Controlling light and matter using cooperative radiation
Part II: 2D single-layer surfaces

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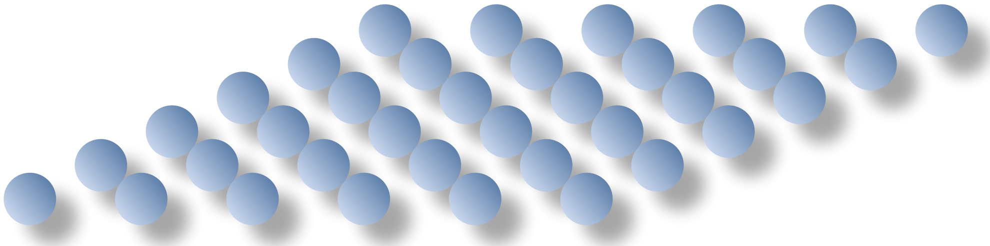
Herrsching, March 7, 2019

Idea

Mirror, consisting of

- single atomic layer,
- dilute,
- couples strongly to single photons,
- nonlinear, …

Quantum optics with atomically thin materials

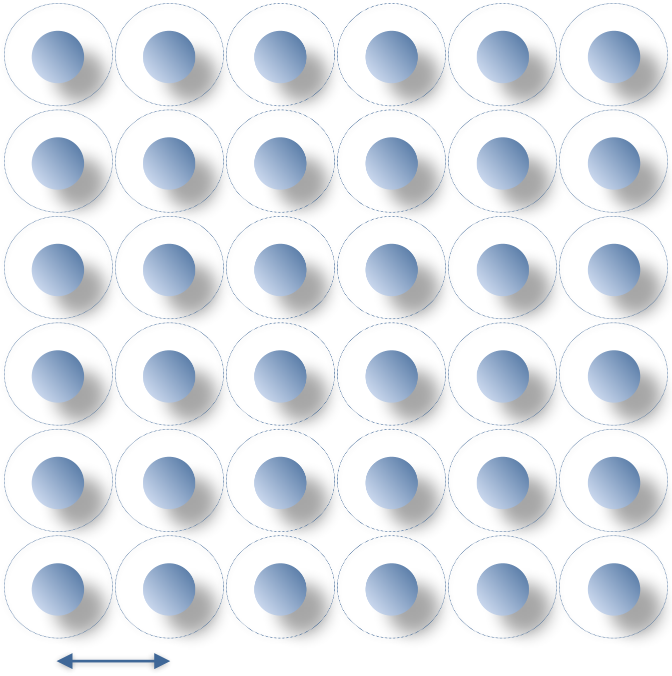


- ➡ can have very strong optical response
- ➡ optical response can be engineered
- ➡ guided modes can be constructed for 2d materials, e.g., for topological phenomena

“atomic metasurfaces”

Simple example: Idea & Setup

array of atoms



$a \sim \lambda$

Complete Reflection!

for $a/\lambda = 0.2$
and $a/\lambda = 0.8$

Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)
cf. Bettles, Gardiner, Adams, PRL **116**, 103602

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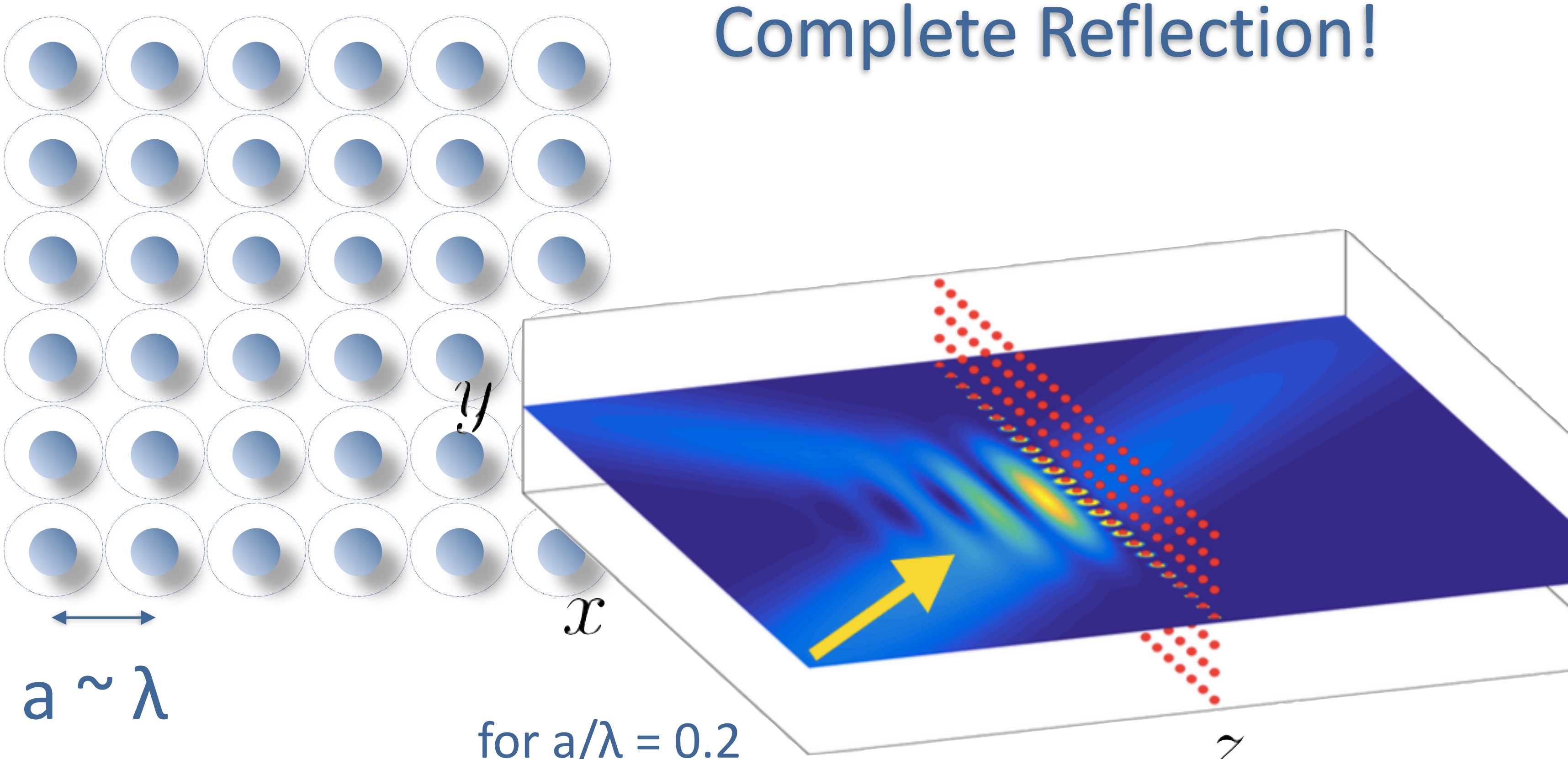

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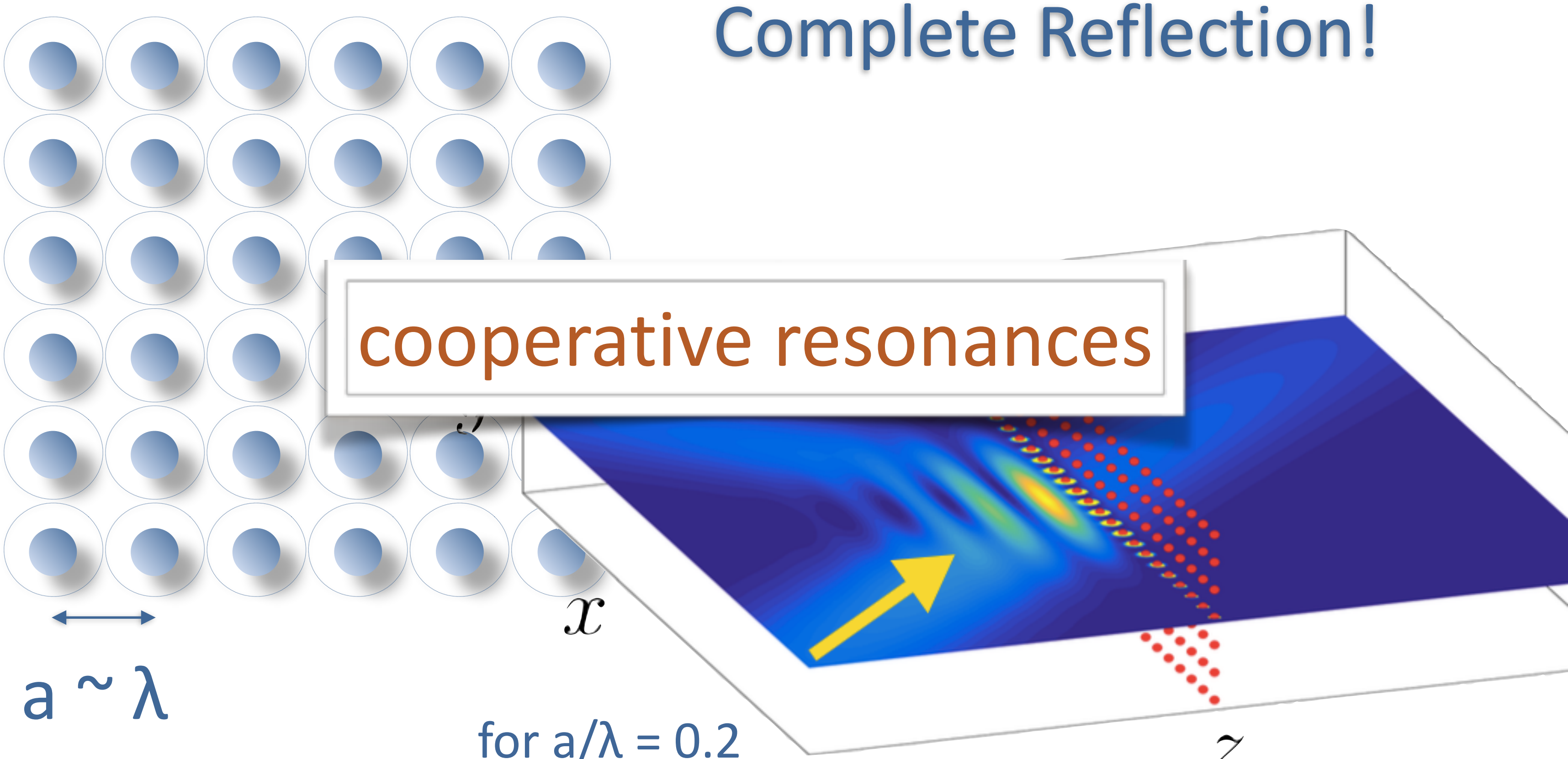

cooperative resonances

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Perfect Reflection

$$\boxed{E_{out} = E_0 \left(e^{ik_z z} + S e^{ik_z |z|} \right)}$$

$$S = -1$$

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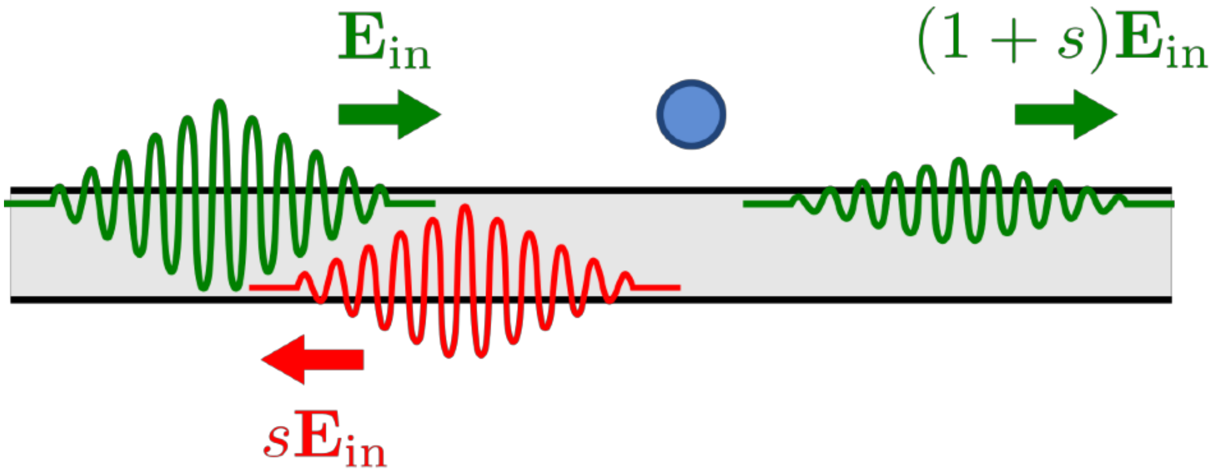
Perfect Reflection

- compare to reflection/transmission of single atom



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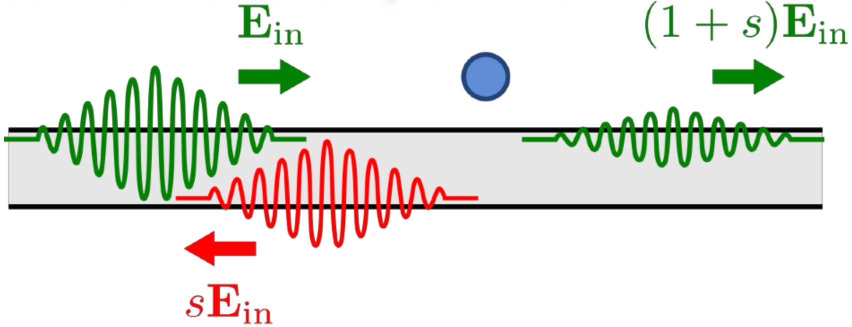

$$\boxed{E_{out} = E_0\left(e^{ik_z z} + Se^{ik_z|z|}\right)}$$

$$S = -\frac{i}{2}\frac{\gamma}{\delta + \frac{i}{2}\gamma}$$

$$\Rightarrow \quad S = -1 \quad \text{for} \quad \delta = 0$$

Perfect Reflection

$$\boxed{E_{\mathrm{out}} = E_0 \left(e^{ik_z z} + S e^{ik_z |z|} \right)}$$

$$S = -\frac{i}{2} \frac{\gamma + \Gamma_{\mathrm{coll}}}{\delta + \Delta_{\mathrm{coll}} + \frac{i}{2}(\gamma + \Gamma_{\mathrm{coll}})}$$

where $\Delta_{\mathrm{coll}} - \frac{i}{2}\Gamma_{\mathrm{coll}} =$ dipolar interaction between all atoms

Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)

Form of collective terms

Sum up all dipole-dipole interactions for each atom with all others:

$$\Delta - \frac{i}{2}\Gamma = -\frac{3}{2}\gamma\lambda \sum_{n \neq 0} G(0, \mathbf{r}_n),$$

Analytical/Numerial form depends on lattice symmetry —
But: only for Δ, not for Γ:

$$\Gamma = \gamma \frac{3}{4\pi} \boxed{\left(\frac{\lambda}{a}\right)^2} - \gamma$$

for all lattices!

Perfect Reflection

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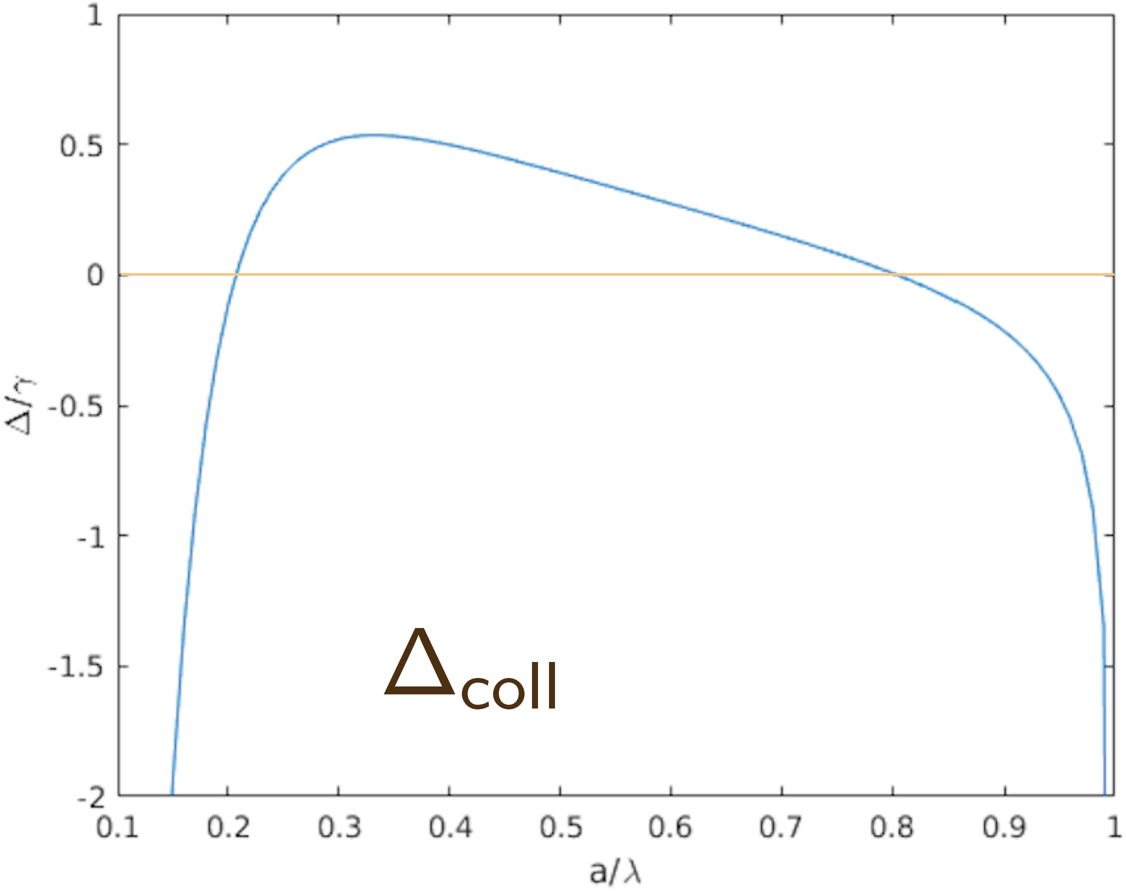
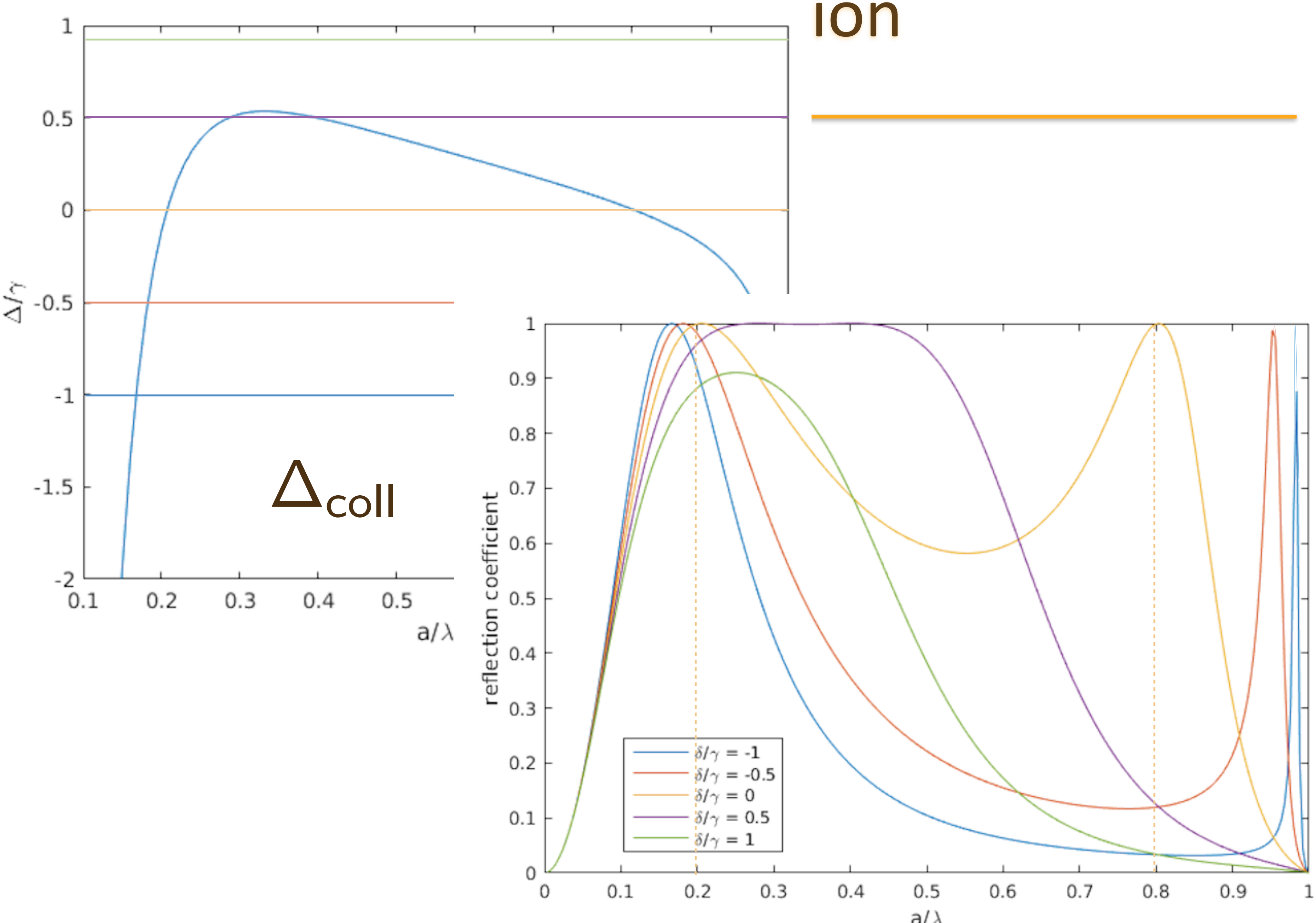
ion



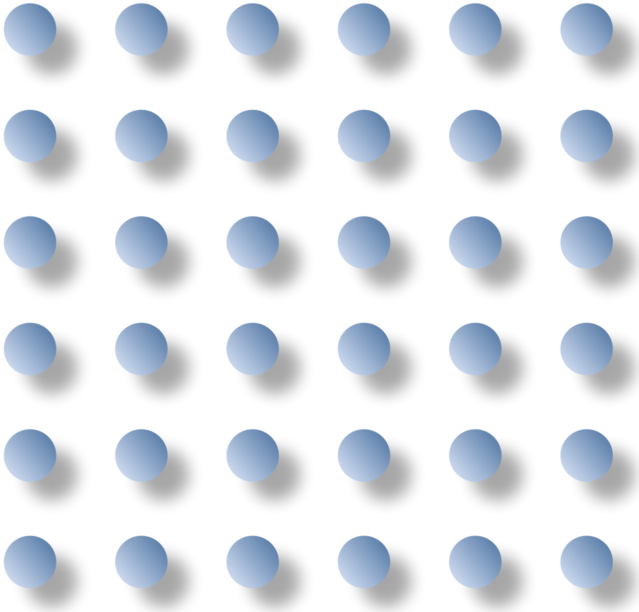
Δ_{coll}

ion



Δ/γ
a/λ
Δ_{coll}
1
0.5
0
-0.5
-1
-1.5
-2
0.1
0.2
0.3
0.4
0.5
reflection coefficient
a/λ
δ/γ = -1
δ/γ = -0.5
δ/γ = 0
δ/γ = 0.5
δ/γ = 1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Works for other lattices



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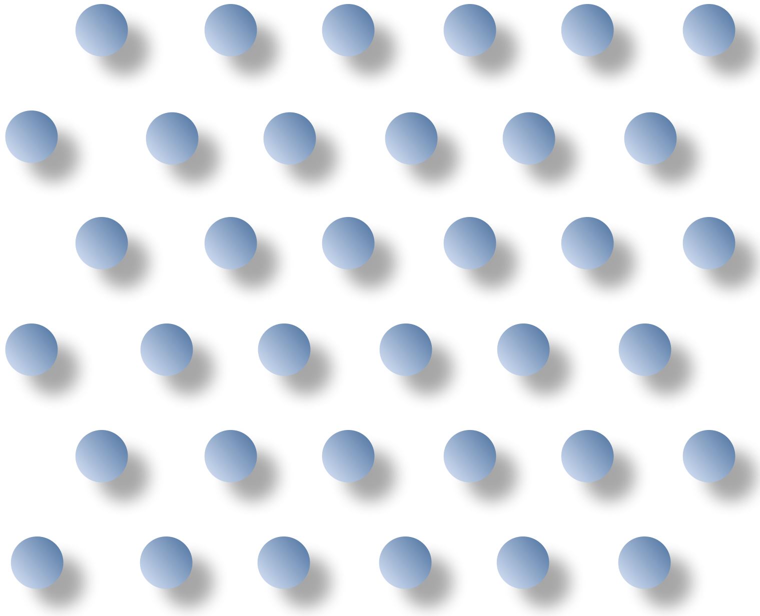

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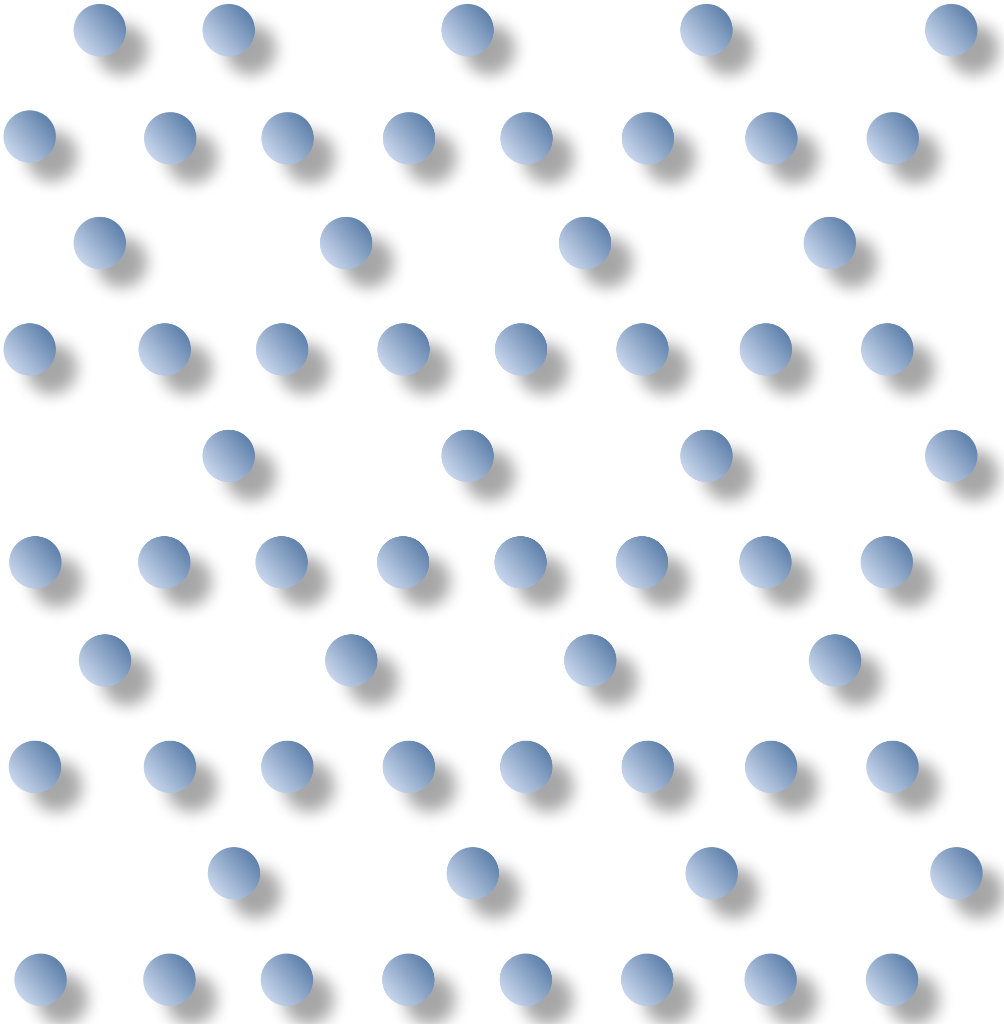

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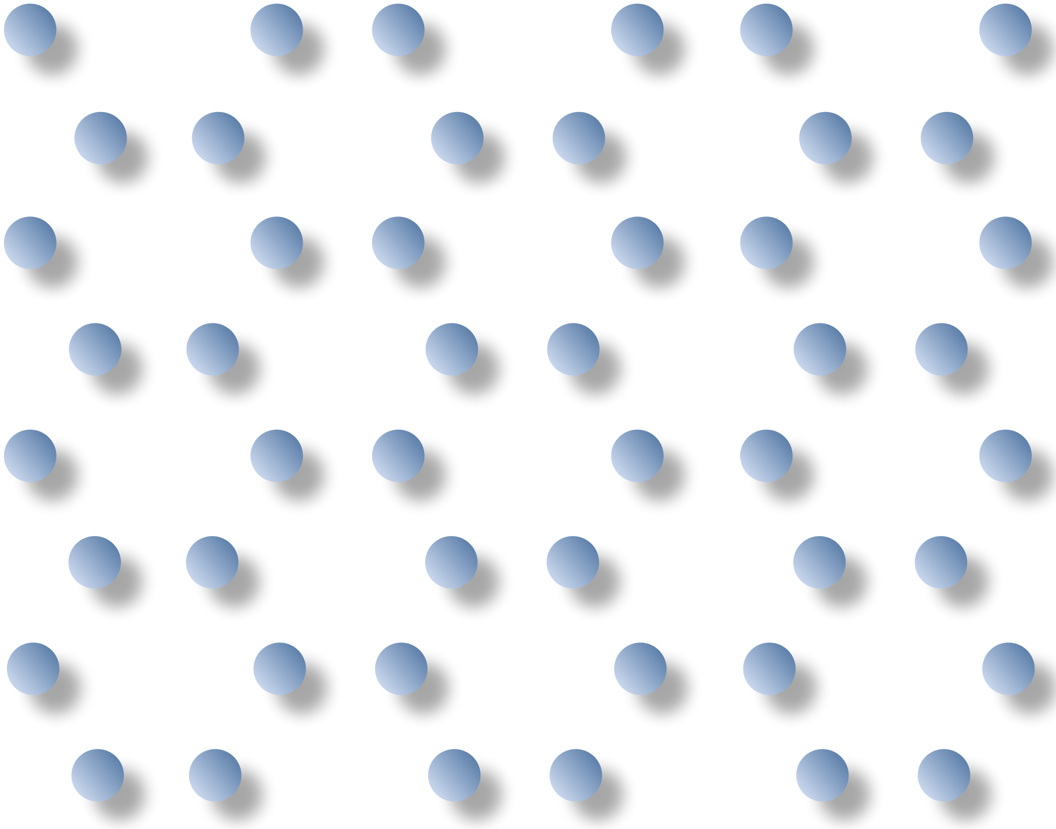
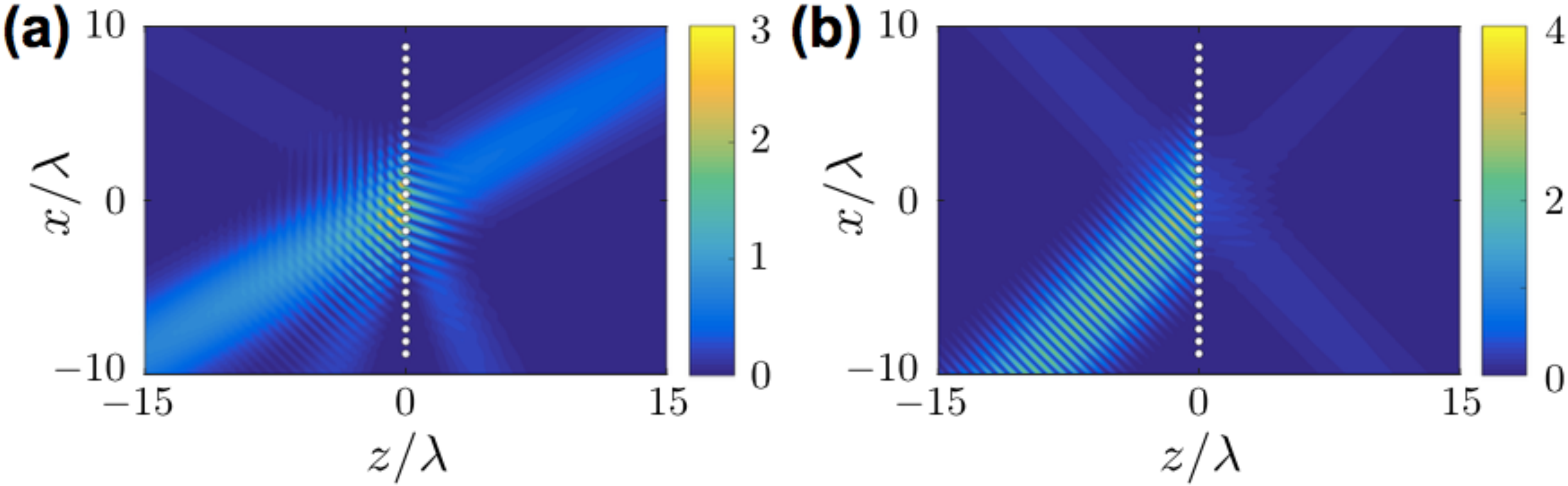


3D setup



Incoming light with all polarizations
from all directions

Experiments?

With non-radiative losses:

$$S = -\frac{i}{2}\frac{\gamma + \Gamma_{\text{coll}}}{\delta + \Delta_{\text{coll}} + \frac{i}{2}\left(\gamma_{\text{nr}} + \gamma + \Gamma_{\text{coll}}\right)}$$

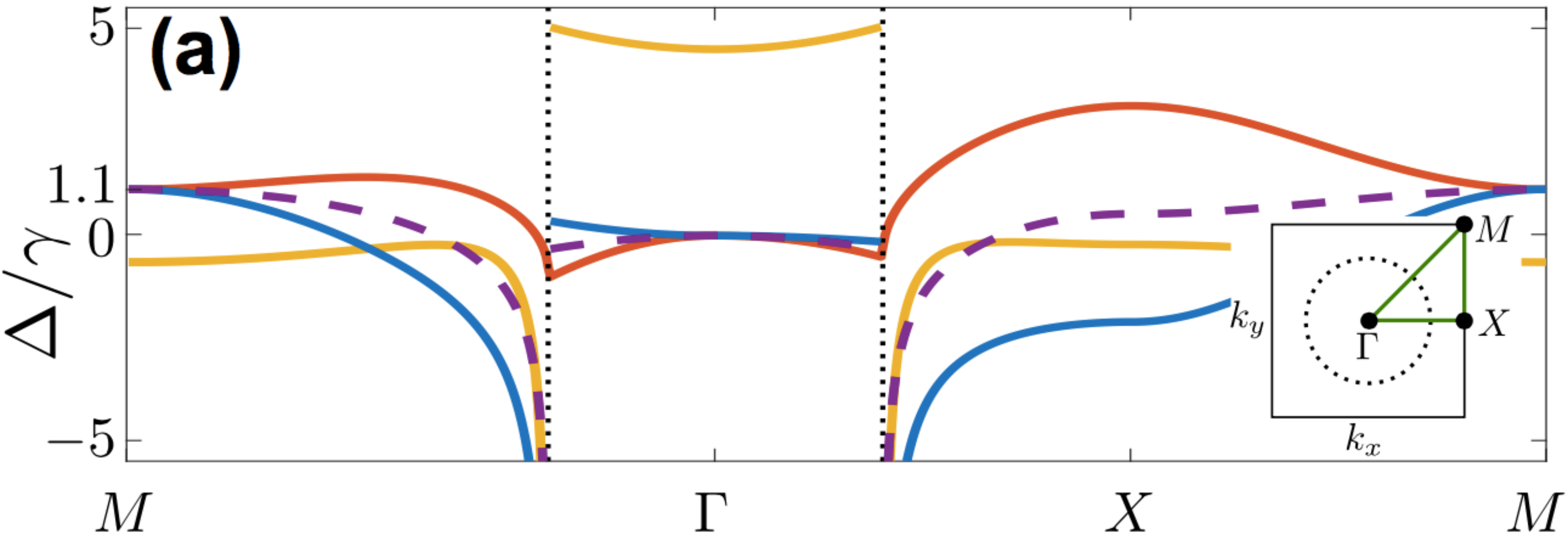
For large Δ_{coll} and Γ_{coll}, non-radiative losses don't play a role!

Perfect Reflection - 3D

$$\boxed{\frac{\gamma + \underline{\underline{\Gamma}}_{\text{coll}}}{\delta + \underline{\underline{\Delta}}_{\text{coll}} + \frac{i}{2}\left(\gamma + \underline{\underline{\Gamma}}_{\text{coll}}\right)}}$$

3D setup

Dispersion relation of collective surface dipole excitations



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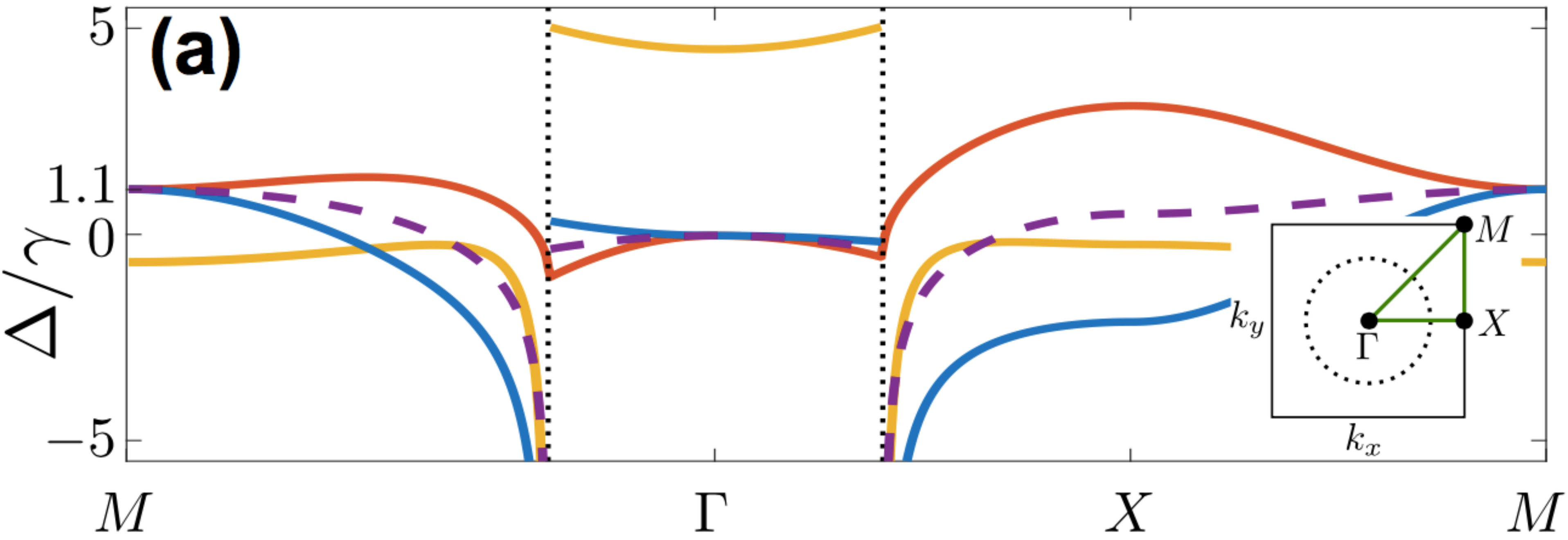

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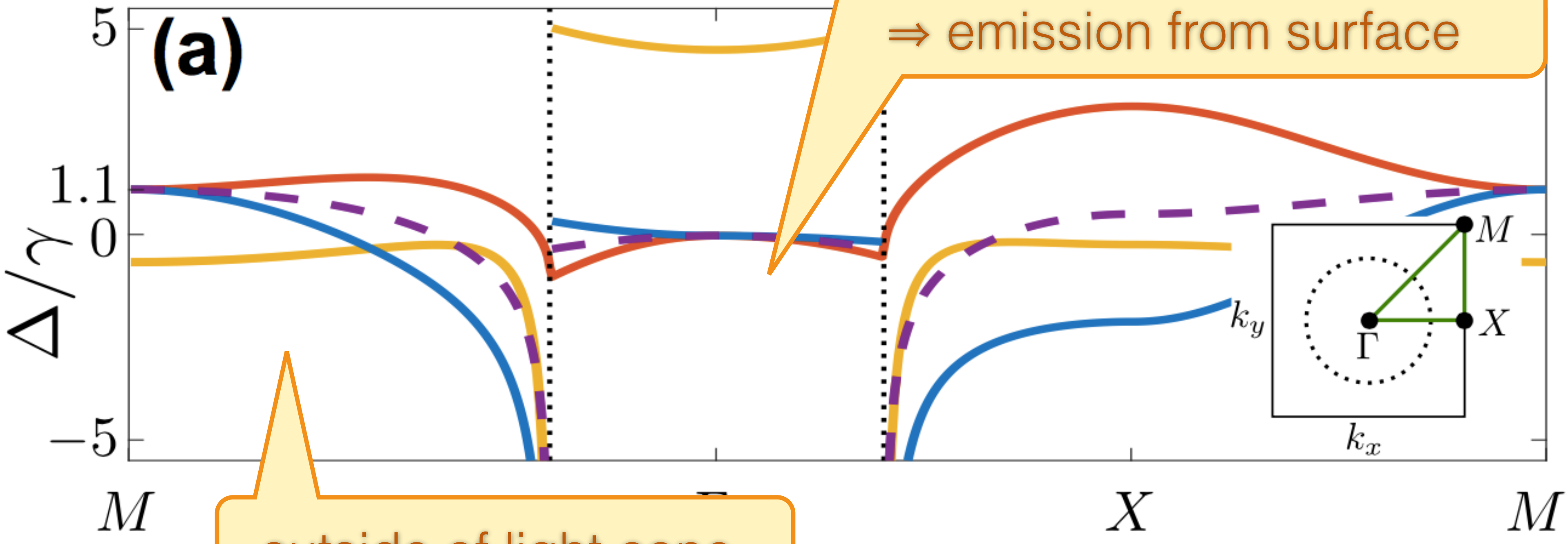
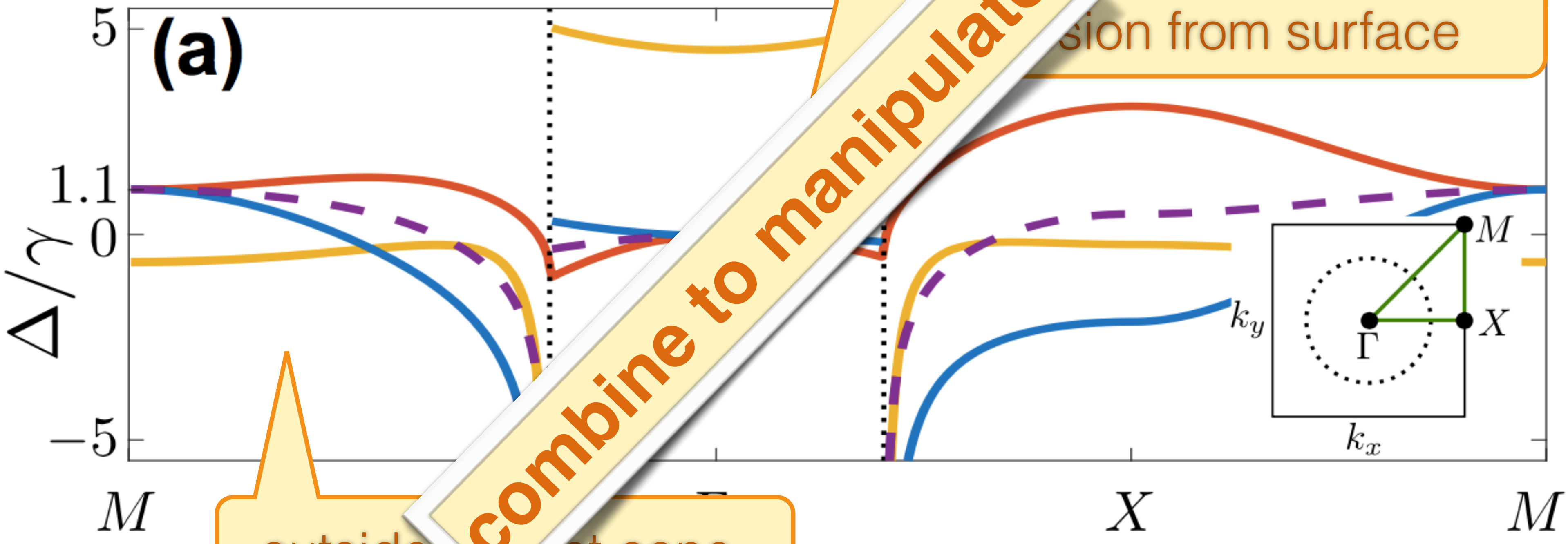


within light cone: couples to far-field (perpendicular) radiation
⇒ emission from surface

outside of light cone
⇒ surface waves only

3D setup



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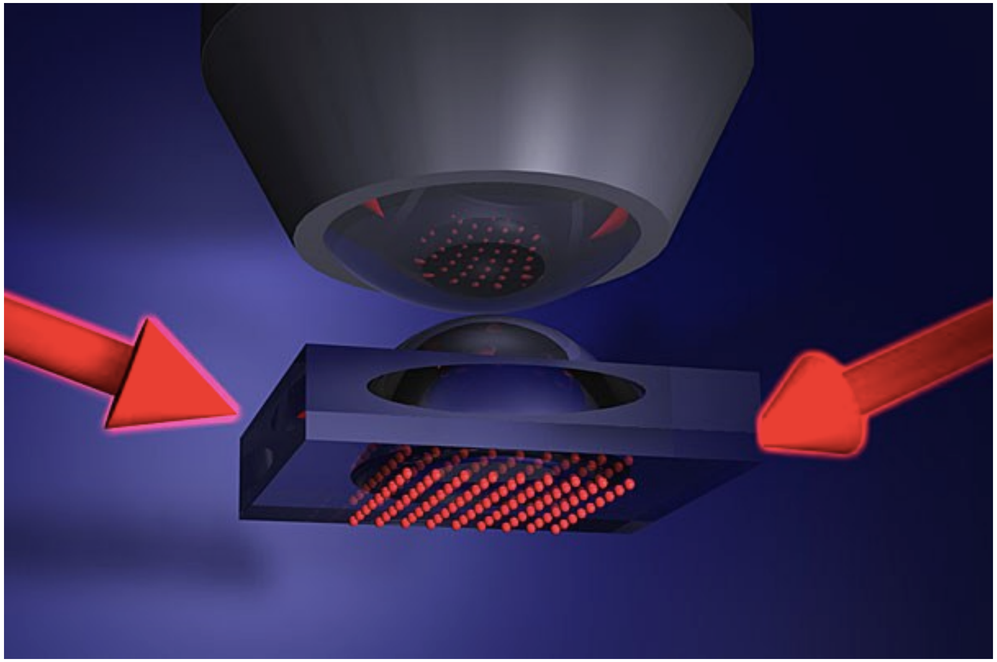
combine to manipulate

Implementations

Examples:

- atoms in optical lattice



Markus
Greiner

Implementations

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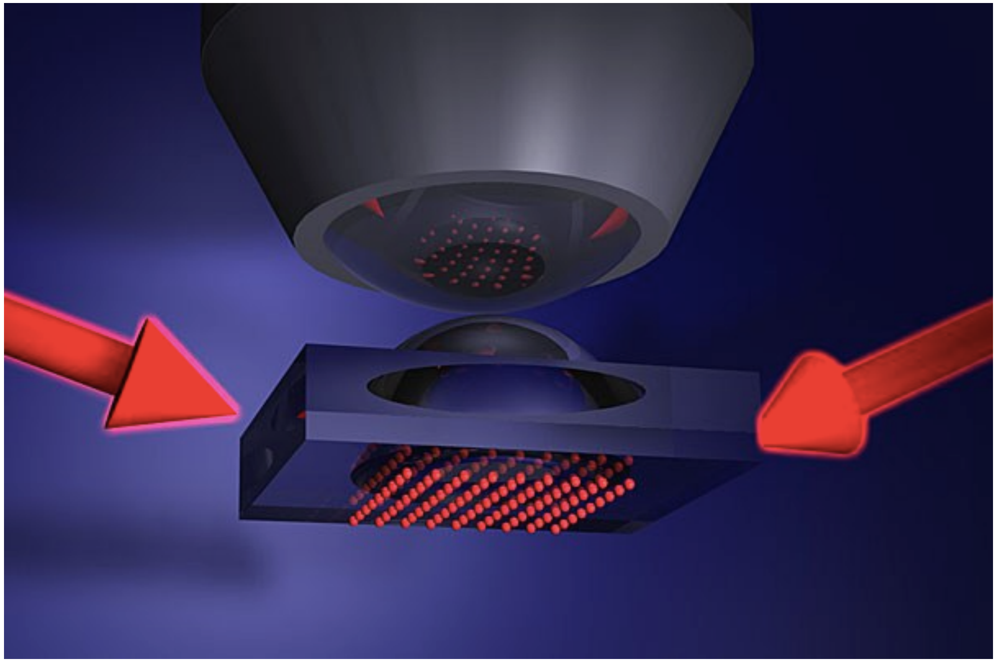

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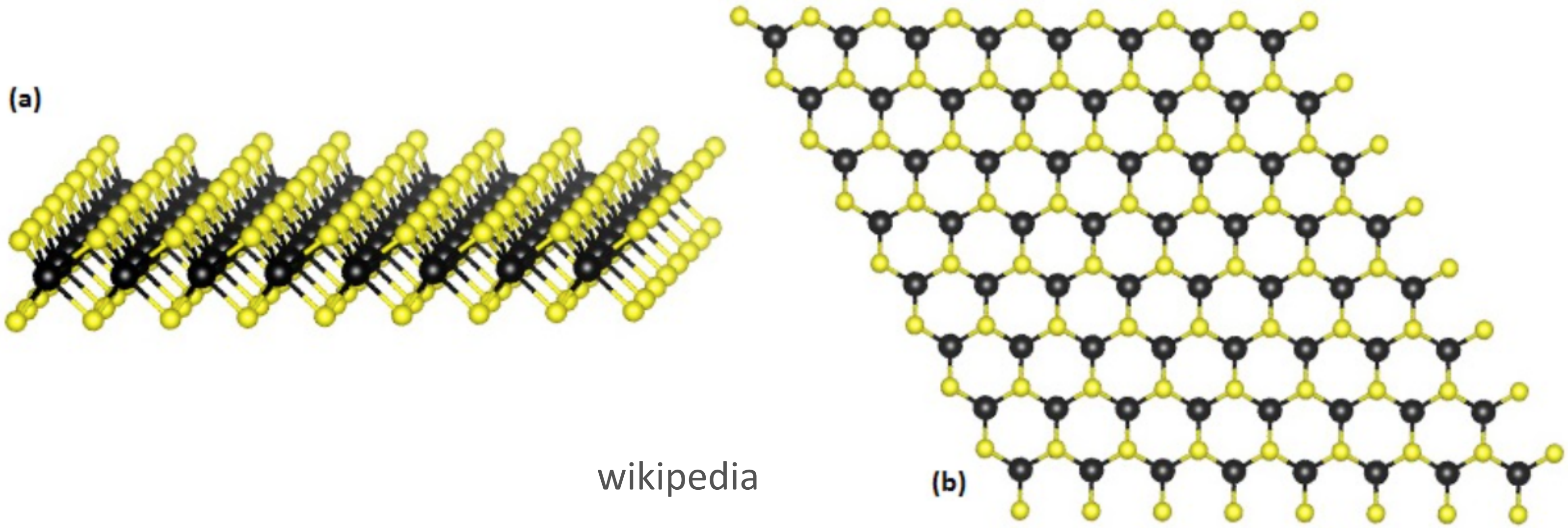
- solid state 2D semiconductors

Implementation in solid state 2D

Excitons in transition metal dichalcogenides (MoS_2, WSe_2, …)



wikipedia

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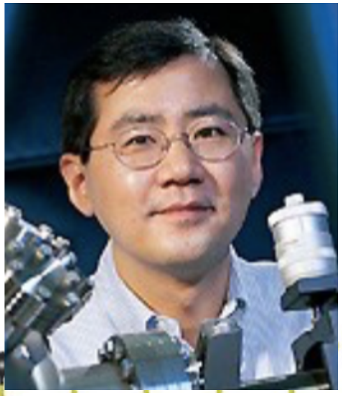
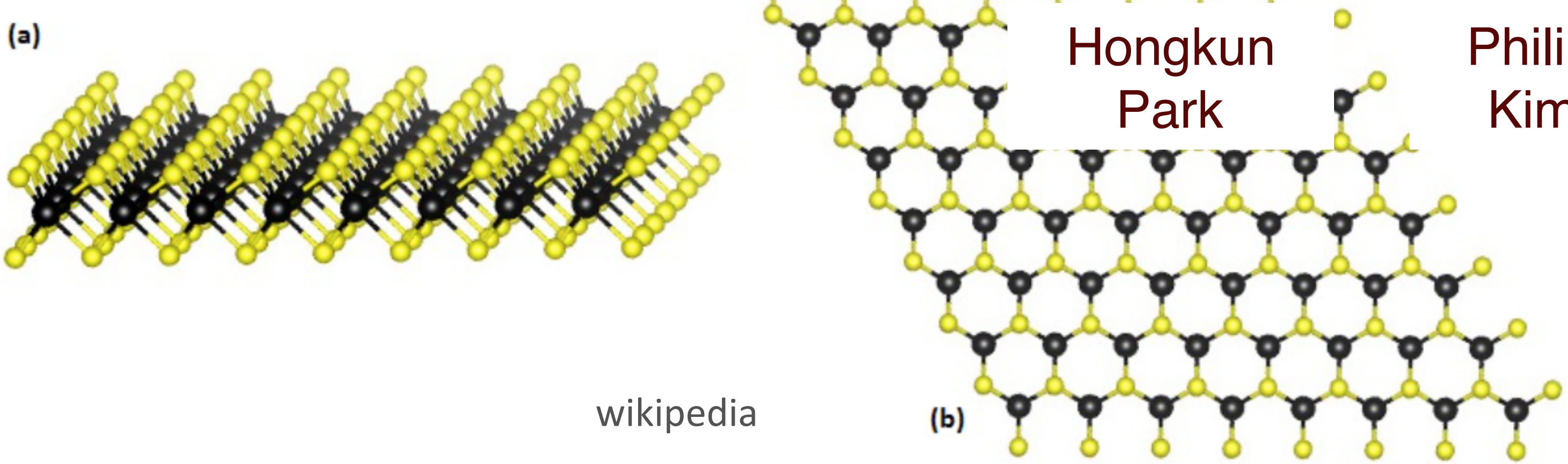


Hongkun Park

Philip Kim



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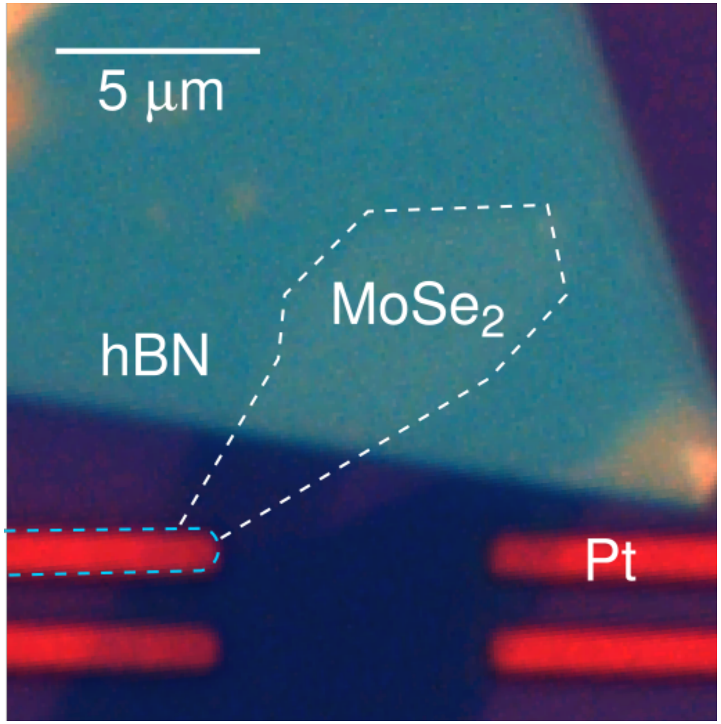
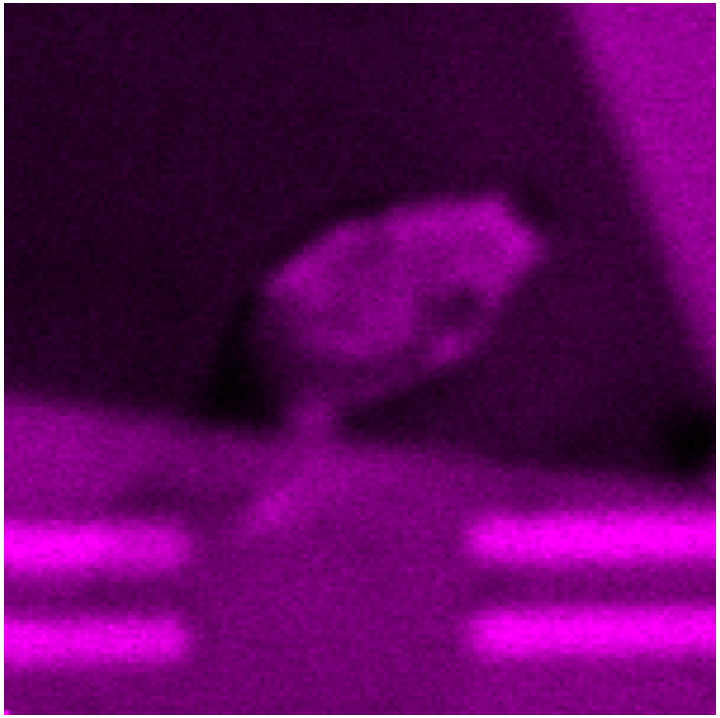
Reflection measurements in $MoSe_2$

- Monolayer is excellent reflector near exciton resonance





Scuri, Zhou, High, Wild, Shu, De Greve, Jauregui, Taniguchi, Watanabe, Kim, Lukin, Park, PRL **120**, 037402
Back, Zeytinoglu, Ijaz, Kroner, Imamoğlu, PRL **120**, 037401

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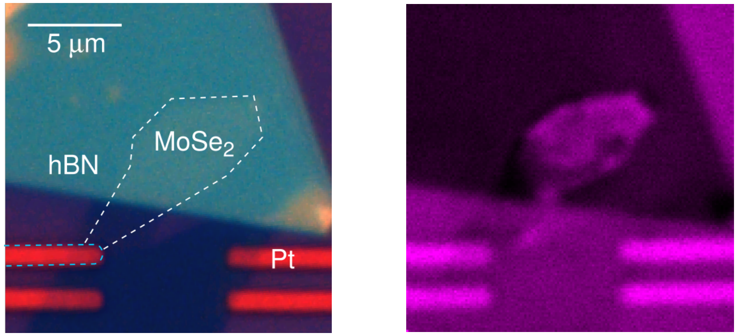
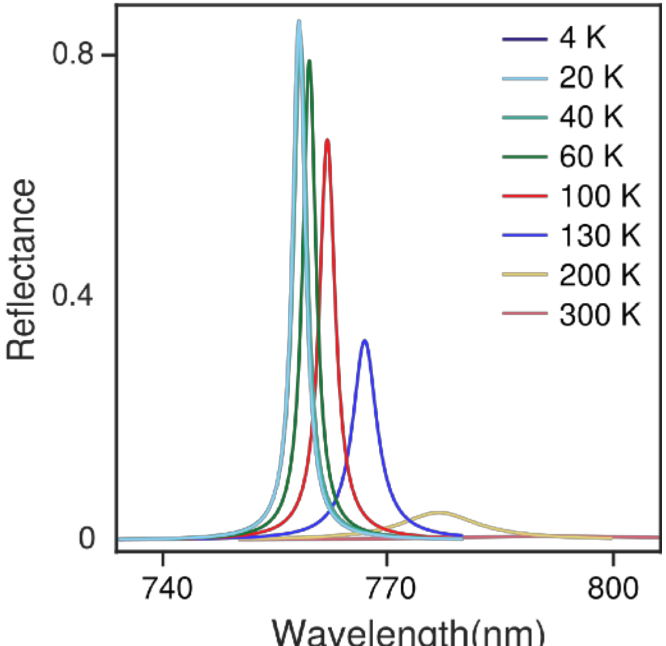
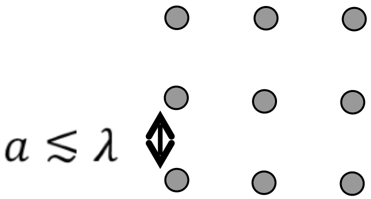




Outlook:quantum optical metamaterials

Metamaterials: Bottom-up design of collective response

	Classical photonics	**Quantum: 2D atom array**
Building blocks	nano-resonators/antennas  Meta-surfaces: Capasso, Hasman, Shalaev,… → classical macroscopic objects	individual atoms  $a \lesssim \lambda$ → Quantum objects: highly nonlinear, extremely light
Designed properties	beam profile, phase,…	**- Quantum states of light**

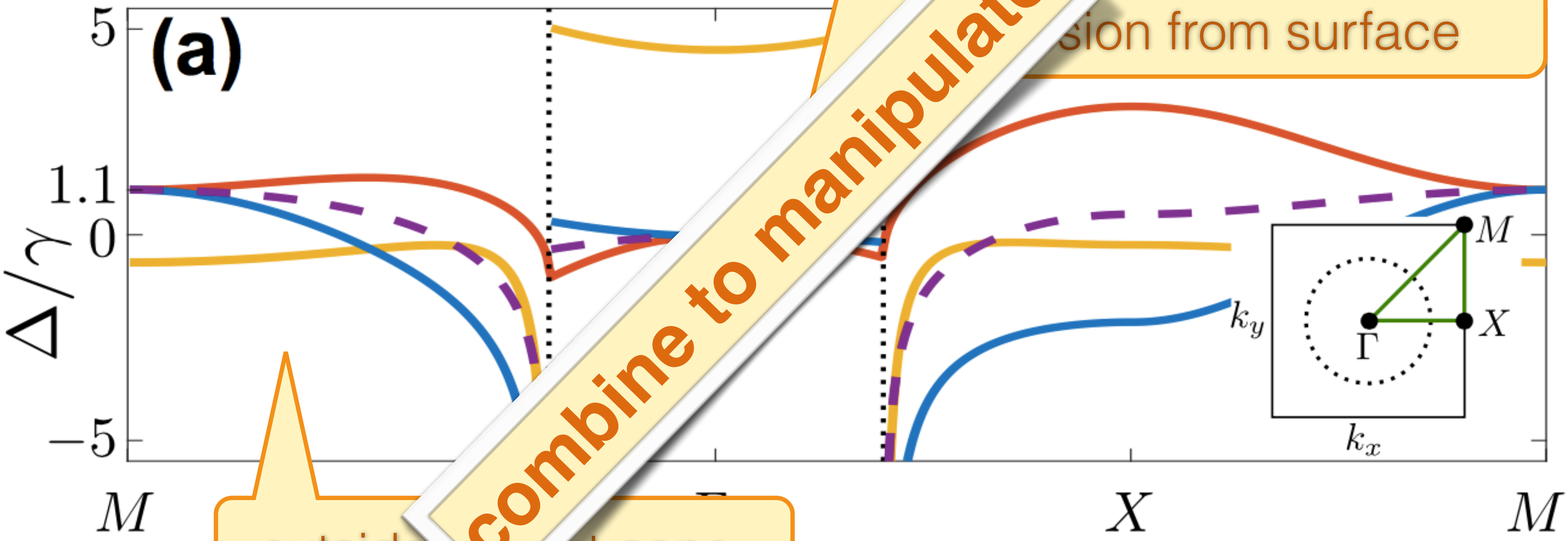
The vision: Optical tool made of quantum matter

This talk

- Cooperative effects in complex systems

- New application: atomically thin mirrors
  - Cooperative resonances
  - Applications
    - topology with photons
    - nonlinear quantum optics
    - Quantum metasurfaces

3D setup



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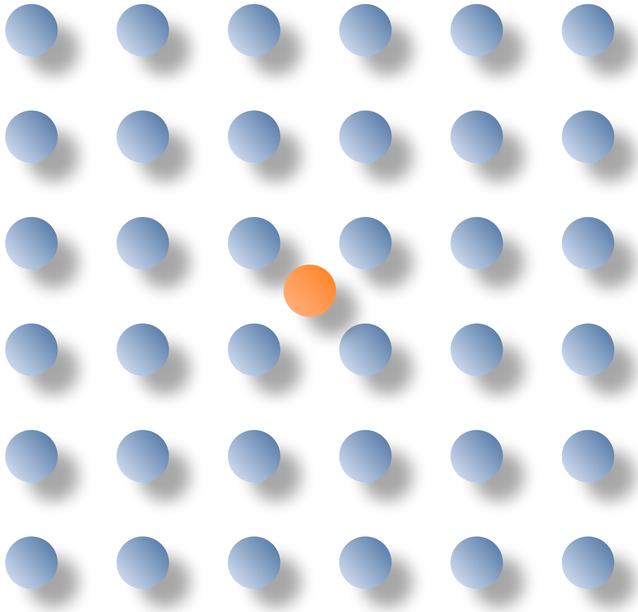
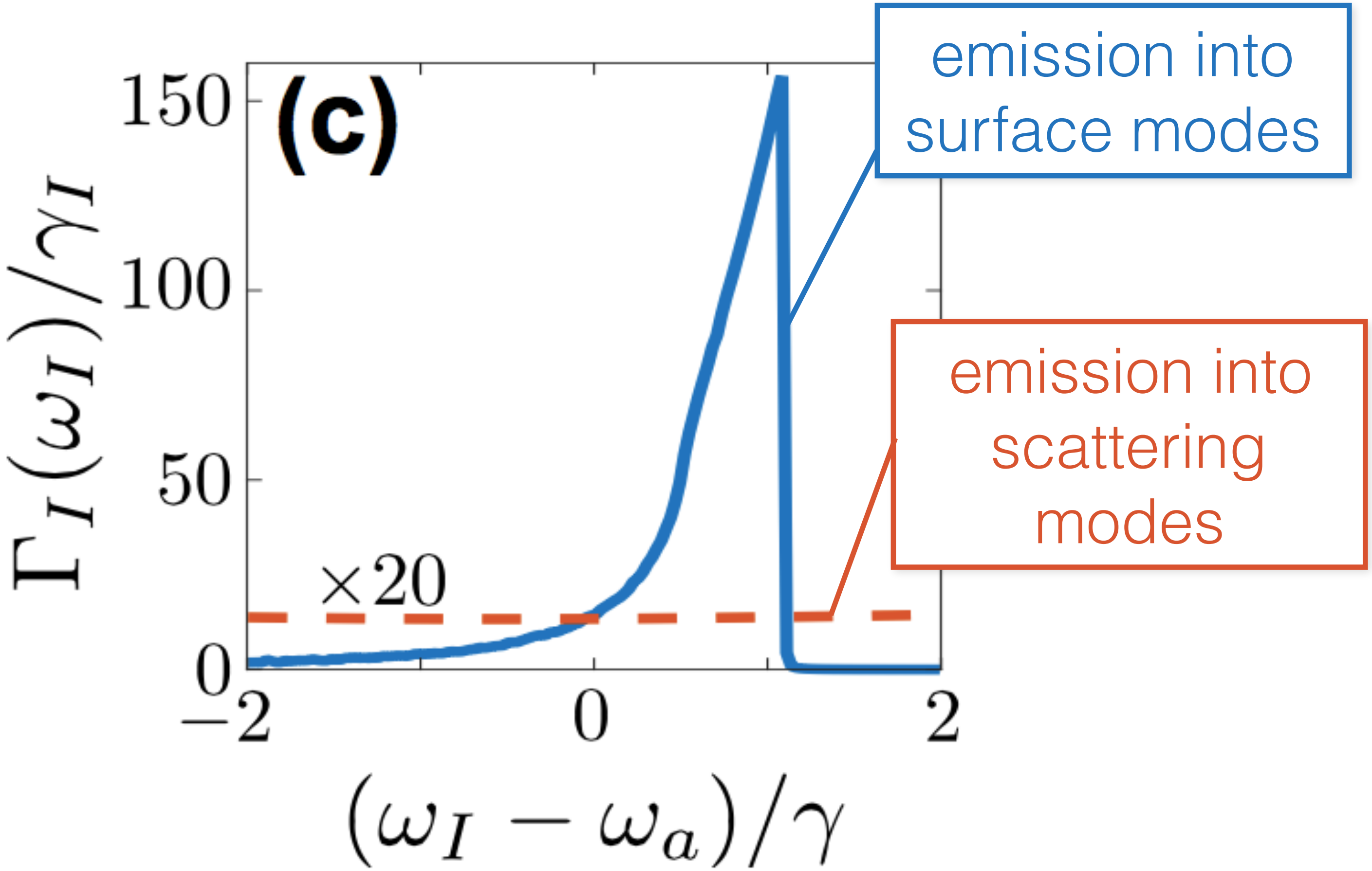
Single-photon manipulation: an example

- Starting point: one impurity excitation in lattice



Single-photon manipulation: an example

- Emission into collective surface modes:

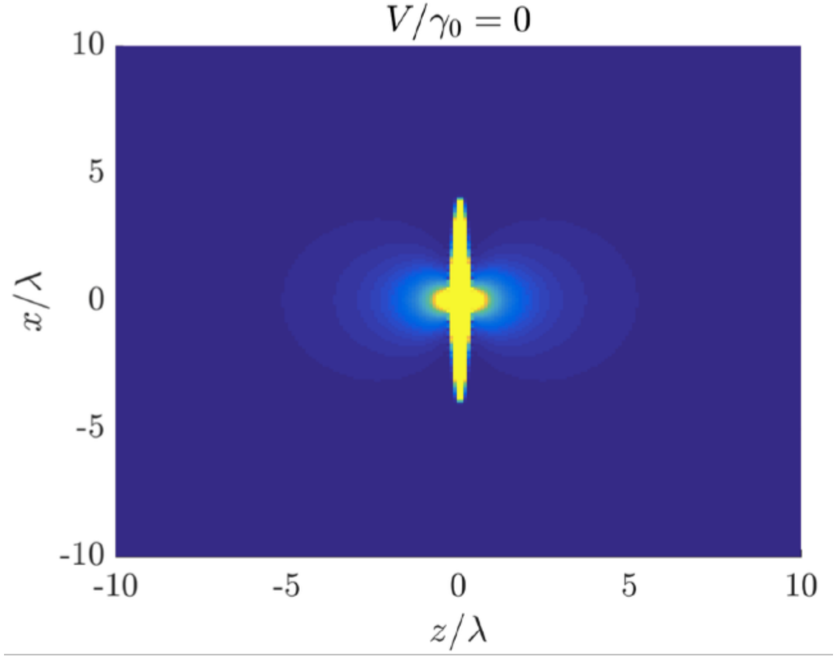


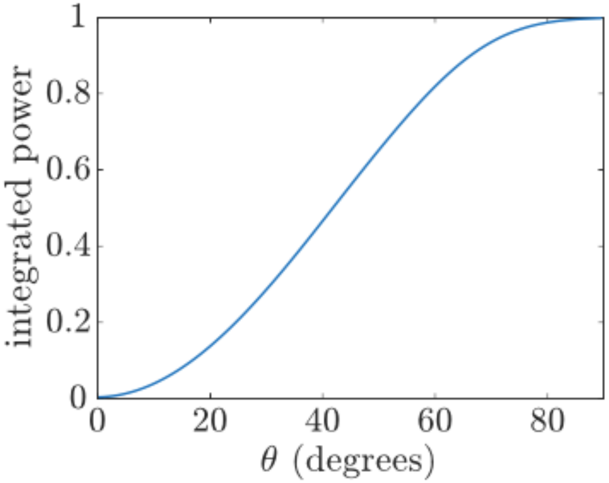
emission into surface modes

emission into scattering modes

Single-photon manipulation: an example

- One excitation in the lattice: no directional emission

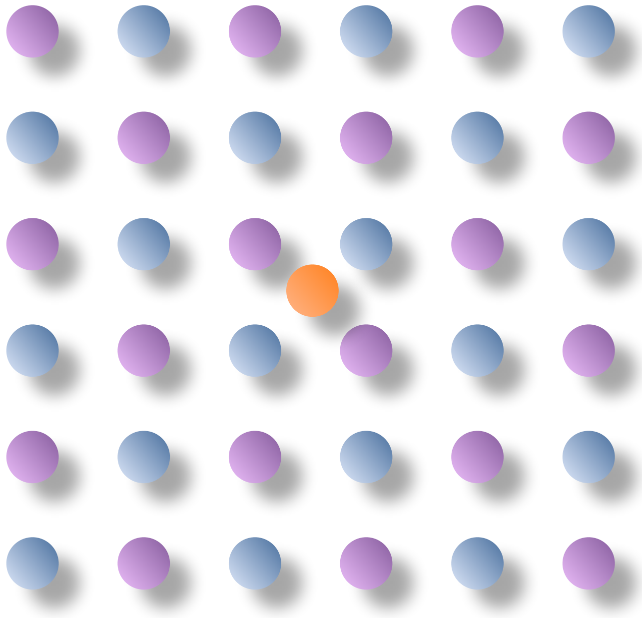




Single-photon manipulation: an example

- Better: couple mode out adiabatically

➡ modulate lattice



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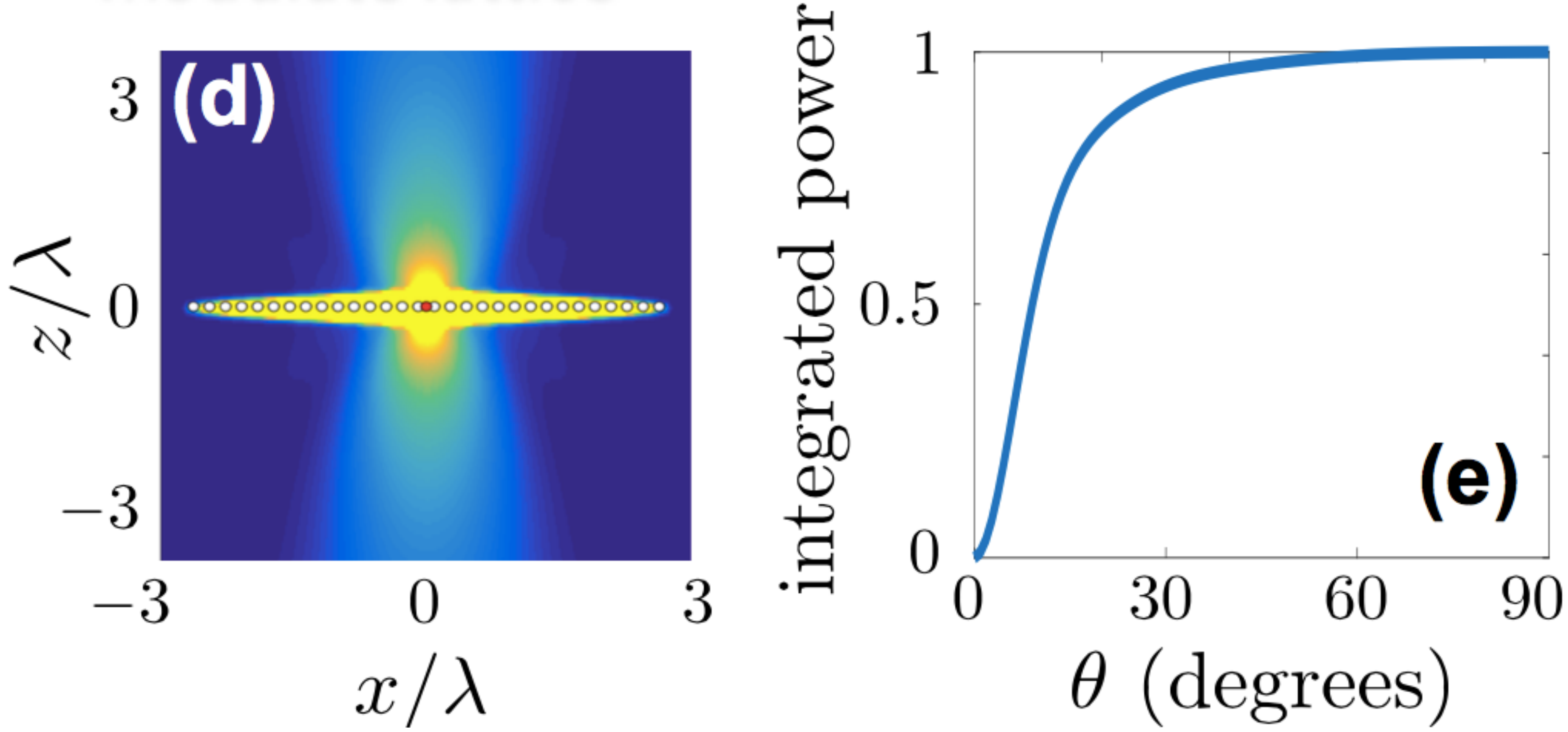
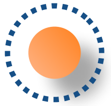


Increase (impurity) cross section?



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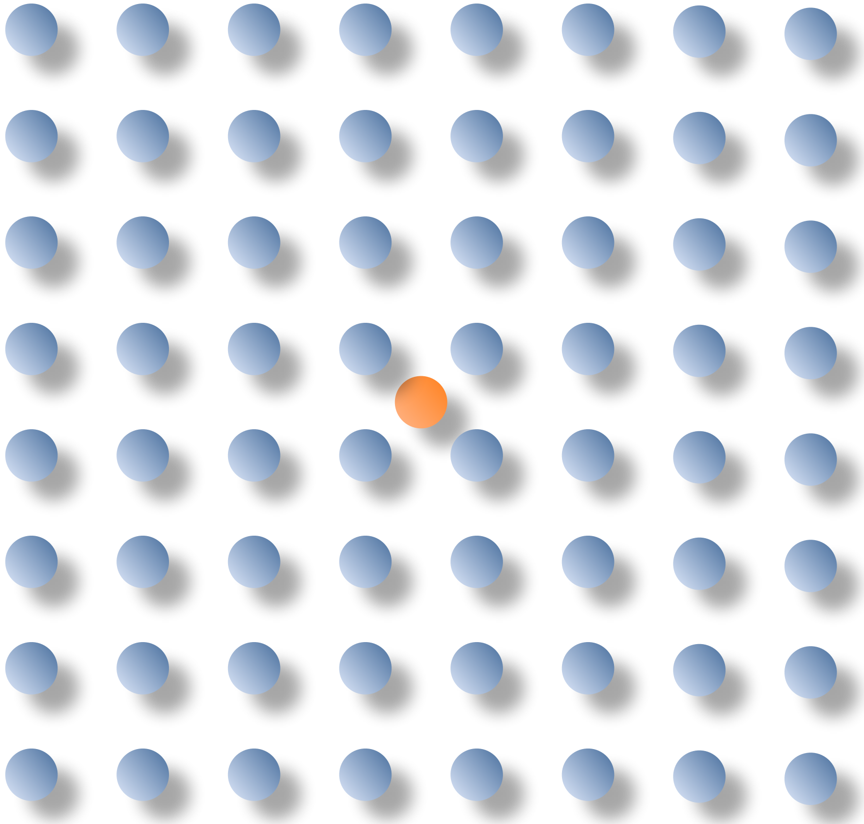

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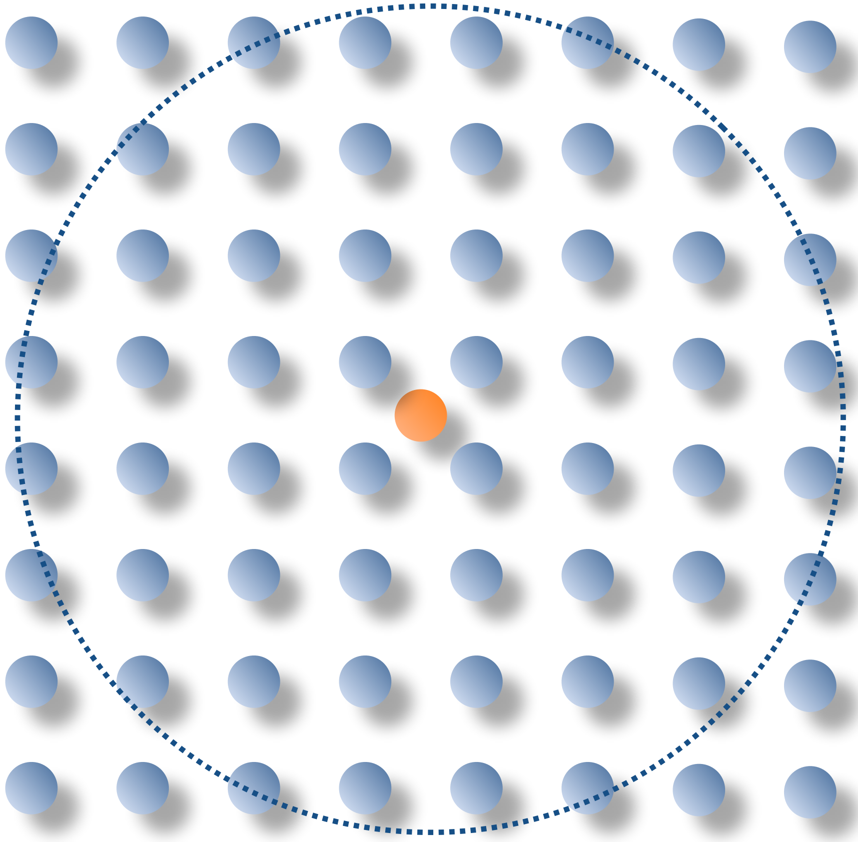
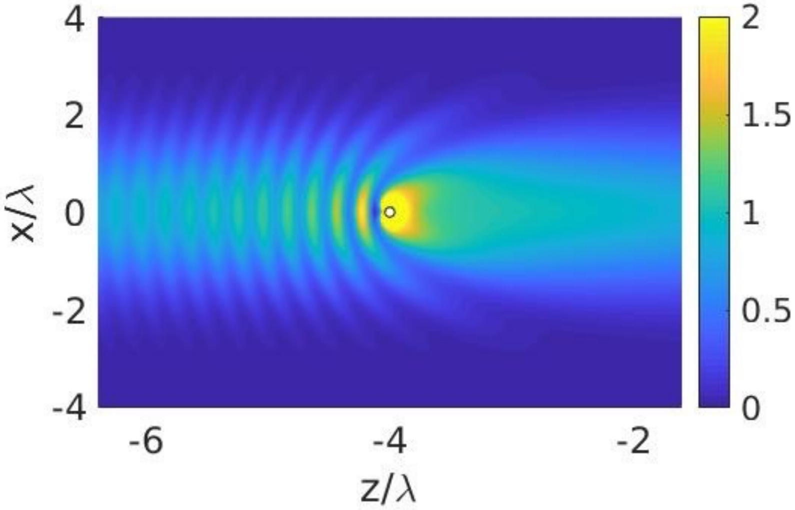
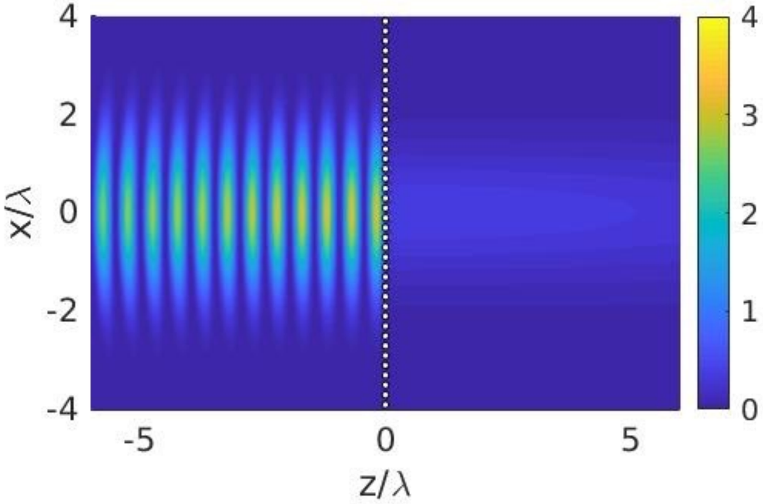


Impurity + Array Scattering


Impurity

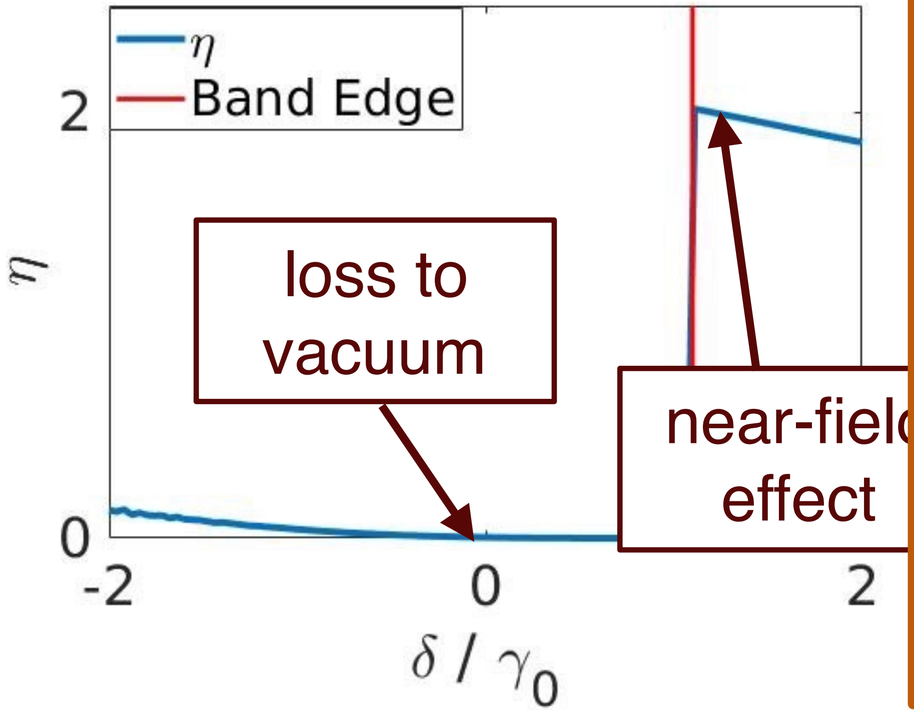

Array

Impurity + Array???

Increase (impurity) cross section

- Factor of η~2 enhancement (near-field)
- Multiple orders of magnitude enhancement - resonant

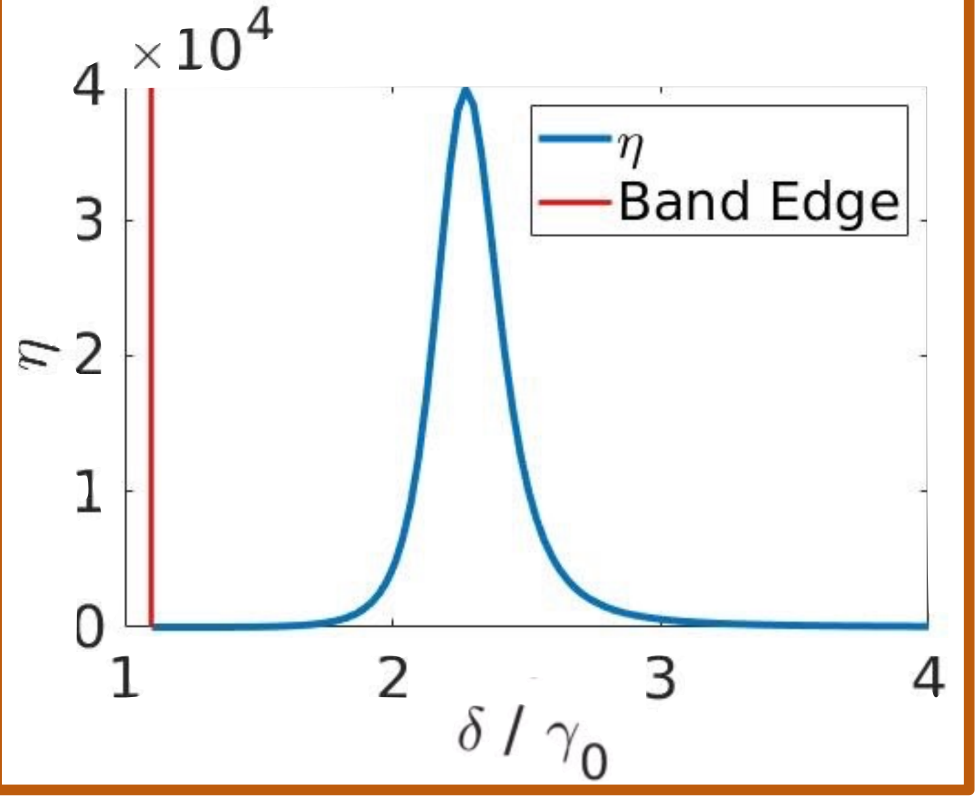
Opposite Polarization between impurity and array atoms



loss to vacuum

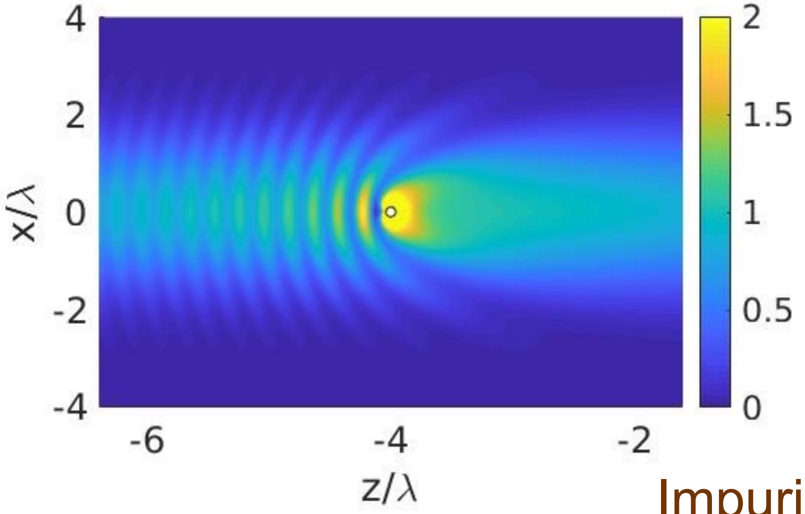
near-fiel effect

Same Polarization



Impurity + Array Scattering

Impurity



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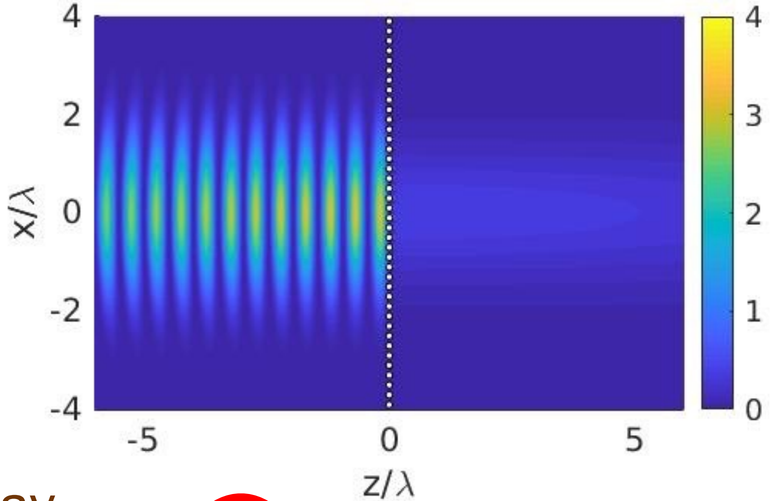

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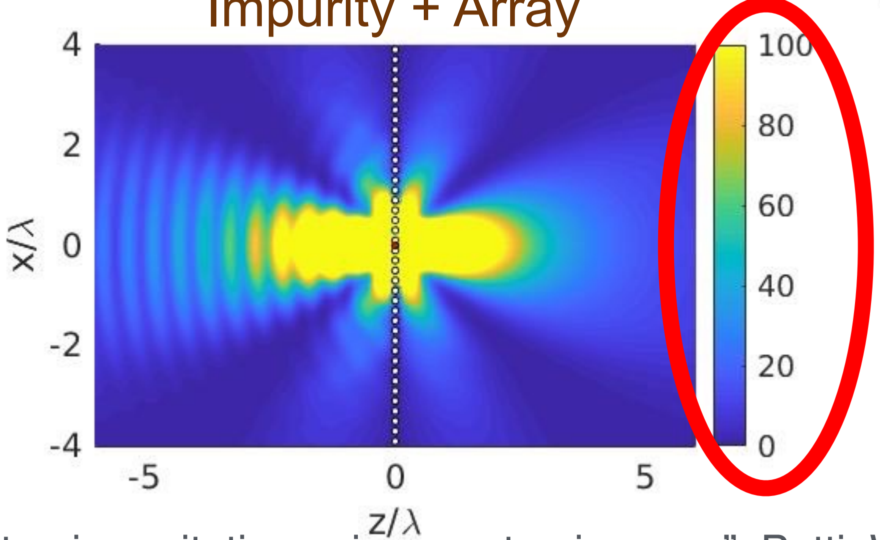


"Enhancing weak field atomic excitation using an atomic array," Patti, Wild, Lukin, Yelin (in prep.)

Outlook: impurities on lattice

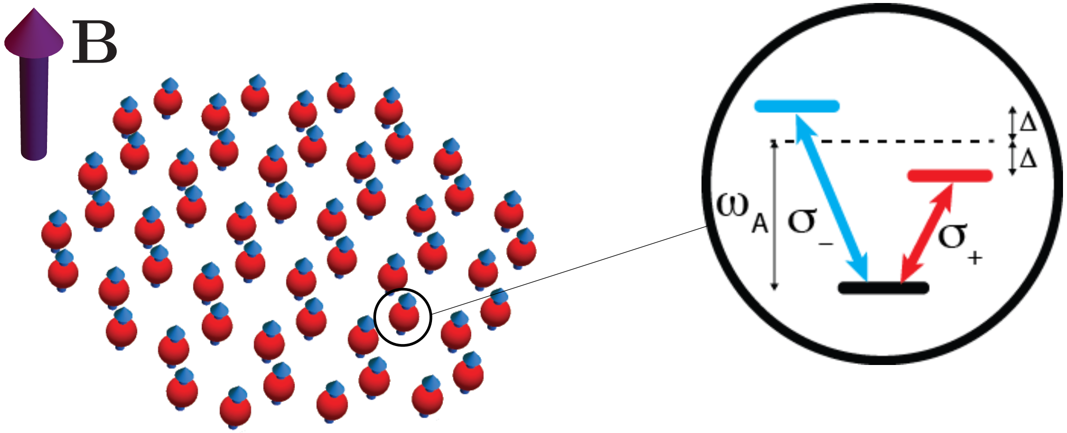
- Single atom: perfect nonlinearity
  - ➡ Use impurities as single atoms
  - ➡ find transmission $g^{(2)}(0)$ function

Outlook: impurities on lattice

- Single atom: perfect nonlinearity
  - ➡ Use impurities as single atoms
  - ➡ find transmission $g^{(2)}(0)$ function
- Make networks of impurity "qubits" on array

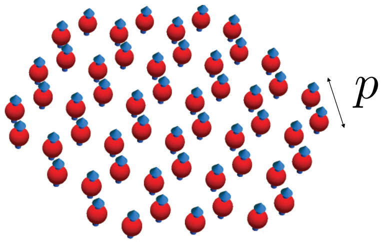
Topological quantum nonlinear systems: the idea

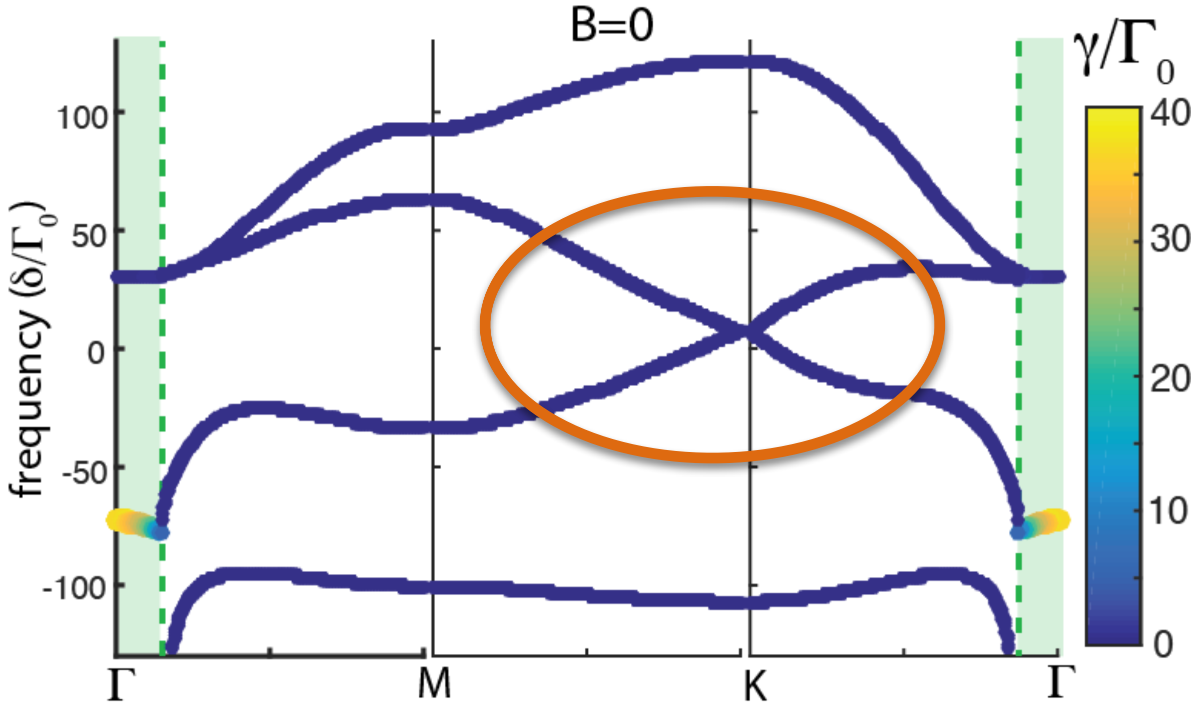
- 2D honeycomb lattice of atoms with sub-wavelength spacing
- 3-level atoms with σ+ and σ- transitions (V-system)



- Out-of-plane magnetic field induces Zeeman-shifts

Band structure of honeycomb lattice





- no bandgap, but Dirac point

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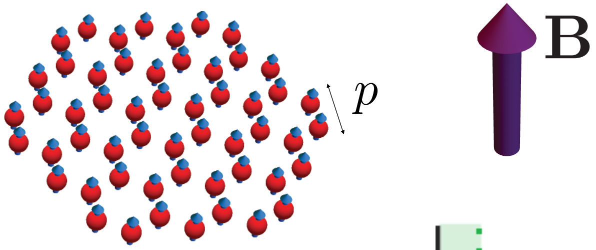
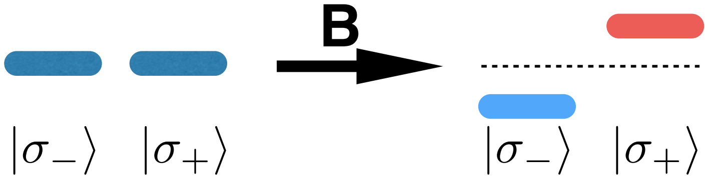
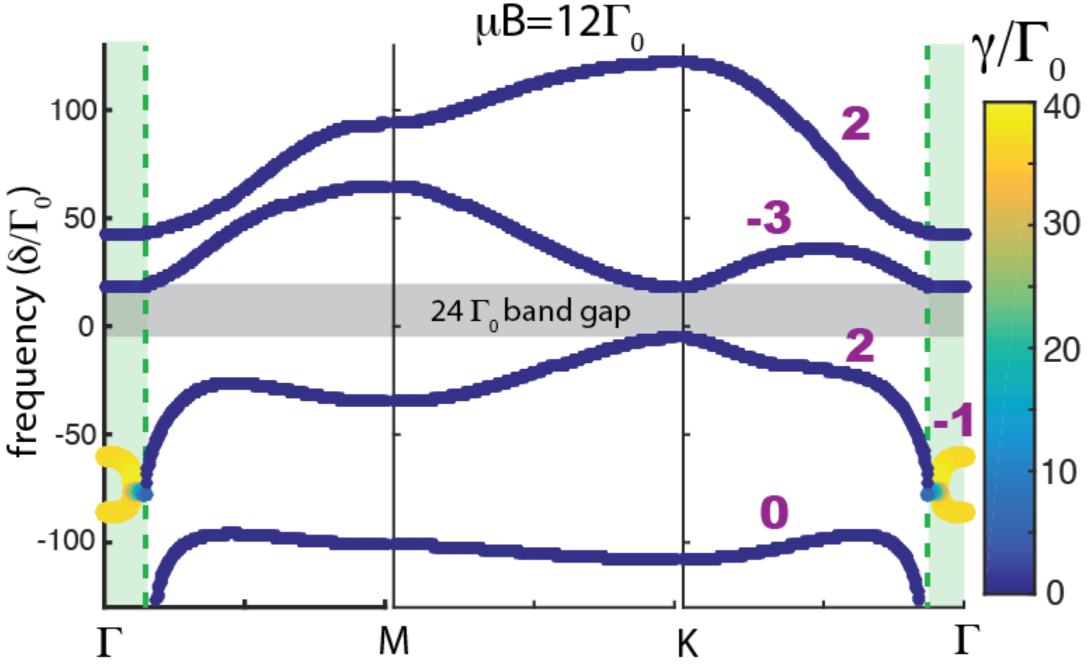
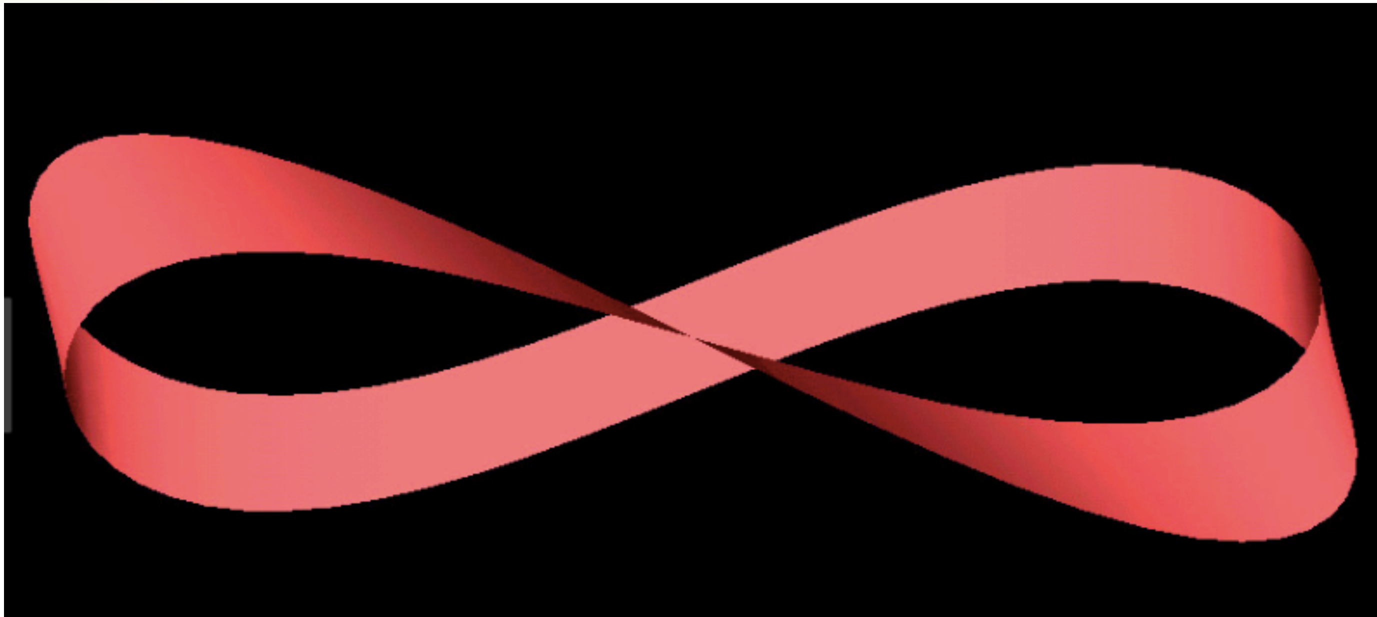






- bandgap opens ⇒ non-zero Chern numbers



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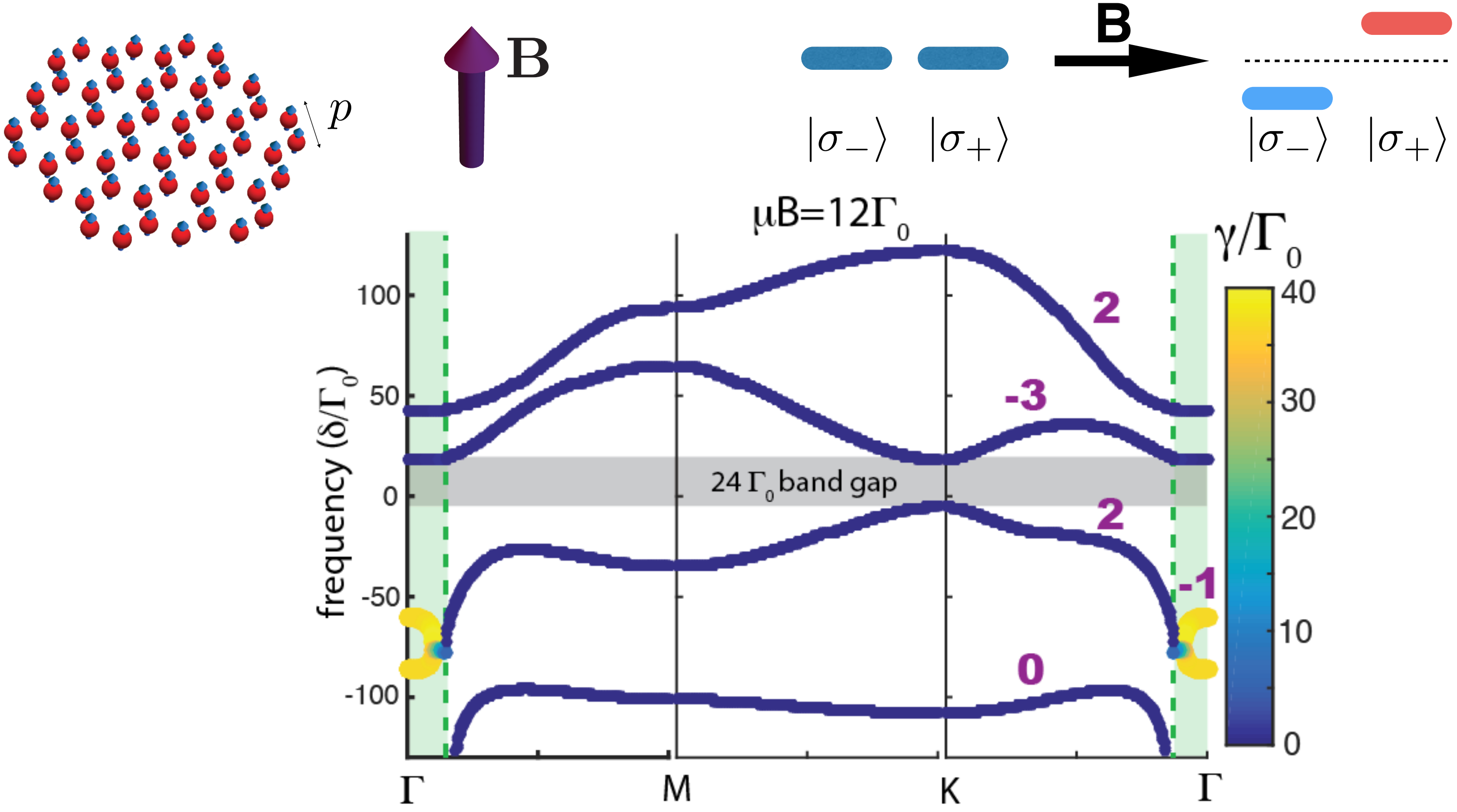
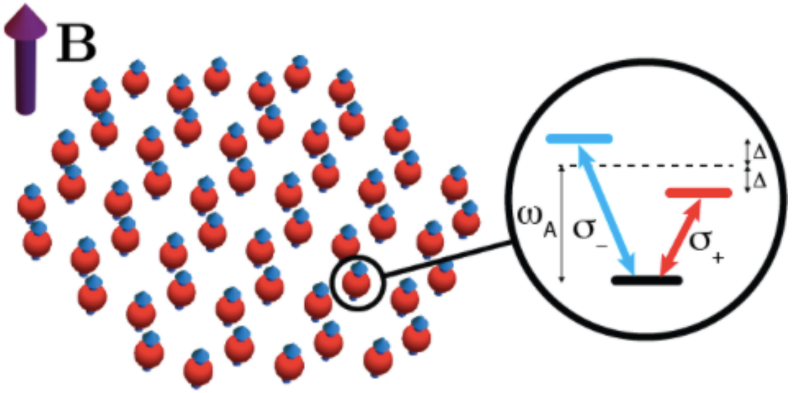


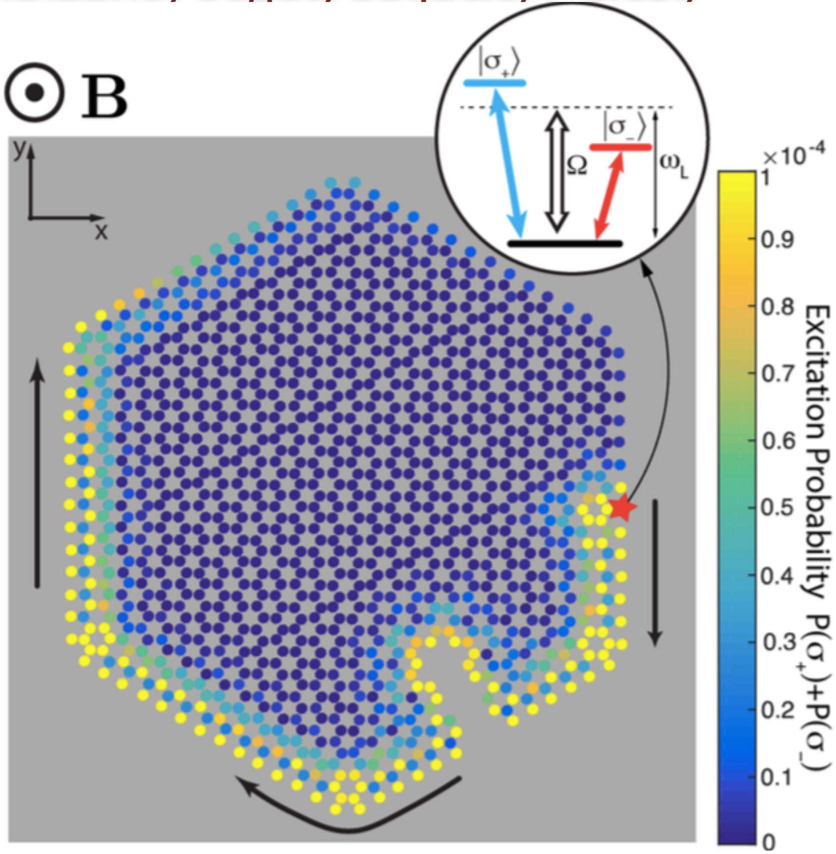
- bandgap opens ⇒ non-zero Chern numbers

⇒ Edge states!

New idea: topological quantum optics

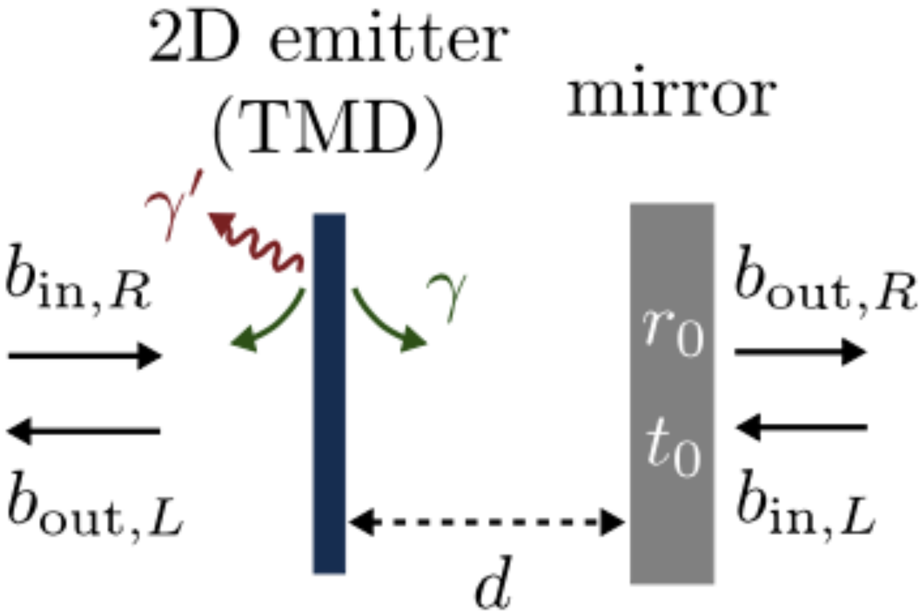
(early ideas, experiments for microwave: Haldane, Segev, Soljacic, Hafezi, …)





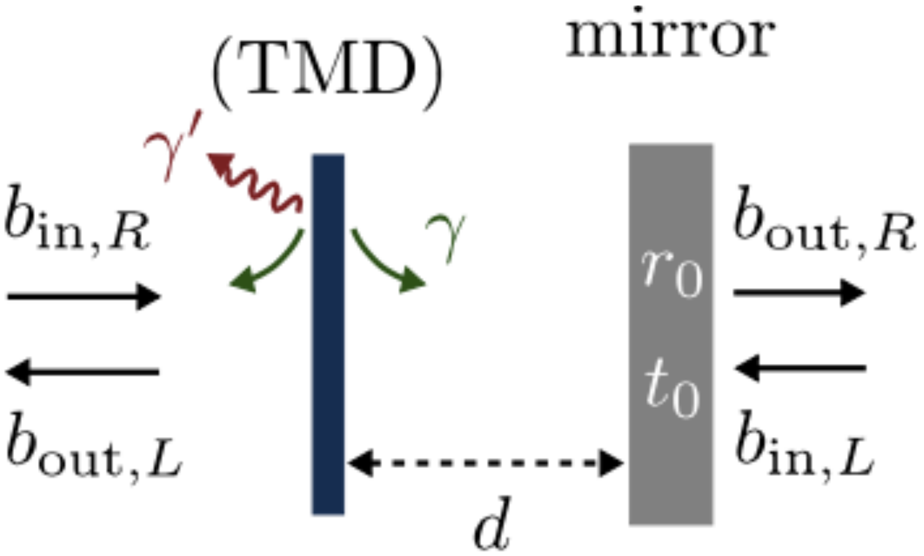
Perczel, Borregaard, Chang, Pichler, Yelin, Zoller, Lukin, PRL 119, 023603 (2017)
see also: Bettles, Minar, Lesanovsky, Adams, Olmos, arXiv:1703.03351

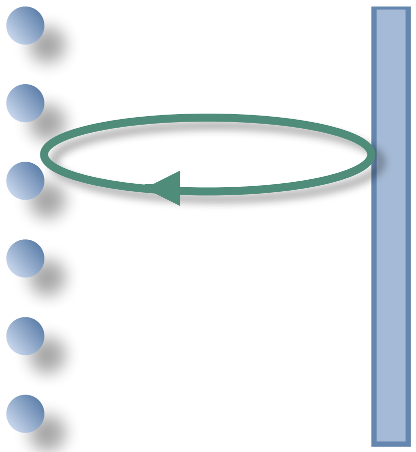
Nonlinear optics: Emitter proximal to mirror



(Wild, Shahmoon, Yelin, Lukin, PRL **121**, 123606 (2018))

Narrowing polariton resonances



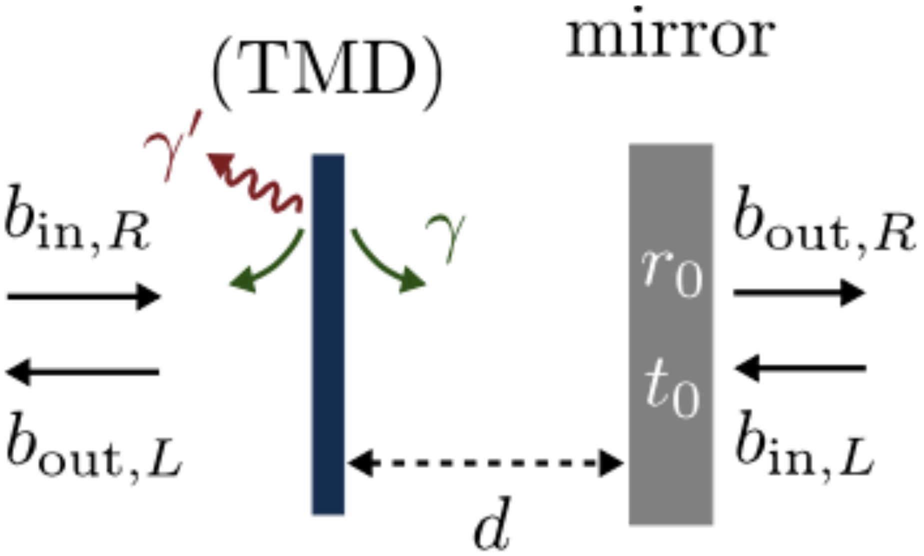


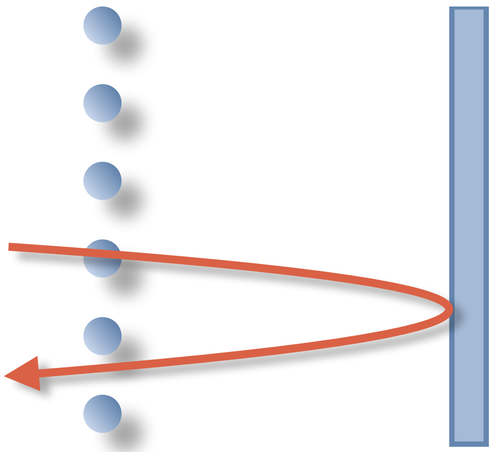
interference of spontaneous emission

resonant

(Wild, Shahmoon, Yelin, Lukin, PRL **121**, 123606 (2018))

Narrowing polariton resonances



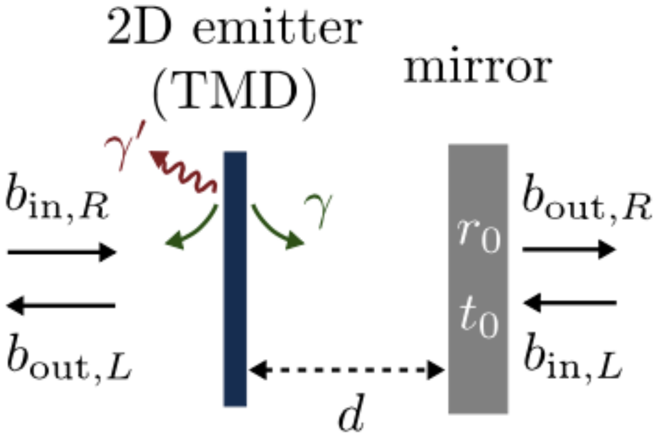


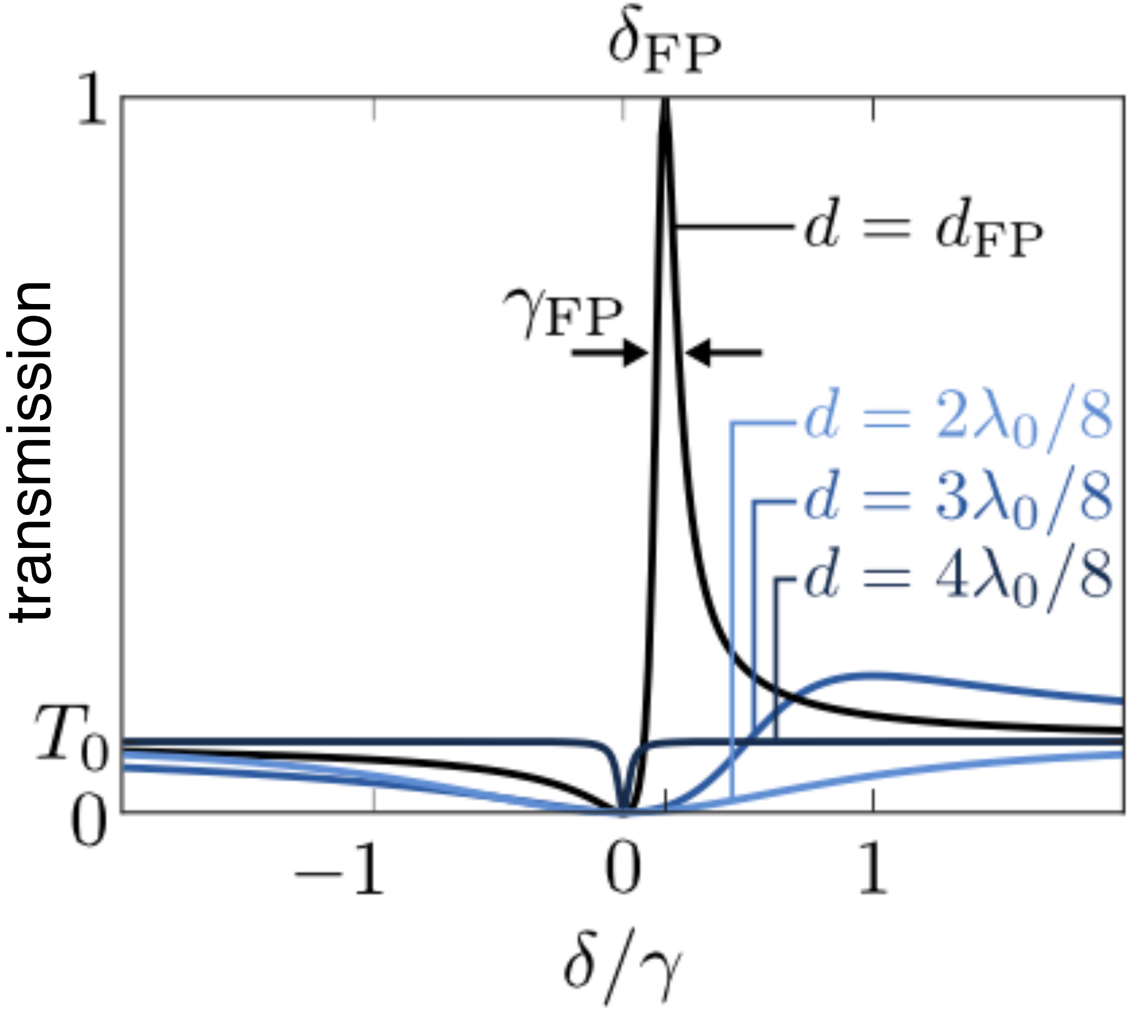
interference of
spontaneous
emission

non-resonant

(Wild, Shahmoon, Yelin, Lukin, PRL **121**, 123606 (2018))

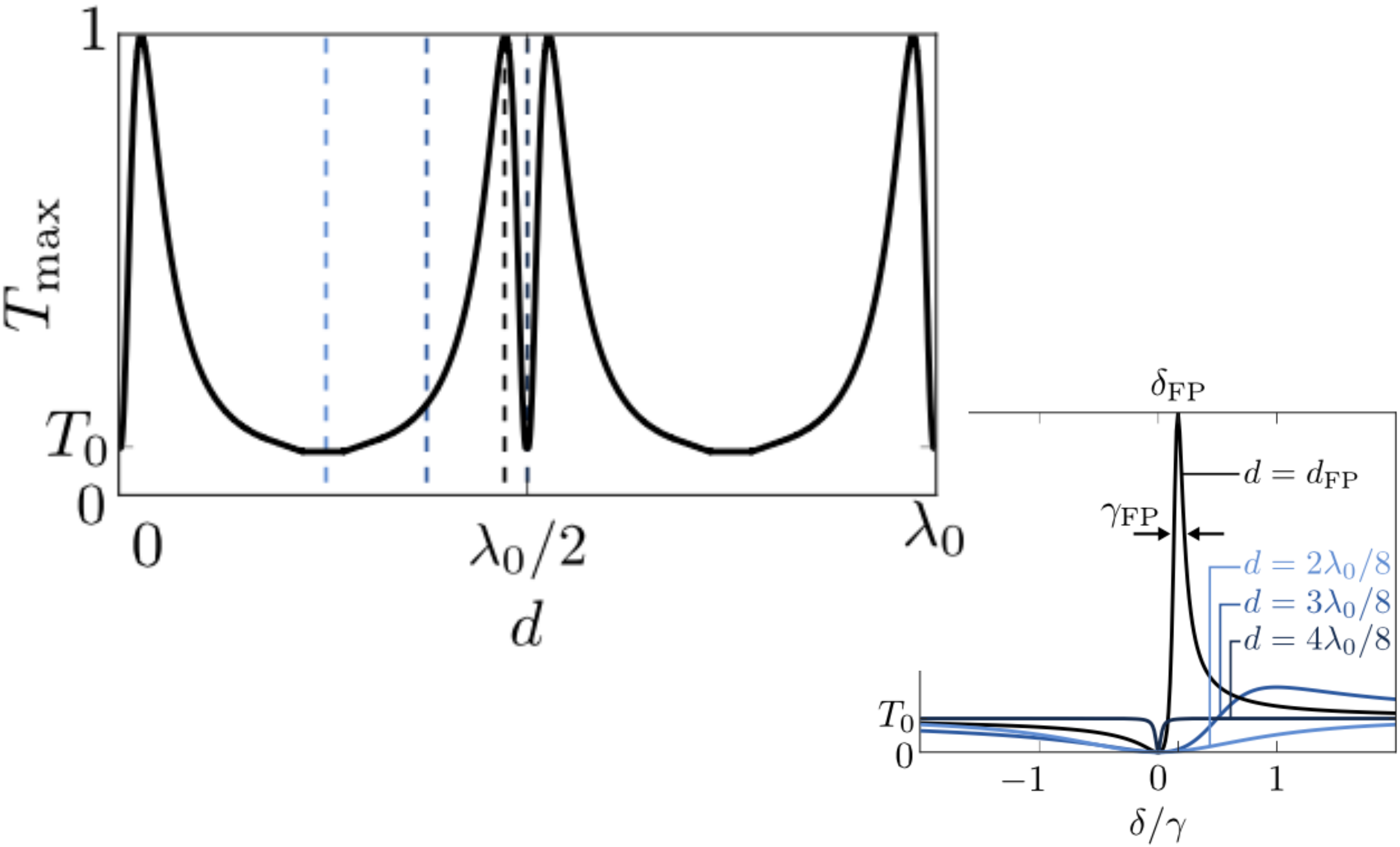
Narrowing polariton resonances



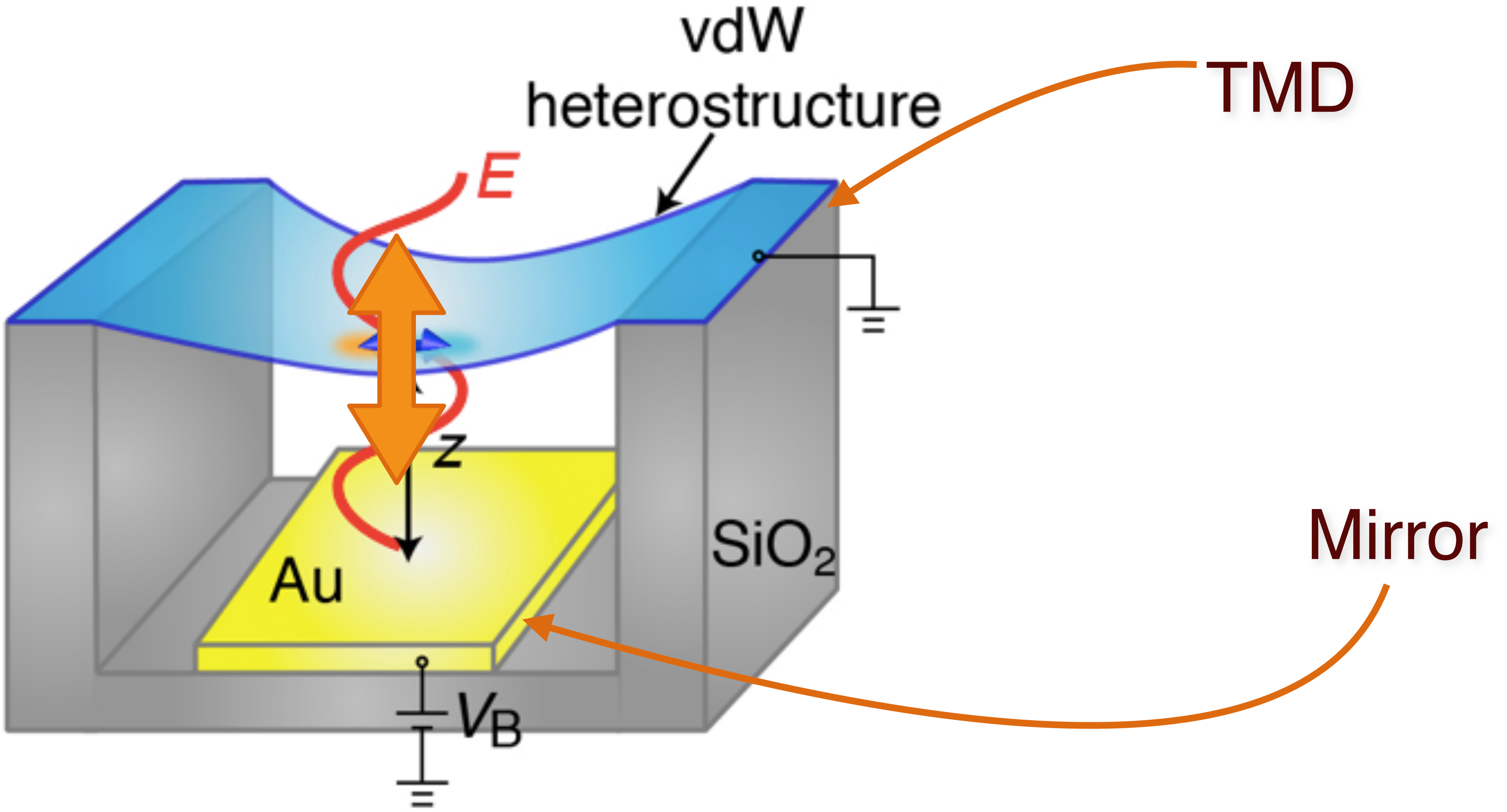


(Wild, Shahmoon, Yelin, Lukin, PRL **121**, 123606 (2018))

Narrowing polariton resonances



New experiment

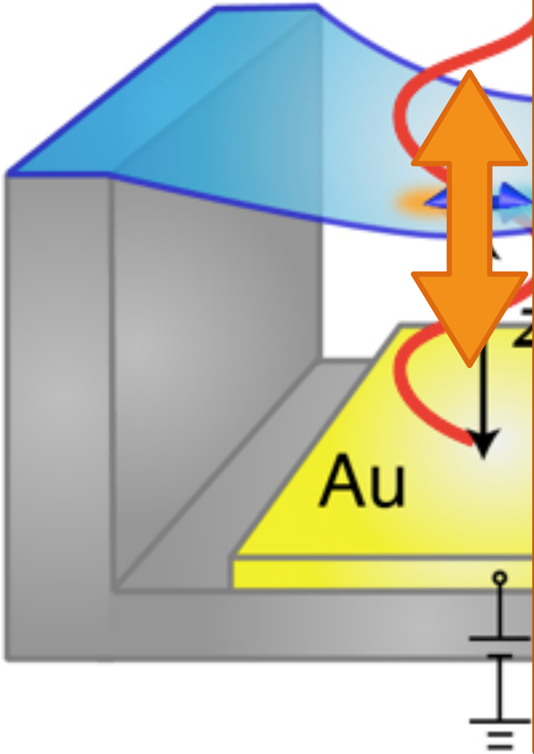


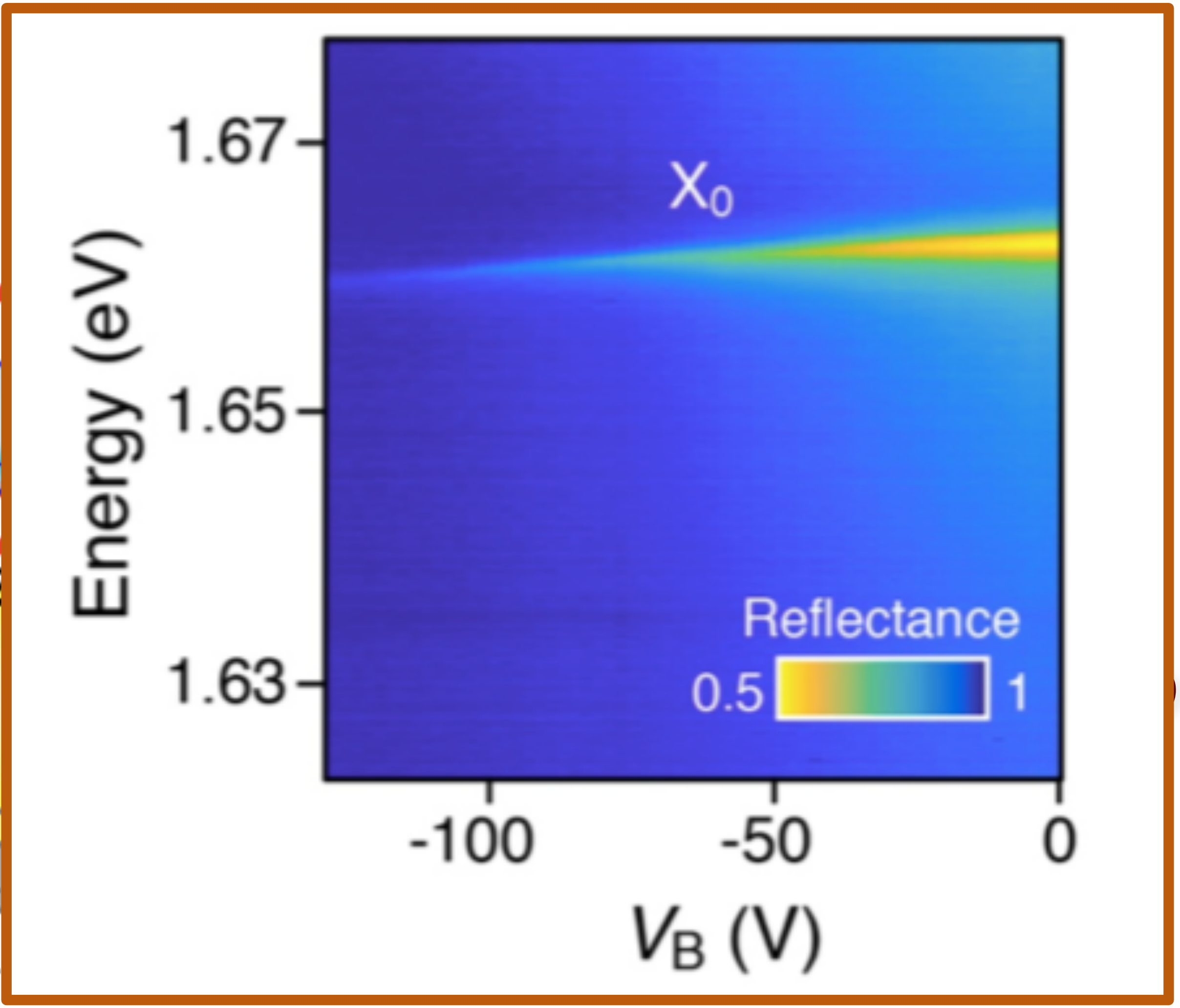
TMD

Mirror

"Controlling Excitons in an Atomically Thin Membrane with a Mirror," Zhou et al., arXiv:1901.08500

New experiment





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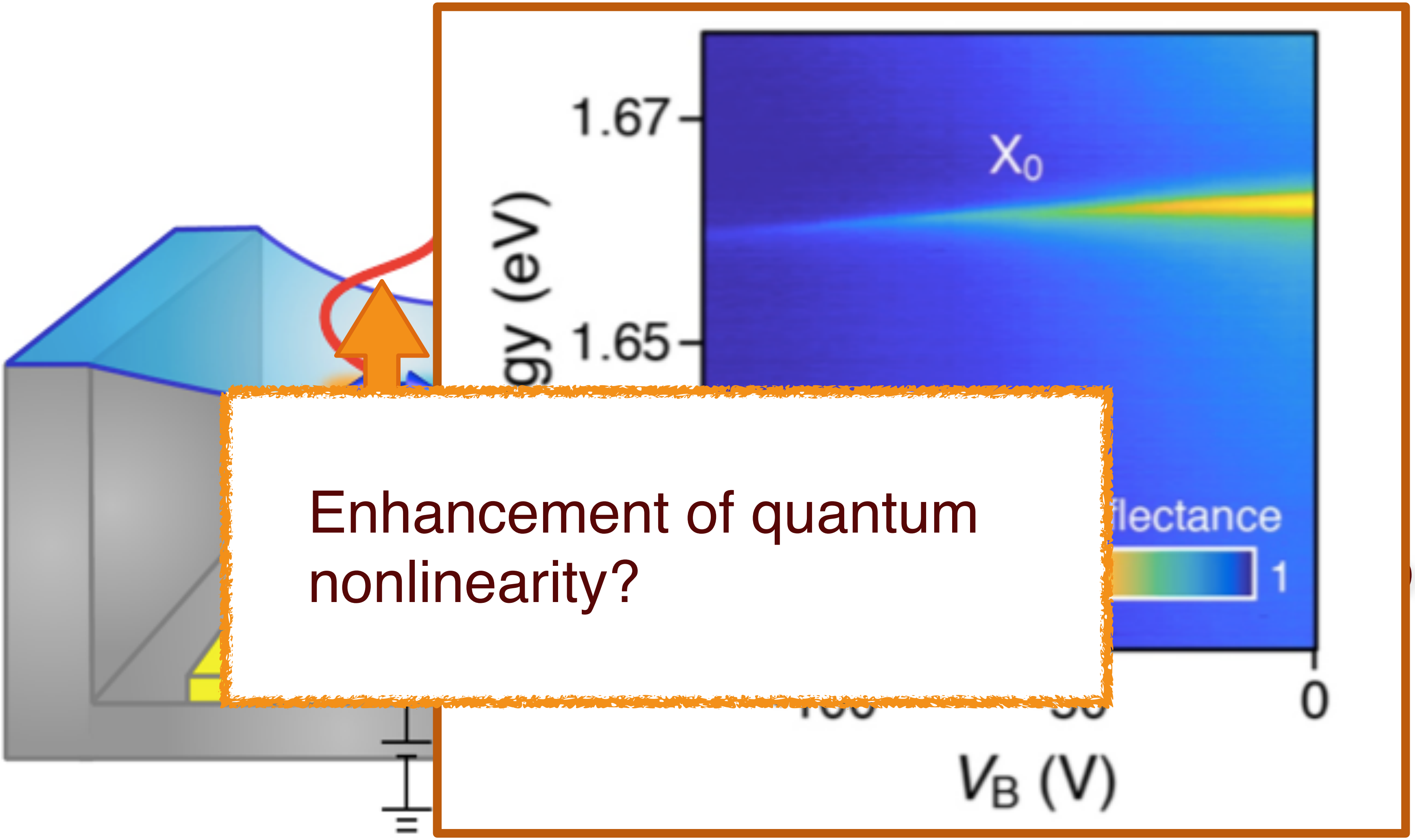
"Controlling Excitons in an Atomically Thin Membrane with a Mirror," Zhou et al., arXiv:1901.08500

New experiment

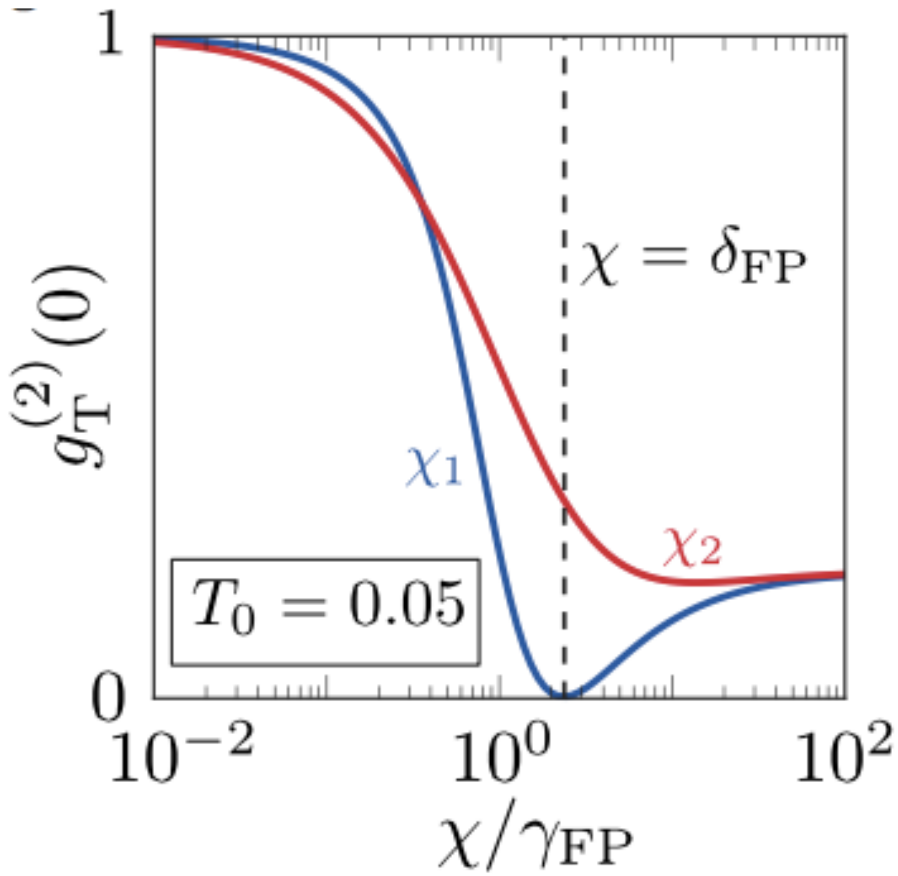


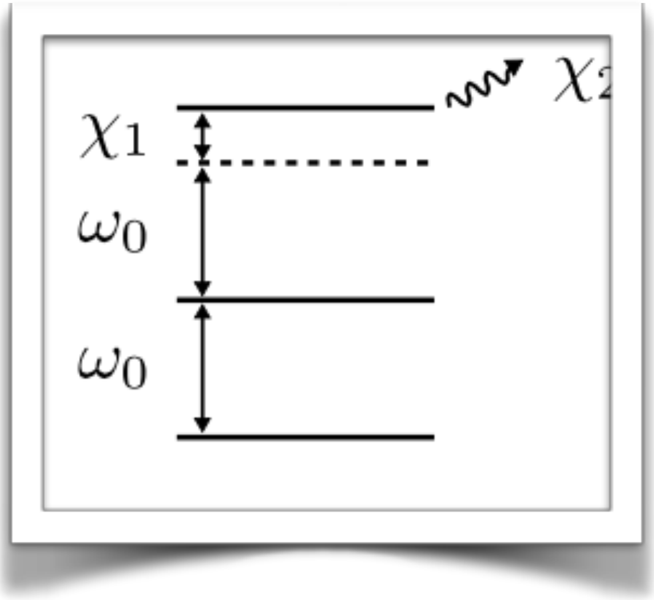
Enhancement of quantum nonlinearity?

"Controlling Excitons in an Atomically Thin Membrane with a Mirror," Zhou et al., arXiv:1901.08500

Quantum nonlinearity

Account for interaction of radiators (of strength χ):

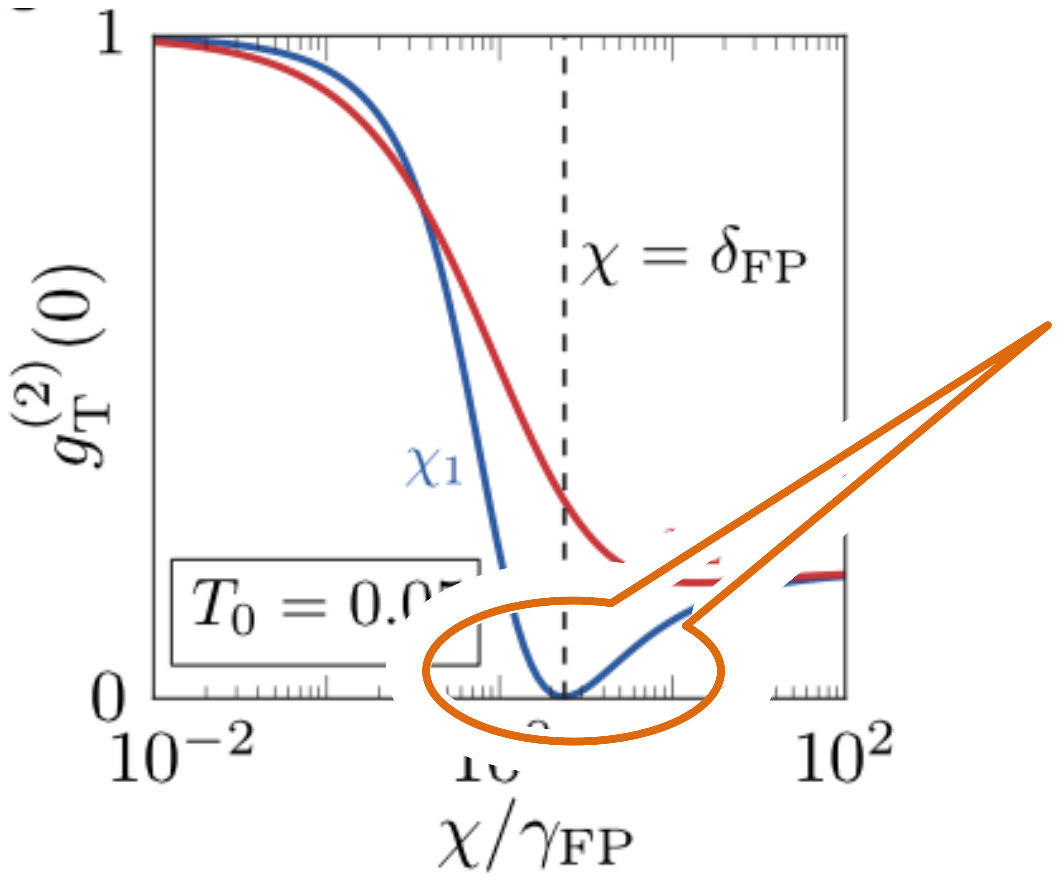




dipole - dipole
interaction

Quantum nonlinearity

Account for interaction of radiators (of strength χ):



Only single-photon transmission!

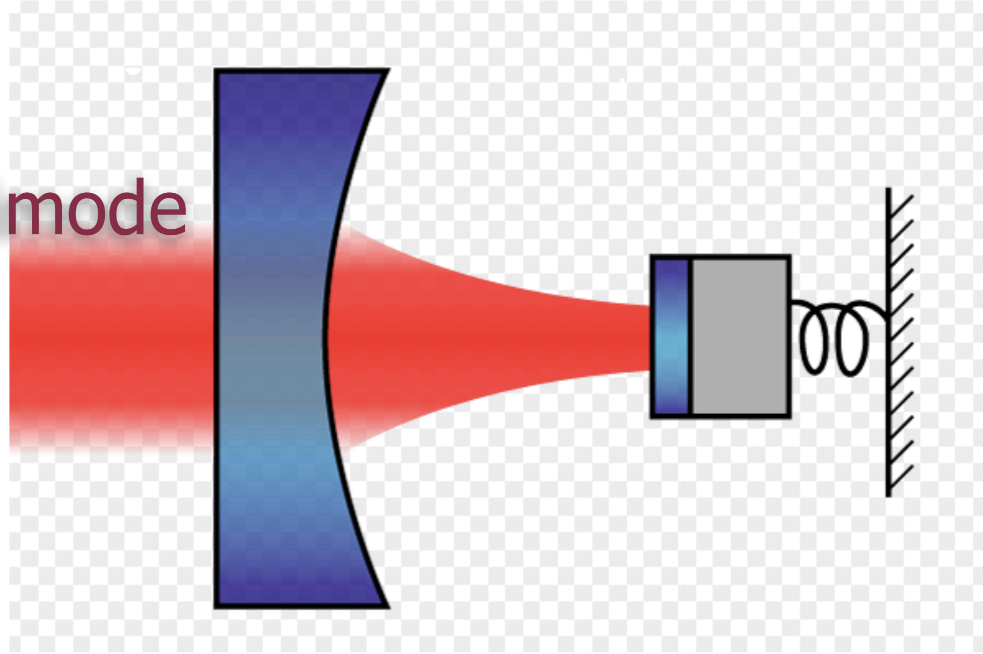
Optomechanics

- Light → motion:

  light-induced collective motion

- Motion → light:

  Motion-induced multimode nonlinear optics



Experiments by Regal, Lehnert, Harris, Painter,…

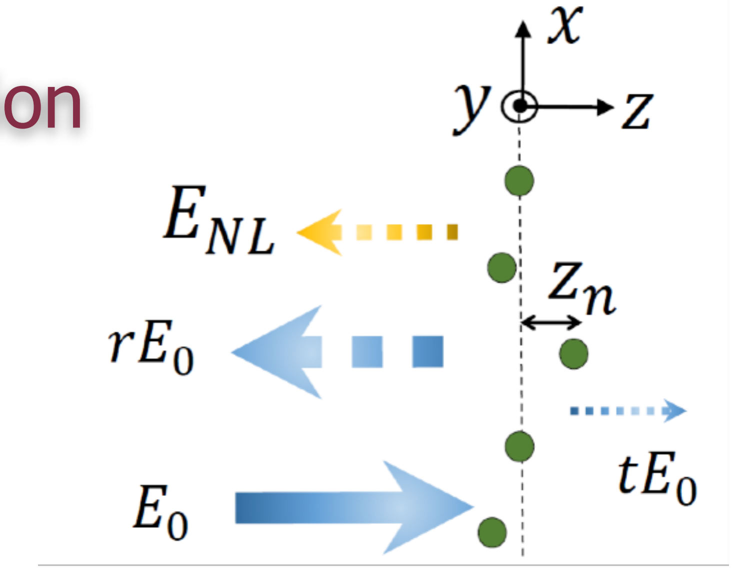
Optomechanics of 2D atom array in free space

- Light → motion:

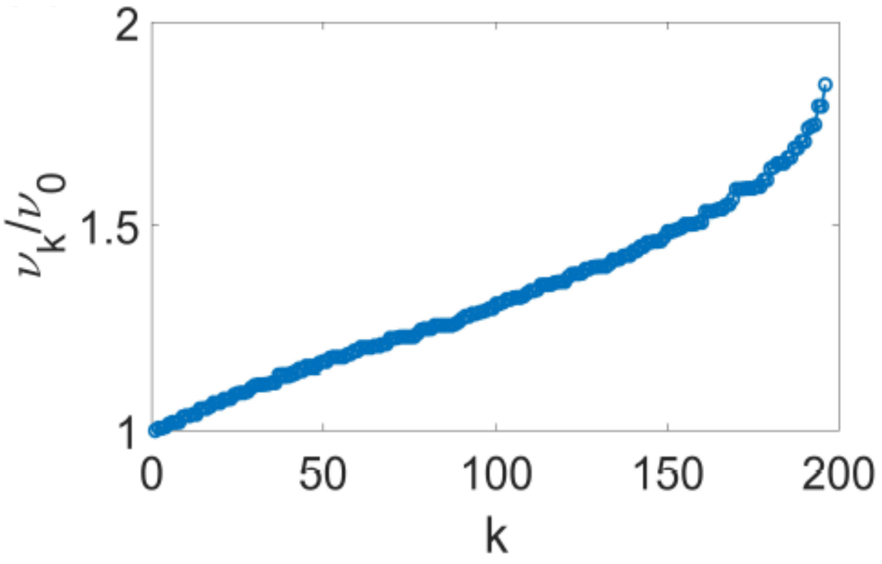
  light-induced collective motion

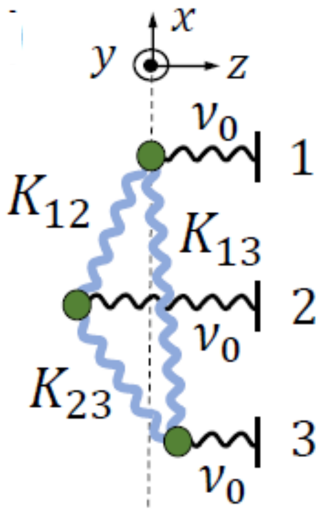
- Motion → light:

  Motion-induced multimode nonlinear optics

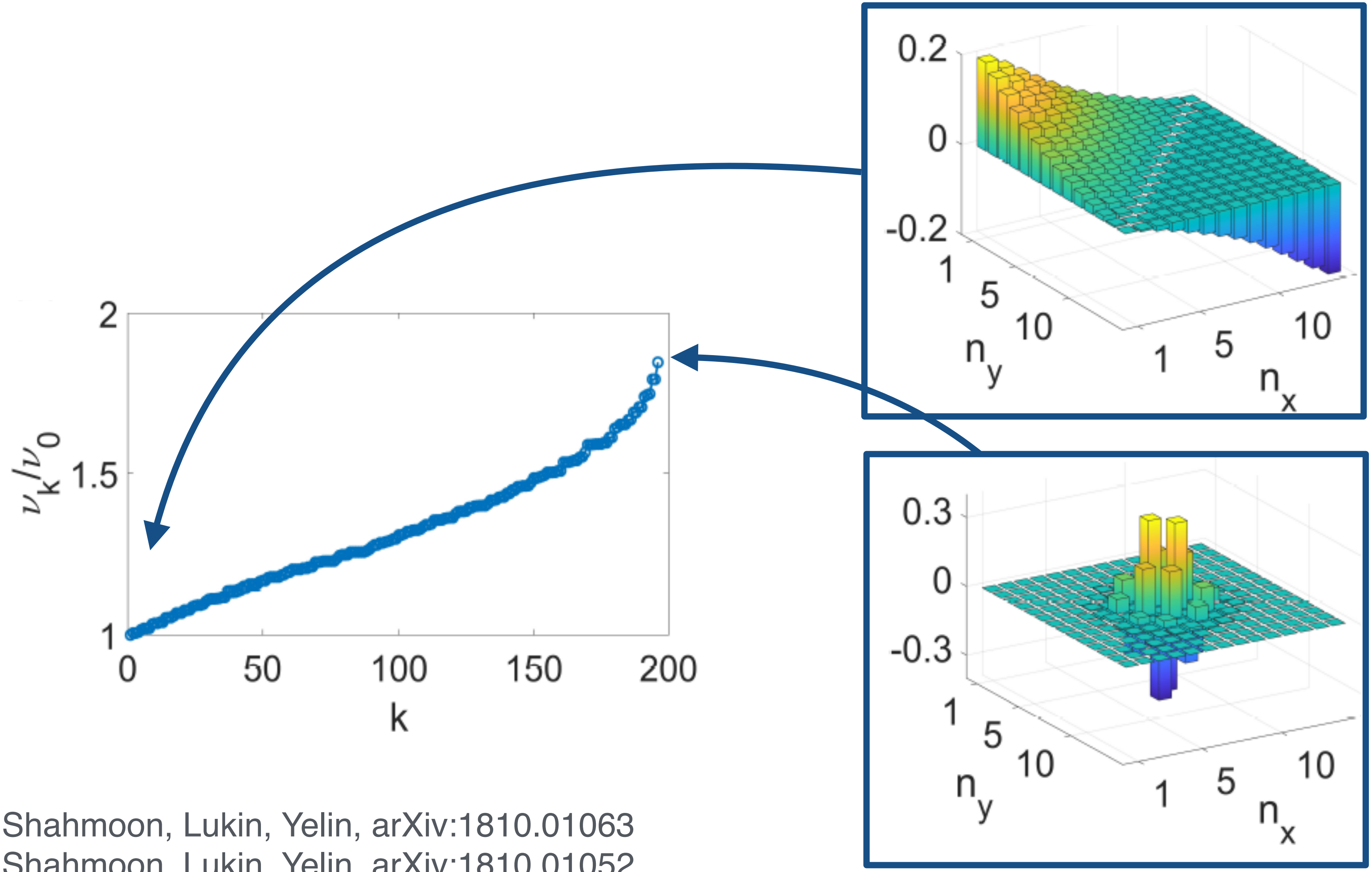


Mechanical modes





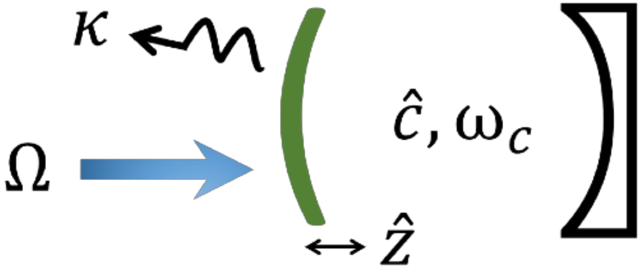
Mechanical modes



Shahmoon, Lukin, Yelin, arXiv:1810.01063
Shahmoon, Lukin, Yelin, arXiv:1810.01052

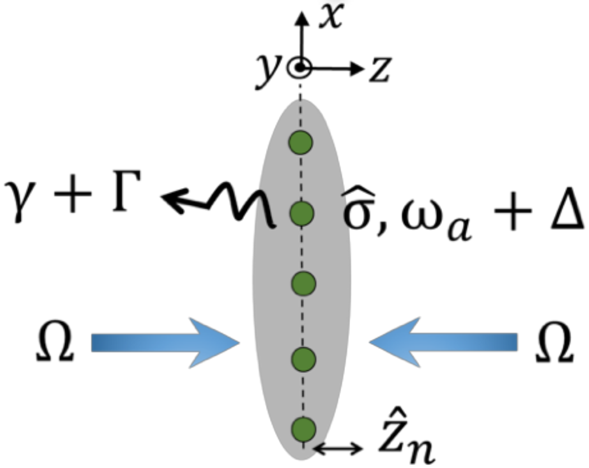
Optomechanics with lightest possible mirror?

Cavity



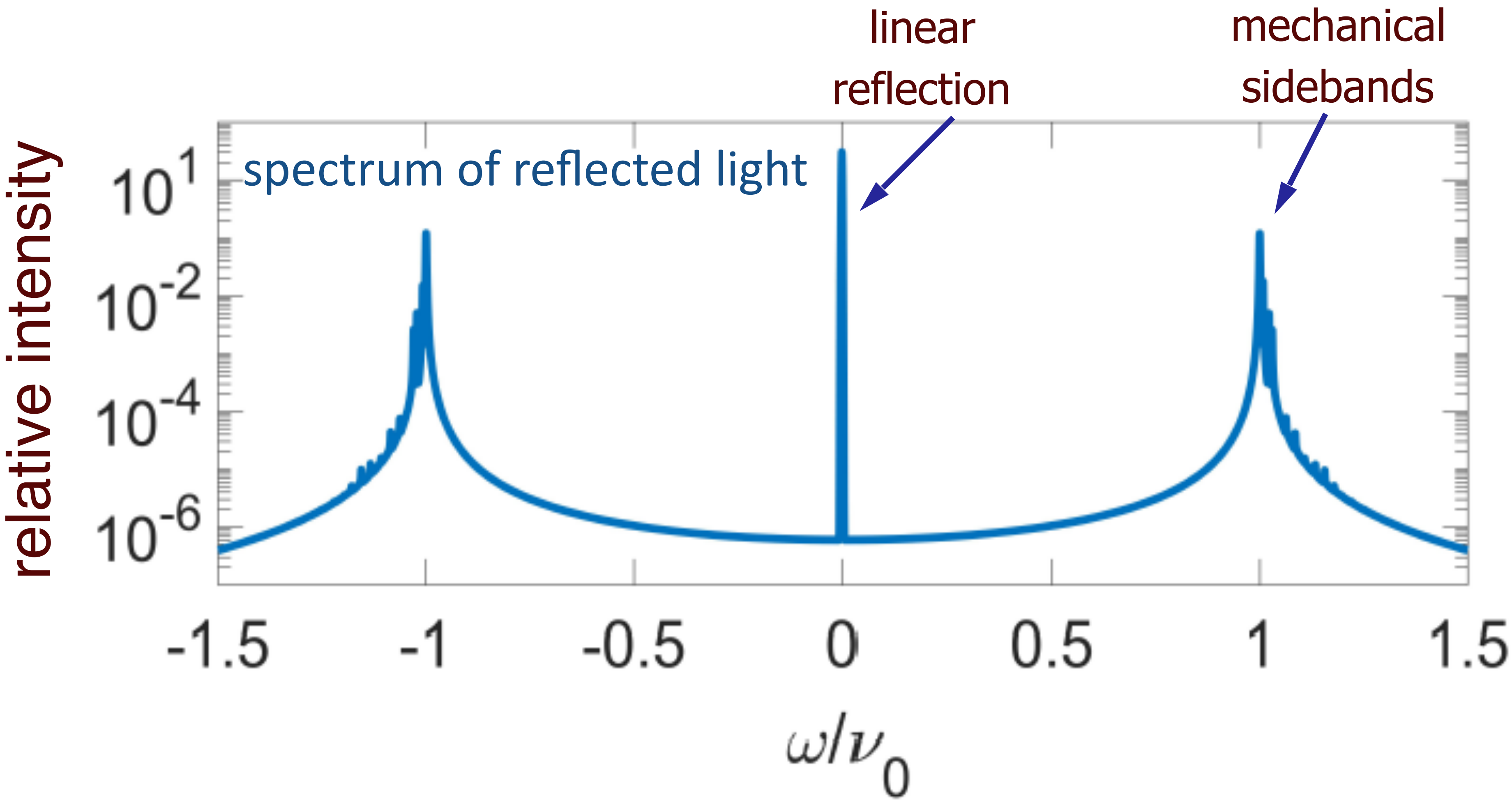
- single-mode oscillator
- bulk mirror
- 10^{-14} m zero-point motion
- optical cavity (single-mode)

Atom array



- multi-mode oscillator
- a few atoms
- 10^{-8} m zpm
- collective atomic dipole (multi-mode)

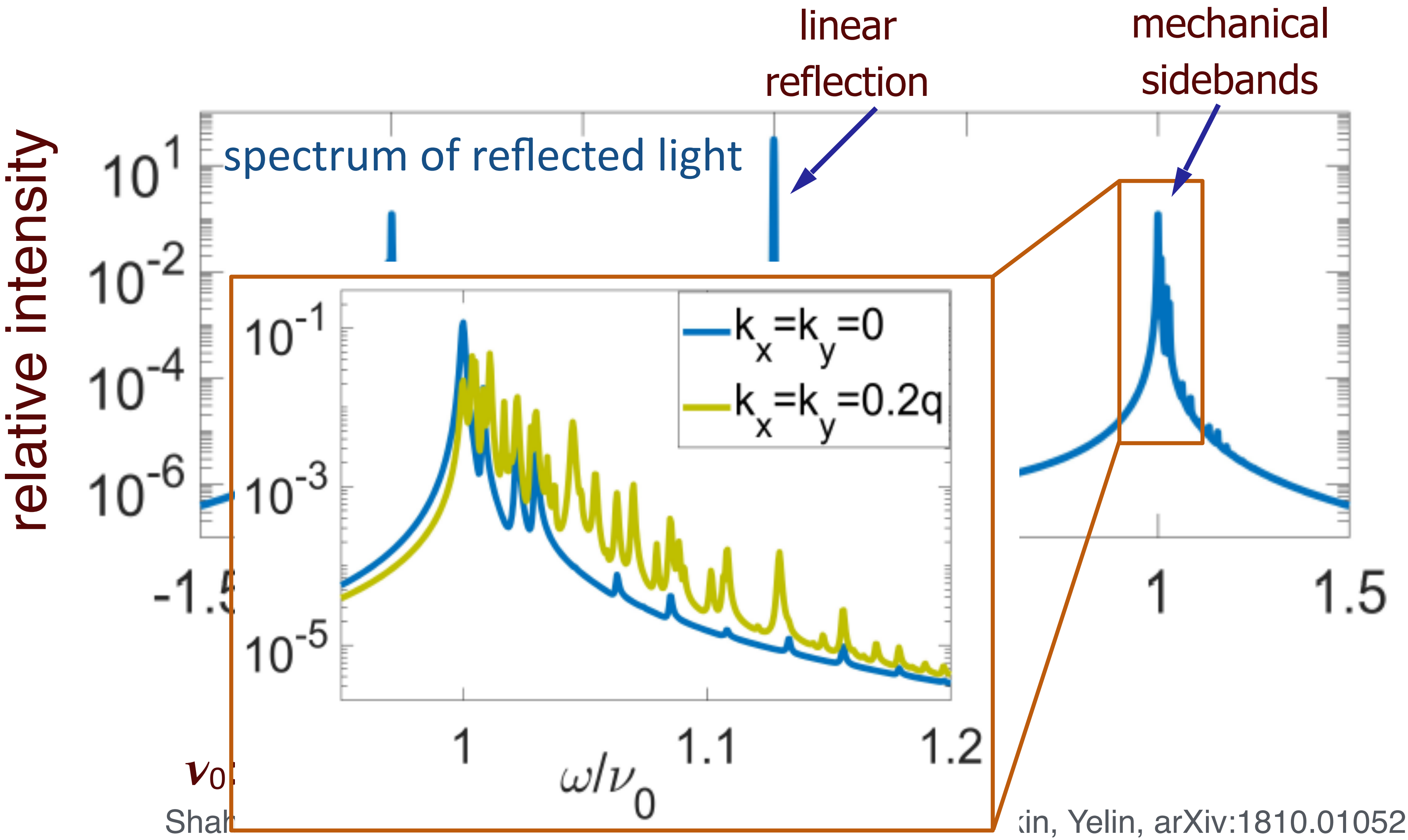
Collective mechanical sidebands



ν_0: fundamental mechanical frequency

Shahmoon, Lukin, Yelin, arXiv:1810.01063 , Shahmoon, Lukin, Yelin, arXiv:1810.01052

Collective mechanical sidebands



spectrum of reflected light

linear reflection

mechanical sidebands

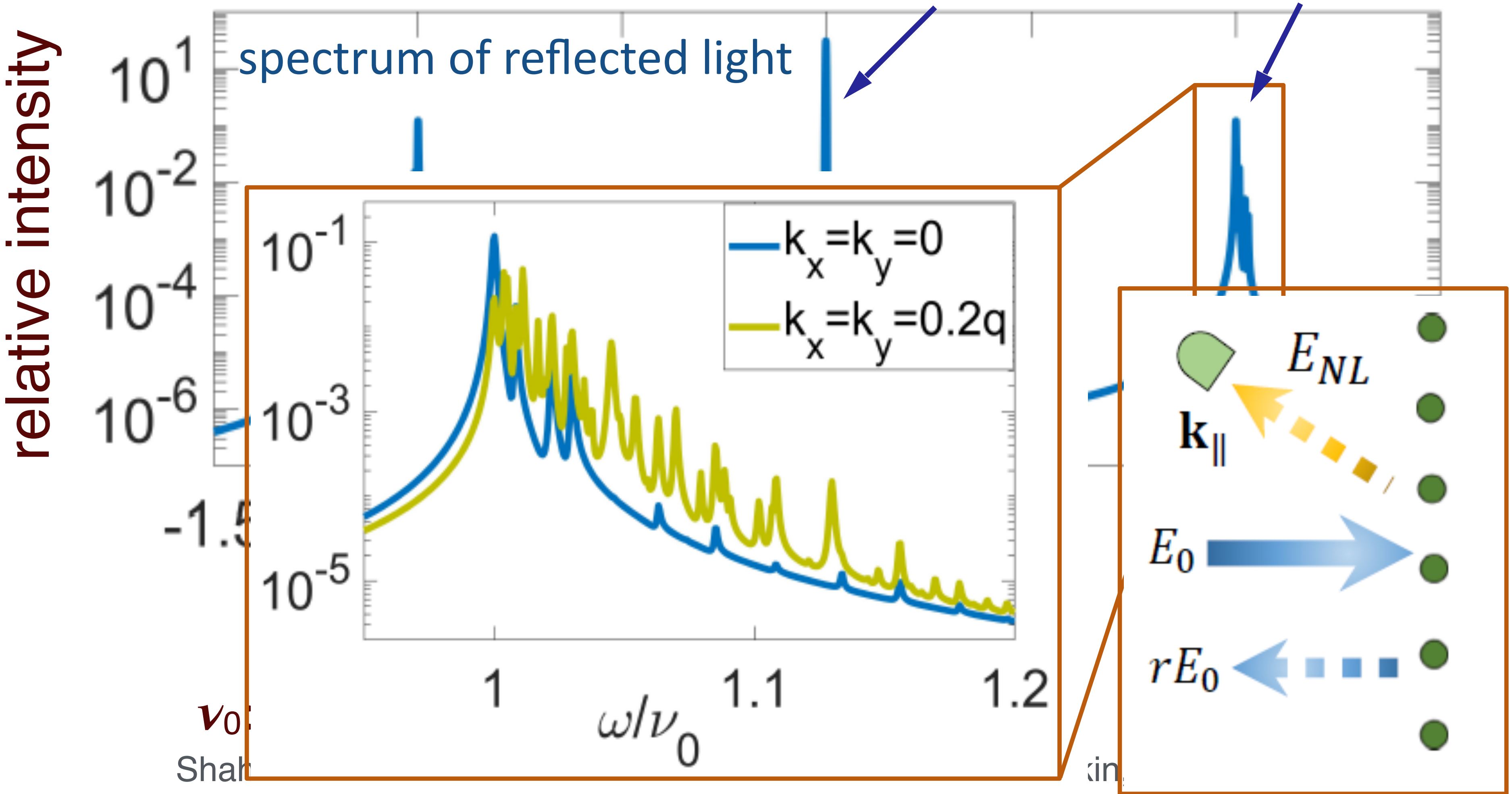
ν_0:

Shah … kin, Yelin, arXiv:1810.01052

Collective mechanical sidebands

linear reflection

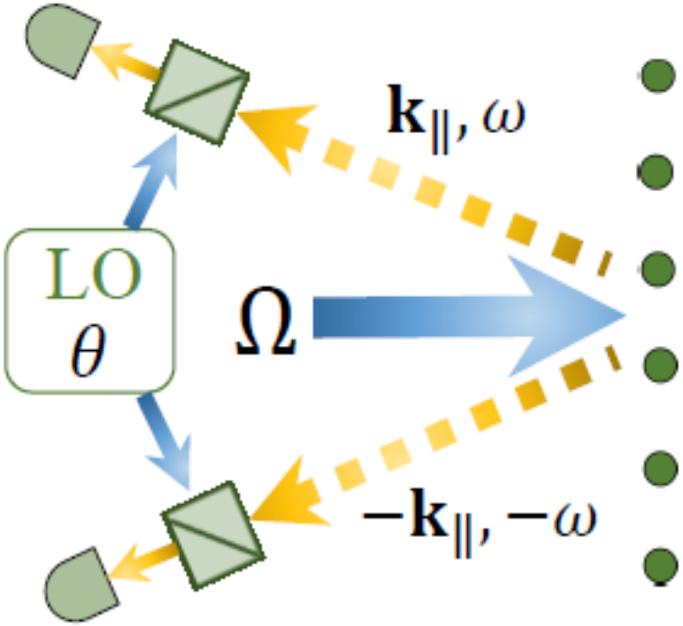
mechanical sidebands



Application: quantum squeezing of reflected field

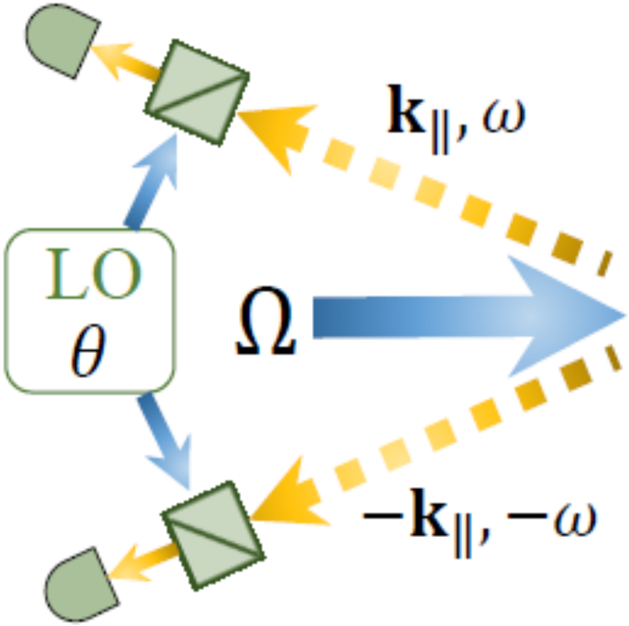
Two-mode squeezing:

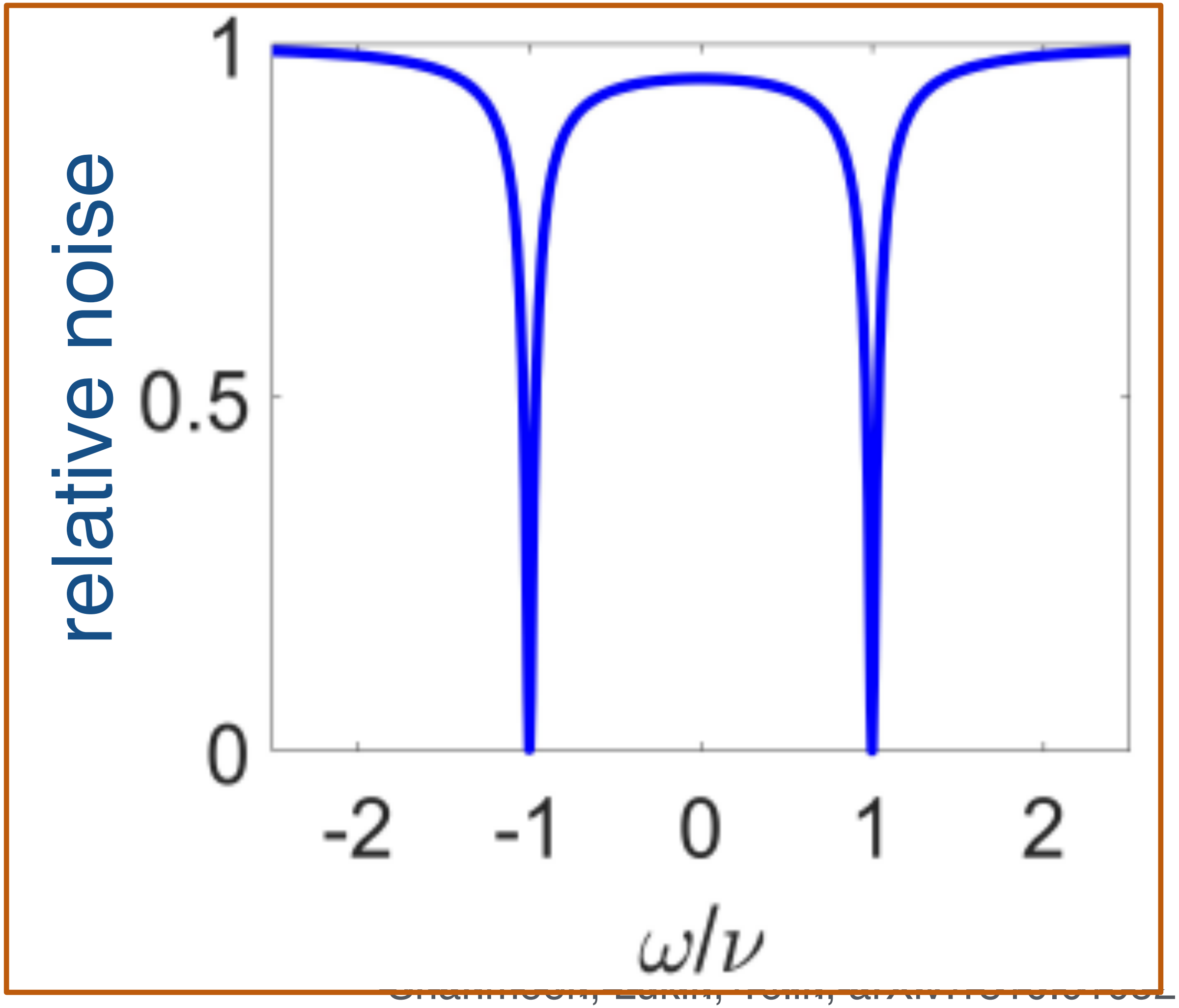
measure correlation using homodyne detection



Shahmoon, Lukin, Yelin, arXiv:1810.01063
Shahmoon, Lukin, Yelin, arXiv:1810.01052

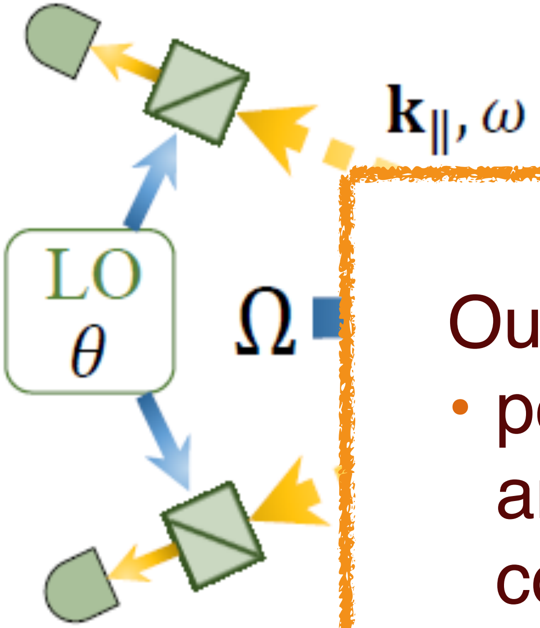
Nonlinear optics: Squeezing of reflected field

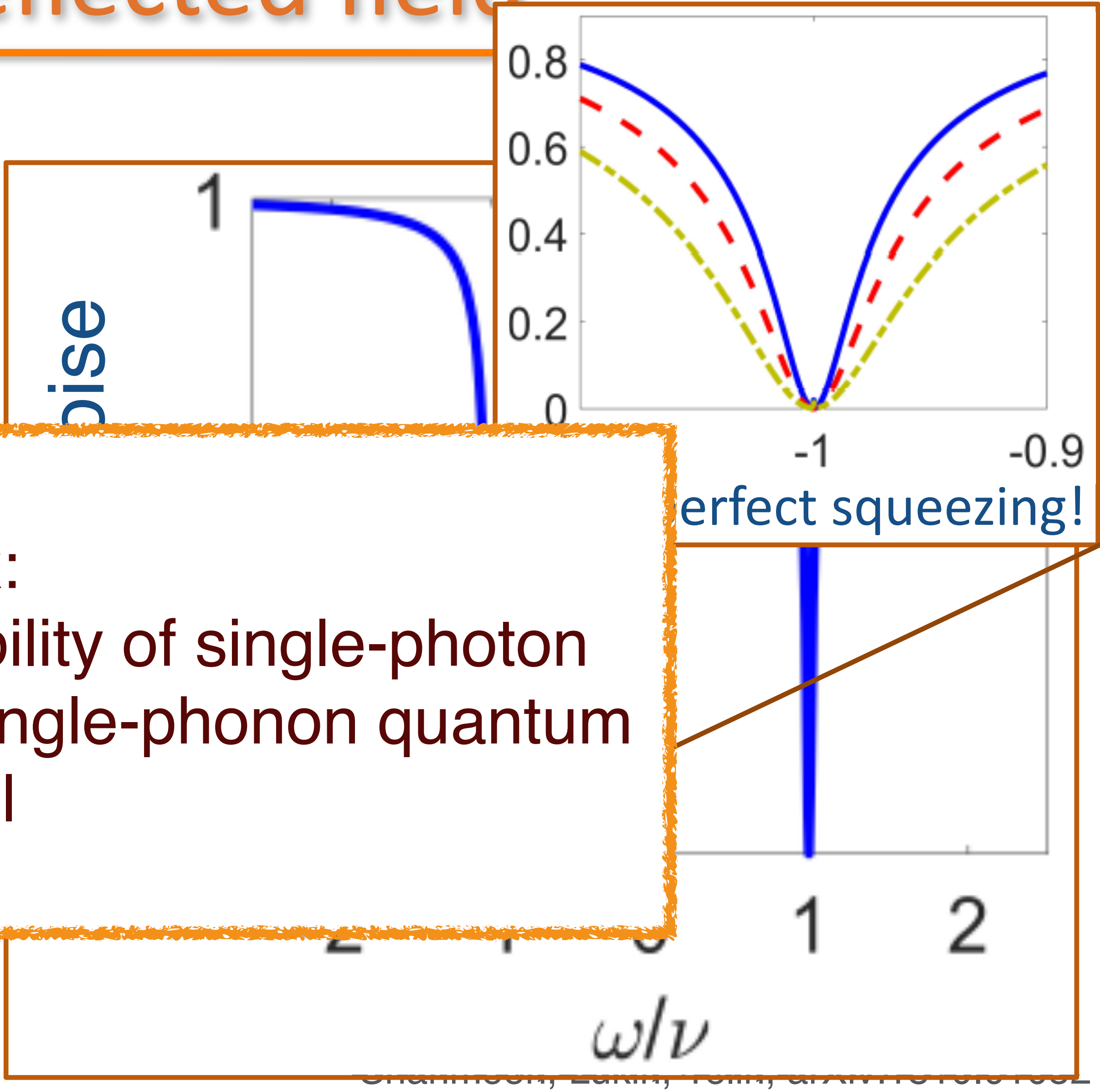




Shahmoon, Lukin, Yelin, arXiv [illegible]

Nonlinear optics: Squeezing of reflected field

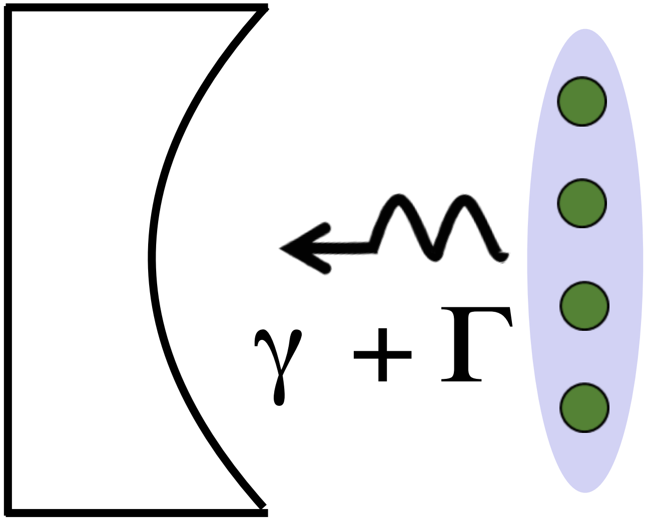


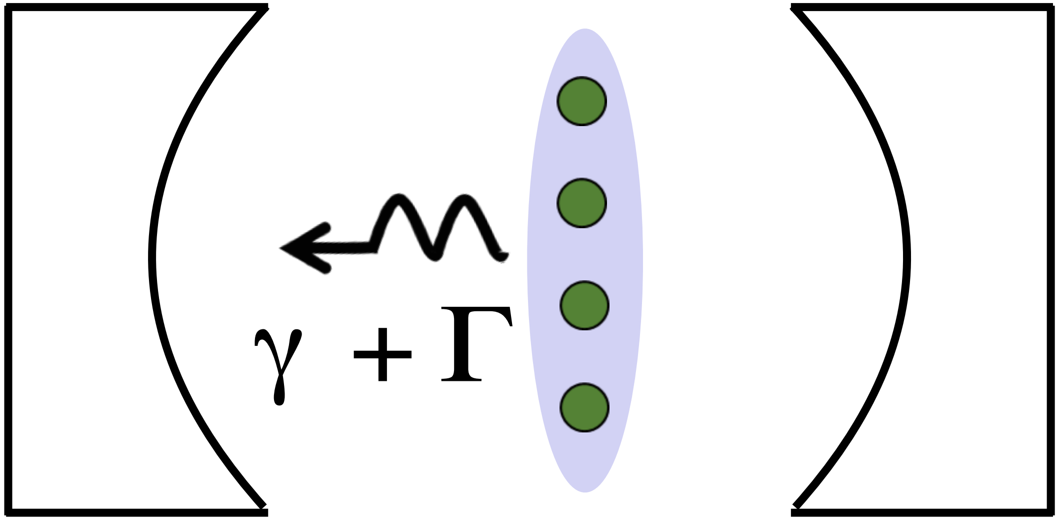


Outlook:

- possibility of single-photon and single-phonon quantum control

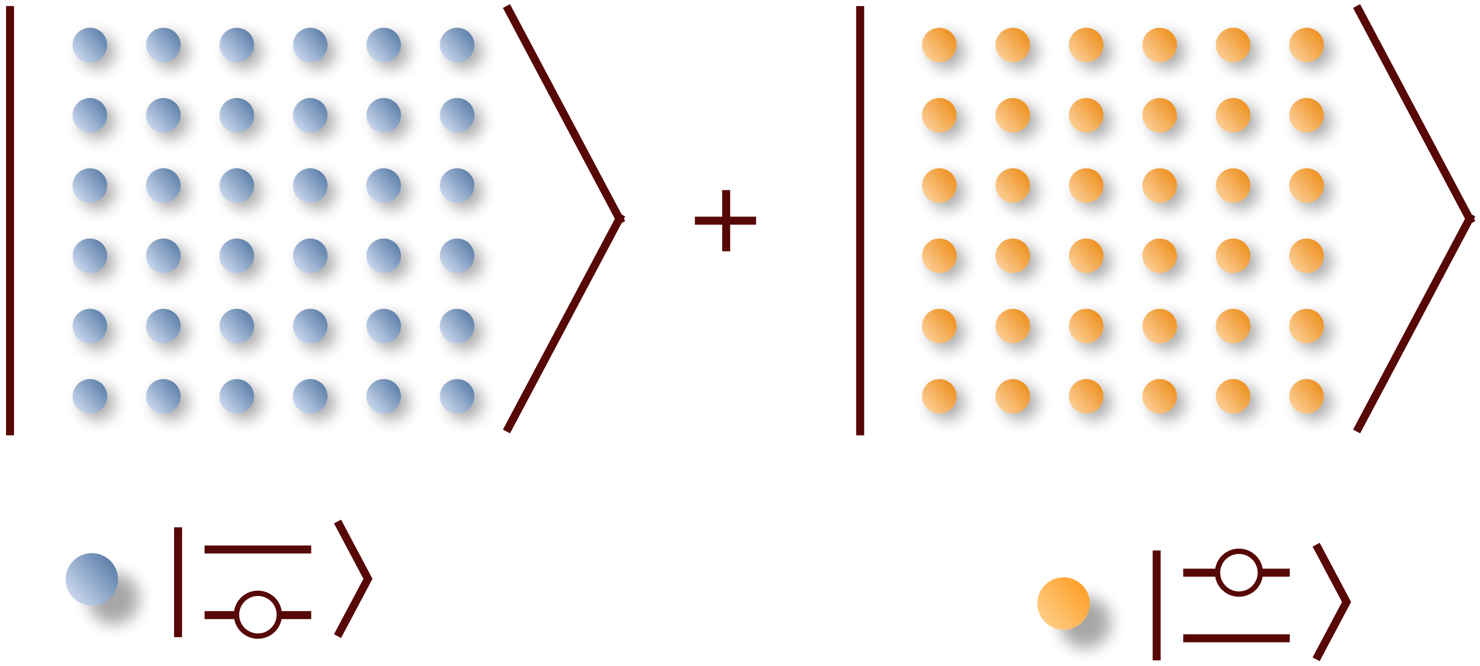
Outlook: Stronger nonlinearities?





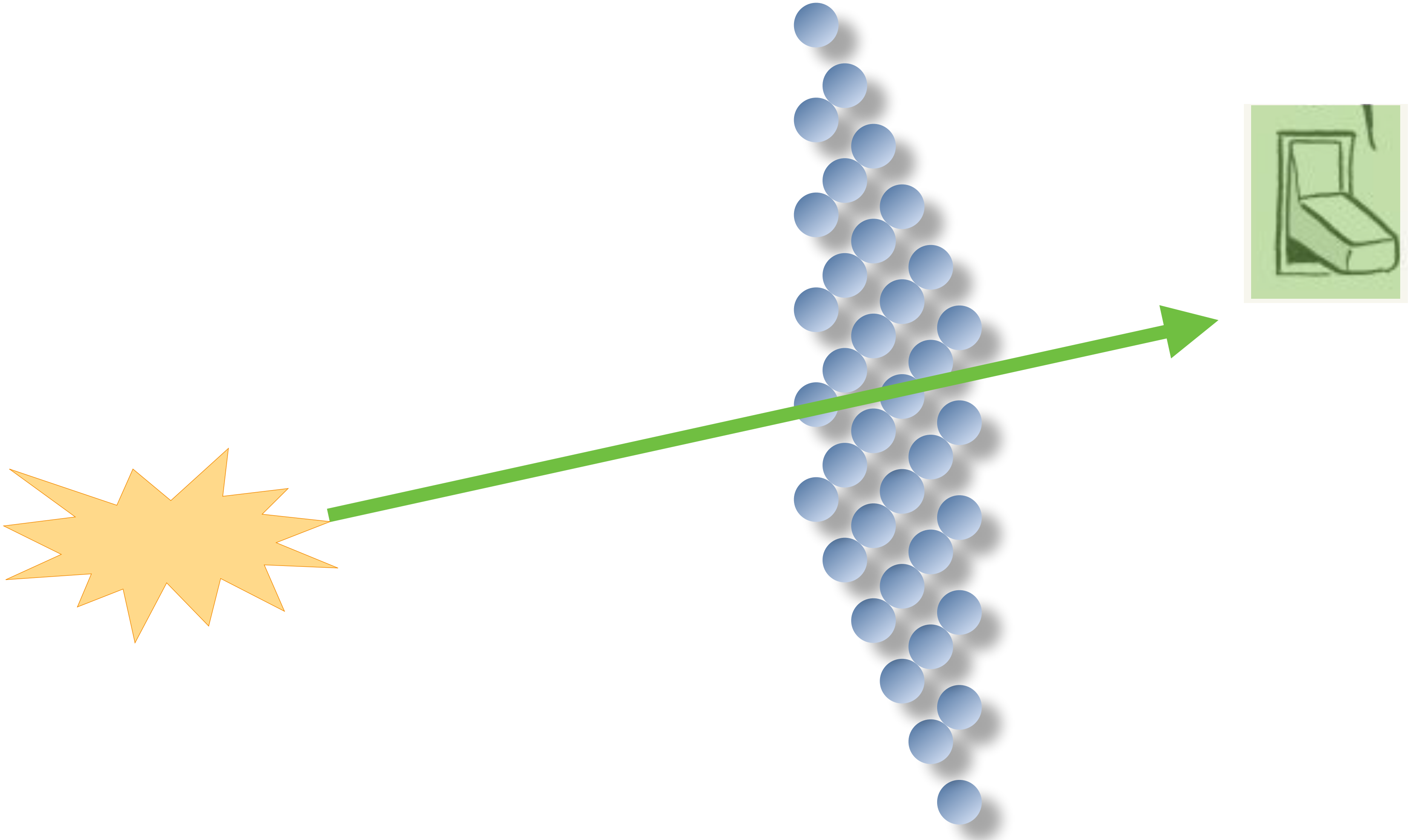
Superposition of atomic mirrors…

Example: cat state

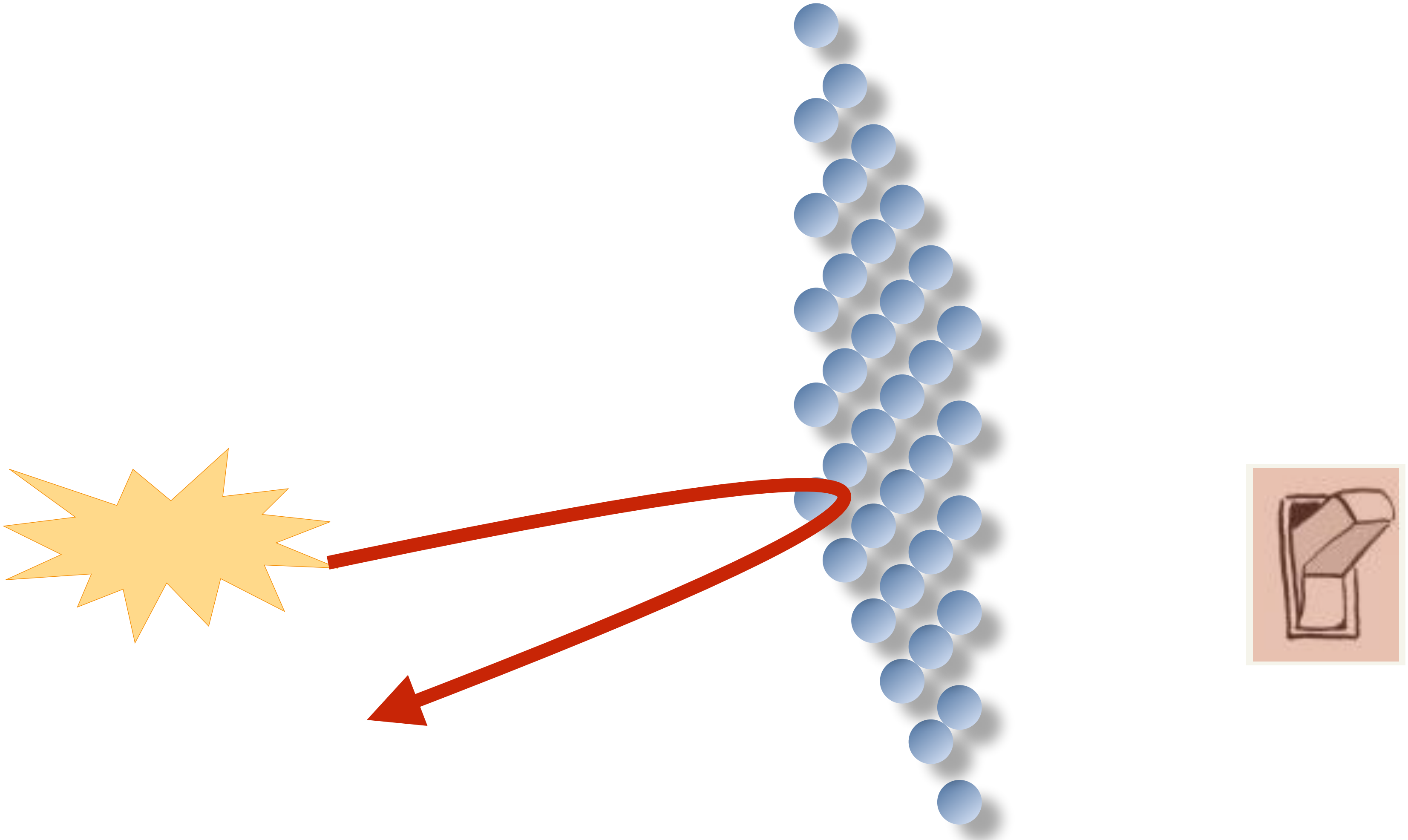


… + quantum reflection = …

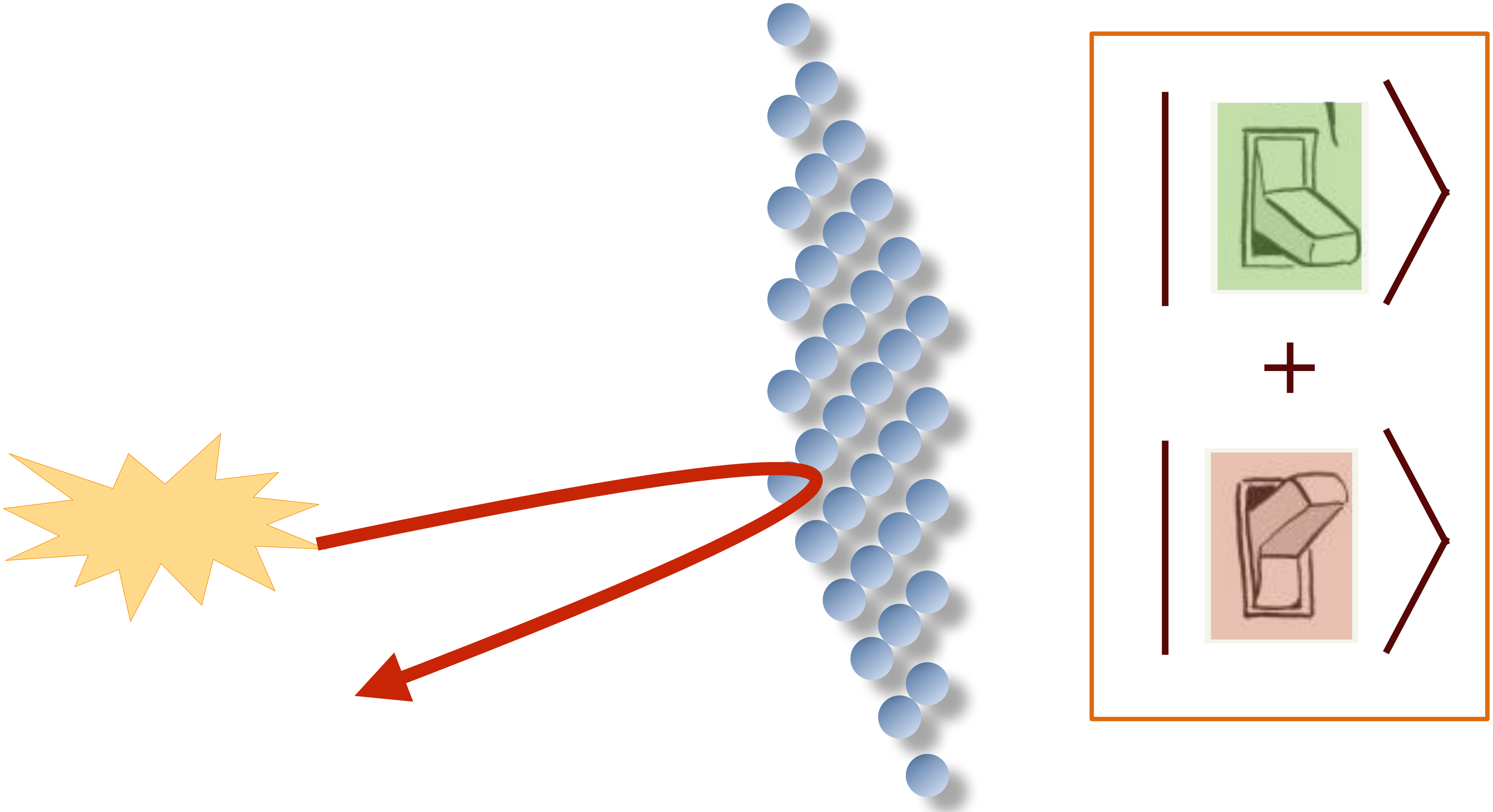
Quantum mirror: Refraction superposition



Quantum mirror: Refraction superposition



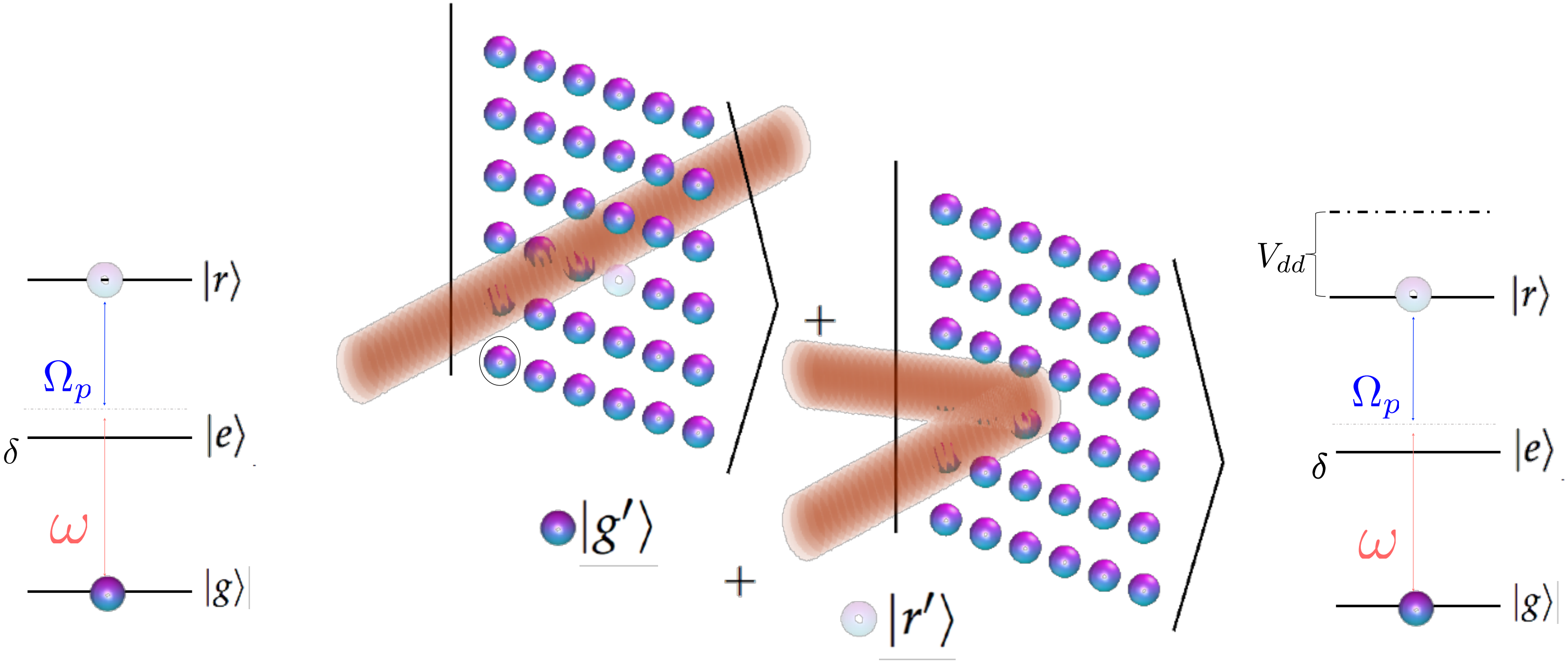
Quantum mirror: Refraction superposition



Quantum mirror: Refraction superposition

whyquantumphysicists.com

Realization with Rydberg EIT

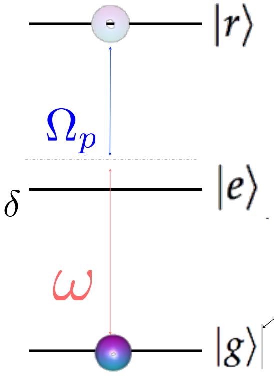


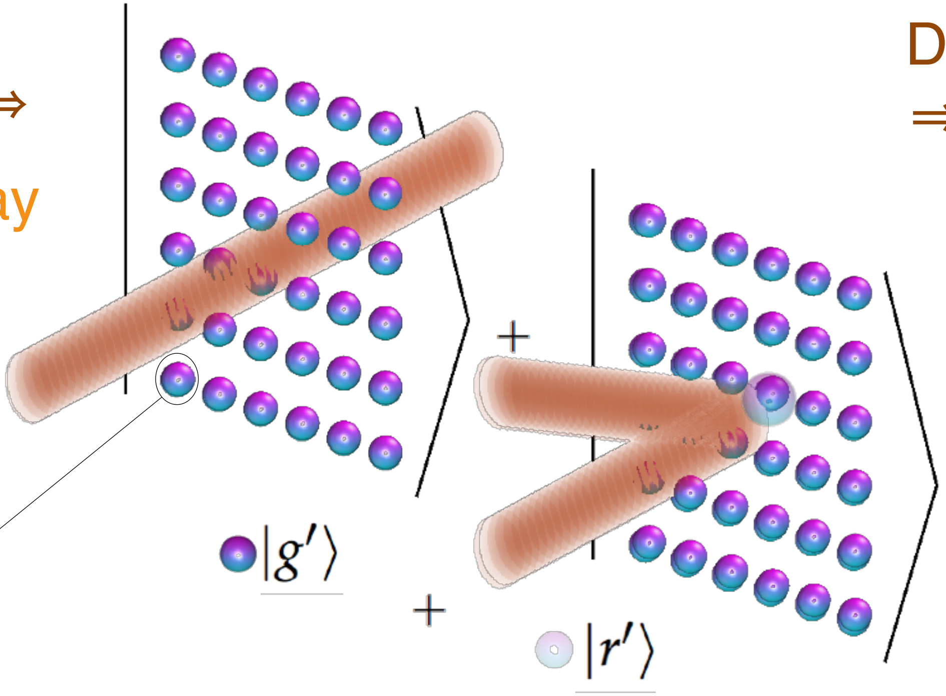
“Quantum Metasurfaces,” Bekenstein, Pikovski, Pichler, Shahmoon, Yelin, Lukin, in prep.

Realization with Rydberg EIT

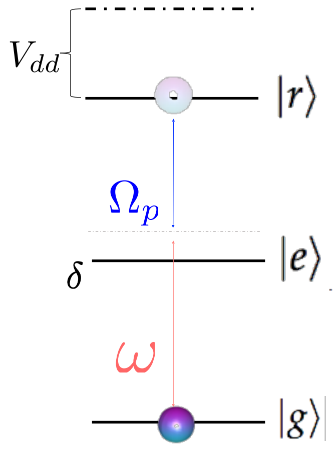
Electromagnetically induced transparency (EIT) ⇒

transparent array





Detuned from EIT ⇒ reflective array



Use Rydberg blockade ⇒ **one atom** detunes from EIT **for whole array**!

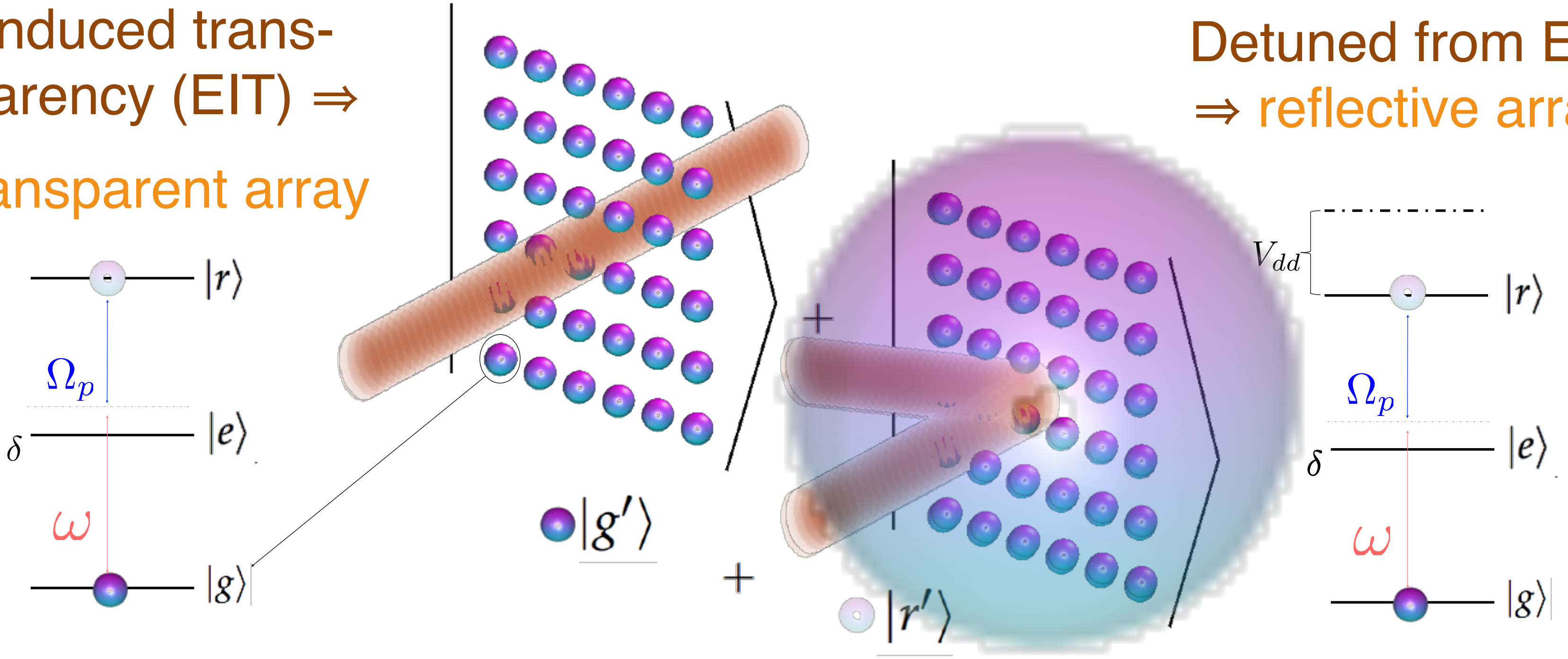
"Quantum Metasurfaces," Bekenstein, Pikovski, Pichler, Shahmoon, Yelin, Lukin, in prep.

Realization with Rydberg EIT

Electromagnetically induced transparency (EIT) ⇒

transparent array

Detuned from EIT ⇒ reflective array



Use Rydberg blockade ⇒ **one atom** detunes from EIT **for whole array**!

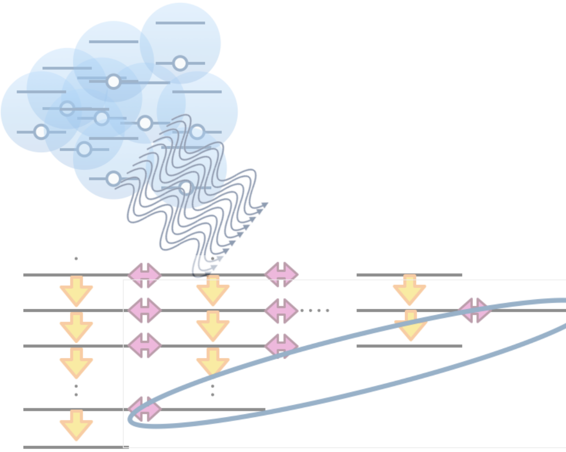
“Quantum Metasurfaces,” Bekenstein, Pikovski, Pichler, Shahmoon, Yelin, Lukin, in prep.

Outlook

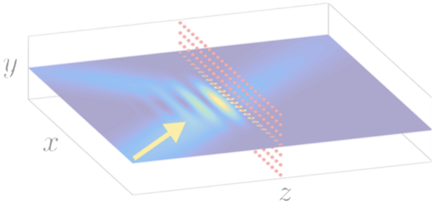
- Quantum nonlinear optics: engineering multi-photon entanglement
- Photonic cluster & tensor network states: applications to robust quantum networking
- Engineering matter states via sub-radiant protections

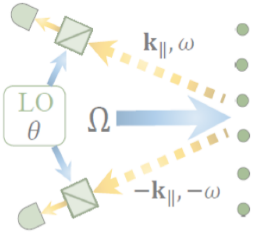
Summary

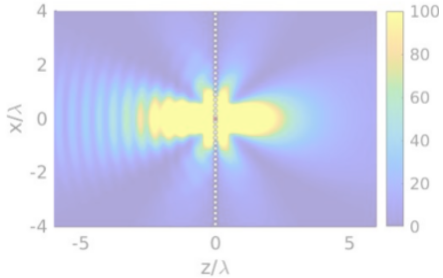
- Concept …
- …and applications of super-radiance



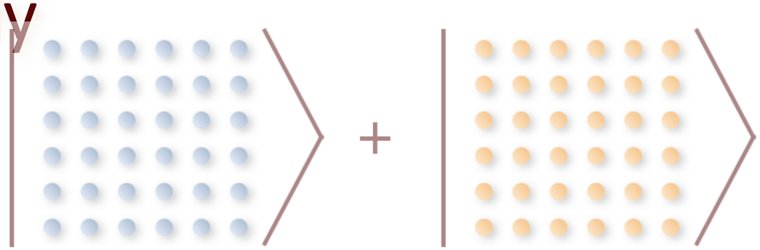
- Concept …







- … and applications of atomically thin arrays



Thank you!