Electrically controllable light-matter coupling using erbium and graphene

ICFO The Institute of Photonic Sciences

Nano-optoelectronics Group

www.koppensgroup.icfo.eu

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March 11th 2015

Benasque, Spain

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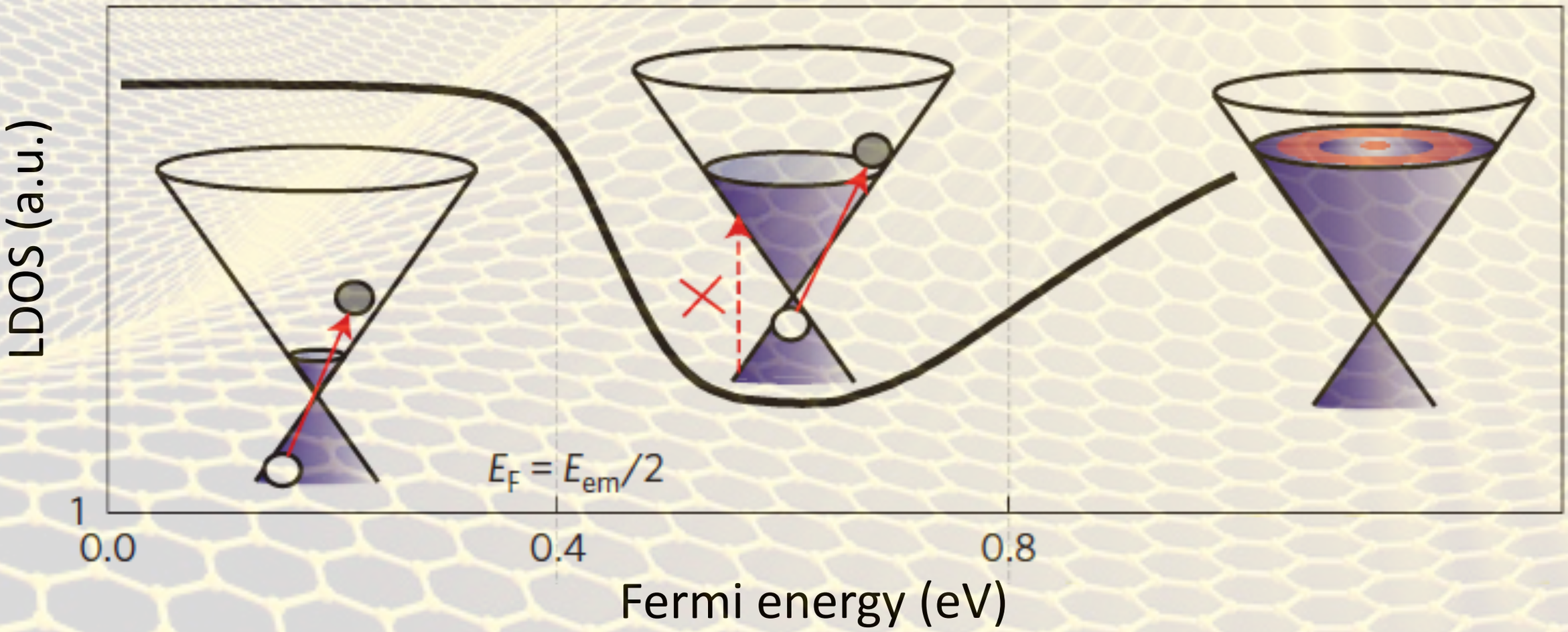

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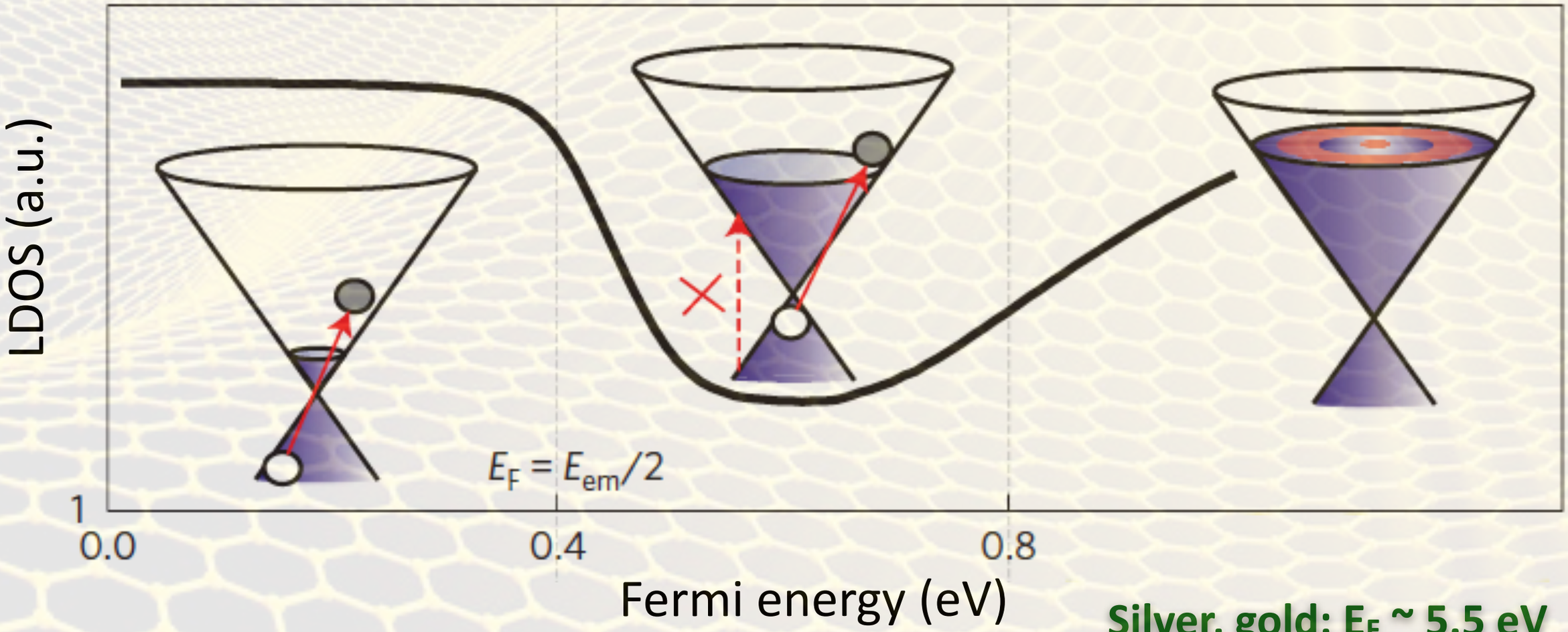
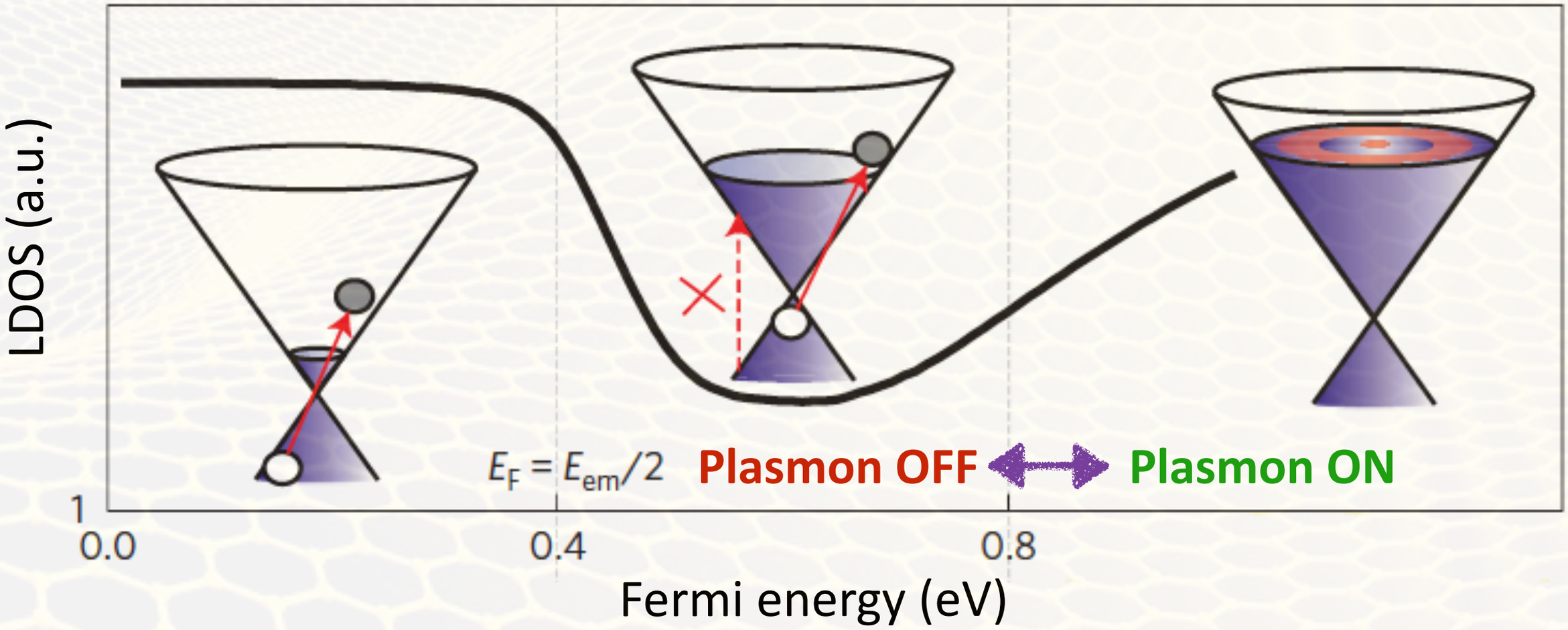


Silver, gold: E_F ~ 5.5 eV

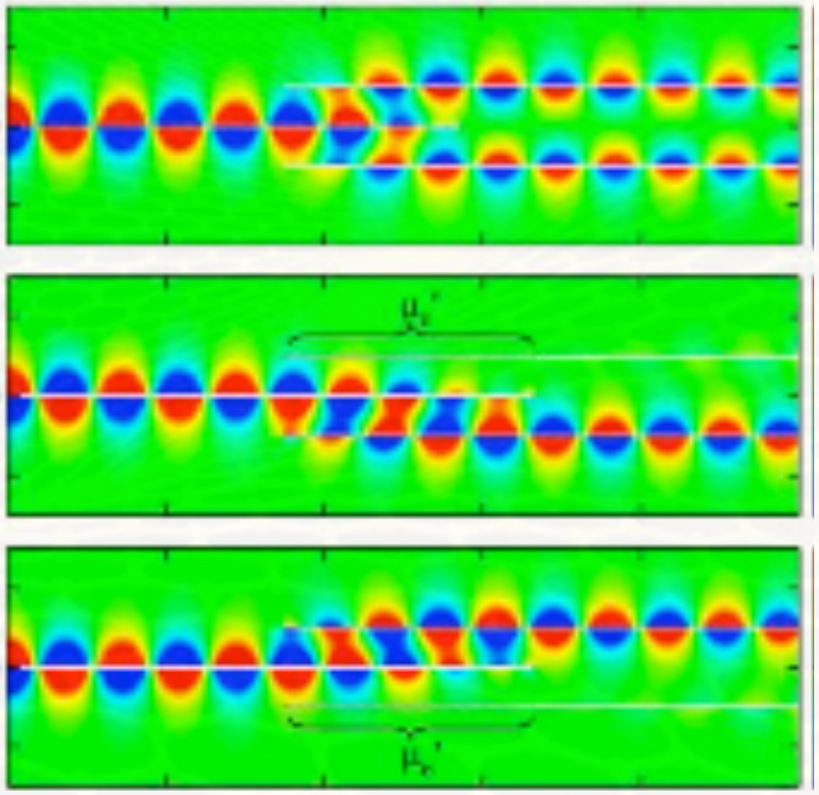
Graphene: -1 < E_F < 1 eV

Electrically controllable light-matter coupling using erbium and graphene

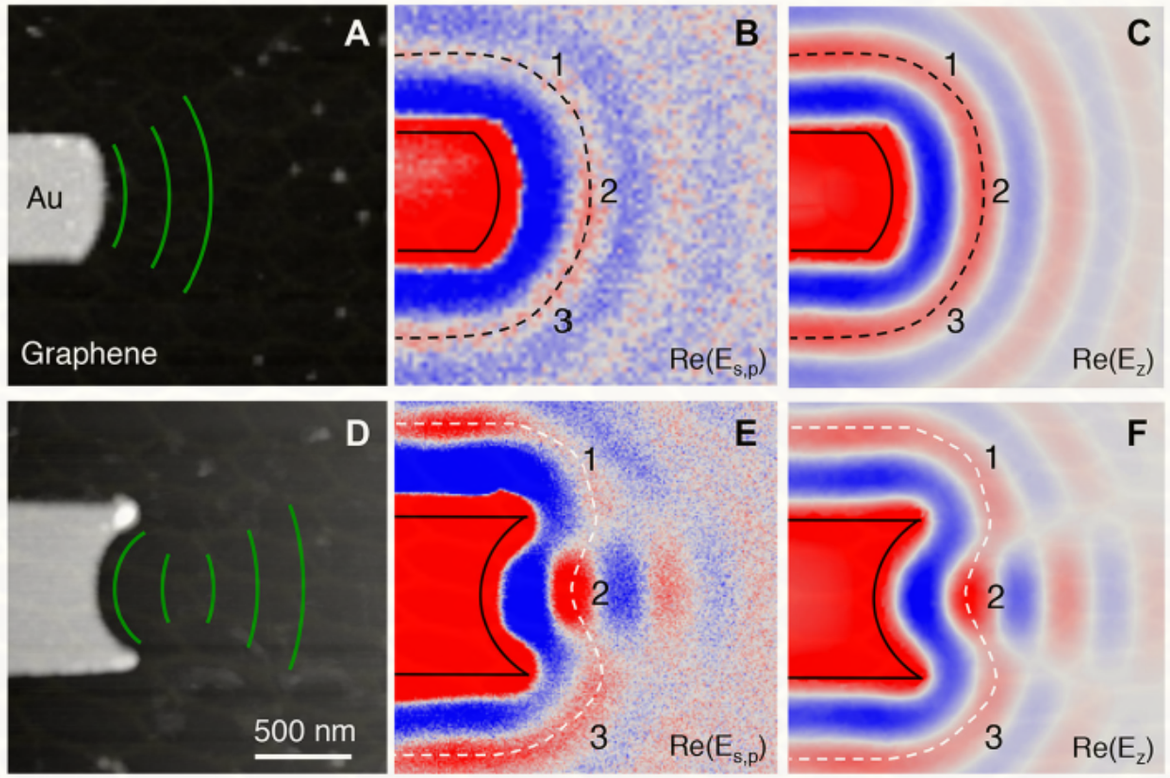


‘Deterministic’ local plasmon launching
Electrical control of interaction

Electrically controllable light-matter coupling using erbium and graphene



Vakil and Engheta, Science (2011)



Alonso-Gonzalez et al, Science (2014)

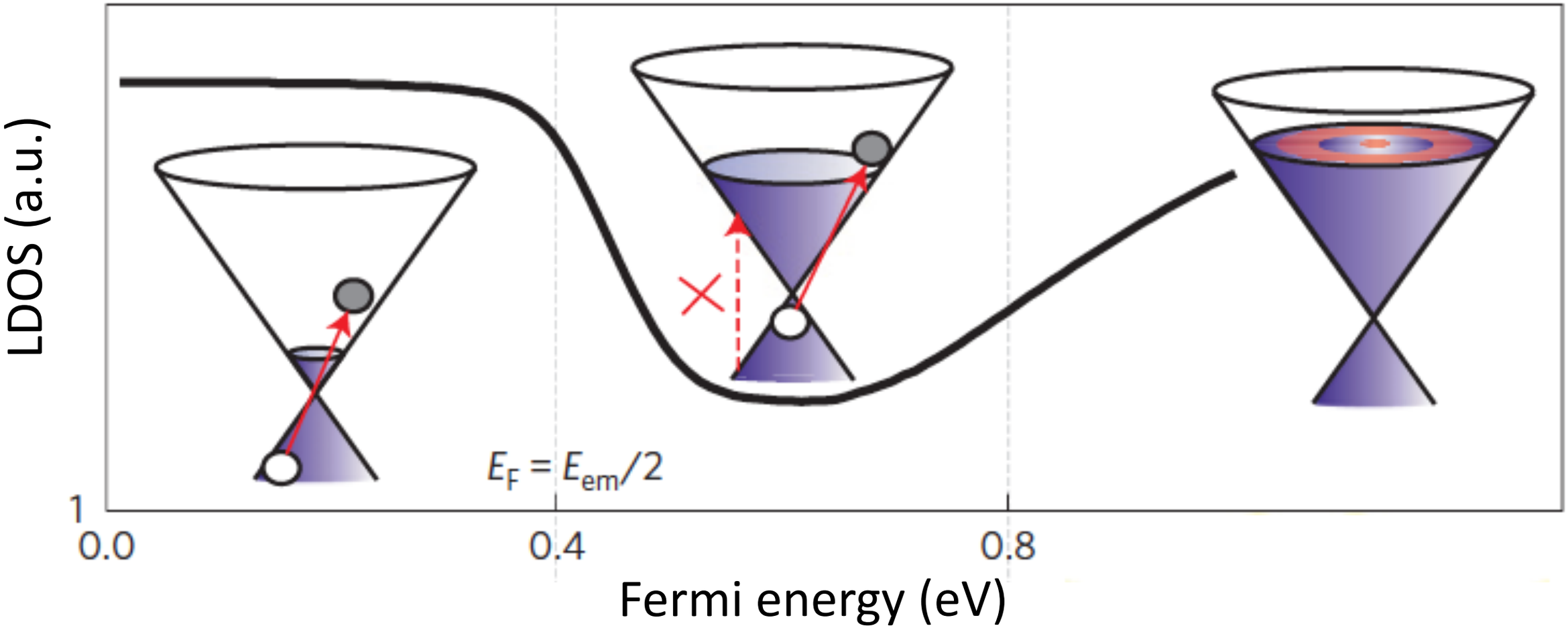
Active plasmonics

Outline

e-h pair excitation
Absorber

photon emission
Transparent

plasmon launching
Metallic



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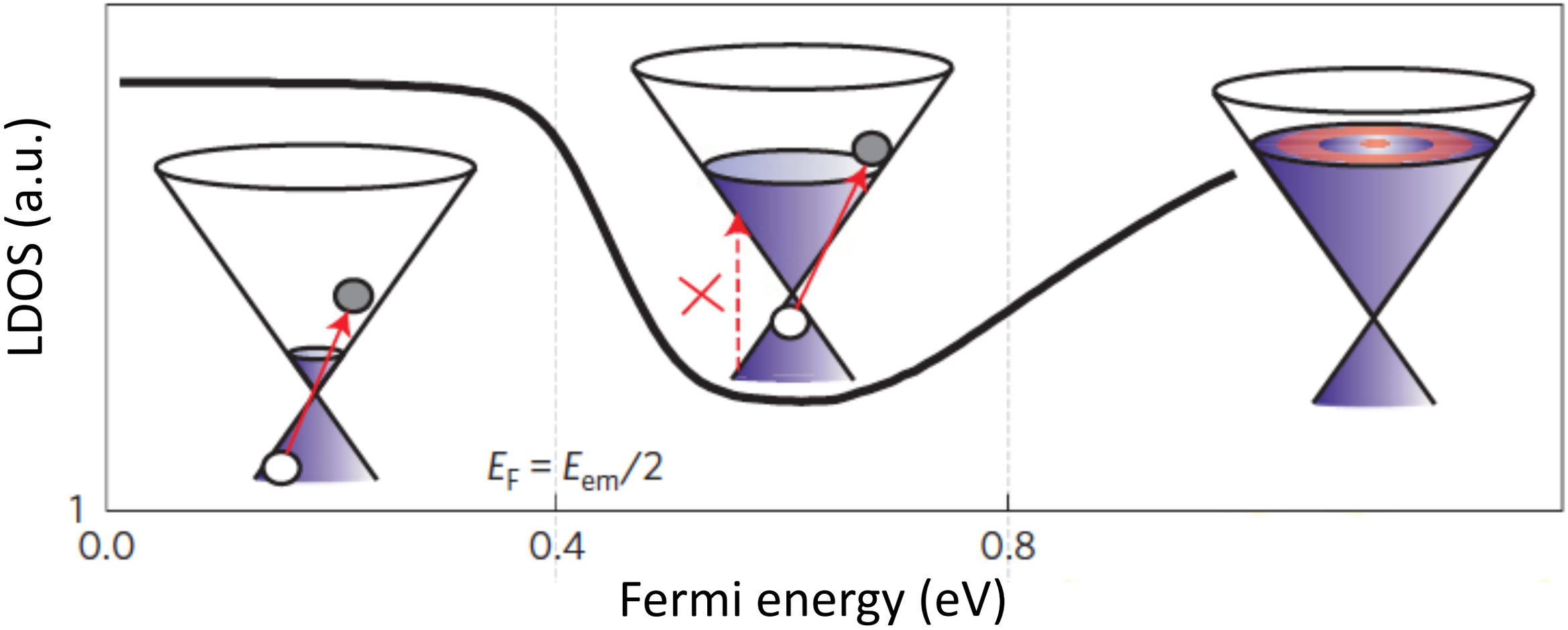
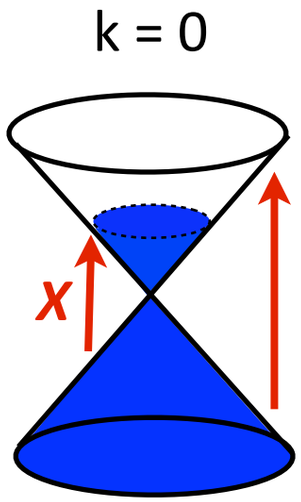
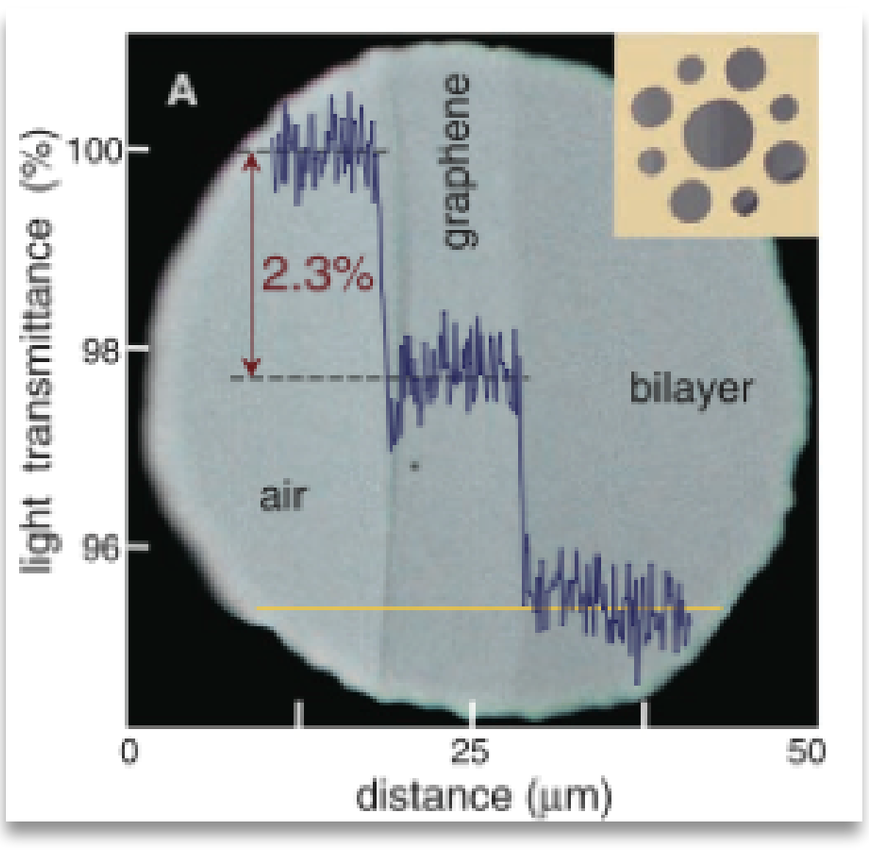


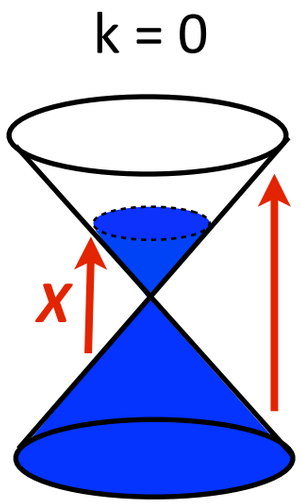
Far-field vs. near-field

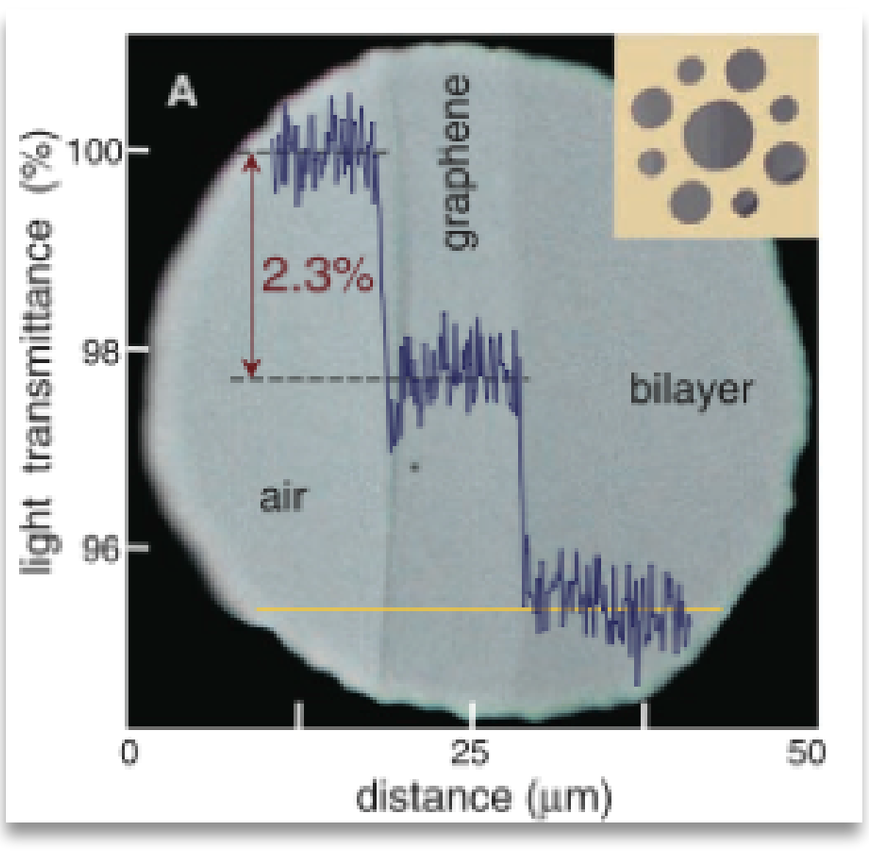




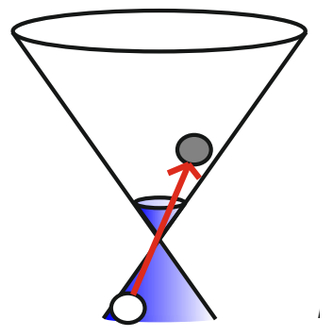
Nair et al, Science (2008)

Far-field vs. near-field





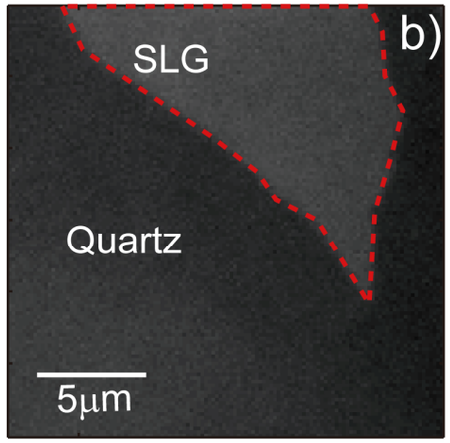
Nair et al, Science (2008)

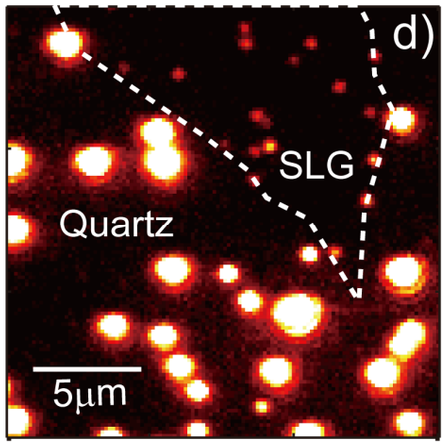


- **Forster resonant energy transfer**
- **Plasmon launching**
- **Electrical tunability**

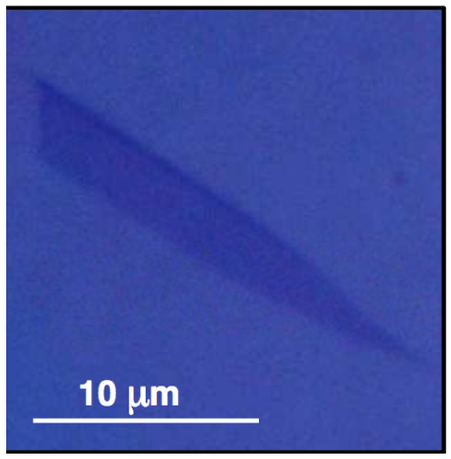
Swathi, JCP (2009)
Gomez-Santos et al. PRB (2011)
Koppens et al, Nano Lett. (2011)
Nikitin et al, PRB (2011)
Velizhanin and Efimov, PRB (2011)

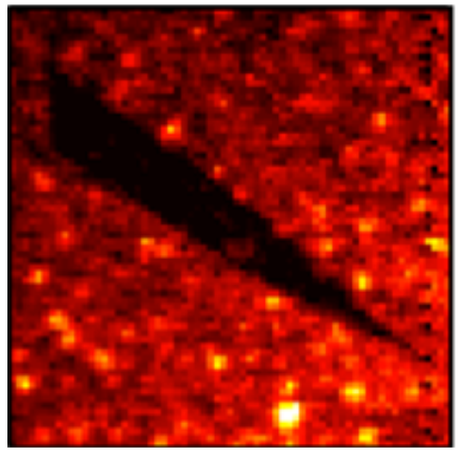
Absorber: experimental





Z. Chen et al., ACS Nano (2010)



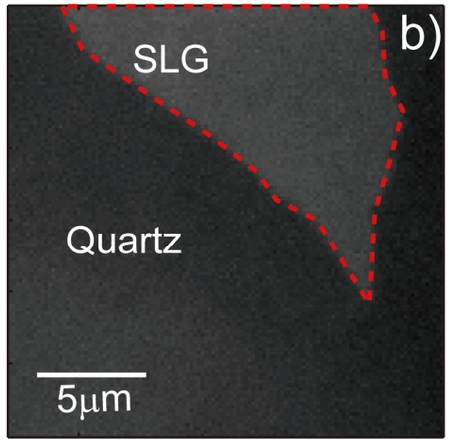


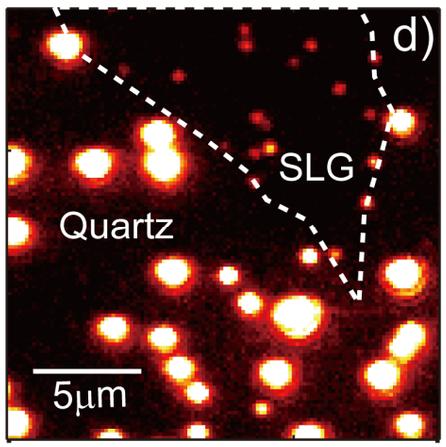
L. Gaudreau et al., Nanoletters (2013)

e-h pair excitation

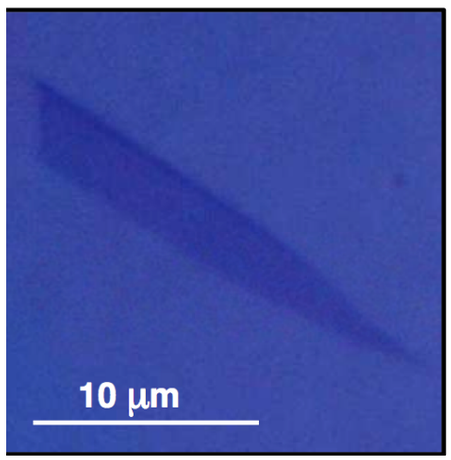
Absorber

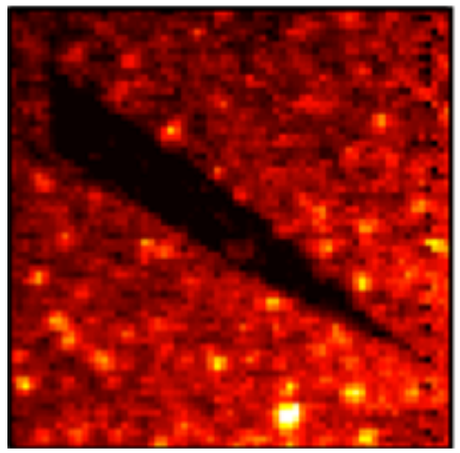
Absorber: experimental





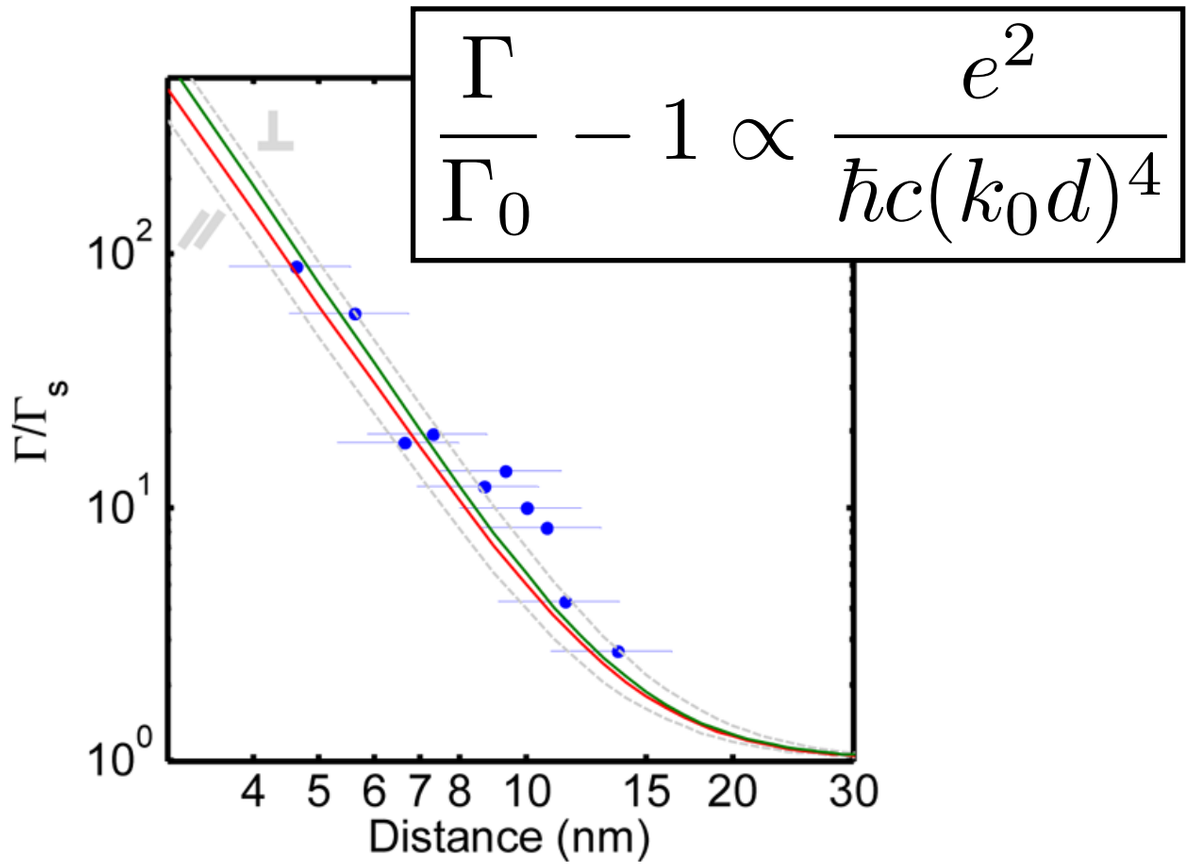
Z. Chen et al., ACS Nano (2010)





L. Gaudreau et al., Nanoletters (2013)
Gomez-Santos et al. PRB (2011)

$$\frac{\Gamma}{\Gamma_0} - 1 \propto \frac{e^2}{\hbar c (k_0 d)^4}$$

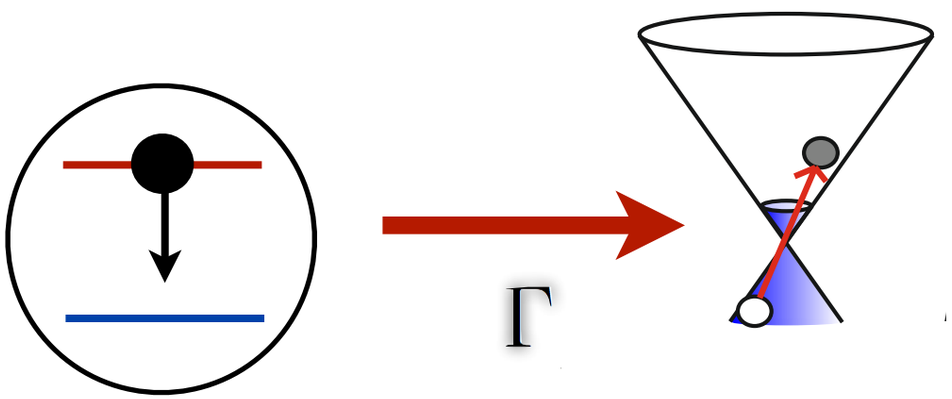


e-h pair excitation

Absorber

Absorber

Non-radiative energy transfer

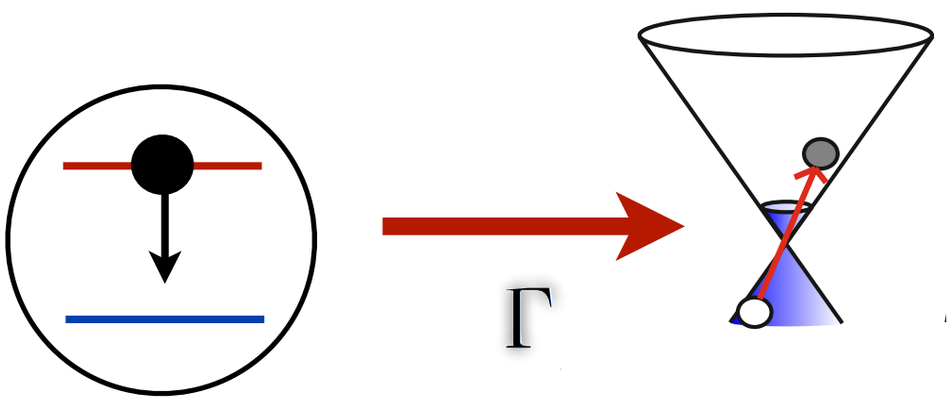


e-h pair excitation

Absorber

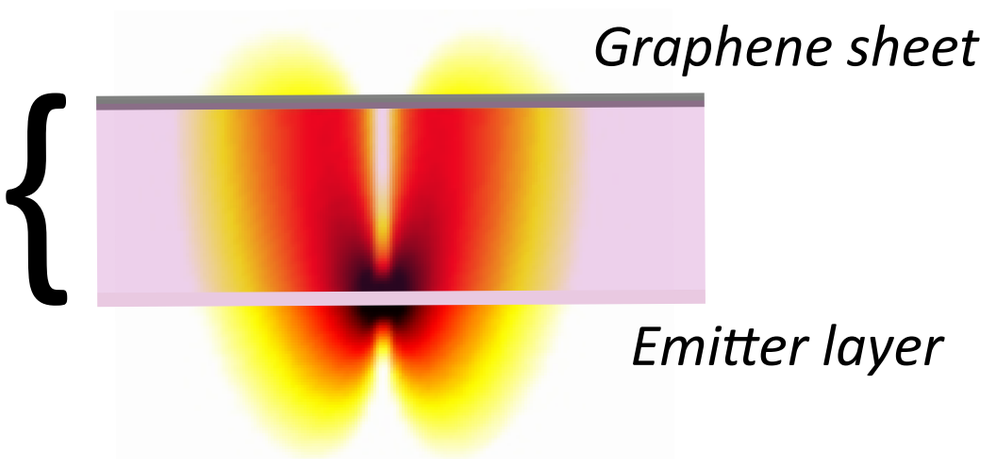
Absorber

Non-radiative energy transfer



Near field

$d < \lambda_{em}$

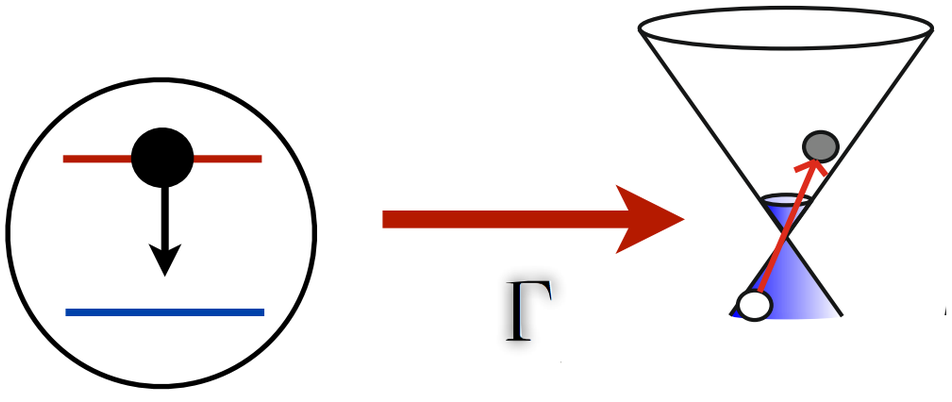


e-h pair excitation

Absorber

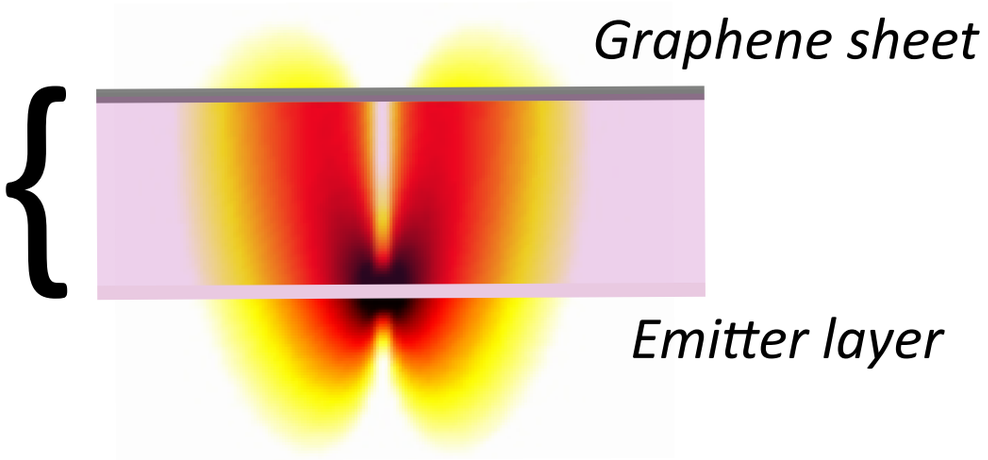
Absorber

Non-radiative energy transfer

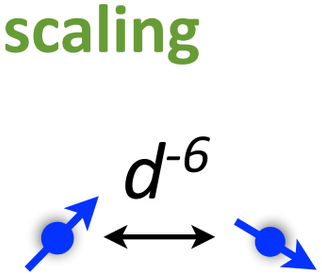


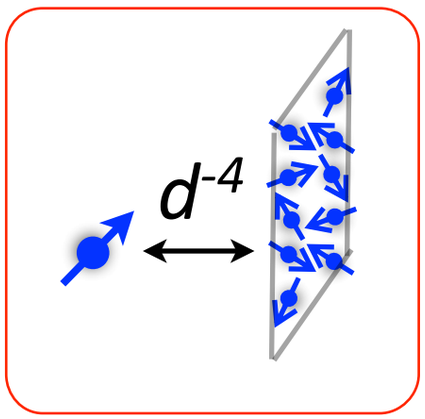
Near field

$d < \lambda_{em}$



Distance scaling



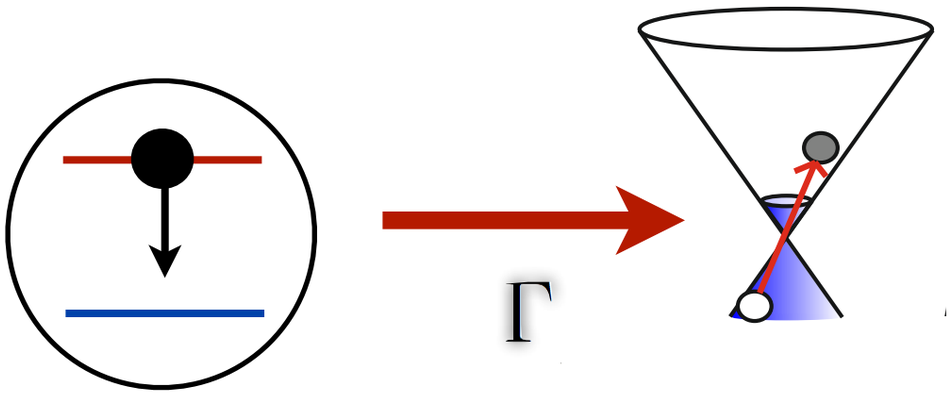


e-h pair excitation

Absorber

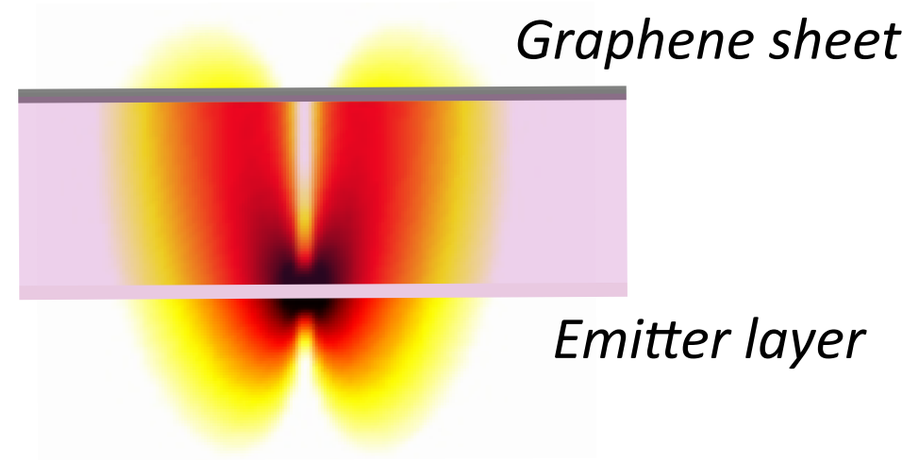
Absorber

Non-radiative energy transfer

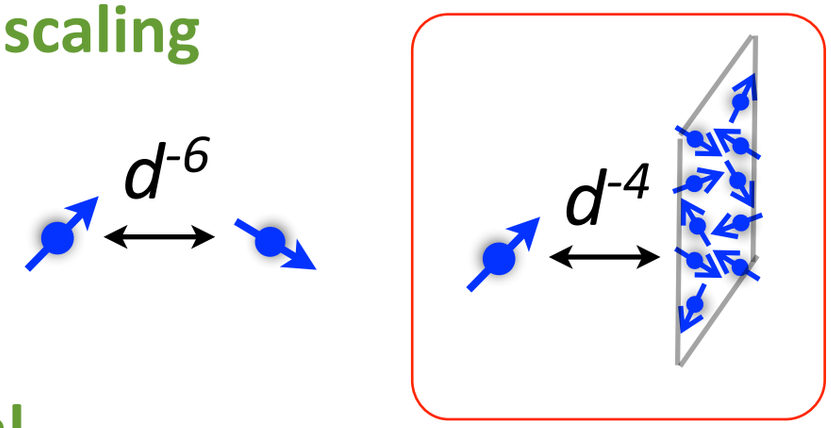


Near field

$d < \lambda_{em}$



Distance scaling



e-h pair excitation

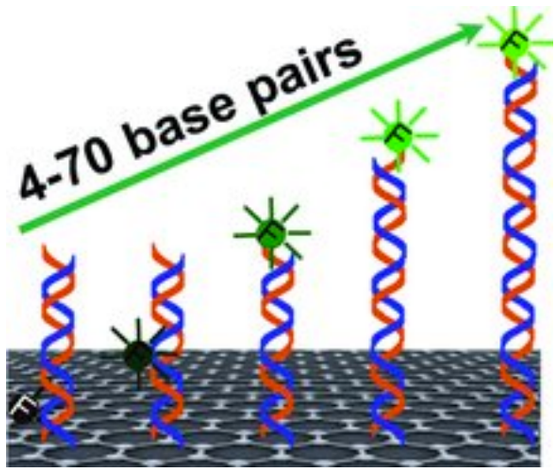
Absorber

Universal

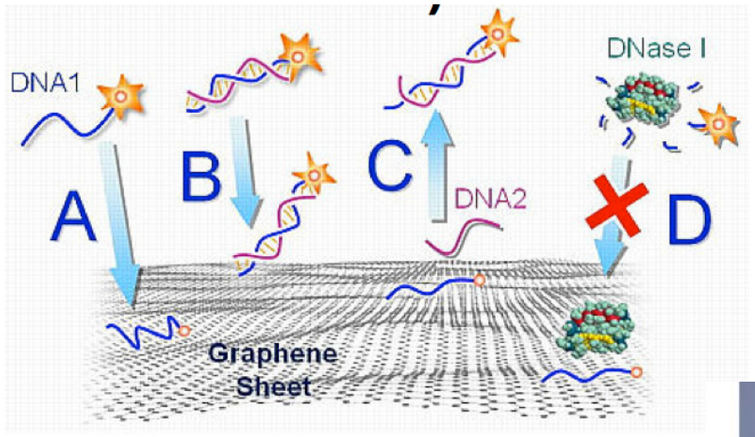
$$\frac{\Gamma}{\Gamma_0} - 1 \propto \frac{e^2}{\hbar c (k_0 d)^4}$$

Absorber: applications

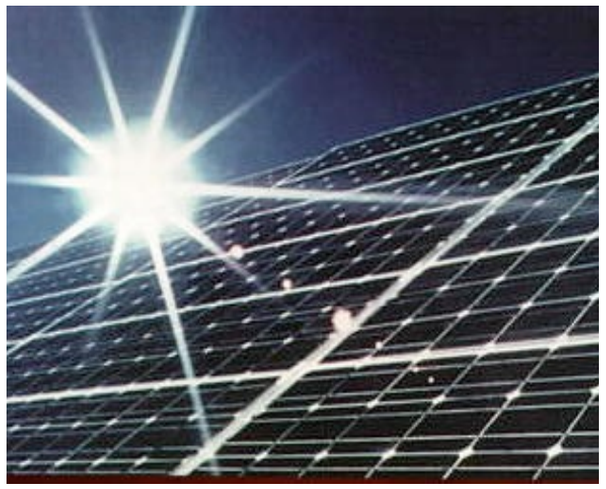
Universal distance ruler



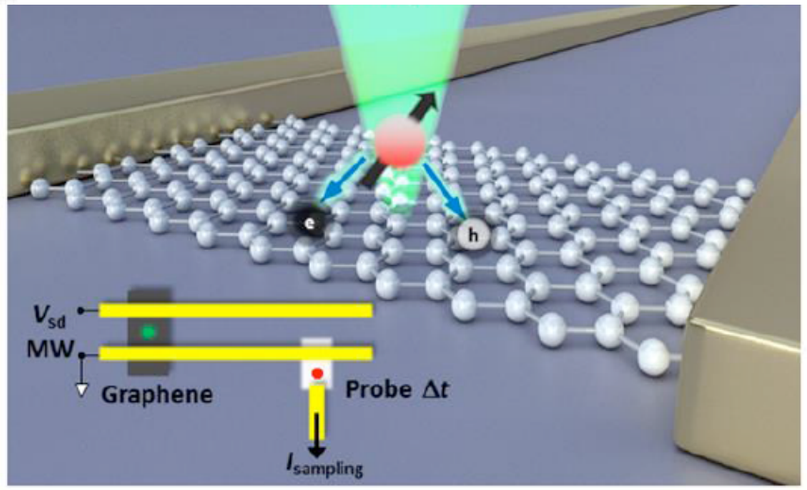
Bio-sensing



Photovoltaics



Electrical read-out

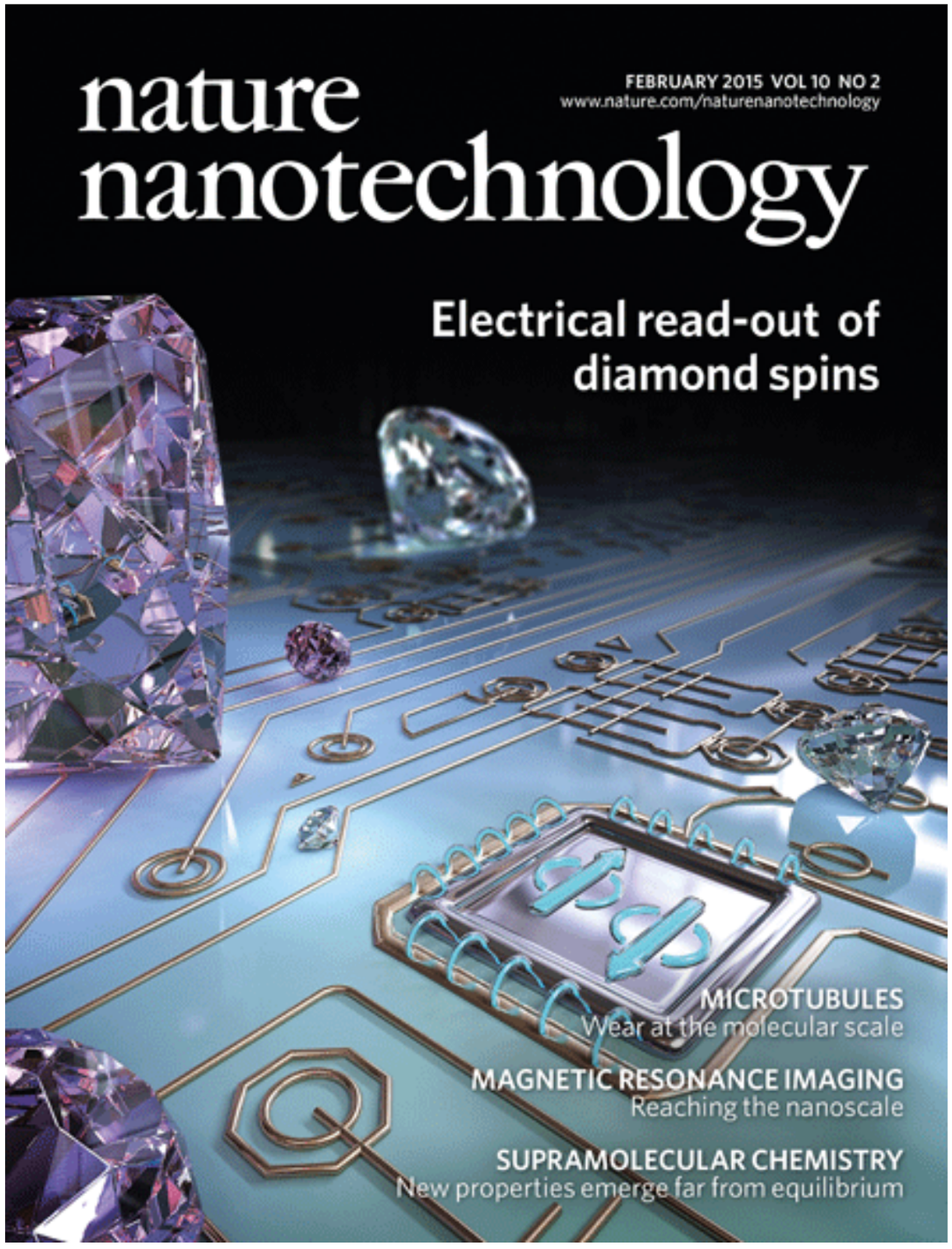


e-h pair excitation

Absorber

Gomez-Santos, PRB (2011)
Swathi et al., JCP (2009)
Huang et al., Small (2012)
Brenneis et al., Nature Nanotech. (2014)

Absorber: applications



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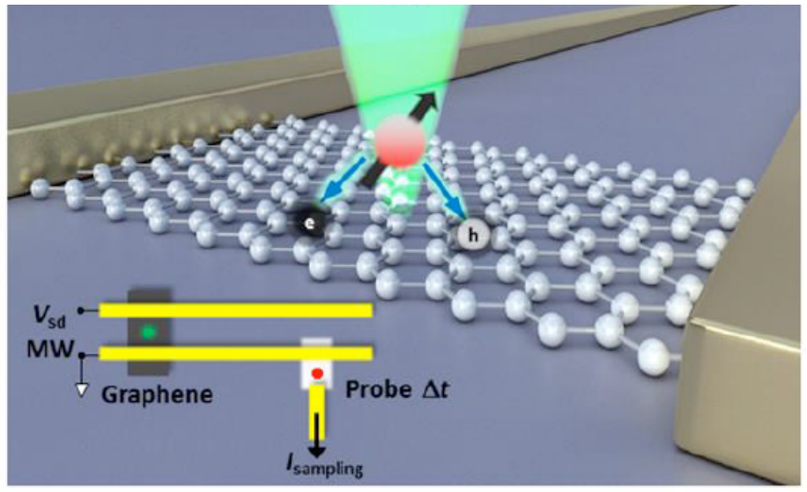
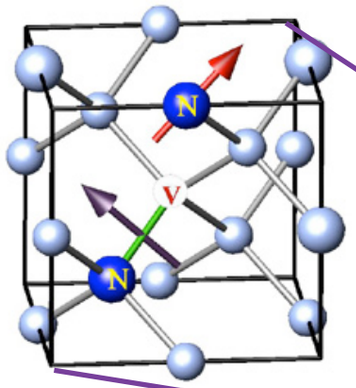
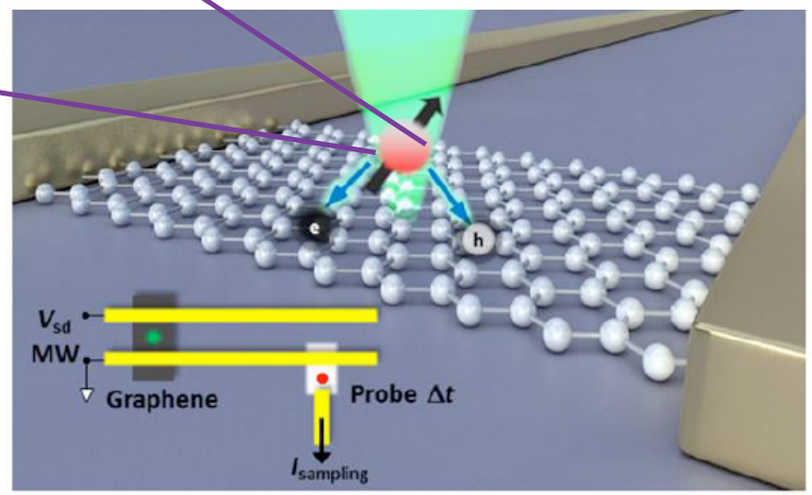


Brenneis et al., Nature Nanotech. (2014)

Absorber: applications

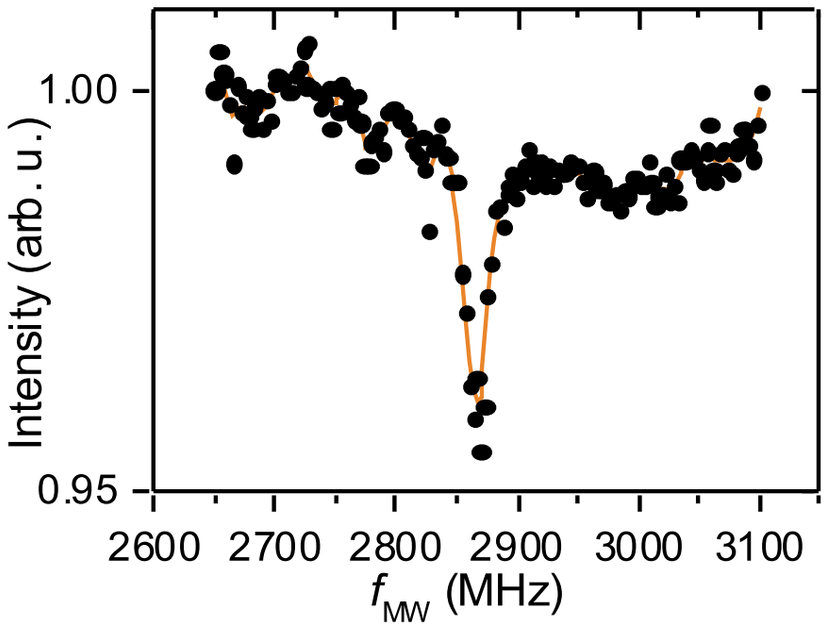


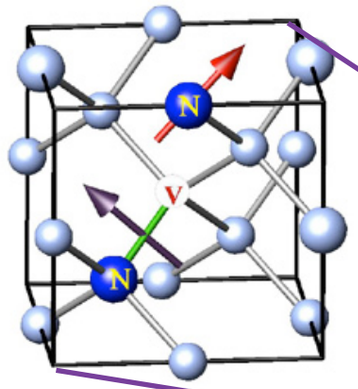
Electrical read-out



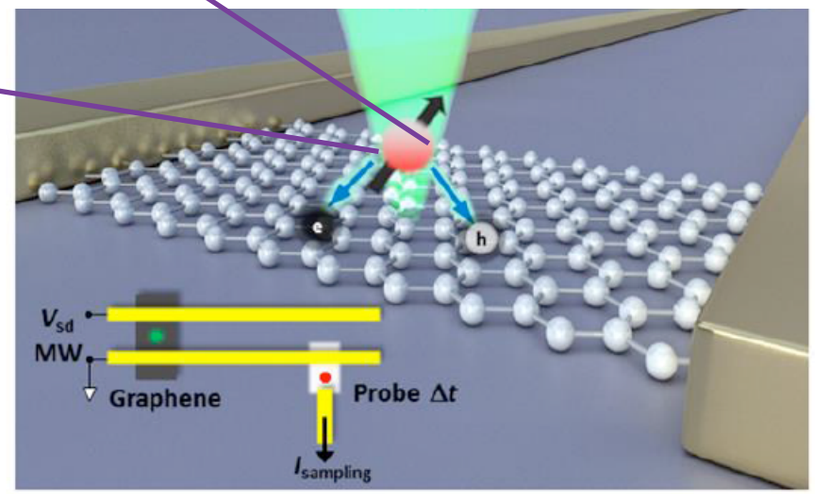
Jelezko and Wrachtrup, (2006)
Brenneis et al., Nature Nanotech. (2014)

Absorber: applications





Electrical read-out

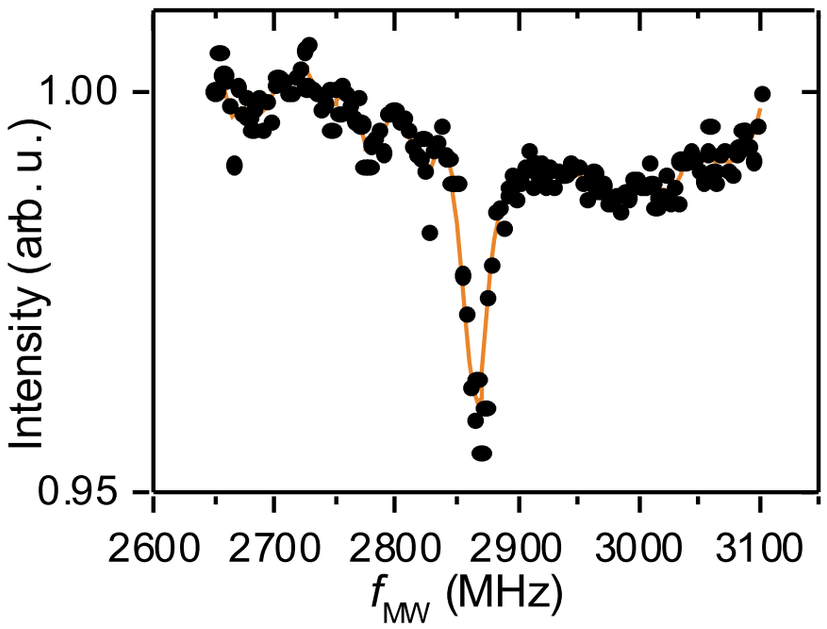


Optical read-out of:

- the NV spin

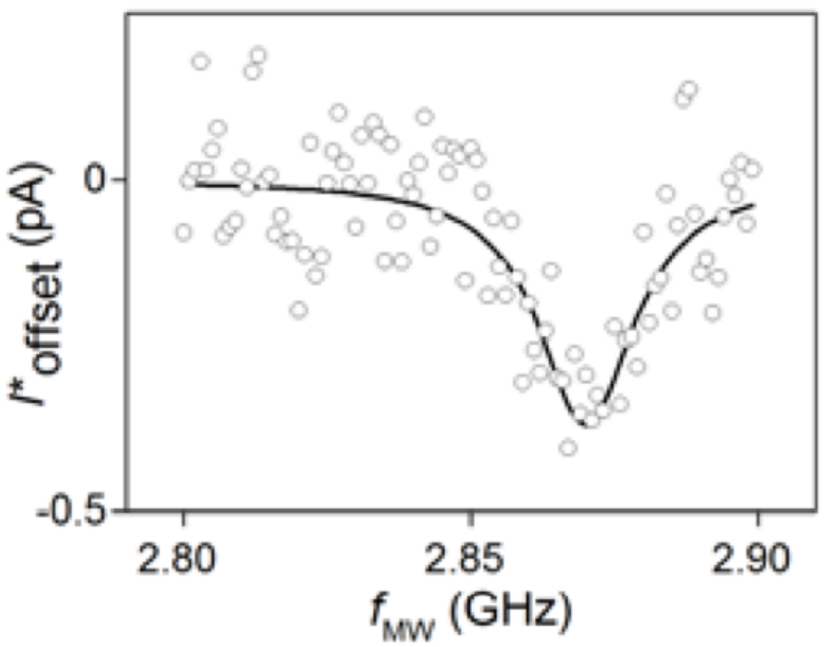
Brenneis et al., Nature Nanotech. (2014)

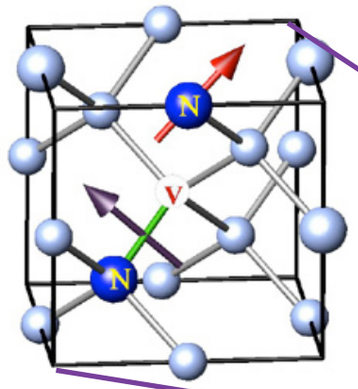
Absorber: applications



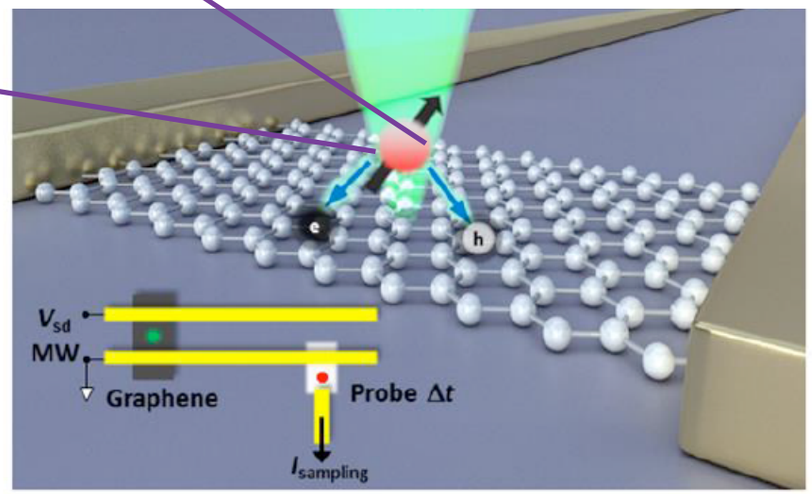
Optical read-out of:

- NV spin state





Electrical read-out



Electrical read-out of:

- energy transfer
- the NV spin state

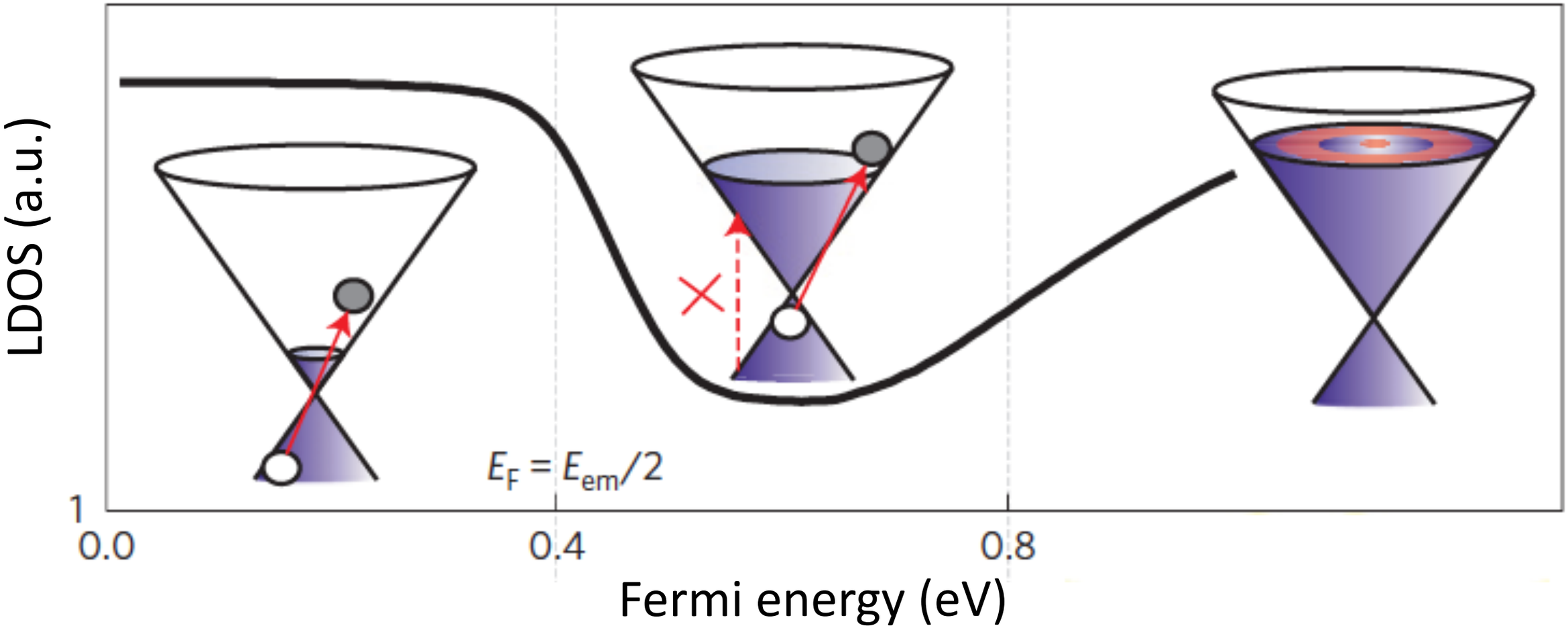
Brenneis et al., Nature Nanotech. (2014)

Outline

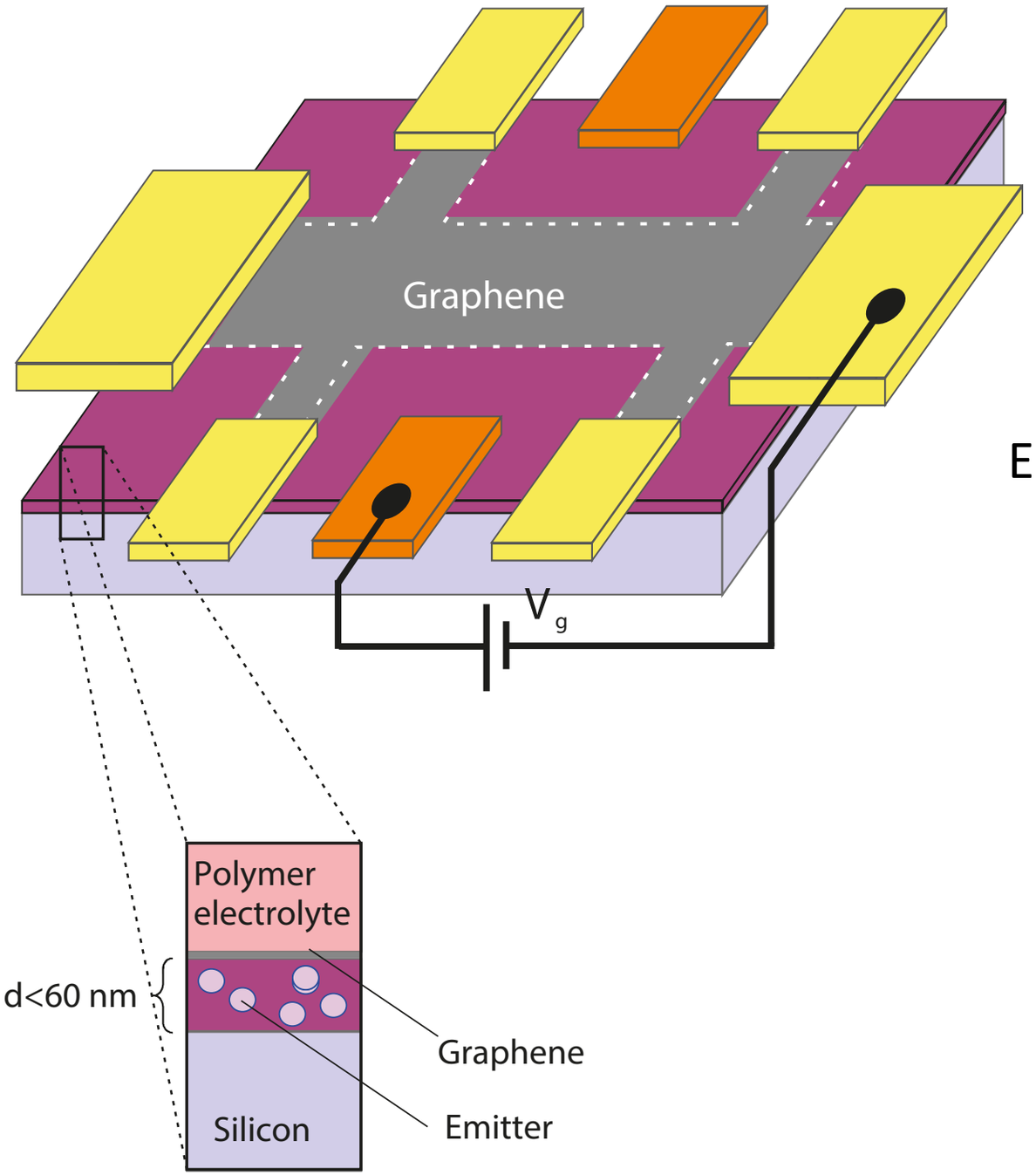
e-h pair excitation
Absorber

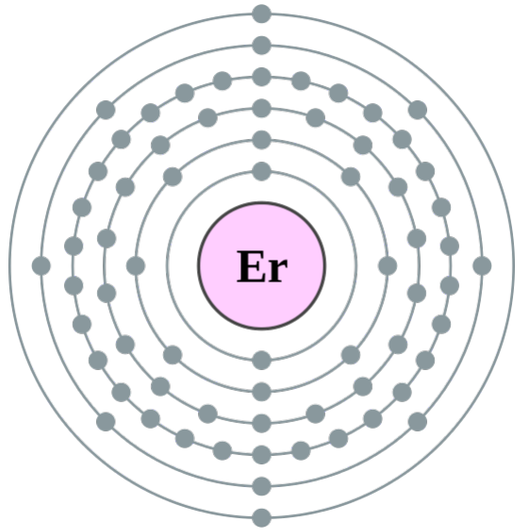
photon emission
Transparent

plasmon launching
Metallic



Device

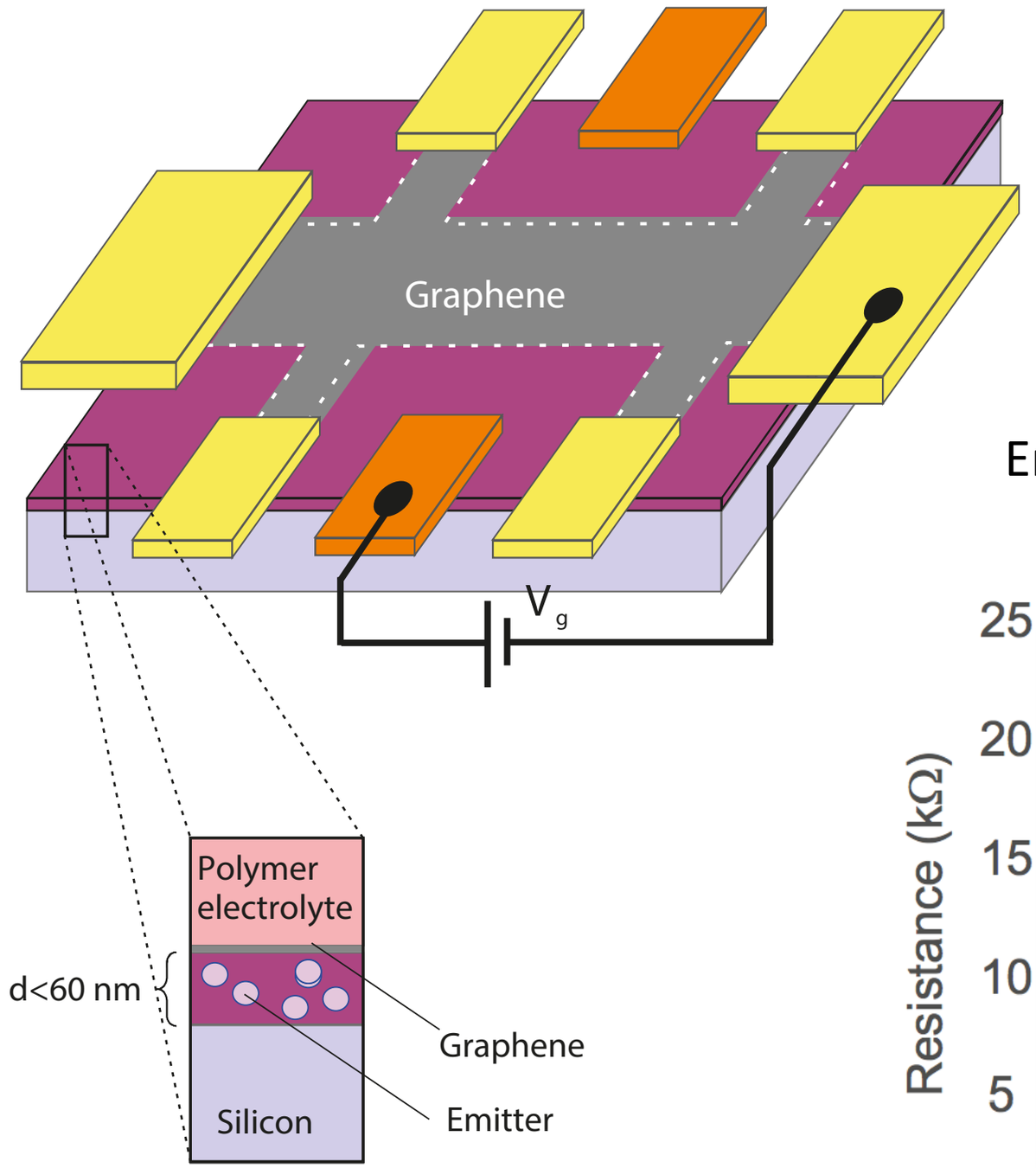




Erbium emission at 1530 nm: $E_{em} = 0.8$ eV

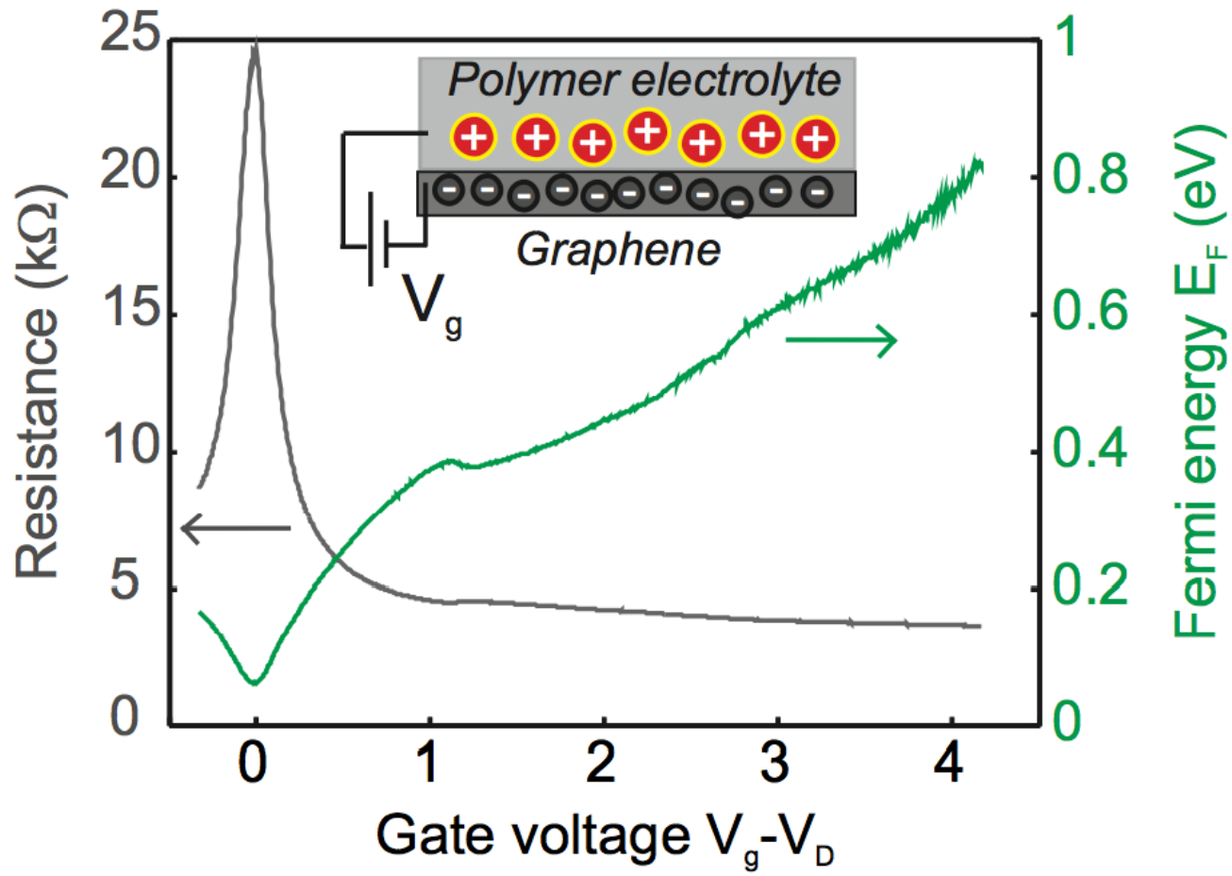
KJT et al., Nature Phys. (2015)

Device

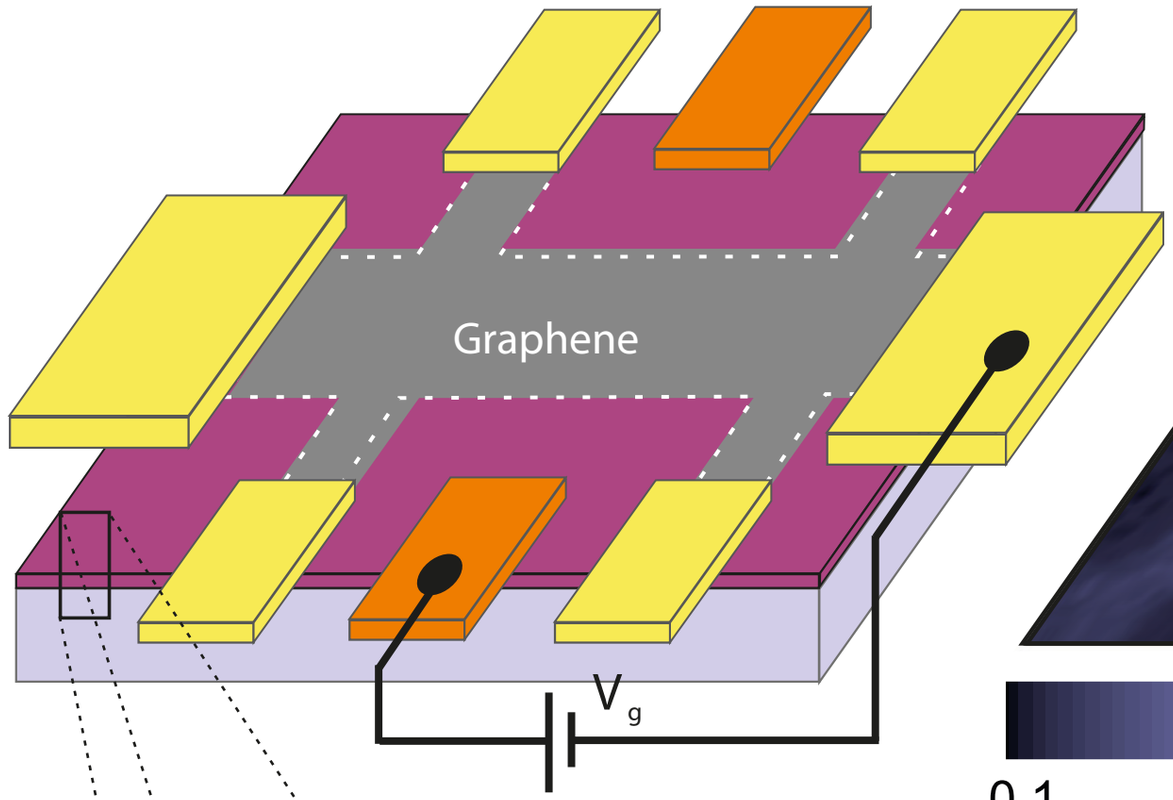


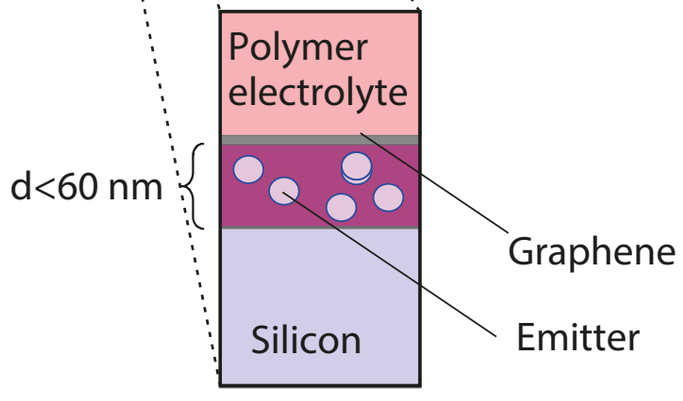
Erbium emission at 1530 nm: $E_{em} = 0.8$ eV

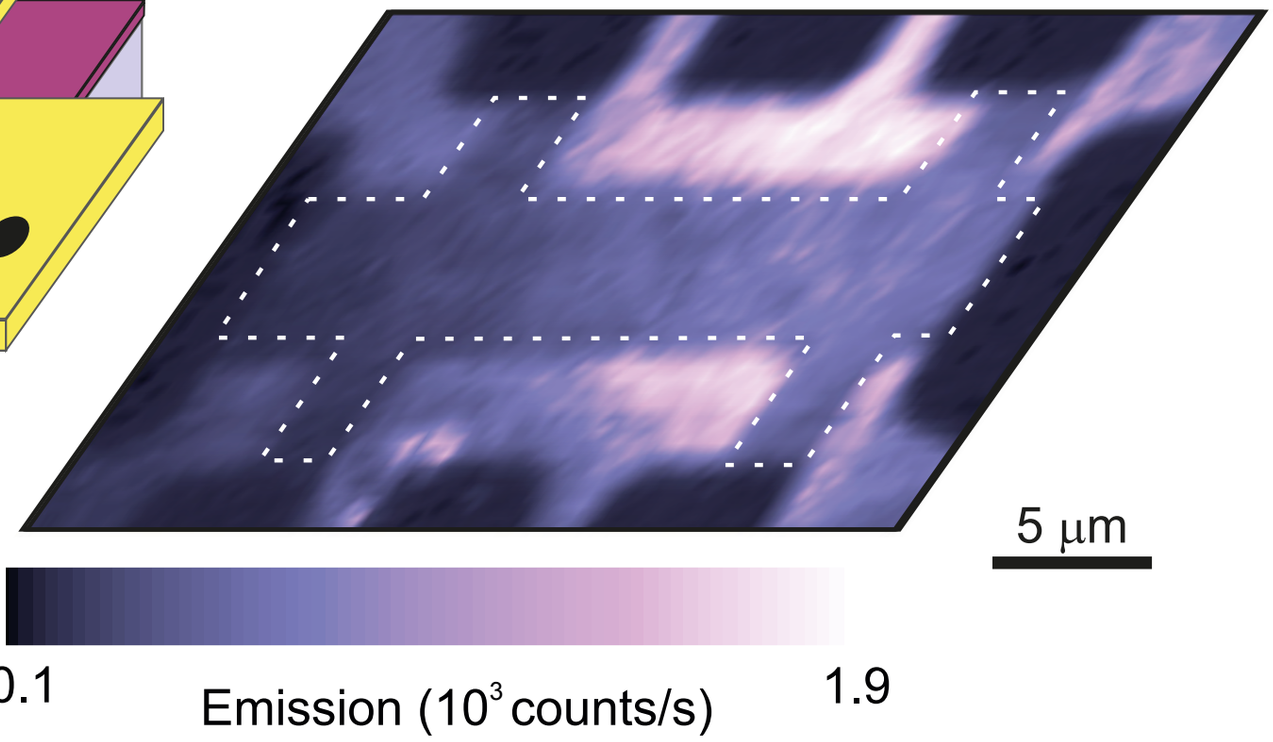
Doping up to $E_F = 1$ eV



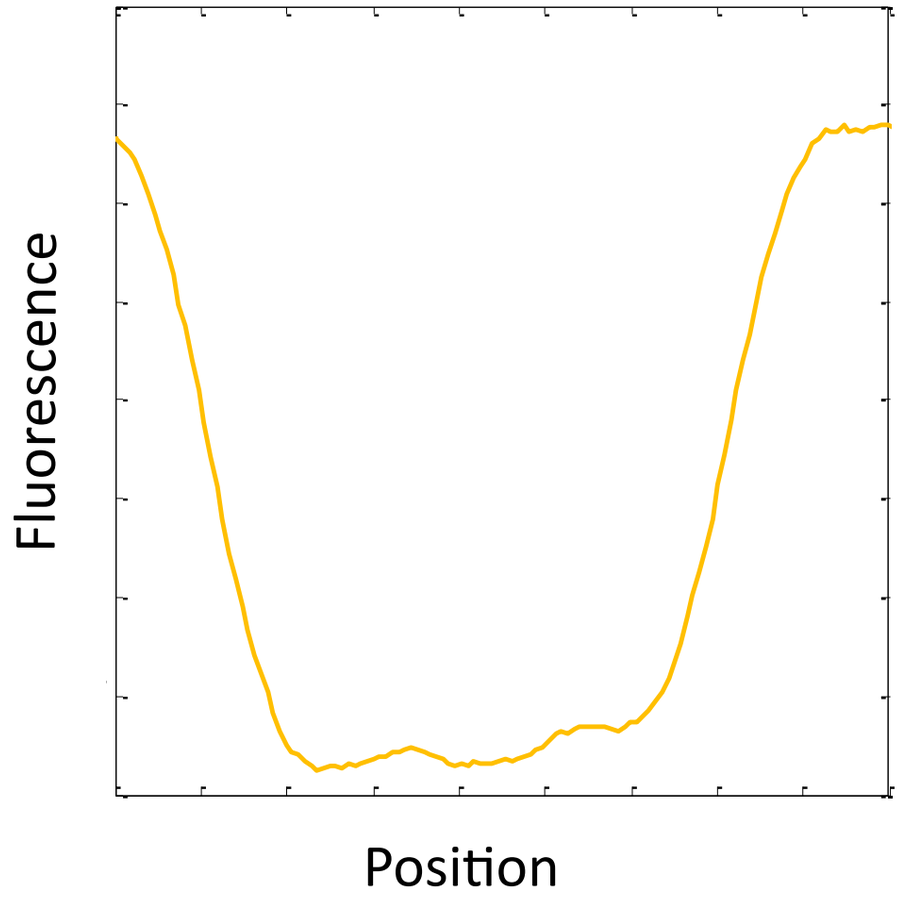
Fluorescence quenching

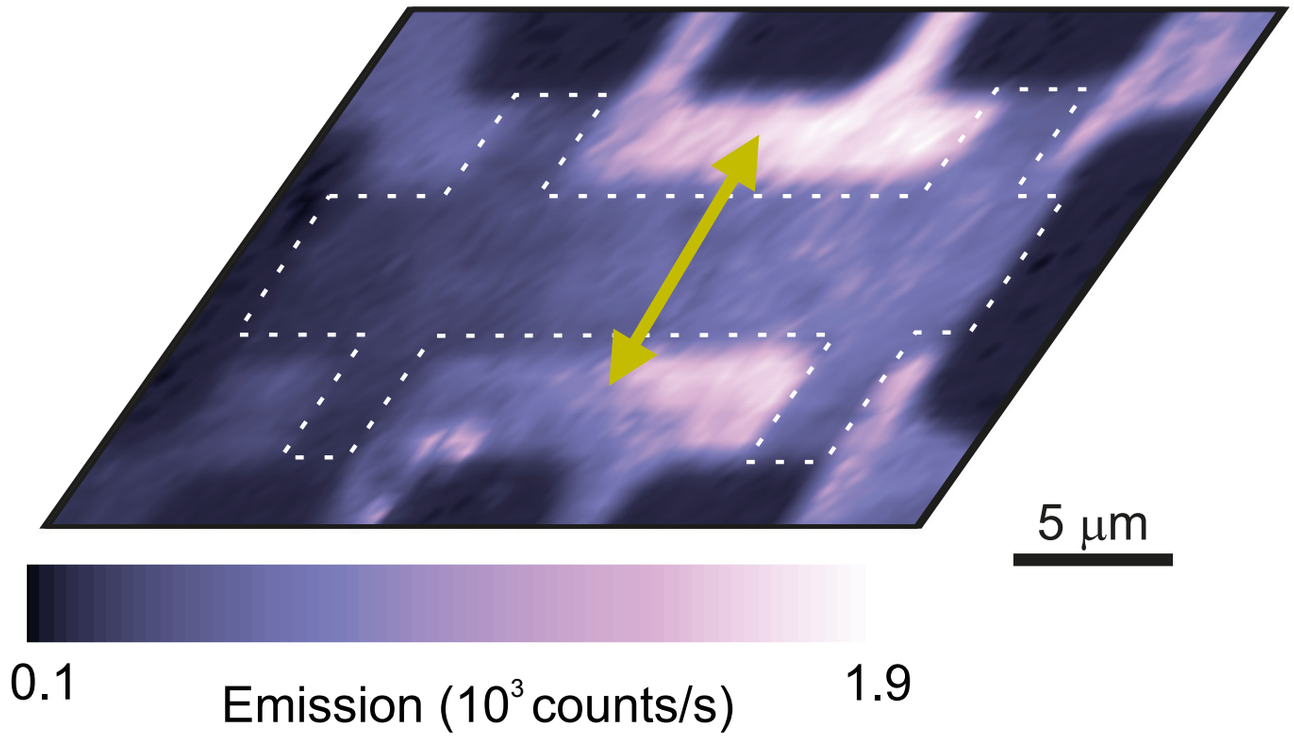






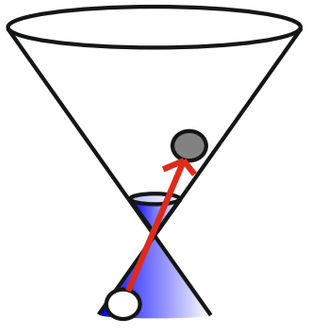
Fluorescence quenching



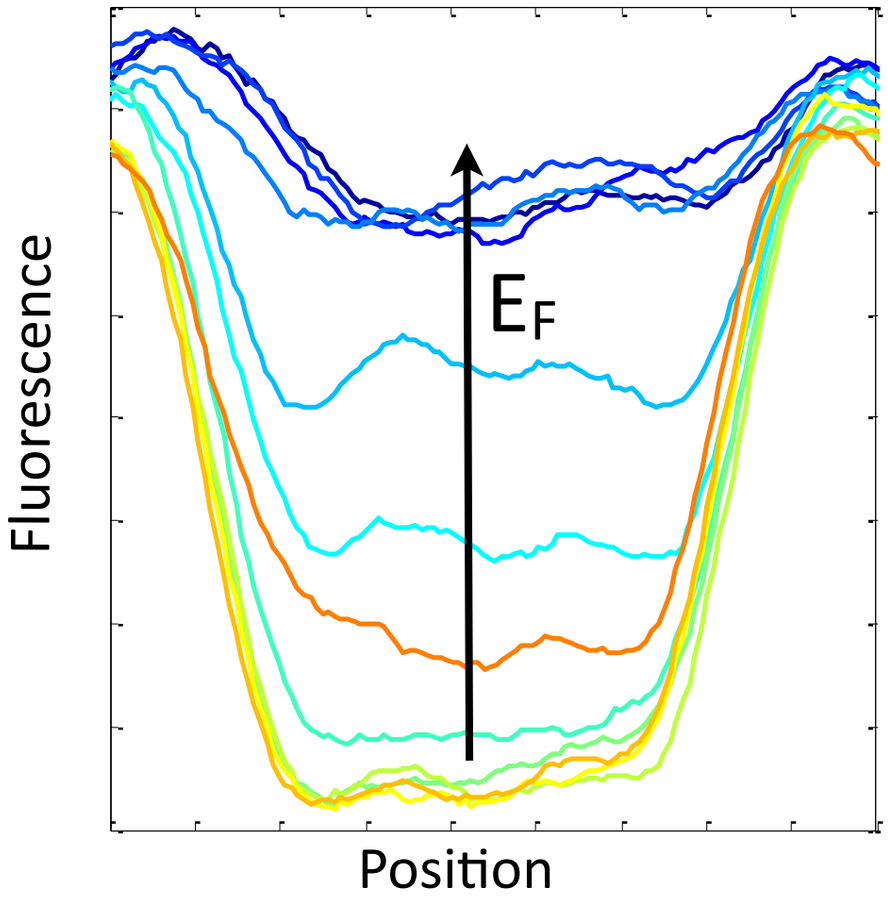


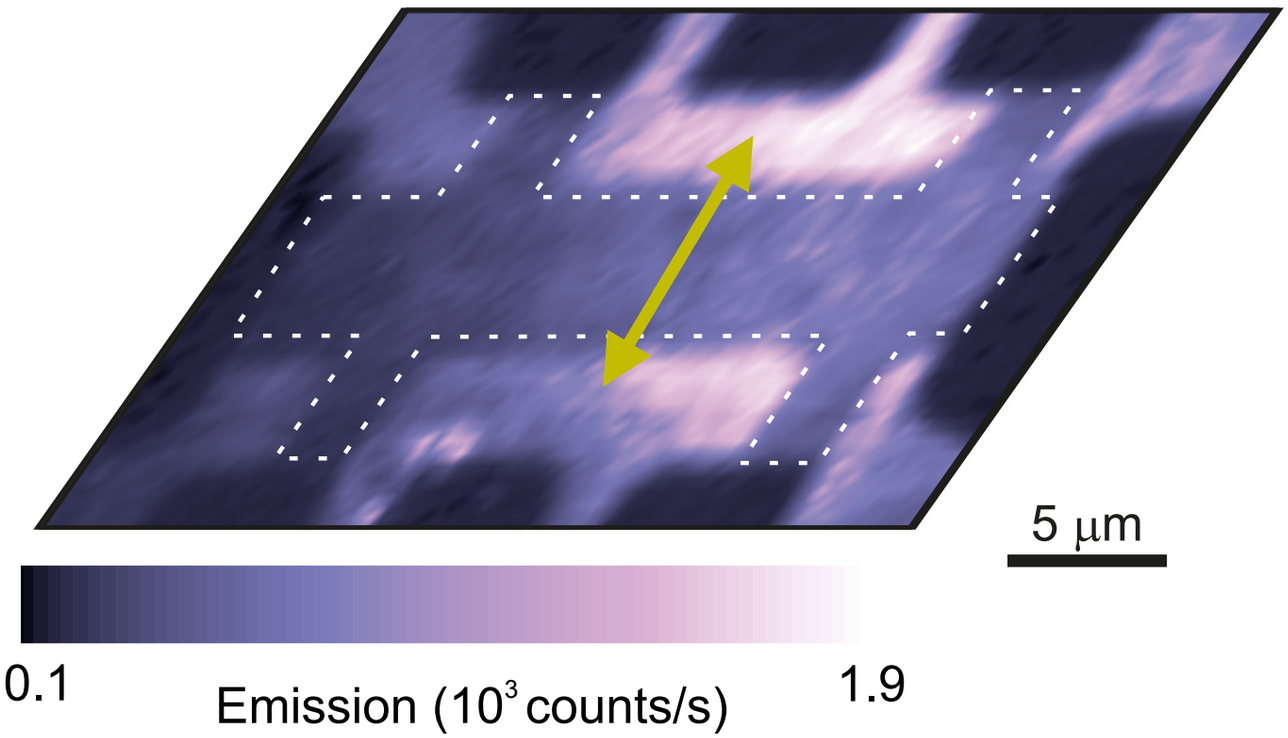
e-h pair excitation

Absorber



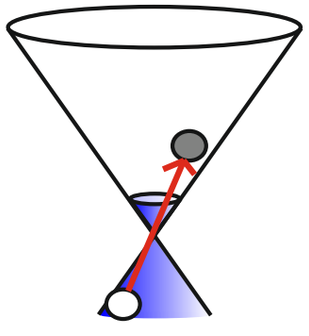
Electrostatic control





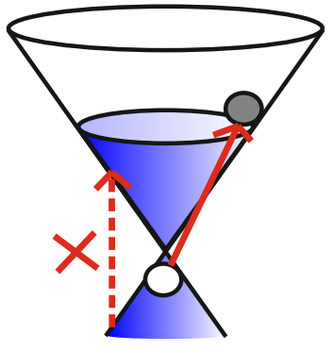
e-h pair excitation

Absorber



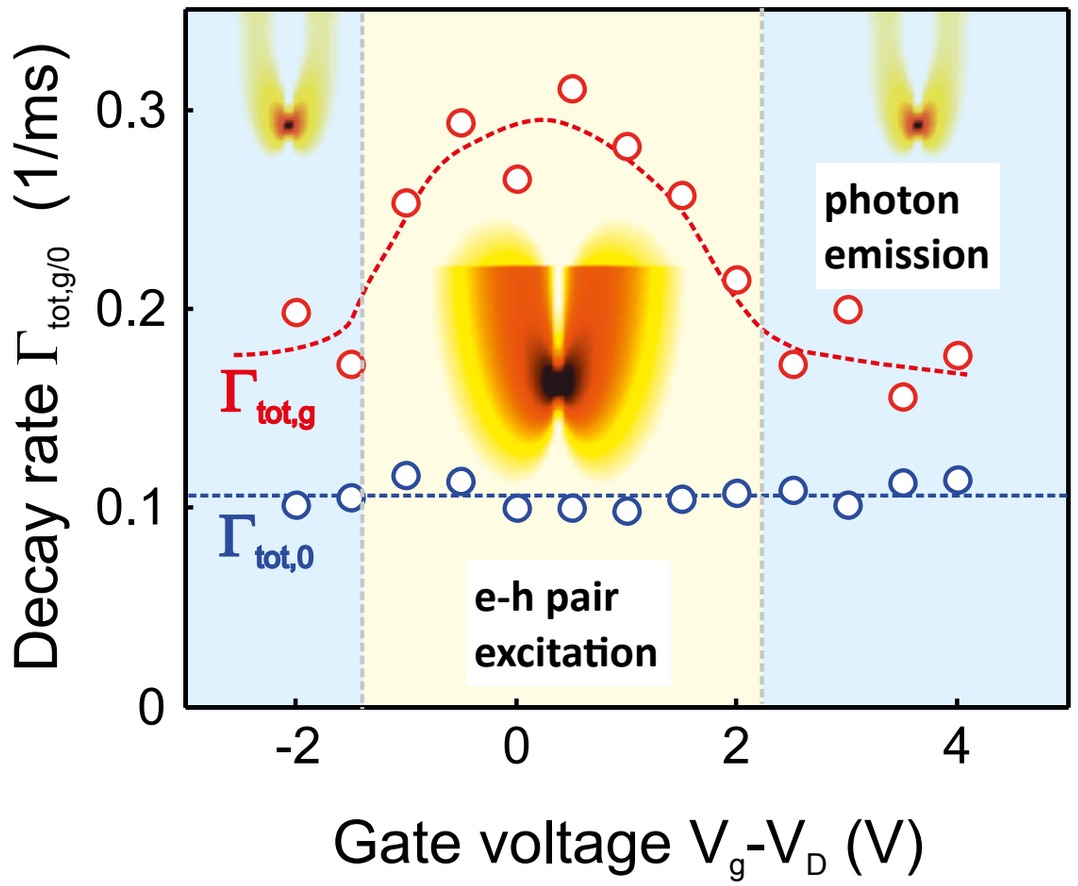
photon emission

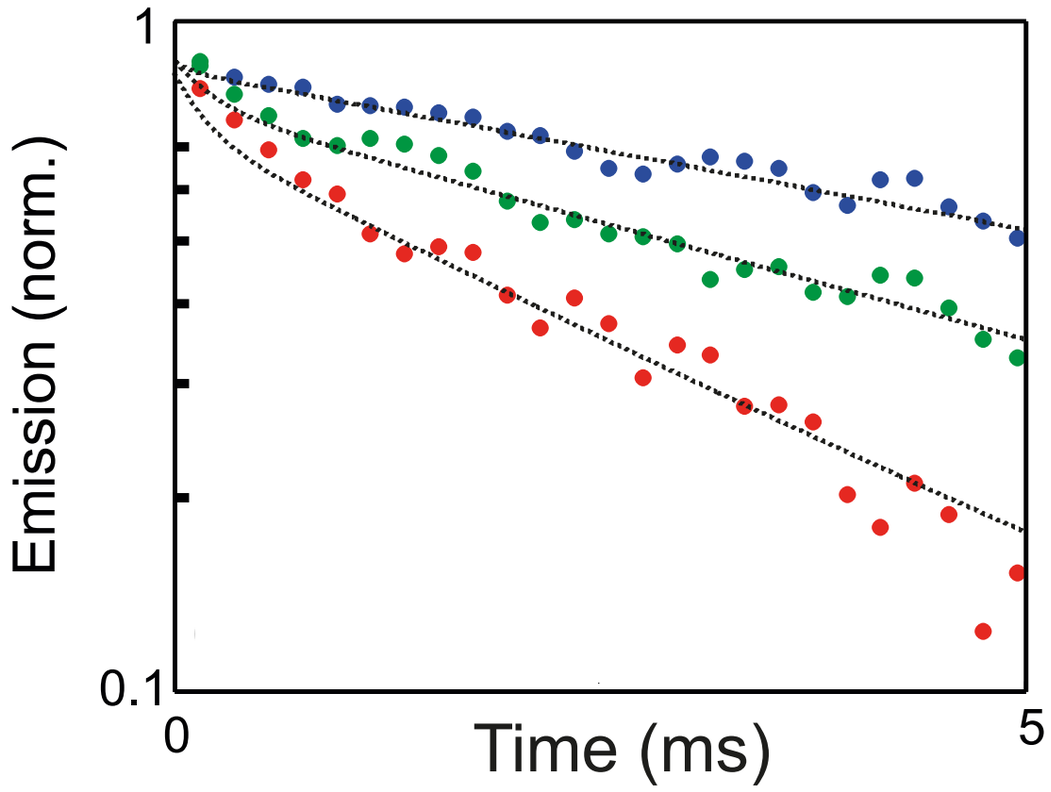
Transparent



E_F

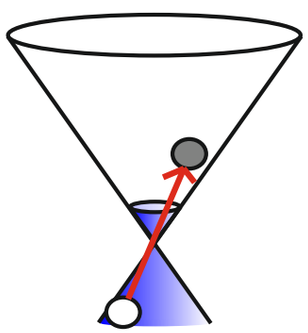
Gate-tunable decay rate





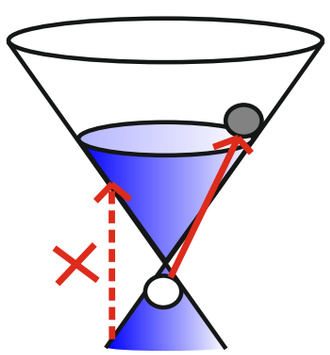
e-h pair excitation

Absorber



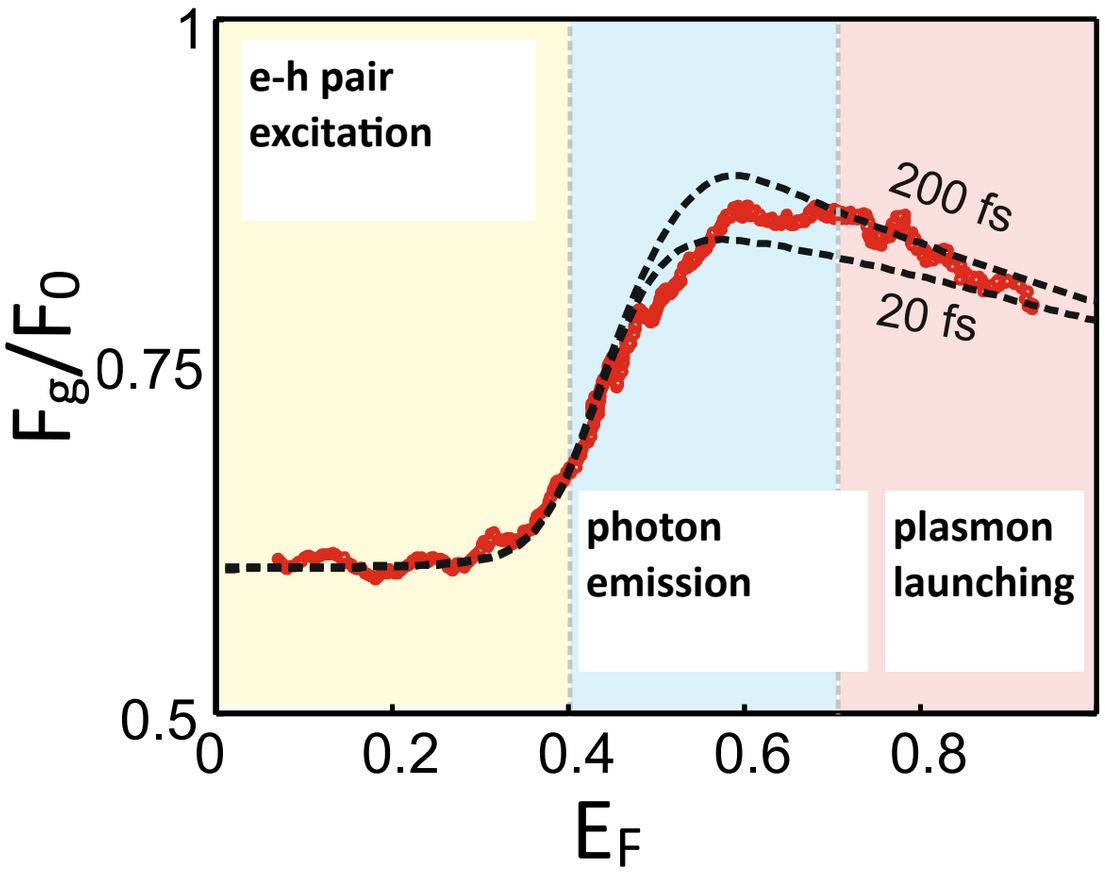
photon emission

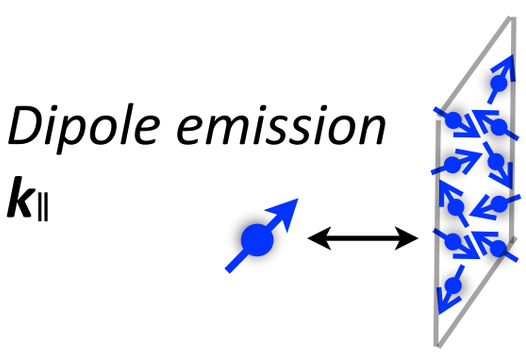
Transparent



E_F

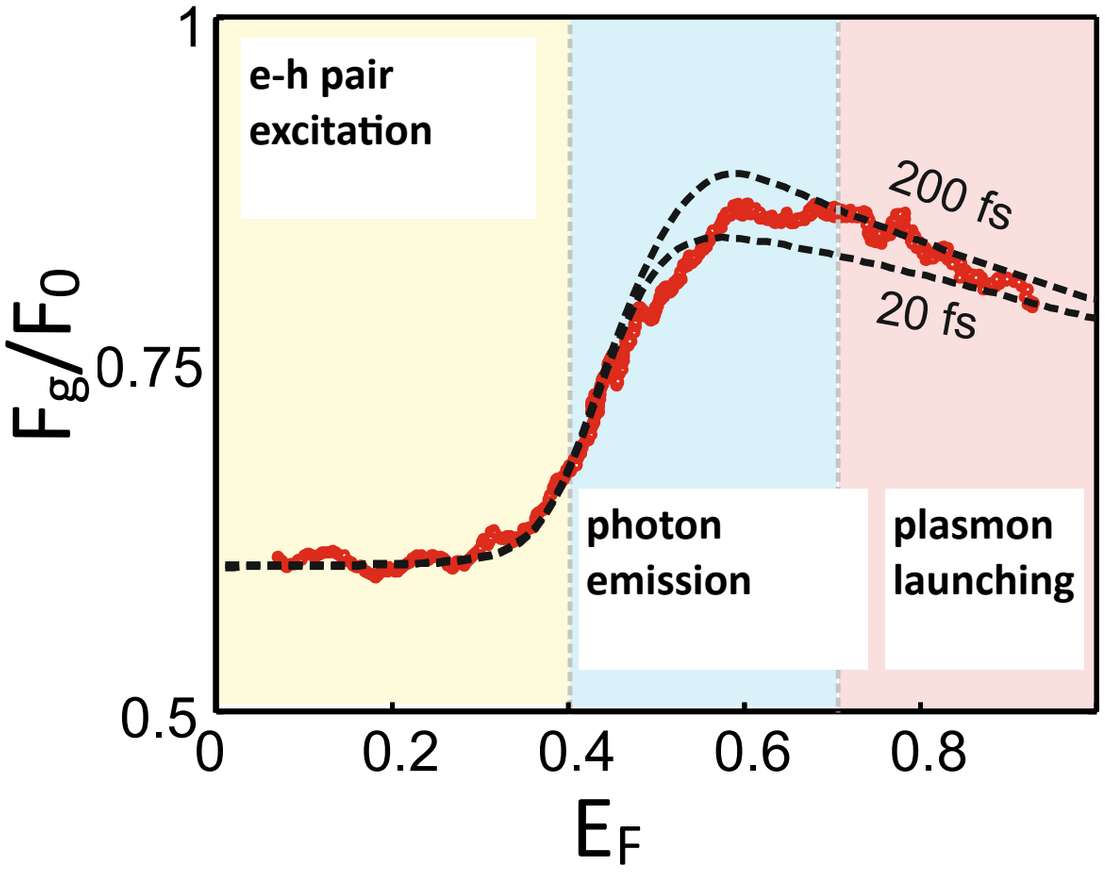
Comparison with model

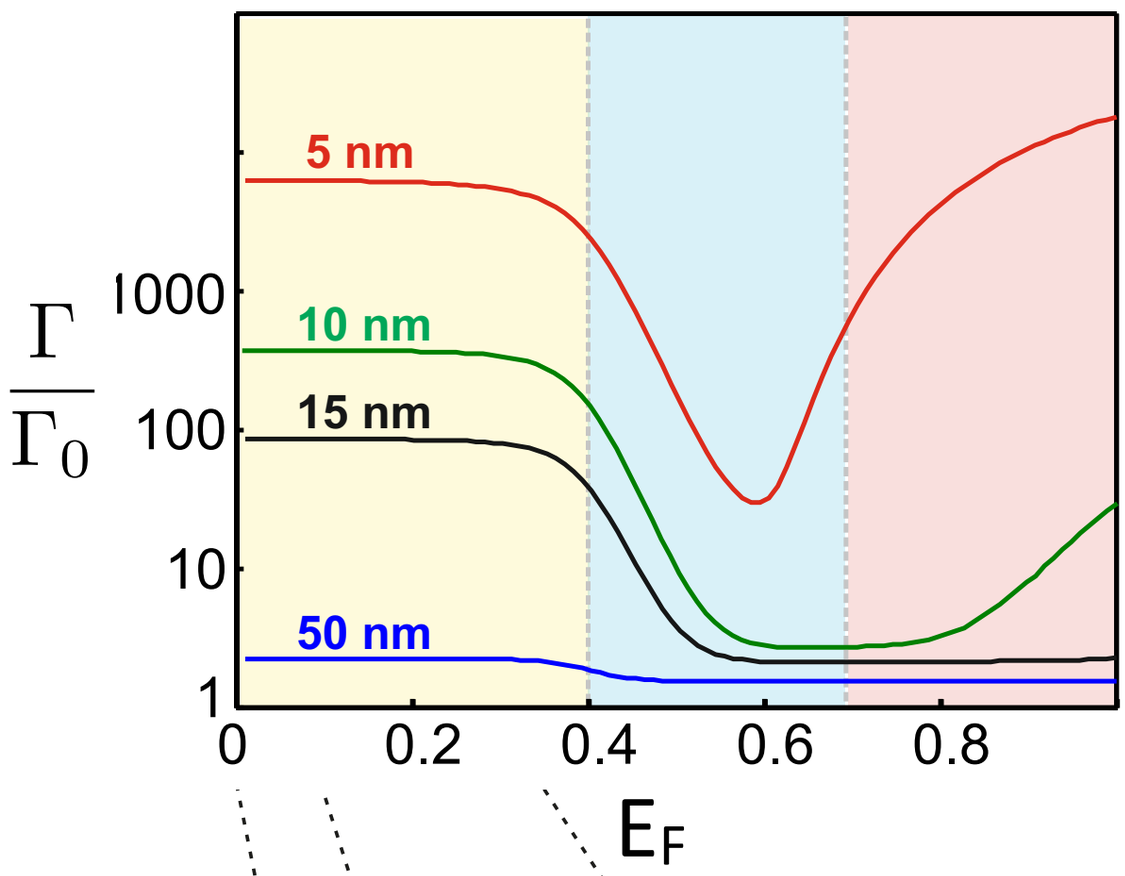


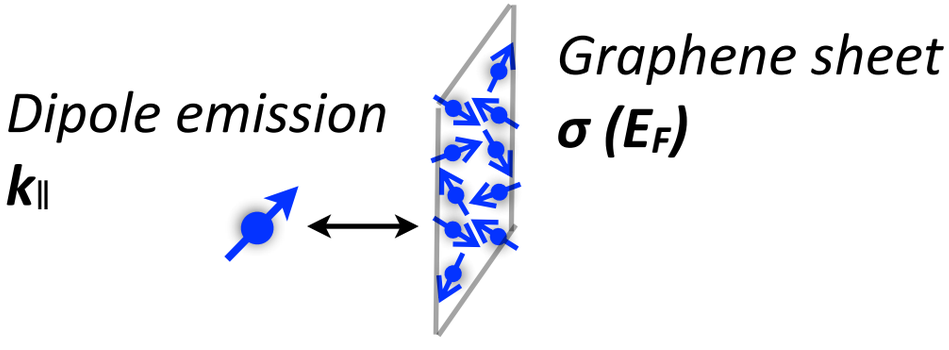


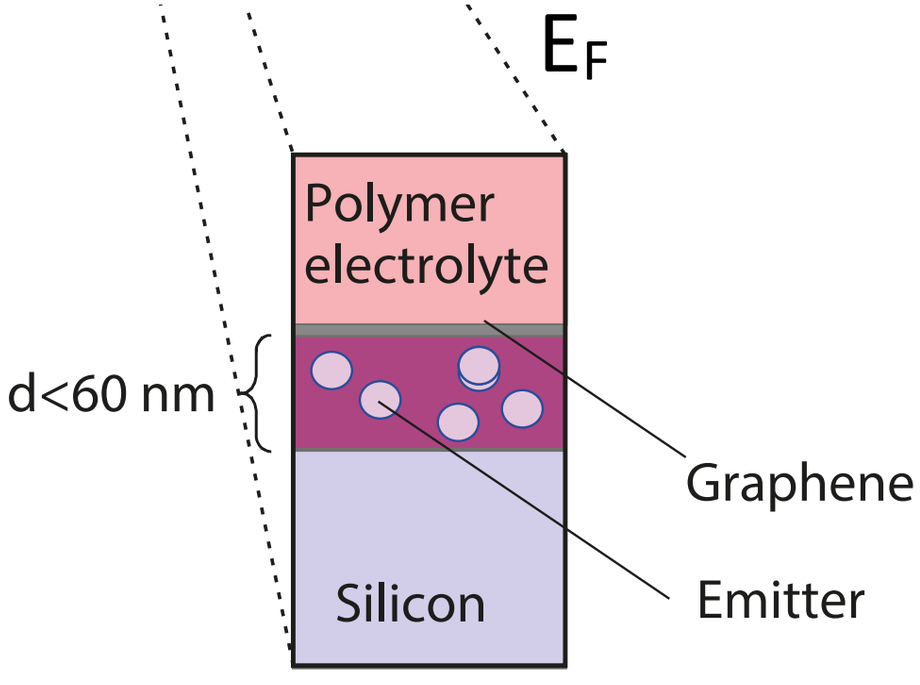
Joulain et al, PRB (2003)
Novotny and Hecht (2006)
Koppens et al. Nano Lett. (2011)
Gomez-Santos et al. PRB (2011)
Koppens et al, Nano Lett. (2011)
Nikitin et al, PRB (2011)
Velizhanin and Efimov, PRB (2011)

Comparison with model

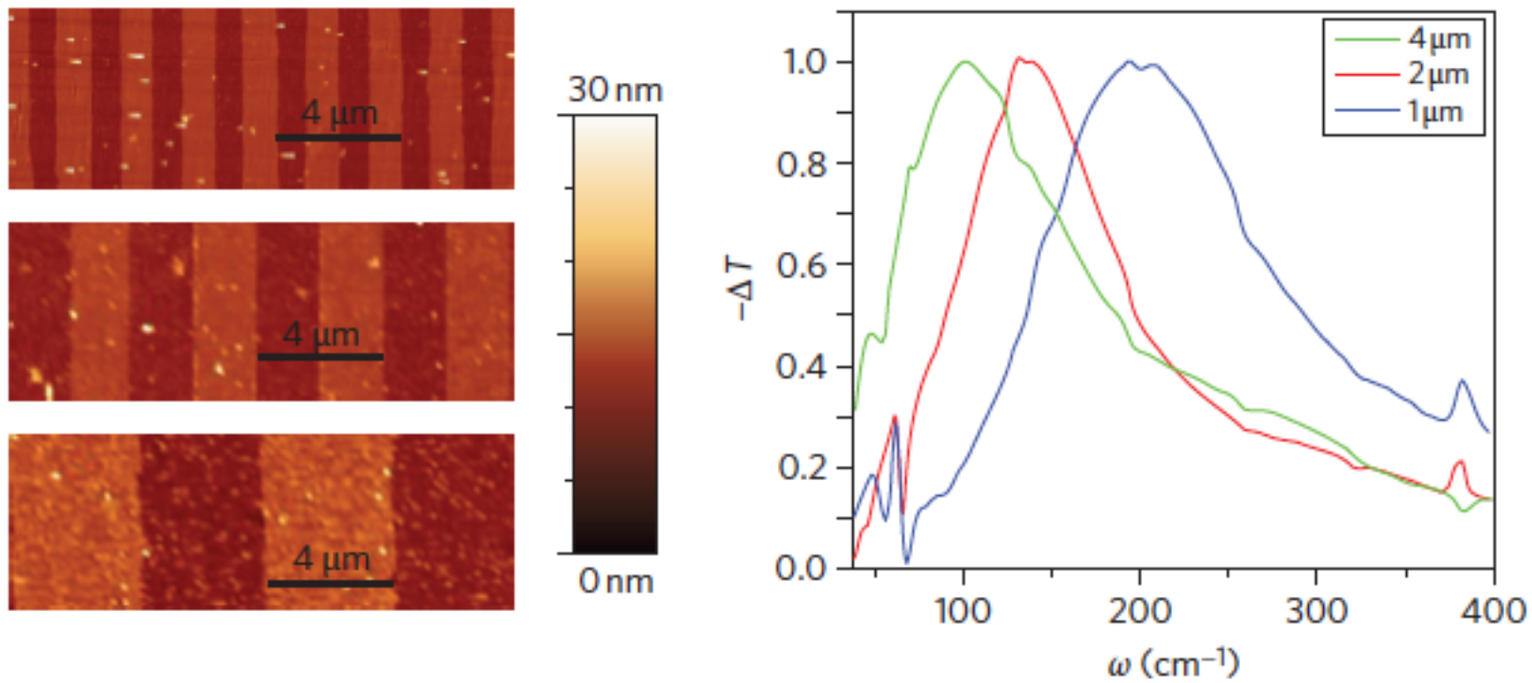








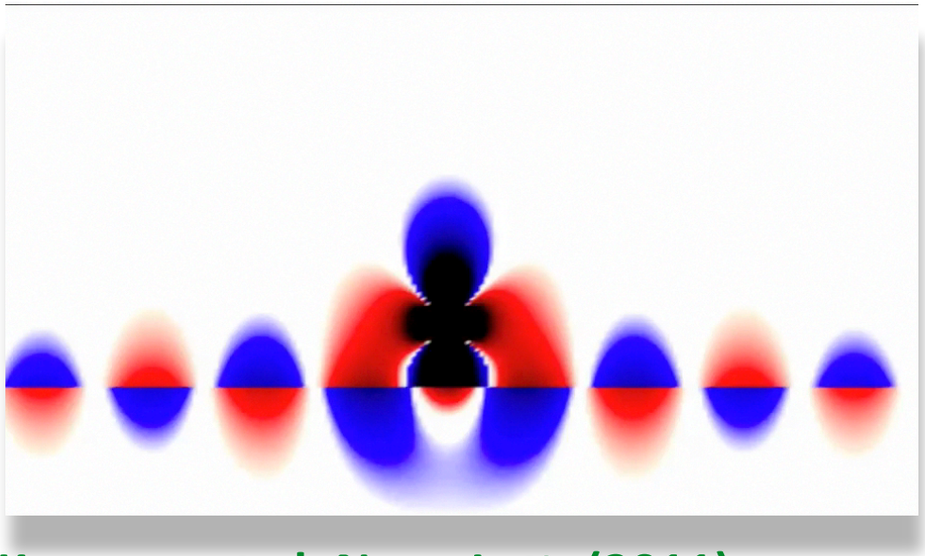
Graphene plasmons



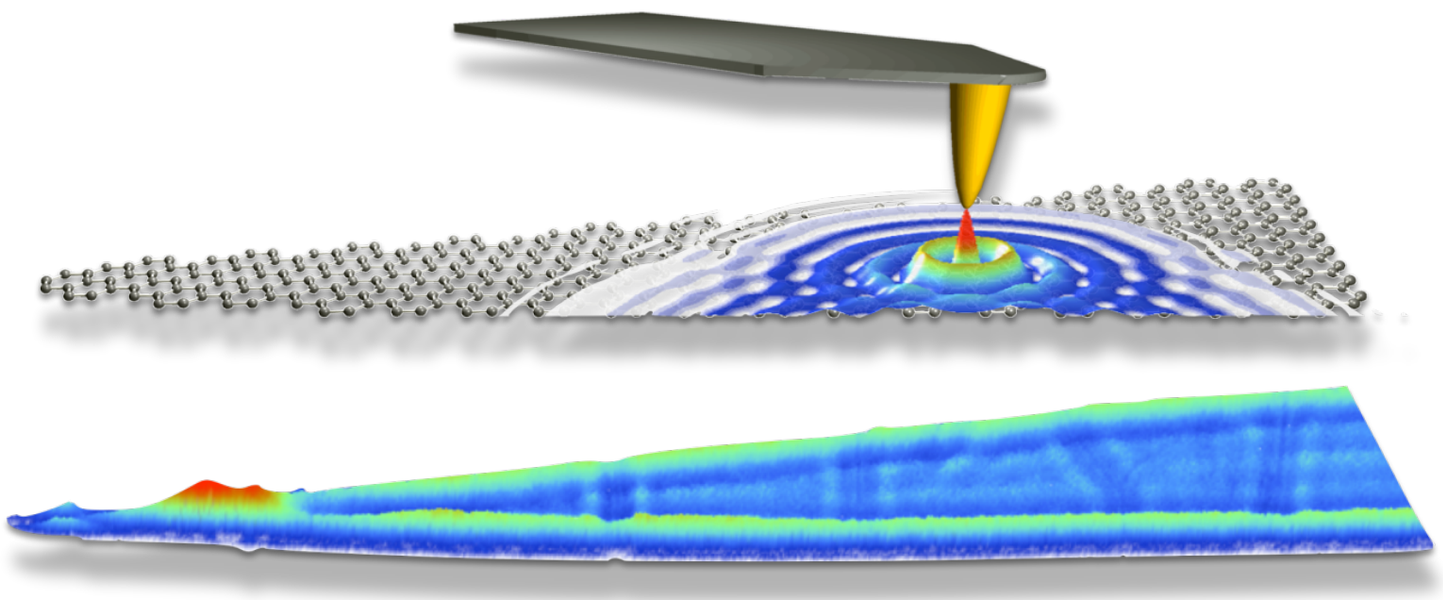
Ju et al. Nature Nanotech. (2011)

…

Graphene plasmons



Koppens et al. Nano Lett. (2011)
Nikitin et al, PRB (2011)
Velizhanin and Efimov, PRB (2011)



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

Plasmon wavelength: <200 nm

$$\frac{\lambda_{\mathrm{sp}}}{\lambda_{\mathrm{em}}} = \frac{4\alpha}{\epsilon_1 + \epsilon_2}\frac{E_F}{\hbar\omega}$$

Excitation wavelength: 10 μm

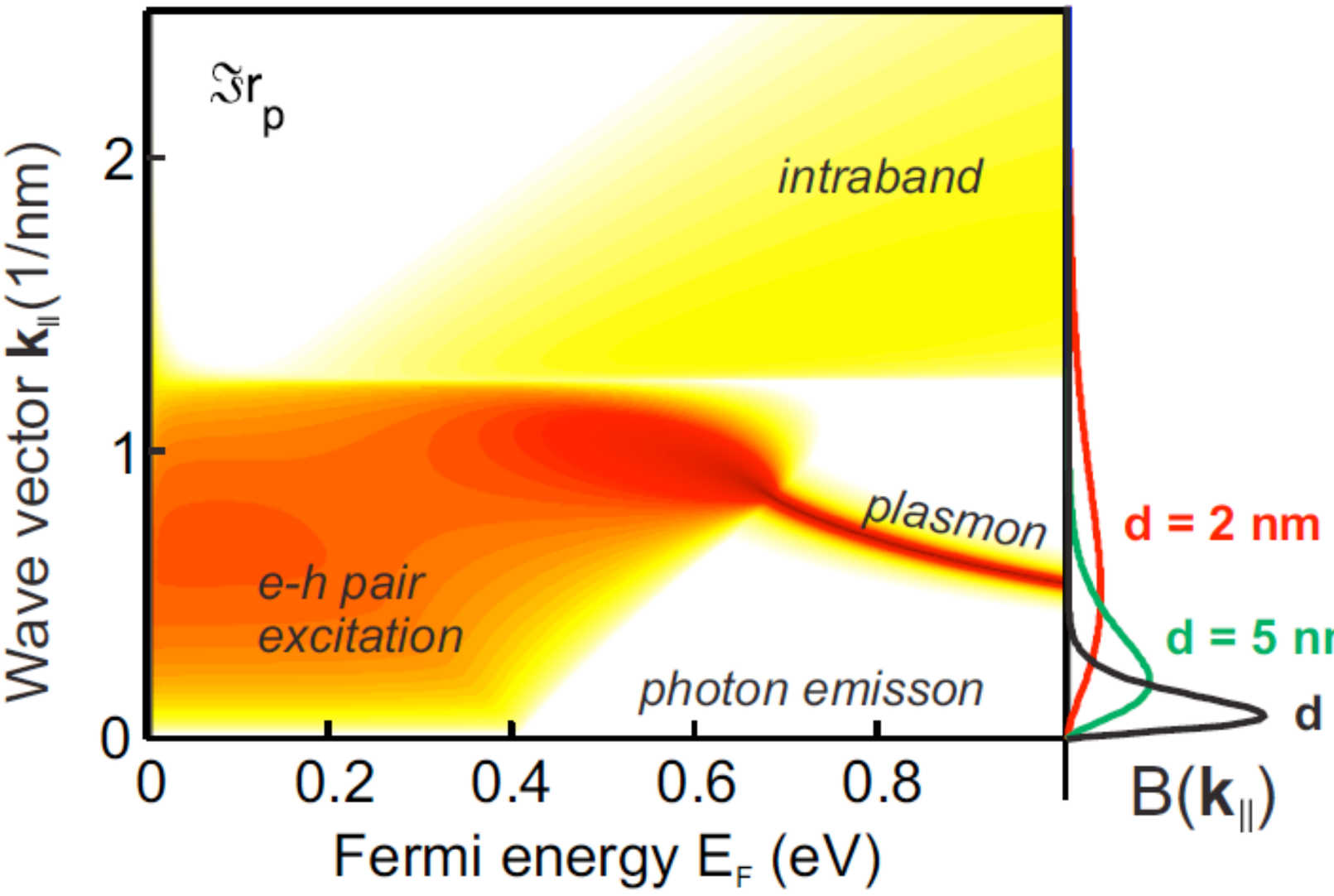
Graphene plasmons @ 1.5 μm

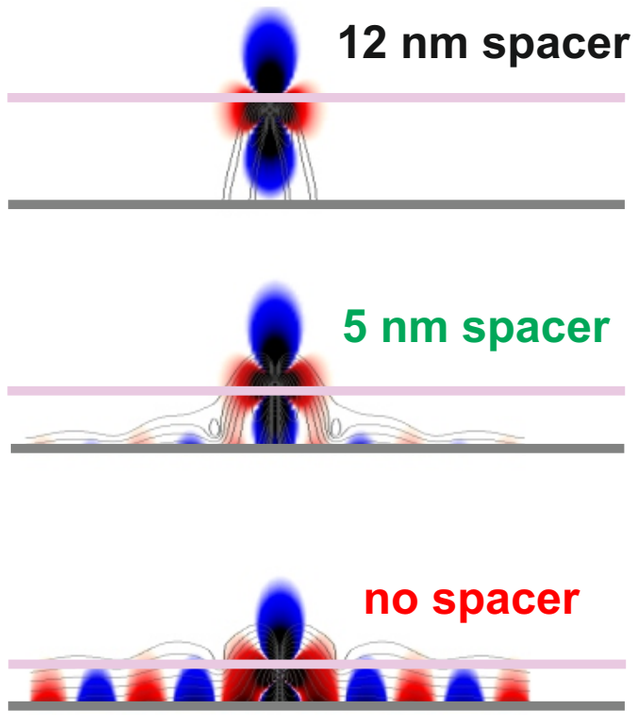
Plasmon wavelength: <15 nm

$$\frac{\lambda_{\mathrm{sp}}}{\lambda_{\mathrm{em}}} = \frac{4\alpha}{\epsilon_1 + \epsilon_2} \frac{E_F}{\hbar\omega}$$

Excitation wavelength: 1.5 μm

Graphene plasmons @ 1.5 µm



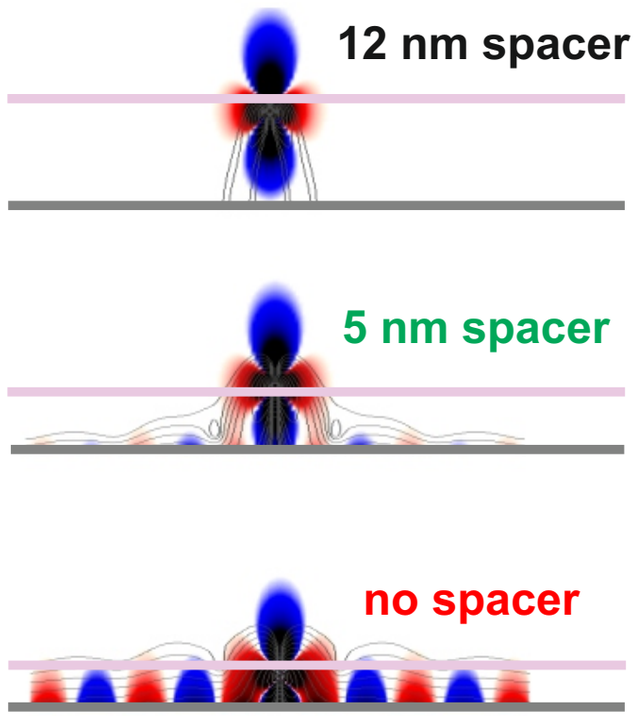


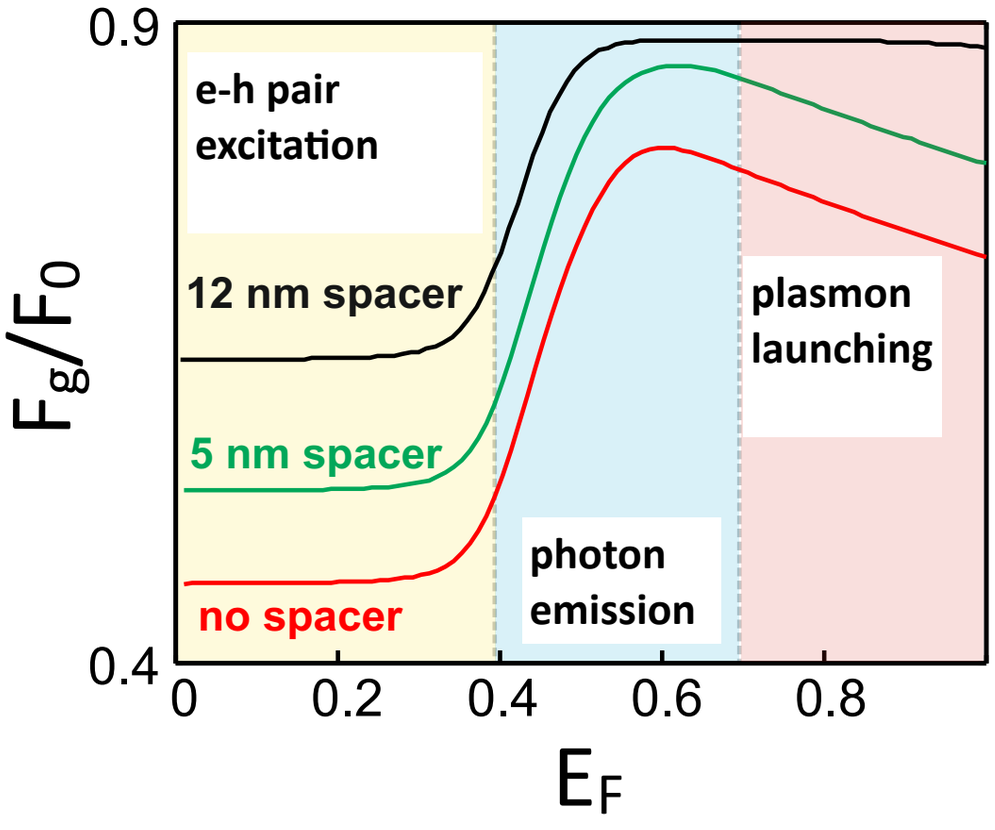
Plasmon wavelength: <15 nm

$$\frac{\lambda_{sp}}{\lambda_{em}} = \frac{4\alpha}{\epsilon_1 + \epsilon_2}\frac{E_F}{\hbar\omega}$$

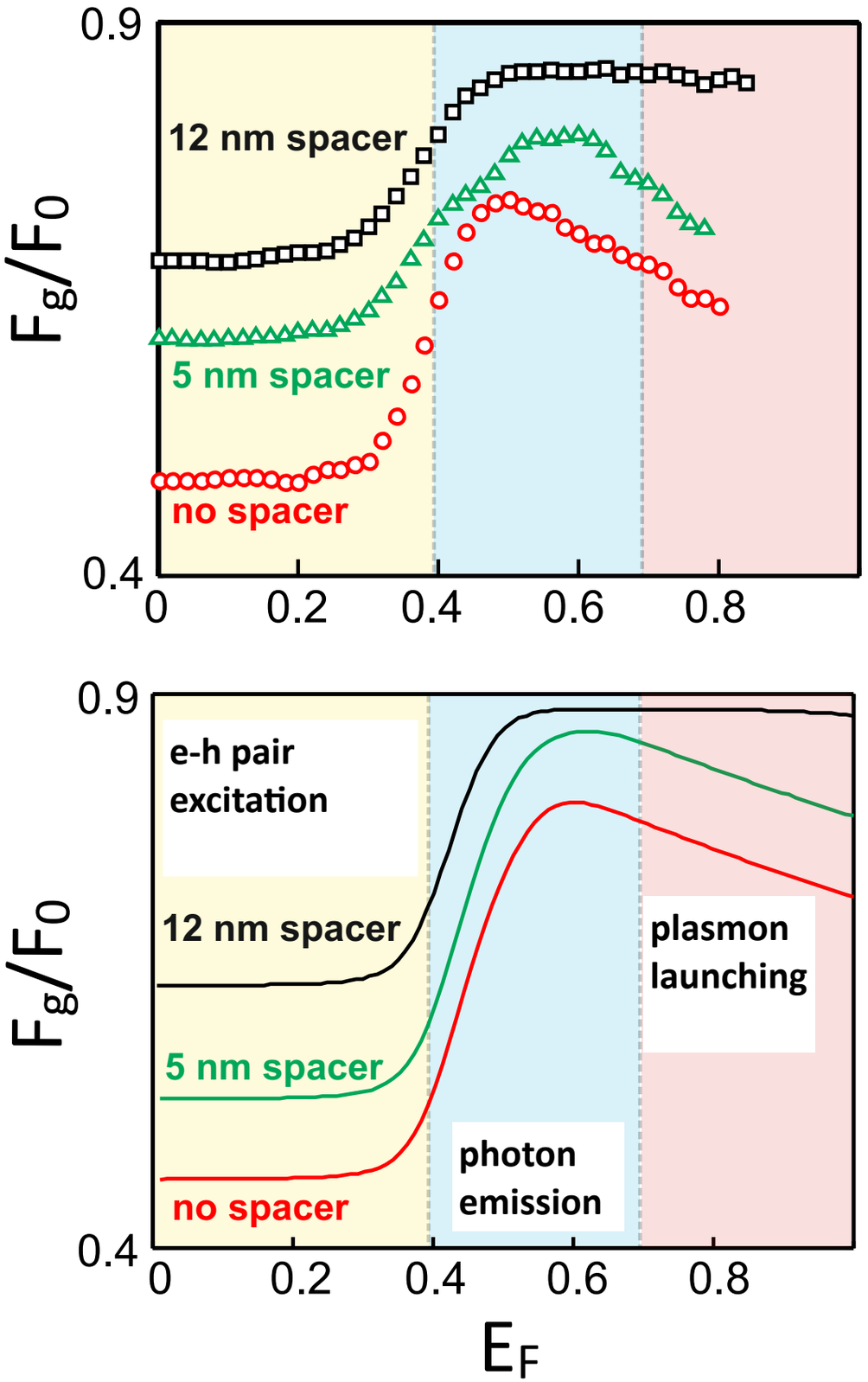
Excitation wavelength: 1.5 µm

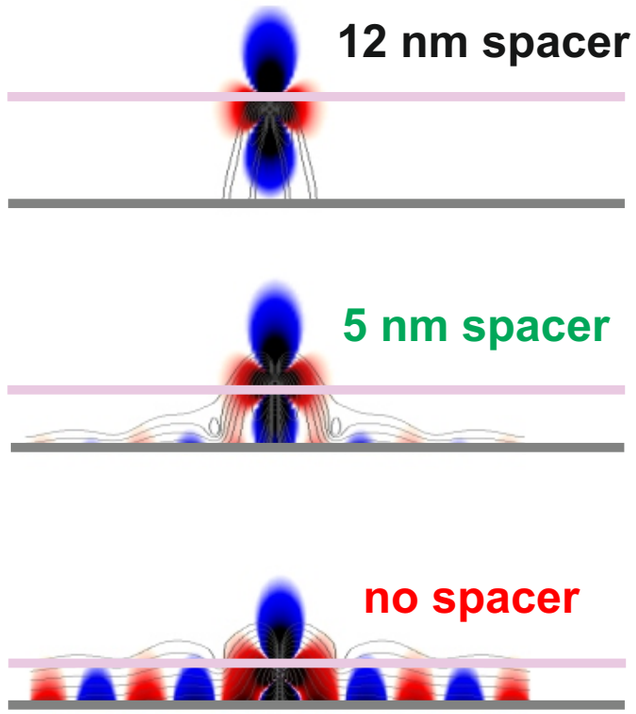
Graphene plasmons @ 1.5 µm



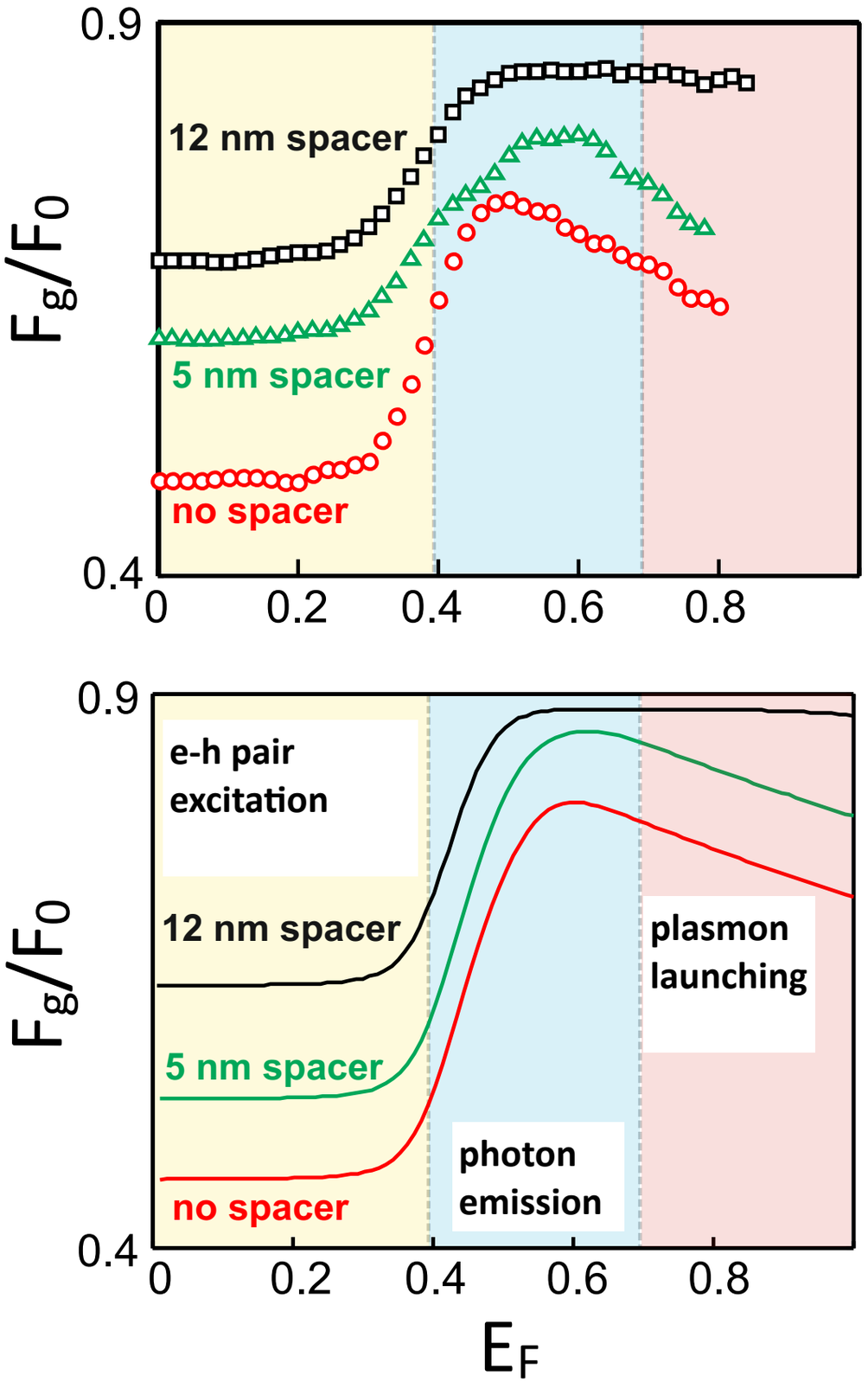


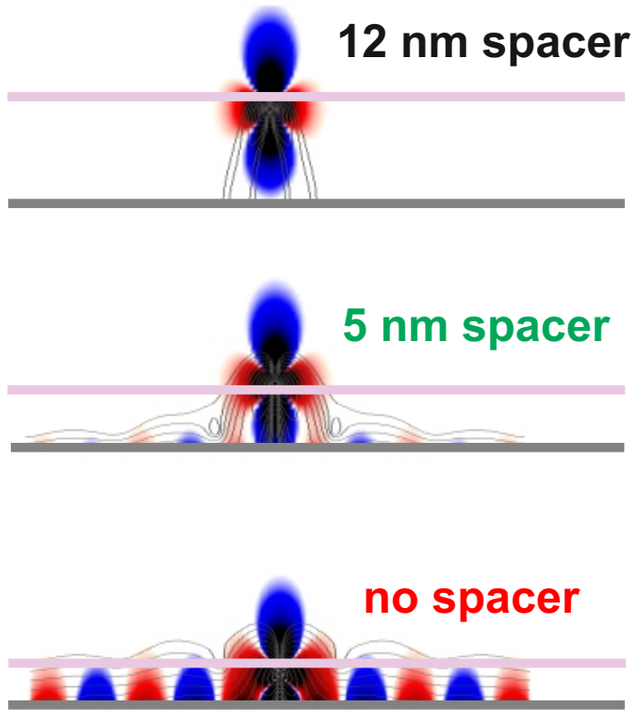
Graphene plasmons @ 1.5 µm





Graphene plasmons @ 1.5 µm



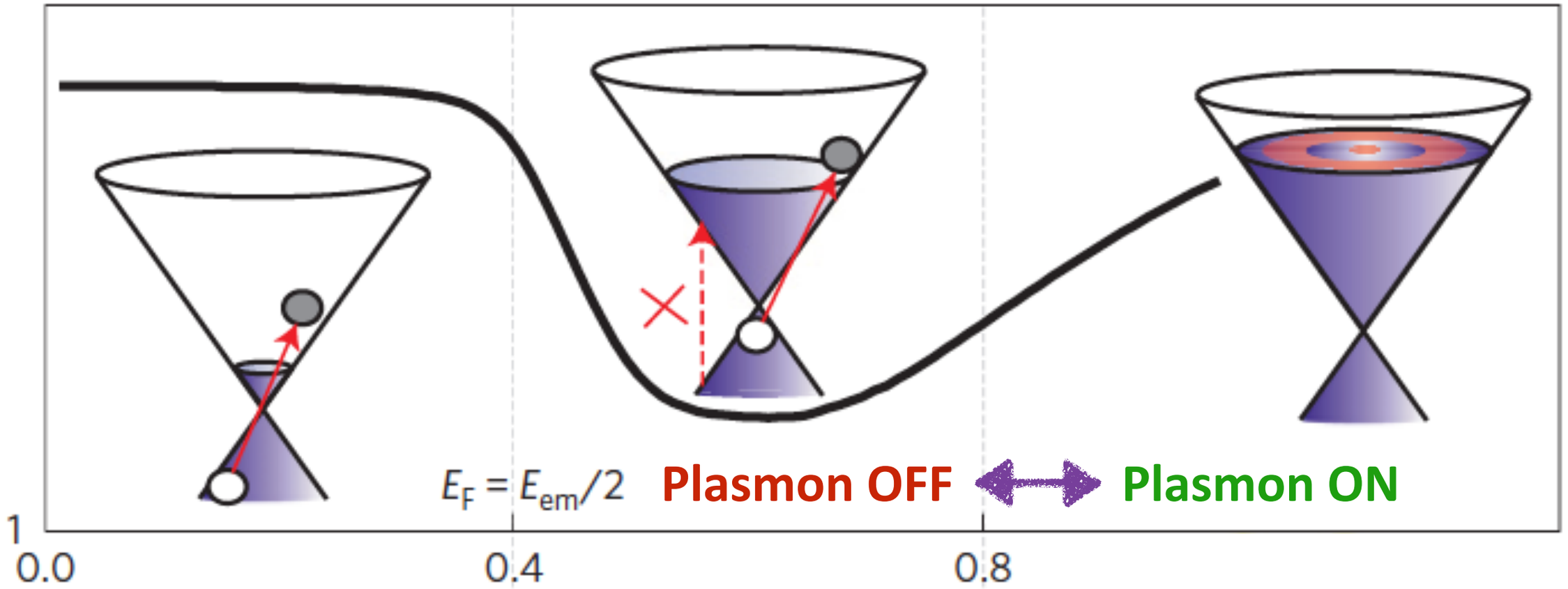


Strongly confined plasmons (<15 nm)

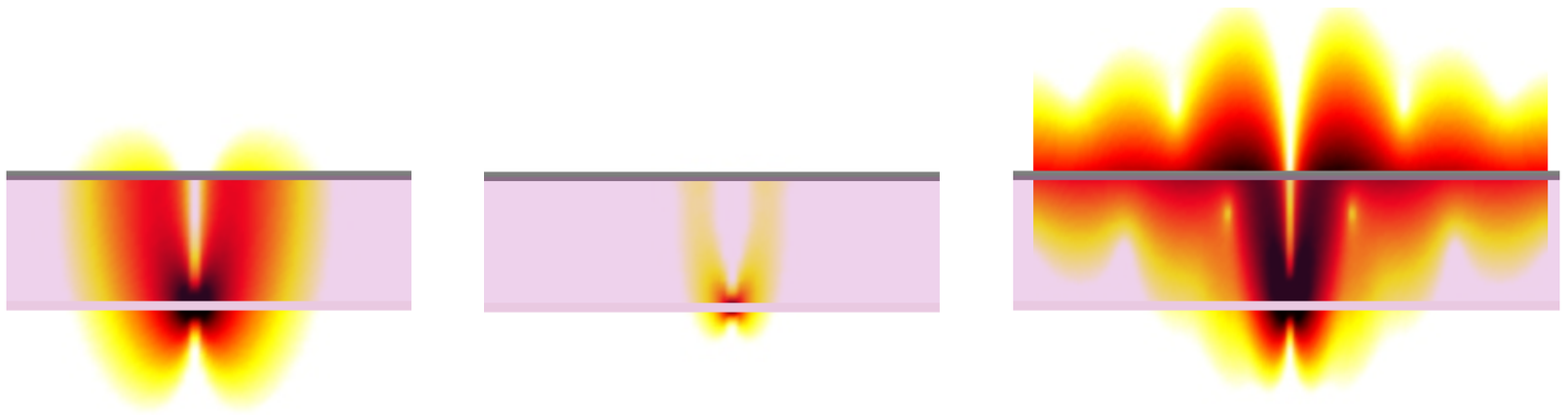
plasmon launching

Metallic

Conclusion



KJT et al., Nature Phys. (2015)

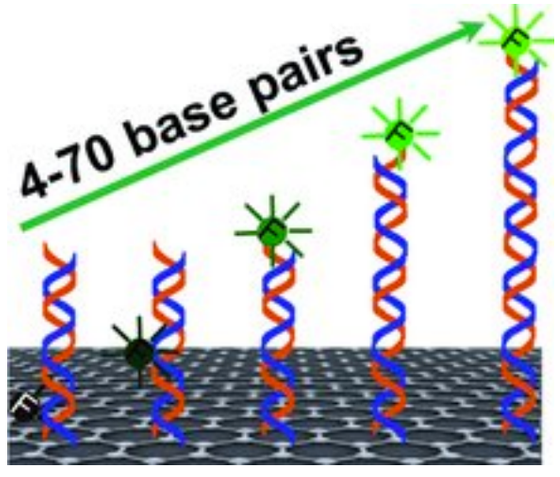


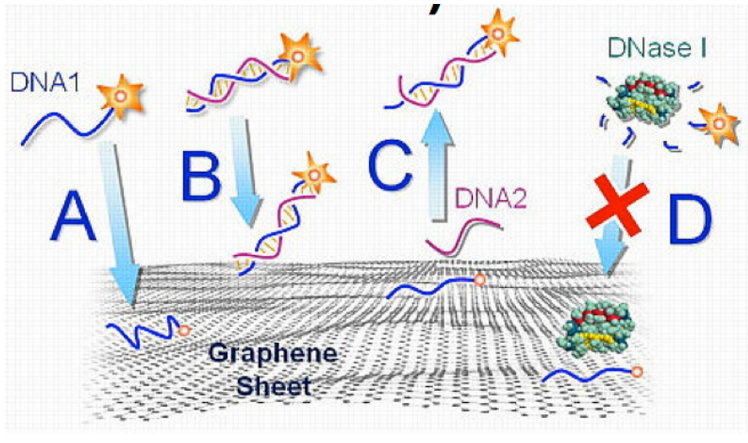
e-h pair excitation
Absorber

photon emission
Transparent

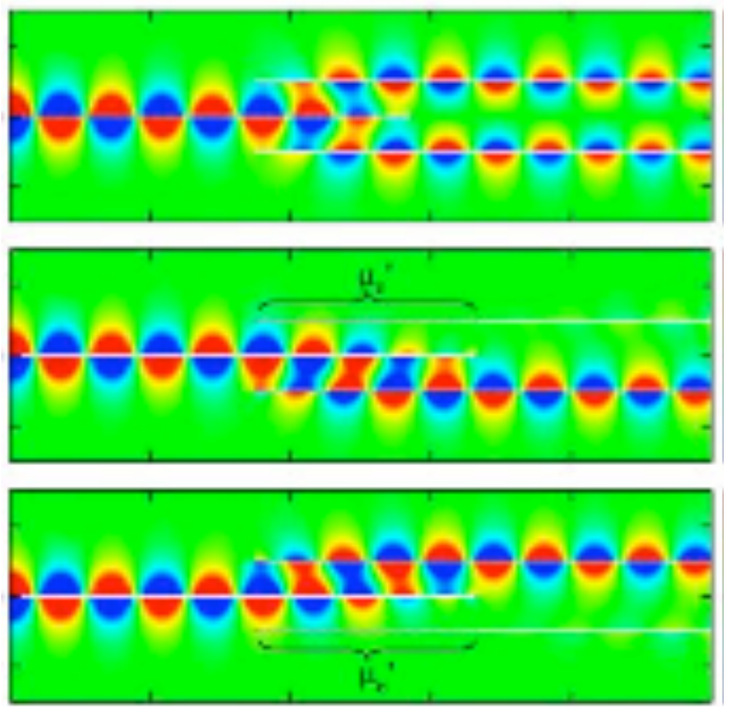
plasmon launching
Metallic

Outlook



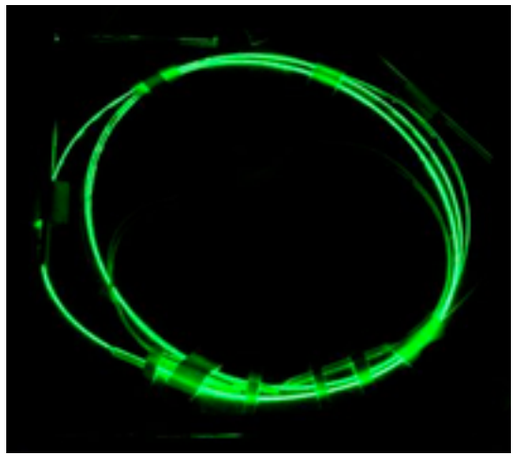


Plasmonics

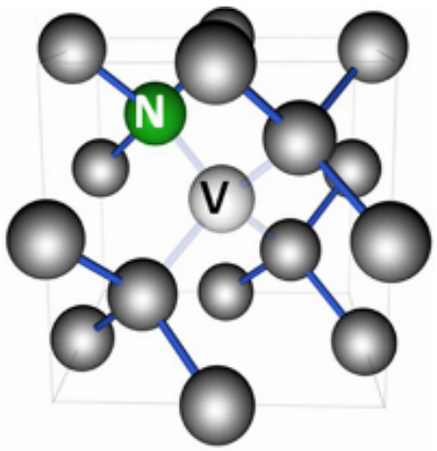


Telecommunications

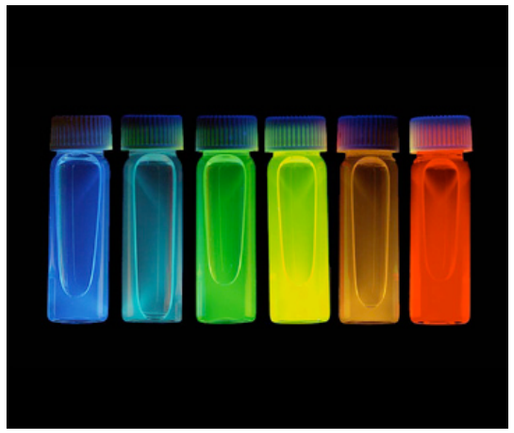
Outlook



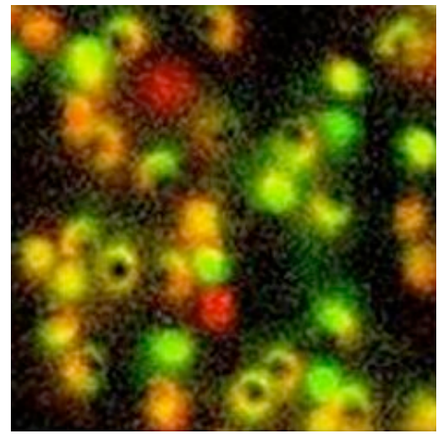
Erbium



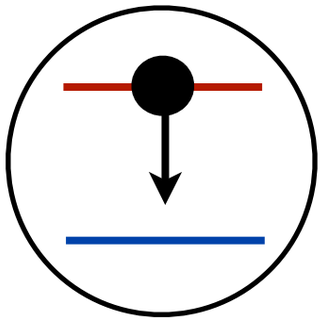
Diamond NV centers

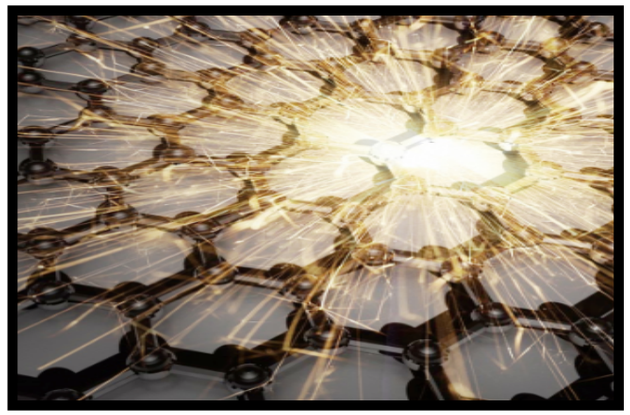


Quantum Dots



Fluorescent molecules





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www.koppensgroup.icfo.eu

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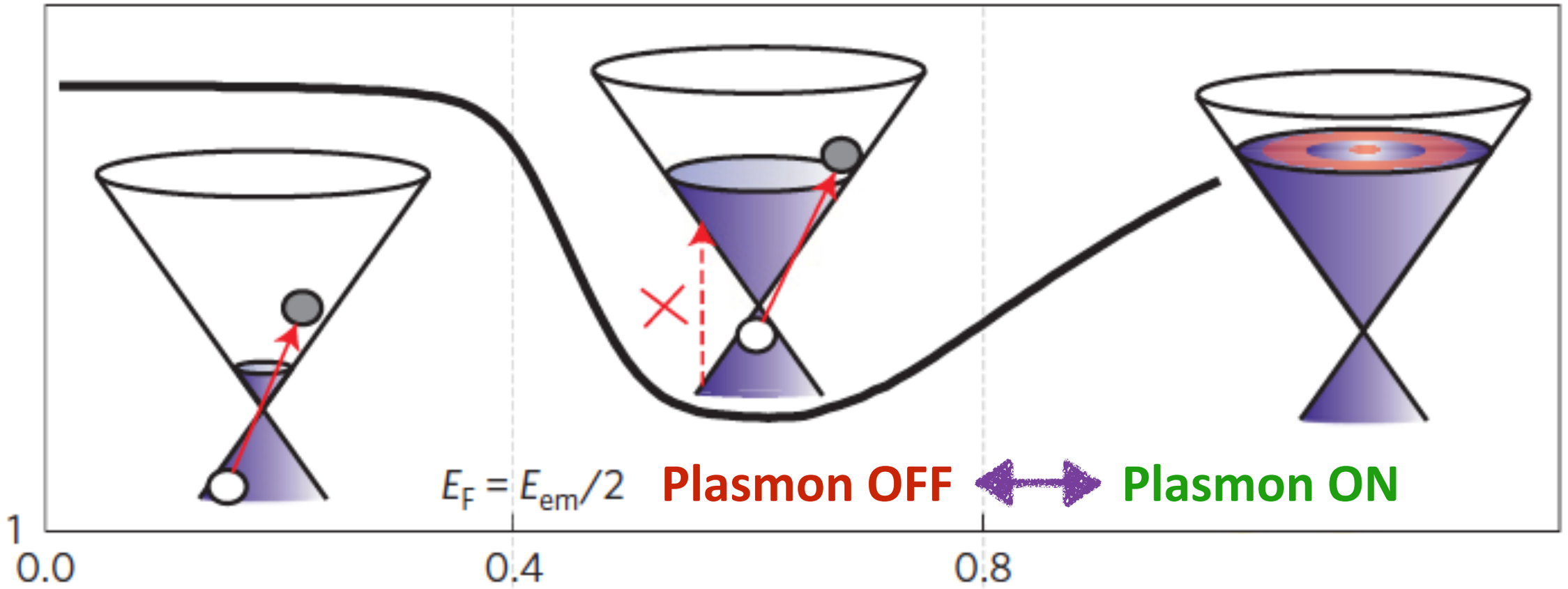
Alban Ferrier
Philippe Goldner

Padova, Italy
Boris Kalinic

Conclusion



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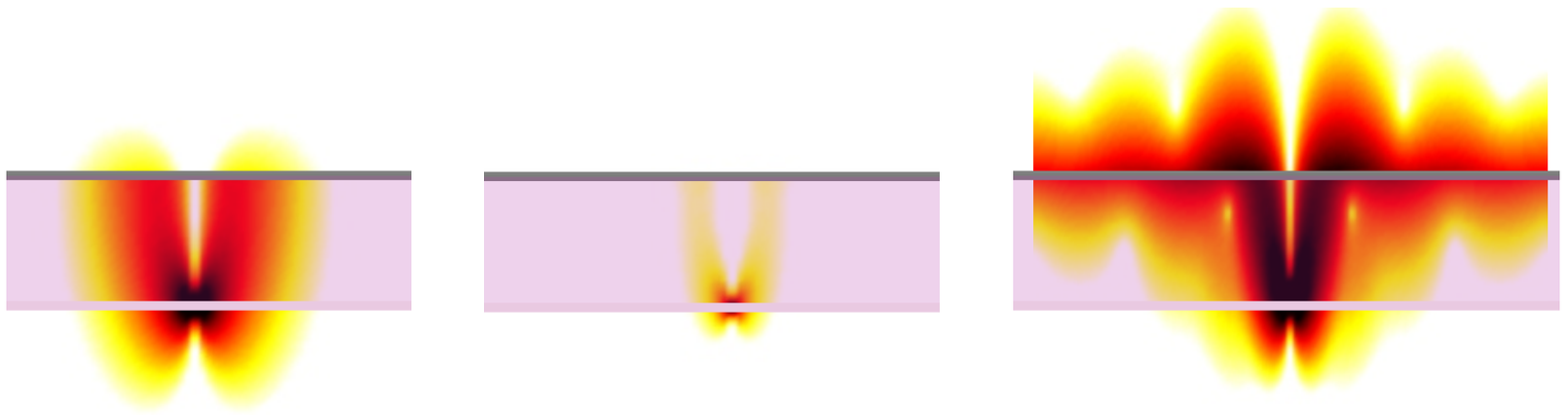

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