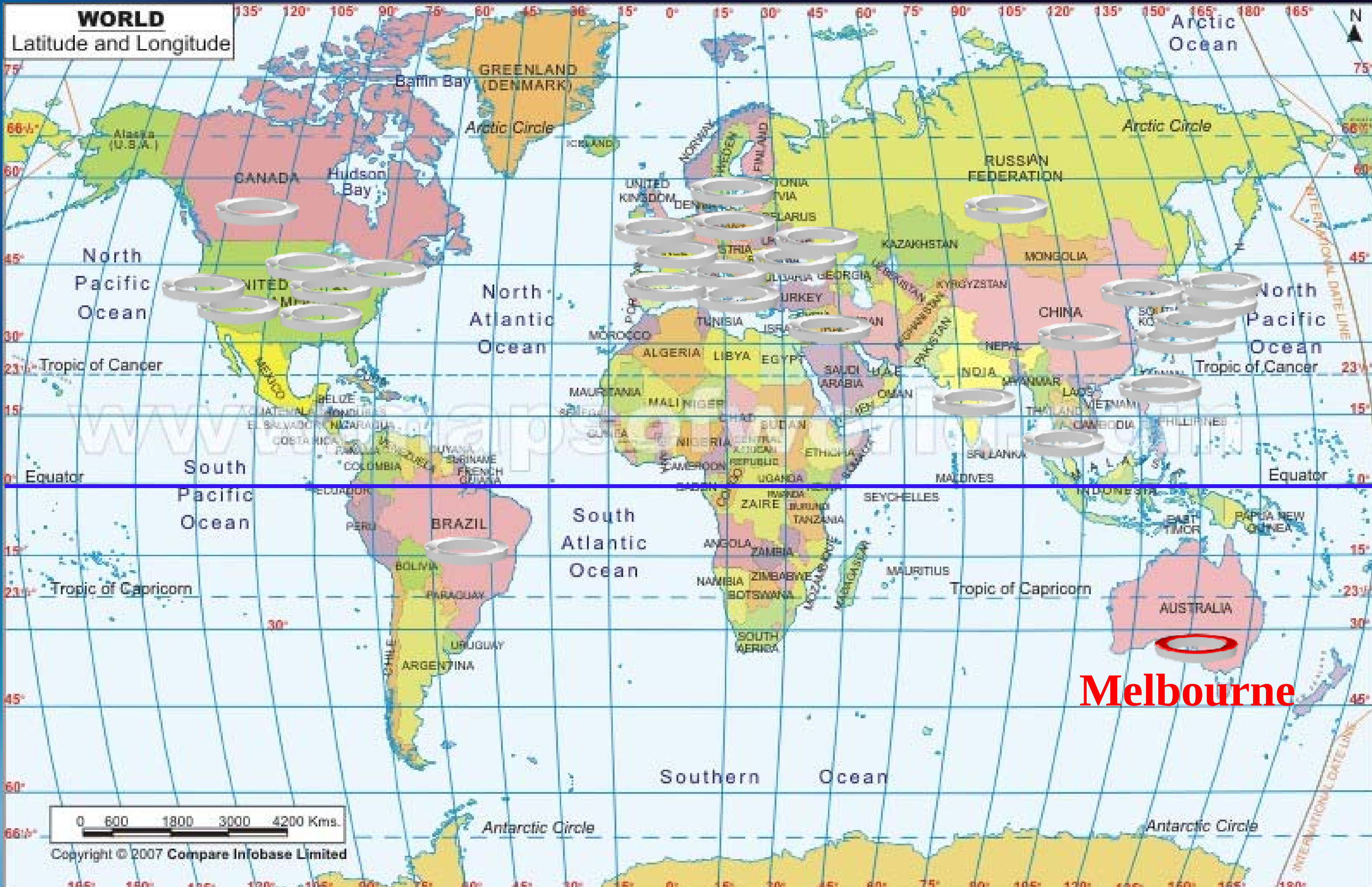
Far-IR/THz & High Spectral Resolution Spectroscopy Using Synchrotron Radiation

Dominique Appadoo
Senior IR Beamline Scientist


WORLD
Latitude and Longitude
Melbourne
North Pacific Ocean
North Atlantic Ocean
South Pacific Ocean
South Atlantic Ocean
Southern Ocean
Arctic Ocean
Tropic of Cancer
Tropic of Capricorn
Equator
Arctic Circle
Antarctic Circle
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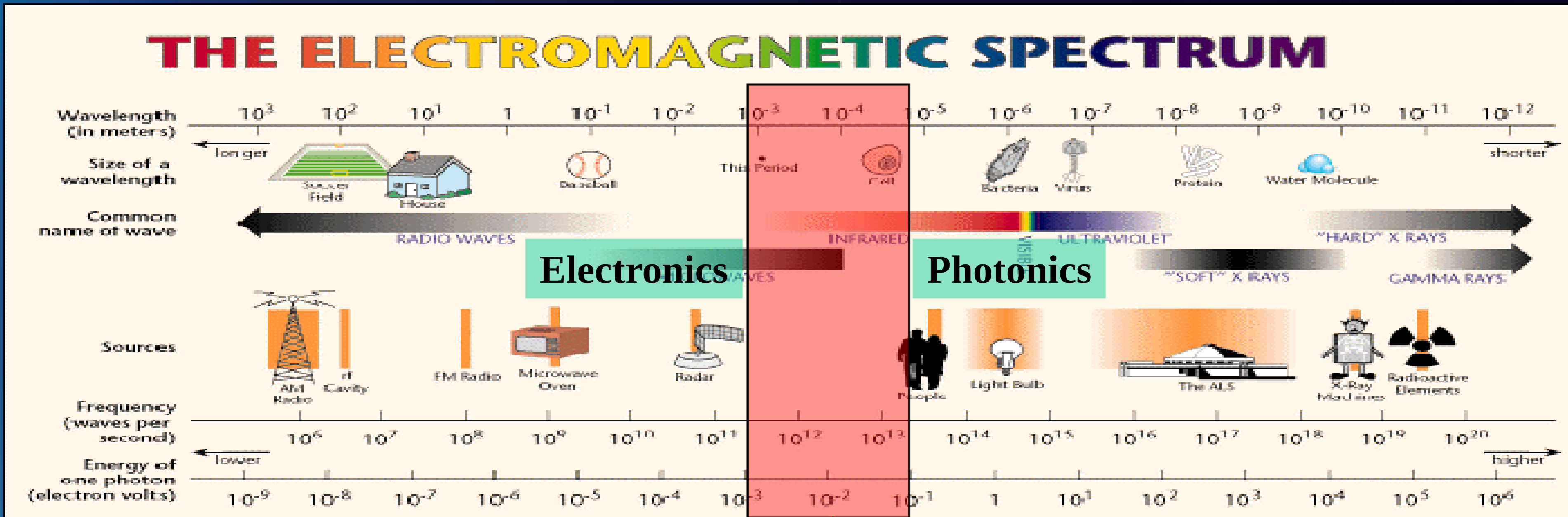
Infrared beamlines worldwide

	Number of beamlines	Purpose	Status
North America			
ALS Berkley	1	Microscopy and **Far-IR**	Operational
CAMD Baton Rouge	1	Microscopy	Planned
CLS Saskatoon	2	1 Microscopy, 1 **Far-IR**	Operational
NSLS Brookhaven	6	3 Microscopy, 2 **Far-IR**, 1 THz	Operational
Surf III Gaithersburg	1	Microscopy	Planned
SRC Madison	1	Microscopy	Operational
Asia and Australia			
Australian Synchrotron	1	Microscopy and **Far-IR**	Operational
INDUS I, India	1	Microscopy	Planned
Helios II, Singapore	1	Microscopy and **Far-IR**	Operational
NSRRC, Taiwan	1	Microscopy	Operational
NSRL, Heife	1	Microscopy and Far-IR	Planned
BSRF, Beijing	1	Microscopy	Planned
Spring-8, Himeji	1	Microscopy and **Far-IR**	Operational
UVSOR, Okazaki	1	**Far-IR**	Operational
Europe			
ESRF, Grenoble	1	Microscopy	Operational
Soleil, St. Aubin	2	1 Microscopy, 1 **Far-IR**	Commissioning
ELETTRA, Trieste	1	Microscopy and **Far-IR**	Operational
DAPHNE, Frascati	1	**Far-IR**	Operational
SLS, Villigen	1	Microscopy and **Far-IR**	Commissioning
ANKA, Karlsruhe	1	Microscopy and **Far-IR**	Operational
BESSY II, Berlin	1	Microscopy and **Far-IR**	Operational
DELTA, Dortmund	1	Microscopy	Planned
MAX II, Lund	2	Microscopy and **Far-IR**	operational
DIAMOND, Didcot	1	Microscopy	Planned

32 IR Beamlines

The far-IR/THz spectral region



THz Energy Gap

λ = 1000 – 10 µm

$\bar{\nu}$ = 10 – 1000 cm^{-1}

ν = 0.3 – 30 THz

E = 1 – 124 mEV

Far-IR/THz ≡ XSX

→ eXtremely Soft X-ray

- lack of adequate tunable lasers
- weakness of conventional thermal sources
- difficulties with far-IR detectors

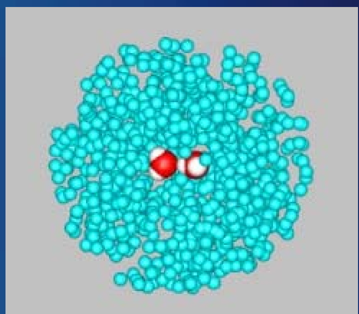
www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html

The Final Frontier

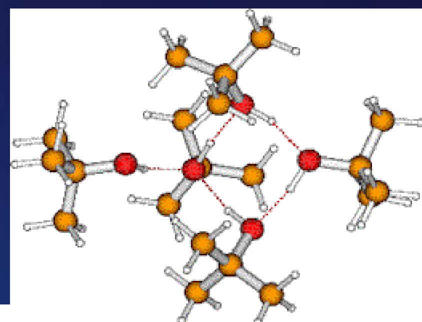
- cw & pulsed THz lasers are now available
- Backward-wave oscillators
- Accelerator-based sources …

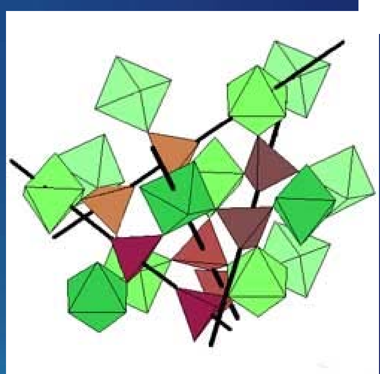
What kind of interactions take place in the far-IR?

van der Waals energies

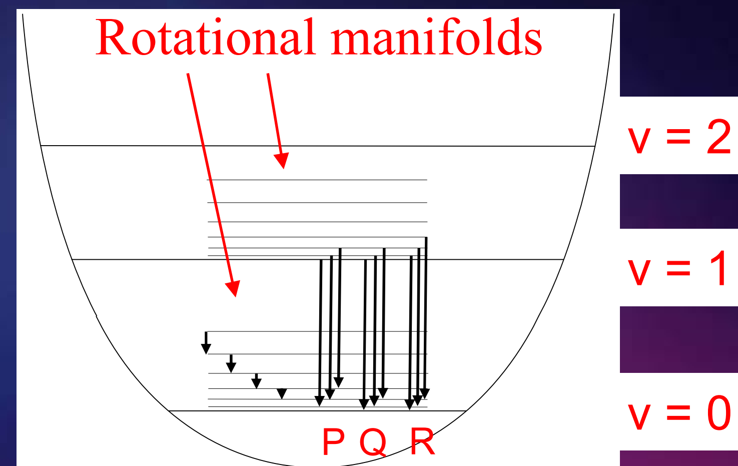


H-bonding





phonon modes



- rotation of smaller molecules
- ro-vibration of larger molecules

- surface/adsorbate interactions
- biological processes
- chemical dynamics

What can we learn from these interactions?

- How does energy flow within a molecule?
- What is the nature of the weak attractive forces that exist among atoms and molecules?
- How do metal atoms bond to other chemical groups?
- What are the structures of long carbon chain molecules?
- How do the optical properties of a material change under ultra-high pressures?

... this is just the beginning!

Overview

I. IR Spectroscopy

II. Synchrotron IR Radiation

III. The IR Beamline at the Australian Synchrotron

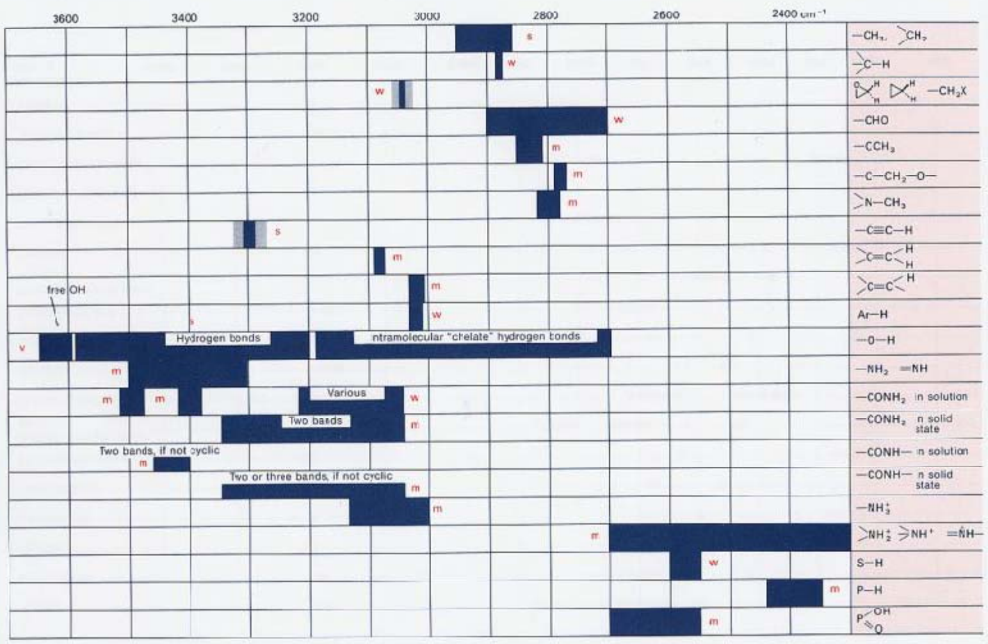
IV. FT Spectroscopy

V. Applications of Far-IR & High Resolution Synchrotron Spectroscopy

VI. Coherent Synchrotron Radiation

I. Introduction to IR spectroscopy

Fingerprint spectral region

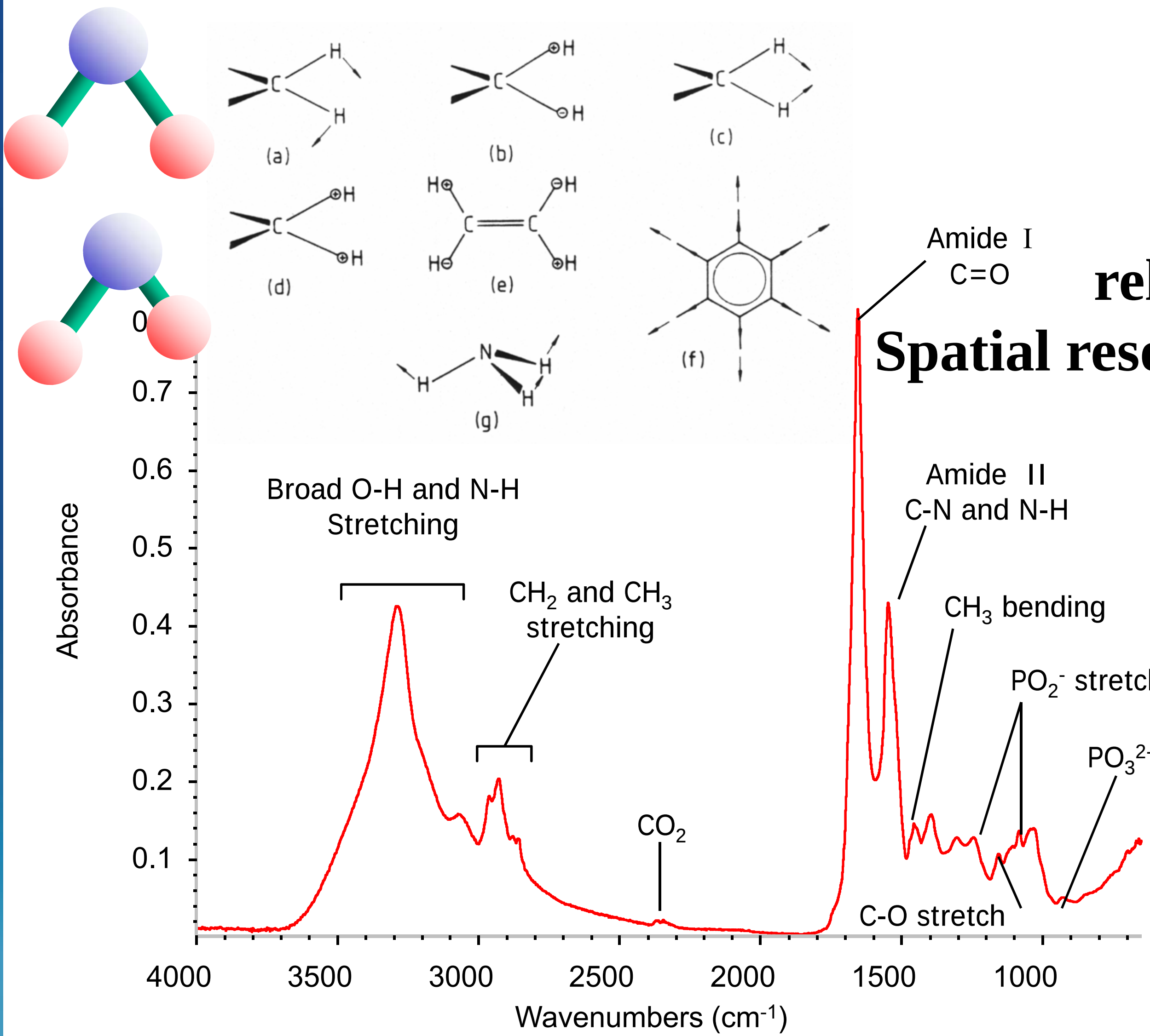


Positions of Stretching Vibrations of Hydrogen (in the hatched ranges the boundaries are not well defined);
Band intensity: s = strong, m = medium, w = weak, v = varying.

Characteristic Absorptions in the Fingerprint Region (s = strong, m = medium, w = weak)

http://www.brukeroptics.com/downloads.html

IR spectroscopy of condensed samples: Vibrational Spectroscopy → spatial resolution



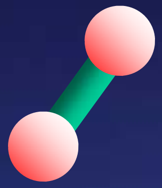
ν-shifts

relative intensities

Spatial resolution required

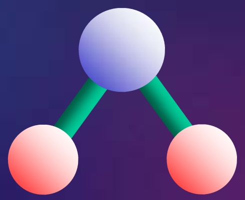
IR spectroscopy of gas-phase samples: Ro-Vibrational Spectroscopy → Spectral Resolution

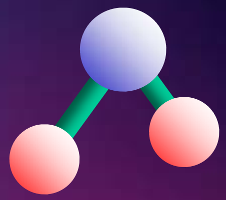
Diatomic molecules



Polyatomic molecules: linear 3N-5 modes

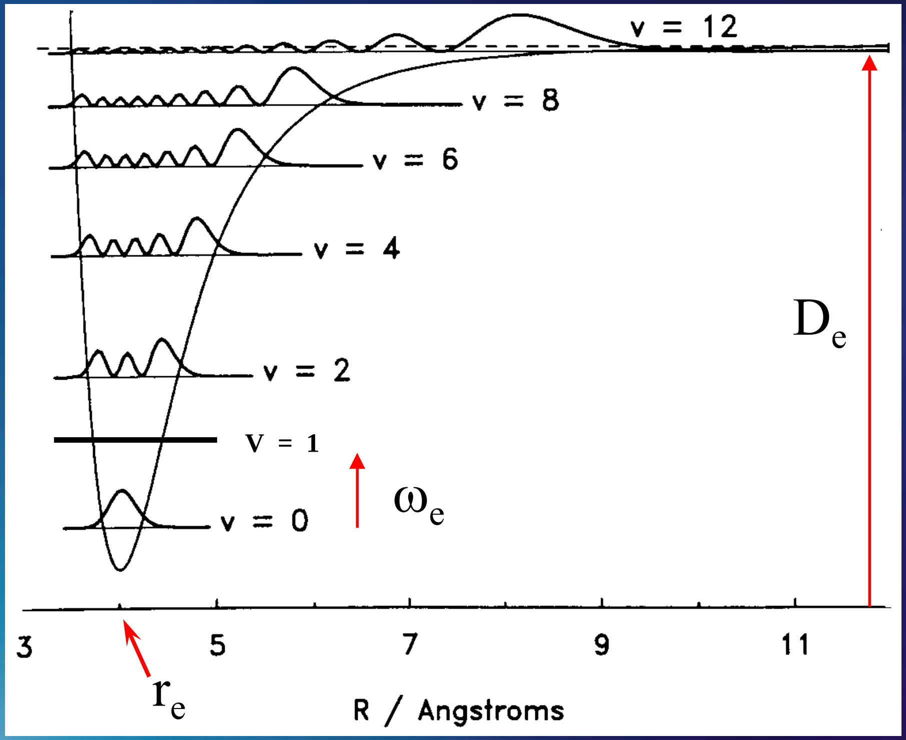
non-linear 3N-6 modes

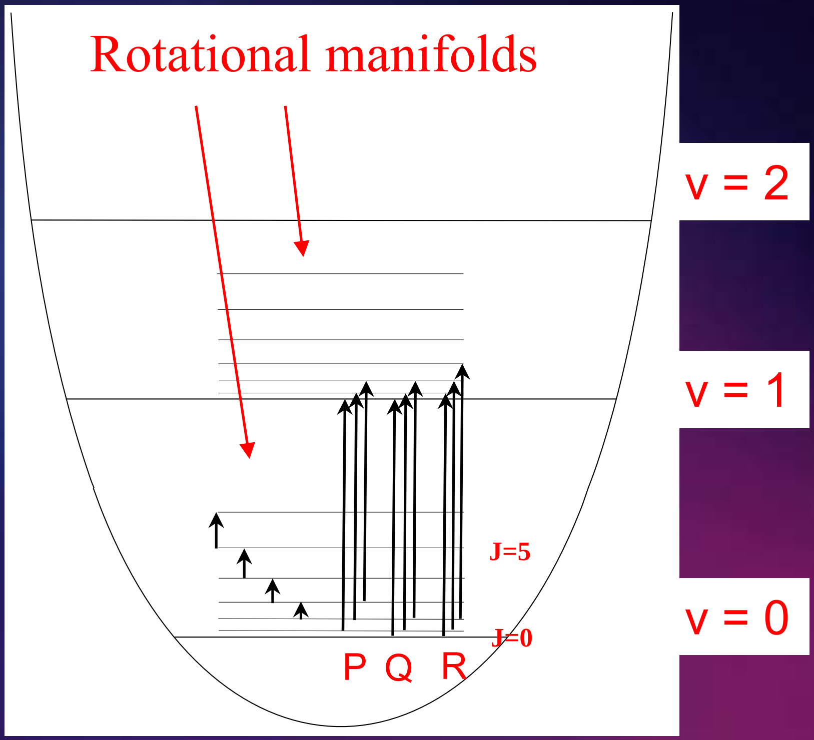




Potential energy curve of a diatomic molecule in its ground electronic state.

Manifold of rotational states within each vibrational level





Diatomic Model

$E(v,J) = T_e + G(v) + F_v(J)$

where

$G(v) = \omega_e(v+ ½) – \omega_e x_e(v+ ½)^2 + \omega_e y_e (v+ ½)^3 + …$

$F_v(J) = B_v J(J+1) – D_v (J(J+1))^2 + H_v (J(J+1))^3 + …$

where

$B_v = B_e – \alpha_e(v+ ½) + \beta_e(v+ ½)^2 + …$

$B_e \ \alpha \ 1/\mu r_e^2$

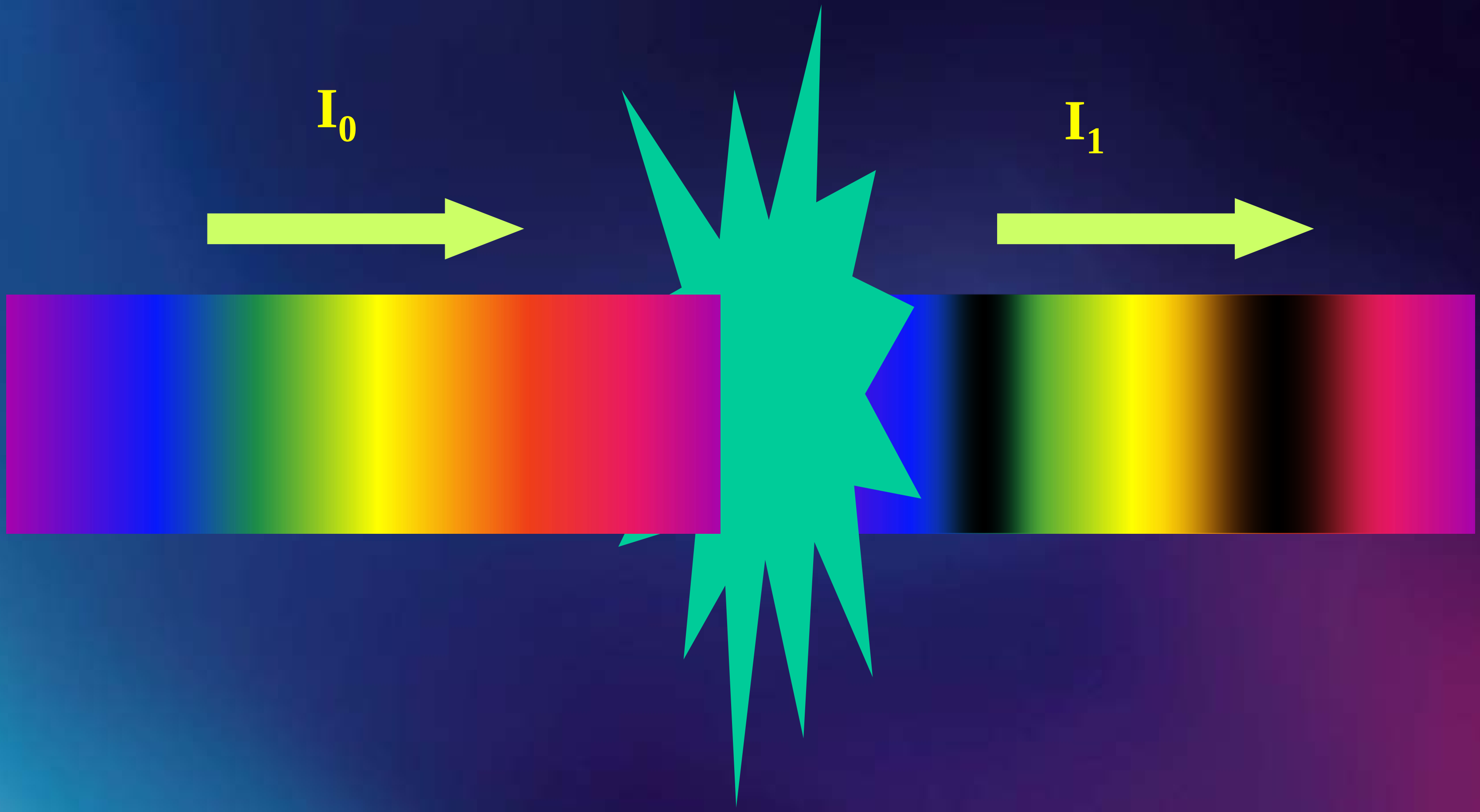
$D_e \sim \sum_{V=0} \Delta G_v$

ω_e is the fundamental frequency ($\alpha \ \mu^{-1/2}$)

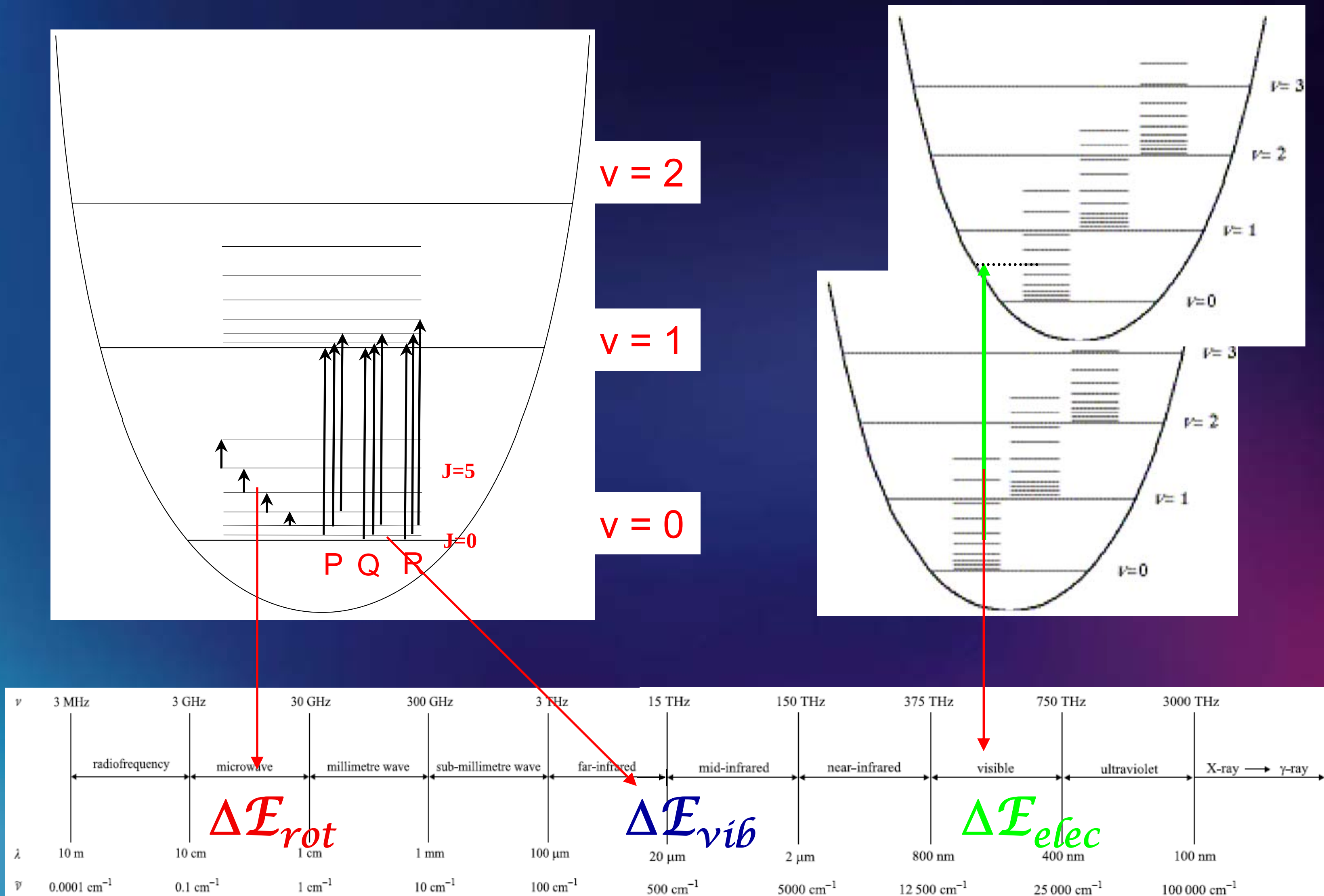
r_e is the bond length

D_e is the dissociation energy

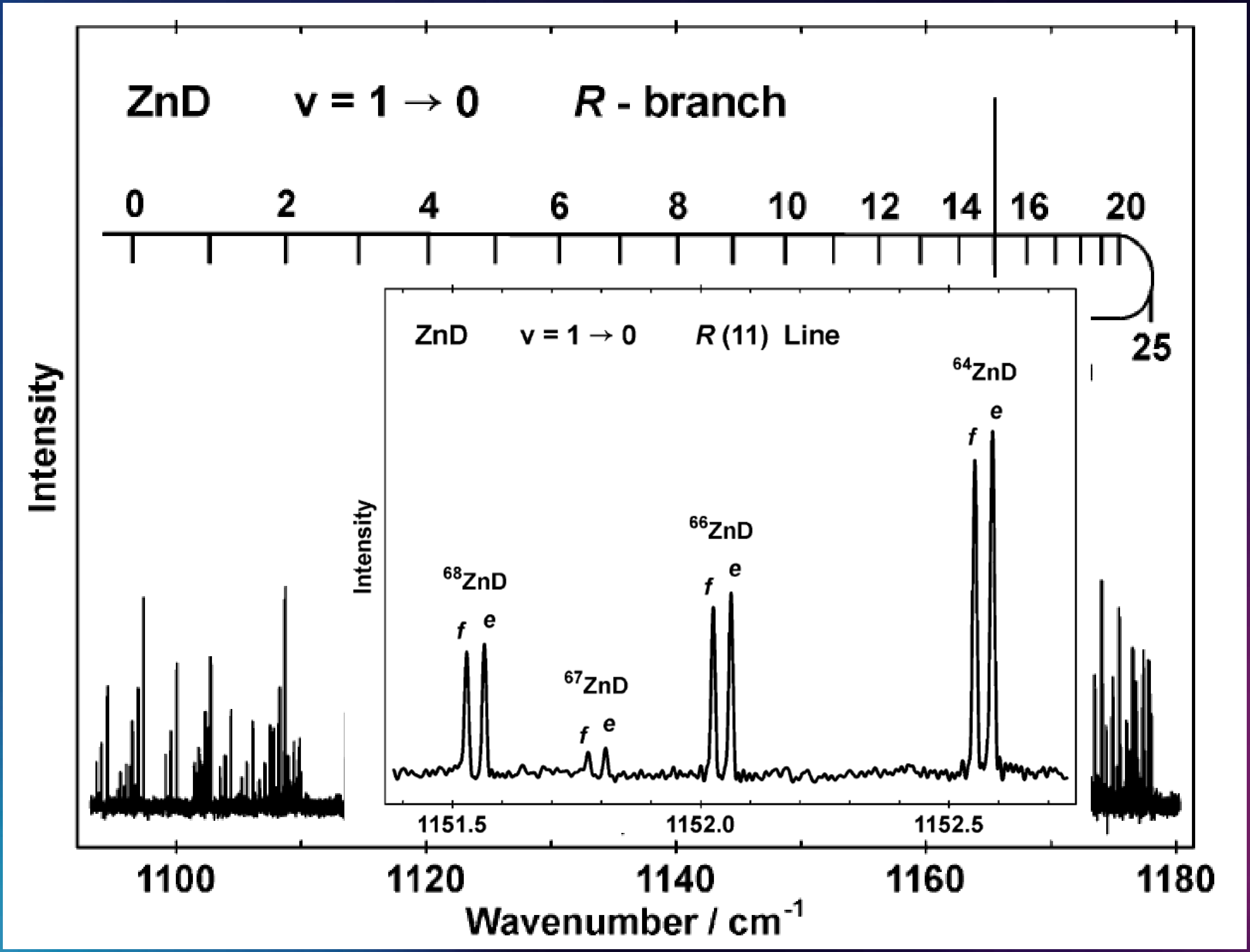
Absorption Spectroscopy…



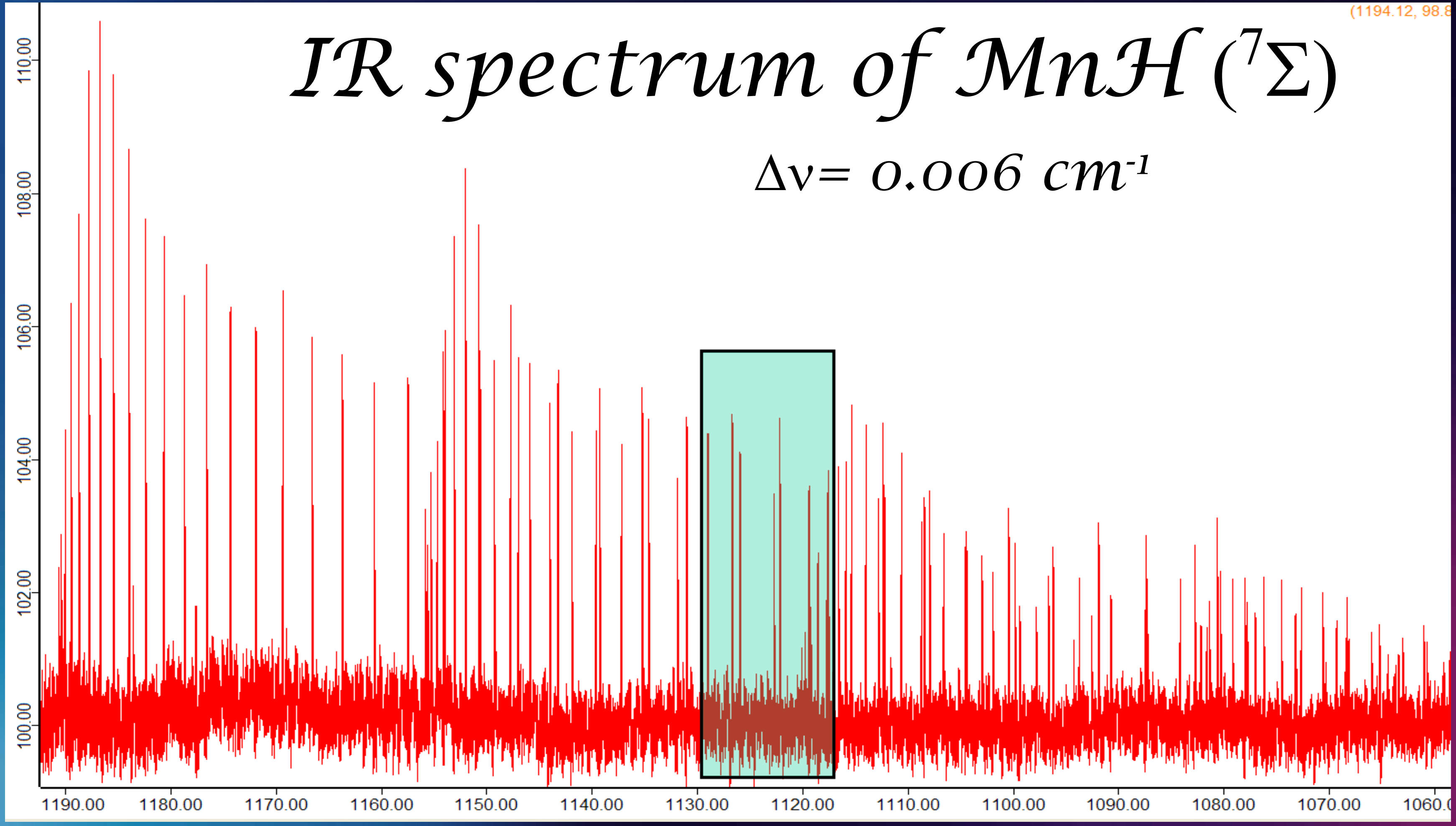
Rotational, vibrational and electronic Transitions



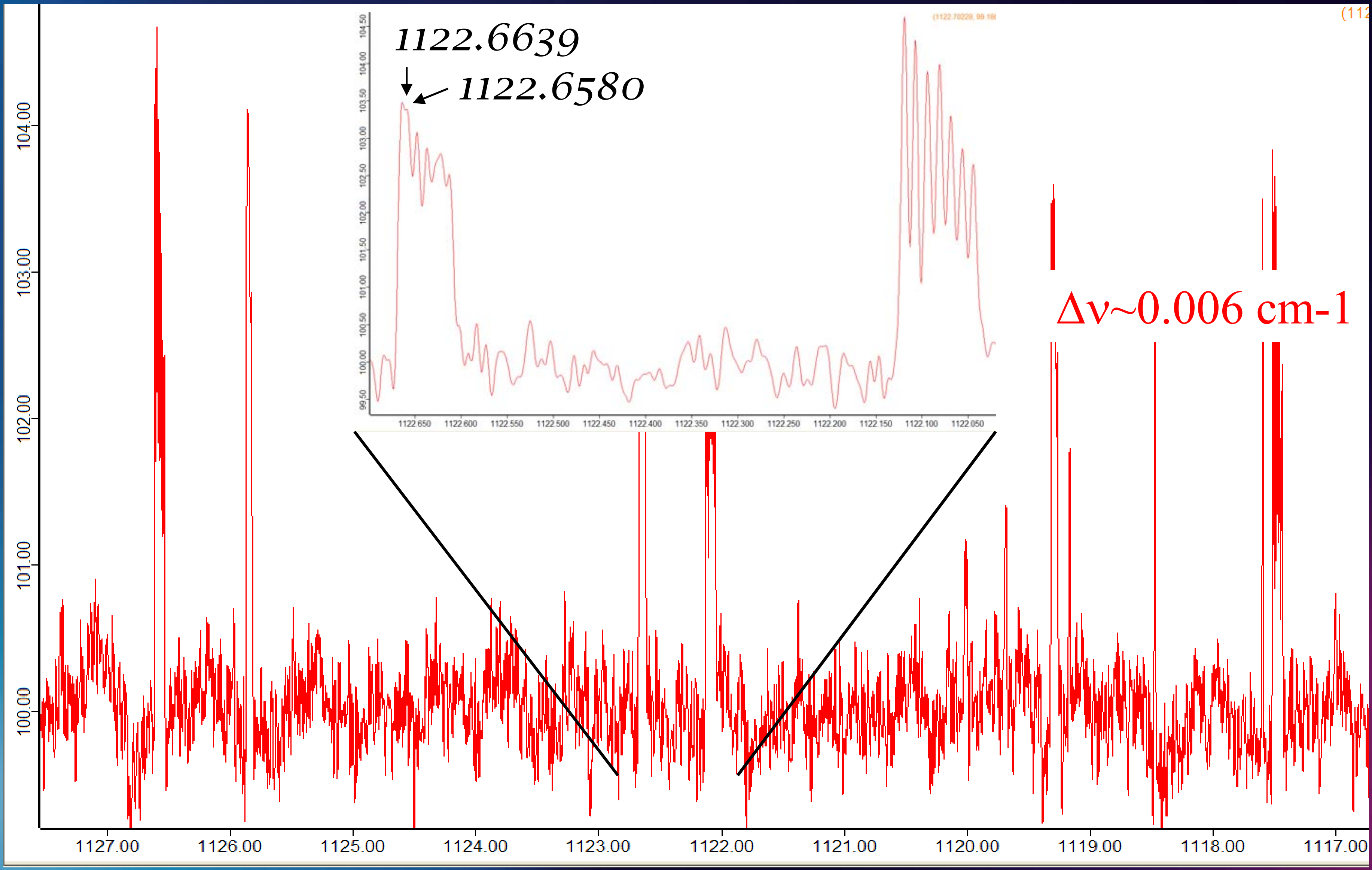
IR emission spectrum of ZnD ($^2\Sigma$)



Life can get complicated even for diatomics



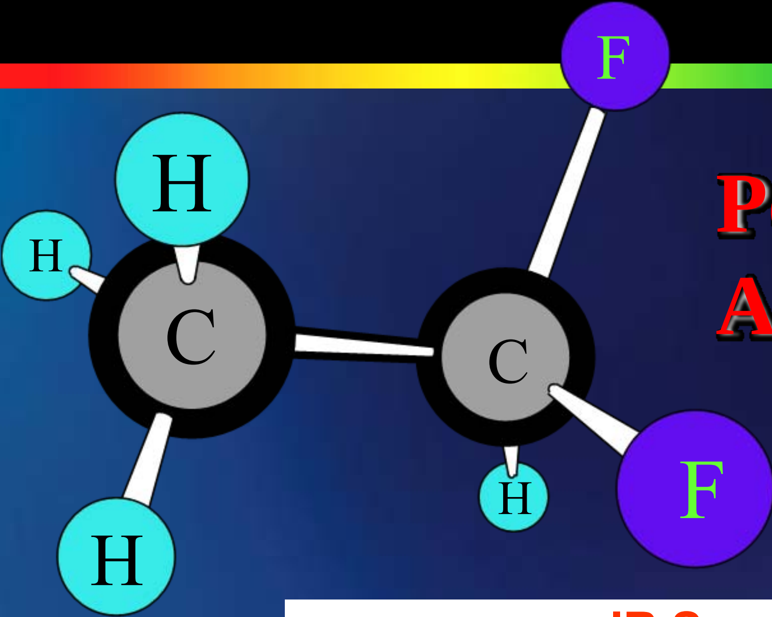
IR spectrum of MnH ($^7\Sigma$)



Simply put, spectra for diatomic molecules can be complicated and congested!

- Heavy molecules: closely-spaced transitions, overlapping bands, and narrow linewidths
- Presence of naturally occurring isotopomers in measurable quantities
- High-spin electronic states due to open-shells: spin-splitting

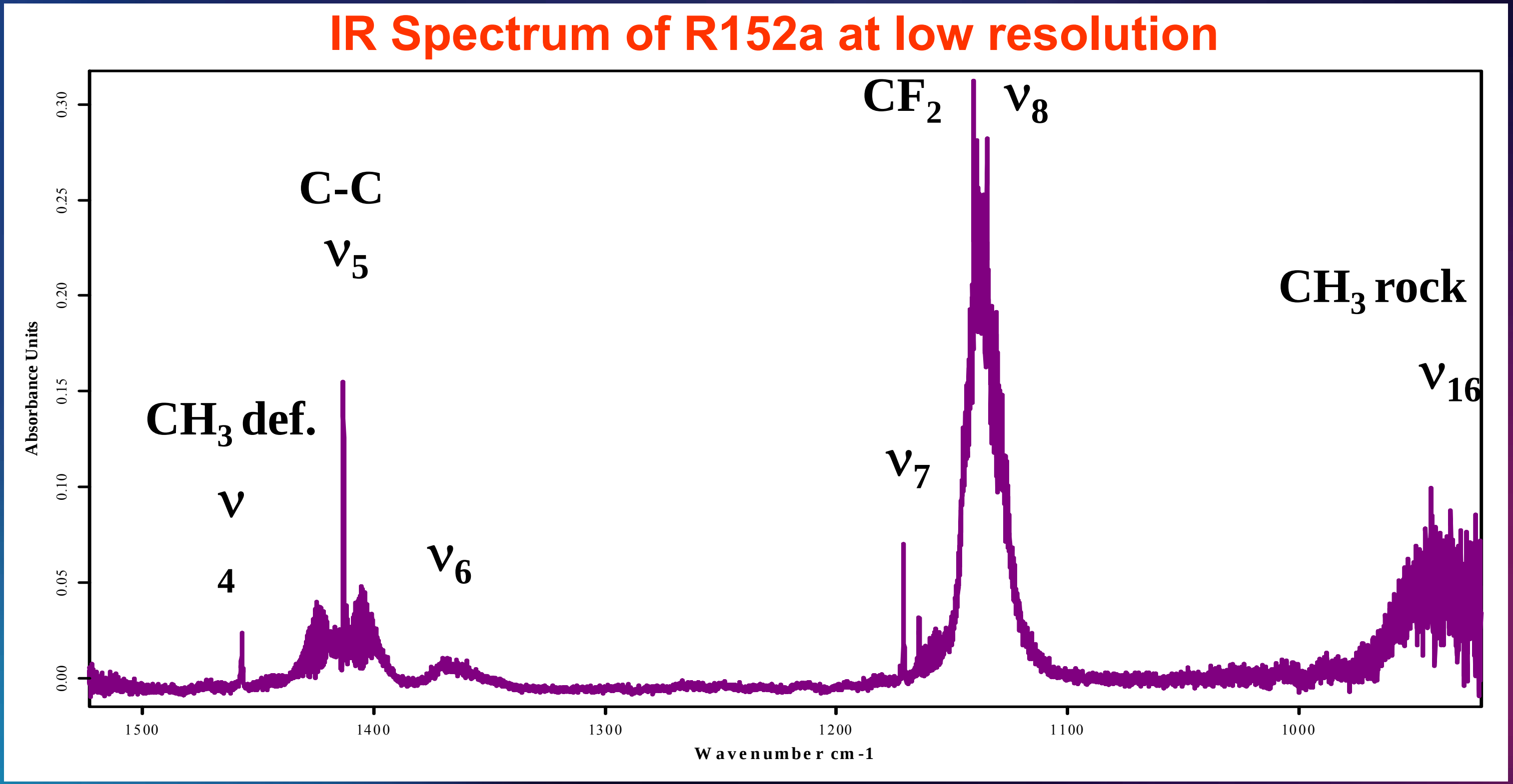
… Need high spectral resolution!



Polyatomics: Asymmetric Top Molecule

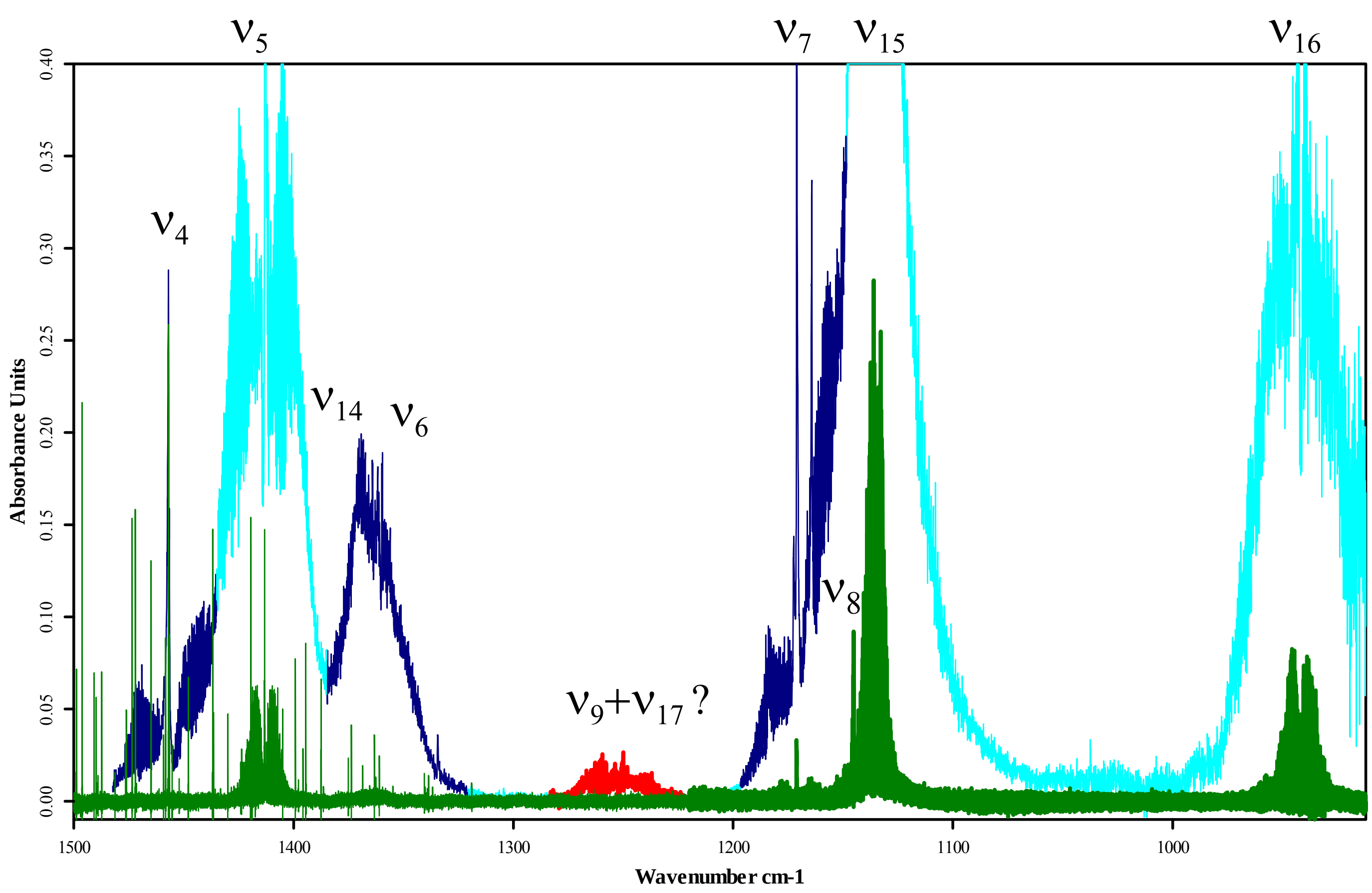
Normal modes of vibration of R152a

3N-6 modes where N=8 ≡ 18 modes



Australian Synchrotron

Part of the IR spectrum of R152a



Low resolution EFC spectrum

Asymmetric Rotor Model

$\langle v{:}J,K|H|\, v{:}J,K\rangle = v + \bar{B}\, J(J+1) + (A - \bar{B})\, K^2$

$- \Delta_{JJ}\, [J(J+1)]^2 - \Delta_{JK}\, J(J+1)\, K^2 - \Delta_{KK}\, K^4$

$+ \Phi_{JJJ}\, [J(J+1)]^3 + \Phi_{JJK}\, [J(J+1)]^2\, K^2 + \Phi_{JKK}\, [J(J+1)]\, K^4 + \Phi_{KKK}\, K^6$

$- \Lambda_{JJJJ}\, [J(J+1)]^4 - \Lambda_{JJJK}\, [J(J+1)]^3\, K^2 - \Lambda_{JJKK}\, [J(J+1)]^2\, K^4 - \Lambda_{JKKK}\, J(J+1)\, K^6 - \Lambda_{KKKK}\, K^8 \quad \ldots.$

$\langle v{:}J,K|H|\, v{:}J,K \pm 2\rangle = [\, \tfrac{1}{2}\bar{B} - \delta_J J(J+1) - \delta_K \{(K \pm 2)^2 + K^2\}$

$+ \phi_{JJ}\, [J(J+1)]^2 + 1/2\phi_{JK}\, [J(J+1)]\, \{(K \pm 2)^2 + K^2\} + 1/2\phi_{KK}\, \{(K \pm 2)^4 + K^4\}$

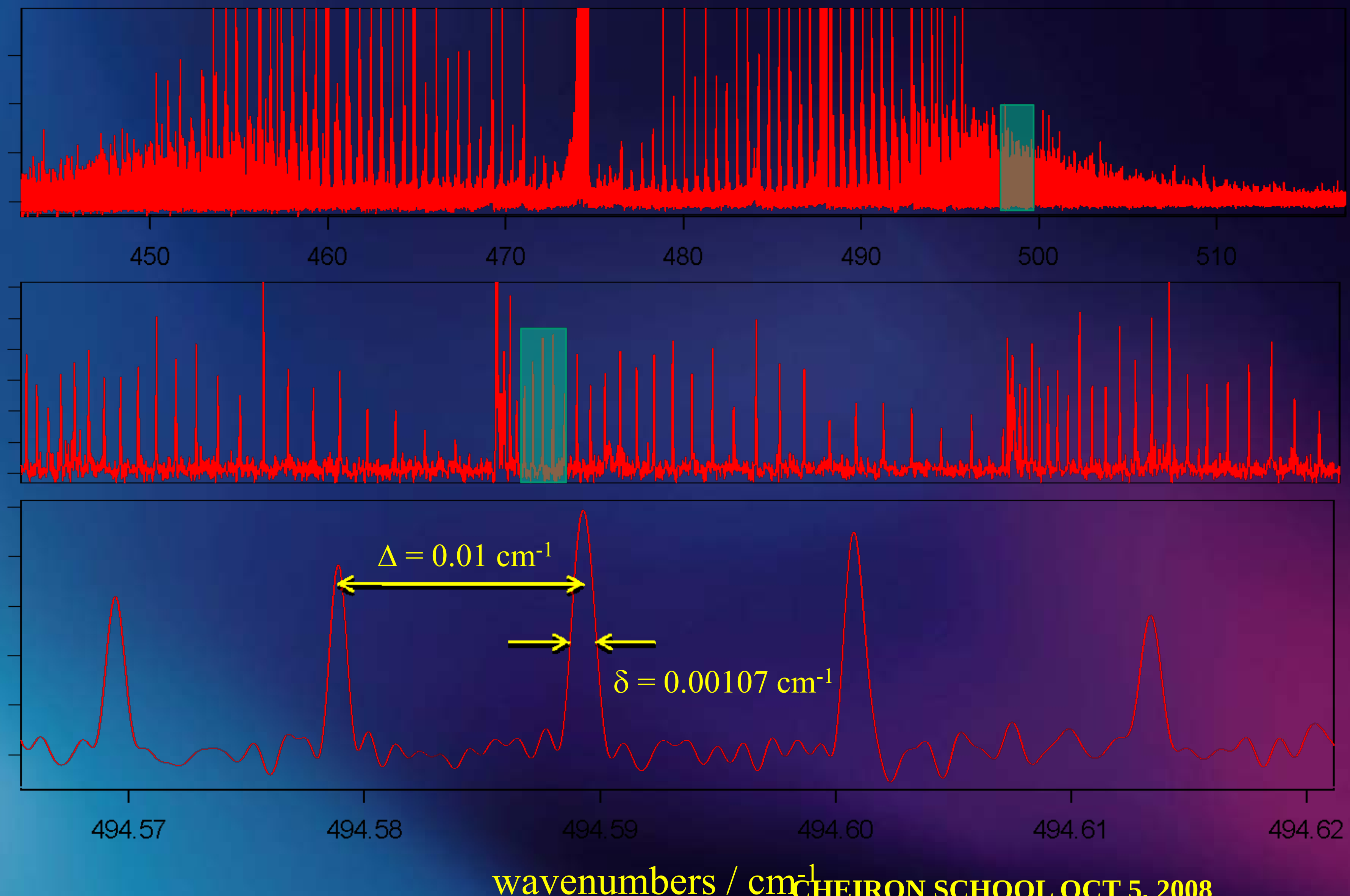
$- \lambda_{JJJ}\, [J(J+1)]^3 - \lambda_{JJK}\, [J(J+1)]^2\, \{(K \pm 2)^2 + K^2\} - \lambda_{JKK}\, [J(J+1)]\, \{(K \pm 2)^4 + K^4\}$

$- \lambda_{KKK}\, \{(K \pm 2)^6 + K^6\} \ldots\,]\; F_{\pm}(J,K)\, F_{\pm}(J,K \pm 1)$

where $F_{\pm}(J,K) = \{\, J(J+1) - K(K \pm 1)\, \}^{1/2}$

$\bar{B} = 1/2\, (B-C)$

Pyrrole at 0.00096 cm^{-1} (~0.1 μeV)



Spectroscopic issues to contend with

- Overlapping & Hot bands
- Coupling of vibrational modes: Coriolis and Fermi resonnances
- Closely spaced lines & Narrow linewidths as the MW increases
- Isotope splitting
- Hyperfine structure

.... Clearly we need **high spectral** resolution in order to resolve these narrow spectral lines!

How high a resolution is required?

Observed Linewidth: $\Delta\nu_{Obs} \sim \sqrt{\Delta\nu_{Dop}^2 + \Delta\nu_{col}^2 + \Delta\nu_{ILW}^2}$

Different factors contribute to the width of an observed transition

Doppler width, $\Delta\nu_D = 2\nu\sqrt{2\ln 2k/c^2}\sqrt{T/M} \sim 7.16E\text{-}7\ \nu\sqrt{T/M}$

Pressure broadening, $\Delta\nu_{col} = 16pr^2/\sqrt{\pi MkT} \sim 3E\text{-}4\ cm^{-1}$ / Torr

Instrument linewidth $\equiv \Delta\nu_{ILW}$ dictated by apodisation function

Therefore, the observed linewidth can be minimised by reducing the Temperature and Pressure!

Spectroscopic issues to contend with

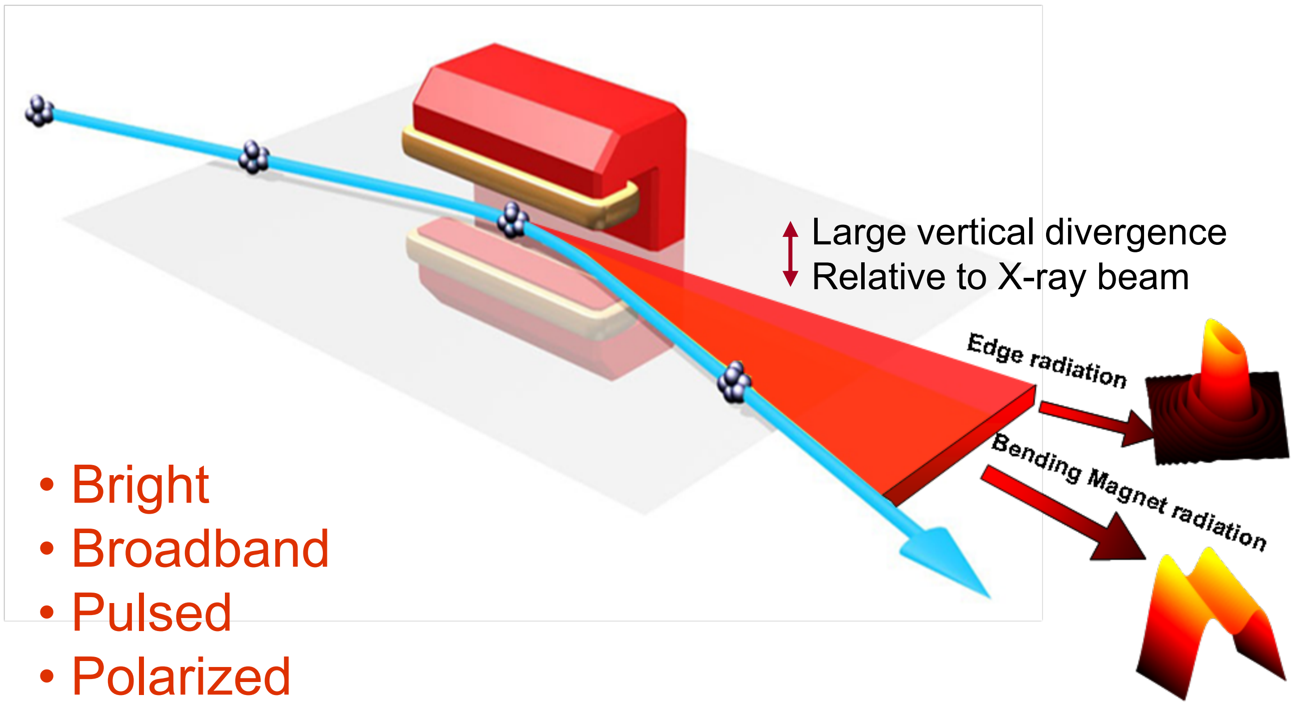
- Small quantity of sample to minimize Pressure broadening effects or hard to synthesize
- Isotopologues with low natural abundance
- Weak absorbers

.... Need **bright source**!

II. SYNCHROTRON INFRARED LIGHT

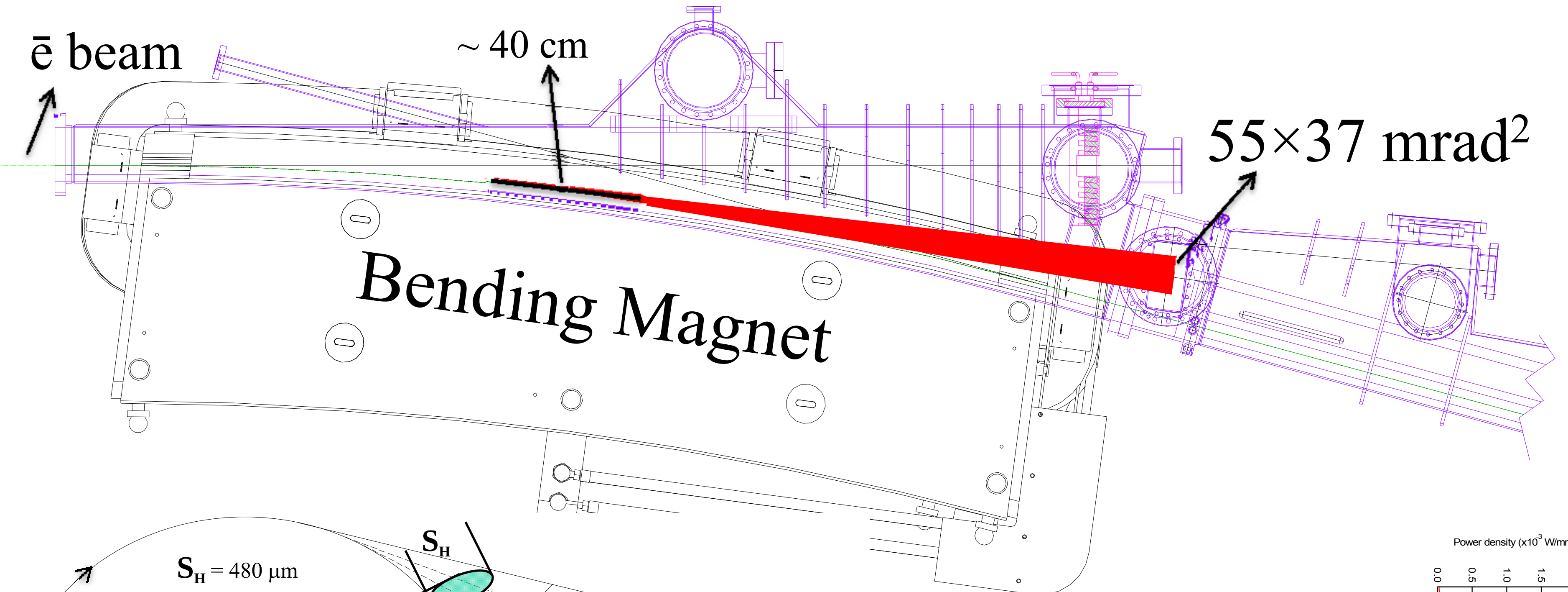
Infrared mission from a synchrotron bending magnet

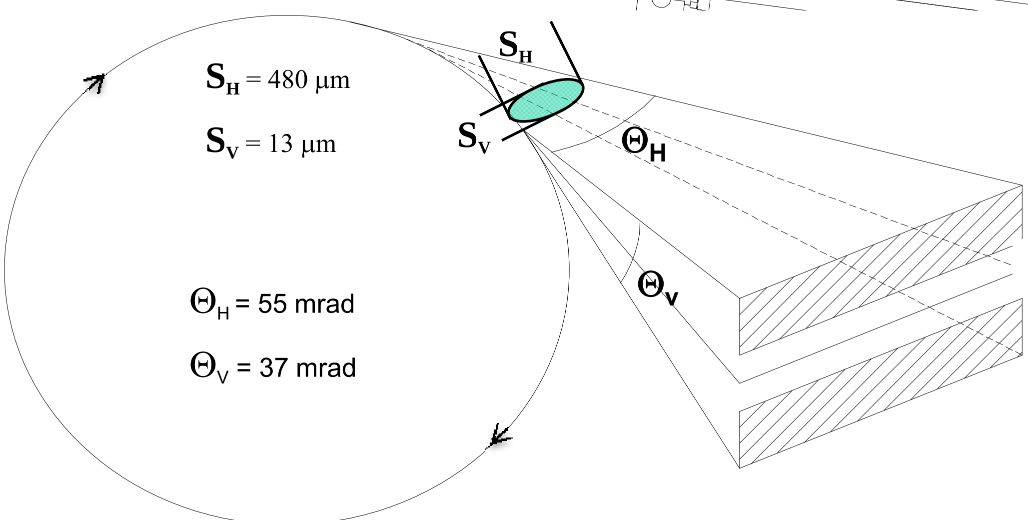
Edge Radiation and Bending Magnet Radiation

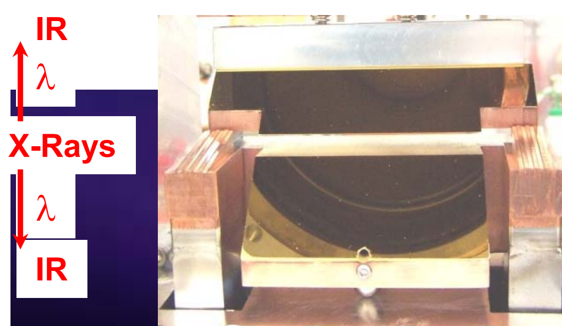


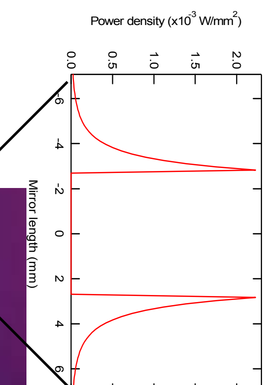
- Bright
- Broadband
- Pulsed
- Polarized

Port 02B1-1 @ CLS: Far-IR

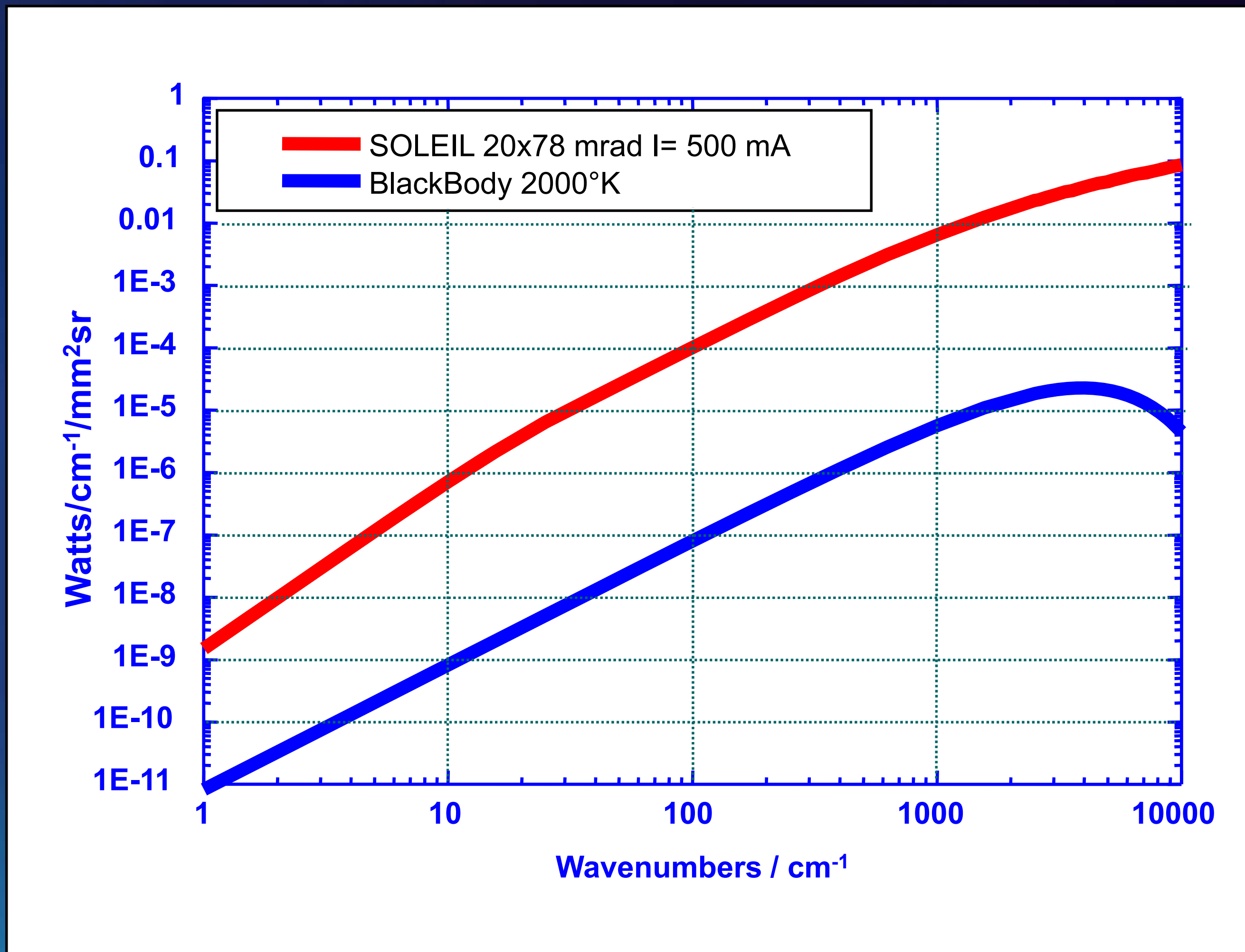








It's the synchrotron brightness that counts



SR Advantages over thermal sources

- Brightness: better S/N
- Small source: better throughput with small samples
- Highly collimated: higher resolution achievable
- Polarized: ellispsometry
- Pulsed: pump & probe experiments

Far-IR SR wavelength limits

- Height of dipole chamber:

$$\lambda_o = 2h\sqrt{h/R}$$

where h is the height of the dipole chamber and R the radius of the bend magnet

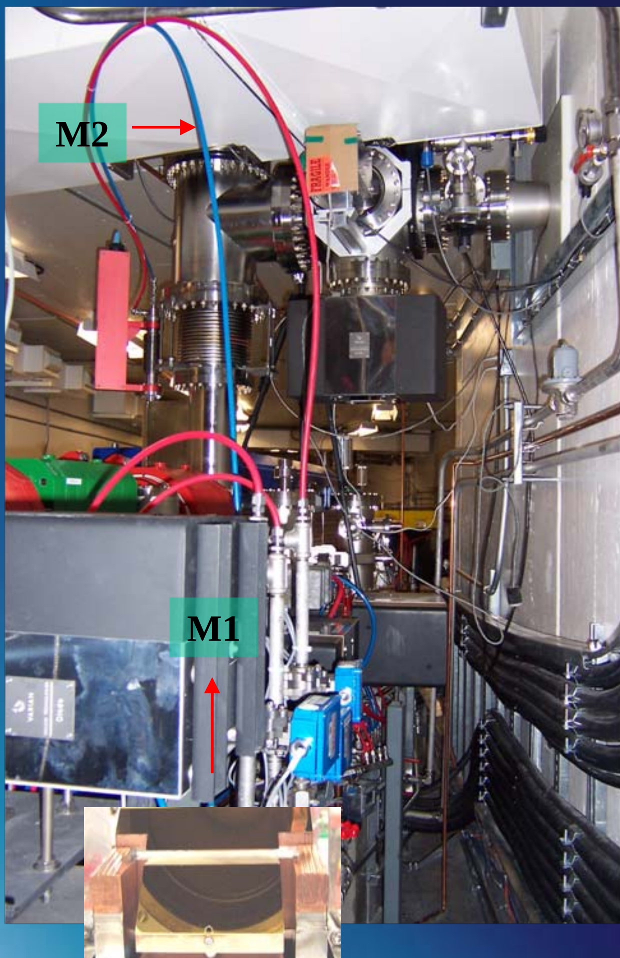
- Extraction aperture:

$$\lambda_c = R(\Theta_{Nat}/1.66188)^3$$

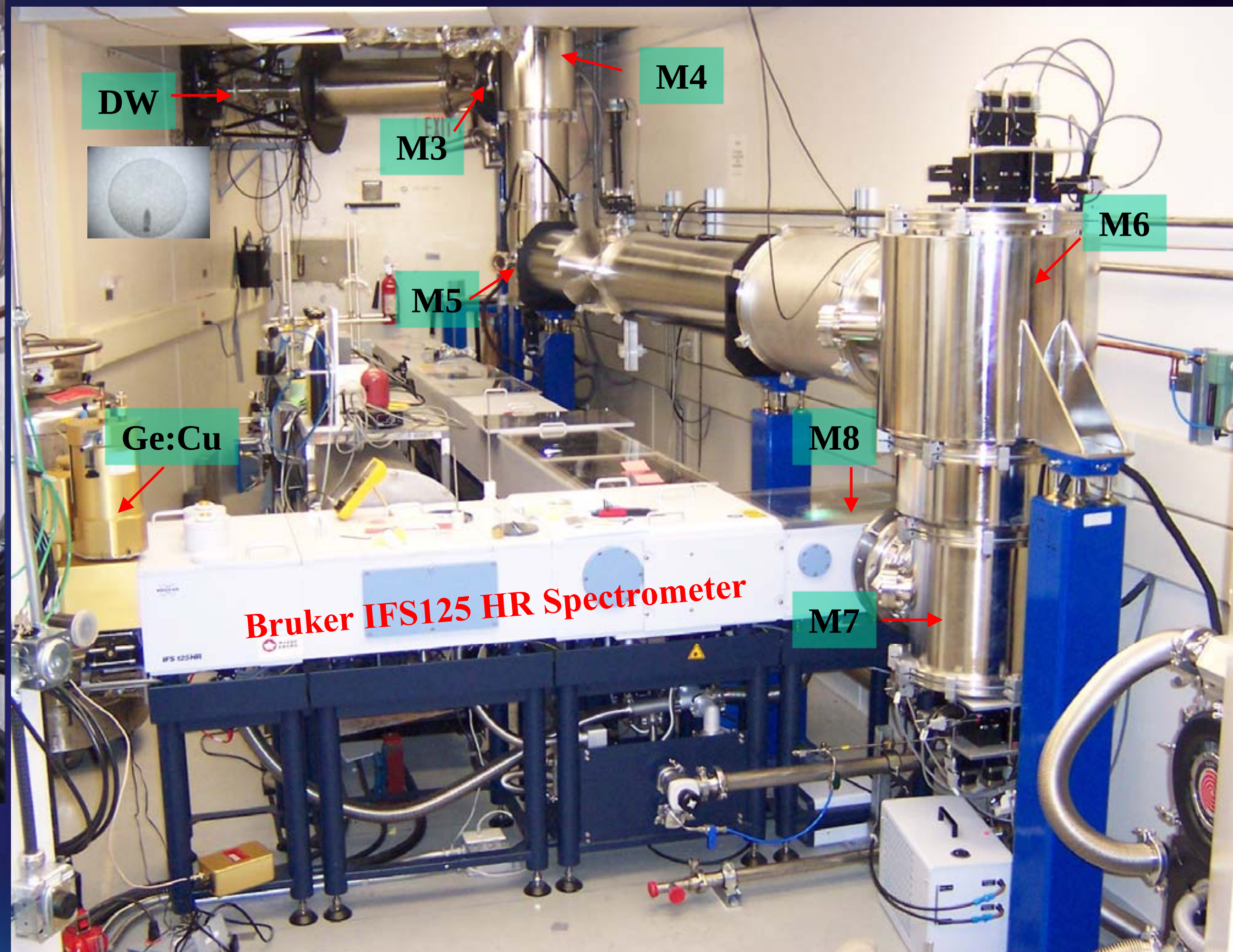
where Θ_{Nat} represents the vertical angle in radians

EXTRACTION OF SYNCHROTRON IR RADIATION

2. Mirror M1 inserted into dipole "crotch" from above or belov

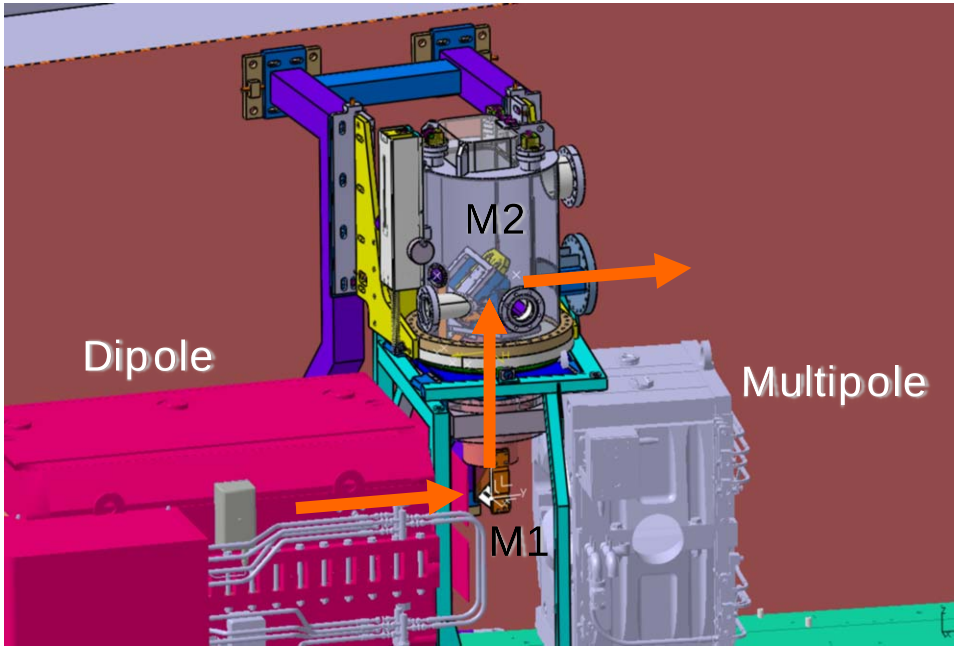


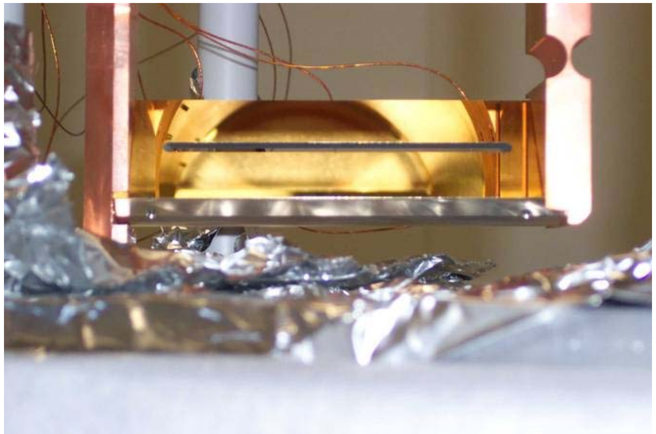
Optical Layout at the CLS



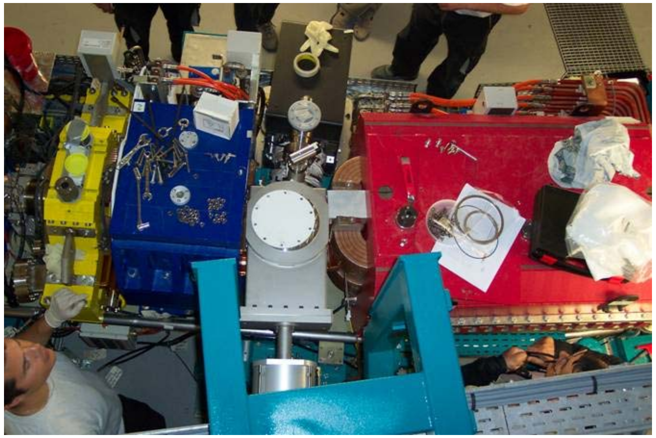
2. Mirror M1 inserted into dipole "crotch" from above or below

e.g. Soleil, ESRF…





M1 Mirror with thermocouple wires

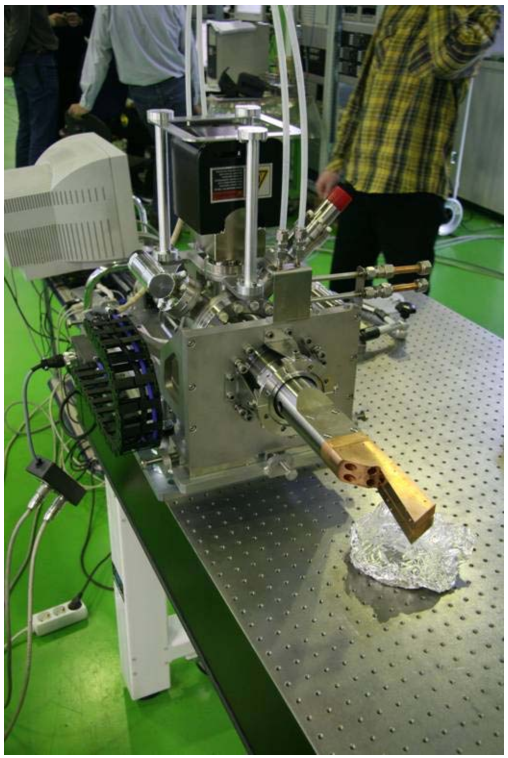


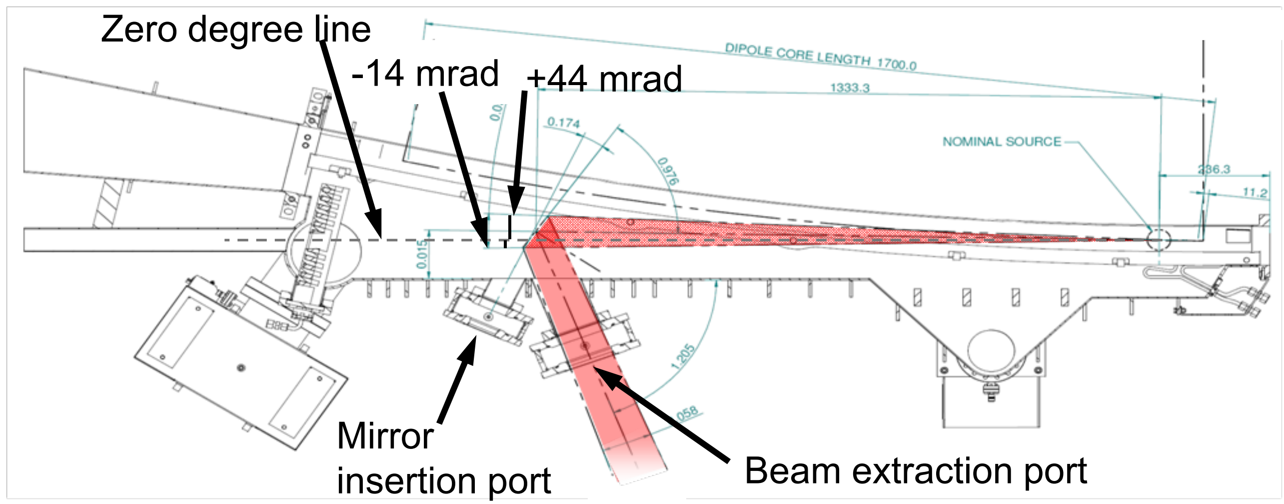
Top view of mirror insertion port

Images courtesy of Paul Dumas, Soleil.

3. Mirror inserted into dipole chamber from side

e.g. Australian Synchrotron

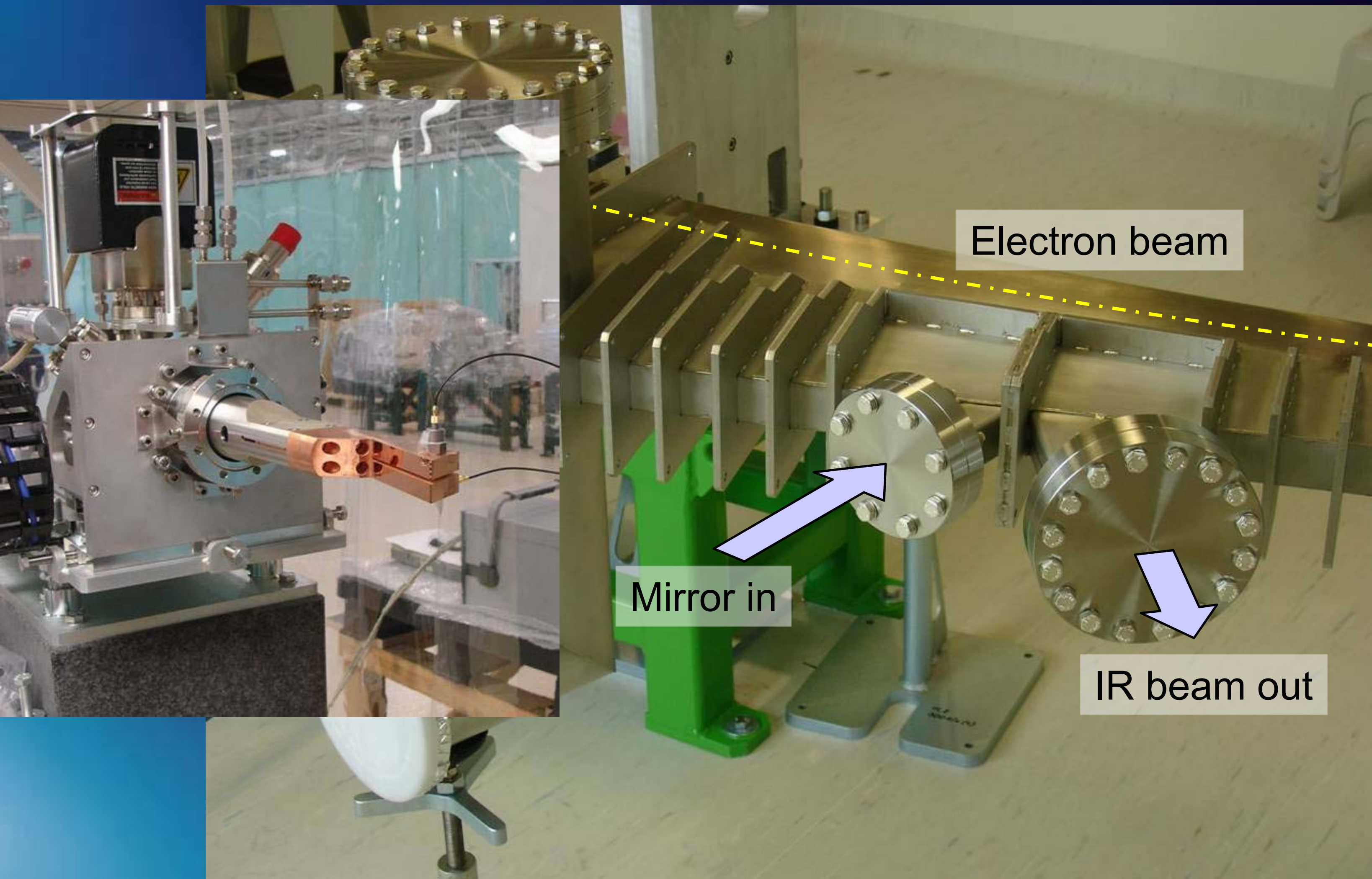


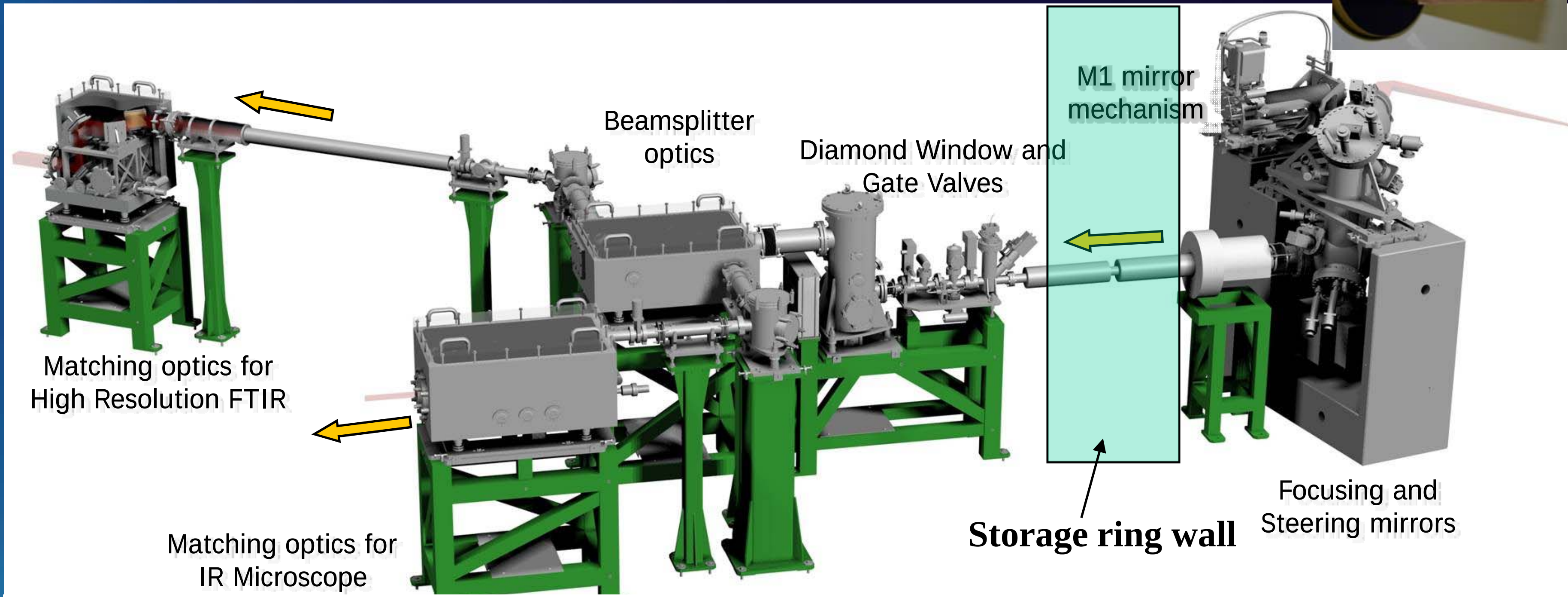


Which brings us to…

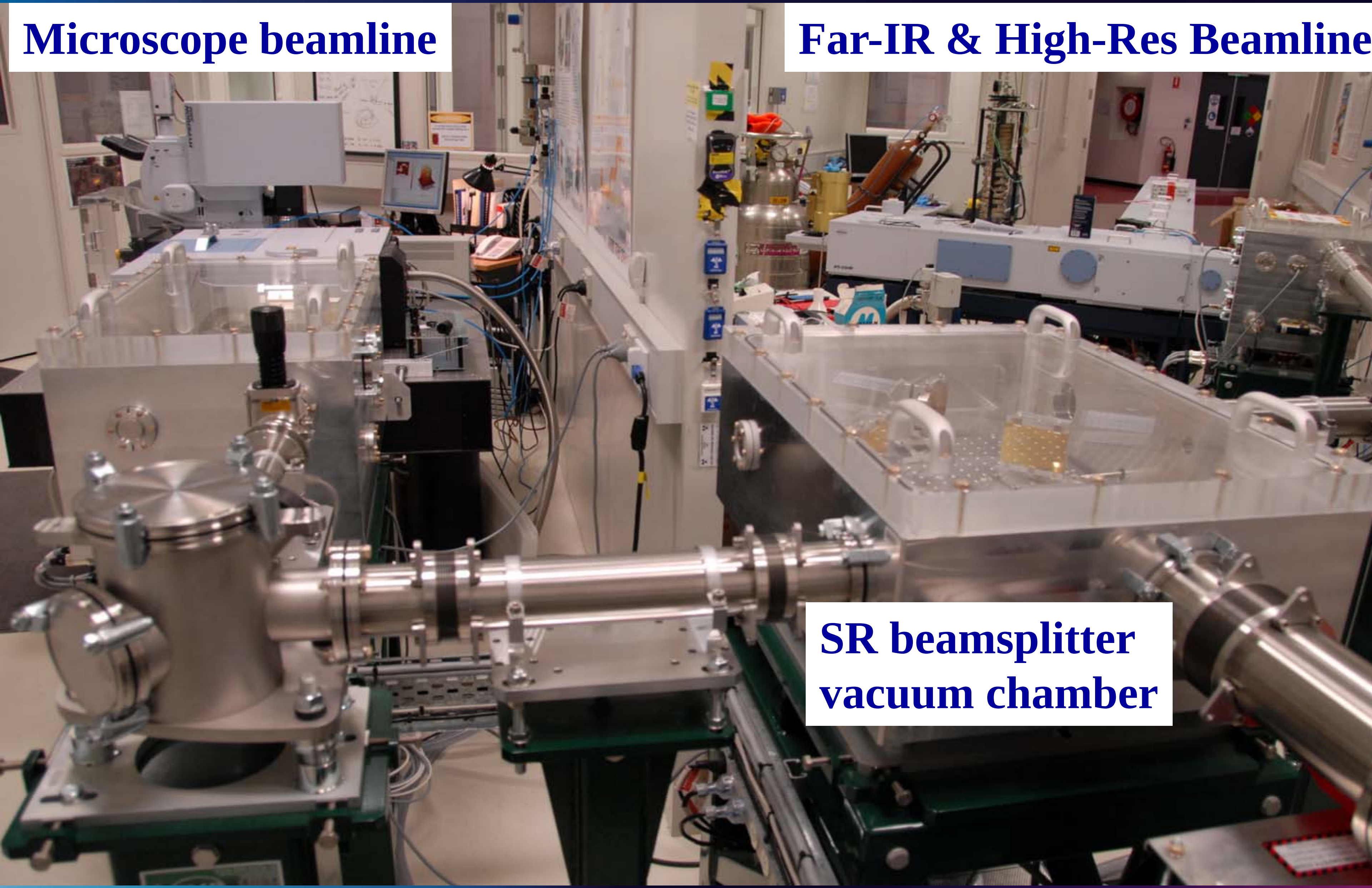
III. The Australian SYNCHROTRON INFRARED BEAMLINE

Adapted Infrared Dipole Chamber at Australian Synchrotron

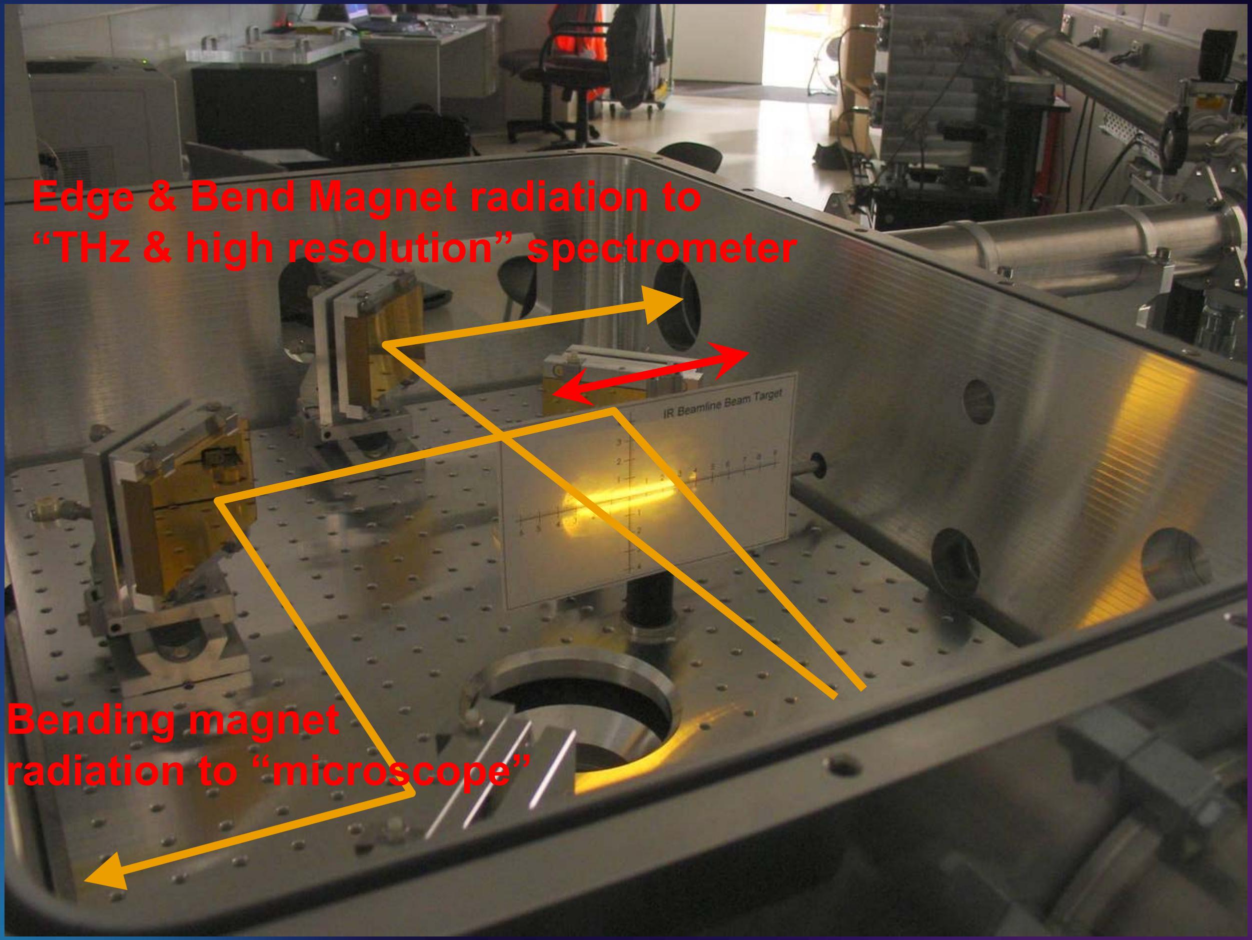


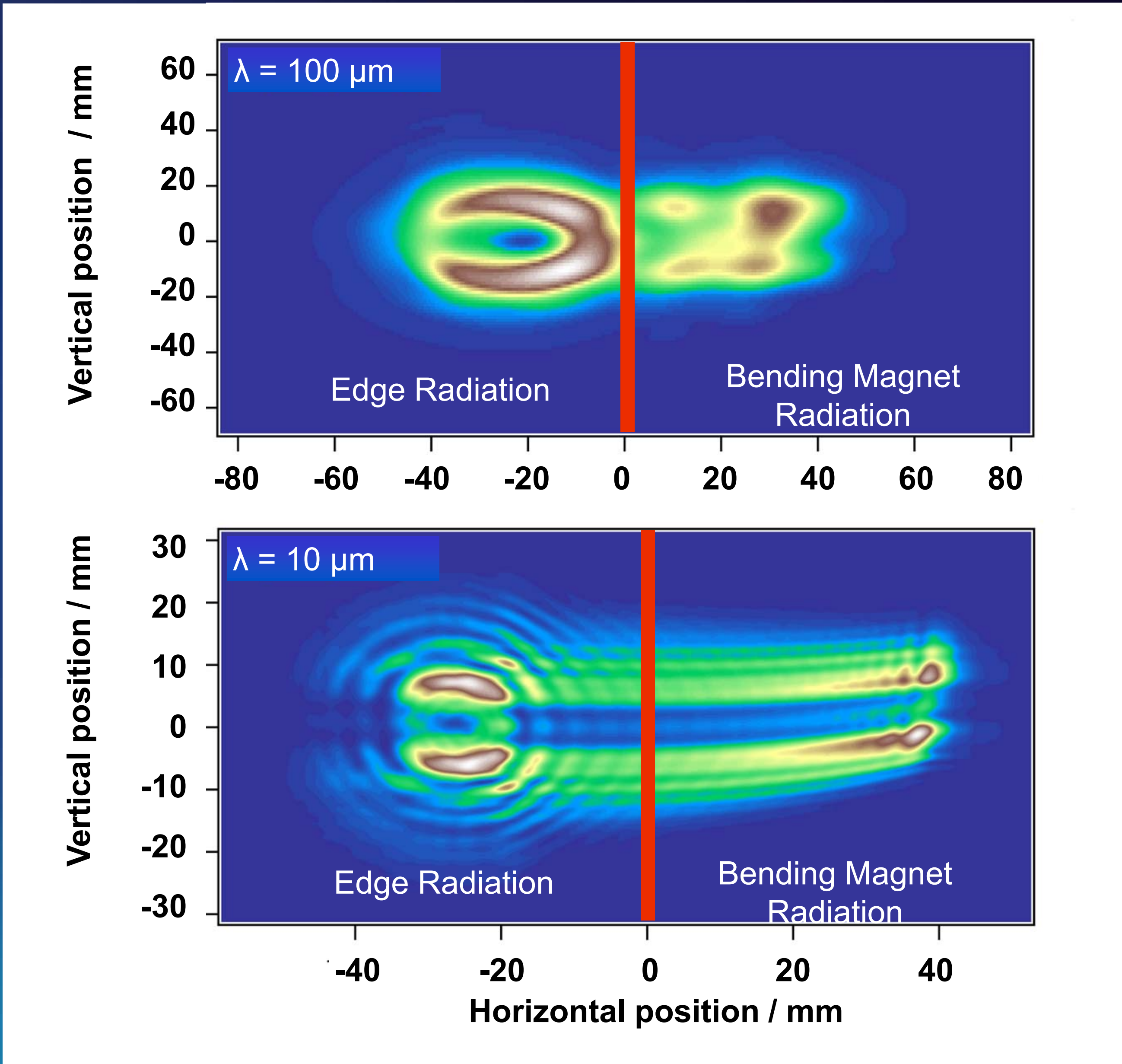


Infrared beamline showing (from right) synchrotron beam entering front end optics (M1, M2, M3, M3a), diamond exit window, beamsplitter optics vessel and matching optics boxes for the two endstation instruments.


Microscope beamline
Far-IR & High-Res Beamline
SR beamsplitter
vacuum chamber

Visible light in the beamsplitter vessel at the Australian Synchrotron Infrared beamline

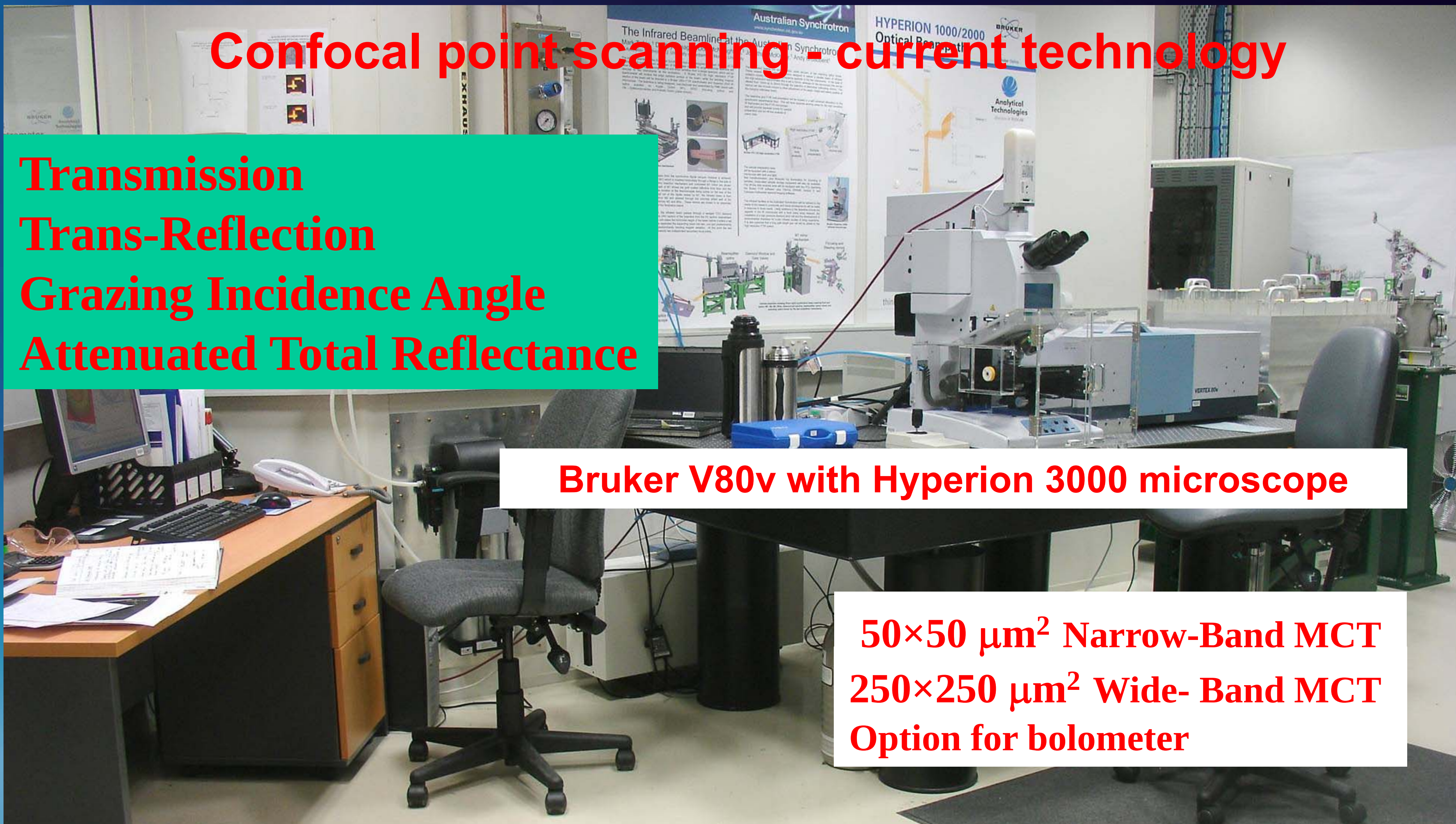



λ = 100 µm
Vertical position / mm
60
40
20
0
-20
-40
-60
Edge Radiation
Bending Magnet Radiation
-80
-60
-40
-20
0
20
40
60
80
λ = 10 µm
Vertical position / mm
30
20
10
0
-10
-20
-30
Edge Radiation
Bending Magnet Radiation
-40
-20
0
20
40
Horizontal position / mm

IR beam profile – comparison with SRW

INFRARED BEAMLINE INSTRUMENTATION

Infrared Beamline at the Australian Synchrotron
Microscope Branch



Confocal point scanning - current technology

- Transmission
- Trans-Reflection
- Grazing Incidence Angle
- Attenuated Total Reflectance

Bruker V80v with Hyperion 3000 microscope

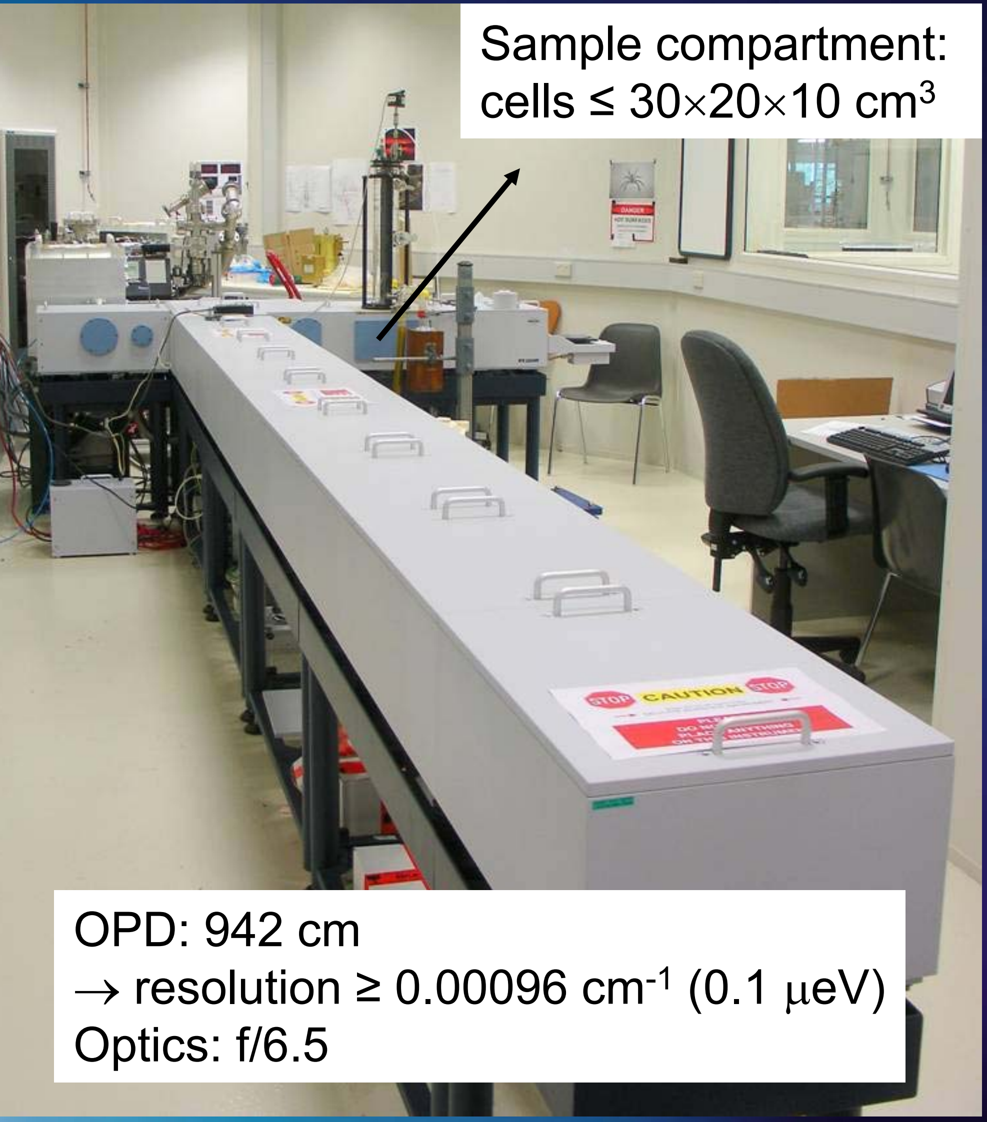
- 50×50 μm² Narrow-Band MCT
- 250×250 μm² Wide- Band MCT
- Option for bolometer

Microscope Branch

Focal Plane Array - next technology

64x64 photovoltaic MCT Focal Plane Array

Infrared Beamline at the Australian Synchrotron
High Resolution branch



Bruker IFS 125HR FTIR Spectrometer

Beamsplitters

- Multi/Mylar 30 – 630 & 12 – 35 cm^{-1}
- Ge/KBr 450 – 4 800 cm^{-1}

IR Detectors

- Si bolometer 10 – 370 cm^{-1}
- Si:B bolometer 300 – 1850 cm^{-1}
- DTGS 100 – 3000 cm^{-1}
- MCT_N 700 – 5 000 cm^{-1}
- MCT_M 600 – 5 000 cm^{-1}

Sources

- **Synchrotron** ***mw – vis***
- Hg-Arc lamp 5 – 1 000 cm^{-1}
- Globar 10 – 13 000 cm^{-1}
- Tunsten lamp 1 000 – 25 000 cm^{-1}

Optical Filters

- series of narrow band pass IR filters

Apertures

- 0.5 – 12.5 mm

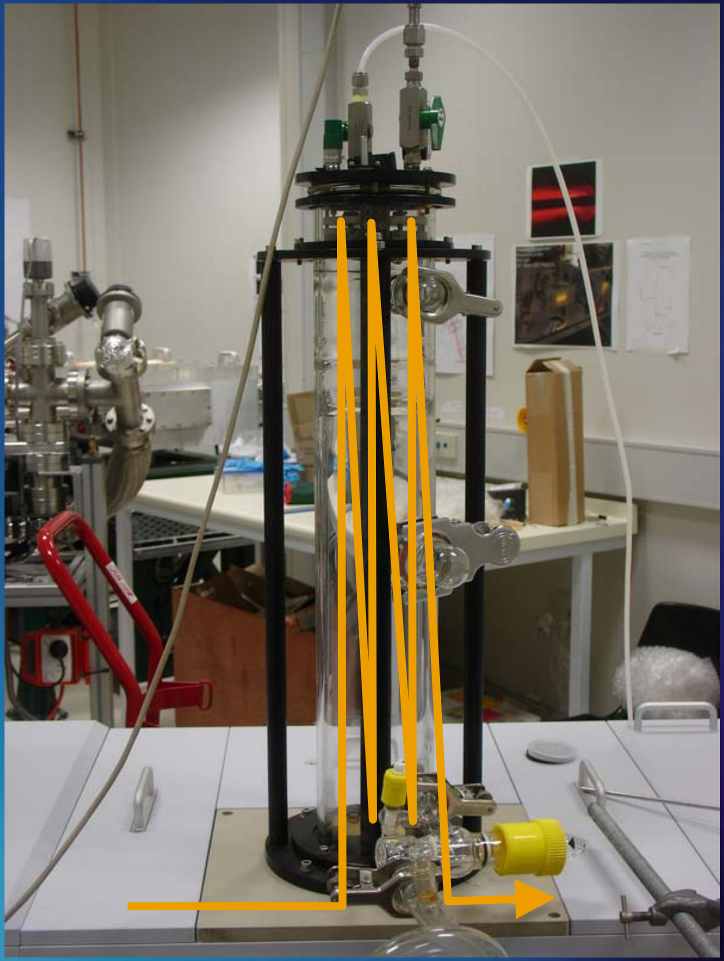
Recall …

Observed Linewidth: $\Delta\nu_{Obs} \sim \sqrt{\Delta\nu_{Dop}^2 + \Delta\nu_{col}^2 + \Delta\nu_{ILW}^2}$

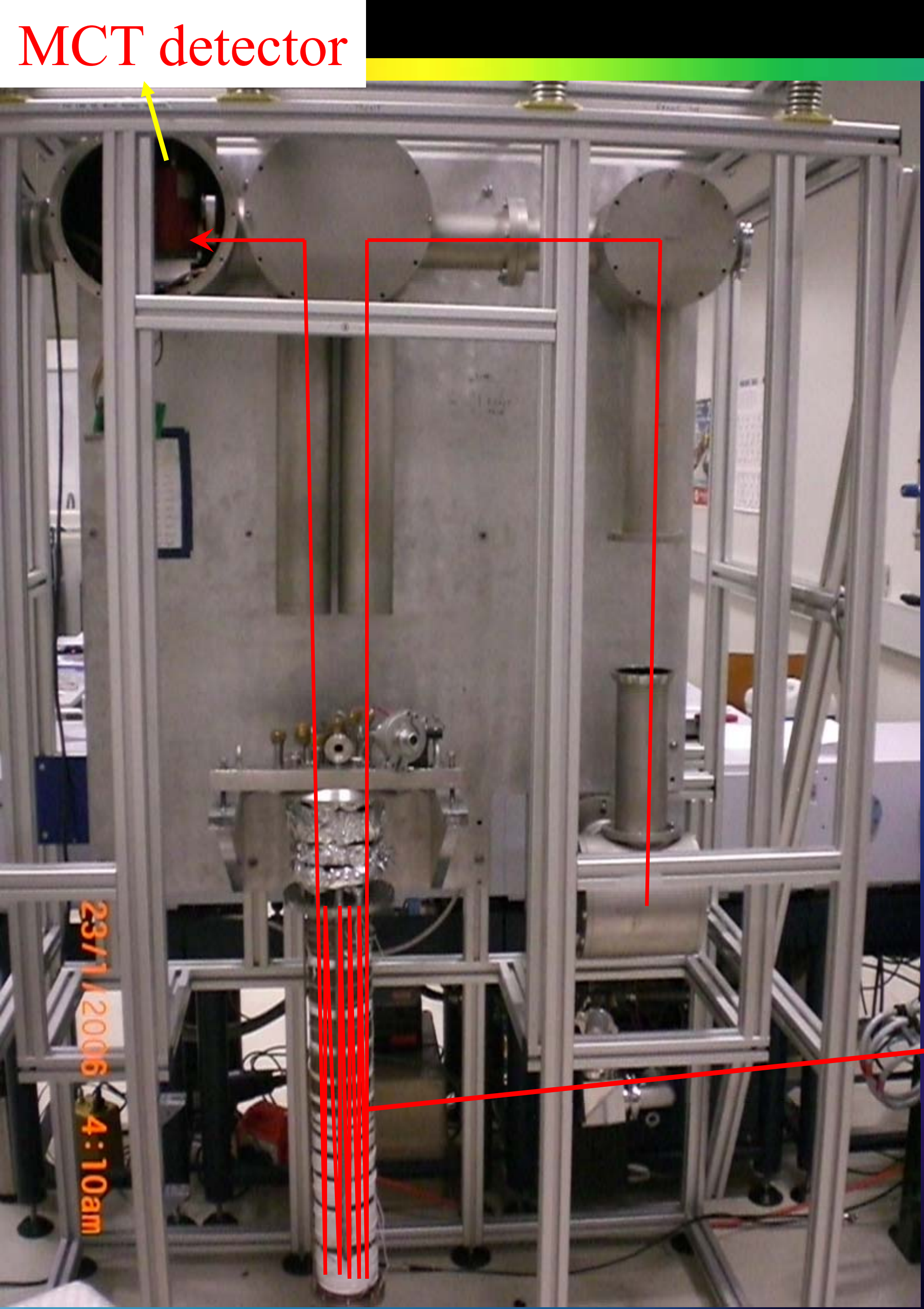
Therefore, the observed linewidth can be minimised by reducing the Pressure and Temperature!

50 cm Multipass gas cell for high resolution spectroscopy of room temperature samples

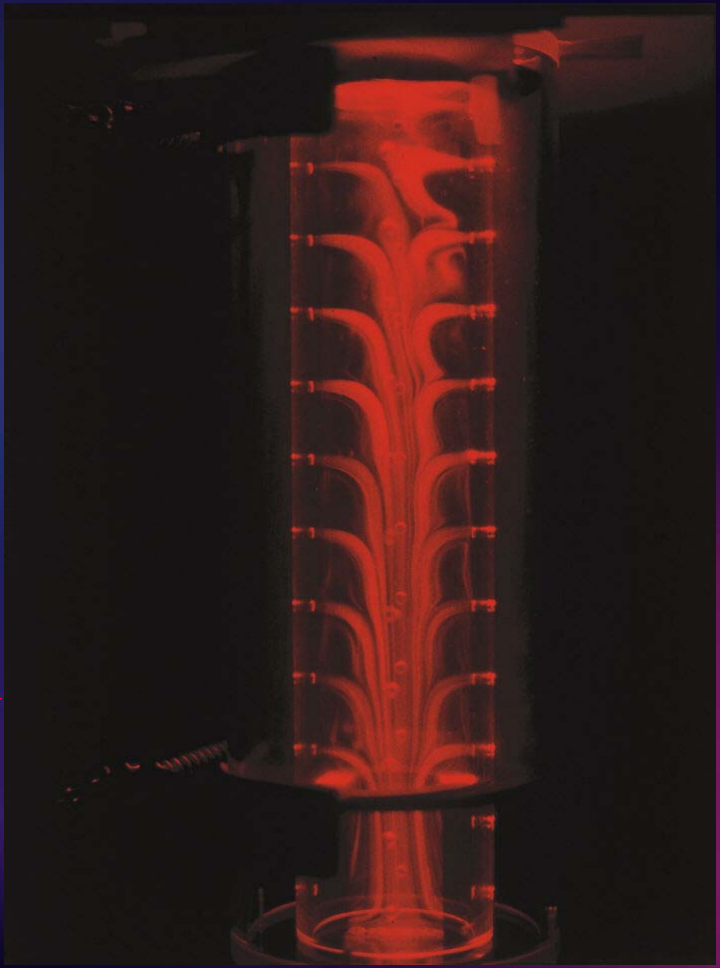
Small quantity of sample to minimize Pressure broadening effects



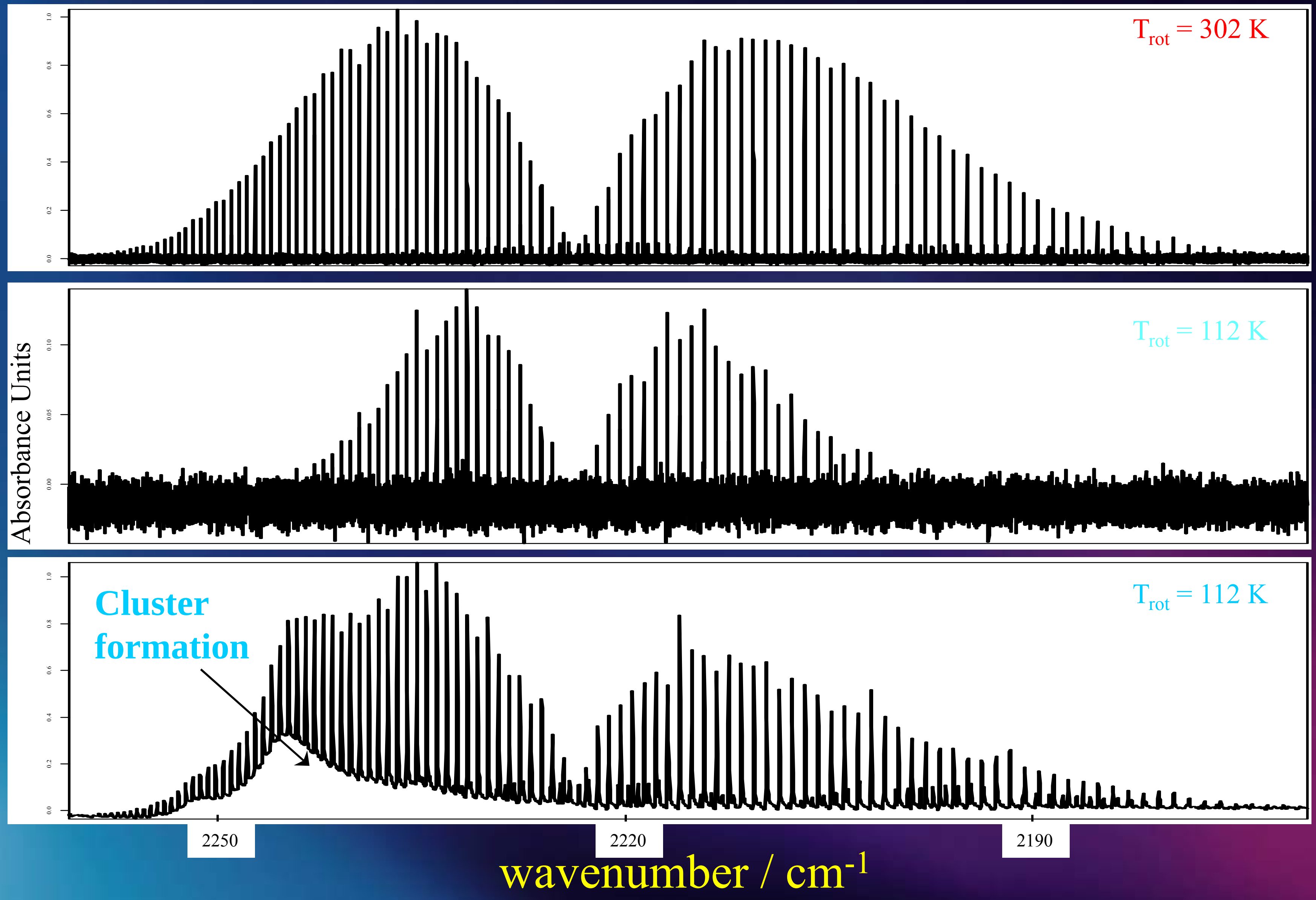
Recall that Absorbance α *εcl* where *c* is the concentration and *l* the interaction path.



Enclosive Flow Cooling multipass cell for gas-phase studies at cryogenic temperatures.

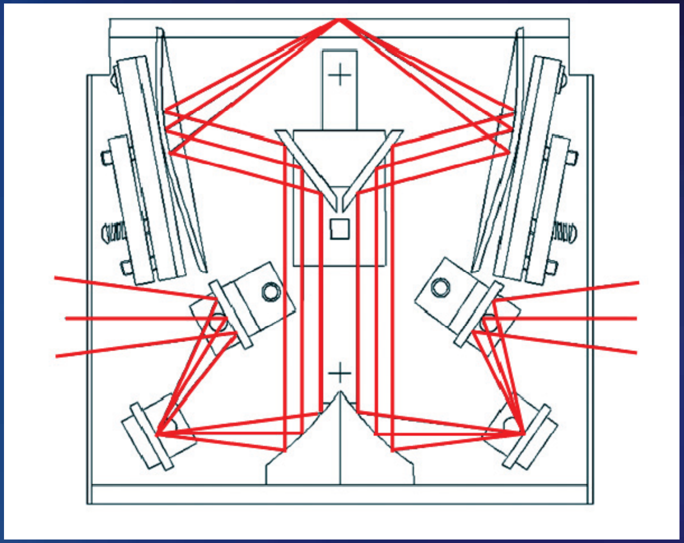


N_2O mid-IR spectrum (0.002 cm^{-1})

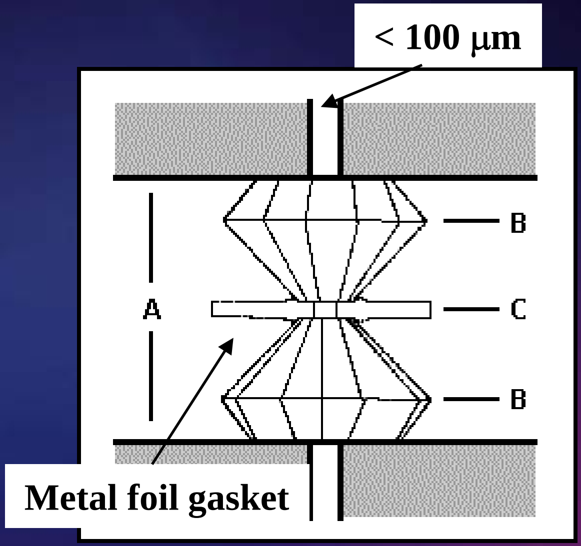


More Scientific Apparatus

Grazing Incidence Angle Cell



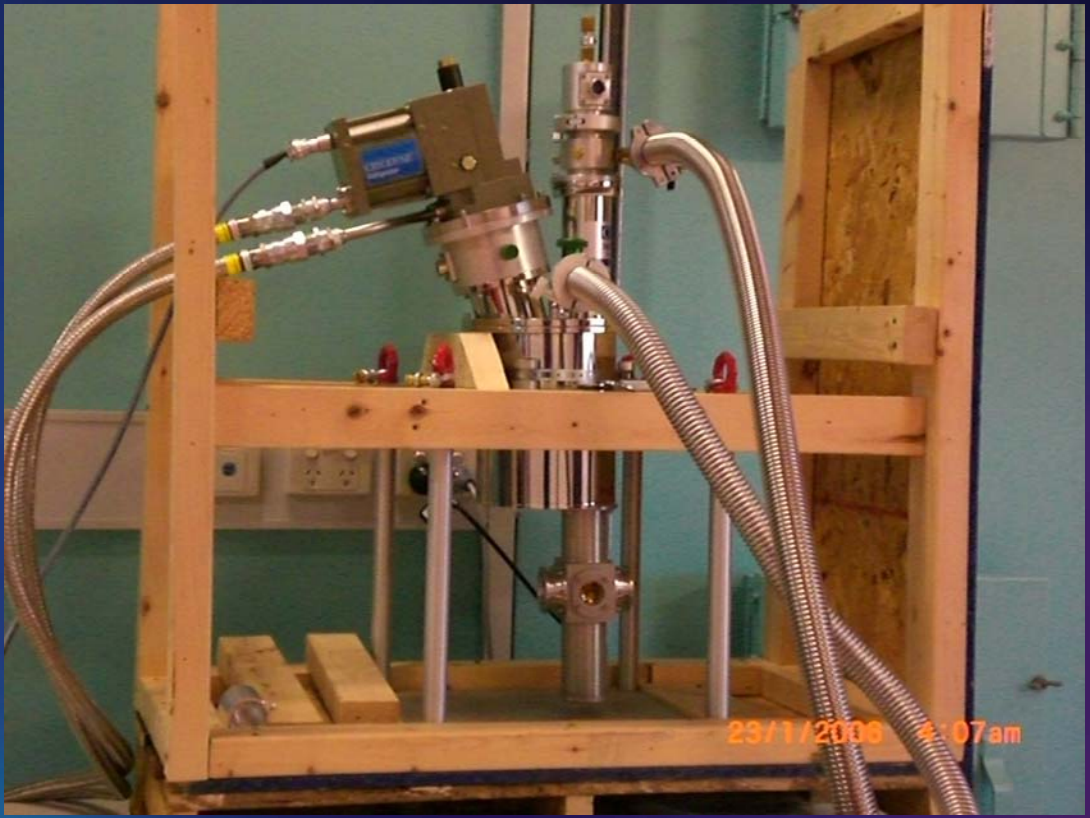
Diamond Anvil Cell



Supersonic Jet Expansion chamber

IR Cryostat for matrix isolation studies

Low freq. vibrations of biological samples



Down to 10 K!

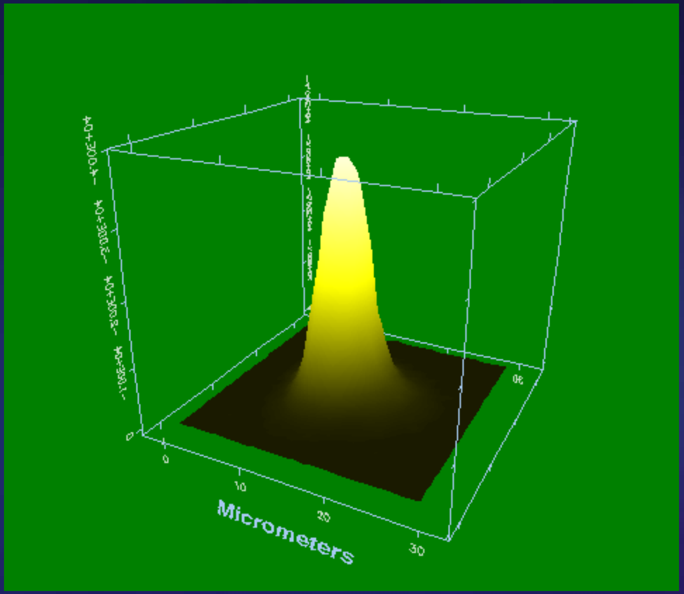
Minimise H_2O interference

Increase Absorption coefficient for a range of substances

Assessing beamline performance

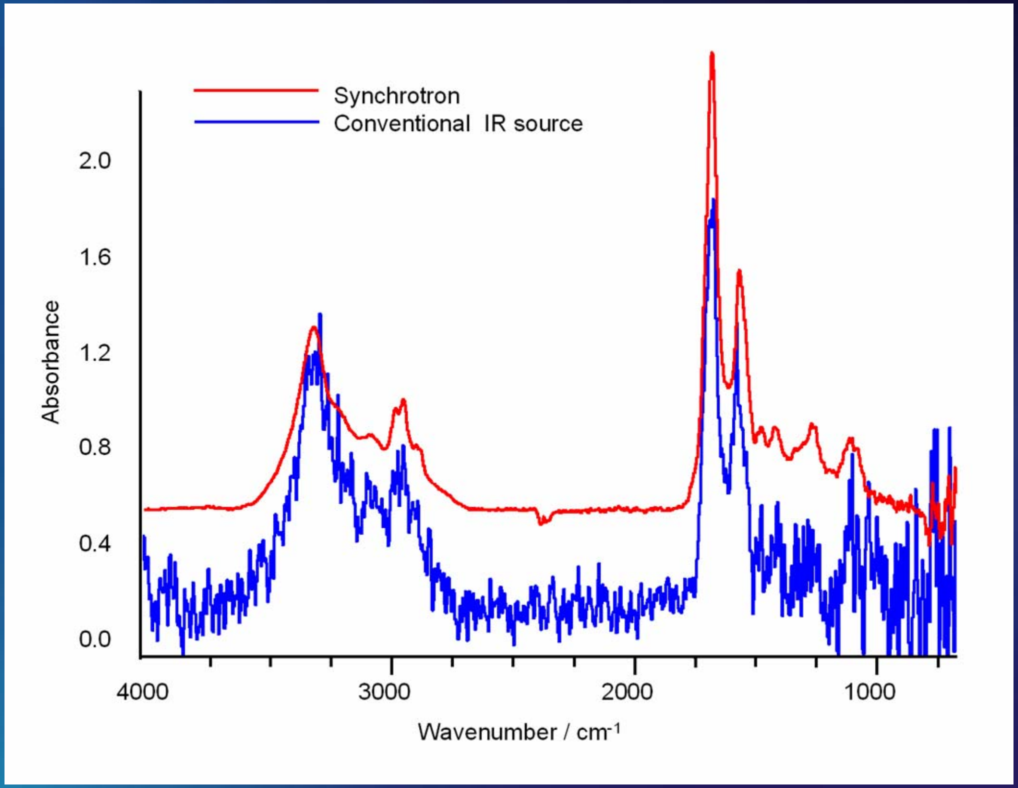
Performance of the microscope beamline

Synchrotron infrared beam focused on sample

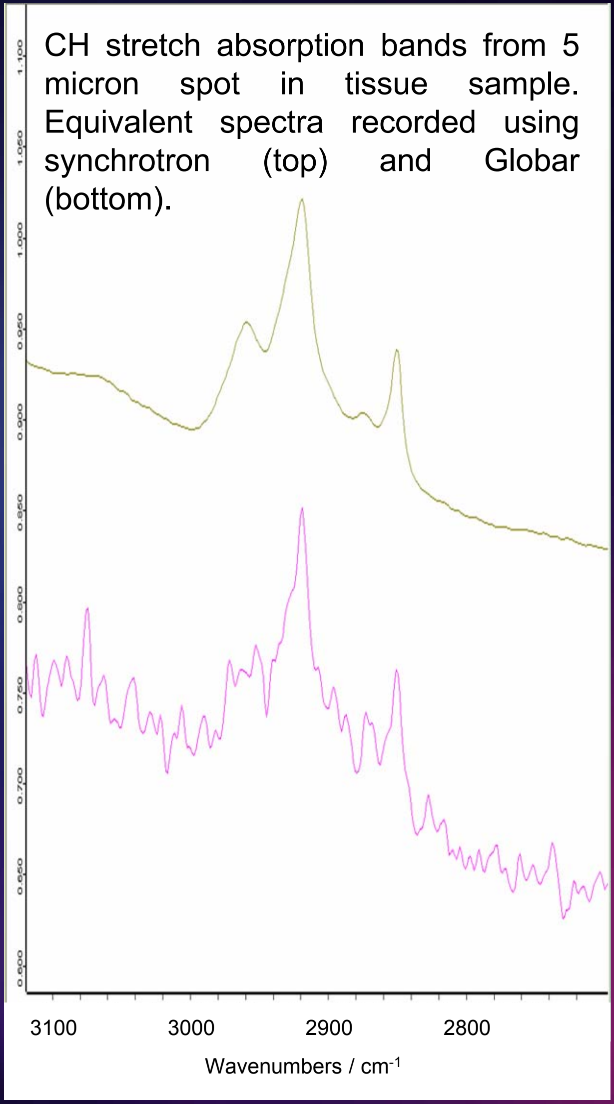


Beamline 11 at SRS - unapertured beam profile at sample stage.
Area mapped = 30x30 μm. **Beam halfwidth = 8x8 μm**.

Advantage of using a synchrotron seen in spectra…

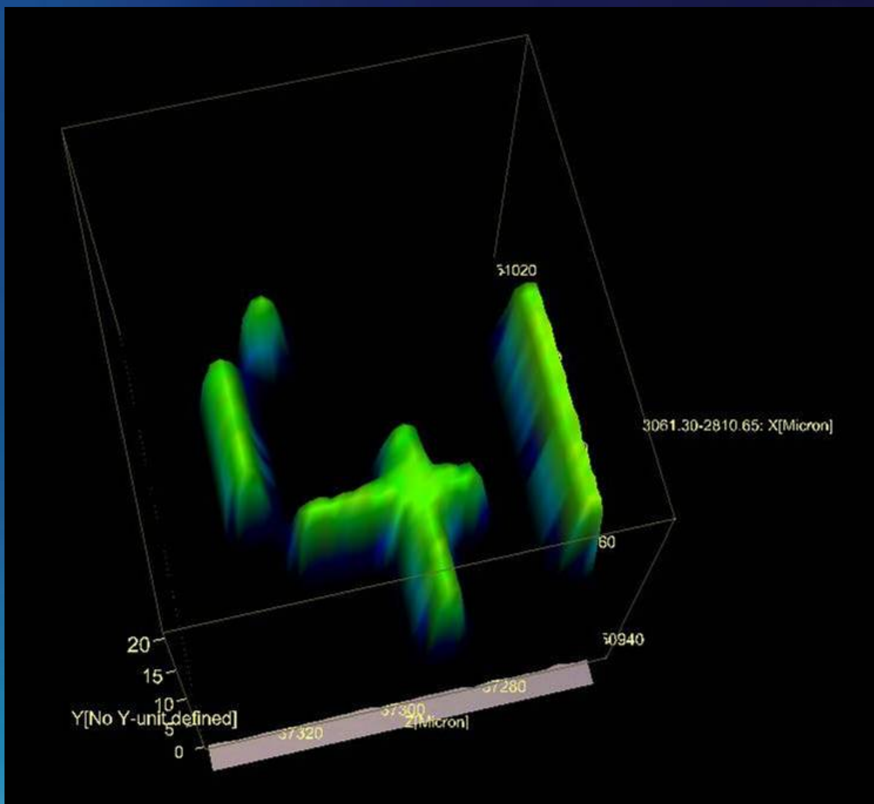


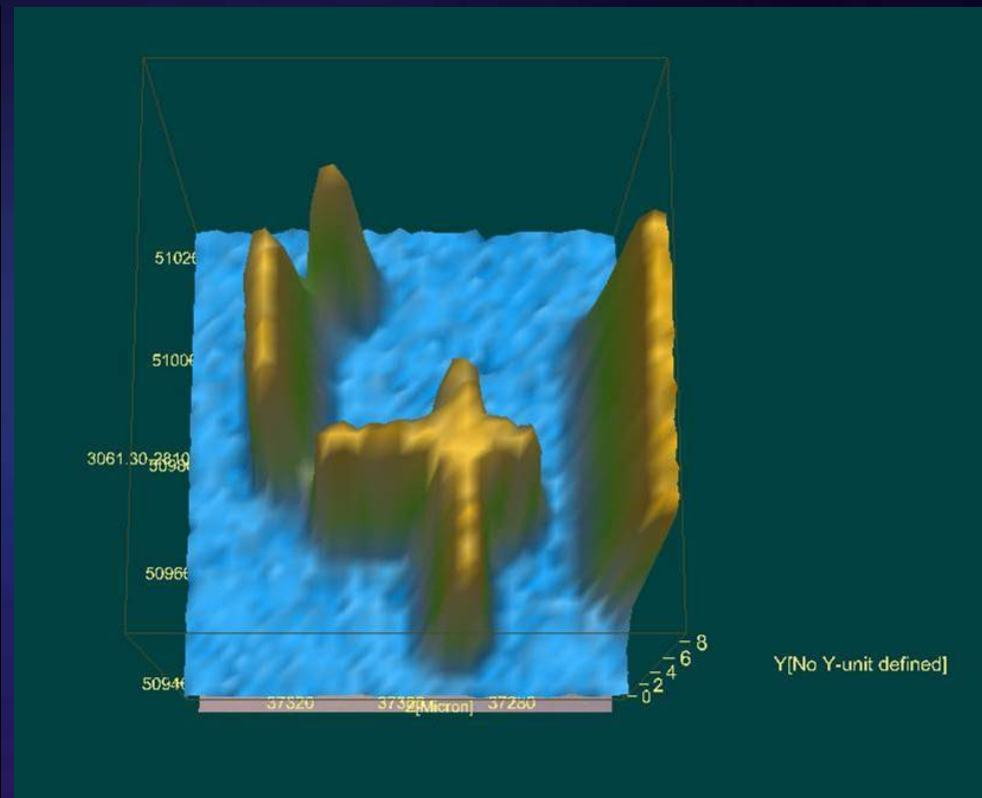
Absorbance spectra of tissue sample recorded at 10 µm spatial resolution under identical collection conditions using a Globar™ infrared source and synchrotron radiation.



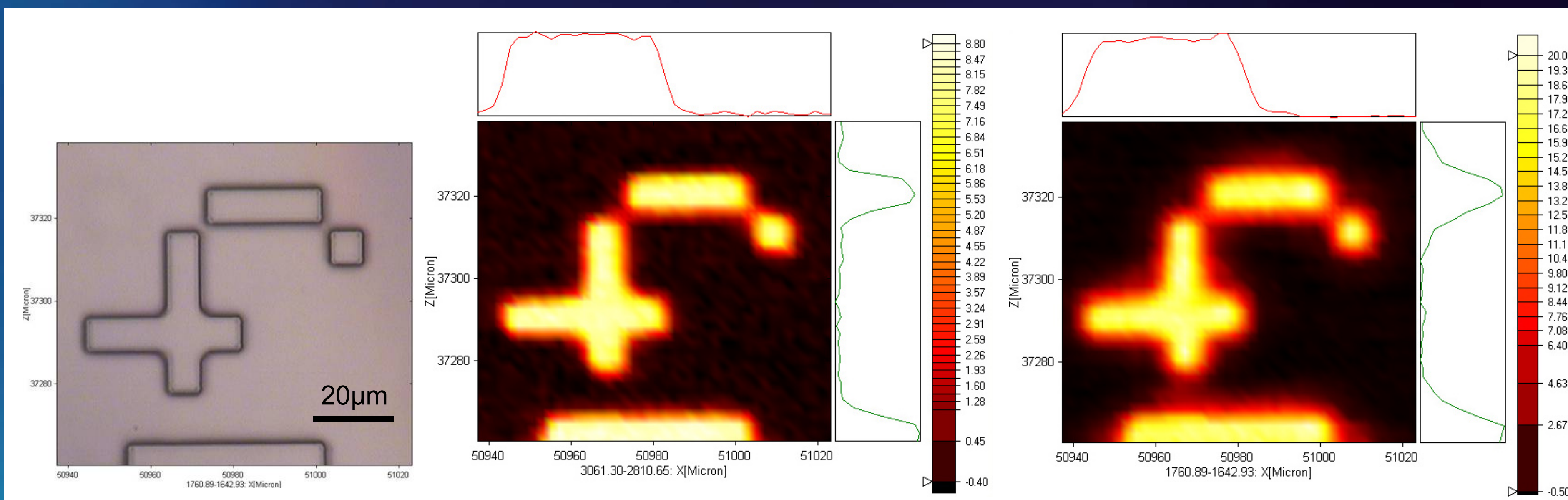
CH stretch absorption bands from 5 micron spot in tissue sample. Equivalent spectra recorded using synchrotron (top) and Globar (bottom).

Testing the IR Beamline Performance with Custom Resolution targets





WAVELENGTH DEPENDENCE OF MICROSCOPE SPATIAL RESOLUTION DEMONSTRATED AT INFRARED BEAMLINE

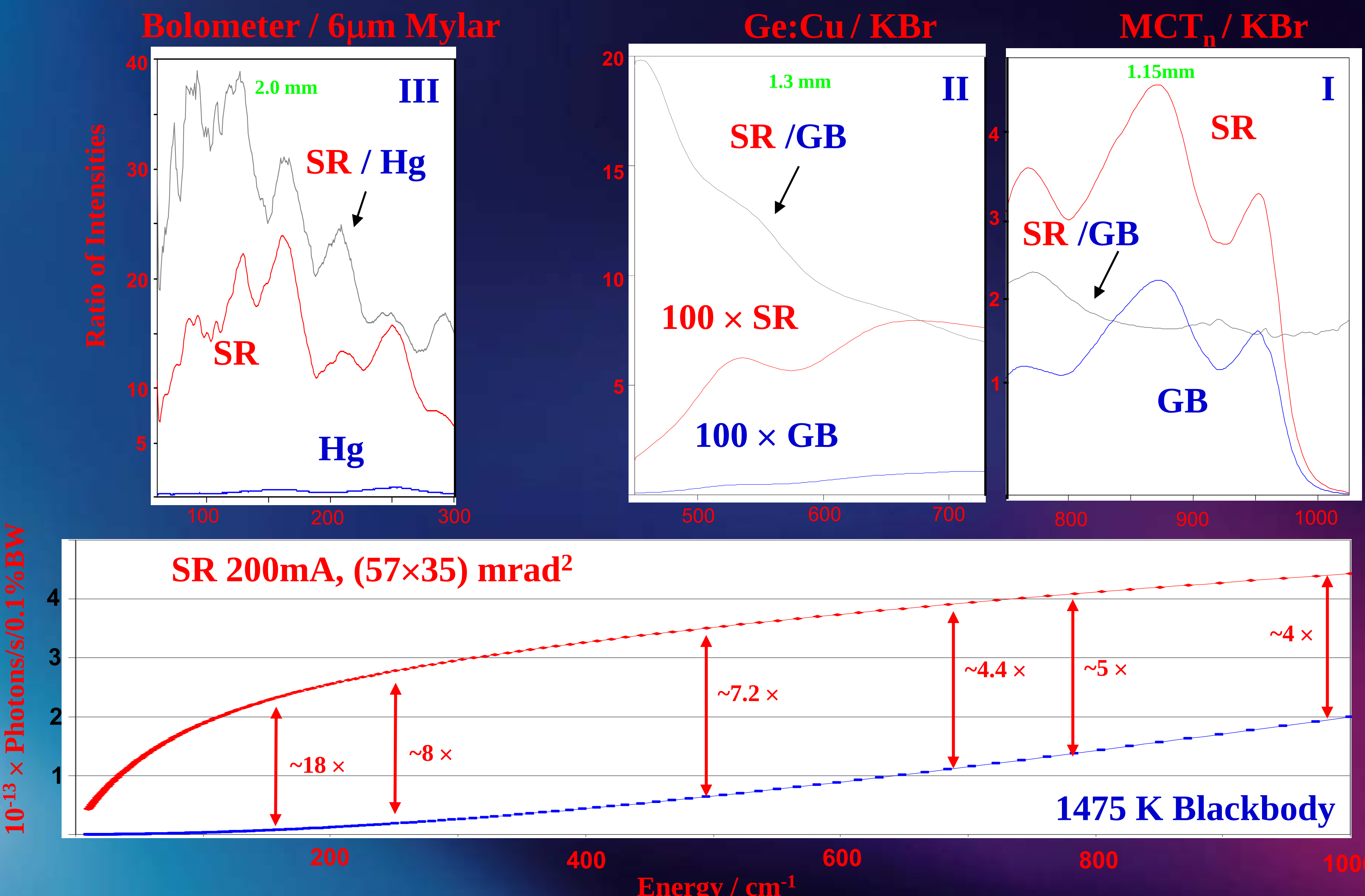


Polymer pattern on CaF_2 produced by photolithography

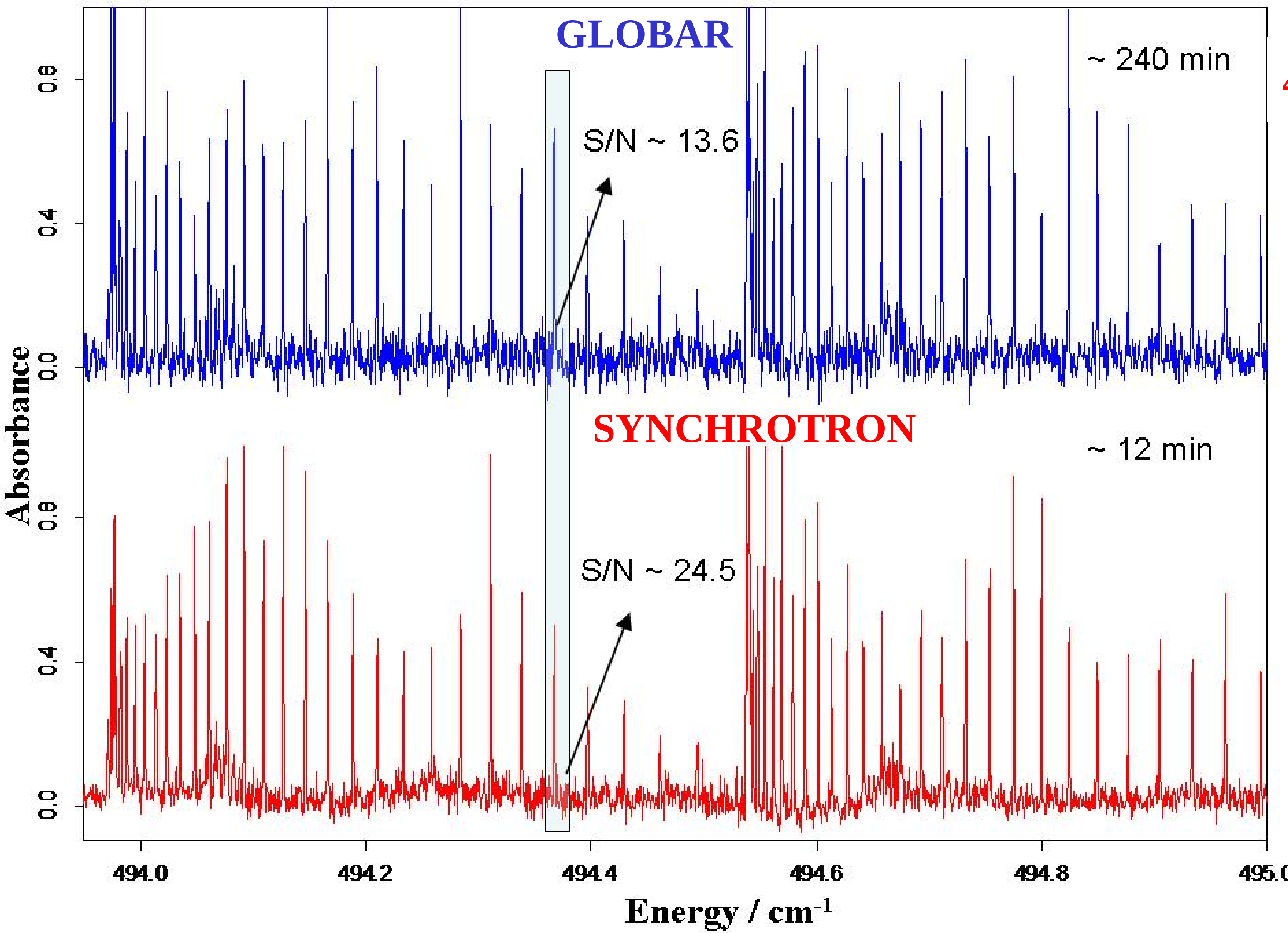
IR absorbance image At 2935 ±125 cm^{-1} CH band region

IR absorbance image At 1701 ±59 cm^{-1} C=O band region

Performance of the far-IR beamline



Spectrum of Pyrrole at 0.001 cm^{-1} resolution

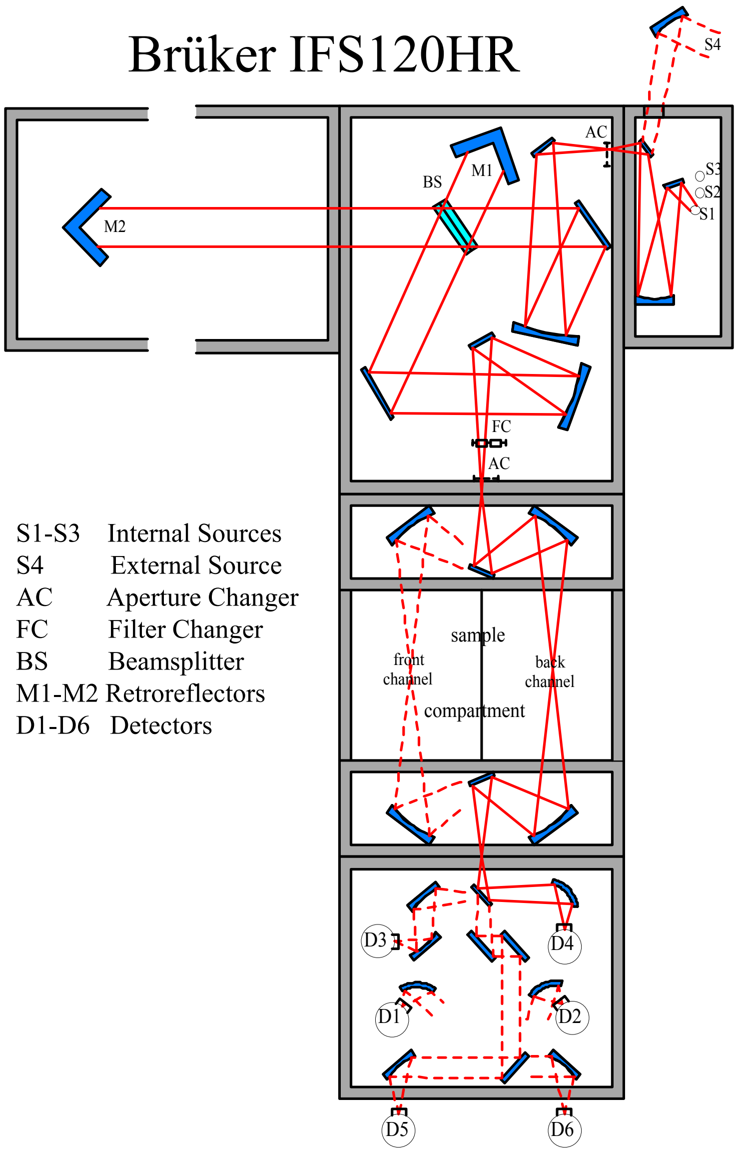


40 days

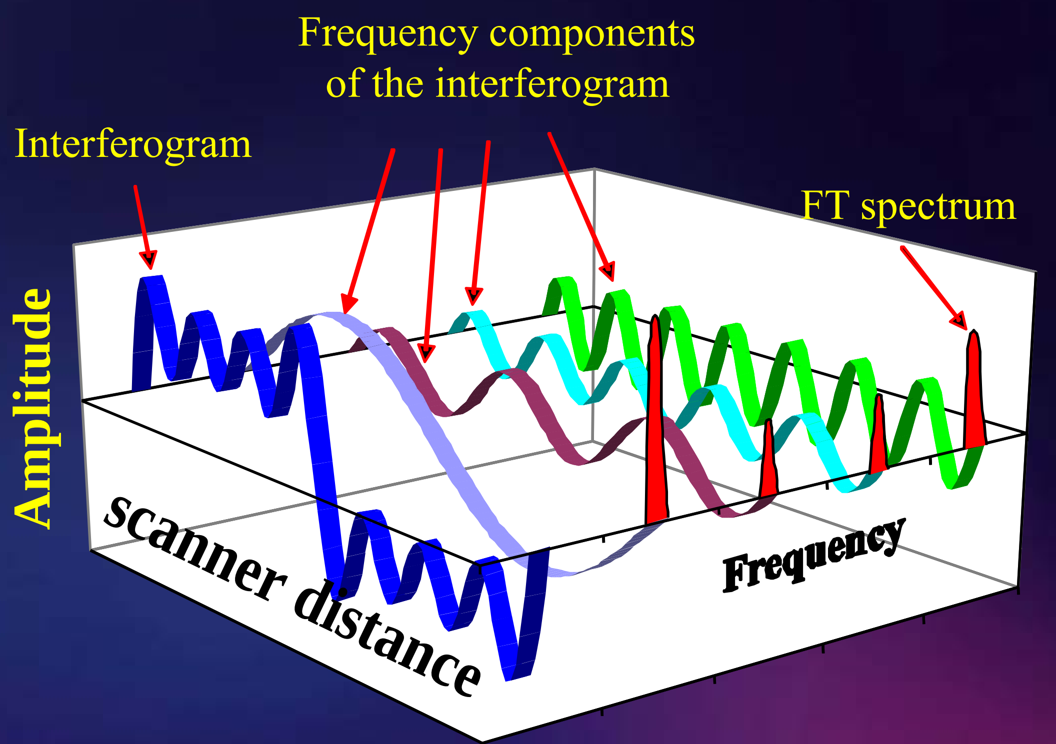
10 hrs

IV. Introduction to Fourier transform Infrared spectroscopy

Fourier transform spectroscopy



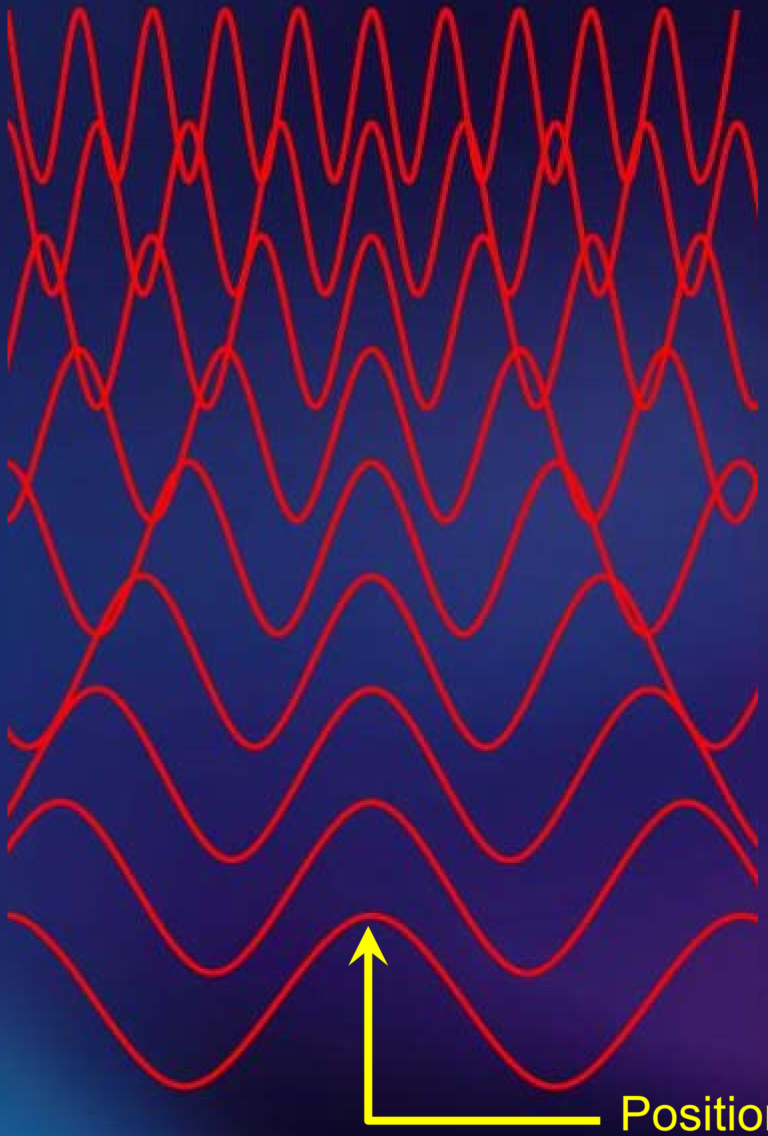
S1-S3 Internal Sources
S4 External Source
AC Aperture Changer
FC Filter Changer
BS Beamsplitter
M1-M2 Retroreflectors
D1-D6 Detectors



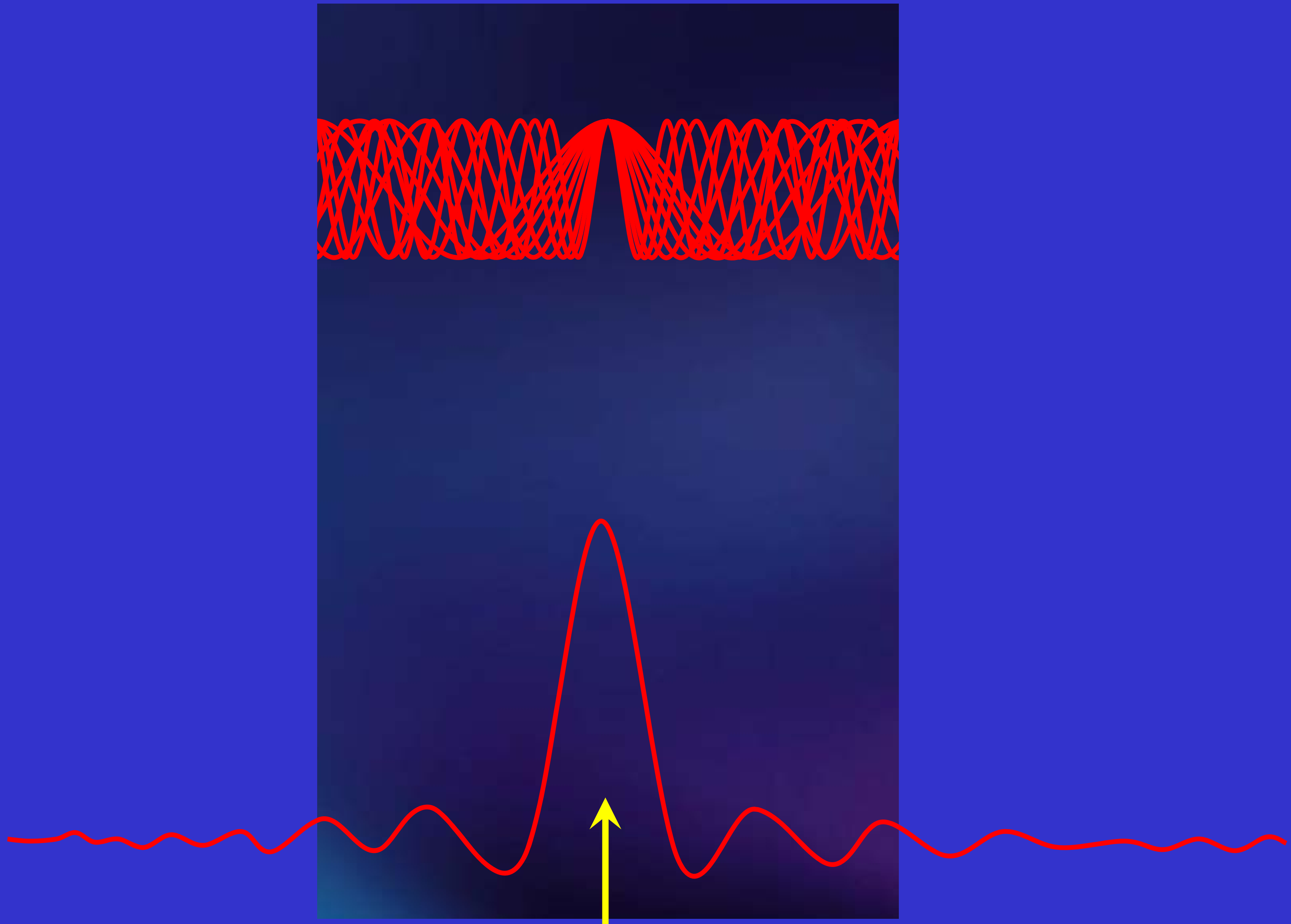
Res = 0.9/OPD

OPD = SCL/2

Many frequencies are present in the infrared beam

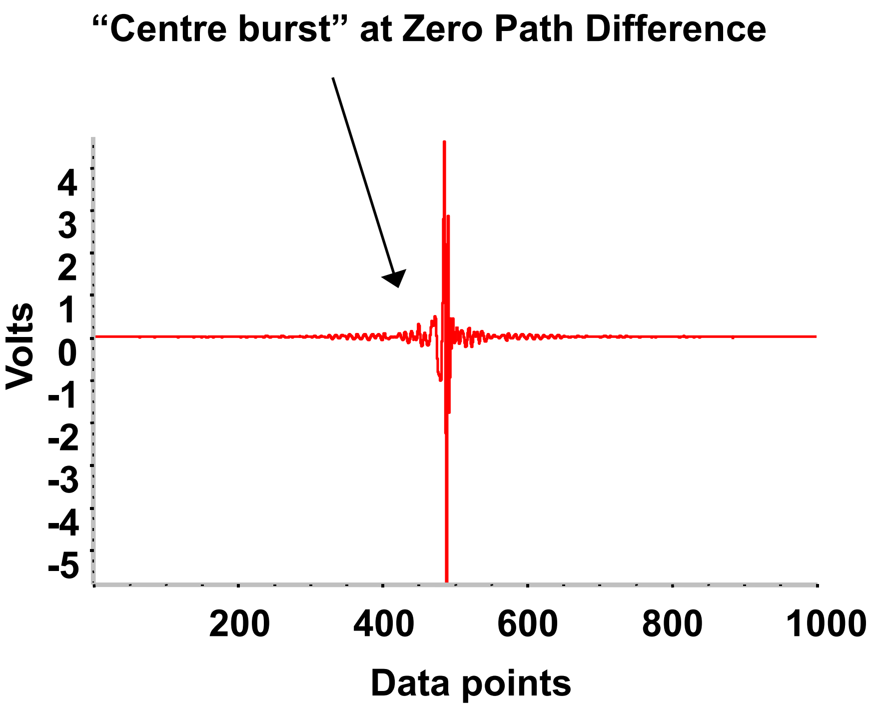


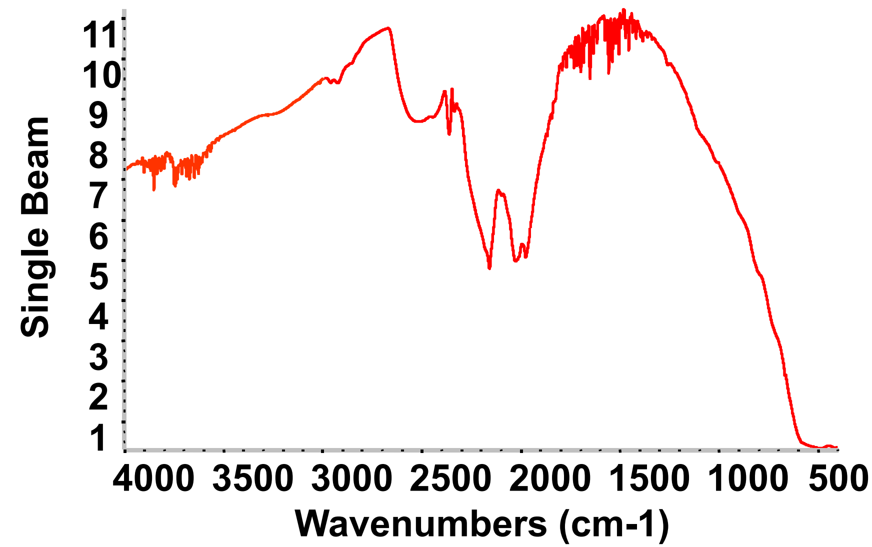
Summing of all frequencies for each position of the mirror



Position of “zero path difference”

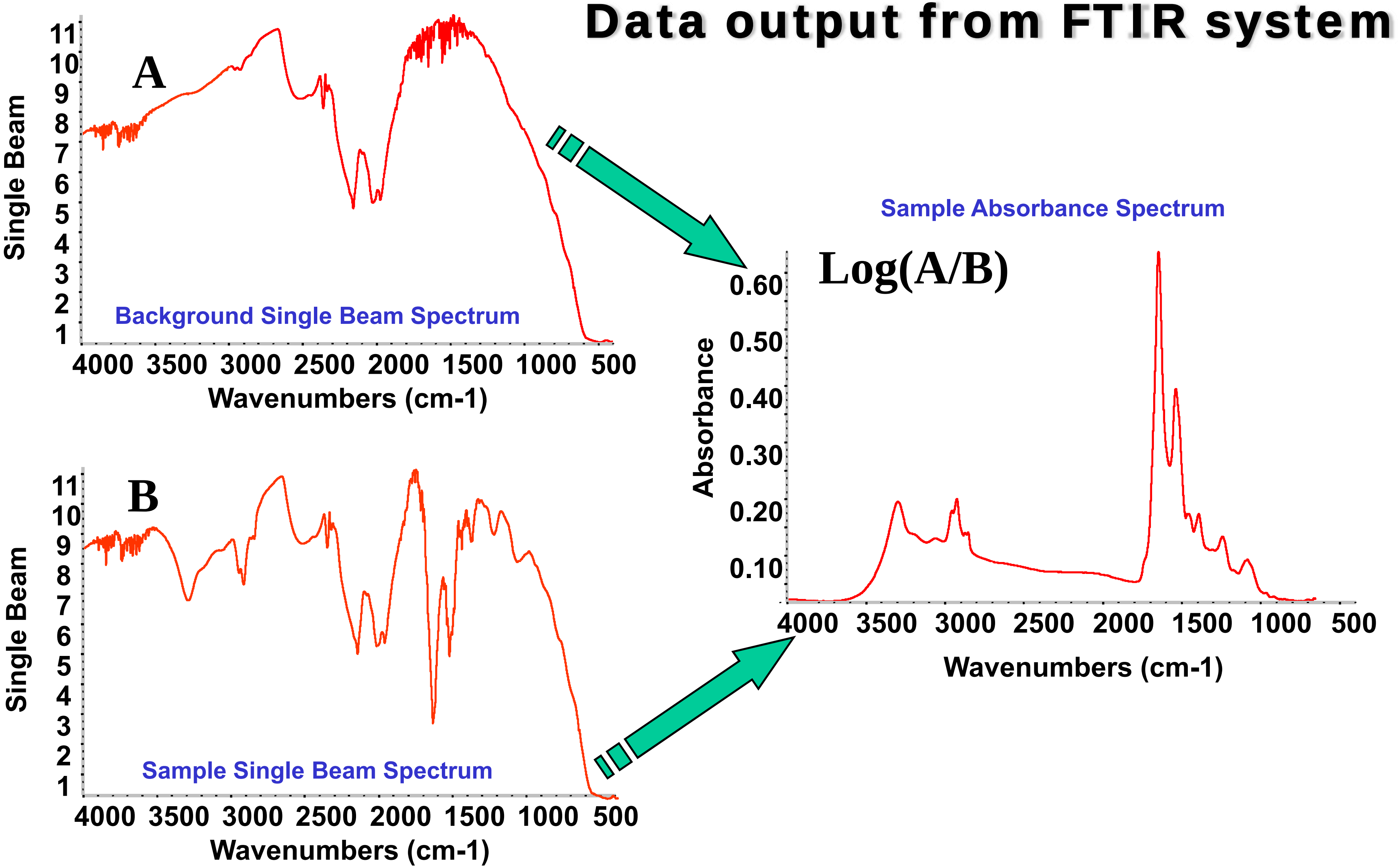
Data output from FTIR system





Interferogram → Fourier Transform → Single Beam Spectrum

Data output from FTIR system



Pros and Cons of Fourier transform spectrometry

Advantages over grating spectrometers

- Felgett or Multiplex
- Jacquinot or throughput: apertures instead of slits
- High wavenumber accuracy: sampling $\lambda_{HeNe}/2$
- High resolving power: ~ 10^6
- Fast

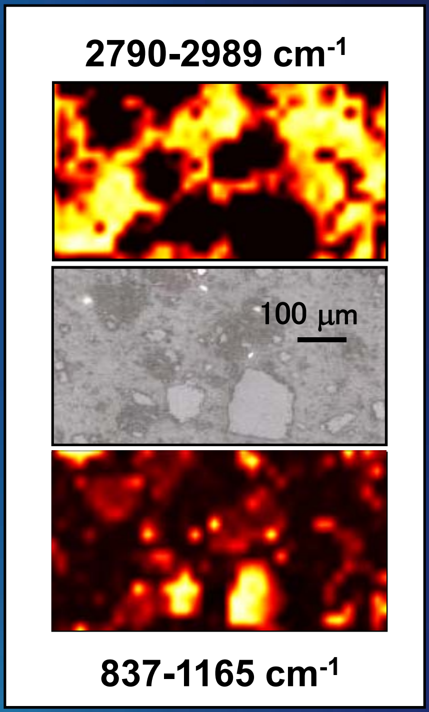
Disadvantages

- Complex system (but can be used as a black box by Users)
- Expensive ....
- Can take a lot of room!

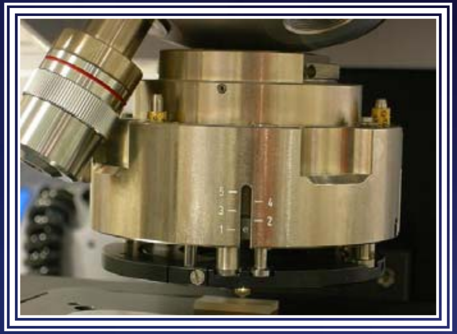
V. APPLICATIONS OF SYNCHROTRON INFRARED LIGHT

Applications of synchrotron IR radiation with a microscope

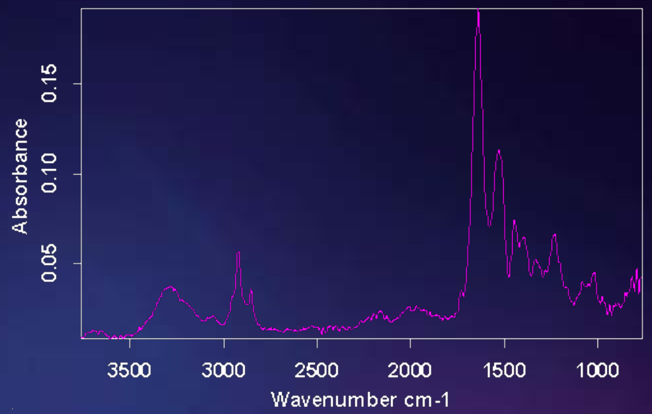
ATR objective



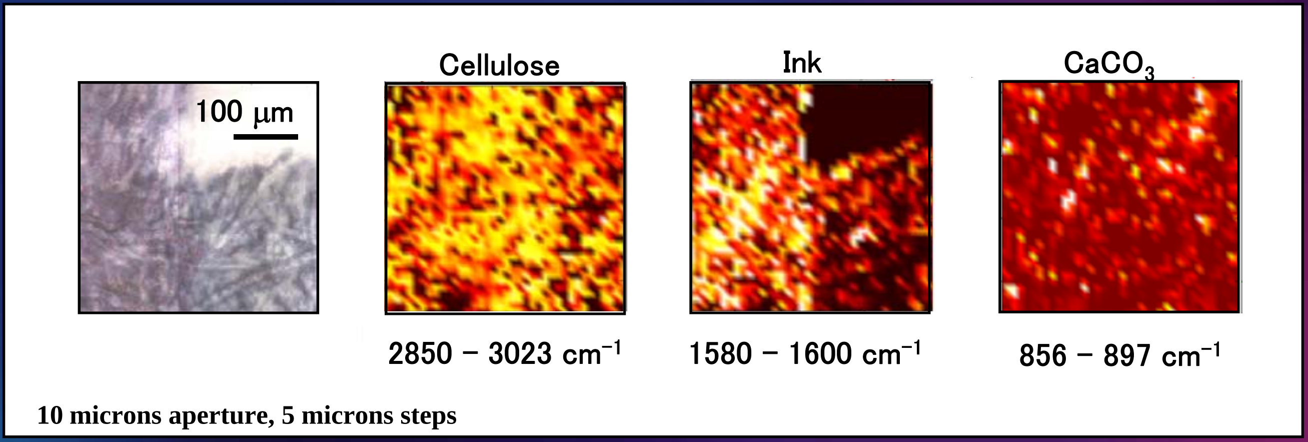
Cross sections of agricultural soils: analysis of distribution and forms of carbon functional groups



19th century parchment sample

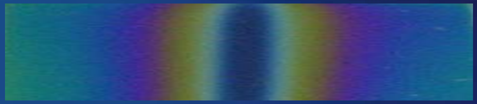


Forensic examination of paper documents

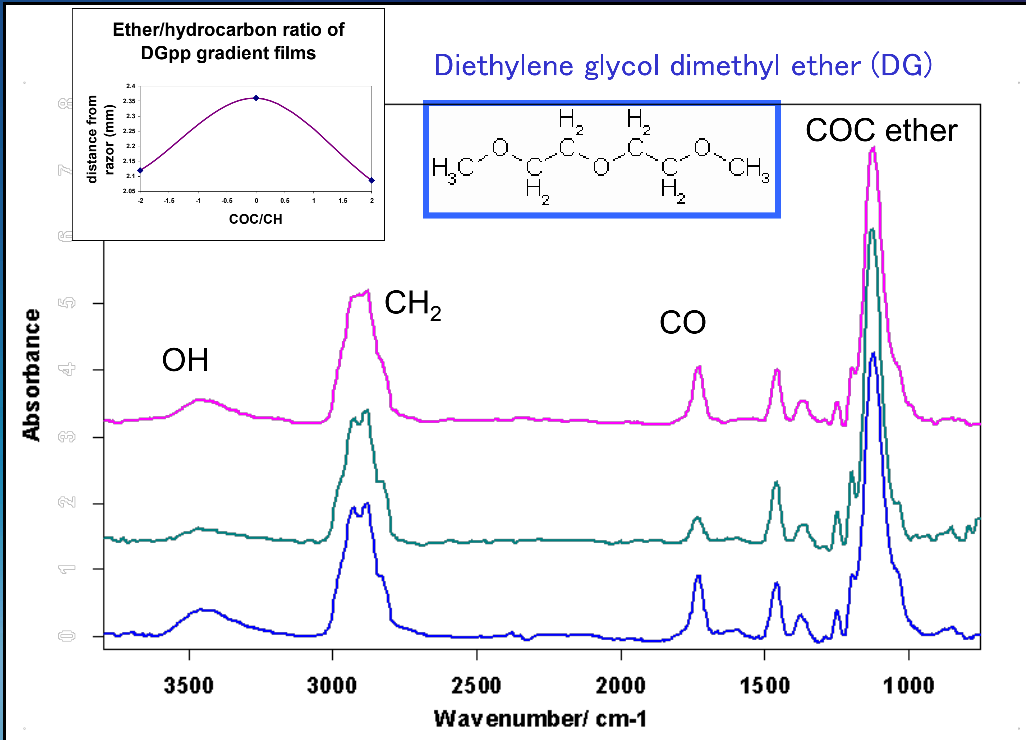


Peter Fisher, Matt Kitching (DPI Victoria) / Simon Lewis, Bill van Bronswijk (Curtin University)
Kenneth Paul Kirkbride, Vincent Otieno-Alego (AFP) / Alana Treasure, Dudley Creagh (Uni Canberra)

Grazing angle objective



Protein resistant plasma polymer thin films



Plasma polimerisation technique used to produce high throughput gradient PEG (poly (ethylene glycol) based films on a nanometer scale.

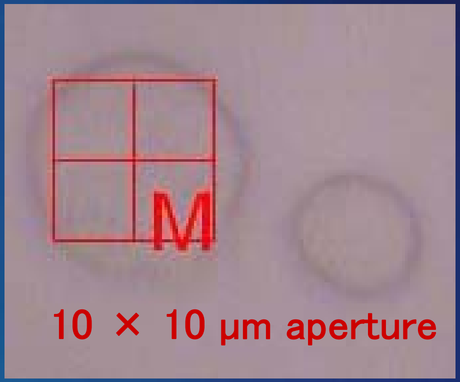
Systematically varied chemistry by altering the plasma processing conditions.

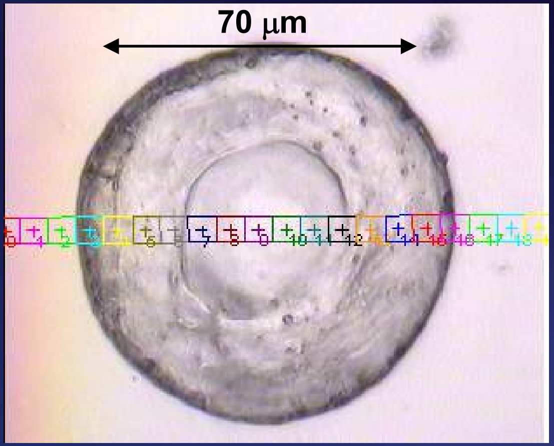
Study the mechanism of protein repellant properties of PEG coatings.

Donna Menzies, Thomas Gengenbach, Celesta Fong, John Forsythe, Ben Muir – CSIRO / Monash

SINGLE CELL WORK

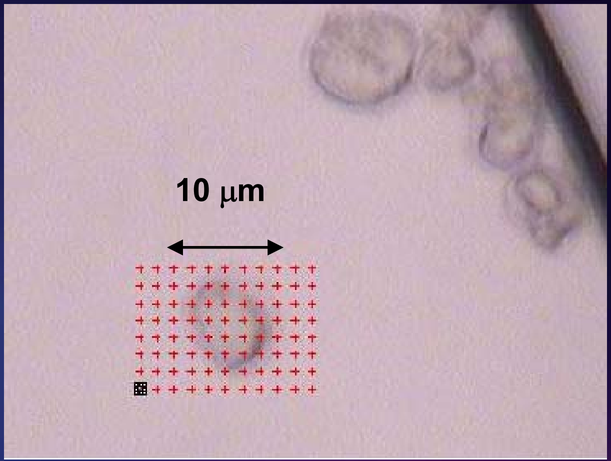
Live Human Mesenchymal Stem Cells



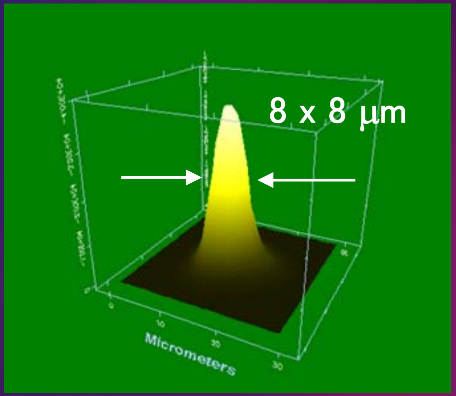


Fixed mouse Oocyte Cell

Live Leukaemia Cells

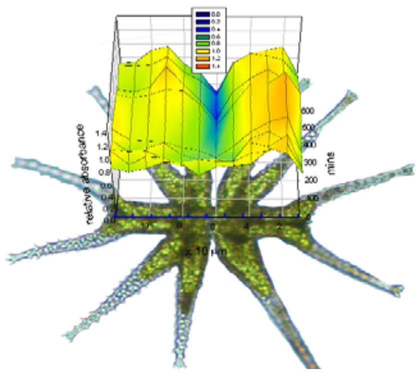


Fixed Malaria infected RBCs

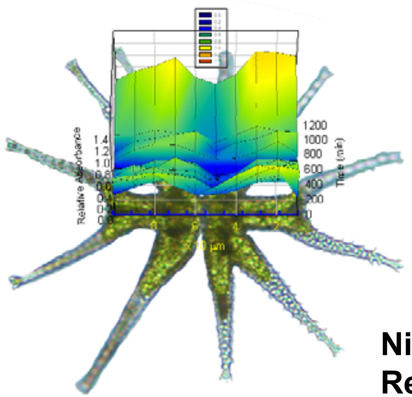


Response of single living phytoplankton cells to changes in the environment

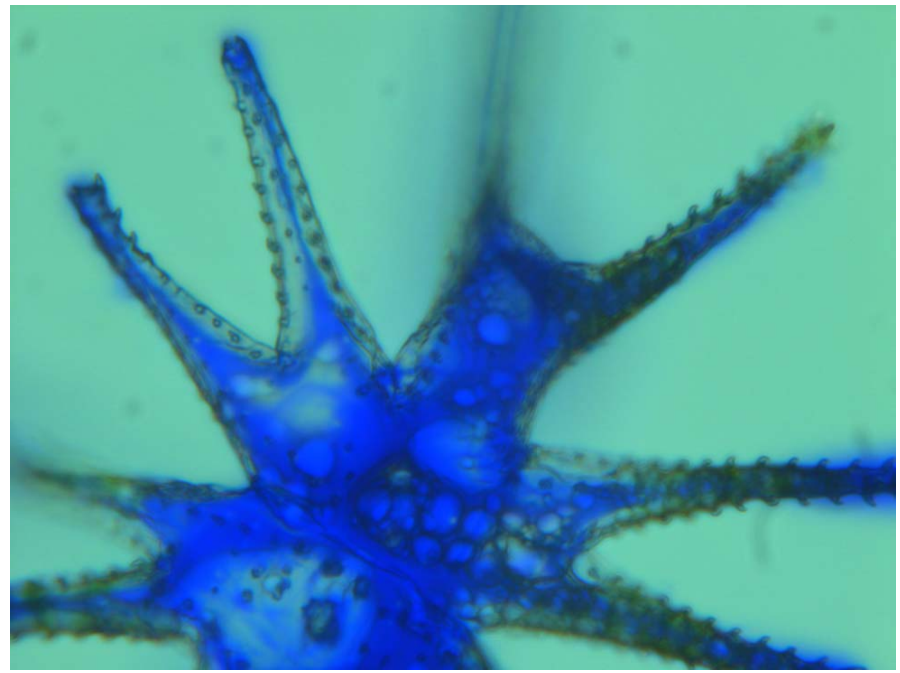
Lipid concentration FTIR maps



Control



Nitrogen starved cell
Re-supplied with nitrogen



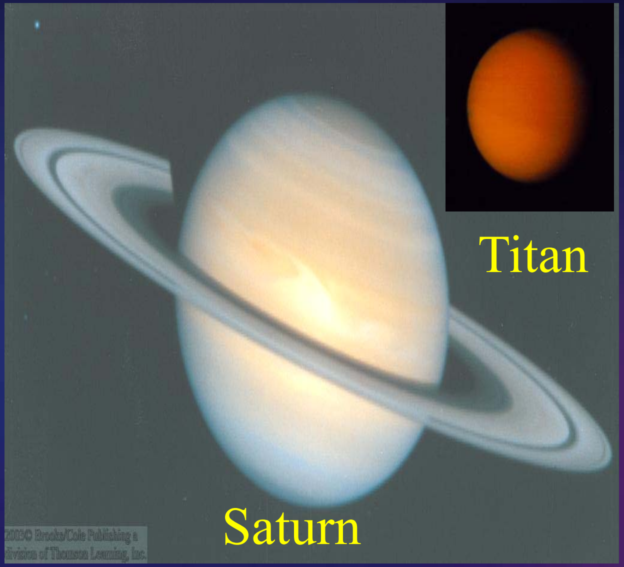
Freshwater alga *Micrasterias hardyi.*

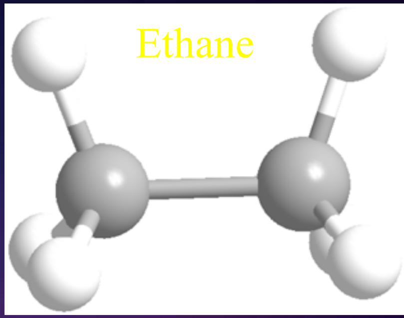
Phil Heraud, Sally Cane, Anthony Eden, Don McNaughton, Bayden Wood, Monash University

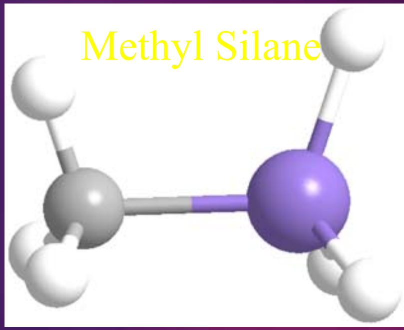
Applications of synchrotron IR radiation with a High-Resolution FT spectrometer

Molecular species of Astrophysical interest

- prototype system for torsional motion
- Intramolecular Vib^{l} Redistribution
- Earth and Jovian atmospheres
- Pluto: clues to evolution early solar system







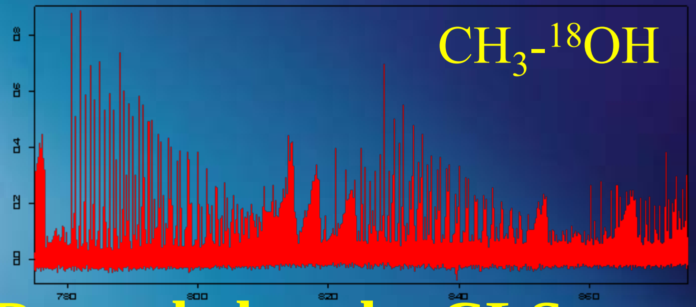
Molecular species of Astrophysical interest

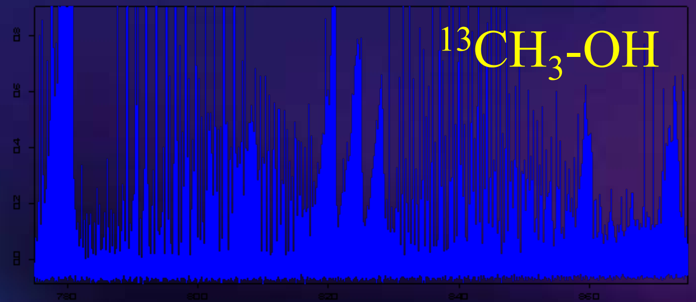
Telescope missions in the submillimeter region for the study of star formation

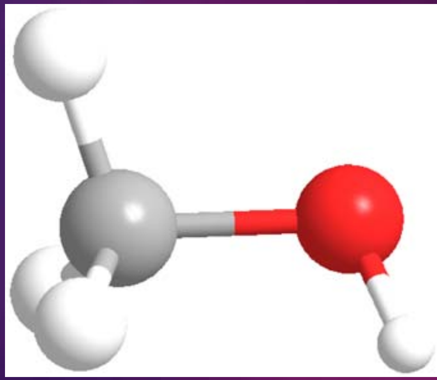
- Herschel Space Observatory (2008, 3-4 years)
- Stratospheric Observatory for Infrared Astronomy: SOFIA (2010, 20 years)
- Atacama Large Millimeter Array: ALMA (2011, decades)

Astrophysical weed-molecules & their isotopologues

-Class I: CH_3OH, $HCOOCH_3$, CH_3OCH_3, C_2H_5CN





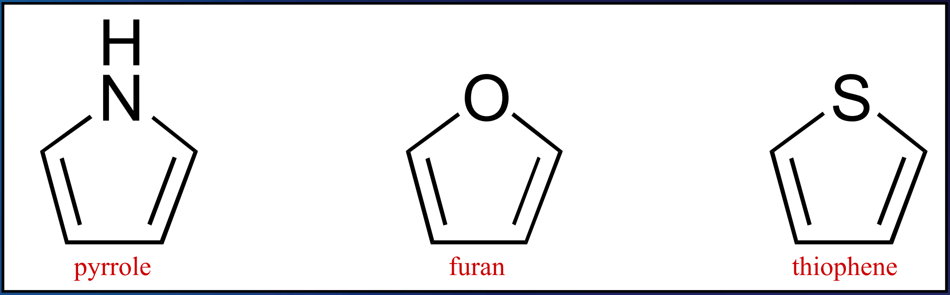


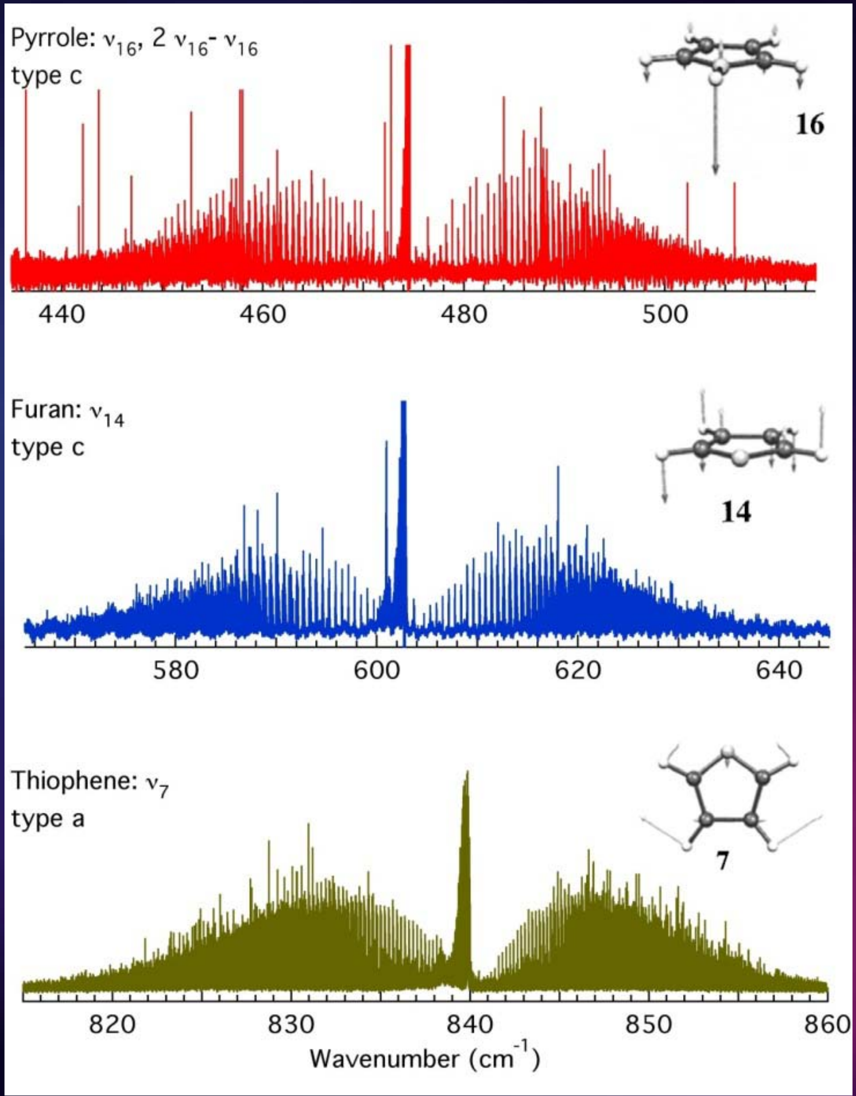
Recorded at the CLS

WAVENUMBER / CM^{-1}

Far-IR spectroscopy of aromatic cycles containing heteroatoms

Dennis Tokaryk (U. of New Brunswick) & Jen van Winjgaarden (U. of Manitoba)



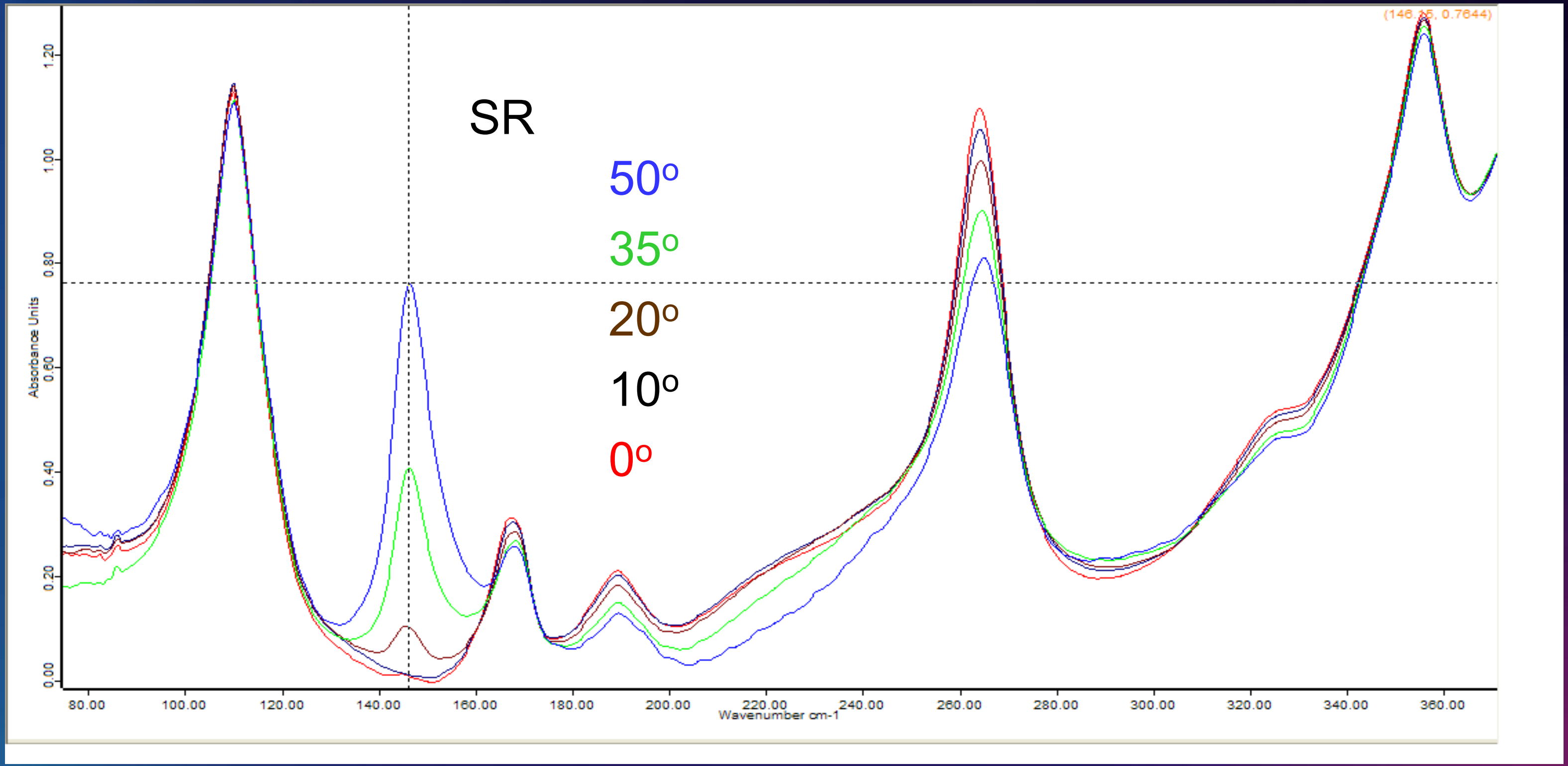


These heterocycles and their derivatives are:

- building blocks of organic chemistry
  -pharmaceuticals, agrochemicals, dyes
- constituents of biologically active molecule such as heme and chlorophyll
- byproducts of combustion processes
- candidates for interstellar detection
- solvents/additives in industrial processes
- naturally found in wood, petroleum

Samples of Environmental interest

Spotted Tiger Muscovite – self supported crystal: Mylar multilayer beamsplitter, Si Bolometer

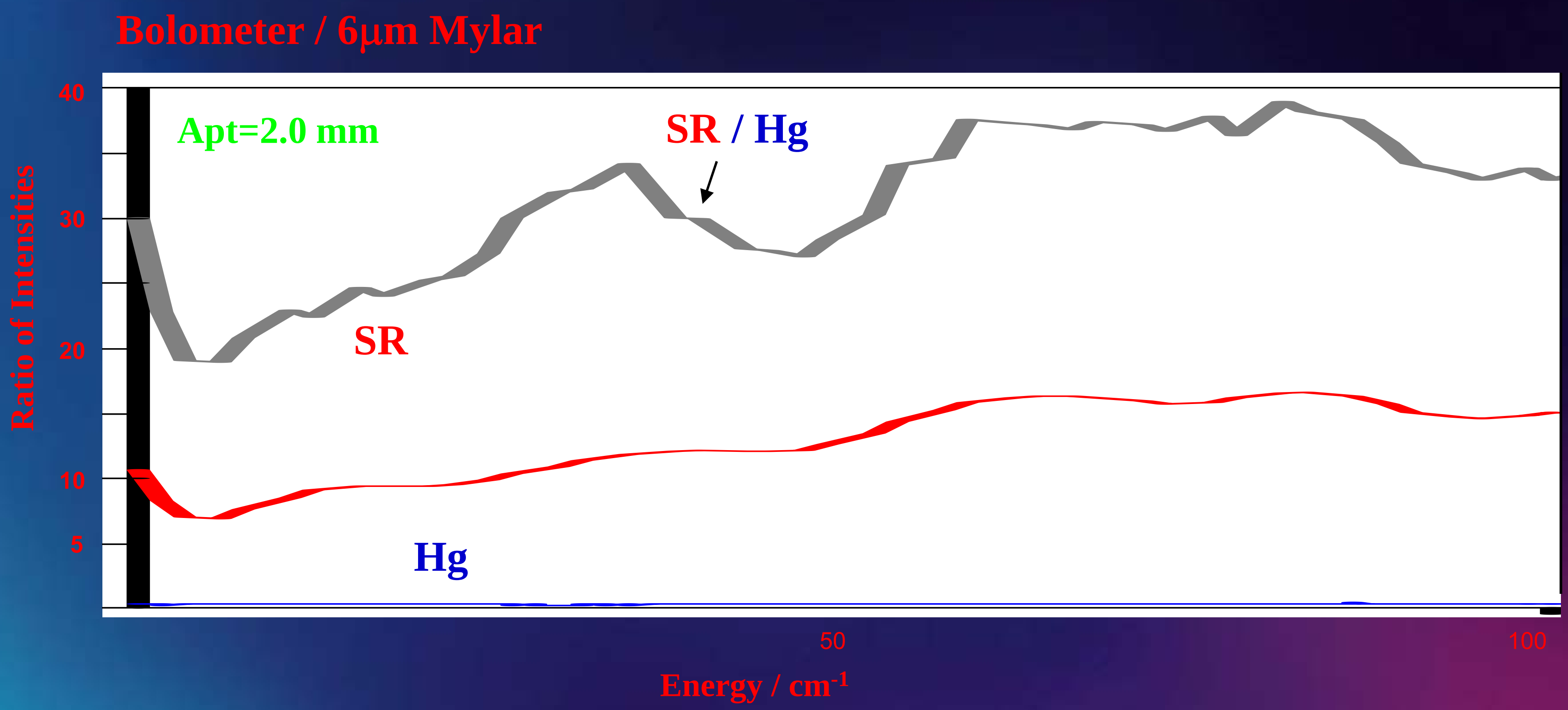


Strong positive pleochroism at 146 cm^{-1} – implies out-of-plane mode
Slight negative at 167,189, 264 cm^{-1} – implies in-plane mode
No change at 110 cm^{-1} – expected if interlayer cation 'rattle'

To better understand the dynamics of cation exchange reactions of important minerals, commonly used as environmental barriers to contaminated wastes such as radionuclides

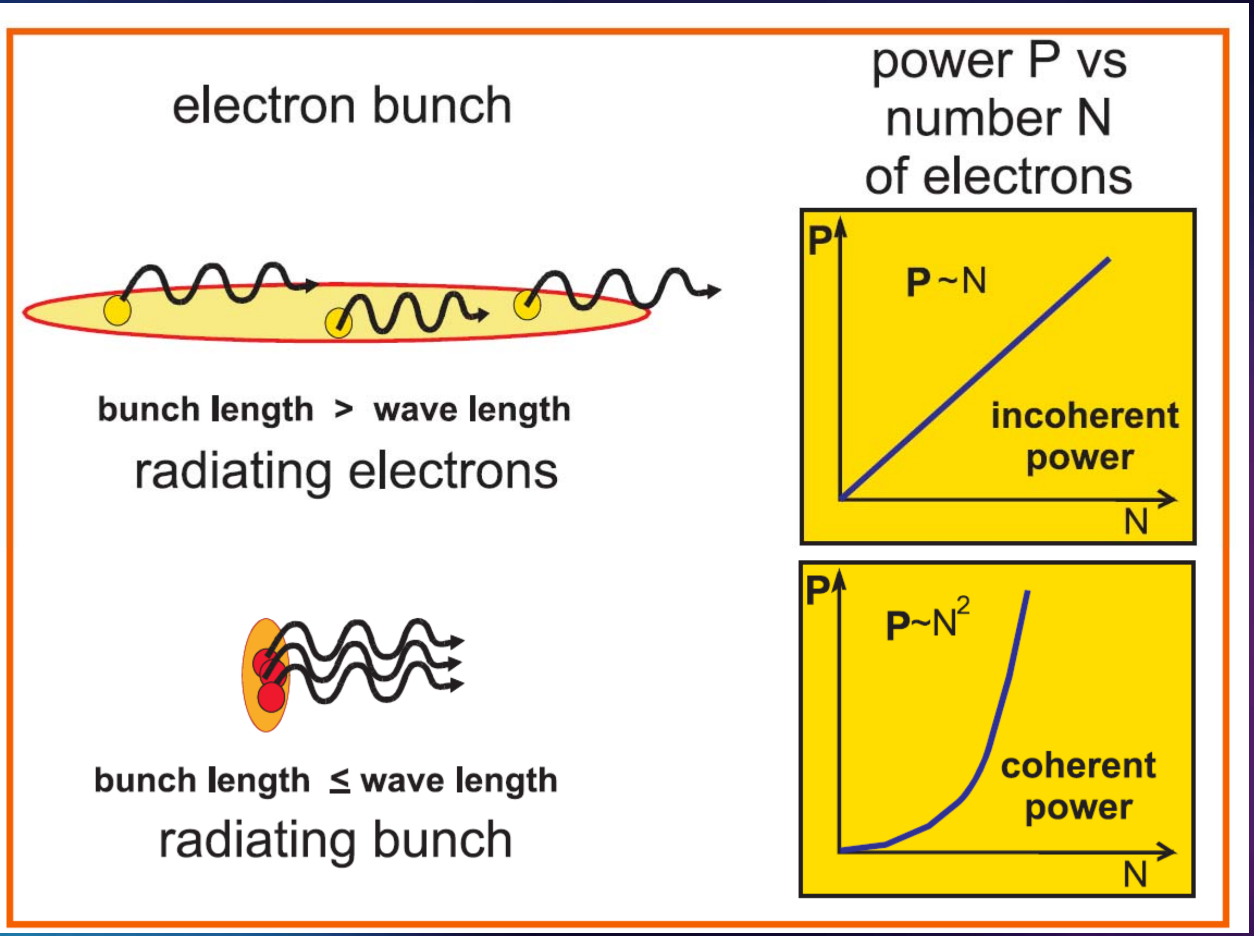
VI. COHERENT SYNCHROTRON RADIATION

Incoherent Synchrotron < 100 cm^{-1}



Coherent Synchrotron Radiation

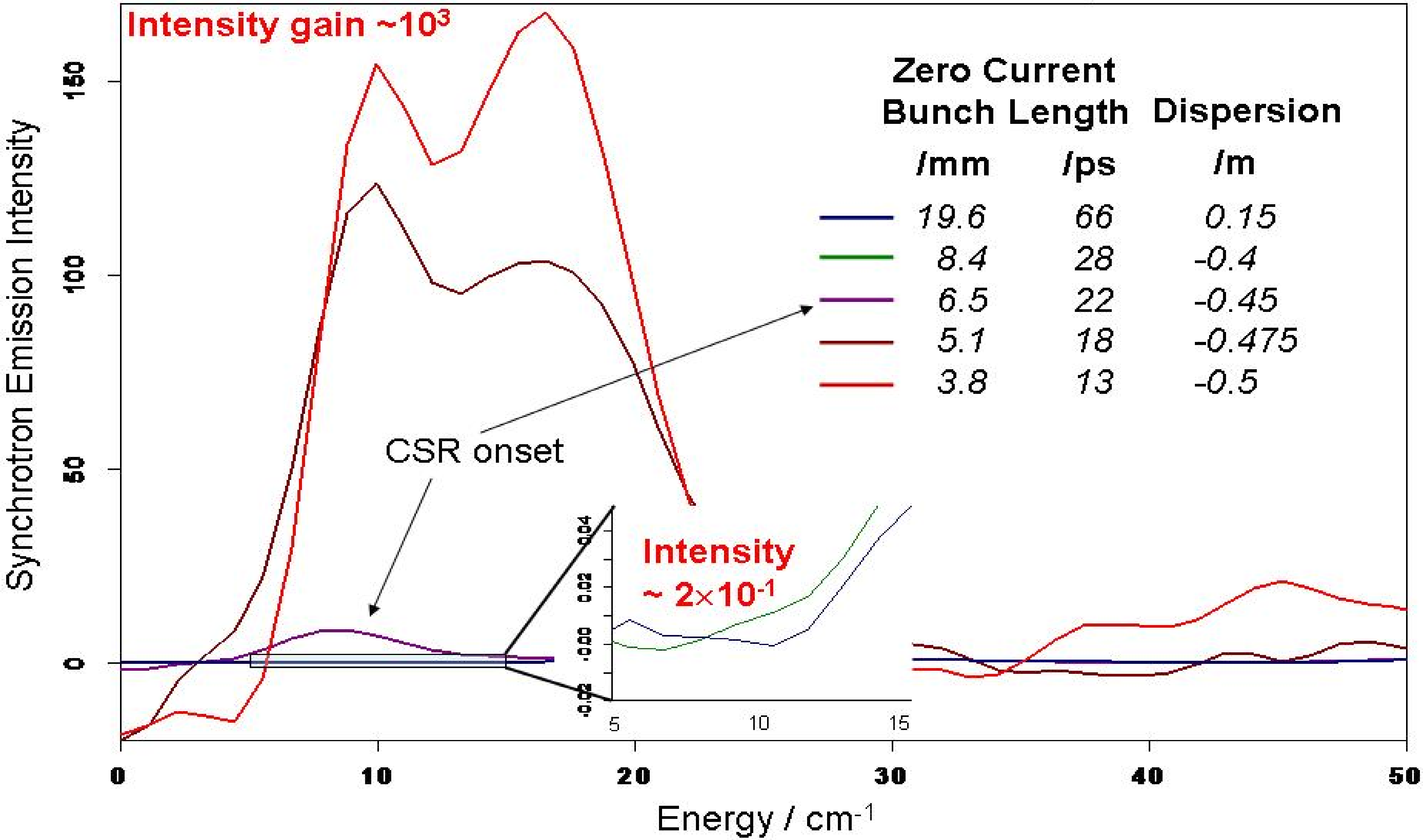
$$P_{SR} \propto N + N^2 e^{-(\omega \sigma_z / c)^2}$$



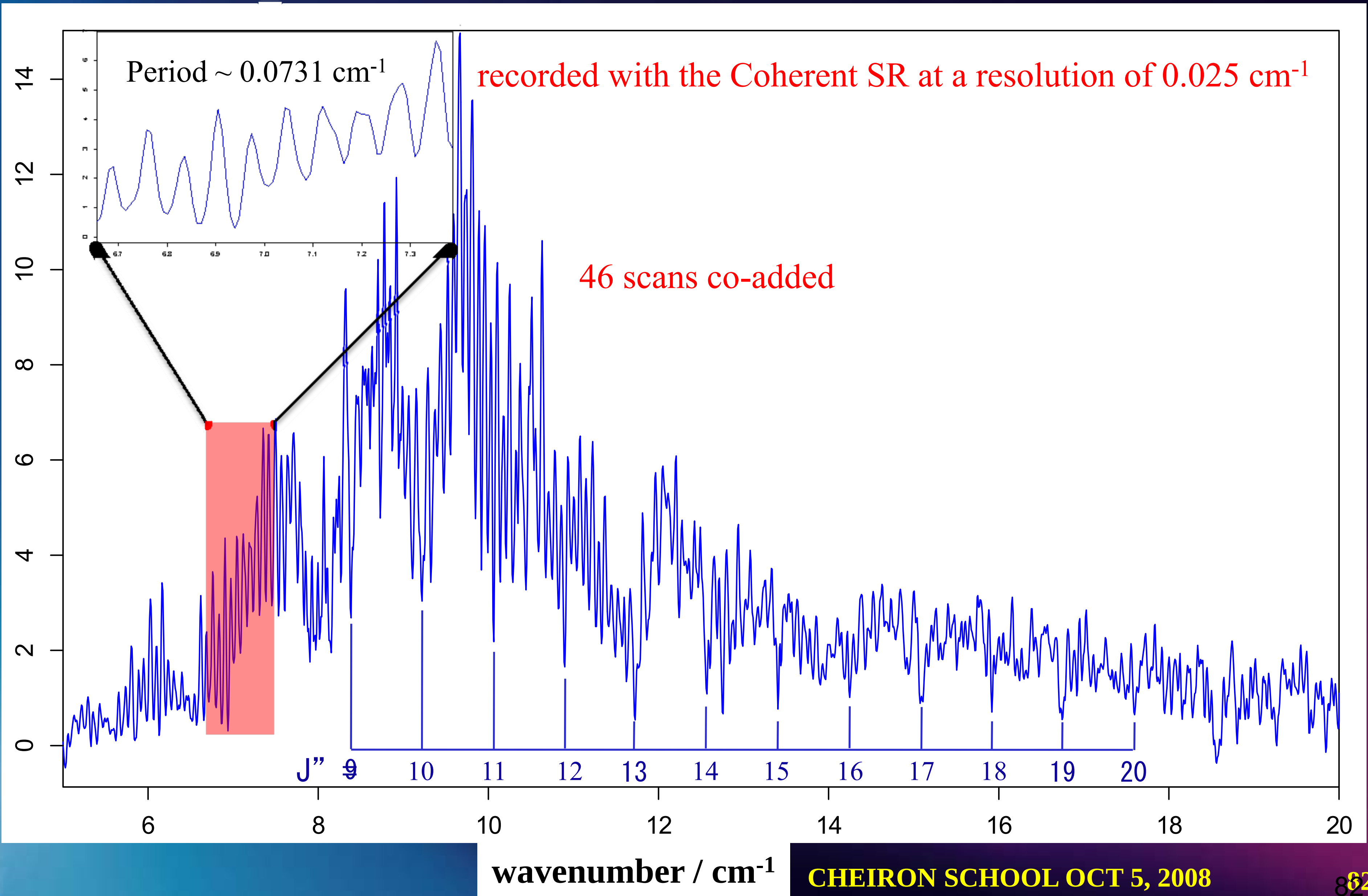
BESSY website

CSR at the CLS

Recorded with a 4.2 K Bolometer at the Far-IR Beamline on Jan 23, 2007: I ~ 11.6 mA



N_2O THz absorption spectrum



Summary

- Synchrotrons provide intense beams at long wavelengths into the Far-IR
- IR spectroscopy is used to provide information on the chemical composition of materials based on the vibration of the bonds present.
- Synchrotron IR allows these measurements to be made rapidly at a few microns dimension (micoscope), or at low concentration (and high SPECTRAL resolution).
- Synchrotron IR has applications in a diverse range of research areas.
- Future developments in the field will allow imaging below the diffraction limit and the use of intense Far-IR and Terahertz beams

Acknowledgements

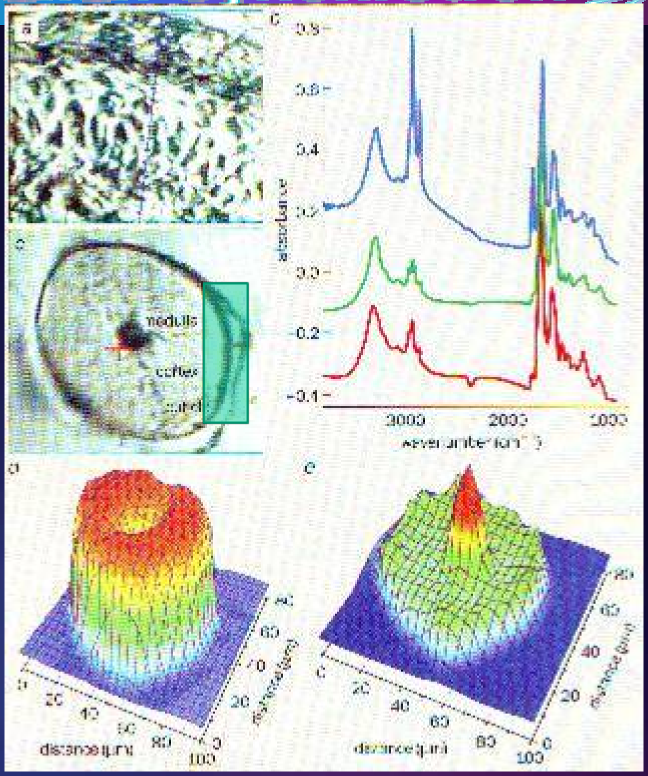
- Dudley Creagh – Canberra University
- Don McNaughton – Monash Univerrsity
- Phil Heraud – Monash Immunology and Stem Cell Laboratories
- Bayden Wood – Monash University
- Liz Carter – University of Sydney
- Peter Lay – University of Sydney
- Mark Hackett – University of Sydney
- Sally Caine - Monash Immunology and Stem Cell Laboratories
- Vivienne Juan - Monash Immunology and Stem Cell Laboratories
- Alice Brandli – Monash University
- Cassie Jean – Monash University
- Alana Treasure – Univerrsity of Canberra
- Bill van Bronswijk – Curtin University
- Evan Robertson – Monash University
- Ljiljana Puskar – Monash University
- Tarekegn Chimdi – Monash University
- Paul Dumas – Soleil
- Mike Martin – ALS
- Ulli Schade - BESSY II
- David Moss – ANKA
- Yves-Laurant Mathis – ANKA
- Jonathan McKinlay – Australian Synchrotron
- Nati Salvado – University of Barcelona
- Azzedine Hammiche – University of Lancaster
- John Prag – Manchester Museum
- FMB – Berlin
- Biolab/Bruker Instruments

Thanks…

Dominique Appadoo
Australian Synchrotron
800 Blackburn Road
Clayton 3168 VIC
AUSTRALIA

Tel: (03) 8540 4127
Email: dominique.appadoo@synchrotron.vic.gov.au

Infrared Spectroscopy



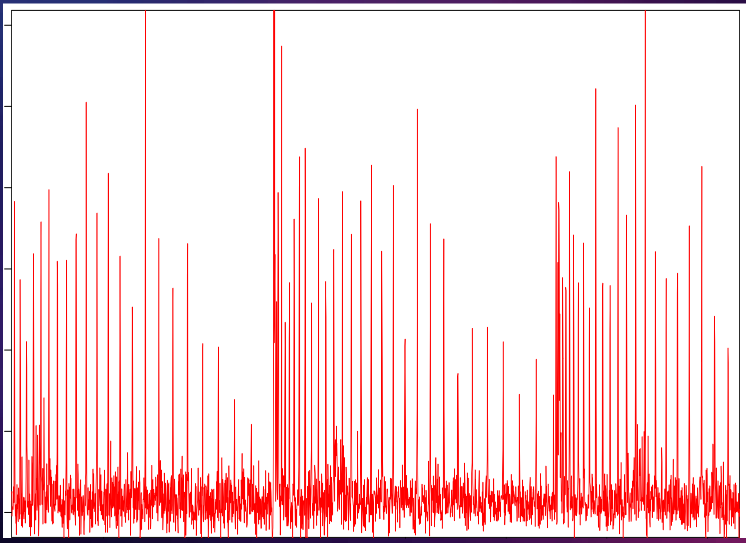
Energy range
0.001 eV to 1 eV (10 cm^{-1} to 10,000 cm^{-1})

Property accessible
molecular vibrations & rotations

Measurements
vibrational & rotational spectra

Information
molecular structure, chemical analysis

Synchrotron Benefits
signal to noise, spatial resolution
(down to the diffraction limit)



AS Contact Scientists

Dr Mark Tobin, 613 8540 4172
Dr Dominique Appadoo, +613 8540 4127
Dr Lillijana Puskar, 613 8540 4185