Open
Quantum Many-Body Systems

Dissipative formation of quantum spin dimers

Peter Zoller

INT discussion, April 6 2015

UNIVERSITY OF INNSBRUCK

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ERC Synergy Grant

SFB
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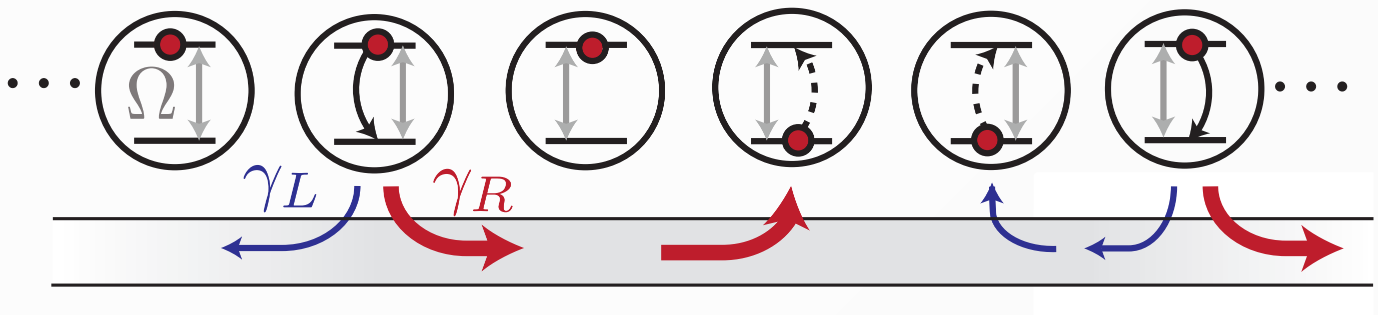
R-ION

COHERENCE

This talk: *Chiral* Spin Networks

driven two-level atoms / spins



wave guide

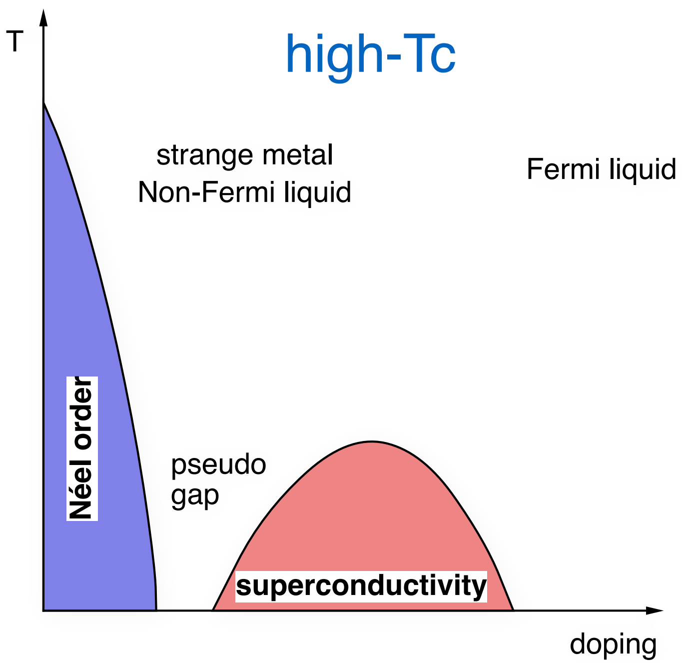
Wave guide for …

- photons
  - ✓ optical - photonic nanostructures
  - ✓ microwave - superconducting circuits
- phonons
  - ✓ spin-orbit coupled BEC
  - ✓ nano-mechanics
- spin-waves
  - ✓ Rydberg atoms
  - ✓ trapped ions

Dissipative formation of quantum spin dimers

Equilibrium vs. Non-Equilibrium Quantum Many-Body Physics

- **thermodynamic equilibrium**

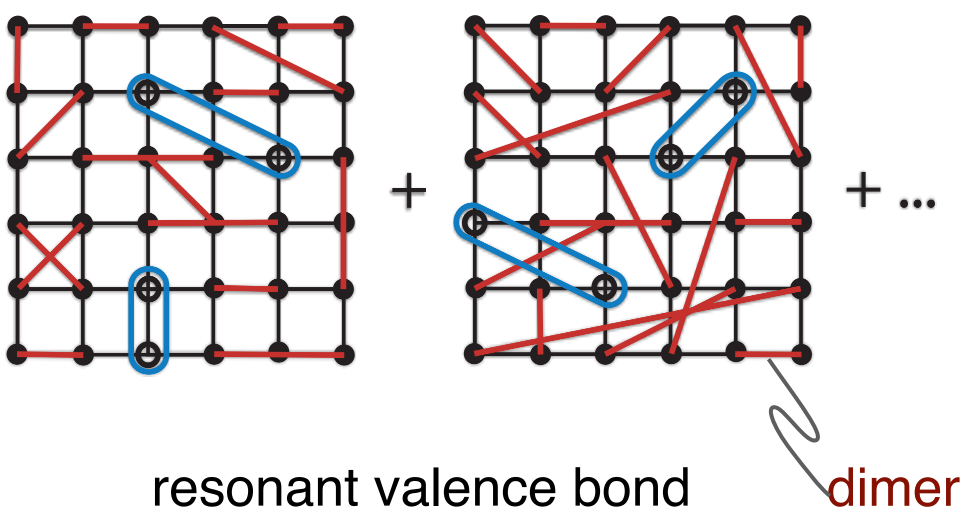


phase diagrams

phase transitions

$$\rho \sim e^{-H/k_B T} \xrightarrow{T\to 0} |E_g\rangle \langle E_g|$$

cooling to ground state



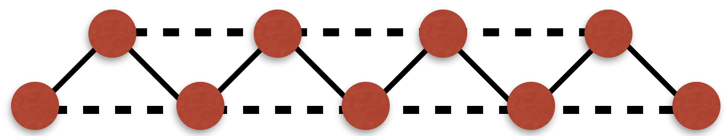
resonant valence bond

quantum magnetism & superconductivity

What "condensed matter physicists / theorists" get excited about

Toy Models (1D)

- Majumdar-Ghosh (spin-½): *parent* Hamiltonian



$$H_{\mathrm{MG}} = \sum_i \left(\boldsymbol{S}_i \boldsymbol{S}_{i+1} + \frac{1}{2} \boldsymbol{S}_i \boldsymbol{S}_{i+2} + \frac{3}{8} \right) \quad \text{with} \quad \boldsymbol{S}_i = \frac{1}{2} \sum_{\tau,\tau'=\uparrow,\downarrow} c^\dagger_{i\tau} \boldsymbol{\sigma}_{\tau\tau'} c_{i\tau'}$$

$$|\psi^{\substack{\text{even}\\(\text{odd})}}_{\mathrm{MG}}\rangle = \prod_{\substack{i \ \text{even}\\(i \ \text{odd})}} \left(c^\dagger_{i\uparrow} c^\dagger_{i+1\downarrow} - c^\dagger_{i\downarrow} c^\dagger_{i+1\uparrow} \right) |0\rangle =$$

quantum dimers

$$= \begin{cases} |\ \circ\!\!-\!\!\circ \quad \circ\!\!-\!\!\circ \quad \circ\!\!-\!\!\circ \quad \circ\ \rangle & \text{“even”} \\ |\ \circ \quad \circ\!\!-\!\!\circ \quad \circ\!\!-\!\!\circ \quad \circ\!\!-\!\!\circ\ \rangle & \text{“odd”} \end{cases}$$

valence bond solid

- AKLT, Haldane Shastry, SU(N) models, …

Below we will show that *pure spin dimers* can also form as *steady state* of driven-dissipative (open system / non-equilibrium) dynamics.

New generation of quantum optics experiments:

Atoms [& Solid State Emitters]
Coupled to Photonic Nanostructures

… challenges in theory

Driven-Dissipative
Many-Body Quantum Systems

Trapping Atoms Close to Photonic Nanostructures

doi:10.1038/nature13188

Nanophotonic quantum phase switch with a single atom

T. G. Tiecke[1,2]*, J. D. Thompson[1]*, N. P. de Leon[1,3], L. R. Liu[1], V. Vuletić[2] & M. D. Lukin[1]

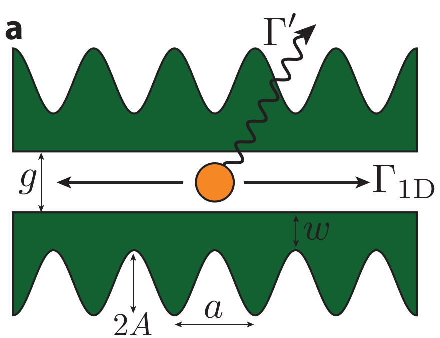
APPLIED PHYSICS LETTERS **104**, 111103 (2014)

CrossMark click for updates

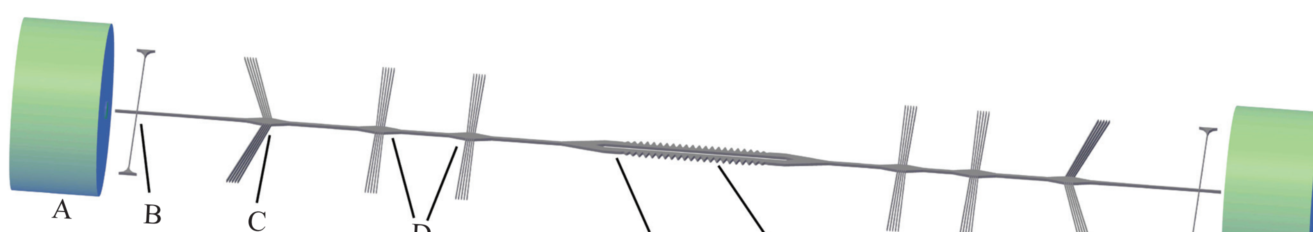
Nanowire photonic crystal waveguides for single-atom trapping and strong light-matter interactions

S.-P. Yu,[1,2,a)] J. D. Hood,[1,2,a)] J. A. Muniz,[1,2] M. J. Martin,[1,2] Richard Norte,[2,3] C.-L. Hung,[1,2]
Seán M. Meenehan,[2,3] Justin D. Cohen,[2,3] Oskar Painter,[2,3,b)] and H. J. Kimble[1,2,c)]

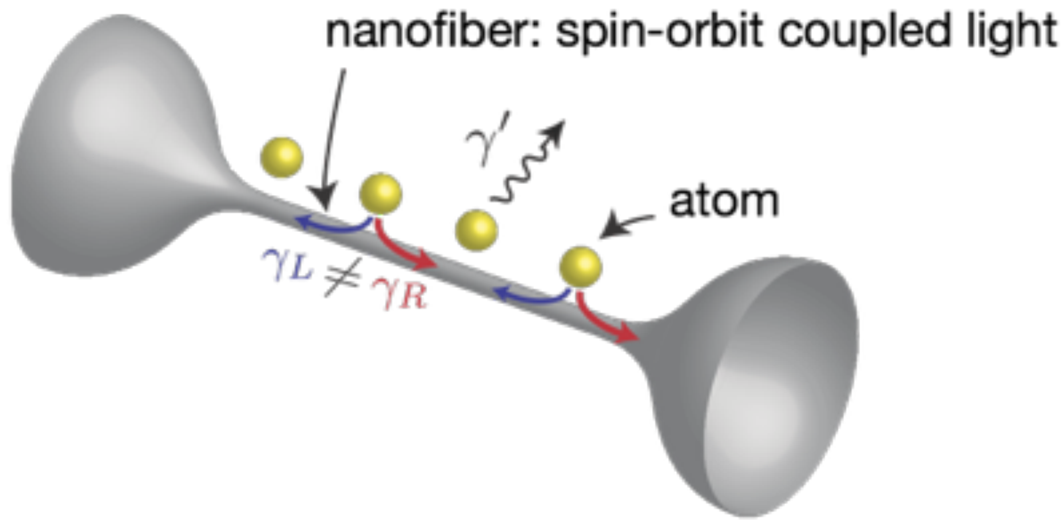
We present a comprehensive study of dispersion-engineered nanowire photonic crystal waveguides suitable for experiments in quantum optics and atomic physics with optically trapped atoms.

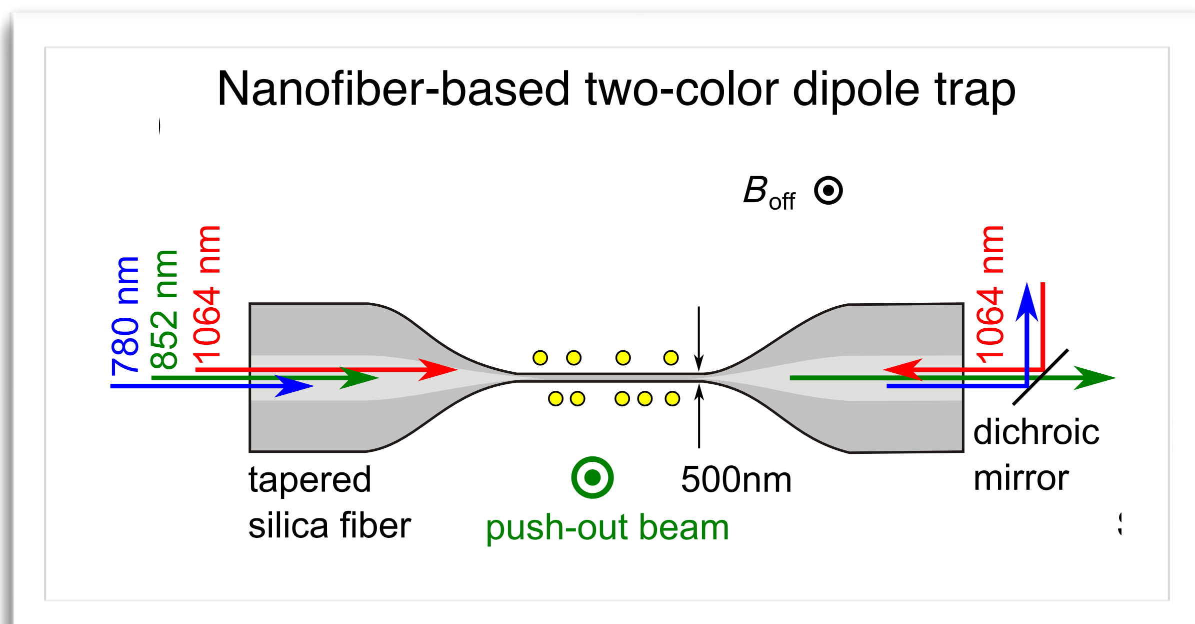


"alligator" photonic crystal wave guide



Chiral Nanophotonic Waveguide Interface





Rauschenbeutel et al. (2014)

f photonic nanostructures

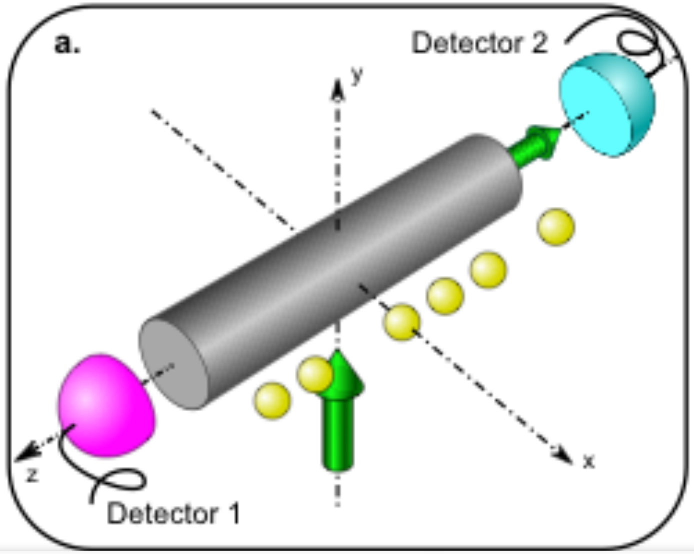
vard

NANOPHOTONICS

Directional nanophotonic atom–waveguide interface based on spin–orbit interaction of light

R. Mitsch, C. Sayrin, B. Albrecht, P. Schneeweiss, and A. Rauschenbeutel
Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria

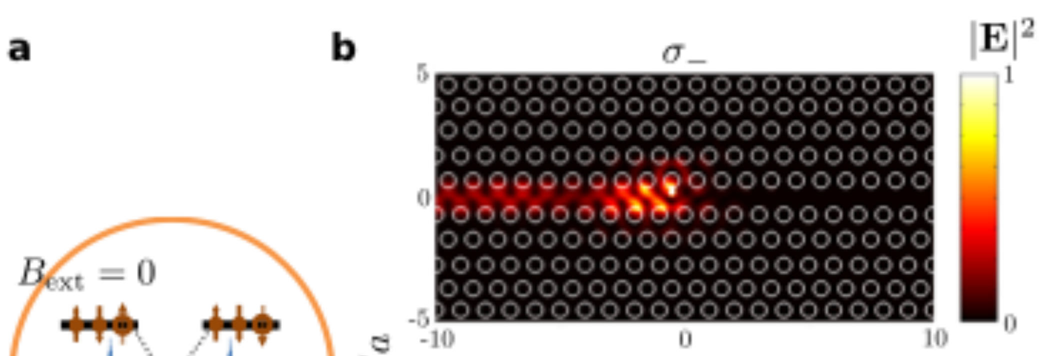
arXiv 1406.2184



A chiral spin-photon interface for scalable on-chip quantum-information processing

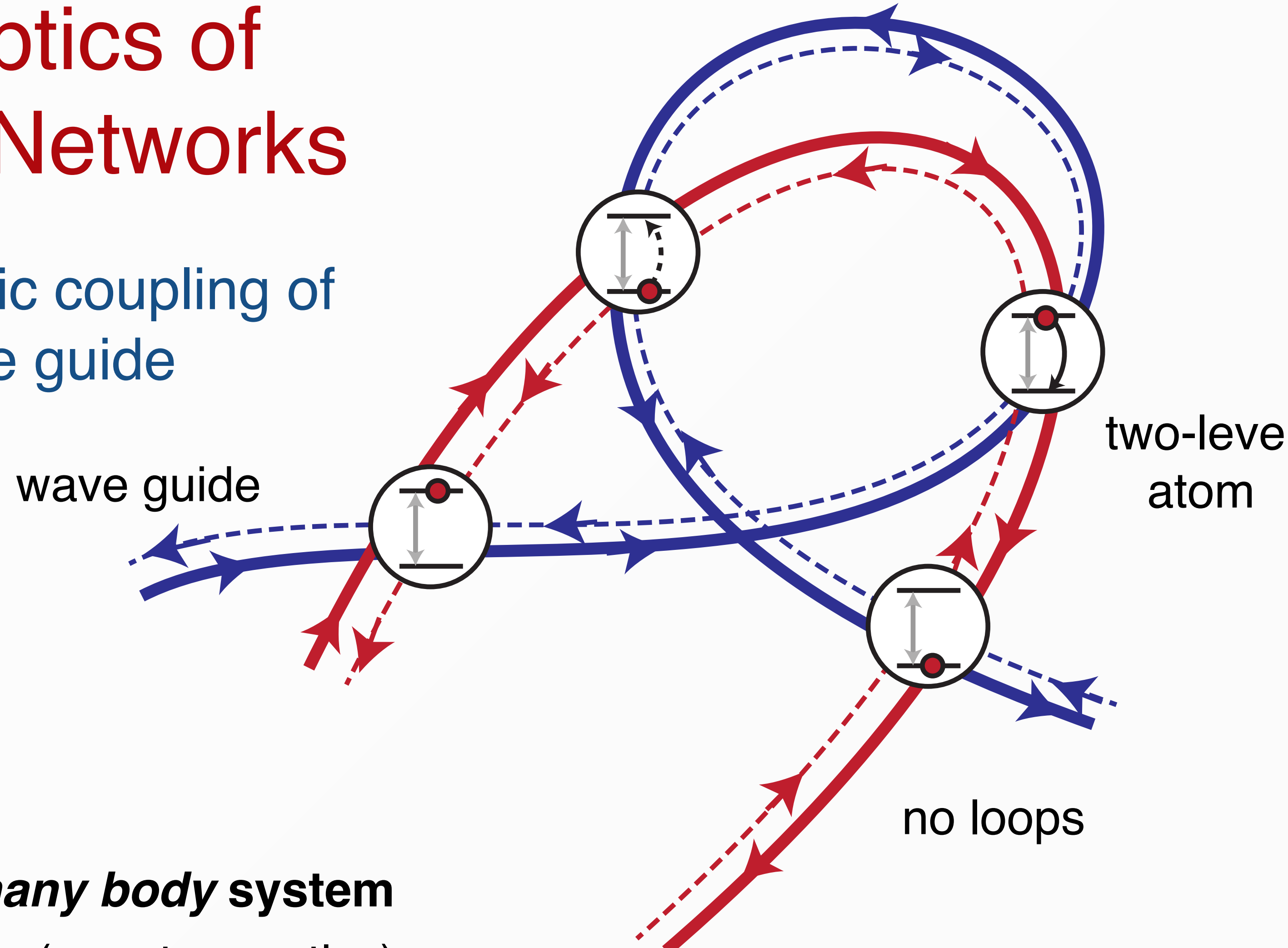
Immo Söllner,* Sahand Mahmoodian,* Alisa Javadi, and Peter Lodahl†
Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
(Dated: June 18, 2014)

arXiv:1406.4295



Quantum Optics of *Chiral* Spin Networks

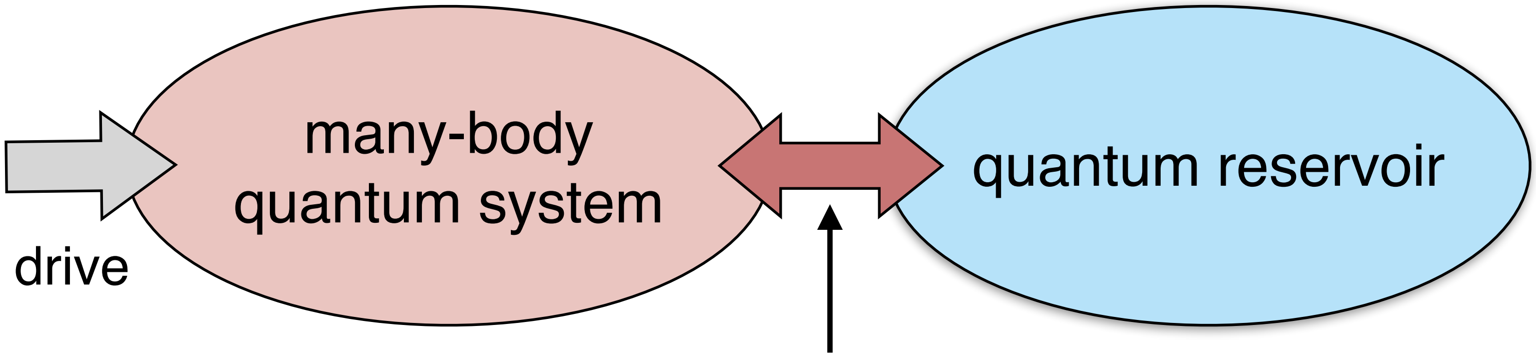
chiral = asymmetric coupling of
spin to wave guide



- ***open*** **quantum *many body* system**
  - driven-dissipative (quantum optics)
- **why?**
  - quantum info / non-equilibrium cond mat (quantum phases)
- **how? - physical realization**
  - photonic & phononic (here - cold gases realization) & 1D spin-wave guide

Equilibrium vs. Non-Equilibrium Quantum Many-Body Physics

- ***non*-equilibrium**



Engineer system-reservoir coupling!

Many body Quantum Optics

- Dynamics: Master equation

$$\dot{\rho}(t) = -\frac{i}{\hbar}[H_{\mathrm{sys}}, \rho(t)] + \mathcal{L}\rho(t)$$

validity …

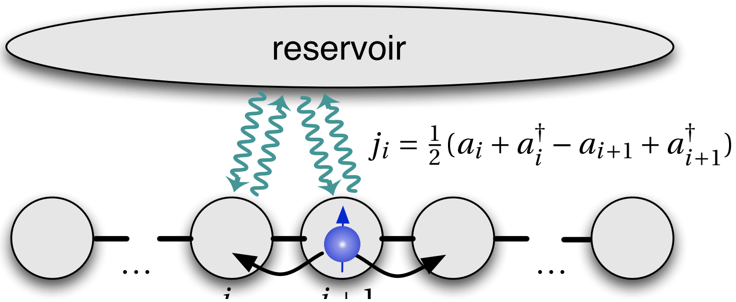
- Steady state:

$$\rho(t) \xrightarrow{t\to\infty} \rho_{ss} \overset{!}{=} |\Psi\rangle\langle\Psi|$$

pure & (interesting) entangled state
(dark state of dissipative dynamics)

Examples: Engineered Dissipative Atomic Systems

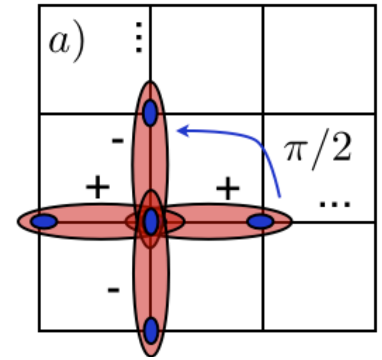
Topology via dissipation



Majorana edge modes

S. Diehl et al., Nature Phys. 2012; PRL 2013
J. Budich et al., preprint

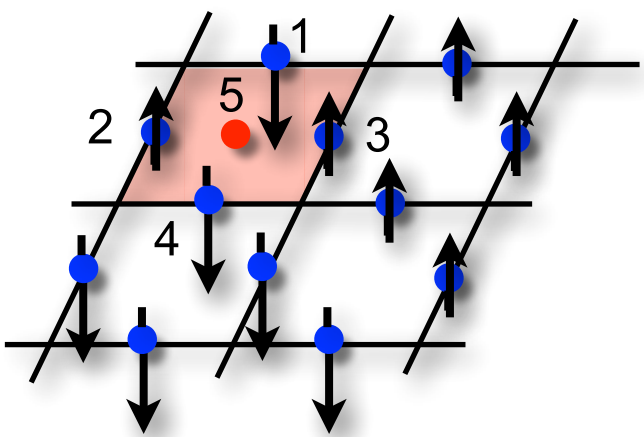
BCS-pairing from dissipation



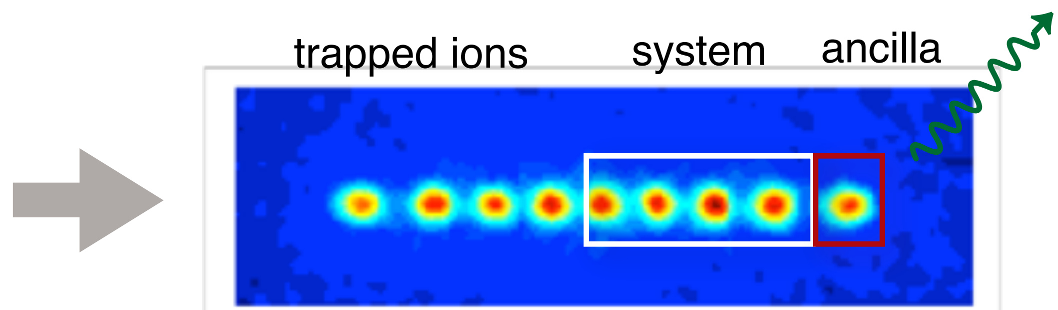
d-wave pairing

S. Diehl et al., PRL 2010

Diss. Quantum Phase transitions



Entangled States from Dissipation



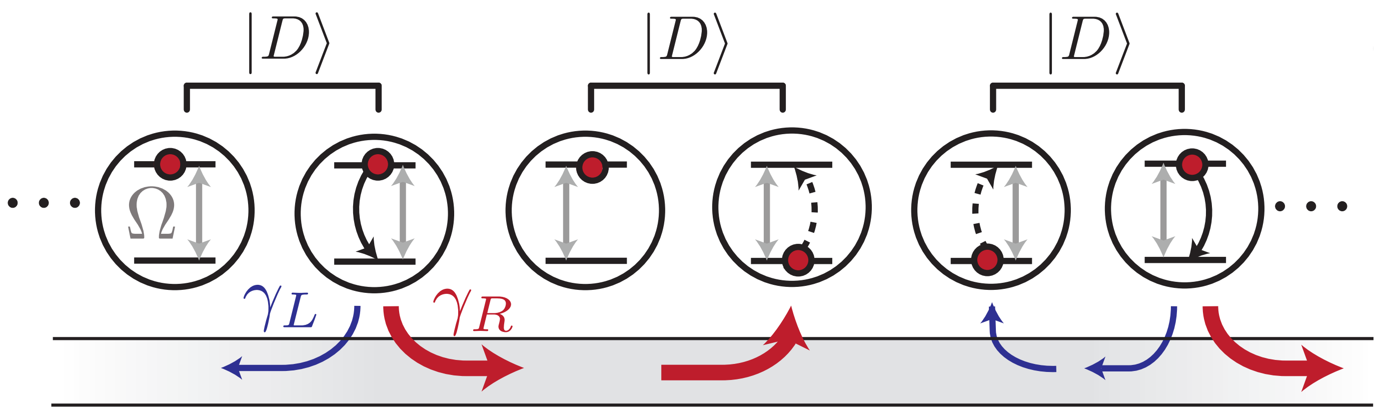
Exp. ions: Blatt et al., Nature '11; Nat Phys '13

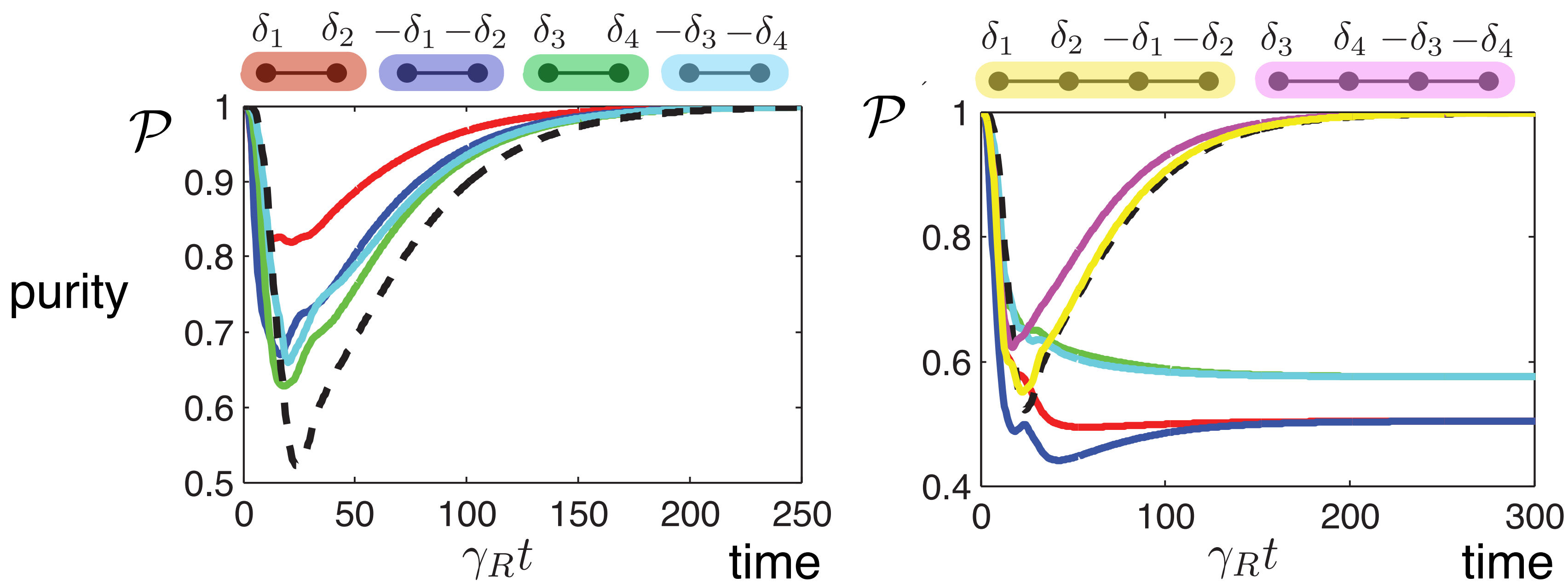
Exp. neutral atoms: DeMarco, Oberthaler, …

[Polzik et al., PRL '11]

Reviews: M Müller et al., Adv Atom Mol Opt Phys, 2012; C Bardyn et al., NJP 2013

This Talk: *Chiral* Spin Chain

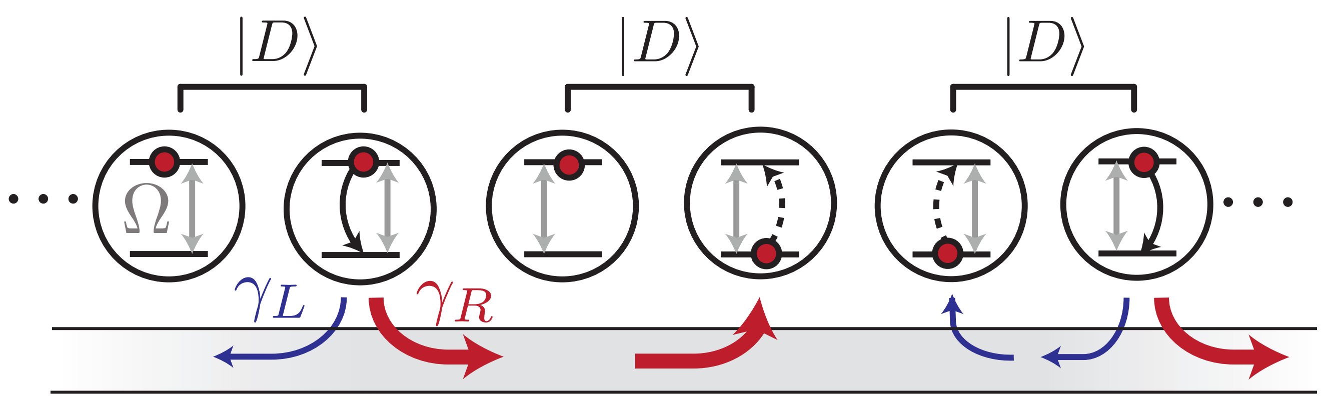




State of many-body spin system cools / purifies to a *pure* state of spin dimers, tetramers, hexamers, …

Plain-Vanilla Markovian :-)

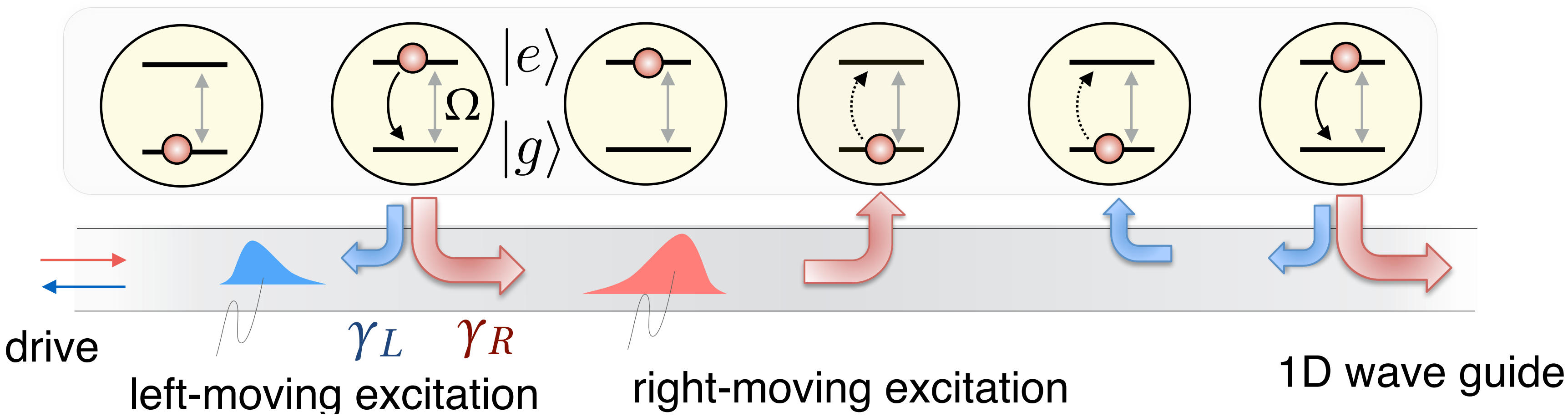
Theory: Master Equation for *Chiral* Spin Chains



Master equation for cascaded (purely unidirectional) quantum systems N=2:
C.W. Gardiner, PRL 1993; H. Carmichael, PRL 1993; CW Gardiner & AS Parkins, PRA 1994

Spins coupled to a **chiral** waveguide

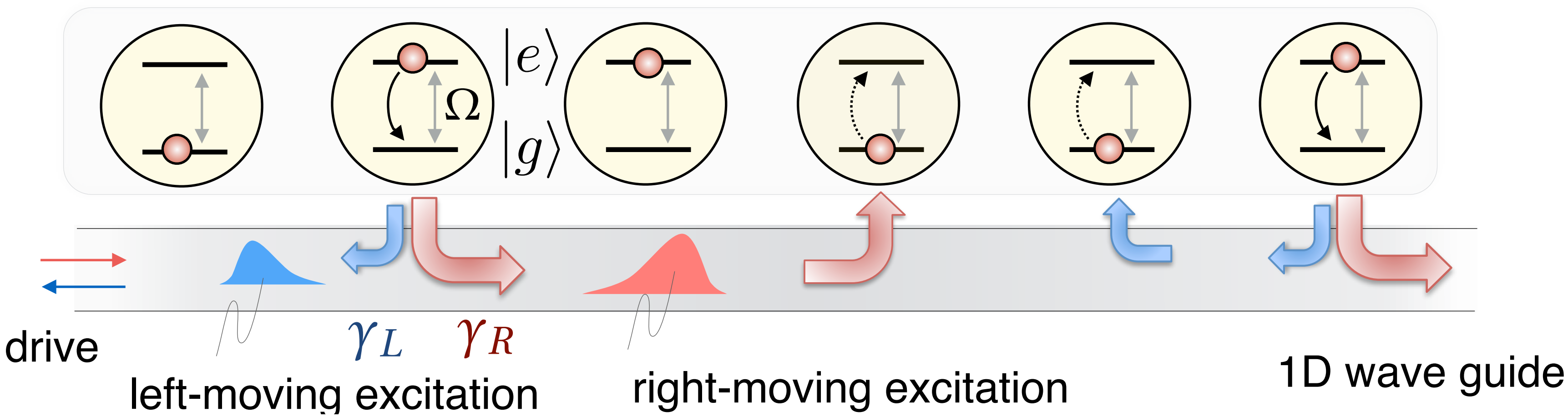
$\gamma_L \neq \gamma_R$



$$\dot{\rho} = -\frac{i}{\hbar}[H_{\rm sys}, \rho] + \mathcal{L}_B \rho + \mathcal{L}_{\rm casc} \rho$$

Spins coupled to a **chiral** waveguide

$$\gamma_L \neq \gamma_R$$



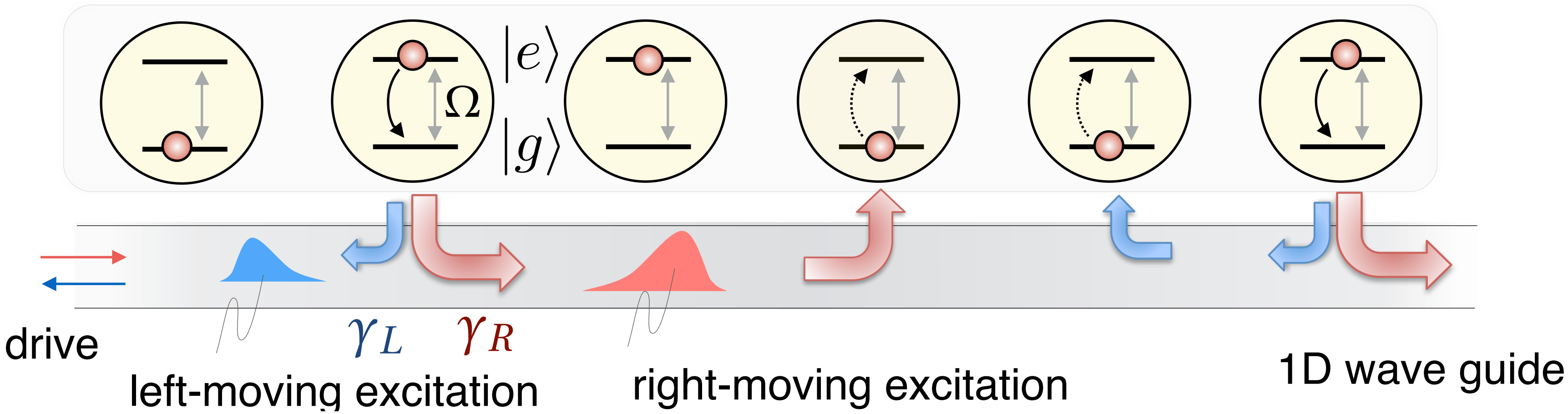
$$\dot{\rho} = -\frac{i}{\hbar}[H_{\rm sys}, \rho] + \mathcal{L}_B\rho + \mathcal{L}_{\rm casc}\rho$$

$$H_{\rm sys} = \sum_i \left(-\delta_i |e\rangle_i\langle e| + (\Omega_i |e\rangle_i\langle g| + \text{h.c.})\right)$$

detuning Coherent drive

Spins coupled to a **chiral** waveguide

$\gamma_L \neq \gamma_R$



$$\dot{\rho} = -\frac{i}{\hbar}[H_{\mathrm{sys}}, \rho] + \mathcal{L}_B \rho + \mathcal{L}_{\mathrm{casc}} \rho$$

$$\sigma_-^{(j)} = |g\rangle_j \langle e|$$

$$\sigma_+^{(j)} = |e\rangle_j \langle g|$$

$$\mathcal{L}_B \rho = -i\Big[\frac{\gamma_L}{2} \sum_{j,l} \sin(k|x_j - x_l|)\sigma_+^{(j)}\sigma_-^{(l)}, \rho\Big]$$

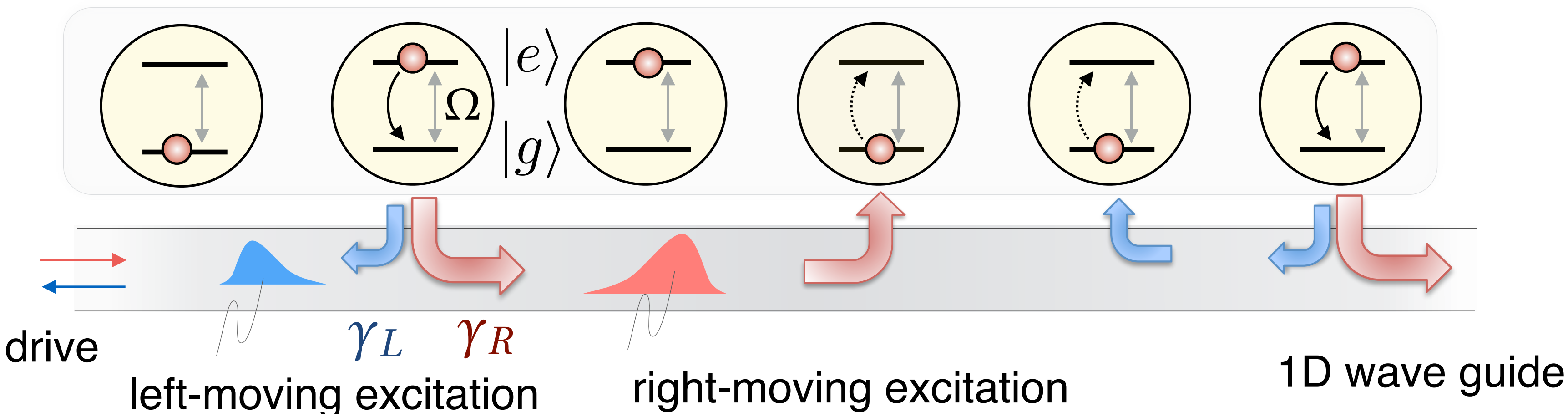
dipole-dipole interactions
(infinite range in 1D)

$$+ \gamma_L \sum_{j,l} \cos(k|x_j - x_l|) \left(\sigma_-^{(l)} \rho \sigma_+^{(j)} - \frac{1}{2}\{\sigma_+^{(j)}\sigma_-^{(l)}, \rho\}\right)$$

“Dicke" master equation for 1D: D E Chang et al 2012 New J. Phys. 14 063003

Spins coupled to a **chiral** waveguide

$$\gamma_L \neq \gamma_R$$



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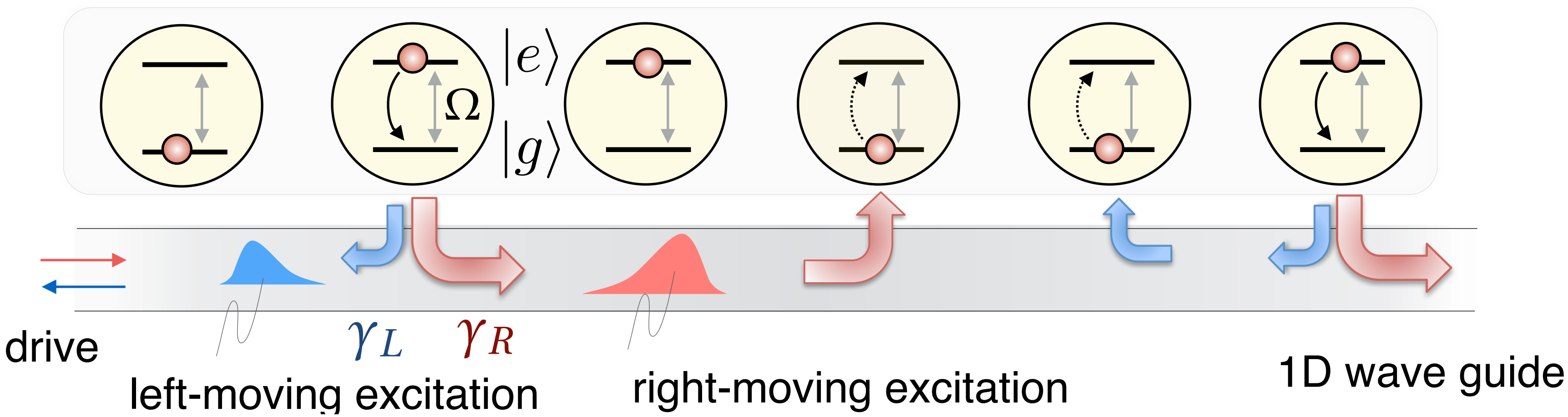
$$+ \gamma_L \sum_{j,l} \cos(k|x_j - x_l|) \left(\sigma_-^{(l)} \rho \sigma_+^{(j)} - \frac{1}{2} \{ \sigma_+^{(j)} \sigma_-^{(l)}, \rho \} \right)$$

collective decay
(super- and sub-radiance)

Spins coupled to a **chiral** waveguide

$$\gamma_L \neq \gamma_R$$



$$\dot{\rho} = -\frac{i}{\hbar}[H_{\rm sys}, \rho] + \mathcal{L}_B \rho + \mathcal{L}_{\rm casc}\rho$$

$$\sigma_-^{(j)} = |g\rangle_j\langle e|$$

$$\sigma_+^{(j)} = |e\rangle_j\langle g|$$

$$\mathcal{L}_{\rm casc} = (\gamma_R - \gamma_L)\left(-\frac{i}{\hbar}(H_{\rm eff}\rho - \rho H_{\rm eff}^\dagger) + c\rho c^\dagger\right)$$

collective decay

cascaded interactions

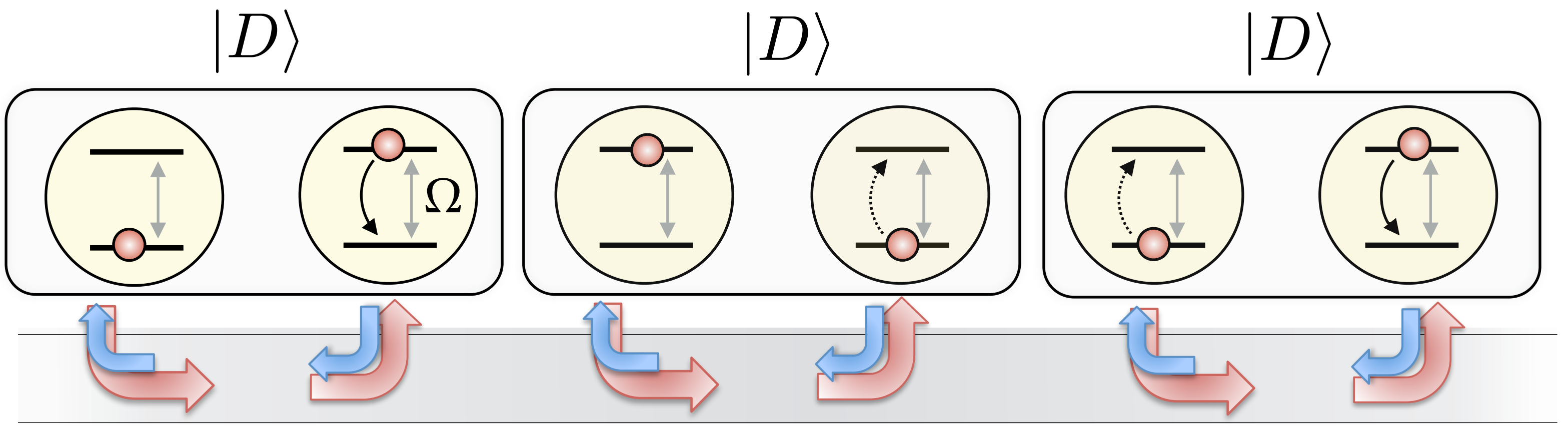
$$H_{\rm eff} = -\frac{i\hbar}{2}\sum_j |e\rangle_j\langle e| - i\hbar \sum_{j>l} e^{ik(x_k - x_l)}\sigma_+^{(j)}\sigma_-^{(l)}$$

$$c = \sum_j e^{-ikx_j}\sigma_-^{(j)}$$

Theory of cascaded quantum systems N=2: C.W. Gardiner, PRL 1993; H. Carmichael, PRL 1993

Steady states for a **chiral** waveguide

$\gamma_L \neq \gamma_R$



- **Unique, pure** steady state: $\rho(t) \xrightarrow{t\to\infty} |\Psi\rangle\langle\Psi|$.
- **Quantum Dimers**

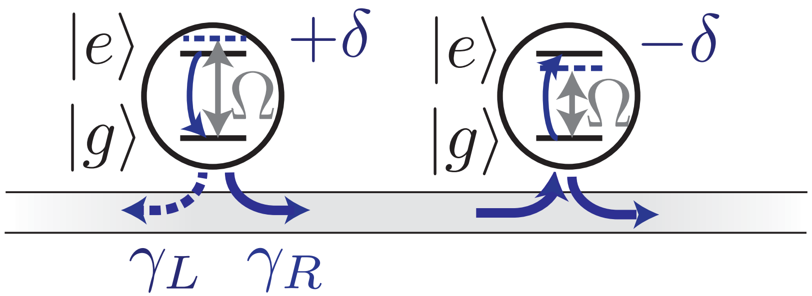
$$|\Psi\rangle = \bigotimes_{i=1}^{N} |D\rangle_{2i-1,2i}$$

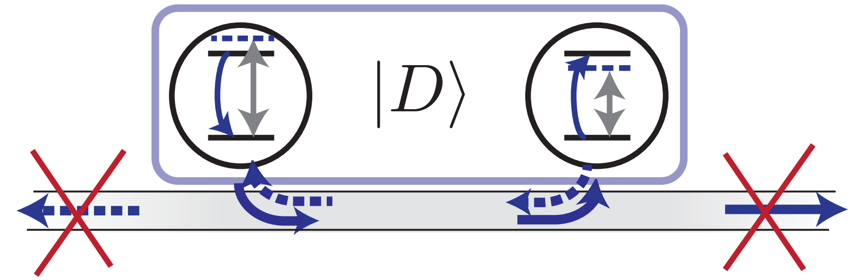
singlet fraction

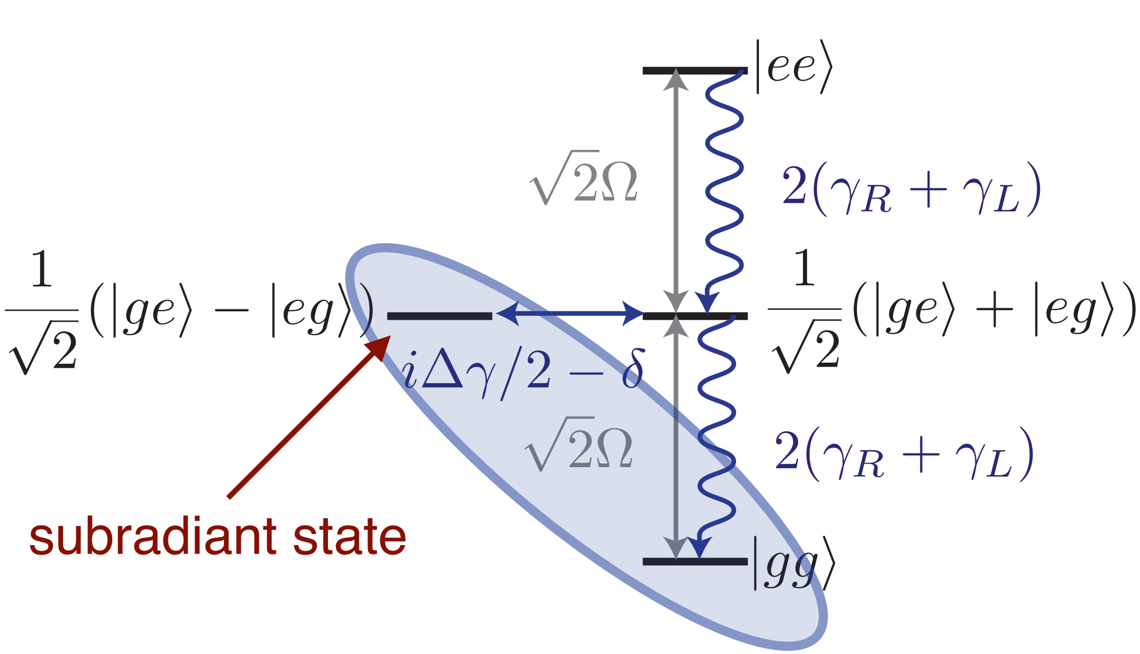
$$|D\rangle = \frac{1}{\sqrt{1+|\alpha|^2}}\left[|gg\rangle + \frac{\alpha}{\sqrt{2}}\left(|ge\rangle - |eg\rangle\right)\right] \qquad \alpha = \frac{\sqrt{2}\Omega}{\delta - i(\gamma_R - \gamma_L)/2}$$

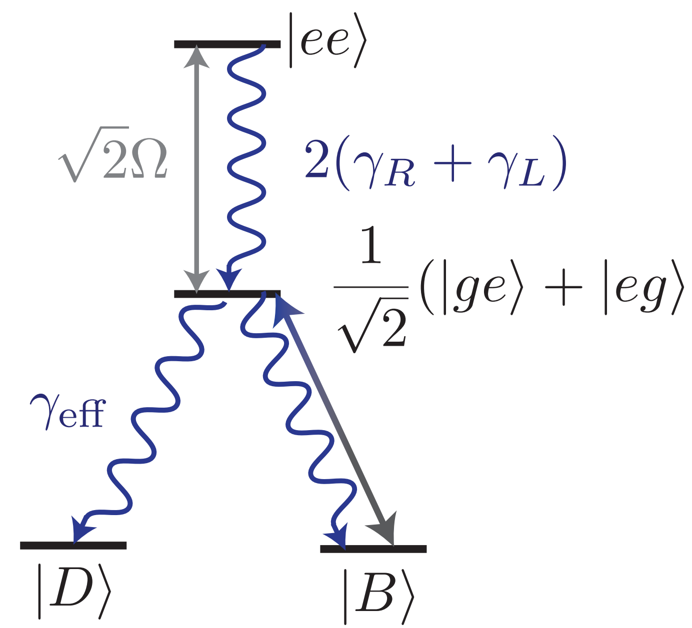
- Note: only for N even

Understanding dark states for **N=2 spins**



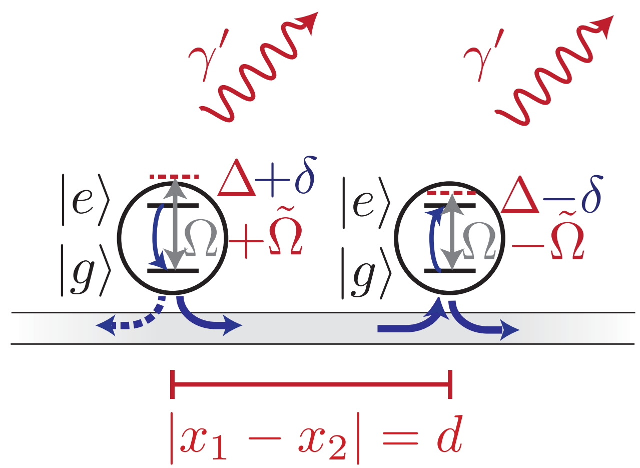




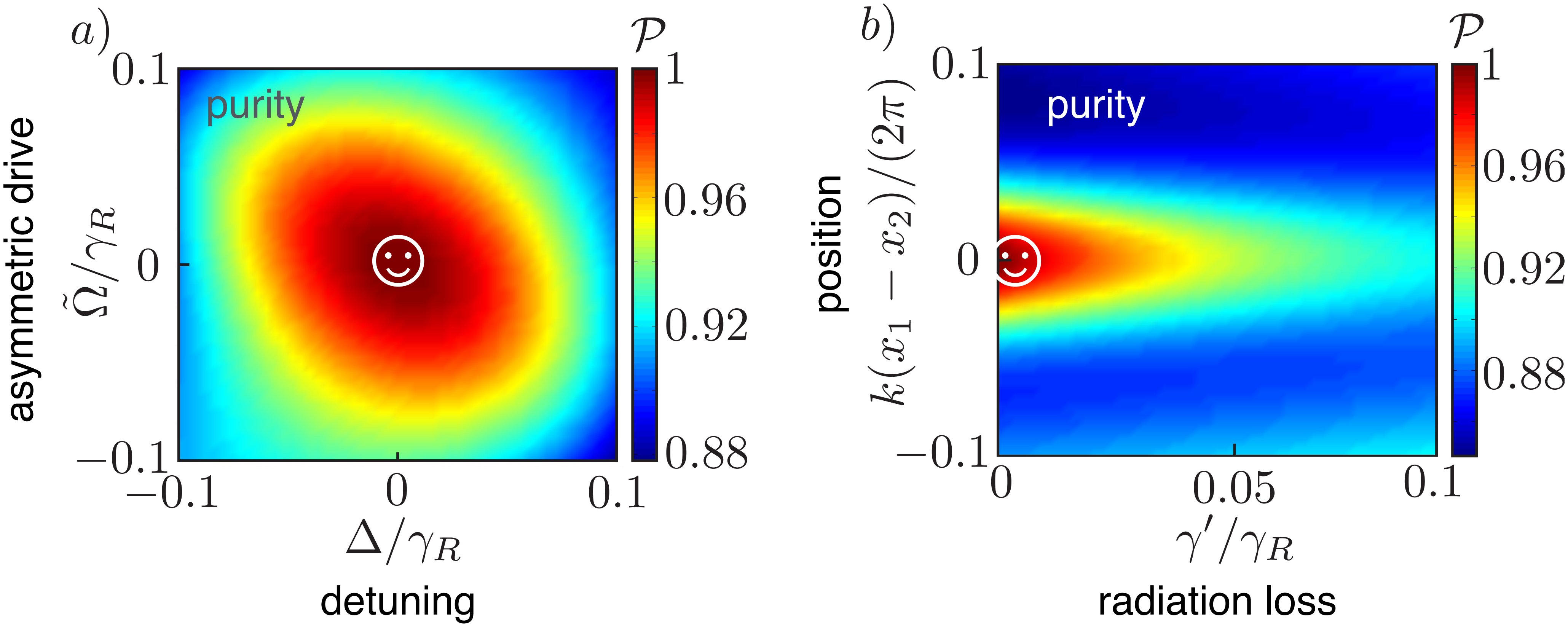


dark state $$|D\rangle = \frac{1}{\sqrt{1+|\alpha|^2}}\left[|gg\rangle + \frac{\alpha}{\sqrt{2}}\left(|ge\rangle - |eg\rangle\right)\right]$$

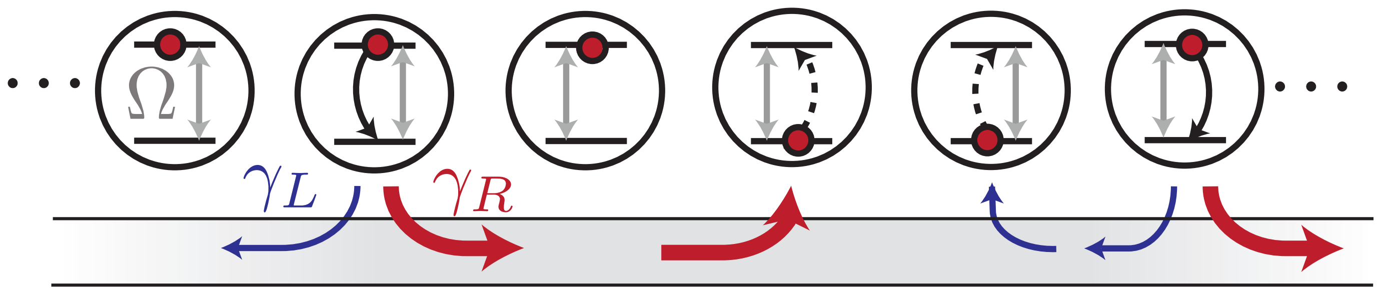
Imperfections & Dark States: N=2



$$\Omega/\gamma_R = 0.5$$
$$\delta/\gamma_R = 0.3$$
$$\gamma_L/\gamma_R = 0.5$$

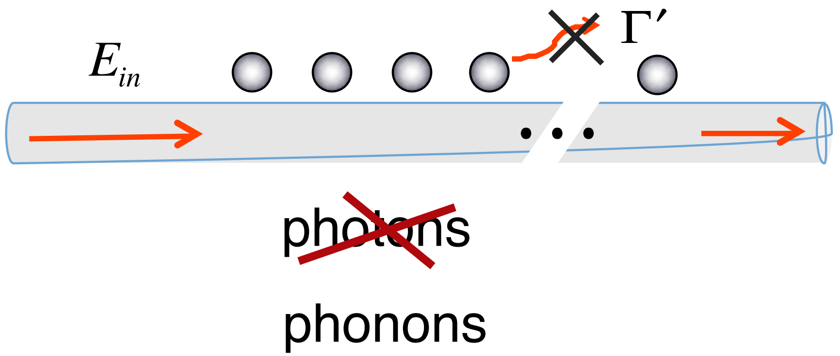


Physical Realizations of *Chiral* Spin Networks

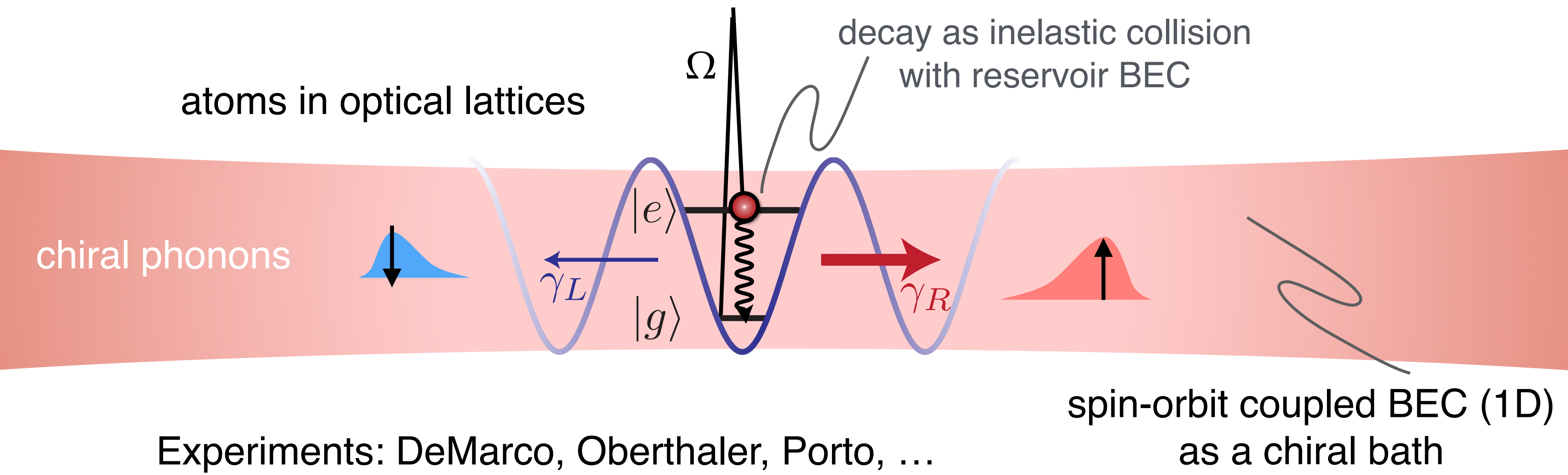


Wave guide for …

- photons
  - ✓ optical - photonic nanostructures
  - ✓ microwave - superconducting circuits
- phonons
  - ✓ spin-orbit coupled BEC
  - ✓ nano-mechanics



1D Chiral Spin Chains with Cold Atoms

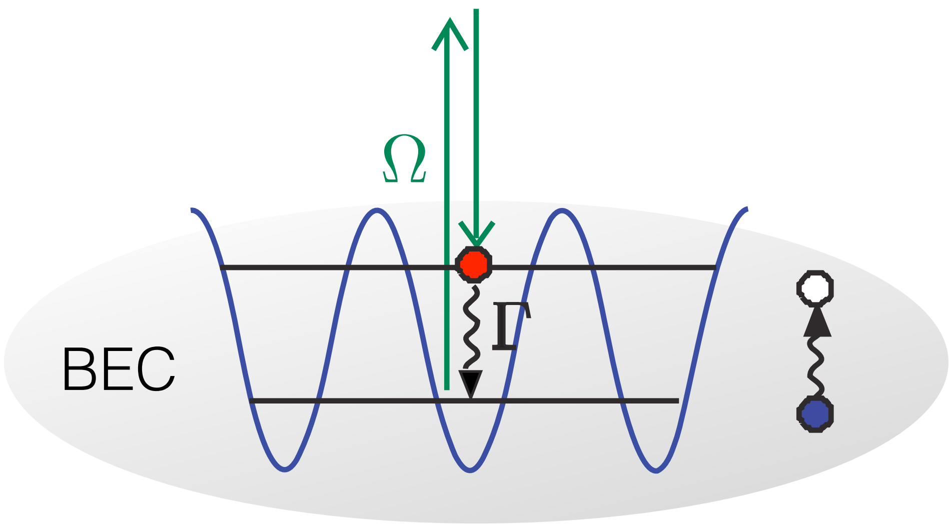


Experiments: DeMarco, Oberthaler, Porto, …

T. Ramos, H. Pichler, A.J. Daley, P.Z., PRL Dec 3 2014

Driven Dissipative Hubbard Dynamics

- **BEC as a "phonon reservoir"**
  - quantum reservoir engineering



- **master equation**
  - reduced system dynamics
  - Quantum Markov process

inelastic scattering from BEC as "spontaneous emission"

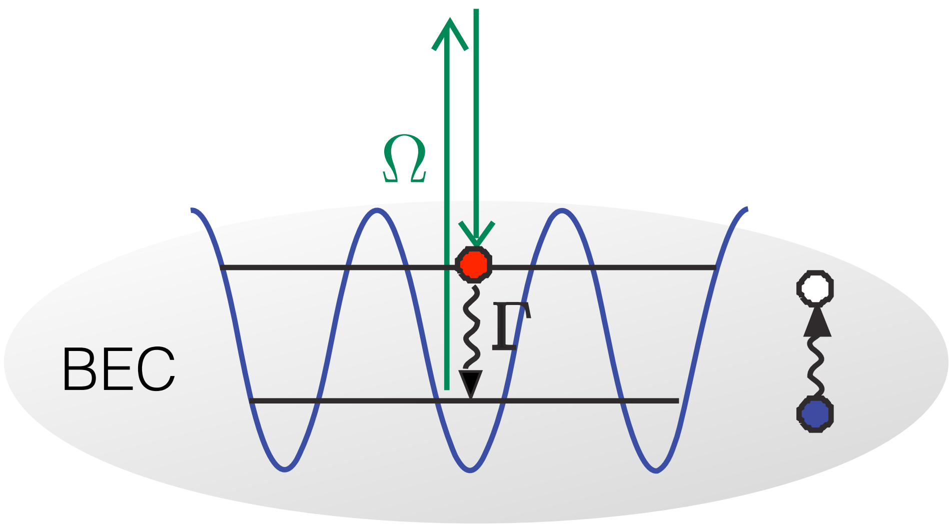
$$\frac{d\rho}{dt} = -i\left[H_{\mathrm{sys}}, \rho\right] + \mathcal{L}\rho$$

2 band Hubbard model — BEC phonons

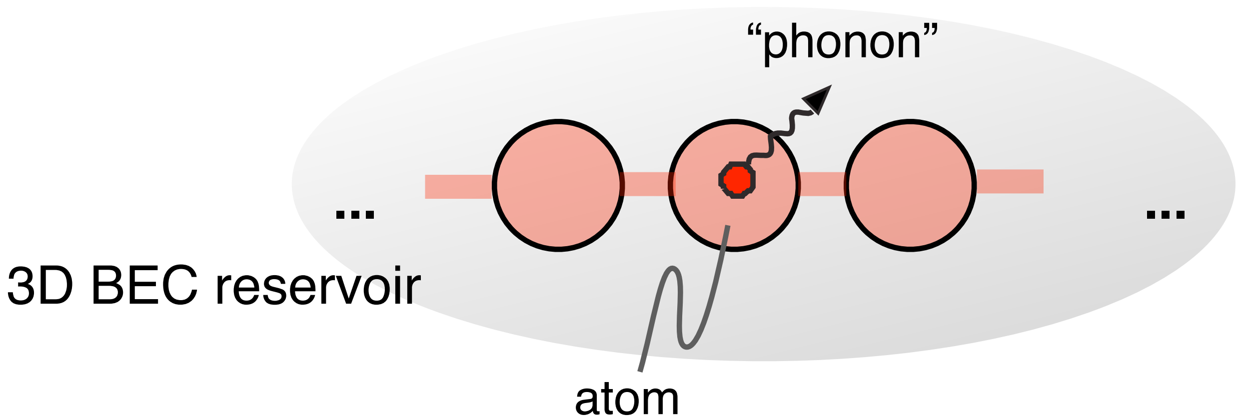
A Griessner, AJ Daley, SR Clark, D Jaksch, and PZ, PRL 2006 & NJPhys 2007
S Diehl, A Micheli, A Kantian, B Kraus, HP Buechler, and PZ, NatPhys 2008

Driven Dissipative Hubbard Dynamics

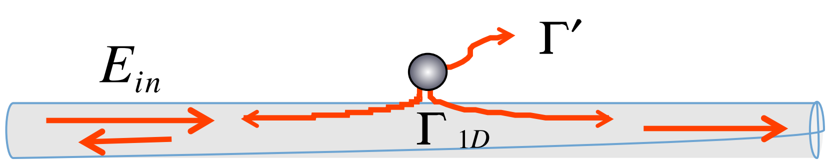
- **BEC as a "phonon reservoir"**
  - quantum reservoir engineering



- **Atoms in a 1D optical lattice**

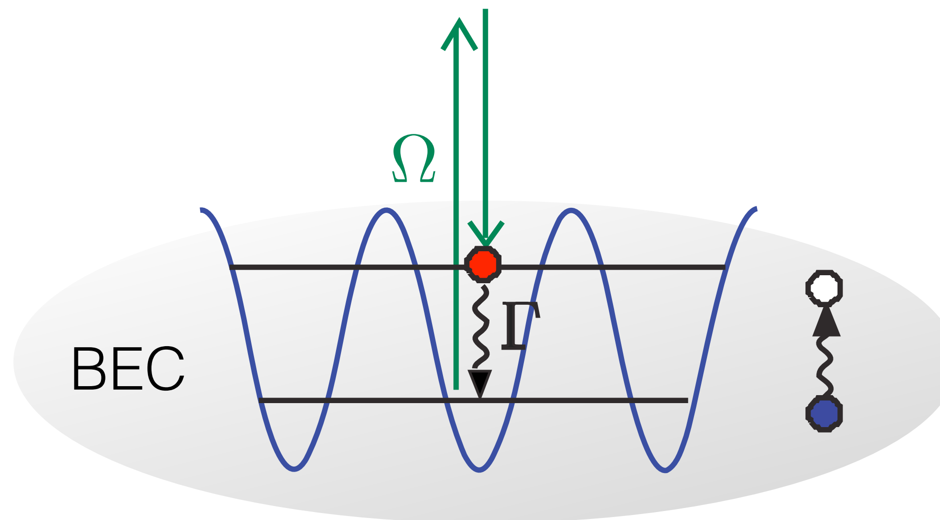


- **Dynamics analogous to ...**



Driven Dissipative Hubbard Dynamics

- **BEC as a "phonon reservoir"**
  - quantum reservoir engineering



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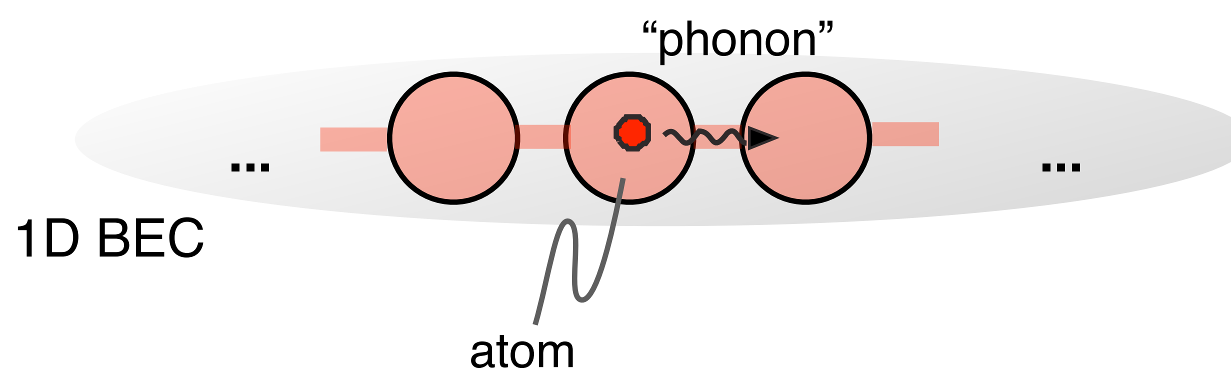

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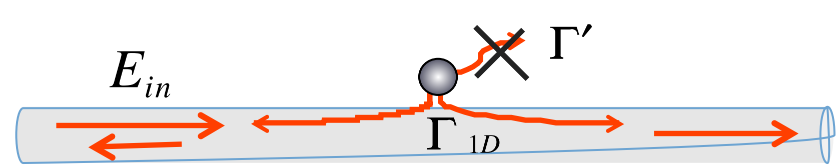
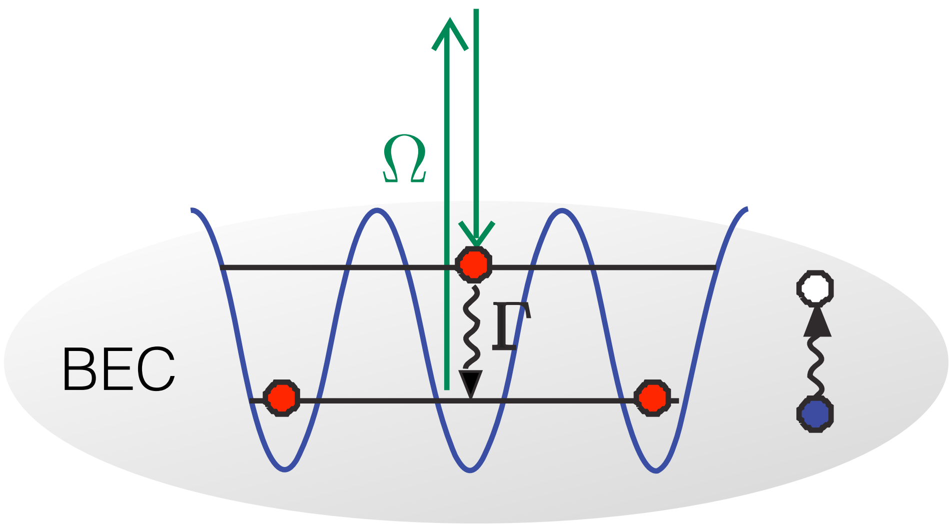
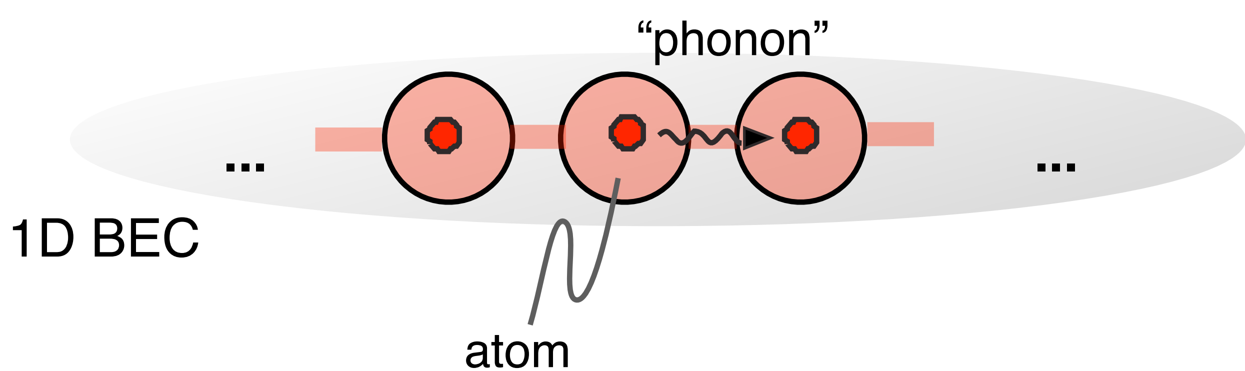


Driven Dissipative Hubbard Dynamics

- **BEC as a "phonon reservoir"**
  - quantum reservoir engineering

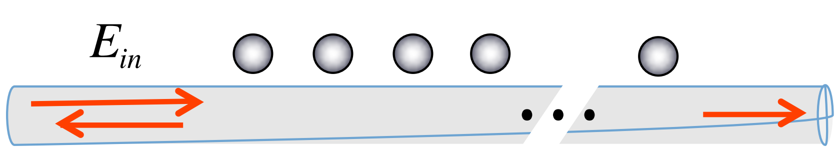


- **N Atoms in a 1D optical lattice**



- **Dynamics analogous to ...**

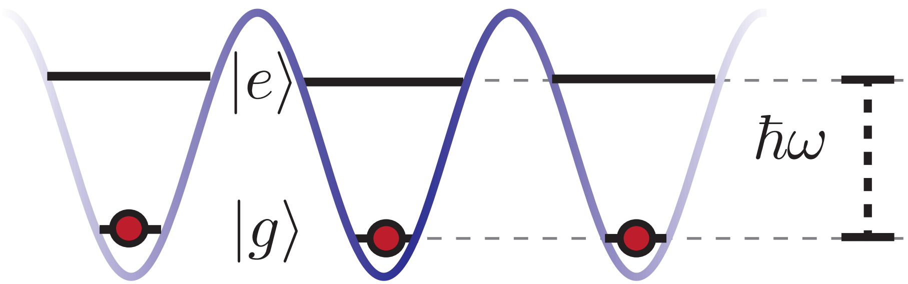
Q.: How to get a chiral reservoir?



Two-species mixture of cold quantum gases

Spin-Chain:

atoms in 1D optical lattice



AJ Daley et al., PRA **69**, 022306 (2004); A Griessner et al., PRL **97**, 220403 (2006).

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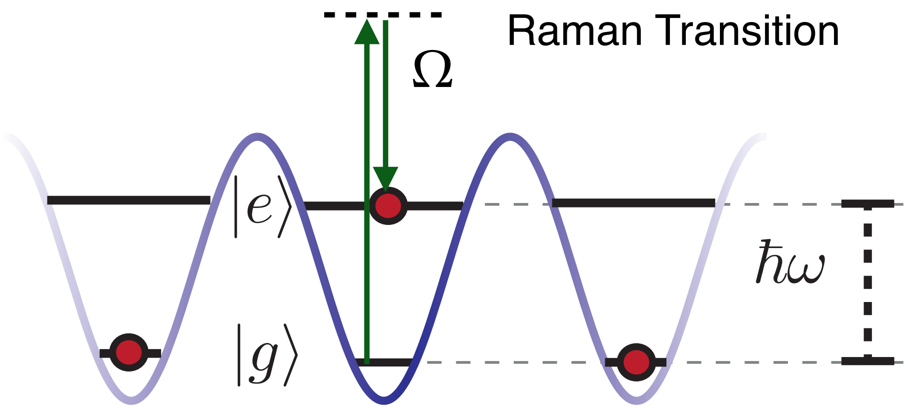

AJ Daley et al., PRA **69**, 022306 (2004); A Griessner et al., PRL **97**, 220403 (2006).

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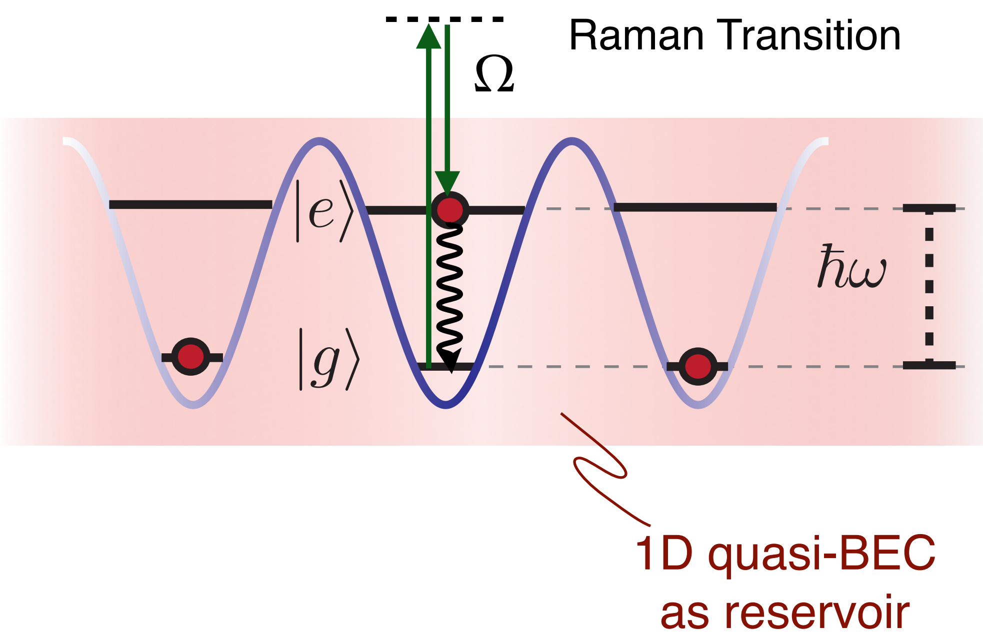
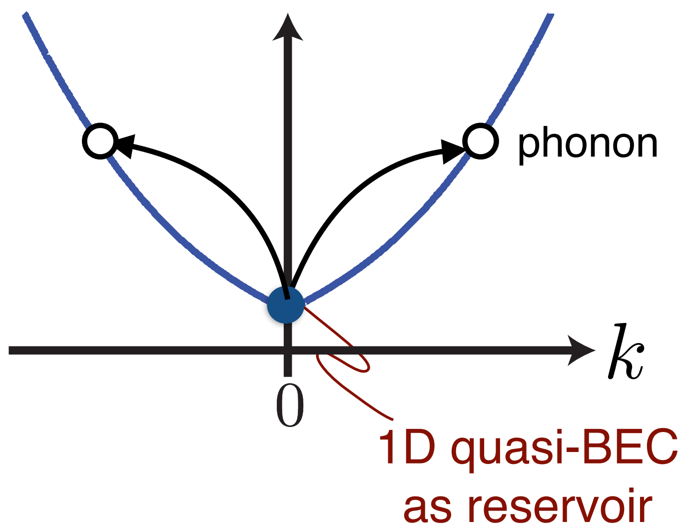


Quantum Reservoir:

1D quasi-BEC

Bogoliubov spectrum



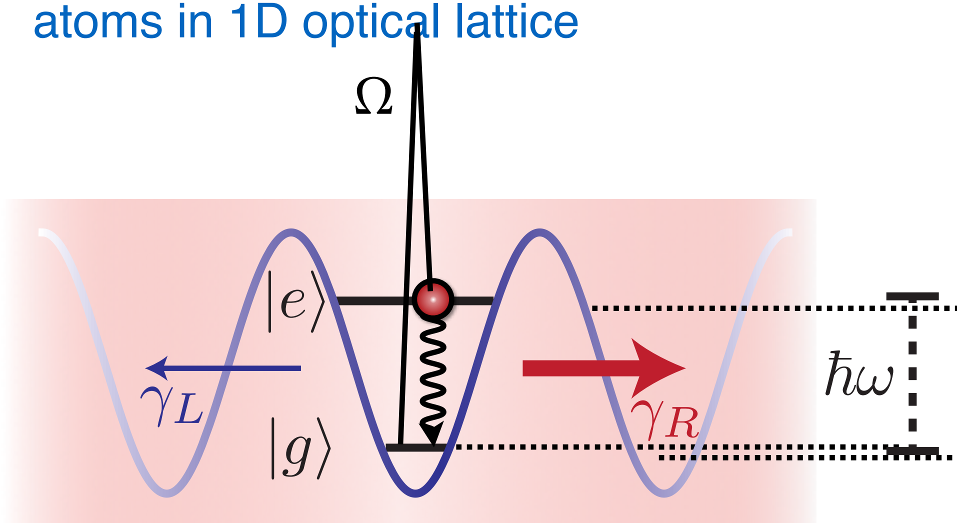
$$\gamma_L = \gamma_R$$

Dicke superradiance
& phase transition

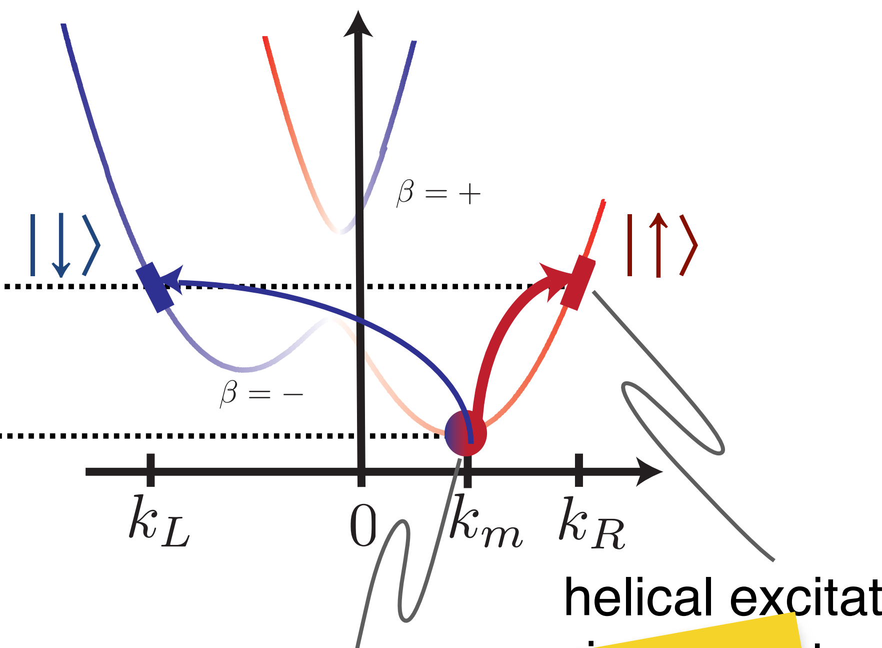
Chiral Reservoir = Spin-Orbit Coupled BEC

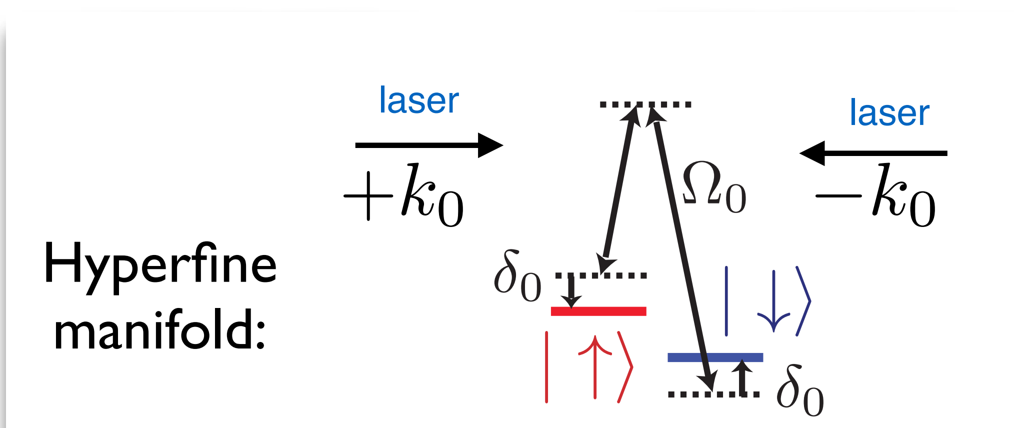
Spin-Chain:

atoms in 1D optical lattice



Quantum Reservoir:



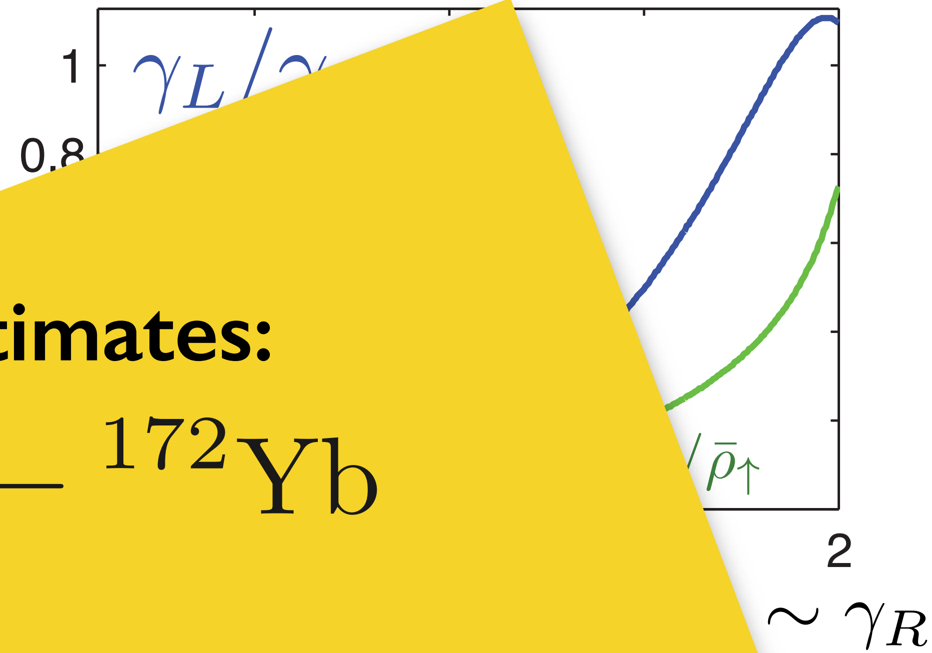


spin-orbit coupled BEC (1D)
in an optical lattice:
"chiral phononic
band gap material"

Two species mixtures of cold atoms

Chirality **tuneable:**

- via Spin-orbit coupling strength (i.e. via polarization of atoms
- via asymmetry in co
  parameters



Estimates:

$$^{87}\mathrm{Rb} - {}^{172}\mathrm{Yb}$$

$$\gamma_L \lesssim \gamma_R \sim 2\pi \times 100\,\mathrm{Hz}$$

$N \sim 30$ $\quad$ $d \sim 800\mathrm{nm}$

Validate RWA, Markov,
no retardation,…

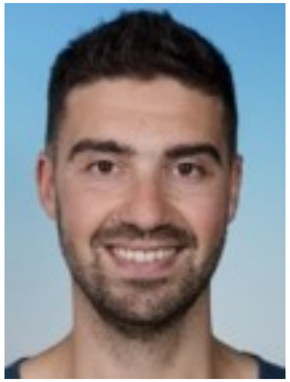
thanks to the collaborators

Tomas Ramos

Hannes Pichler

Benoit Vermersch

Philipp Hauke



Hugo Tercas

Andrew Daley