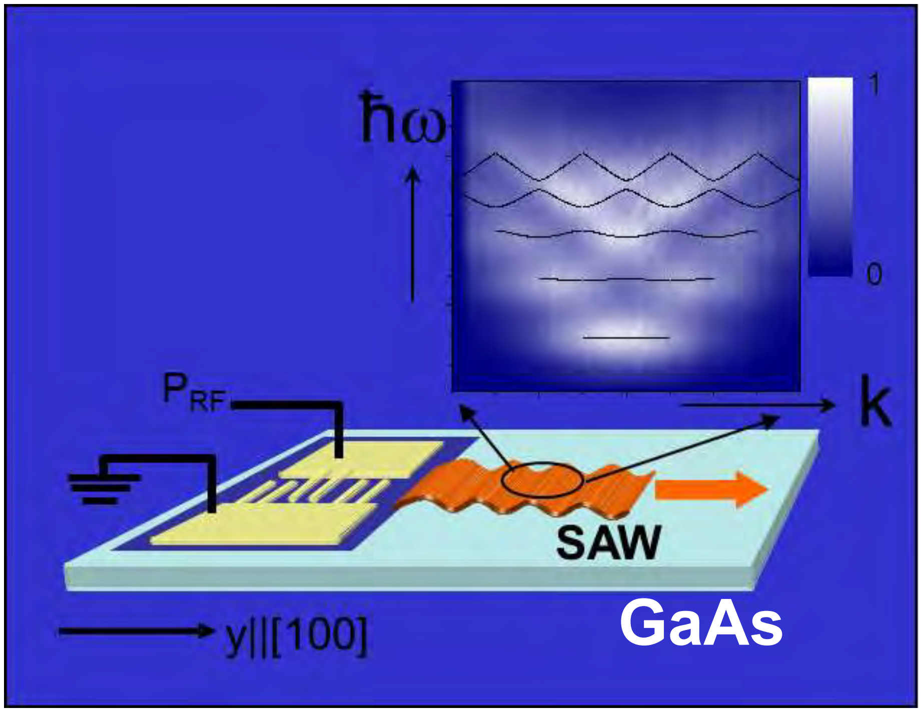
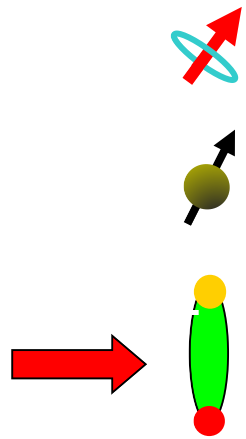
Control of excitons and exciton-polariton condensates in acoustic lattices

P. V. Santos



Surface acoustic waves (SAWs)



photons

electrons, holes and spins

excitons, polaritons polariton condensates

DFG Deutsche Forschungsgemeinschaft

GIF German-Israeli Foundation for Scientific Research and Development

NÉEL institut

PROCOPE

DAAD Deutscher Akademischer Austausch Dienst Office allemand d'échanges universitaires

Collaborations

- PDI
  - A. Violante
  - C. Hubert
  - S. Lazic

excitons

- Hebrew Univ. of Jerusalem
  - K. Cohen, R. Rapaport
- Univ. Autonoma Madrid
  - S. Lazic
- Institut Néel, Grenoble
  - C. Bauerle

polaritons

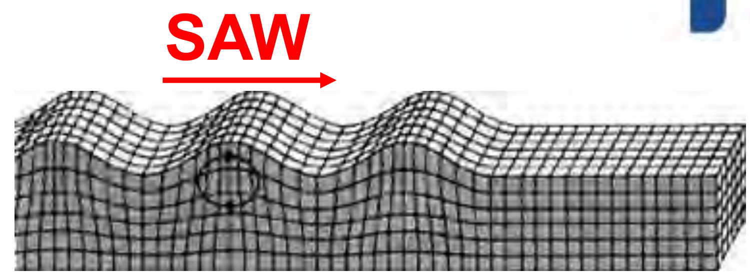
- Univ. of Sheffield (UK)
  - D. Krizhanovskii, M. Sich, D. Sarkar, S.S. Gavrilov (Chernogolovka),M. Skolnick
- Univ. Autonoma San Luis Potosi, Mexico
  - E. Cerda, R. Balderas

- E. Cerda
- J. Buller

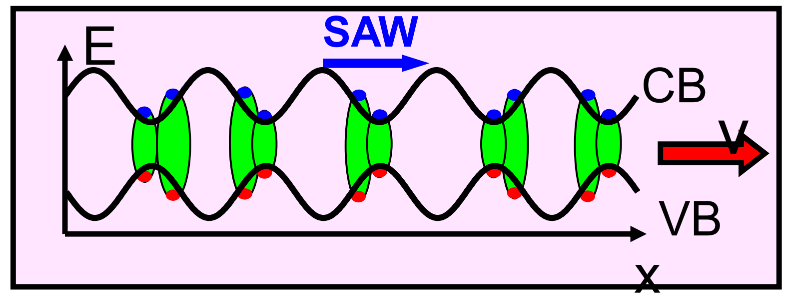
- Samples
  - K. Biermann
  - M. Höricke
- SAW technology
  - W. Seidel, B. Drescher, S. Rauwerding
  - S. Krauss, A. Tahraoui

Outline

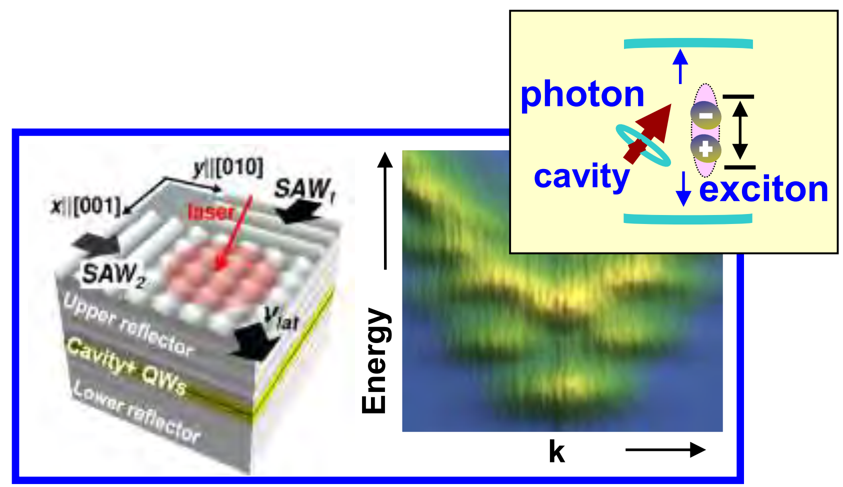
- Surface acoustic waves
  - modulation of the semiconductor band structure
  - tunable acoustic lattices



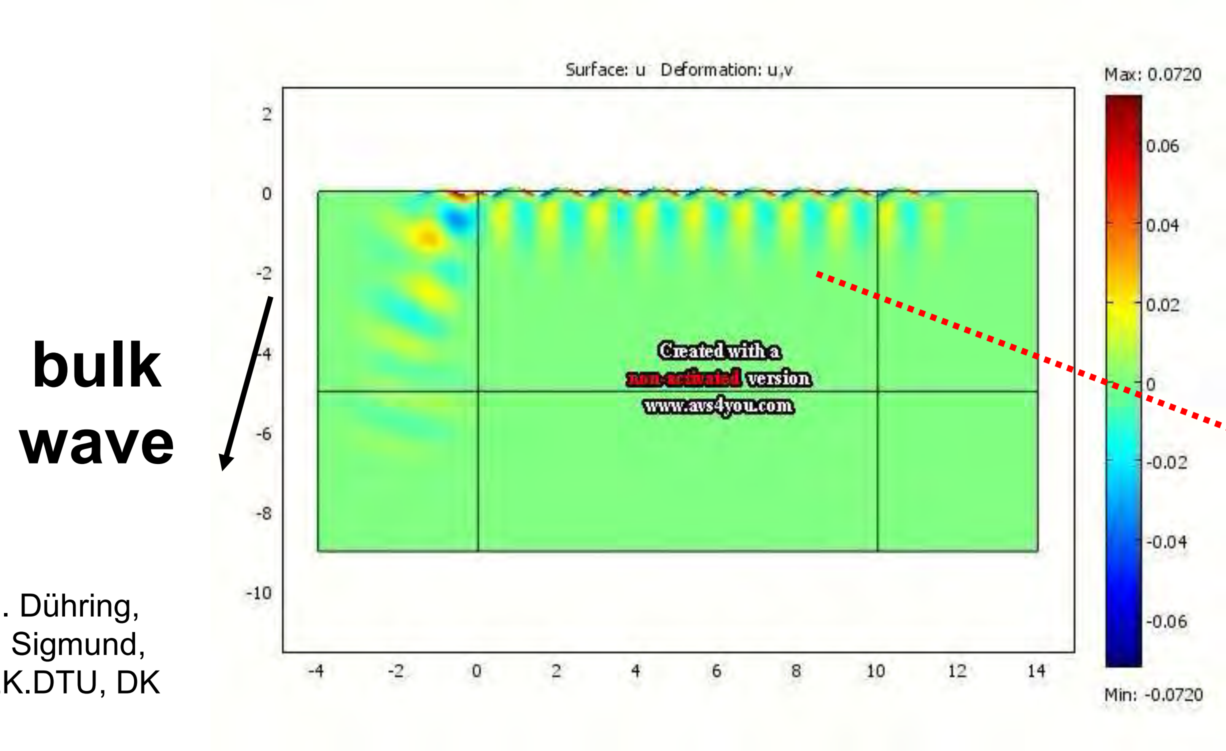
- Acoustic exciton transport
  - indirect excitons (IXs)
  - IX transport dynamics



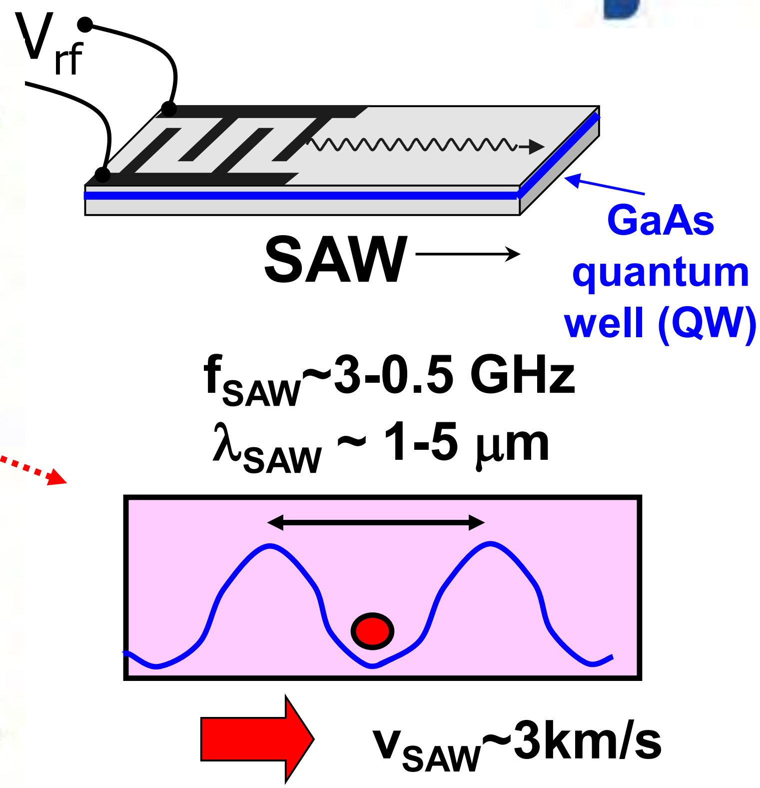
- Polariton modulation
  - tunable polaritonic crystals
  - control of polariton condensates



SAWs in semiconductors



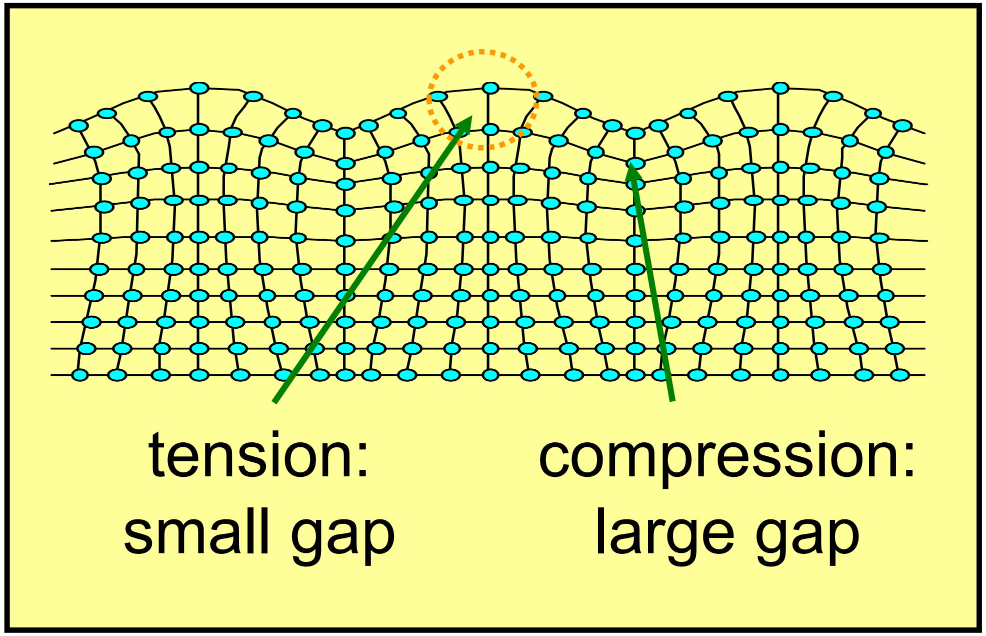
M. Dühring,
O. Sigmund,
MEK.DTU, DK



- Dynamic acoustic fields in nanostructures
  - spatial dependence: lateral pattering without interfaces
    - penetration depth (μm) comparable to thickness of planar structures
  - time dependence: dynamic control
  - mobile character: transport with well-defined velocity v_{SAW}

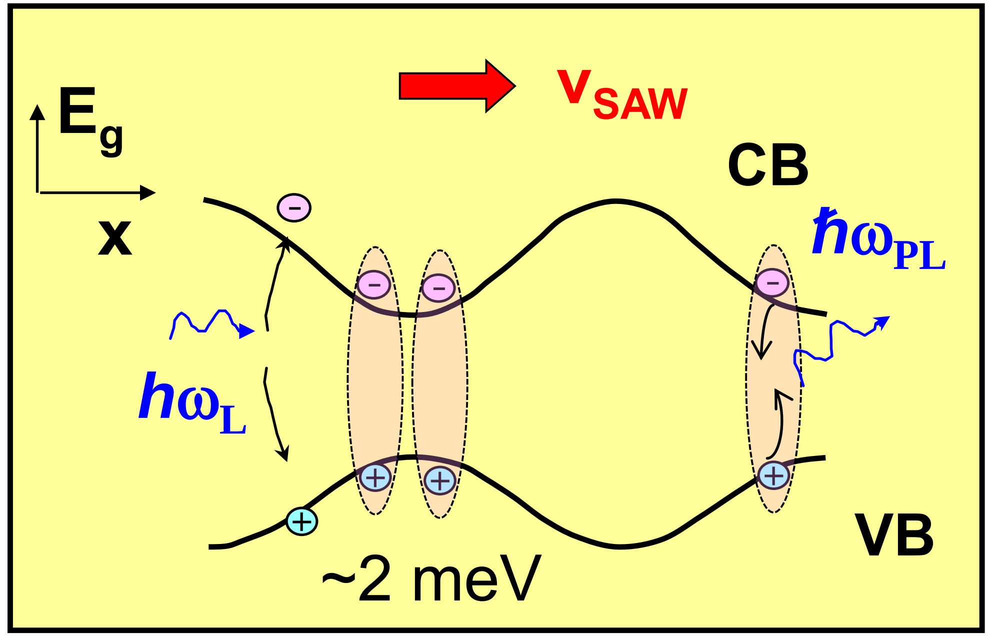
Modulation mechanisms

- **strain field**



- **dimensions**
- **deformation pot. modulation**
  - band gap modulation
  - refractive index modulation

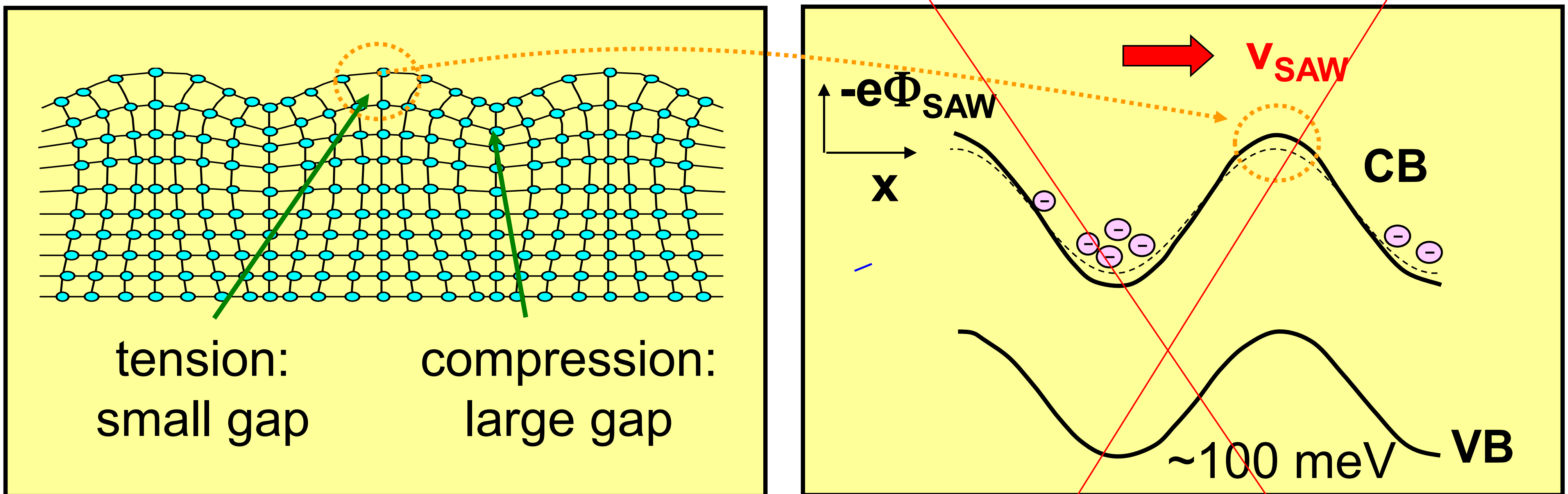
- **type I band gap mod.**



- **exciton confinement/transport**
  - IX trapping and transport
    - $\mu_X\, \delta E_g/\delta x > v_{SAW}$

Modulation mechanisms

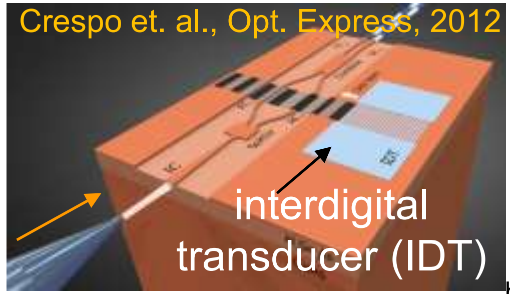
- **strain field** → piezoelectric materials → **type II band gap mod.**

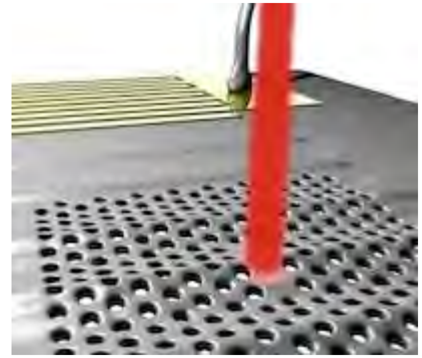


- **deformation pot. modulation**
  - band gap modulation
  - refractive index modulation
    - photon manipulation
- **piezoelectric potential Φ_{SAW}**
  - electrical generation
  - IX dissociation and e-h transport
    - $\mu E_x = \mu\, \delta\Phi_{SAW}/\delta x > v_{SAW}$

Semiconductor-related SAW activities

Photonic structures
- **membranes**
- **waveguide mod.**



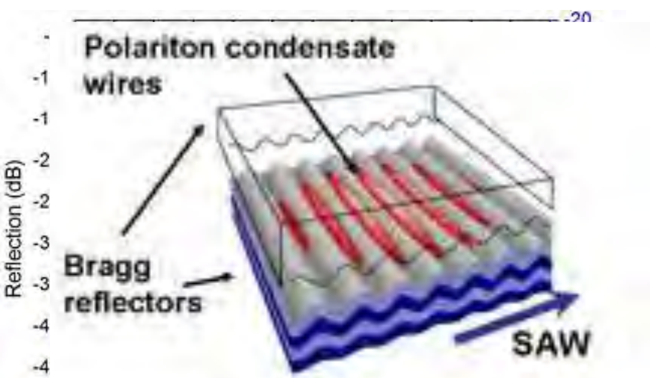


http://www.physik.uni-augsburg.de/exp1/emmynoether/

light control: WG, photonic systems

SAWs: materials and technology

Carrier and spin transport and manipulation



http://www.pdi-berlin.de/research/core-research-areas/control-of-elementary-excitations-by-acoustic-fields/main-research-projects/exciton-polariton-condensates/

High frequency SAWs on Si

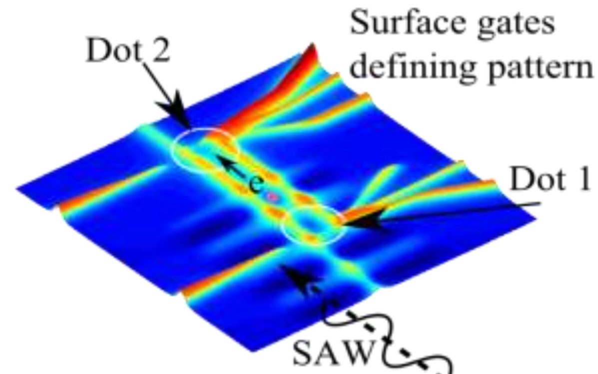
polariton modulation lattice for polariton condensates

Büyükköse et al. Nanotechnology 23, 315303 (2012)

Quantum acoustics

- $hf_{SAW}>kT$ (Gustafsson et al., Science 346, 207 (14))

Exciton manipulation
-exciton transport
-polariton condensates

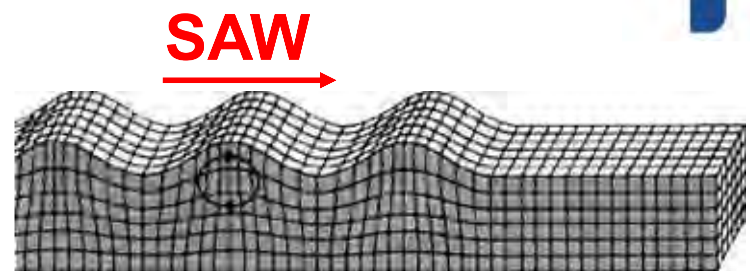


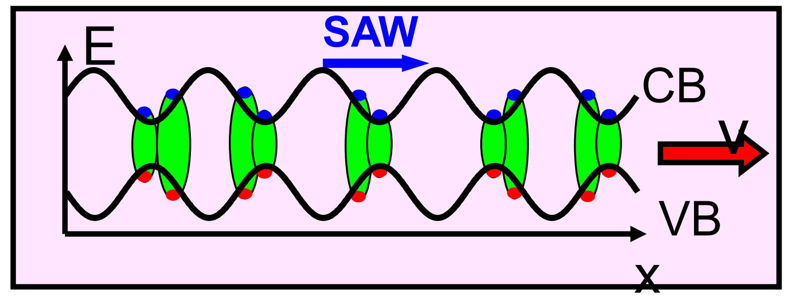
http://www.sp.phy.cam.ac.uk/research/surface-acoustic-waves-saws/sawqcp

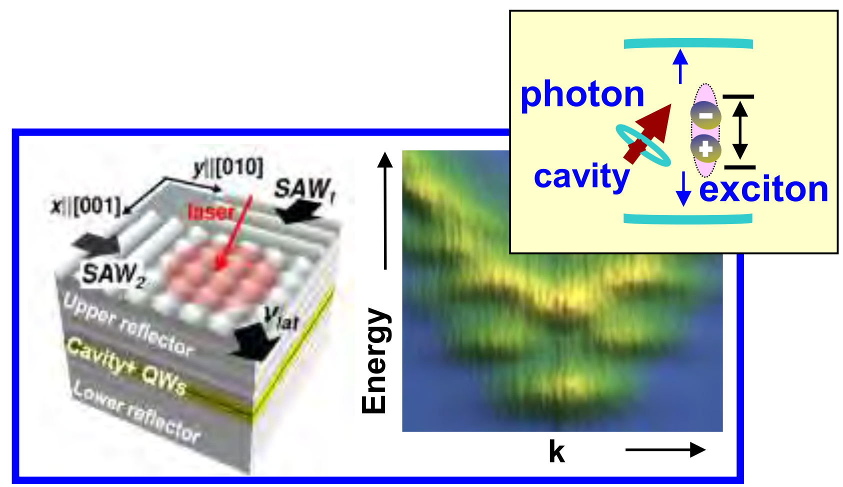
single carrier transport
spin transport/manipulation
single-photon sources/detectors

Outline

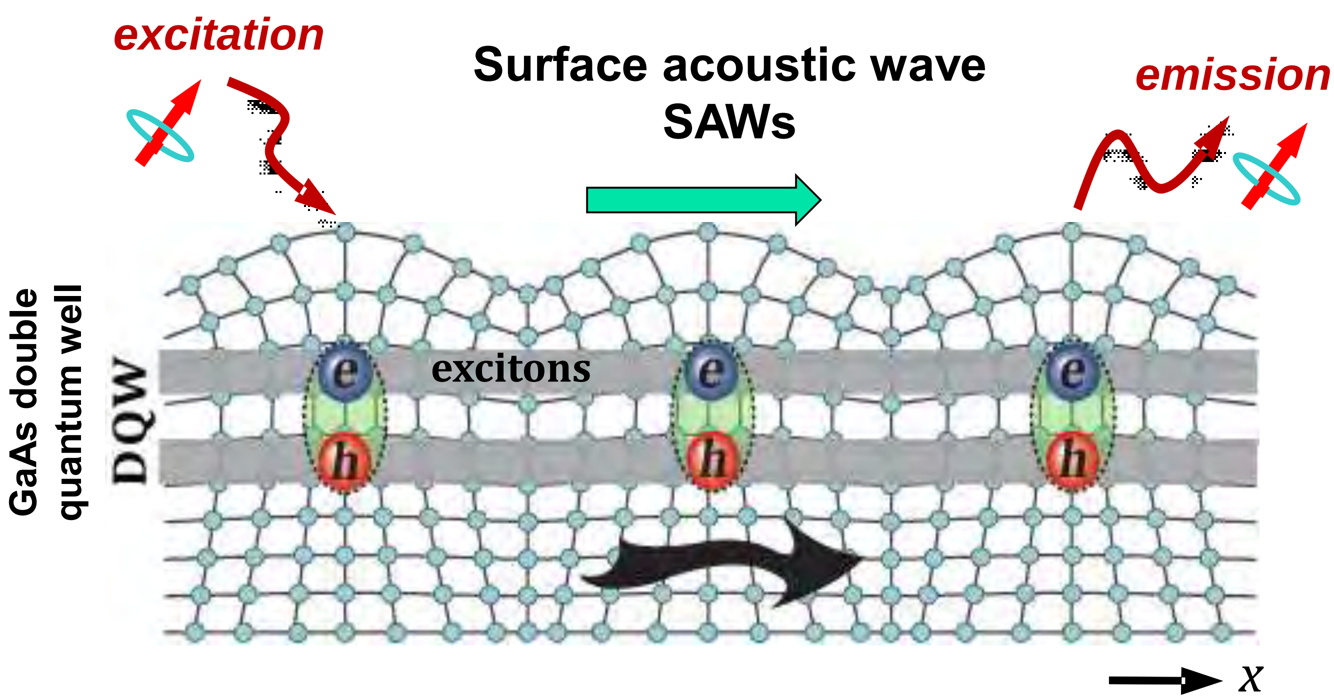
- Surface acoustic waves
  - modulation of the semiconductor band structure
  - tunable acoustic lattices
- Acoustic exciton transport
  - indirect excitons (IXs)
  - IX transport dynamics
- Polariton modulation
  - tunable polaritonic crystals
  - control of polariton condensates





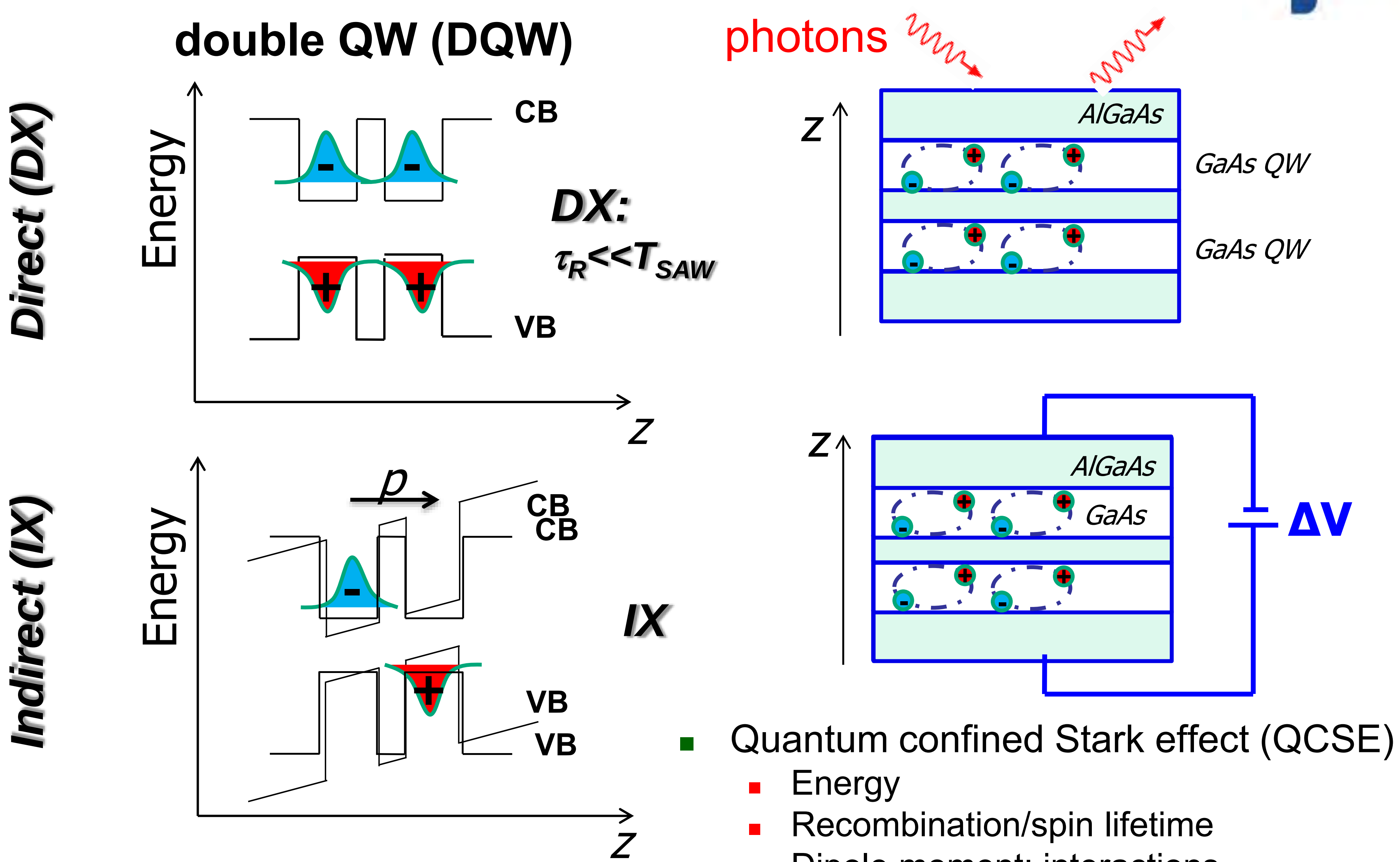


Acoustic exciton transport



Acoustically driven flying excitons: interface to photons!

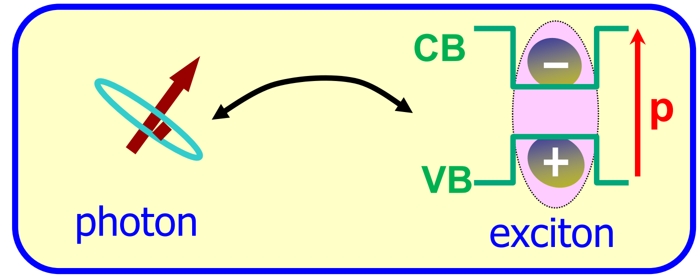
Quantum well (QW) excitons



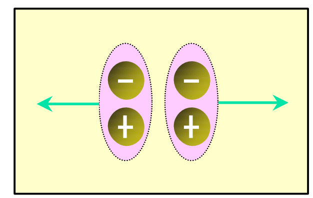
- Quantum confined Stark effect (QCSE)
  - Energy
  - Recombination/spin lifetime
  - Dipole moment: interactions

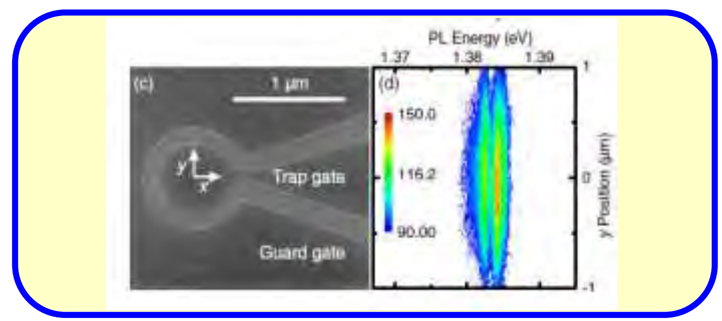
Indirect exciton

- electrically controlled coupling to photons
  - coherent manipulation
  - coherent spin control
    - long lifetimes[1]
    - control of spin-orbit (so) interaction[2,3]



- strong nonlinearities
  - electric dipolar (p) interactions: devices
  - confinement: single-excitons
    - Schinner et al., PRL 110, 127403 (2013)





- bosonic character
  - exciton condensates[4,5]

1 *Kowalik-Seidl et al., Appl. Phys. Lett.* ***97****, 11104 (10)*
2 *Larionov and Golub, Phys. Rev. B78,033302 (08)*
3 *Leonard et al., Nano Lett.* ***9****, 4204 (09)*

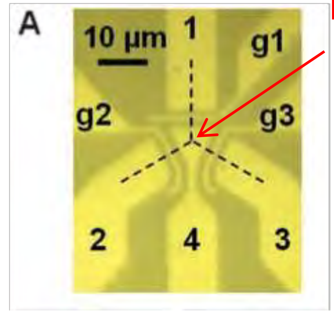
4 Blatt, Phys. Rev. 126, 1691 (61), Keldysh, JETP 27, 521 (68)
5 High et al., Nature 483, 584 (2012)

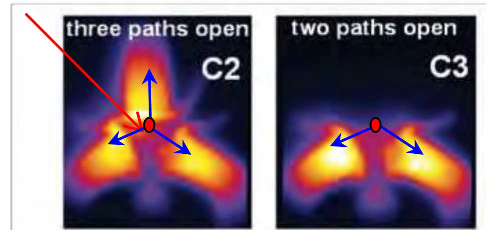
IX motion-based functionalities

neutral particles!

light

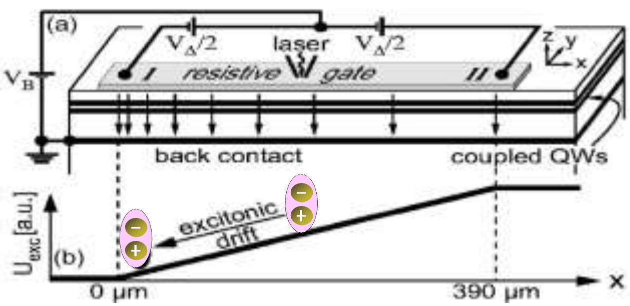
- Electrostatic gates
  - exciton transistor – EXOT
    - T: 10 to >100K





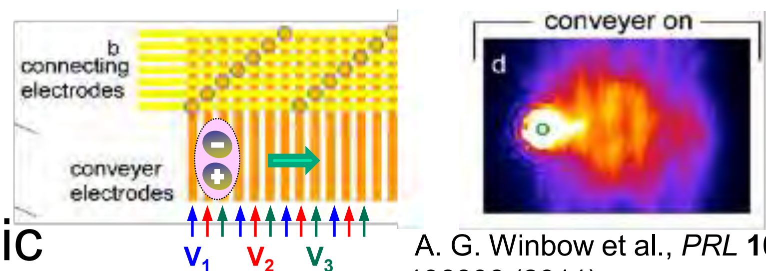
A. A. High et al., *Science* **321**, 229-231 (2008)

- Transport by field gradients
  - approx 50 μm



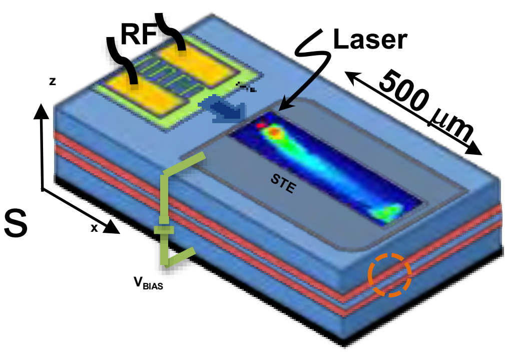
[1]Gärtner, APL 89, 052108 (06)

- Transport conveyers
  - electrostatic
    - 30 μm



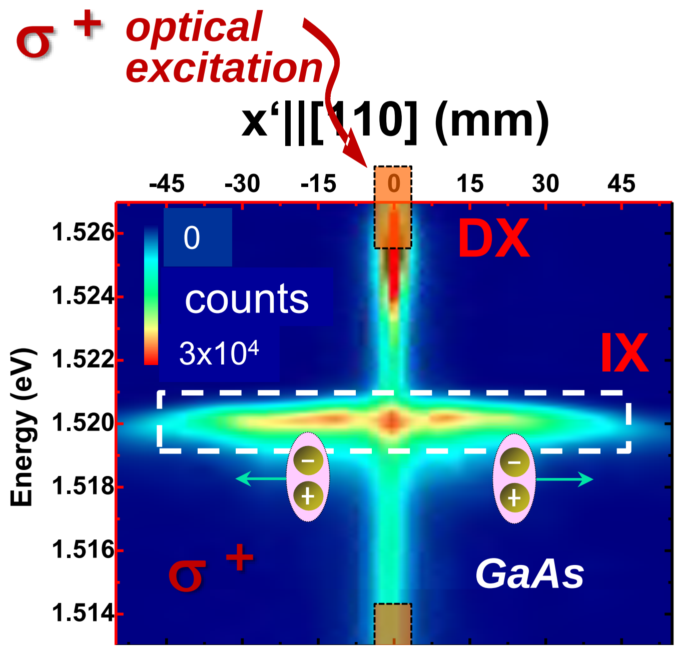
A. G. Winbow et al., *PRL* **106**, 196806 (2011)

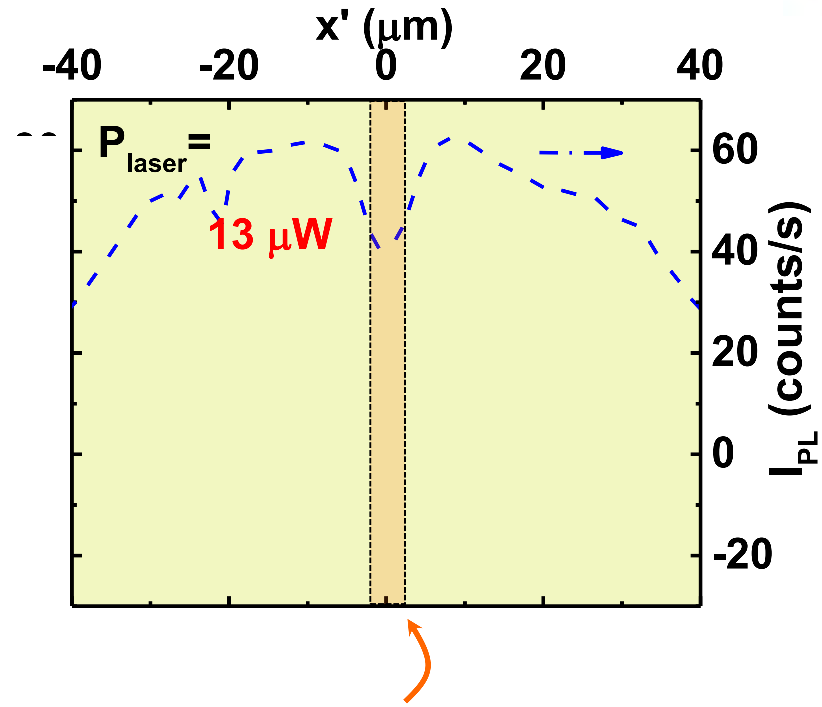
  - acoustic
    - moving strain fields
      - 1000 μm

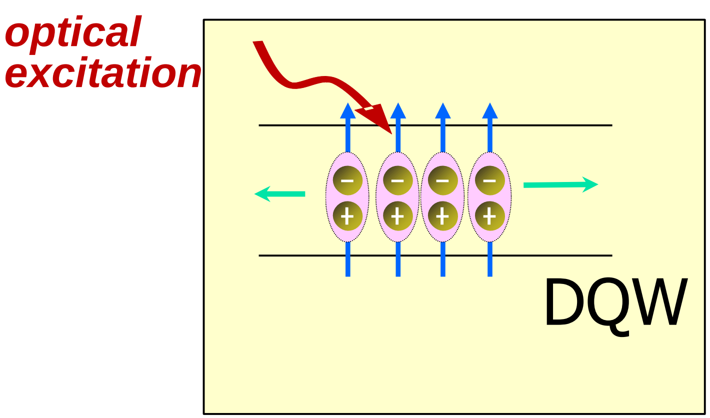


J. Rudolph et al., *PRL***99**, 047602 (07)

Spin precession during transport

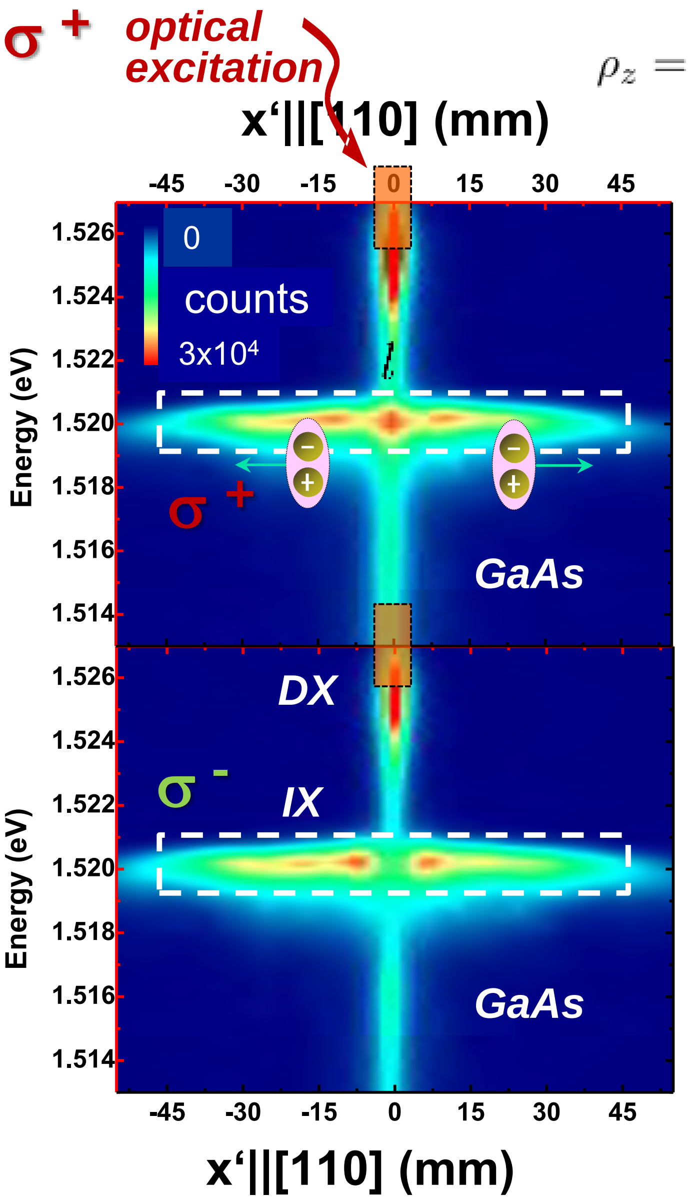




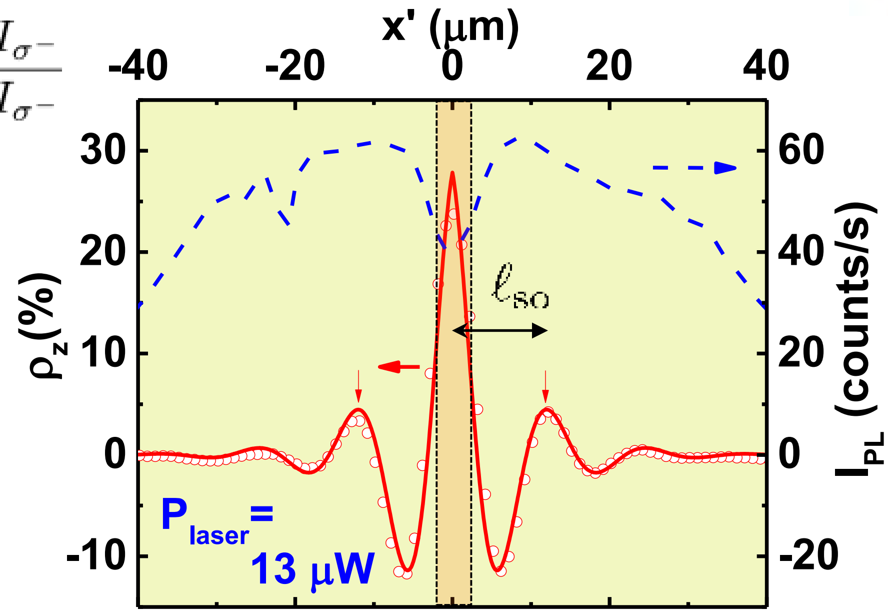


- I_{PL} profiles
  - extent >> excitation region
  - exciton drift diffusion
    - repulsive interactions

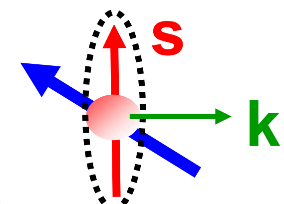
Spin precession during transport



$$\rho_z = \frac{I_{\sigma^+} - I_{\sigma^-}}{I_{\sigma^+} + I_{\sigma^-}}$$



$B_{so} \sim \gamma(F_z)(k)$

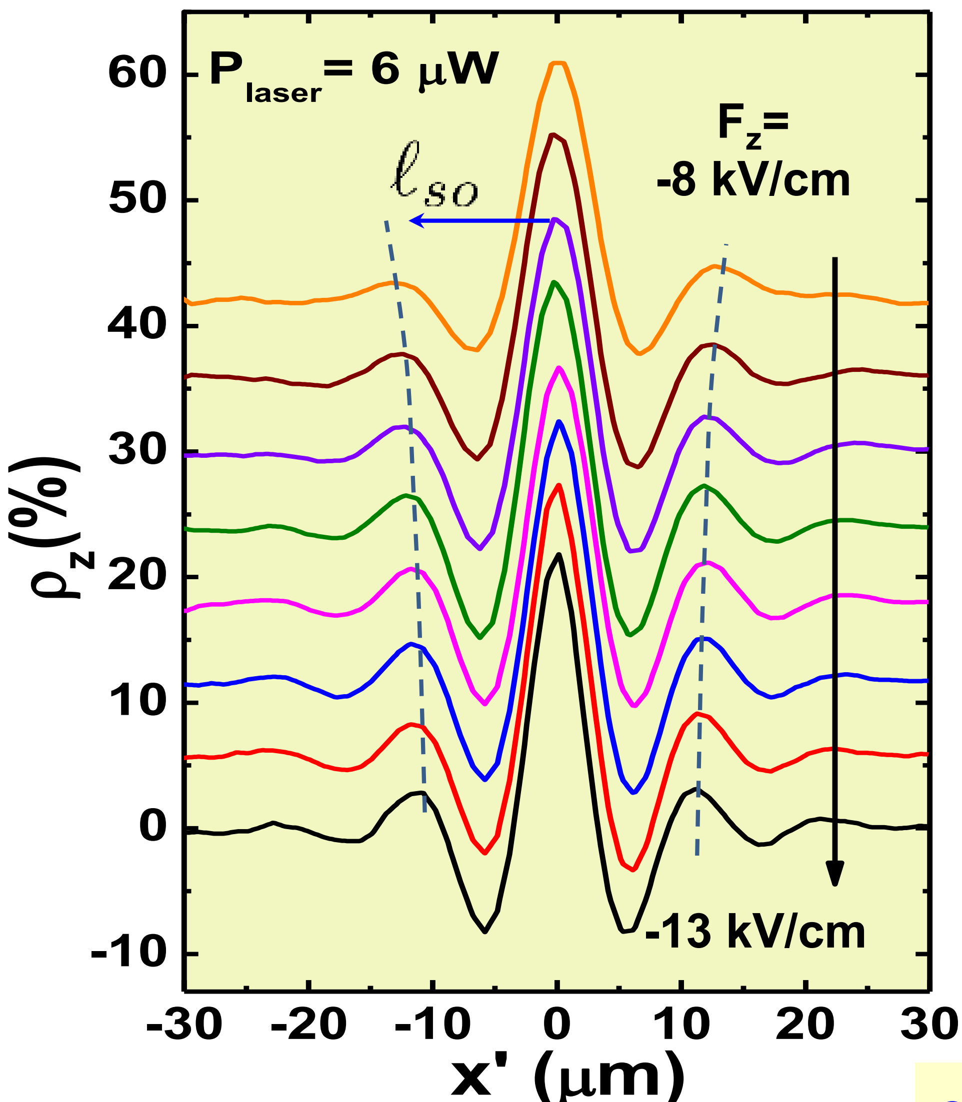


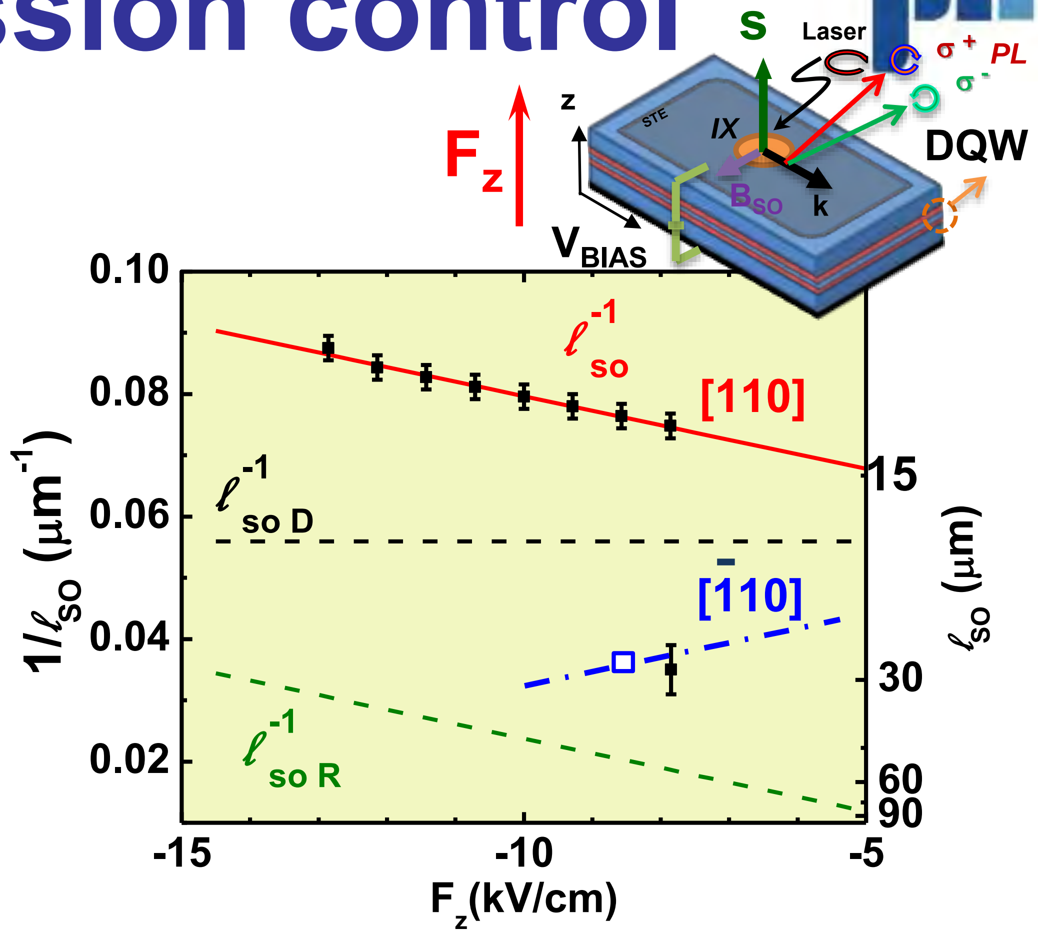
- Oscillating spin polarization ρ_z
  - Precession in the spin orbit field B_{so}

$$\rho_s(\mathbf{r}) = \rho_s(0) e^{-r/\ell_s(r)} \cos\left(2\pi r/\ell_{so}(\hat{\mathbf{r}})\right)$$

    - precession period l_{so}

Electric precession control





- Fits to model
  - spin-splitting constants
    - Dresselhaus: γ =+/-17.9 eVA^3
    - Rashba: r_{41}= -/+8.5 eA^2

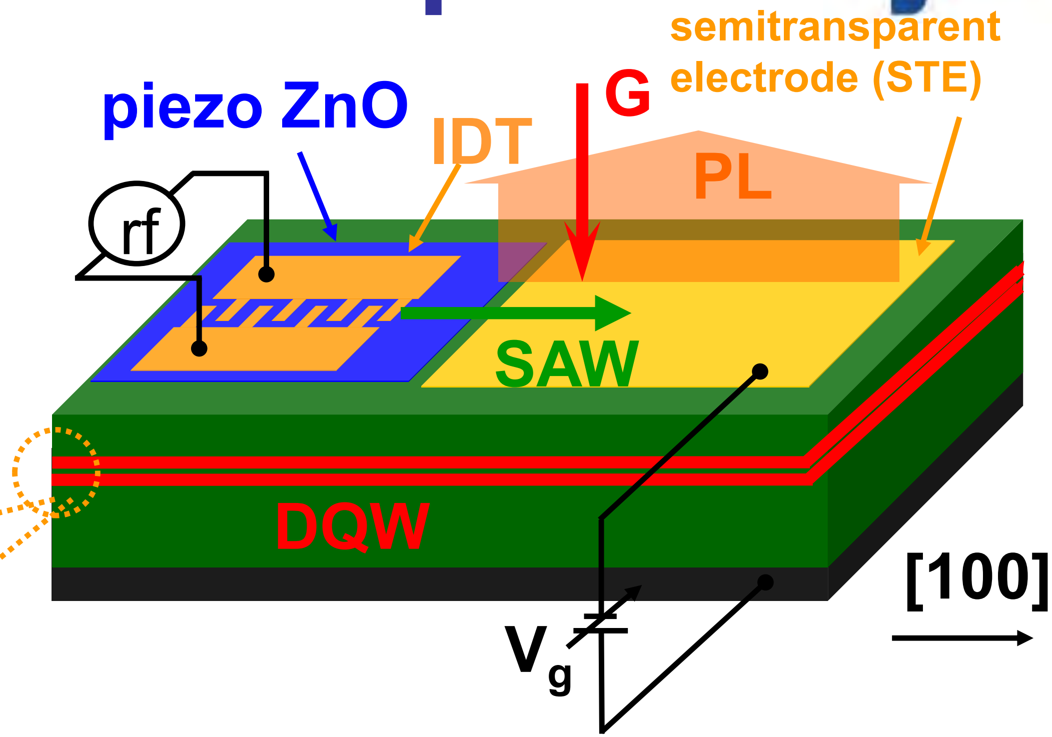
electrical control of spin precession!

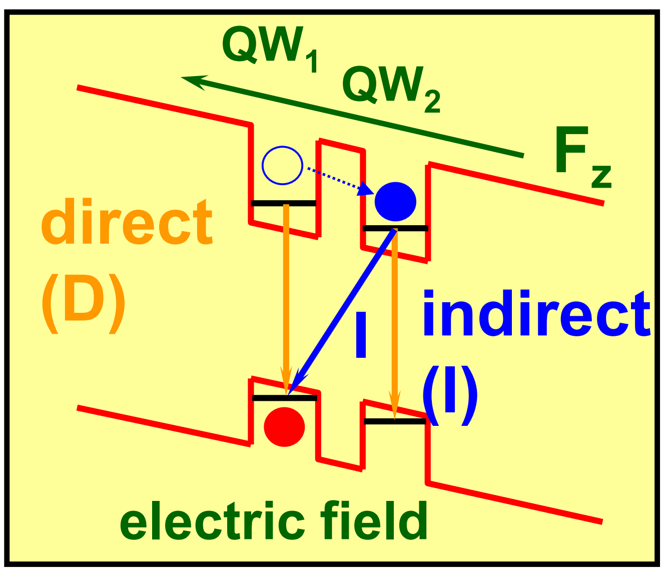
A. Violante, R. Hey, and P. V. Santos, *Phys. Rev. B* 91, 125302 (15)

Experimental setup

- SAW along x=[100]
  - non-piezoelectric, λ_{SAW}=2.8μm
    - piezo ZnO-layer for generation

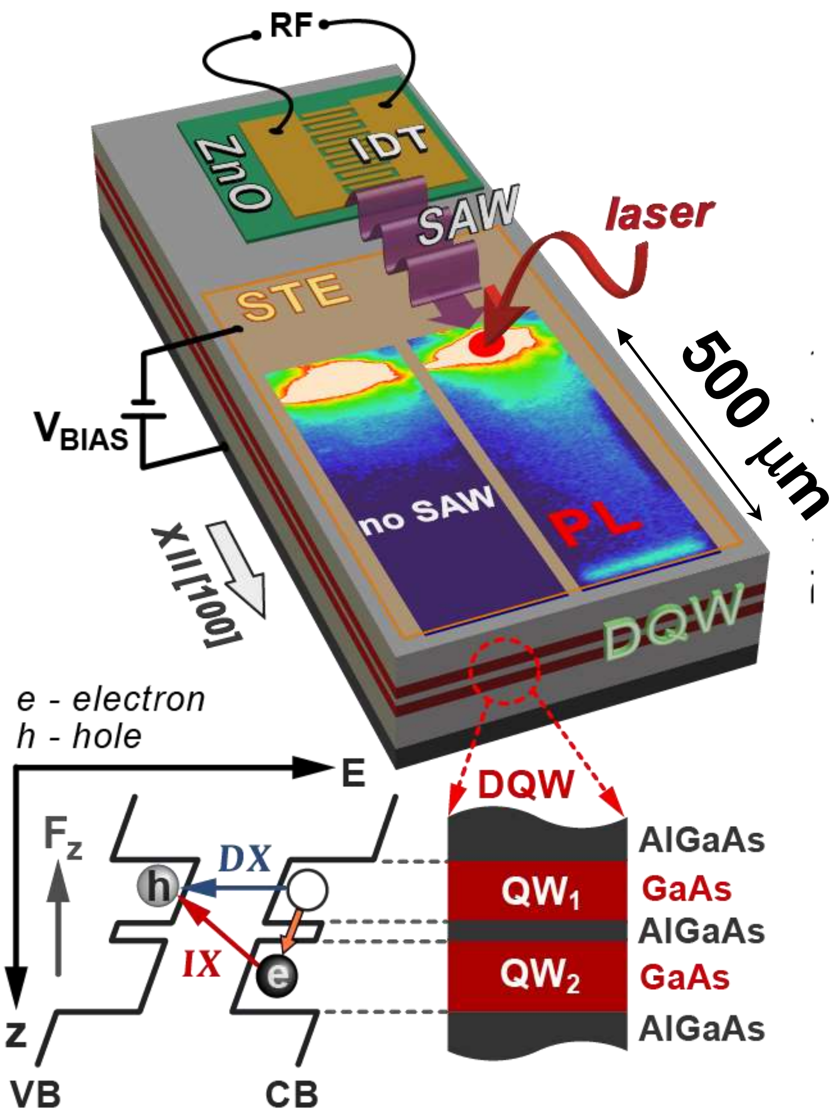
- semitransparent top gate: V_g
  - control of exciton lifetime

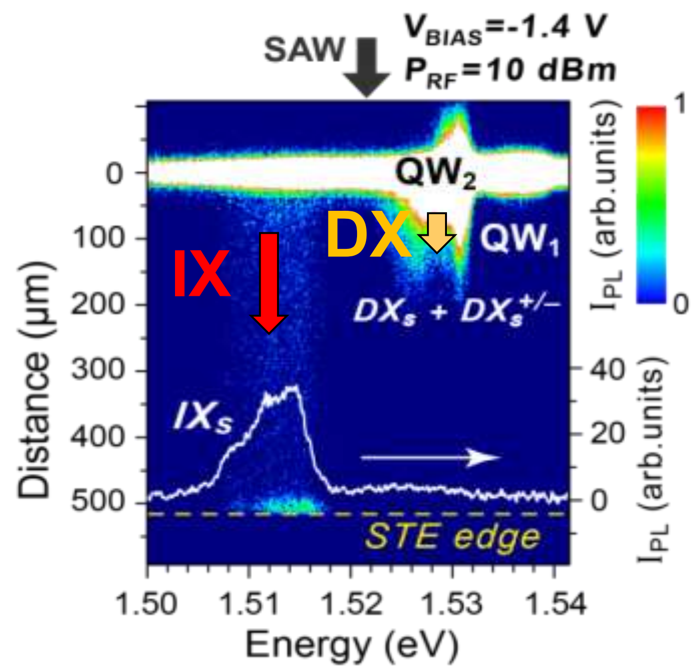




- Detection: photoluminescence (PL)
  - T: 2-4 K
  - laser focused on spot **G**
  - spatially resolved PL along SAW path

Acoustic transport of indirect excitons

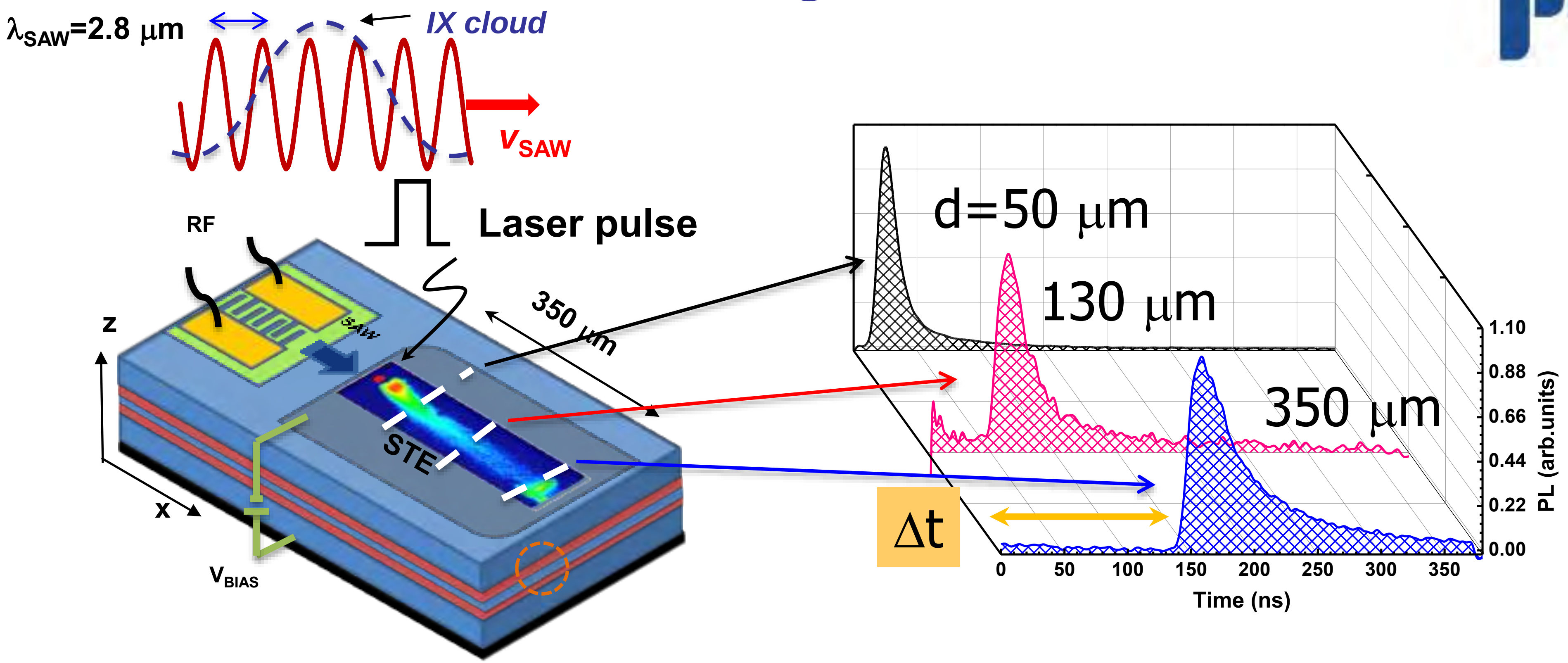




- Spectrally resolved PL
  - recombination at edge of STE
  - transport distances ~ 500 µm
    - limited by channel length
  - transport efficiency ~ 50 %

Lazic et al., Phys. Rev. B**89**, 085313 (14)

Transport dynamics



- pulse delay $\Delta t = d/v_{IX}$
  - v_{IX}: transport velocity
- pulsed shape:
  - essentially maintained during transport
    - conceptually different from drift!

Violante et al., *New J. Phys.* **16**, 033055 (14)

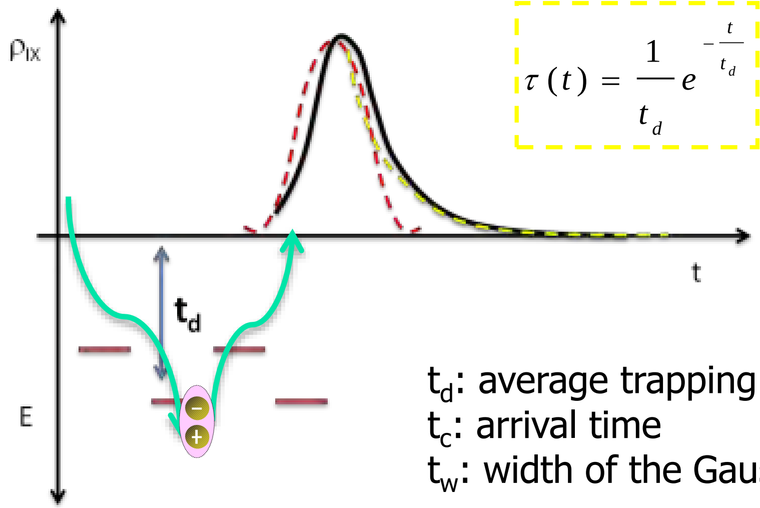
Trapping model

Gaussian Packet

$$g(t) = A_g e^{-\frac{(t-t_c)^2}{2t_w^2}}$$

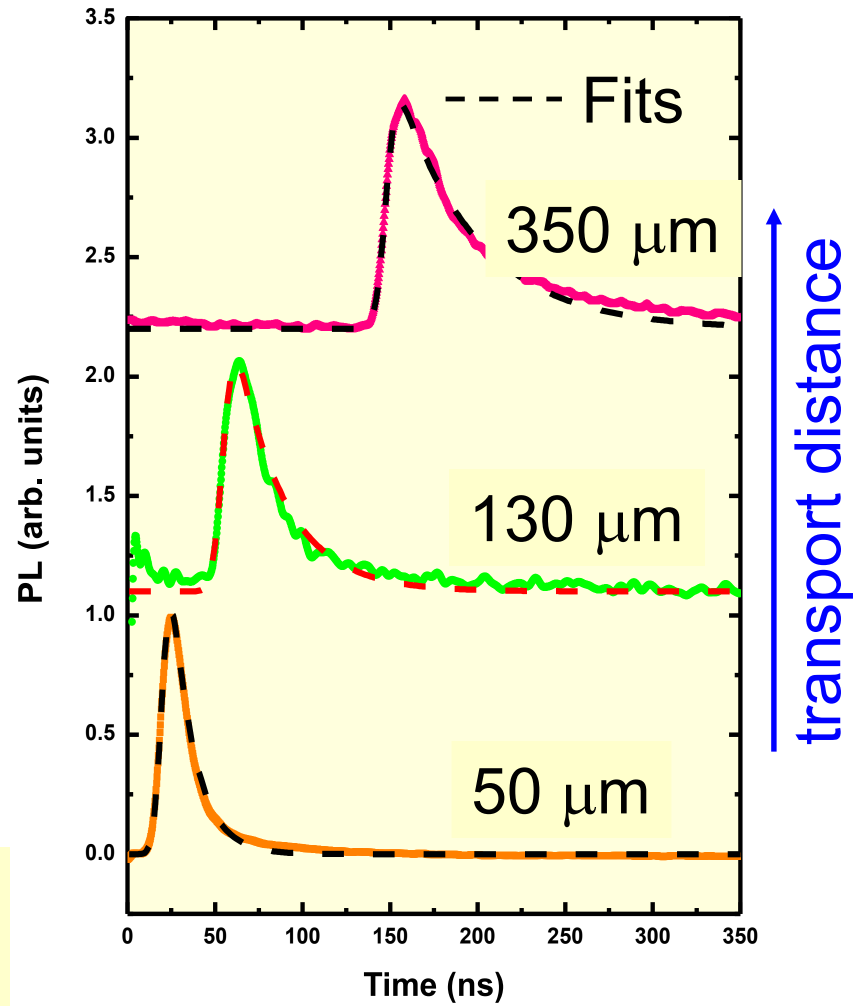
delayed excitons

$$\tau(t) = \frac{1}{t_d} e^{-\frac{t}{t_d}}$$



t_d: average trapping time
t_c: arrival time
t_w: width of the Gaussian packet

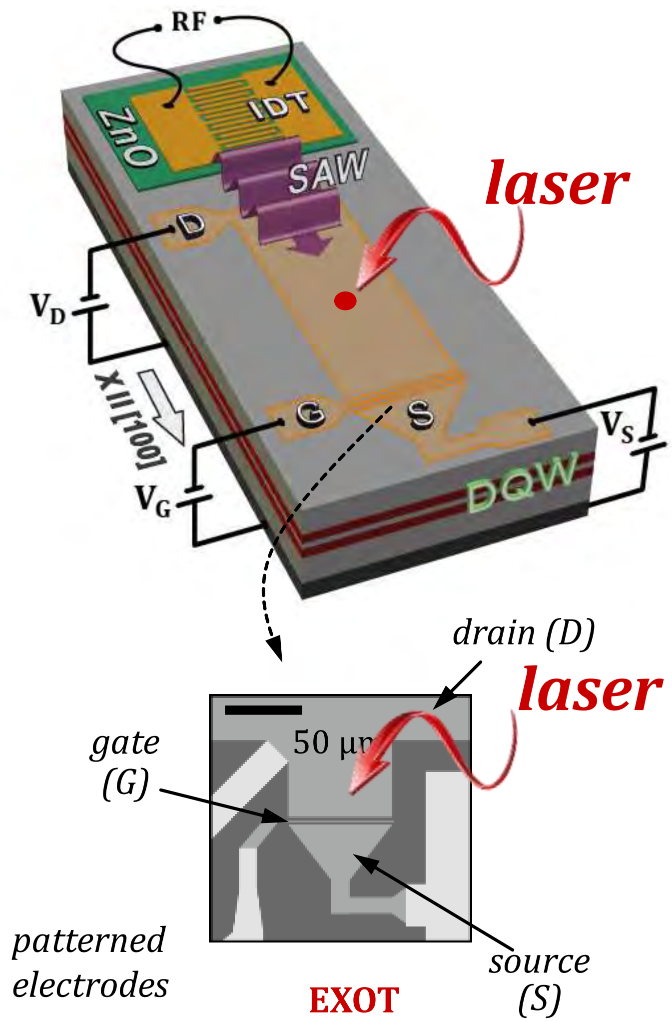
Fit to: $h(t,d) \approx (g * \tau)(t,d)$



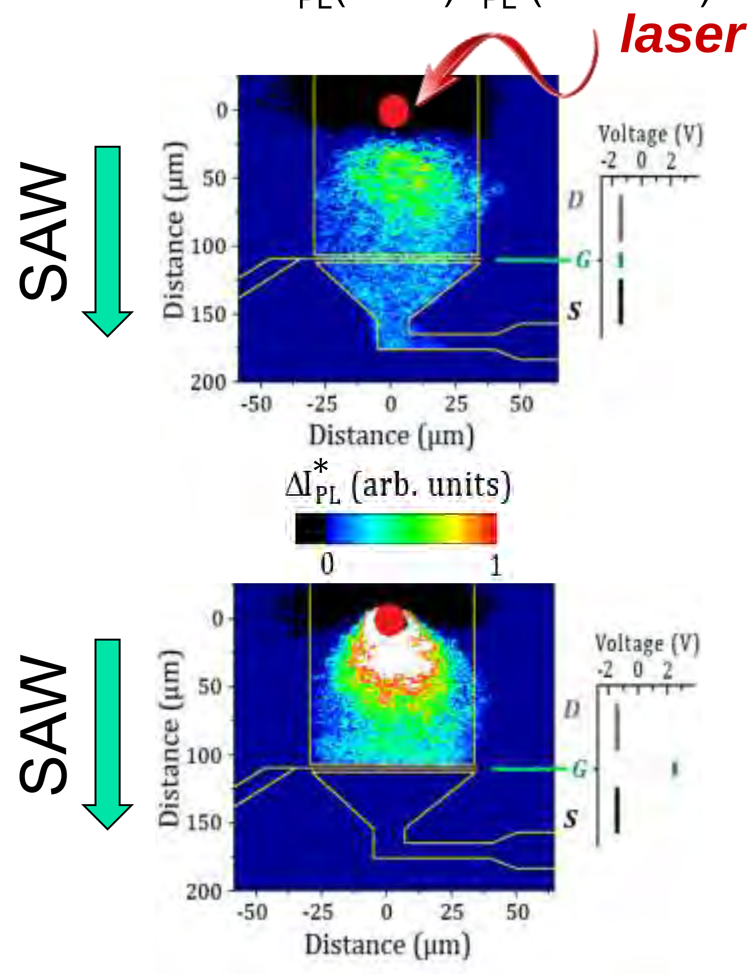
Pulse shape:
gaussian packet
+
tail: delayed IXs due to trapping

A. Violante, K. Cohen, S. Lazic, R. Hey, R. Rapaport, and P. V. Santos, *New J. Phys.* 16, 033055 (14)

Acoustic exciton transistor



Differential images:
I_{PL}(SAW)-I_{PL} (no SAW)



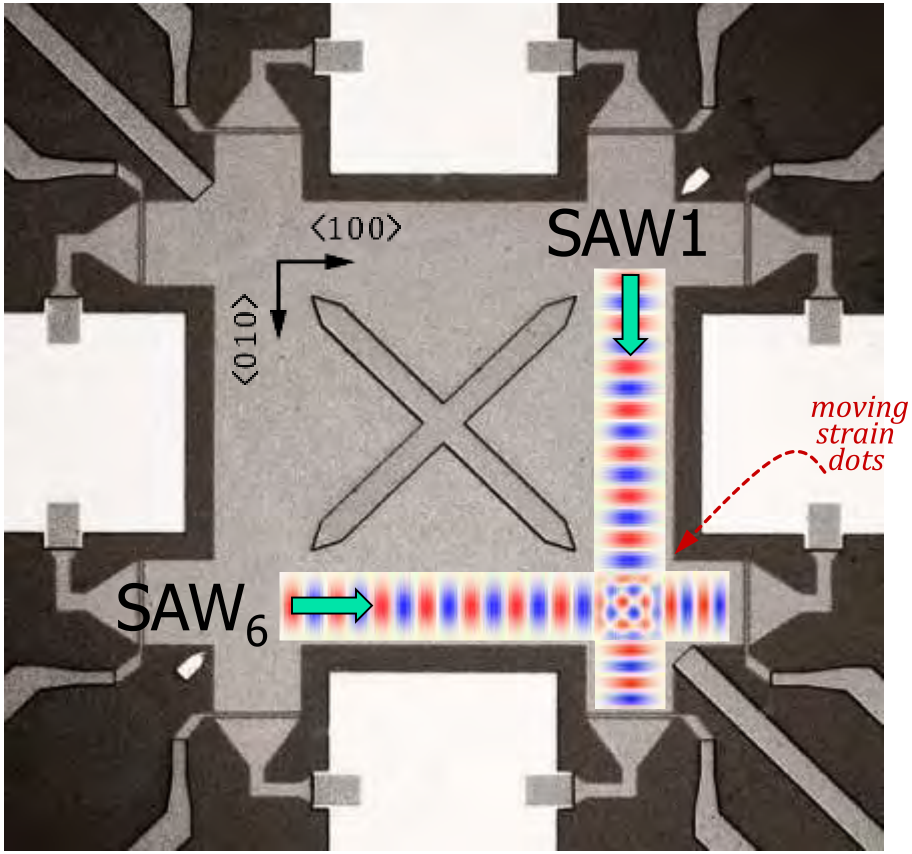
Gate:
open

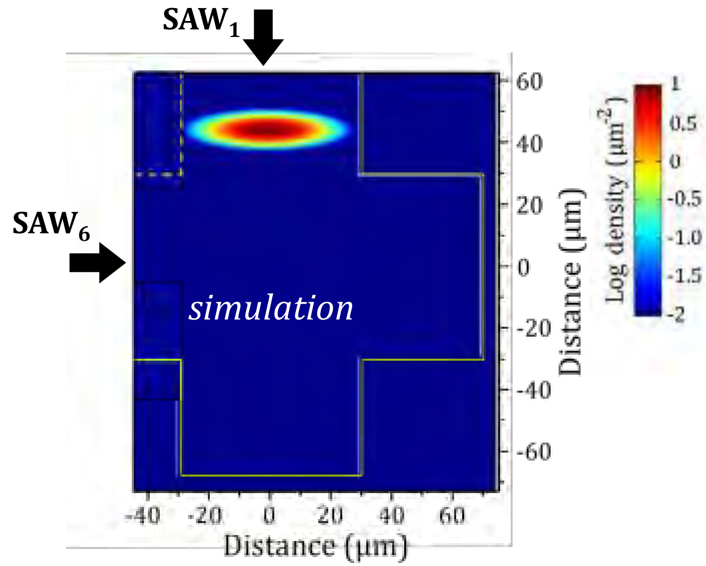
closed

electrostatic control of acoustic IX transport

Lazic et al., Phys. Rev. B**89**, 085313 (14)

Control of the flow direction: DQDs





✓interference of two orthogonal SAW beams

→ **moving** and **tunable** potential dots for ***IX*** storage and transport

Blue regions: areas under compressive strain

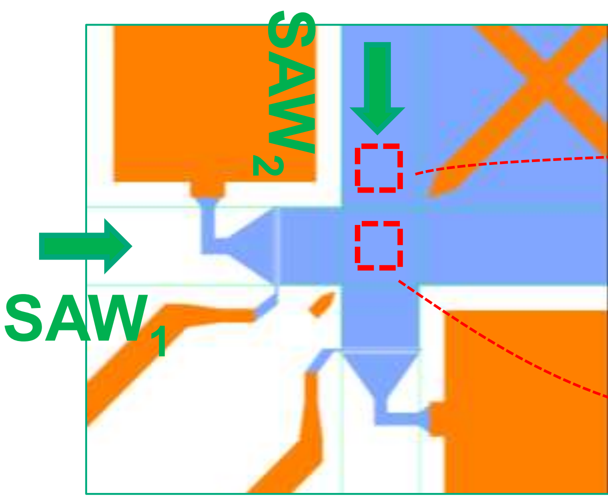
Red regions: areas under tensile strain
→ reduced bandgap: ***IX*** confinement

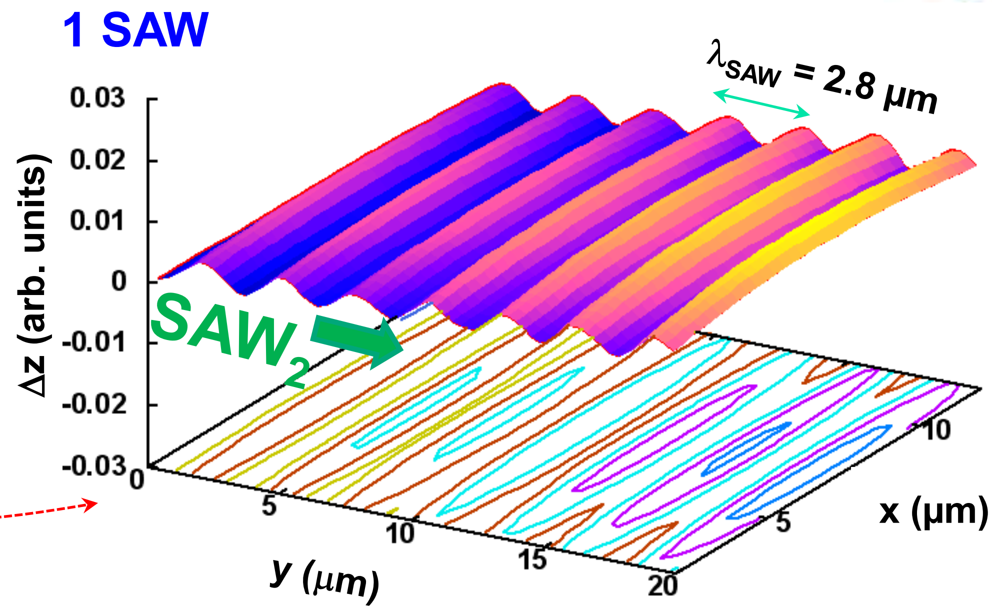
A. Govorov et al., PRL 87, 226803 (2001)

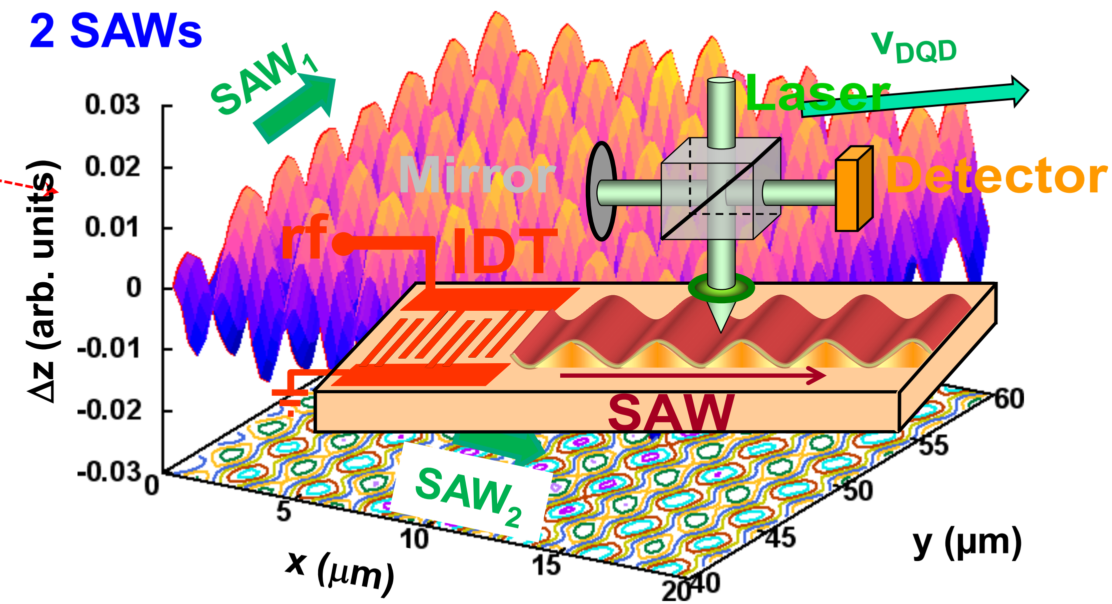
S. Lazić et al., Physica E 42, 2640 (2009)

Lazic et al., Phys. Rev. B**89**, 085313 (14)

Interferometric mapping

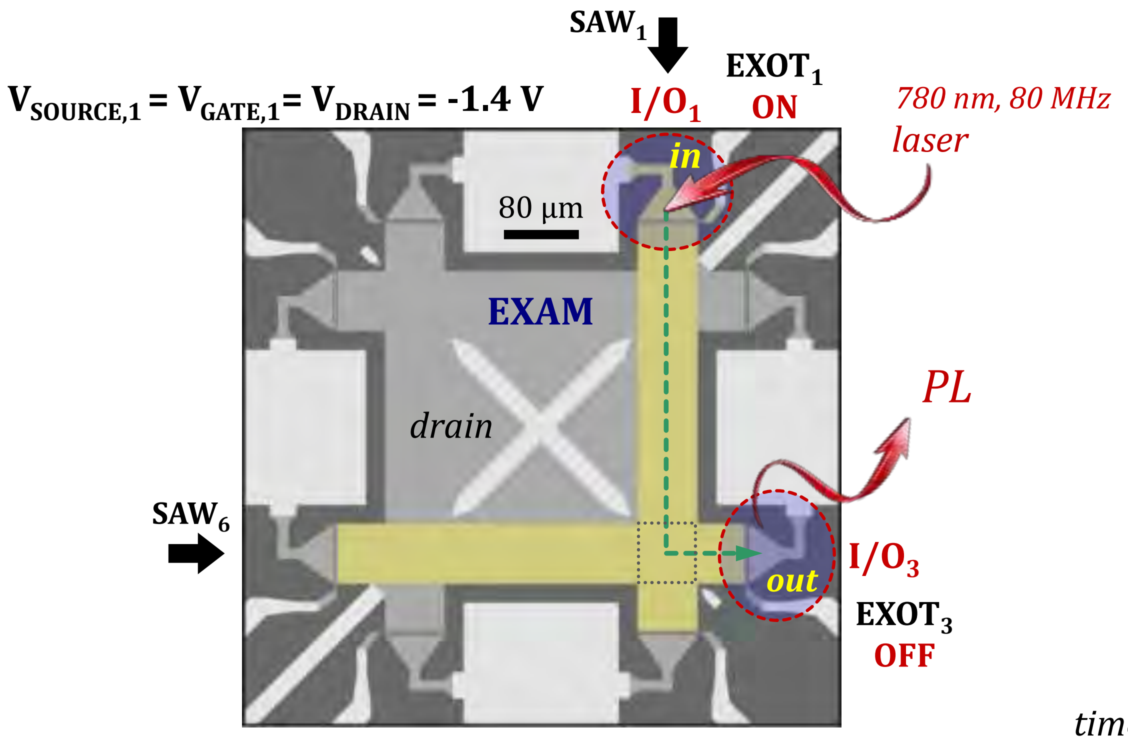


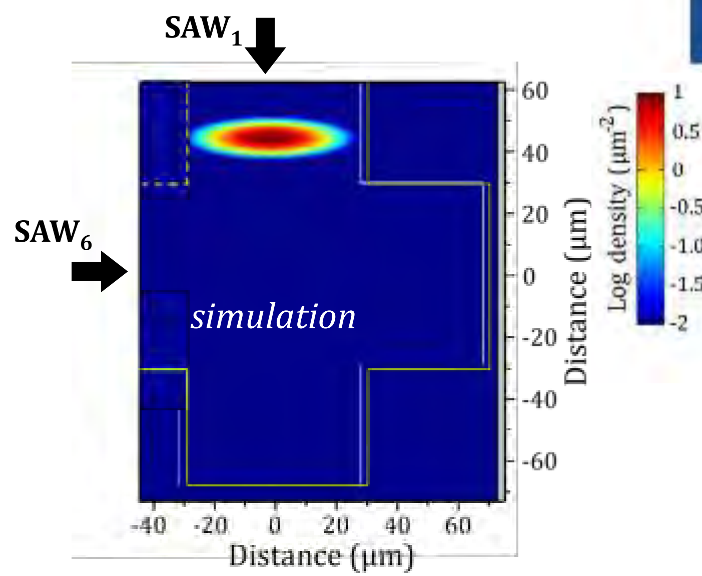


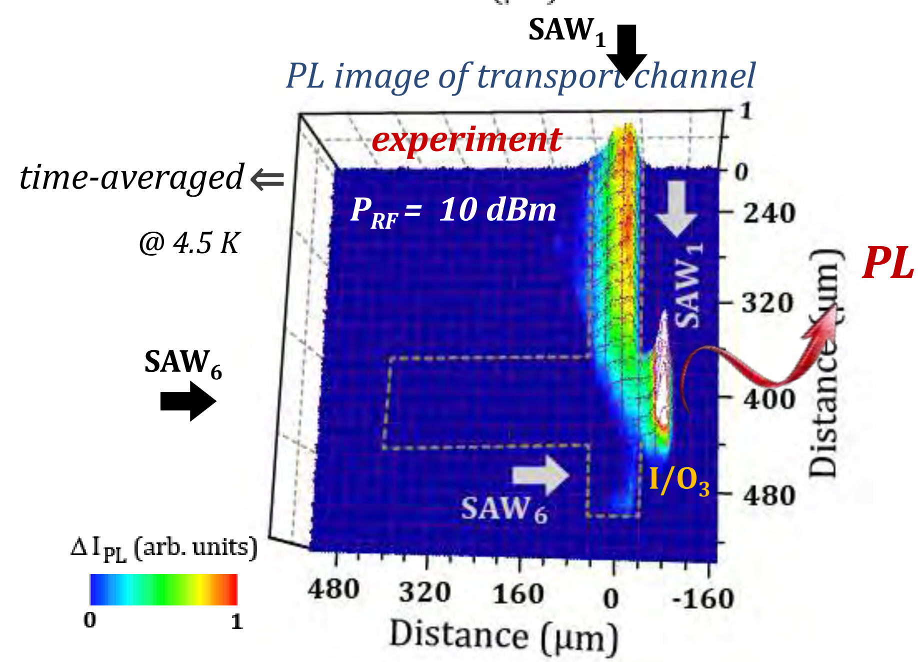


Lazic et al., Phys. Rev. B**89**, 085313 (14)

IX multiplexer (EXAM) – switching direction







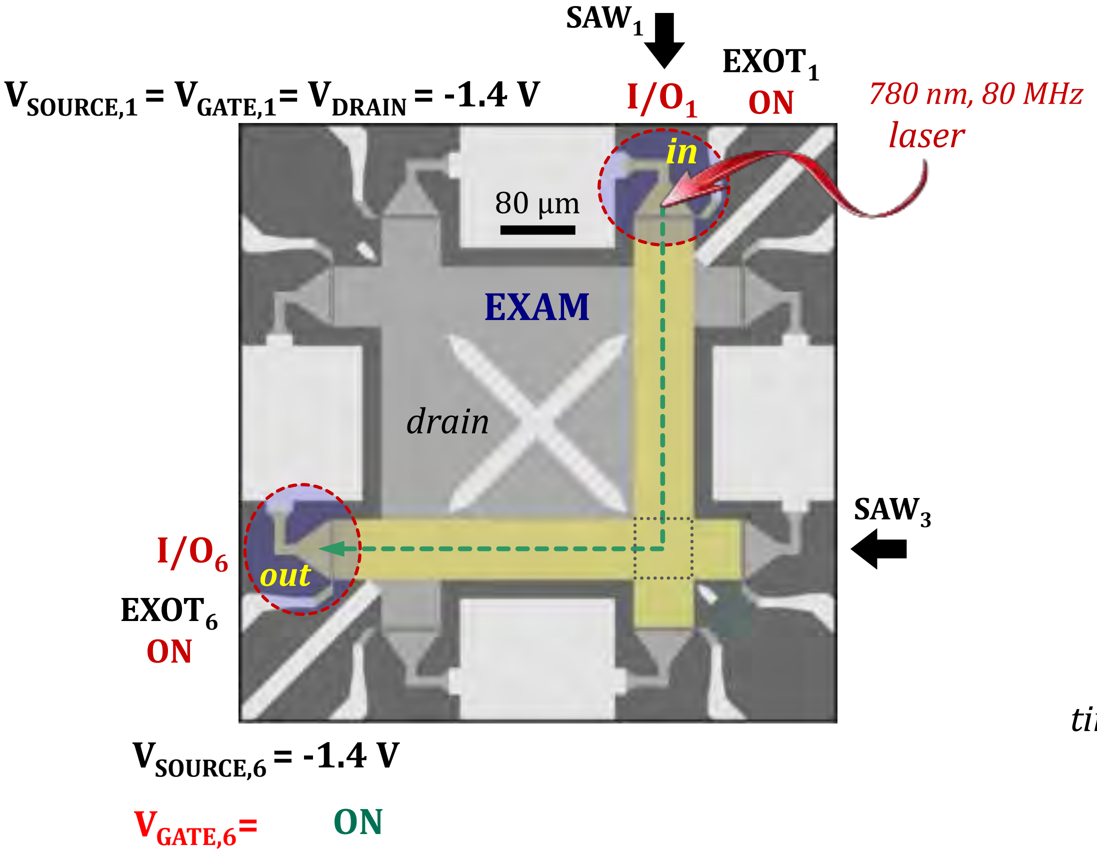
IX transport with **SAW$_1$** and **SAW$_6$**:

→ ***IXs*** transport from **I/O$_1$** to **I/O$_3$**

→ ***IXs*** switching efficiency > 90%

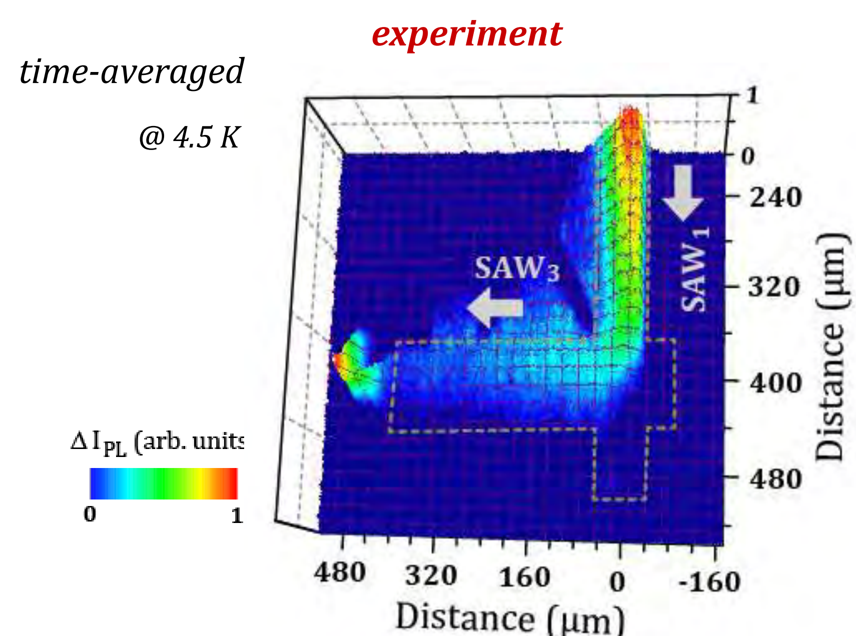
Lazic et al., Phys. Rev. B**89**, 085313 (14)

EXAM – electrostatic switching (EXAT)



- EXAM
  - channel width: 50 µm
    - defined by SAW beam width
  - long transport IX distances
    - ~1 mm: lifetime > 330 ns
    - SAW clock: synchronization!
  - scalable!
    - dimensions~√#ports
    - planar fabrication

PL image of transport channel

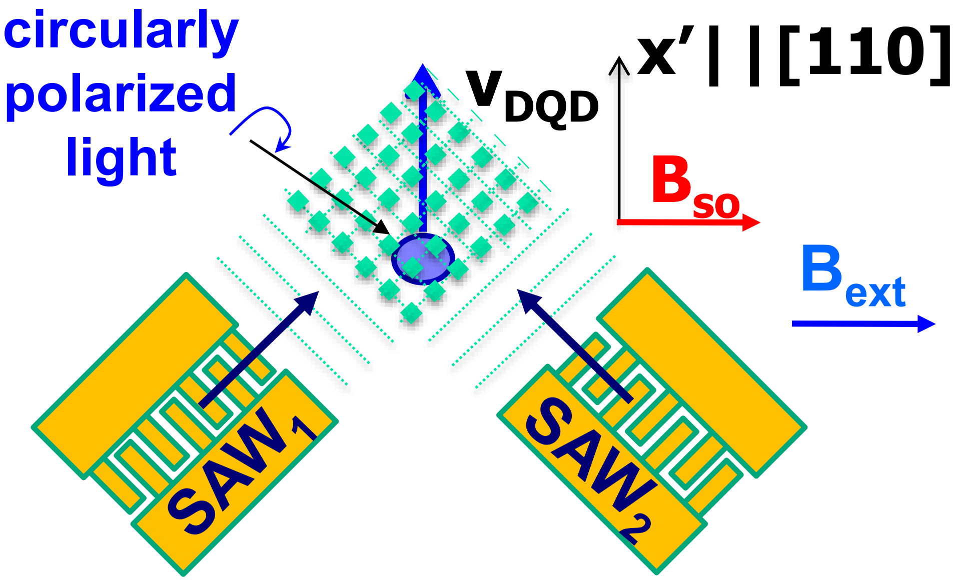


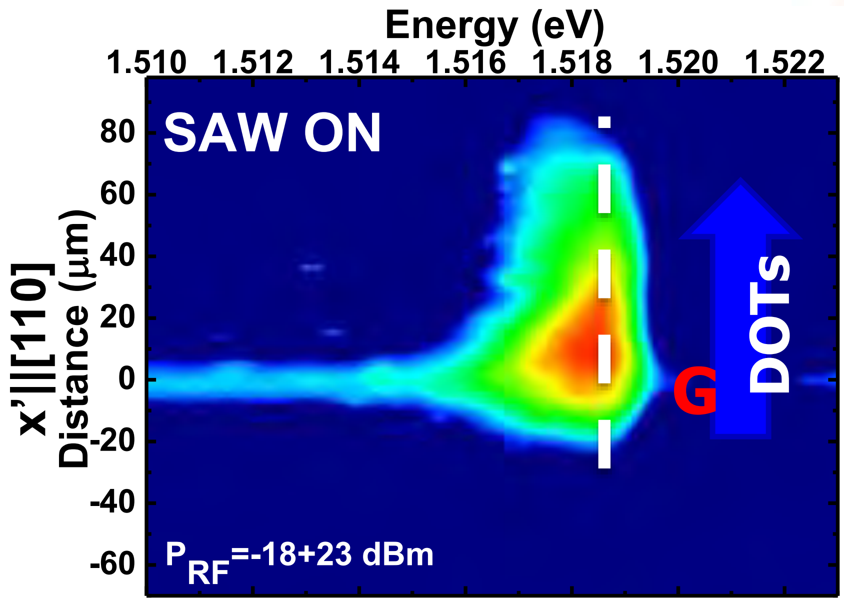
Electrostatic switching: EXOT$_6$:

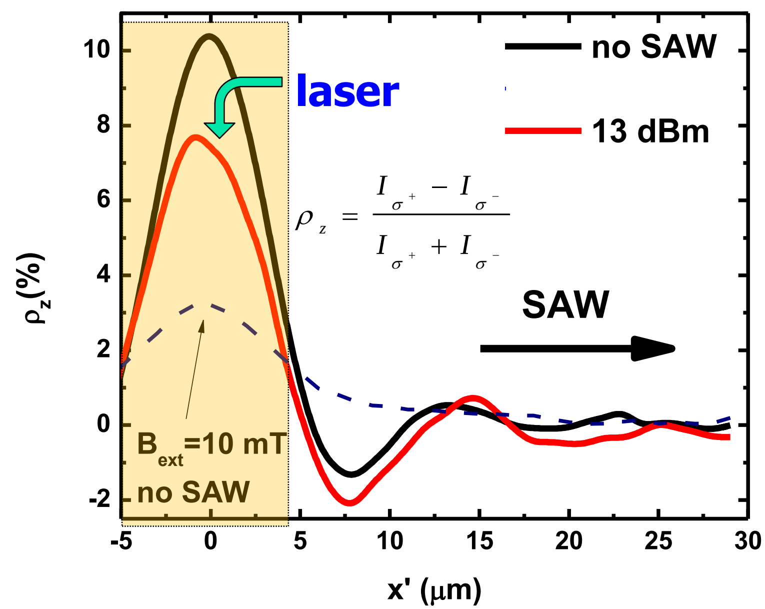
→ isolation of **I/O** ports

Lazic et al., Phys. Rev. B**89**, 085313 (14)

Acoustic spin transport



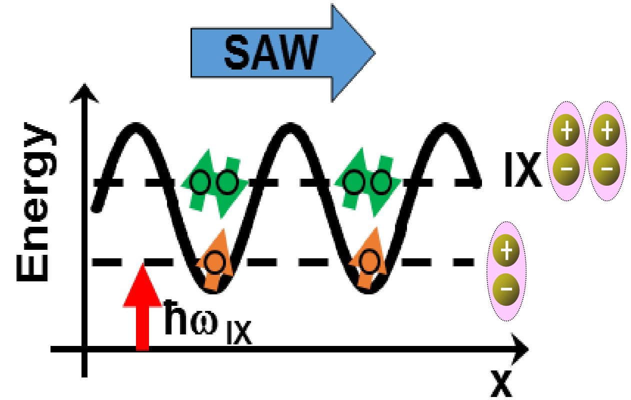


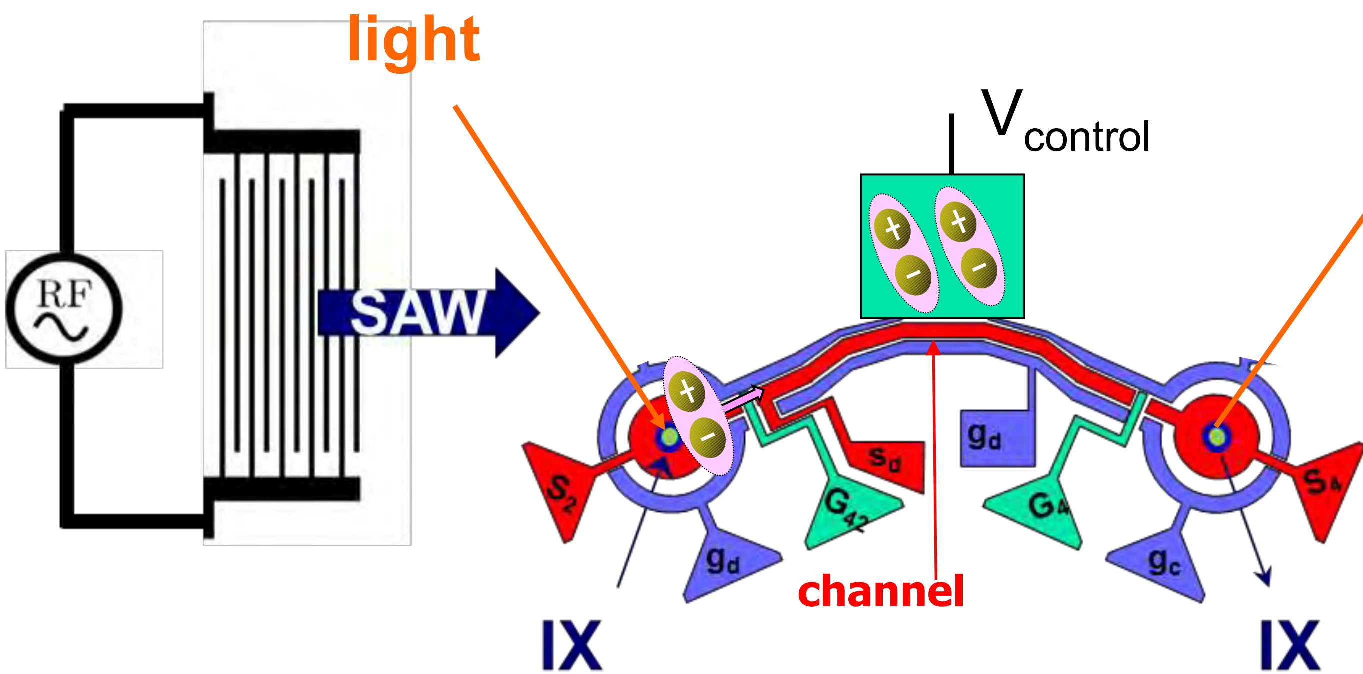


- ρ_z oscillations
  - IX spin precession in the spin orbit field B_{SO}
  - spin lifetime: 6 ns (Hanle effect, B_{ext})
- Low spin transport efficiency
  - changes in amplitude/precession frequency
  - weak IX confinement

Few/single IX transport

- Few/single IX manipulation
  - small traps for IX confinement
    - small SAW wavelengths
  - lateral IX-IX interactions
    - short IX interaction range



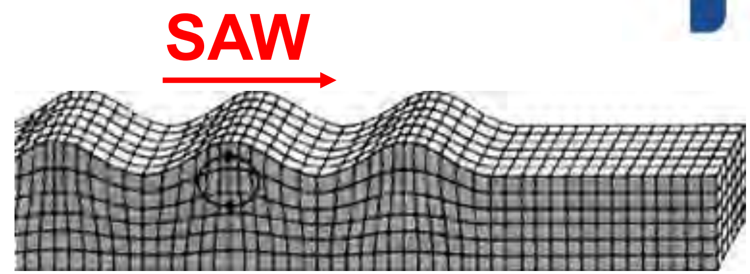


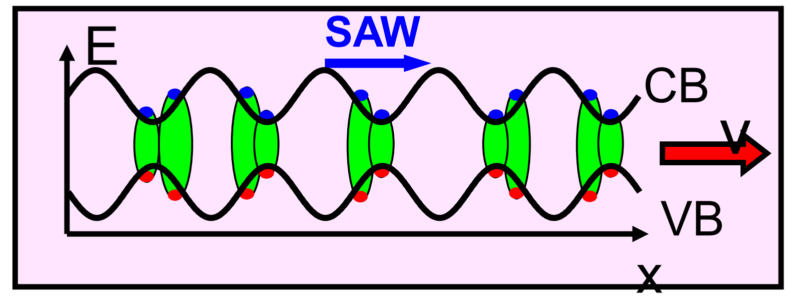
Cohen, Rapaport, Santos, PRL106, 126402 (11)

collaboration: Neel Institute

Outline

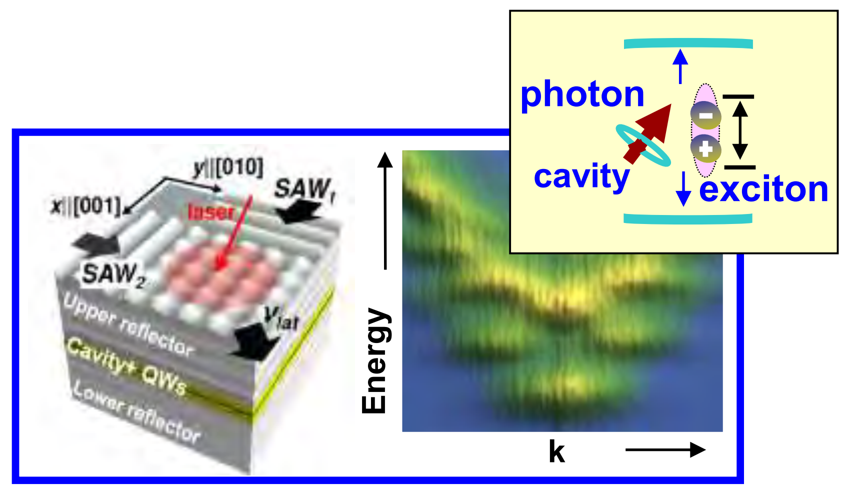
- Surface acoustic waves
  - modulation of the semiconductor band structure
  - tunable acoustic lattices



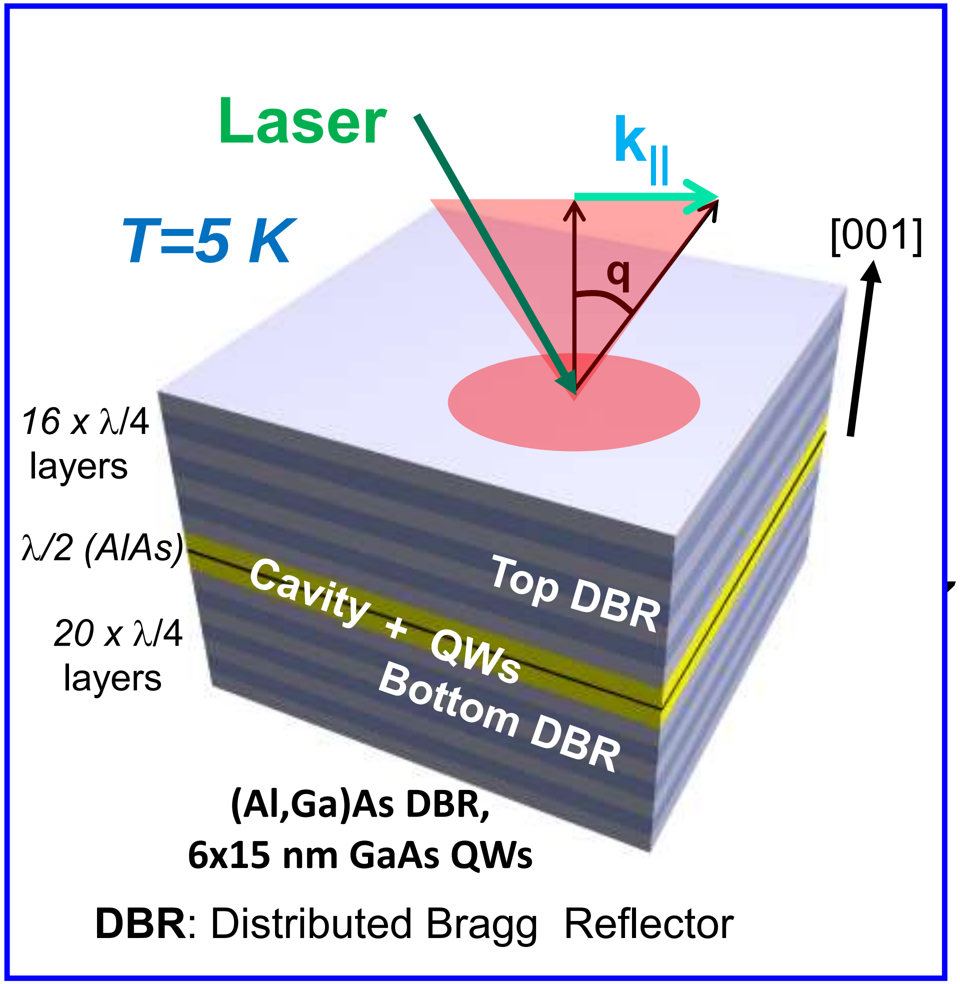


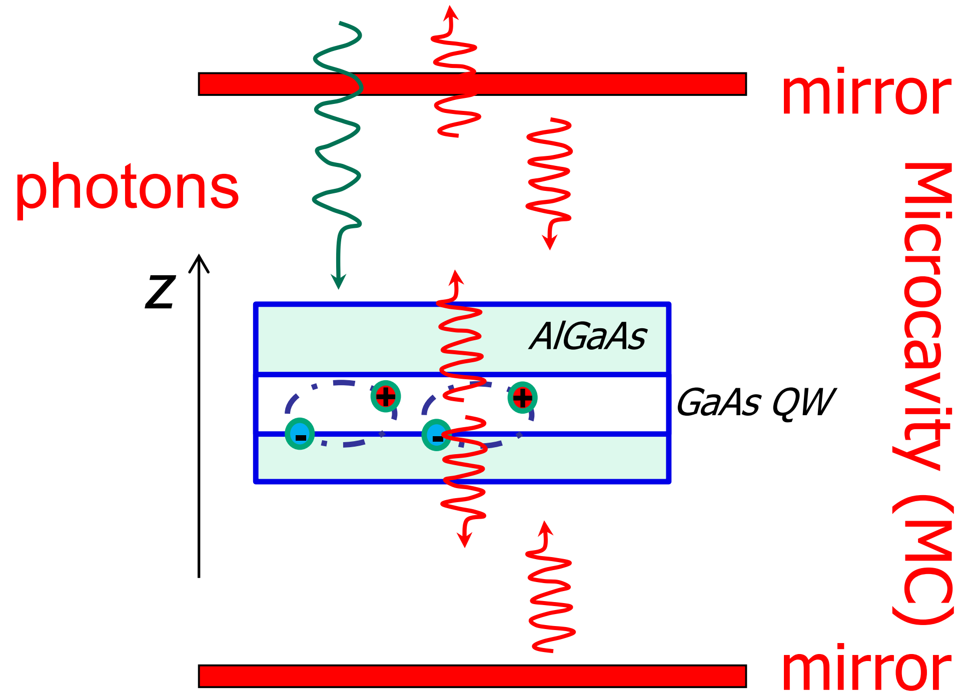
- Acoustic exciton transport
  - indirect excitons (IXs)
  - IX transport dynamics

- Polariton modulation
  - tunable polaritonic crystals
  - control of polariton condensates



Exciton-polaritons in microcavities





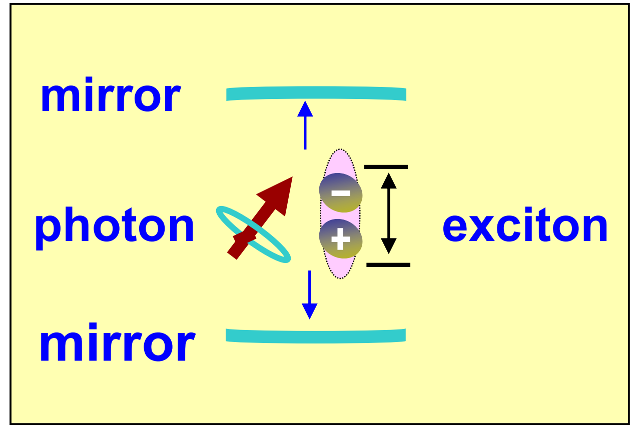
- Excitons in a microcavity
  - strong coupling to photons
    - **exciton polaritons**:
      - matter-wave particles
      - short (sub-ns) lifetimes: photon loss

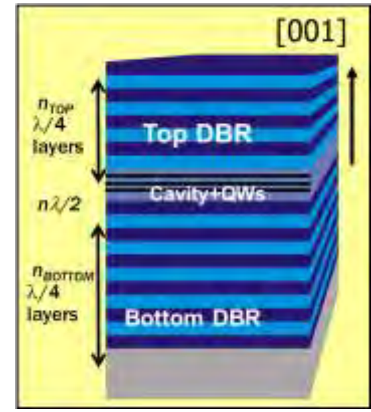
Weisbuch, C.; Nishioka, M.; Ishikawa, A. & Arakawa, Y.
Phys. Rev. Lett., **1992** , *69* , 3314

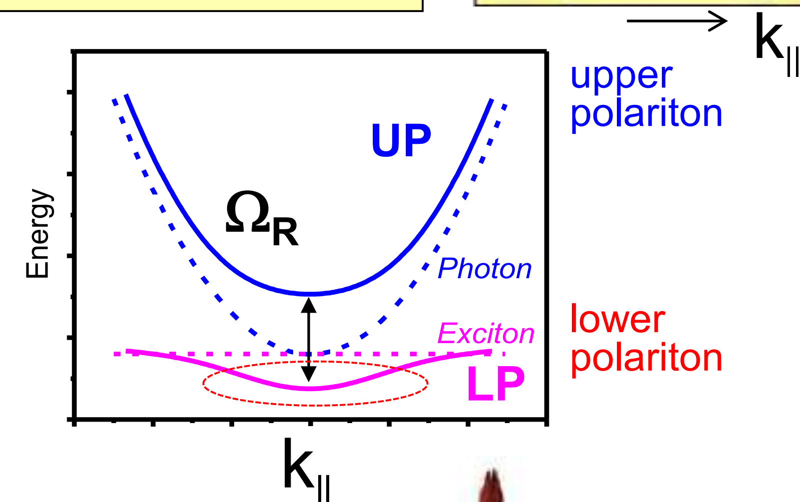
Exciton polaritons properties

- Microcavity (MC) polaritons
  - QW excitons + MC photons
- Properties
  - very small mass
    - $m_p \sim 10^{-4} - 10^{-5}\, m_e$
    - long de Broglie wavelength (μm)
      - spatial coherence: $\lambda_B > \lambda_{SAW}$
  - bosonic character: condensation
    - non-equilibrium
    - densities $n_{Cond} > \lambda_B^{-2}$
      - temporal coherence

$$\lambda_B = \sqrt{\frac{2\pi^2\hbar^2}{2m_p kT}}$$







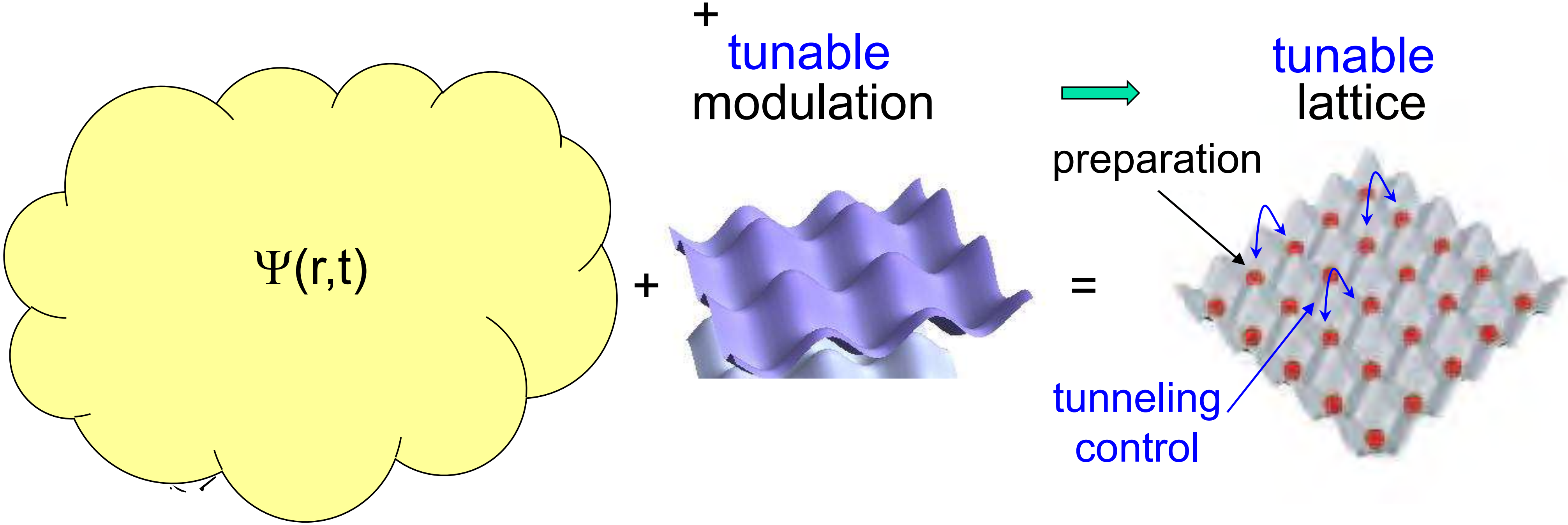
Kasprzak, J. et al., Nature 443, 409 (06).

Pump intensity →

macroscopic quantum phases!

Tunable modulation

Macroscopic quantum phase - MQP

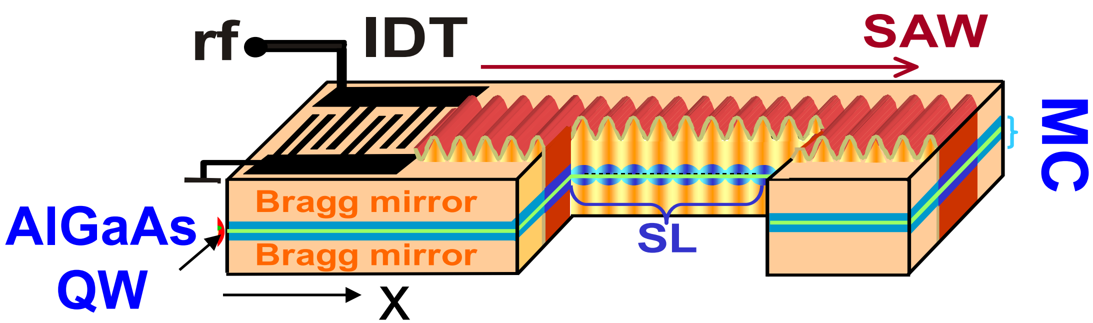


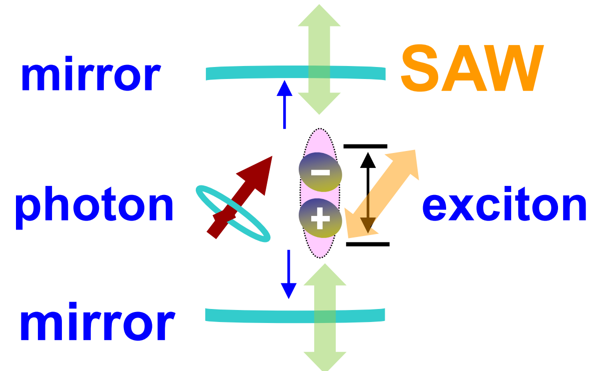
Realizations:

Cold atom condensates + lasers → optical lattices

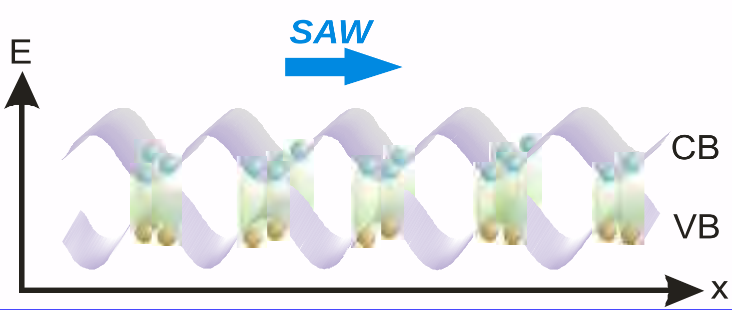
Exciton-polariton condensates + SAWs → acoustic lattices

Tunable strain modulation





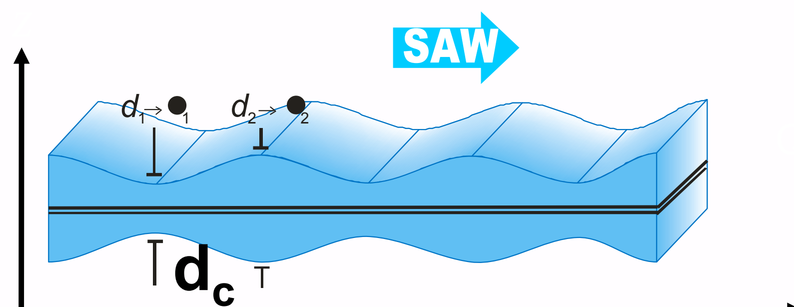
- **Excitonic modulation:**
  - *type I bandgap due to SAW strain*
    - Deformation potential



In phase!

- **Photonic modulation:**
  Microcavity
  - **refractive index (n_c)**
  - **strain (ε_{zz}) → thickness (d_c)**

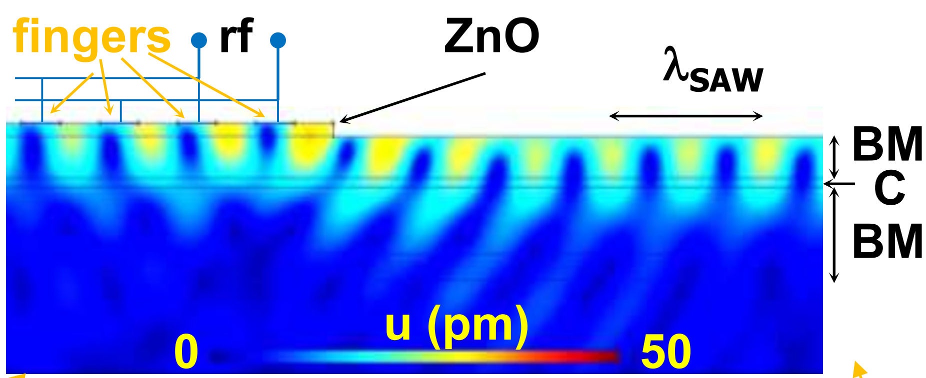
  mechanic > elasto-optic

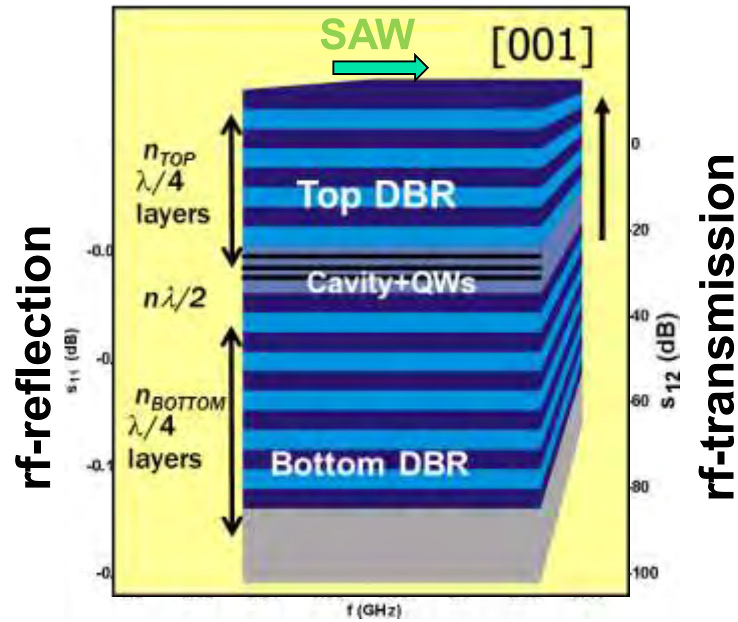


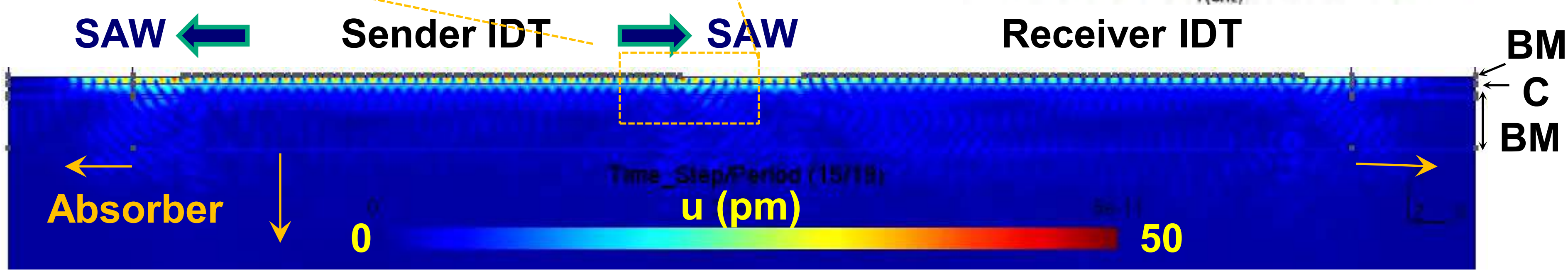
M. M. de Lima et al. Phys. Rev. Lett. 97, 045501 (2006); M. M. de Lima, Jr. and P. V. Santos, Rep. Prog. Phys. 68, 1639 (2005).

SAW propagation: simulations

- SAW wavelength λ_{SAW}=8 μm
- SAW frequency f_{SAW}=0.37 GHz

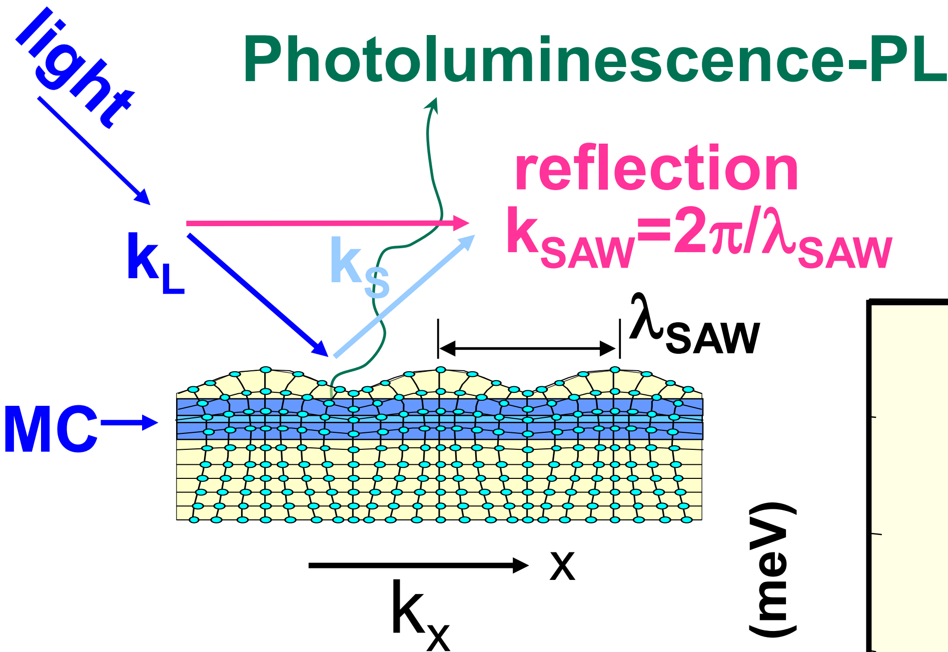


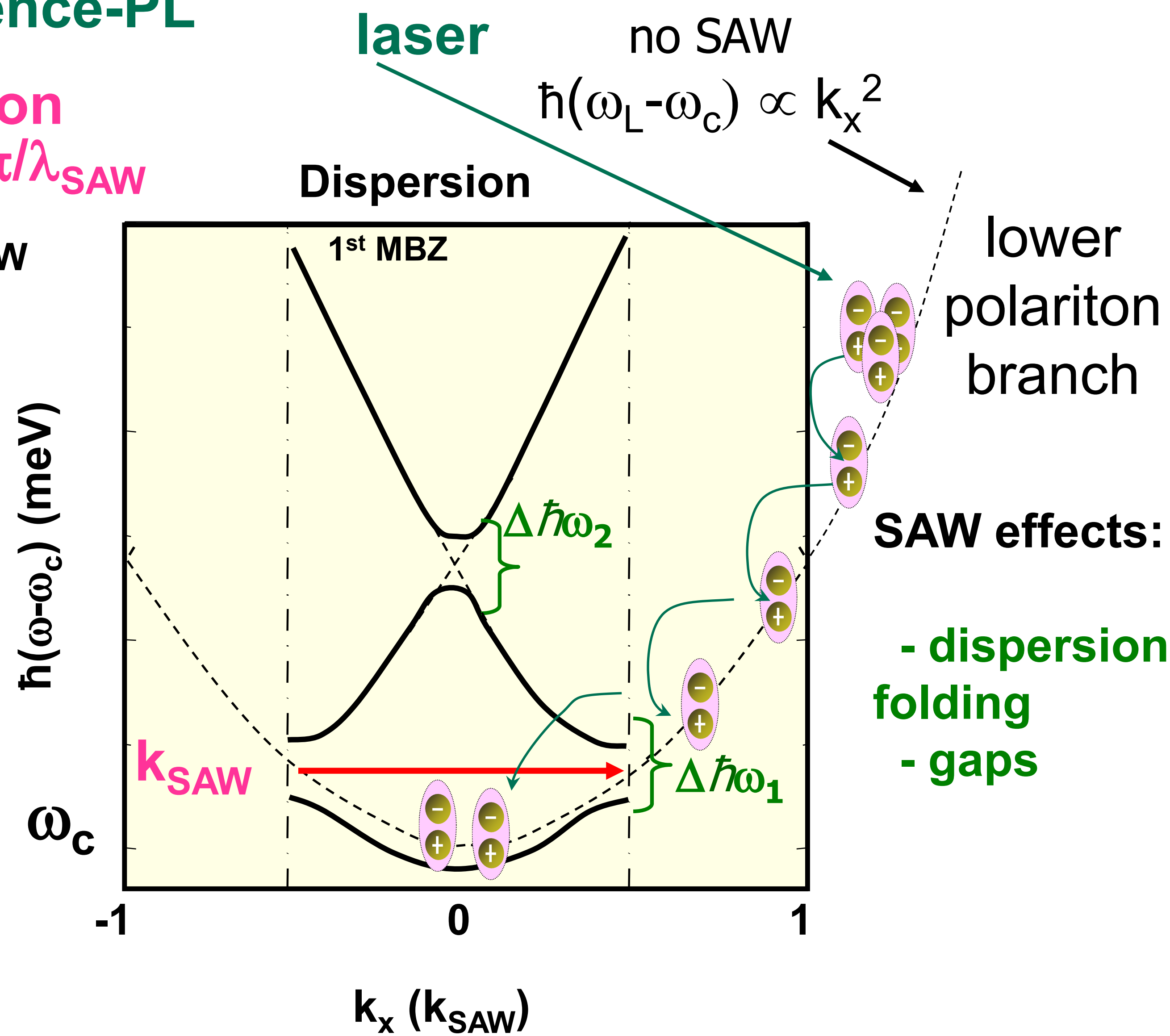




GetDP/gmsh, www.onelab.info

Periodic SAW modulation





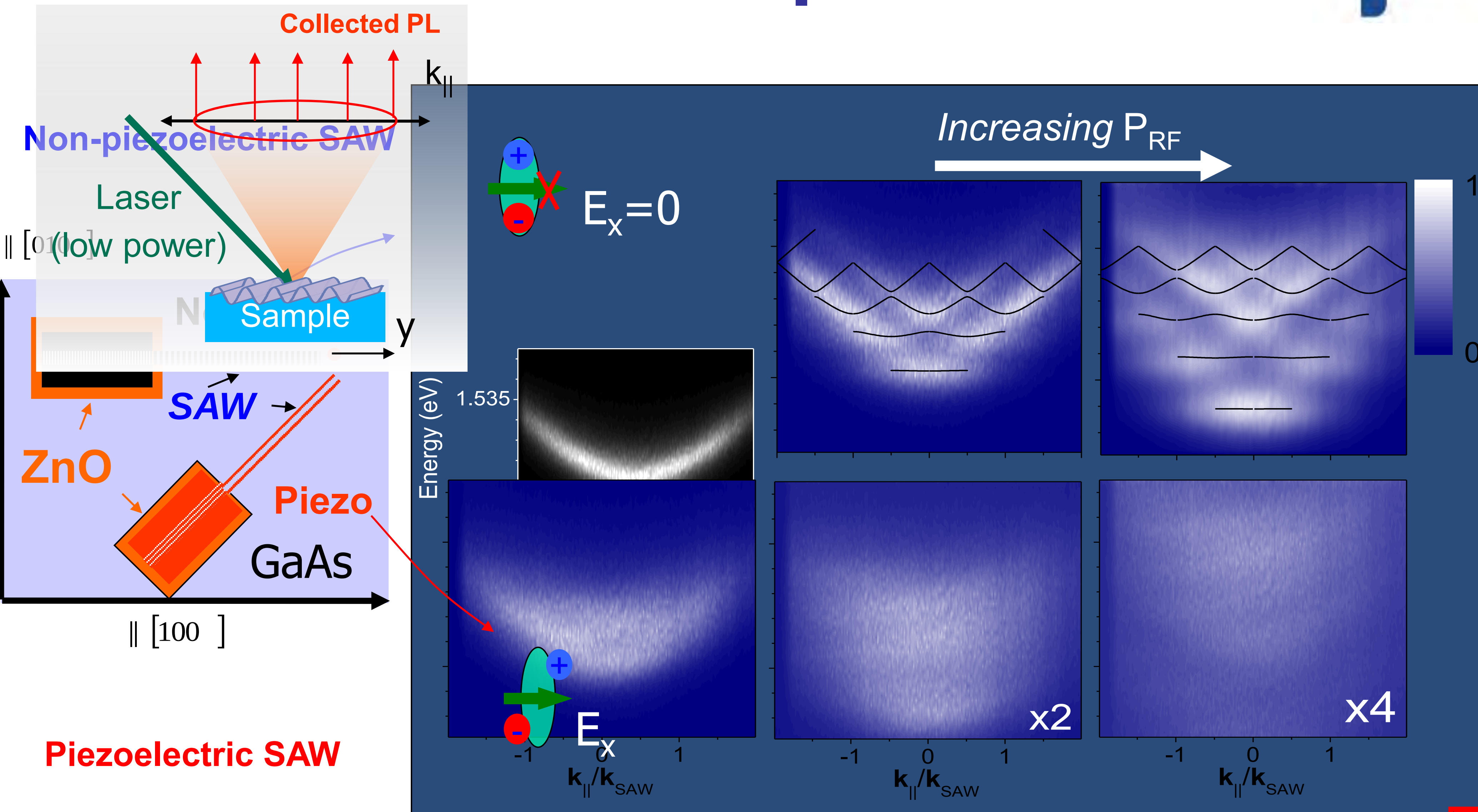
SAW effects:

- dispersion folding
- gaps

tunable polaritonic crystal

M. M. Lima Jr., et al., Phys. Rev. Lett. 97, 045501 (06)

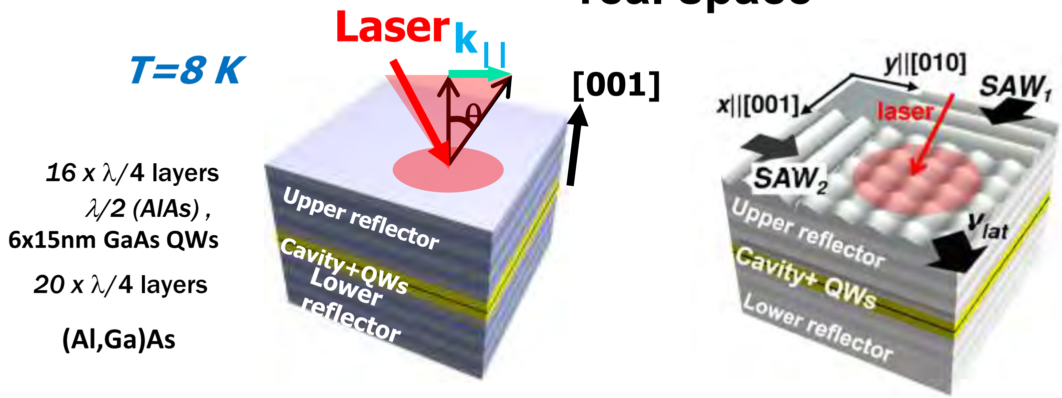
Polariton dispersion



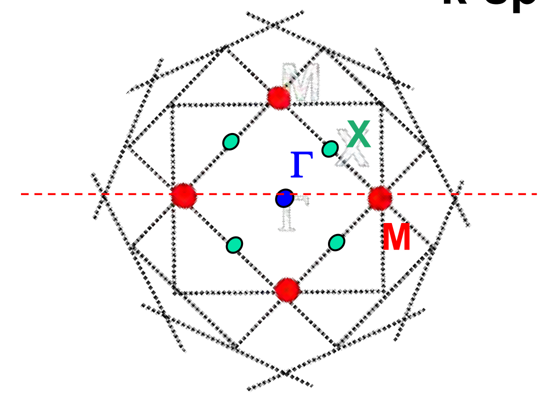
E. Cerda et al., Superlattices and Microstruct.49, 233 (11)

Polariton in a square lattices

real space



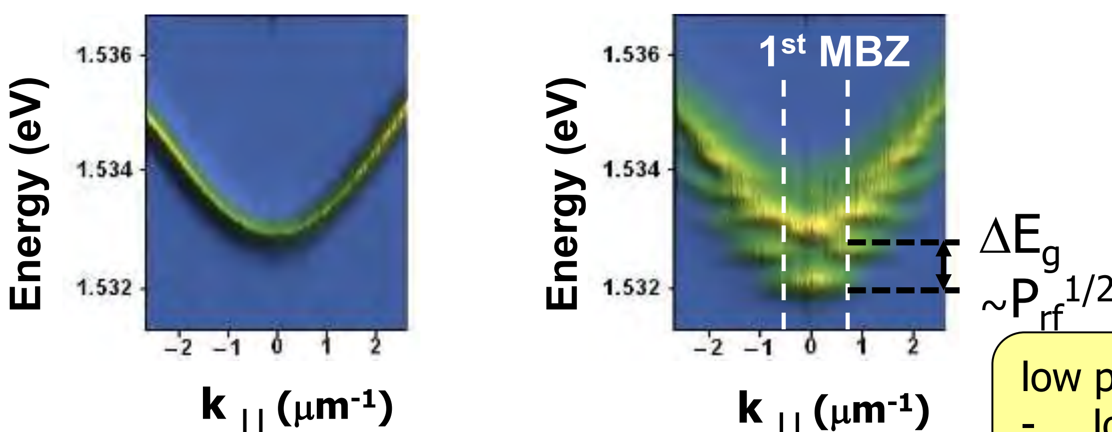
k-space

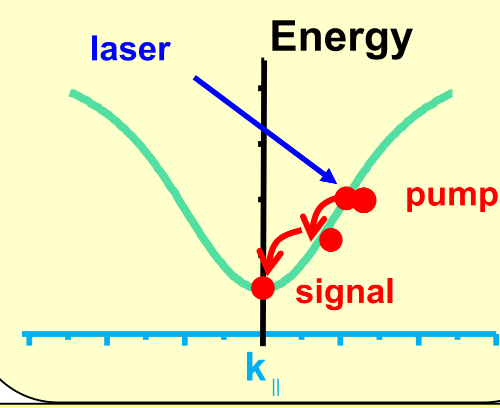


Angle (k) resolved PL spectra

low density

SAWs off **SAWs on**





low particle density
- long spatial coherence >> λ_{SAW} !!!
- short time coherence

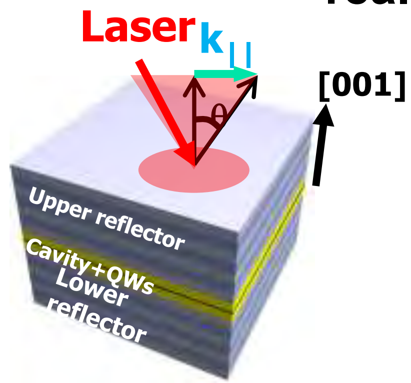
E. Cerda et al., Phys. Rev. Lett.105, 116402 (10)

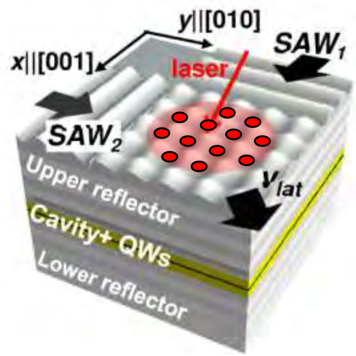
Polariton condensate in a square lattices

T=8 K

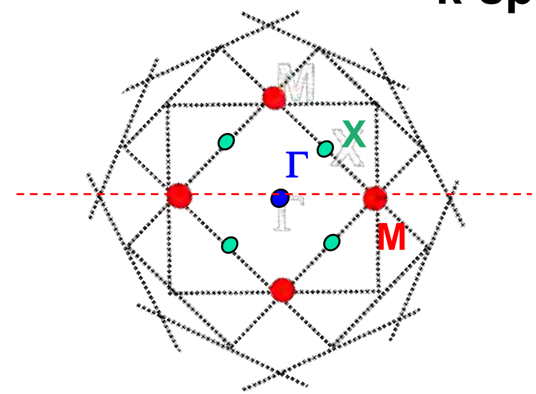
16 x λ/4 layers
λ/2 (AlAs) ,
6x15nm GaAs QWs
20 x λ/4 layers
(Al,Ga)As

real space



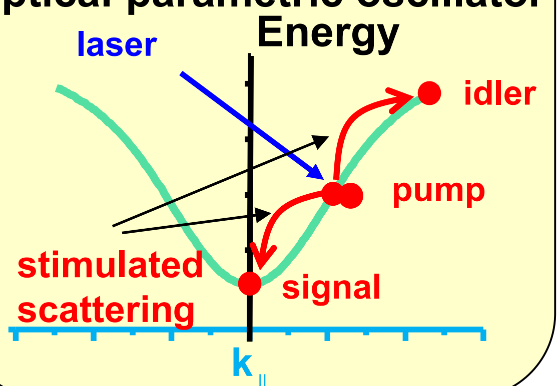


k-space



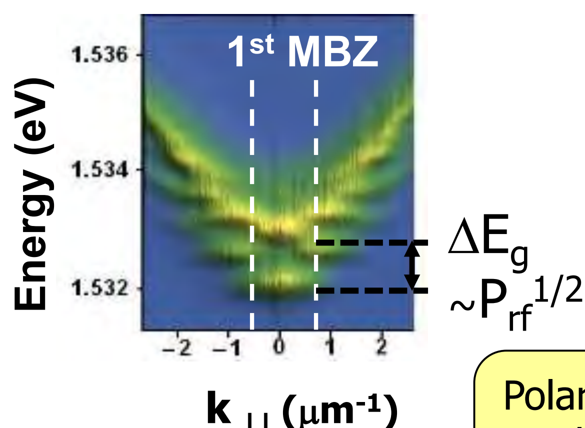
Angle (k) resolved PL spectra

High density
Optical parametric oscillator



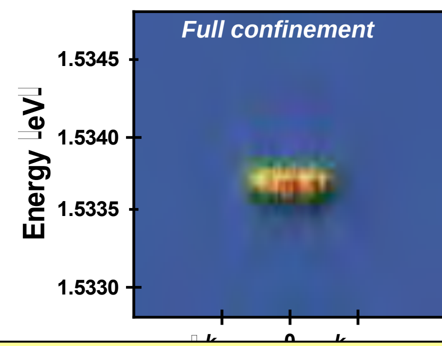
low density

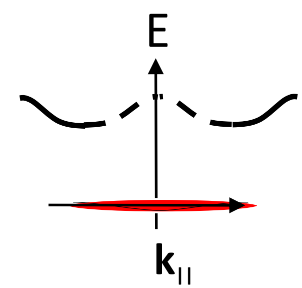
SAWs on



high density

SAWs on



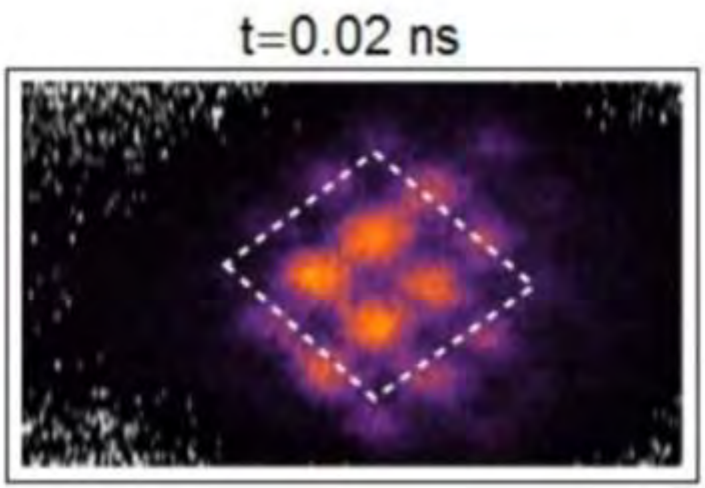


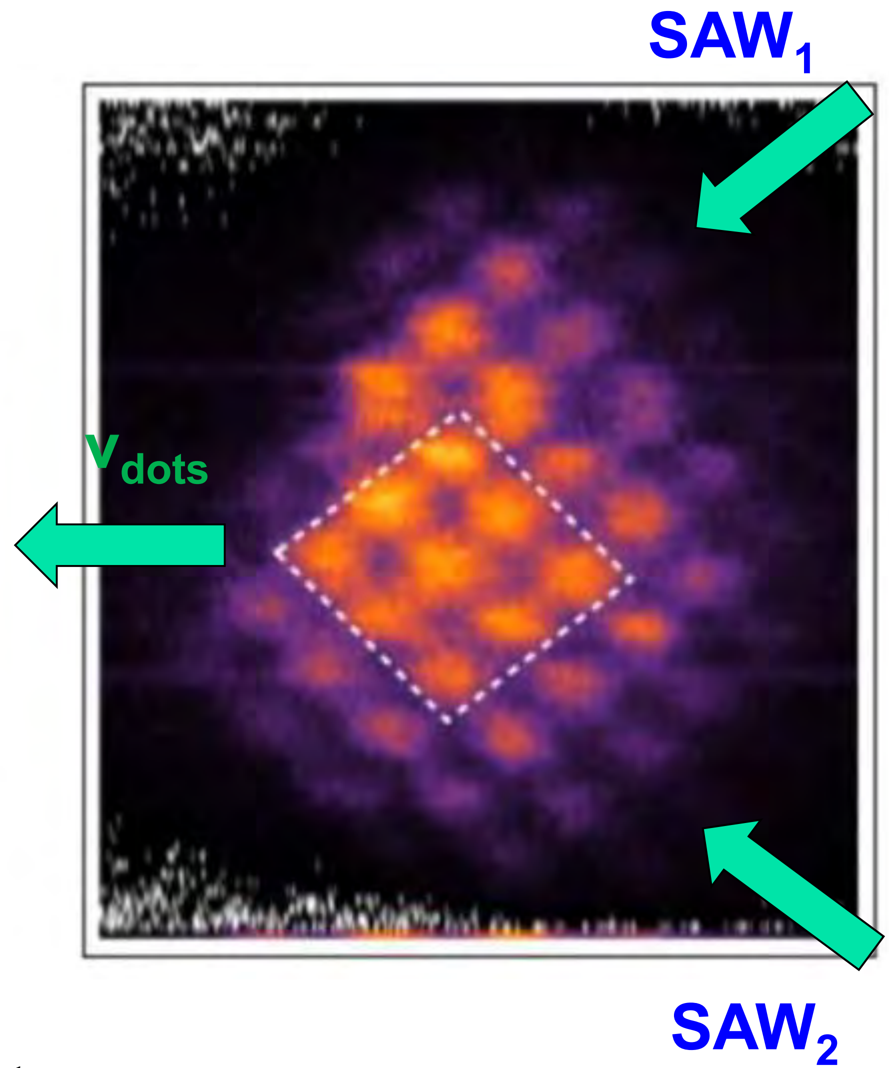
Polariton condensation
- long temporal coherence (100’ s ps)
- tunable spatial coherence

E. Cerda et al., Phys. Rev. Lett.105, 116402 (10)

Imaging dot condensates

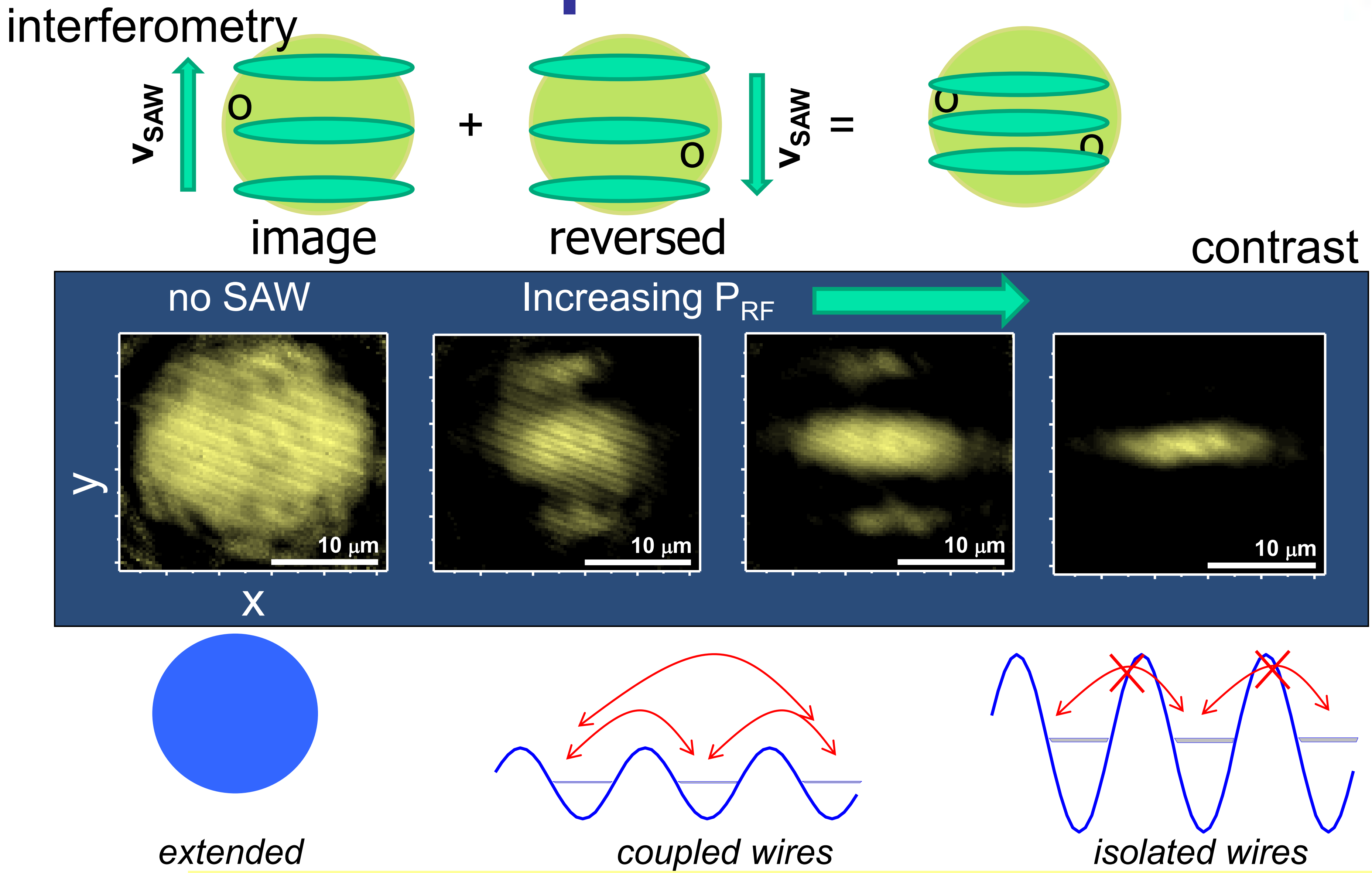
- Square lattice: 8 μm
- Time-resolved PL





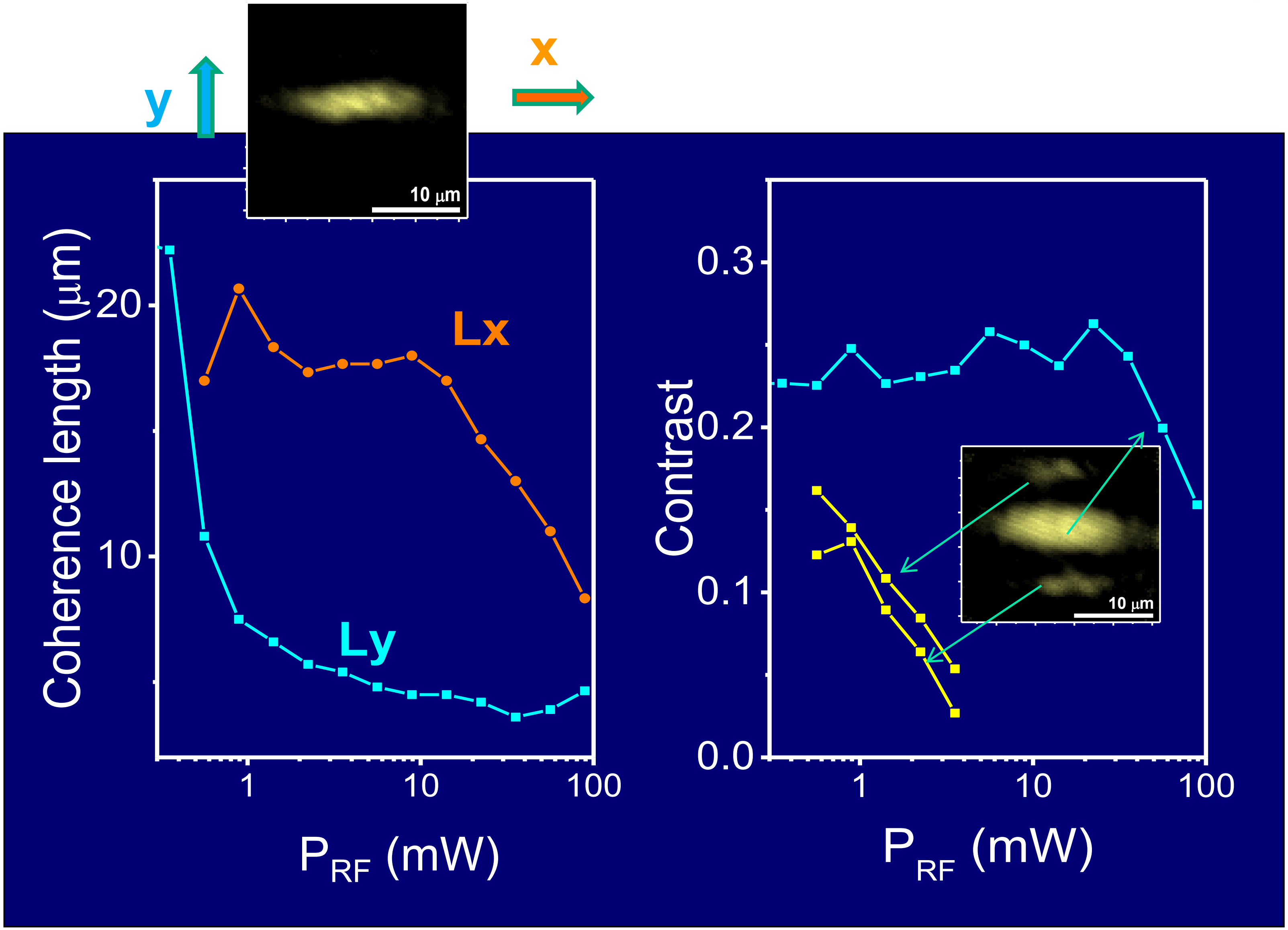
- homogeneity
  - gaussian laser profile
- no transport of coherence!
  - condensate coherence time (~150 ps) << SAW period (3 ns)

Tunable spatial coherence



Acoustic tunability: controlled interaction between neighboring sites!

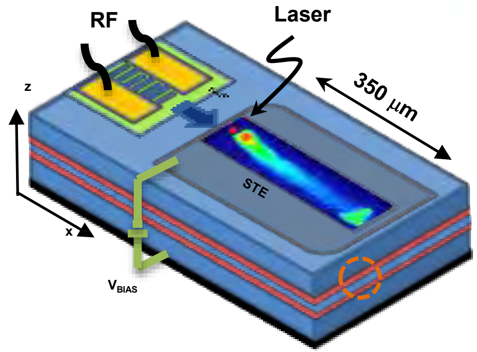
Coherence control

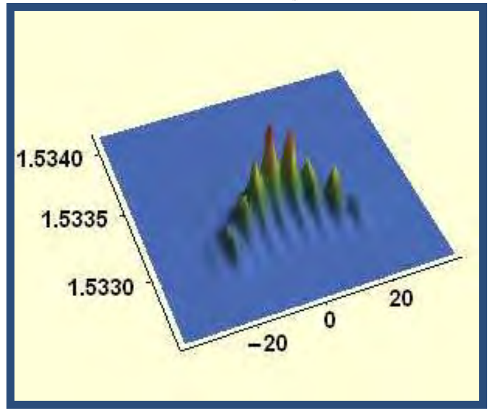


E. Cerda et al., NJP14 075011 (12)

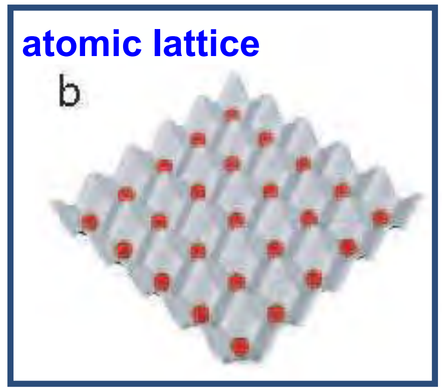
Summary and outlook

- Acoustic manipulation of excitonic structures
  - storage and long-range transport of excitons as well-defined packets
  - optical control of microcavity polaritons
    - tunable photonic/polaritonic crystal
    - control coherence length



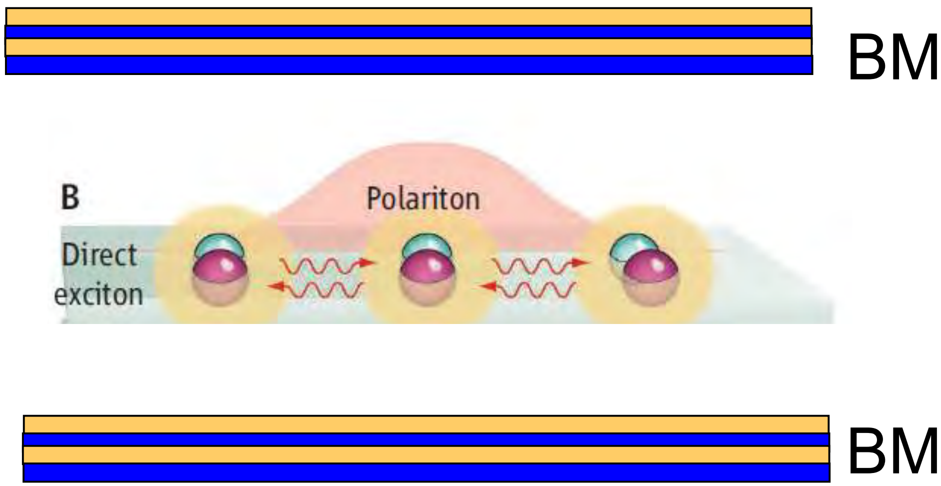


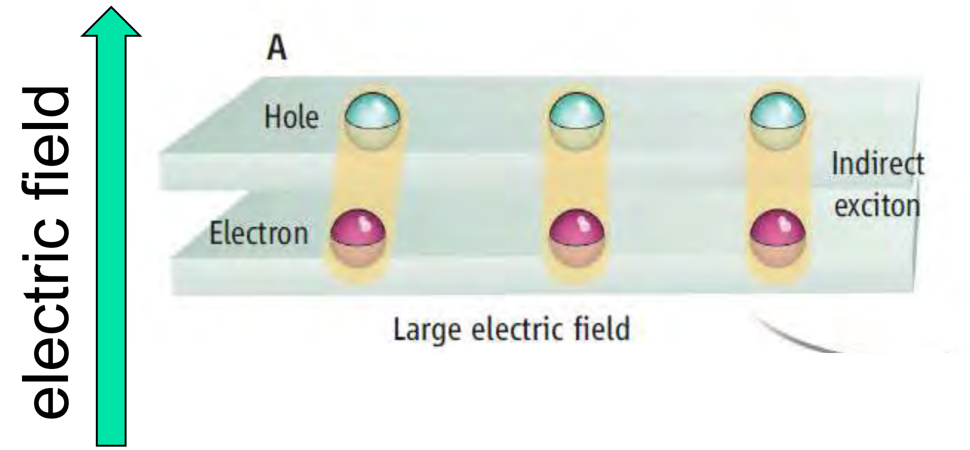
- **Future perspectives**
  - single IX transport
  - polariton condensates
    - explore analogy with atomic optical lattices
      - Josephson oscillations, polariton blockade
  - IX-polariton interconversion



Treutlein et al., Fortschr. der Physik 54, 701 (06)

SAW-modulated excitons





- Polaritons
  - strong coupling to photons
  - controllable coherence in acoustic lattices
- Indirect excitons
  - long lifetimes
  - long-range transport by SAWs

Interconversion: polariton ↔ IX

Shahnazaryan, PRB91, 85302 (15)
Szymanska, Science 336, 679 (12)