POLITECNICO DI MILANO

Conference

Project MONALISA

ENVIRONMENTAL SENSING

Advanced optical methods for non-destructive assessment of food quality

Alessandro Torricelli

Politecnico di Milano, Dipartimento di Fisica, Milan (Italy)
Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche, Milan (Italy)

25 November 2016 – Bozen (Italy)

Department of Physics, Politecnico di Milano
Photonics for Health, Food and Cultural Heritage

Staff @PoliMi

POLITECNICO DI MILANO

Rinaldo Cubeddu
Antonio Pifferi
Paola Taroni
Alessandro Torricelli
Gianluca Valentini
Andrea Bassi
Daniela Comelli
Cosimo D'Andrea
Davide Contini
Alberto Dalla Mora

Staff @ IFN-CNR

Lorenzo Spinelli
Austin Nevin
Andrea Farina

Post-Docs

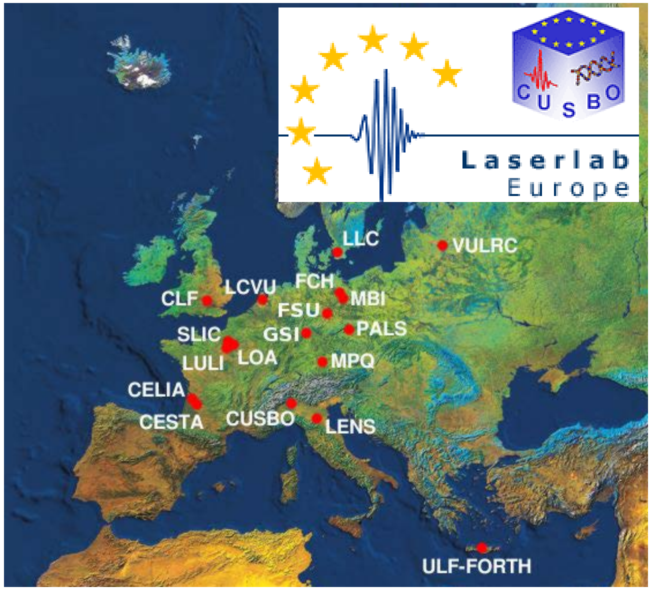
Alessia Candeo
Laura DI Sieno
Sanathana Konugoglu
Edoardo Martinenghi
Rebecca Re
Maristella Vanoli

+ PhD Students
+ Undergraduate Students
+ Facilities (mechanic and electronic workshop)

Center for Ultrafast Science and Biomedical Optics
LaserLab-EUROPE
Politecnico di Milano - Dipartimento di Fisica
Milan, Italy

European Large Scale Facility since 2002

Access to infrastructure
Full reimbursment of travel and accomodation expenses

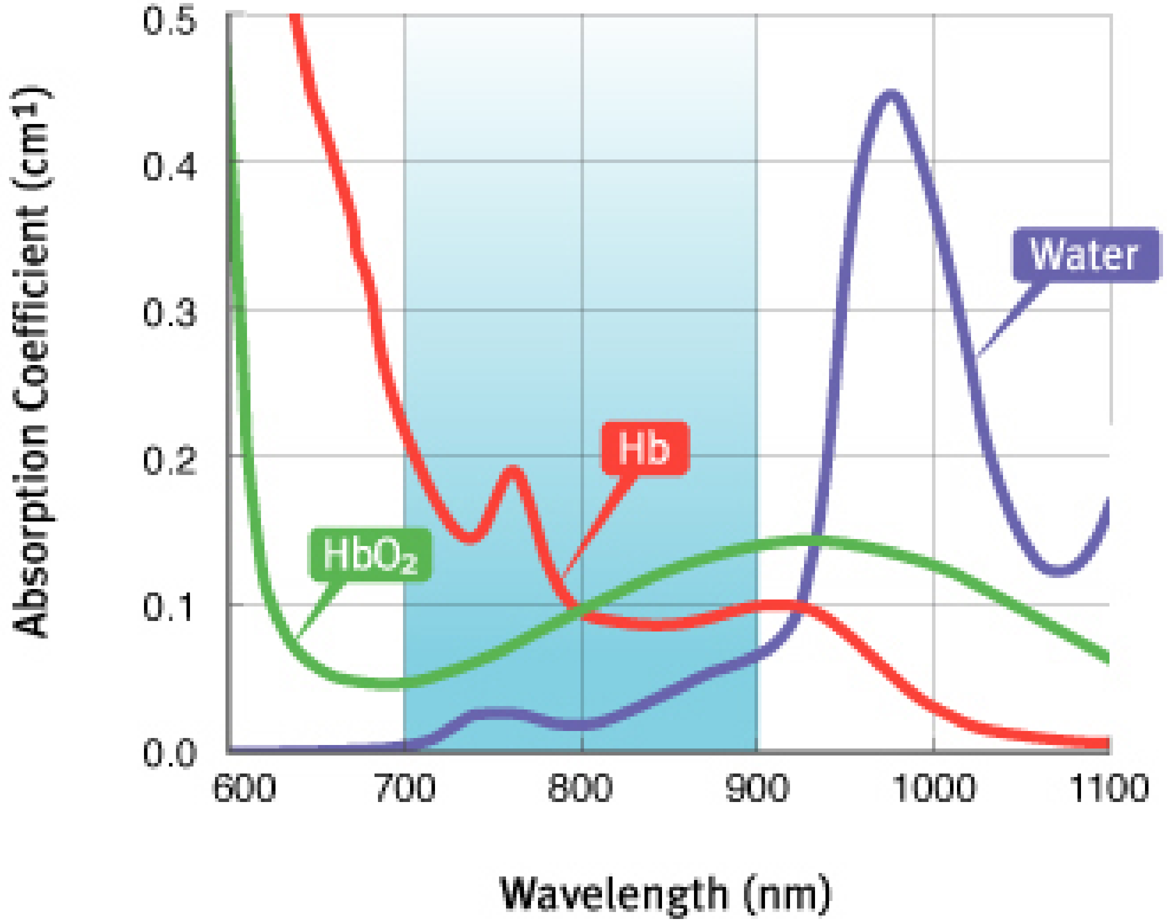


Can light penetrate biological tissues?

Georges de La Tour (1593 – 1652)

St Joseph, 1642, Louvre, Paris

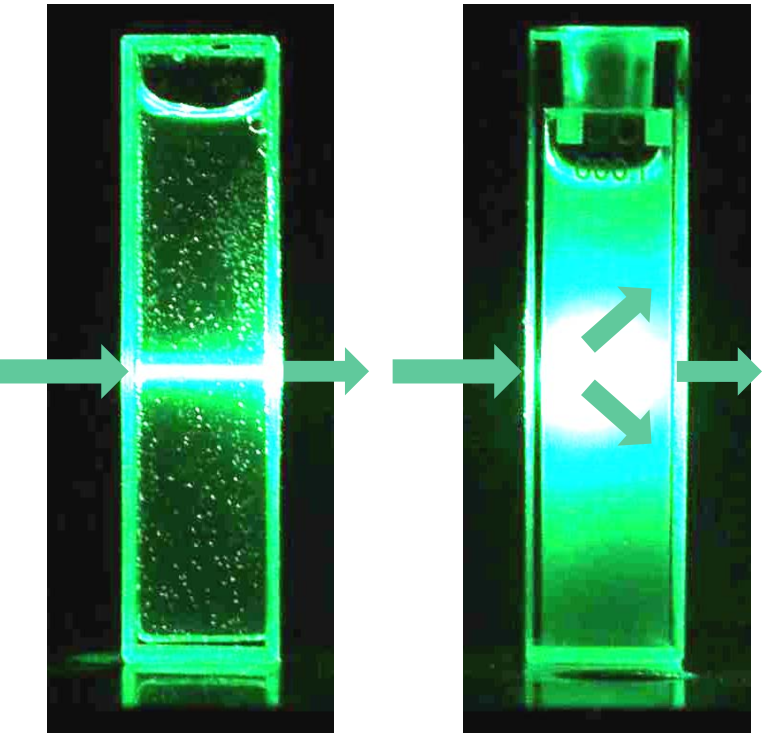
Thanks to Marco Ferrari (UnivAQ)



The therapeutic and diagnostic window

Light propagation in diffusive media: absorption and scattering

clear   diffusive



$$I_{out} = I_{in} e^{-\mu_a L} \qquad I_{out} = I_{in} e^{-(\mu_a + \mu_s) L}$$

Absorption: related to tissue components

Absorption coefficient:

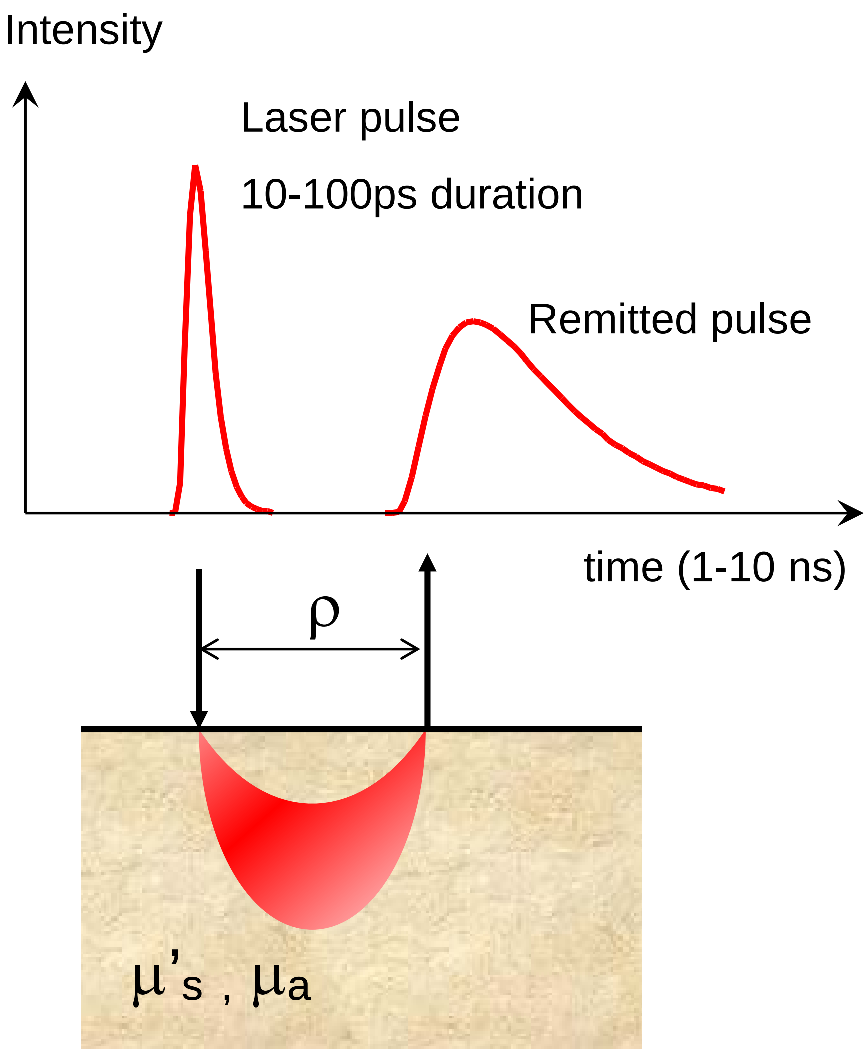
$\mu_a = 1/\ell_a$ (cm^{-1})

Scattering: related to tissue structure

Scattering coefficient:

$\mu_s = 1/\ell_s$ (cm^{-1})

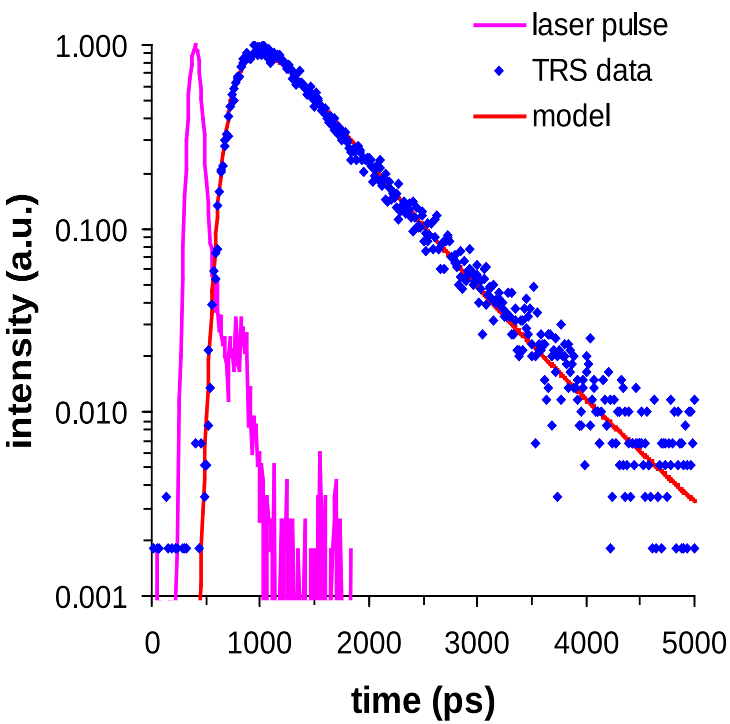
Time-resolved Reflectance Spectroscopy (TRS) Basics



Photon diffusion

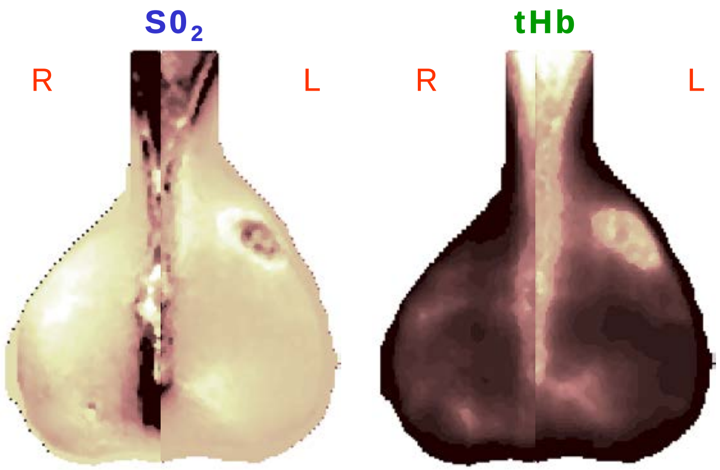
$$R(\rho,t) = A t^{-5/2} \mu_s'^{1/2} e^{-\left(\frac{\rho^2 + z_0^2}{4Dvt}\right)} e^{-\mu_a vt}$$

$$D = (3\mu_s')^{-1} \qquad z_0 = (\mu_s')^{-1}$$



Patient #47, oblique view

age: 36 y
thickness = 5.7 cm
Lesion size = 3.0 cm
Lesion type = tumor



52%-89%   62%-95%   17 - 91 μM   16 - 66 μM

Clinical study
(225 lesion)

Type	View	Cases	Detection rate	Failures	Corrected detection rate
Cancer	**2**	**41**	**73%**		**80%**
	1	9	89%	4	96%
	0	6	11%		
Cyst	**2**	**59**	**72%**	8	**83%**
	1	5	78%	3	90%
	0	18	22%		
Fibroadenoma	**2**	**17**	**33%**	2	**39%**
	1	5	43%	5	50%
	0	29	57%		

Taroni *et al.*, TRTC 4:527-537 (2005).

An optical neuro-monitor of cerebral oxygen metabolism & blood flow for neonatology

Clinical testing @ Copenhagen & Milan

Microvascular, local, cerebral

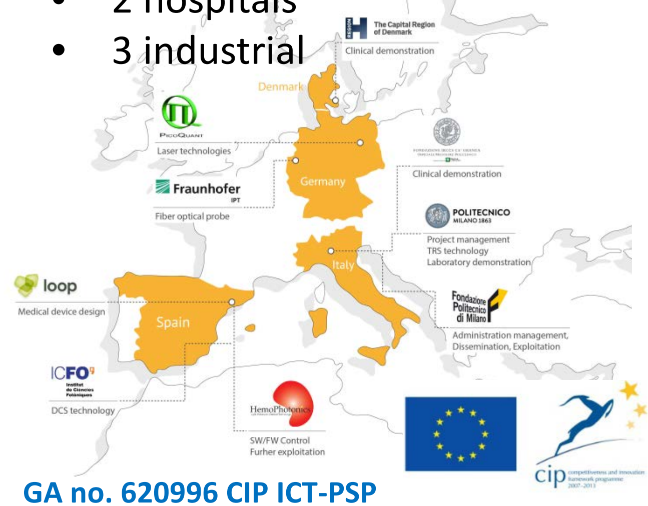
blood oxygen saturation

blood volume

blood flow

4 countries / 9 partners

- 4 academic
- 2 hospitals
- 3 industrial



BabyLux

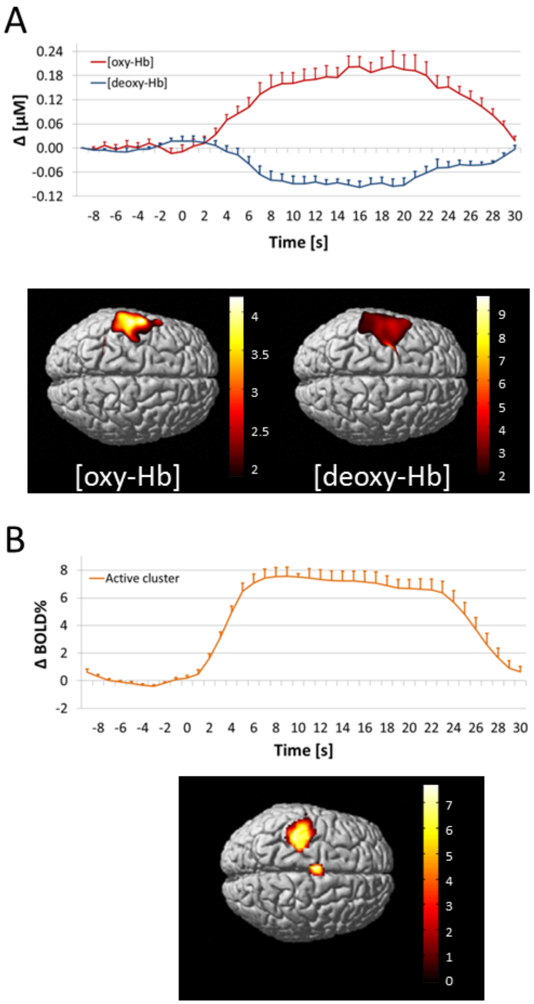
http://www.babylux-project.eu

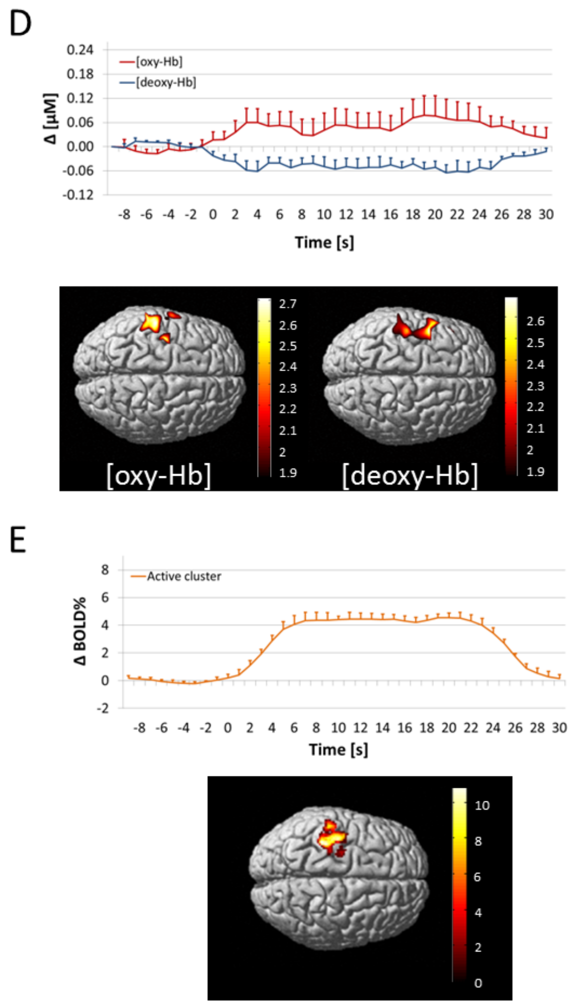
GA no. 620996 CIP ICT-PSP

Noninvasive imaging of brain function and disease by pulsed near infrared light (nEUROPt FP7 2008-2012)

healthy

ULD patients





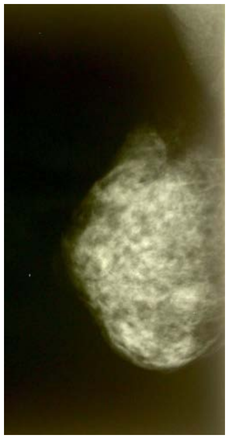
A, D:
O_2Hb and HHb time-courses in the most reactive channel and the corresponding GLM activation maps.

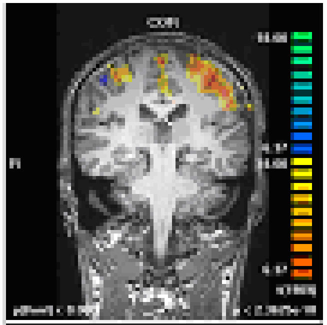
B, E:
BOLD signal extracted from the active cluster and fMRI maps.

nEUROPt
Non-invasive imaging of brain function and disease by pulsed near infrared light

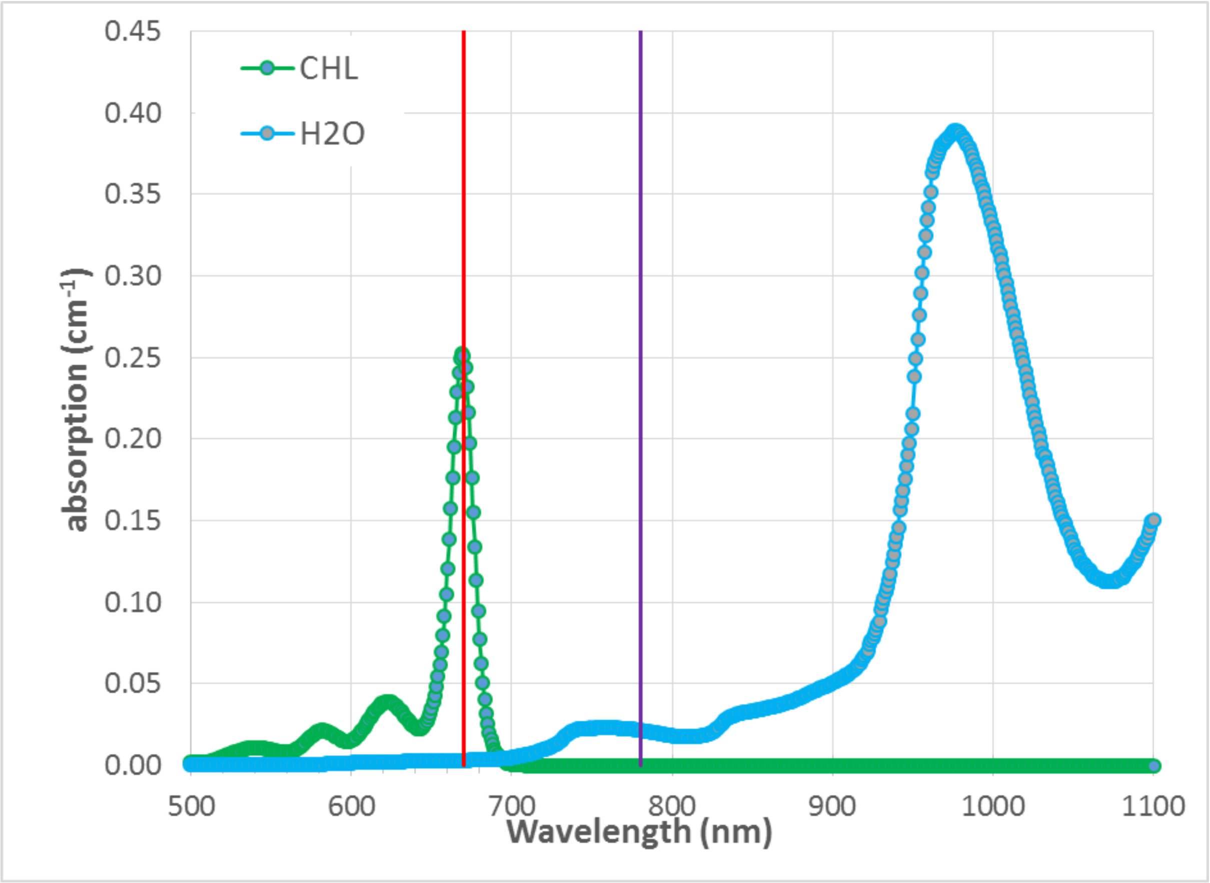
In collaboration with: I.Gilioli, S.Franceschetti, F. Panzica, E.Visani @ IRCCS Besta Milan, Italy

Photonics for Health ←→ Photonics for Food





Choice of operating wavelengths



Wavelength:
650-670 nm chlorophyll
780 nm background

Visible (VIS) and near infrared (NIR) spectroscopy: continuous wave (CW) approach

VIS: 400-700 nm (nondestructive assessment of EXTERNAL properties)
NIR: 700-3000 nm (nondestructive assessment of INTERNAL properties)

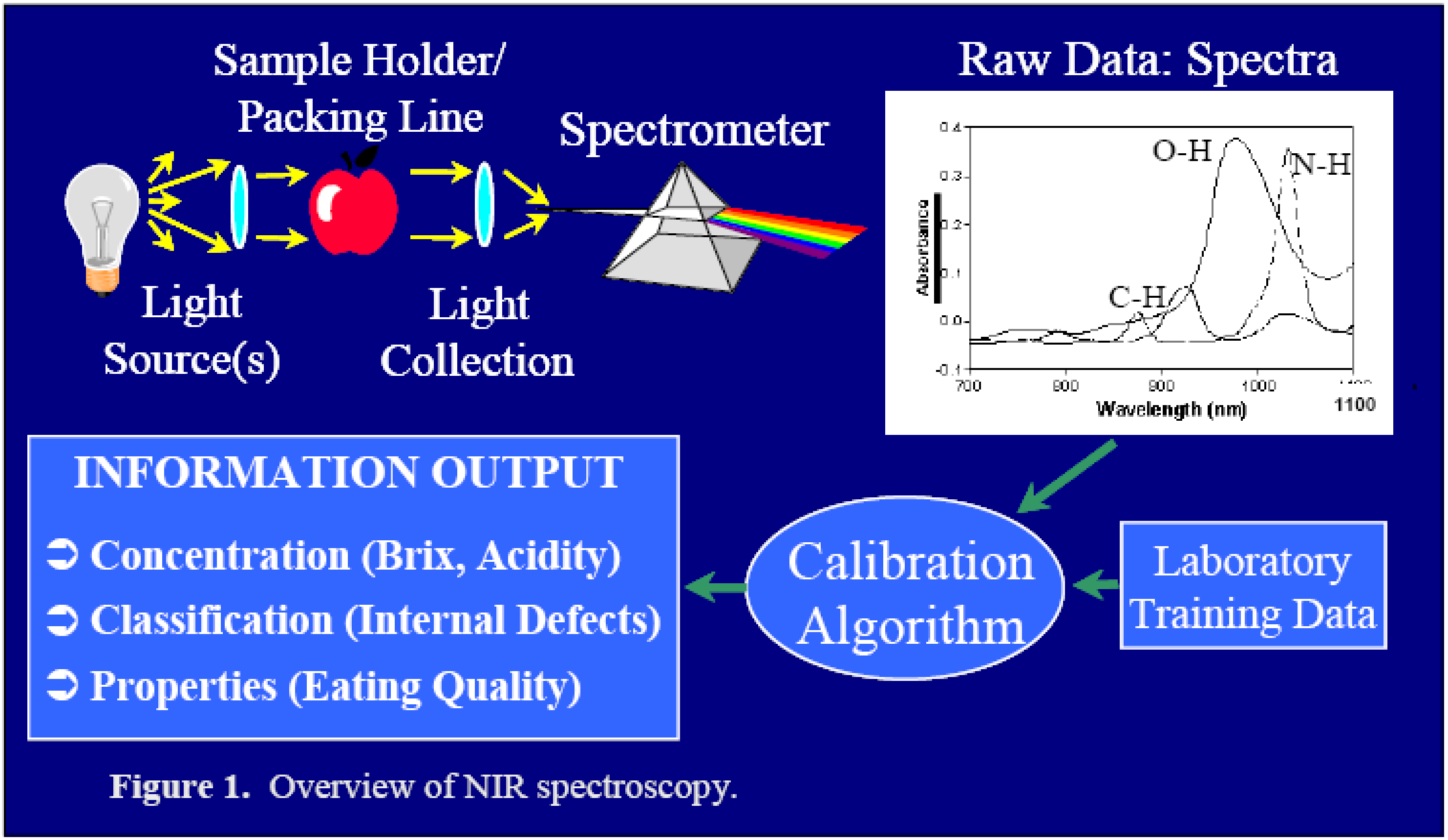


Figure 1. Overview of NIR spectroscopy.

Rich Ozanich, Berkeley Instruments Inc., Richland, WA

Instrumentation for CW NIR spectroscopy

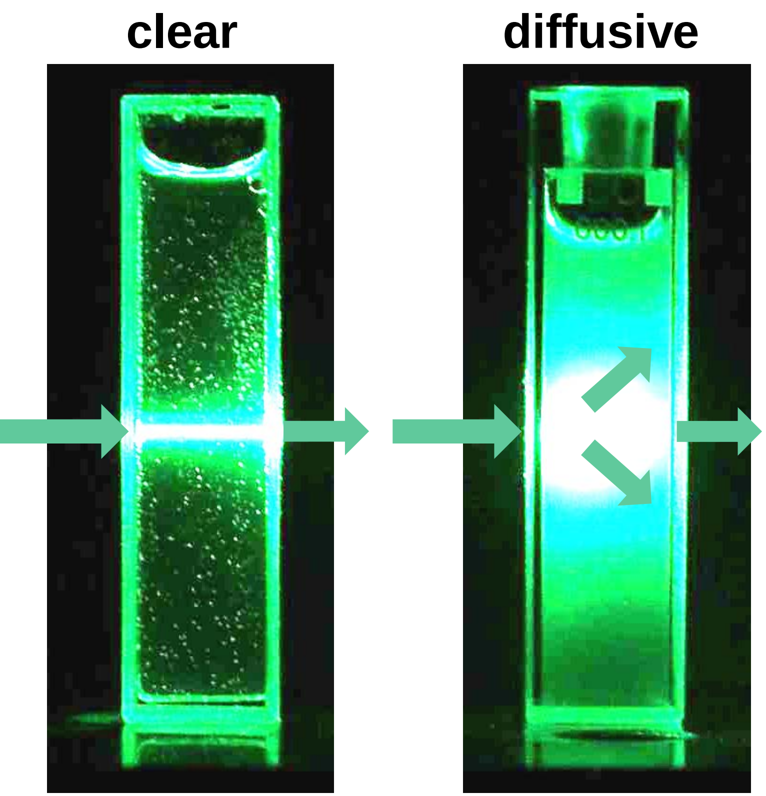
HL200 Ocean Optics ≈ 1000 €

Notebook ≈ 1000 €

USB4000 Ocean Optics ≈ 2000 €

DA-meter, courtesy of P. Rozzi, Sinteleia (Italy)

Spider, courtesy of Manuela Zude ATB Potsdam (Germany)



$$I_{out} = I_{in} e^{-\mu_a L} \qquad I_{out} = I_{in} e^{-(\mu_a + \mu_s) L}$$

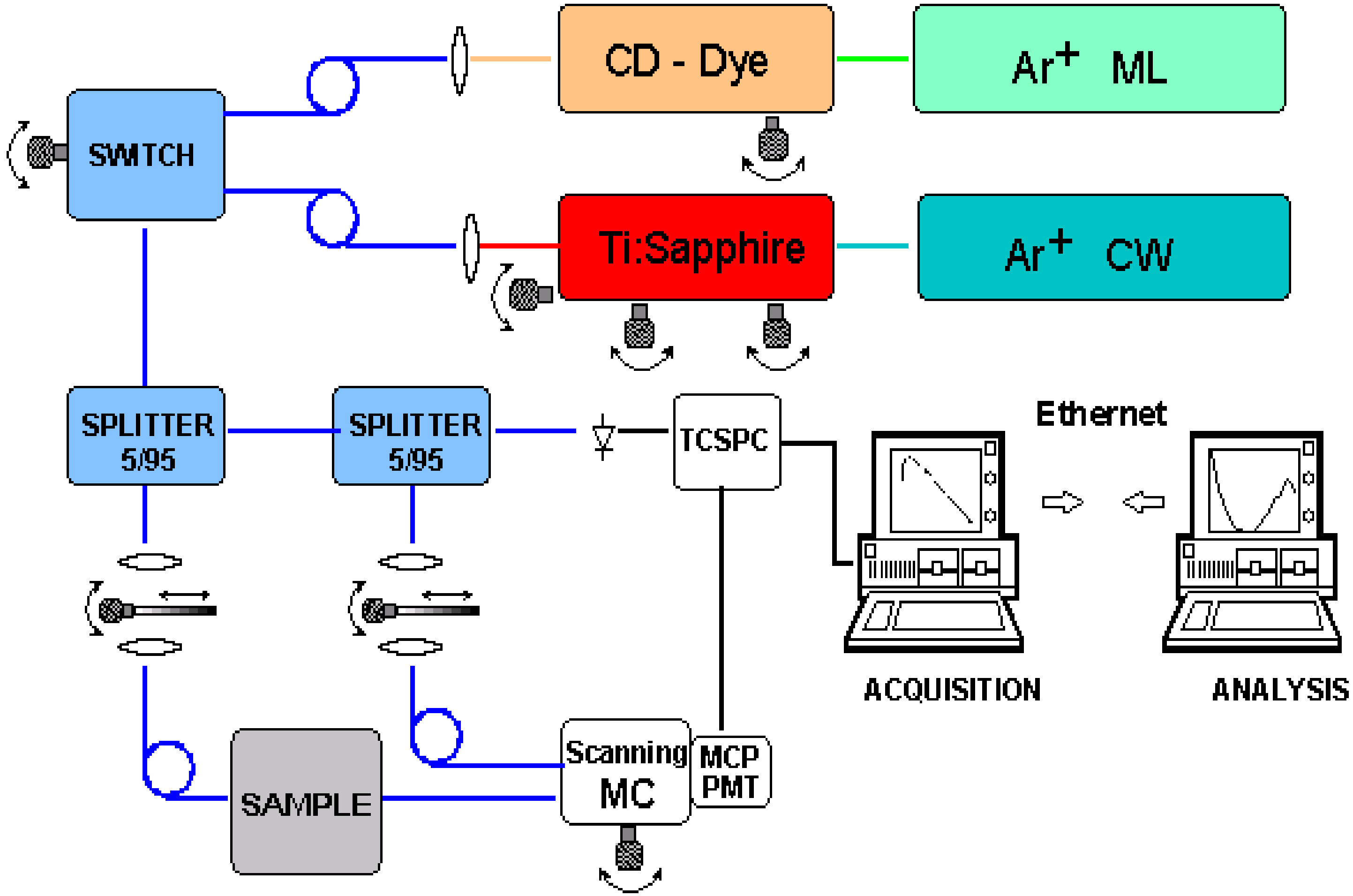
Absorption: related to tissue components

Absorption coefficient:
$\mu_a = 1/\ell_a$ (cm^{-1})

Scattering: related to tissue structure

Scattering coefficient:
$\mu_s = 1/\ell_s$ (cm^{-1})

1st generation TRS
Laboratory set-up for broadband TRS

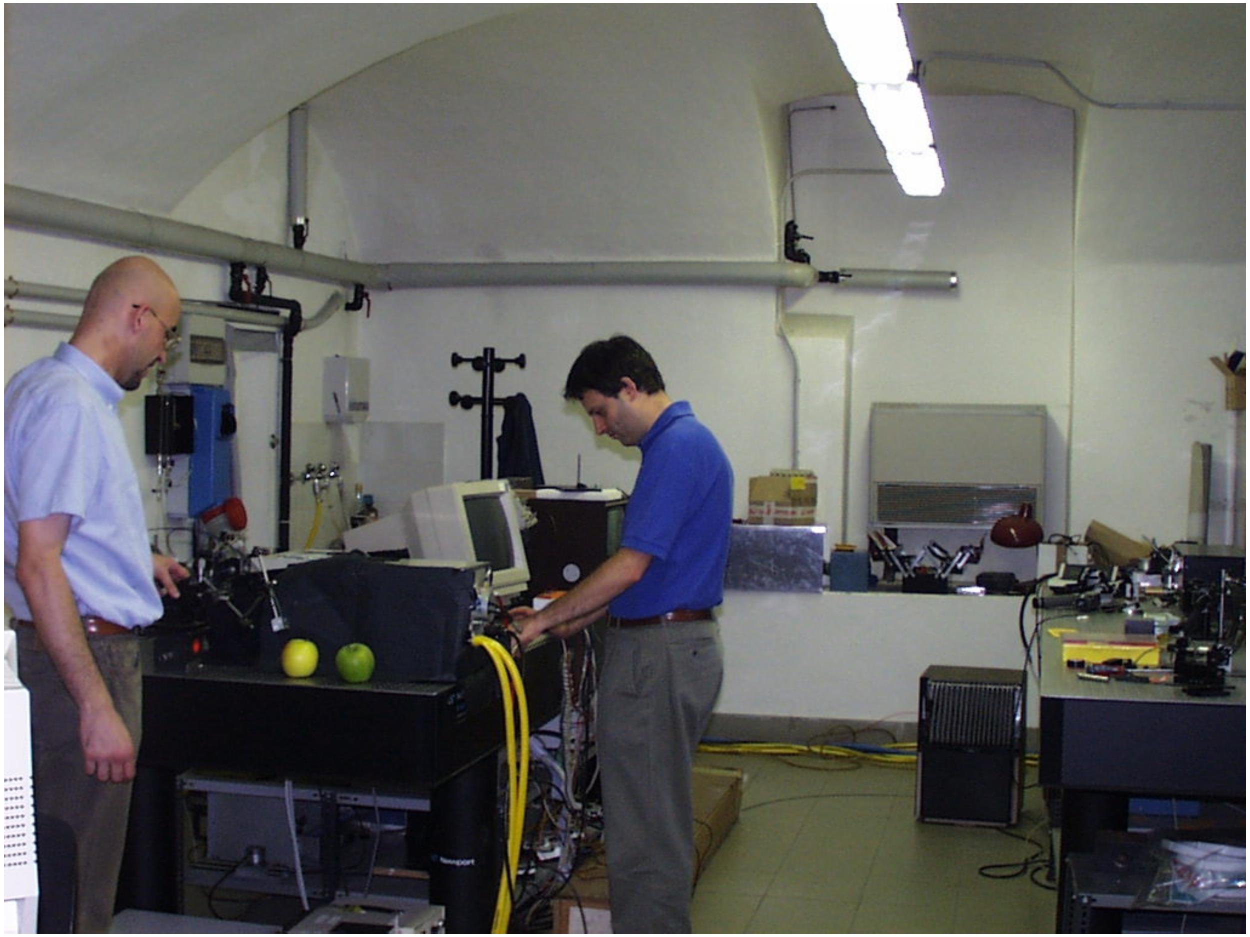


Fully automated system

spectral range: 540 -1100 nm

Pifferi *et al.*, Review of Scientific Instrument 78, 053103 (2007)

Laboratory set-up for broadband TRS



Fully automated system

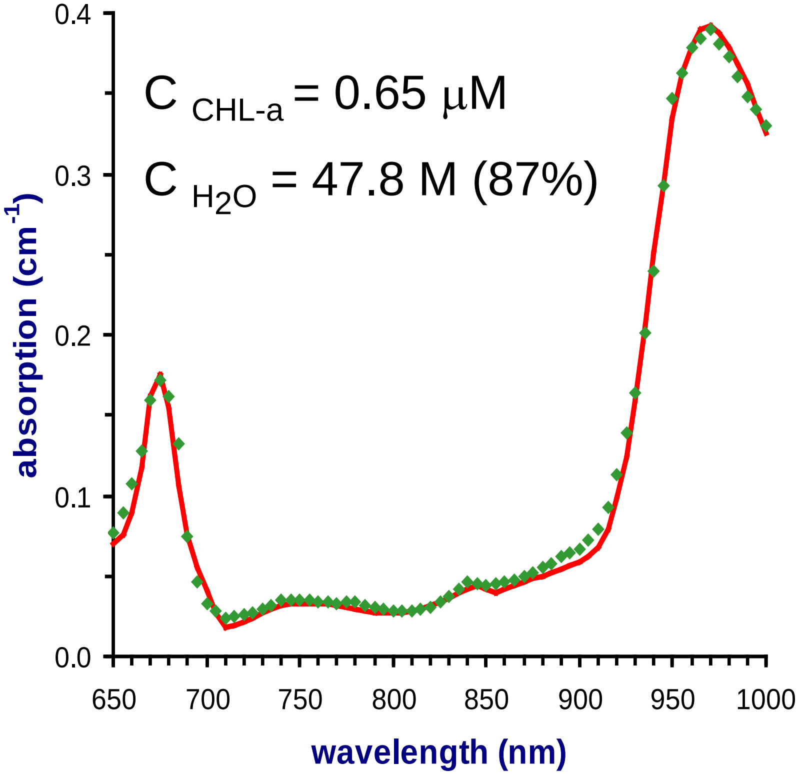
spectral range: 540 -1100 nm

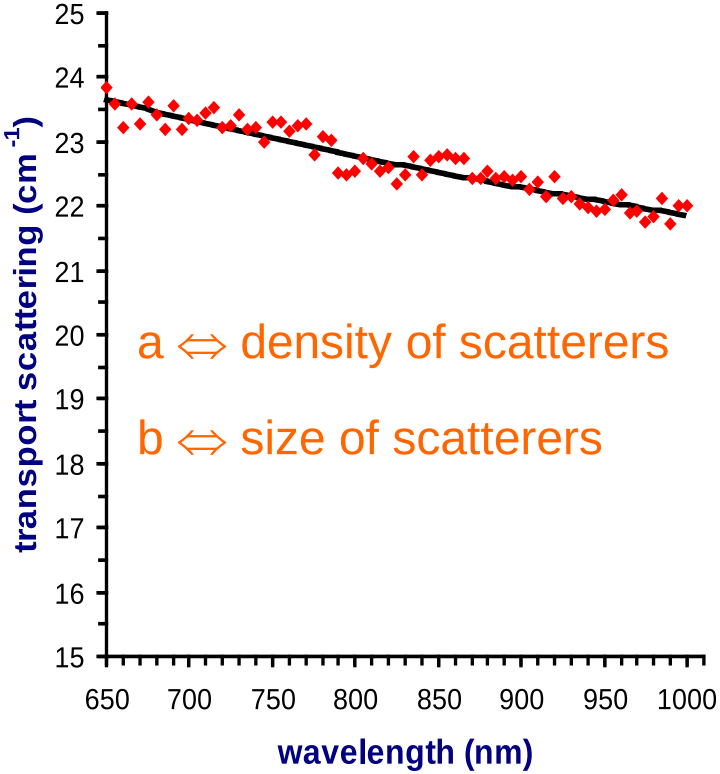
Pifferi *et al.*, Review of Scientific Instrument 78, 053103 (2007)

Quantitative analysis: chemical and structural parameters

Beer's law $$\mu_a(\lambda) = \sum_i C_i \, \varepsilon_i(\lambda)$$

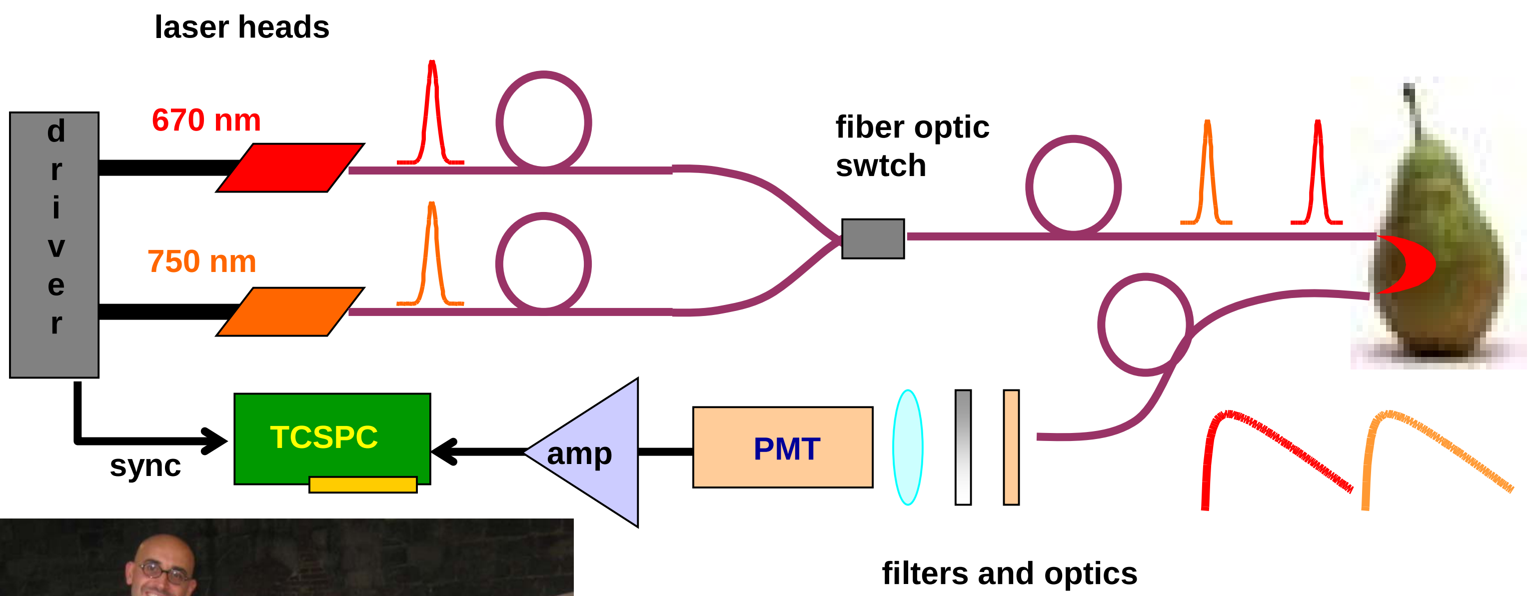
Mie theory $$\mu_s'(\lambda) \approx a\, \lambda^{-b}$$





Cubeddu *et al.*, Applied Optics 40:538-543 (2001)

Dual-wavelength transportable system for TRS

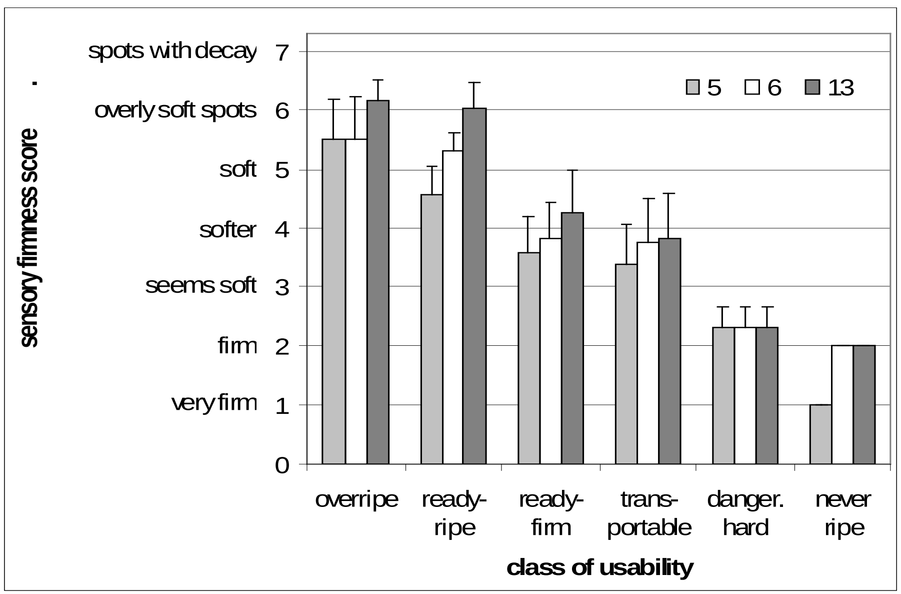


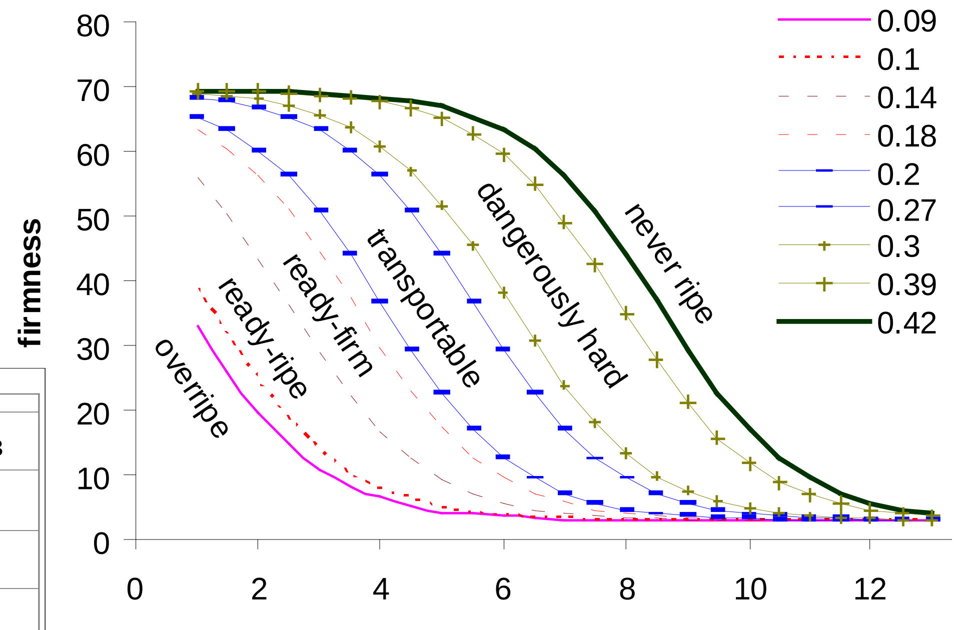
Cubeddu *et al.*, Appl Spectroscopy 55:1368-1374 (2001)
Torricelli *et al.* Sens. & Instrumen. Food Qual. 2:82–89 (2008)

Nondestructive assessment of maturity at harvest

$$\Delta t_F^{*} = \alpha\left(\log\left(\frac{\mu_{a,max}}{\mu_a} - 1\right) + \beta\right)$$

$$F = \frac{F_{max} - F_{min}}{1 + e^{k_f \cdot (F_{max} - F_{min}) \cdot t + \Delta t_F^{*}}} + F_{min}$$





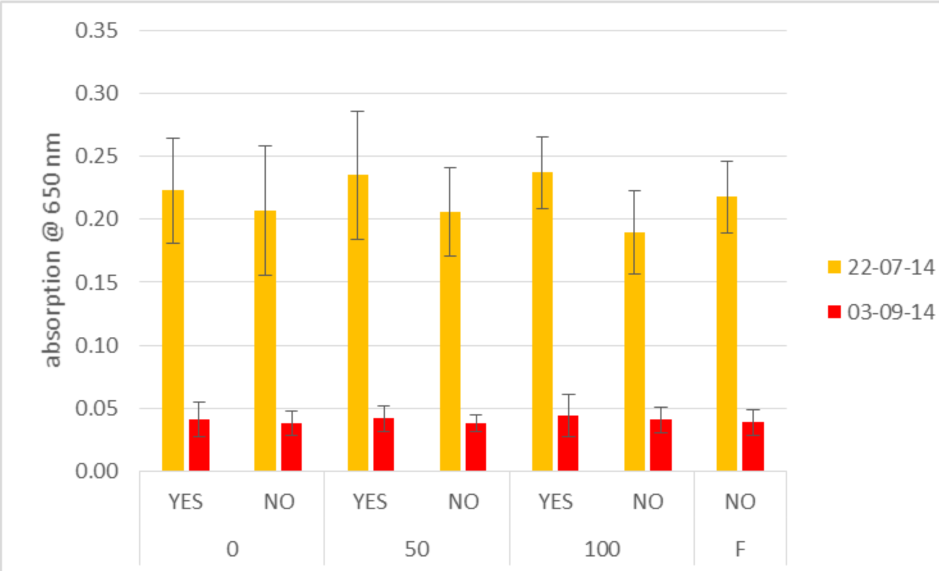
Eccher Zerbini *et al.*, Postharvest Biology and Technology 39:223-232 (2006)
Tijskens *et al.*, Int. J. Postharvest Technology and Innovation, 1 (2), 178-188 (2006)
Tijskens *et al.*, Postharvest Biology and Technology 45:204-213 (2007)
Eccher Zerbini *et al.*, Biosystems Engineering (2009)

3rd generation
Transportable TRS for measurements in the orchards

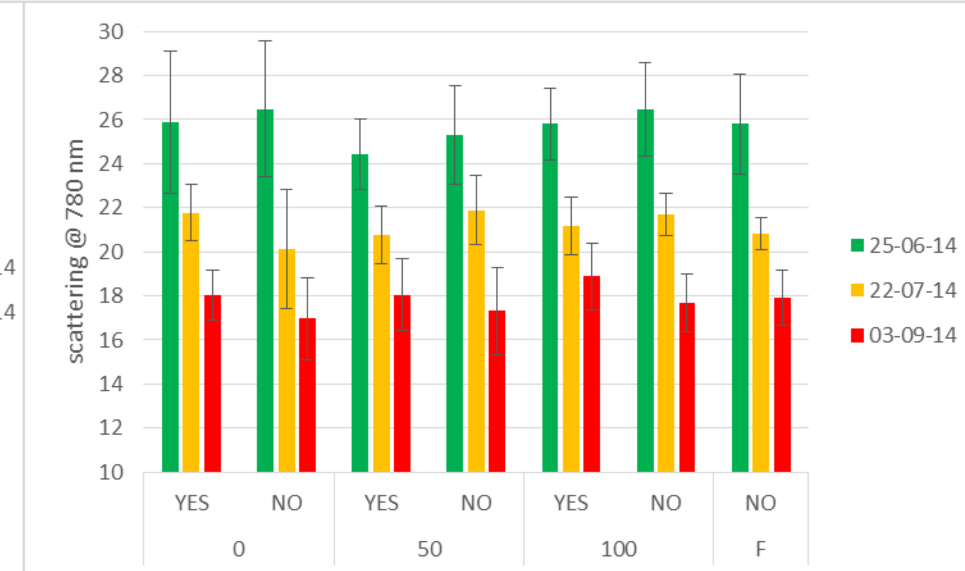
Photo of the TRS set-up

Alessandro Torricelli analysant, à l'aide d'un rayon laser, structure cellulaire et composition chimique du fruit. B. MESSERLI

Absorption coefficient



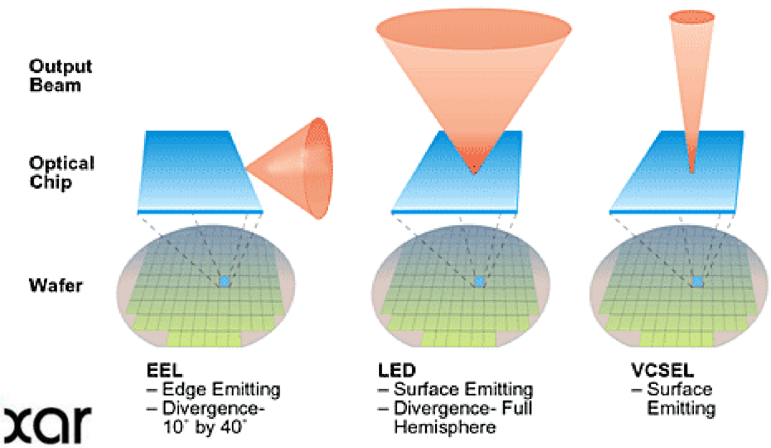
Scattering coefficient



Chlorophyll absorption and scattering decrease during fruit growth
(agreement with Seifert *et al.* Physiologia Plantarum 53(2):327–336 (2015)

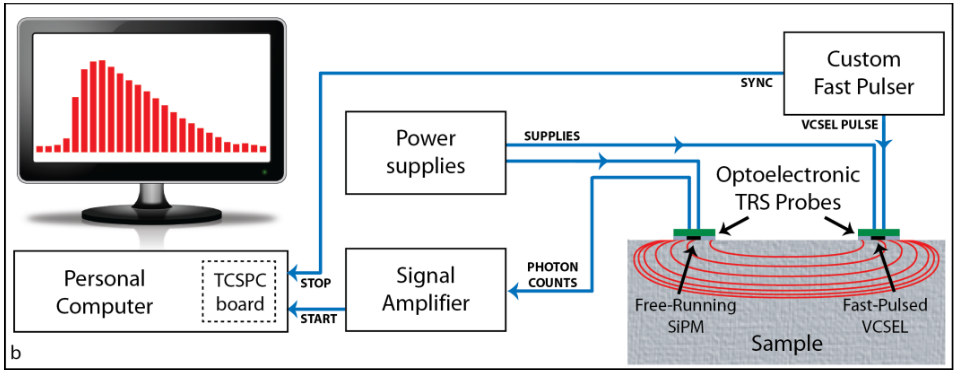
- **In collaboration with**
  - Dominique Fleury, Jeanne Giesser, Reynald Pasche @ University of Applied Sciences: Changins (VD), Switzerland
  - Jana Kaethner, Manuela Zude @ Leibniz Institute for Agricultural Engineering Potsdam-Bornim, Potsdam, Germany

Next generation TRS
VCSEL + SiPM

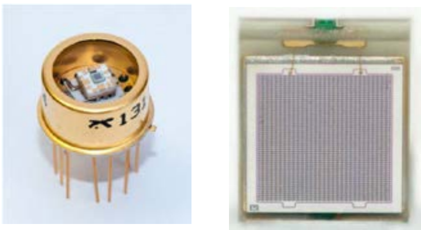


Vixar

Feature	Edge Emitter	LED	VCSEL
Power dissipation	Med-High (10s-100s mW)	High (100s mW)	Lowest (a few mW)
Beam quality, ease of coupling	Fair (asymmetric, wider divergence)	Poor (very wide divergence, incoherent)	Best (round low divergence beam)
Speed	Fair (0.1-1 Gbps)	Slow (10-100 Mbps)	Fastest (1-10 Gbps)
Temperature stability	Fair (3nm/K)	Fair (~3nm/K)	5X better (0.6nm/K)



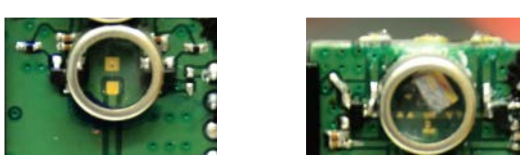
1 x 1 mm^2 3 x 3 mm^2

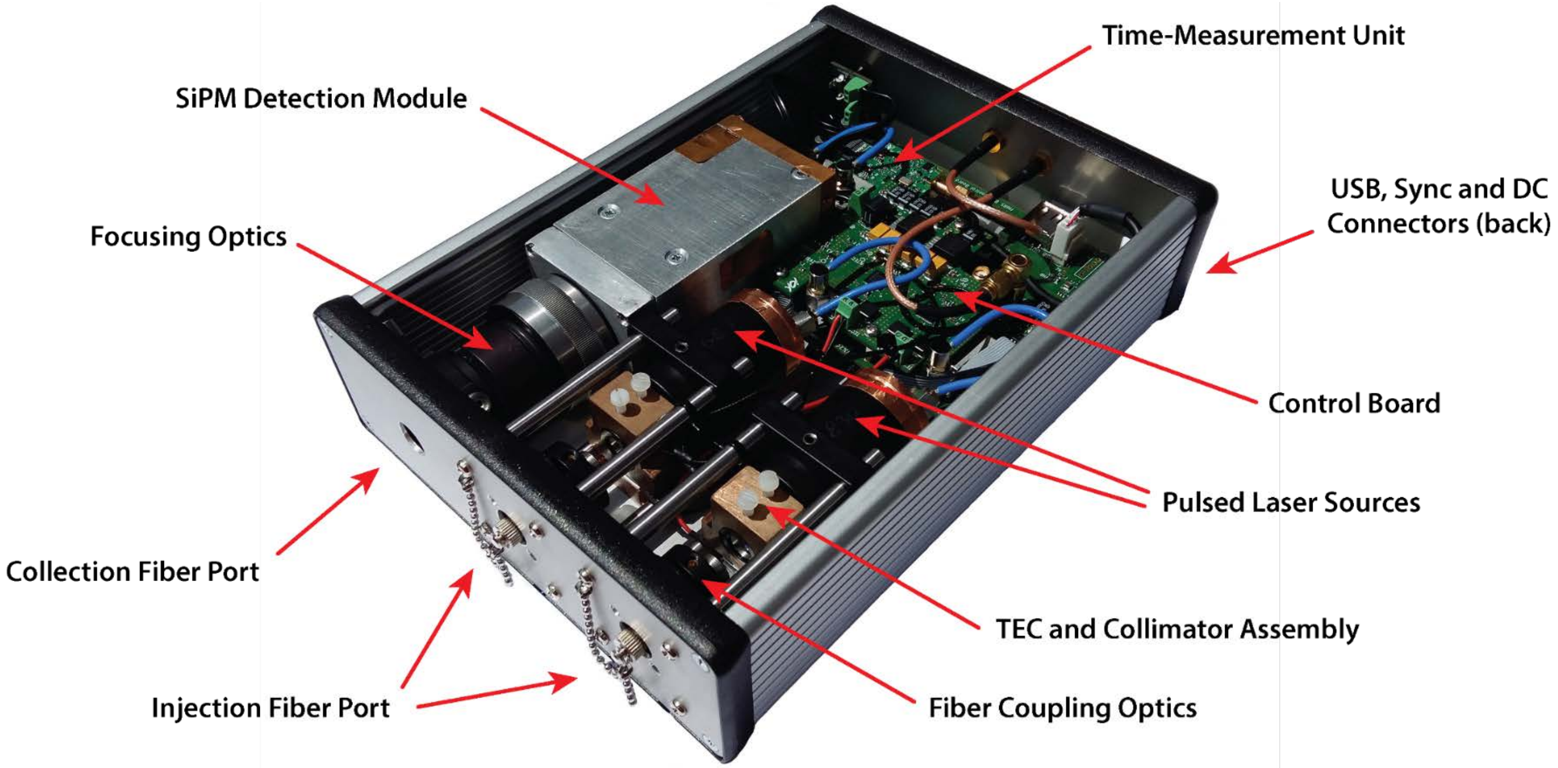


EXCELITAS TECHNOLOGIES

Features
- Low afterpulse
- High fill factor
- High photon detection efficiency
- Wide operating voltage range
- Short recovery time
- High count rate
- High dark count rate

30 mm





total power consumption lower than 10 W (ready for battery operation)

size 200 x 160 x 50 mm^3

M.Buttafava et al., “A compact two-wavelengths Time-Domain NIRS system based on SiPM and Pulsed Diode Lasers”, IEEE Photonics Journal (2016) in press

Conclusions

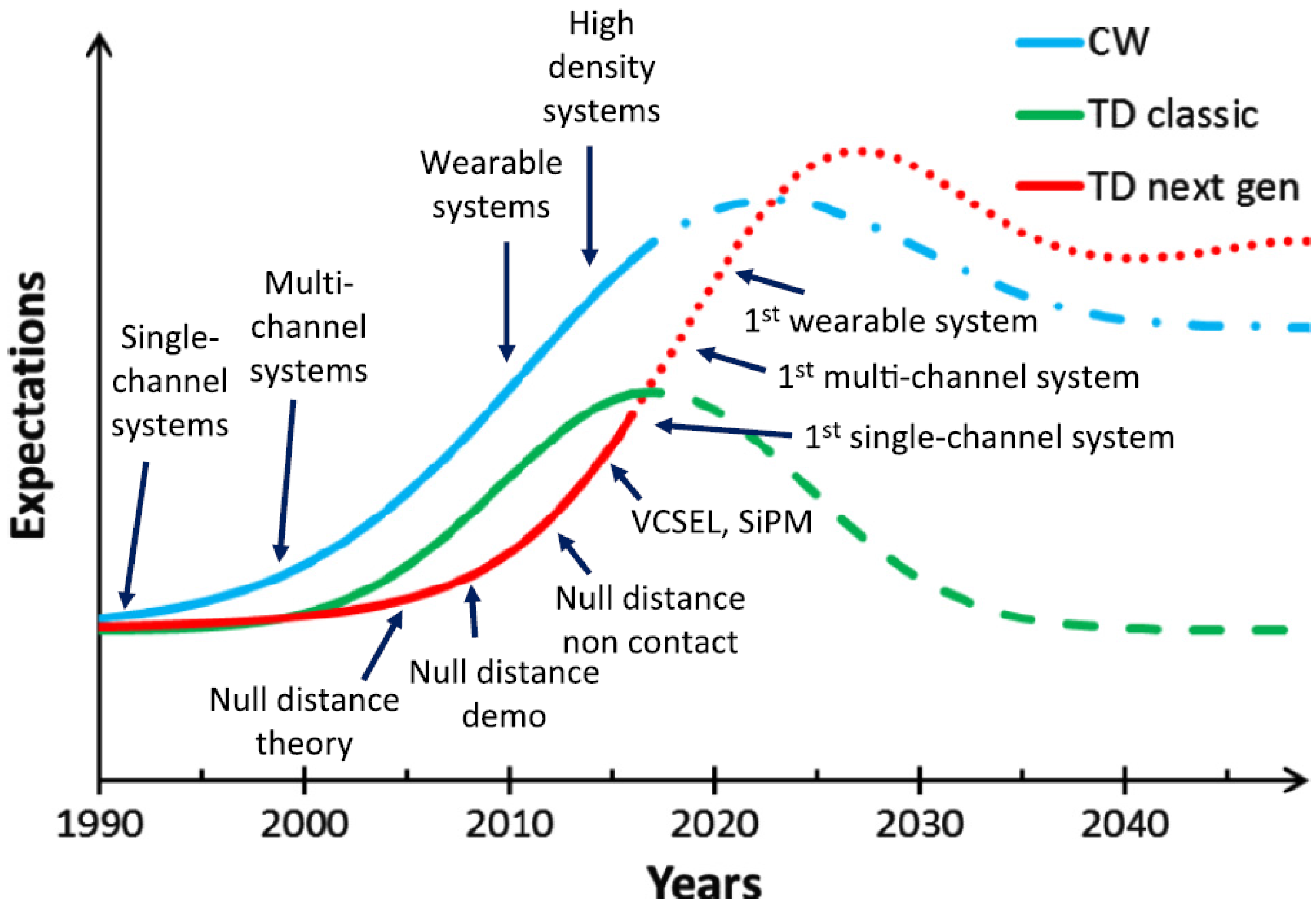
• Time-resolved reflectance spectroscopy (TRS) naturally yields discrimination between light absorption (related to tissue constituents) and light scattering (related to tissue structure)

• Physical and mathematical models for TRS are available and allow quantitative data analysis for non destructive fruit quality assessment

• We have demonstrated in the last years several applications of TRS in the health sector at the clinical level and in the food sector, mainly at research level

• We are at the forefront of a new era where recent advances in photonic technologies might allow TRS to bridge the gap between research and market (the development is mostly driven by the biomedical sector)

CW and TRS hype-cycle for the biomedical field



A. Pifferi et al.,"New frontiers in time-domain diffuse optics, a review," J. Biomed. Opt. 21(9), 091310 (2016), doi: 10.1117/1.JBO.21.9.091310.

Acknowledgments

People

- M. Vanoli, A, Rizzolo, M. Grassi, CRA-IAA, Milan (I)
- A. Zanella, Laimburg (I)
- P. Tijskens, P. Eccher-Zerbini, WUR-HPC, Wageningen (NL)
- B. Nicolai, W. Sayes, P. Verboven, KUL-MeBios, Leuven (B)
- D. Fleury, J. Giesser, R. Pasche,
University of Applied Sciences: Changins (CH)
- J. Kaethner, M. Zude, ATB Potsdam-Bornim (D)
- S. Lurie, R. Rud, V. Alchanati, Volcani Center ARO (IL)
- M. Ruiz-Altisent, C.Valero, UPM, ETSI Agronomos Madrid (E)
- D. Johnson, C. Dover, Horiculture Research International, East Malling, (UK)
- …

Funding

- DIFFRUIT, EU FP4, 1996-1999
- TRS APPLE, MAFF (UK), 2000
- AGROTEC, MIUR (I), 2000-2002
- INSIDEFOOD, EU FP7 2009-2013
- TROPICO, Regione Lombardia (I), 2010-2012
- 3D Mosaic, EU ICT-AGRI, 2011-2013
- USER-PA EU ICT-AGRI 2013-2016
- MONALISA, Autonome Provinz Bozen - Südtirol