Realization of synthetic (quantum) materials using light

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Centre de Nanosciences et de Nanotechnologies C2N

cnrs

université PARIS-SACLAY

UNIVERSITÉ PARIS SUD

RENATECH French national nanofabrication network

A new laboratory: C2N

Centre de Nanosciences et de Nanotechnologies

cnrs

UNIVERSITÉ PARIS SUD

The polariton team at C2N

Permanent members:

J. Bloch
Research director
Group leader

S. Ravets
CNRS researcher

Postdoc:

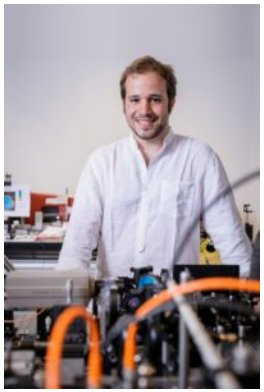
P. St-Jean

Former member and collaborator

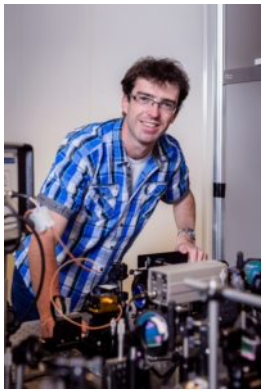
A. Amo
CNRS Researcher
Now at PhLAM

Lille, France

Graduate students:



N. Carlon Zambon



V. Goblot

M. Milicevic

Master students:

N. Pernet

A. Loirette Pelous

The polariton team at C2N

Permanent members: **Postdoc:** **Former member and collaborator**

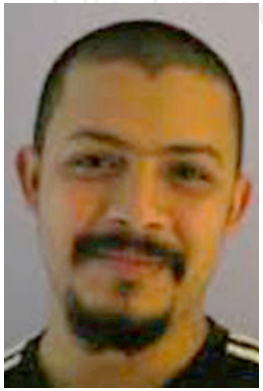
Sample fabrication:

A. Lemaitre

C. Gomez

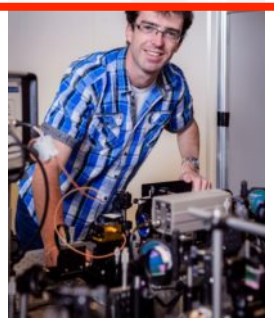
I. Sagnes

L. Legratiet



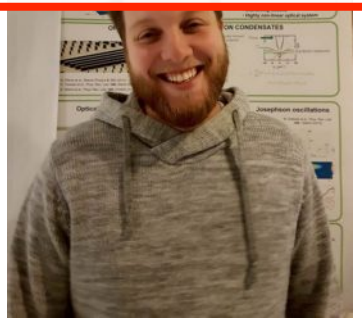
A. Harouri

N. Carlon Zambon

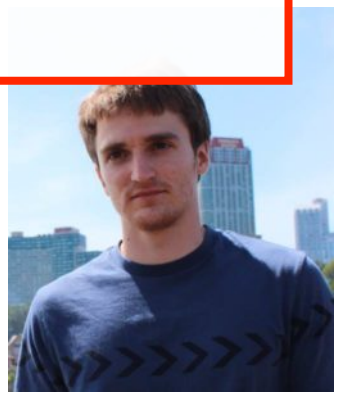


V. Goblot

M. Milicevic



N. Pernet



A. Loirette Pelous

The polariton team at C2N

Permanent members: **Postdoc:** **Former member and collaborator**

Theory:

I. Carusotto

T. Ozawa

G. Malpuech

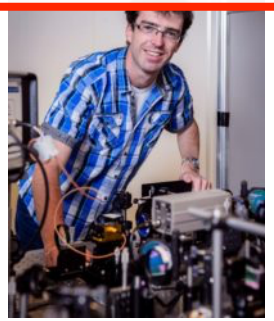
D. Solnishkov

C. Ciuti

G. Montambaux

Gr

N. Carlon Zambon


V. Goblot

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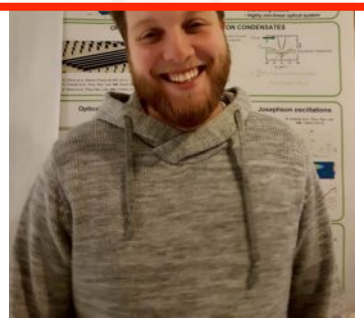
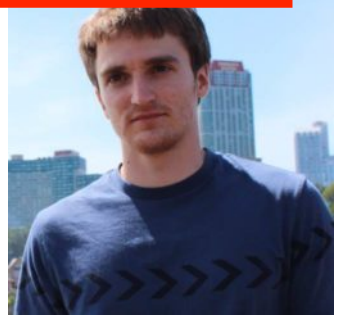
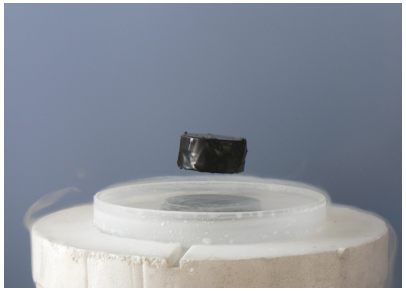

N. Pernet

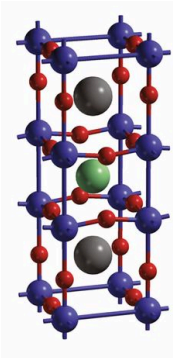

A. Loirette Pelous

Open problems in condensed matter physics

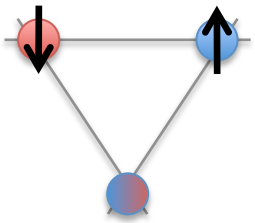
Quantum many-body problems

High-T_c superconductivity





Quantum magnetism



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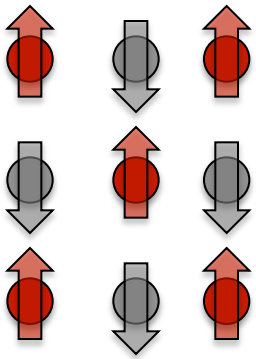
Typical examples of many-body Hamiltonians: spin Hamiltonians

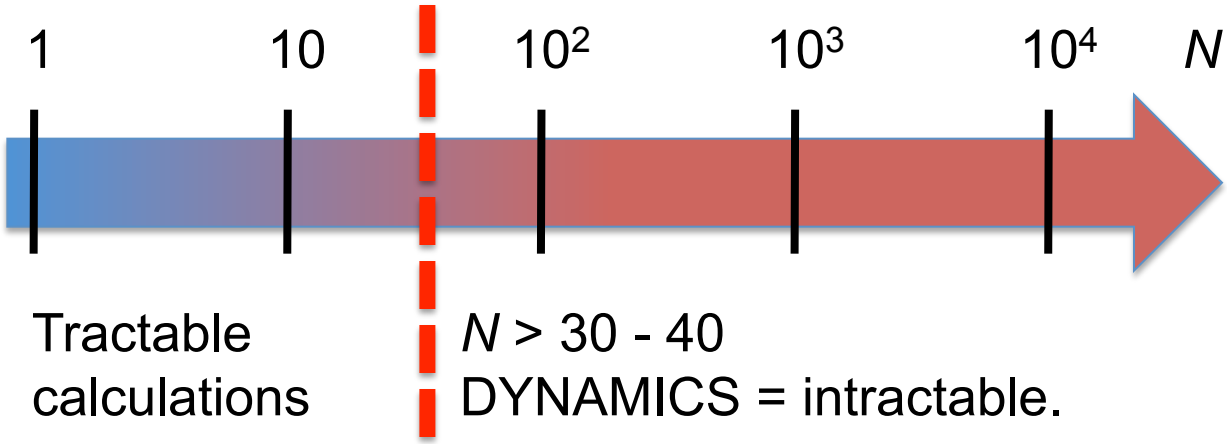


Ising $$H_z = \sum_{i \neq j} J_{ij} \hat{S}_i^z \hat{S}_j^z$$

XY model $$H_{XY} = \sum_{i \neq j} J_{ij} \left(\hat{S}_i^+ \hat{S}_j^- + \hat{S}_i^- \hat{S}_j^+ \right)$$

Quantum simulation

Problem: Hilbert space: 2^N

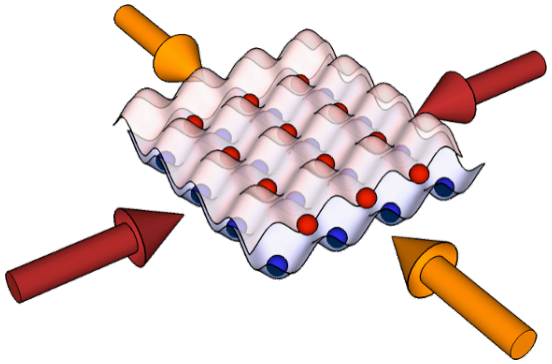


CREATE SYNTHETIC MATERIALS

Engineer a Hamiltonian in the lab. Measure on the system properties that can not be calculated.

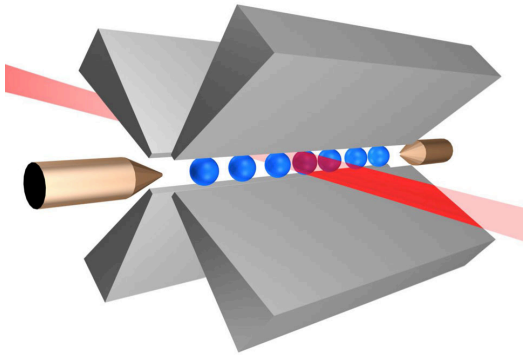
Original idea: R. Feynman., Int. J. Theor. Phys. **21**, 467 (1982)

Examples of artificial systems



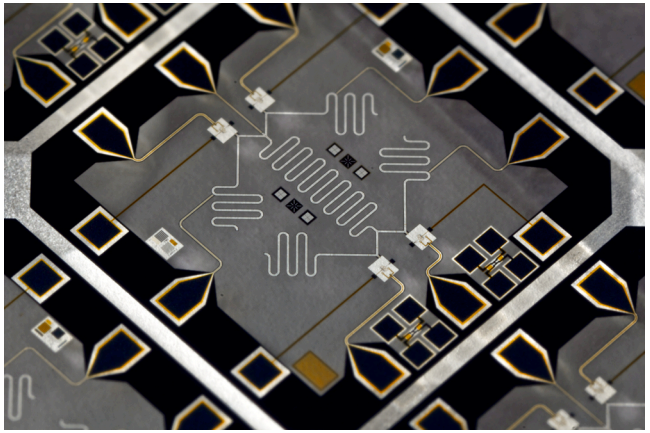
Neutral atoms

See work by: I.Bloch, J Dalibard, A. Aspect, A. Browaeys, M. Lukin, M. Greiner, T. Esslinger…



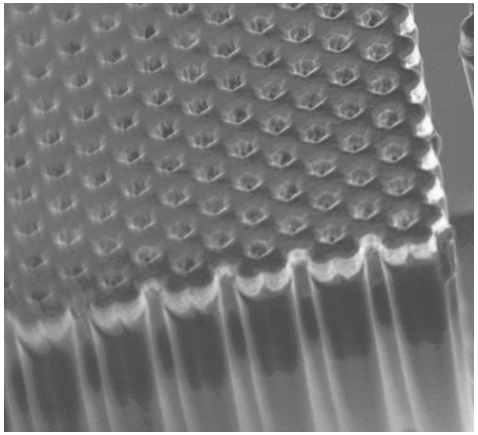
Ions

See work by: R. Blatt, C. Monroe, D. Wineland, J. Home…



Superconducting qubits

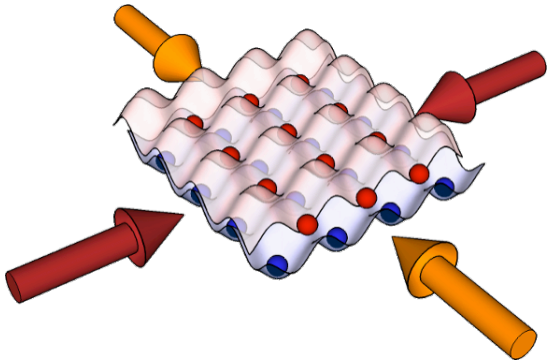
See work by: J. Martinis, D. Esteve, R. Schoelkopf, M. Devoret, A. Walraff, D-Wave…



Photons

See work by: M. Hafezi, Y. Yamamoto, A. Aspuru-Guzik, J. Bloch, M. Segev,…

Examples of artificial systems



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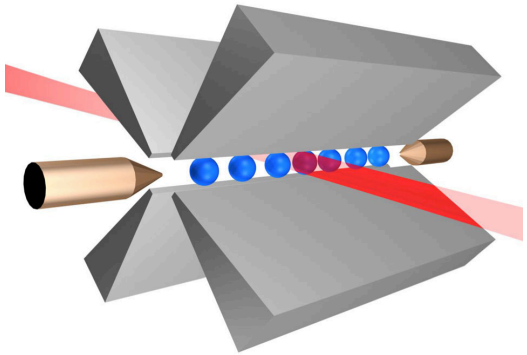

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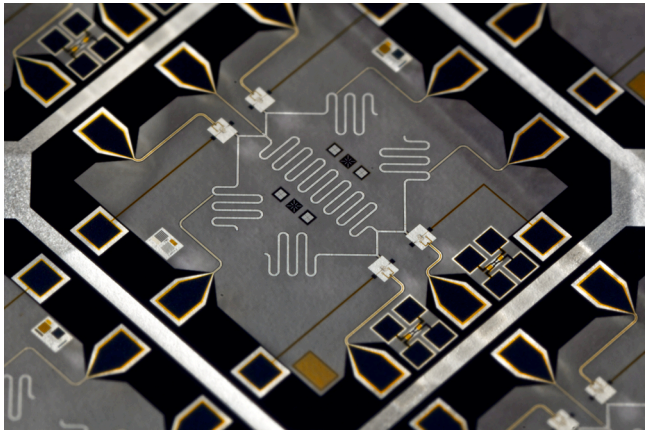

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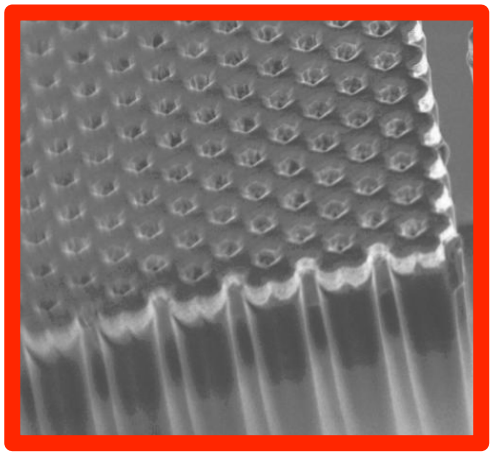


Photons

See work by: M. Hafezi, Y. Yamamoto, A. Aspuru-Guzik, J. Bloch, M. Segev,…

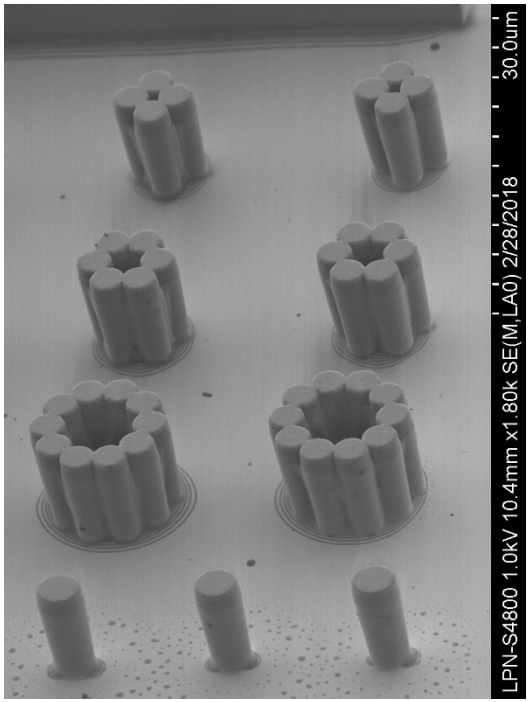
Quantum fluids of light as an analogous system

Use nanotechnologies to fabricate artificial systems:

- Perform experiments in a system easier to probe, manipulate.

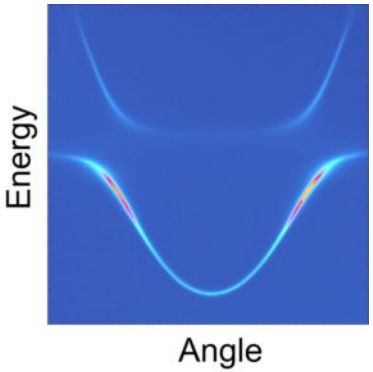
- Create new geometries, new properties which do not exist in nature.

- Realize experiments which are impossible to predict because of complexity of simulations (many body): **quantum simulation.**



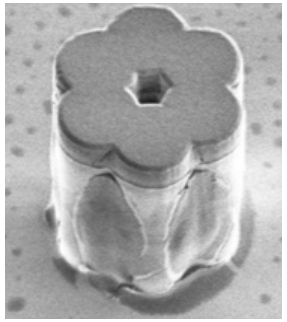
Outline

- **Introduction to cavity polaritons**



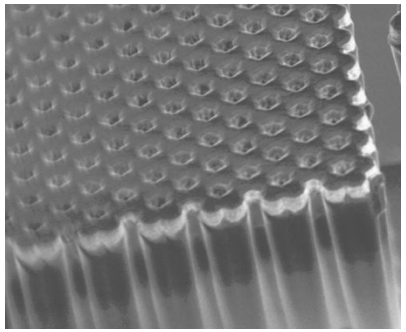
- **Benzene photonic molecule:**

  Lasing with angular momentum



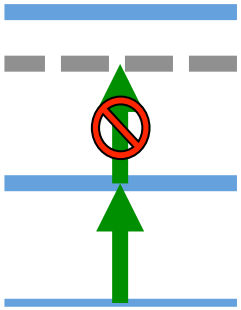
- **Photonic graphene:**

  Manipulation of Dirac cones



- **Towards synthetic quantum materials:**

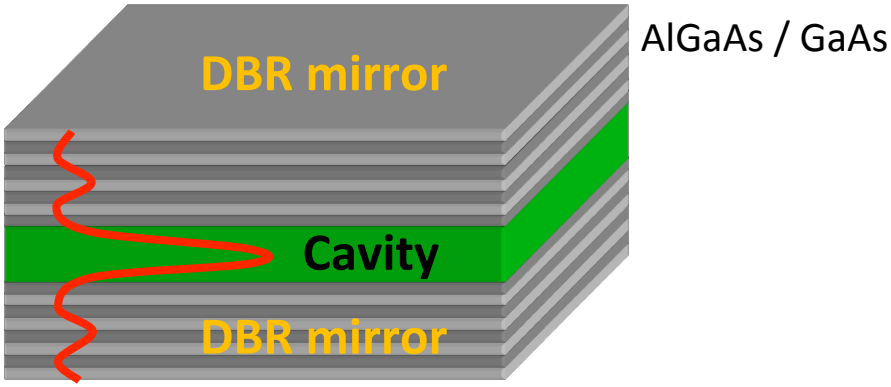
  Enhancing polariton-polariton interactions

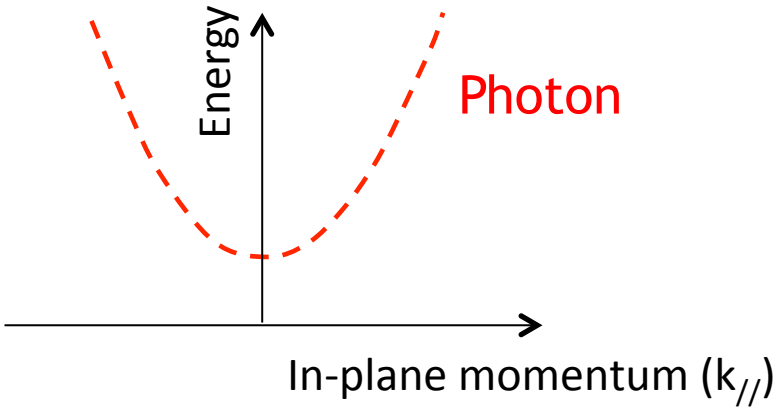


- **Perspectives**

Semiconductor microcavity polaritons

Cavity photon

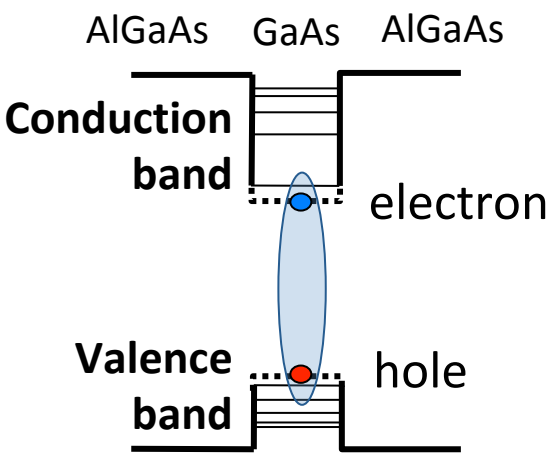


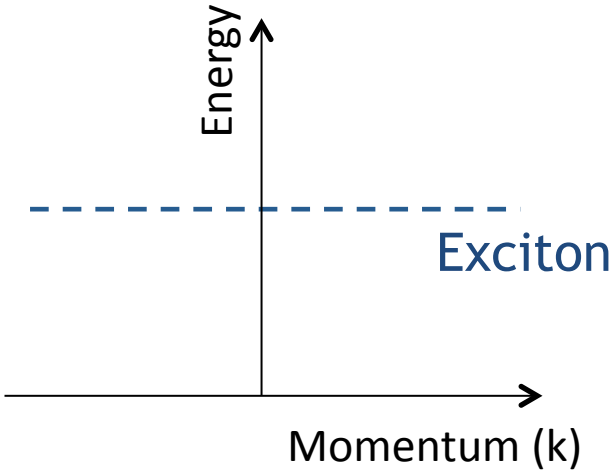


$$E_{\mathrm{cav}} = \frac{\hbar c}{n}\sqrt{k_x^2 + k_y^2 + \left(\frac{p\pi}{L_{\mathrm{cav}}}\right)^2}$$

$$E_{\mathrm{cav}}(k) \simeq E_{\mathrm{cav}}(k=0) + \frac{\hbar^2 k^2}{2M_{\mathrm{phot}}}$$

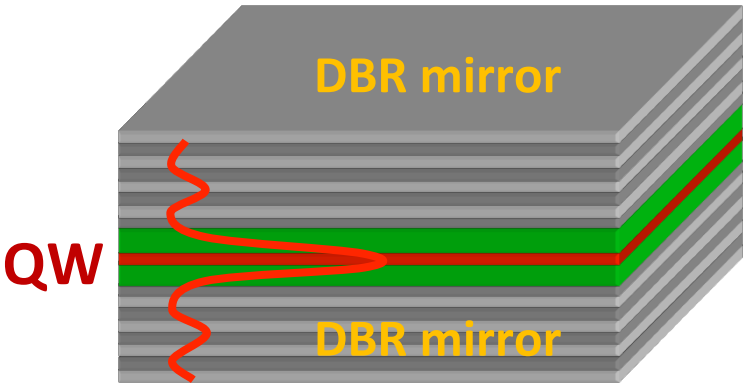
Quantum well exciton

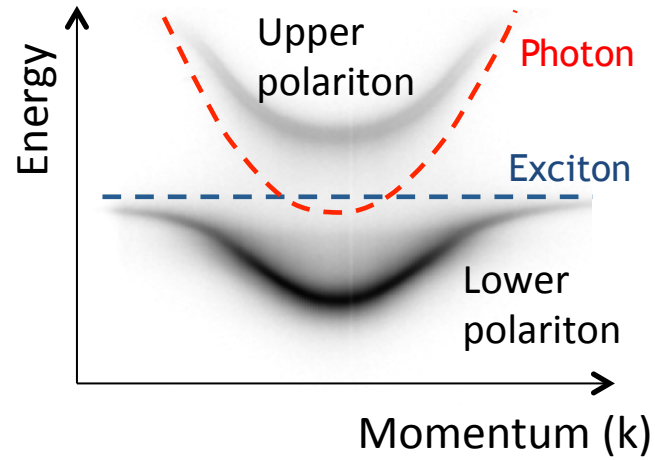




Semiconductor microcavity polaritons

Microcavity polaritons : mixed exciton-photon states PRL **69**, 3314 (1992)





$$|\mathrm{pol}\rangle = C_k\,|\mathrm{phot}\rangle + X_k\,|\mathrm{exc}\rangle$$

PROPERTIES

Photonic component:

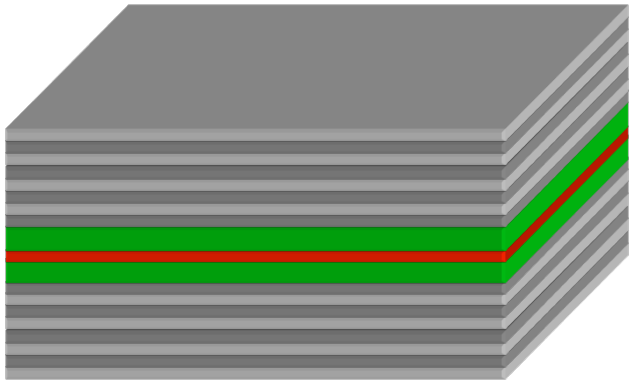
- confinement in microstructures
- real space, k-space imaging

Excitonic component:

- Interactions - $\chi^{(3)}$ (dominated by exchange)
- Gain (lasing)
- Sensitivity to magnetic field

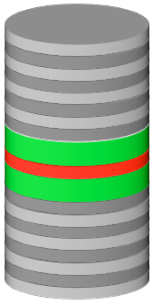
Our building blocks: polariton micropillars

2D
(MBE grown)



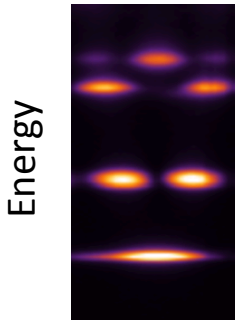
etching

single pillar
2-4 μm



"Photonic atom"

discrete energy states



photonic orbitals

d
p
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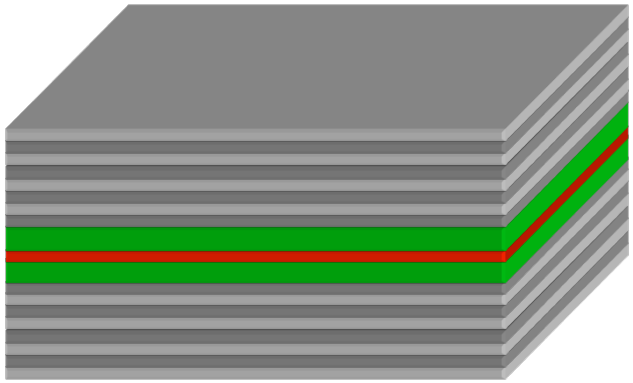
Our building blocks: polariton micropillars

2D (MBE grown)



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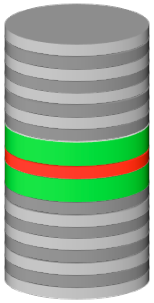

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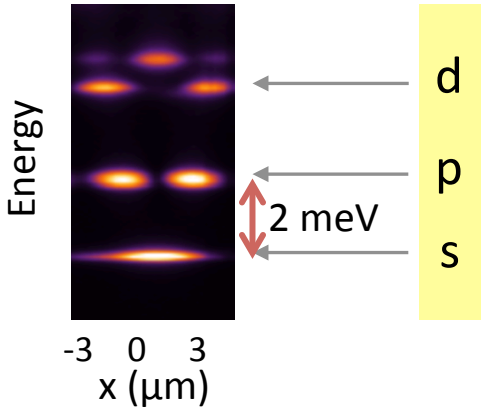
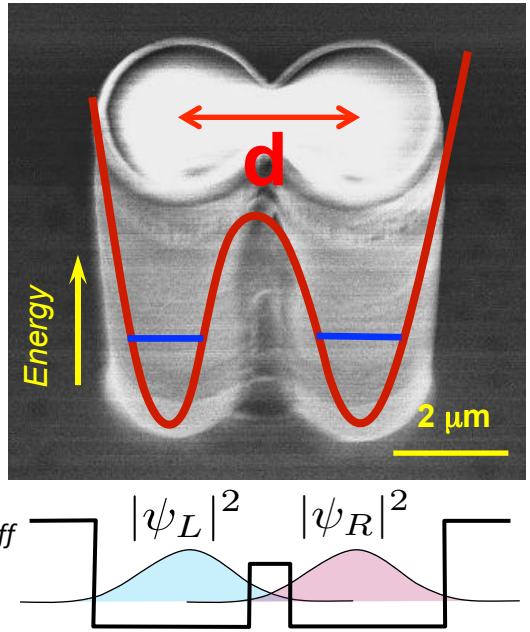
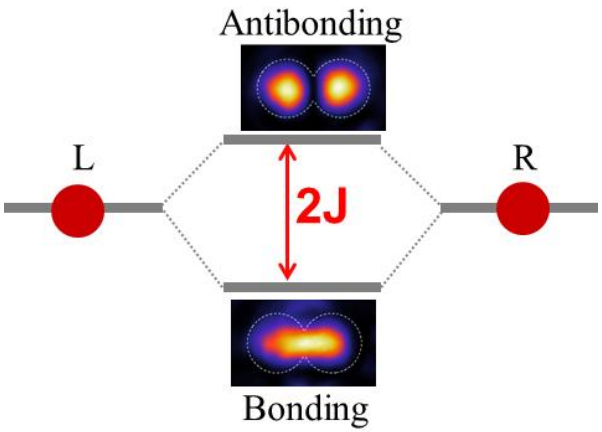


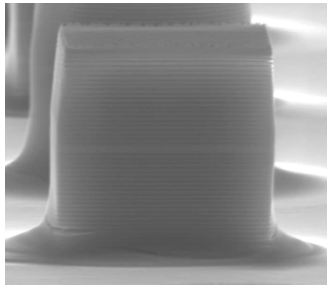
Tight-binding approach: Coupling through the photonic component

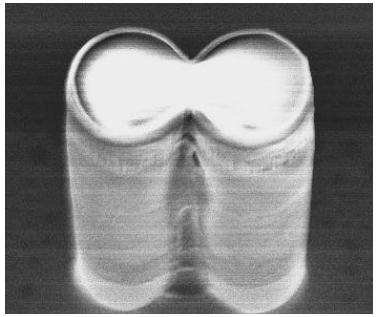


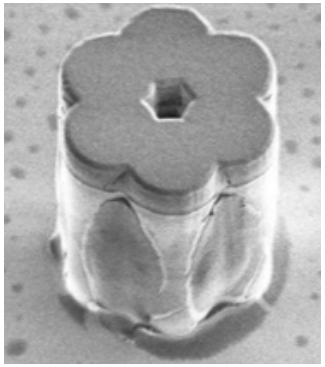


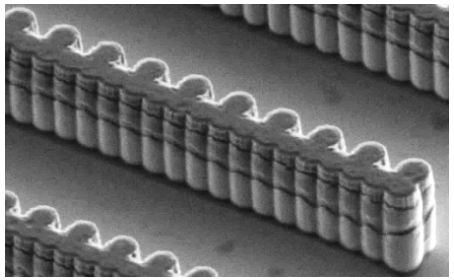
Michaelis de Vasconcellos et al., APL **99**, 101103 (2011)
Galbiati et al., PRL **108**, 126403 (2012)

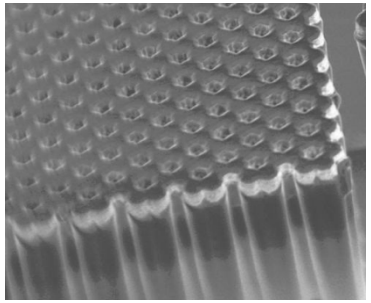
Polariton lattices: tight-binding approach





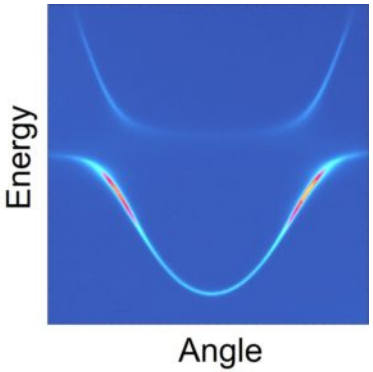






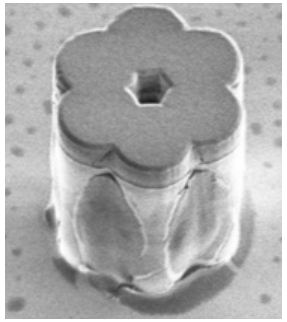
Outline

- Introduction to cavity polaritons



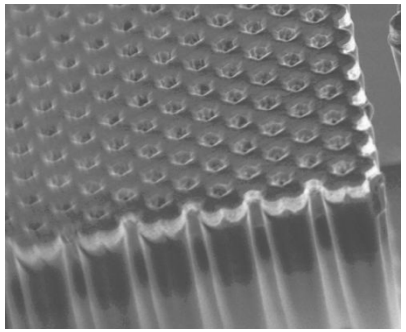
- **Benzene photonic molecule:**

  Lasing with angular momentum



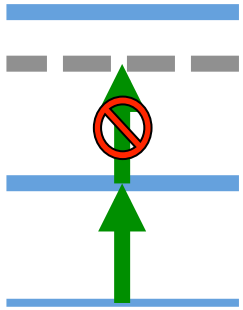
- Photonic graphene:

  Manipulation of Dirac cones



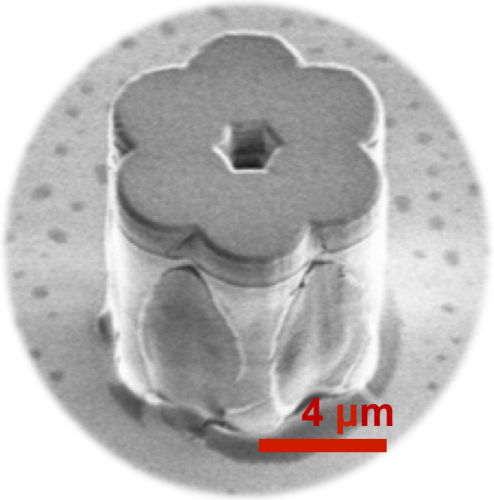
- Towards synthetic quantum materials:

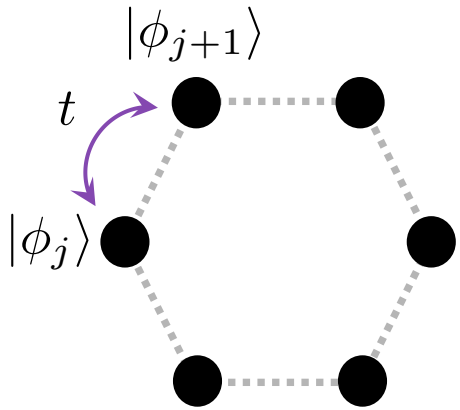
  Enhancing polariton-polariton interactions



- Perspectives

Periodic structures: photonic benzene





Periodic boundary conditions

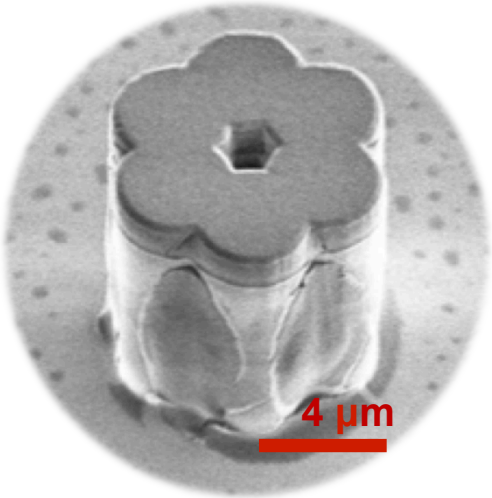
Tight binding model

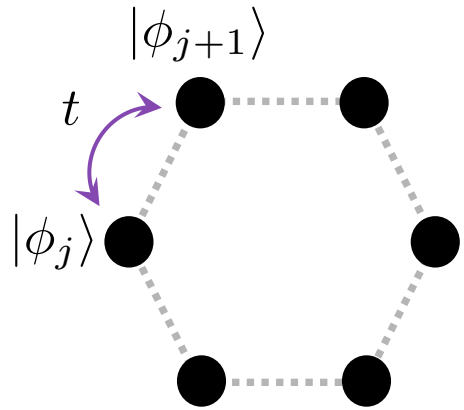
$$H = -t \sum_{j=1}^{6} (|\phi_j\rangle \langle\phi_{j+1}| + |\phi_{j+1}\rangle \langle\phi_j|)$$

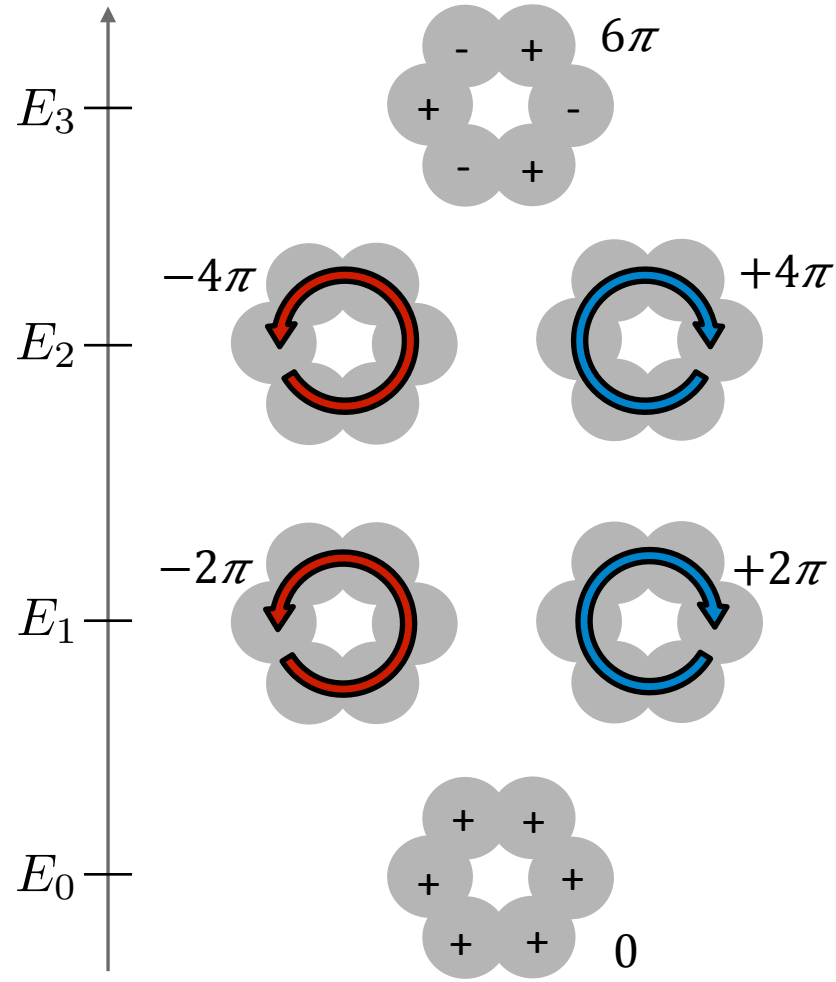
Vortical eigenstates

$$|l\rangle = \frac{1}{\sqrt{6}} \sum_{j=1}^{6} e^{\frac{2i\pi j}{6} l} |\phi_j\rangle$$

Periodic structures: photonic benzene







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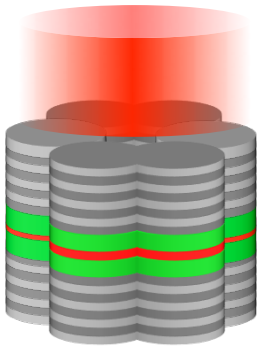
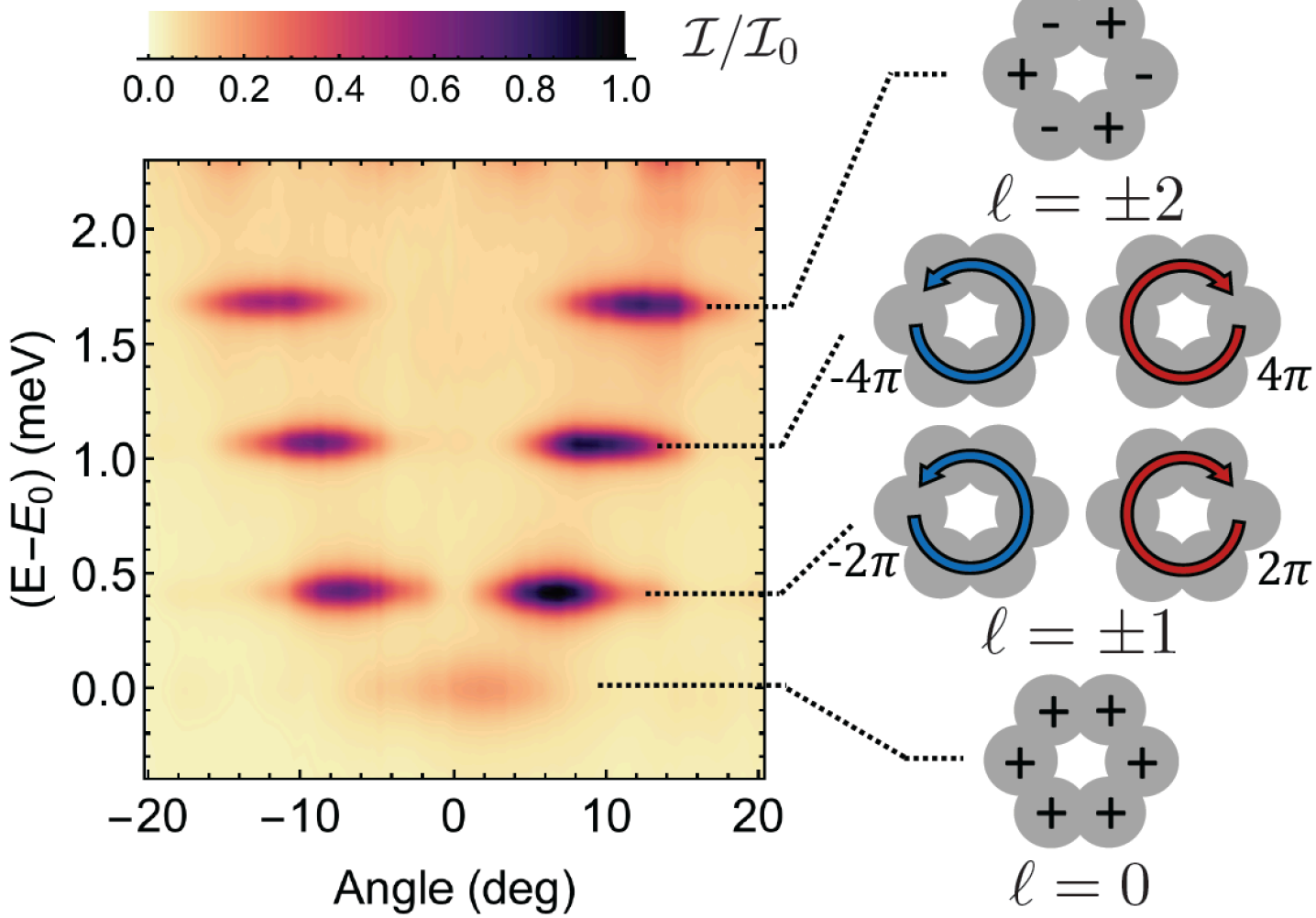
L: angular momentum

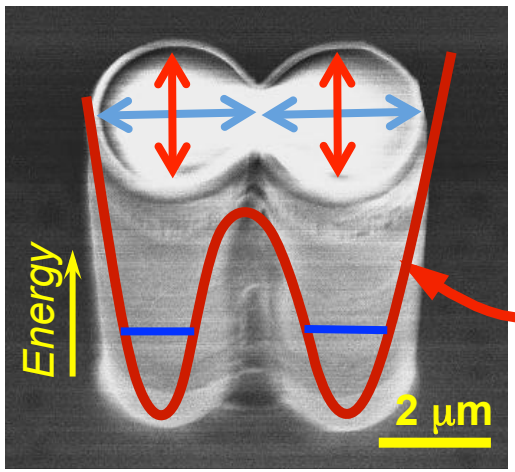
Polariton eigenstates

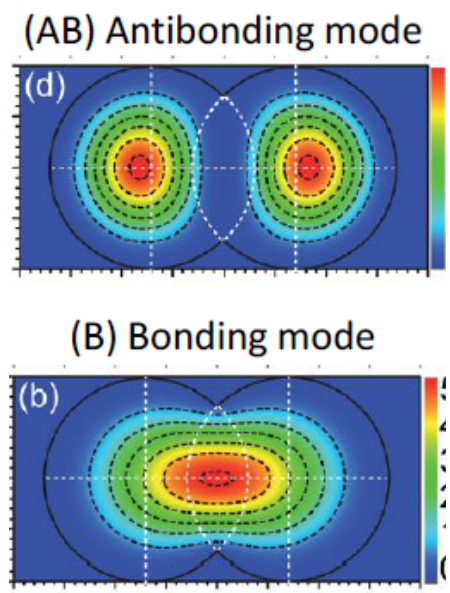


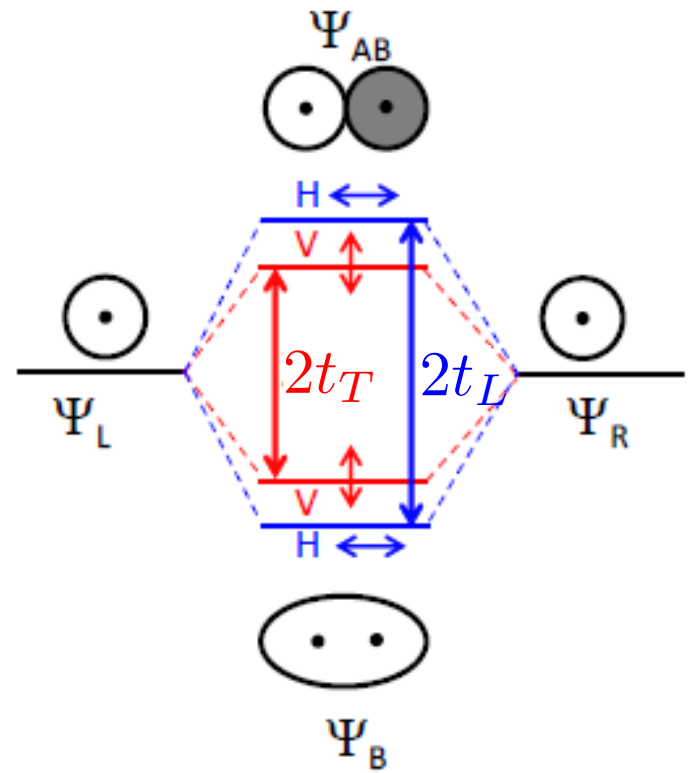


Polarisation dependent tunnelling

Tunnel coupling depends on incident polarisation!





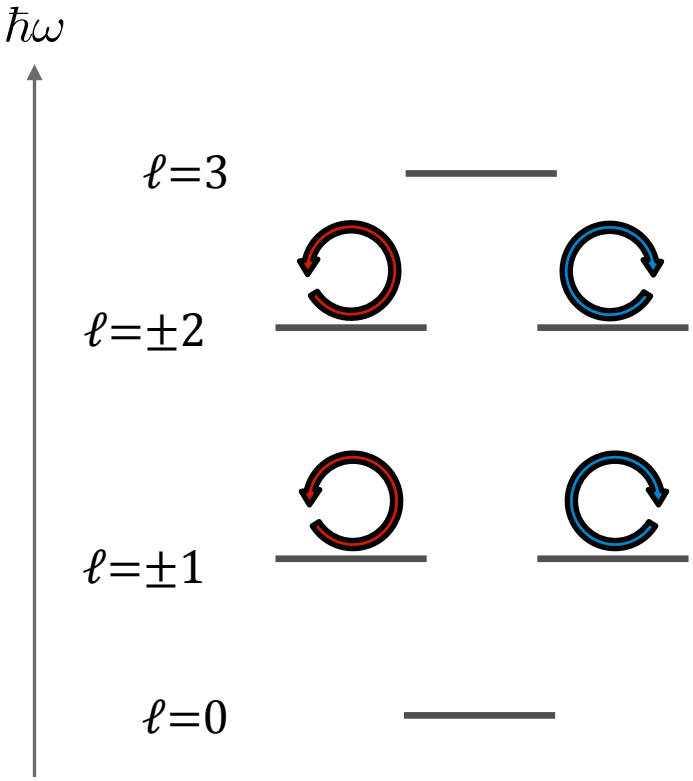


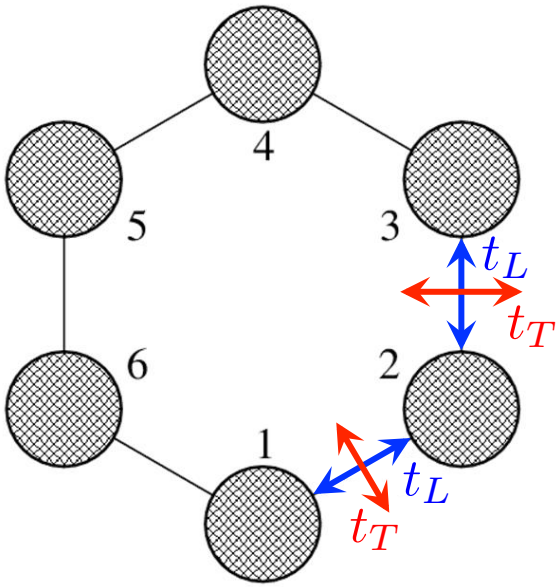
$$t_L \neq t_T$$

Michaelis de Vasconcellos et al., APL **99**, 101103 (2011)

Spin-orbit coupling

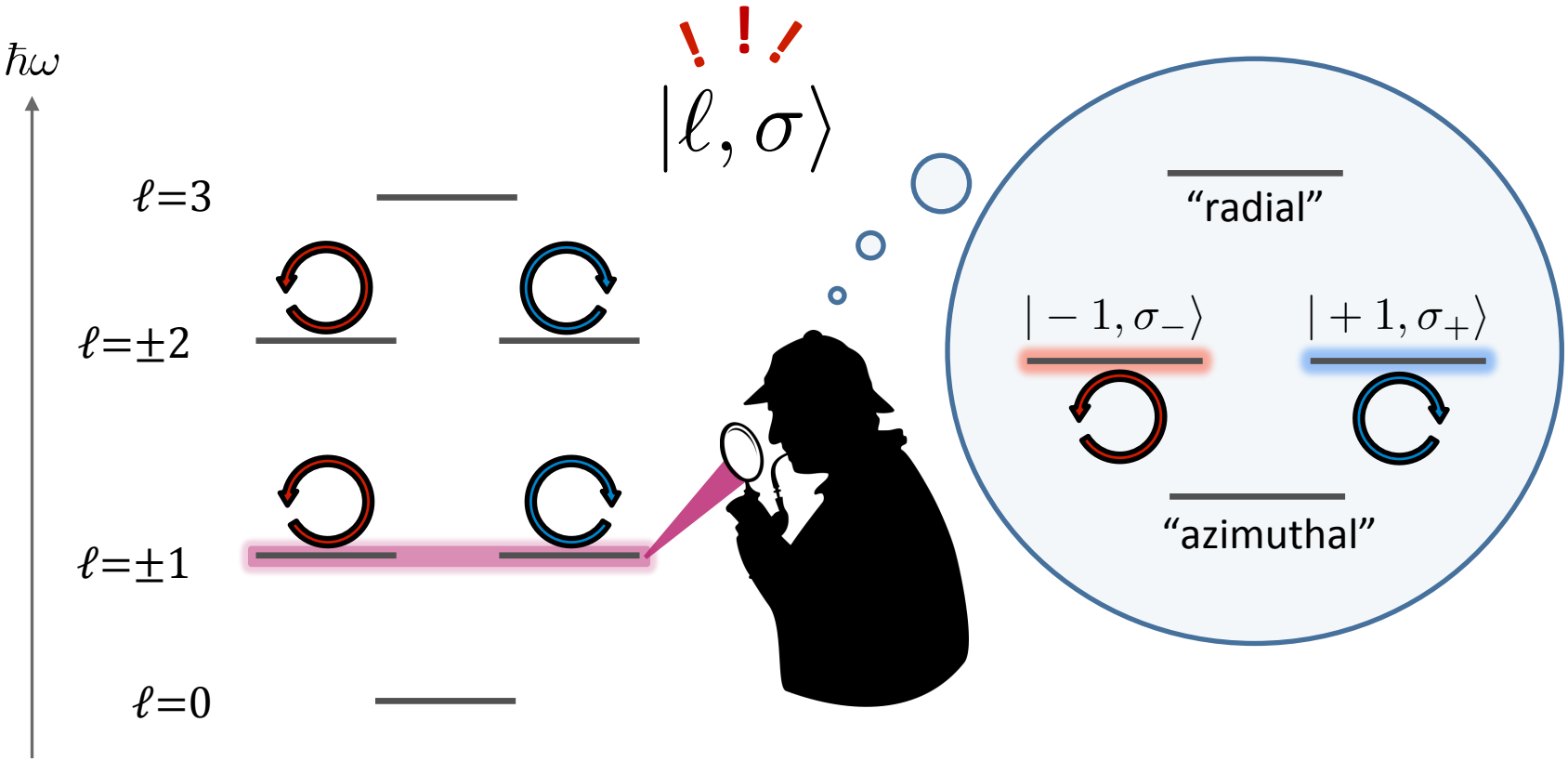
Double degeneracy σ+, σ-





$$H = -\sum_{j=1}^{6} \hbar t_L (\hat{\mathbf{a}}_{j+1}^{\dagger} \cdot \mathbf{e}_L^{(j)})(\mathbf{e}_L^{(j)\dagger} \cdot \hat{\mathbf{a}}_j) + \hbar t_T (\hat{\mathbf{a}}_{j+1}^{\dagger} \cdot \mathbf{e}_T^{(j)})(\mathbf{e}_T^{(j)\dagger} \cdot \hat{\mathbf{a}}_j) + \mathrm{h.c.}$$

Spin-orbit coupling -|L|=1 Fine Structure



Radial & Azimuthal modes:

$$|\psi_{r,a}\rangle = \frac{1}{\sqrt{2}}\left(e^{\frac{2\pi i}{6}}|-1,\sigma_+\rangle \pm e^{-\frac{2\pi i}{6}}|+1,\sigma_-\rangle\right)$$

V.G. Sala et al., Phys. Rev. X 5, 011034 (2015)

Orbital Angular Momentum Lasing

Non resonant
optical excitation

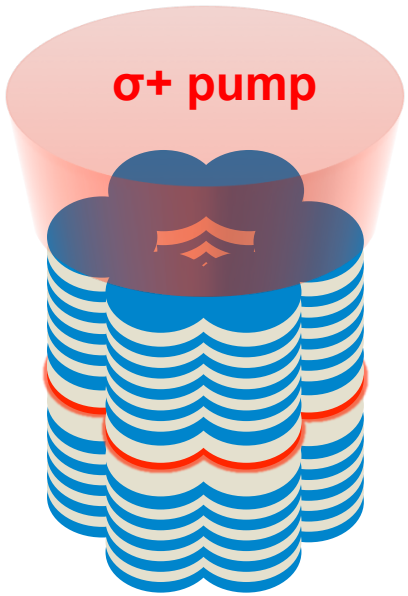
Excitons provide optical gain ⇒ **LASING**

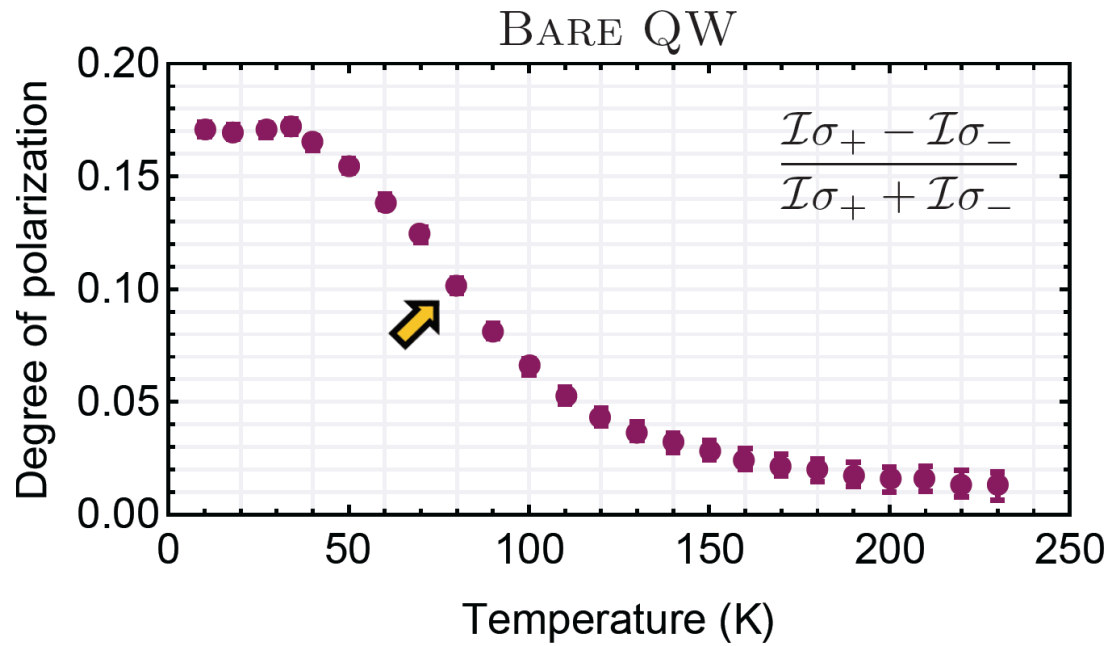
Lasing in which mode?

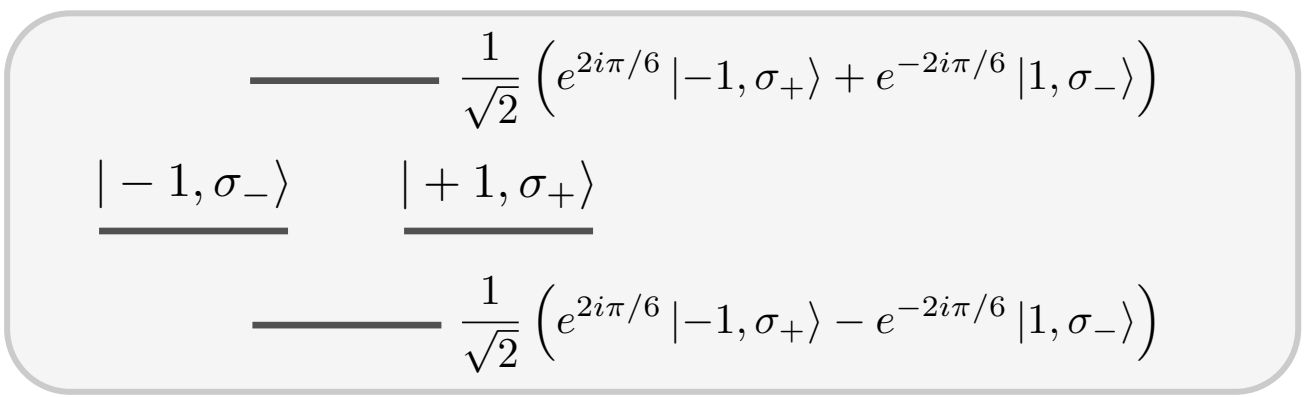
Lasing in mode with largest gain

Orbital Angular Momentum Lasing

Excitons can be spin polarized up to 100K in InGaAs QWs:







Orbital Angular Momentum Lasing

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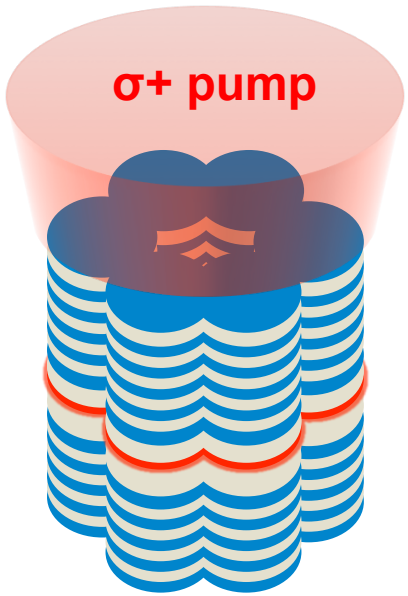
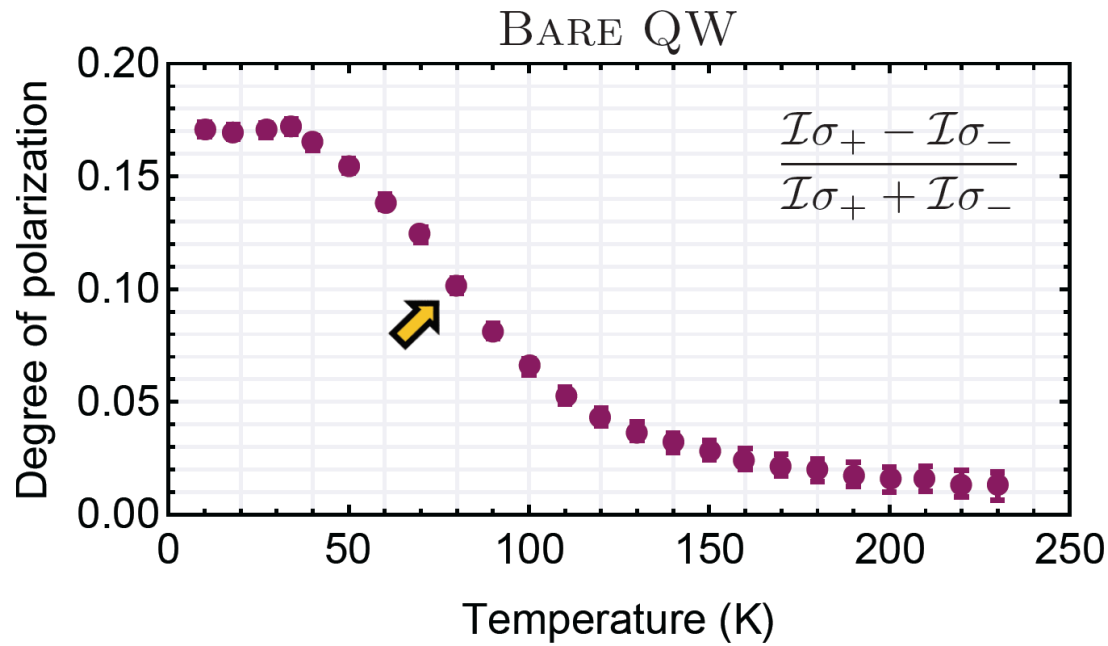
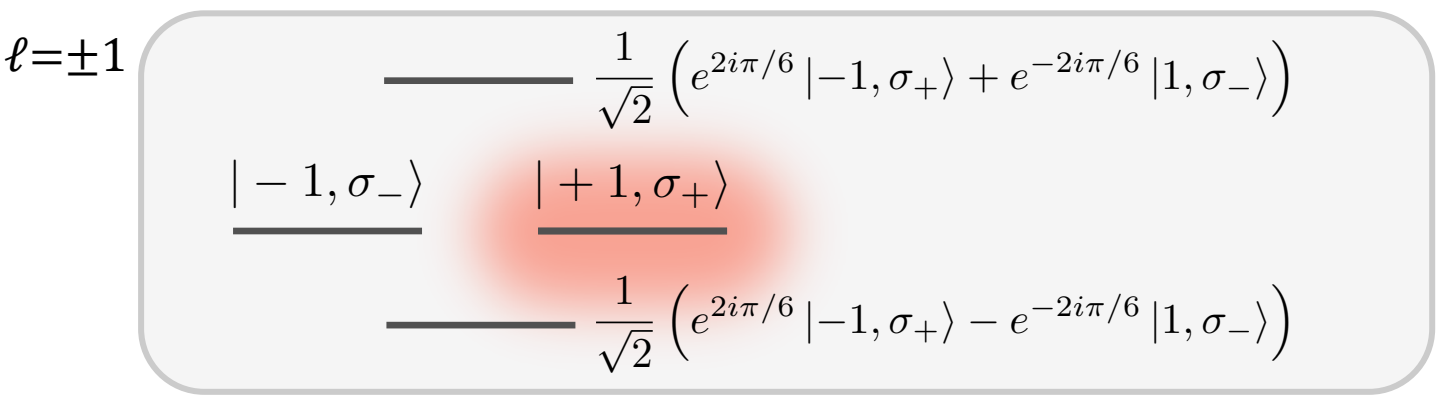
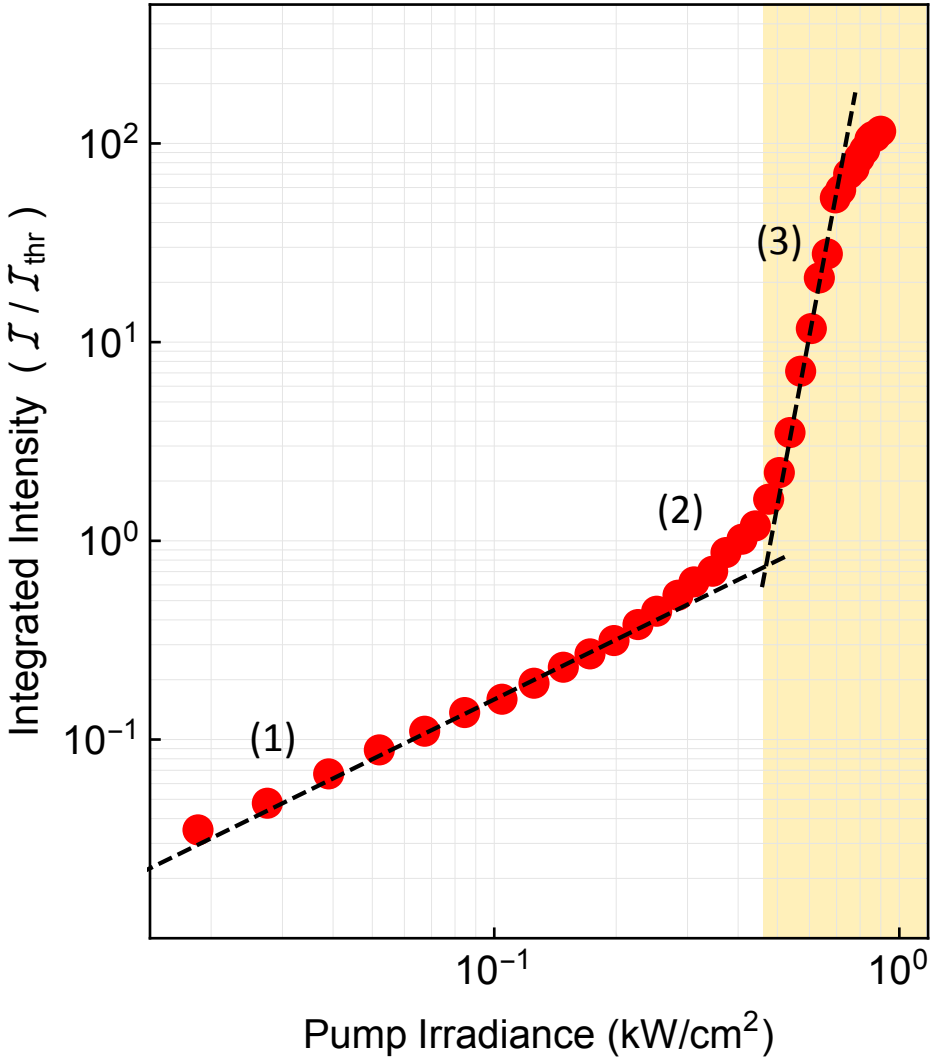


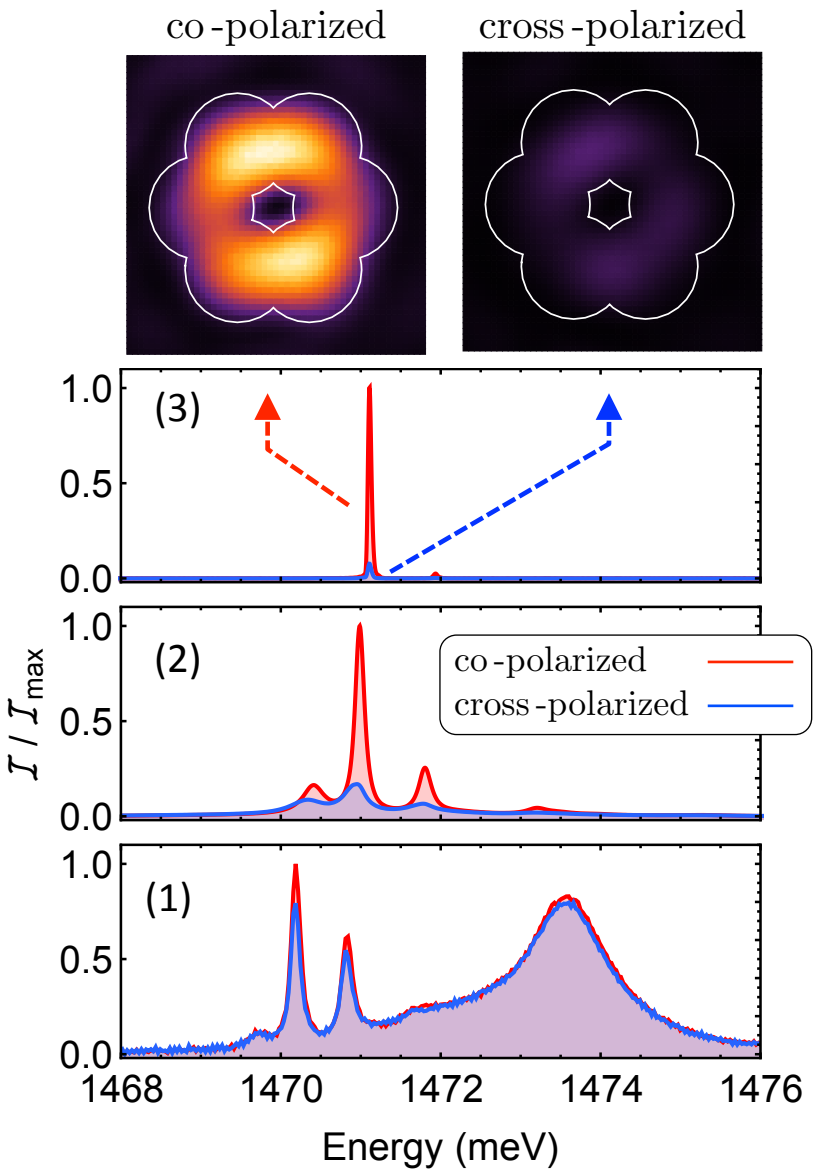




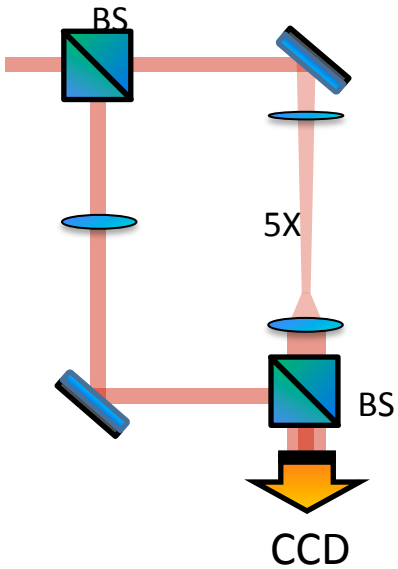
Lasing mode with angular momentum

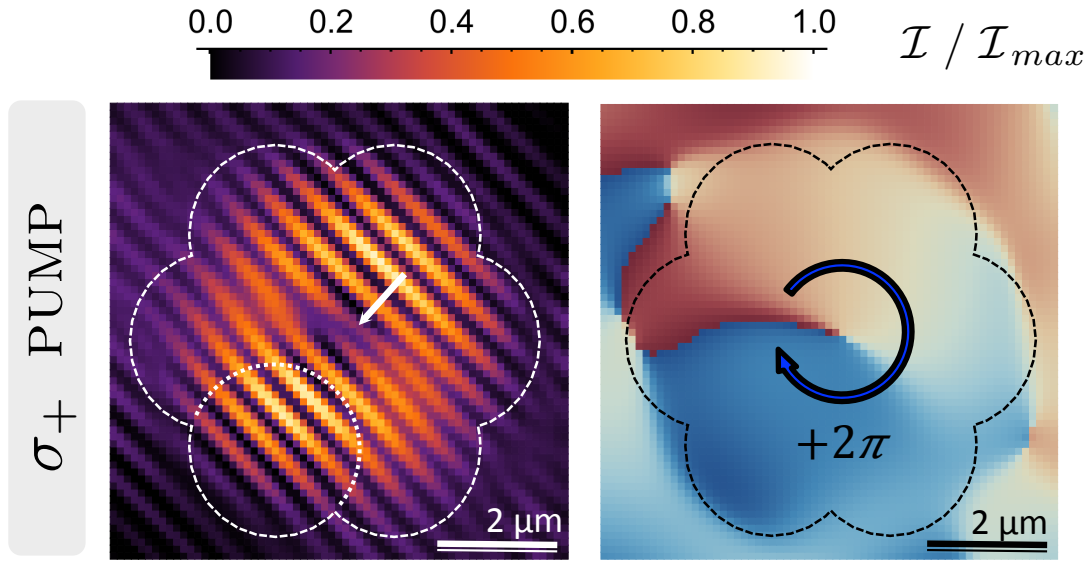
OAM Lasing with |L|=1

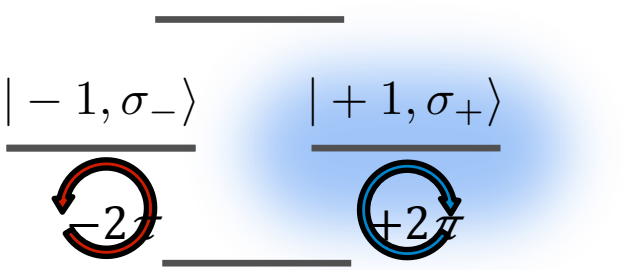


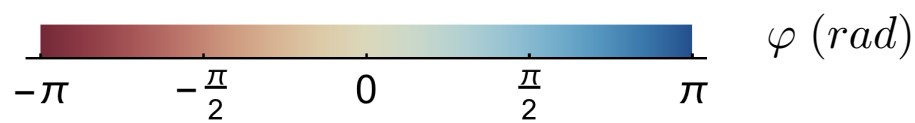


OAM Lasing with |L|=1









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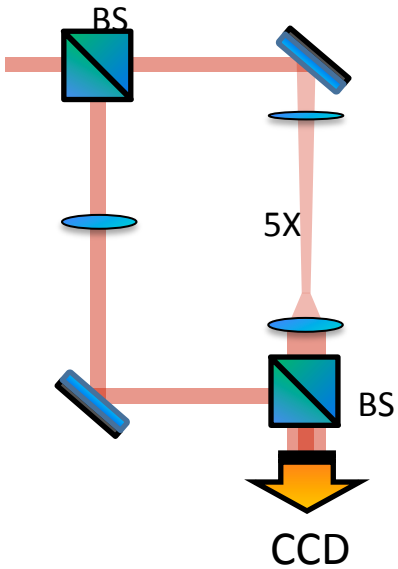
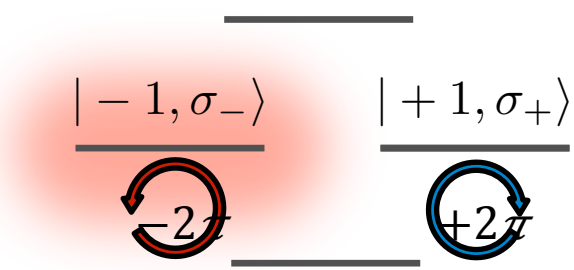
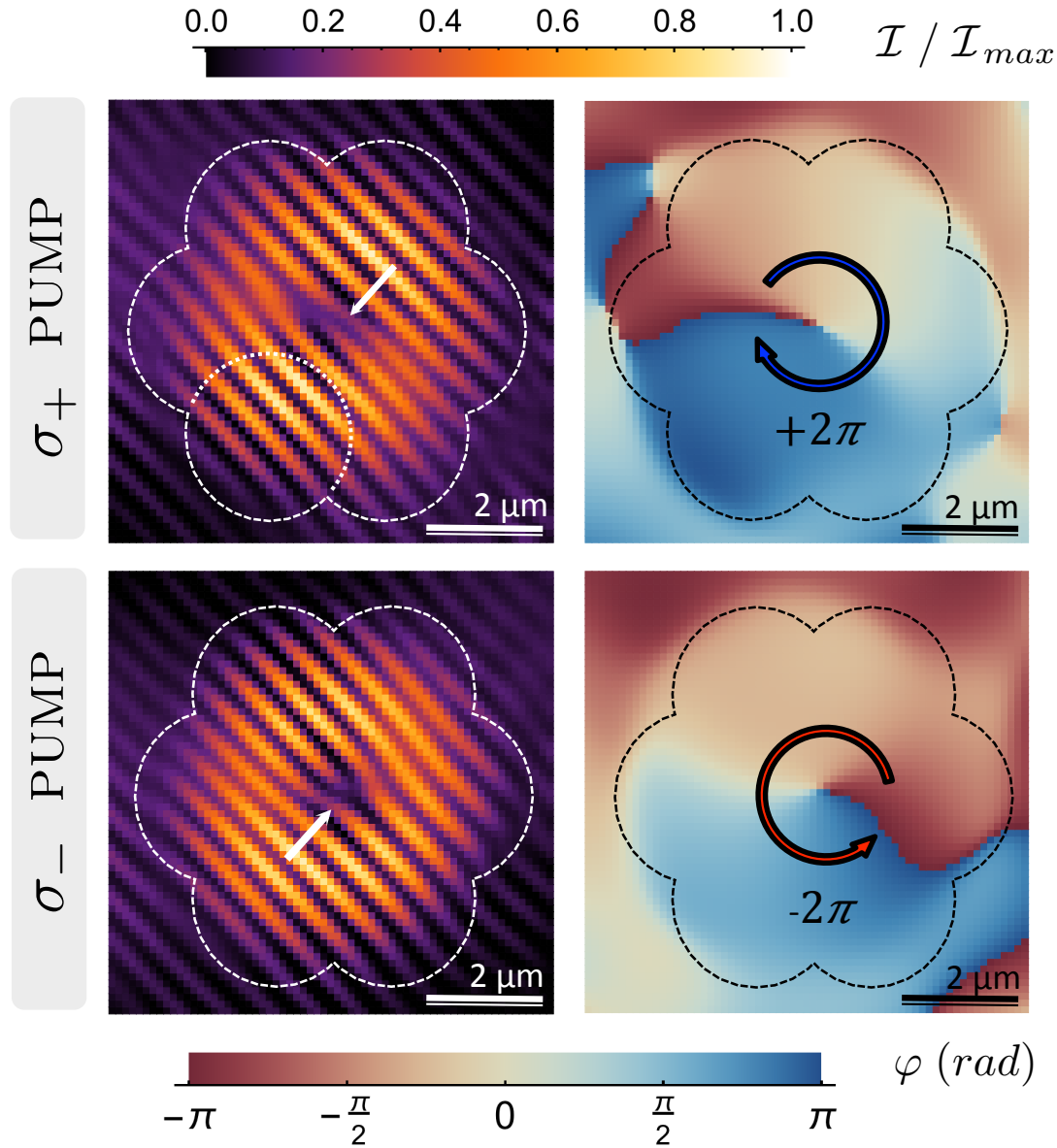
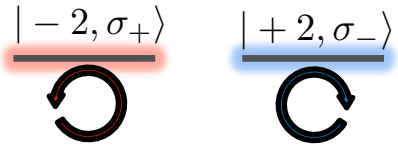
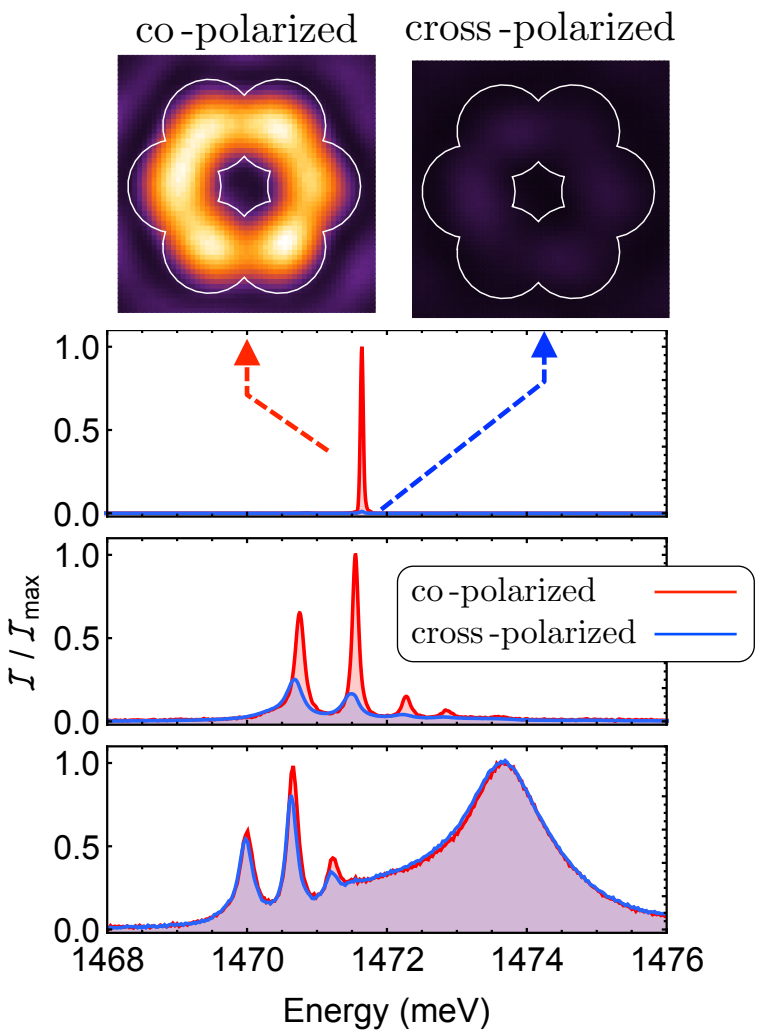


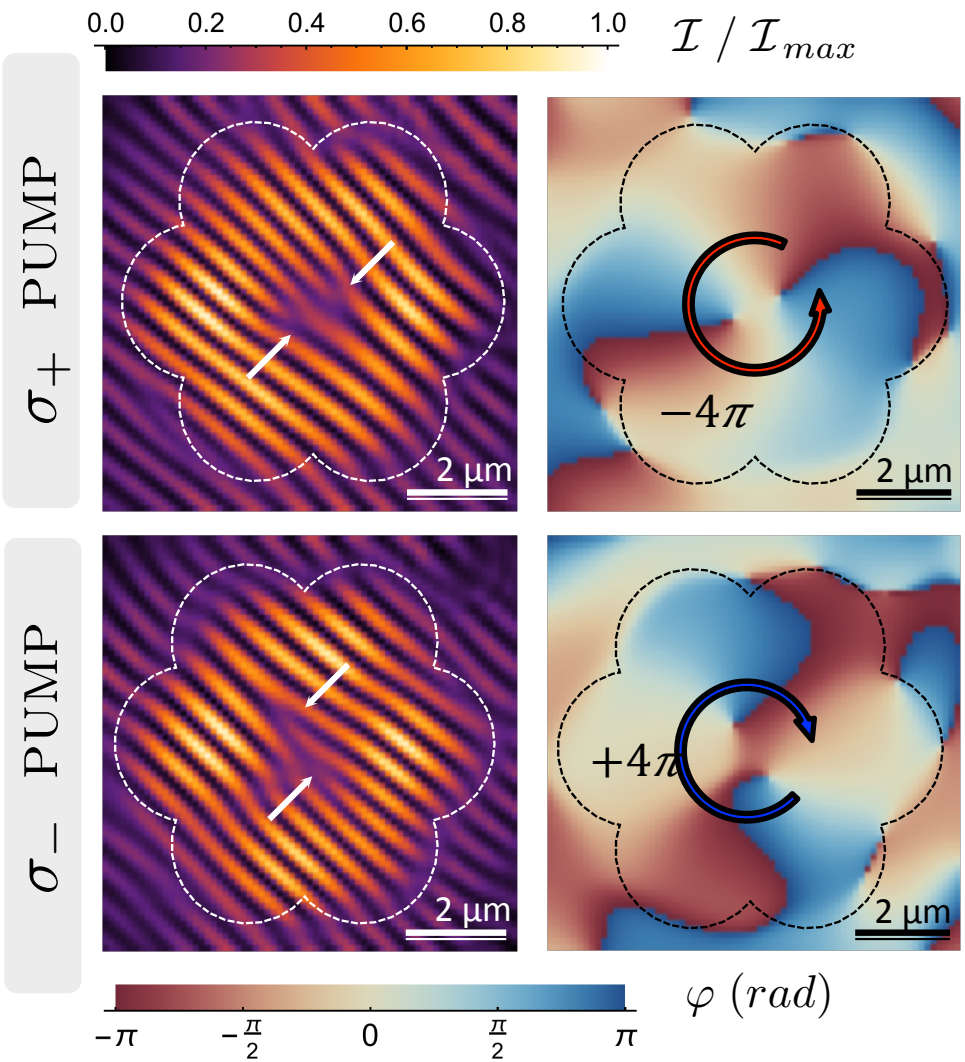




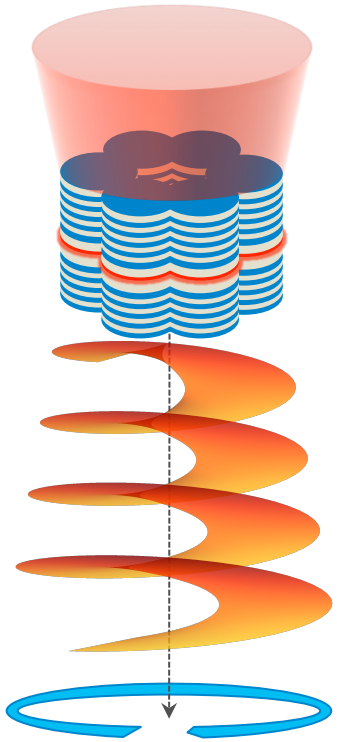
OAM Lasing with |L|=2







Summary: A General Recipe



Spin-Orbit interactions of light

Spin-polarized gain medium

Optical control of the chirality in a OAM microlaser via polarization of the excitation

N. Carlon Zambon et al., in preparation (2018)

Outline

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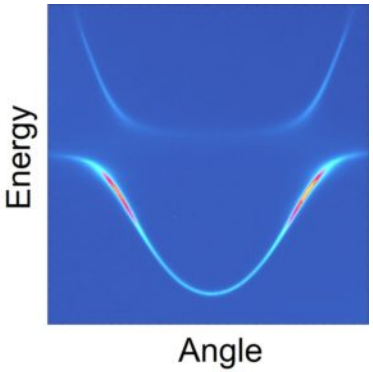

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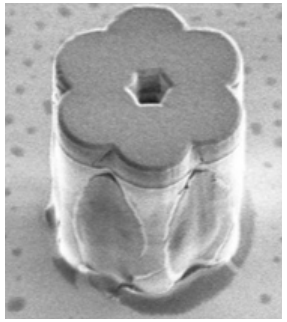
  Lasing with angular momentum



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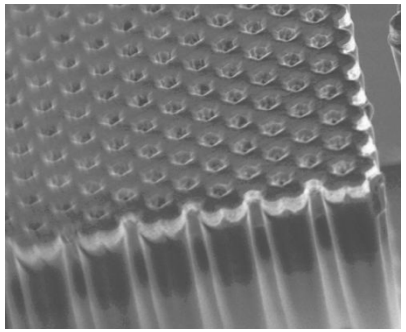

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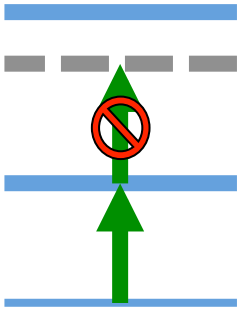
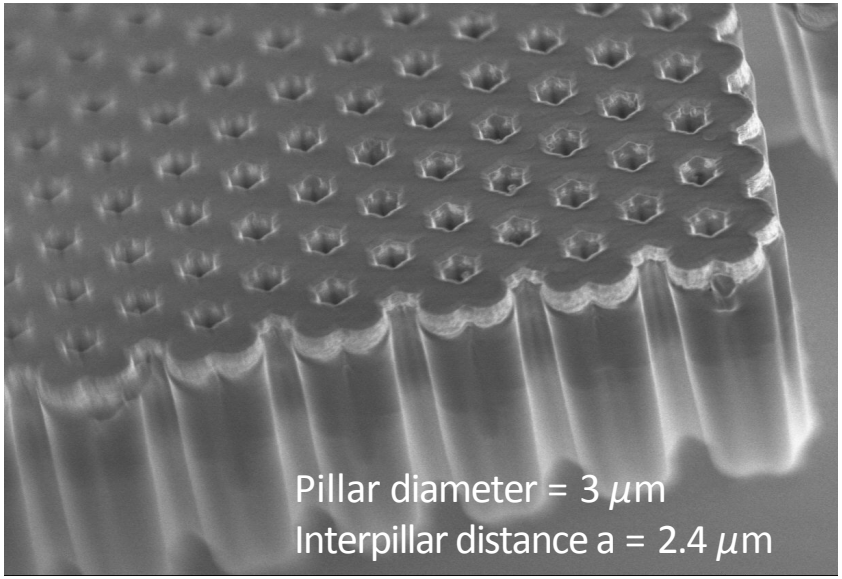


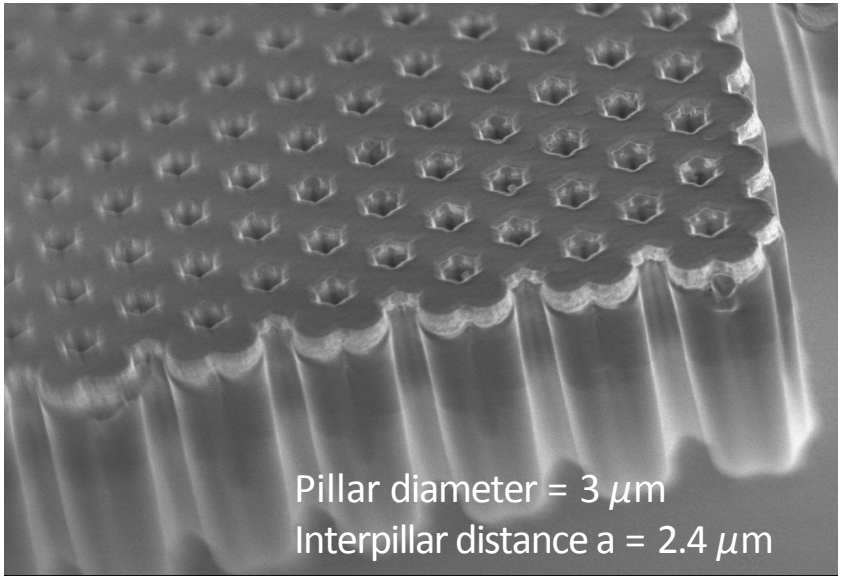
- Perspectives

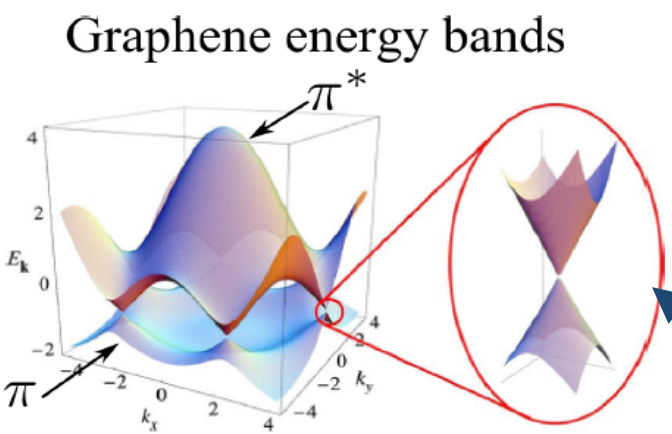
Polariton honeycomb lattice



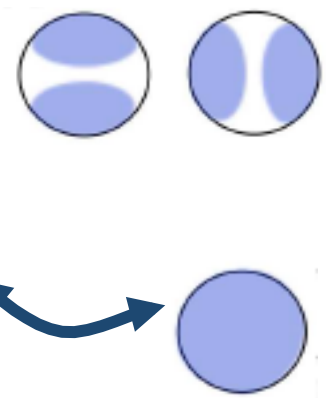
Jacqmin *et al.,* PRL **112,** 116402 (2014)

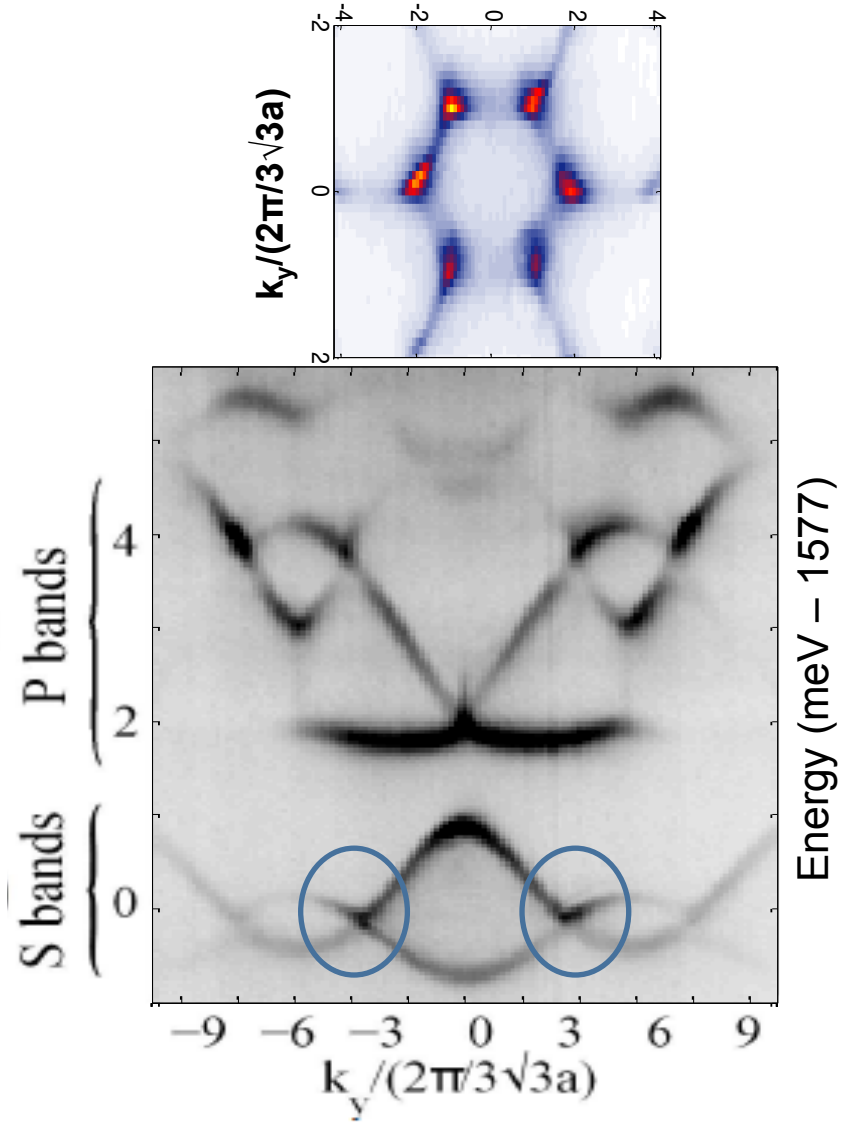
Polariton honeycomb lattice





Castro Neto et al., Rev. Mod. Phys. 81 (2009)



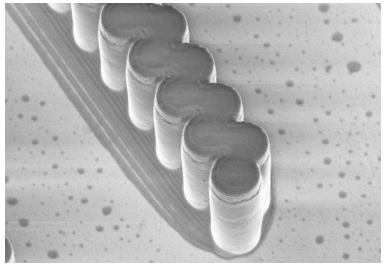


Polariton Dirac cones

Jacqmin *et al.,* PRL **112,** 116402 (2014)

Emulation of other systems with polaritons

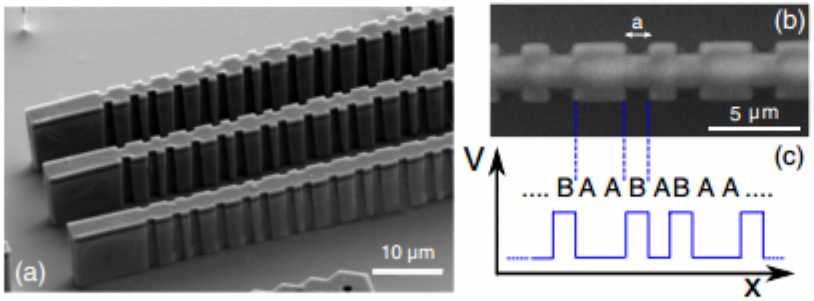
SSH dimer chains (1D)



Solnyshkov et al.,
Phys. Rev. Lett **116**, 046402 (2016)

St-Jean et al.,
arXiv:1704.07310 (2017)

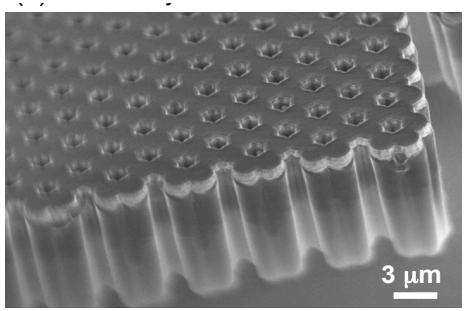
Fibonacci quasicrystals (1D)

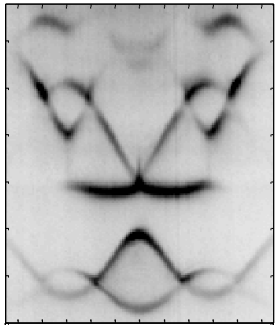


Tanese et al.,
Phys. Rev. Lett **112**, 116404 (2014)

Baboux et al.,
Phys. Rev. B (R) **95**, 161114(R) (2017)

Graphene (2D)





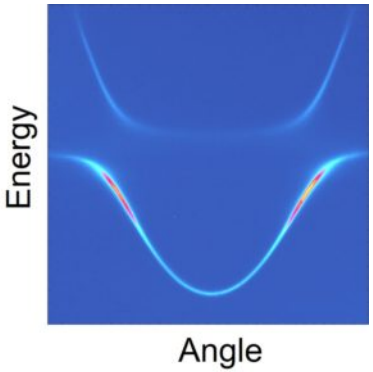
Jacqmin et al.,
Phys. Rev. Lett **112**, 116402 (2014)

Milicevic et al.,
2D Materials **2**, 034012 (2015)

Milicevic et al.,
Phys. Rev. Lett **118**, 107403 (2017)

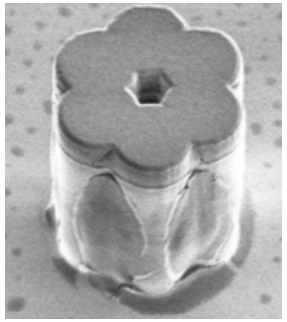
Outline

- Introduction to cavity polaritons



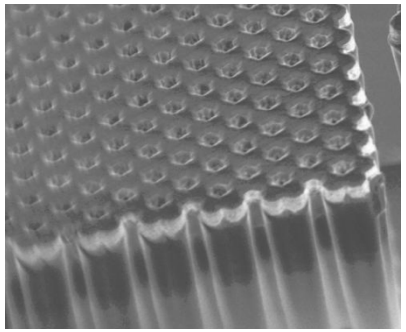
- Benzene photonic molecule:

  Lasing with angular momentum



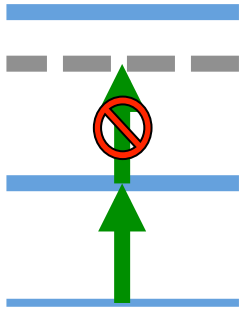
- Photonic graphene:

  Manipulation of Dirac cones



- **Towards synthetic quantum materials:**

  Enhancing polariton-polariton interactions

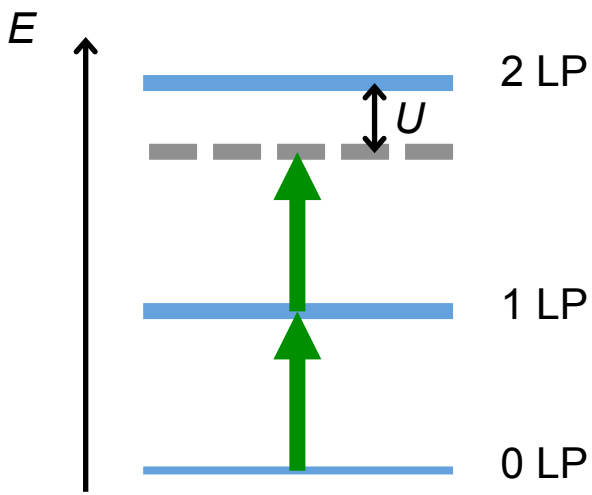


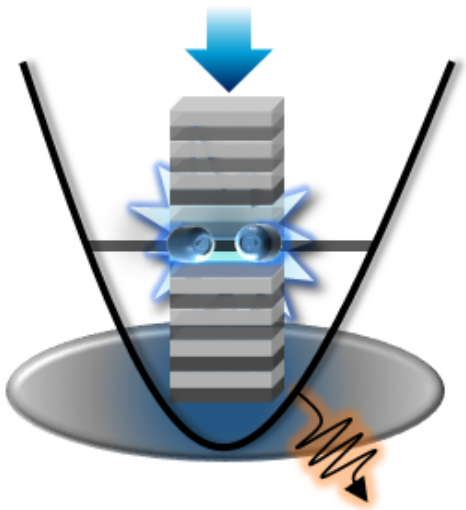
- Perspectives

Polariton blockade

- Reminder: polaritons are interacting particles!

- Consequence: **non linearity** in the excitation spectrum

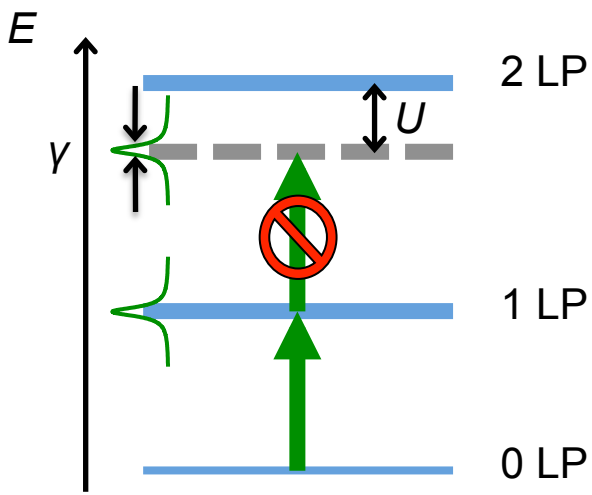


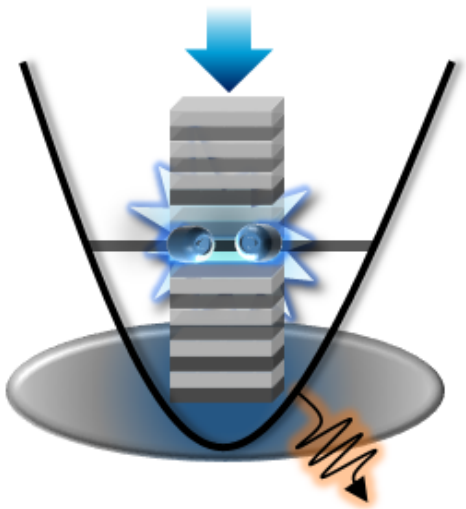


Polariton blockade

- Reminder: polaritons are interacting particles!

- Consequence: **non linearity** in the excitation spectrum





ULTIMATE GOAL: Single polariton regime $U > \gamma$

Polariton blockade

- Reminder: polaritons are interacting particles!

STATE OF THE ART

- Our cavities at C2N: ***γ* > 10 *μ*eV.**
- **Typical value of the interactions: U ≈ 1 *μ*eV**.

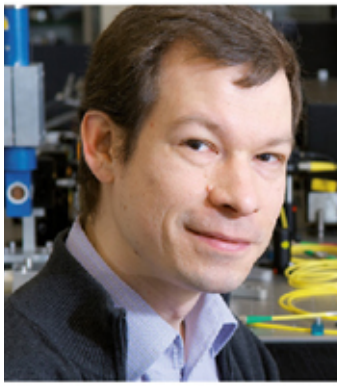
⇒ Enhance interactions by a factor of ≈ 10 (at constant linewidth).

ULTIMATE GOAL: Single polariton regime *U* > *γ*

Quantum photonics group at ETH Zurich

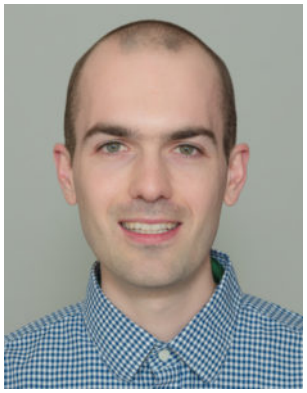
Permanent members:

A. Imamoglu
Professor
Group leader



M. Kroner
Senior scientist

Postdoc:



S. Ravets
(now at C2N)

Graduate student:

P. Knüppel

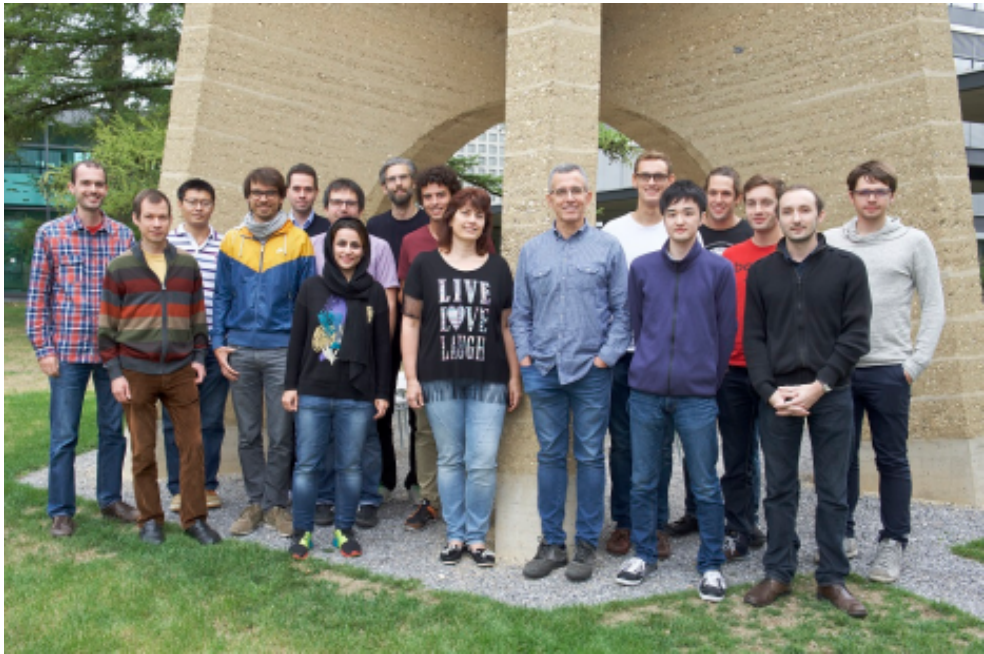
ETH zürich

quantum Φotonics

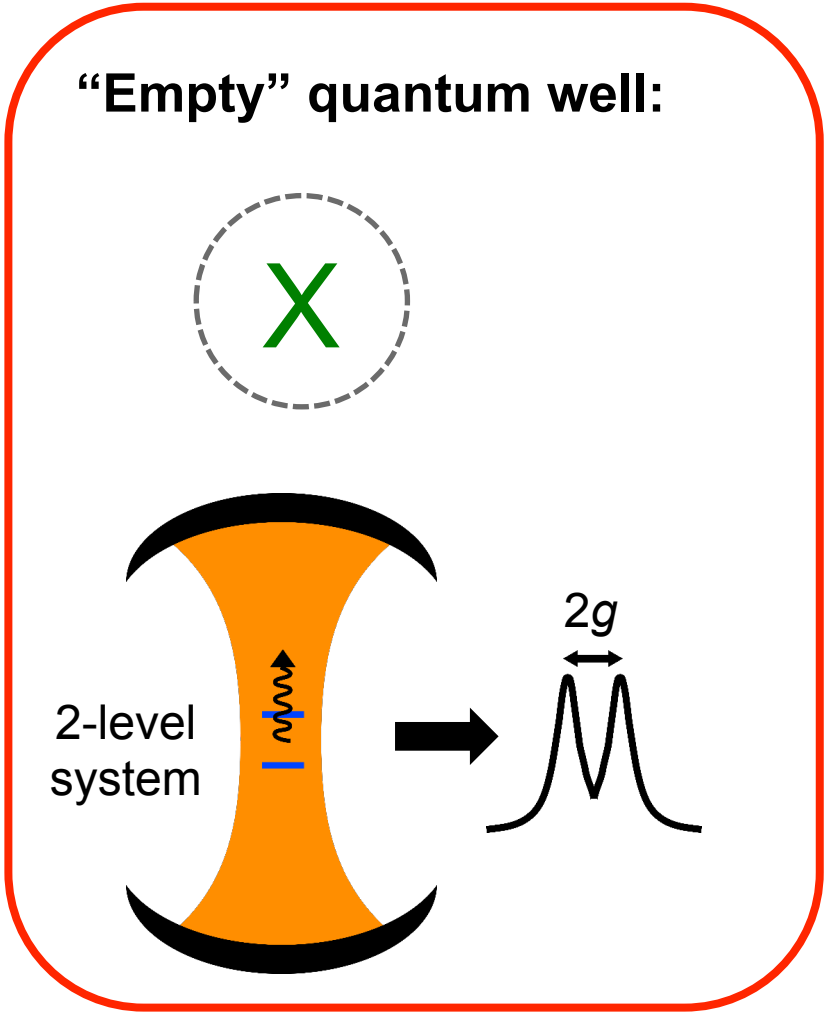
Sample fabrication:

W. Wegscheider
Professor

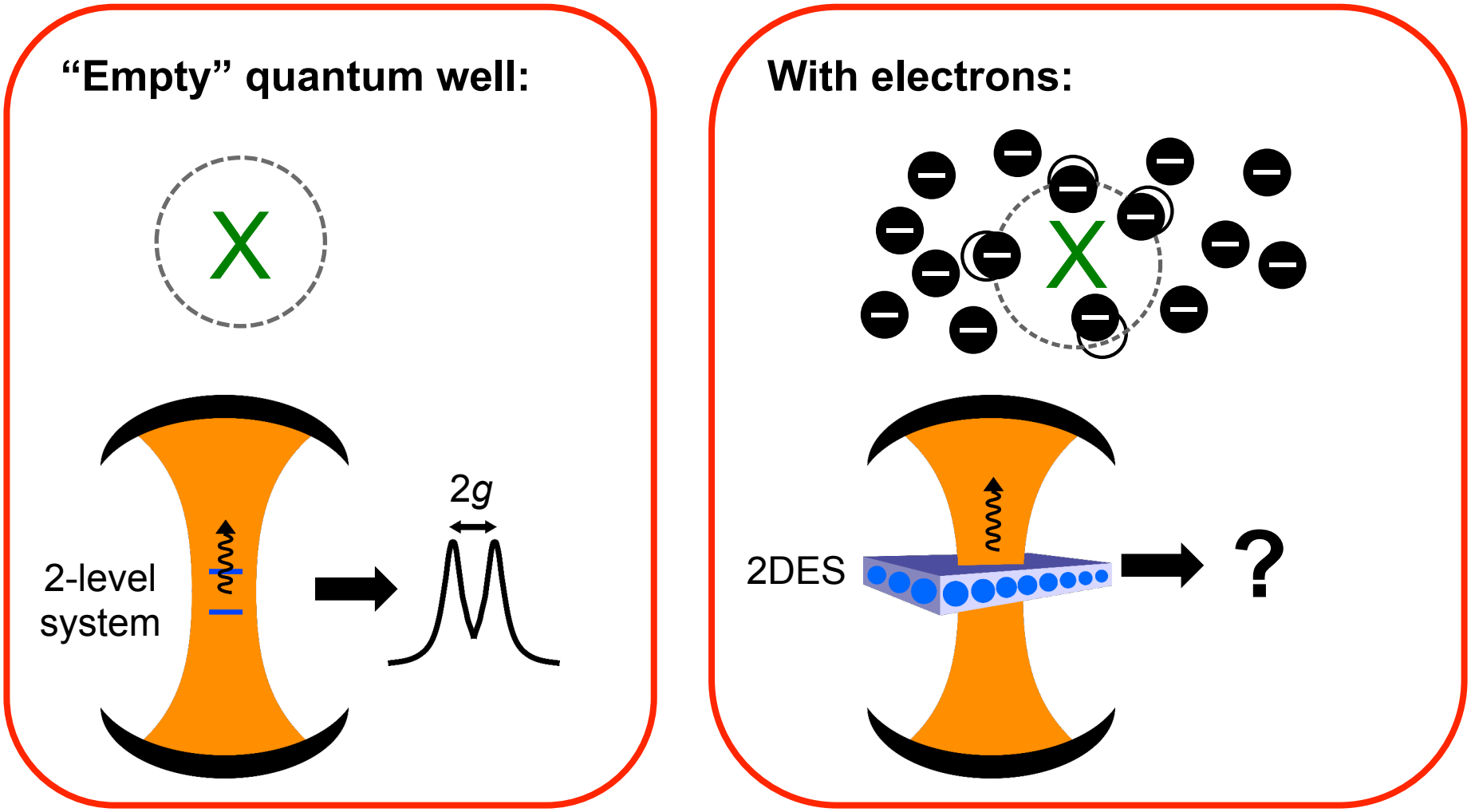
S. Faelt
Grower



The strategy: Fermi polarons in a 2DES



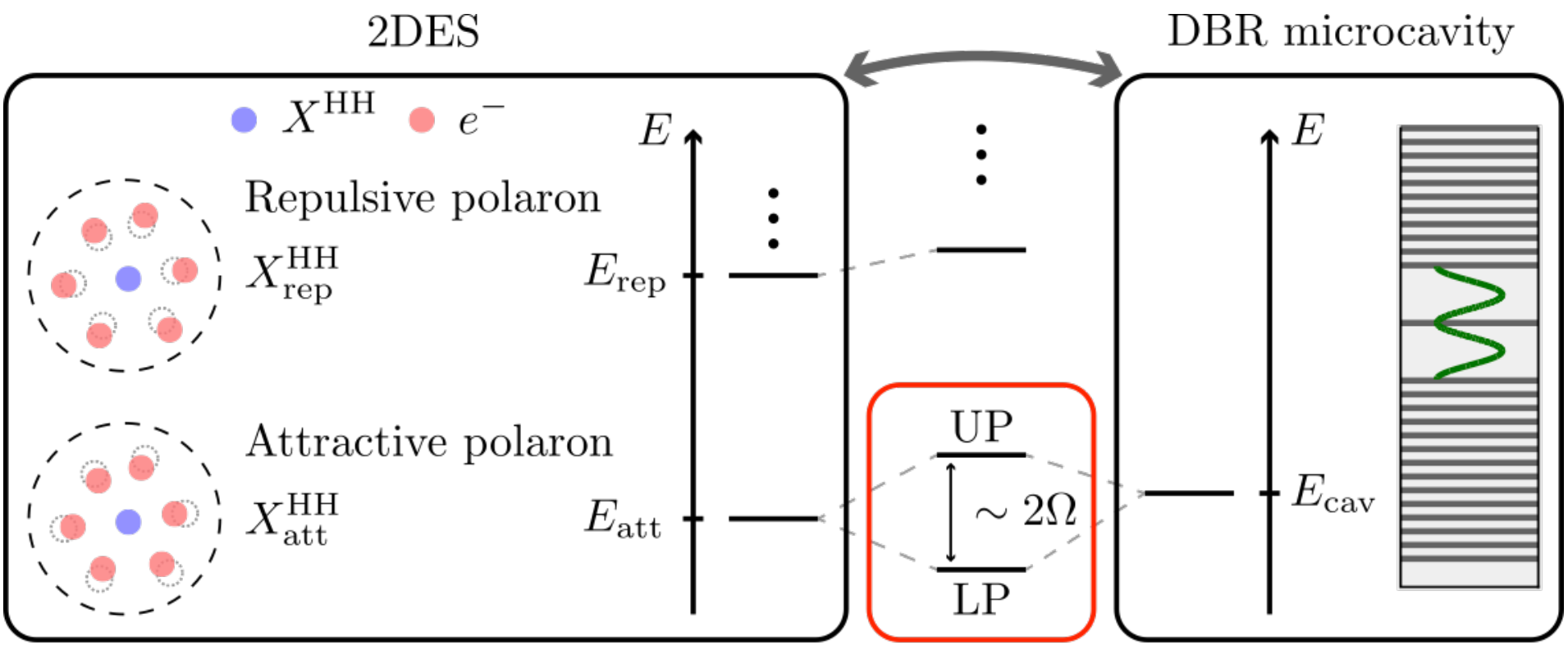
The strategy: Fermi polarons in a 2DES



Recent observation of polaron-polariton in TMDs: Nat. Phys. **13**, 255 (2017).

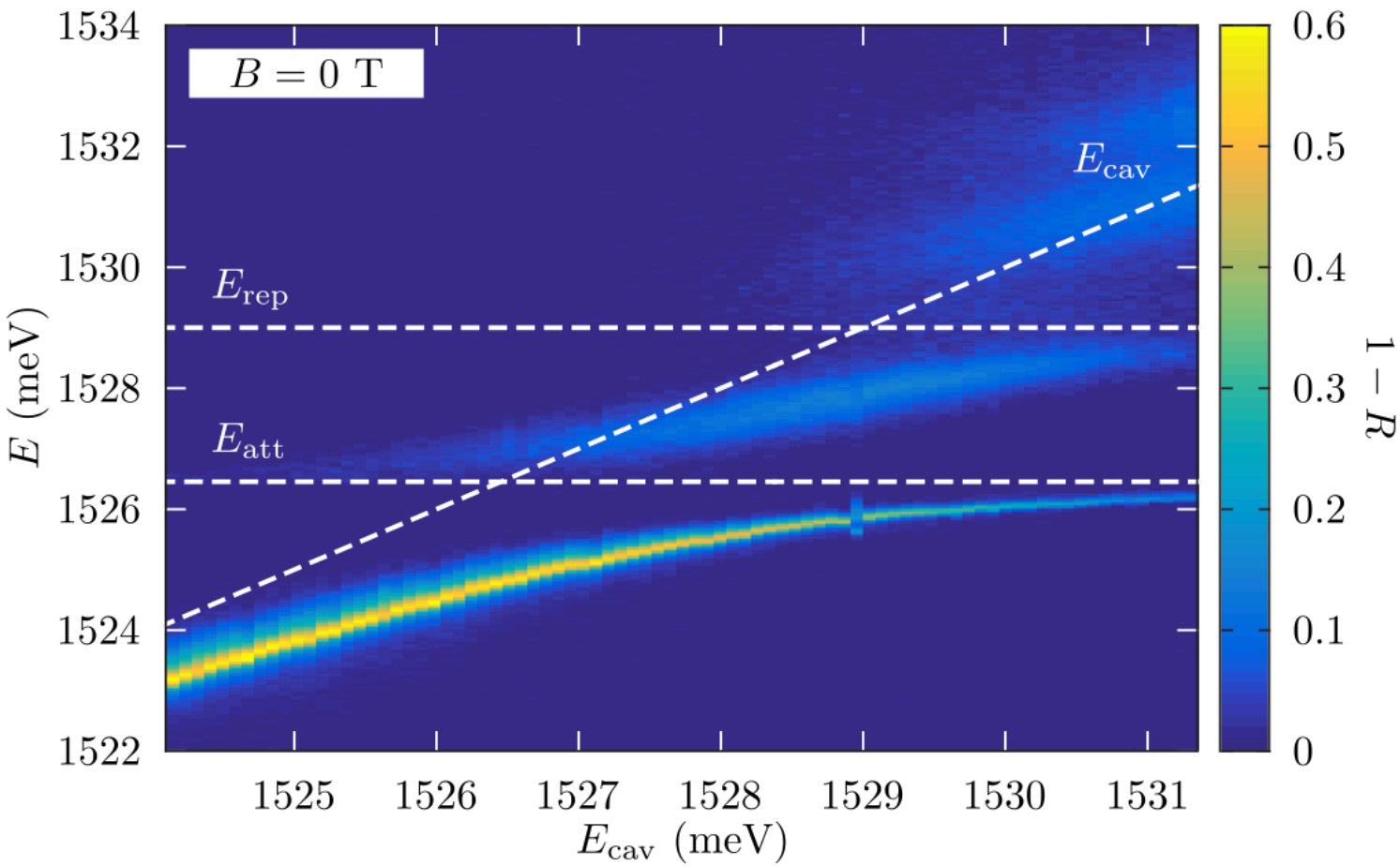
See also theory works by E. Demler, A. Imamoglu, A. MacDonald…

Fermi polaron polaritons in GaAs



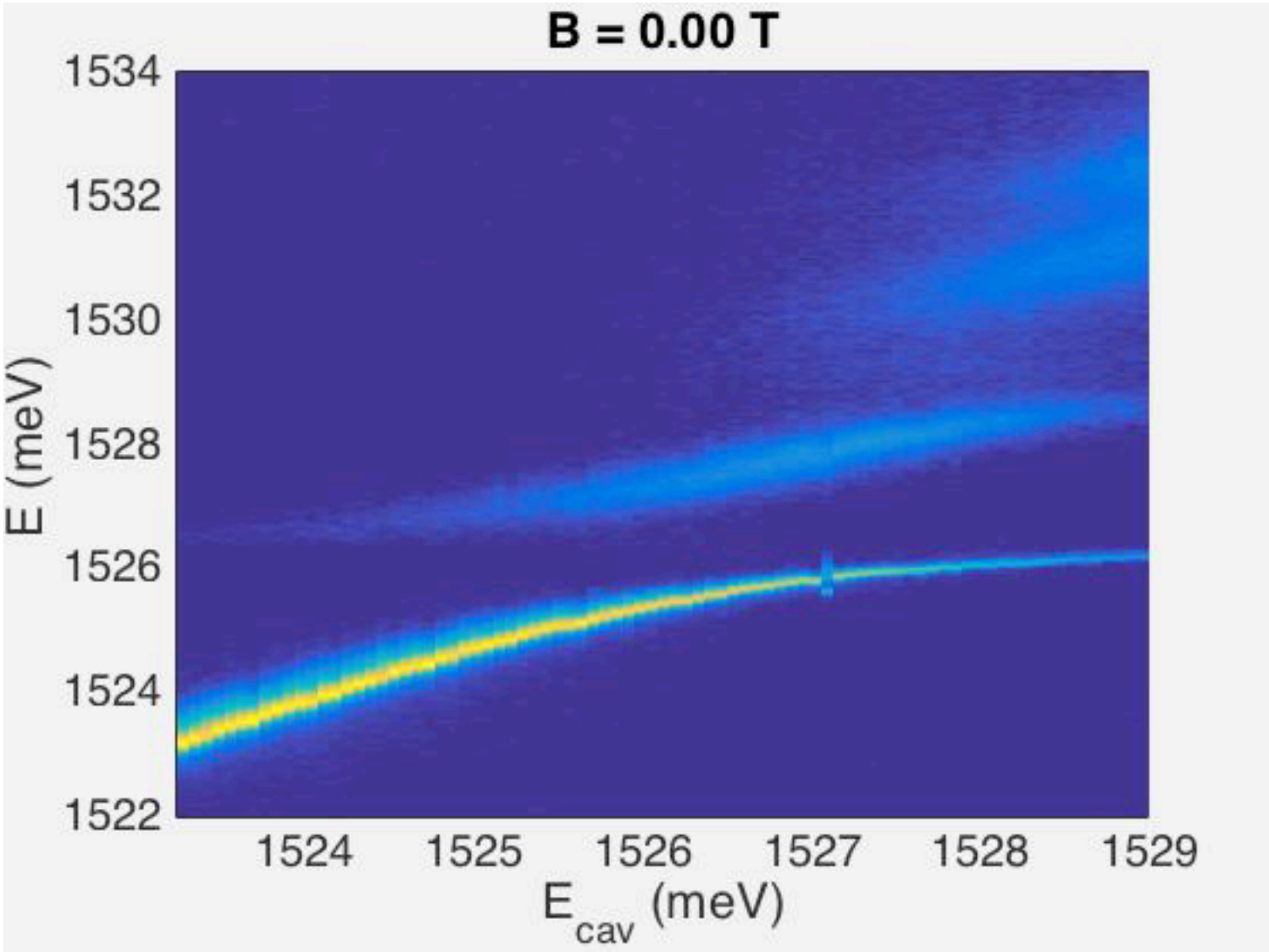
Fermi polaron polaritons in GaAs

- White light reflectivity spectrum:

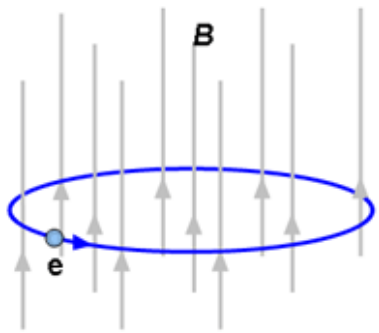


Applying a magnetic field

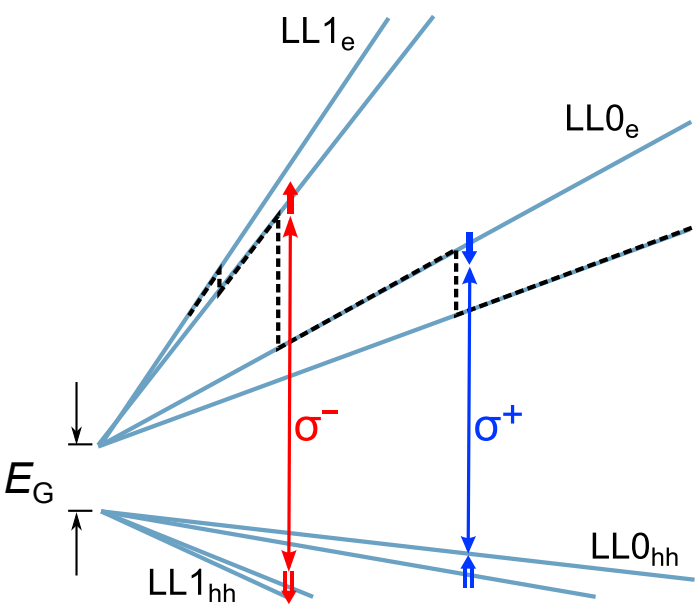
Reflectivity measurement – σ^- polarization



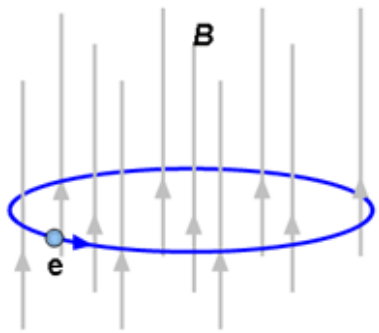
Landau levels



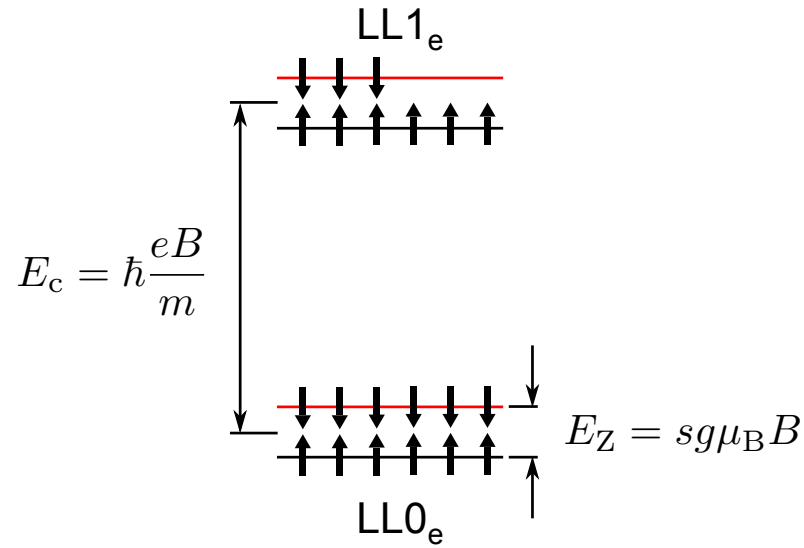
Magnetic field ⇒ discrete **Landau levels**

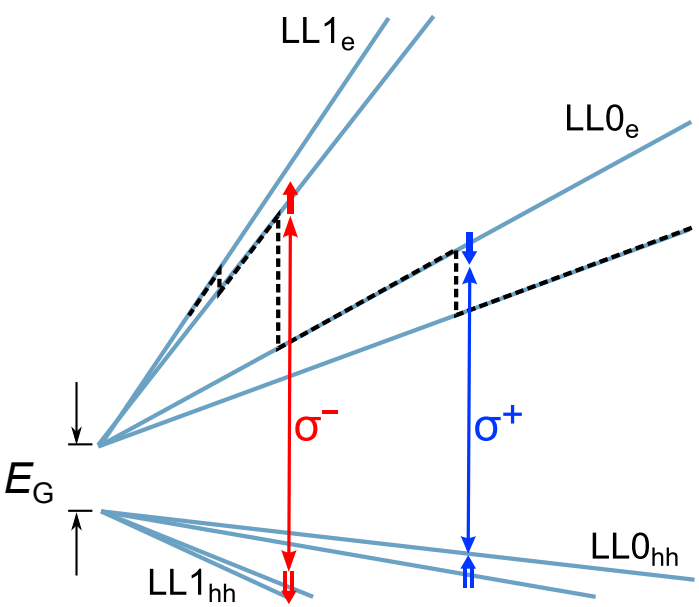


Landau levels



Magnetic field ⇒ discrete **Landau levels**



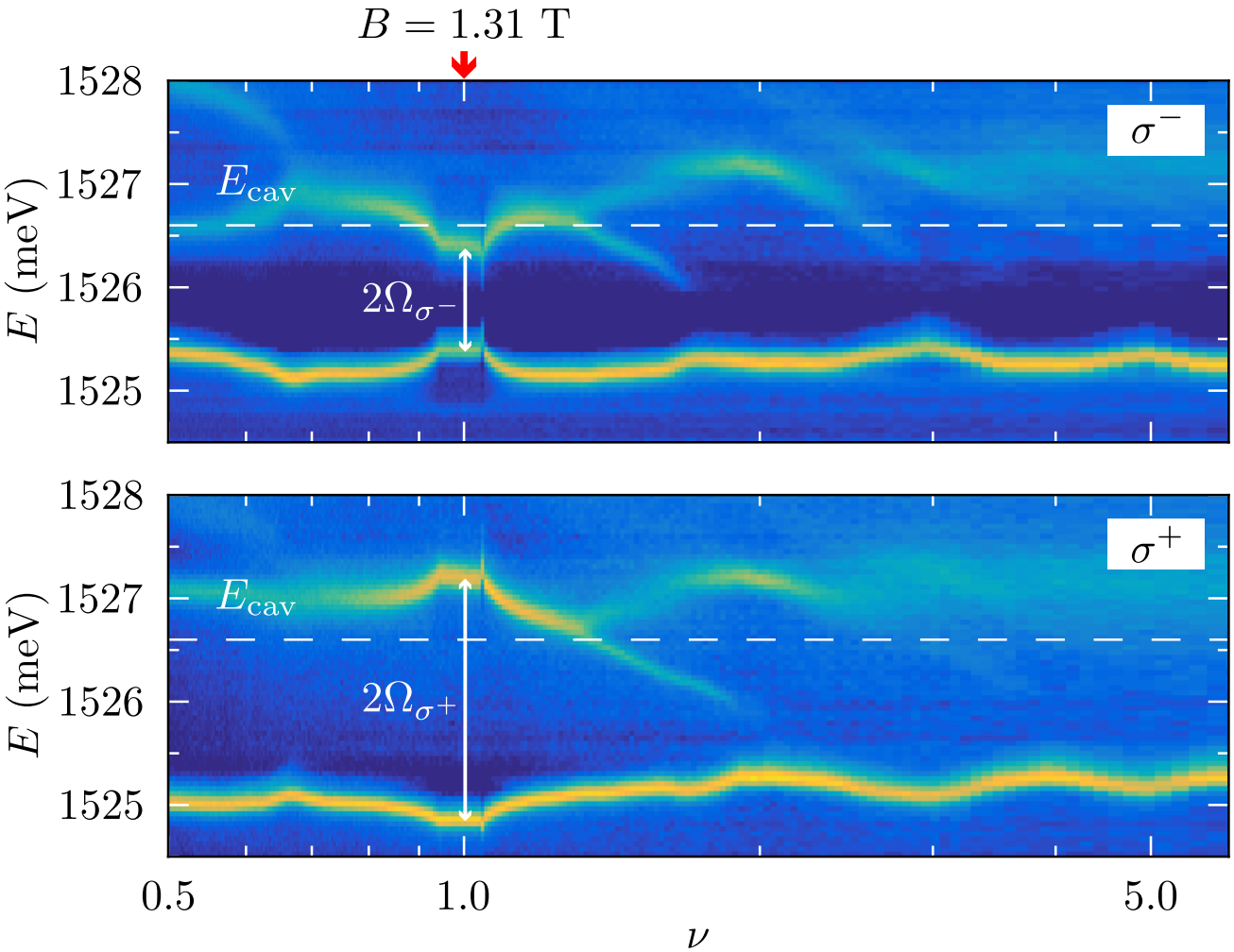


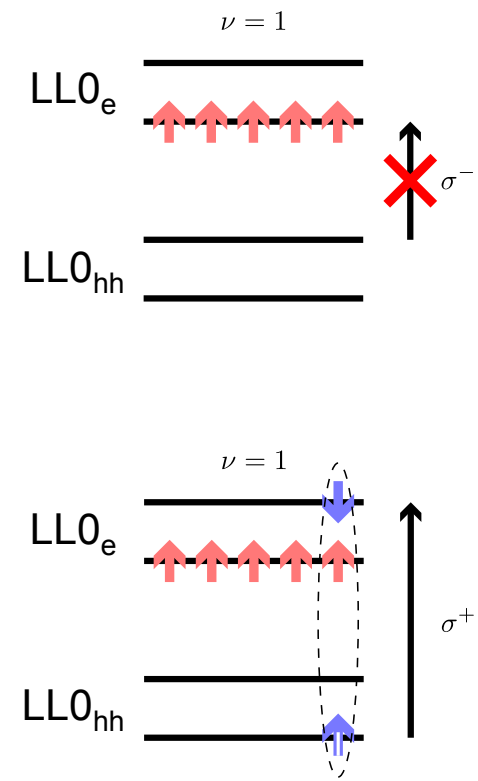
- Level degeneracy: $n_D = \frac{eB}{h}$
- Filling factor: $\nu = \frac{n_e h}{eB}$

➢ *Example:* ν = 3.5

Quantum Hall polaritons (IQHE)

- ν = 1 state:

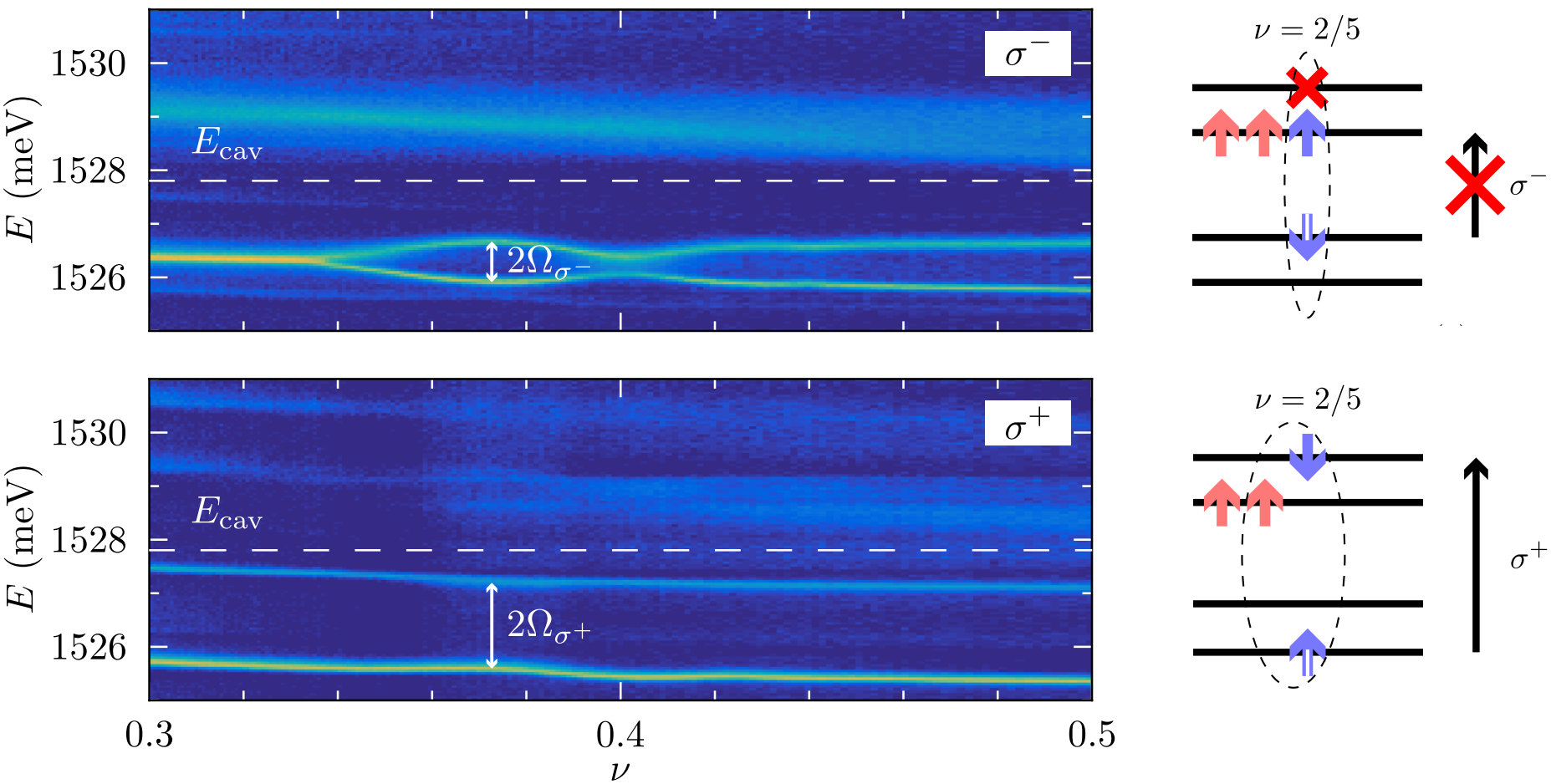




S. Ravets et al., PRL 120, 057401 (2018)

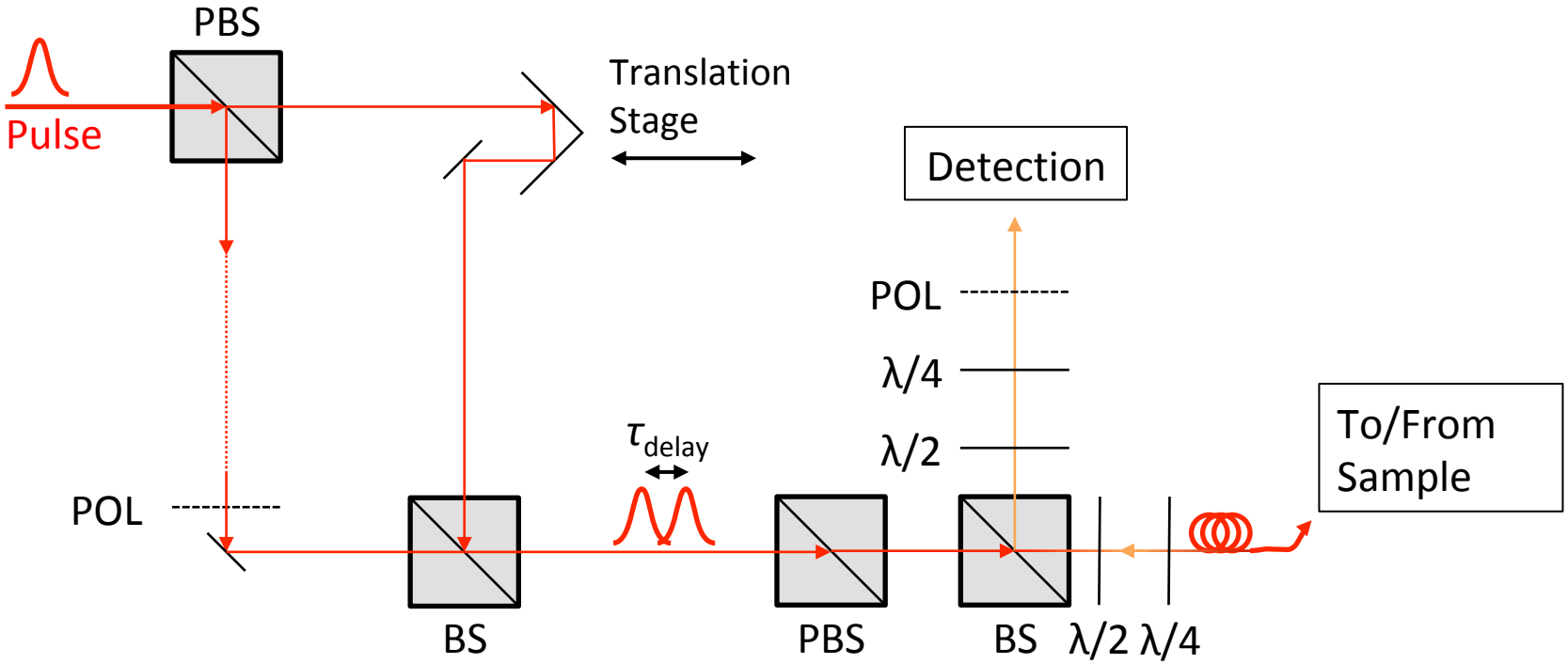
Quantum Hall polaritons (FQHE)

- ν = 2/5 state:



S. Ravets et al., PRL 120, 057401 (2018)

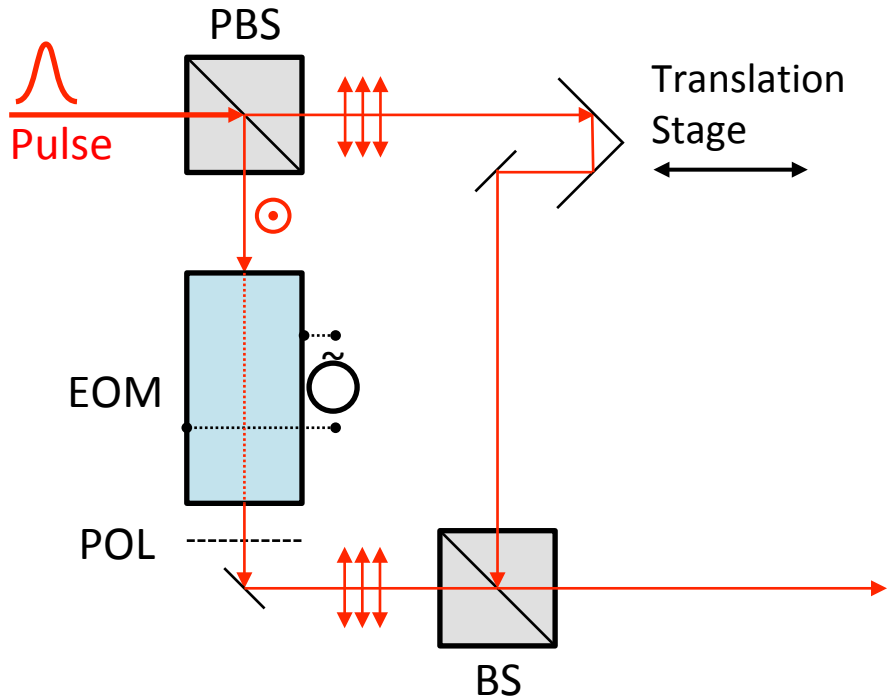
Pump-probe spectroscopy



- Use pulsed laser with $\tau_{pulse} \approx 4$ ps < $\tau_{lifetime} \approx 20$ ps.
  ⇒ Measure non linear response vs delay.

$$I_{\mathrm{Det}} = \left| P^{(1)}_{\mathrm{Probe}} + P^{(1)}_{\mathrm{Pump}} + P^{(3)} \right|^2$$

Pump-probe spectroscopy



$$P^{(1)}_{\text{Probe}} \propto E_{\text{Probe}} \longrightarrow \text{DC}$$

$$P^{(1)}_{\text{Pump}} \propto E_{\text{Pump}} \longrightarrow \omega_0$$

$$P^{(3)} \propto E^3_{\text{Pump}} \longrightarrow \omega_0,\ 3\omega_0$$

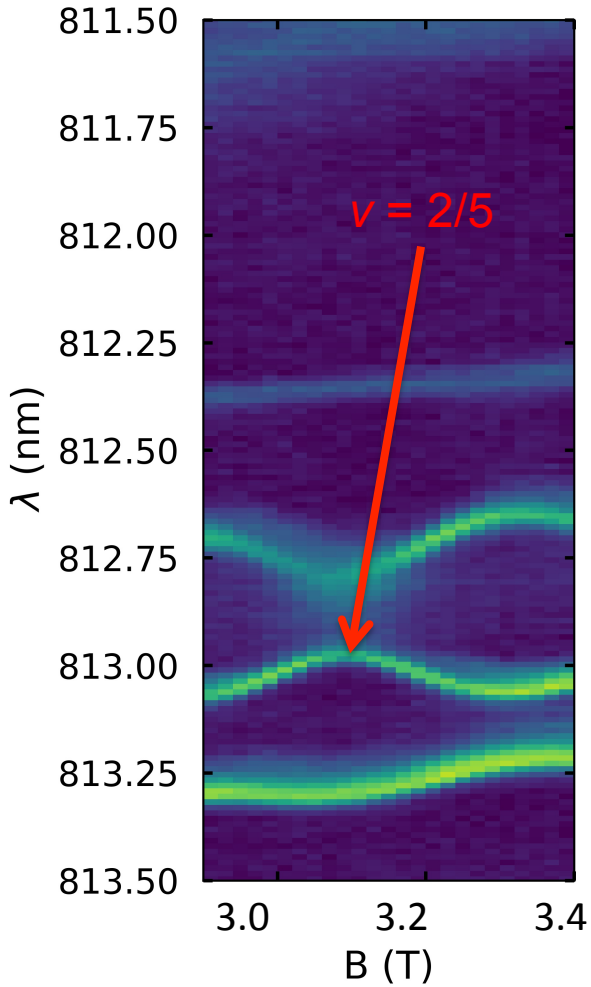
$$P^{(3)} \propto E^2_{\text{Pump}} E_{\text{Probe}} \longrightarrow \text{DC},\ 2\omega_0$$

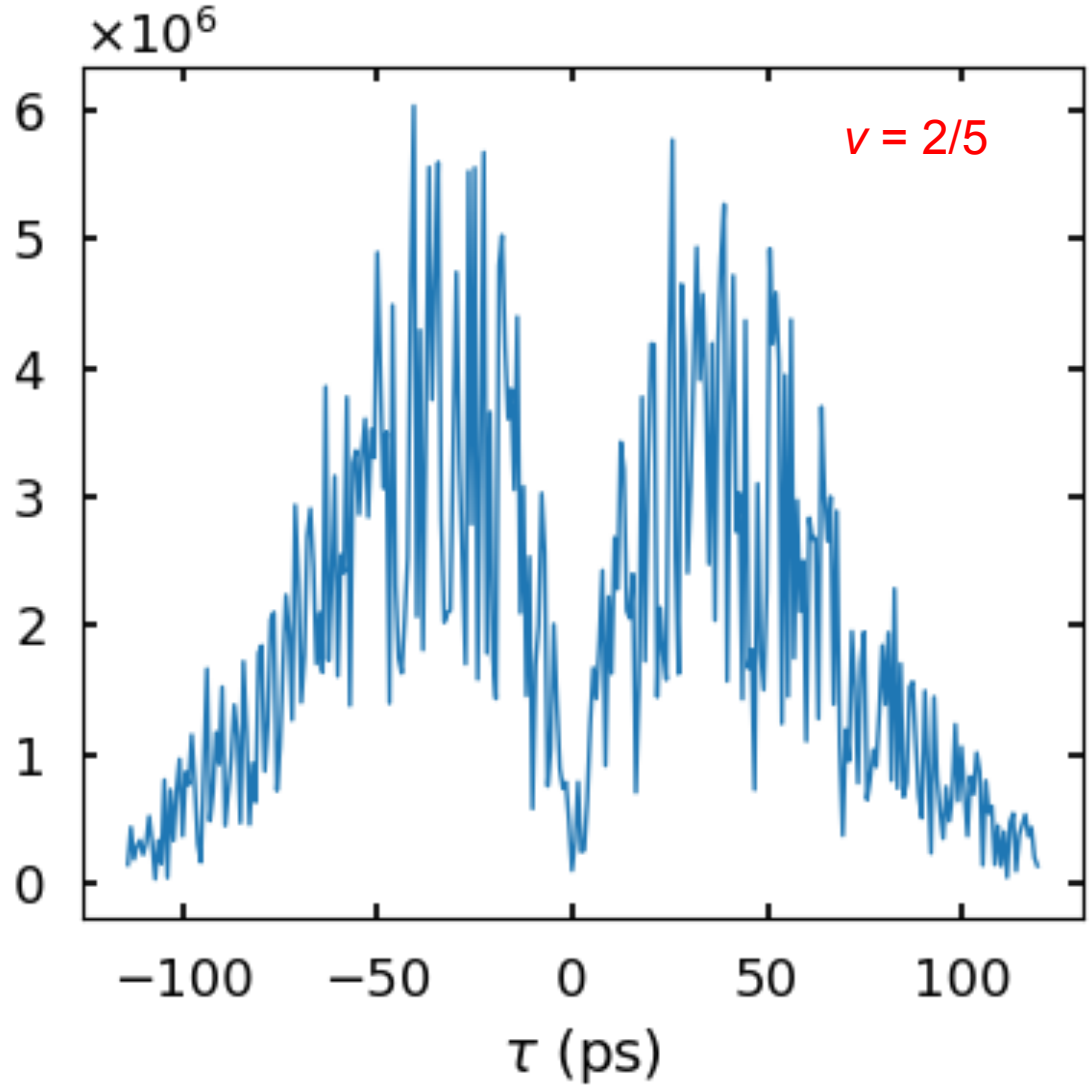
$$P^{(3)} \propto E_{\text{Pump}} E^2_{\text{Probe}} \longrightarrow \omega_0$$

$$P^{(3)} \propto E^3_{\text{Probe}} \longrightarrow \text{DC}$$

- SOLUTION: modulate one of the fields (e.g. E_{pump}) at frequency ω_0.
- **Detection at $\omega_0 \Rightarrow$ linear response (background free).**
- **Lock in detection at $3\omega_0 \Rightarrow$ nonlinear response (background free).**

Nonlinear response

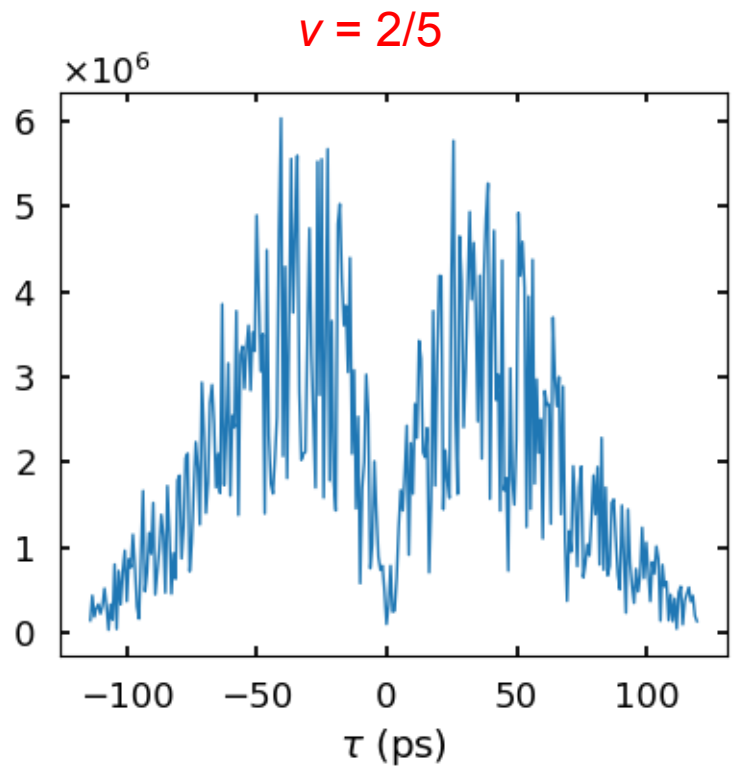


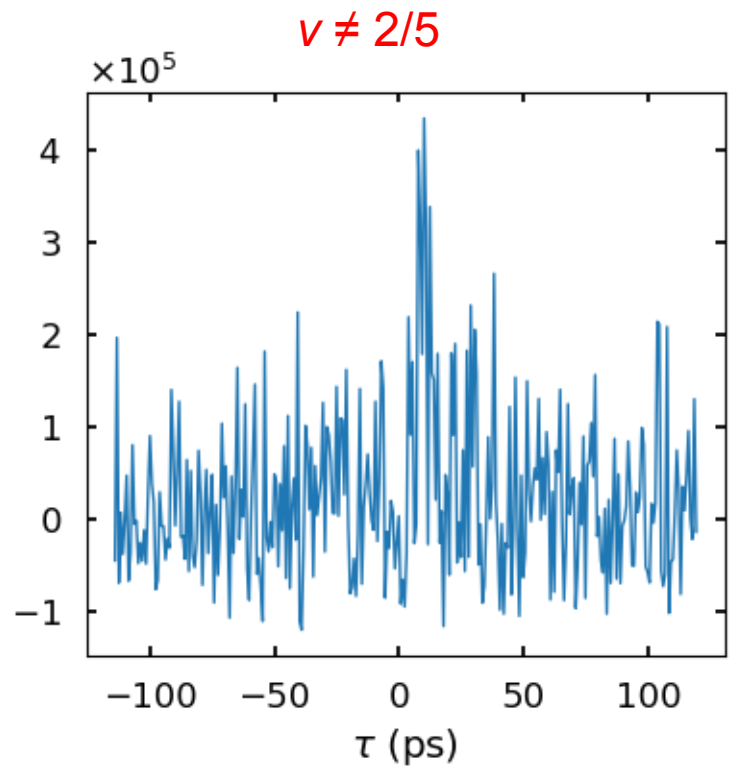


⇒ **Fast nonlinearity (due to polariton-polariton interactions)!**

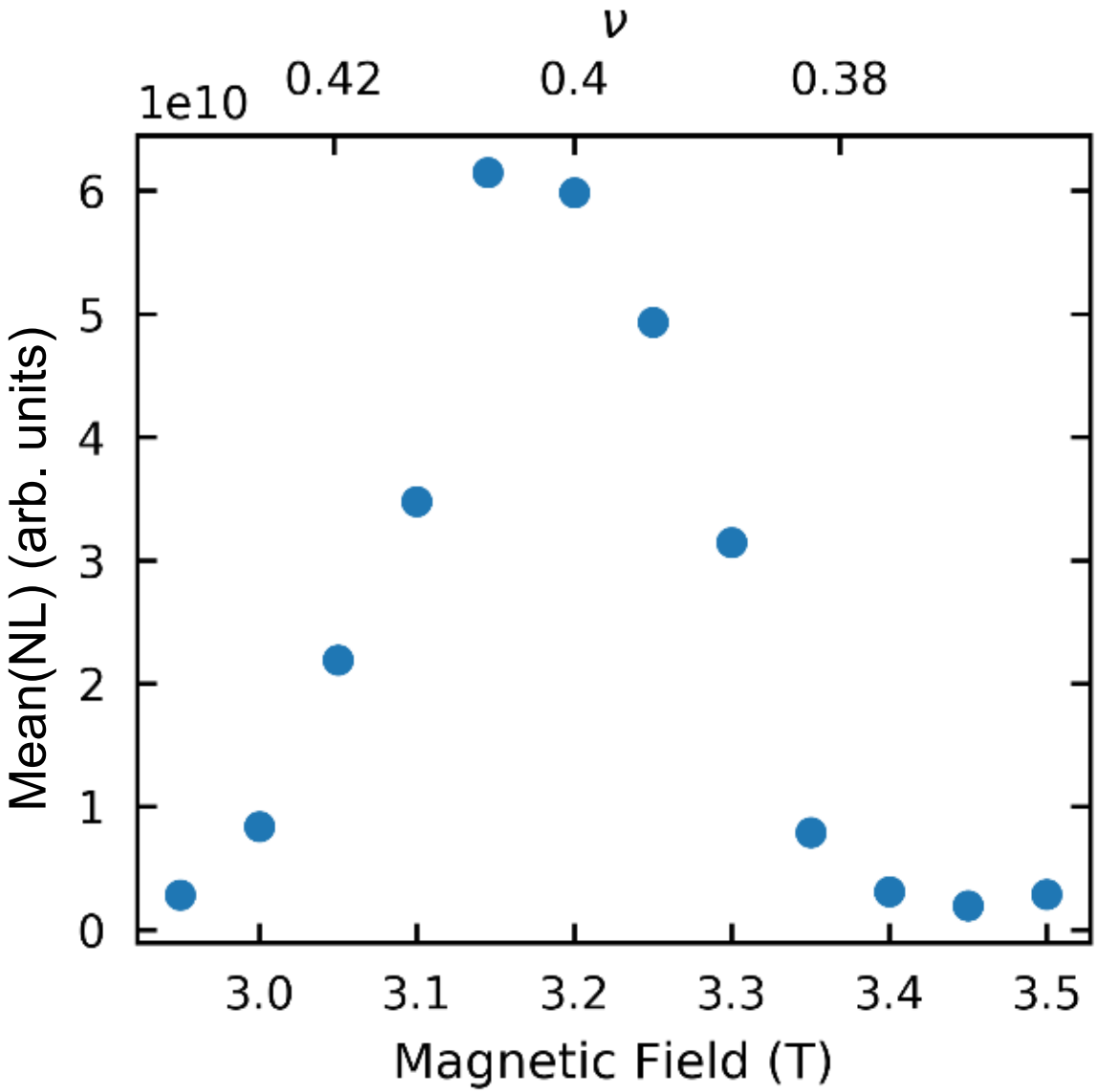
Enhancing polariton-polariton interactions

- Compare nonlinear signal at and away from $\nu = 2/5$.





Enhancing polariton-polariton interactions



⇒ **Enhancement of non-linearity by more than a factor of 10!**

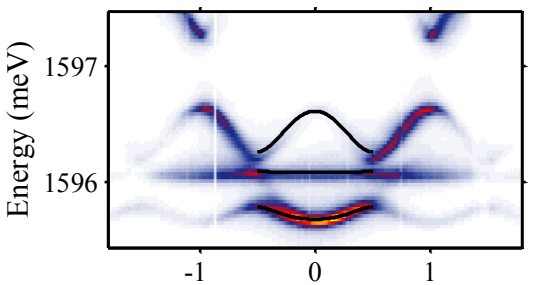
Perspectives

- Strong Kerr non-linearity (χ^3) in lattices

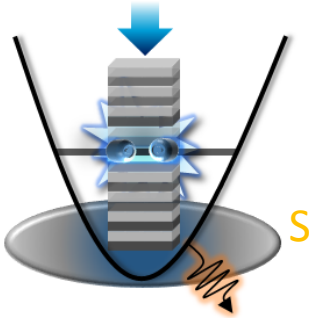
Ex: Non-linearity in a flat band:

Hadad et al., PRB 93 155112 (2016)

F. Baboux et al., Phys. Rev. Lett. 116, 066402 (2016)



- Toward polariton blockade: emulation of quantum many body physics

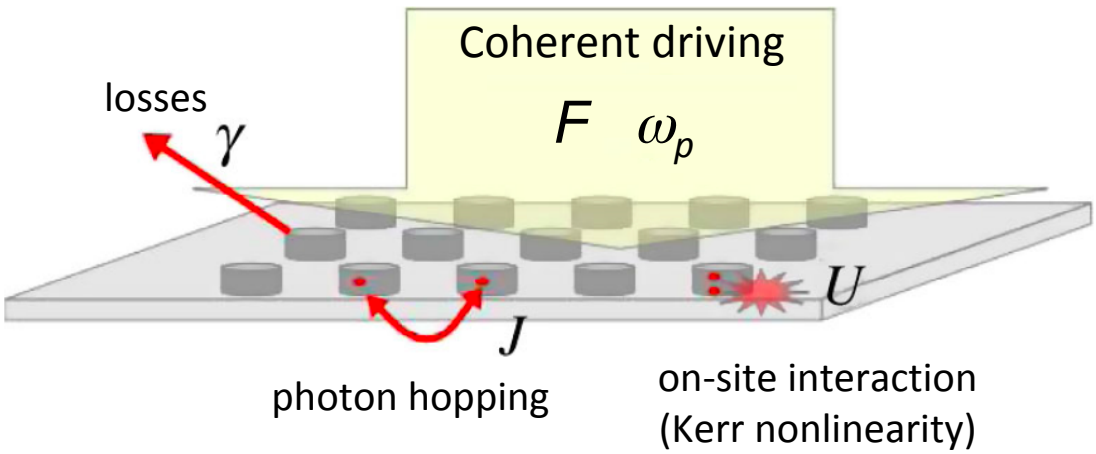


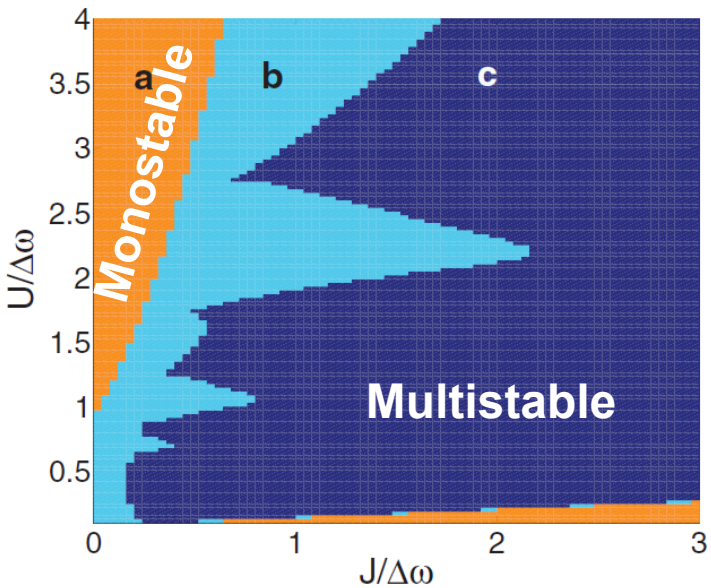
Single photon emission

Thanks!

Driven-dissipative photonic Bose-Hubbard model

Interplay of photon **hopping, interaction, coherent driving, and decay**, leads to strongly correlated steady-state phases and instabilities.





Le Boité *et al.*, PRL 110, 233601 (2013); PRA **90**, 063821 (2014).

Review on Quantum Fluids of Light:
Ciuti & Carusotto, Rev. Mod. Phys. **85**, 299 (2013).

Quantum simulation with photons:
M. J Hartmann, et al., Nature Phys. 2, 849{855 (2006).
A. D Greentree, et al., Nature Phys. 2, 856{861 (2006).
D. G. Angelakis, et al., Phys. Rev. A 76, 031805 (2007).

Quantum fluids of light as an analogous system

Use nanotechnologies to fabricate artificial systems:

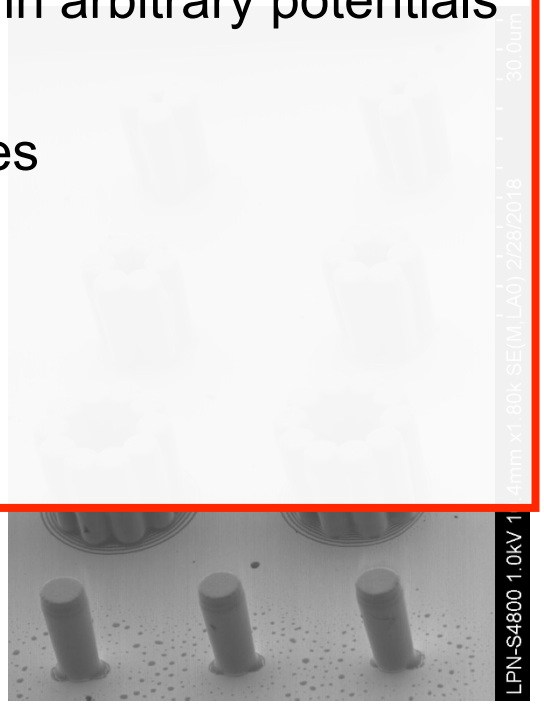
THE EXPERIMENTALIST'S TOOLBOX TO IMPLEMENT SYNTHETIC **QUANTUM** MATERIALS

- Perform experiments easier to probe, manipulate.
- Create new geometries, new properties which do not exist in nature.
- Realize experiments which are impossible to predict because of complexity of simulations (many body): **quantum simulation.**

☑ Photons must behave as massive particles in arbitrary potentials

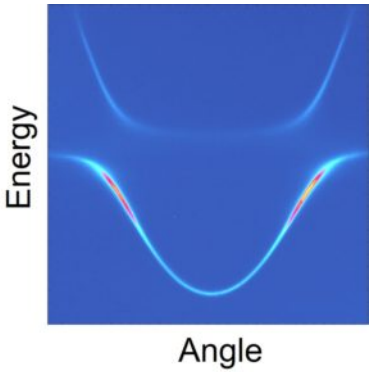
☑ Photons must behave as interacting particles

☐ Interactions need to be strong enough



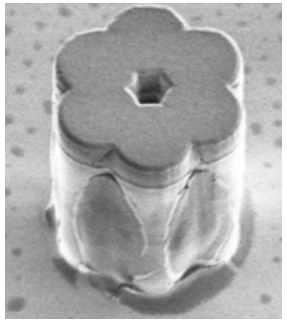
Outline

- **Introduction to cavity polaritons**



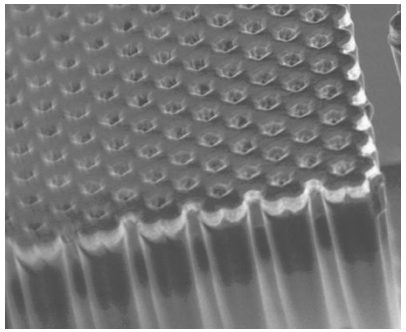
- **Benzene photonic molecule:**

  Lasing with angular momentum



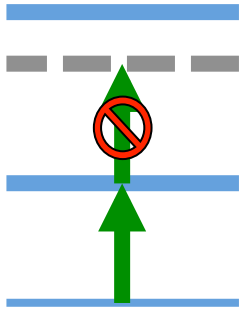
- **Photonic graphene:**

  Manipulation of Dirac cones



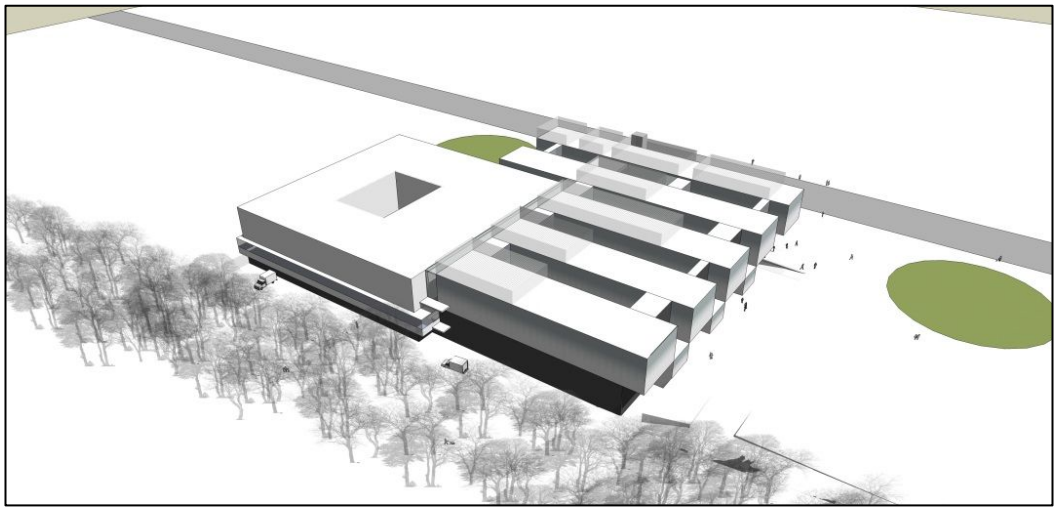
- **Towards synthetic quantum materials:**

  Enhancing polariton-polariton interactions



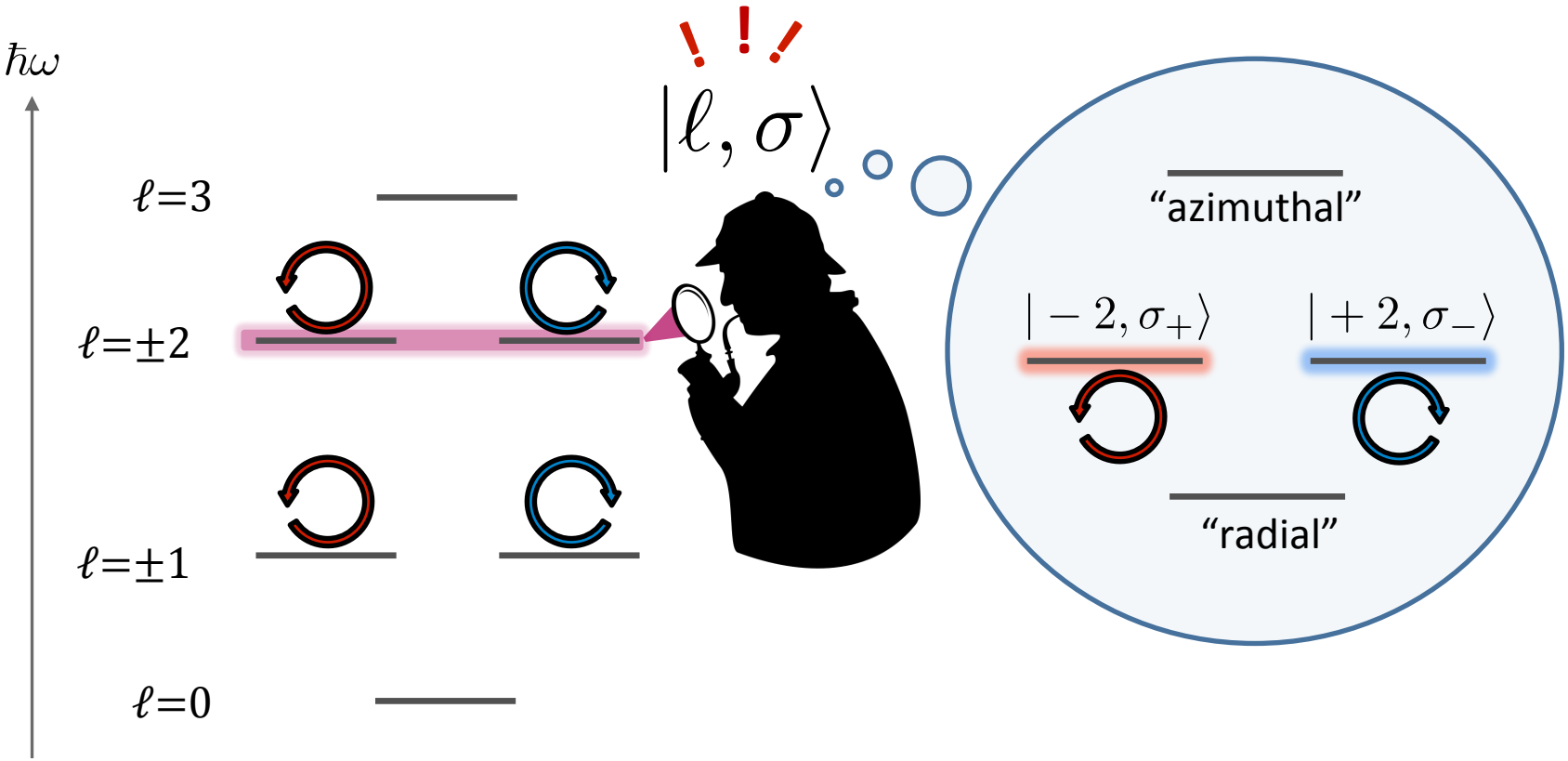
- **Perspectives**

A few numbers



- **450** researchers, post-doc, PhD students, engineers, technicians, administrative staff.
- **4 Departments:** Photonics, Nanoelectronics, Microsystems & NanoBioFluidics, Materials.
- **2800 m² high-class clean-room facility**

Spin-orbit coupling -|L|=2 Fine Structure

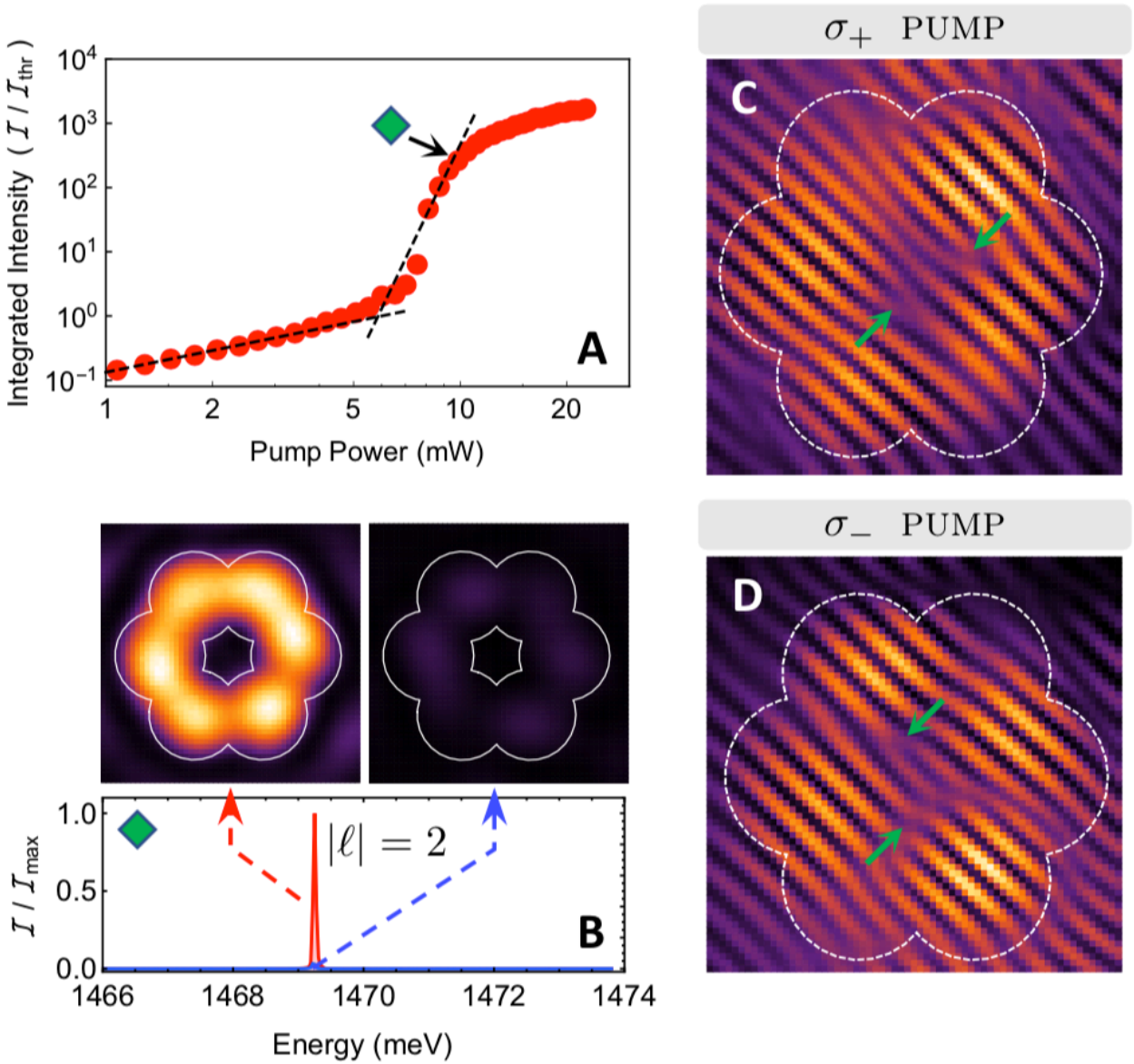


Radial & Azimuthal modes:

$$|\psi_{r,a}\rangle = \frac{1}{\sqrt{2}}\left(e^{\frac{2\pi i}{6}}|+2,\sigma_+\rangle \mp e^{-\frac{2\pi i}{6}}|-2,\sigma_-\rangle\right)$$

V.G. Sala et al., Phys. Rev. X 5, 011034 (2015)

OAM Lasing at 80 K



Generation of light with OAM

Relevance

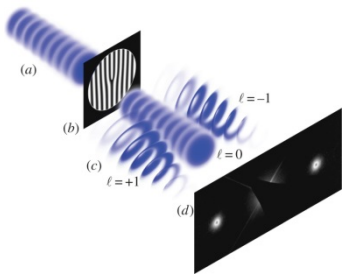
- Exotic phases of light
- Quantum information

- Sensing
- Nano-manipulation,
- Biological processes

F. Cardano and L. Marrucci,
Nature Photonics 9, 776 (2015)
K.Y. Bliokh et al.,
Nature Photonics 9, 796 (2015)

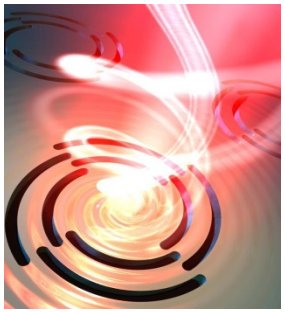
Bulk Optics

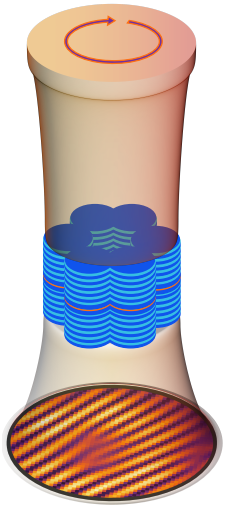
- Versatile but slow, difficult to scale



Integrated Devices, metamaterials

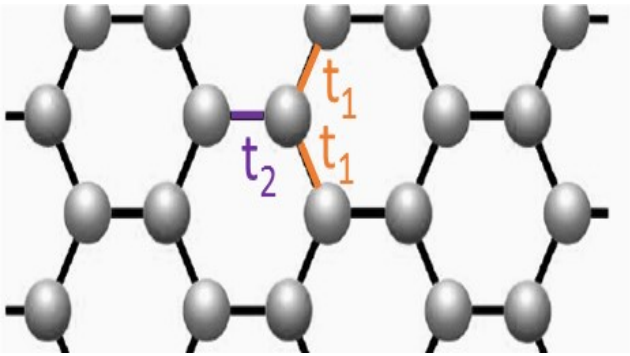
- Easily scalable, efficient, limited versatility





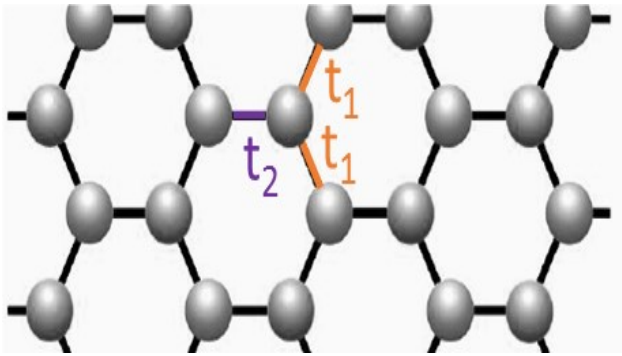
➢ Photonic benzene: control of the helicity via polarization of the excitation

Uniaxial strain in graphene



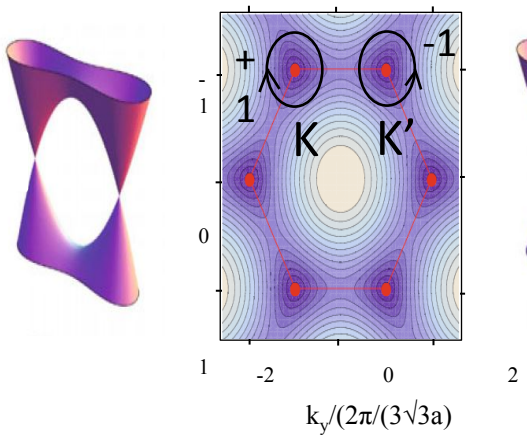
$\beta = t_2/t_1$

Uniaxial strain in graphene

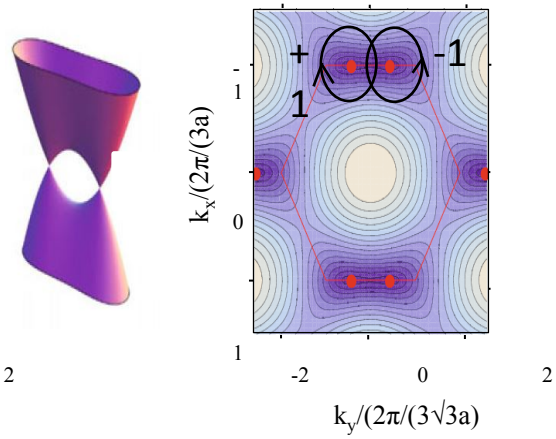


$\beta = t_2/t_1$

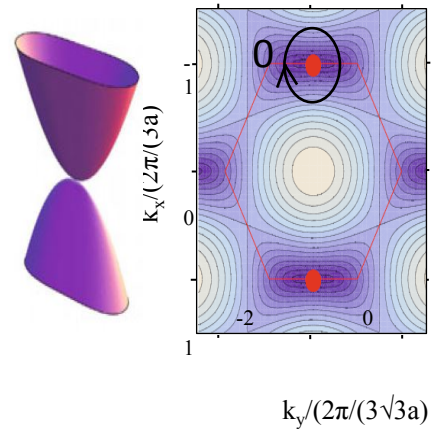
β=1



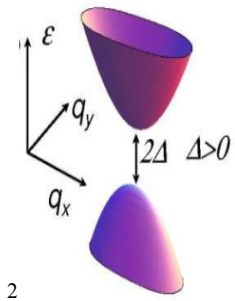
β=1.5



β=2



β>2



Gap opens!

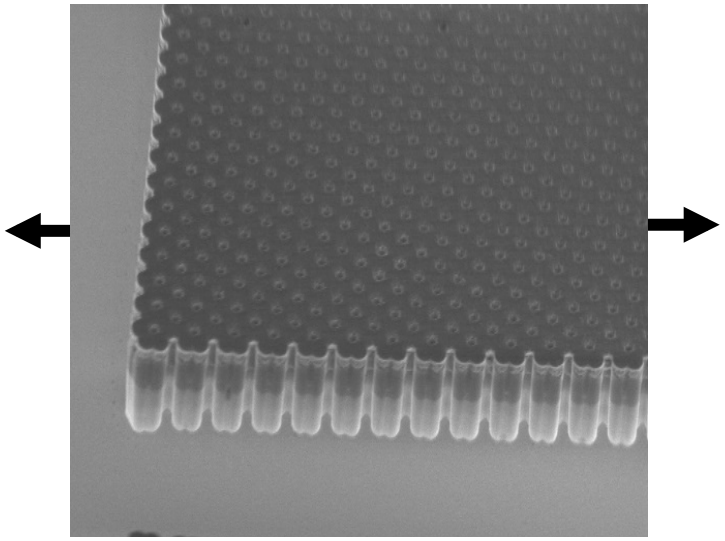
$$\mathcal{W} = \oint i \langle \Psi | \partial_k | \Psi \rangle \cdot dk$$
$$= \frac{1}{2\pi} \oint \partial_k \phi(k) \cdot dk$$

$$H_{\pm} = \left(\frac{1}{2} - \frac{1}{\beta} + \frac{q_x^2}{2m}\right)\sigma_x + c q_y \sigma_y$$

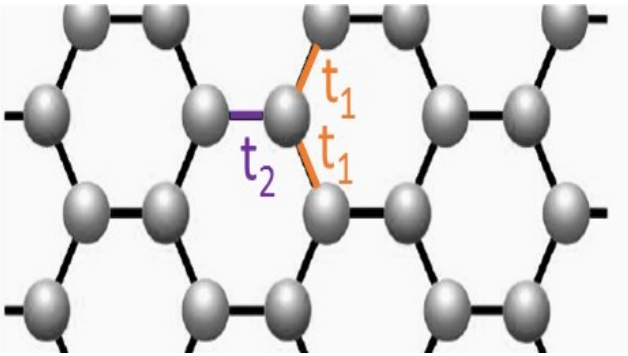
Hamiltonian at merging of +1 and -1 Dirac cones

Montambaux G. et al., *Phys. Rev. B* **80**, 153412 (2009)

Strain engineering with micropillars



Strain engineering with micropillars



$\beta = t_2/t_1$

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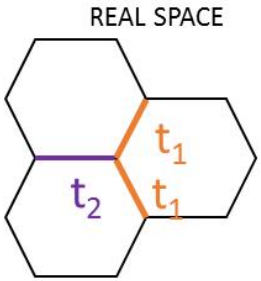
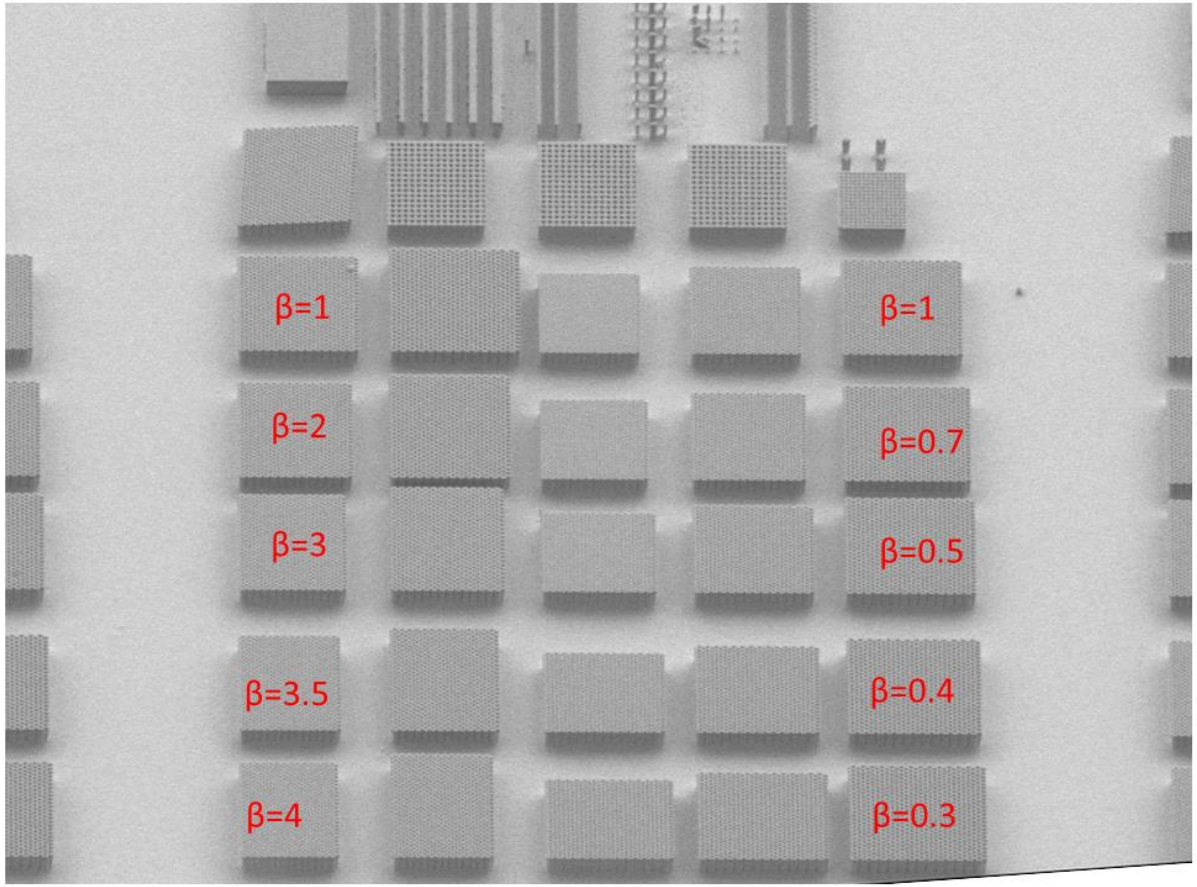
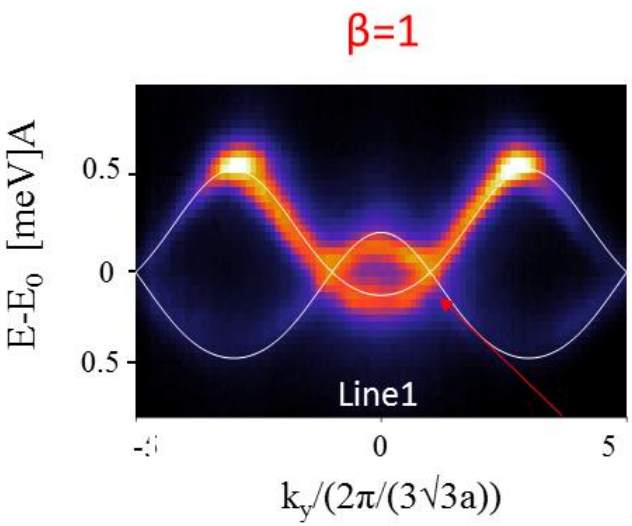
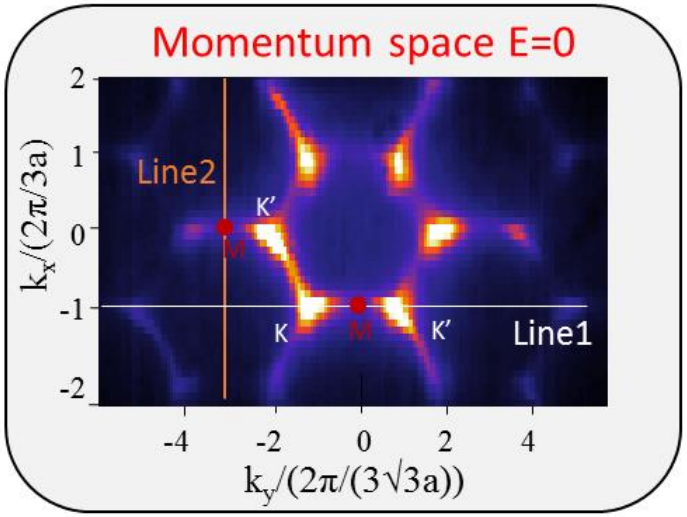
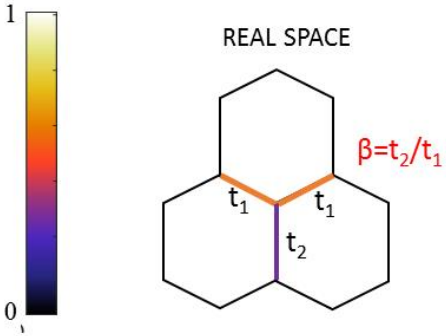




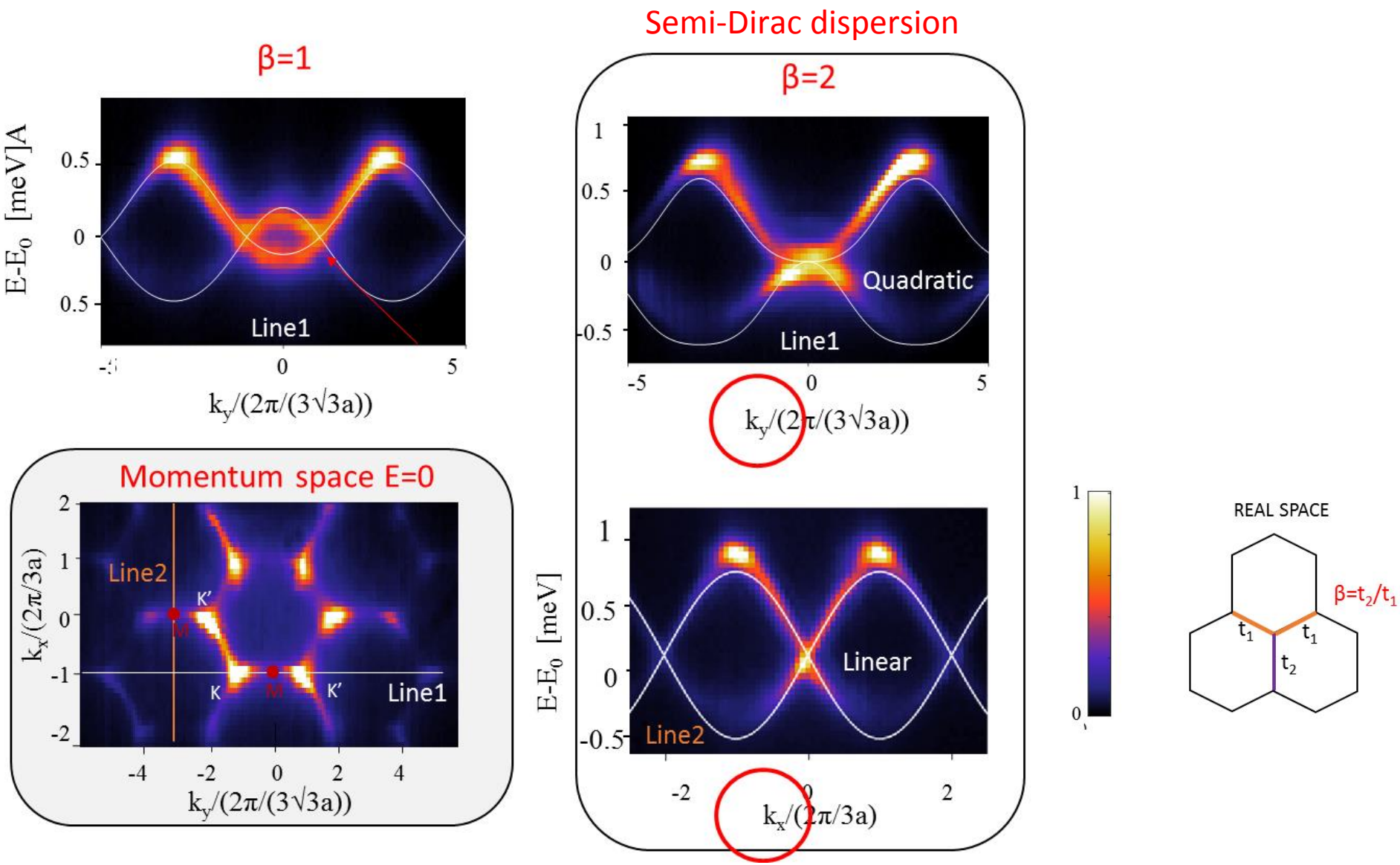
Merging of +1 and -1 Dirac cones





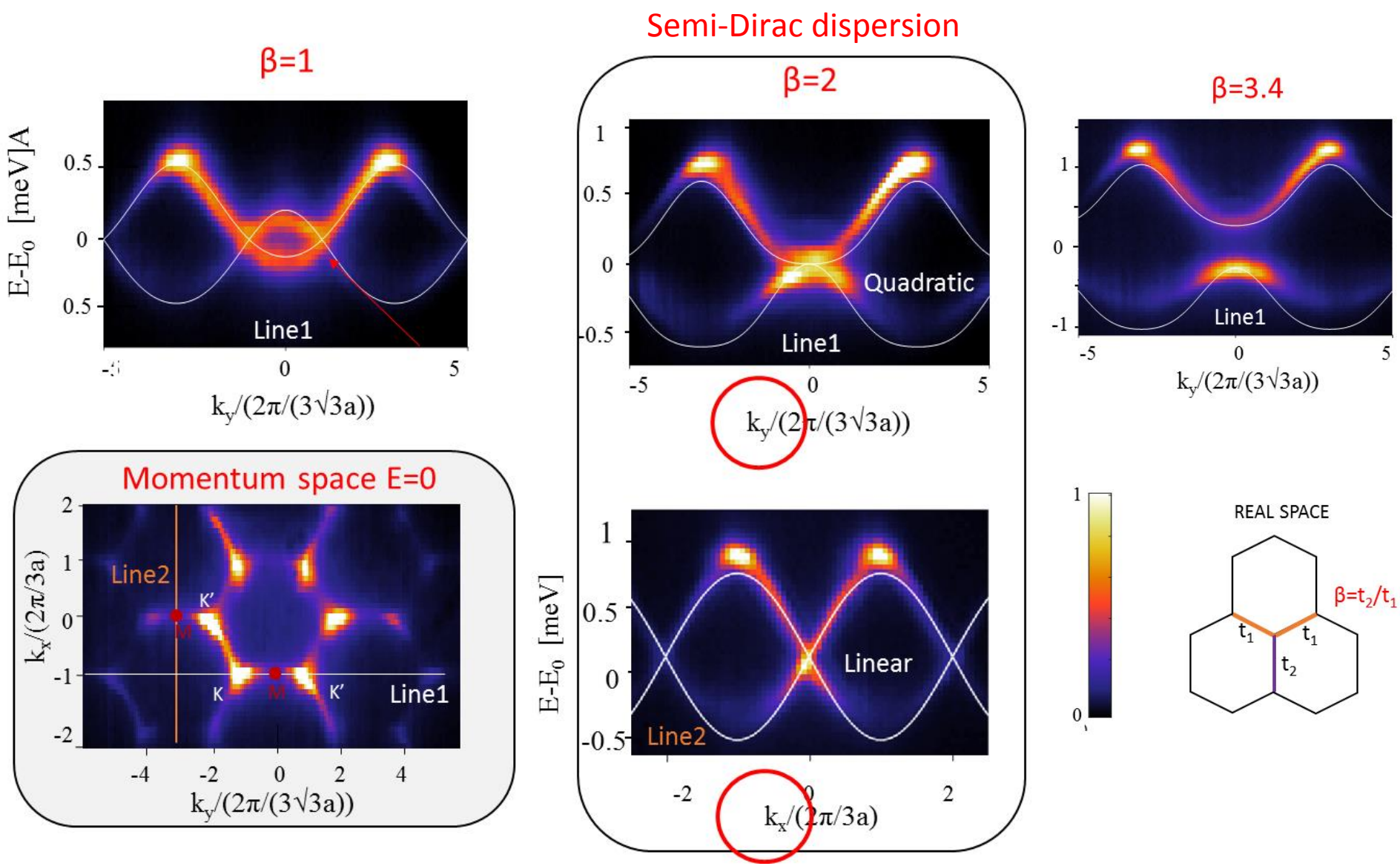


Merging of +1 and -1 Dirac cones



see also: Kim et al., Science, 349, 6249 (2015)
Tarruell et al., Nature, 483, 7389 (2012)

Merging of +1 and -1 Dirac cones



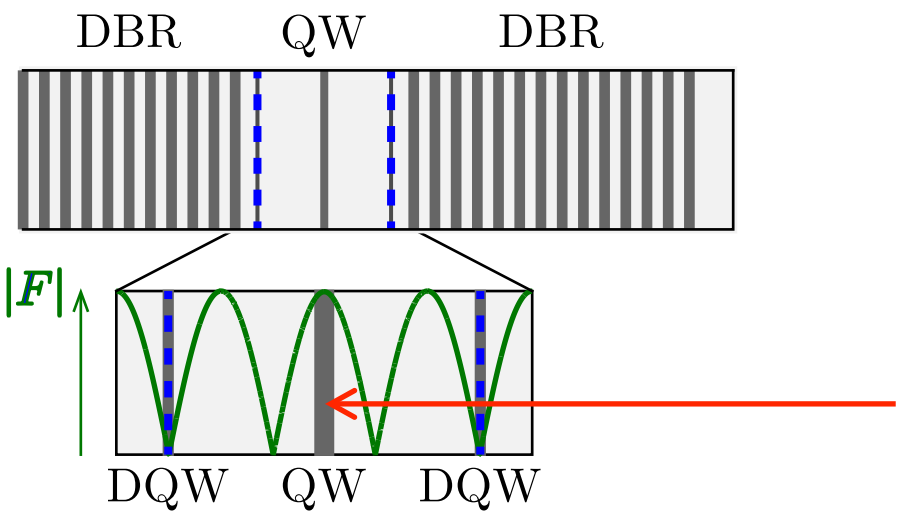
see also: Kim et al., Science, 349, 6249 (2015)
Tarruell et al., Nature, 483, 7389 (2012)

M. Milicevic et al., in preparation (2018)

Sample design

S. Faelt
Grower

- Two-sided **doped GaAs quantum well** (20 nm).

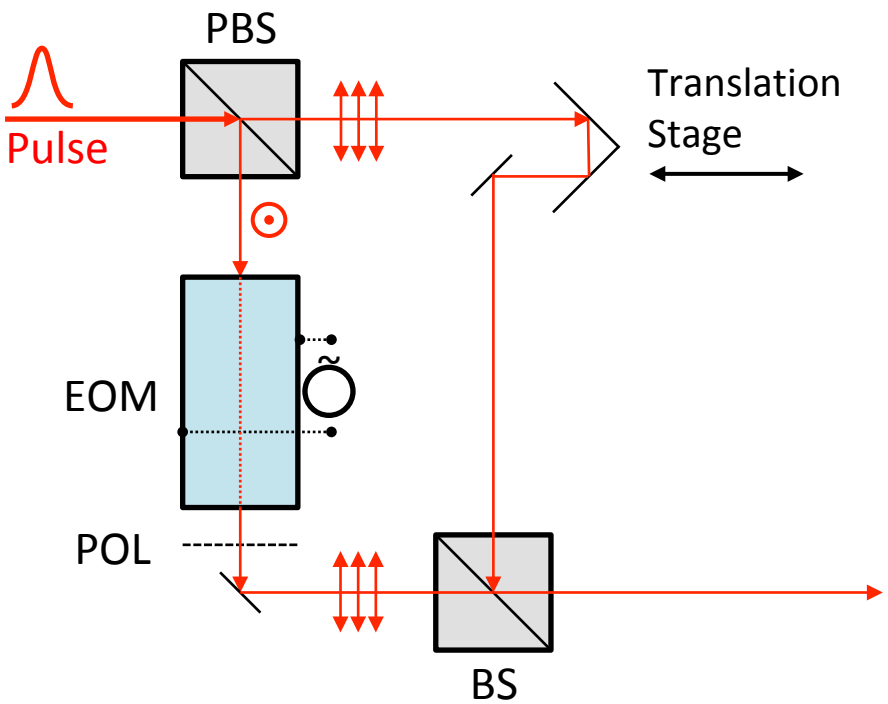


2D electron gas:
$n_e = 3.0\times10^{10}$ cm^{-2}
$\mu = 1.6\times10^{6}$ cm^2.V^{-1}.s^{-1}

- Fiber-based measurements in dilution refrigerator (30 mK).

Pump-probe spectroscopy

- SOLUTION: modulate one of the fields (e.g. E_{pump}) at frequency ω_0.



Pump-probe spectroscopy

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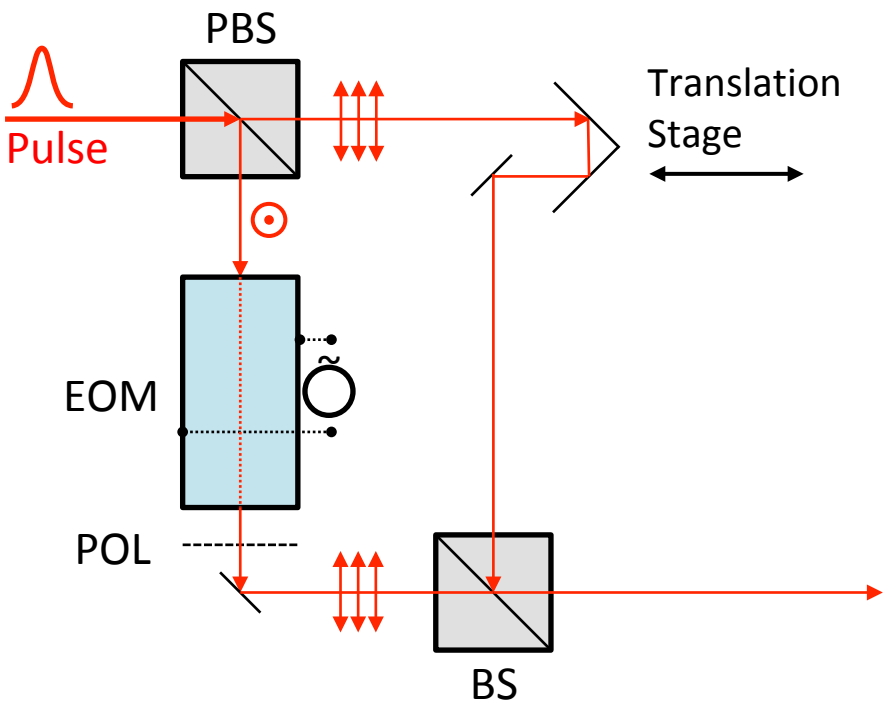


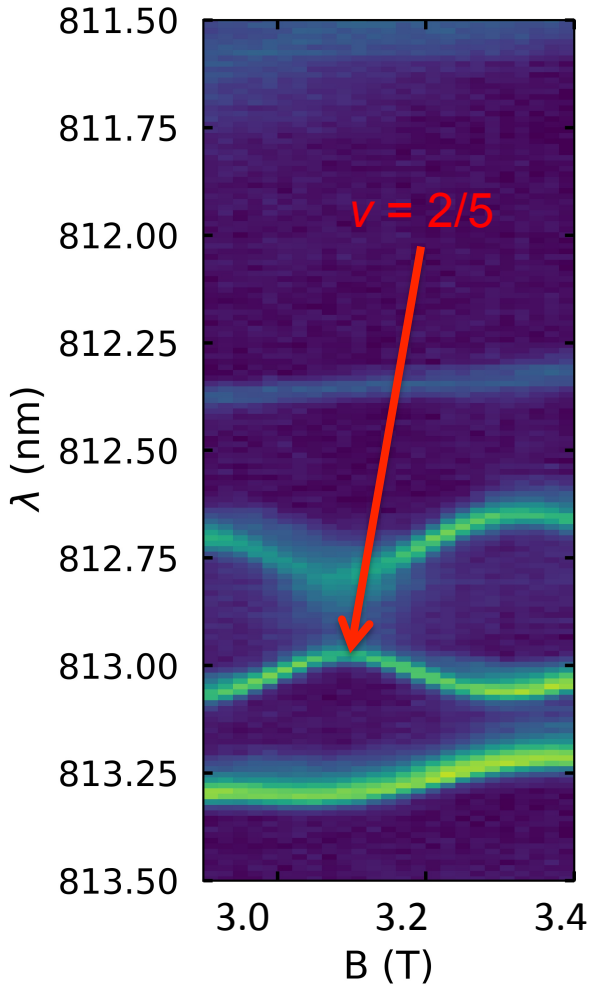
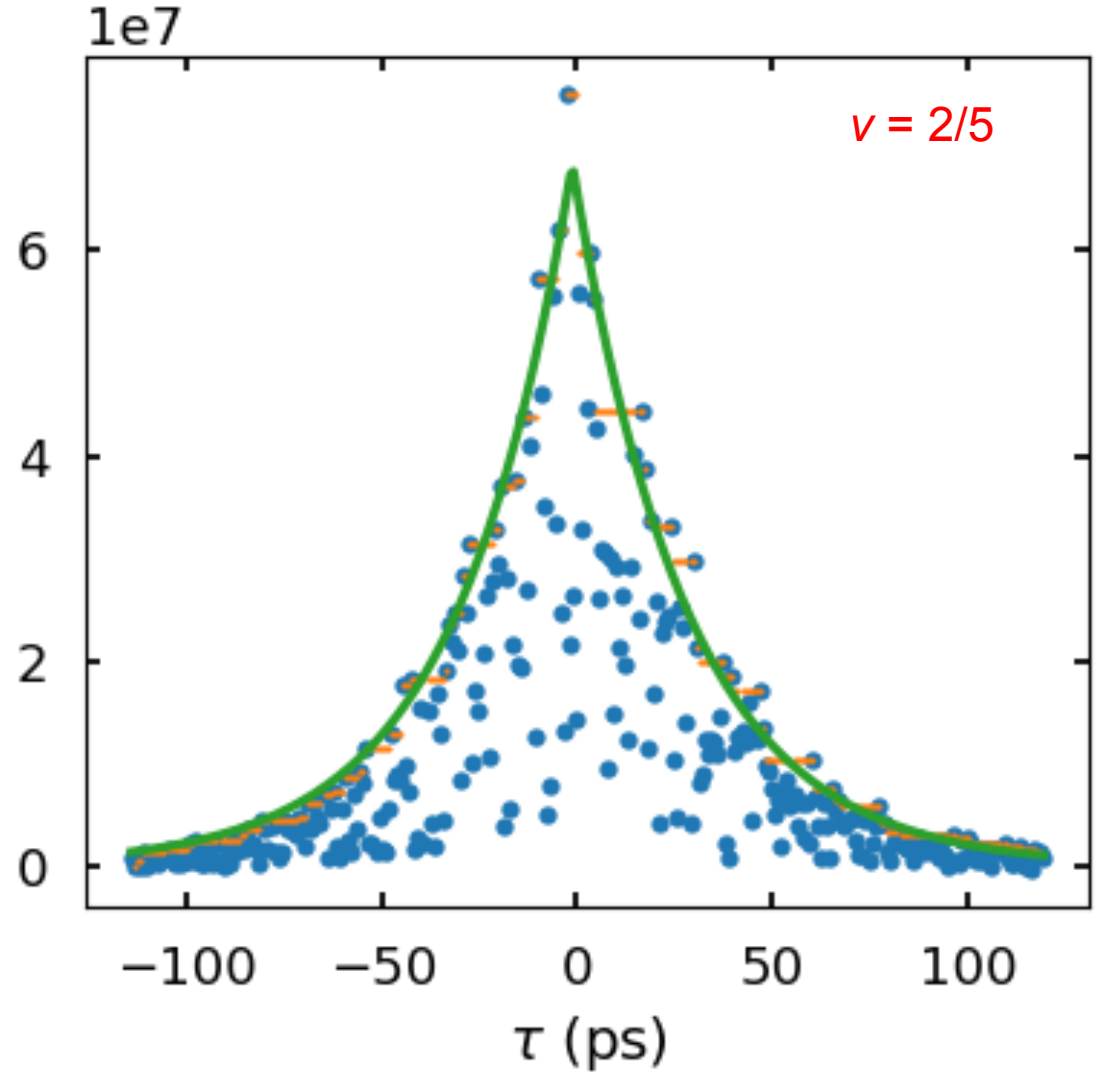
$$P^{(1)}_{\text{Probe}} \propto E_{\text{Probe}} \longrightarrow \text{DC}$$

$$P^{(1)}_{\text{Pump}} \propto E_{\text{Pump}} \longrightarrow \omega_0$$

$$P^{(3)} \propto E^3_{\text{Pump}} \longrightarrow \omega_0,\ 3\omega_0$$

$$P^{(3)} \propto E^2_{\text{Pump}} E_{\text{Probe}} \longrightarrow \text{DC},\ 2\omega_0$$

$$P^{(3)} \propto E_{\text{Pump}} E^2_{\text{Probe}} \longrightarrow \omega_0$$

$$P^{(3)} \propto E^3_{\text{Probe}} \longrightarrow \text{DC}$$

Linear response