Infrared Detectors

an overview

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Sinbad IR beamline @ DaΦne

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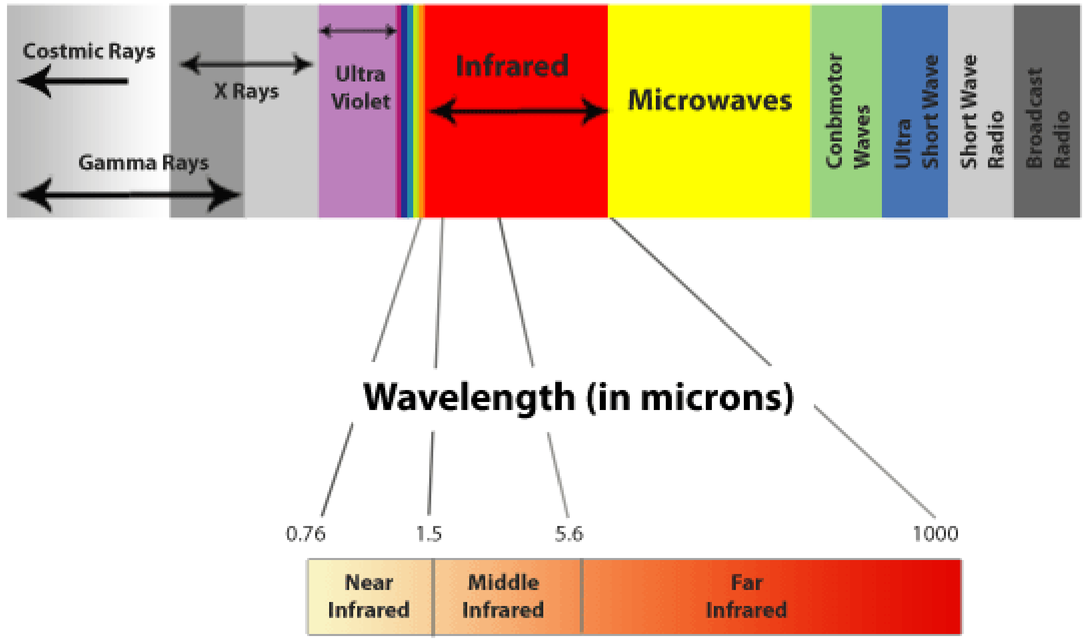
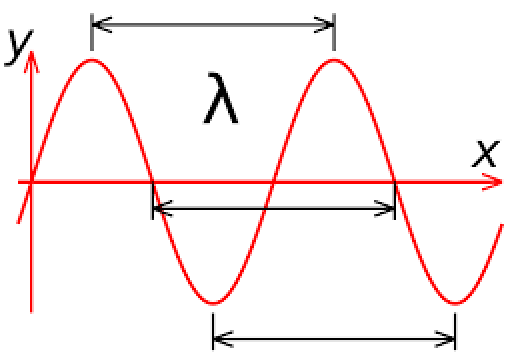
Fig. 1. Herschel's first experiment: A,B – the small stand, 1,2,3 – the thermometers upon it, C,D – the prism at the window, E – the spectrum thrown upon the table, so as to bring the last quarter of an inch of the read colour upon the stand (after Ref. 1). Inside Sir Frederick William Herschel (1738–1822) measures infrared light from the sun – artist's impression (after Ref. 2).

Frederick William Herschel
(1738–1822)
was born in Hanover, Germany but emigrated to Britain at age 19, where he became well known as both a musician and an astronomer.

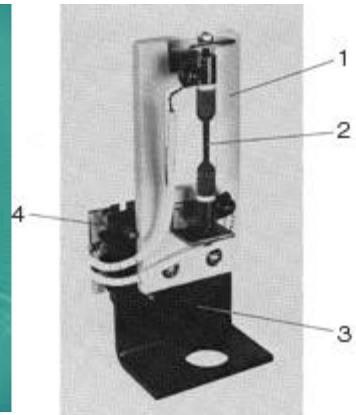
Herschel became most famous for the discovery of Uranus in 1781 in addition to two of its major moons, Titania and Oberon. He also discovered two moons of Saturn and infrared radiation. Herschel is also known for the twenty−four symphonies that he composed.

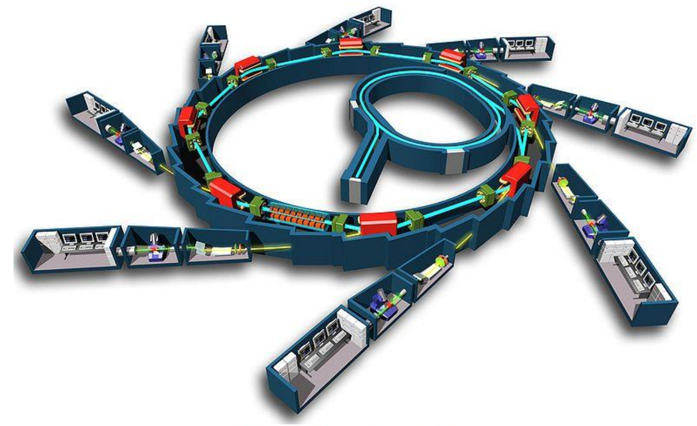


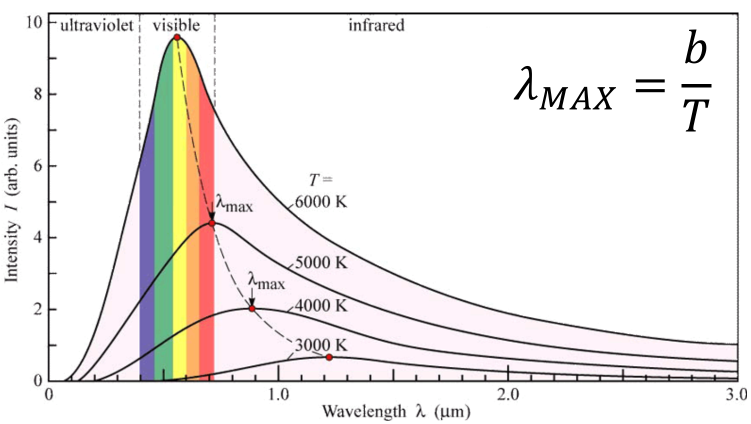


$$\tilde{\nu}\ (cm^{-1}) = 1/\lambda\ (cm) = 10^{7}/\lambda\ (nm)$$

IR radiation sources

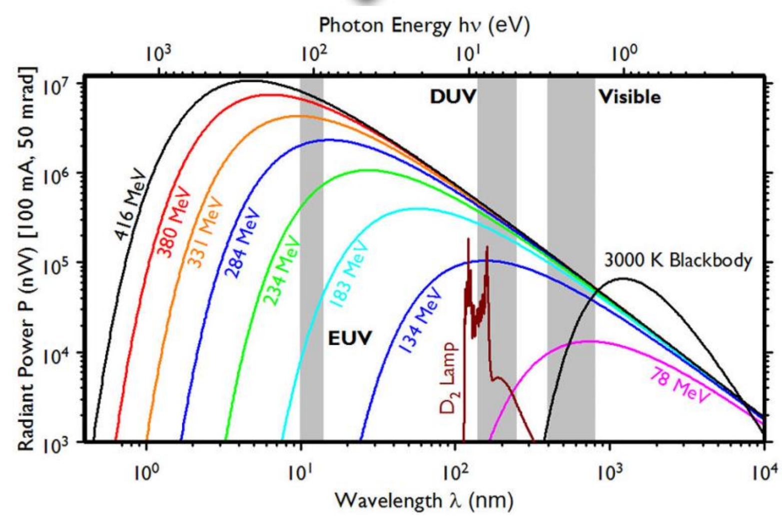






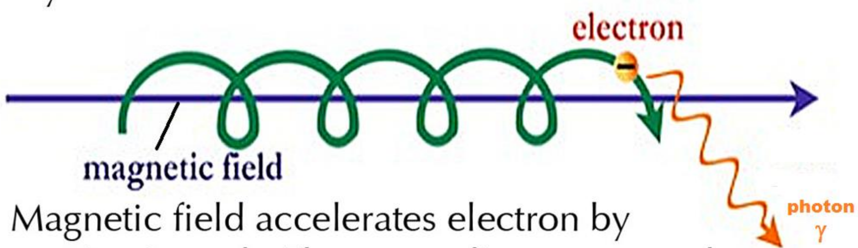
$$\lambda_{MAX} = \frac{b}{T}$$

Black body radiation, thermal source
Plank spectral distribution



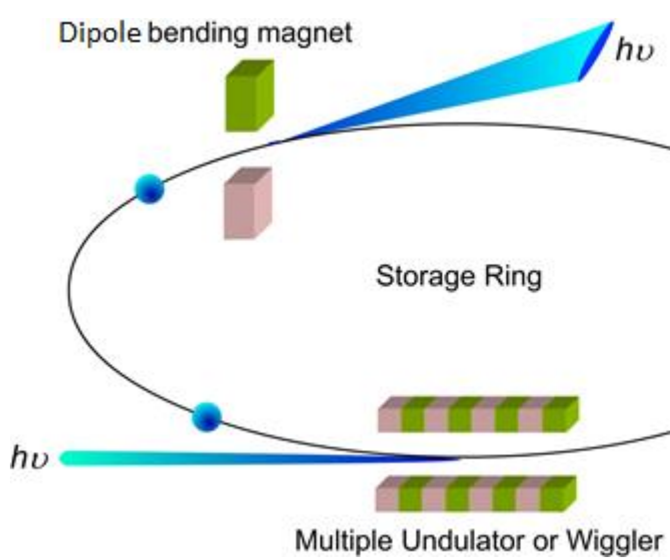
Synchrotron radiation: the emitted power depends on the particle energy

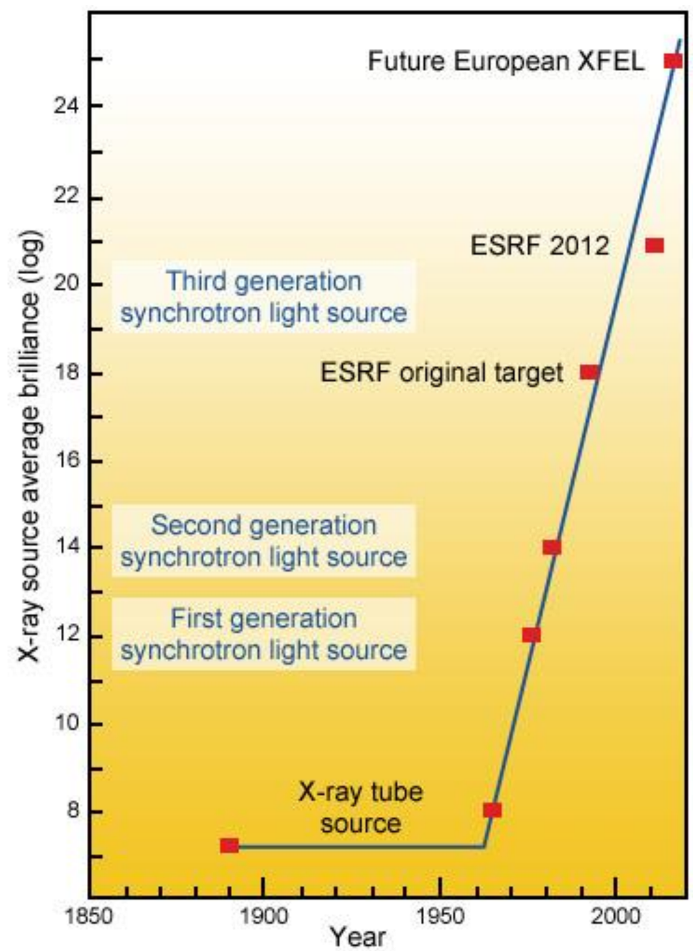
Synchrotron radiation



Magnetic field accelerates electron by curving its path. Electron radiates as a result.

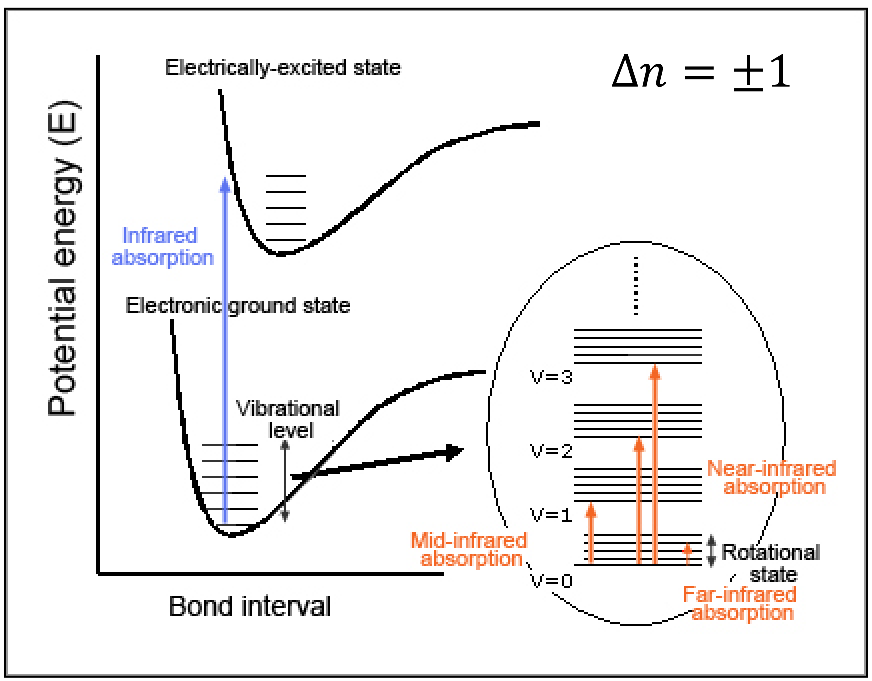
$$\text{brilliance} = \frac{\text{photons}}{\text{second} \cdot \text{mrad}^2 \cdot \text{mm}^2 \cdot 0.1\%\ \text{BW}}$$

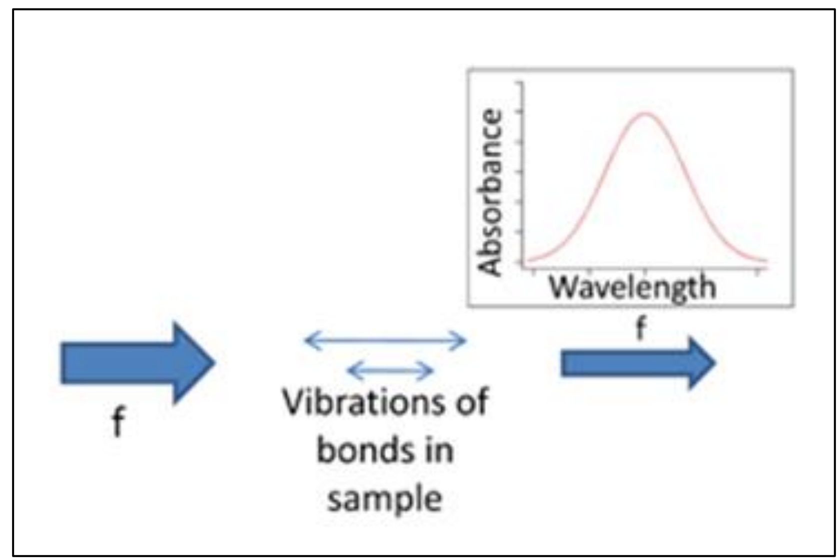


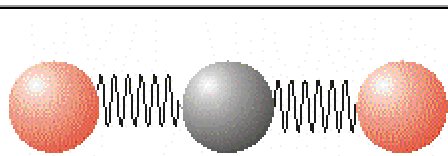


Infrared spectroscopy

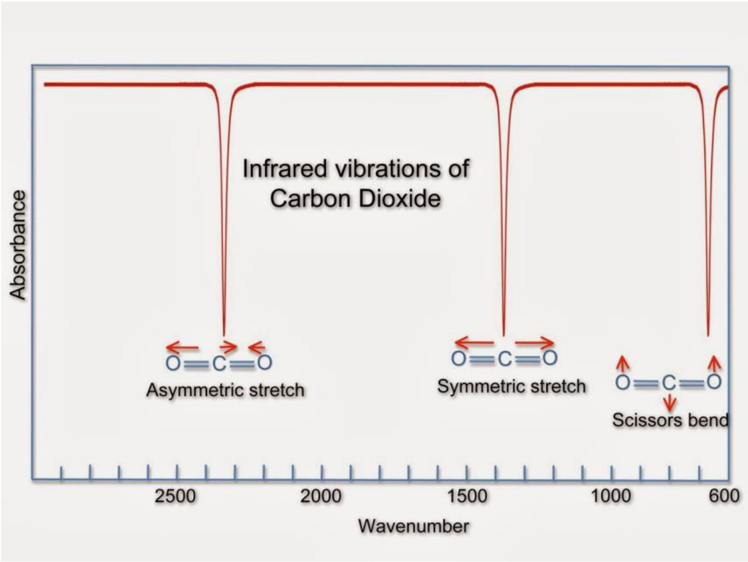
Infrared spectroscopy measures the absorption of IR light by a molecule:

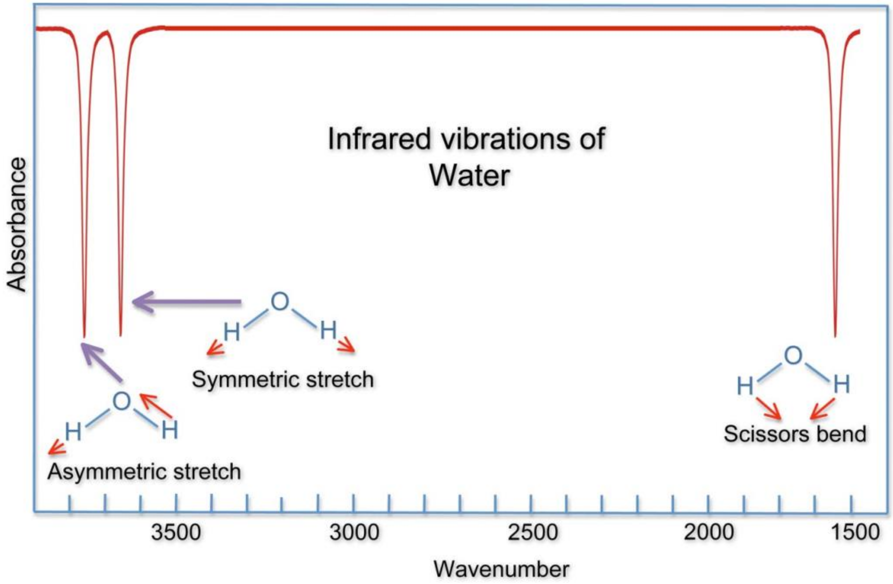




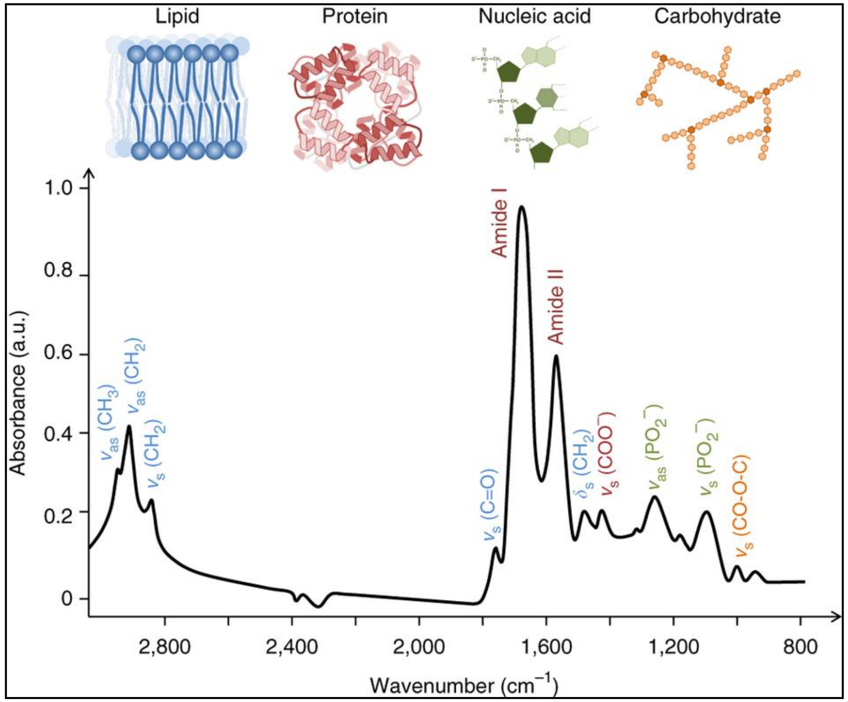


IR active modes

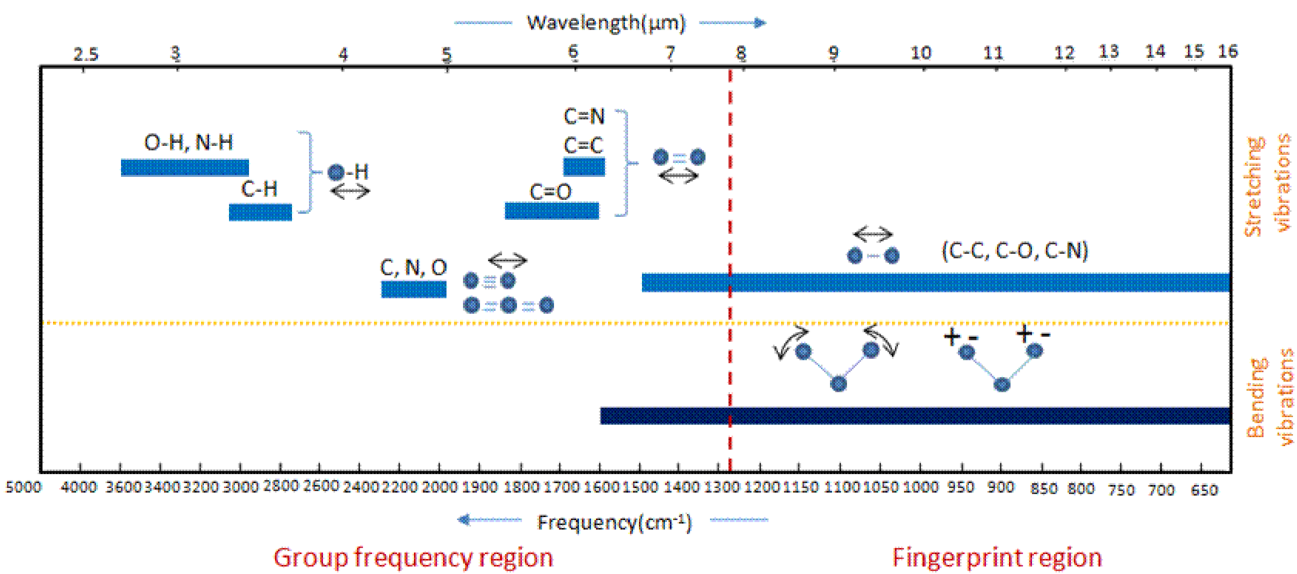




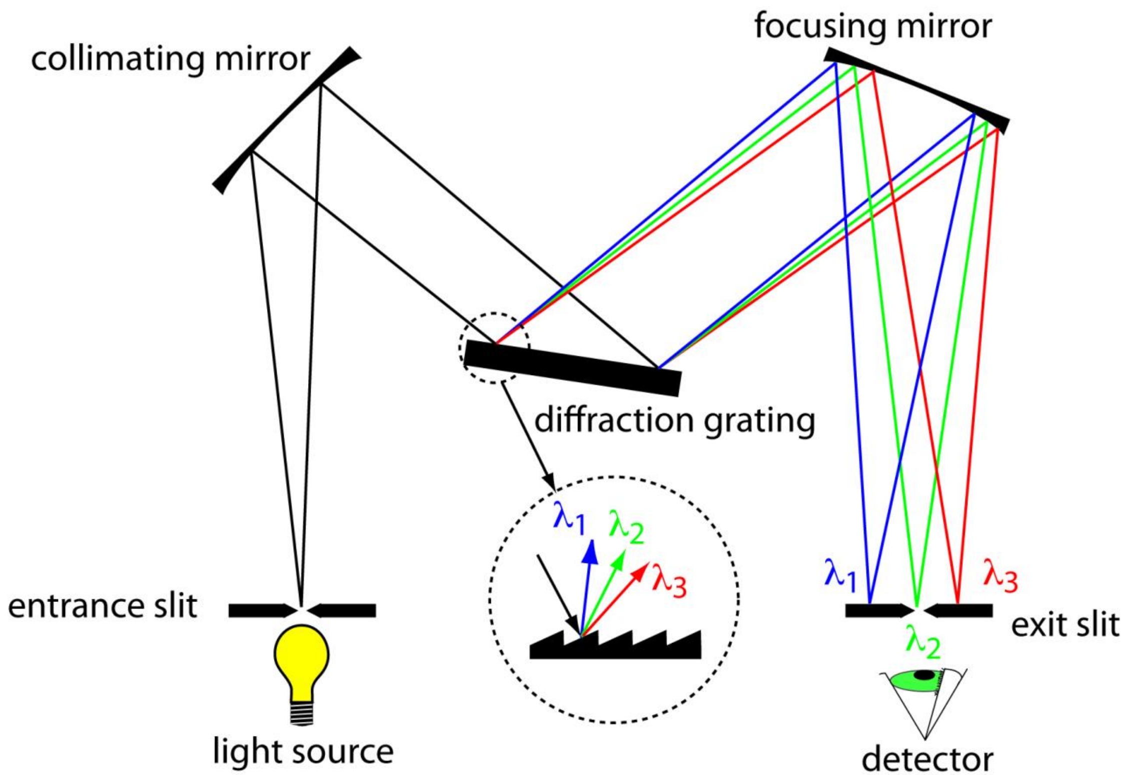
(http://giantsoftheinfinitesimal.co.uk/)



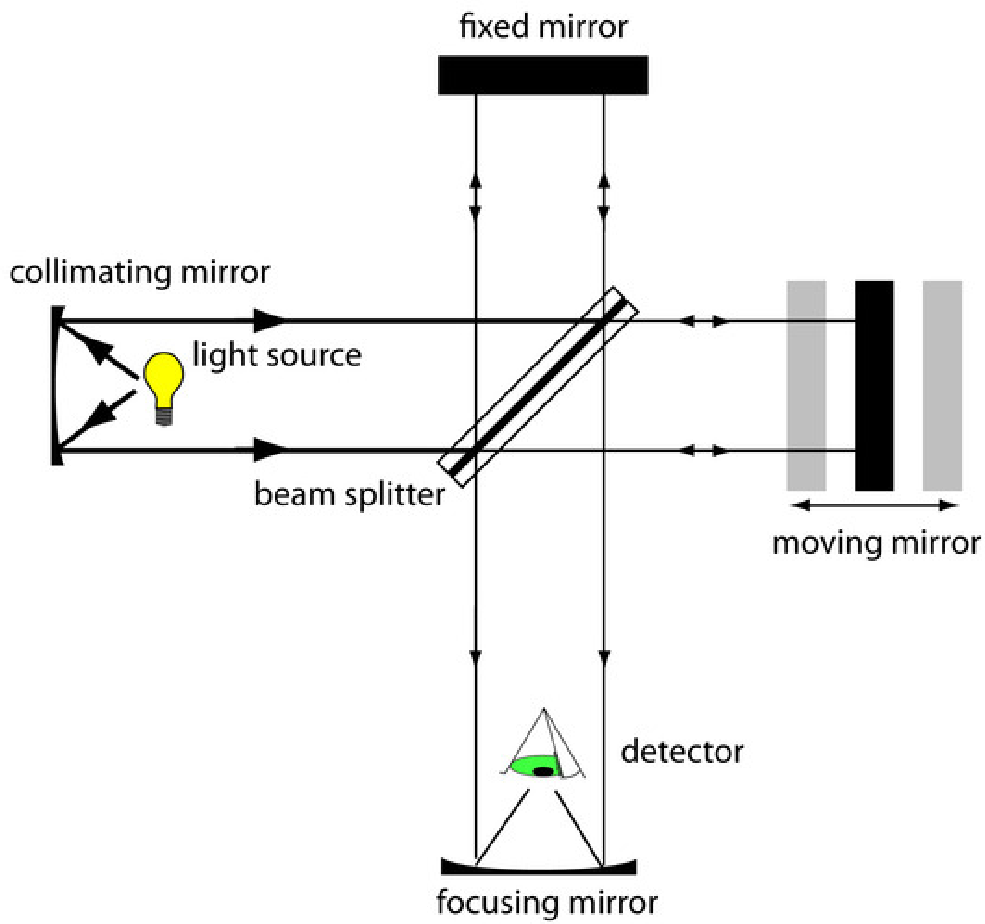
Nature Protocols 9, 1771–1791 (2014)

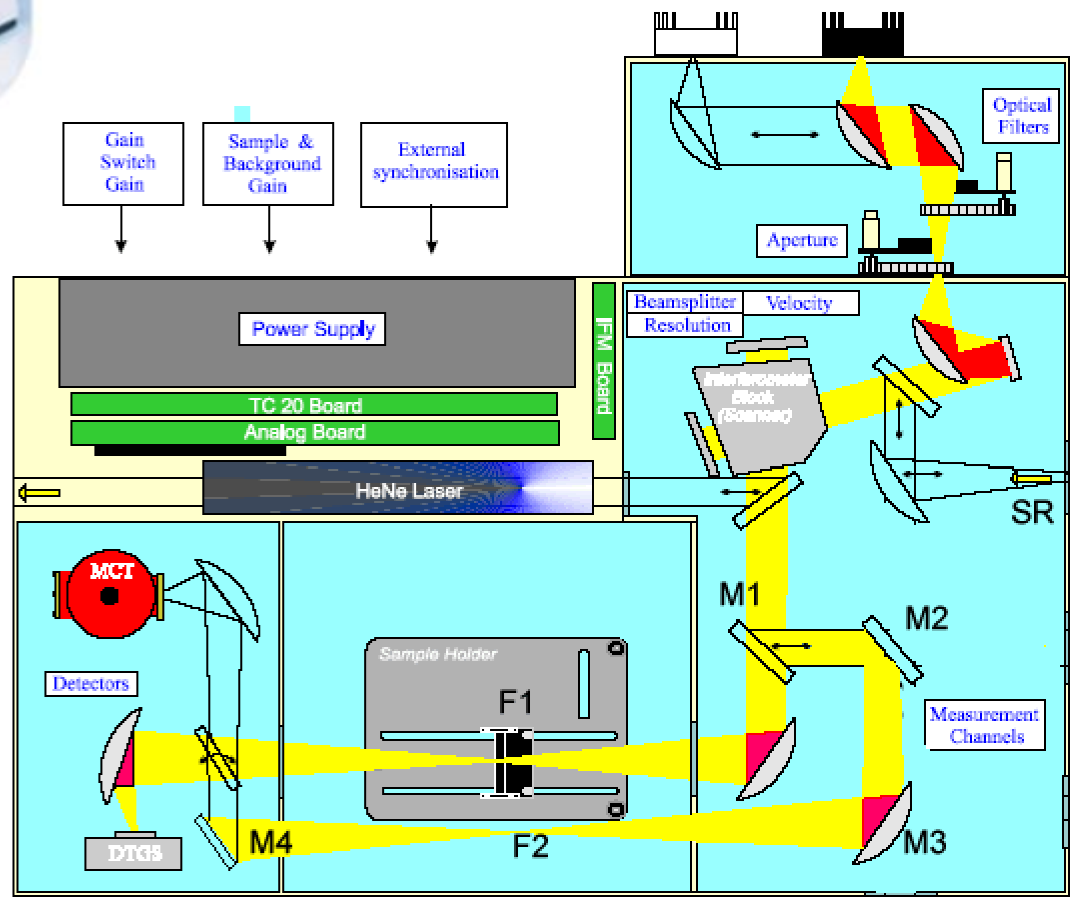


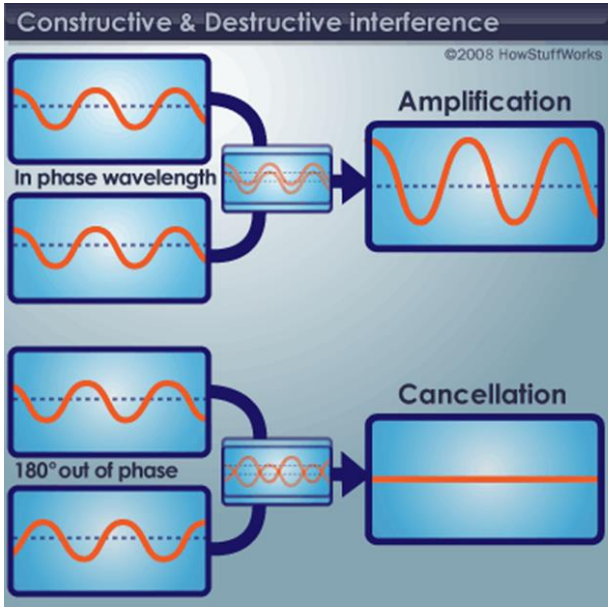
Wavelength Selection: Monochromators



Wavelength selection: Michelson interferometer



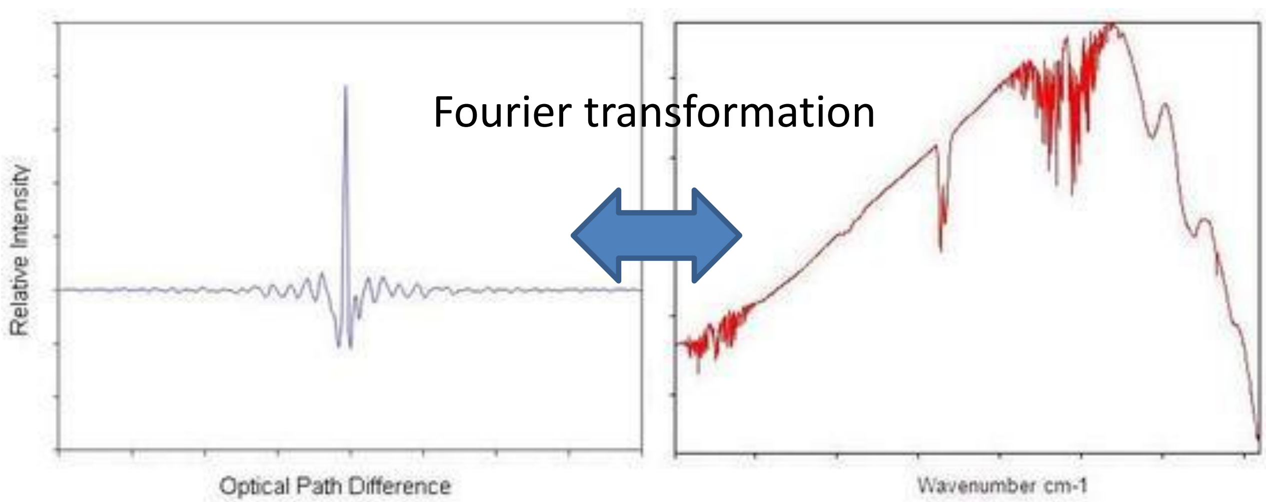

Gain Switch Gain
Sample & Background Gain
External synchronisation
Power Supply
TC 20 Board
Analog Board
IFM Board
HeNe Laser
Optical Filters
Aperture
Beamsplitter
Resolution
Velocity
SR
M1
M2
M3
M4
F1
F2
Sample Holder
Measurement Channels
MCT
Detectors
DTGS



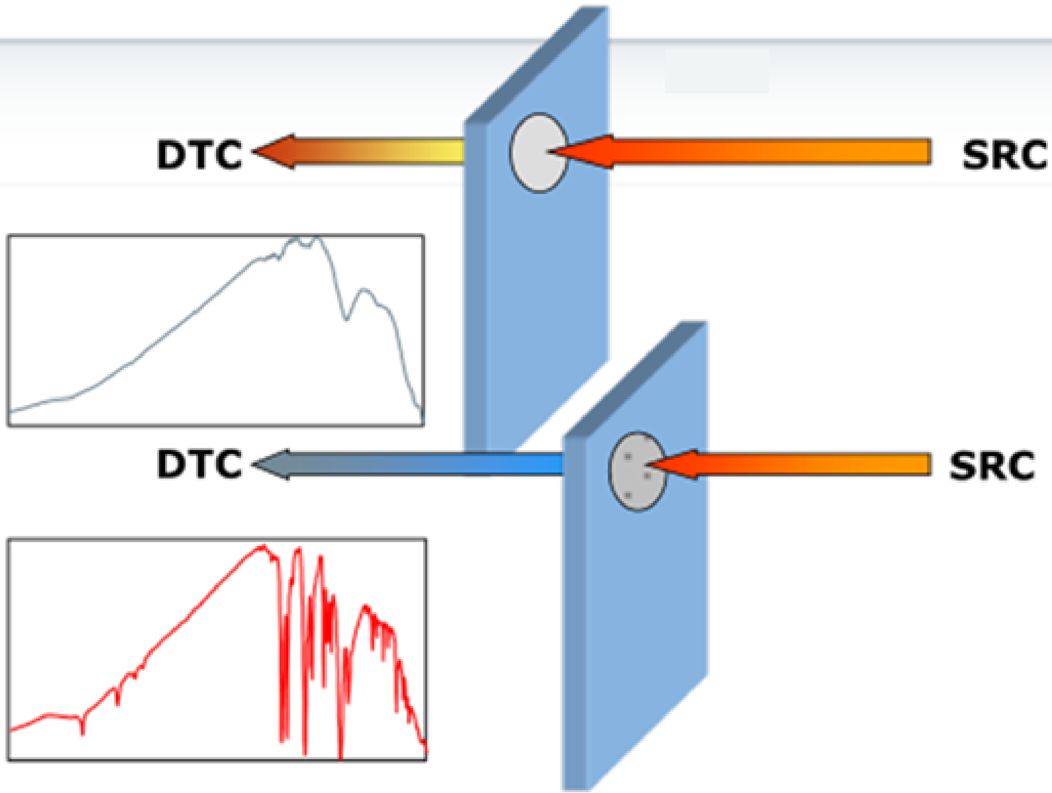
$$\text{OPD} = 2n\frac{\lambda}{2}\ (n = 0, \pm1, \pm2, \ldots)$$

$$\text{OPD} = (2n+1)\frac{\lambda}{2}\ (n = 0, \pm1, \pm2, \ldots)$$

The interferogram gives the amplitude of each frequency contained in the IR source of radiation:



- Background (I_0)
- sample (I)

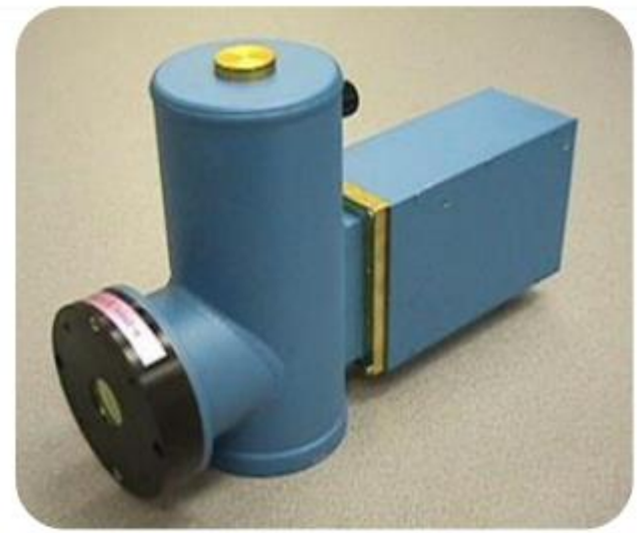


$$T = \frac{I}{I_0} \qquad A = \log\frac{1}{T} = -\log T$$

Infrared detectors

Bolometer (FAR IR)

Mercury Cadmium Telluride (MCT)
Pyroelectrics (DTGS FIR, MIR)

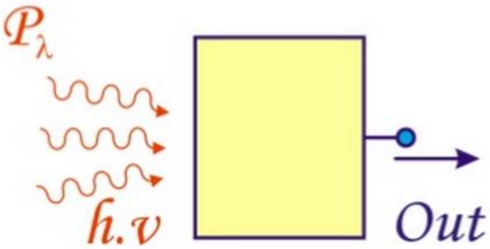


Focal Plane Array (FPA) 64x64 pixel

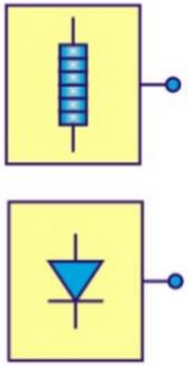
We shall not attempt to cover the entire field of light detection, which is very broad. Instead, we shall emphasize those detectors that are most commonly encountered. We shall also define some of the common terminology.

How detect IR radiation ?

- We have to use a “Photo-Detector”



- A photo-detector has to convert :
  - Incident radiation P_λ (W/m²)
  - Into an output electrical signal



- This electrical signal can be :
  - A resistance change ΔR
    - *In case of a photoconductor or a bolometer*
  - A photocurrent
    - *In case of a Photo Voltaic detector*

Infrared detectors

Thermal

- Bolometers
- Pyroelectrics
- Golay cells

In a thermal detector the incident radiation is absorbed to change the material temperature and the resultant change in some physical property is used to generate an *electrical output*. The signal does not depend upon the photonic nature of the incident radiation. Thus, thermal effects are generally **wavelength independent**.

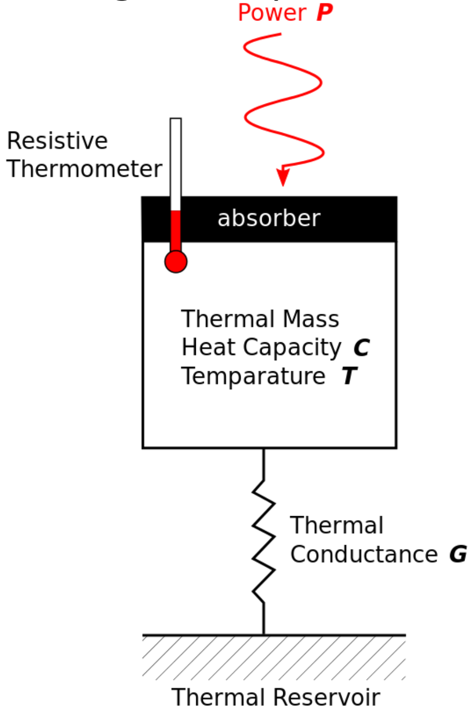
Photonic

- Photomultipliers
- Photoresistances
- Photodiodes

In photon detectors the radiation is absorbed within the material by **interaction with electrons** either bound to lattice atoms or to impurity atoms or with free electrons. The observed electrical output signal results from the changed electronic energy distribution.

Thermal detectors

In a thermal detector the incident radiation is absorbed to change the material temperature and the resultant change in *some physical property* (resistivity, magnetization, pressure) is used to generate an electrical output. The detector is suspended on legs which are connected to the heat sink. The signal does not depend upon the photonic nature of the incident radiation. Thus, thermal effects are generally wavelength independent.



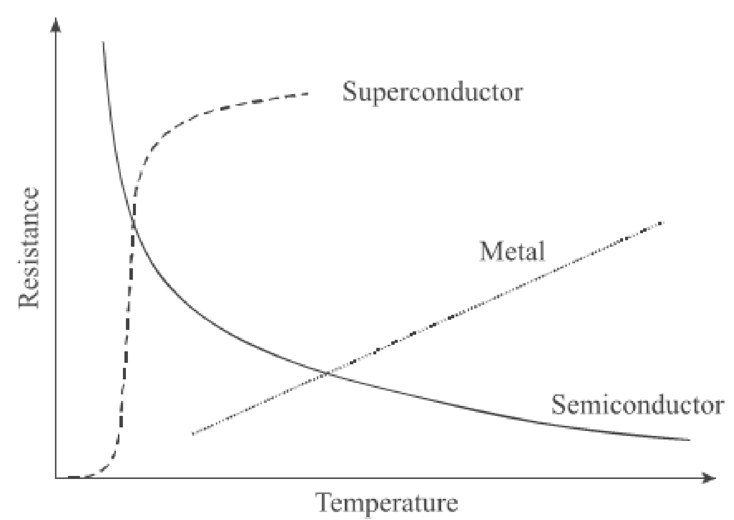
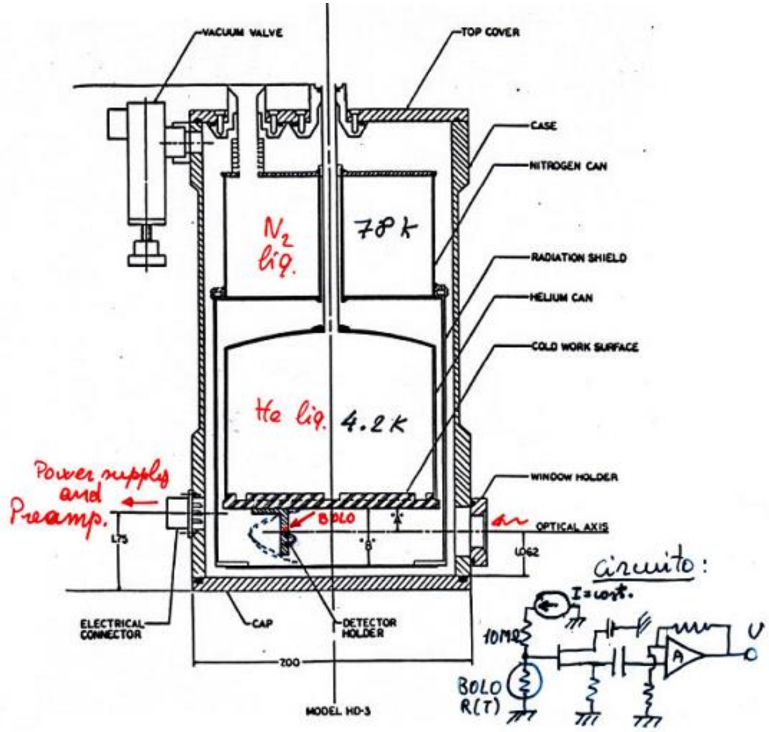


Fig. 11. Temperature dependence of resistance of three bolometer material types.

For a long time, thermal detectors were **slow (ms)**, **insensitive**, **bulky** and **costly** devices. But with developments of the semiconductor technology, they can be optimized for specific applications.

Usually, a **Bolometer** is a thin, blackened flake or slab, whose *impedance* is highly temperature dependent.



Photon detectors

In photon detectors the radiation is absorbed within the material by **interaction with electrons** either bound to lattice atoms or to impurity atoms or with free electrons. The observed electrical output signal results from the **changed electronic energy distribution**. The thermal transitions compete with the optical ones, making non−cooled devices very noisy.

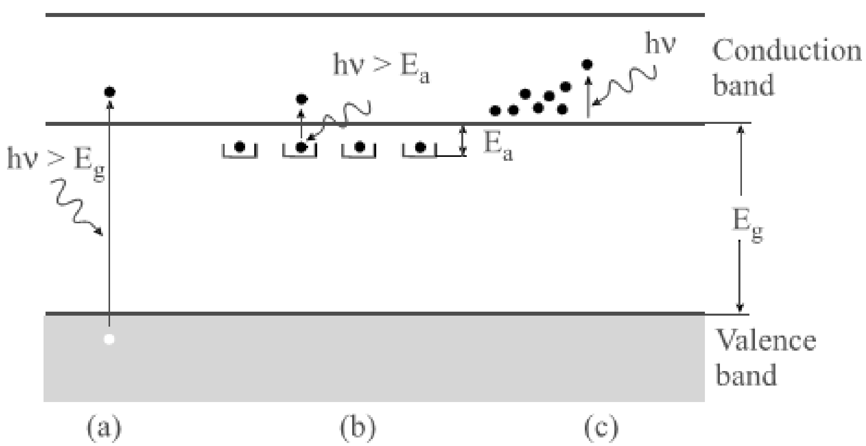
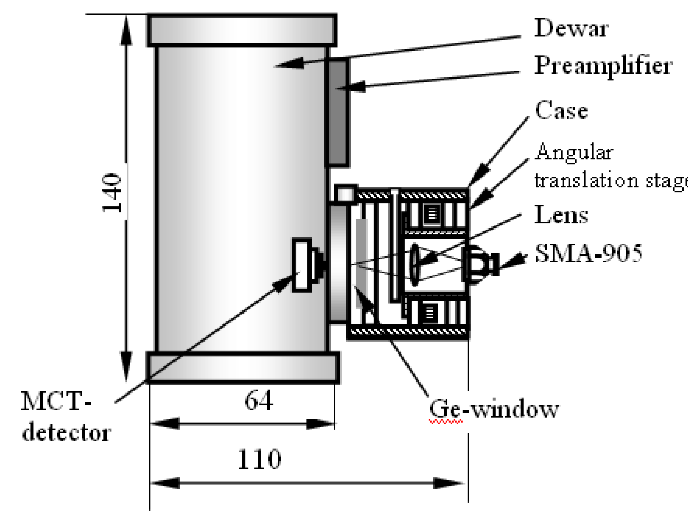


Fig. 7. Fundamental optical excitation processes in semiconductors: (a) intrinsic absorption, (b) extrinsic absorption, (c) free carrier absorption.



Photon detectors may be further subdivided into the following groups:

- **<u>Photoconductive</u>**. The electrical conductivity of the material changes as a function of the intensity of the incident light. Photoconductive detectors are *semiconductor* materials. They have an external electrical bias voltage.

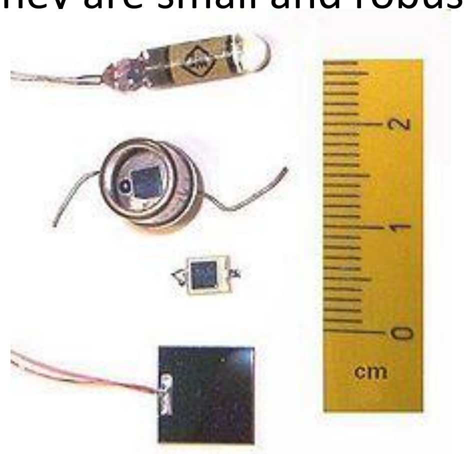
- **<u>Photovoltaic</u>**. These detectors contain a p-n semiconductor junction and are often called photodiodes. A voltage is self generated as radiant energy strikes the device. The photovoltaic detector may operate without external bias voltage. A good example is the solar cell used on spacecraft and satellites to convert the sun's light into useful electrical power.

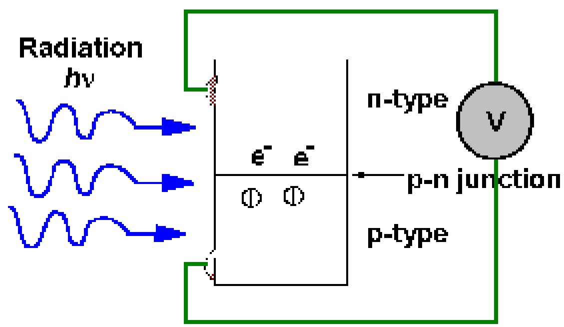
- **<u>Photoemissive</u>**. These detectors use the photoelectric effect, in which incident photons free electrons from the surface of the detector material. These devices include vacuum photodiodes, bipolar phototubes, and photomultiplier tubes.

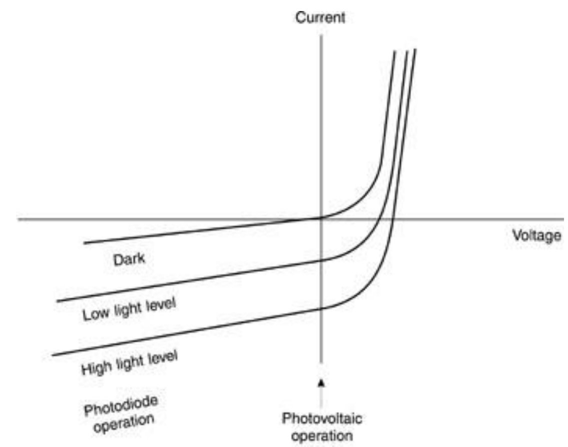
Photodiodes

When a photon strikes a semiconductor, it can promote an electron from the valence band (filled orbitals) to the conduction band (unfilled orbitals) creating an electron(-) - hole(+) pair. The concentration of these electron-hole pairs is dependent on the amount of light striking the semiconductor, making the semiconductor suitable as an optical detector.

There are two ways to monitor the concentration of electron-hole pairs. In **photodiodes**, a voltage bias is present and the concentration of light-induced electron-hole pairs determines the current through semiconductor. **Photovoltaic detectors** (zero bias) contain a p-n junction, that causes the electron-hole pairs to separate to produce a voltage that can be measured. Photodiode detectors are not as sensitive as PMTs but they are small and robust.

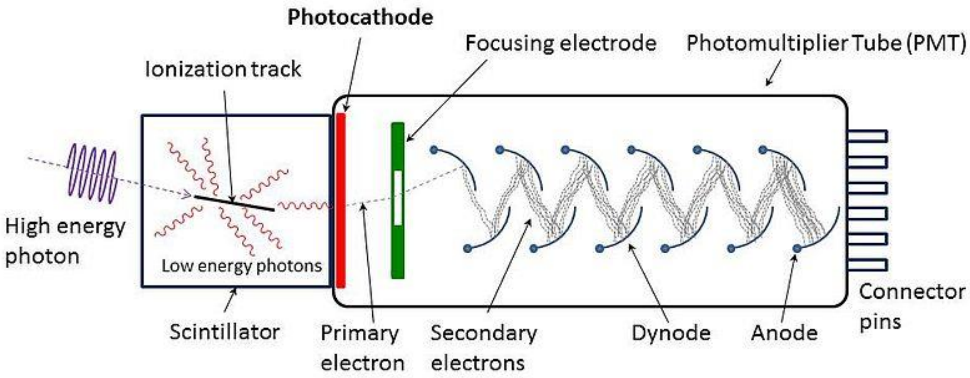






PMTs and the photoelectric effect

In a photomultiplier tube (PMT), when an incident photon hits the entrance photocathode, a primary electron is produced, ejected, and further collected and amplified by a series of dynodes. The resulting current generated at the exit anode is proportional in amplitude to the incident light intensity. Due to high internal gain (10^5 to 10^7 electrons for each photon hitting the first cathode), PMTs are very sensitive detectors, useful in low intensity applications such as fluorescence spectroscopy.



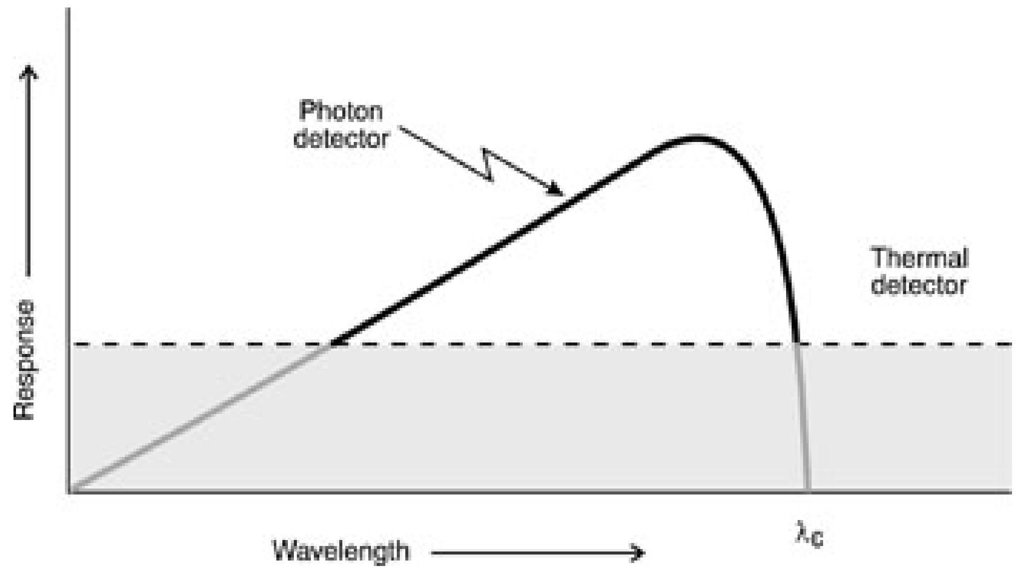
Figures of merit

- Responsivity: measures the input–output gain of a detector system.

$$\Re = \frac{Vout}{IRinput} = \frac{V_s}{HA_d} \qquad [A/W]$$

- The responsivity can be represented as a function of the wavelength
  - Which will define a band where the device is active

Because **thermal detectors** rely on only the amount of heat energy delivered, their response is independent of wavelength.



The wavelength response of **photon detectors** shows a long-wavelength cutoff. When the wavelength is longer than the cutoff wavelength, the photon energy is too small to excite an electron to the conduction band and the response of the detector drops to zero.

- NEP (Noise Equivalent Power)

is a measure of the sensitivity of a photodetector or detector system. This is defined as the radiant power that produces a signal voltage (current) equal to the noise voltage (current) of the detector. Since the noise is dependent on the bandwidth of the measurement, that bandwidth must be specified.

$$NEP = \frac{Noise}{Responsivity} \qquad [W/Hz^{1/2}]$$

NEP depends on the detector area!

- Detectivity $D^* = \frac{\sqrt{A f}}{NEP}$ [cm x $Hz^{1/2}$/W]

The importance of D* is that this figure of merit permits comparison of detectors of the same type, but having different areas.

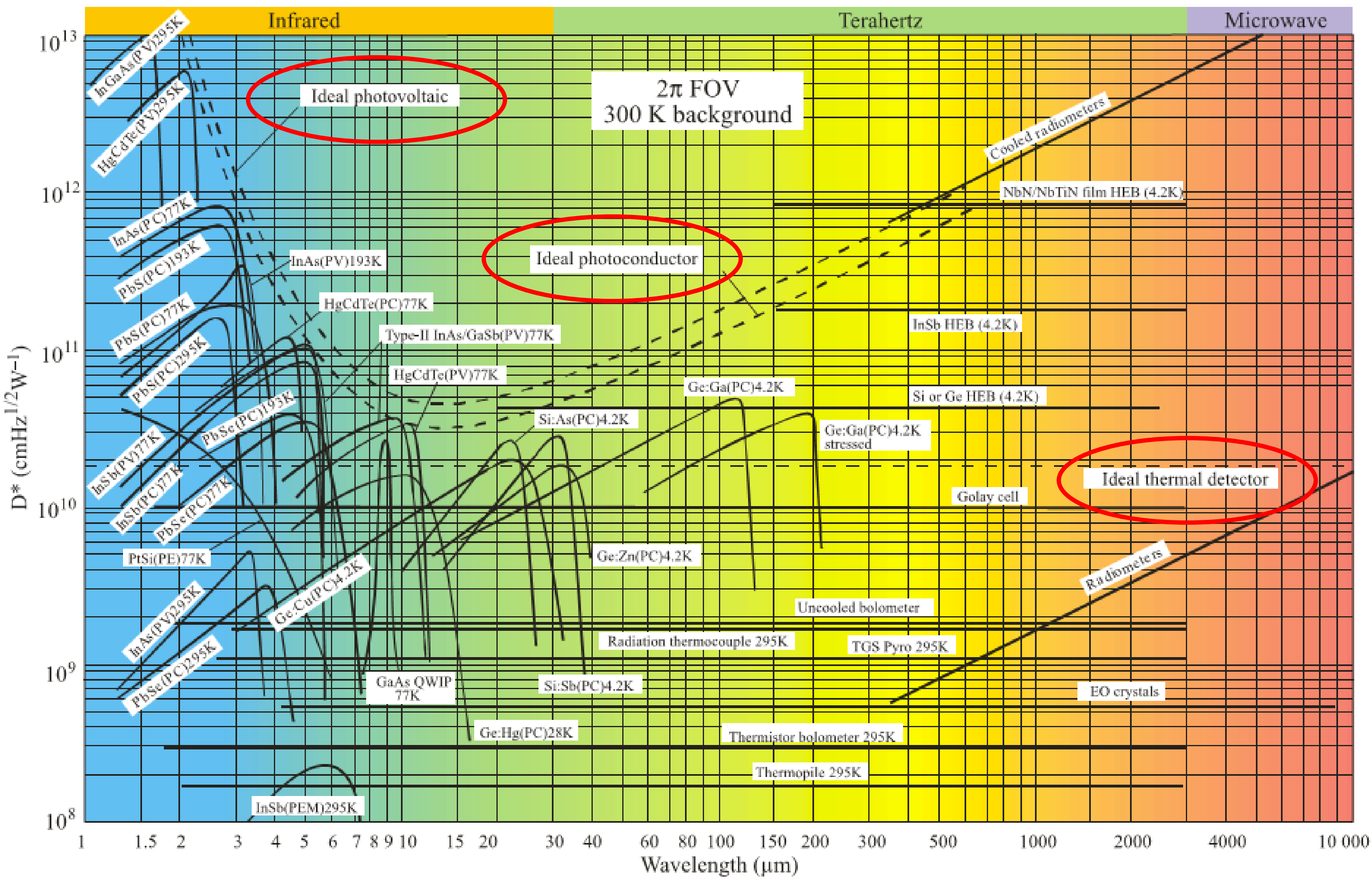
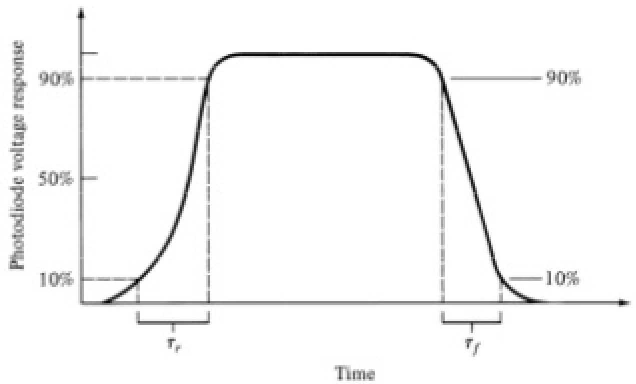


Fig. 9. Comparison of the D^* of various available detectors when operated at the indicated temperature. Chopping frequency is 1000 Hz for all detectors except the thermopile (10 Hz), thermocouple (10 Hz), thermistor bolometer (10 Hz), Golay cell (10 Hz) and pyroelectric detector (10 Hz). Each detector is assumed to view a hemispherical surrounding at a temperature of 300 K. Theoretical curves for the background-limited D^* (dashed lines) for ideal photovoltaic and photoconductive detectors and thermal detectors are also shown. PC – photoconductive detector, PV – photovoltaic detector, PEM – photoelectromagnetic detector, and HEB – hot electron bolometer.

Speed of the detector response to changes in light intensity

If a constant source of light energy is instantaneously turned on and irradiates a photodetector, it will take a finite time for current to appear at the output of the device and for the current to reach a steady value. If the same source is turned off instantaneously, it will take a finite time for the current to decay back to its initial zero value. The term **response** time generally refers to the time it takes the detector current to rise to a value equal to 63.2% (1- 1/e) of the steady-state value reached after a relatively long period of time. The recovery time is the time photocurrent takes to fall to 36.8% of the steady-state value when the light is turned off instantaneously.



Because photodetectors often are used for detection of fast pulses, a more important term, called **rise time**, is often used to describe the speed of the detector response. Rise time is defined as the time difference between the points at which the detector has reached 10% of its peak output and the point at which it has reached 90% of its peak response, when it is irradiated by a very short pulse of light. The **fall time** is defined as the time between the 90% point and the 10% point on the trailing edge of the pulse waveform. This is also called the decay time. We note that *the fall time may be different numerically from the rise time.*

Linearity of the detector response

Another important characteristic of detectors is their linearity. **Photodetectors** are characterized by a response that is linear with incident intensity over a broad range, perhaps many orders of magnitude.

Noise will determine the lowest level of incident light that is detectable. The upper limit of the input/output linearity is determined by the maximum current that the detector can handle without becoming saturated. Saturation is a condition in which there is no further increase in detector response as the input light is increased.

Linearity may be quantified in terms of the maximum percentage deviation from a straight line over a range of input light levels. For example, the maximum deviation from a straight line could be 5% over the range of input light from 10^{-12} W/cm^2 to 10^{-4} W cm^2. One would state that the linearity is 5% over eight orders of magnitude in the input.

Focal plane arrays – revolution in imaging systems

The term “focal plane array” (FPA) refers to an assemblage of individual detector picture elements (“pixels”) located at the focal plane of an imaging system

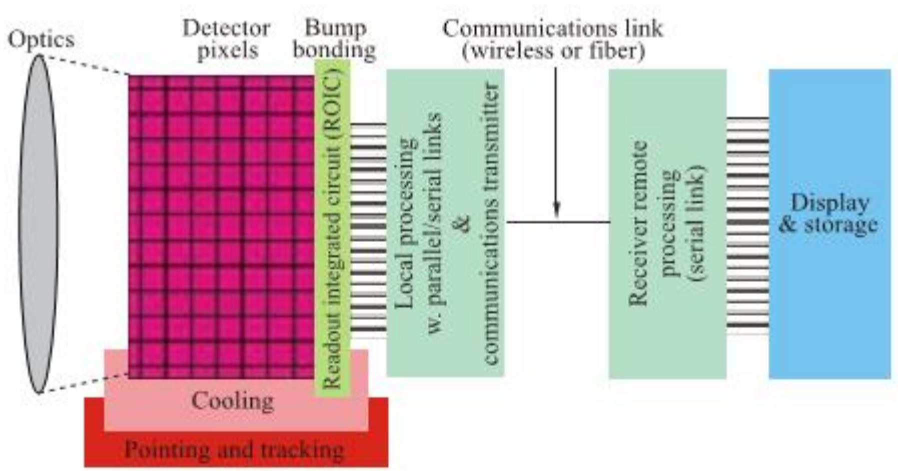


Fig. 27. Schematic representation of an imaging system showing important sub-systems (after Ref. 93).

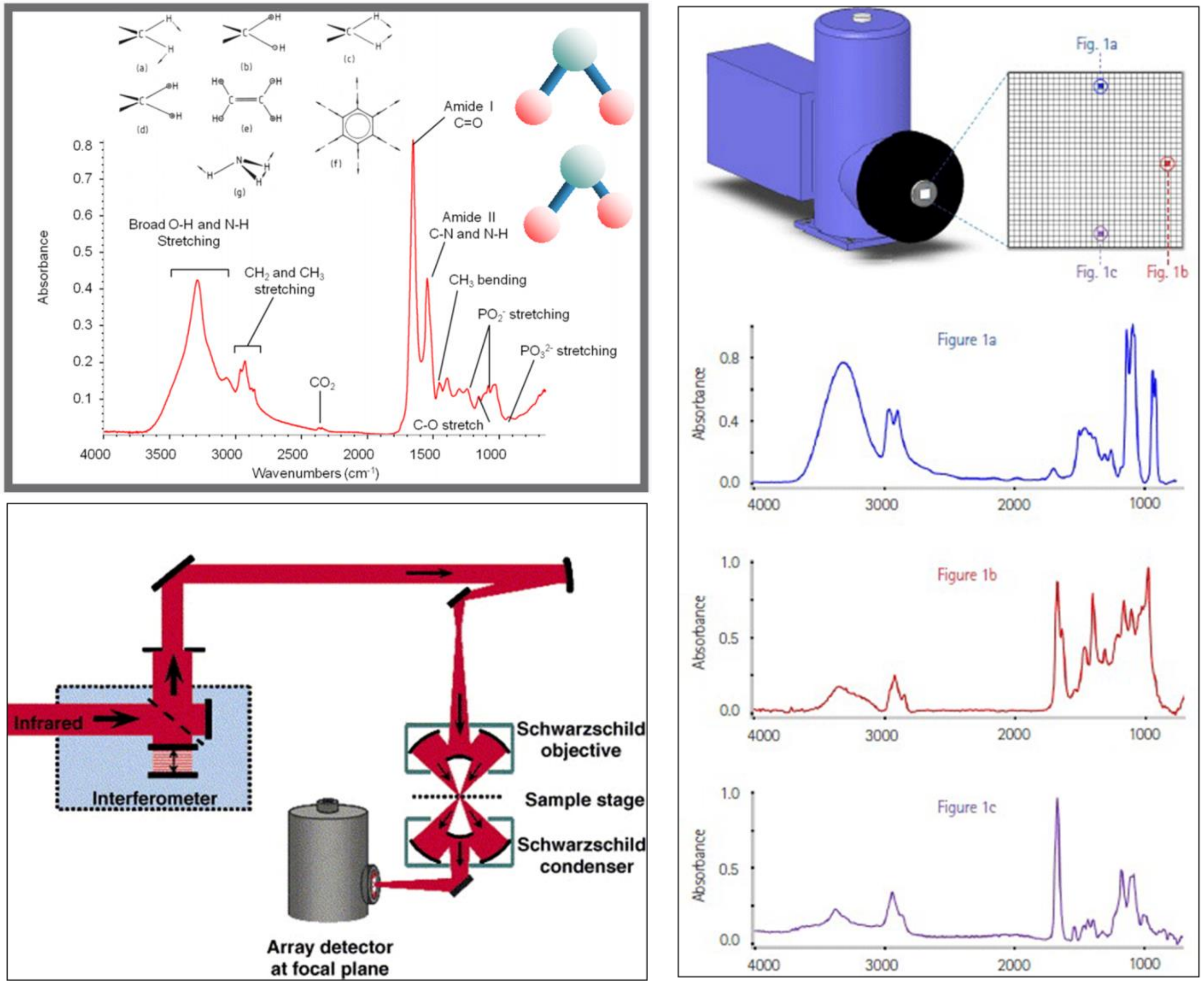
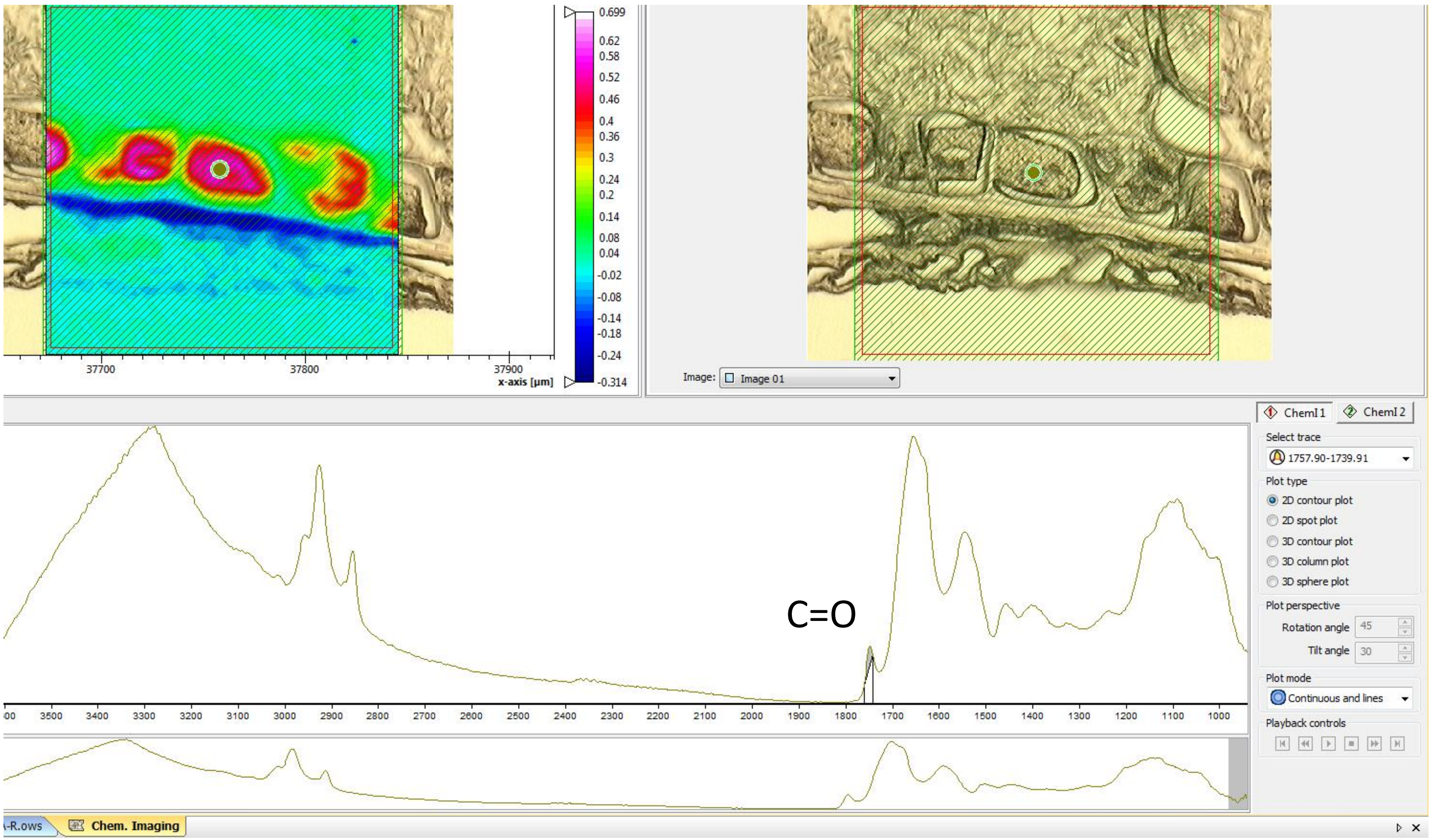
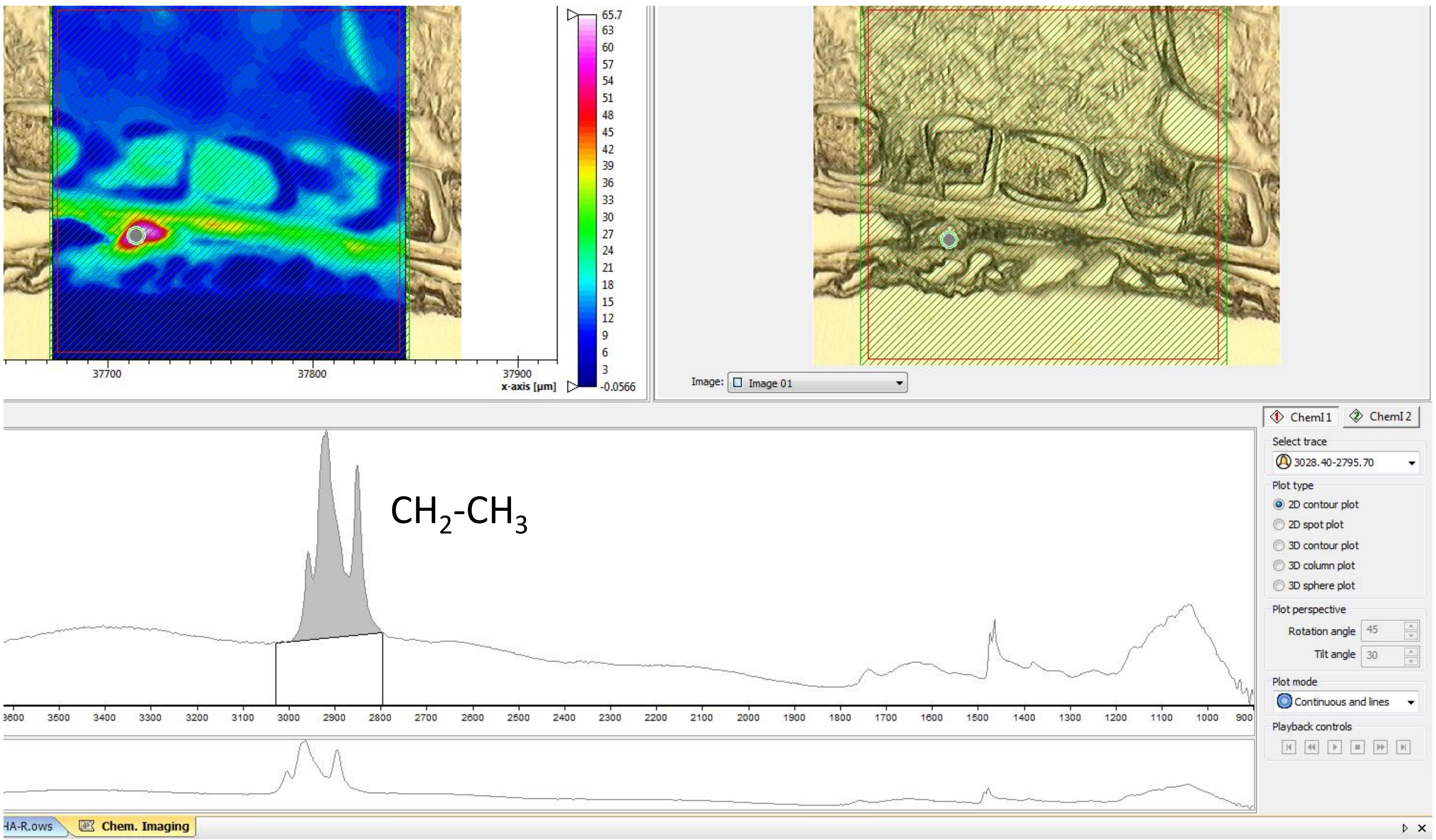


Figura 2: (a) Lo spettro IR di un composto organico mostra gli assorbimenti dovuti alle vibrazioni molecolari. (b) Schema ottico del microscopio IR accoppiato allo spettrometro ed al detector FPA. (c) Schema di funzionamento di un detector FPA.

Chemical imaging with FPA detector




CH2-CH3
65.7
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51
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6
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-0.0566
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Plot type
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2D spot plot
3D contour plot
3D column plot
3D sphere plot
Plot perspective
Rotation angle
45
Tilt angle
30
Plot mode
Continuous and lines
Playback controls
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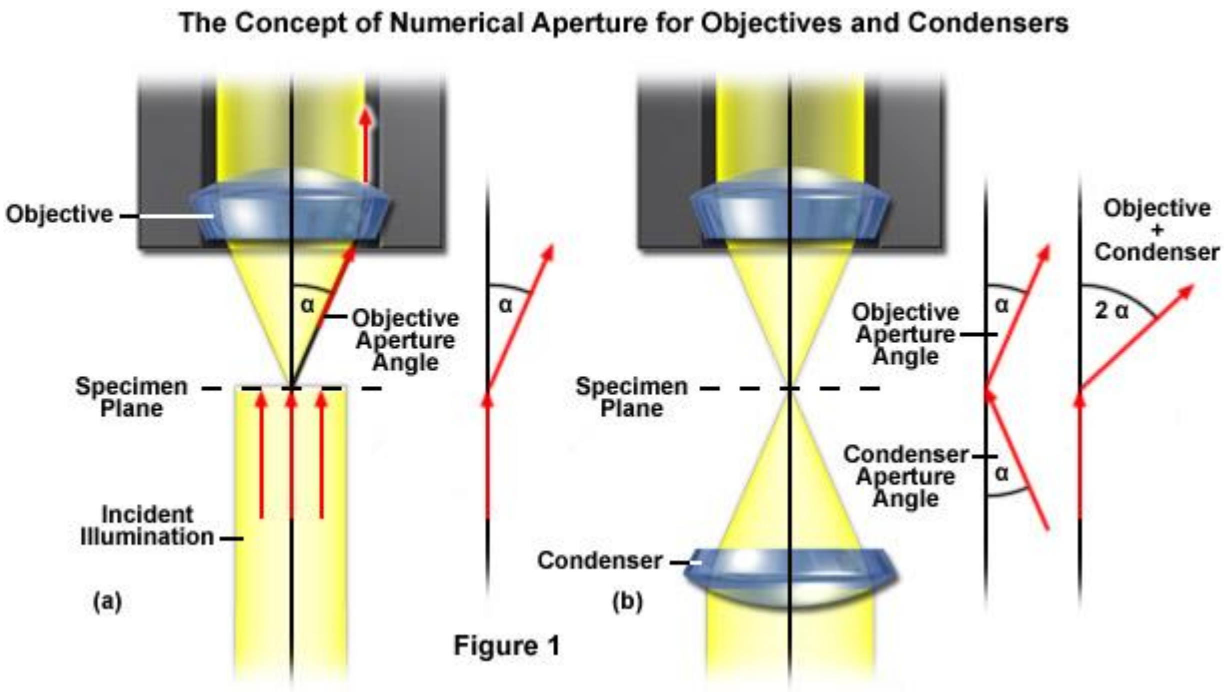
Chem. Imaging

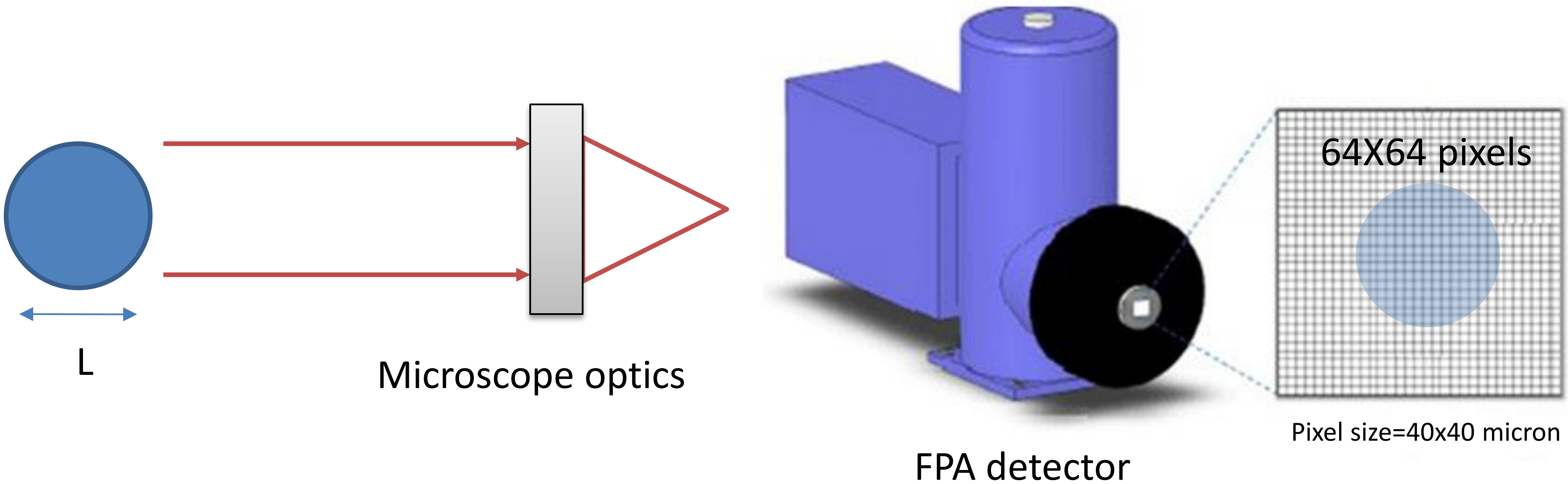
Numerical aperture



In optics, the numerical aperture (NA) of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light.

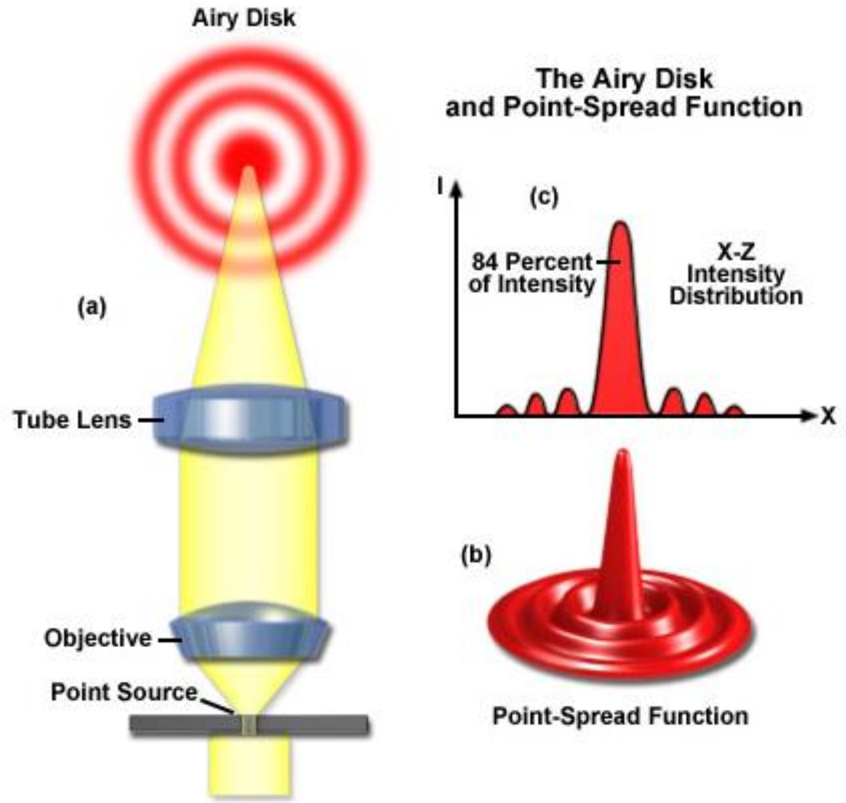
Numerical Aperture (NA) = n (sin α)

The pixel resolution



Microscope objective	NA	FPA pixel resolution	sample area covered
15X	0.4	40 μm/15 = 2.6 μm	170x170 μm^2
20X	0.6	40 μm/20 = 2 μm	128x128 μm^2
36X	0.5	40 μm/36 = 1.1 μm	102x102 μm^2

The lateral resolution



PSF (point spread function)

The **Rayleigh criterion** is the generally accepted criterion for the minimum resolvable detail - the imaging process is said to be diffraction-limited when the first diffraction minimum of the image of one source point coincides with the maximum of another

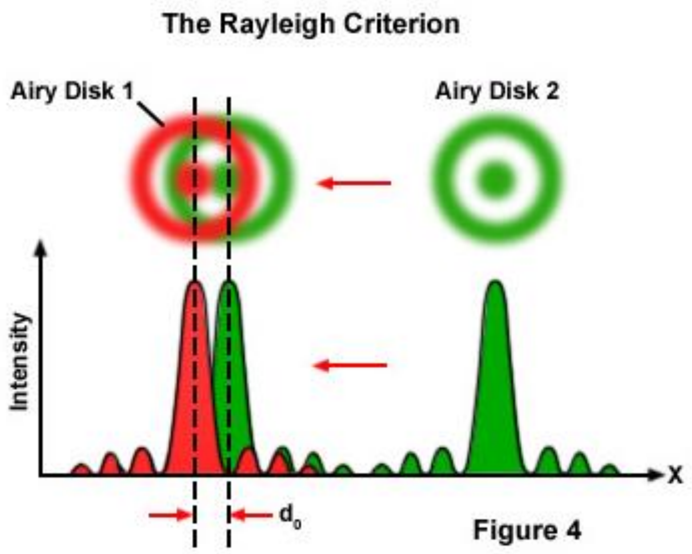
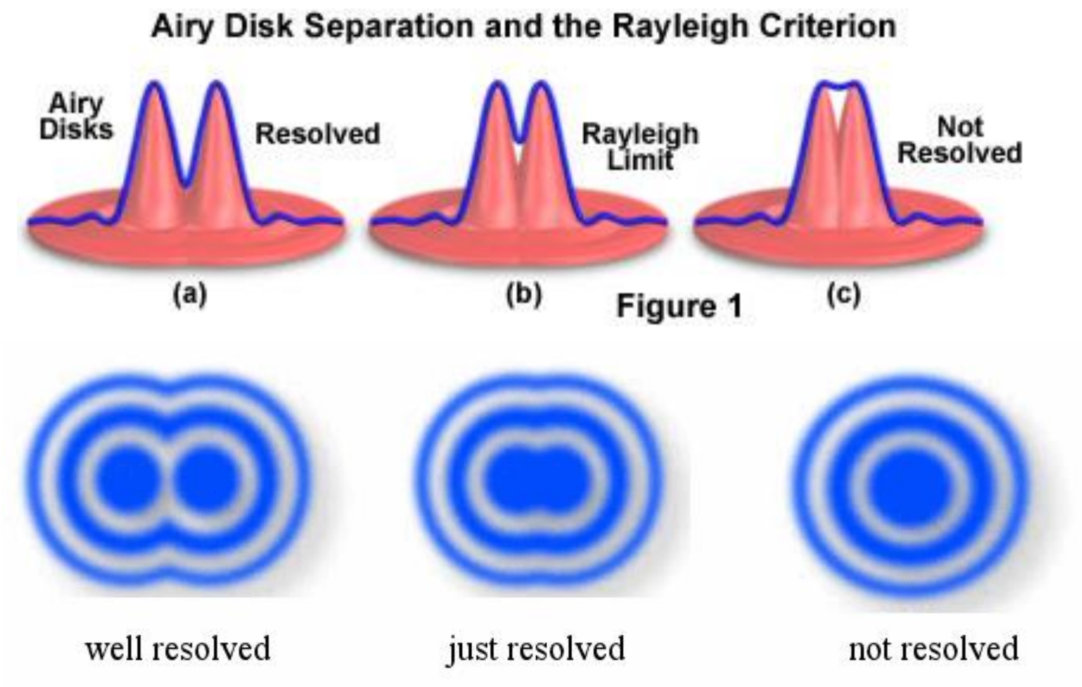
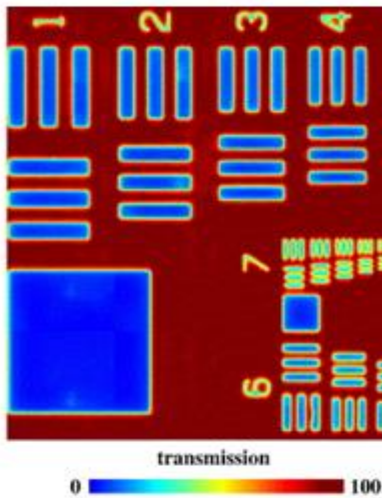


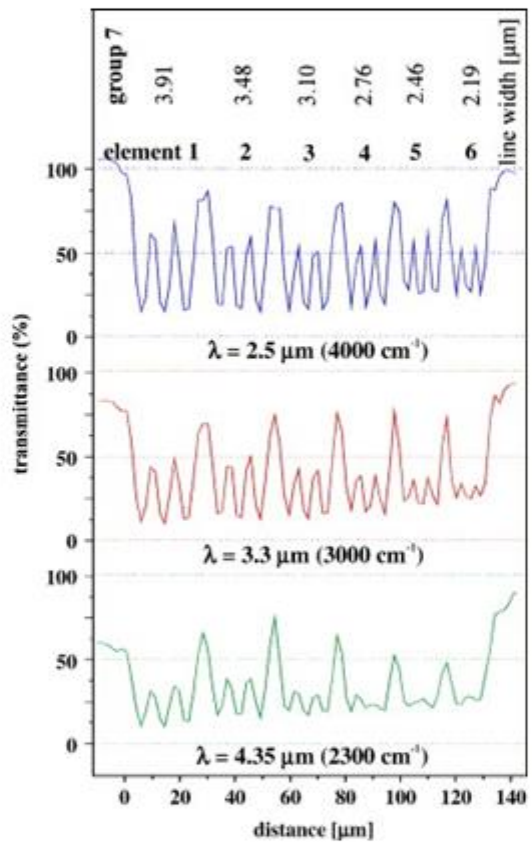
Figure 4

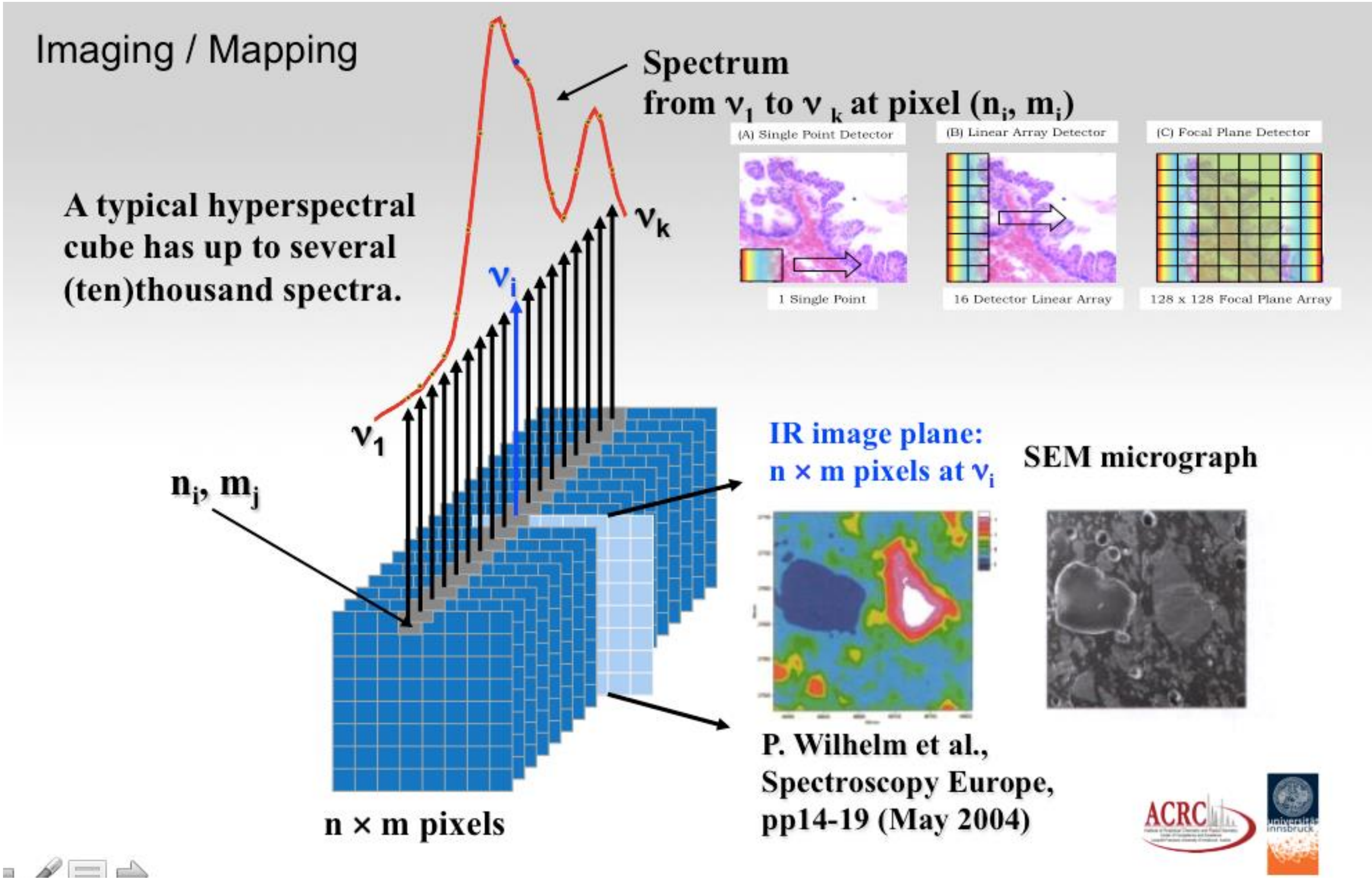


Circular aperture: $d_0 = 1.22\,\frac{\lambda}{N.A.}$

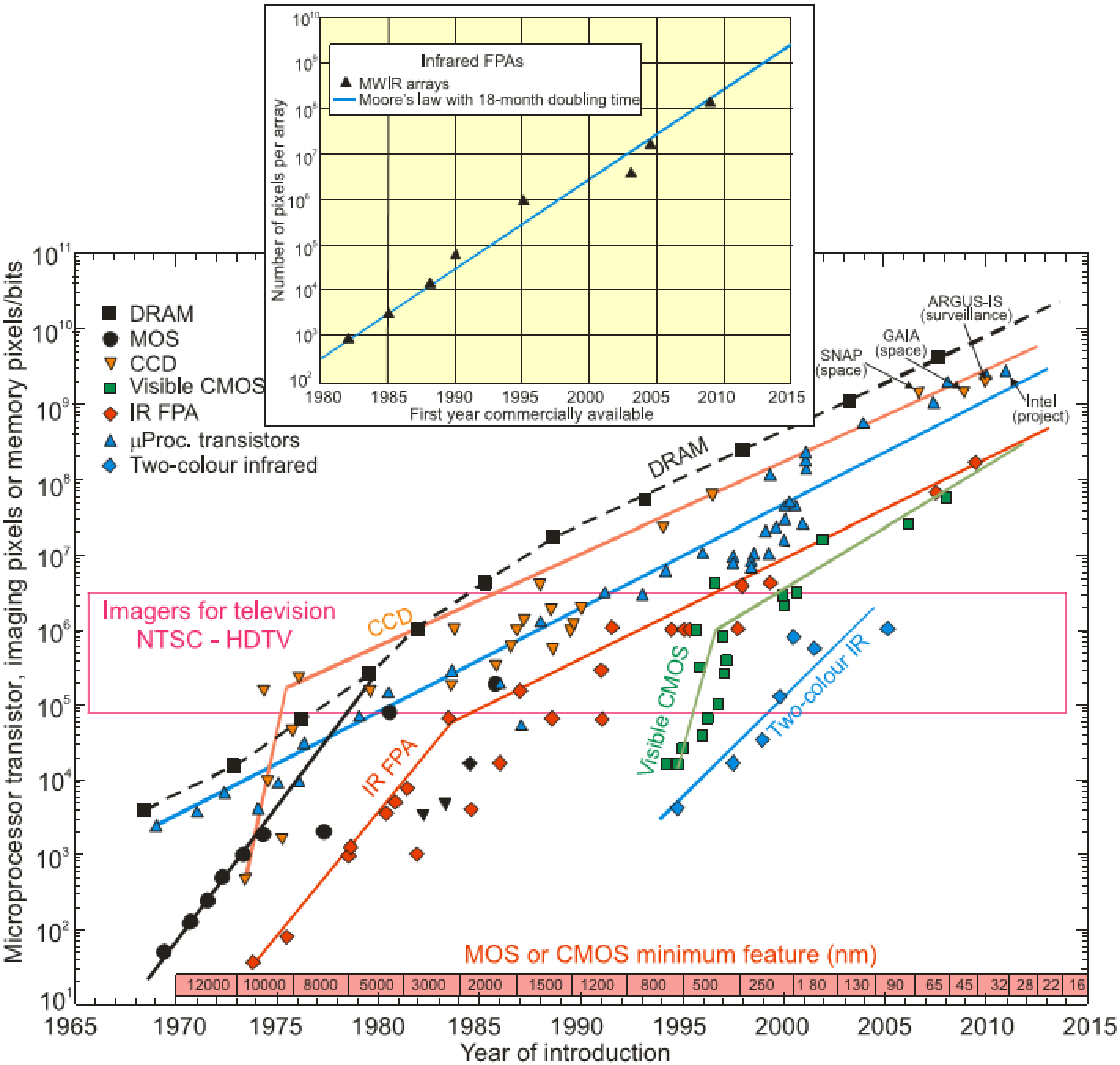
$$d > 2\,d_0 = 0.6\,\frac{\lambda}{N.A} \sim \lambda$$


1
2
3
4
5
6
7
6
transmission
0
100


group 7
3.91
3.48
3.10
2.76
2.46
2.19
line width [µm]
element 1
2
3
4
5
6
100
50
0
λ = 2.5 µm (4000 cm⁻¹)
100
50
0
λ = 3.3 µm (3000 cm⁻¹)
100
50
0
λ = 4.35 µm (2300 cm⁻¹)
transmittance (%)
0
20
40
60
80
100
120
140
distance [µm]



http://dx.doi.org/10.5772/51915



Infrared FPAs
MWIR arrays
Moore's law with 18-month doubling time
Number of pixels per array
First year commercially available
DRAM
MOS
CCD
Visible CMOS
IR FPA
μProc. transistors
Two-colour infrared
Imagers for television
NTSC - HDTV
SNAP (space)
GAIA (space)
ARGUS-IS (surveillance)
Intel (project)
Visible CMOS
Two-colour IR
MOS or CMOS minimum feature (nm)
12000
10000
8000
5000
3000
2000
1500
1200
800
500
250
1 80
130
90
65
45
32
28
22
16
Microprocessor transistor, imaging pixels or memory pixels/bits
Year of introduction

Anticipated evolution of IR technology in the near future

The future applications of IR detector systems require:

• higher pixel sensitivity,
• further increase in pixel density to above 106 pixels,
• cost reduction in IR imaging array systems through the use of less cooling sensor technology combined with integration of detectors and signal-processing functions (with much more on-chip signal processing),
• improvement in the functionality of IR imaging arrays through development of multispectral sensors.

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