COLLECTIVE ELECTRONIC EXCITATIONS FOR ULTRA-STRONG COUPLING AND SUPERRADIANCE

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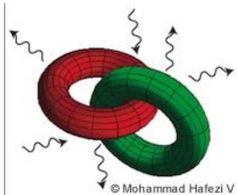
KITP, 5-9 october 2015



Acknowledgements

Yanko Todorov and Carlo Sirtori

PhD students: Pierre Jouy (ETH-Zurich), **Aymeric Delteil** (ETH-Zurich), **Giulia Pegolotti**, **Benjamin Askenazi**, Baptiste Dailly
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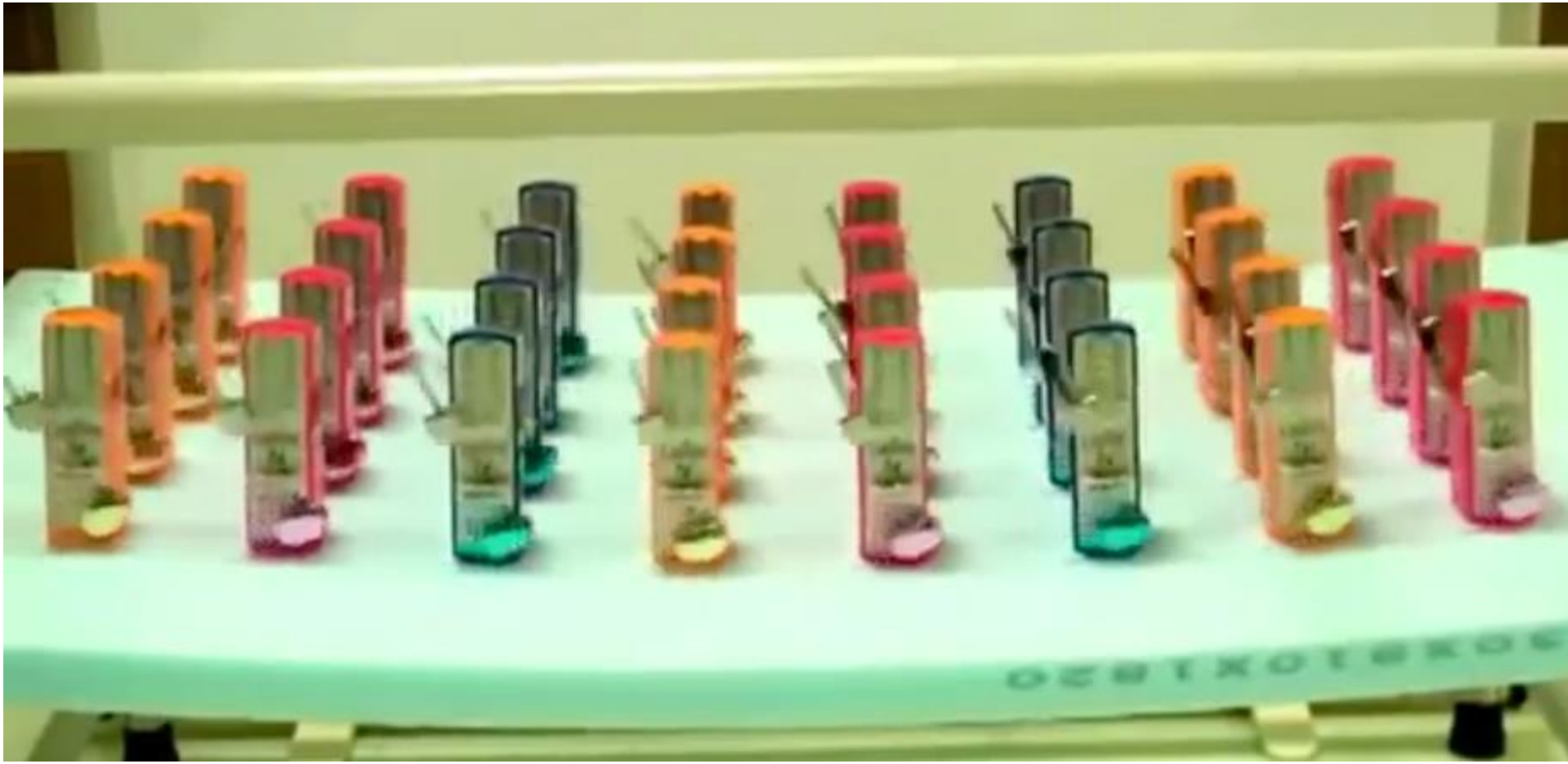
Funding:

ADEQUATE

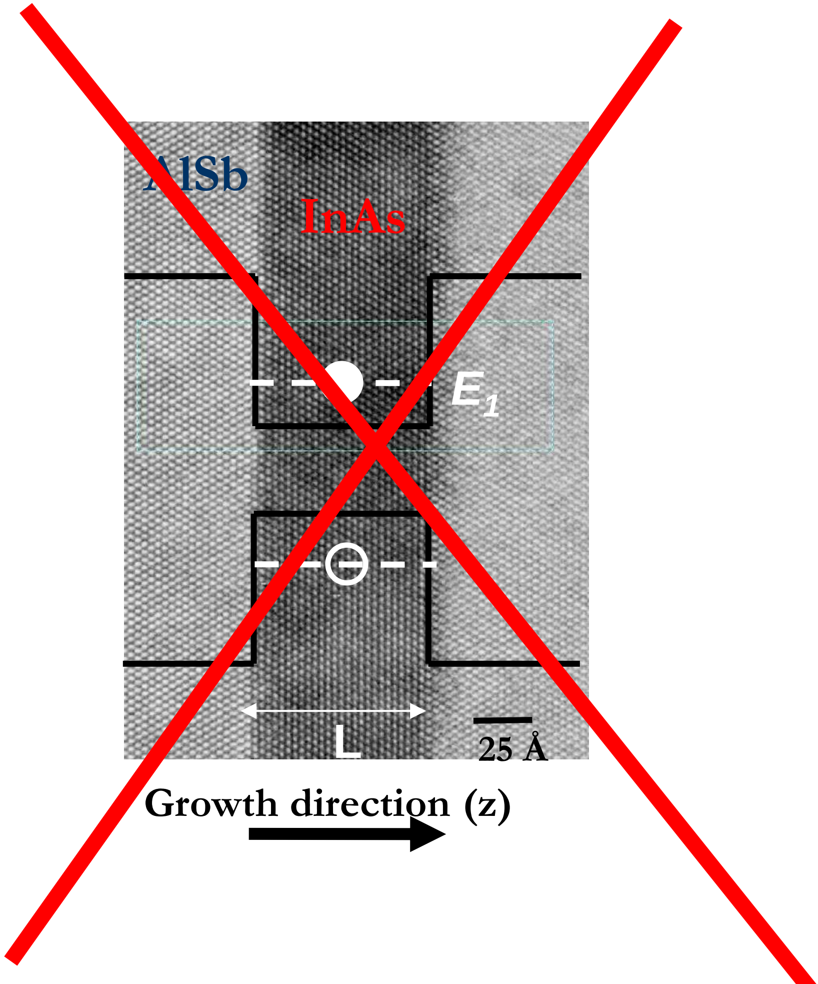
DOMANY

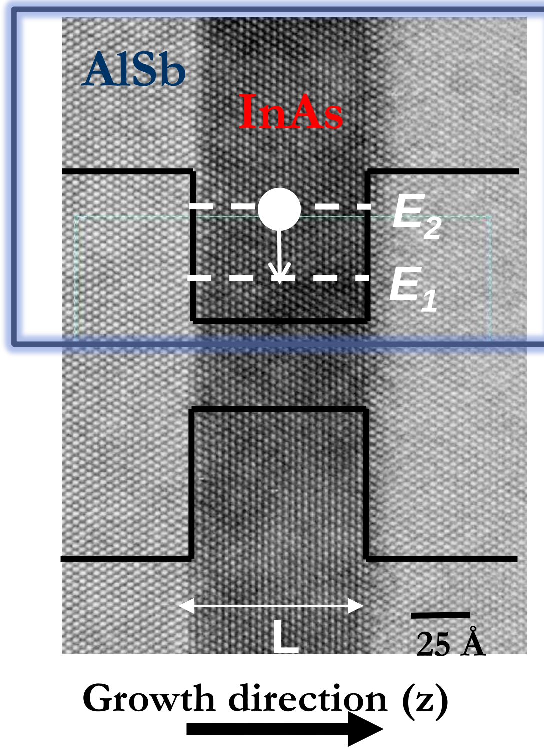
This work is not on interacting photons…



…but on interacting electrons!

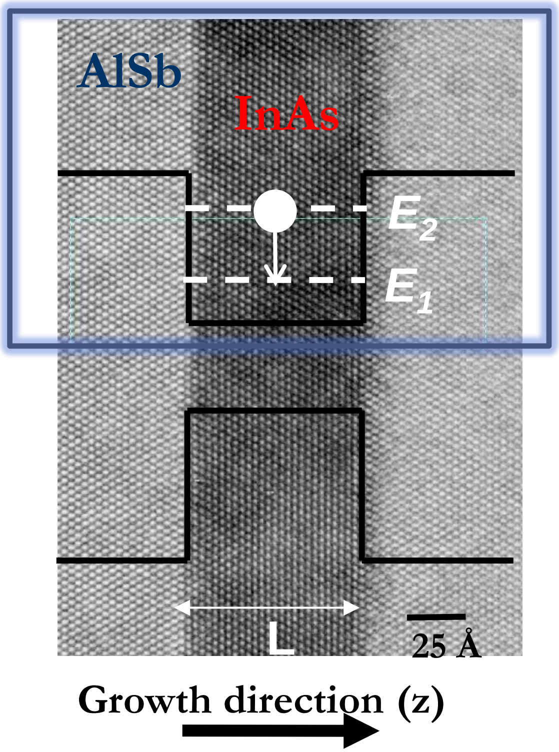
It is not about excitons…



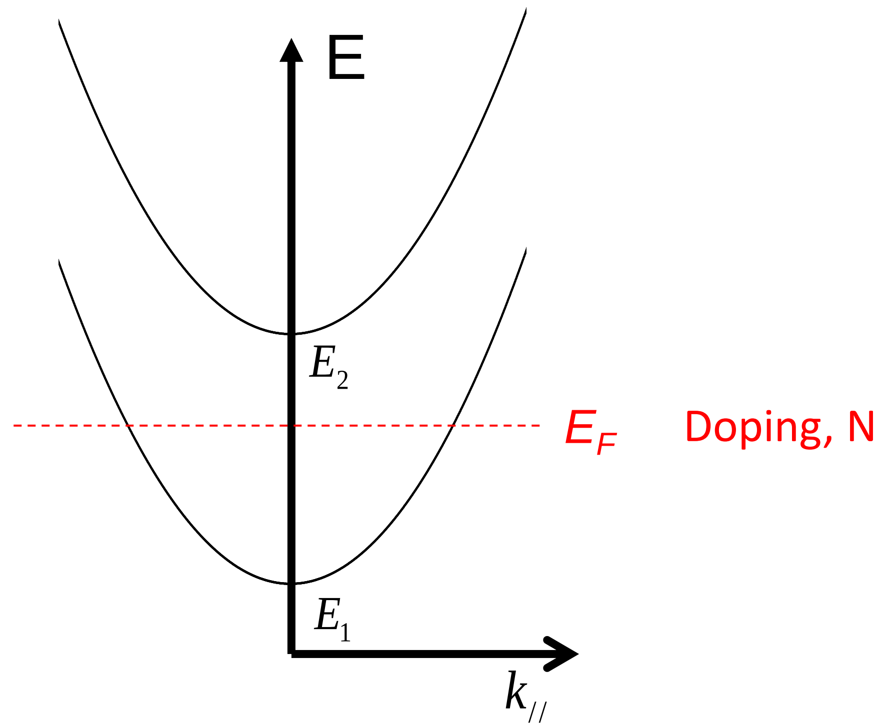


…everything happens in the conduction band of a semiconductor quantum well

Intersubband transition in quantum wells



$$E_2 - E_1 \propto \frac{1}{L^2}$$



$$E_{n,k_{//}} = E_n + \frac{\hbar^2 k_{//}^{\;2}}{2m^*}$$

Photon wavelength : mid and far infrared

Spontaneous emission lifetime ~ 10 – 100 ns

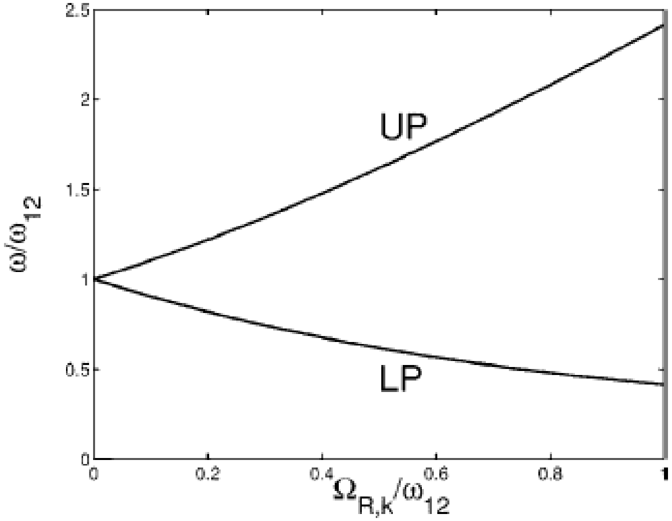
Non-radiative lifetime ~ 1 ps

Two different quantum phenomena:

- ❑ Ultra-strong light-matter coupling
- ❑ Superradiance

Two different quantum phenomena:

- **Ultra-strong light-matter coupling (USC)**

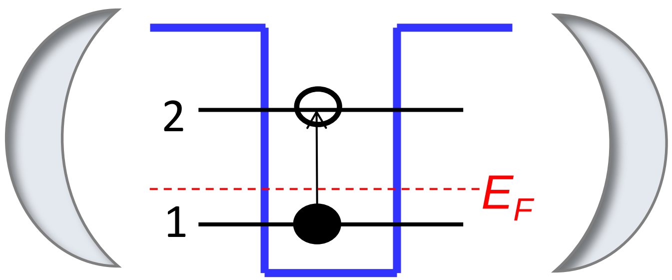


C. Ciuti *et al.*, PRB 2005

$$\frac{\text{Rabi energy}}{\text{Matter excitation energy}} = \frac{E_R}{E_{exc}} \approx 1$$

Anti-resonant and quadratic terms of the light – matter interaction are not negligible

Günter et al Nature 2009, Todorov et al. PRL 2010, Delteil et al. PRL 2012, Geiser et al. PRL 2012; Niemczyk et al Nat. Phys. 2010; Scalari et al Science 2012, Schwartz et al. PRL 2011 , Kéna-Cohen et al. Adv. Opt. Mater. 2013, Schlather et al. Nano Lett. 2013, Nagasawa et al. Phys. Chem. Lett. 2014…

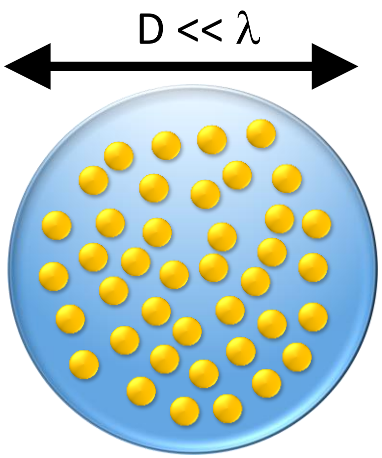


<u>Rabi splitting:</u> $\Omega_R \propto \sqrt{f_{12} \frac{N_{QW}}{L_{cav}} N_1}$

D. Dini et al. PRL 2003

Two different quantum phenomena:

- **Superradiance**



Phenomenon of cooperative recombination taking place in an ensemble of two-level emitters, when they are separated by a distance smaller than the wavelength.

Only one atom is excited:

$$|\psi\rangle = (|egg\ldots\rangle + |geg\ldots\rangle + |gge\ldots\rangle)/\sqrt{N_e}$$

$1/(N_e \Gamma_0^{sp})$ **Spontaneous decay time**

Spontaneous emission rate for a single atom

R. H. Dicke, PR 1954
M. Gross, S. Haroche, Phys. Rep. 1982
Skribanowitz et al. PRL 1973
Scheibner et al. Nat. Phys. 2007

Van Loo et al. Science 2013
Zhang et al. PRL 2014
Goban et al. PRL 2015
Laurent et al. PRL 2015

Common point:
Many electronic excitations!

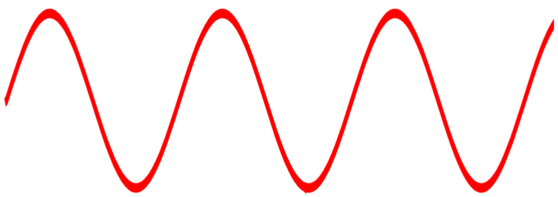
→ Dense electron gases in semiconductor QWs

Outline

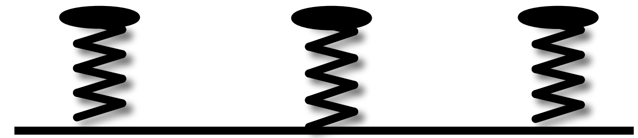
- Many-body excitations in dense electron gases
- Ultra-strong coupling regime with collective electronic excitations
- Spontaneous emission of collective states: superradiance
- Conclusion and perspectives

Many-body excitations in dense electron gases

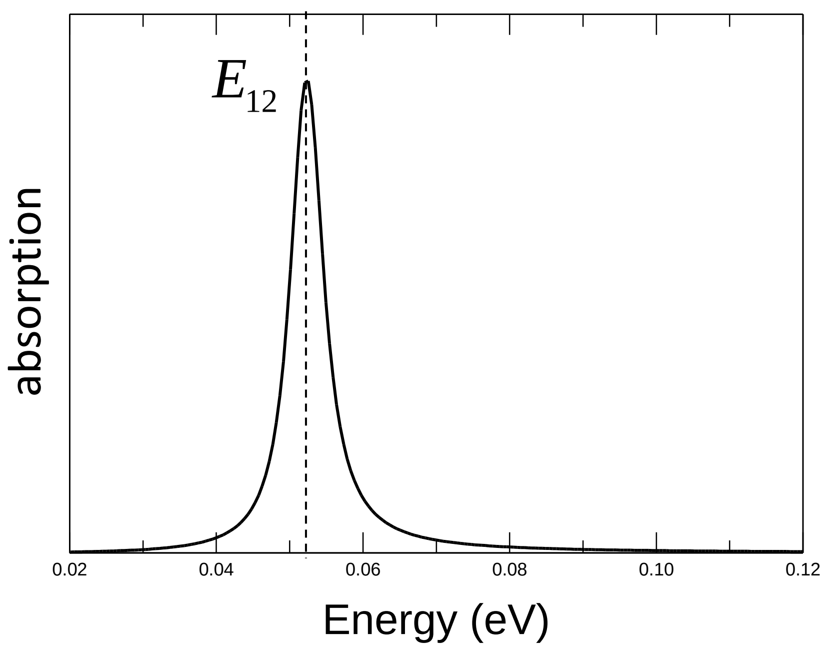
Interaction free space radiation – 2DEG

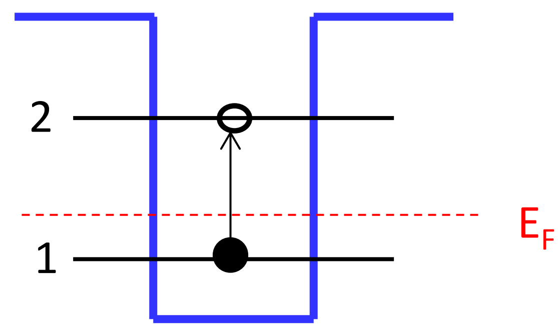


Radiation



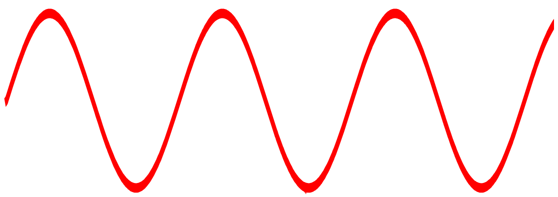
Matter polarization: excitation of an ensemble of non interacting dipolar oscillators



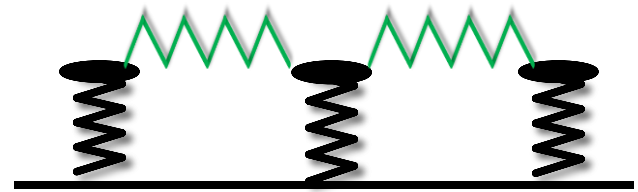


$$\alpha \propto N_s f_{12}$$

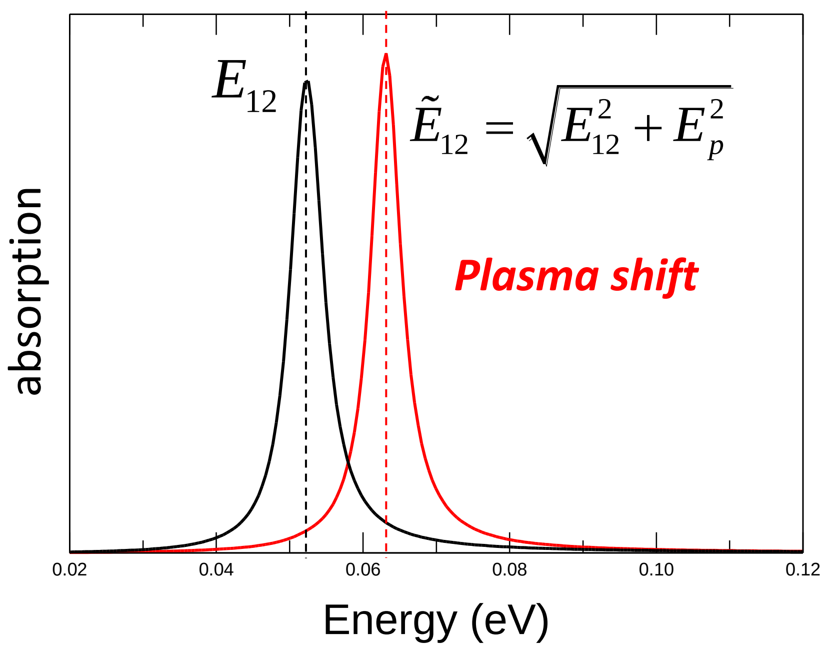
Interaction free space radiation – 2DEG



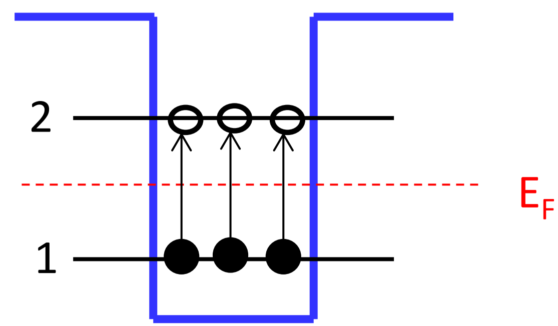
Radiation



Matter polarization: excitation of an ensemble of interacting dipolar oscillators

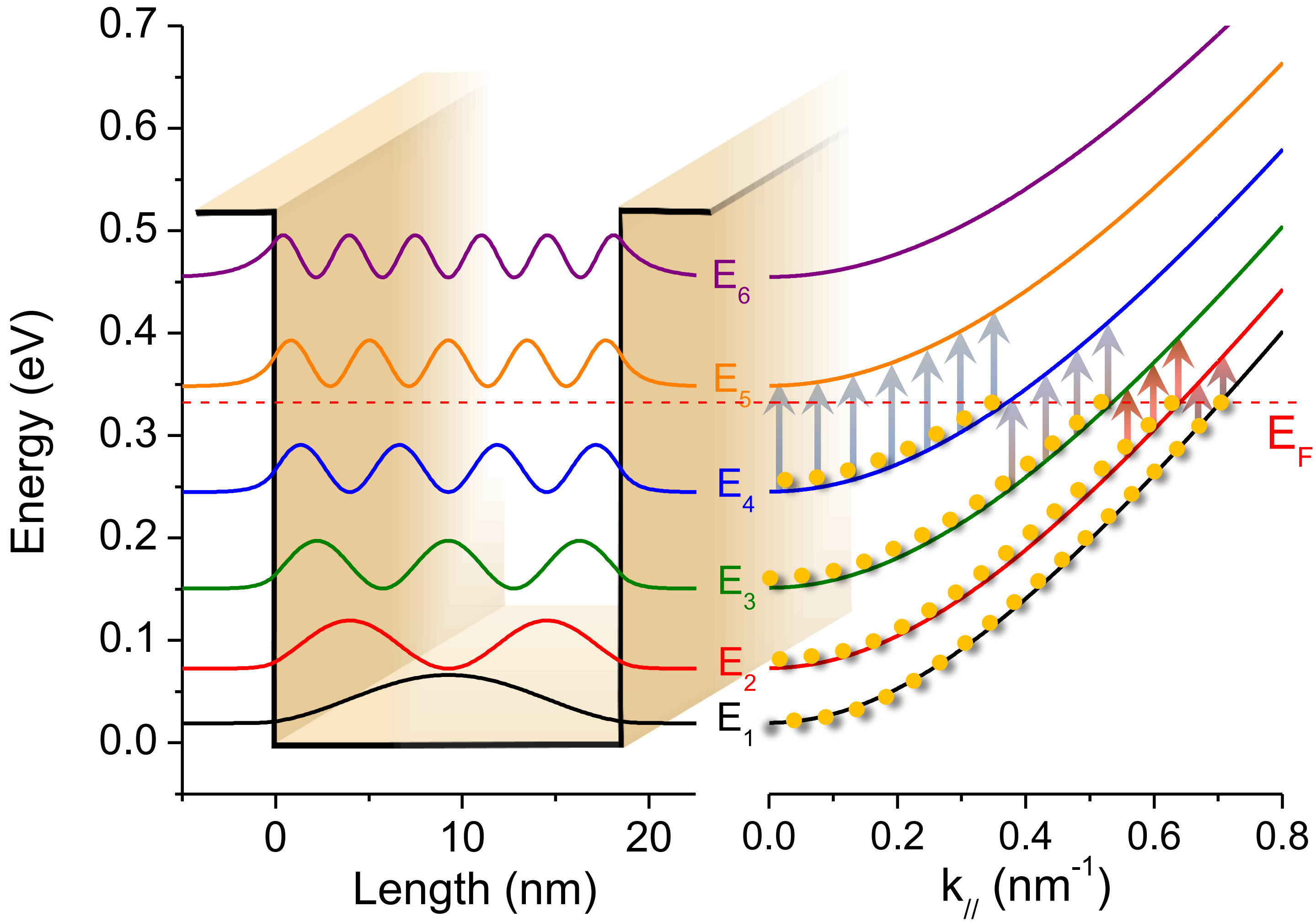


Ando, Fowler and Stern Rev. Mod. Phys. 1982



$$\alpha \propto E_p^2 = \frac{\hbar^2 e^2 f_{12}}{m^* \varepsilon_0 \varepsilon_{st} L_{eff}} \left(N_1 - N_2\right)$$

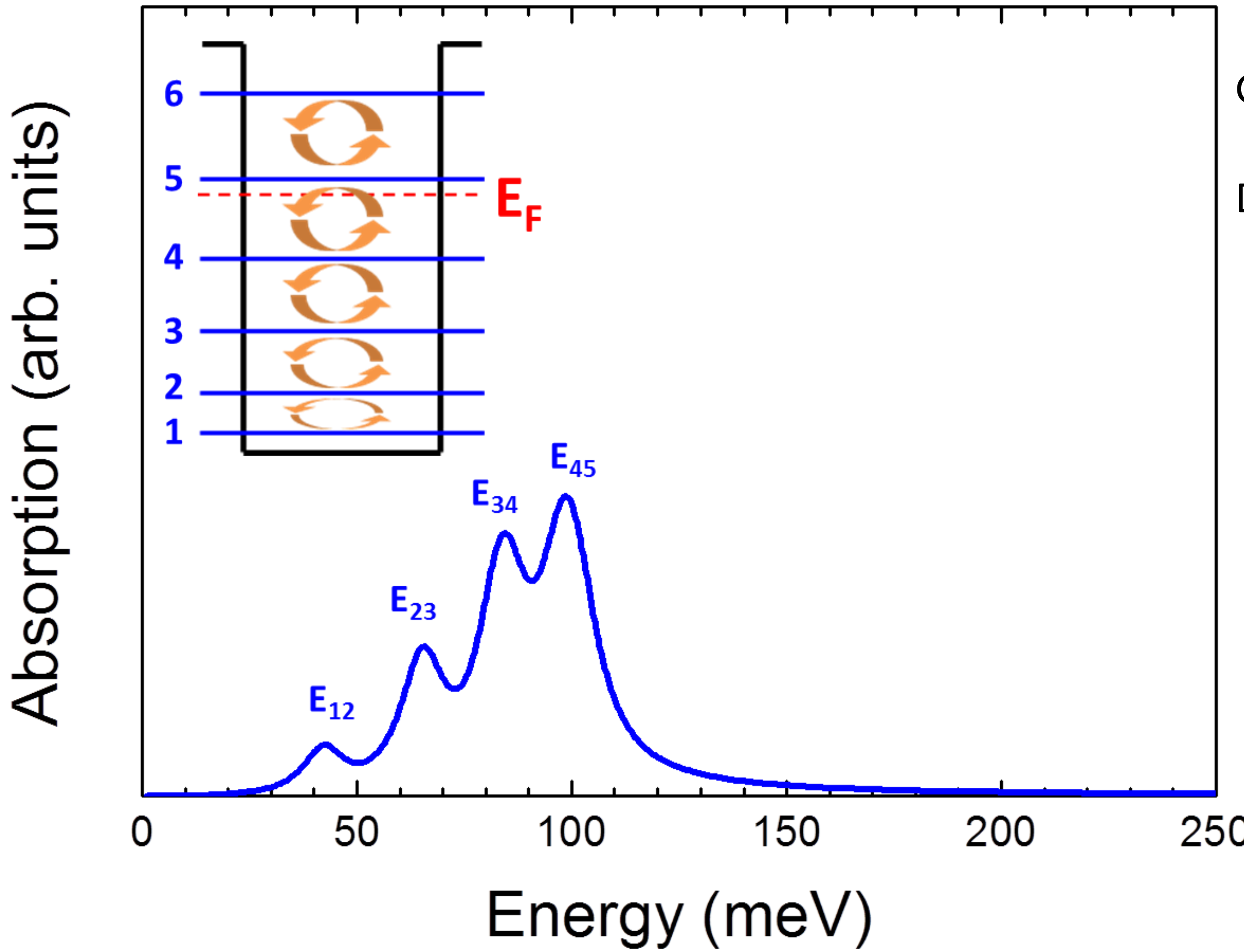
Highly doped quantum well



18.5 nm GaInAs/AlInAs quantum well

Uniformly doped in the well: 2.2 x 10^{13} cm^{-2} (N_v= 1.2 x $10^{19}$$cm^{-3}$)

Single particle absorption spectrum

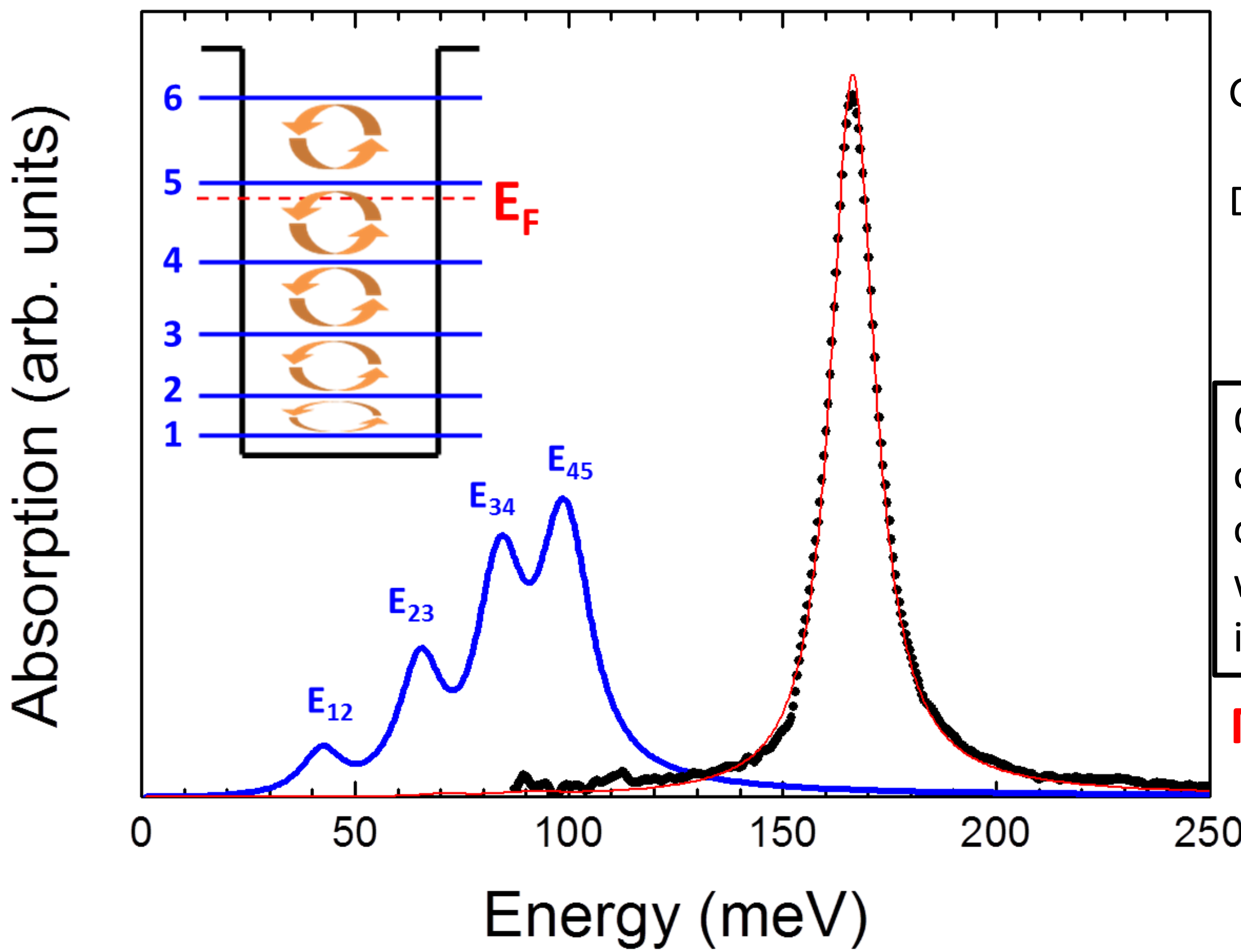


GaInAs/AlInAs quantum well

Doping 2.2 x 10^{13} cm^{-2}

A. Delteil et al., PRL (2012)

Observation of the cooperative regime



GaInAs/AlInAs quantum well

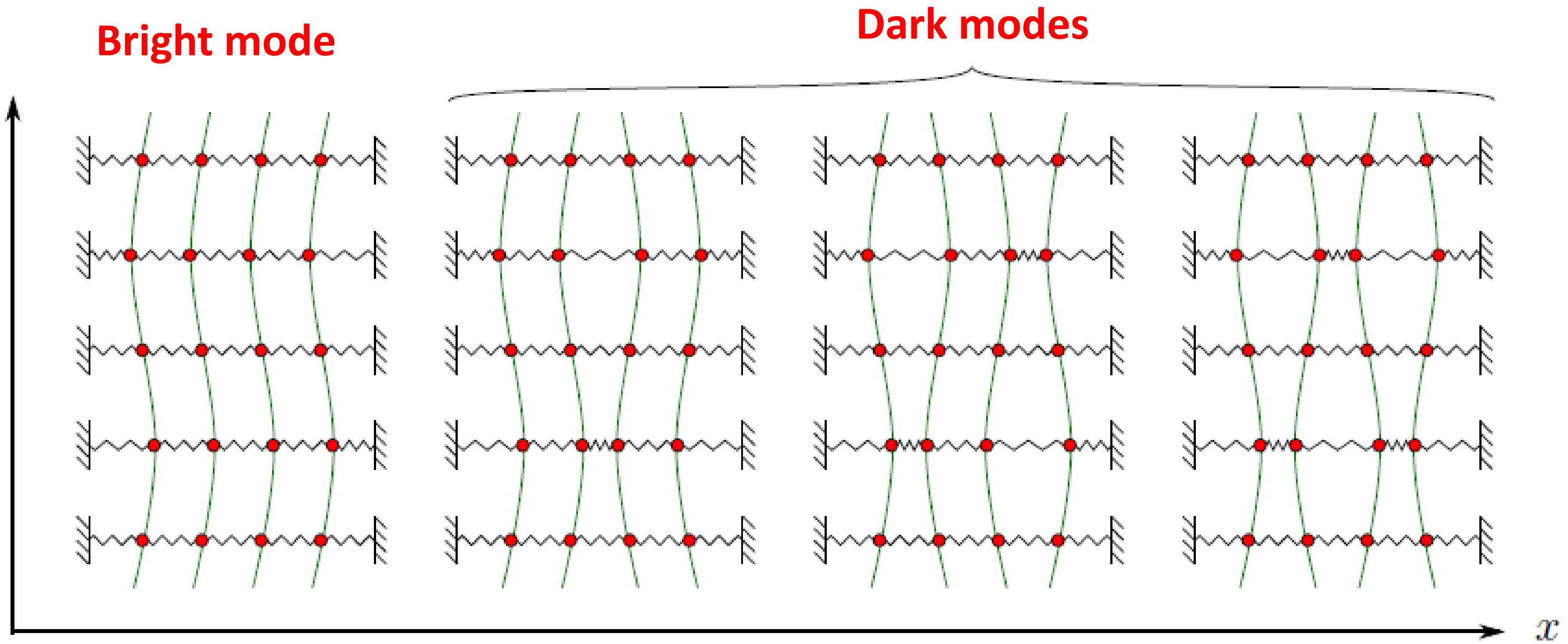
Doping 2.2 x 10^{13} cm^{-2}

Observation of a single optical resonance at a completely different energy with respect to those of the intersubband transitions

Multisubband plasmon

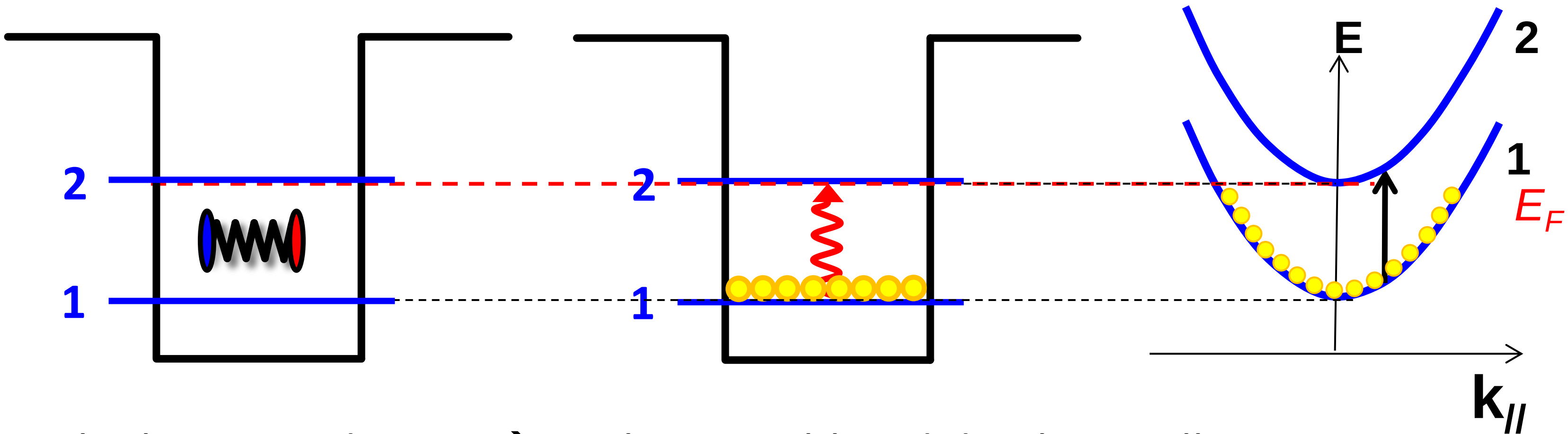
A. Delteil et al., PRL (2012)

Bright mode: intersubband dipoles locked in phase



The bright mode is the one in which the center of mass moves

Quantum model: basic ideas



High electronic density → each intersubband dipolar oscillator interacts not only with the external field, but also with all the other oscillators (**depolarization field**).

This can be taken into account by using the dipole representation to describe the light-matter interaction:

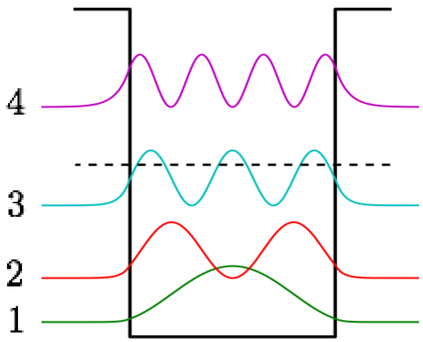
$$\hat{H}_{\text{int}} = \int \frac{1}{\varepsilon_0 \varepsilon(z)} \left[-\hat{\mathbf{D}}(\mathbf{r}) \cdot \hat{\mathbf{P}}(\mathbf{r}) + \frac{1}{2} \hat{\mathbf{P}}^2(\mathbf{r}) \right] d^3\mathbf{r}.$$

Dipole – dipole interaction between intersubband excitations

Y. Todorov and C. Sirtori, PRB **85**, 045304 (2012)

Basic steps of the calculation

1



Polarization operator

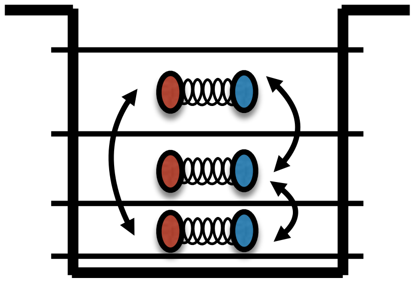
$$P_z = \sum_\alpha \frac{j_\alpha(z)}{\omega_\alpha}[b_\alpha^\dagger + b_\alpha]$$

intersubband excitation operator

$$j_{ij} \propto \psi_i \frac{\partial \psi_j}{\partial z} - \psi_j \frac{\partial \psi_i}{\partial z}$$

2

$$\hat{H}_{\text{int}} = \int \frac{1}{\varepsilon_0 \varepsilon(z)} \left[-\hat{\mathbf{D}}(\mathbf{r}) \cdot \hat{\mathbf{P}}(\mathbf{r}) + \frac{1}{2}\hat{\mathbf{P}}^2(\mathbf{r}) \right] d^3\mathbf{r}.$$



Dipole – dipole interaction

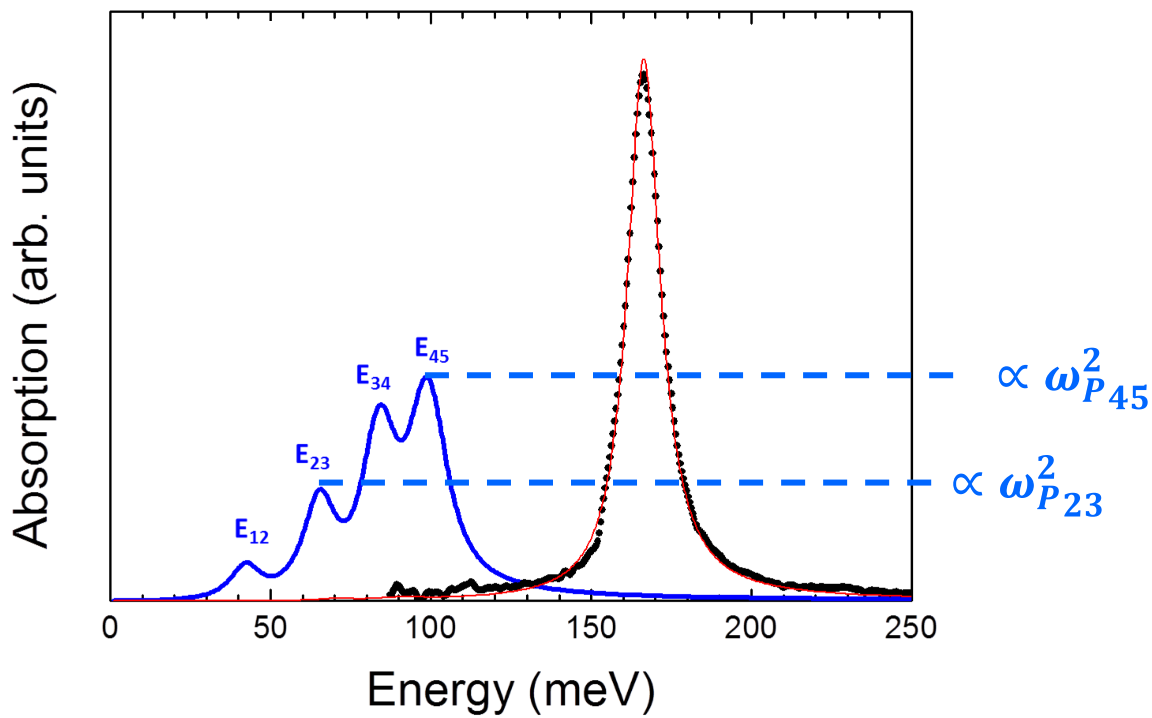
Collective modes of the system (bright + dark)

3

Y. Todorov and C. Sirtori, PRB 2012

G. Pegolotti, A. Vasanelli, Y. Todorov, C. Sirtori, PRB 2014

Properties of the multisubband plasmon



The multisubband plasmon (MSP) concentrates the whole interaction with light

We can associate to the MSP an effective plasma frequency:

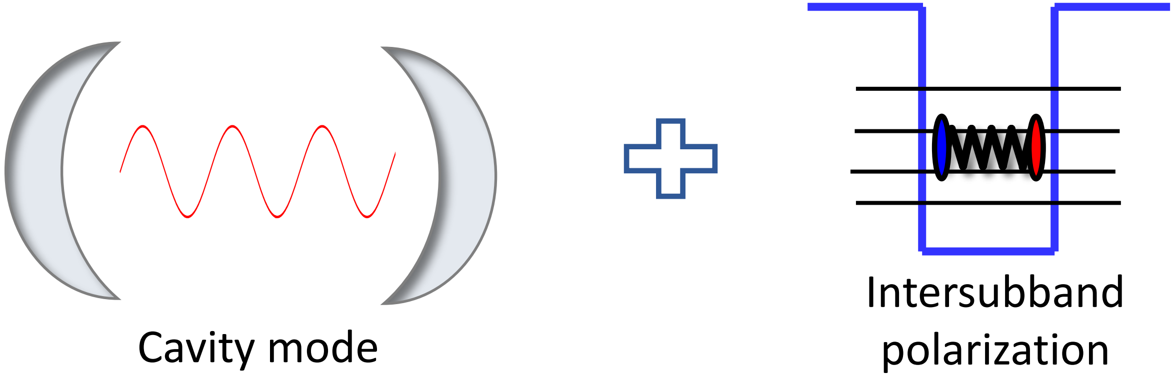
$$\Omega_P^2 = \sum_i \omega^2_{P\,i,i+1}$$

We can also define an intersubband contribution such that:

$$E^2_{MSP} = E^2_{ISB} + (\hbar\Omega_P)^2$$

$$E^2_{ISB} = \frac{(\hbar\Omega_P)^2}{\sum_i \frac{\omega^2_{P\,i}}{(\omega_{i+1} - \omega_i)^2}}$$

Harmonic mean of the intersubband transitions



Ultra-strong light-matter coupling regime

$$H = E_{MSP} P^{+} P + E_c \left(a^{+} a + \frac{1}{2} \right) + i\, E_R (a^{+} - a)(P^{+} + P)$$

$$E_R \propto \hbar \Omega_P$$

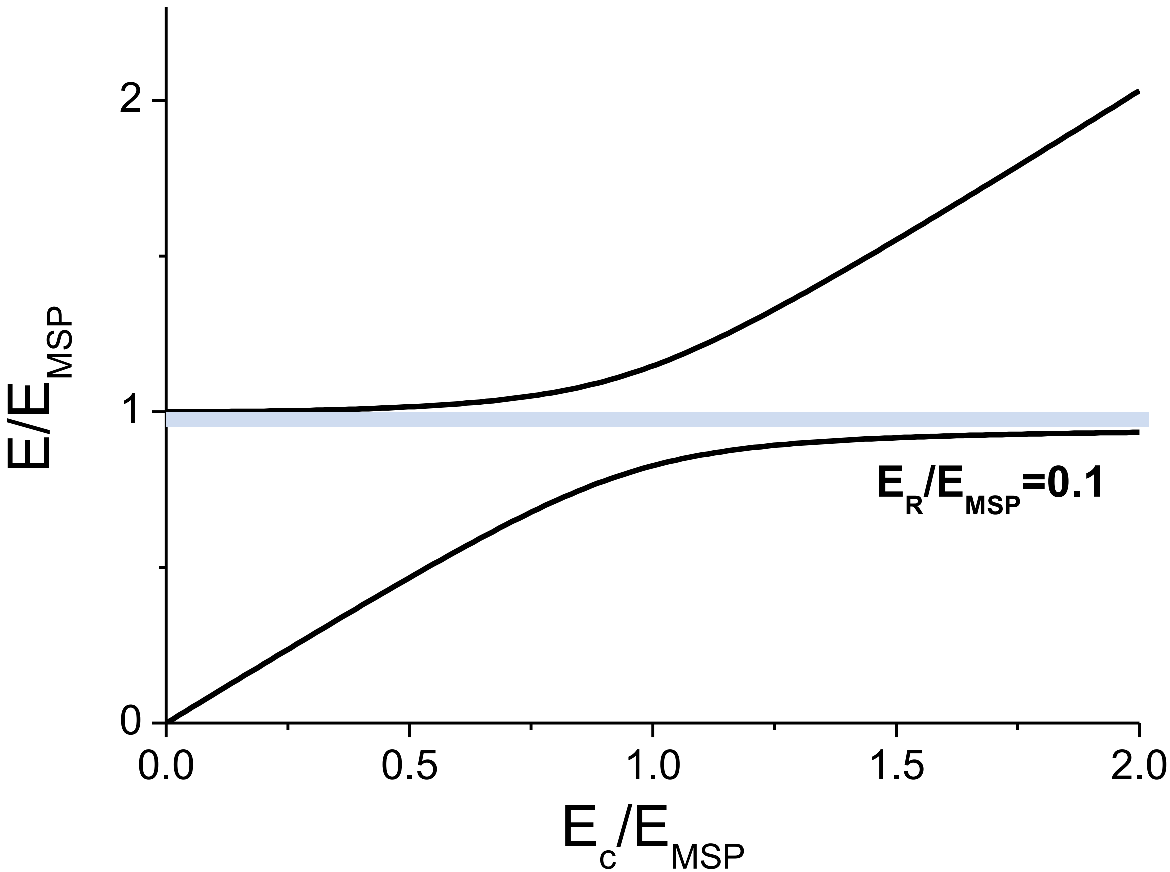
MSP plasmon

light

Light-matter coupling

Coupling of a MSP and a cavity mode

$$(E^2 - E_{MSP}^2)(E^2 - E_c^2) = E_R^2 E_c^2$$



Opening of a polaritonic gap in the polariton dispersion

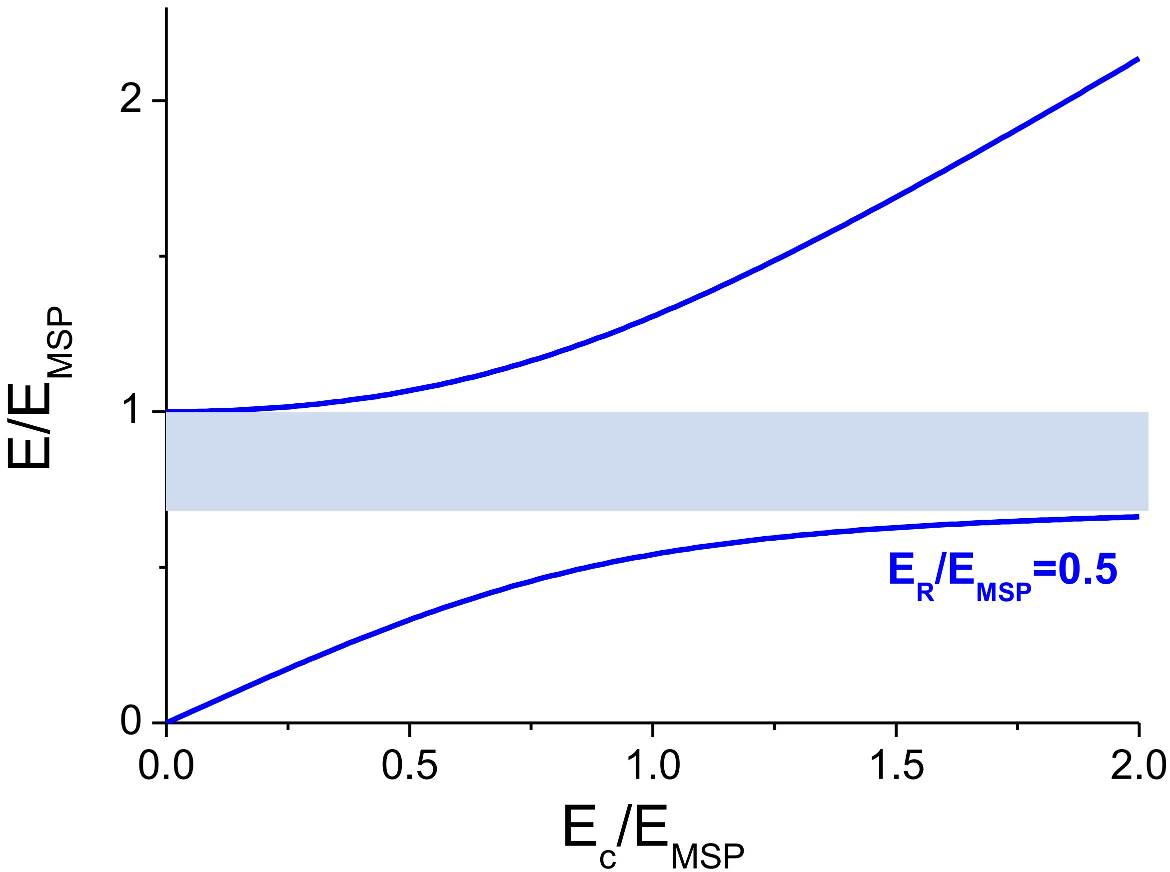
$$E_{MSP}\sqrt{1-\left(\frac{E_R}{E_{MSP}}\right)^2}$$

Y. Todorov et al. PRL 2010

A. Delteil et al. PRL 2012

Coupling of a MSP and a cavity mode

$$(E^2 - E_{MSP}^2)(E^2 - E_c^2) = E_R^2 E_c^2$$



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Y. Todorov et al. PRL 2010

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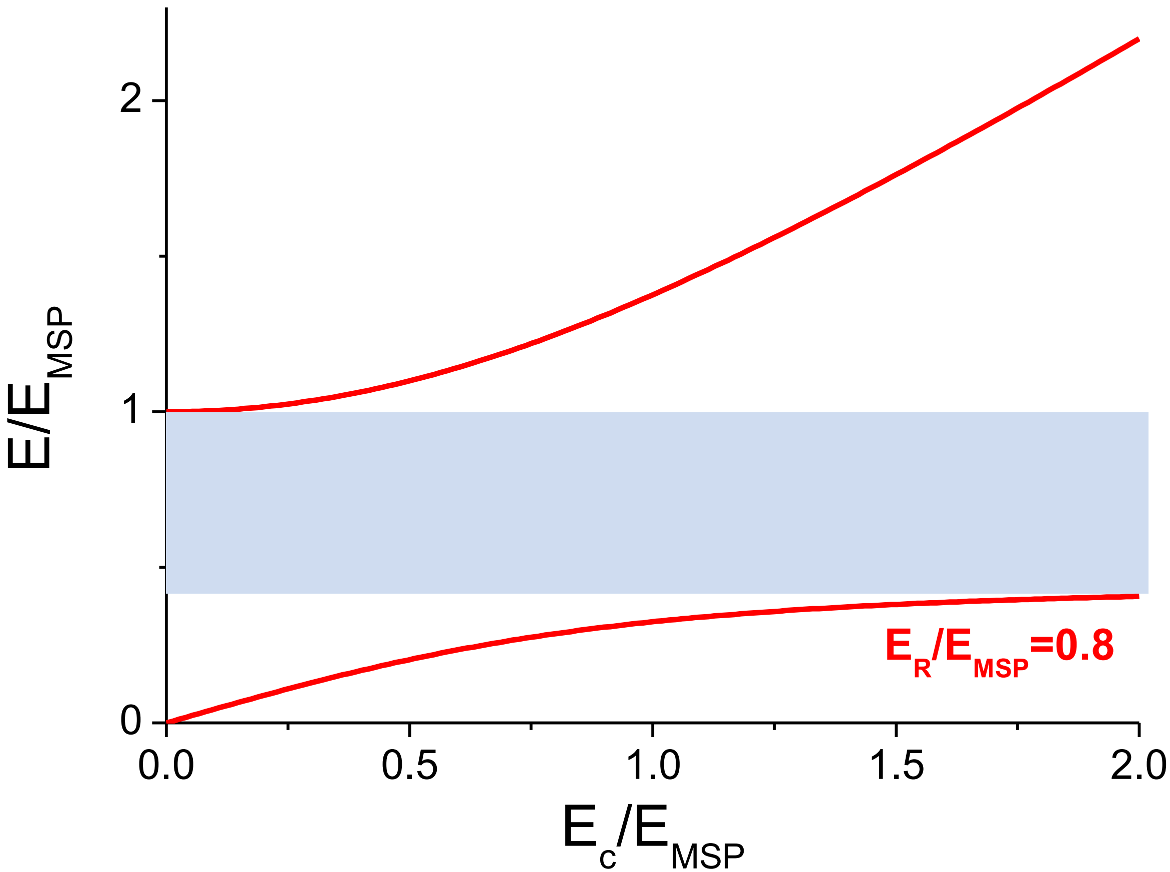

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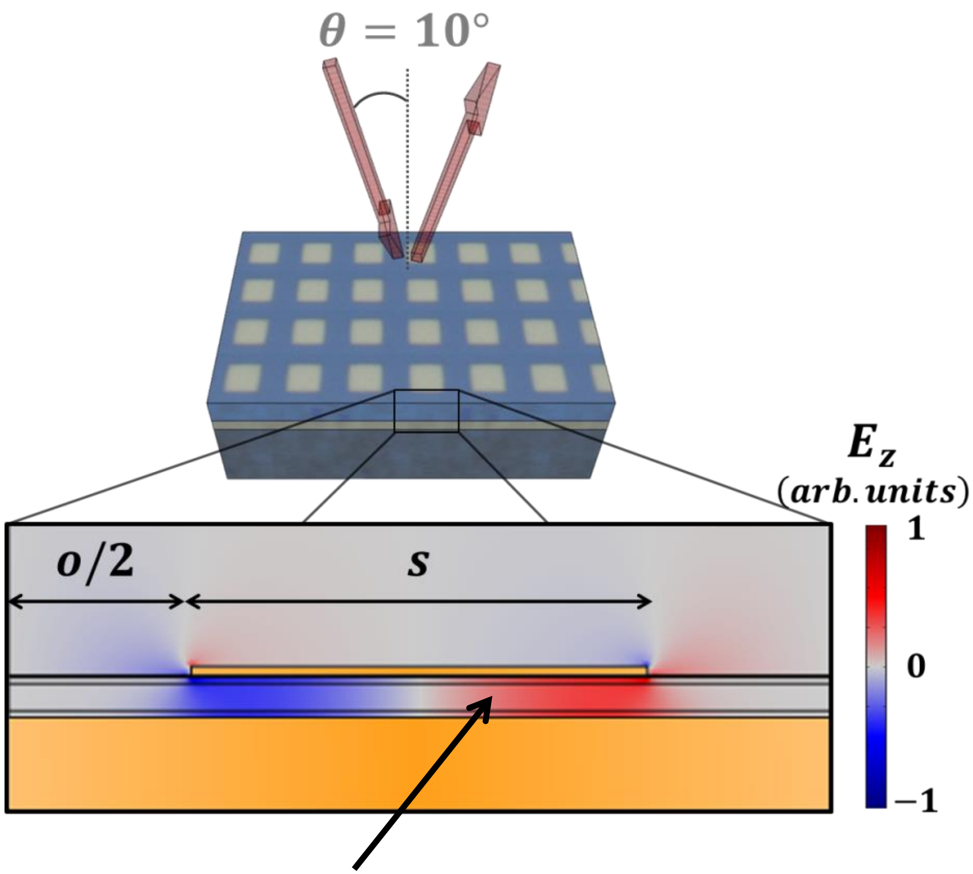
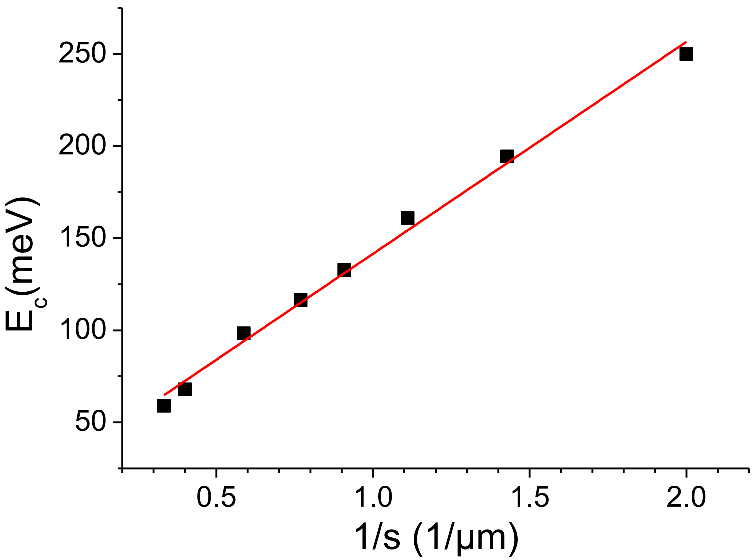
Y. Todorov et al. PRL 2010

A. Delteil et al. PRL 2012

Highly sub-λ plasmonic cavities



Highly doped semiconductor layer displaying a Berreman mode
Cavity thickness: 240nm

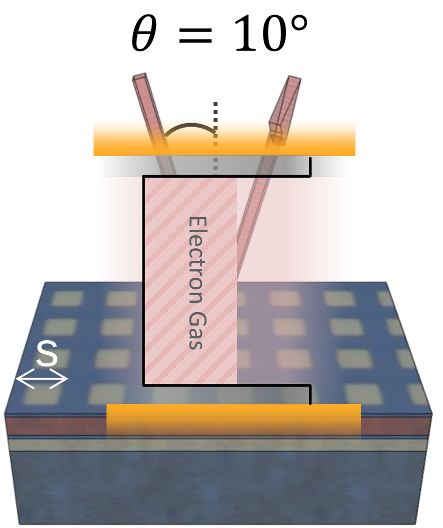


First order cavity mode

$$s = \lambda/(2n_{eff})$$

Y. Todorov *et al*, PRL **105**, 196402 (2010)
P. Jouy et al. APL **98**, 231114 (2011)

Reflectivity Spectra



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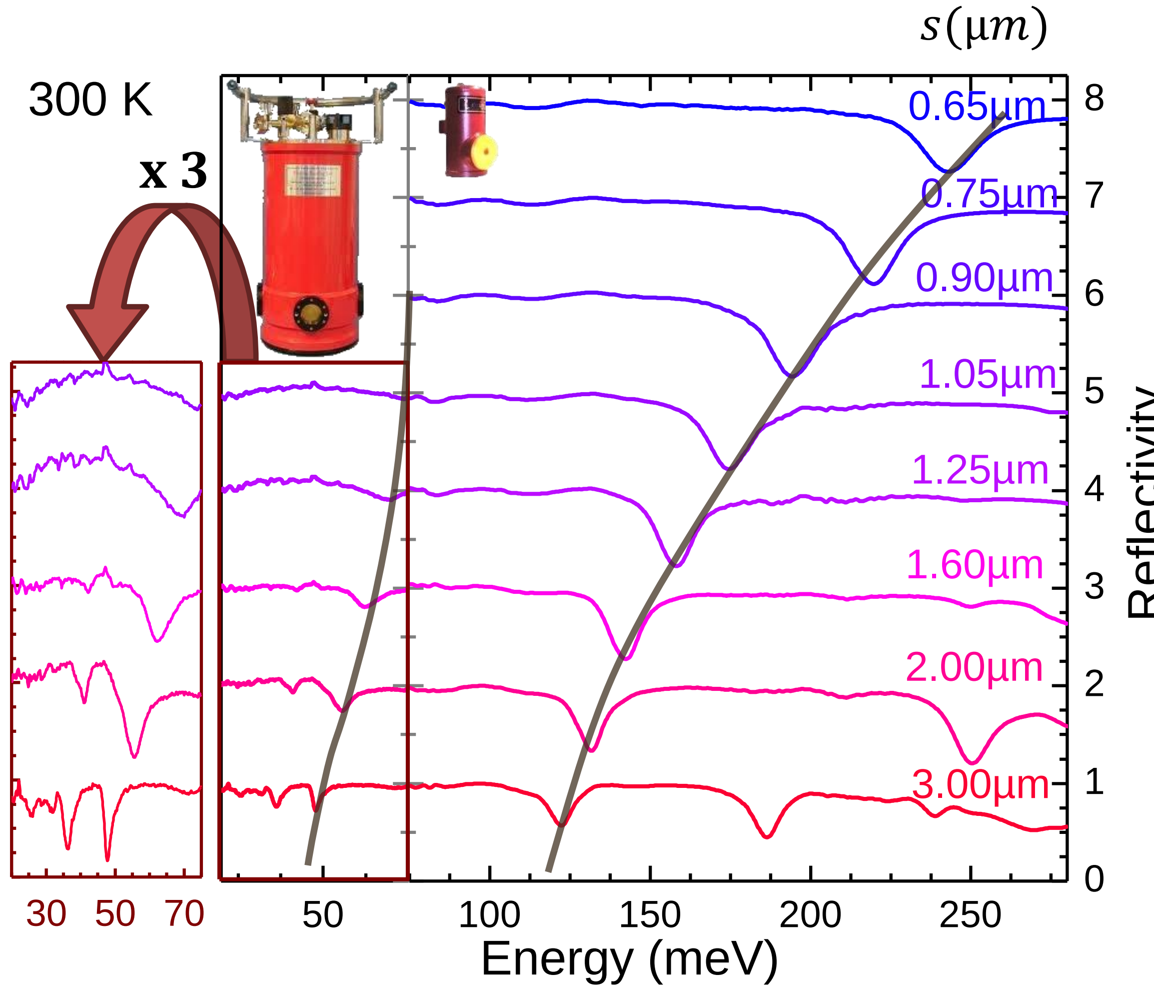
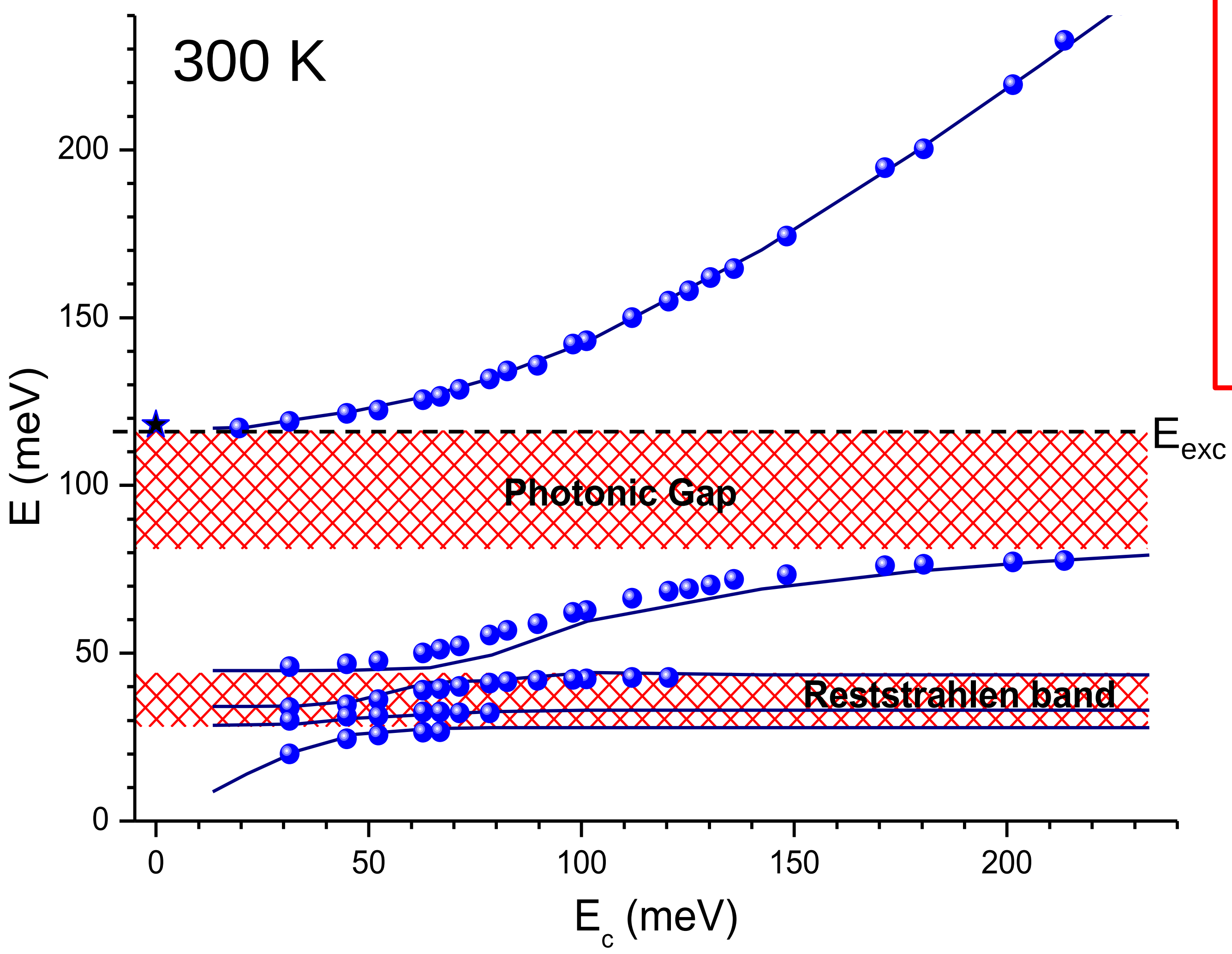
Y. Todorov *et al*, PRL (2010)
P. Jouy et al. APL (2011)



B. Askenazi *et al*., New Journal of Physics **16**, 043029 (2014)

Ultra-strong coupling dispersion



$$E_R = 86meV$$

$$\frac{E_R}{E_{exc}} = 73\%$$

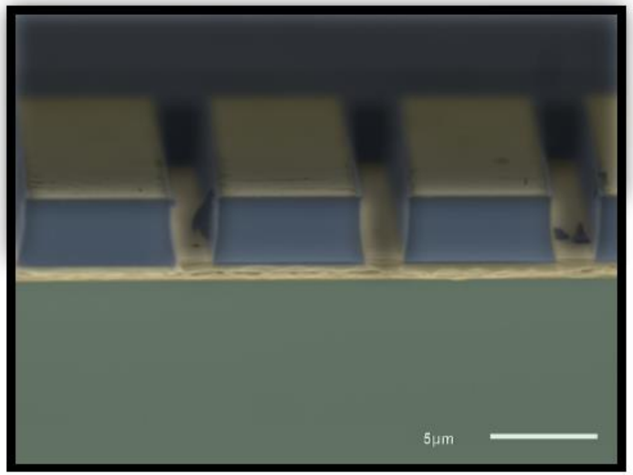
$$\frac{E_R}{E_{exc}} \approx 1$$

Ultra-strong coupling regime

C. Ciuti et al. PRB 2005

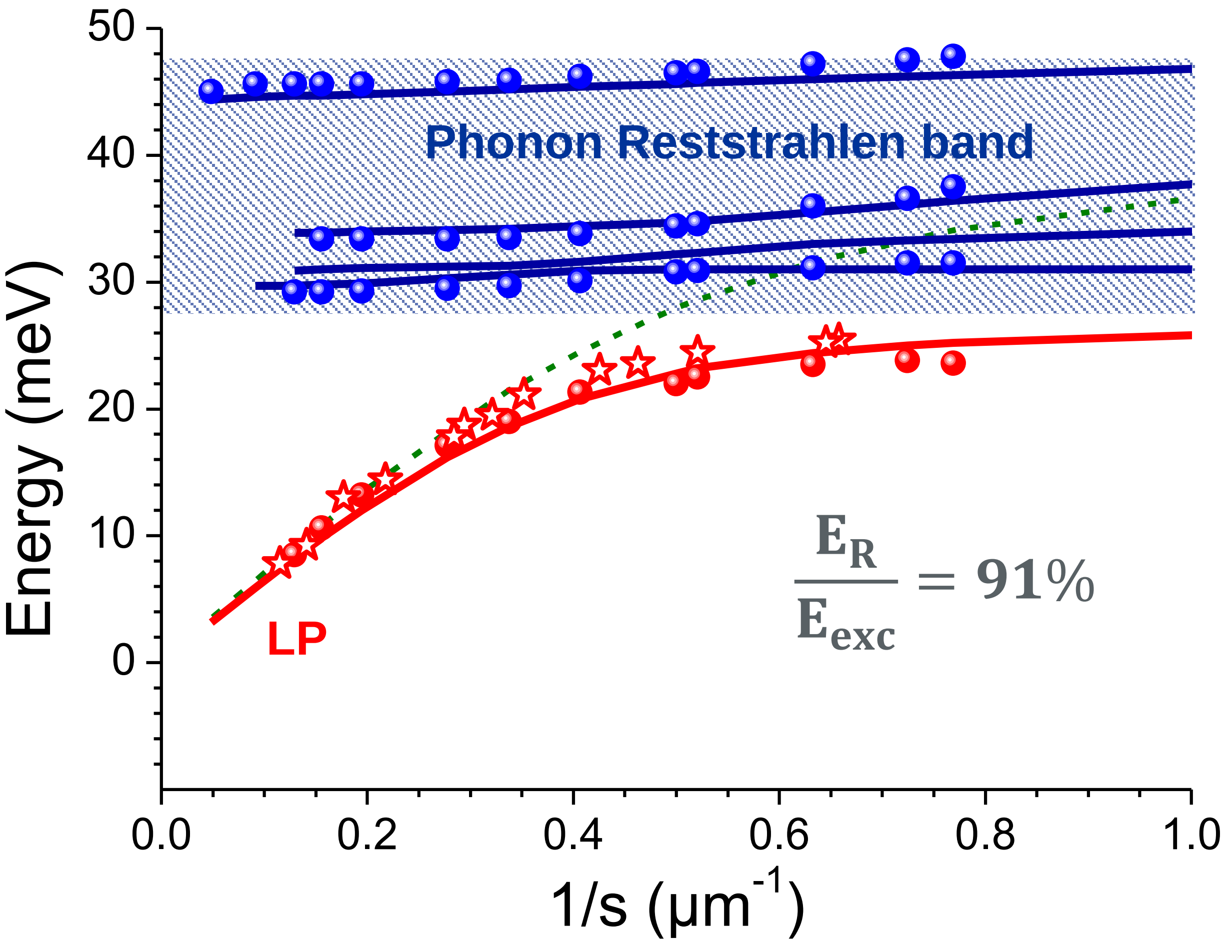
B. Askenazi *et al.*, New Journal of Physics **16**, 043029 (2014)

Increasing the overlap factor



Etched cavities to improve the mode confinement

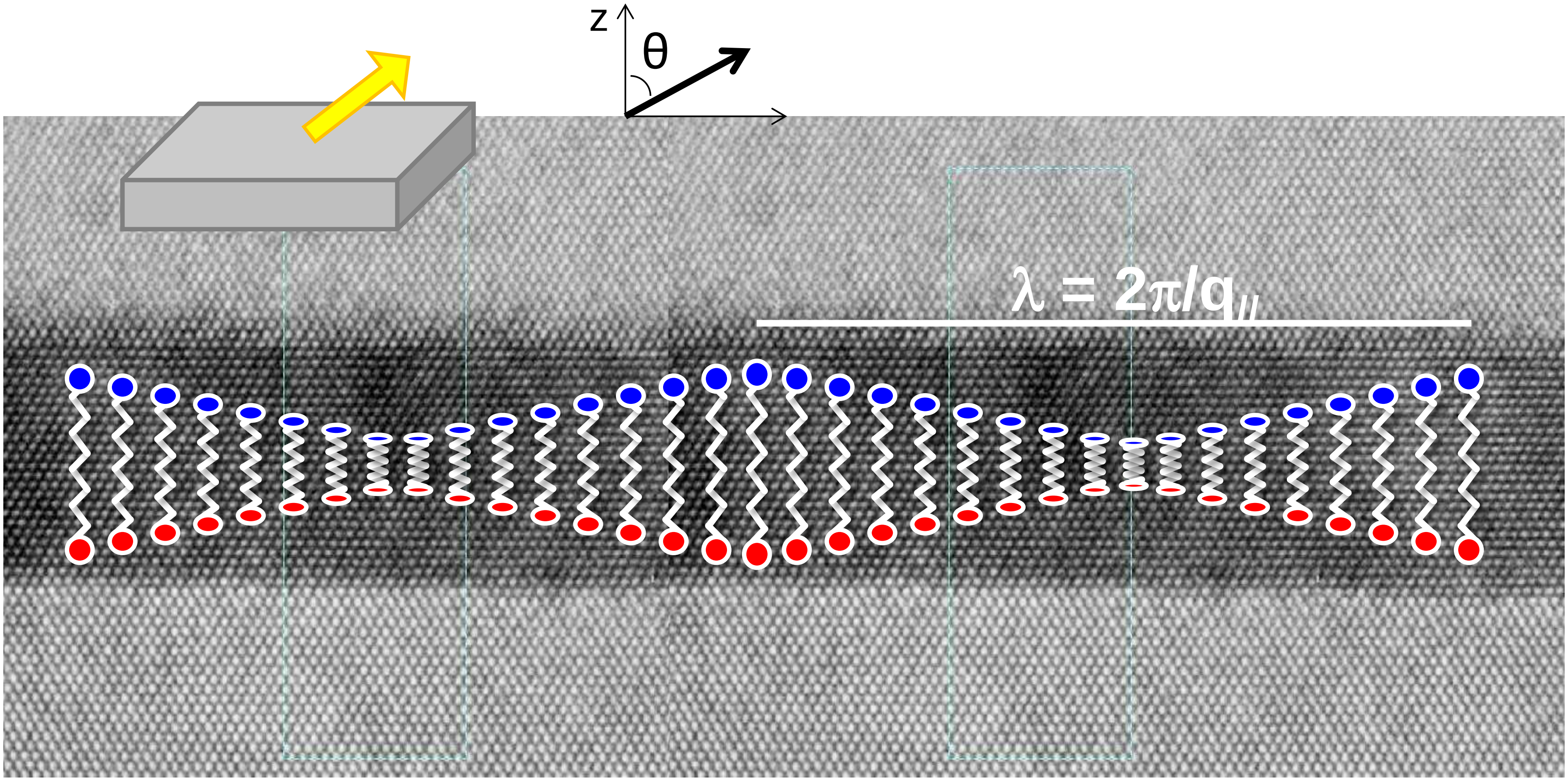
$$E_R = 90.0\ \text{meV}$$
$$E_{exc} = 99\ \text{meV}$$



B. Askenazi et al. , in preparation

Coupling of the plasmon with free space radiation

The multisubband plasmon: a transverse density wave



The dipole of the collective excitation is proportional to *N*, the number of particles involved

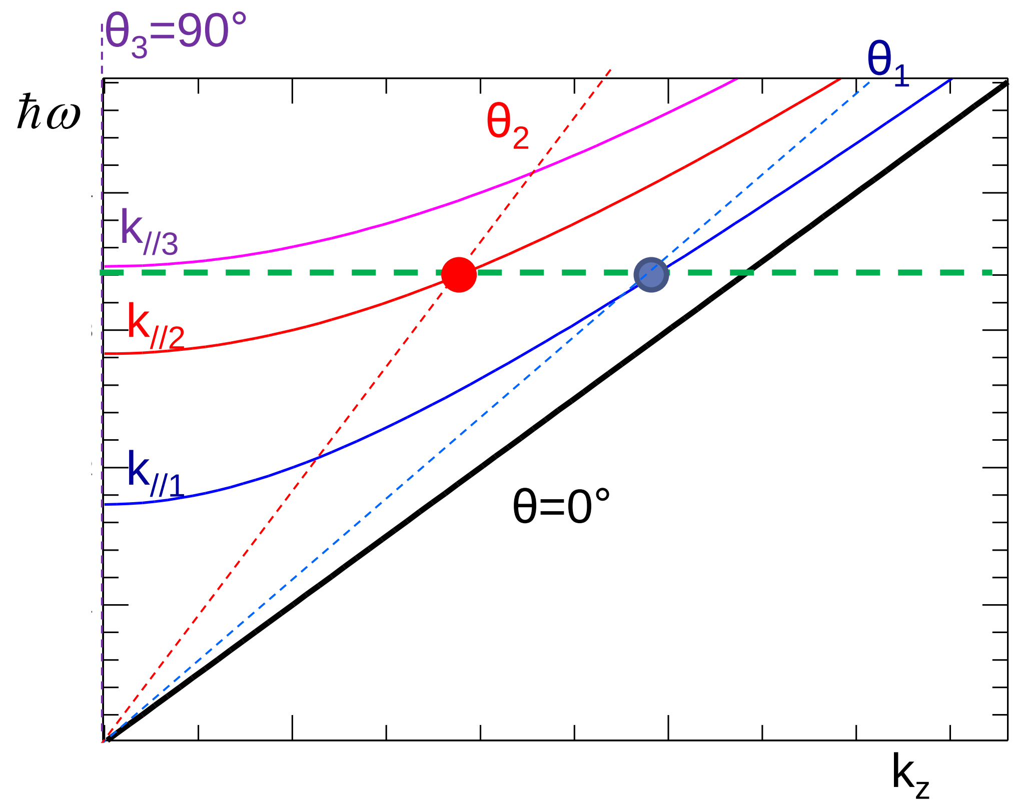
Macroscopic polarization!

Spontaneous emission rate of a plasmon

Intrinsic radiative decay due to the lack of wavevector conservation along the confinement direction z → The 2D plasmon interacts with a quasi-1D density of photon states:

$$\rho(k_{//},\omega) = \sum_{k_z} \delta\left(\hbar\omega - \frac{\hbar c}{n}\sqrt{k_{//}^2 + k_z^2}\right)$$

$$\propto \frac{1}{\cos\theta}$$



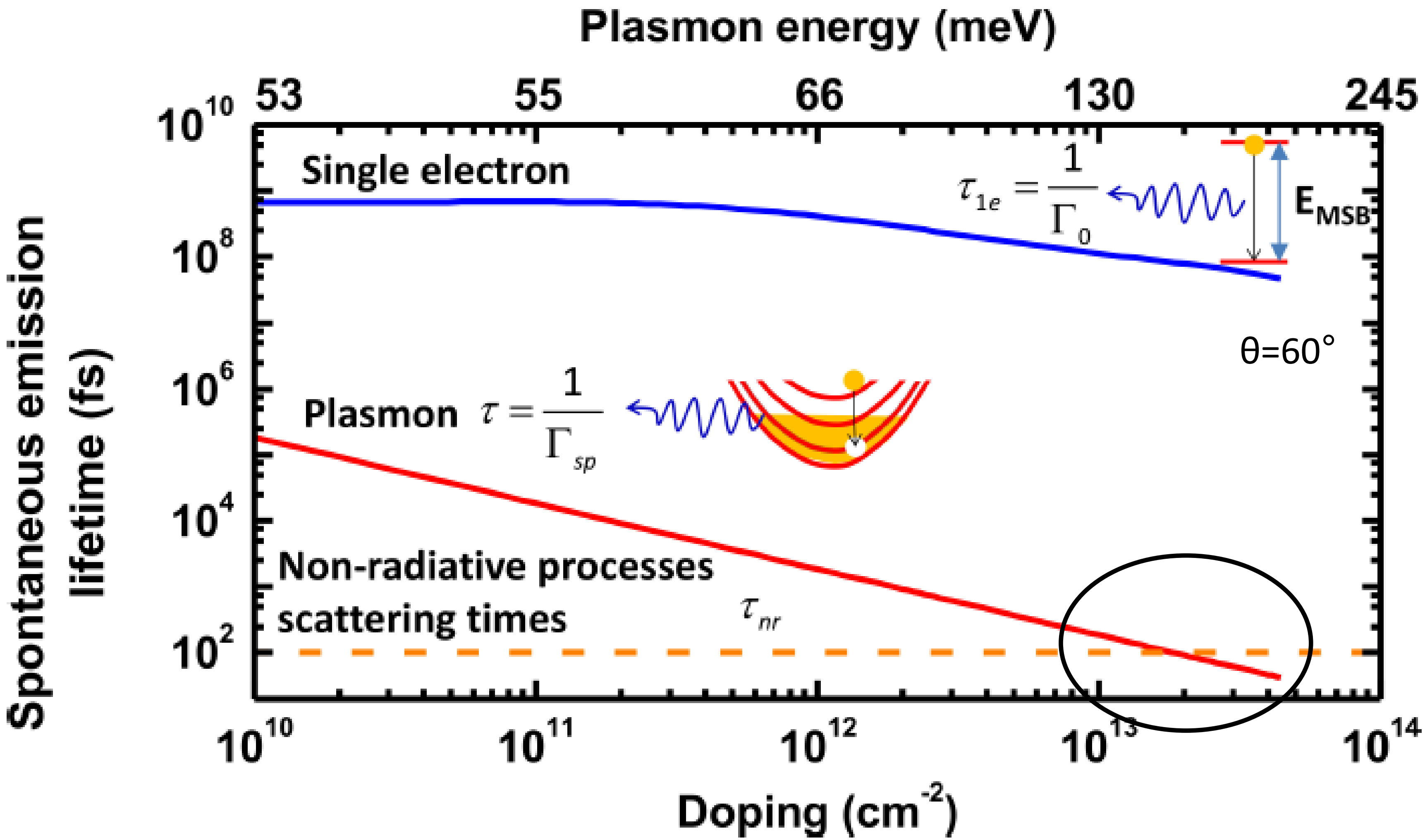
Spontaneous emission rate by Fermi golden rule for a given plasmon state
(selected by θ angle):

$$\Gamma_\theta = N_s \frac{1}{2}\frac{e^2}{m^* c\, n\, \varepsilon_0}\frac{\sin^2\theta}{\cos\theta}$$

Superradiant decay!

C. Ciuti and I. Carusotto, PRA 2006
F. Alpeggiani and L. C. Andreani, PRB 2014
T. Laurent et al. PRL (in press)

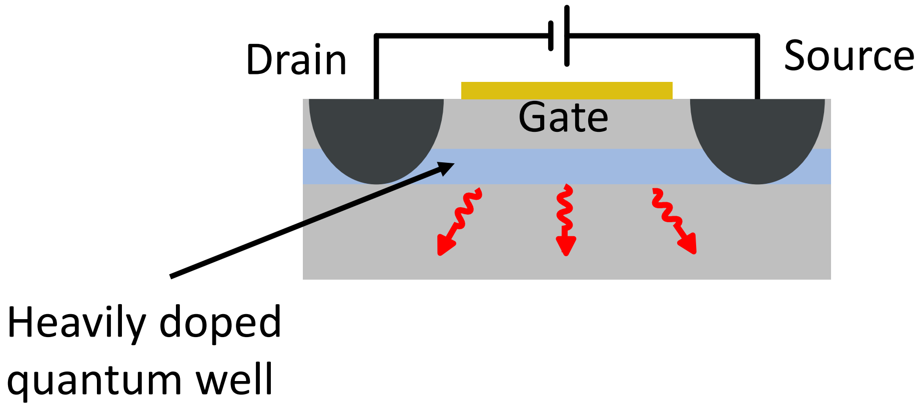
Spontaneous emission rate of a plasmon

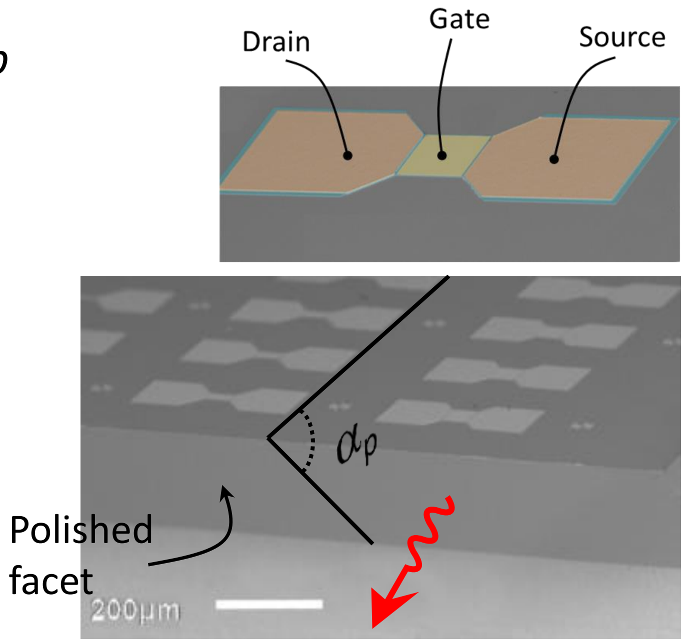


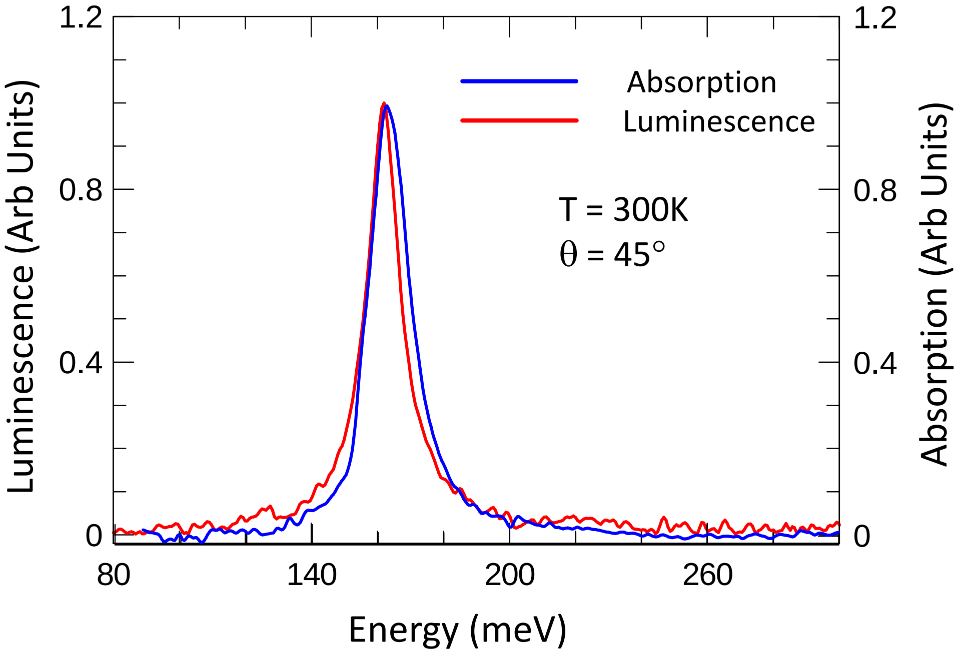
Spontaneous emission can be the dominant relaxation mechanism for multisubband plasmons!

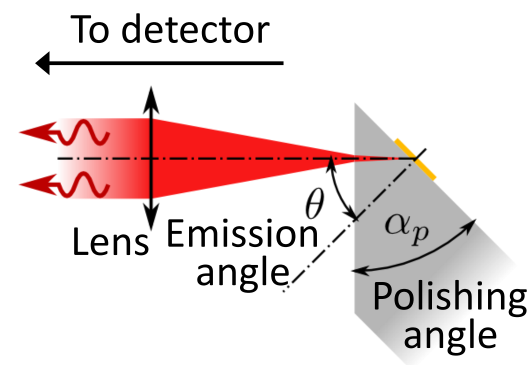
Thermal excitation

Plasmons are heated by the current*: the plasmonic lamp*





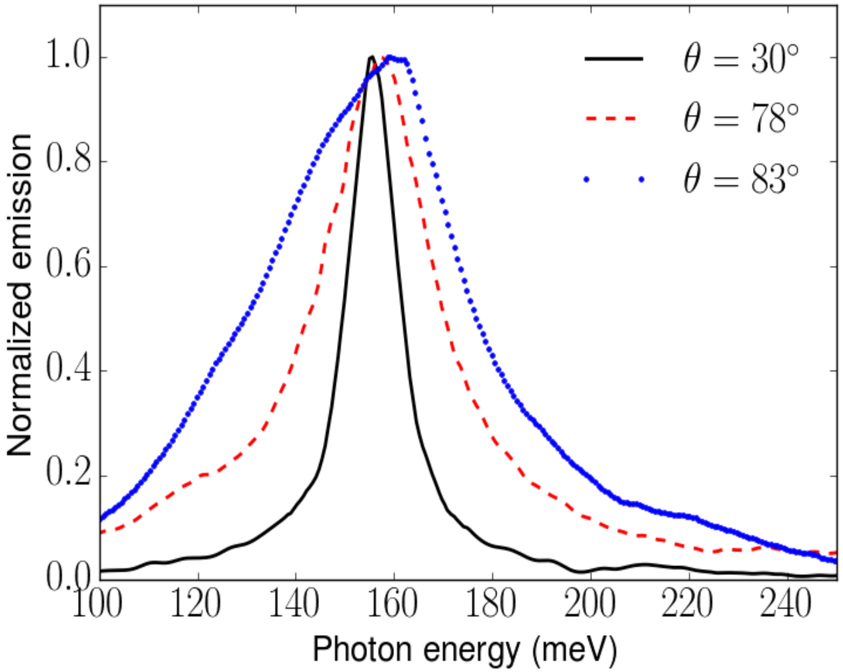


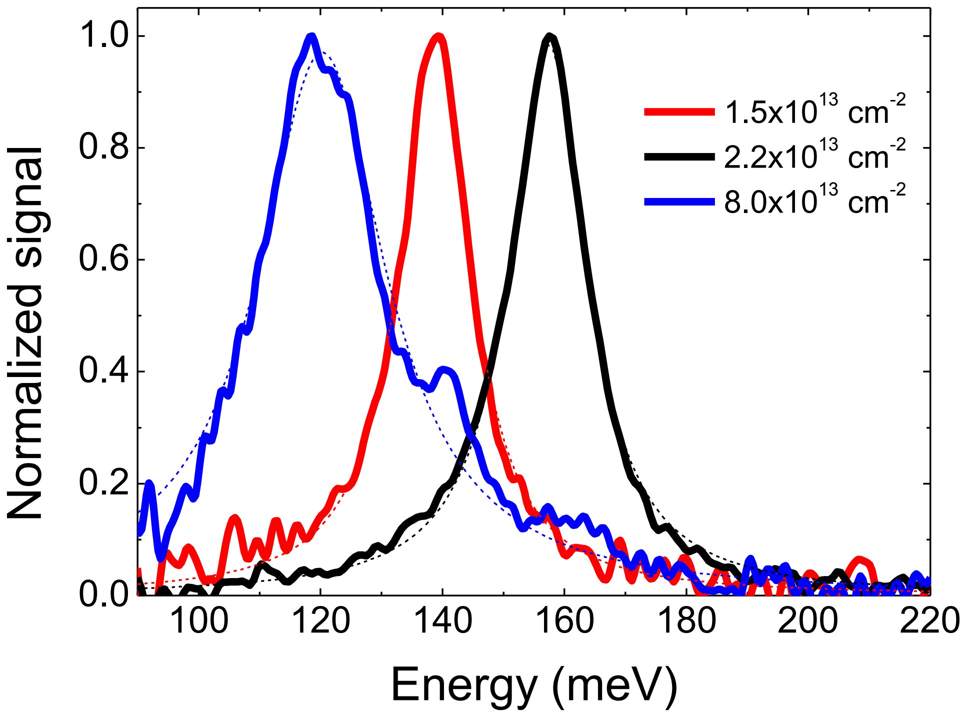


T. Laurent et al, PRL (in press)

Plasmon linewidth

The linewidth of the resonance reflects the plasmon lifetime





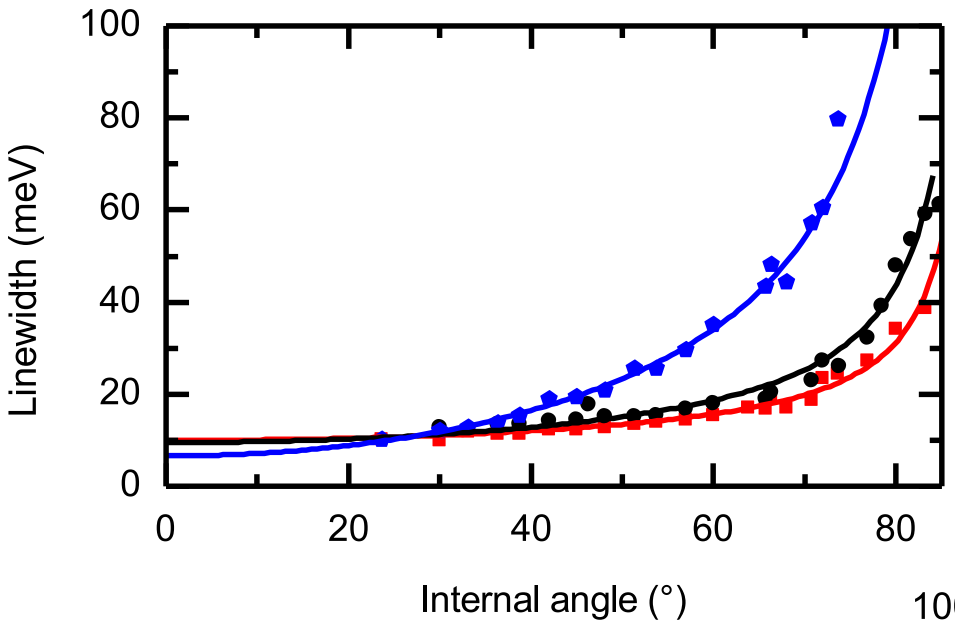
Doping N_s = 2.2 x 10^{13} cm^{-2}

θ=55°

GaInAs/AlInAs quantum wells

T. Laurent et al, PRL (in press)

Radiative broadening

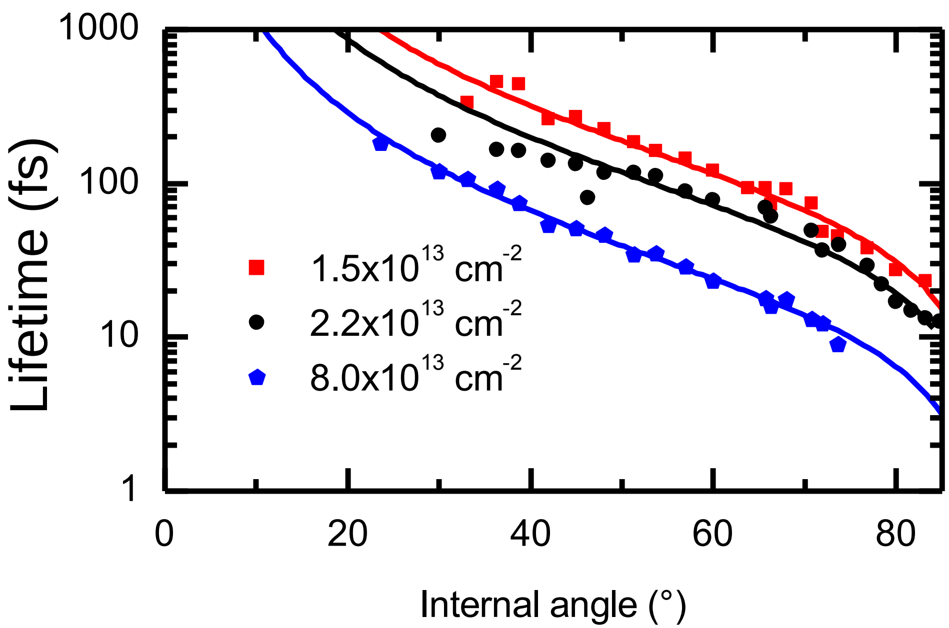


$$\Gamma = \Gamma_{sp}(\theta) + \gamma$$

$$\Gamma_{sp}(\theta) = N_s \frac{1}{2} \frac{e^2}{m^* c\, n\, \varepsilon_0} \frac{sin^2\theta}{\cos\theta}$$

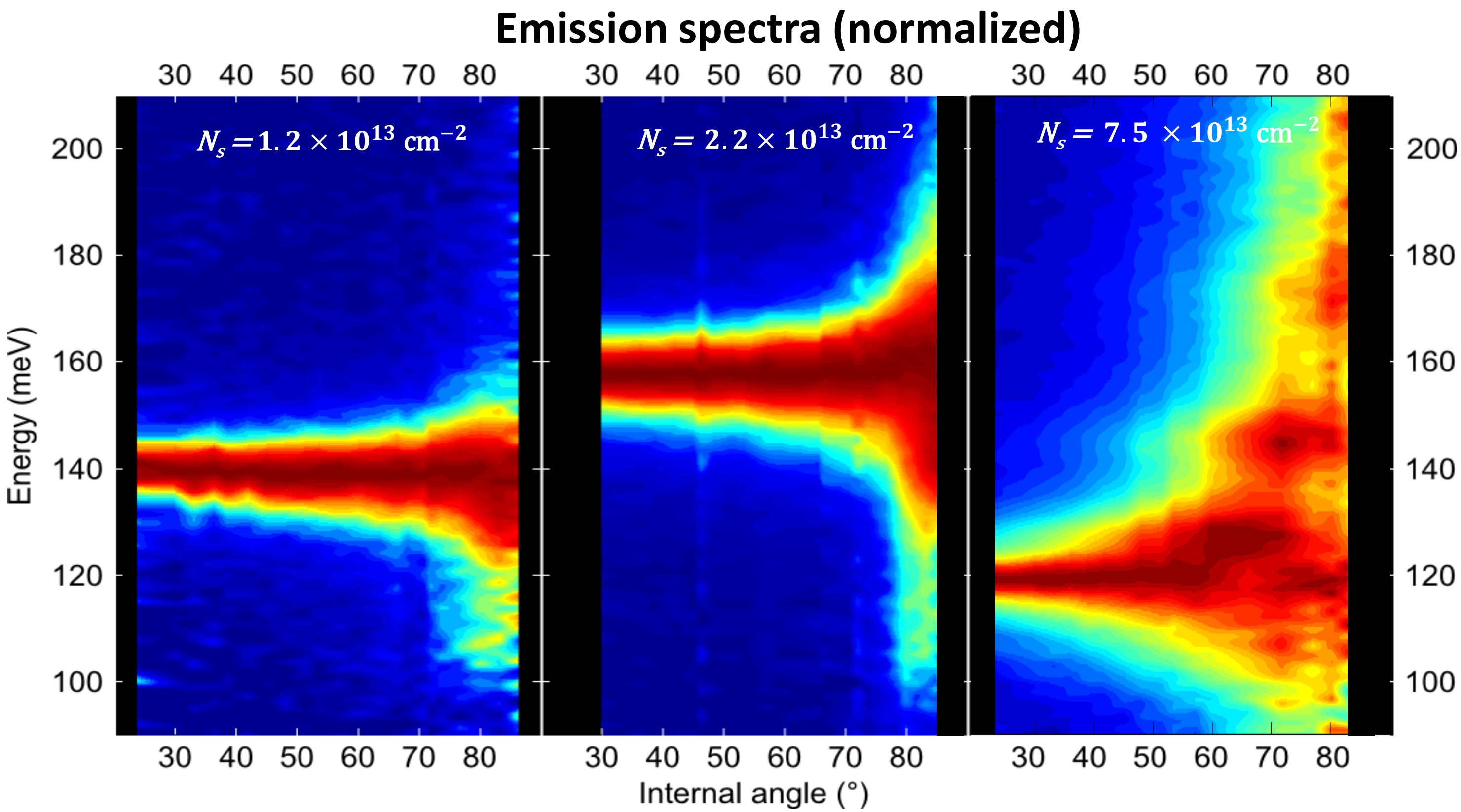
Spontaneous emission of 10's of fs!

$\Gamma_0 \sim 50\text{ns}$ → $\frac{\Gamma_{sp}}{\Gamma_0} \sim 10^6$



T. Laurent et al, PRL (in press)

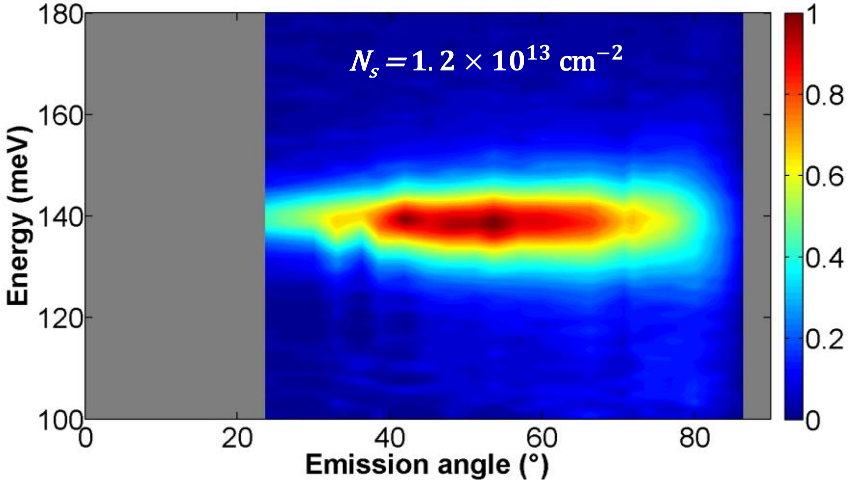
Radiative broadening color maps

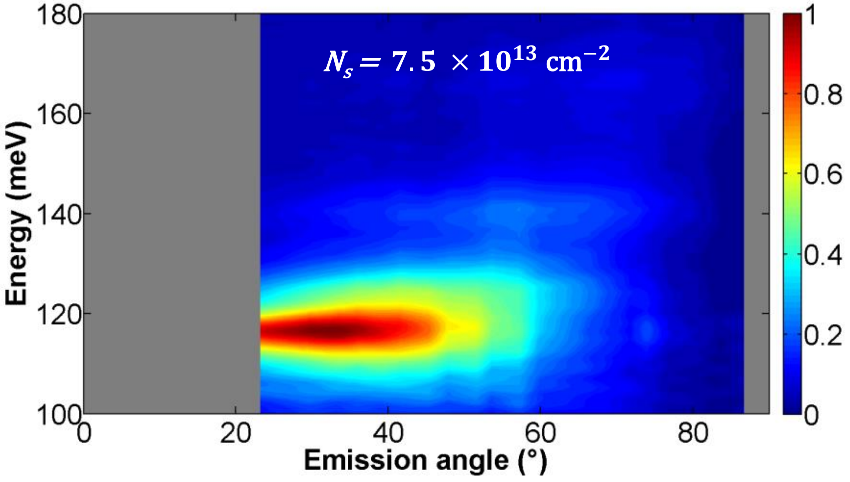


- Emission spectra are radiatively broadened
- Density dependence
- Extra features at high energy in highly doped samples

Directional emission

Emission spectra (non-normalized)





- **Existence of a preferential emission direction**
- **The emission direction strongly depends on the electron density**

Emitted power per unit solid angle:

$$dP = E_{MSP}\Gamma_{sp}(\theta)\, n(E_{MSP},T)dN_{pl} \propto \sin^2\theta$$ (Larmor formula)

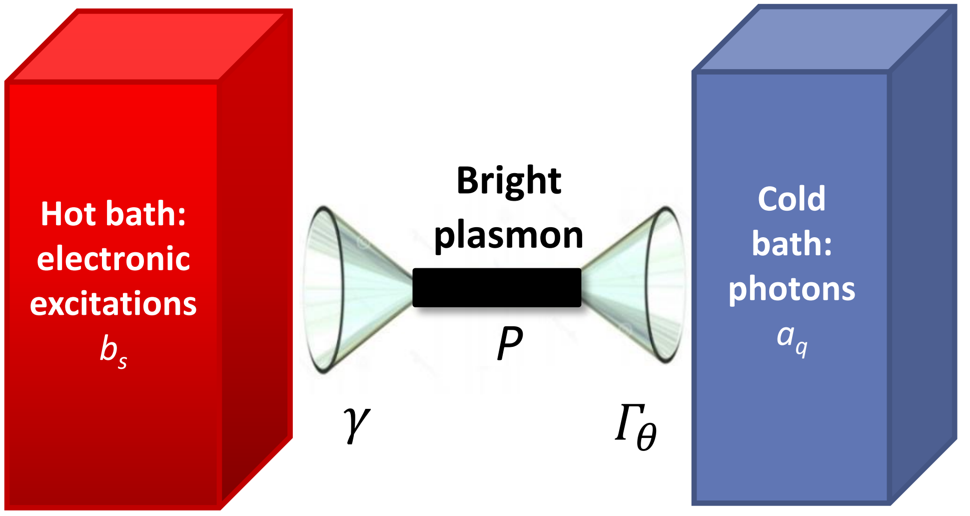
Plasmon occupancy

Number of plasmon modes in the solid angle of detection

S. Huppert et al, *arXiv:1510.03209*

Quantum Langevin model

Bright plasmons are generated by thermal electronic excitation and decay by emitting a photon



Coupled system hamiltonian :

$$H = \sum_n \hbar\omega_n P_n^\dagger P_n + \sum_s \hbar\omega_s b_s^\dagger b_s + \sum_q \hbar\omega_q \left(a_q^\dagger a_q + \frac{1}{2}\right)$$
$$+ i\hbar \sum_{n,q} W_{n,q}\left[a_q^\dagger P_n - a_q P_n^\dagger\right] + i\hbar \sum_{n,s} K_{n,s} b_s^\dagger P_n - K_{n,s}^* b_s P_n^\dagger$$

Light-matter coupling → Γ_θ

Coupling to the electronic bath → γ

C. Ciuti and I. Carusotto, PRA (2006)

S. Huppert et al, *arXiv:1510.03209*

Kirchhoff's law of thermal emission

Analytical solutions in the one-plasmon approximation
(including anti-resonant terms)

$$I_{\omega}^{e} = \epsilon_{\omega} I_{\omega}^{BB}(T)$$

Intensity of the plasmon emission

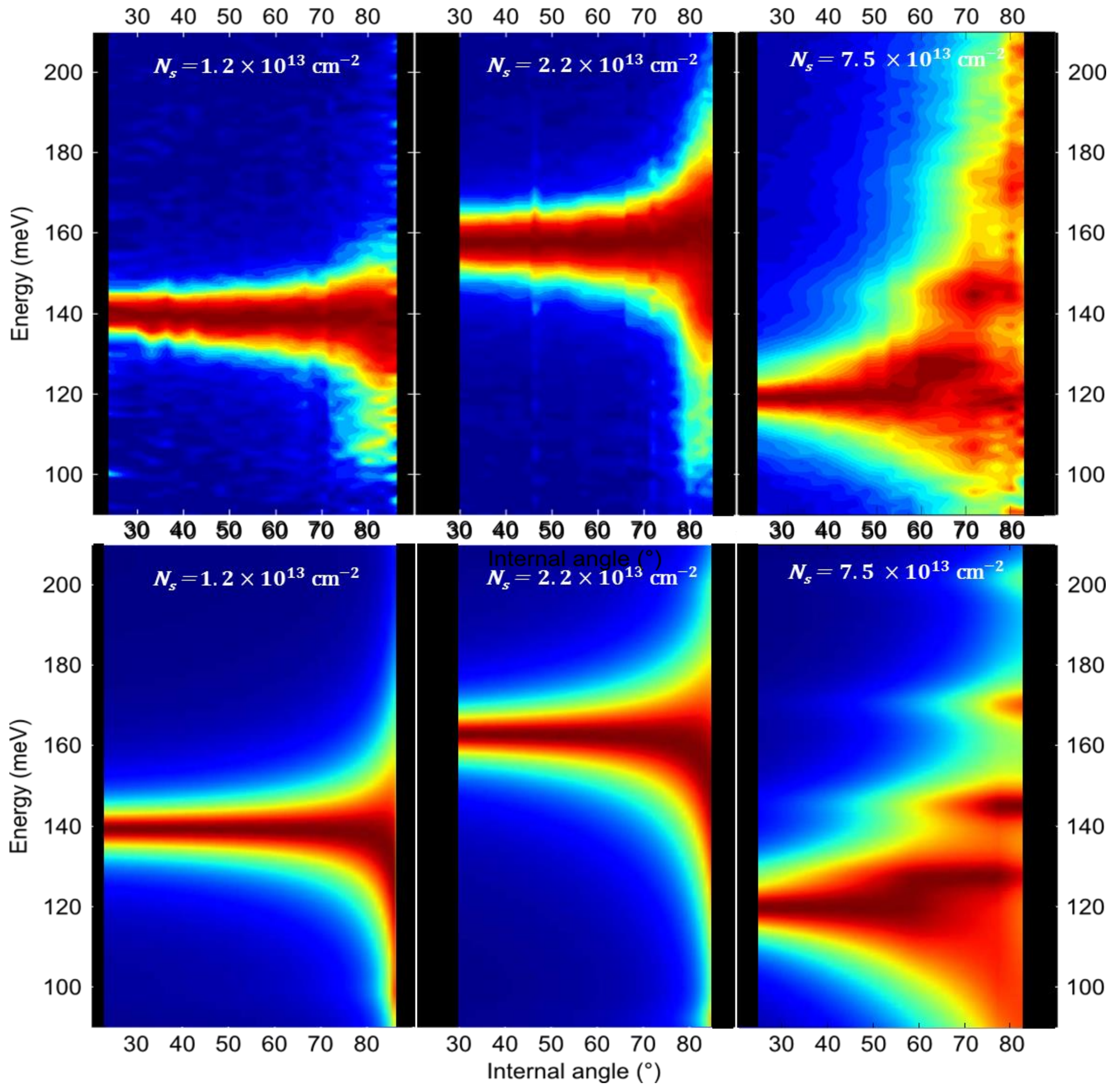
Blackbody intensity

Emissivity = Absorptivity

$$\alpha_{\vartheta}(\omega) = \frac{4\dfrac{4\omega_{MSP}^{2}}{\left(\omega_{MSP}+\omega\right)^{2}}\gamma\,\Gamma_{\vartheta}(\omega)}{\left(\omega_{MSP}-\omega\right)^{2}+\dfrac{4\omega_{MSP}^{2}}{\left(\omega_{MSP}+\omega\right)^{2}}\left(\gamma+\Gamma_{\vartheta}(\omega)\right)^{2}}$$

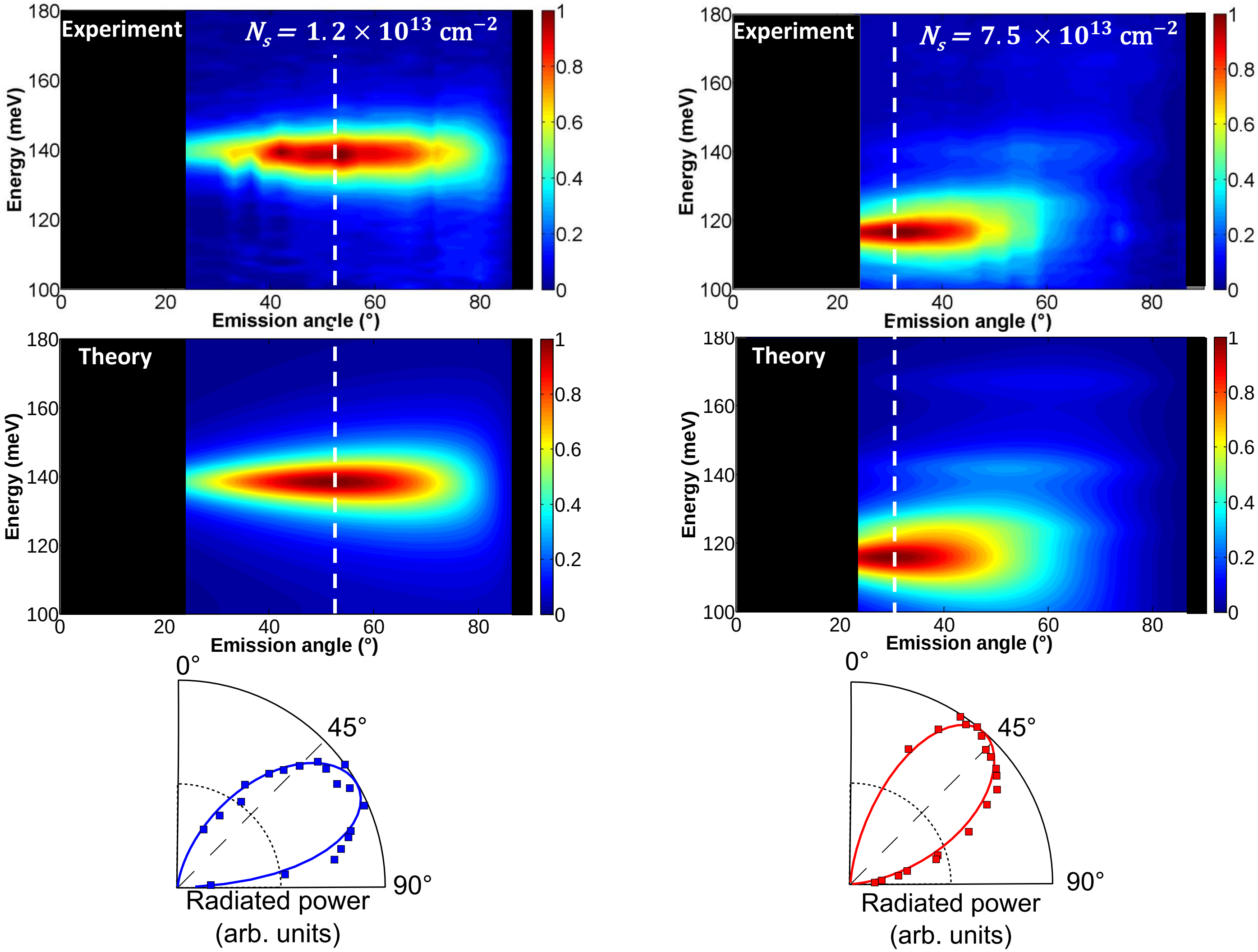
S. Huppert et al, *arXiv:1510.03209*

Experiment *vs* theory



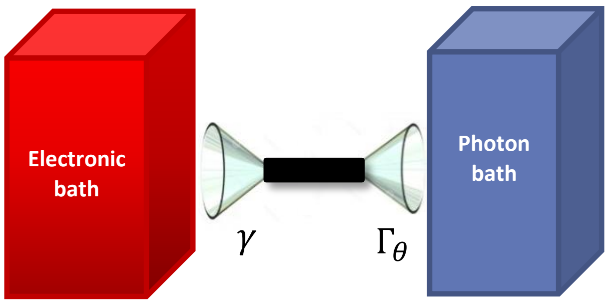
Directional emission

Emission spectra (non-normalized)



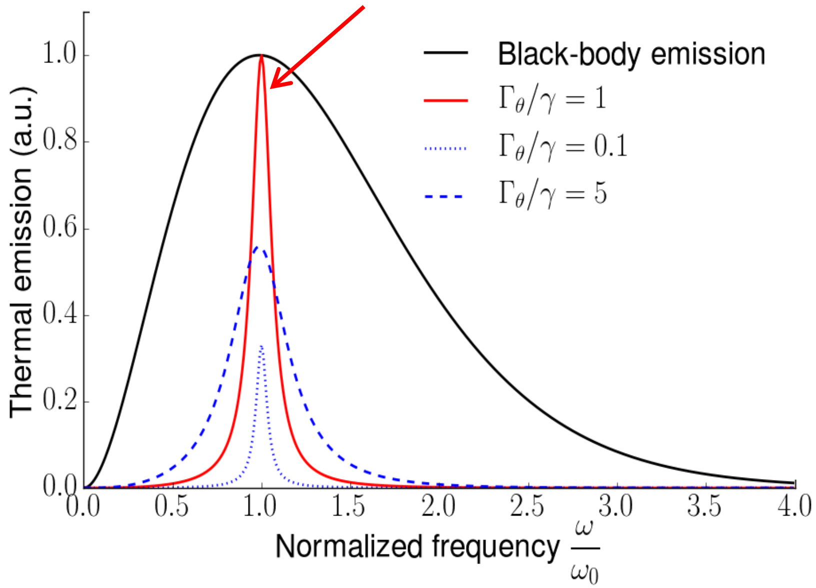
S. Huppert et al, *arXiv:1510.03209*

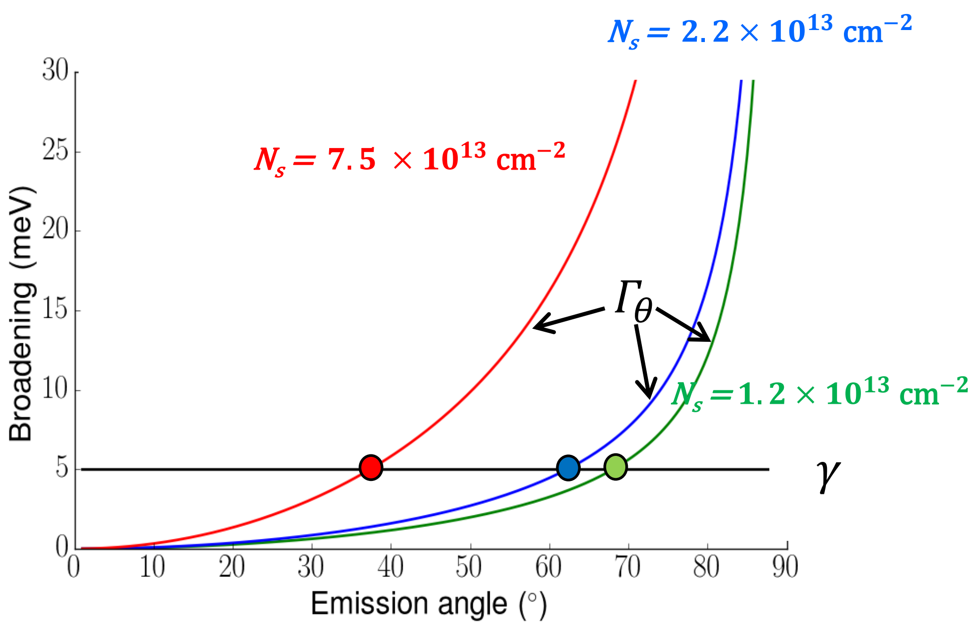
Critical coupling



Thermal emission is a twofold process: the limiting step depends on the ratio between radiative and non-radiative rates

Critical coupling
→ maximum emissivity





The critical coupling condition is always met at a certain angle

S. Huppert et al, *arXiv:1510.03209*

Conclusions

- Emergence of multisubband plasmon modes in the optical spectrum of dense electron gases
- Ultra-strong coupling regime with record values of the relative coupling at room temperature
- Superradiant decay of the multisubband plasmon
- Directional thermal emission

Perspectives

- **Transport + quantum optics:**
  - **Signatures of the light-matter coupling in the electronic transport (see G. Pupillo's talk)**
  - **Engineer the resonant injection of plasmons/polaritons**
- New devices based on quantum engineering of plasmons
- Superradiance with spatially separated quantum wells
- *Quantum optics with intersubband plasmons/polaritons?*