Localized light absorption by **nanoscale** semiconducting tips in laser-assisted Atom Probe Tomography

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[2]IMEC, KAPELDREEF 75, B-3000 LEUVEN, BELGIUM

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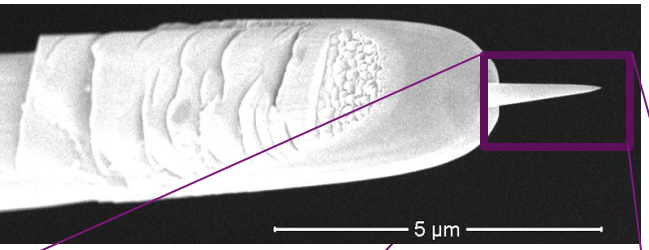
KATHOLIEKE UNIVERSITEIT LEUVEN

imec

LASER-ASSISTED ATOM PROBE TOMOGRAPHY



R_{apex}~10-100 nm

α_{shank}~2 -15°

L ~ 1-5 µm

Position Sensitive Detector

V_{DC}

Potential of surface atoms

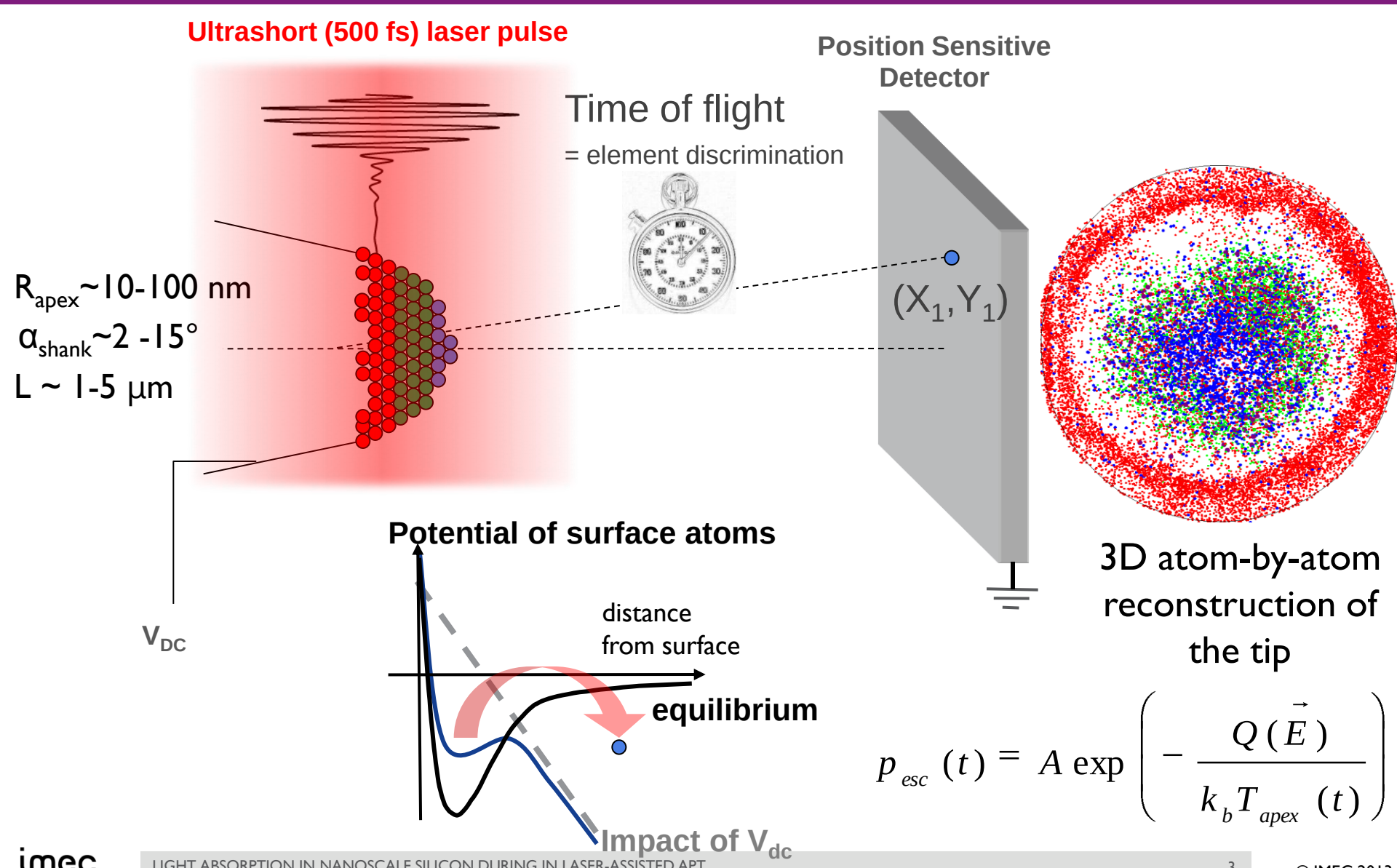
distance from surface

equilibrium

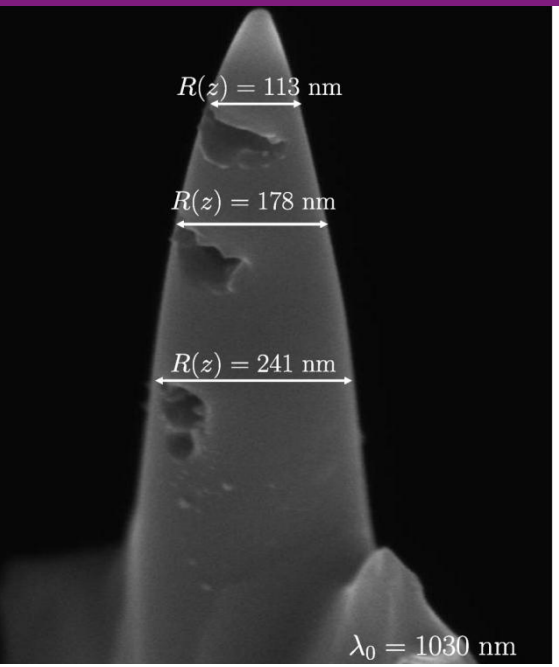
Impact of V_{dc}

$$p_{esc}(t) = A \exp\left(-\frac{Q(\vec{E})}{k_b T_{apex}(t)}\right)$$

LASER-ASSISTED ATOM PROBE TOMOGRAPHY



EXPERIMENTAL OBSERVATION OF SHARPLY LOCALIZED LASER IMPACT



Light absorption in conical silicon particles

J. Bogdanowicz,[1,2,*] M. Gilbert,[2] N. Innocenti,[2,5] S. Koelling,[2,5] B. Vanderheyden,[4] and W. Vandervorst[1,2]

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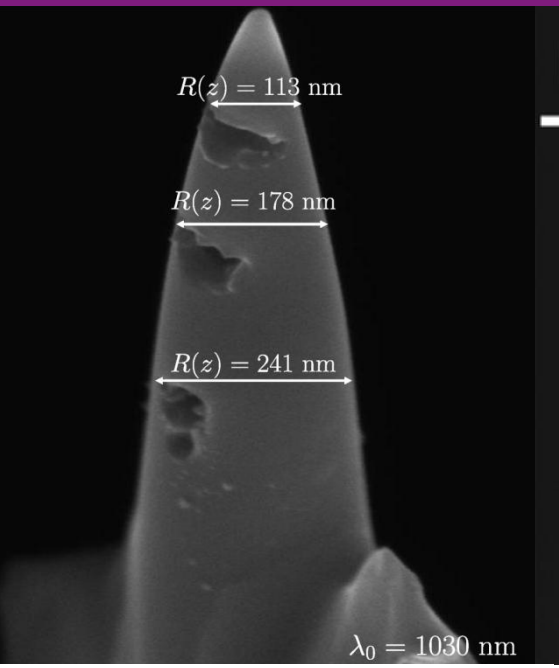
Infrared:

LOCALIZED holes

EXPERIMENTAL OBSERVATION OF SHARPLY LOCALIZED LASER IMPACT



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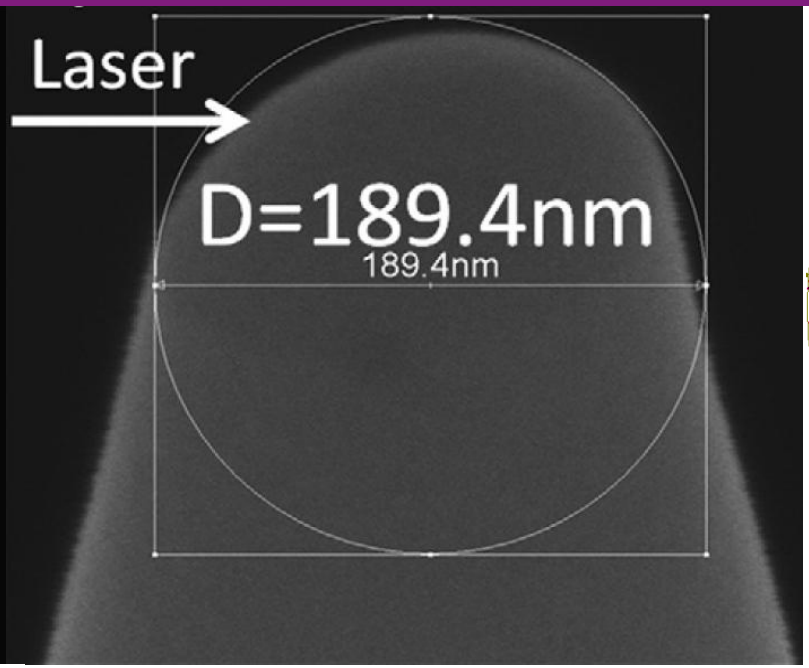
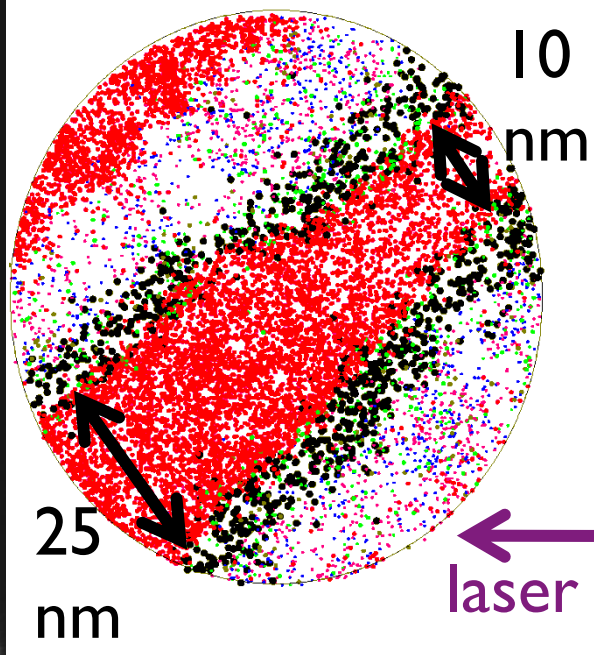


In-situ observation of non-hemispherical tip shape formation during laser-assisted atom probe tomography

S. Koelling, N. Innocenti, A. Schulze, M. Gilbert, A. K. Kambham et al.

Citation: J. Appl. Phys. **109**, 104909 (2011); doi: 10.1063/1.3592339



Si^{2+}, TiN^{+}

Ti^{+} HfO_2^{+}

Infrared:

LOCALIZED holes

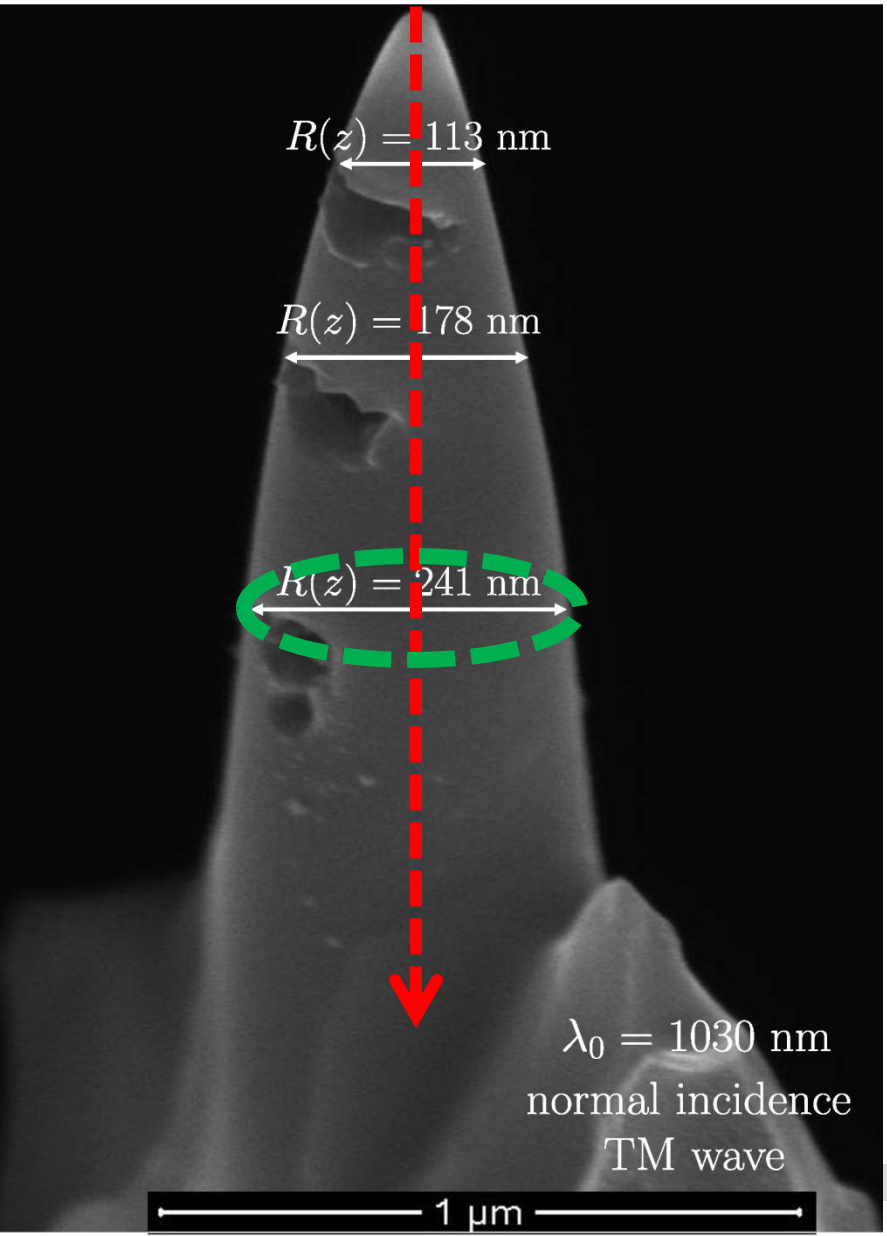
Ultraviolet:

LOCALLY flattened tip

Ultraviolet:

LOCAL Variation in fin width

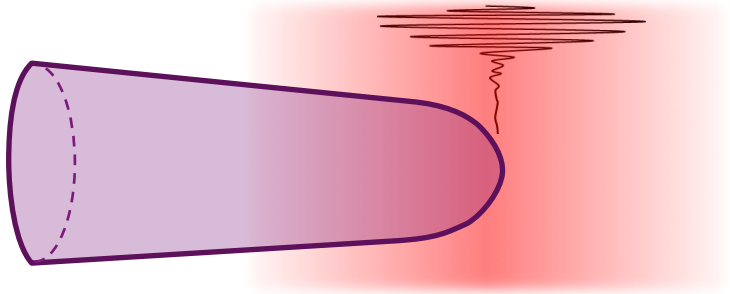
OUTLINE



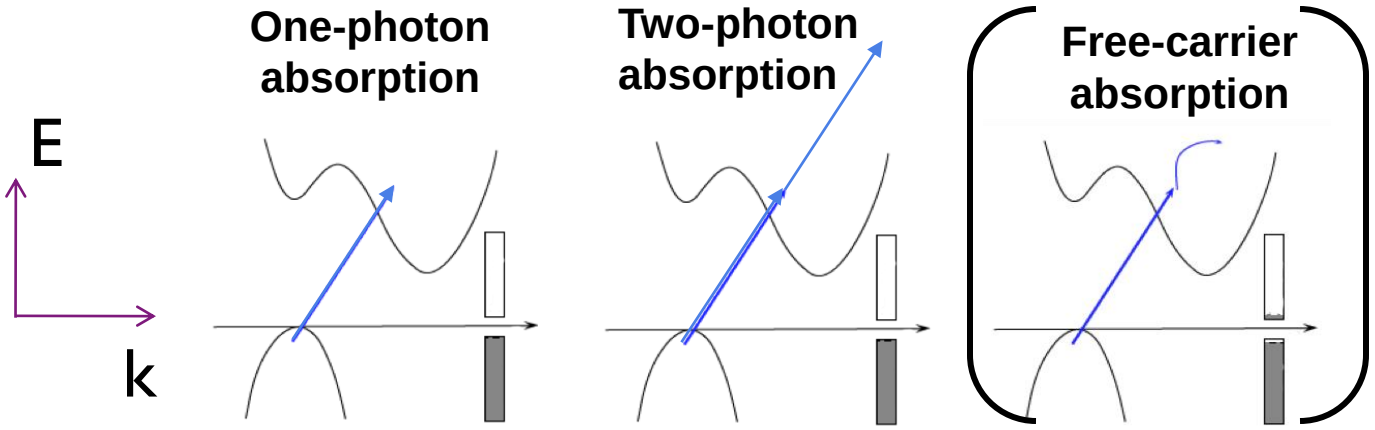
- **Localized absorption along the tip axis**
- Localized absorption in cross-sections
- Localized heating

LASER INTERACTION WITH A SEMICONDUCTING TIP

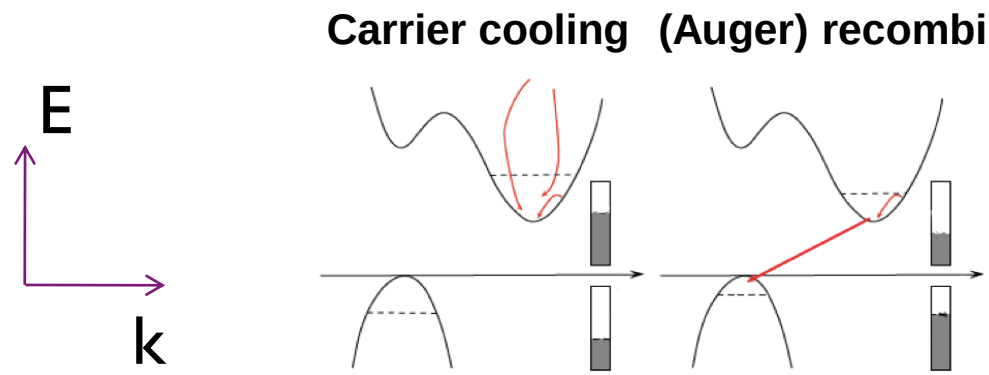
Electric field (rectification)



Free carriers

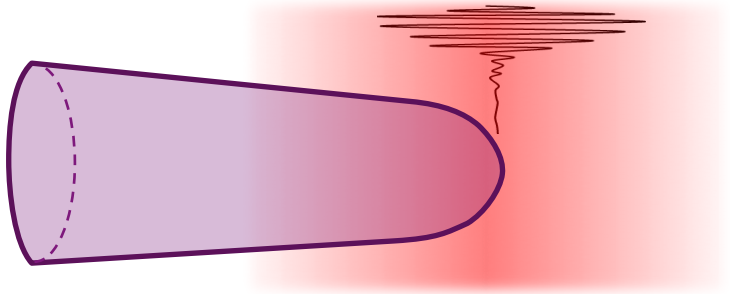


HEATING



LASER INTERACTION WITH A SEMICONDUCTING TIP

Electric field (rectification)



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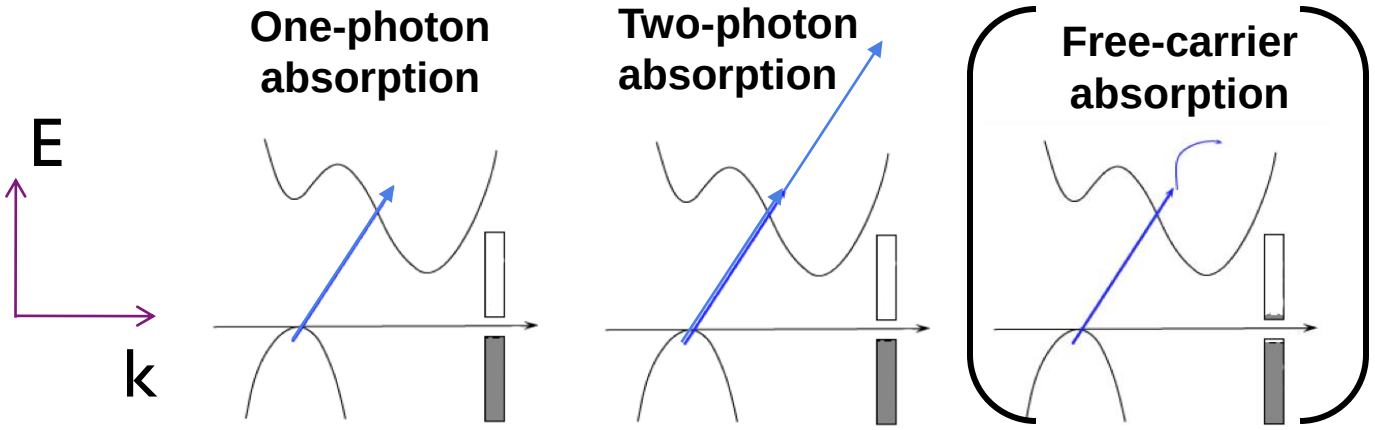

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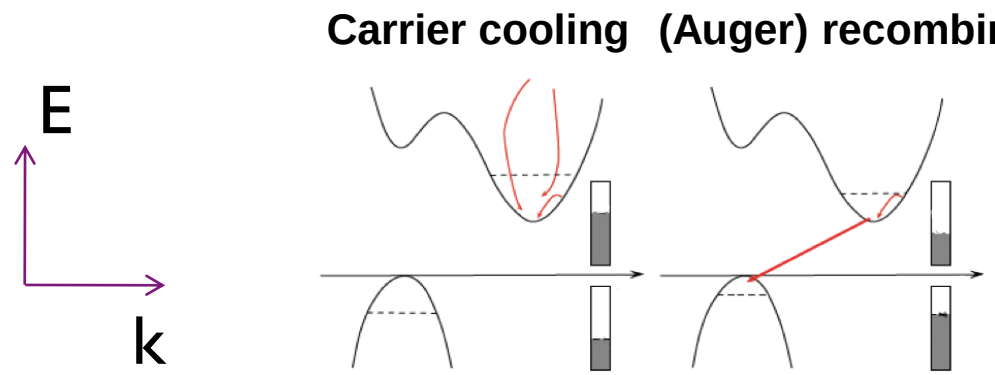
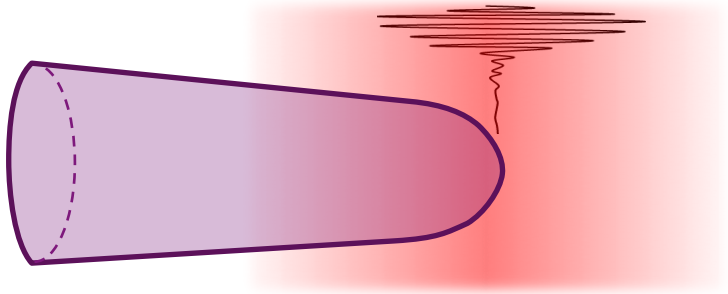


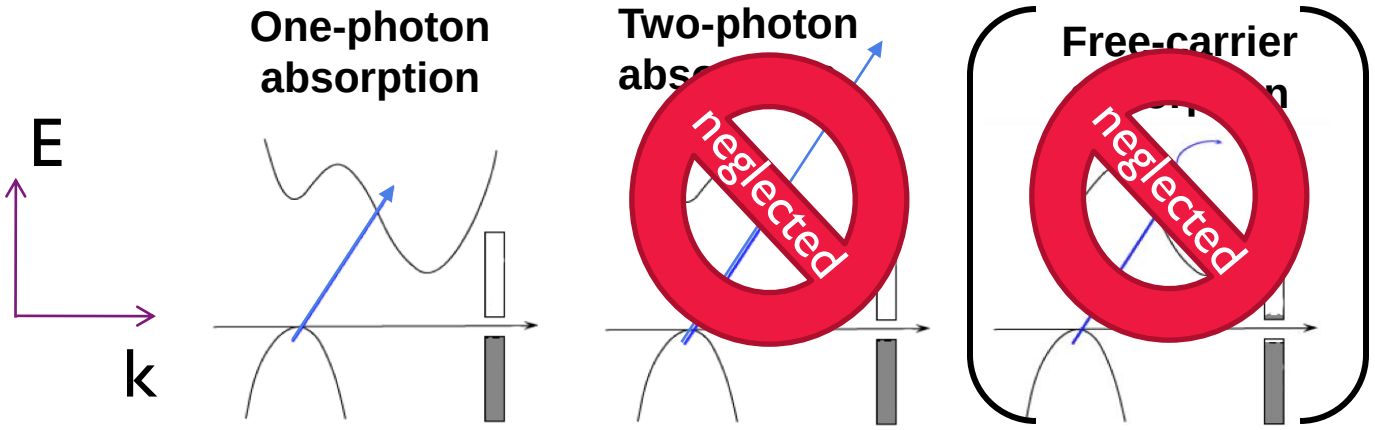
LASER INTERACTION WITH A SEMICONDUCTING TIP

Electric field (rectification)

neglected



Free carriers



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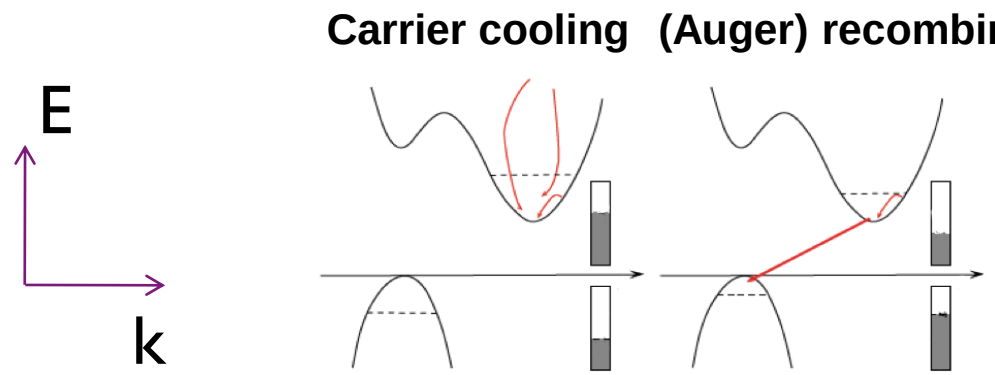
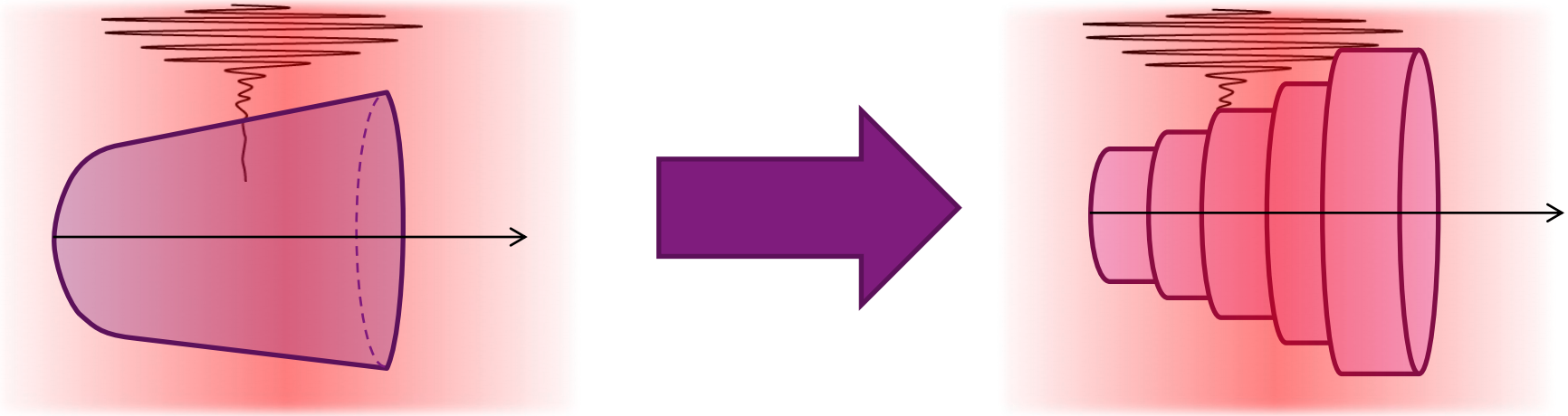
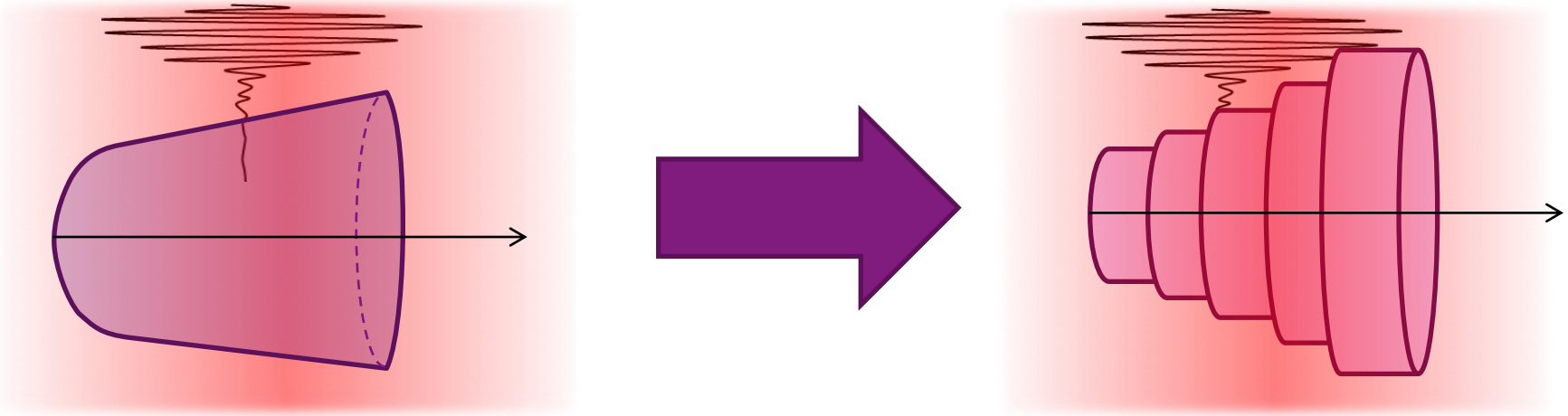


ANALYTICAL MIE-BASED THEORY

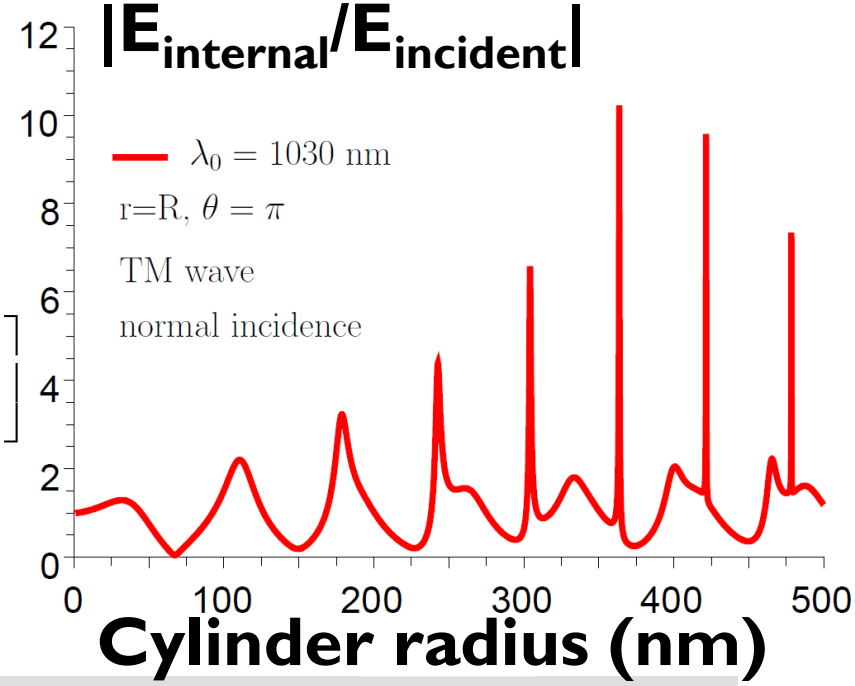


ANALYTICAL MIE-BASED THEORY

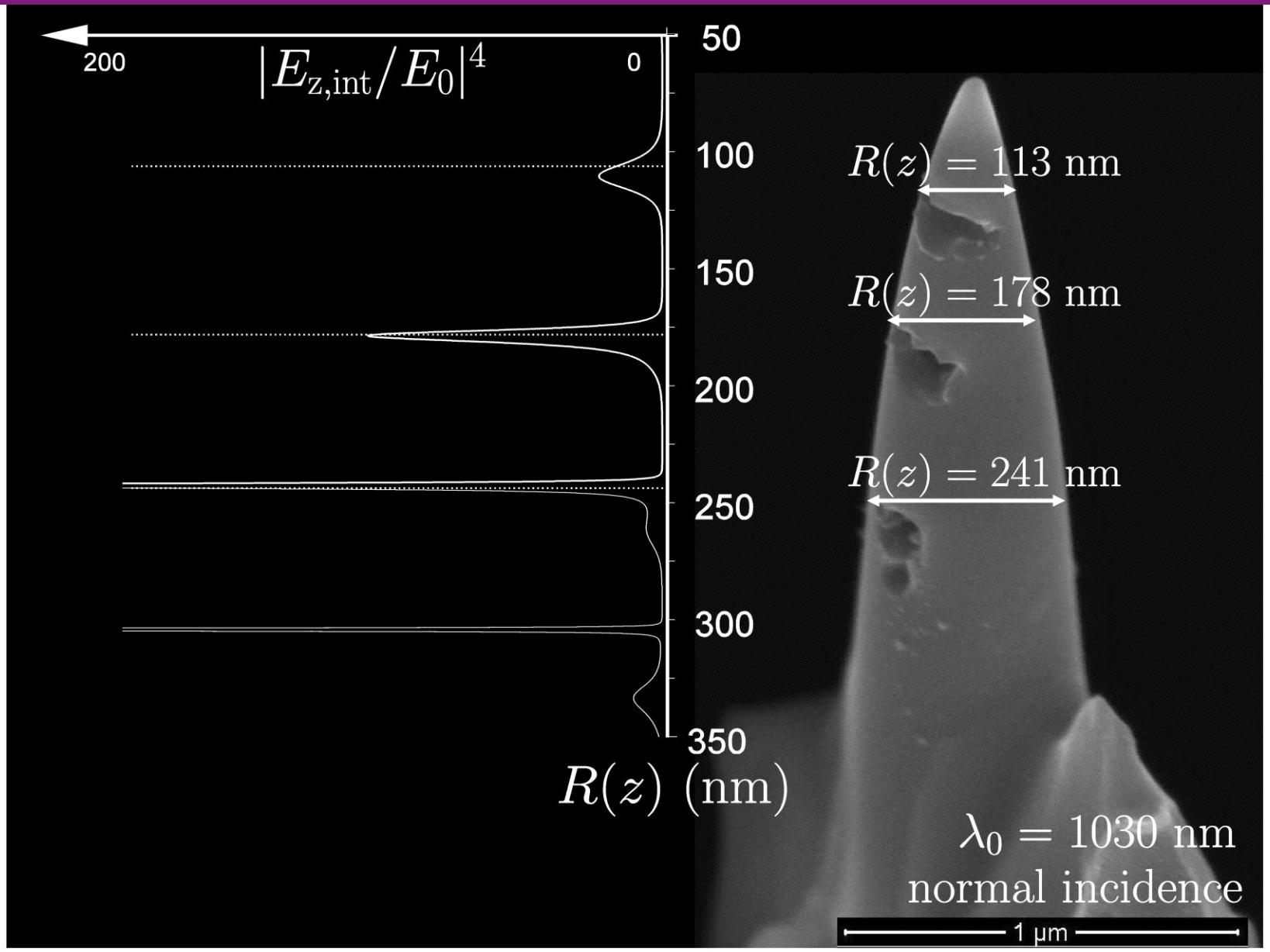


Field inside an infinite cylinder:

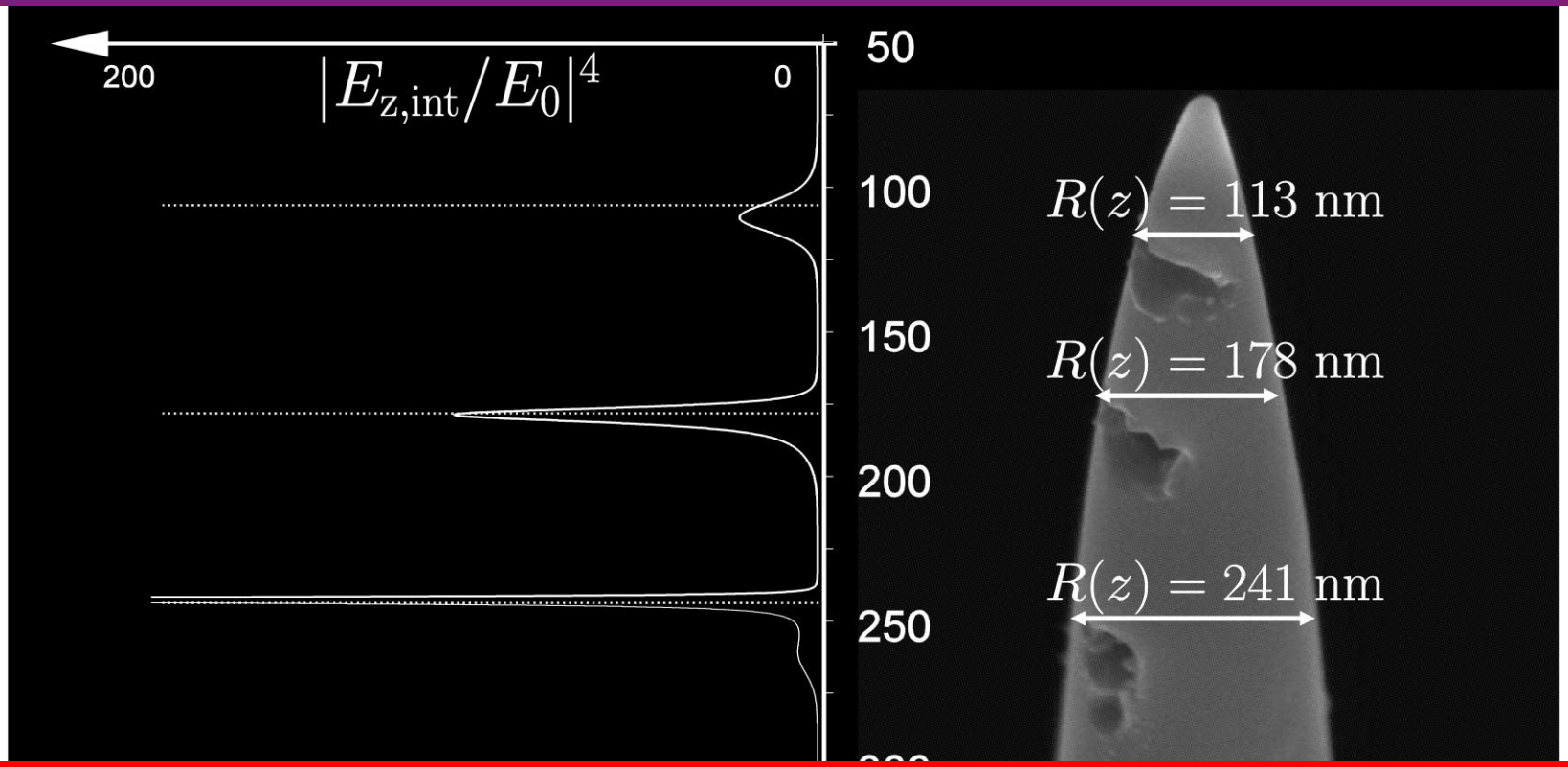
$$E_{z,\mathrm{int}}(r,\vartheta) = E_{\mathrm{incident}}\left[d_0\left(\frac{R}{\lambda_0}\right) J_0\left(\frac{2\pi\tilde{n}}{\lambda_0} r\right) + \sum_{k=1}^{\infty} 2 i^k d_k\left(\frac{R}{\lambda_0}\right) J_k\left(\frac{2\pi\tilde{n}}{\lambda_0} r\right) \cos(k\vartheta) \right]$$



ANALYTICAL MIE-BASED THEORY



ANALYTICAL MIE-BASED THEORY



Localized absorption along the axis

constructive interference between transmitted light and internal reflections at **resonant radii**

Light absorption in conical silicon particles

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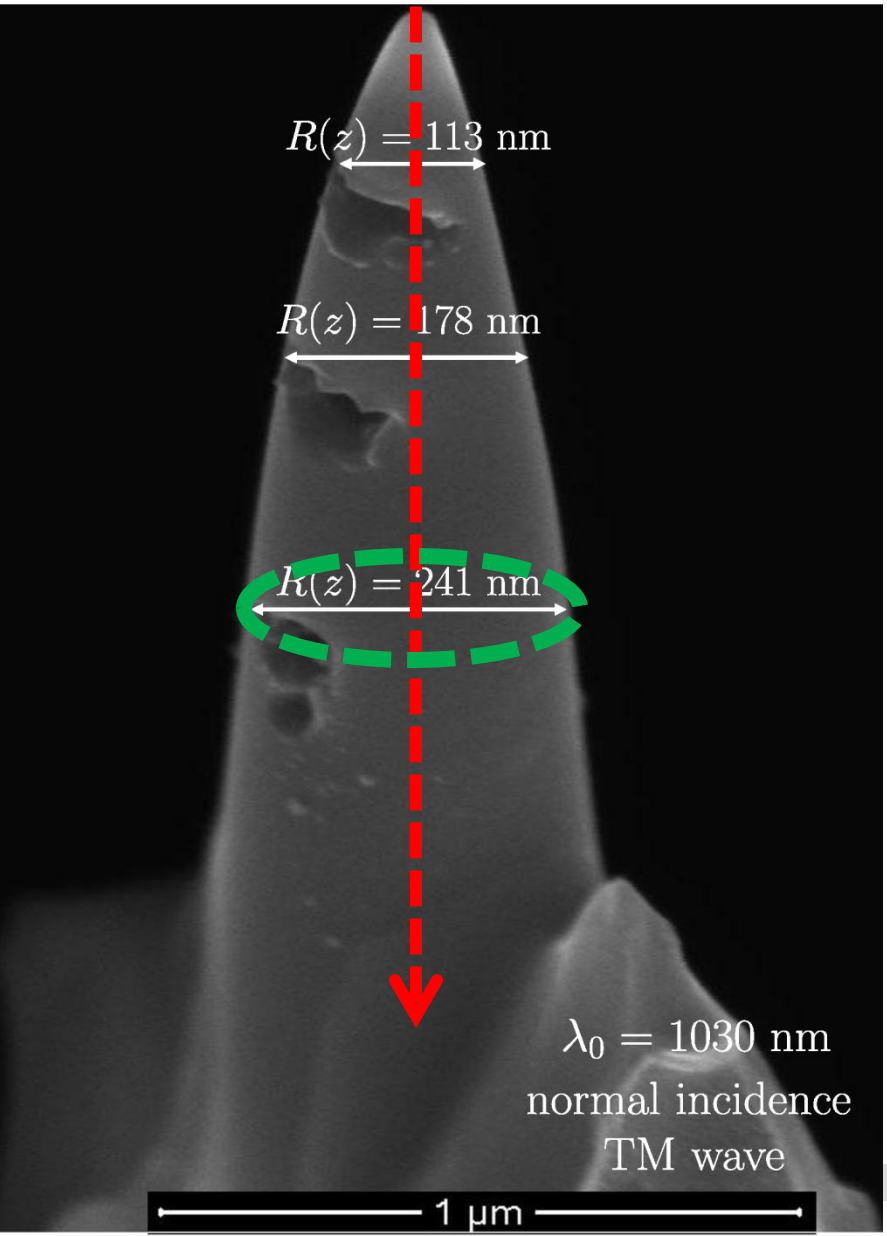
OUTLINE



- Localized absorption
along the tip axis

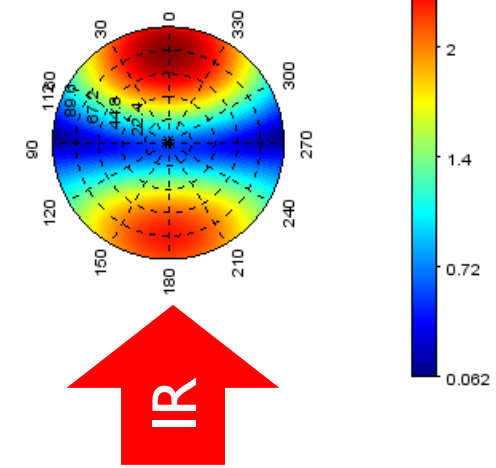
- **Localized absorption**
in cross-sections

- Localized heating

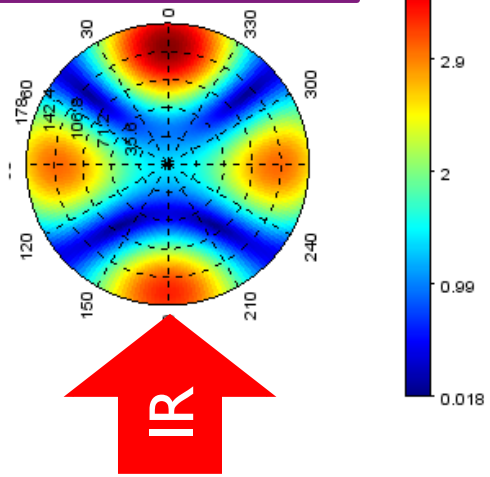
ANALYTICAL MIE-BASED THEORY

$|E_{internal}/E_{incident}|$ distributions in resonant cross-sections:

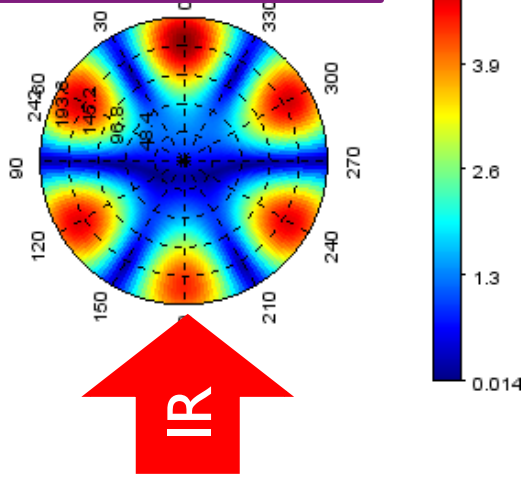
R=113 nm



R=178 nm

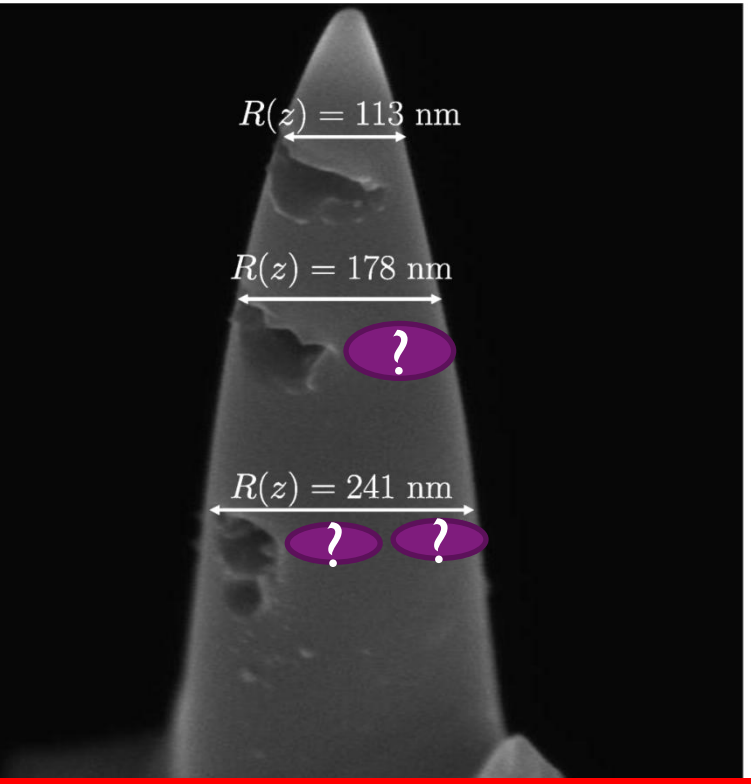


R=241 nm

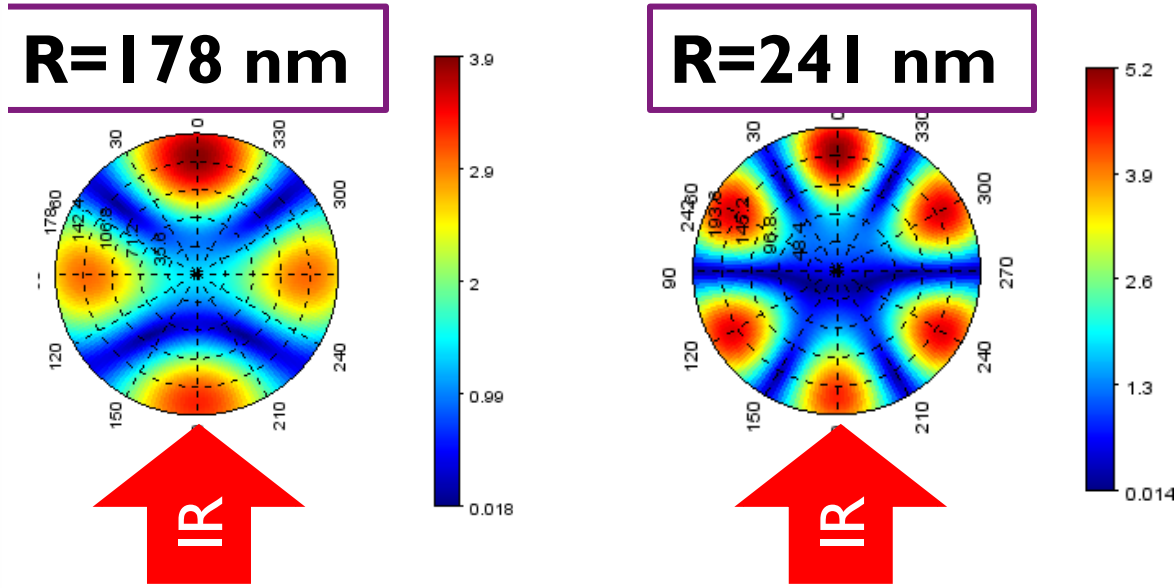


- Maximum electric field is always on the **shadow** side
- Other maxima are observed along the perimeter (whispering gallery modes)

ANALYTICAL MIE-BASED THEORY



…utions in resonant cross-sections:

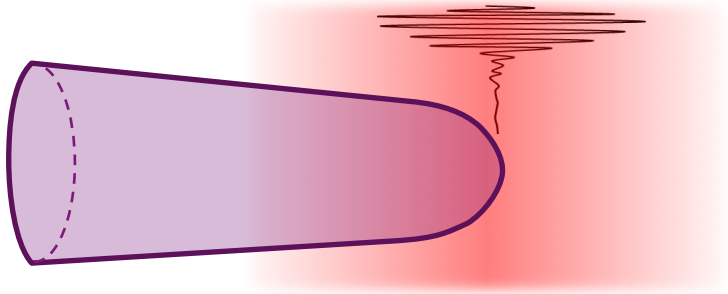


…is always on the **shadow** side

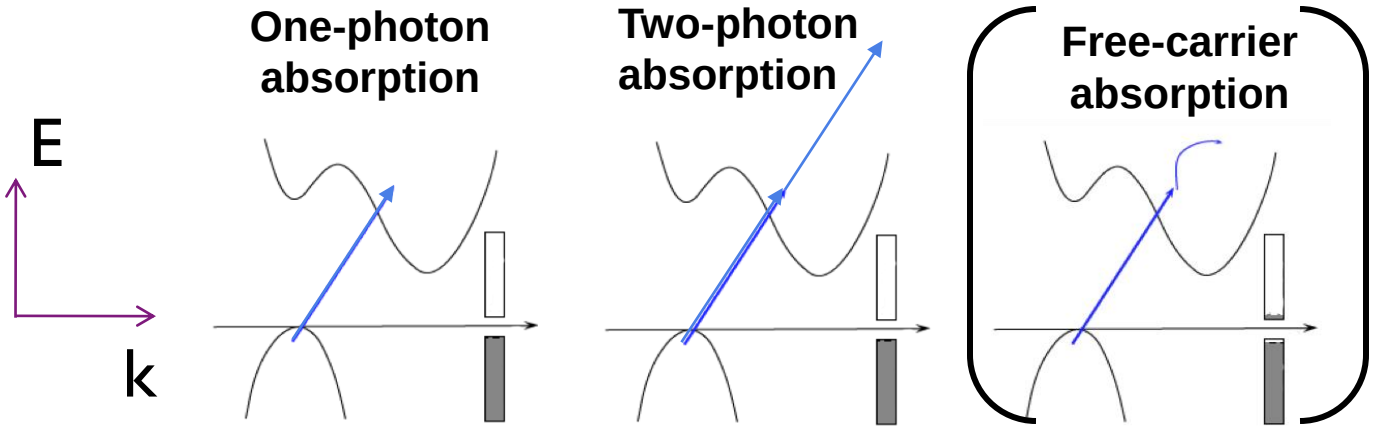
- **Non uniform (localized)** absorption in resonant cross sections
- Mie-based theory cannot account for **one-sided** holes

LASER INTERACTION WITH A SEMICONDUCTING TIP

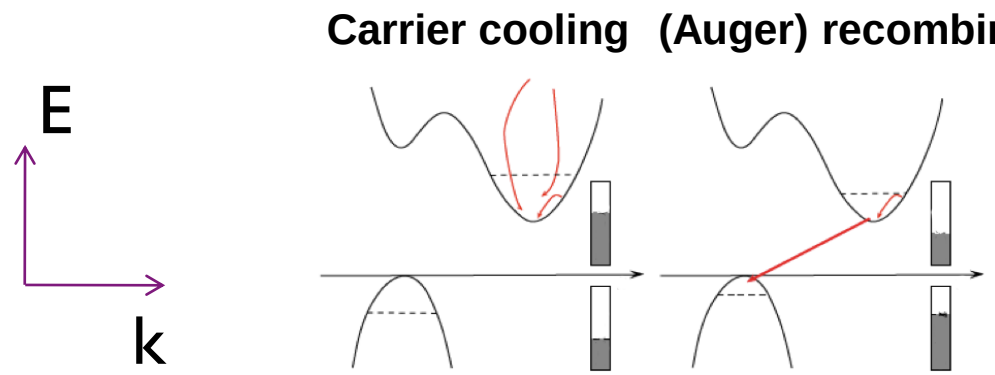
Electric field (rectification)



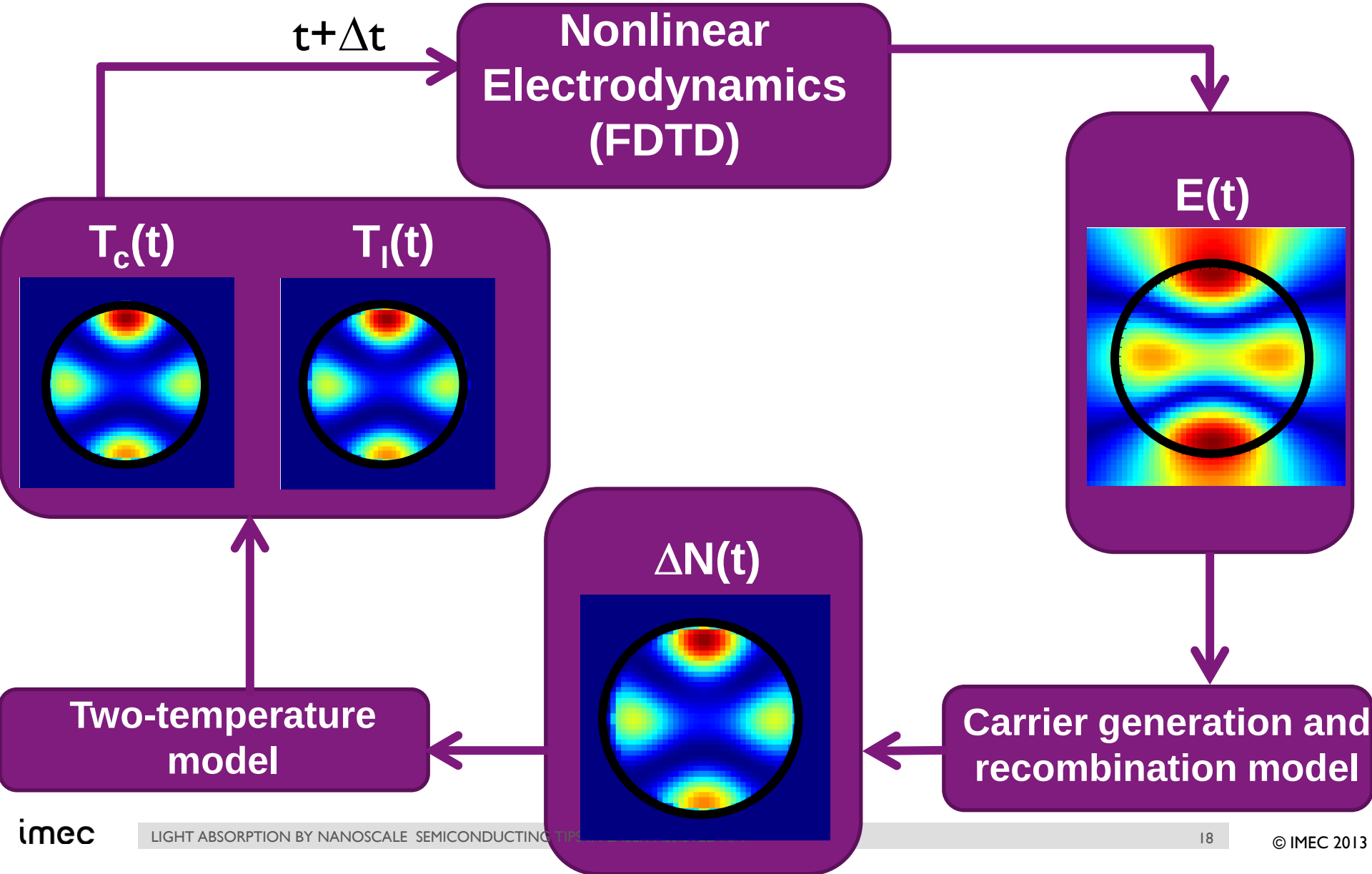
Free carriers



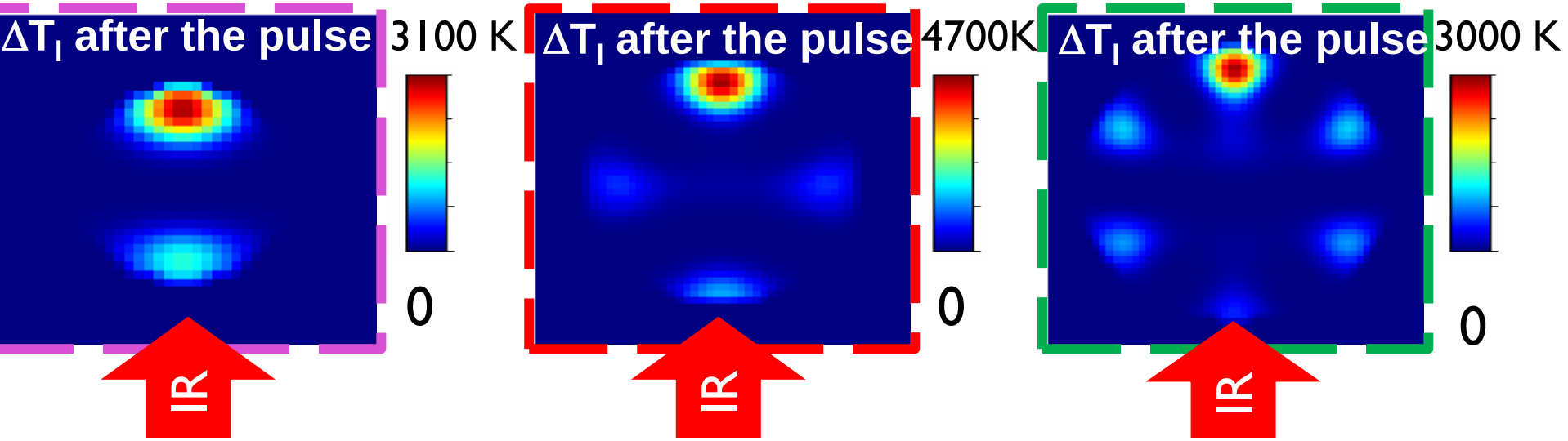
HEATING

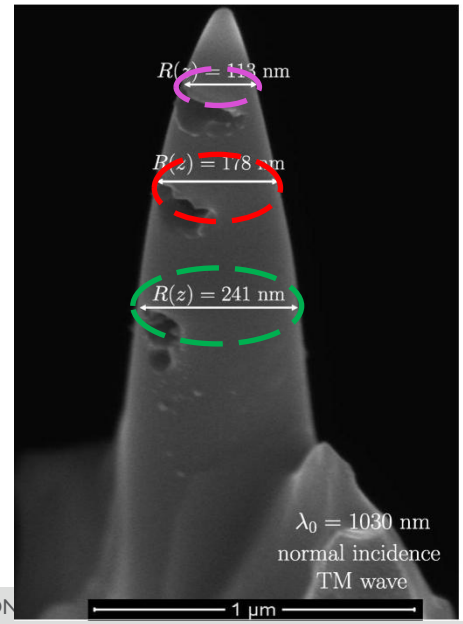


NONLINEAR 2D MULTIPHYSICS SIMULATIONS



HIGH-FLUENCE INFRARED IRRADIATION WITH NONLINEAR ABSORPTION





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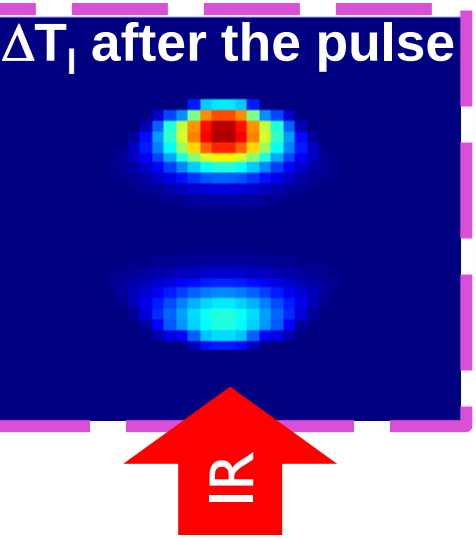
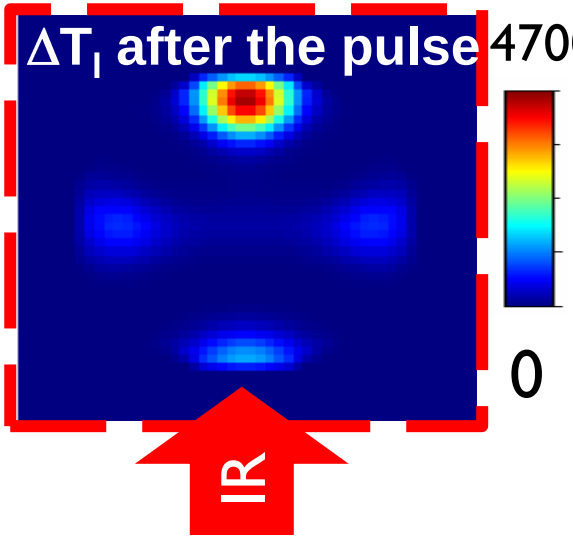
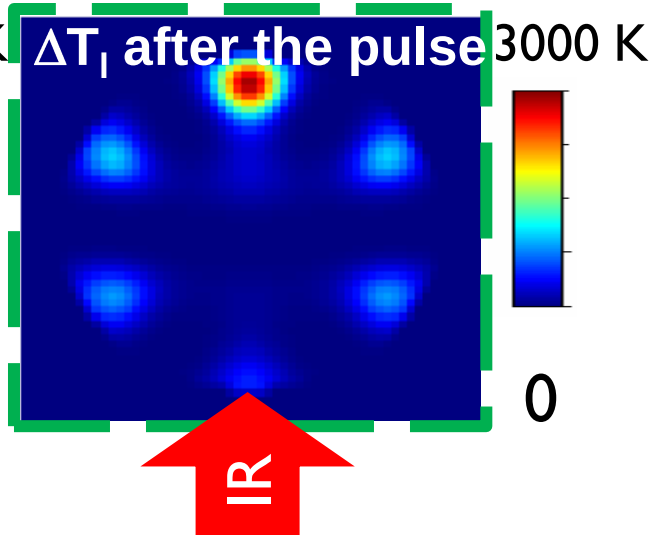
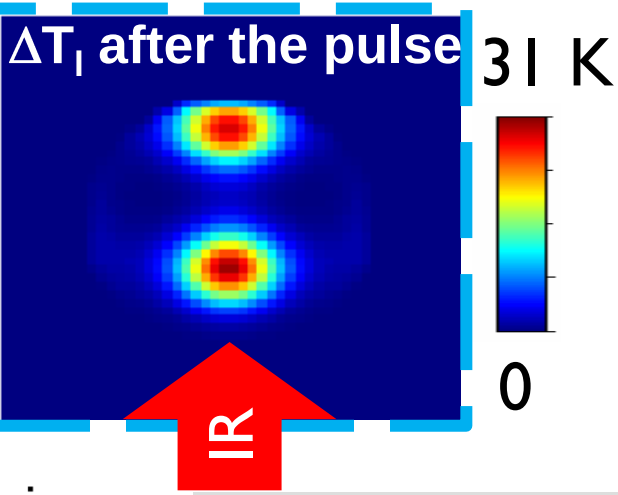
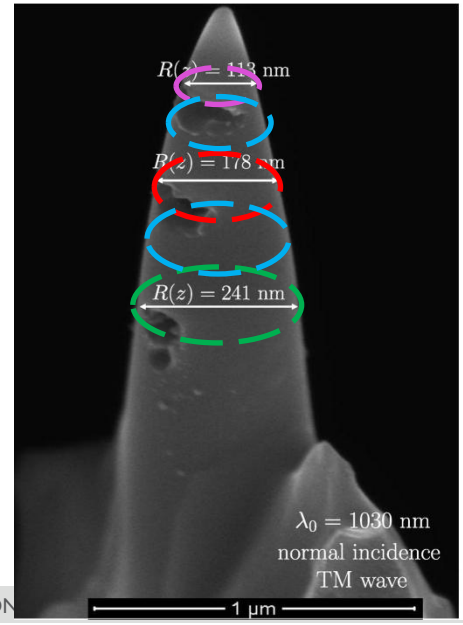
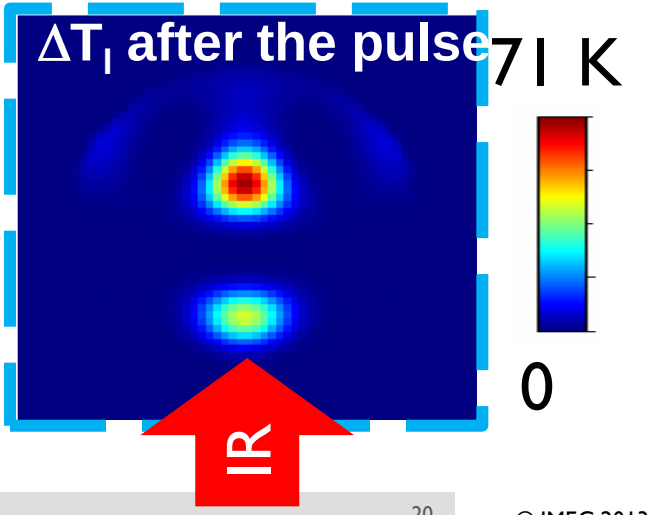




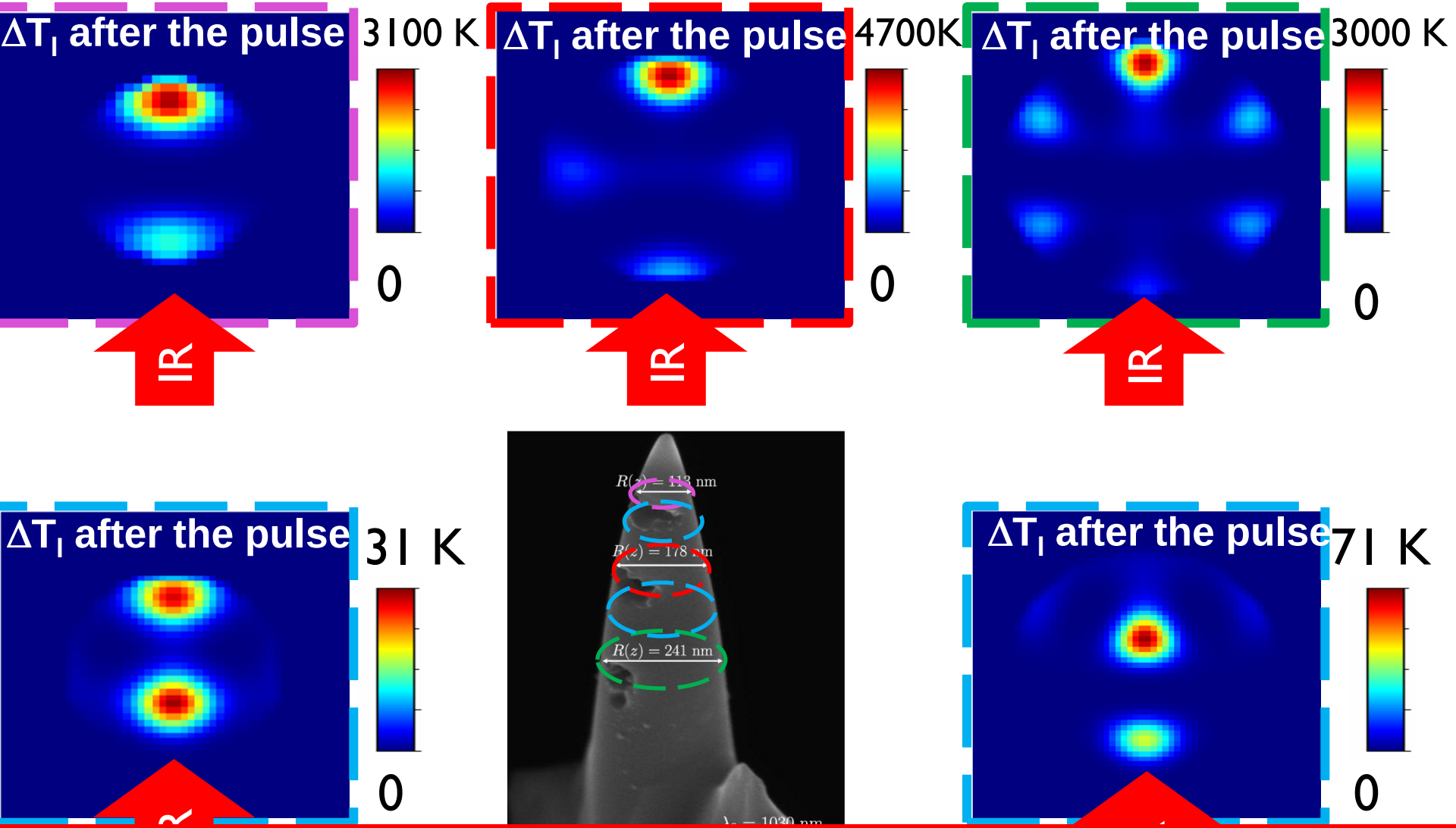








HIGH-FLUENCE INFRARED IRRADIATION WITH NONLINEAR ABSORPTION

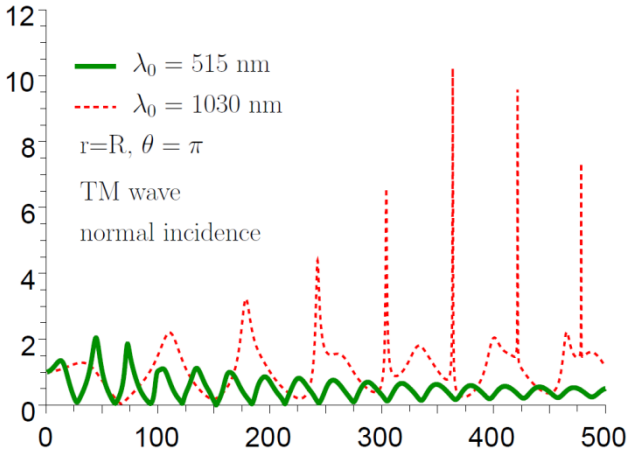


one-sided holes due to nonlinear absorption

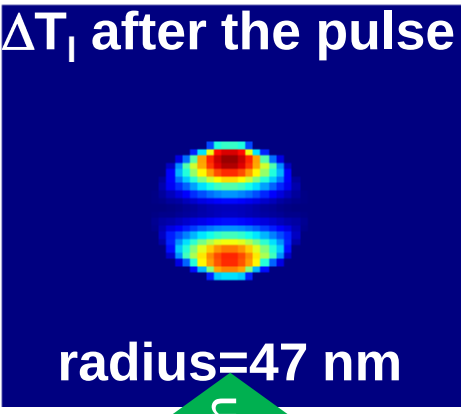
SIMULATION OF A GREEN PULSE (515 nm, 2 mW, 500 fs)

Mie :

$|E_{internal}/E_{incident}|$



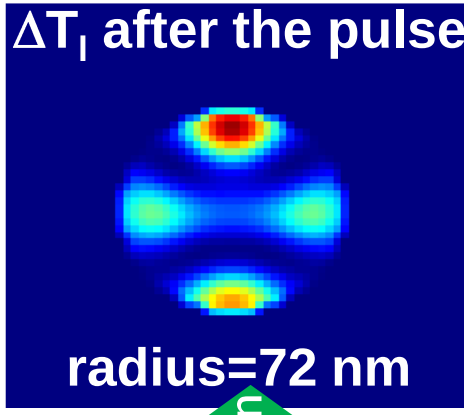
SIMULATION OF A GREEN PULSE (515 nm, 2 mW, 500 fs)



600 K

0

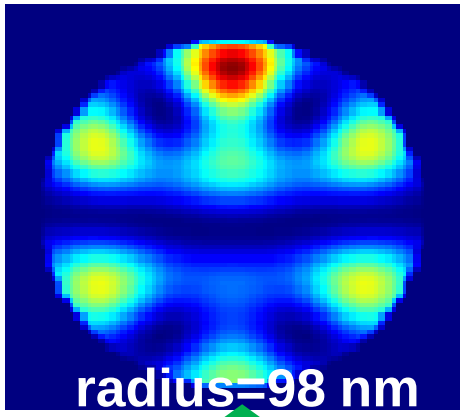
green



960 K

0

green



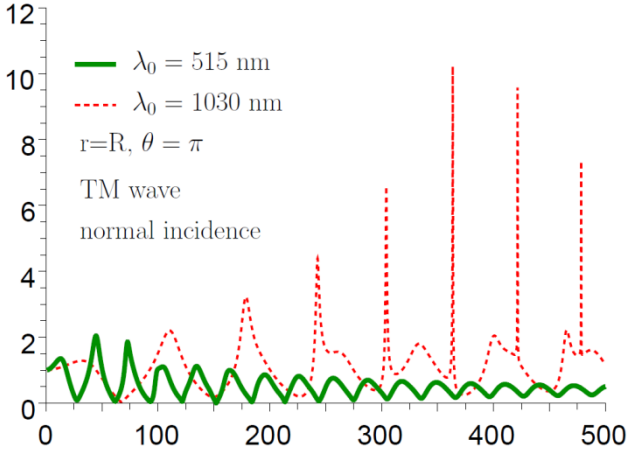
490 K

0

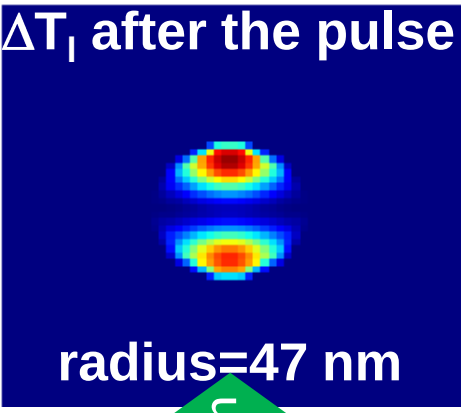
green

Mie :

$|E_{internal}/E_{incident}|$



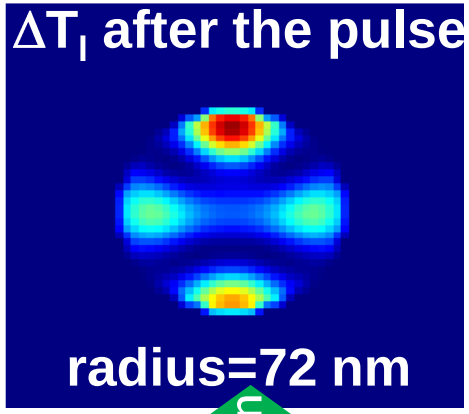
SIMULATION OF A GREEN PULSE (515 nm, 2 mW, 500 fs)



600 K

0

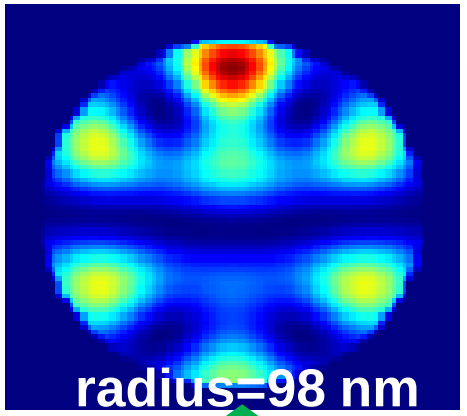
green



960 K

0

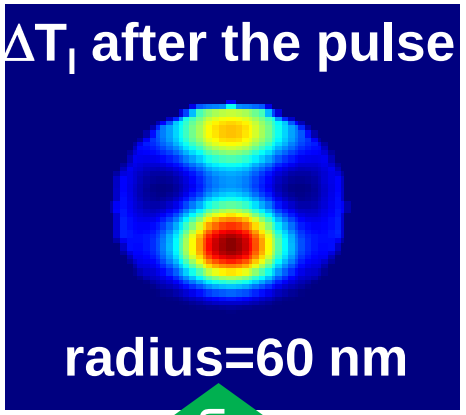
green



490 K

0

green



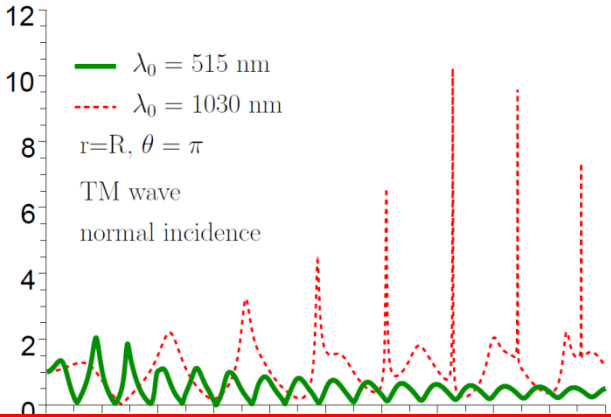
100 K

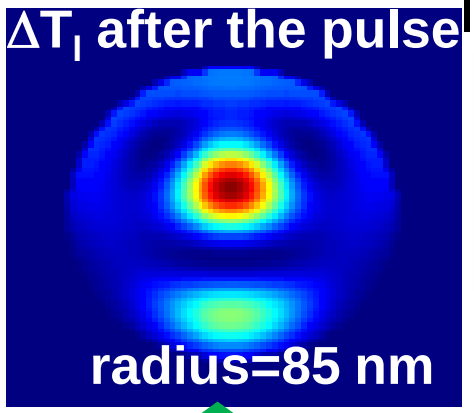
0

green

Mie :

$|E_{internal}/E_{incident}|$





170 K

0

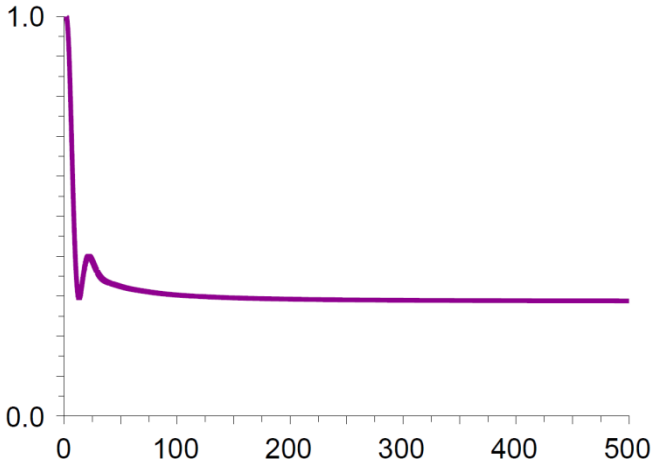
green

More uniform absorption in all directions

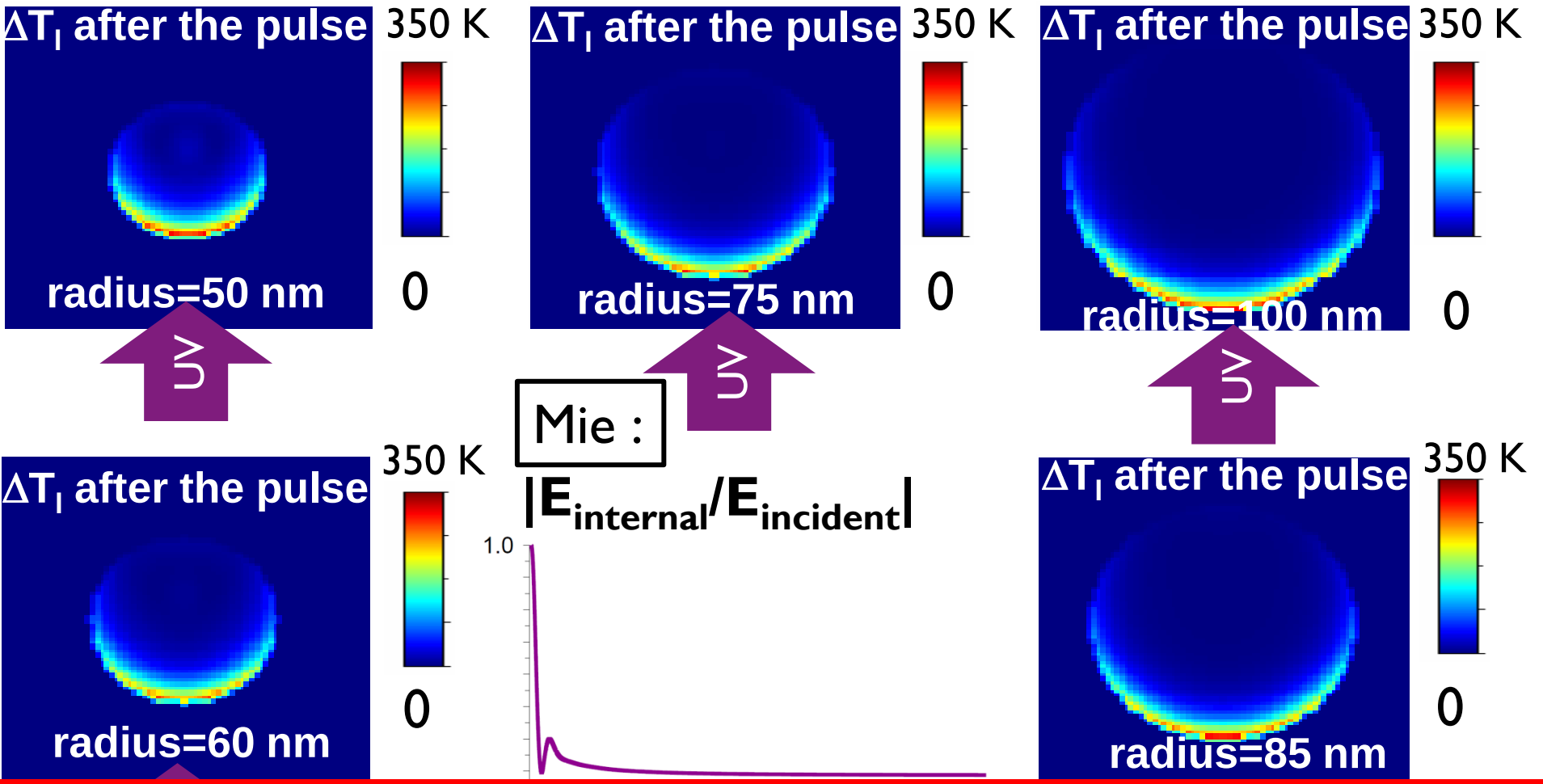
SIMULATION OF AN ULTRAVIOLET PULSE (343 nm, 0.5 mW, 500 fs)

Mie :

$|E_{internal}/E_{incident}|$

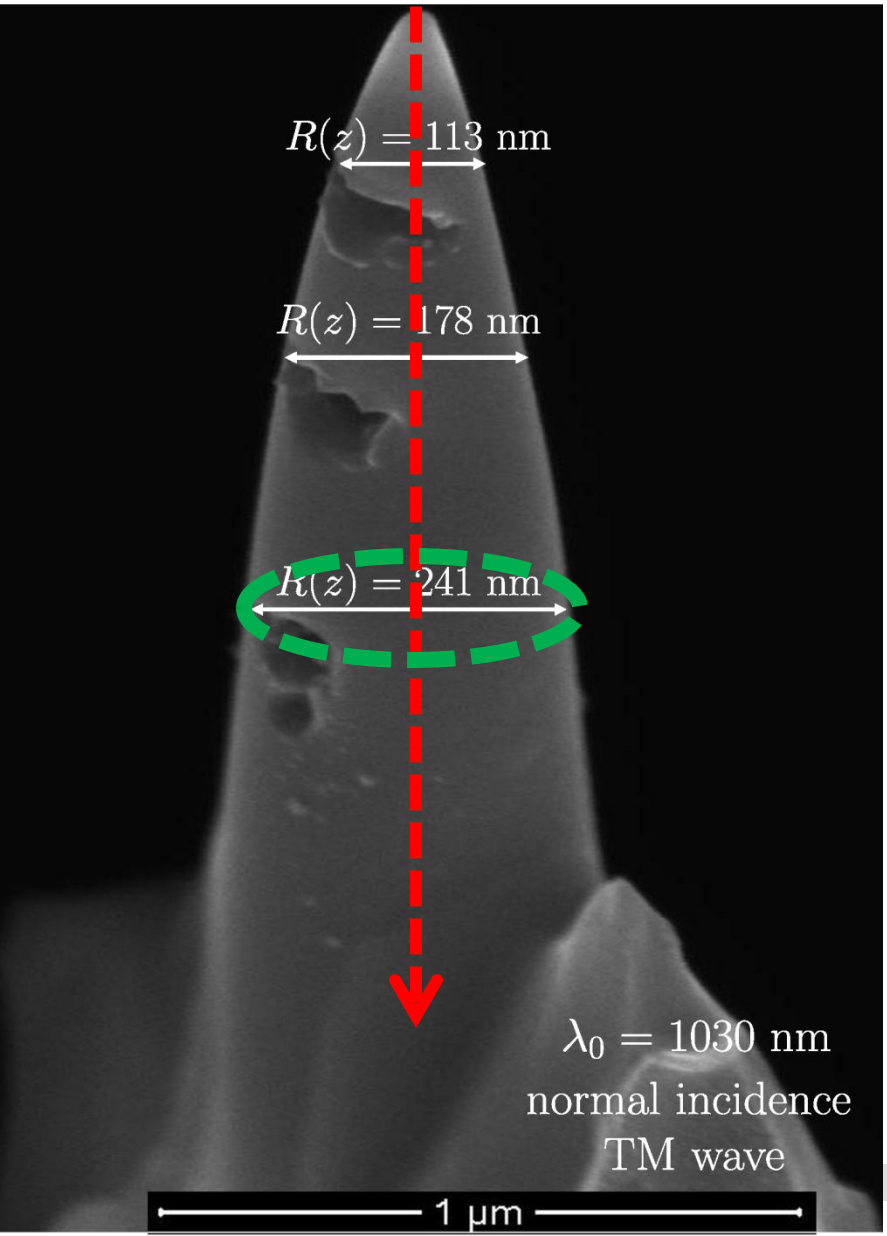


SIMULATION OF AN ULTRAVIOLET PULSE (343 nm, 0.5 mW, 500 fs)



- Excellent uniformity along the axis
- Strong localization in the cross section

OUTLINE

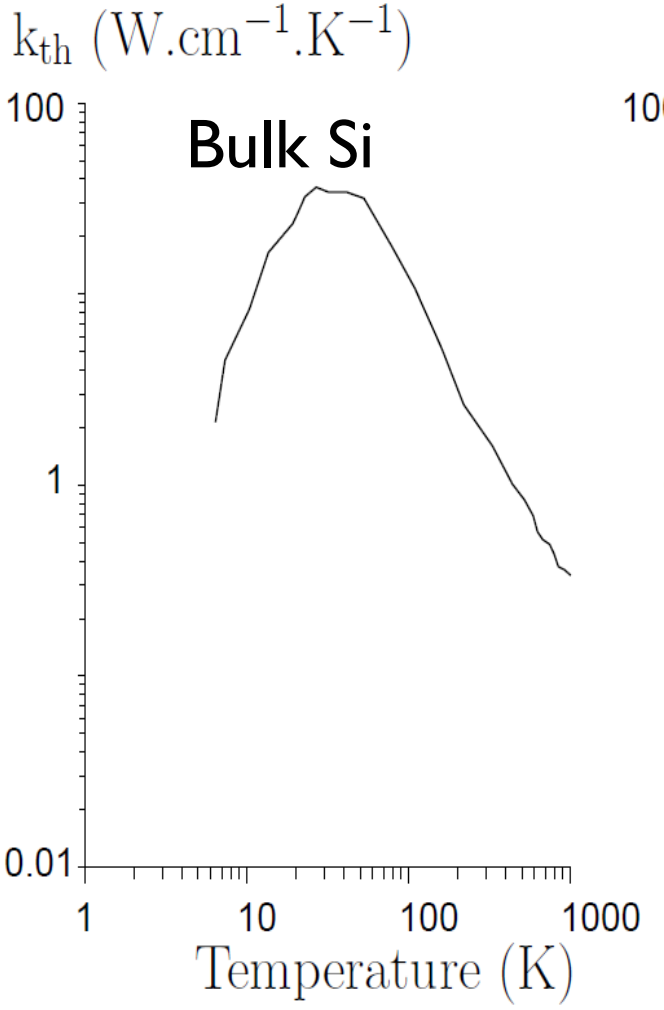


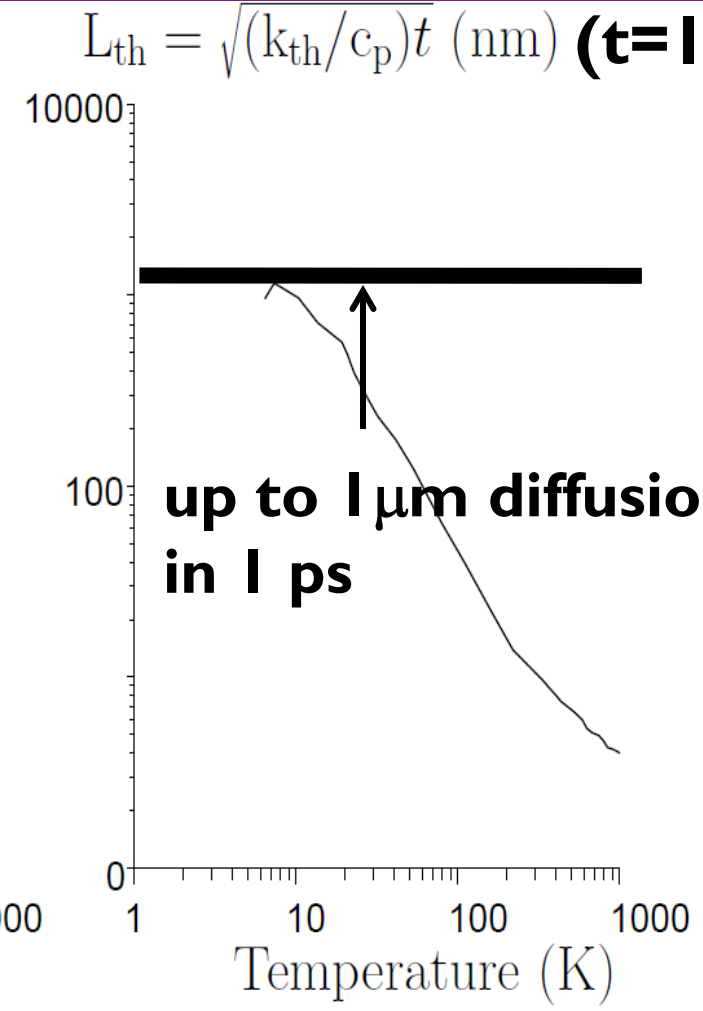
- Localized absorption
along the tip axis

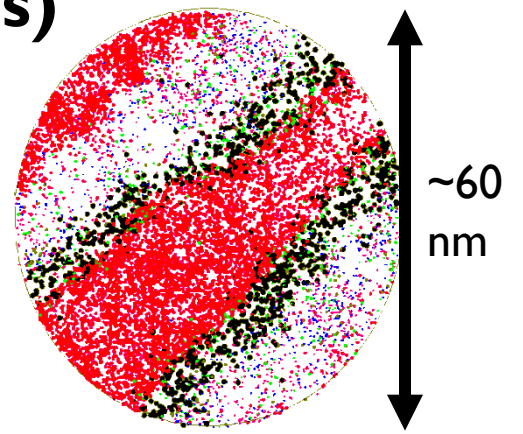
- Localized absorption
in cross-sections

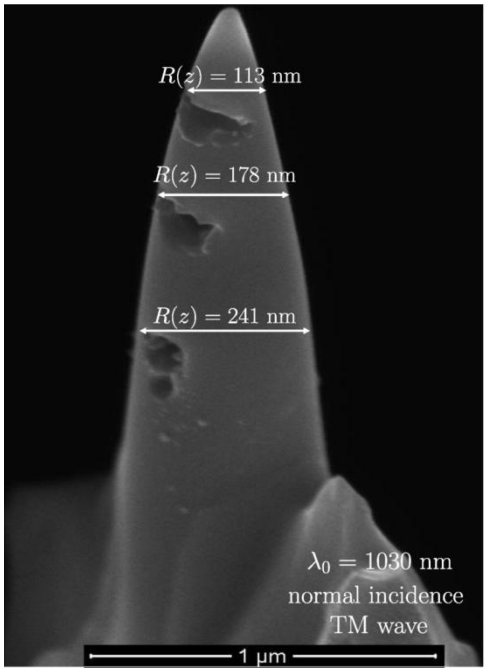
- **Localized heating**

DEGRADED HEAT DIFFUSIVITY IN Si NANOWIRES

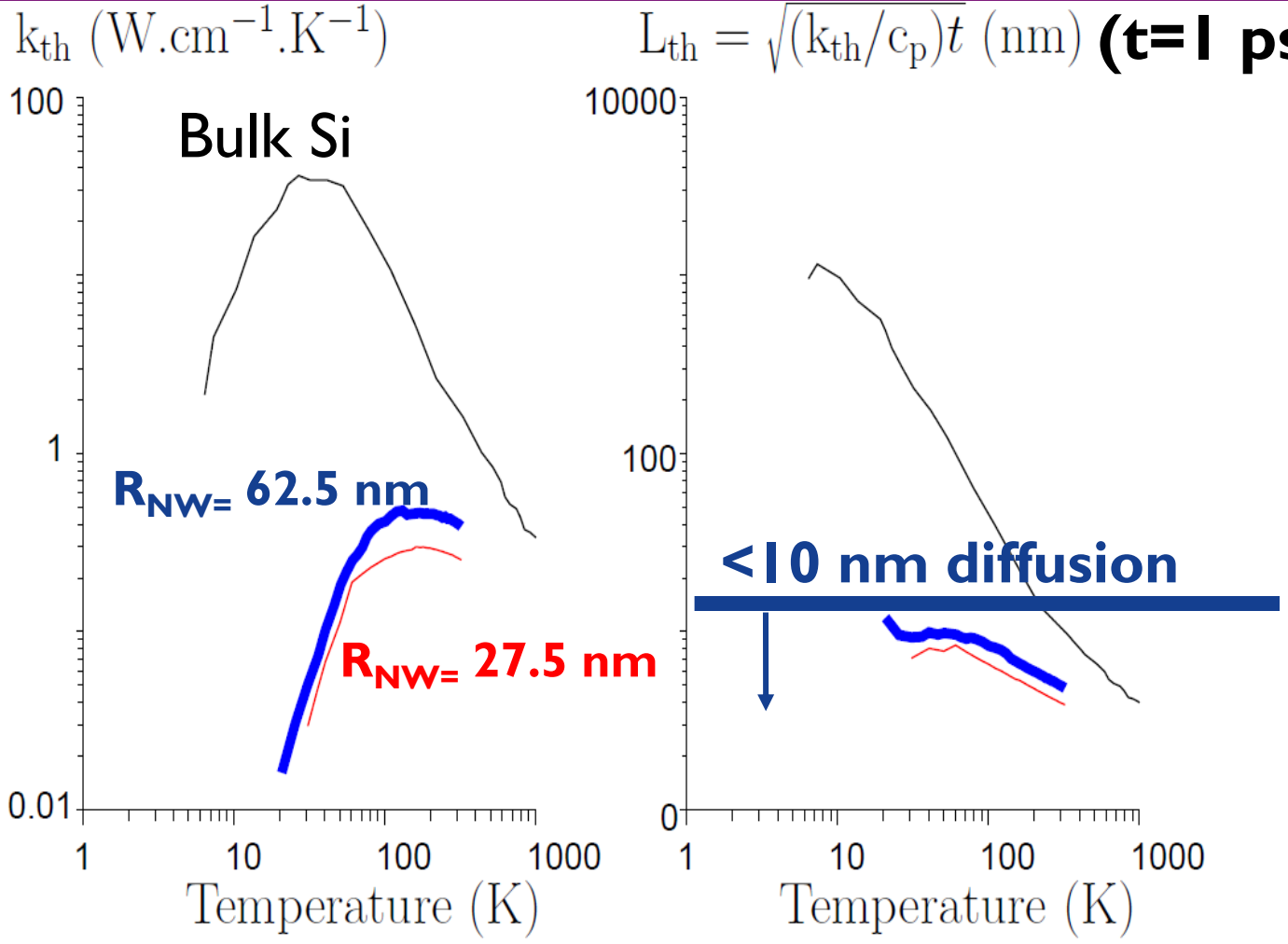


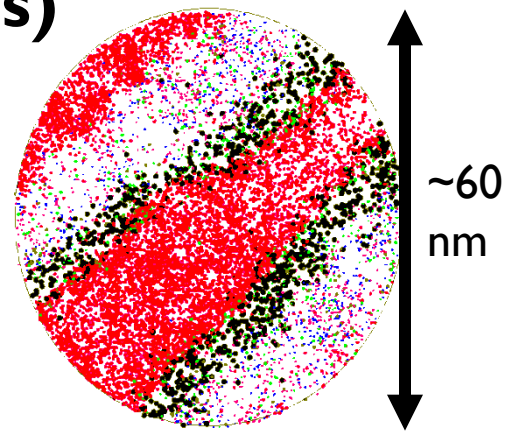


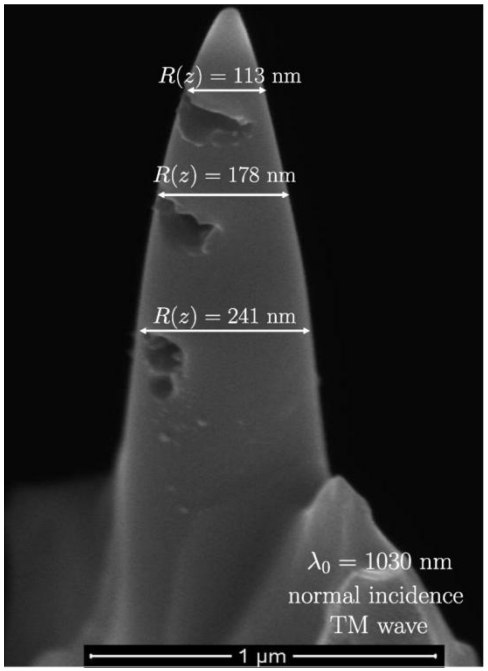




DEGRADED HEAT DIFFUSIVITY IN Si NANOWIRES







CONCLUSION

Nanoscale dimensions of AP tip induce:

- **Localized** light **absorption**:
  - **in resonant** cross sections along the tip axis
  - **along the perimeter** inside each resonant cross section
  - Contrast between absorbing and non-absorbing regions is enhanced by **nonlinear** free-carrier and two-photon absorption phenomena

- **Localized heating** due to:
  - localized absorption
  - **heat diffusivity degraded** by nanoscale dimension

ASPIRE
INVENT
ACHIEVE

imec