Plasmonics: An overview and some new trends

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nanophotonics.es

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Complex Photonics – International School of Physics “Enrico Fermi”
Varenna, July 13-18, 2015

Plasmonics:
An overview and some new trends

Introduction to plasmons

Graphene plasmons

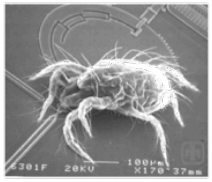
- **Quantum-mechanical description**
- **Classical description**
- **Complete optical absorption**
- **Quantum optics with graphene plasmons**
- **Sensing with graphene plasmons**

Plasmons in other atomically thin materials

The scales of light

nanophotonics.es

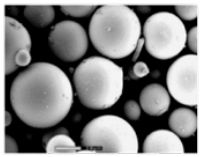
Things Natural



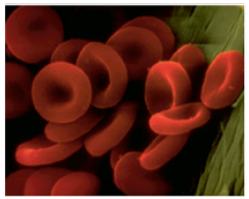
Dust mite
200 μm

Ant
~ 5 mm

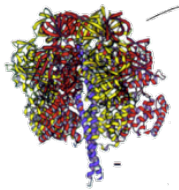
Human hair
~ 60-120 μm wide



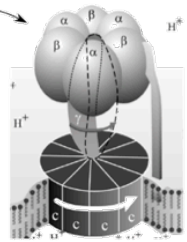
Fly ash
~ 10-20 μm



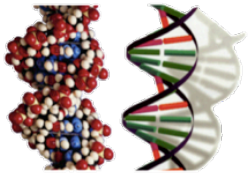
Red blood cells
(~7-8 μm)



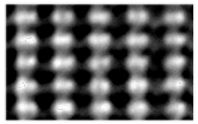
~10 nm diameter



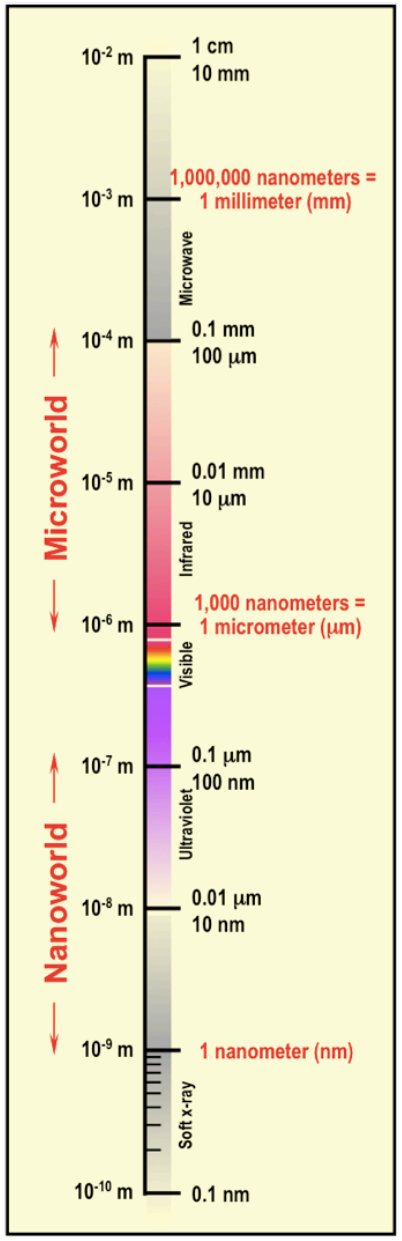
ATP synthase



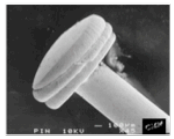
DNA
~2-1/2 nm diameter



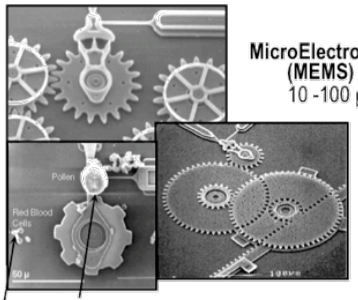
Atoms of silicon
spacing 0.078 nm



Things Manmade

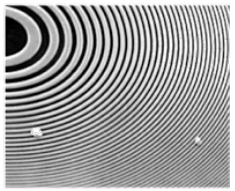


Head of a pin
1-2 mm

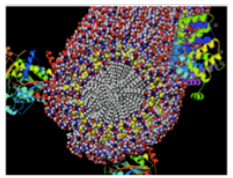


MicroElectroMechanical
(MEMS) devices
10 -100 μm wide

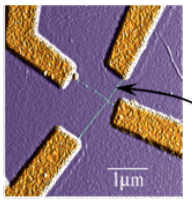
Pollen grain
Red blood cells



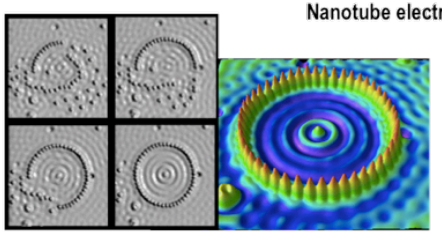
Zone plate x-ray "lens"
Outer ring spacing ~35 nm



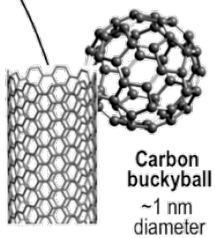
Self-assembled,
Nature-inspired structure
Many 10s of nm



Nanotube electrode



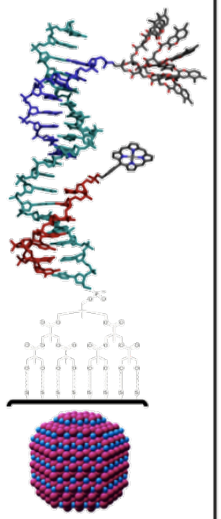
Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm



Carbon
buckyball
~1 nm
diameter

Carbon nanotube
~1.3 nm diameter

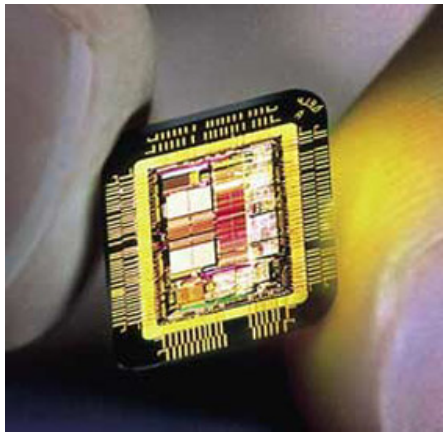
The Challenge



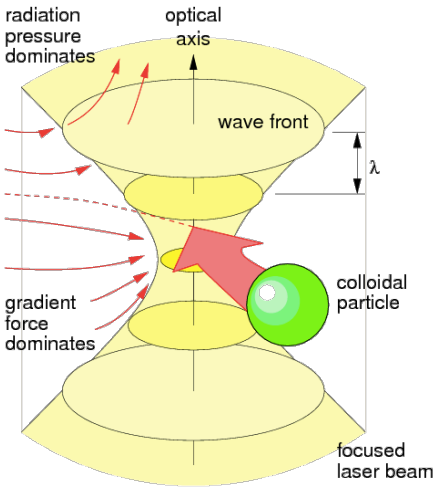
Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.

www.nasa.gov

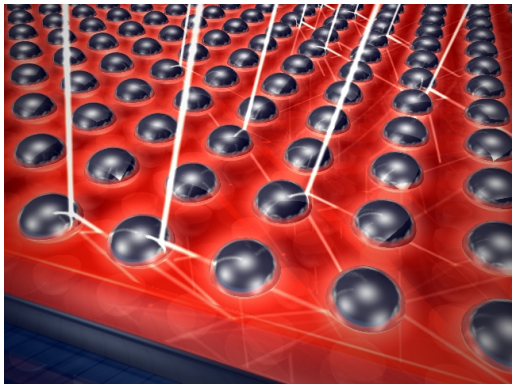
Light in technology



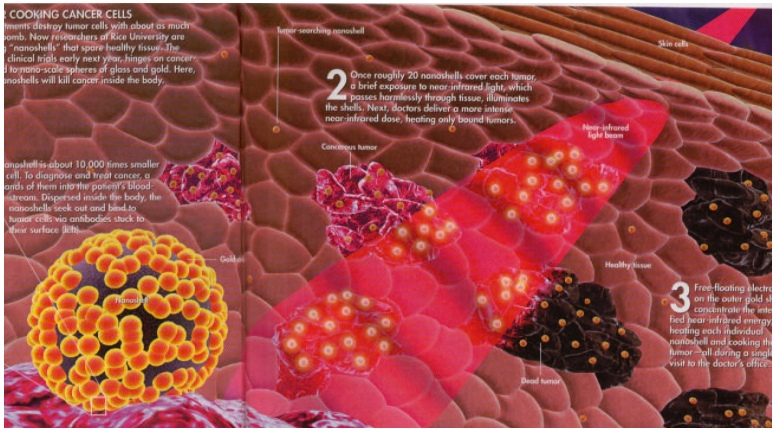
optical lithography



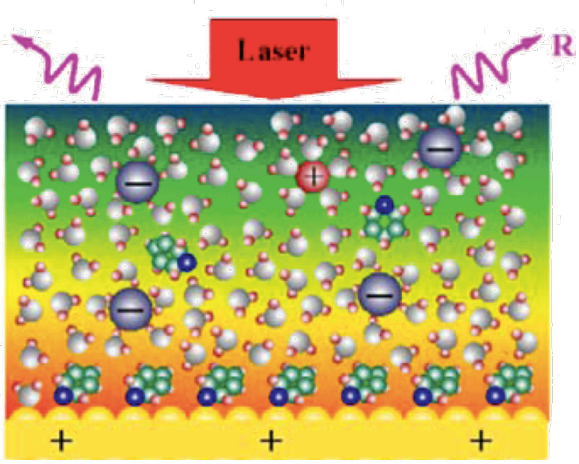
optical trapping



improved photovoltaics

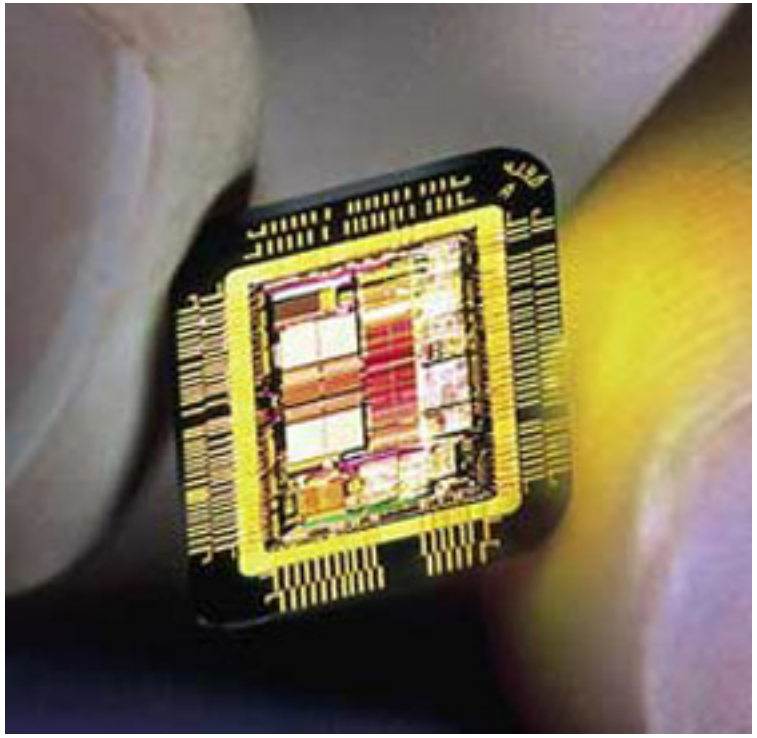


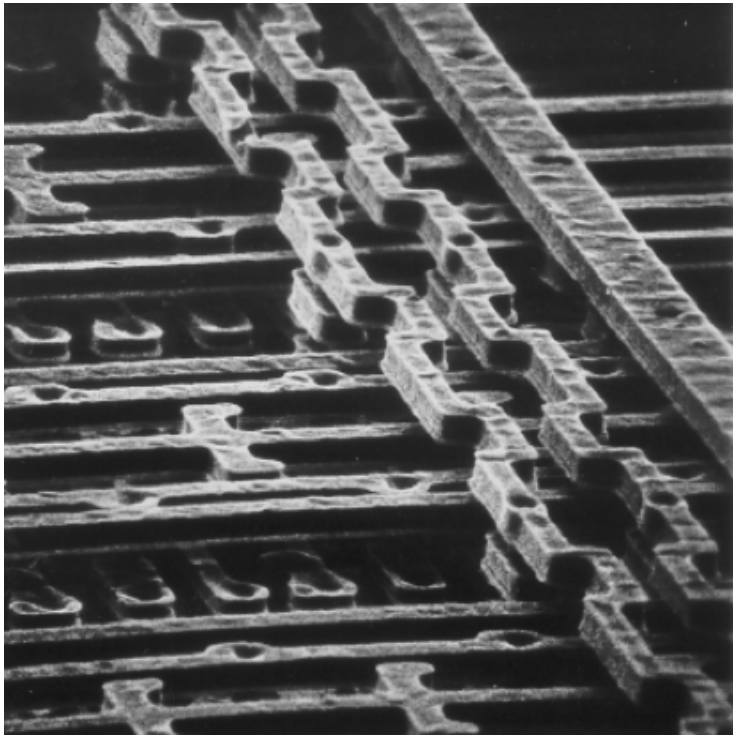
cancer therapy



single-molecule sensing
photocatalysis

Optical lithography limited by diffraction

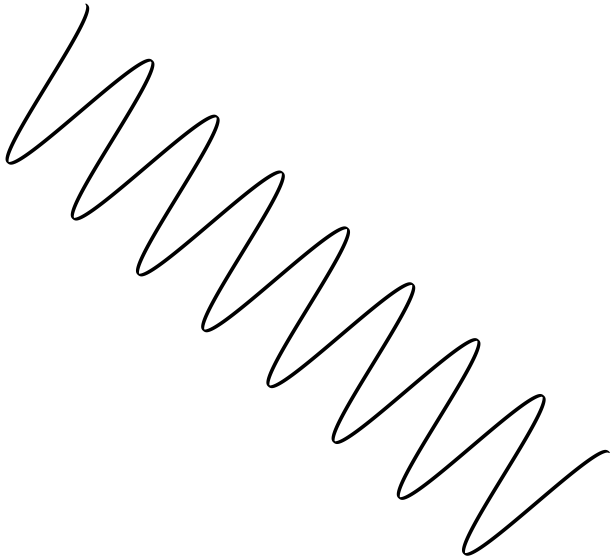




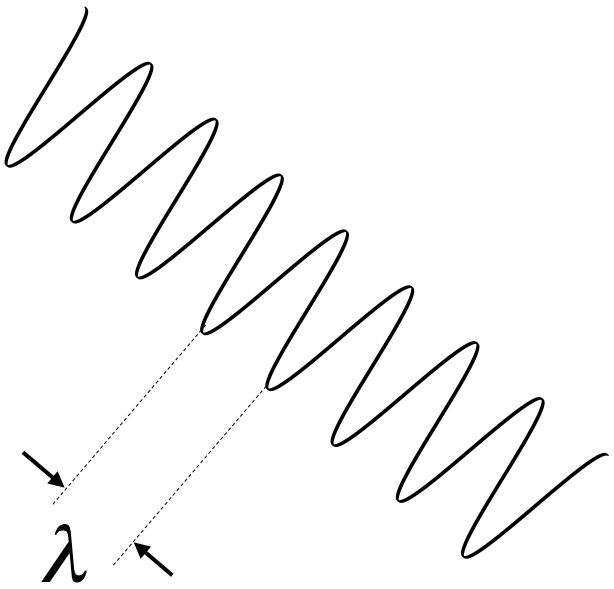
32 nm lines

193 nm ArF excimer laser in water (refractive index 1.44)

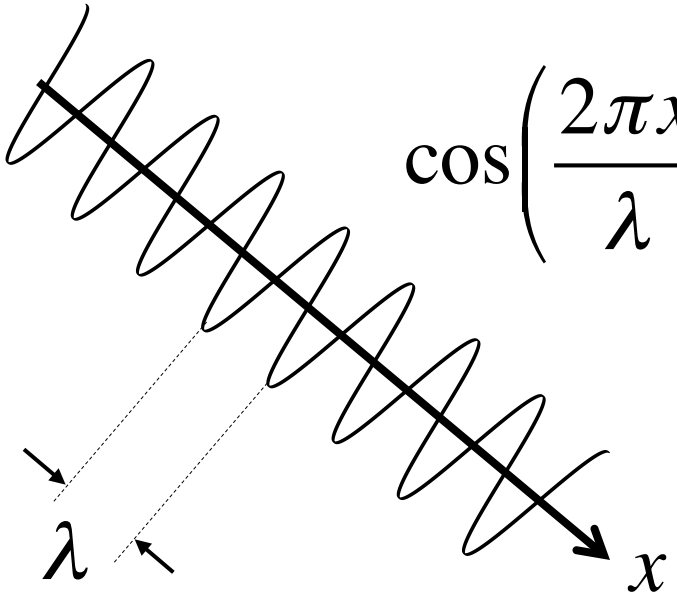
The diffraction limit



The diffraction limit



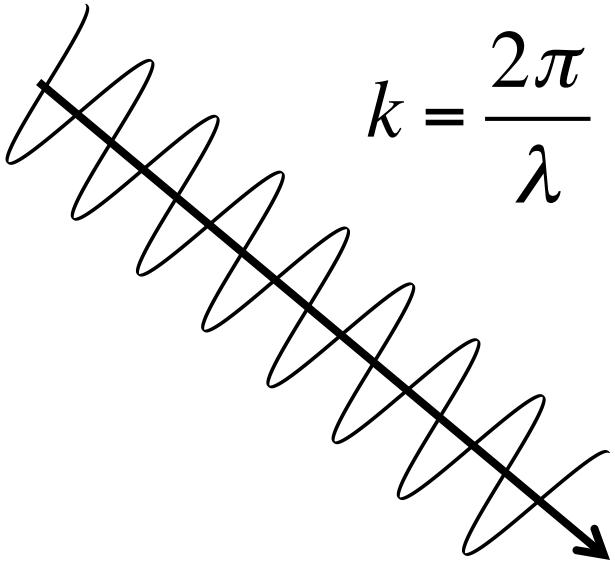
The diffraction limit



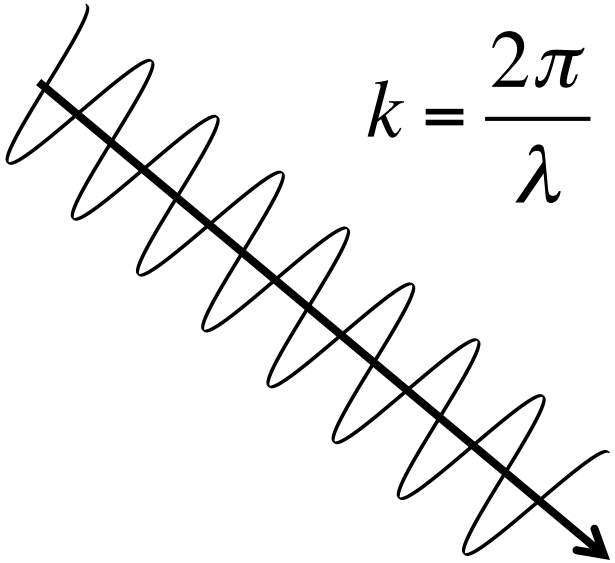
$$\cos\left(\frac{2\pi x}{\lambda}\right) = \cos(kx)$$

$$k = \frac{2\pi}{\lambda}$$

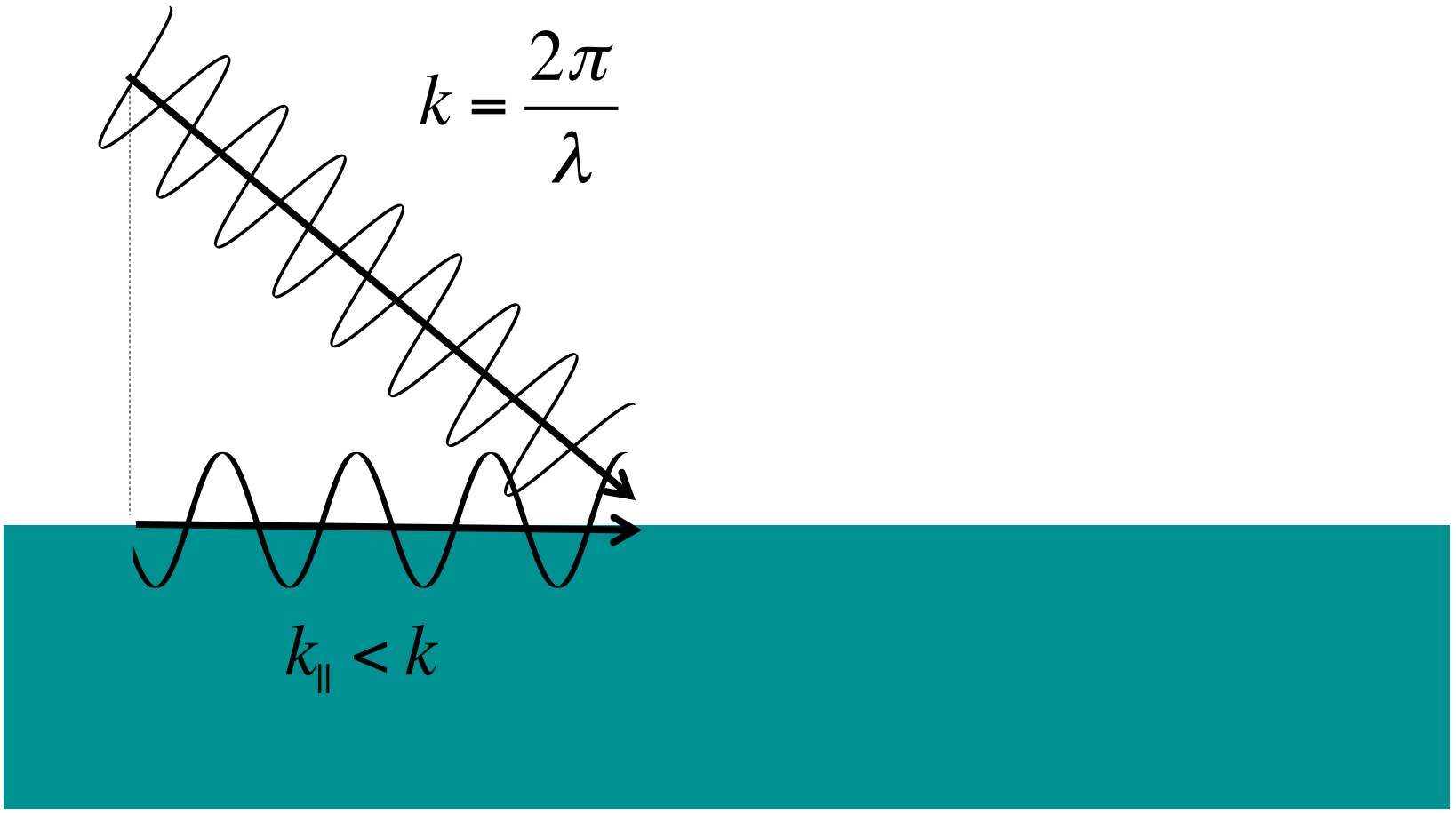
The diffraction limit



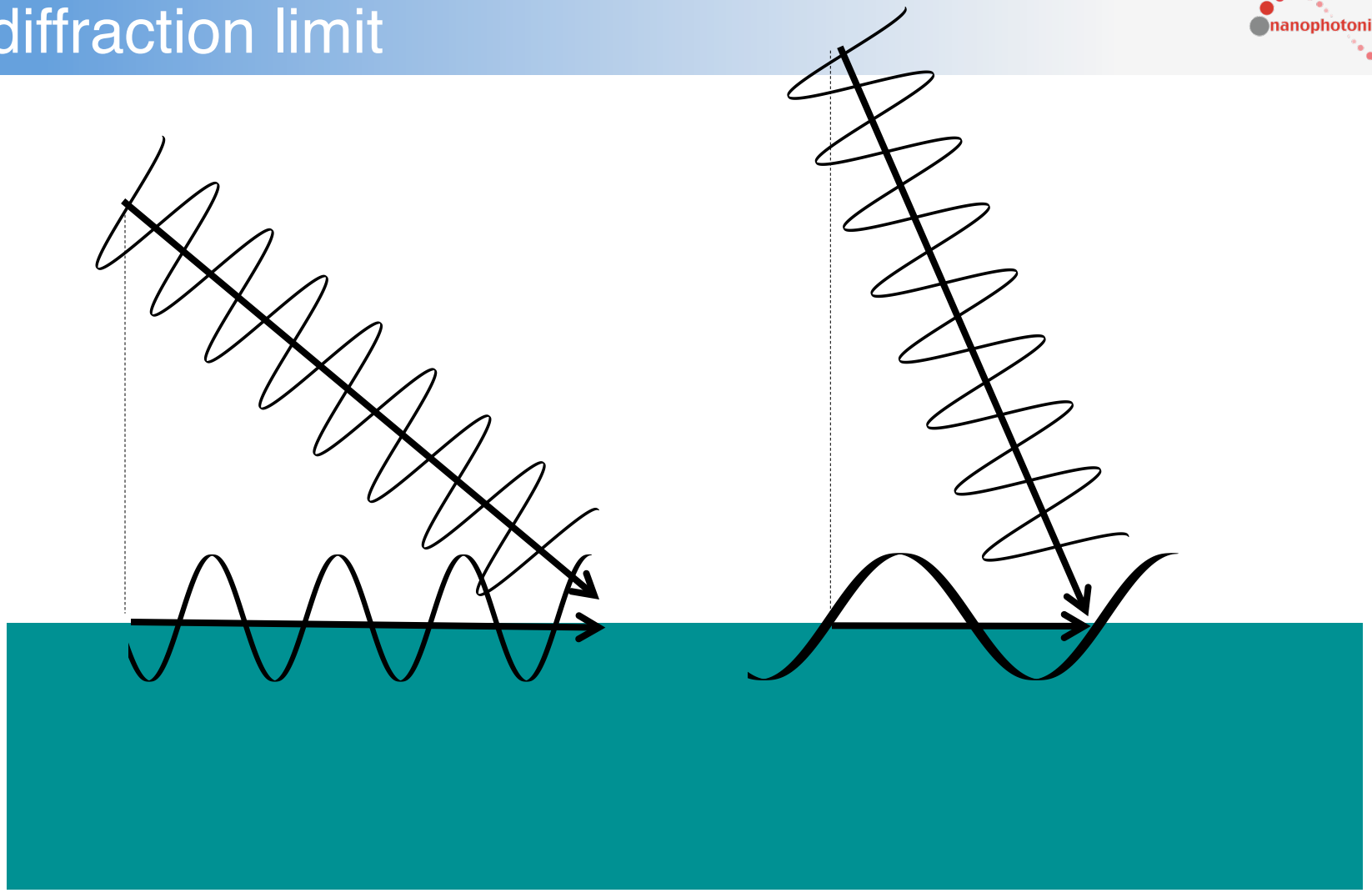
The diffraction limit



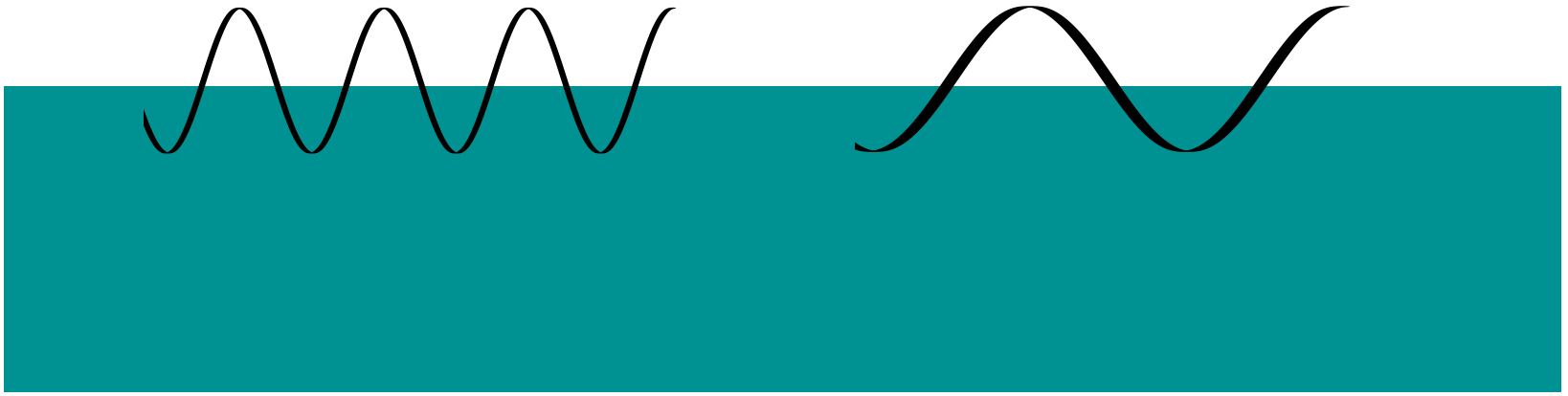
The diffraction limit



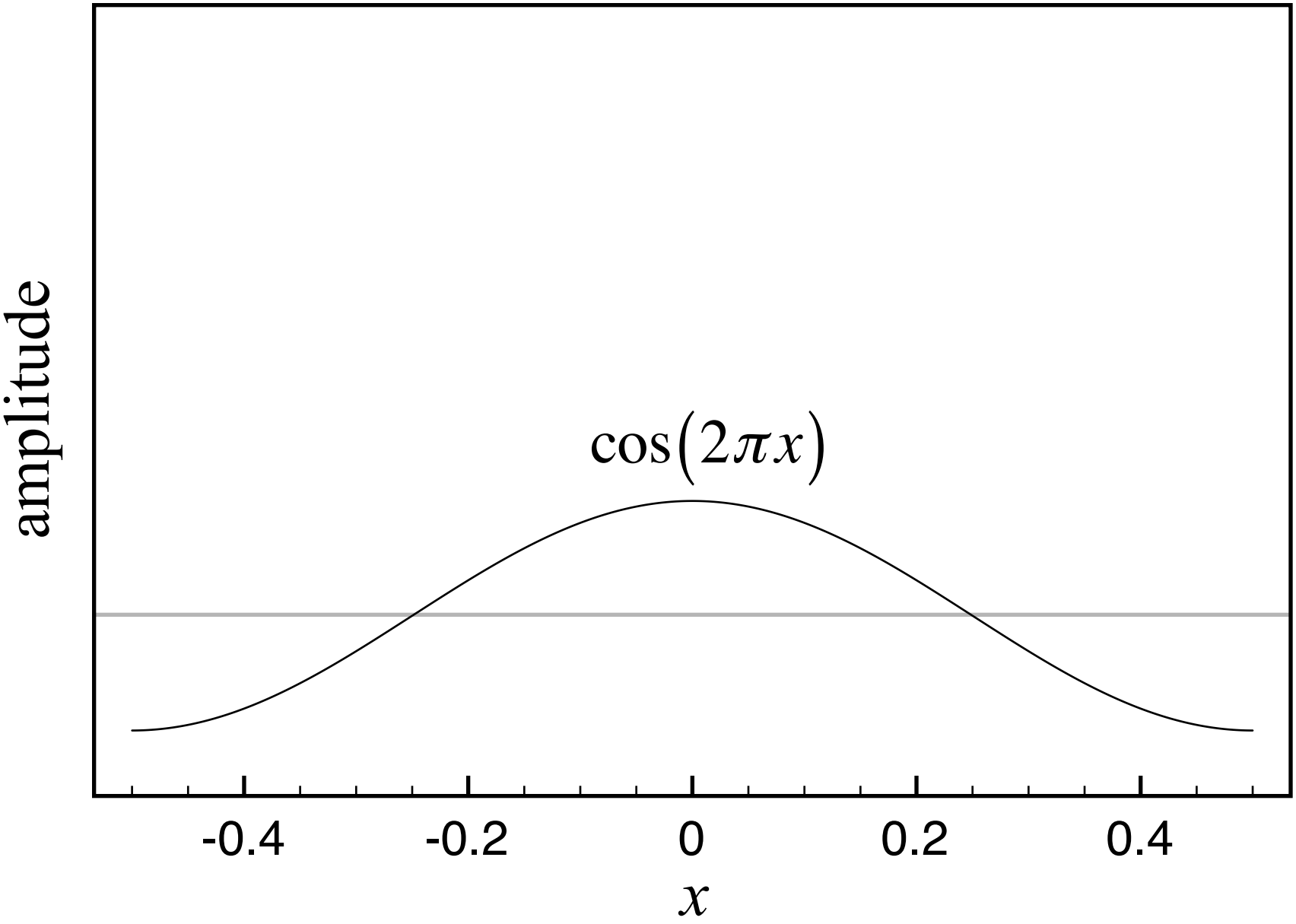
The diffraction limit



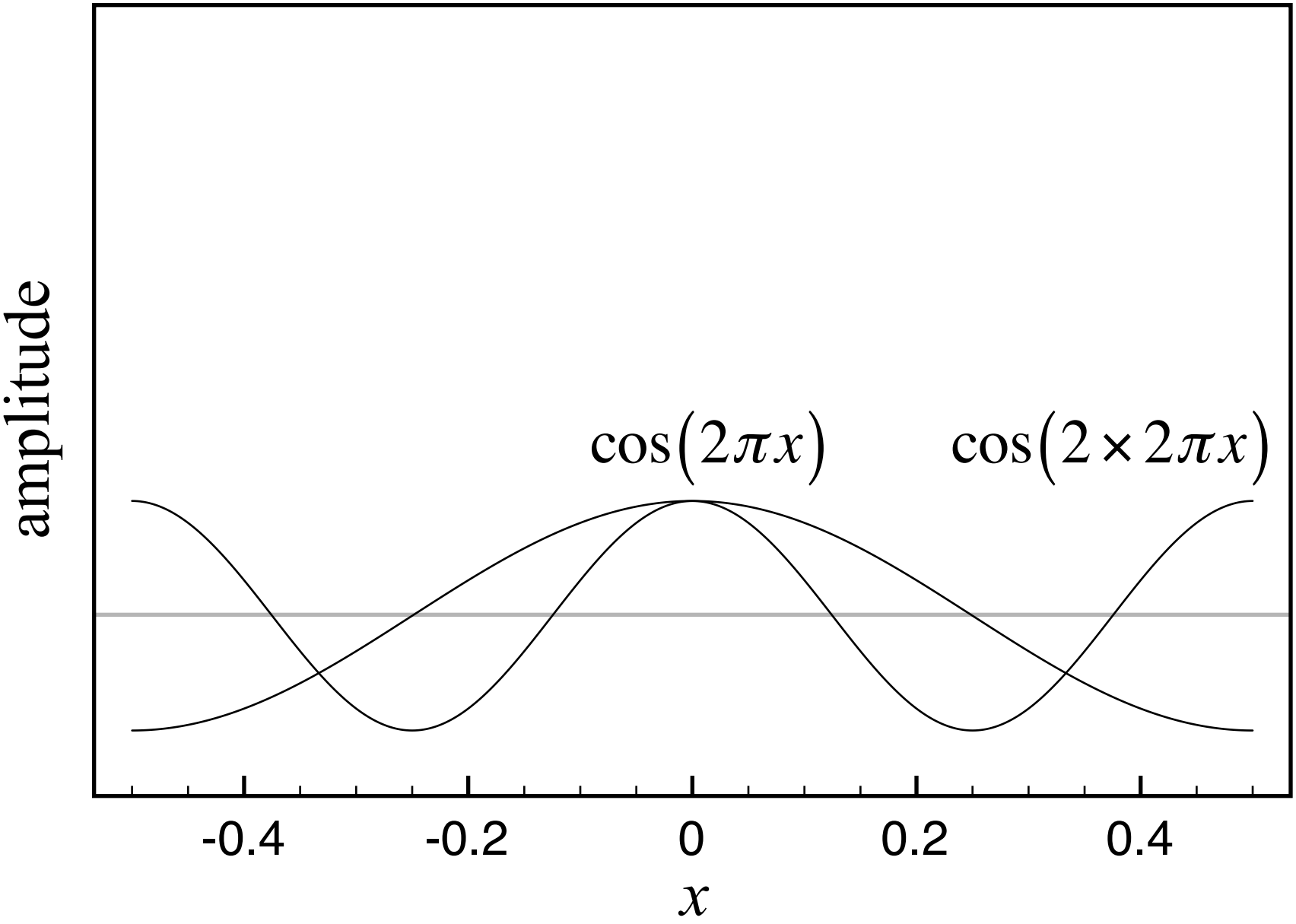
The diffraction limit



The diffraction limit



The diffraction limit



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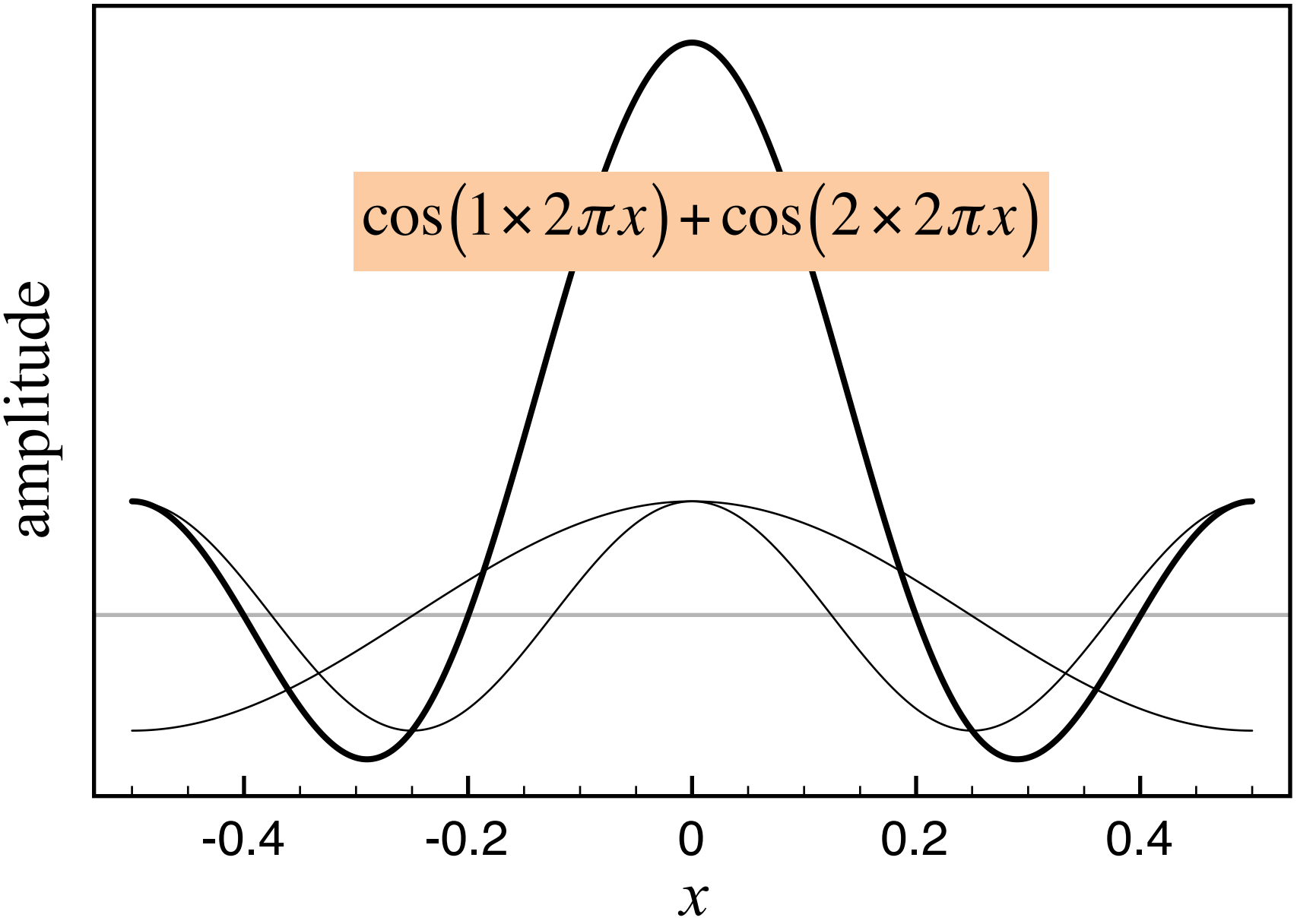
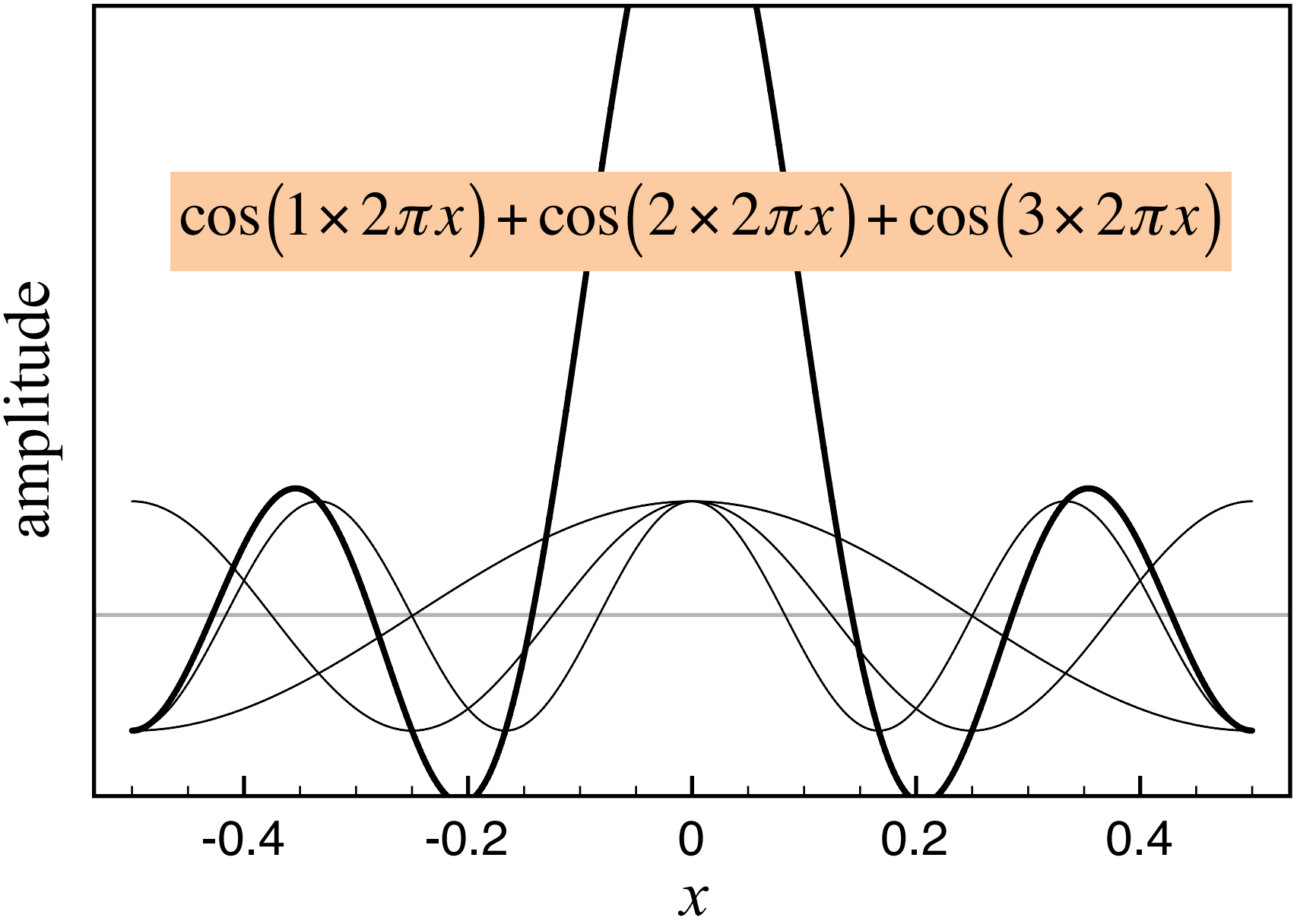
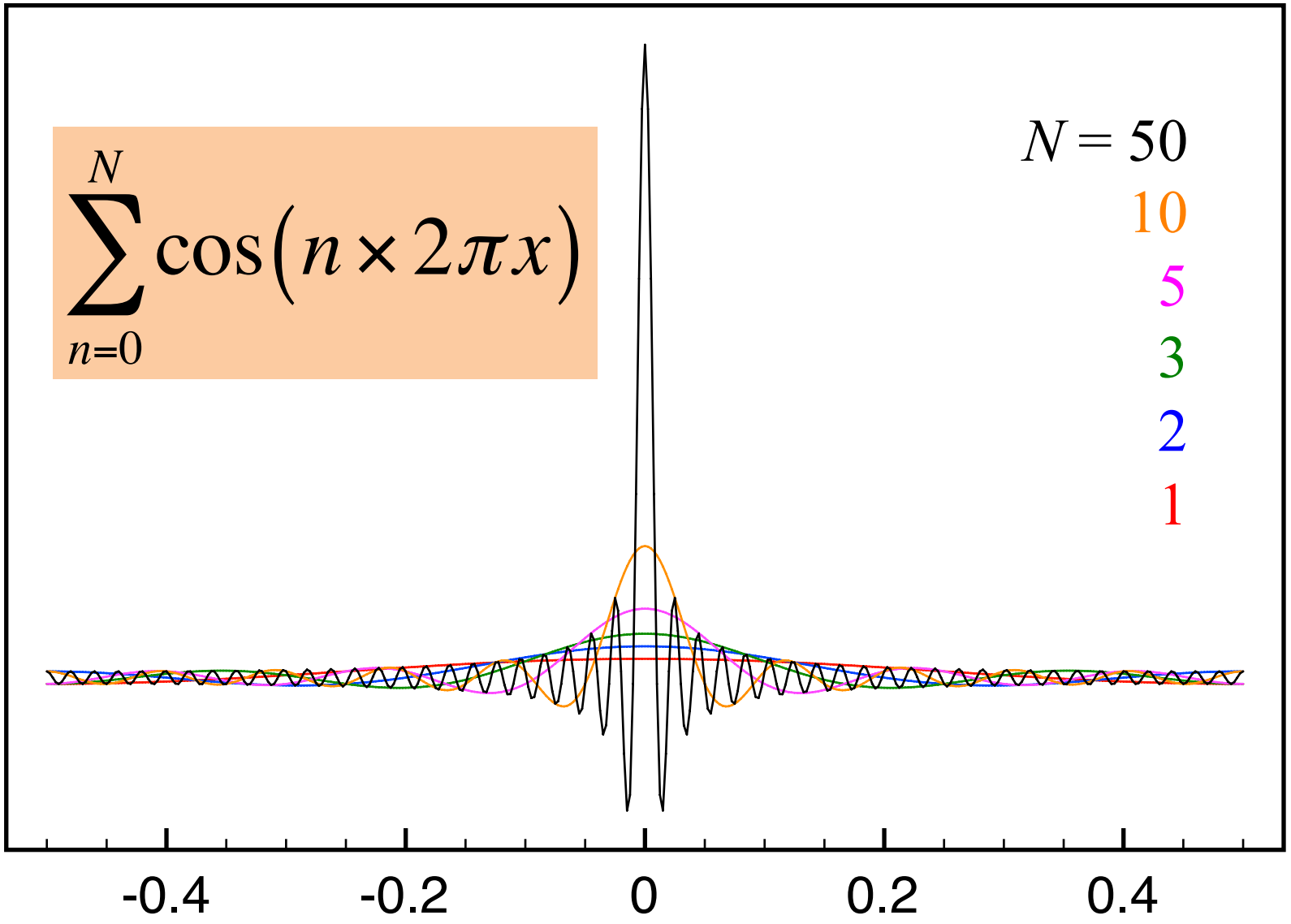


The diffraction limit



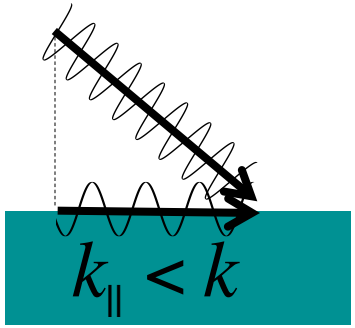
The diffraction limit



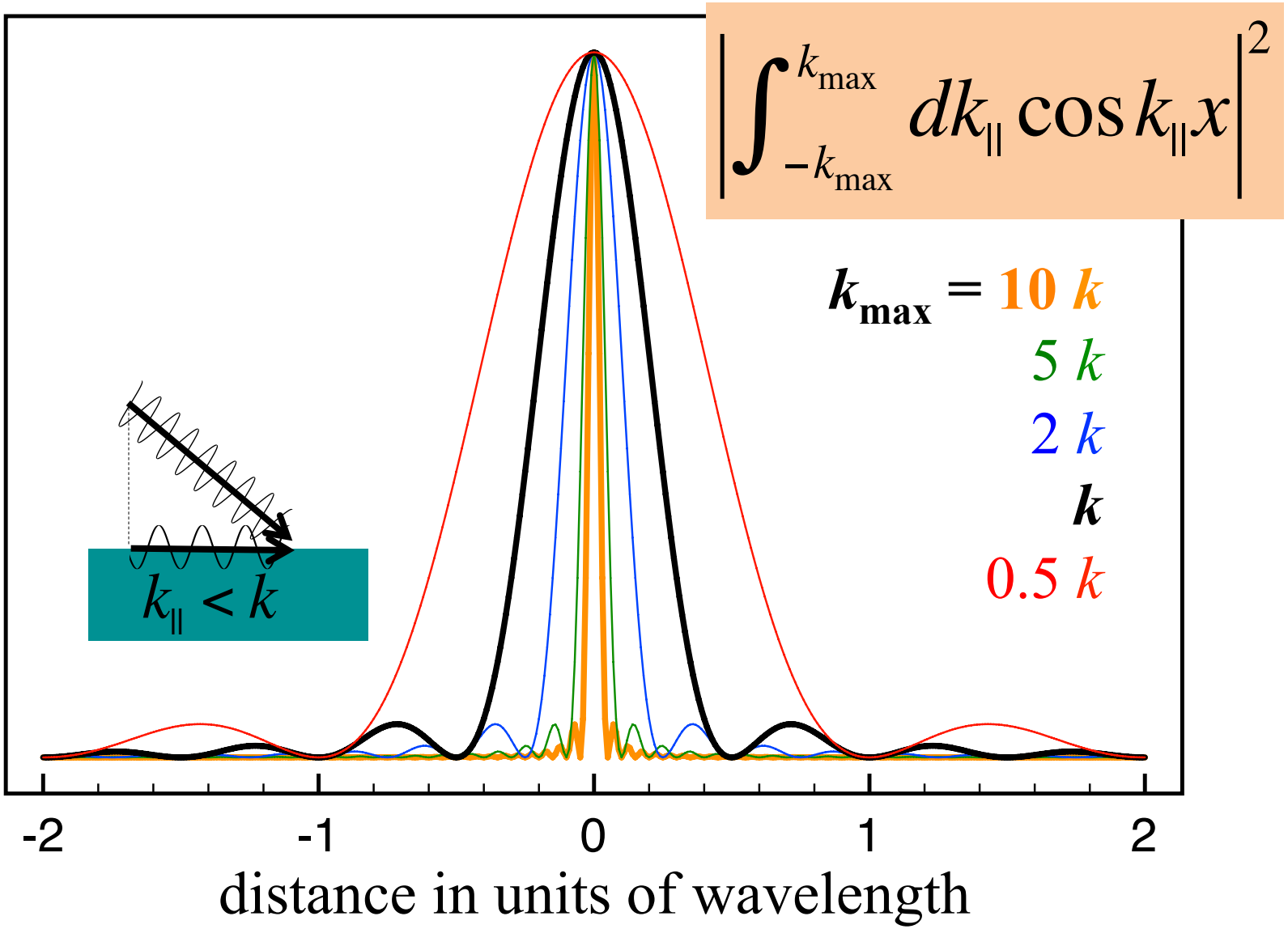
The diffraction limit

$$\sum_{n=0}^{N} \cos\left(n \times 2\pi x\right)$$

$$\int_{-k_{\max}}^{k_{\max}} dk_{\parallel} \cos k_{\parallel} x$$

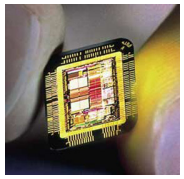


The diffraction limit

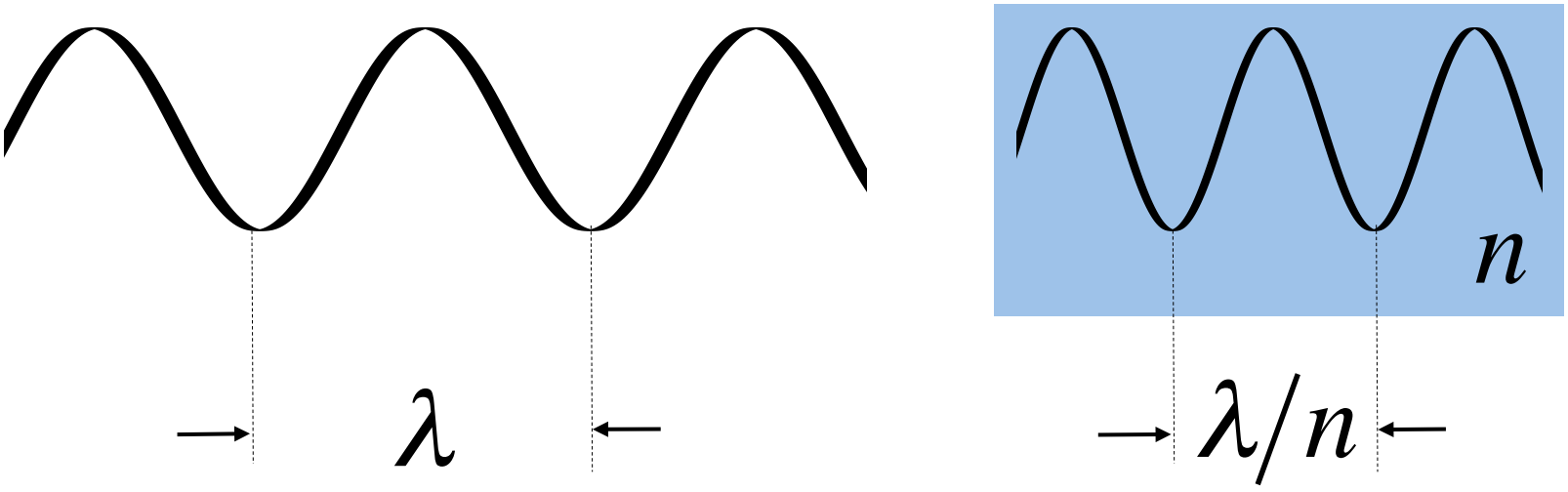


How to beat the diffraction limit

Dielectric materials



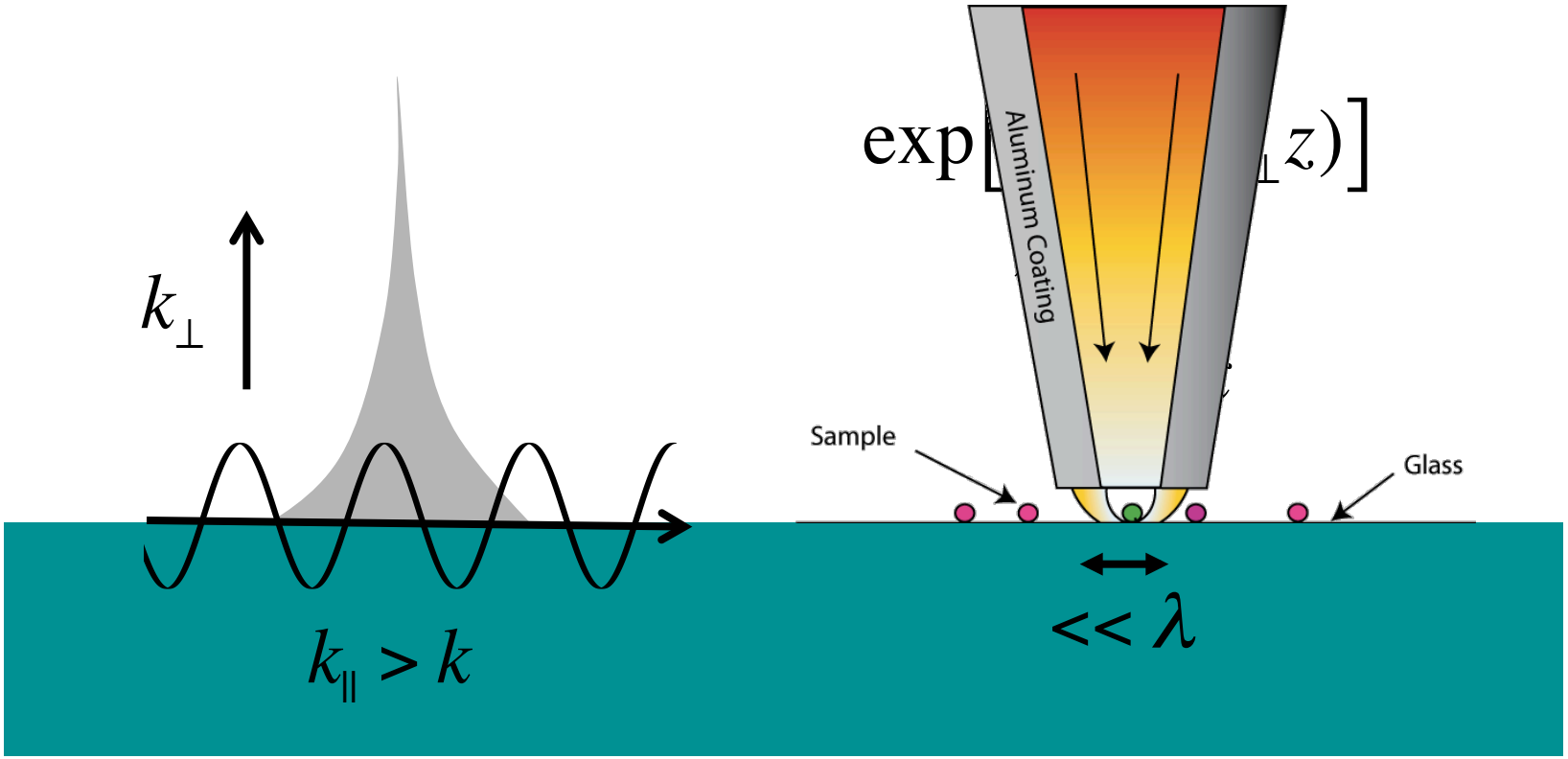
32 nm lines
193 nm ArF excimer laser in **water** (refractive index ***n*=1.44**)



Limited by *n* ☹

How to beat the diffraction limit

Evanescent waves

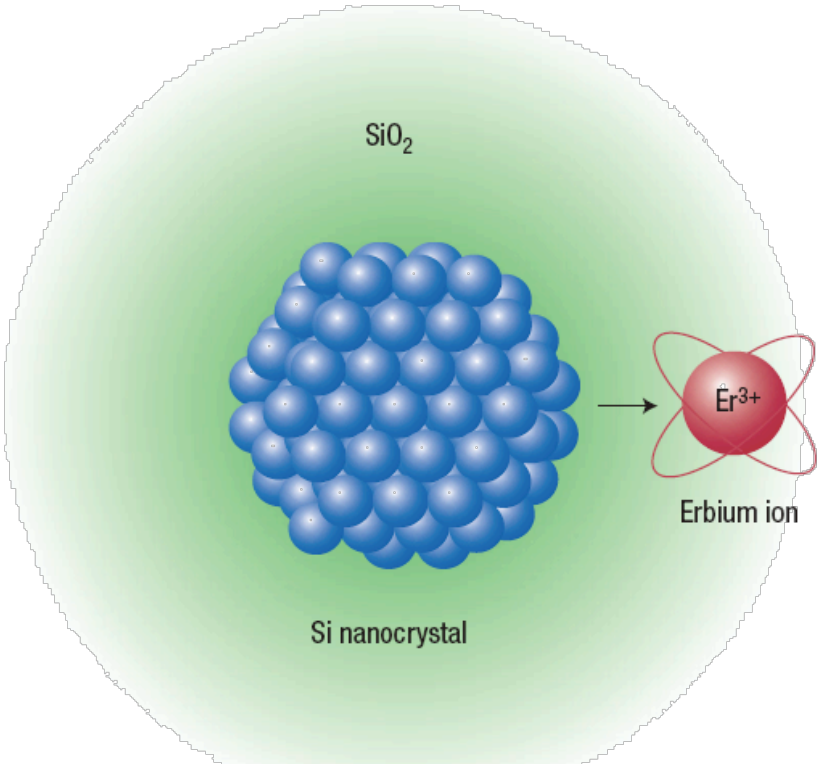


$$k_\parallel^2 + k_\perp^2 = k^2 \quad \rightarrow \quad k_\perp \text{ is imaginary}$$

How to beat the diffraction limit

Hybridize light and electronic excitations

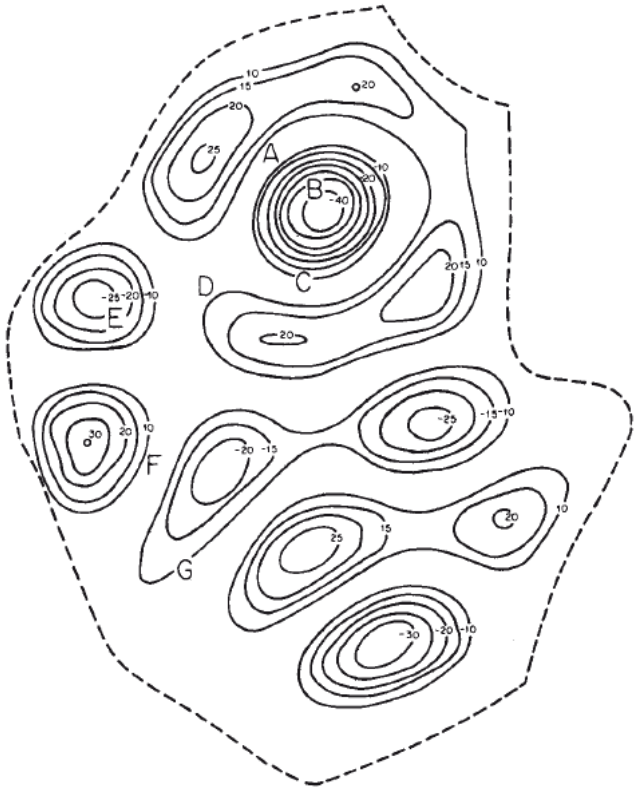
- single of few electrons in atoms
- many electrons in metal nanostructures: **plasmons**



Surface plasmons are surface waves …

Propagating surface waves

Propagating surface waves



Flores *et al.*, Nature (1987)

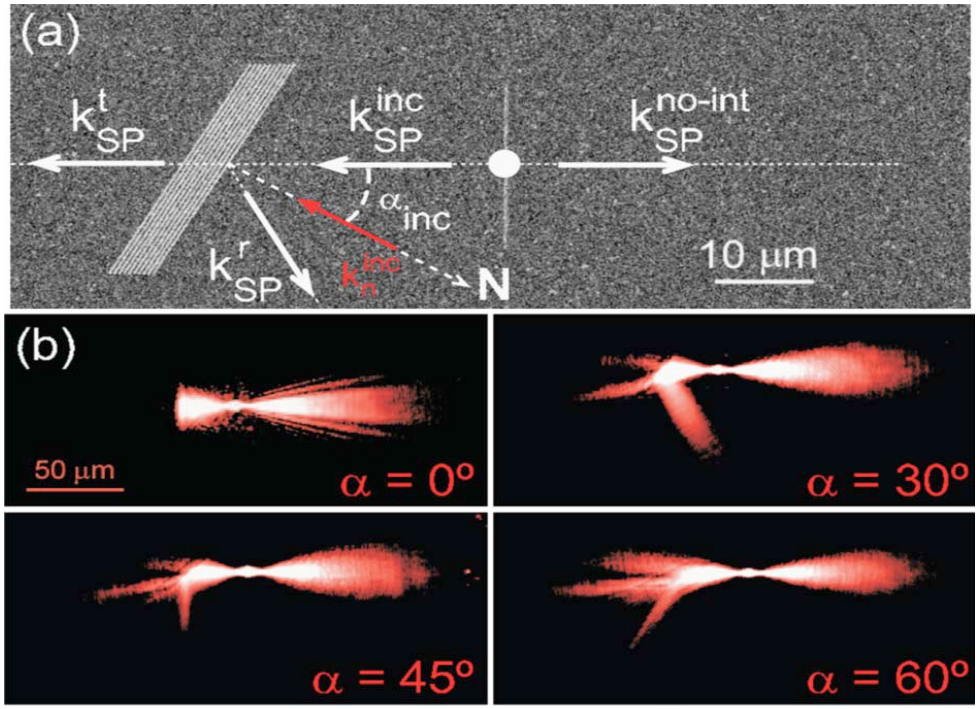
Level of damage in the 1985 earthquake in Mexico city

Introduction to plasmons

Surface plasmons are surface waves
involving collective electron motion
and propagating on metal surfaces …

Interference and diffraction of surface plasmons

Plasmon Bragg mirrors

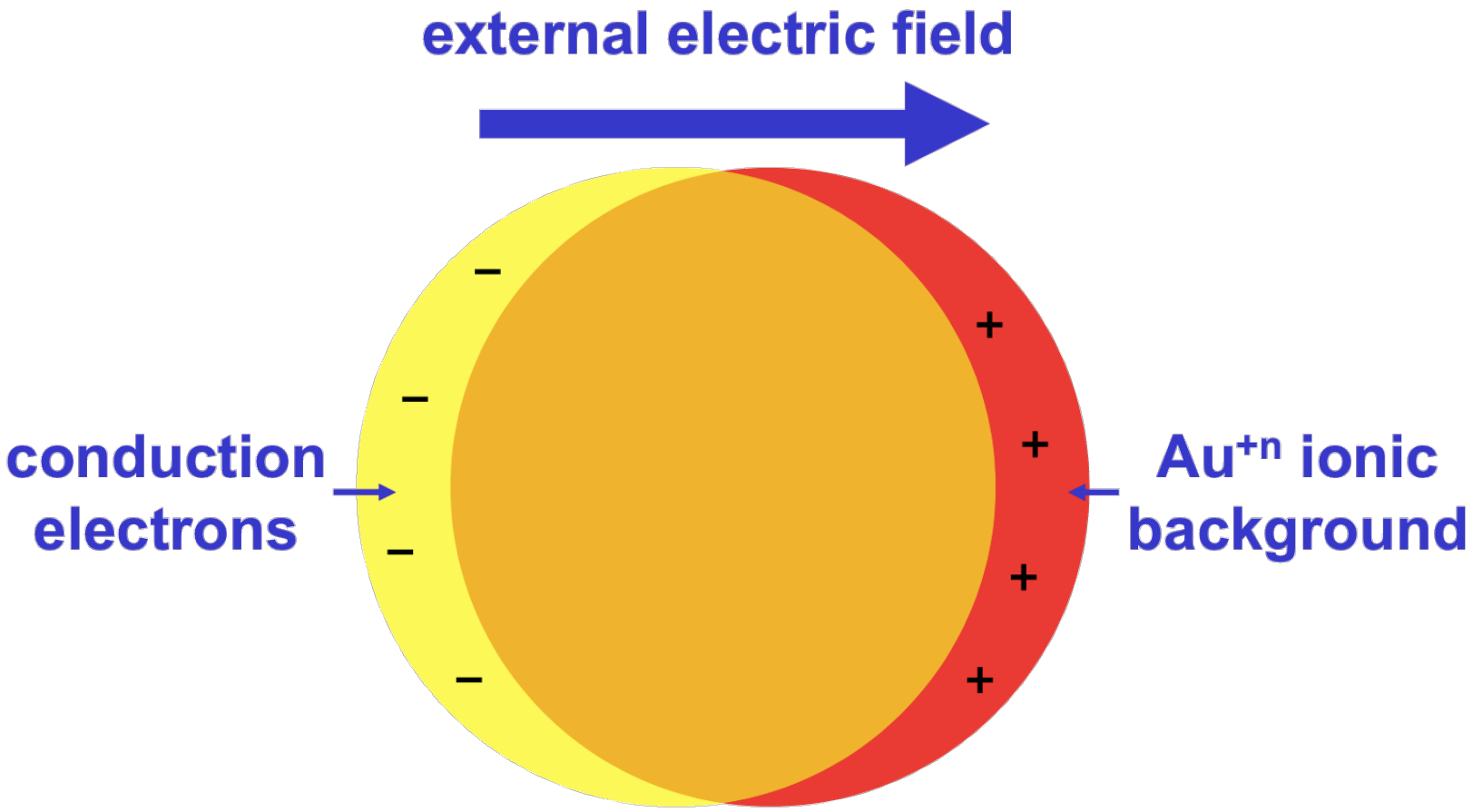


González, …, Dereux, Quidant, Krenn, Opt. Lett. (2007)

Introduction to plasmons

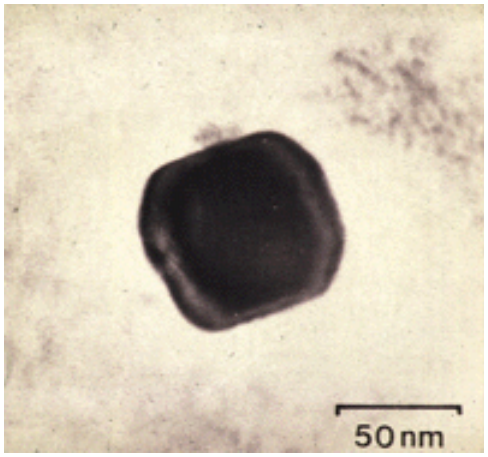
Surface plasmons are surface waves involving collective electron motion and propagating on metal surfaces or localized in metal (nano)structures (e.g., nanoparticles), where they couple efficiently to light …

Localized plasmons



Romans played empirically with nanoparticle plasmons: the Licurgo cup dating from the IV century

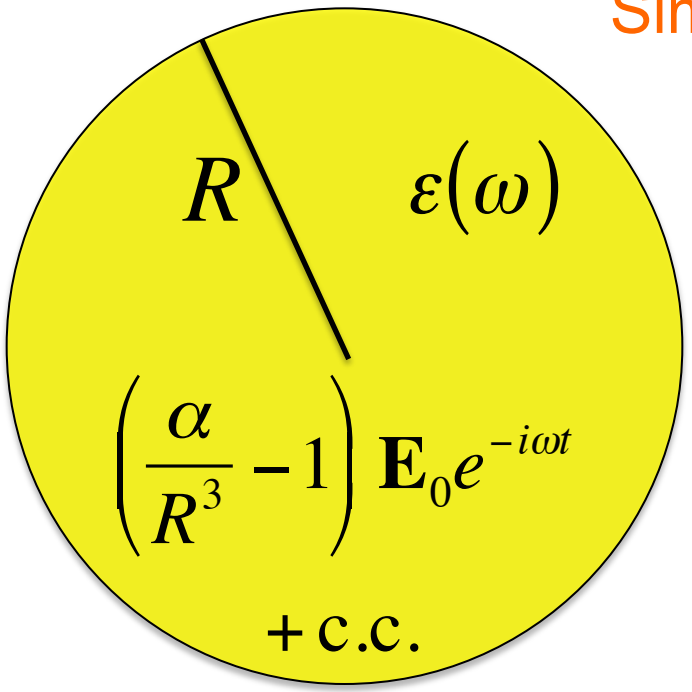
In reflection



In transmission

An electron microscope image shows 70-nm Au-Ag nanoparticles inside the glass

Simple derivation from Poisson's equation



$$\mathbf{E}^{\text{ext}}(t) = \mathbf{E}_0 e^{-i\omega t} + \mathbf{E}_0^* e^{i\omega t}$$

$$\alpha(\omega)\left[\frac{3\mathbf{r}(\mathbf{E}_0\cdot\mathbf{r})/r^2 - \mathbf{E}_0}{r^3}\right]e^{-i\omega t} + \text{c.c.}$$

$$\alpha(\omega) = R^3\frac{\varepsilon - 1}{\varepsilon + 2} \qquad \varepsilon = -2$$

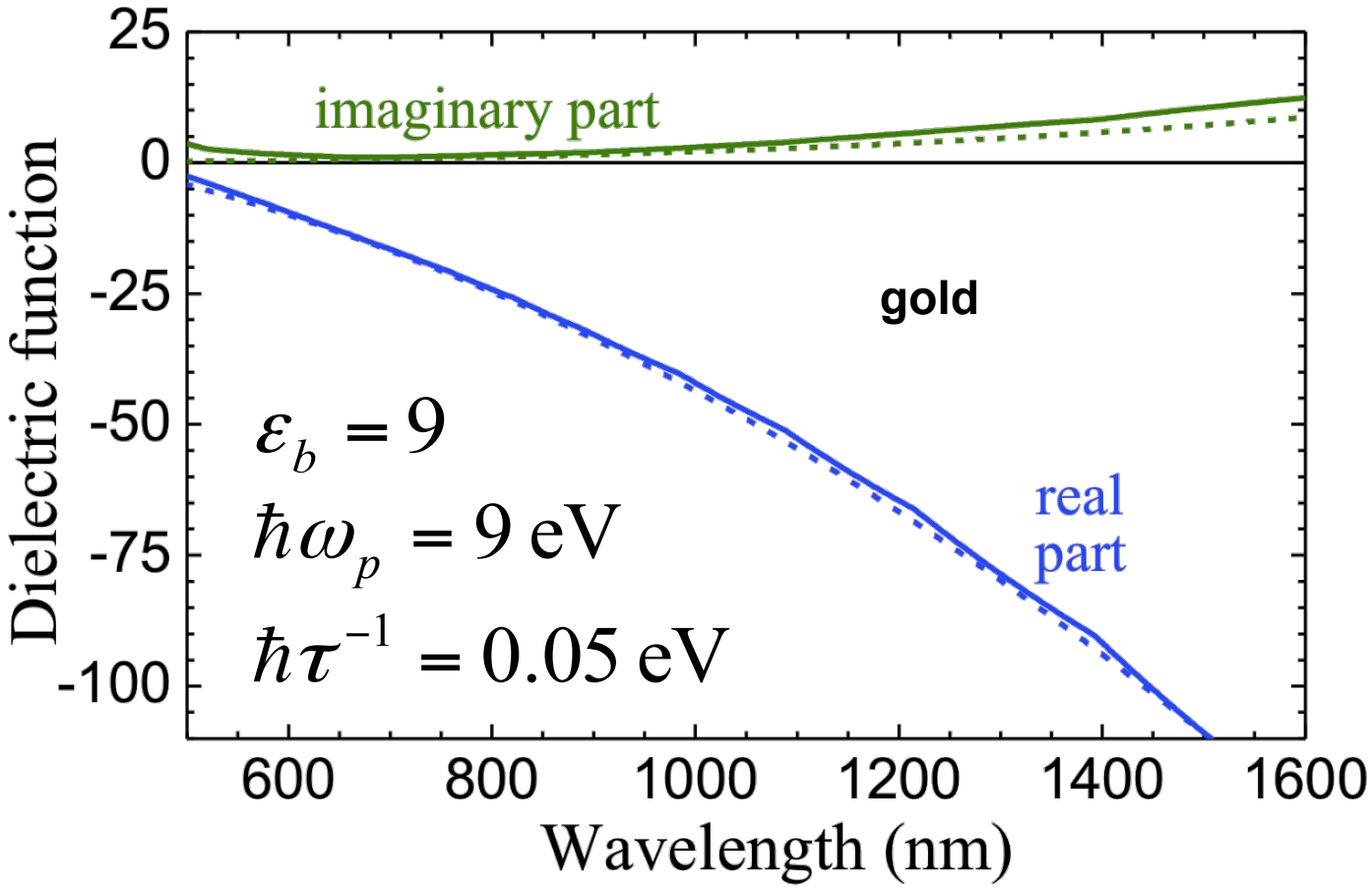
$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

$$\alpha(\omega) = \frac{R^3\omega_0^2}{\omega_0^2 - \omega(\omega + i\gamma)}$$

$$\omega_0 = \frac{\omega_p}{\sqrt{3}}$$

Localized plasmons

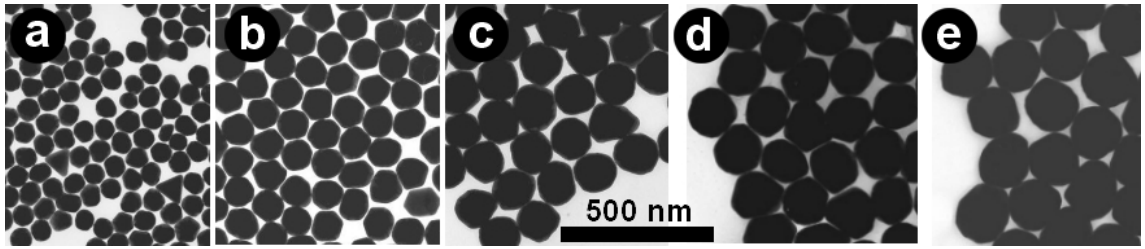
$$\varepsilon(\omega) = \varepsilon_b - \frac{\omega_p^2}{\omega\left(\omega + i\tau^{-1}\right)}$$

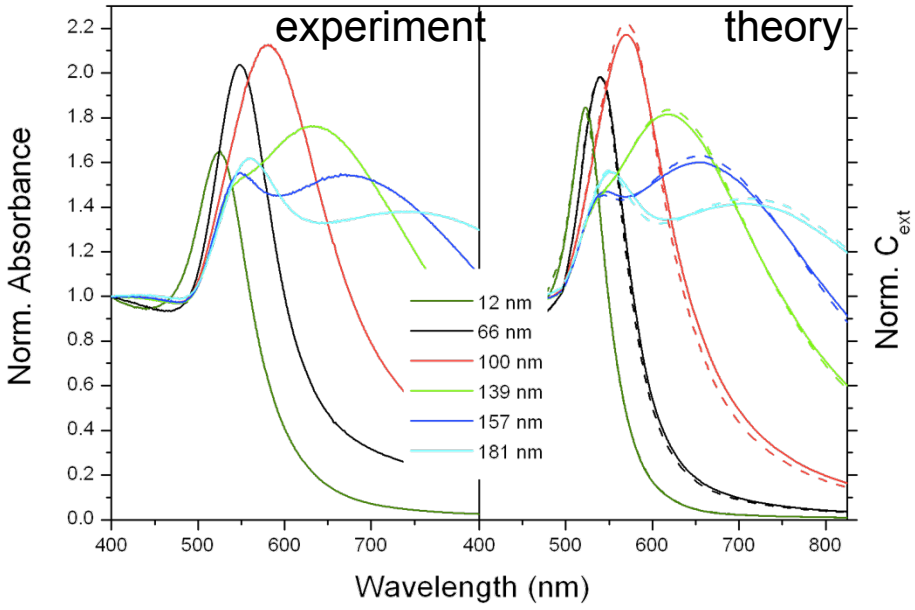


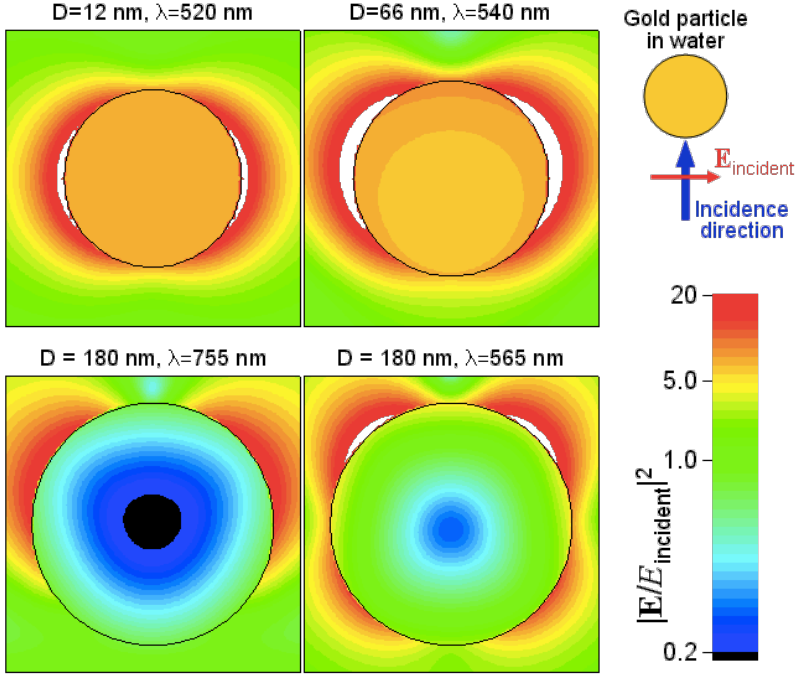
Solid curves: Johnson and Christy, Phys. Rev. B (1972)

Broken curves: Drude model

Multipolar plasmons and retardation effects

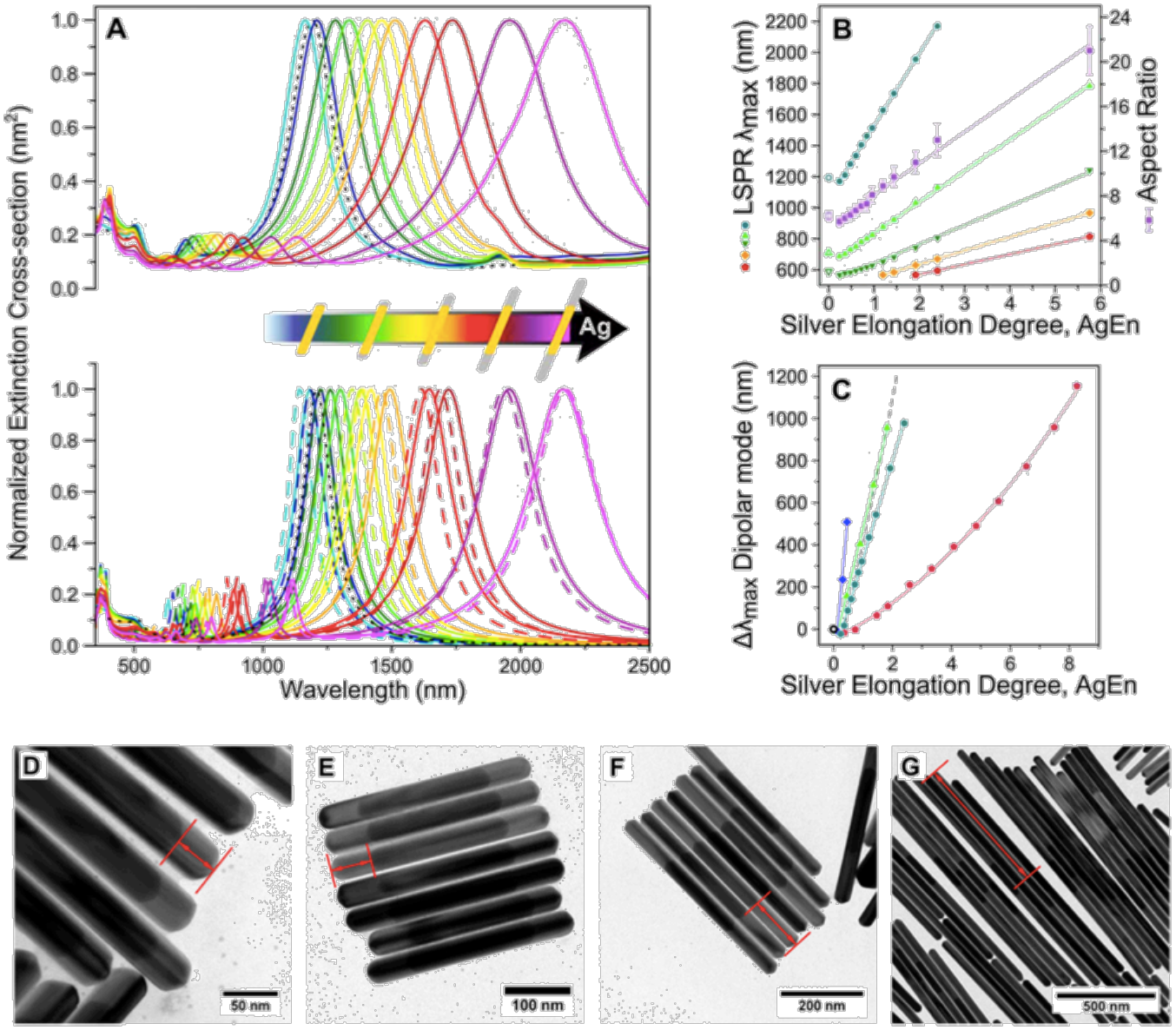






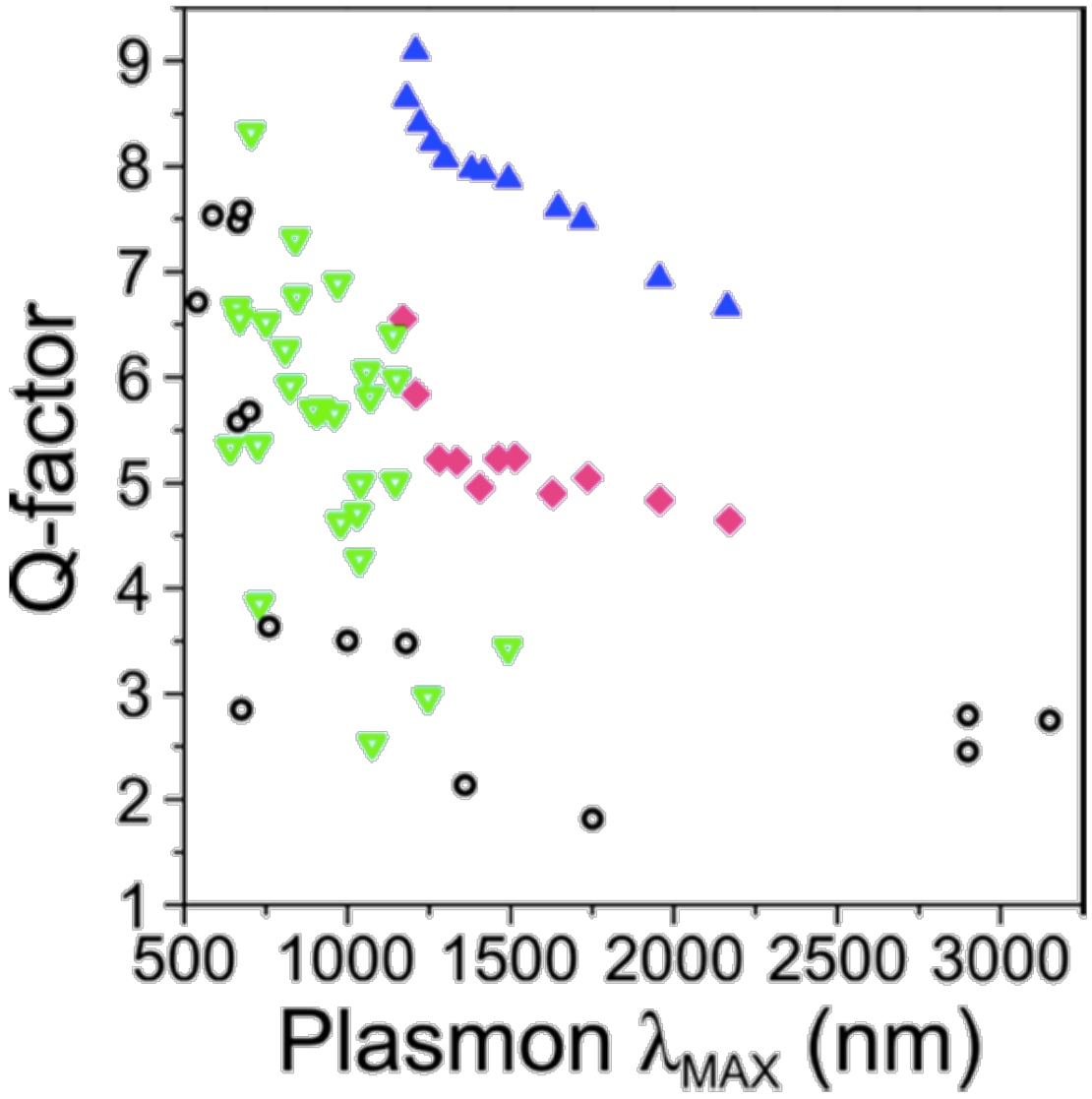
Rodríguez-Fernández *et al.*, Langmuir (2006)

Localized plasmons



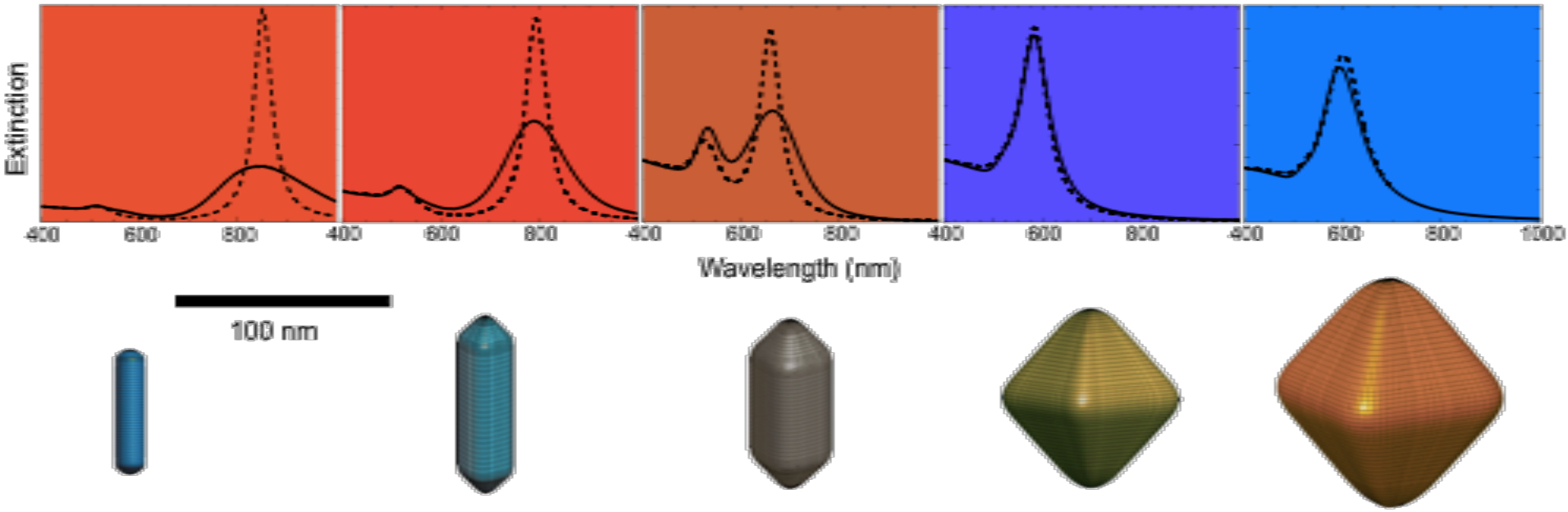
Mayer *et al.*, Nano Lett. (2015)

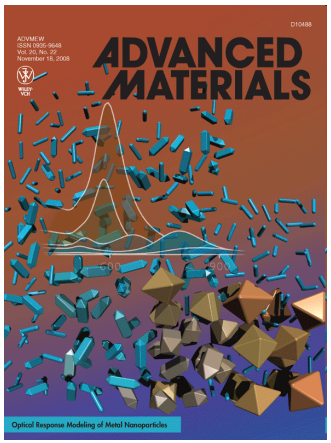
Localized plasmons



Mayer *et al.*, Nano Lett. (2015)

Localized plasmons





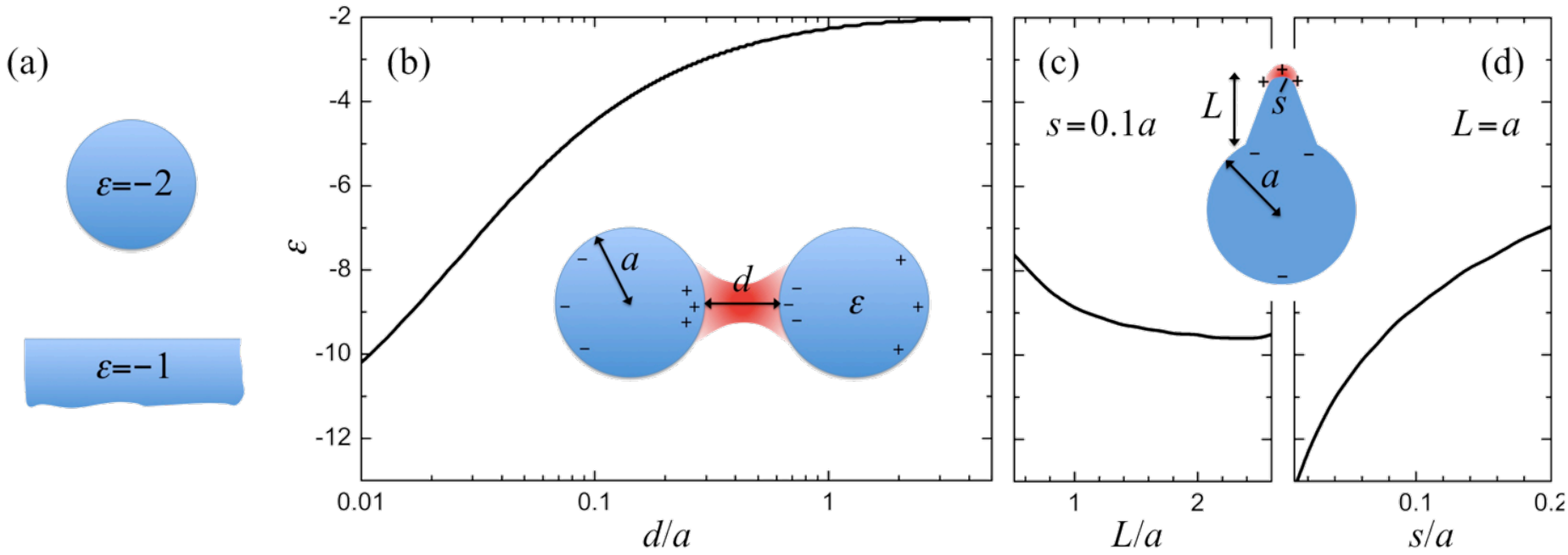
Myroshnychenko *et al*., Adv. Mater. (2008)

Introduction to plasmons

Surface plasmons are surface waves involving collective electron motion and propagating on metal surfaces or localized in metal (nano)structures (e.g., nanoparticles), where they couple efficiently to light, they produce strong confinement of the electromagnetic field (size << wavelength) …

Why do we need metals?

Plasmons in the long wavelength limit (Poisson equation) are scale-invariant, and therefore, they exist for structures down to a few nm.



Localized excitations require negative permittivity

Álvarez-Puebla *et al*., J. Phys. Chem. Lettt. (2010)

Why do we need metals?

Maxwell equations for small particles

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}(\mathbf{r},\omega)e^{-i\omega t} + \mathbf{E}^*(\mathbf{r},\omega)e^{i\omega t}$$

$$\nabla\cdot\varepsilon(\mathbf{r},\omega)\mathbf{E}(\mathbf{r},\omega) = 0 \qquad \mathbf{E}(\mathbf{r},\omega) = -\nabla\phi(\mathbf{r},\omega)$$

$$\boxed{\nabla\cdot\varepsilon(\mathbf{r},\omega)\nabla\phi(\mathbf{r},\omega) = 0}$$

The Poisson equation also describes stationary heat transport:

$\varepsilon \rightarrow k$, thermal conductivity
$\phi \rightarrow$ temperature

Thermodynamics:

- flow towards lower temperature regions → k>0
- absence of trapped thermal energy

Applications of plasmon confinement

Optical trapping - nanotweezers

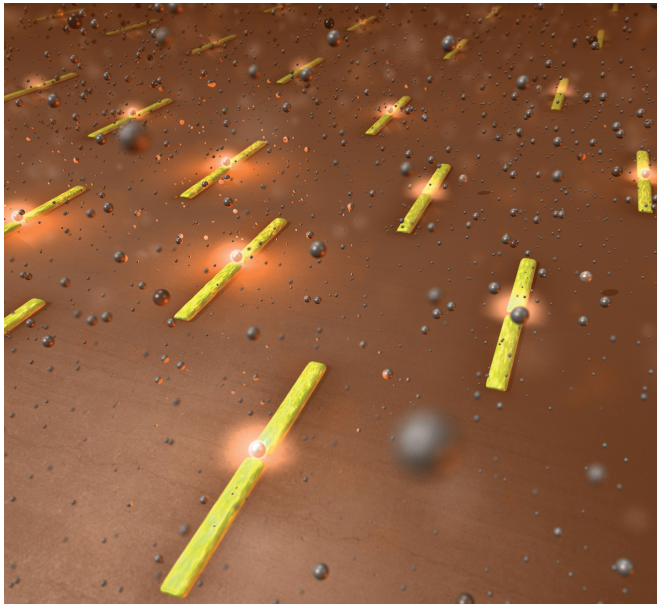
PUBLISHED BY THE AMERICAN CHEMICAL SOCIETY

A JOURNAL DEDICATED TO NANOSCIENCE AND NANOTECHNOLOGY

NANO LETTERS

OCTOBER 2009

VOLUME 9, NUMBER 10 pubs.acs.org/NanoLett



Nanoparticle Trapping with Resonant Optical Antennas

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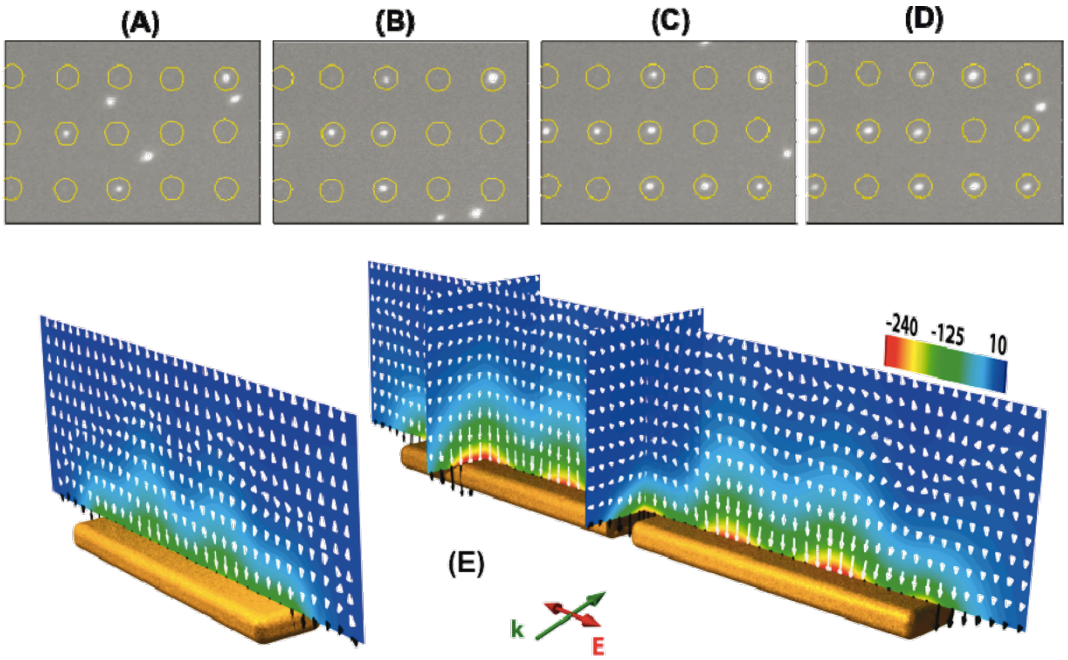
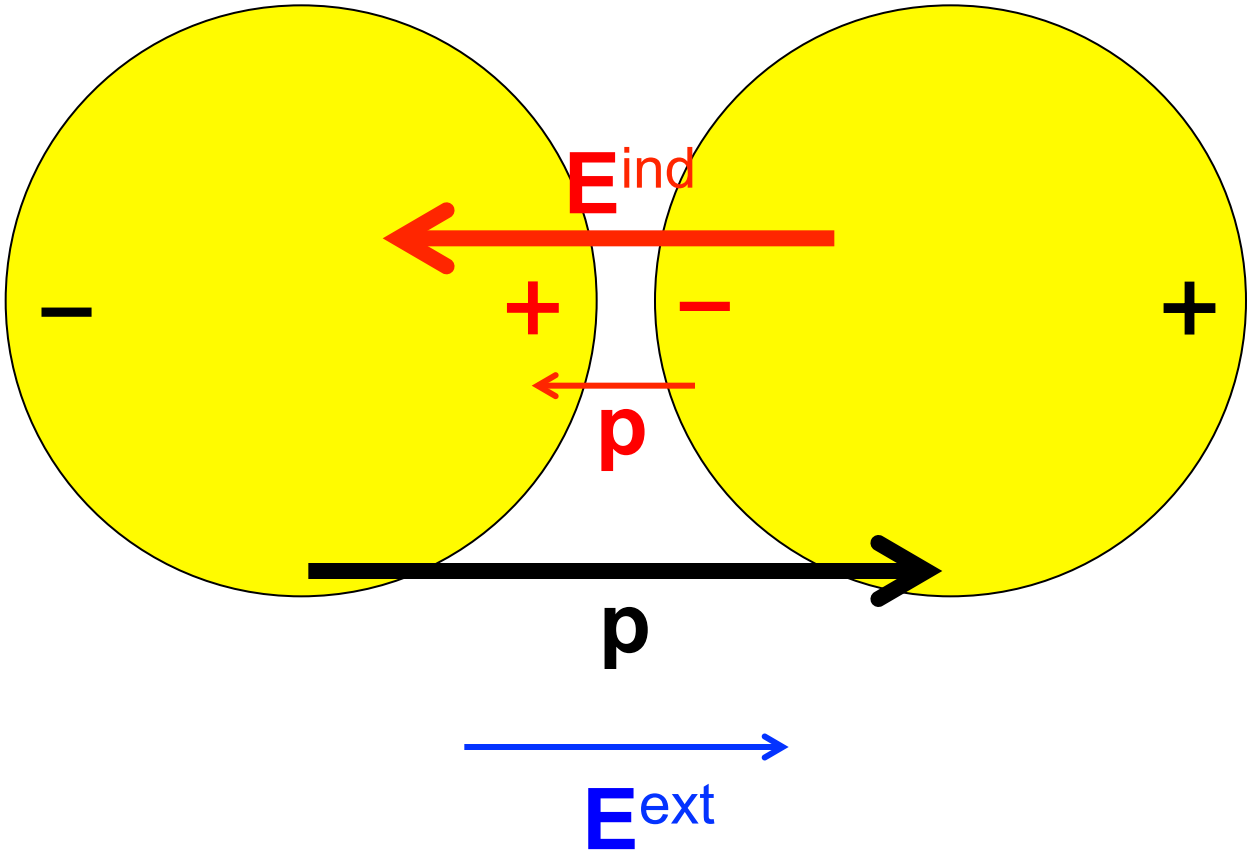


Righini *et al*. (2009)

Introduction to plasmons

Surface plasmons are surface waves involving collective electron motion and propagating on metal surfaces or localized in metal (nano)structures (e.g., nanoparticles), where they couple efficiently to light, they produce strong confinement of the electromagnetic field (size << wavelength), and they generate huge enhancement of the optical electric-field intensity.

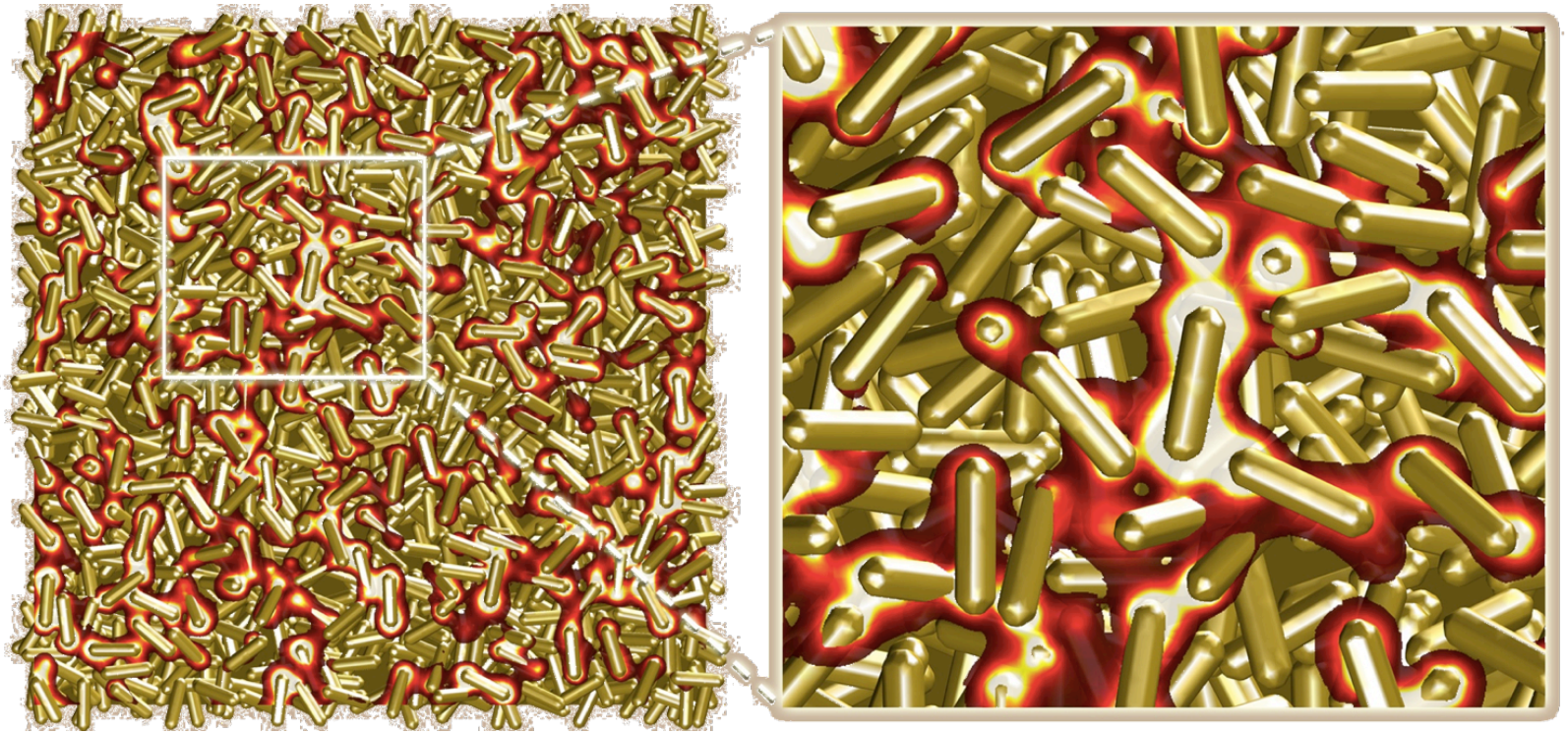
Field enhancement and confinement



Charge neutrality → strong coupling to light though **p**, strong enhancement in the gap

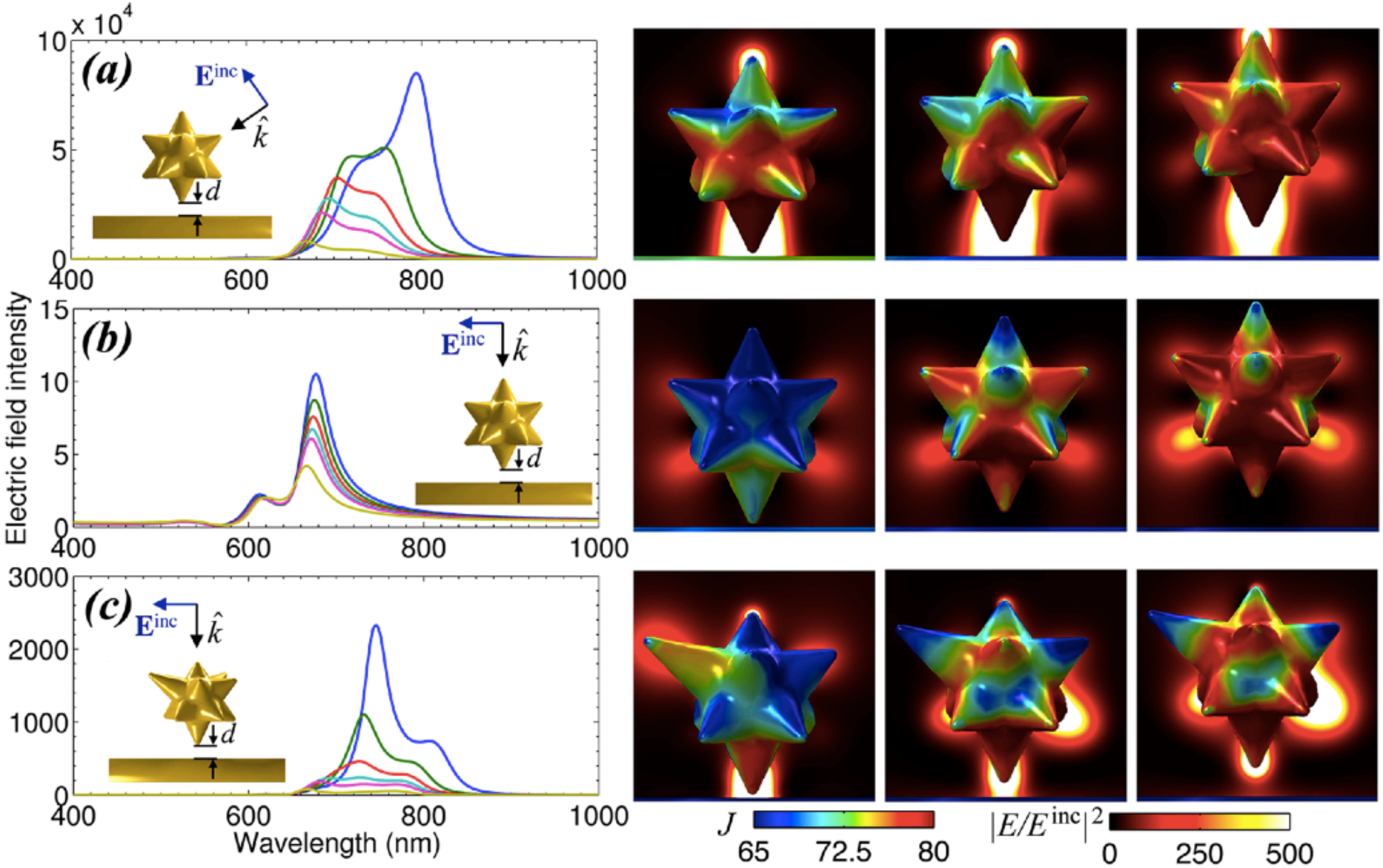
Thongrattanasiri and García de Abajo, Phys. Rev. Lett. (2013)

Designing field enhancers



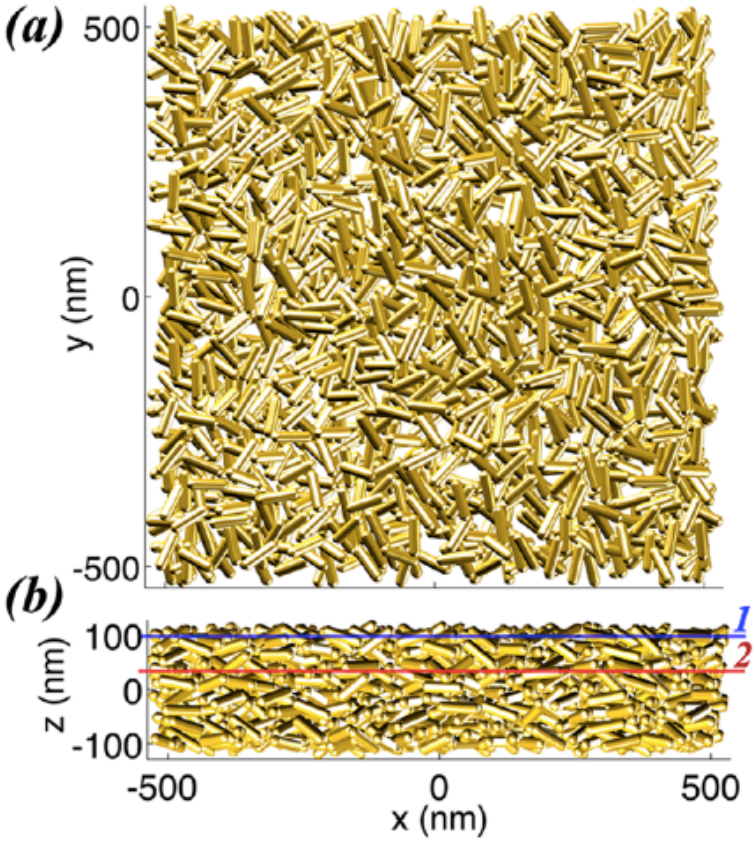
Solis, Taboada, Obelleiro, Liz-Marzán, García de Abajo, ACS Nano **8**, 7559 (2014)

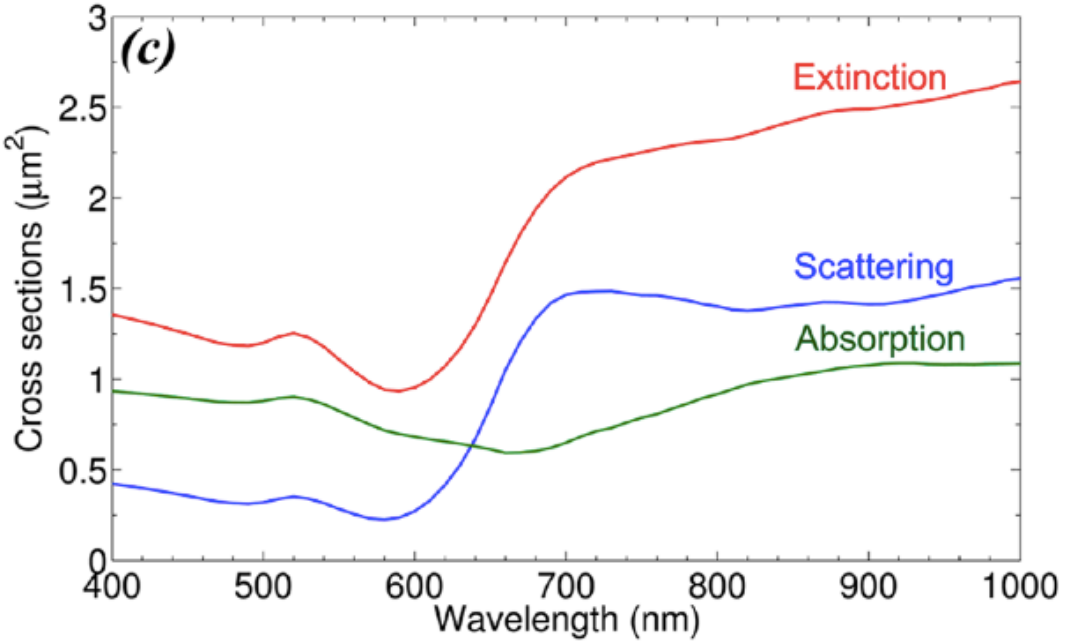
Designing field enhancers



Solis, Taboada, Obelleiro, Liz-Marzán, García de Abajo, ACS Nano **8**, 7559 (2014)

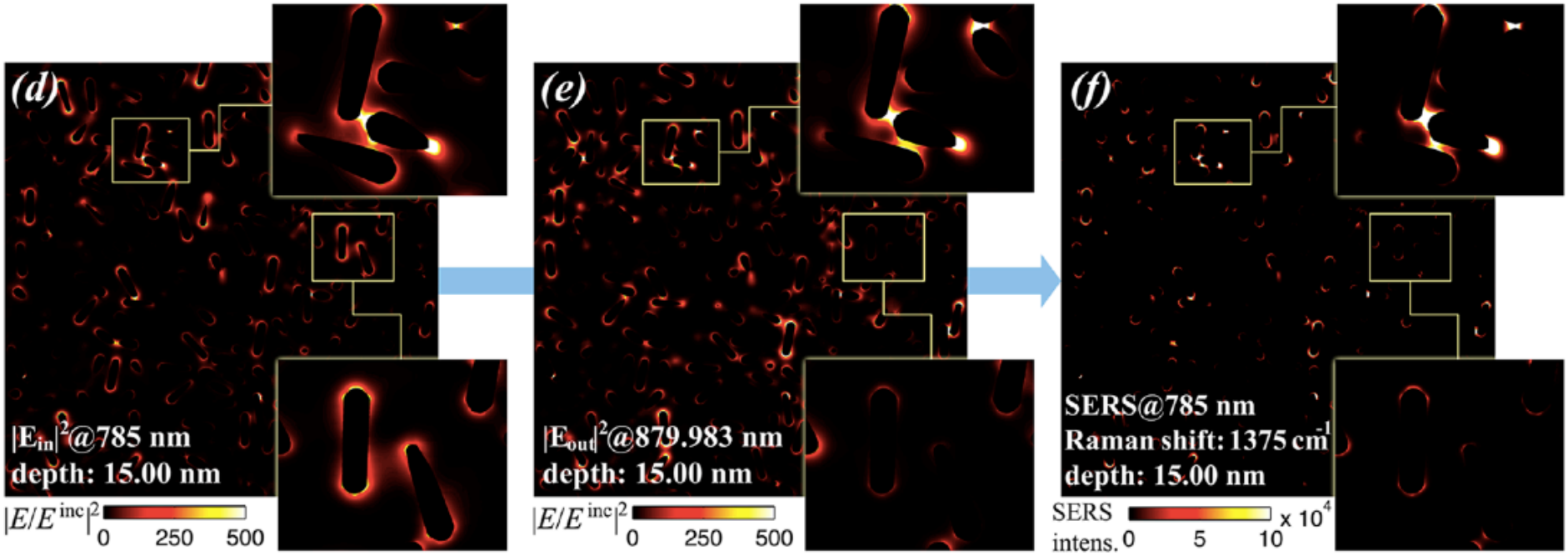
Designing field enhancers





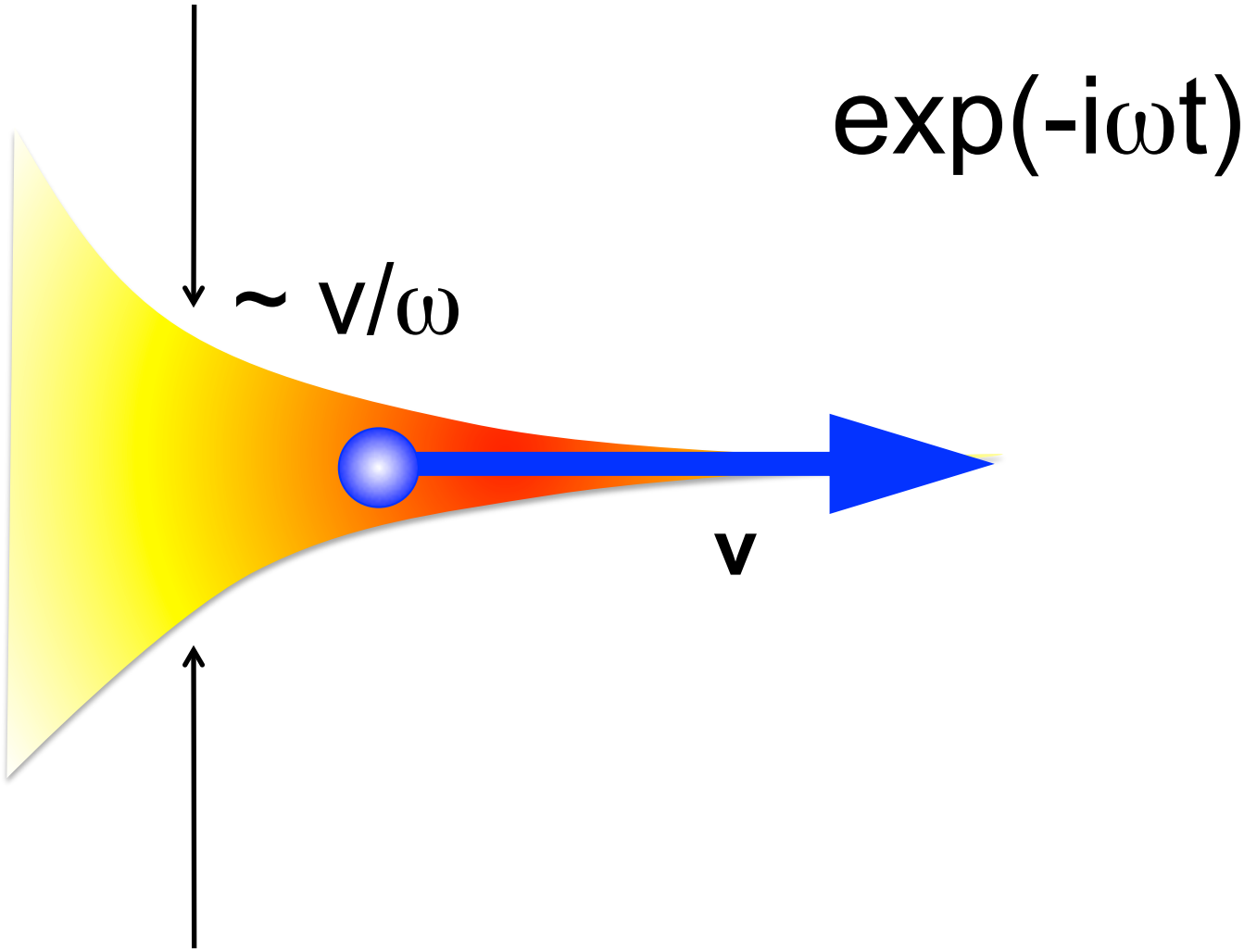
Solis, Taboada, Obelleiro, Liz-Marzán, García de Abajo, ACS Nano **8**, 7559 (2014)

Designing field enhancers



Solis, Taboada, Obelleiro, Liz-Marzán, García de Abajo, ACS Nano **8**, 7559 (2014)

Probing plasmons with electron beams



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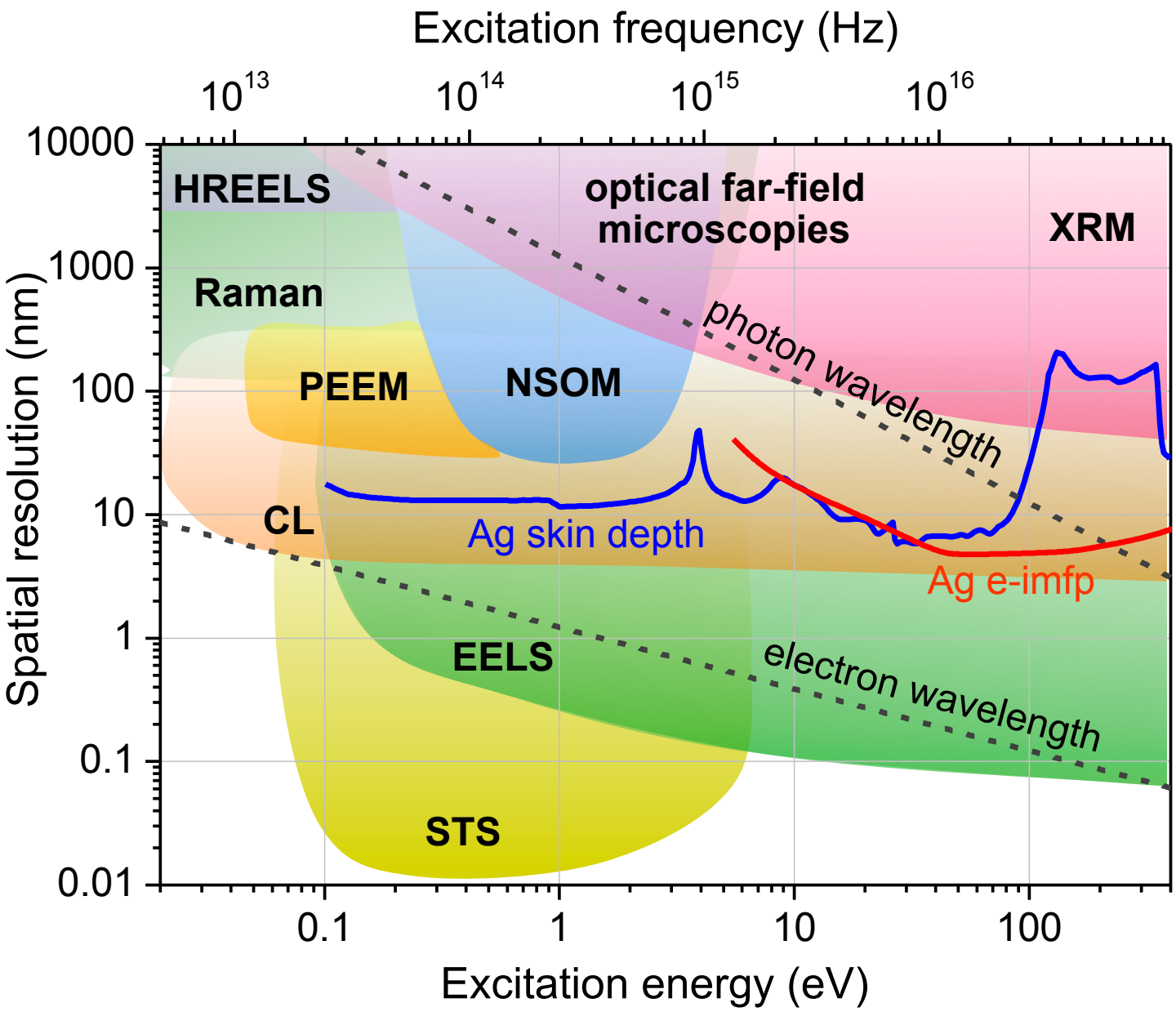
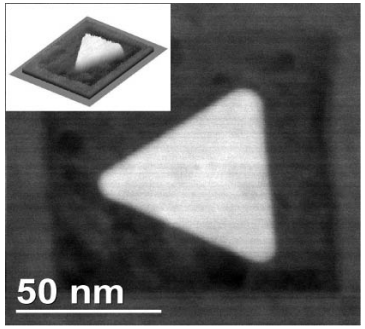
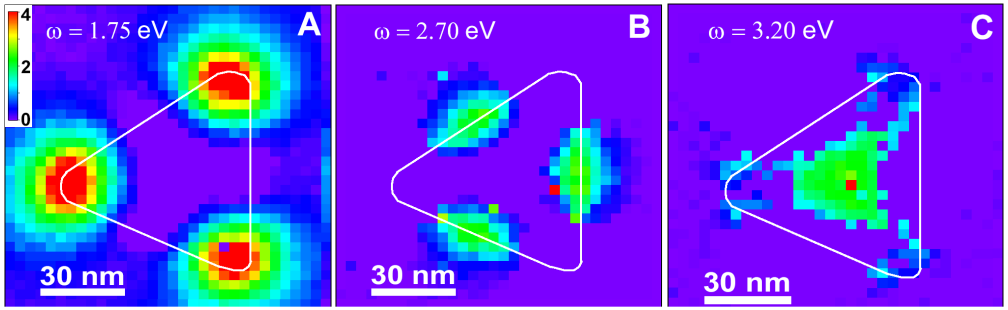


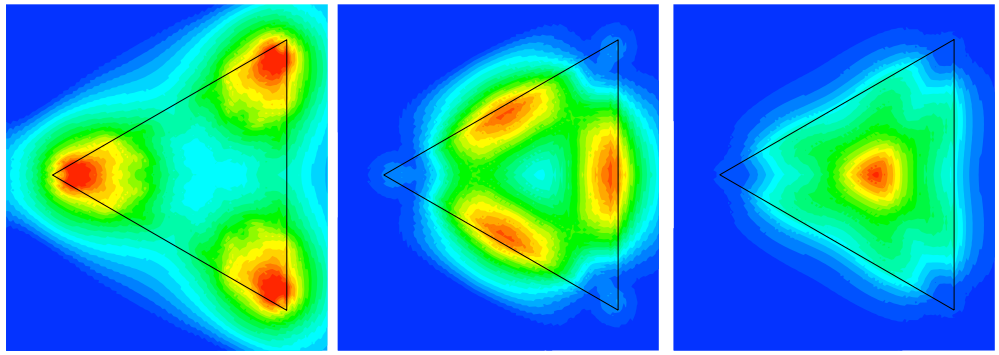
Probing plasmons with electron beams

Ag nanotriangle on mica

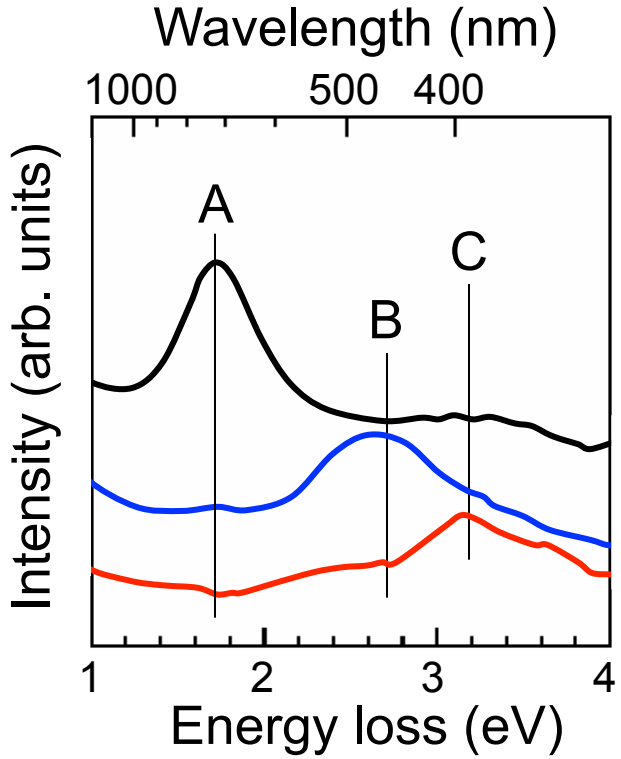


EXPERIMENT: EELS MAPS





THEORY



Nelayah *et al.*, Nature Physics (2007)

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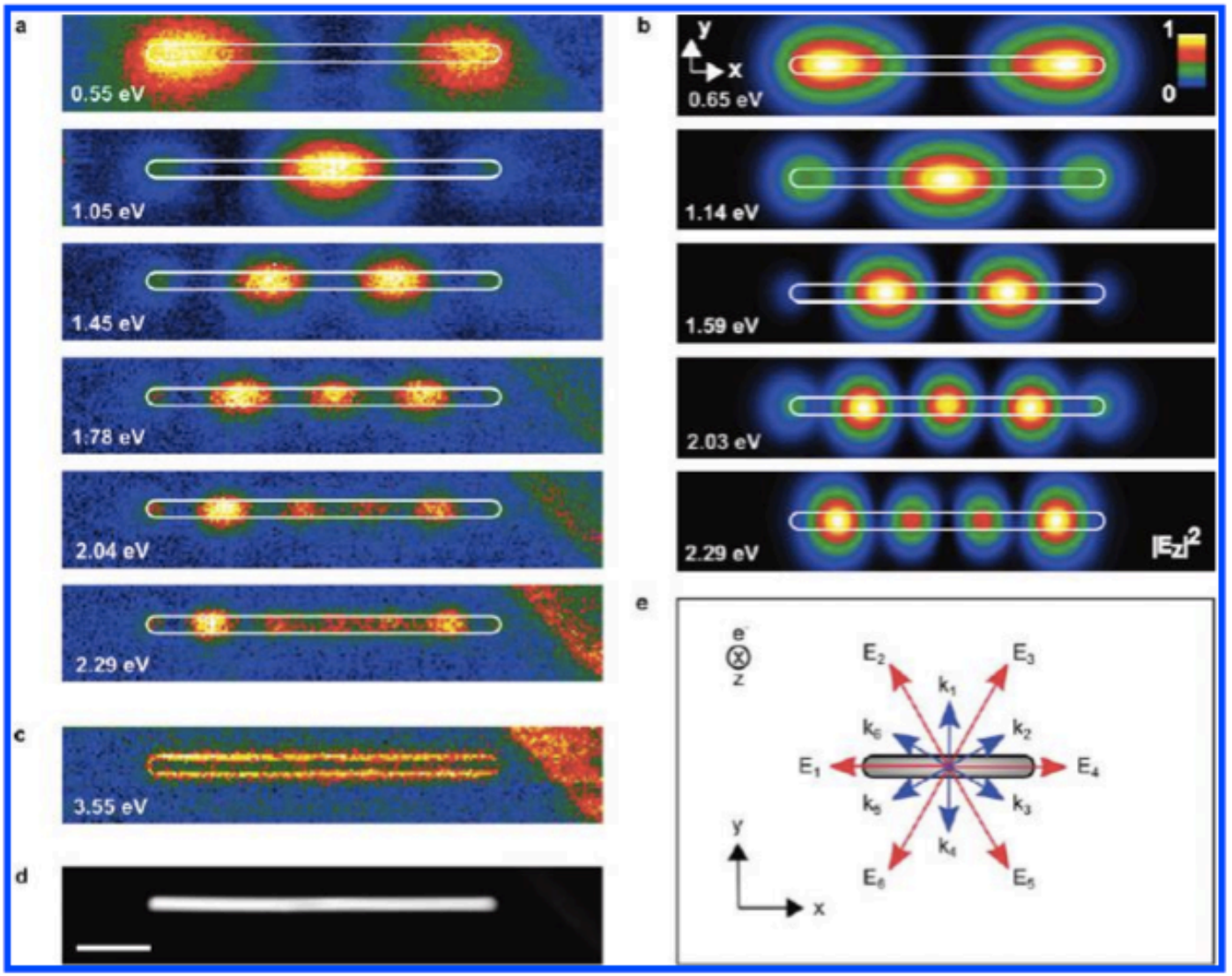

Rossouw et al., Nano Lett. (2011)

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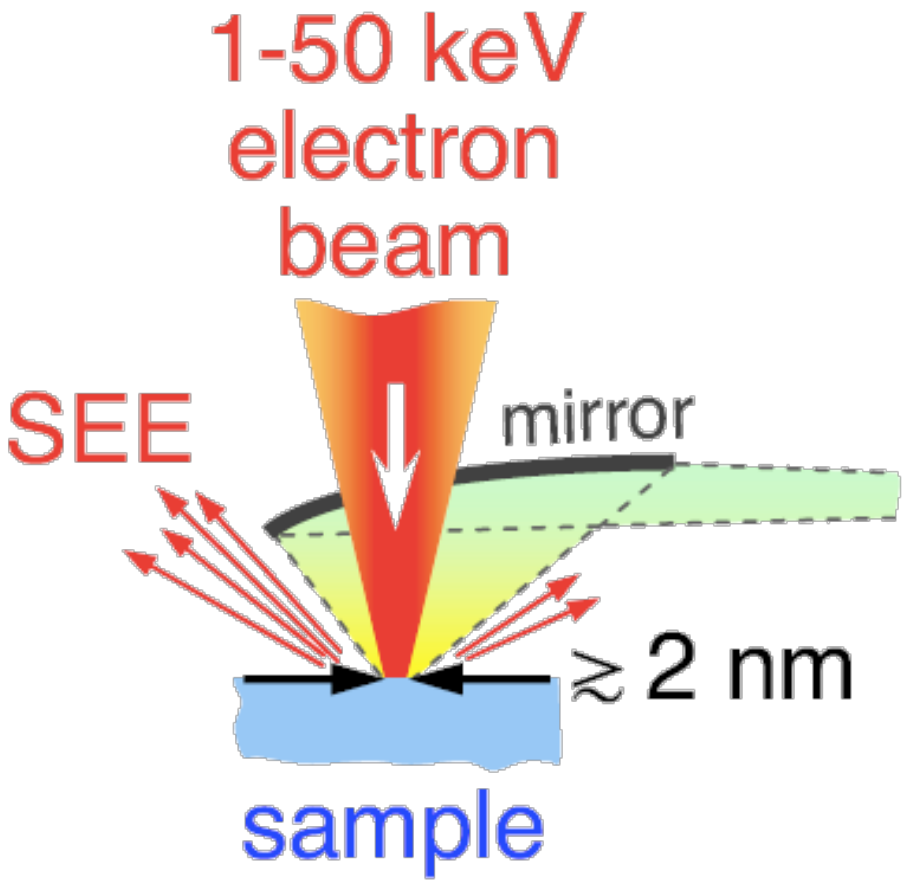

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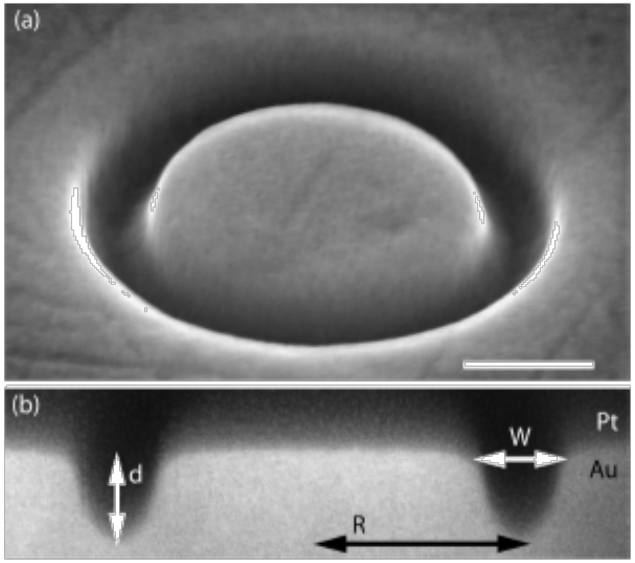
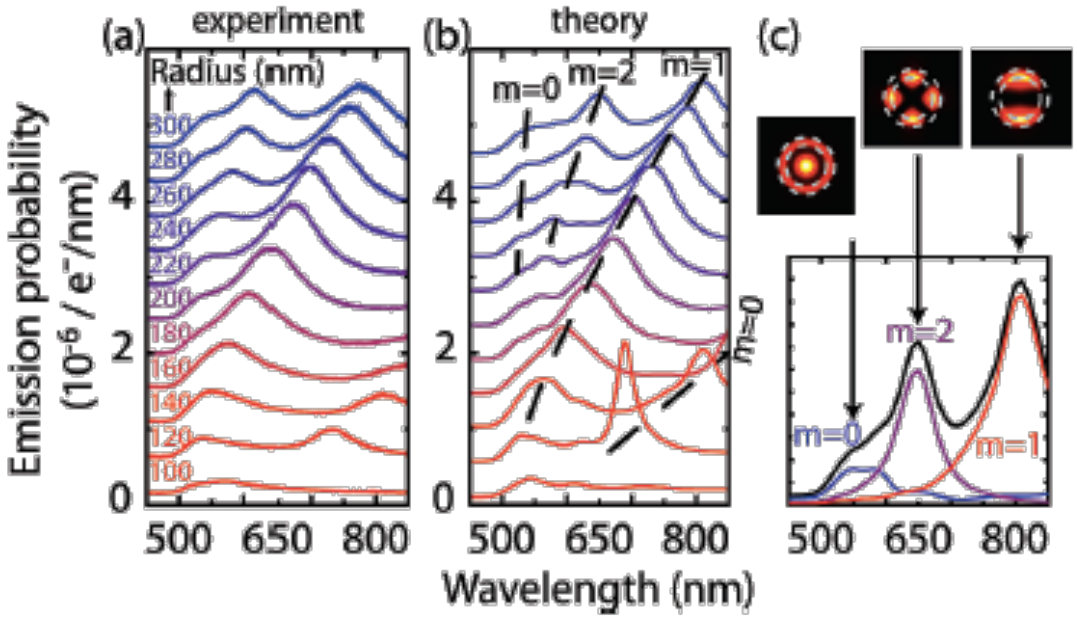


NANO LETTERS
2009
Vol. 9, No. 9
3147-3150

Modal Decomposition of Surface–Plasmon Whispering Gallery Resonators

Ernst Jan R. Vesseur,*,† F. Javier García de Abajo,‡ and Albert Polman†



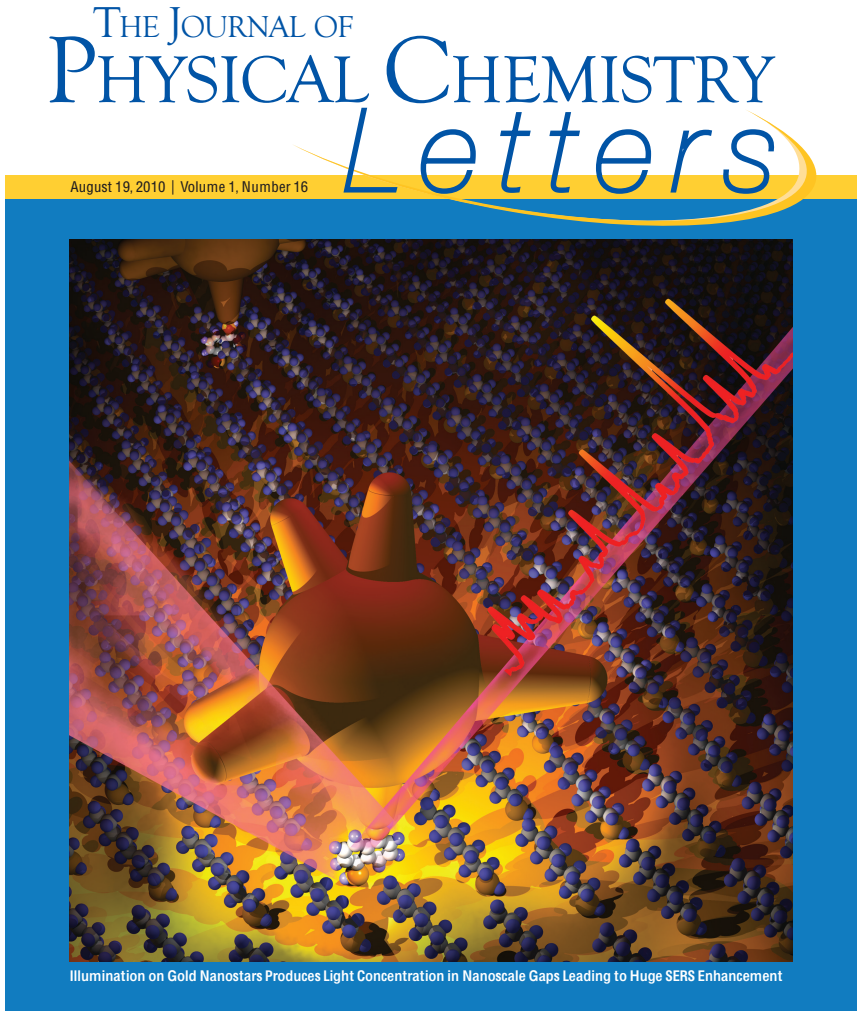
Why are surface plasmons interesting?

- Light concentration: plasmon size << wavelength
- Field enhancement: induced field >> external field

Applications of optical electric-field enhancement

nanophotonics.es

Controlled 10^{10} SERS enhancement → 10^5 intensity enhancement



Álvarez-Puebla *et al.*
JACS (2009), JPCL (2010)

Plasmon facts

Plasmons are the quanta of conduction-electron collective oscillations in metals

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

Plasmons are observed when $\varepsilon<0$ (metallic behavior)

- Aluminum and other materials at UV frequencies
- 0D and 1D carbon structures at UV frequencies
- Noble metals (Ag, Cu, Au) at visible-NIR frequencies
- 2D carbon structures (graphene) at IR frequencies
- Alkali-halides at THz frequencies
- The ionosphere at (AM) radio frequencies

- Pure conduction-electron oscillations in deep-subwavelength structures
- Hybridization with photons for larger sizes

Applications

- Medical applications – imaging
- Medical applications – drug delivery
- Medical applications – bio-molecule ultrasensitive sensing
- Medical applications – thermal cell-apoptosis
- Optical signal processing
- Metamaterials (extensive light manipulation at subwavelength scales)
- Optical manipulation
- Enhanced radiative transfer
- Signal amplification (spacer)
- More metamaterials ($\mu \neq 1$ at high frequency, negative refraction, …)
- Solar cells
- …

Why are surface plasmons interesting?

- Light concentration: plasmon size << wavelength

- Field enhancement: induced field >> external field

- Fast tunability: electrical doping

Plasmonics:
An overview and some new trends

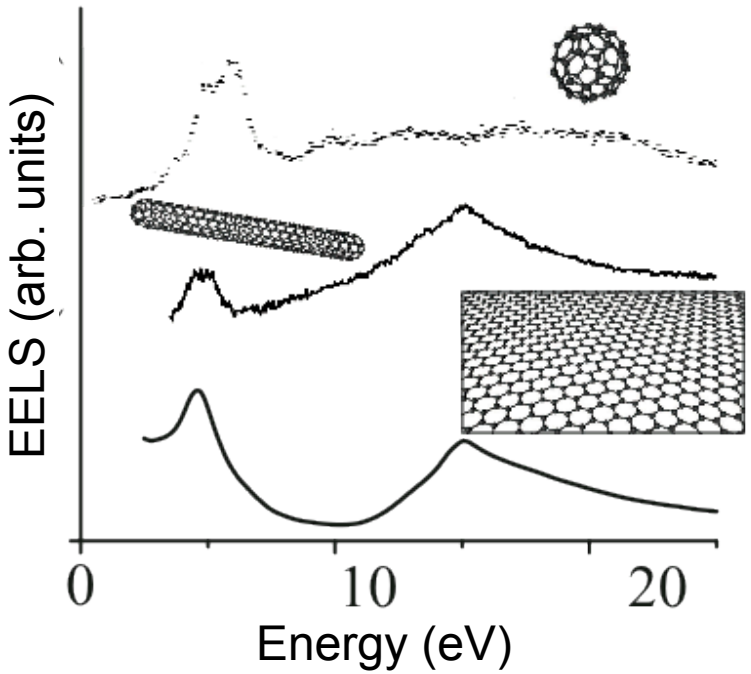
Introduction to plasmons

Graphene plasmons

- **Quantum-mechanical description**
- **Classical description**
- **Complete optical absorption**
- **Quantum optics with graphene plasmons**
- **Sensing with graphene plasmons**

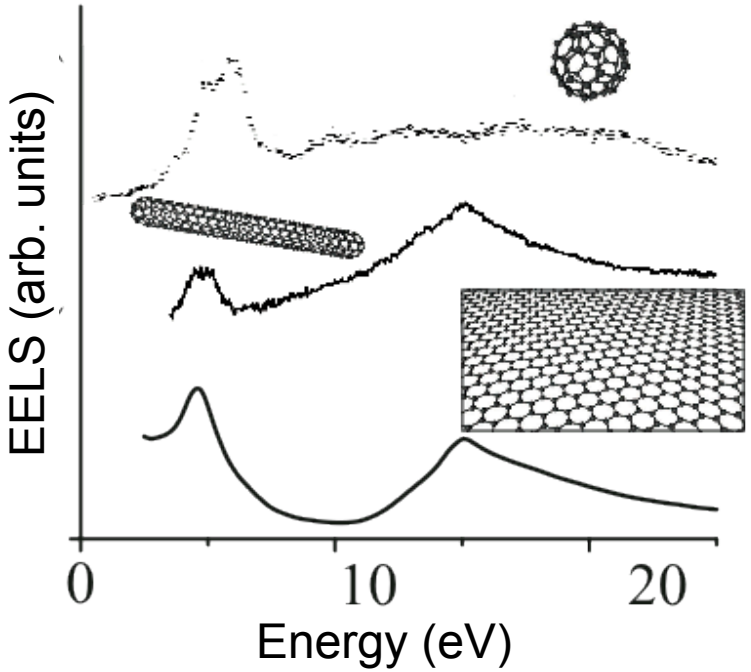
Plasmons in other atomically thin materials

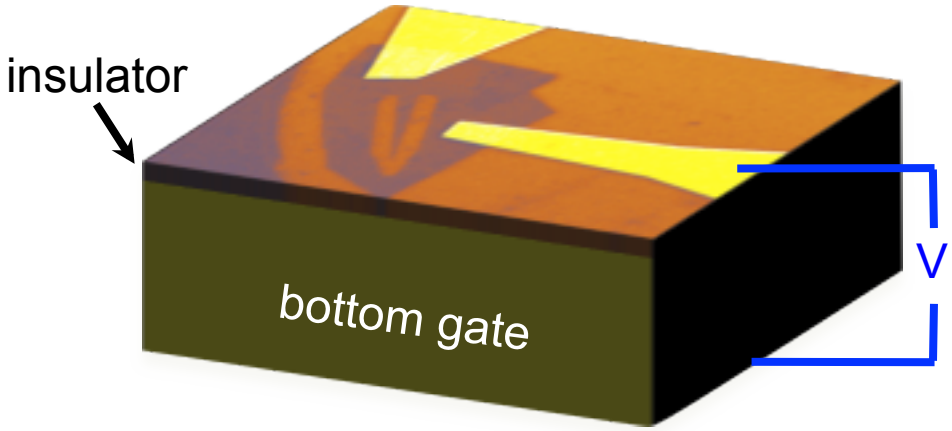
Graphene plasmons



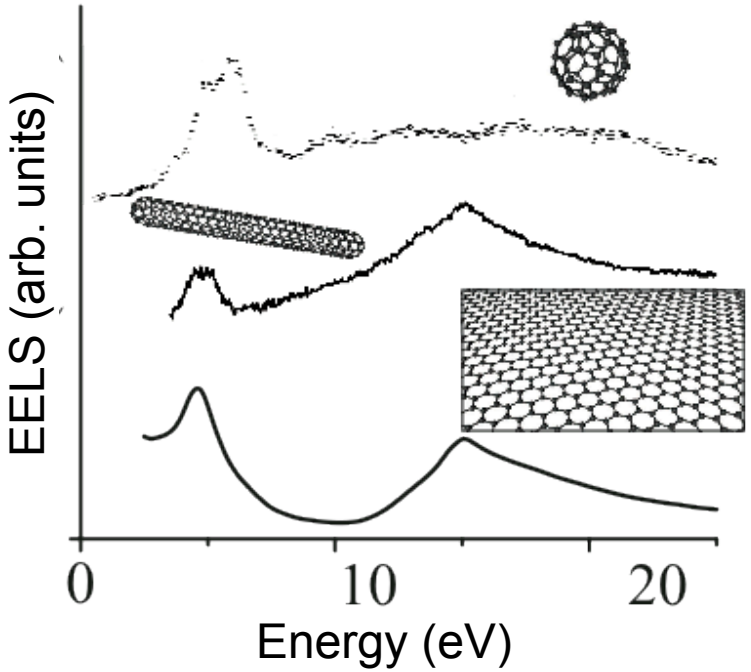
Keller and Coplan, Chem. Phys. Lett. (1992)
Stéphan, …, Colliex, Phys. Rev. B (2002)
Zhou, …, Idrobo, Nat. Nanotech. (2012)

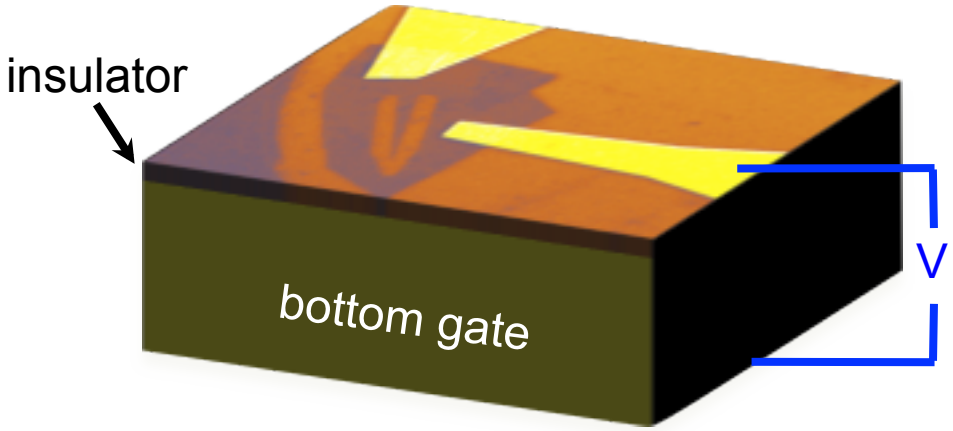
Graphene plasmons

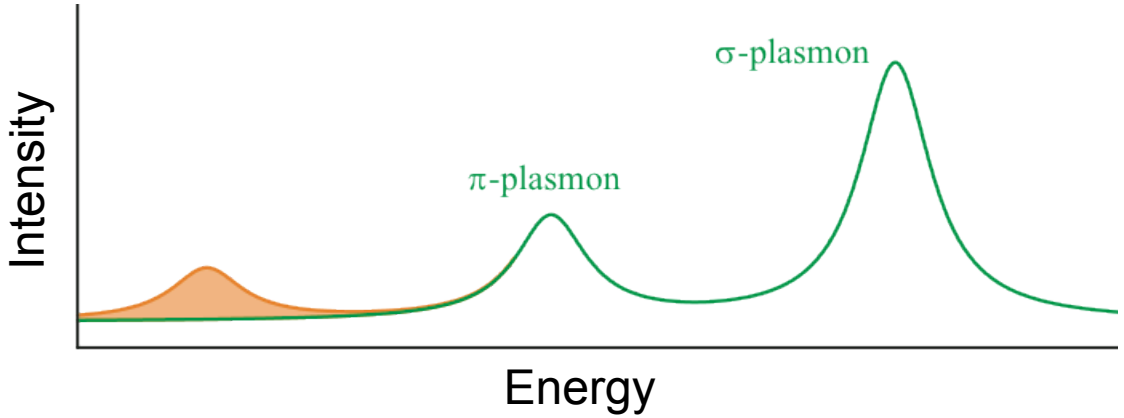




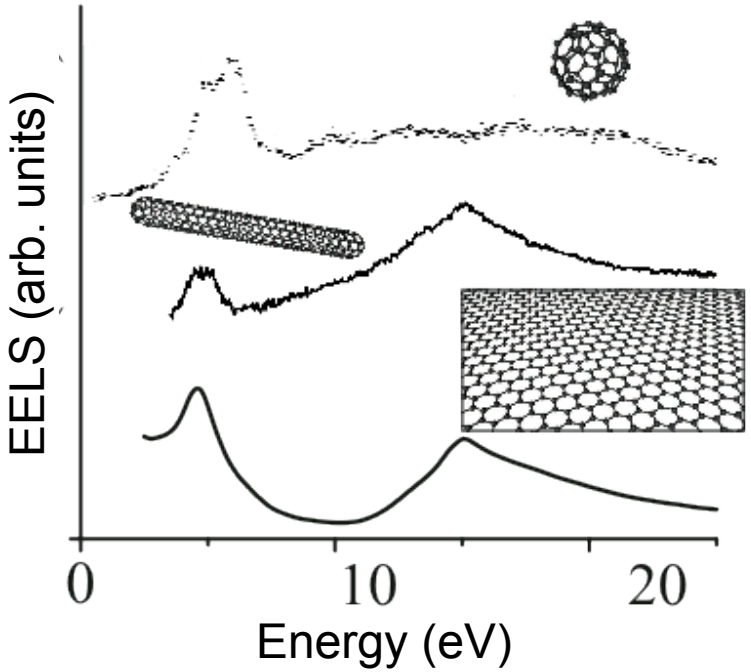
Graphene plasmons

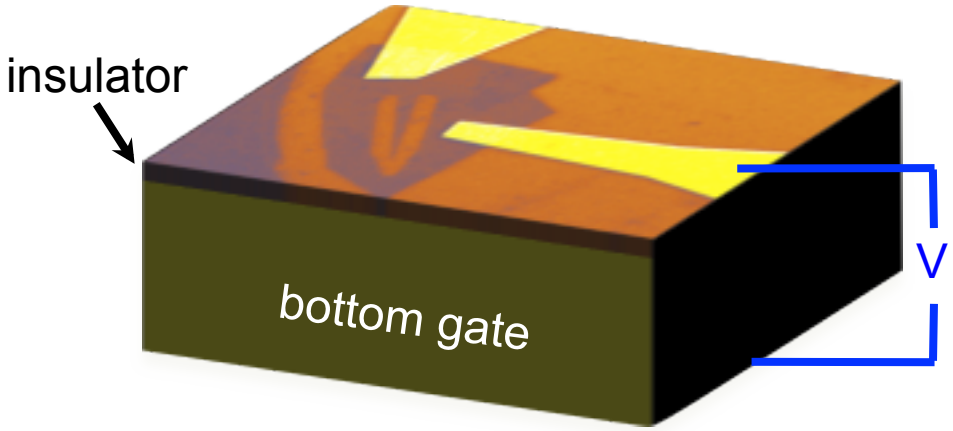


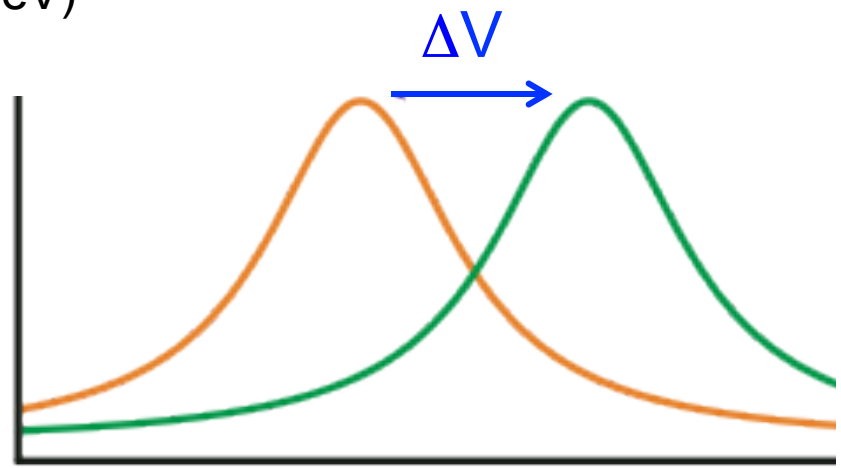




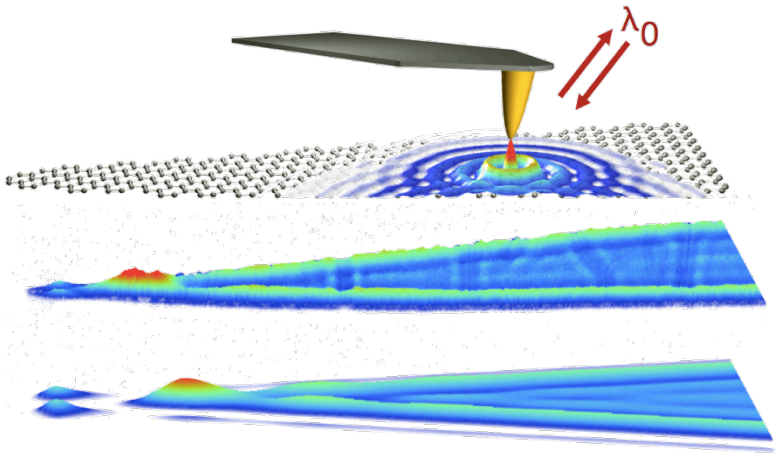
Graphene plasmons

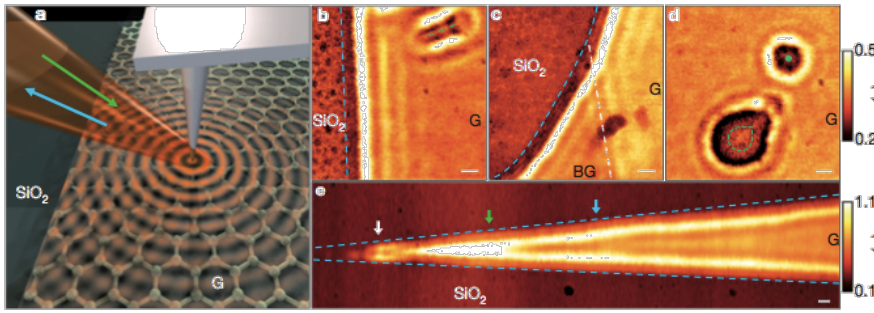






Experimental demonstration of spatial mapping and electrical tunability of graphene plasmons

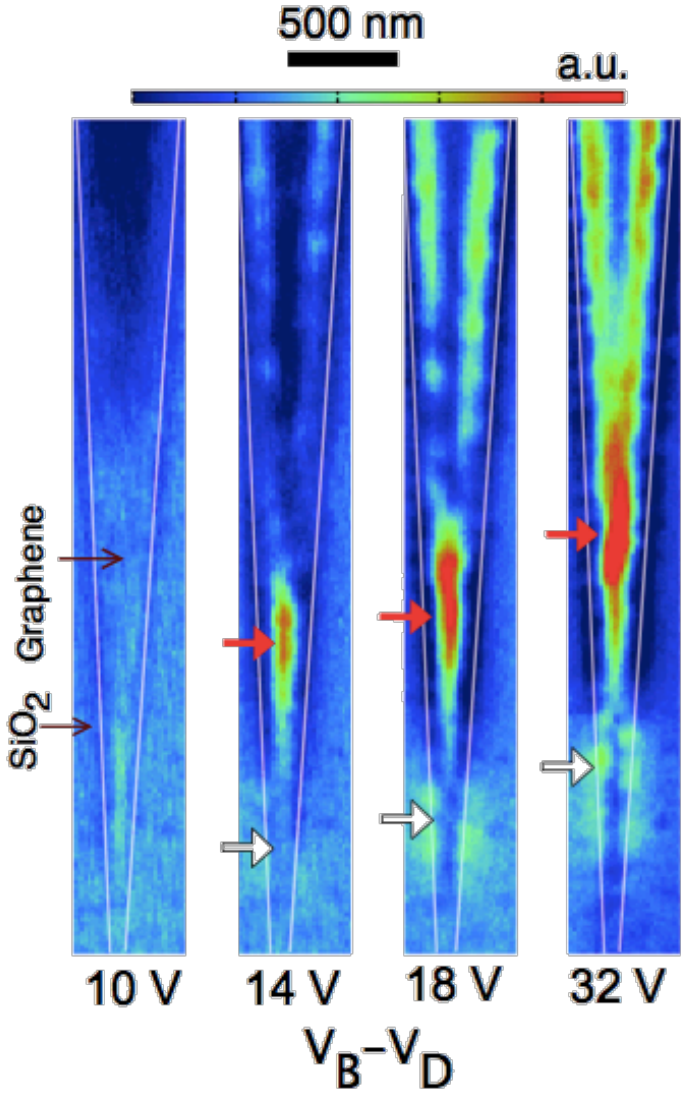


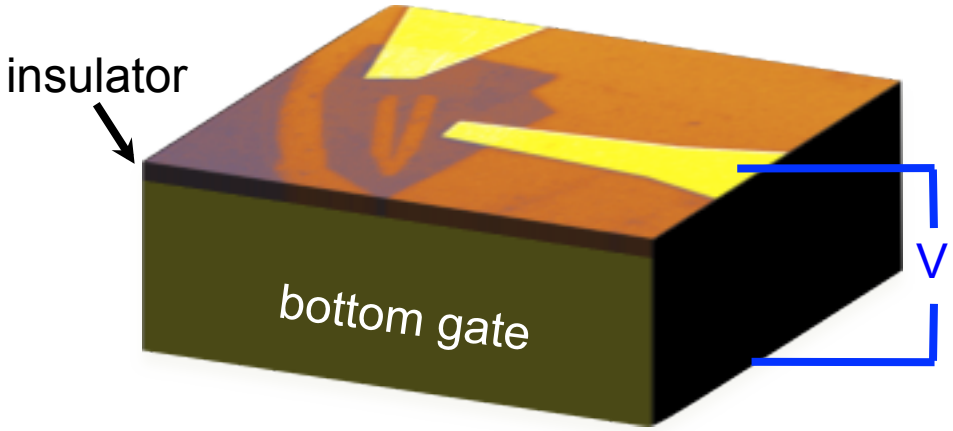


Chen *et al*., Nature (2012)

Basov's group Fei *et al*., Nature (2012)

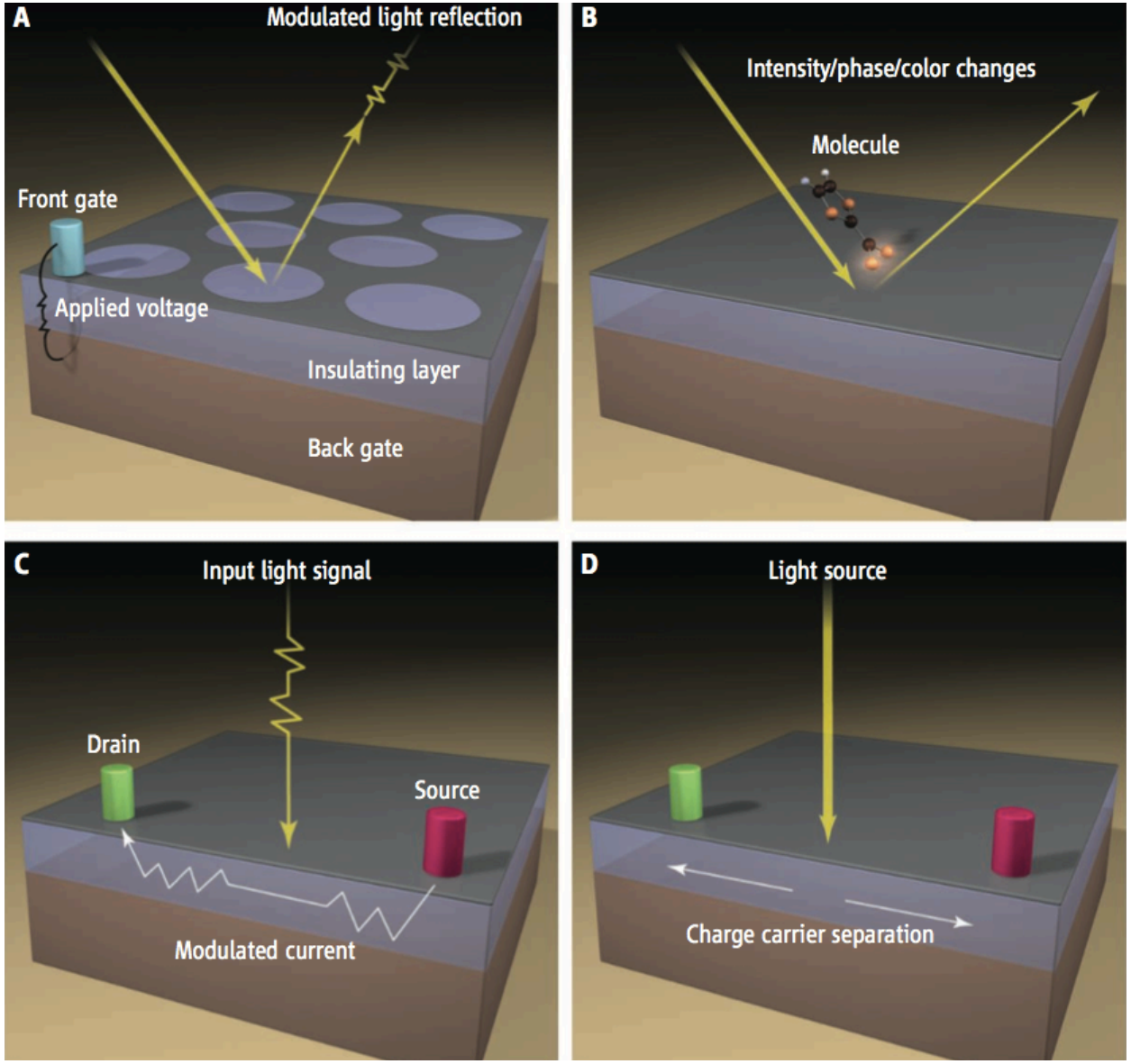
Experimental mapping of graphene plasmons





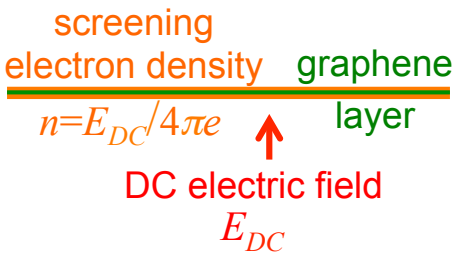
Chen *et al.*, Nature (2012)
Fei *et al.*, Nature (2012)

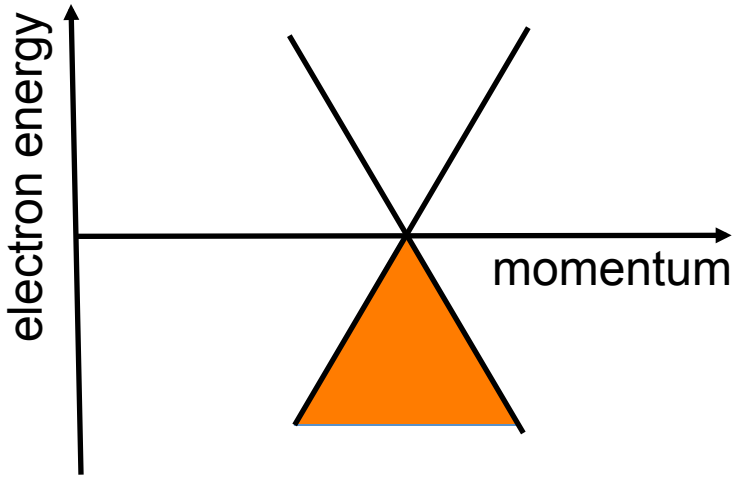
Graphene plasmons perspectives



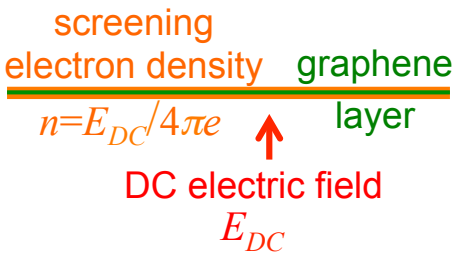
García de Abajo, Science (2013)

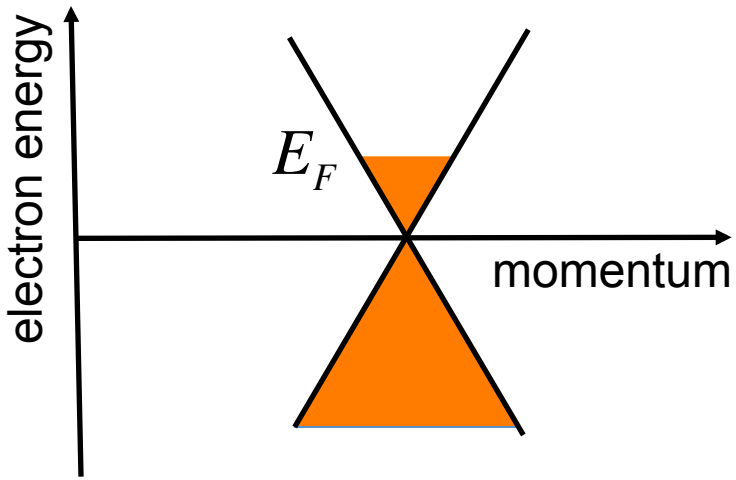
Electrostatic doping of graphene





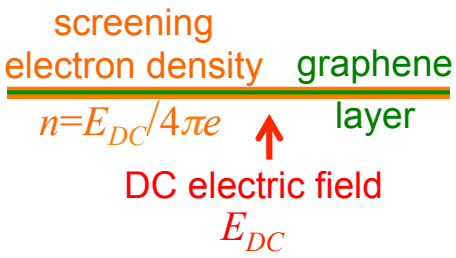
Electrostatic doping of graphene

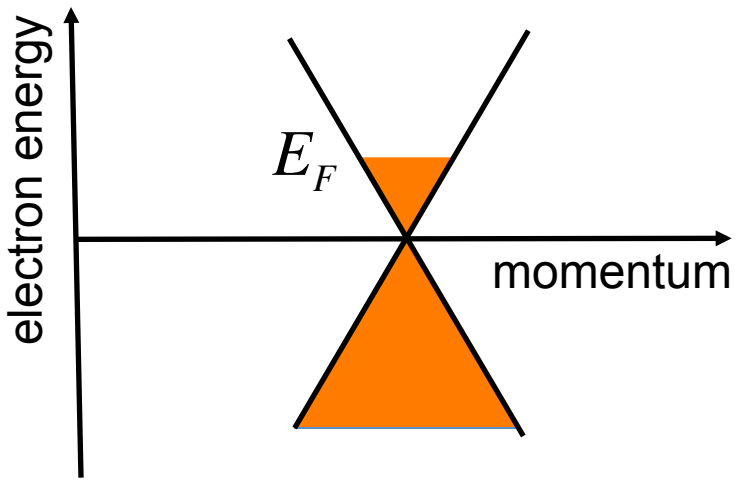




$$\sigma \approx \frac{e^2 E_F}{\hbar^2 \pi} \frac{i}{\omega + i\tau^{-1}}$$

Electrostatic doping of graphene

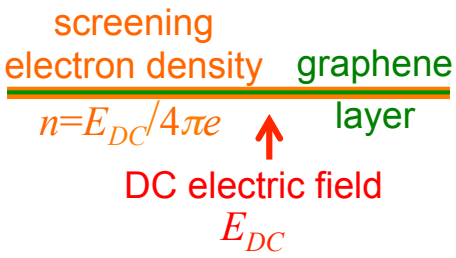


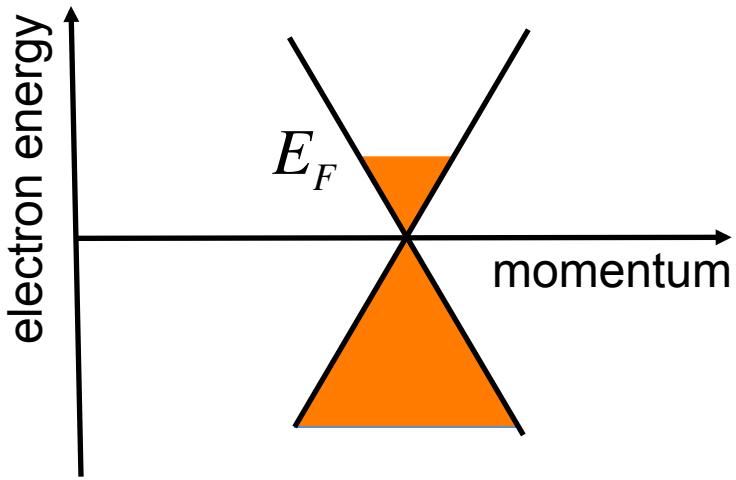


$$\sigma \approx \frac{e^2 E_F}{\hbar^2 \pi} \frac{i}{\omega + i\tau^{-1}}$$

$$\lambda_{sp} = \frac{-2\pi i \sigma}{c} \lambda_0$$

Electrostatic doping of graphene

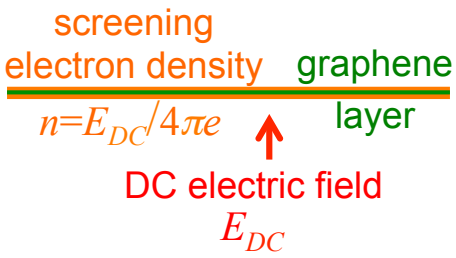


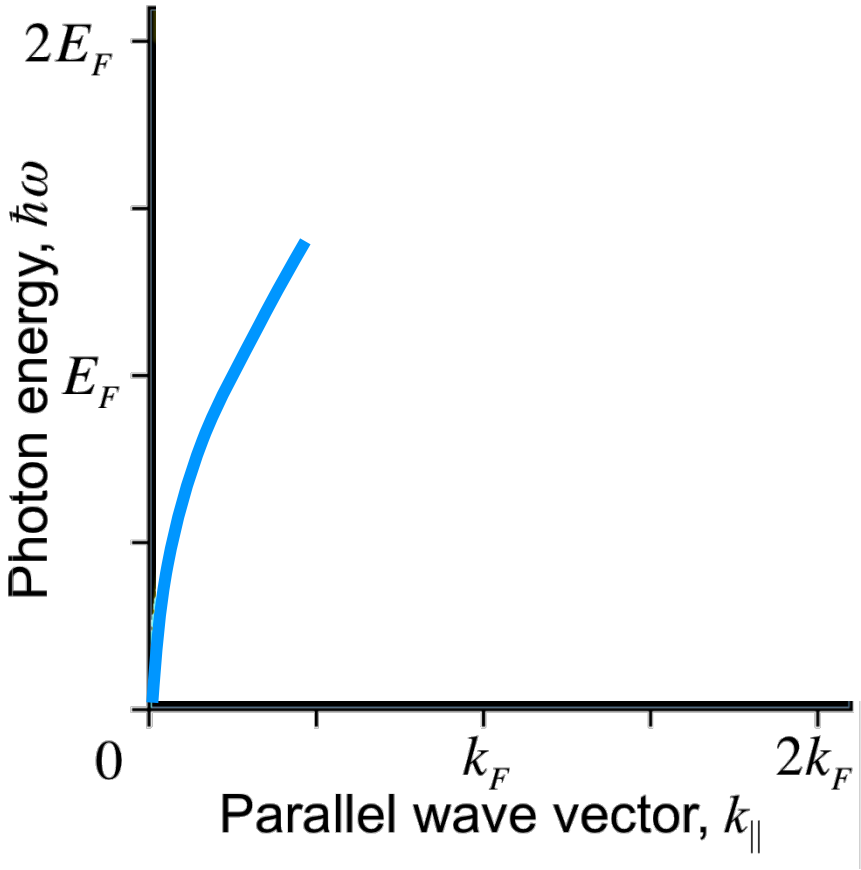


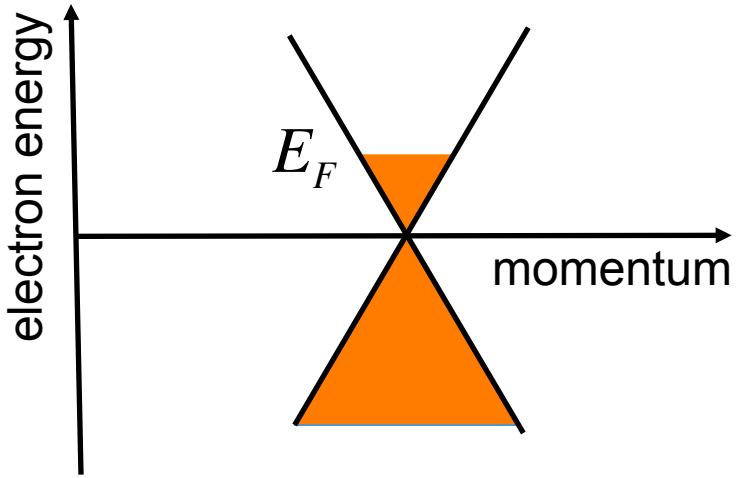
$$\sigma \approx \frac{e^2 E_F}{\hbar^2 \pi} \frac{i}{\omega + i\tau^{-1}}$$

$$\lambda_{sp} = 2\alpha \frac{E_F}{\hbar\omega} \lambda_0$$

Electrostatic doping of graphene

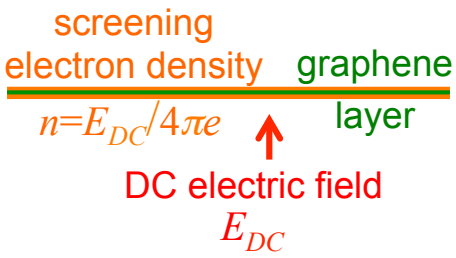


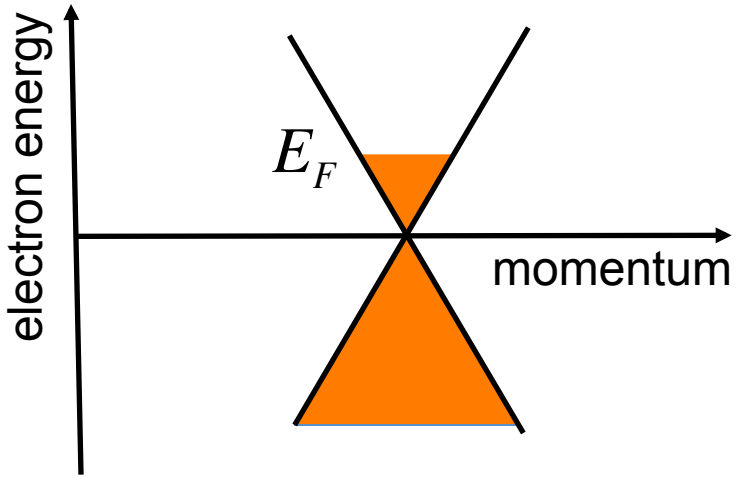


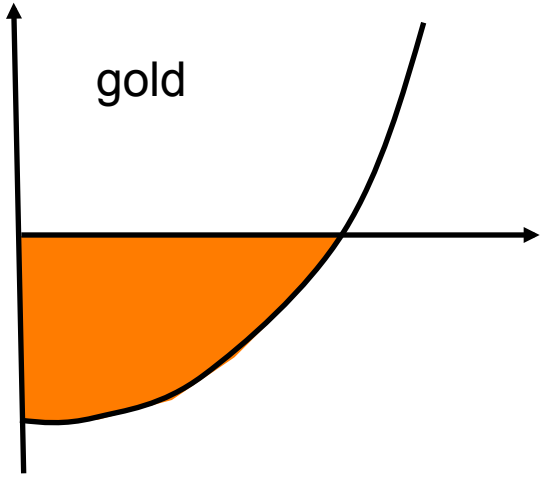


$$\lambda_{sp} = 2\alpha \frac{E_F}{\hbar\omega} \lambda_0$$

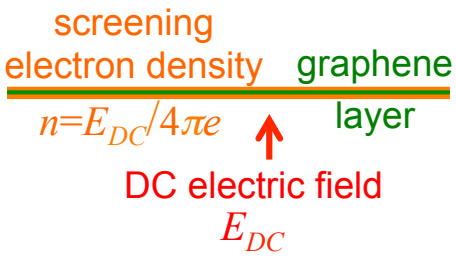
Electrostatic doping of graphene

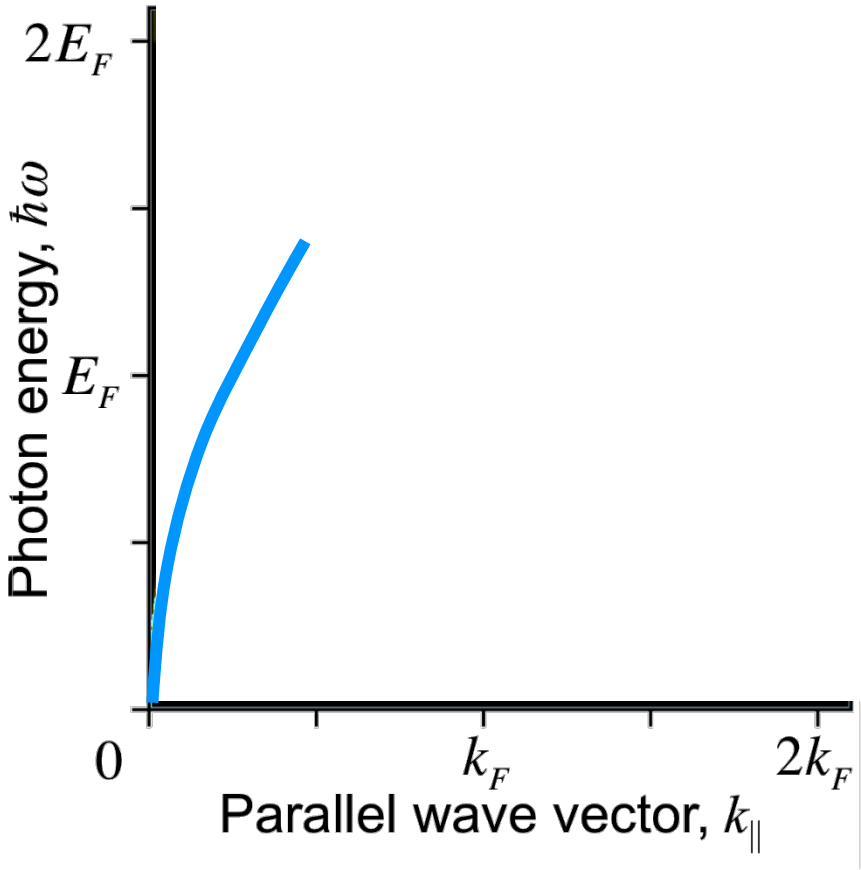


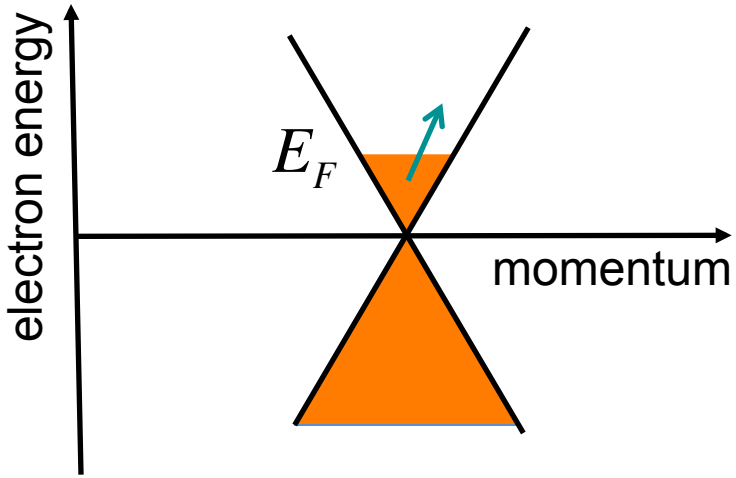




Electrostatic doping of graphene

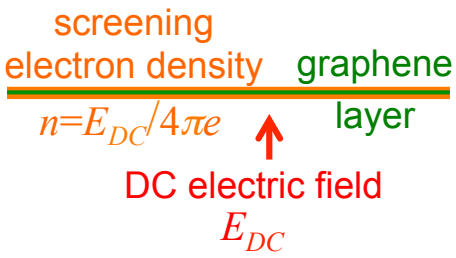


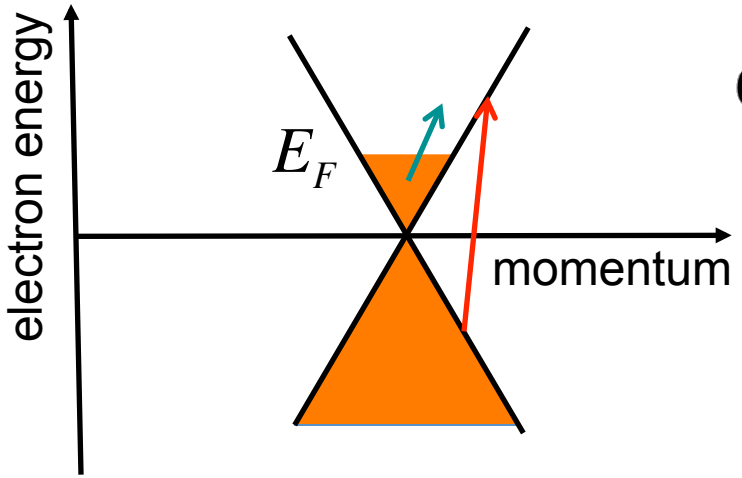


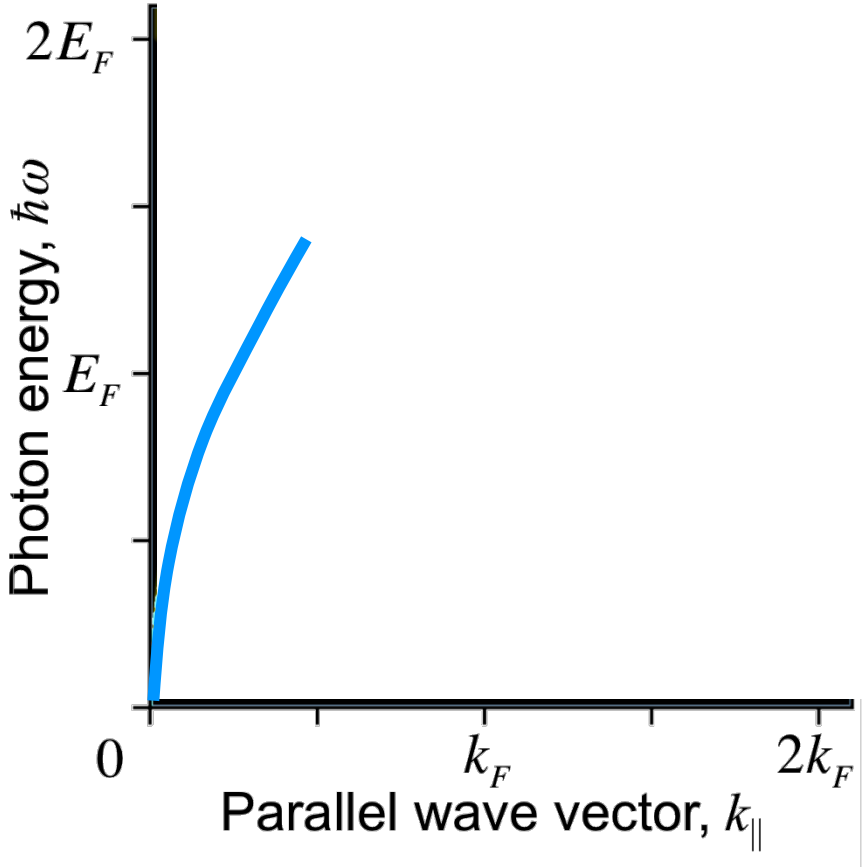


$$\lambda_{sp} = 2\alpha \frac{E_F}{\hbar\omega} \lambda_0$$

Electrostatic doping of graphene







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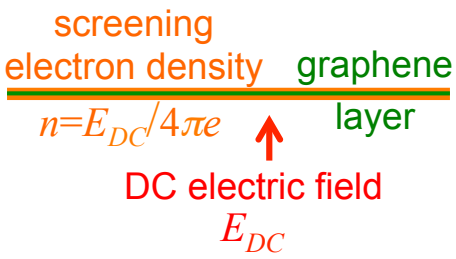
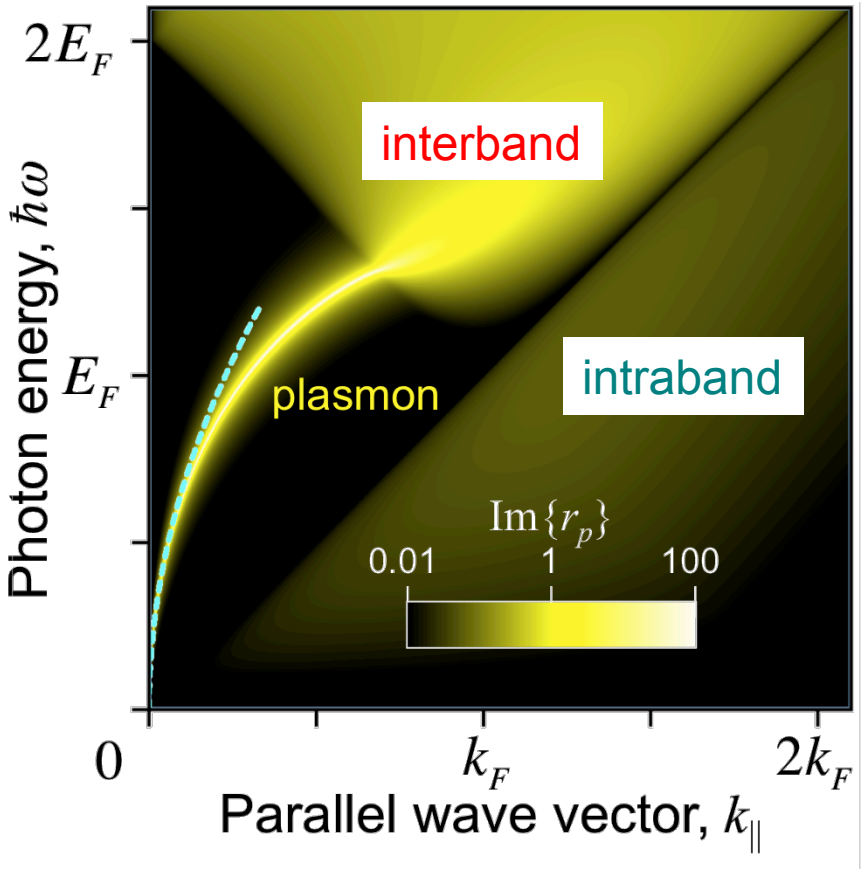
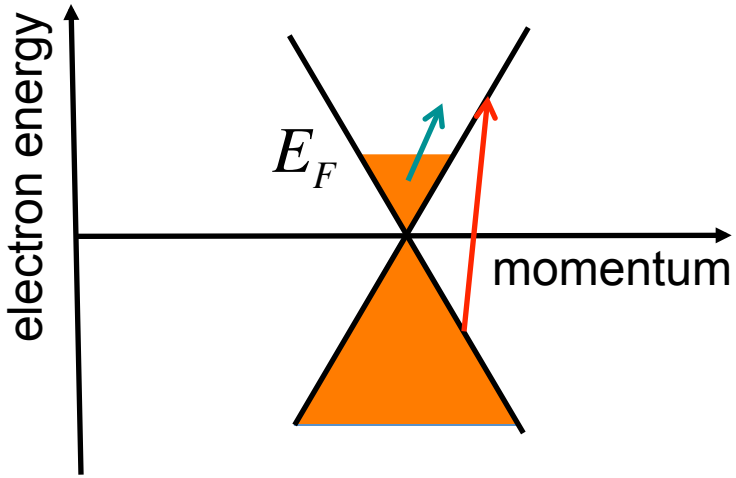
Electrostatic doping of graphene



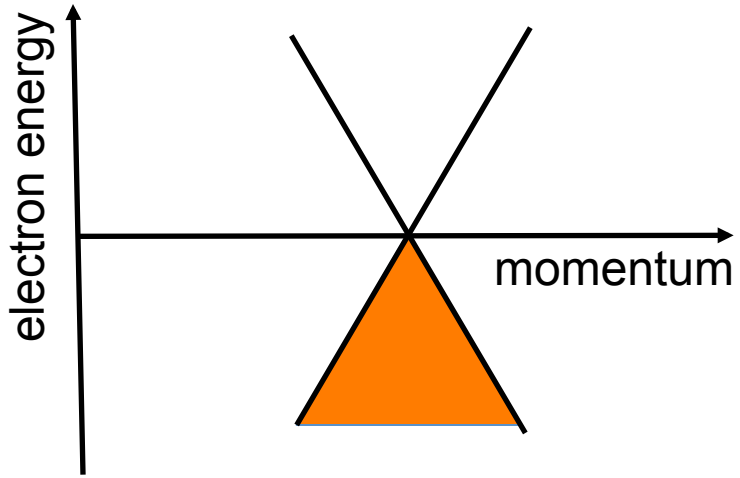




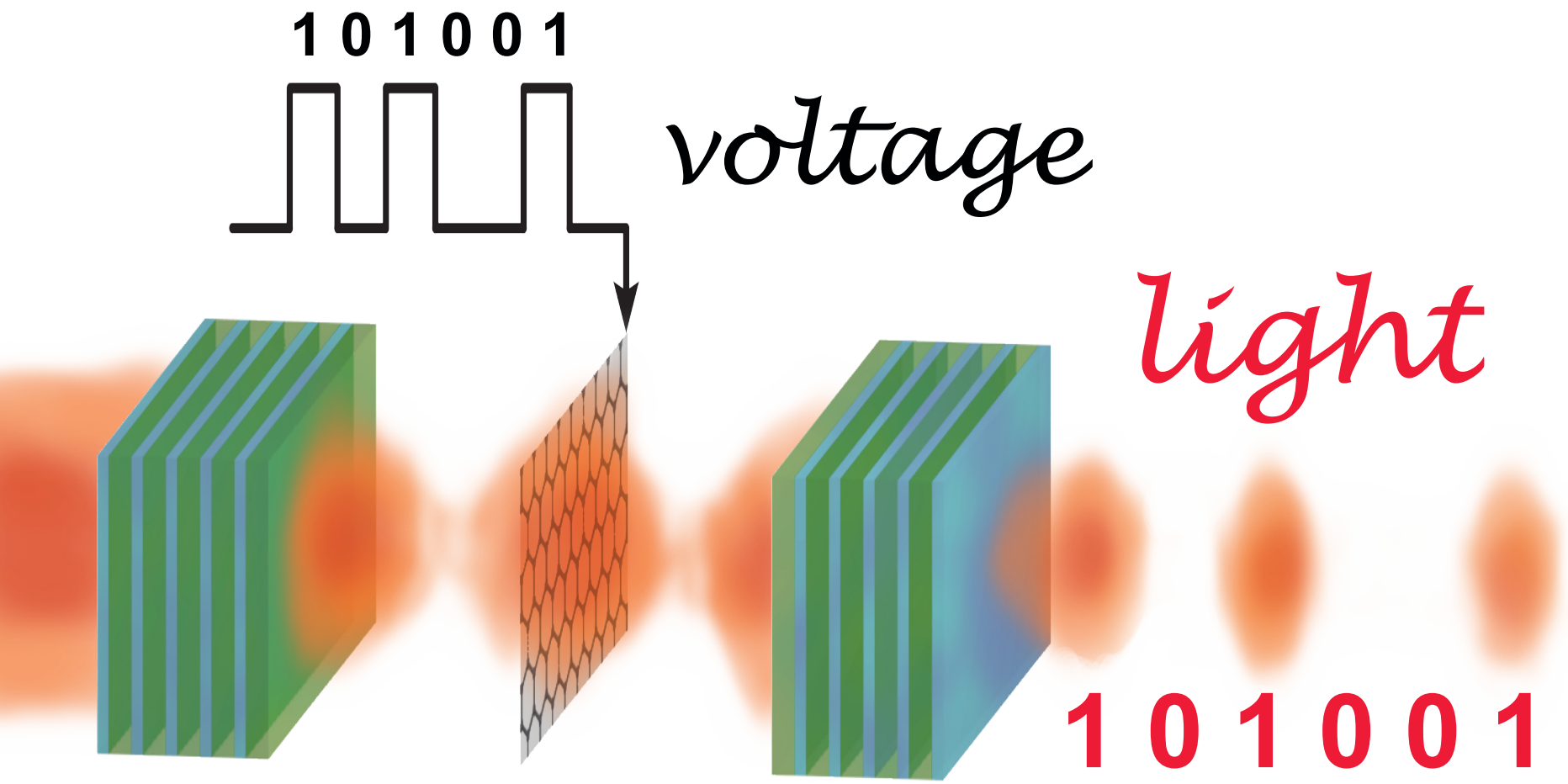
$$\lambda_{sp} = 2\alpha \frac{E_F}{\hbar\omega} \lambda_0$$

Electrostatic doping of graphene

$$\sigma \approx \frac{e^2}{4\hbar} \quad \Rightarrow \quad \text{Absorption} \approx \pi\alpha \approx \frac{\pi}{137}$$

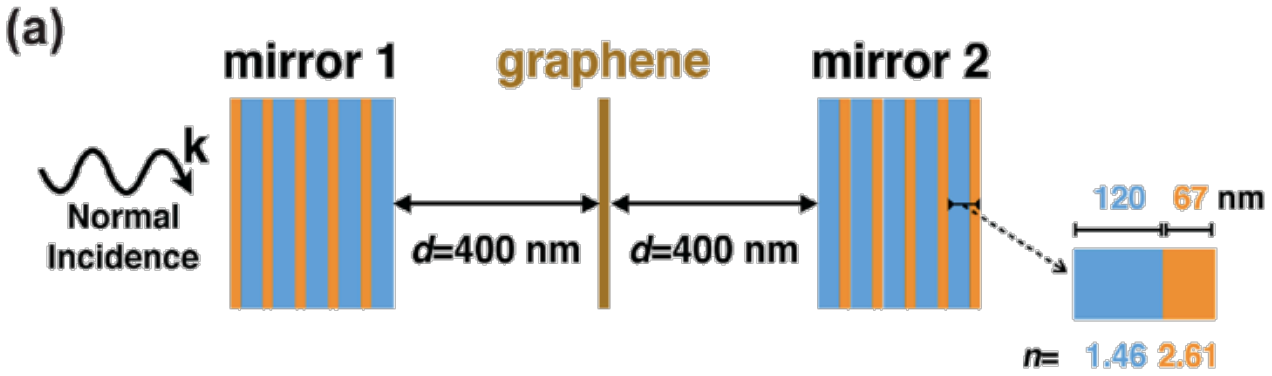


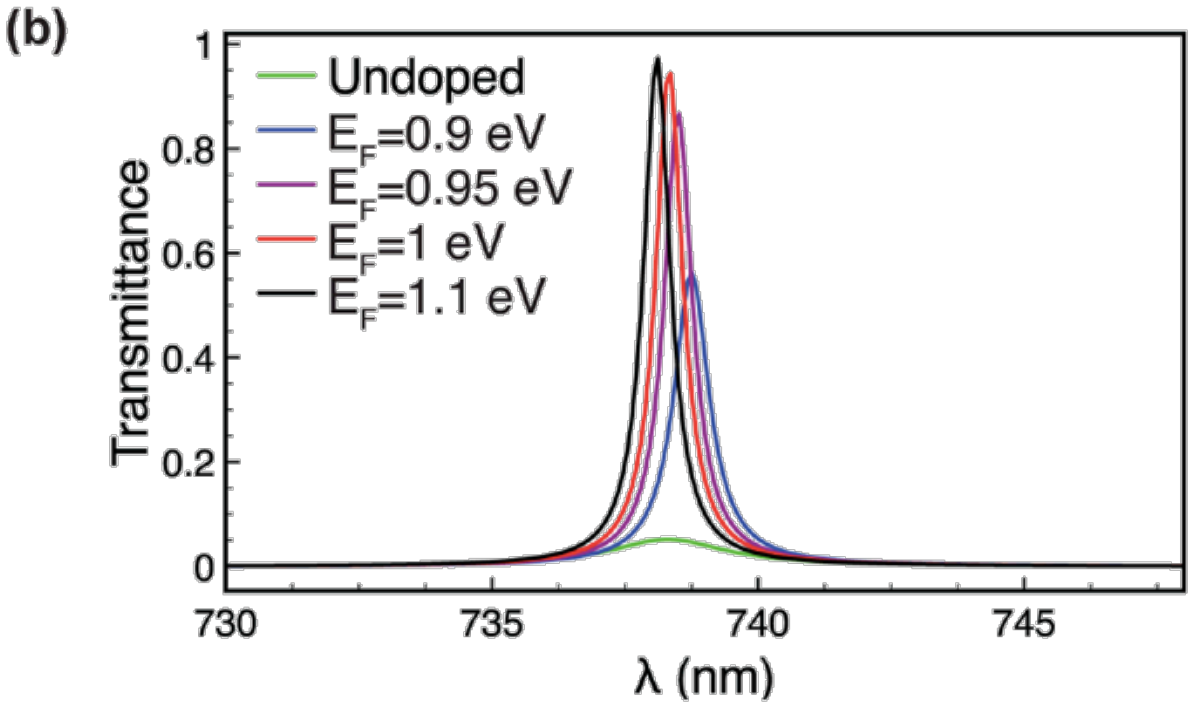
Optical modulation with graphene



Yu *et al.*, ACS Photonics **2**, 550 (2015)

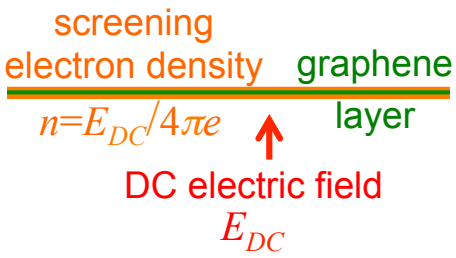
Optical modulation with graphene

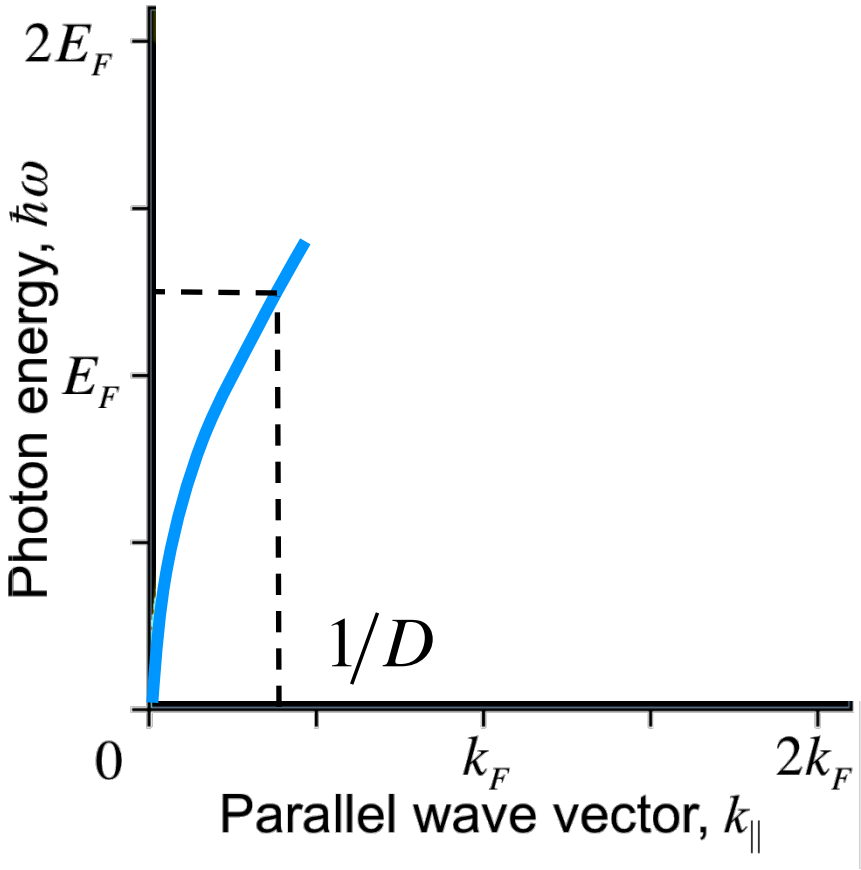


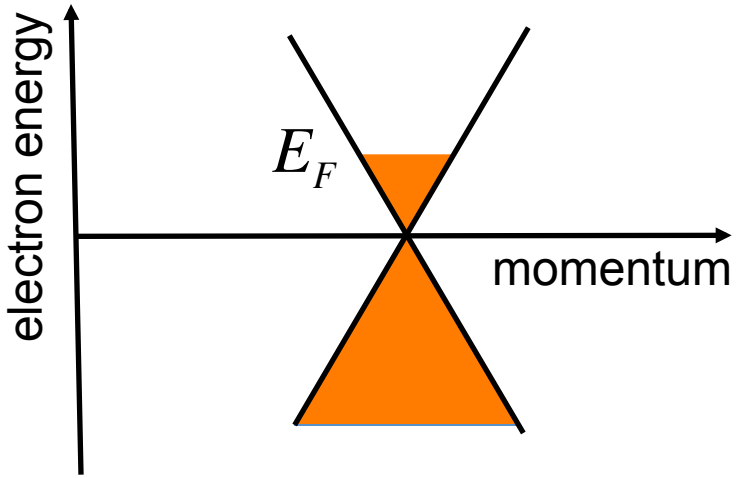


Yu *et al.*, ACS Photonics **2**, 550 (2015)

Electrostatic doping of graphene

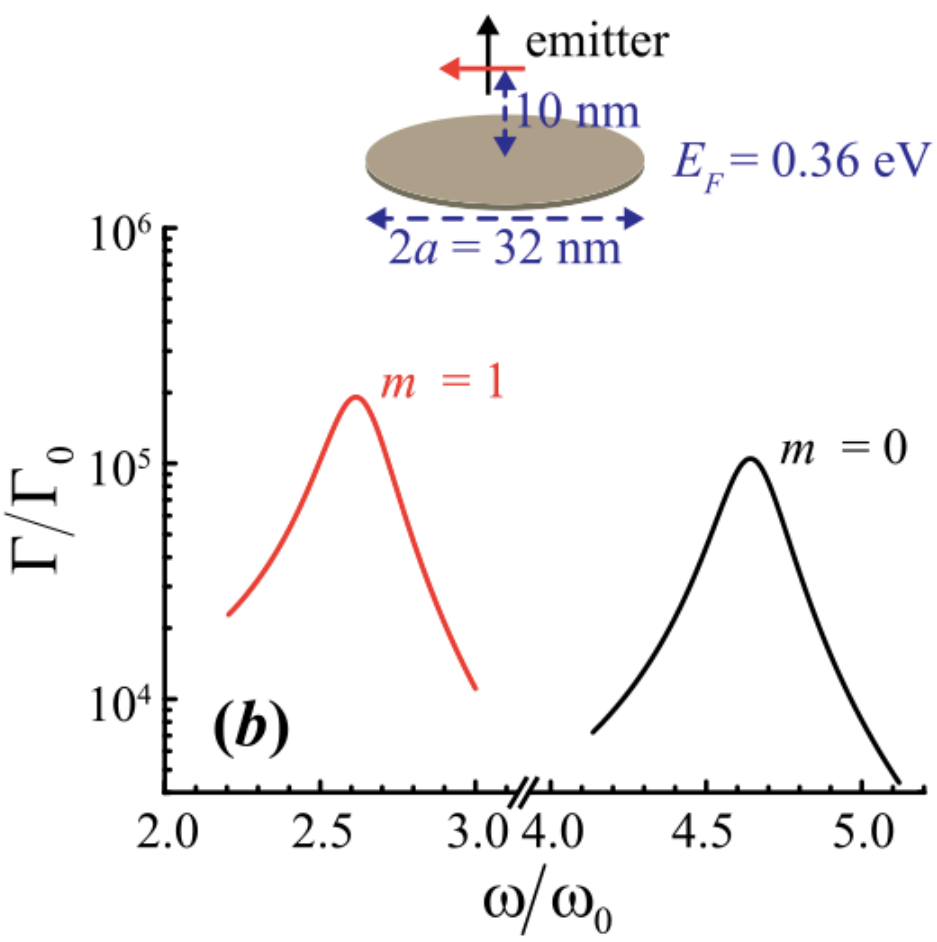


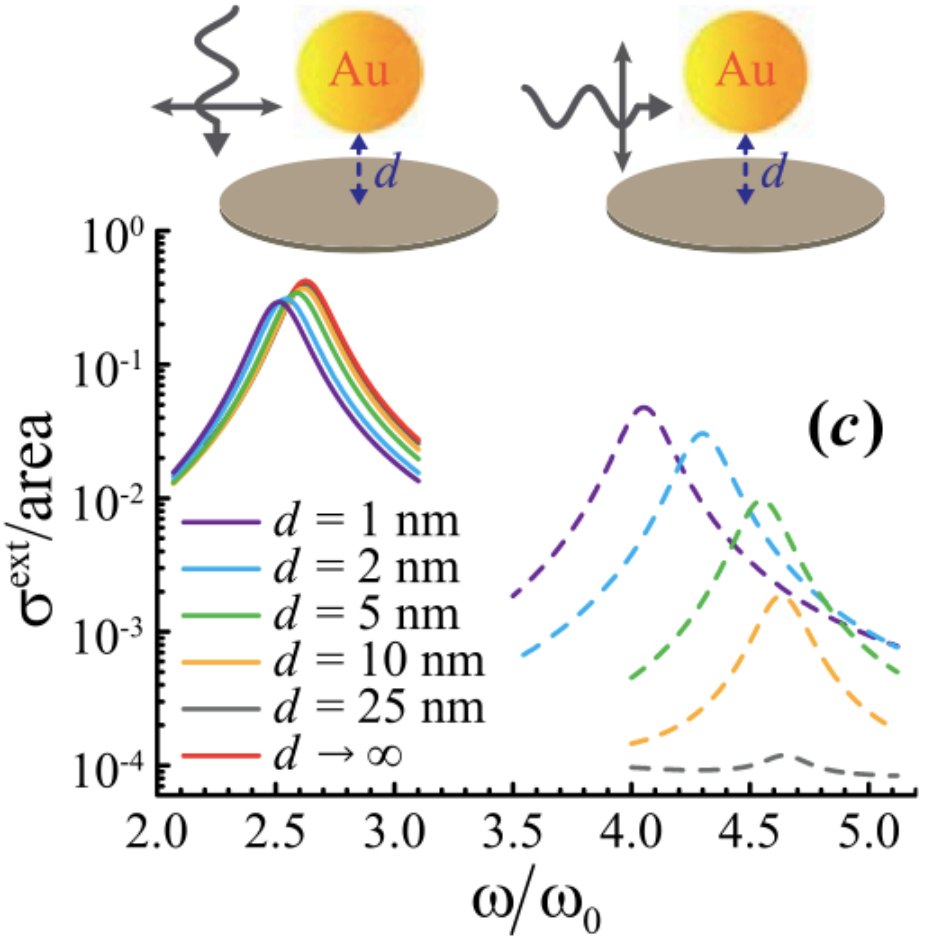




$$\lambda_{sp} = 2\alpha \frac{E_F}{\hbar\omega} \lambda_0$$

Plasmons in graphene nanodisks





Silveiro and García de Abajo, APL (2014)

Plasmonics:
An overview and some new trends

Introduction to plasmons

Graphene plasmons

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- **Classical description**
- **Complete optical absorption**
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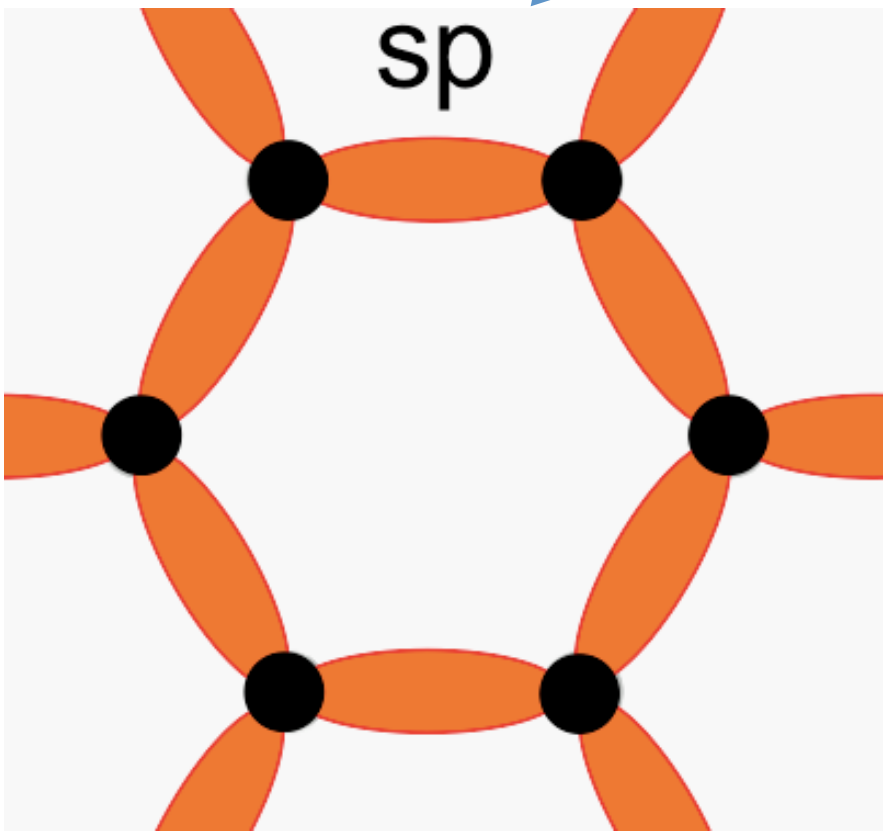
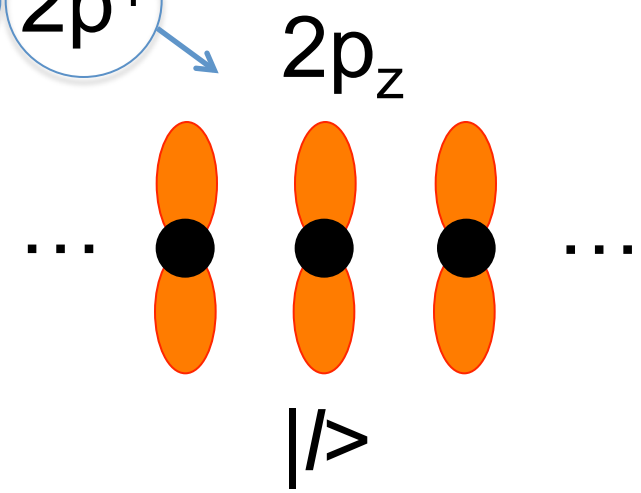
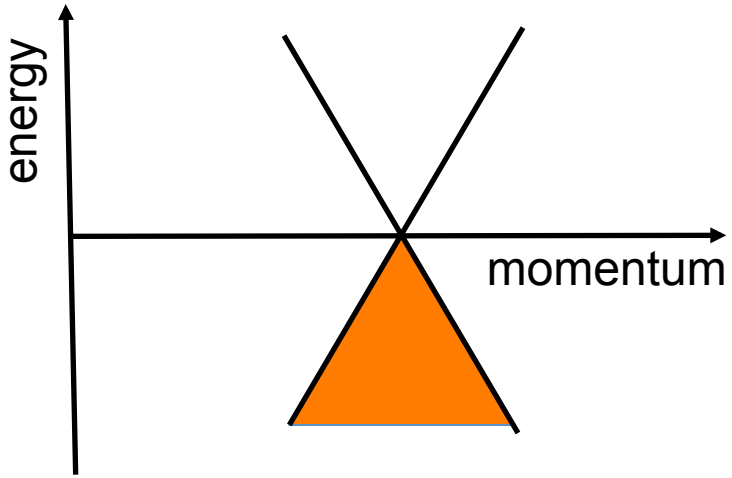
Plasmons in other atomically thin materials

Quantum description of graphene plasmons

$1s^2\,2s^2\,2p^2 \rightarrow 1s^2\,(2sp^2)^3\,2p^1$







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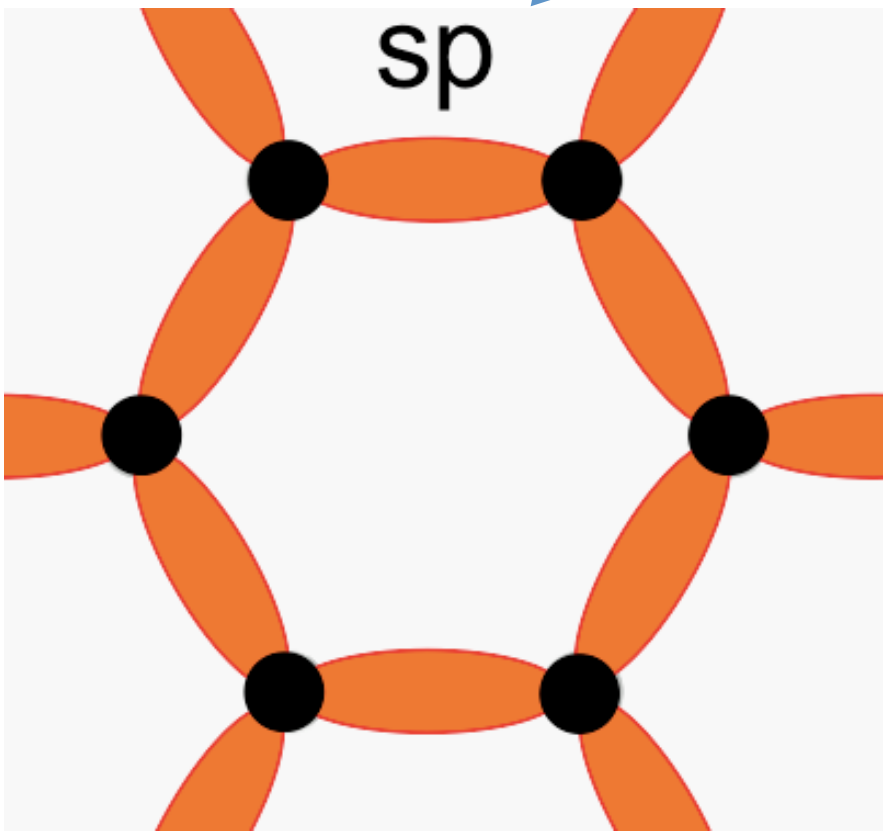
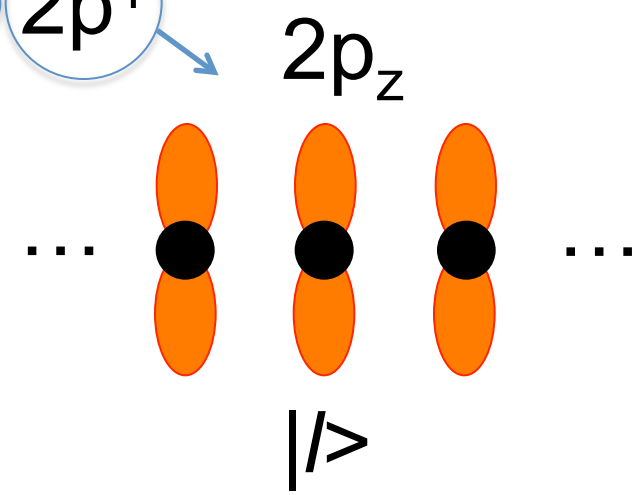
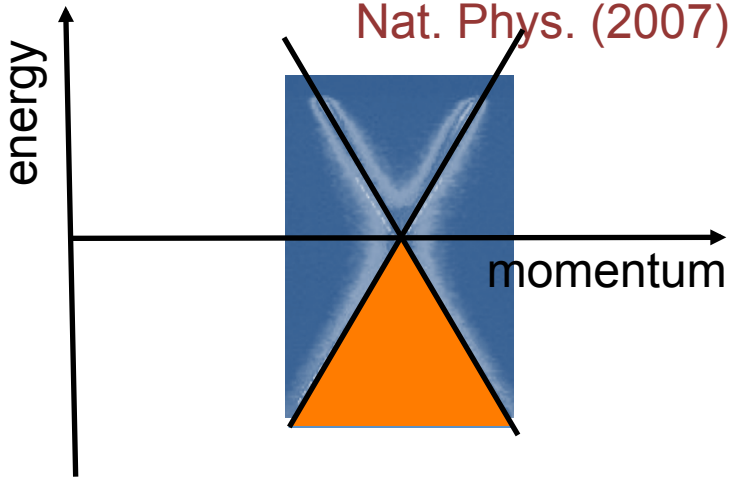




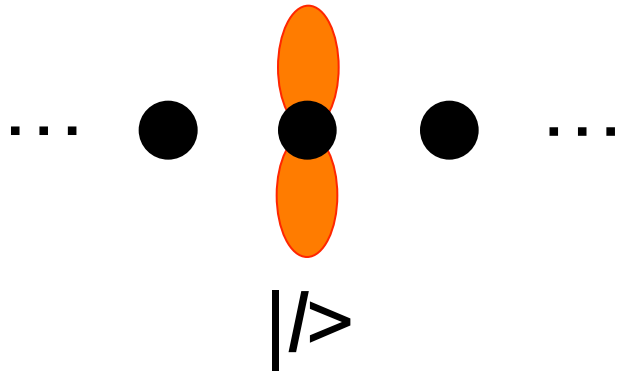
Bostwick *et al.*, Nat. Phys. (2007)



Quantum description of graphene plasmons

Electron state j
of energy ε_j

$$\sum_l a_{jl} |l\rangle$$

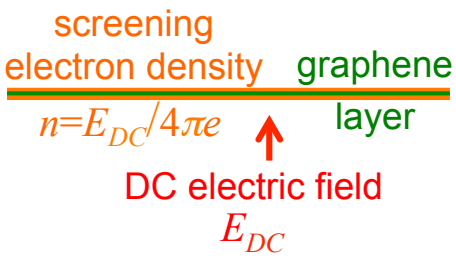


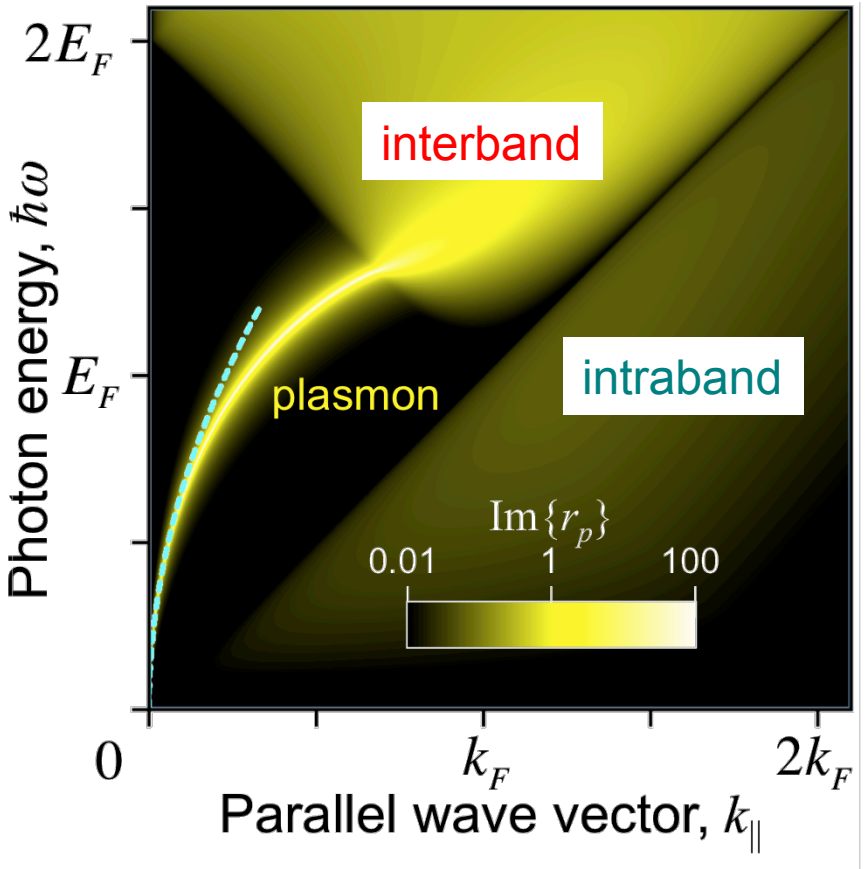
RPA response

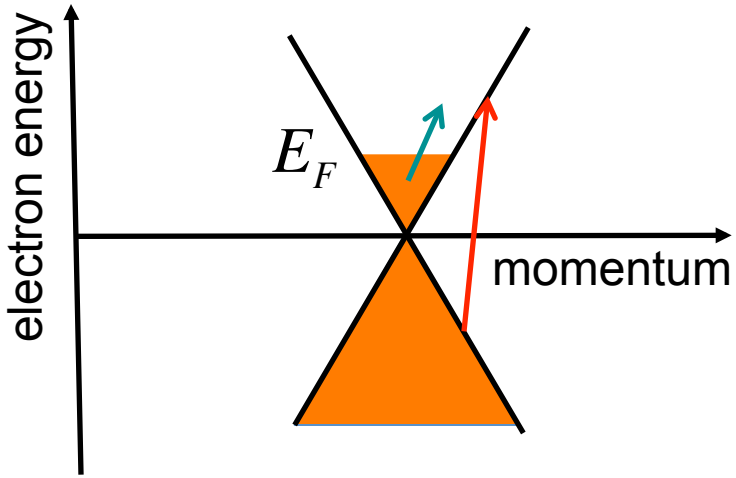
$$\chi^0_{ll'}(\omega) = \frac{2e^2}{\hbar} \sum_{jj'} (f_{j'} - f_j) \frac{a_{jl} a^*_{jl'} a^*_{j'l} a_{j'l'}}{\omega - (\varepsilon_j - \varepsilon_{j'}) + i/2\tau}$$

Thongrattanasiri *et al*., ACS Nano (2012)

Electrostatic doping of graphene

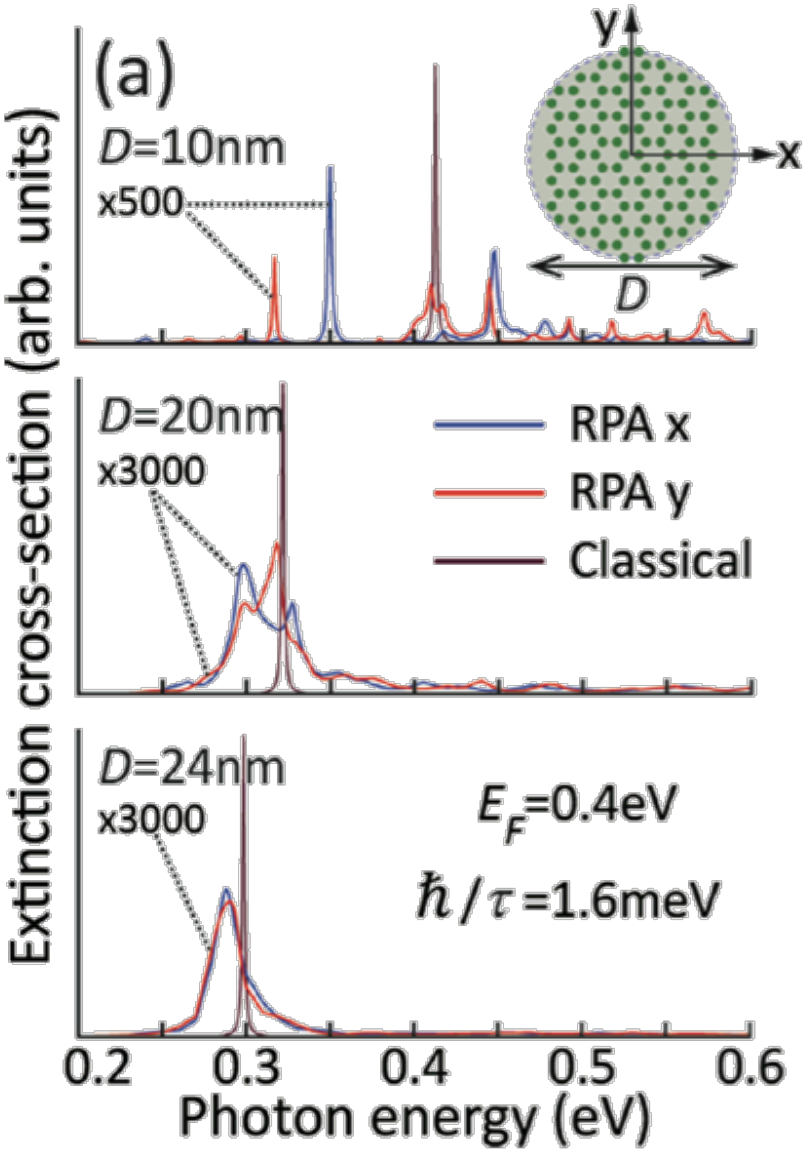


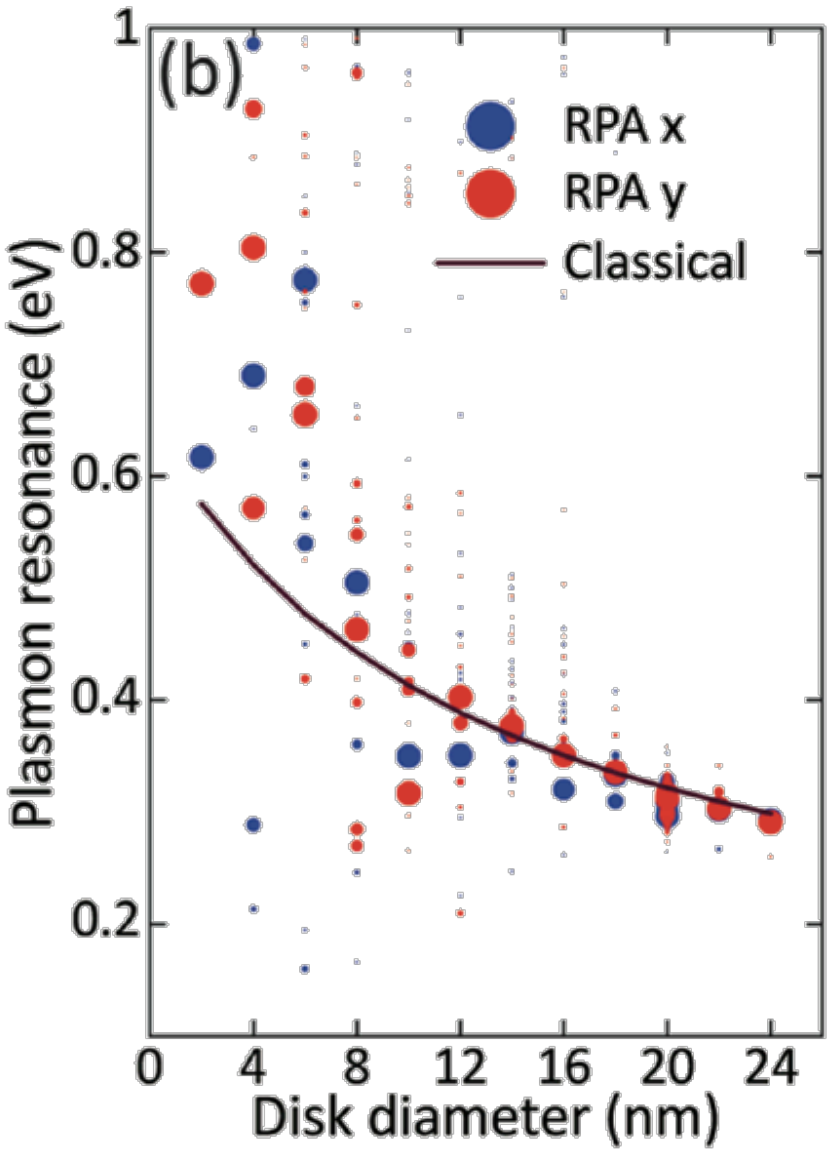




$$\lambda_{sp} = 2\alpha \frac{E_F}{\hbar\omega} \lambda_0$$

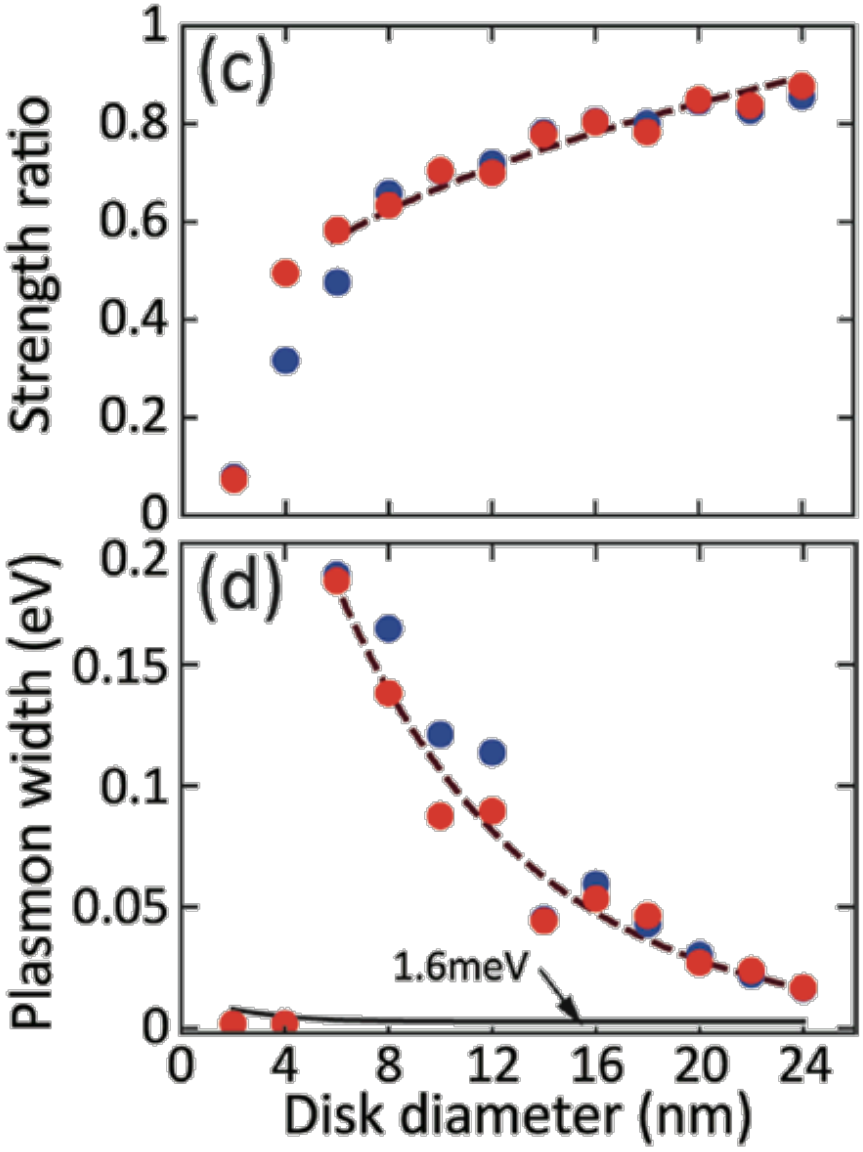
Quantum effects in graphene plasmons

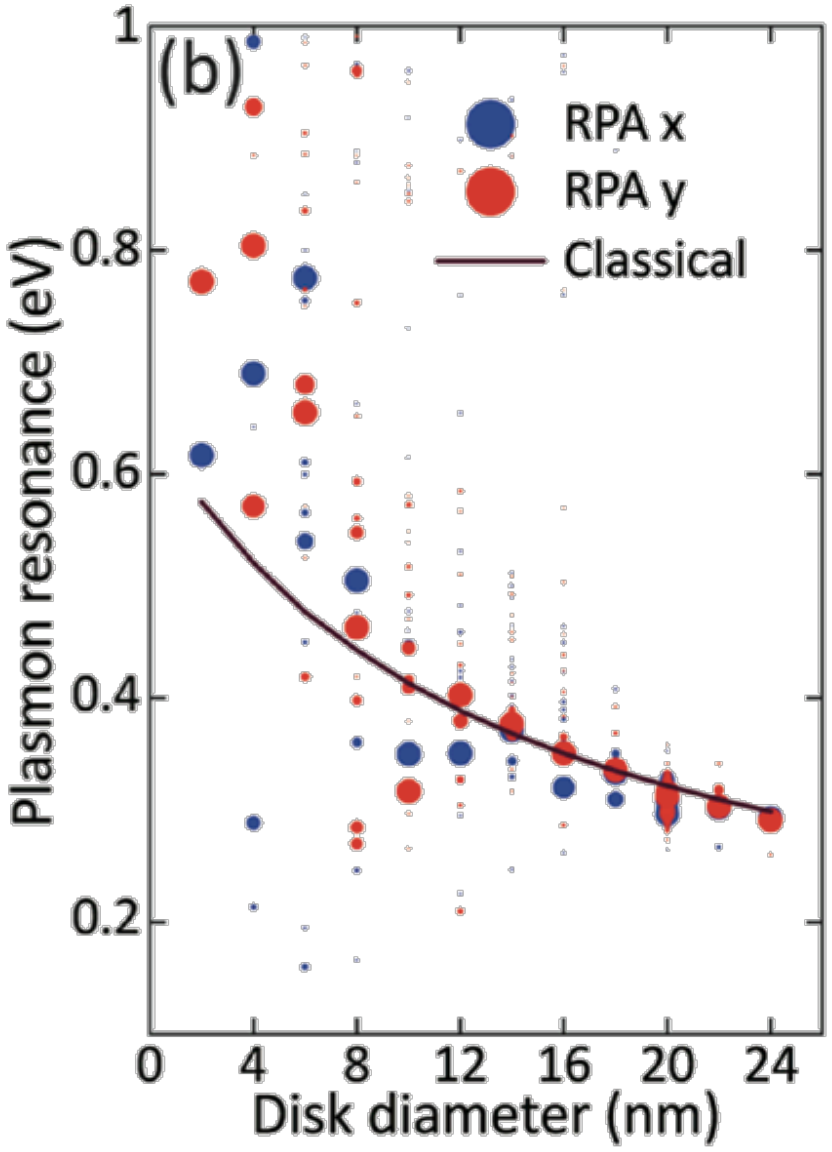




Thongrattanasiri *et al.*, ACS Nano (2012)

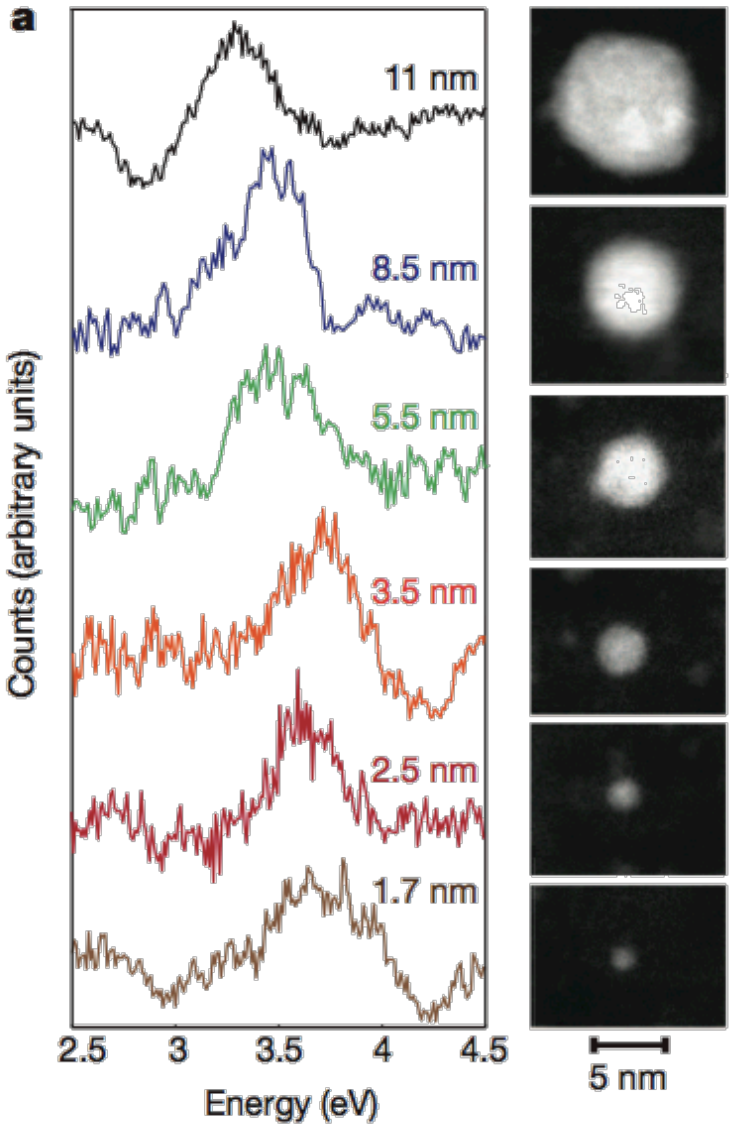
Quantum effects in graphene plasmons

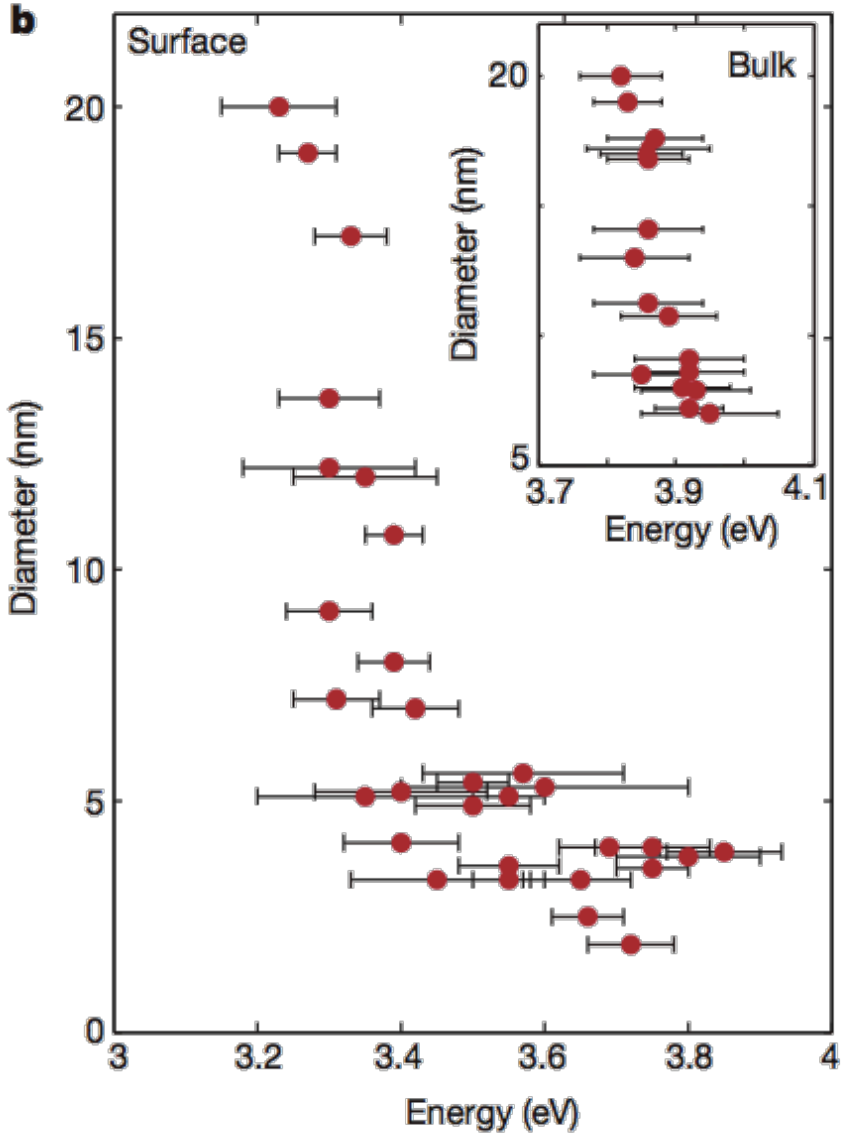




Thongrattanasiri *et al*., ACS Nano (2012)

Quantum effects in silver nanoplasmons

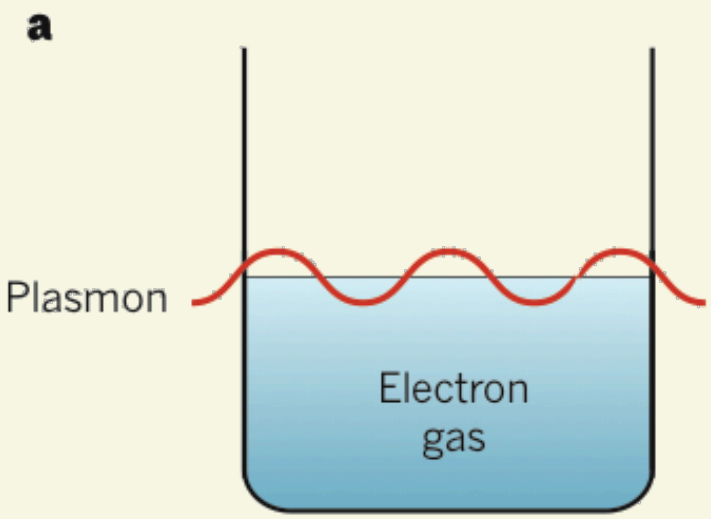


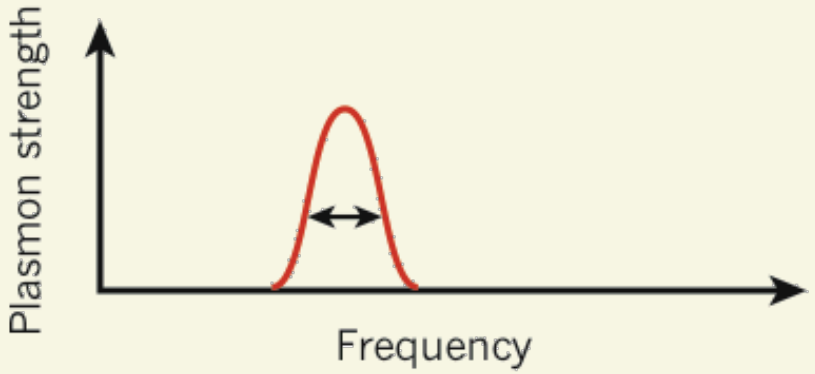


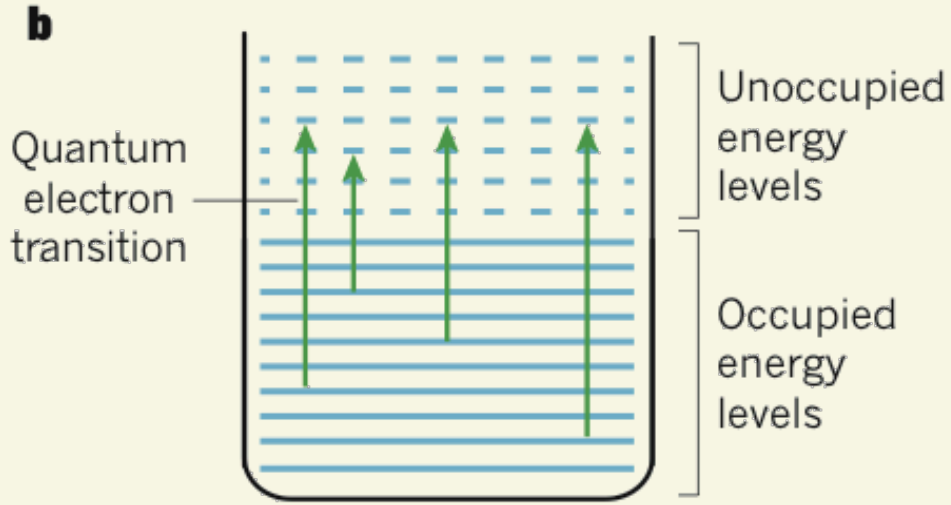
Scholl, Koh, and Dionne, Nature (2012)

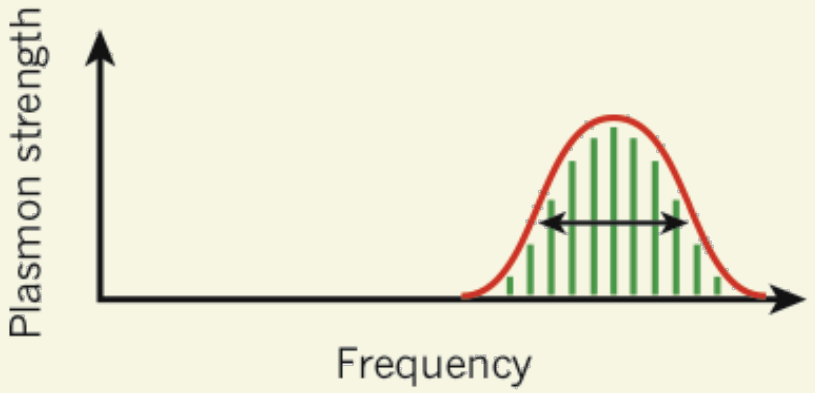
Quantum-classical transition

News and Views, Nature **483**, 861 (2012)









Electron state j
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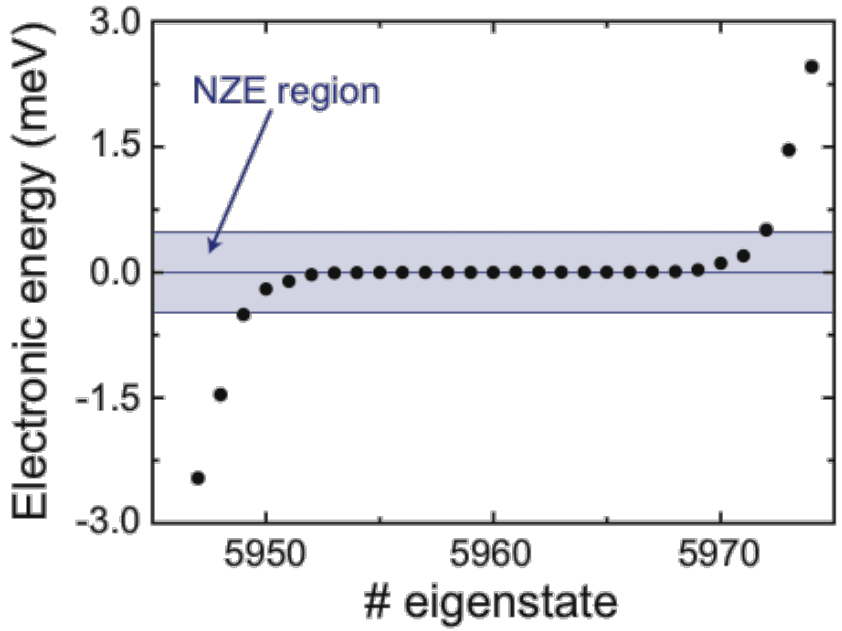
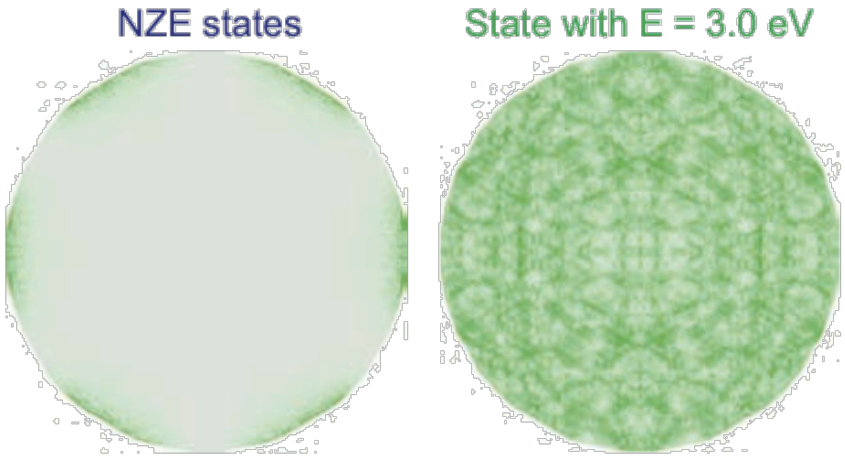
$$\sum_l a_{jl} |l\rangle$$

(a)

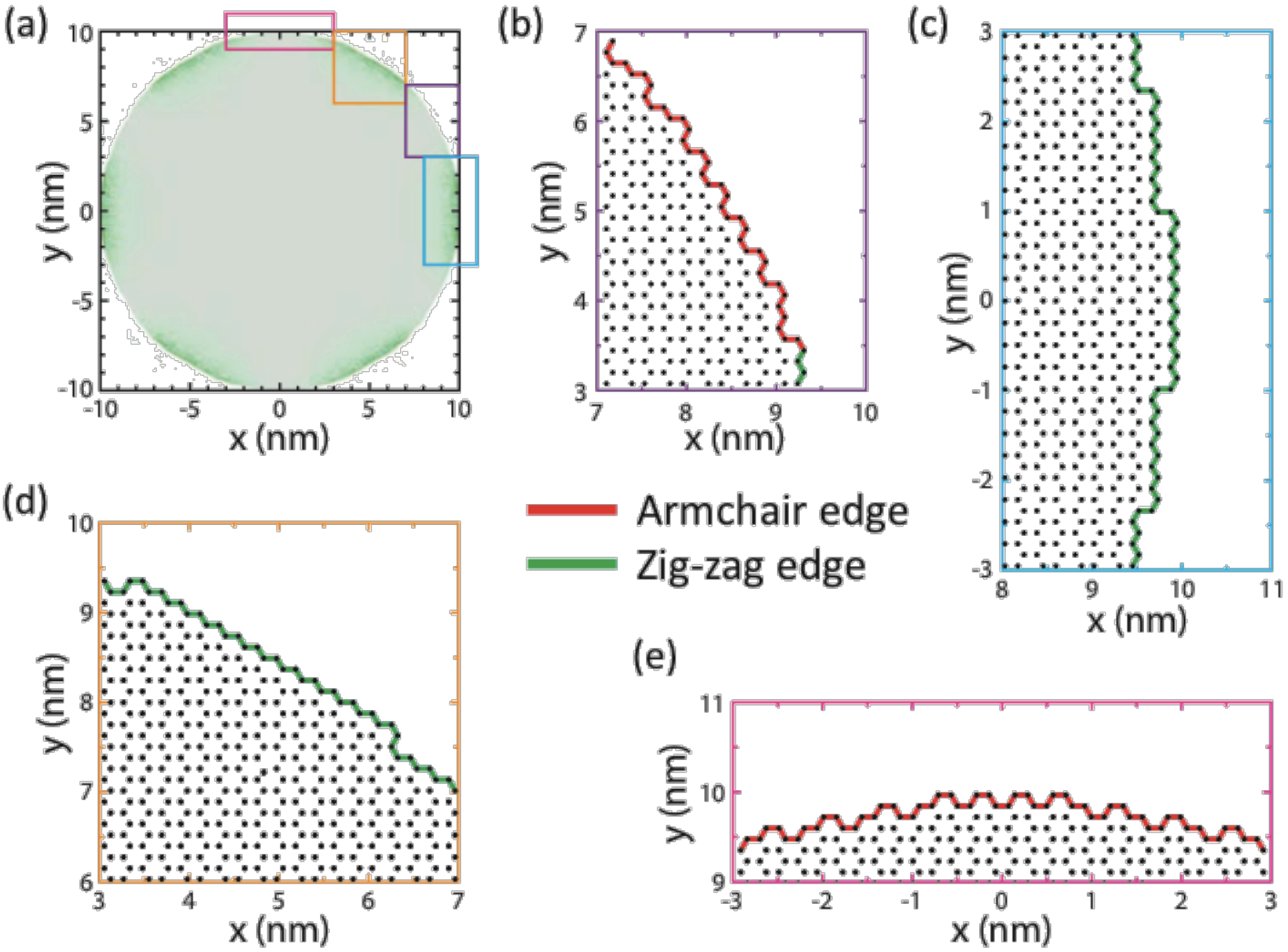


(b)



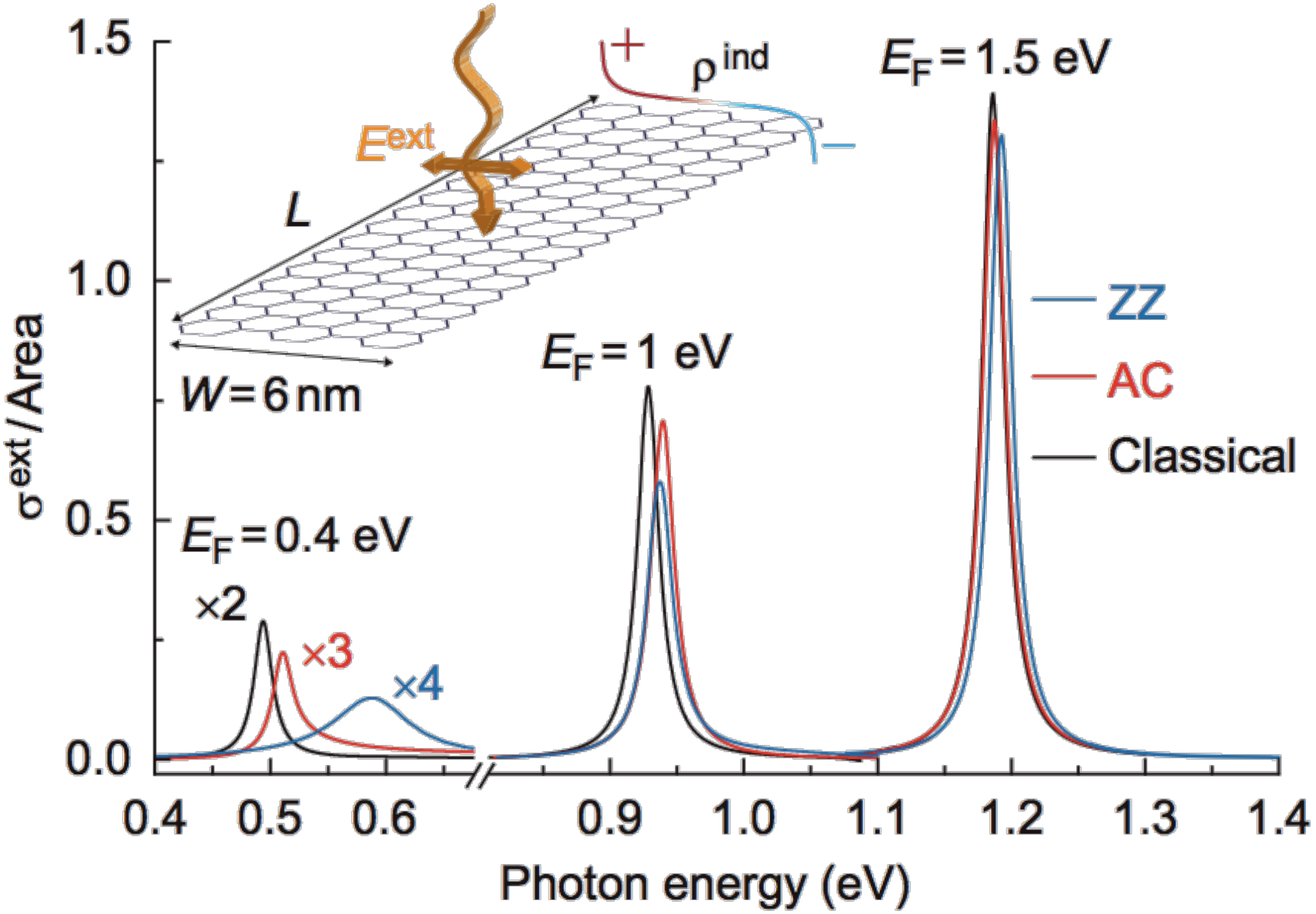
Thongrattanasiri *et al.*, ACS Nano (2012)

Quantum effects in graphene plasmons



Thongrattanasiri *et al*., ACS Nano (2012)

Quantum description of graphene plasmons



Silveiro *et al.*, Light: Sci. & Appl. (2015)

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Electrostatic scaling law

$$\phi(\mathbf{R},\omega) = \phi^{\text{ext}}(\mathbf{R},\omega) + \int d\mathbf{R}' \frac{1}{|\mathbf{R}-\mathbf{R}'|} \rho^{\text{ind}}(\mathbf{R}',\omega)$$

García de Abajo, ACS Photonics (2014)

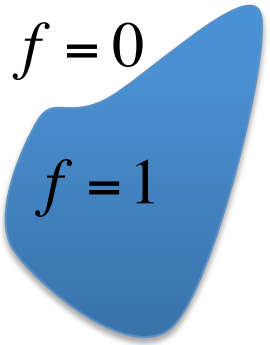
Electrostatic scaling law

$$\phi(\mathbf{R},\omega) = \phi^{\text{ext}}(\mathbf{R},\omega) + \int d\mathbf{R}' \frac{1}{|\mathbf{R}-\mathbf{R}'|}\left[\frac{1}{i\omega}\nabla'\cdot\mathbf{j}^{\text{ind}}(\mathbf{R}',\omega)\right]$$

García de Abajo, ACS Photonics (2014)

Electrostatic scaling law

$$\phi(\mathbf{R},\omega) = \phi^{\text{ext}}(\mathbf{R},\omega) + \int d\mathbf{R}' \frac{1}{|\mathbf{R}-\mathbf{R}'|}\left[\frac{1}{i\omega}\nabla'\cdot f(\mathbf{R})\sigma(\omega)\left(-\nabla'\phi(\mathbf{R}',\omega)\right)\right]$$



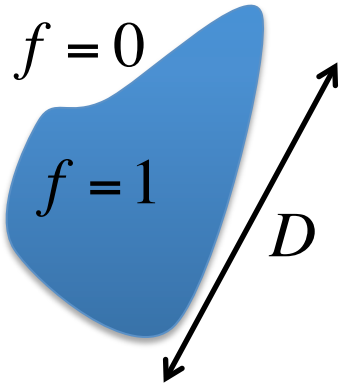
García de Abajo, ACS Photonics (2014)

Electrostatic scaling law

$$\phi(\mathbf{R},\omega) = \phi^{\text{ext}}(\mathbf{R},\omega) + \eta \int d\mathbf{R}' \frac{1}{|\mathbf{R}-\mathbf{R}'|} \nabla' \cdot f(\mathbf{R}') \nabla' \phi(\mathbf{R}',\omega)$$

$$\eta = \frac{i\sigma(\omega)}{\omega D} = \frac{-\omega_0^2}{\omega(\omega + i\tau^{-1})} \qquad \omega_0 = \frac{e}{\hbar}\sqrt{\frac{E_F}{\pi D}}$$

$$\omega_{pl} = \frac{\omega_0}{\sqrt{-\eta}} - i\frac{\tau^{-1}}{2}$$



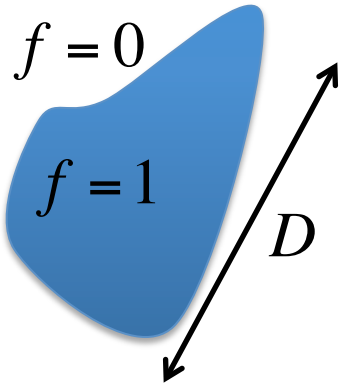
García de Abajo, ACS Photonics (2014)

Electrostatic scaling law

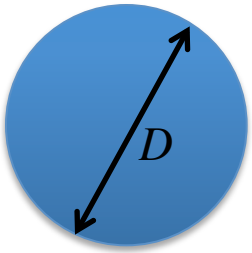
$$\phi(\mathbf{R},\omega)=\phi^{\text{ext}}(\mathbf{R},\omega)+\eta\int d\mathbf{R}'\frac{1}{|\mathbf{R}-\mathbf{R}'|}\nabla'\cdot f(\mathbf{R}')\nabla'\phi(\mathbf{R}',\omega)$$

$$\eta=\frac{i\sigma(\omega)}{\omega D}=\frac{-\omega_0^2}{\omega(\omega+i\tau^{-1})}$$

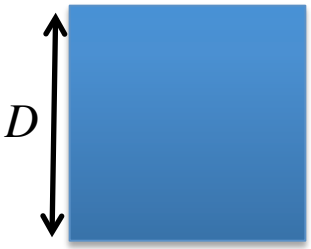
$$\omega_0=\frac{e}{\hbar}\sqrt{\frac{E_F}{\pi D}}$$



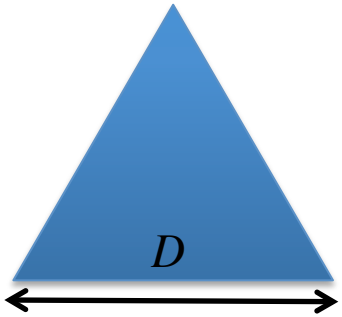
$$\omega_{pl}=\frac{\omega_0}{\sqrt{-\eta}}-i\frac{\tau^{-1}}{2}$$



$\eta=-0.080$



$\eta=-0.053$



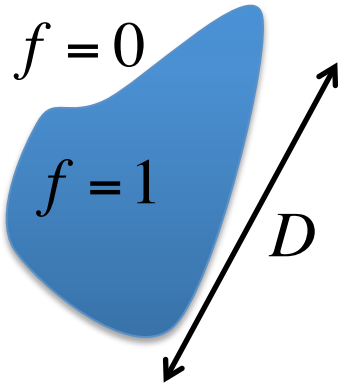
$\eta=-0.048$

García de Abajo, ACS Photonics (2014)

Electrostatic scaling law

$$\phi(\mathbf{R},\omega)=\phi^{\text{ext}}(\mathbf{R},\omega)+\eta\int d\mathbf{R}'\frac{1}{|\mathbf{R}-\mathbf{R}'|}\nabla'\cdot f(\mathbf{R}')\nabla'\phi(\mathbf{R}',\omega)$$

$$\eta=\frac{i\sigma(\omega)}{\omega D}=\frac{-\omega_0^2}{\omega(\omega+i\tau^{-1})} \qquad \omega_0=\frac{e}{\hbar}\sqrt{\frac{E_F}{\pi D}}$$



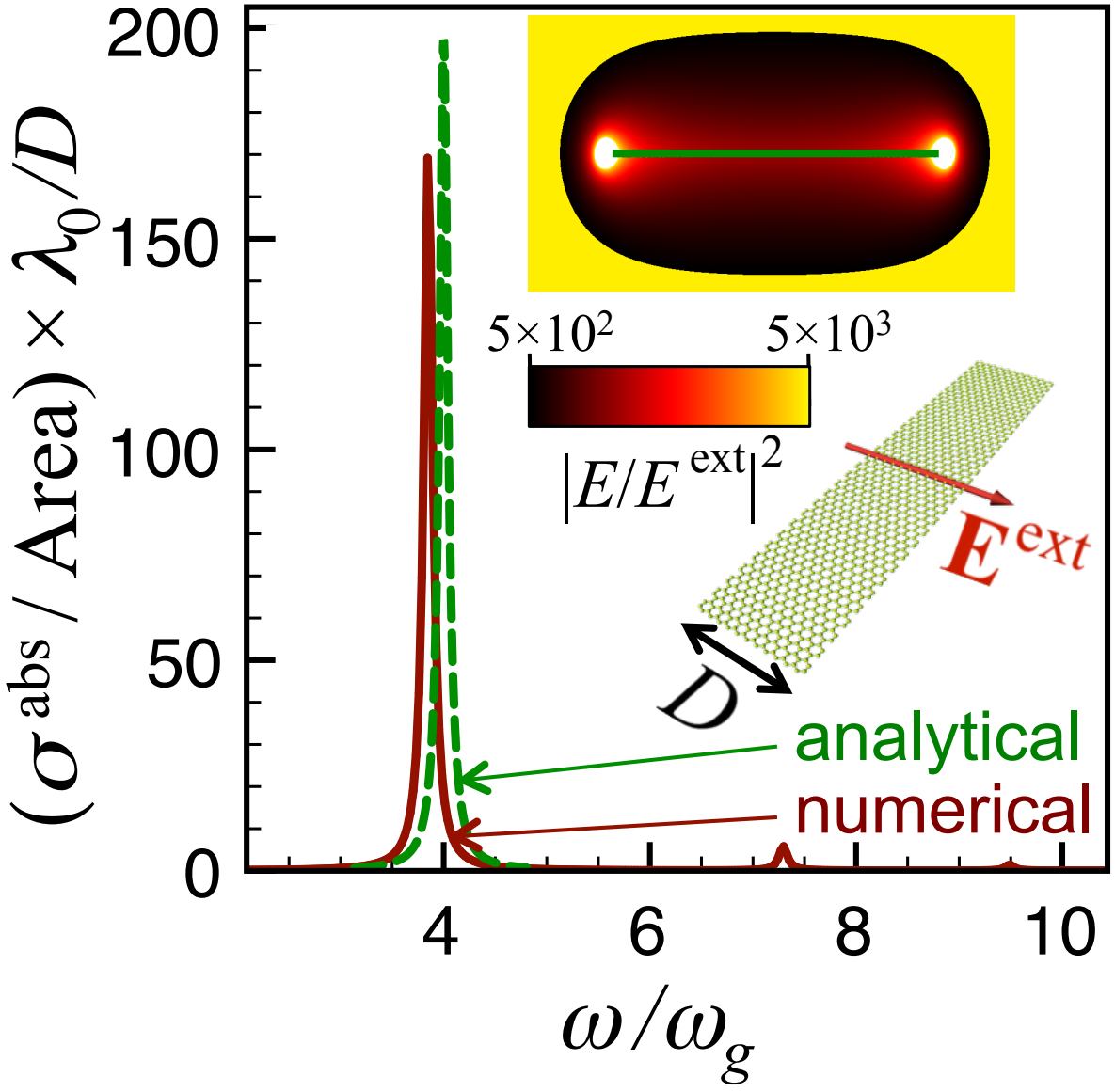
$$\omega_{pl}=\frac{\omega_0}{\sqrt{-\eta}}-i\frac{\tau^{-1}}{2}$$

$$\alpha(\omega)=D^3\sum_j\frac{A_j}{\frac{-2}{\eta_j}-\frac{i\omega D}{\sigma(\omega)}} \qquad \sum_j A_j=\frac{\text{Area}}{D^2}$$

$$-\sum_j\eta_j A_j=\frac{1}{4\pi} \quad \text{(disk)}$$

García de Abajo, ACS Photonics (2014)

Electrostatic scaling law

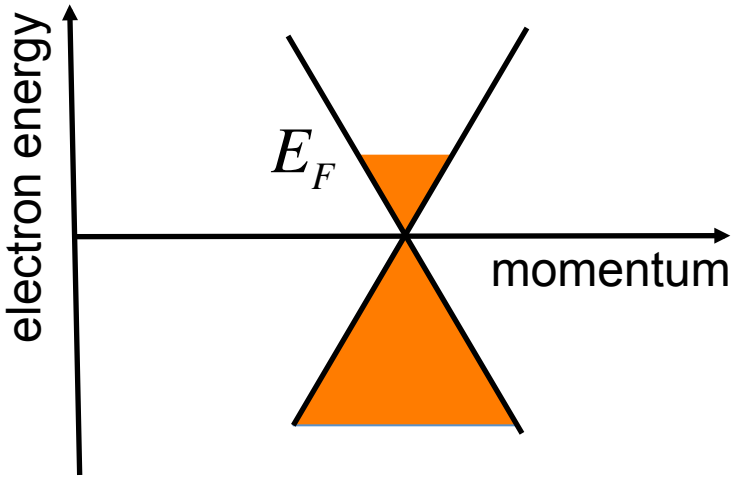


$$\frac{\sigma^{abs}}{\text{Area}} = \frac{8\pi^2 D}{\lambda}\,\text{Im}\left\{\frac{\omega_g^2}{16\omega_g^2 - \omega(\omega + i\gamma)}\right\}$$

$$\omega_g = \frac{e}{\hbar}\sqrt{\frac{E_F}{\pi D}}$$

García de Abajo, ACS Photonics (2014)

Why graphene enables facile tunability



$$\int_{\text{plasmon}} \omega\, d\omega\, \mathrm{Im}\{\alpha(\omega)\} = \frac{\pi e^2}{2m_e} N_e$$

f-sum rule

$$N_e \sim \sqrt{N_{\text{doping}} N_{\text{C atoms}}}$$

García de Abajo, ACS Photonics (2014)

Plasmonics:
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Introduction to plasmons

Graphene plasmons

- **Quantum-mechanical description**
- **Classical description**
- **Complete optical absorption**
- **Quantum optics with graphene plasmons**
- **Sensing with graphene plasmons**

Plasmons in other atomically thin materials

Short historical overview of perfect absorption

Partially disordered silver films

- O. Hunderi and H. P. Myers, J. Phys. F: Metal Phys. 3, 683 (1973)

Diffraction in gratings, double-period metal gratings, and metamaterials

- M. C. Hutley and D. Maystre, Optics Communications 19, 431 (1976)
- D. Maystre and R. Petit, Optics Communications 17, 196 (1976)
- W.-C. Tan, J. R. Sambles, and T. W. Preist, Phys. Rev. B 61, 13177 (1999)
- E.Popov and L.Tsonev, Surface Science Letters 271, L378 (1992)
- N. I. Landy et al., Phys. Rev. Lett. 100, 207402 (2008)
- N. Liu et al., Nano Lett. 10, 2342 (2010)

Doped silicon lamellar grating

- F. Marquier, M. Laroche, R. Carminati, J.-J. Greffet, Journal of Heat Transfer 129, 11 (2007)
- J.-J. Greffet, R. Carminati, K. Joulain, J.-P. Mulet, S. Mainguy, Y. Chen, Nature 416, 61 (2002)

Semiconductor and metal-semiconductor-metal nanostructures

- S. Collin, F. Pardo, R. Teissier, and J.-L. Pelouard, Appl. Phys. Lett. 85, 194 (2004)
- T.V. Teperik, F.J. García de Abajo, V.V. Popov, and M.S. Shur, Appl. Phys. Lett. 90 251910 (2007)

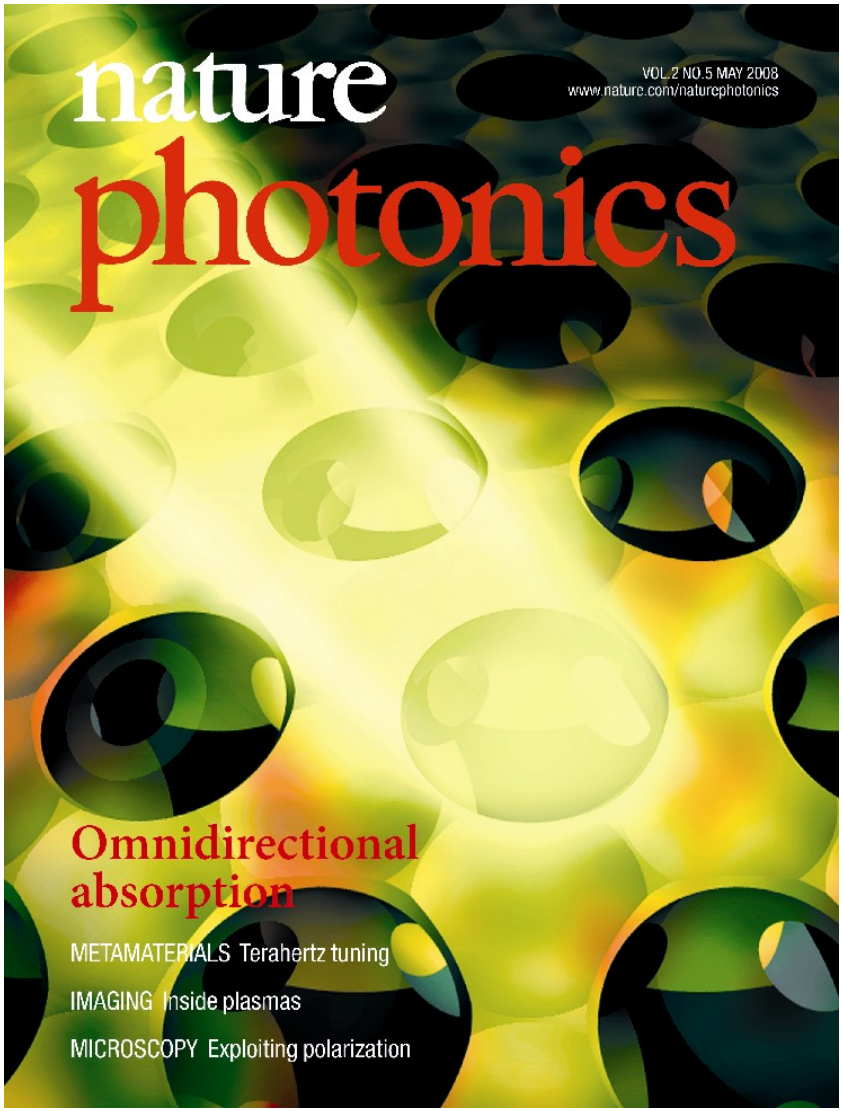
Multiplayer of metallic nanoparticles and nanopores in metal

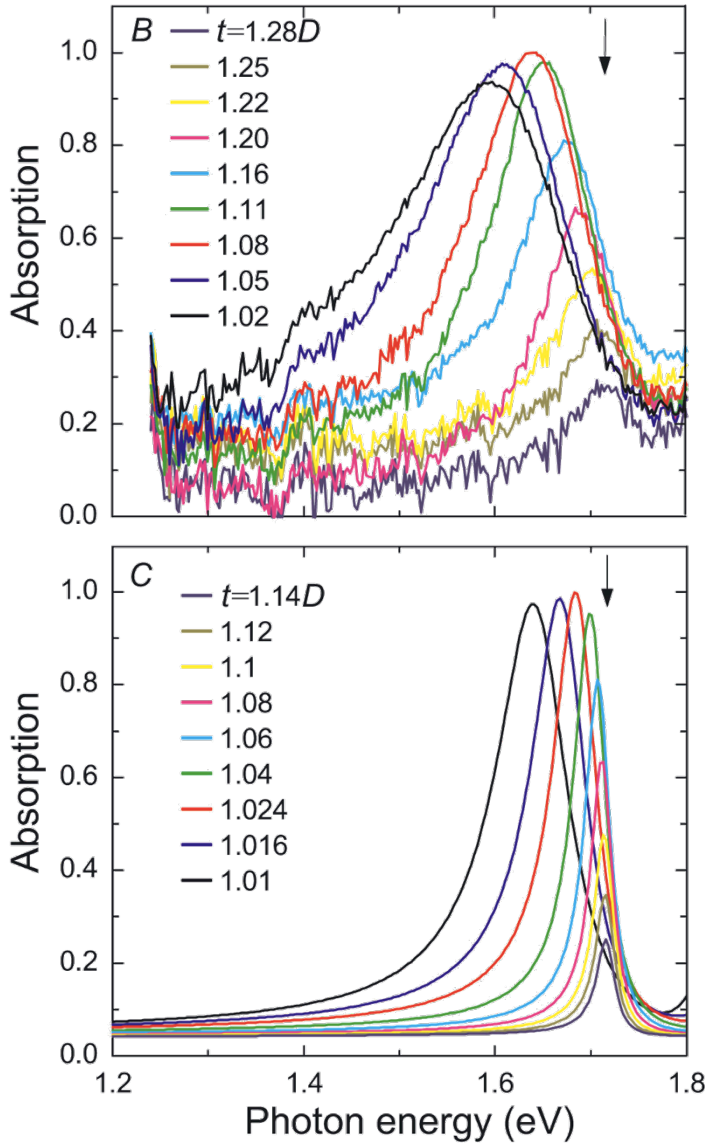
- T. V. Teperik, V. V. Popov, and F. J. García de Abajo, Phys. Rev. B 71, 085408 (2005)
- T. Teperik, V. Popov, and F. Garcıa de Abajo, J. Opt. A: Pure Appl. Opt. 0, 0 (2007)
- S.Kachan, O. Stenzel, and A. Ponyavina, Appl. Phys. B 84, 281 (2006)

Overdense plasma slab (in the microwave frequency range)

- Y. P. Bliokh, J. Felsteiner, and Y. Z. Slutsker, Phys. Rev. Lett. 95, 165003 (2005)

Nanovoids as perfect absorbers

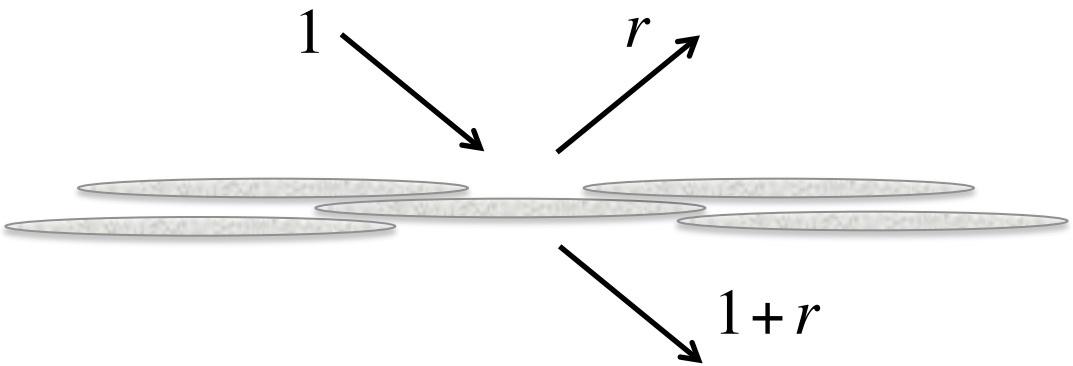




T.V.Teperik *et al.*, Nature Photon. (2008)

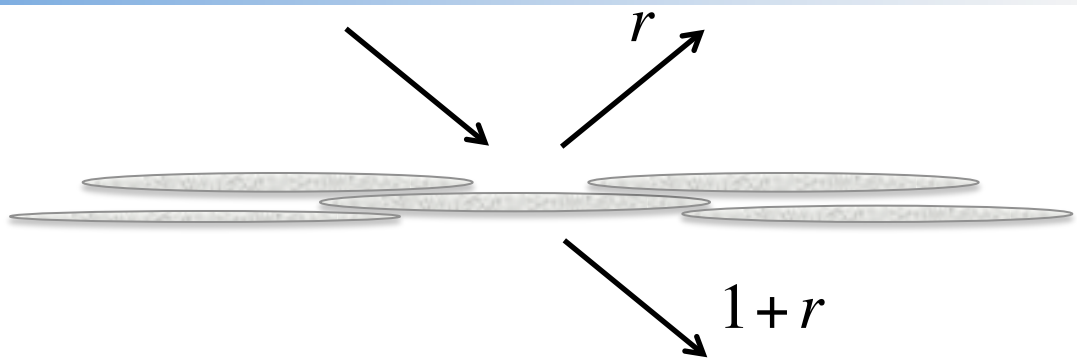
Light absorption in graphene

$$\text{Absorption} \approx \pi/137 \approx 2.3\%$$



$$\text{Absorption} = 1 - |r|^2 - |1+r|^2 \quad \rightarrow \quad 50\% \text{ maximum}$$

Maximum absorption in graphene



$$\text{Absorption} = 1 - |r|^2 - |1+r|^2 \quad \rightarrow \quad 50\% \text{ maximum for } r = -1/2$$

$$r = \frac{\pm iS}{\alpha^{-1} - G} \qquad S = \frac{2\pi\omega}{Ac}(\cos\theta)^{\mp 1} \qquad G \approx \frac{g}{a^3} + i\left(S - \frac{2\omega^3}{3c^3}\right)$$

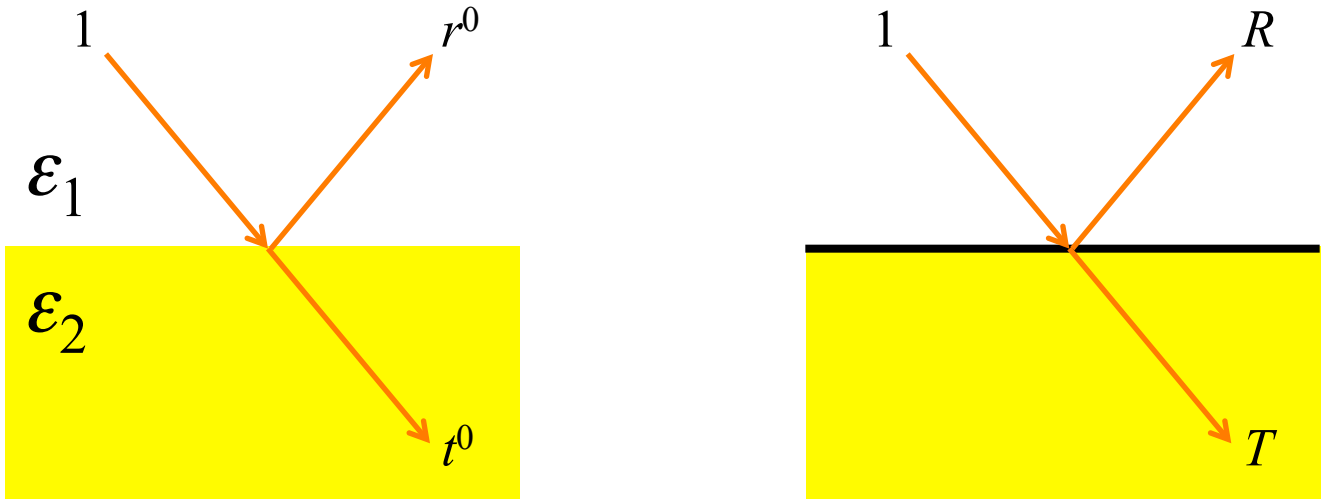
$$\alpha(\omega) = \frac{3c^3}{4\omega^3}\frac{\kappa_r}{\omega_p - \omega - i\kappa/2}$$

$$\omega \approx \omega_p - 3g\kappa_r/4(\omega a/c)^3$$

$$\sigma_{\max}^{\text{ext}} = 2A \times \begin{cases} \cos\theta, & s \text{ polarization}, \\ \cos^{-1}\theta, & p \text{ polarization}. \end{cases}$$

Thongrattanasiri *et al*., Phys. Rev. Lett. (2012)

Absorption in asymmetric environments

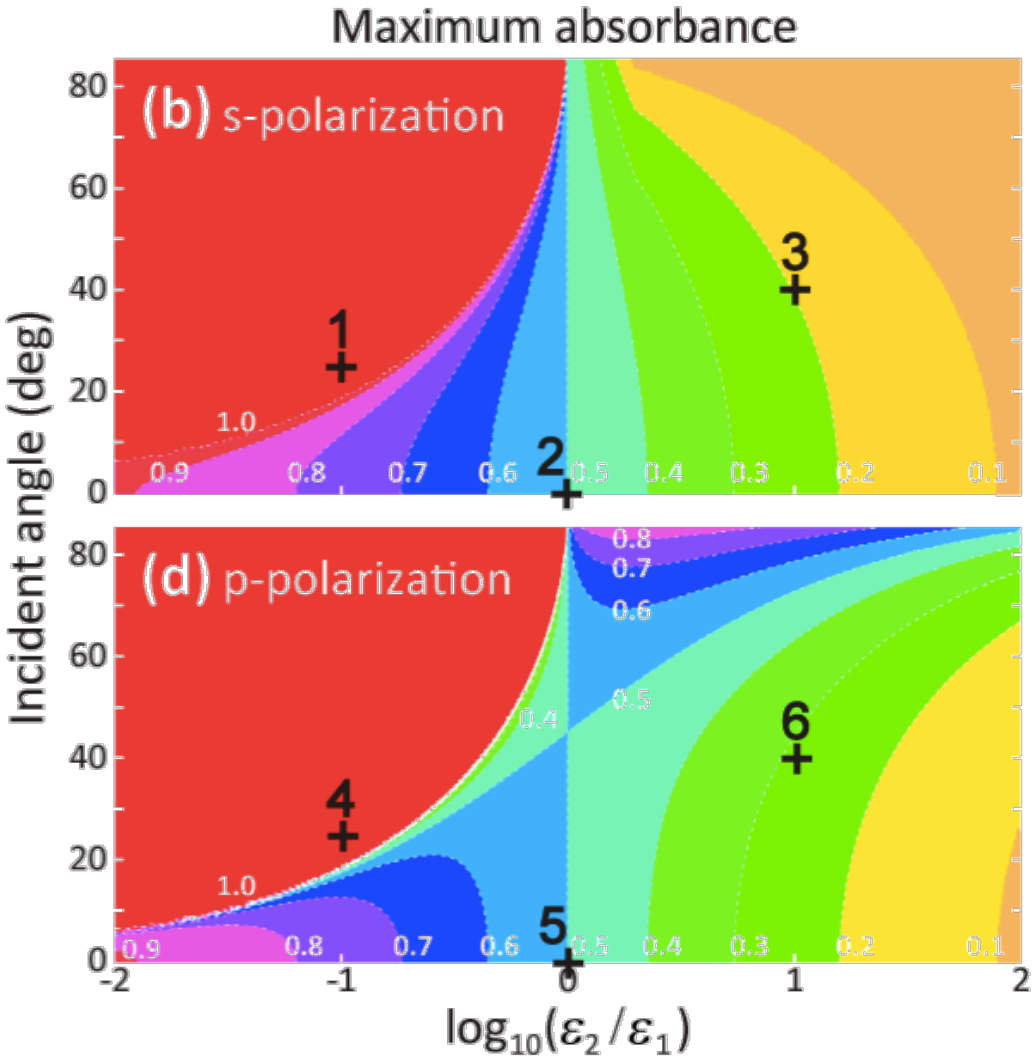


$$\eta = -\frac{r^0 \pm |r^0|^2 \pm \mathrm{Re}\{f\}|t^0|^2}{|1 \pm r^0|^2 + \mathrm{Re}\{f\}|t^0|^2}$$

$$\mathcal{A} = 1 - |r^0 + (1 \pm r^0)\eta|^2 - \mathrm{Re}\{f\}|t^0|^2|1 \pm \eta|^2$$

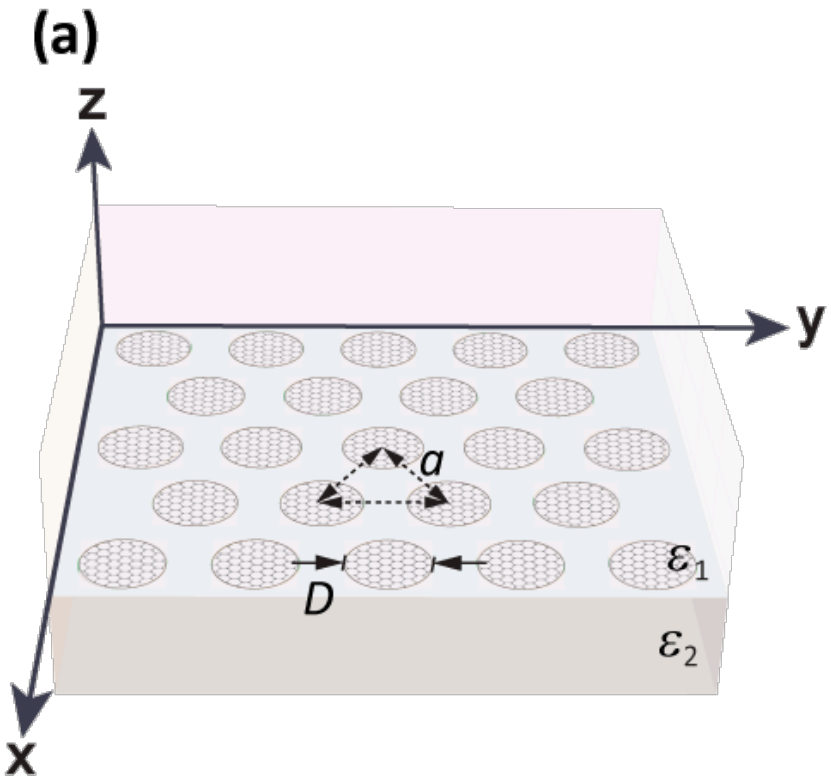
$$f = (\epsilon_2/\epsilon_1 - \sin^2\theta)^{1/2}/\cos\theta$$

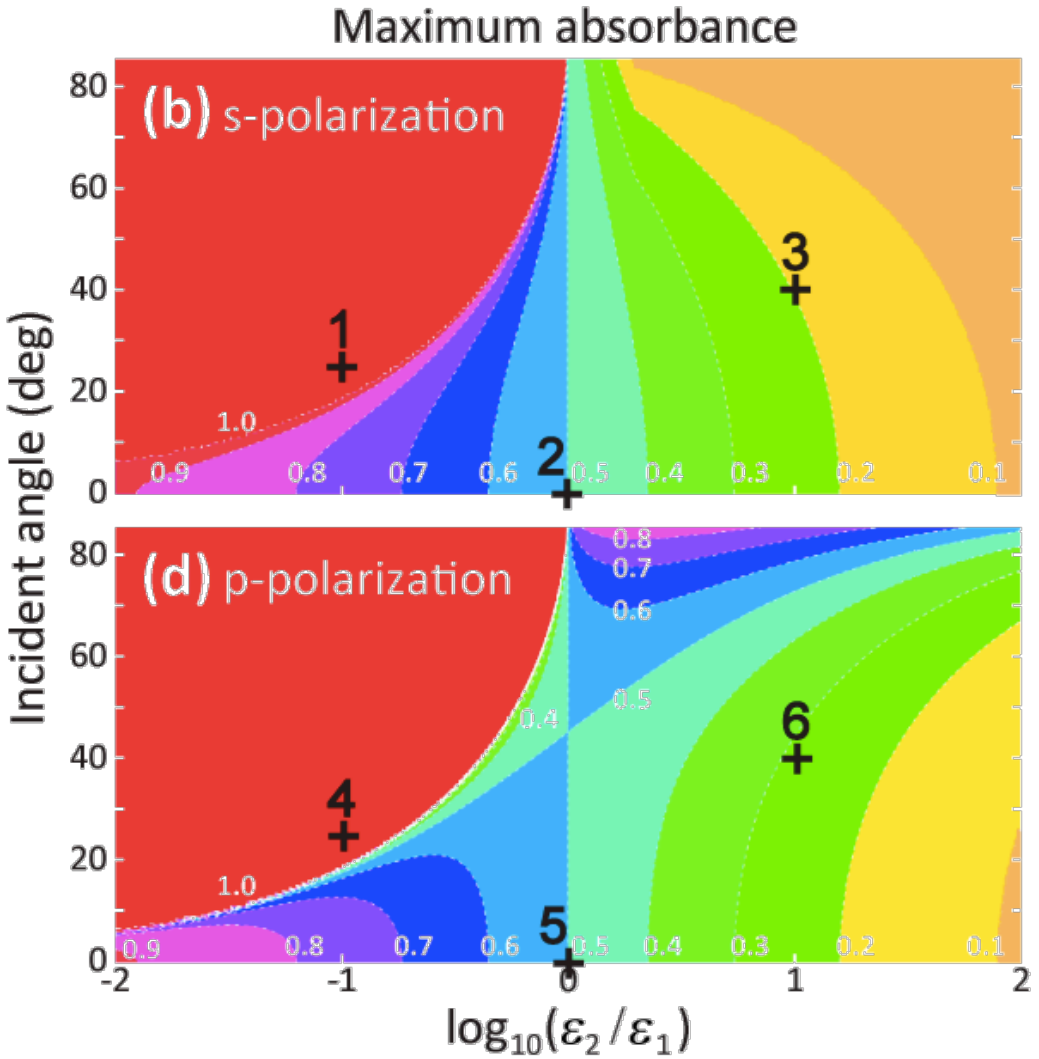
Absorption in asymmetric environments



Thongrattanasiri *et al*., Phys. Rev. Lett. (2012)

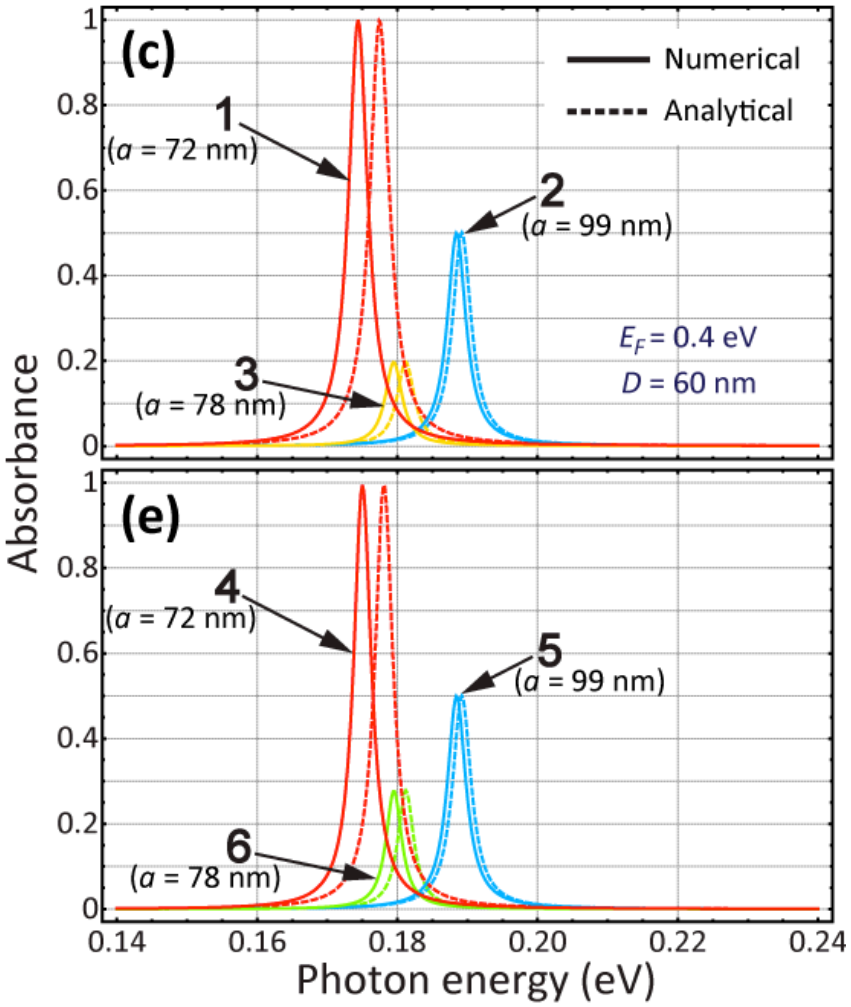
Absorption in asymmetric environments

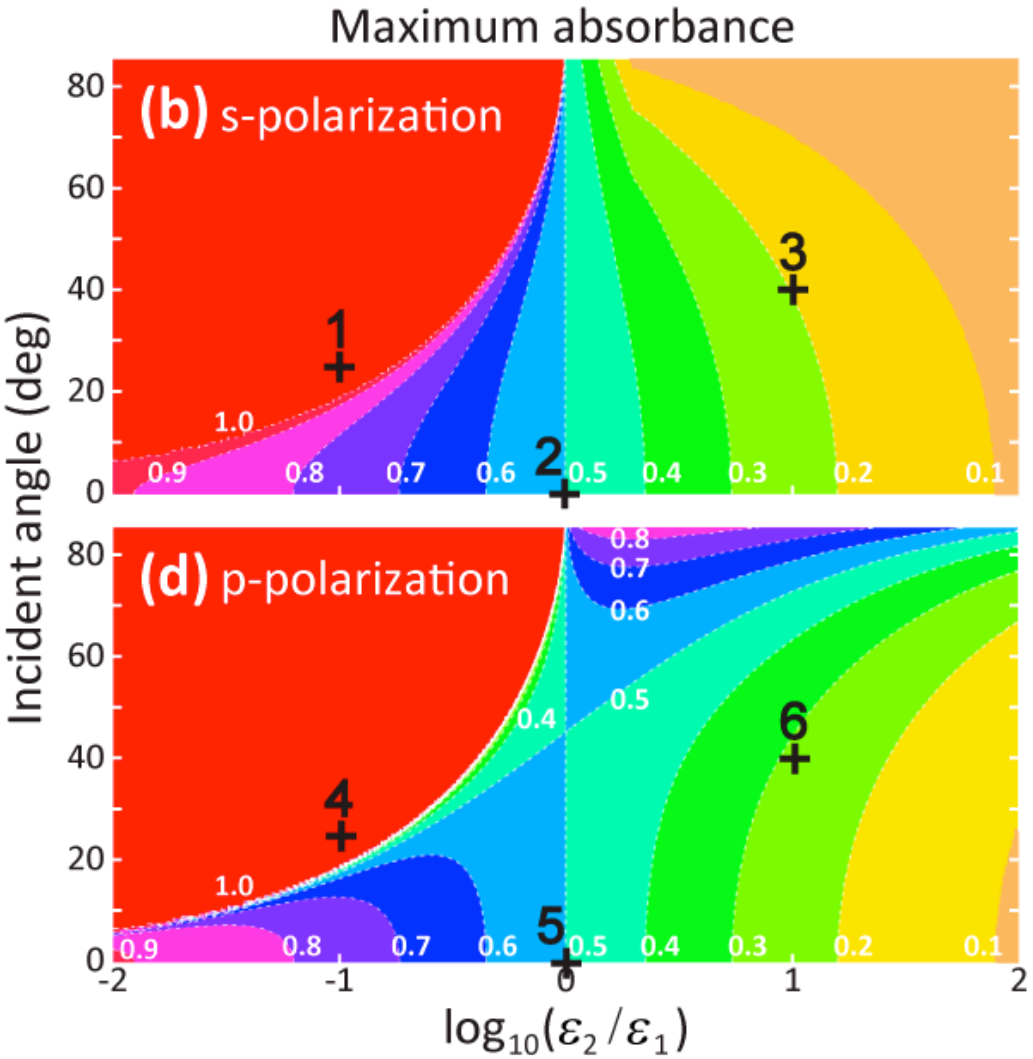




Thongrattanasiri *et al.*, Phys. Rev. Lett. (2012)

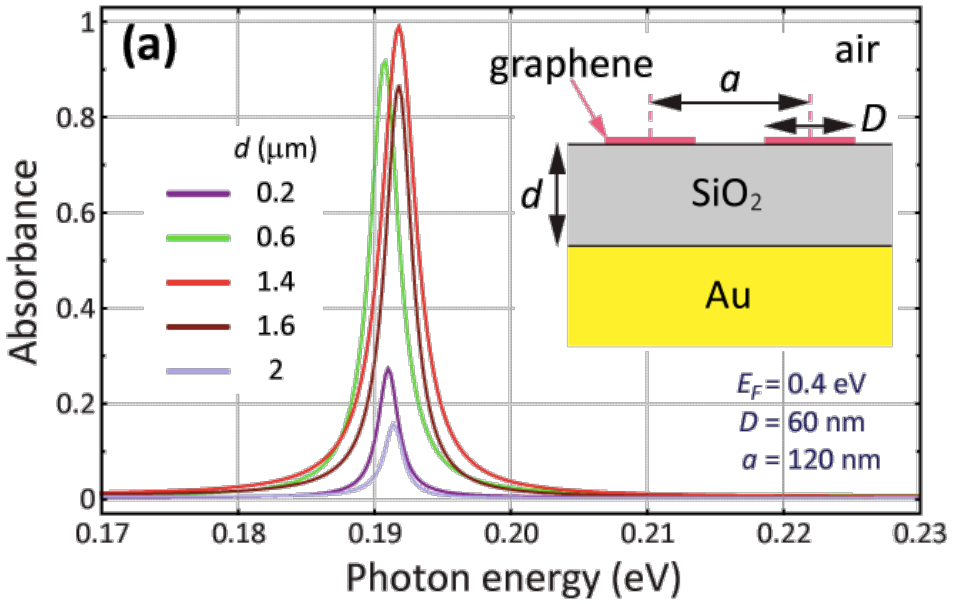
Absorption in asymmetric environments

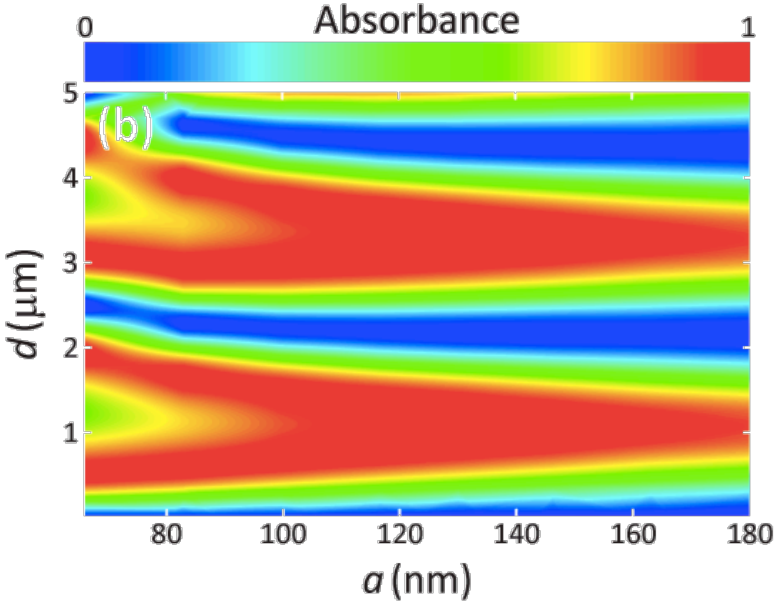


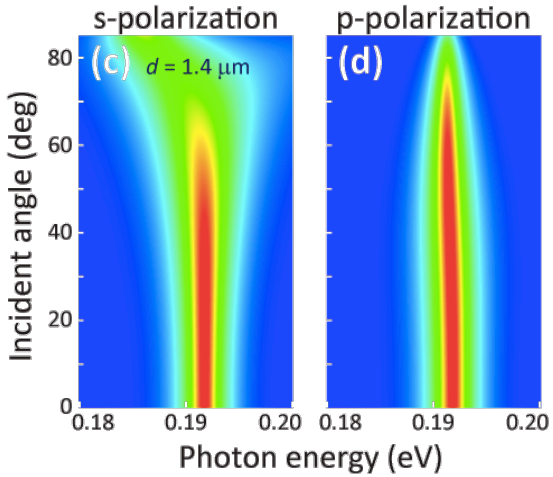


Thongrattanasiri *et al.*, Phys. Rev. Lett. (2012)

Complete absorption in graphene

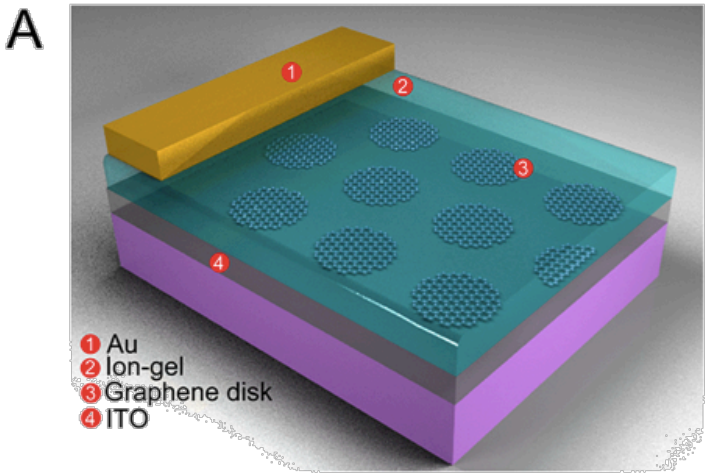


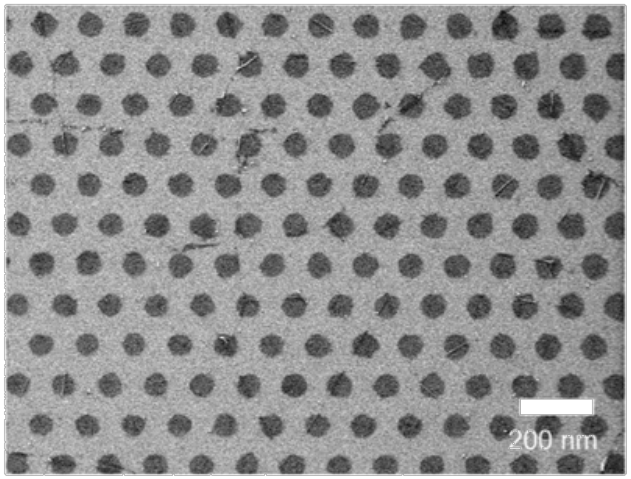


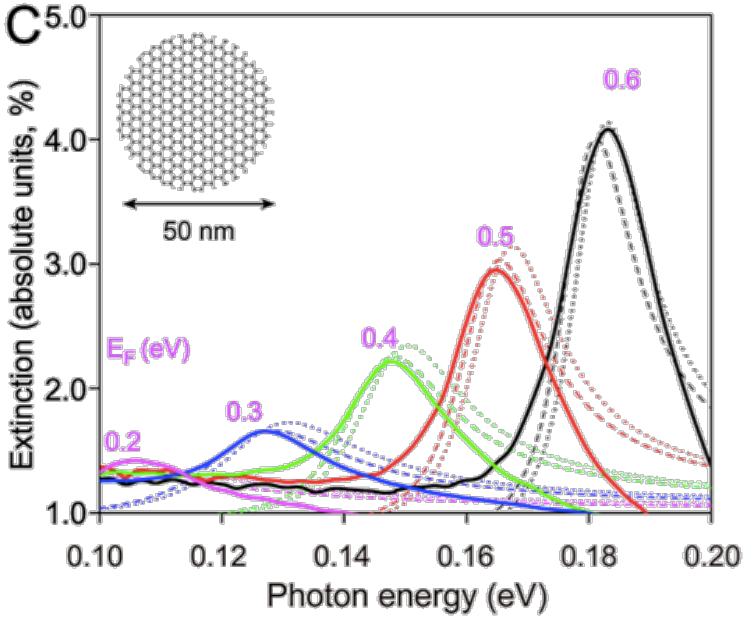


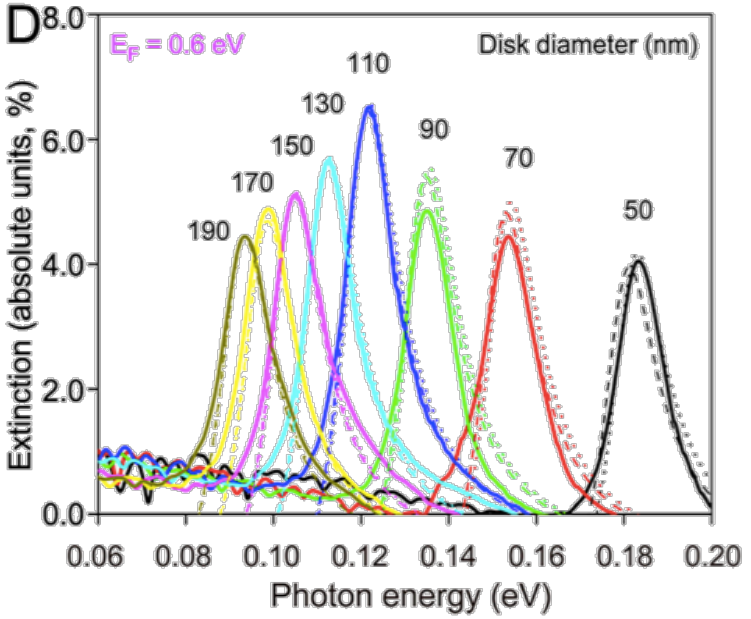
Thongrattanasiri *et al*., Phys. Rev. Lett. (2012)

Plasmon tuning





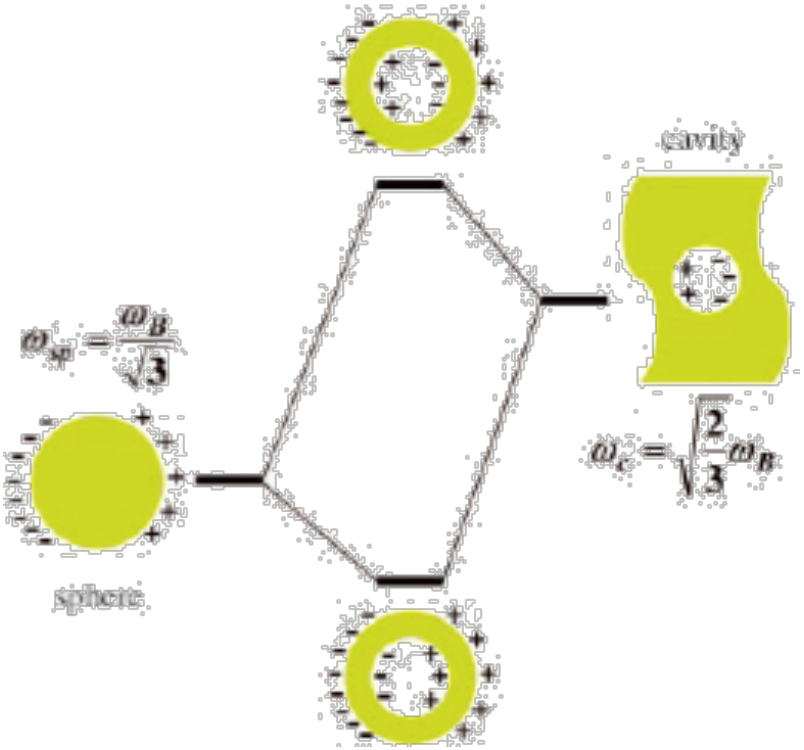




Fang *et al.*, ACS Nano (2013)

Graphene plasmon hybridization

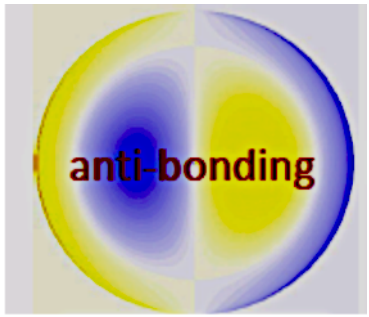
Anti-bonding mode

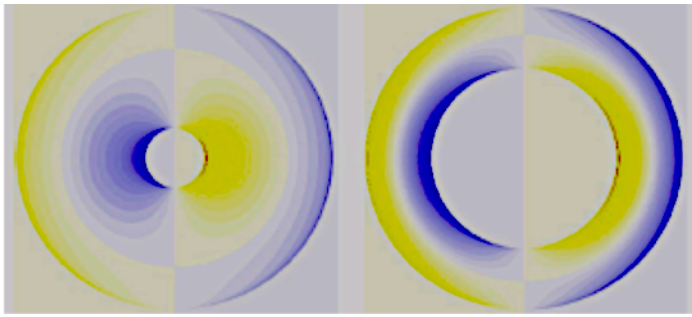


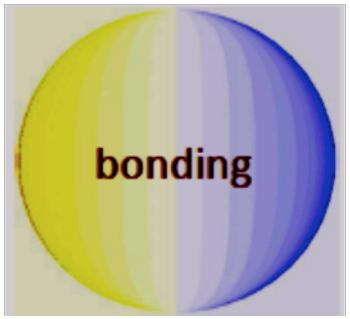
Bonding mode

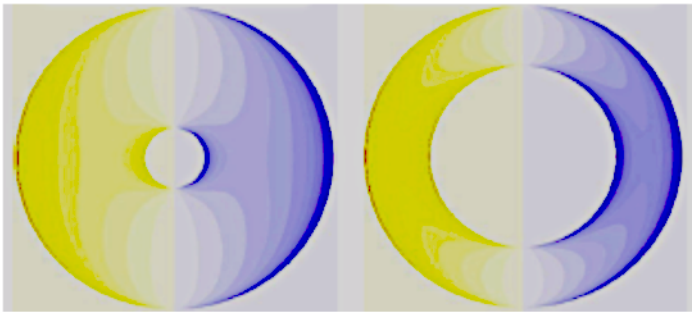
Prodan *et al.*, Science (2003)

Graphene nanorings



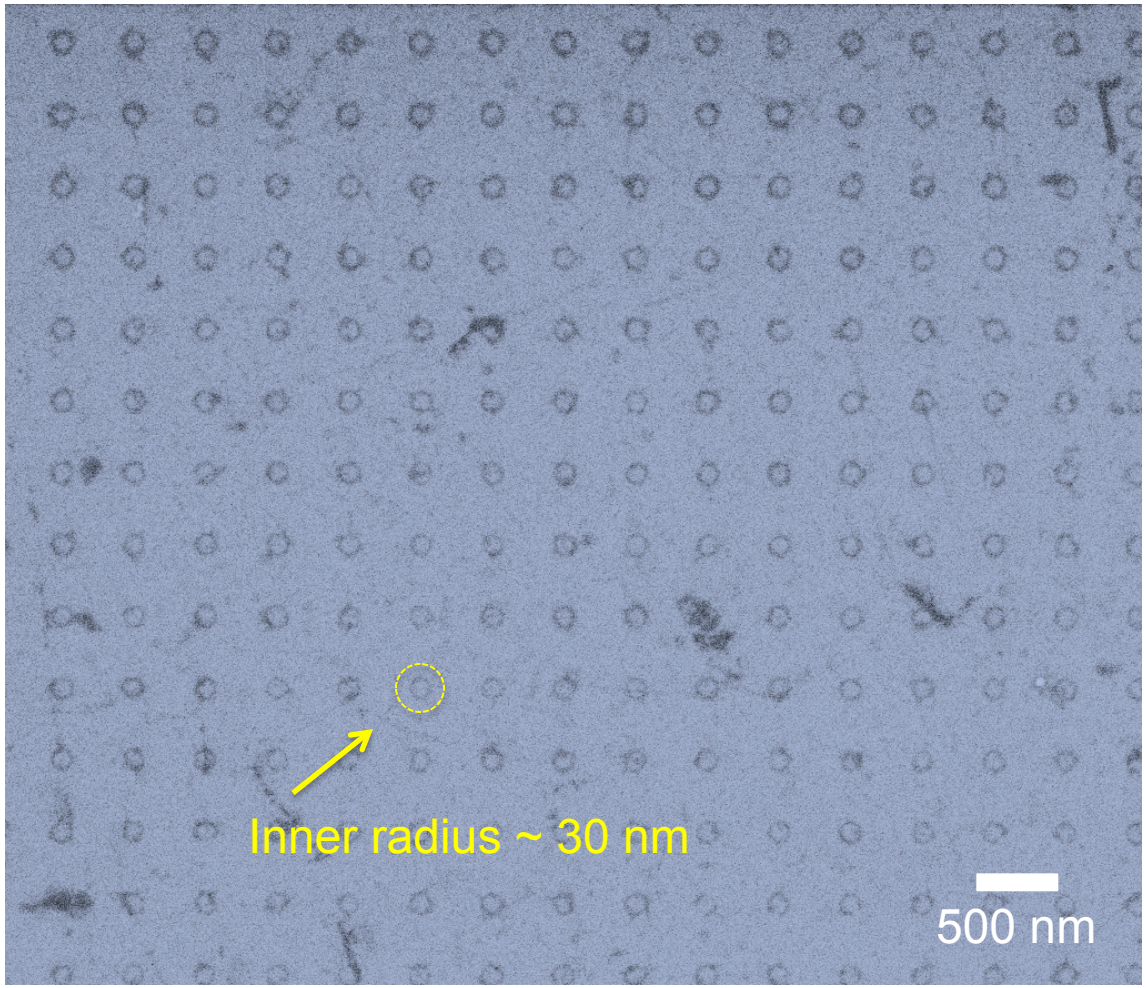


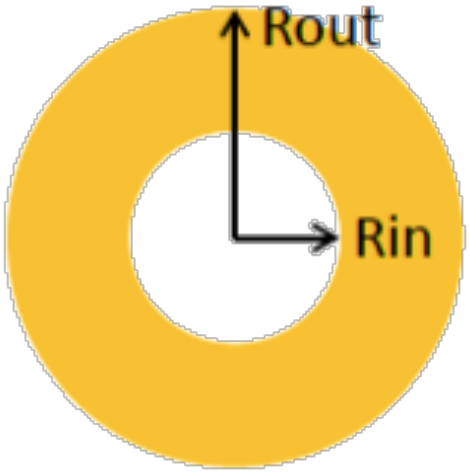




Fang, Thongrattanasiri, …, Ayajan, Nordlander, Halas, JGA, ACS Nano (2013)

Graphene plasmon hybridization



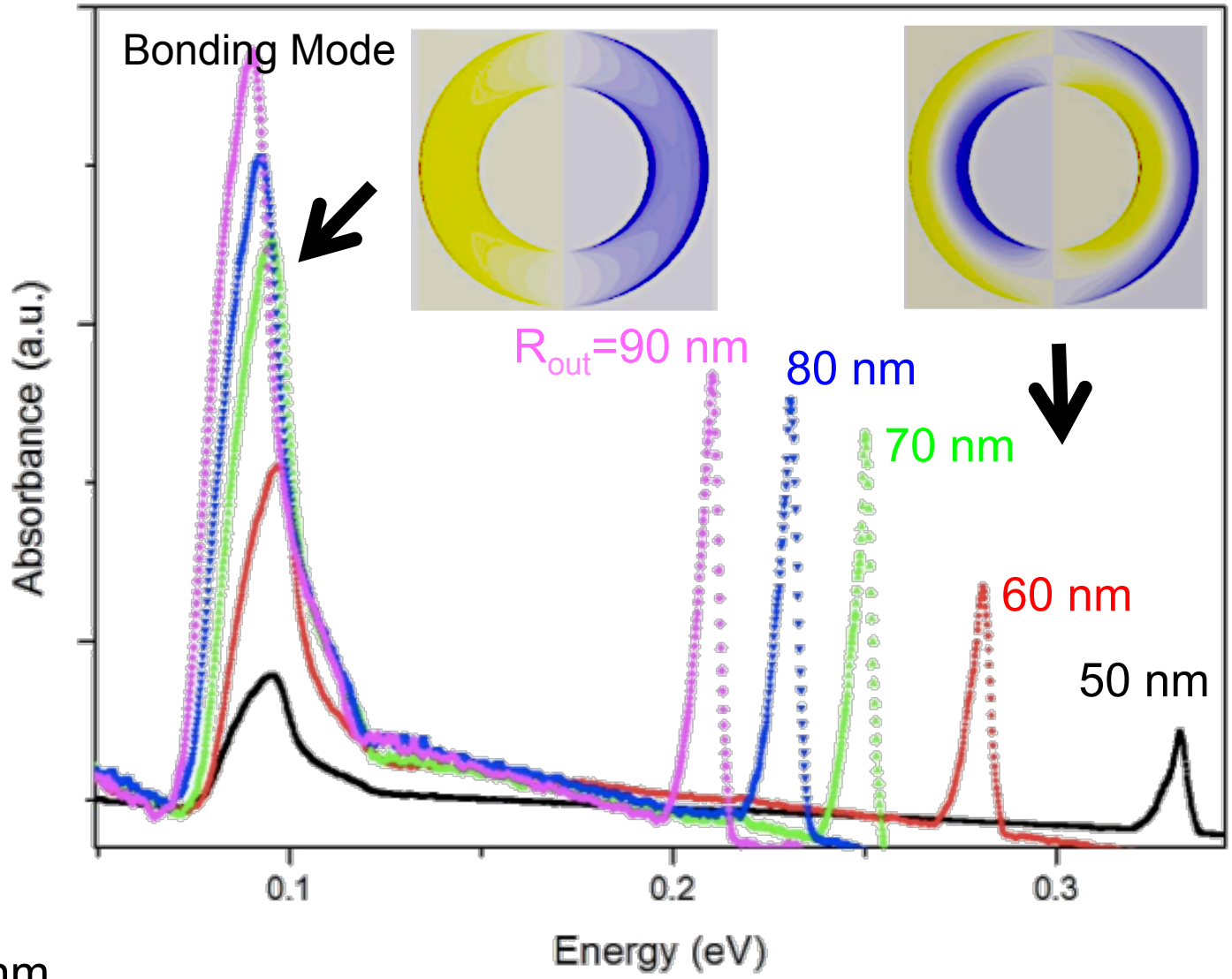


R_{out}= 50 nm
R_{in}=30 nm

Period=500 nm

Fang, Thongrattanasiri, …, Ayajan, Nordlander, Halas, JGA, ACS Nano (2013)

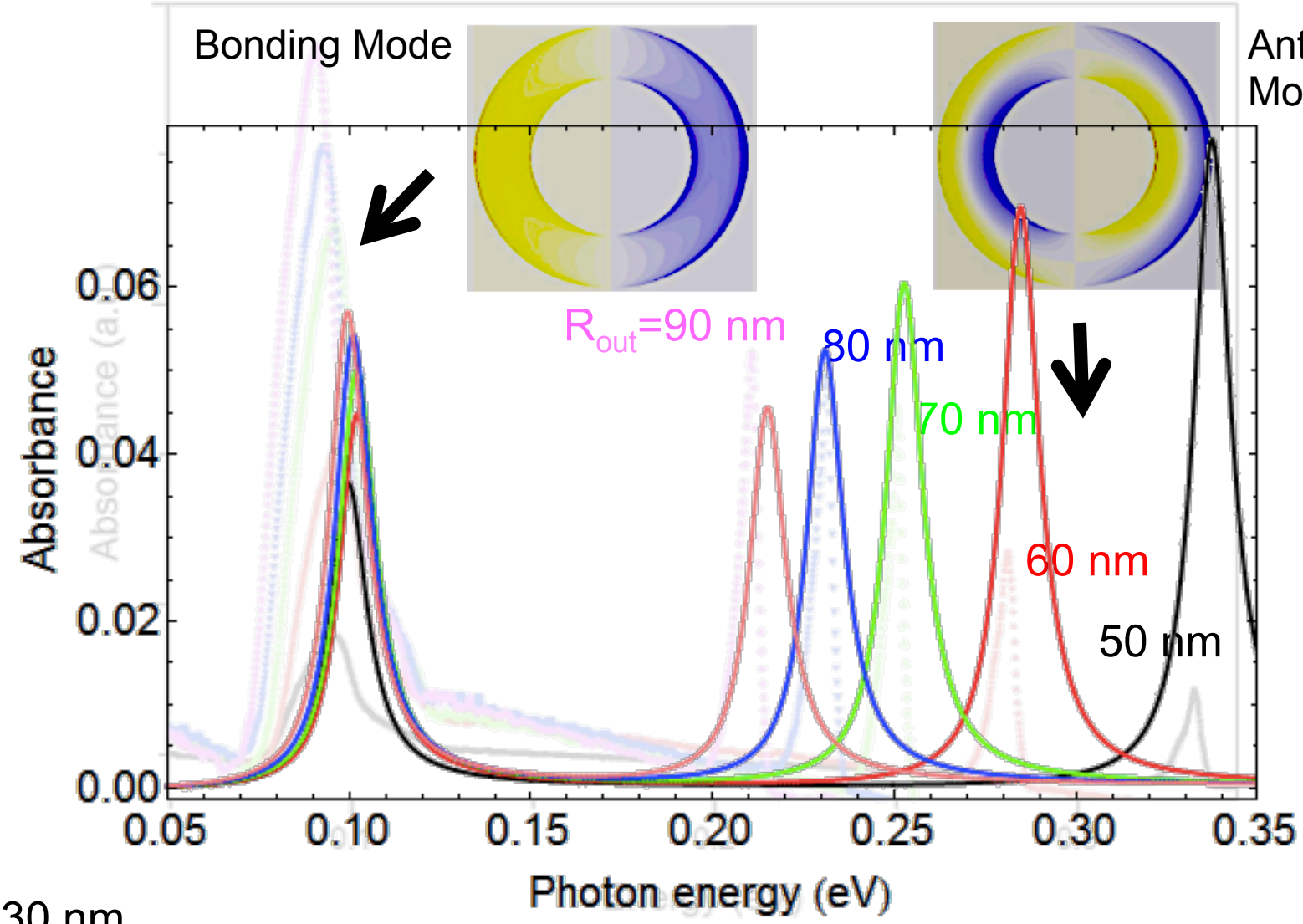
Graphene plasmon hybridization



R_{in}=30 nm

Fang, Thongrattanasiri, …, Ayajan, Nordlander, Halas, JGA, ACS Nano (2013)

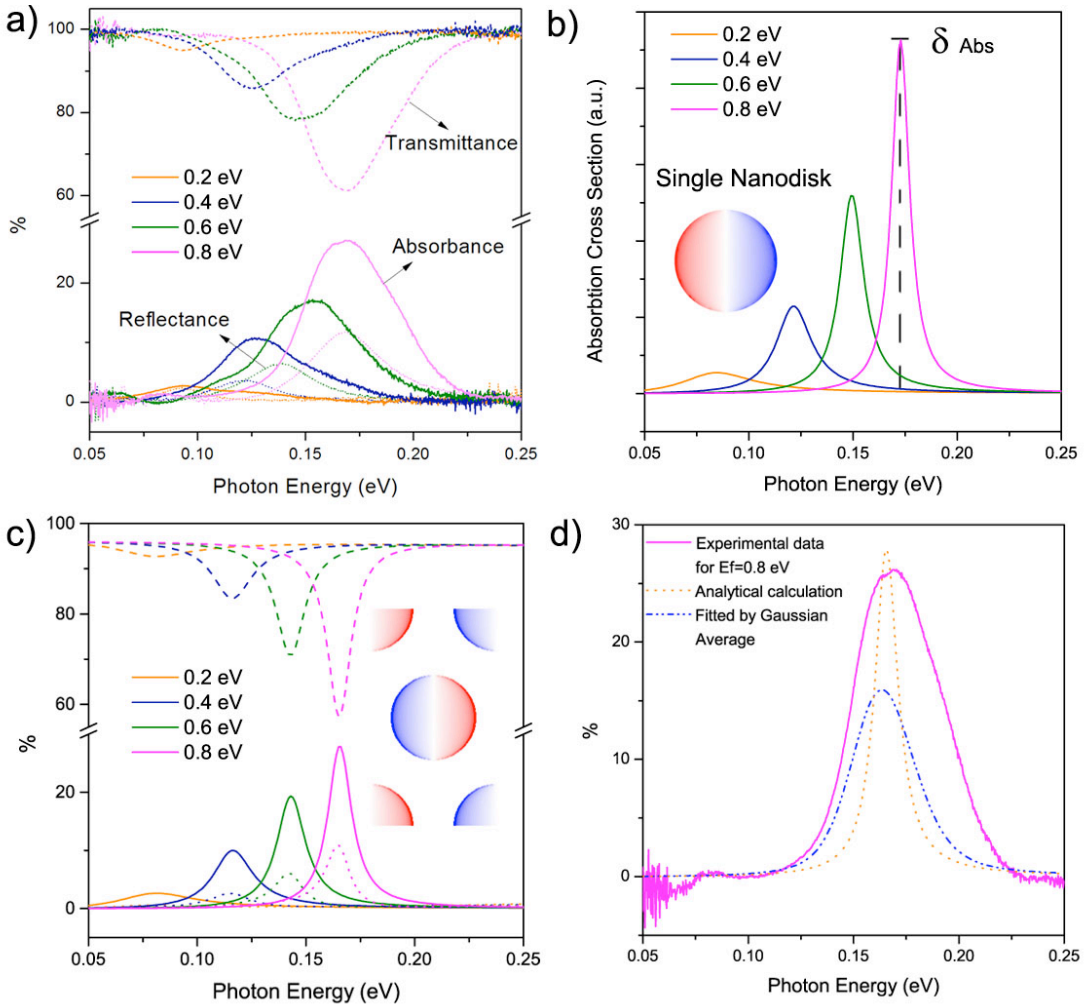
Graphene plasmon hybridization



R_{in}=30 nm

Fang, Thongrattanasiri, …, Ayajan, Nordlander, Halas, JGA, ACS Nano (2013)

Towards complete absorption in graphene



Fang *et al*., Nano Lett. (2014)

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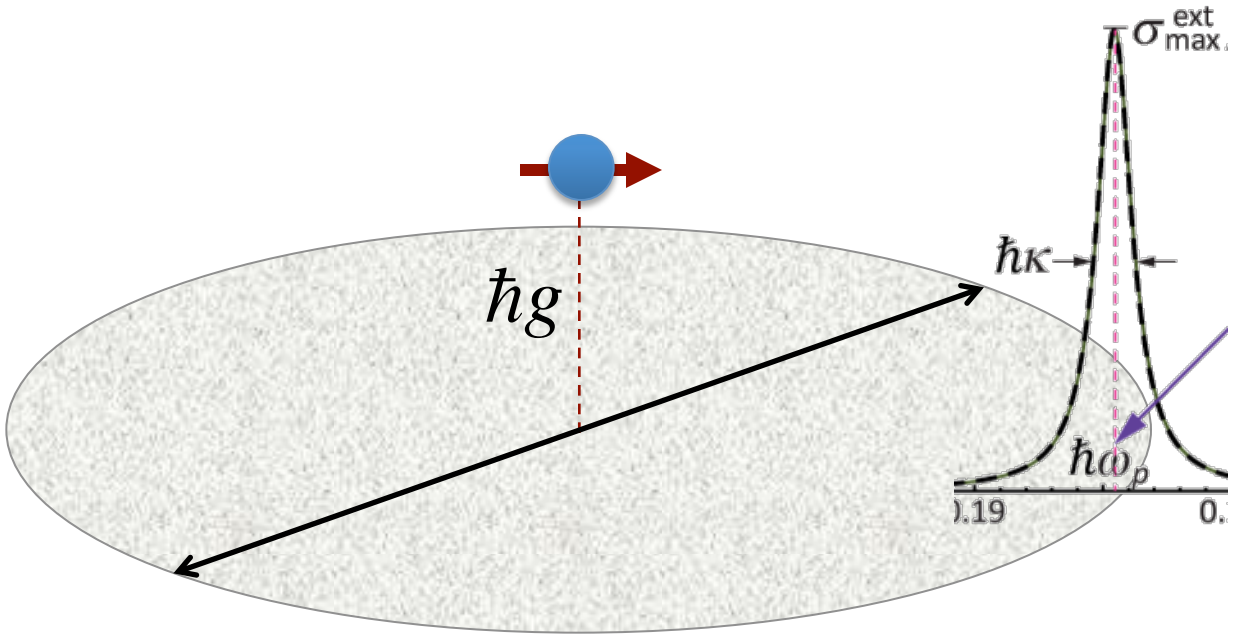
Plasmons in other atomically thin materials

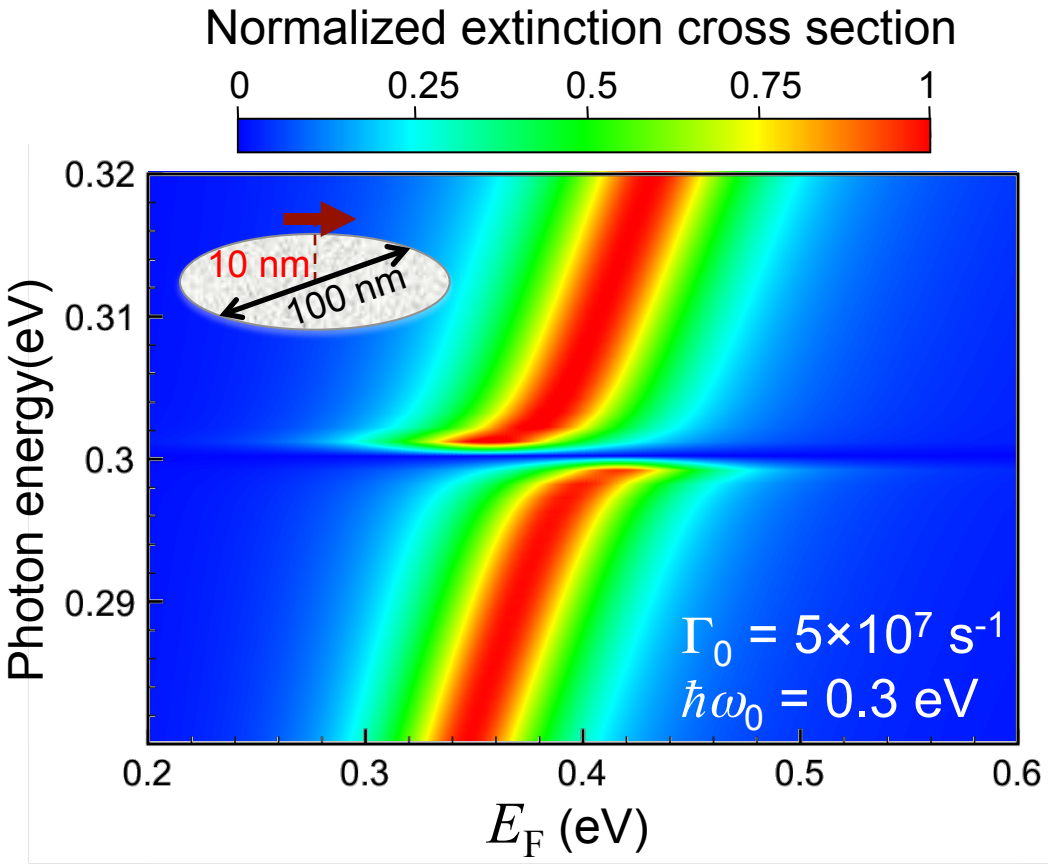
Vacuum Rabi splitting



Strong-coupling regime $g >> \kappa$

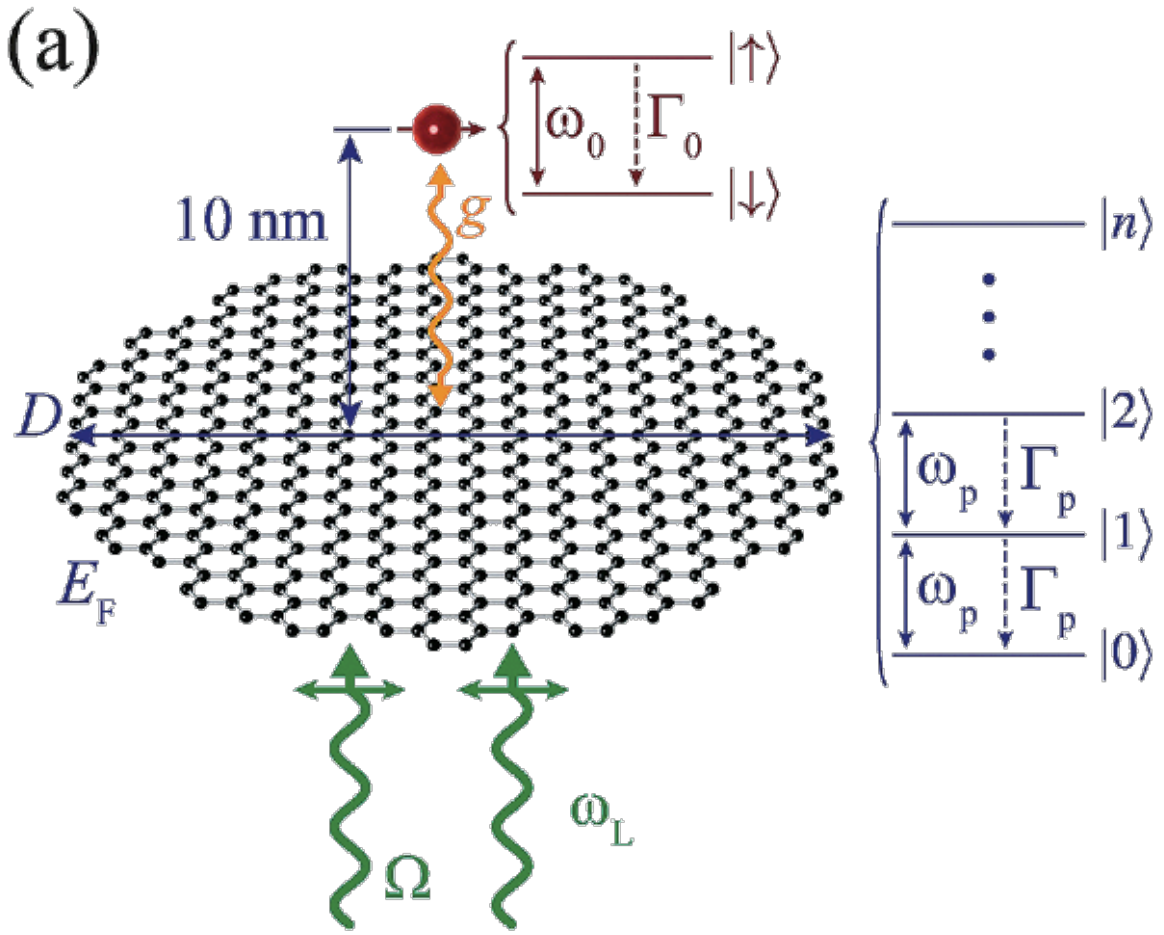
Koppens, Chang, and García de Abajo, Nano Lett. (2011)

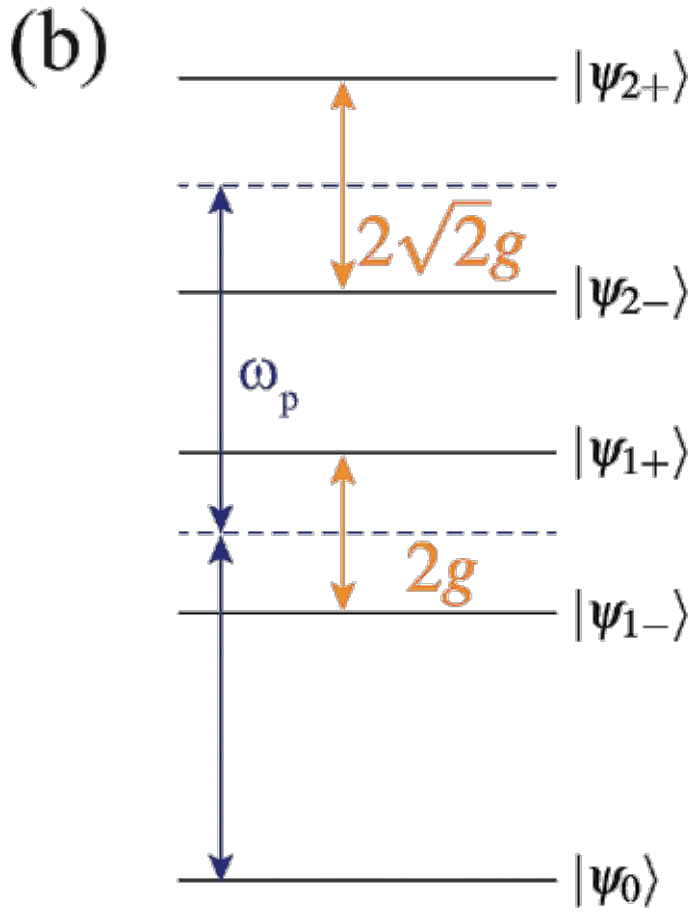
Vacuum Rabi splitting



Koppens, Chang, and García de Abajo, Nano Lett. (2011)

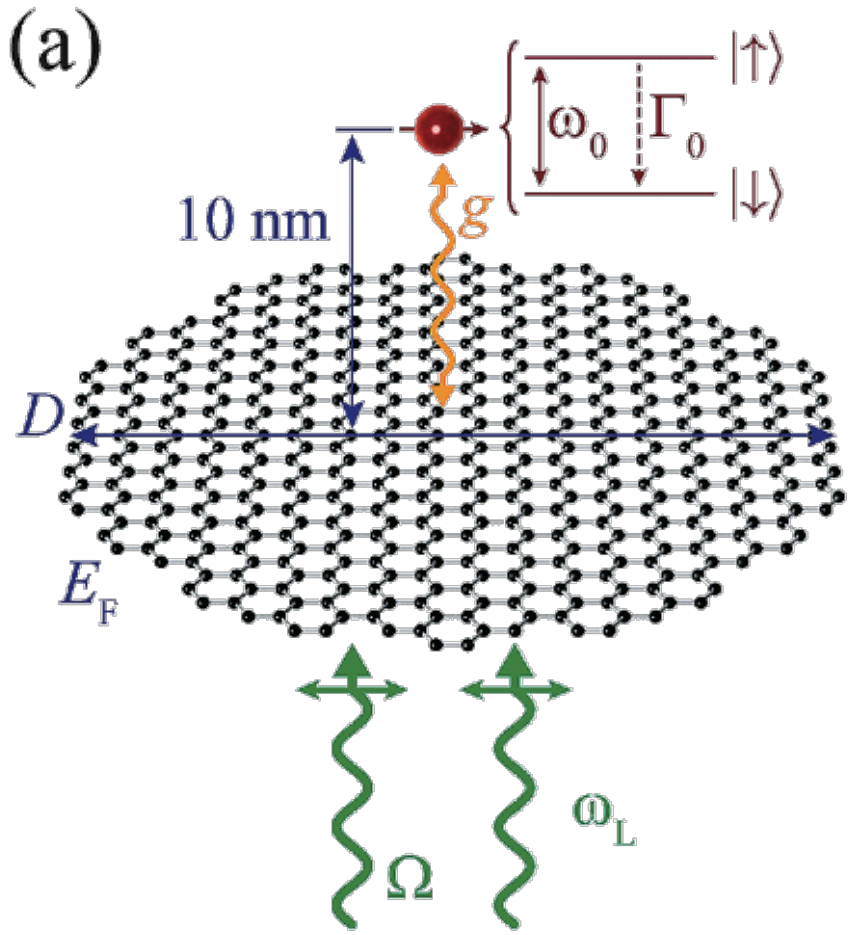
Jaynes-Cummings ladder

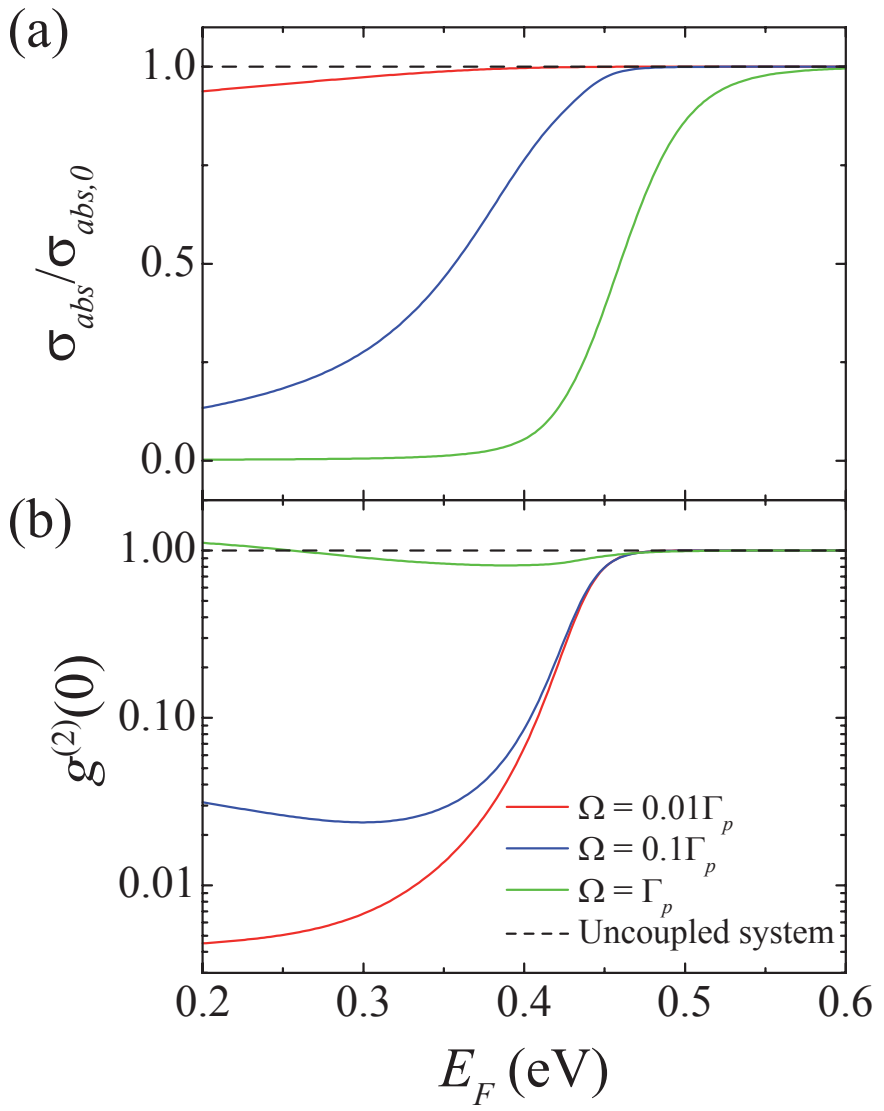




Manjavacas *et al*., ACS Nano (2012)

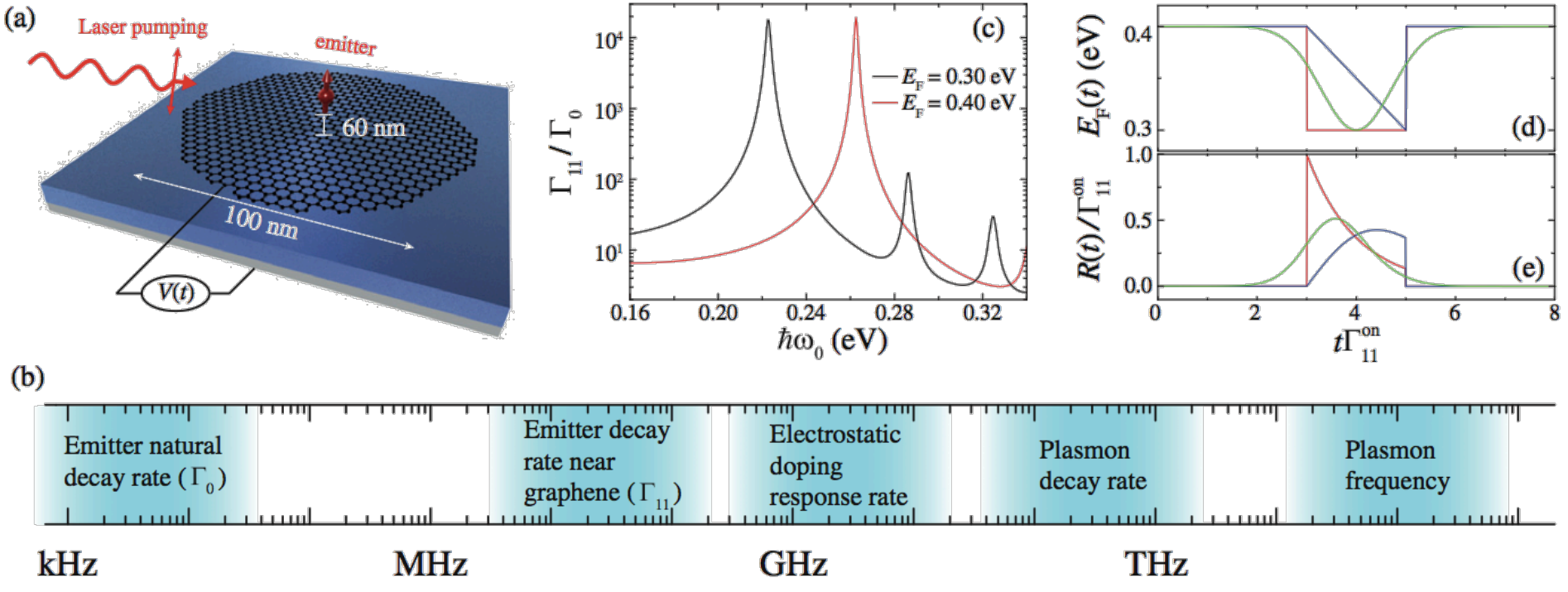
Plasmon blockade





Manjavacas *et al.*, ACS Nano (2012)

Electrical control of quantum states



Manjavacas *et al.*, New J. Phys. (2012)

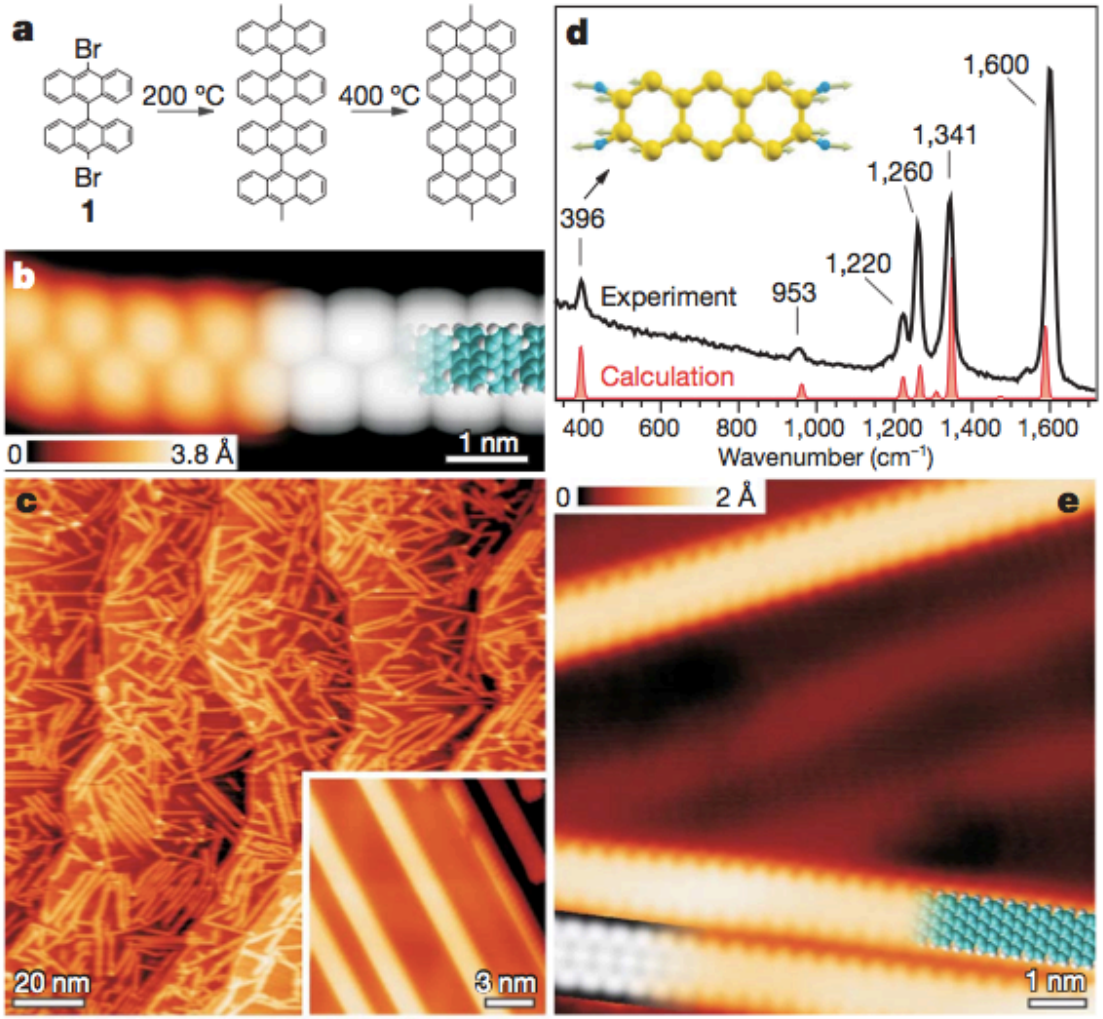
How to move towards the visible-NIR

1) Increasing doping

2) Making smaller structures

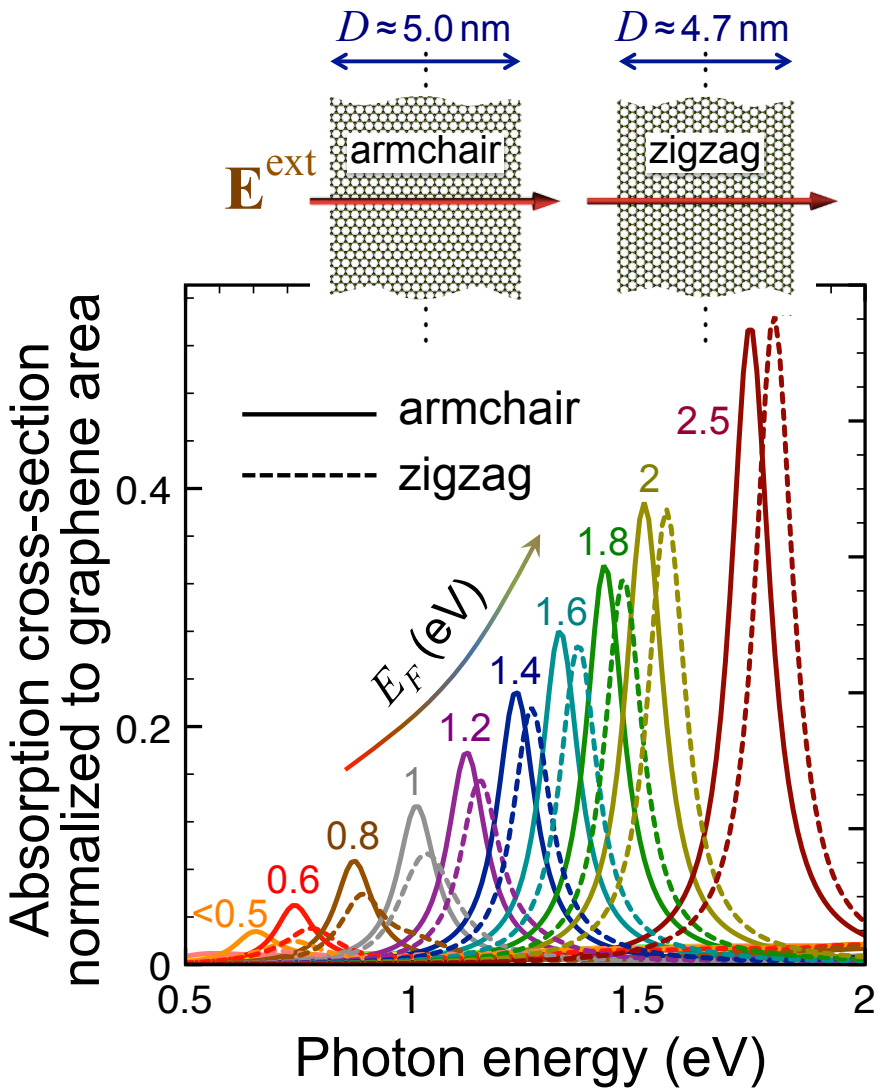
$$\omega_{sp} \propto \sqrt{\frac{E_F}{D}}$$

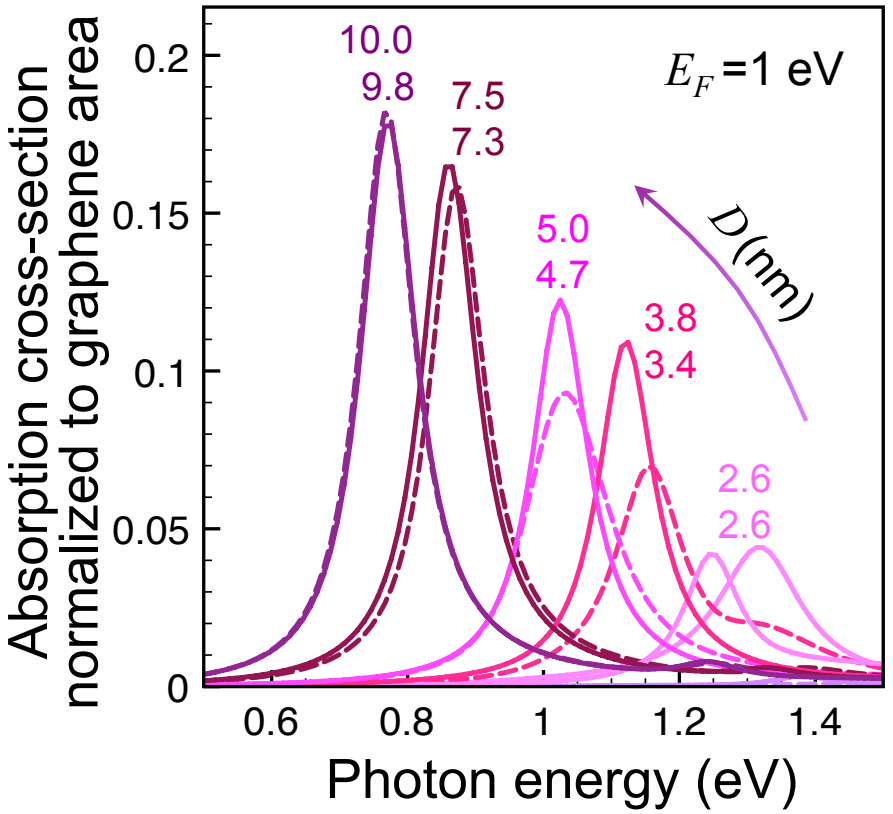
Molecular self-assembly



Cai *et al.*, Nature **466**, 470 (2013)

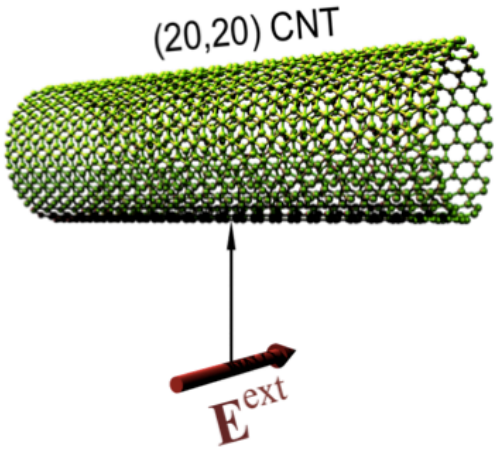
vis-NIR graphene plasmons

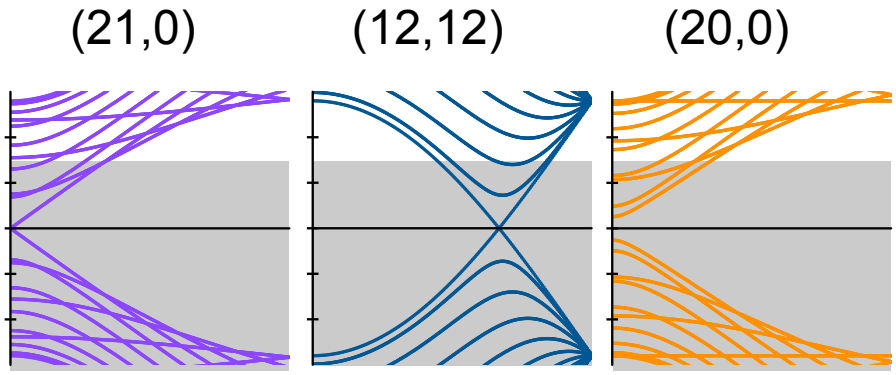


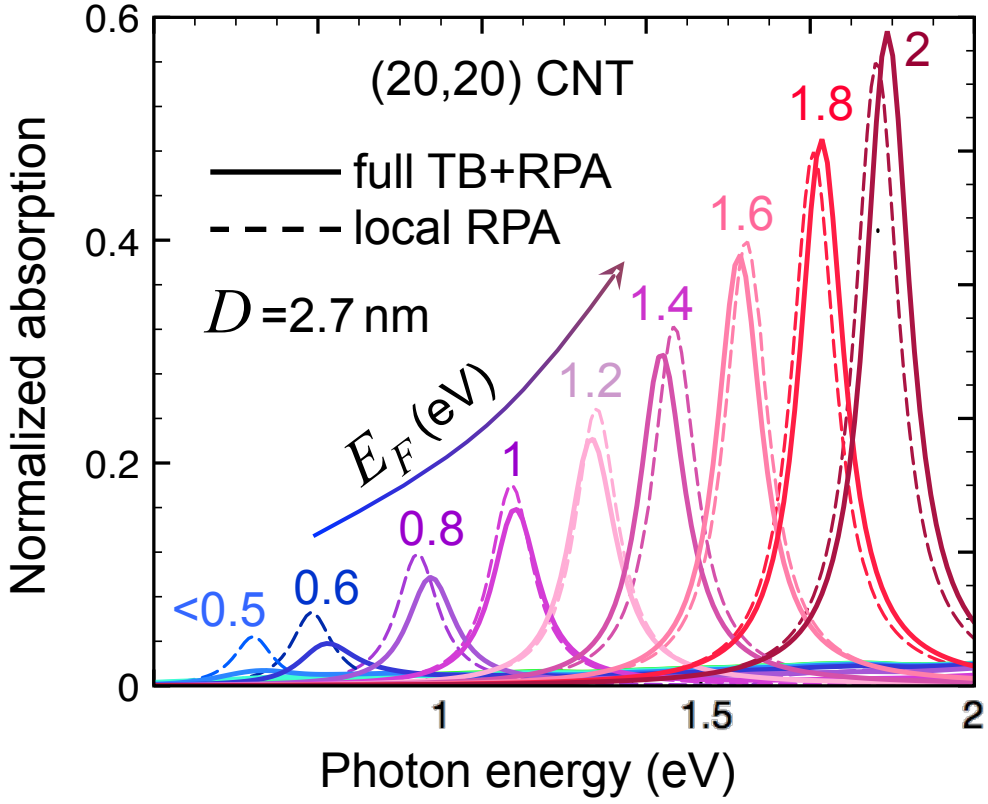


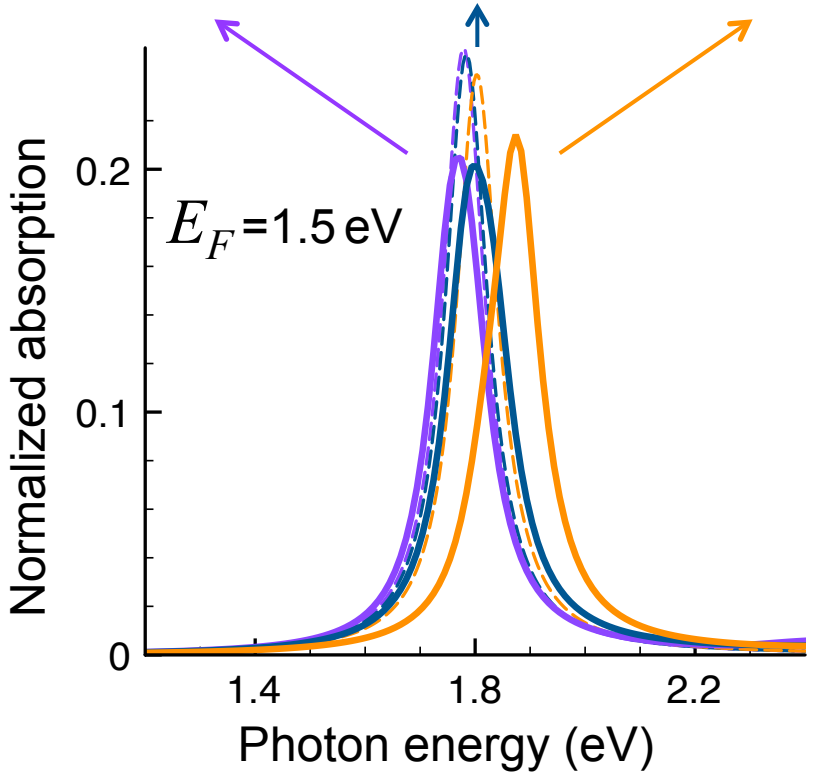
García de Abajo, ACS Photonics (2014)

vis-NIR plasmons in CNTs



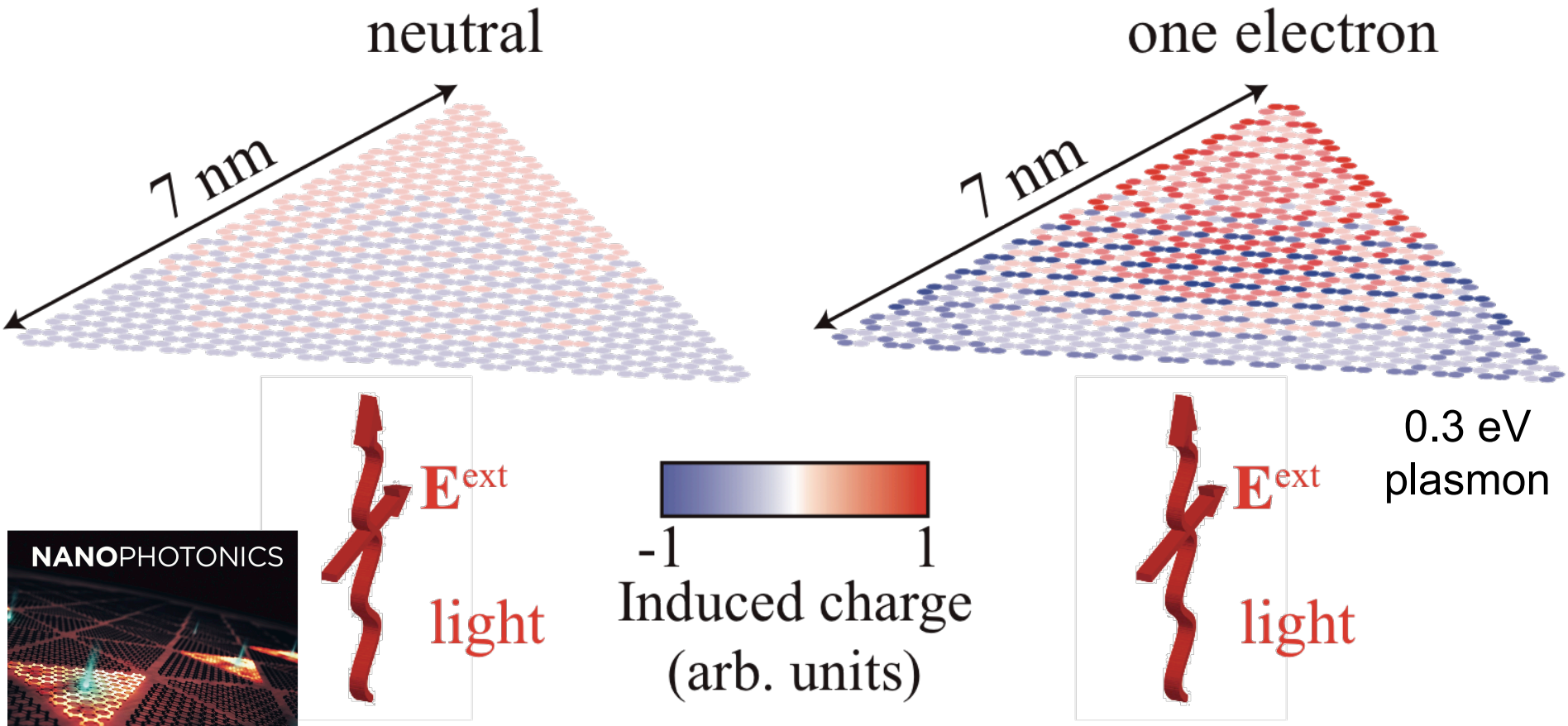






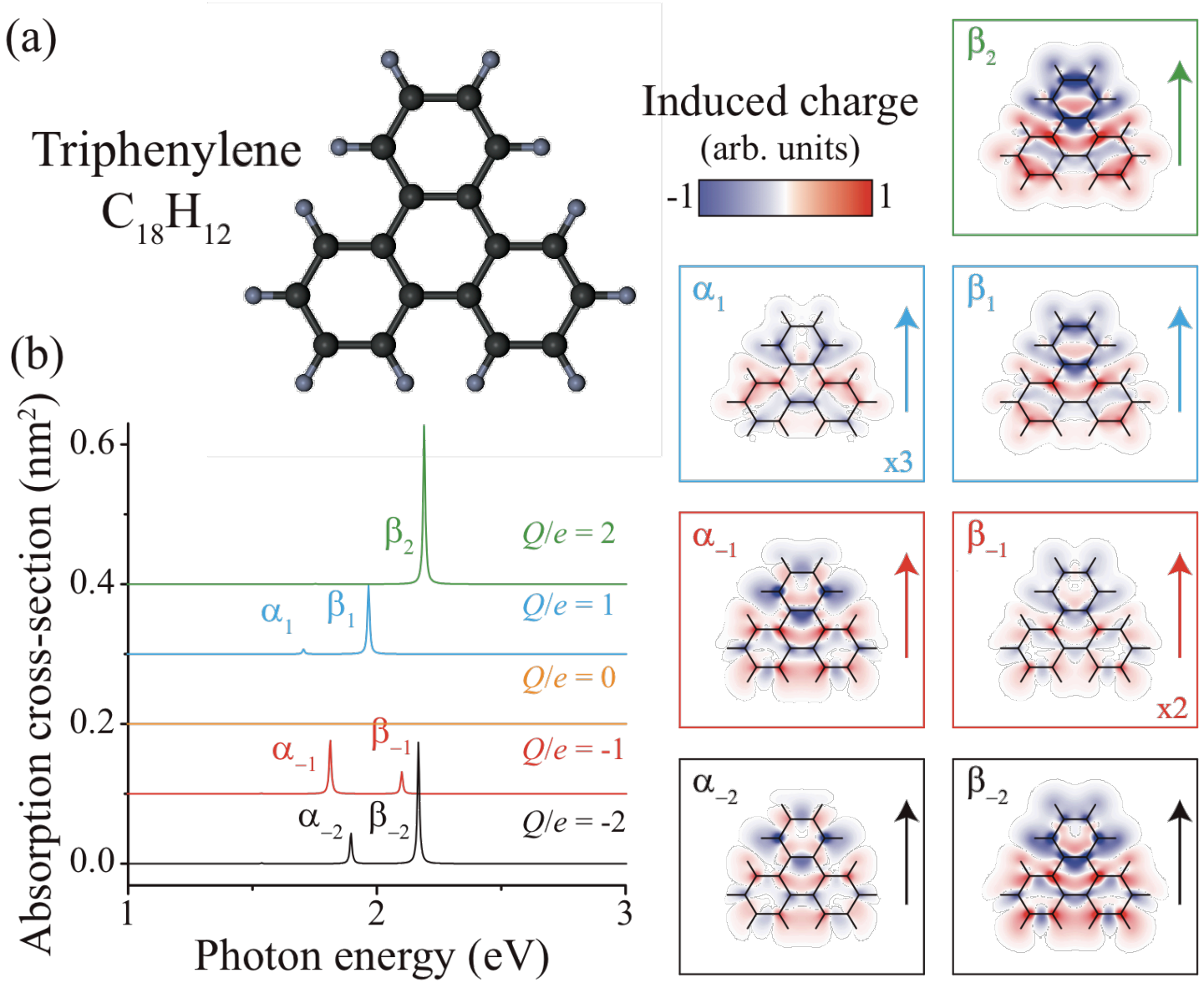
García de Abajo, ACS Photonics (2014)

Single-electron plasmon switching



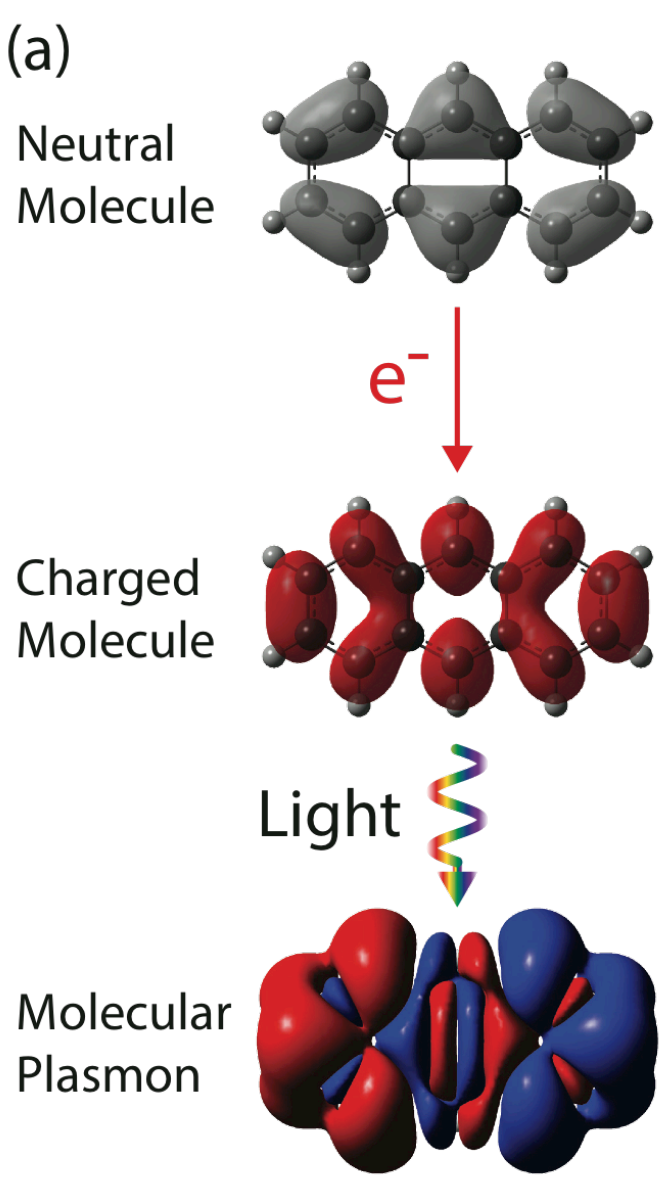
Manjavacas *et al.*, Nanophotonics (2013)

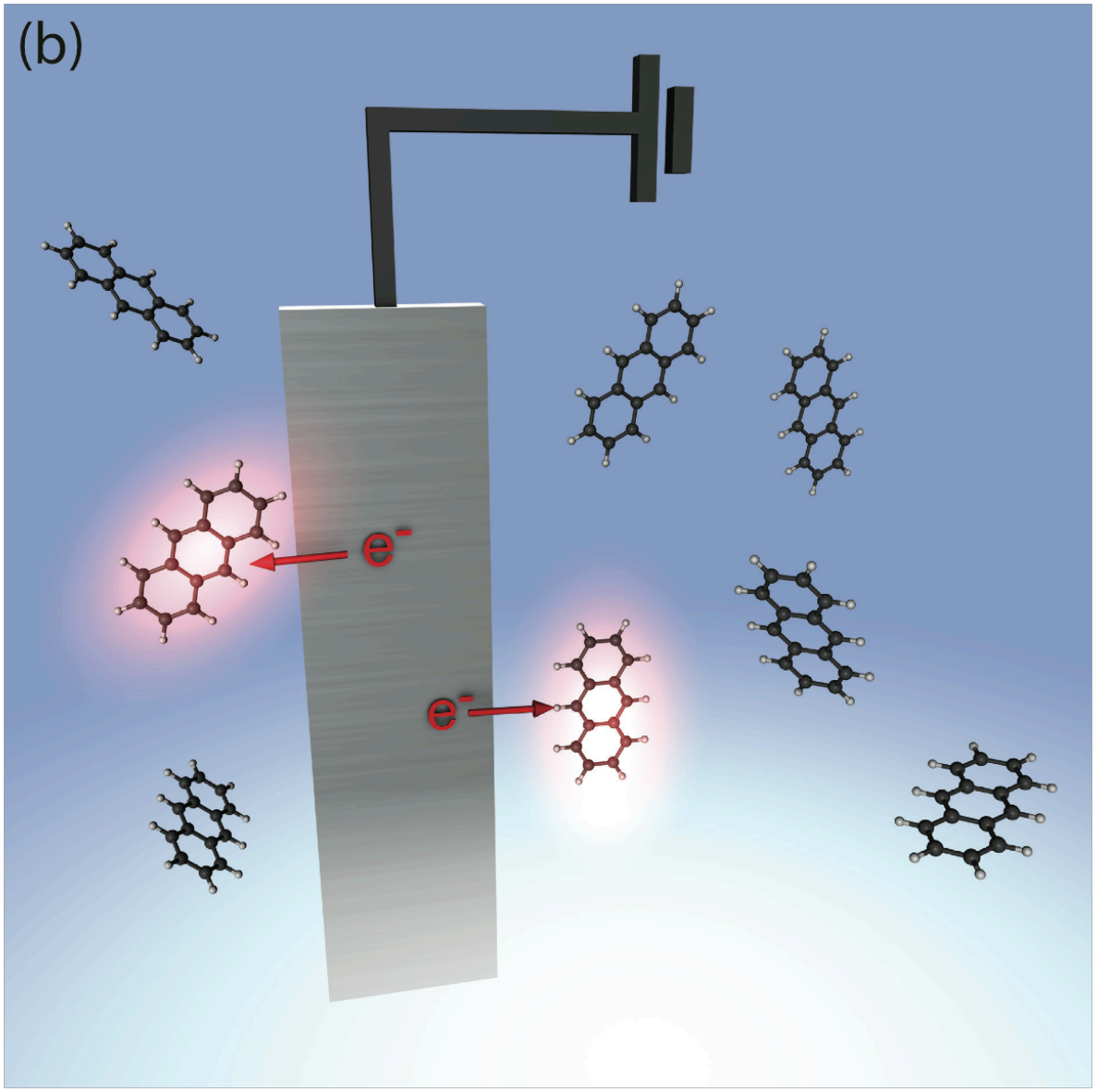
Down to molecules



Manjavacas *et al.*, ACS Nano (2013)

Tunable molecular plasmons





Adam Lauchner *et al*., in collaboration with Naomi Halas and Peter Nordlander groups

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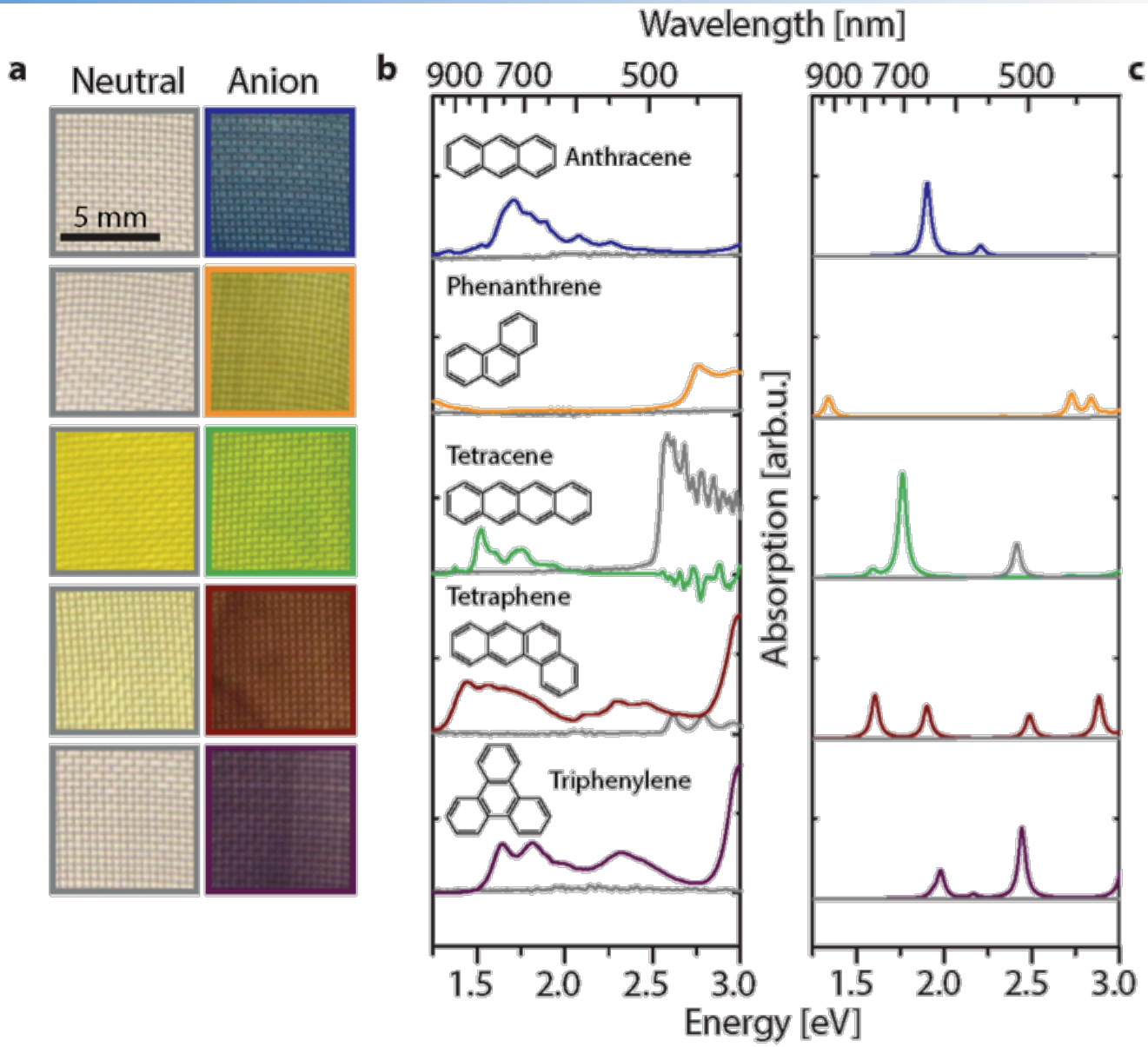

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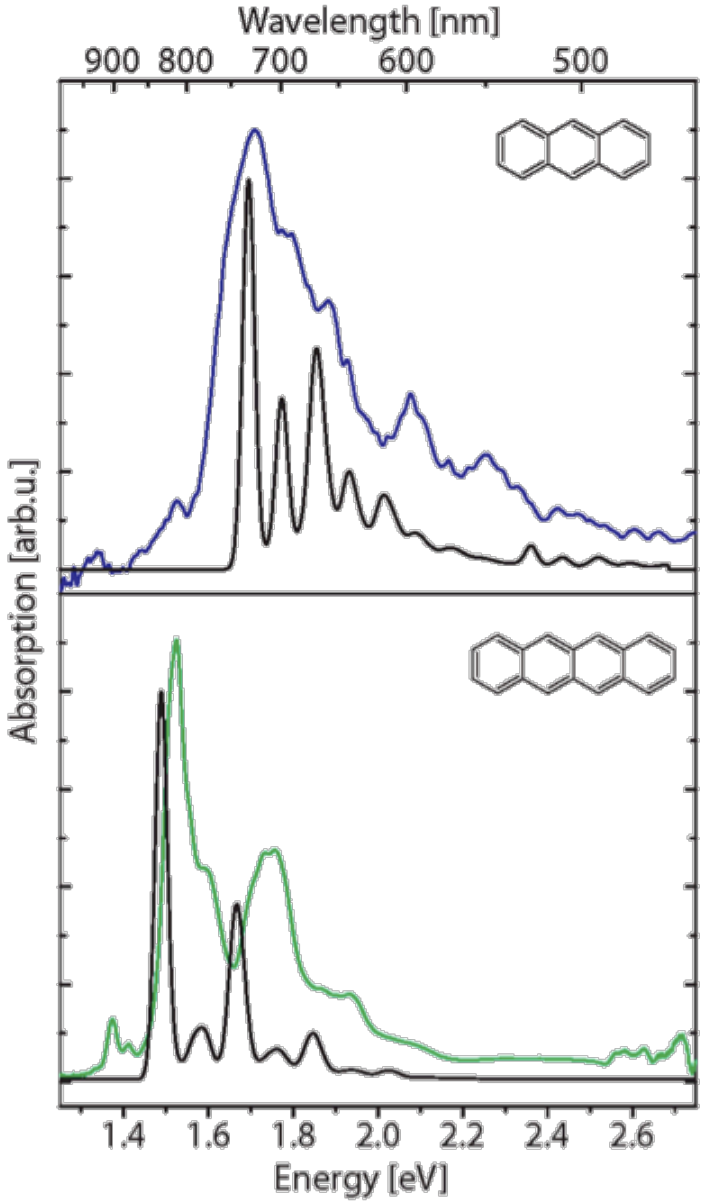

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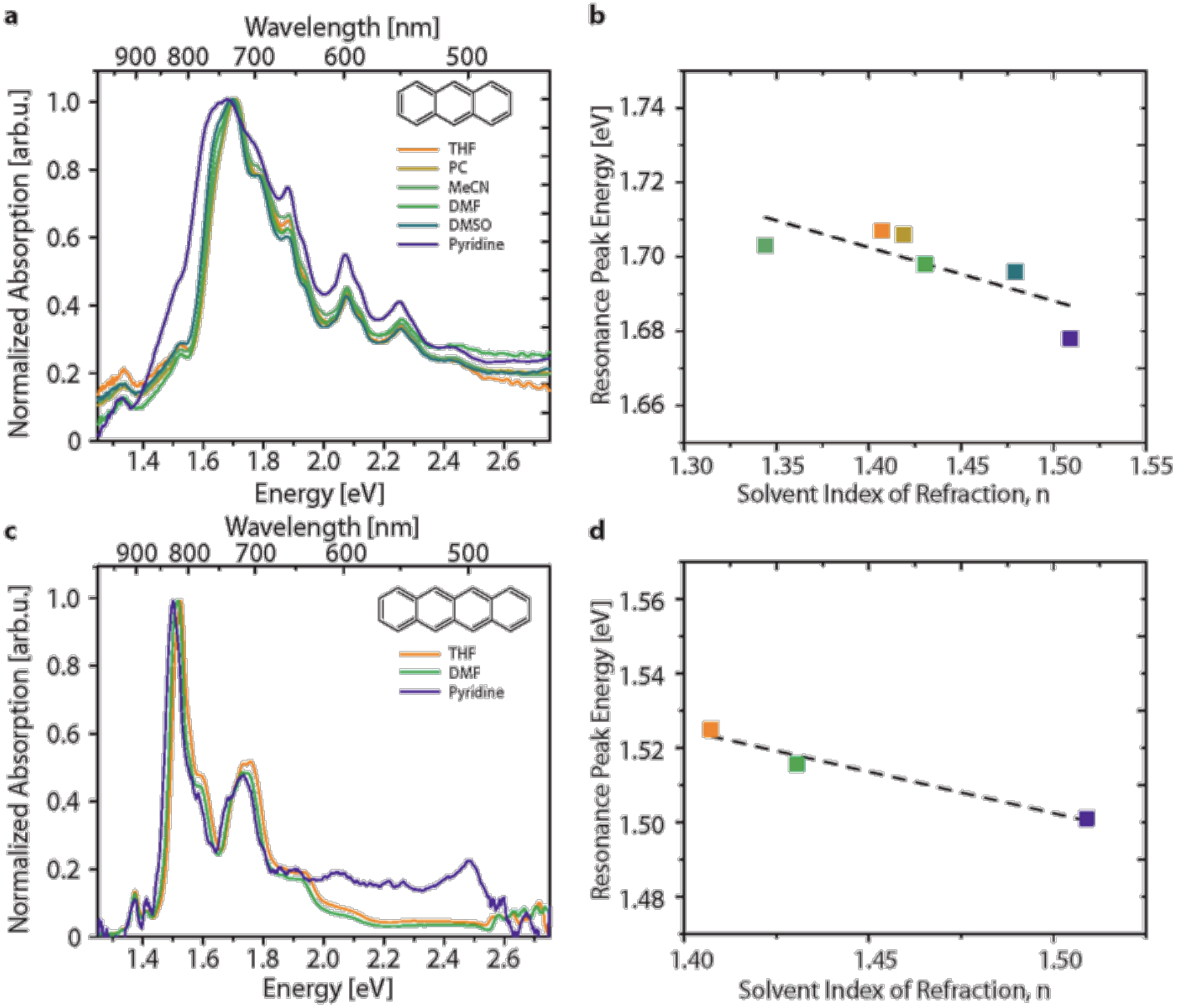

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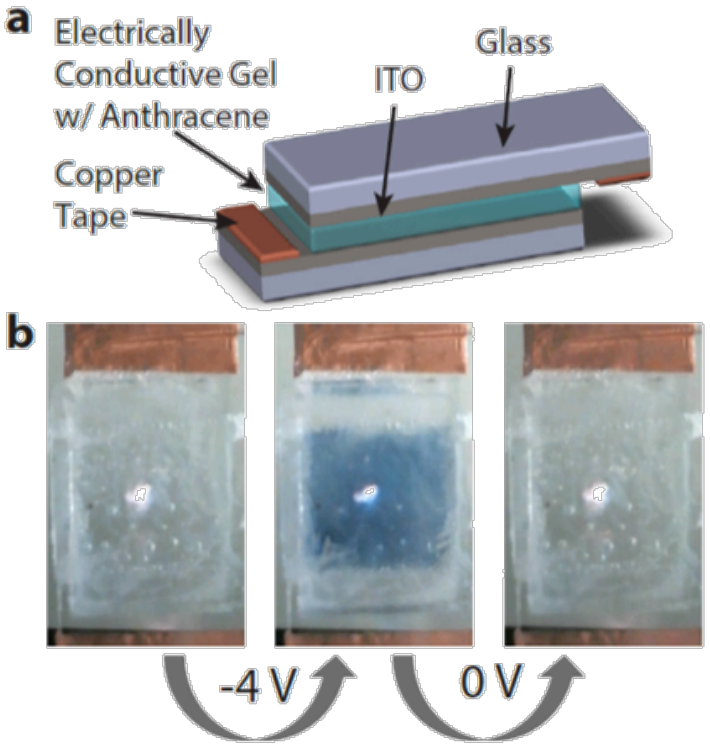
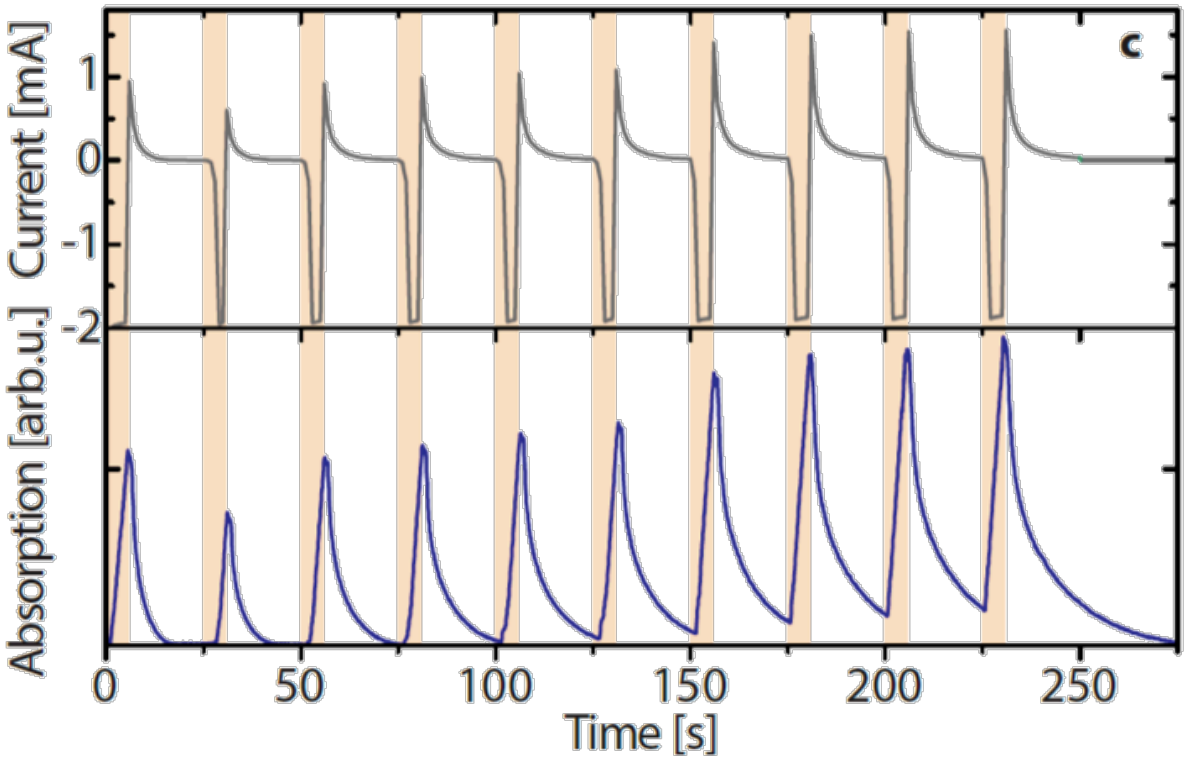
Electrochromic device





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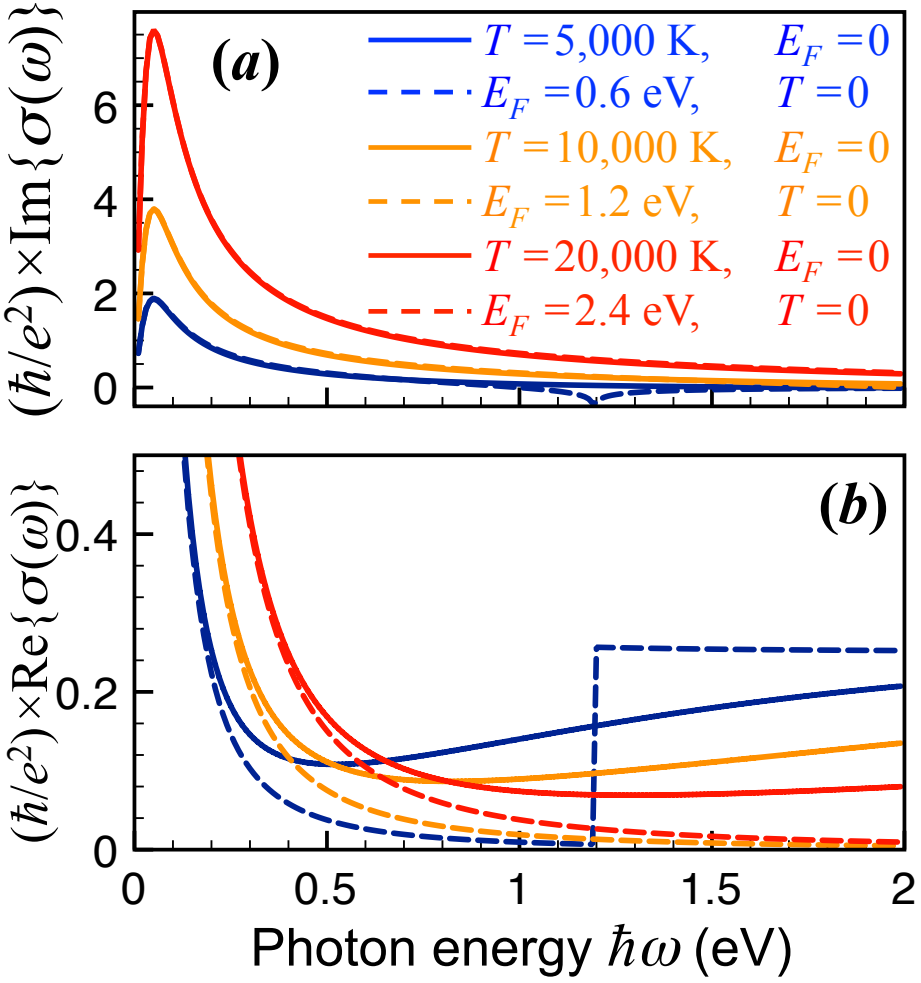
How to move towards the visible-NIR

1) Increasing doping

2) Making smaller structures

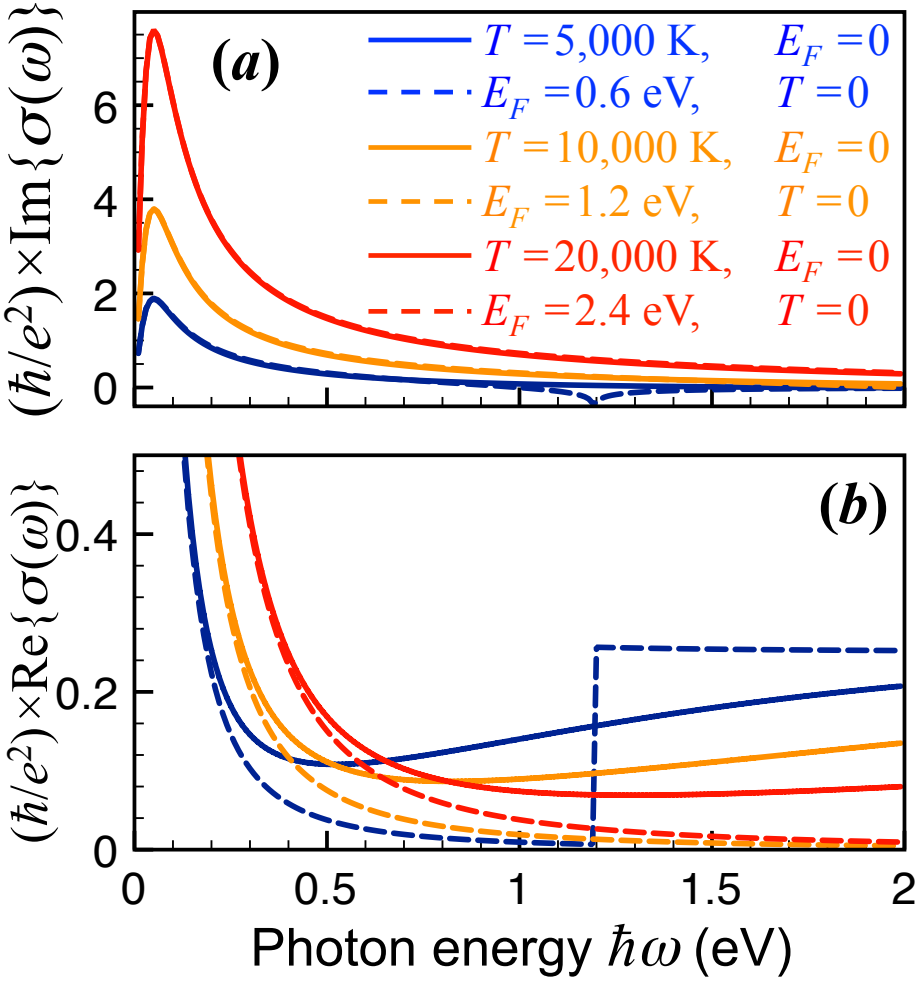
3) Exploiting transient phenomena

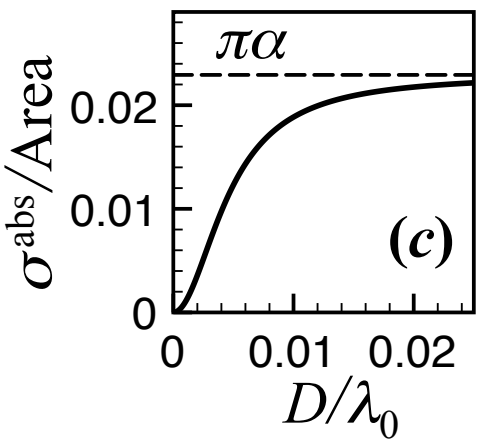
Transient graphene plasmons

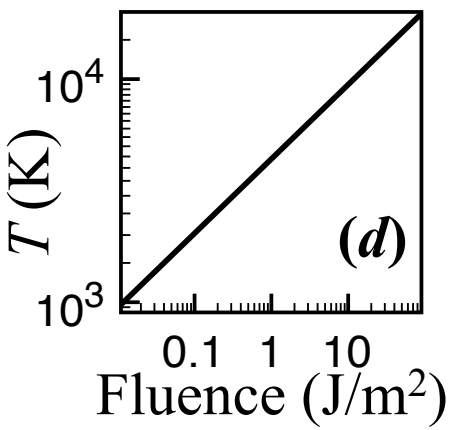


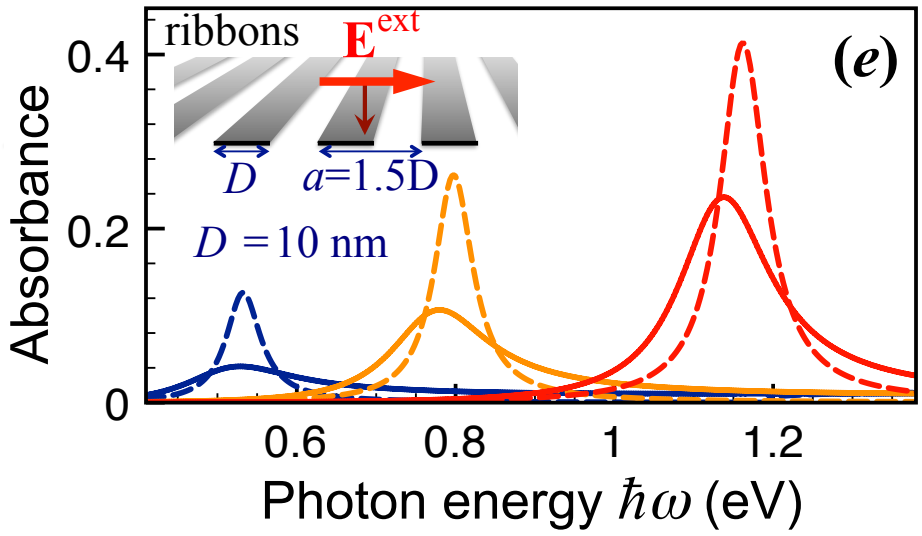
García de Abajo, ACS Photonics (2014)

Transient graphene plasmons









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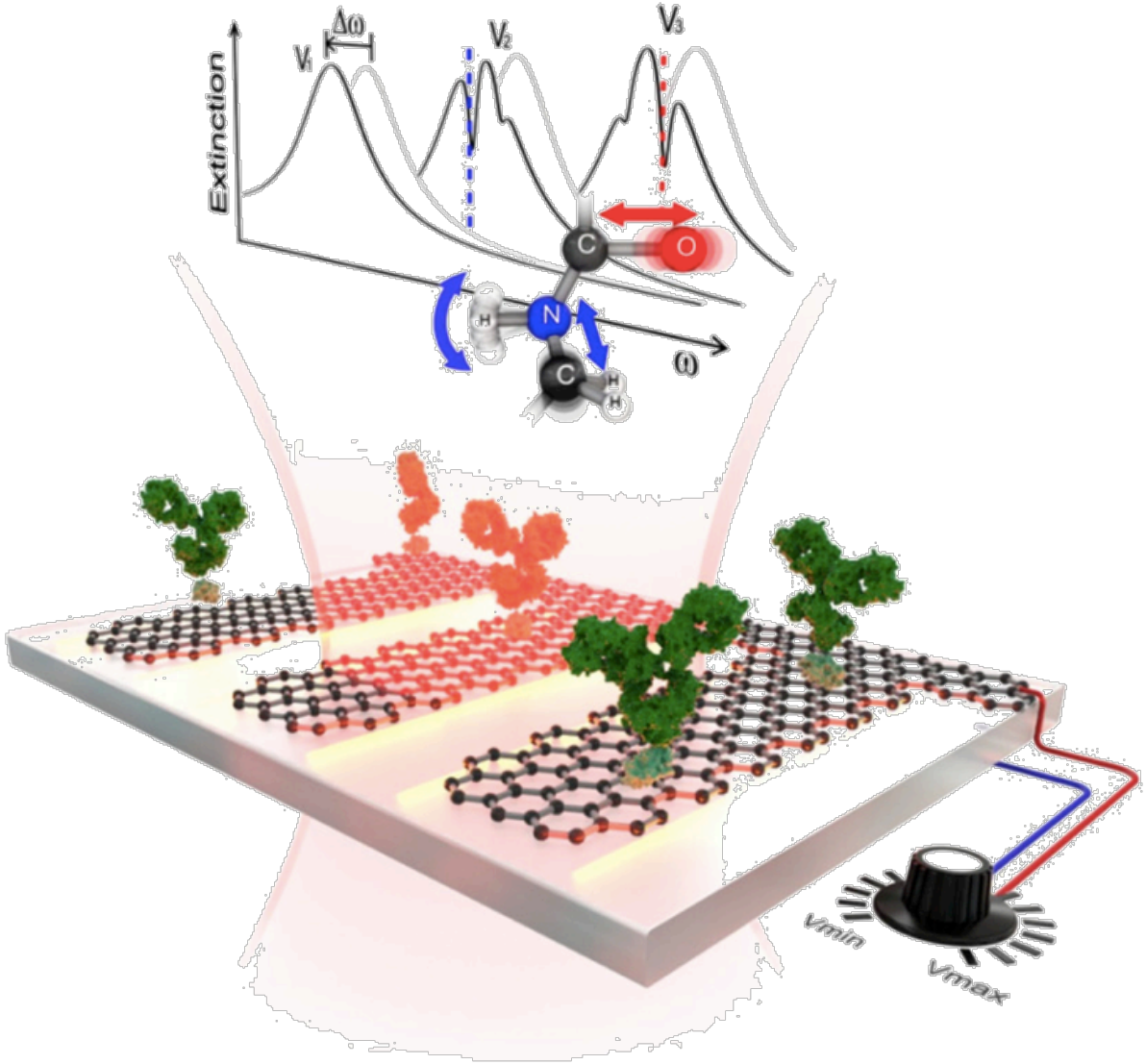
Plasmons in other atomically thin materials

Mid-IR sensing with graphene plasmons



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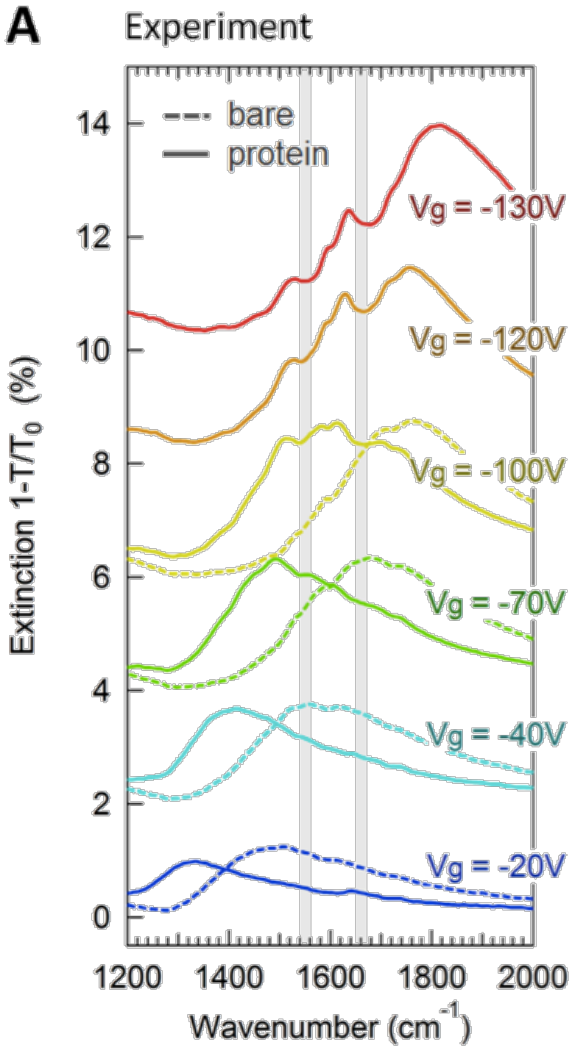

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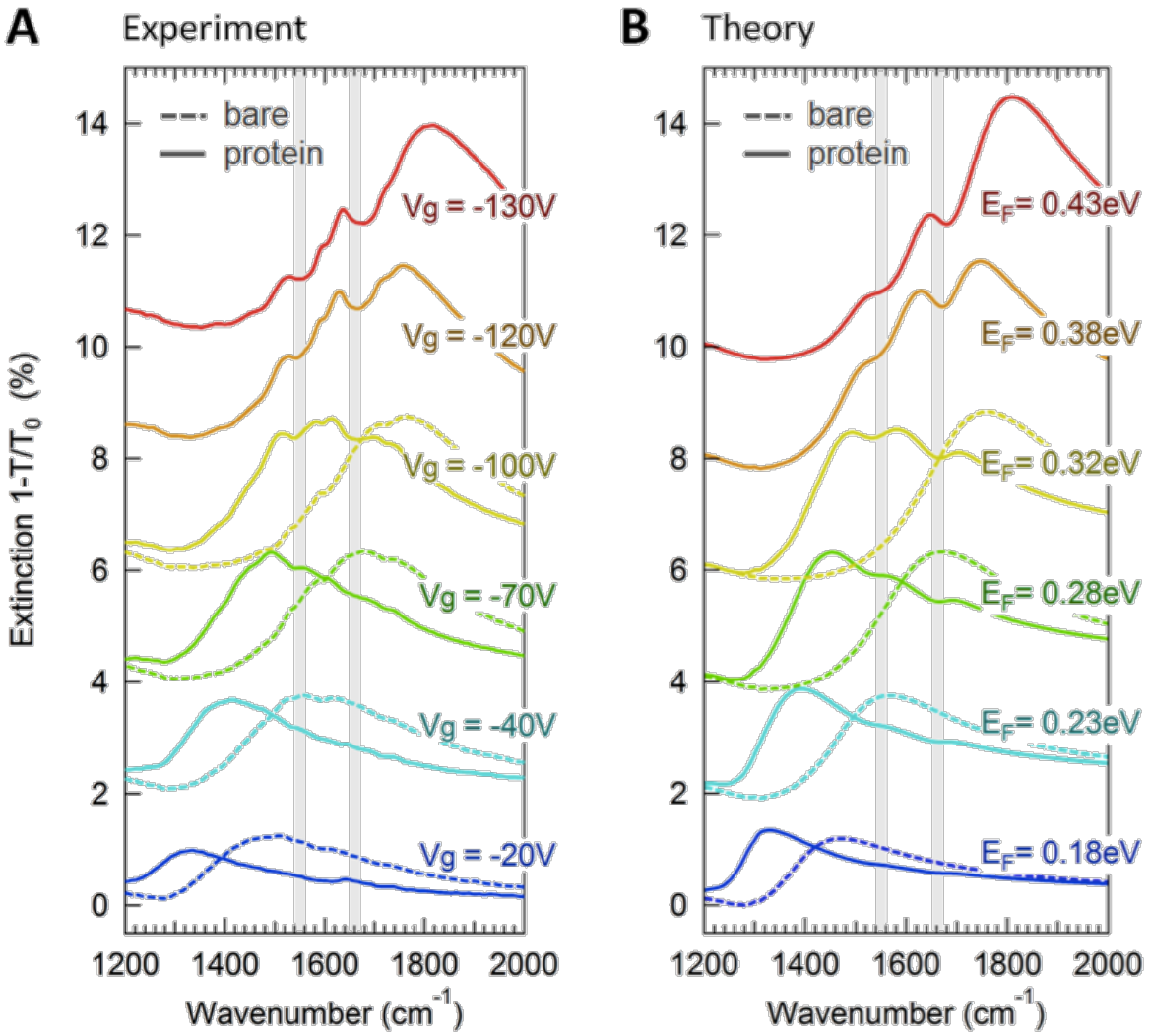

$$\Delta t \propto \alpha^{\text{eff}}$$

$$\alpha^{\text{eff}}(\omega) = \frac{0.894\,W^2}{A/(n_1^2+n_2^2) - \omega W/\mathrm{i}\sigma(\omega)}$$

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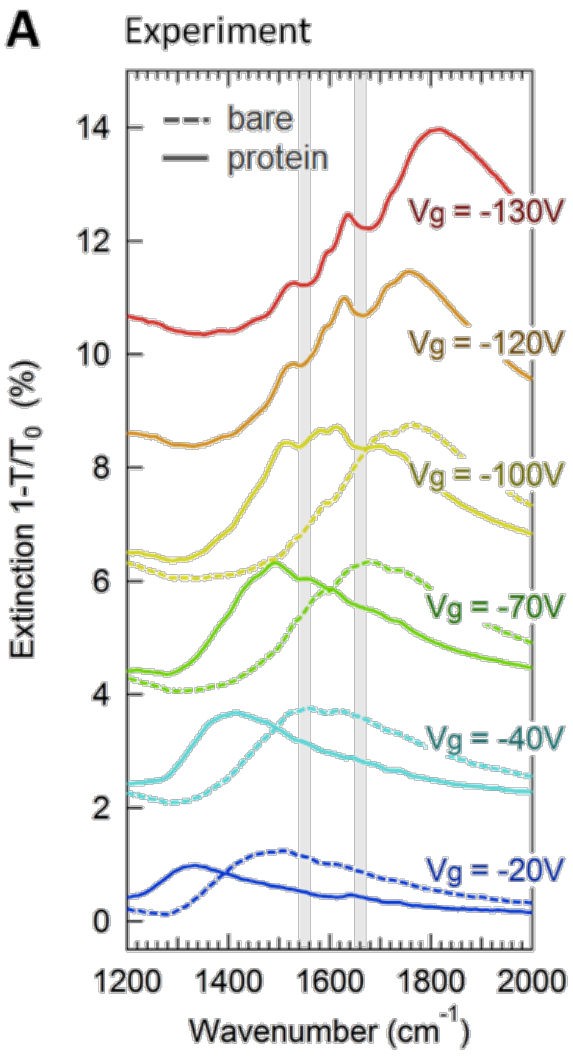

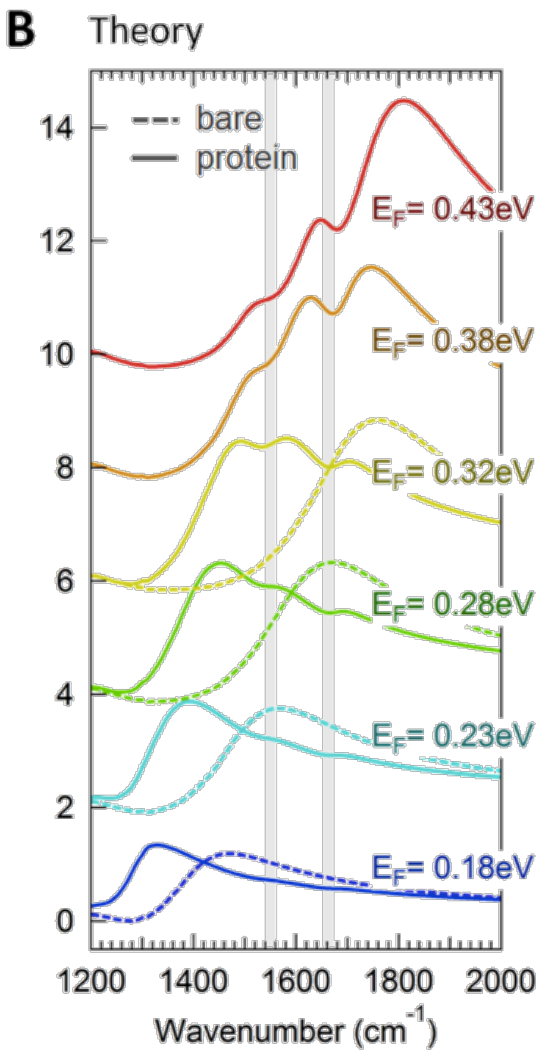

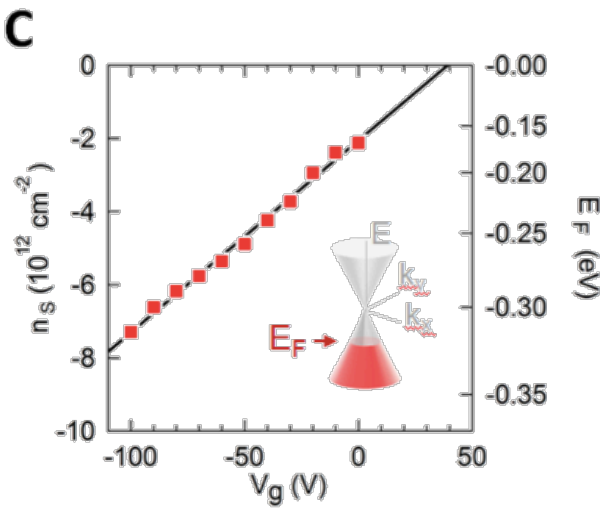

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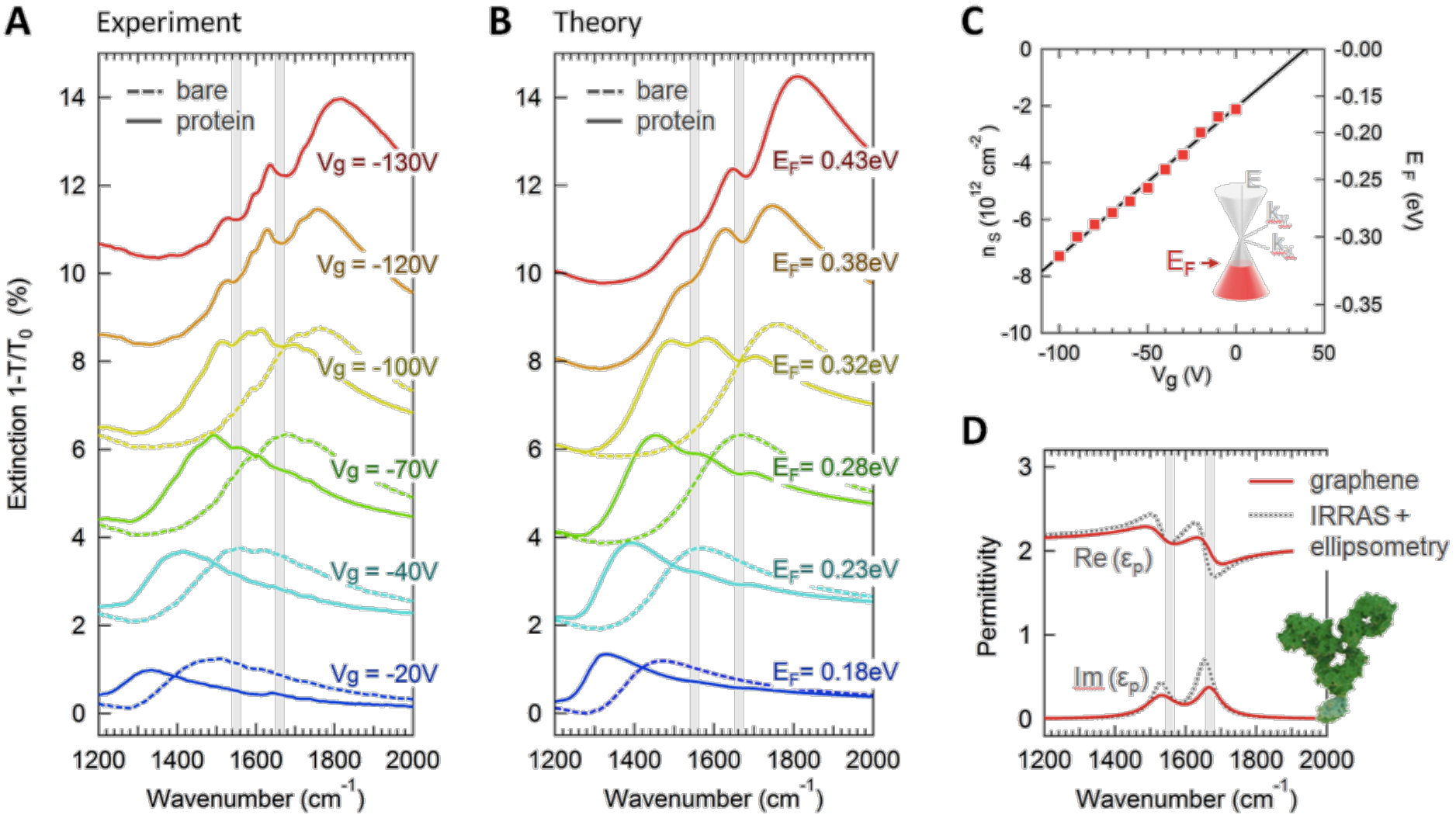

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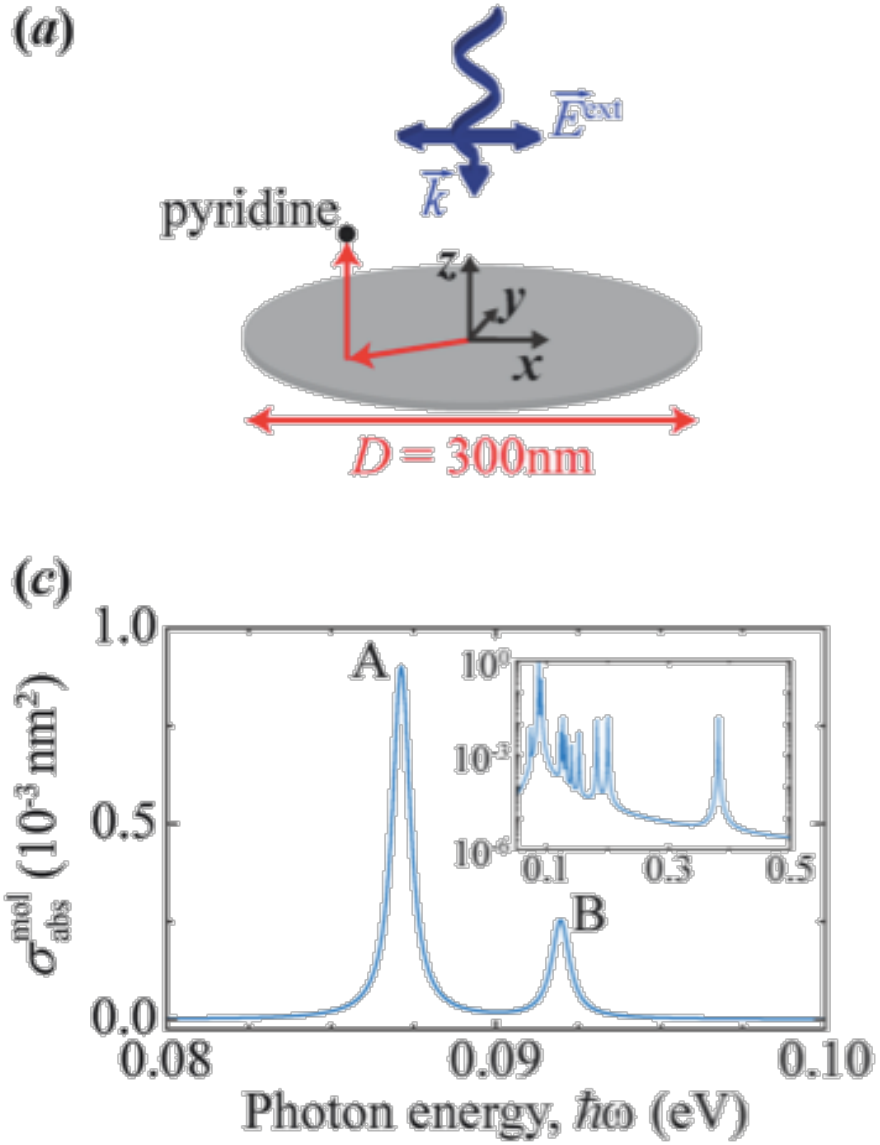
Infrared absorption spectroscopy



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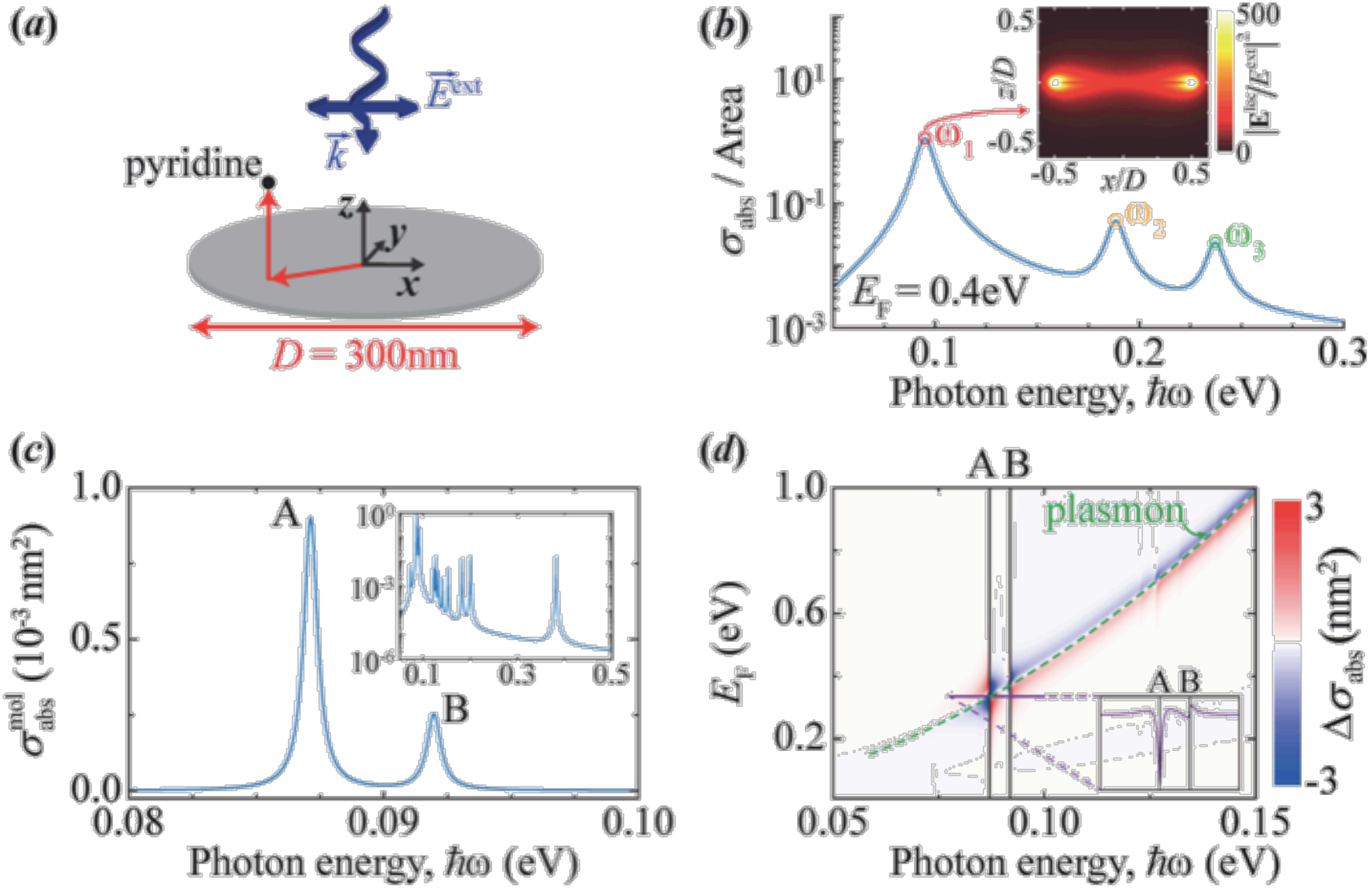

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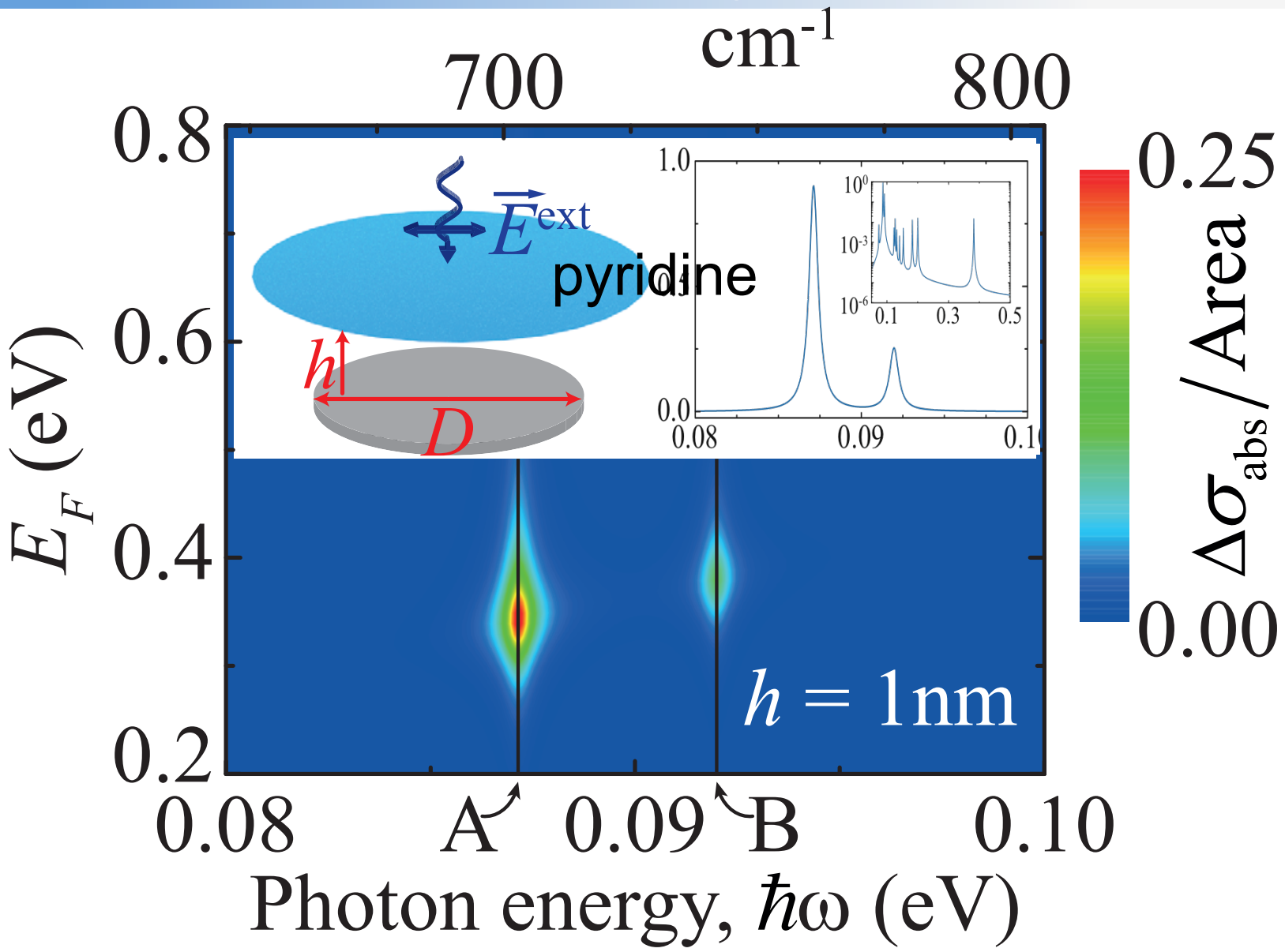

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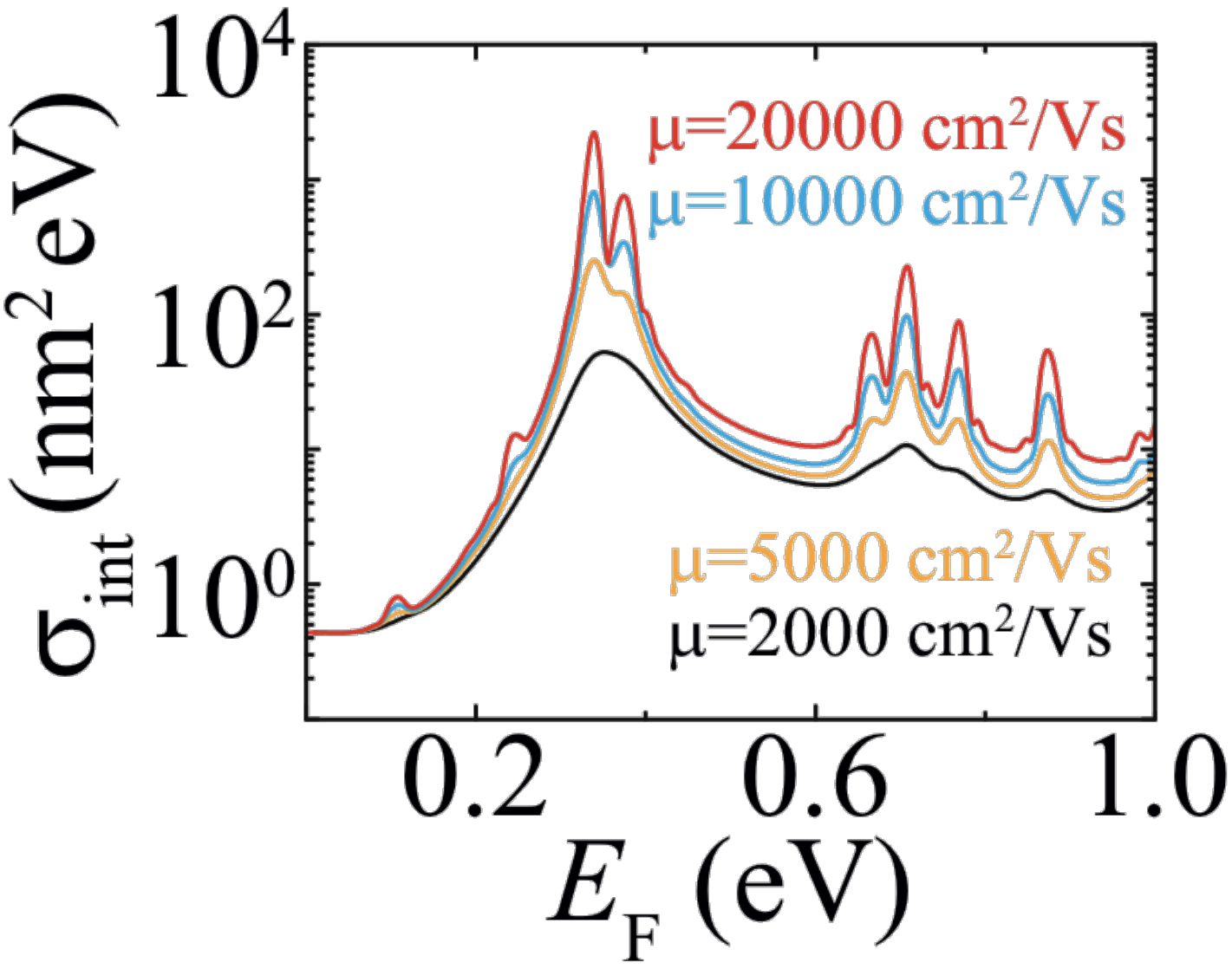

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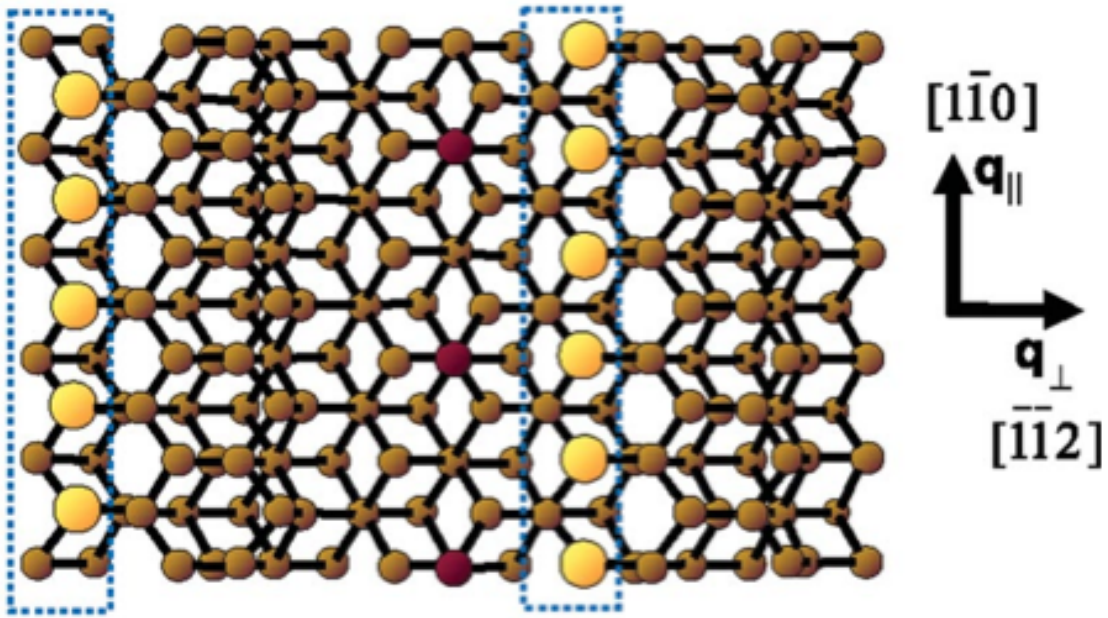
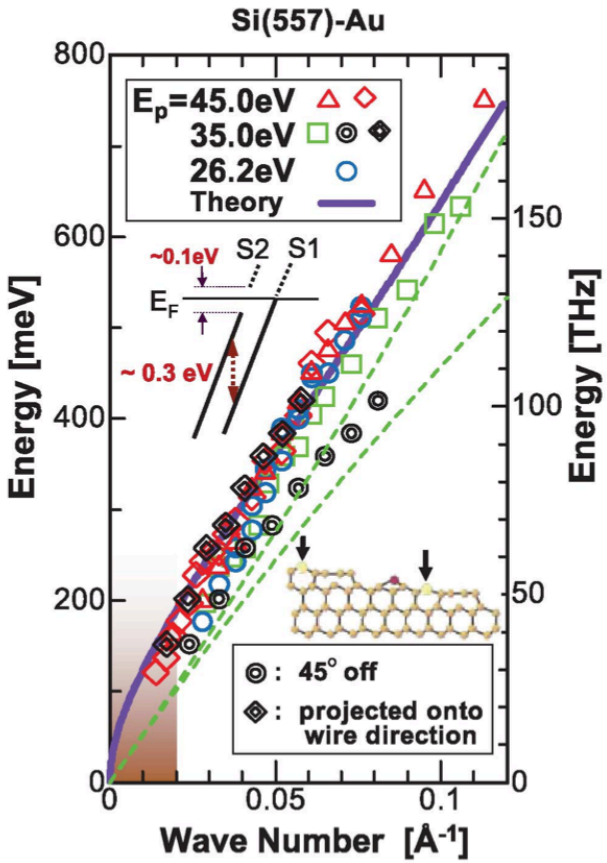
Plasmons in other atomically thin materials

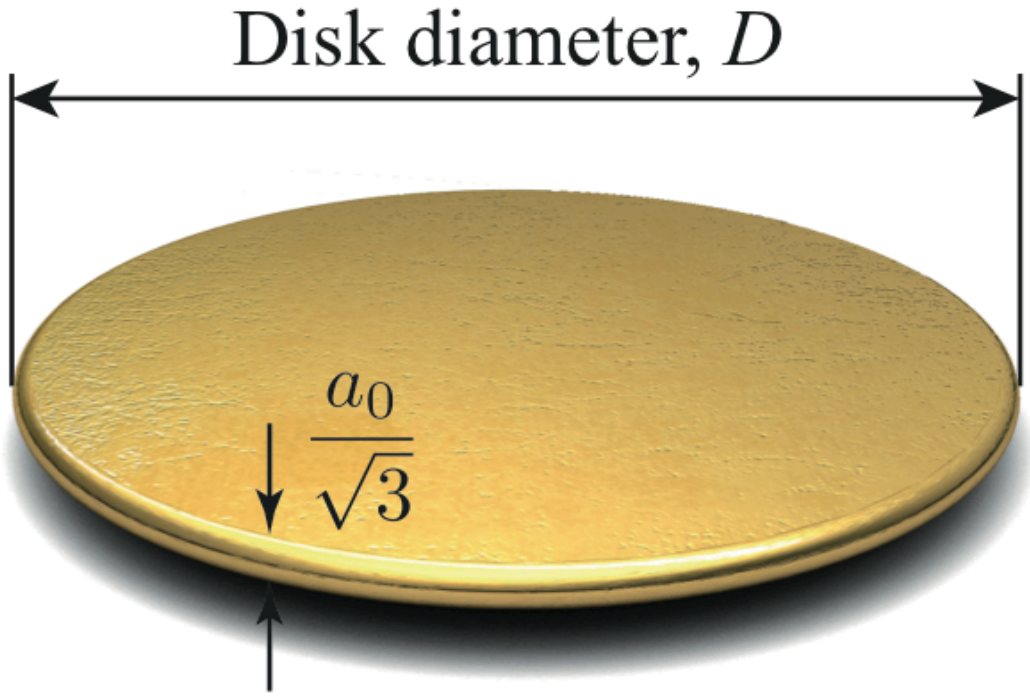
Single-atom-layer metal plasmons

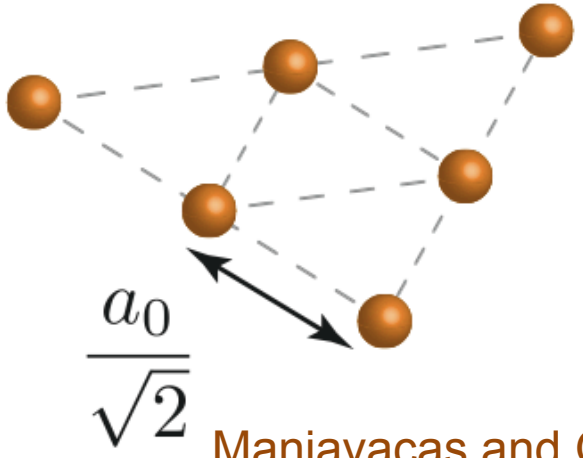




Nagao *et al*., Phys. Rev. Lett. (2006)

Single-atom-layer metallic structures





Gold
111 plane

Manjavacas and García de Abajo, Nat. Commun. (2014)

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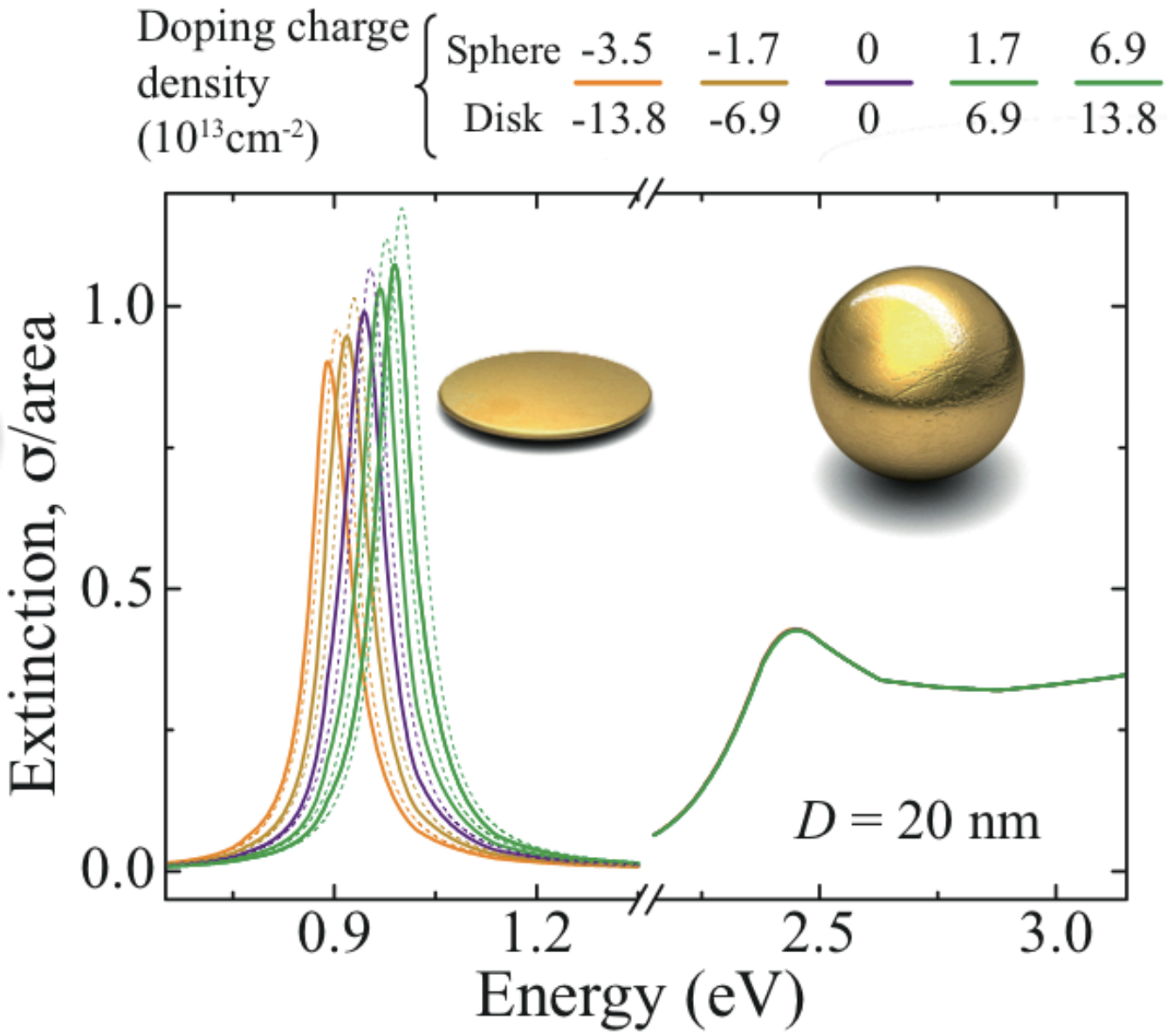

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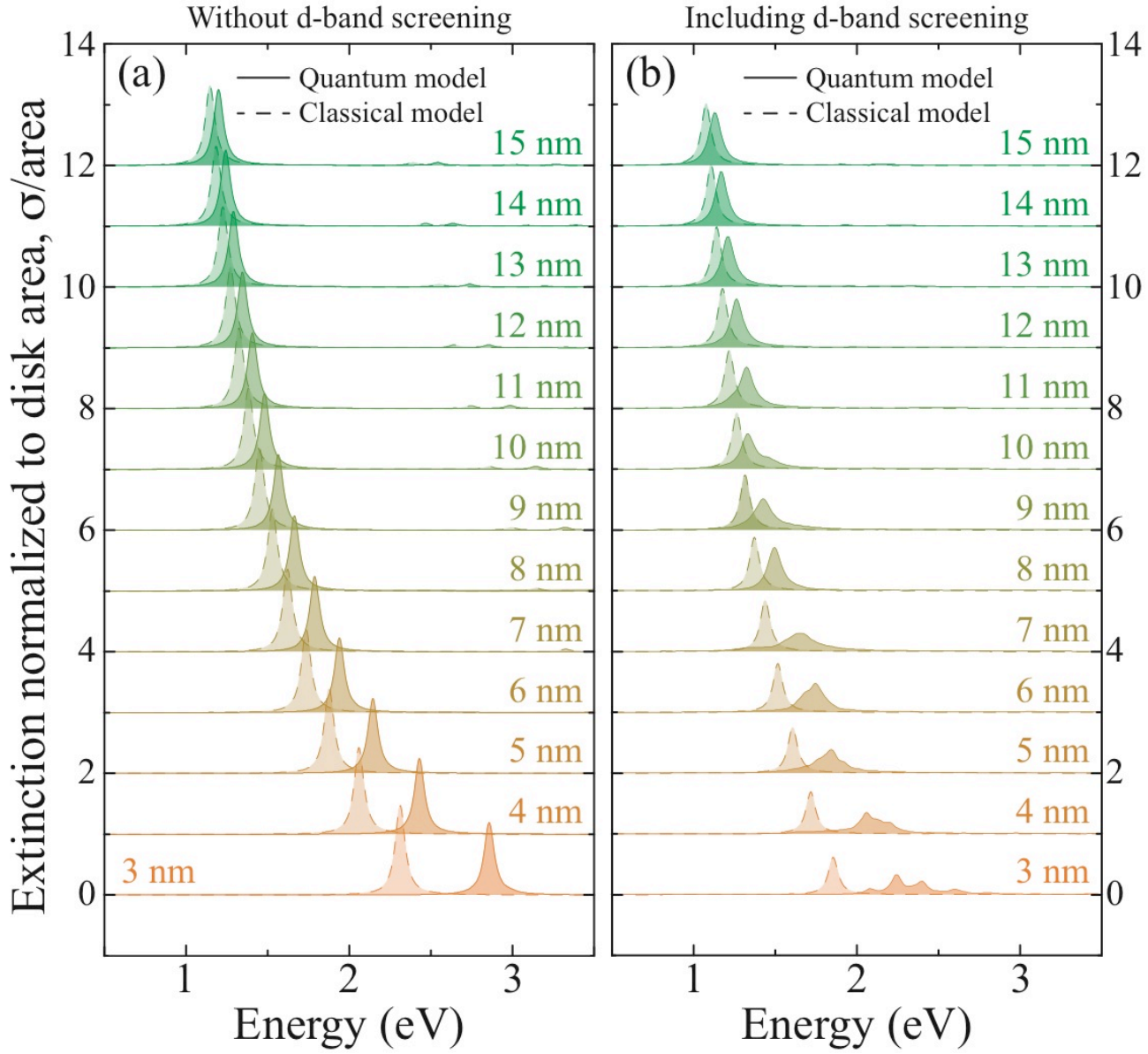

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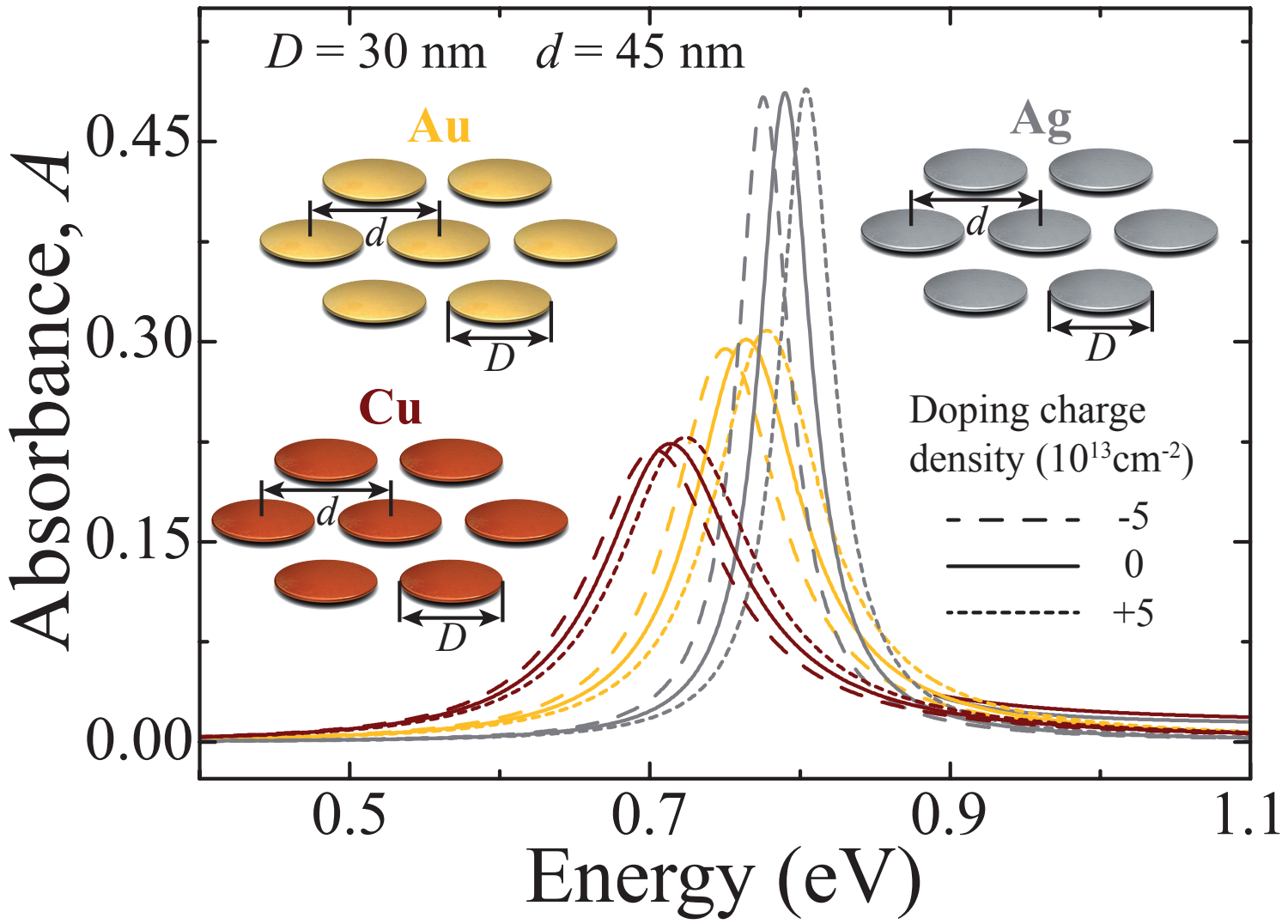
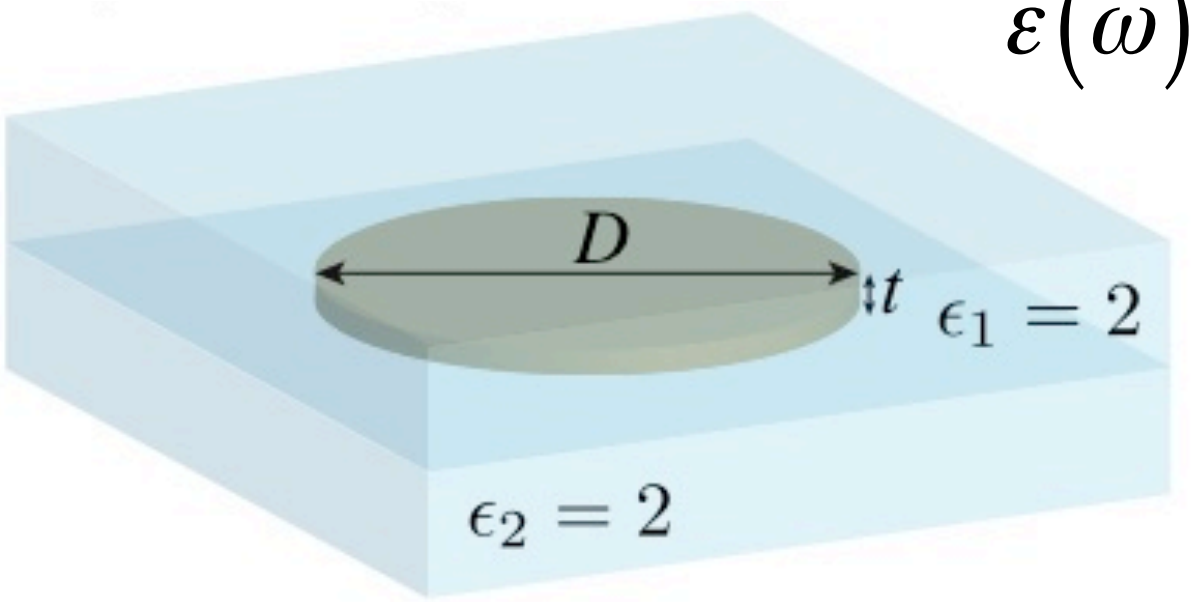


Manjavacas and García de Abajo, Nat. Commun. (2014)

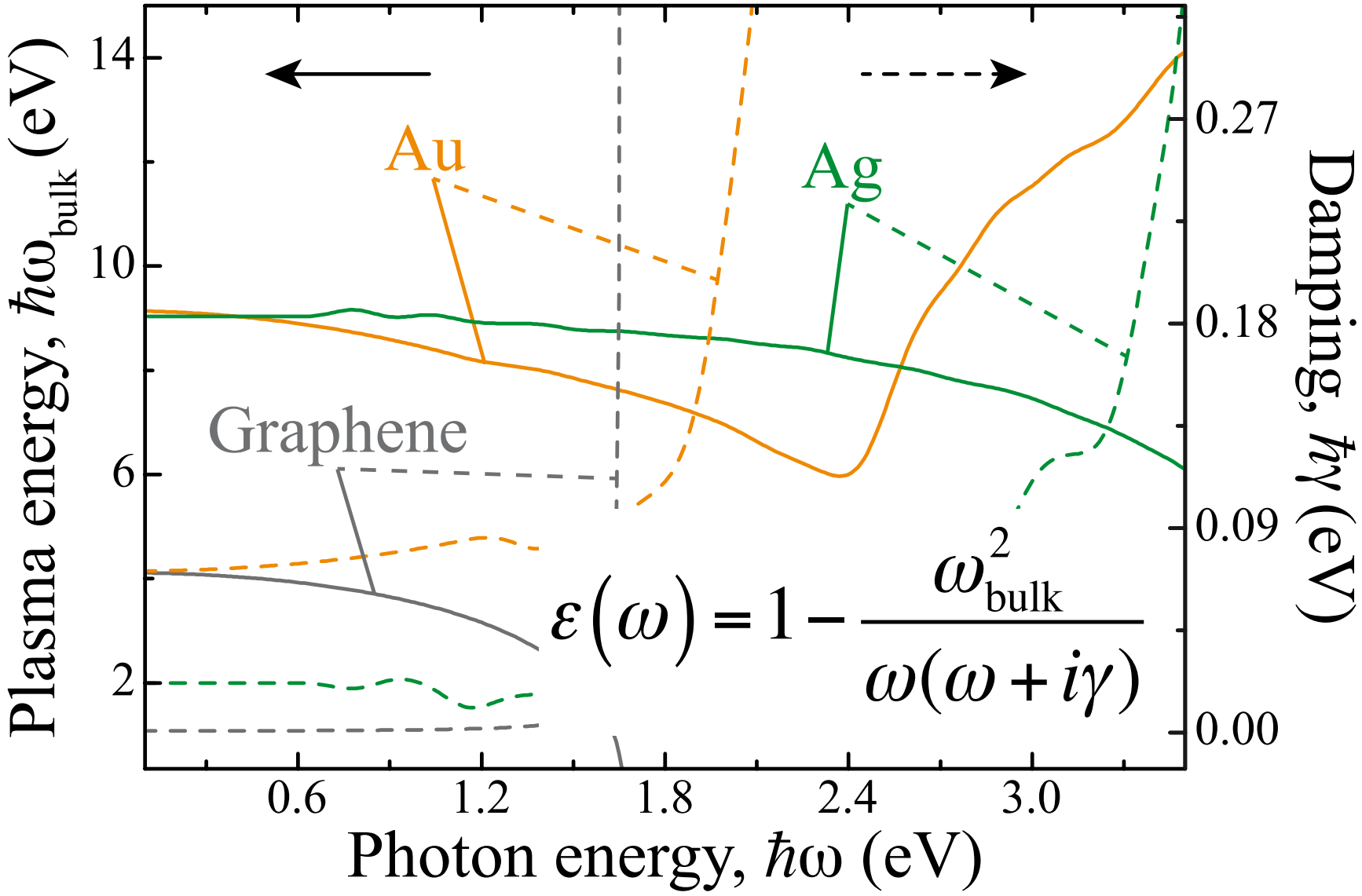
Plasmonics in atomically thin materials



$$\varepsilon(\omega) = 1 - \frac{\omega_{\text{bulk}}^2}{\omega(\omega + i\gamma)}$$

García de Abajo and Manjavacas, Faraday Discussion 178 (2015); arXiv:1411.4780

Plasmonics in atomically thin materials



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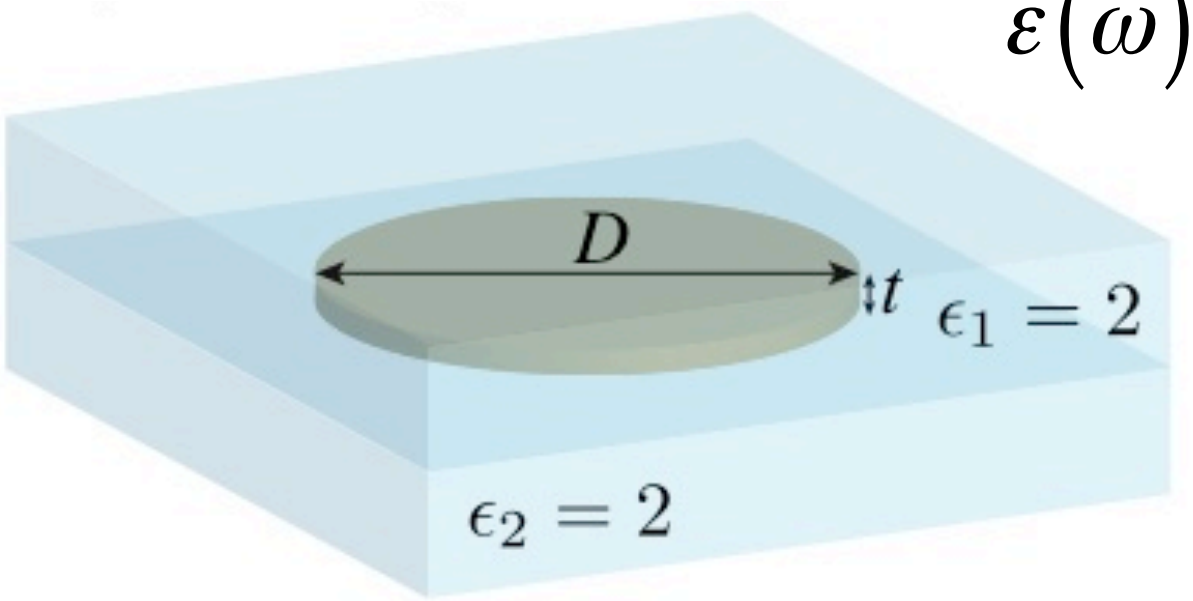

$$\omega_p \approx \frac{\omega_{\text{bulk}}}{n_{\text{eff}}} \sqrt{\frac{3\pi t}{8D}}$$

$$n_{\text{eff}} = \sqrt{(\varepsilon_1 + \varepsilon_2)/2}$$

García de Abajo and Manjavacas, Faraday Discussion 178 (2015); arXiv:1411.4780

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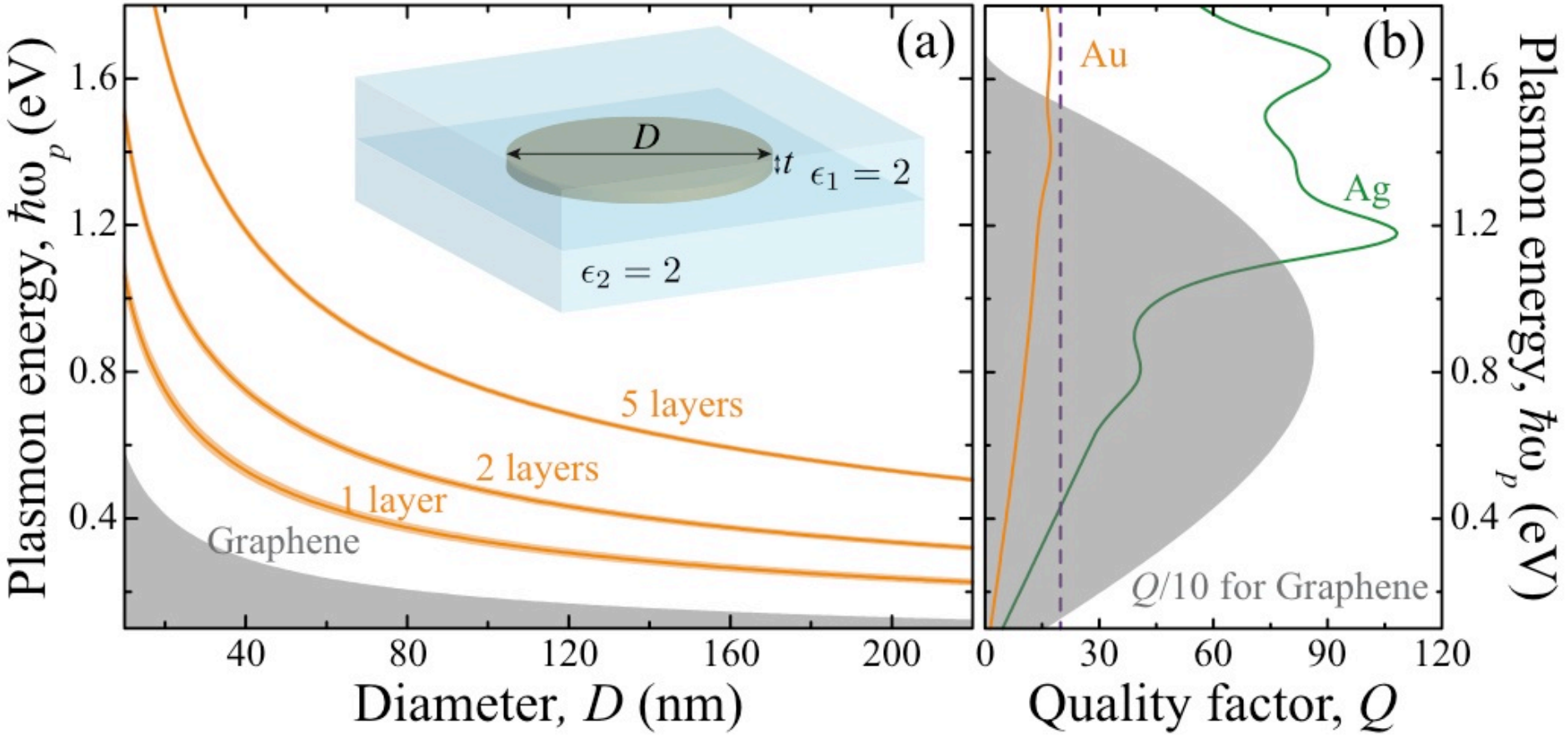

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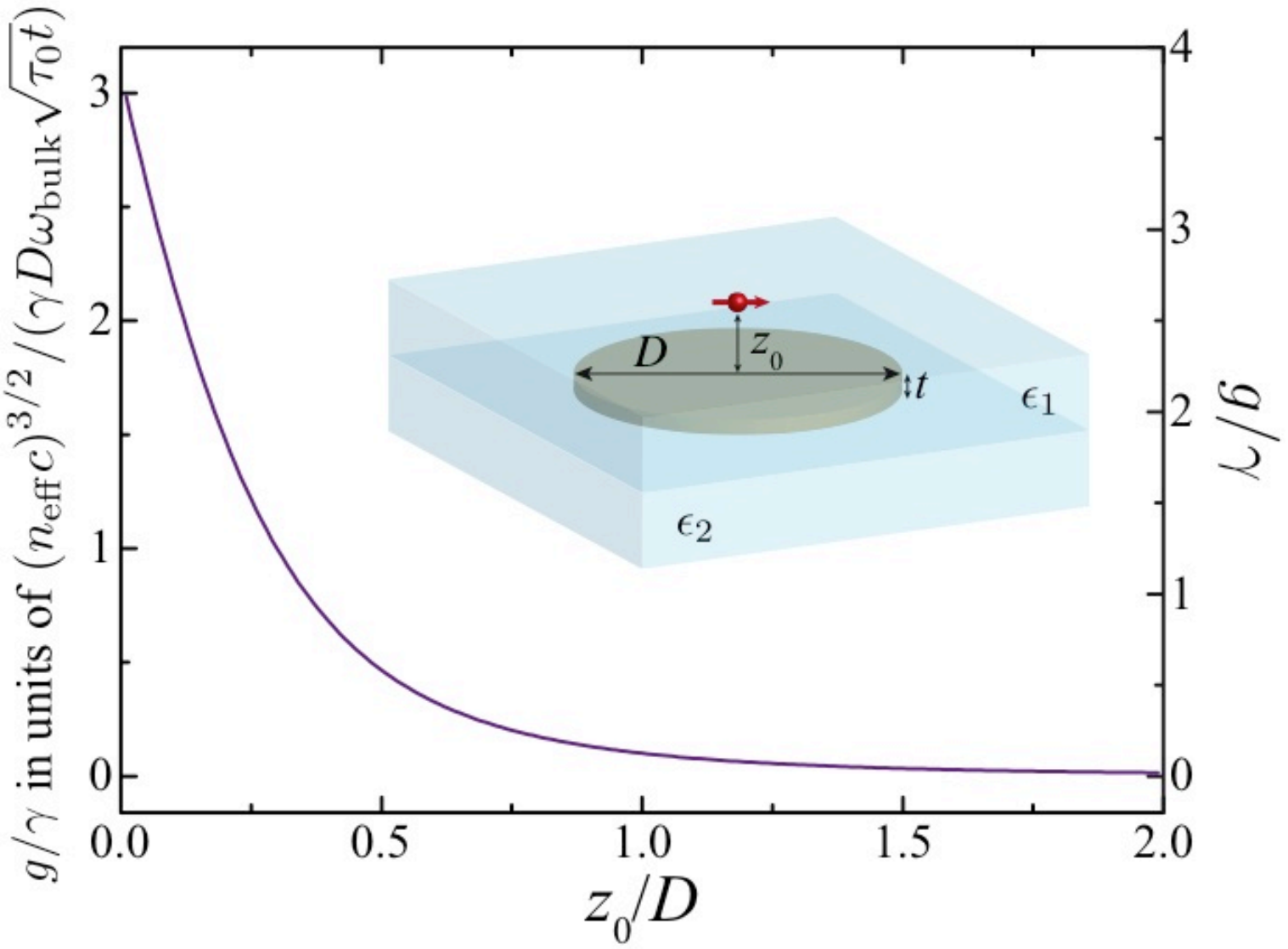

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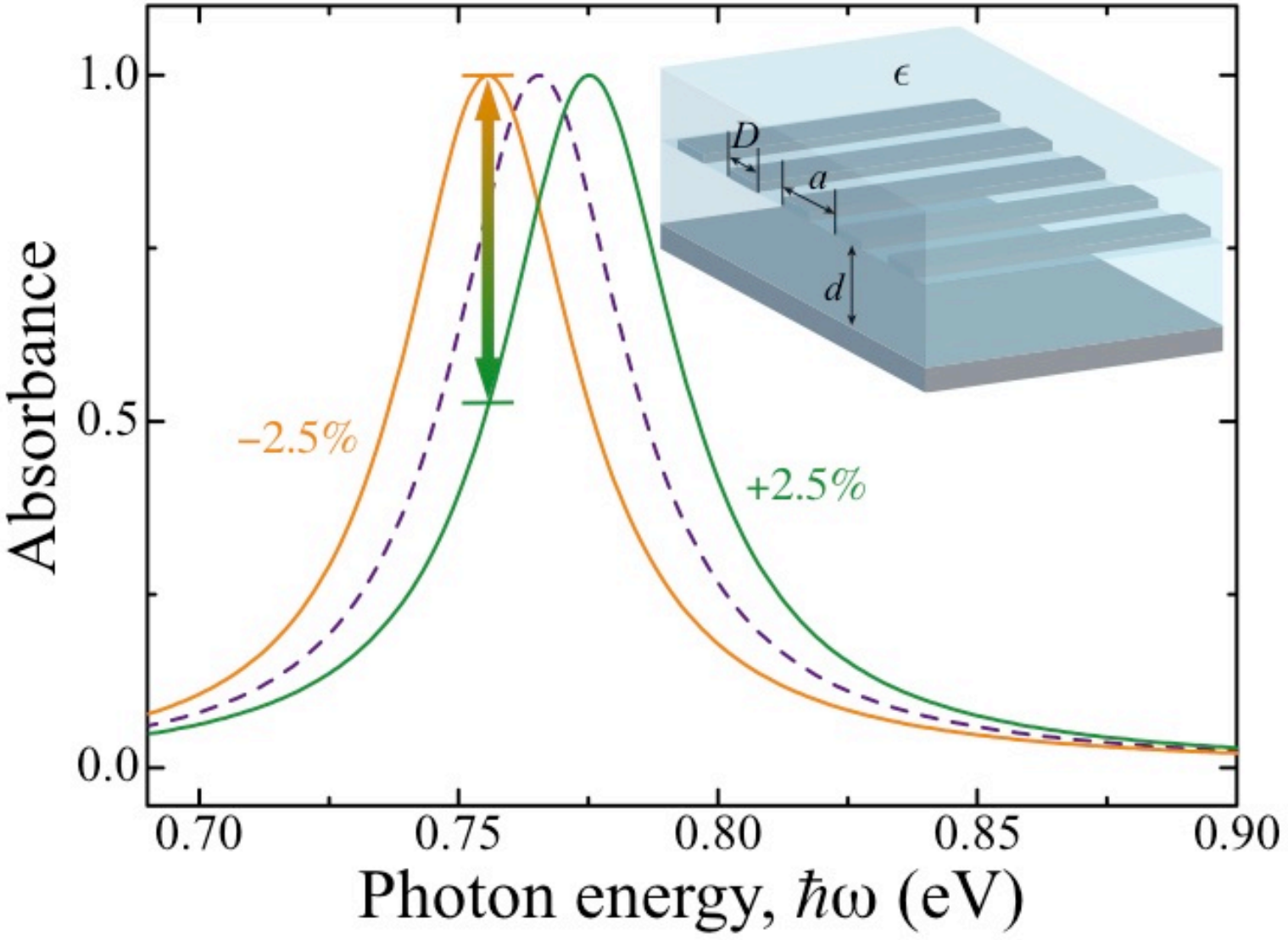

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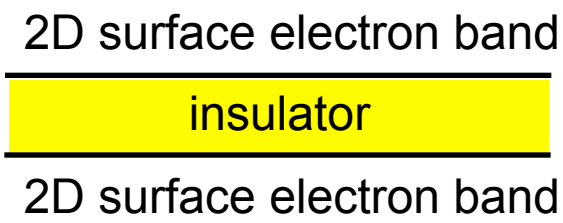
Plasmons in topological insulator rings



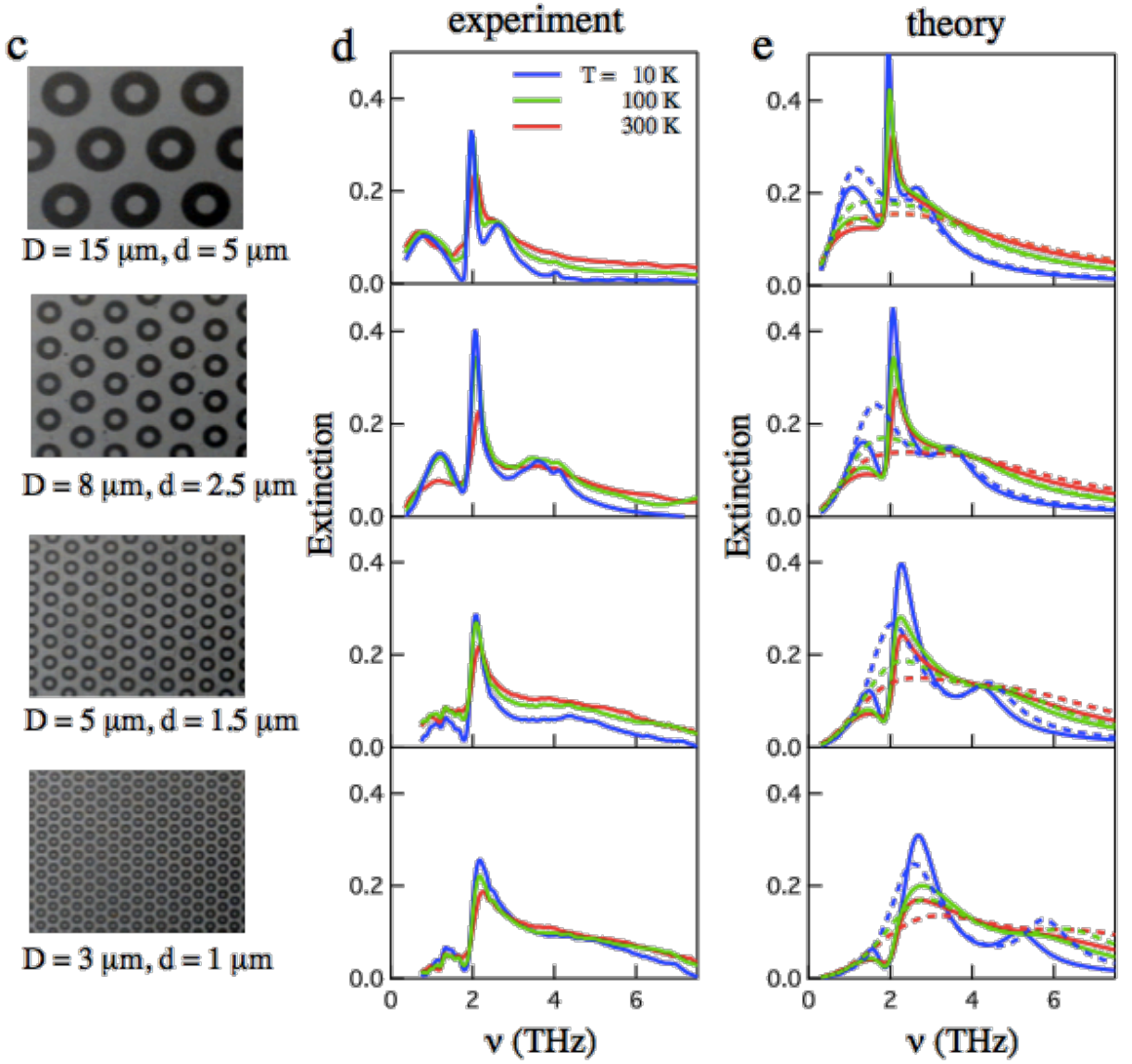
Stefano Lupi's, Autore *et al.*, Adv. Opt. Mater. (2015)

Plasmons in topological insulator rings

2D surface electron band

insulator

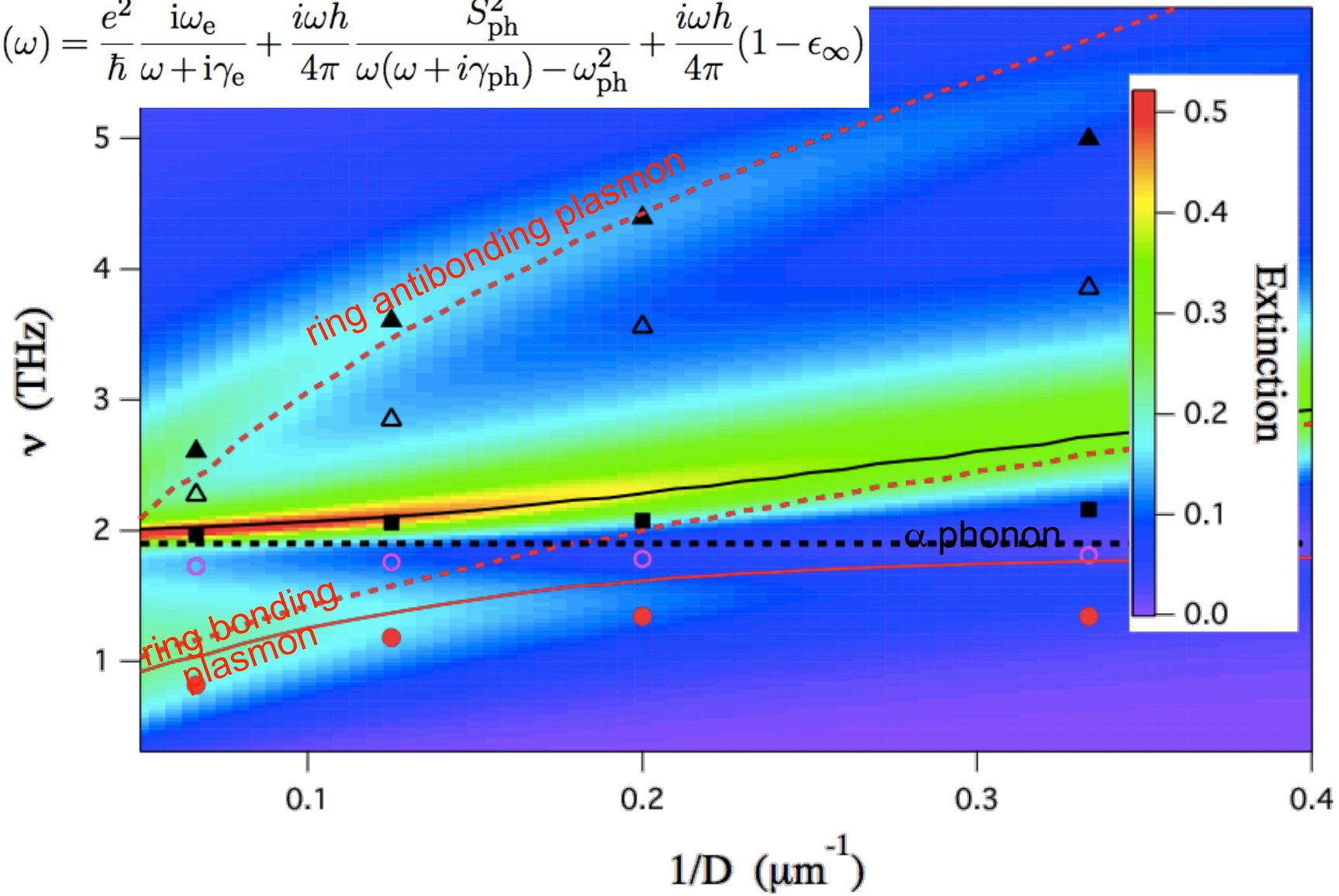
2D surface electron band



Stefano Lupi's, Autore *et al.*, Adv. Opt. Mater. (2015)

Plasmons in topological insulator rings

$$\sigma(\omega) = \frac{e^2}{\hbar}\frac{i\omega_e}{\omega + i\gamma_e} + \frac{i\omega h}{4\pi}\frac{S_{ph}^2}{\omega(\omega + i\gamma_{ph}) - \omega_{ph}^2} + \frac{i\omega h}{4\pi}(1 - \epsilon_\infty)$$



Stefano Lupi's, Autore *et al.*, Adv. Opt. Mater. (2015)

Further reading

Further reading:

- Myroshnychenko *et al*., Chem. Soc. Rev. (2008)
- García de Abajo, Rev. Mod. Phys. (2010)
- Koppens, Chang, García de Abajo, Nano Lett. (2011)
- García de Abajo, ACS Photonics (2014) ← arXiv:1402.1969
- Manjavacas and García de Abajo, Nature Commun. (2014)
- García de Abajo and Manjavacas, Faraday Discussions (2015) ← arXiv:1411.4780
- Rodrigo *et al*., Science (2015) ← arXiv:1506.6800

GRAPHENE FLAGSHIP

GRASP

*iCrea
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