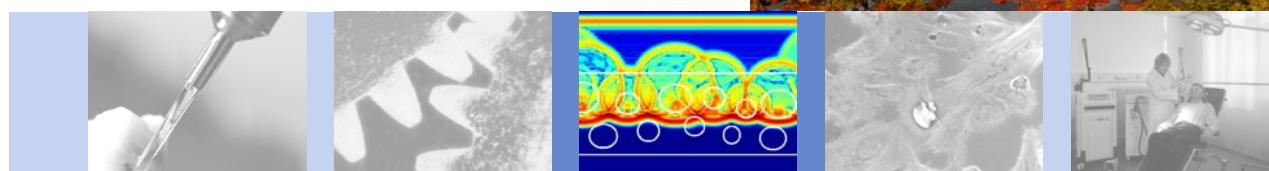


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# Lichtausbreitung in streuenden Medien: Prinzip und Anwendungsbeispiele

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06.12.2013



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in der Medizin und Meßtechnik  
an der Universität Ulm

## Overview

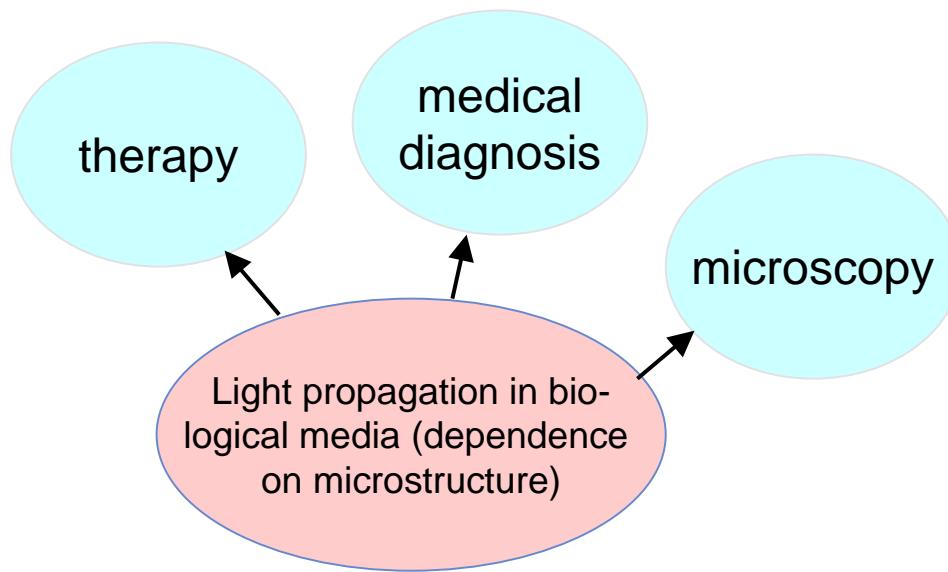
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- 1) Theory of light transport in scattering media based on
  - a) Maxwell's equations (FDTD simulation, analytical solutions)
  - b) Transport theory (analytical solution, Monte Carlo simulation)
- 2) Determination of the optical properties of scattering media
  - a) Spatially resolved reflectance
  - b) Spatially modulated imaging
  - c) Goniometric measurements
  - d) Scattering light microscopy



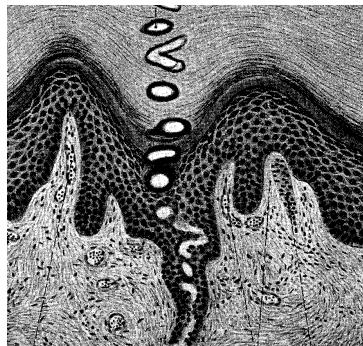
## Motivation

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# Description of light propagation in scattering media

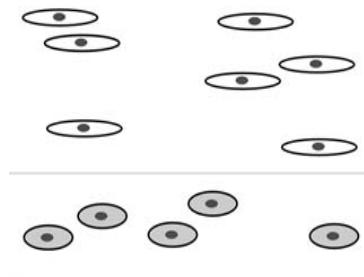
Maxwell's theory



microscopic scale  
(FDTD, PSTD,  
analytical solutions)

complex refractive  
index:  $n_k(r)$

transport theory



mesoscopic scale  
Monte Carlo

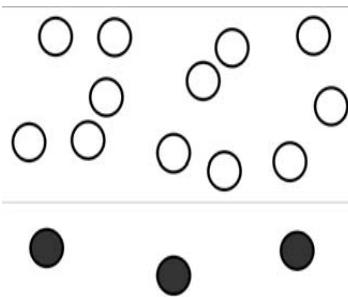
scattering coeff.:  $\mu_s$   
absorption coeff.:  $\mu_a$   
scattering function:  $p(\theta, \phi)$   
refractive index:  $n$

simplified spherical harmonics theory

analytical solutions

analytical solutions (semi-infinite ...)

diffusion theory



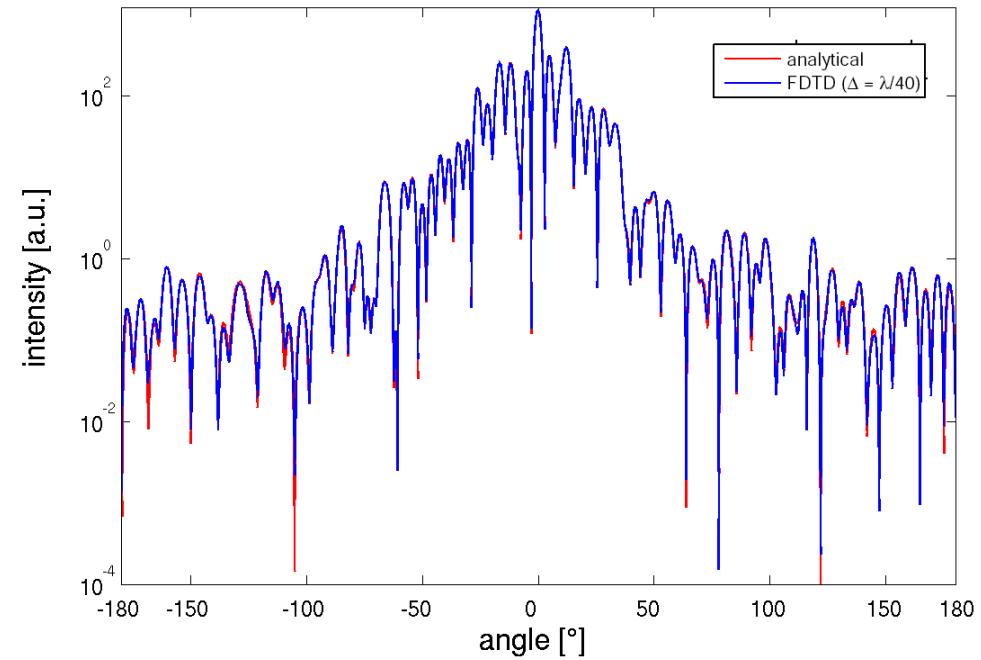
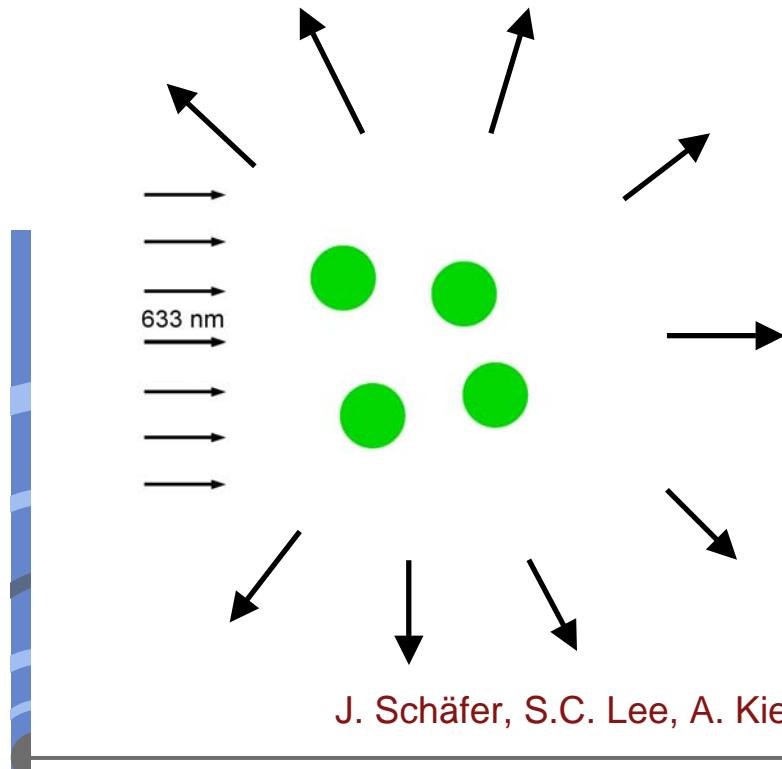
macroscopic scale

analytical solutions  
(N-layered ...)

effective scattering coeff.:  
 $\mu_s' = \mu_s(1-g)$  ( $g = \langle \cos(\theta) \rangle$ )  
absorption coeff.:  $\mu_a$   
refractive index:  $n$

## Maxwell theory – verification of methods

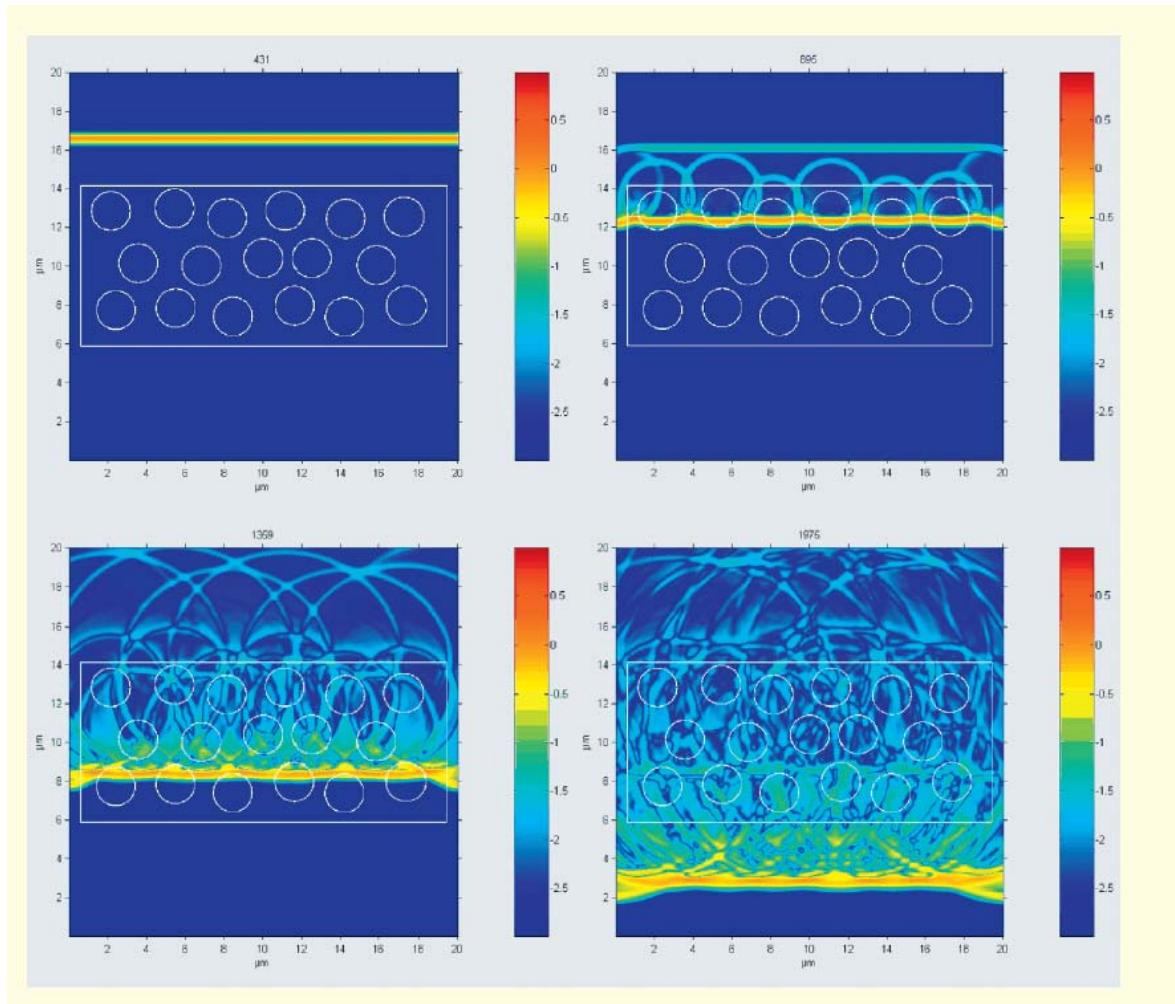
Comparison of analytical solution and FDTD simulation  
for scattering by many cylinders ( $d=2 \mu\text{m}$ ,  $n_o=1.52$ ,  
 $n_i=1.33$ ,  $\lambda = 633 \text{ nm}$ ).



J. Schäfer, S.C. Lee, A. Kienle: J.Quant.Spectr.Radiat.Transfer, 2113-2123 (2012).

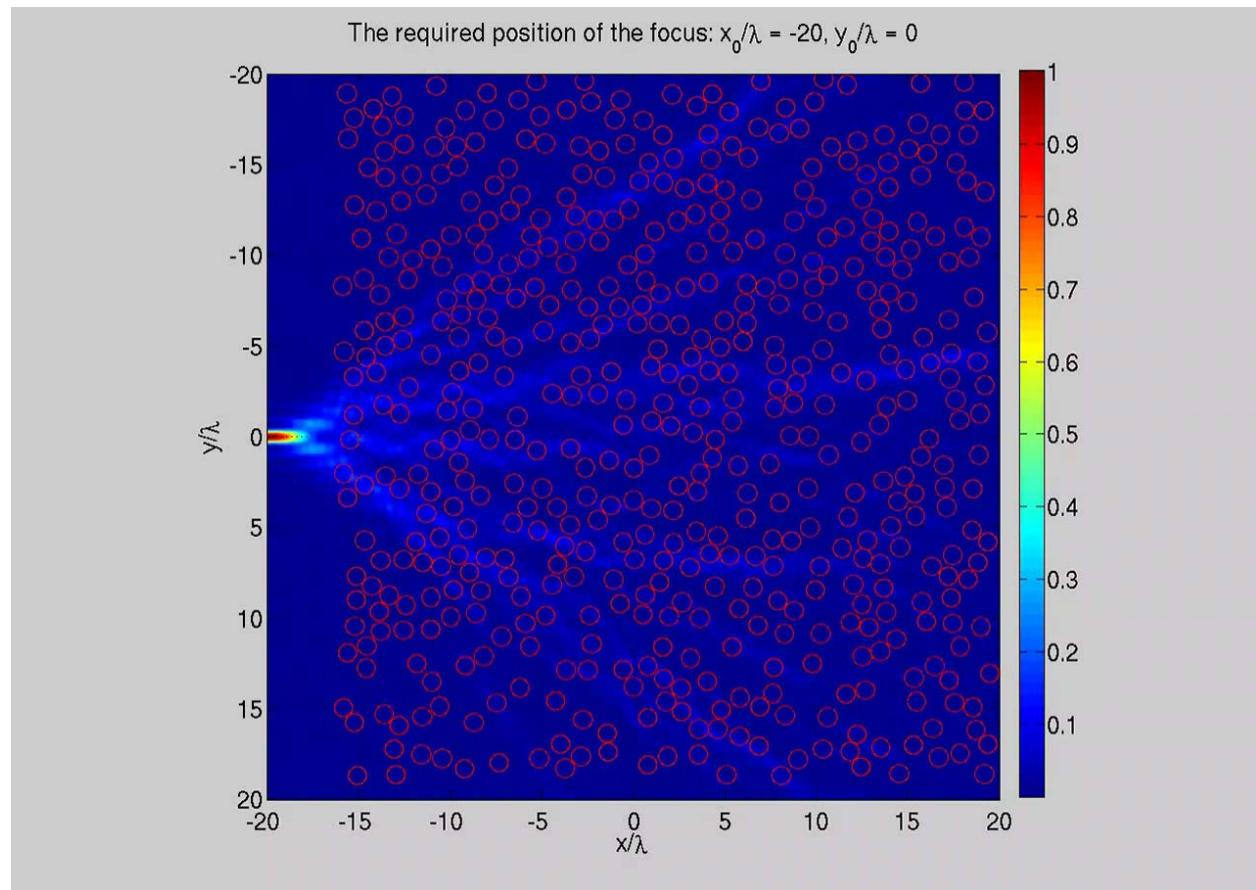
# Numerical solutions of Maxwell's equations: FDTD (Finite Difference Time Domain)

Light propagation in human dentin:  
dental tubules (cylinders with  $d=2 \mu\text{m}$ ,  $n_{\text{med}}=1.50$ ,  $n_{\text{ext}}=1.33$ ,  $n_{\text{cyl}}=1.37$ ;  $\lambda = 633 \text{ nm}$ ).



# Numerical solutions of Maxwell's equations: laser scanning microscope

Scanning a focused beam through a scattering medium (cylinders with  $n_o=1.33$ ,  $n_{cyl}=1.40$ ).

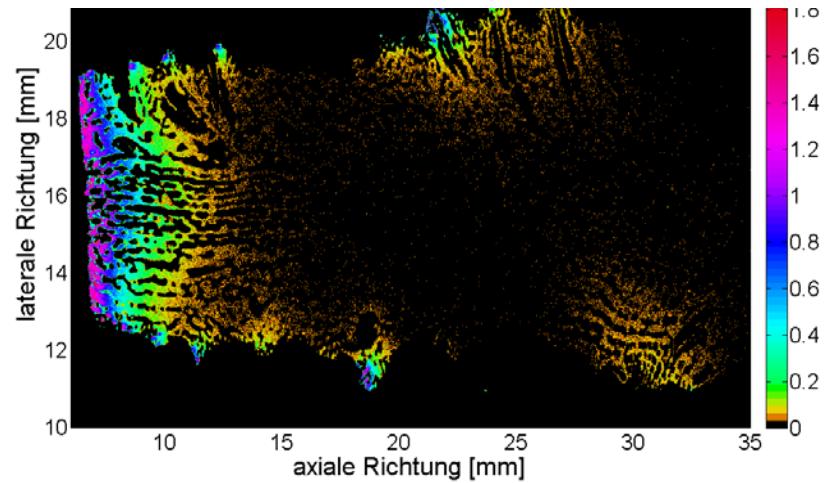
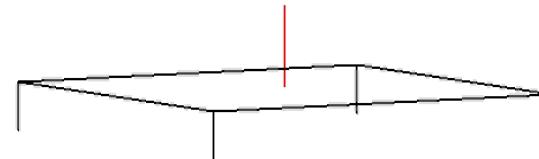


## Transport theory

Transport theory is often considered a 'gold standard' for calculation of light propagation in biological tissue

Flexible solution: Monte Carlo method

- CW-, frequency-, time domains
- multi-layered (spheres, cylinders ...)
- voxel-based/tetrahedron based
- laser Doppler
- fluorescence
- polarisation (Stokes, Jones)
- arbitrary surfaces
- electric field Monte Carlo
- GPU accelerated



# Transport theory – analytical solutions verified with Monte Carlo method

- Fluence rate for infinitely extended 3D-space for different sources

A.Liemert, A.Kienle, Phys. Rev. E 83, 015804 (2011)

- Radiance for infinitely extended 3D-space for different sources

A.Liemert, A.Kienle, Phys. Rev. A 83, 015804 (2011)

- for infinitely extended 3D-space in the time domain isotropic source and unidirectional source

A.Liemert, A.Kienle, Biomed. Opt. Express 3, 543-551 (2012)

A.Liemert, A.Kienle, Phys. Rev. E 86, 036603 (2012)

- for infinitely extended 2D-space

A.Liemert, A.Kienle, J.Phys.A: Math. Theor. 44, 505206 (2011)

- for circle in 2D-space

A.Liemert, A.Kienle, J.Phys.A: Math. Theor. 45, 175201 (2012)

- for a layered semi-infinite medium in 2D-space

A.Liemert, A.Kienle, JQSRT 113, 559-564 (2012)

- for a semi-infinite medium in spatial domain (3D)

A.Liemert und A. Kienle, Scientific Reports 3, 2018 (2013)

- for a semi-infinite medium in spatial frequency domain (3D)

A.Liemert, A.Kienle, Opt. Lett. 37; 4158-4160 (2012)

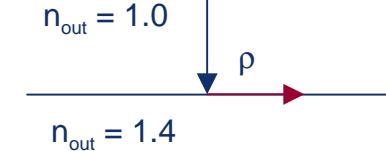
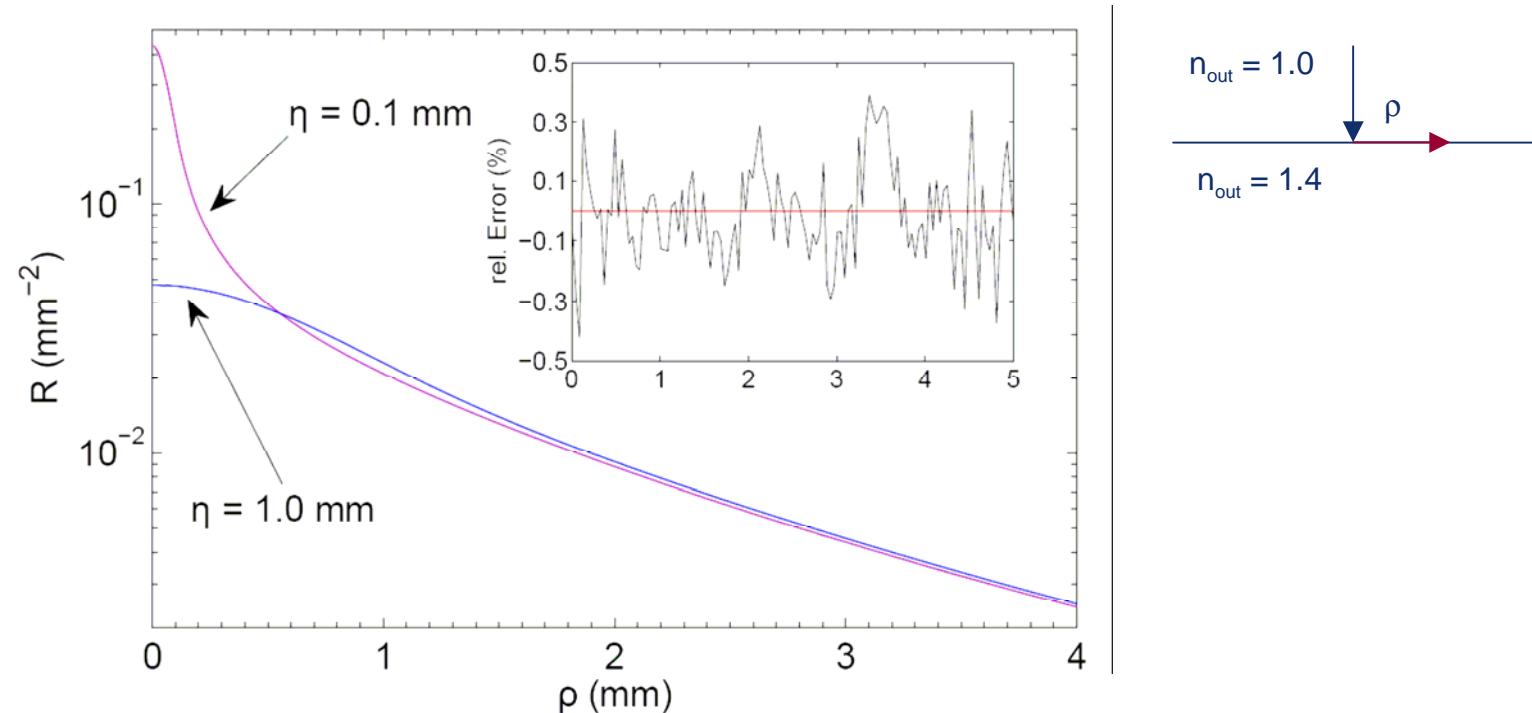
- for an arbitrary source in 2D-space

A.Liemert, A.Kienle, Waves Rand. Comp. Media (2013)

## Transport theory – Comparison Monte Carlo with analytical solutions

Analytical solution for a semi-infinite medium in the steady-state domain

Perpendicularly incident beam with radius  $\eta$  (reflectance)

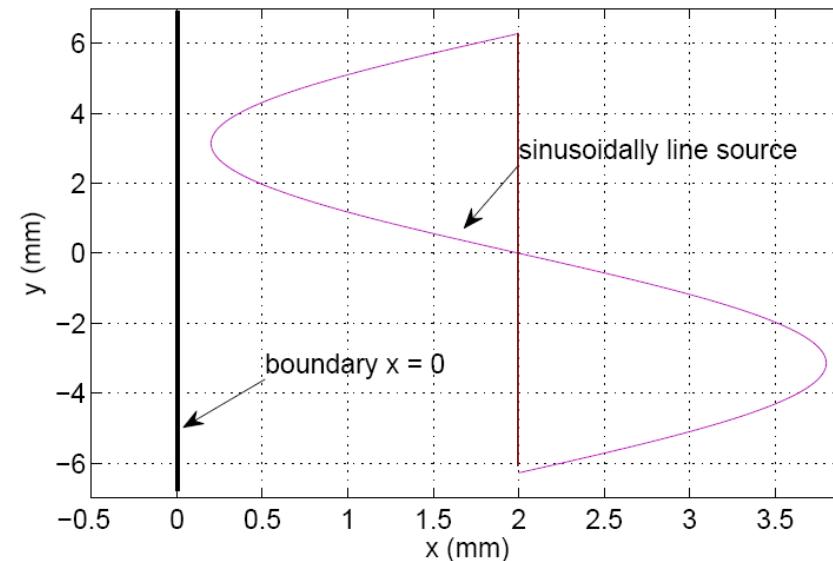


$$\mu'_s = 1 \text{ mm}^{-1}, \mu_a = 0.01 \text{ mm}^{-1}, g = 0.8 \text{ (Henyey-Greenstein)}$$

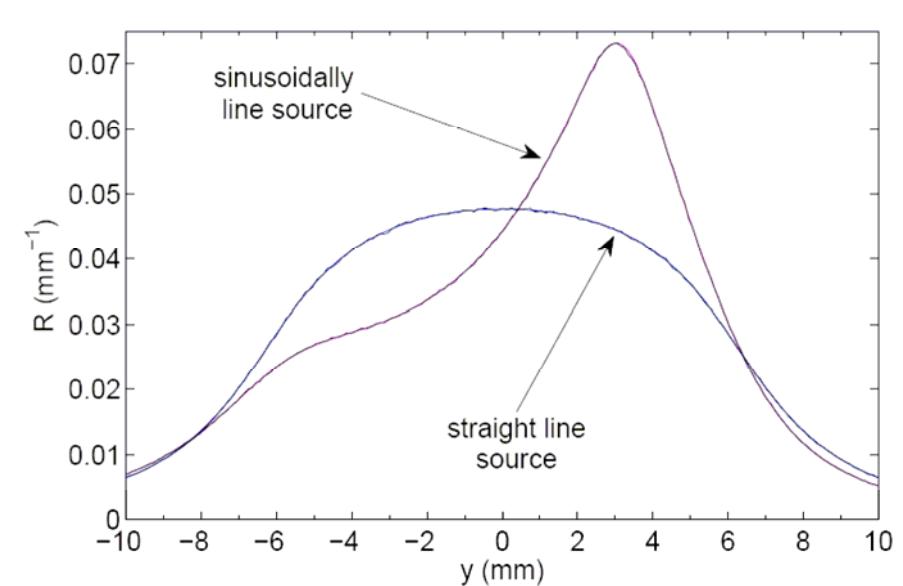
# Transport theory – Comparison Monte Carlo with analytical solutions

Analytical solution for a two-dimensional semi-infinite medium with internal sources

Source:



Reflectance

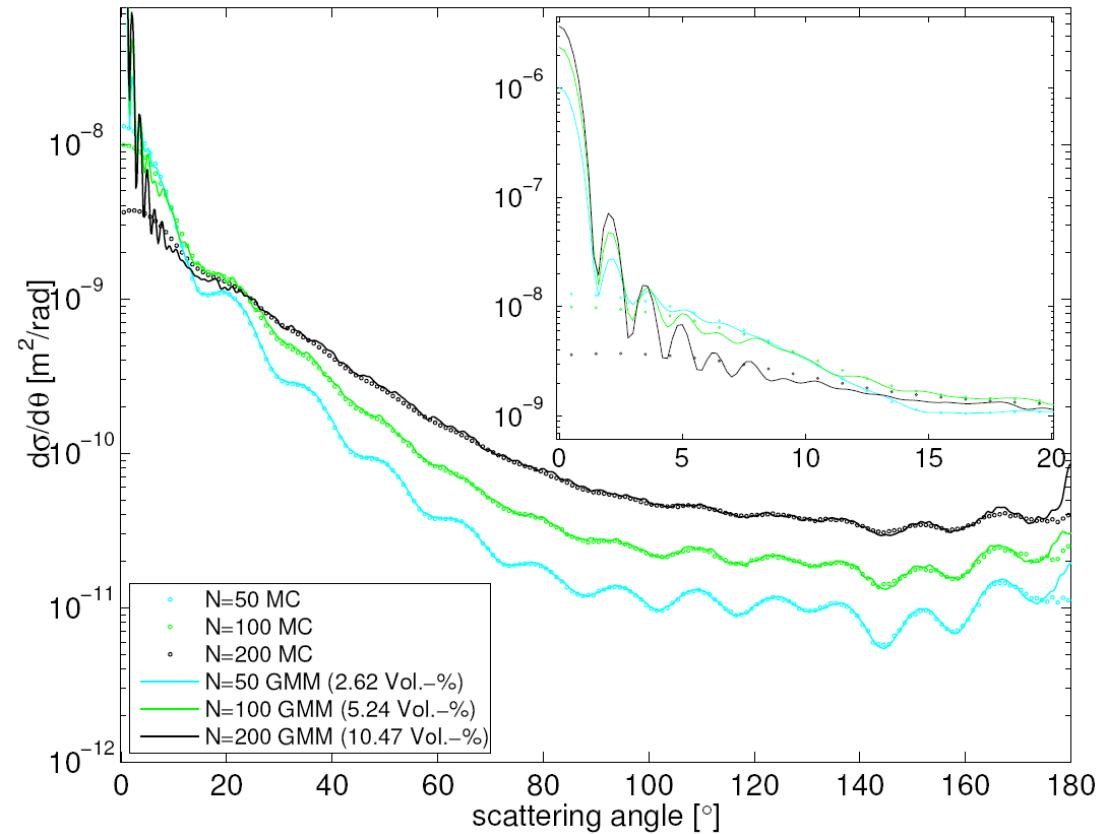
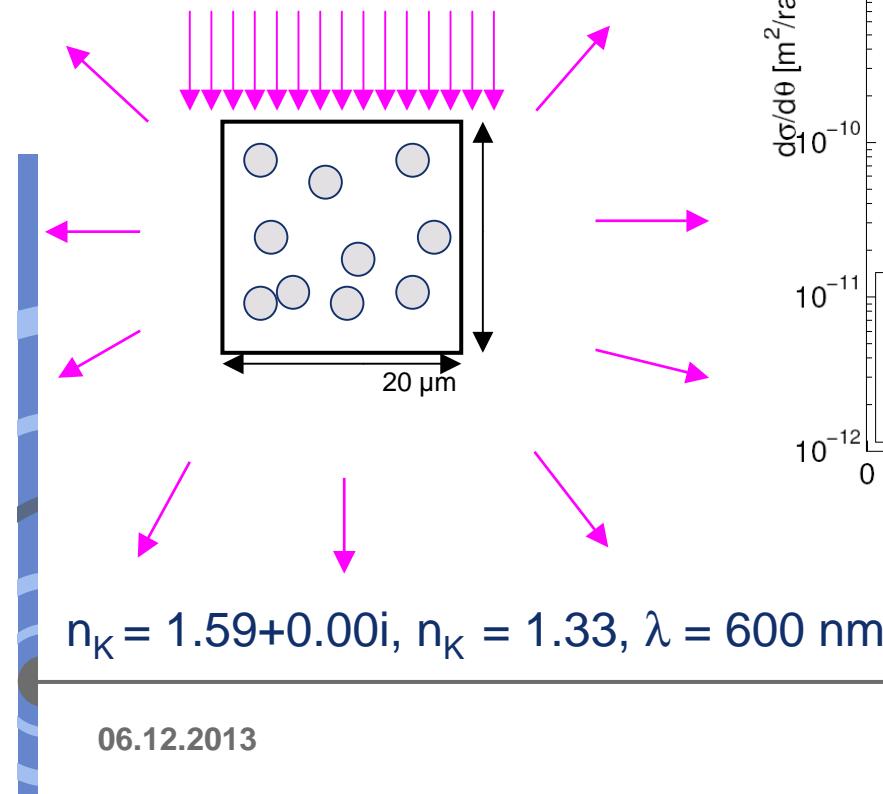


$\mu'_s = 1.0 \text{ mm}^{-1}$ ,  $\mu_a = 0.01 \text{ mm}^{-1}$ ,  $g = 0.8$  (Henyey-Greenstein), matched condition

## Maxwell theory – comparison with transport theory

Monte Carlo method versus Maxwell theory (analytical)

Plain wave incident  
on spheres ( $\emptyset = 2 \mu\text{m}$ ),  
which are located in a  
cube

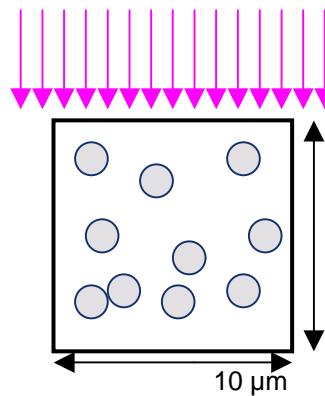


F.Voit, J.Schäfer, A.Kienle,  
*Opt. Lett.*, 34, 2593 - 2595 (2009)



# Maxwell theory – comparison with transport theory inclusive polarisation (Müller-Matrix)

Plain wave incident on spheres ( $\varnothing = 2\mu\text{m}$ ), which are located in a cube

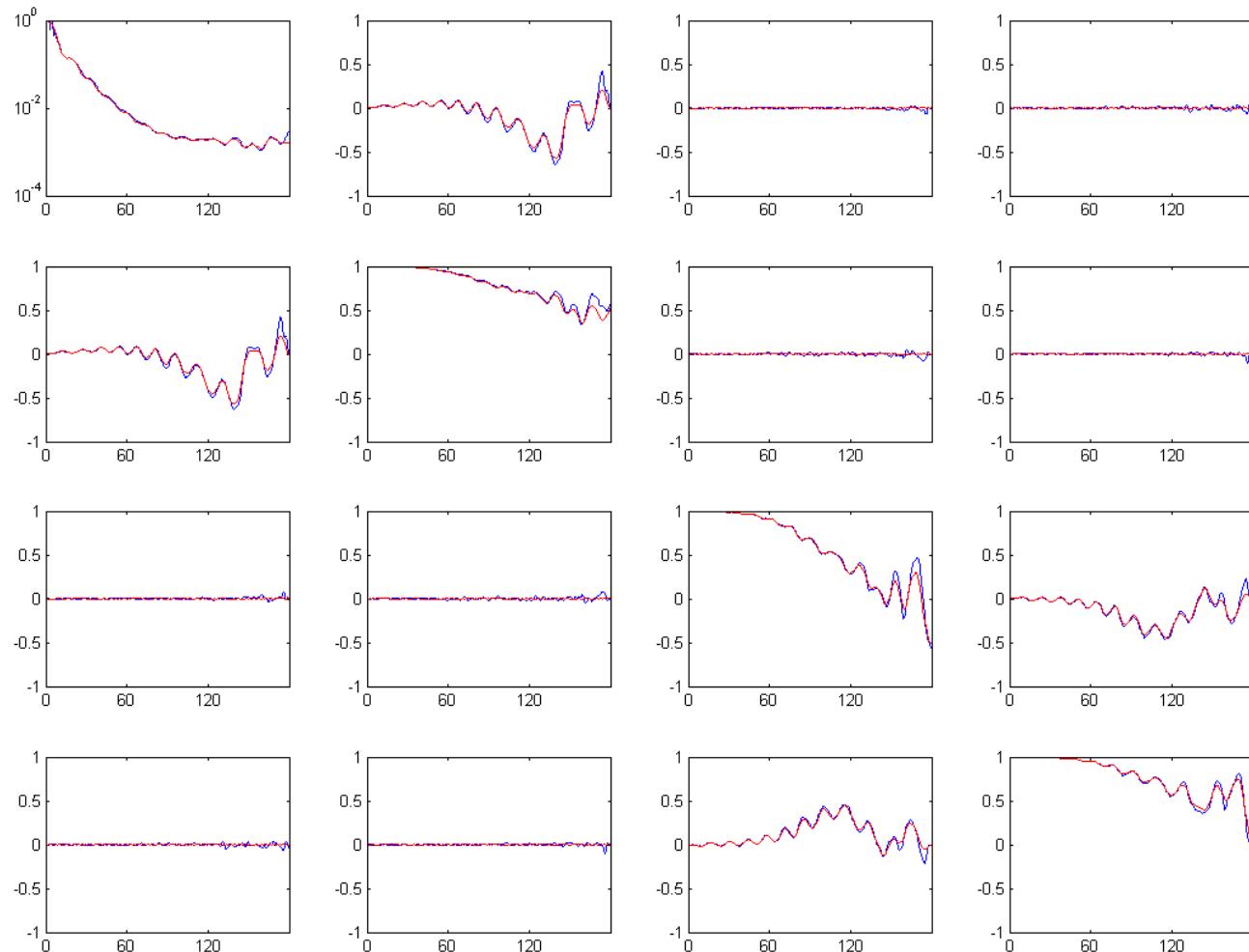


$$n_K = 1.59 + 0.00i$$

$$n_K = 1.33, \lambda = 600 \text{ nm}$$

24 spheres

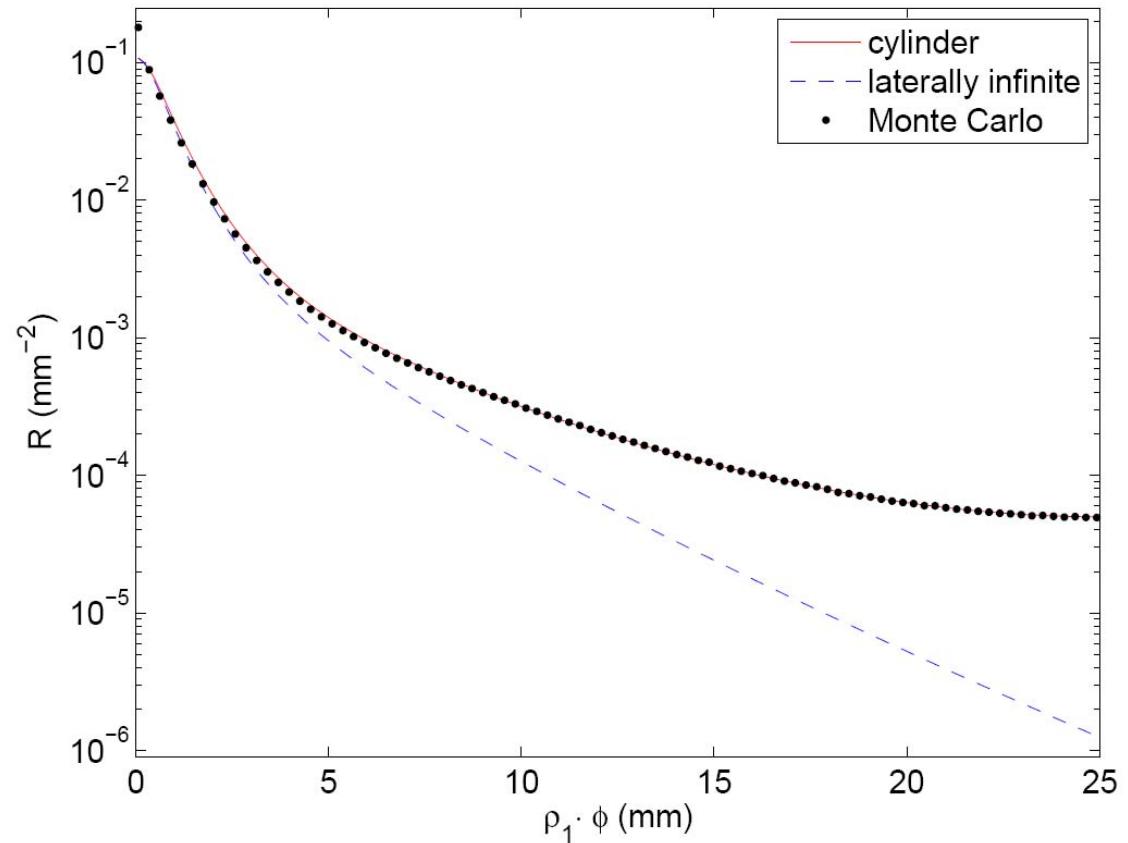
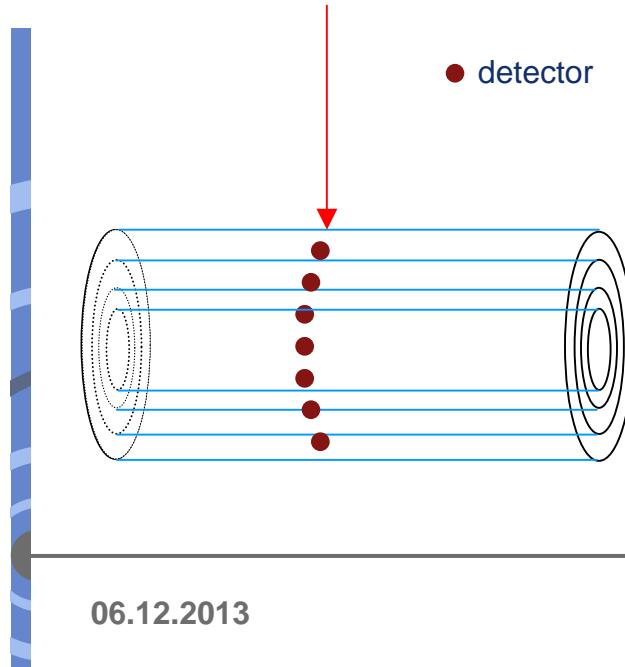
(10% concentration)



## Diffusion theory - radially N-layered cylinder

Geometry ( $\emptyset = 16$  mm; finger): azimuthal direction

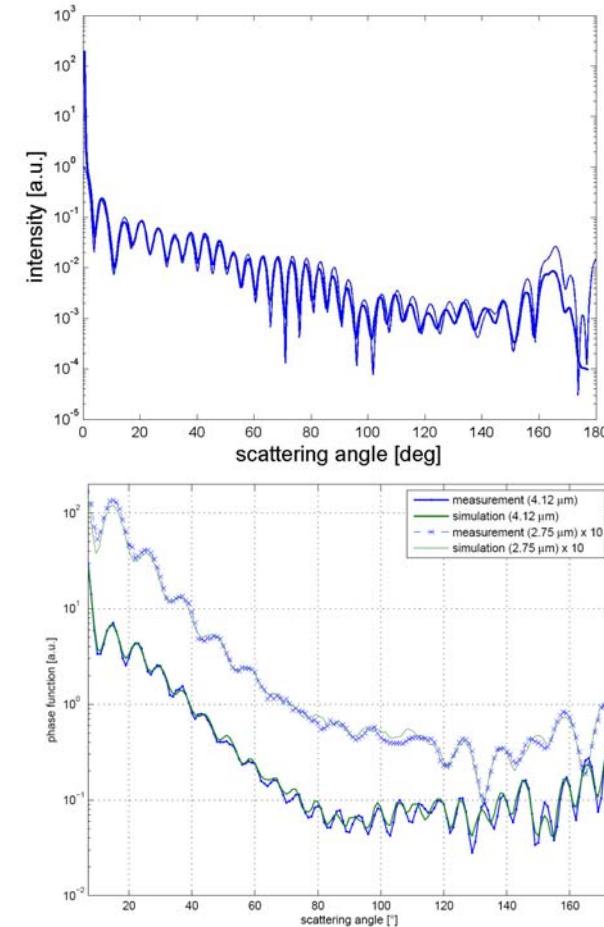
| layers | thickness |
|--------|-----------|
| skin   | 1 mm      |
| fat    | 1 mm      |
| muscle | 2 mm      |
| bone   | 4 mm      |



## Determination of optical properties: experimental setups

Determination of the optical properties (absorption and scattering)

- spatially resolved reflectance
  - camera-based
  - fiber-based
- time domain reflectance
- integrating sphere measurements
- goniometric setup  
( $4\pi$ -measurements)
- collimated transmission
- photothermal absorption measurements
- spatial frequency domain imaging
- light scattering microscope



## Calculation of optical properties

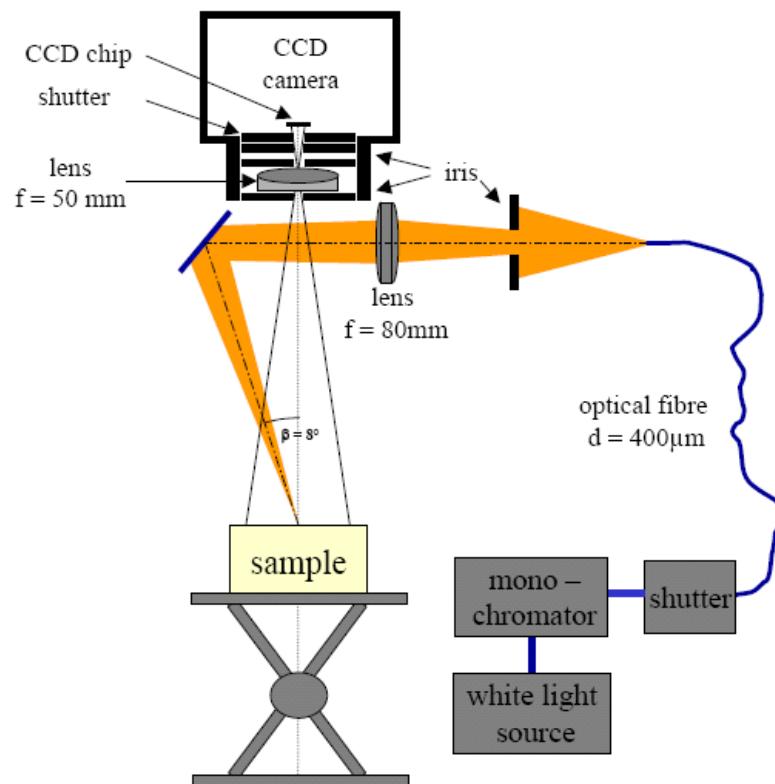
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### Solution of inverse problem

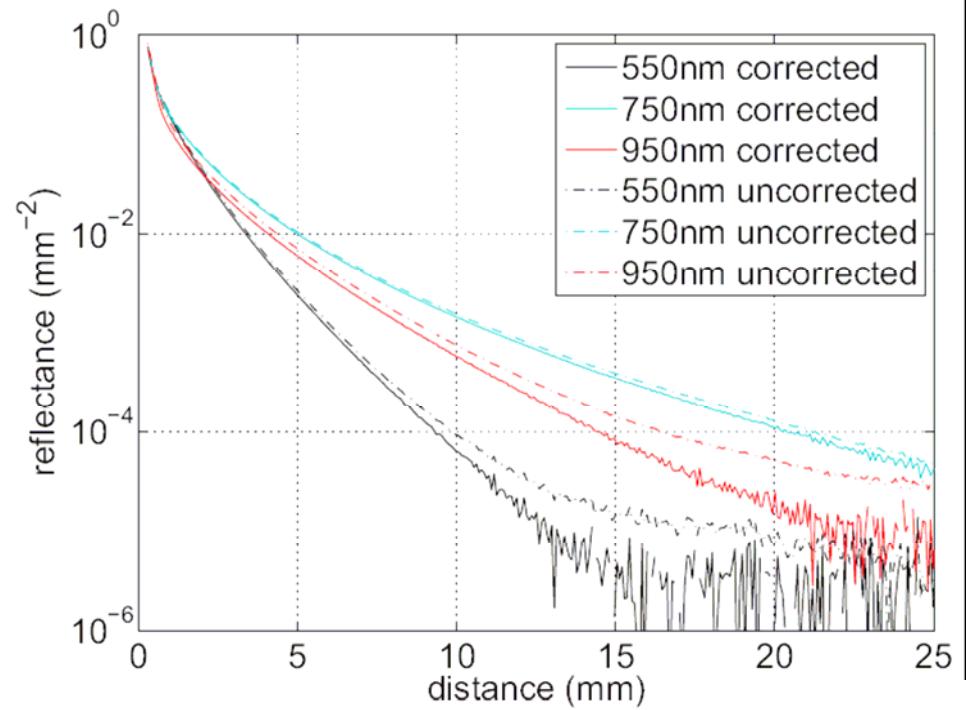
- analytic solutions of diffusion equation
- analytical solutions of  $SP_N$  –Methode
- analytical solutions of transport equation
- Monte Carlo simulations (GPU) (A.Kienle et al, Opt. Lett. (2001))
- scaling methods of Monte Carlo method (A.Kienle, M.Patterson, Phys. Med. Biol. (1996))
- Neural network (M.Jäger, A.Kienle, Phys. Med. Biol. (2011))  
(M.Jäger, F. Foschum, A.Kienle, J. Biomed. Opt. (2013))  
(M.Jäger, F. Foschum, A.Kienle, Phys. Med. Biol. (2013))

# Determination the effective scattering and absorption coefficients

Spatially resolved reflectance measurements



With and without correction of transfer function

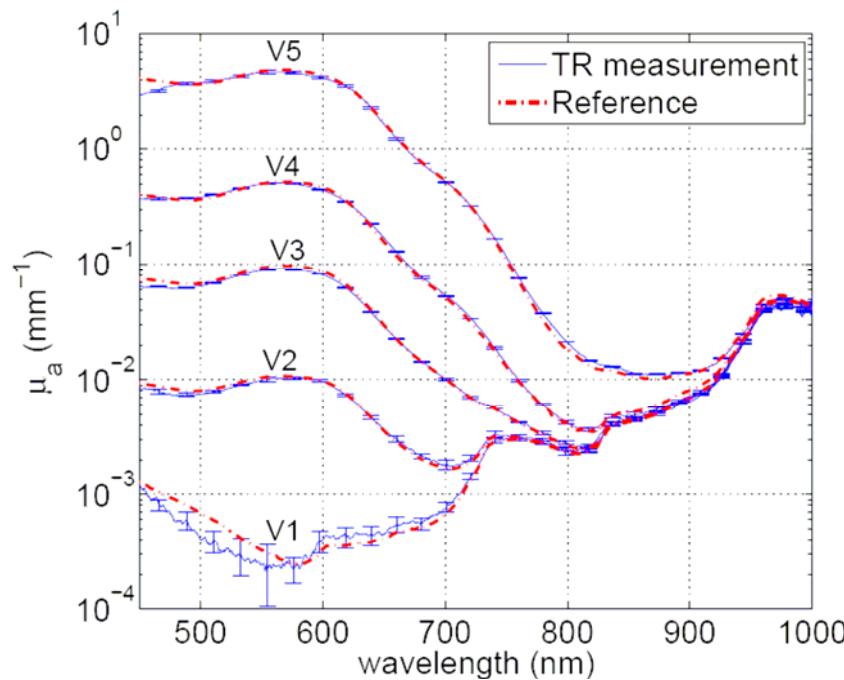


(F.Foschum, A.Kienle, J.Biomed. Opt. (2012))

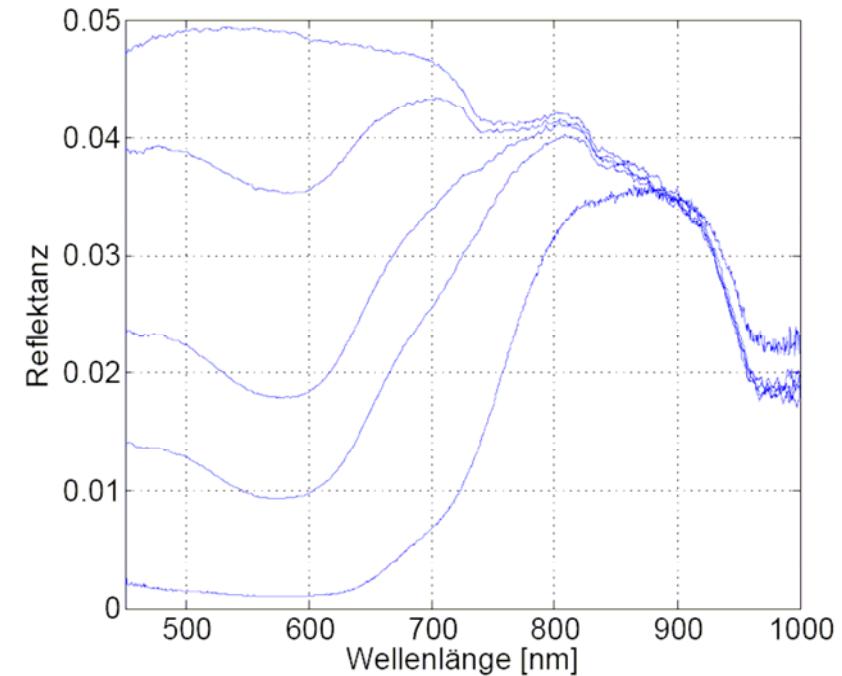


## Determination the effective scattering and absorption coefficients

Obtained absorption coefficient of Intralipid/ink emulsions

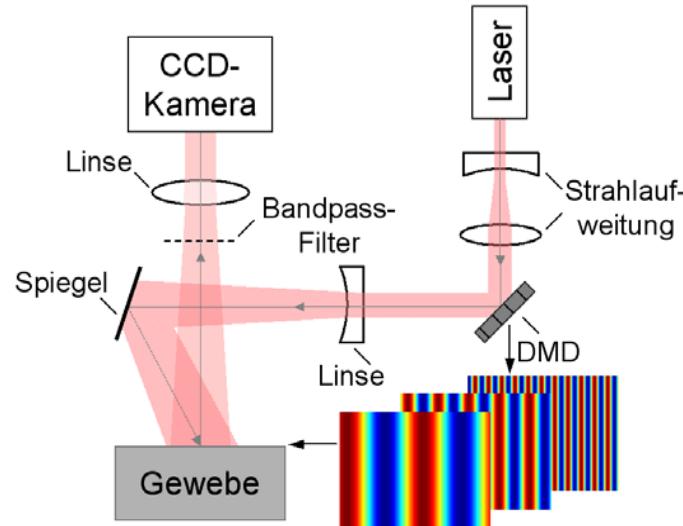


Total remitted light

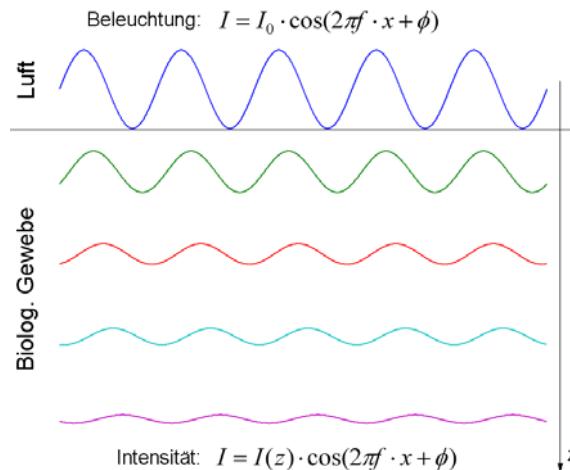


# Spatial frequency domain measurements

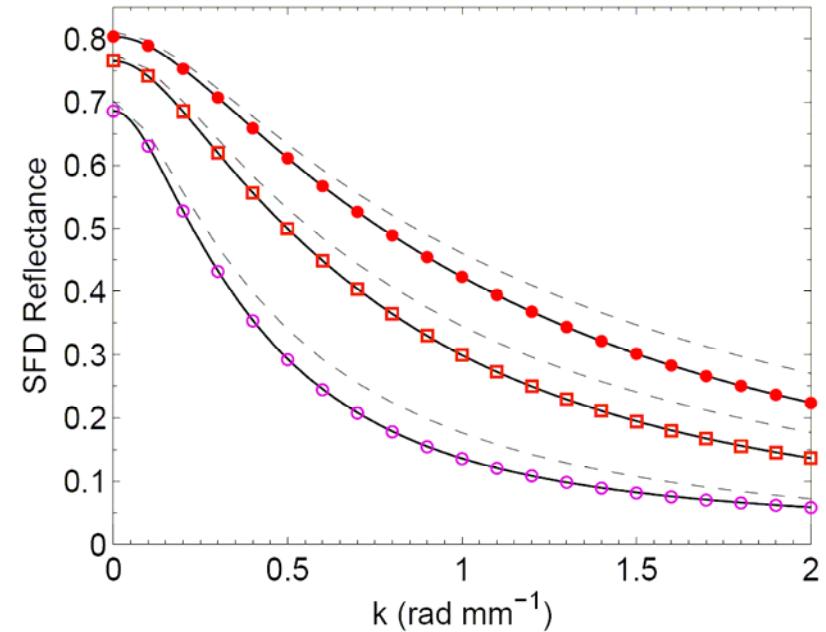
Setup:



Light scattering:



Amplitude versus frequency:



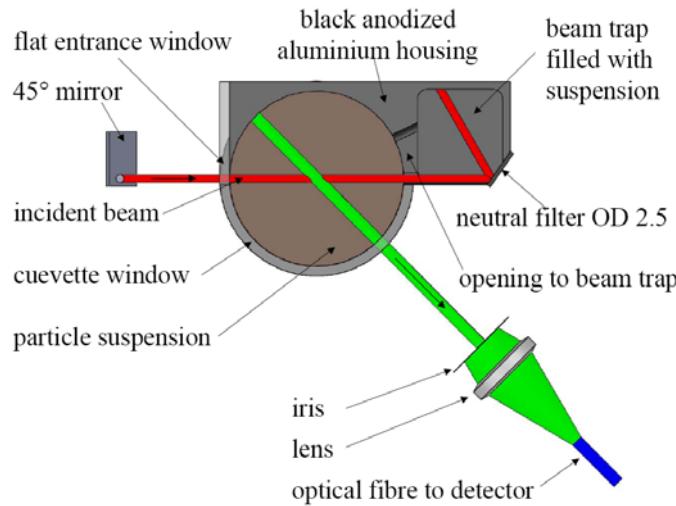
$$\mu_a = 0.01 \text{ mm}^{-1}$$

$$\mu_s' = 0.6 \text{ (open circle)} / 1.2 \text{ (square)} / 1.8 \text{ mm}^{-1} \text{ (circle)}.$$

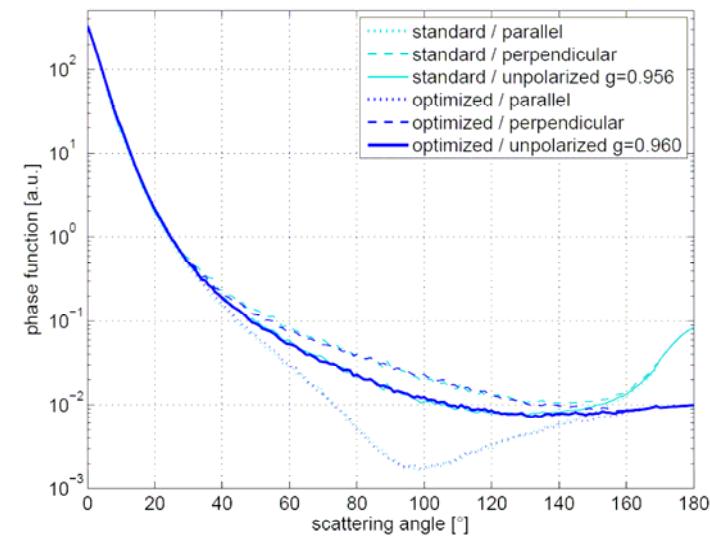
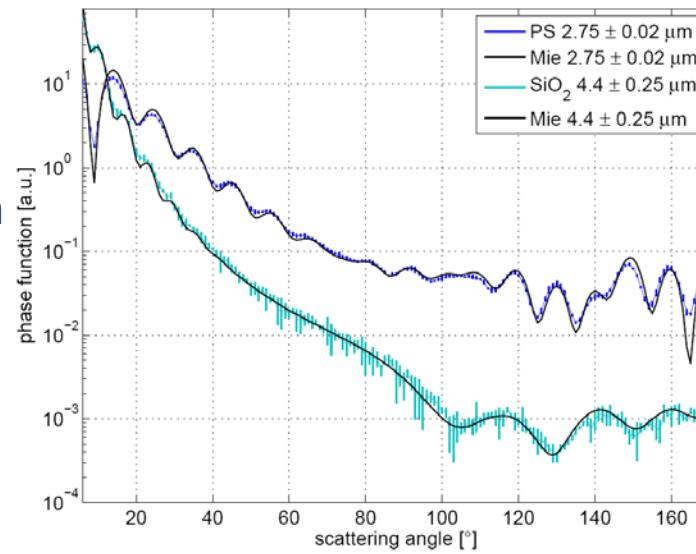


# Goniometric scattering by $\text{SiO}_2$ -spheres ( $n \approx 1.42$ )

Setup constructed based  
on Monte Carlo  
simulations

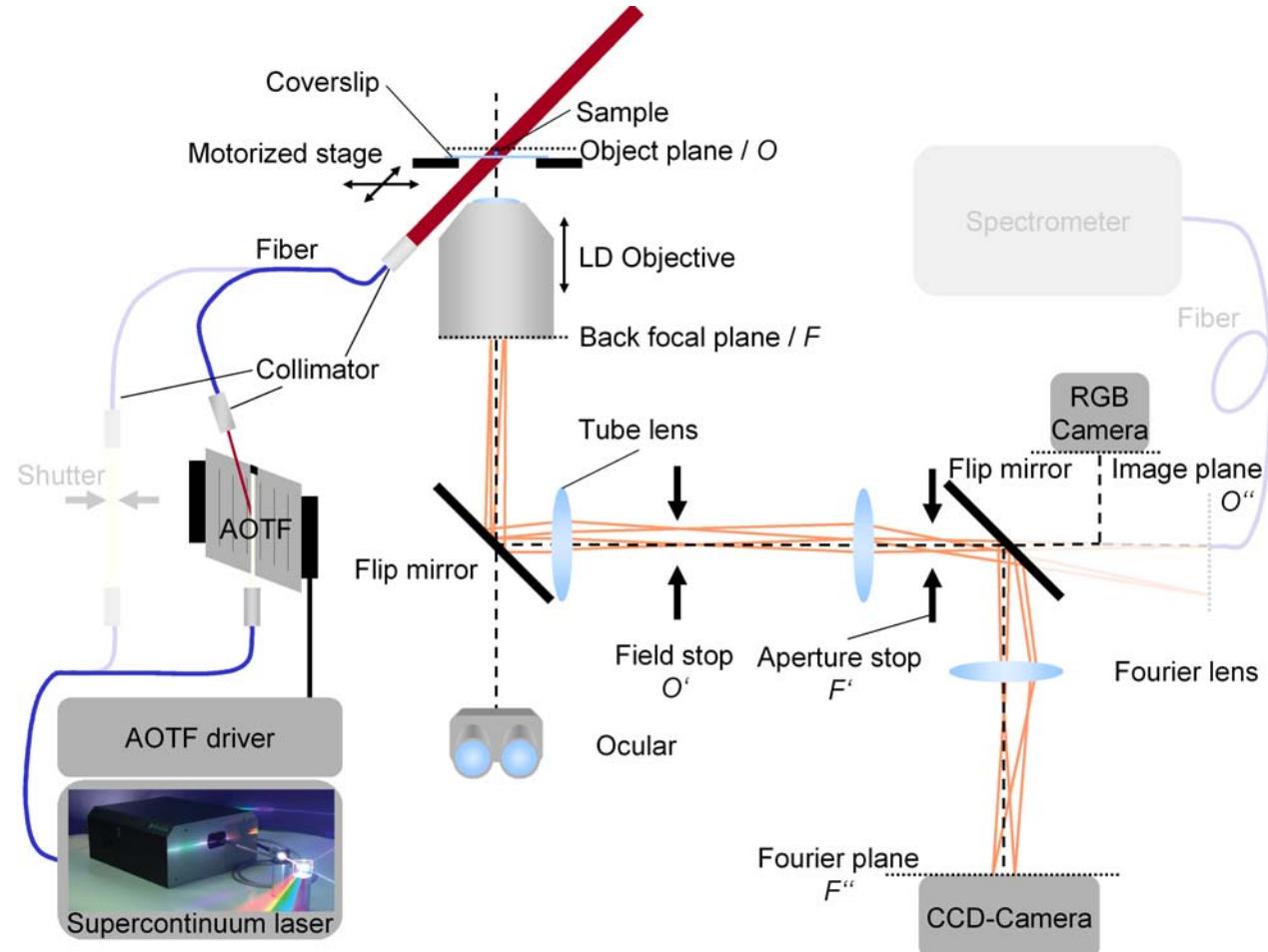


Measurements on  
spheres (left)  
and on yeast cells  
(right) (wave length  
= 635 nm)



# Light scattering microscope

Setup:



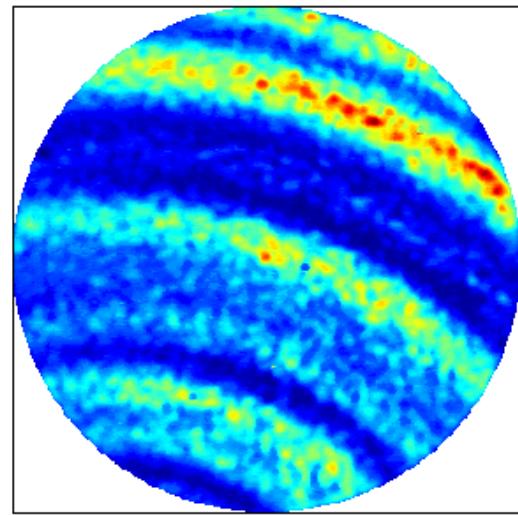
(M.Schmitz, T.Rothe, A.Kienle, Biomed. Opt. Express (2011))

(T.Rothe, M.Schmitz, A.Kienle, J. Biomed. Opt., 2012))

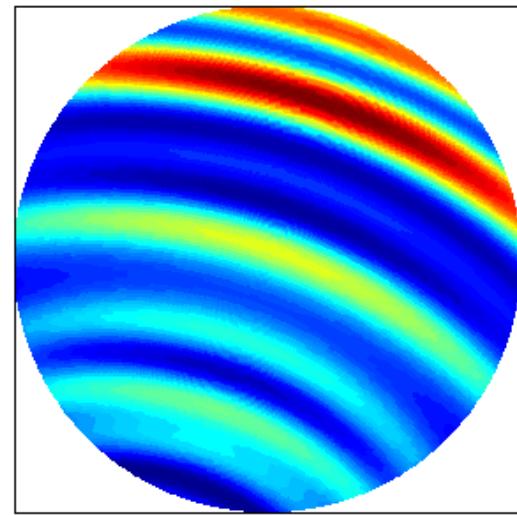
## Angularly resolved scattering by SiO<sub>2</sub>-sphere

- Comparison of measurement with Mie-theory

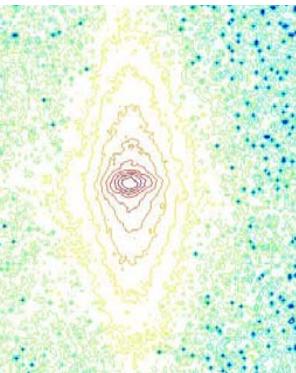
Measurement  $\lambda=545\text{nm}$ , single bead



Theory  $\lambda=545\text{nm}$ ,  $D=4.720\mu\text{m}$ , NA 0.53



# Summary



technical  
materials

therapy

medical  
diagnosis

microscopy

process  
control

Light propagation in turbid  
media (dependence  
on microstructure)

