New Dimensions in Synchrotron Infrared Spectroscopy and Imaging

ALS Synchrotron Infrared Beamlines

BERKELEY LAB

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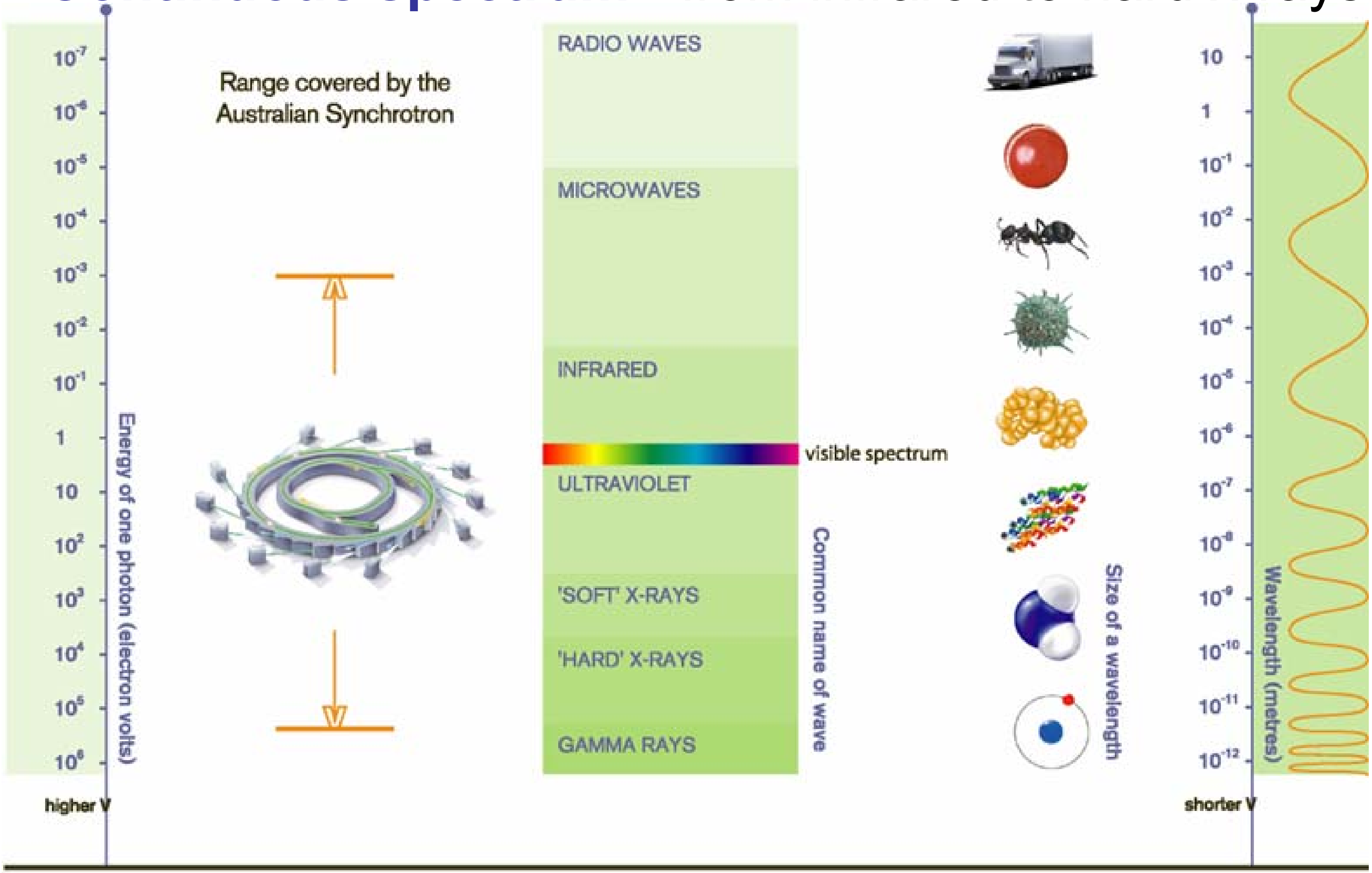
ALS INFRARED BEAMLINE 5.4

Office of Science
U.S. DEPARTMENT OF ENERGY

Introduction: SRIR

Introduction

Continuous spectrum - from infrared to hard x-rays

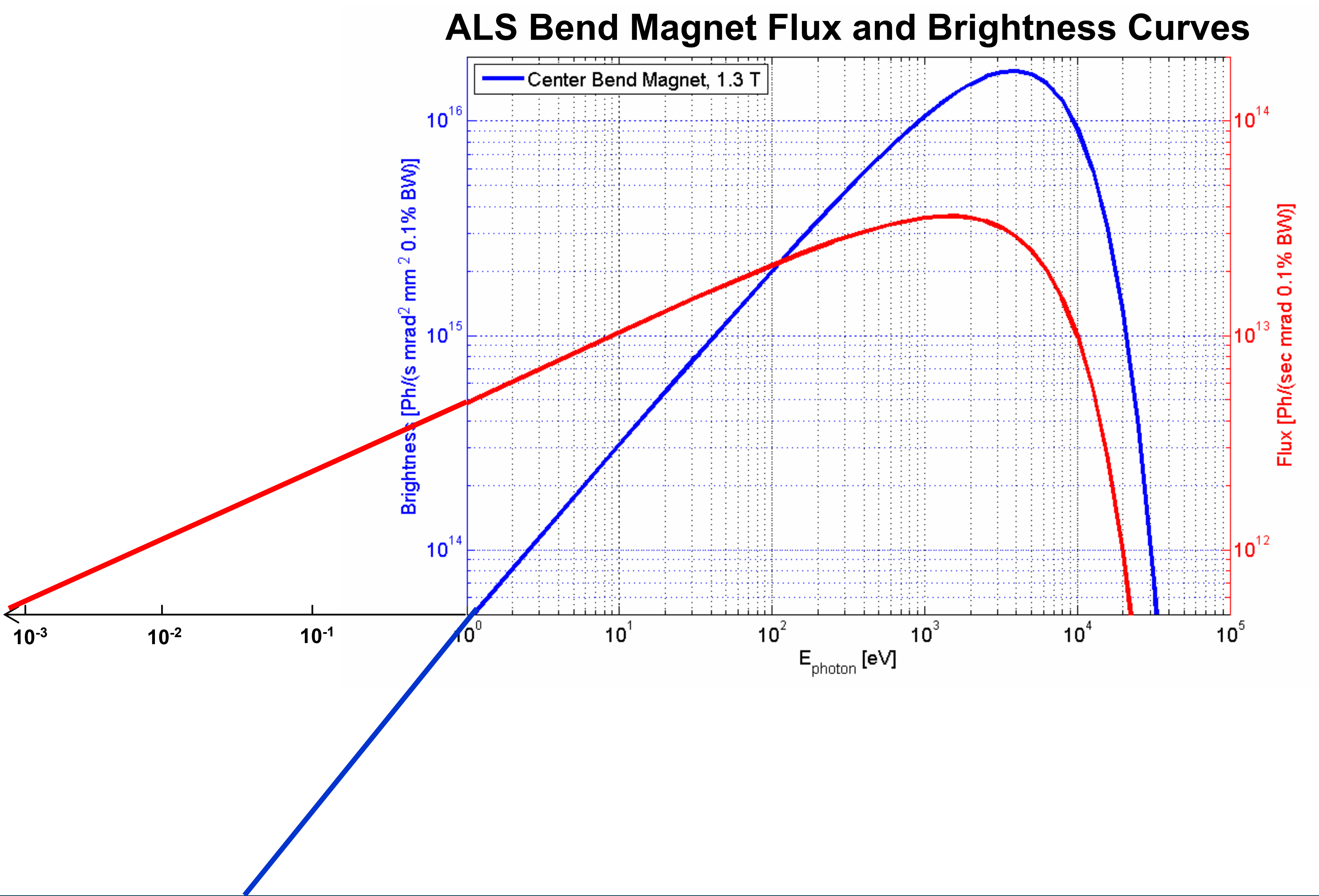


EMR The Electromagnetic Spectrum

Synchrotrons produce useful IR too!

Introduction

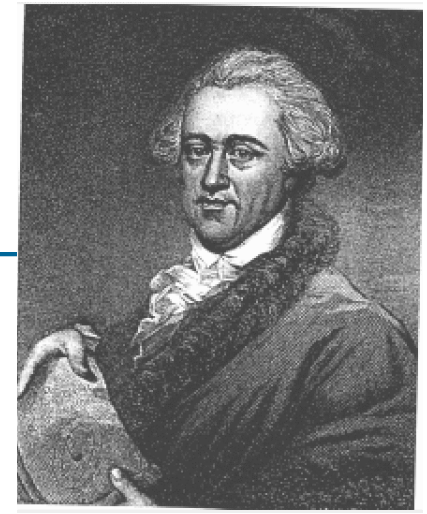
Continuous spectrum - from infrared to hard x-rays



ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

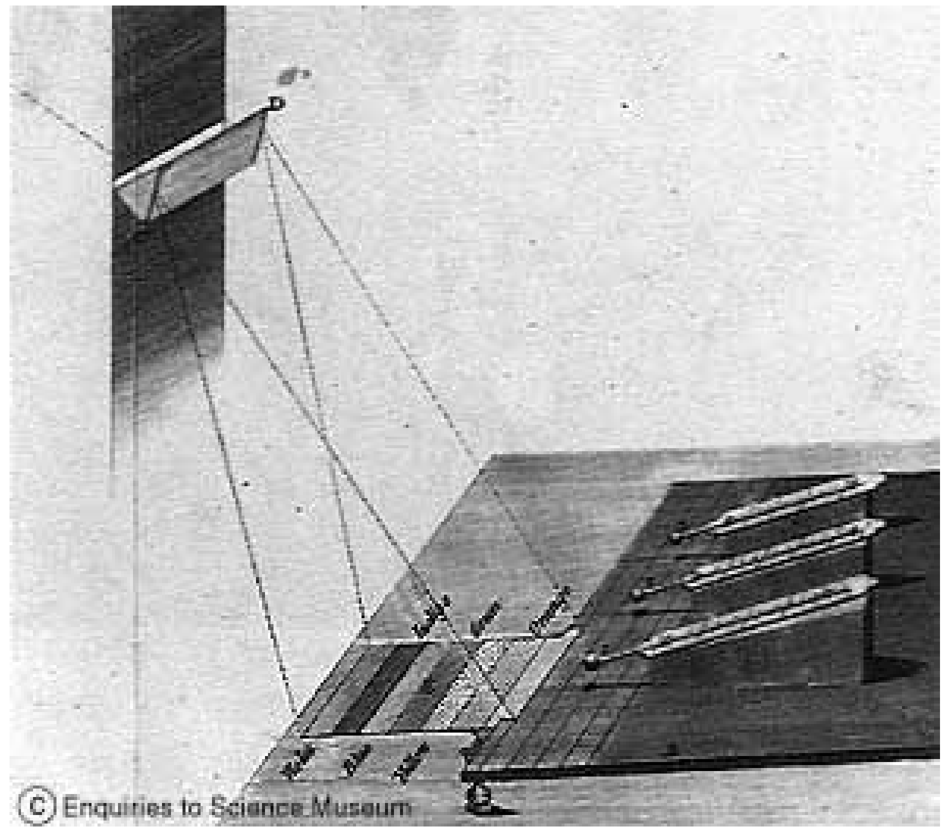
William Herschel

The discovery of infrared light



In 1800, Herschel studied the spectrum of sunlight with a prism. He measured the temperature of each color, and found the highest temperature was just beyond the red, what we now call the infrared ('below the red').

The Science Museum, UK



F.W. Herschel, Phil. Trans. Royal Soc. London **90**, 49 (1800).

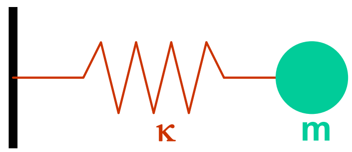
Ernest Orlando Lawrence Berkeley National Laboratory

What can we learn from IR spectroscopy?

- **Atoms vibrate with frequencies in the IR range**

- **Chemical Analysis:**
    - **Match spectra to known databases**
        - **Identifying an unknown compound, Forensics, etc.**
    - **Monitor chemical reactions *in-situ***
- **Structural ideas:**
    - **Can determine what chemical groups are in a specific compound**
- **Electronic Information:**
    - **Measure optical conductivity**
        - **Determine if Metal, Insulator, Superconductor, Semiconductor**
        - **Band Gaps, Drude model**

A Simple Oscillator



Imagine the mass is an atom, carrying a charge. This will then couple to the electric field in light.

Ball & Spring equation: F = -k Dx

Spring constants for chemical bonds:

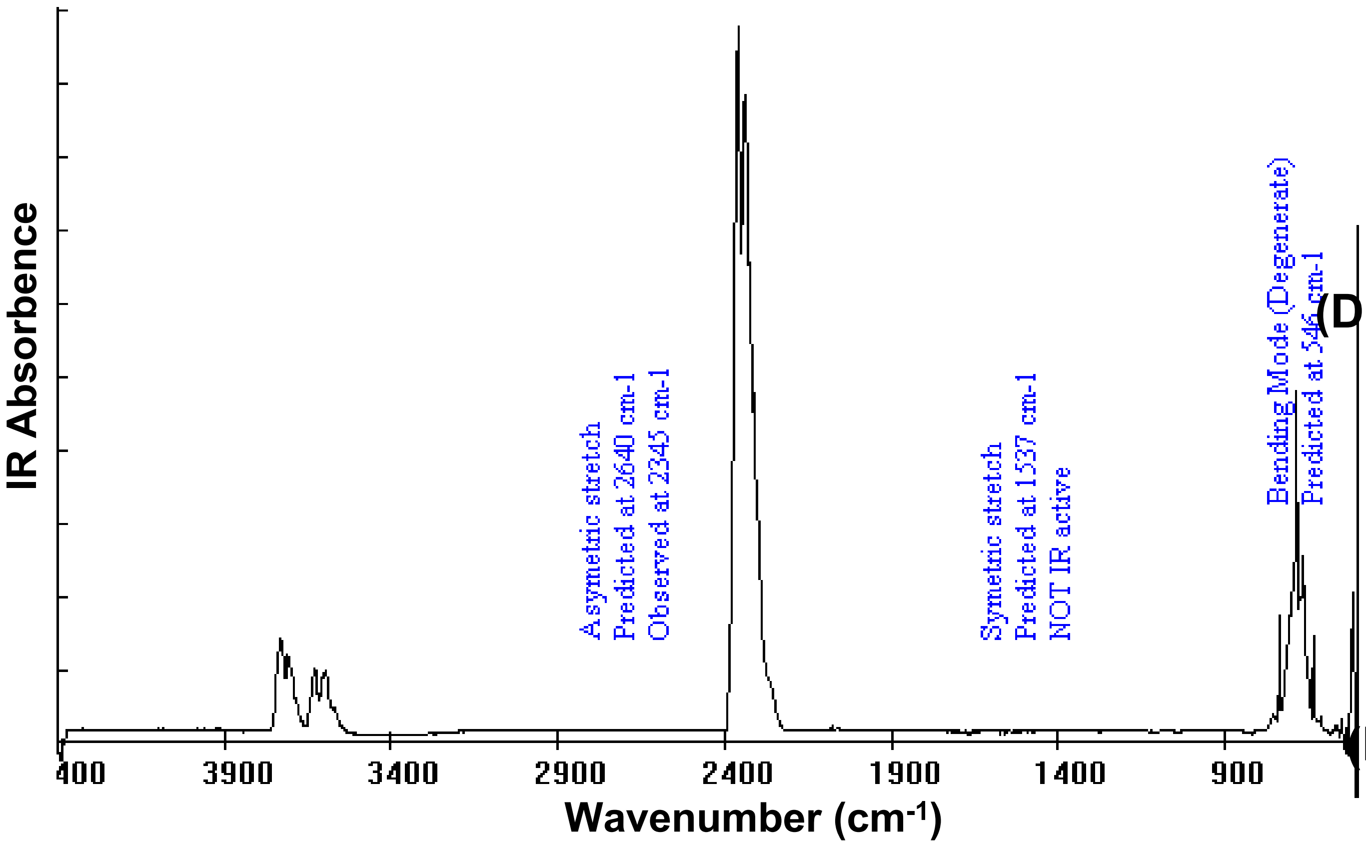
- k = 40 – 400 N/m for covalent bonds
- k = 20 – 200 N/m for ionic bonds
- k = 0.5 – 4 N/m for Van der Waals bonds

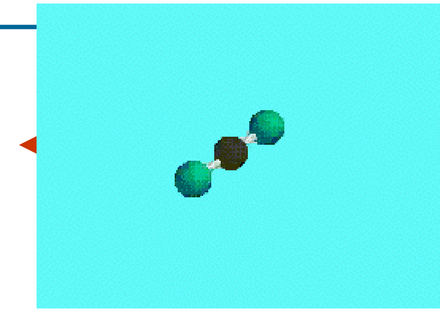
Solution to resonance frequency for ball & spring:

$$\omega_0 = \sqrt{\frac{\kappa}{m}}$$

A hydrogen atom has a mass of 1.6735 x 10^{-27} kg
An oxygen atom has a mass of 2.6561 X 10^{-26} kg

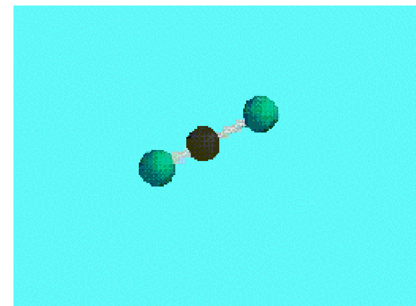
An Example: CO_2





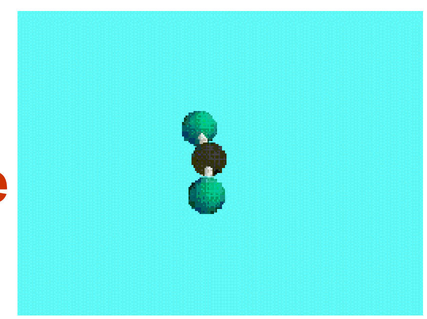
Symmetric Stretch

(Dipole moment = 0 so not IR active



Asymmetric Stretch

(Has dipole moment so IR active)

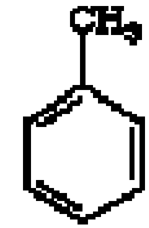


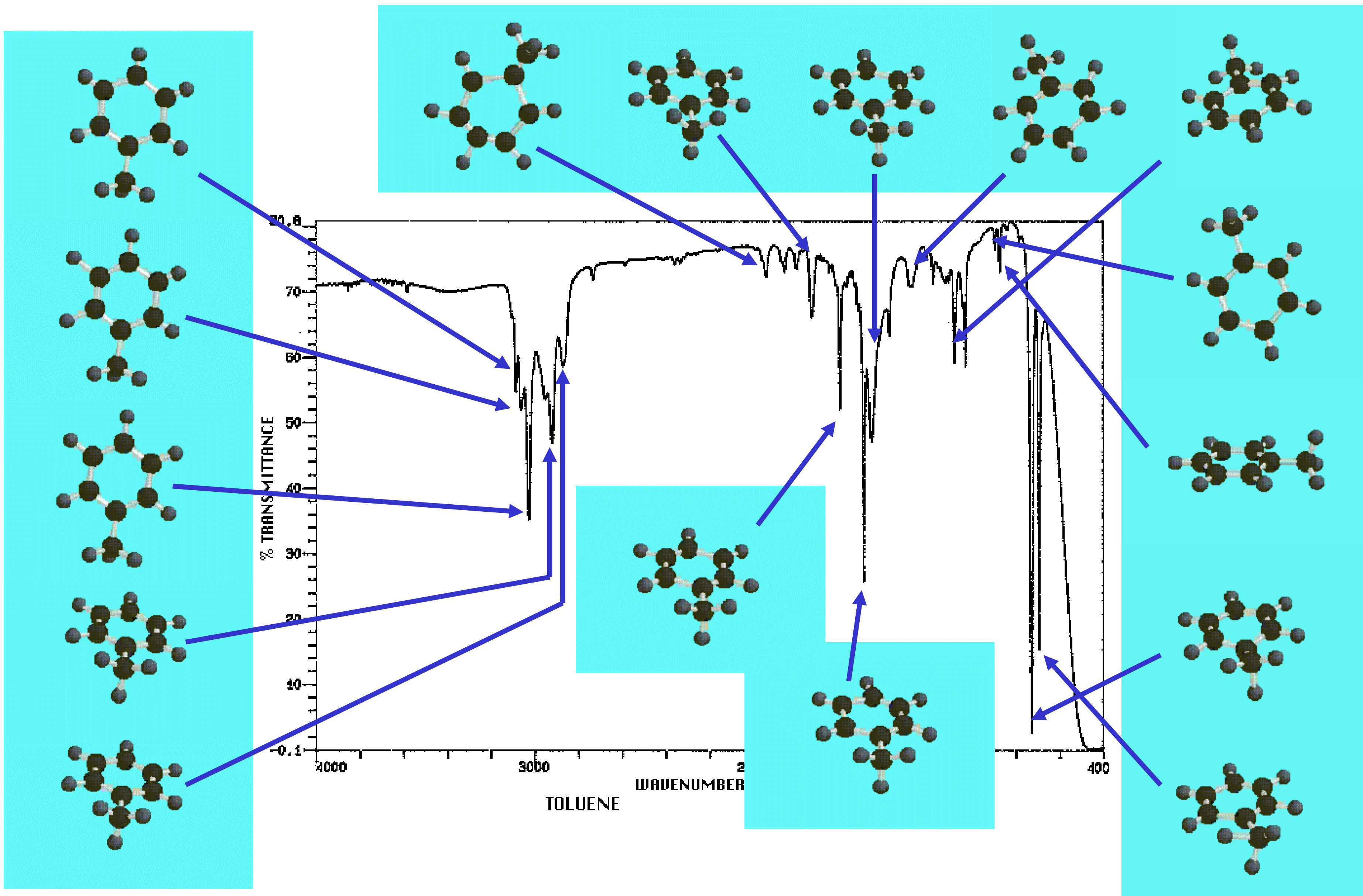
Bending Mode

(Has dipole moment so IR active

A Dipole Moment = charge imbalance in the molecule

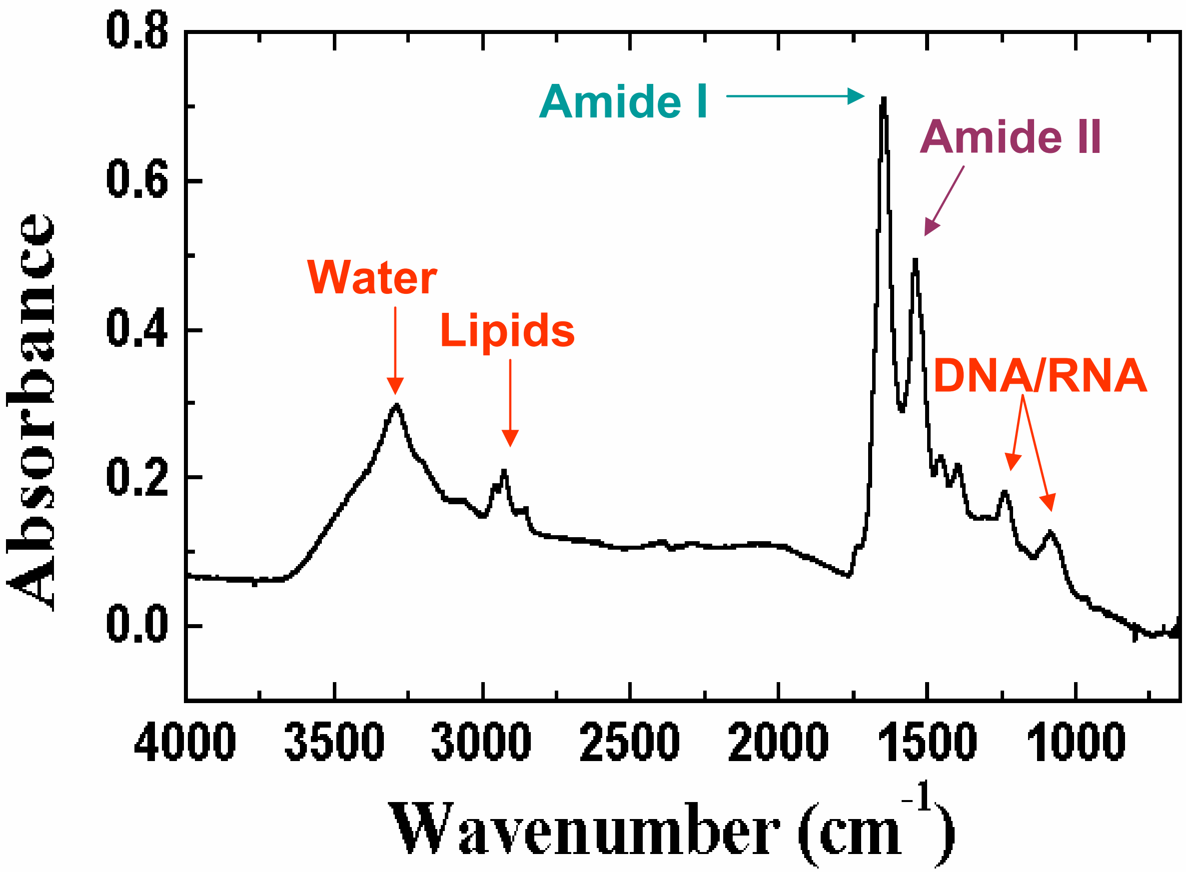
A more complex example: Toluene

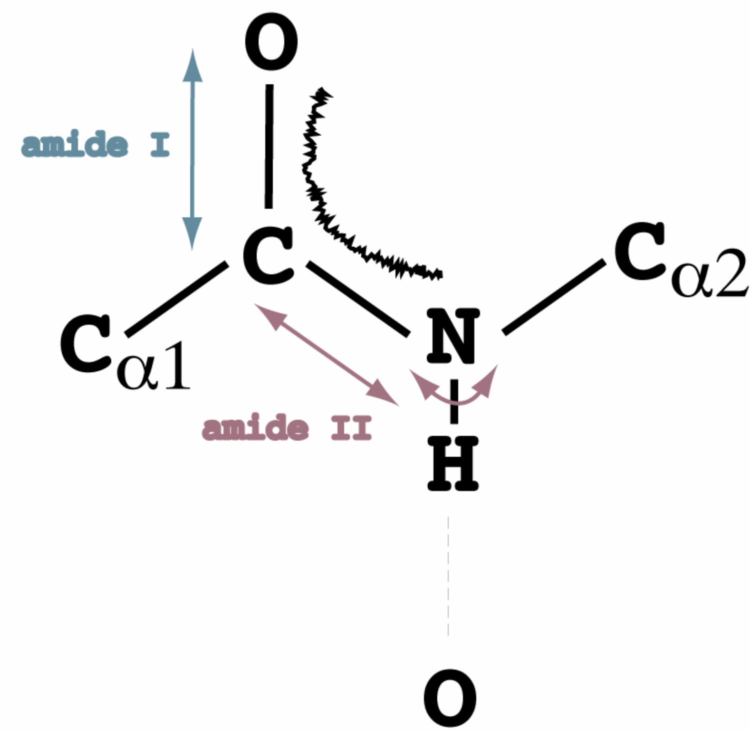




From: http://www.cem.msu.edu/~parrill/AIRS/

Example infrared spectrum of a biological system





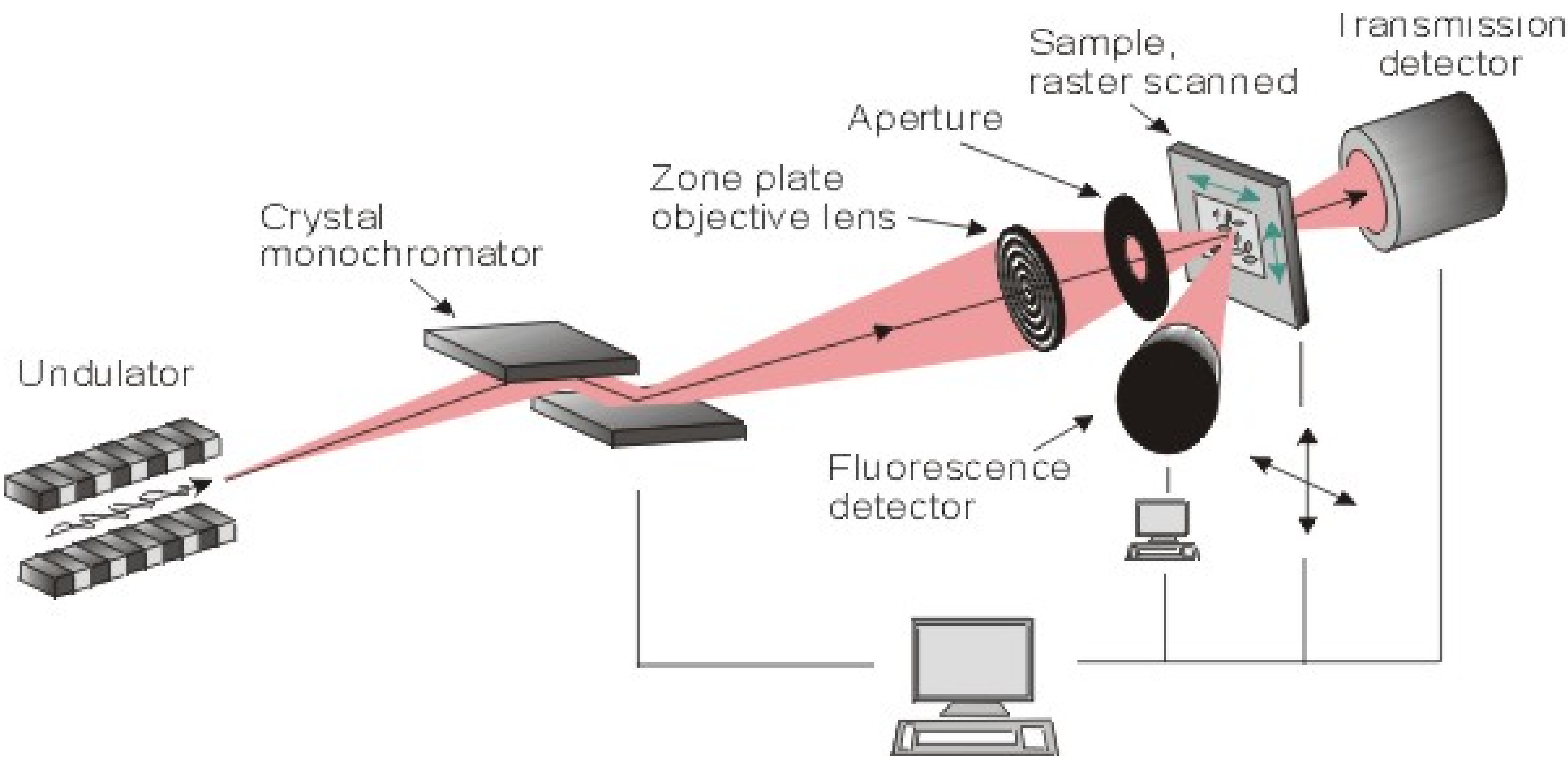
Typical IR absorbance positions:

Protein Amide I:	1690-1600
Protein Amide II:	1575-1480
Lipid $=CH_2$:	3100-3000
Lipid $-CH_2$, $-CH_3$:	3000-2850
Nucleic Acid $-PO_2^-$:	1225, 1084

The peak positions of Amide I and II are sensitive to the protein secondary structure (α-helix, β-sheet, random coils, etc.)

A good reference: Mantsch and Chapman, *Infrared spectroscopy of biomolecules*. 1996, New York: Wiley-Liss.

Monochomators



Albert Michelson (1852-1931)

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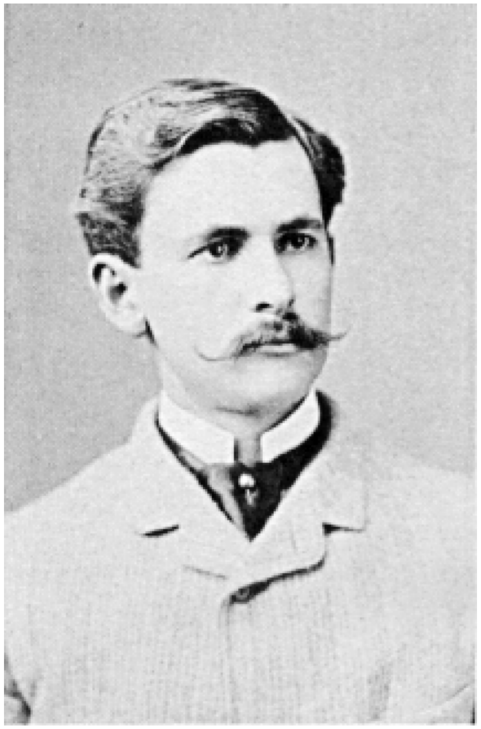
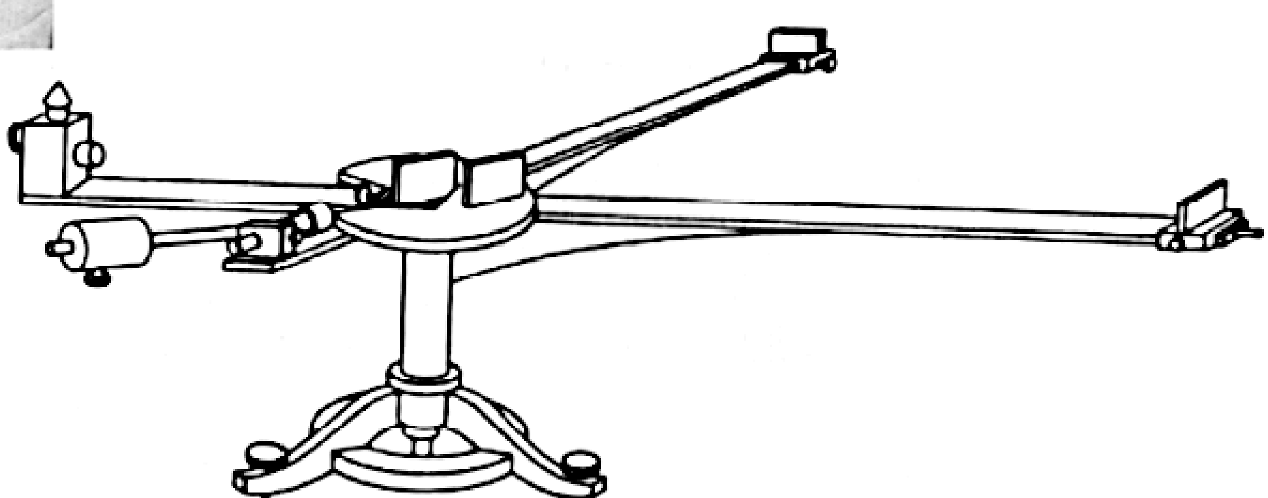
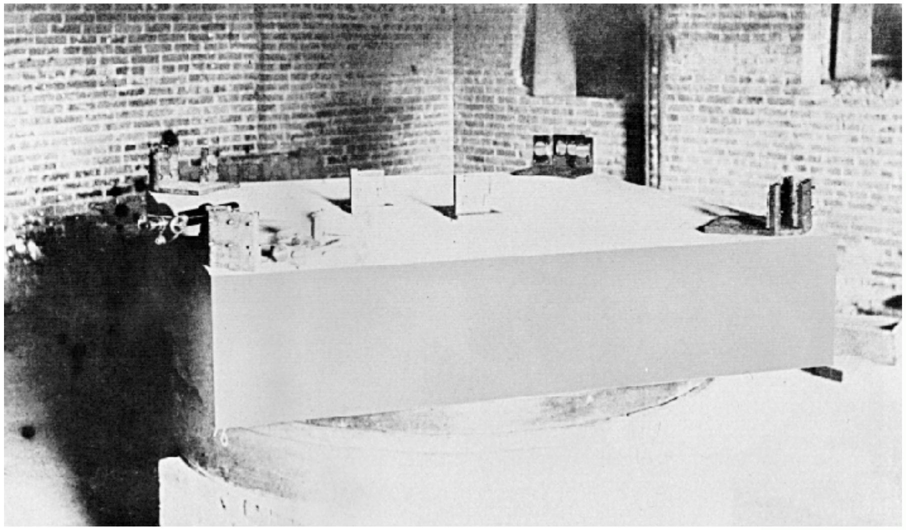


Michelson wanted to measure the speed the the earth moves through the ether (the medium in which light travels). By measuring the interference between light paths at right angles, one could find the direction & speed of the ether.

Michelson's first interferometer (1881)



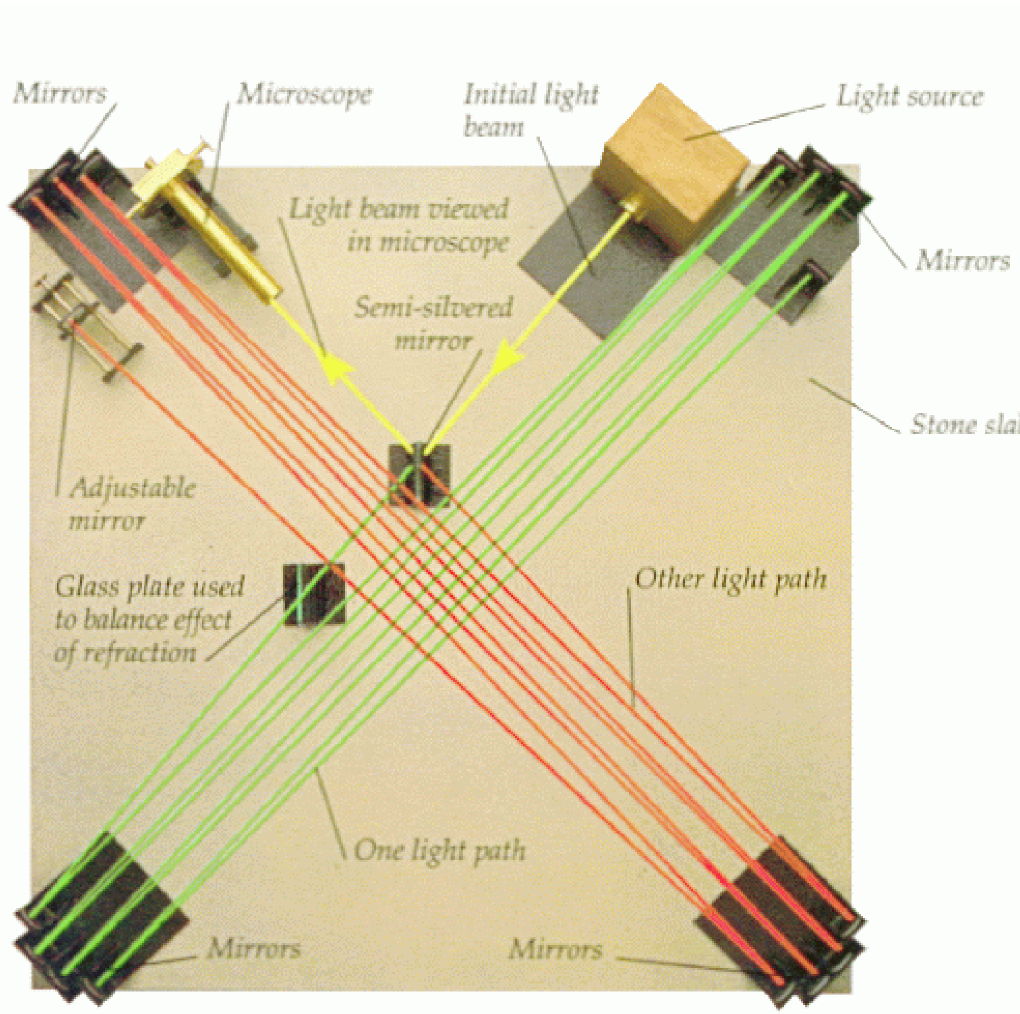
Michelson-Morley Experiment



Still no fringes → No ether.
The speed of light is constant.
A new physics of light was needed.

"My honored Dr. Michelson, it was you who led the physicists into new paths, and through your marvelous experimental work paved the way for the development of the theory of relativity." – Albert Einstein, 1931.

Michelson-Morley interferometer (1887)



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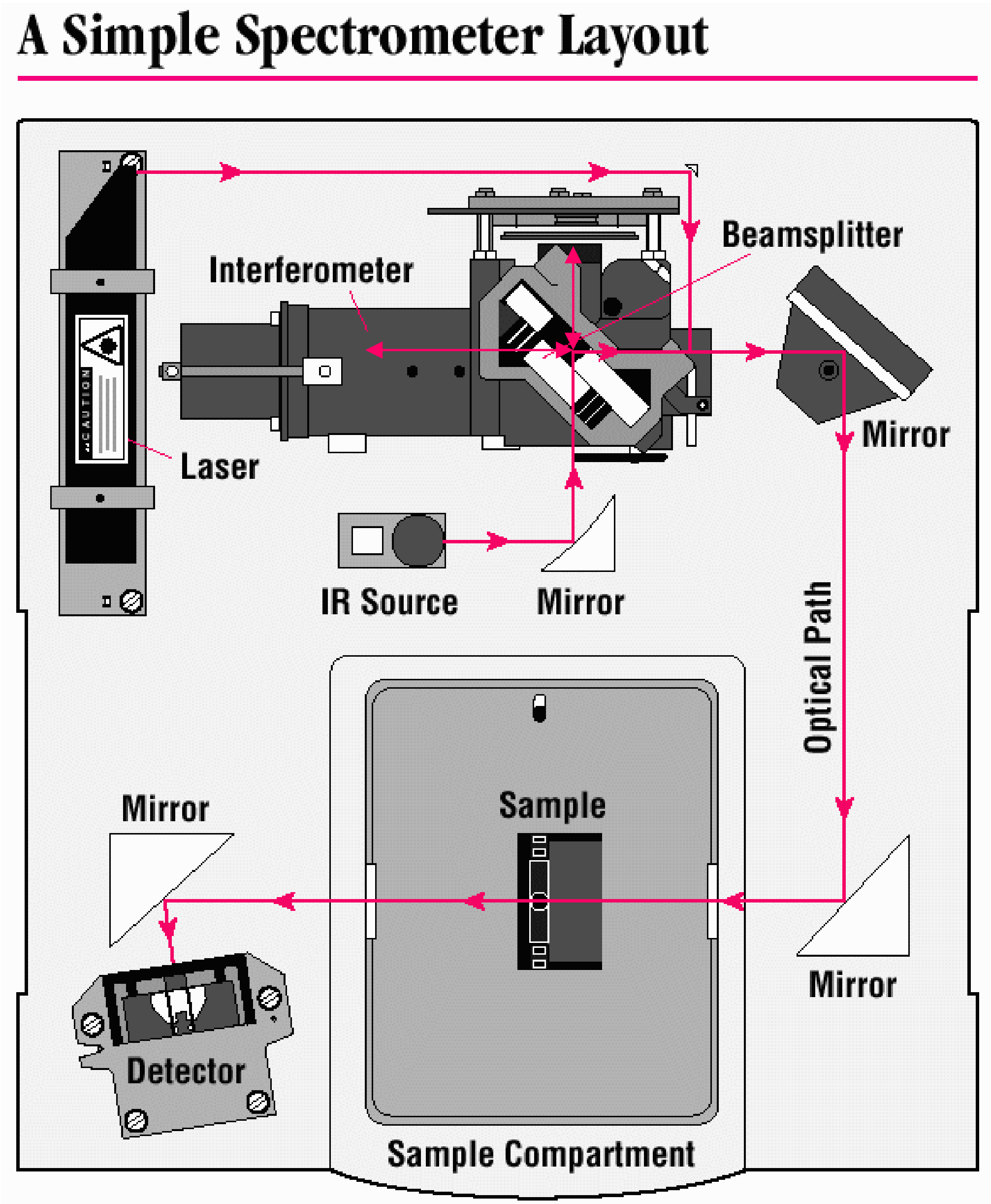
More about Michelson

Michelson won the Nobel Prize in physics in 1907.

He continued pioneering optical measurements:

- **The speed of light**
- **The size of stars**
- **Using a particular wavelength of light as a distance standard**

How an FTIR Spectrometer Works



Pathlength difference = x

The intensity detected of two plane waves:

$$I = \left|\vec{E}\right|^2 = \left|E_1\right|^2 + \left|E_2\right|^2 + 2\vec{E}_1 \bullet \vec{E}_2 \cos(\theta)$$

Normal incidence, θ = kx, can simplify to:

$$I(x) = 2\left[1 + \cos(kx)\right]$$

For non-monochromatic light:

$$I(x) = \int_0^\infty \left[1 + \cos(kx)\right] G(k)\,dk$$

$$= \int_0^\infty G(k)\,dk + \int_0^\infty G(k)\frac{e^{ikx} + e^{-ikx}}{2}\,dk$$

$$= \frac{1}{2} I(0) + \frac{1}{2}\int_{-\infty}^{\infty} G(k) e^{ikx}\,dk$$

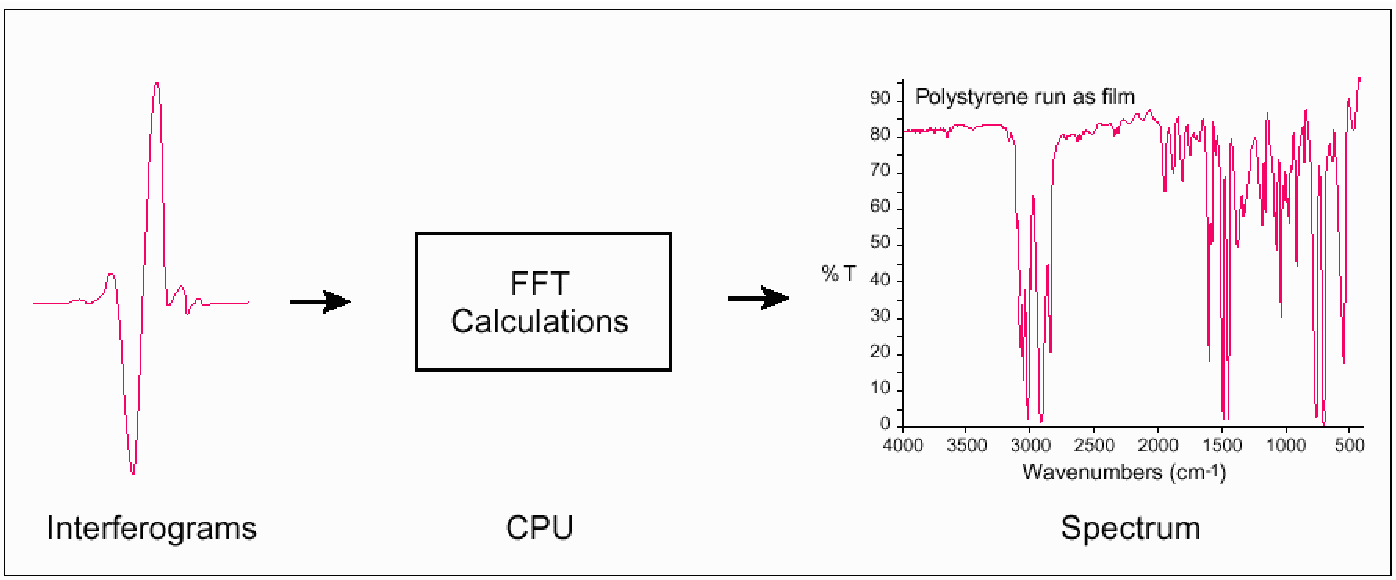
FTIR Math Continued

We can rewrite this to something more familiar:

$$W(x) \equiv \frac{2I(x) - I(0)}{\sqrt{2\pi}} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} G(k) e^{ikx} dk$$

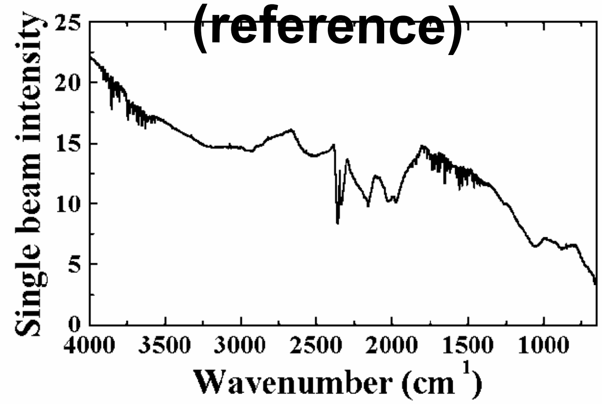
A Fourier Transform!

The detected intensity as a function of moving mirror position, I(x), can therefore be converted into G(k), the intensity spectrum as a function of frequency by a simple Fourier transform.

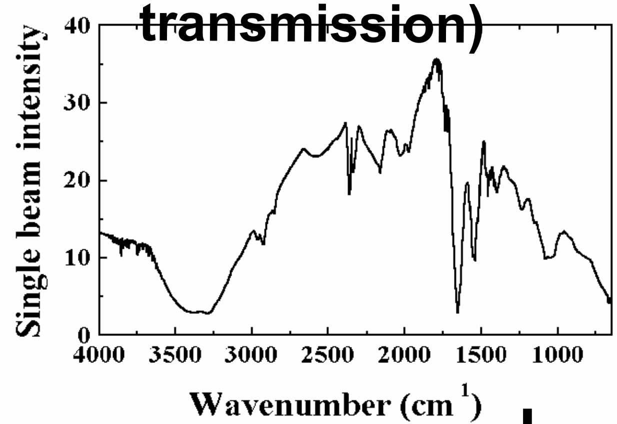


Infrared Spectroscopy Measurements

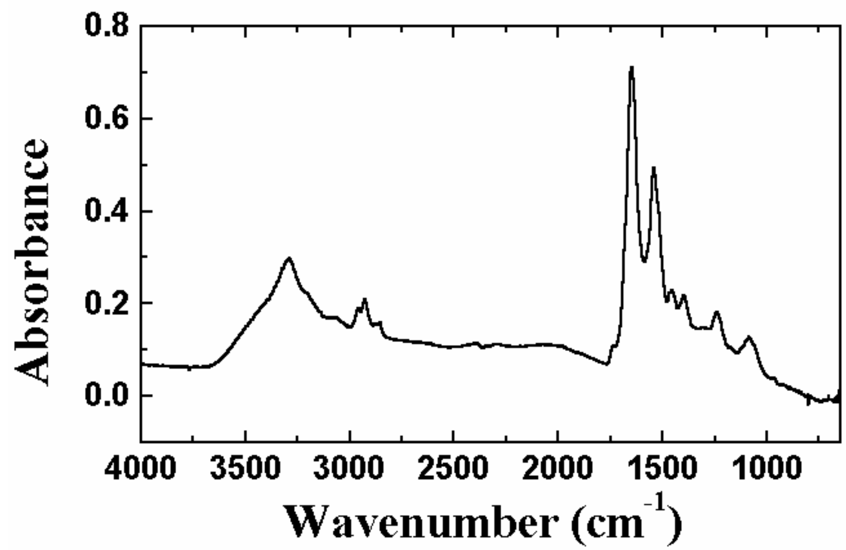
Incoming IR signal (reference)



Measured reflection (or transmission)



Focussed onto sample



Resultant absorbance spectra (or reflection, or transmission)

Why use a synchrotron for IR?

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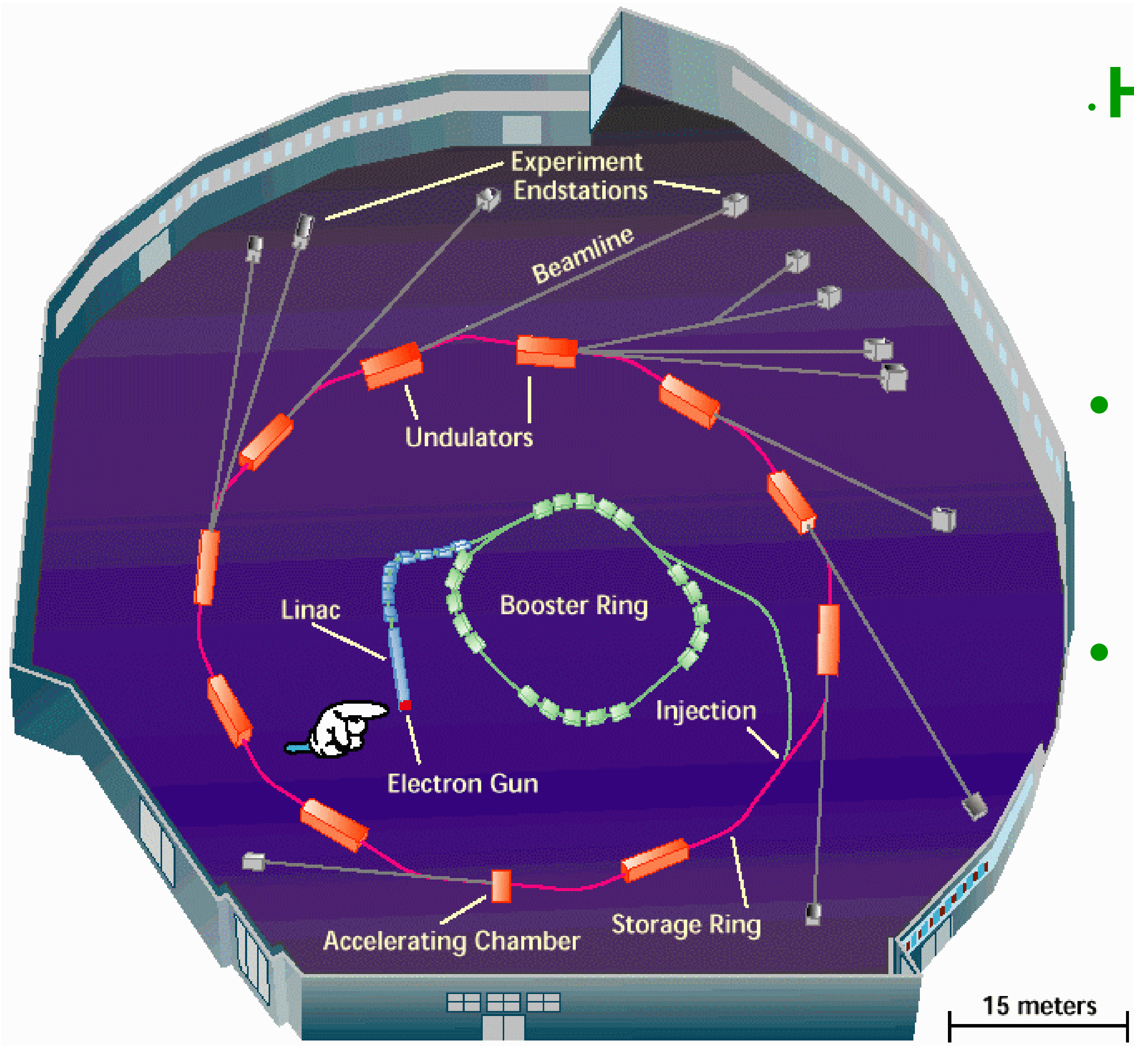


• High brightness

- Essentially a point source
- Can focus light to a diffraction-limited size: Microscopy

• More far-IR flux

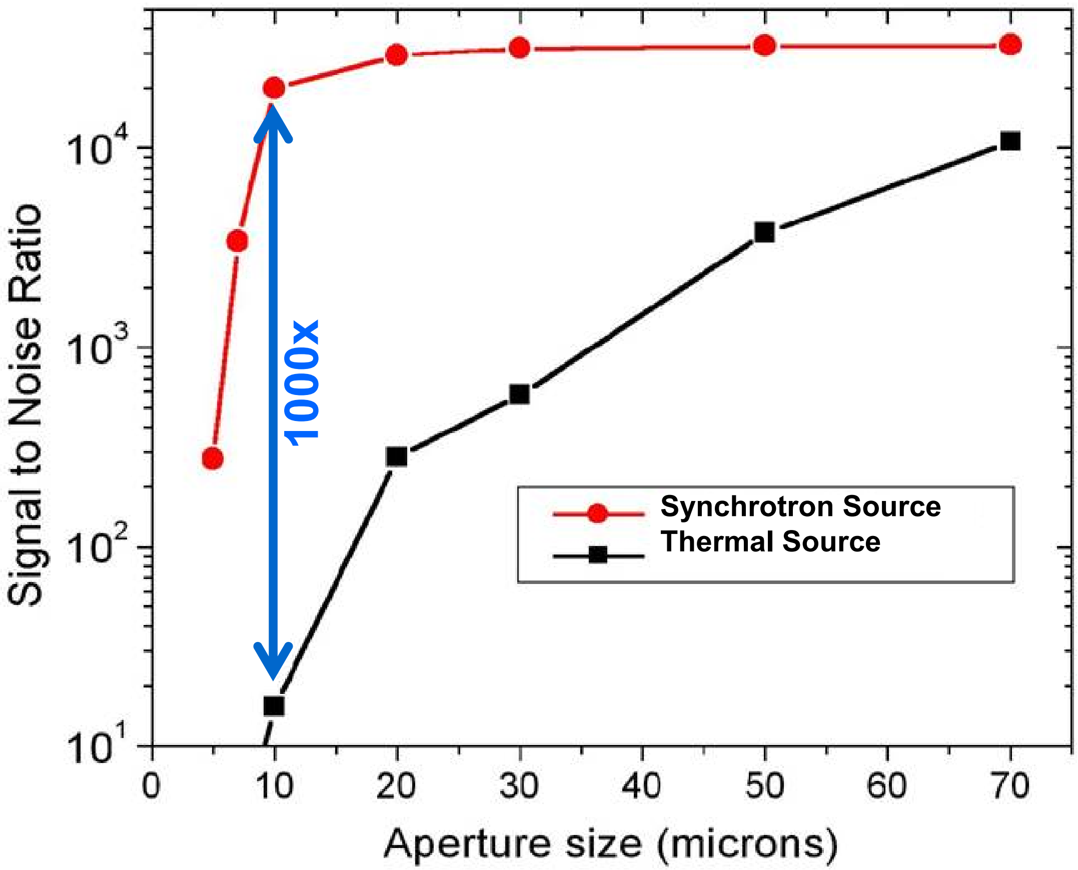
- Smaller samples
- Better signal-to-noise

• Pulsed source

- Light is from electron bunches
- Fast timing measurements (nsec)

Synchrotron IR Advantage

Synchrotron IR is 1000x *brighter* than a conventional blackbody source



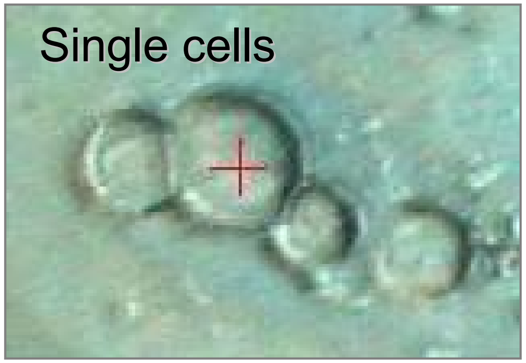
Advantages

- Diffraction-limited spot sizes for microscopy (2-10 μm)
Levenson, Lerch & Martin, *J. Synch. Rad.* (2008)
- Superior collimation for high spectral resolution
- Smaller samples
- Better signal to noise ratios
- Faster data acquisition

Holman et al., Spectroscopy - An International Journal 17(2-3), 139-159 (2003).

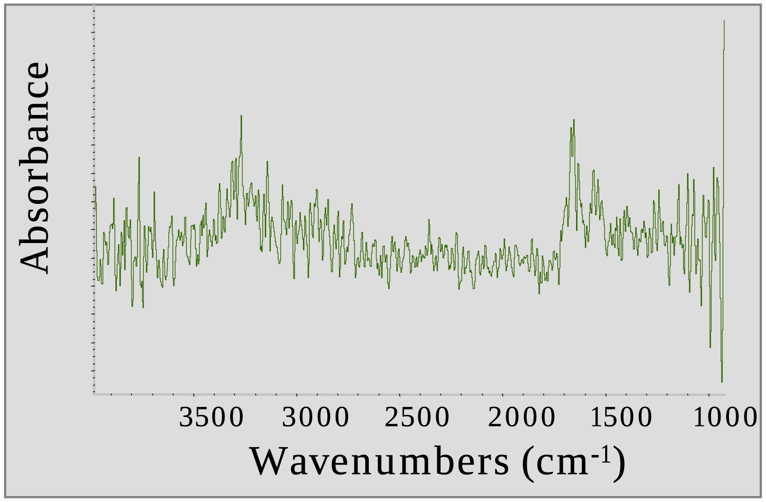
High Brightness = Better Biology

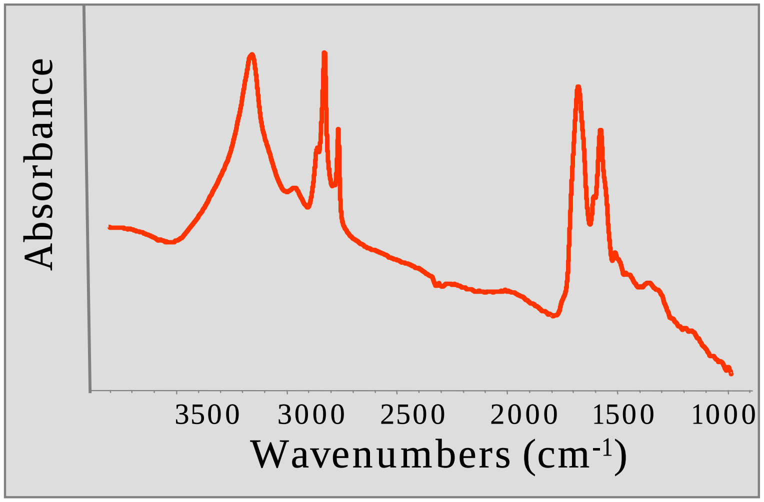
Better Signal-to-Noise and Faster Collection



Globar: 6x6 μm^2
1000 scans = 500s

Synchrotron: 6x6 μm^2
32 scans = 16 s



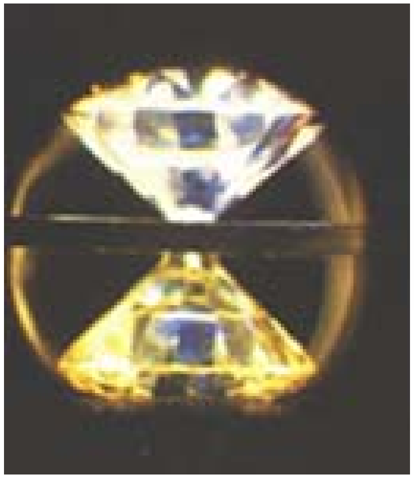


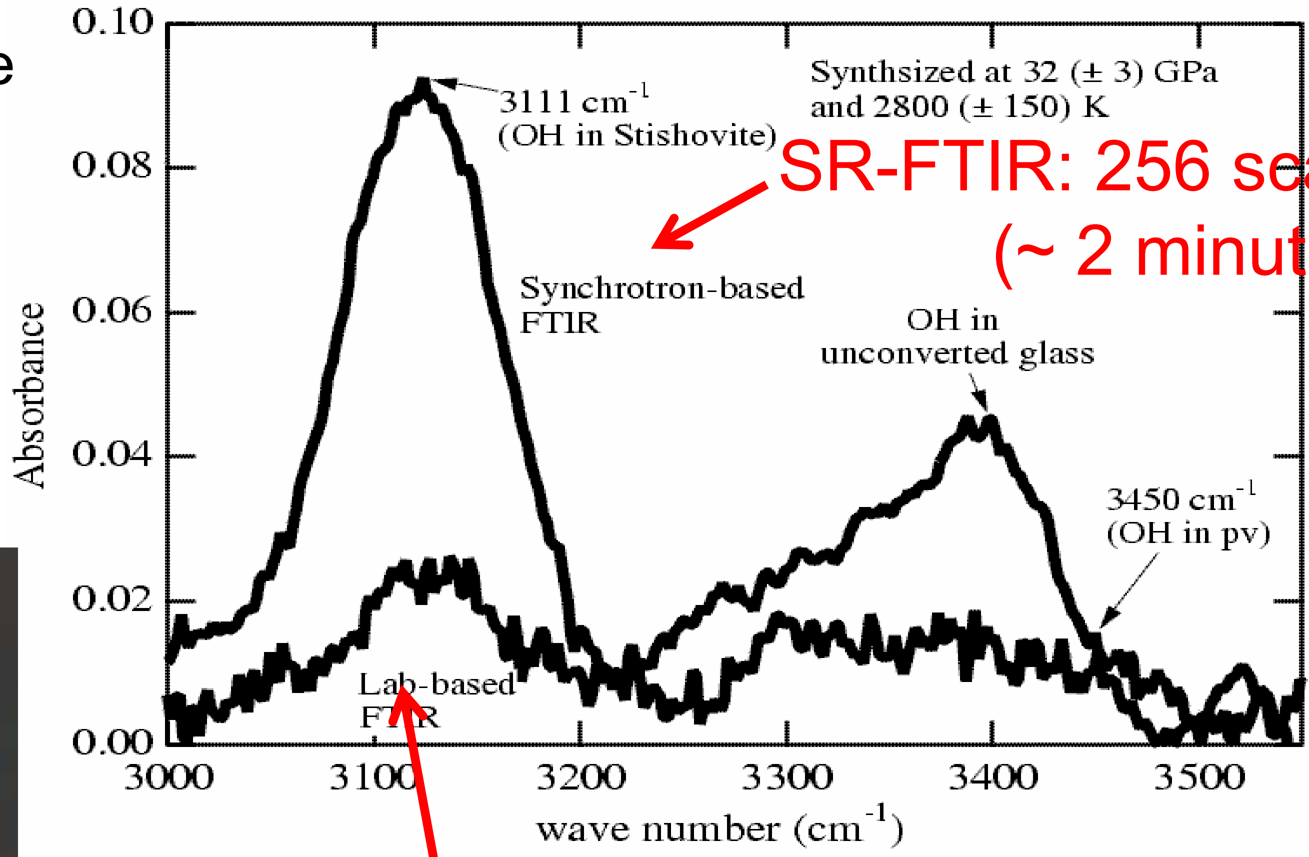
From Paul Dumas, SOLEIL

High Brightness = Better for small samples

Better Signal-to-Noise and Faster Collection

Mineral sample (ocean basalt) in diamond anvil cell at high pressure (32 GPa)





SR-FTIR: 256 scans (~ 2 minutes)

Lab FTIR: 60,000 scans averaged (~ 16 hours averaging!)

Panero, Benedetti, Jeanloz

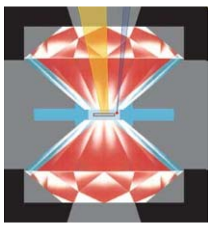
Synchrotron Light Sources with IR beamlines worldwide

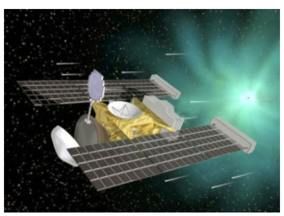
Conclusions

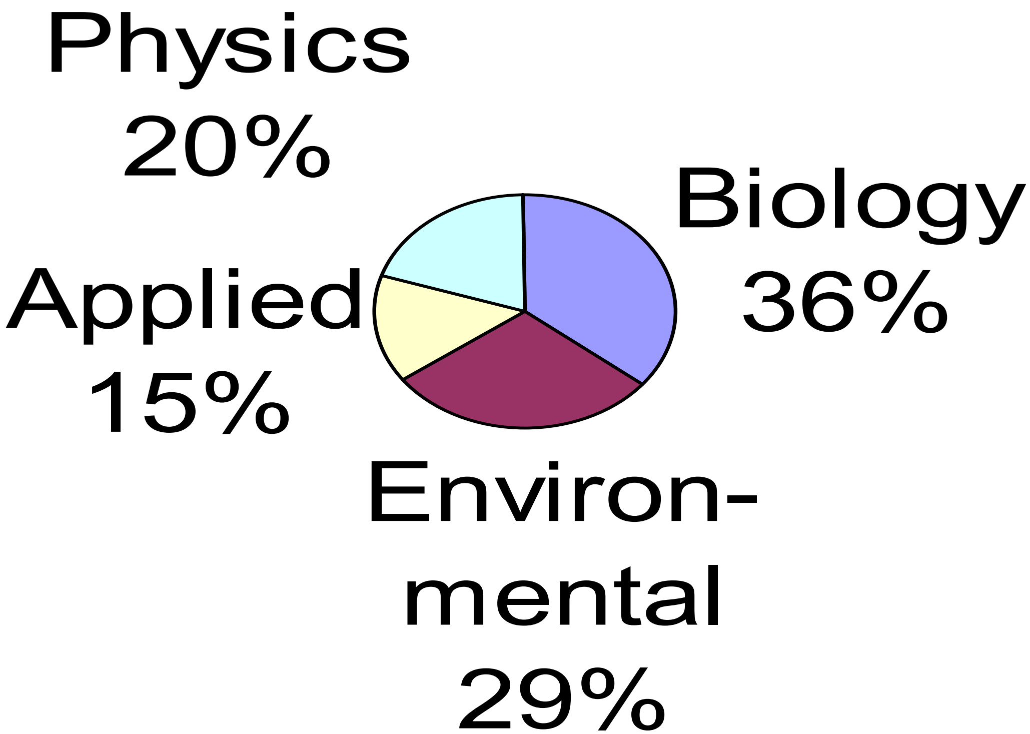
- High-impact science with a cost-effective beamline.
- Diffraction-limited spot size: analysis of micron-scale cells, tissues, particles, novel materials, fibers, heterogeneity, etc.

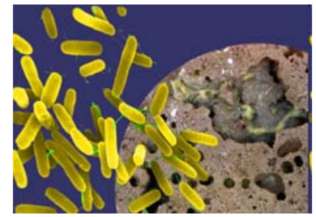
Science and Applications of SR IR

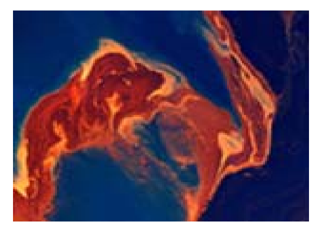
Beamtime allocated for the ALS IR Beamlines



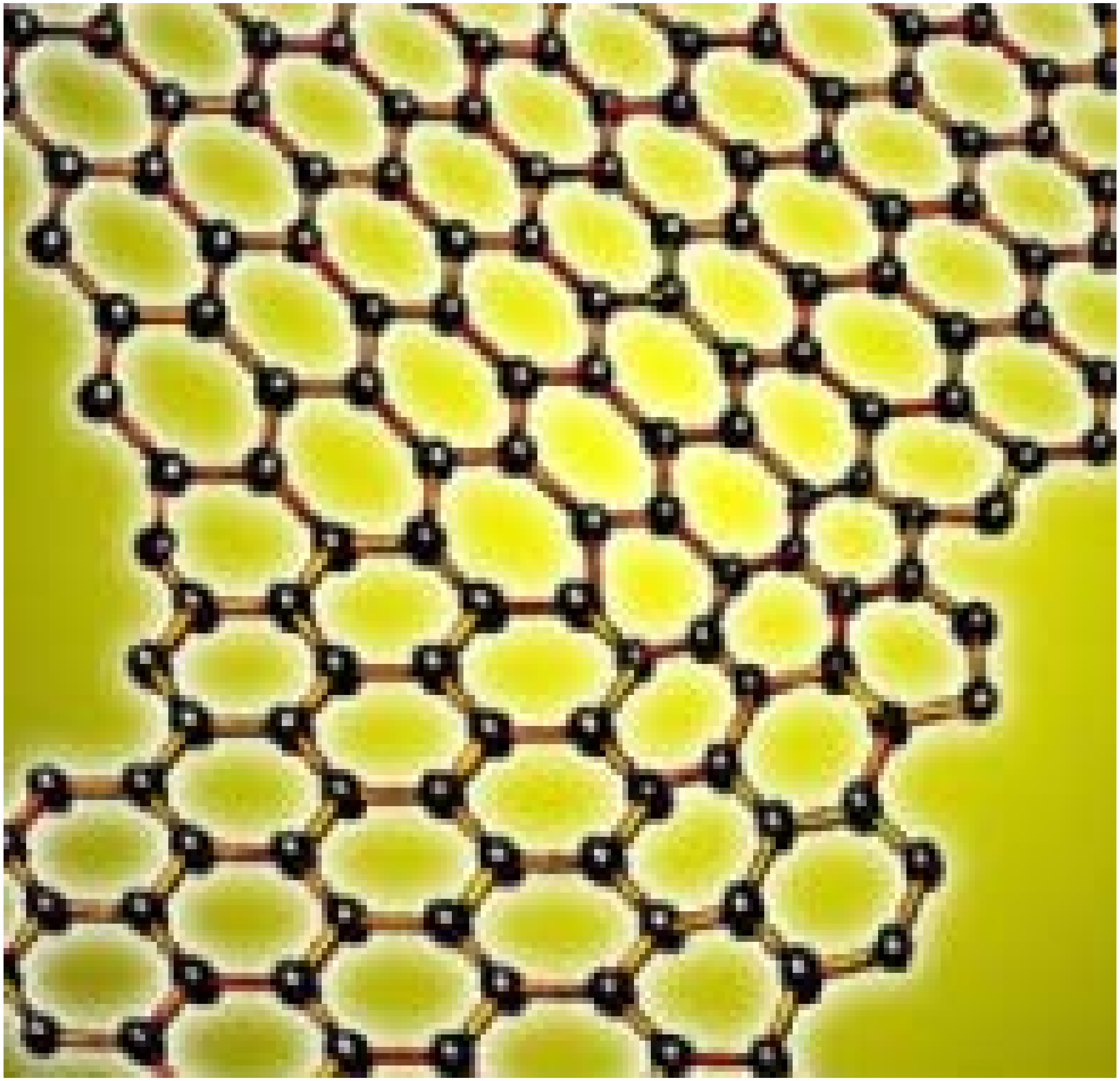




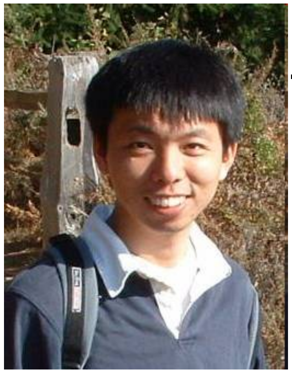




Graphene

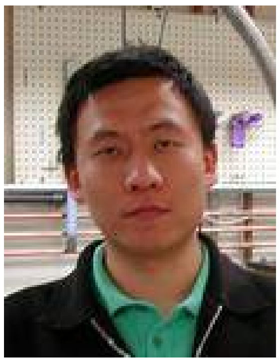


Graphene work done by



Prof. Feng Wang, Yuanbo Zhang, Tsung-Ta Tung, Cheol-Hwan Park, Baisong Geng, Caglar Girit

Profs. Mike Crommie, Steve Louie, Ron Shen, and Alex Zettl, UC Berkeley

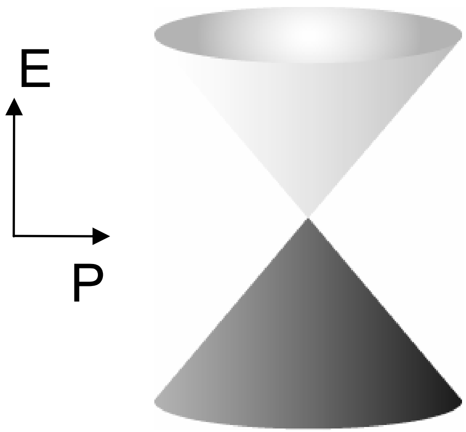


Dimitri Basov, Zhiqiang Li, UC San Diego

E. A. Henriksen, Z. Jiang, P. Kim, H. L. Stormer, Colombia

Michael C. Martin, Hans Bechtel, ALS, LBNL
Zhao Hao, Earth Sciences Division, LBNL

Fascinating Graphene



$$E = v_F \cdot P$$

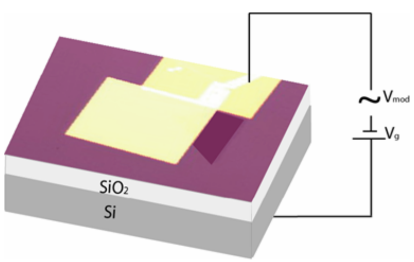
Massless Dirac fermion.

Ballistic Transport.

Attractive for both fundamental physics and technological applications.

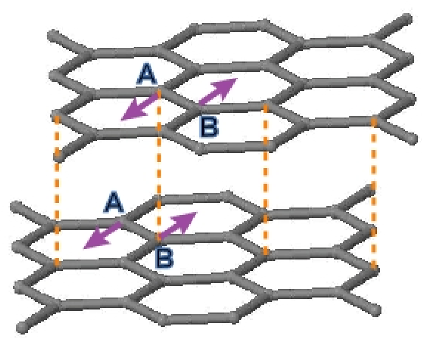
Tunable via:

Electrical Field



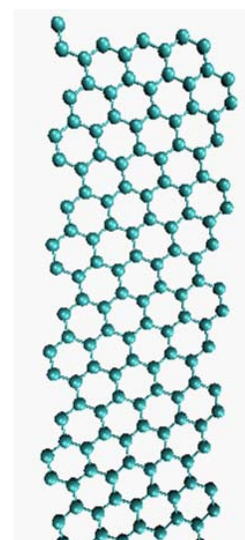
Field effect devices

Layer-Layer interactions



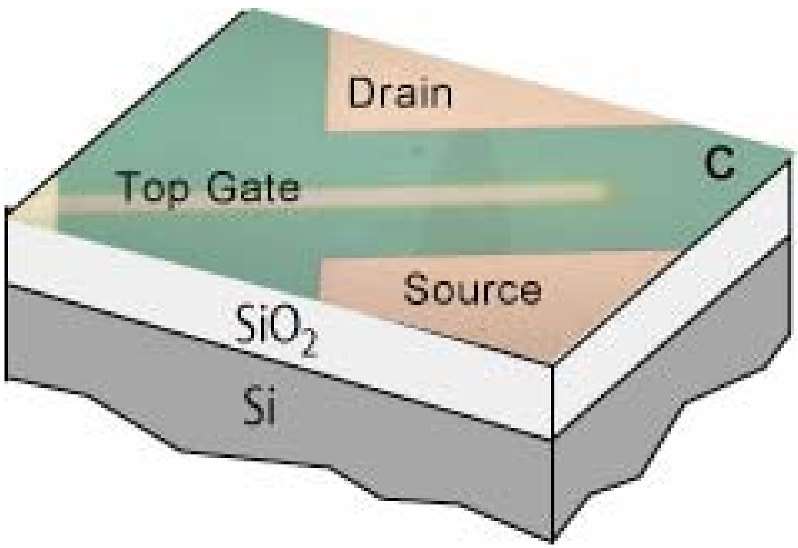
Bilayer

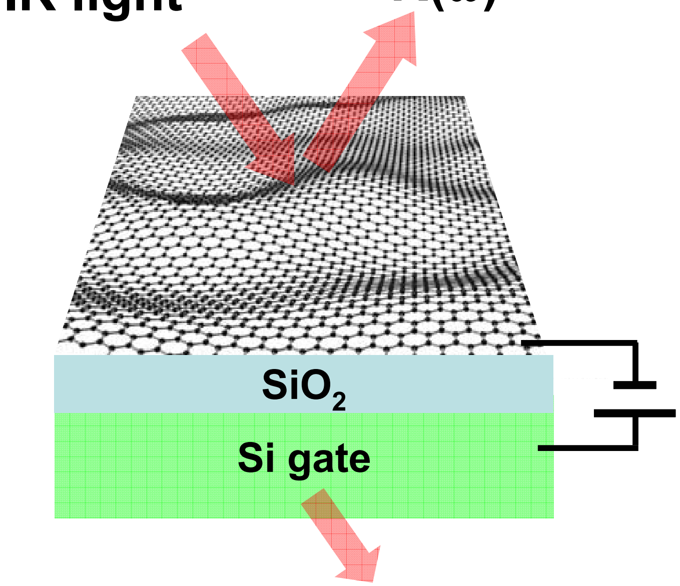
Nanopatterning



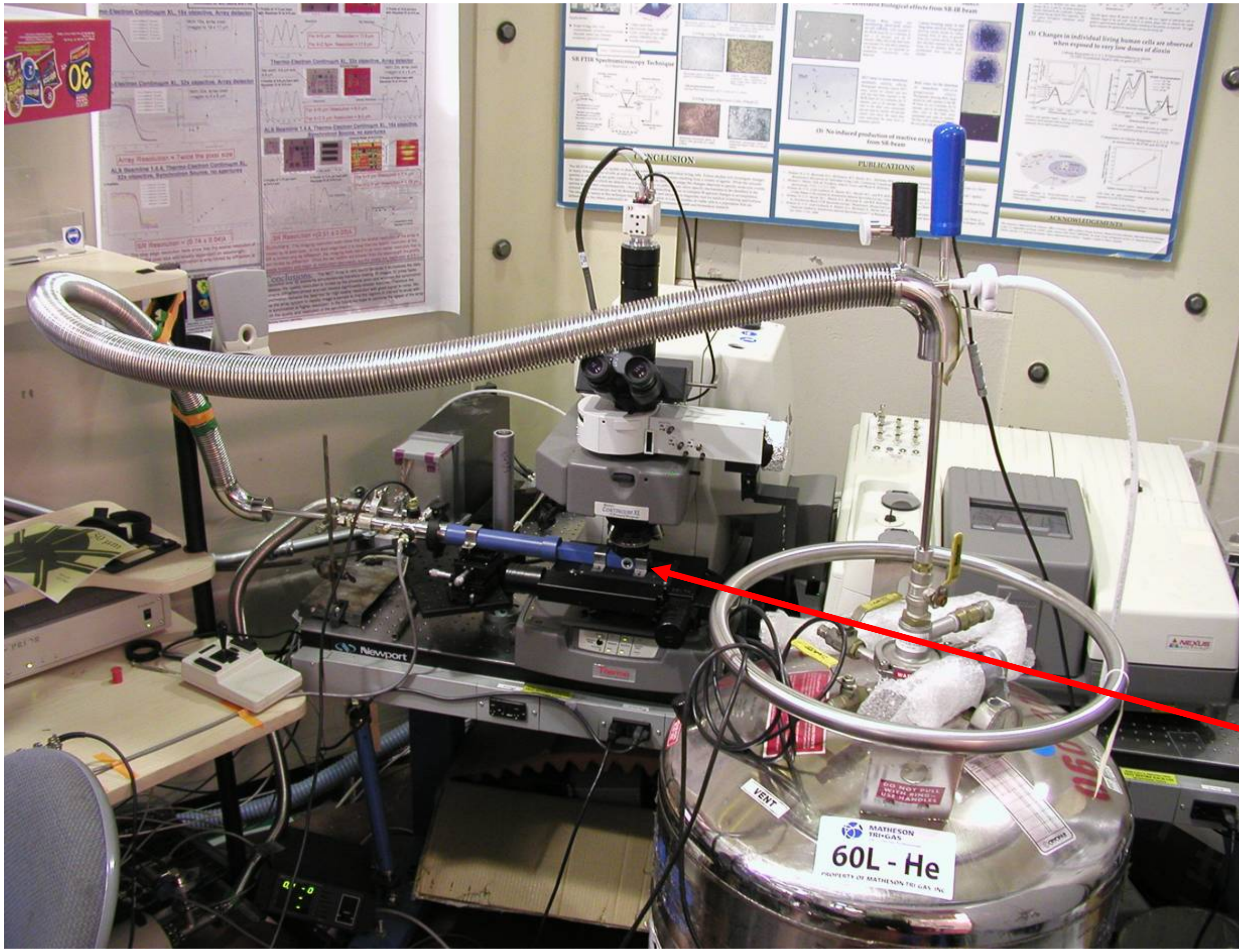
Nanoribbon

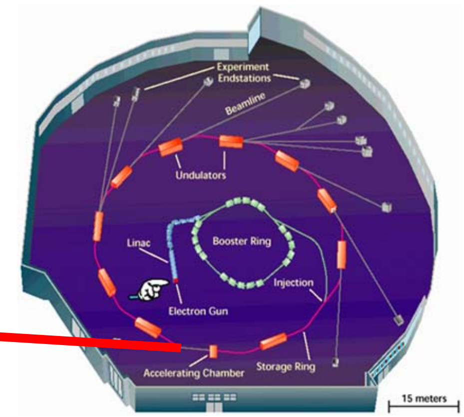
Measuring Graphene with SR IR

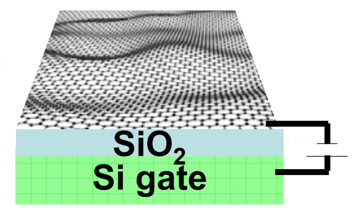




We can vary temperature and gate voltage

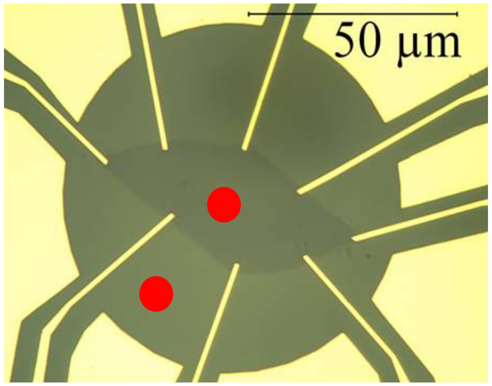


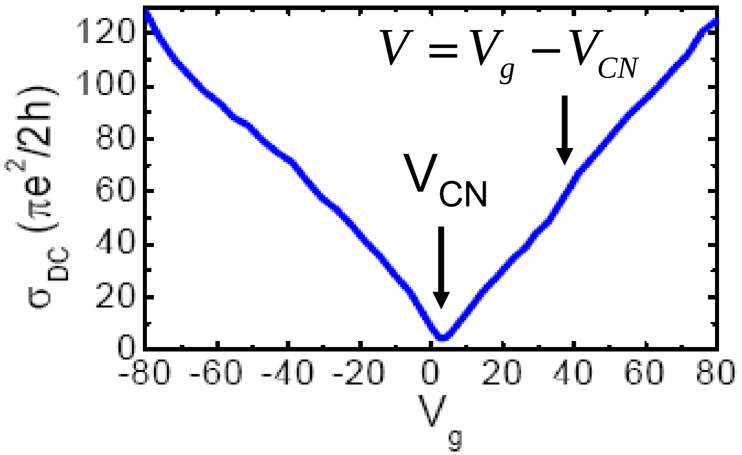


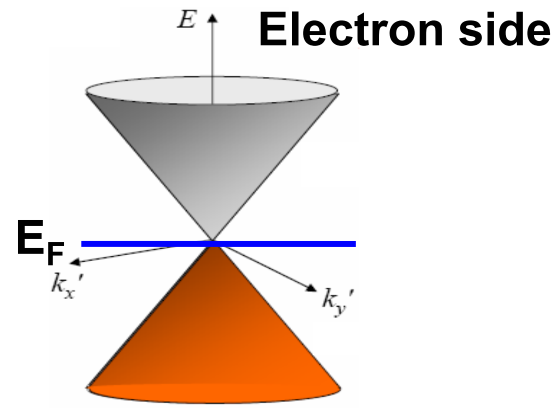


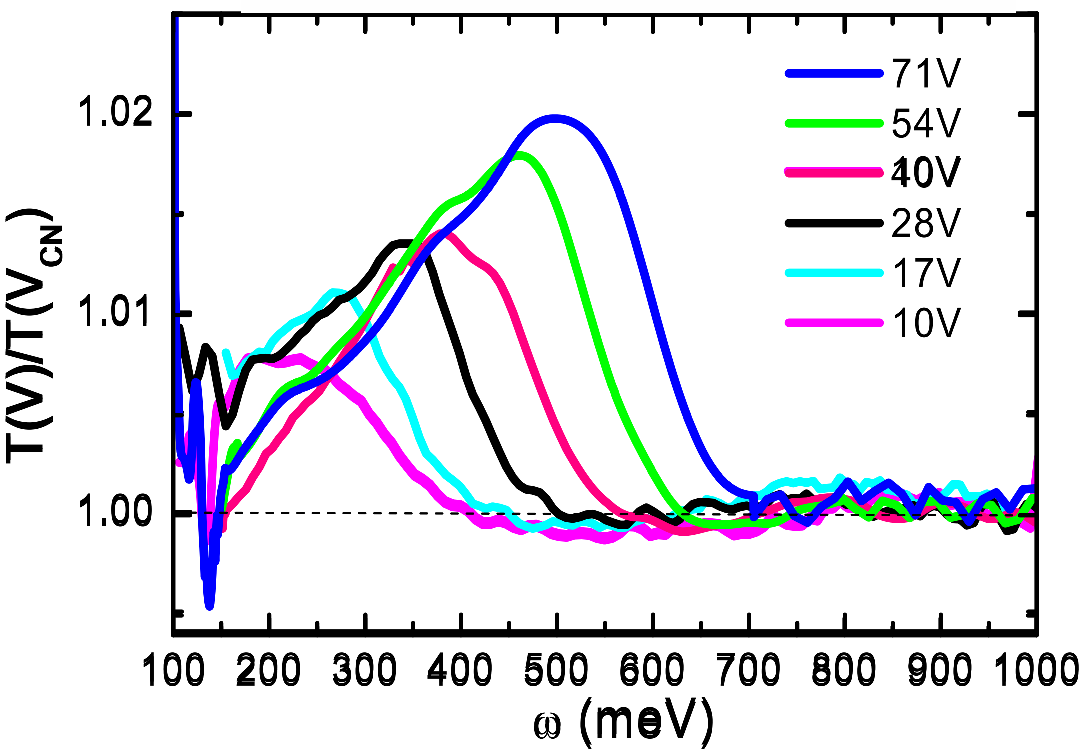
SR-FTIR spectromicroscopy with Oxford microstat for samples at 4 - 400 Kelvin at ALS beamline 1.4.4.

Transmission ratio at finite V

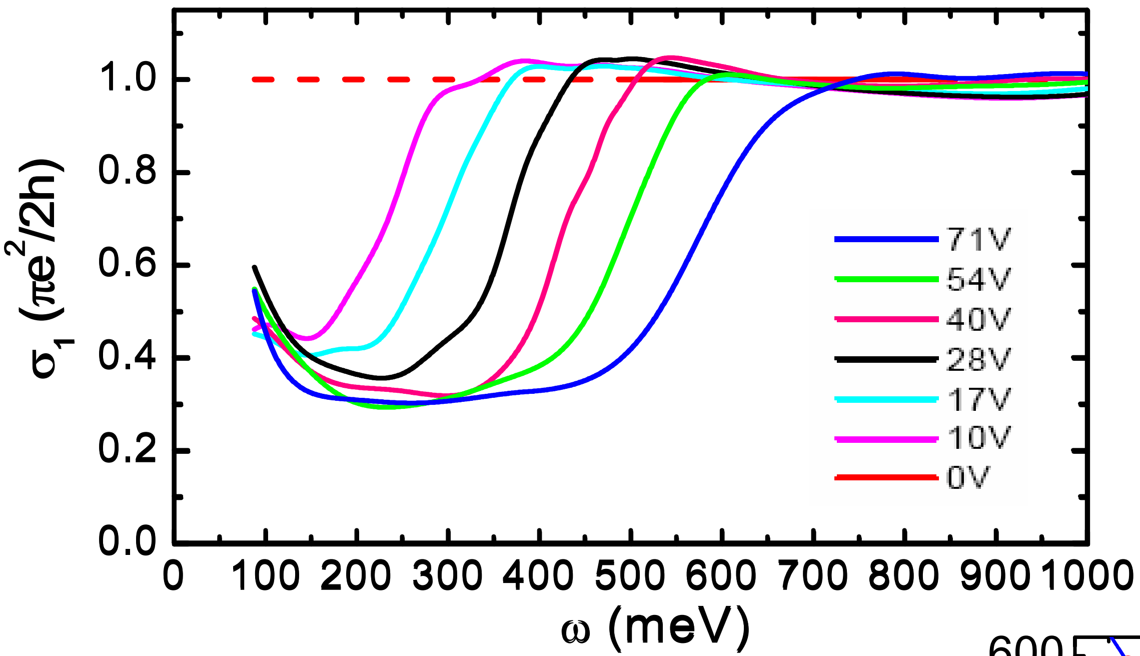


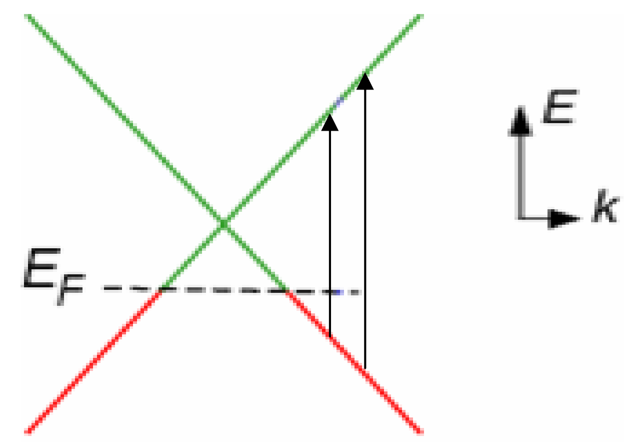




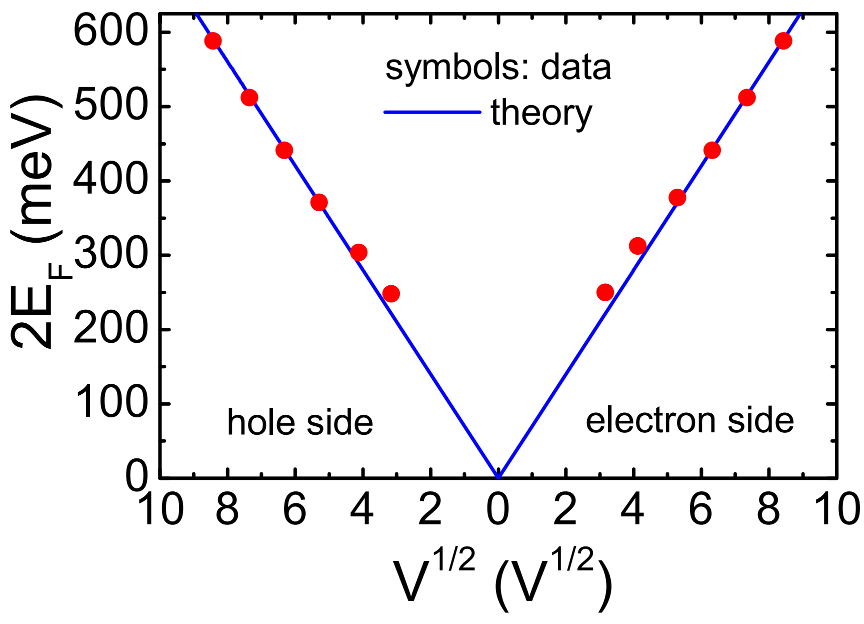


Optical conductivity at finite V





Vertical optical transition



Driac quasiparticle: $E_F = \hbar v_F \sqrt{\pi N}$

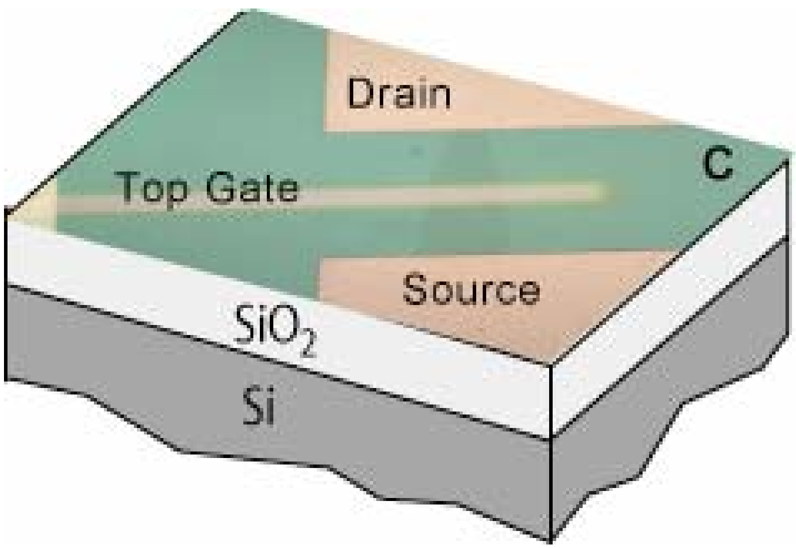
$$N = 7 \times 10^{10}\, cm^{-2} / V$$

$$v_F = 1.12 \pm 0.04 \times 10^{6}\, m/s$$

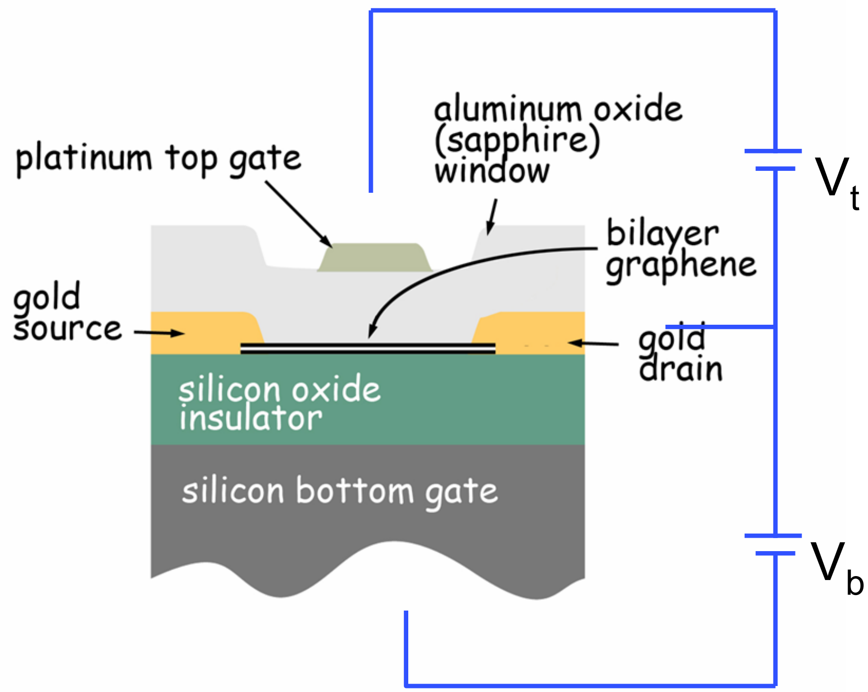
nature physics

Z.Q. Li *et al.*, Nature Physics, 4(7), 532 (2008).

Dual-Gate Bilayer Graphene Devices

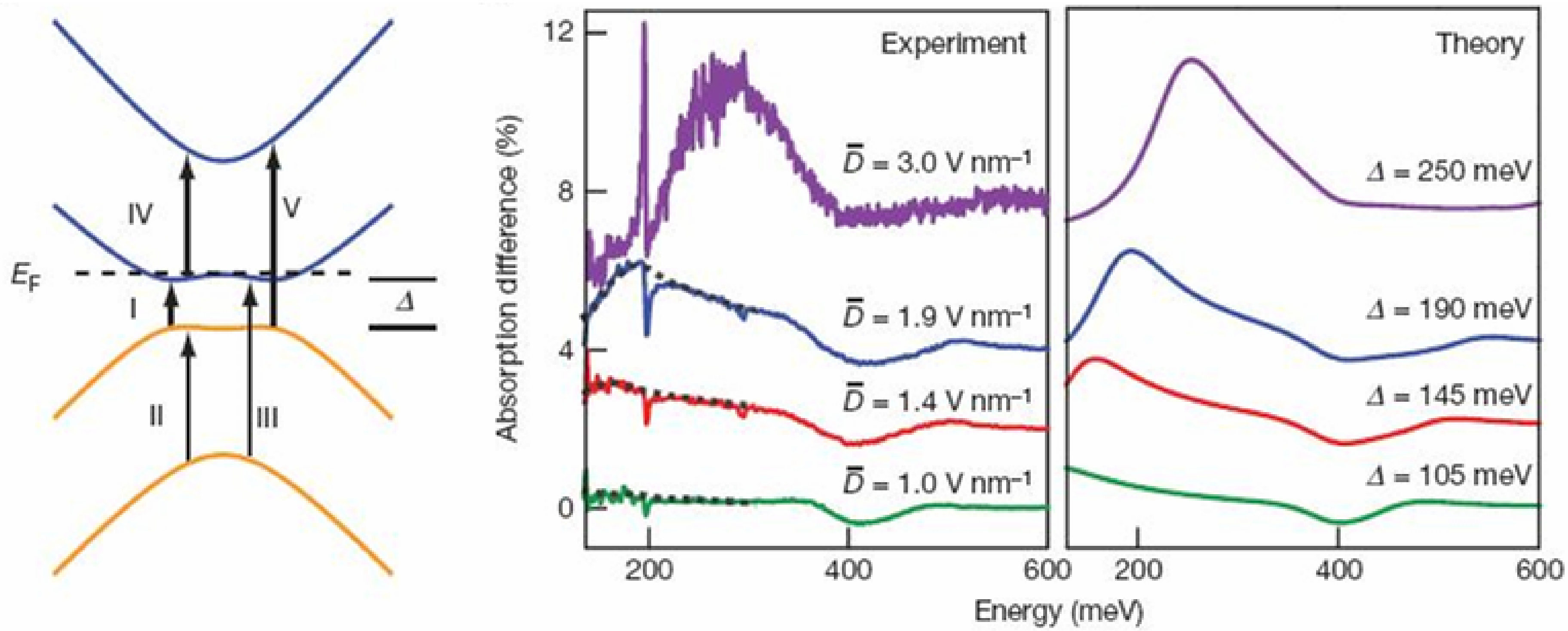


Top View

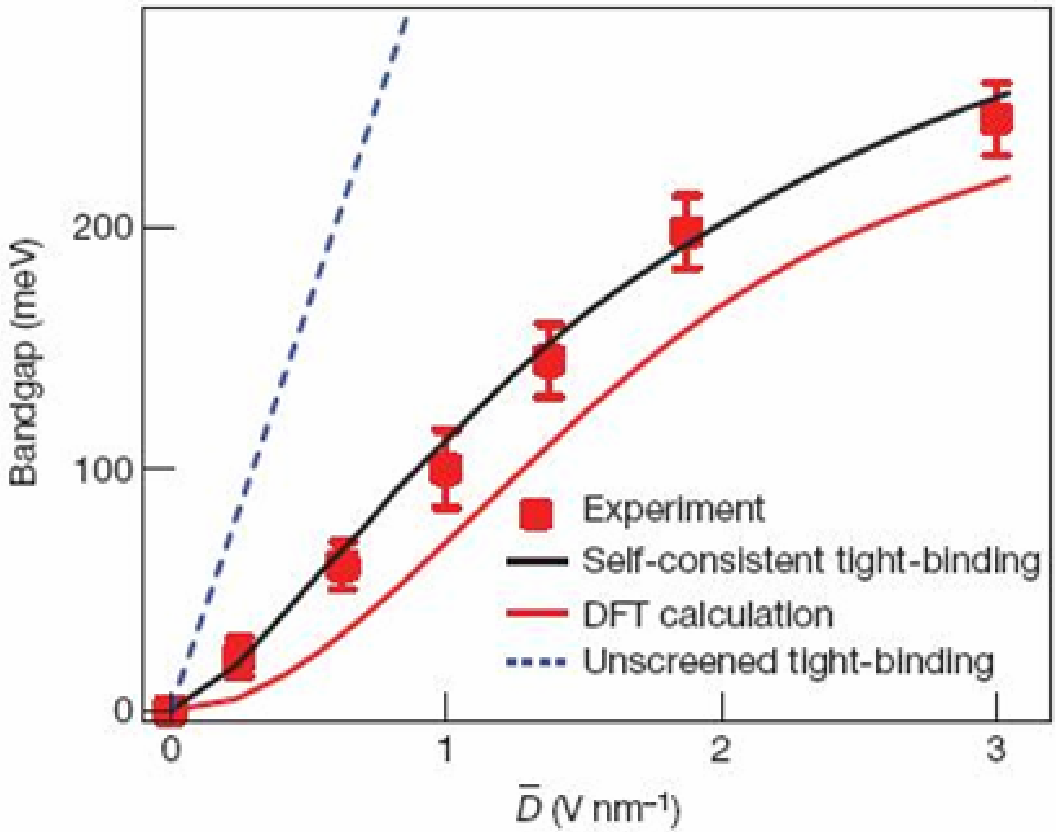


Side View

Tunable Bandgap in Bilayer Graphene



Tunable Bandgap in Bilayer Graphene



Dual-gated bilayer graphene is a remarkably flexible tool for nanoscale electronic devices.

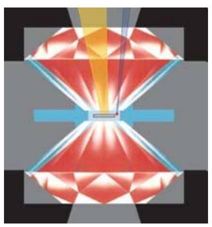
<u>A bandgap over 250 meV can be achieved.</u>

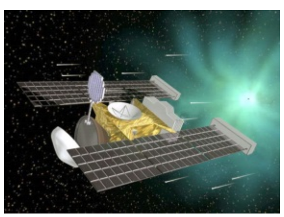
Zhang, Tang, Girit, Hao, Martin, Zettl, Crommie, Shen, and Wang, Nature, **459**, 820-823 (2009).

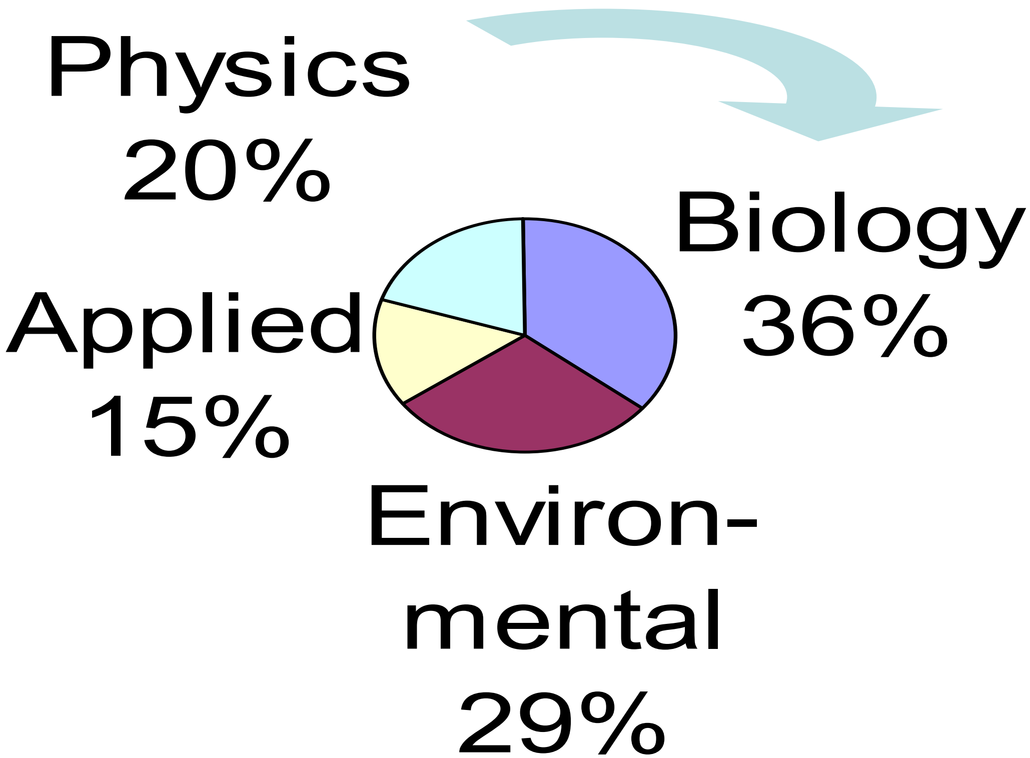
(Currently the highest cited paper from our beamline with >1200 citations)

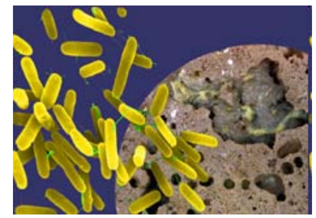
Science and Applications of SR IR

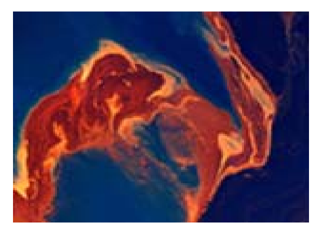
Beamtime allocated for the ALS IR Beamlines







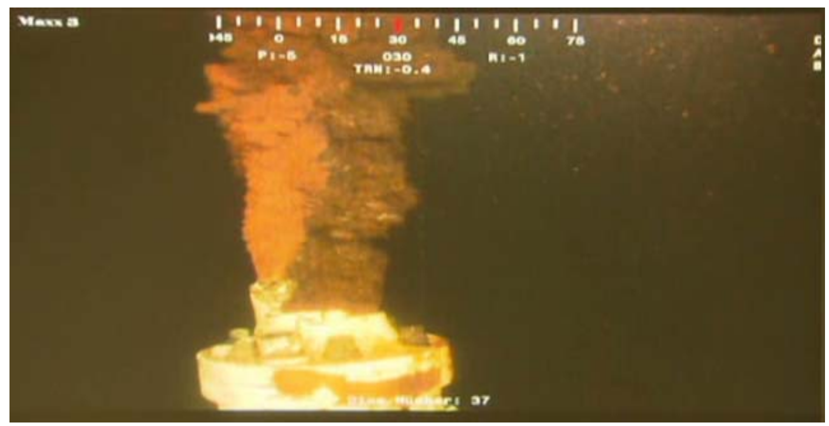




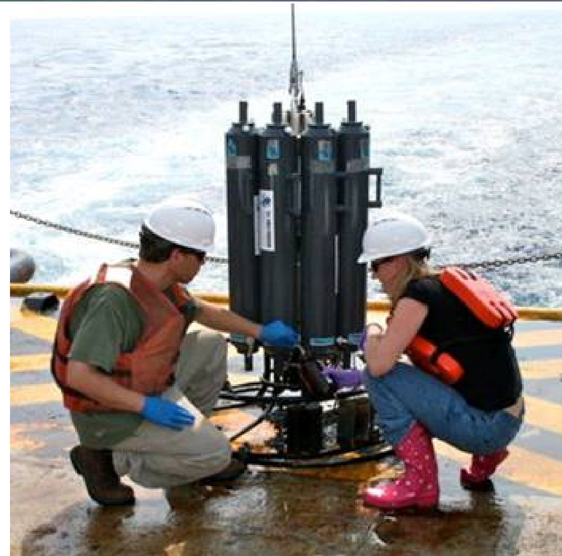
Gulf of Mexico Oil Disaster

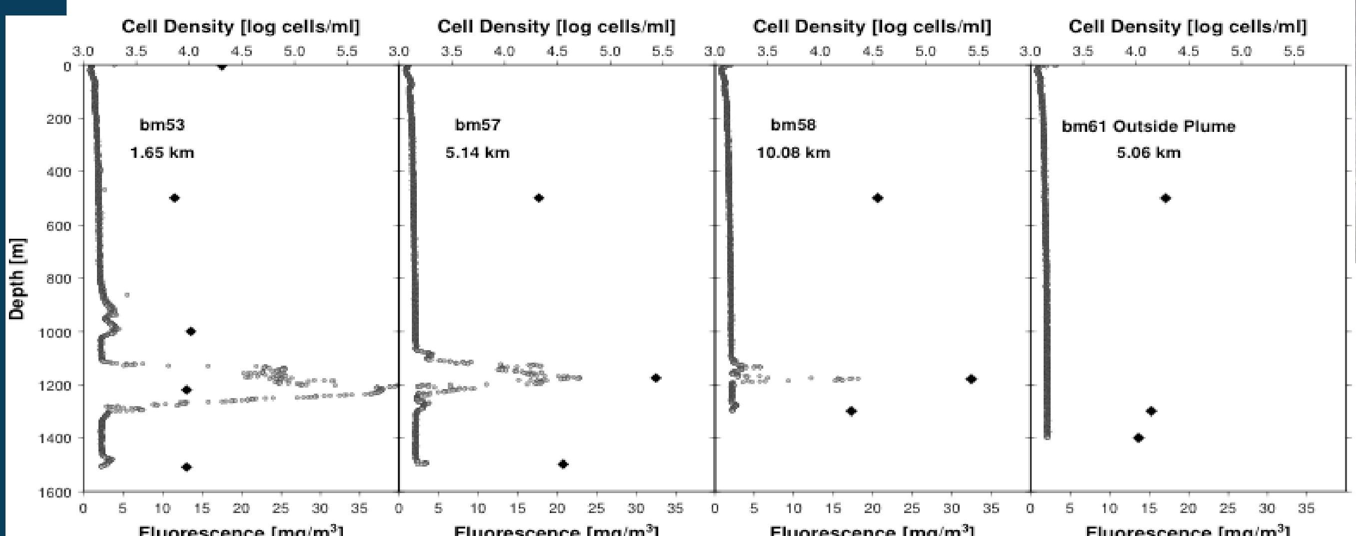
- On April 20, 2010 the *Deepwater Horizon* exploded.
- The floating rig burned for 2 days then sank, shearing the 21-inch riser pipe 600 ft above the BOP.
- Leak estimated at ~65,000 barrels per day
- 87 days of flow into Gulf until containment.
- Largest offshore oil spill in history.

- Scientific Response:
- Measurements revealed a large lens of oil
- Deepest and largest lens was at 1,200m and measured approx. 15 km long
- Oil aggregates and mousse floated



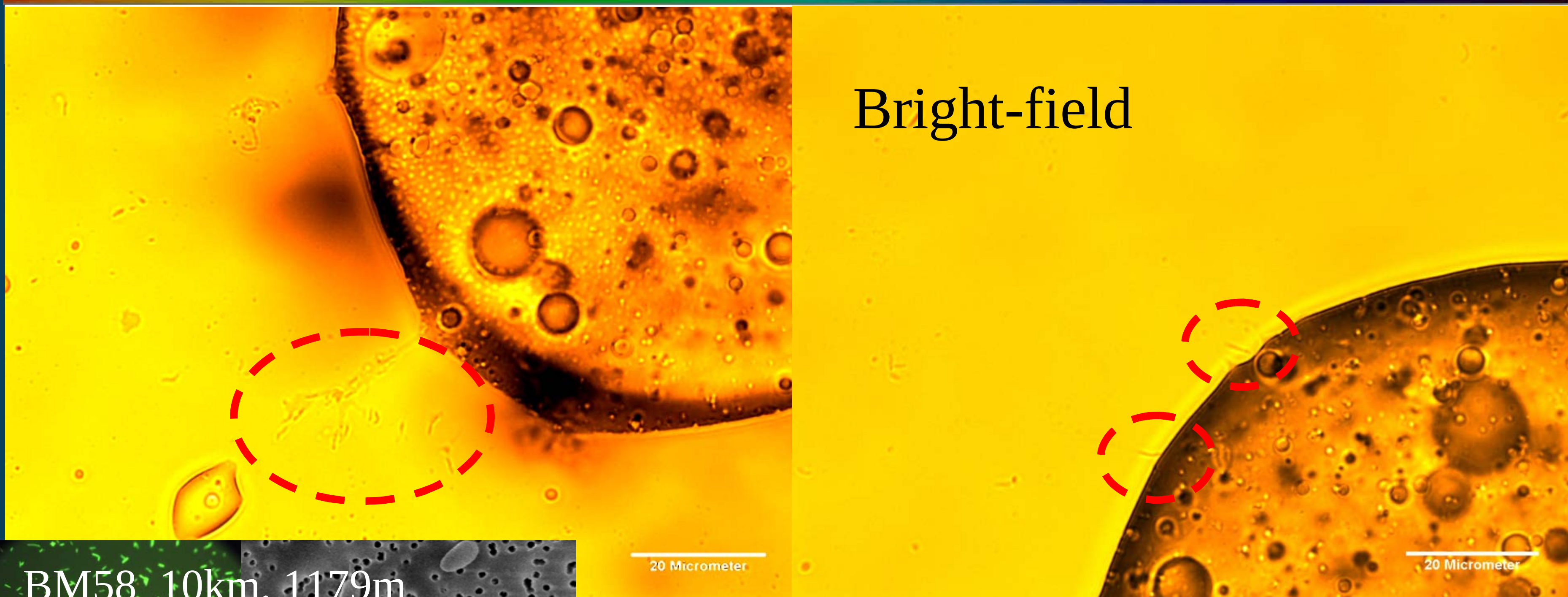
Sampling Gulf of Mexico Oil

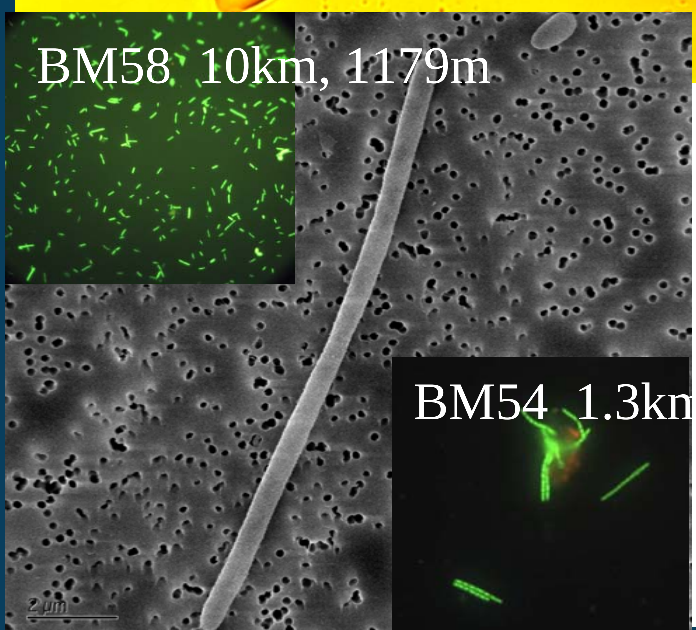




A significant plume of oil was found at a depth of 1200 m.

Bacteria and oil droplets

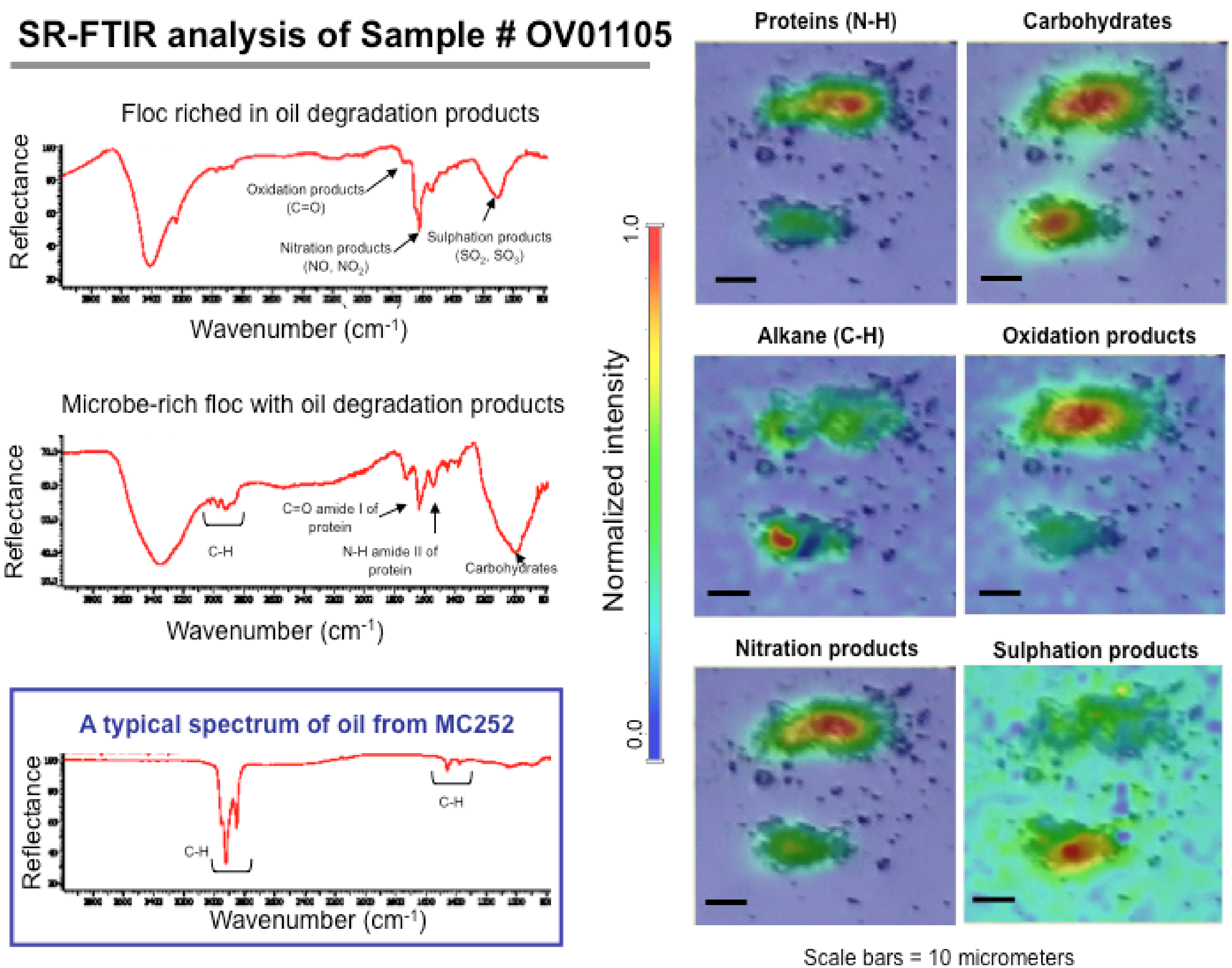




Hazen, et al., **Science 330**(6001), 204-208 (2010).

Oil degradation by microbes within the 1200 m deep oil plume

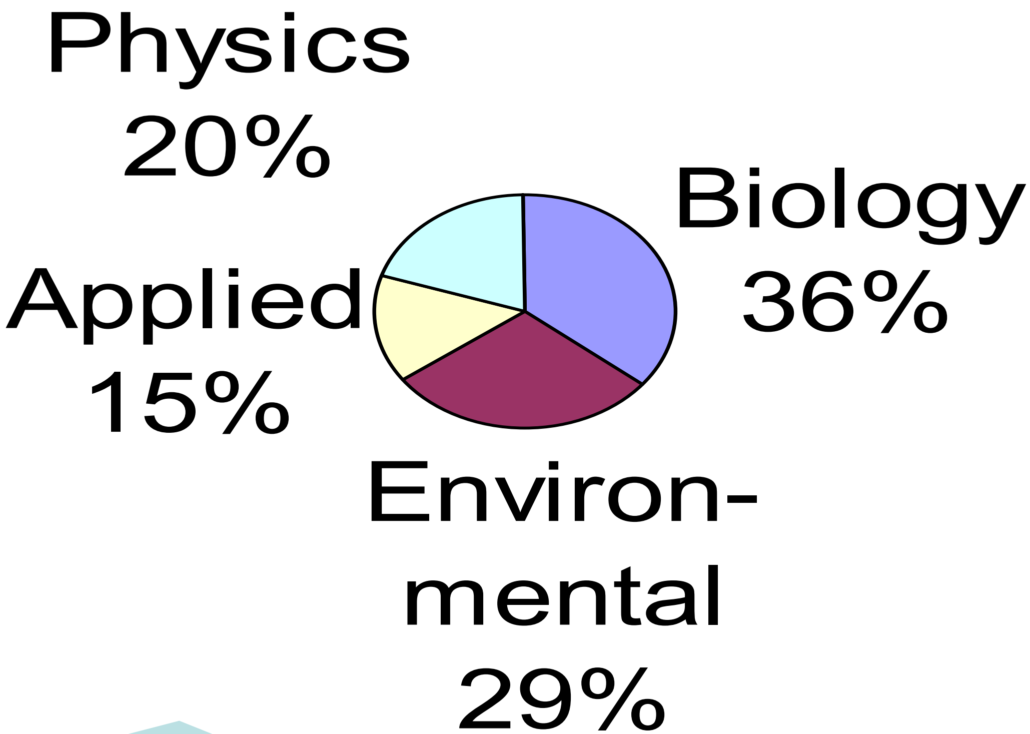
SR-FTIR analysis of Sample # OV01105

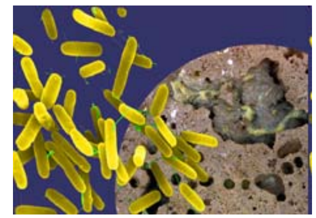


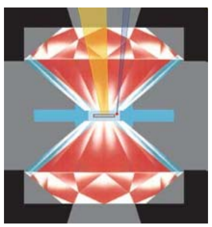
Hazen, et al., **Science** **330**(6001), 204-208 (2010).

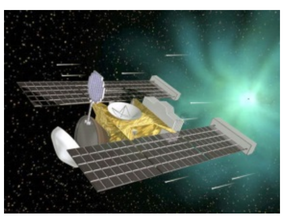
Science and Applications of SR IR

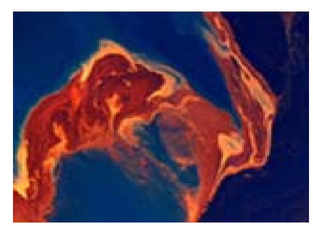
Beamtime allocated for the ALS IR Beamlines



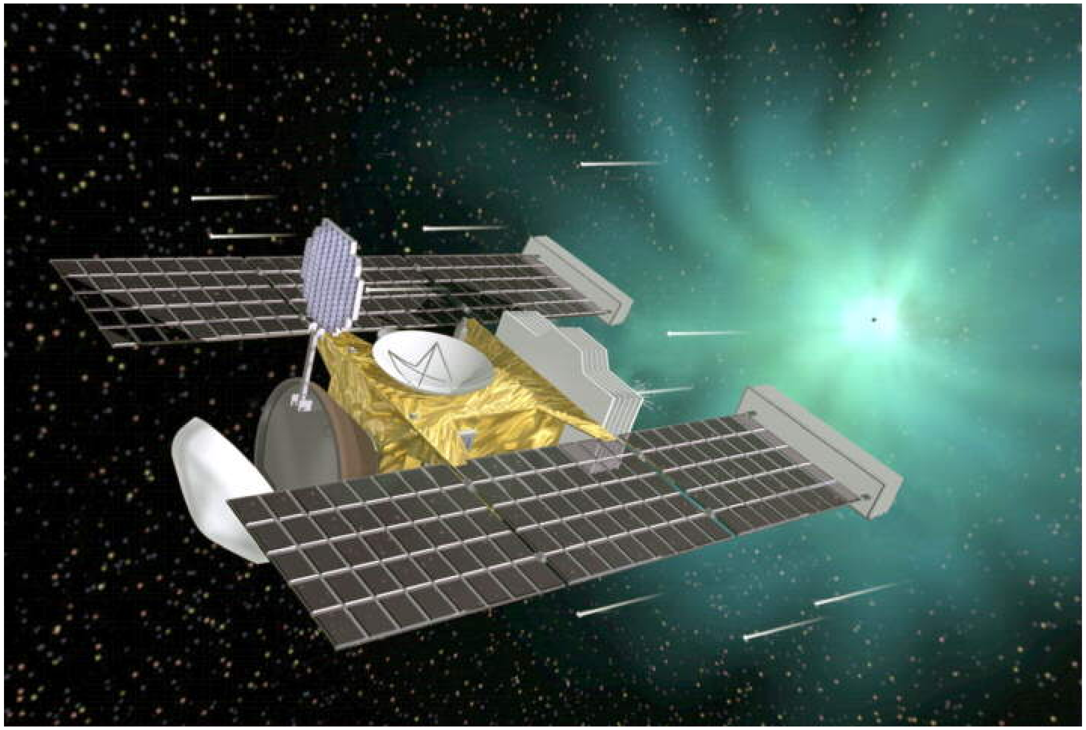


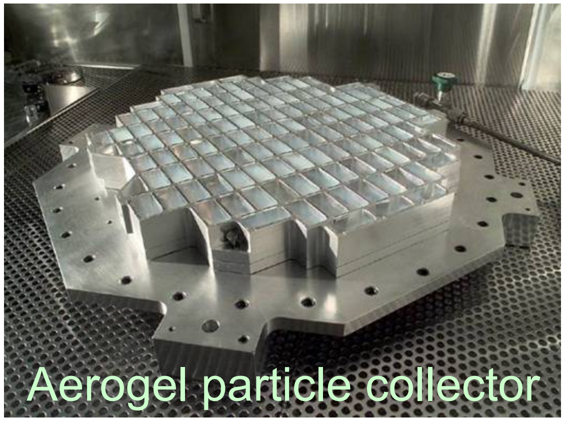






Lunar and Planetary Science





STARDUST flew threw comet WILD-2's tail…

…and landed January 15, 2006.

Organics in Stardust

Organics Captured from Comet Wild 2 by the Stardust Spacecraft

Sandford *et al*. *Science*, **314,** 1720-1724 (December 2006)

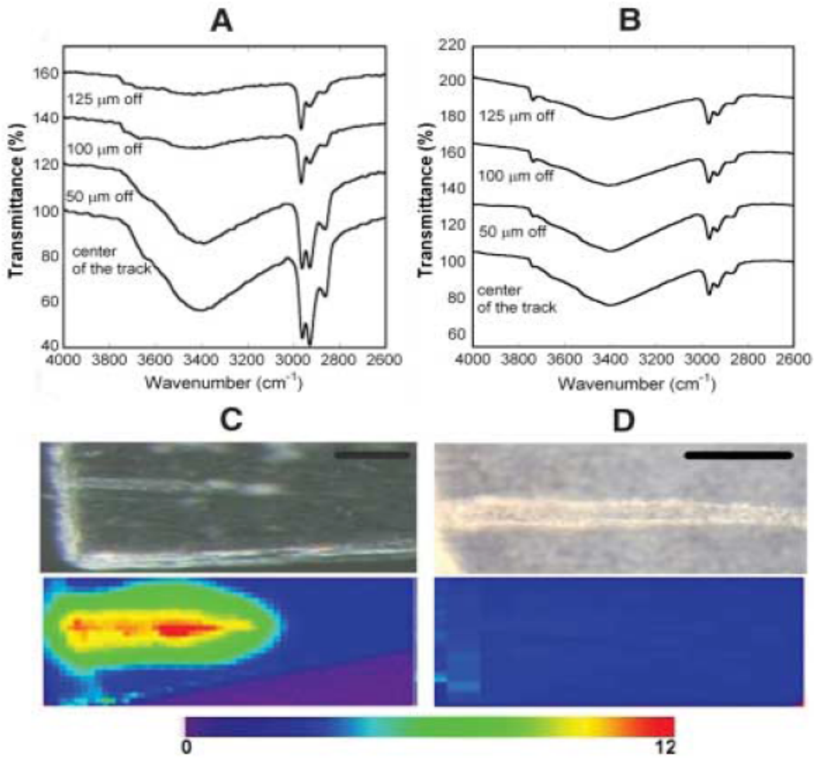
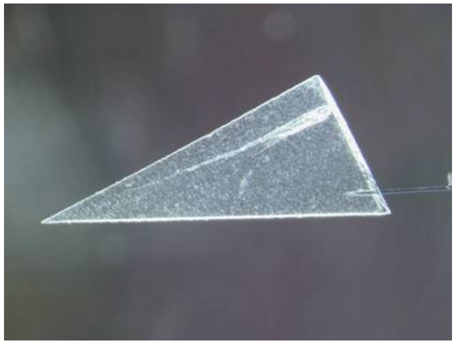
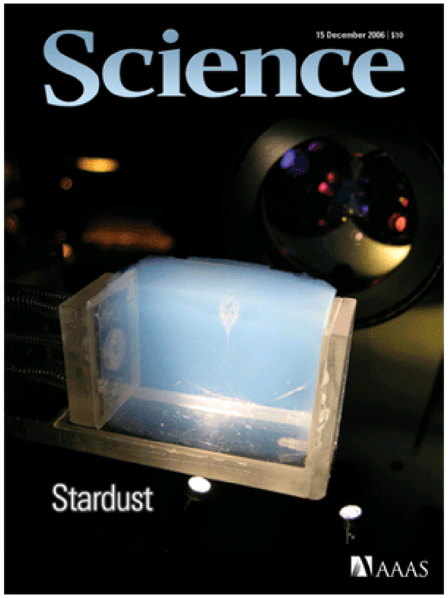


Fig. 2. IR transmittance spectra obtained along a line perpendicular to cometary impact tracks (**A**) track 59 and (**B**) track 61. In addition to aerogel features, the spectra of track 59 (A) display peaks at 3322 (broad), 2968, 2923, 2855, and 1706 cm^{-1} (not shown), both inside the track and extending outward into the aerogel. (B) track 61 exhibits only the aliphatic CH stretching feature dominated by the 2968 cm^{-1} peak and (Si-O) bands (not shown) characteristic of the flight aerogel. The optical images of the same tracks, with corresponding maps to the same scale showing the intensity distribution of the 2923 cm^{-1} peak (–CH_2–), are displayed in (**C**) and (**D**). The false-color image scale shown at the bottom is used in both maps, and the black scale bars correspond to 100 μm. In both cases, the entrance of the cometary particle is on the left side. The false-color map in (C) shows an increase in intensity of the 2923 cm^{-1} –CH_2– peak in and near the track. The distributions of other organics peaks are similar. In contrast, the second track shown in (D) shows almost uniform distribution of the peak area centered at 2923 cm^{-1}; that is, the track shows only the features of aerogel.



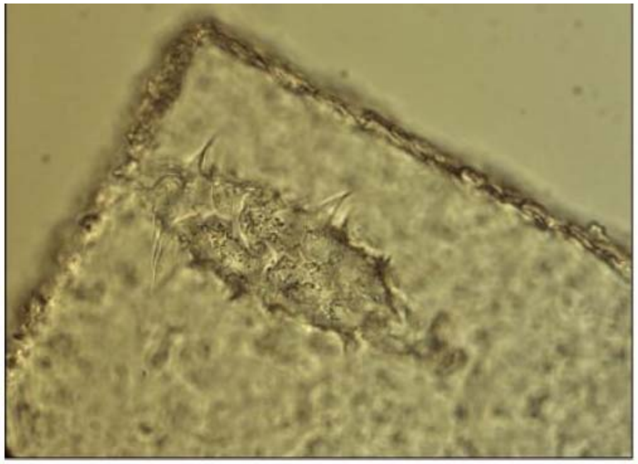


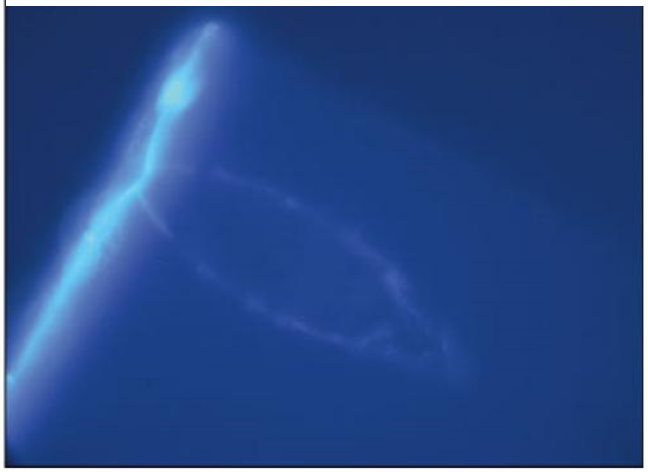
Lunar and Planetary Science

Assessment and control of organic and other contaminants associated with the Stardust sample return from comet 81P/Wild 2

Scott A. Sandford, Sasa Bajt, Simon J. Clemett, George Cody, Bradley T. Degregorio, Vanessa De Vera, Jason P. Dworkin, Jamie E. Elsila, George J. Flynn, Daniel P. Glavin, Antonio Lanzirotti, Thomas Limero, Mildred P. Martin, Christopher J. Snead, Maegan K. Spencer, Thomas Stephan, Andrew J. Westphal, Sue Wirick, Richard N. Zare, Michael Zolensky

Meteoritics & Planetary Science, **45(3),** 406-433 (March 2010).





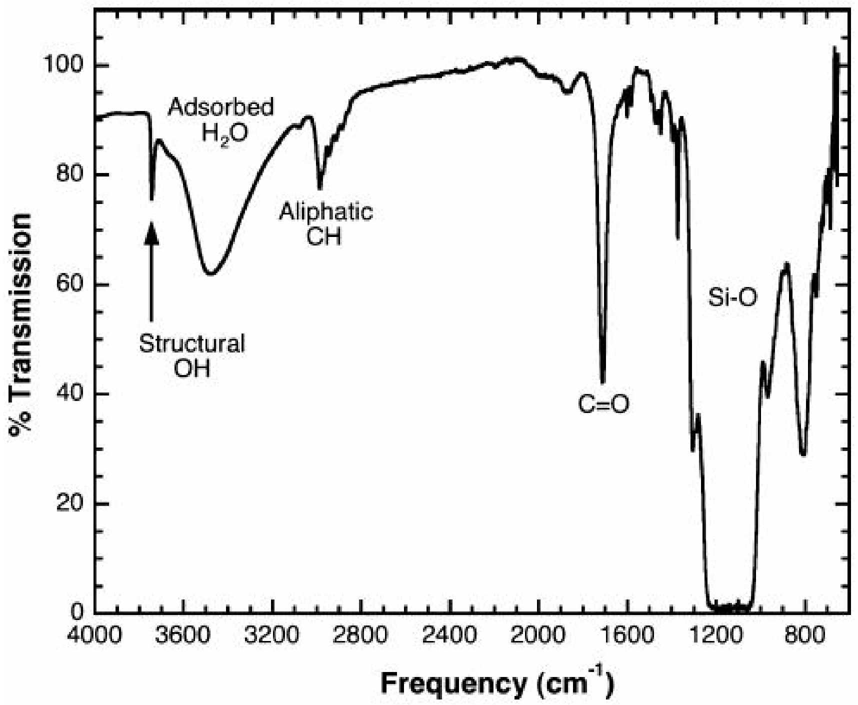


Fig. 1. Infrared spectrum of an approximately 10 μm × 10 μm spot on C2115,23,21, a keystone extracted from the C2115 Stardust aerogel flight cell. The strong Si-O, C=O, aliphatic $-CH_2-$ and $-CH_3$, structural –OH, and adsorbed H_2O absorption features were seen at all the spots examined and their presence is typical of Stardust flight aerogels.

Next Challenges for SRIR

How can we go beyond diffraction-limited spectro-microscopy?

- **3D FTIR Spectro-Microtomography**

  Martin *et al.*, Nature Methods **10**, 861-864 (2013)

- **Synchrotron Infrared Nano Spectroscopy**

  Bechtel *et al.,* PNAS **111**(20), 7191–7196 (2014).

ALS Synchrotron Infrared Beamlines

SRC Home of Aladdin

3D Imaging with Infrared Spectral Microtomography

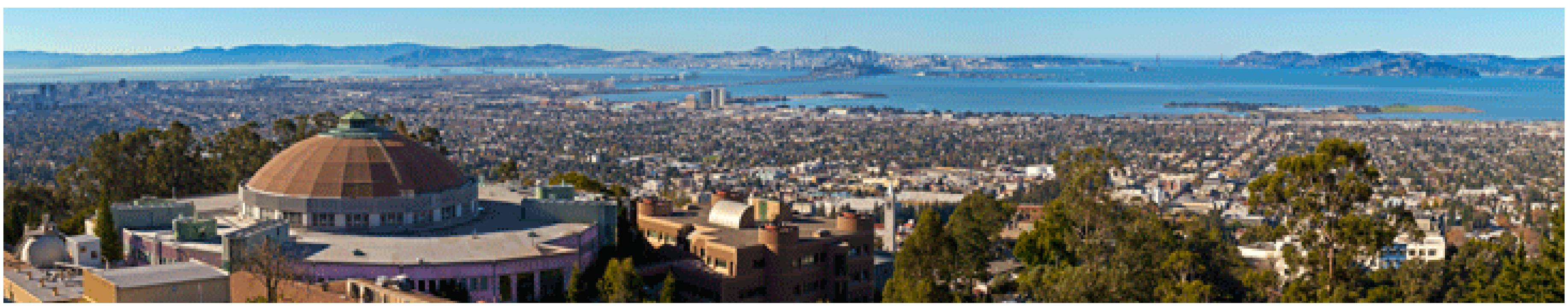
Michael C. Martin, Charlotte Dabat-Blondeau, Hans A. Bechtel, Dula Parkinson
Advanced Light Source, Lawrence Berkeley National Laboratory

Carol Hirschmugl, Miriam Unger
Physics Department, University of Wisconsin-Milwaukee

Julia Sedlmair, Barbara Illman
Forrest Products Laboratory and SRC, Madison

Jonathan M. Castro, *Institute of Geosciences, University of Mainz*

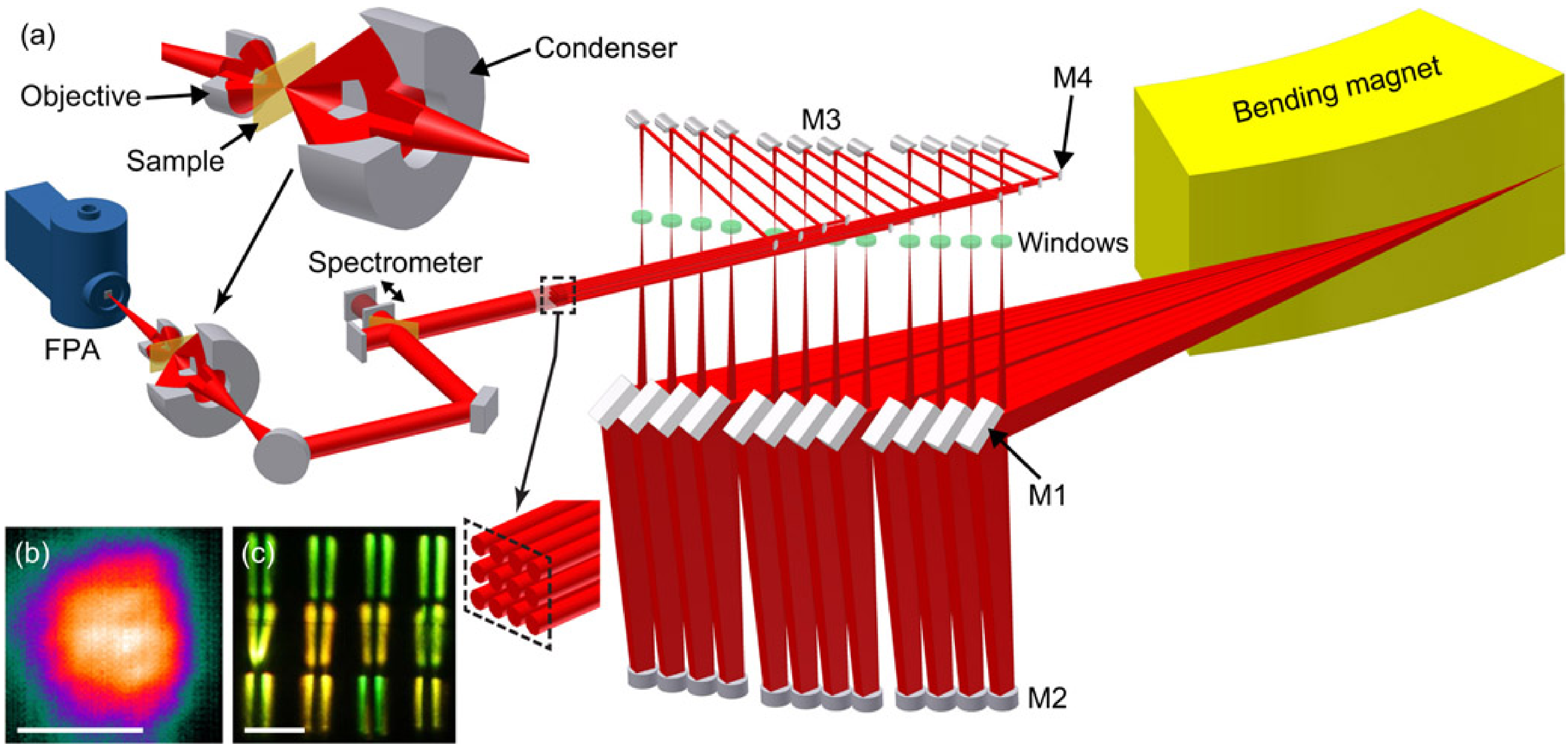
Marco Keiluweit, *Lawrence Livermore National Laboratory*



Faster full-field imaging

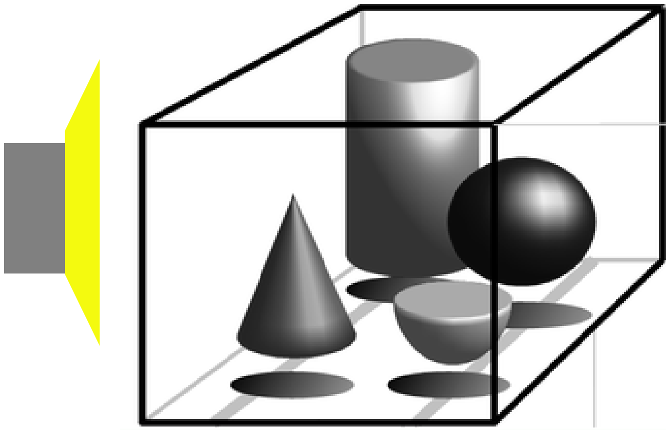
FPA detector systems can be used for faster full-field imaging.

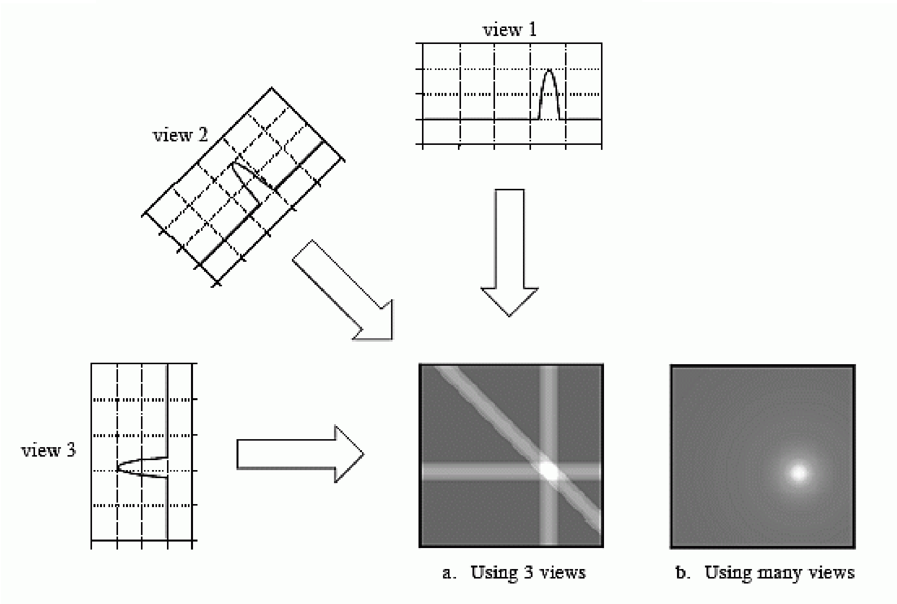
IRENI (Nasse, Hirschmugl, *et al.*)



Brief primer on Tomography

Measure projected transmission image:





In a single 2D projection, cannot tell the depth or 3D extent of each object.

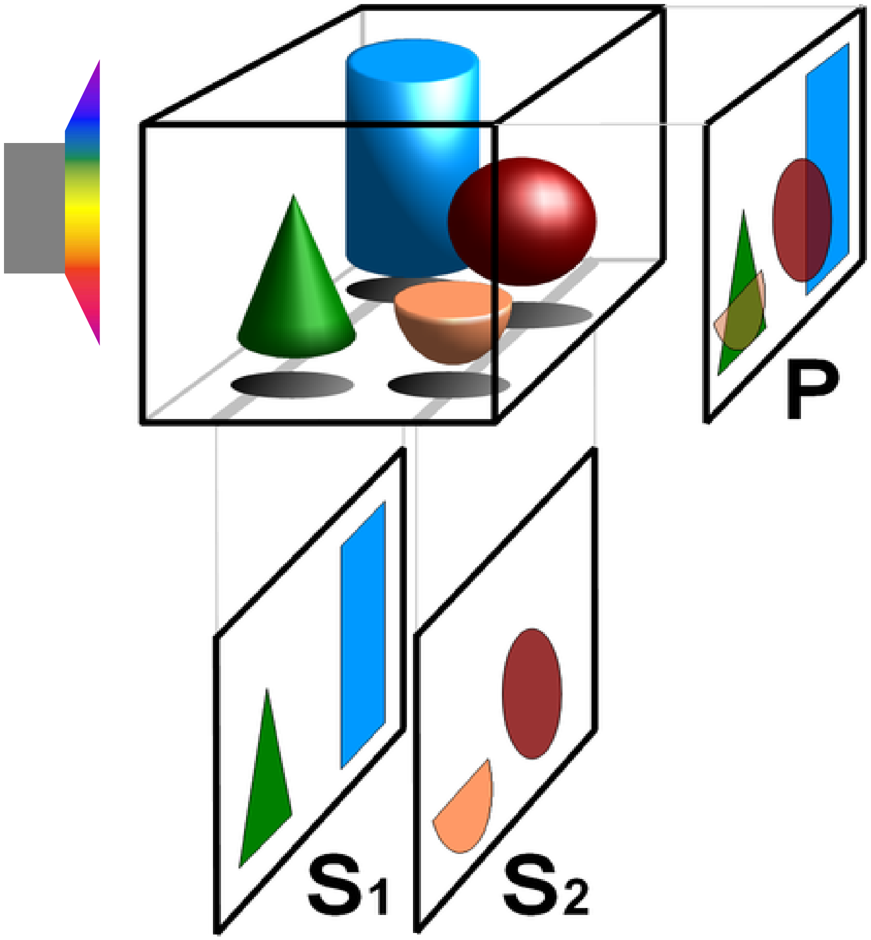
Rotate sample and measure many projection images.

Then computed tomography algorithms reconstruct slices through the sample, revealing the 3D nature.

3D picture remains gray scale: can observe different densities.

Full-color Spectral Tomography

Can we do this in “Full-Color”??



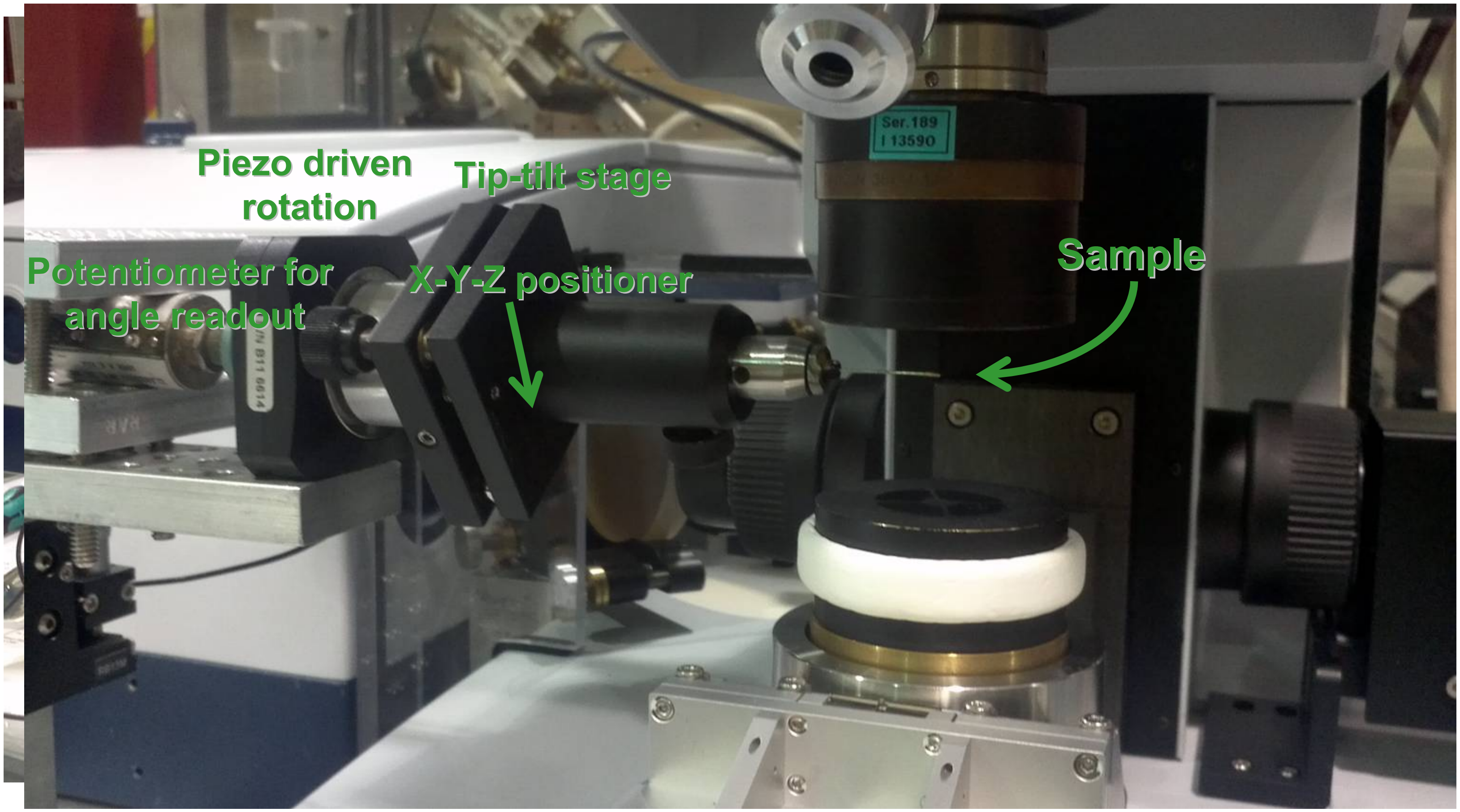
Use the power of **FTIR spectroscopy** to provide meaningful colors based on full spectral identification.

What’s needed:

1. A fast FTIR imaging instrument with complete spectral images obtained in ~1 minute so a full 180 degrees of sample rotation can be measured within a reasonable time.
2. A sample rotation stage.
3. Tomography reconstruction algorithms that are spectroscopy aware.

Fast Imaging + Rotation = 3D IR Tomography

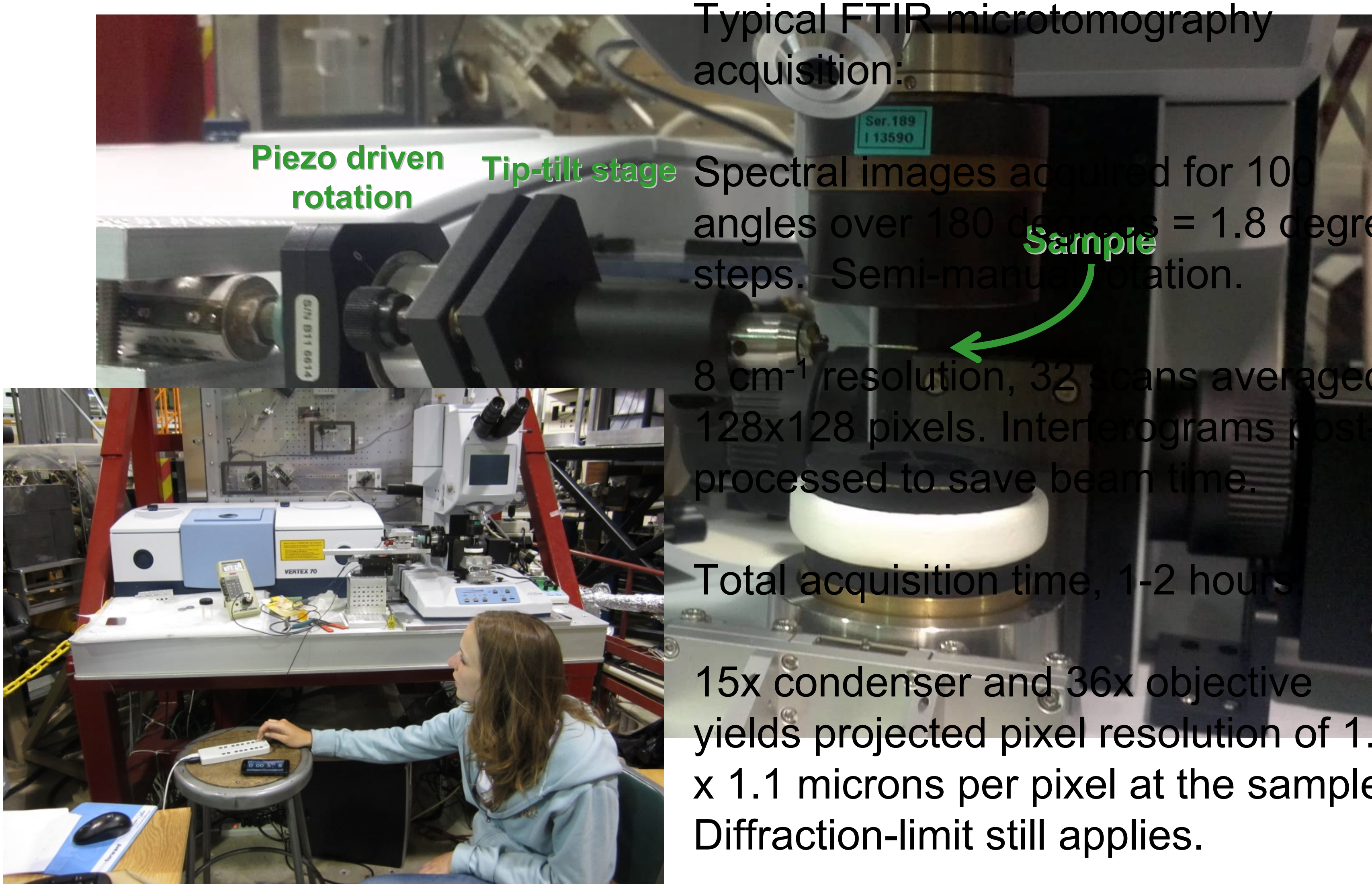
Proof of principle experiments, 2012



We removed the x-y sample stage at the IRENI beamline and installed a test sample rotation stage.

The combination of the tip-tilt stage and the x-y-z stage allows us to place the center of rotation at any sample location of interest.

Fast Imaging + Rotation = 3D IR Tomography



Typical FTIR microtomography acquisition:

Spectral images acquired for 100 angles over 180 degrees = 1.8 degree steps. Semi-manual rotation.

8 cm^{-1} resolution, 32 scans averaged, 128x128 pixels. Interferograms post-processed to save beam time.

Total acquisition time, 1-2 hours.

15x condenser and 36x objective yields projected pixel resolution of 1.1 x 1.1 microns per pixel at the sample. Diffraction-limit still applies.

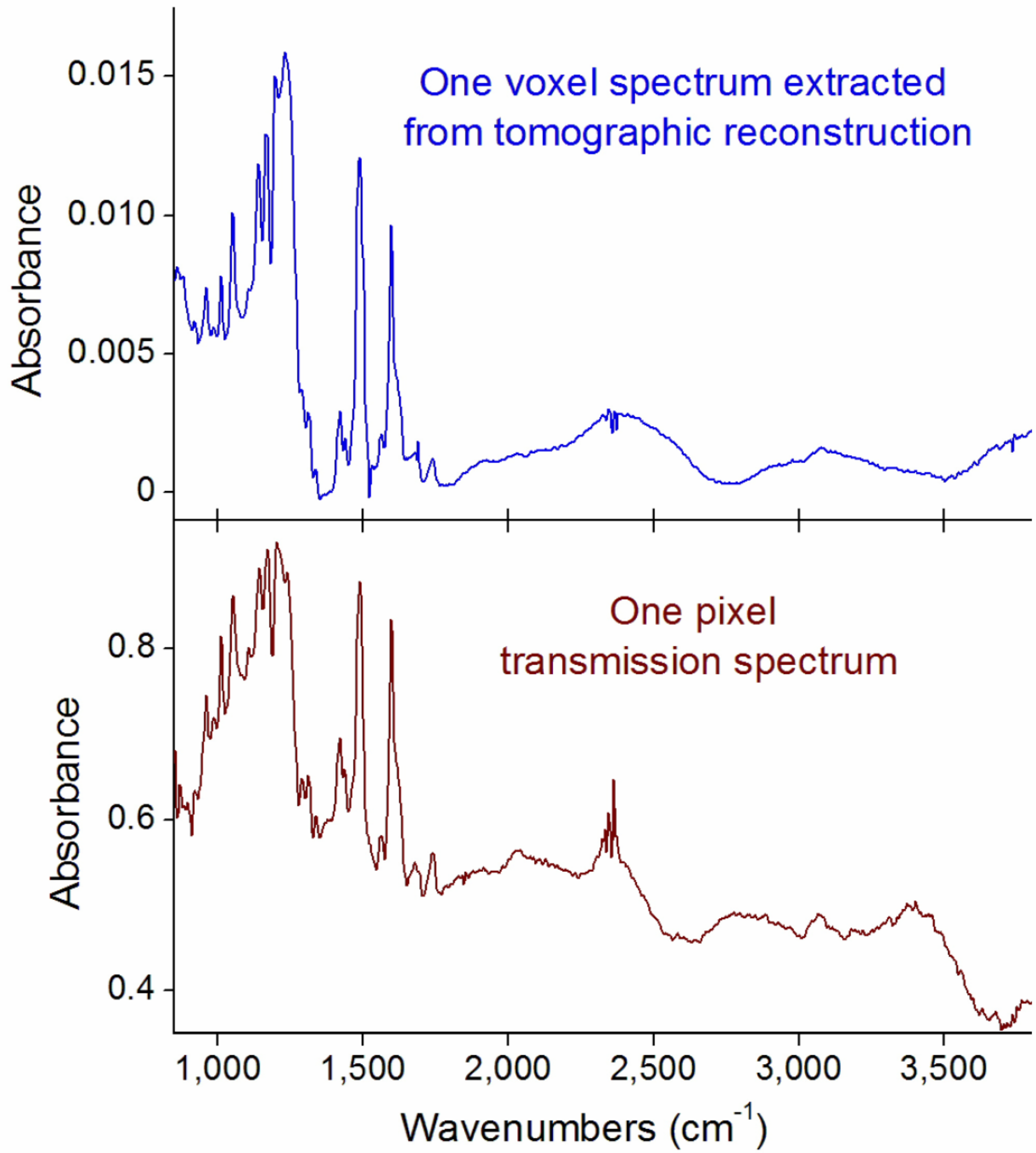
3D FTIR Tomography Demonstration

Test sample: MiTeGen protein crystallography microloop holder.

1574-1655 cm^{-1}
Polyimide absorption

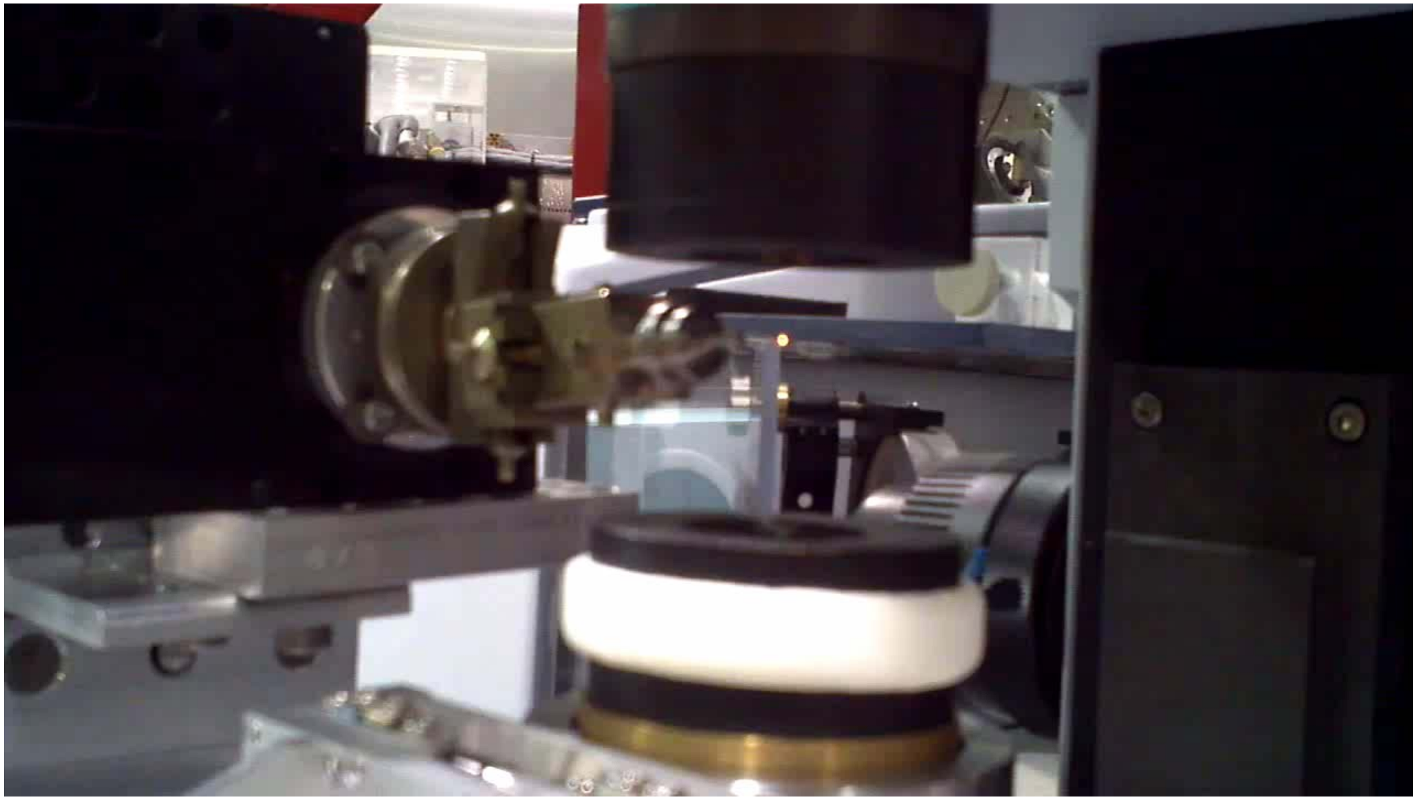
2287-2415 cm^{-1}
Edge scattering

3D FTIR Tomography Demonstration



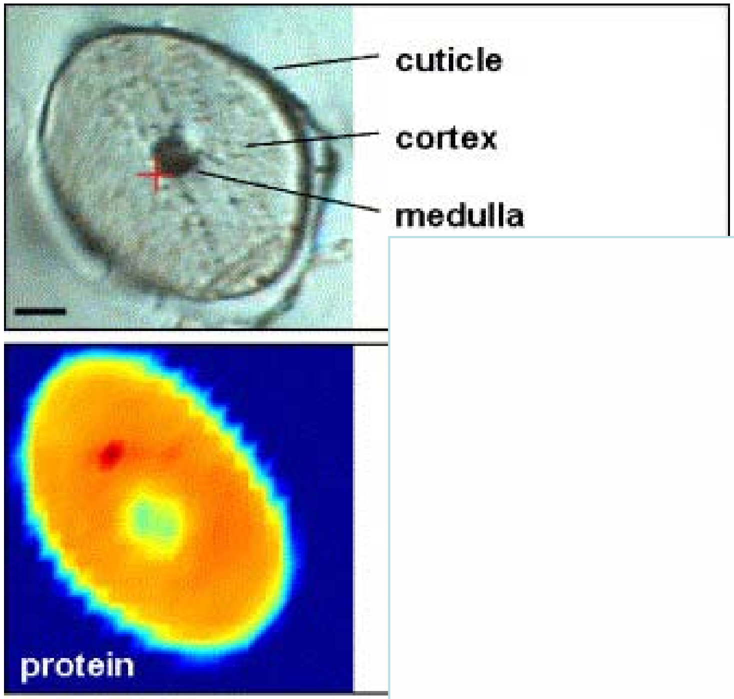
Fast Imaging + Rotation = 3D IR Tomography

Better automation at IRENI, 2013



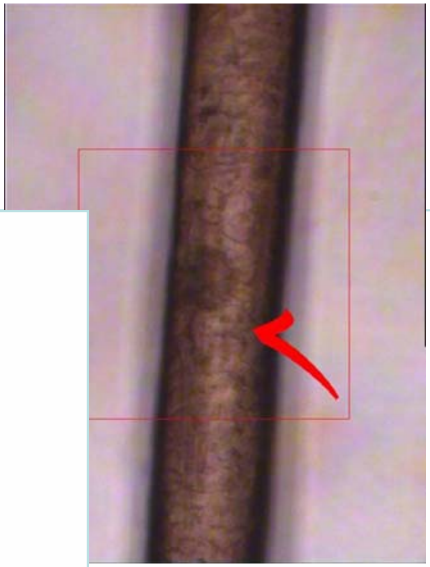
Programmed macro automates tomographic data acquisition.
Reconstruction programs coded to be spectroscopy aware.

Human Hair in 3D



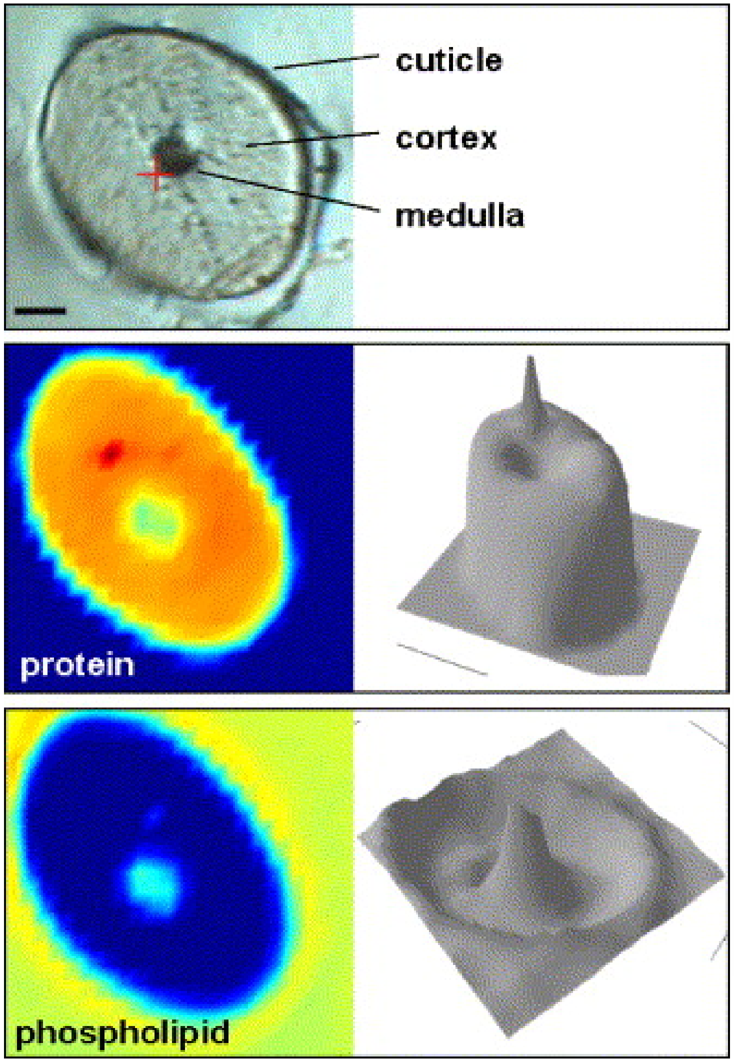
Paul Dumas, et al., SOI

Can we get similar information from an intact human hair?



1640 cm^{-1}
Protein absorption

Human Hair in 3D



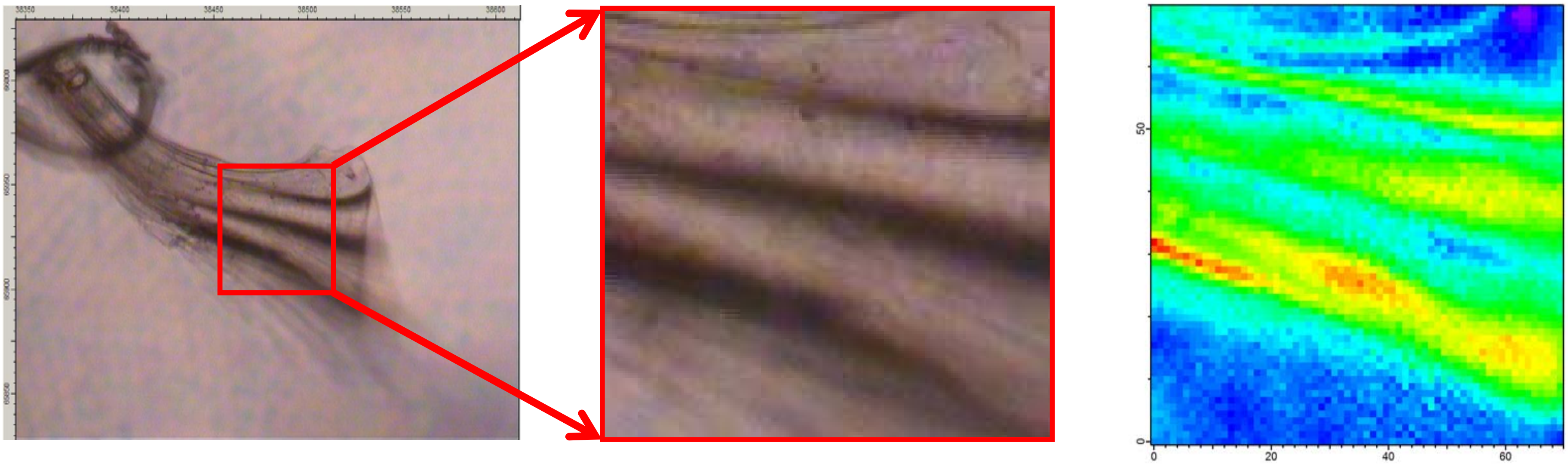
Paul Dumas, et al., SOLEIL

1640 cm^{-1}
Protein absorption

+

1705 cm^{-1}
Phospholipid absorption

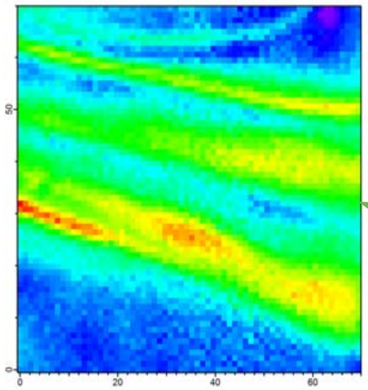
Microtomography of Volcanic Glass



Volcanic glass filament from the Puyehue volcano, Chile.
Sample collected by Jon Castro, Jan 2012.

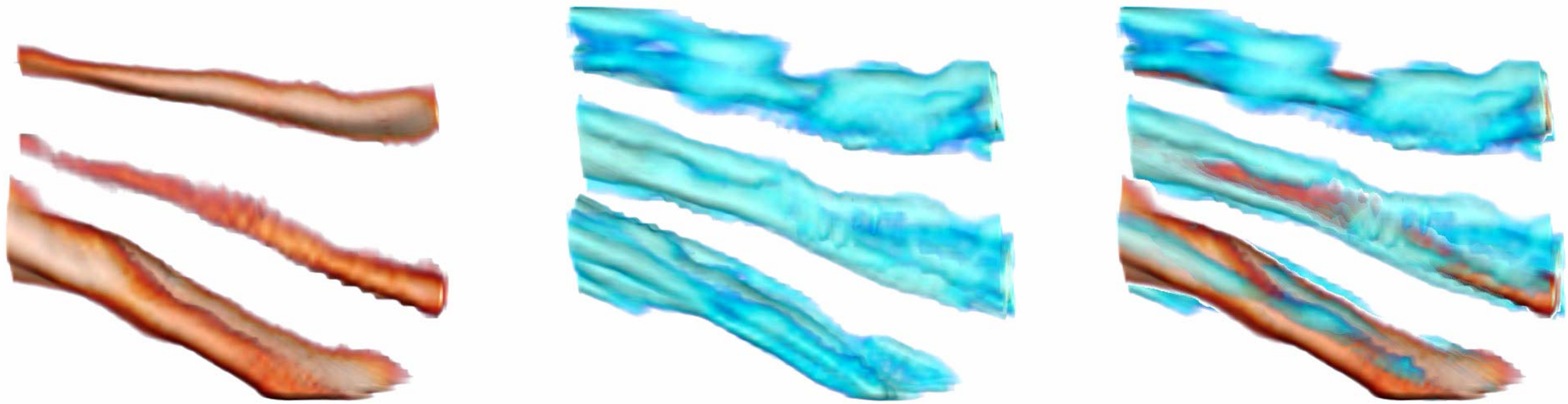
IR image shows density variations and water concentration changes along darker stripes relevant to mechanism of eruption.

Microtomography of Volcanic Glass



Becomes

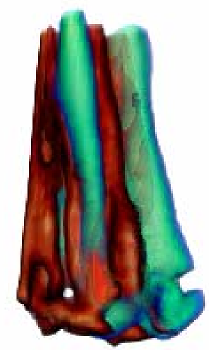
Brown = 1789 cm^{-1} = Silicate glass
Blue = 3495 cm^{-1} = Water O-H



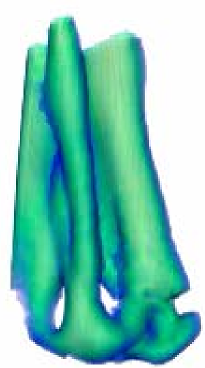
Correlation between glass and water can be seen well.

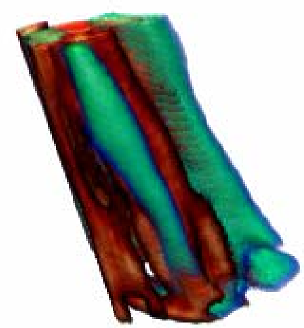
Poplar wood fibers

2800 – 3000 cm^{-1} C-H region



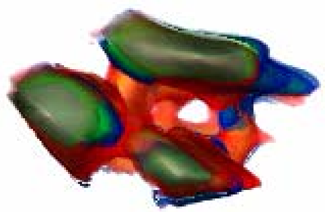
1524 – 1628 cm^{-1}
region:
Shows channels
made of lignin





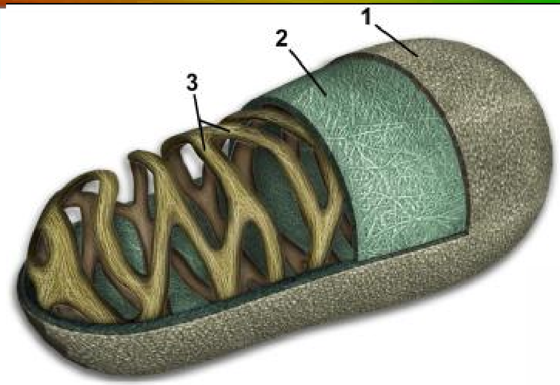
Poplar wood fibers

1689 – 1782 cm^{-1} region (red)
Hemicellulose: Outlines channels

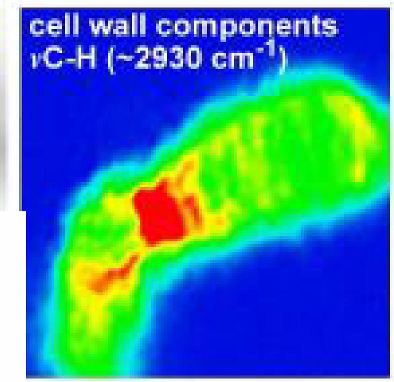


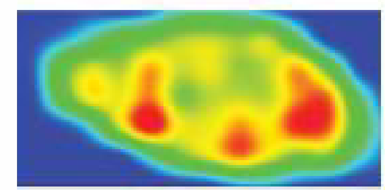
1524 – 1628 cm^{-1} region (blue)
Lignin: Fills channels

Zinnia elegans plant cells



Cellulose microfibrils arranges in a parallel orientation.



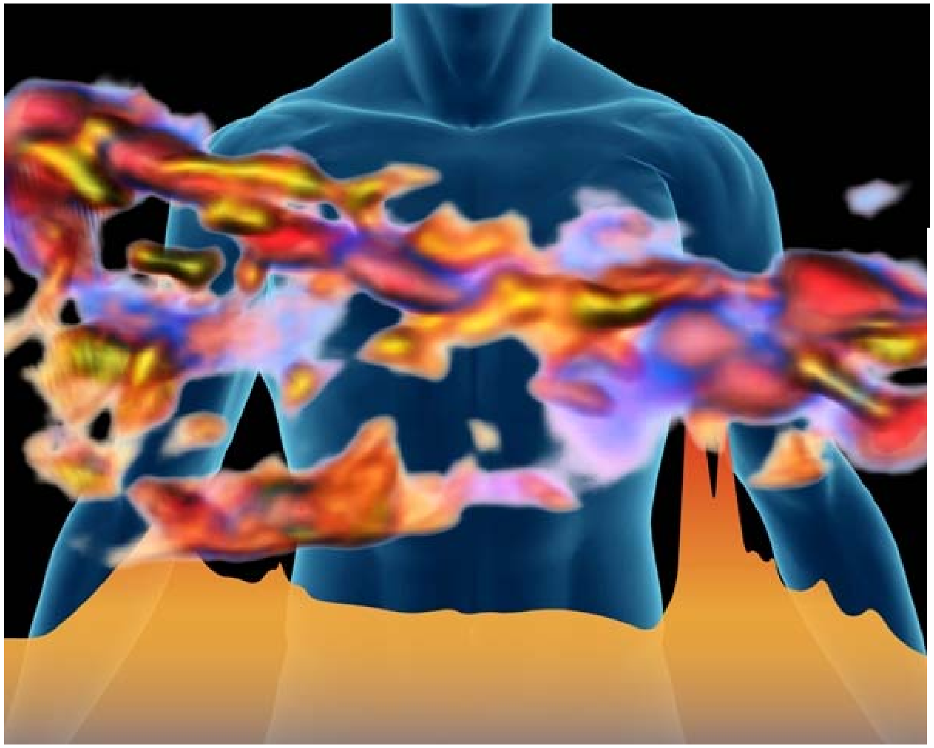


Lacayo et al., Plant Physiology (2010).

2360 cm^{-1}
region (red)
Scatter outline of holder

3330 cm^{-1}
region (blue-green):
Shows water in Zinnia

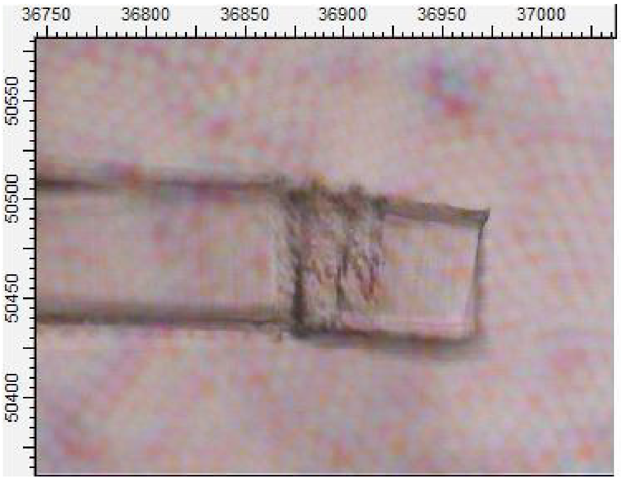
Embryonic Stem Cell Colony

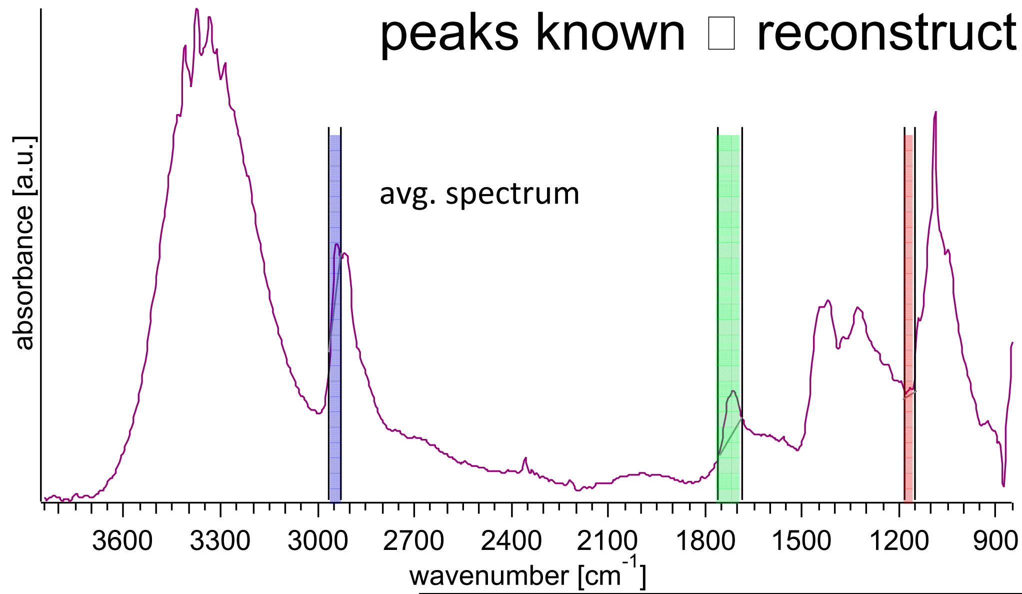


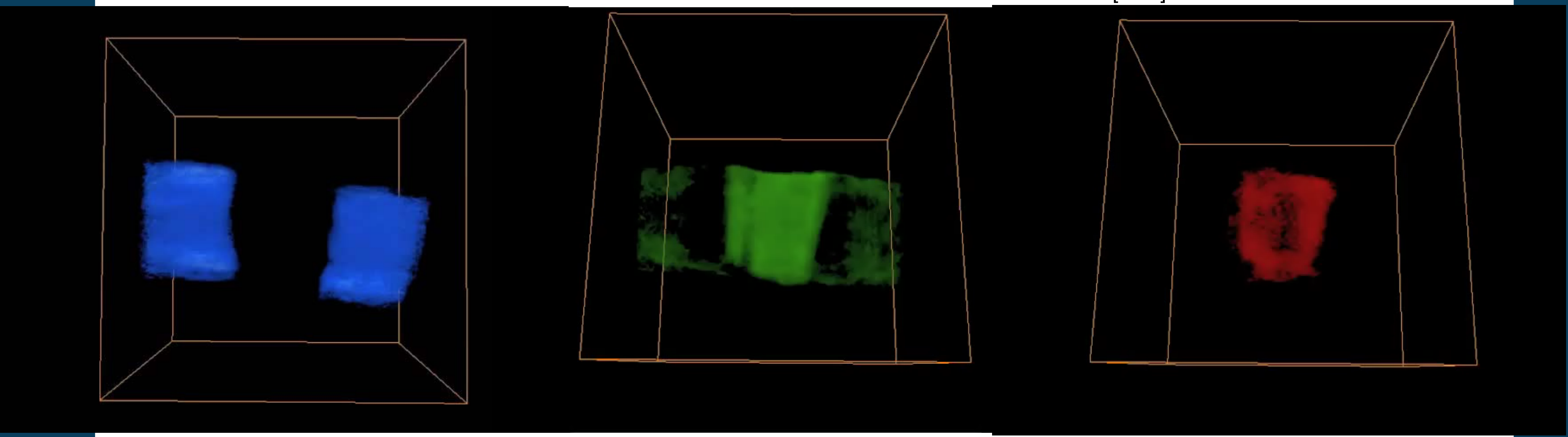
1650 cm^{-1}
region (red-blue)
Proteins

2850 cm^{-1}
region (yellow-orange):
Lipids

Nano Fiber Cellulose composite







PVOH: 2928-2966 cm^{-1}

PAA: 1684-1759 cm^{-1}

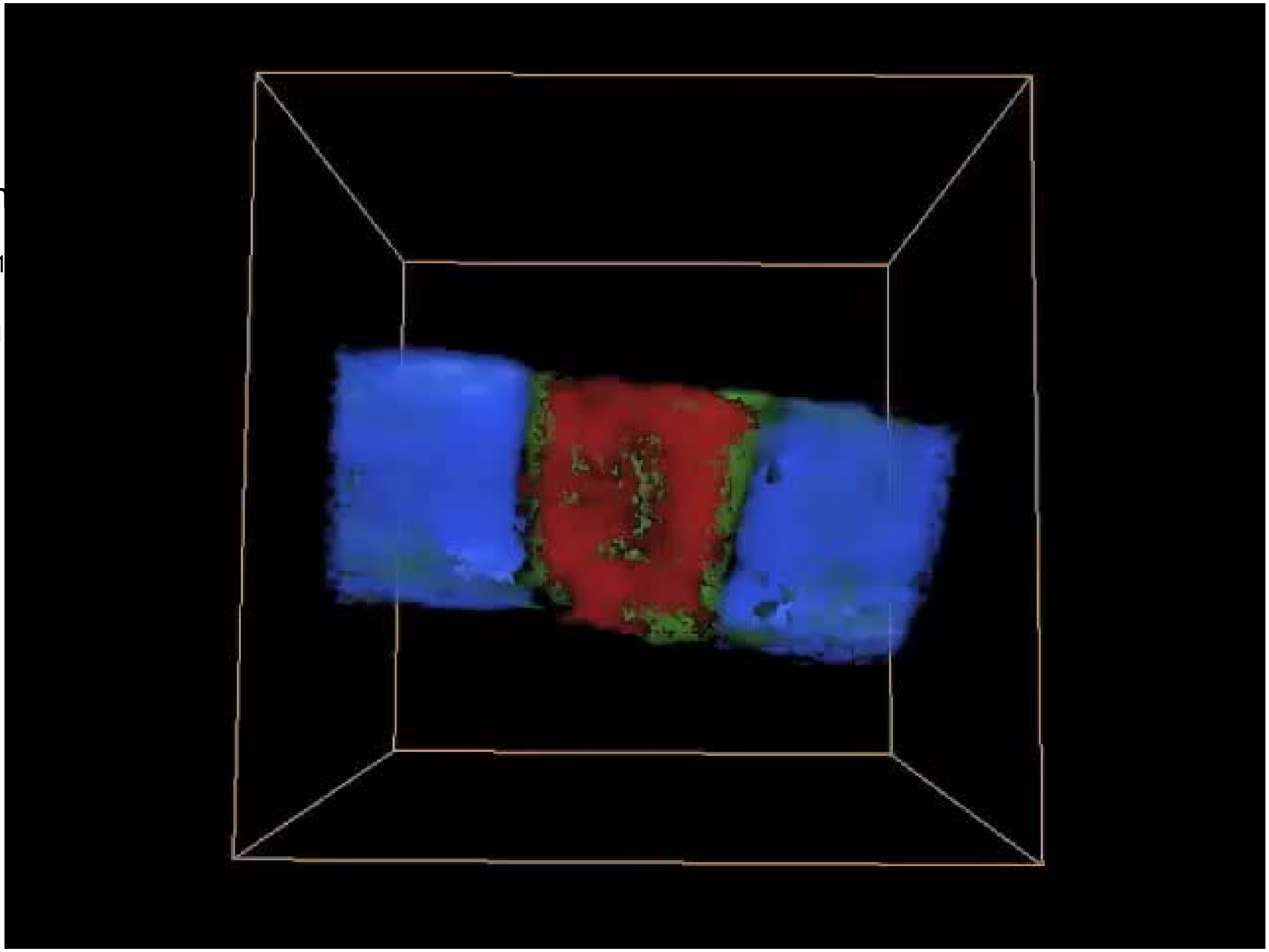
NFC: 1151-1181 cm^{-1}

Nano Fiber Cellulose composite

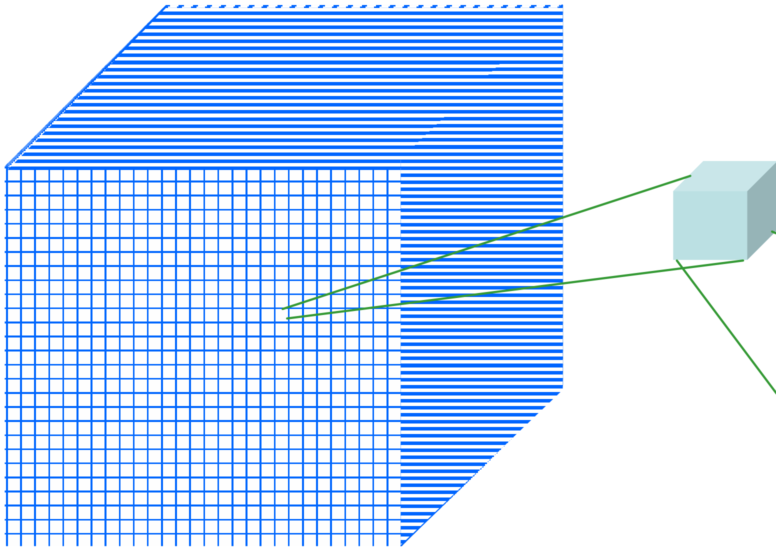
PVOH: 2928-2966 cm

PAA: 1684-1759 cm^{-1}

NFC: 1151-1181 cm^{-1}

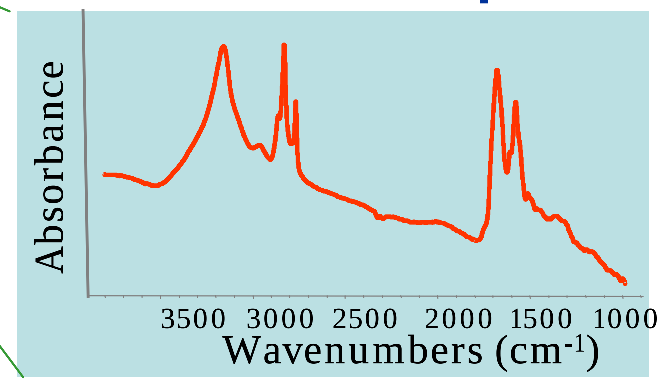


Partnership for Data analysis



4D spectral hypercube:

1.6 Million voxels, each with a fully reconstructed FTIR spectrum = 1.3 Billion datapoints



Fast data pipeline to super computer center

Web portal to reconstructed spectral 3D data

3D Data Visualization and Analysis room at the ALS

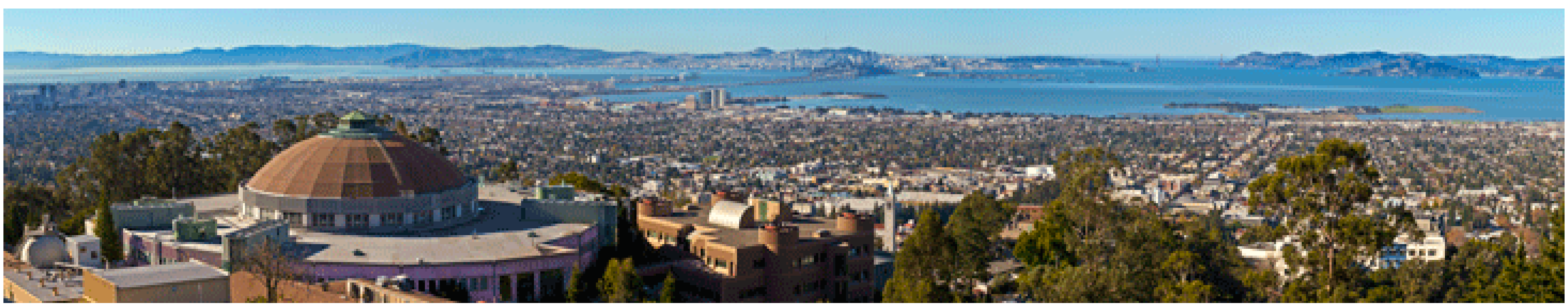
with Dula Parkinson, Craig Tull

ALS Synchrotron Infrared Beamlines

Broadband vibrational nano-spectroscopy with a synchrotron infrared source

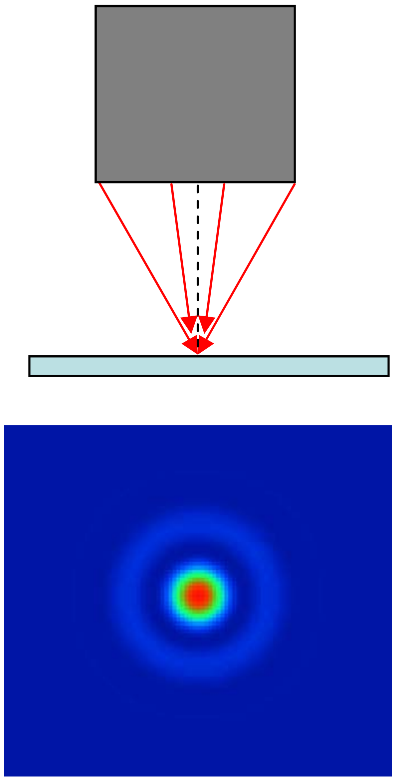
Hans A. Bechtel and Michael C. Martin
Advanced Light Source

Robert L. Olmon, Eric A. Muller, Benjamin Pollard, and Markus B. Raschke
University of Colorado, Boulder

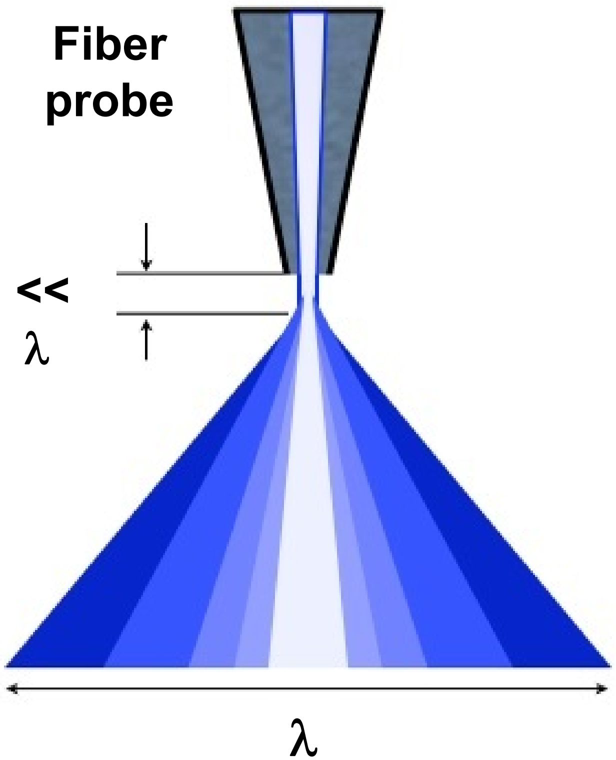


Beating the diffraction limit

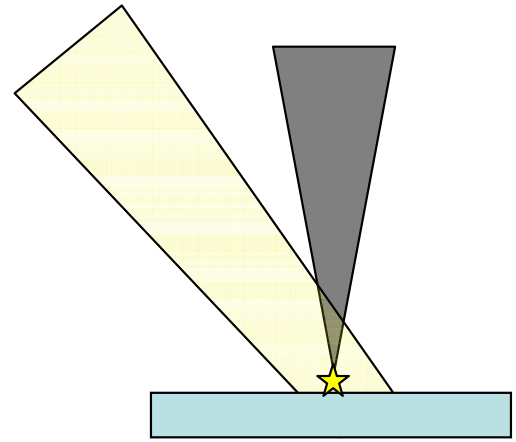
Far-field



Near-field



Apertureless

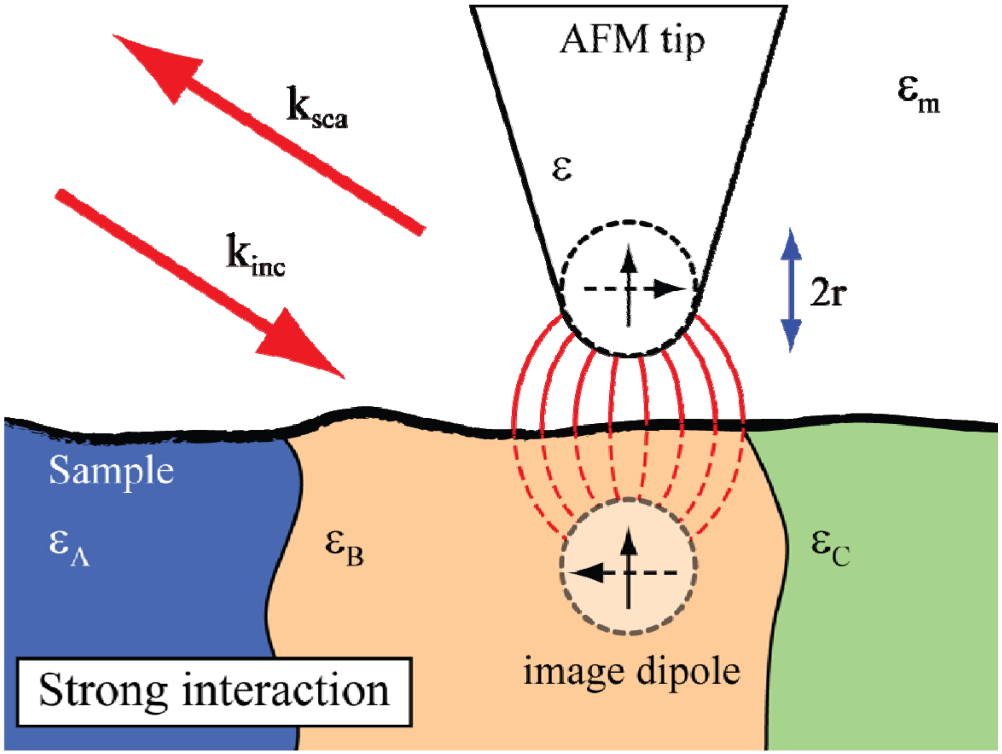


$$R = \frac{\lambda}{2\, n \sin\theta}$$

$$S \propto \left(\frac{d}{\lambda}\right)^4$$

$$R = tip\ size$$

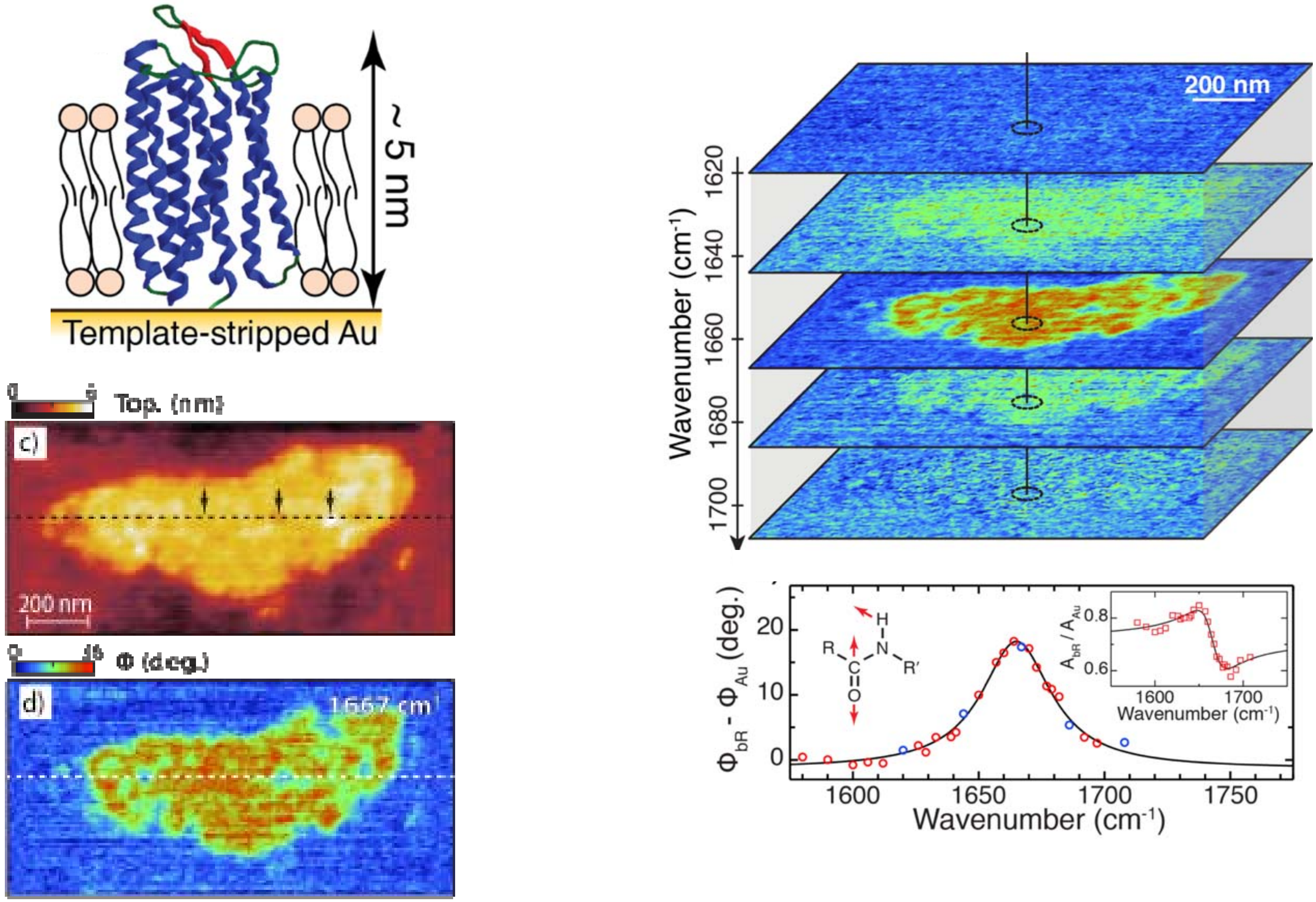
Scattering-type scanning near-field optical microscopy (s-SNOM)



Advantages

- Nanometer spatial resolution
- Wavelength independent
- Soft and hard matter
- Amplitude and phase of optical field

Laser s-SNOM of purple membrane protein



S. Berweger, D.M. Nguyen, E. A. Muller, H. A. Bechtel, T. T. Perkins, and M. B. Raschke, *JACS* ***135***, 18292 (2013).

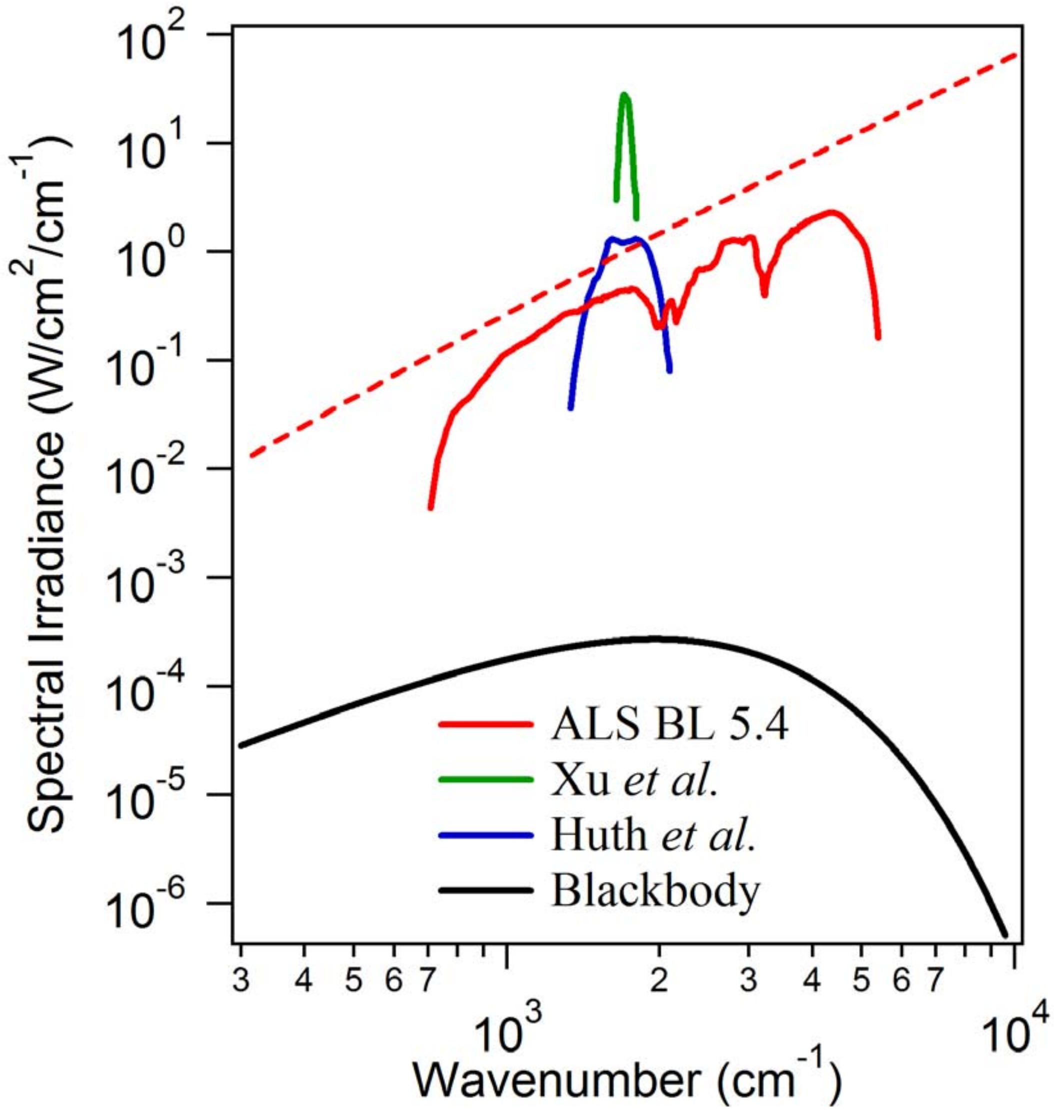
Broadband sources for s-SNOM

Broadband sources

- More efficient spectral collection
- Improved spectral accuracy

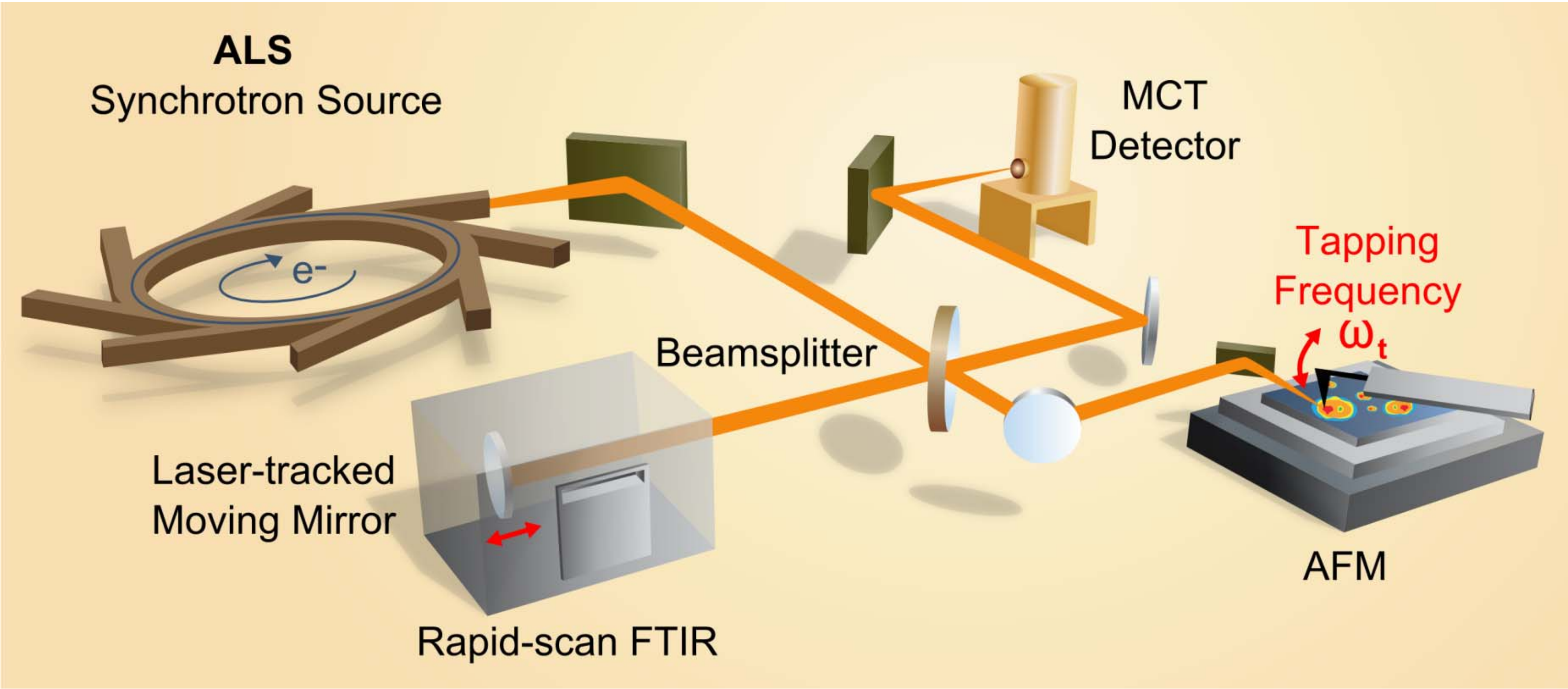
Synchrotron IR

- Ultra-broadband
- High spectral irradiance
- Spatially coherent
- Good spectral stability



Optical layout

Synchrotron Infrared Nano-Spectroscopy



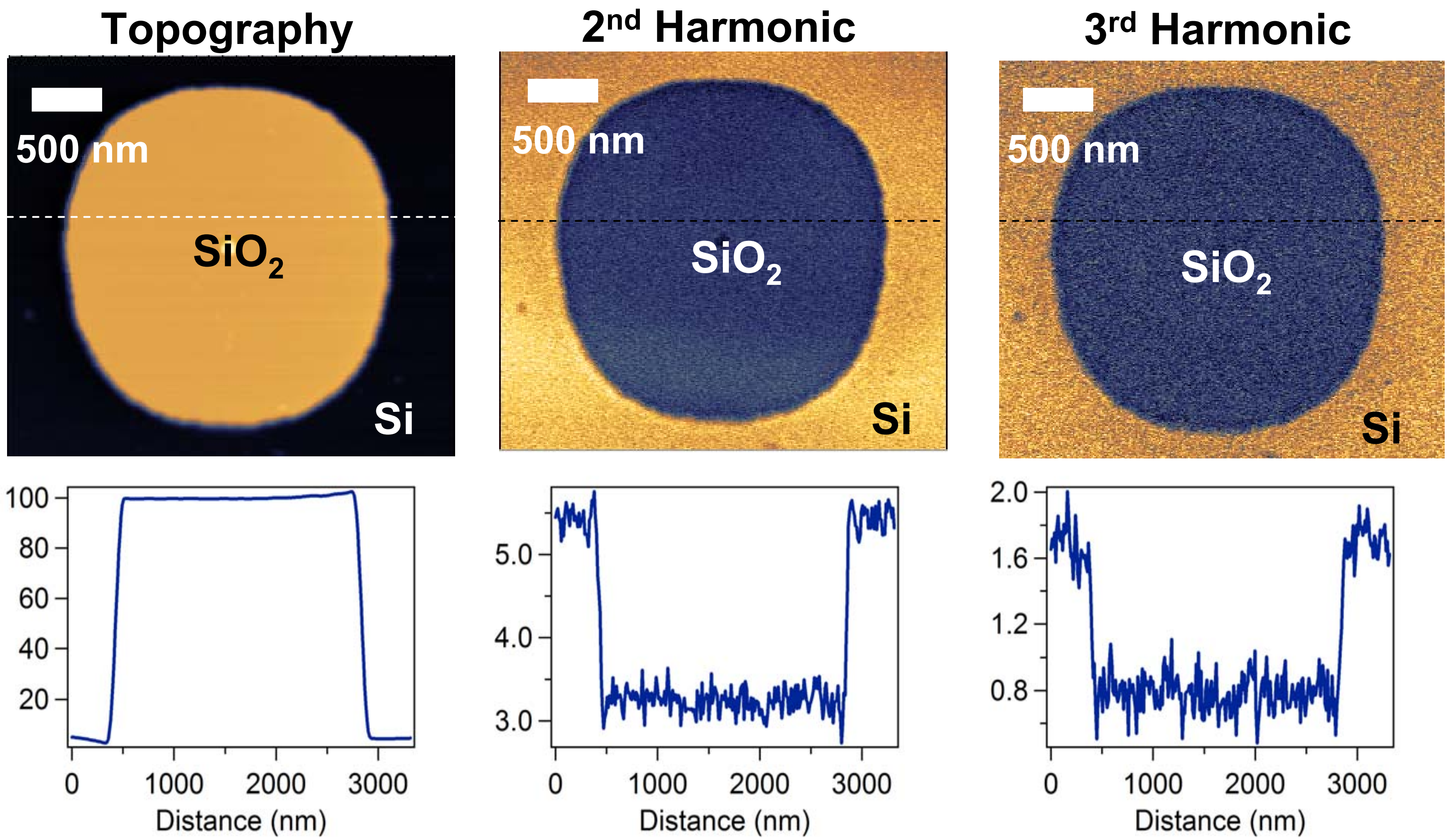
Bechtel *et al.*, PNAS **111**(20), 7191–7196 (2014).

ALS Beamline 5.4 SINS

Key Components

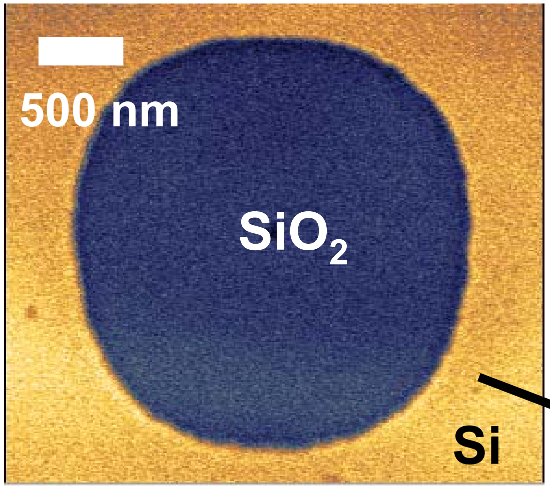
- •Floating table
- •Modified Bruker Innova AFM
- •Zurich Instruments lock-in amplifier
- •Commercial Thermo FTIR
- •Kolmar MCT (100 um)

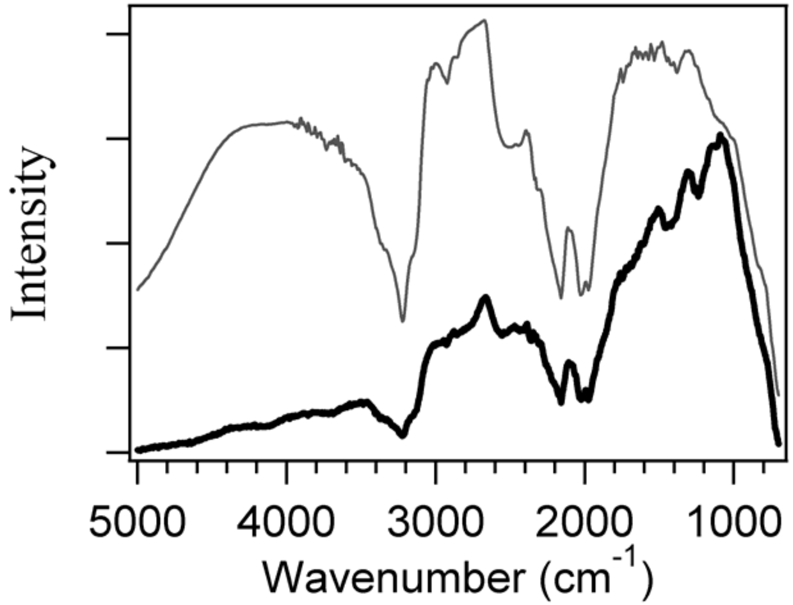
SiO_2 Microstructures

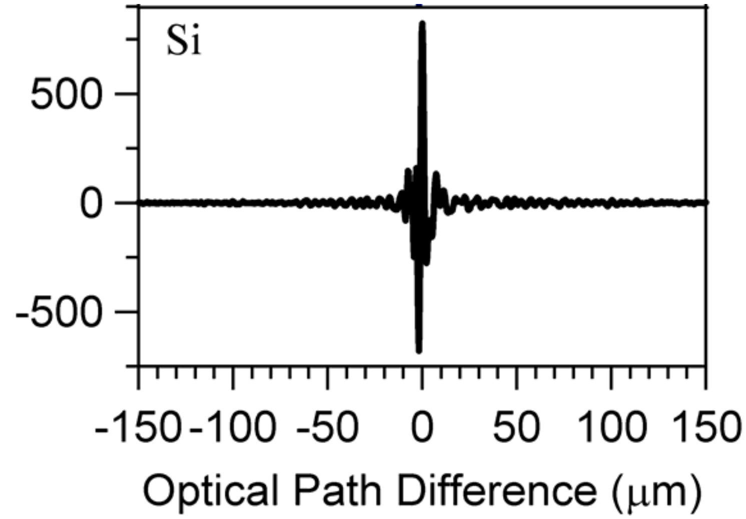


Spatial Resolution < 45 nm
better than λ/200!

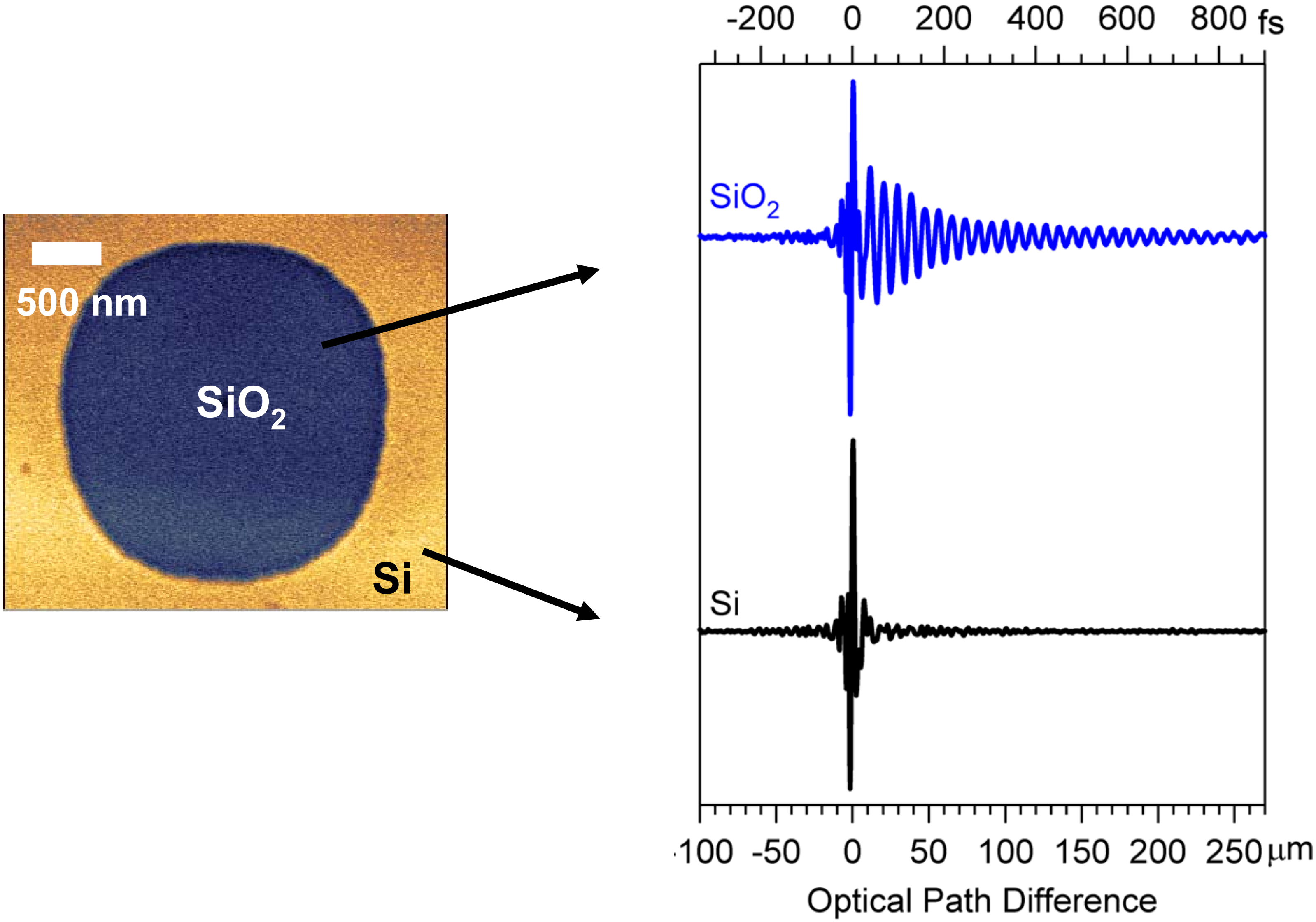
SiO_2 Microstructures: Si response



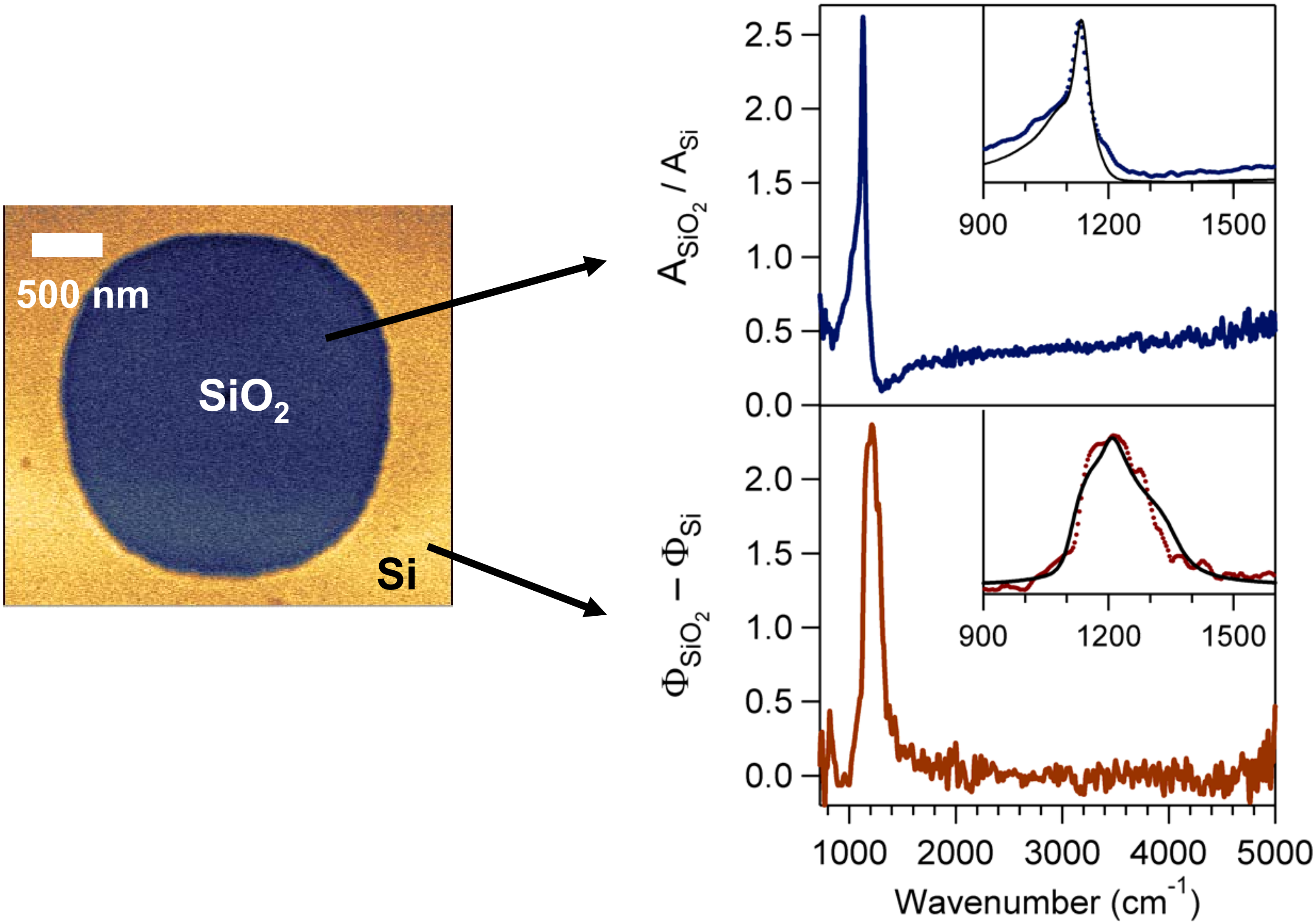




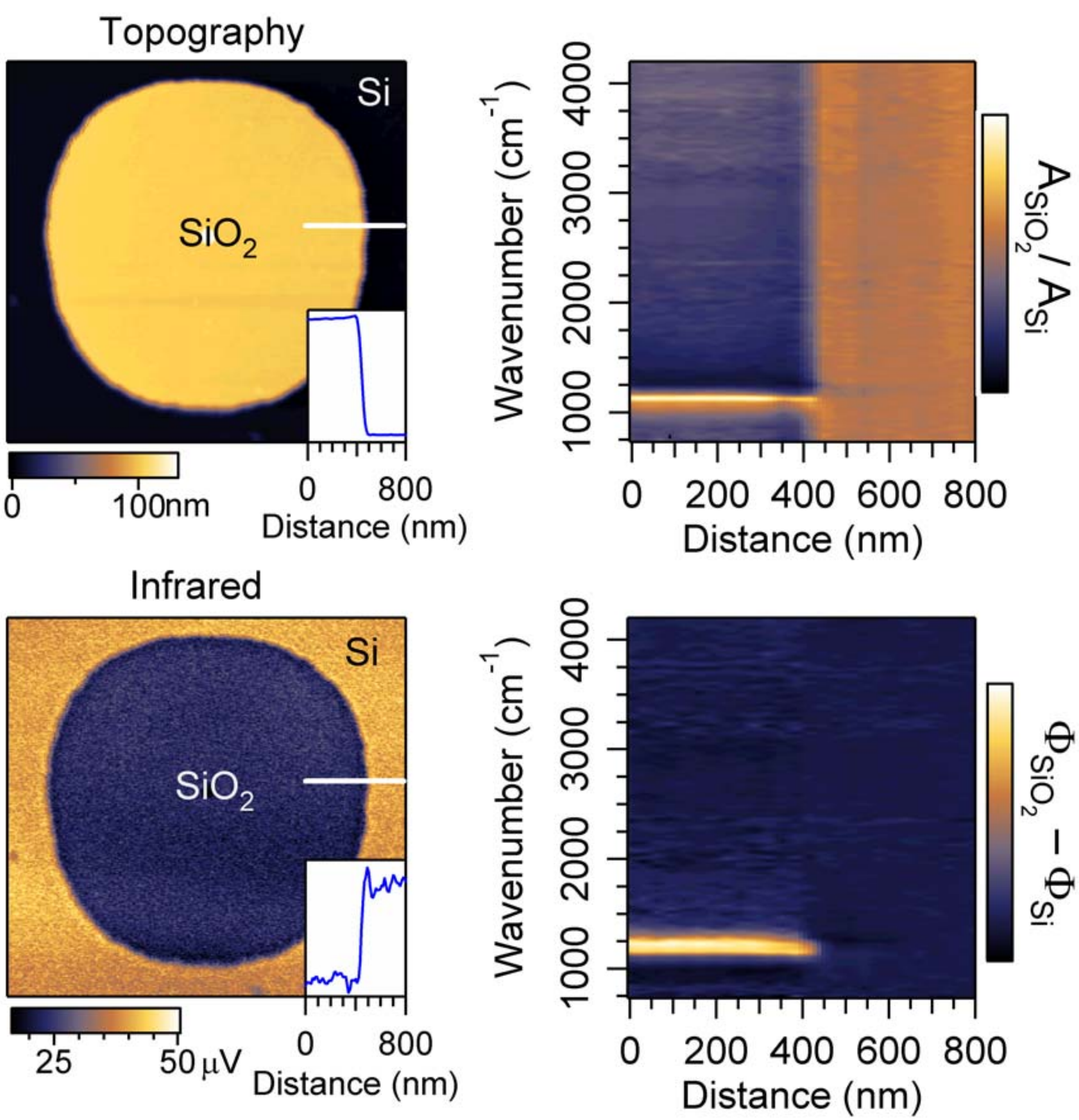
SiO_2 Microstructures: Interferrograms



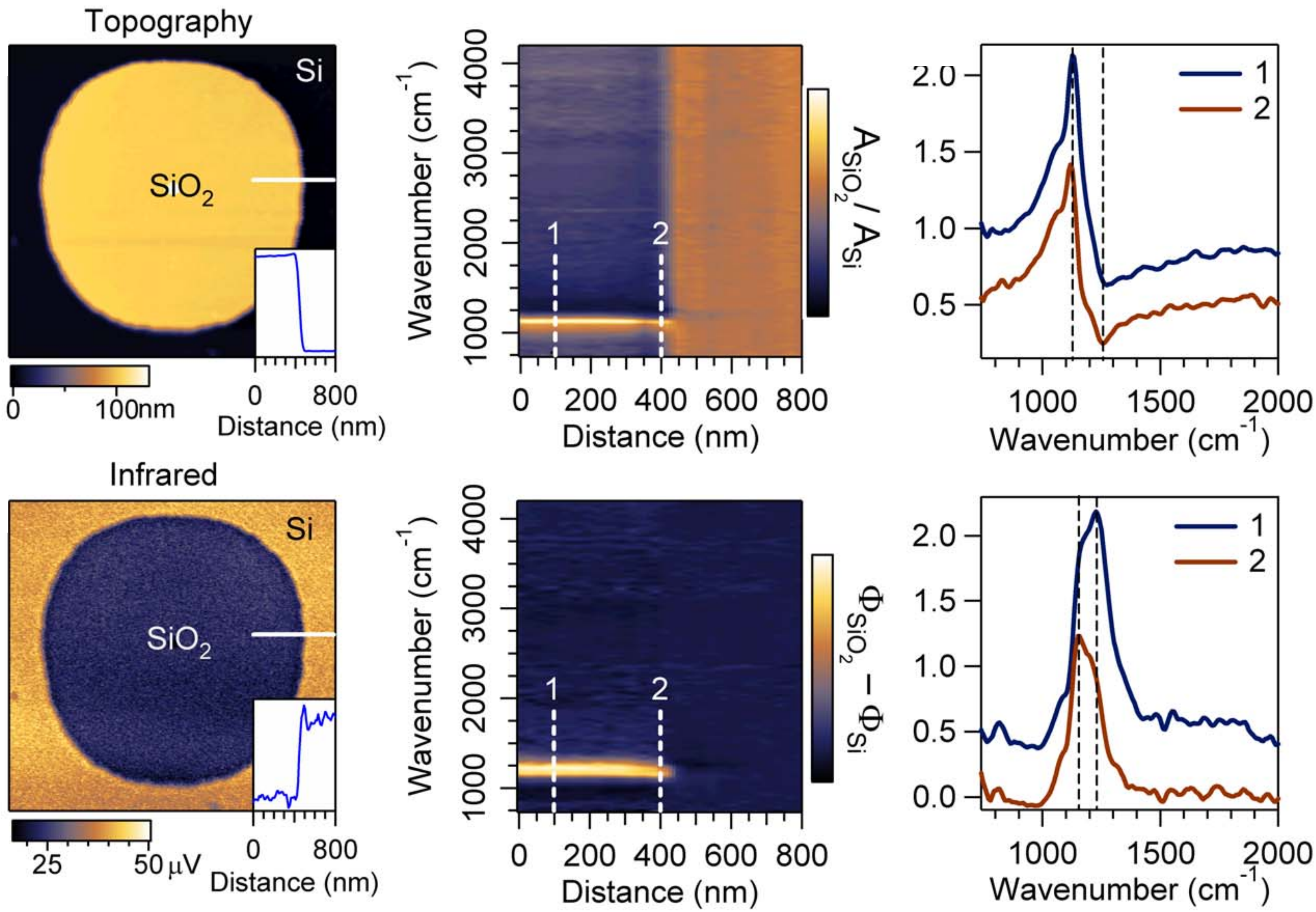
SiO_2 Microstructures: spectra



SiO_2 spatio-spectral imaging

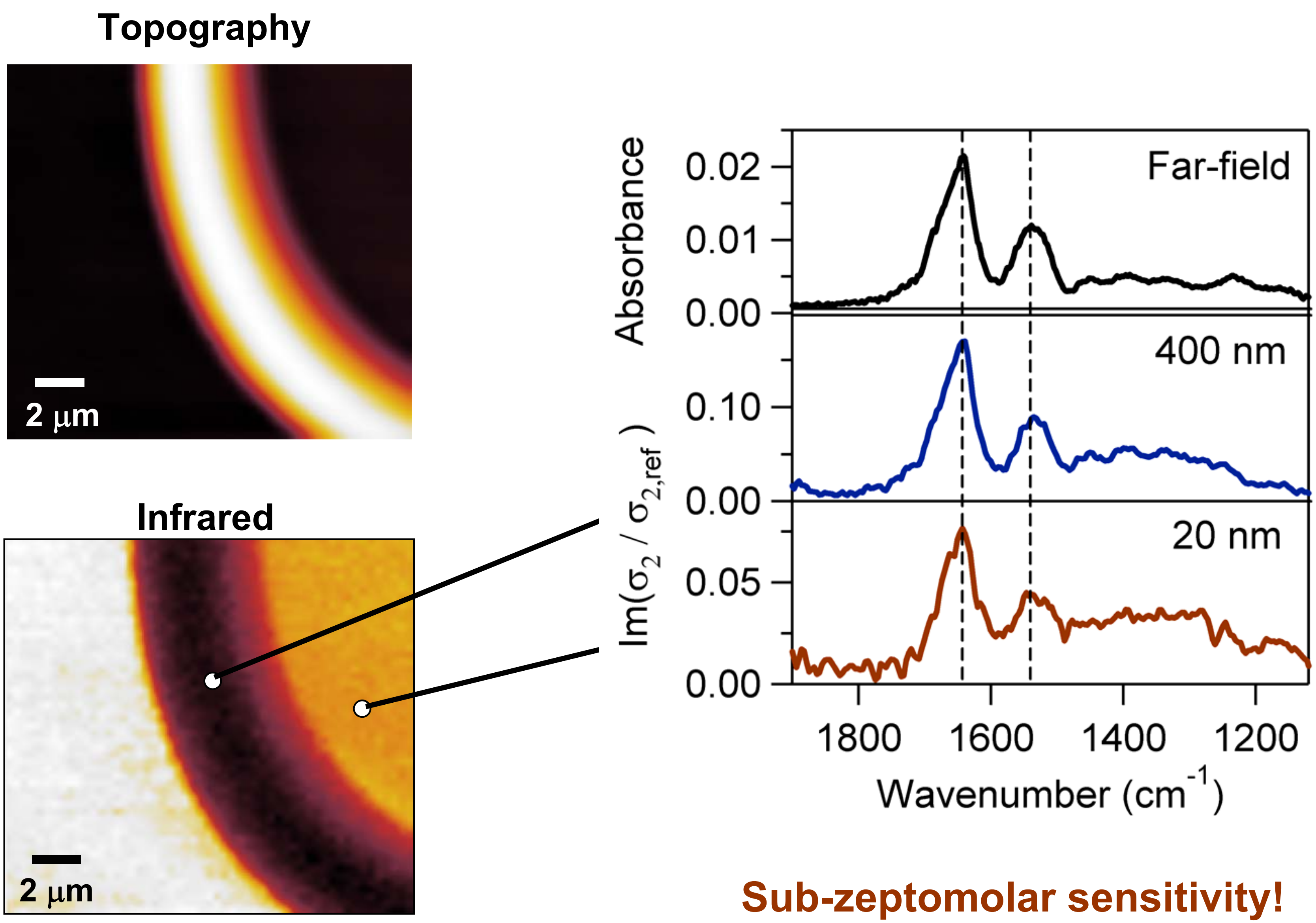


SiO_2 spatio-spectral imaging



Protein sensitivity

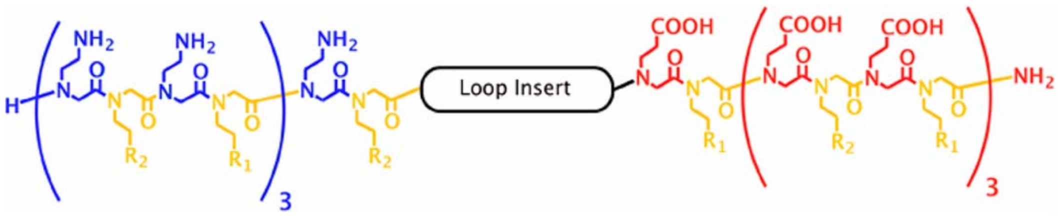
Samples: Sun Choi and Hoi-Ying Holman (ESD, LBNL)

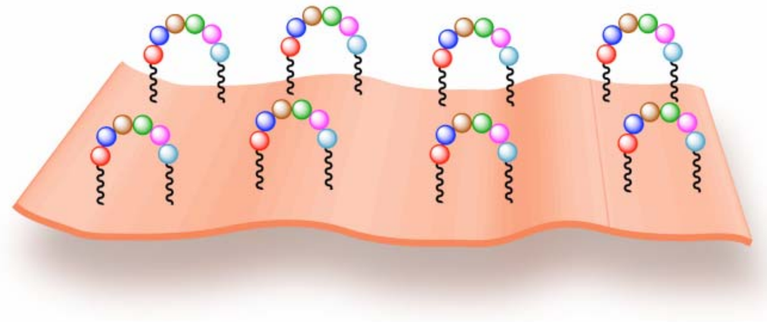


Sub-zeptomolar sensitivity!

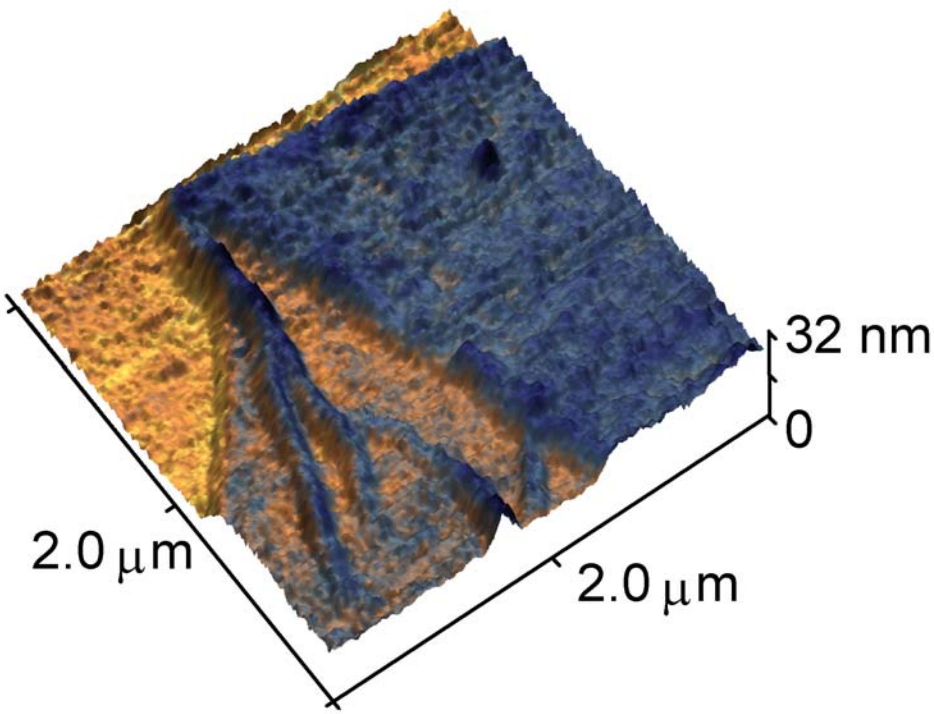
Biomimetic nanosheets and membranes

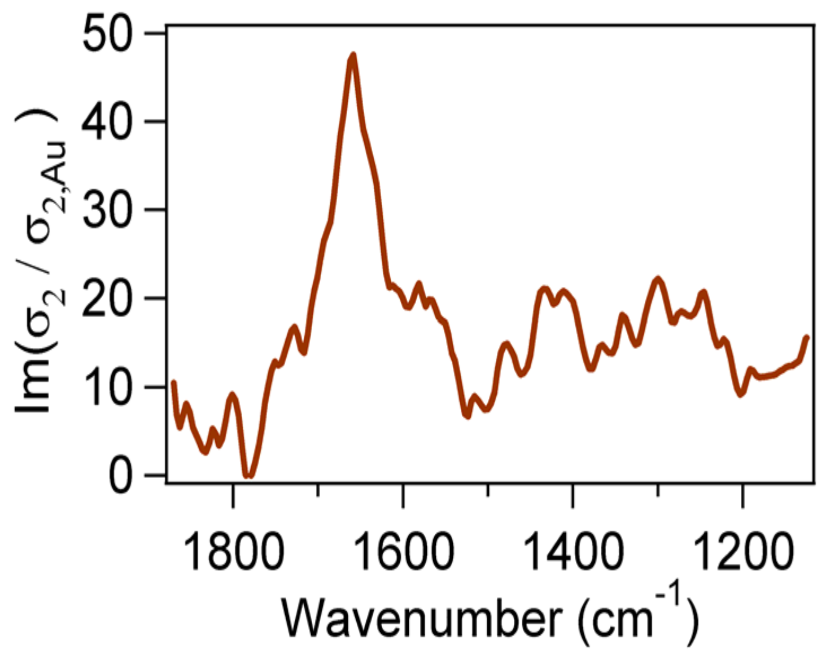
Samples: Gloria Olivier and Ron Zuckermann (Molecular Foundry, LBNL)





Olivier et al. ACS Nano, 7, 9276 (2013)

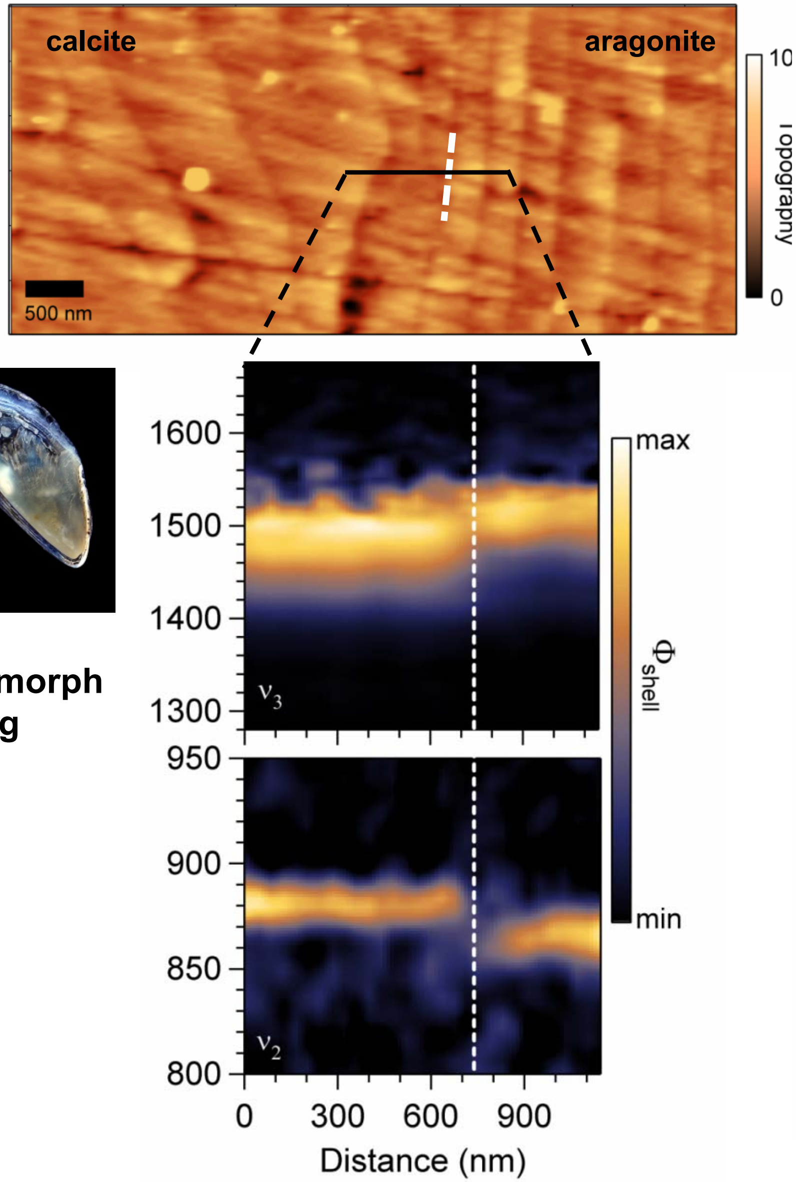


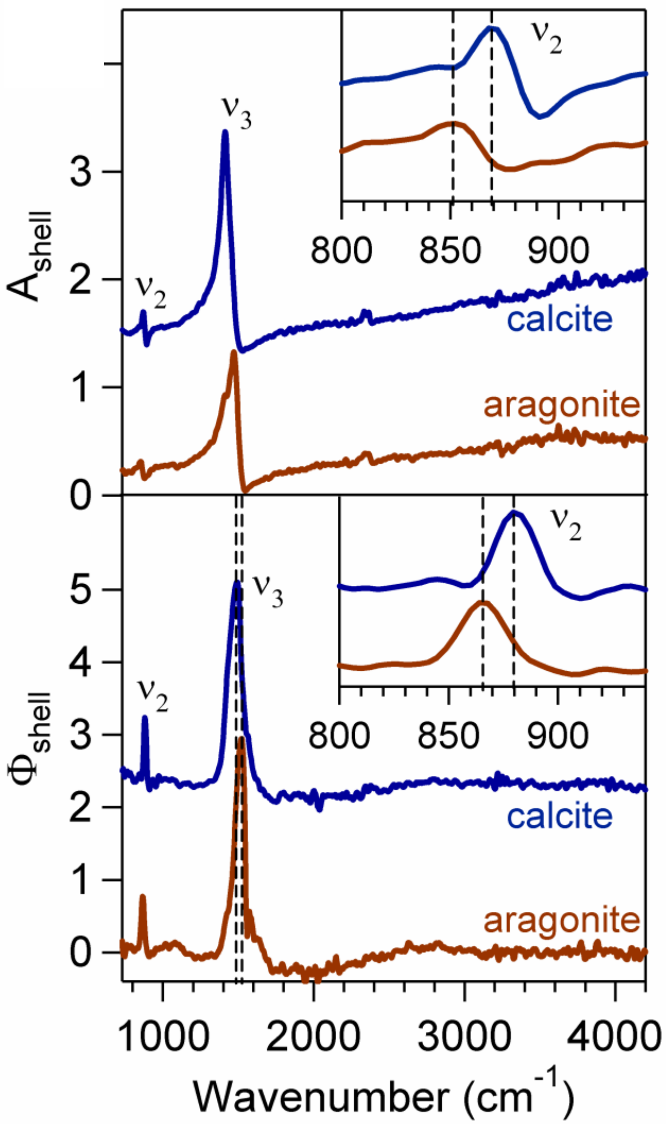


Natural biomineral systems

Samples: Ian Olson and Pupa Gilbert (U. Wisconsin)

$CaCO_3$ polymorph imaging

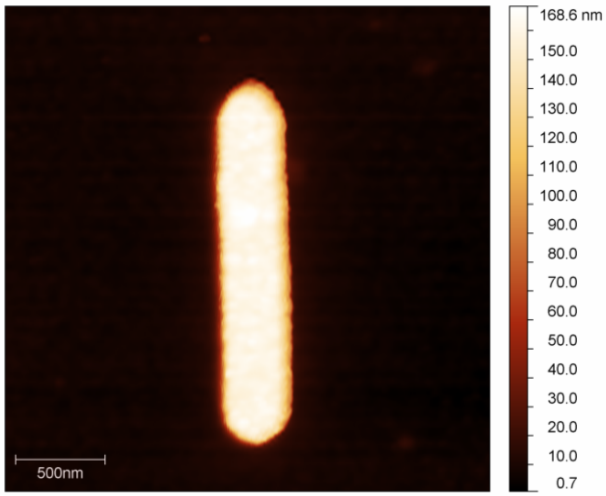




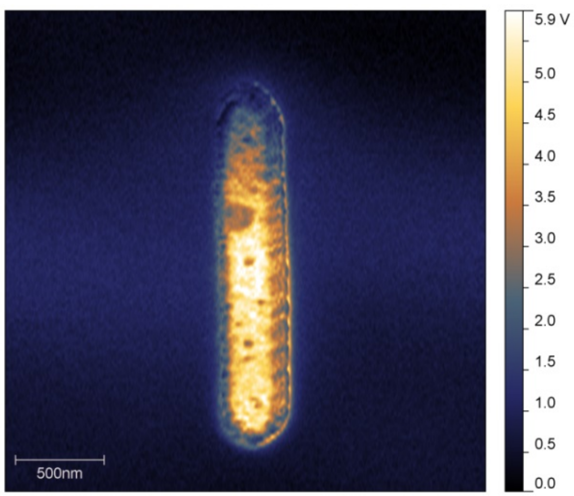
Antenna near-field imaging

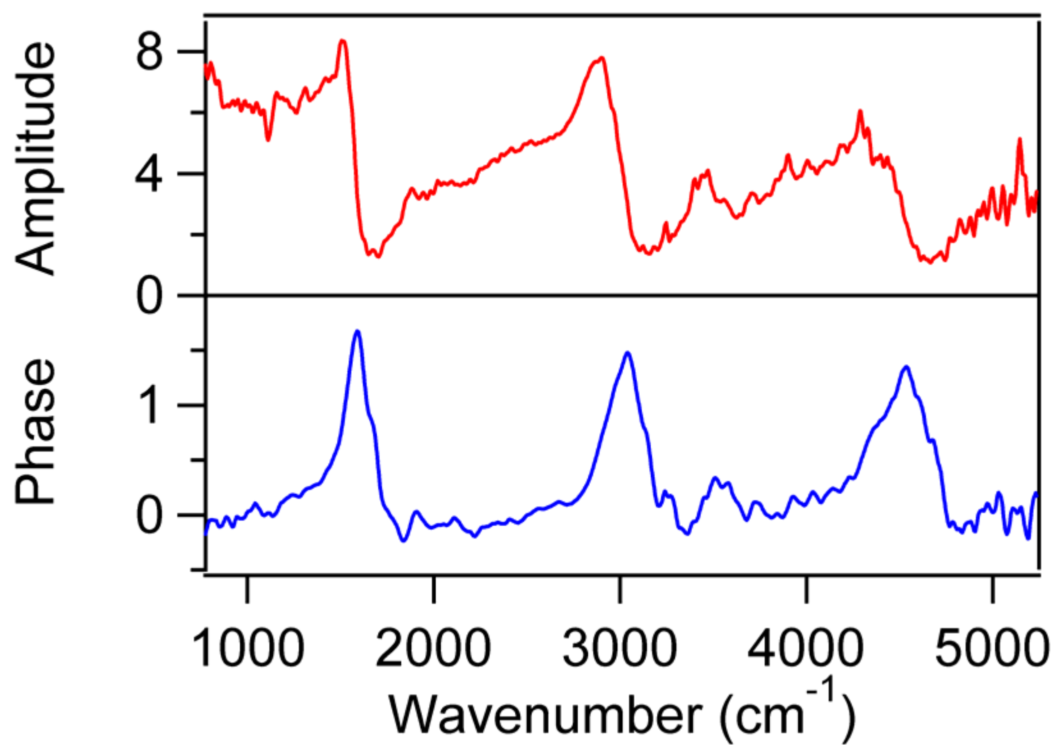
Eric Muller, Benjamin Pollard, and Markus Raschke (U. Colorado)

Topography



Infrared





Antenna near-field imaging

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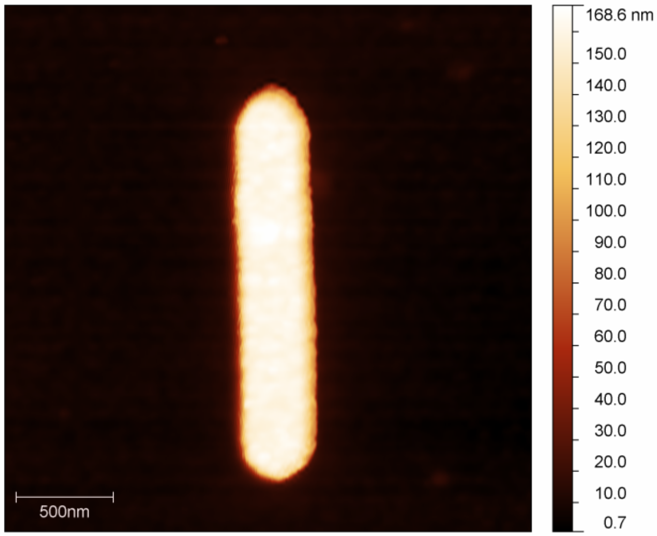
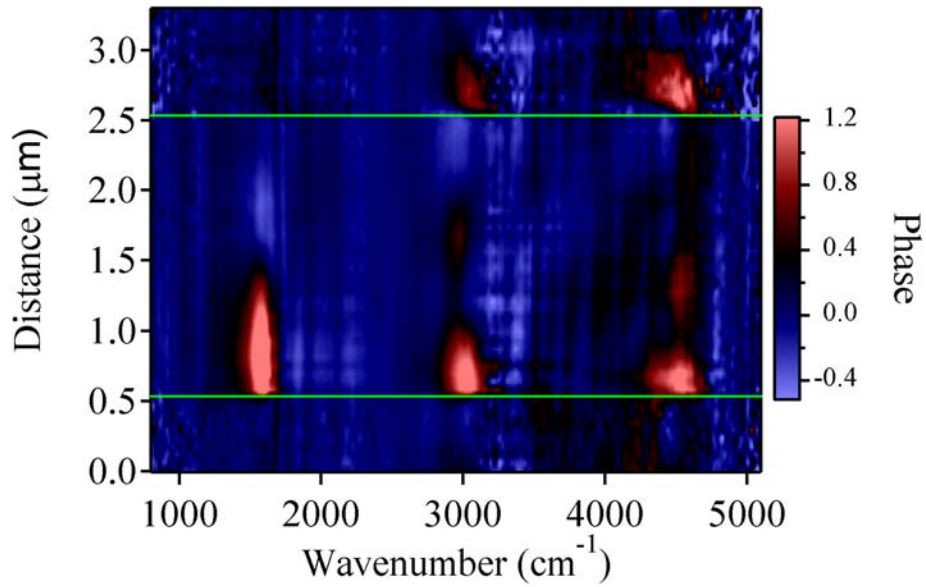
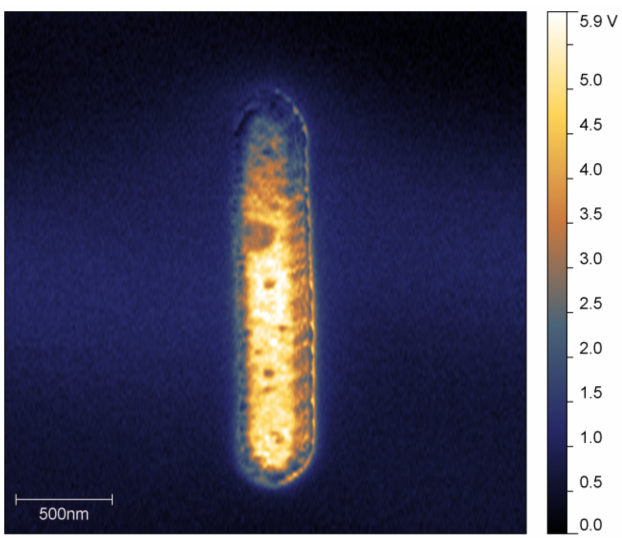
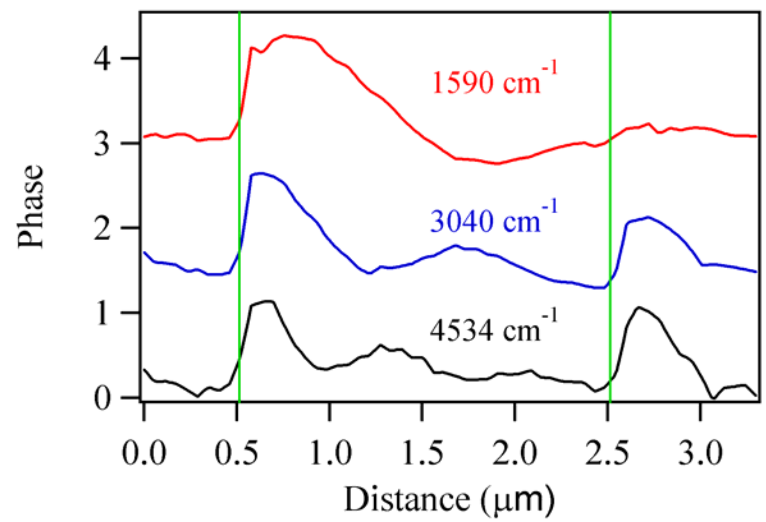
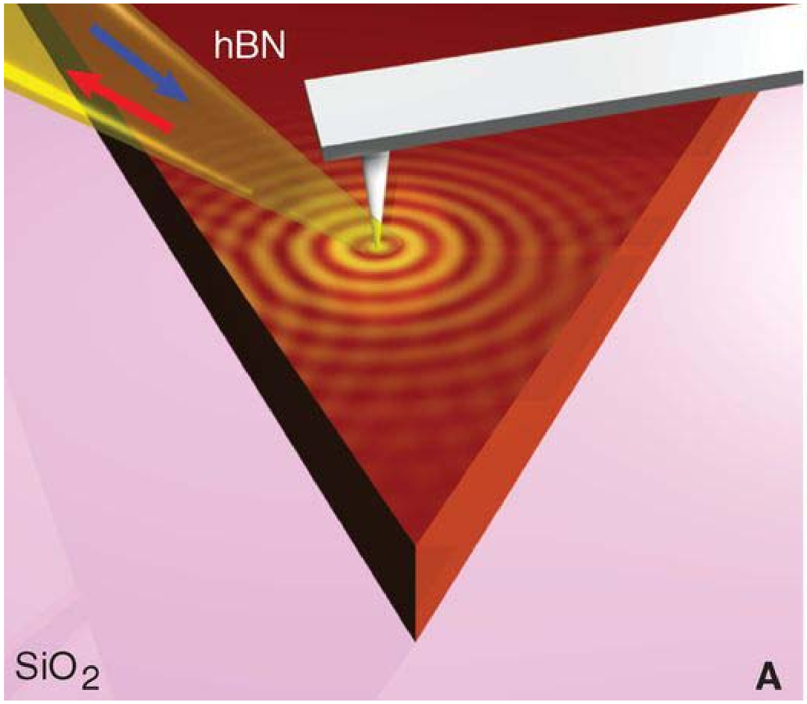


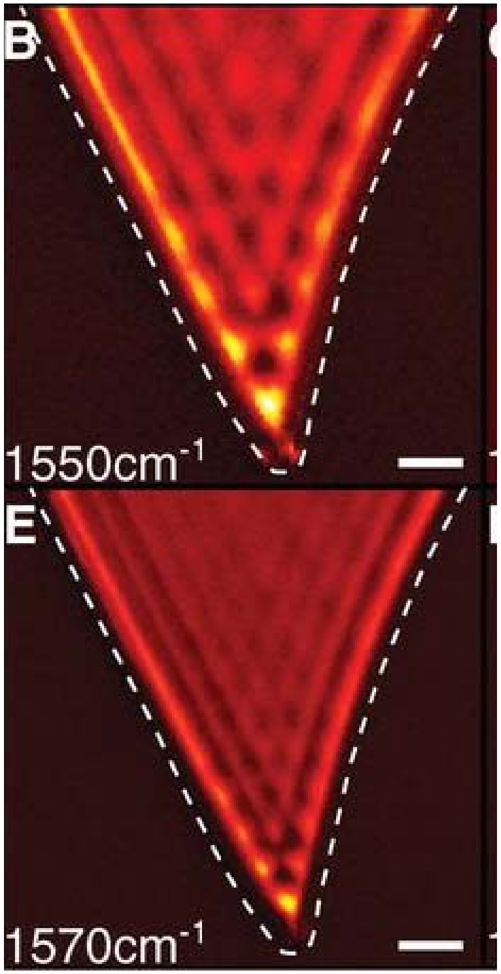






Surface Phonon Polaritons in Boron Nitride

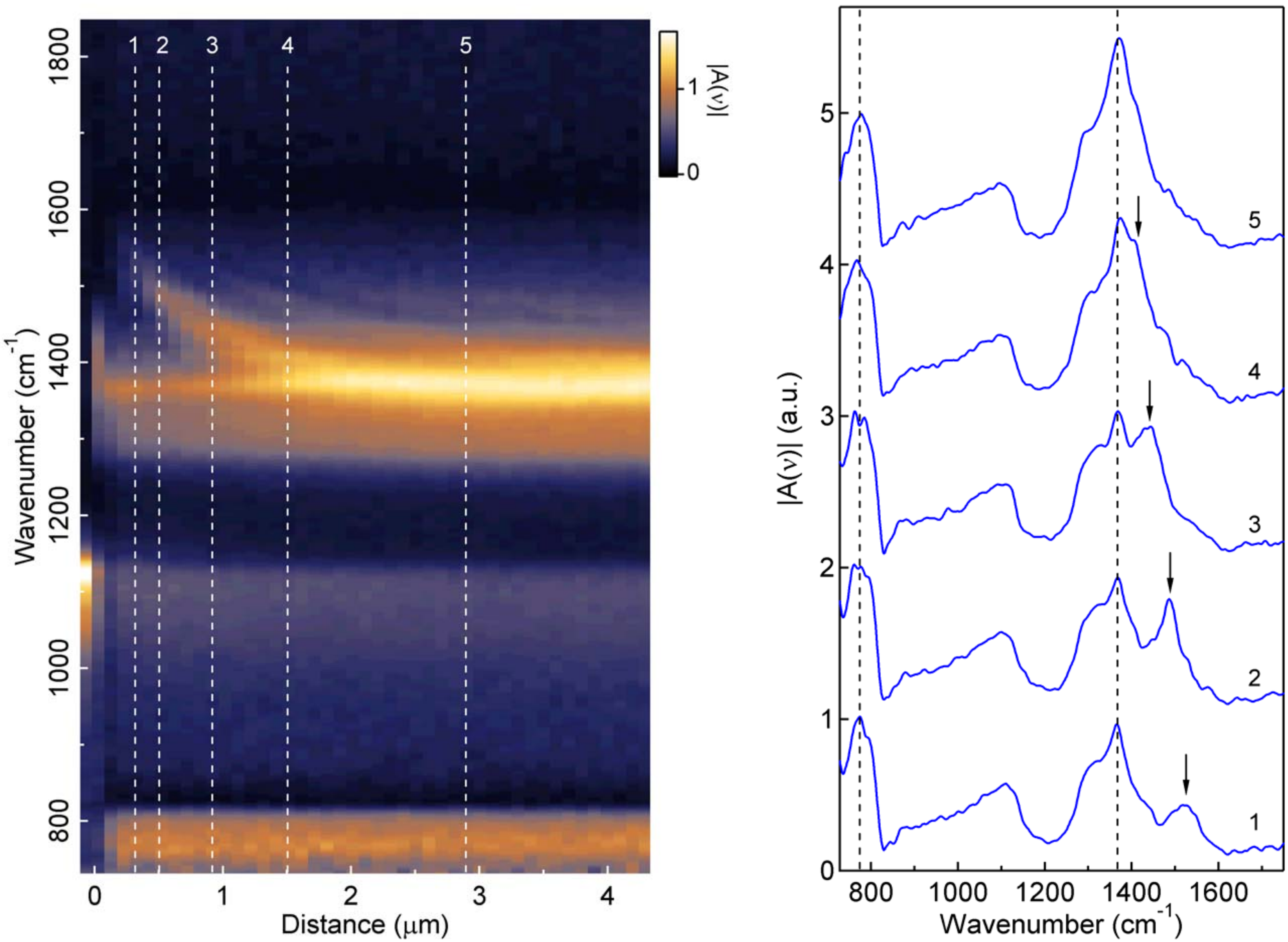




S. Dai *et al.*, *Science* ***343*** *,1125-1129 (2014)*

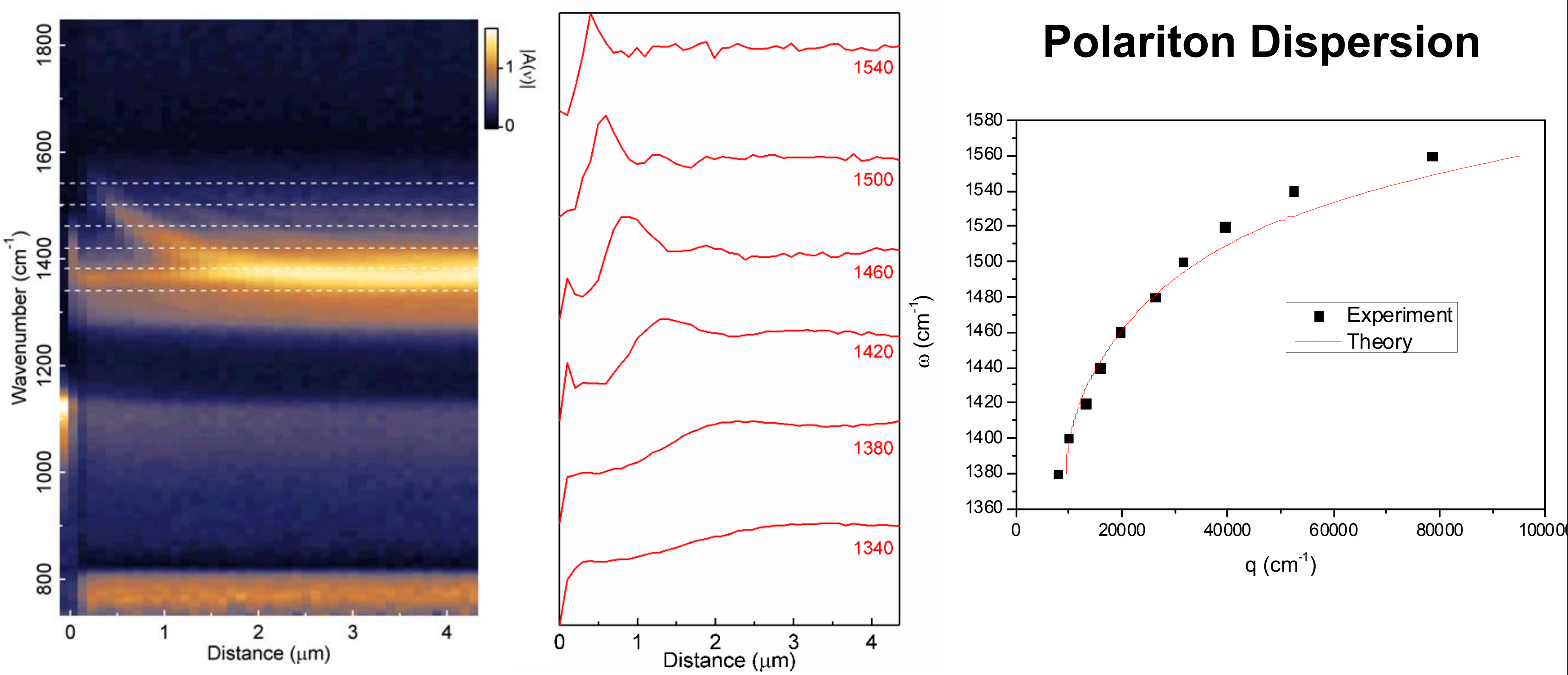
Surface Phonon Polaritons in Boron Nitride

Zhiwen Shi and Feng Wang (UC Berkeley)



Surface Phonon Polaritons in Boron Nitride

Zhiwen Shi and Feng Wang (UC Berkeley)



Surface Phonon Polaritons in Boron Nitride

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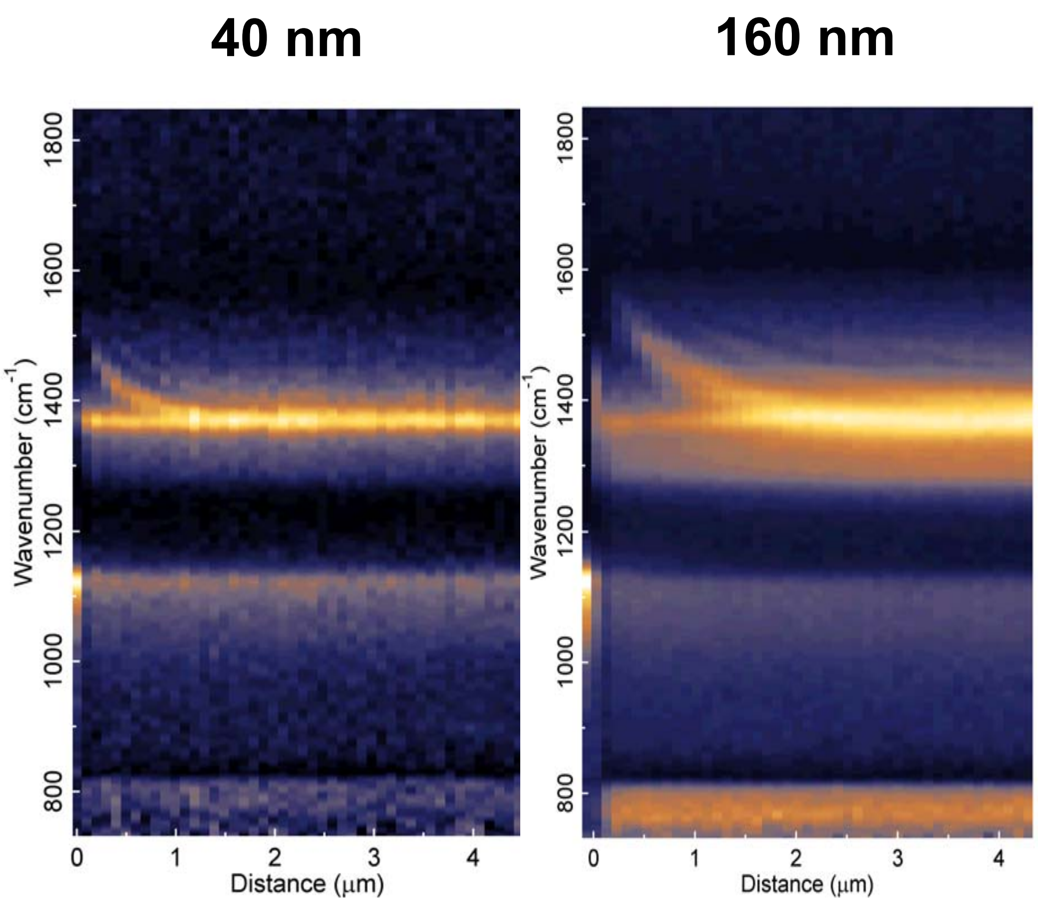
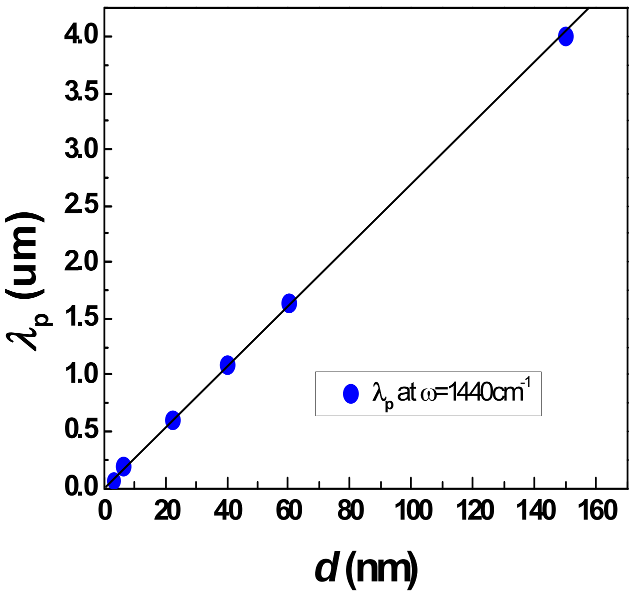
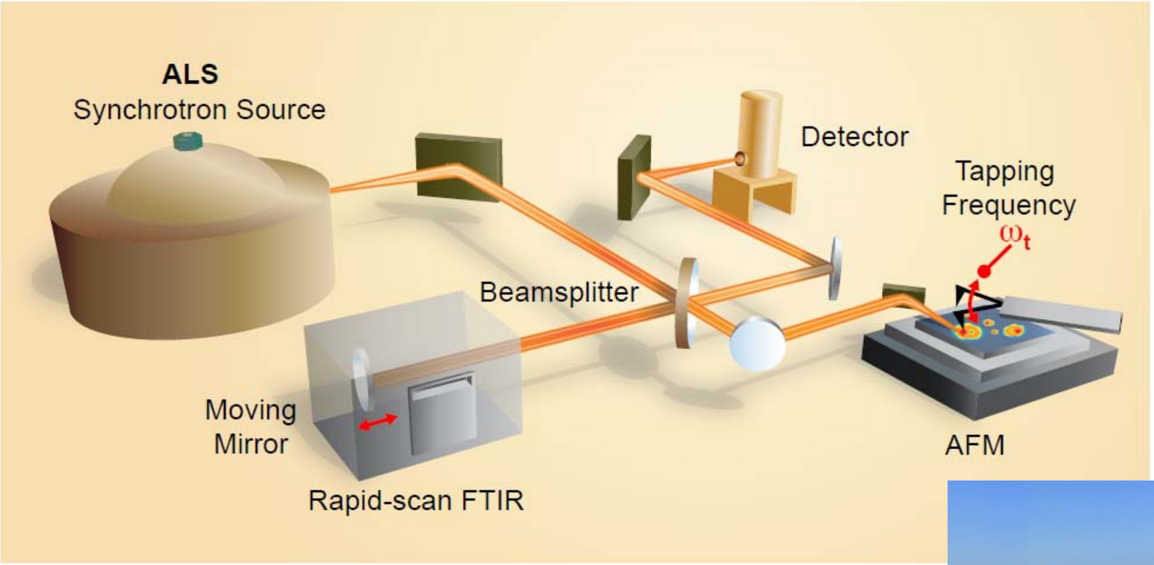


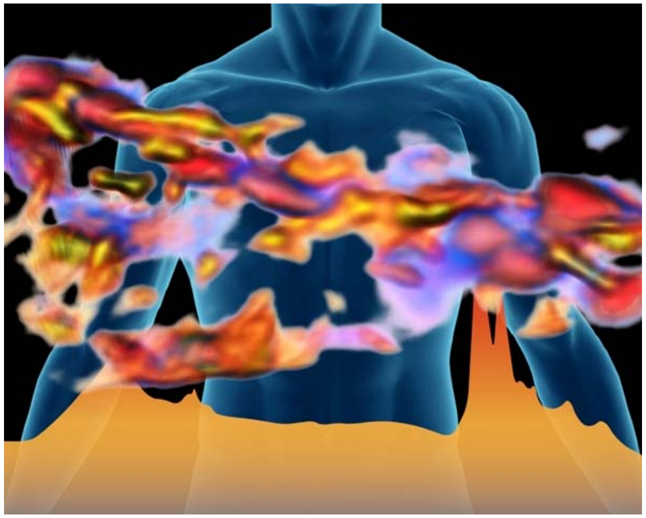


Summary

Exciting new directions for synchrotron infrared science.



Synchrotron Infrared Nano-Spectroscopy



3D FTIR Tomography