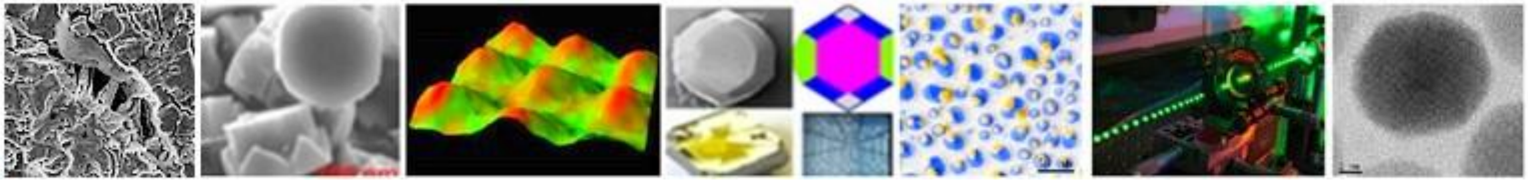


LABEX SEAM

TERAPLASMA

WHEN PLASMAS MEET PLASMONICS:

OPTOELECTRONIC DEVICES BASED ON COLLECTIVE ELECTRONIC EXCITATIONS

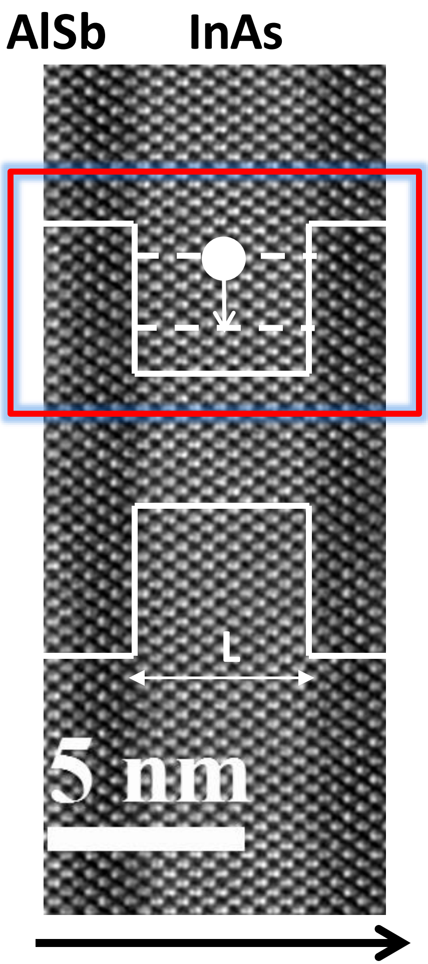
MPQ

A. Vasanelli, Y. Todorov, D. Gacemi, P. Filloux, C. Sirtori
S. Cosme (PhD)
S. Ribeiro (post-doc 1/1/2018 – 31/12/2018)

LSPM

K. Hassouni, A. Michau, P. Swaminathan
Post-doc to be hired

Mid and far infrared emitters



Growth direction (z)

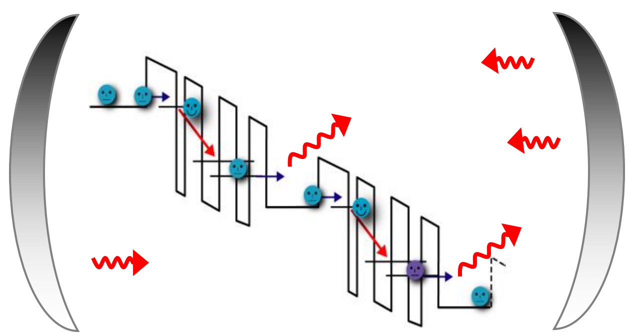
$$E_2 - E_1 \propto \frac{1}{L^2}$$

TEM image : G. Wang, J. Nelayah, C. Ricolleau (MPQ)
Growth: A. Baranov, R. Teissier (IES)

Spontaneous emission lifetime ~ 10 – 100 ns
Non-radiative lifetime ~ 1 ps

Quantum efficiency ~ 10^{-5} (mid-infrared)

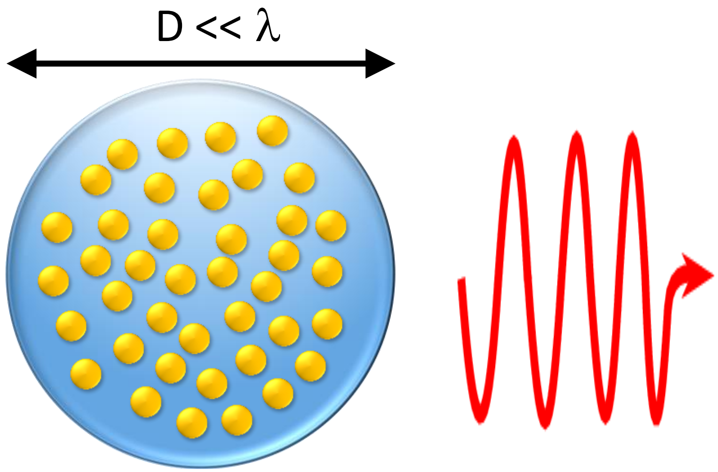
Stimulated emission
Quantum cascade lasers



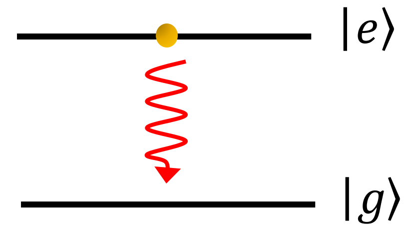
J. Faist *et al.*, Science (1994)

« Dressed » spontaneous emission

Superradiance



Cooperative emission in an ensemble of two-level emitters



Γ_0 Spontaneous emission rate for a single emitter

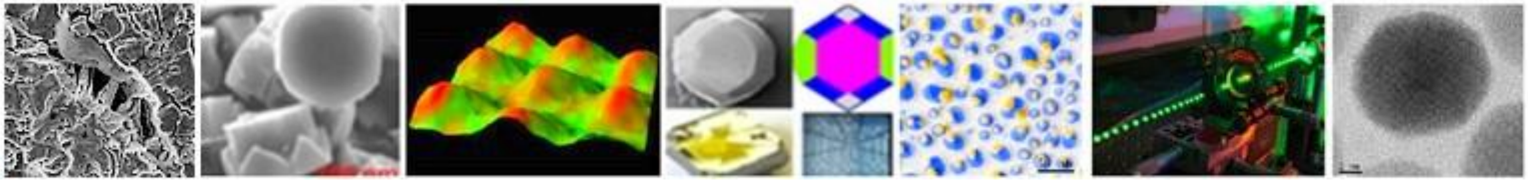
For an excitation distributed among all emitters (only one is excited):

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

$$\Gamma_\psi = \boxed{N_e}\,\Gamma_0$$

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
A. Angerer et al., Nature Phys. 2018

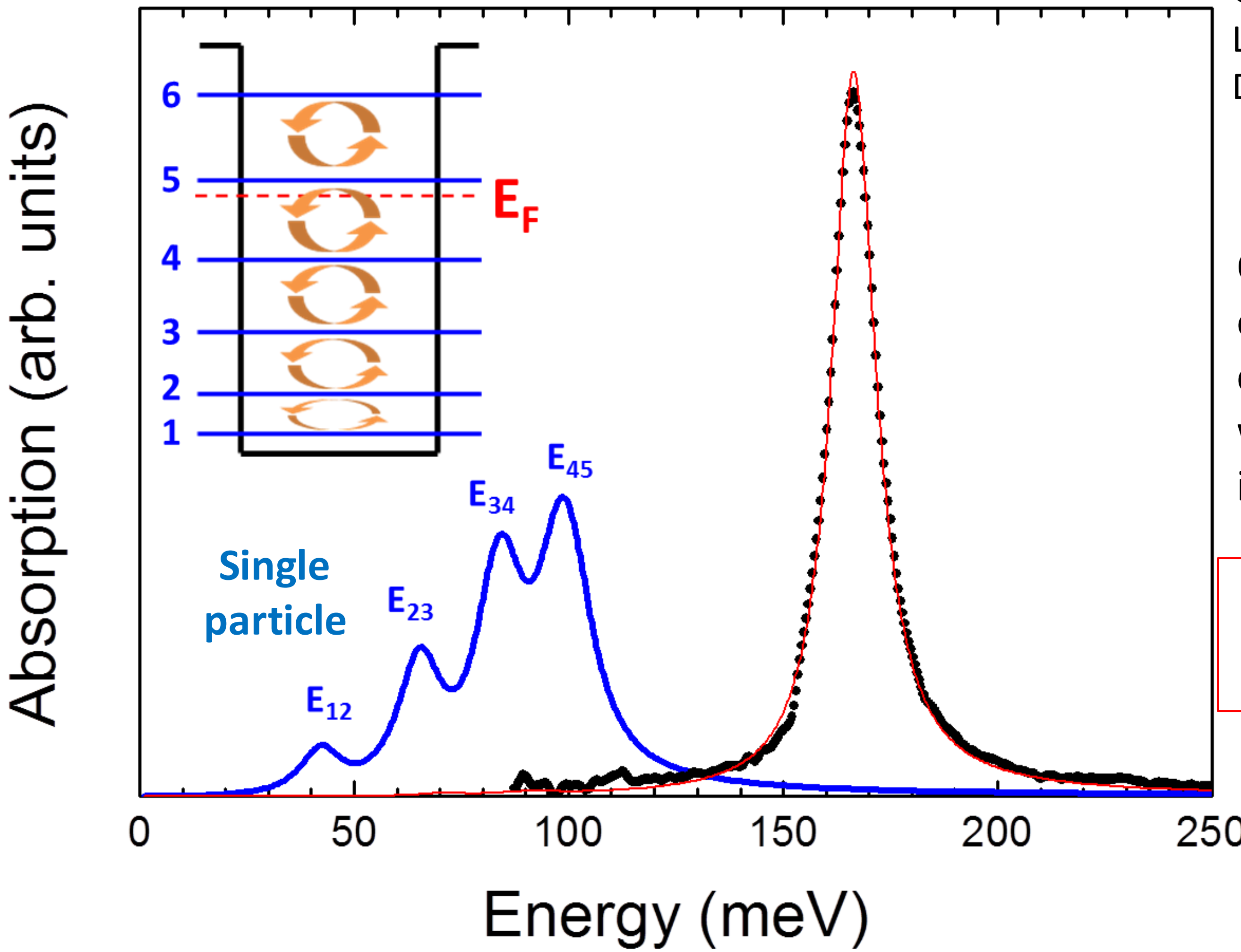


Aim of the project

- Realizing mid-infrared emitters based on superradiant plasmons in highly doped semiconductors

- Employing models and techniques used in plasma physics to efficiently excite the superradiant emission.

Collective excitations in highly doped quantum wells



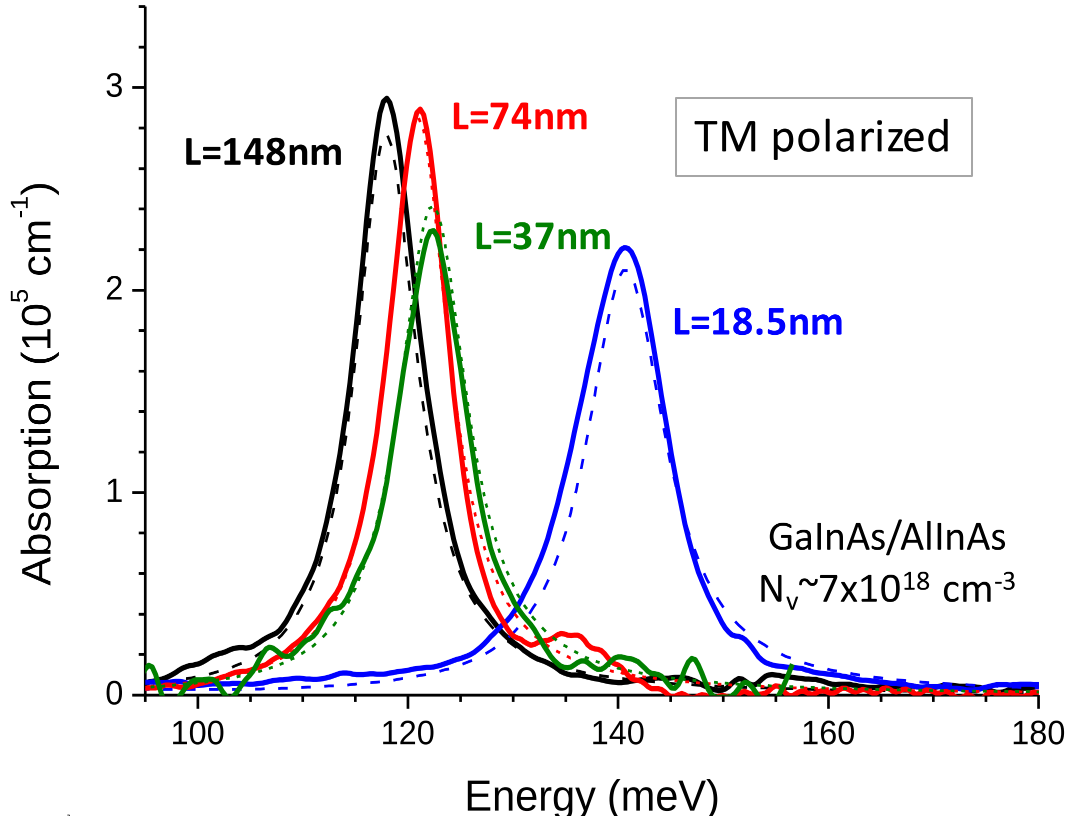
GaInAs/AlInAs quantum well
L_{QW} = 18.5 nm
Doping 2.2 x 10^{13} cm^{-2}

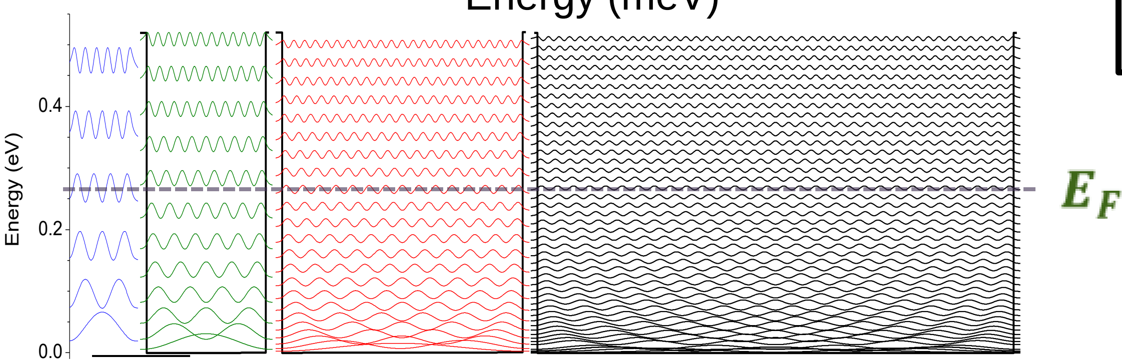
Observation of a single optical resonance at a completely different energy with respect to those of the intersubband transitions

Plasmon confined in the quantum well

A. Delteil *et al.*, PRL **109**, 246808 (2012)

Absorption spectrum of 2D plasmons





Quantum model to describe the plasmon modes based on the dipole representation

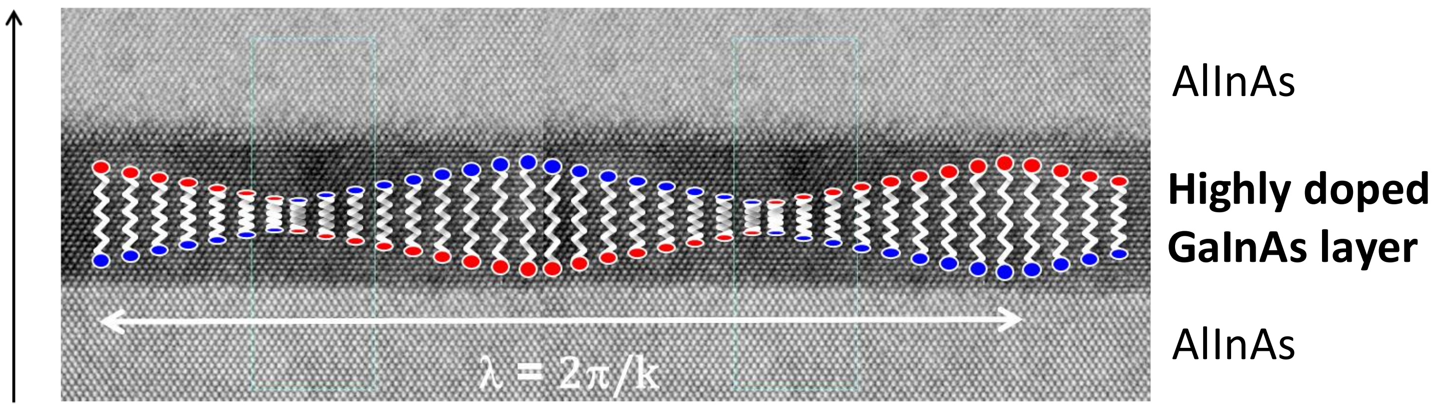
Y. Todorov and C. Sirtori PRB2012
G. Pegolotti *et al.*, PRB 2014

The 2D plasmon carries a huge **dipole, proportional to *N***, the number of particles involved

Review: A. Vasanelli, Y. Todorov, C. Sirtori, C. R.Physique **17**, 861 (2016)

B. Askenazi *et al.* NJP **16**, 043029 (2014)

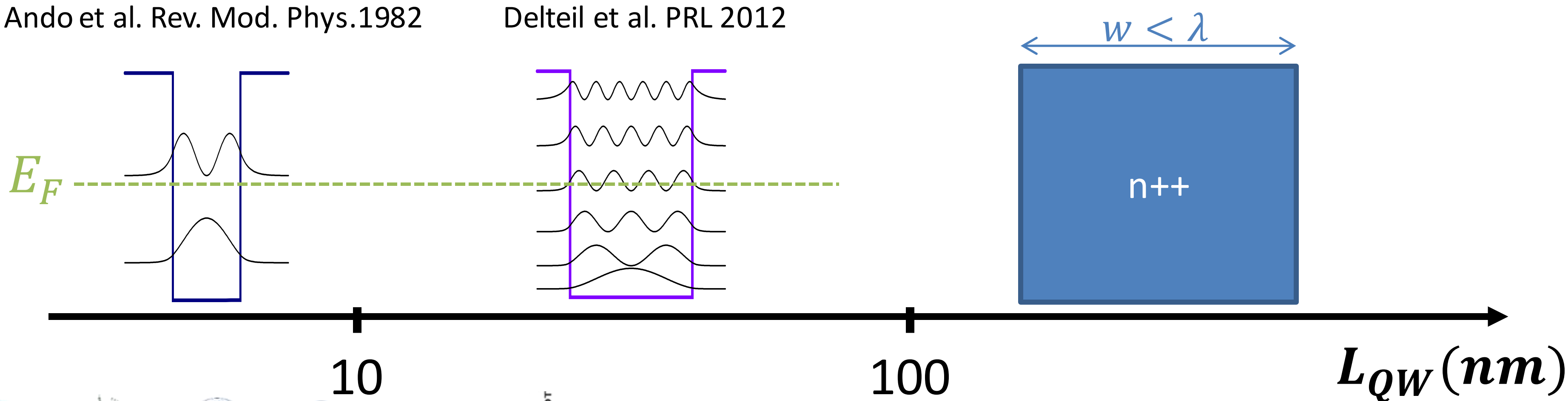
2D plasmons in highly doped semiconductors



Intersubband Plasmon
Ando et al. Rev. Mod. Phys.1982

Multisubband Plasmon
Delteil et al. PRL 2012

Berreman mode
Harbecke et al. Appl. Phys. A 1985

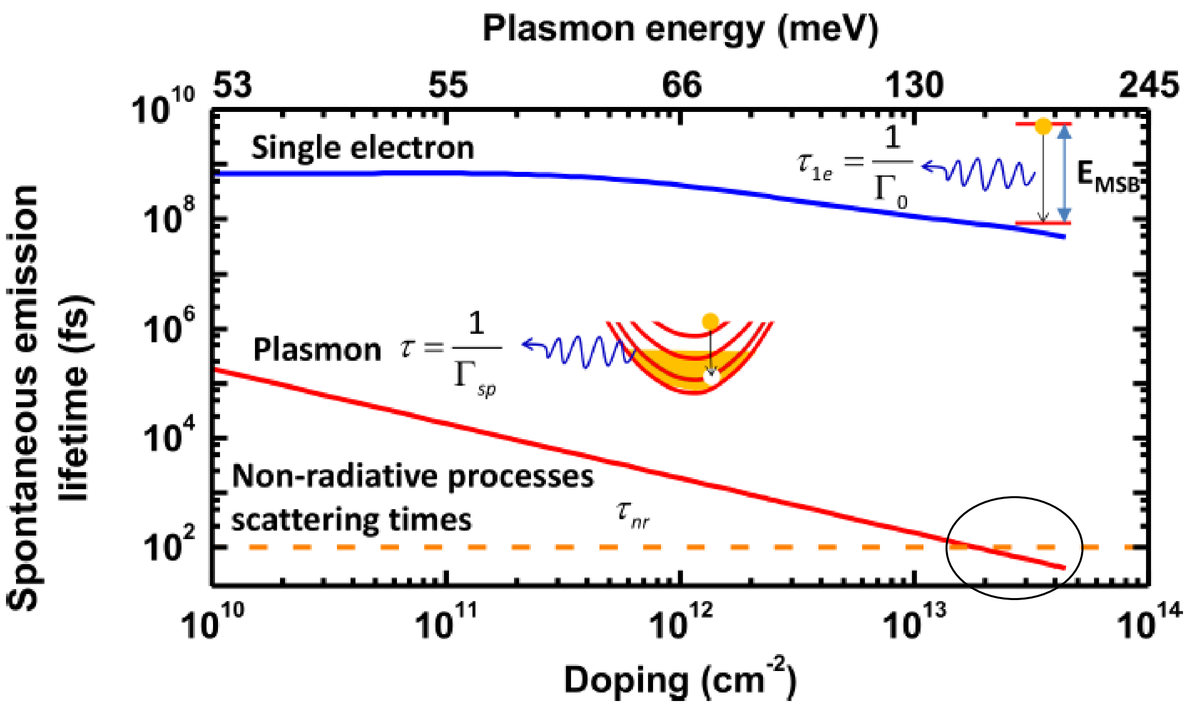


Spontaneous emission rate of a 2D plasmon

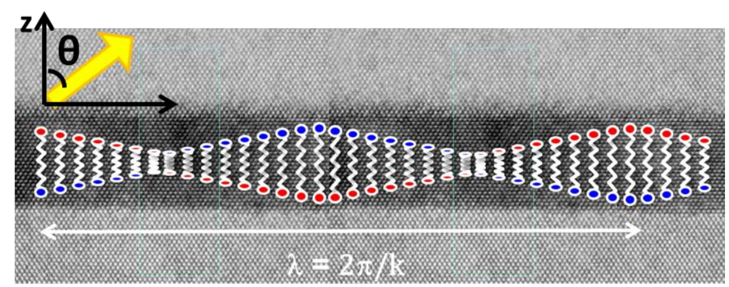
Spontaneous emission rate by Fermi golden rule for a given plasmon state
(selected by θ angle):

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

Superradiance



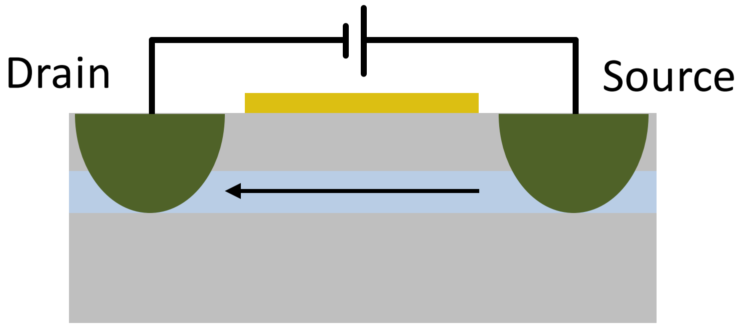
Spontaneous emission can be the dominant relaxation mechanism for 2D plasmons!



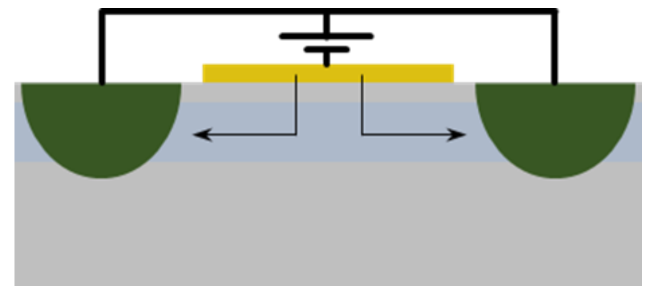
C. Ciuti and I. Carusotto, PRA 2009
F. Alpeggiani and L. C. Andreani, PRB 2014
T. Laurent et al. PRL (2015)

How to electrically excite a superradiant plasmon?

Two possible excitation schemes:



Thermal excitation



Resonant excitation

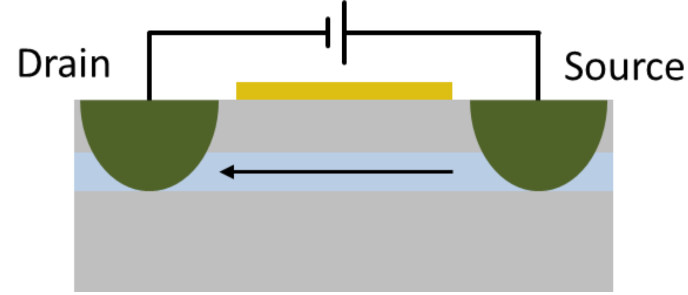
- Application of an in-plane current
- Increase of the electronic temperature
- Excitation of the plasmon

- Interaction between the injected electrons and the plasmon
- Mechanism of the interaction?

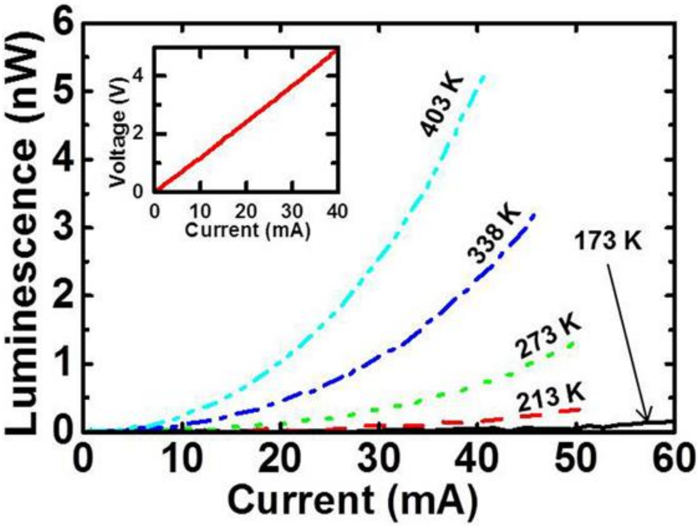
Post-doc: S. Huppert (Labex), T. Laurent, G. Frucci
PhD: B. Dailly, S. Cosme

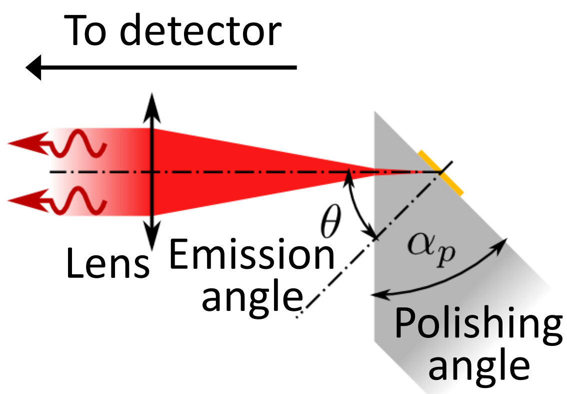
Post-doc: S. Ribeiro (Labex), LSPM (to be recruited)
PhD: S. Cosme

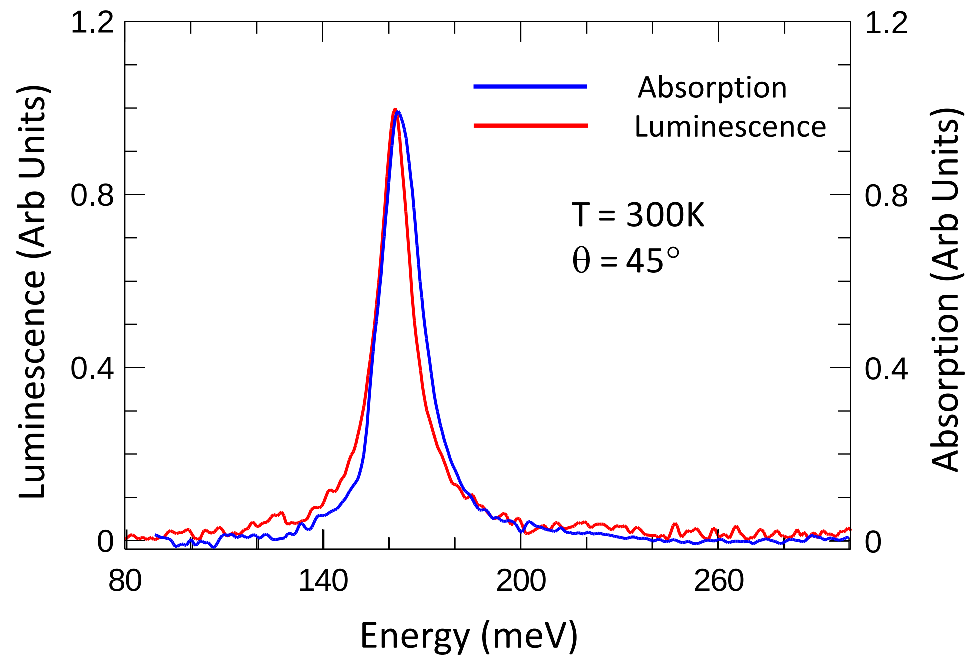
Thermal emission device



The electron gas is heated by a current modulated at 10 kHz





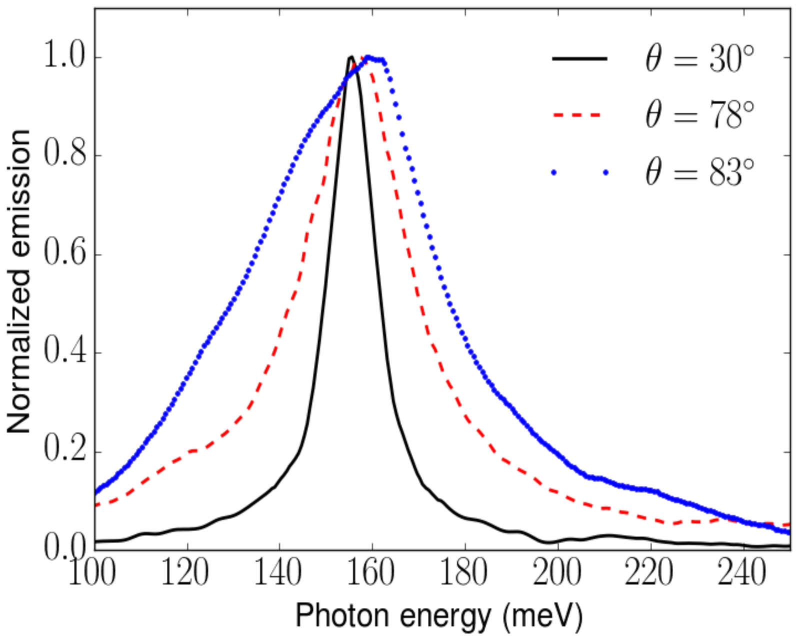


18.5 nm GaInAs/AlInAs QW
n-doped $1\text{x}10^{19}$ cm^{-3}

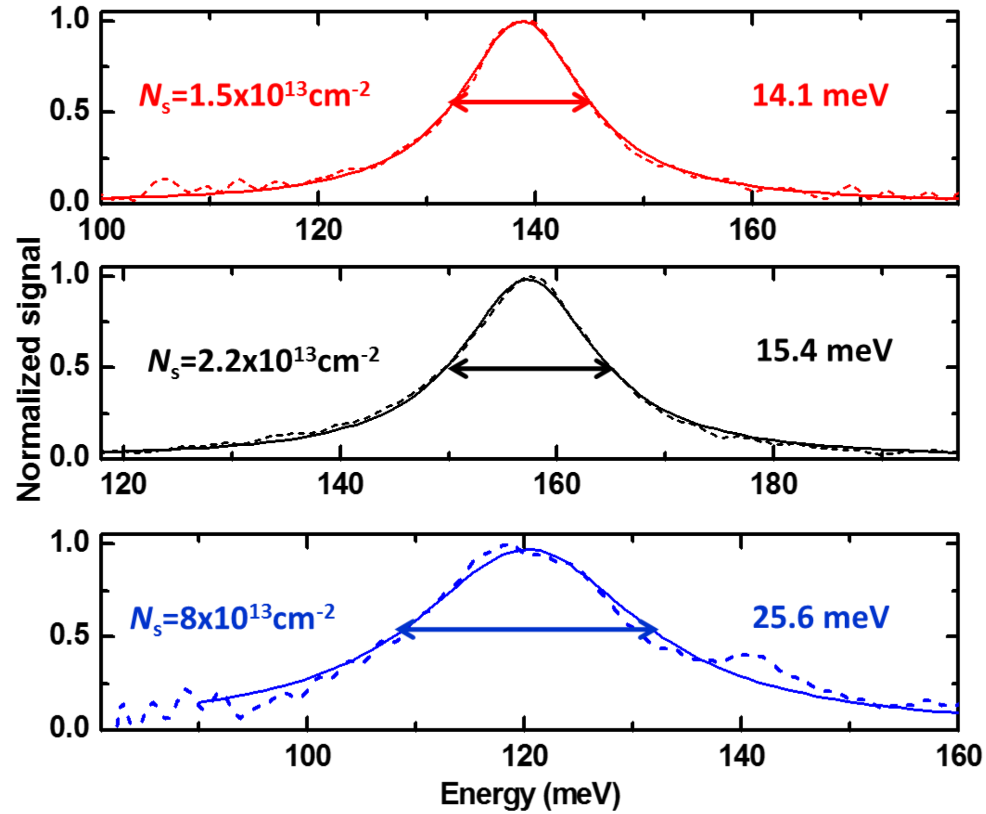
T. Laurent *et al.*, PRL **115**, 187402 (2015)

Linewidth of the collective mode

Fixed electronic density
N_s = 2.2 x 10^{13} cm^{-2}



Fixed angle
θ=55°



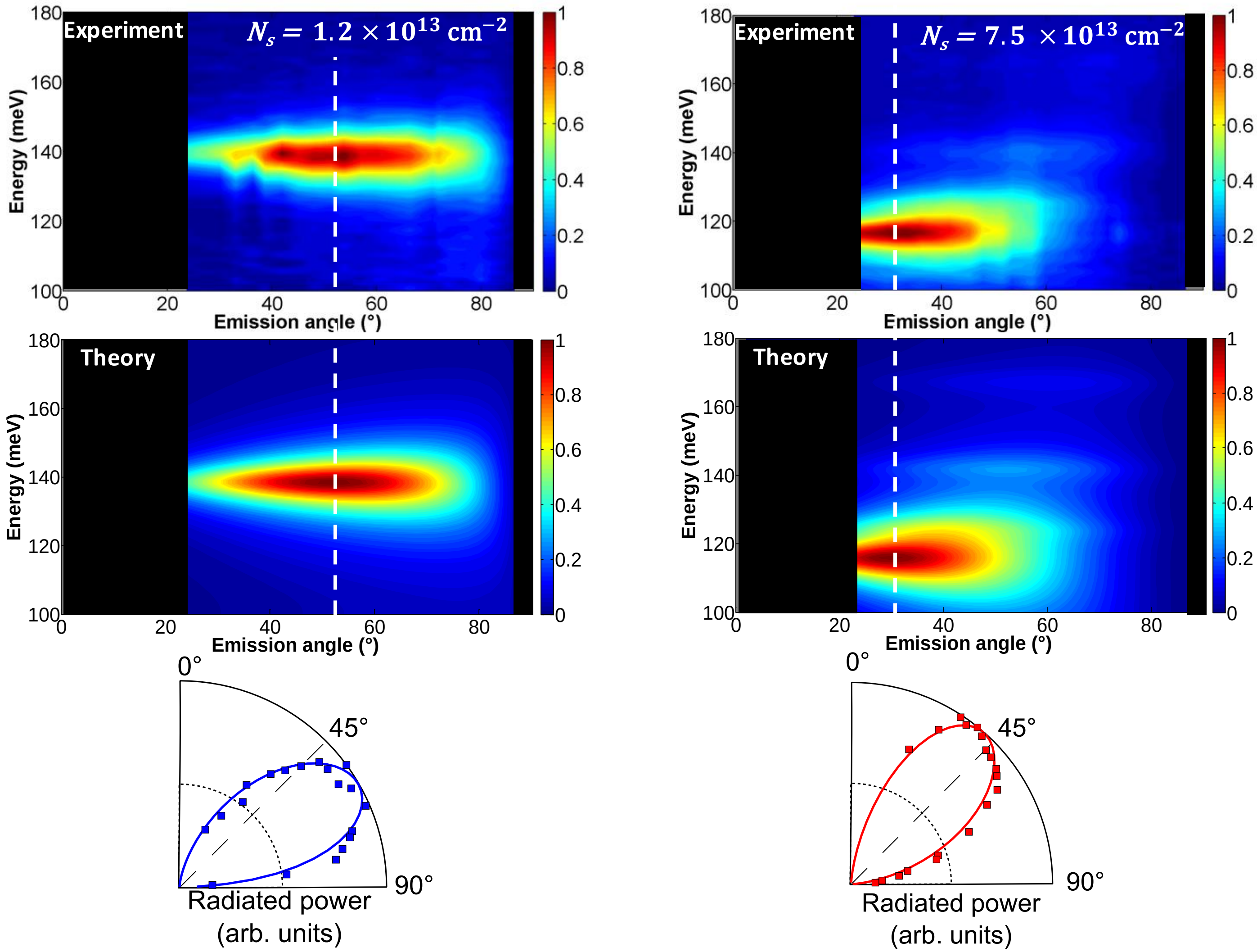
$$\Gamma_{tot}(\theta) = \Gamma(\theta) + \gamma$$

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

T. Laurent *et al.*, PRL **115**, 187402 (2015)

Directional emission without photonic structure

S. Huppert et al, ACS Photonics **2**, 1663 (2015)

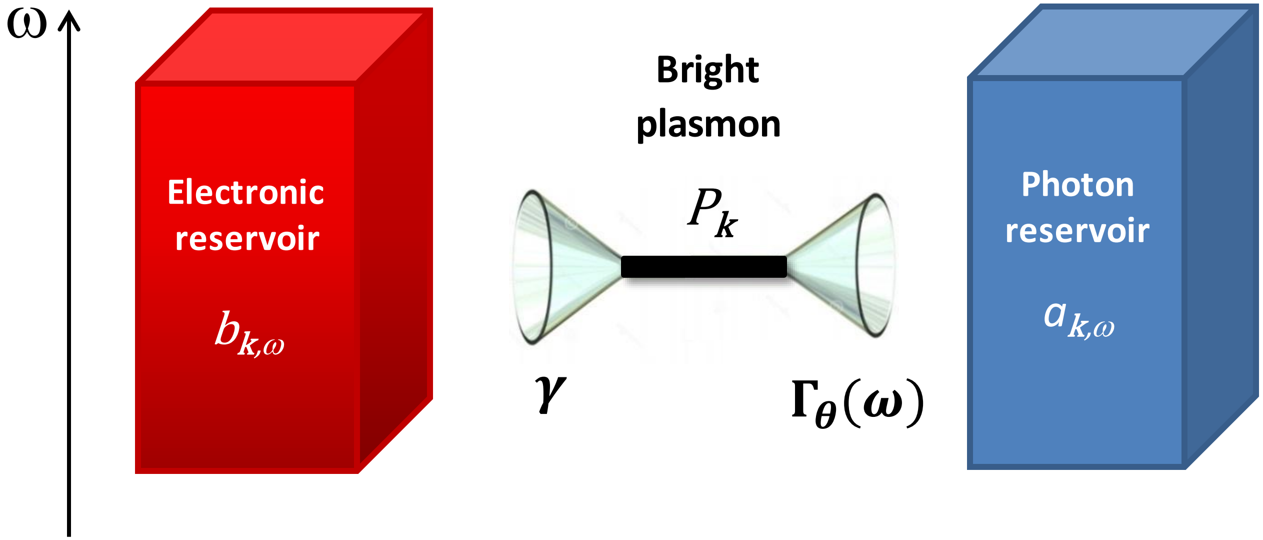


Preferential direction of emission at an angle which depends on the electronic density

Quantum model

Post-doc Simon Huppert (Labex)

S. Huppert et al., Phys. Rev. B **94**, 155418 (2016)



$$\langle a^{out\dagger}_{\mathbf{k},\omega} a^{out}_{\mathbf{k},\omega'} \rangle = \epsilon(\mathbf{k},\omega)\, \delta(\omega-\omega')\, \frac{1}{e^{\frac{\hbar\omega}{k_B T}}-1}$$

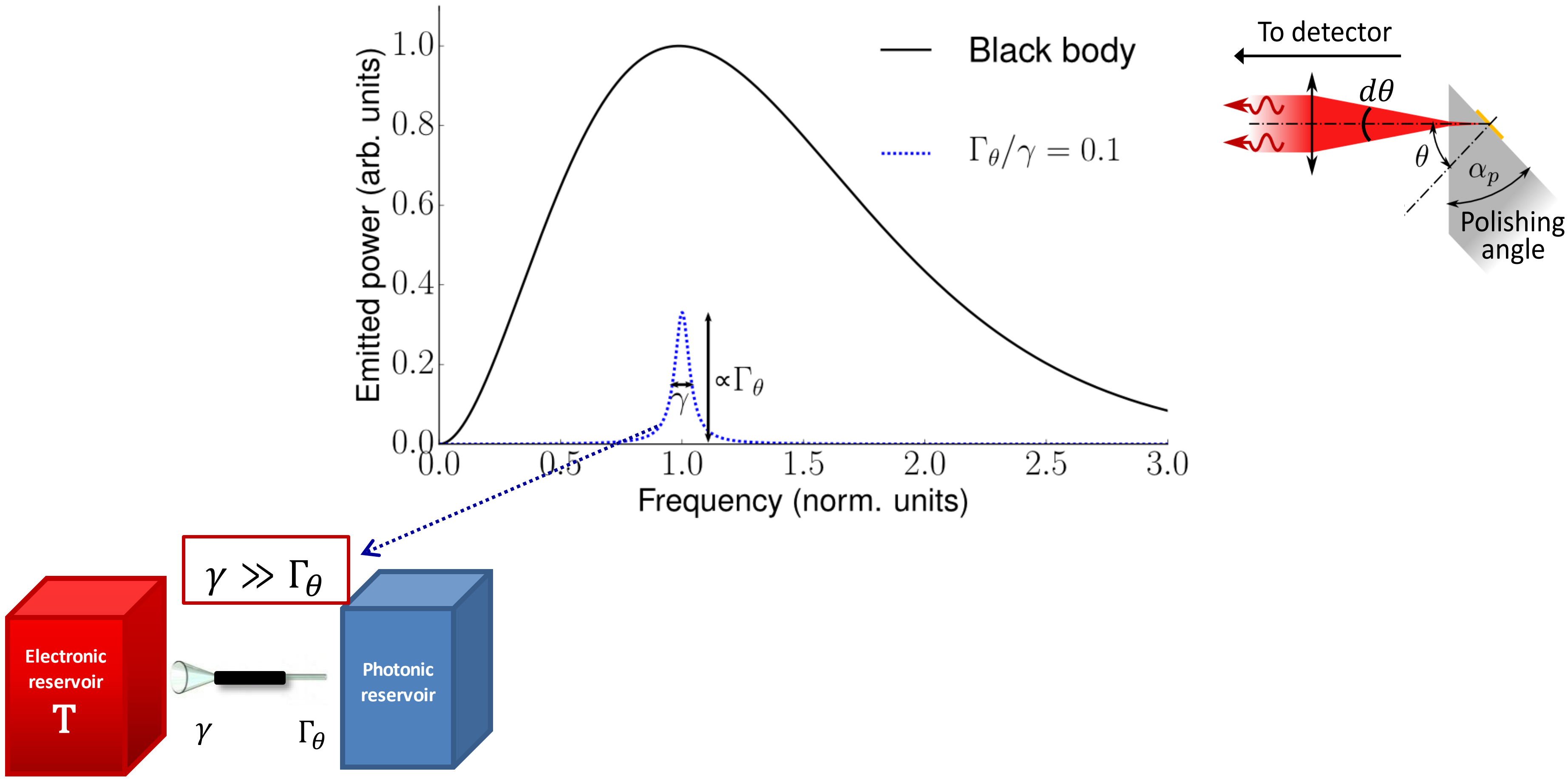
→ Thermal occupation at **T**

Emissivity = Absorptivity

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

Kirchhoff law of thermal emission

Weak coupling (perturbative) regime: $\gamma \gg \Gamma$

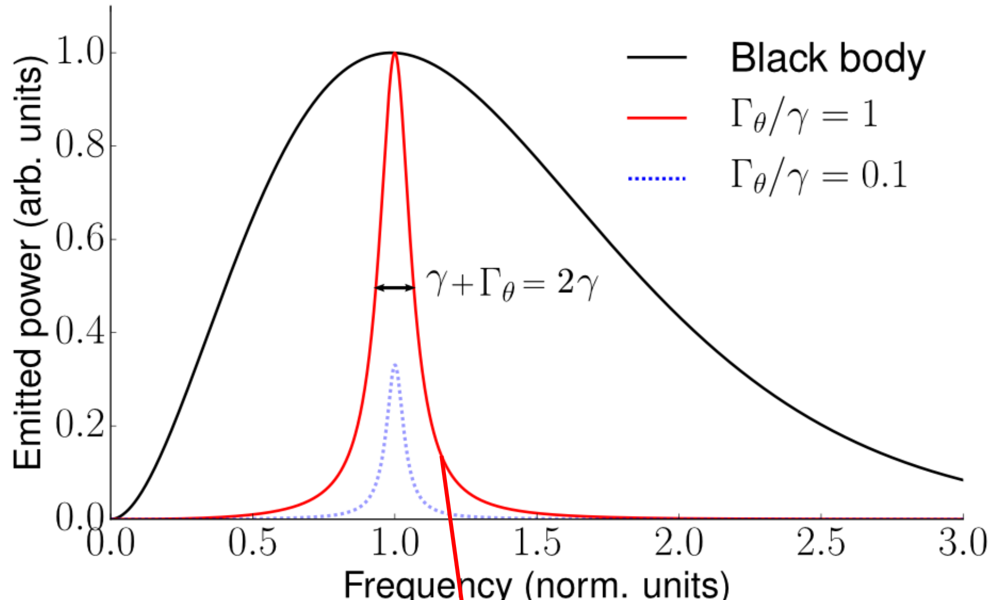


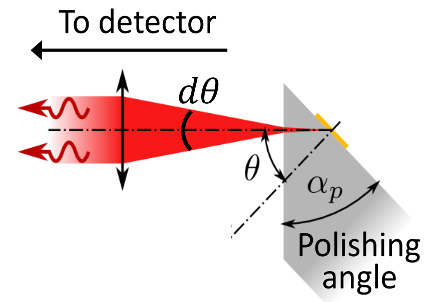
Weak coupling regime

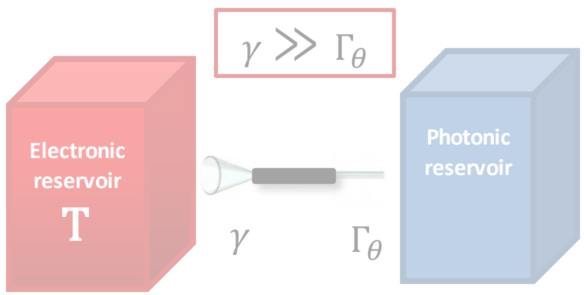
Total emitted power:

$$\frac{dP}{d\Omega} \rightarrow A\cos\theta \frac{1}{e^{\frac{\hbar\omega_P}{kT}} - 1}\Gamma(\theta)$$

Critical coupling: $\Gamma = \gamma$



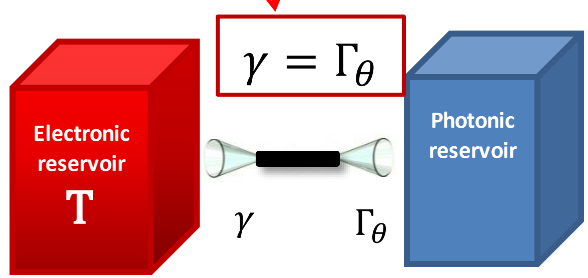




Weak coupling regime

Total emitted power:

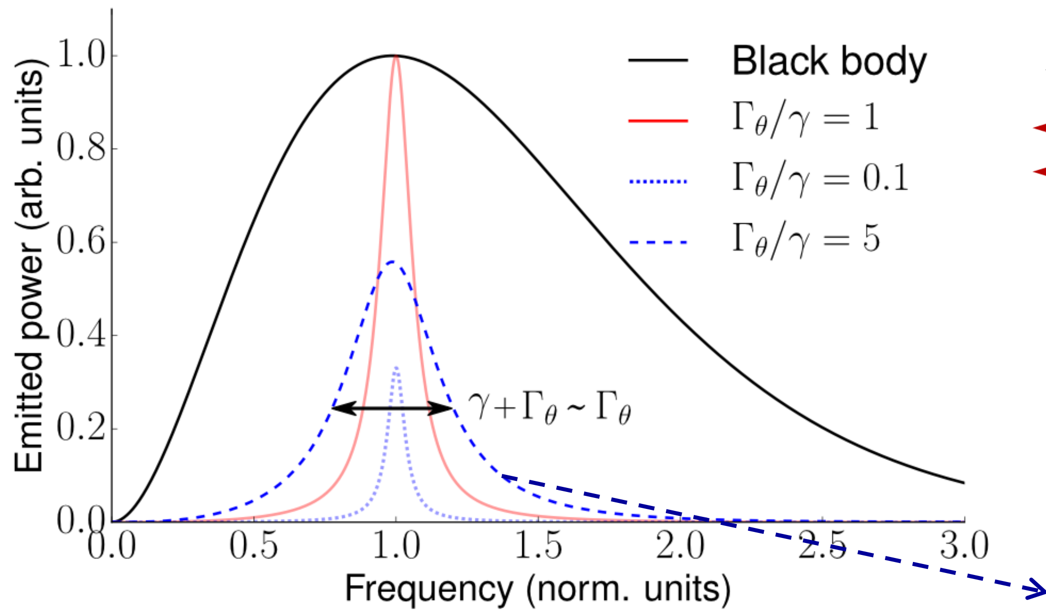
$$\frac{dP}{d\theta} = A\cos\theta \frac{1}{e^{\frac{\hbar\omega_P}{k_B T}} - 1}\Gamma_\theta$$

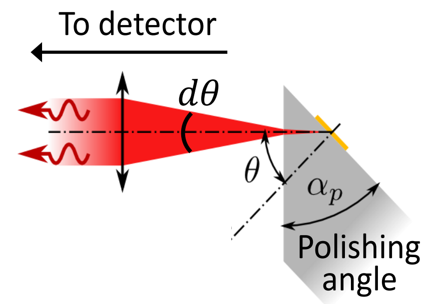


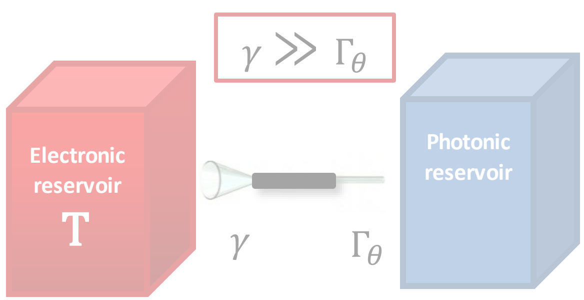
Critical coupling

→ maximum emissivity: $\alpha(\omega_P)=1$

Strong coupling (non perturbative) regime: $\boldsymbol{\Gamma > \gamma}$



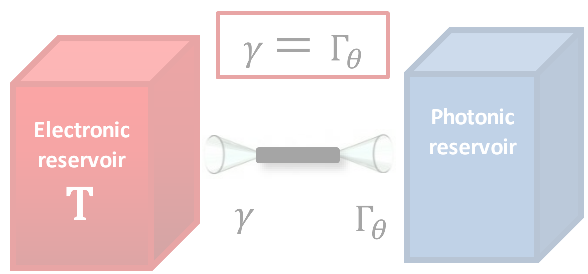




Weak coupling regime

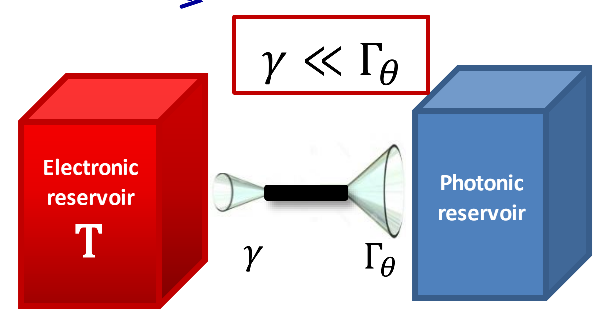
Total emitted power:

$$\frac{dP}{d\theta} = A\cos\theta \, \frac{1}{e^{\frac{\hbar\omega_P}{k_B T}} - 1} \, \Gamma_\theta$$



Critical coupling

→ maximum emissivity: $\alpha(\omega_P)=1$



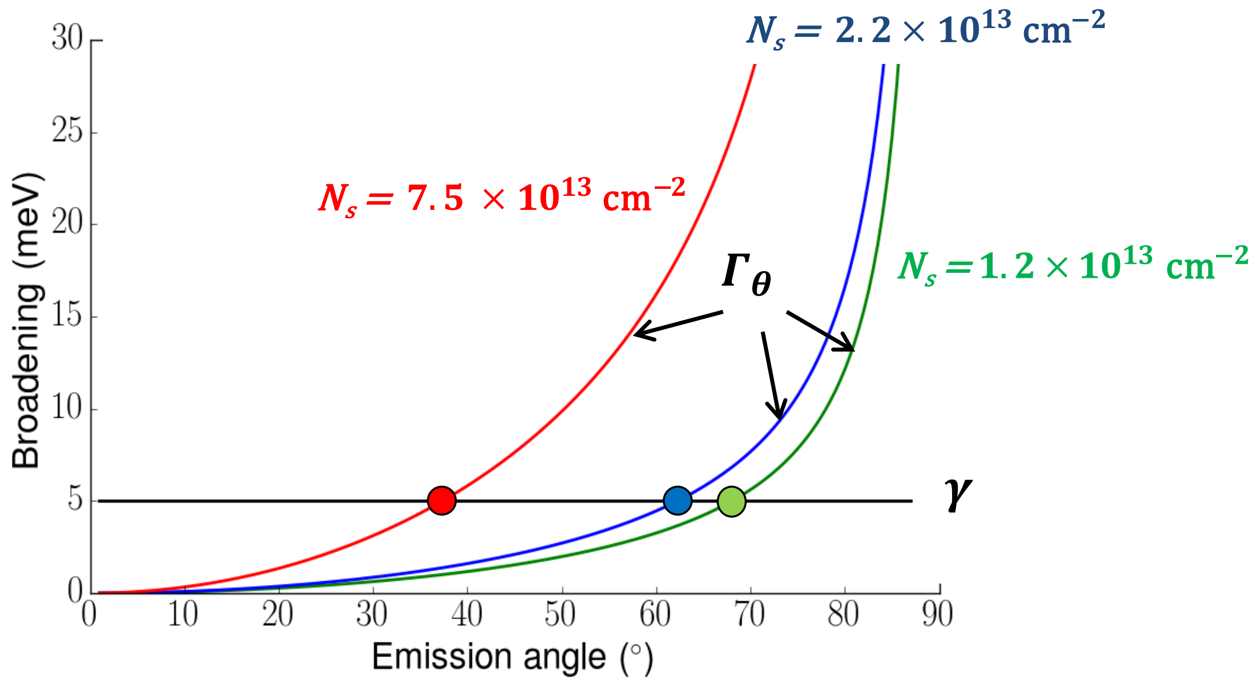
Strong coupling regime

Total emitted power:

$$\frac{dP}{d\Omega} \rightarrow A\cos\theta \, \frac{1}{e^{\frac{\hbar\omega_P}{kT}} - 1} \, \gamma$$

Critical coupling

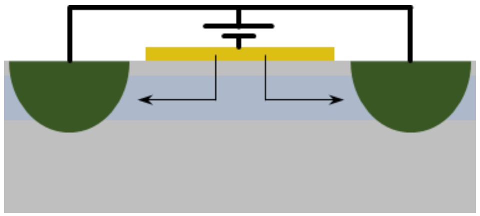
The critical coupling angle depends on the density

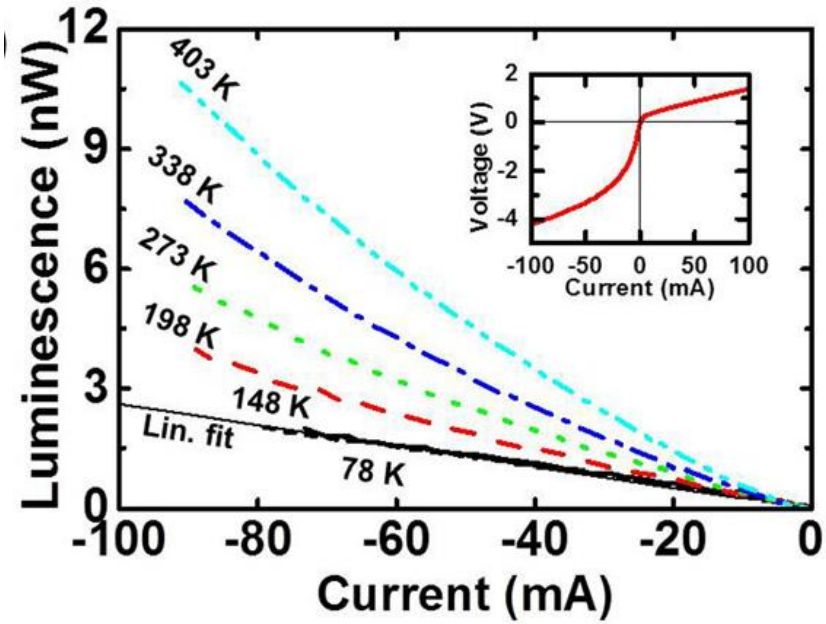


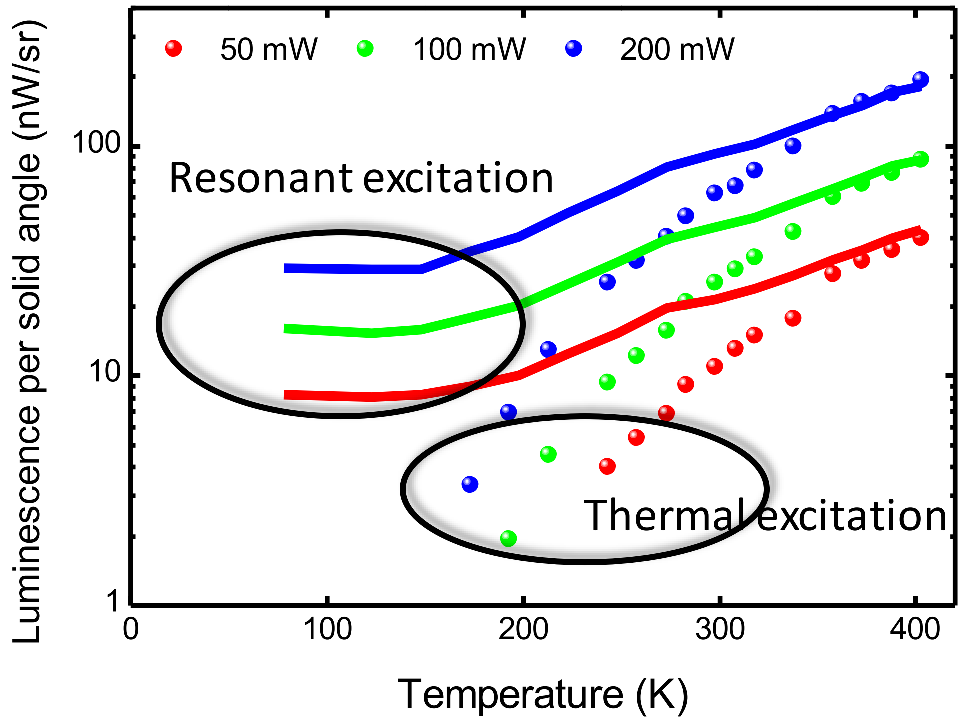
Radiative rate: $$\Gamma_\theta = N_s \frac{1}{4} \frac{e^2}{m^* c\, n\, \varepsilon_0} \frac{\sin^2\theta}{\cos\theta}$$

S. Huppert et al., Phys. Rev. B **94**, 155418 (2016)

Resonant excitation: experimental results



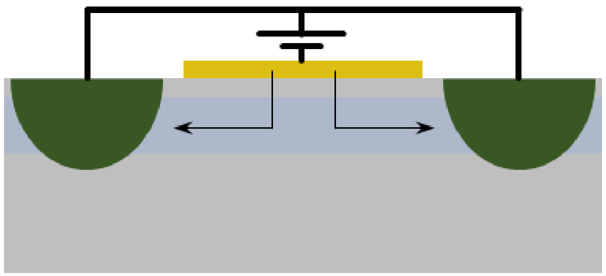


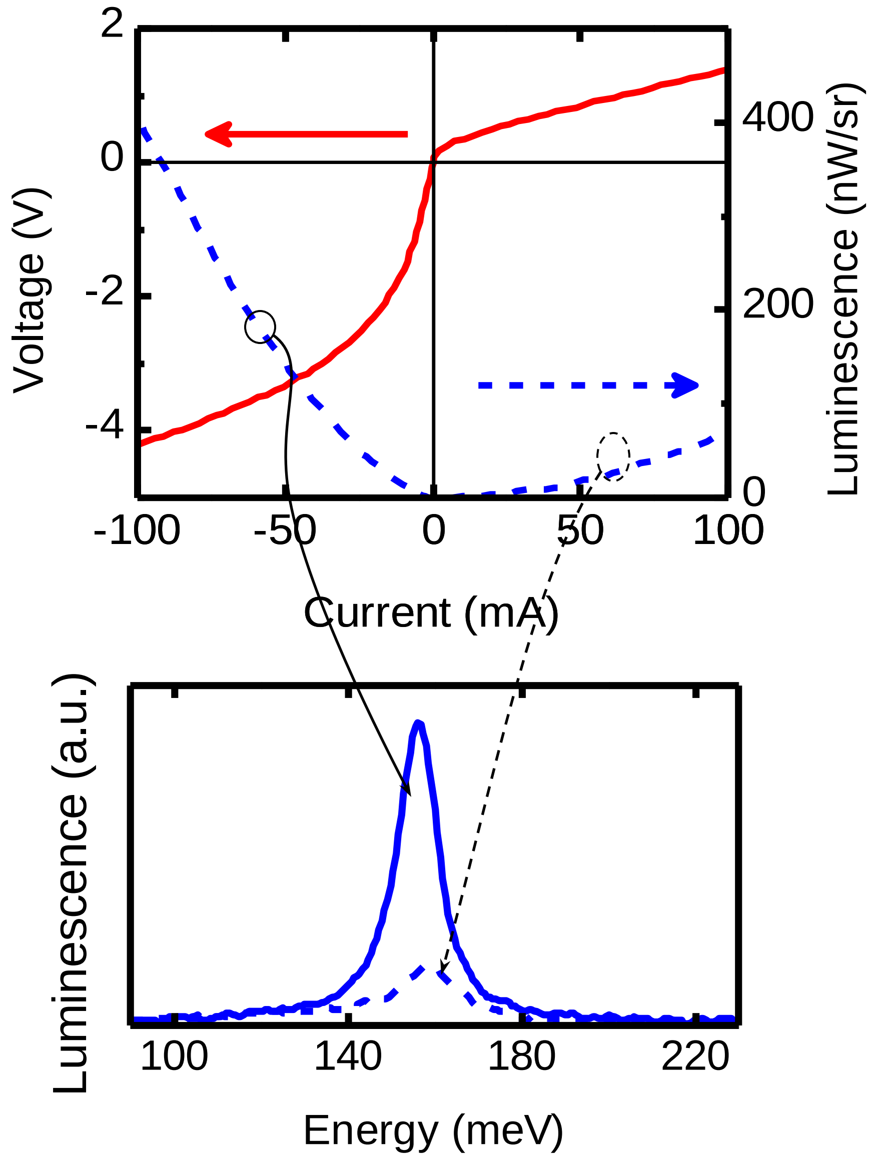


- Observation of luminescence signal at low temperature
- Linear luminescence vs current characteristics

T. Laurent et al. APL 2015

Resonant excitation: experimental results





- Observation of plasmon emission under vertical excitation
- The emitted luminescence depends on the kinetic energy of the injected electrons.

S. Cosme (in progress)

PHYSICAL REVIEW B VOLUME 43, NUMBER 11 15 APRIL 1991-I

Spontaneous generation of plasmons by ballistic electrons

K. Kempa, P. Bakshi, J. Cen, and H. Xie
Department of Physics, Boston College, Chestnut Hill, Massachusetts 02167-3811
(Received 26 November 1990)

A beam of ballistic electrons moving with a velocity of about twice the Fermi velocity ($\sim 10^7$ cm/s) with respect to a stationary electron gas is shown to lead to a spontaneous generation of plasmons.

APPLIED PHYSICS LETTERS VOLUME 84, NUMBER 13 29 MARCH 2004

Terahertz emission by plasma waves in 60 nm gate high electron mobility transistors

W. Knap and J. Lusakowski[a)]
GES, CNRS-Université Montpellier 2, 34900 Montpellier, France and Electrical, Computer and System Engineering Department, Rensselaer Polytechnic Institute, Troy, New York 12180

T. Parenty, S. Bollaert, and A. Cappy
IEMN-DHS UMR CNRS 8520, Avenue Poincaré, 59652 Villeneuve d'Ascq, France

V. V. Popov
Institute of Radioengineering and Electronics, Russian Academy of Sciences, 410019 Saratov, Russia

M. S. Shur
Center for Broadband Data Transport and Electrical, Computer and System Engineering Department, Rensselaer Polytechnic Institute, Troy, New York 12180

(Received 4 August 2003; accepted 2 February 2004)

We report on the resonant, voltage tunable emission of terahertz radiation (0.4–1.0 THz) from a gated two-dimensional electron gas in a 60 nm InGaAs high electron mobility transistor. The emission is interpreted as resulting from a current driven plasma instability leading to oscillations in the transistor channel (Dyakonov–Shur instability).
[DOI: 10.1063/1.1689401]

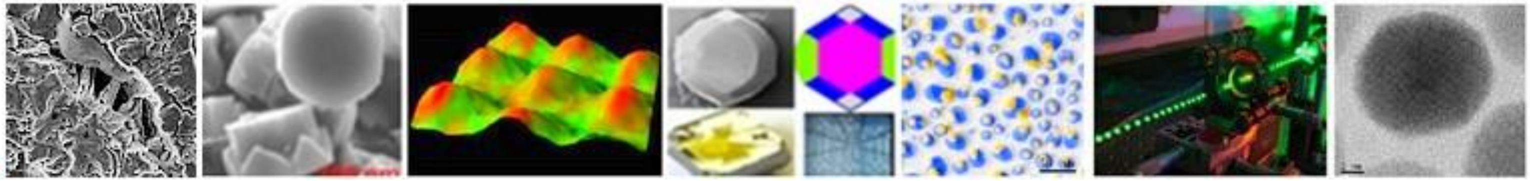
A dense cold plasma: theoretical modelling (LSPM)

Anisotropic plasma :
Free in-plane 2D plasma
Bounded 1D plasma along the growth direction

PIC/MCC simulations in 1D and then 2D to model plasma instabilities in the electron gas.
We will consider the generation of plasma instabilities through the following processes:

- Excitation of an electrostatic wave by subnanosecond pulsed voltage
- Coupling between the transverse electromagnetic wave and the charge density waves excited along the growth direction
- Application of a static magnetic field

- The radiative emission will be considered first a posteriori, then included in the calculation through a kinetic model.



Conclusions and perspectives

- Investigation of similar effects in other material systems: GaN, Hg(Cd)Te, ZnO, graphene…
- Investigation of plasmon – phonon interaction (S. Ribeiro)
- Investigation of optical pumping of plasmons
- Link between electronic transport and quantum optics (see work by Ebbesen's group and Scalari/Faist): *hot topic!!*

European Research Council
Executive Agency
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Acknowledgements

Yanko Todorov, Djamal Gacemi, Carlo Sirtori

Aymeric Delteil
(2009-2012)
now CR @ CNRS

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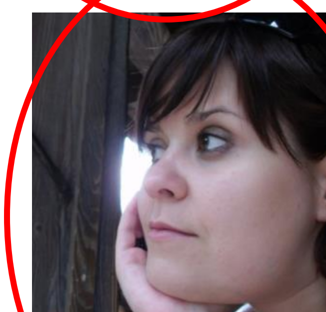
(2011-2015)
now @ L'Oréal

Baptiste Dailly
(2014-2018)
now @ Alten

Sébastien Cosme
(2015-)

Giulia Frucci
(now @ ID Quantique)



Sofia Ribeiro
(2018-)

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Clean room

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C2N

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Grégoire Beaudoin

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