(Engineered) Dissipation & Cold Atoms

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Many body systems ...

THE GOOD

- engineering dissipation → quantum information
  engineering dissipation → cond mat

THE BAD

- decoherence, heating in optical lattices

THE DIFFICULT

- solving (driven) open system / non-equilibrium

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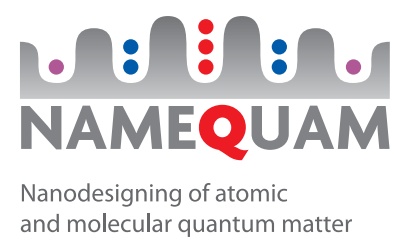
see also last week's UCSB colloquium by I. Cirac



FWF Der Wissenschaftsfonds.

Example 1:
Non-Equilibrium Dynamics on Optical Lattices:
Heating & Decoherence due Spontaneous Emission

$$\dot{\rho} = -i\left[H_{BH/FB} + \ldots, \rho\right] + \mathcal{L}\rho$$

strongly correlated
Hubbard dynamics

decoherence,
e.g. spontaneous emission

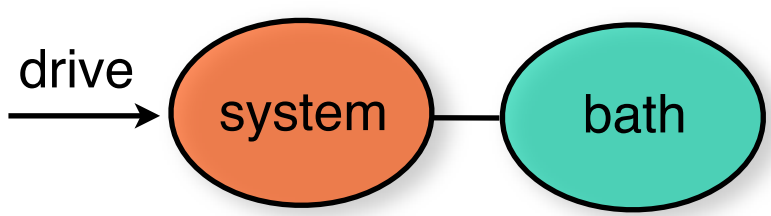
Motivation: quantitative comparison theory / exp of phase diagrams:
M. Troyer, I. Bloch et al., Nat Phys 2010

- **Q.: interplay decoherence & many body**
- **Master equations**
  - derive equations
  - how to solve it: e.g. in 1D with tDMRG quantum trajectories; mean field

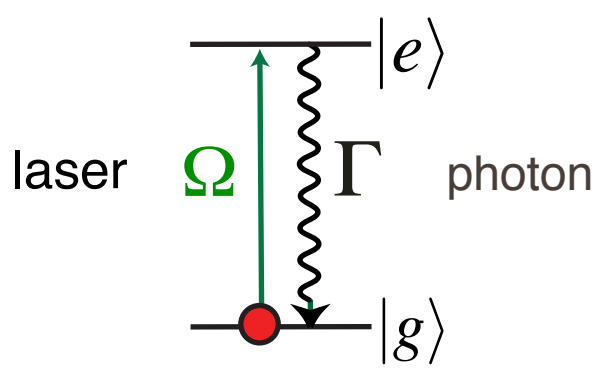
H. Pichler, A. Daley, and PZ, PRA 2010

A note on
master equations in quantum optics

- ***Driven*** **open quantum systems**



$$\frac{d\rho}{dt} = -i\,[H,\rho] + \mathcal{L}\rho$$ master equation



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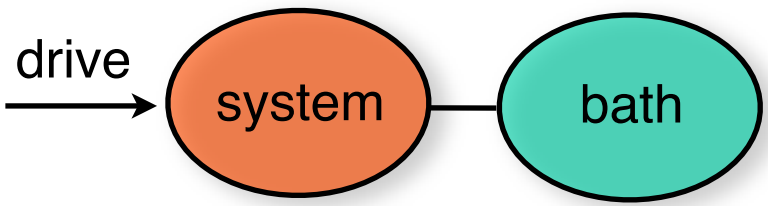
Generic Quantum Optical Model



$$H = H_{\rm sys} + H_B + H_{\rm int}$$

$$H_B = \int_{\omega_0-\vartheta}^{\omega_0+\vartheta} d\omega\, \omega\, b^\dagger(\omega) b(\omega)$$

bath of oscillators

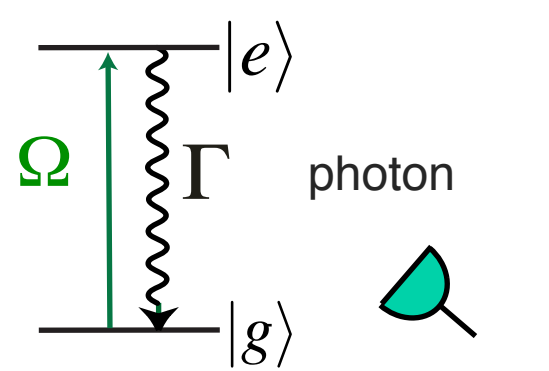
$$\left[b(\omega), b^\dagger(\omega')\right] = \delta(\omega - \omega')$$

$$H_{\rm int} = i \int_{\omega_0-\vartheta}^{\omega_0+\vartheta} d\omega \kappa(\omega) \left[b^\dagger(\omega) c - c^\dagger b(\omega)\right]$$

system "quantum jump" operator

- ✓ Rotating wave approximation
- ✓ Markov / white noise

Example: spontaneous emission from two level system



$$c = |g\rangle\langle e| \equiv \sigma^-$$

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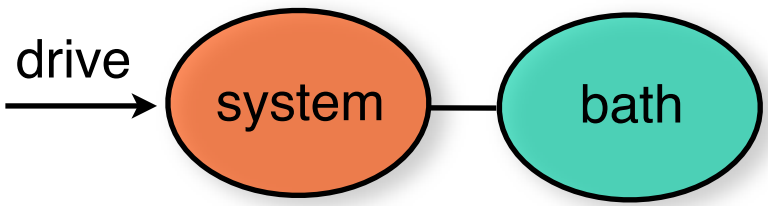
Generic Quantum Optical Model



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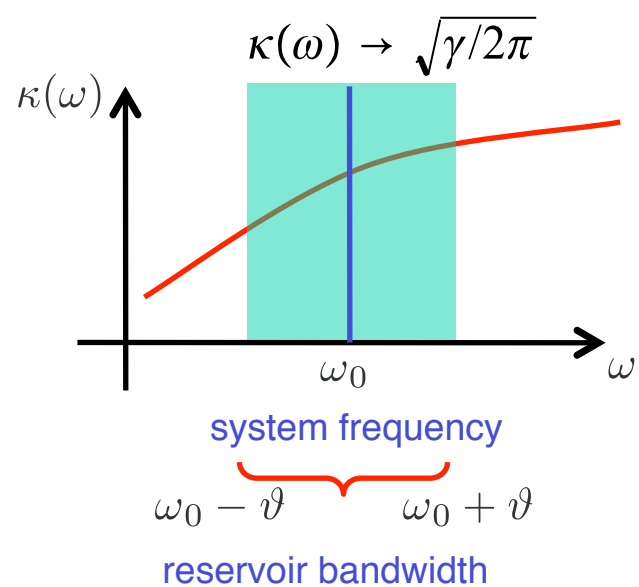

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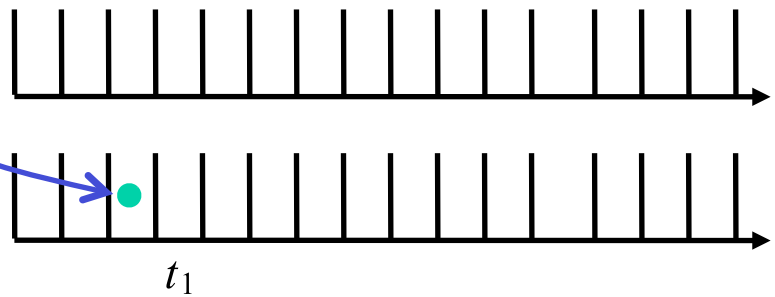
Quantum Trajectories & Master Equation

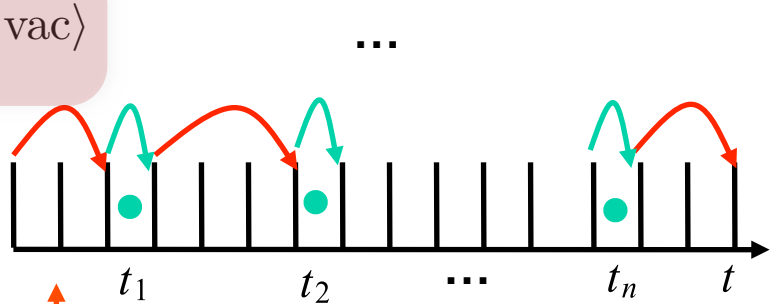
Entangled state of system and bath:

photon emission

$$|\Psi(t)\rangle = |\psi_{\rm sys}(t|)\rangle|{\rm vac}\rangle + \sum_{t_1} |\psi_{\rm sys}(t|t_1)\rangle \Delta B^\dagger(t_1)|{\rm vac}\rangle + \ldots$$

$$+ \sum_{t_n>\ldots>t_1} |\psi_{\rm sys}(t|t_n,\ldots,t_1)\rangle\, \Delta B^\dagger(t_n)\ldots\Delta B^\dagger(t_1)|{\rm vac}\rangle + \ldots$$





Master equation:

- trace over the radiation field

$$\dot\rho = -[H_{\rm sys},\rho] + \gamma\left(c\rho c^\dagger - \frac{1}{2}c^\dagger c\rho - \rho\frac{1}{2}c^\dagger c\right)$$

quantum jump operators

click:

"quantum jump" = effect of detecting a photon on system

$$|\psi_{\rm sys}(t)\rangle \to \sqrt{\gamma}c\,|\psi_{\rm sys}(t)\rangle$$

no click:

$$|\psi_{\rm sys}(0)\rangle \to e^{-iH_{\rm eff}t}|\psi_{\rm sys}(0)\rangle$$

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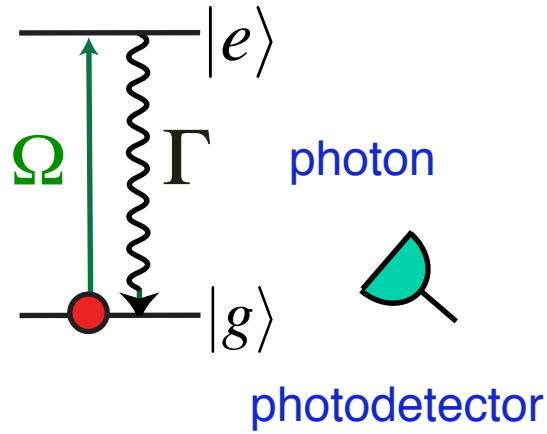
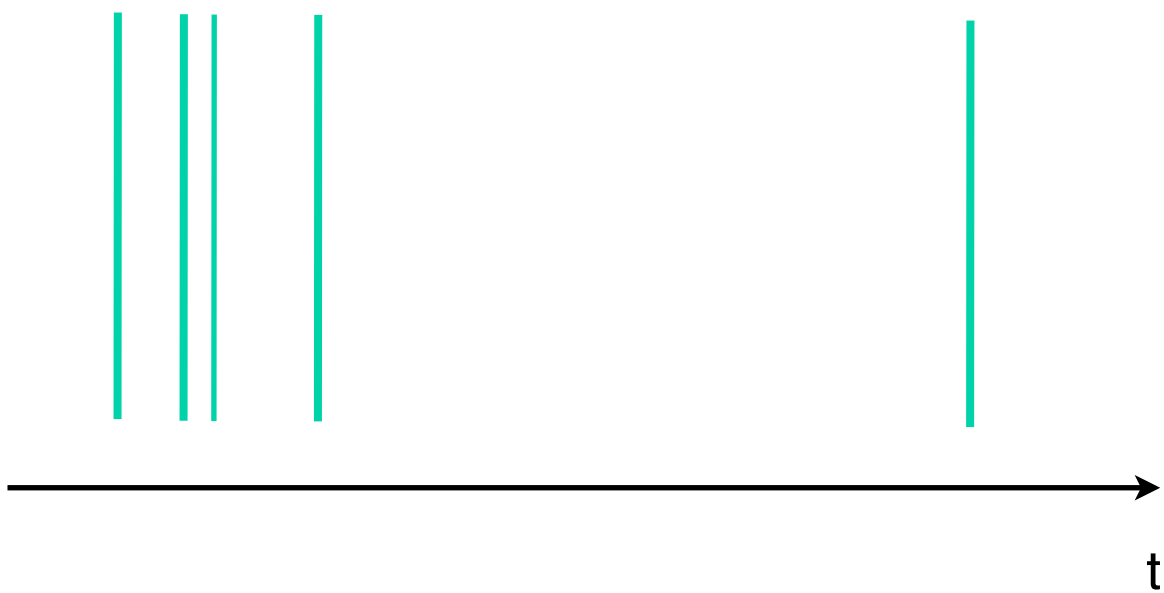
Quantum Trajectories



photon count trajectory (single run)



Evolution of the atom, *given* this counting trajectory?

conditional time evolution / wave function

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Quantum Trajectories

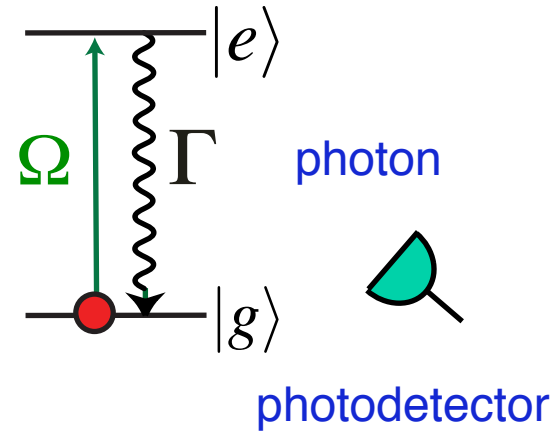
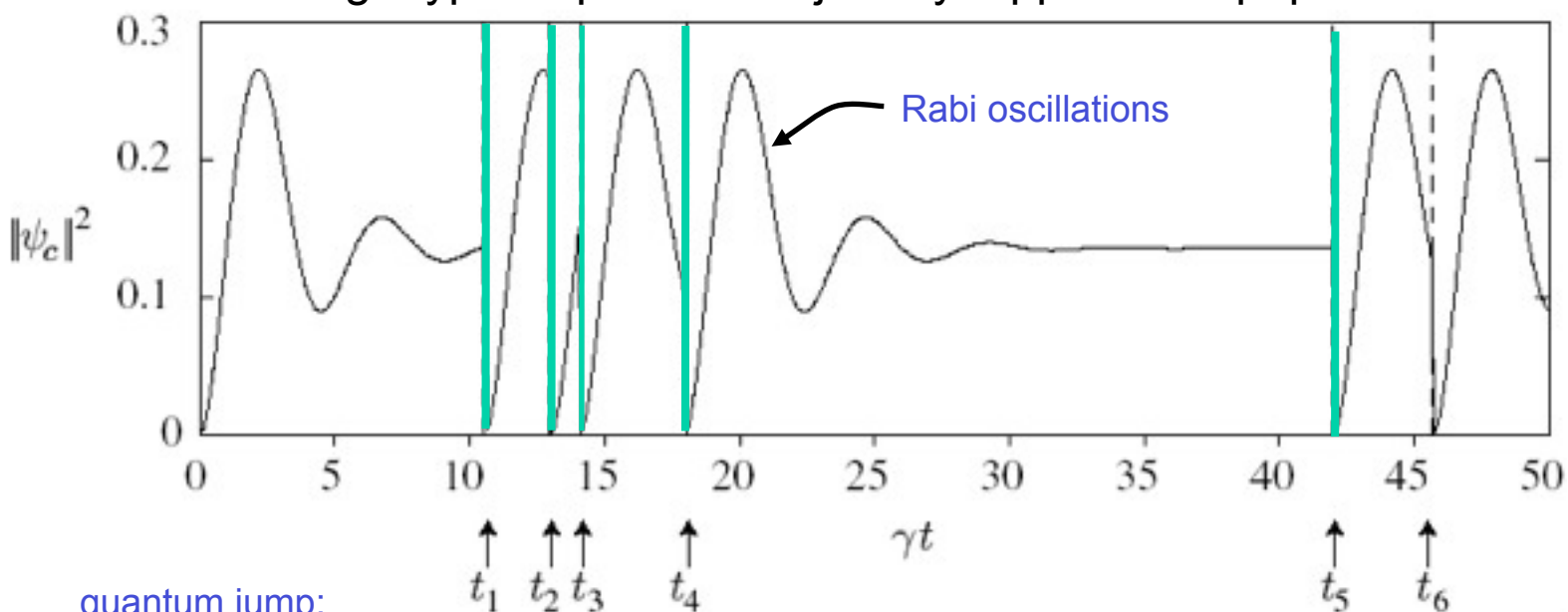


Fig.: typical quantum trajectory: upper state population



quantum jump: electron returns to the ground state

(prepares the system)

- describes: single "quantum trajectory"
- useful: Monte Carlo wave function simulation

stochastic wavefunction $|\psi(t)\rangle_{\rm sys}$ (dim d)

$\leftrightarrow$

DMRG + wave function simulation $\longleftrightarrow$ density matrix $\rho_{\rm sys}(t)$ (dim $d \times d$)

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Non-Equilibrium Dynamics on Optical Lattices: Heating & Decoherence due Spontaneous Emission

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strongly correlated Hubbard dynamics

decoherence, e.g. spontaneous emission

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H. Pichler, A. Daley, and PZ, PRA 2010

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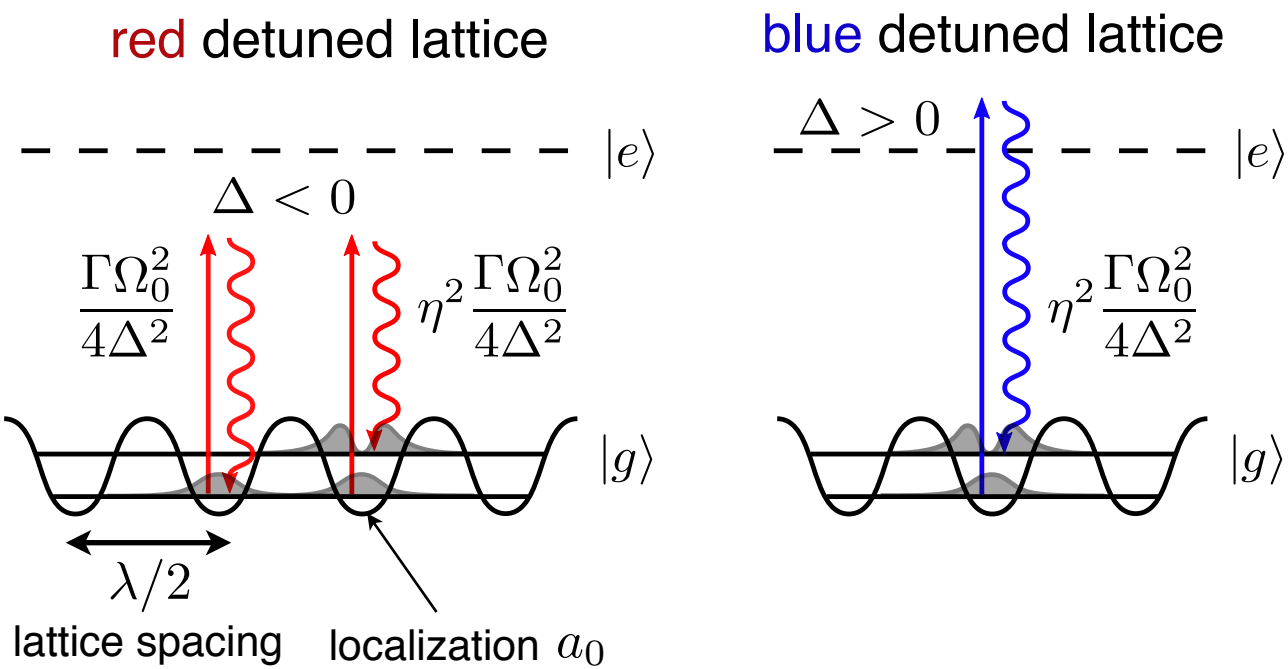
Heating in optical lattices: single particle

- **Spontaneous emission**



Lamb-Dicke parameter: $\eta = 2\pi a_0/\lambda << 1$

- Red detuning gives rise to more spontaneous emission events in deep lattices
- Processes returning atoms to the lowest band are strongly suppressed for blue detuning

J. I. Cirac, R. Blatt, and P. Zoller, Laser cooling of trapped ions in a standing wave, PRA (1992)

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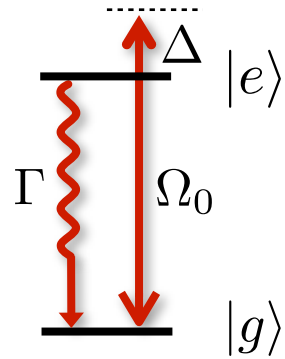
N-boson master equation



- **master equation for atoms in ground state:**

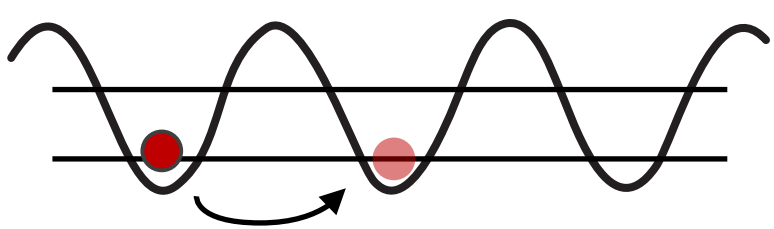
$$\dot{\rho} = -i\left(H_{\rm eff}\rho - \rho H_{\rm eff}^{\dagger}\right) + \mathcal{J}_{\rm rad}\rho$$

- effective non-Hermitian Hamiltonian:

$$H_{\rm eff} = H_0 + H_{\rm eff}^{\rm rad} + H_{\rm eff}^{\rm coll}.$$

- **single particle motion in optical lattice**

$$H_0 = \int d^3x \hat{\psi}^{\dagger}(\boldsymbol{x})\left(-\frac{\hbar^2}{2m}\nabla^2 + V_{\rm opt}(\boldsymbol{x})\right)\hat{\psi}(\boldsymbol{x})$$



$$V_{\rm opt} = \frac{|\Omega(\mathbf{x})|^2}{4\Delta}$$

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N-boson master equation

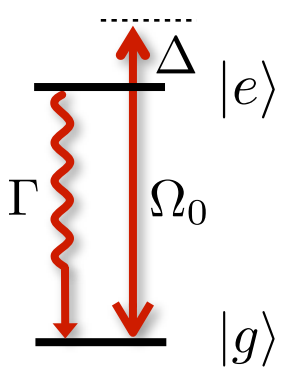
- **radiative processes**

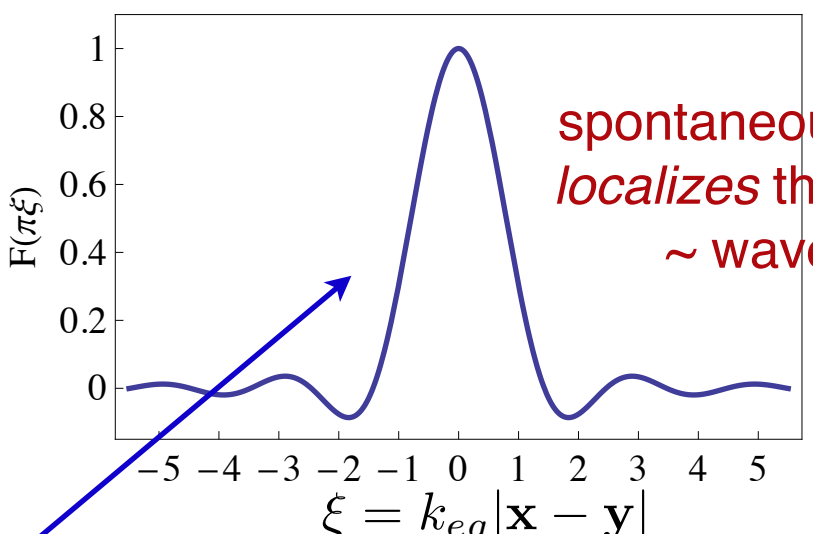
dipole-dipole interaction

$$H_{\rm eff}^{\rm rad} = \iint d^3x d^3y \frac{\Gamma\Omega(\boldsymbol{y})\Omega^*(\boldsymbol{x})}{4\Delta^2} G(k_{eg}(\boldsymbol{x}-\boldsymbol{y}))\hat{\psi}^\dagger(\boldsymbol{x})\hat{\psi}^\dagger(\boldsymbol{y})\hat{\psi}(\boldsymbol{y})\hat{\psi}(\boldsymbol{x})$$
$$- i\frac{1}{2}\int d^3x \frac{\Gamma|\Omega(\boldsymbol{x})|^2}{4\Delta^2}\hat{\psi}^\dagger(\boldsymbol{x})\hat{\psi}(\boldsymbol{x}) - i\frac{1}{2}\iint d^3x d^3y \frac{\Gamma\Omega(\boldsymbol{y})\Omega^*(\boldsymbol{x})}{4\Delta^2} F(k_{eg}(\boldsymbol{x}-\boldsymbol{y}))\hat{\psi}^\dagger(\boldsymbol{x})\hat{\psi}^\dagger(\boldsymbol{y})\hat{\psi}(\boldsymbol{y})\hat{\psi}(\boldsymbol{x})$$

single particle optical pumping

super- / subradiant effects





spontaneous emission *localizes* the particle to ~ wavelength

recycling term: return of electron to ground state after emission

$$\mathcal{J}\rho = \iint d^3x d^3y \frac{\Gamma\Omega(\boldsymbol{x})\Omega(\boldsymbol{y})}{4\Delta^2} F(k_{eg}(\boldsymbol{x}-\boldsymbol{y}))\hat{\psi}^\dagger(\boldsymbol{x})\hat{\psi}(\boldsymbol{x})\rho\hat{\psi}^\dagger(\boldsymbol{y})\hat{\psi}(\boldsymbol{y})$$

density density

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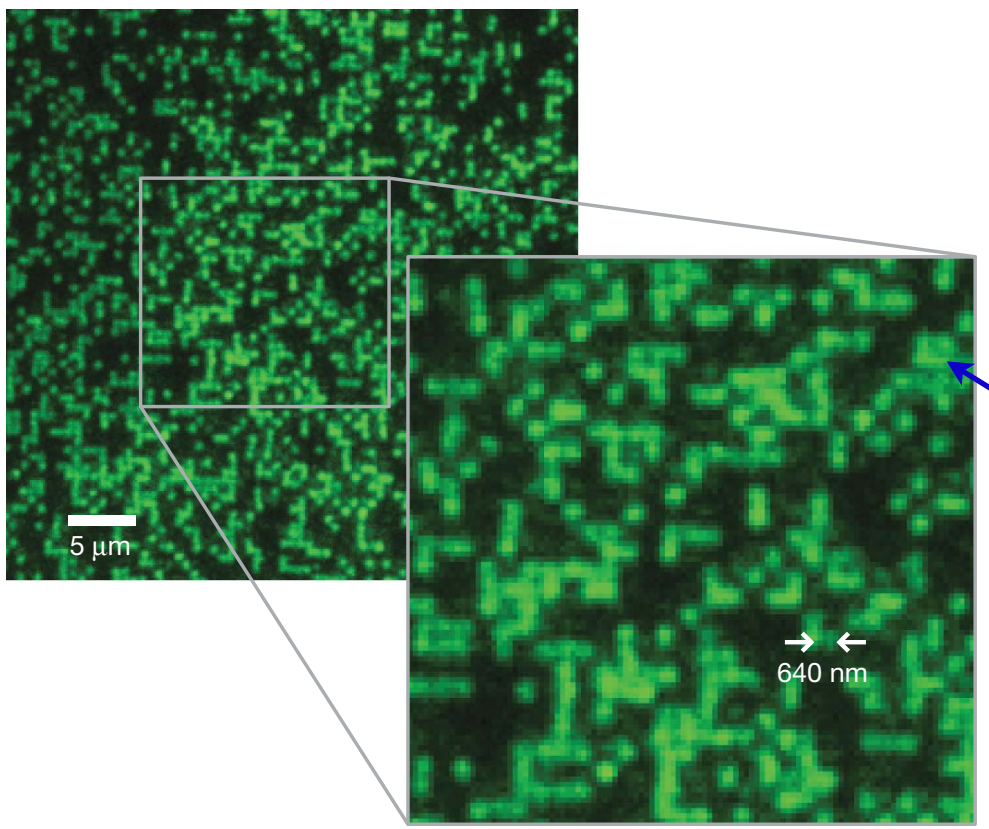
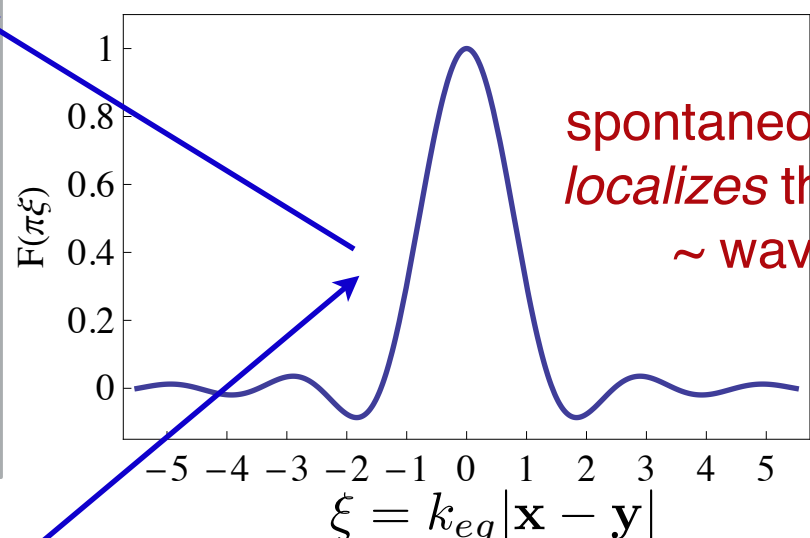
N-boson master equation

- **Imaging Hubbard models:**
  Harvard, Munich, Chicago, Penn State, ...





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density density

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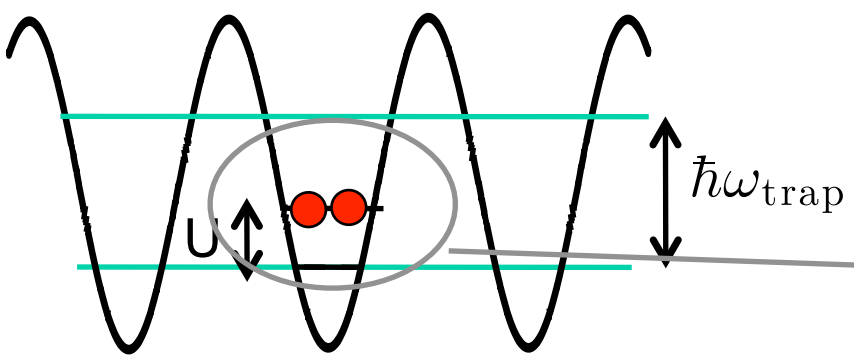
N-boson master equation

- **short range collisions & light induced collisions**

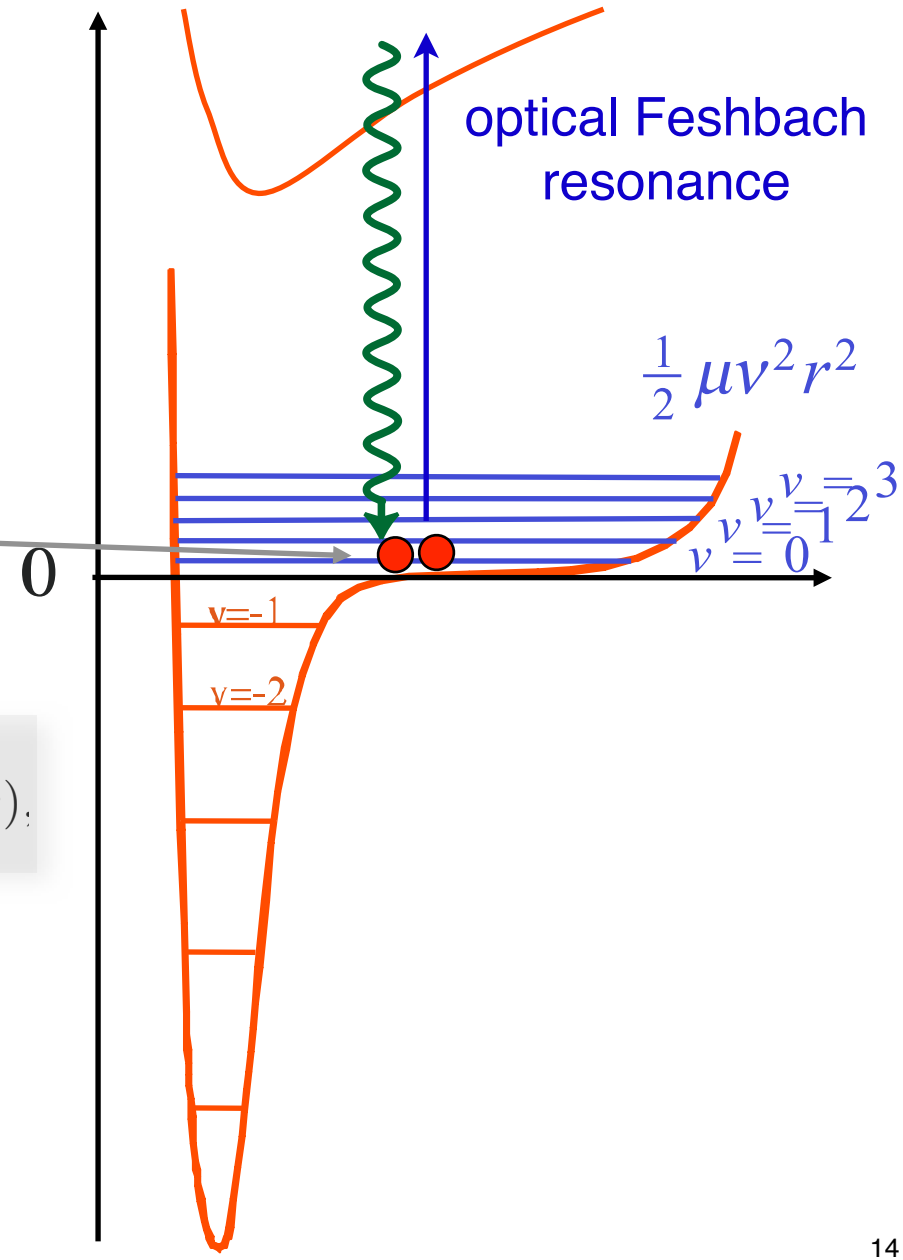
two atoms on one lattice site



$$H_{\mathrm{eff}}^{\mathrm{coll}} = \int d^3x \left(g(\boldsymbol{x}) - i\frac{1}{2}\gamma_2(\boldsymbol{x}) \right) \hat{\psi}^\dagger(\boldsymbol{x})\hat{\psi}^\dagger(\boldsymbol{x})\hat{\psi}(\boldsymbol{x})\hat{\psi}(\boldsymbol{x}),$$

contact potential:
real & light induced imaginary scattering length

Born-Oppenheimer potential



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Hubbard Master Equation

- **projecting of Wannier functions …**

$$\dot{\rho} = -i\left[\hat{H}, \rho\right] + \sum_{\boldsymbol{n},\mu} \gamma_{\boldsymbol{n},\mu} \left(b^{\dagger}_{\boldsymbol{n},\boldsymbol{i}} b_{0,\boldsymbol{i}} \rho b^{\dagger}_{0,\boldsymbol{i}} b_{\boldsymbol{n},\boldsymbol{i}} - \frac{1}{2} b^{\dagger}_{0,\boldsymbol{i}} b_{\boldsymbol{n},\boldsymbol{i}} b^{\dagger}_{\boldsymbol{n},\boldsymbol{i}} b_{0,\boldsymbol{i}} \rho - \rho \frac{1}{2} b^{\dagger}_{0,\boldsymbol{i}} b_{\boldsymbol{n},\boldsymbol{i}} b^{\dagger}_{\boldsymbol{n},\boldsymbol{i}} b_{0,\boldsymbol{i}} \right)$$

band site

Hubbard decoherence

- **Solution**
  - time dependent perturbation theory in spontaneous emission
  - tDMRG + quantum trajectories

$$\dot{\rho} = -i[H_{BH}, \rho] + \sum_i \gamma(\hat{n}_i \rho \hat{n}_i - 1/2 \hat{n}_i \hat{n}_i \rho - 1/2 \rho \hat{n}_i \hat{n}_i)$$

  - mean field Gutzwiller:

Hamiltonian (here: single band)

$$|\Psi\rangle = \Pi_i |\phi_i\rangle = \prod_i \sum_n f_n^{(i)} |n\rangle_i$$

$$H_{MF} = \sum_i \left(-J\left(\psi_i b_i^{\dagger} + \psi_i^* b_i\right) + \frac{1}{2} U b_i^{\dagger 2} b_i^2 \right)$$

master equation (multiband)

$$\rho = \bigotimes_i \rho_i \quad \text{with} \quad \rho_i = \mathrm{Tr}_{\neq \mathrm{i}}\{\rho\}$$

$$\dot{\rho}_{\boldsymbol{i}} = -i\left[h_{MF,\boldsymbol{i}}, \rho_{\boldsymbol{i}}\right] + \mathscr{L}_{MF,\boldsymbol{i}} \rho_{\boldsymbol{i}}$$

nonlinear master equation

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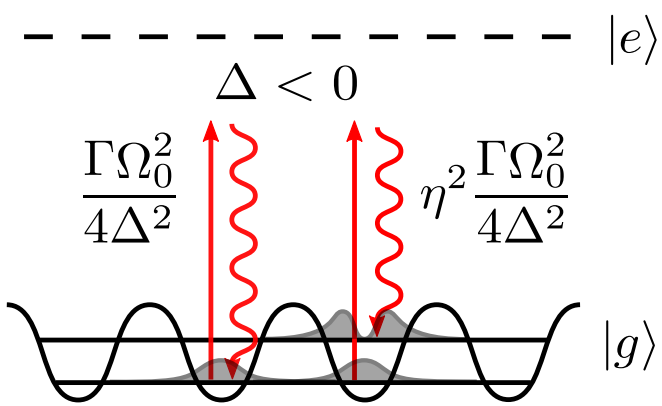
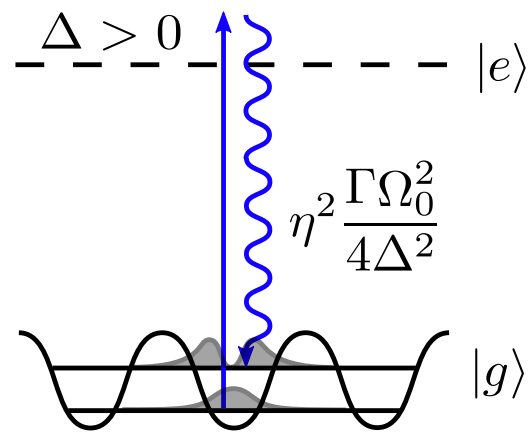
Heating in optical lattices: single particle

- **Spontaneous emission**

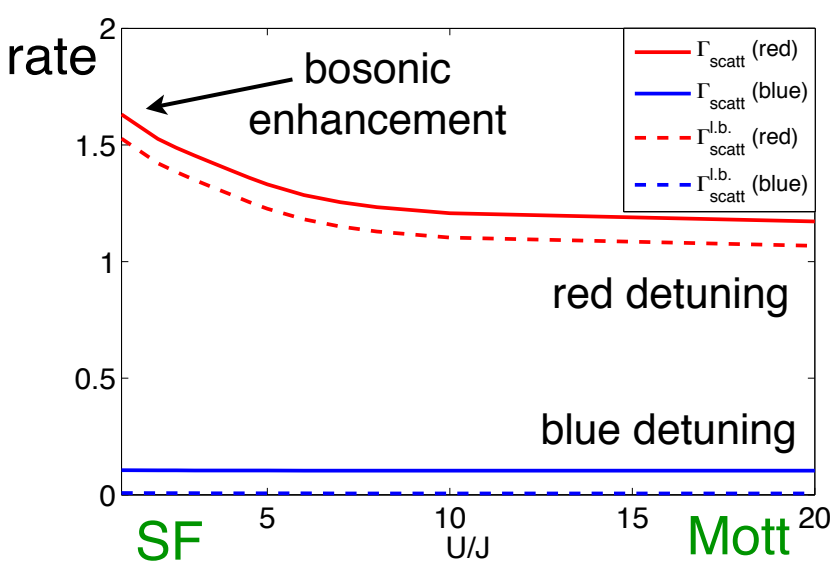
red detuned lattice



blue detuned lattice



- **total light scattering rate**



- **energy heating rate / atom**

$$\dot{E} = \frac{\Gamma|\Omega_0|^2}{4\Delta^2} E_R$$

heating is the same in red and blue lattice

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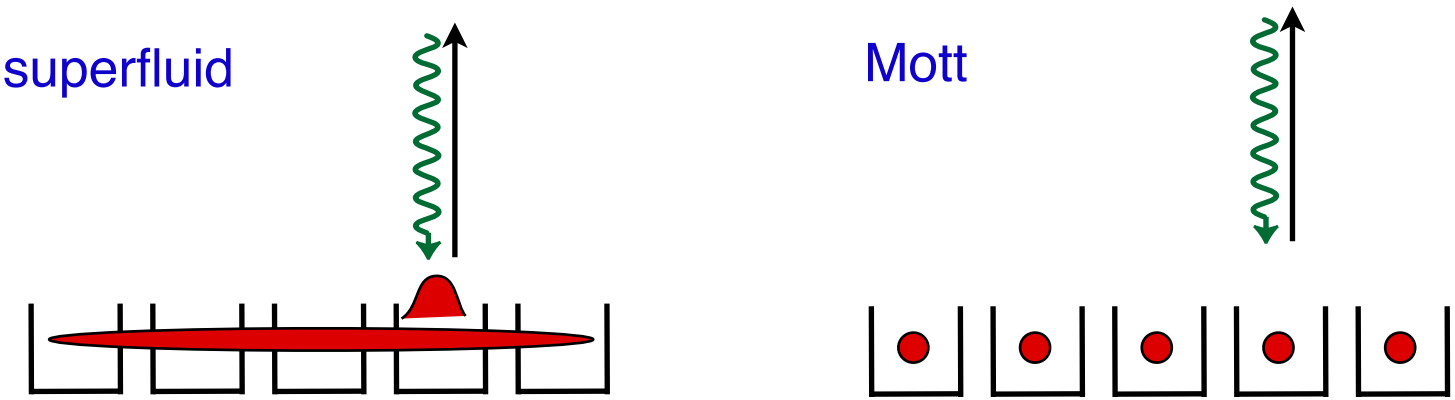
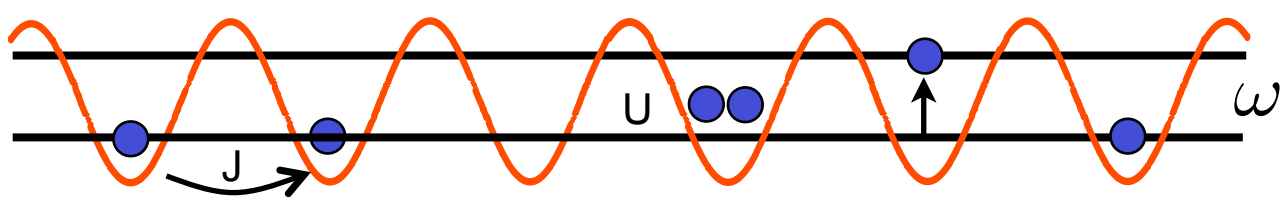
Destruction of Coherence, Collisions etc.

- spontaneous emission = localization



- collisions



collisions do not necessarily thermalize on experimental time scales; this is particularly true for excited bands

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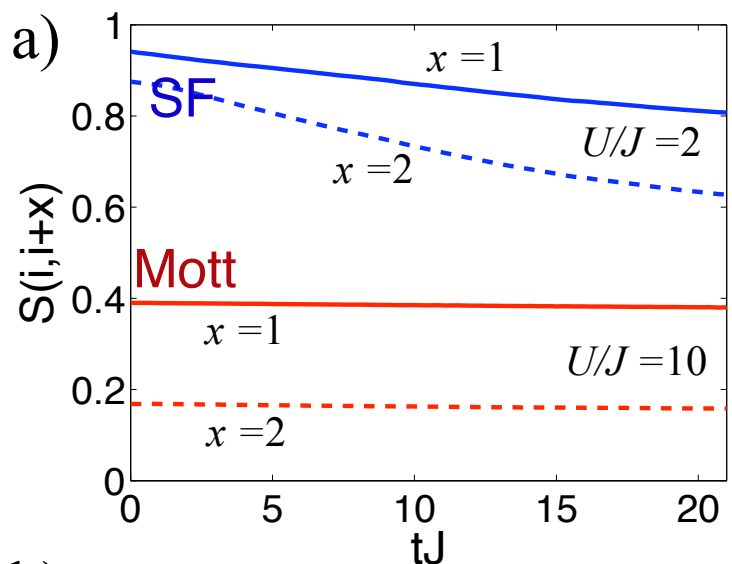
Destruction of Coherence, Collisions etc.

- decay of off-diagonal single particle correlation functions

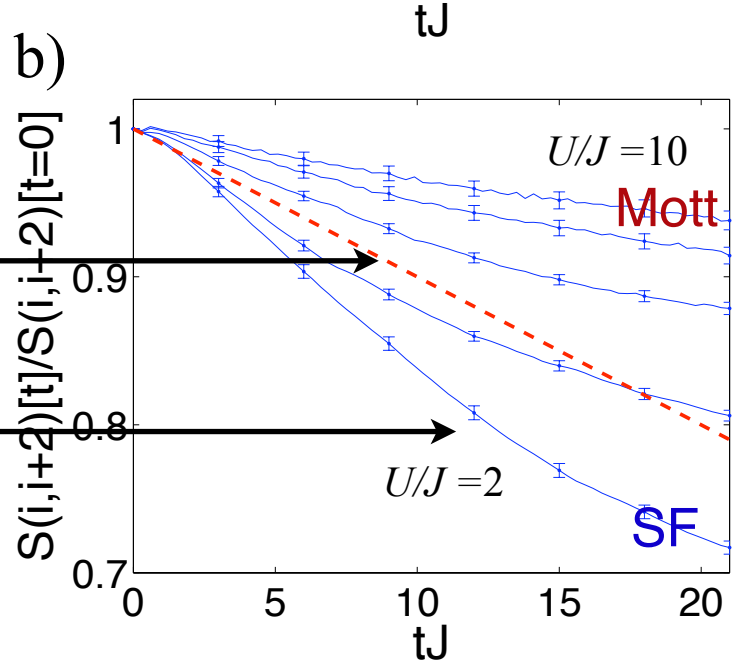
$$S(i,j) = \langle b_i^\dagger b_j \rangle$$



- decay of initial correlations

perturbation theory

exact: t-DMRG
+ Monte Carlo wave functions



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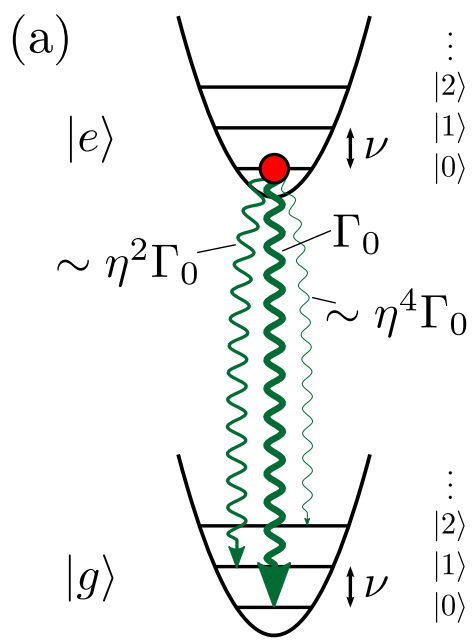
Fermions: Pauli blocking of spontaneous emission

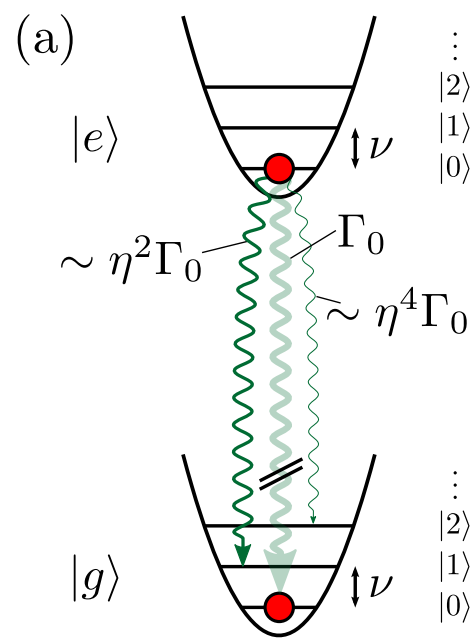
- **Momentum space**
- **Position space**

Busch et al., Europhysics Lett 1998 ;
B. Shuve et al., JPB 2010

R. Sandner, 2010

Alkaline Earth





blocking by a single atom
in an optical lattice

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Engineered Quantum Dissipation

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Hamiltonian Engineering in Many Body Systems

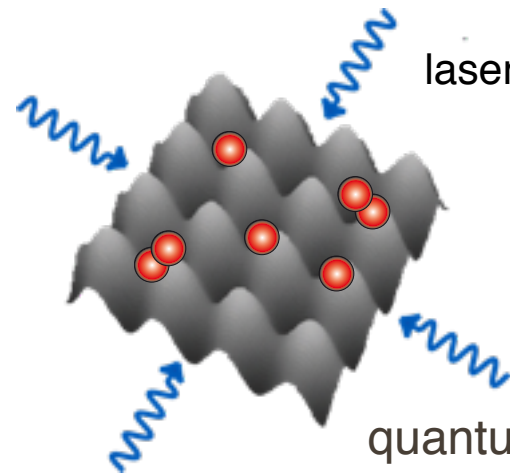
- **condensed matter physics**

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

strongly correlated states

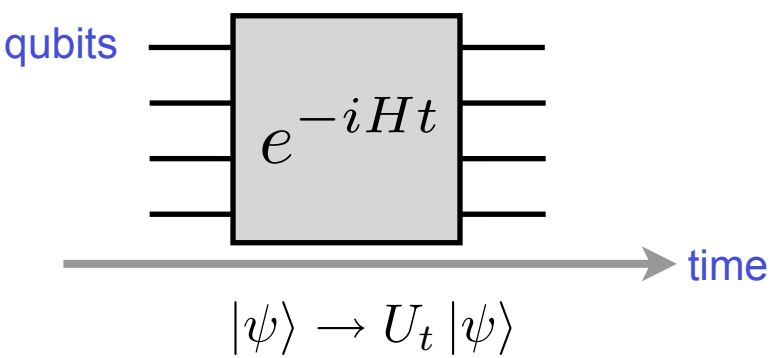
equilibrium cond mat

- **cold atoms in optical lattices**



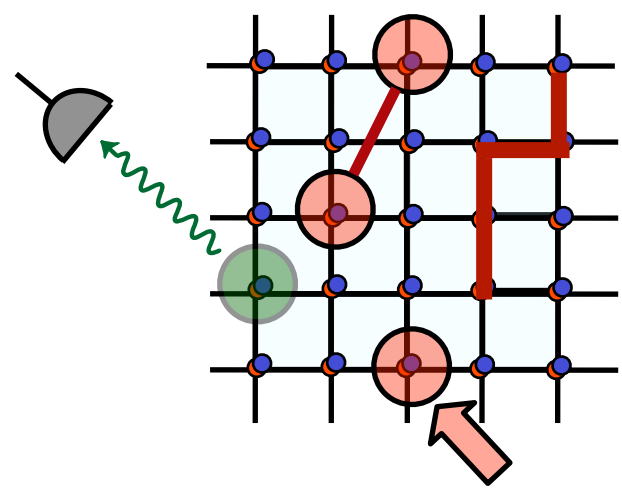
quantum simulation

- **quantum computing**



$|\psi\rangle \rightarrow U_t |\psi\rangle$

dynamics



addressable optical lattices

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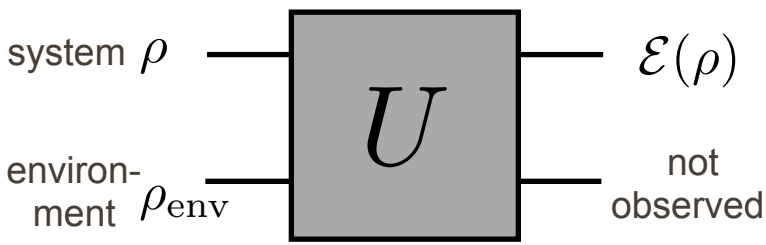
Open Many Body Systems

- **open system & nonunitary evolution**



completely positive maps

$$\rho \to \mathscr{E}(\rho) = \mathrm{tr}_{\mathrm{env}}\left\{U(\rho \otimes \rho_{\mathrm{env}})U^{\dagger}\right\} = \sum_k E_k \rho E_k^{\dagger}$$

entanglement with environment

Kraus operators: $\sum_k E_k^{\dagger} E_k = 1$

decoherence ☹

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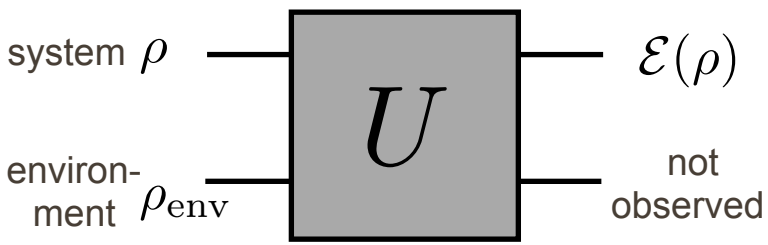
Open Many Body Systems

- **open system & nonunitary evolution**



completely positive maps

$$\rho \to \mathcal{E}(\rho) = \mathrm{tr}_{\mathrm{env}}\left\{U(\rho \otimes \rho_{\mathrm{env}})U^\dagger\right\} = \sum_k E_k \rho E_k^\dagger$$

- **Markovian**

if exists infinitesimal generator ...

master equation

$$\dot{\rho} = -[H,\rho] + \sum_\alpha \gamma_\alpha \left(c_\alpha \rho c_\alpha^\dagger - \frac{1}{2} c_\alpha^\dagger c_\alpha \rho - \rho \frac{1}{2} c_\alpha^\dagger c_\alpha \right)$$

Lindblad operators

Q.: validity … (see below)

quantum control theory: open-loop [vs. closed loop = measurement + feedback]

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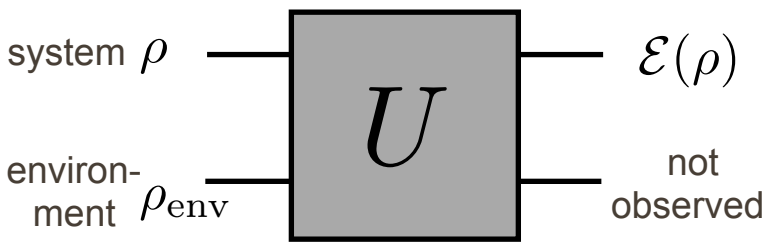
Engineering Quantum Reservoirs

- **open system & nonunitary evolution**



completely positive maps

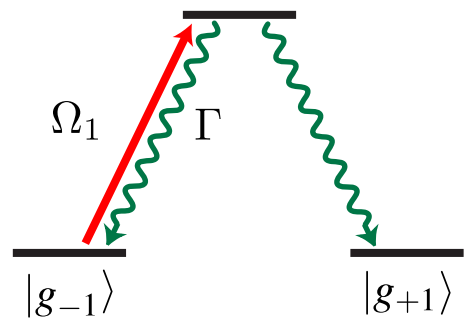
$$\rho \to \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger$$

$$\stackrel{!}{=} |\psi\rangle\langle\psi|$$

- **Markovian**

quantum optics (on *single* particle level)

optical pumping,
laser cooling



master equation

$$\rho(t) \stackrel{t\to\infty}{\longrightarrow} \rho_{\rm ss}$$

mixed state

$$\stackrel{!}{=} |\psi\rangle\langle\psi|$$

desired pure state

"dark state"

Q.: prepare desired pure *many body state* by open system dynamics? resources?

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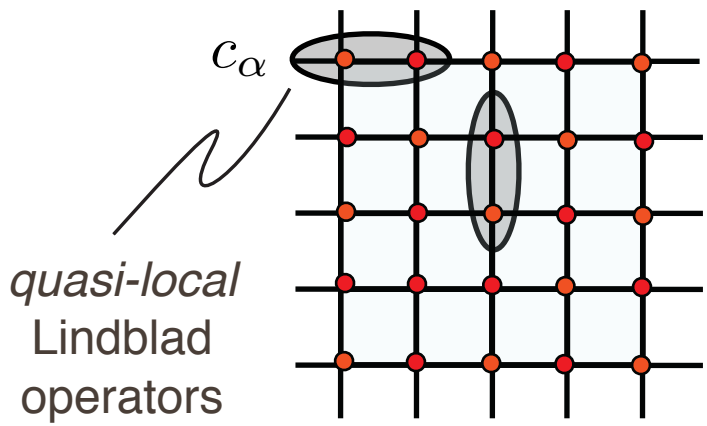
Dark States of Many Body Master Equation

- master equation

$$\dot{\rho} = -[H, \rho] + \sum_{\alpha} \gamma_{\alpha} \left(c_{\alpha} \rho c_{\alpha}^{\dagger} - \frac{1}{2} c_{\alpha}^{\dagger} c_{\alpha} \rho - \rho \frac{1}{2} c_{\alpha}^{\dagger} c_{\alpha} \right)$$

Lindblad operators

qubits or particles on a lattice



- constructing parent Liouvillians for given dark state

$$H|\psi\rangle = E|\psi\rangle$$
$$\forall \alpha \quad c_{\alpha}|\psi\rangle = 0$$

"dark state"

uniqueness (?)

engineer quantum reservoirs (implementation)

B. Kraus et al., PRA 2008
S. Diehl et al., Nat Phys 2008
F. Verstraete et al. Nat Phys 2009

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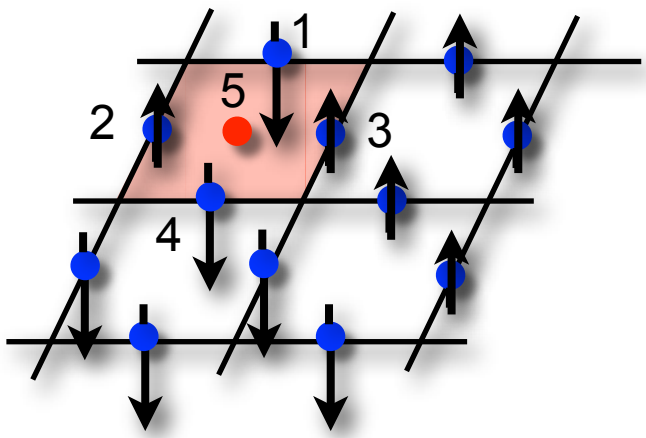
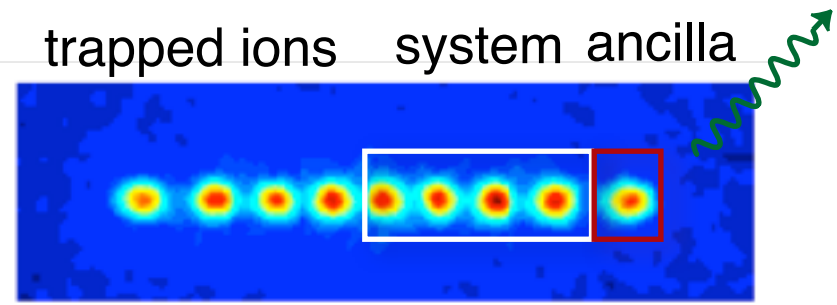
Applications: Quantum Information

- **dissipative state preparation:** example stabilizer cooling

optical pumping

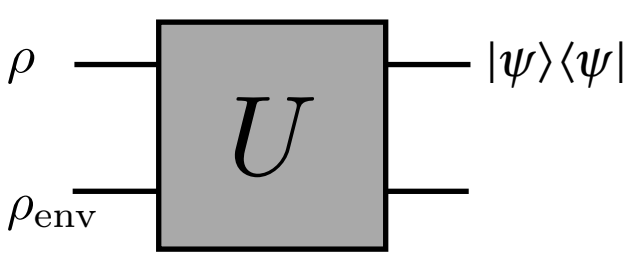




experiment: J. Barreiro, M. Müller et al., submitted
see also Polzik et al., submitted

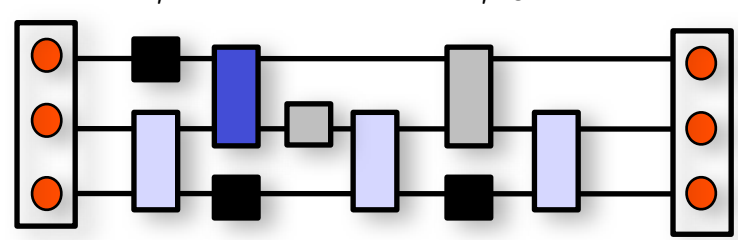
- **dissipative quantum computing and quantum memory**

dissipative quantum computing



quantum logic network model

$|\psi\rangle = U_M \cdots U_1 |\psi_0\rangle$



F. Verstraete et al. Nat Phys 2009

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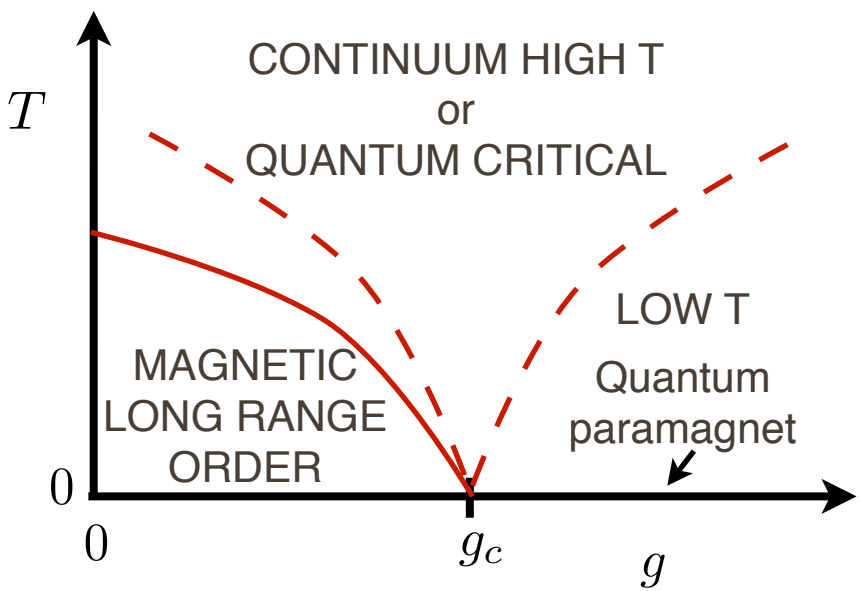
S. Diehl et al., Nat Phys 2008
S. Diehl et al., PRL 2010

Applications: Non-equilibrium cond mat

- **thermodynamic equilibrium**

O(N) Rotor Model Phase Diagram



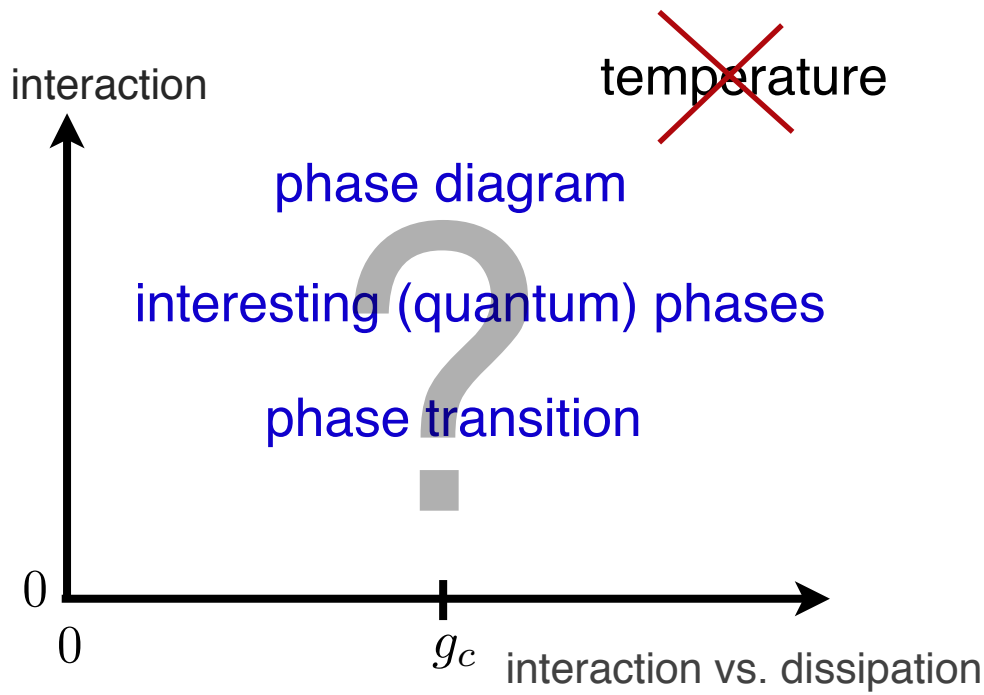
quantum phase transition

$$H\,|E_g\rangle = E_g\,|E_g\rangle$$

$$H = H_0 + gH_1$$

Hamiltonian (many body)

- **non-equilibrium**



dynamical quantum phase transition

Superfluid
(pure state)

"thermal"
(mixed state)

$$\frac{d\rho}{dt} = -i\,[H,\rho] + \mathcal{L}\rho$$

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Q.: Identifying and engineering Lindblad operators

- **Example 1:** *dissipative* d-wave pairing
- **Example 2:** driven BEC & dynamical quantum phase transition

S. Diehl et al., Nat Phys 2008
S. Diehl et al., PRL 2010

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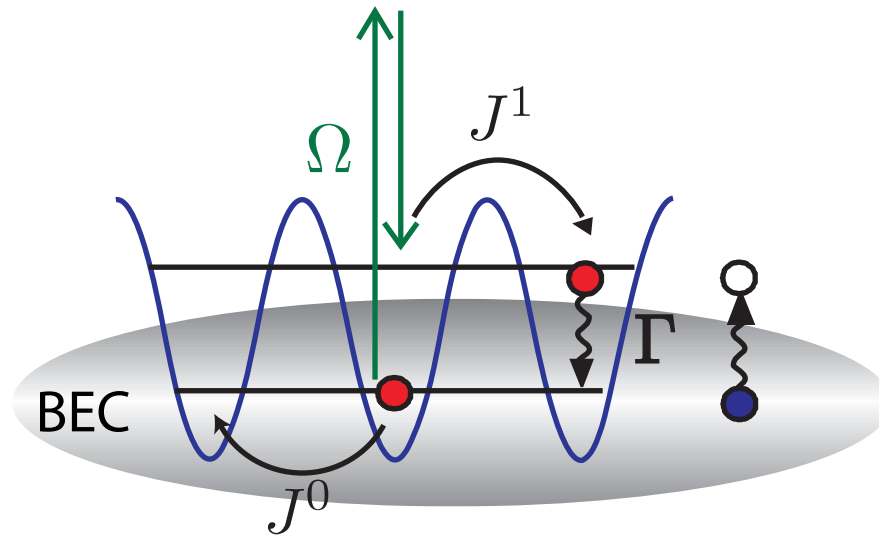
A. Griessner et al.,
PRL 2006

Driven Dissipative Hubbard Models

- BEC as a “phonon reservoir”
  - quantum reservoir engineering



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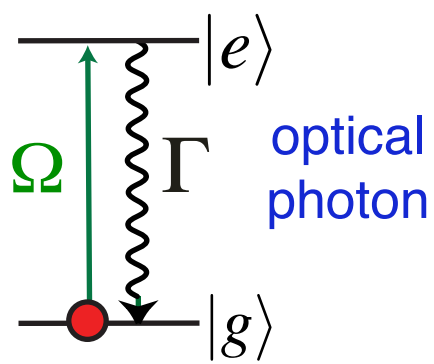
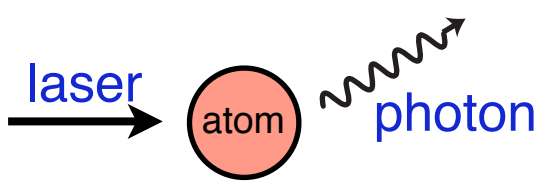
“think quantum optics”

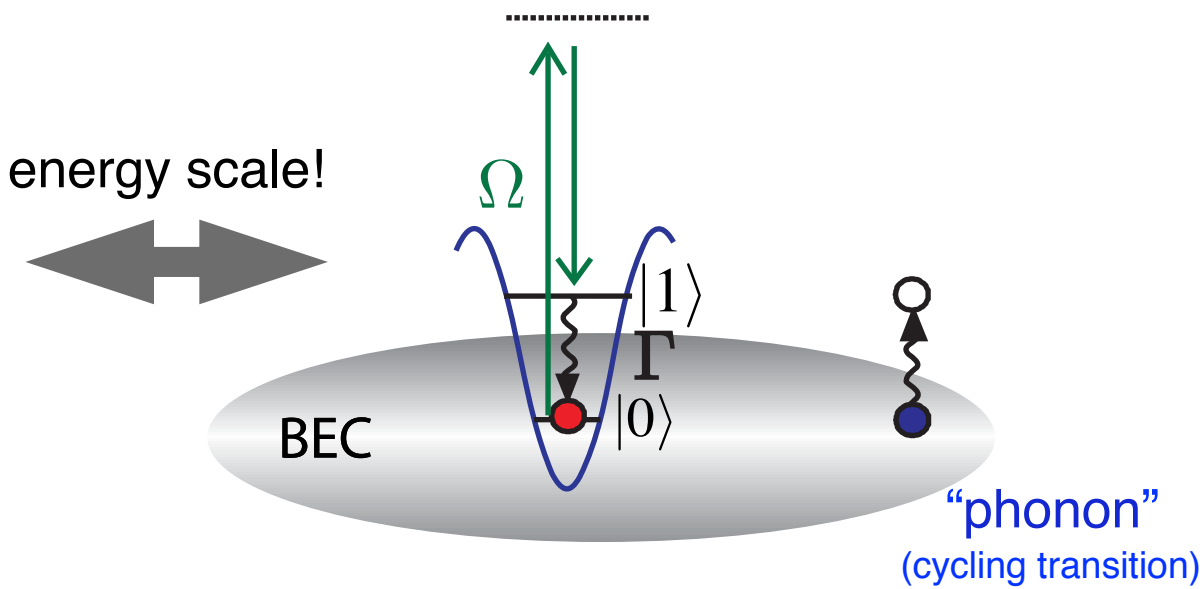
- driven two-level atom + spontaneous emission





- reservoir: vacuum modes of the radiation field (T=0)

- trapped atom in a BEC reservoir



laser assisted atom + BEC collision

- reservoir: Bogoliubov excitations of the BEC (@ temperature T)

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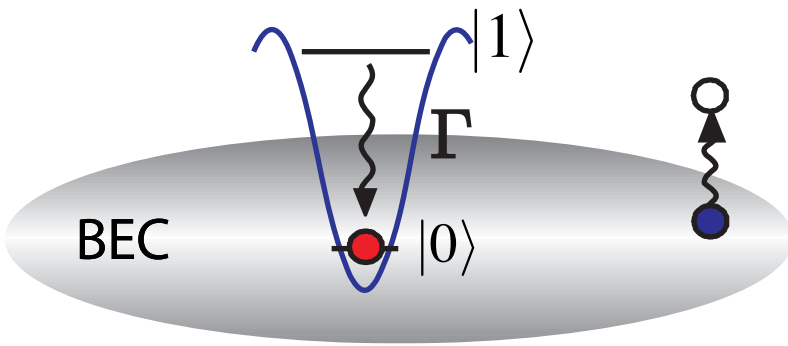
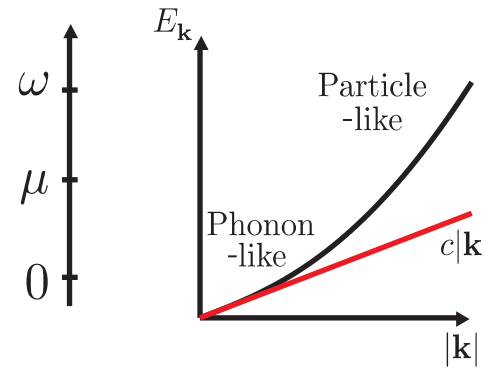
“Spontaneous Emission”



spectrum of
Bogoliubov excitations



$$E_k = \sqrt{c^2k^2 + k^4/(2m_b)^2}$$

- BEC reservoir

$$\hat{H}_b = \sum_{\mathbf{k}} E_{\mathbf{k}} \hat{b}^\dagger_{\mathbf{k}} \hat{b}_{\mathbf{k}}$$

Bogoliubov

- interaction: *inter*band 0 - 1

$$\hat{H}_{\text{collision}} \sim g_{ab} \sum_{\mathbf{k}} S(\mathbf{k},\omega)^{1/2} \, |1\rangle \langle 0| \, \hat{b}_{\mathbf{k}} + h.c.$$

“spontaneous emission”

- “spontaneous emission rate”

$$\Gamma = 2\pi \times 1.1 \text{ KHz}$$

weak coupling

$$a_s = 100 a_0$$ scattering length

$$\rho_0 = 5 \times 10^{14} \text{cm}^{-3}$$ density

$$\omega = 2\pi \times 100 \text{ KHz}$$ trap frequency

tunable !

- [tayloring the reservoir, e.g. phononic band gap]

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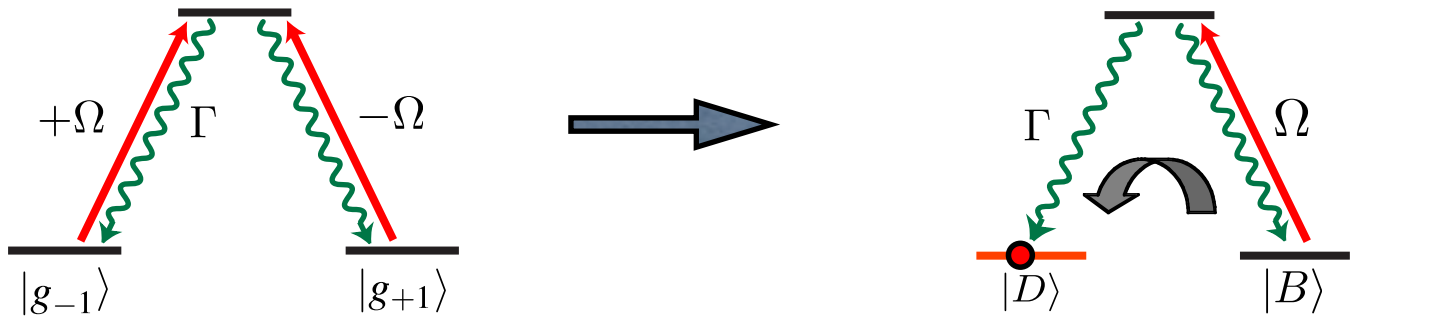
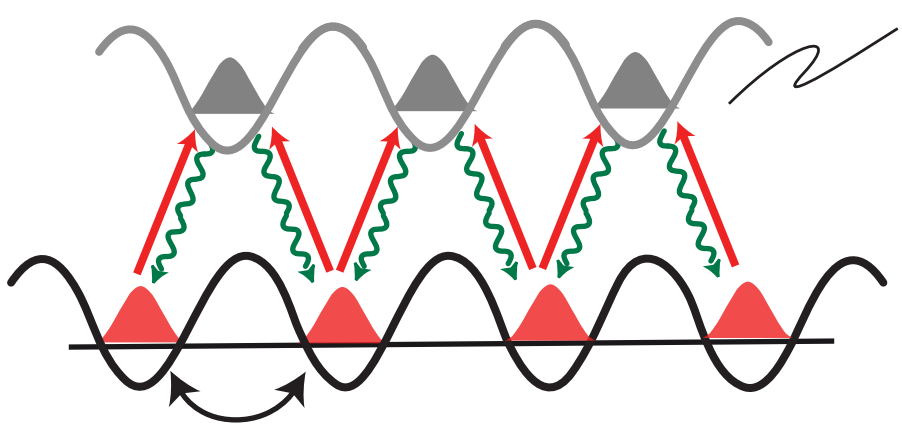
“think quantum optics”

- Λ-system



three electronic levels dark state bright state

- N atom on M sites



local dissipation

$$\rho(t) \xrightarrow{t\to\infty} |\mathrm{BEC}\rangle\langle\mathrm{BEC}|$$

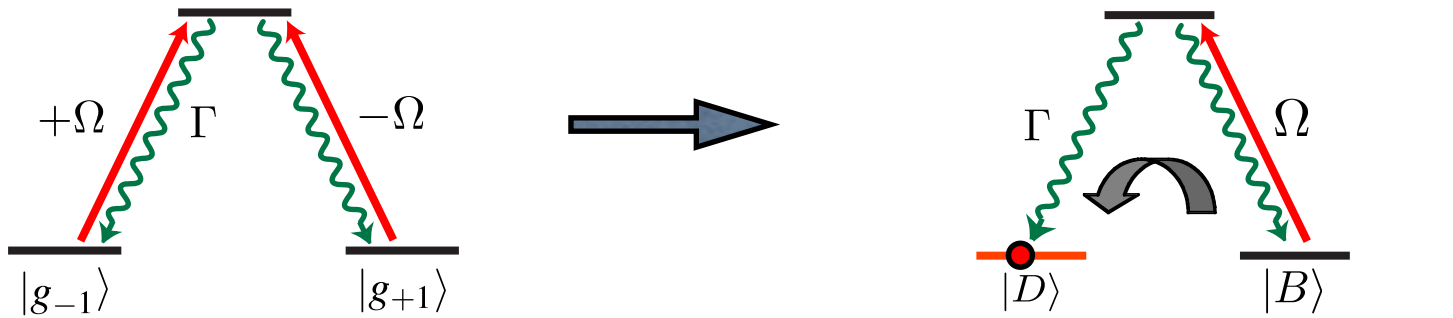
driven dissipative BEC

cond mat: ~ array of dissipative Josephson junctions

quantum optics: spatial chain of Λ-systems

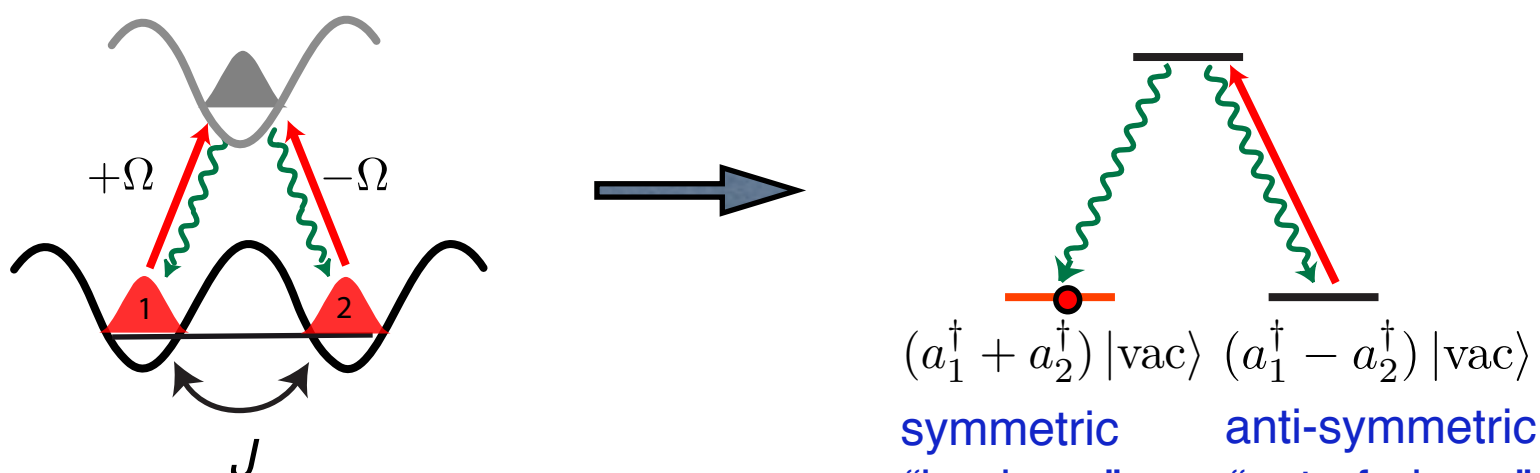
“think quantum optics”

- Λ-system



dark state bright state

- 1 atom on 2 sites



symmetric “in-phase”

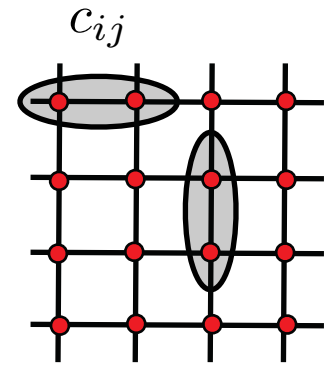
anti-symmetric “out-of-phase”

~ dissipative Josephson junction

pumping into symmetric state

“phase locking”

Driven Dissipative Bose Hubbard Model



- master equation

$$\frac{d}{dt}\rho = -i\left[H,\rho\right] + \kappa \sum_{\langle ij \rangle} \left[2c_{ij}\rho c_{ij}^{\dagger} - c_{ij}^{\dagger}c_{ij}\rho - \rho c_{ij}^{\dagger}c_{ij} \right]$$

adjacent sites

1. Bose Hubbard Hamiltonian

$$H = -J \sum_{<i,j>} a_i^{\dagger} a_j + \tfrac{1}{2} U \sum_i a_i^{\dagger 2} a_i^2$$

SF - Mott insulator physics

Rem.: we have a microscopic justification for this model

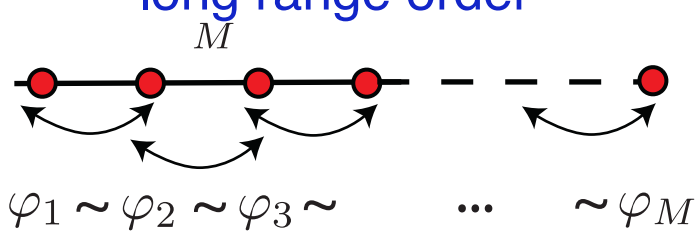
2. Liouvillian

$$c_{ij} = \left(a_i^{\dagger} + a_j^{\dagger}\right)\left(a_i - a_j\right)$$

jump operator (quasi-local)

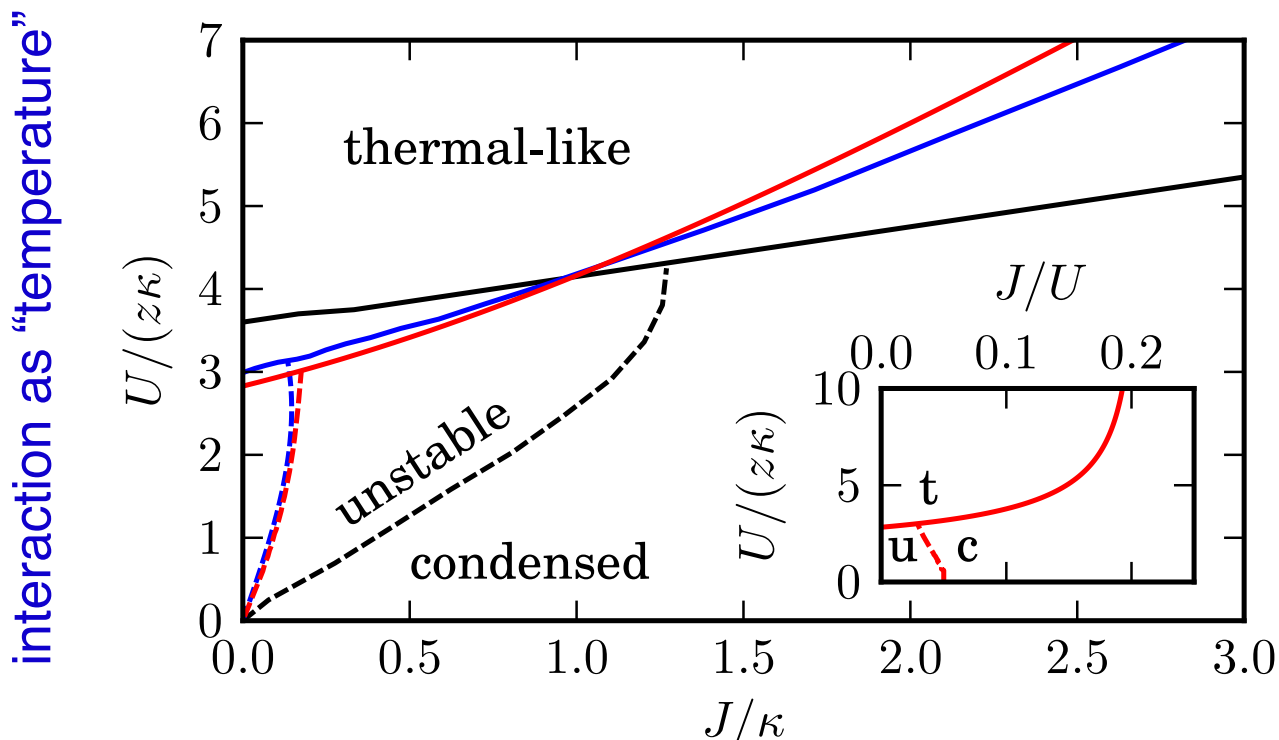
"cooling" to a BEC

local "driving/dissipation" causes long range order



Non-equilibrium phase diagram

- **non-equilibrium phase diagram** (in Gutzwiller mean field theory: non-linear master equation)



hopping vs. dissipation

S. Diehl, A. Tomadin, A. Micheli, R. Fazio, P. Zoller, Phys. Rev. Lett. 105, 015702, (2010)

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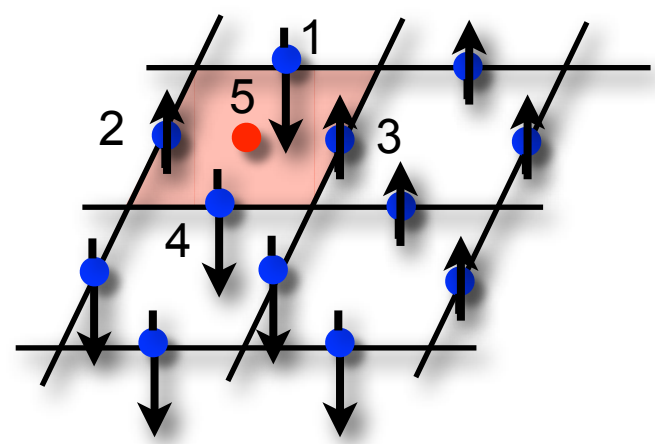
Example 4:
Stabilizer Pumping (cold atom → ion trap experiment)

Motivation:

- Quantum simulation of Kitaev's toric code Hamiltonian
- Cooling to the ground state



Weimer et al., Nat Phys 2010 (Rydberg)
Aguado et al., PRL 2008 (cold atom)

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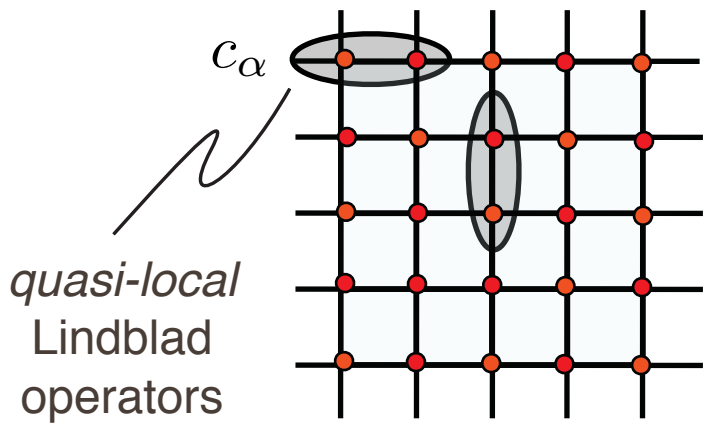
Dark States of Many Body Master Equation

- master equation

$$\dot{\rho} = -[H, \rho] + \sum_{\alpha} \gamma_{\alpha} \left(c_{\alpha} \rho c_{\alpha}^{\dagger} - \frac{1}{2} c_{\alpha}^{\dagger} c_{\alpha} \rho - \rho \frac{1}{2} c_{\alpha}^{\dagger} c_{\alpha} \right)$$

Lindblad operators

qubits or particles on a lattice



- constructing parent Liouvillians for given dark state

$$H|\psi\rangle = E|\psi\rangle$$
$$\forall \alpha \quad c_{\alpha}|\psi\rangle = 0$$

"dark state"

uniqueness (?)

engineer quantum reservoirs (implementation)

B. Kraus et al., PRA 2008
S. Diehl et al., Nat Phys 2008
F. Verstraete et al. Nat Phys 2009

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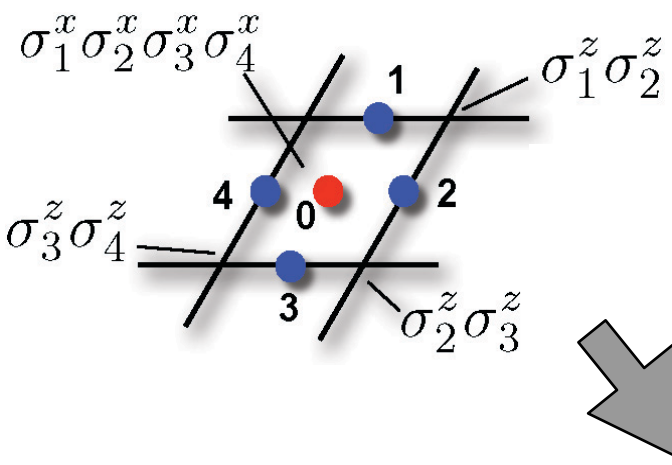
Implementation with Trapped Ions

- **stabilizer pumping**

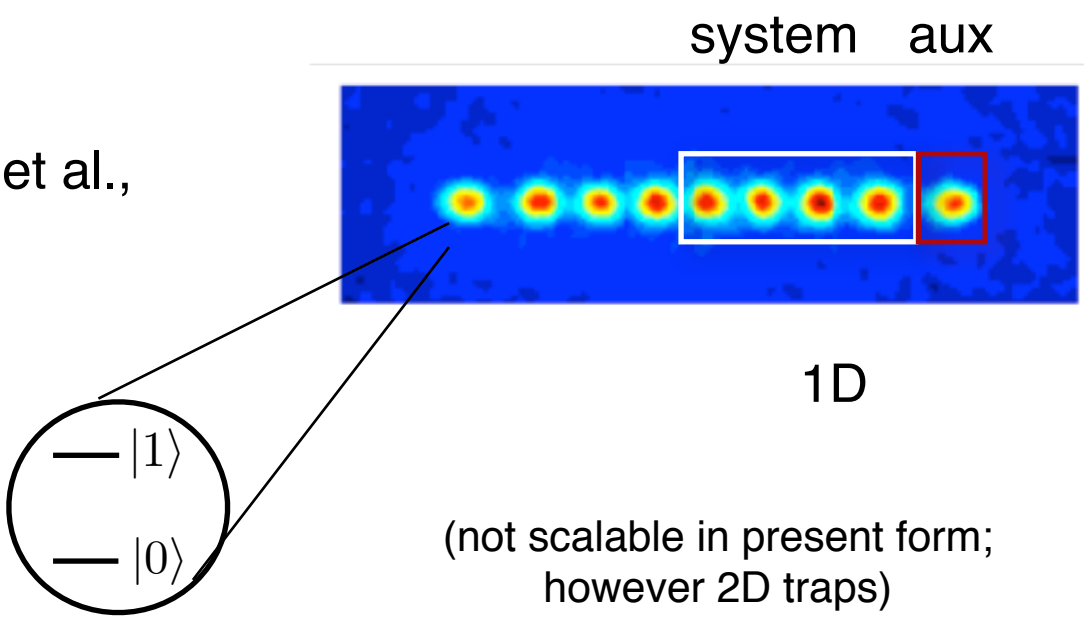


✓commuting operators
✓eigenvalues +1 and -1
✓common eigenvector with eigenvalues +1

GHZ state: $|0000\rangle + |1111\rangle$

engineer master equation / Kraus map
which achieves stabilizer pumping

J. Barreiro, M. Müller et al.,
preprint



1D

(not scalable in present form;
however 2D traps)

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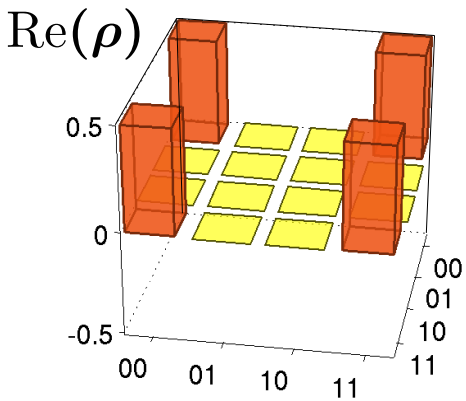
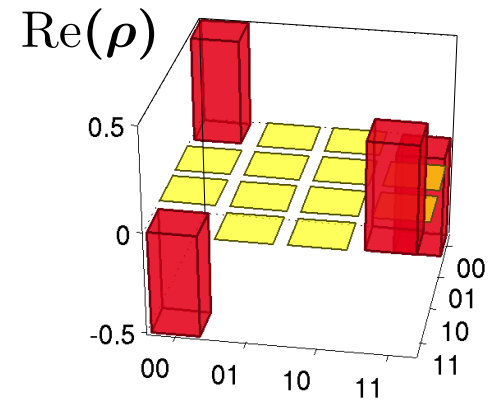
A simpler example: “Bell State” Cooling

- Bell states are a basis of the Hilbert space of 2 qubits

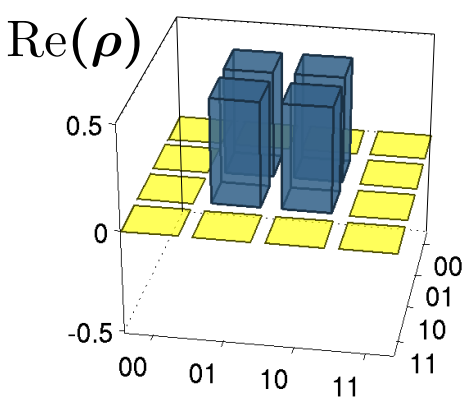
$$|\phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$



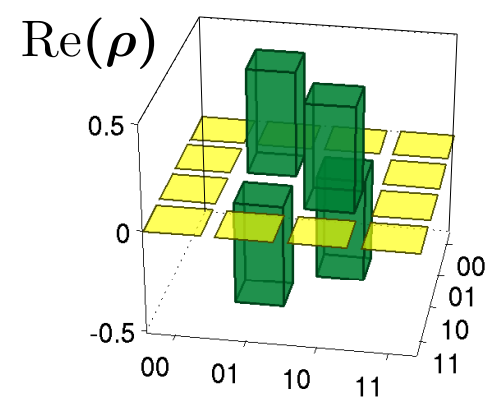
$$|\phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$



$$|\psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$



$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$



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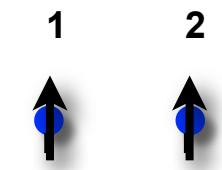
Cooling into Bell States

- Our goal: engineer two-body jump operators c_i for cooling into a Bell state



two spins / qubits

$$\mathcal{L}(\rho) = \gamma \sum_{i=1,2} \left(c_i \rho c_i^\dagger - \frac{1}{2} c_i^\dagger c_i \rho - \rho \frac{1}{2} c_i^\dagger c_i \right)$$

target state $|\Psi_+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

$$|\Psi_-\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$|\Phi_+\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$|\Phi_-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

two-body jump operator $c_1 = \frac{1}{2}\sigma_1^x(1 - \sigma_1^z\sigma_2^z)$

How does the jump operator act on the different Bell states?

$\|\Psi_+\rangle$	$\|\Phi_+\rangle$
$\|\Psi_-\rangle$	$\|\Phi_-\rangle$

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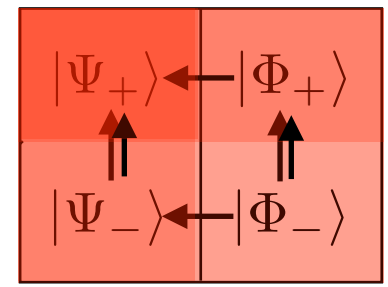
$$c_1 = \frac{1}{2}\sigma_1^x(1-\sigma_1^z\sigma_2^z)$$ applied to $|\Psi_+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$



$$c_1|\Psi_+\rangle \sim \quad (1-\sigma_1^z\sigma_2^z)(|00\rangle + |11\rangle)$$

$$= \quad (|00\rangle + |11\rangle - |00\rangle - |11\rangle)$$

$$\sigma_1^z\sigma_2^z|00\rangle = (+1)(+1)|00\rangle = |00\rangle$$
$$\sigma_1^z\sigma_2^z|11\rangle = (-1)(-1)|11\rangle = |11\rangle$$

$$= 0$$

- $|\Psi_+\rangle$ is a dark state of the jump operator, and therefore left invariant.

Similarly, one finds $c_1|\Psi_-\rangle = |\Psi_+\rangle$ with $|\Psi_-\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$

Second jump operator pumps into other half-sector $c_2 = \frac{1}{2}\sigma_1^z(1-\sigma_1^x\sigma_2^x)$

... both together pump the two spins into $|\Psi_+\rangle$

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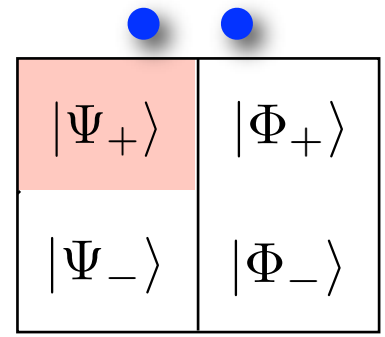
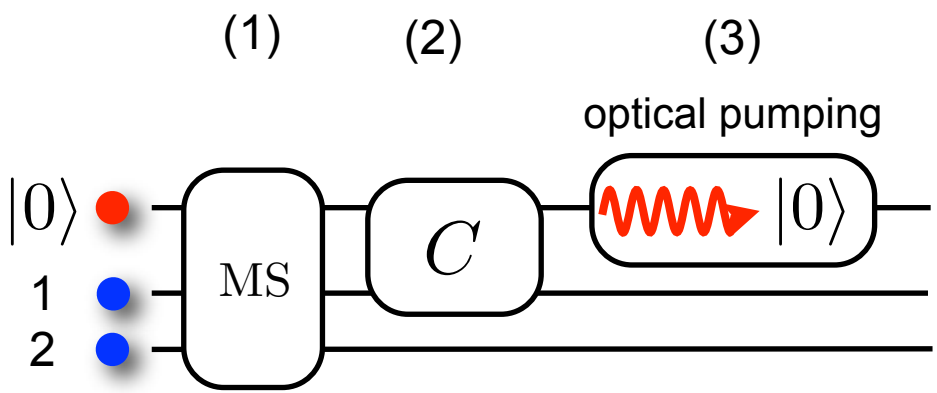
How to engineer jump operators?

Implementation:

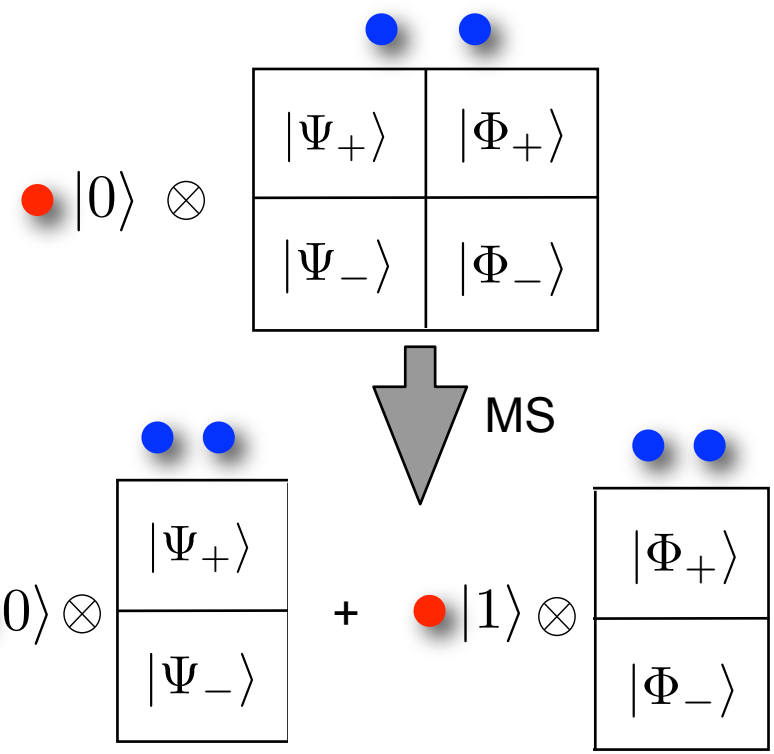
three ions: aux 1 2

ingredients:
- 3-ion MS gates
- single-ion rotations
- optical pumping of one ion

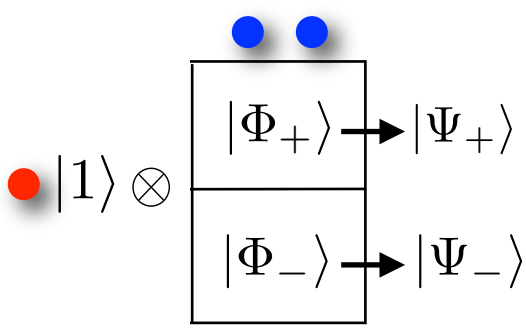




(1) MS gate: mapping on aux. ion



(2) two-qubit gate $C = |0\rangle\langle 0| \otimes 1 + |1\rangle\langle 1| \otimes \sigma_1^z$



(3) optical pumping of the aux. ion:

$$|0\rangle \rightarrow |0\rangle$$
$$|1\rangle \rightarrow |0\rangle$$

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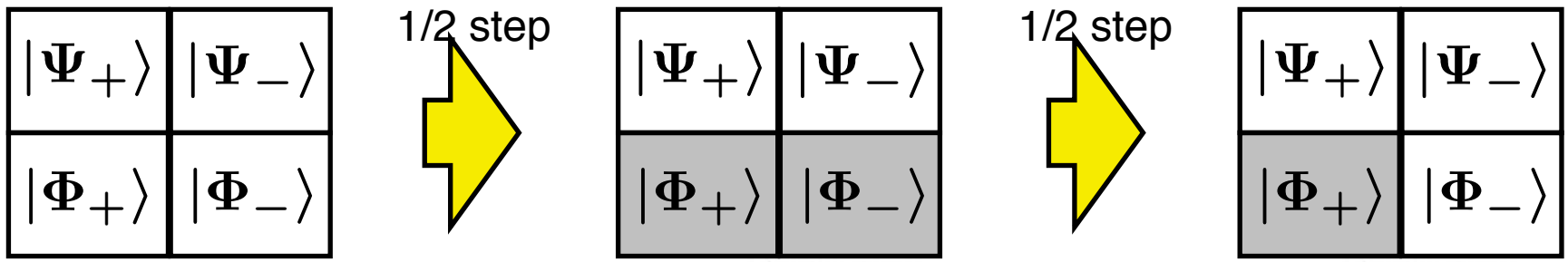
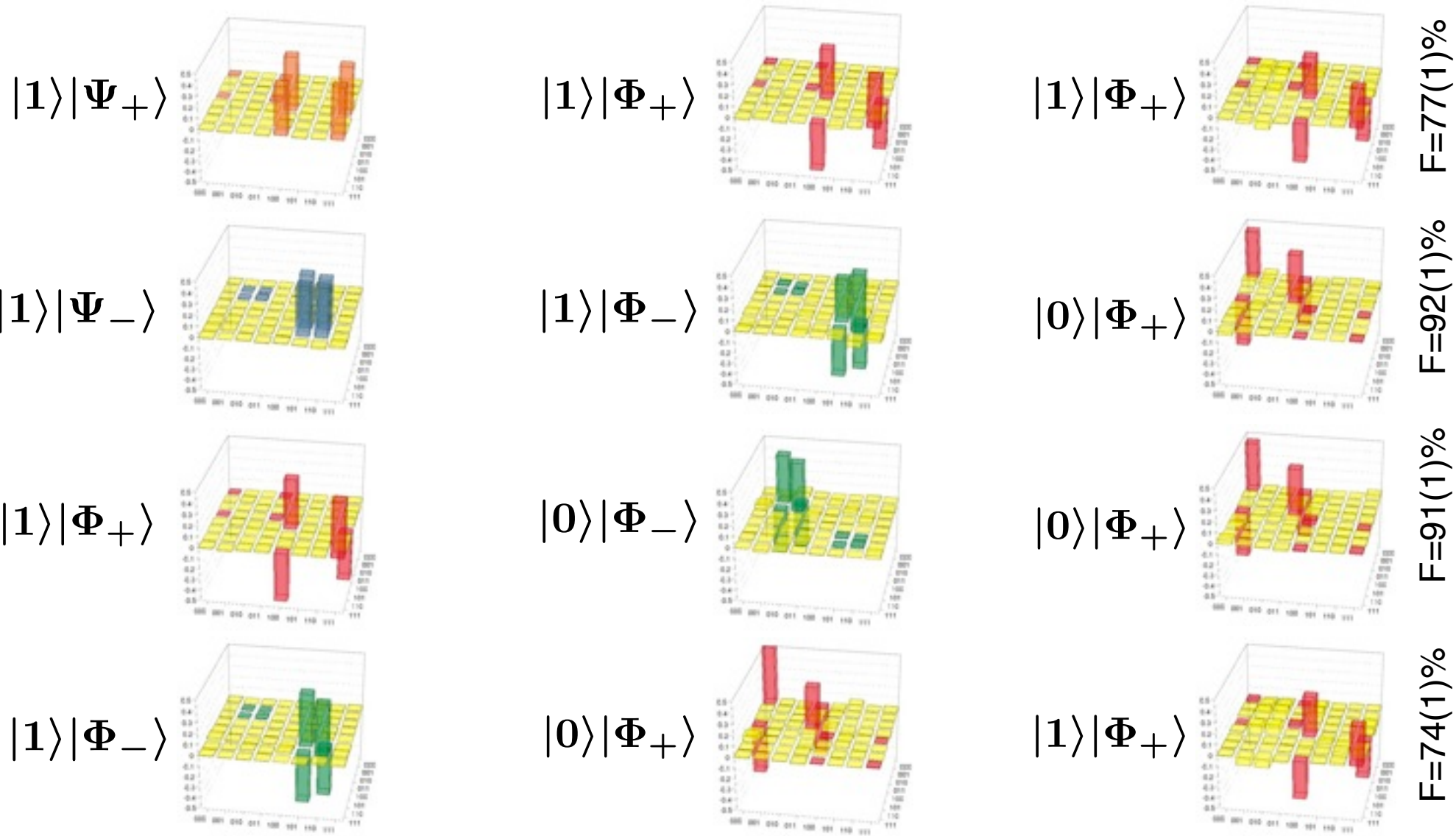
Deterministic cooling into Bell States





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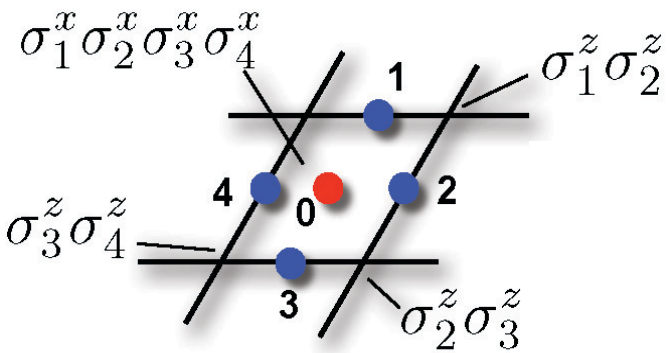
4+1 Stabilizer "Pumping"

- **stabilizer**

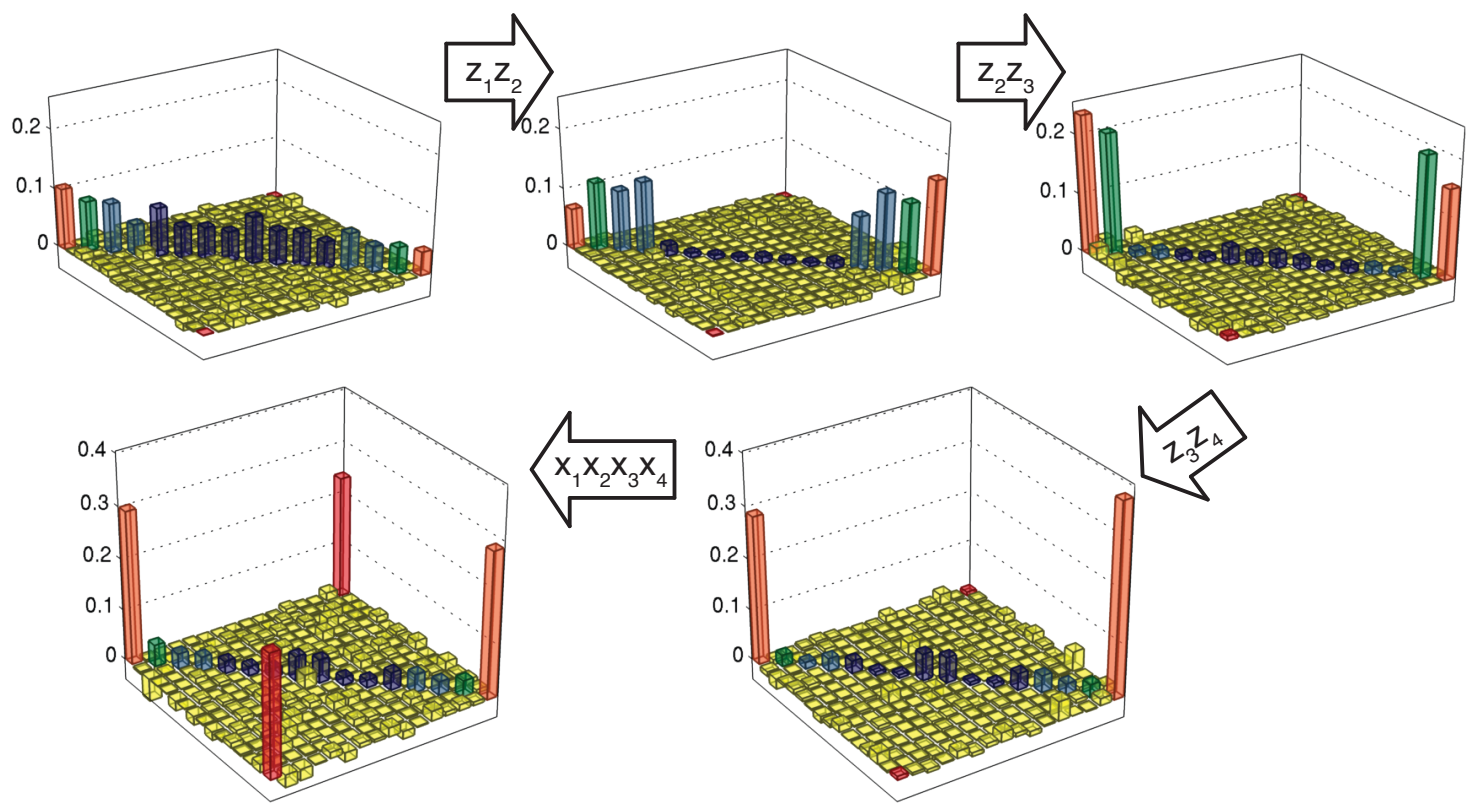


✓commuting operators
✓eigenvalues +1 and -1
✓common eigenvector with eigenvalues +1

GHZ state: $|0000\rangle + |1111\rangle$

- **Cooling**

mixed state



GHZ state

$|0000\rangle + |1111\rangle$

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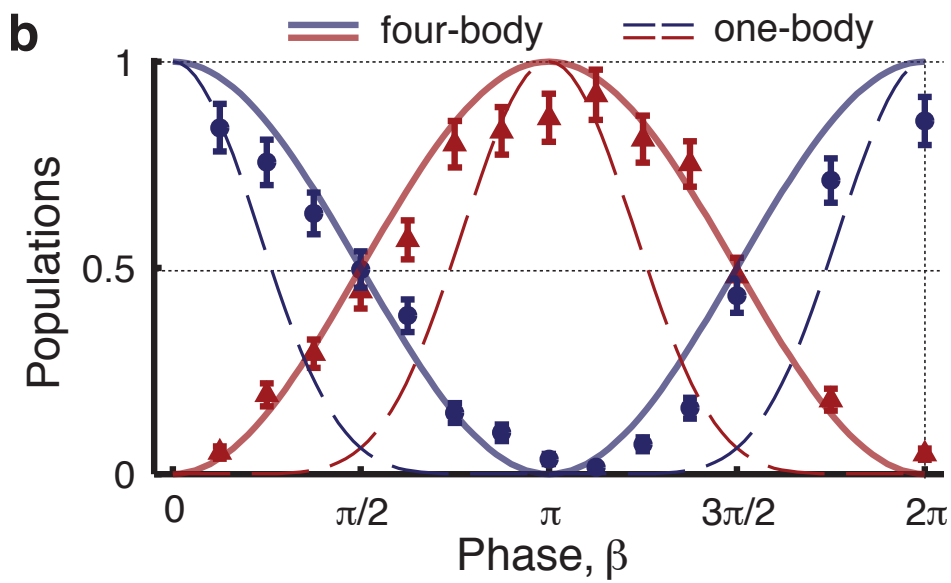
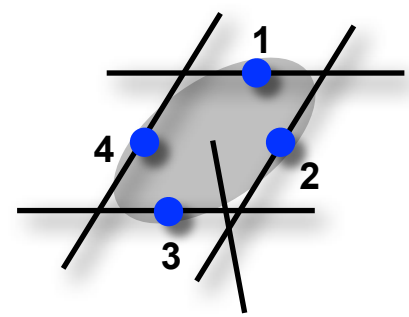
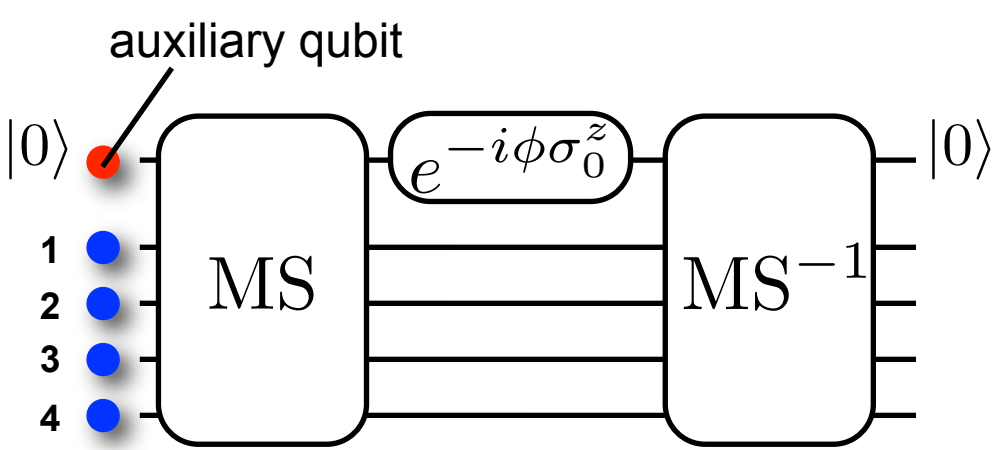
4-Spin Interactions





$$H = E\sigma_1^x\sigma_2^x\sigma_3^x\sigma_4^x$$



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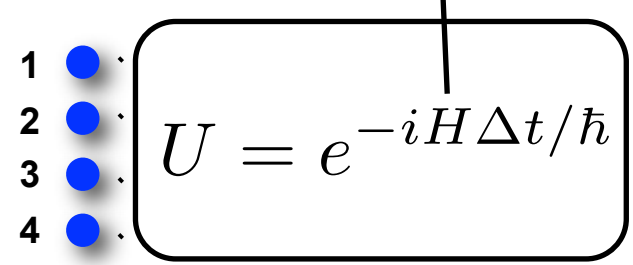

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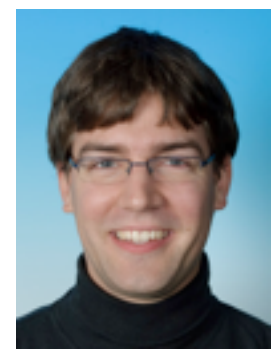
The Team

Innsbruck ion trap group

Markus Hennrich Daniel Nigg Julio Barreiro

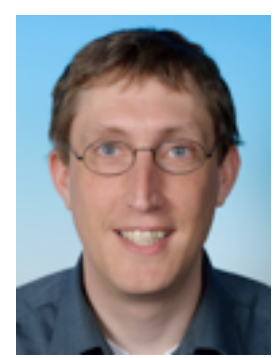
Thomas Monz Michael Chwalla



Cornelius Hempel, Ben Lanyon

Christian Roos, Rainer Blatt

Theory



M. Müller, K. Hammerer, PZ

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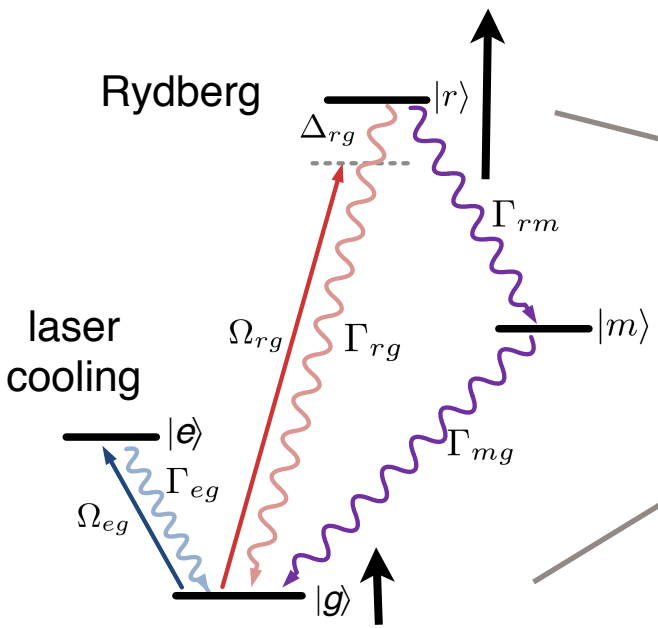
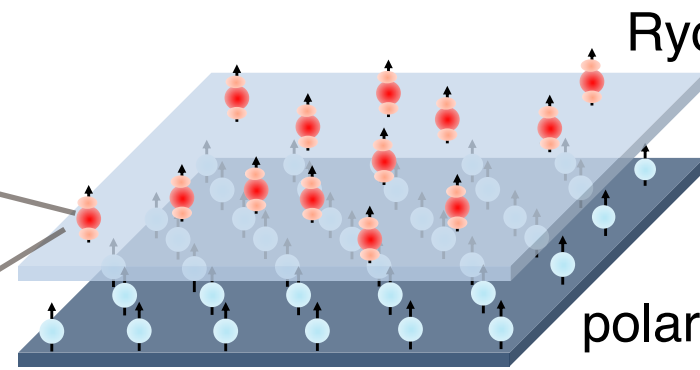
Bo Zhao, A Glätzle et al.

Example 5: Bilayer Cooling

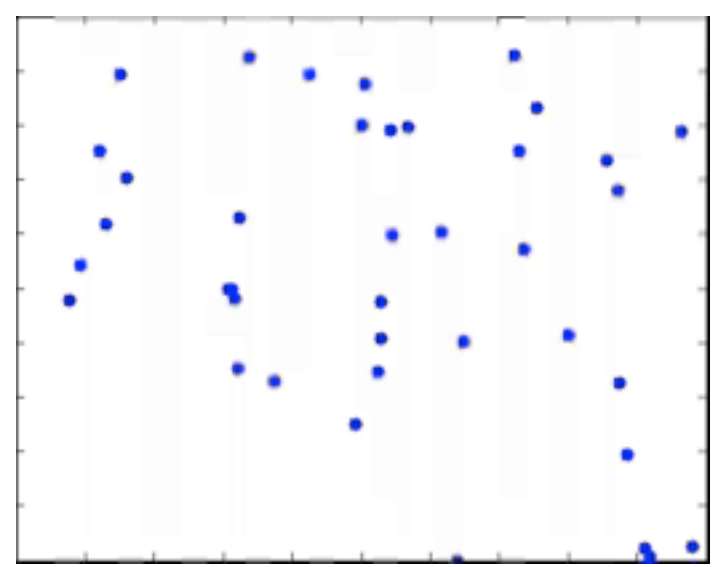
- Bilayer system: atom + molecules



atomic ground state dressed with dipole moment



movie by A. Glätzle



- atomic dynamics (classical)

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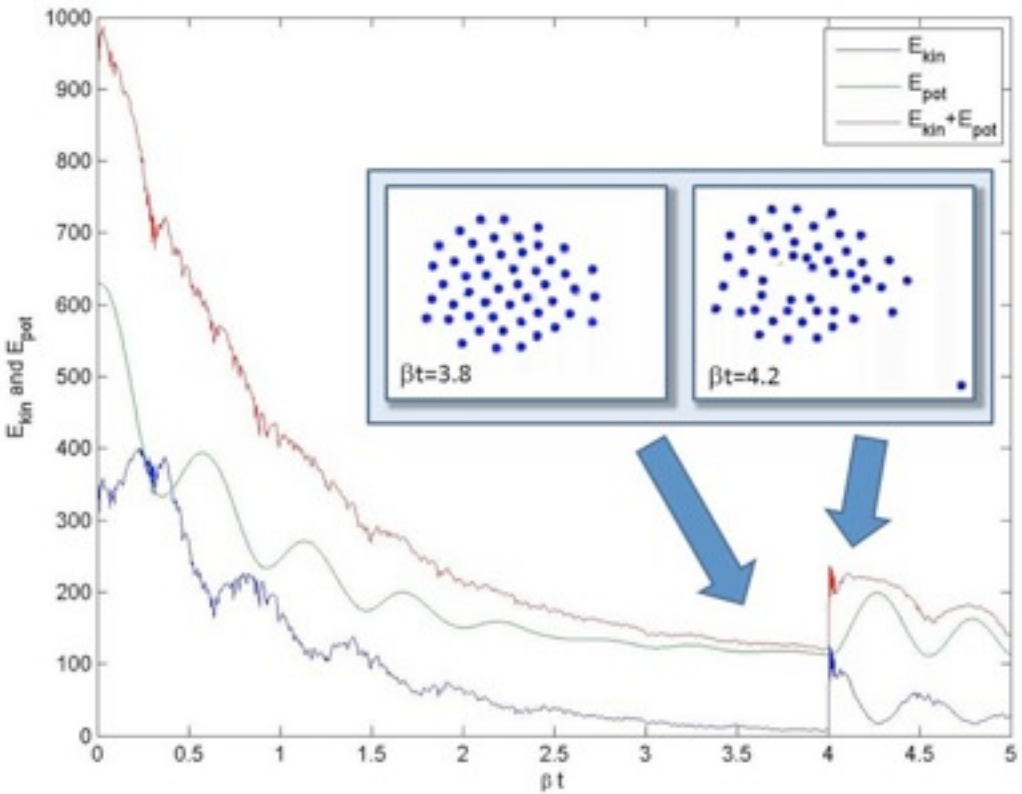
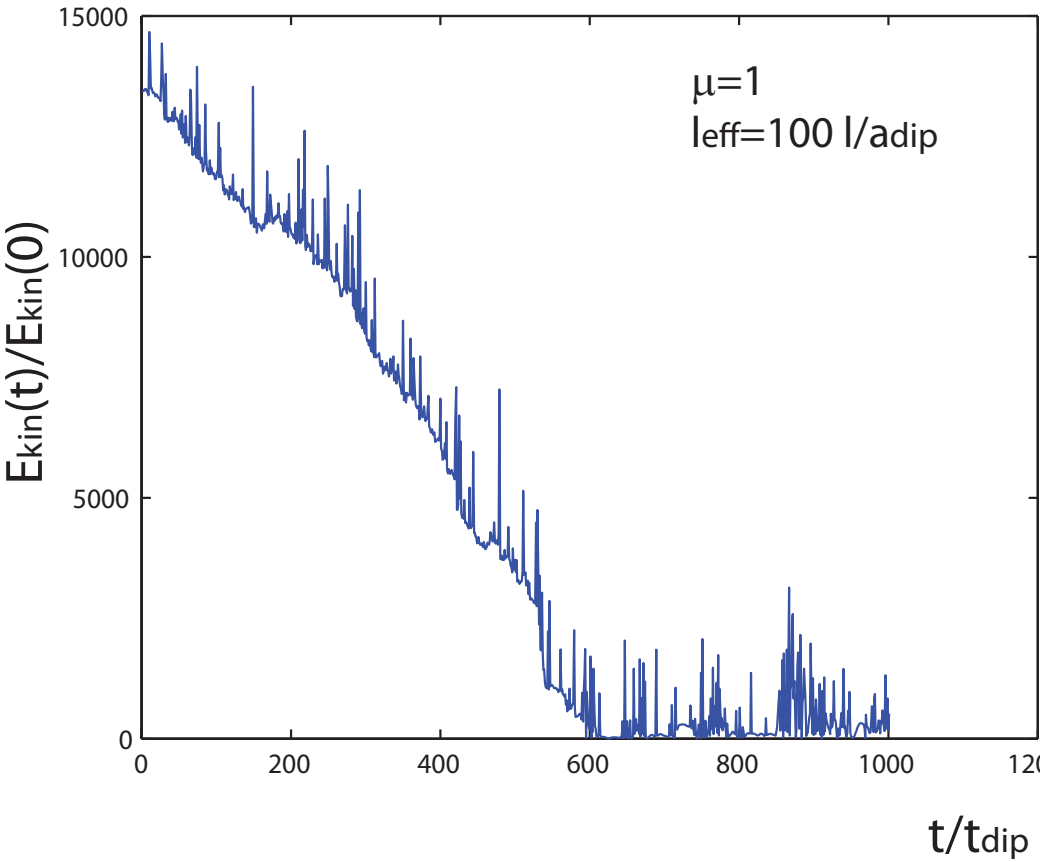
laser cooling of atoms



sympathetic cooling of molecules via long range dipole-dipole



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Summary: Dissipation & Cold Atoms

Many body systems ...

THE GOOD

- engineering dissipation → quantum information
- engineering dissipation → cond mat

THE BAD

- decoherence, heating in optical lattices

THE DIFFICULT

- solving (driven) open system / non-equilibrium

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