# Coherence in semiconductor nanostructures
# Part VII: Coherent coupling between individual excitons

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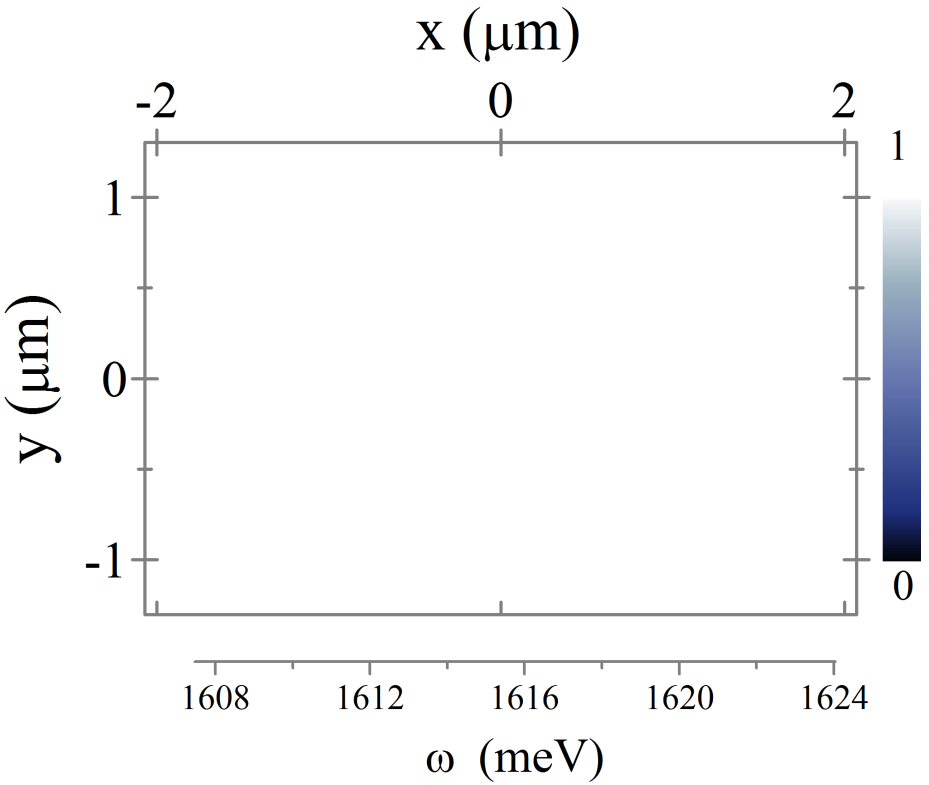
Institut Néel - CNRS
Grenoble France

Warsaw University, October-December 2020

# Outline

# Mutual coherence in a small set of quantum dots ?

## Four-Wave Mixing hyperspectral imaging

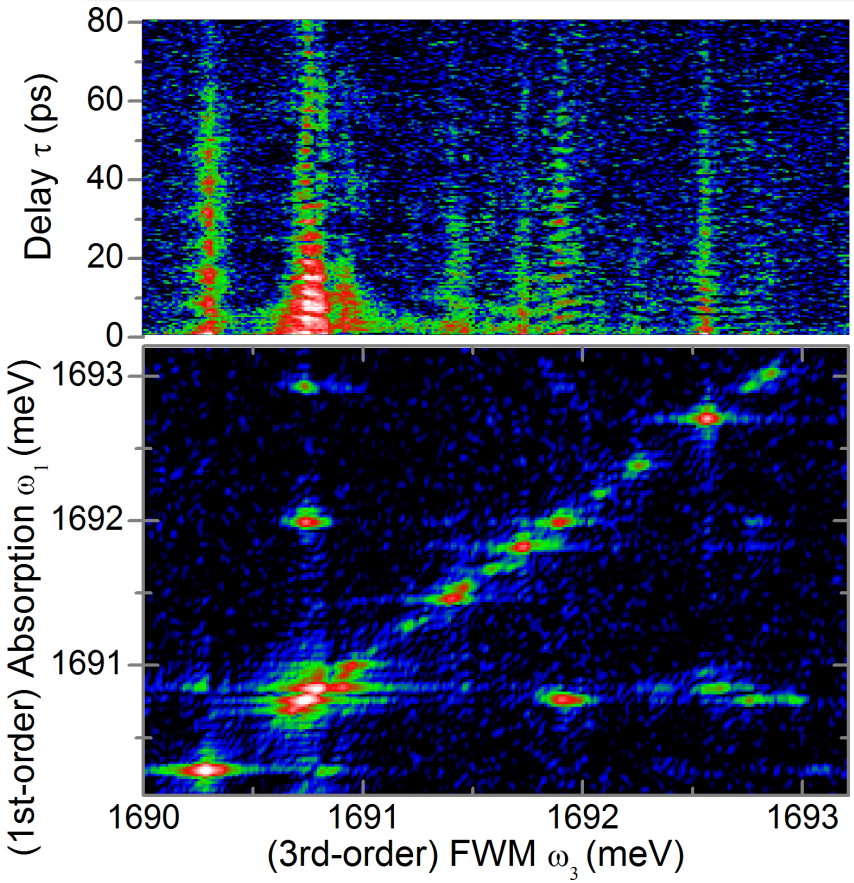



Closely lying QDs in a data cube $(x, y, \omega) \Rightarrow$ Coherent coupling ?

# 2D FWM ⇒ a sensitive probe of coherent coupling

Individual excitons loosely bound on disorder in a quantum well

Procedure: $\mathrm{P}(\omega, \tau) \xrightarrow{\mathrm{FT\ vs.}\ \tau} \mathrm{P}(\omega, \omega_1)$




Diagonal ⇔ All transitions

Non-diagonal ⇒ Coherent Coupling

**Spatial position of coupled excitons ?**

2D FWM + FWM imaging ⇒
Coupling between distant excitons

Mechanism ?

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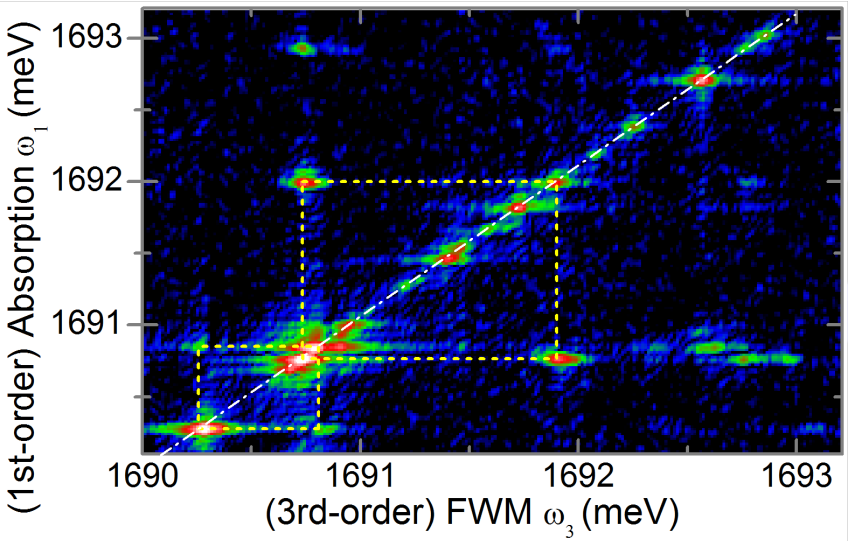


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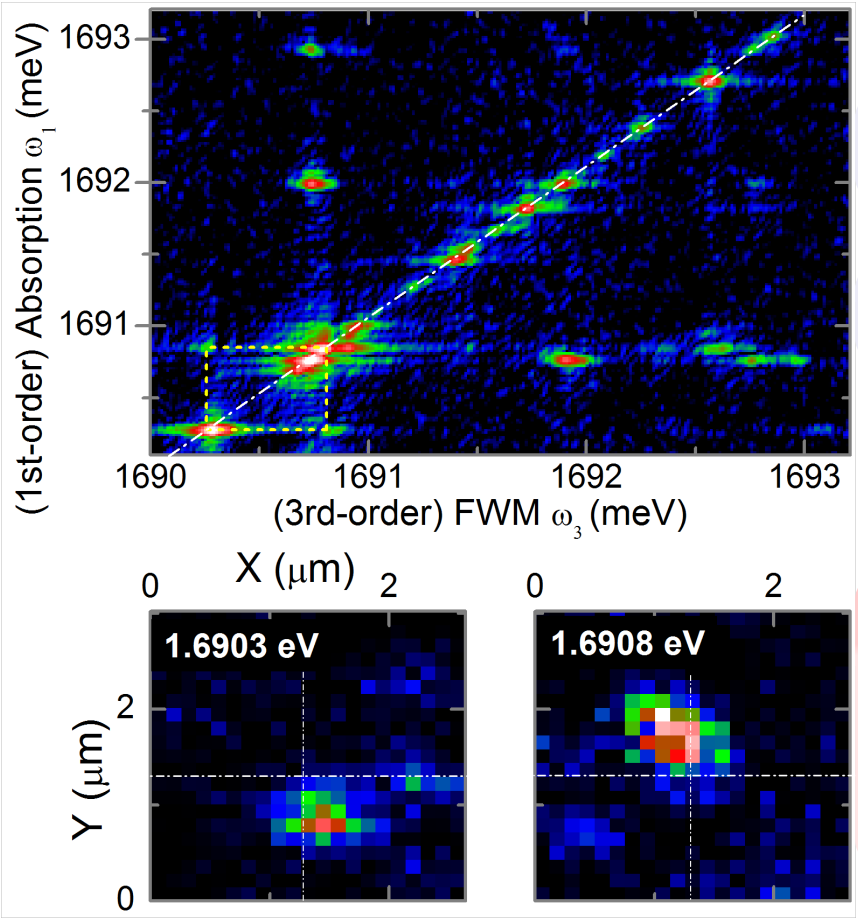


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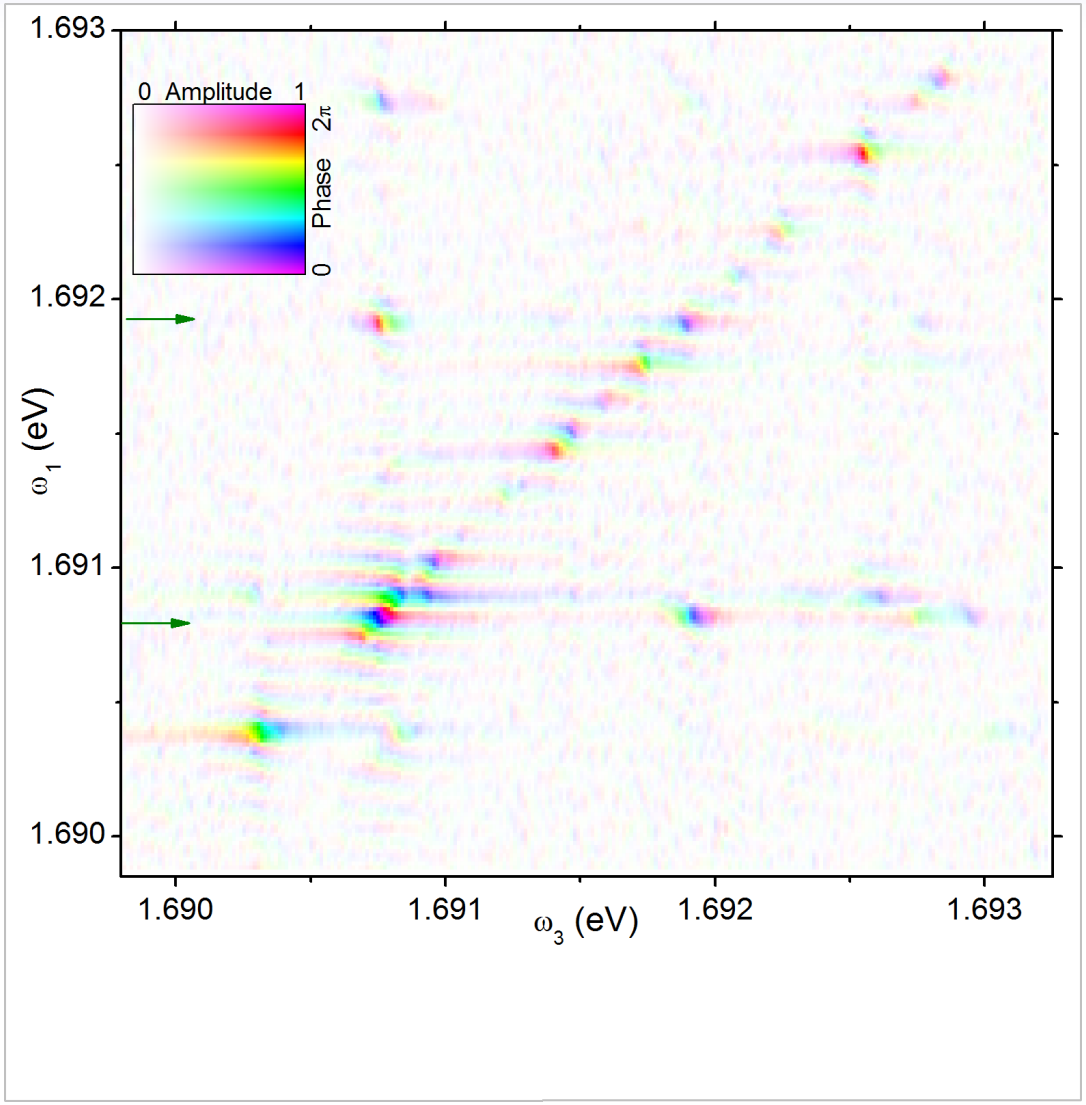
# Coulomb Induced Coupling

## Experimental Verification with a Phase-Resolved 2DFWM




### Off-diagonals

- Double-peak structure NOT-resolved
- $2\pi$ phase-shifts measured
- $\delta = ((10 - 100) + 0i)\mu eV$

$\Rightarrow$ Coulomb Repulsion of a 2-Exciton State

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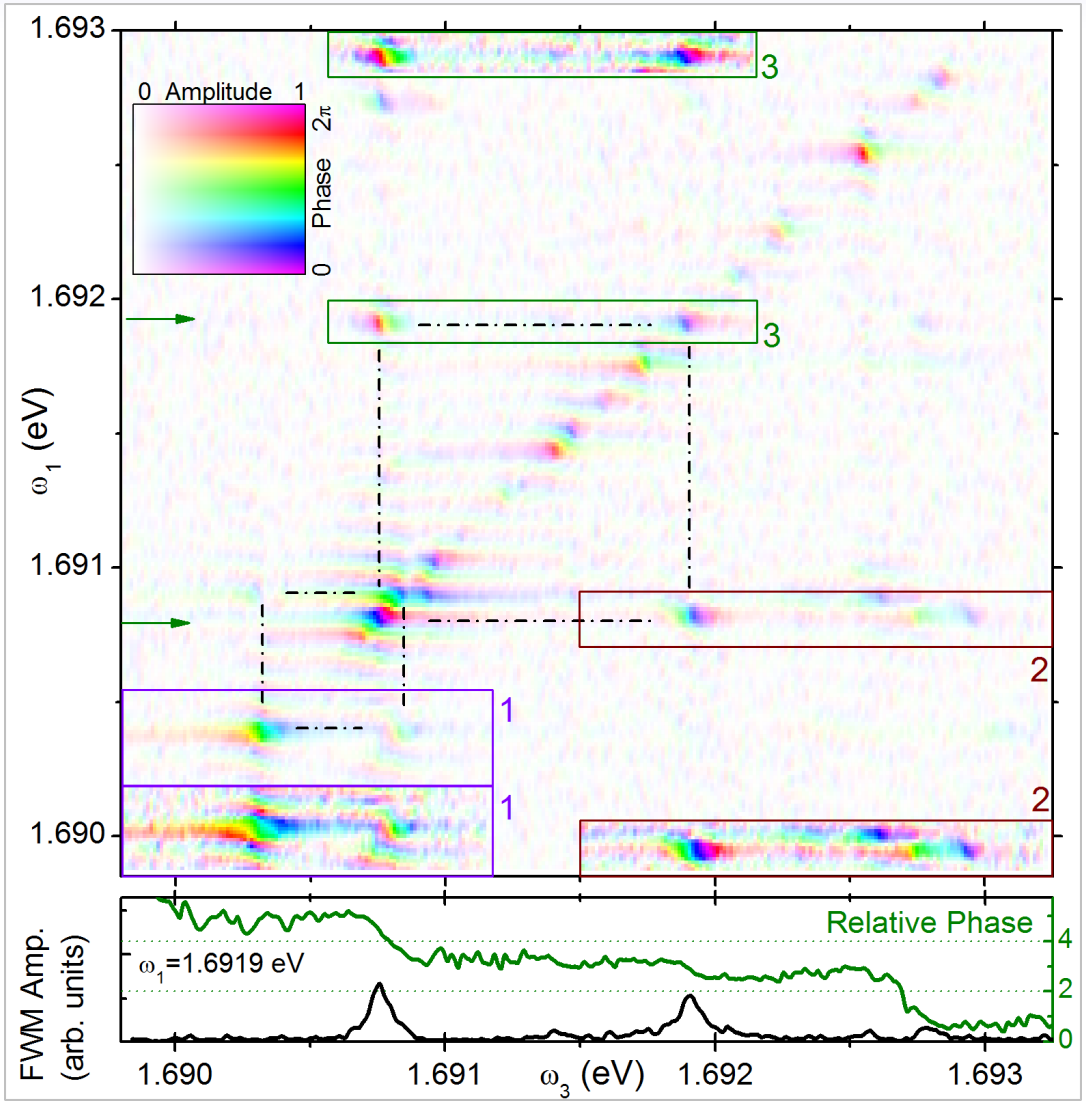


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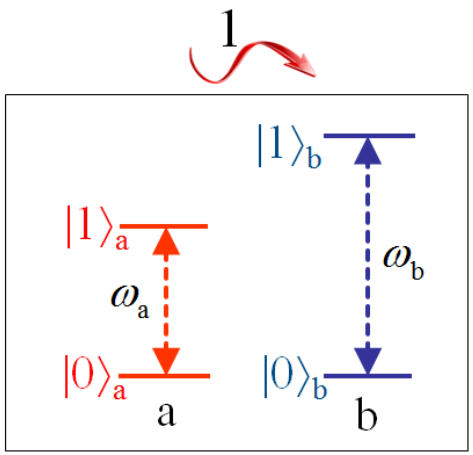
# Origin of inter-exciton coherent linking ?

## Coupling Mechanisms in a pair of 2-Level Systems

### 2 Uncoupled 2-Level Systems

a: $|0\rangle_a, |1\rangle_a, \omega_a,$ b : $|0\rangle_b, |1\rangle_b, \omega_b$



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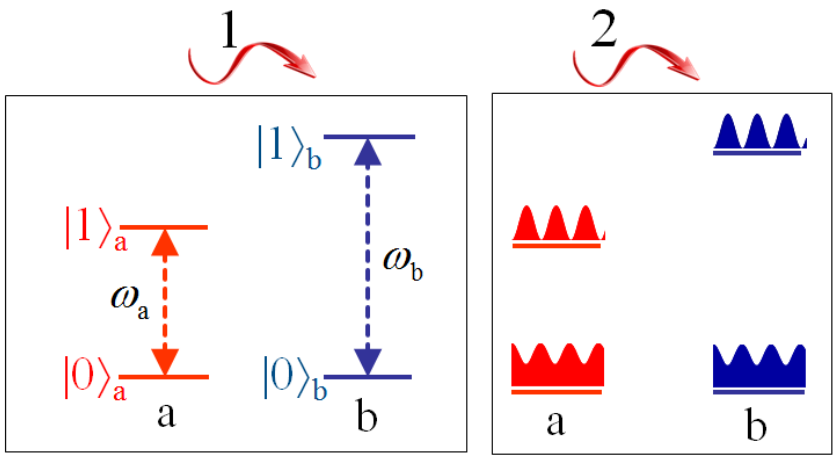

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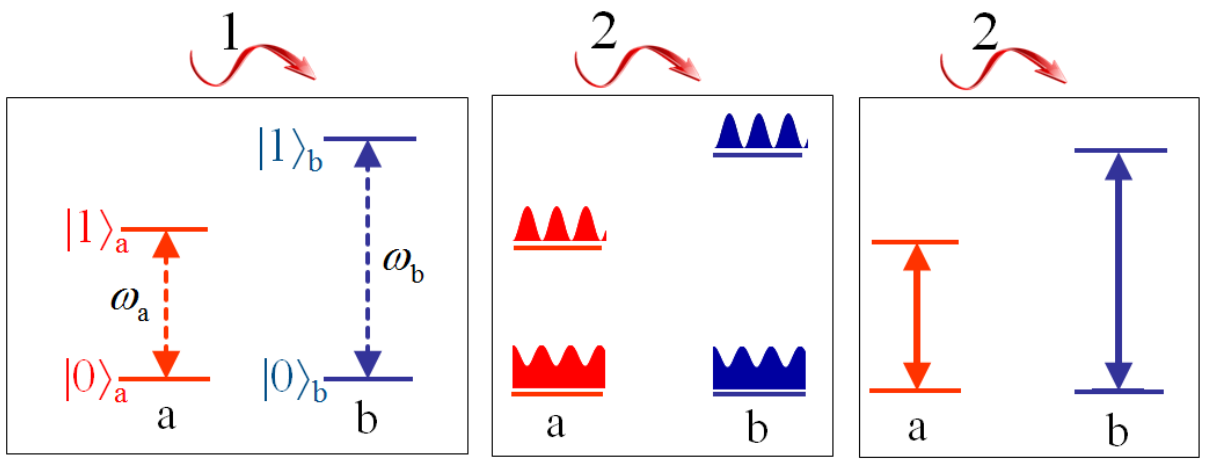

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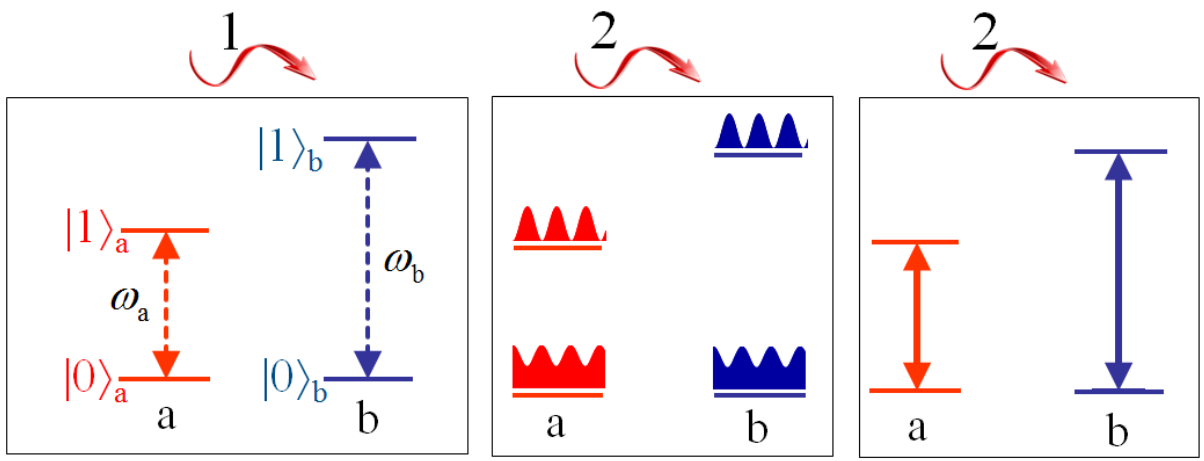


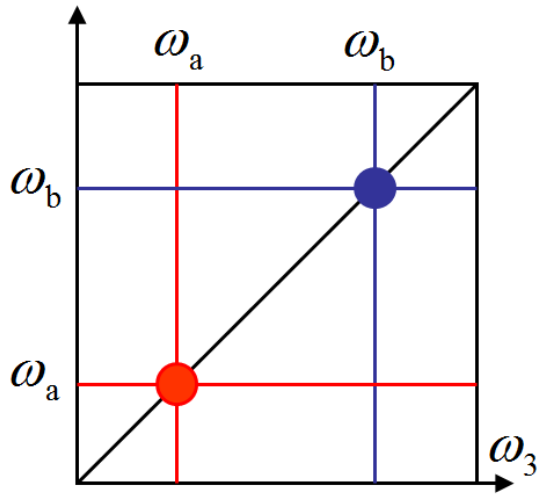

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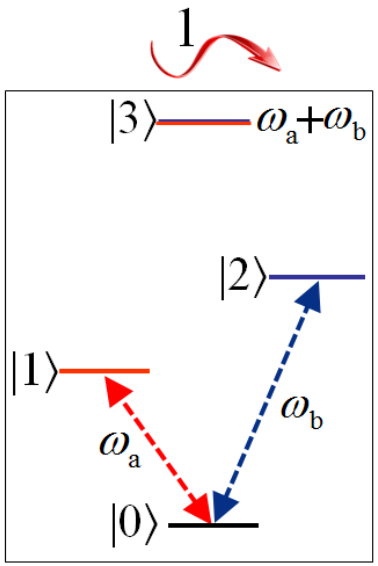

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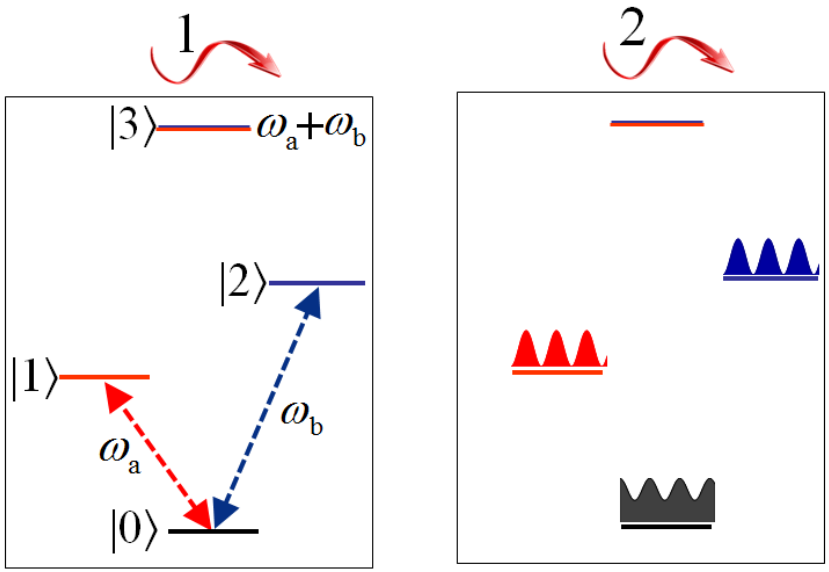

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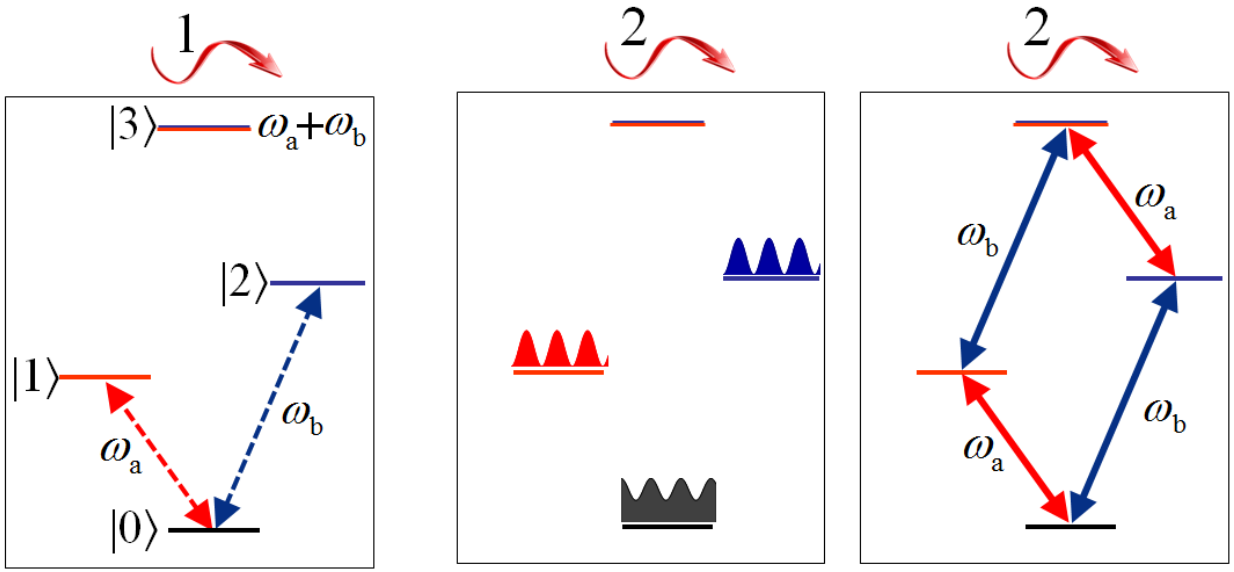


Out of Phase

$|0\rangle \leftrightarrow |1\rangle$ & $|2\rangle \leftrightarrow |3\rangle$

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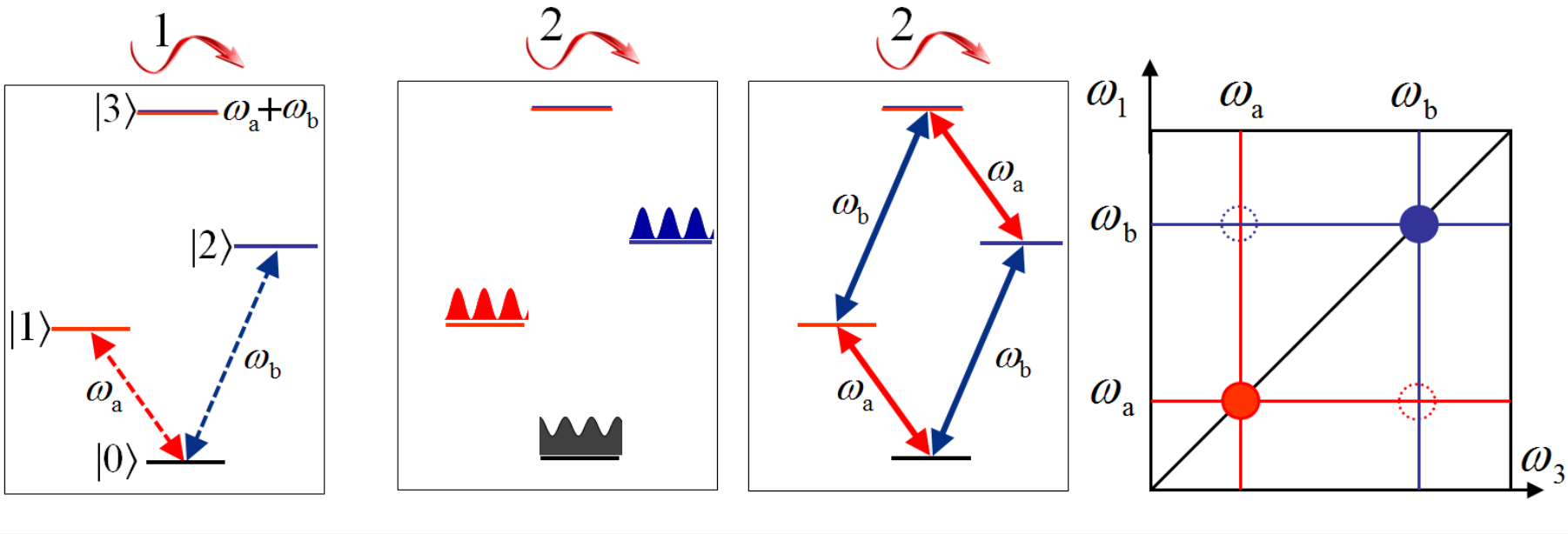

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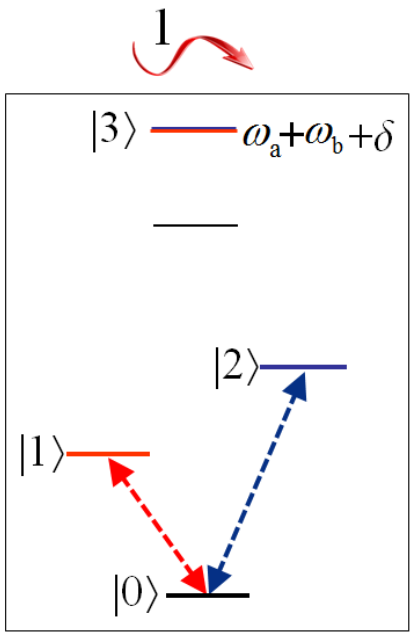
### Lift of Spectral Degeneracy

Coulomb Repulsion $\delta$ in a 2-Exciton state $|3\rangle$



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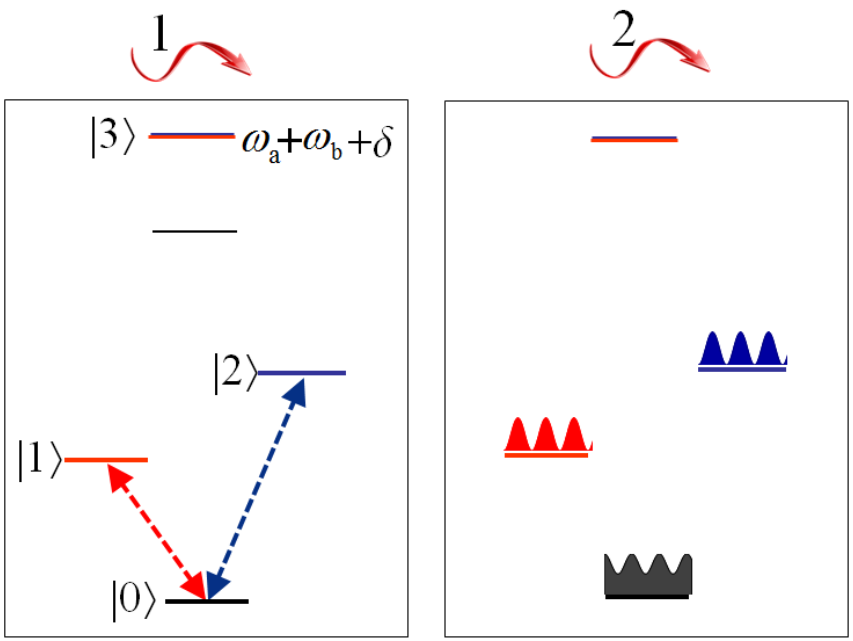

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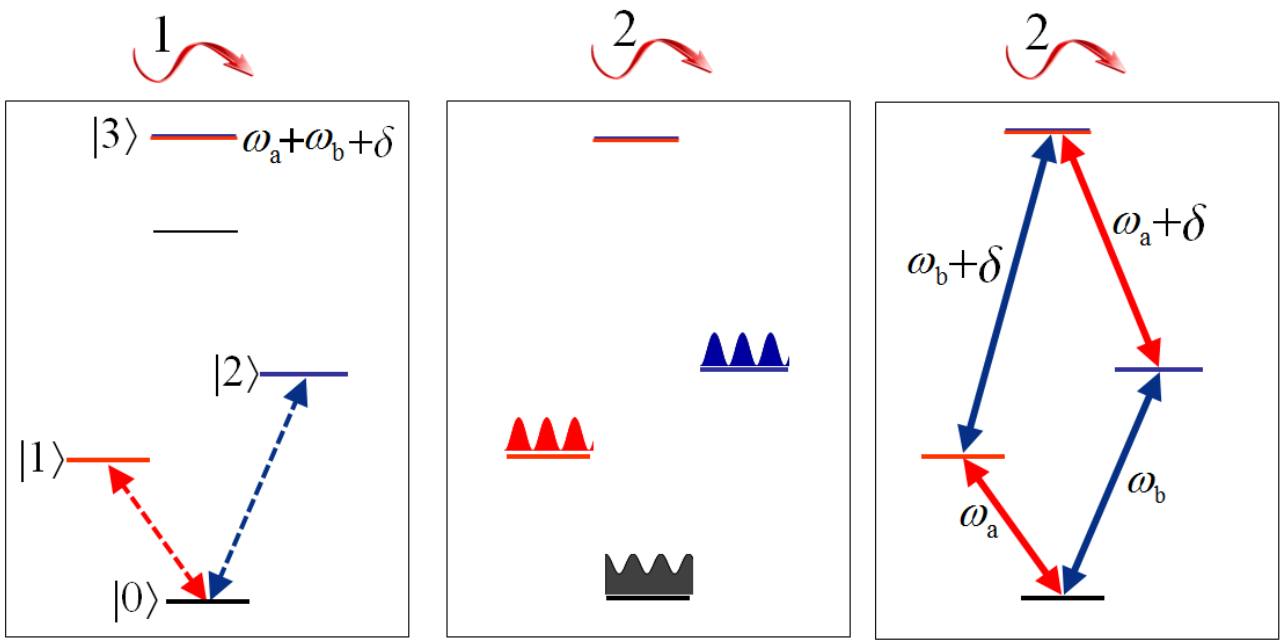


Out of Phase

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**But shifted by $\delta$**

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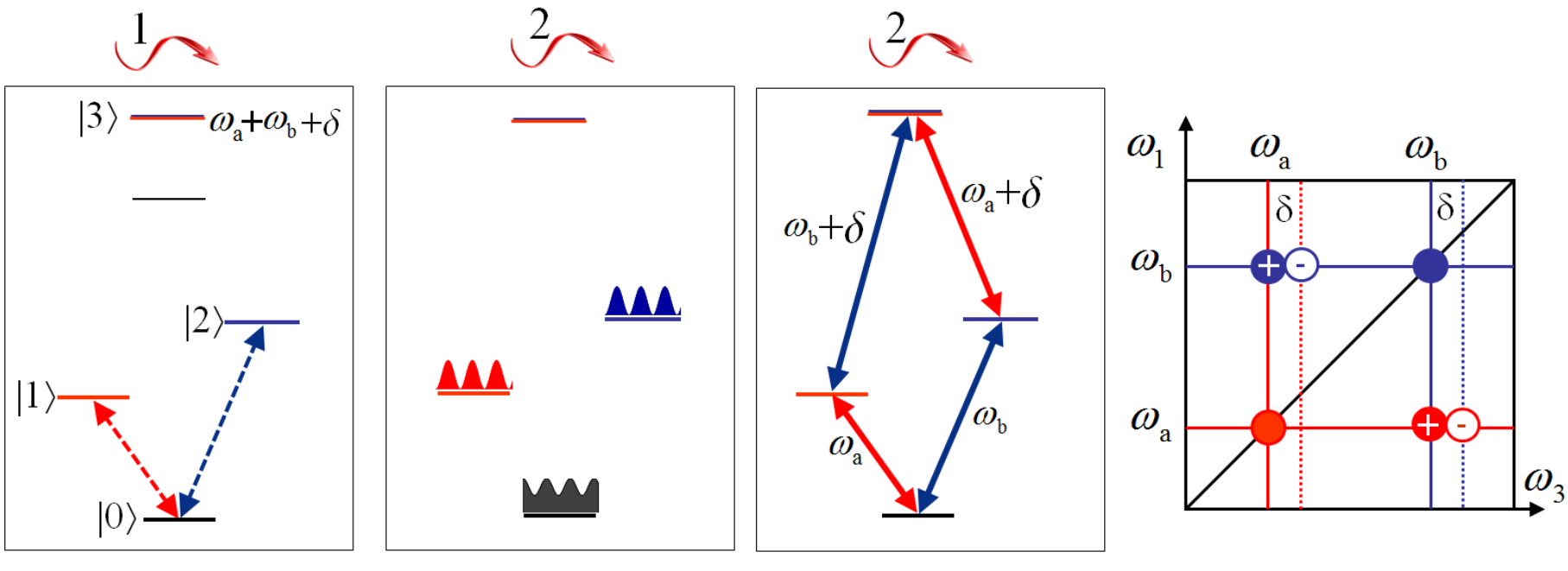
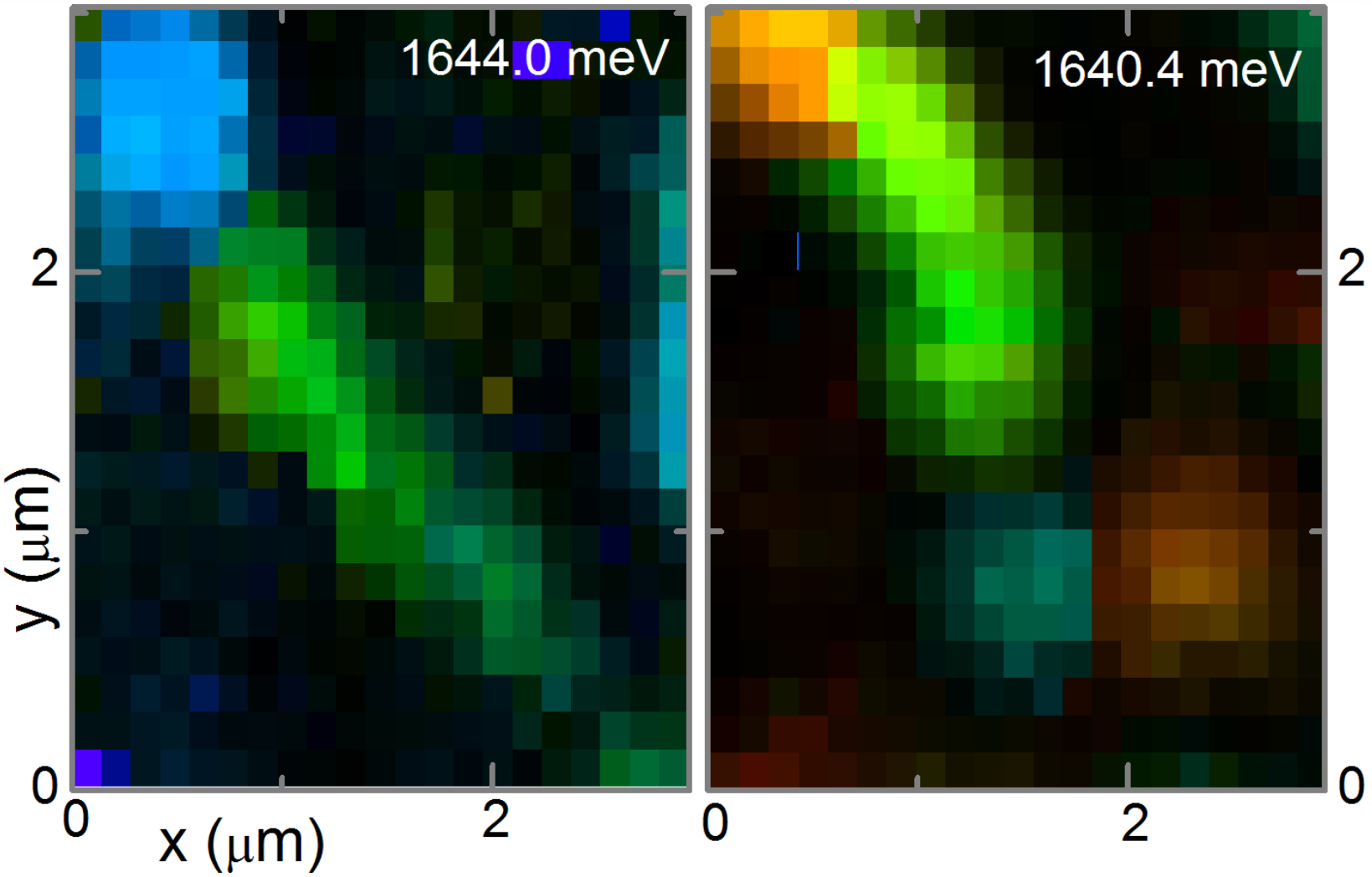


# How to couple single excitons over 1 $\mu$m ?

Formation of QW polaritons $\Rightarrow$ Extended natural coupling channels



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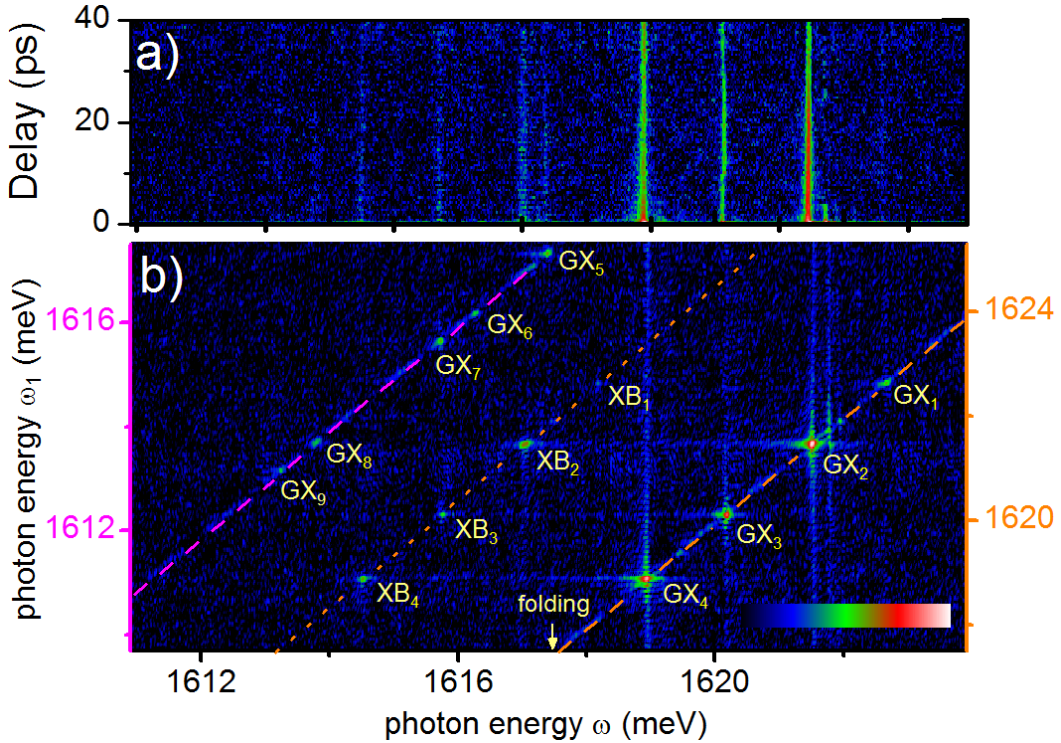
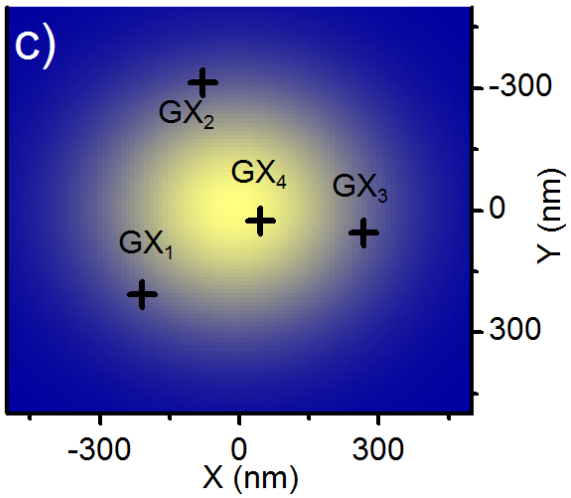


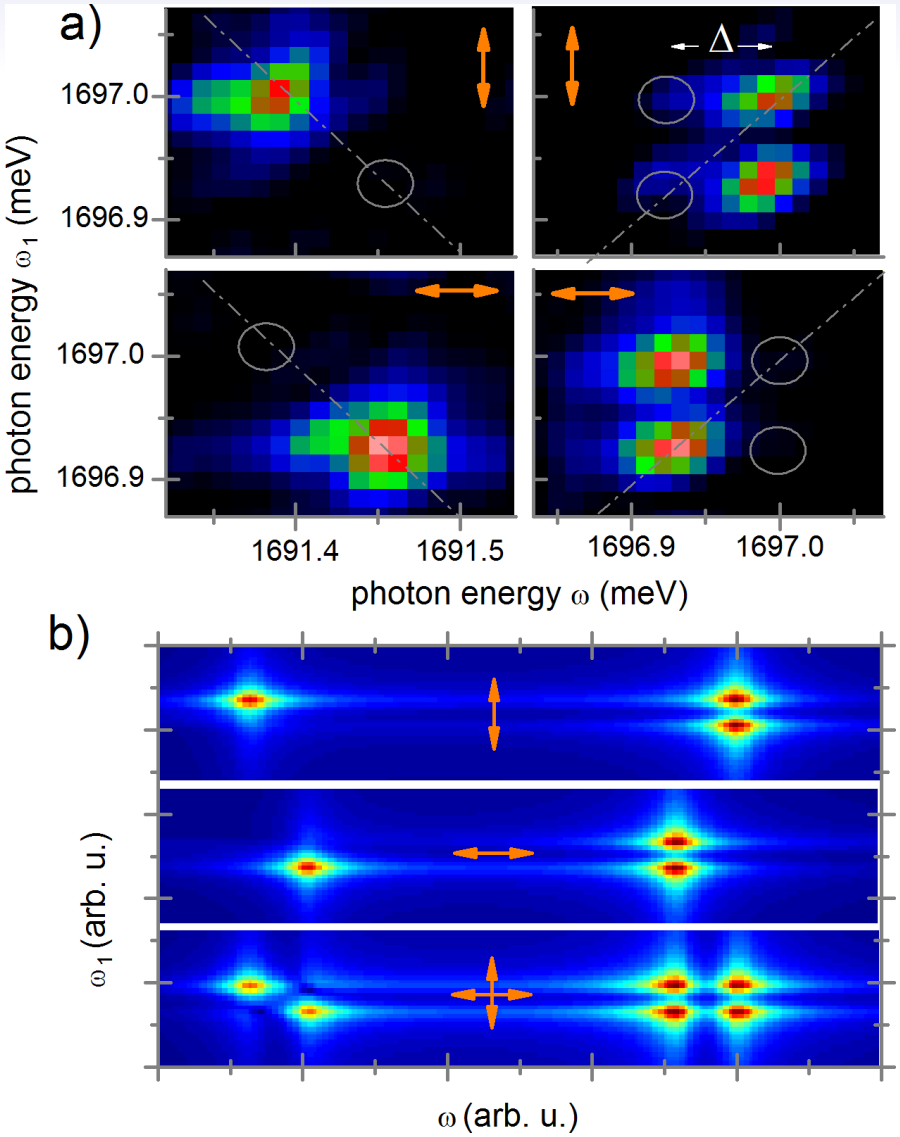

imaging yields relative spatial position of $X_{1..4}$




diagonal ⇒ all transitions, off-diagonal ⇒ coherent coupling,

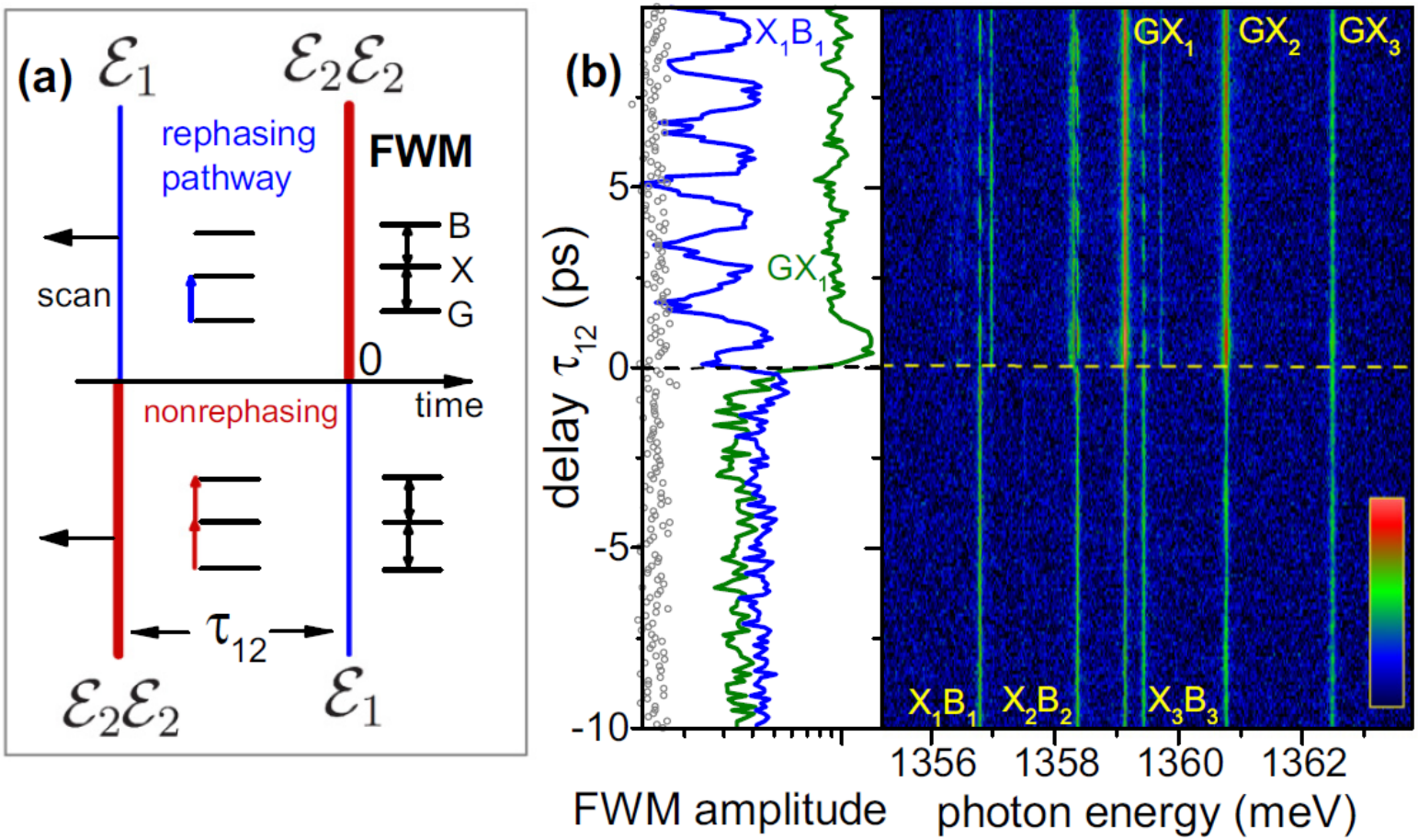
FWM imaging ⇒ relative position

# Coherent coupling within a fine structure-split exciton



# Coherent coupling

## Single- versus double-quantum coherence



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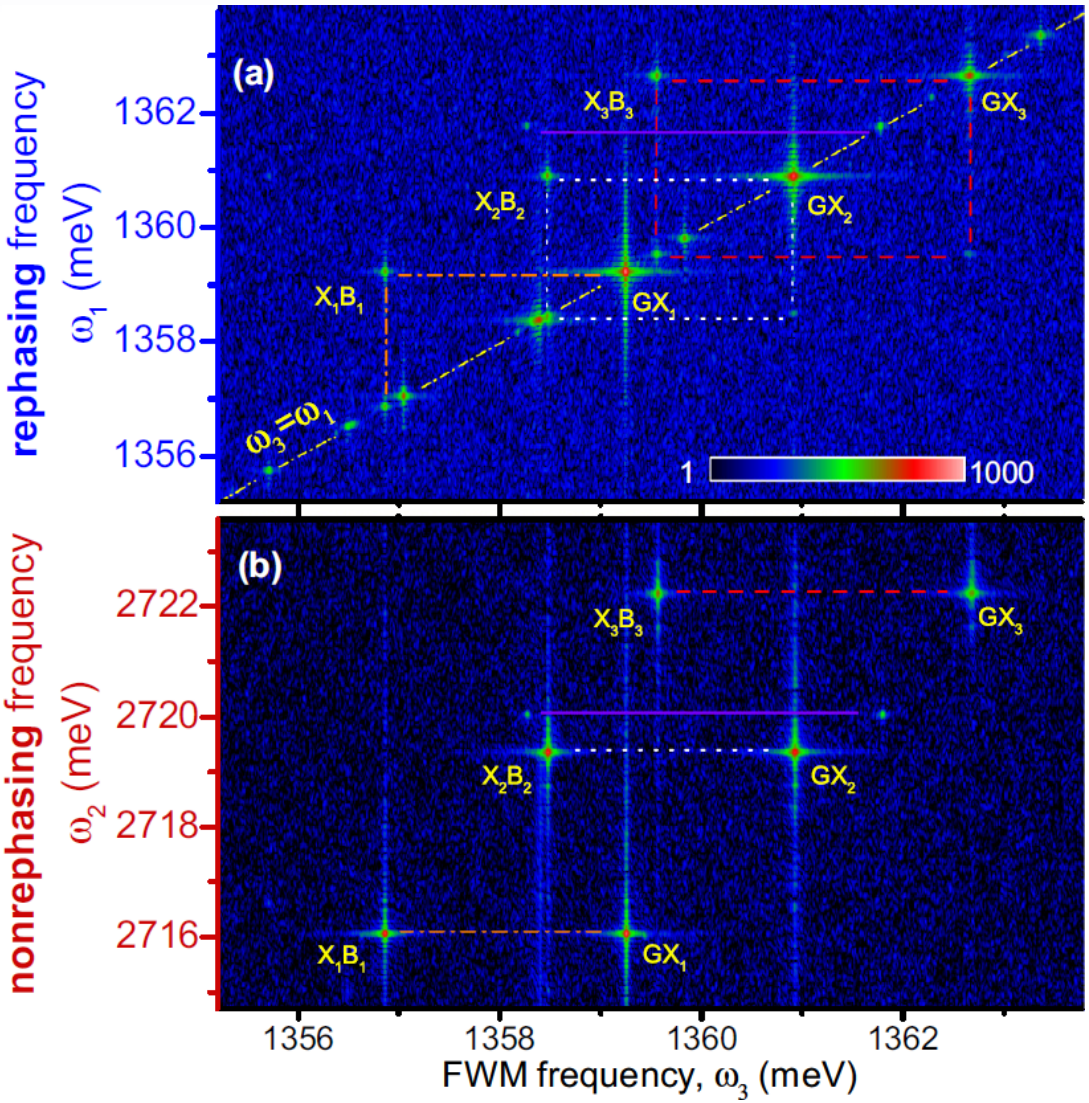
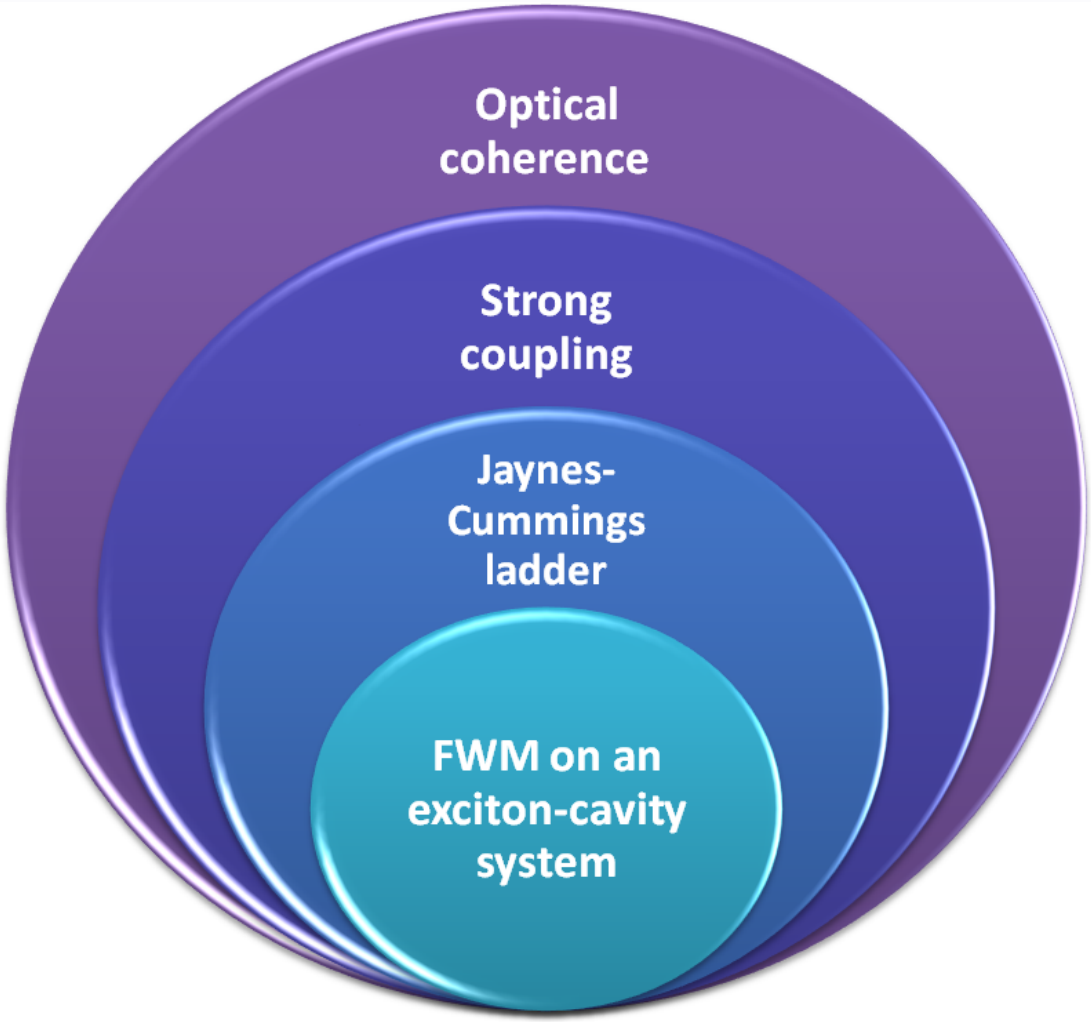
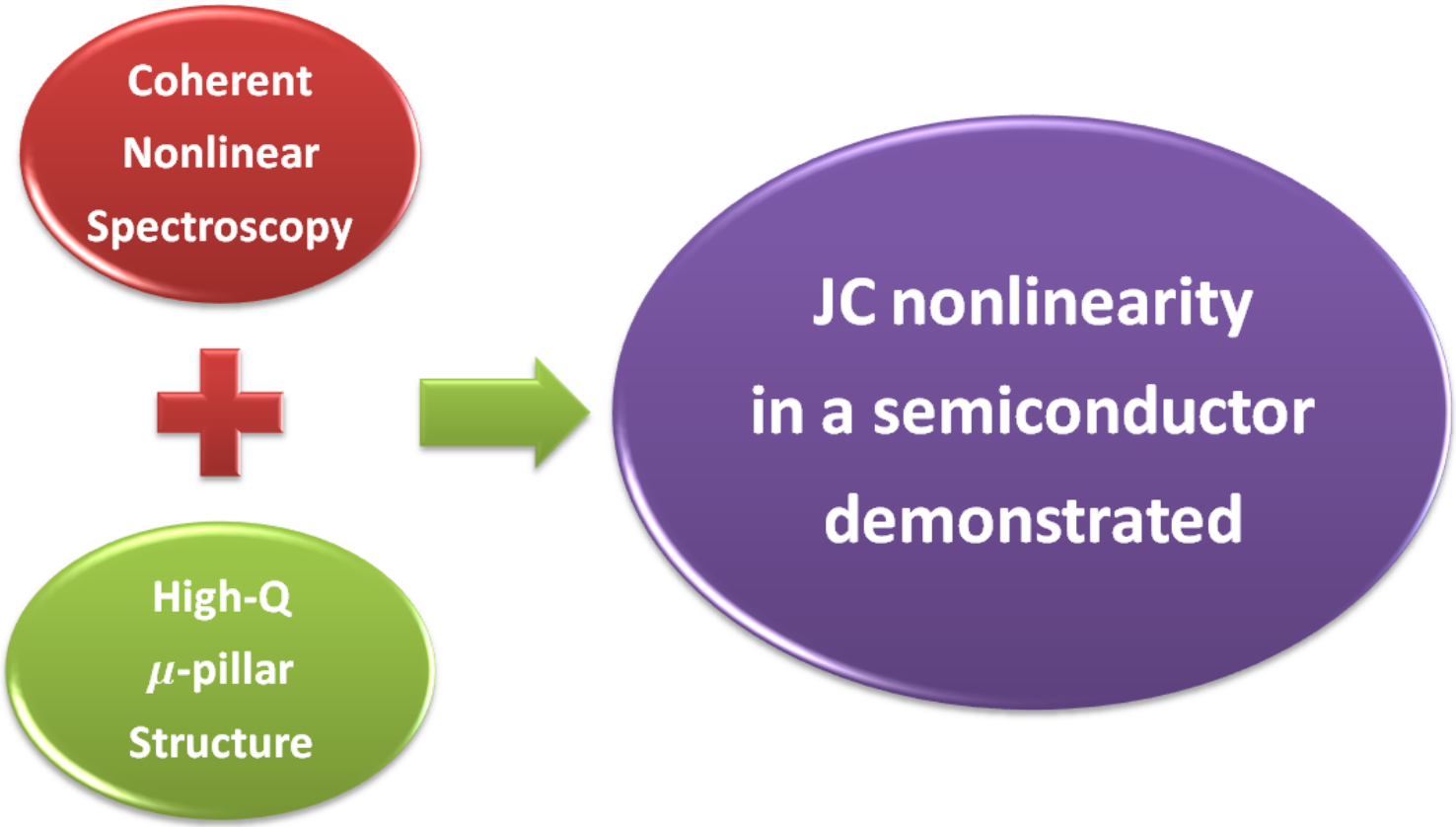


# Outline

# Summary II

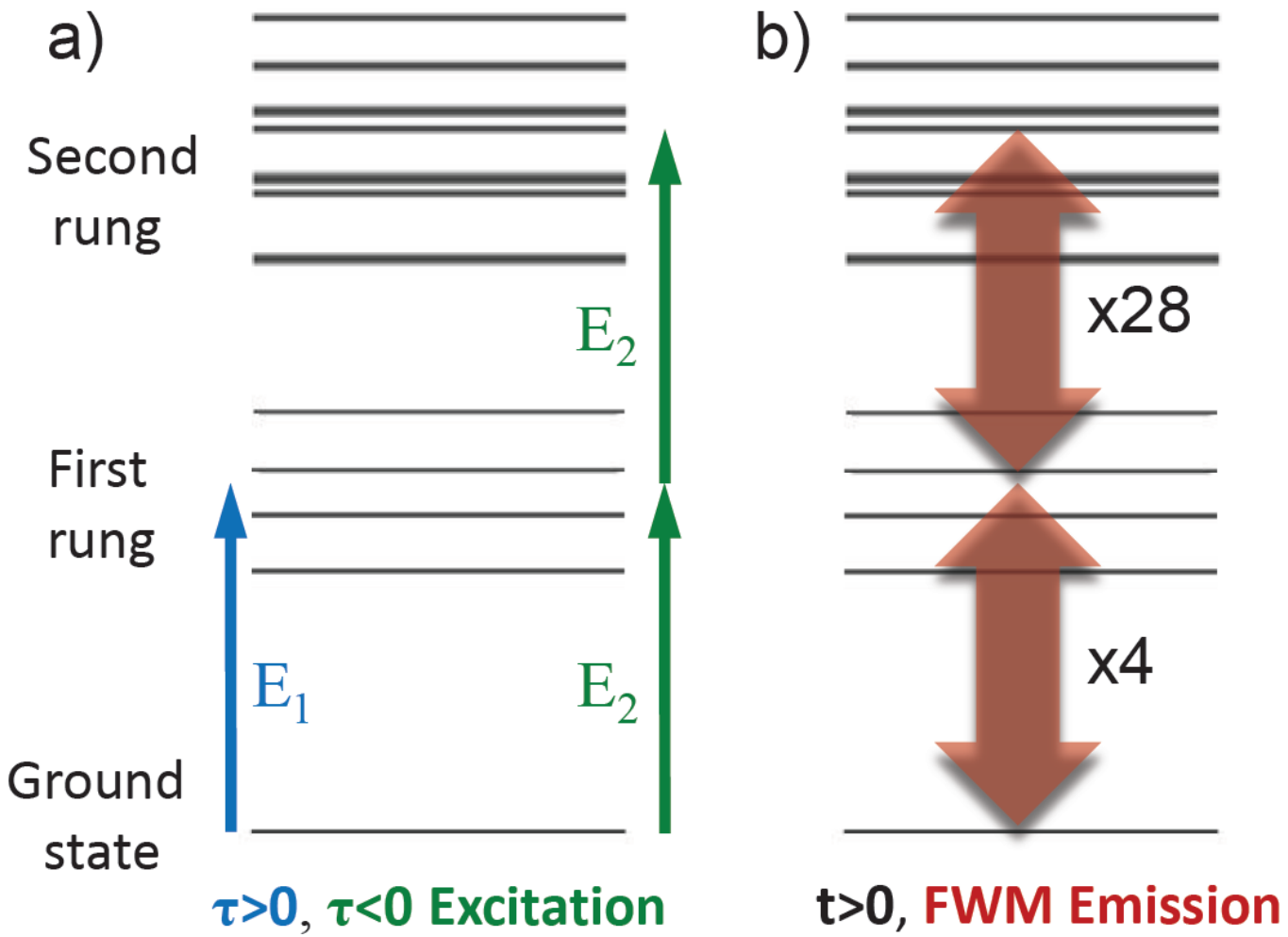

Optical coherence
Strong coupling
Jaynes-Cummings ladder
FWM on an exciton-cavity system

# Summary II


Coherent
Nonlinear
Spectroscopy
High-Q
μ-pillar
Structure
JC nonlinearity
in a semiconductor
demonstrated

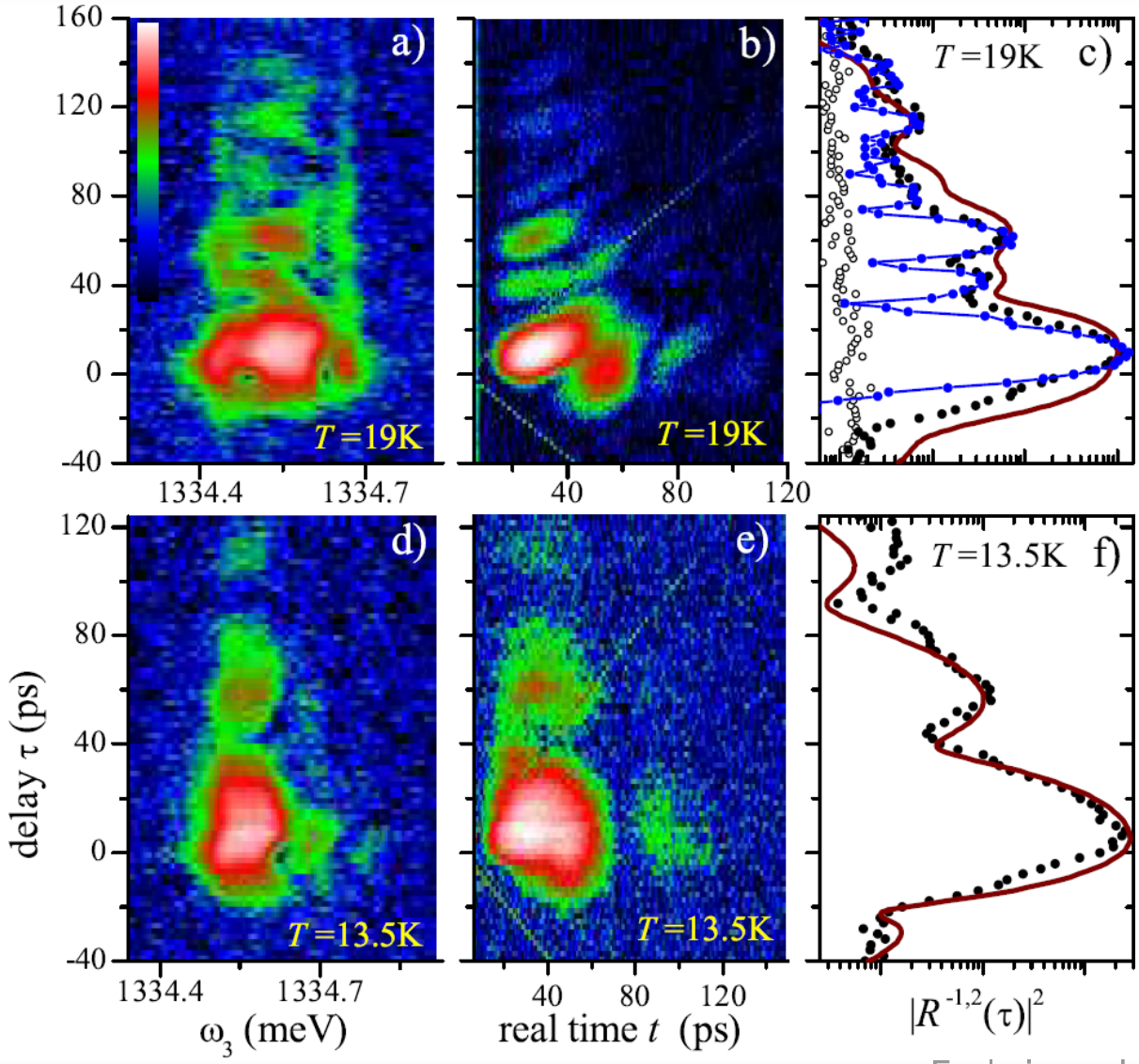
# Cavity-controlled inter-exciton coupling

## FWM pathway within the Tavis-Cummings model



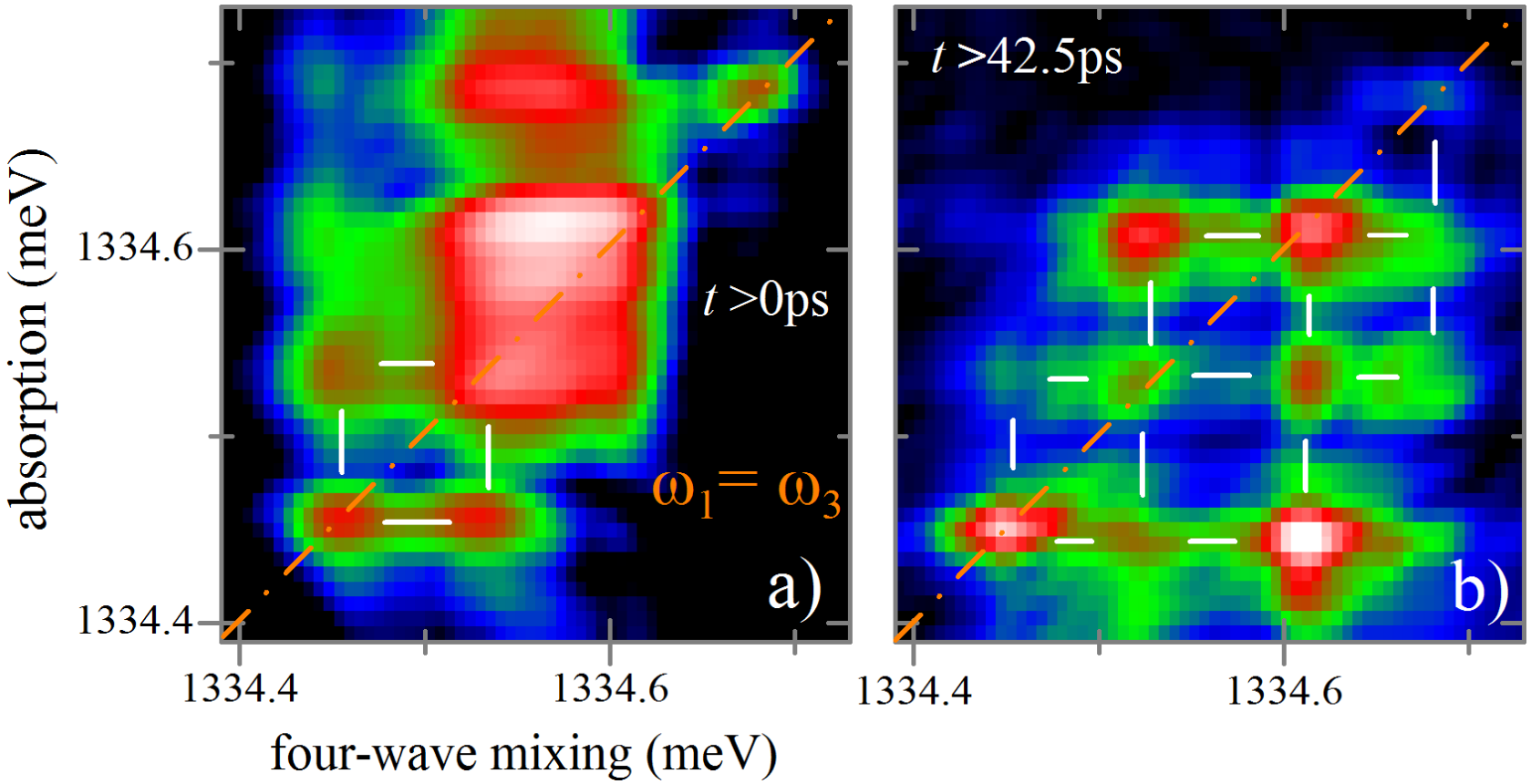
# Cavity-controlled inter-exciton coupling

## Coherent dynamics measured in FWM($\tau$)



# Cavity-controlled inter-exciton coupling

revealed with two-dimensional FWM, 19 K



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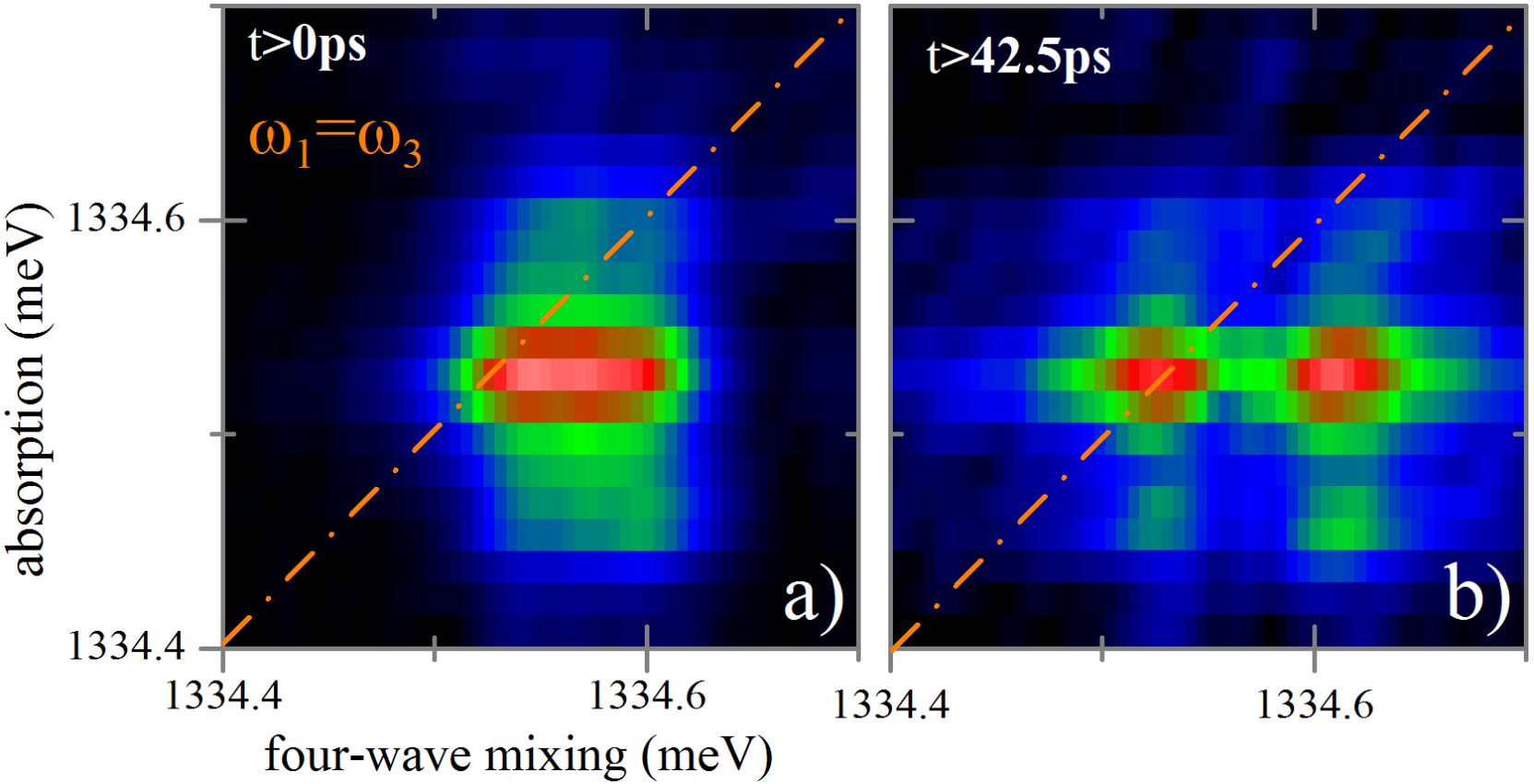

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# Towards long-range radiative coupling of excitons

Spatially-resolved FWM on a pair of excitons in a structure with an extended photon mode: photonic crystal, 1D waveguide,...

| System | Coupling Mechanism | Coupling range | Remarks |
|---|---|---|---|
| individual, localized excitons in a QW **2D** | Coulomb repulsion in a 2-exciton state | Up to 1 $\mu$m | mediated via extended delocalized excitons, disorder |
| cluster of excitons in a $\mu$-pillar cavity **0D** | radiative, polaritonic | ~100 nm | photon-mediated, boosted by strong coupling |
| pair of excitons in a photonic wire **1D** | radiative | ? | enabled by waveguiding, requires resonant emitters |



J.-H. Kim,...E. Waks Super-radiant emission from quantum dots in a nanophotonic waveguide Nano Letters (2018)

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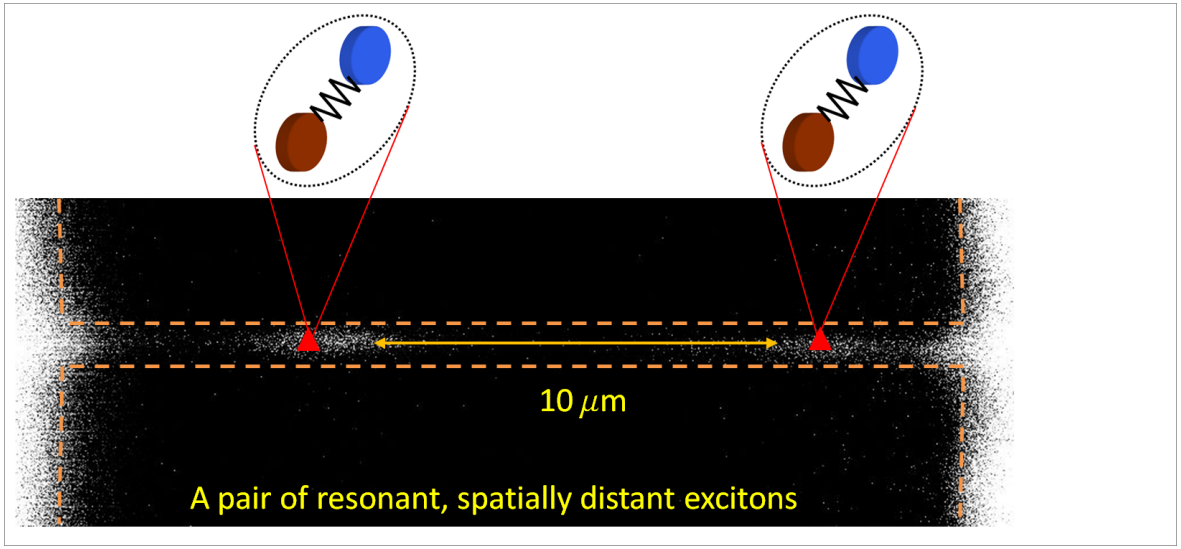


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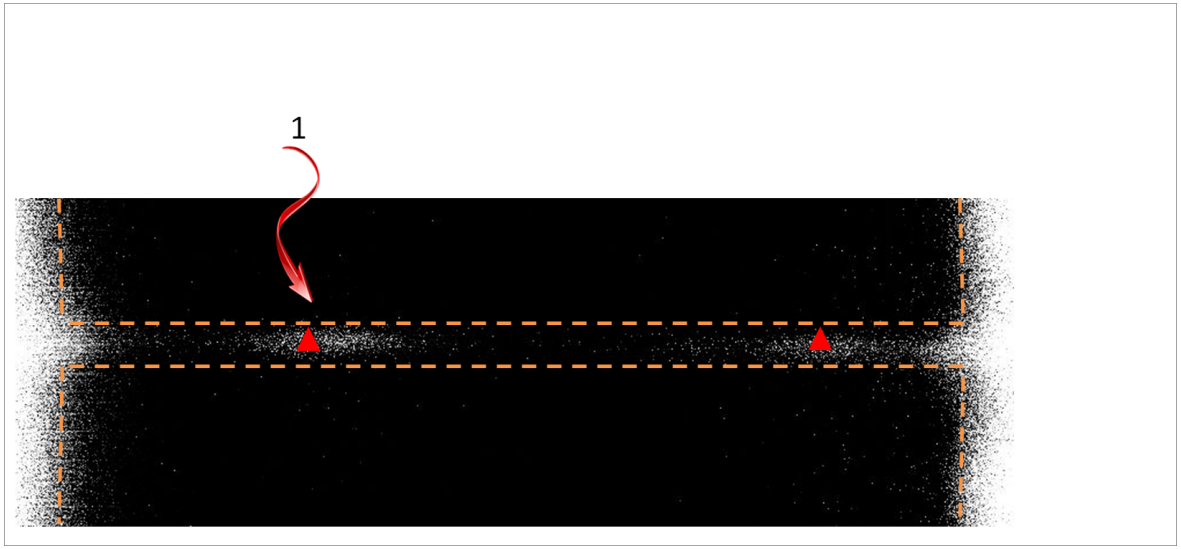


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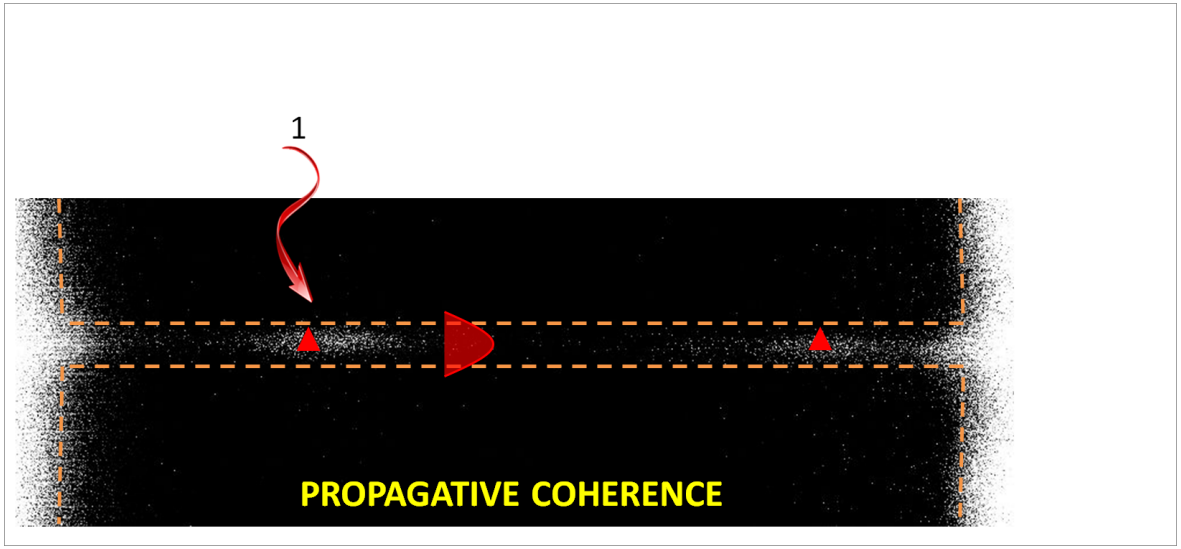


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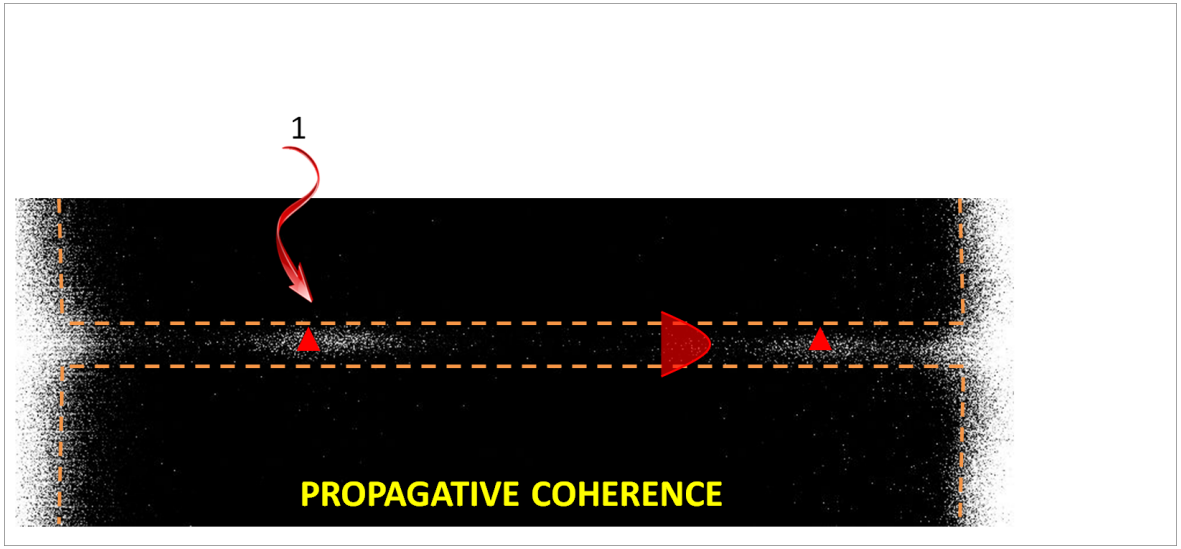


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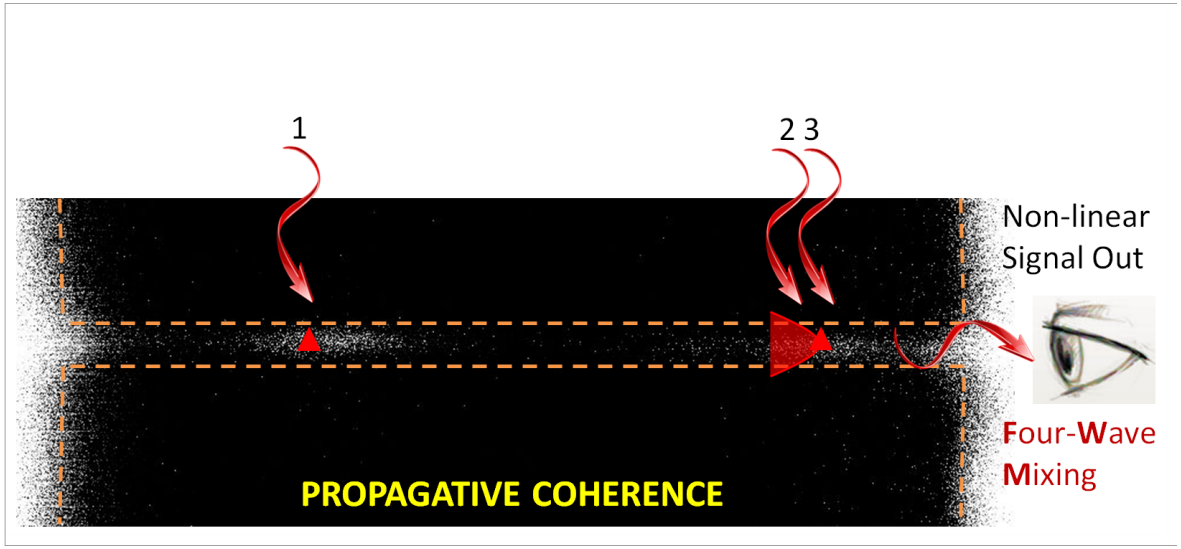


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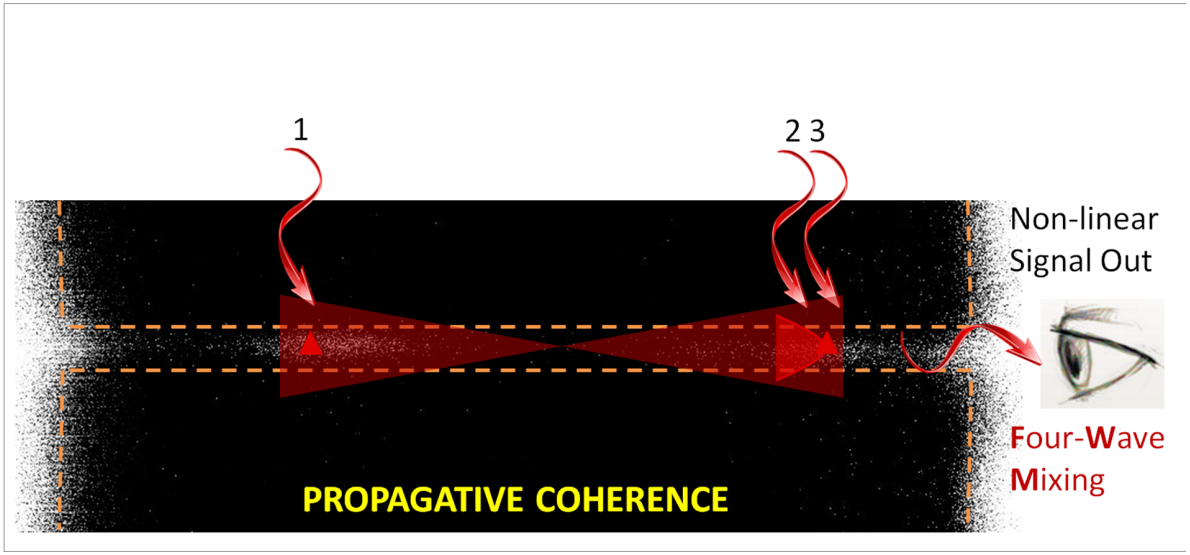


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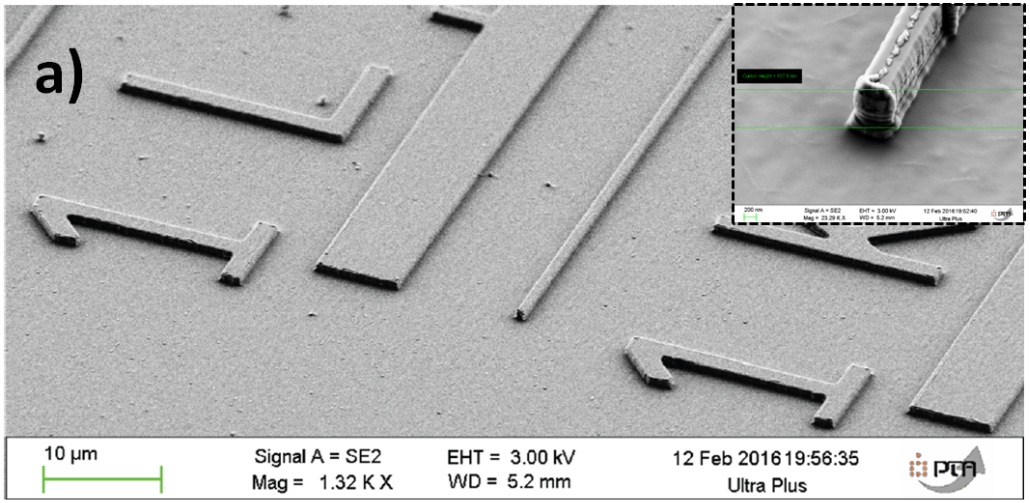
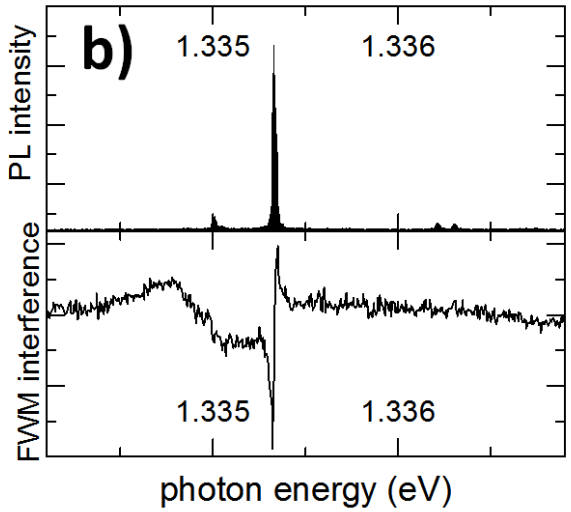
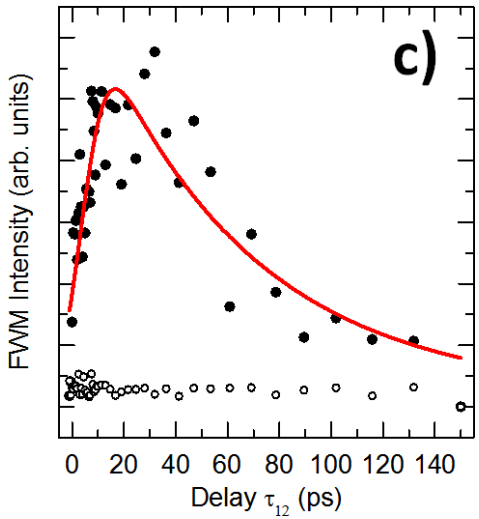
# Spatially-resolved FWM

**Deterministic** wave-guides at hand, frequency tuning still needed

P. Schnauber & S. Reitzenstein (TU Berlin)



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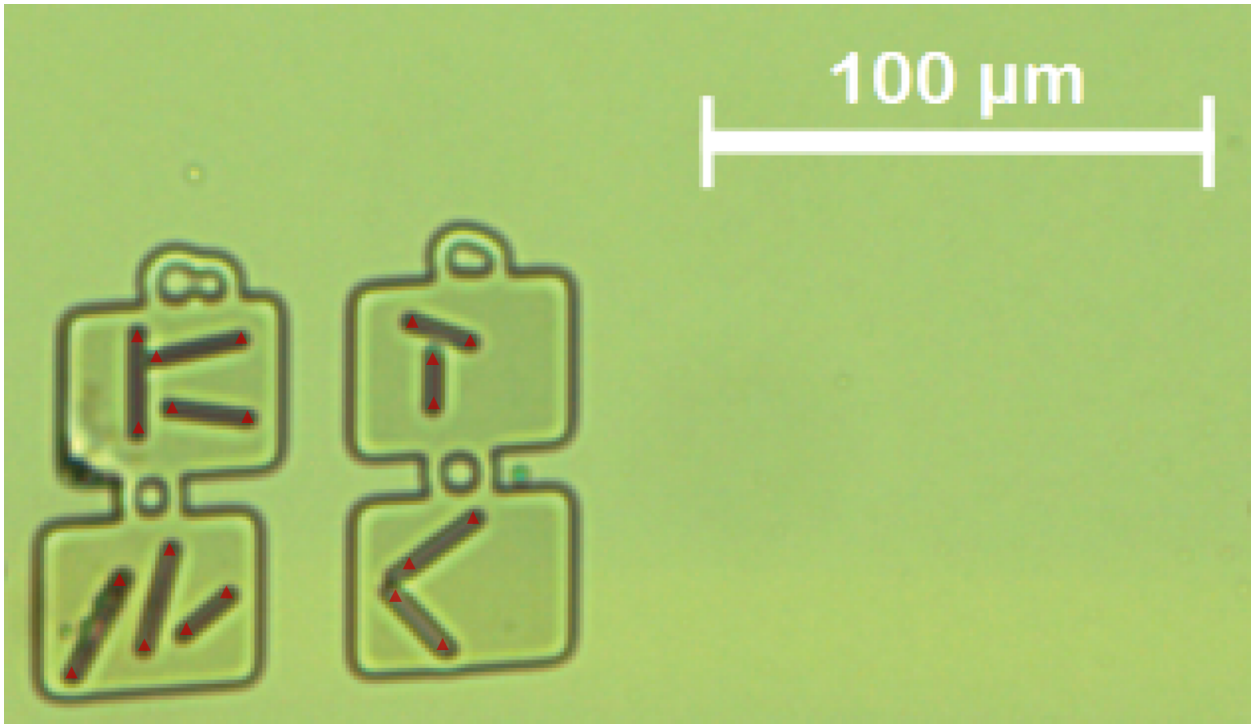

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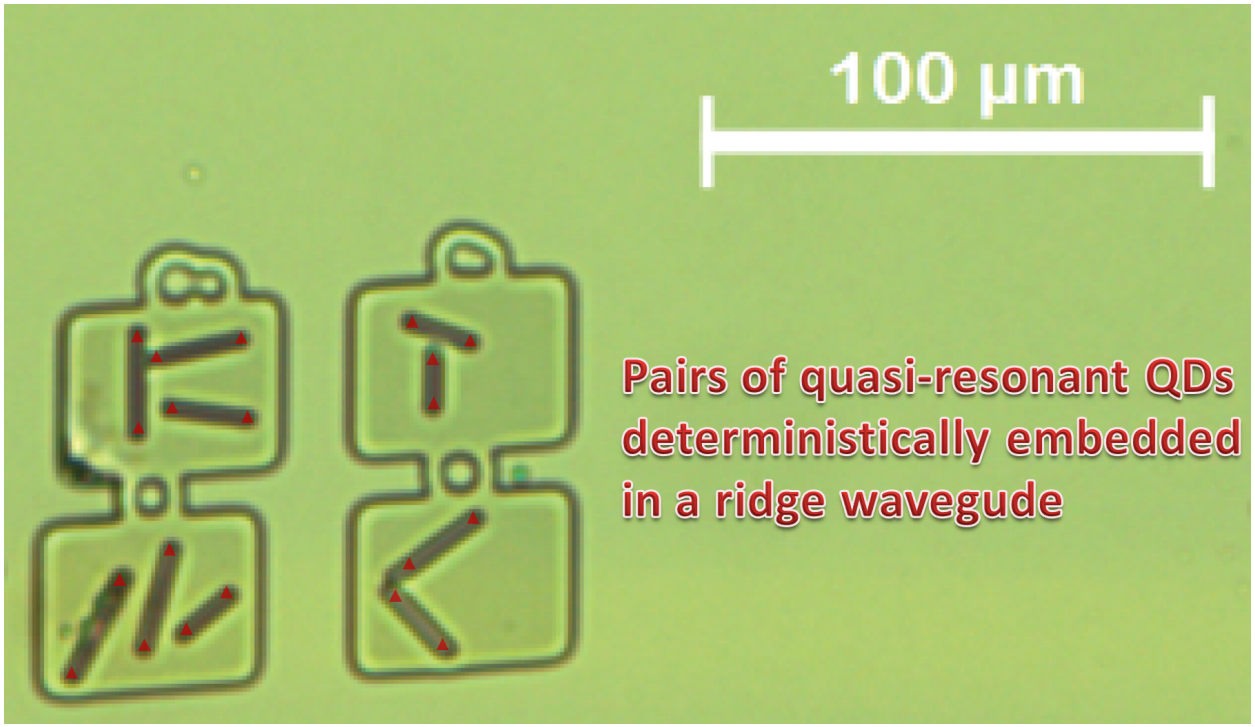

# Summary

**Two-dimensional FWM:**

- 2D spectroscopy of individual emitters & their small ensembles
- Assessment of coupling mechanism of weakly-confined excitons $\Rightarrow$ Coulomb coupling
- Single- versus double-quantum coherence in 2D FWM
- Photo mediated coupling in a $\mu$-pillar cavity
- Toward long-range radiative coupling