Coherence in semiconductor nanostructures
Part VI: Coherent dynamics and control of single excitons

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UNIWERSYTET WARSZAWSKI | ZINTEGROWANY PROGRAM ROZWOJU

Equipe mixte CEA-CNRS "Nanophysique et semicondcuteurs"
Institut Néel - CNRS
Grenoble France

Warsaw University, October-December 2020

Outline

Research field

Coherent dynamics & control of individual transitions in solids

Obstacles & Requirements

- Linear response dominated by dielectric function of the bulk
- $\tau_c < \mathrm{ns}$
- Isotropic emission & weak signal from an individual state
- Readout in Phase & Amplitude
- State switching
- Intrinsic small osc. strength

Solution

- Use non-linear optical response like FWM
- Ultra-Fast spectroscopy
- Heterodyne Detection
- Spectral Interferometry
- Use Multi-Pulse Resonant excitation
- High signal integration rate

Bulk⇒QWs⇒Ensemble of QDs⇒Interface QD⇒ **Self-assembled QD**

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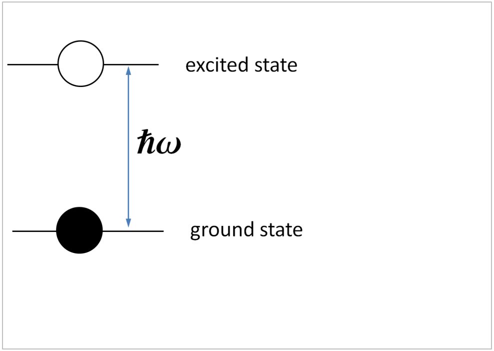
Quantum Engineering

Controlling **coherence** and densities in two-level systems:

T_1, T_2, Rabi, echo, coupling...



- Accessing the Qubit→ favoring the light-matter coupling
- Avoiding losses & dephasing → environmental decoupling

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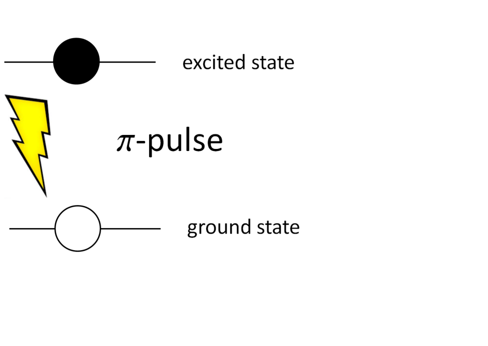

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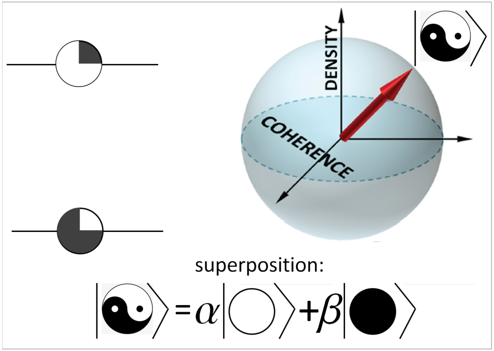

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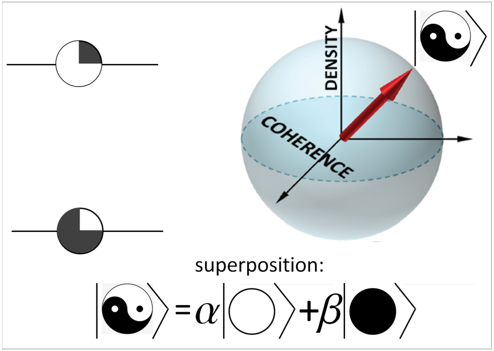

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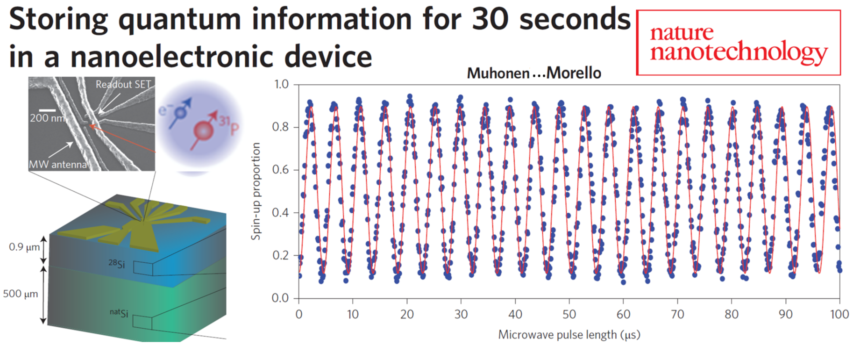
Quantum Engineering in Solids

Superconducting circuits, electron and nuclear spins, rare-earths…



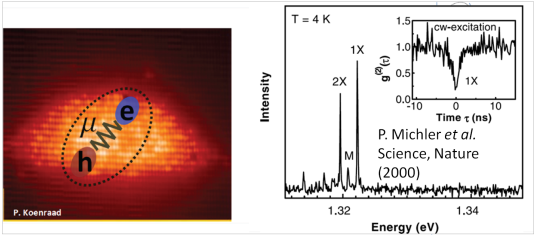
Silicon platform for quantum computation
♭ ultra-low temperatures, μ-waves

10^2 Rabi oscillations before any signs of decay, 10^5 observable

A quantum dot exciton

Bright, nano-scopic source of quantum light from the solid:

Optically driven, fast qubit ?



two-level system

embedded in the crystal $\longrightarrow$ phonons

robust coupling with UV-VIS-NIR light $\longrightarrow$ coherent control

price to pay: short lifetime, ns

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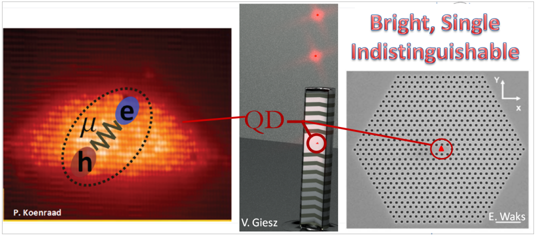

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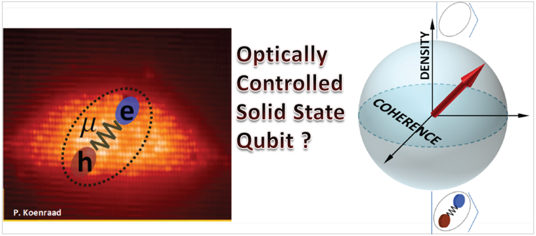

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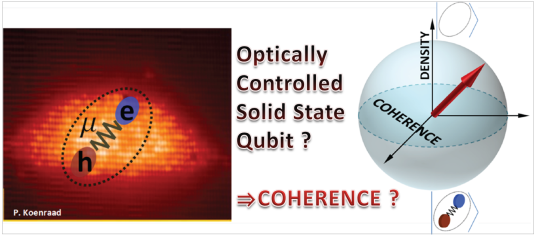

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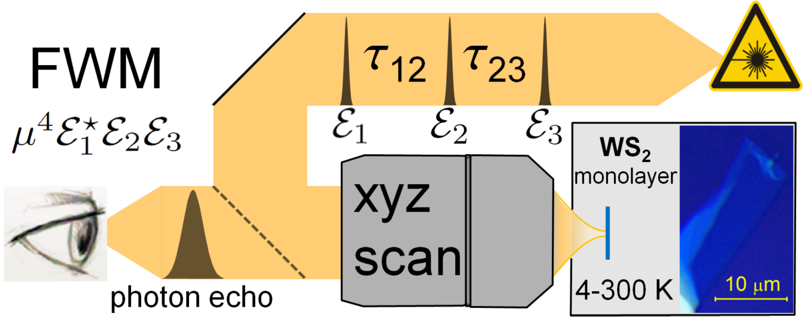
FWM micro-spectroscopy ⇒ optical lock-in

W. Langbein et al.Optics Letters 31, 1151 (2006)

intensly developed & exploited in Grenoble



3-beam heterodyne detection & spectral interferometry

Measurement of the exciton polarization and density dynamics with an enhanced spatio-temporal resolution: (100 fs, 300 nm)

FWM micro-spectroscopy $\Rightarrow$ optical lock-in

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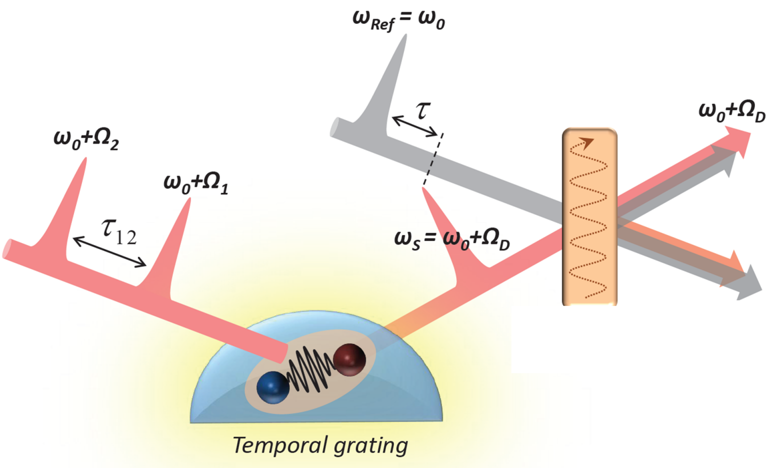

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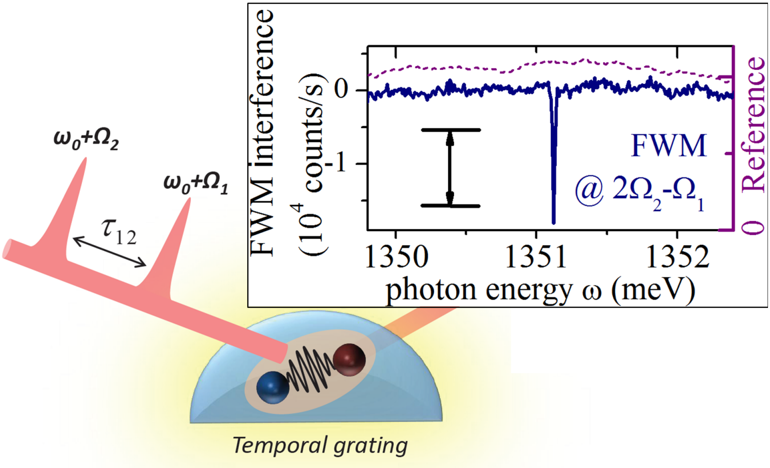
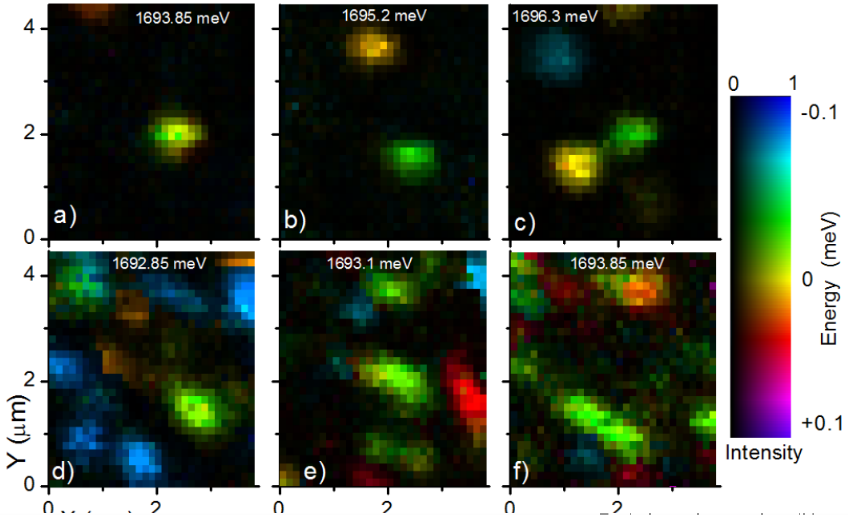


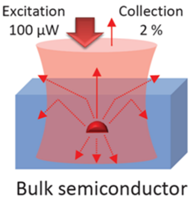
Microscopy ⇒ Scanning ⇒ Hyperspectral Imaging

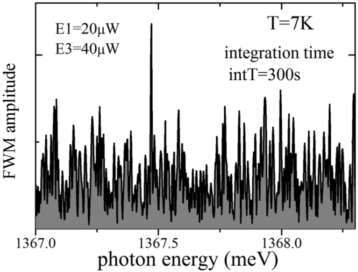
Interface fluctuation QDs



Microscopy ⇒ Scanning ⇒ Hyperspectral Imaging

InAs QDs in a low-Q microcavity





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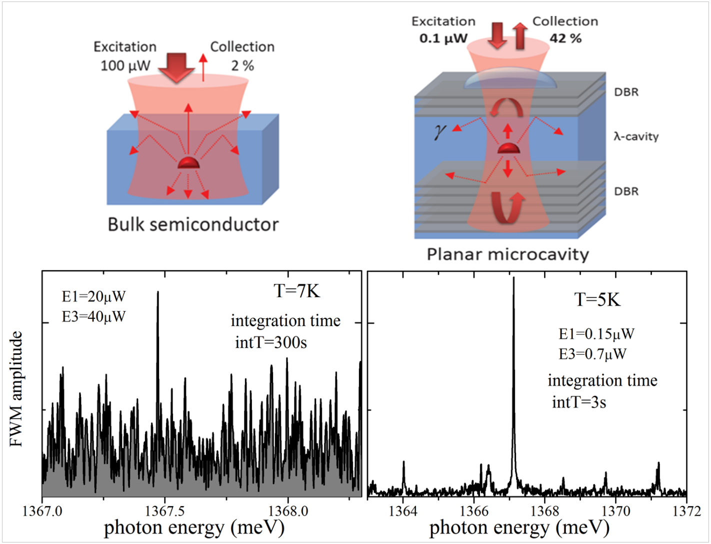

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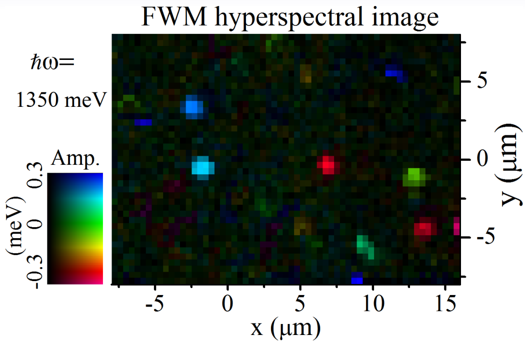


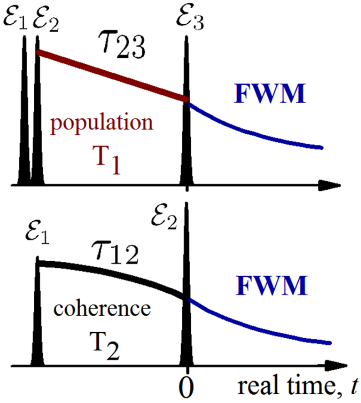
Spectacular Signal-to-Noise Improvement by ∼1000

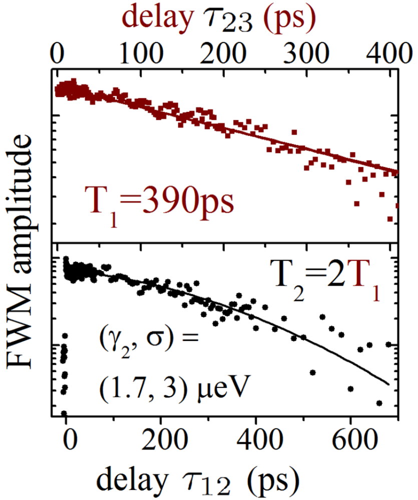
- intra-cavity field amplification
- spectral matching with the excitation
- presence of natural micro-lenses

Outline

Measuring coherence & population dynamics

Radiatively limited dephasing of an InAs QD: $T_2 = 2T_1$

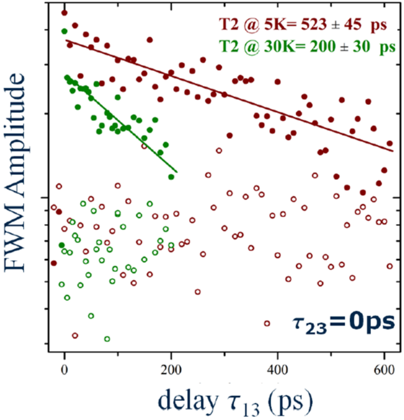


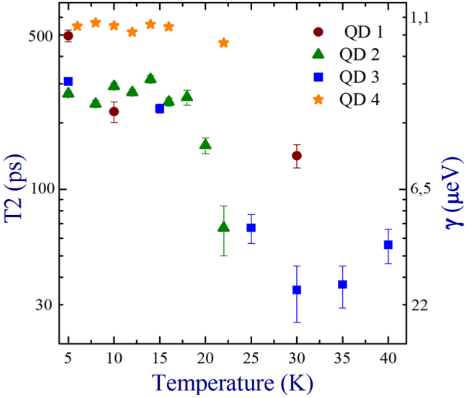


Phonon broadening of the zero phonon line

Consistent with measurements on ensembles

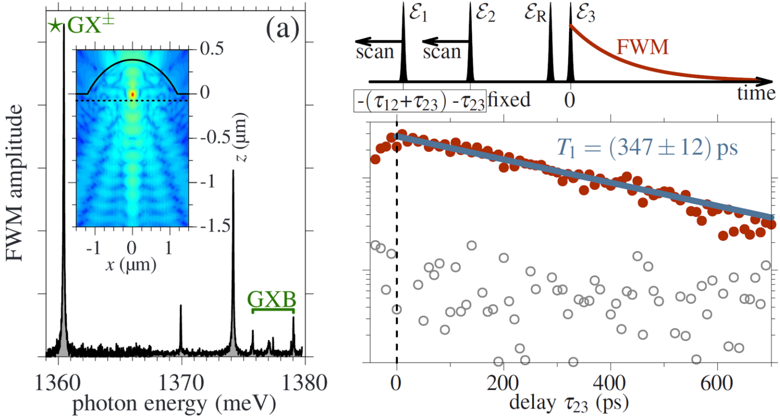
P. Borri et al. Phys. Rev. B. 71, 115328 (2005)





Deterministic, broadband micro-lenses

Density & coherence dynamics, inhomogeneous broadening



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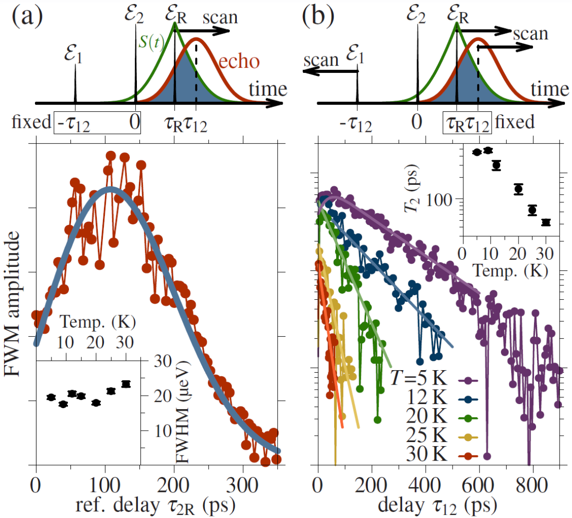
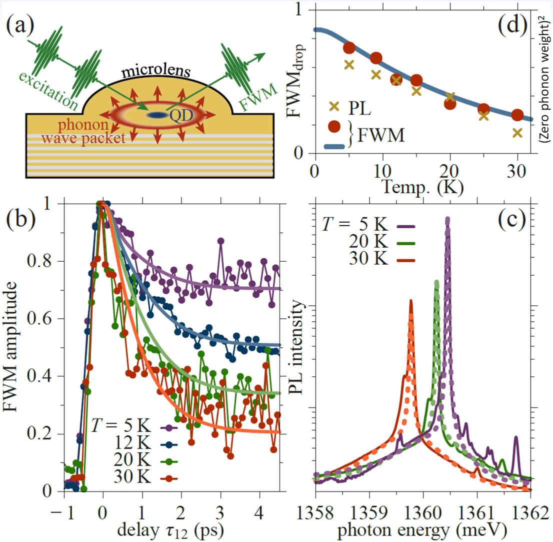
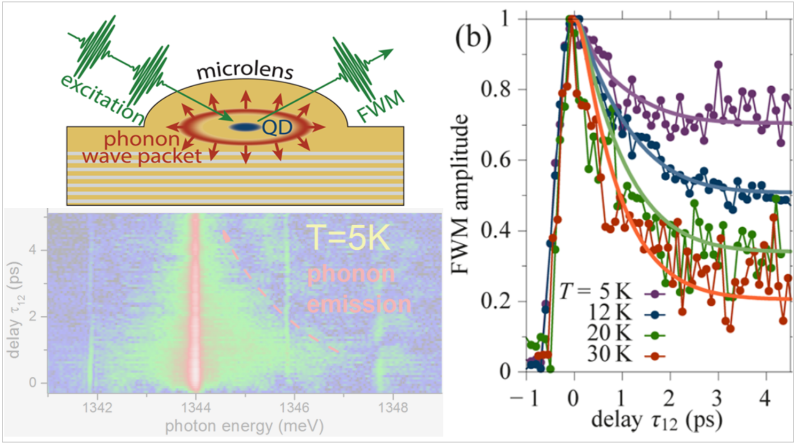


Dephasing during the polaron formation



Phonon Dephasing: Always a handicap ?

A part of exciton coherence leaks with the phonon packet



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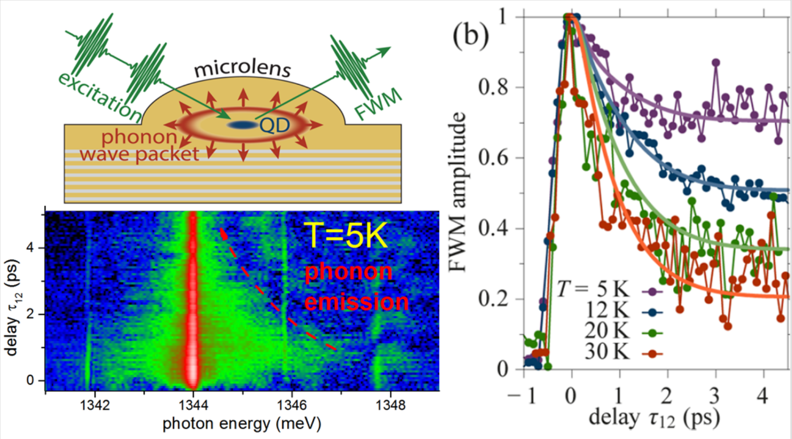

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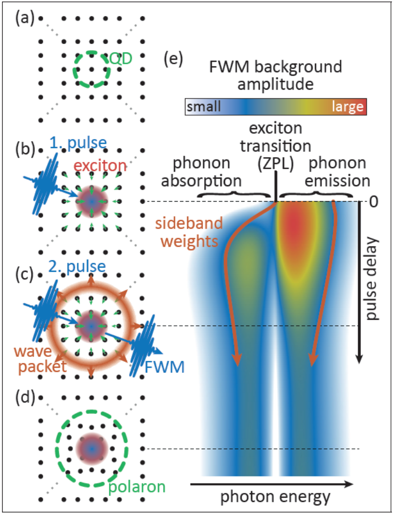

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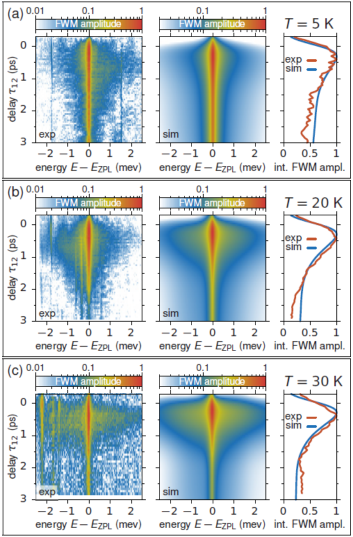
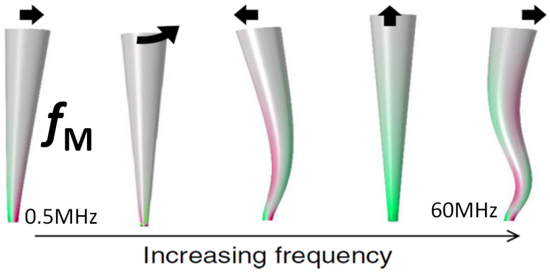


Project ⇒ optomechanics inferred via FWM

Photonic waveguide as a mechanical resonator

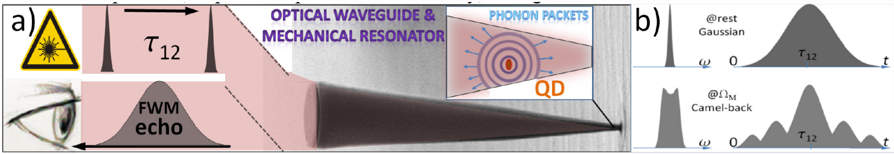
Nat. Commun. 8, 76 (2017), Nat. Nanotechnol. 9, 106 (2013) (collegues)



Original Idea ⇒ pile up nanoscopic displacements to optically drive and detect the macroscopic motion

Controlling motion via Four-Wave Mixing

Linking Nonlinear Spectroscopy, Phononics & Optomechanics



How to induce the motion ?

Fine adjust exciton and polaron generation to f_{M}

How to detect it ?

Motion $\Rightarrow$ Varying strain $\Rightarrow$ More σ $\Rightarrow$ echo narrows down at f_{M}

Required Setup Development

Digital heterodyning $\Rightarrow$ Tuning RF modulation across f_{M}

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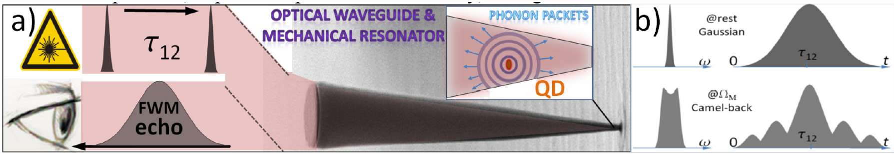

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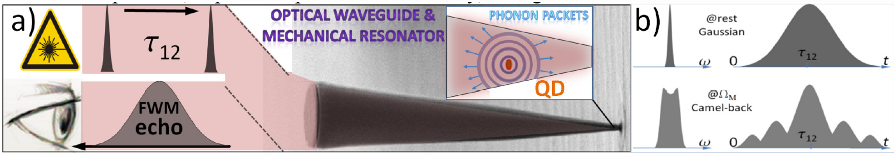

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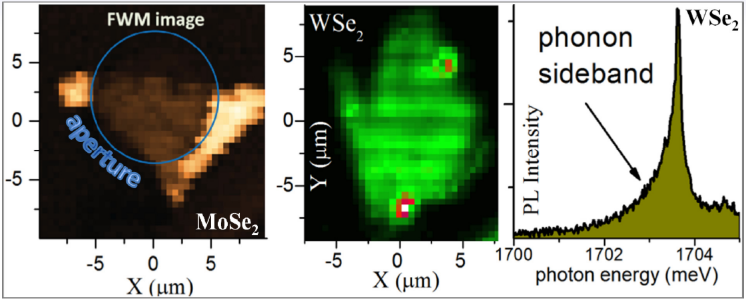
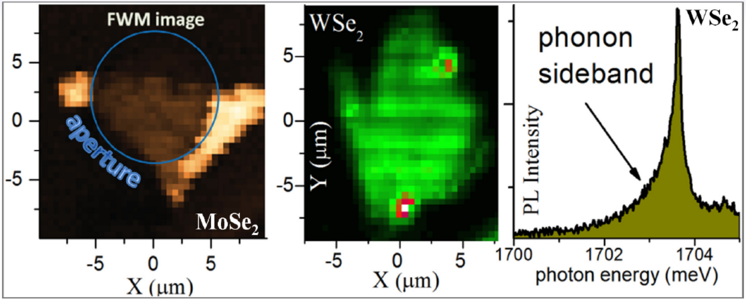
Optomechanics of TMD membranes



Challenges:

1. Fabricating high Q-factor drum-head resonators
2. Suppressed disorder $\Rightarrow$ TMD hetero-structures
3. Deterministic generation of single emitters

Optomechanics of TMD membranes



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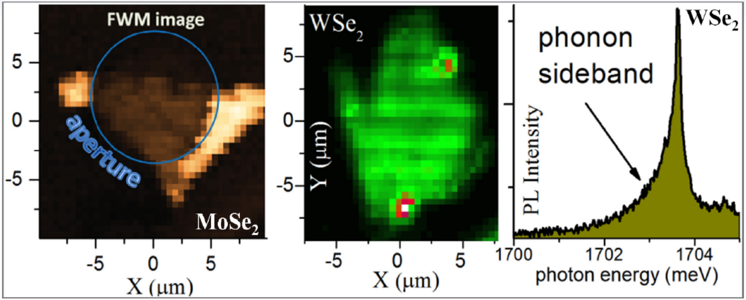

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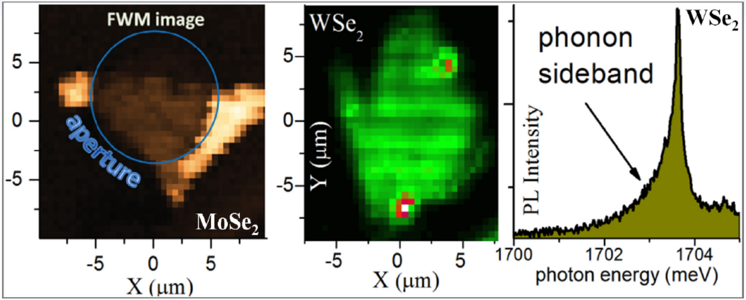

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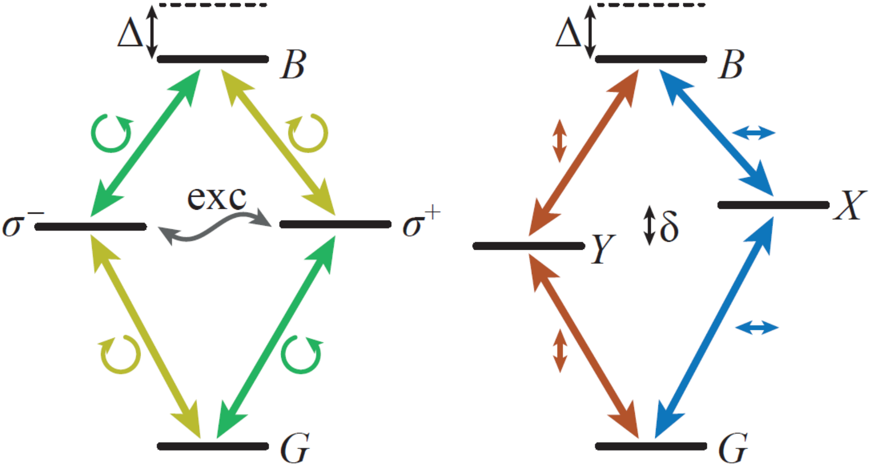
Coherence dynamics in realistic QD system

fine-structure splitting δ & biexciton binding energy Δ



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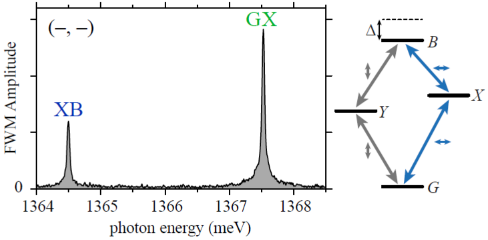

- FWM signal detected on spectrometer
- polarization along $X \rightarrow 3$ level system GXB
- peaks separated by BBE Δ

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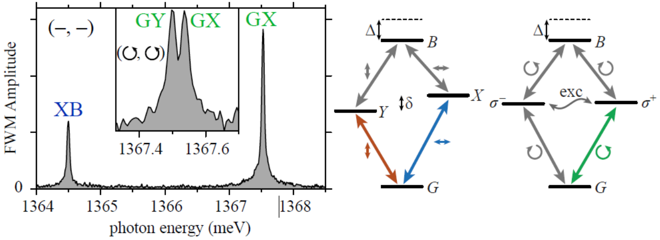

- FWM signal detected on spectrometer
- polarization along $X \to$ 3 level system GXB
- peaks separated by BBE Δ
- σ-polarization $\to$ X and Y are excited
- GX splits by FSS δ into GX and GY
- no biexciton signal

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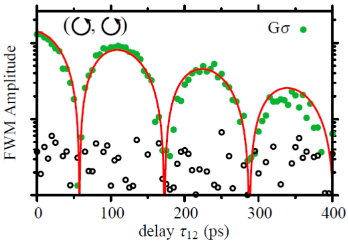

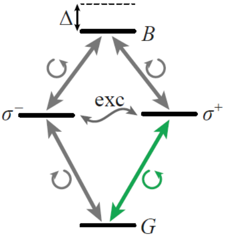

- $G\sigma$ signal beats

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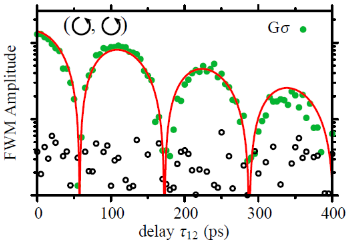
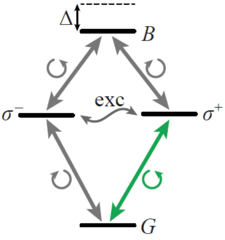
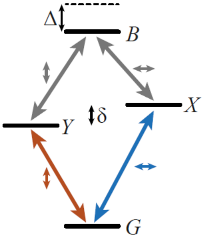


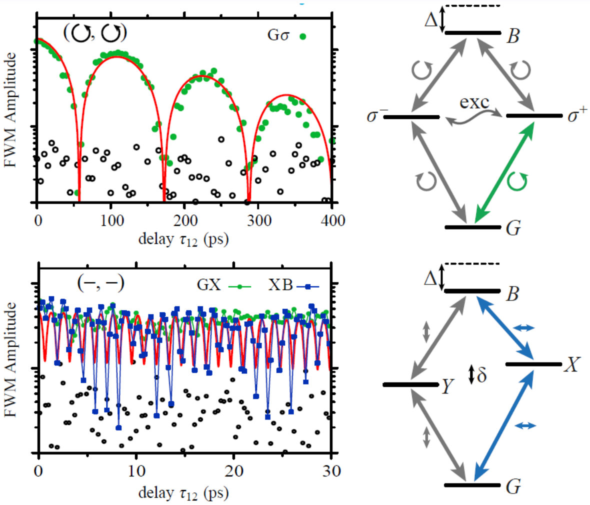


- $G\sigma$ signal beats
- σ is superposition of X and Y
  $\rightarrow$ relative phase changes with $\delta/\hbar$
- exctraction: FSS $\delta = 36\,\mu$eV
  decoherence rate



Coherence dynamics in realistic QD system

fine-structure splitting δ & biexciton binding energy Δ



- XB signal beats with BBE $\Delta = 3.25$meV

Coherence dynamics in realistic QD system

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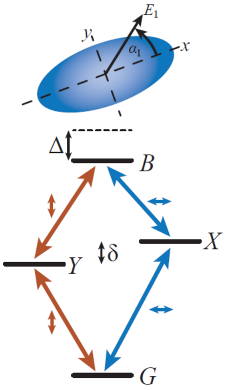
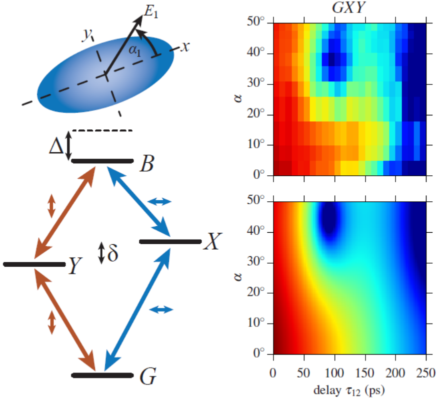


- varying polarization angle excites superposition of X and Y

Coherence dynamics in realistic QD system

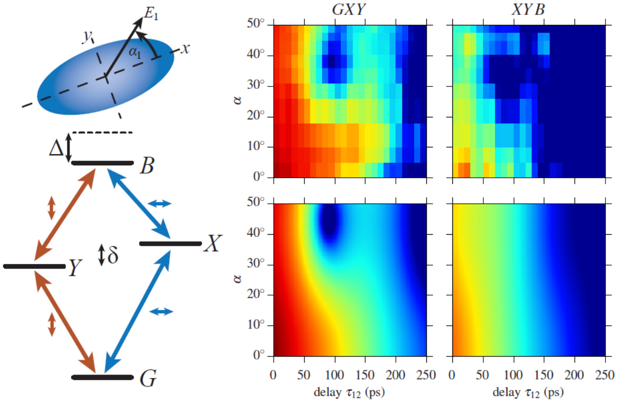
fine-structure splitting δ & biexciton binding energy Δ



- varying polarization angle excites superposition of X and Y
- strong beating on GXY for equal contributions of X and Y

Coherence dynamics in realistic QD system

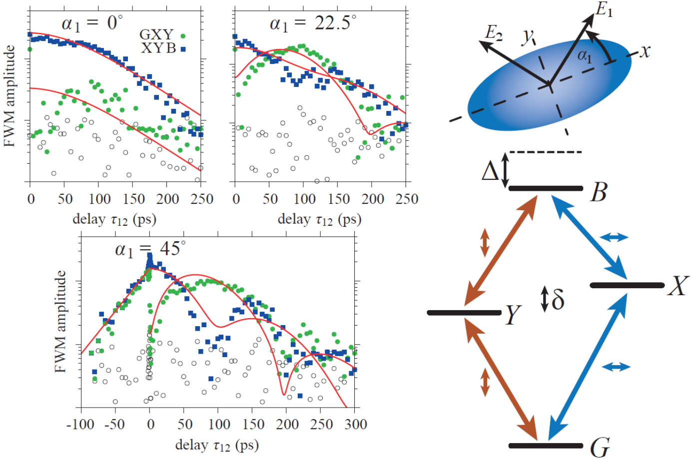
fine-structure splitting δ & biexciton binding energy Δ



- varying polarization angle excites superposition of X and Y
- strong beating on GXY for equal contributions of X and Y
- no beat on XYB due to small pulse areas

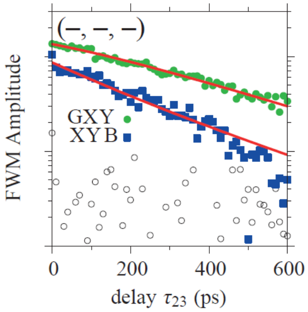
Coherence dynamics in realistic QD system

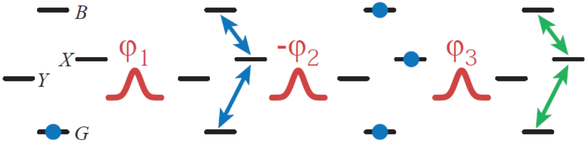
fine-structure splitting δ & biexciton binding energy Δ



Population dynamics in Realistic QD system

fine-structure splitting δ & biexciton binding energy Δ

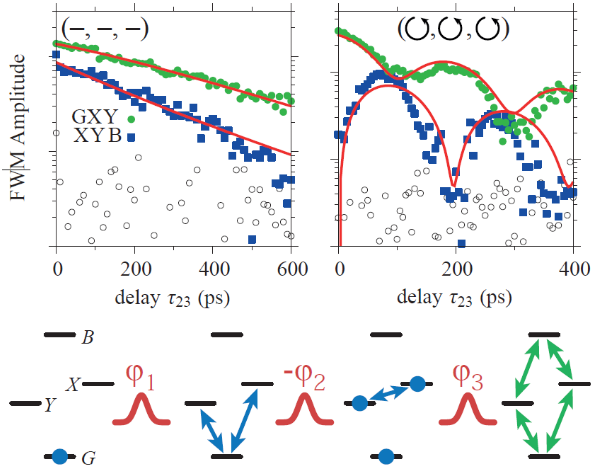




- extraction: decay rate

Population dynamics in Realistic QD system

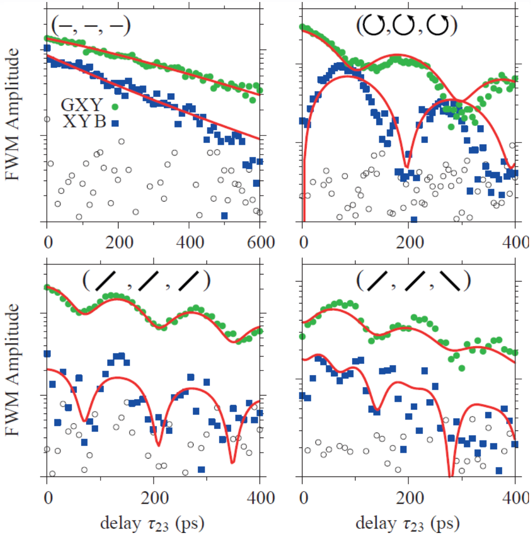
fine-structure splitting δ & biexciton binding energy Δ



- extraction: decay rate + decoherence rate XY

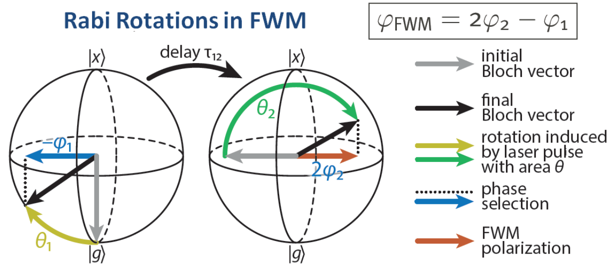
Population dynamics in Realistic QD system

fine-structure splitting δ & biexciton binding energy Δ

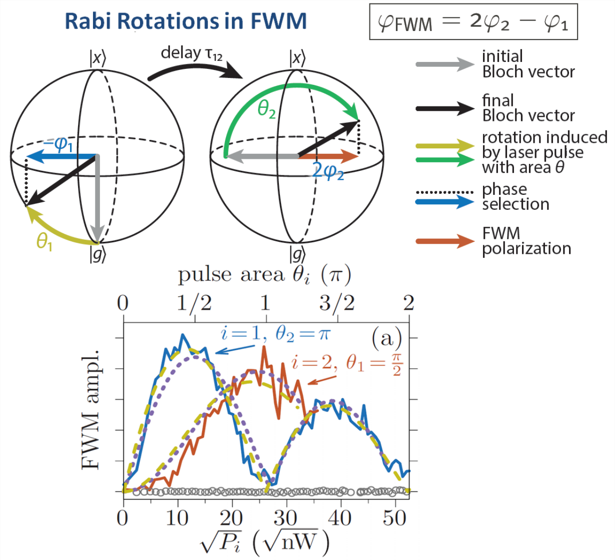


Outline

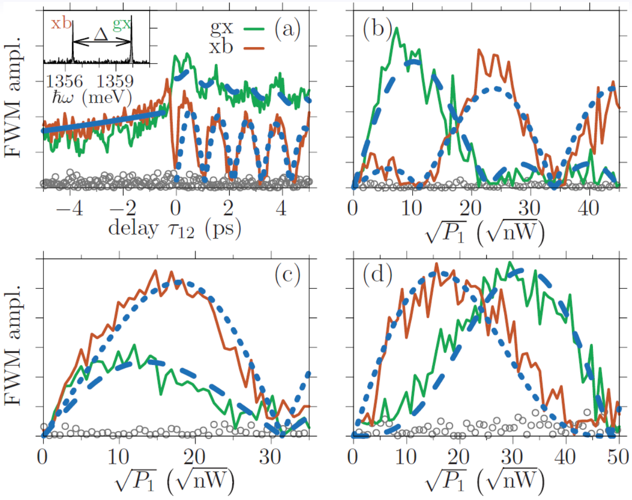
Rabi rotations



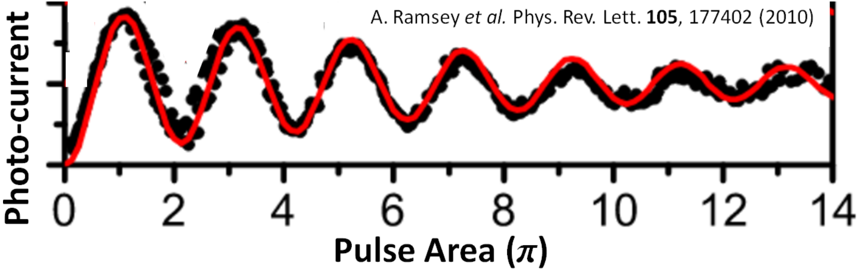
Rabi rotations



Rabi rotations

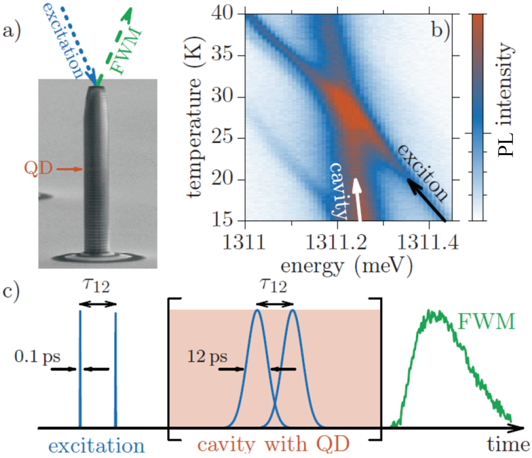


Rabi rotations



QD-micropillar system in a weak-coupling regime

Q-factor$\simeq$ 24000 $\Rightarrow$ intra-cavity pulse 12 ps $\Rightarrow$ time-resolved Rabi oscillations measured



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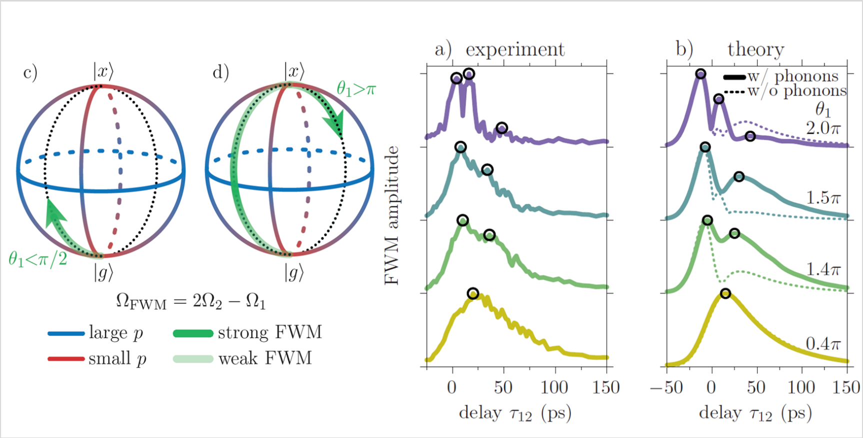

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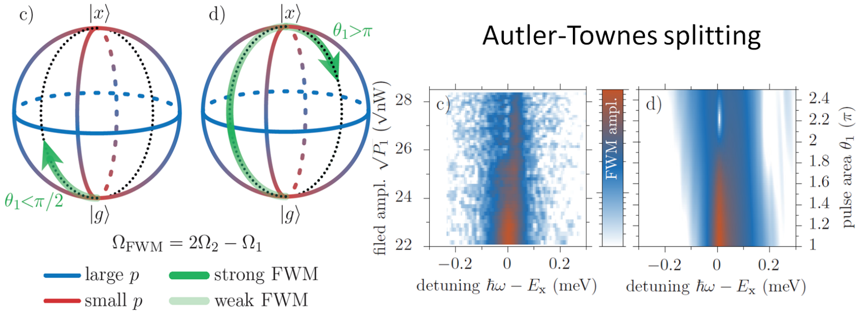

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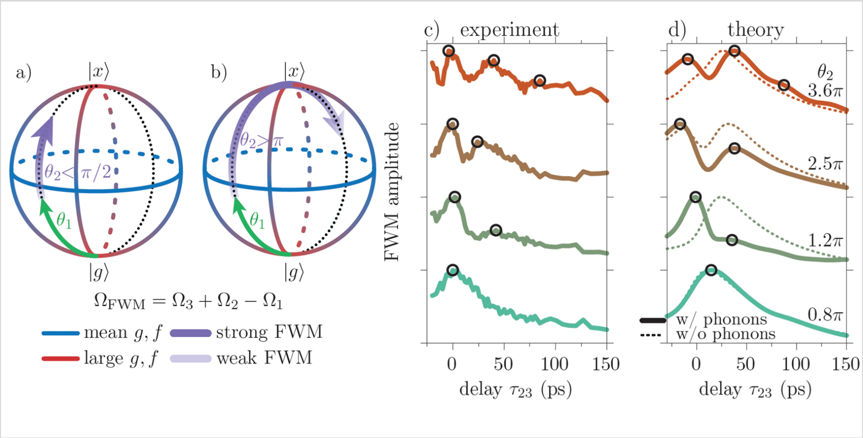
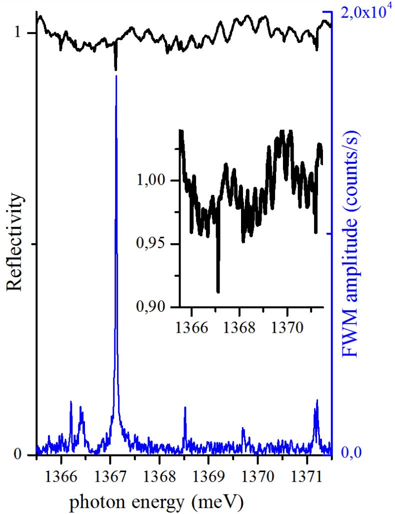
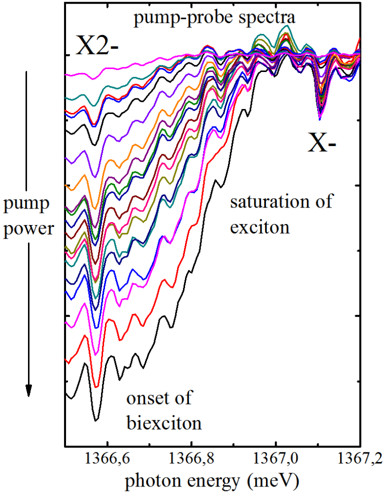


Outline

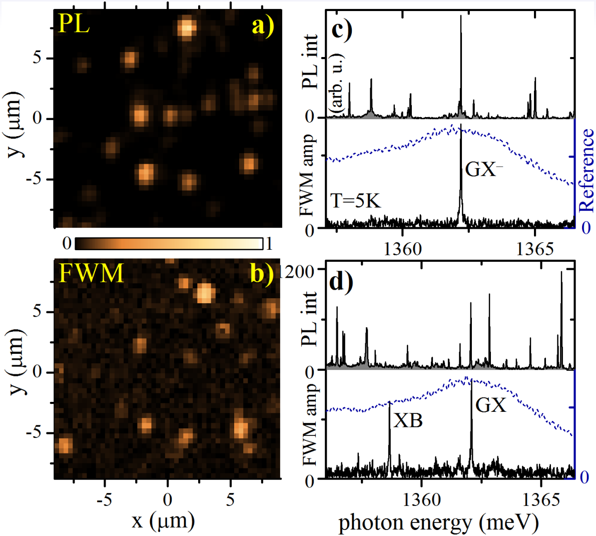
Back to linear spectroscopy

reflectivity & pump-probe on a single QD

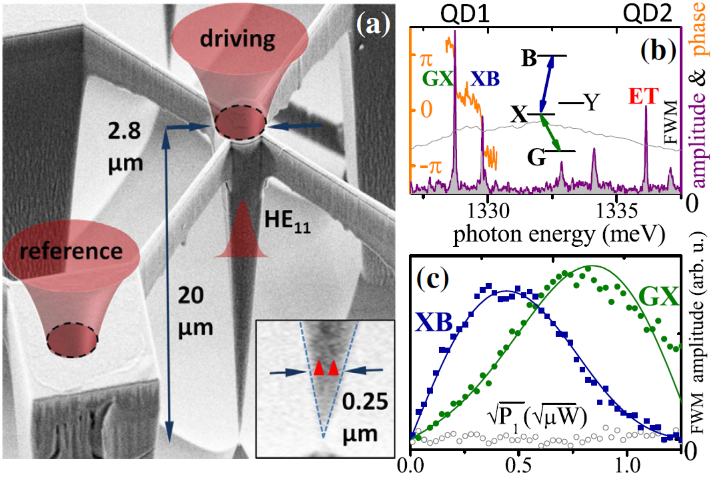




FWM versus PL imaging



FWM in photonic trumpets



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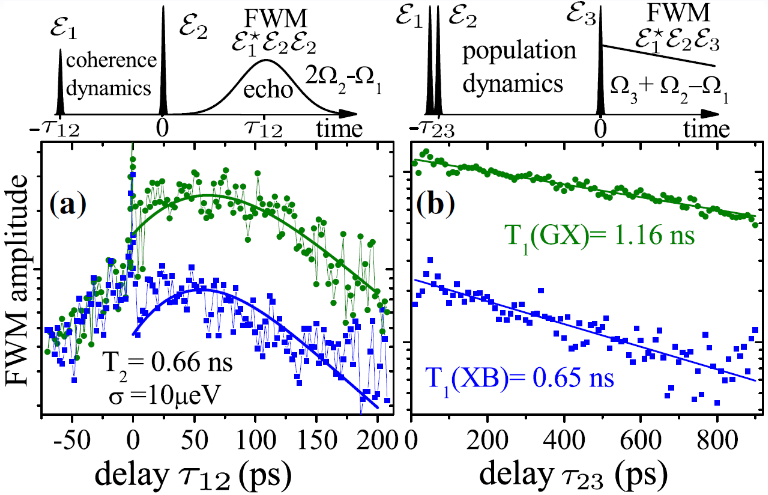
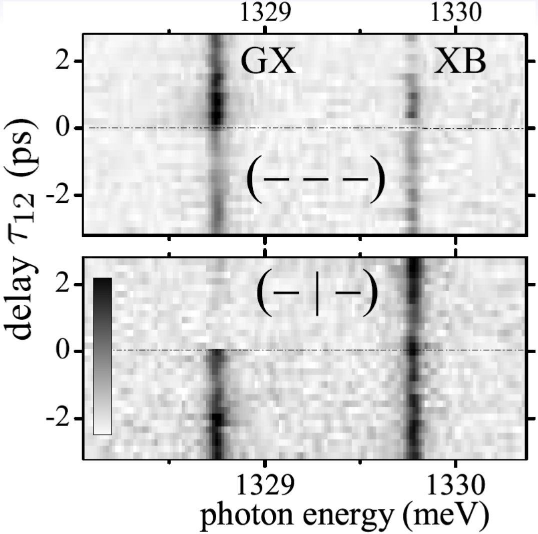
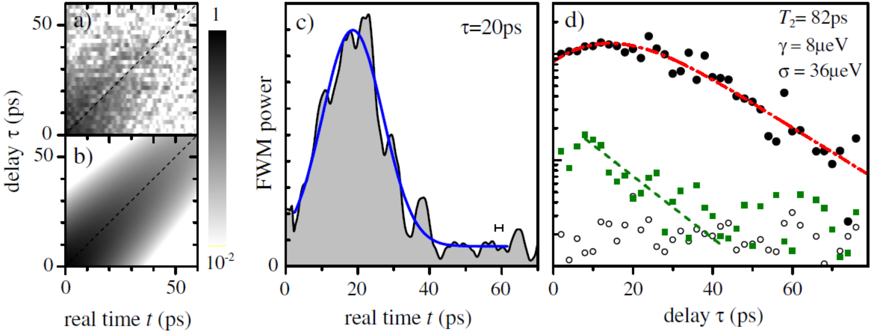


FWM in photonic trumpets



FWM in GaAs/AlGaAs QDs



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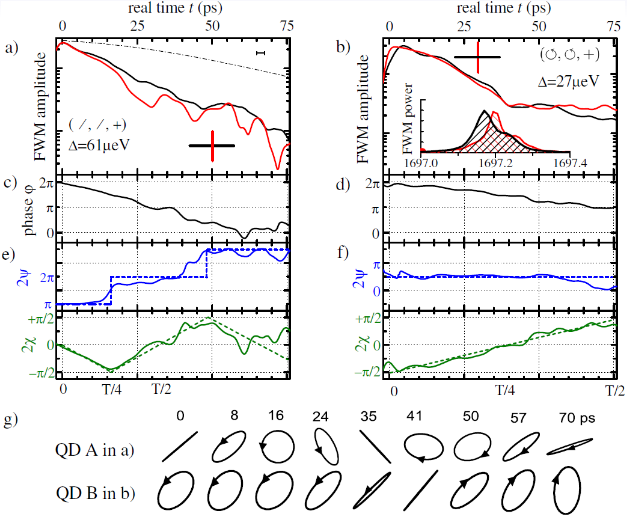

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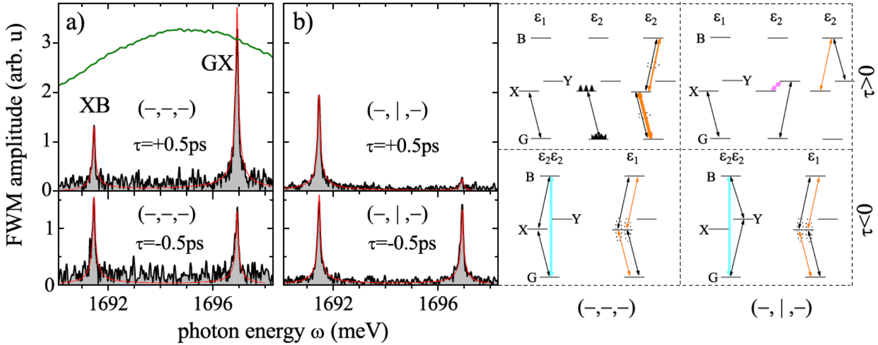
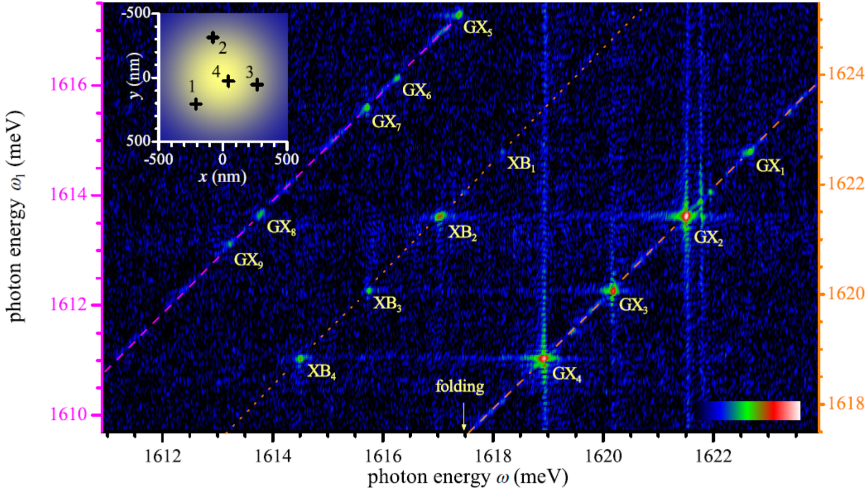
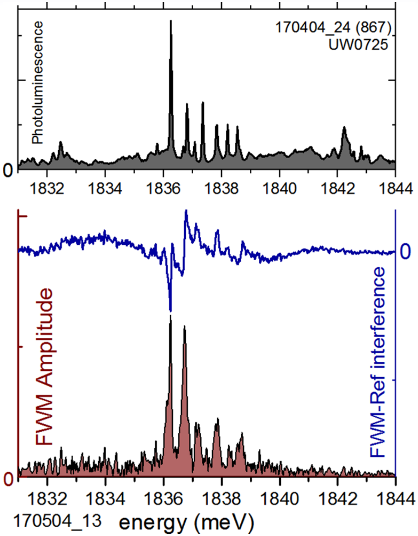


FWM in GaAs/AlGaAs QDs



Single CdTe QDs+Mn in a $\mu-$cavity

exciton coherence in a vicinity of a **single fluctuating spin**



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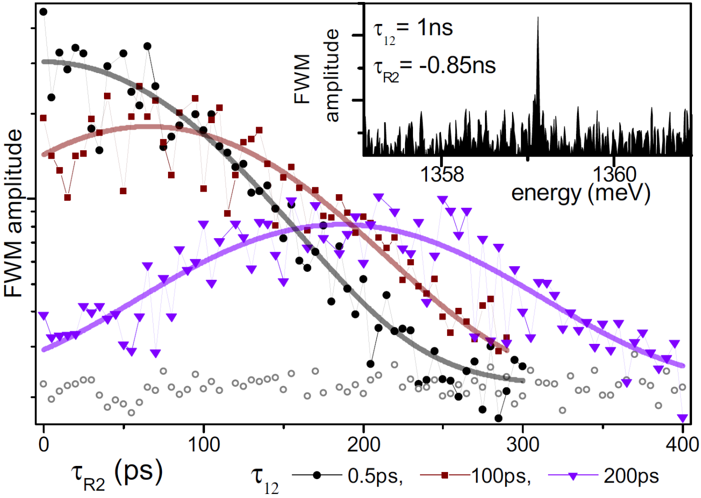

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