Coupling of Light-Sound-Matter: Dynamic acoustic control of single and coupled optically active nanosystems

Hubert J. Krenner

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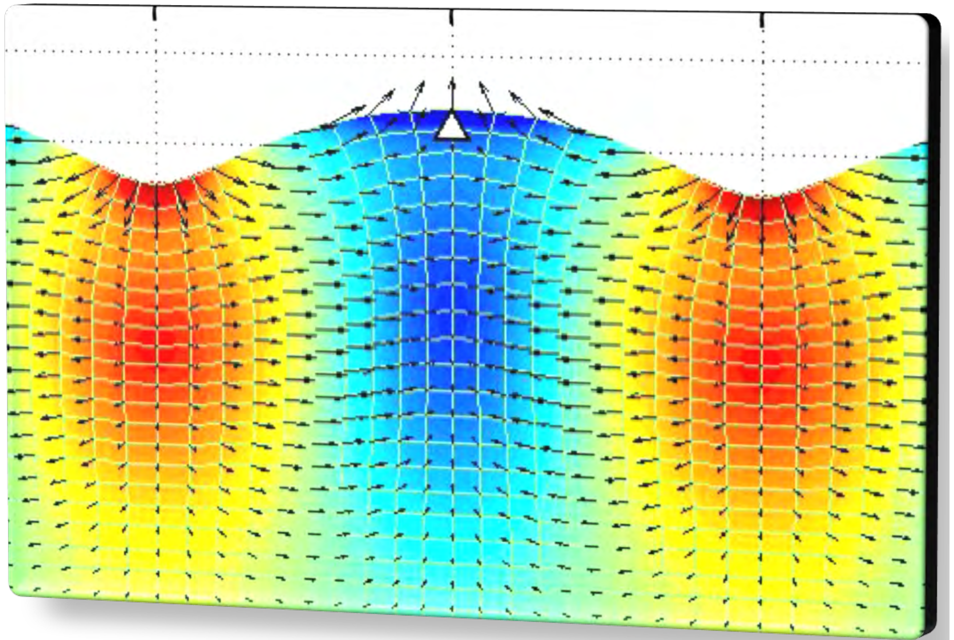

EXP1

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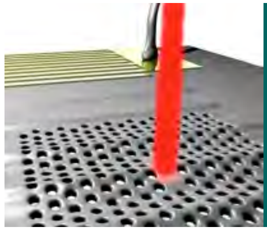
Experimentalphysik I

SFB 631

SAWtrain
network

nim
nanosystems initiative munich

Emmy
Noether-
Programm
Deutsche
Forschungsgemeinschaft
DFG



Surface acoustic waves – fundamentals

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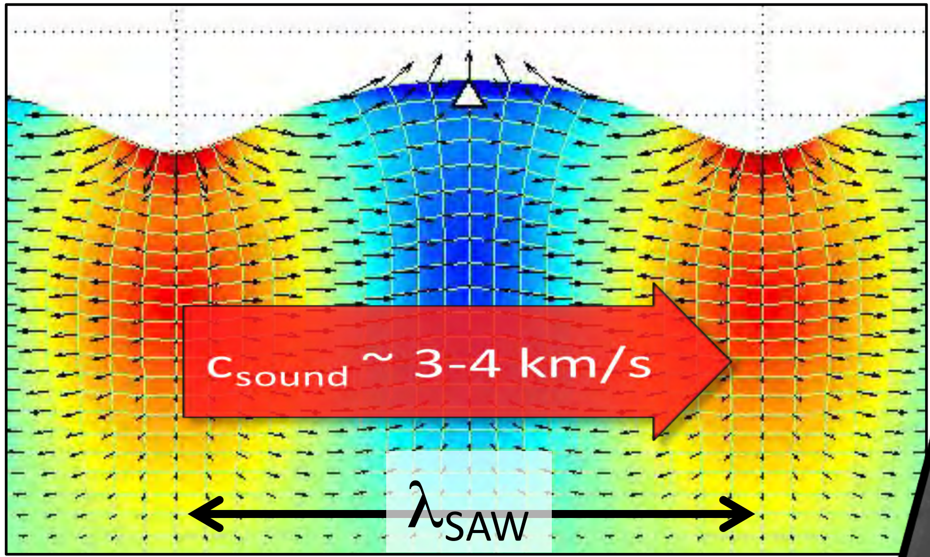
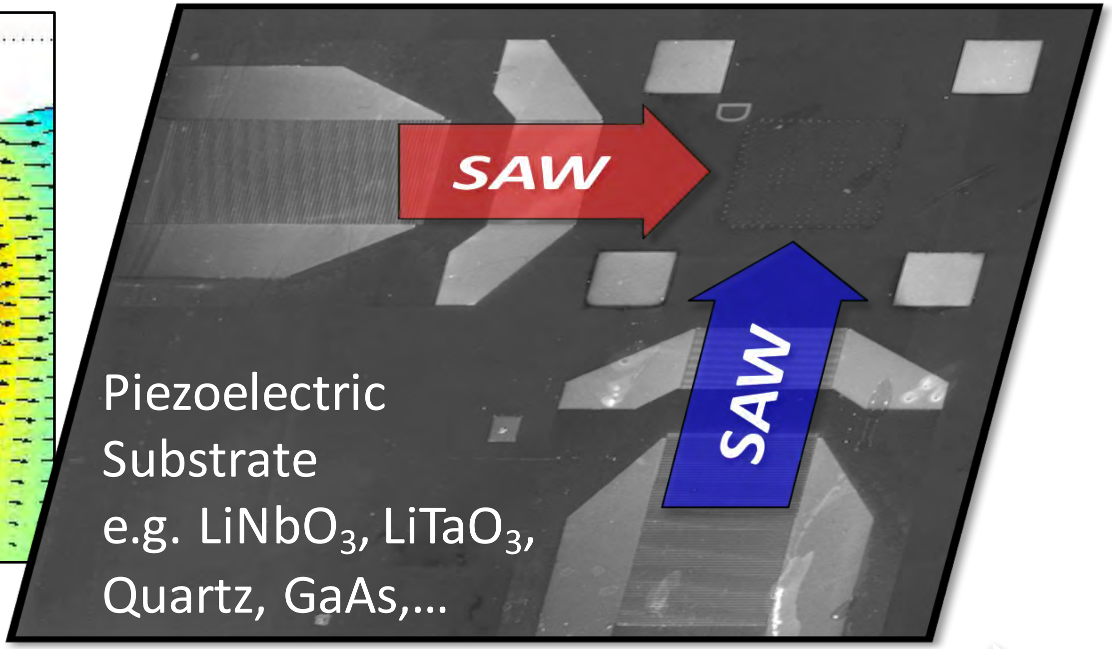
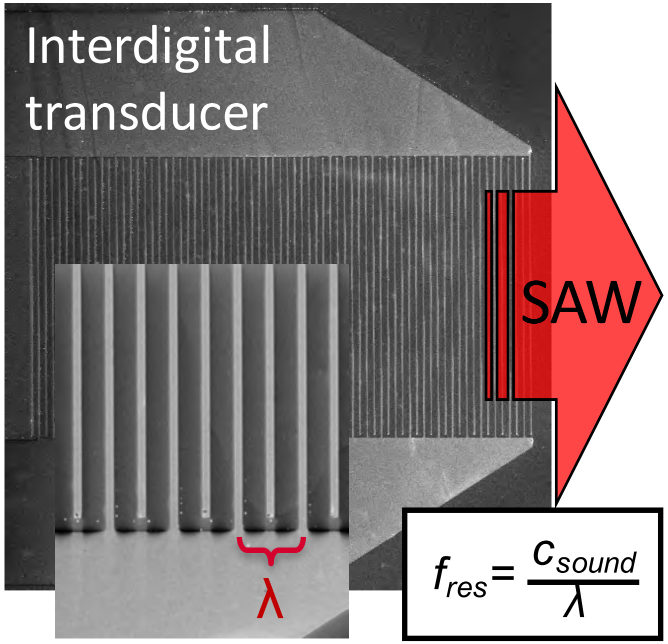
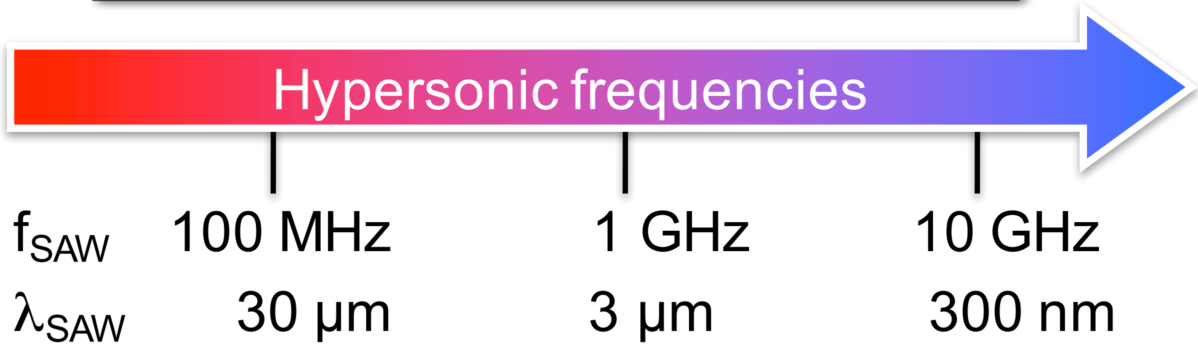
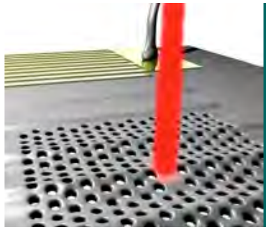








Coherent propagating phonon field to control and probe nanosystems at hypersonic frequencies



Surface Acoustic Waves interfacing quantum nanosystems

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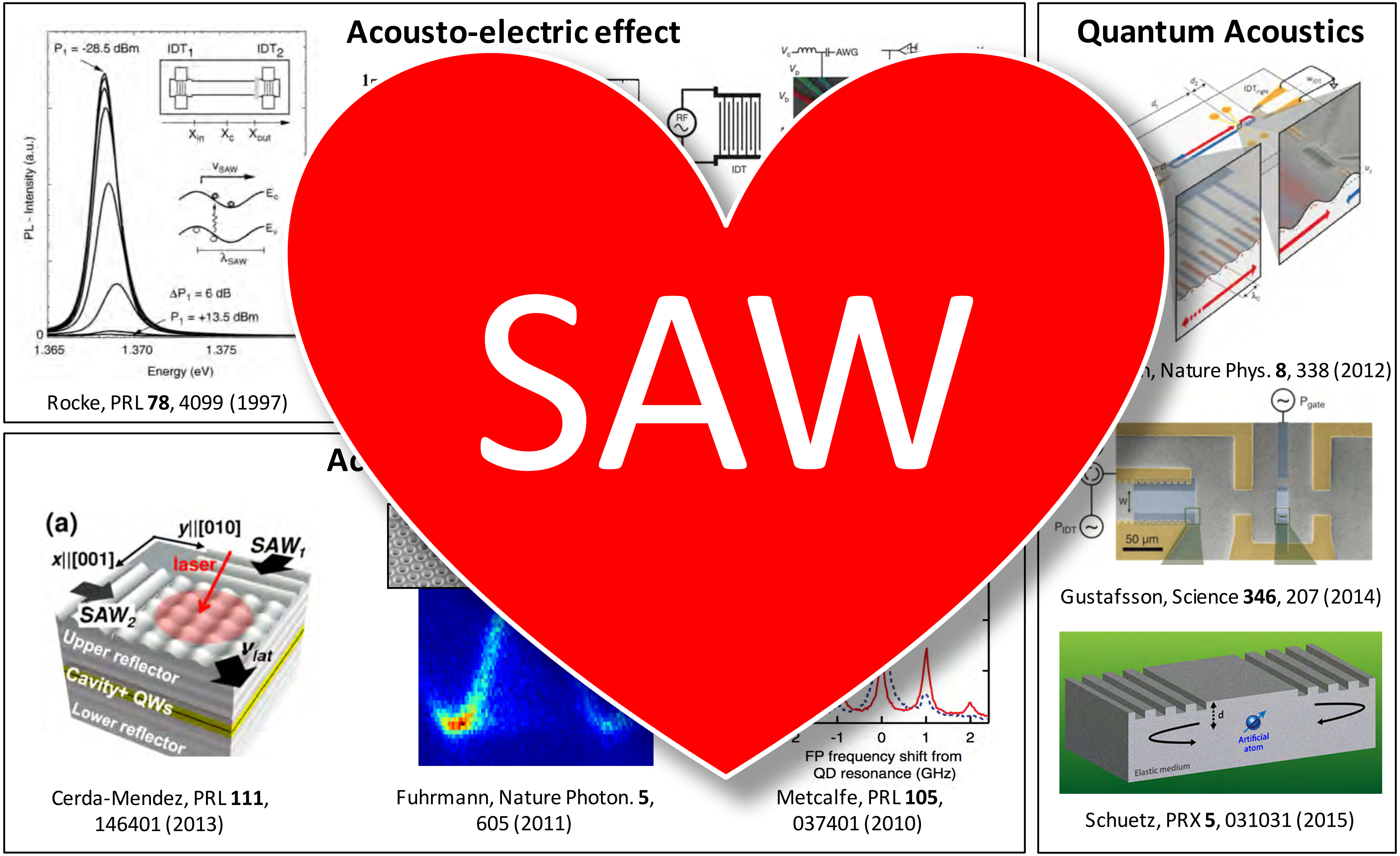
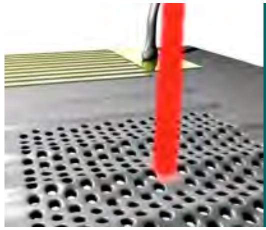
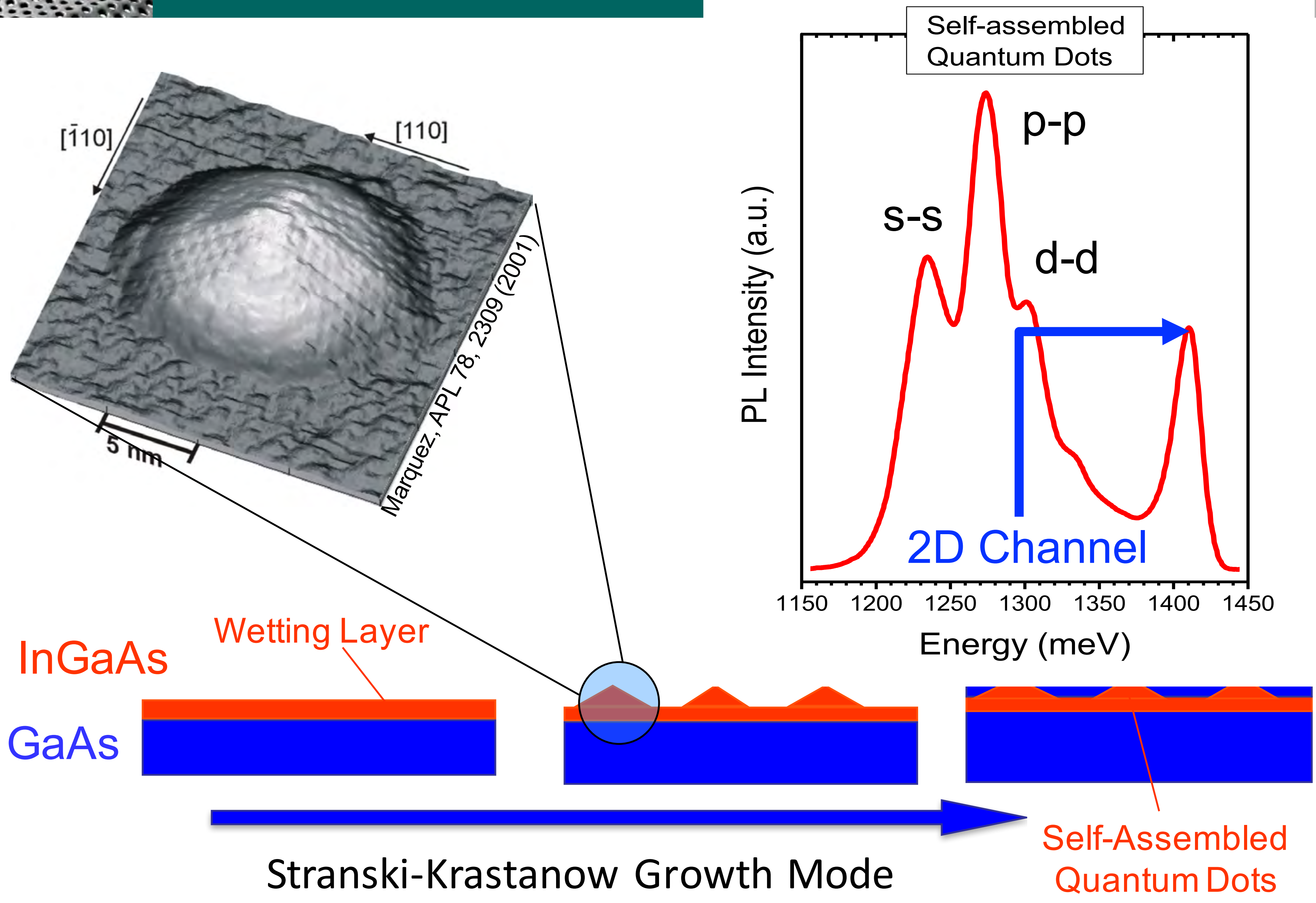
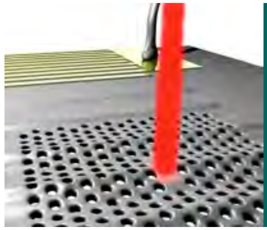


Self assembled QD nanostructures







Single dot PL with weak excitation

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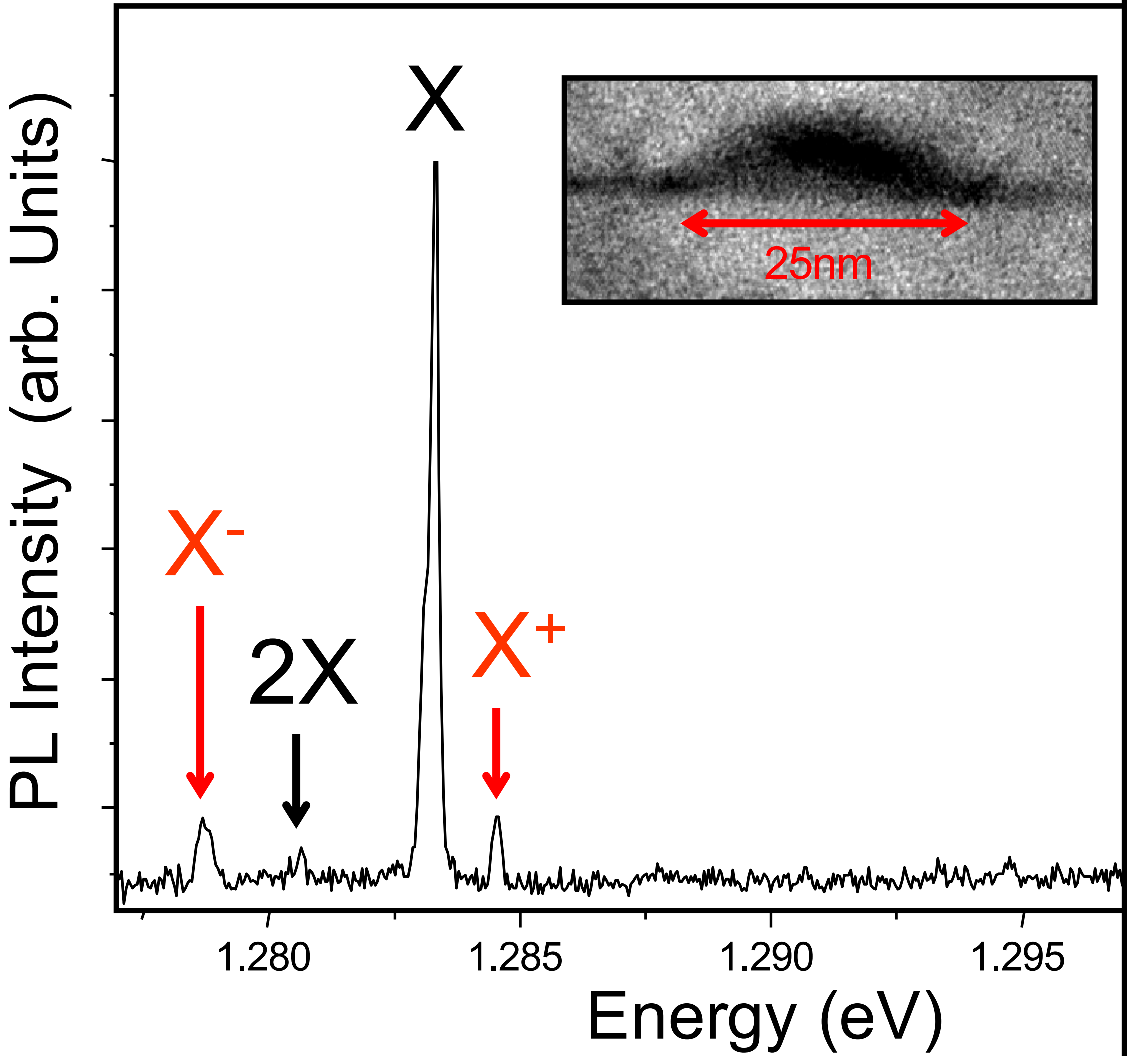
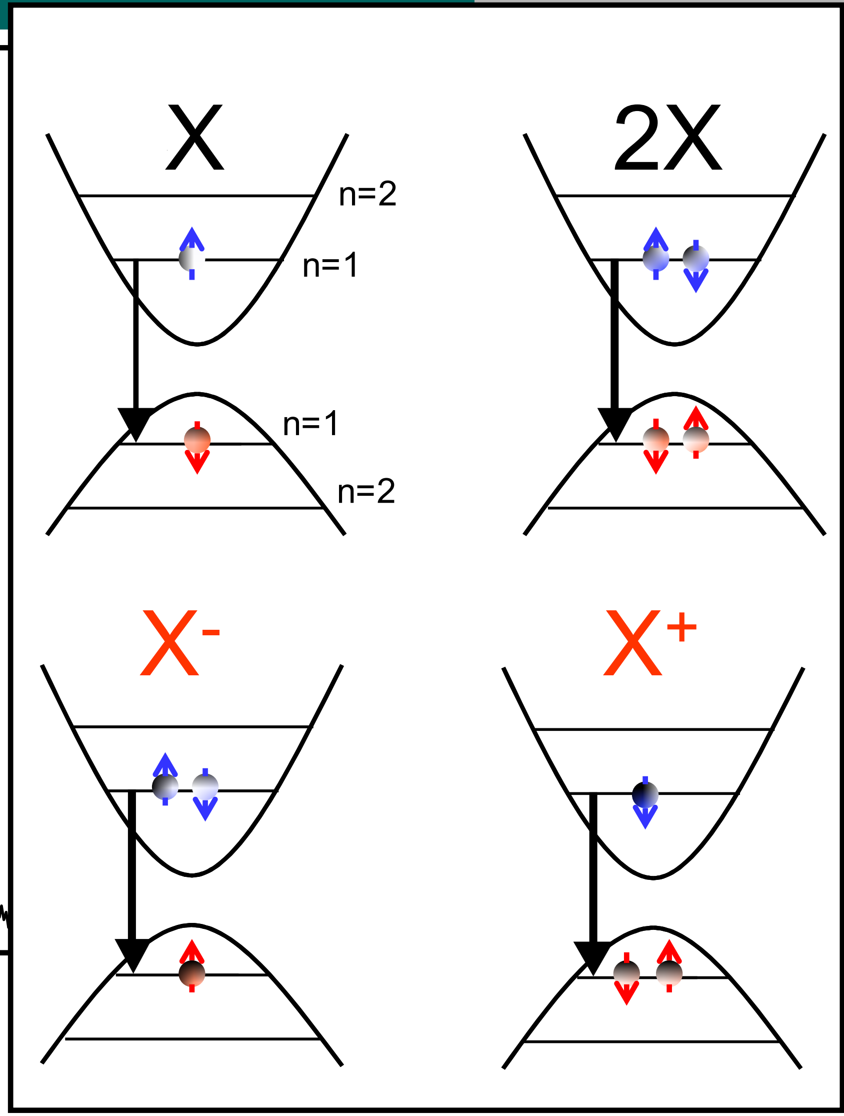
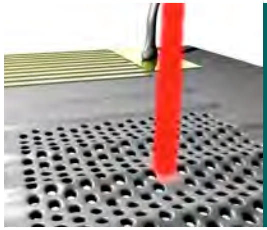


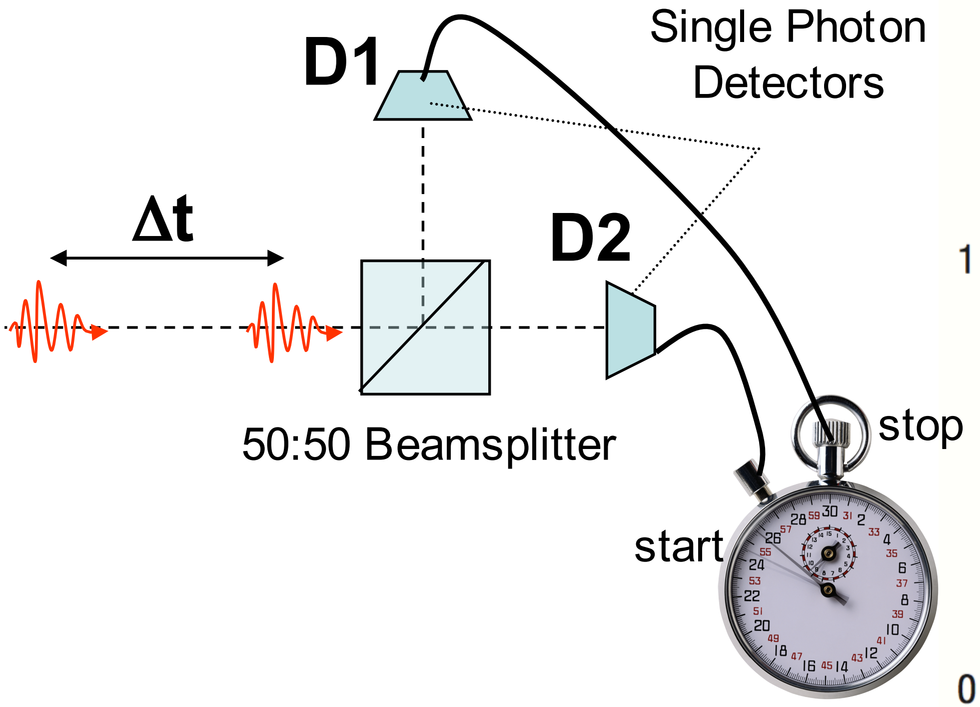


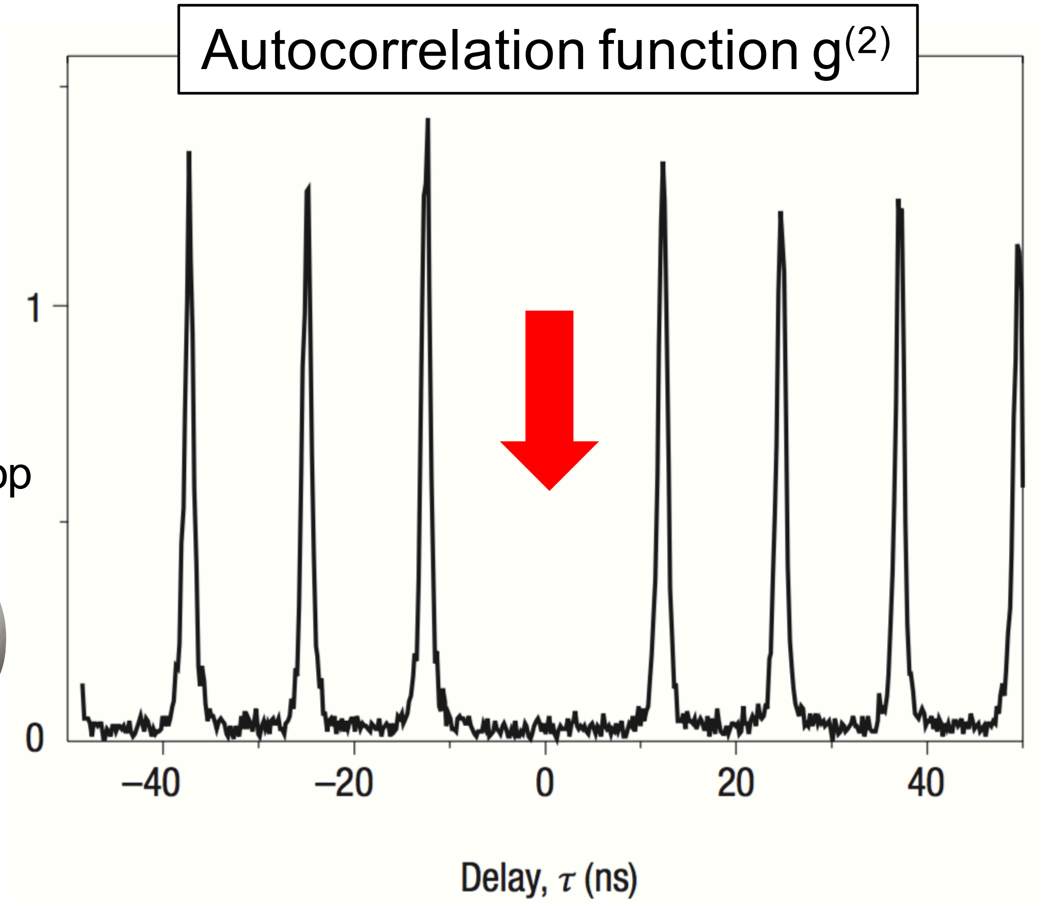
Charged excitons (Trions) e.g. X^- = singlet-electrons + 3/2 hole

Studied by many groups over the past >20 years



Single photon emission



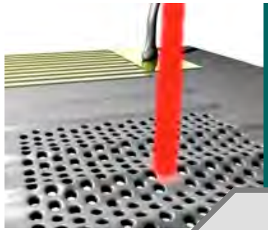


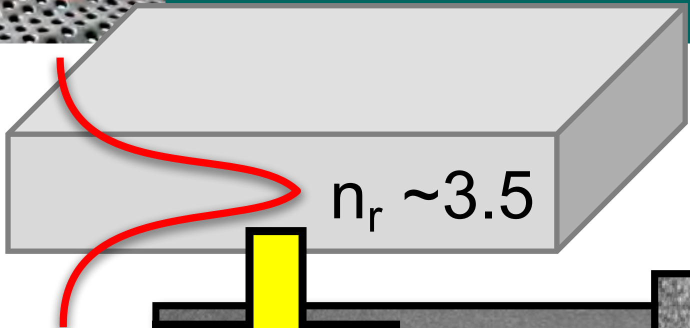
Hanbury Brown & Twiss (HBT) Photon Correlation Measurement

Missing peak at t=0s
Indicative for single photon emission

P. Michler *et al.* – Science **290,** 2282 (2000)
C. Santori *et al.* – Phys. Rev. Lett. **86,** 1502 (2000)
A. Shields – Nat. Photonics **1**, 215 (2007)

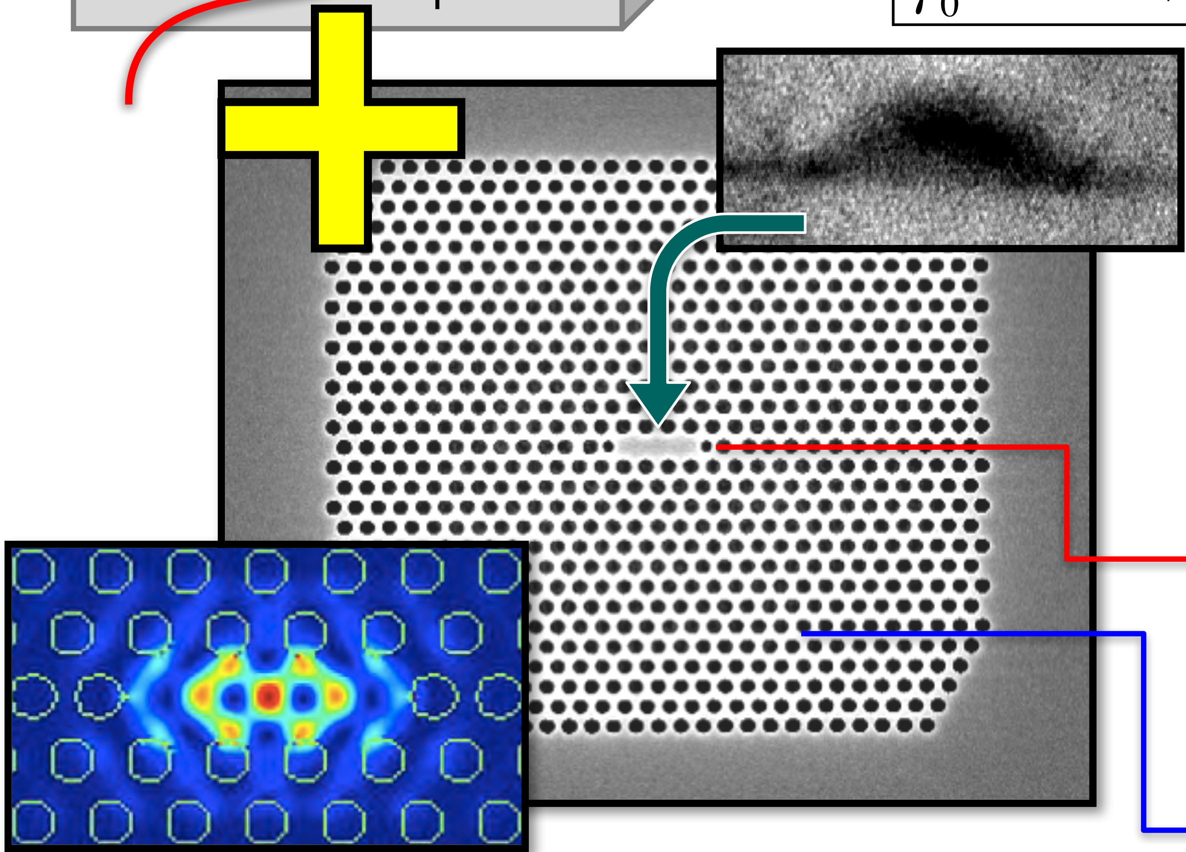
2-D photonic crystal membranes

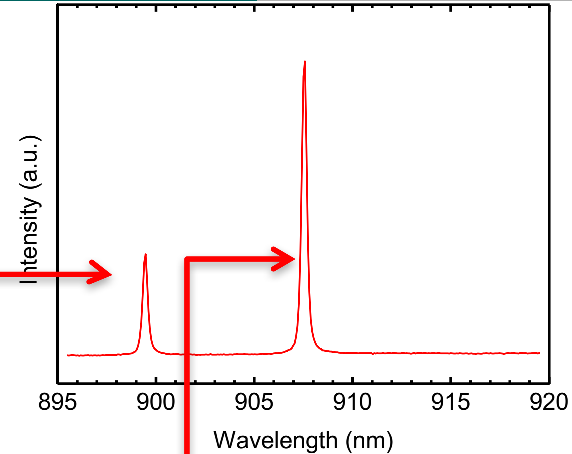


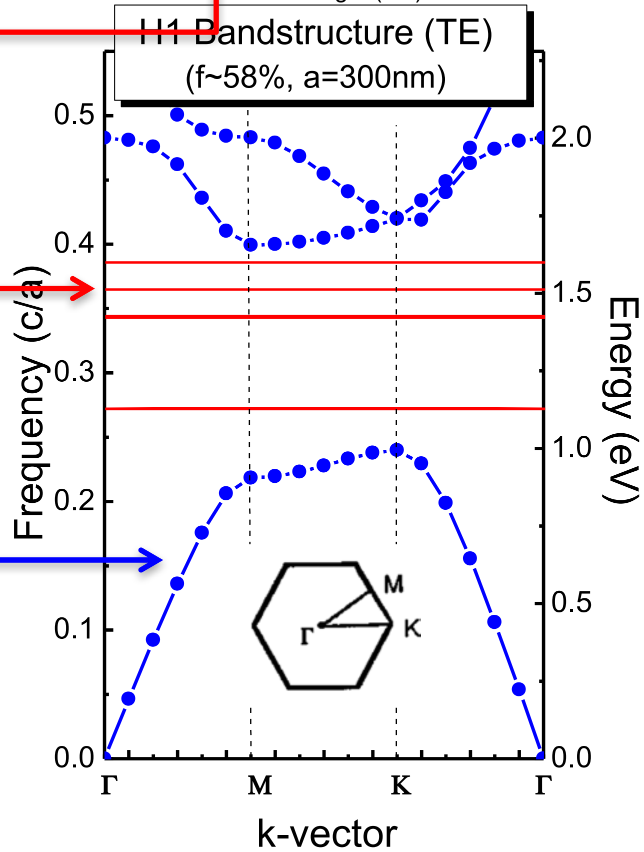


Purcell Factor

$$\frac{\gamma}{\gamma_0} \propto \frac{Q\cdot(\lambda/n)^3}{V}$$



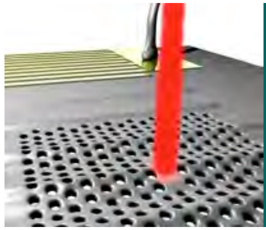




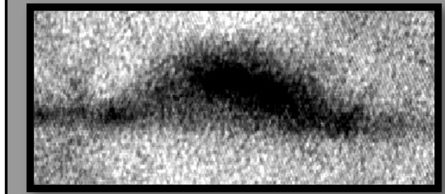
Three-dimensional confinement of light

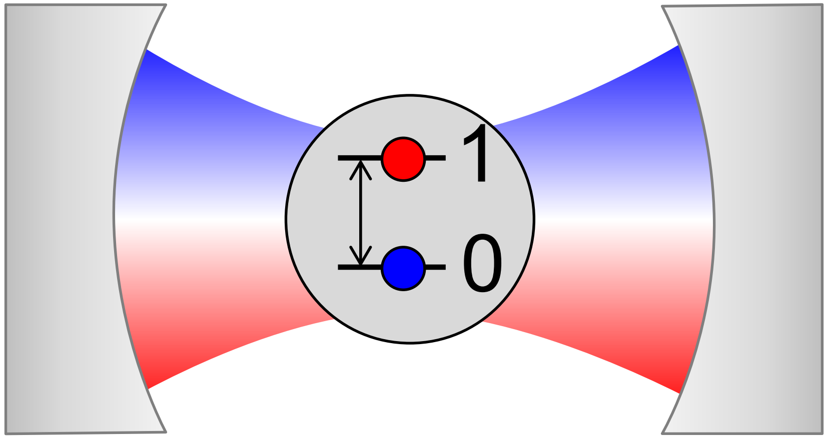
Confined optical modes with

- high quality factors
- small mode volumes

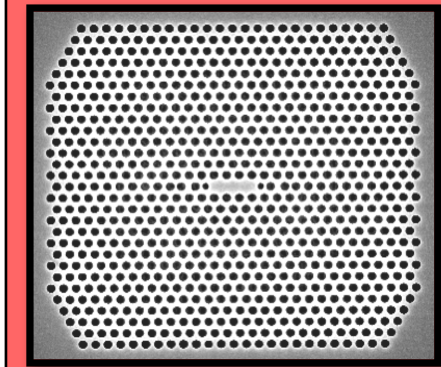


Exciton in Quantum Dot

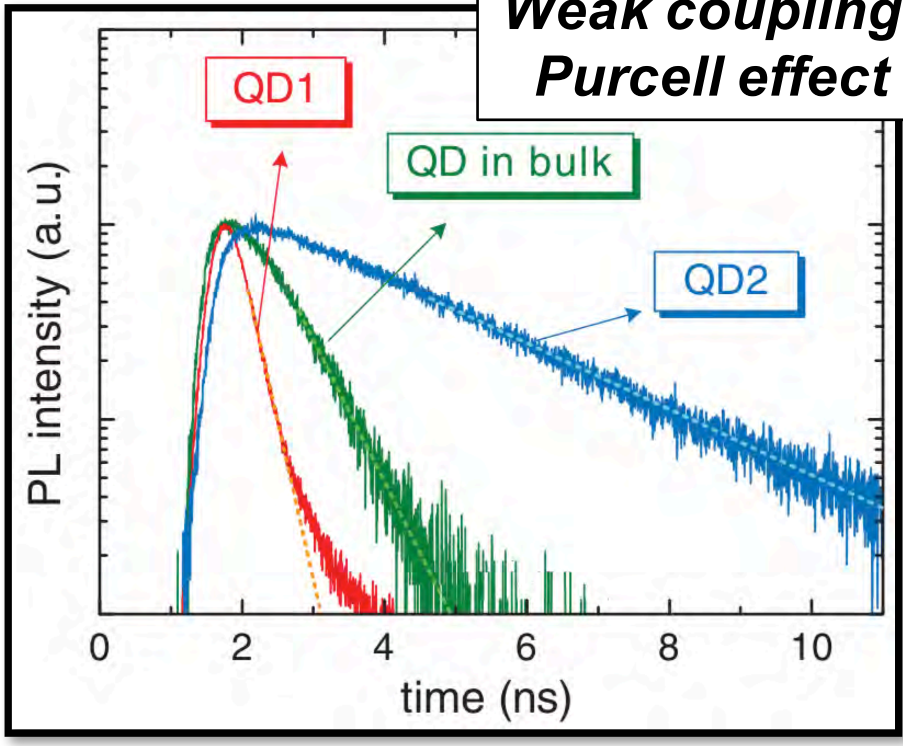




Photonic crystal cavity



Weak coupling: Purcell effect



Chang et al., Phys. Rev. Lett. 96, 117401 (2006)

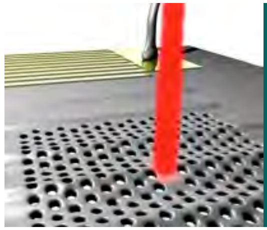
Radiative lifetime of QD in bulk ~ 1 ns – rate ~ 1 GHz

Purcell effect leads to fast single photon emission

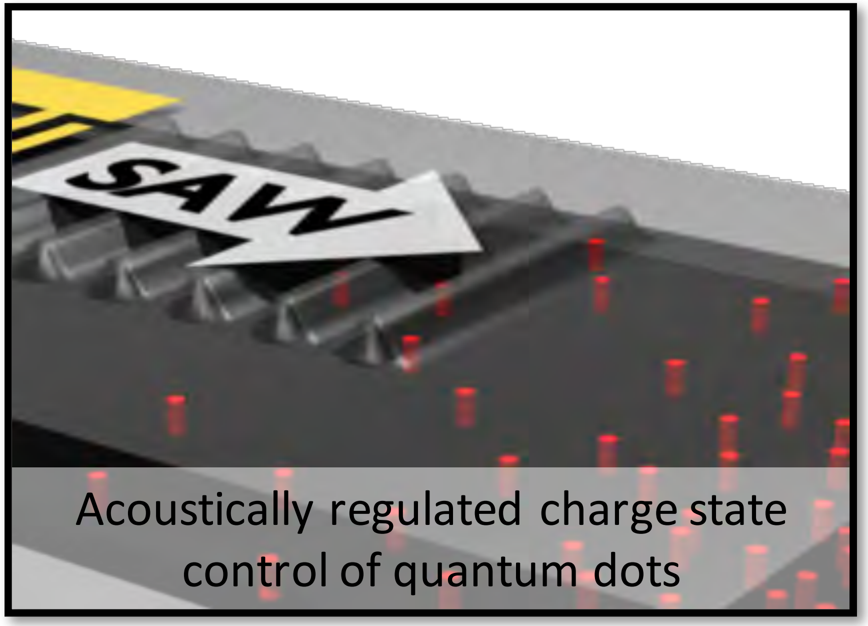
$$\frac{\gamma}{\gamma_0} \propto \frac{Q \cdot (\lambda/n)^3}{V}$$

Cavity with high Q/V required

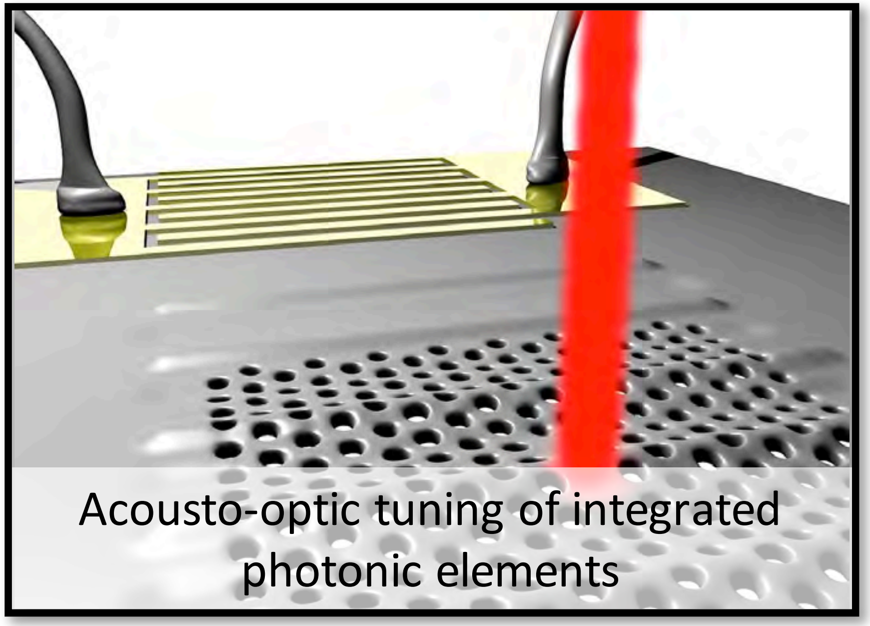
Thon et al., APL 94, 111115 (2009)



Outline

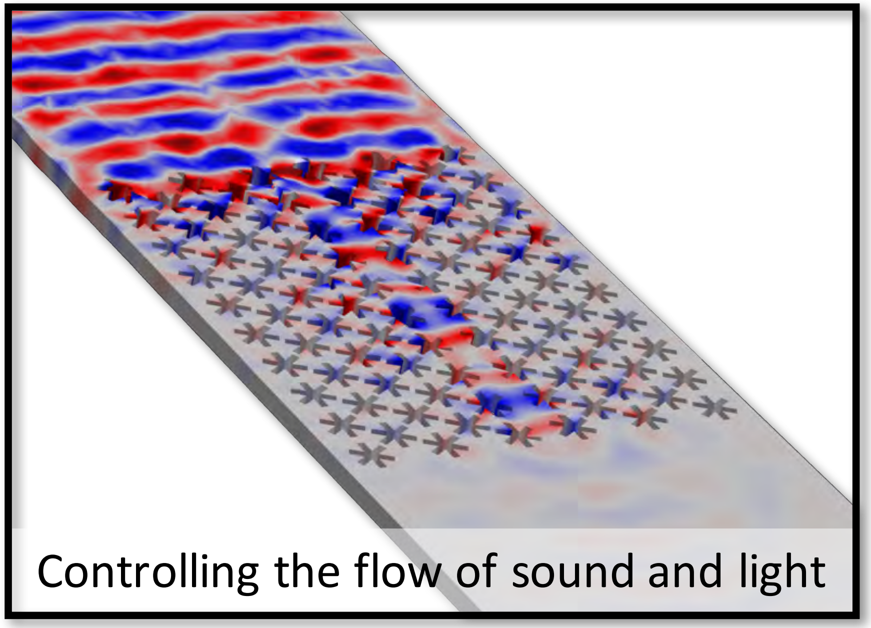


Acoustically regulated charge state control of quantum dots

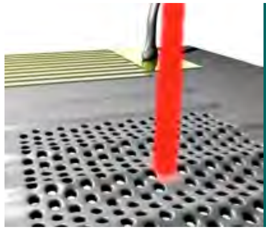


Acousto-optic tuning of integrated photonic elements

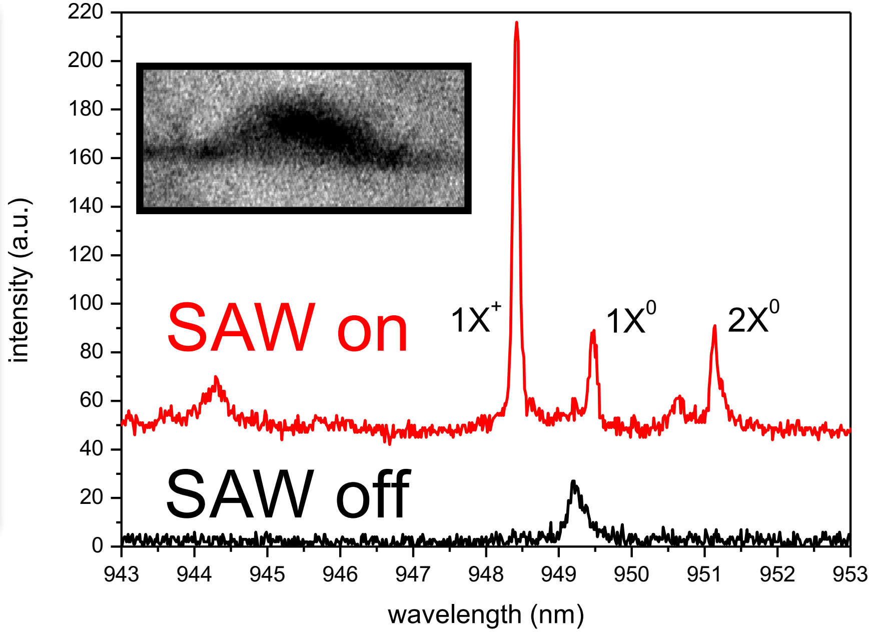
Nanomechanical pulse shaper



Controlling the flow of sound and light



Dynamic acoustic control of the occupancy state of single optically active quantum dots



S. Völk et al., Nano Lett. **10**, 3399 (2010)

Sample growth:

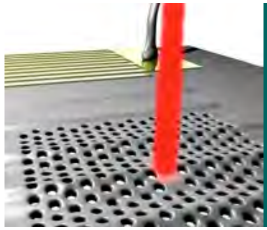
Gregor Koblmüller, Kai Müller, Jonathan Finley,
Walter Schottky Institut, TU München

Pierre Petroff
UC Santa Barbara

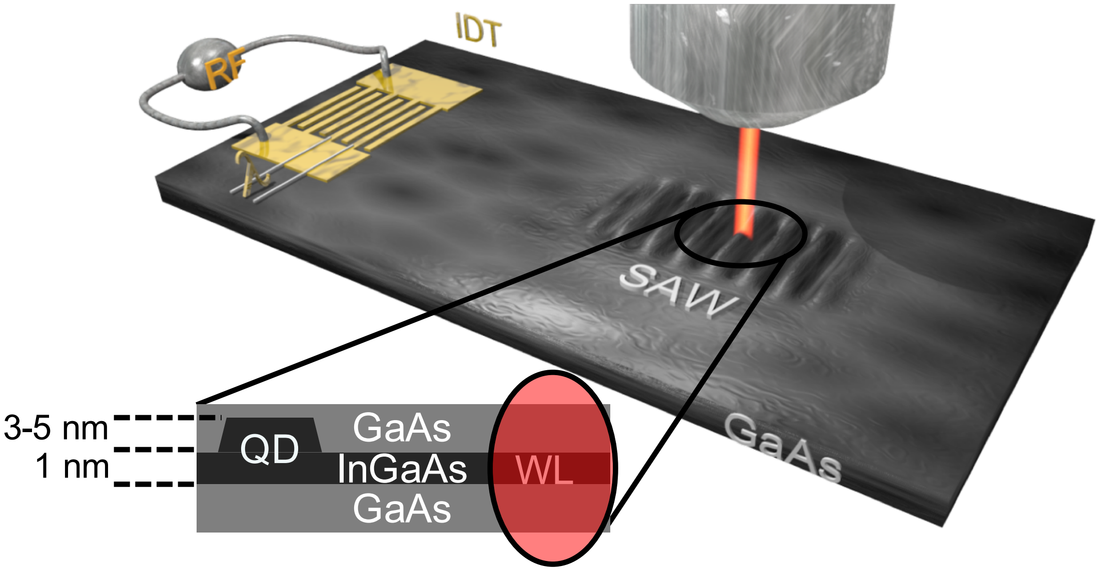
Andreas Wieck, Dirk Reuter
Ruhruniversität Bochum

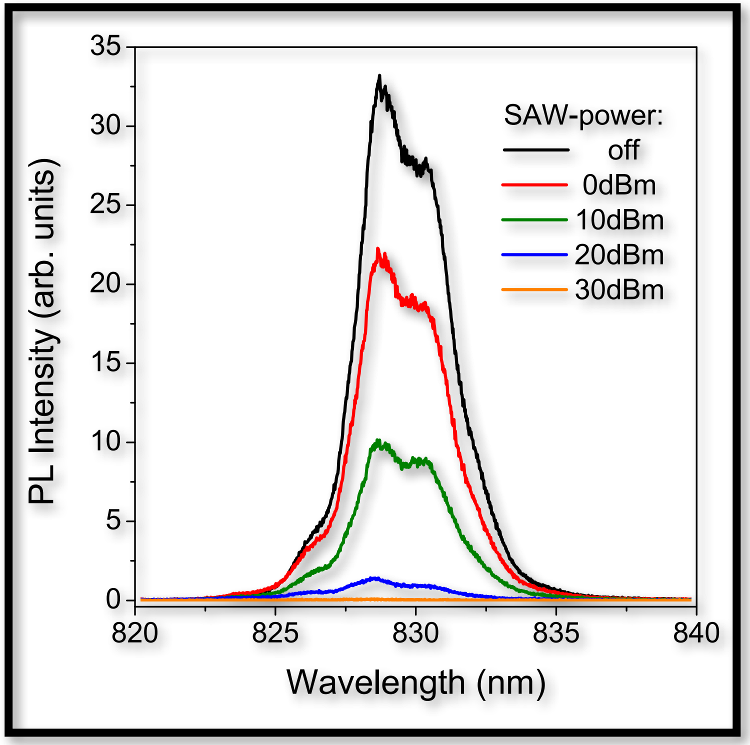
Florian Schülein

Matthias Weiß

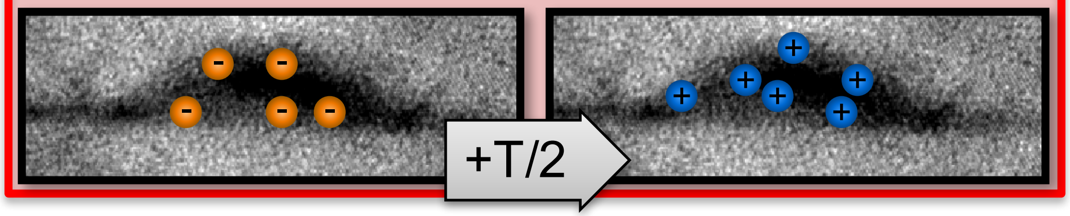


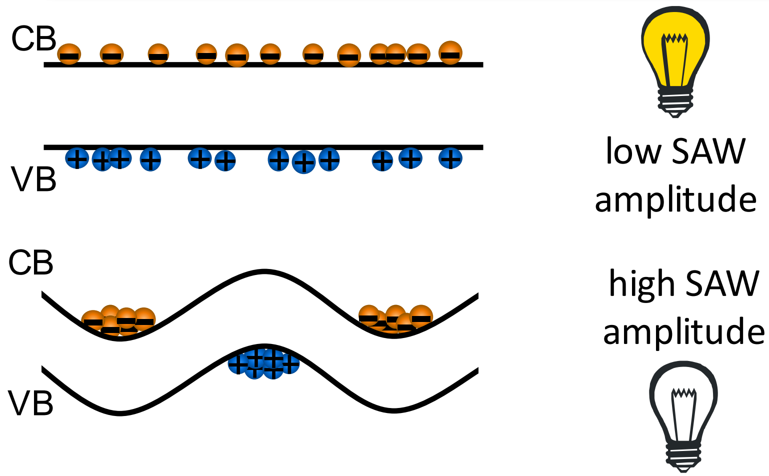
SAW-induced conveyance of electrons and holes



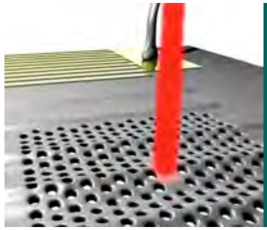


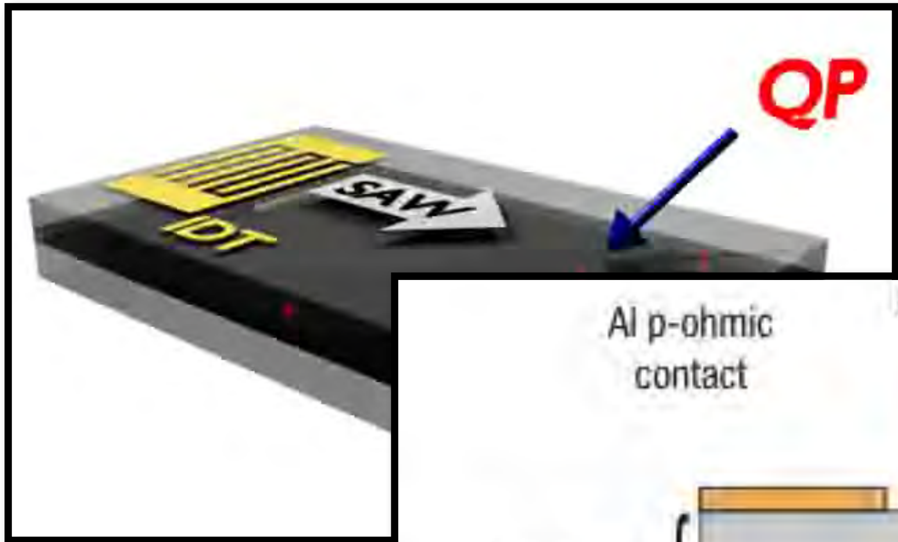
Precise, SAW-regulated & **inherently sequential** carrier injection



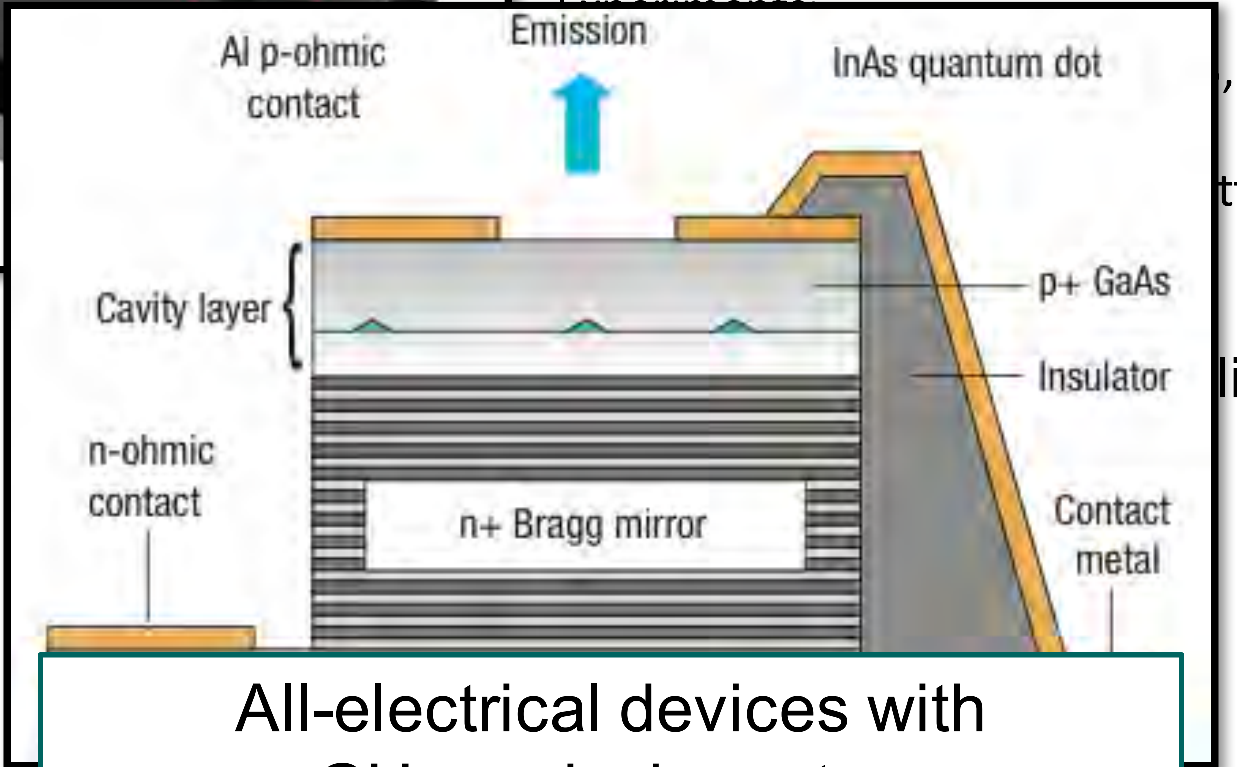


C. Rocke *et al.*, Phys. Rev. Lett. **78,** 4099 (1997)





Proposal by A. Wixforth and F. Haake:
Acoustically regulated single photon source
C. Wiele *et al.*, Phys. Rev. A **58**, R2680 (1998)



, 645 (2009)

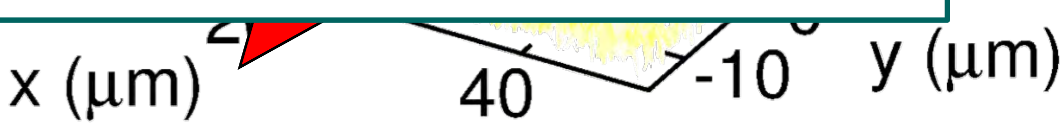
tt. **12**, 252 (2012)

light out

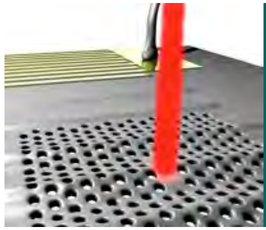
All-electrical devices with
GHz emission rates

Planar heterostr

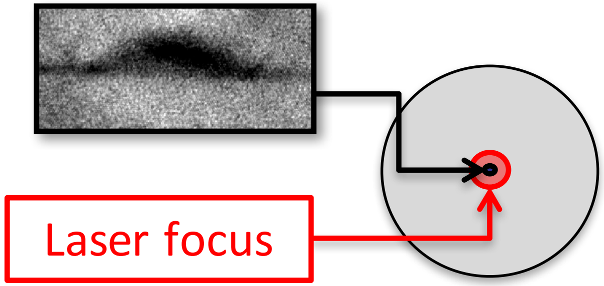
quantum post



Völk et al., Nanotechnology **23**, 285201 (2012)

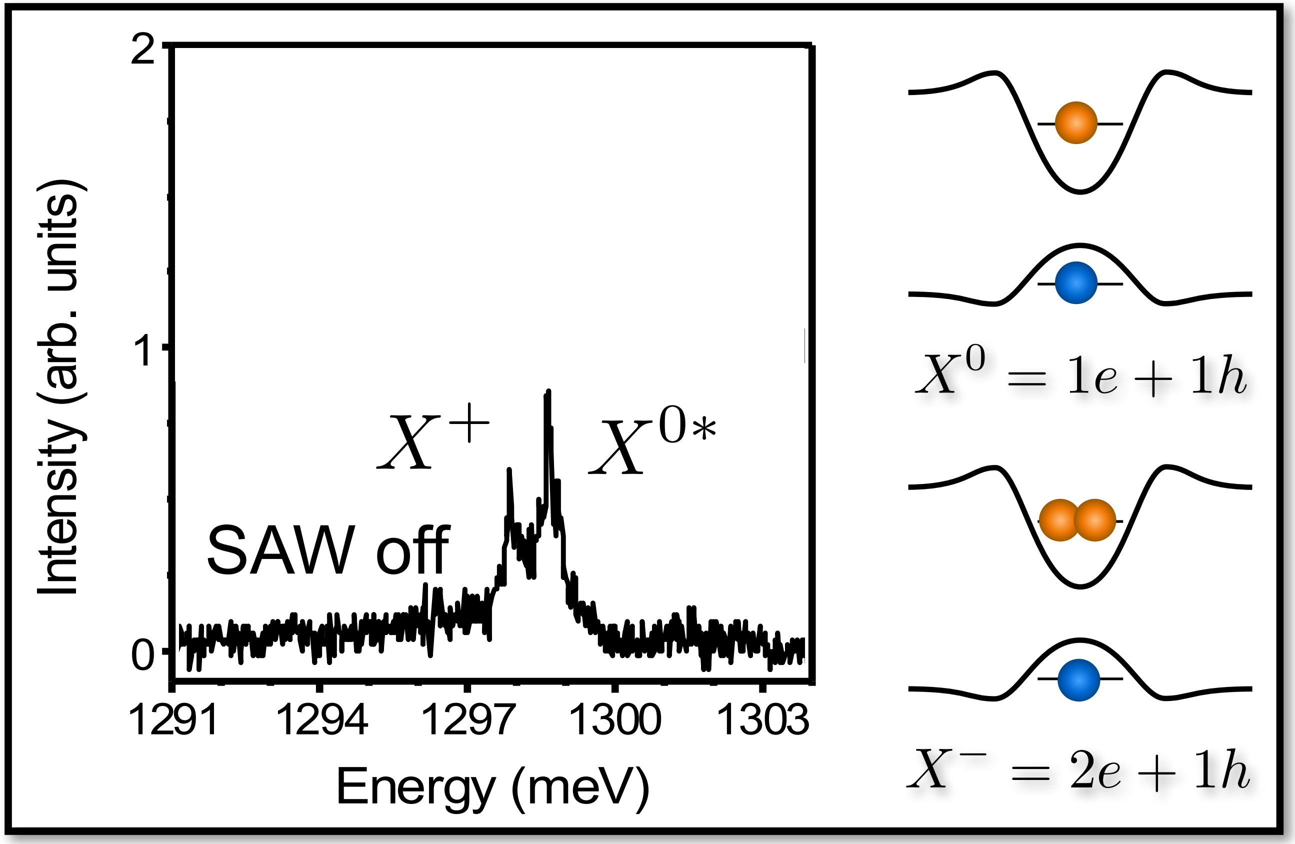


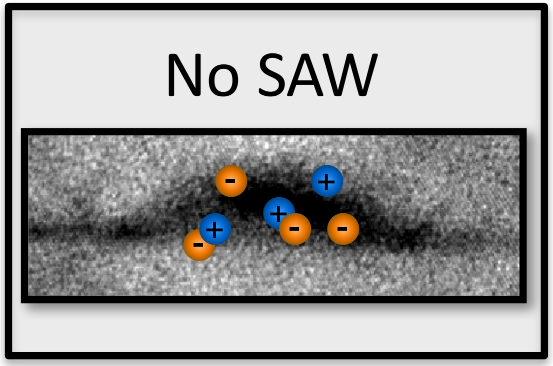
SAW-programming of QD excitonic occupancy state

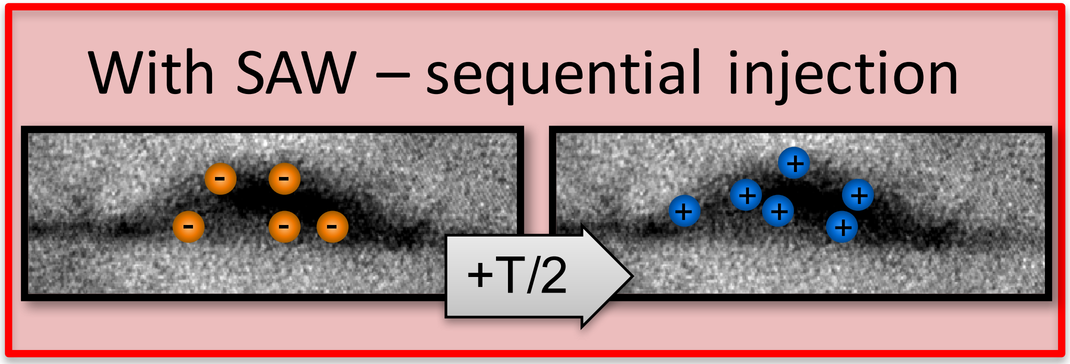


Direct excitation: QD **and** laser focus

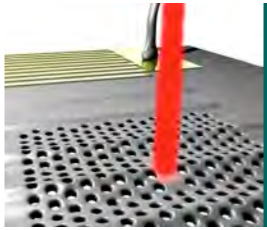
f_{SAW} = 240 MHz
$T_{SAW}/4$ = 1.05 ns
λ_{SAW} = 12 µm
P_{RF} = +28 dBm







S. Völk et al., Nano Lett. **10**, 3399 (2010)



Occupancy state programming – time integrated experiments

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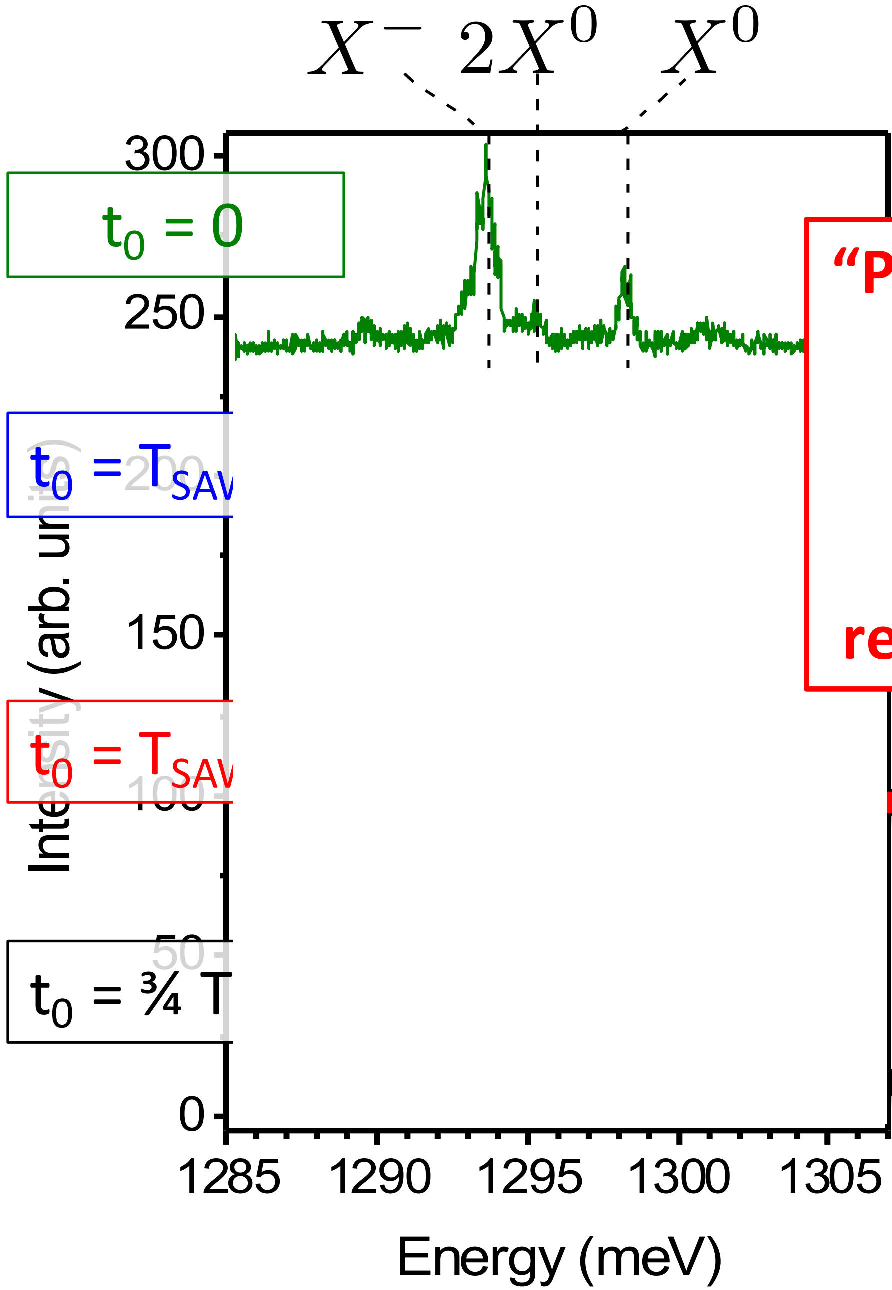
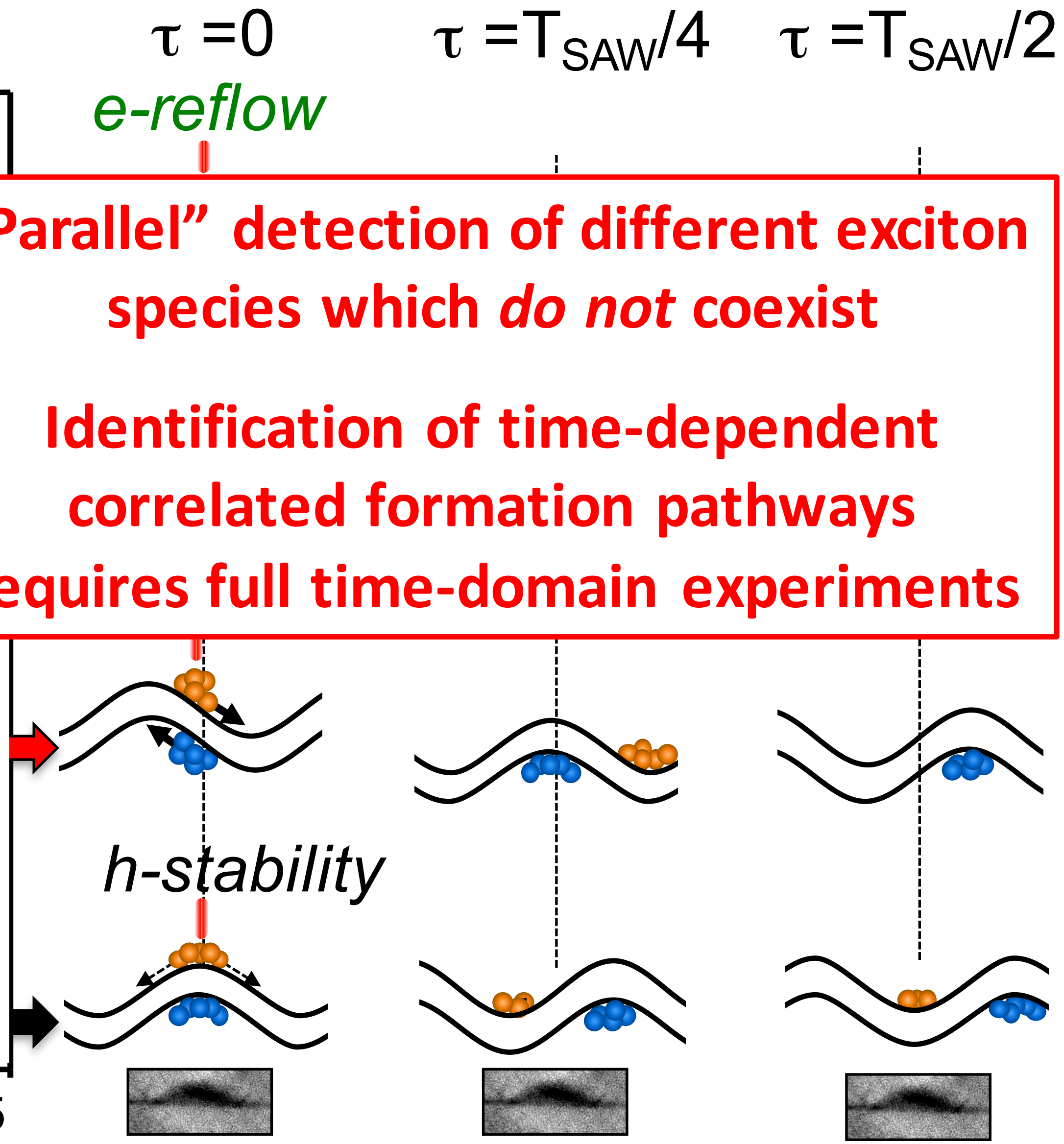
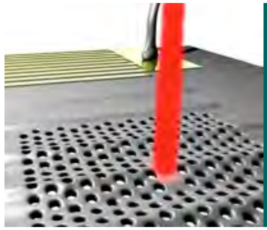




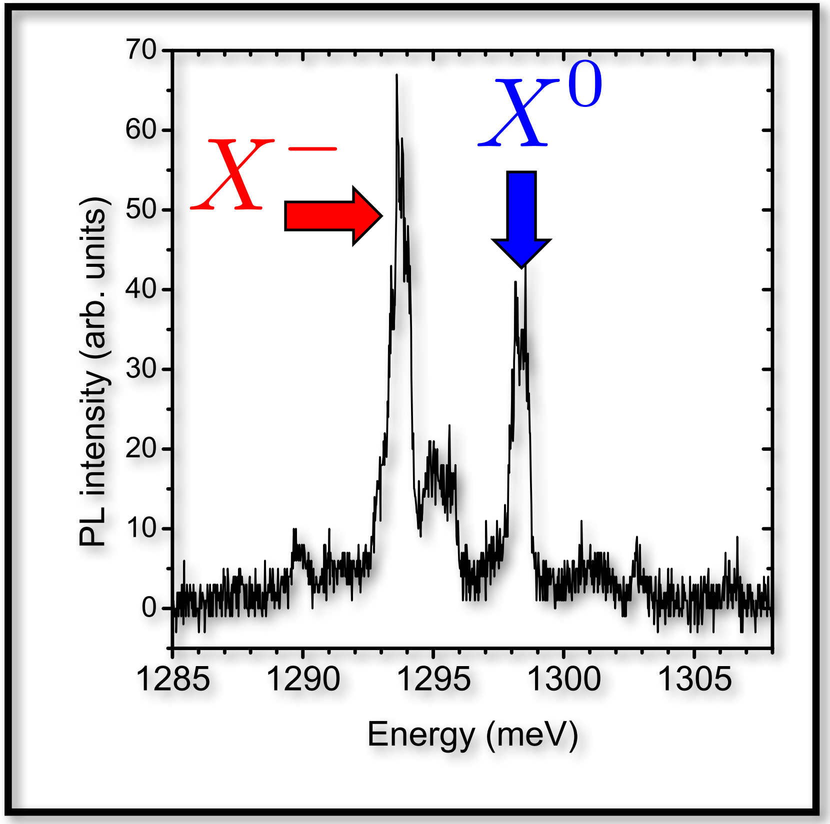
"Parallel" detection of different exciton species which *do not* coexist

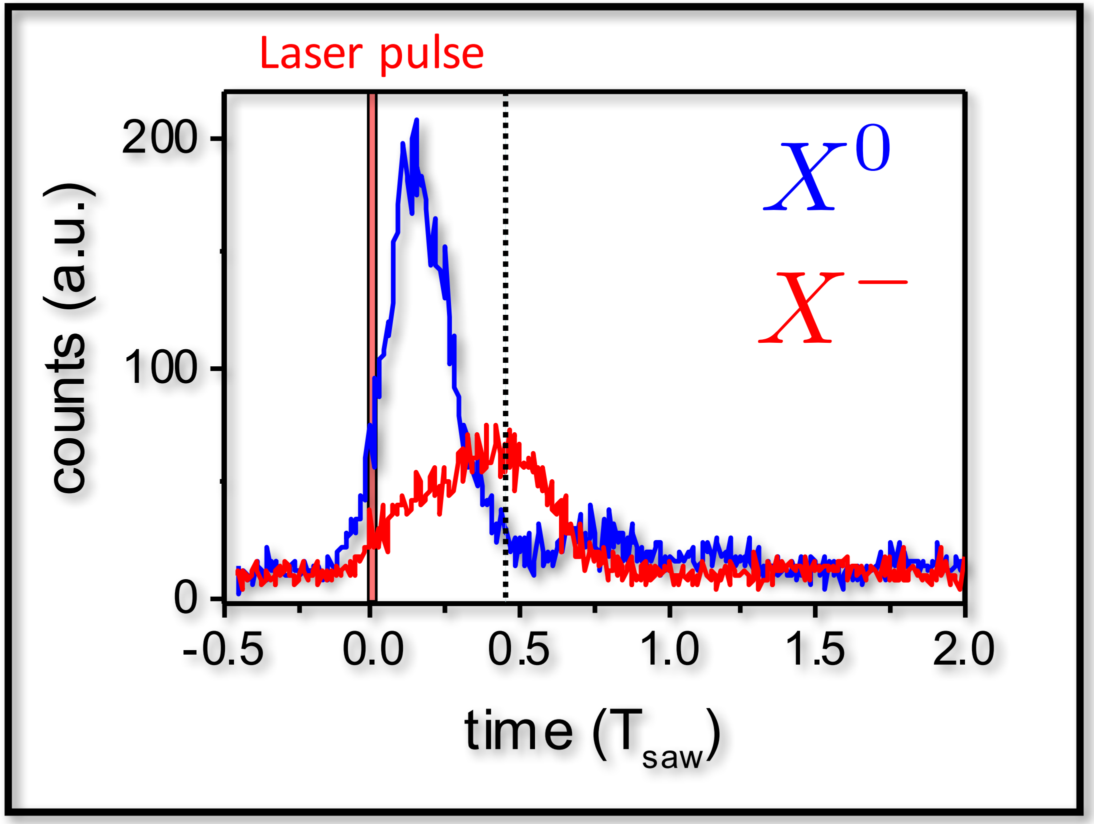
Identification of time-dependent correlated formation pathways requires full time-domain experiments

QDs in NWs: M. Weiß et al., J. Phys. D. **47**, 394011 (2014)

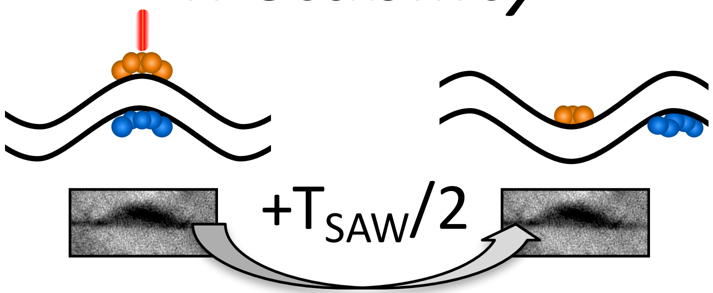


Time-resolved detection at *h-stability*





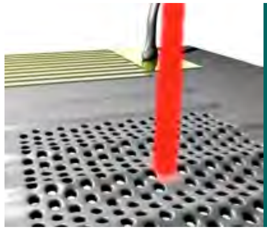
h-stability

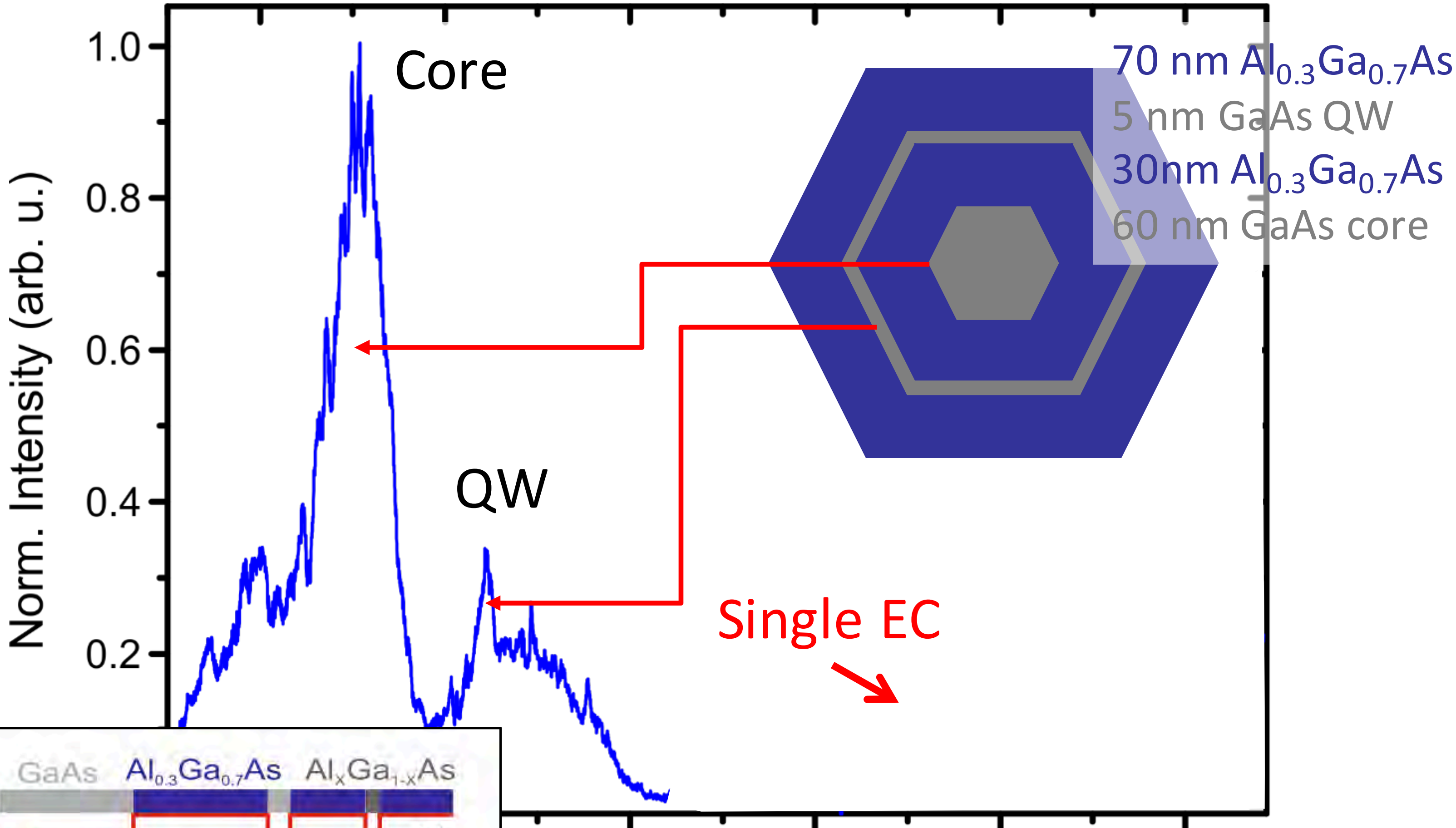


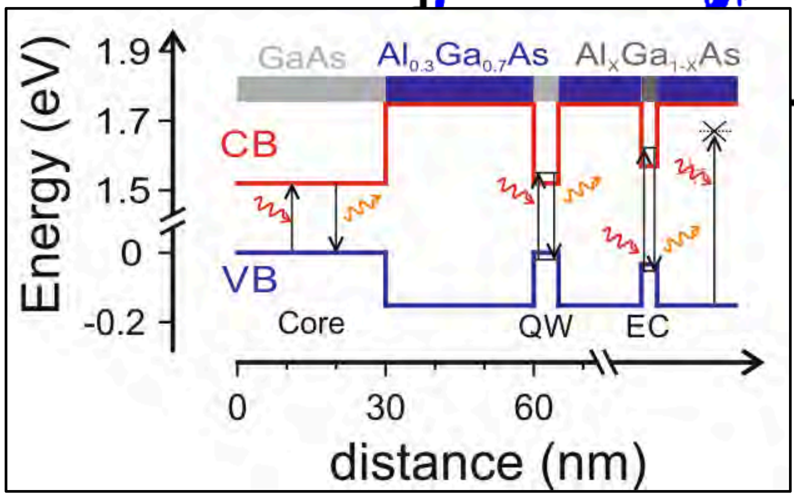
- Neutral exciton X^0 formed with high probability with optical pump
- Time-delayed conversion of X^0 to negative trion X^- at $\tau = T_{SAW}/2$ by SAW-driven electron injection

Schülein et al., Phys. Rev. B **88**, 085307 (2013)

Radial heterostructure nanowire
Quantum dot-like emitters



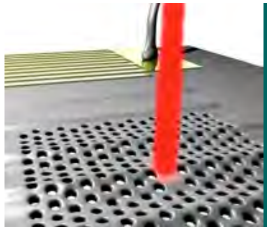




Quantum Dot-like emission centers:

- ➢ Perfectly aligned Quantum Dots?
- ➢ Native alloy fluctuations and/or defects?

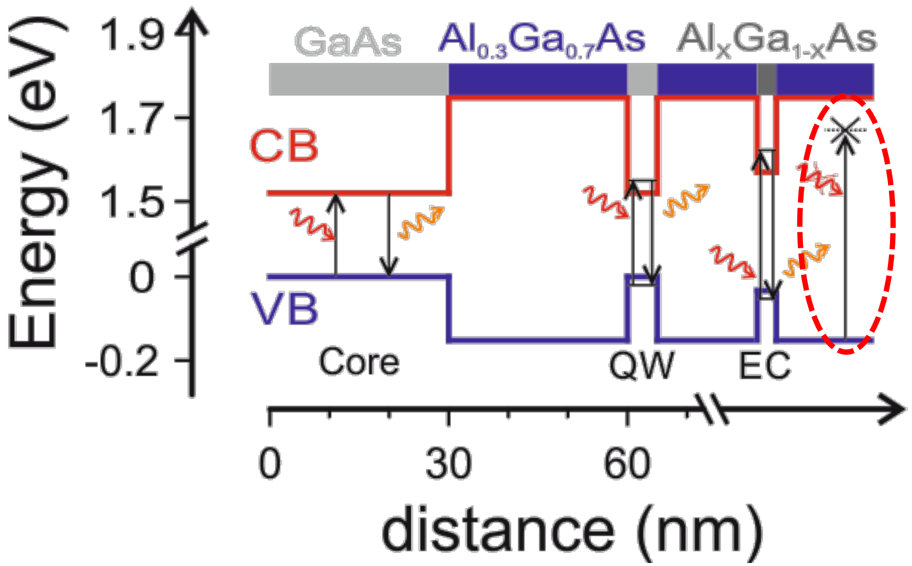
M. Heiss *et al.*, Nature Materials **12**, 439 (2013)
D. Rudolph *et al.*, Nano Letters **13**, 1522 (2013)

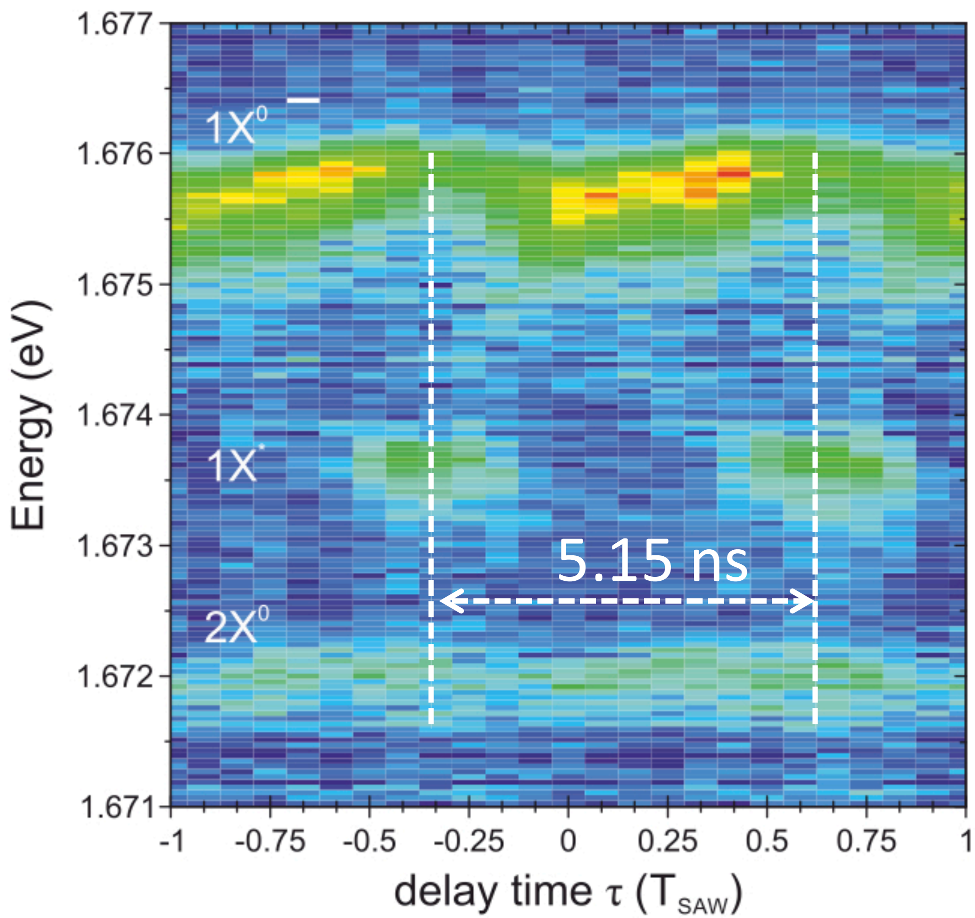


SAW-regulated carrier injection???

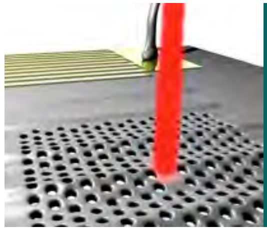
C. Rocke *et al.*, Phys. Rev. Let… (1997)
C. Wiele *et al.*, Phys. Rev. A … 80 (1998)
O. D. D. Couto *et al.*, Na… ics **3**, 645 (2009)
S. Völk *et al.*, Nano Lett… 99 (2010)
F. J. R. Schülein *et al.* … ys. Rev. B **88**, 085307 (2013)
M. Weiß *et al.*, J. Phys. D. **47**, 394011 (2014)

Occurs always from a 2D or 3D-system at higher energies into low energy EC/QD-levels

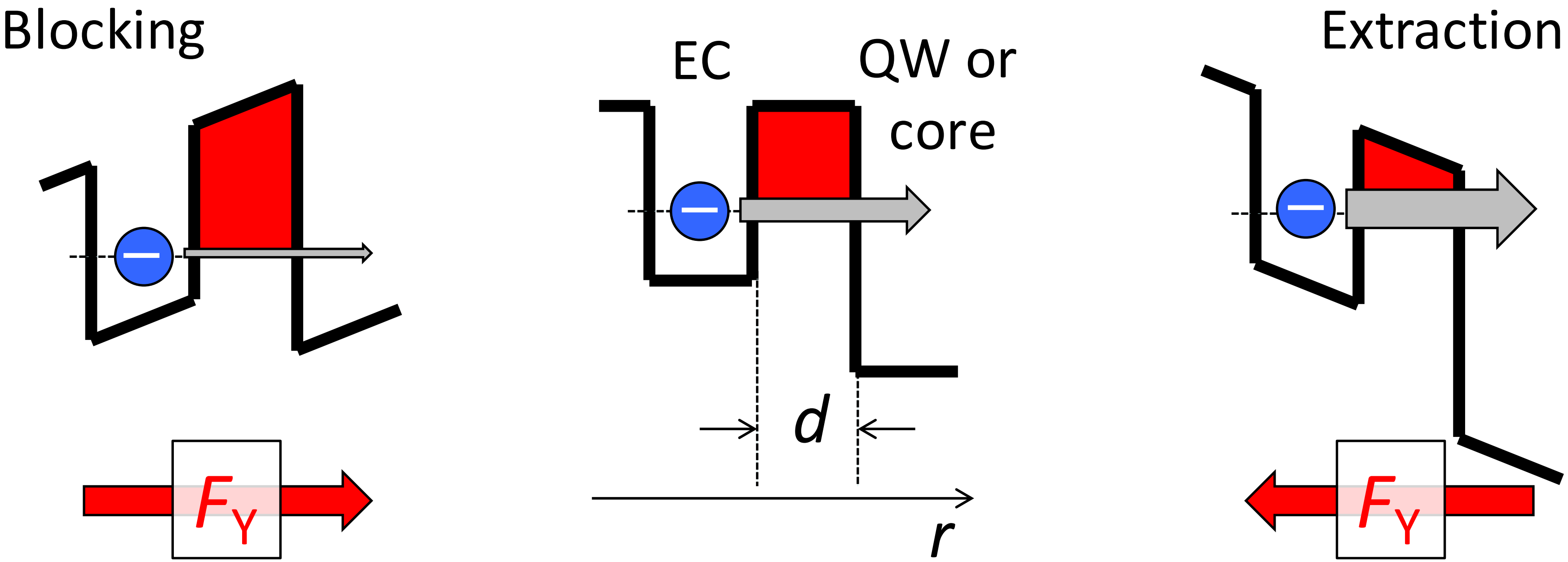


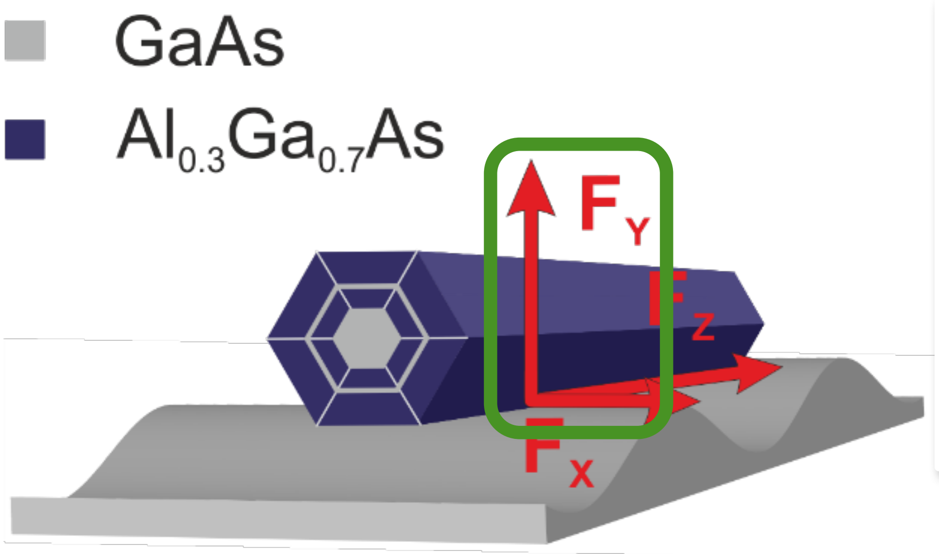


No generation in bulk AlGaAs!
>> NEW mechanism
>> Quantum tunneling



Acoustically controlled tunneling

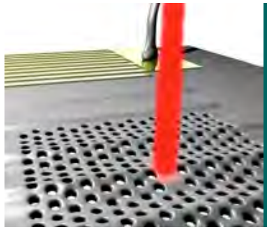




Transverse electric field component periodically raises and lowers tunneling barrier

Dynamic switching of Fowler-Nordheim-like tunneling by SAW

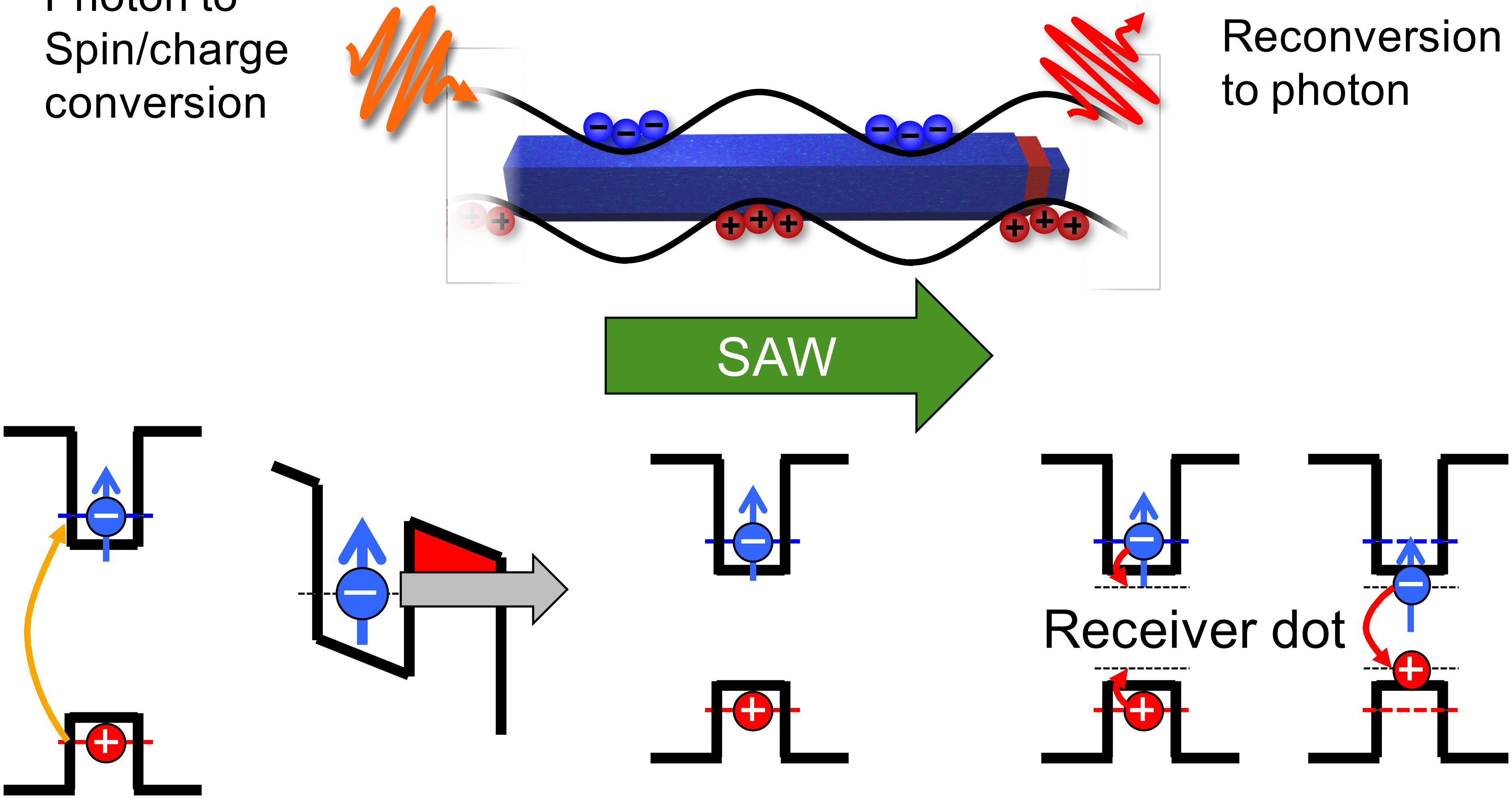
M. Weiß *et al.*, Nano Lett. **14**, 2256 (2014)



Perspectives – on-nanowire quantum state transfer

Photon to Spin/charge conversion

Reconversion to photon



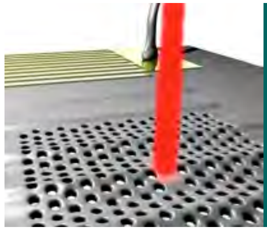
Initialization and Extraction

Transfer

Injection and Reconversion

M. Weiß *et al.*, Nano Lett. **14**, 2256 (2014)

M. Weiß *et al.*, J. Phys. D. **47**, 394011 (2014)



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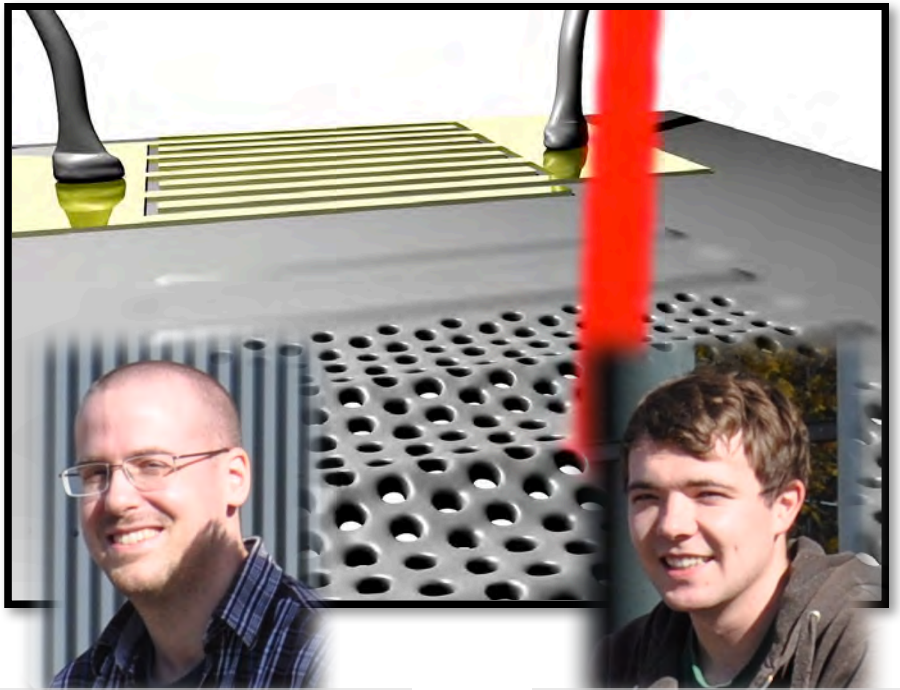
Dynamic acousto-optic control of nanophotonic elements on a chip



Stephan Kapfinger

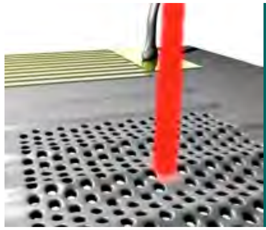
Matthias Weiß

In collaboration with:

Michael Kaniber, **Jonathan Finley**, Thorsten Reichert, Kai Müller,
Stephan Lichtmannecker
Walter Schottky Institut, TU München

Dirk Bouwmeester, **Pierre Petroff,** Susanna Thon, Hyochul Kim
UC Santa Barbara

UCSB



Dynamic nanocavity tuning by Surface Acoustic Waves

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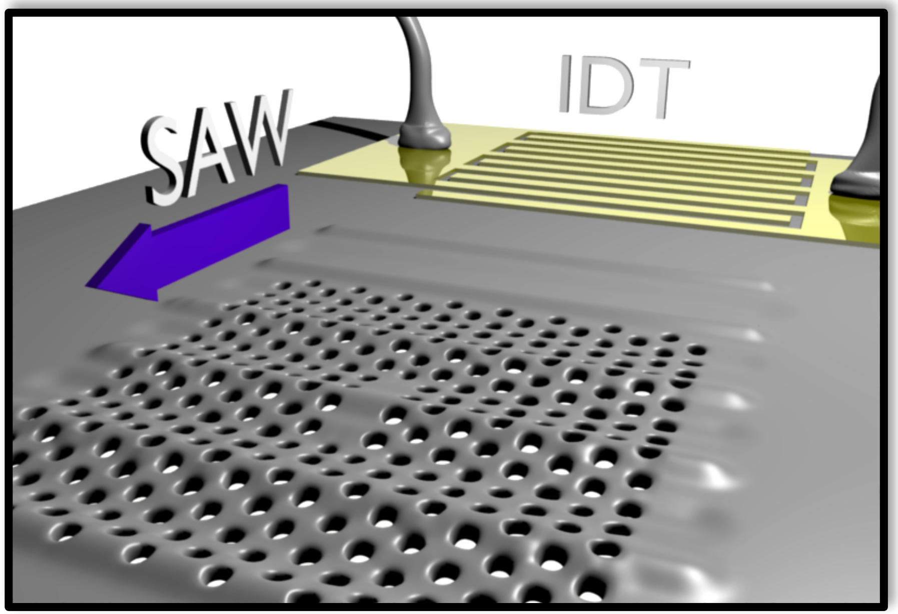
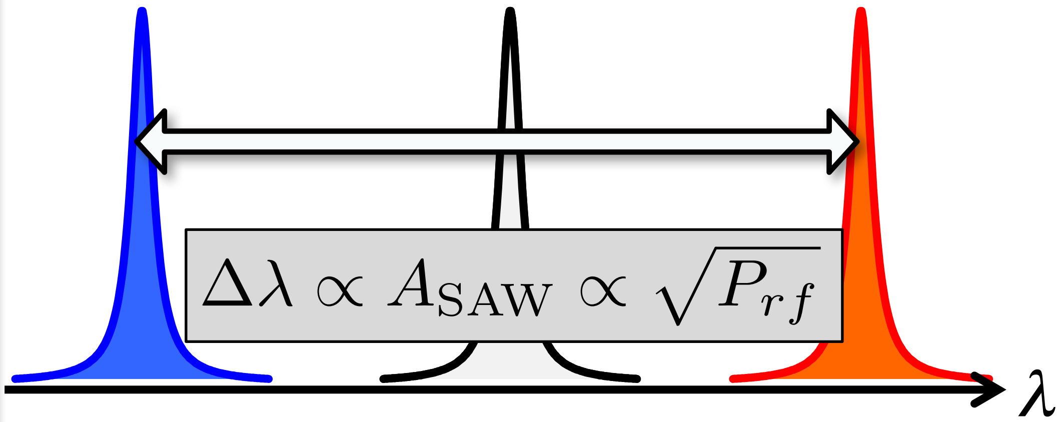
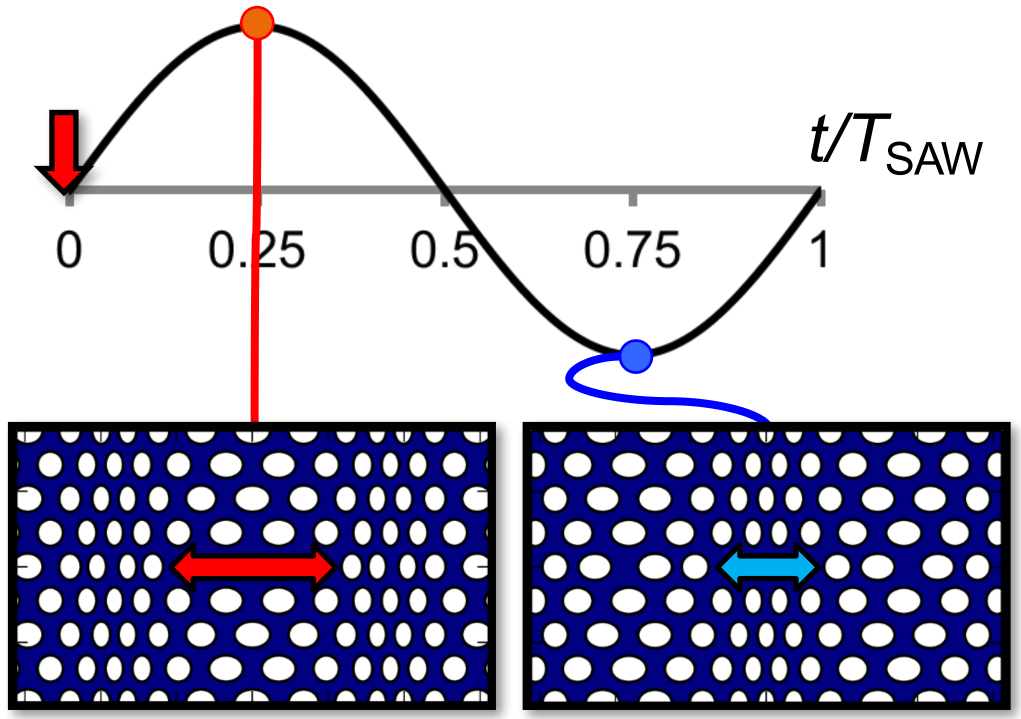
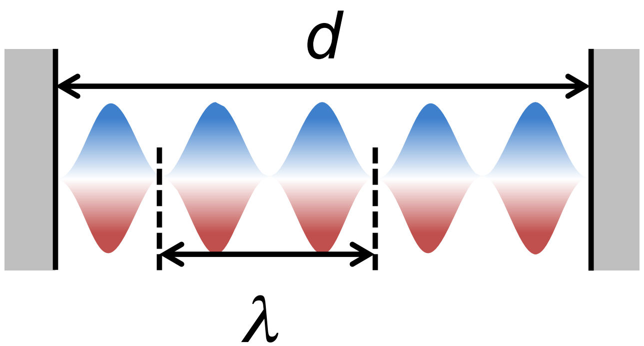


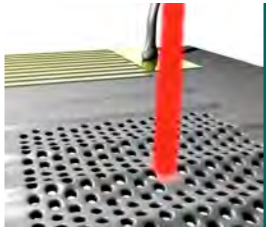




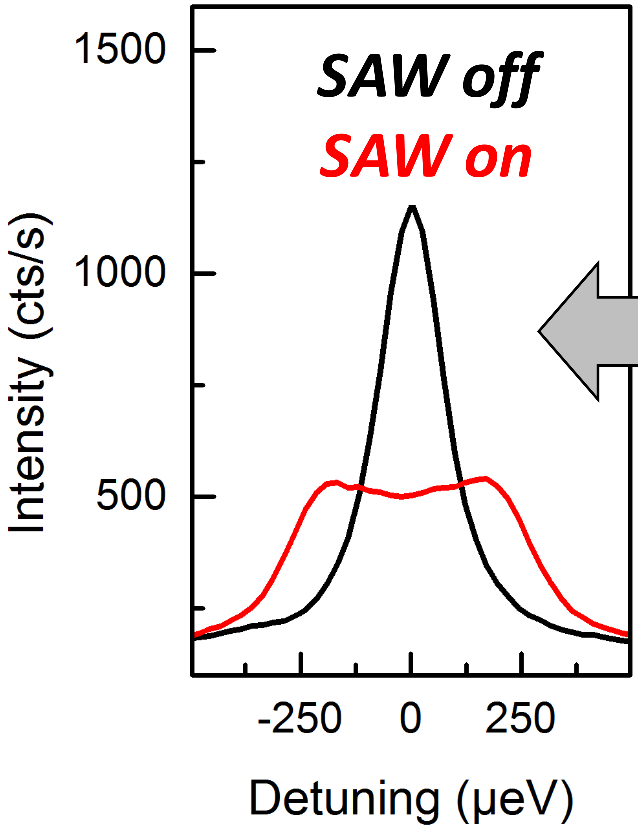
Fabry-Perot model



Fuhrmann et al., *Nature Photonics* **5**, 605-609 (2011)

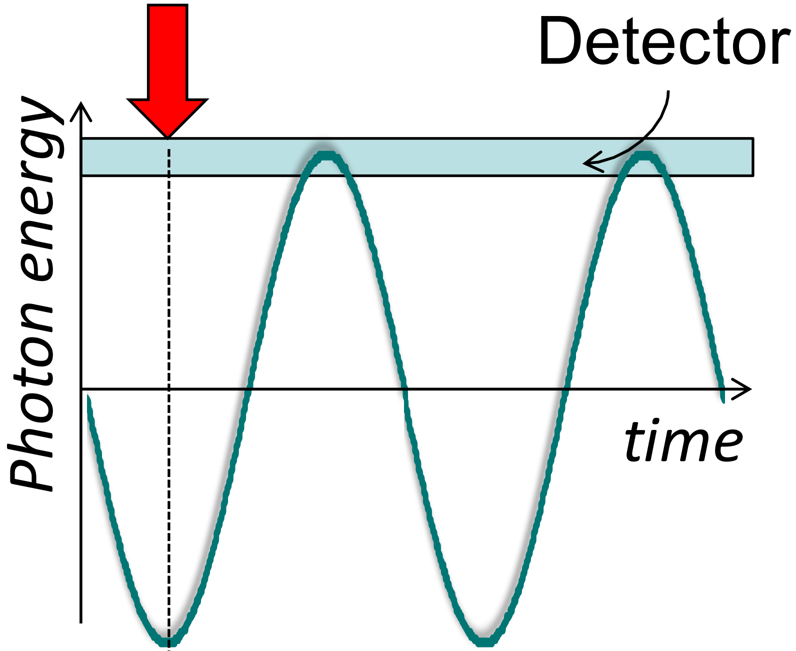


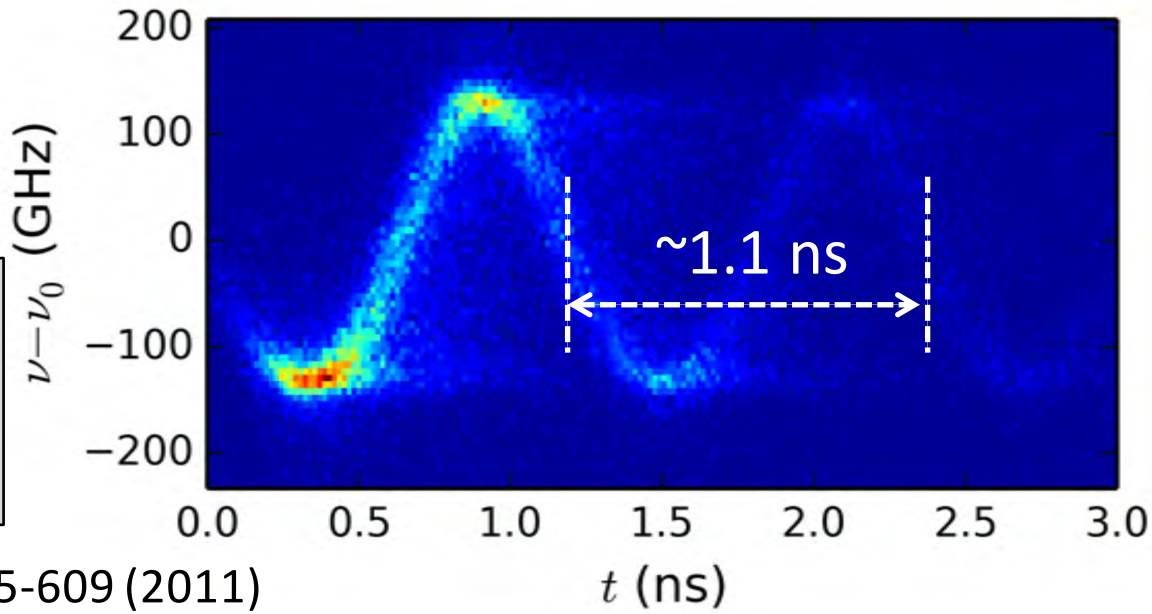
Optomechanical Nanocavity Tuning of an empty cavity



f_{SAW}= 850 MHz

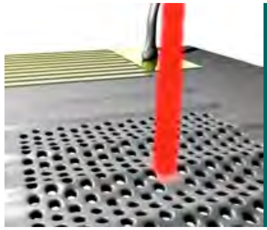
Nanocavity mode
Q = 10'000

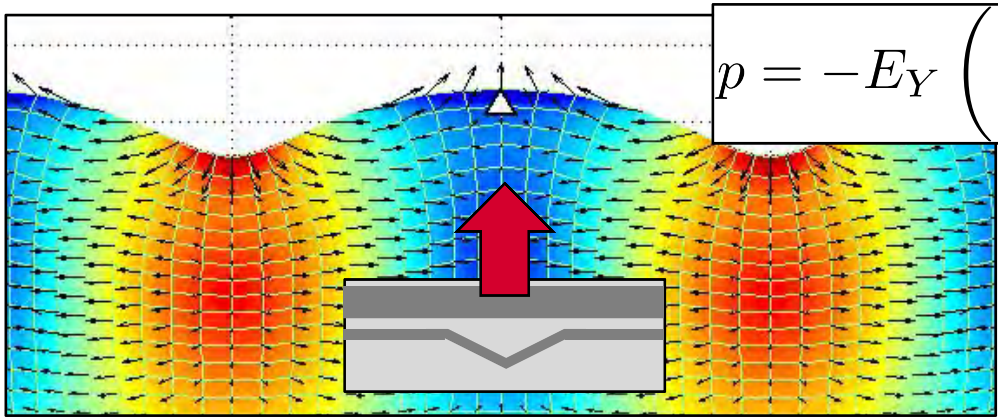




Time-domain observation of dynamic nanocavity tuning at radio frequencies

Fuhrmann et al., *Nature Photonics* **5**, 605-609 (2011)

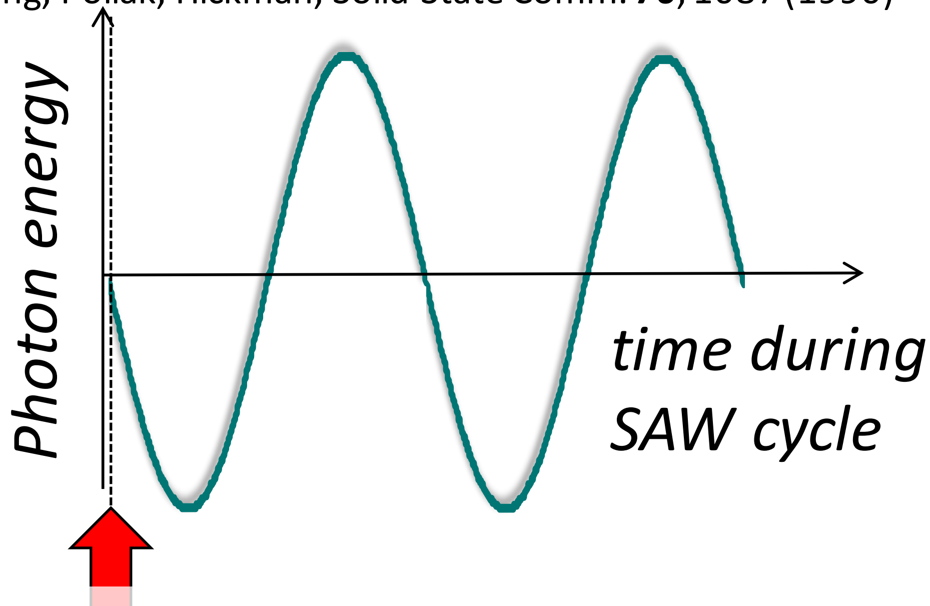


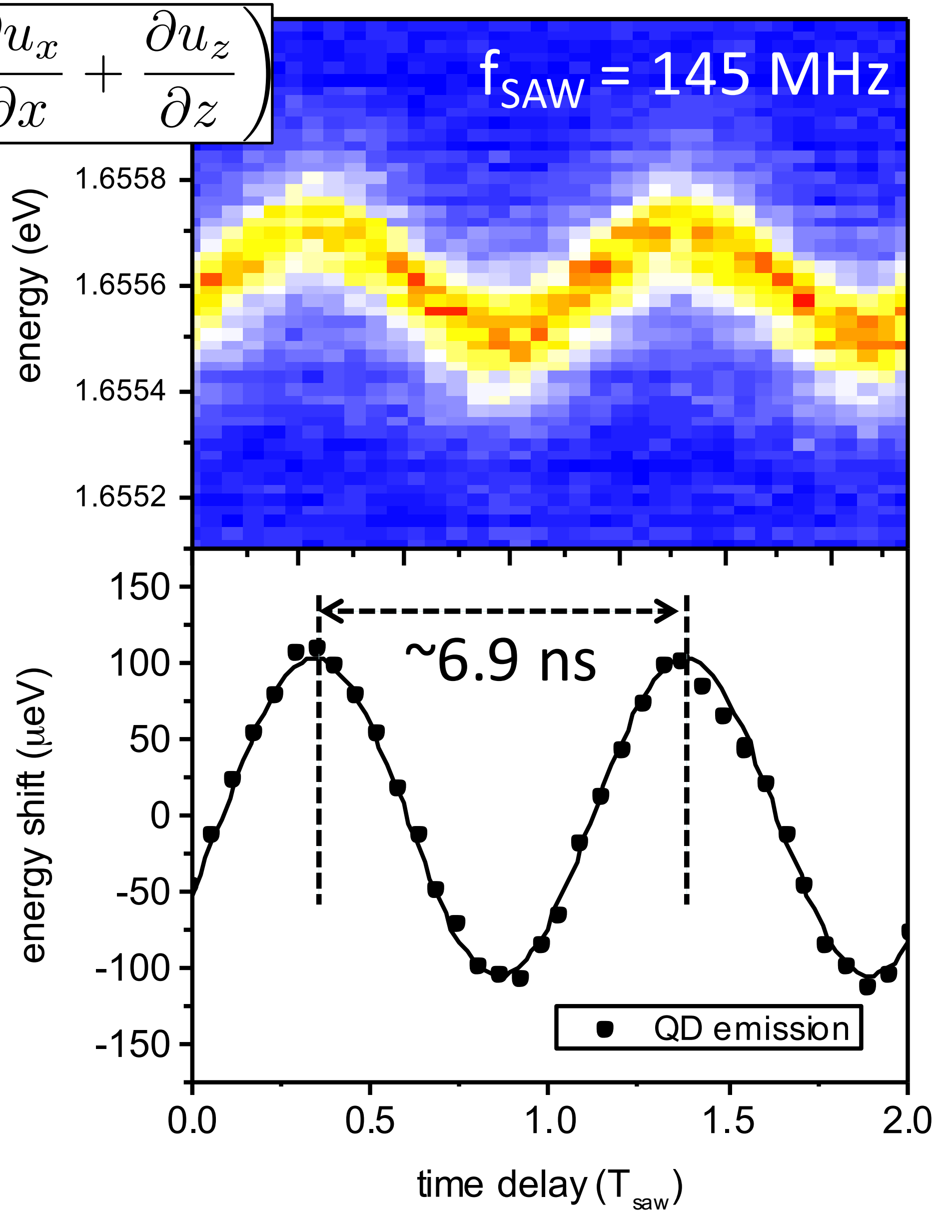


$$p = -E_Y \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} \right)$$

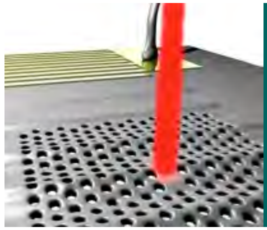
Deformation potential coupling $\frac{dE}{dp} = 150 \frac{\mu\mathrm{eV}}{\mathrm{MPa}}$

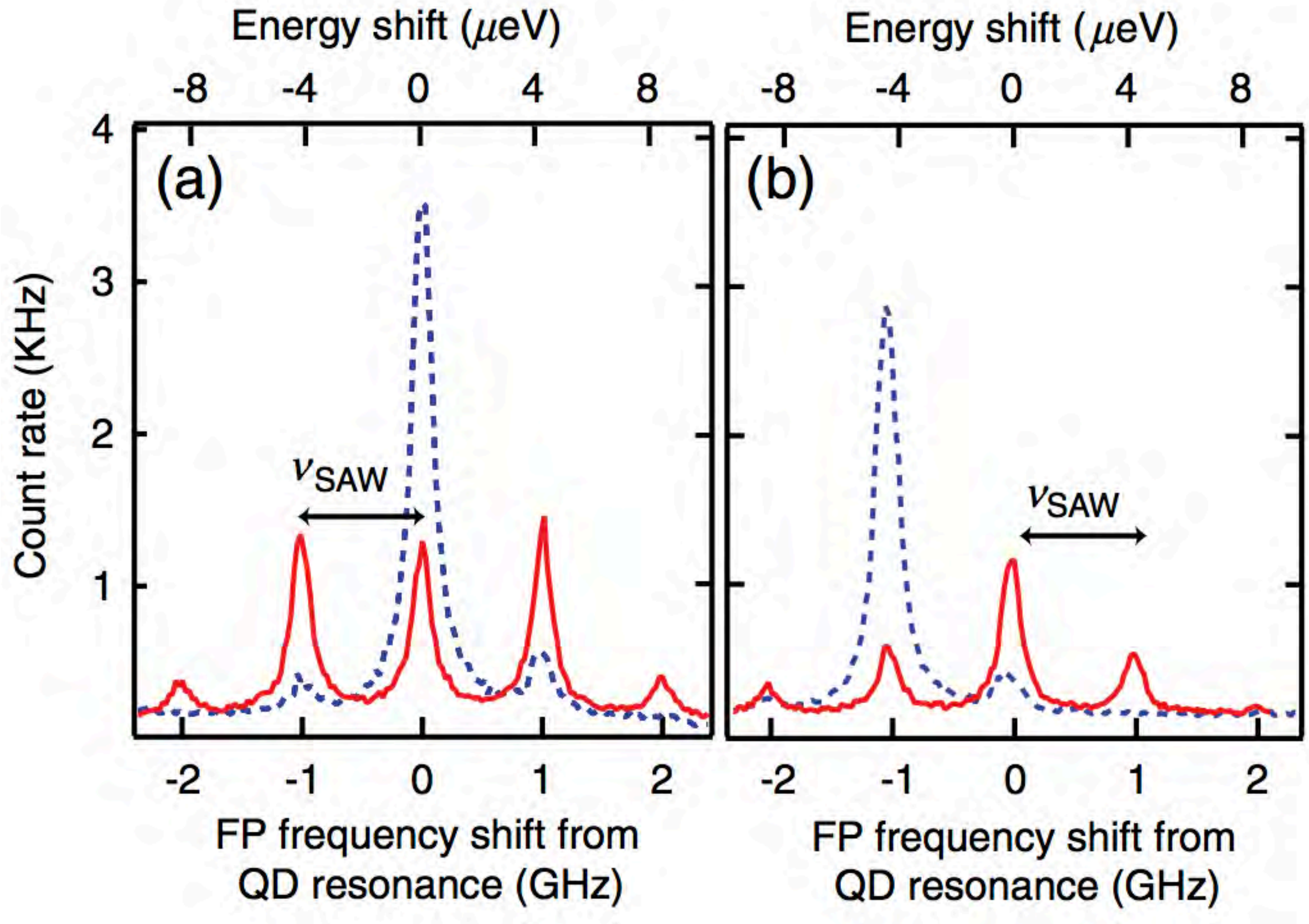
Qiang, Pollak, Hickman, Solid State Comm. **76**, 1087 (1990)



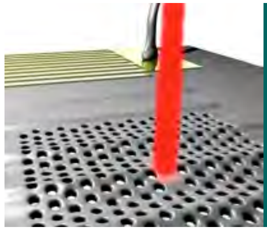


Gell, Appl. Phys. Lett. **93**, 081115 (2008)





M. Metcalfe et al. PRL **105**, 037401 (2010)



Controlling coherent interactions between quantum systems

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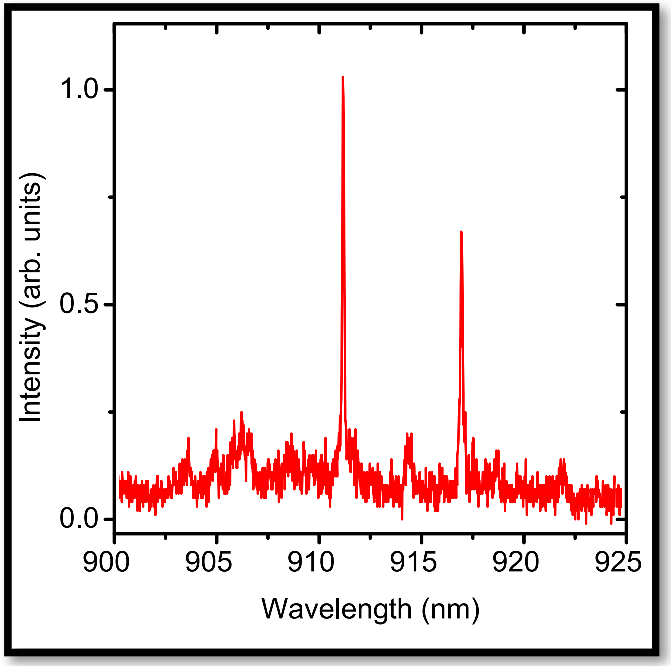
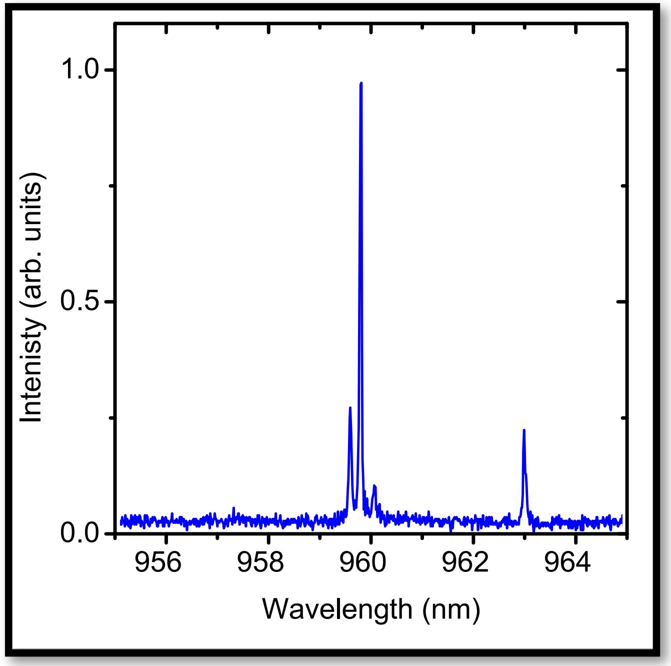
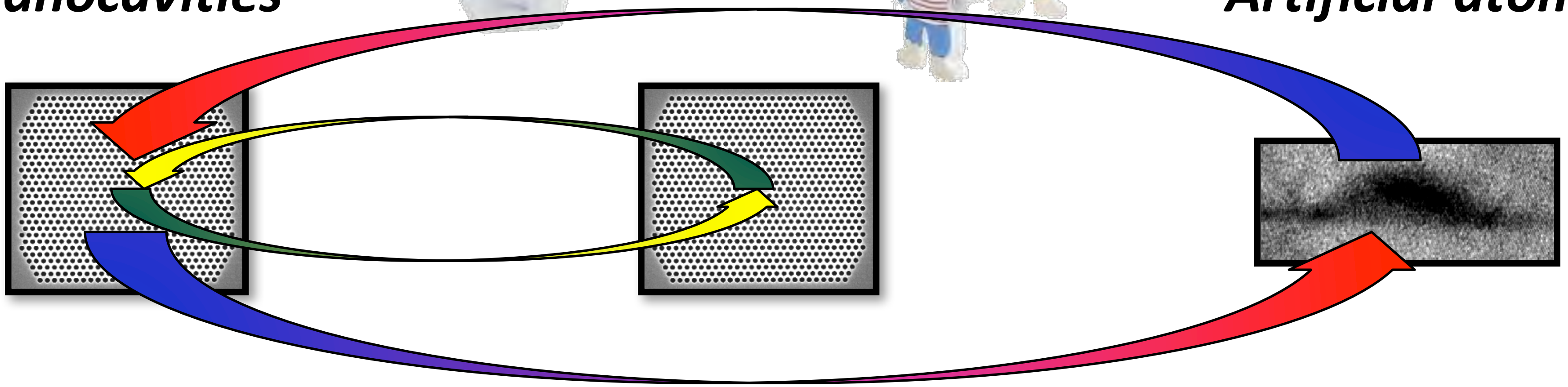
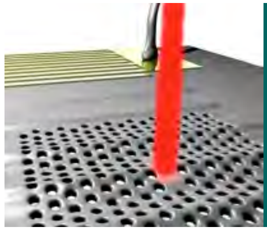


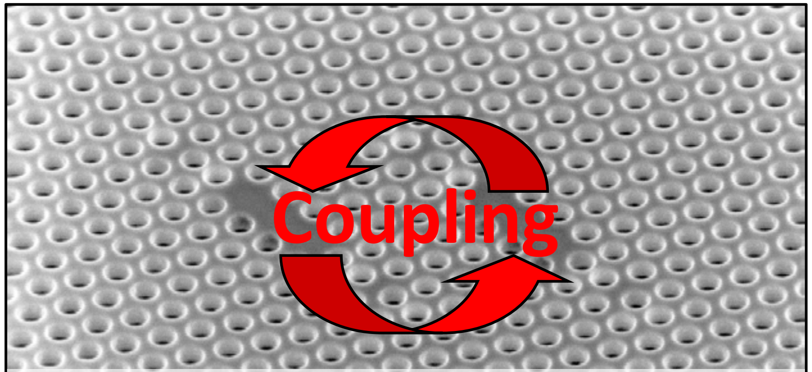


Photonic Crystal Nanocavities

Quantum Dot Artificial atoms

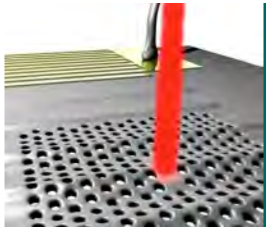


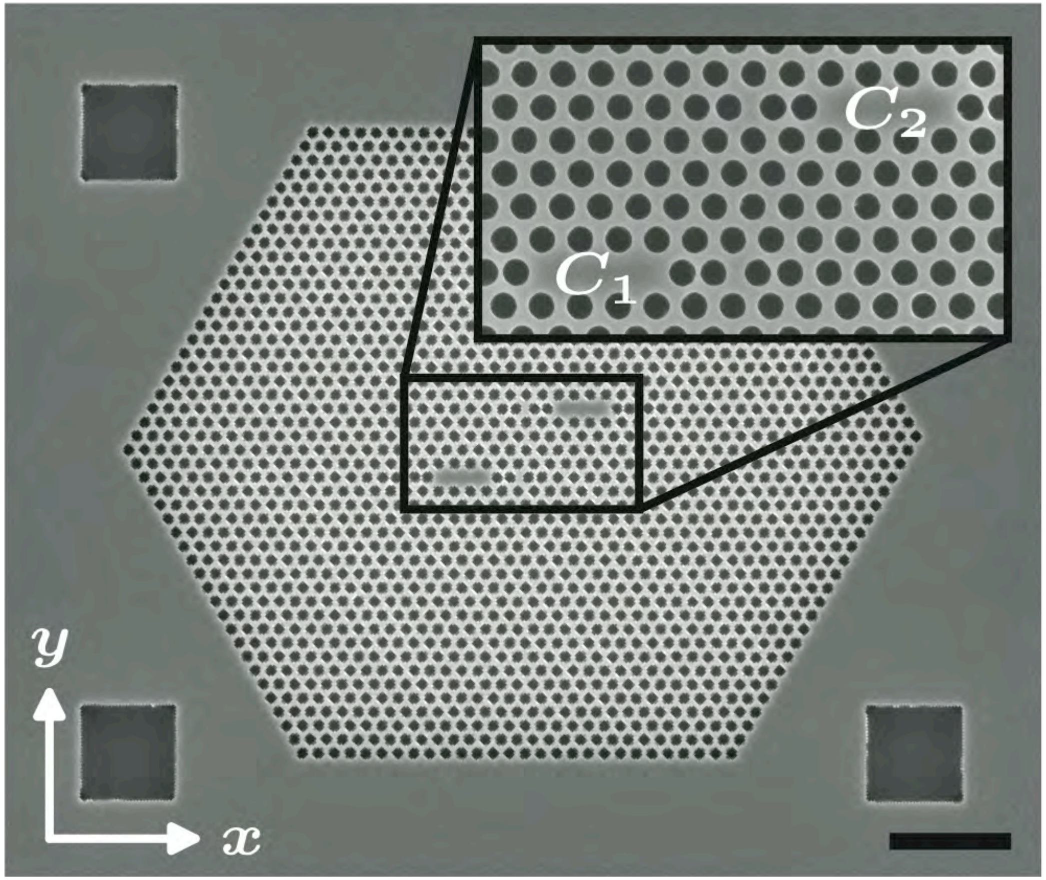


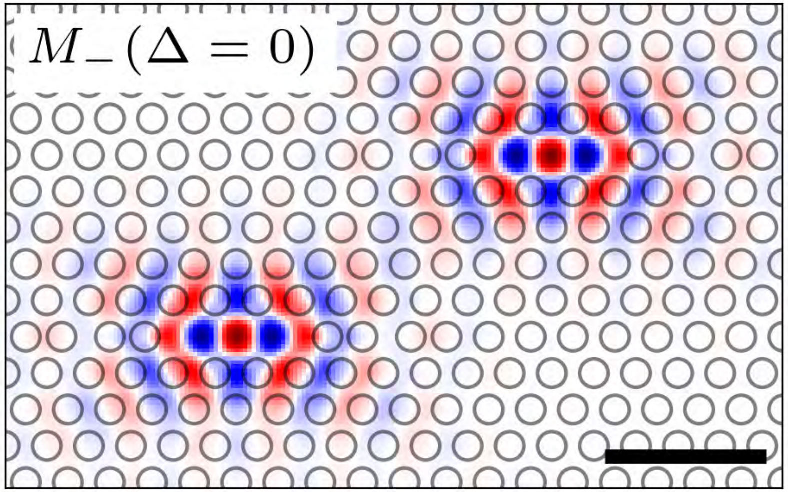


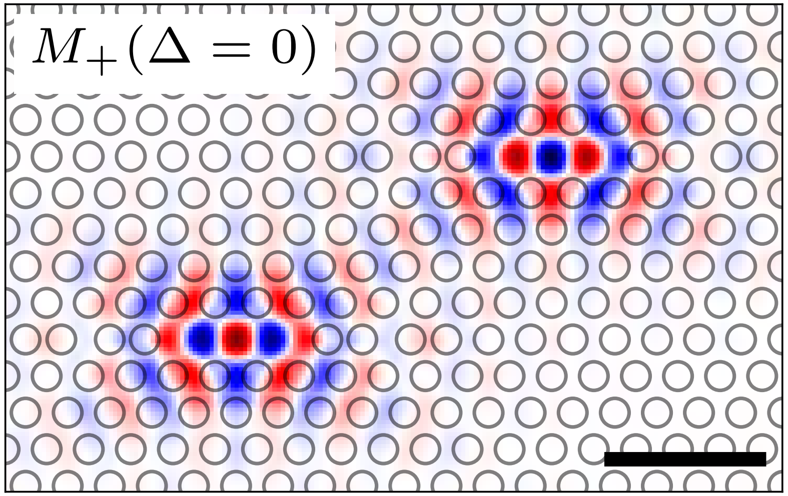
Dynamically controlled coupling

Scalable architecture:
Acousto-optic intercavity coupling



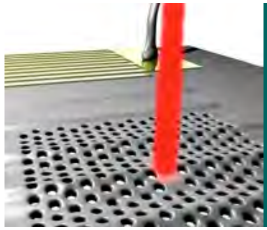




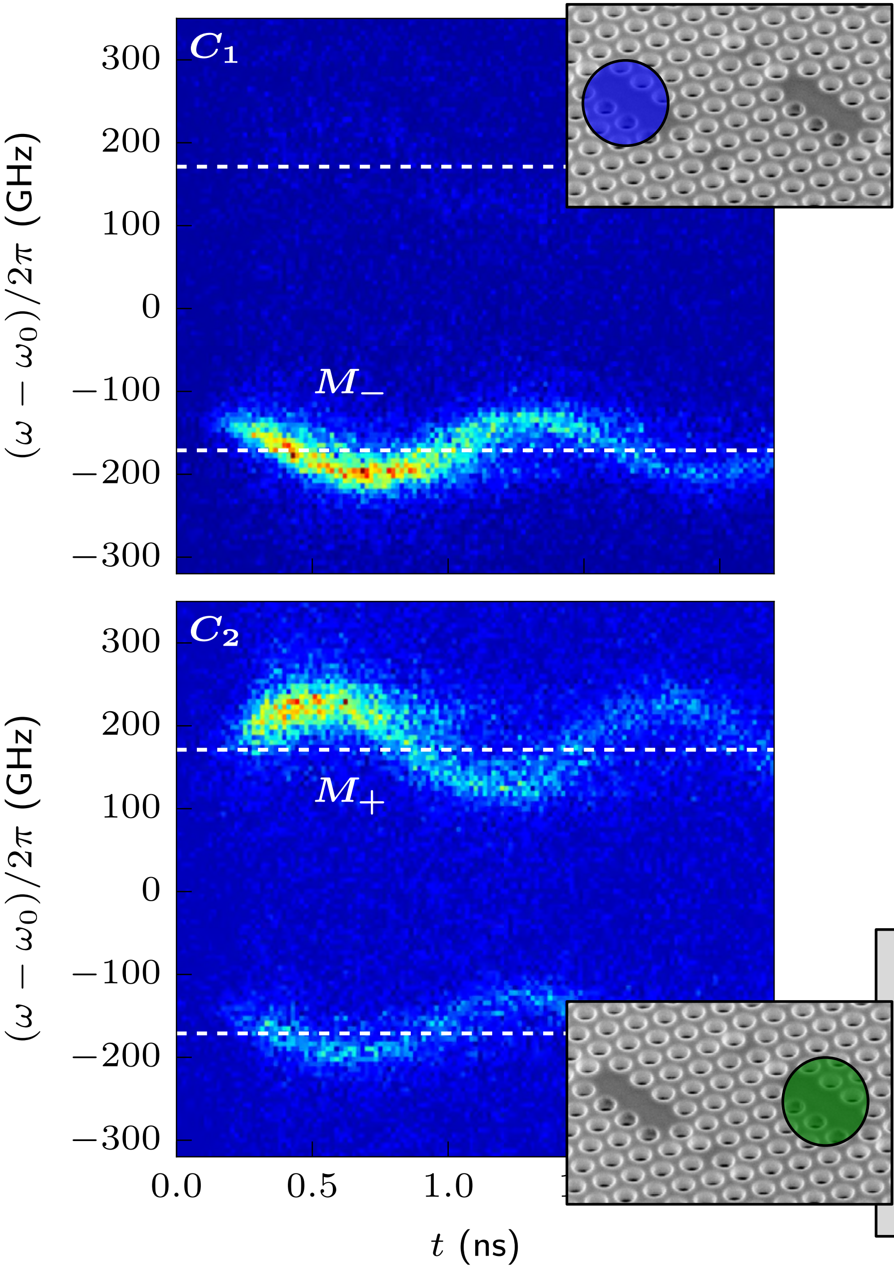


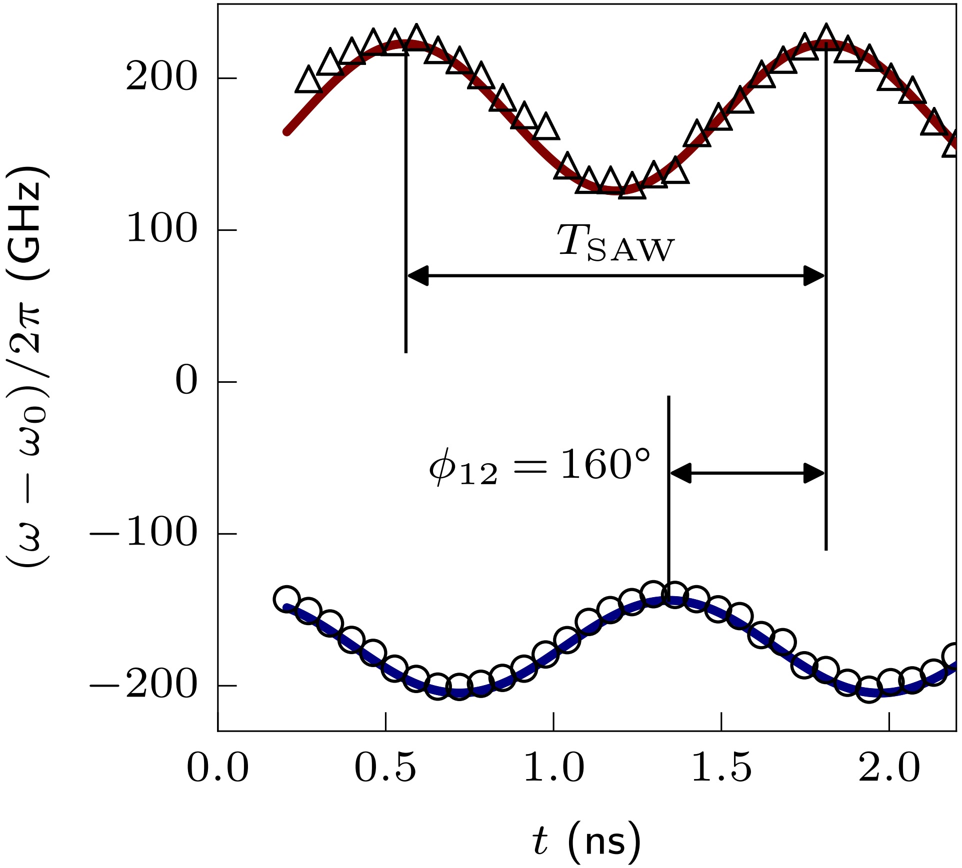
$$\omega_\pm = \omega_0 \pm \frac{1}{2}\sqrt{\Delta^2 + J^2}$$

Normal mode splitting – bonding and anti-bonding modes



Low modulation ($J < \Delta_{mod}$)

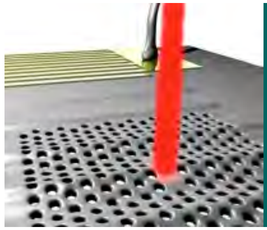




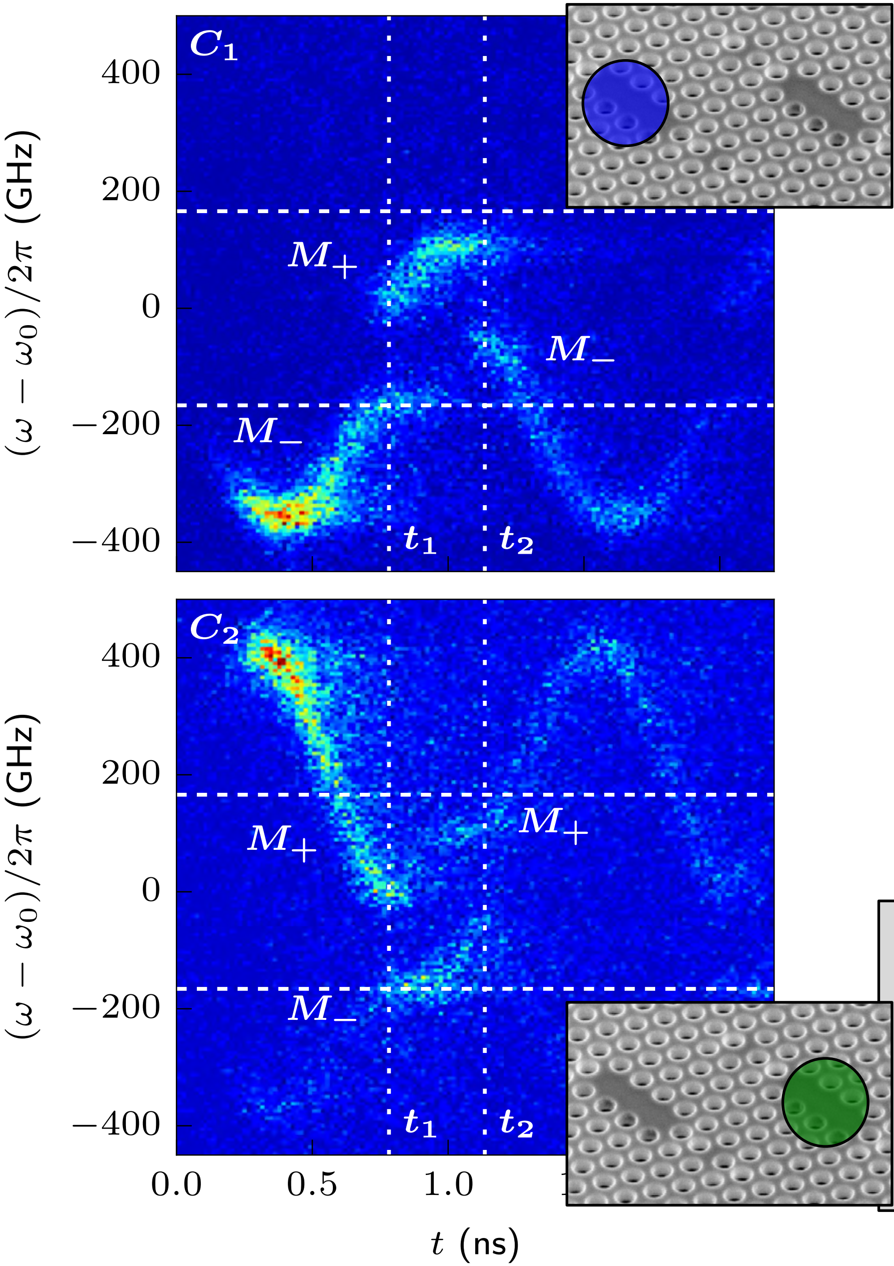
Anti-phased dynamic tuning

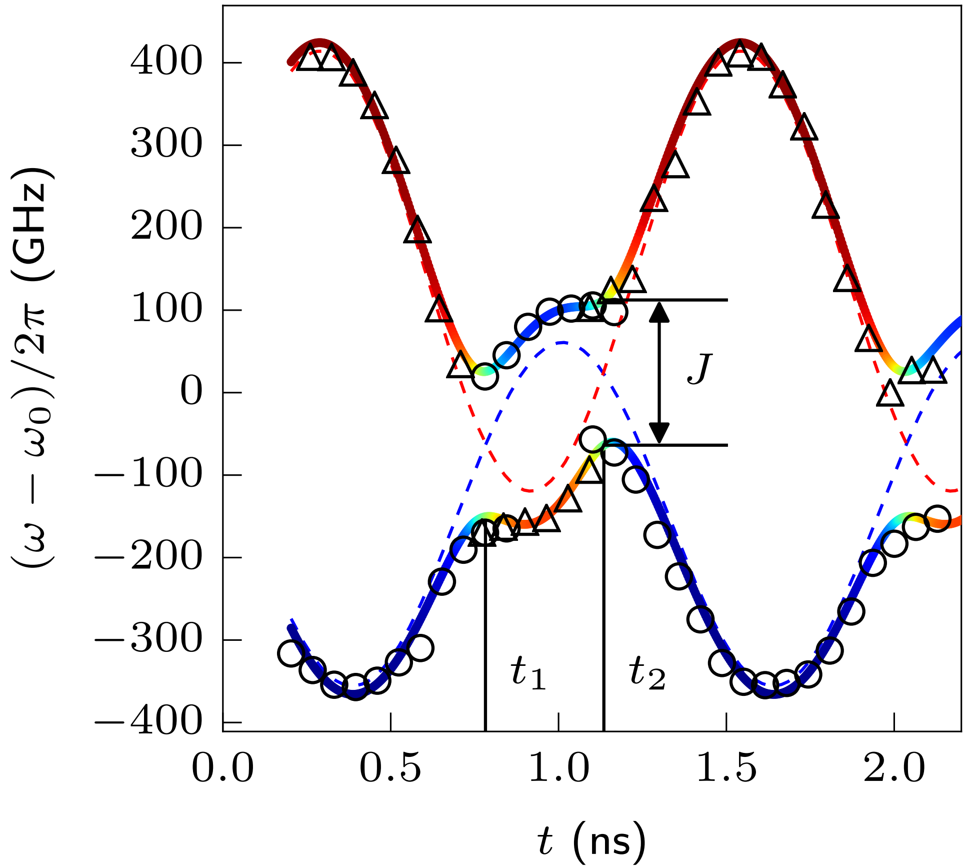
Time-dependent detuning

$$\Delta(t) = \omega_2 - \omega_1 \quad \Delta(t) \ll J$$



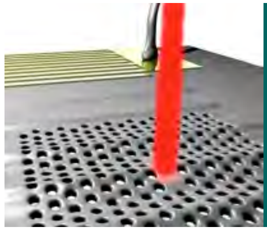
Strong modulation ($\Delta_{mod} > J$)

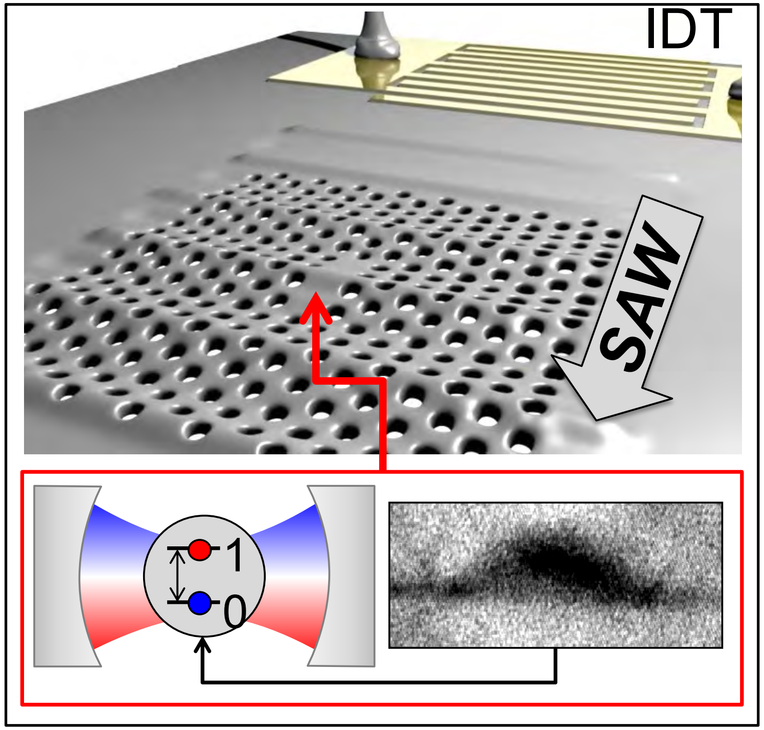




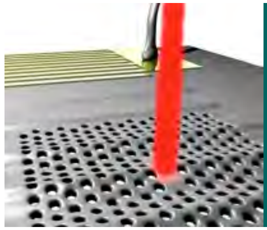
Double resonances
time-dependent programming of
mode characters

S. Kapfinger et al., Nature Communications **8**, 8540 (2015)

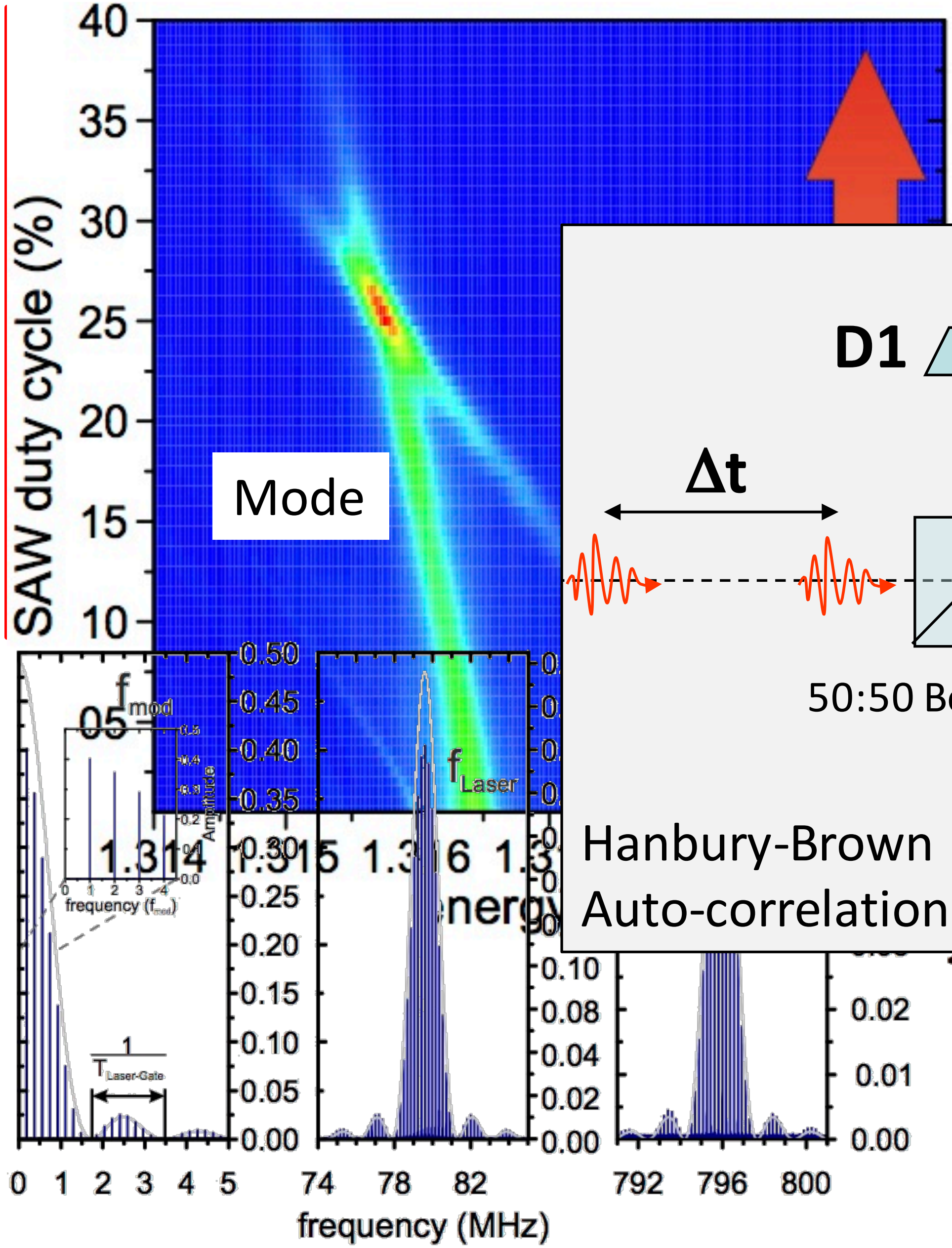


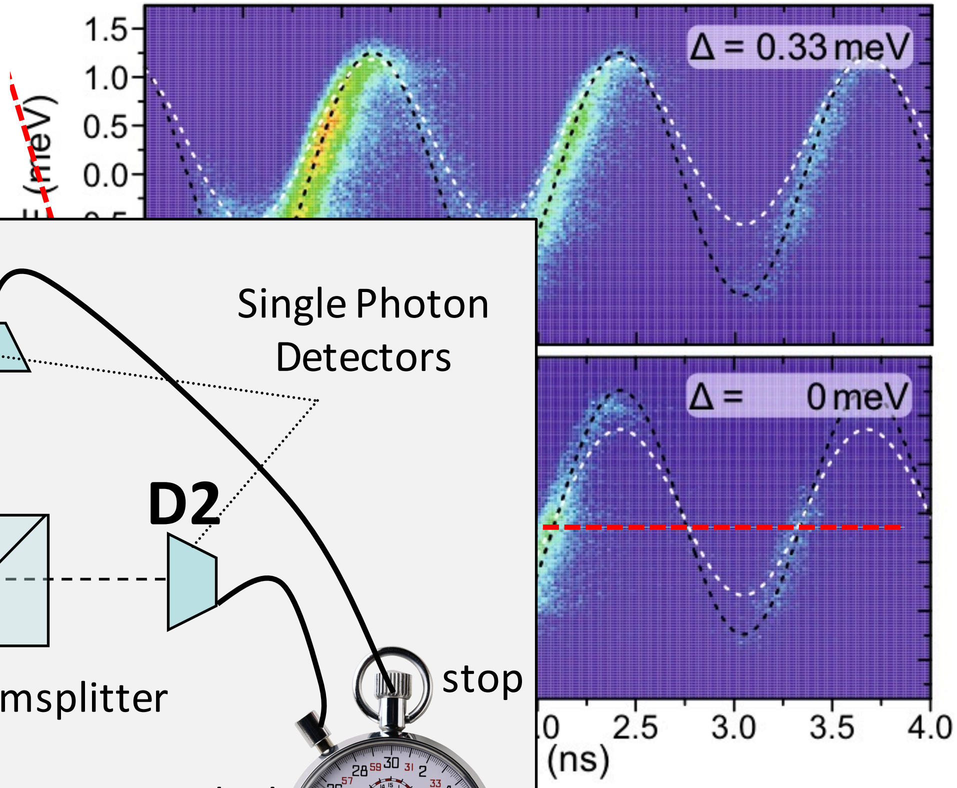


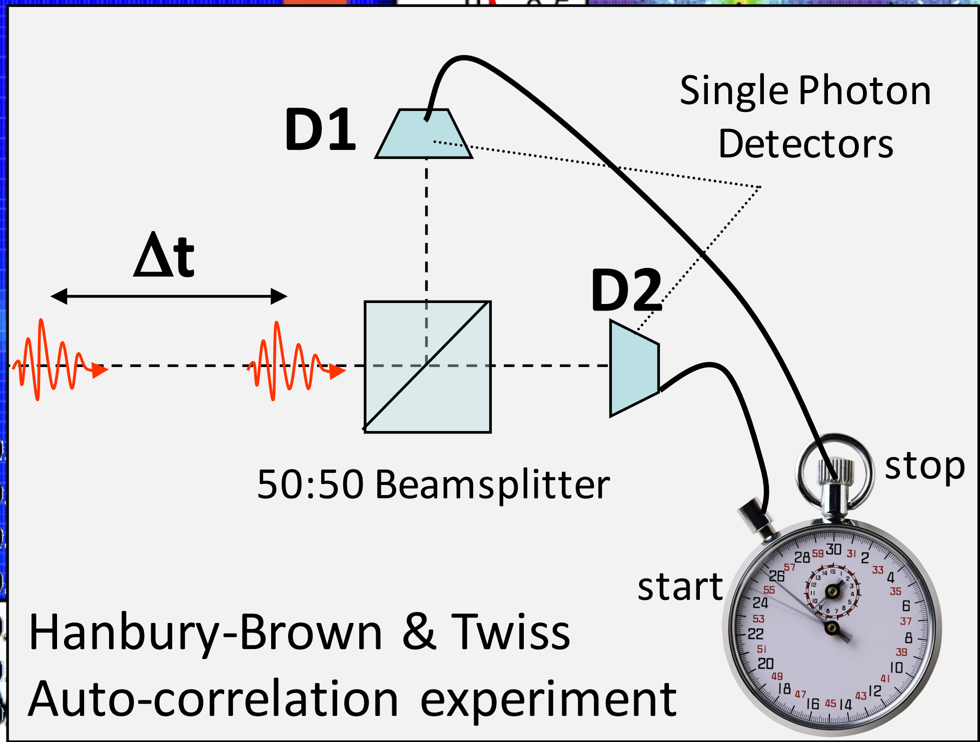
Acousto-optical dot-cavity coupling



Coupled Quantum dot–nanocavity system
Dynamic tuning



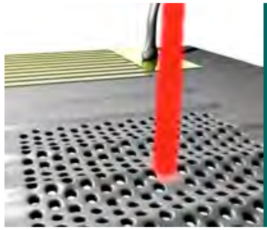


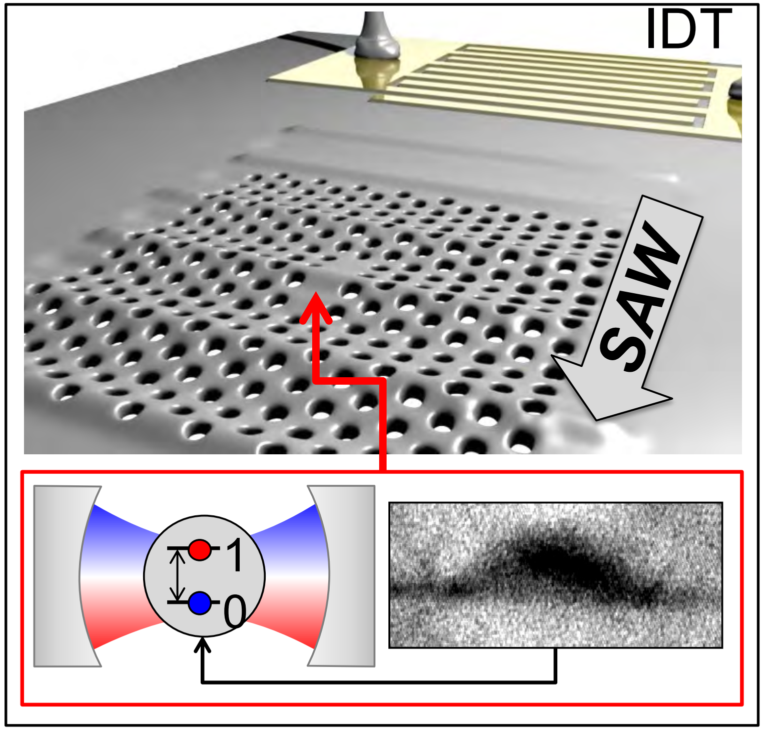


…ed single photons
from a coupled dot – Nanocavity system

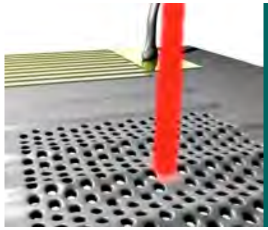
Weak coupling – Purcell effect, but
losses dominate!

M. Weiß, submitted, arXiv:1605.04956

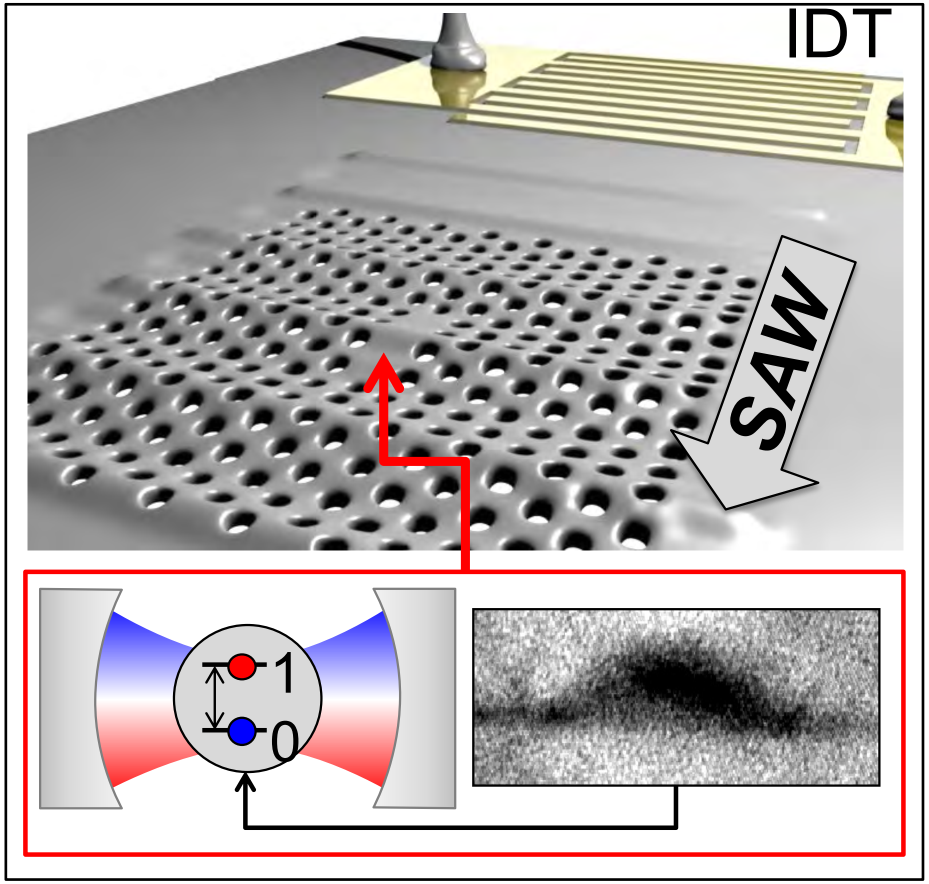


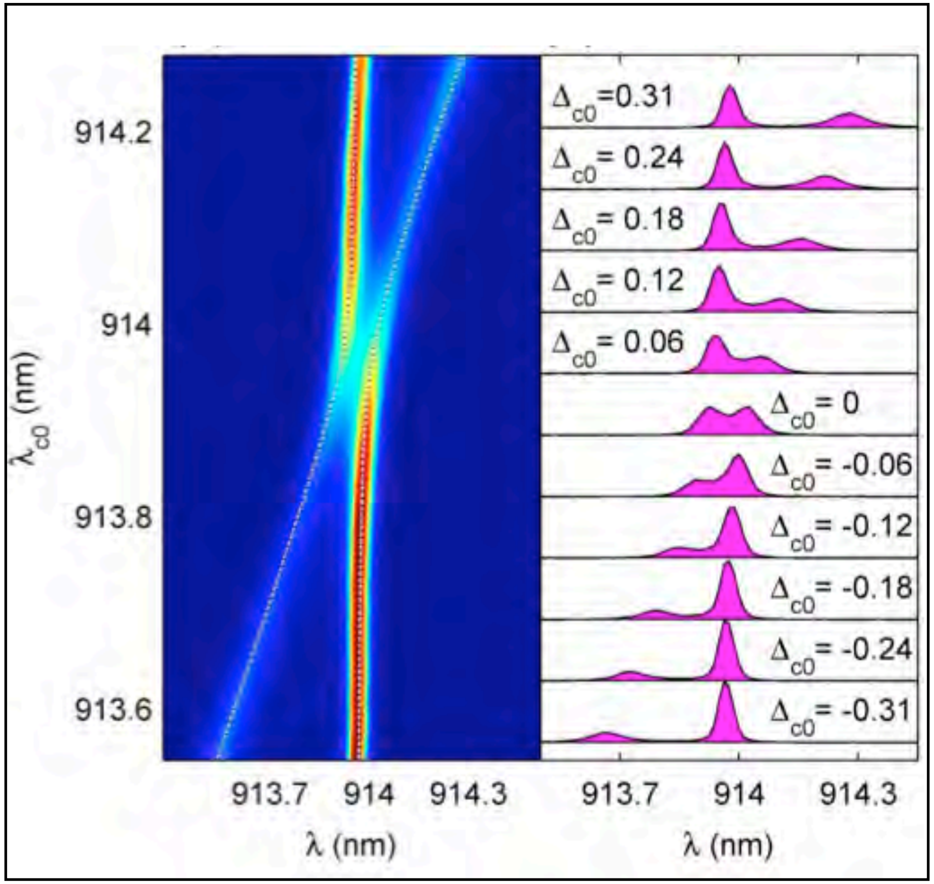


SAW-driven quantum gates

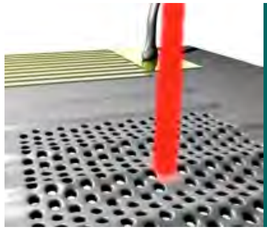


Can we generate an entangled state between a single exciton in the QD and a single photon in the cavity by a SAW?





Blattmann, Krenner, Kohler, Hänggi, PRA **89**, 012327 (2014)



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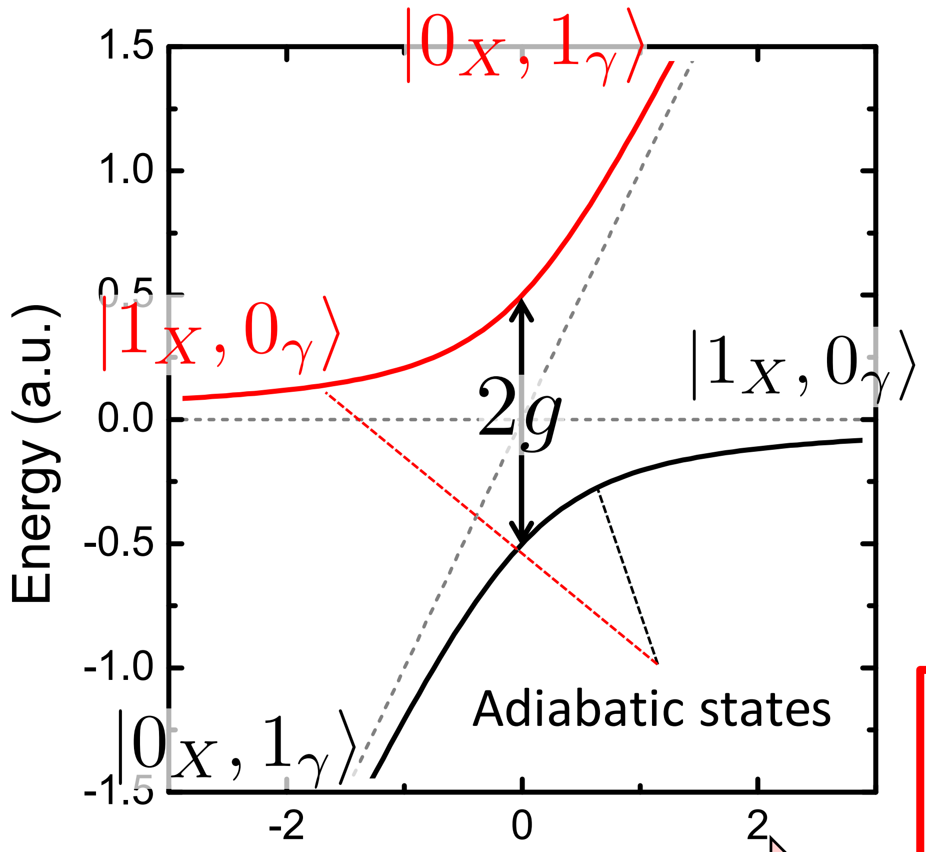


$$\Delta(t) = vt$$

Dynamic detuning

LZS-Transition probability

Landau, Zener, Stückelberg, Majorana – 1932

$$P_{LZ}(\infty) = \exp\left(-\frac{\pi g^2}{2\hbar v}\right)$$

$$P(\infty) = 1$$ "LZS-Tunneling"

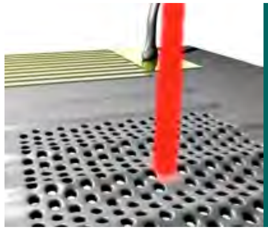
$$P(\infty) = 0.5$$ "Mixed states"

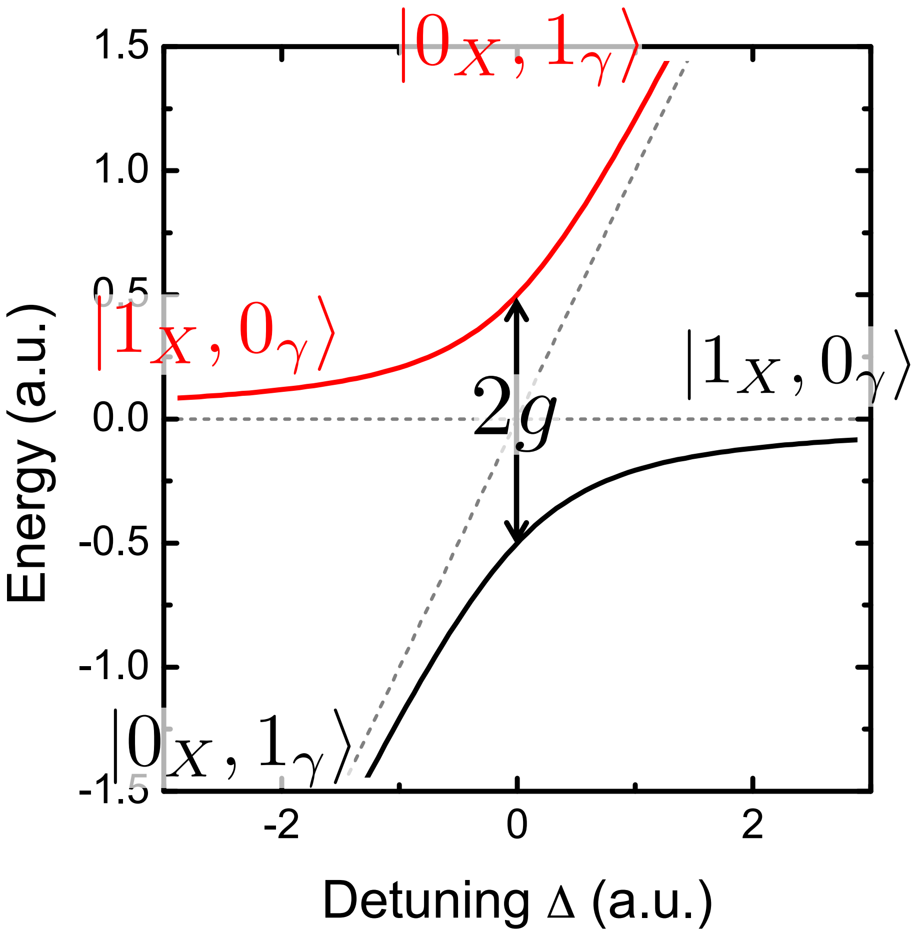
$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\left(|1_X, 0_\gamma\rangle + |0_X, 1_\gamma\rangle\right)$$

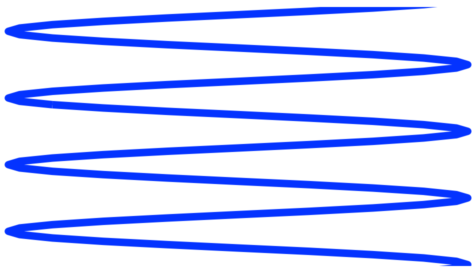
Bell state preparation

K. Saito *et al.*, EPL **76**, 22 (2006) (circuitQED)

Dissipative LZS-Transitions for quantum gates: K. Saito *et al.*, PRB **75**, 214308 (2007)







SAWs: ***oscillatory*** drive

$$\Delta = \Delta_0 + \Delta_{max} \sin(2\pi f_{\mathrm{SAW}} t)$$

Static offset — Amplitude — Frequency

Periodic drive: Floquet-Markov Theory

$$H(t) = H(t+T)$$

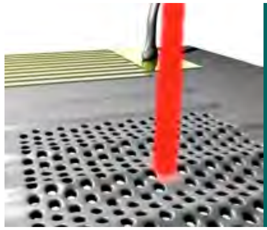
M. Grifoni et al., Phys. Rep. **304**, 299 (1998)

Floquet theory with dissipation:

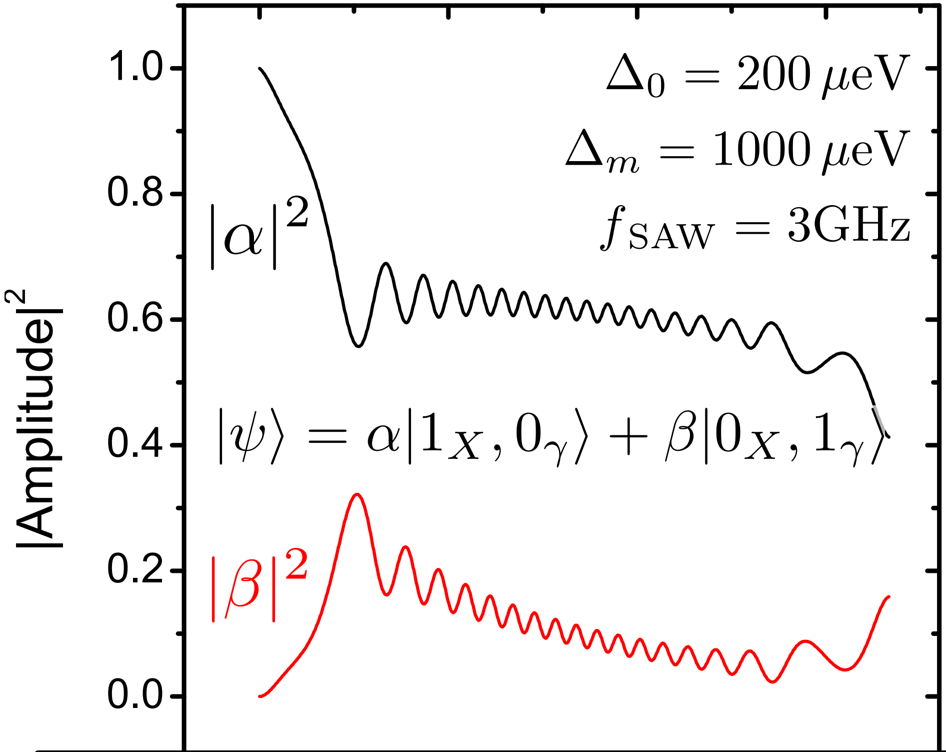
R. Blümel et al., Phys. Rev. A **44**, 4521 (1991)

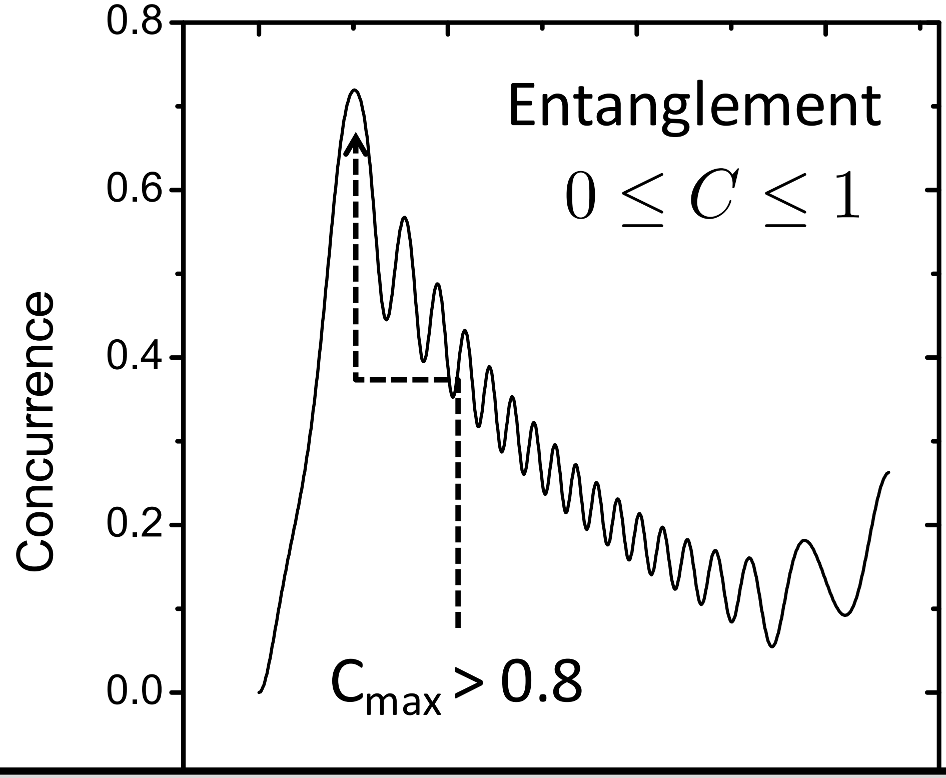
S. Kohler et al., Phys. Rev. E **55**, 300 (1997)

$$|\psi\rangle = \alpha|1_X, 0_\gamma\rangle + \beta|0_X, 1_\gamma\rangle$$



LZS-Transition of QD-nanocavity system





Experimentally accessible!

Optimum performance for tailored tuning rates

Blattmann et al., Phys. Rev A **89**, 012327 (2014)

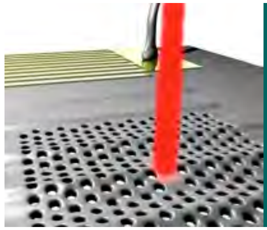
Ex

N

Q = 55000 [Ota, PRL **107**, 233602 (2011)] @ onset of strong coupling (κ = 25 μeV = *g*)

SAW tuning:

Amplitude: Δ_{max} = 1 meV & f_{SAW} = 3 GHz [Fuhrmann, *Nat. Photon.* **5**, 605 (2011)]



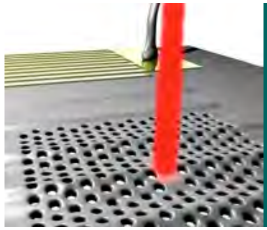
Freely programmable nanomechanic waves: Phononic pulse shaping

Florian Schülein

In collaboration with:

Armando Rastelli, Rinaldo Trotta
JKU Linz

Oliver Schmidt, Eugenio Zallo, Paola Atkinson
IFW Dresden



Pulse shaping – electromagnetic domain

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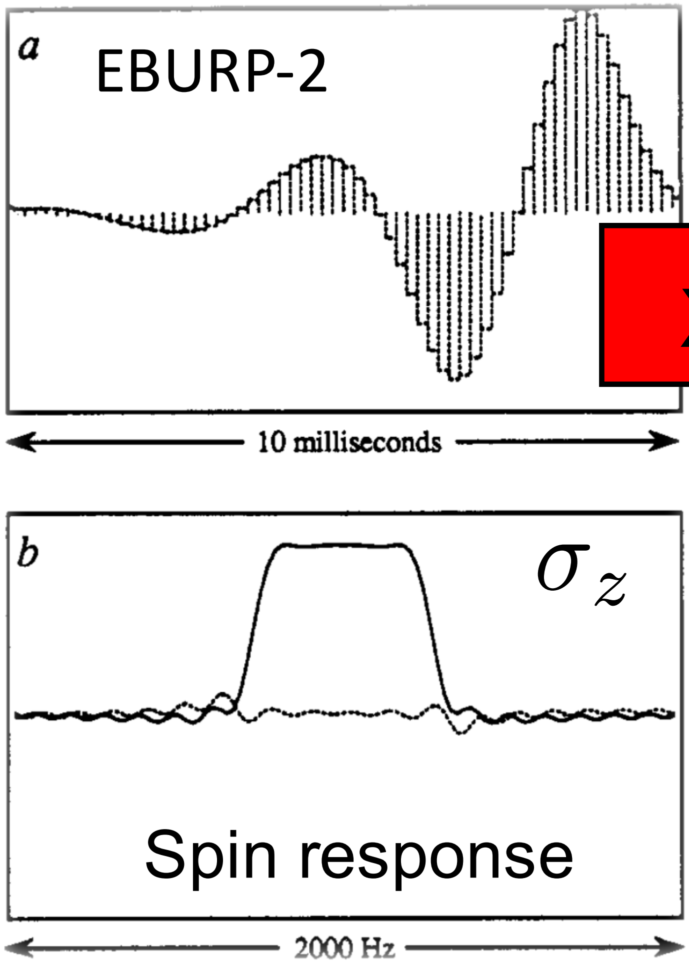
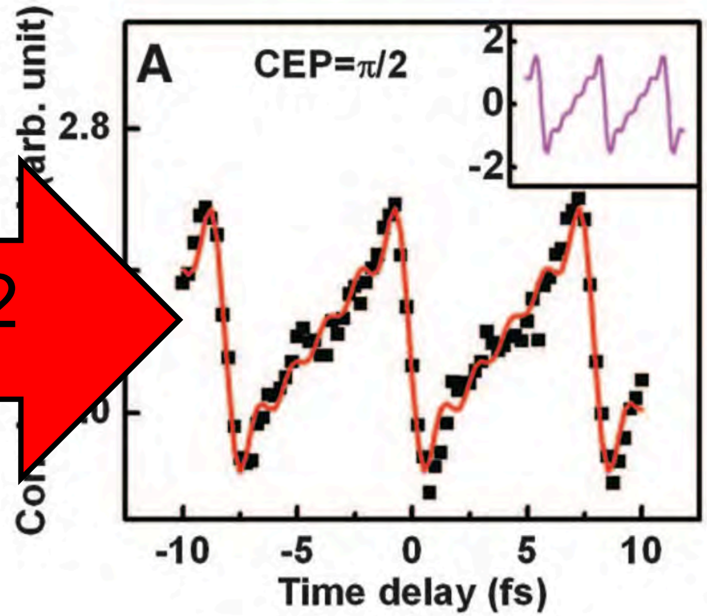
NMR: radio frequencies



$x10^{-12}$

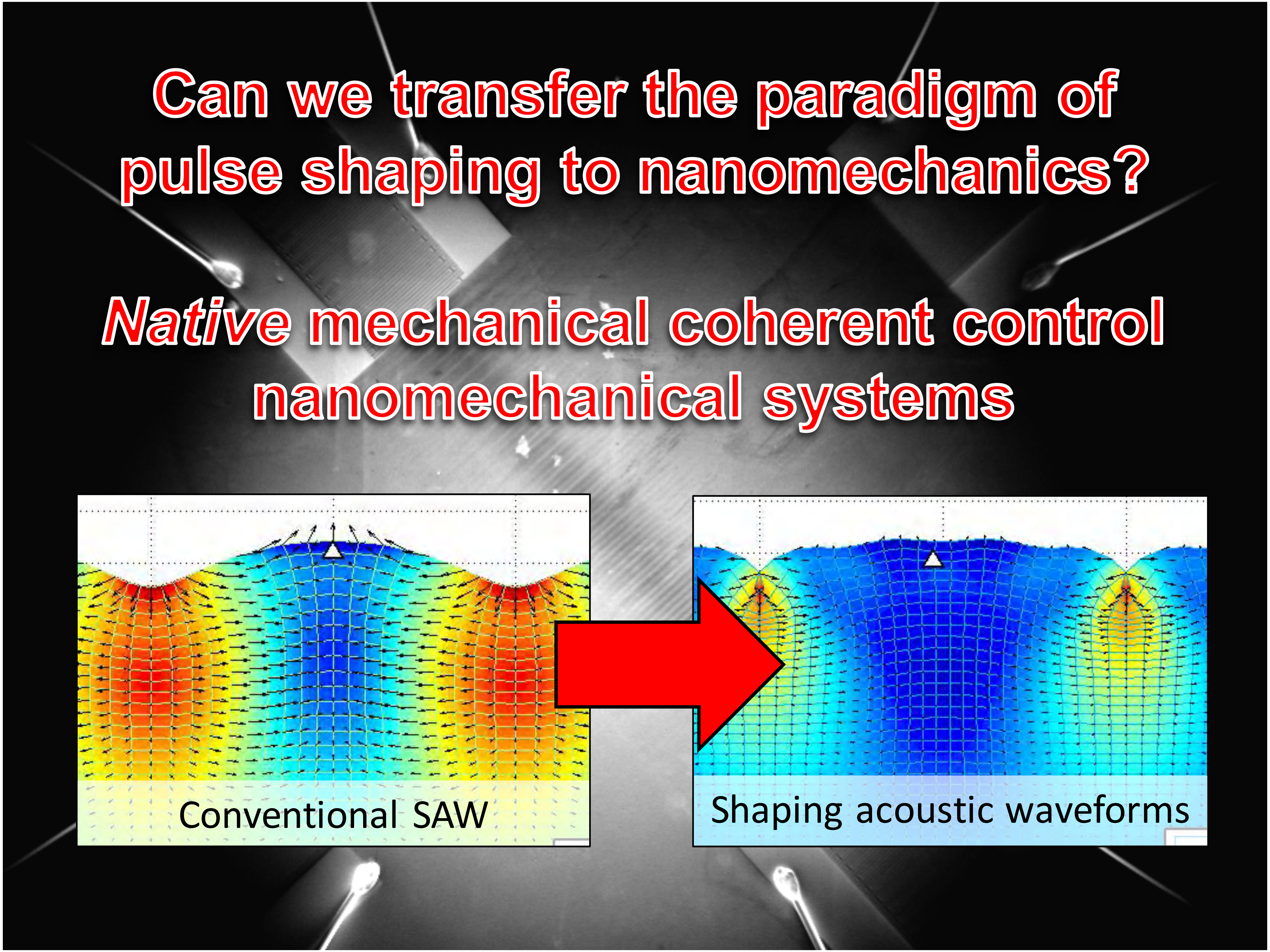
Optical frequencies

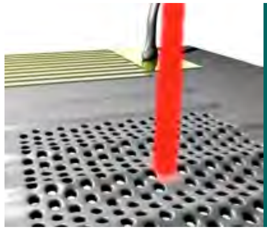


Chan, Science **331**, 1165 (2011)

Freeman, Chem. Rev. **91**, 1397 (1991)
Quantum gates:
Vandersypen, Rev. Mod. Phys. **76**, 1037 (2004)

Paradigm of pulse shaping is key to initialize and manipulate classical and quantum states


Can we transfer the paradigm of pulse shaping to nanomechanics?
Native mechanical coherent control nanomechanical systems
Conventional SAW
Shaping acoustic waveforms



Universität Augsburg University

UNITED STATES PATENT OFFICE

1,956,350

ELECTRICAL MUSICAL INSTRUMENT

Laurens Hammond, Chicago, Ill.

Application January 19, 1934, Serial No. 707,280

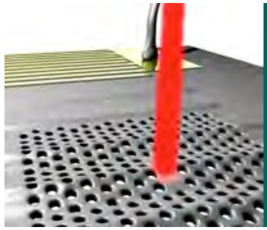
74 Claims. (Cl. 84—1)

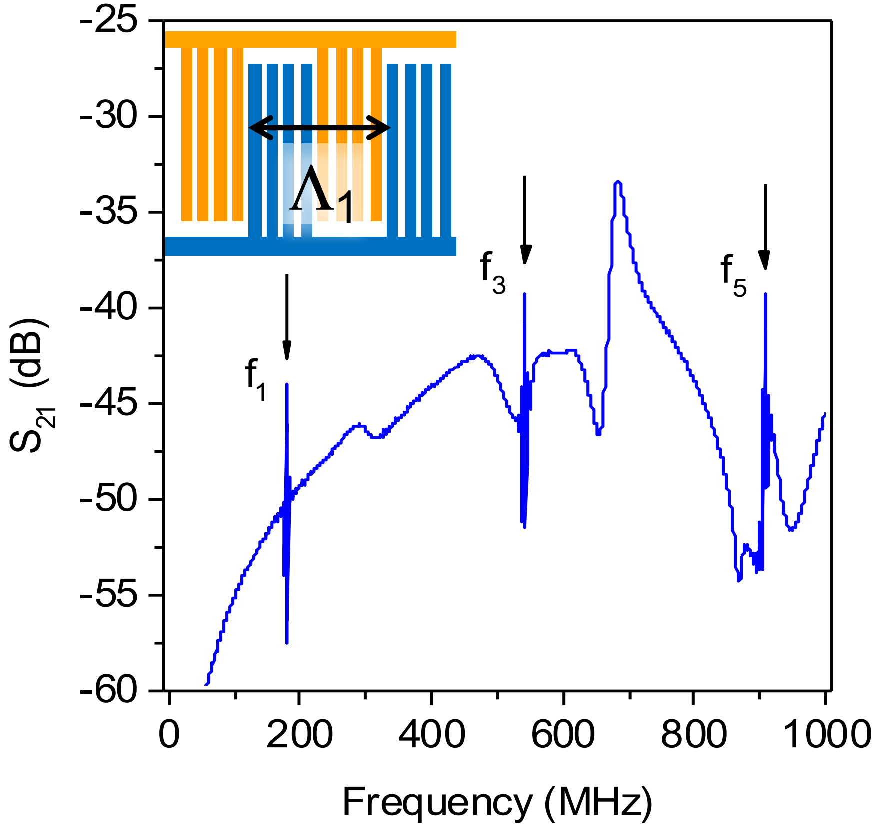
It is a well known fact that any sustained musical sound can be analyzed into sine wave components, and for a given pitch the tone may be analyzed into a fundamental tone of certain amplitude and various amplitudes of different harmonics of the fundamental. It has been found

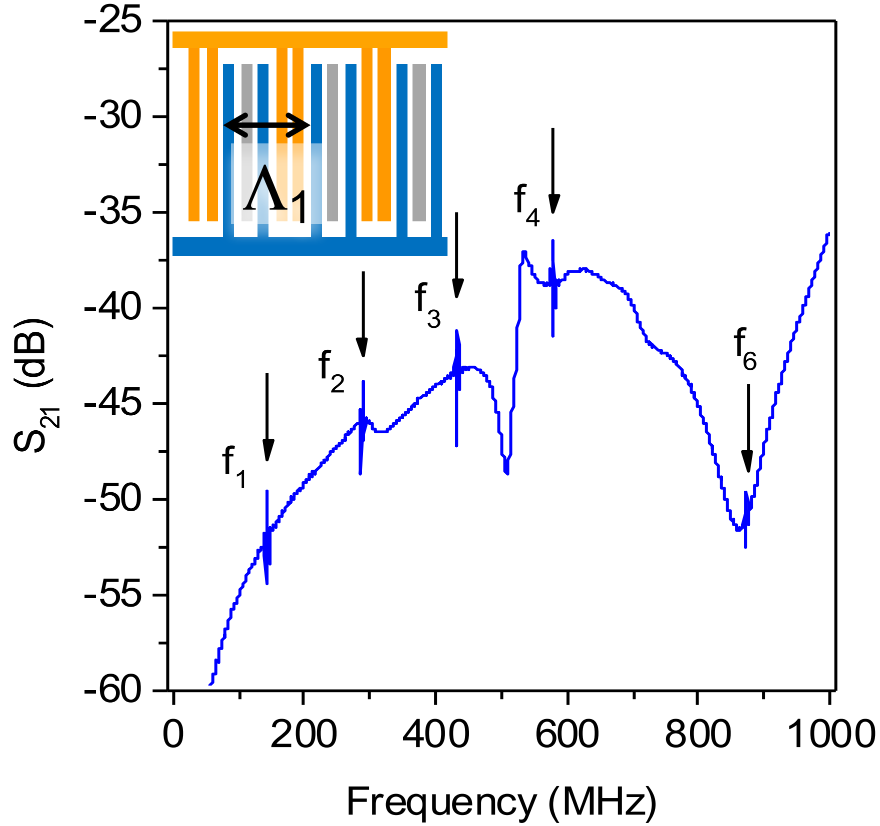
Fourier Series Expansion

Thus most musical tones may be produced by definite combinations of the fundamental tone with various proportions of the first eight harmonics.

Additive Fourier Synthesis

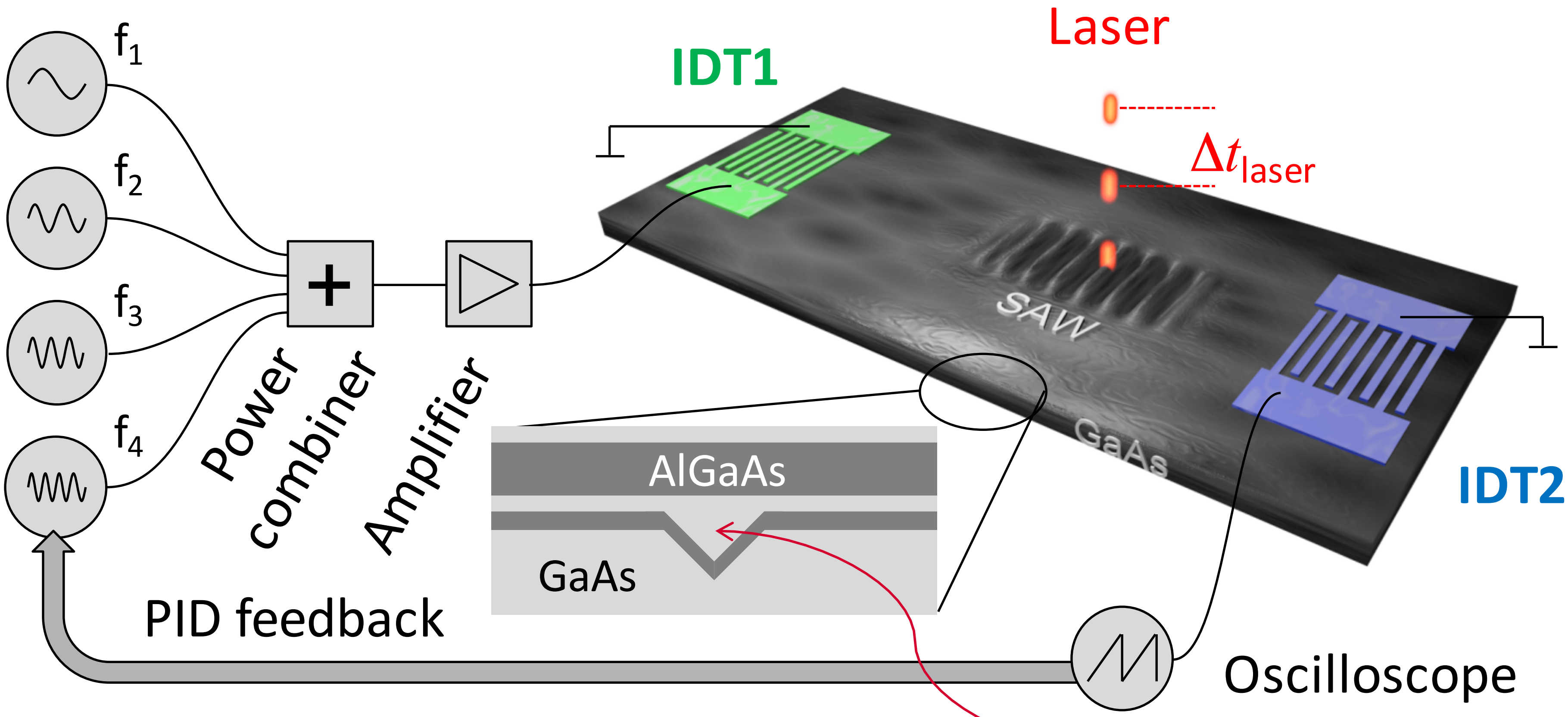






Split 4-design
odd harmonics only
n= 1,3,5,7,9

Split 52-design
even ***and*** odd harmonics
n= 1,2,3,4,6

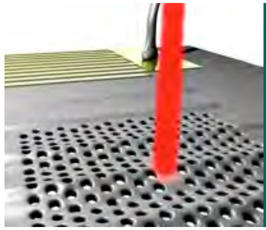


Optomechanical coupling
via deformation potential

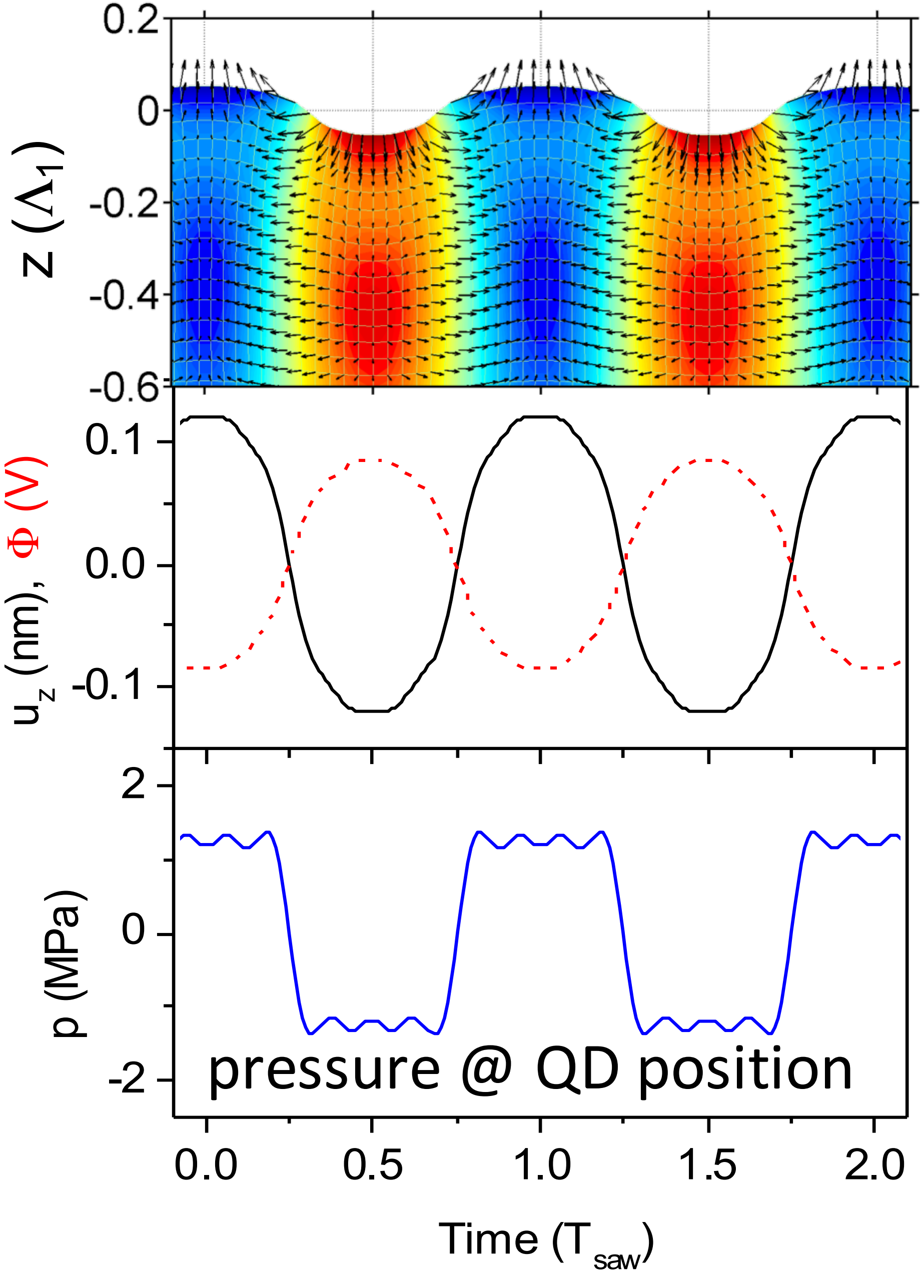
Nanoscale pressure sensor

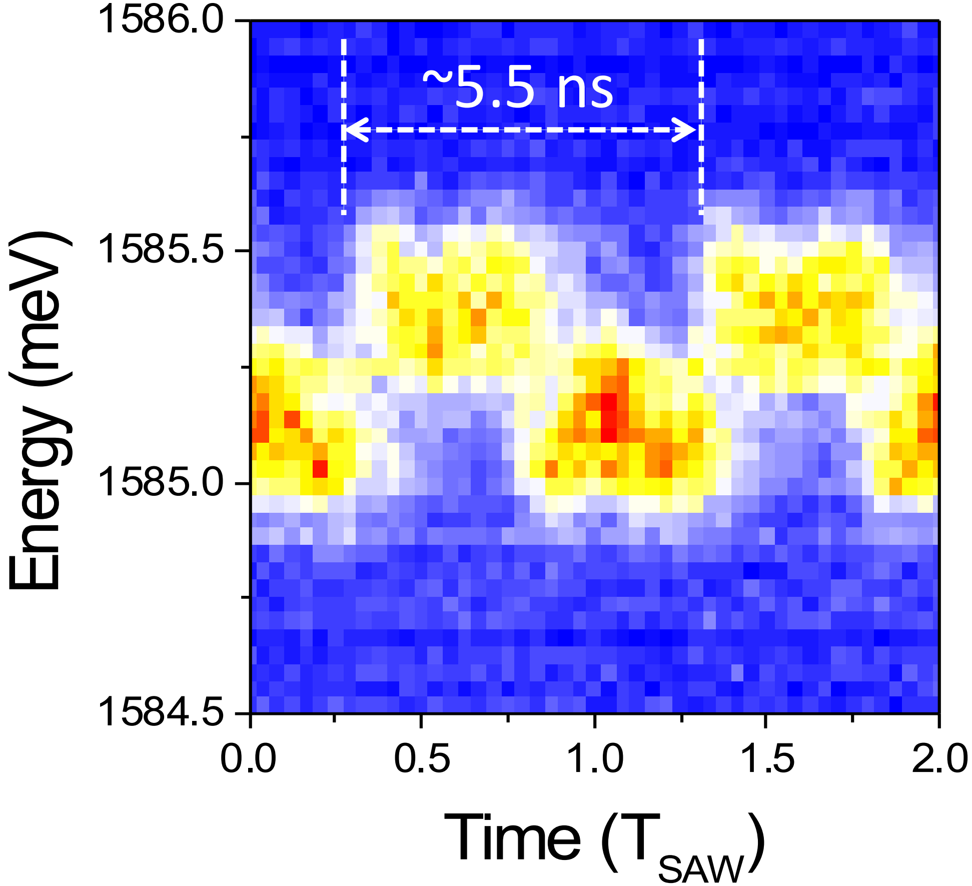
Single Quantum Dots
~ 100 nm below surface

Gell et al., Appl. Phys. Lett. **93**, 081115 (2008)

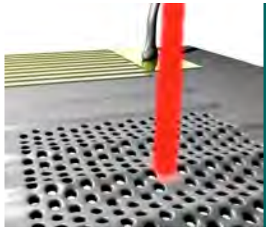


Example: Square wave

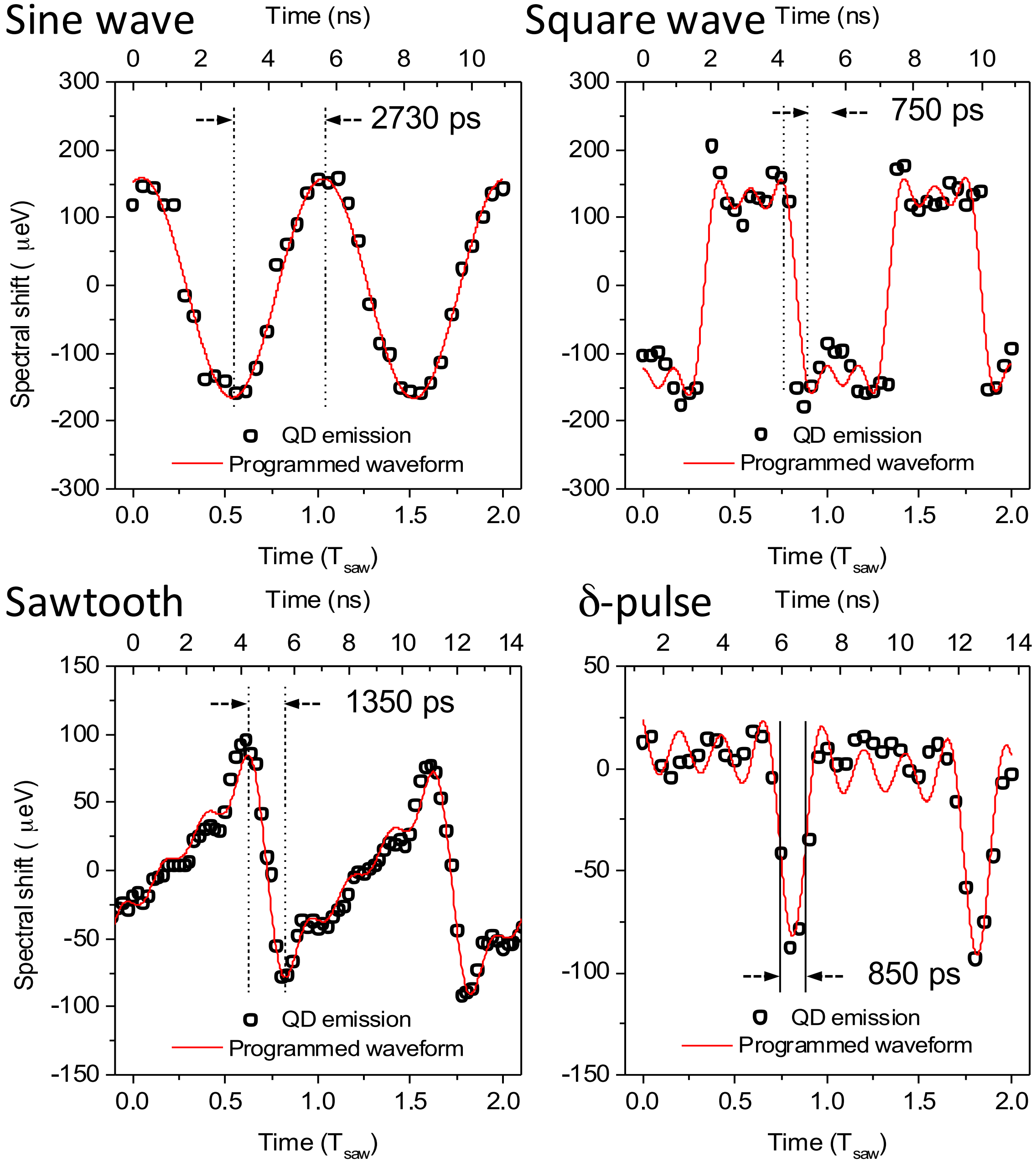


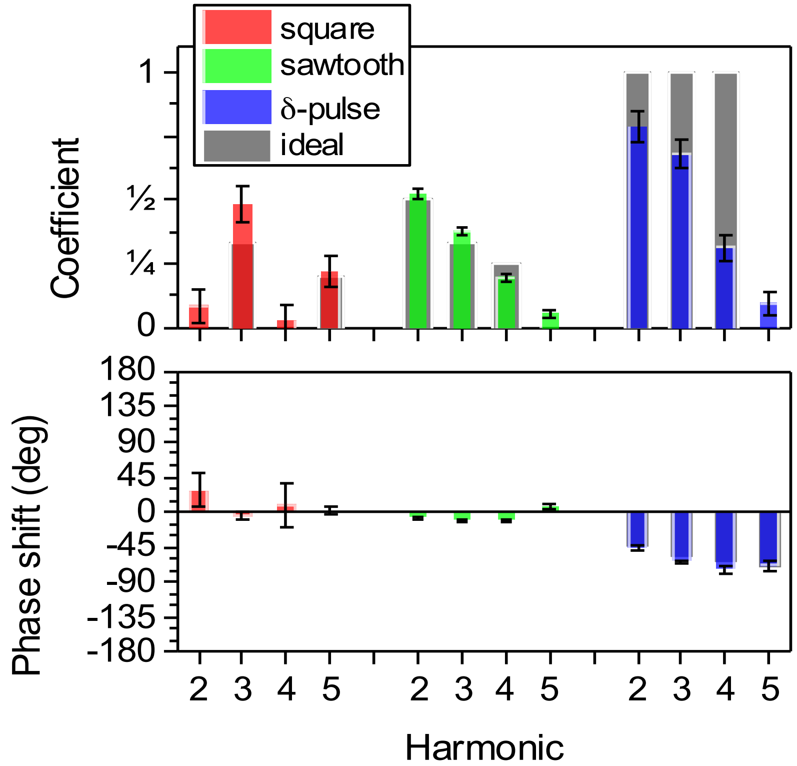


3-component nanomechanical square wave with f_1 = 183 MHz confirmed via a single QD's optomechanical response



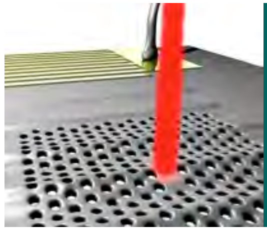
A close look…



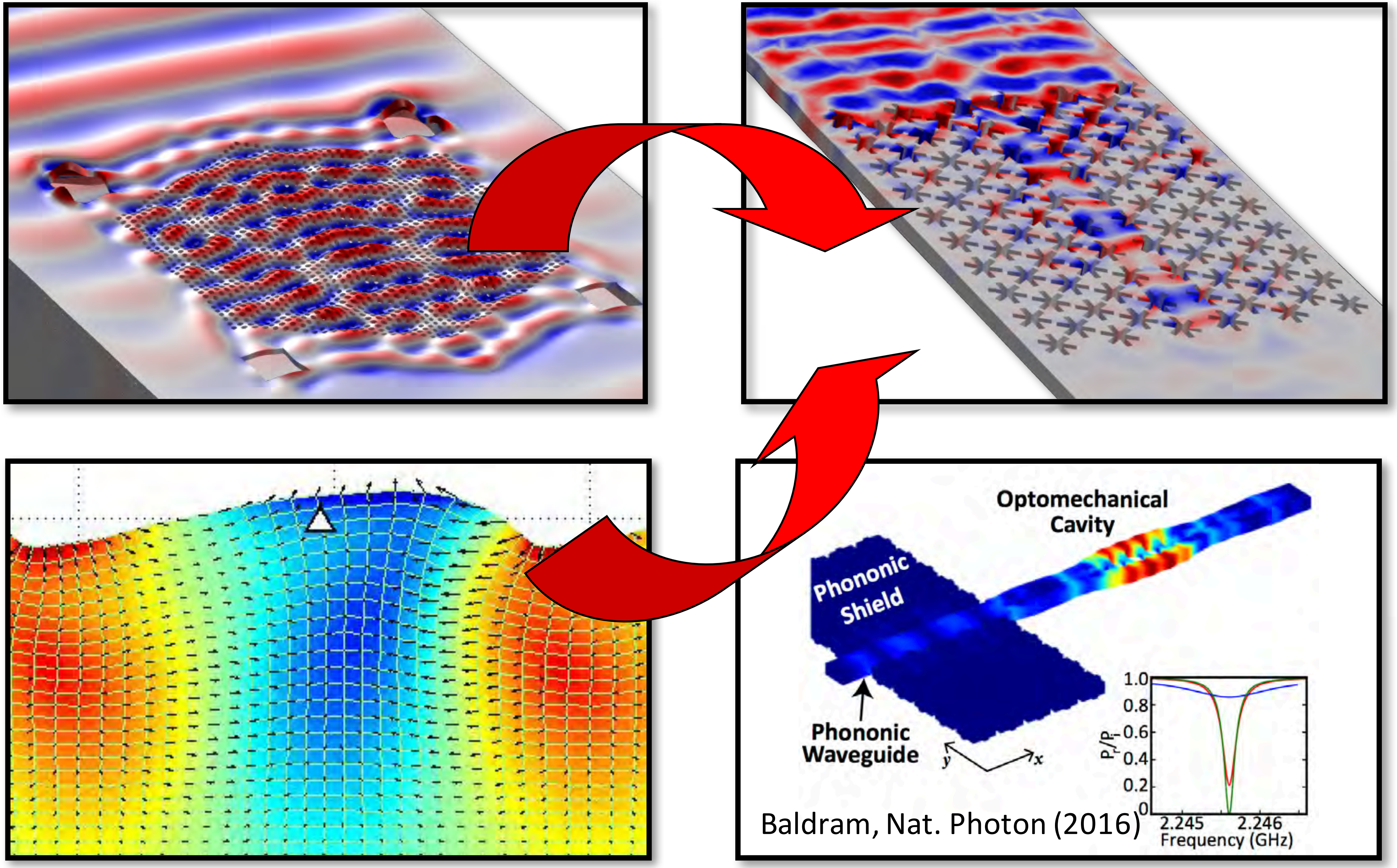


Direct observation of shaped and tailored classical phonon fields at radio frequencies

F. J. R. Schülein et al.,
Nature Nanotech. **10**, 512 (2015)



Perspectives



Baldram, Nat. Photon (2016)


SAWtrain Summer School
INSTITUT D'ÉTUDES SCIENTIFIQUES DE CARGÈSE
Physics and applications of GHz vibrations
Date: 11-21 July 2017
Place: Cargèse, Corsica, France
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