Thermal radiation scanning tunnelling microscope (TRSTM): Near-field imaging and spectroscopy probe of the thermal emission

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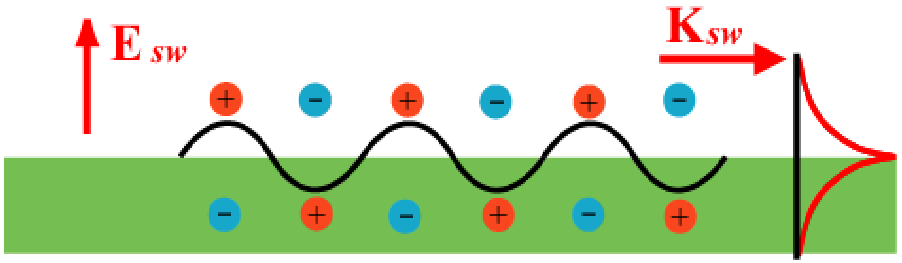
Nanoscale Radiative Heat Transferï May 13, 2013

Motivation : Theoretical predictions

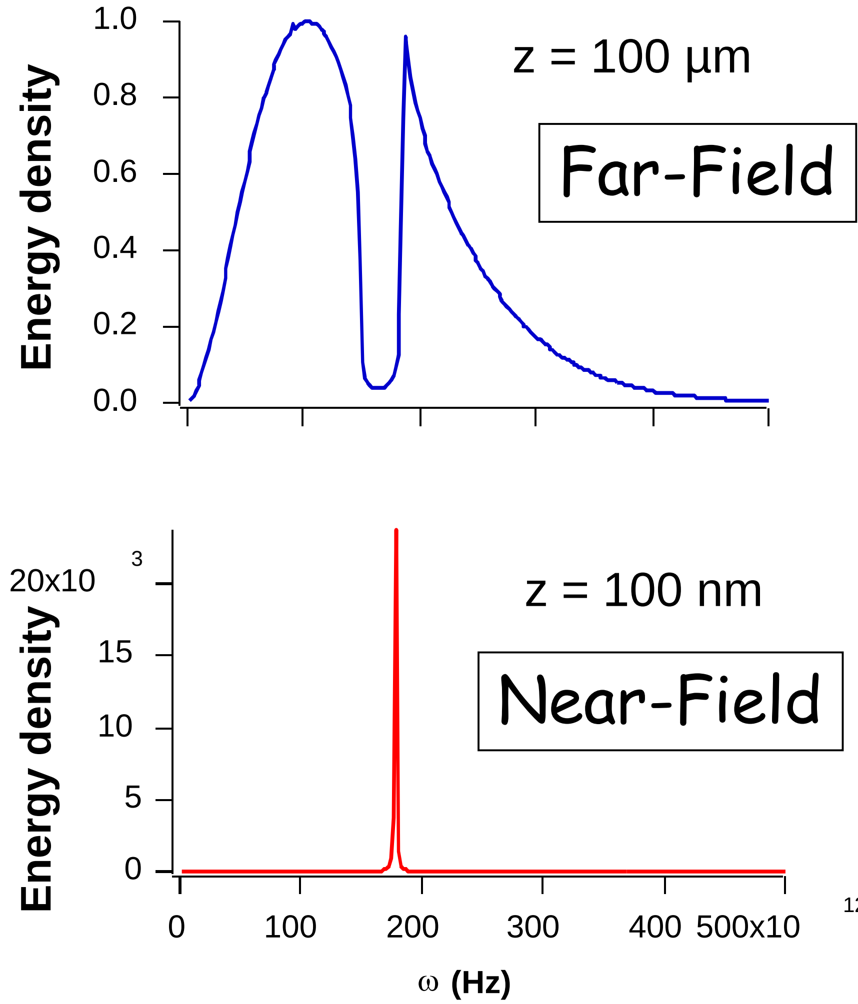


SiC = polar material which supports surface phonon-polaritons
=> Evanescent waves thermally stimulated

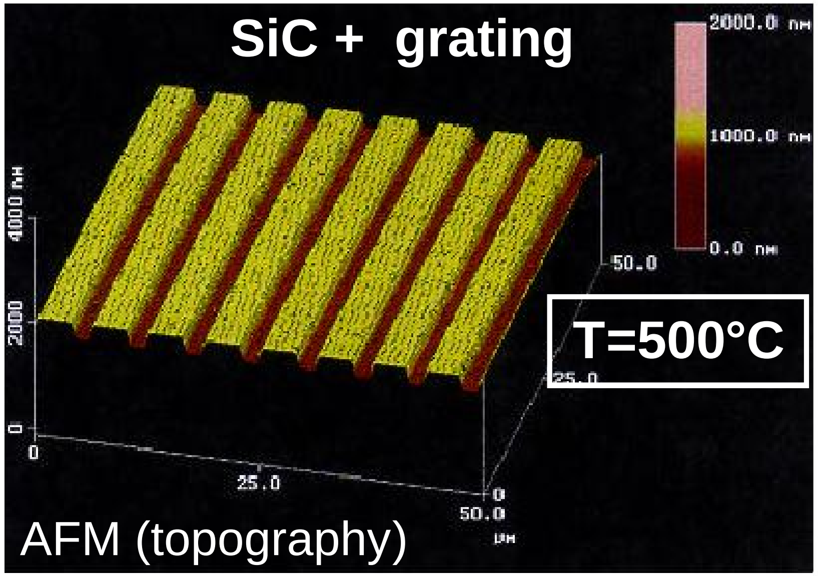
$\omega_{resonance} = 178.7 * 10^{12}\ s^{-1}$
$= 948\ cm^{-1}$

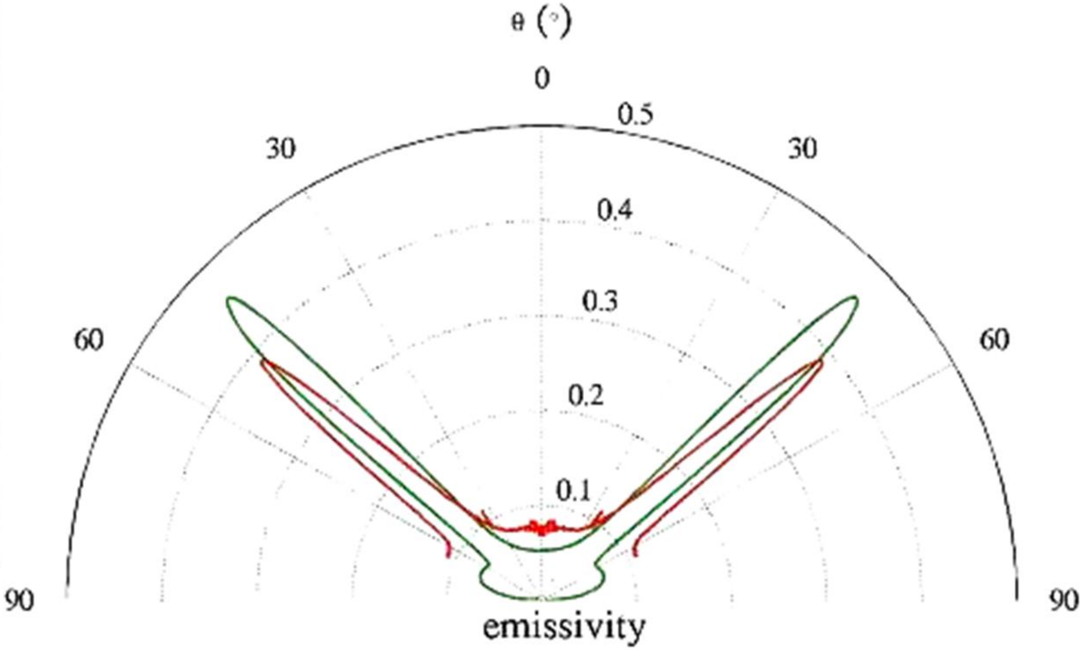
$\lambda_{resonance} = 10.55 \mu m$

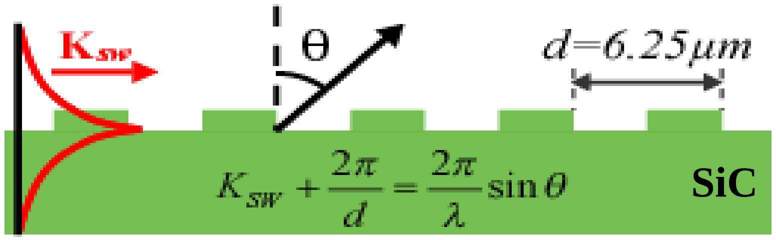
Shchegrov, Joulain, Carminati, Greffet,
Phys. Rev. Lett., 85, 1548 (2000)



Motivation : Far-field measurements





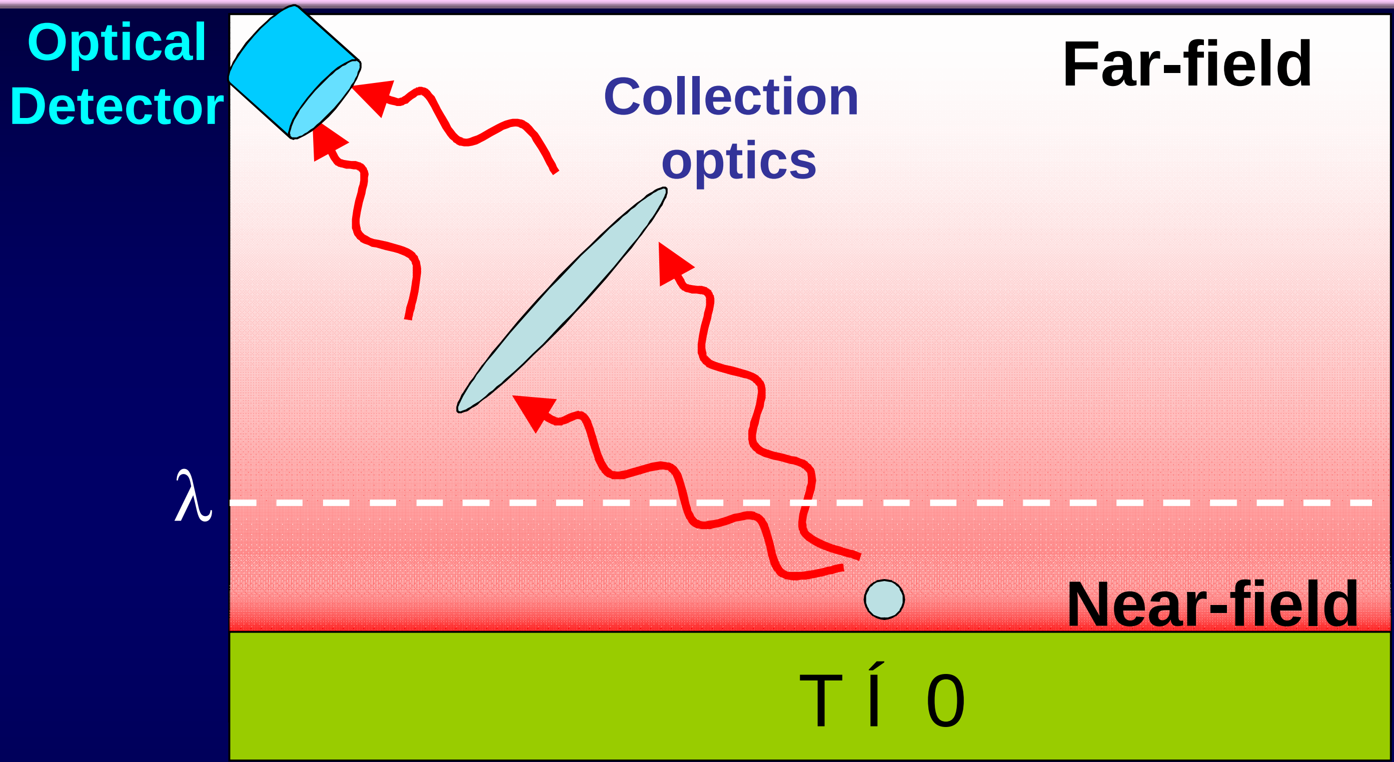


Antenna like emission pattern

Greffet, Carminati, Joulain, Mulet, Mainguy, Chen, Nature 416, 61 (2002)

DIFFRACTION ➡ **SPATIAL COHERENCE** OF THERMAL EMISSION !!!

Probe of thermal emission in the near-field



$$U(\mathrm{r},\omega) = \rho(\mathrm{r},\omega)\,\hbar\omega \frac{1}{\exp\left(\hbar\omega / kT\right) - 1}$$

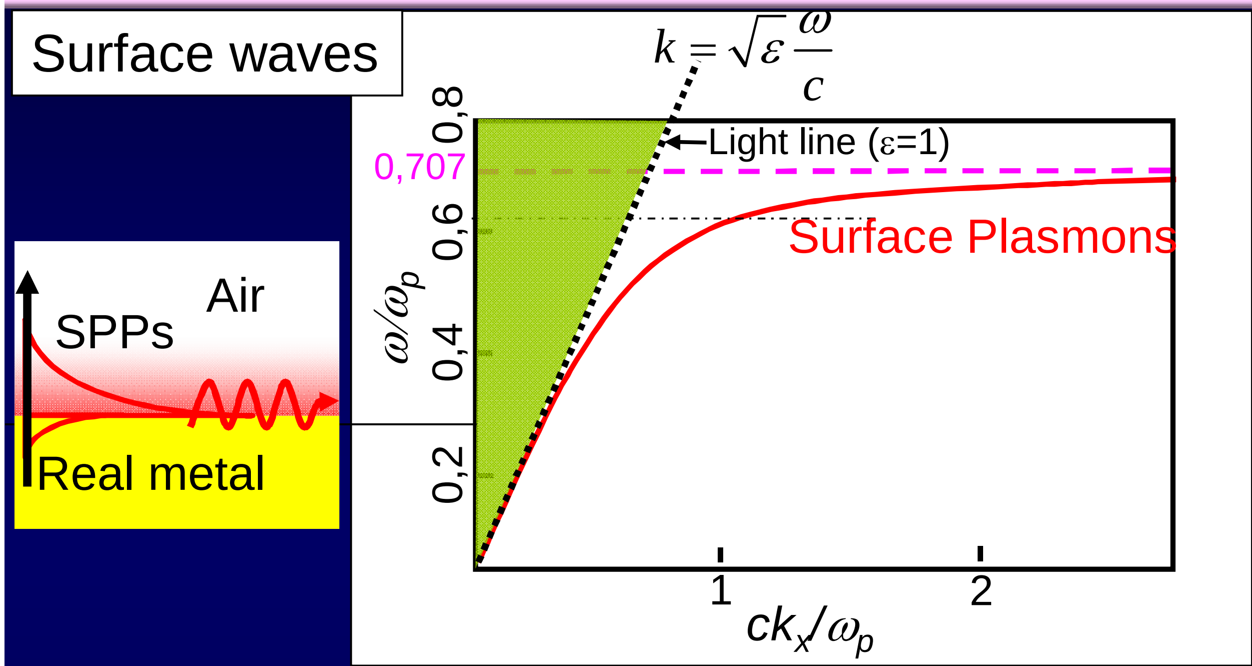
LDOS

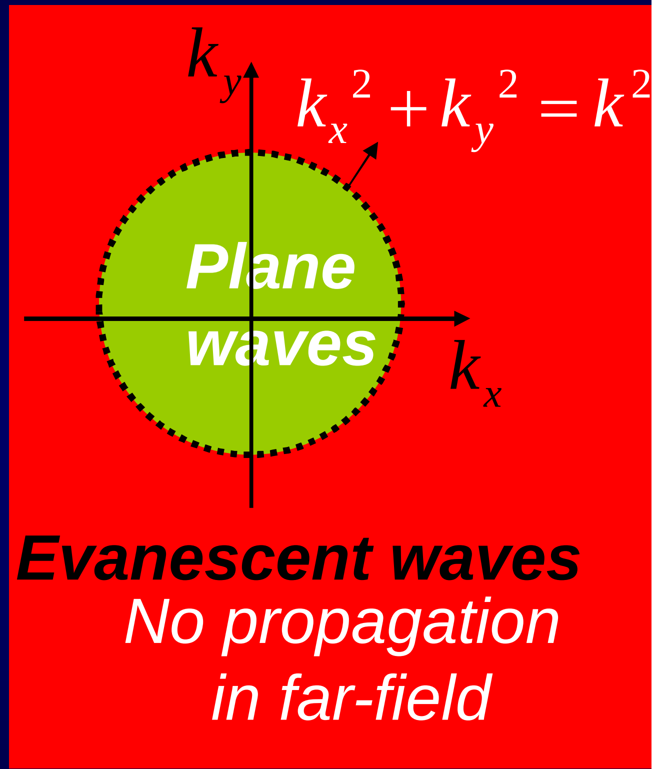
Photon statistics
(Bose Einstein distribution)

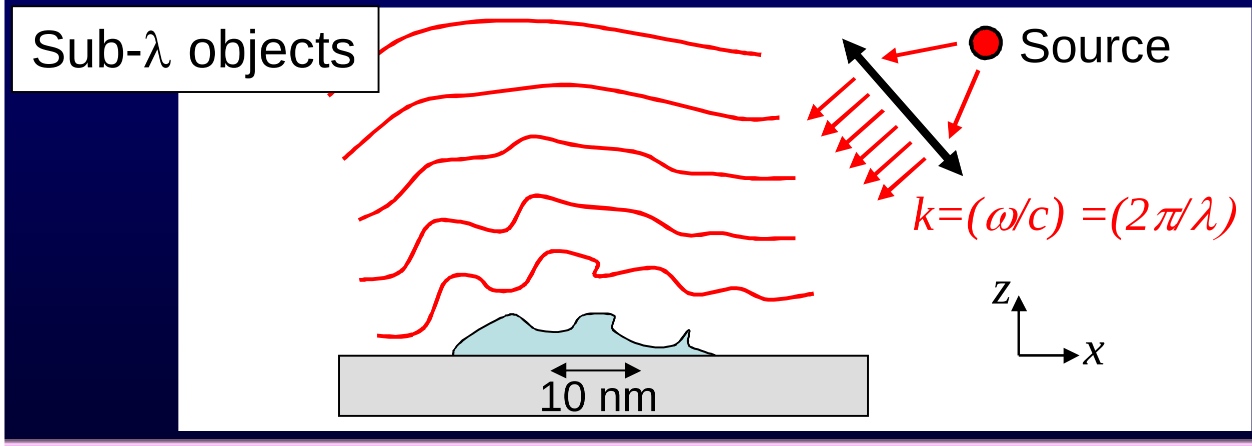
OUTLINE

- Infrared-NSOM & Thermal radiation scanning tunnelling (TRSTM) setup.
- Examples using laser sources.
- TRSTM for imaging thermal radiation in the near-field.
- TRSTM for spectroscopy measurements.

Optical near-field :definition

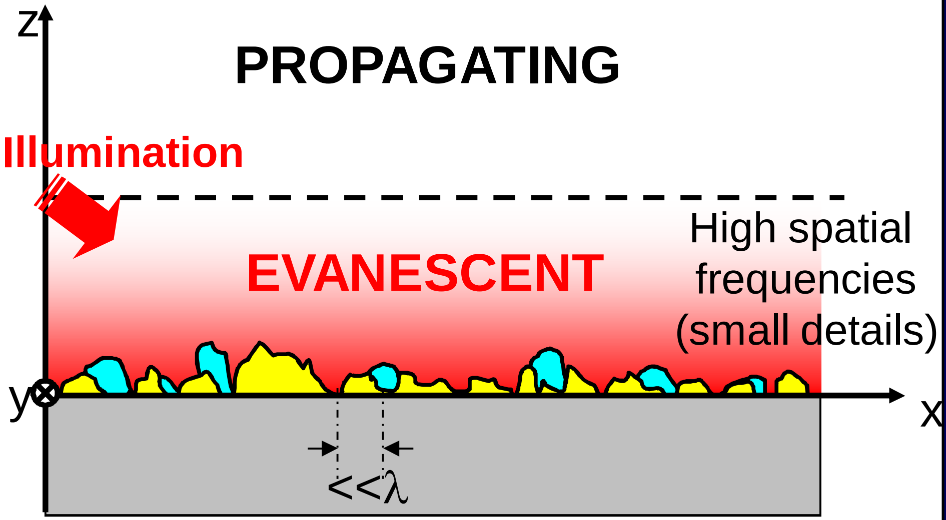






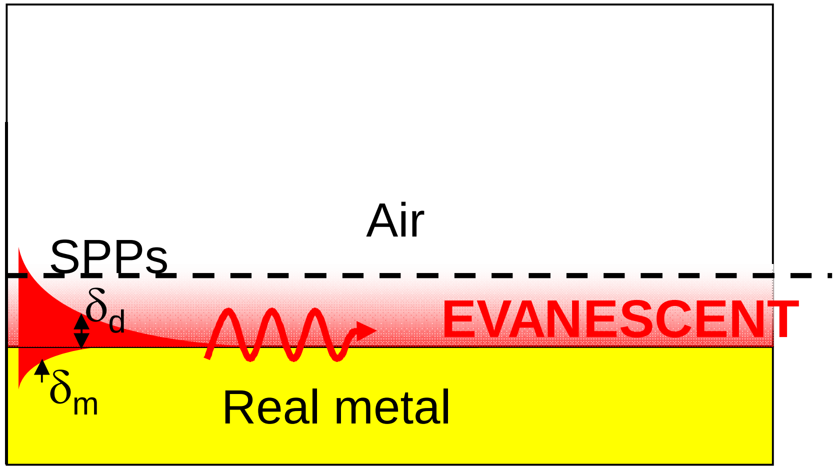
Applications of near-field probes

NANOMATERIALS



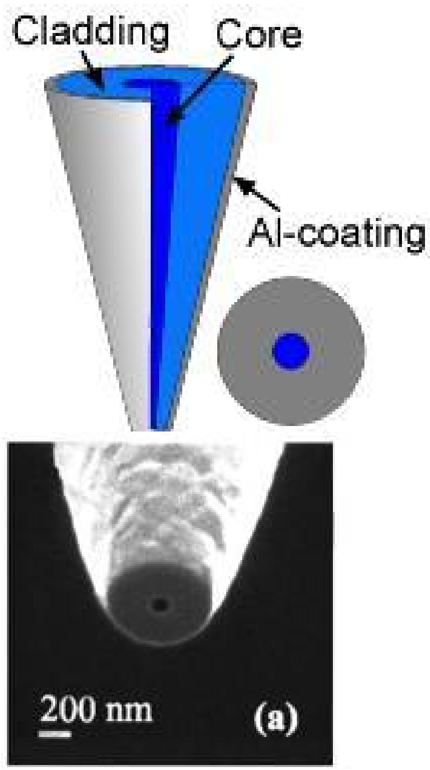
Optical imaging
of nano-materials
(resolution << λ)

CONFINED FIELDS

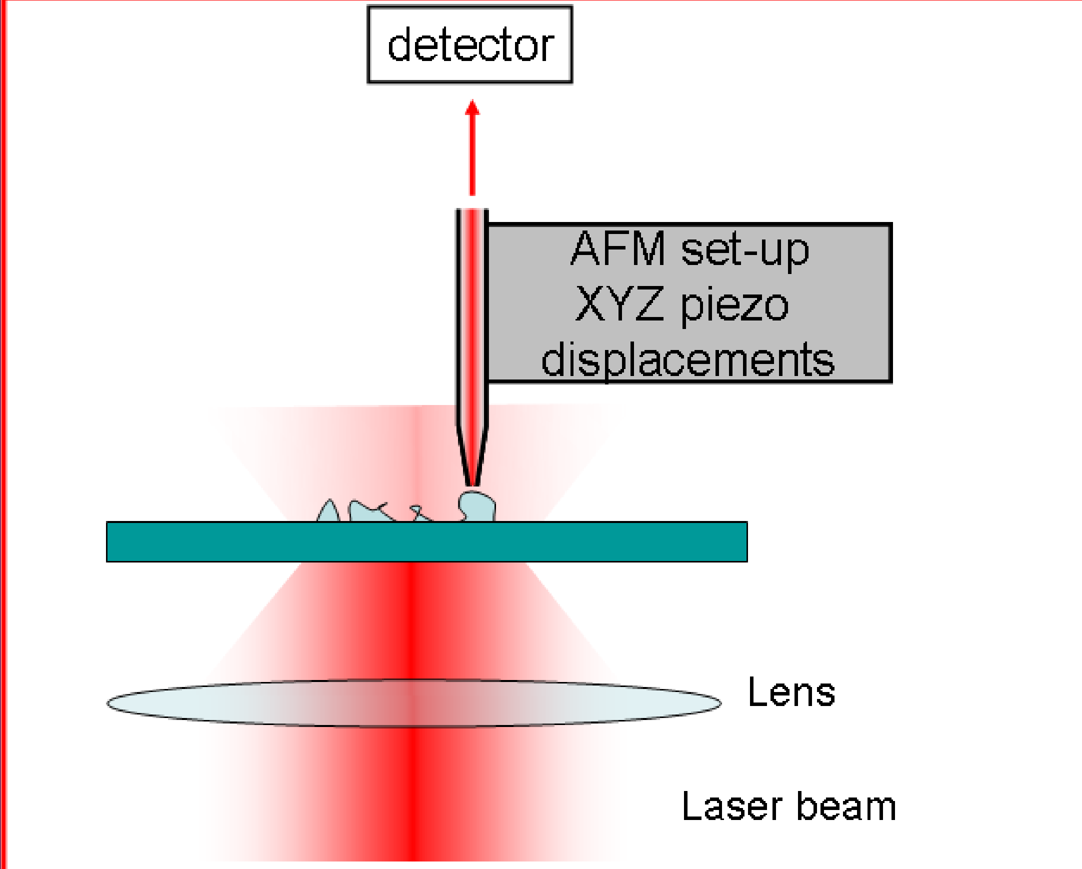


Detection of purely
evanescent fields
(example: **surface plasmons**)

Aperture NSOM



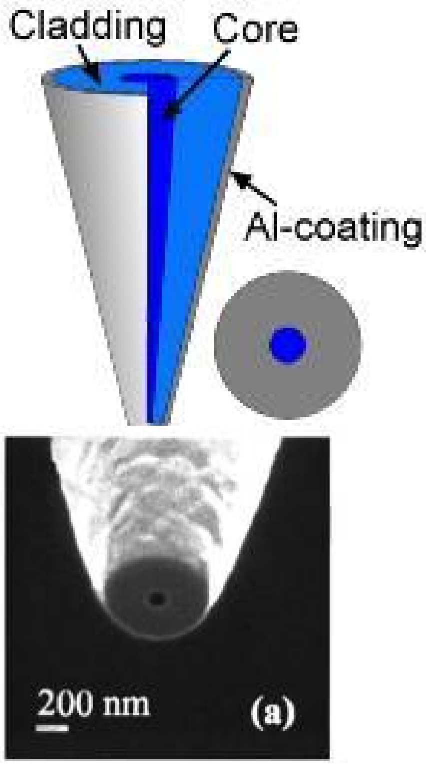
Veerman et al. ,
Appl. Phys. Lett. **72**, 3115 (1998)



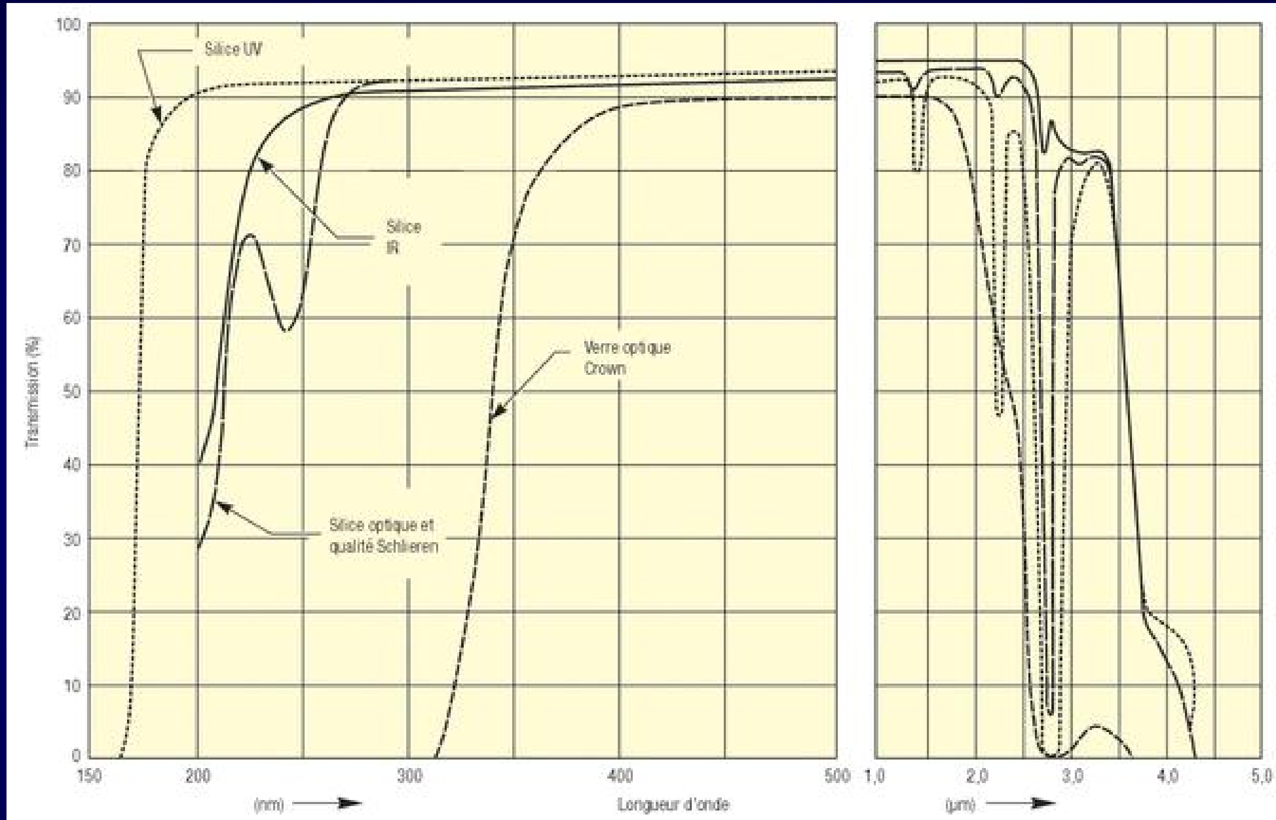
Pohl et al. , Appl. Phys. Lett **44**, 651 (1984)

NSOM= near-field scanning optical microscope

Aperture NSOM



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



Silica fiber : Well-suited for visible and near-IR but **not for the mid-IR** !!!

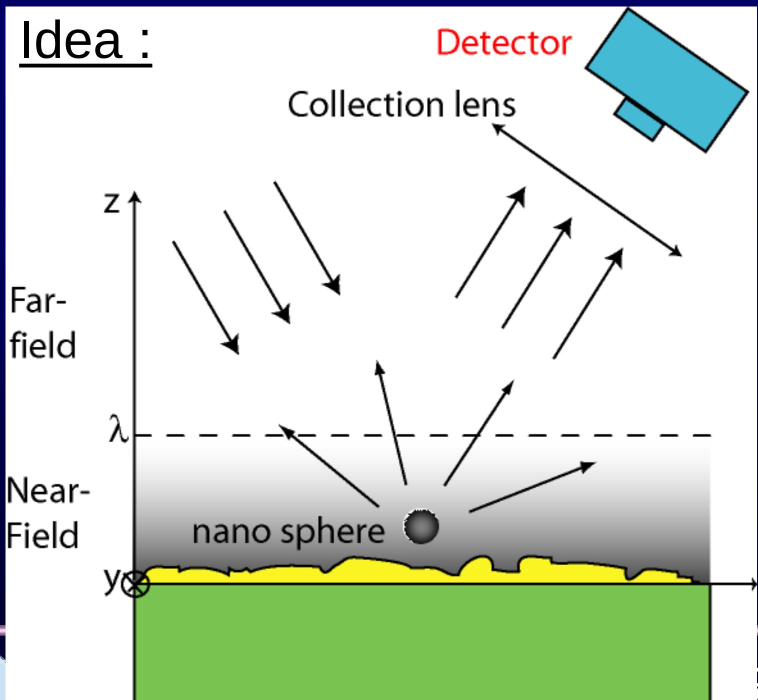
A. Claude Boccara

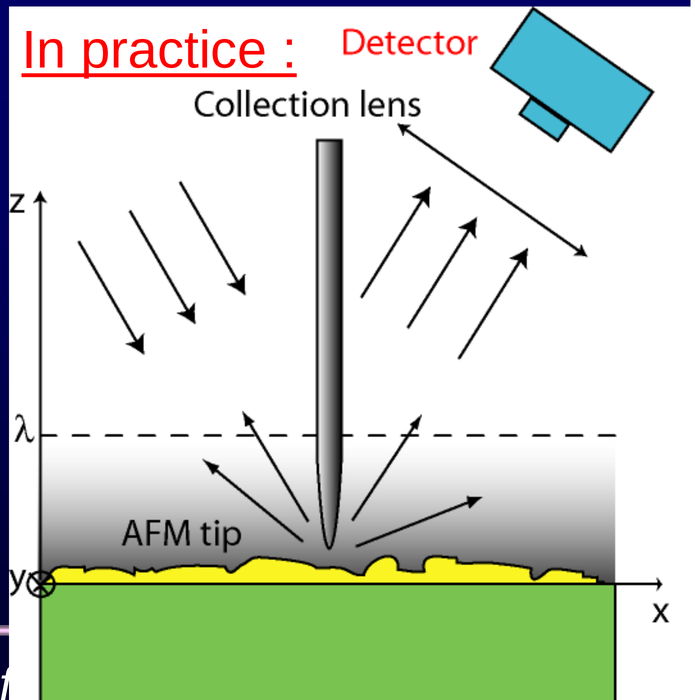
Wikramasynghe et al., APL65,1623 (1994);
Boccara et al., Micro. Microanal. Microstruct. 5, 389 (1994)

- Perhaps one could try instead *to disturb* the near-field with a small subwavelength scatterer…

« Scattering-type NSOM » (s-NSOM)

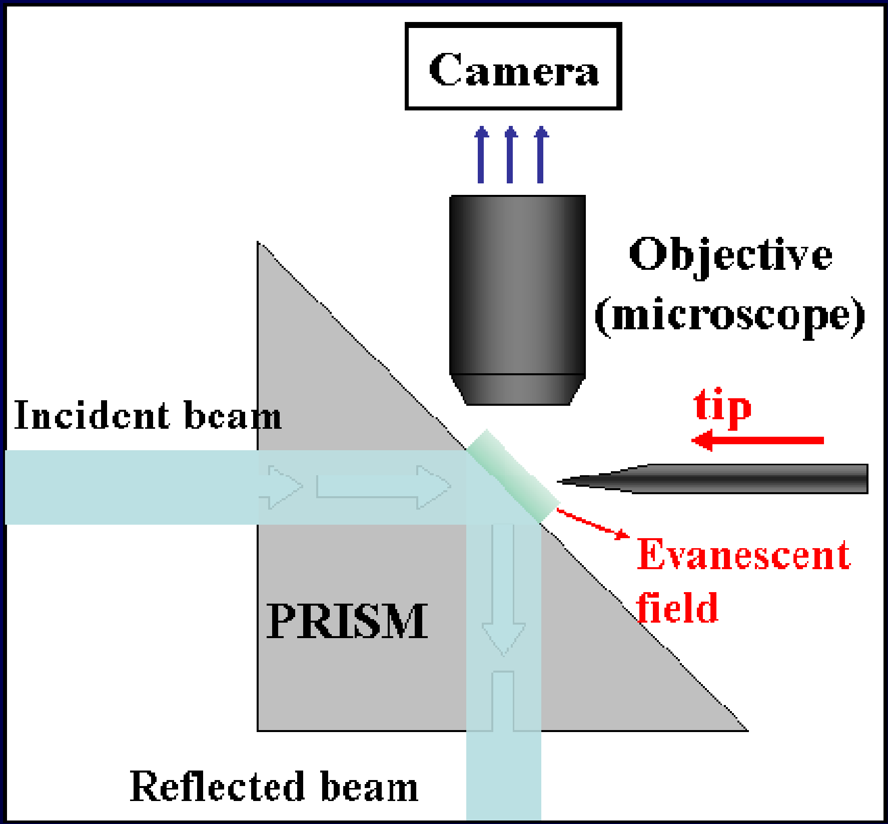
$$I_{scat.}(x_t, y_t) = \sigma \left| E(x_t, y_t) \right|^2$$





Tip approach in an evanescent field.

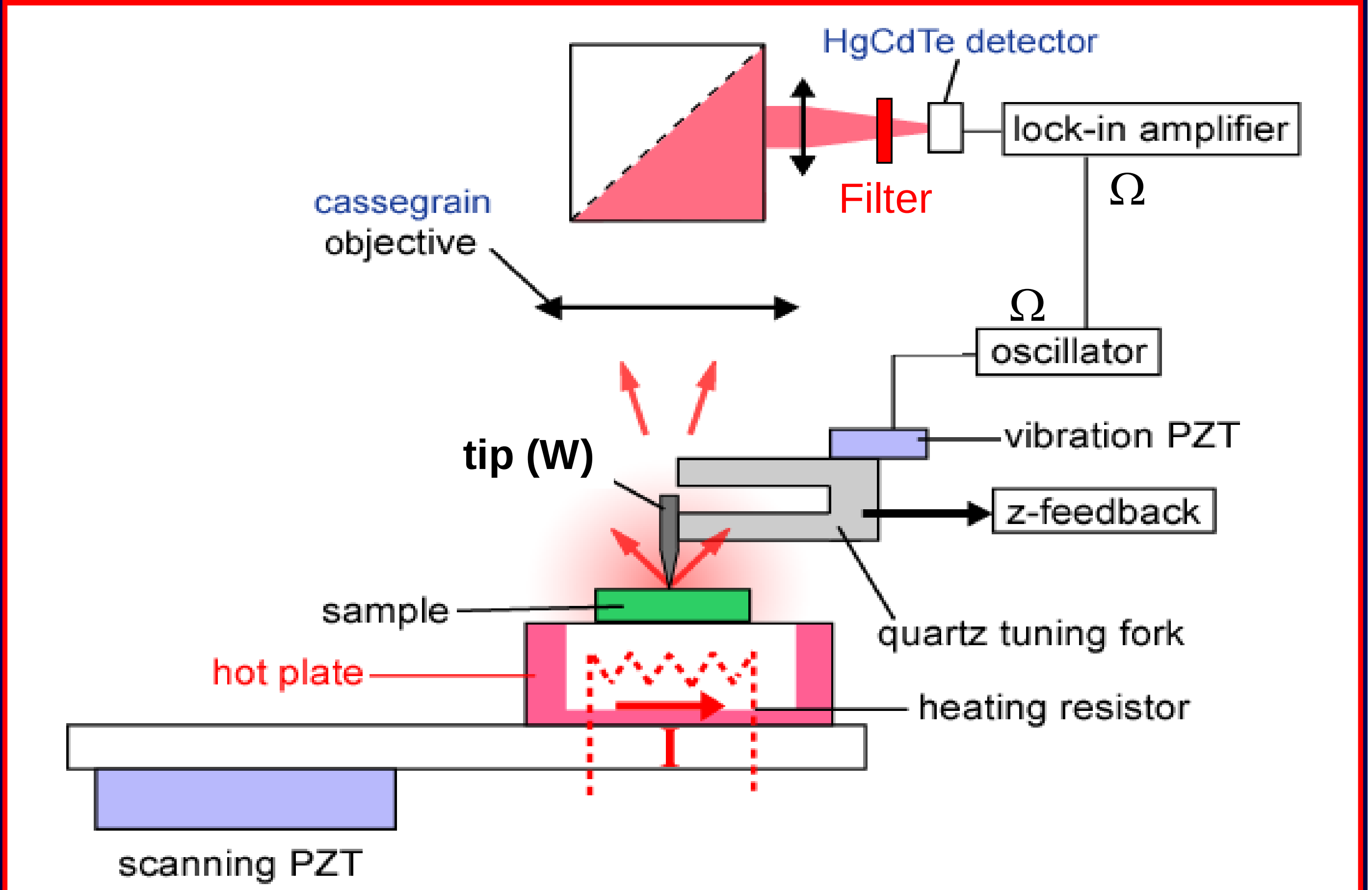
$$I_{scat.}(x_t, y_t) = \sigma \left| E(x_t, y_t) \right|^2$$



s-NSOM for mid-infrared detection of near-field thermal emission

Thermal radiation scanning tunnelling microscope

« TRSTM »



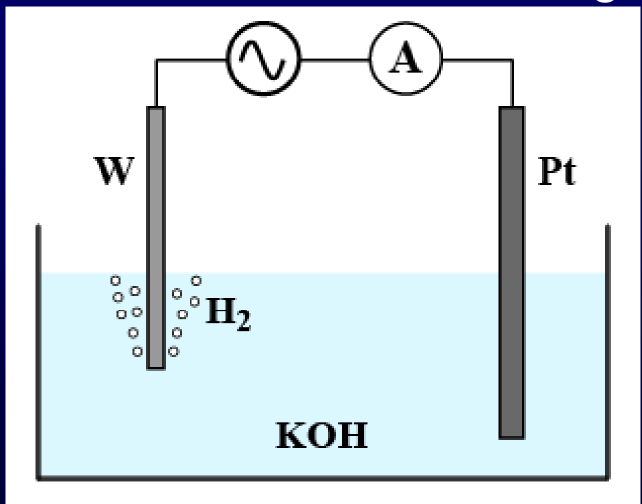
IMAGING De Wilde, Formanek, Carminati, Gralak, Lemoine, Mulet, Joulain, Chen, Greffet, Nature **444**, 740 (2006)

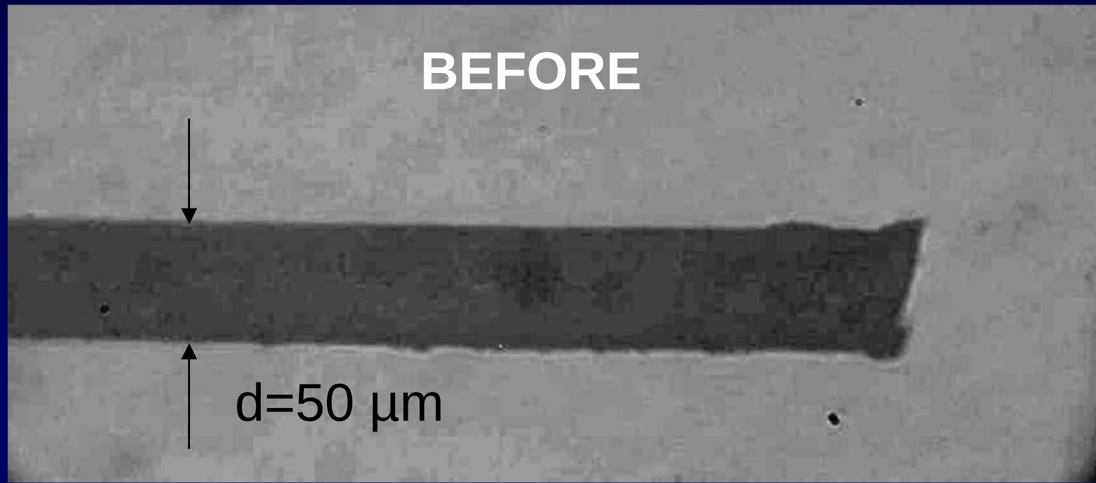
SPECTROSCOPY Babuty,, Joulain, Chapuis, Greffet, De Wilde, Phys. Rev. Lett. 110, 146103 (2013).

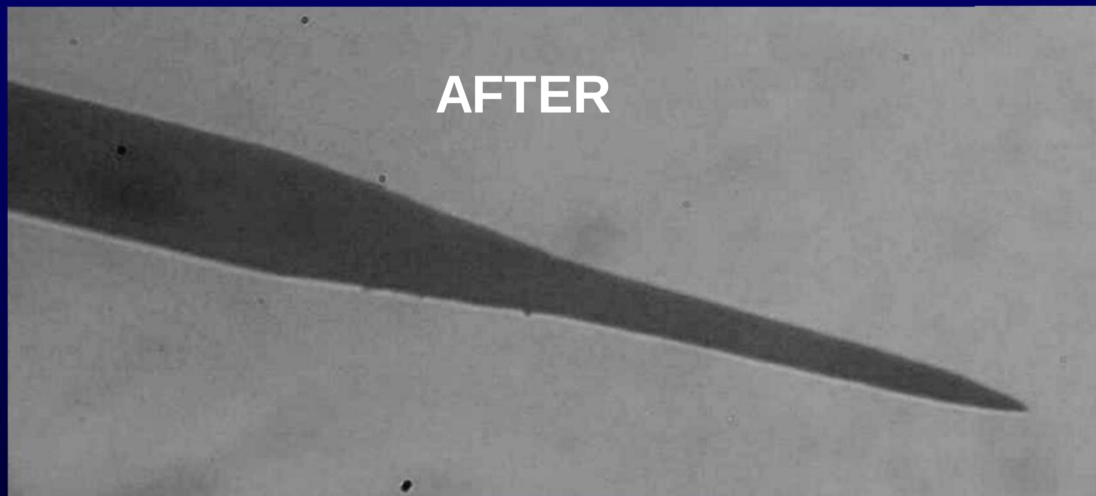
Mid IR s-NSOM ï TRSTM:
Tip preparation

Tungsten wire

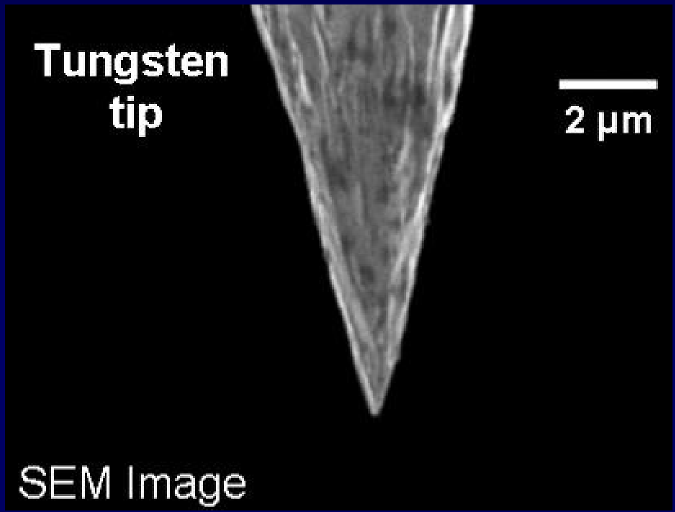
Electrochemical etching

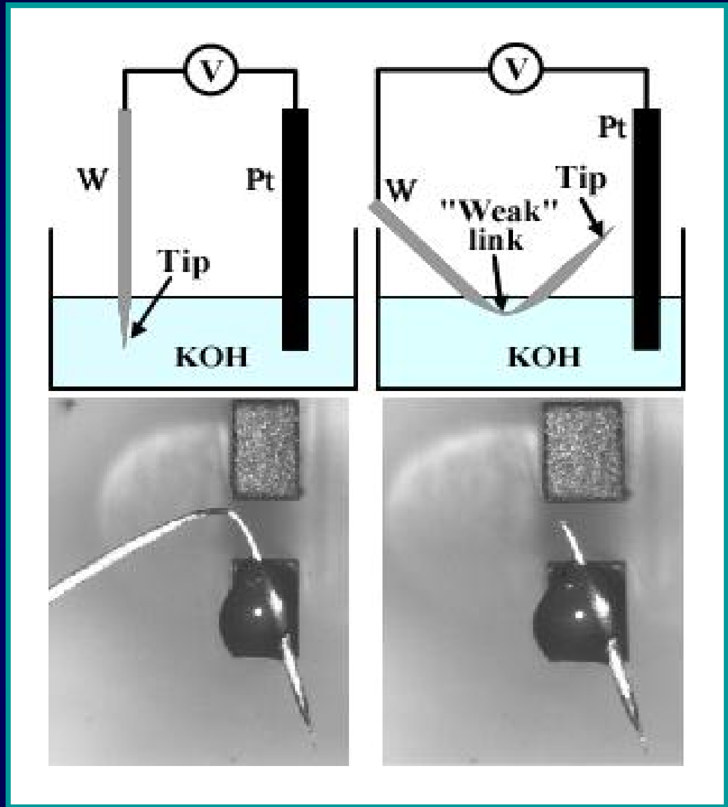






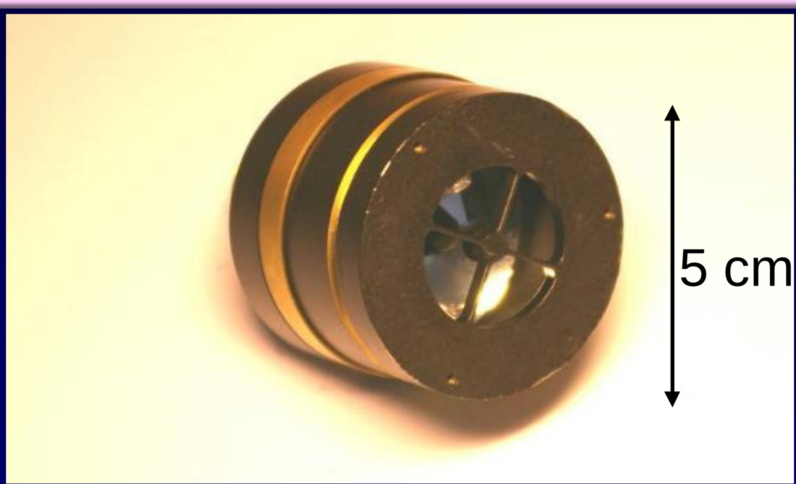
Mid IR s-NSOM ï TRSTM:
Tip gluing





De Wilde, Formanek, Aigouy,
Rev. Sci. Instrum. 74, 3889 (2003)

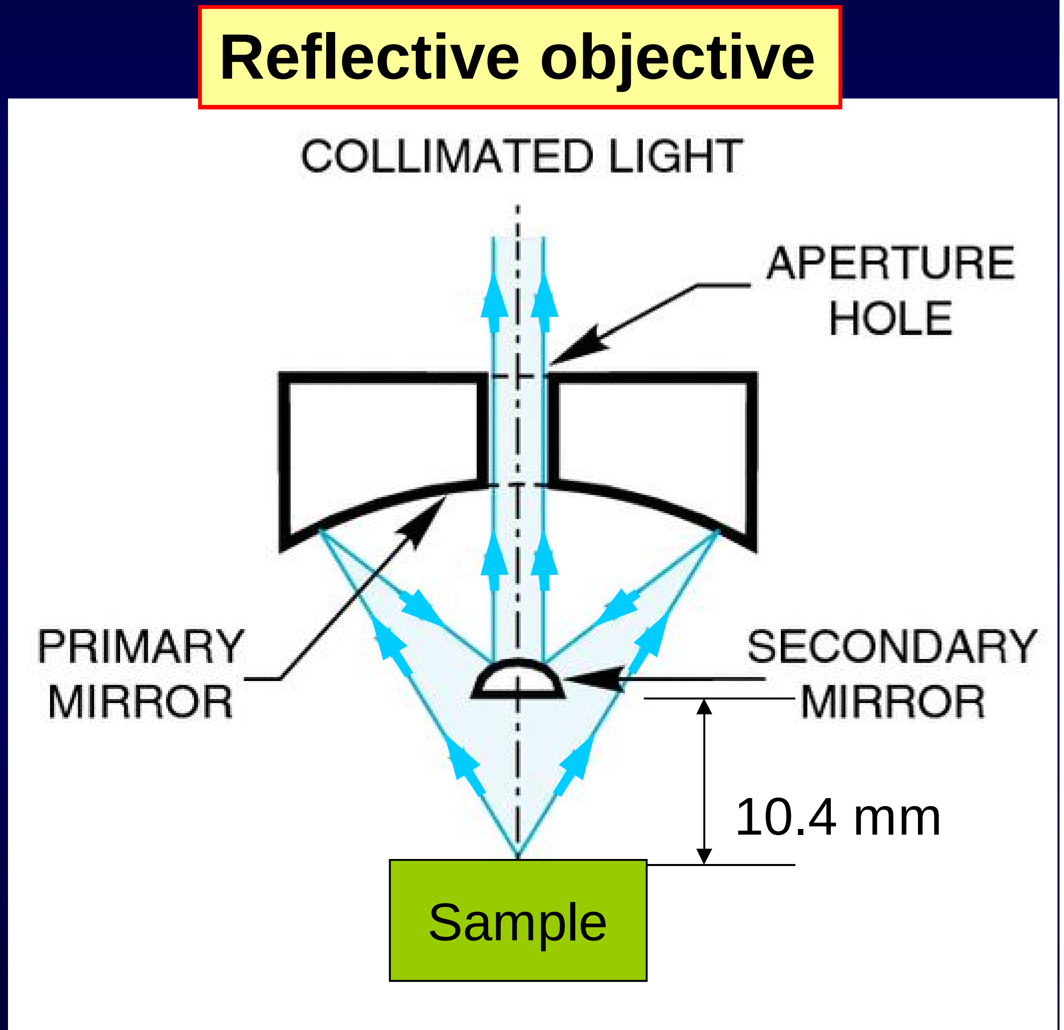
Mid IR s-NSOM ï TRSTM: Cassegrain objective



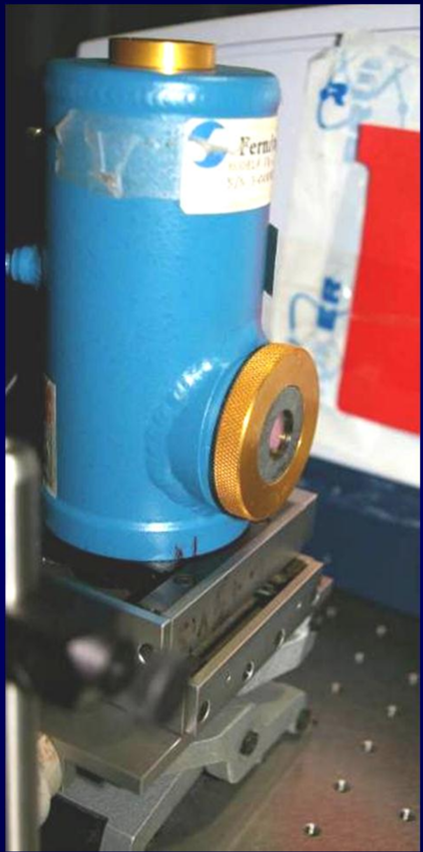
Two gold spherical mirrors:

- Broad spectral range (UV, Vis, IR, THz)
- No chromatic aberrations

Magnification= x36
Numerical aperture= 0.5
Working distance= 10.4 mm



Mid IR s-NSOM ï TRSTM: HgCdTe detector



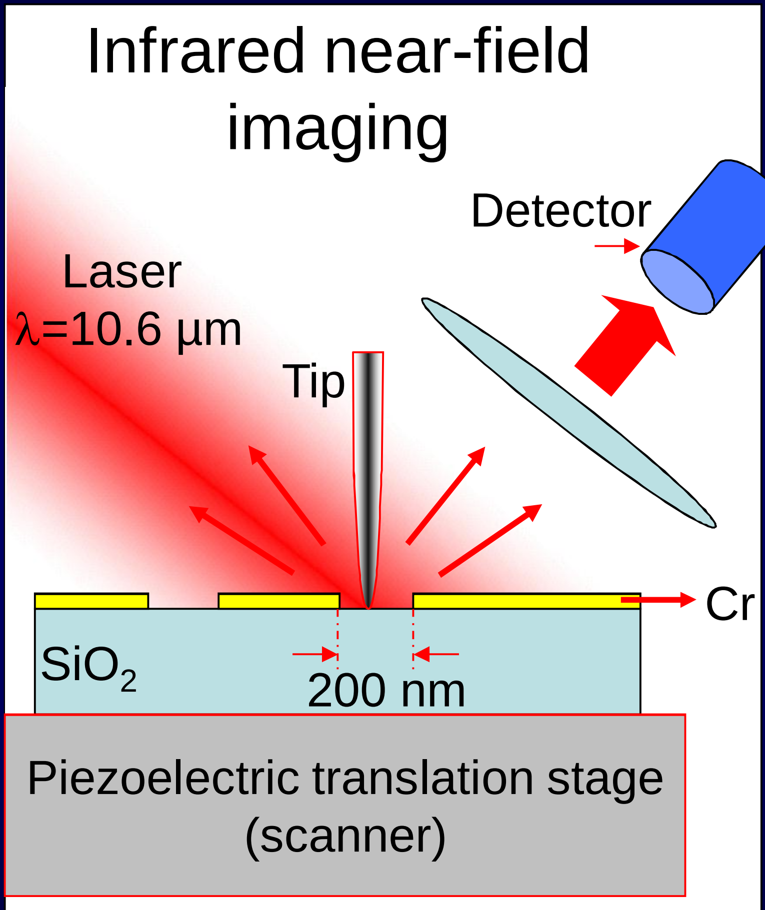
Liquid N_2 cooled
Size: d=0.5 mm (5 10^{-2} cm)

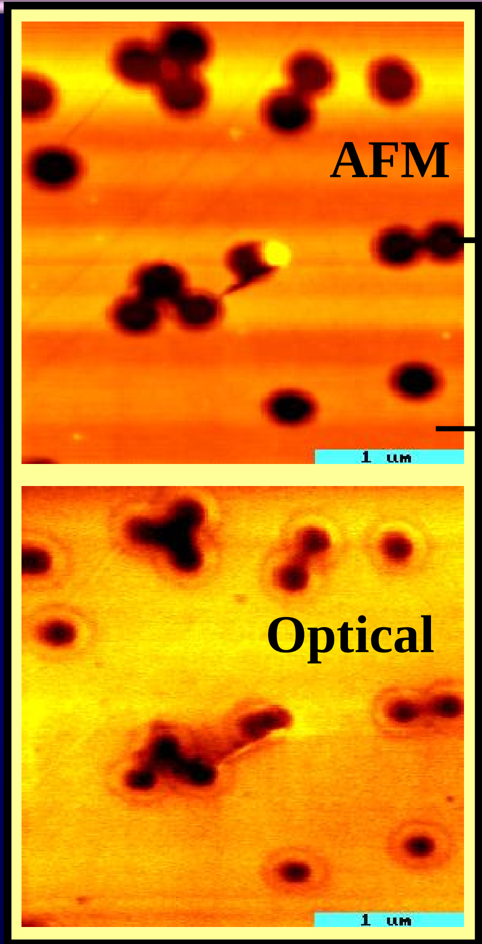
Detectivity: $D^* \approx 4\ 10^{10}$ cm $Hz^{1/2}$ W^{-1}

(>50 % between $\lambda \approx$ 7 µm - 12 µm)

$$Noise = \frac{d}{D^*} \approx 10^{-12}\, W \big/ Hz^{1/2}$$

Super-resolution with external source: Imaging of nano-materials





Holes sub-λ (ϕ=200nm) :

SiO_2

Chromium

Optical resolution
~ 30 - 50 nm
~ λ/200

NSOM (3µmx3µm)

λ=10.6 µm

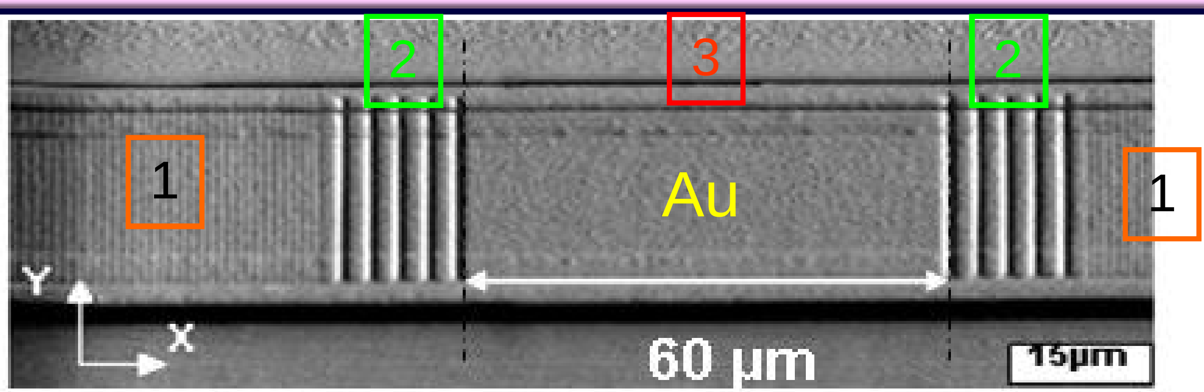
Diffraction limit

Formanek, De Wilde, Aigouy,
J. Appl. Phys. **93**, 9548 (2003)

Building block of active plasmonics: Slit doublet experiment

Measured topography (AFM)

Top electrode of quantum cascade laser

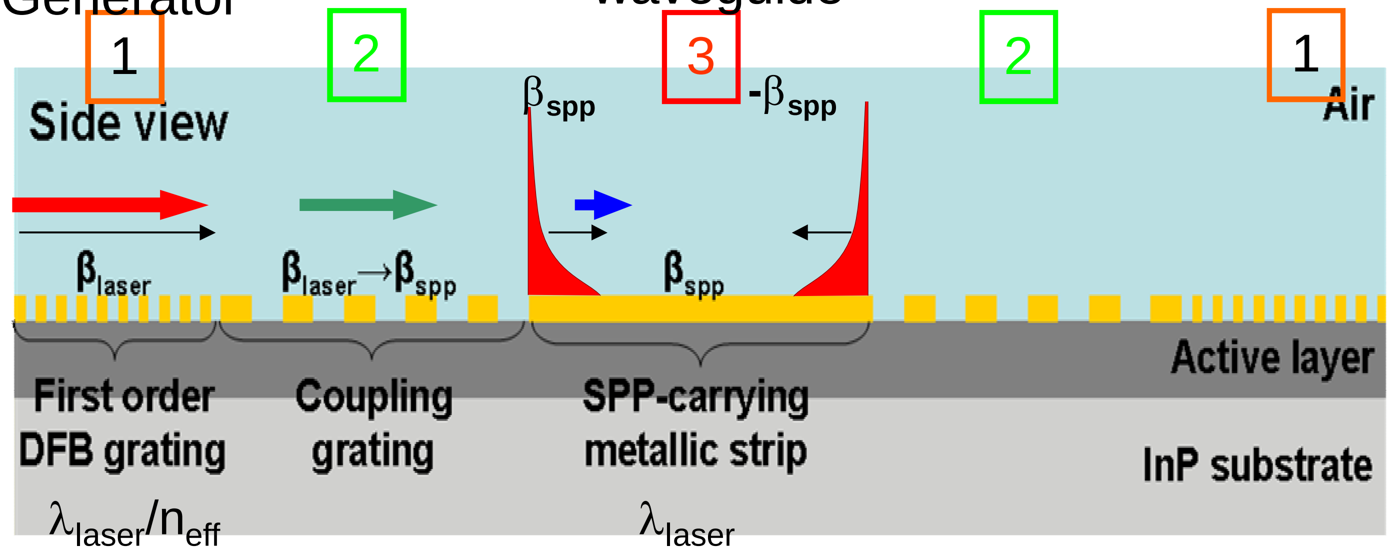


λå7.5µm

SPP Generator

Coupler

Passive waveguide



λ_{laser}/n_{eff}

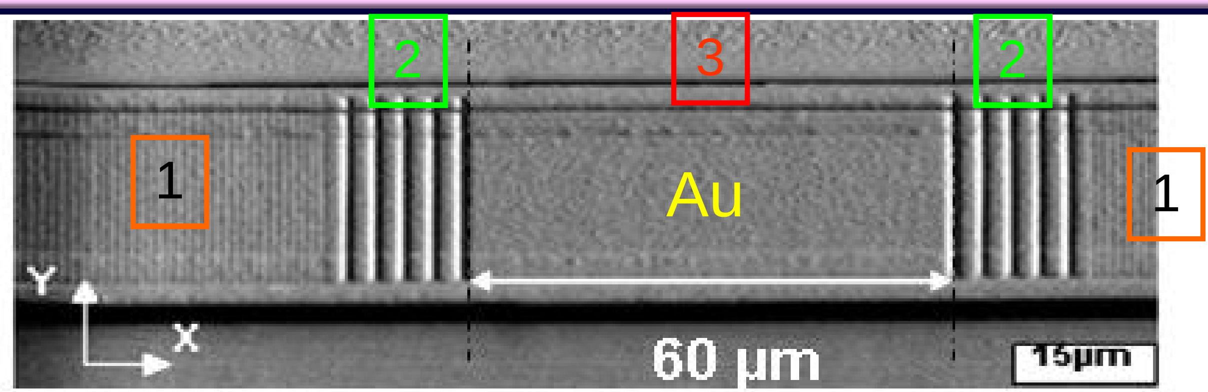
λ_{laser}

Collaboration: *R. Colombelliô group, IEF*

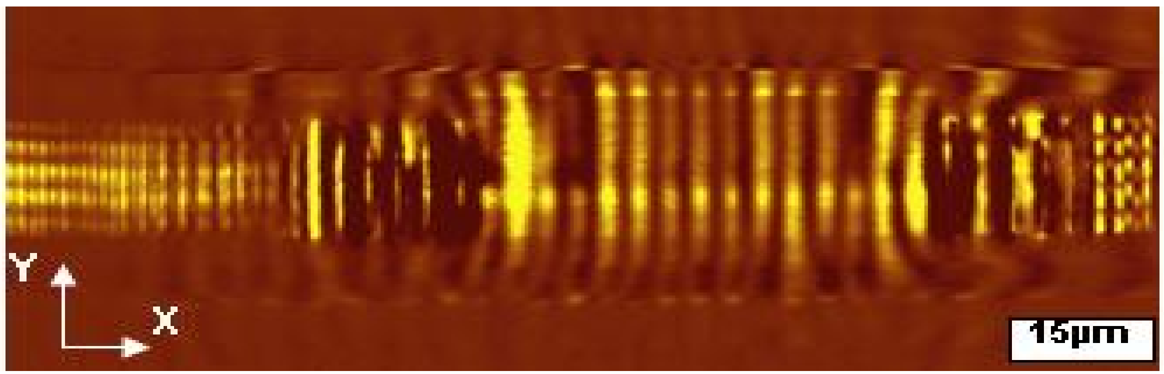
Babuty, et al., Phys. Rev. Lett., 104, 226806, (2010)

Building block of active plasmonics: Slit doublet experiment

Measured topography (AFM)



Measured near-field λå7.5µm

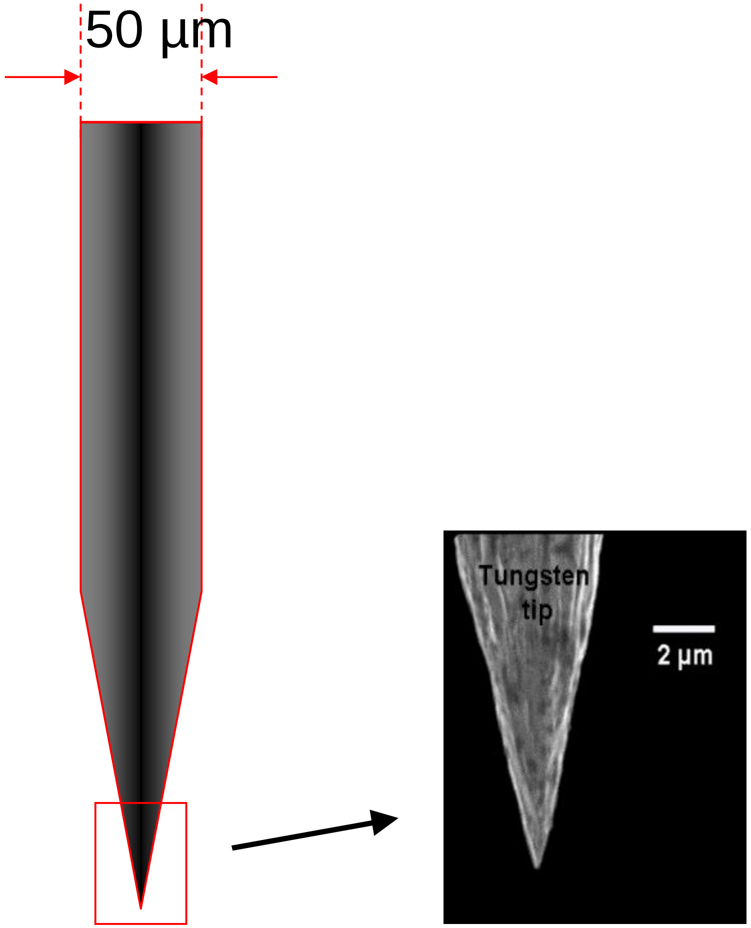


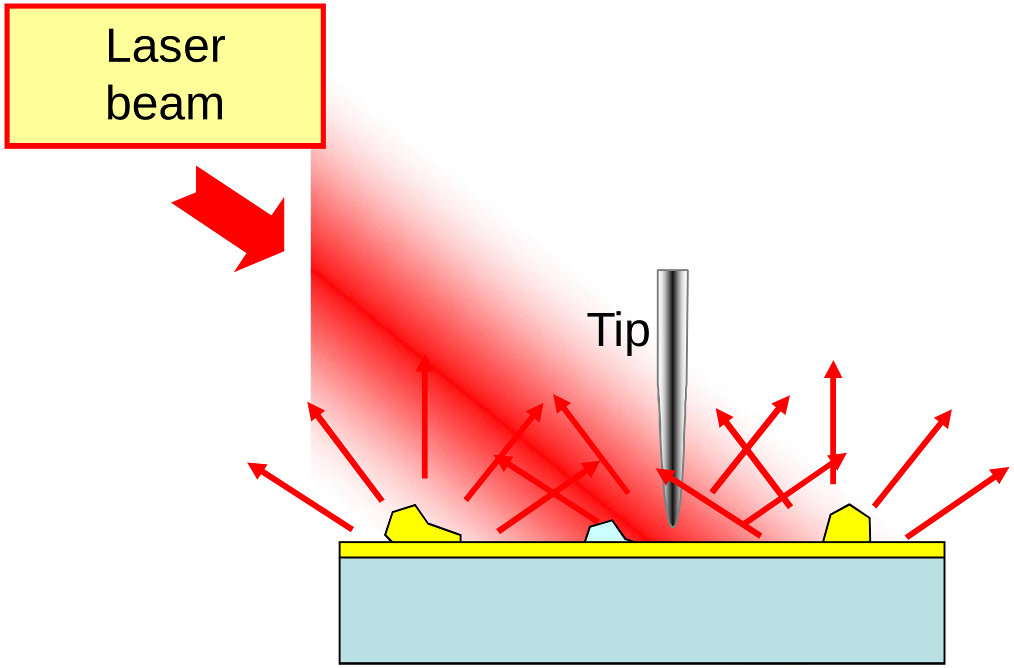
Interference of counterpropagating SPPs generated by electrical pumping of a QC laser.

<u>Collaboration:</u> R. Colombelliŝ group, IEF

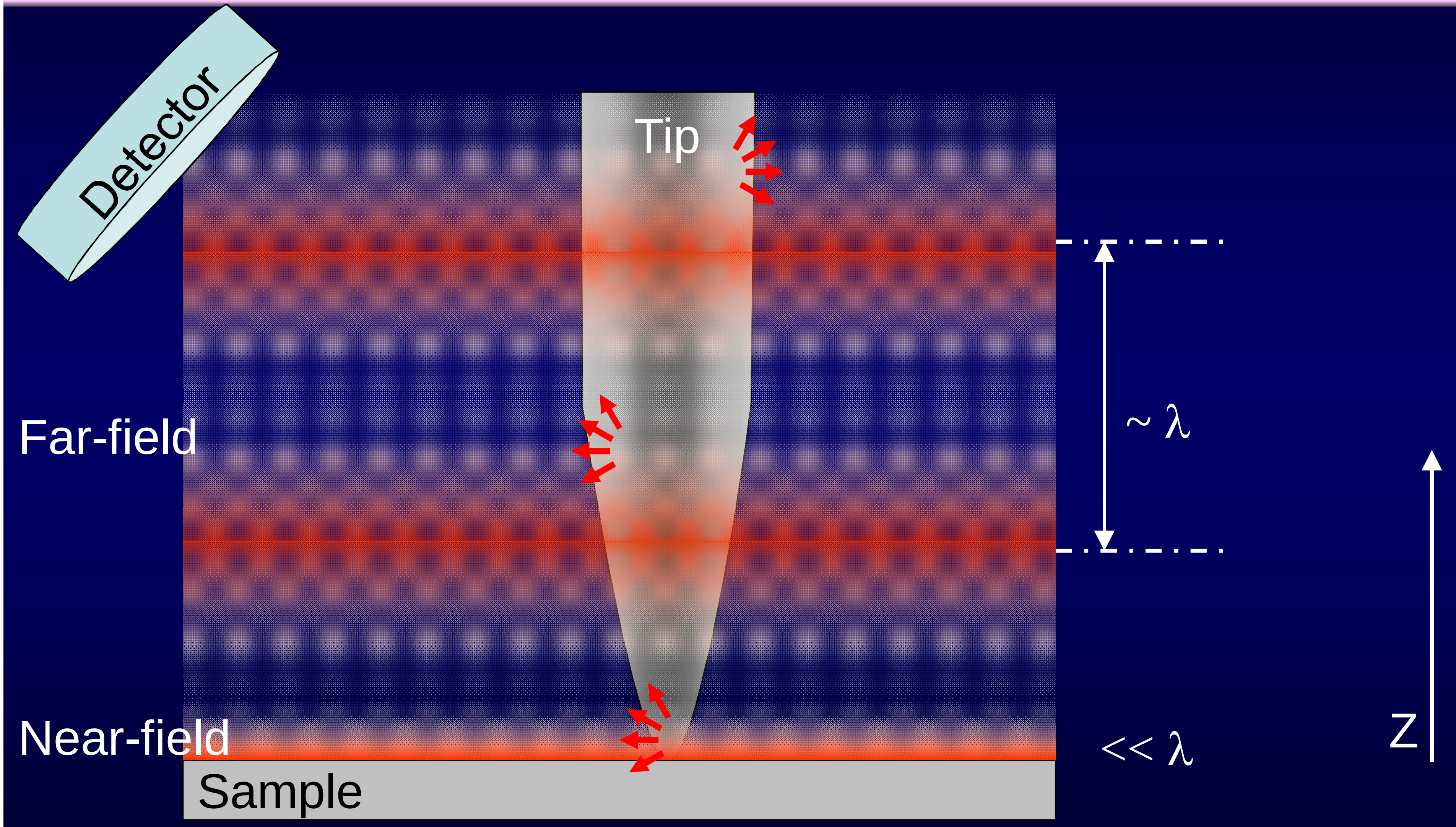
Babuty, et al., Phys. Rev. Lett., 104, 226806, (2010)

Remark 1: Far field background issue

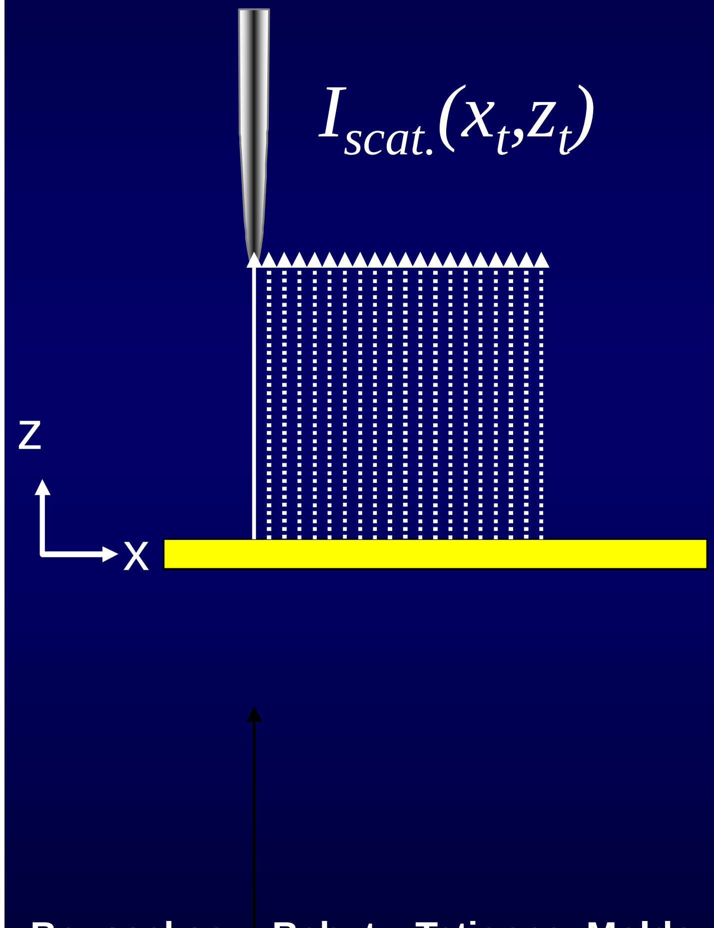


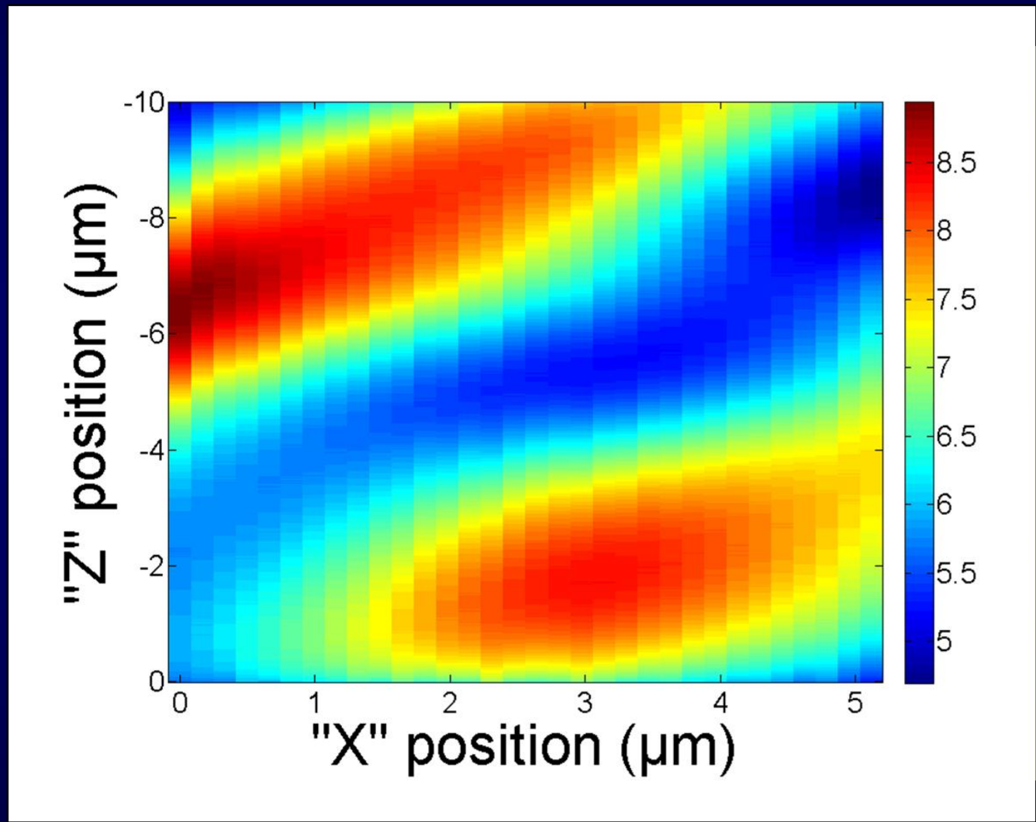


Extracting the near-field contribution in the detector signal.



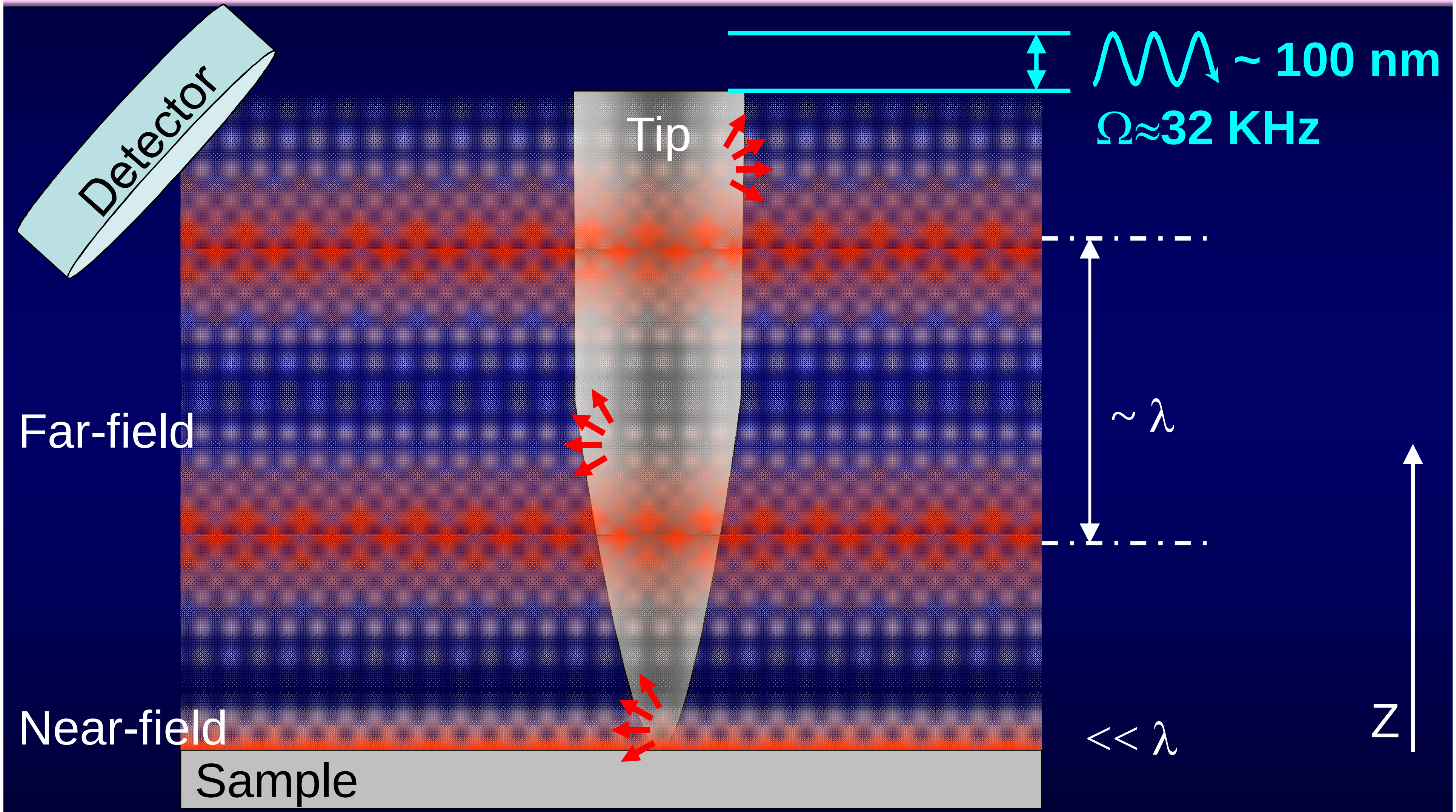
Tip-Scattered intensity in a plan perpendicular to metal surface.



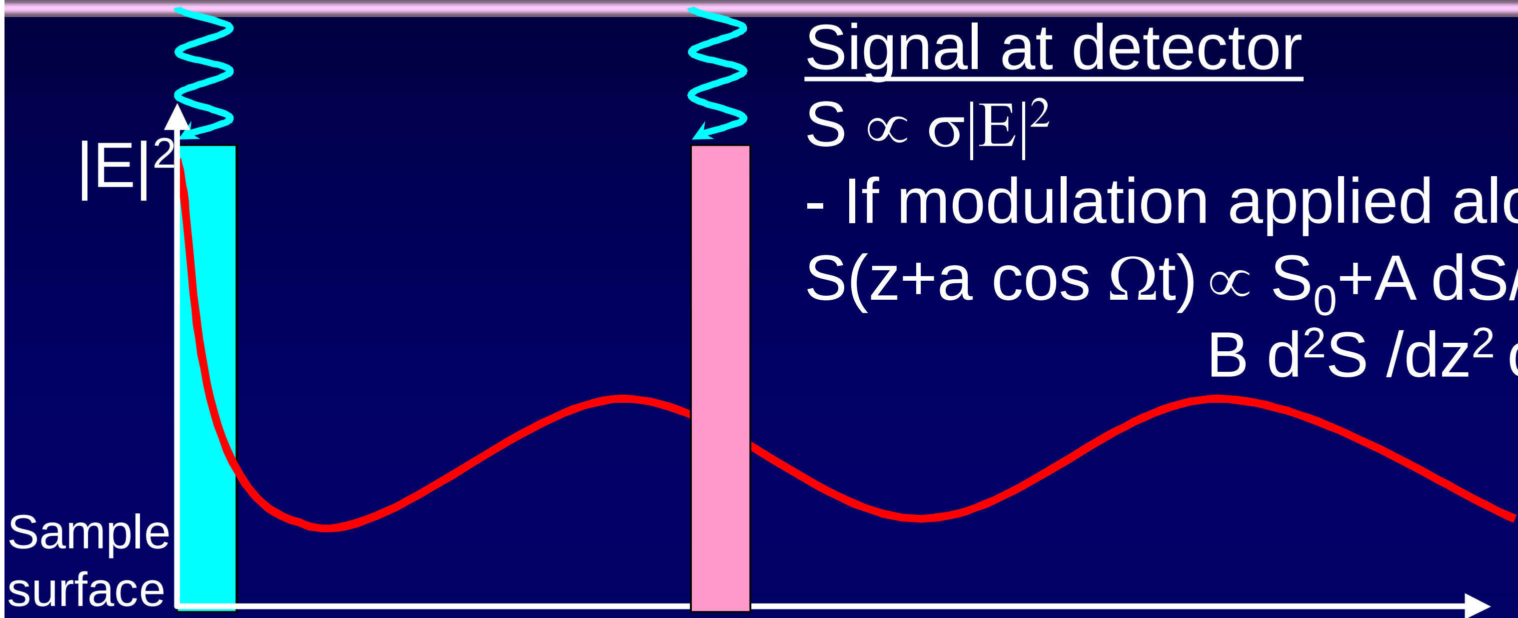


Bousseksou, Babuty, Tetienne, Moldovan, Braive, Beaudoin, Sagnes, De Wilde, Colombelli, Optics Express 20, 13738 (2012).

Extracting the near-field contribution in the detector signal.



Lock-in demodulation



Signal at detector

$S \propto \sigma|E|^2$

- If modulation applied along z:

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

Signal demodulation with a lock-in :

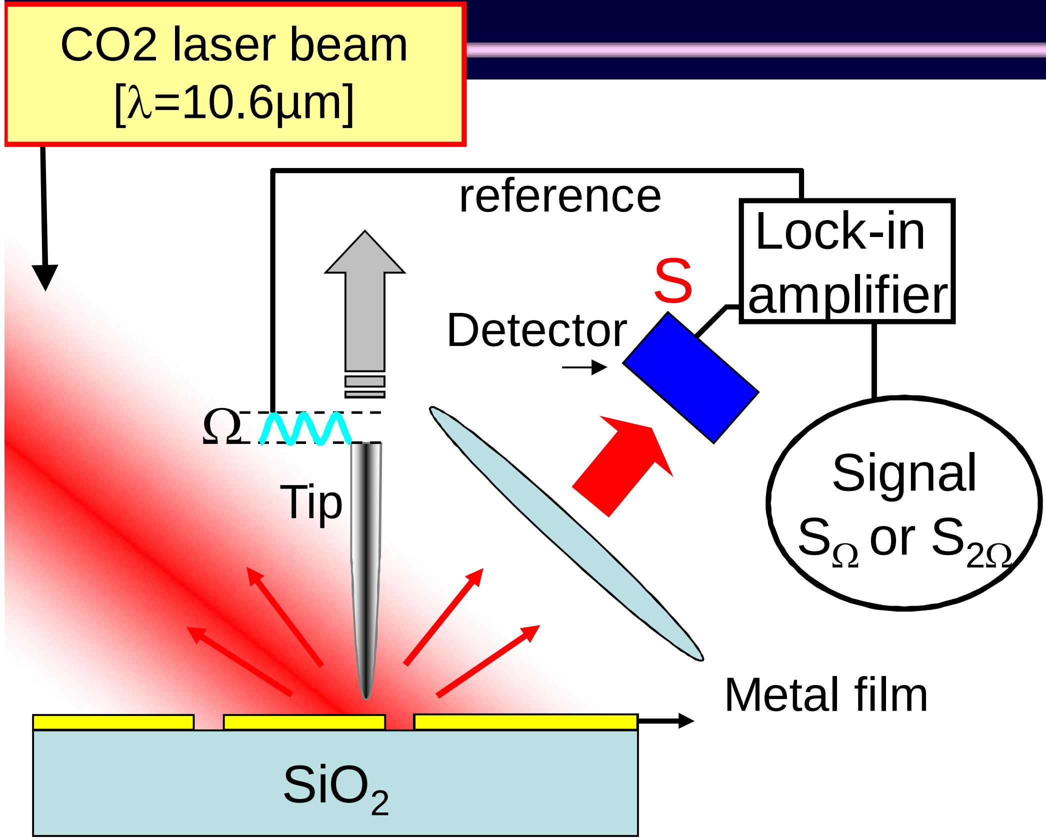
$S_\Omega \propto dS/dz$

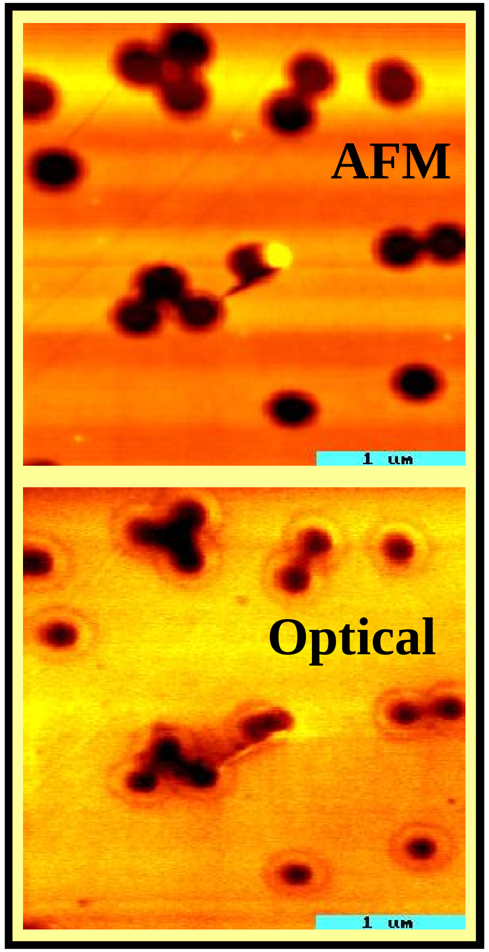
$S_{2\Omega} \propto d^2S/dz^2$

- Rejection of far-field contribution
- Improvement of near-field/far-field ratio when demodulating at tip oscillation frequency Ω or higher harmonics.

Bousseksou, Babuty, Tetienne, Moldovan, Braive, Beaudoin, Sagnes, De Wilde, Colombelli, Optics Express 20, 13738 (2012).

Infrared apertureless SNOM with laser source



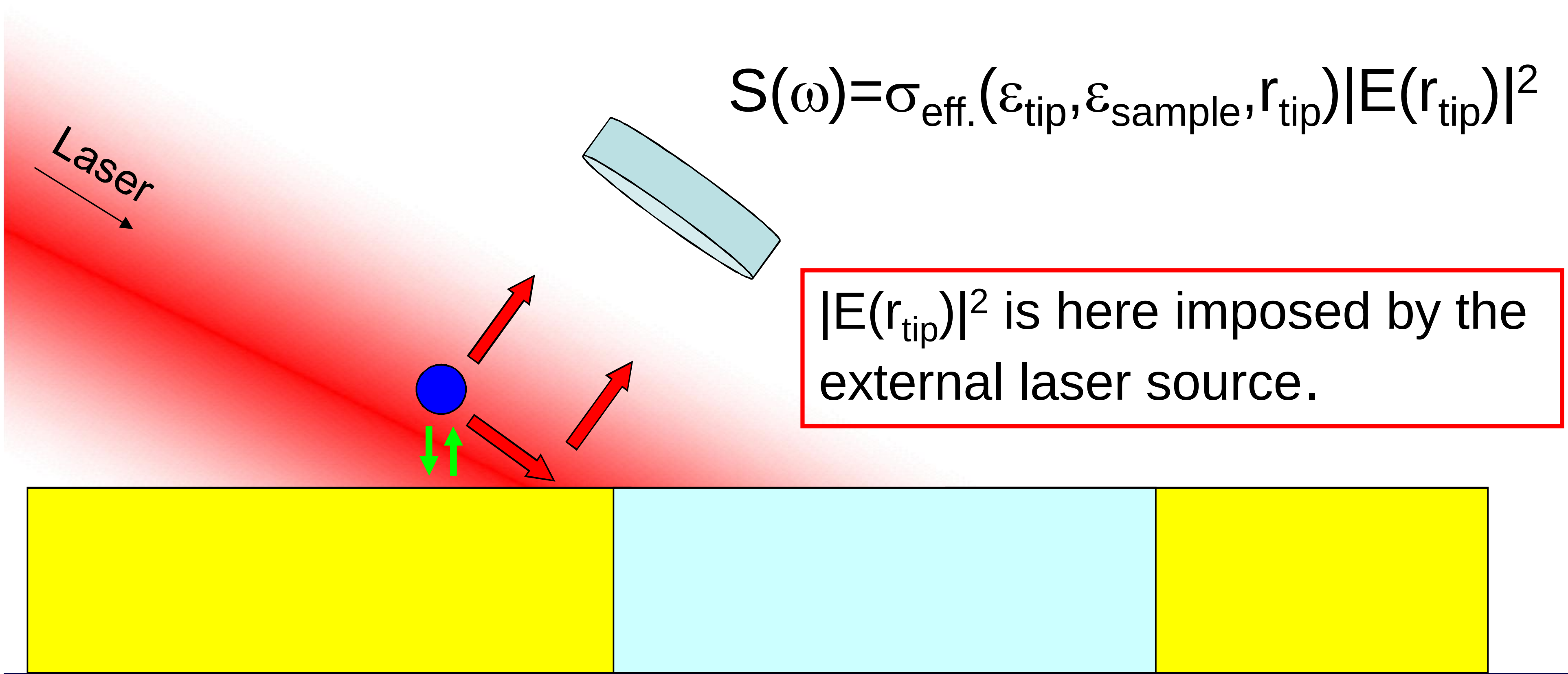


$= S_\Omega$ or $S_{2\Omega}$

Formanek, De Wilde, Aigouy, J. Appl. Phys. **93**, 9548 (2003)

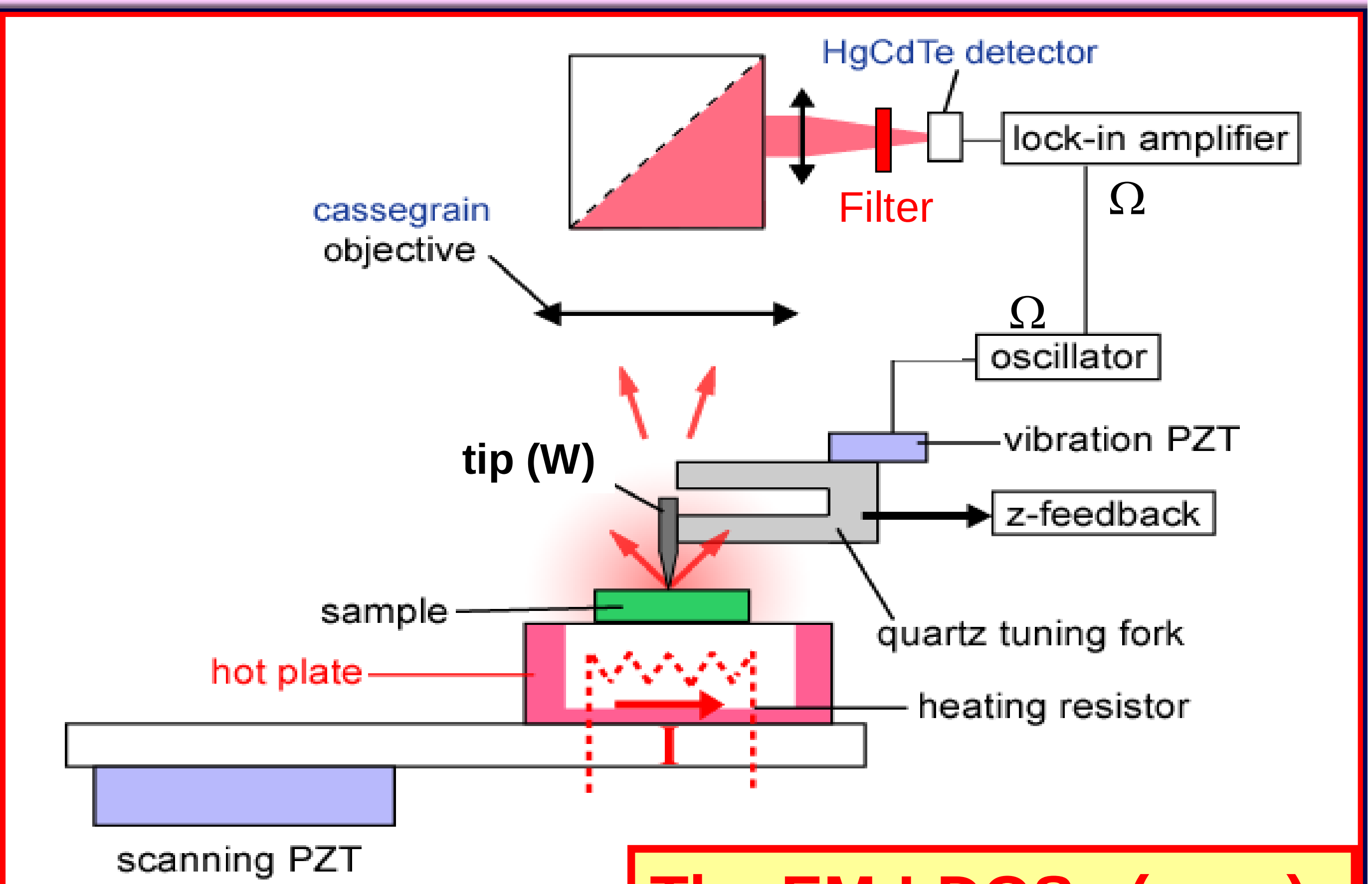
Remark 2: Tip illumination conditions

$$S(\omega)=\sigma_{eff.}(\varepsilon_{tip},\varepsilon_{sample},r_{tip})|E(r_{tip})|^2$$



$|E(r_{tip})|^2$ is here imposed by the external laser source.

Thermal Radiation STM: New paradigm



$$\left|E(r_{tip},\omega)\right|^2 = \underline{\rho(\mathrm{r}_{\mathrm{tip}},\omega)}\,\hbar\omega\frac{1}{\exp\left(\hbar\omega/kT\right)-1}$$

The EM-LDOS $\rho(r_{tip},\omega)$ can be probed with the TRSTM.

Jean-Jacques Greffet

Karl Joulain

Rémi Carminati

Boris Gralak

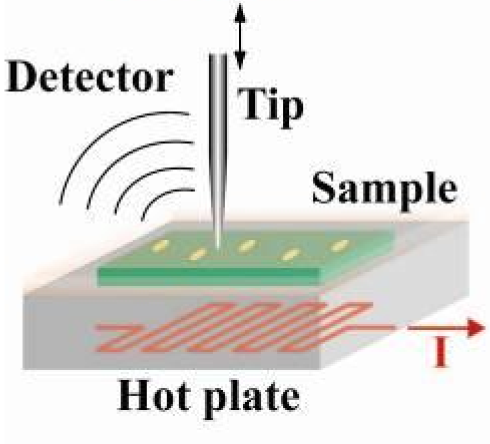
Near-field imaging with the TRSTM

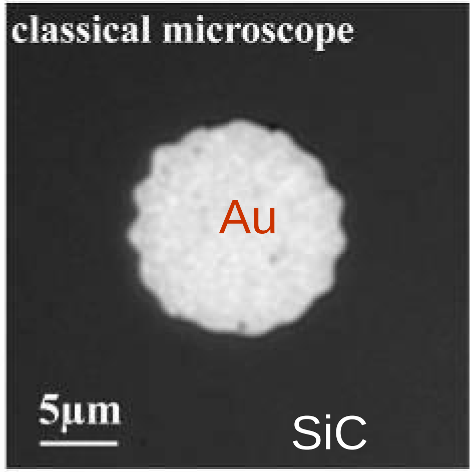
Experiments:
F. Formanek
(ex-PhD,ESPCI)

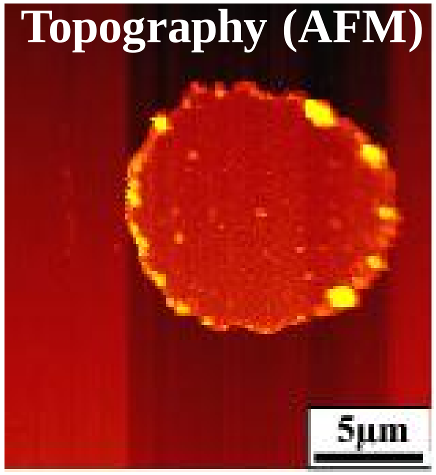
- De Wilde, Formanek, Carminati, Gralak, Lemoine, Mulet, Joulain, Chen, Greffet, Nature **444**, 740 (2006).
- Shchegrov, Joulain, Carminati, Greffet, Phys. Rev. Lett., 85, 1548 (2000).
- Joulain, Carminati, Mulet, Greffet, PRB 68, 245405 (2003).

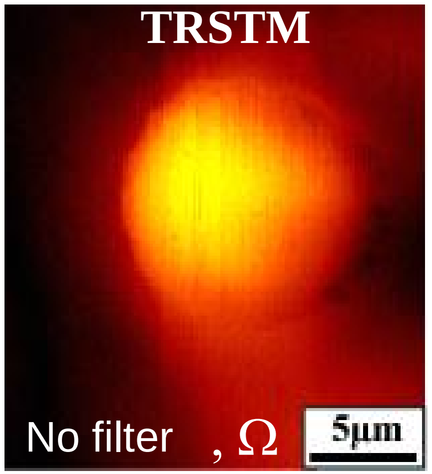
TRSTM Images of pattern of Au on SiC

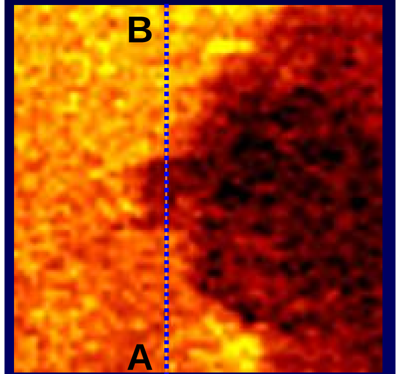
$T_{sample} \approx 500$ K
$T_{tip} \approx 300$ K

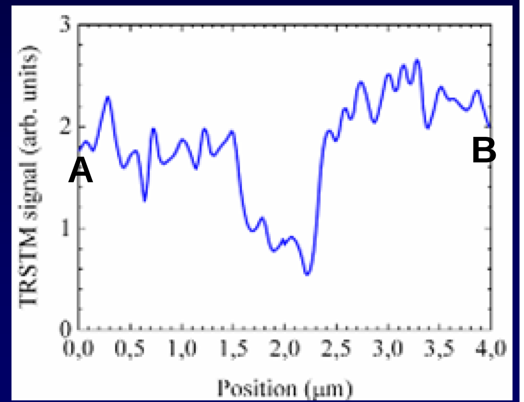










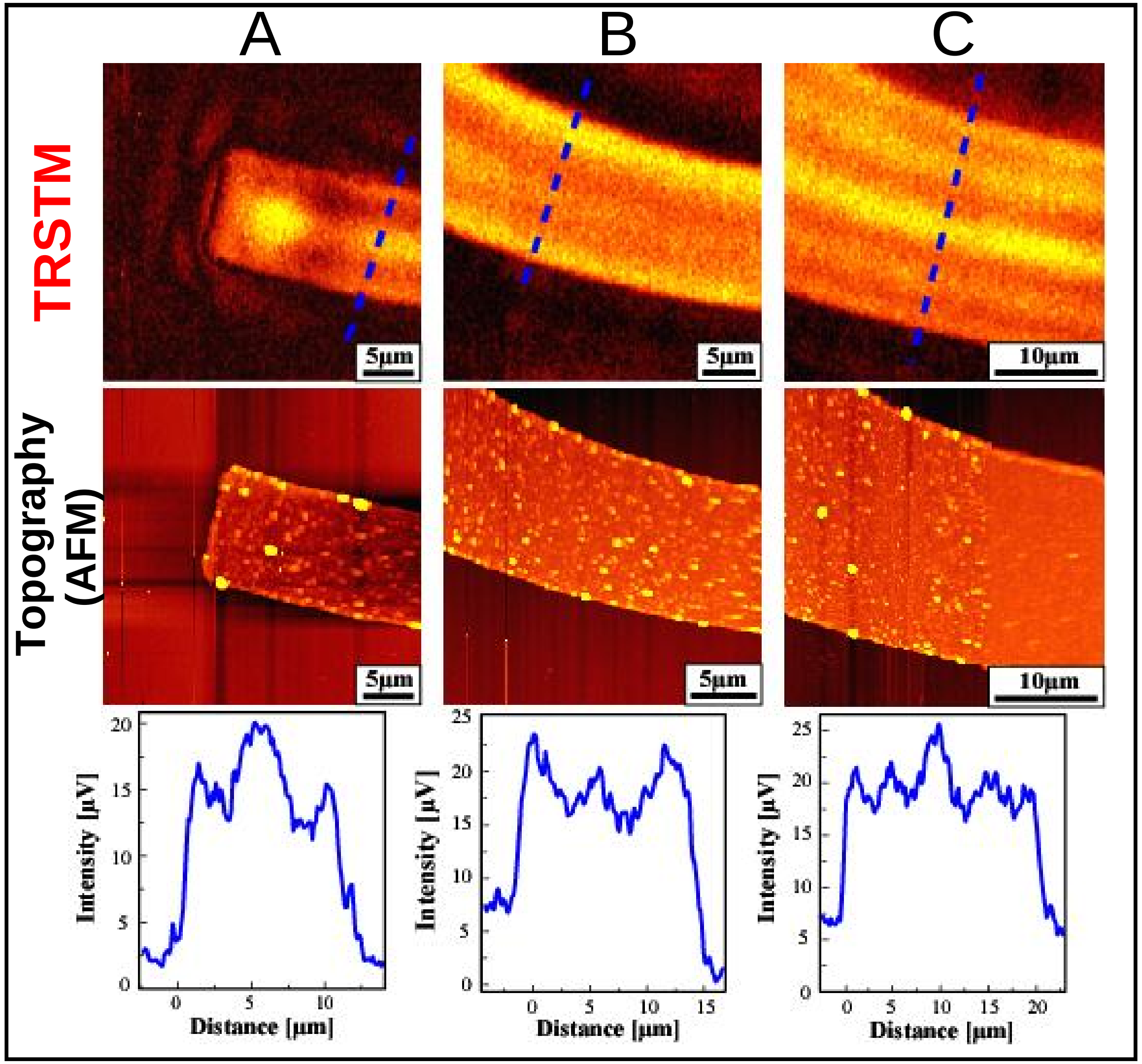


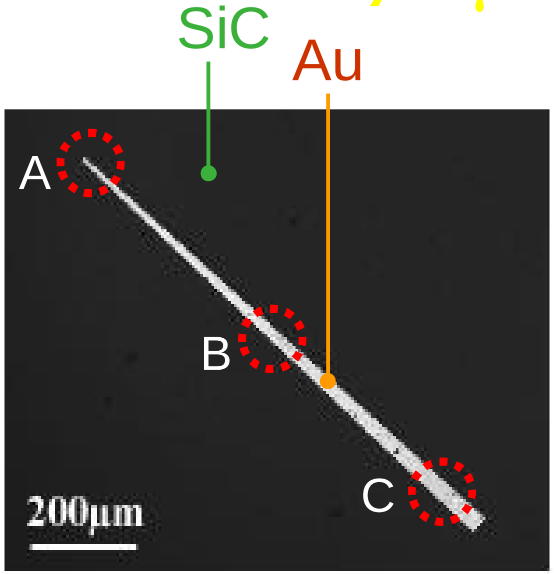
Resolution ~ 100 nm

TRSTM signal ~ 20 pW

$$\sim \frac{\text{IR-SNOM signal}}{10^3}$$

Energy selection :
TRSTM images with filter at λ = 10,9 μm



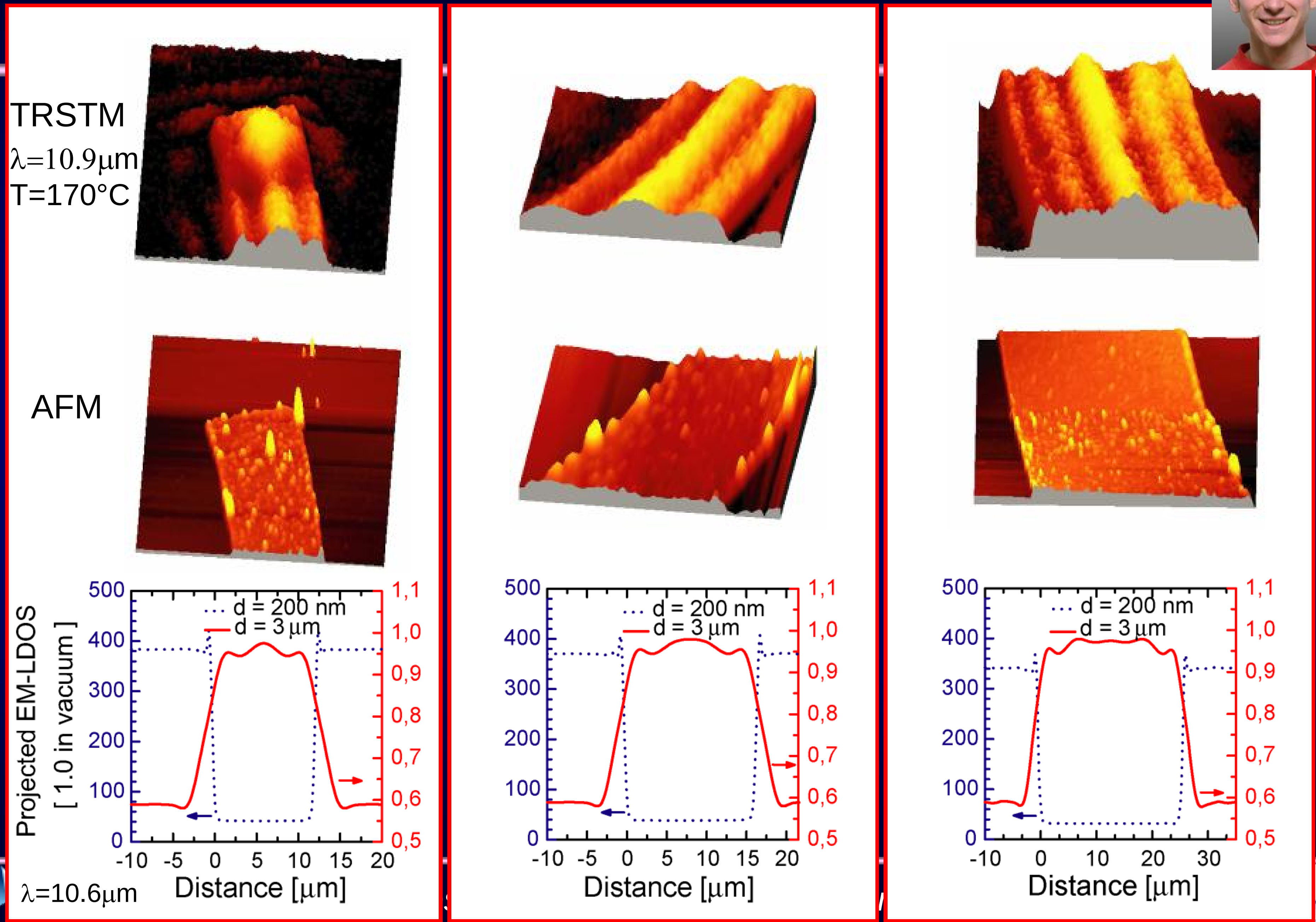


FRINGES
=
Thermally excited surface plasmon modes in a planar cavity

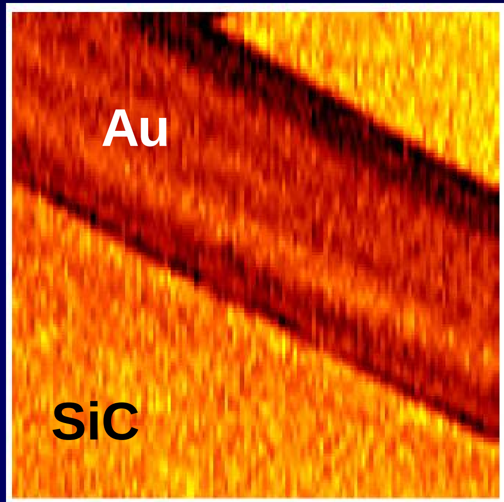
Nature **444**, 740 (2006).

Images TRSTM vs. EM-LDOS

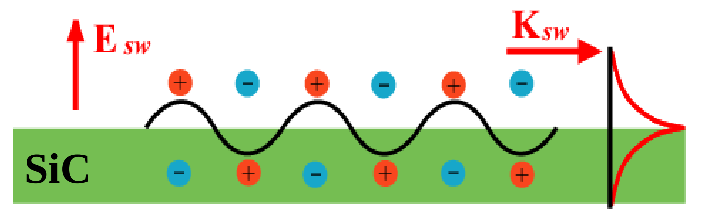
B. Gralak
Inst. Fresnel



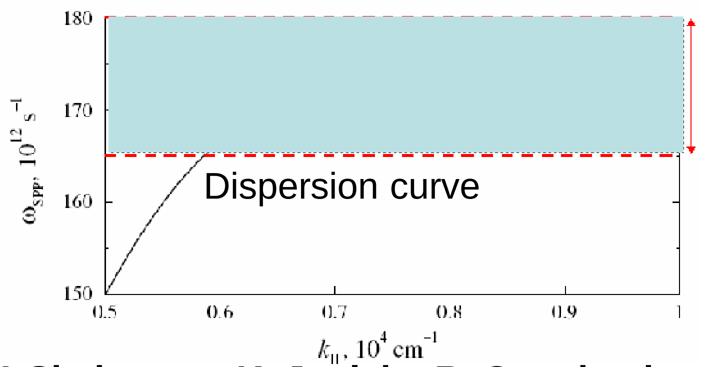
Higher harmonic demodulation



TRSTM image at 2Ω
Filter at 10.9μm (width 1 μm)



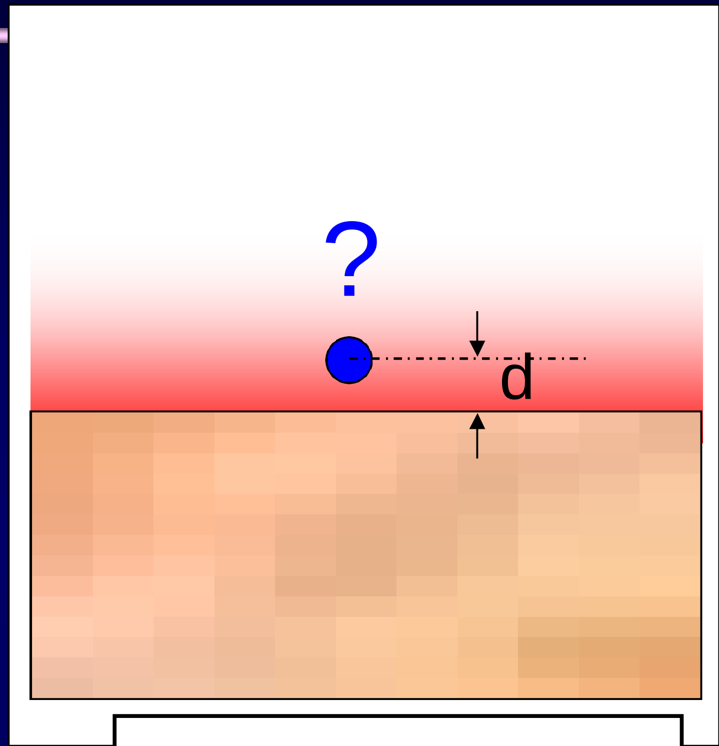
SiC = Polar material with surface : phonon polaritons.



V. Shchegrov, K. Joulain, R. Carminati, J-J. Greffet, Phys.Rev.Lett. 85, 1548(2000)

ÅNear-field energy density peaked at 10.55 μm.
ÅLarge k_{ε} => higher confinement

Revisiting « blackbody radiation » spectra in the near-field.



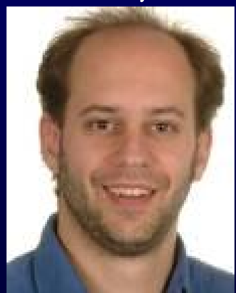
$d \ll \lambda_{emission}$

Near-field spectroscopy with the TRSTM

Karl Joulain

Jean-Jacques Greffet

Pierre-Olivier Chapuis

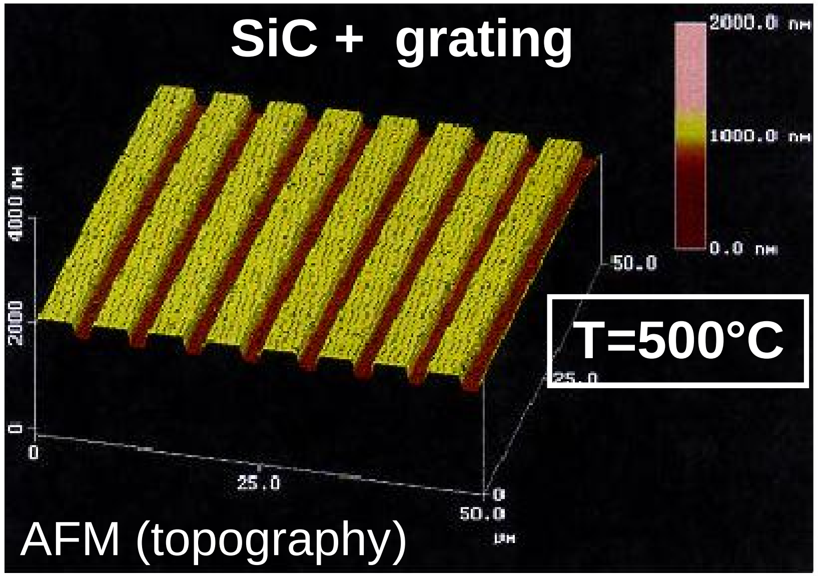


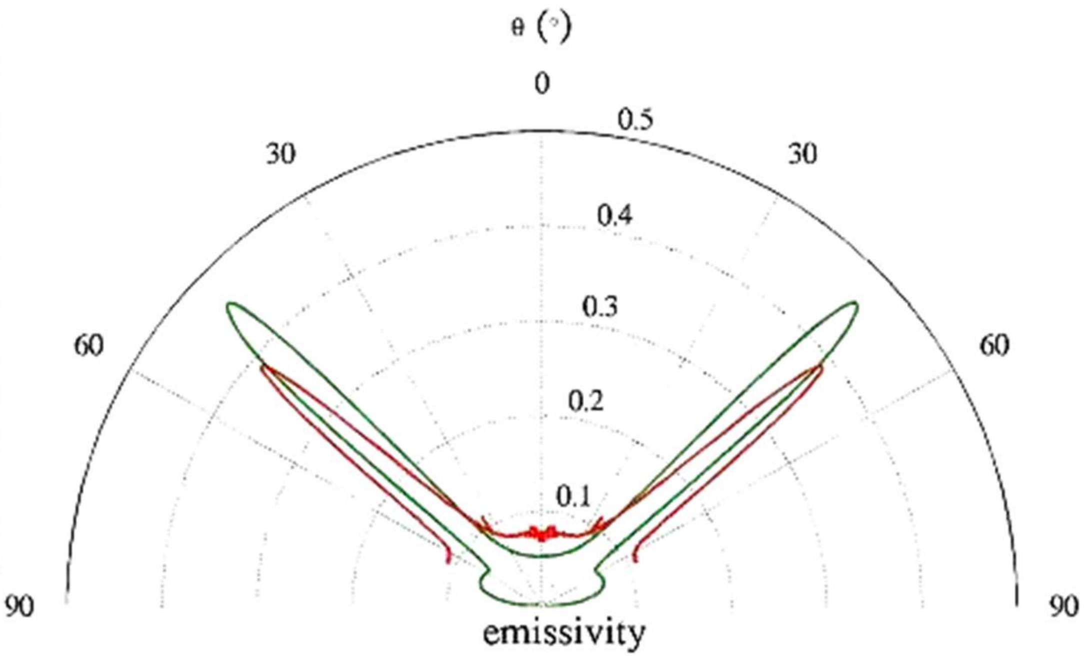
Arthur Babuty

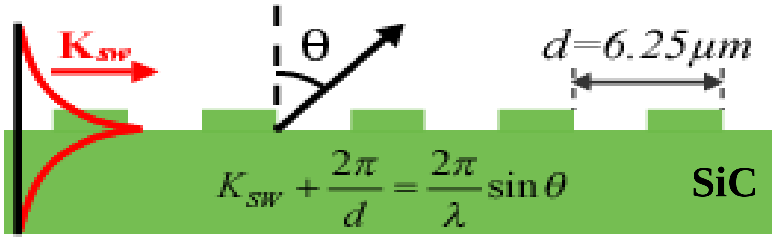
ÅBabuty, Joulain, Chapuis, Greffet, De Wilde, Phys. Rev. Lett. 110, 146103 (2013).

ÅJoulain, Ben-Abdallah, Chapuis, Babuty, De Wilde, arXiv:1201.4834.

Spatial coherence of thermal emission in the near-field of SiC







Antenna like emission pattern

Greffet, Carminati, Joulain, Mulet, Mainguy, Chen, Nature 416, 61 (2002)

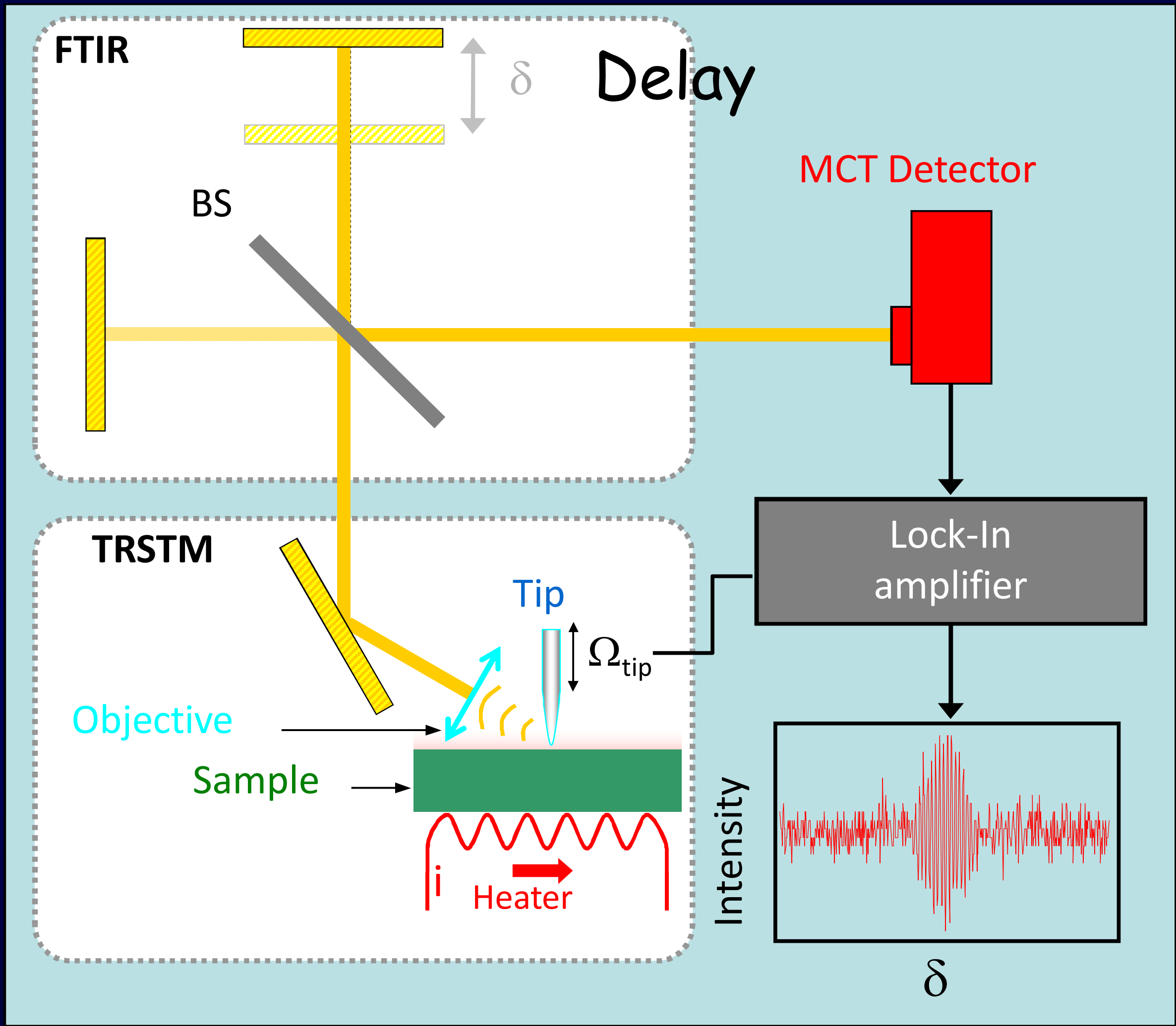
DIFFRACTION → **SPATIAL COHERENCE** OF THERMAL EMISSION !!!

What about the temporal coherence ?

Local FTIR spectroscopy probe of near-field thermal emission

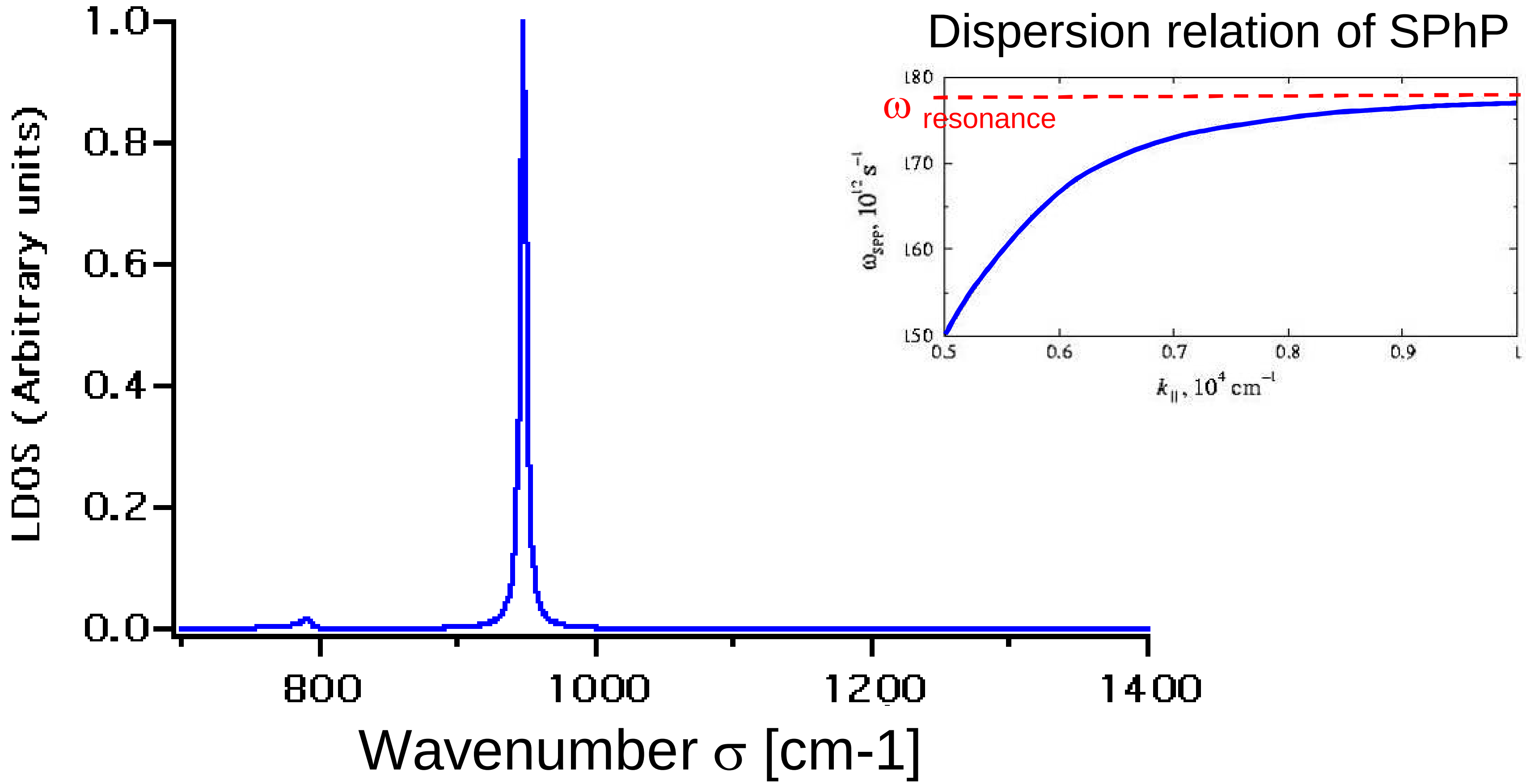
TRSTM

FTIR



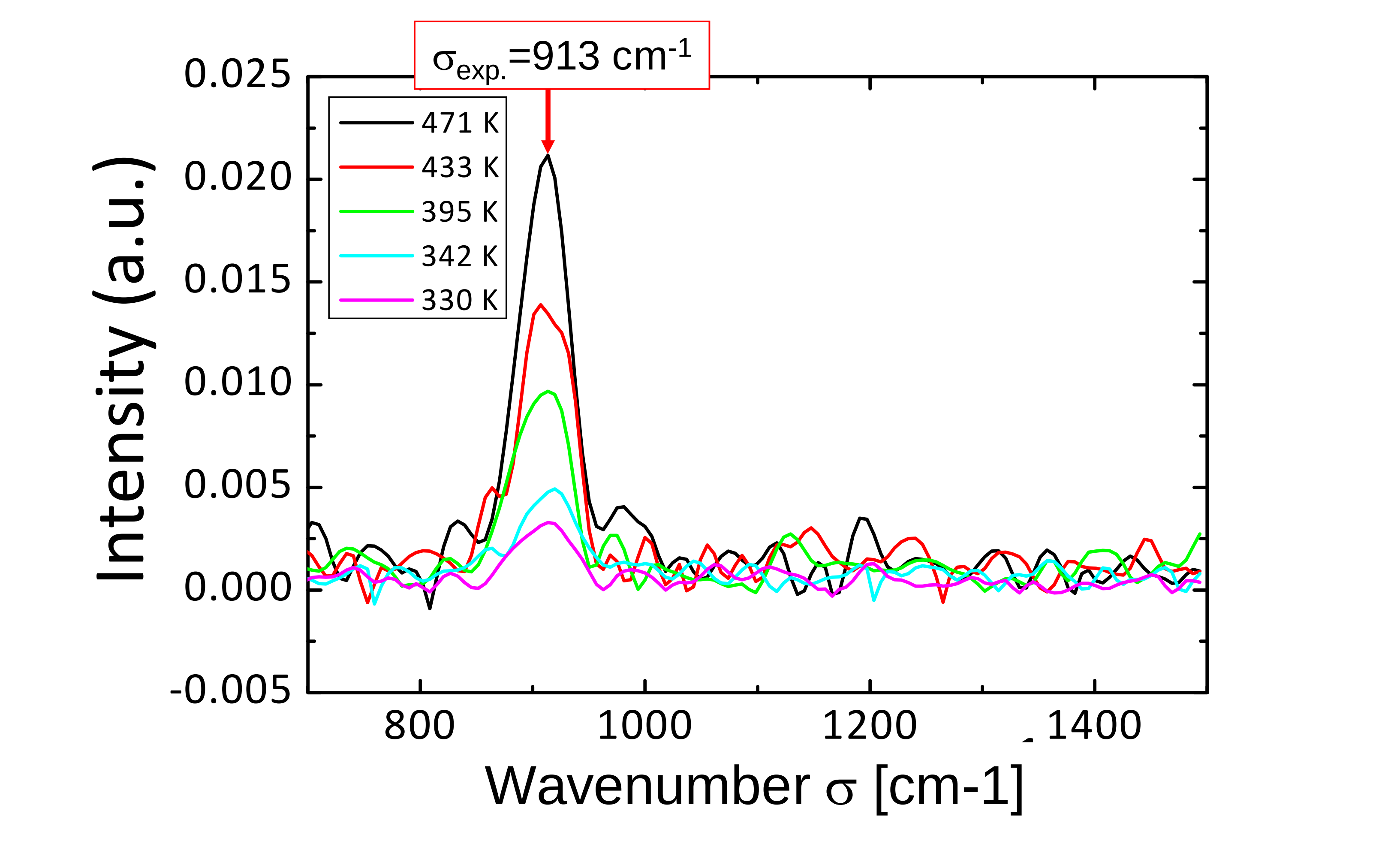
LDOS on SiC : Theoretical predictions

$\sigma_{theo.}$=948 cm^{-1}



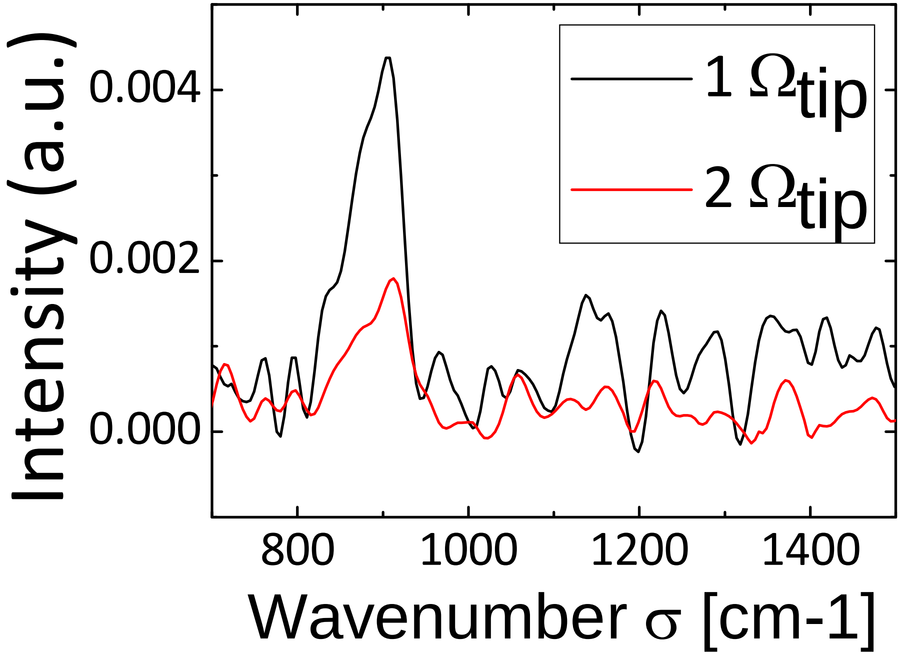
Shchegrov, Joulain, Carminati, Greffet, Phys. Rev. Lett., 85, 1548 (2000)

Near-field thermal emission on SiC



Babuty, Joulain, Chapuis, Greffet, De Wilde, Phys. Rev. Lett. 110, 146103 (2013).

Test of near-field origin of the signal

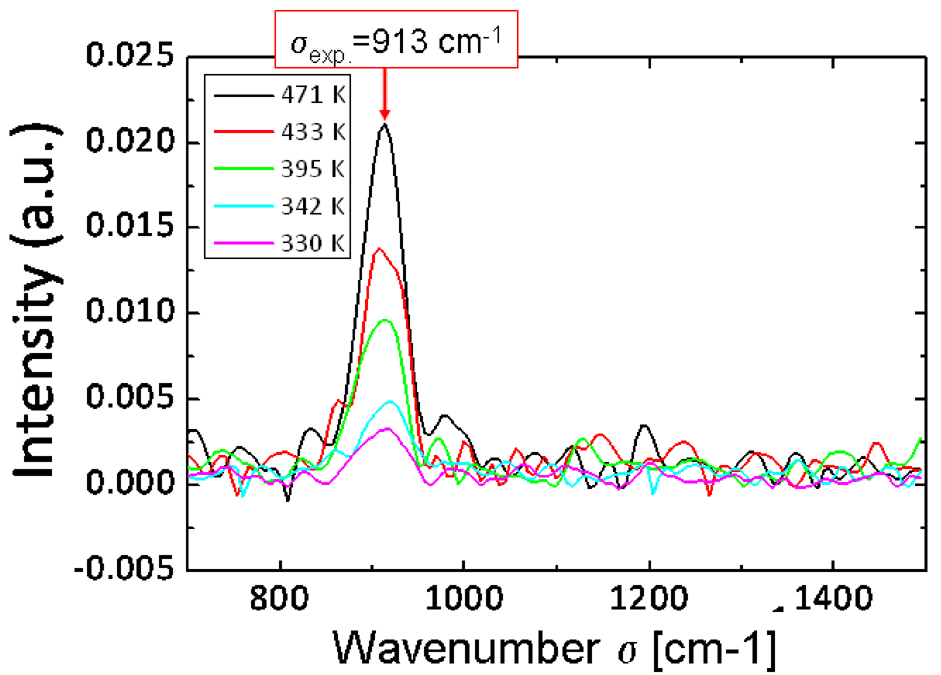


Peak present at 1 Ω_{tip} and 2 Ω_{tip}

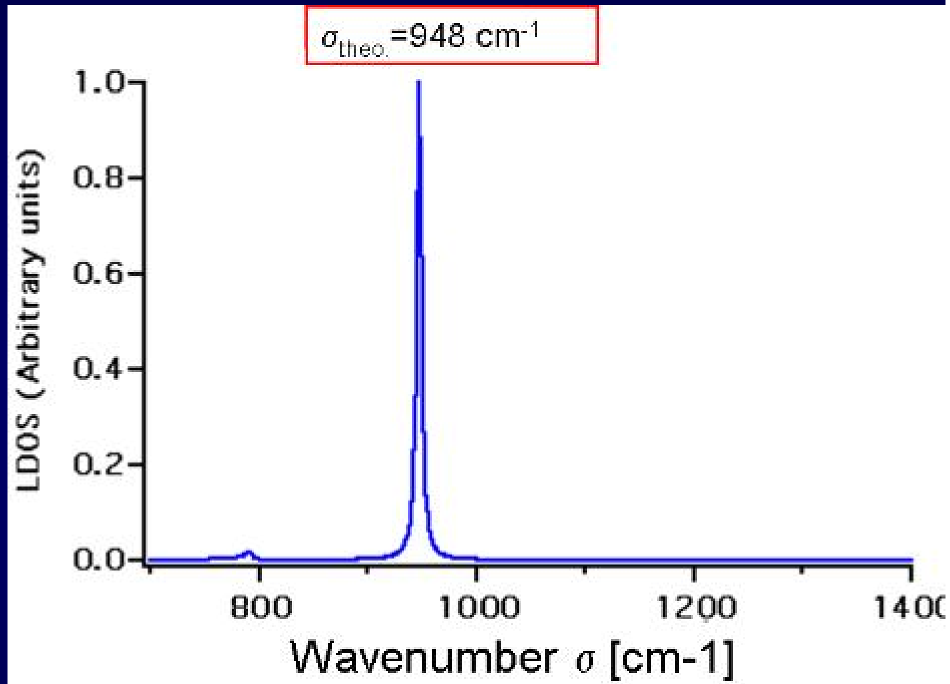
Babuty, Joulain, Chapuis, Greffet, De Wilde, Phys. Rev. Lett. 110, 146103 (2013).

SiC : Experiment vs. LDOS

Experiment

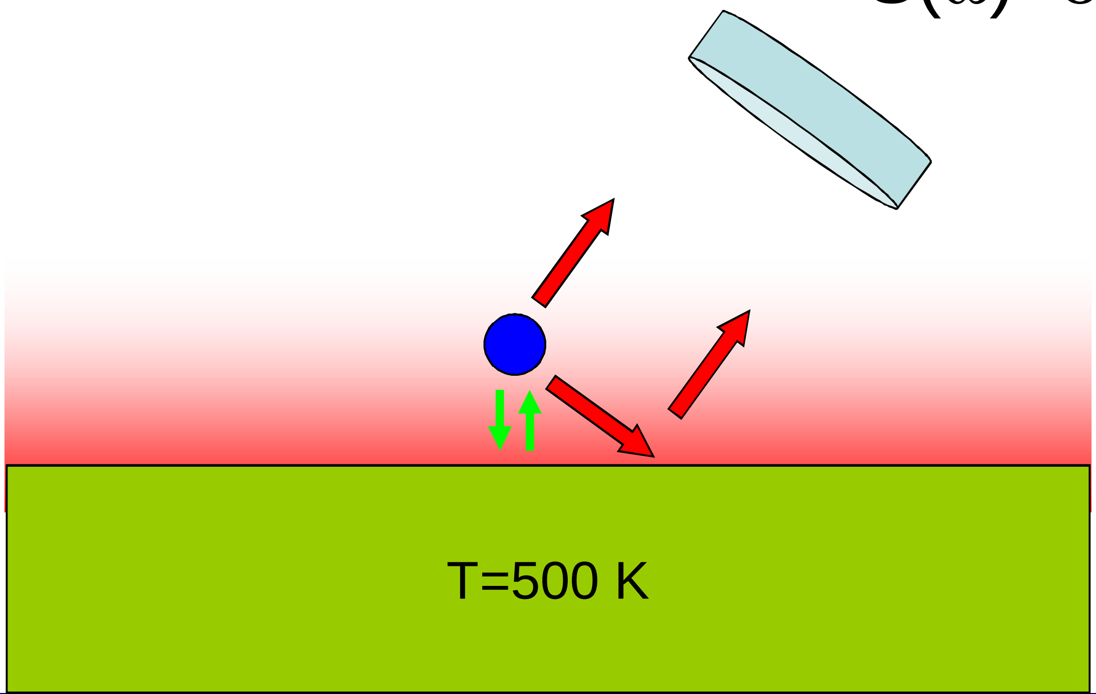


Theory



Partial temporal coherence is demonstrated, but a redshift and broadening is observed in the experimental peak with respect to theory.

$$S(\omega)=\sigma_{eff.}(\varepsilon_{tip},\varepsilon_{sample},r_{tip})|E(r_{tip})|^2$$



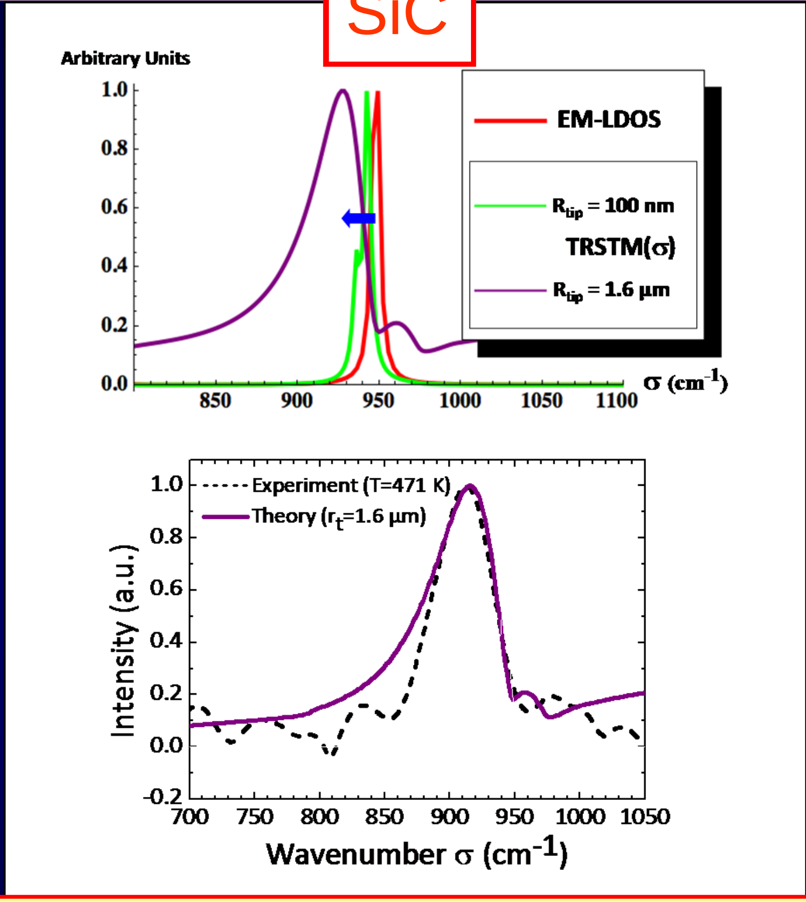
$|E(r_{tip})|^2 \propto$ EM-LDOS

See Karl Joulainŝ Talk at 2 pm.

Joulain, Ben-Abdallah, Chapuis, Babuty, De Wilde, arXiv:1201.4834.

SiC: Theoretical modelling vs. experiment

SiC

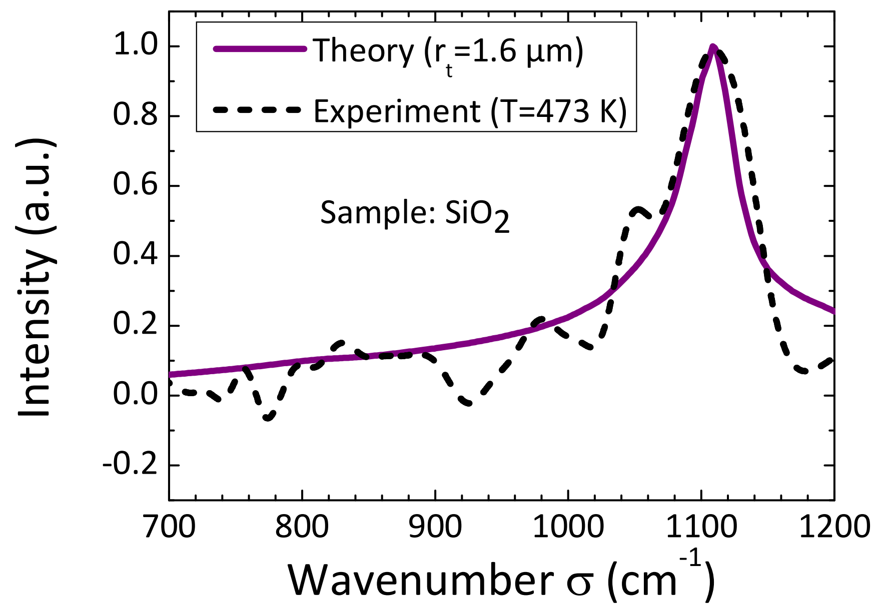


Good agreement with experiments (R_{tip}=1.6 μm)

Babuty, Joulain, Chapuis, Greffet, De Wilde, Phys. Rev. Lett. 110, 146103 (2013).
Joulain, Ben-Abdallah, Chapuis, Babuty, De Wilde, arXiv:1201.4834.

SiO_2: Theory modelling vs. experiment

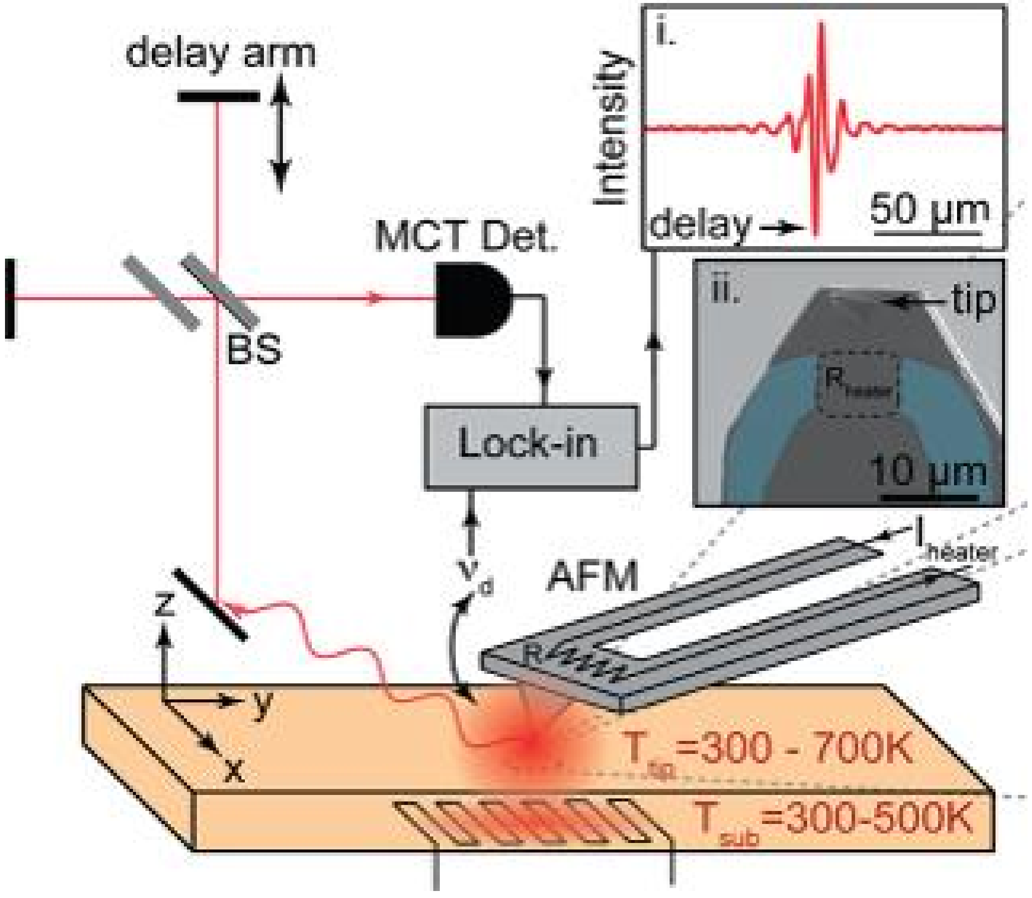
SiO_2

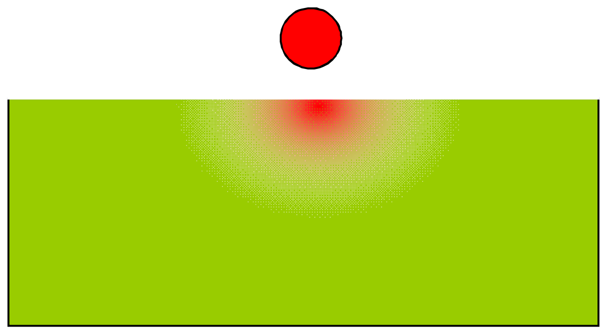


Good agreement with experiments (R_{tip}=1.6 µm)

Babuty, Joulain, Chapuis, Greffet, De Wilde, Phys. Rev. Lett. 110, 146103 (2013).
Joulain, Ben-Abdallah, Chapuis, Babuty, De Wilde, arXiv:1201.4834.

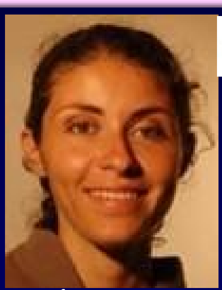
TRSTM spectroscopy with a heated tip (Markus B. Raschke group)





Jones, Raschke, Nanoletters 12, 1475 (2012).

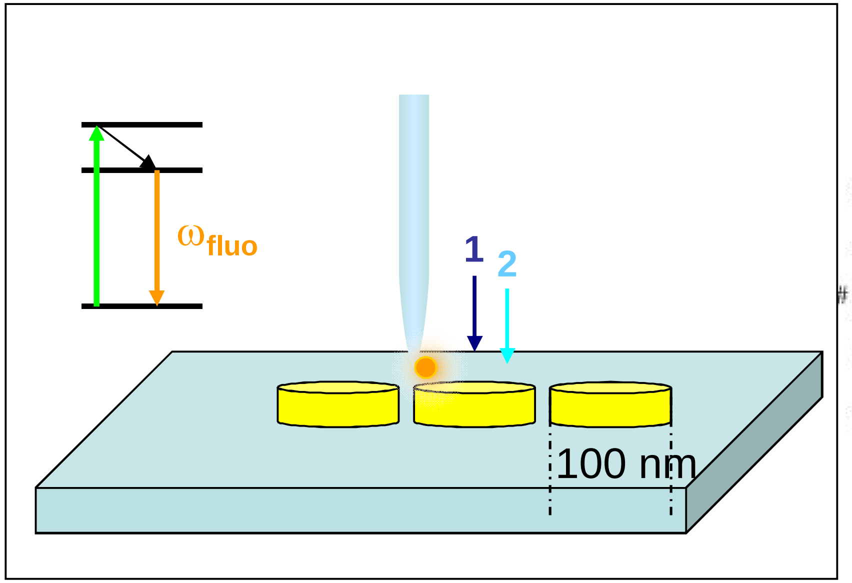
Mapping the EM-LDOS in the visible



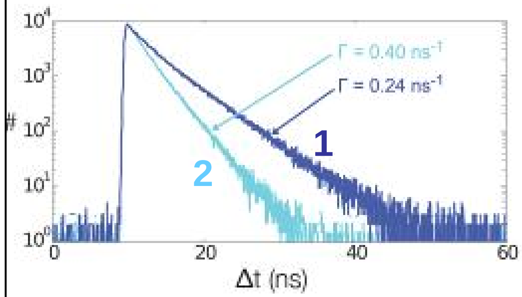
Valentina Krachmalnicoff

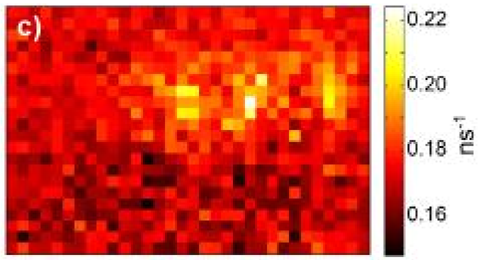
Da Cao

Rémi Carminati



Mapping of LDOS at $\omega_{fluo.}$ based on measurements of Γ .





Decay rate map

V.Krachmalnicoff, et al., Phys. Rev. Lett. 105,183901 (2010).
Krachmalnicoff, Cao, Cazé, Castanié, Pierrat, Bardou, Collin, Carminati, De Wilde, Optics Express 21, 11536 (2013).

+ Romain Pierrat, Alexandre Cazé, Etienne Castanié

CONCLUSIONS

Infrared-NSOM based on home-built system for subwavelength imaging of materials and investigations of plasmonic devices.

The set-up can operate without any external source in the « TRSTM mode », allowing the detection of thermal emission in the near-field.

TRSTM images and FTIR spectra have been obtained. They probe the spatial and frequency dependence of the EM-LDOS (see Karl Joulainõs talk this afternoon).

TRSTM spectra have revealed the temporal coherence of the near-field thermal emission in SiC and SiO2.

THANK YOU !

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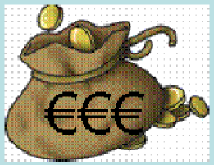

= ANR + NanoSciences ILE-DE-FRANCE