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Infrared spectroscopy with synchrotron and FEL radiation

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SISSI-Bio & TeraFERMI

1st on-line School on Synchrotron Radiation "Gilberto Vlaic": Fundamentals, Methods and Application

13-17 September 2021
Virtual

Outlines

Part 1_ Infrared spectroscopy with synchrotron radiation

- Infrared Synchrotron Radiation: production and properties
- Far-field FTIR microscopy
- Near-field FTIR nanoscopy

Part 2_ THz studies with SR and FEL radiation

- The THz spectral range
- THz spectroscopy with Synchrotron Radiation
- THz non-linear studies

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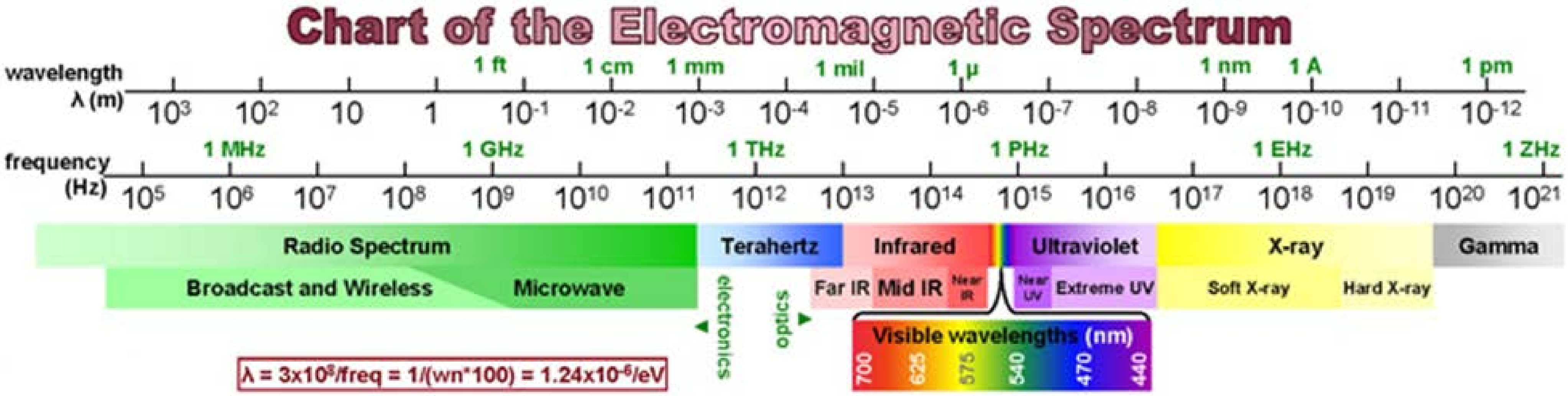
Infrared Spectroscopy with Synchrotron Radiation

Electromagnetic Spectrum

A closer view into the IR-THz spectral range



	NIR	MIR		FIR	THz
λ (μm)	0.74	3	30	300	3000
$\overline{\nu}$ (THz)	400	100	10	1	0.1
ν (cm^{-1})	~13000	~3333	~333	~33	~0.33
E (eV)	1.65	0.413	0.041	0.004	0.0004
E (Kcal/mol)	37	10	1	0.1	0.01

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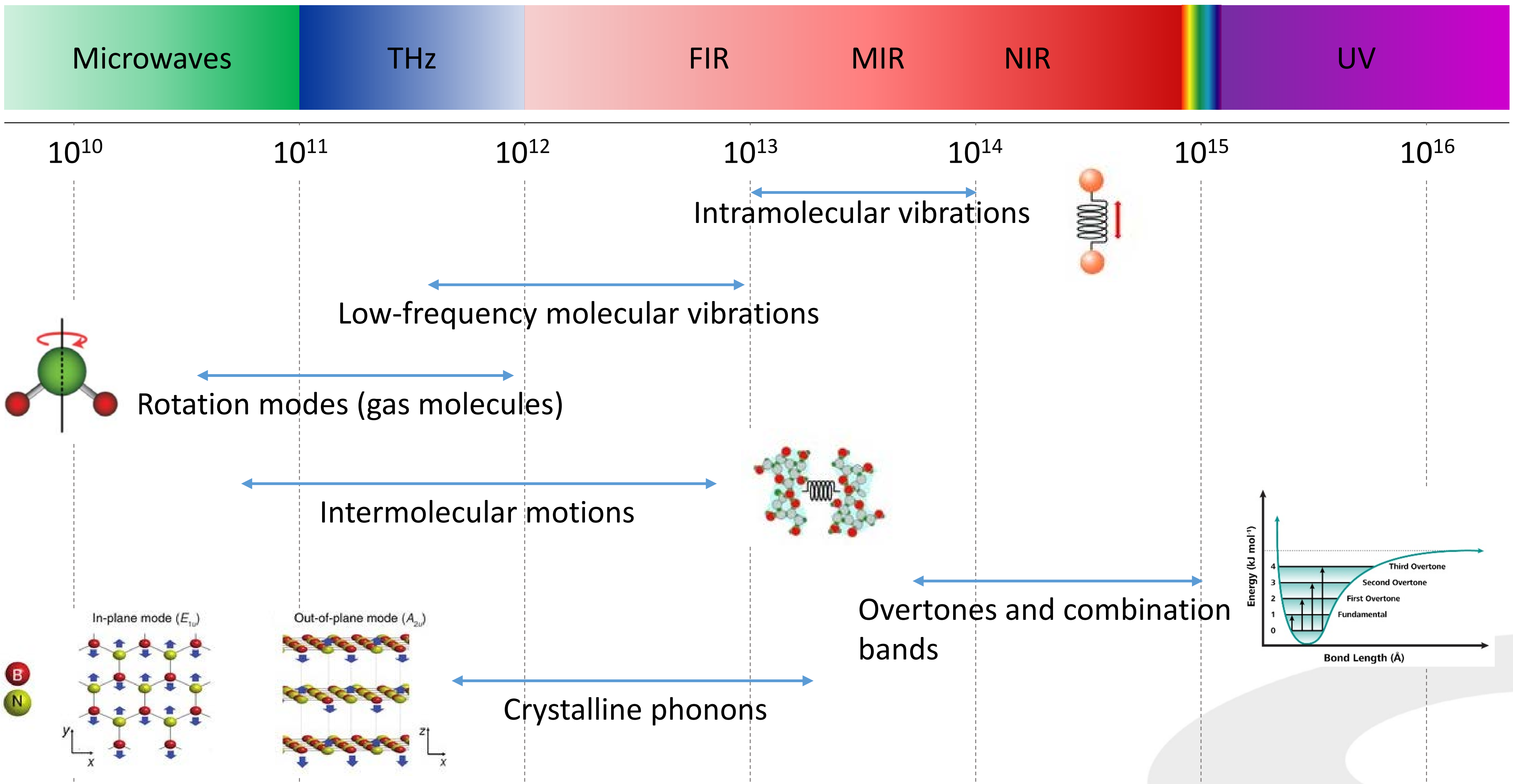
What is IR spectroscopy used for?



Infrared vibrational spectroscopy: Basic concepts on theory

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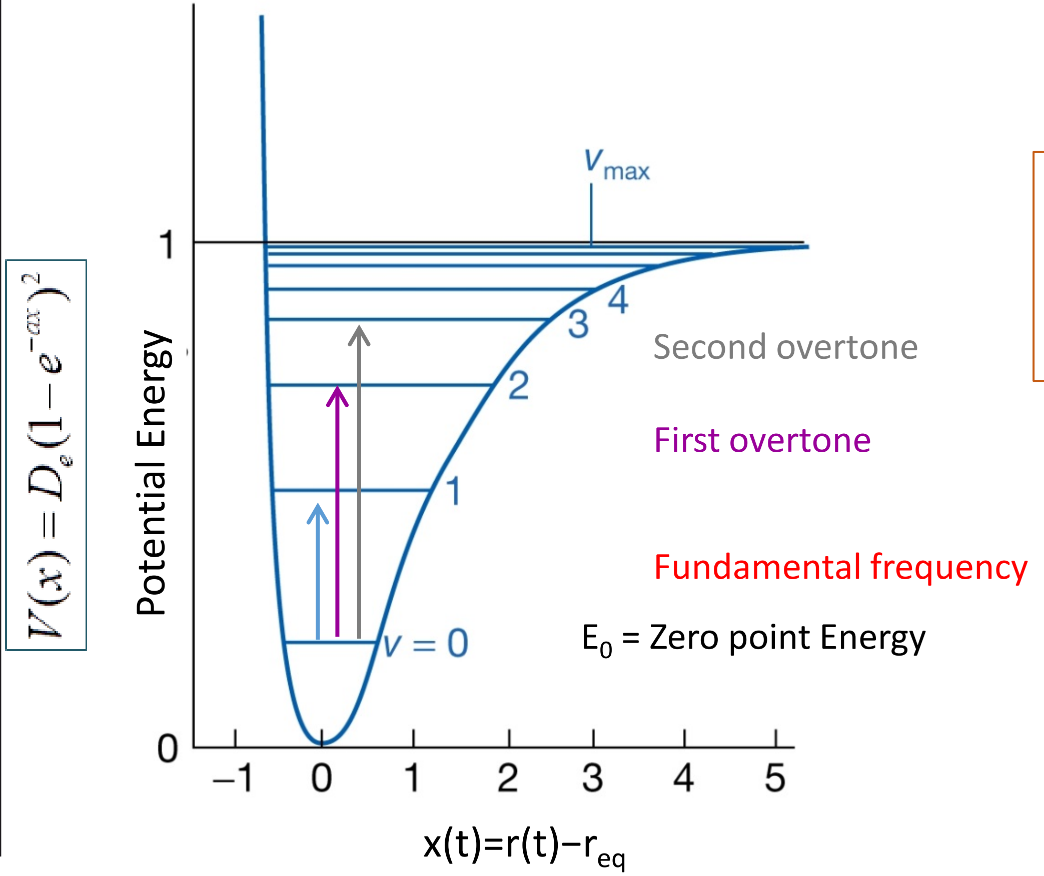
Quantum mechanical Model of anharmonic oscillator

$$E_{vib} = h\nu_e[(n+1/2) - x_o(n+1/2)^2 + higher\ terms\ ]$$

$$\nu_e = \text{harmonic frequency} \quad x_0 = \text{anharmonic constant}$$



Selection Rules

$$\mu_{trans} = \left(\frac{d\mu}{dx}\right)\langle\psi_n|x|\psi_{n'}\rangle$$

$$\mu_{trans} \neq 0$$

$$\left(\frac{d\mu}{dx}\right) \neq 0$$

$$\langle\psi_n|x|\psi_{n'}\rangle \neq 0$$

Δn=±integer

Overtone bands are observed, with frequencies usually lower than the whole multiples of fundamental.

Combination bands are also allowed (two vibrational quantum number changes at the same time)

Infrared vibrational spectroscopy: Basic concepts on theory

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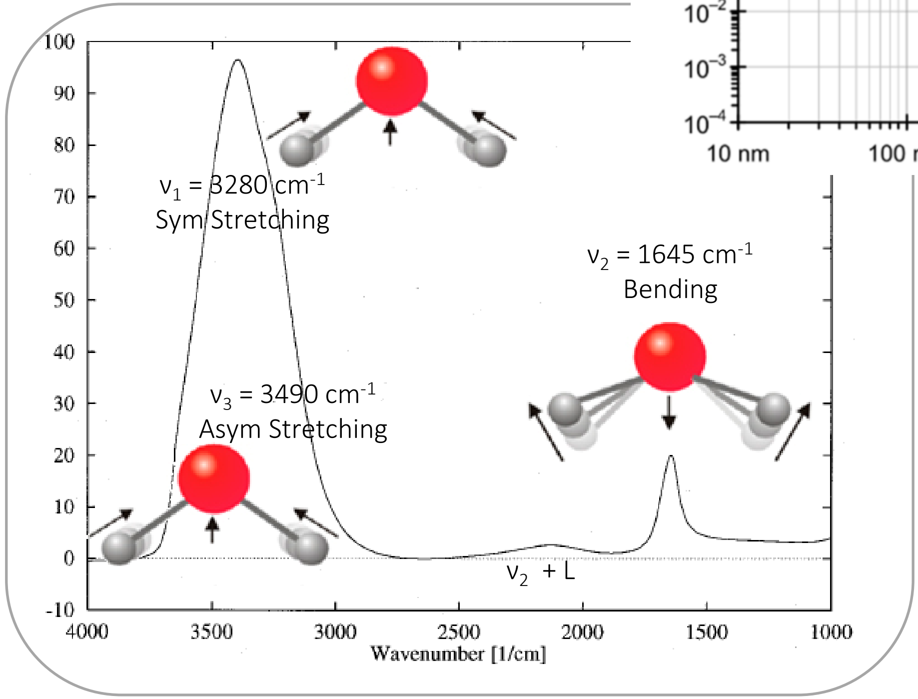
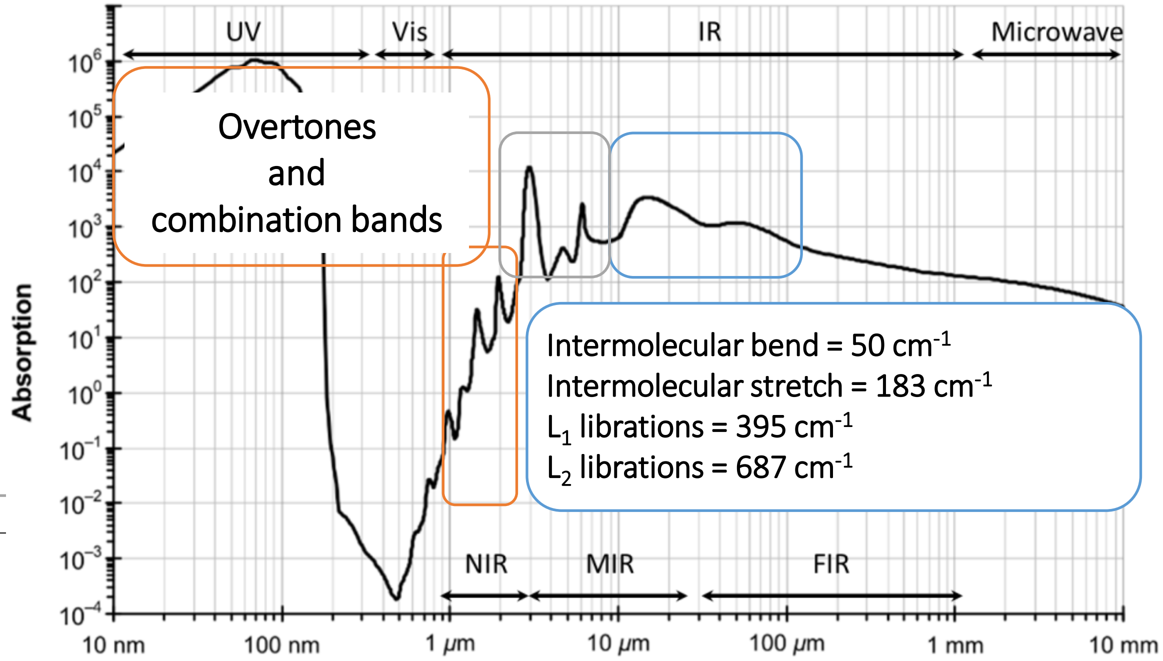
Polyatomic molecules

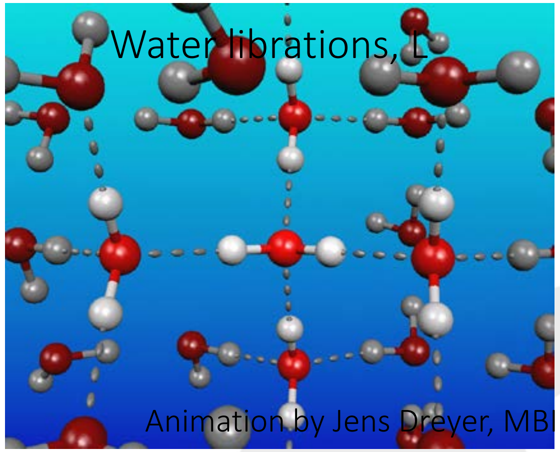
Normal modes of vibrations

3N-6 (5)

Vibrational Spectrum of liquid water







Infrared Spectroscopy: a brief history

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Volume I. *July–August, 1893.* *Number 1.*

THE

PHYSICAL REVIEW.

A STUDY OF THE TRANSMISSION SPECTRA OF CERTAIN SUBSTANCES IN THE INFRA-RED.

By Ernest F. Nichols.

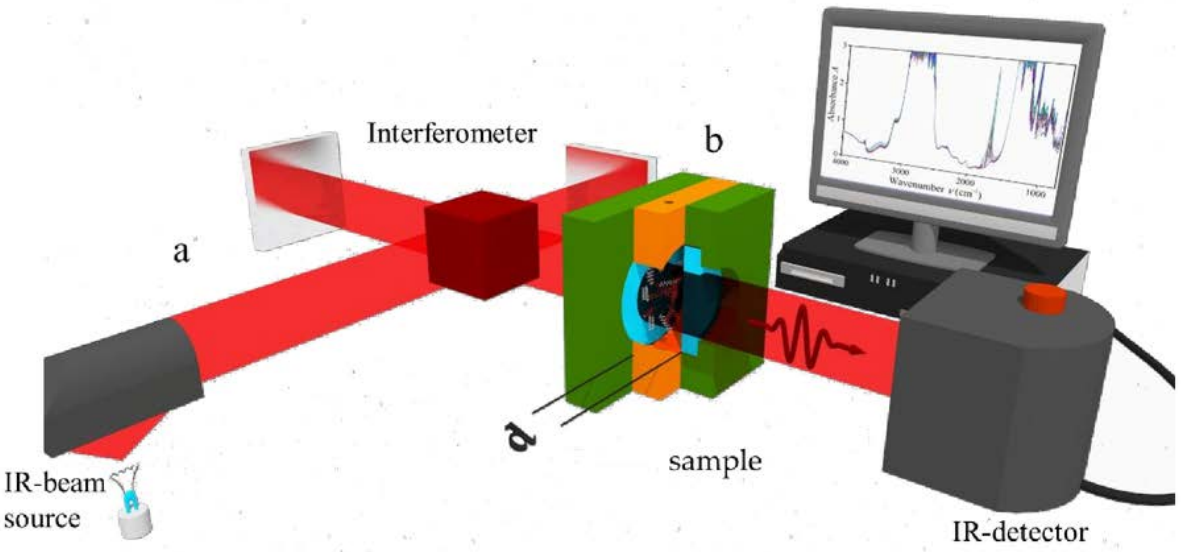
Within a few years the study of obscure radiation has been greatly advanced by systematic inquiry into the laws of dispersion of the infra-red rays by Langley,[1] Rubens,[2] Rubens and Snow,[3] and others. Along with this advancement has come the more extended study of absorption in this region. The absorption of atmospheric gases has been studied by Langley[1] and by Ångstrom.[4] Ångstrom[5] has made a study of the absorption of certain vapors in relation to the absorption of the same substances in the liquid state, and the absorption of a number of liquids and solids has been investigated by Rubens.[6]

In the present investigation, the object of which was to extend this line of research, the substances studied were: plate glass, hard rubber, quartz, lamp-black, cobalt glass, alcohol, chlorophyll, water, oxyhæmoglobin, potassium alum, ammonium alum, and ammonium-iron alum.

[1] Report on Mt. Whitney Expedition, Profess. Papers, U. S. Signal Service, XV.
[2] Annalen der Physik und Chemie, N. F. XLV., p. 238.
[3] Annalen der Physik und Chemie, N. F. XLVI., p. 529.
[4] Bihang till K. Svenska Vet.-Akad. Handlingar, Band 15, Afd. 1, No. 9.
[5] Ofversigt af Kongl. Vetenskaps-Academiens Forhandlingar, 1890, No. 7, Stockholm.
[6] Annalen der Physik und Chemie, N. F. XLV., p. 258.

1

Despite born in the 1800's, infrared spectroscopy became popular only in the second half of the 20th century thanks to advent of Fourier Transform InfraRed (FTIR) interferometer.

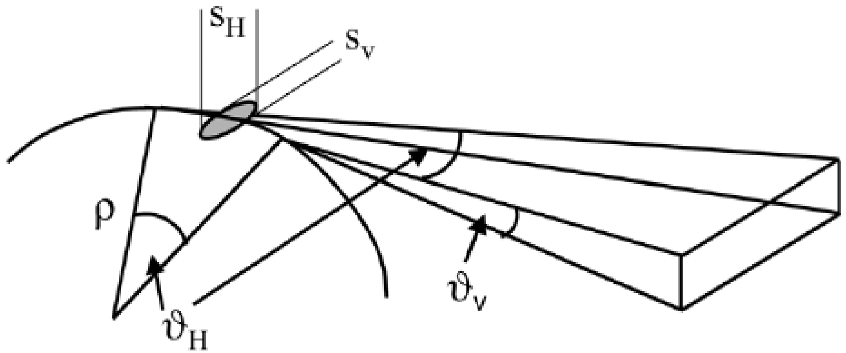


Alex Risos, Nicholas Long, Arvid Hunze, Gideon Gouws, "Mid-IR absorbance and its relation to static permittivity as a robust in-field tool tracking oil deterioration," Proc. SPIE 10215, Advanced Environmental, Chemical, and Biological Sensing Technologies XIV, 102150O

IR beamlines: The Cinderella Story

1976	Meyer and Lagarde (LURE, Orsay) published the first paper on IRSR
1981	Duncan and Yarwood observed at Daresbury the first IRSR emission
1985	The first IRSR spectrum (on N_2O) is collected at Bessy (Berlin)
1986	The first beamline was opened to users at UVSOR (Japan)
1987	Started the brilliant story of IR-beamlines at NSLS Brookhaven (USA)
1992	In Europe: Orsay (France), Lund (Sweden), Daresbury (GB)
1995	First international workshop on IRSR, Rome (Italy)
2001	First IR beamline in Italy (SINBAD@DAΦNE)
2006	Second beamline in Italy (SISSI@Elettra)
⋮	⋮
Today	Many mores

IRSR Generation_Bending Magnet IRSR



$$P_{BM}(\lambda) = 4.38\times10^{14}\times I\times\theta_H\times bw\times\left(\frac{\rho}{\lambda}\right)^{1/3}\quad \text{photons}\cdot\text{s}^{-1}\quad [1]$$

$I =$ Current (A)

$\theta_H =$ Horizontal Collection Angle (rads)

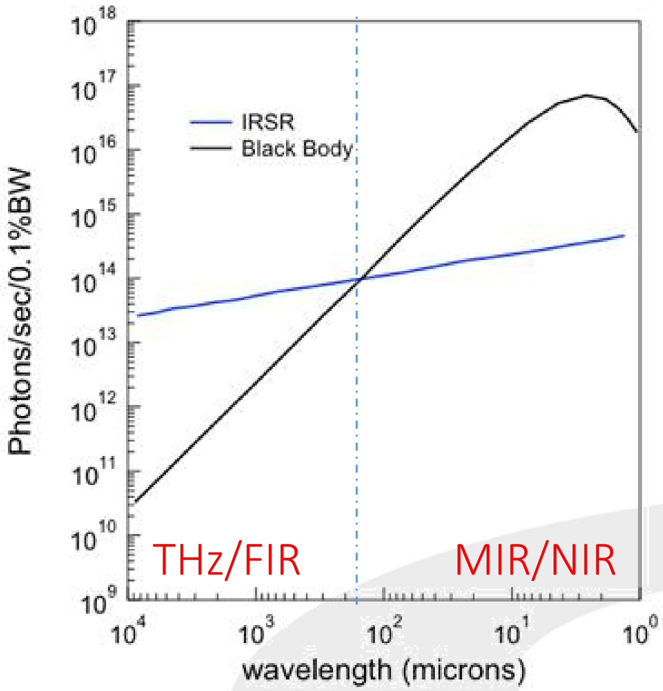
$bw =$ Bandwidth (%)

$\rho, \lambda =$ Radius of the ring, Wavelength (same units)

P(λ) as obtained in [1], in the spectral range 1 to 10^4 µm (10^4 to 1 cm^{-1}), for a current of **1 A**, a horizontal angle ***ϑ*$_H$ = 100 mrads** and ***ρ* = 5 m**.
Comparison with the emission for a BB source at 2000K.

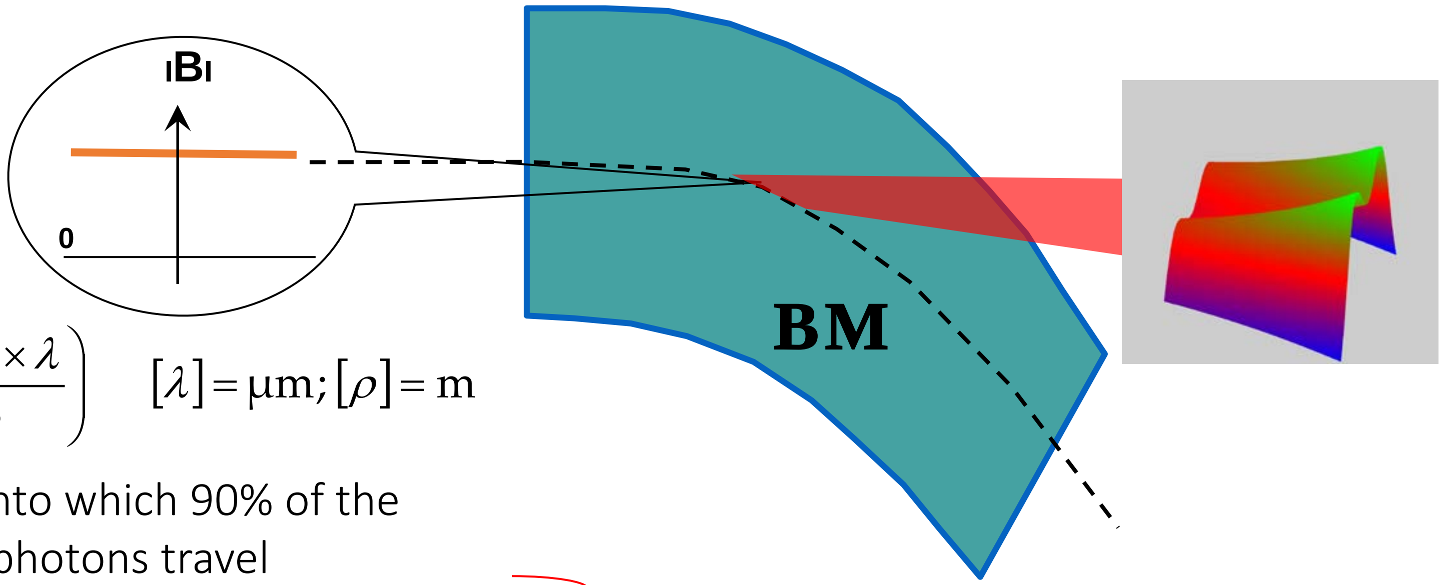
Extrapolation of the Schwinger equations (1949) by WD Ducan and GP William (1980s)

Infrared synchrotron radiation from electron storage rings; Appl Opt. 1983 22(18):2914.



IRSR Generation_Bending Magnet IRSR

Constant Field Emission



$$\theta_{V-Nat} = 1.66\left(\frac{1000\times\lambda}{\rho}\right) \qquad [\lambda]=\mu m; [\rho]=m$$

Angular range into which 90% of the emitted photons travel

	λ [μm]	υ [cm^{-1}]	THz	$\theta_{V\text{-}Nat}$
NIR	1	10000	300	9.2
	10	1000	30	19.8
	100	100	3	42.2
FIR	1000	10	0.3	90.3

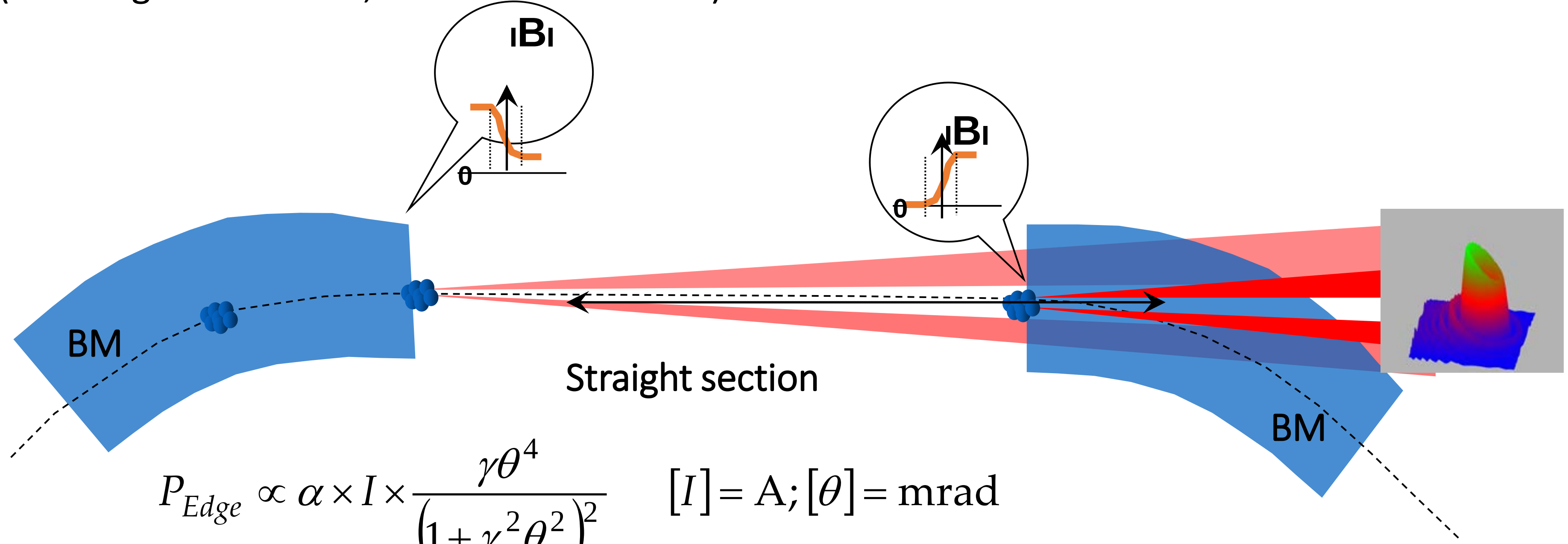
Calculated for Elettra ρ = 5.5 m.

Very large extraction apertures are needed for IR beamlines for:

- Maximizing the flux (θ_H)
- Allowing efficient extraction of lower energy components of IR synchrotron emission (θv)

IRSR Generation_IR Edge Radiation

Edge radiation is produced when electrons experience a changing magnetic field (entering or exit a BM, where B is constant).



$$P_{Edge} \propto \alpha \times I \times \frac{\gamma\theta^4}{(1+\gamma^2\theta^2)^2} \qquad [I] = \mathrm{A}; [\theta] = \mathrm{mrad}$$

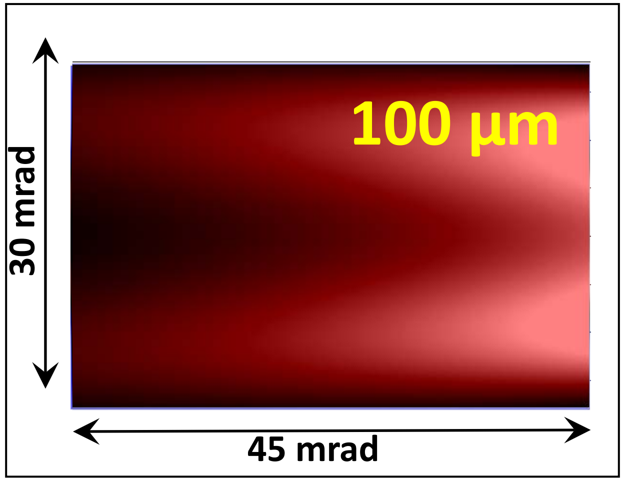
$$\gamma = \text{Lorentz Factor}; \alpha = \text{Fine Structure Constant}$$

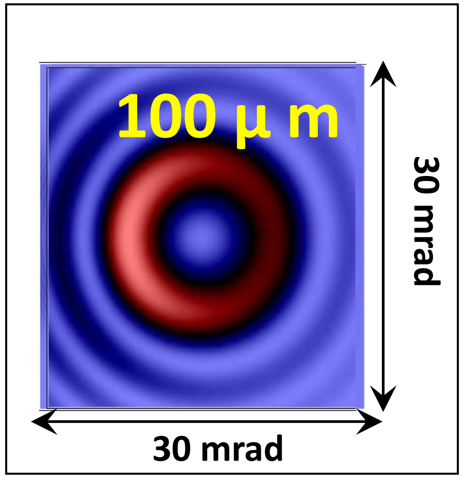
- Edge radiation has a ring structure characterized by interference pattern
- Being **Θ** $_{max}$ ~ 1/ **γ** ~10 mrads, it is spatially confined and intrisically bright
- It is radially polarized

By courtesy of Paul Dumas, SOLEIL

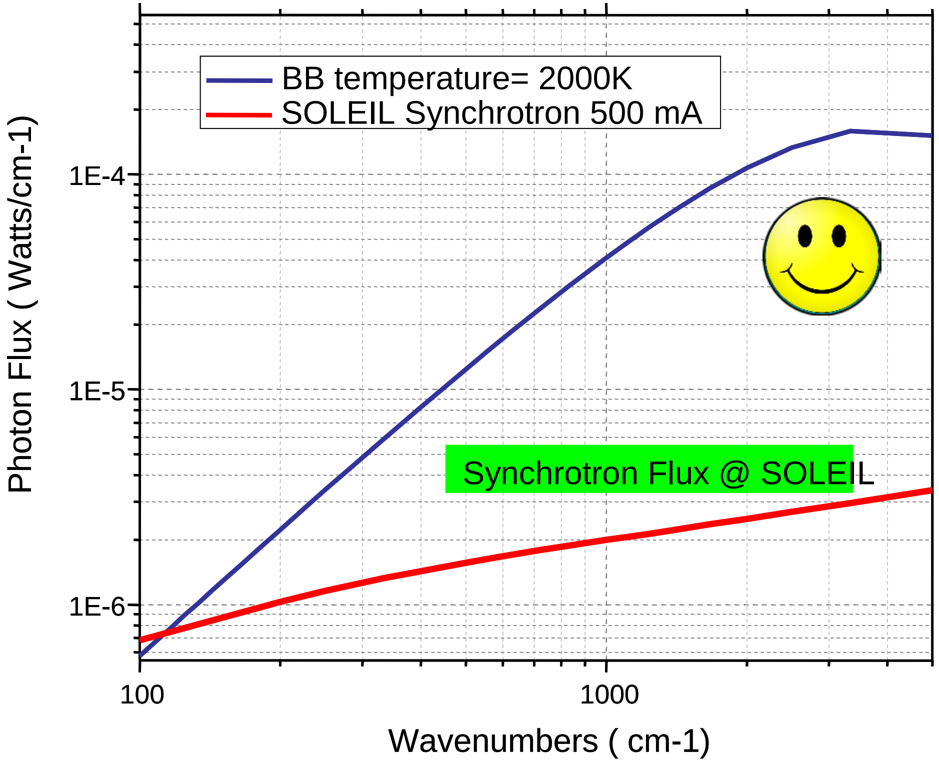
IRSR Generation_IR BM and Edge Radiation

SOLEIL 2.75 GeV 45 mrad H X 30 mrad V BM	*SOLEIL* 2.75 GeV 30 mrad H X 30 mrad V BM





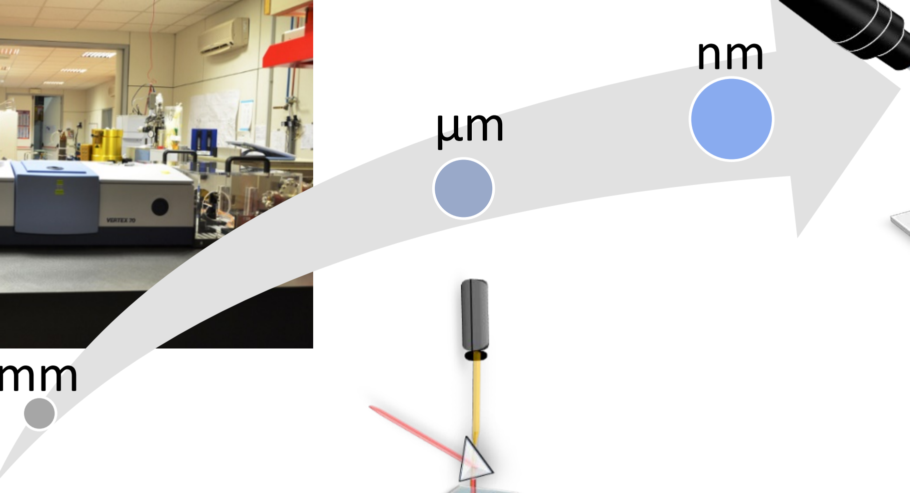
IRSR
The brightness advantage

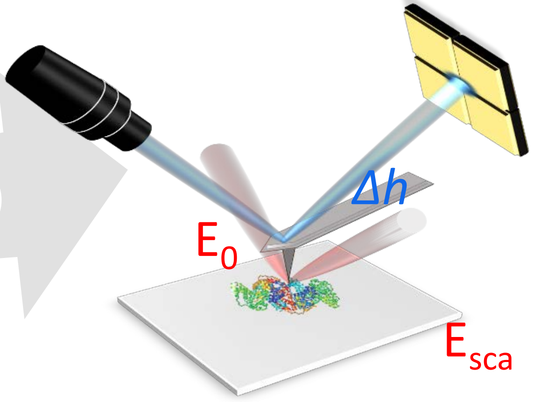


By courtesy of Paul Dumas, SOLEIL

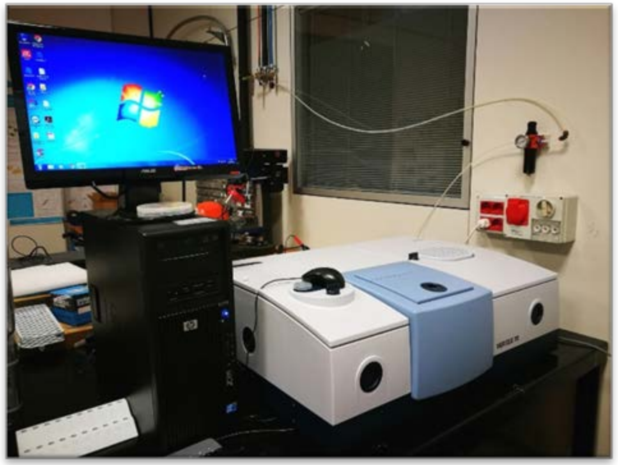
The space domain of infrared

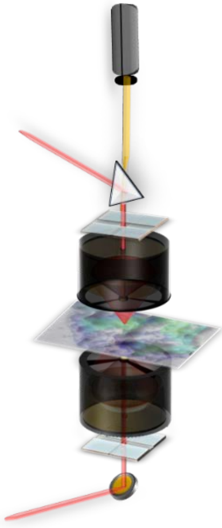
Vibrational information on the sample can be achieved at different level of detail, depending on instrumentation and IR source (IR conventional, IR-Synchrotron radiation, IR laser)





IR spectroscopy



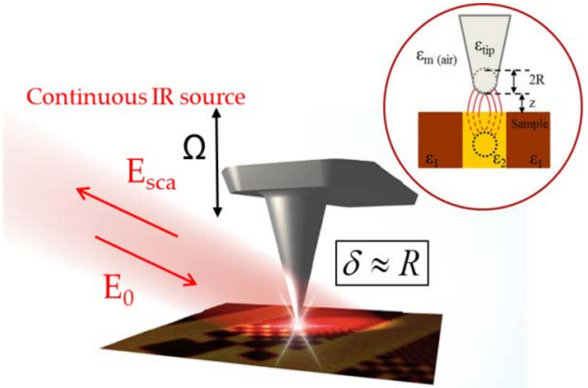


Far Field

IR microscopy

Near filed

IR nanoscopy



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Exploitation of IRSR advantages

Advantage		Application
Flux Adavantage in FIR and THz	• Higher S/N • Faster data collection	FIR and THz spectroscopy
Broad band nature	• Complete data collection	Spectroscopy, Microscopy, Nanoscopy
Polarization	• BM Linear polarization • ER circular polarization	Spectroscopy and Microscopy
Brigthness advantage	• Higher S/N ratio • Faster data collection	Microscopy and Nanoscopy

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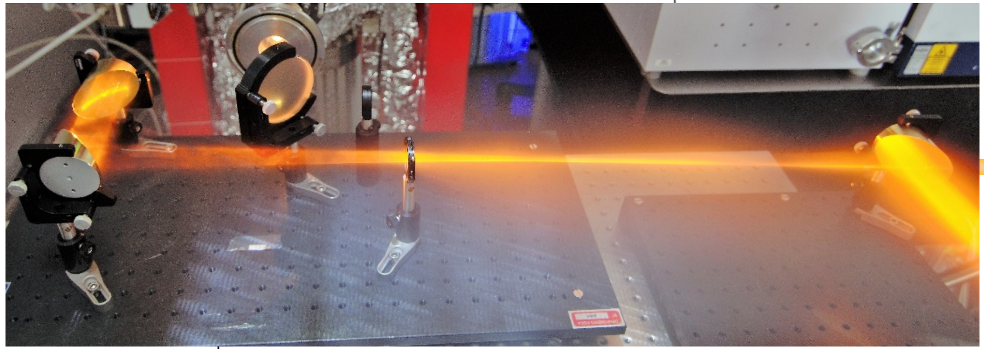
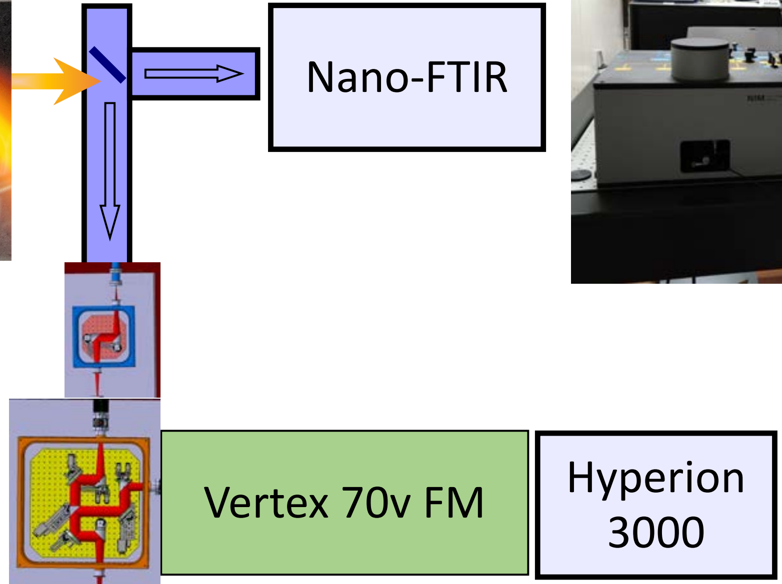
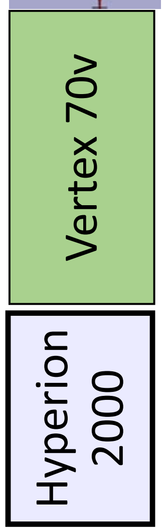
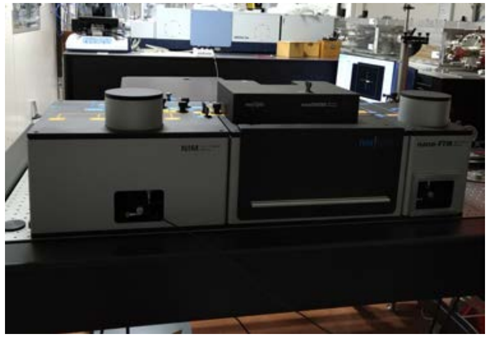
SISSI-Synchrotron Infrared Source for spectroscopy and imaging









SISSI–Nano

The new endstation for IR nanoscopy

IRSR & Lasers

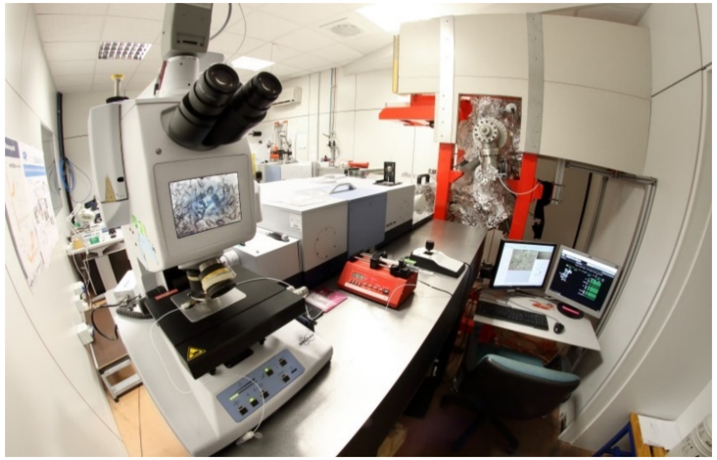
SISSI–MAT

Material Sciences branch

FIR and THz

SISSI–BIO

Chemical and Life Sciences branch



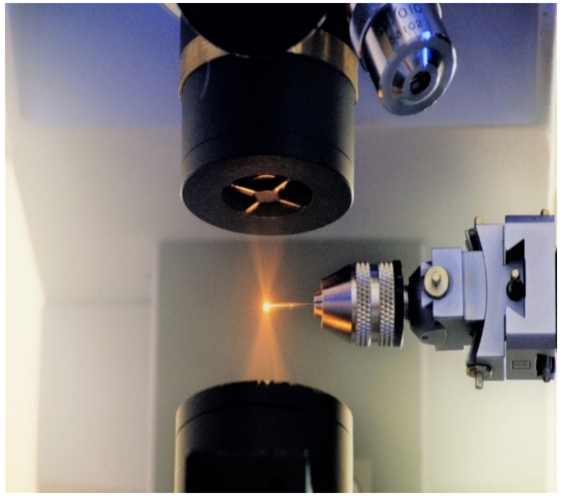
FTIR spectroscopy in the FIR-MIR regime, FTIR imaging and microscopy in the MIR

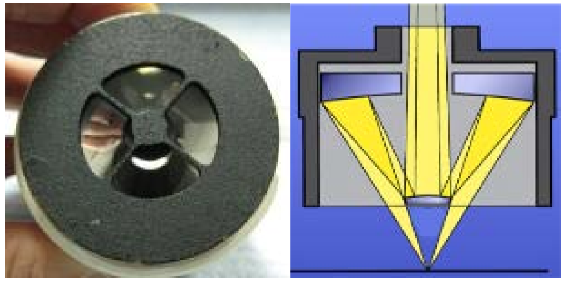
IRSR & Conventional IR source

SISSI-Bio @Elettra - Photo courtesy of CERIC-ERIC , Photographer: Roberto Barnabà

Far-field FTIR microscopy for biospectroscopy

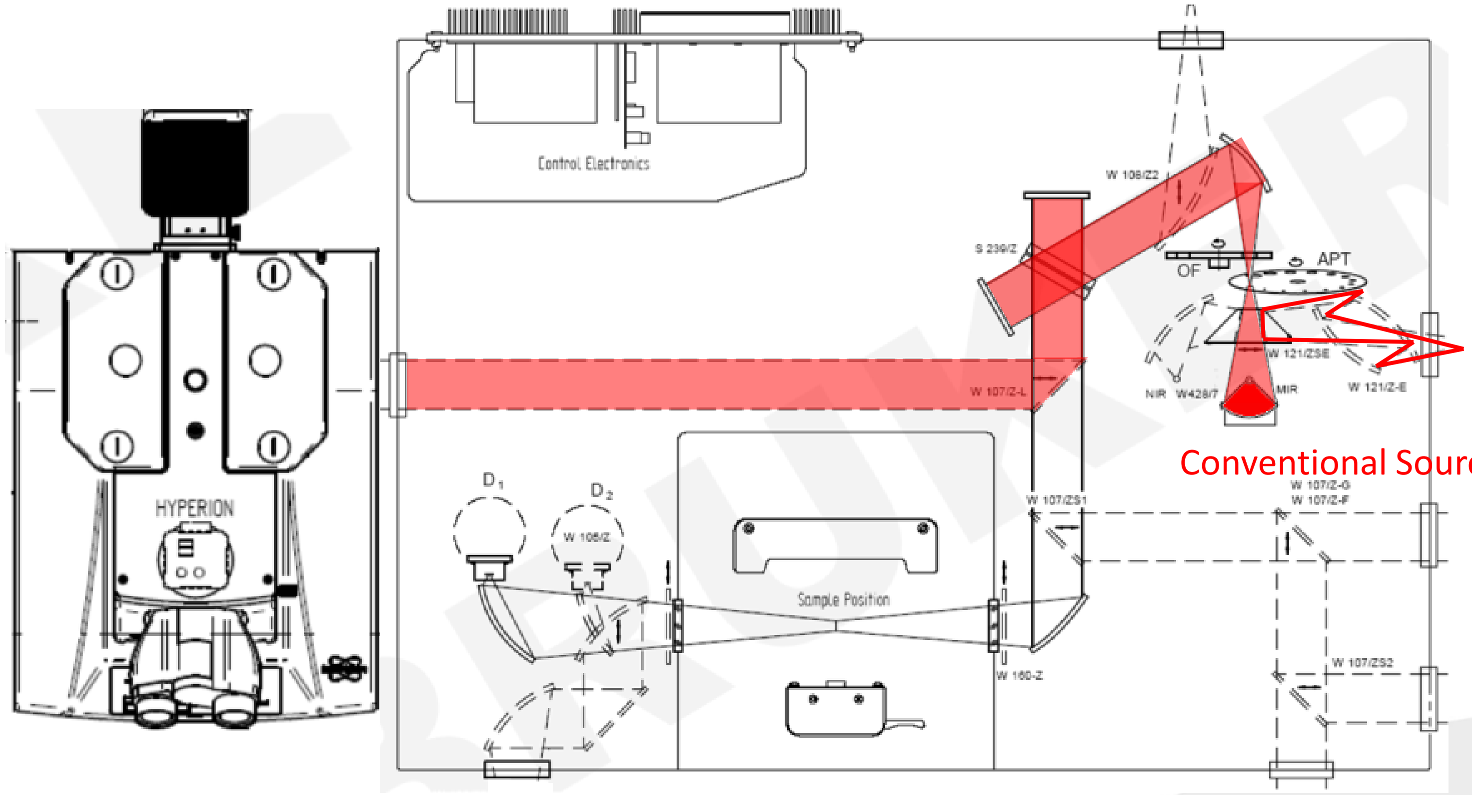
FTIR microscopy_Instrumentation





Schwarzschild/Cassegrain objective

Bruker 70v interferometers



Bruker Hyperion 3000 microscope

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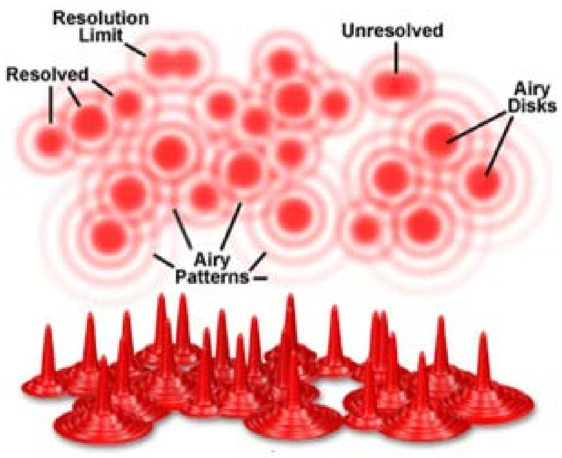
FTIR microscopy_Lateral resolution

The Rayleigh criterion

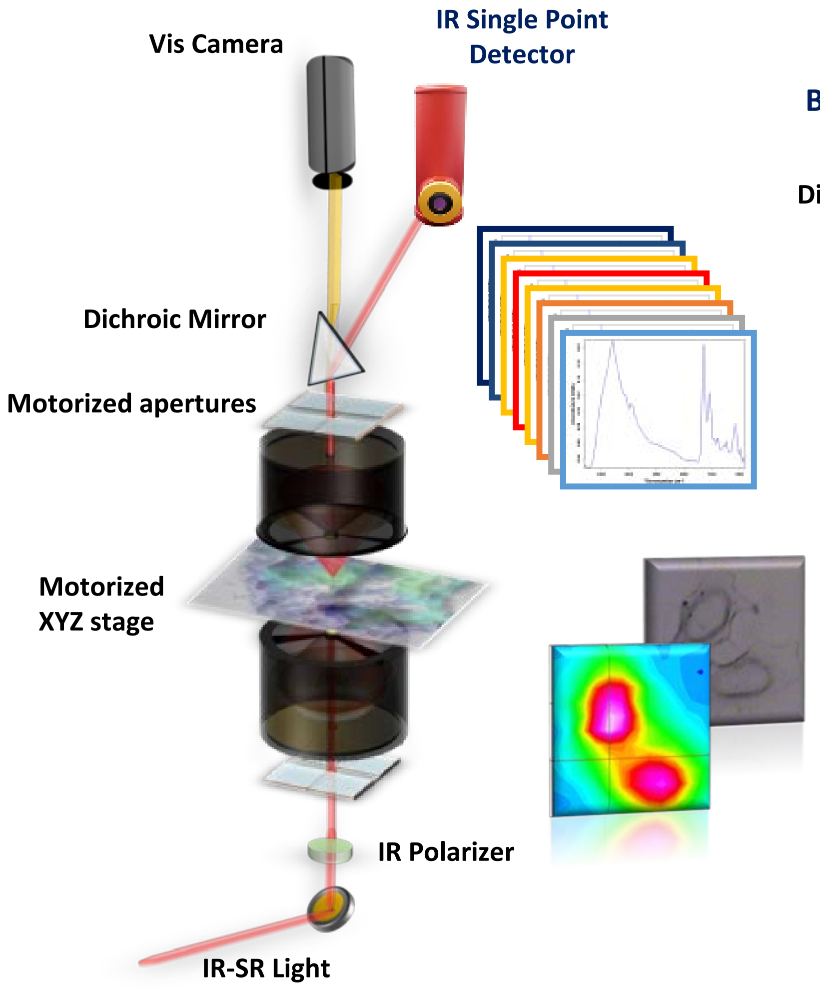


$$\delta = 0.66 \frac{\lambda}{nNA}$$

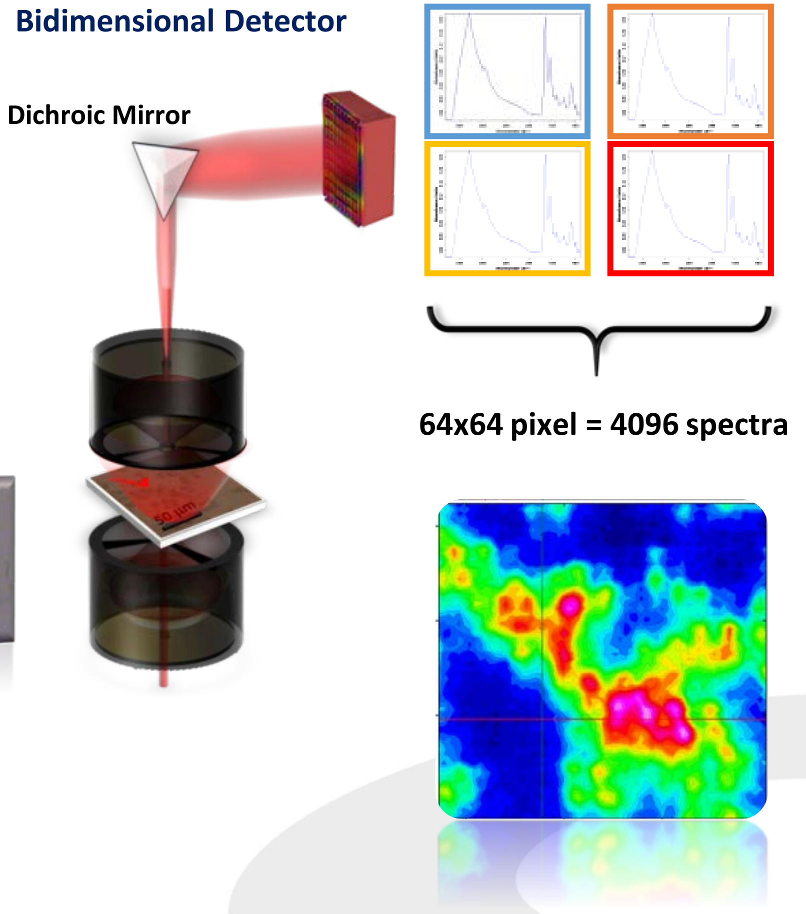
Far filed microscopy
Achievable lateral resolution

Wavelength	δ (NA=0.65)
10 mm (1 cm^{-1})	~ 10 mm
100 μm (100 cm^{-1})	~ 100 μm
10 μm (1000 cm^{-1})	~ 10 μm
2.5 μm (4000 cm^{-1})	~ 2.5 μm

FTIR mapping



FTIR imaging



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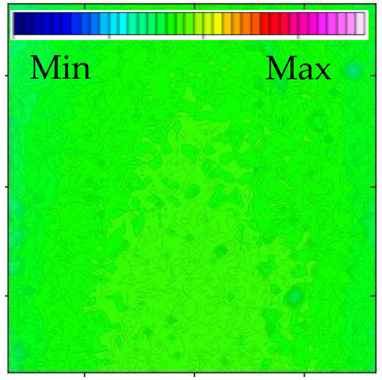
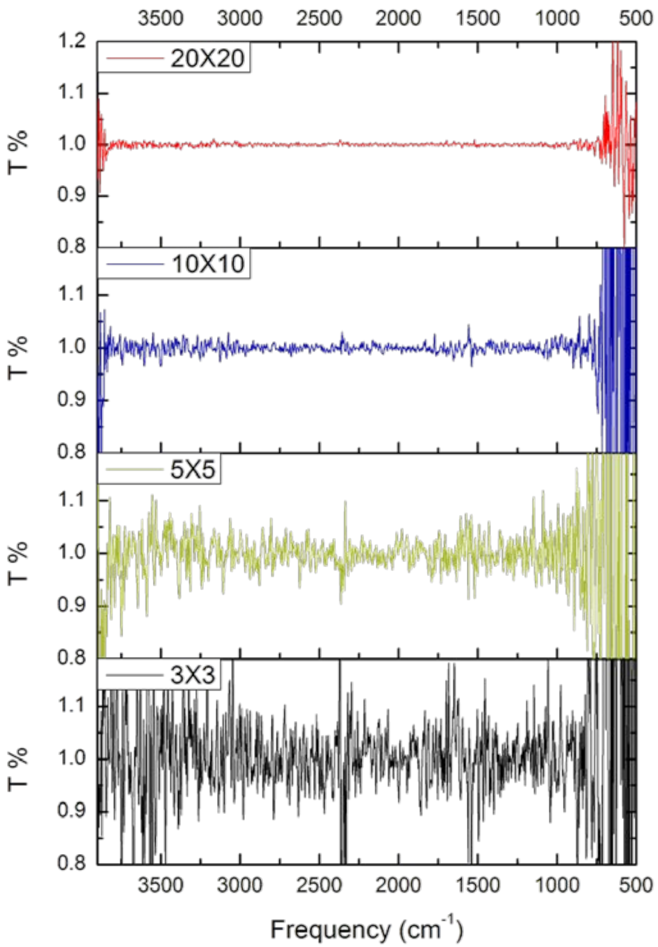
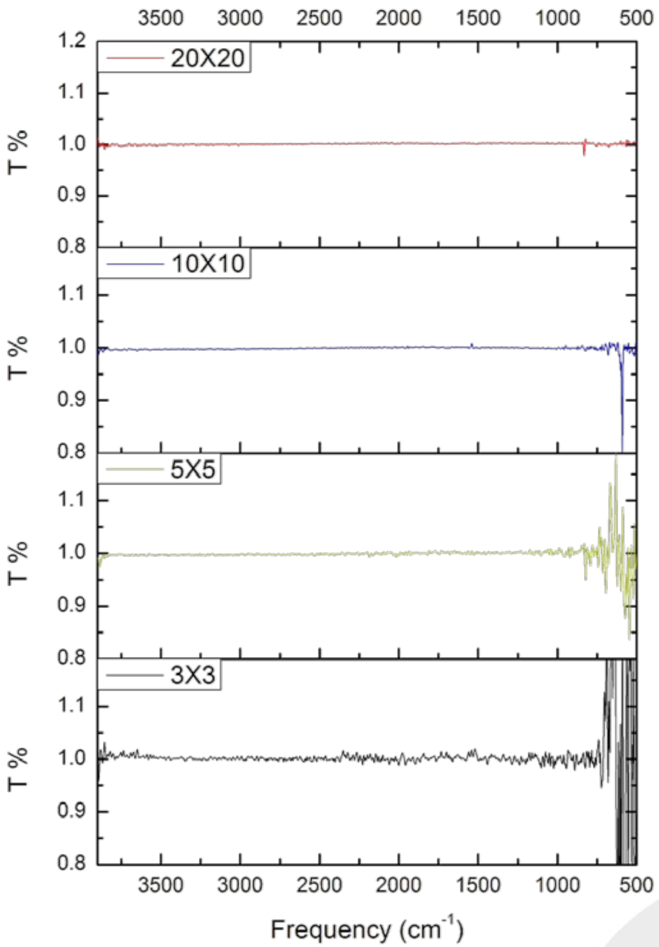
IRSR advantage for FTIR microscopy

Diffraction Limited FTIR Microscopy is practically achievable only with IRSR

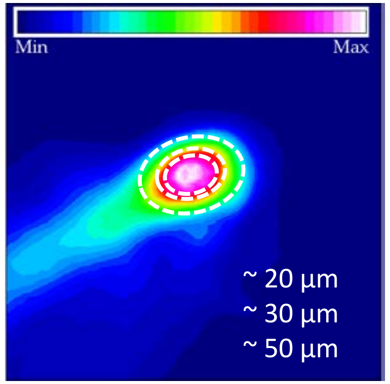
Conventional Source







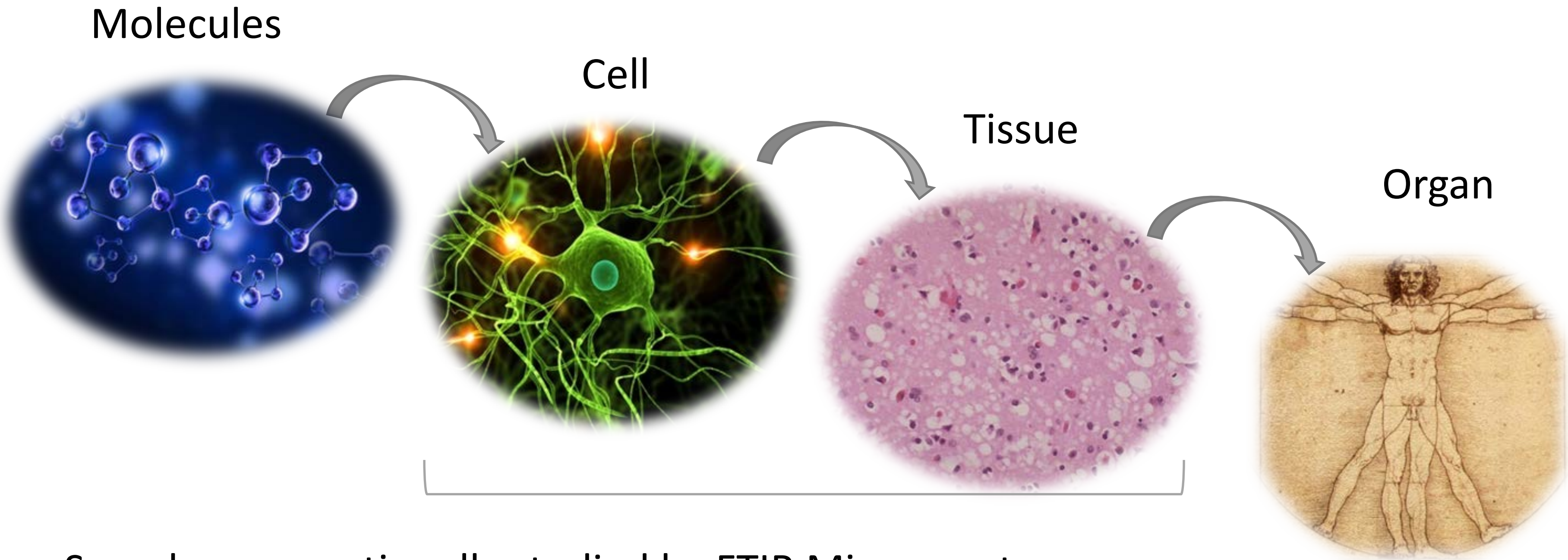
IRSR



S/N ratio at SISSI for diverse knife-edge aperture settings (lateral resolution)

A few words on bio-spectroscopy

Samples conventionally FTIR Bio-spectroscopy

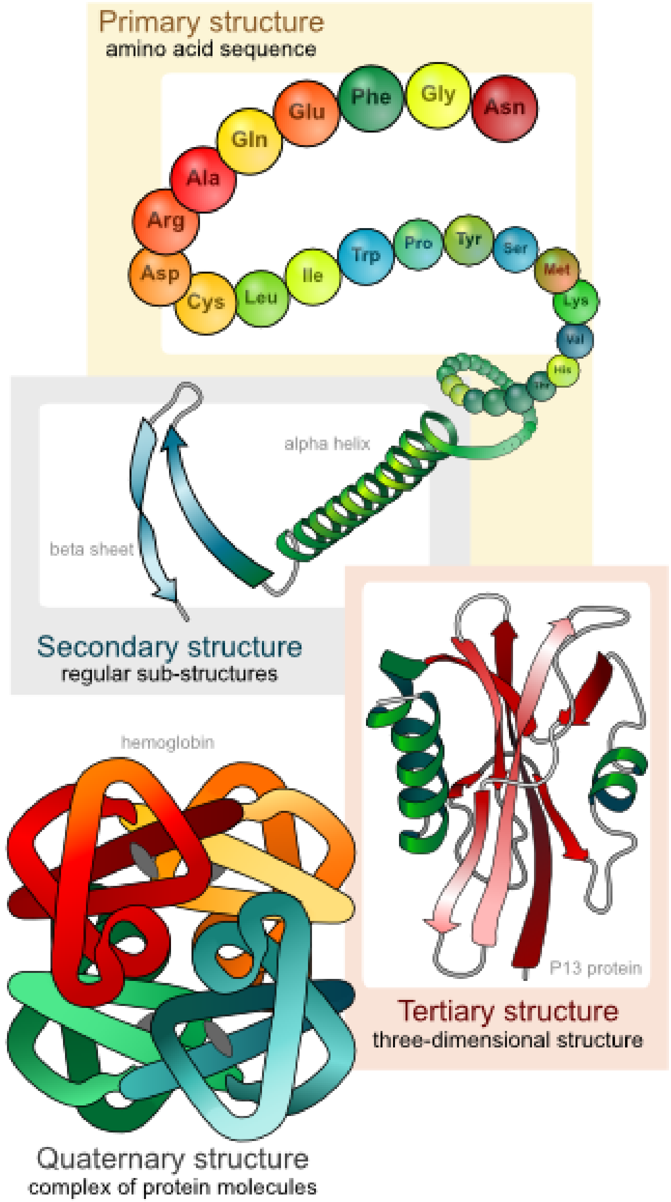


Samples conventionally studied by FTIR Microspectroscopy

FTIR Microscopy allows to investigate several aspects of the **sample biochemistry**, from individual molecules to cells and tissues.

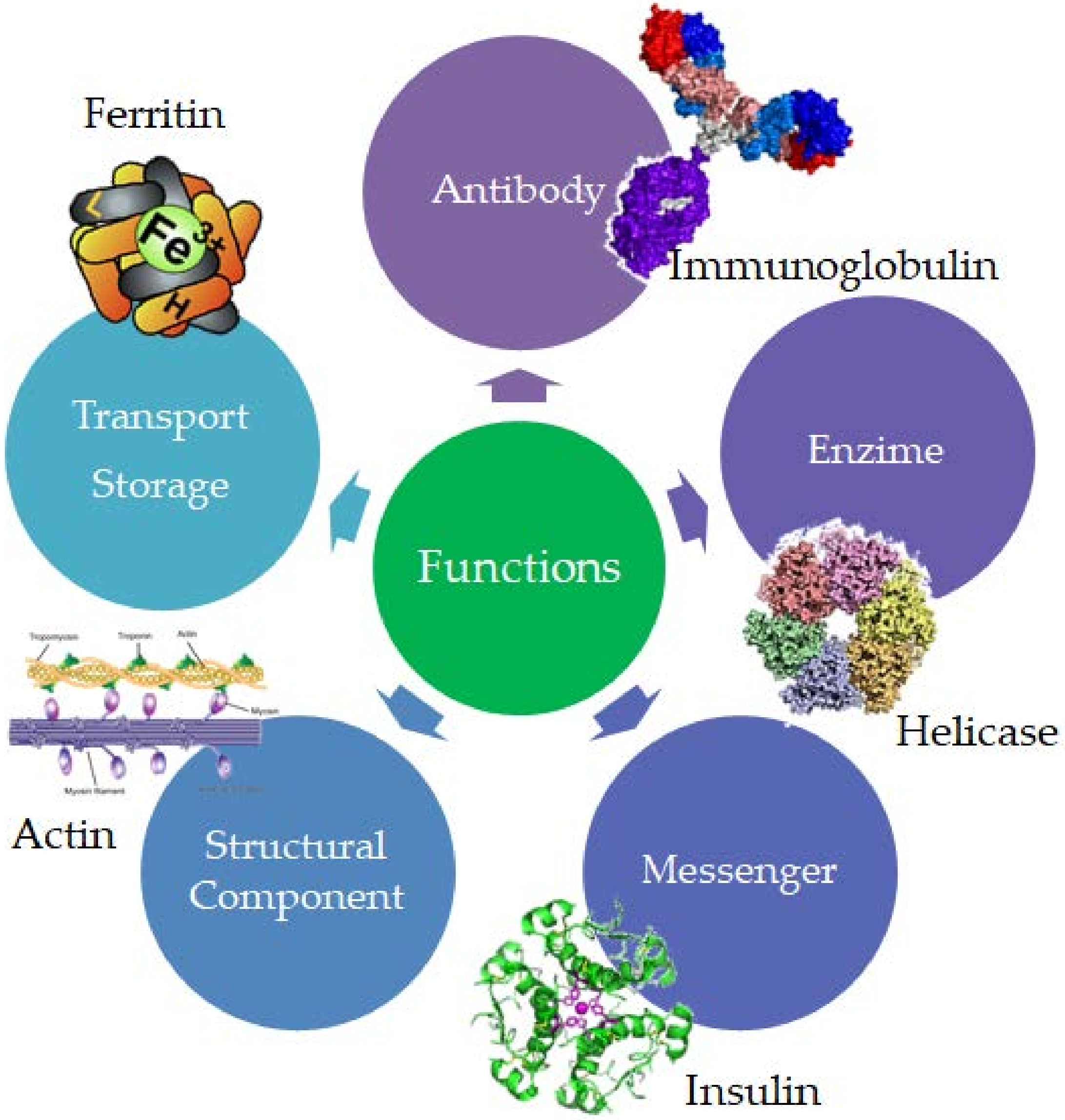
On the most relevant biomolecules (proteins, lipids, nucleic acids, carbohydrates), information can be retrieved on their relative proportion, conformation, state of order, dynamics and much more….

A quick dip in protein structure and function



Structure

Activity



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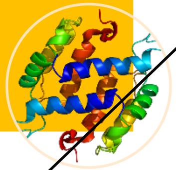
Drug discovery and development process

- **Cellular and genetics targets**
  Bioinformatics
- Genomics
- Proteomics

Target selection



- **Synthesis and isolation**
- Combinatorial Chemistry
- High throughput screening
- Biophysical methods

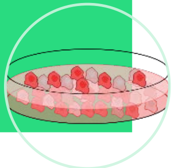
Lead discovery

- **Library development**
- Structure Activity studies
- Chemical Synthesis

Medical chemistry

- **Drug Affinity & Selection**
  - Cellular disease models
  - Mechanisms of actions
  - Lead Candidate refinement

In vitro studies



Does the drug bind?

Biophysical methods are fast, unexpensive, requires minimal sample preparation but they are blind to the protein structure

- **Animal Models and Disease States**
  - Behavioural studies
  - Functional Imaging
  - Ex vivo studies

In vivo studies

- Drug production and marketing

Clinical trails and Therapeutics

What's the drug effect on the protein structure?

Conventional technique for protein structural analysis may present some drawbacks

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Conventional techniques for protein structural analysis

X-ray crystallography

- ✓ About 90%* of protein structures
- ✓ 3D structure
- ✓ Atomic resolution (Å)
- ✓ Protein-ligand interaction
- x Samples preparation (crystalization)
- x Not native conditions
- x No protein dynamic behavior

Nuclear Magnetic Resonance (NMR)

- ✓ About 8%* of protein structures
- ✓ 3D structure
- ✓ Atomic resolution
- ✓ Measure in buffer
- ✓ Protein dynamic behaviour
- x Expensive sample preparation
- x Time and material consuming
- x Limited for little proteins (less 30kDa)

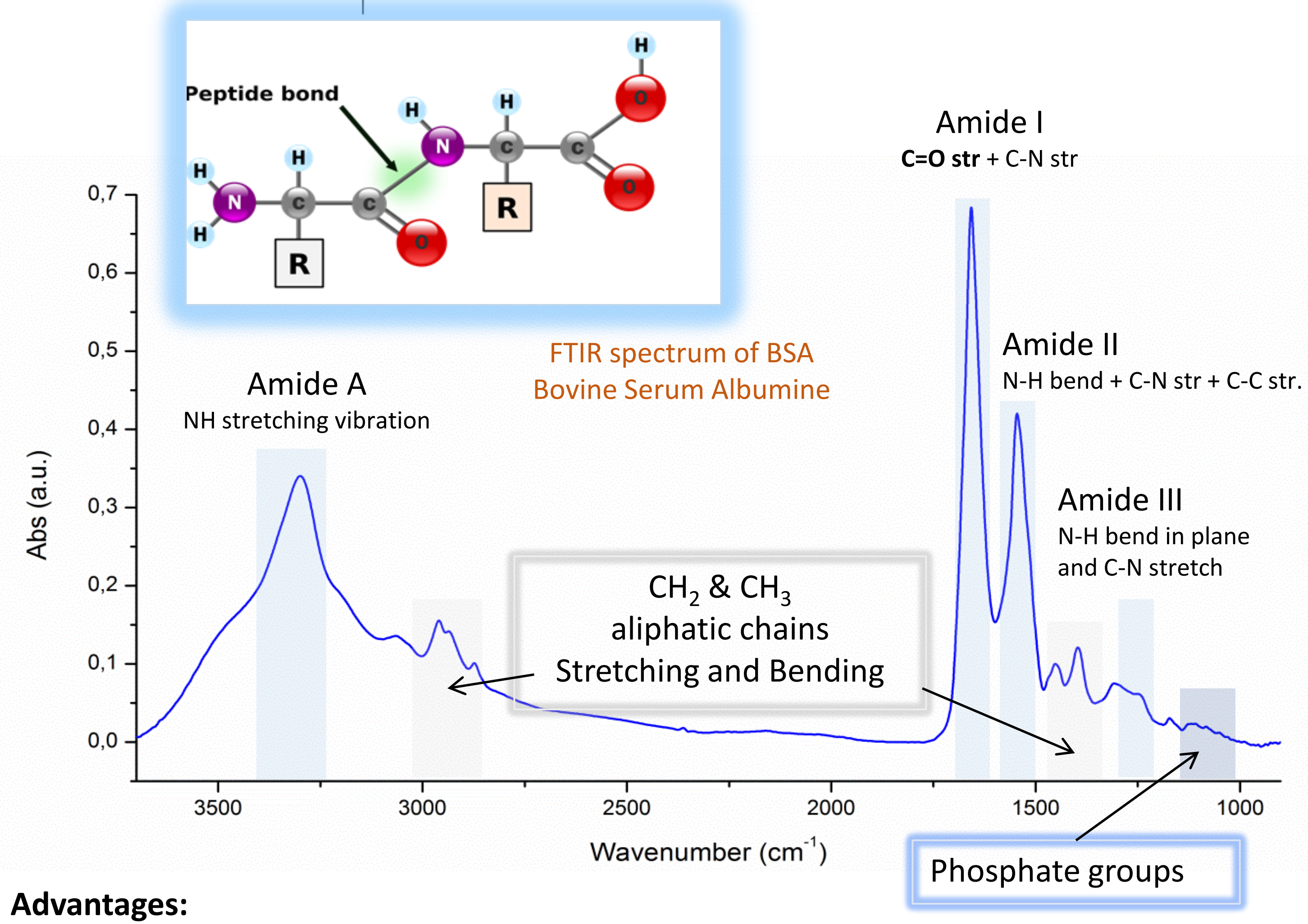
Cryo Electron Microscopy (Cryo-EM)*

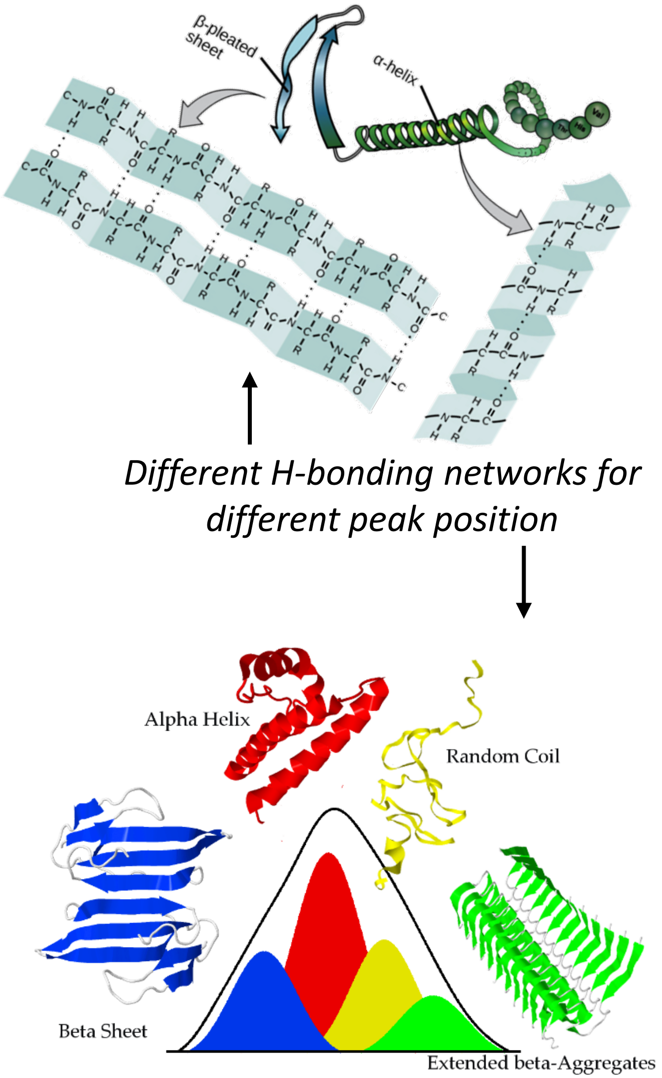
- ✓ About 2%* of protein structure
- ✓ 3D structure
- ✓ Near-atomic resolution
- ✓ Fast sample preparation: froze samples in their NATIVE form
- x Only larger proteins (more than 50-75 Kda)
- x No protein dynamic behavior

Does exist a method able to bridge biophysical and structural protein studies?

*statistics by PDB – March 2019

FTIR spectroscopy for protein conformational studies





Advantages:

Relevant also for non-crystallizable proteins

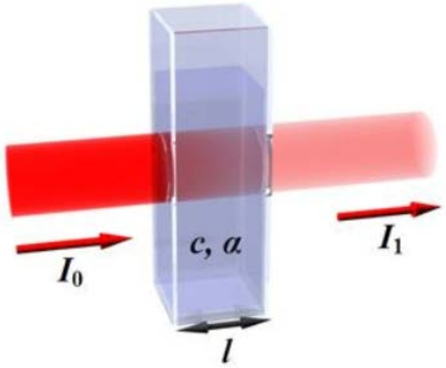
Limitations:

Sensitivity Limit

Water barrier

Sensitivity limit and water barrier

Sensitivity Limit



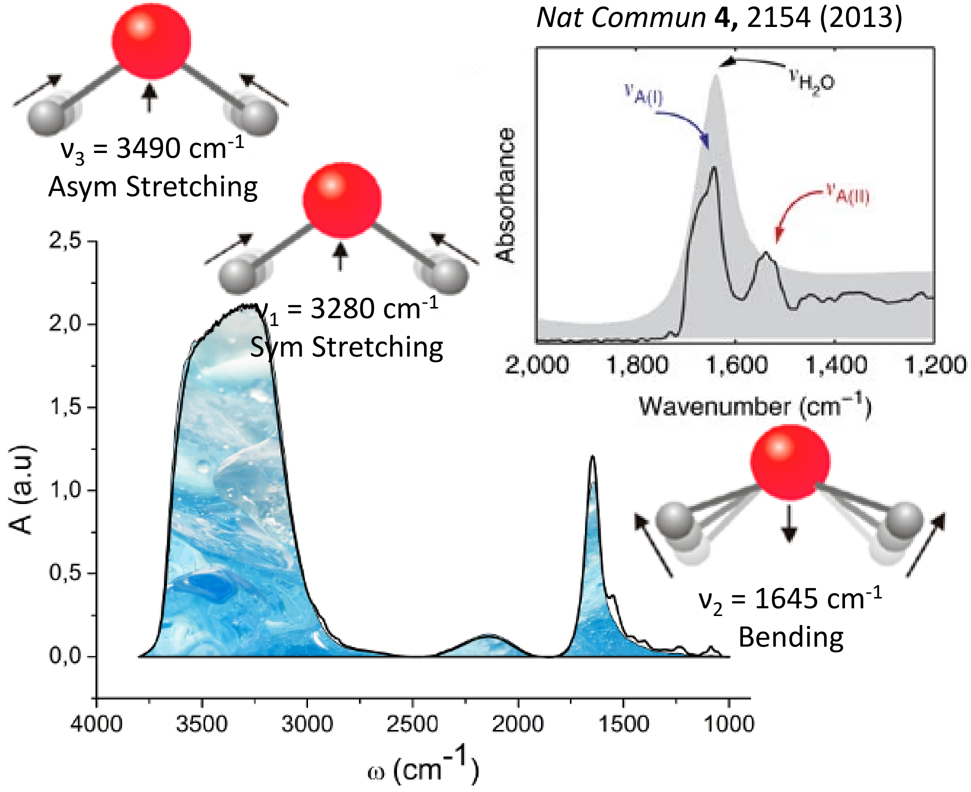
Beer's Law

$$T = \frac{I}{I0} \approx e^{-\alpha d}$$

- **Requires extremely high concentrations, in the mM regime**
  - These concentrations are often not-relevant in physiological conditions
- **Prohibits measurements from monolayers with nanometer thickness**

Water Barrier

Adato, R., Altug, H.
Nat Commun **4,** 2154 (2013)

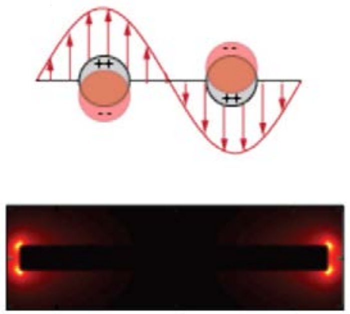


- **Water bands overlaps with the vibrational features of biomolecules**
  - Requires dried samples or D2O, that are not compatible with biomolecules

Defeat the sensitivity limit: the plasmonic approach

IR absorbance ∝ Oscillator strength of molecular bond x |Electric field|²

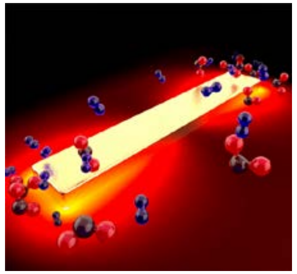
Plasmonic nanostructure



Adato, R., et al.
Materials Today, **18 (8),** 436-446 (2015)

Optical nano-resonators

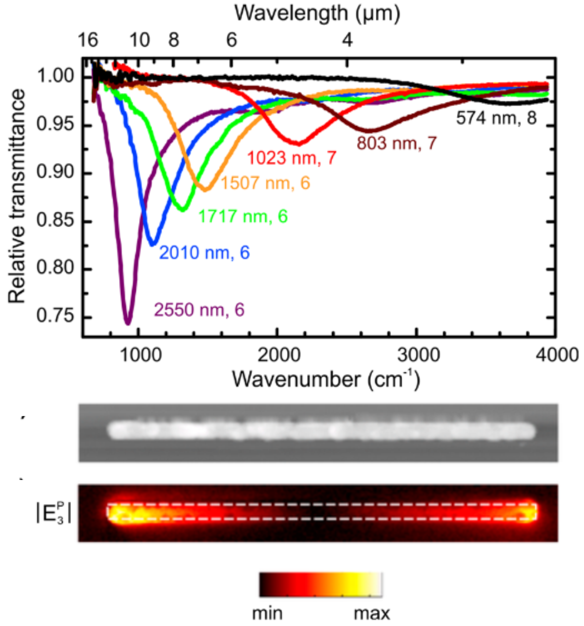
- Focus light into nanoscale volumes
- Enable strong light-matter interaction
- Ideal to achieve ultra-high sensitivity



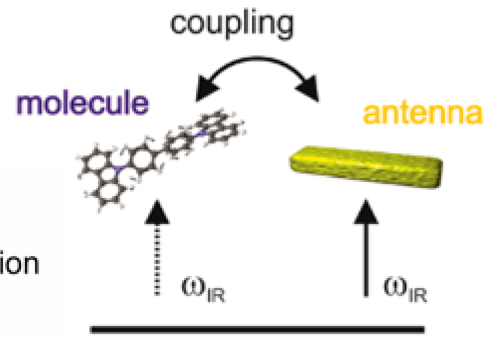
Neubrech,F., et al.
Chem. Rev., **117 (7),** 5110-5145 (2017)

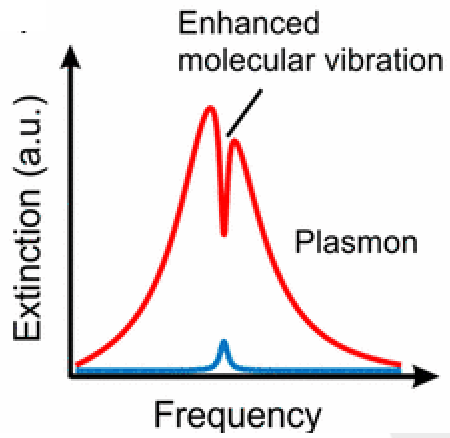
Resonance tuning

Antenna's material, shap and dimension are the key parameters for tuning position and bandwidth of the antenna response



Spectral coupling

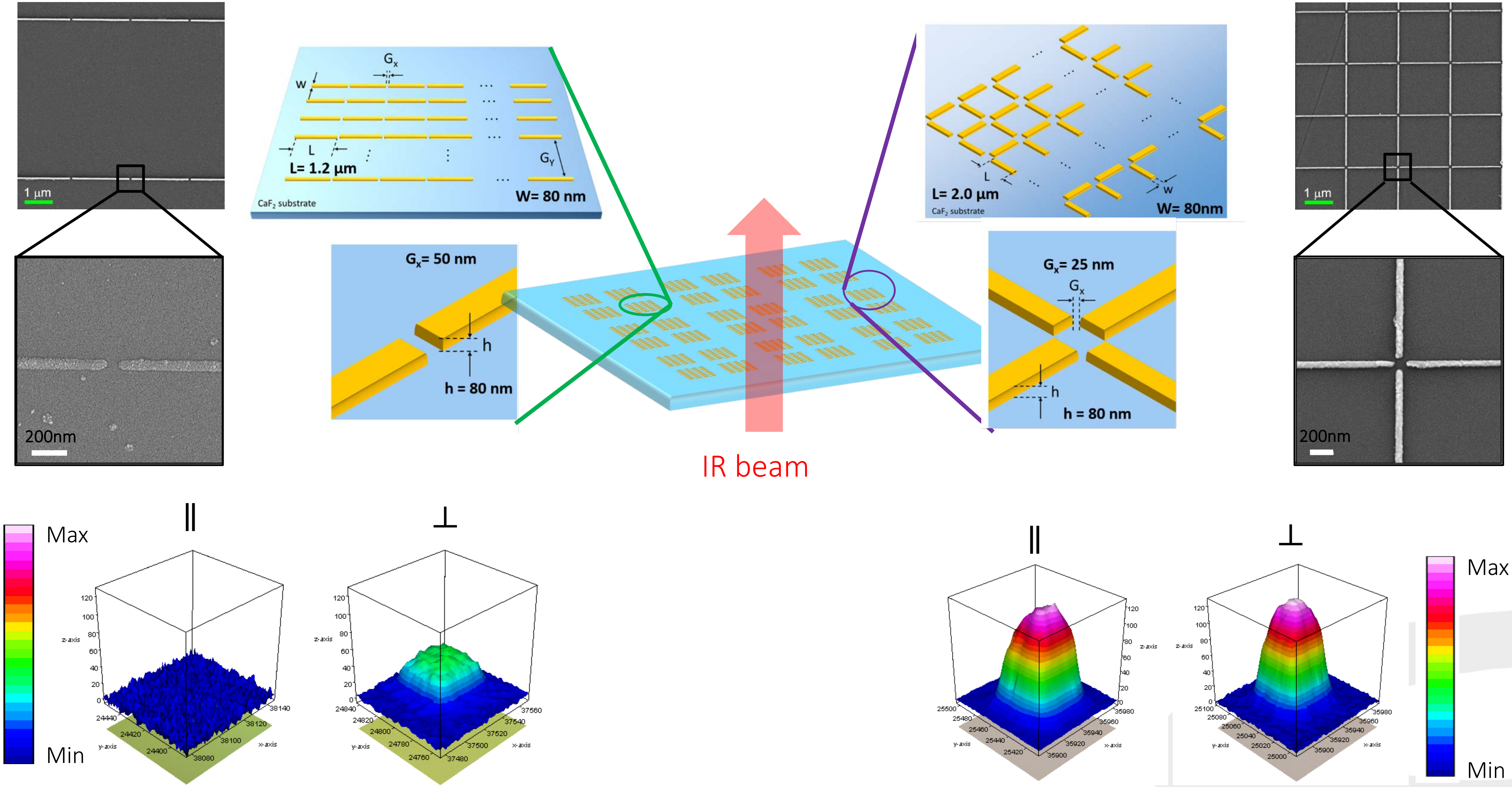




Signal enhancement of several order of magnitude can be achieved

Defeat the sensitivity limit: the plasmonic approach

Surface Enhanced Infrared Absorption Spectroscopy (SEIRA) on protein monolayers

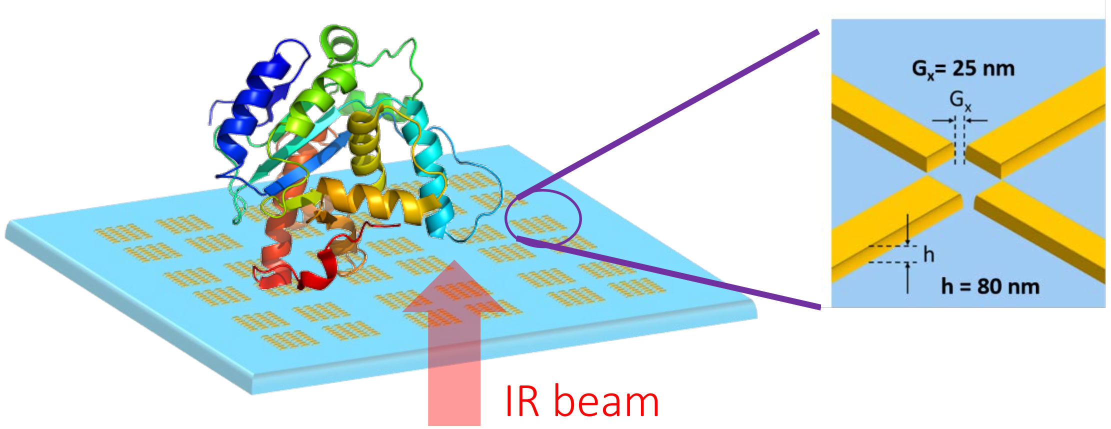


Defeat the sensitivity limit: the plasmonic approach

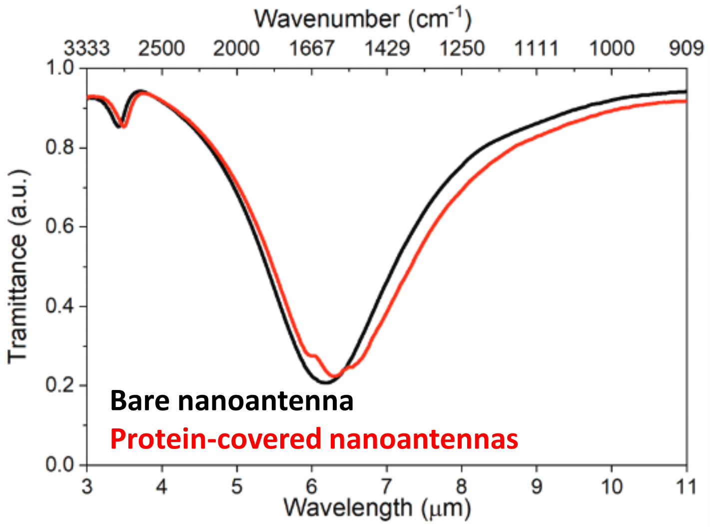
Elettra Sincrotrone Trieste

Surface Enhanced Infrared Absorption Spectroscopy (SEIRA) on protein monolayers

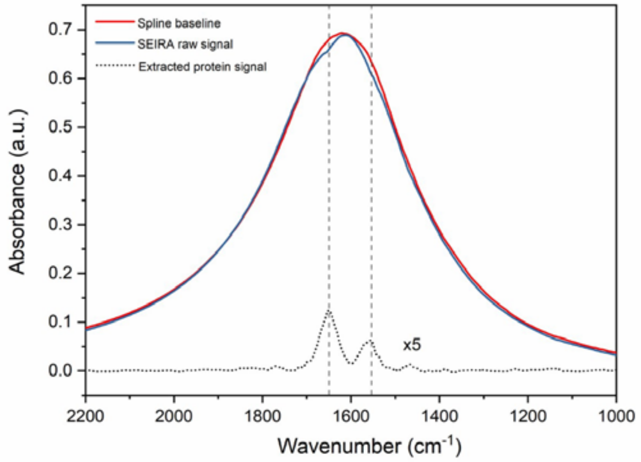
1_Protein layer formation



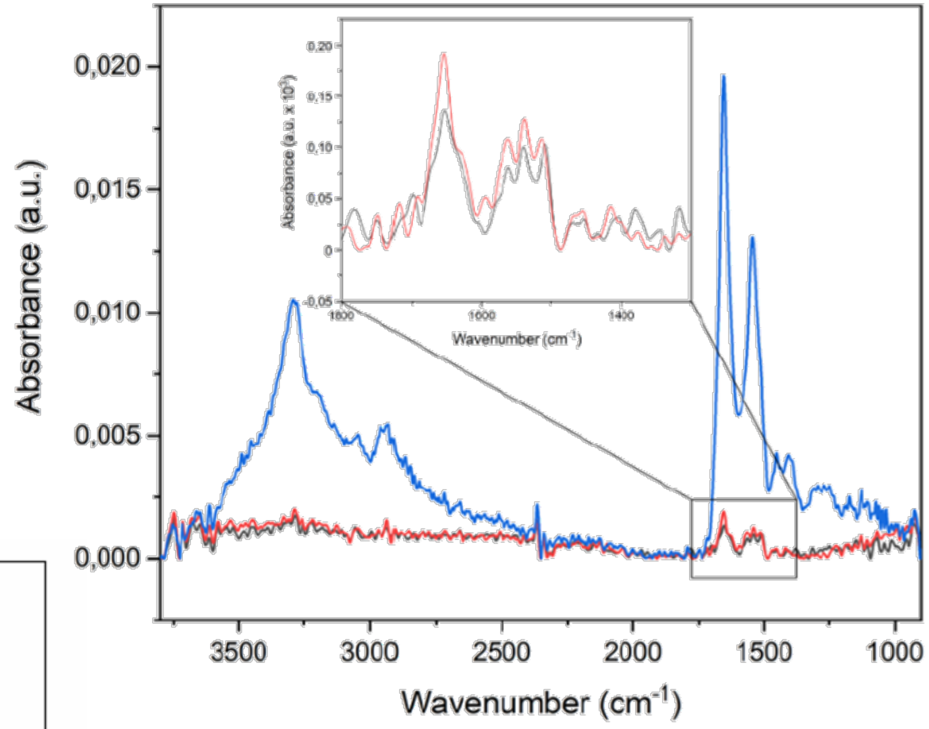
2_Plasmonic response



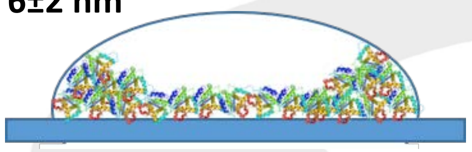
3_Signal Extraction



Conventional FTIR vs SEIRA



Protein layer 6±2 nm



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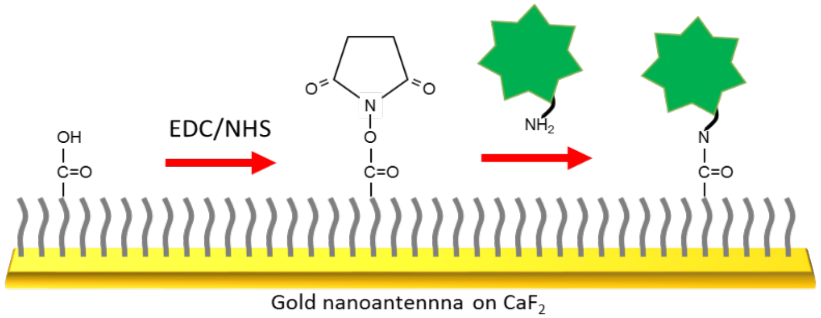
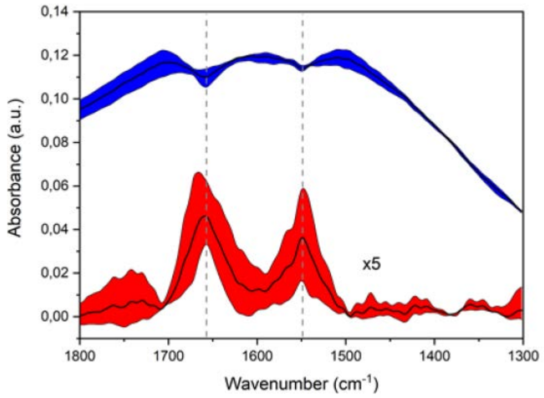
Defeat the sensitivity limit: the plasmonic approach

SEIRA on BSA and ConA protein monolayers

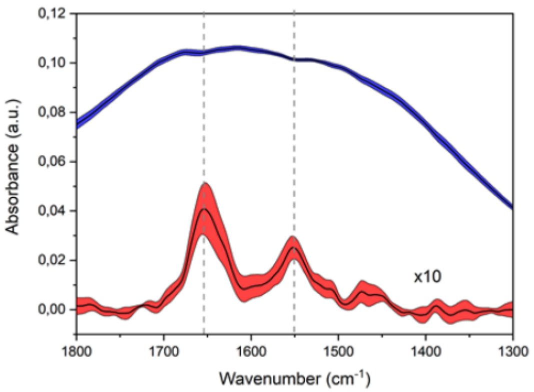
Protein monolayer formation
Amine coupling

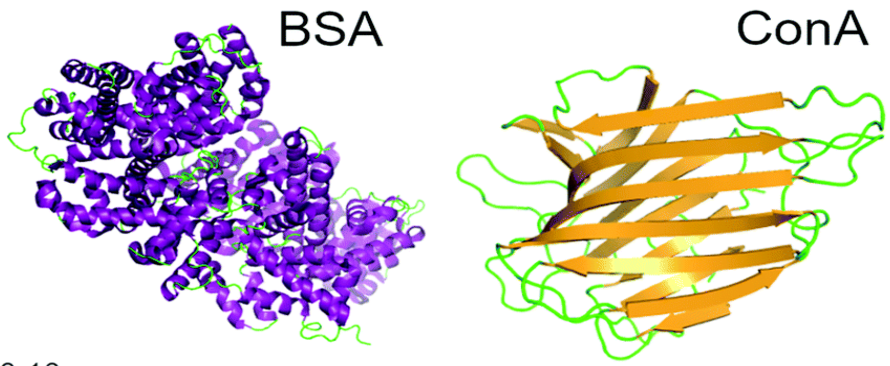


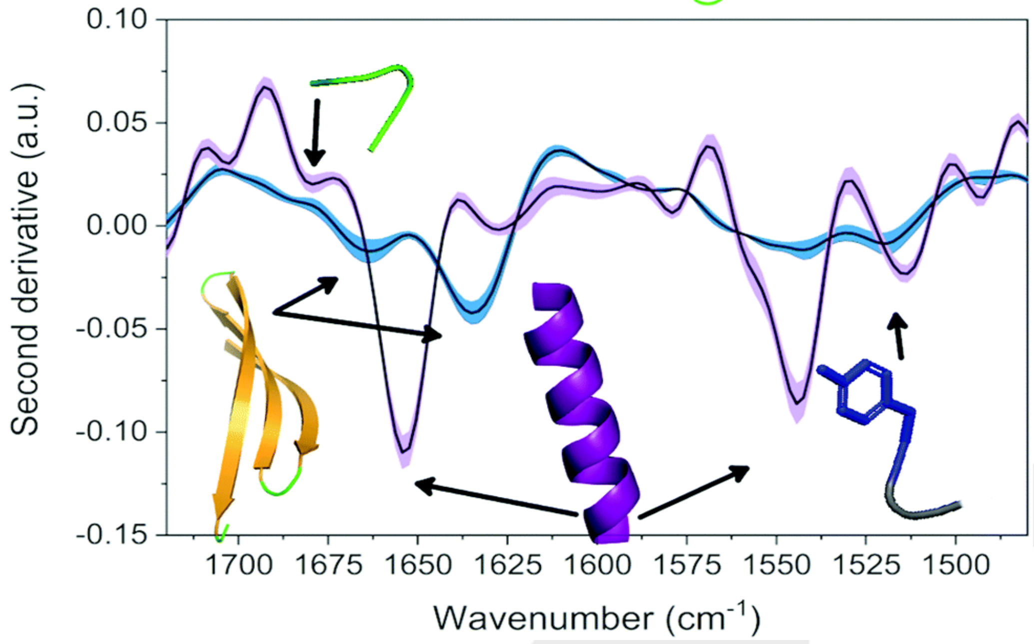


Standard deviation is much reduced

Drop casting
vs
Amine coupling



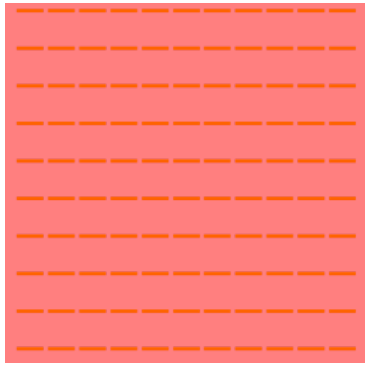




Defeat the sensitivity limit: the plasmonic approach

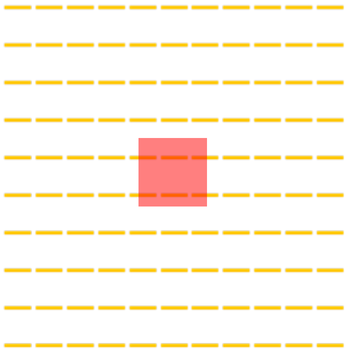
Protein Signal enchantment in dried conditions: Conventional source vs IRSR

Globar
Conventional
Source
(50x50) μm^2

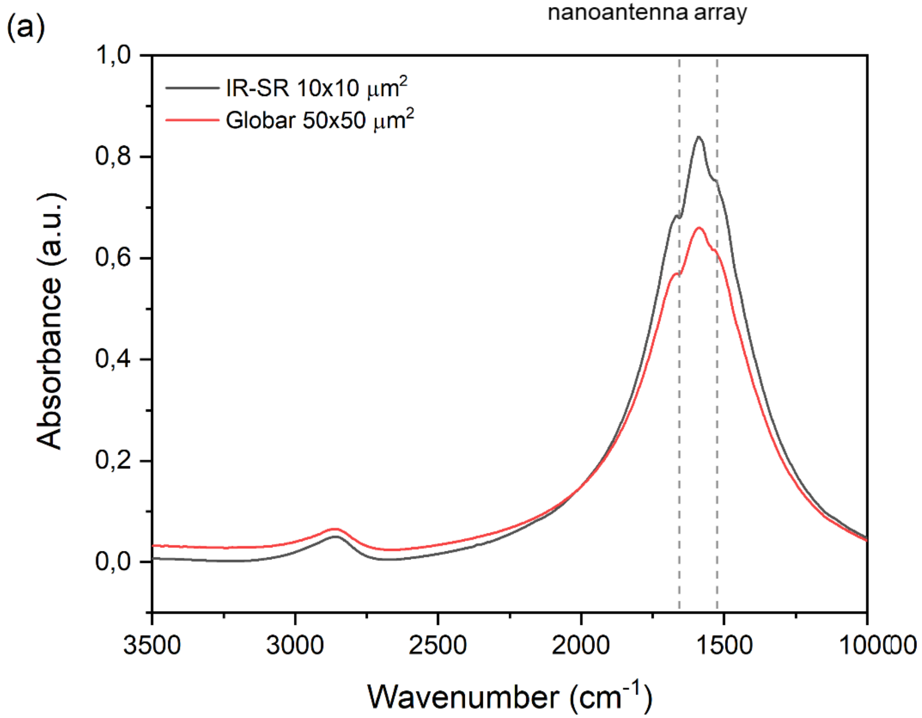


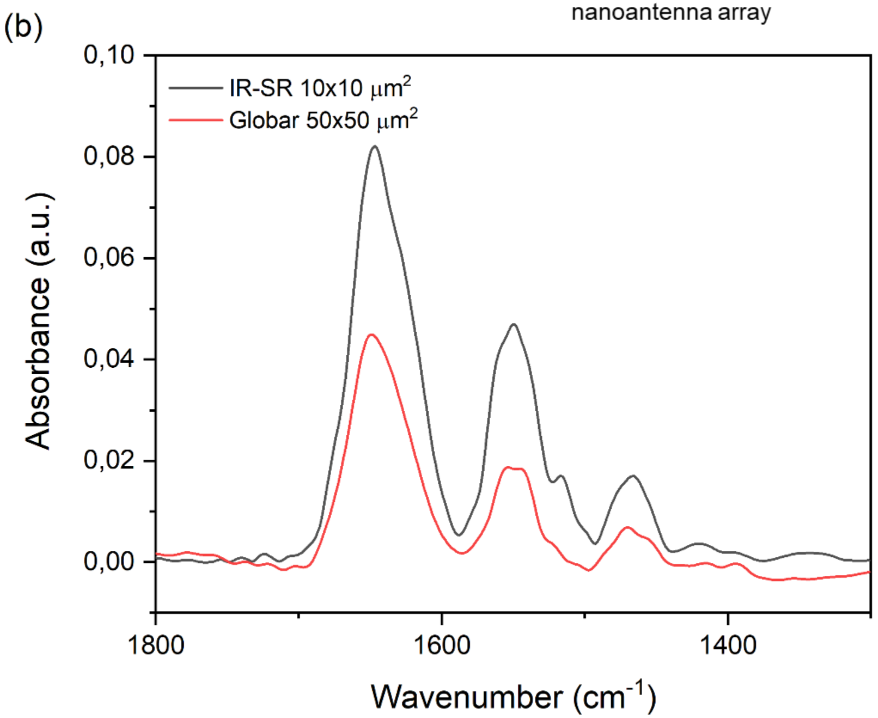
Single ordered
nanoantenna array

InfraRed
Synchrotron
Radiation
(10x10) μm^2



Single ordered
nanoantenna array

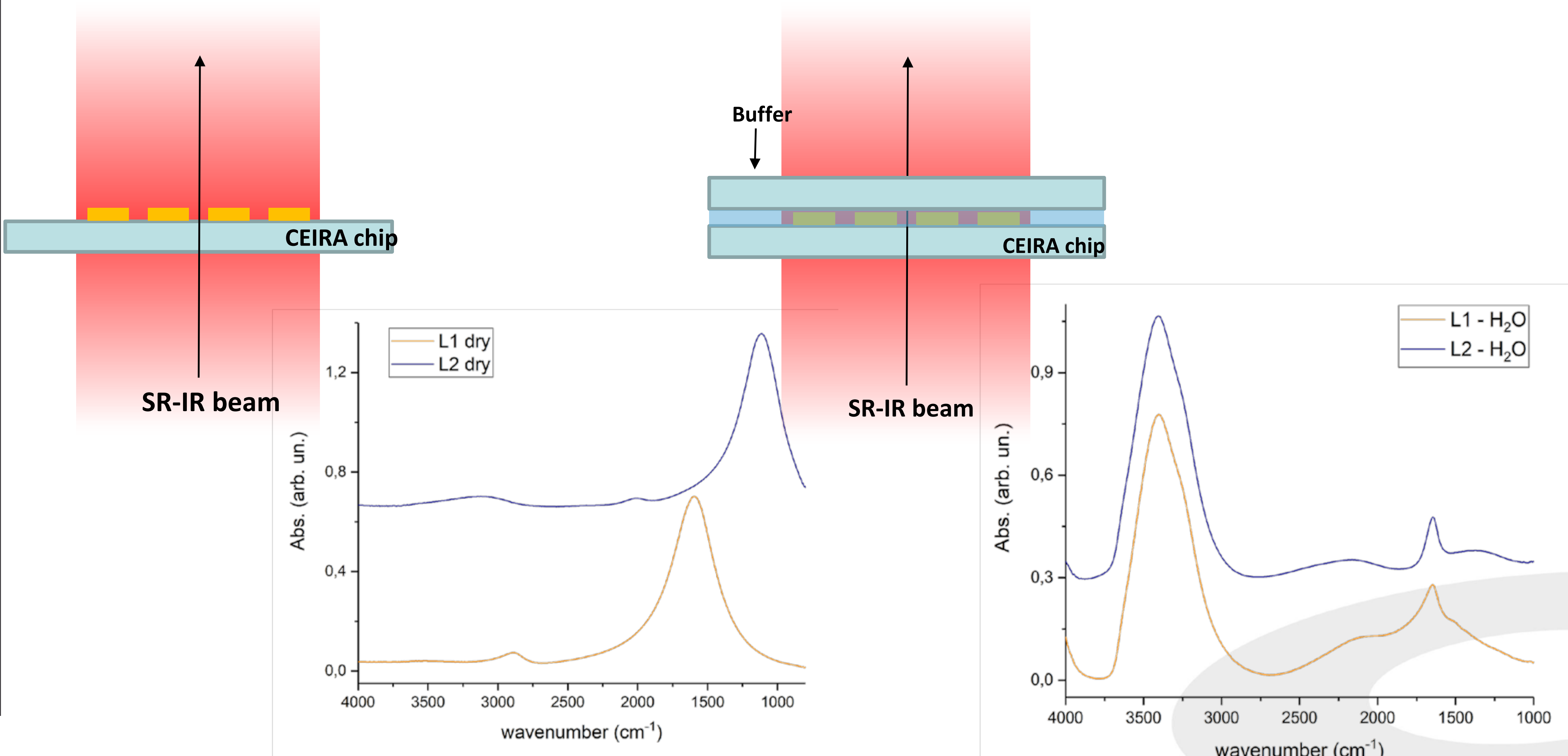




Defeat the water absorption barriers: the PIR approach

Elettra Sincrotrone Trieste

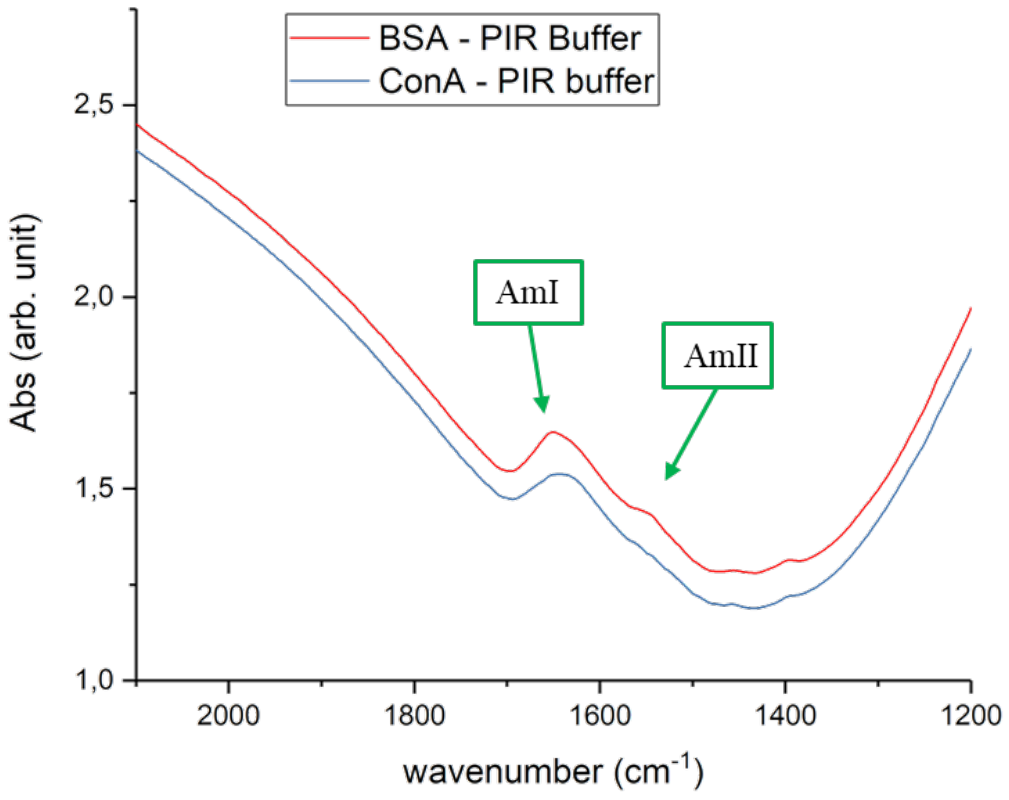
SEIRA measurements in transmission mode in dried and wet conditions

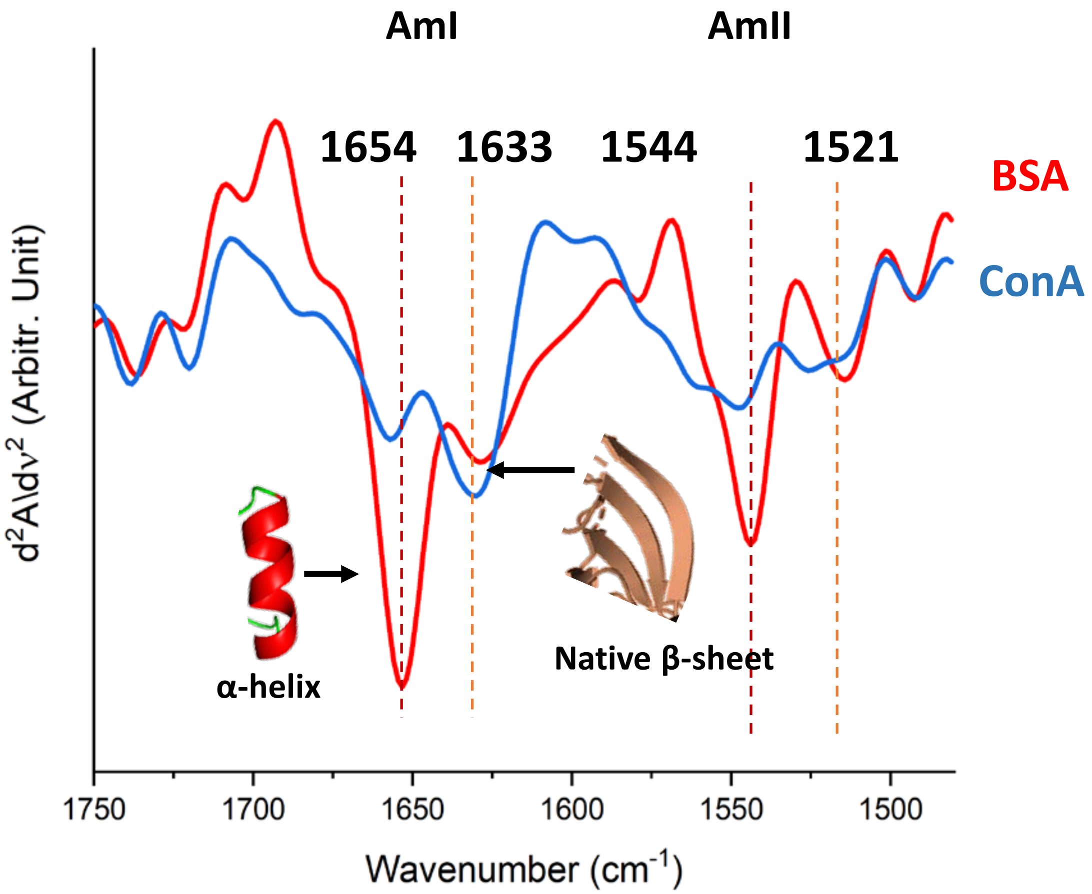


Defeat the water absorption barriers: the PIR approach

SEIRA measurements PIR geometry

Plasmonic Internal Reflectance PIR





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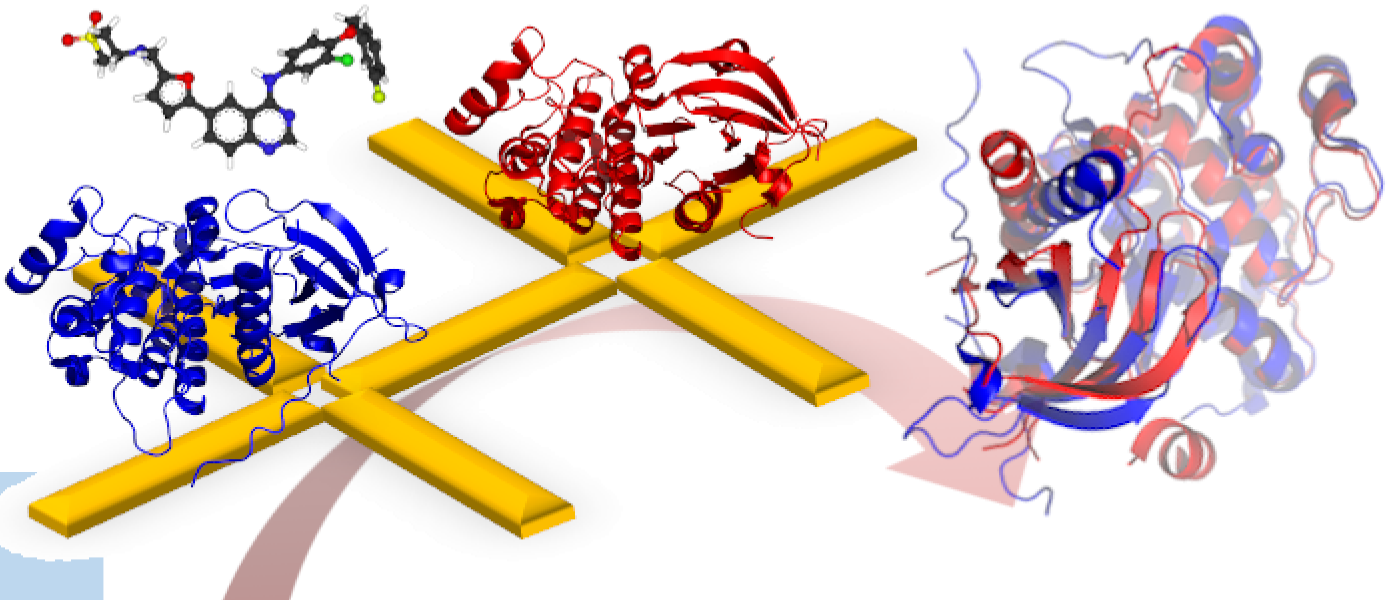
Bridging biophysical and structural studies with PIR-SEIRA

EGFR-KD Lapatininb binding and conformational changes detected by PIR-SEIRA

Kinase domain of Epidermal Growth Factor Receptor (EGFR-KD)



Receptor for members of the epidermal growth factor family (EGF family) of extracellular protein ligands.

Mutations that lead to EGFR overexpression (upregulation) or over-activity have been associated with squamous-cell carcinoma of the lung (80% of cases).

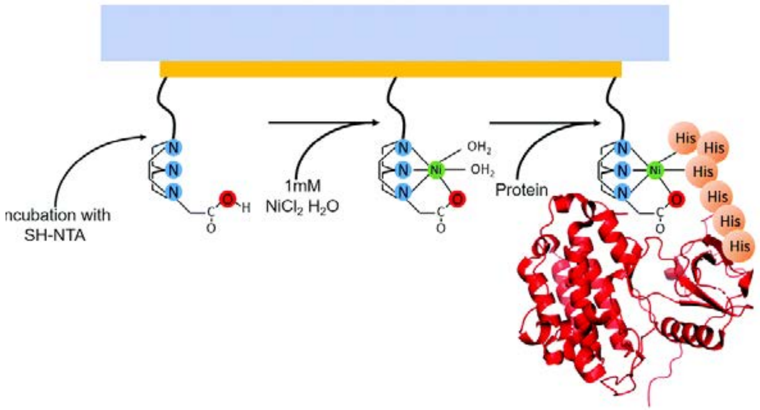
Drug-target for anticancer therapies (Lapatinib, Gefatinib etc…).

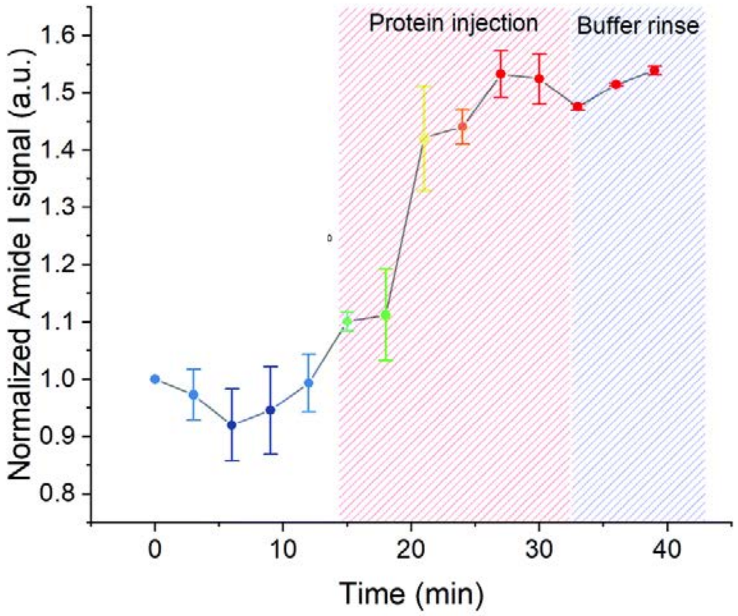
EGFR-KD	Lapatinib/EGFR-KD
36% helices (both alpha and 3_{10})	32% helices (both alpha and 3_{10})
15% beta sheet strands	14% beta sheet strands.

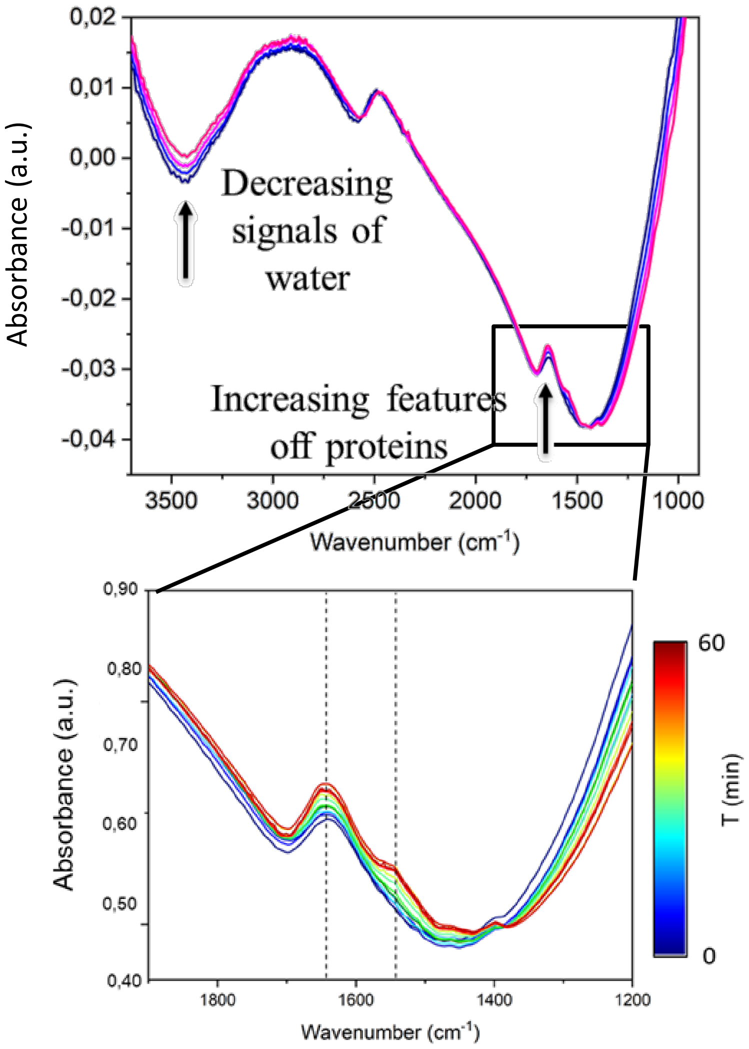
Elettra Sincrotrone Trieste

Bridging biophysical and structural studies with PIR-SEIRA

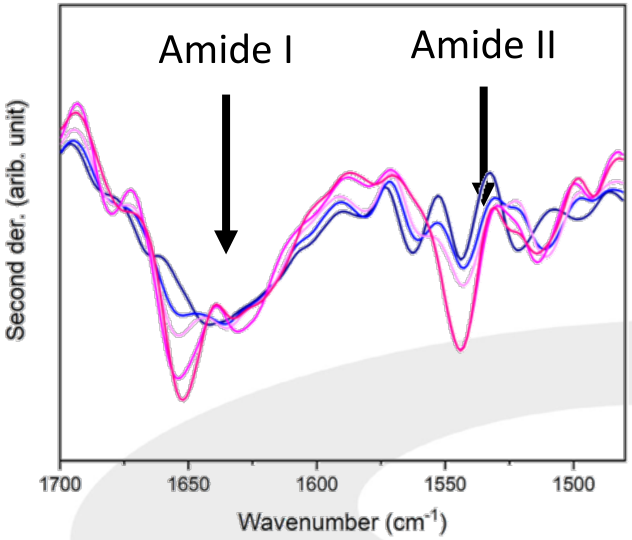
EGFR-KD Lapatininb binding and conformational changes detected by PIR-SEIRA







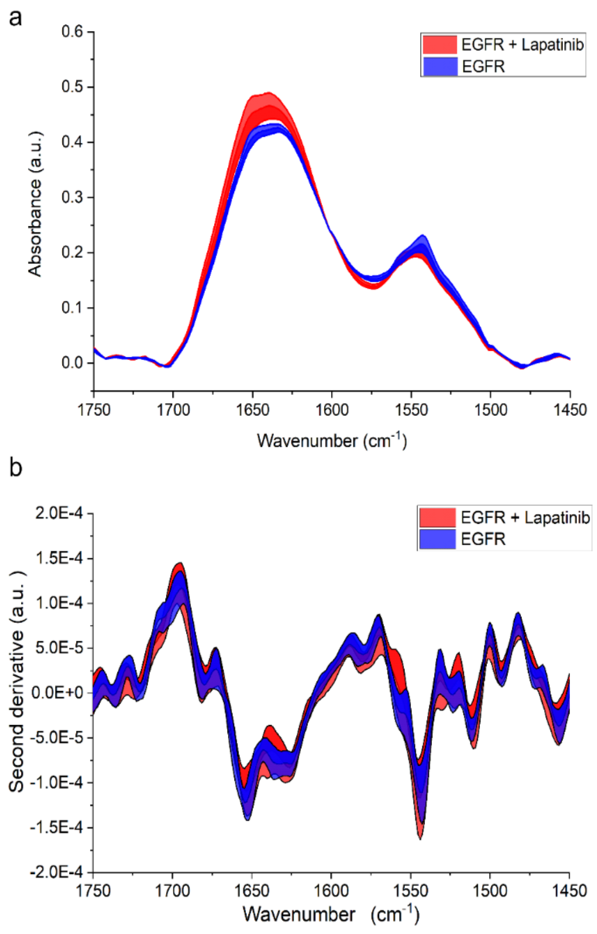
Dynamic EGFR-KD protein binding



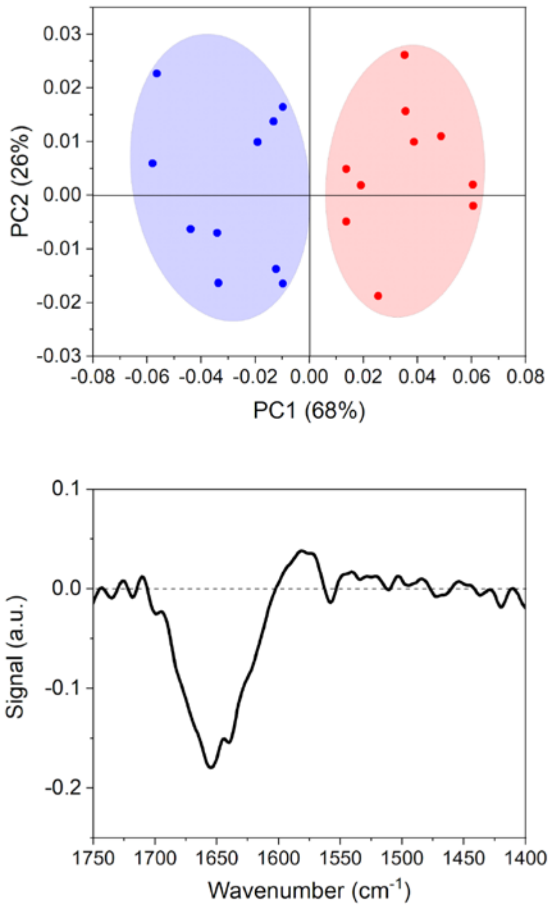
Bridging biophysical and structural studies with PIR-SEIRA

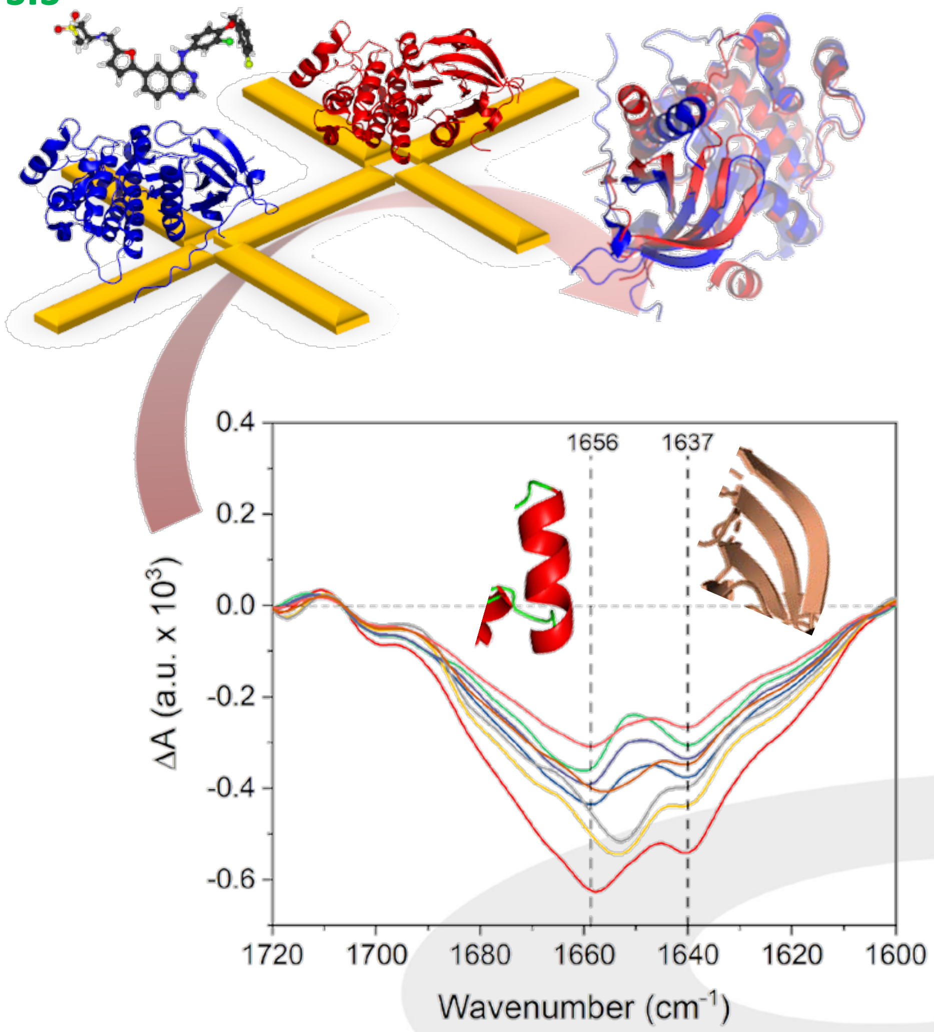
EGFR-KD Lapatininb binding and conformational changes detected by PIR-SEIRA

Raw spectra comparison



PCA
Principal component Analysis



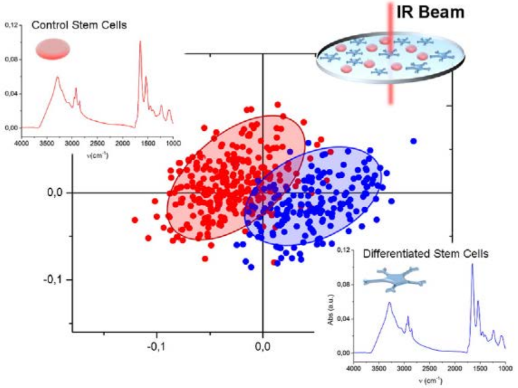


Further application of IRSR for Life Sciences

Cell differentiation

Prof. Alessandro Vindigni

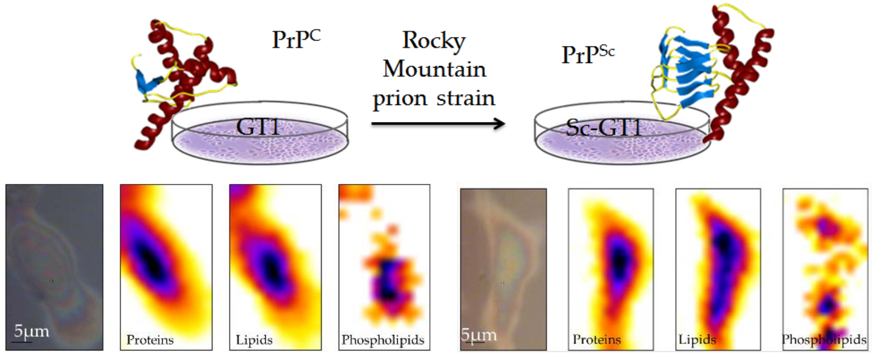
Fourier transform infrared microspectroscopy reveals biochemical changes associated with glioma stem cell differentiation



S. Kenig. et al., *Biophysical Chemistry*, (2015); **207**:90-96

Prion Disorders

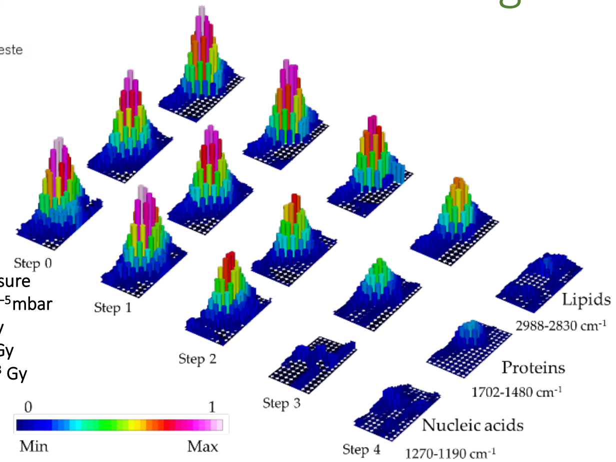
Prof. Giuseppe Legname



Didonna A, et al., *ACS Chemical Neuroscience*, (2014); *2*(**3**): 160-174

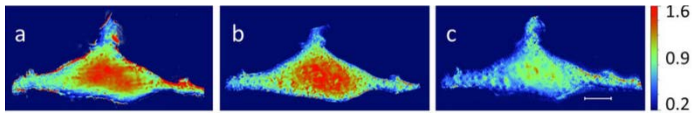
Radiation Damage

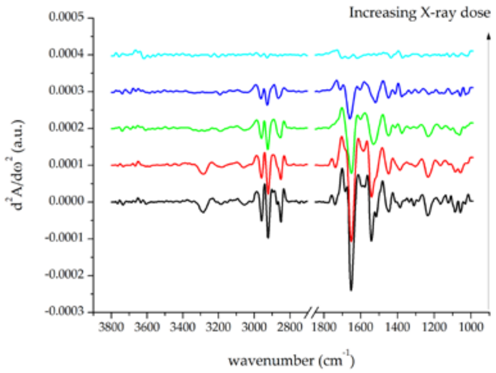
Elettra Sincrotrone Trieste

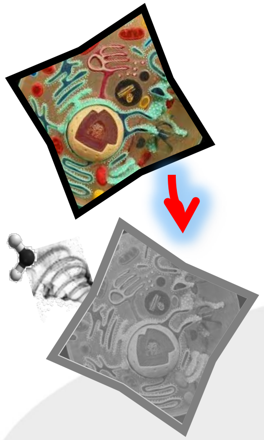


0 – Ambient pressure
1 – Pressure $5 \cdot 10^{-5}$ mbar
2 – Dose: $2 \cdot 10^{6}$ Gy
3 – Dose: $2.2 \cdot 10^{7}$ Gy
4 – Dose: $6.22 \cdot 10^{8}$ Gy

Density maps at the 3 dose levels







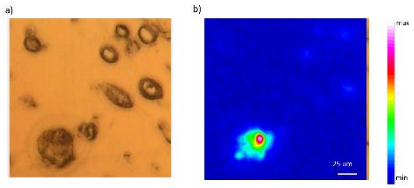
A. Gianoncelli, L. Vaccri et al, *Scientific Reports* (2015); **5**:article number 10250

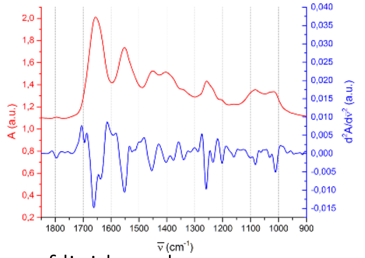
Further application of IRSR for Life Sciences

Rare disease

Prof. Annalisa Santucci

A synchrotron light on Alkaptonuria: a comparative XRF and FTIR study on a rare disease



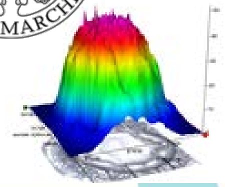


Extended beta-aggreagates, accumulation of lipids and proteoglycans, accumulation of bio-calcite

Mitri E. et al., *BBA Genral Subjects* **2016**, doi.org/10.1016/j.bbagen.2017.02.008

Fertility and sterility

Prof. Oliana Carnevali



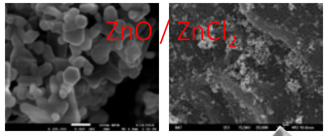
Vibrational characterization of female gametes

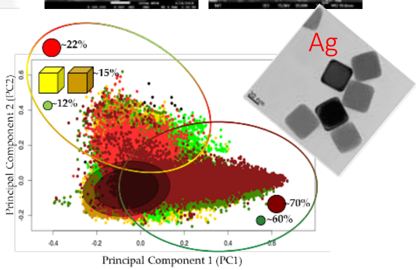
IR Microspectroscopy on GCs: a new non-invasive oocyte assessment

Giorgini E. et al., *Anal Bional Chem* **2010**, 398, 3063–72
Gioacchini G. et al,. *Biology of Reproduction* **2012,** *86(3):65,* 1–11
Giorgini E. et al., *Vibrational Spectroscopy* **2012**,62, 279–285
Gioacchini G et al., *Fertility and Sterility*, **2014**, 101(1): 120–127
Giorgini E et al, *Analyst*, **2014**, 139(20):5049-60

Nanotoxicology

Prof. Damjana Drobne





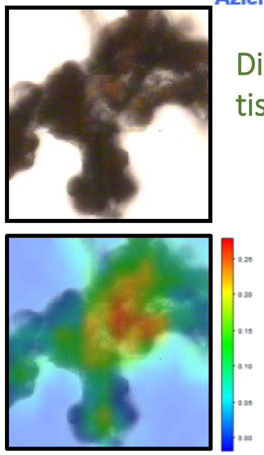
T. Romih et al., *Nanotoxicology*, **2016**, *10(4):462-70*
S. Novak et al., *Environmetal Science and Technology*, **2013**, *57: 11284-11292*
S. Novak et al., *Nanotoxicology*, submitted 2017

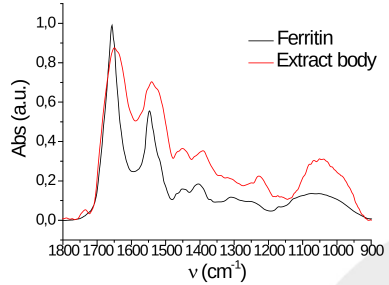
Dr. Lorella Pascolo

Azienda per l'Assistenza Sanitaria n.2 Bassa Friulana-Isontina

BURLO

Differential protein folding and chemical changes in lung tissues exposed to asbestos or particulates



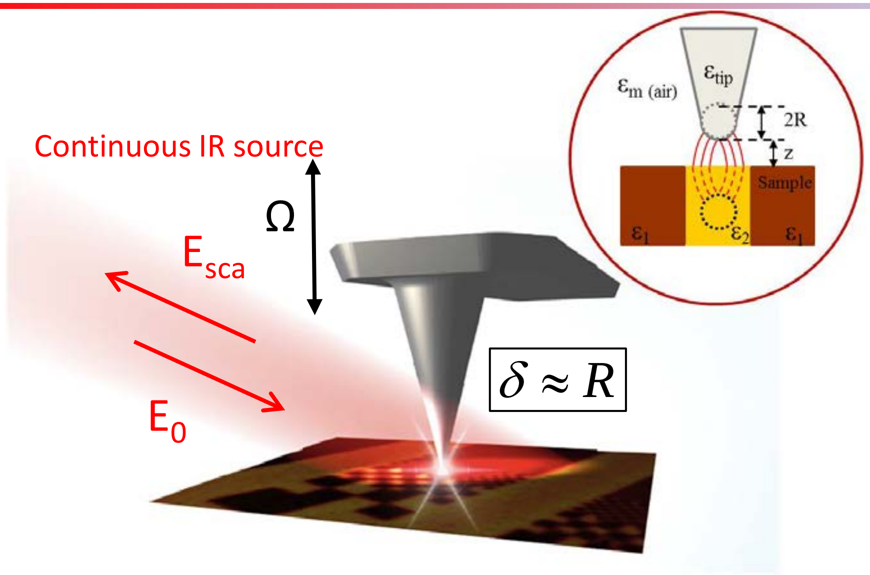


L. Pascolo et al. *Scientific Reports* **2015**, *5*, *Article number 12129*

FTIR nanoscopy

IR Nanoscopy

Scattering-type Scanning Near-field Infrared Microscopy: s-SNIM



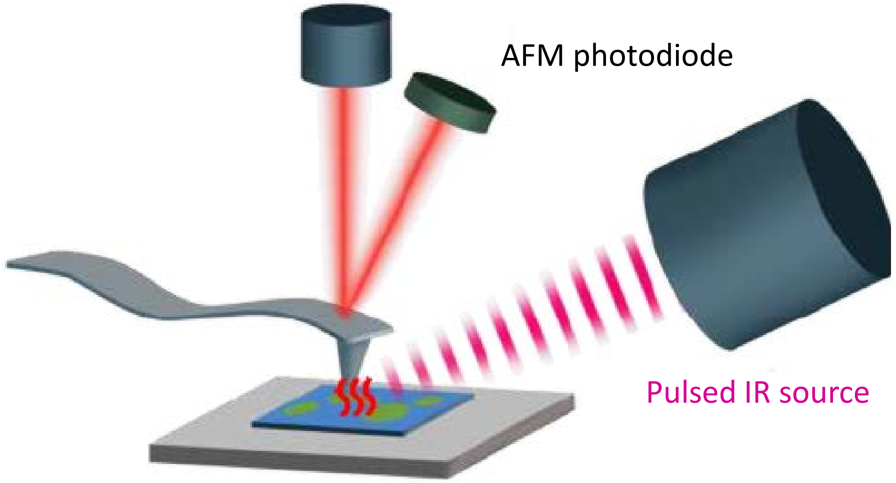
$$E_{sca} \propto \alpha_{eff} E_0 = s e^{i\varphi} E_0$$

$$\alpha_{eff} = \alpha_{eff}(\varepsilon_{mdium}, \alpha_{tip}, R, z, \varepsilon_{sample})$$

Fritz Keilmann and Rainer Hillenbrand
Optical oscillation modes of plasmon particles observed in direct space by phase-contrast near-field microscopy,
Applied Physics B 73, 239 (2001)

Photo-Thermal Expansion: PTE

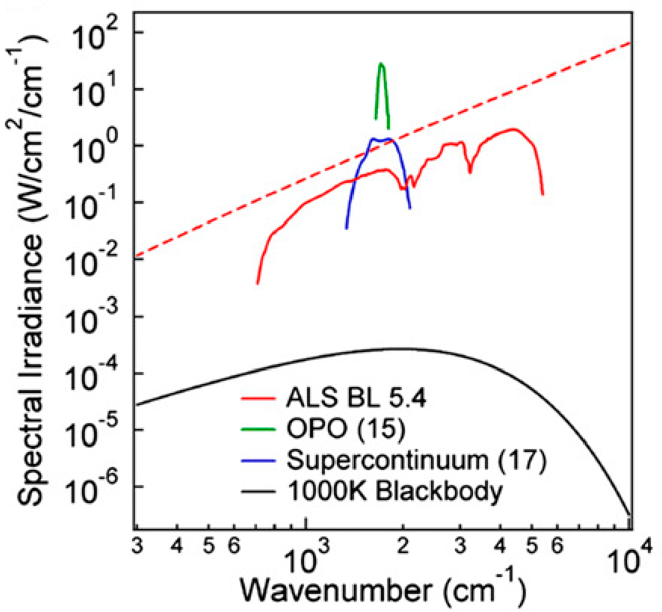
$$\Delta h \propto T_{max} \propto Pabs \propto \frac{\mathrm{Im}(n)}{\lambda} \propto Abs$$



$$\delta \approx \frac{1}{\text{Thermal diffusivity}}$$

A. Dazzi, R. Prazeres, F. Glotin, and J. M. Ortega
Local infrared microspectroscopy with subwavelength spatial resolution with an atomic force microscope tip used as a photothermal sensor, Optics Letters, 30(18), pp. 2388-2390 (2005)

IR Nanoscopy – IRSR adavantage

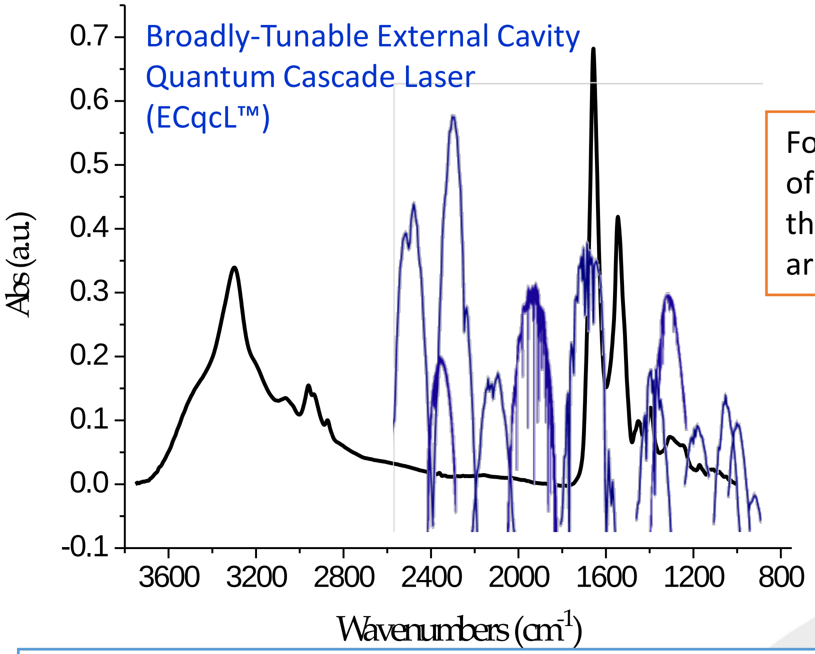


Hans A. Bechtel, Eric A. Muller , Robert L. Olmon, Michael C. Martin and Markus B. Raschke, *Proceedings of the National Academy of Sciences*, 111, 7191–7196 (**2014**)

S/N ratio is the key parameter for vibrational analysis.
The superior stability of IRSR compensate for the lower spectral density, without inducing radiation damage

- Ultra-broadband nature
- Superior density of power for spectral interval
- Superior spectral stability

The ultra-broadband nature of IRSR makes it the ideal source for IR nanospectrsocopy

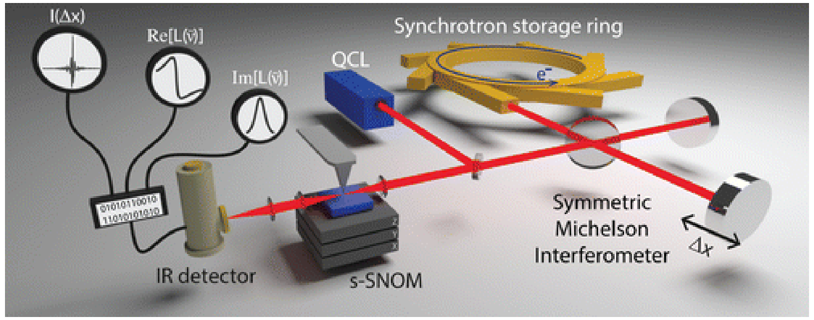


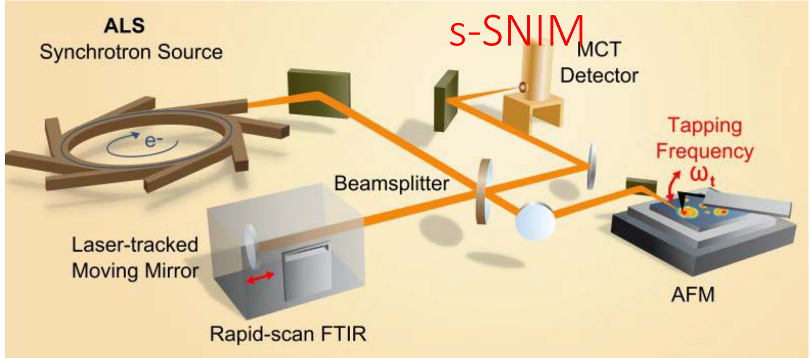
For barely covering almost half of the interesting MIR part of the spectrum, several QCL chips are needed.

Only the ultra-broadband nature of IRSR can guarantee the **selectivity** requirements for chemical and biochemical analysis

Elettra Sincrotrone Trieste

IR Nanoscopy at SR facilities worldwide





P. Hermann, A. Hoehl, A. Patoka, F. Huth, E. Rühl, and G. Ulm, *Optics Express* 21, 2913 (2013)

Not user dedicated

Benjamin Pollard, Francisco C. B. Maia, Markus B. Raschke, and Raul O. Freitas, *Nano Lett.*, 16 (1), 55–61 (2016)

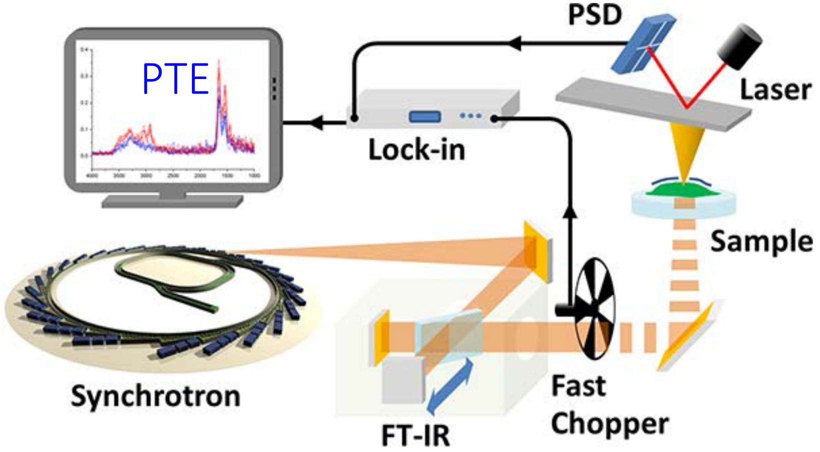
Open to users since 2015

Hans A. Bechtel, Eric A. Muller, Robert L. Olmon, Michael C. Martin and Markus B. Raschke, *Proceedings of the National Academy of Sciences*, 111, 7191–7196 (2014)

5.4 open to users since 2014; Second endstation opening soon

Projects just started

Commissioning phase

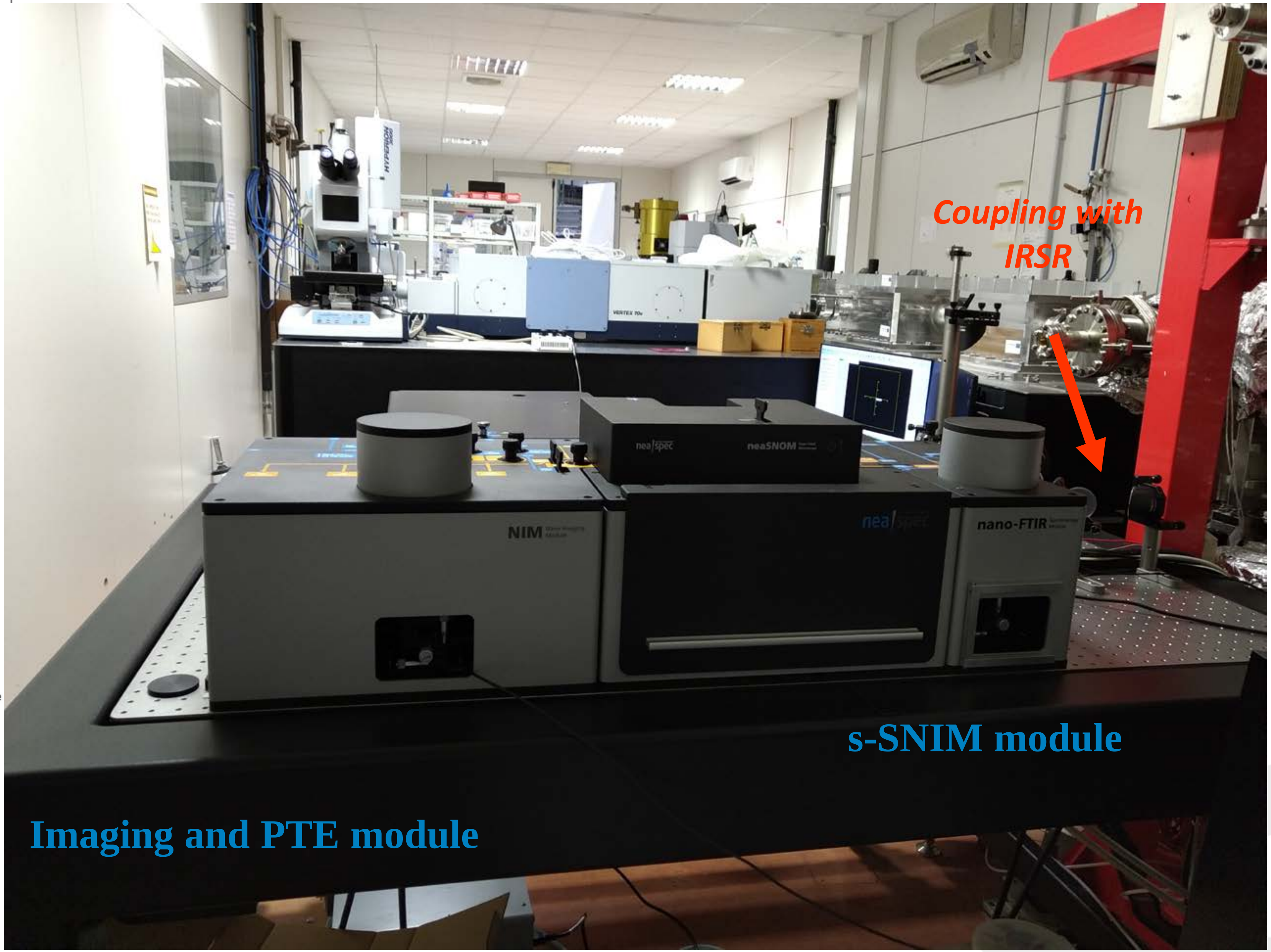


Paul M. Donaldson, Chris S Kelley, Mark D. Frogley, Jacob Filik, Katia Wehbe, and Gianfelice Cinque, *Optics Express* 24, 1852-1864 (2016)

End of commissioning phase

Elettra Sincrotrone Trieste

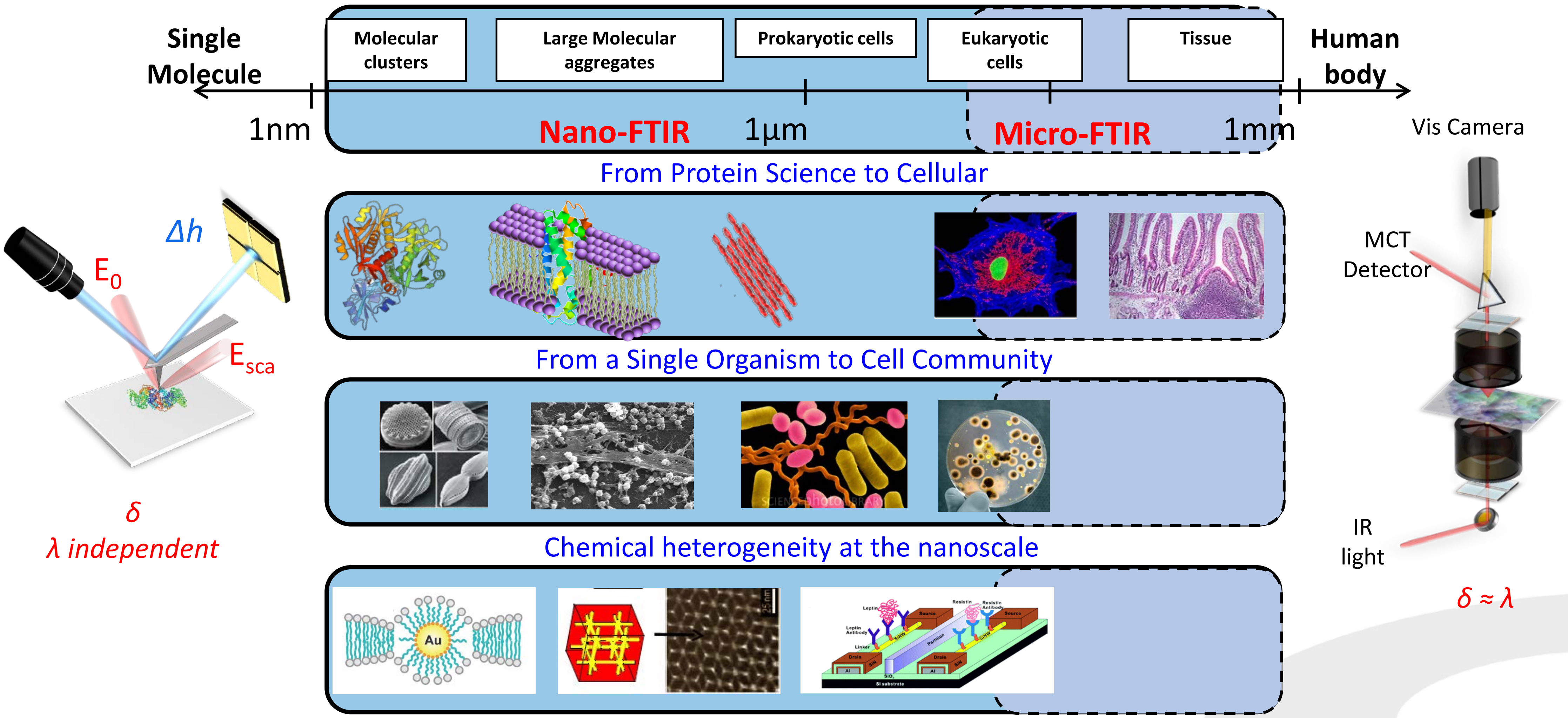
IR Nanoscopy endstation at SISSI-Bio



Integra

CERIC Central European Research Infrastructure Consortium

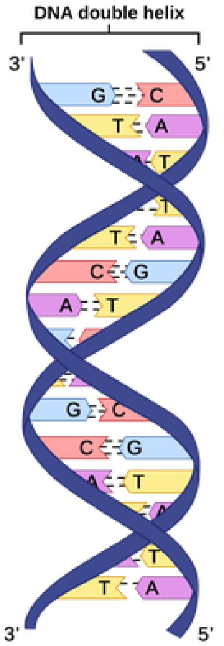
IR Nanoscopy at SISSI-Bio: Opportunities for Life Sciences

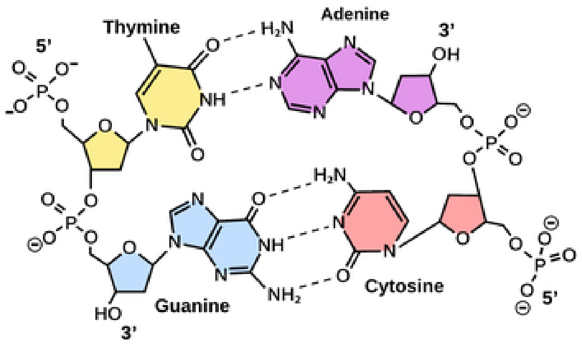


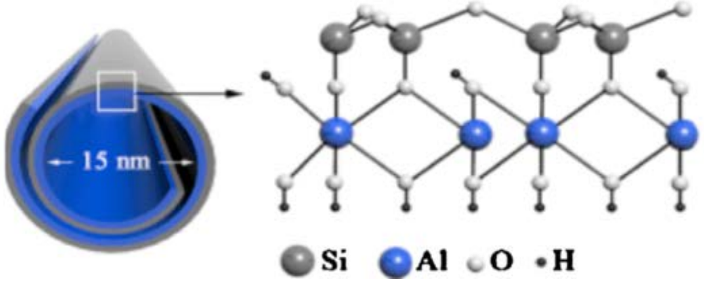
Probing DNA molecules on clay nanotubes

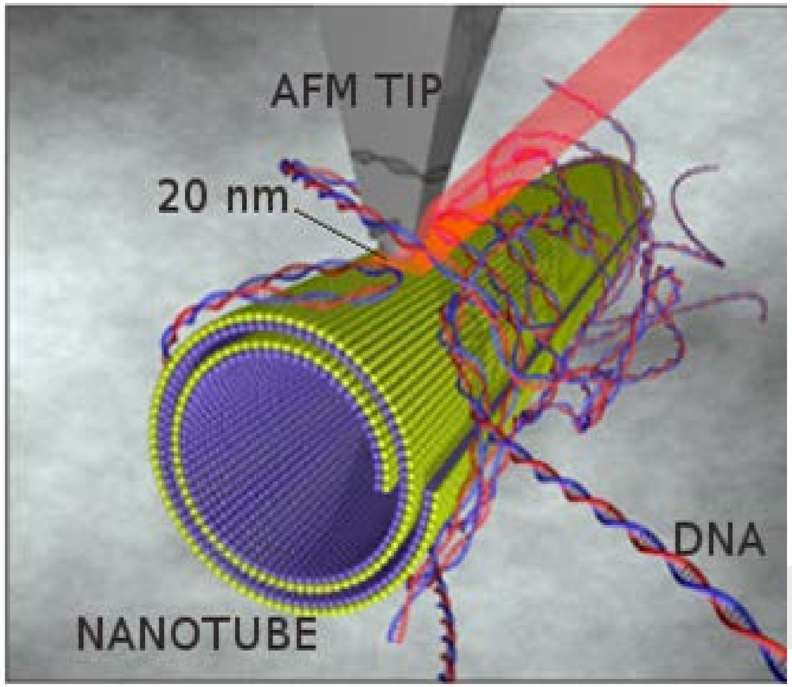
Halloysite nanotubes are natural biocompatible structures with high affinity for loading biomolecules, thus they are good candidates for drug delivery and gene transfer

- siloxane external surface −
- aluminum oxide internal surface +





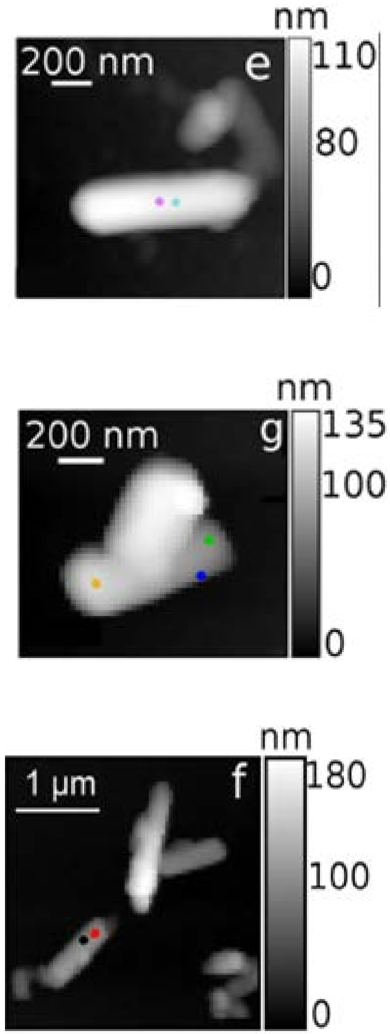


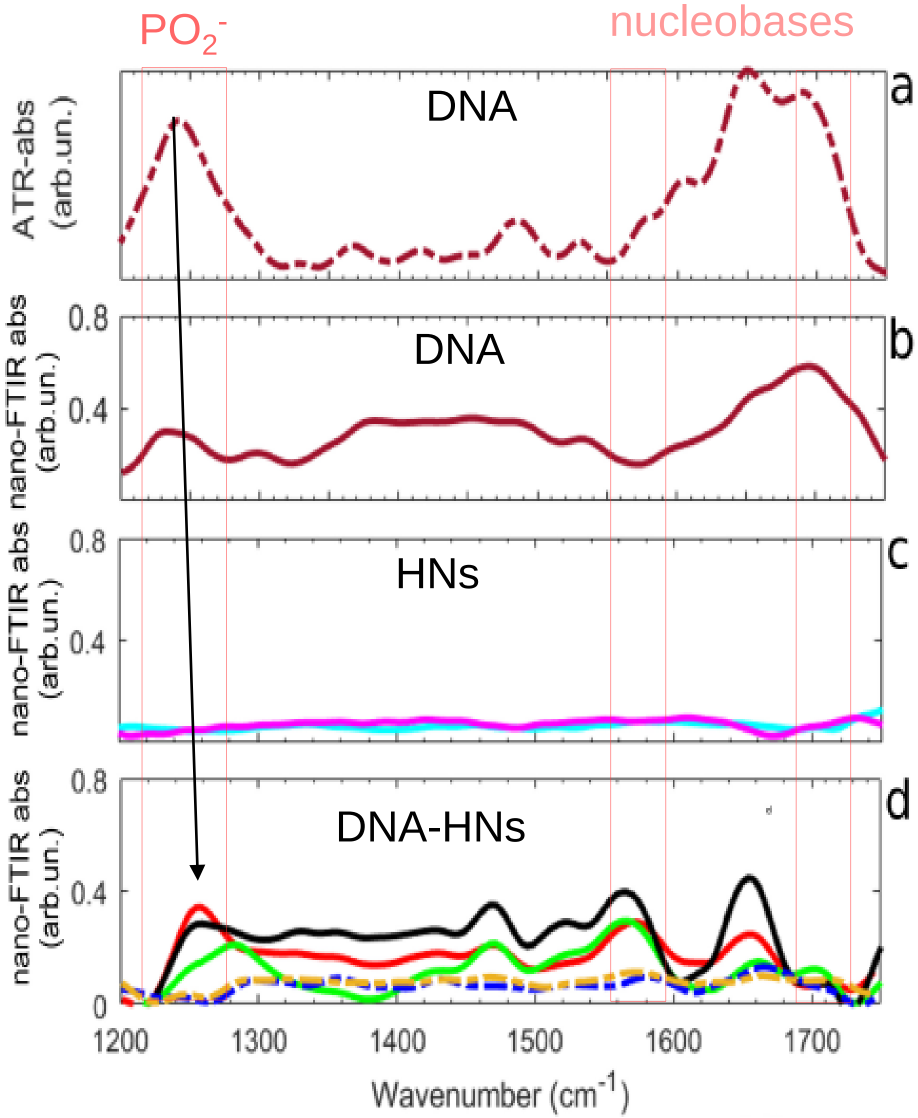


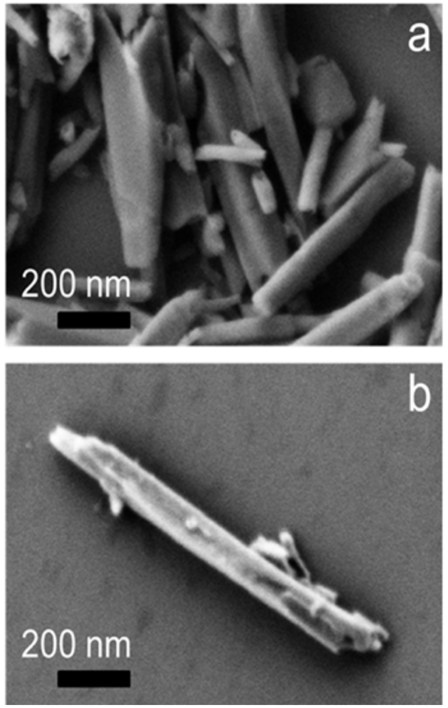
DUE TO ELECTROSTATIC FORCES DNA SPONTANEOUS ADSORPTION ON HALLOYSITE NANOTUBES IS COUNTERINTUITIVE!

Piccirilli et al., *Nanomaterials* 2021, 11(5), 1103

Probing DNA molecules on clay nanotubes

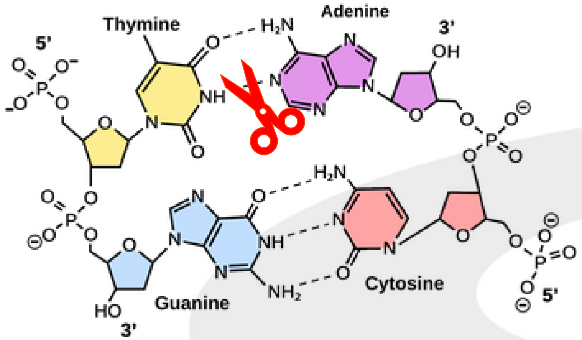






Pristine nanotubes

Nanotube with DNA



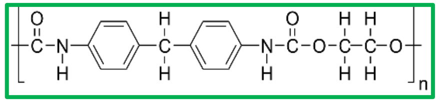
DNA modify its structural arrangement when loaded onto nanotubes

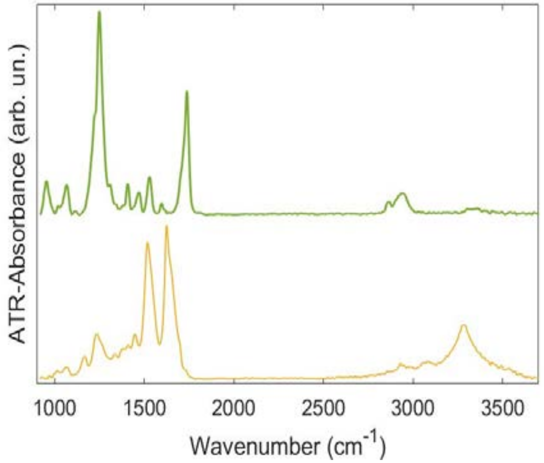
Relating morphology to chemical composition in composite matrices for in situ vascular tissue engineering

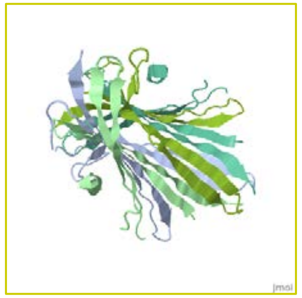
Elettra Sincrotrone Trieste

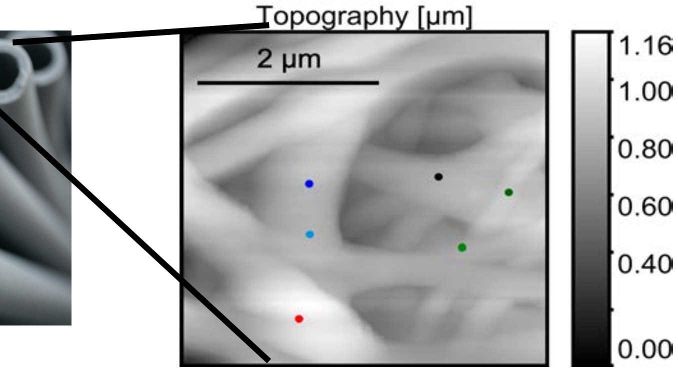
SILKELASTOGRAFT

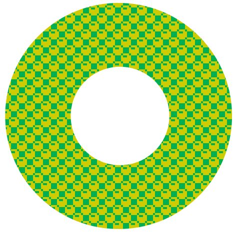
https://www.silkelastograft.polimi.it/?page_id=237&lang=en





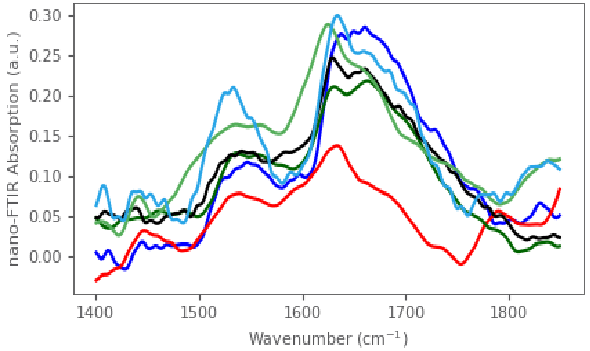


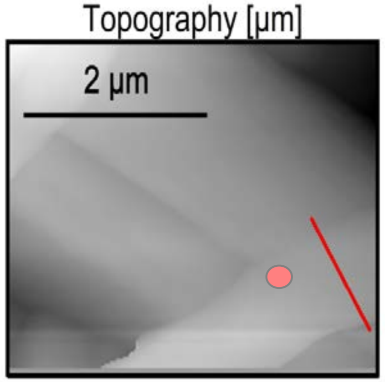


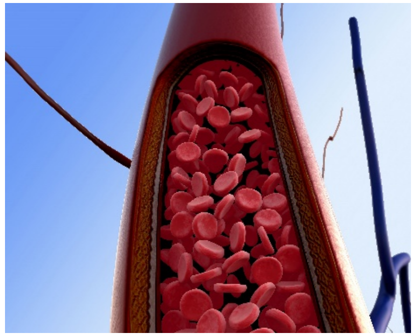


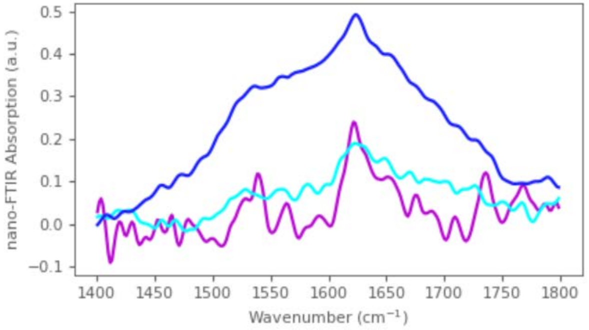
PU polyurethane

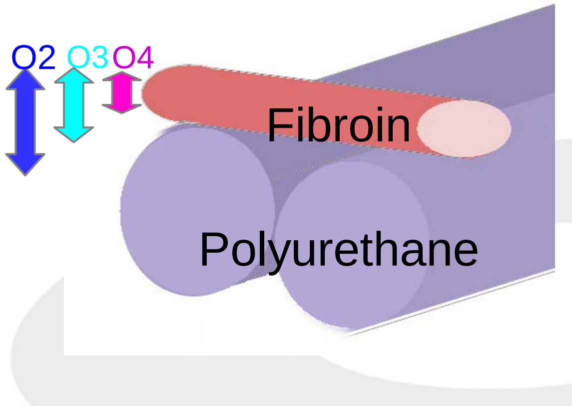
SF Silk fibroin











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Thank for your attention!

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