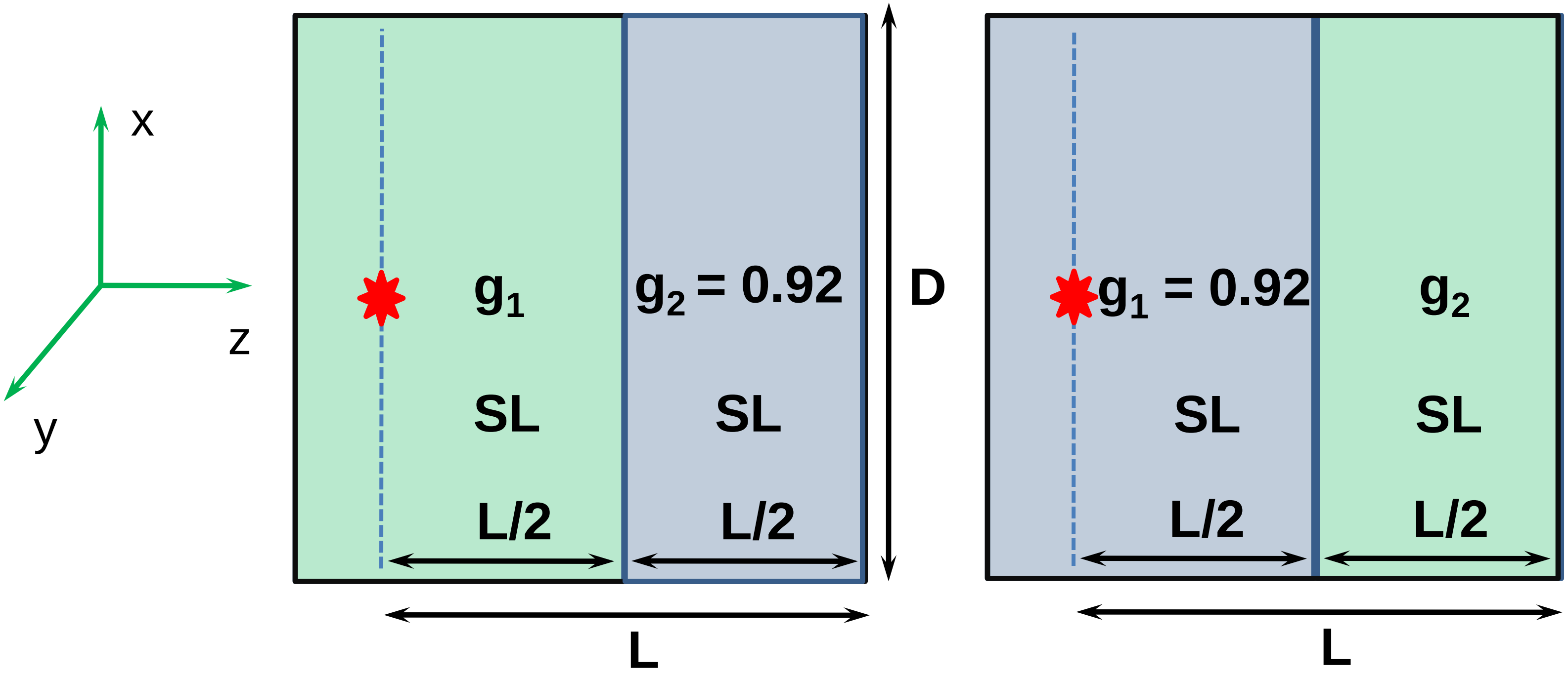
Equation	y = A*x + B		
Adj. R-Square	0,93196		
		Value	Standard Error
D	A	1,56939	0,21012
D	B	10,27134	2,33278

The best fitting curve in this case was a linear equation:

y = Ax + B

Efficiency Measurements for Two Volumes

- Efficiency calculation for two different materials having always the same scattering lengths **SL_1 = SL_2** but for different average cosines **g_1** and **g_2**. (for simplicity we keep the average cosine in one of the two volumes constant with 0.92).
- With red color charts correspond to the first case scenario (left) depicted in the figure wile the blue ones to the second.



<u>In all the following simulations D/L=1</u>

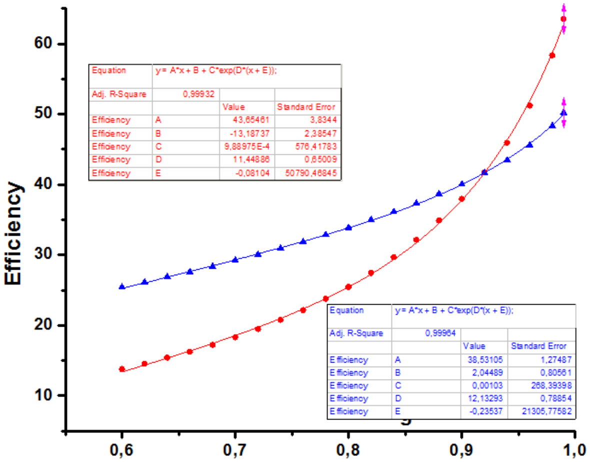
and the

Total number of photons initiated: 1000000

Efficiency vs g-Factor for Interchanged Volumes

Same Scattering Lengths

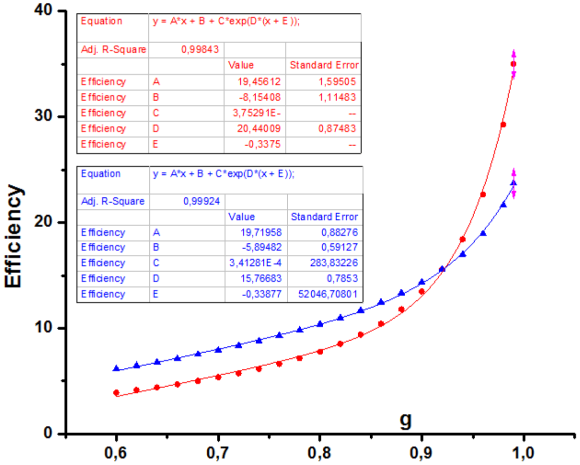
05 Scatterings



Equation	y= A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99932		
		Value	Standard Error
Efficiency	A	43,65461	3,8344
Efficiency	B	-13,18737	2,38547
Efficiency	C	9,88975E-4	576,41783
Efficiency	D	11,44886	0,65009
Efficiency	E	-0,08104	50790,46845

Equation	y= A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99964		
		Value	Standard Error
Efficiency	A	38,53105	1,27487
Efficiency	B	2,04489	0,80561
Efficiency	C	0,00103	268,39398
Efficiency	D	12,13293	0,78854
Efficiency	E	-0,23537	21305,77582

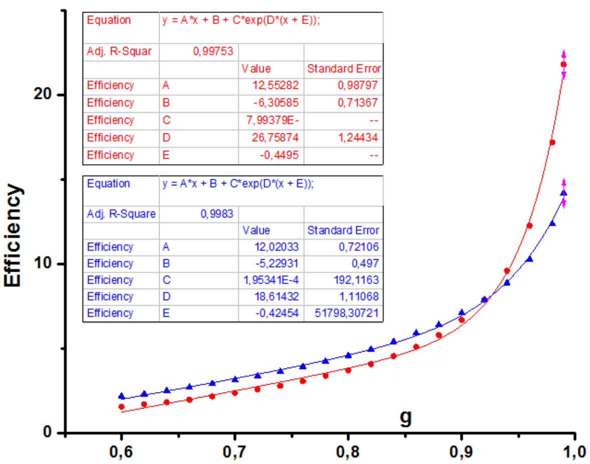
10 Scatterings



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99843		
		Value	Standard Error
Efficiency	A	19,45612	1,59505
Efficiency	B	-8,15408	1,11483
Efficiency	C	3,75291E-	--
Efficiency	D	20,44009	0,87483
Efficiency	E	-0,3375	--

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99924		
		Value	Standard Error
Efficiency	A	19,71958	0,88276
Efficiency	B	-5,89482	0,59127
Efficiency	C	3,41281E-4	283,83226
Efficiency	D	15,76683	0,7853
Efficiency	E	-0,33877	52046,70801

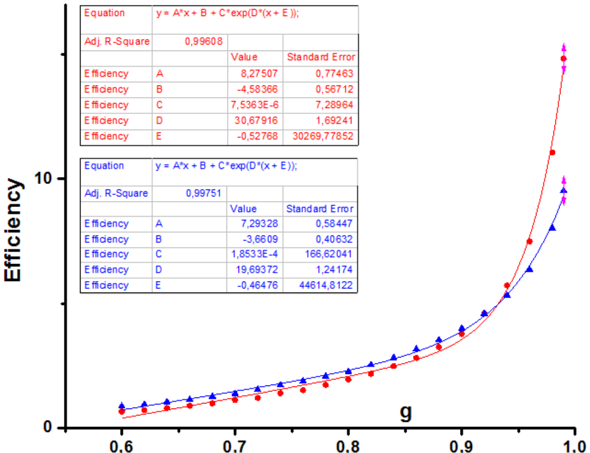
15 Scatterings



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Squar	0,99753		
		Value	Standard Error
Efficiency	A	12,55282	0,98797
Efficiency	B	-6,30585	0,71367
Efficiency	C	7,99379E-	--
Efficiency	D	26,75874	1,24434
Efficiency	E	-0,4495	--

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,9983		
		Value	Standard Error
Efficiency	A	12,02033	0,72106
Efficiency	B	-5,22931	0,497
Efficiency	C	1,95341E-4	192,1163
Efficiency	D	18,61432	1,11068
Efficiency	E	-0,42454	51798,30721

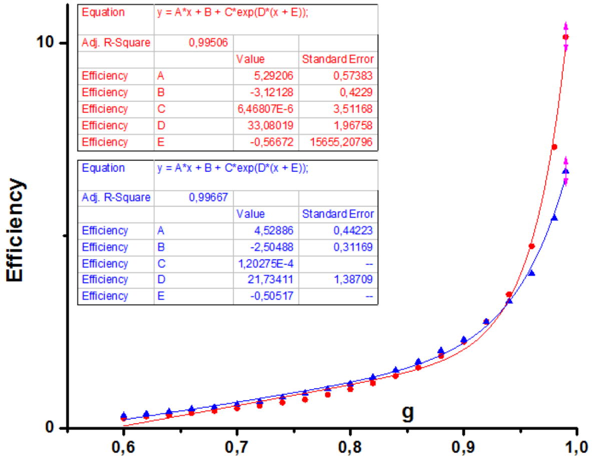
20 Scatterings



Equation	y= A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99608		
		Value	Standard Error
Efficiency	A	8,27507	0,77463
Efficiency	B	-4,58366	0,56712
Efficiency	C	7,5363E-6	7,28964
Efficiency	D	30,67916	1,69241
Efficiency	E	-0,52768	30269,77852

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99751		
		Value	Standard Error
Efficiency	A	7,29328	0,58447
Efficiency	B	-3,6609	0,40632
Efficiency	C	1,8533E-4	166,62041
Efficiency	D	19,69372	1,24174
Efficiency	E	-0,46476	44614,8122

25 Scatterings



Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99506		
		Value	Standard Error
Efficiency	A	5,29206	0,57383
Efficiency	B	-3,12128	0,4229
Efficiency	C	6,46807E-6	3,51168
Efficiency	D	33,08019	1,96758
Efficiency	E	-0,56672	15655,20796

Equation	y = A*x + B + C*exp(D*(x + E));		
Adj. R-Square	0,99667		
		Value	Standard Error
Efficiency	A	4,52886	0,44223
Efficiency	B	-2,50488	0,31169
Efficiency	C	1,20275E-4	--
Efficiency	D	21,73411	1,38709
Efficiency	E	-0,50517	--

Results and Discussion

- We can observe that the efficiency, in every case, follows an exponential declination for high values of **g** (0.99 → 0.88) and for the lower values (**g** < 0.88), a linear declination despite the average number of scattering (ANoS) or the orientation of different materials used. Therefore it is safe to use the following function

$$\varepsilon = Ag + B + Ce^{D(g+E)}$$

in order to approximate our results and thus derive a general rule that we could use. Where **ε** is the efficiency and **g** is the average cosine, all the other (A, B, C, D, E) are constants to be calculated.

- Another important discovery derived from the second and the third simulation cases:

If a two layer volume (and it is safe to guess, a higher layered one) is to be probed by near infrared radiation in order to increase the detection efficiency the area with the fewer ANoS or the greater **g** value or the one with the better combination of **g** and ANoS leading to less diffusion, must be used as the starting point.

Ευχαριστώ

Thank you