Microscope de champ proche à pointe diffusante

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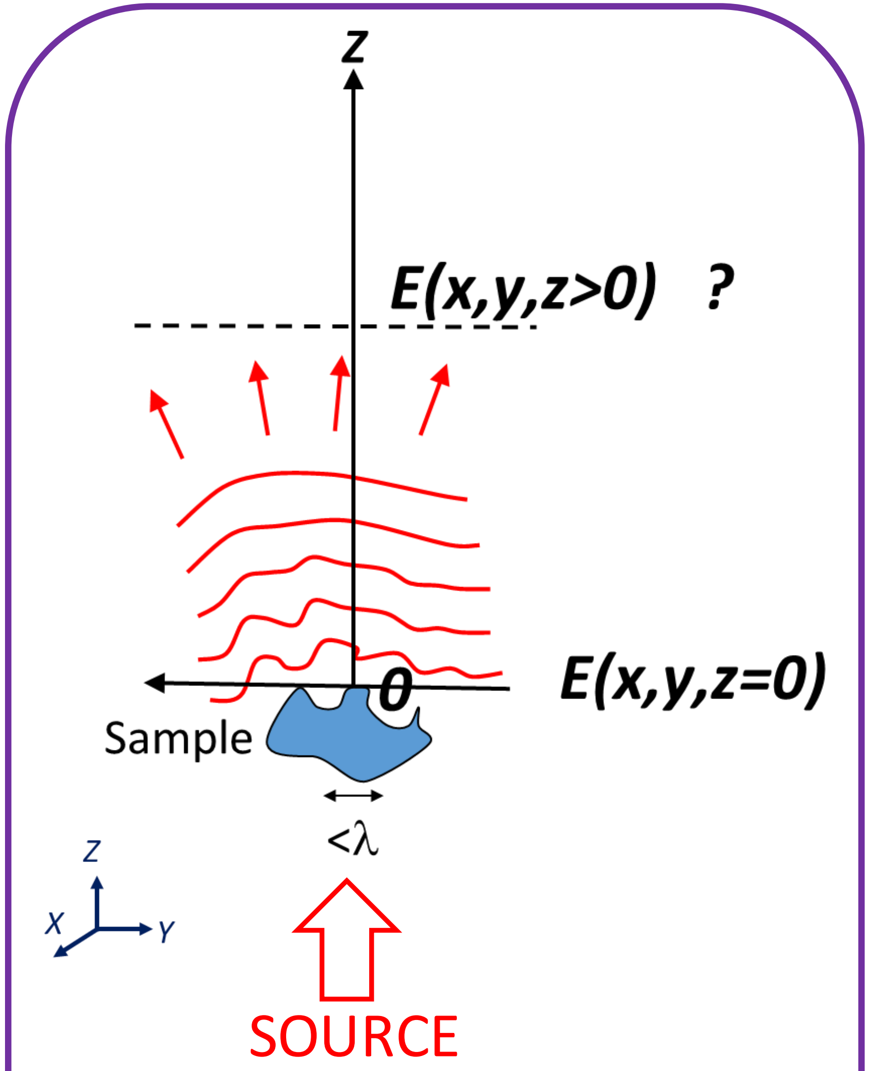
Journée ANF : Couplage microscopie à sonde locale et nanophotonique (6 décembre 2022)

Basic notions: Angular spectrum representation



$\omega = 2\pi c/\lambda$

$k = \omega/c = 2\pi/\lambda$

Helmholtz equation :

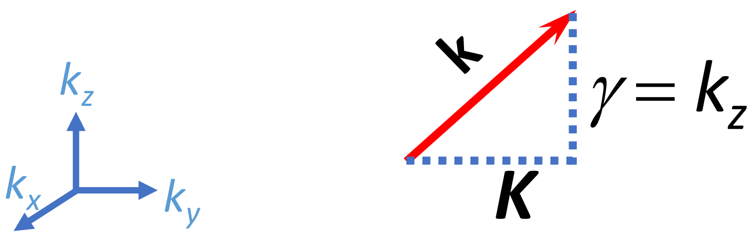
$$\Delta E + \frac{\omega^2}{c^2} E = 0$$

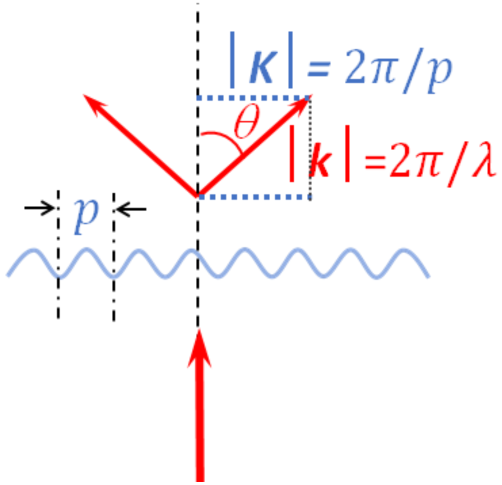
Solution:

Superposition of plane waves

$$\sin\theta = \frac{\lambda}{p}$$

$$\tilde{E}(\alpha, \beta\,; z=0)\, e^{i\alpha x} e^{i\beta y} e^{i\gamma z}$$

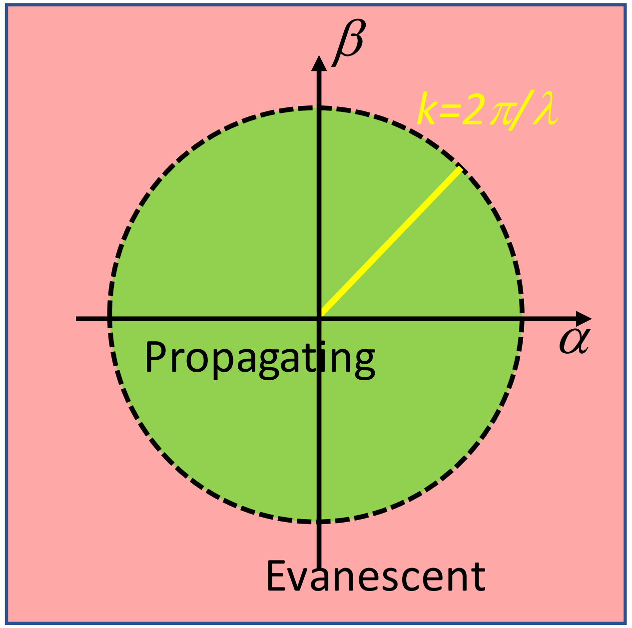




K=(α,β) *Transverse (in-plane) wavevector*

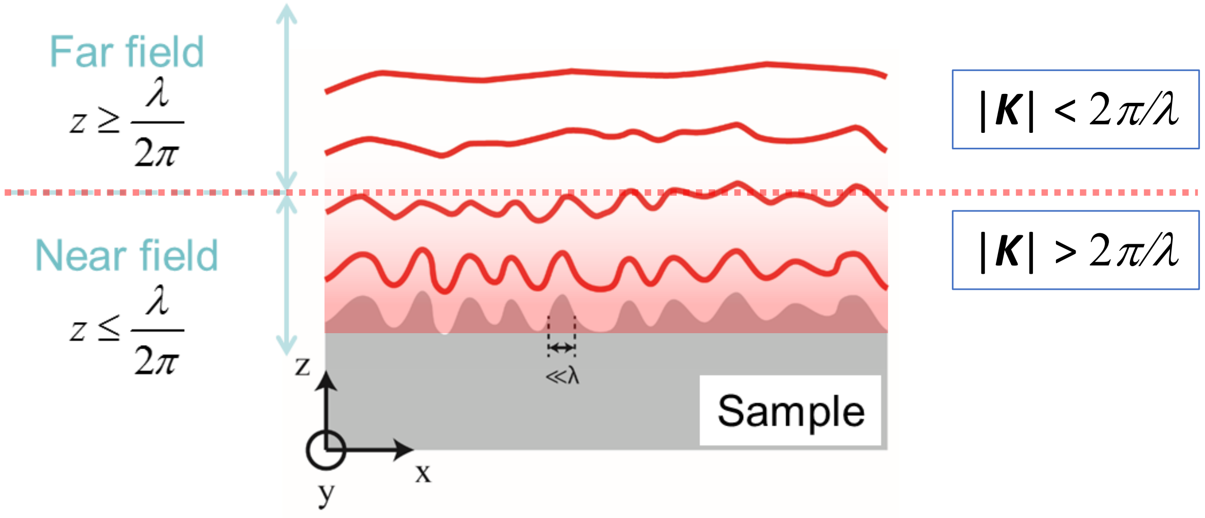
→ Spatial frequencies

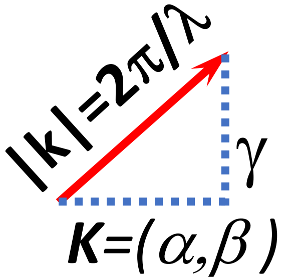
Evanescent vs. propagating EM fields



Real space: $\mathbf{r}=(x,y,z)$

Fourier space: $\mathbf{k}=(\alpha,\beta,\gamma)$





$$\boxed{\left(\frac{2\pi}{\lambda}\right)^2 = |\mathbf{K}|^2 + \gamma^2}$$

$$\tilde{E}(\alpha,\beta\,;z=0)\,e^{i\alpha x}e^{i\beta y}e^{i\gamma z}$$

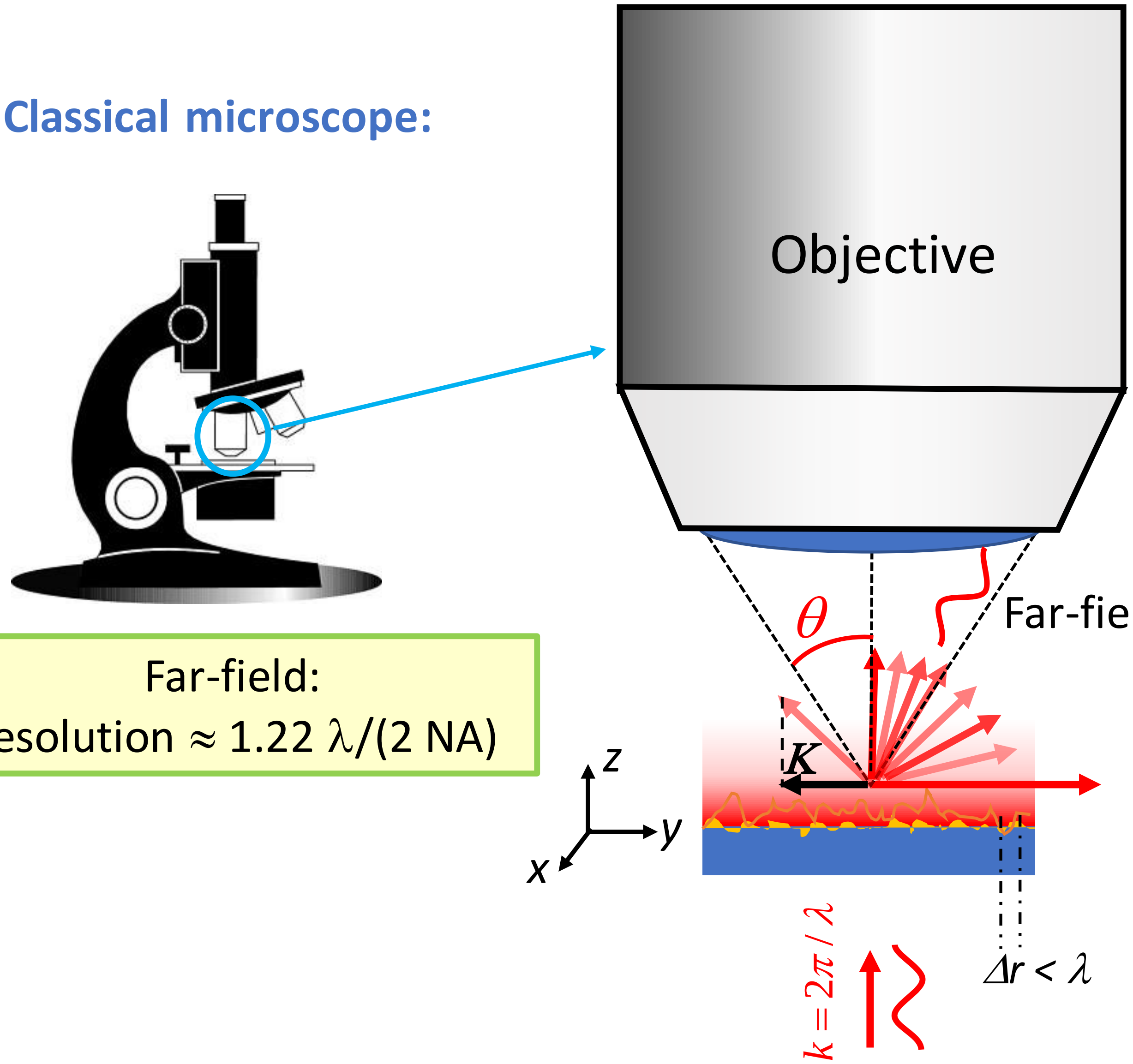
$|K| < 2\pi/\lambda$ ⟶ **Propagating (γ real)**

$|K| > 2\pi/\lambda$ ⟶ **Evanescent (γ imaginary)**

L. Novotny & B. Hecht « Principles of Nano-optics »
R. Carminati (Lecture notes)

Limits of classical microscopy :

Classical microscope:

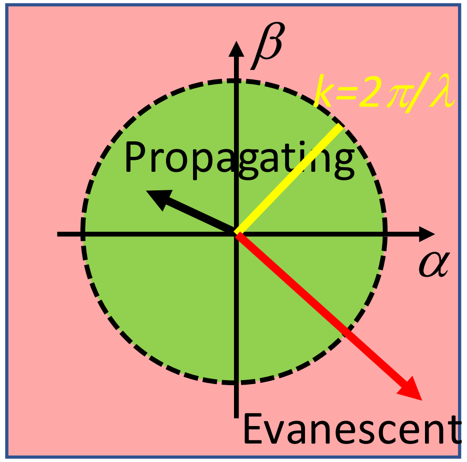


Far-field:
Resolution ≈ 1.22 λ/(2 NA)

Far-field ($|\boldsymbol{K}| < |k| = 2\pi/\lambda$)
propagating

Near-field ($|\boldsymbol{K}| > |k| = 2\pi/\lambda$)
evanescent

Spatial frequencies in xy plane

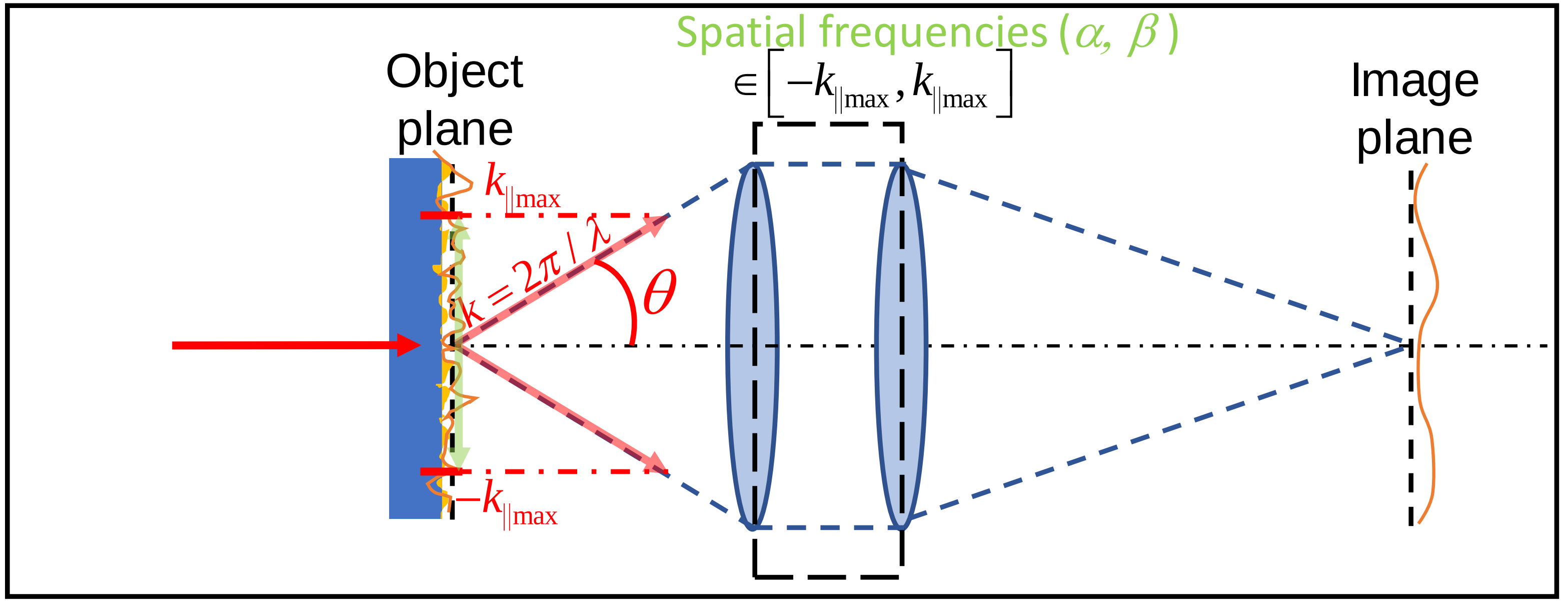


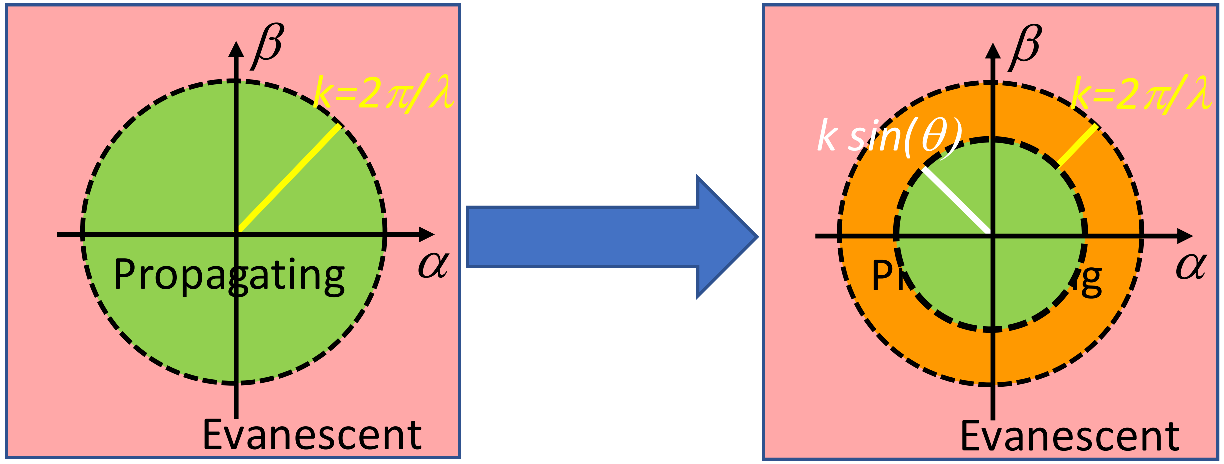
$$\gamma^2 = (k_z)^2 = |\boldsymbol{K}|^2 - (2\pi/\lambda)^2$$

1. Distance= low-pass filter on evanescent fields

Characteristic decay distance: $\boldsymbol{\delta \approx \Delta r/2\pi}$

Far-field regime: resolution limit



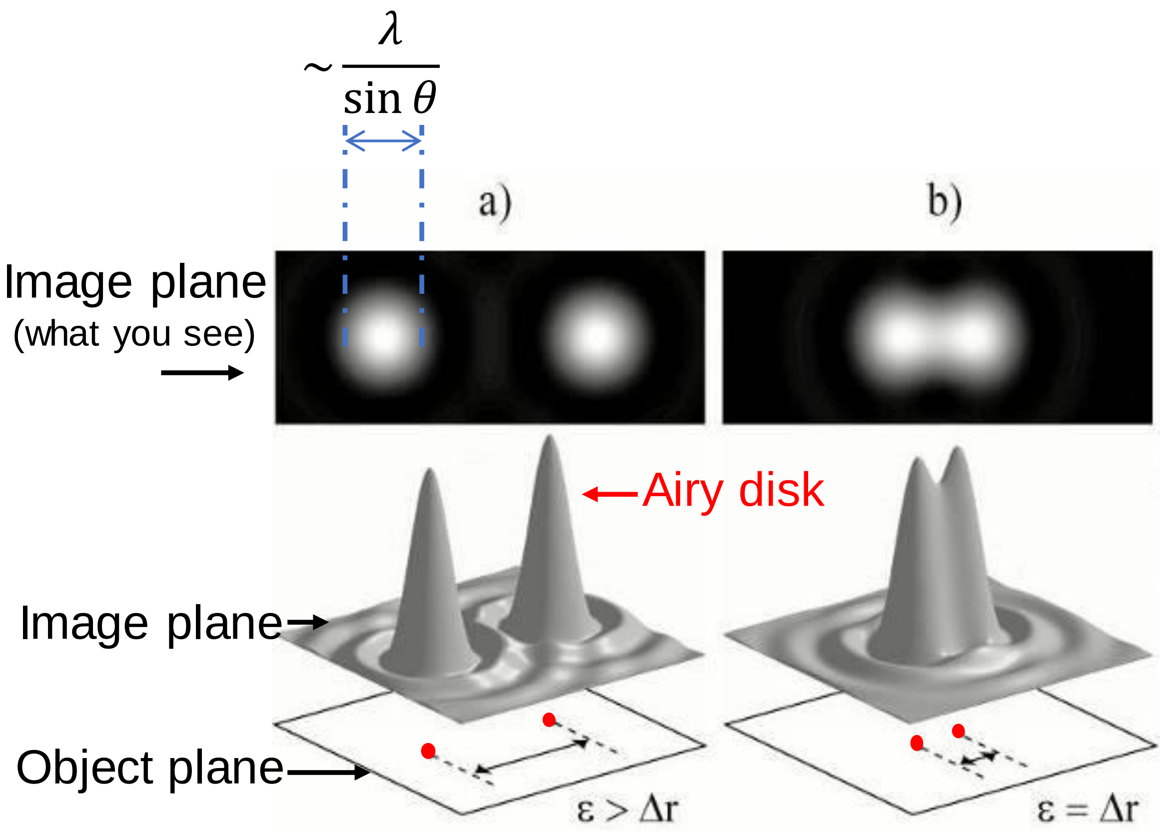


2. The far-field instrument is a low-pass filter of propagating fields. **Diffraction limit.**

Rayleigh criterion :

$$\Delta r = \frac{1.22 \cdot \lambda}{2 n \sin \theta}$$

Far-field regime: diffraction limit



$\sim \dfrac{\lambda}{\sin\theta}$

Image plane

(what you see)

Airy disk

Image plane

Object plane

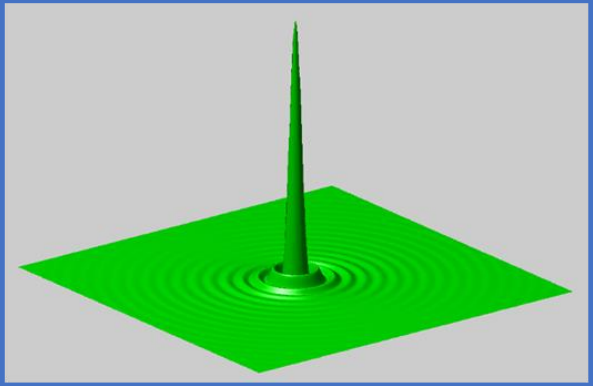
Rayleigh criterion :

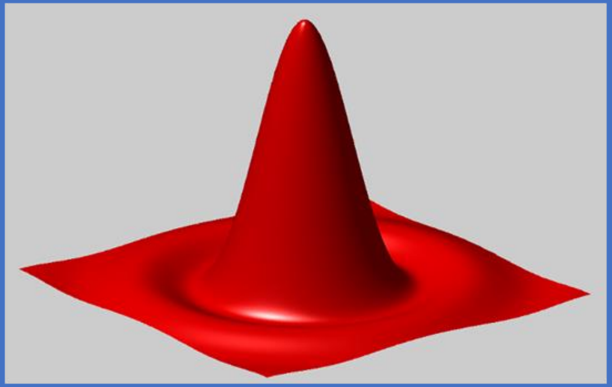
$$\Delta r = \frac{1.22 \cdot \lambda}{2 \sin\theta}$$

Rayleigh criterion (λ dependence)

Image of 1 point : λ= 550 nm (green)

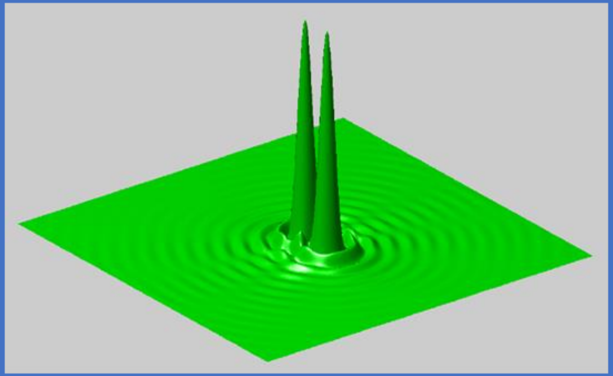
λ= 10 μm (Infrared)





(@ Gilles Tessier)

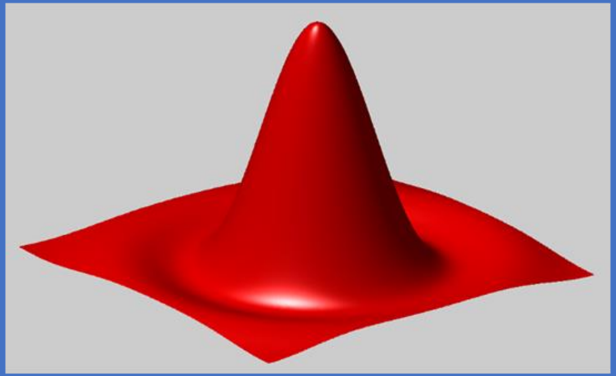
2 points 1000 nm appart :



λ~0.5 μm (visible)

n = 1 ; sin θ= 0.95

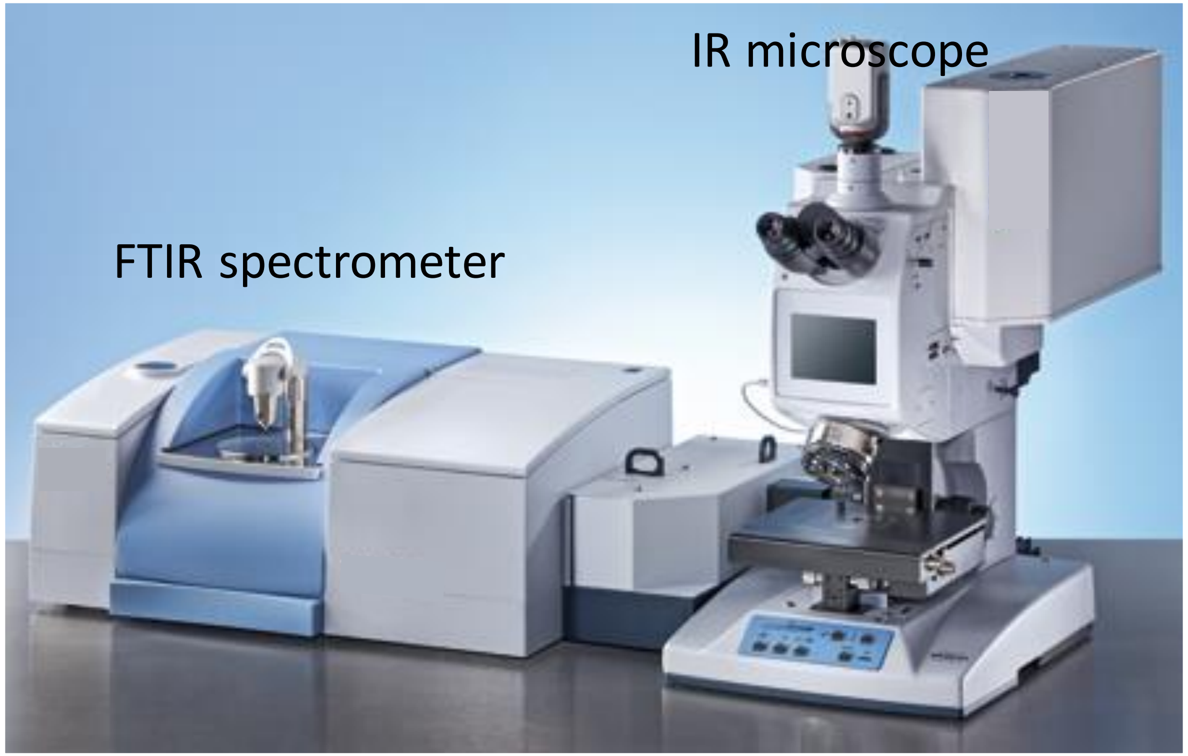
$\Delta r_{vis} \approx 320$ nm



λ~10 μm (IR)

n = 1 ; sin θ= 0.75

$\Delta r_{IR} \approx 9$ μm

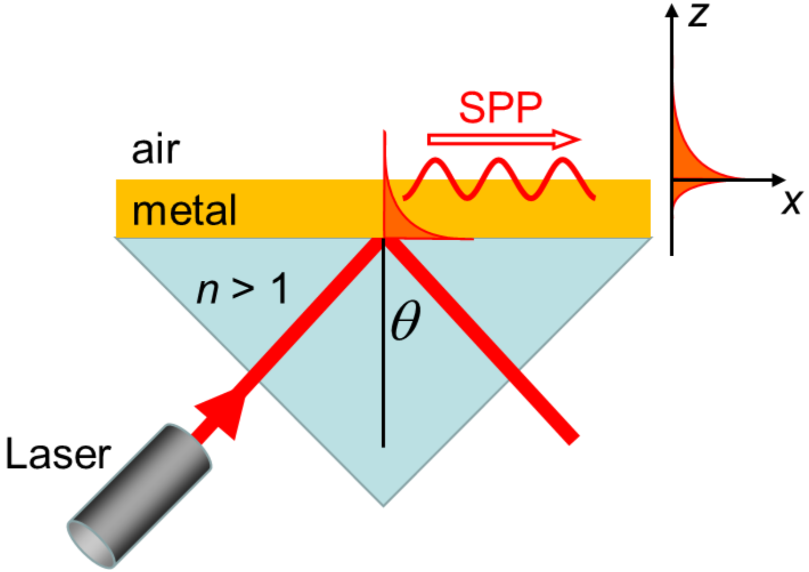


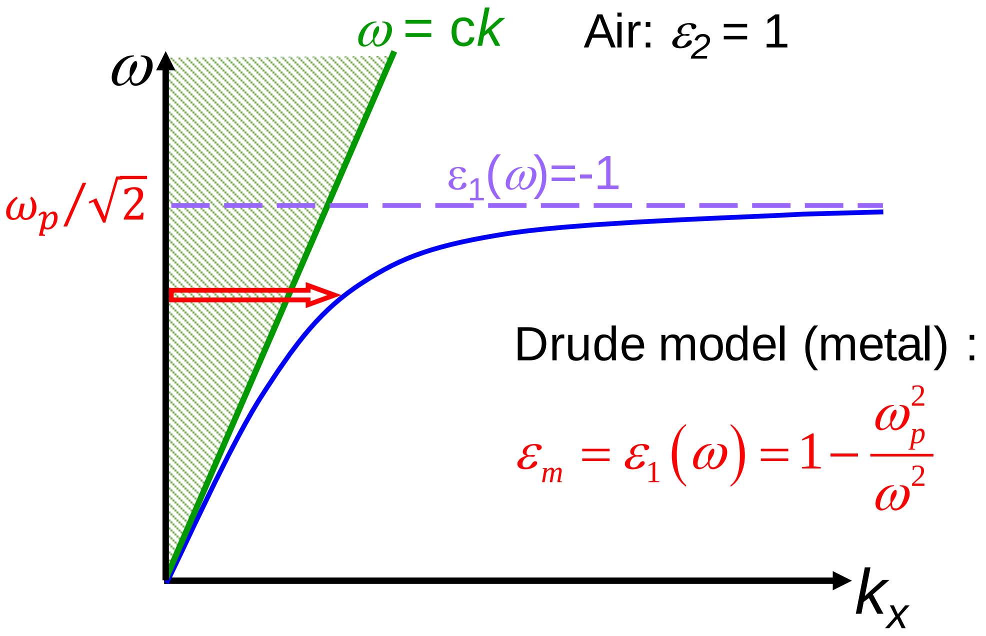
SPATIAL RESOLUTION STRONGLY LIMITTED IN THE INFRARED (~10 μm)

+

CANNOT DETECT SURFACE WAVES

Surface plasmons polaritons:

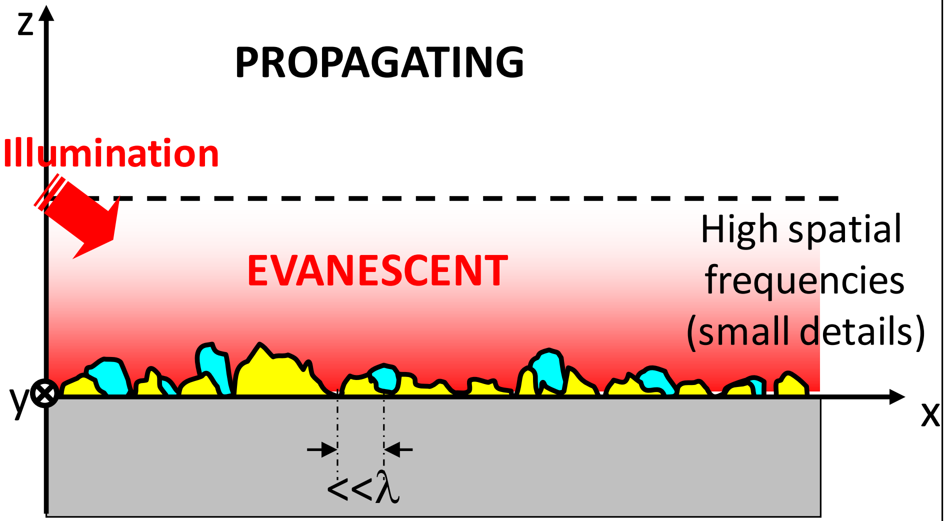




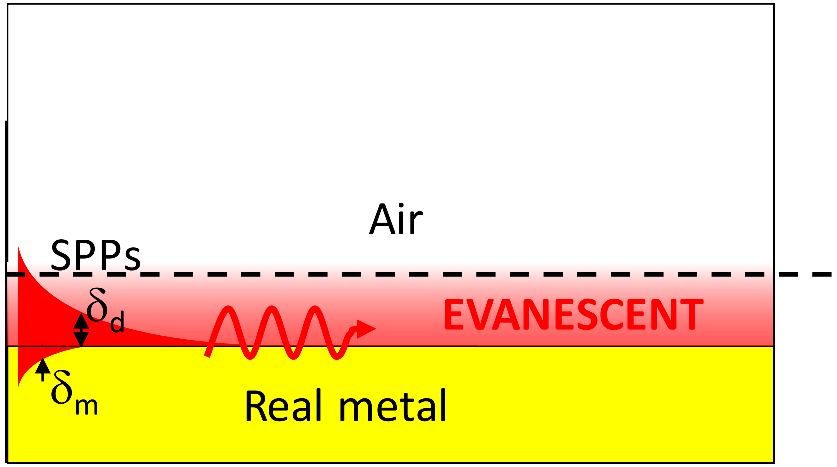
Drude model (metal) :

$$\varepsilon_m = \varepsilon_1(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

How can we probe the near-field ?



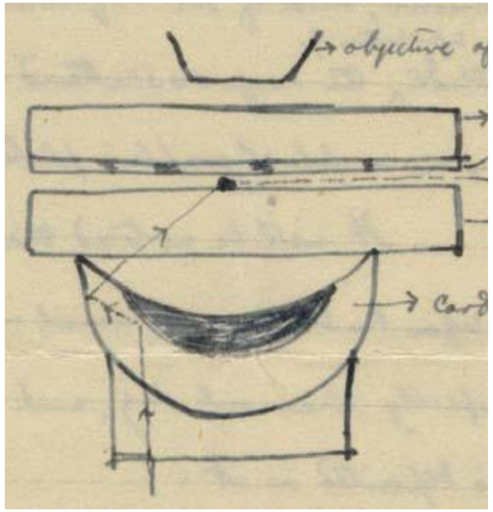
Optical imaging
of nano-materials
(resolution << λ)

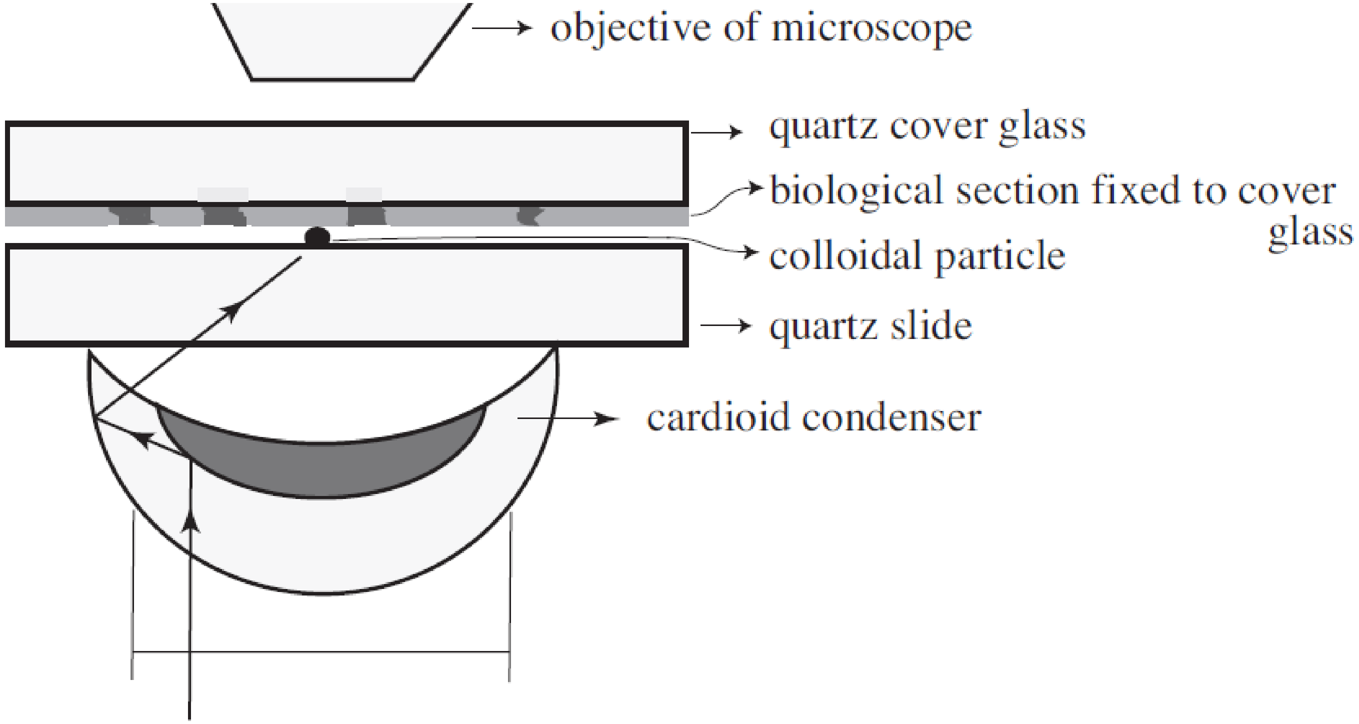


Detection of purely
evanescent fields
(example: **surface plasmons**)

Synge original idea (1928)

Sub-λ LOCAL PROBE = OPTICAL ANTENNA





Novotny, ”The History of Near-field Optics,” *Progress in Optics 50*, E. Wolf (ed.), 2007.

Letter from E.H. Synge to A. Einstein (April 1928)

E. H. Synge, Phil. Mag. S.7, **6**, 356 (1928).

Synge original idea (1928)

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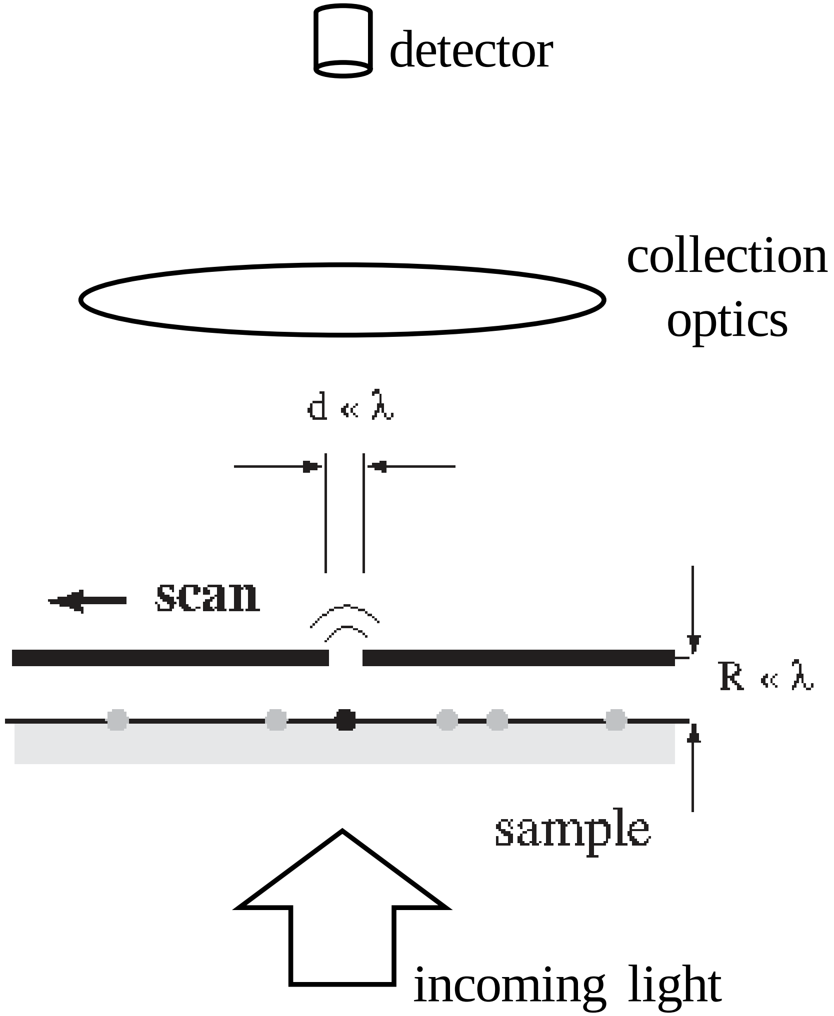

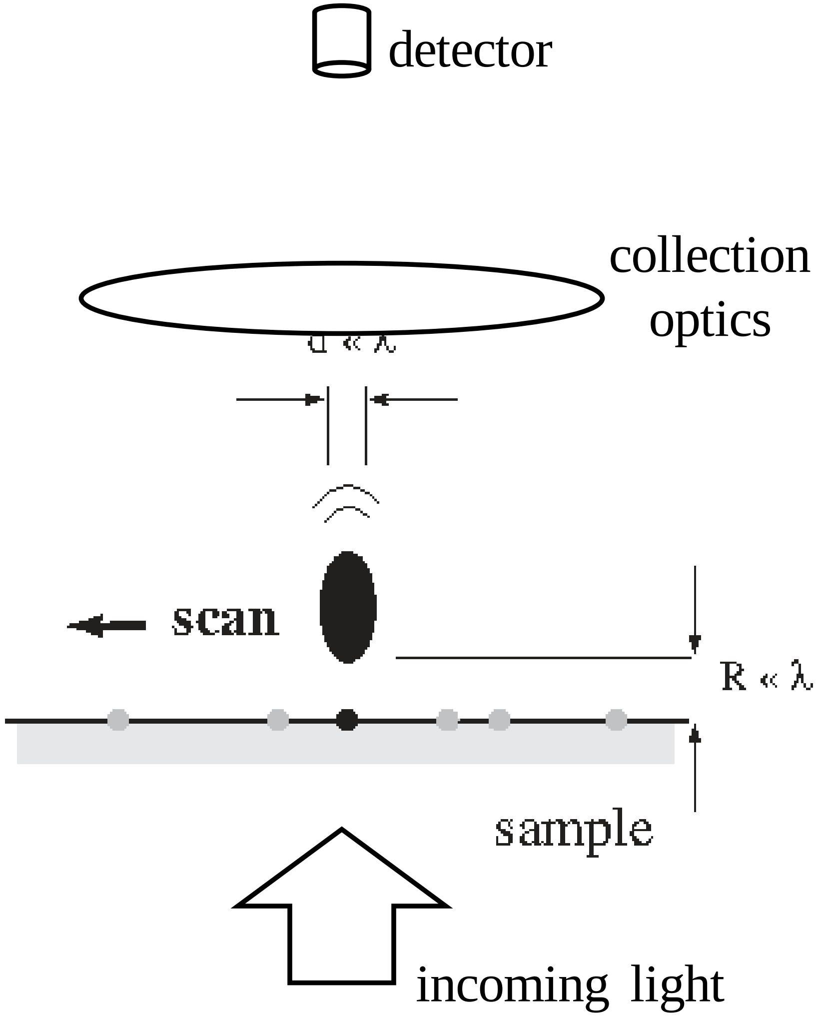

E. H. Synge, Phil. Mag. S.7, **6**, 356 (1928).

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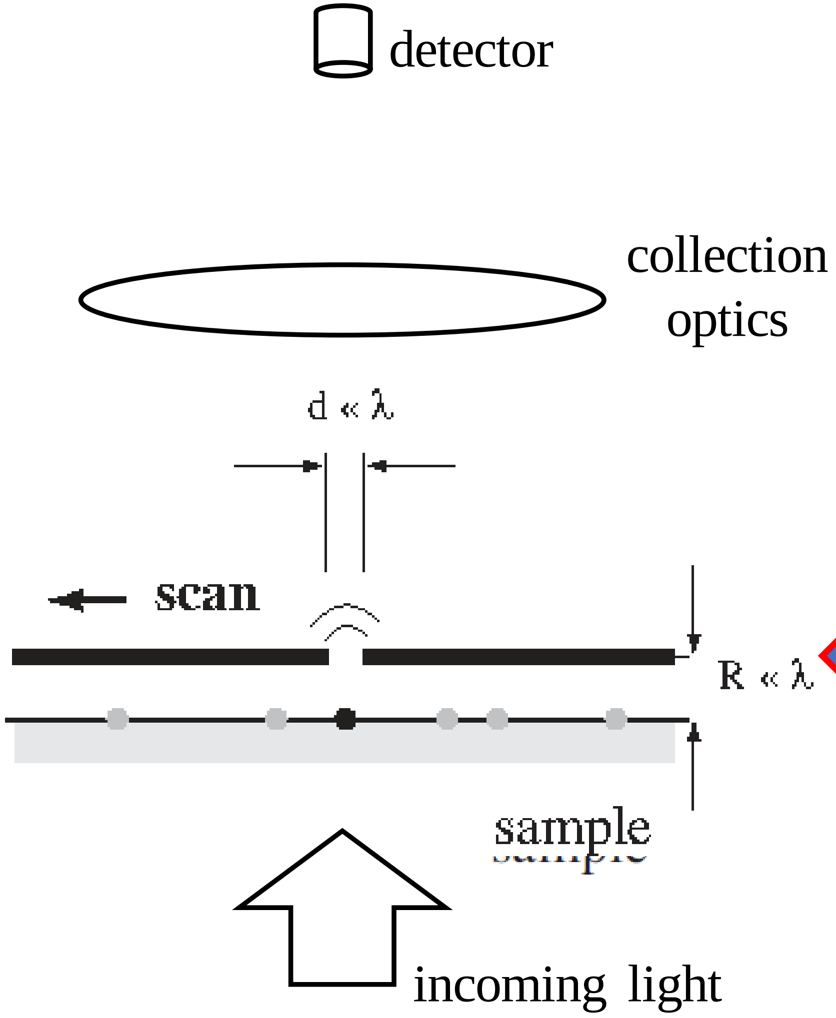


PERFORM THE LATERAL SCANS USING A PIEZOELECTRIC ELEMENT

E. H. Synge, Phil. Mag.S.7, **13**, 297 (1932).

E. H. Synge, Phil. Mag. S.7, **6**, 356 (1928).

History of NSOM

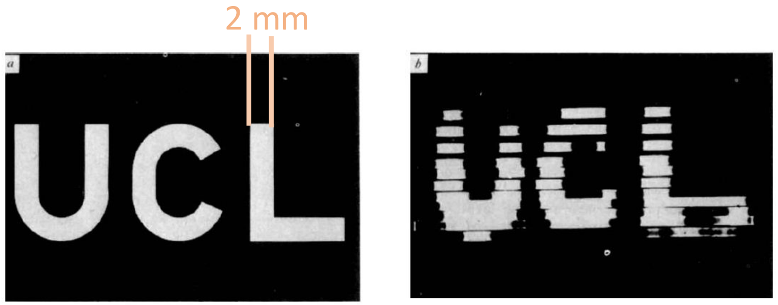
(NSOM = near-field scanning optical microscopy)

- **Concept of « ultramicroscopy » instrument**

E.H. Synge, "A suggested method for extending the microscopic resolution into the ultramicroscopic region," Phil. Mag. 6, 356 (1928).
E.H. Synge, "An application of piezoelectricity to microscopy," Phil. Mag. 13, 297 (1932).

- **Proof of Concept with microwaves (λ=3cm)**

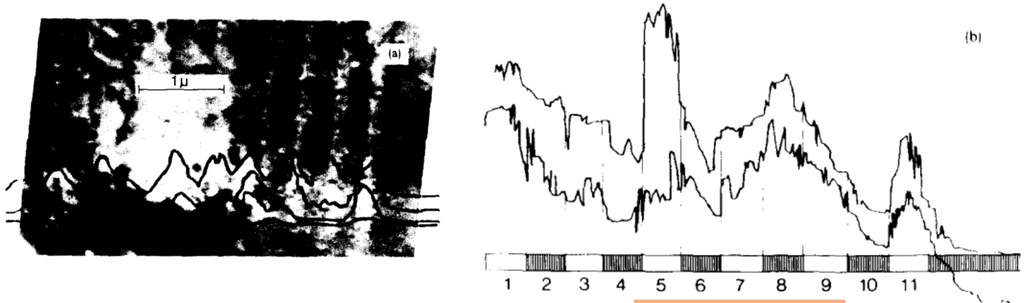
E.A. Ash and G Nichols, Nature 237, 510 (1972).



- **Sub-λ imaging in the visible (λ=488 nm)**

D.W. Pohl, W. Denk, and M. Lanz, « Optical stethoscope », Appl. Phys. Lett. 44, 651 (1984).

Resolution = 25 nm
(λ/20)



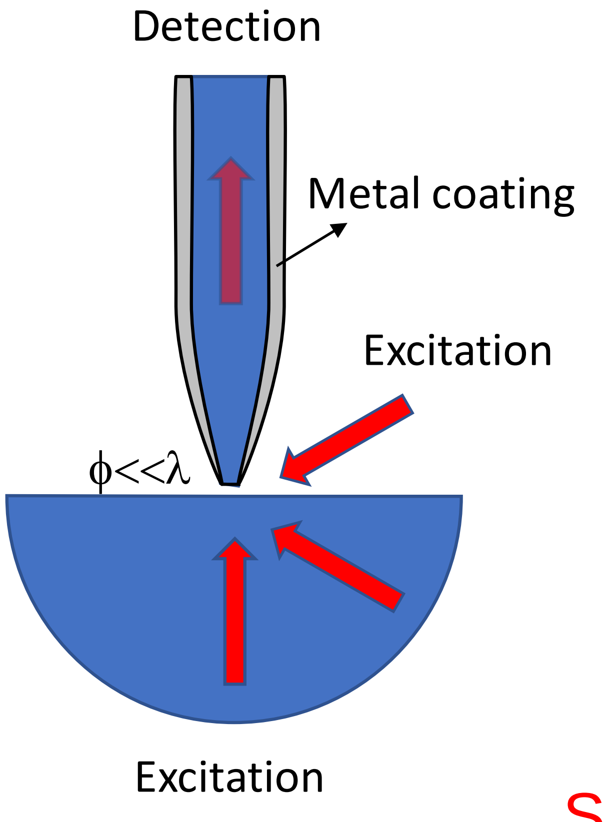
Grating (period 400 nm)

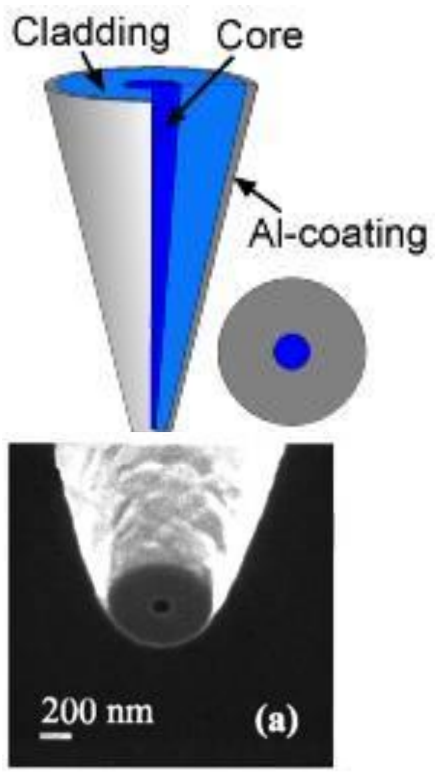
- **« Routine » NSOM instrument:**

E. Betzig, J.K. Trautman, *et al.*,
Science **251**, 1468 (1991)

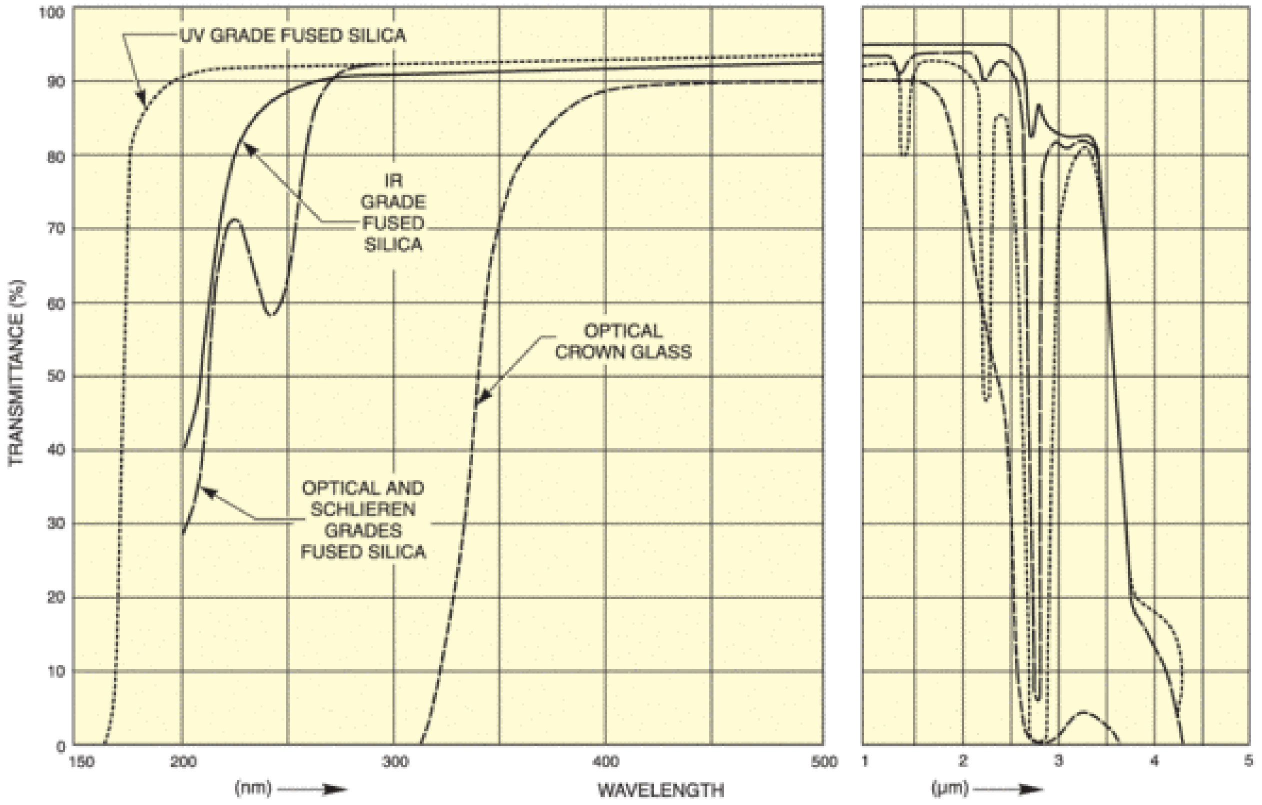
Aperture NSOM

Tapered
optical fiber





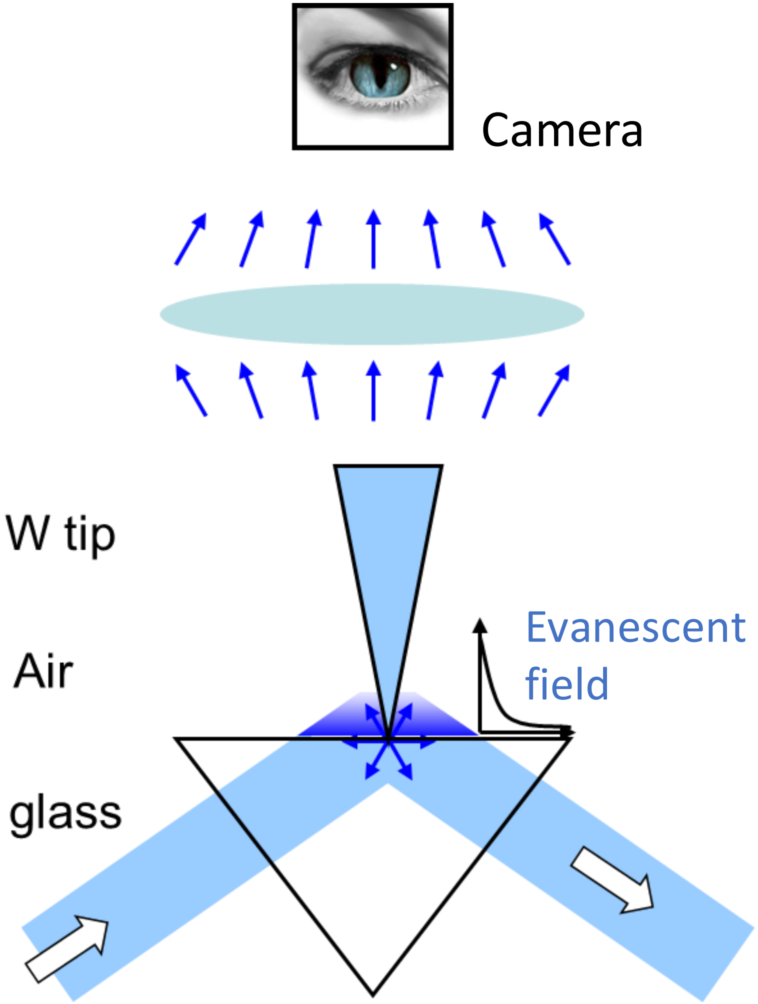
Veerman et al. ,
Appl. Phys. Lett. **72**, 3115 (1998)



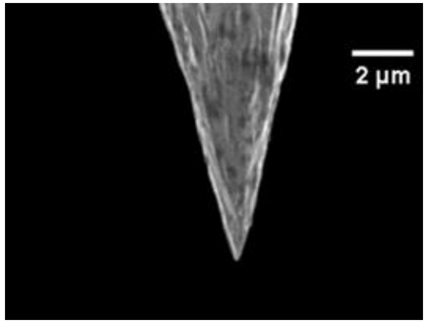
Spectral limitation

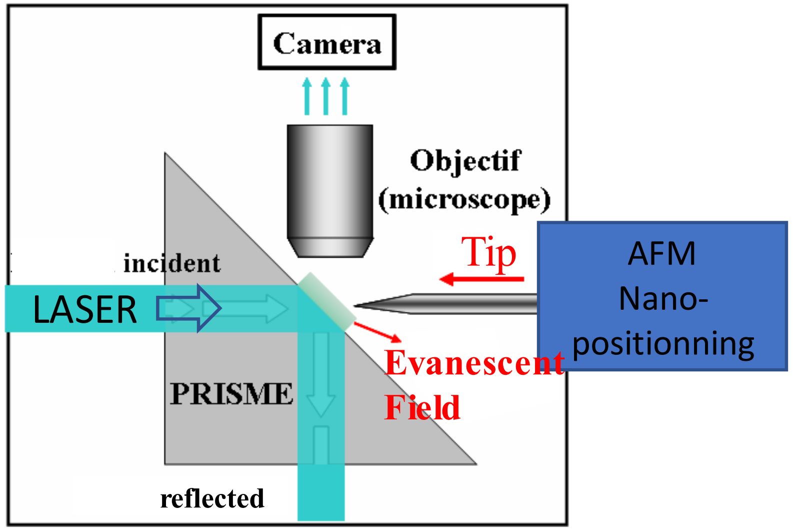
Silica fiber : Well-suited for visible and near-IR but **not for the mid-IR** (nor for THz) !!!

Photon tunneling experiment with scattering tip



Tungsten tip
SEM image





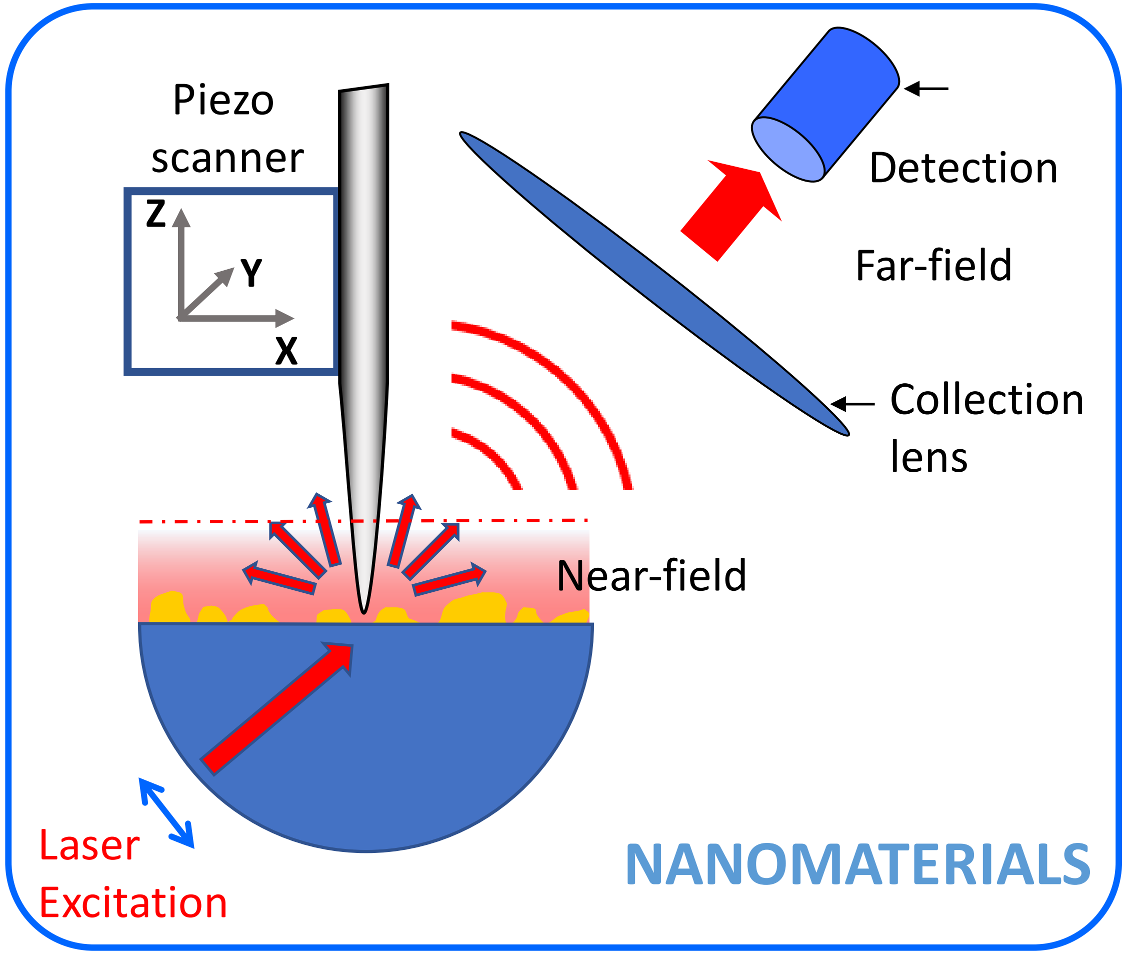
Scattering-type near-field scanning optical microscope (Scattering-type NSOM)

Principle : controlled scanning of a scattering nano-object (tip apex)

$$I_{scat.}(x_t, y_t) = \sigma \left| E(x_t, y_t) \right|^2$$

By measuring $I_{scat.}(x_t,y_t)$, the local field $E(x_t,y_t)$ at the tip's position is probed.

Optical imaging at sub-λ scale
« **SUPER-RESOLUTION** »



Claude Boccara

Wikramasynghe et al., APL 65,1623 (1994)
Bachelot, Gleize, Boccara, Microanal. Microstruct. 5, 389 (1994)

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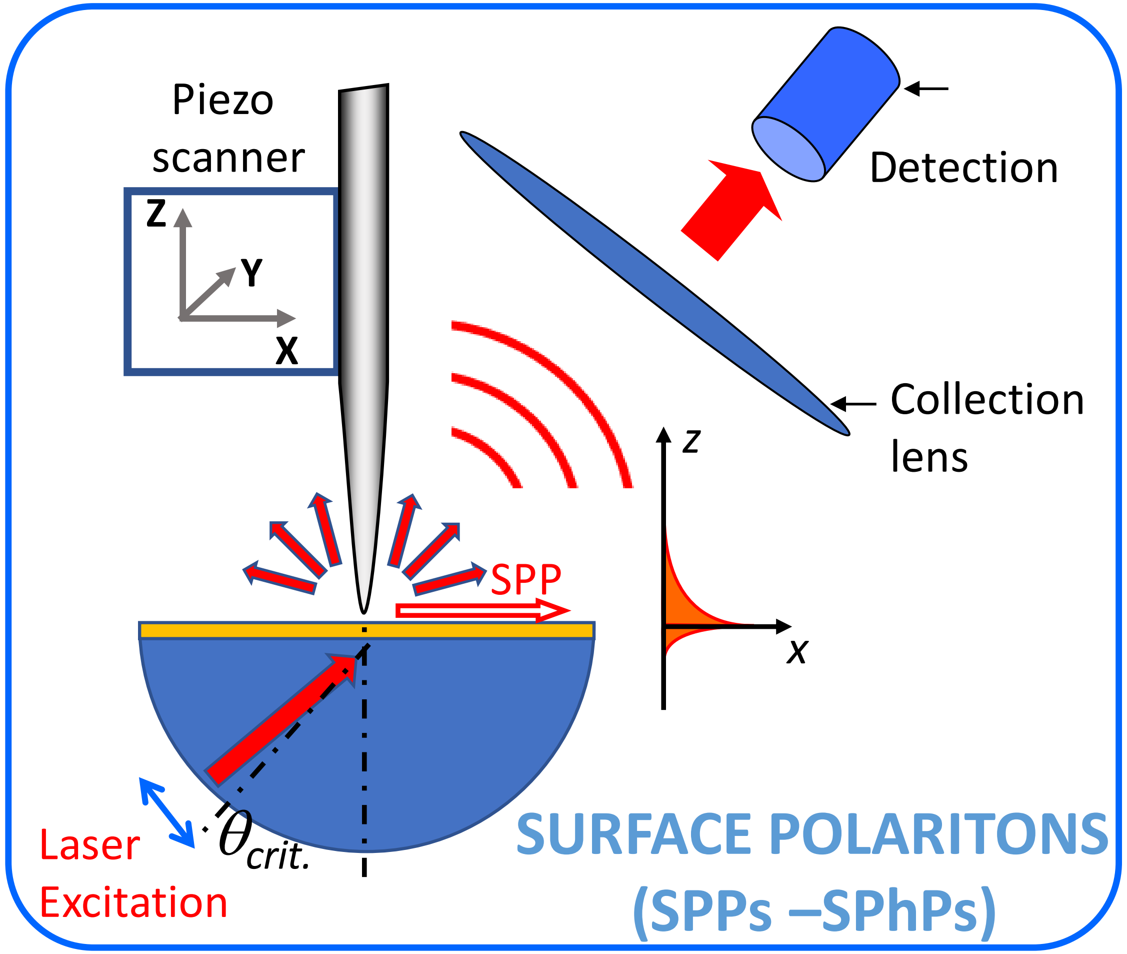
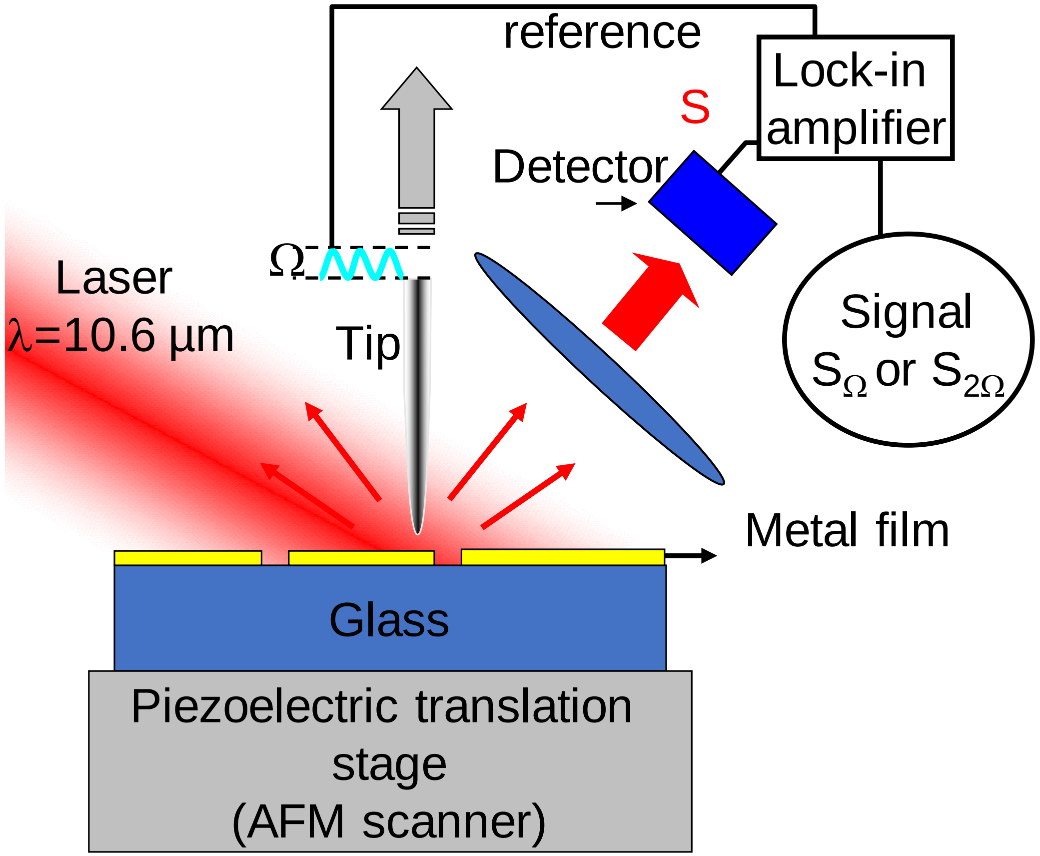


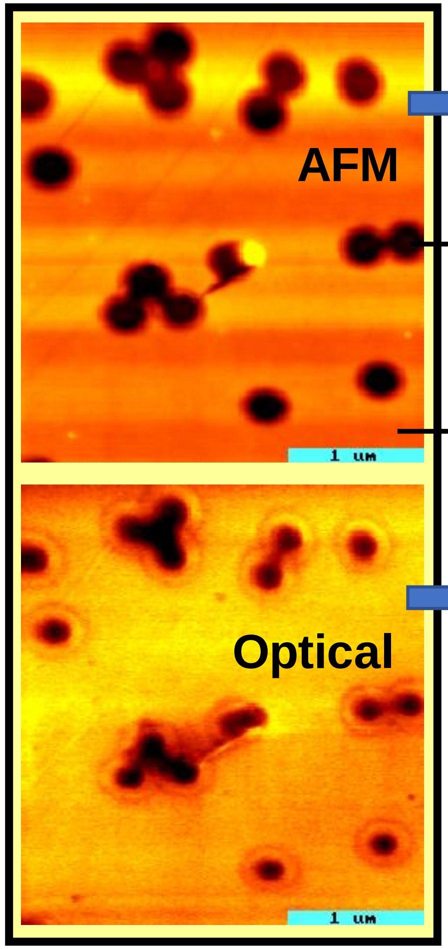
SURFACE POLARITONS (SPPs –SPhPs)

Claude Boccara

Wikramasynghe et al., APL 65,1623 (1994)
Bachelot, Gleize, Boccara, Microanal. Microstruct. 5, 389 (1994)

Sub-λ imaging of nano materials with external IR source





Topography (AFM)

SiO_2 (ϕ=200nm)

Chromium

NSOM (3μmx3μm) λ=10.6 μm

= S_Ω or $S_{2\Omega}$

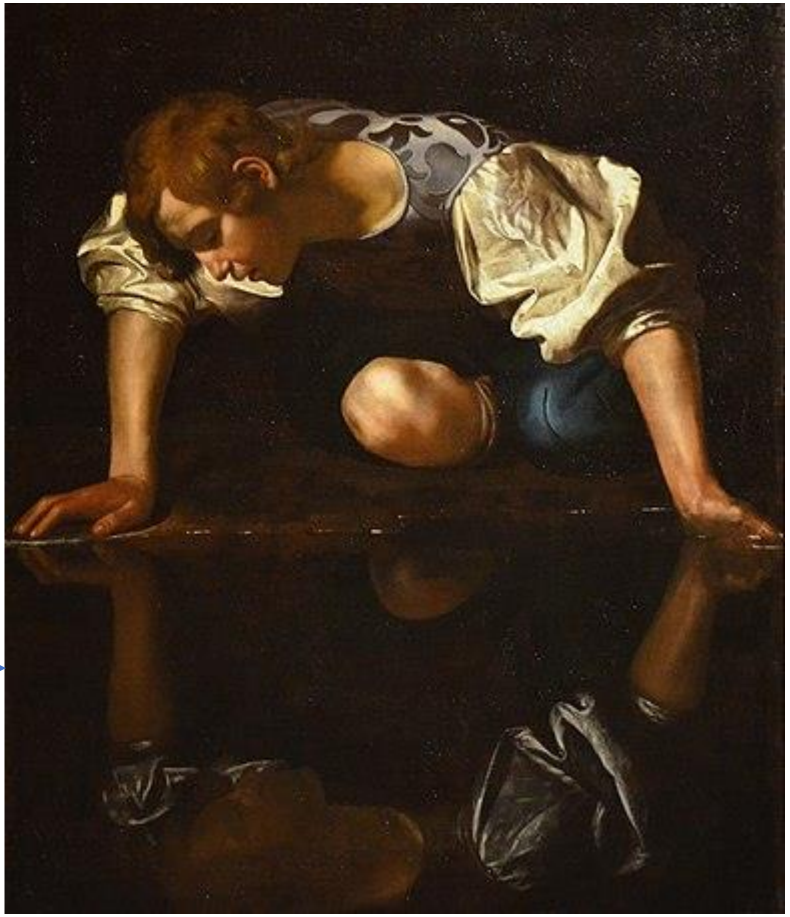
Formanek, et al., JAP **93**, 9548 (2003)

λ = 10.6 μm

Origin of the contrast

FAR-FIELD

EAU



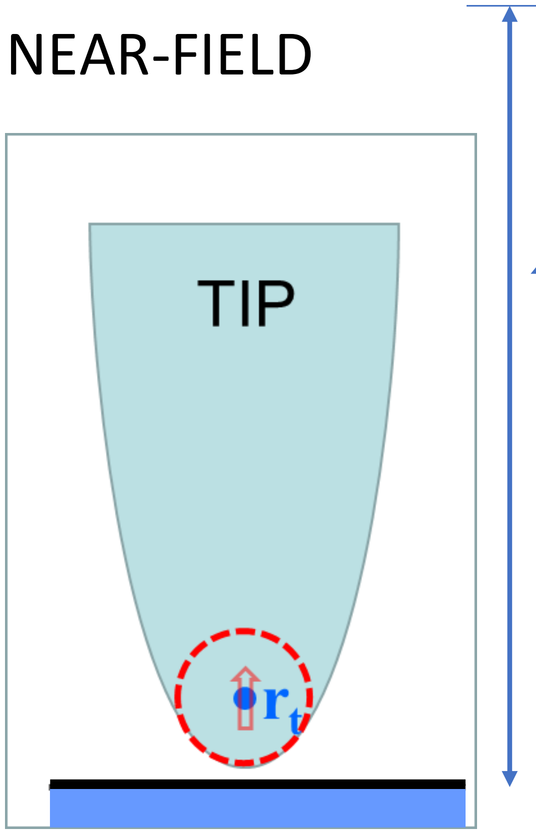
Caravage
Narcisse (1598-1599)

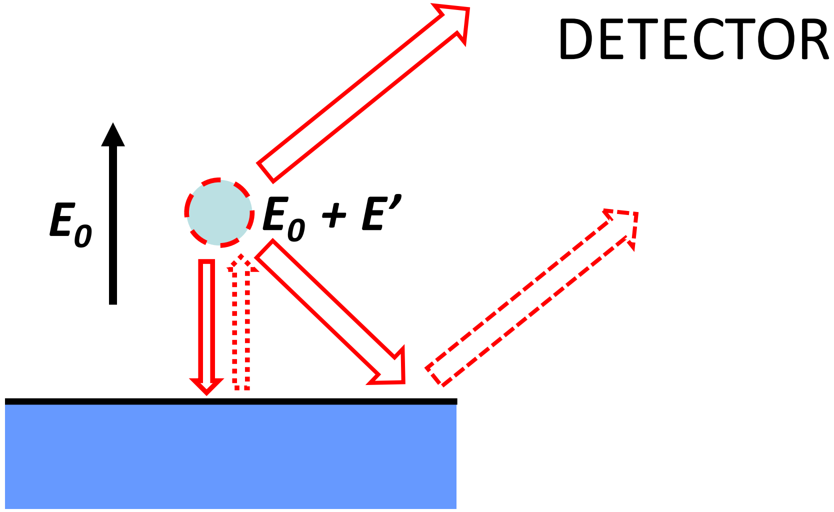
METAL

Pierre Paul Rubens
Venus au miroir (1613-1614)

Origin of the contrast

NEAR-FIELD

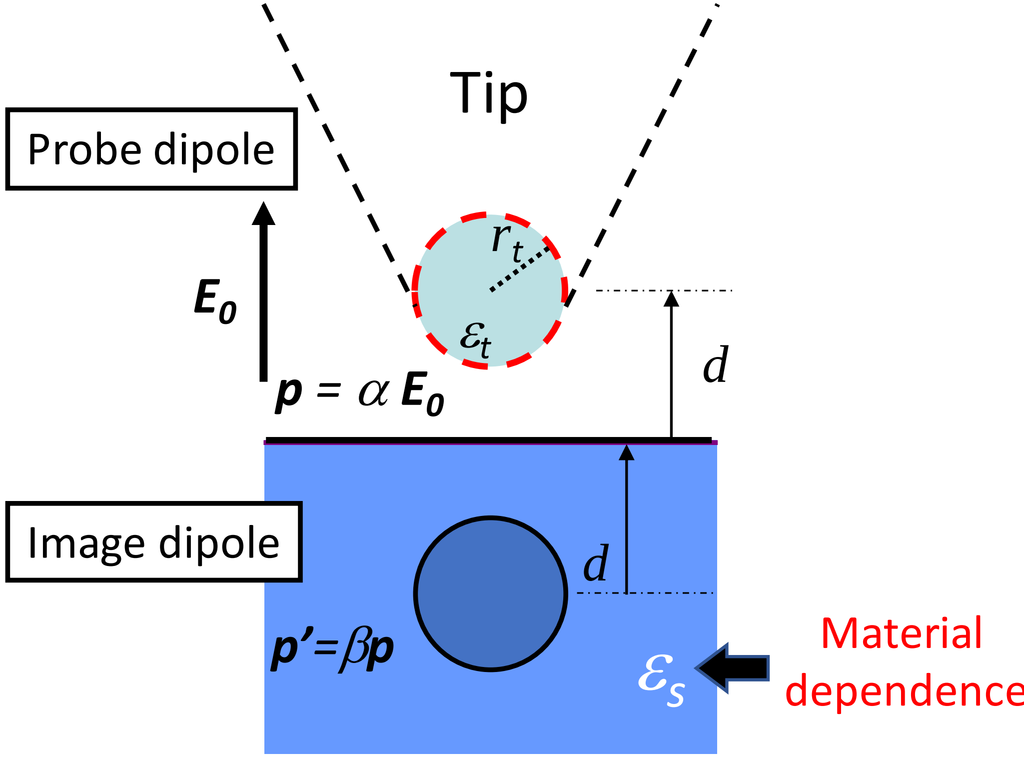




Probe/image dipole model

Effective scattering cross section:

$$\sigma(\varepsilon_t,\varepsilon_s)$$

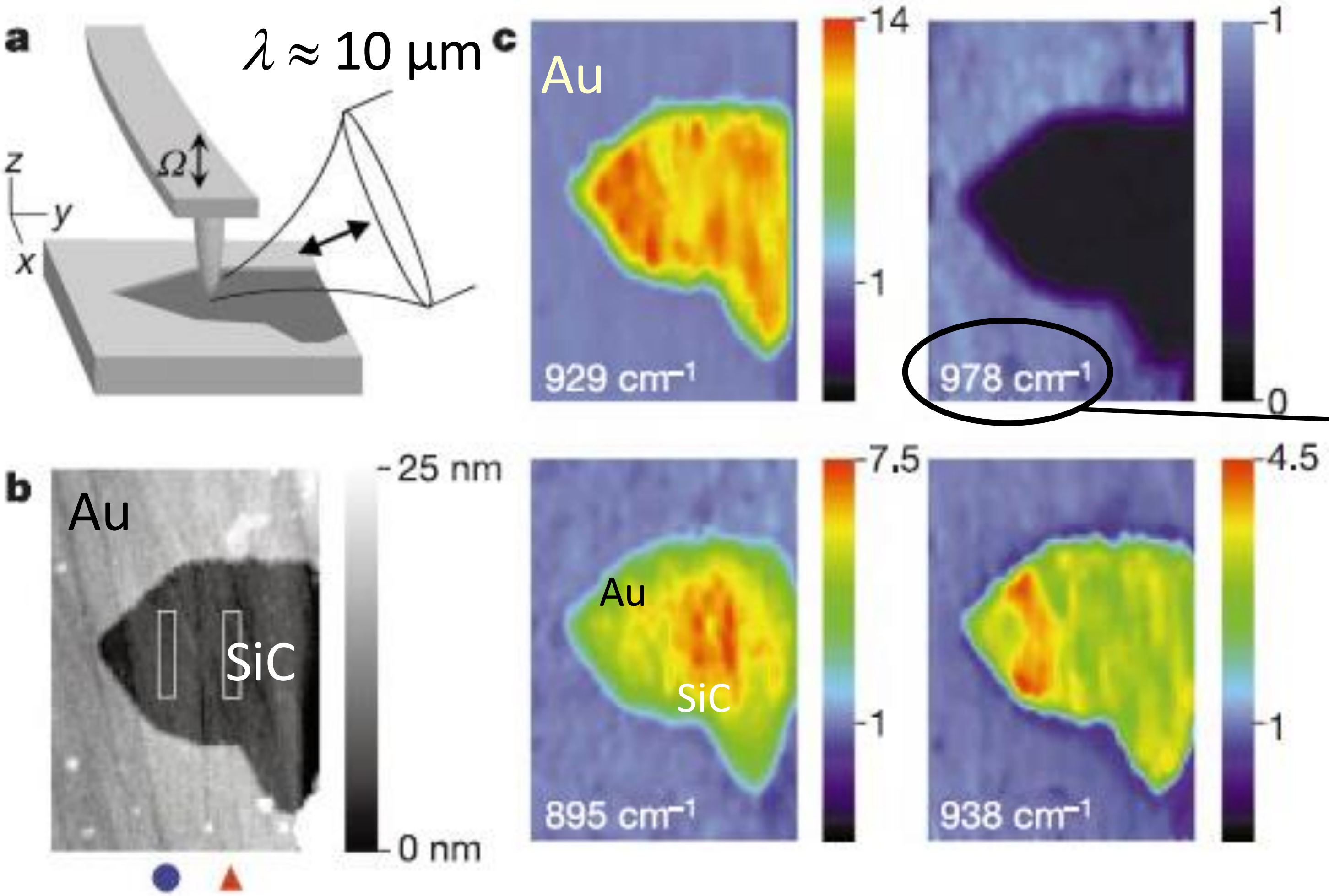


B. Knoll and F. Keilmann, Opt. Comm. **182**, 321 (2000).
K. Joulain *et al.*, JQSRT **136**, 1-15 (2014).

$$E' = E_{dipole} = \frac{p}{2\pi r^3}$$

Avec $r=2d$

Example: Sample Au + SiC



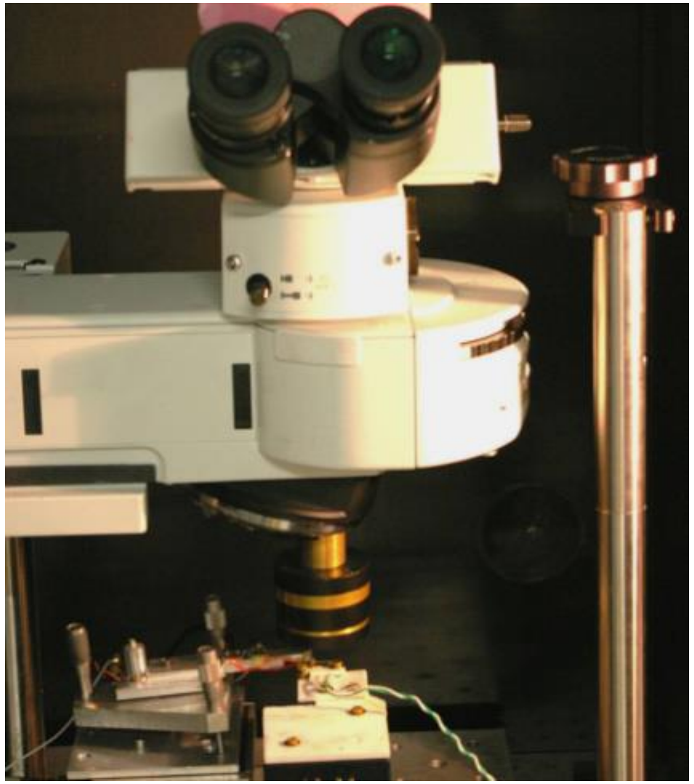
$$\frac{1}{\lambda}$$

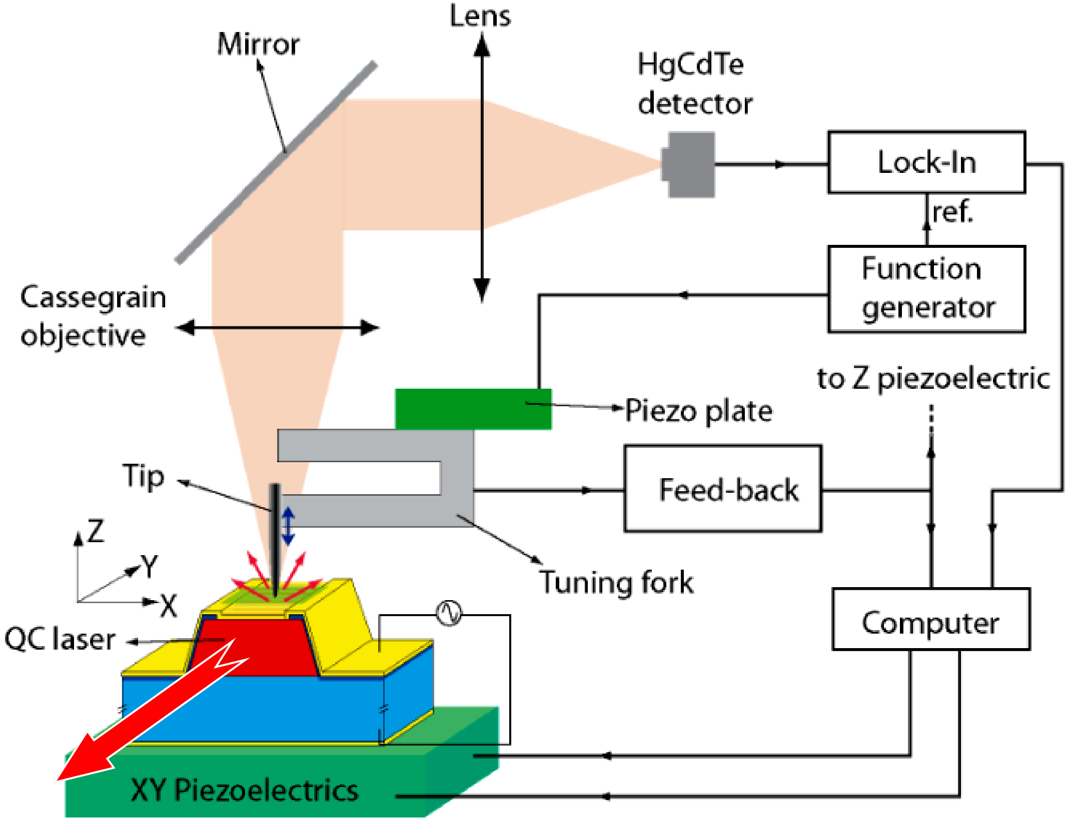
(1000 $cm^{-1} \equiv$ 10 μm)

Image size: 1.6 × 2.3 μm

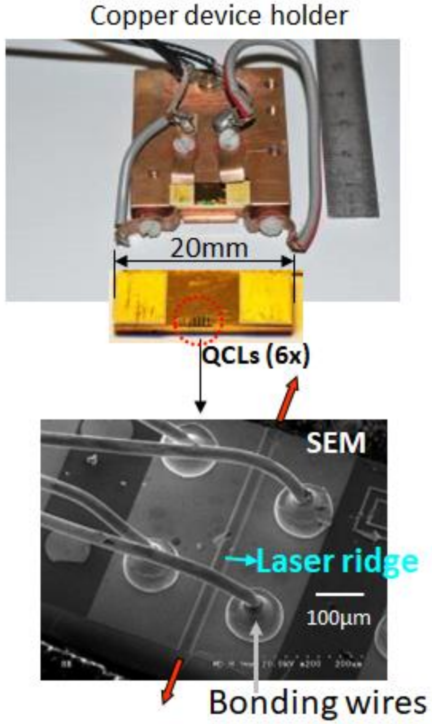
Hillenbrand et al. , Nature **418**, 159 (2002)

Scattering-type NSOM (s-NSOM) on active plasmonic devices (QCLs)





AFM/NSOM stage



Collaboration: R. Colombelli, A. Bousseksou

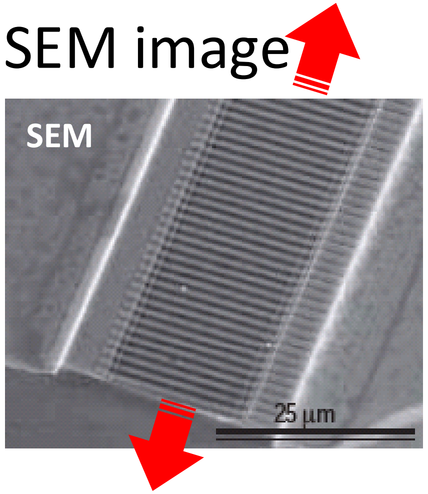
QCLs: Quantum Cascade Lasers

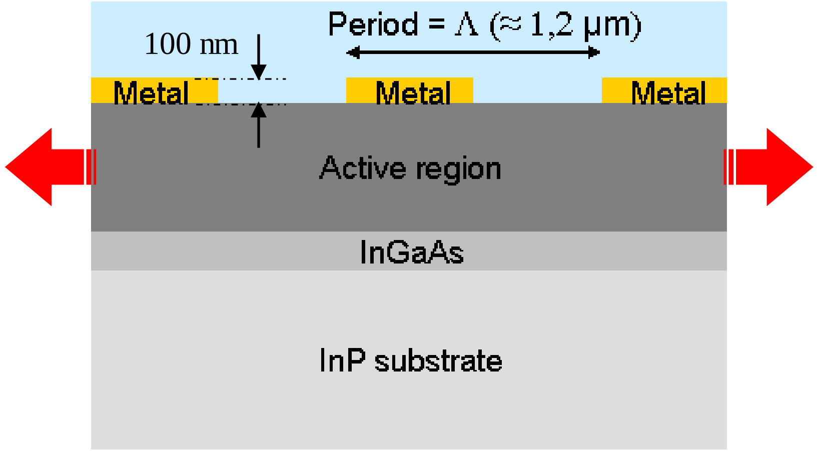
QCL with metal grating

$\lambda \approx 7.5 \mu m$

$$\boxed{\Lambda \approx \lambda/2n_{eff.}}$$

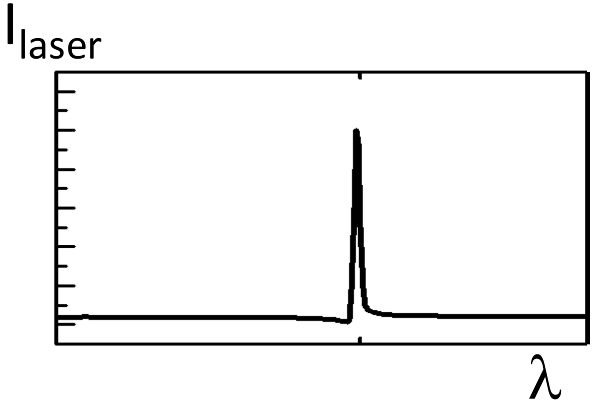
SEM image





Side view

Far-field spectrum



Single mode emission

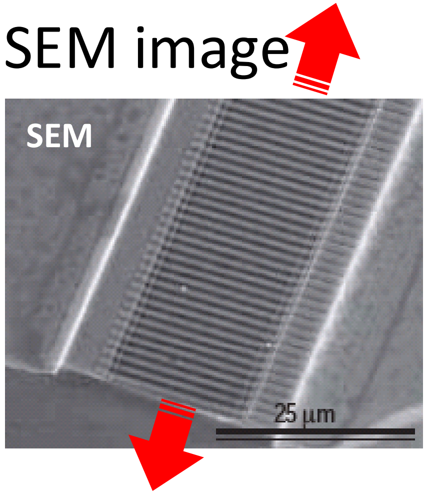
Bousseksou et al, Opt. Express 17, 9391 (2009)

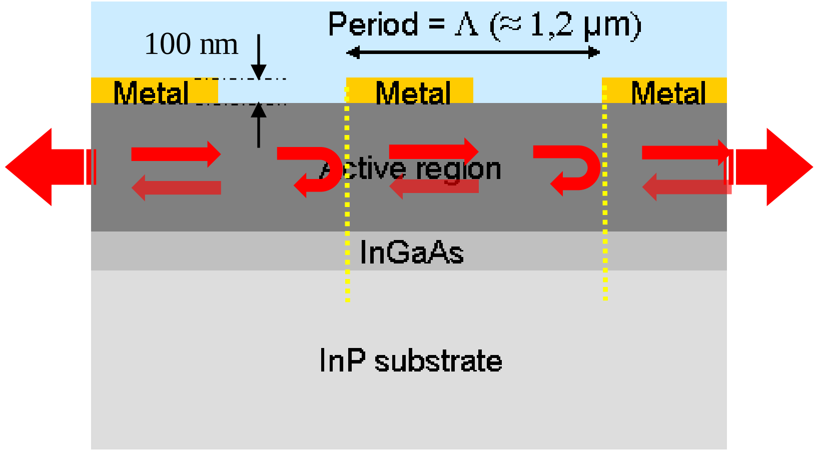
QCL with metal grating

$\lambda \approx 7.5\mu m$

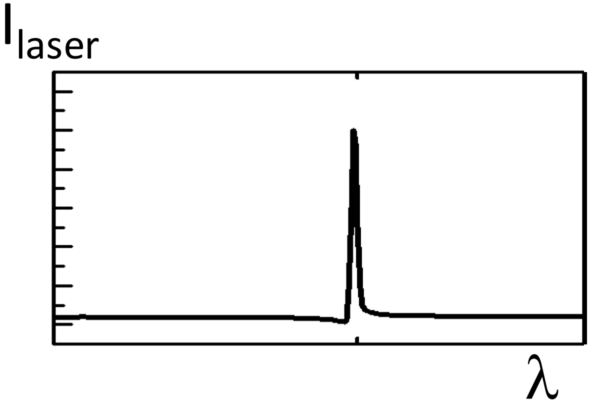
$\Lambda \approx \lambda / 2n_{eff.}$

SEM image





Far-field spectrum

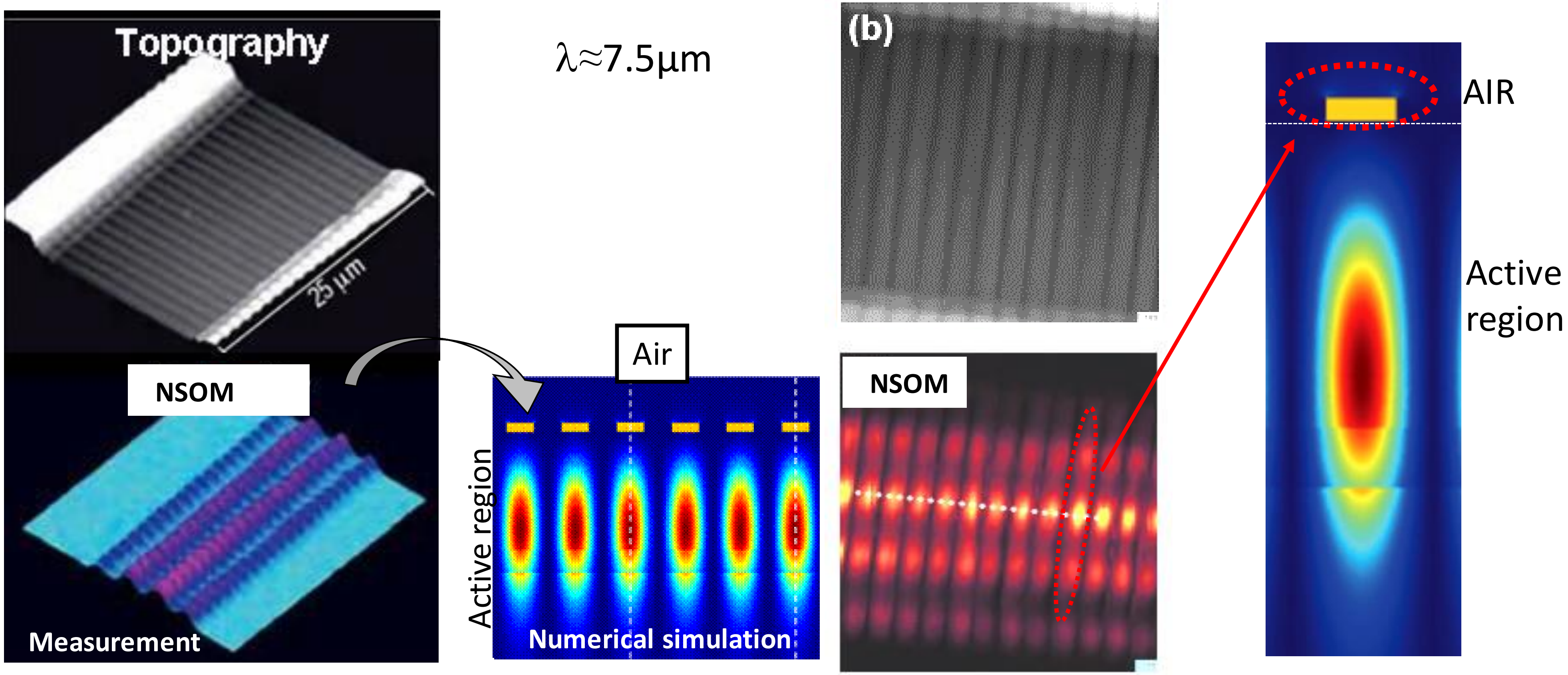


→ Single mode emission

Bousseksou et al, Opt. Express 17, 9391 (2009)

QCL with metal grating : NSOM images

λ≈7.5µm



numerical simulation (xz)

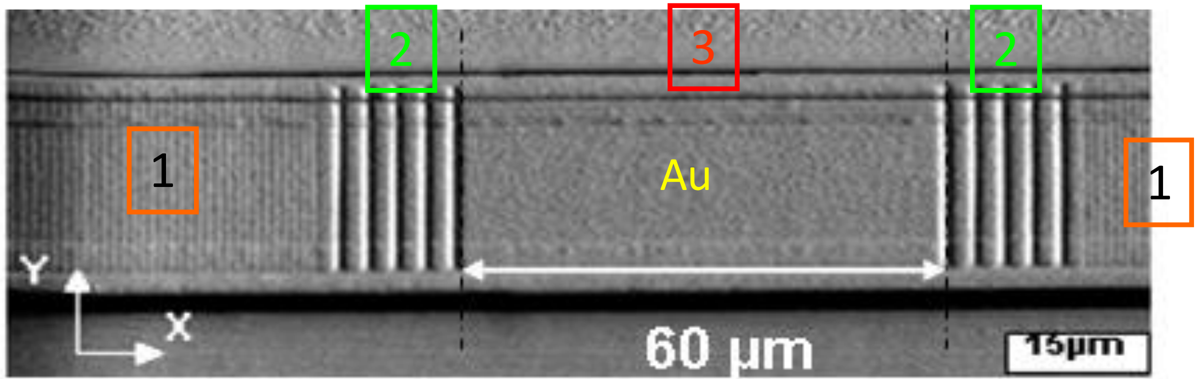
Direct visualisation of the EM modes

<u>Hybrid</u> surface plasmons are generated on the metal grating

Bousseksou et al, Opt. Express 17, 9391 (2009)

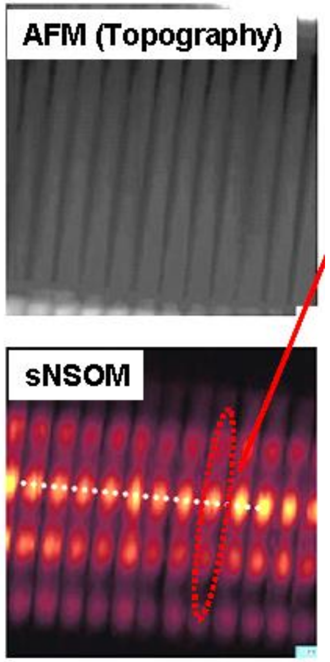
Building block of active plasmonics: generator, coupler, passive SPP waveguide

Measured topography (AFM)



1. DFB grating

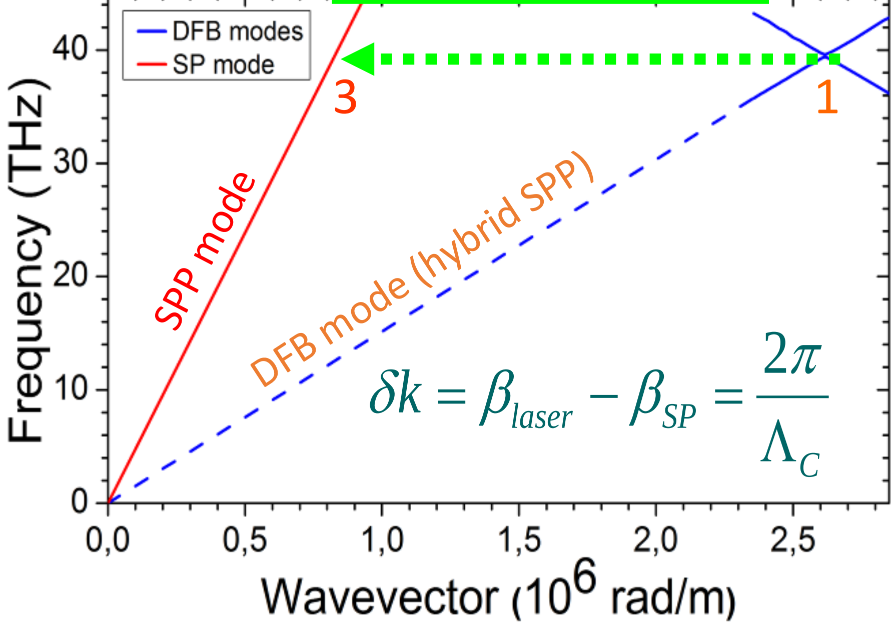
Generator



Hybrid SPPs

2. Grating coupler

3. Passive waveguide

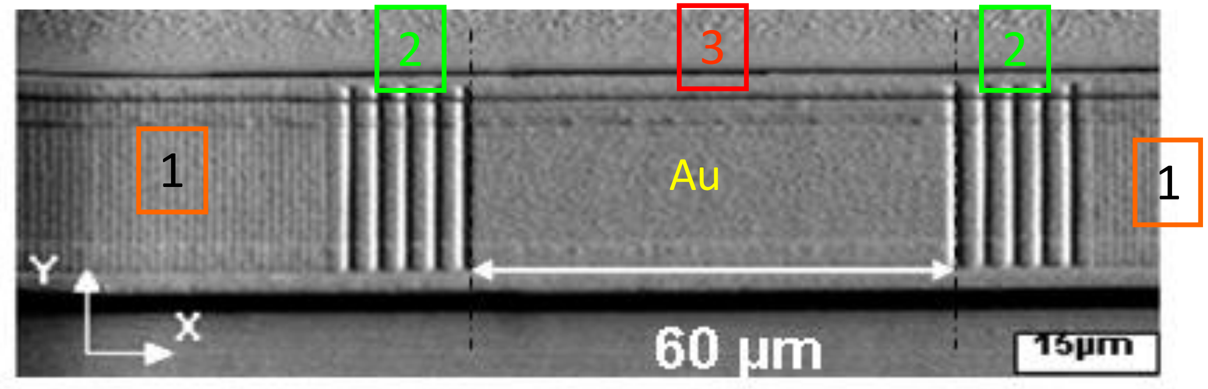


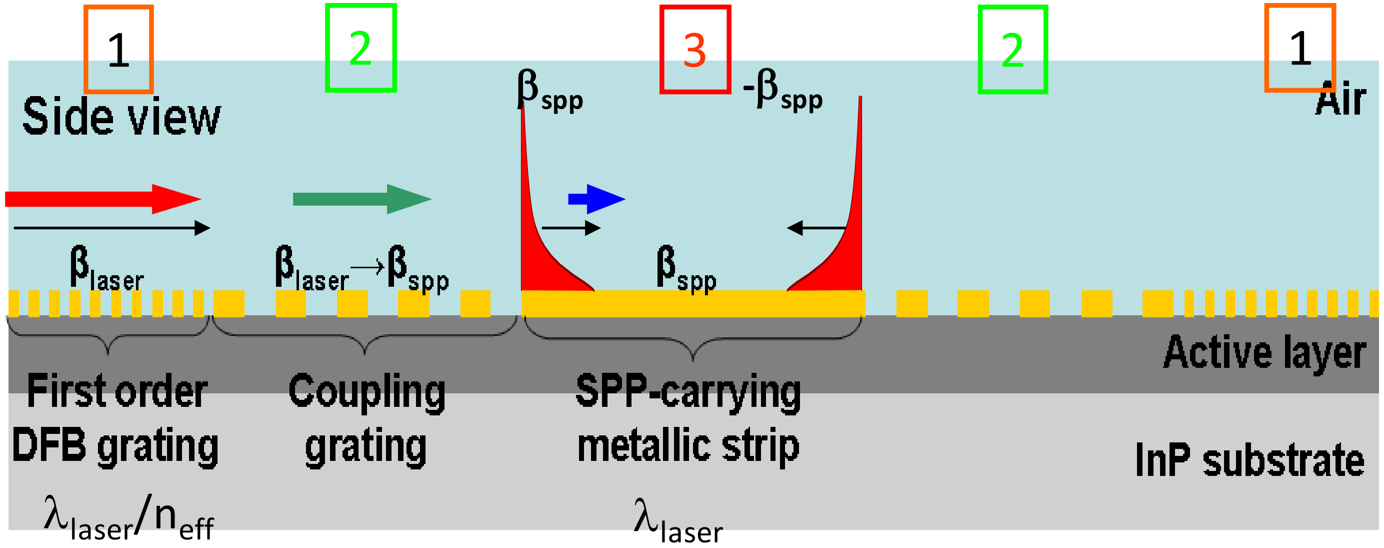
$$\delta k = \beta_{laser} - \beta_{SP} = \frac{2\pi}{\Lambda_C}$$

Babuty et al., Phys. Rev. Lett., 104, 226806, (2010)

Building block of active plasmonics: Slit doublet experiment

Measured topography (AFM)

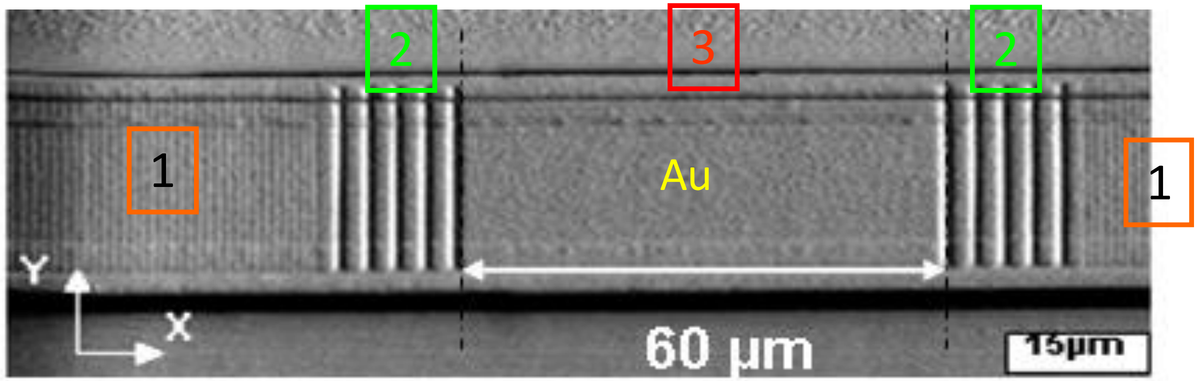




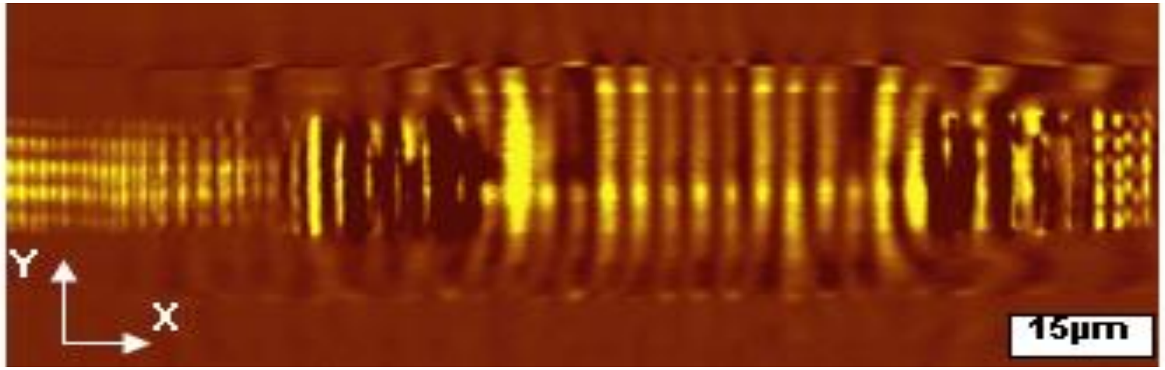
Babuty et al., Phys. Rev. Lett., 104, 226806, (2010)

Building block of active plasmonics: Slit doublet experiment

Measured
topography
(AFM)



Measured
near-field
λ≈7.5µm

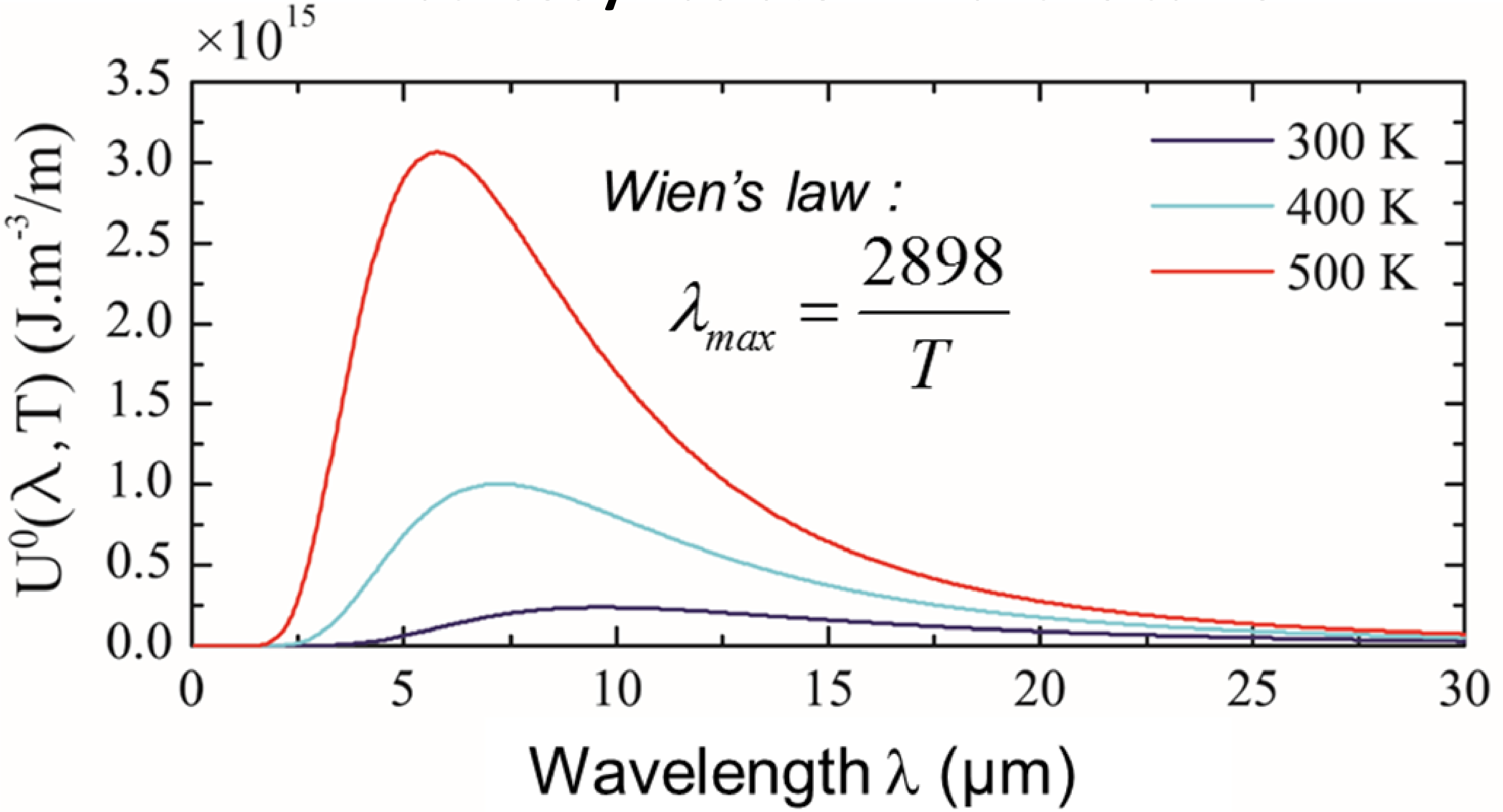


Generation and launching of SPPs

SPP generation at 7.5 µm
Babuty et al., Phys. Rev. Lett. 104, 226806, (2010)
Spoof plasmons at 7.5 µm
Bousseksou et al., Opt. Expr. 20, 13738 (2012)
SPP generation at 1.3 µm
Costantino et al., Nano letters 12, 4693 (2012)
Greusard et al., Opti. Expr. 21, 10422 (2013)

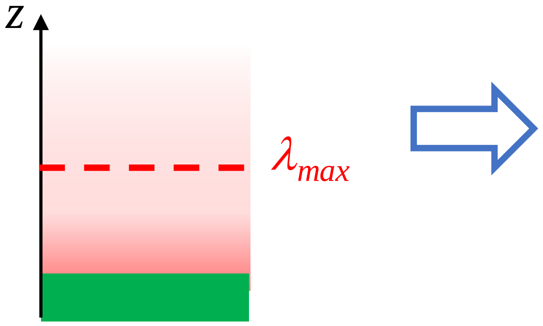
Thermal Radiation

Blackbody Radiator – Planck's curve



Far field:

$$z \gg \lambda_{max}$$

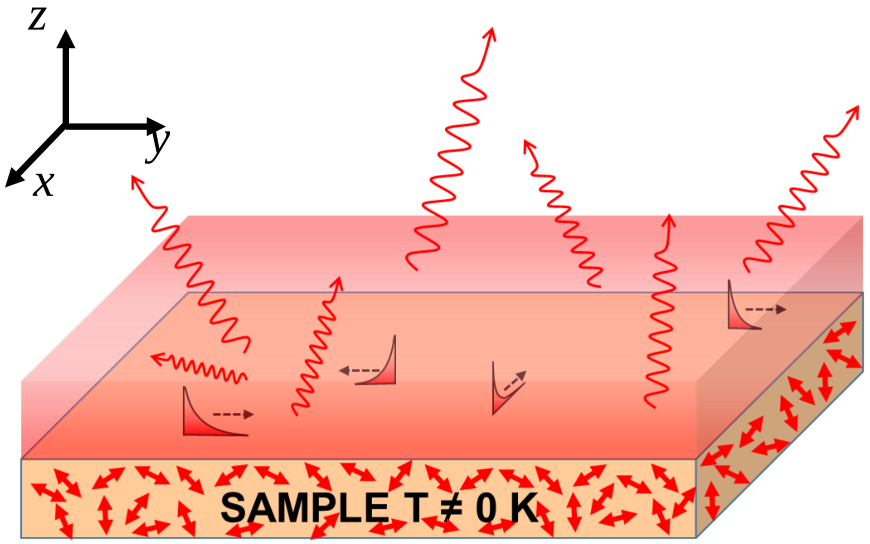


$$U(\omega, T) = \varepsilon^{\mathrm{RM}}(\omega) U^{BB}(\omega, T)$$

Emissivity

$$0 \le \varepsilon^{\mathrm{RM}}(\omega) \le 1$$

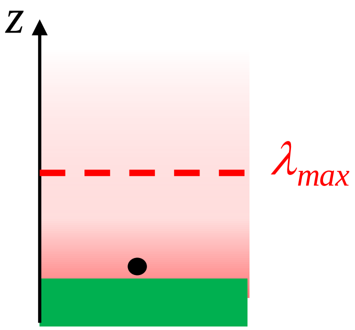
Real material radiation:



?

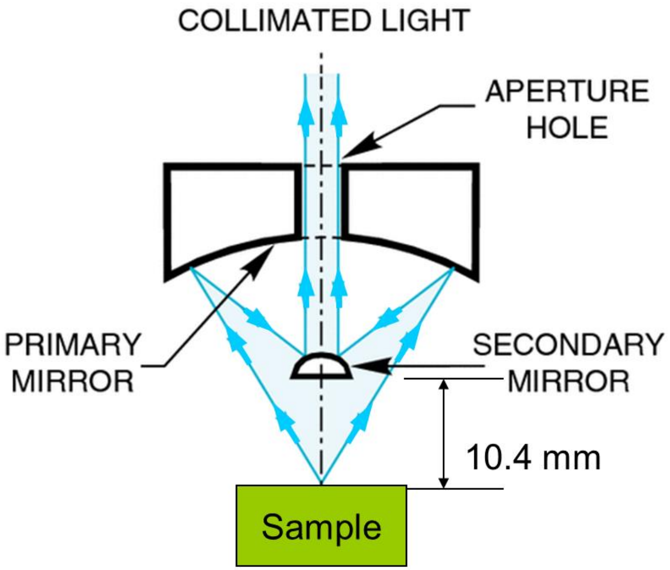
Near field:

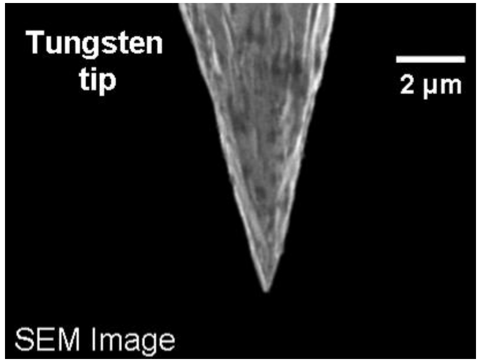
$$z \ll \lambda_{max}$$

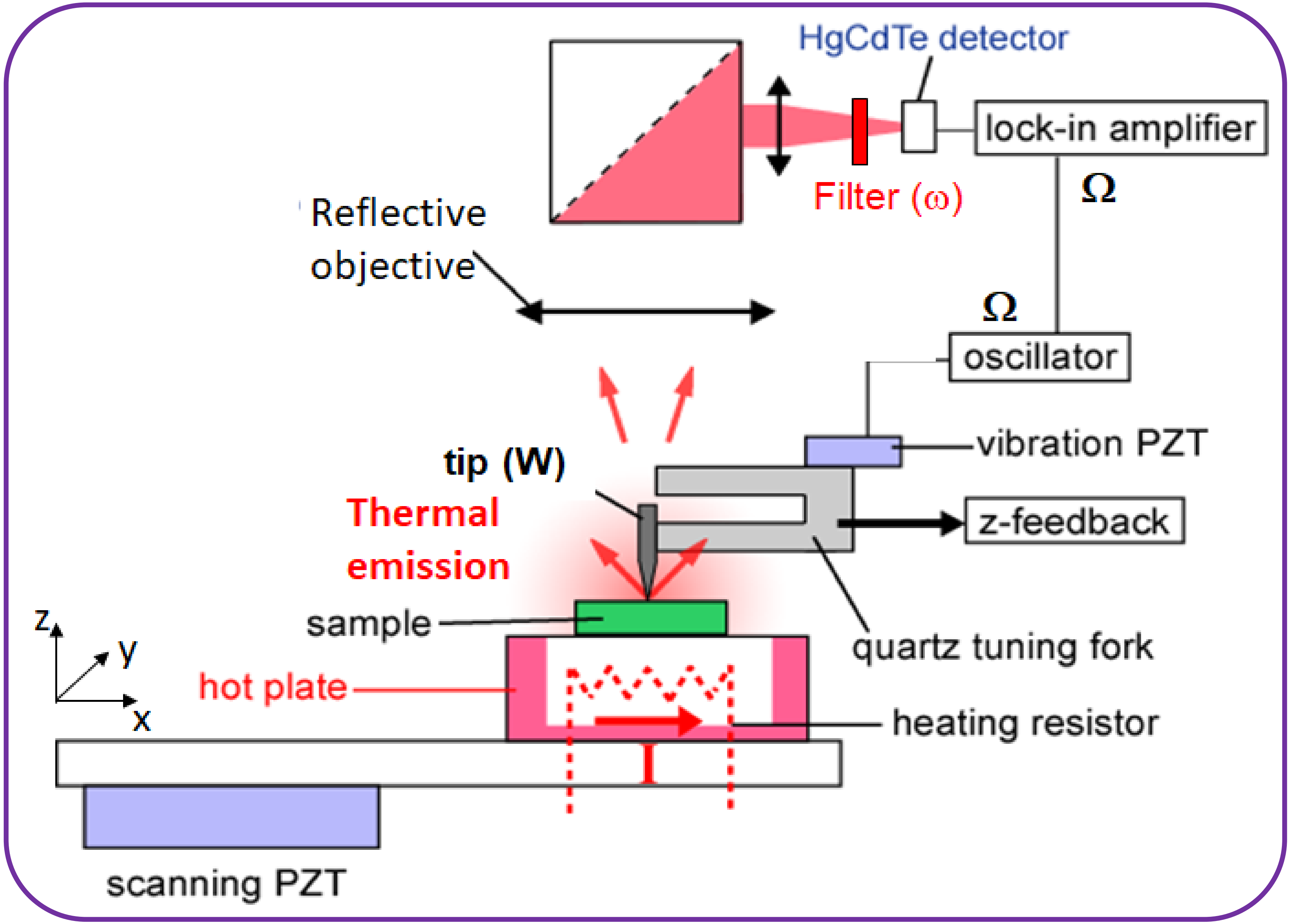


Thermal Radiation STM (TRSTM):

Reflective objective (Cassegrain)



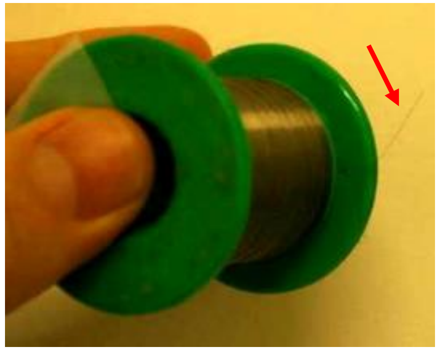


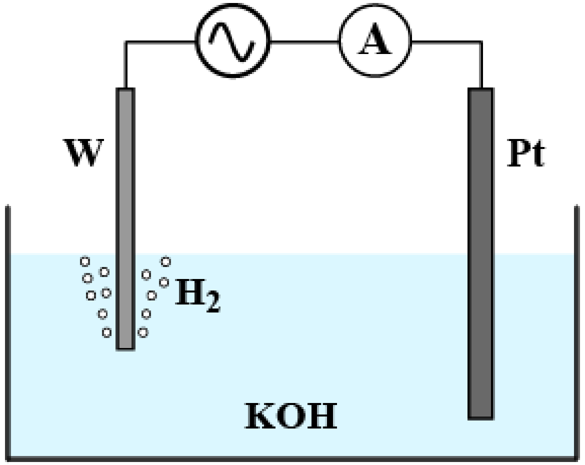


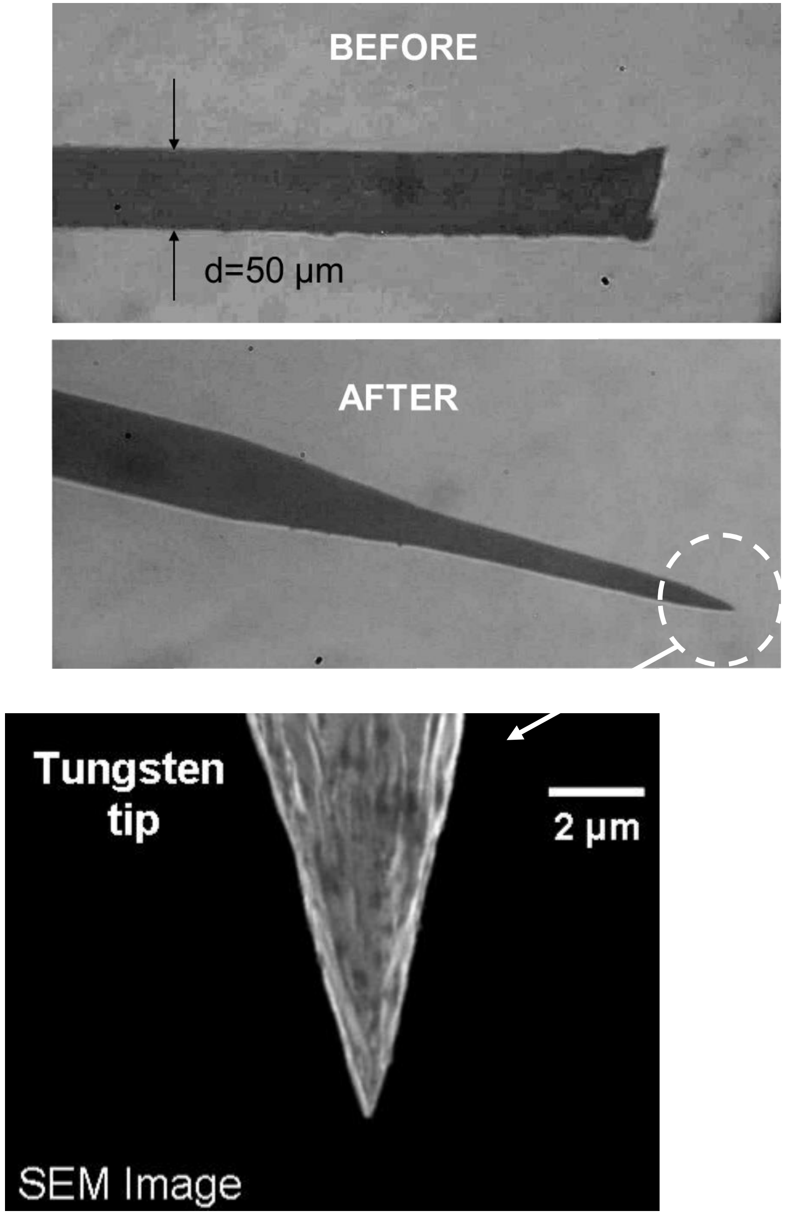
De Wilde *et al.*, *Nature* **444**, 740 (2006).

Tip preparation

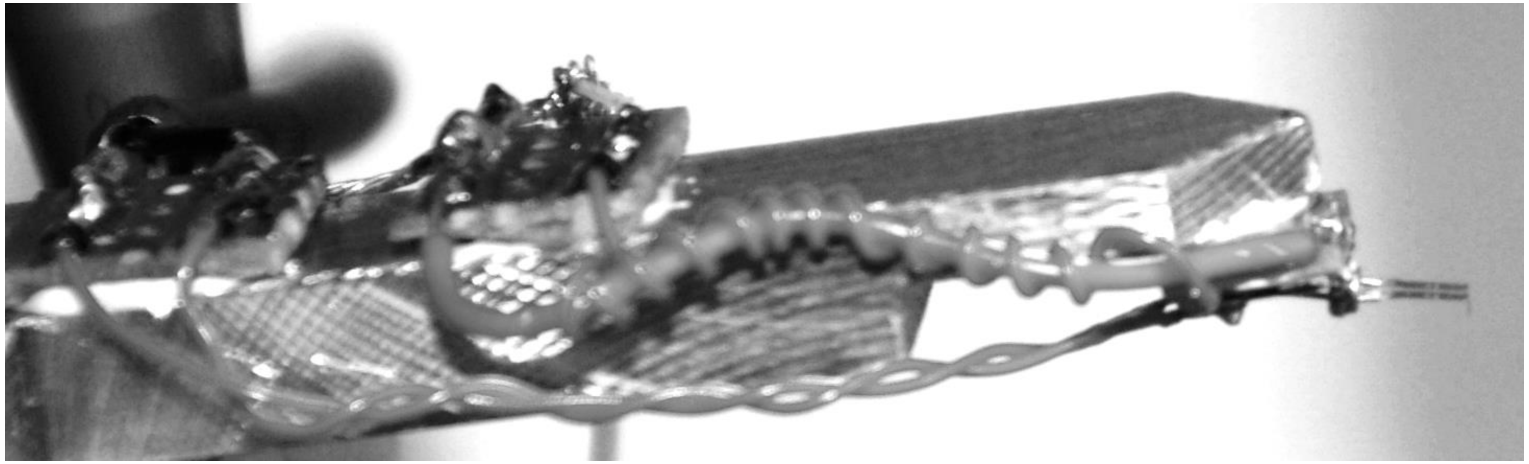
Tungsten wire

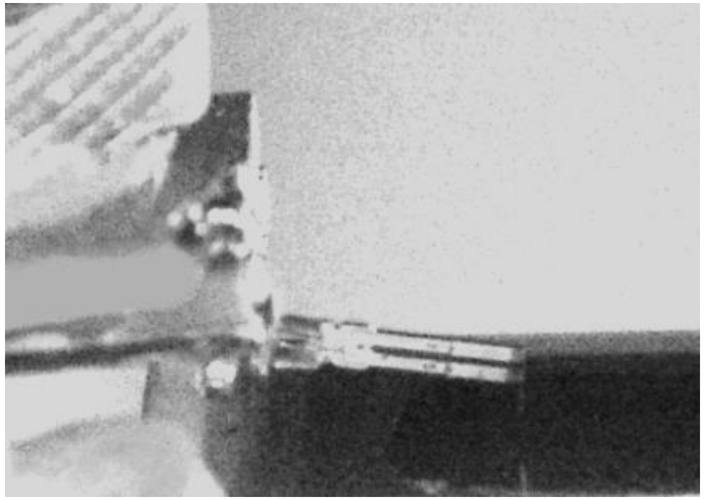




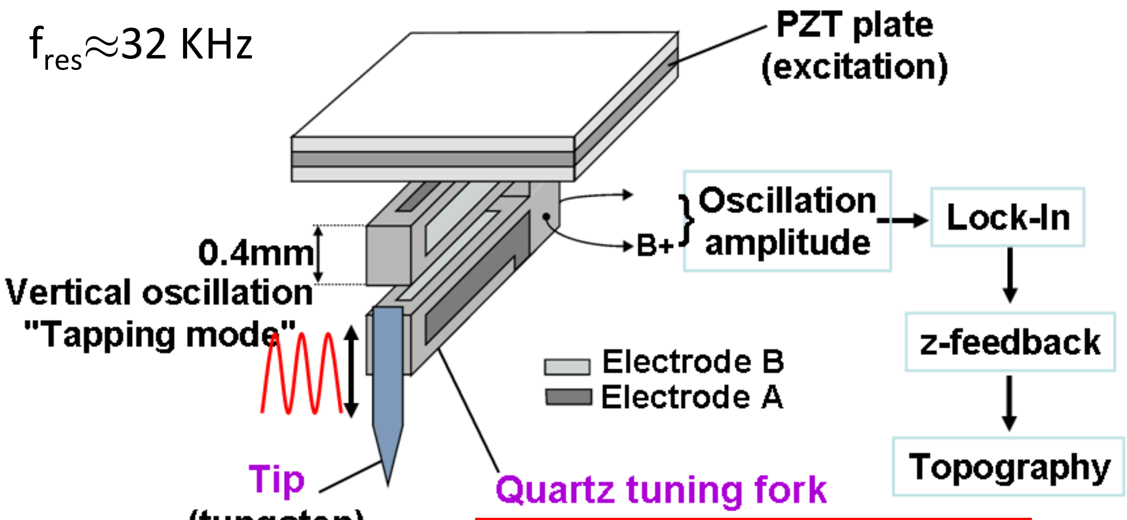


Mid IR s-NSOM – TRSTM:
Tip mounting and oscillation detection





$f_{res} \approx 32$ KHz

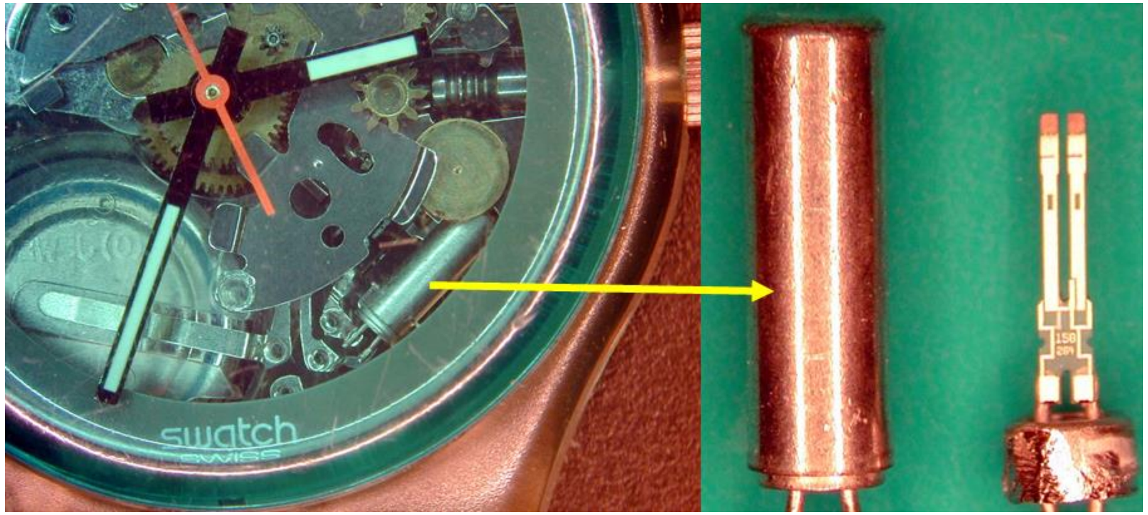


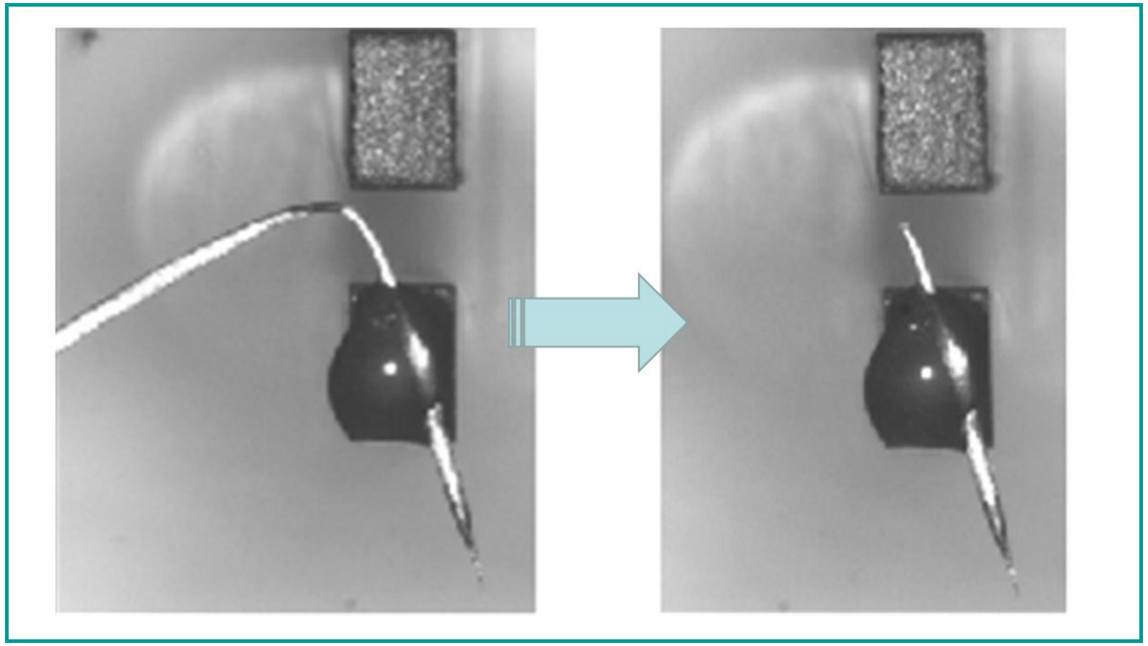
Constant amplitude mode

Tip gluing

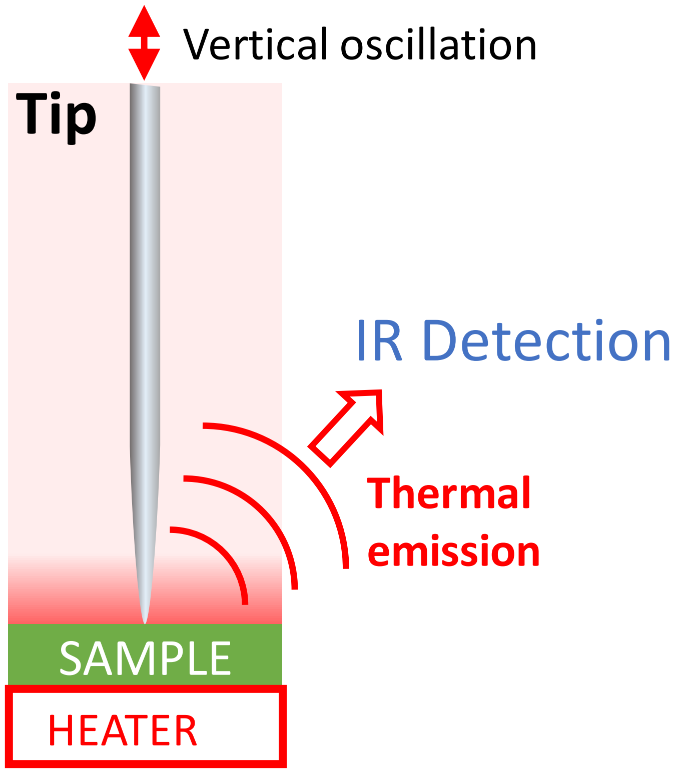
Quartz tuning fork

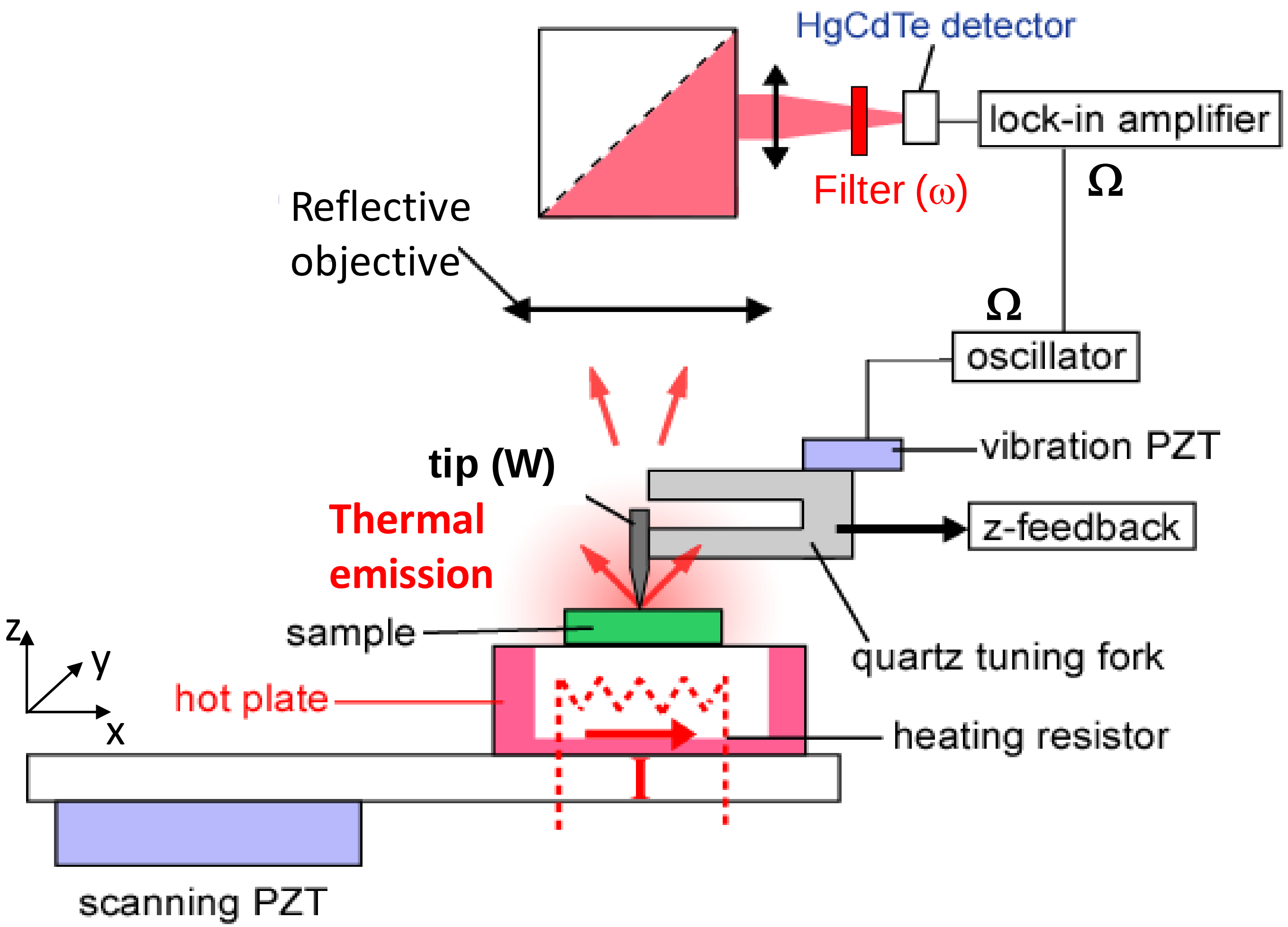
Ω_{res}=32768 Hz





Tip modulation





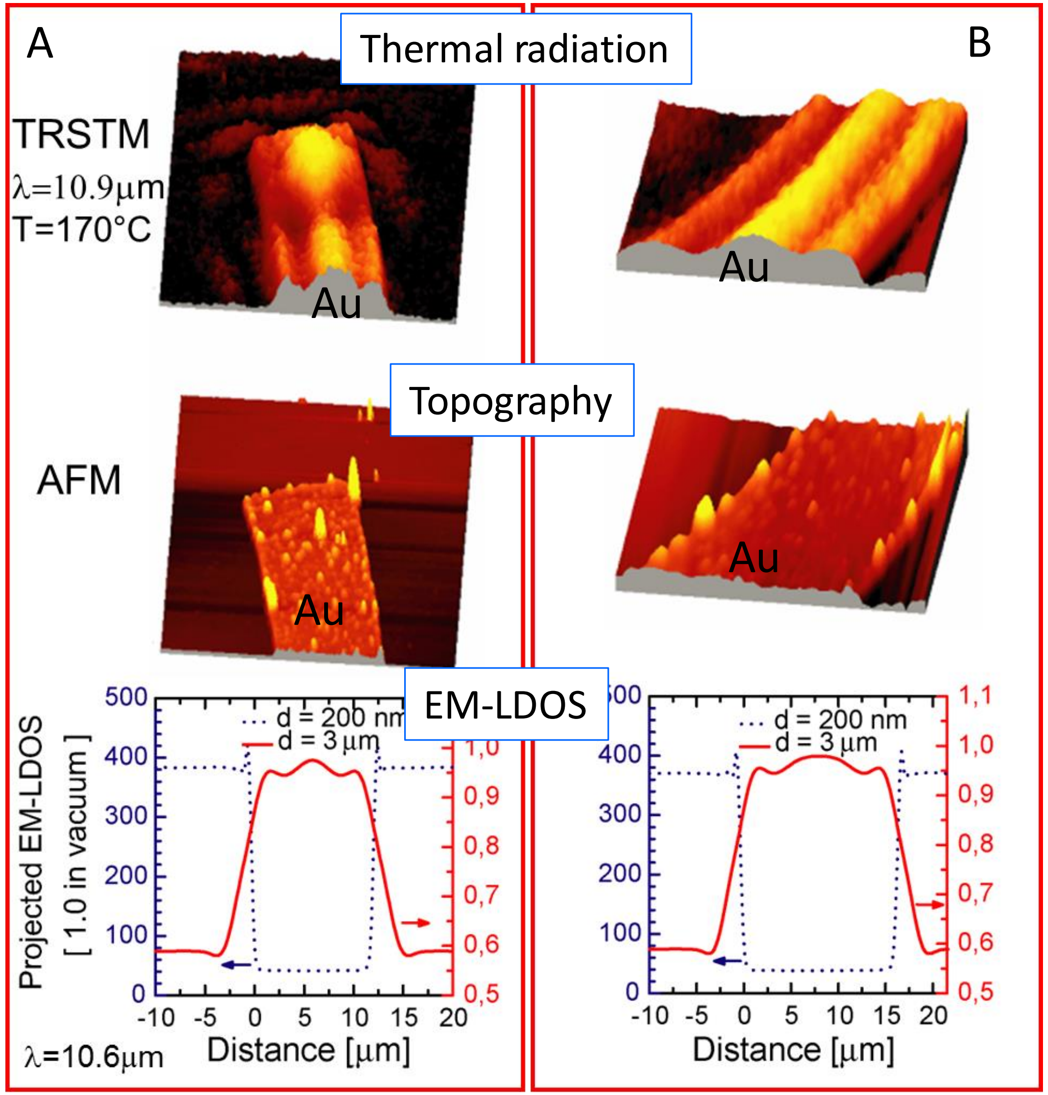
$S(z_0 + a\cos\Omega t) \propto S_0 + A\, dS/dz \cos\Omega t + B\, d^2S/dz^2 \cos 2\Omega t + \dots$

Lock-In signal: $S_\Omega \propto dS/dz$ at z_0 ⇨ Suppression of far-field background.

De Wilde *et al.*, *Nature* **444**, 740 (2006).

Near-field imaging of EM-LDOS

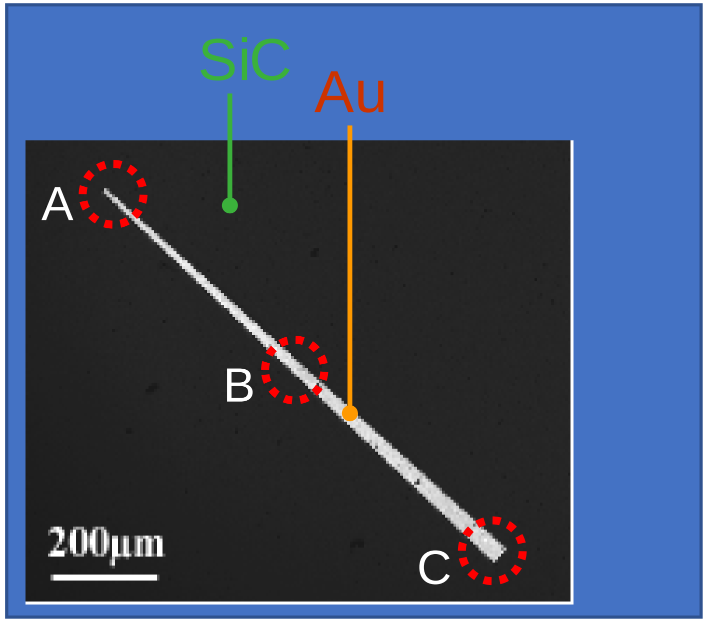
IMAGING (λ≈11μm , T≈440 K)

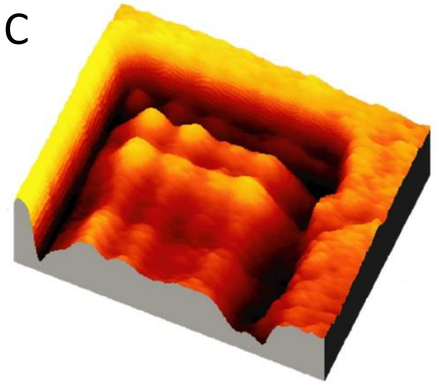


Thermal radiation

Topography

EM-LDOS

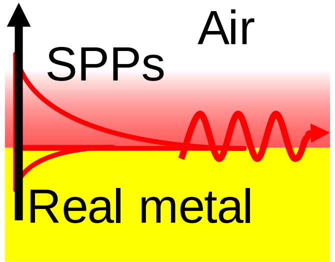


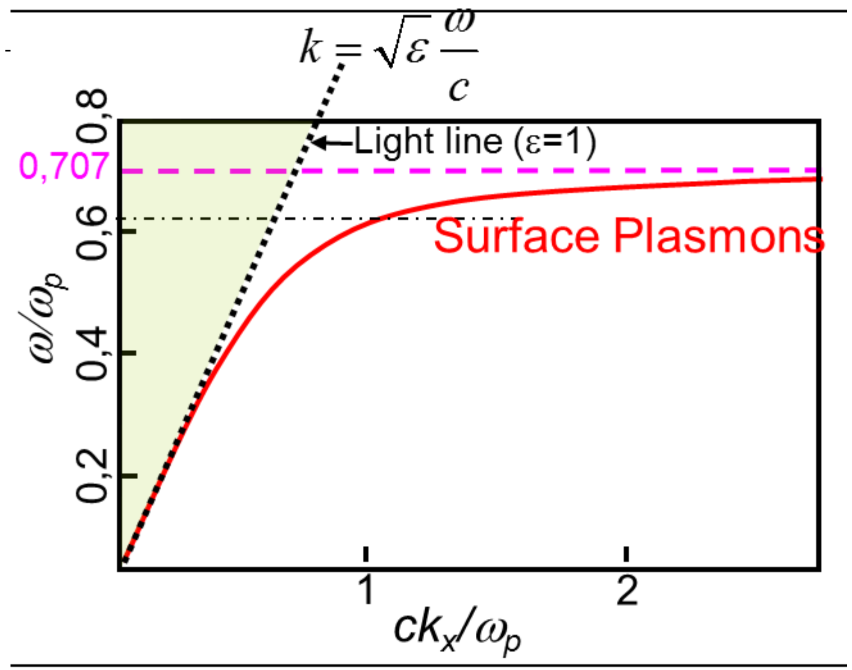


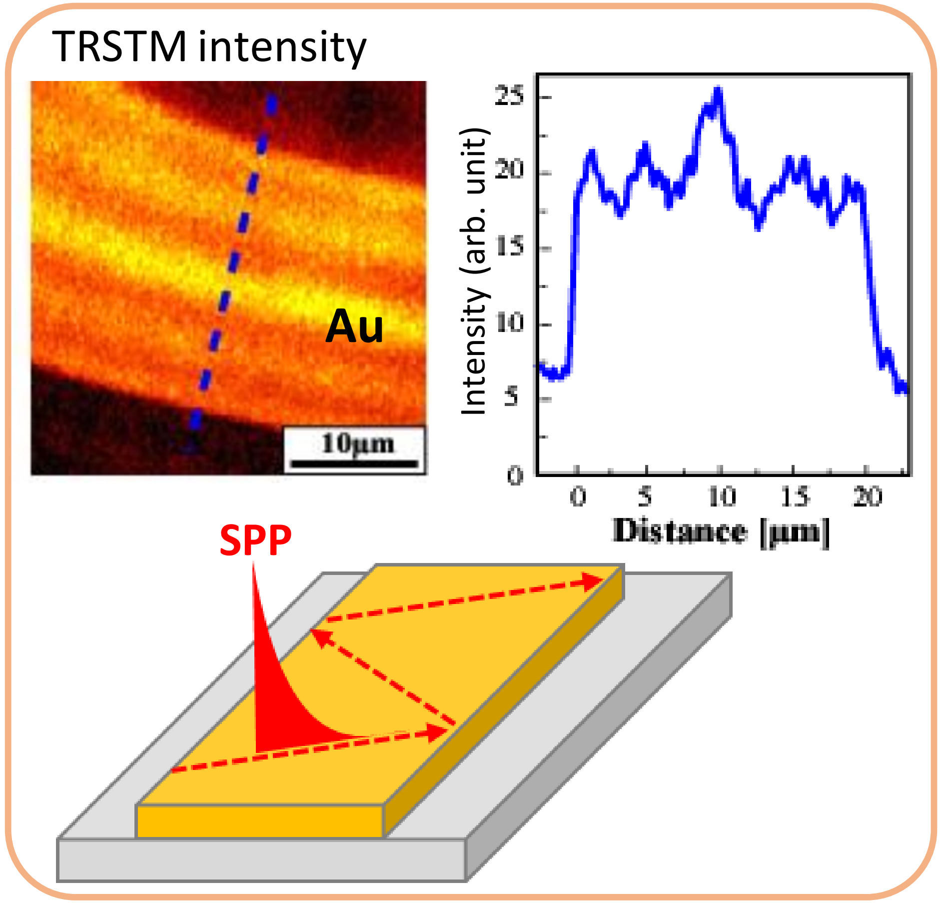
De Wilde *et al.*, *Nature* **444**, 740 (2006).

Cavity modes of SPPs on Au

Surface waves

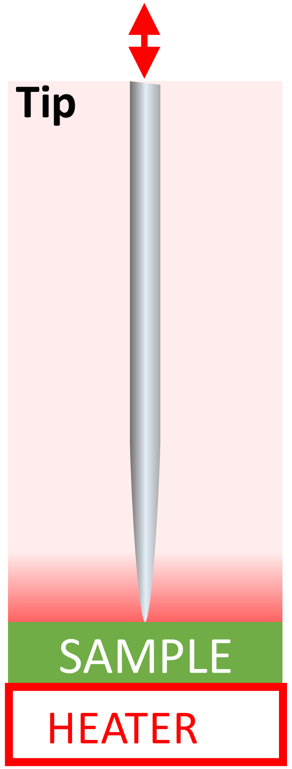


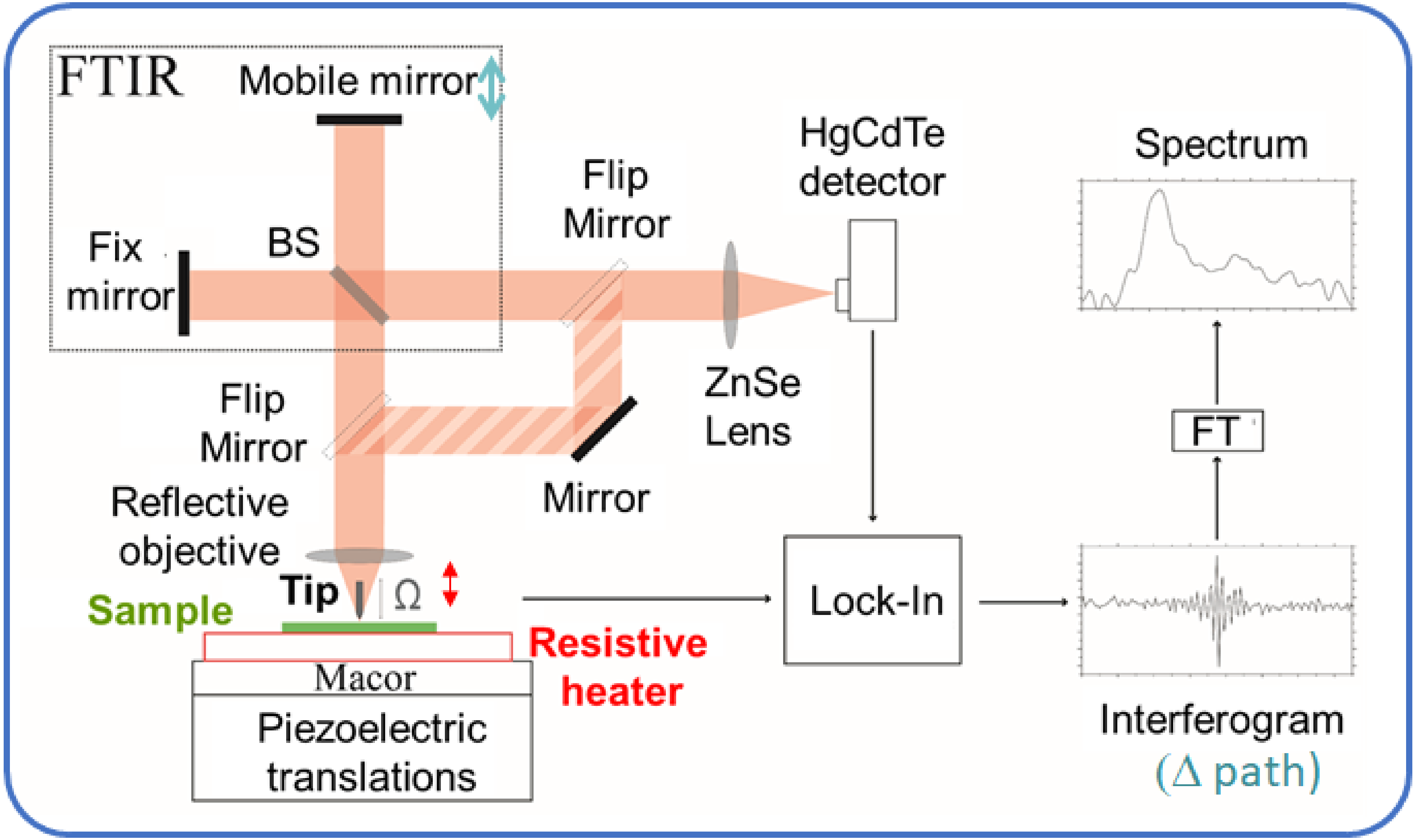




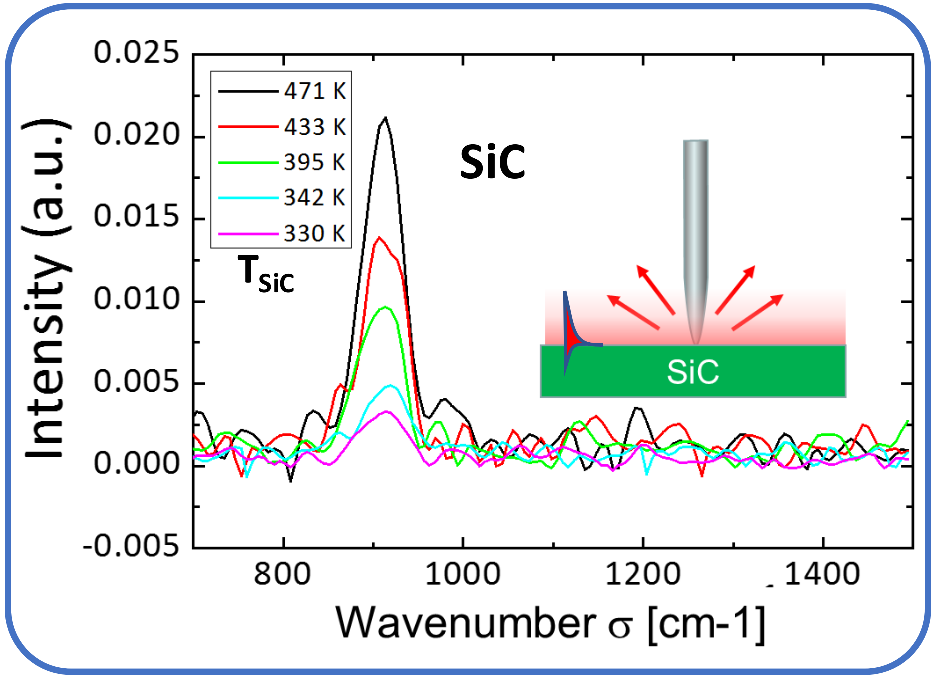
De Wilde *et al.*, *Nature* **444**, 740 (2006).

TRSTM coupled with FTIR spectrometer

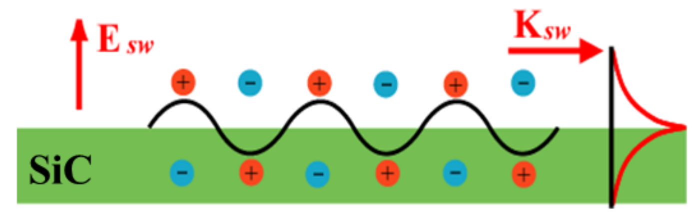




TRSTM spectra on SiC:



Non-planckian behavior



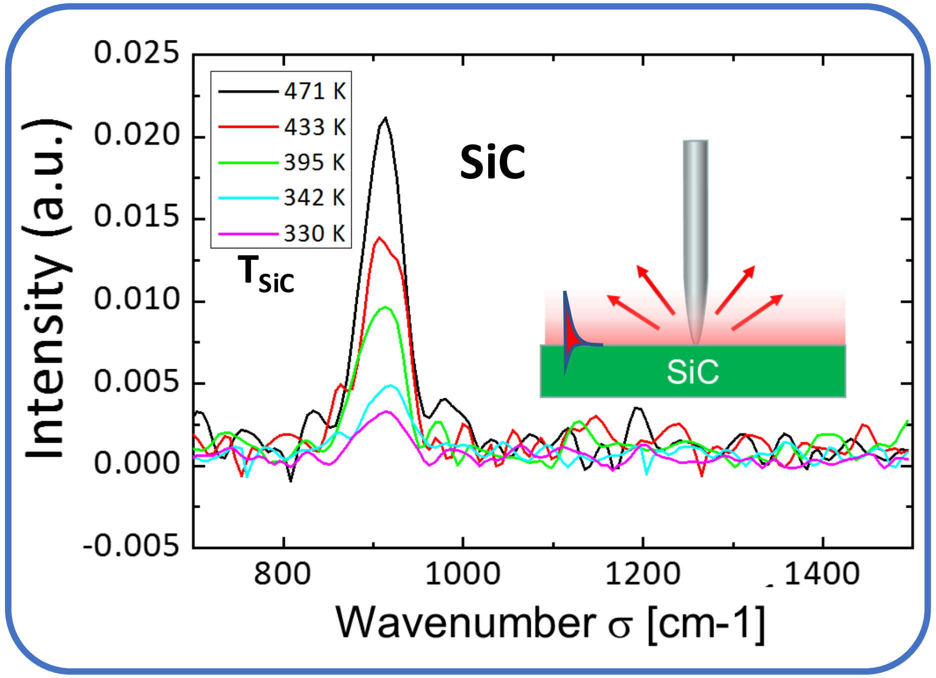
SiC = Polar material with surface phonon polaritons.

Prediction: **Shchegrov *et al.*, PRL 85, 1548 (2000).**

Near-field thermal radiation from surface phonon polaritons (SPhP).

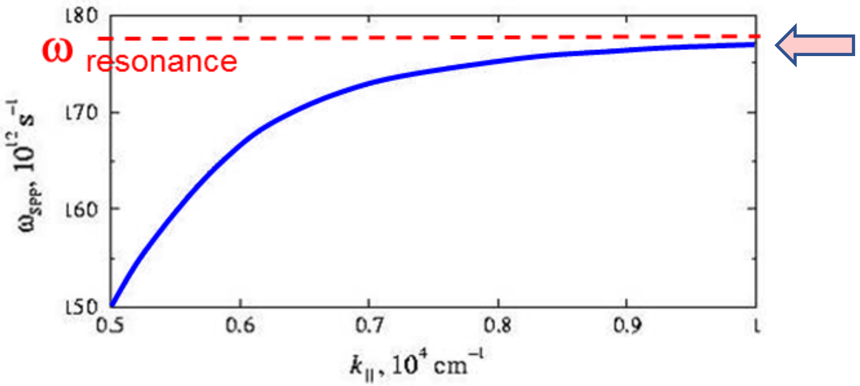
Babuty *et al., Phys. Rev. Lett.* **110**, 146103 (2013).
Joulain *et al., JQSRT* **136**, 1-15 (2014).
Peragut *et al., Appl. Phys. Lett.* **104,** 251118 (2014).

TRSTM spectra on SiC:

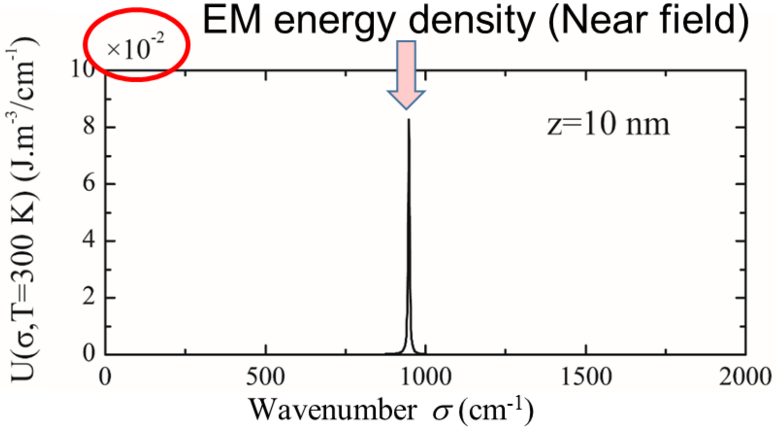


Non-planckian behavior

Dispersion relation of SPhP



EM energy density (Near field)

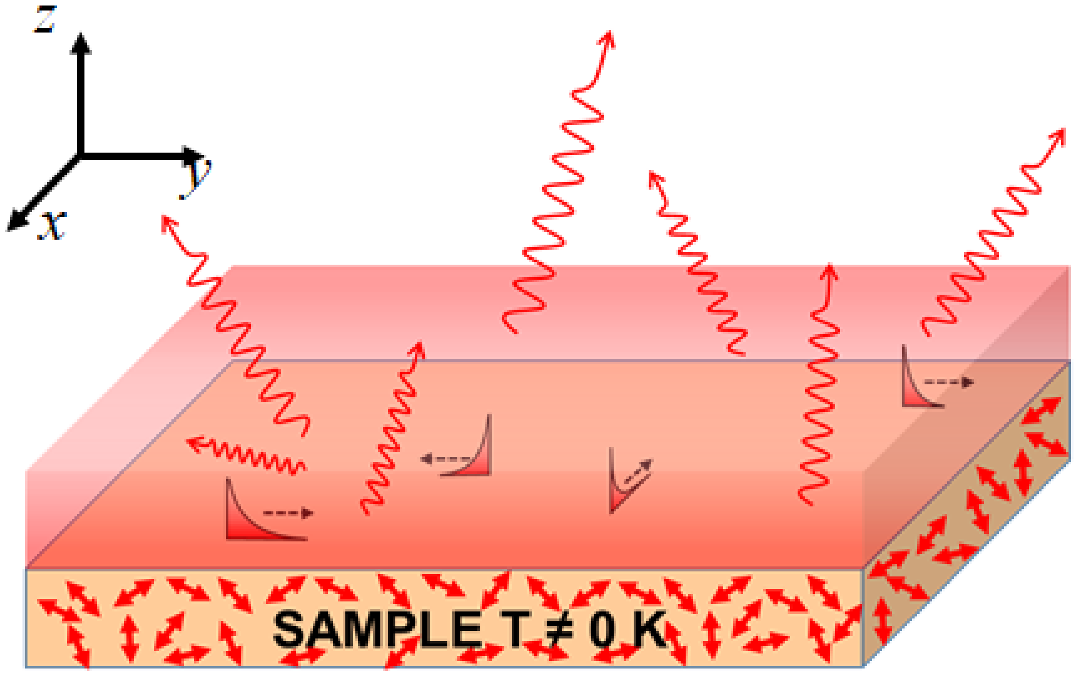


Prediction: **Shchegrov *et al.*, PRL 85, 1548 (2000).**

Near-field thermal radiation from surface phonon polaritons (SPhP).

Babuty *et al., Phys. Rev. Lett.* **110**, 146103 (2013).
Joulain *et al., JQSRT* **136**, 1-15 (2014).
Peragut *et al., Appl. Phys. Lett.* **104,** 251118 (2014).

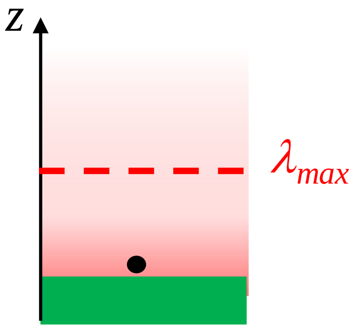
Origin of the signal



The TRSTM probes the electromagnetic local density of states (EM-LDOS) in the near-field.

Near field:

$z \ll \lambda_{max}$



Predictions:
- EM-LDOS
- Contribution of surface waves
- Coherence properties

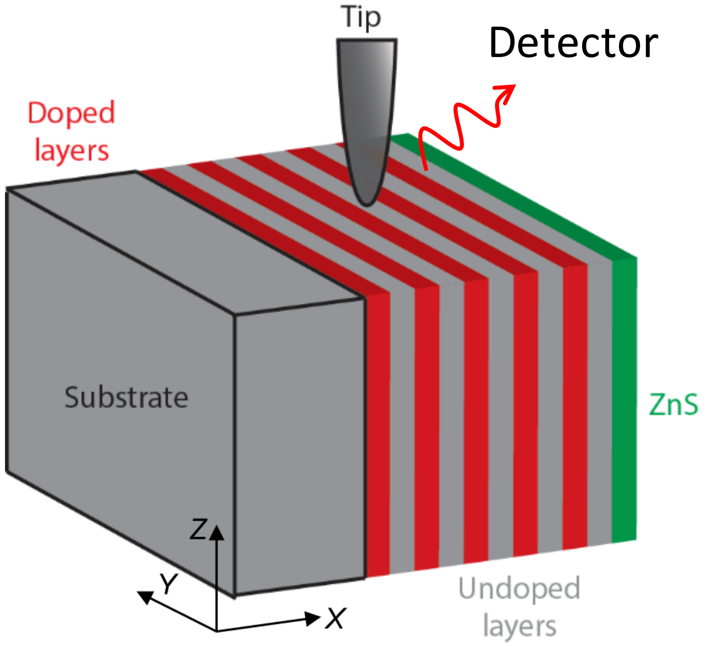
$$U\left(\mathbf{r},\omega,T\right)=\underline{\underline{\rho\left(\mathbf{r},\omega\right)}}\,\theta\left(\omega,T\right)$$

Local density of state (EM-LDOS)

$$\theta(\omega,T)=\hbar\omega\frac{1}{\exp\left(\hbar\omega/kT\right)-1}$$

Shchegrov, Joulain, Carminati, Greffet, *Phys. Rev. Lett*. **85**, 1548 (2000)
Joulain et al., *Phys.Rev.B* **68**, 245405 (2003).
Carminati, Cazé, Cao, Peragut, Krachmalnicoff, Pierrat, De Wilde, *Surf. Sci. Rep.* **70**, 1 (2015)

TRSTM study of doped/undoped semiconductor multilayer:



T=433 K

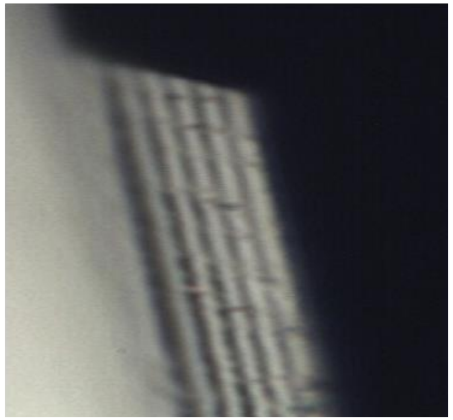
5 pairs InAs/InAs(Si)

Undoped InAs layers: ~ 10^{16} cm^{-3}, thickness: 290 nm

Doped InAs layers: 5.10^{19} cm^{-3}, thickness: 370 nm

ZnS layer, thickness: 2 µm

Cleaved edge ⇒



Collaboration :

ies l'institut d'électronique

T. Taliercio
L. Cerutti
A. Baranov

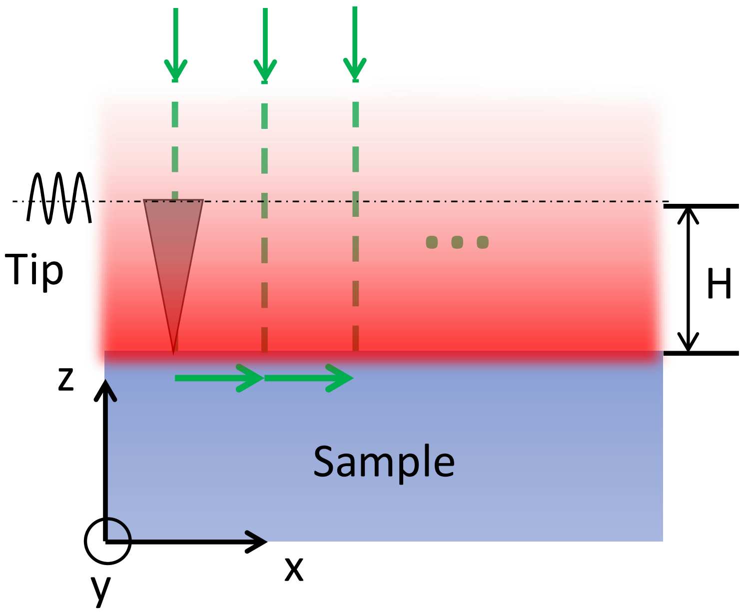
INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech

J.-J. Greffet
J.-P. Hugonin

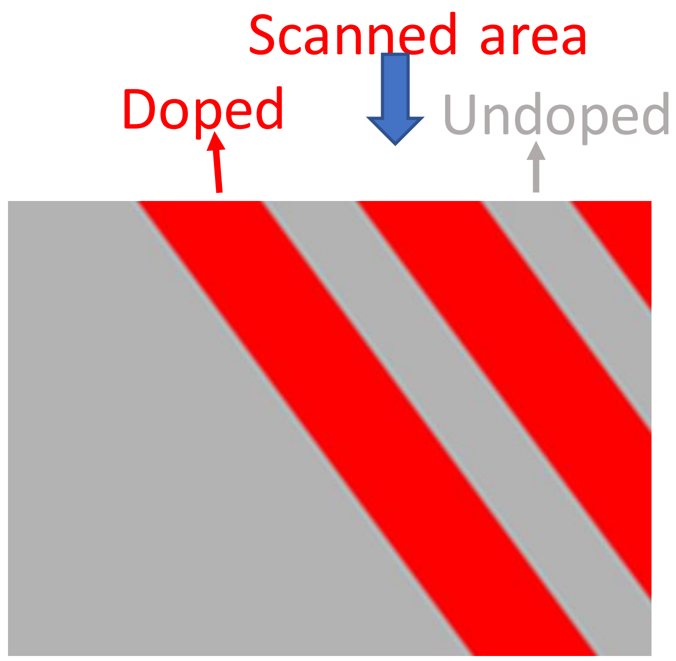
Peragut *et al.*, *OPTICA* **4**, 1406 (2017).

TRSTM imaging from far-field to near-field

3D-scans



H = 0 nm ➡ Tip in intermittent contact with sample surface.



Scan size = 2 µm x 0.7 µm x 200 nm

From H=200 nm to 0

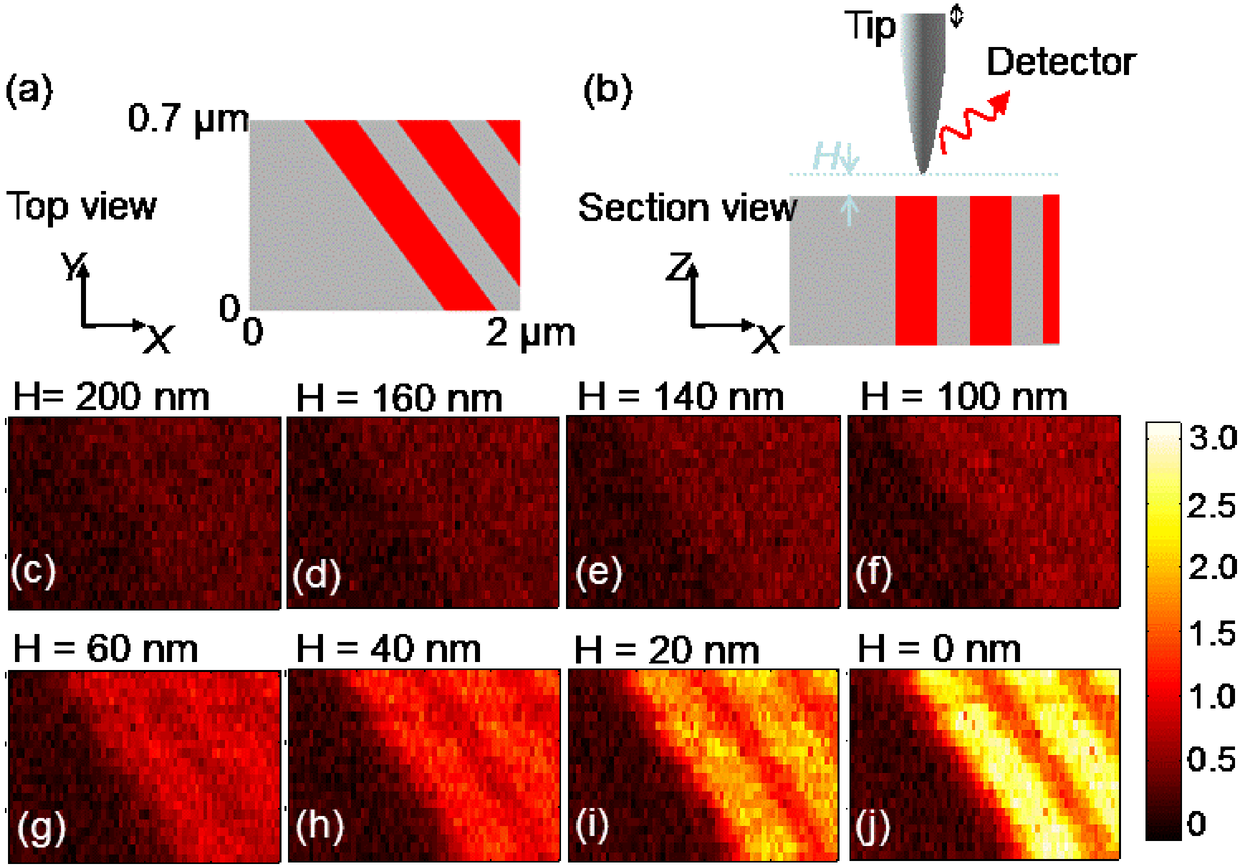
Peragut *et al.*, *OPTICA* **4**, 1406 (2017).

TRSTM imaging from far-field to near-field

$$\boxed{\left(\frac{2\pi}{\lambda}\right)^2 = |\mathbf{K}|^2 + \gamma^2}$$

$$\Downarrow$$

$$\boxed{z^* = \frac{\Delta r_\parallel}{2\pi}}$$

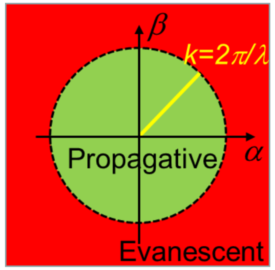


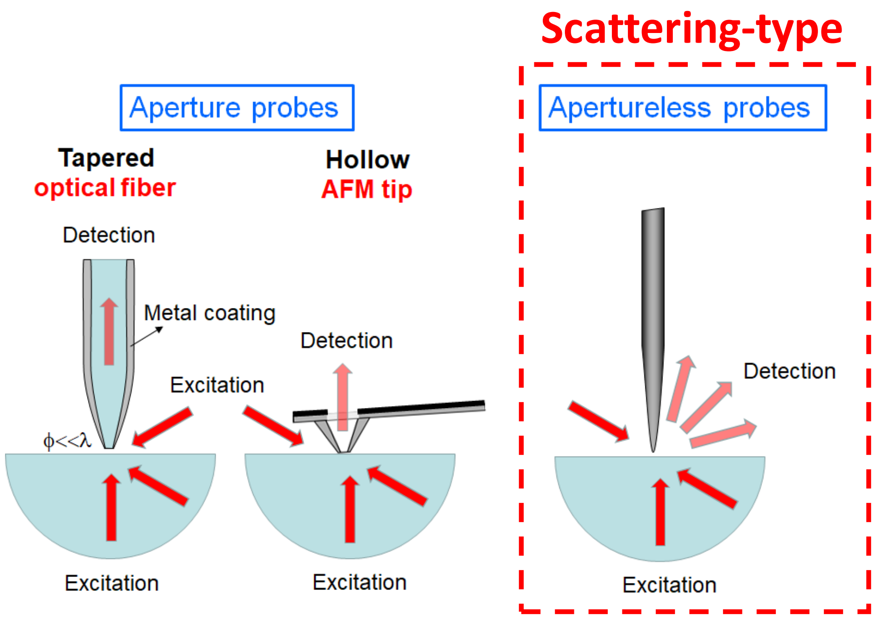
- Distance = Low-pass filtering.
- Homogeneous to heterogeneous EM-LDOS transition.

Peragut *et al.*, *OPTICA* **4**, 1406 (2017).

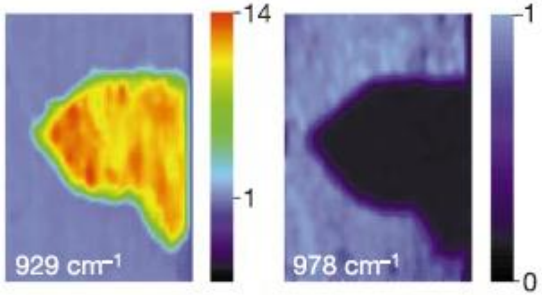
Conclusion

- **NSOM information on evanescent fields**

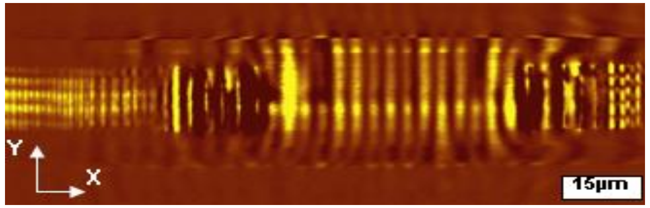




Materials at sub-λ scale

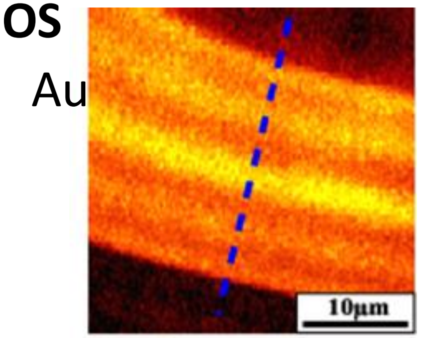


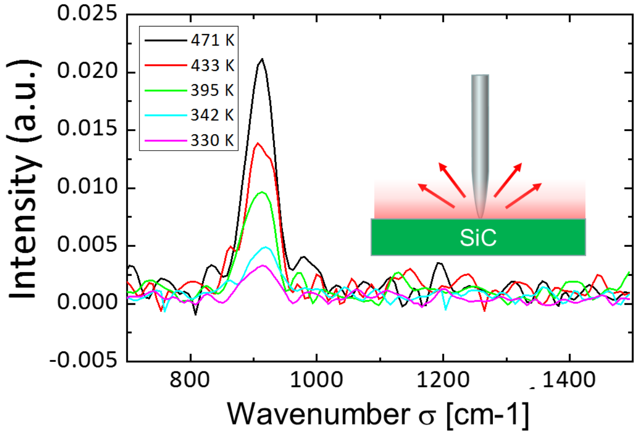
Surface wave studies



- **TRSTM: Thermal radiation in the near-field probes the EM-LDOS**

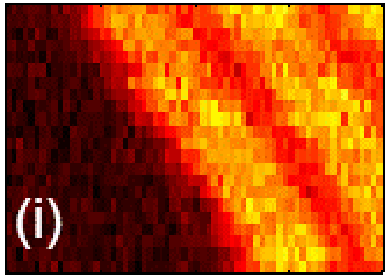
  + Coherence effects





- **Super-resolution is achieved both for imaging and spectroscopy**

H = 20 nm



NSOM in FRANCE

<u>**Liste non-exhaustive**</u>:

Lille: IEMN

Paris: ESPCI (Institut Langevin, LPEM), Sorbonne Université (INSP)

Paris-Saclay: C2N, ONERA, CEA, SOLEIL, Inst. Chimie Physique (UPS)

Versailles: GEMaC (UVSQ)

Troyes: L2n laboratory (UTT)

Dijon: Laboratoire ICB, Université de Bourgogne

Besançon: FEMTO St

Nantes: IMN

Lyon: STMS/INL (Ecole Centrale Lyon), ILM

Grenoble: Inst. Néel

Marseille: Inst. Fresnel

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