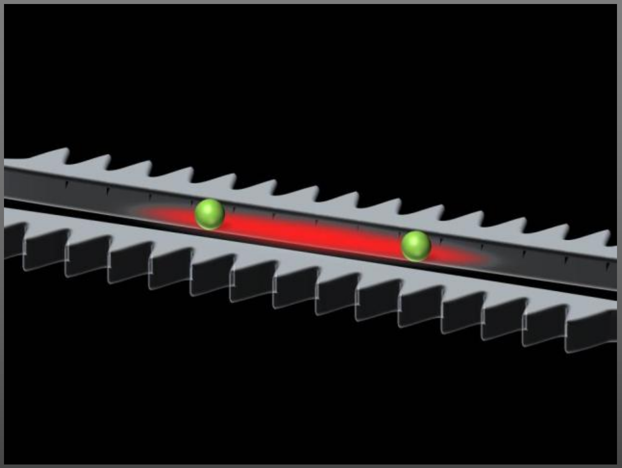


Many-body physics with cold atoms coupled to photonic crystals

Darrick Chang
ICFO – The Institute of Photonic Sciences
Barcelona, Spain

Non-equilibrium dynamics of strongly interacting photons
October 9, 2015

ICFO Institut de Ciències Fotòniques

Fundació Privada CELLEX

MARIE CURIE ACTIONS

MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

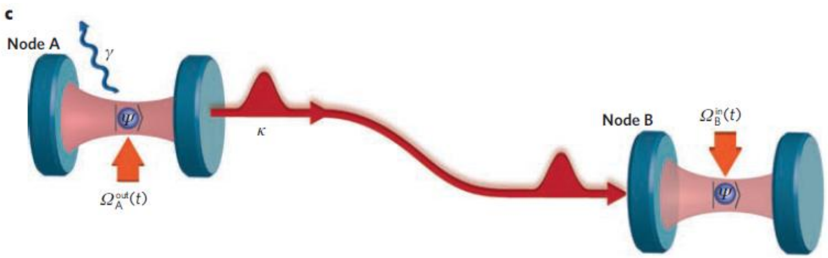
erc

My group

- Also thanks to: Jeff Kimble (Caltech), Chen-Lung Hung (Purdue), Alexey Gorshkov (JQI), Ludwig Mathey (Hamburg)

Toward an atom-nanophotonics interface

- Goal: building blocks for complex quantum systems/devices



Review: HJ Kimble, "The quantum internet," Nature (2008)

Expt: Rempe (MPQ), Nature (2012)

  - Atoms provide quantum functionality, photonics provide control and scalability

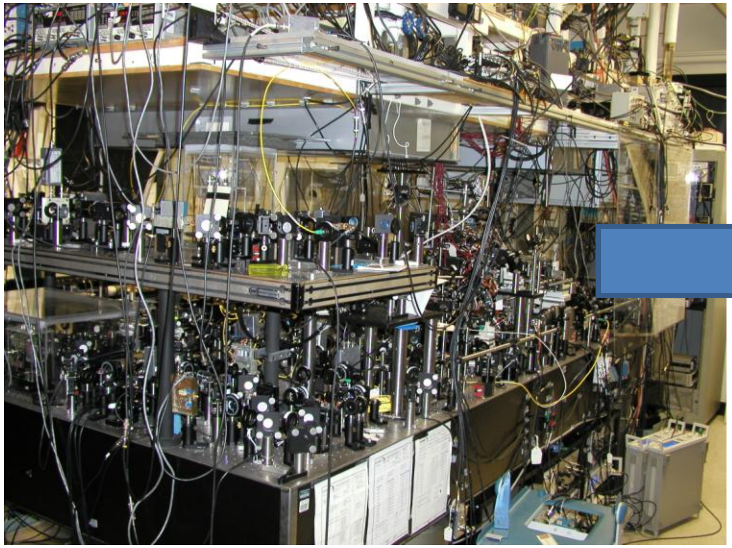
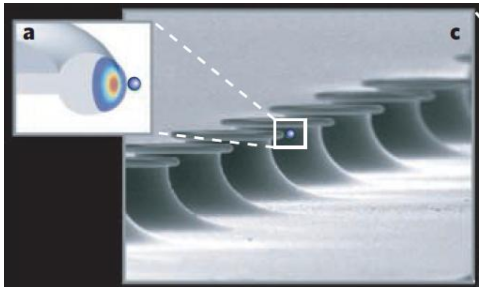
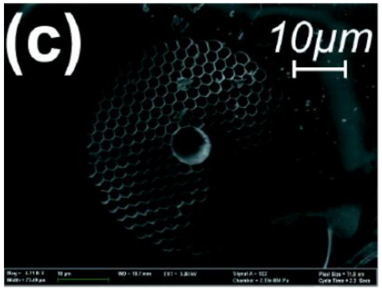


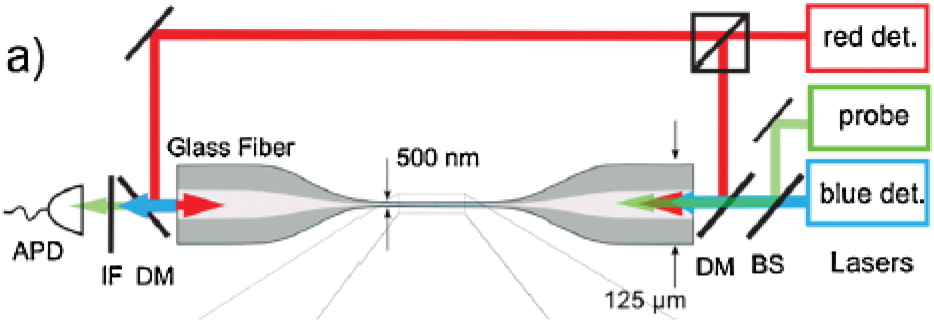
Image from Kimble group



Vahala, Kimble (Caltech)



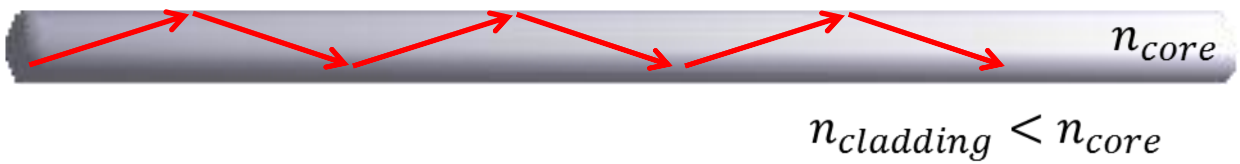
Lukin (Harvard), Vuletic (MIT)

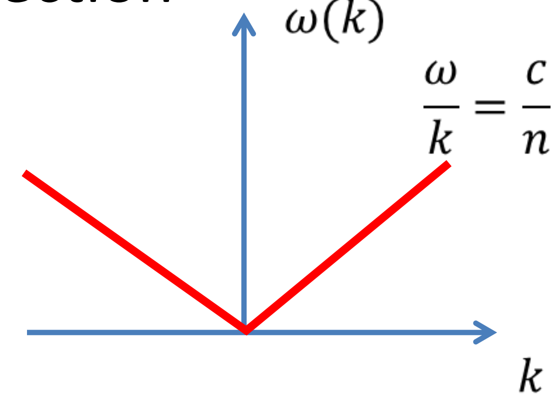


Rauschenbeutel (Vienna)

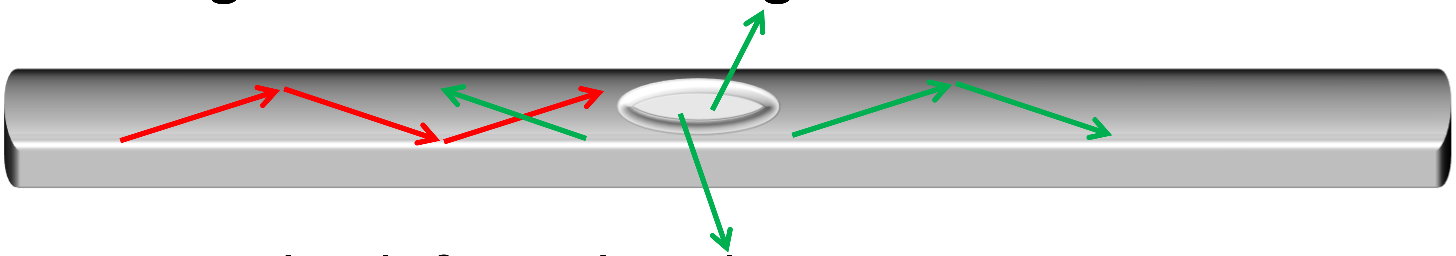
Photonic crystal waveguides

- Normal fiber: light guided by total internal reflection

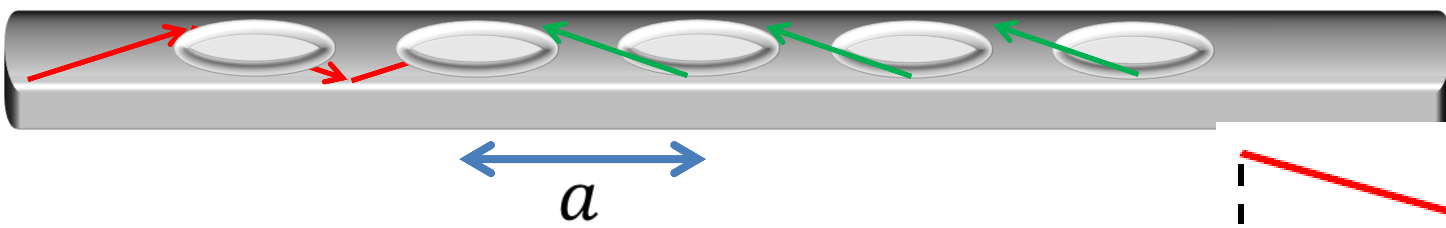


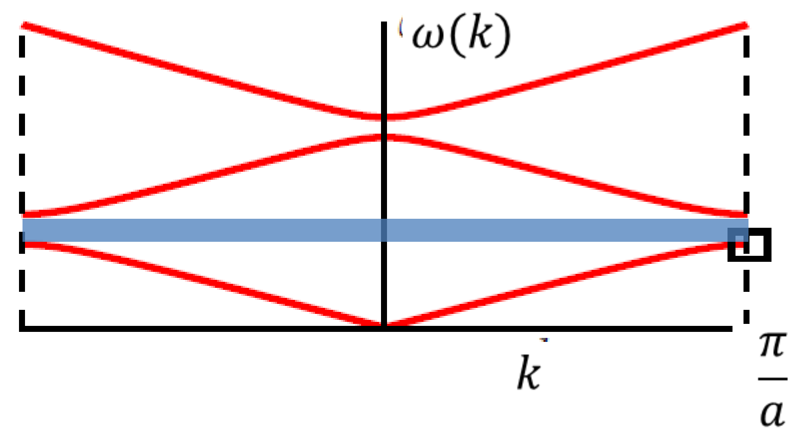


- Single defect: scattering



- Periodic defects: band structure

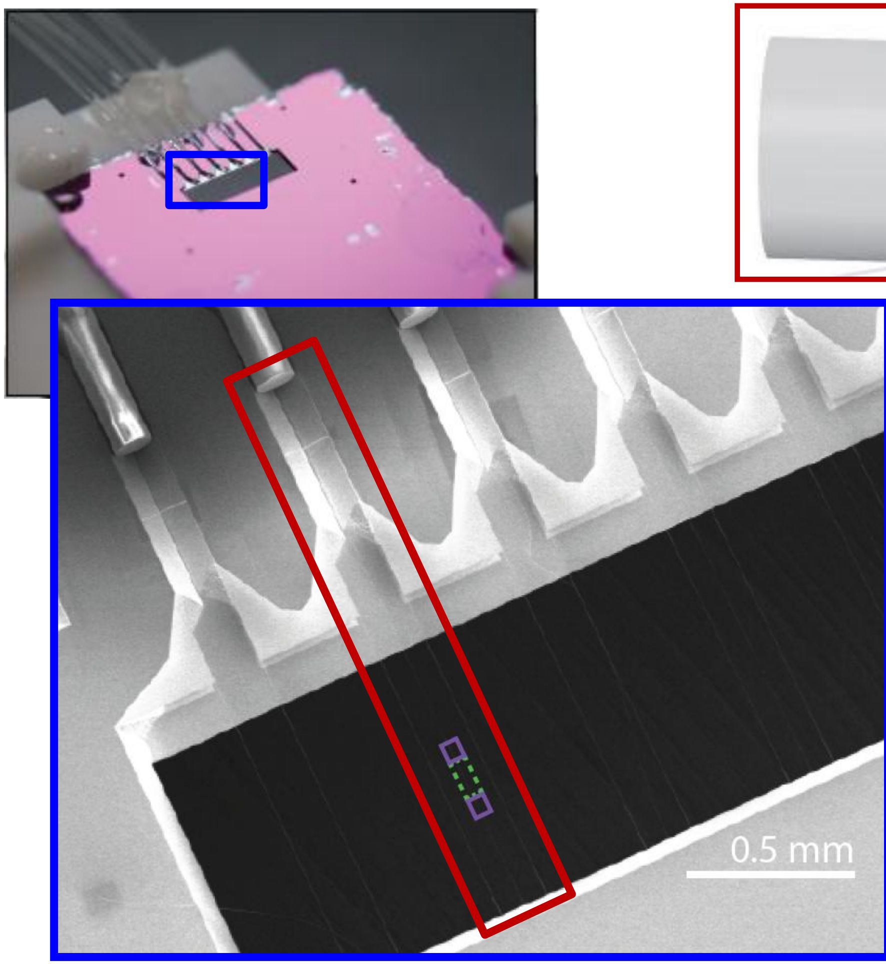


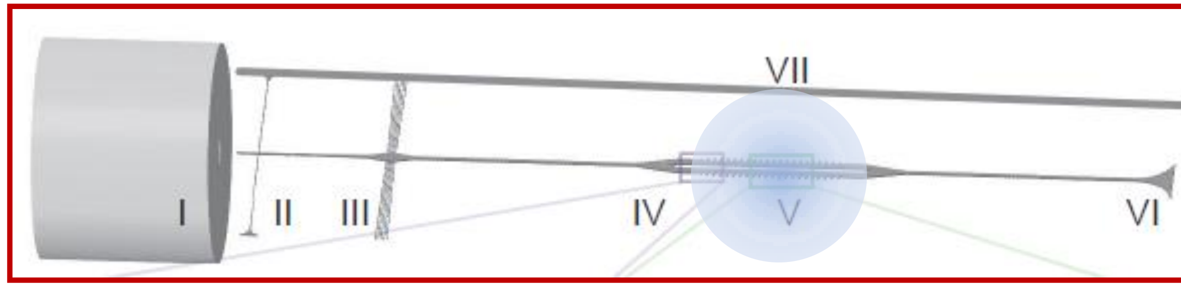


- Control over dispersion / spatial modes
- Band gaps – forbidden propagation

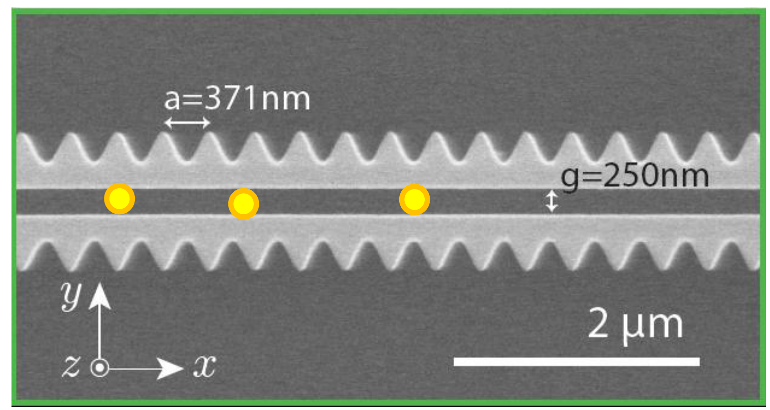
Coupling atoms to PhC waveguides

- Experiments with “alligator” photonic crystal waveguide





MOT

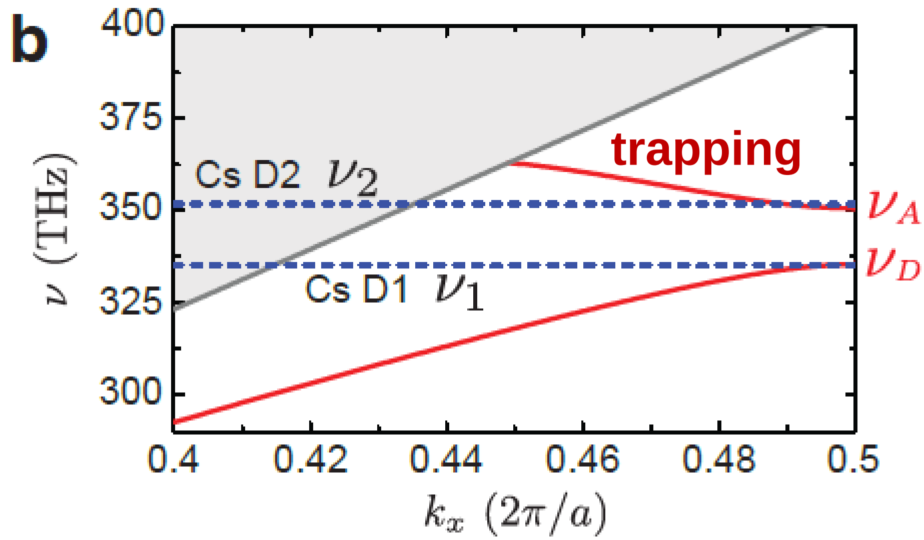


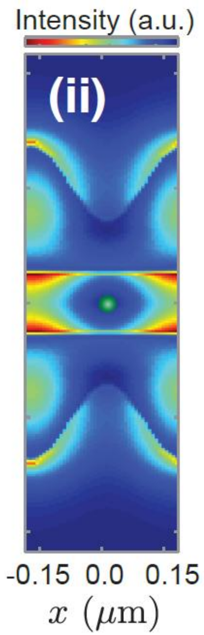
A. Goban et al., Nature Commun. 5, 3808 (2014) (Kimble, Caltech)

(also expts. with PhC cavities in Lukin group at Harvard)

Overview of PhC-atom experiment

- Dispersion engineering: separation of "trapping" and "physics" bands





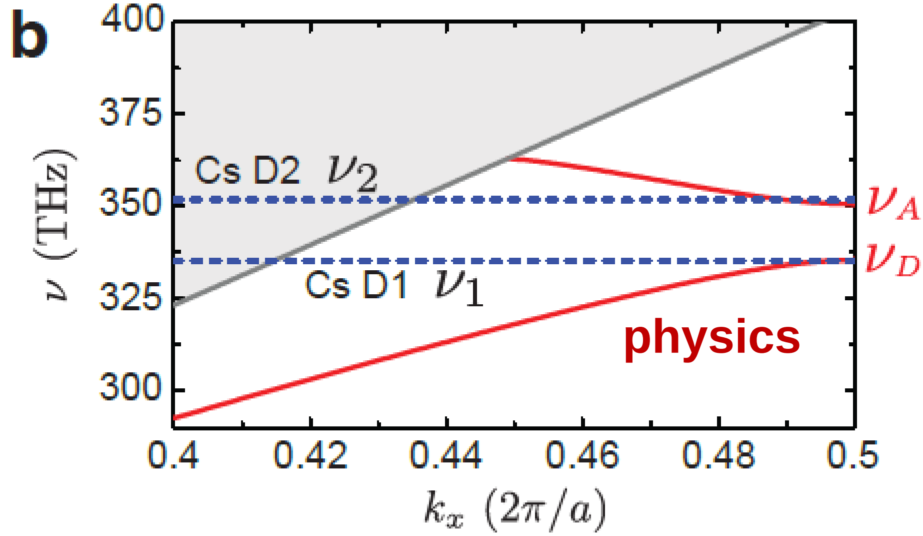
Trapping band

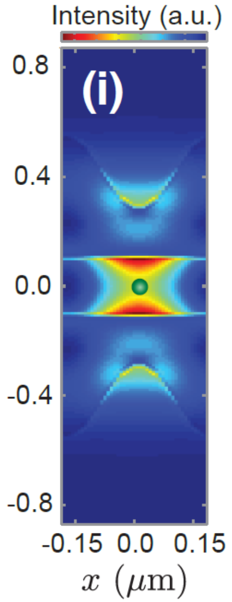
- Local intensity minimum (zero)
- Trap atoms by exciting a guided mode blue-detuned relative to atomic transition ($\nu_{\text{laser}} > \nu_2$)

Few atoms trapped $\langle N \rangle \sim 3$

Overview of PhC-atom experiment

- Dispersion engineering: separation of "trapping" and "physics" bands





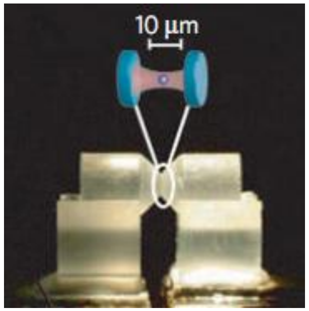
Physics band

- Strong atom-light interactions on atomic resonance ν_1
  - Slow group velocity and large local field

Emission probability $P \sim 0.5$ ($P \sim 0.05$ in nanofibers)

What's next?

- Do these new systems just enable us to do old things better?



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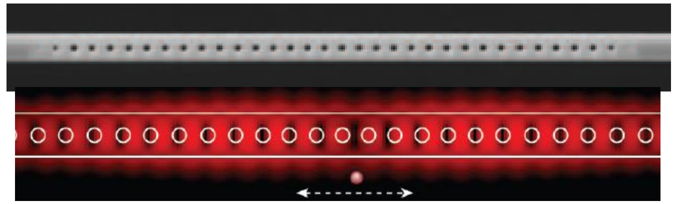

≈

Jaynes-Cummings model

OR

New paradigms

Quantum information processing

Single-photon nonlinear optics

Many-body physics

Atom trapping

What's next?

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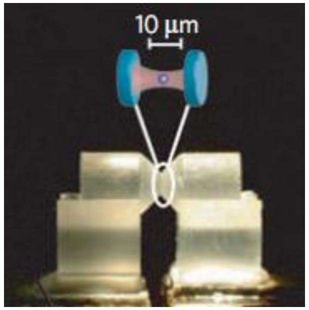

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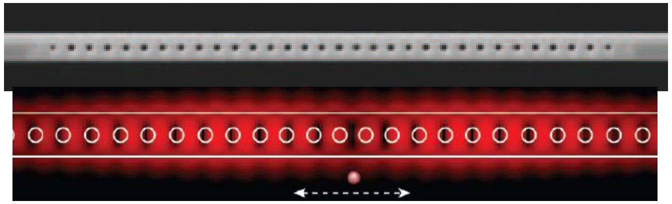


≈

Jaynes-Cummings model

OR

Surface & vacuum forces

Dimensionality & dispersion

Large per-photon forces

Strong atom-photon interactions

New paradigms

Quantum information processing

Single-photon nonlinear optics

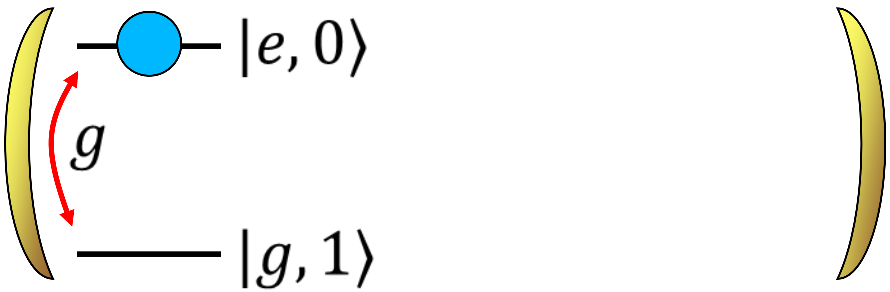
Many-body physics

Atom trapping

Many-body physics: engineering long-range interactions between atoms

Light-mediated interactions

- Infinite-range interactions are “easy” with light
- Cavity QED:



$\Delta = \omega_{\text{cavity}} - \omega_{\text{atom}}$

Dressed state $|e\rangle$

Light-mediated interactions

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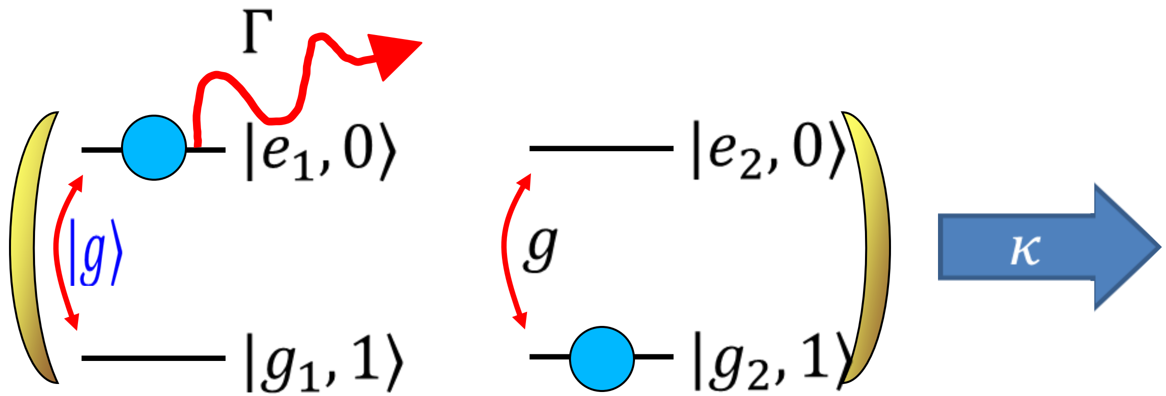


- Second atom: absorbs photonic component of first dressed atom

$$H_{\text{eff}} \approx \frac{g^2}{\Delta} \sigma_{eg}^1 \sigma_{ge}^2 + h.c.$$

- Optimize exchange probability via detuning

$$\text{Loss rate} \approx \Gamma + \left(\frac{g}{\Delta}\right)^2 \kappa$$

$$\text{Error} \sim \frac{1}{\sqrt{C}} \sim \sqrt{\frac{\kappa\Gamma}{g^2}}$$

Cavity QED

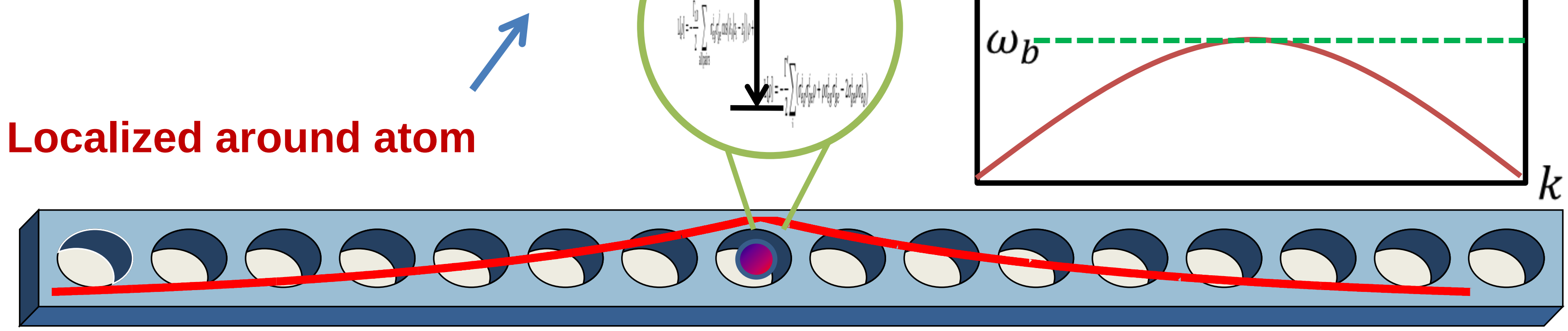
- ✓ (Mostly) coherent dynamics
- ✓ Infinite-range interactions
  - All atoms between the cavity mirrors interact

- ✘ Range not tunable
- ✘ Infinite-range interactions are an “aberrant” case
  - Well-solved by collective operators or mean-field

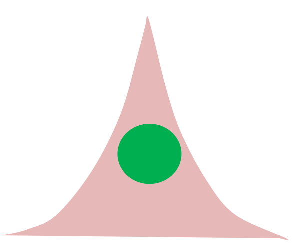
Dynamic "atom-induced cavity"

- Initial work: S. John (Toronto) in 1990's
- Excited atom dressed by photonic "cloud" in the bandgap

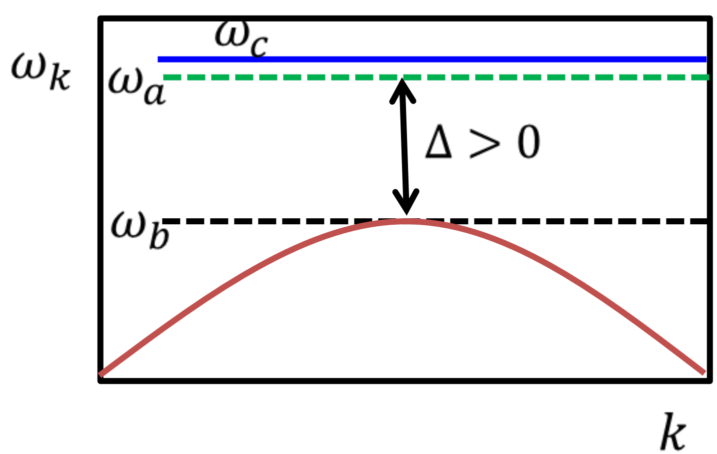
- Strong intensity at the trapping point
- Strong atom-light interaction on atomic resonance ν_1
  - Further enhancement via slow group velocity



- Atom-cavity properties:



Atom-like



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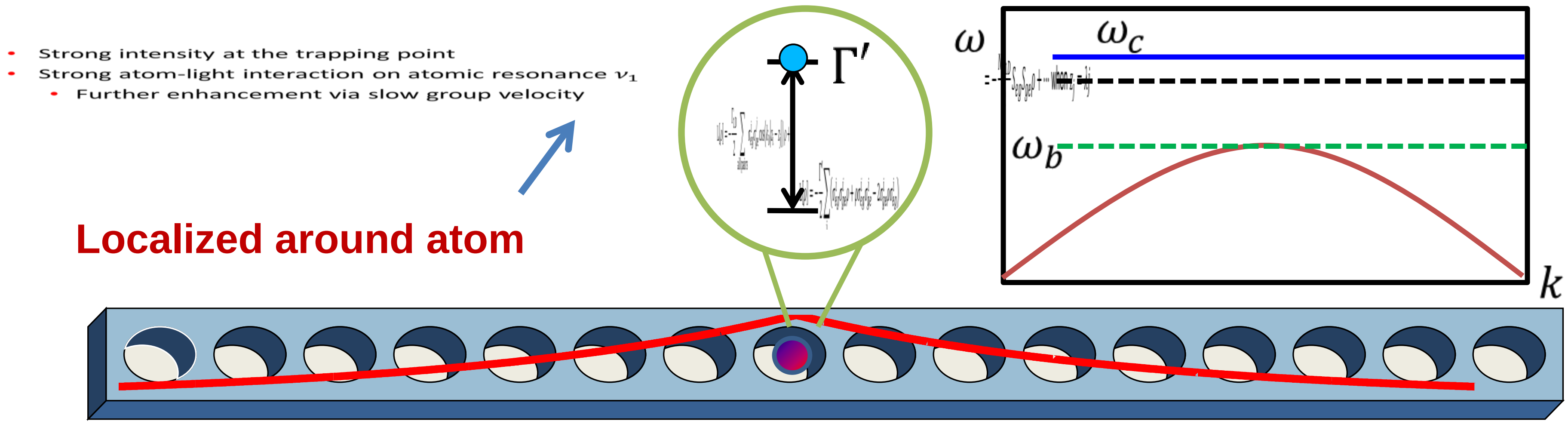

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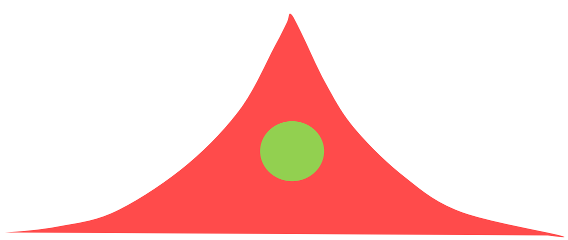

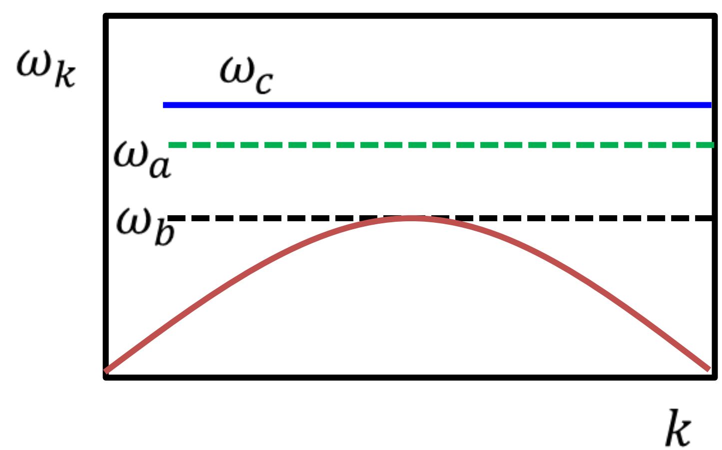

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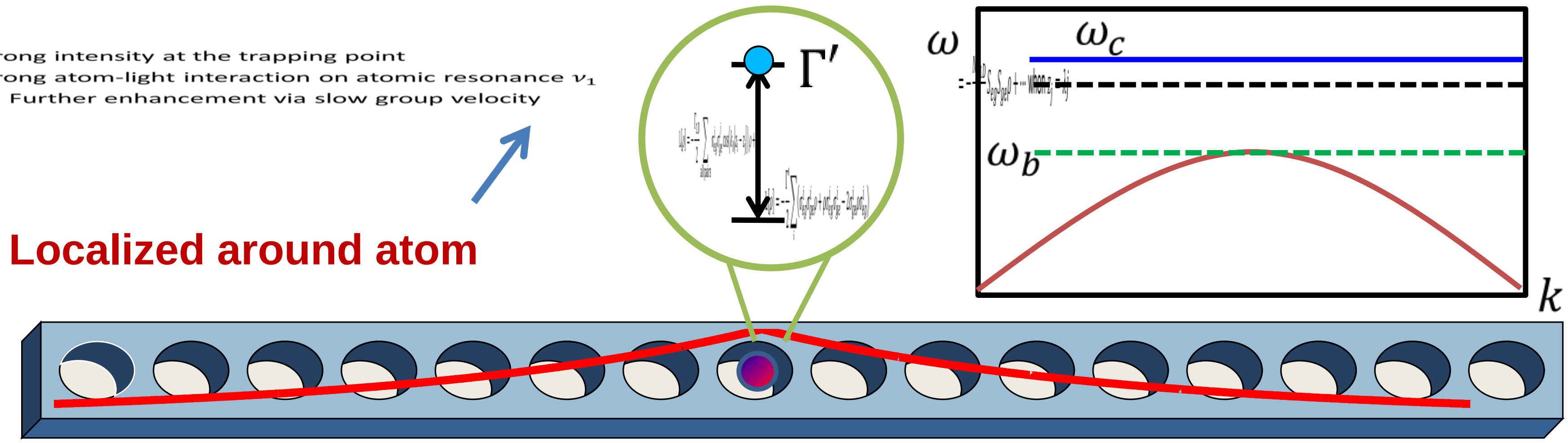

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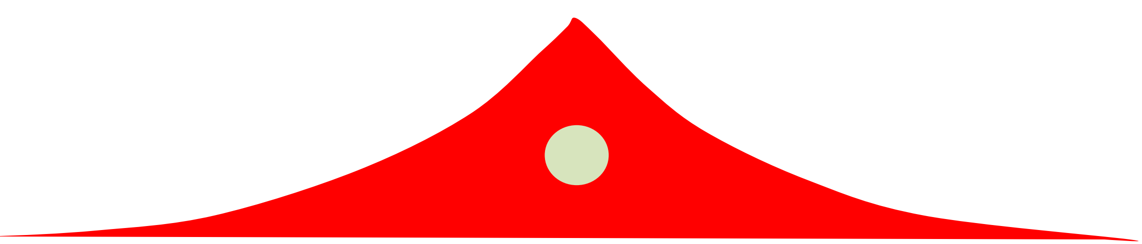
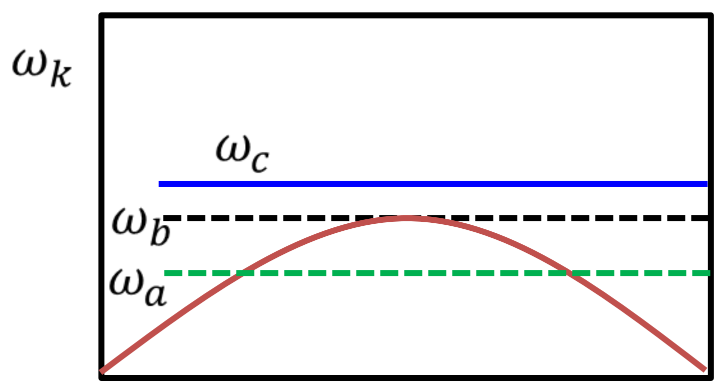


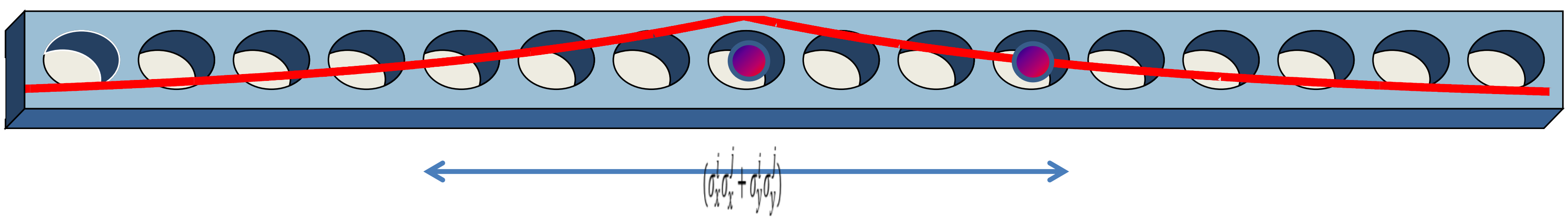
Photon-like



- Arbitrarily weak dielectric defect can create a cavity mode (1D)

Long-range interactions

- Photonic cloud has all the same functionality as a *real* cavity of the same size
  - But centered around the atom, and follows it around!



- *Long-range* dipole-dipole interactions

$$H_{\text{eff}} \approx U(r_1 - r_2)\sigma_{eg}^1\sigma_{ge}^2 + h.c.$$

$\frac{U_{\max}}{2\pi} \sim$ few GHz for $L \sim \lambda$

- Same loss mechanisms as a real cavity

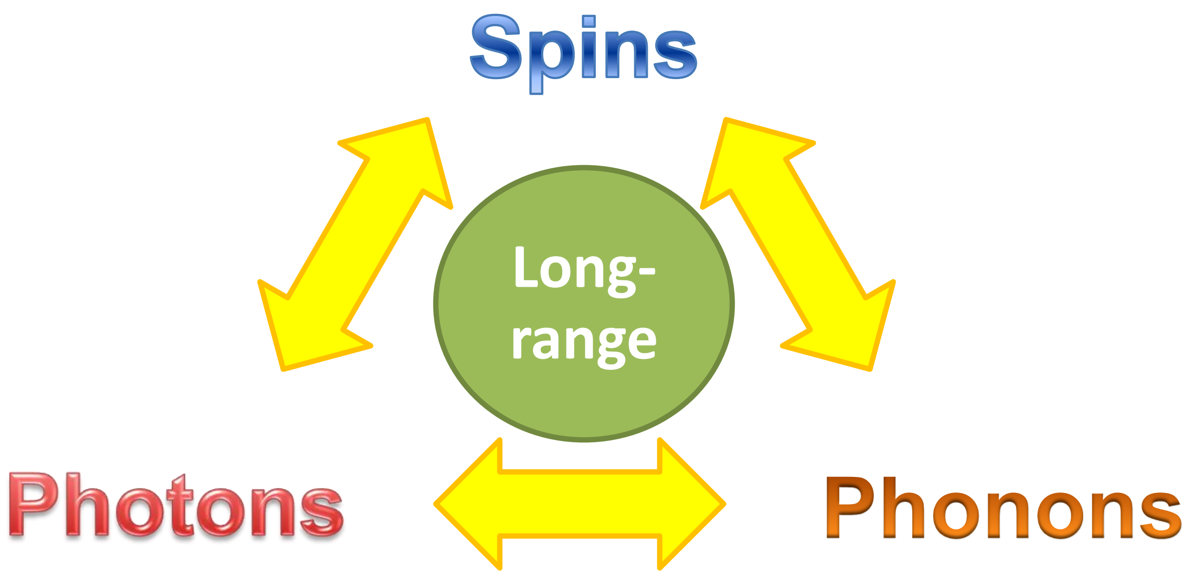
$$C \sim 10^5 \frac{\lambda}{L} \text{ for } Q \sim 10^6$$

- Apply toolbox of atomic physics to engineer interactions
  - Ground-state manifold, external pump fields, time dependence …

Strong multi-physics coupling

$$H_{\text{eff}} \approx \sum_{i,j} U(x_i - x_j)\sigma^i \sigma^j$$

- More than just long-range spin interactions:
  - $U(r_i - r_j)$ is a mechanical potential acting on atoms
  - Strong coupling of photons to spin excitations
- An exciting **quantum material**



Many-body physics in “optomechanical arrays” of atoms

Naïve question

$$H_{\text{eff}} \approx \sum_{i,j} U(x_i - x_j)\sigma^i \, \sigma^j$$

Spatial interactions
Leads to crystallization, etc.

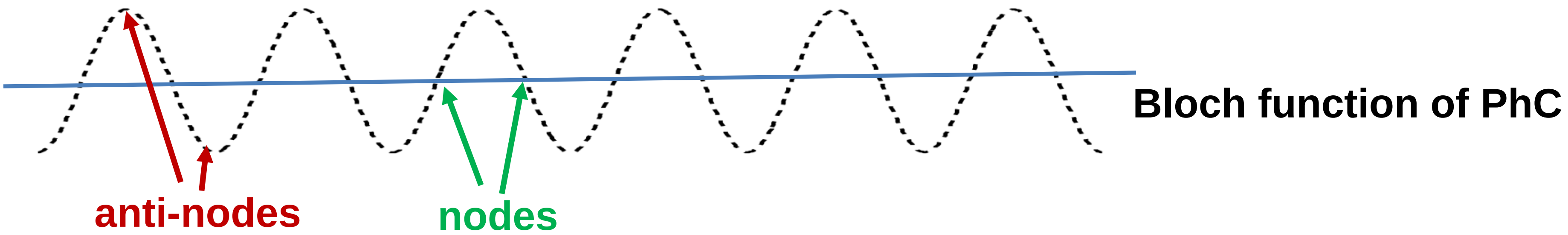
Spin interactions
Leads to entanglement, etc.

- Crystals held together by entanglement?
  - What kinds of phases are possible?
  - Destroying entanglement ↔ phonon excitations
  - Transport properties of system?

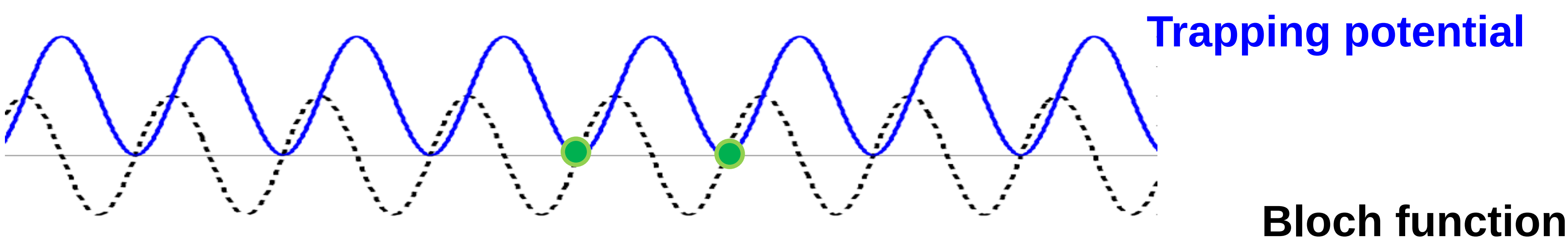
Ingredients for a simple model

- Photonic crystal mediated interaction

Few atoms trapped $\langle N \rangle \sim 3$



- Add external optical lattice



  - Atoms trapped at nodes!
  - External potential and PhC interaction compete against each other

Entangled dimers of two atoms

$(P \sim 0.05 \text{ in nanofibers})$

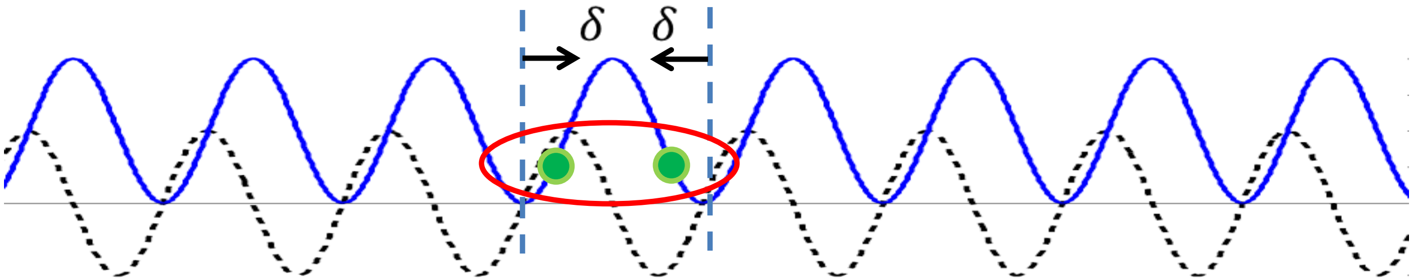
$+1 \quad |T\rangle$
$-1 \quad |S\rangle$

- Atoms can lower their total energy by displacing from trap centers

Without exponential envelope:

$|LL, T\rangle$
$|RR, T\rangle$
$|RL, S\rangle$
$|LR, S\rangle$

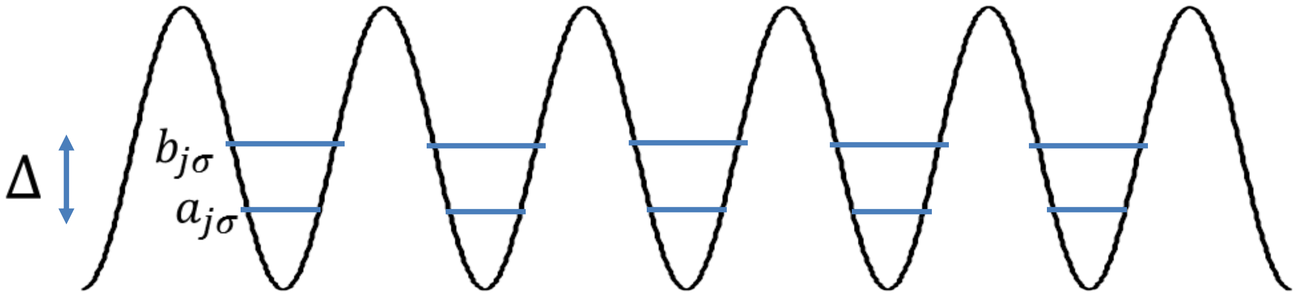
Including exponential



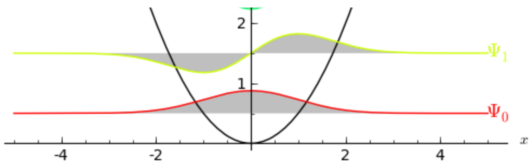
$|\psi\rangle \sim |RL, S\rangle$

Quantum motion and spins

- Minimal model: two bands



Deep lattice limit



$$(a \pm b)_j^\dagger |0\rangle \sim |R\rangle_j, |L\rangle_j$$

- Hard core limit, one atom per site, nearest-neighbor interactions
- Treat the band occupation as a pseudo-spin $\tilde{\sigma}$

$$H \approx \sum_i \Delta \tilde{\sigma}_i^z + h\sigma_i^z + g\left(\tilde{\sigma}_i^x \tilde{\sigma}_{i+1}^x + \xi\left(\tilde{\sigma}_i^x - \tilde{\sigma}_{i+1}^x\right)\right)\left(\sigma_i^+ \sigma_{i+1}^- + h.c.\right)$$

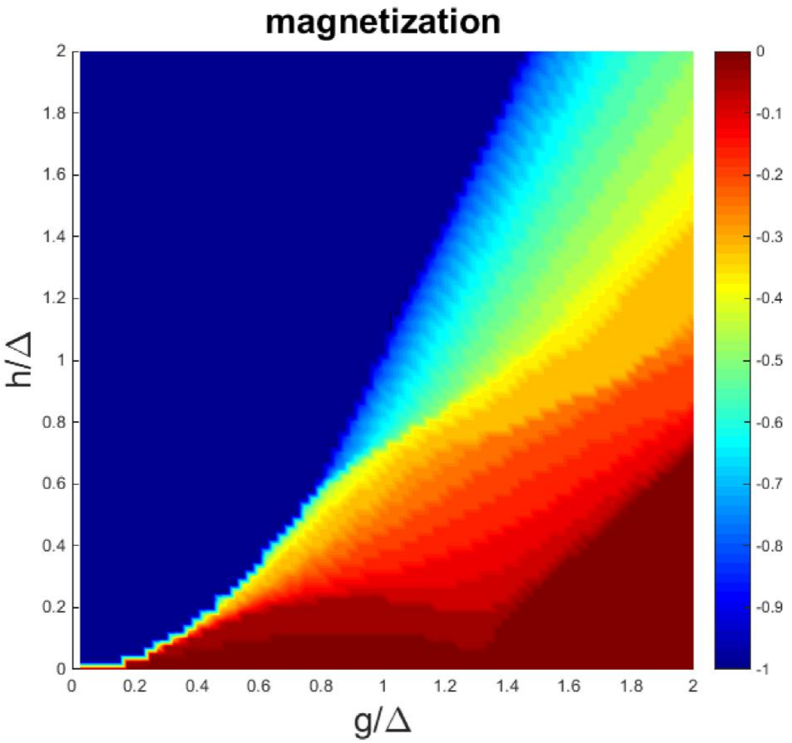
four-fold degeneracy in motion

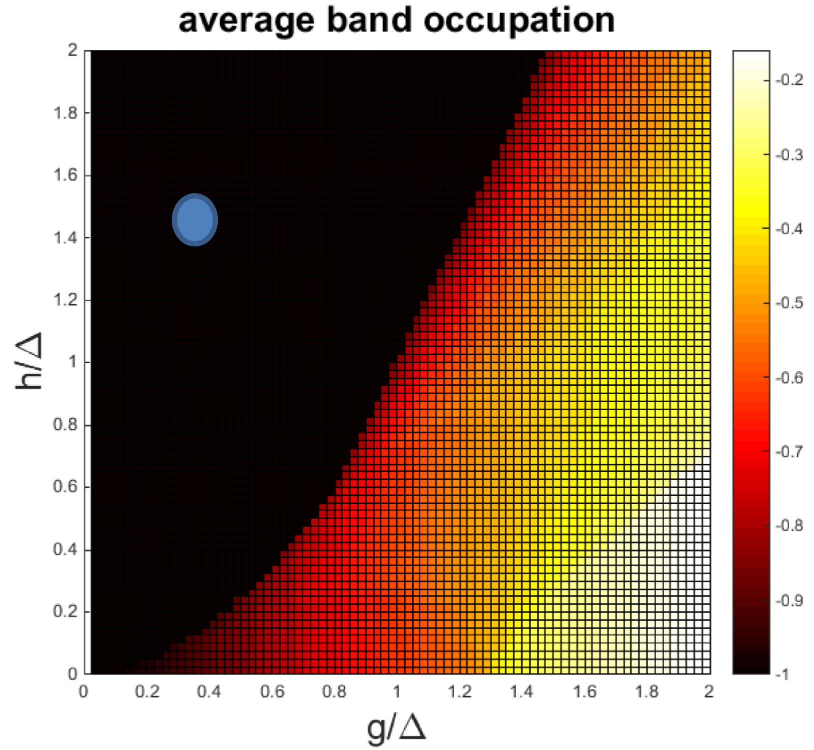
dimerization

spin flip exchange

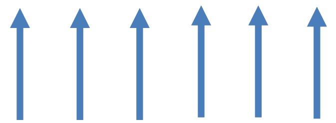
Phase diagram

- Magnetization $\langle \sigma_z \rangle$ and band occupation $\langle \tilde{\sigma}_z \rangle$ (calculated by DMRG)





Polarized spins in lowest band



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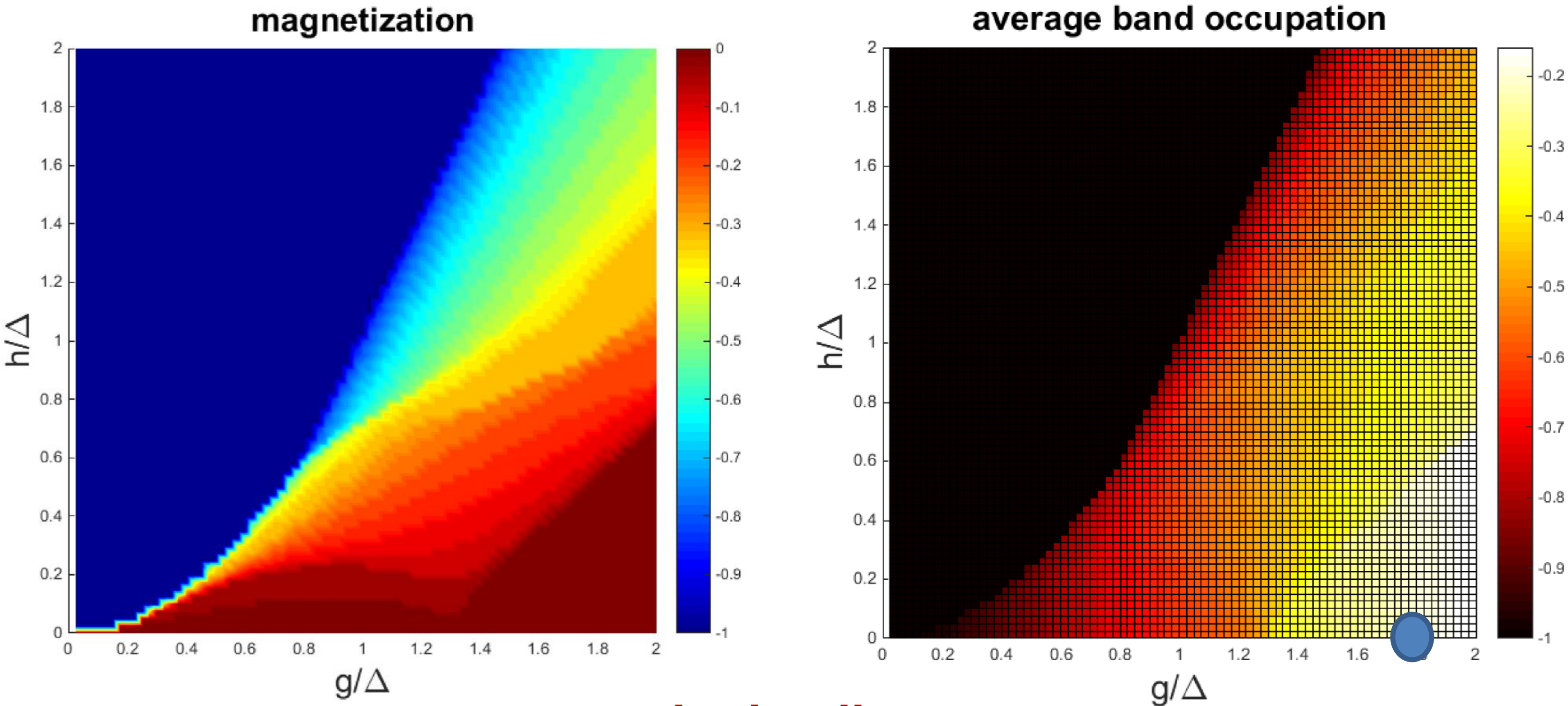

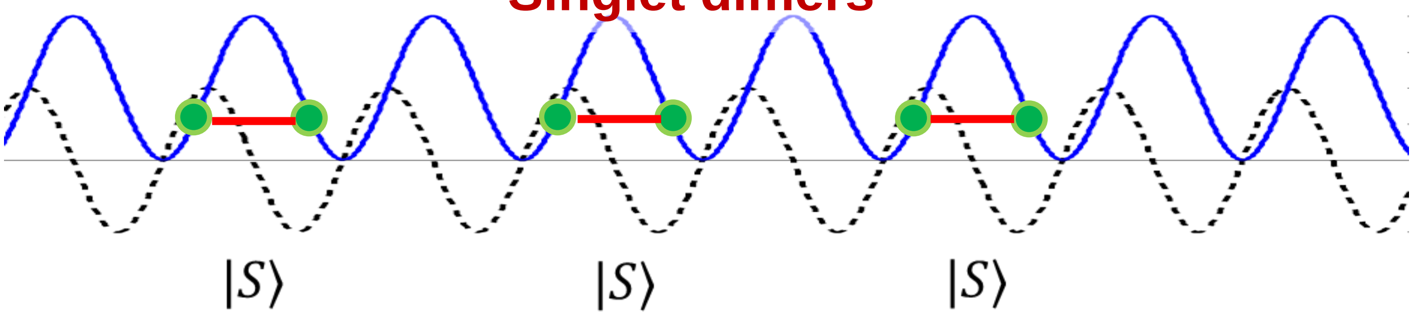

- Entanglement and spin-squeezing induced by motion

Phase diagram

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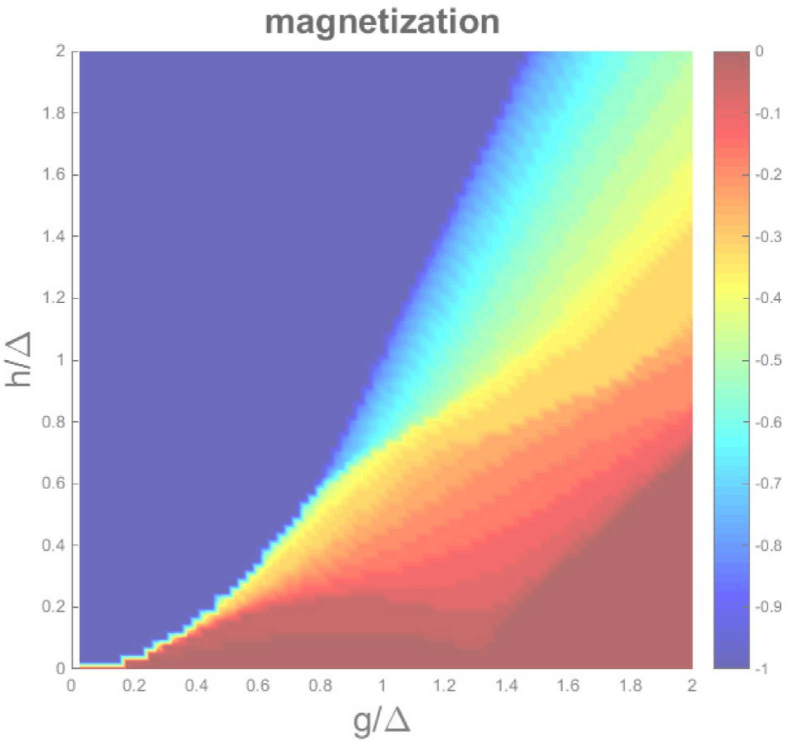
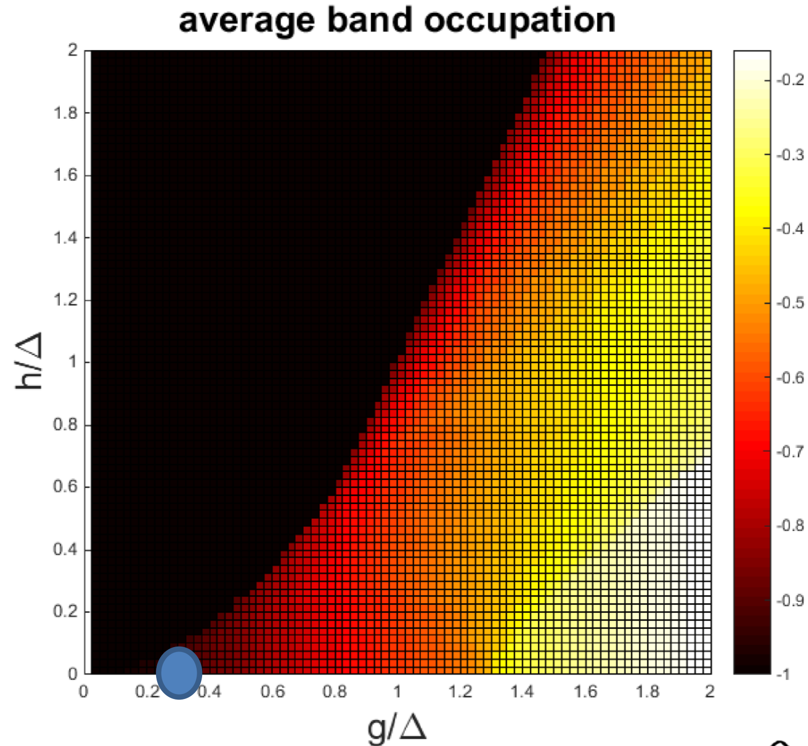
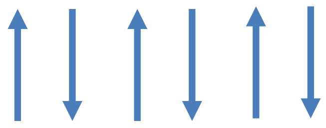
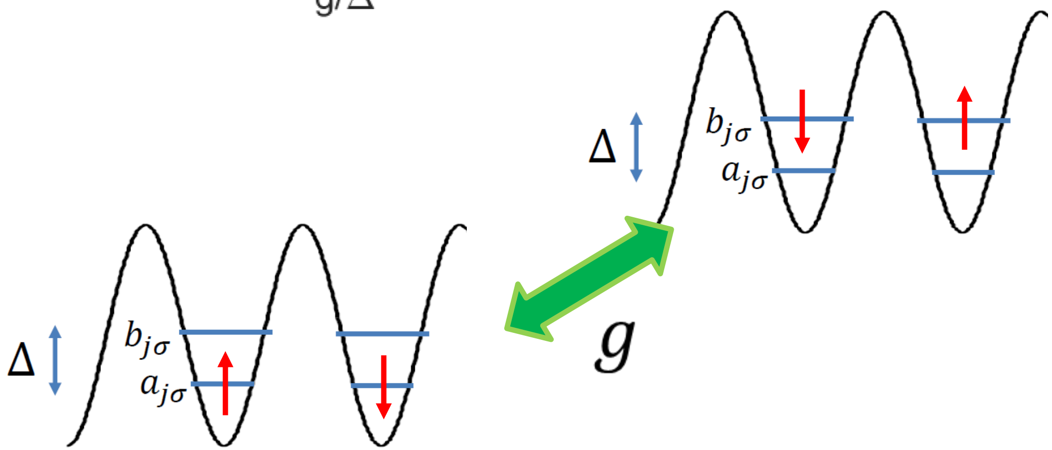




Phonon-induced AF in lowest band





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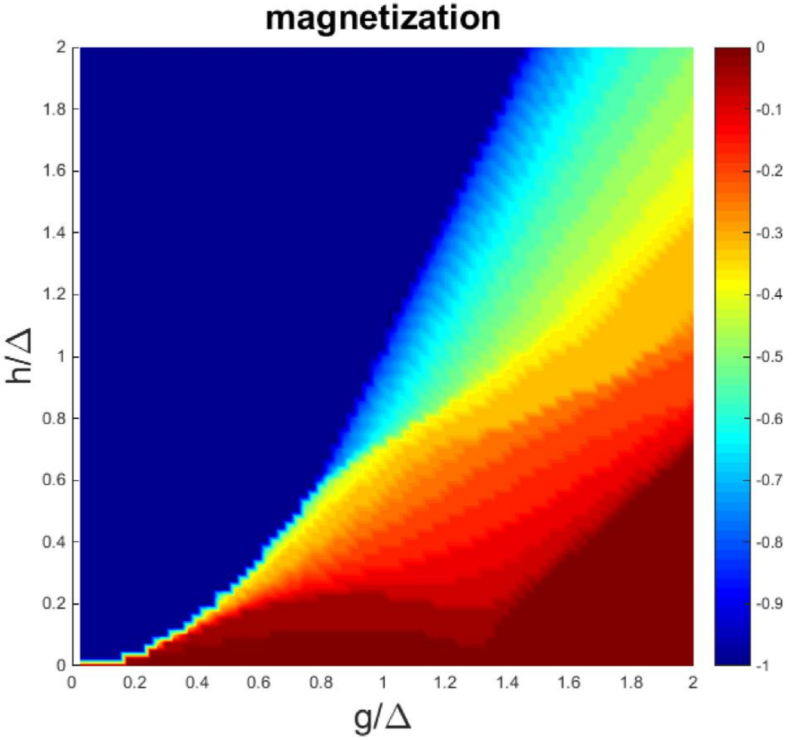
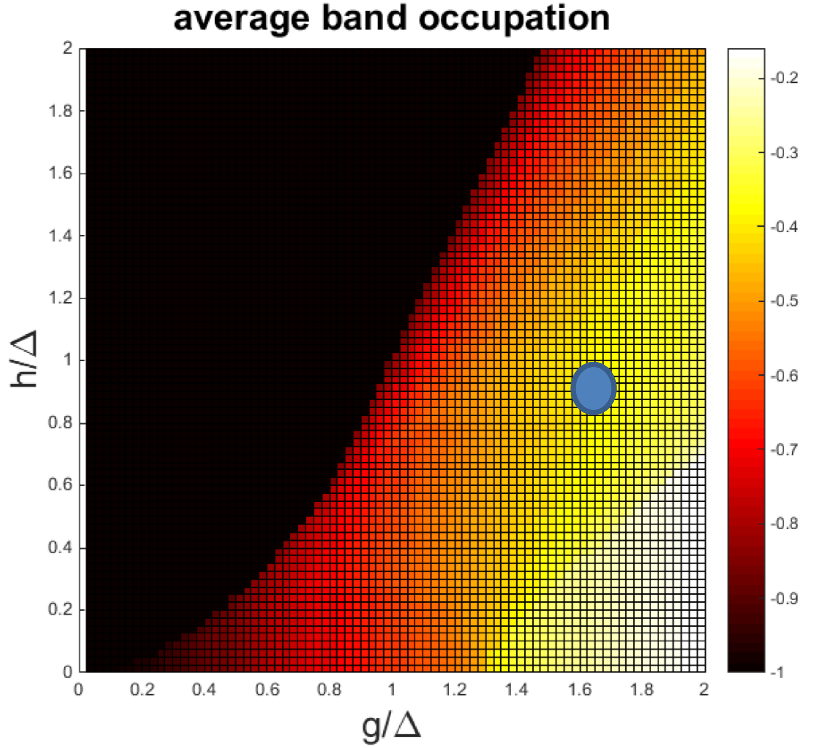
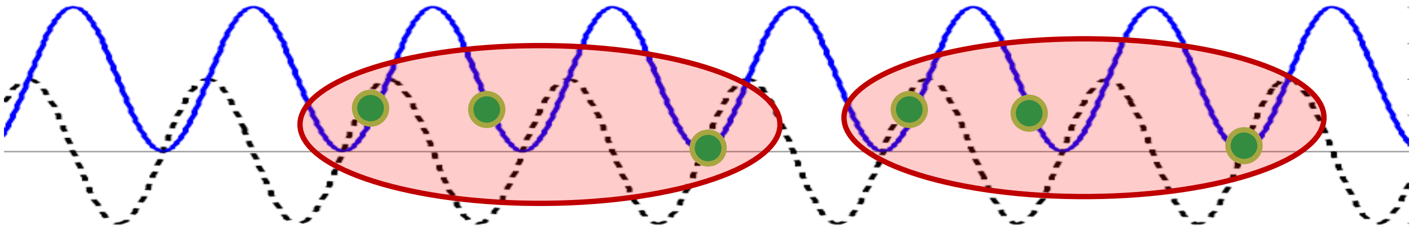




Beyond dimerization (e.g., 1/3 magnetization)



Quantum Science: Implementations

2016, Jul 10 -- Jul 29

Organizers:

D. Chang (ICFO, Barcelona)

J. J. García-Ripoll (IFF-CSIC, Madrid)

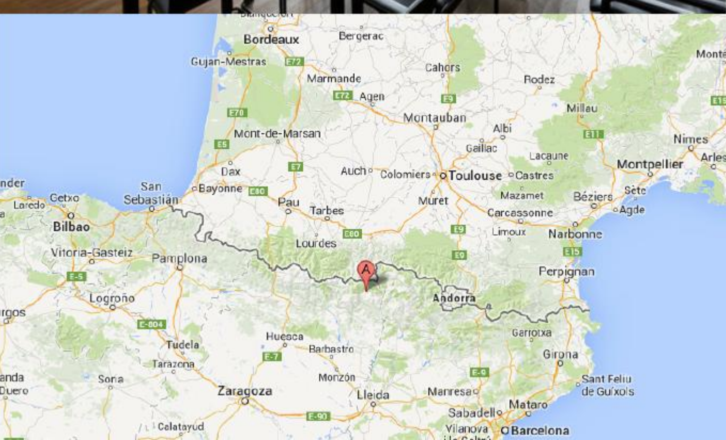
L. Jiang (Yale U., USA)

O. Romero-Isart (IQOQI, Innsbruck)

CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

Deadline 20.05.16

http://benasque.org/2016qsi/

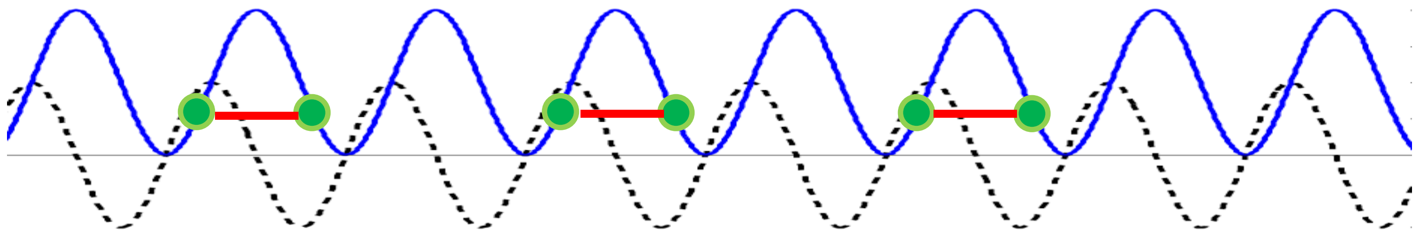


Many-body physics

$(P \sim 0.05$ in nanofibers)

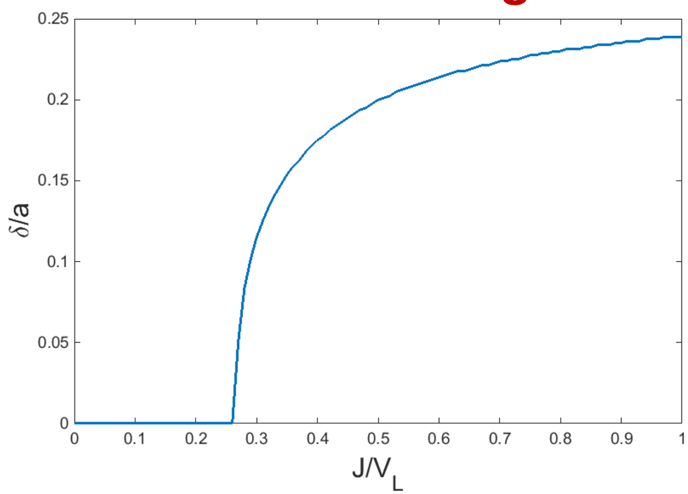
$+1 \quad |T\rangle$
$-1 \quad |S\rangle$

- Short-range (nearest neighbor) interactions $L \sim a$

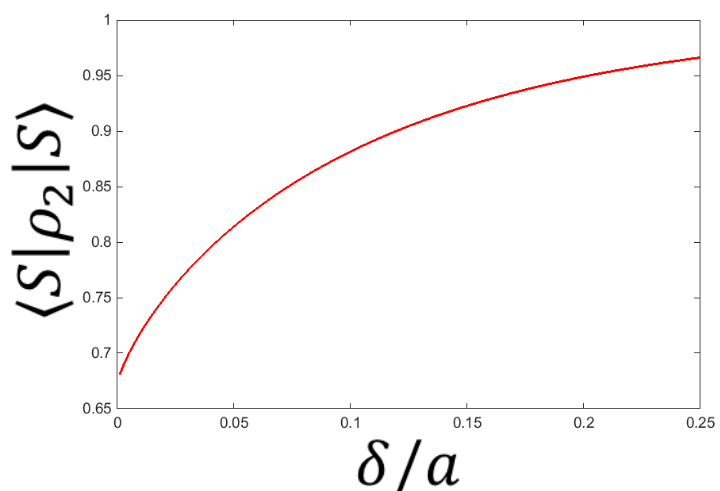


- Spatial dimerization ansatz (variational parameter), exact Jordan-Wigner spin solution

Dimerization vs. spin interaction strength



Singlet fraction vs. dimerization



Properties of 1/3 magnetized state