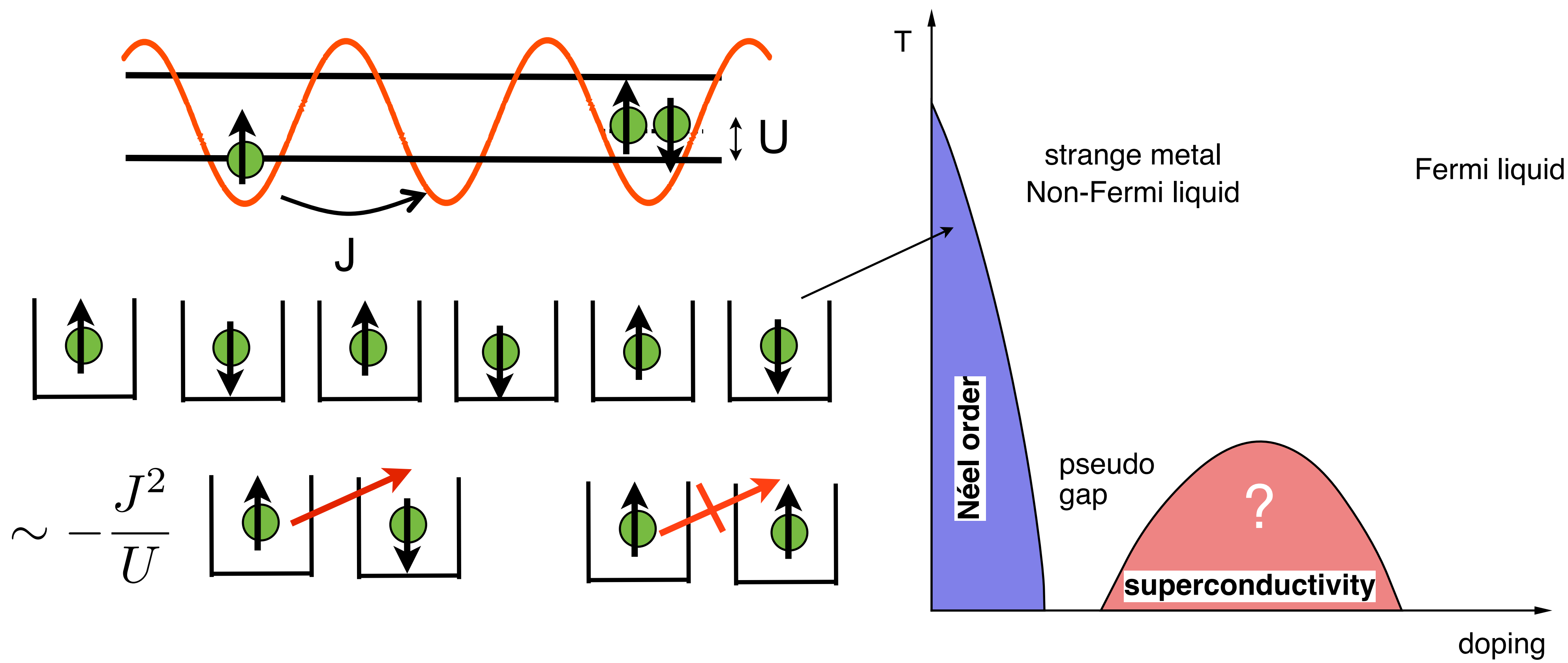
Engineered dissipation and state preparation with cold atoms

Andrew Daley

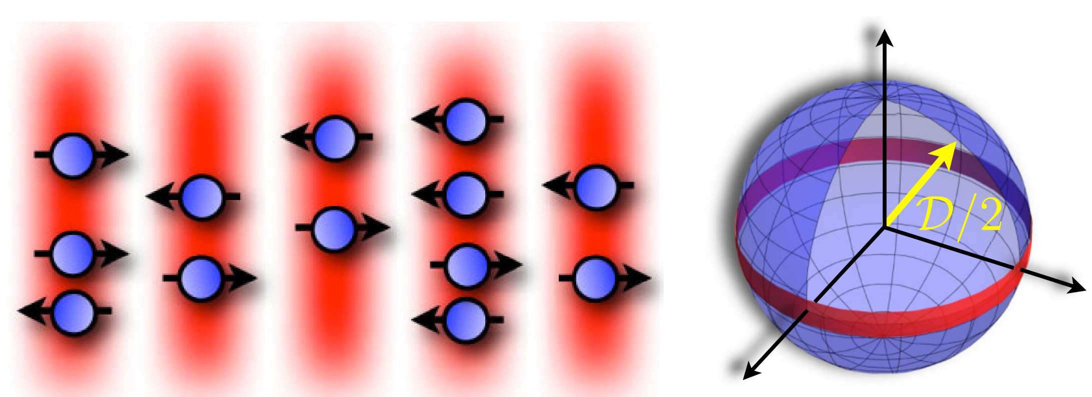
Department of Physics and SUPA
University of Strathclyde

Cooling and State preparation with atoms in optical lattices

- Sensitive many-body phases, e.g., quantum magnetism with two-component gases:



- Preparation of squeezed / entangled states for quantum metrology:

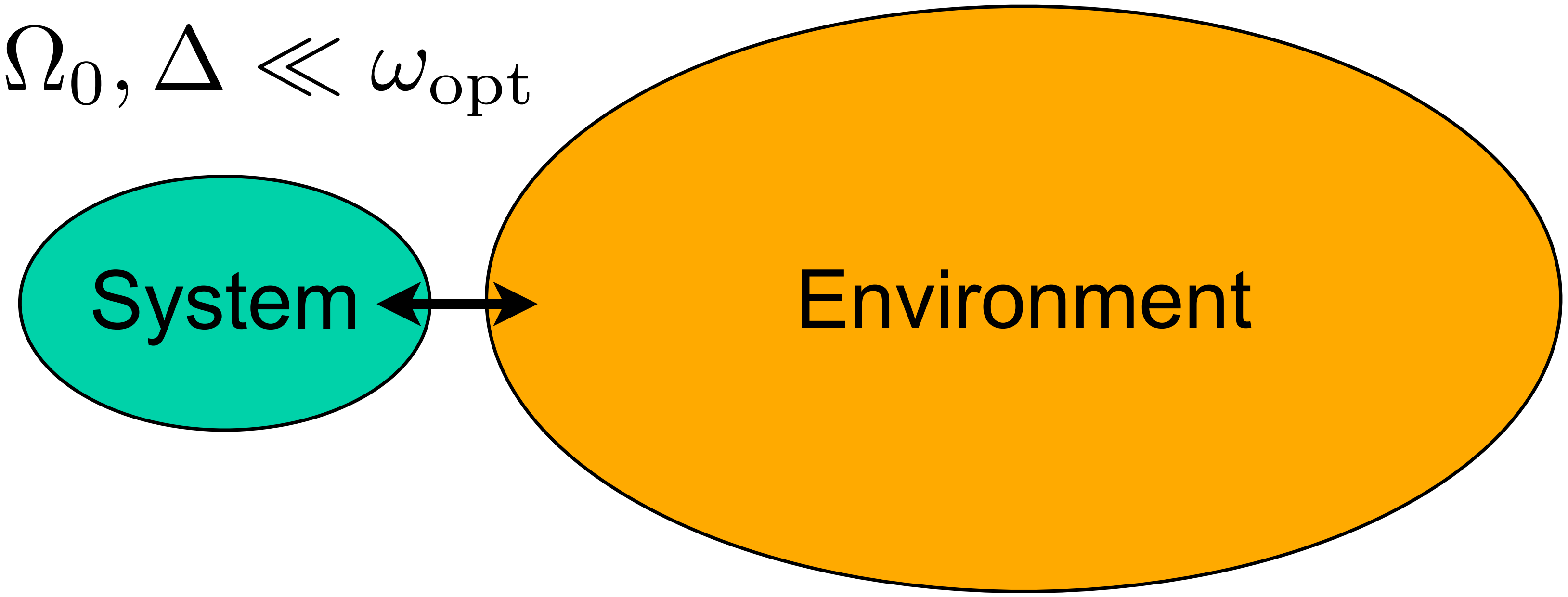


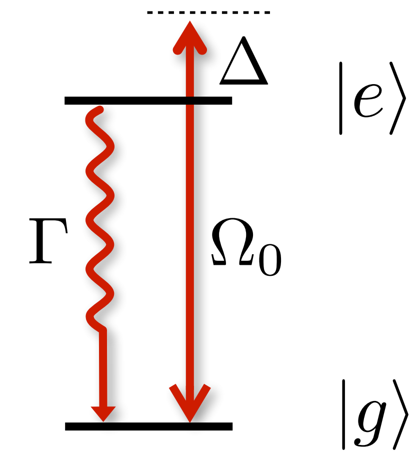
Key challenges:

- Cooling to low temperatures
- Characterisation and control of decoherence / noise / heating

Dissipative dynamics / open many-body quantum systems:

$\Gamma, \Omega_0, \Delta \ll \omega_{\mathrm{opt}}$





Analogies to quantum optics in many-body systems:

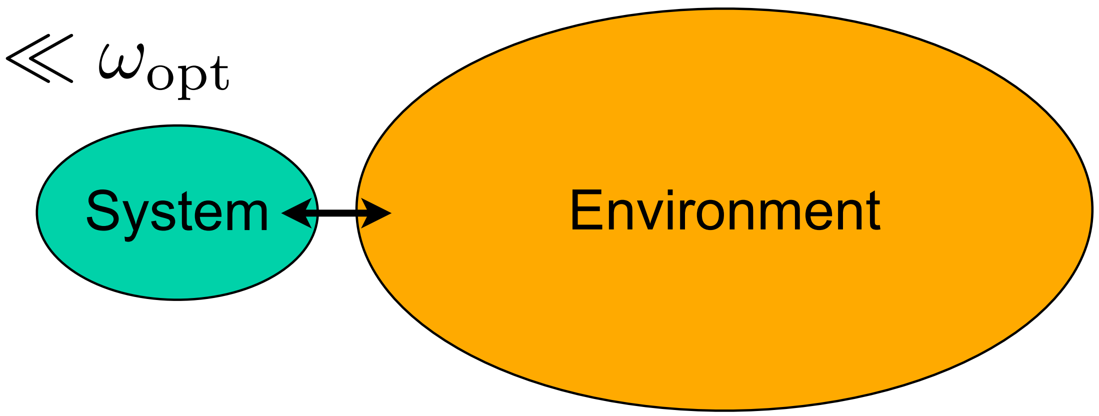
- Quantum Optics description - microscopic models, well-controlled approximations (master equation, quantum stochastic Schrödinger equations)

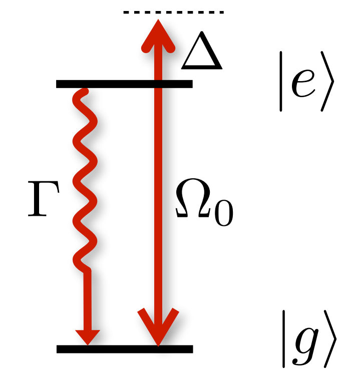
- Quantum Optics tools (laser cooling, optical pumping / dissipative preparation)

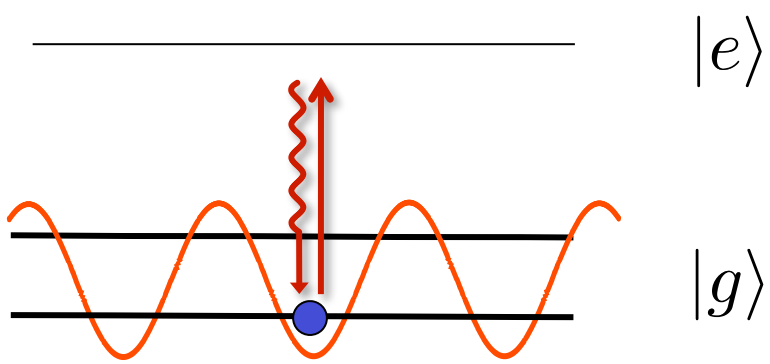
REVIEWS: A. J. Daley, Advances in Physics **63**, 77 (2014)
M. Müller, S. Diehl, G. Pupillo, and P. Zoller, Adv. At. Mol. Opt. Phys **61**, 1 (2012)

Dissipative dynamics / open many-body quantum systems:

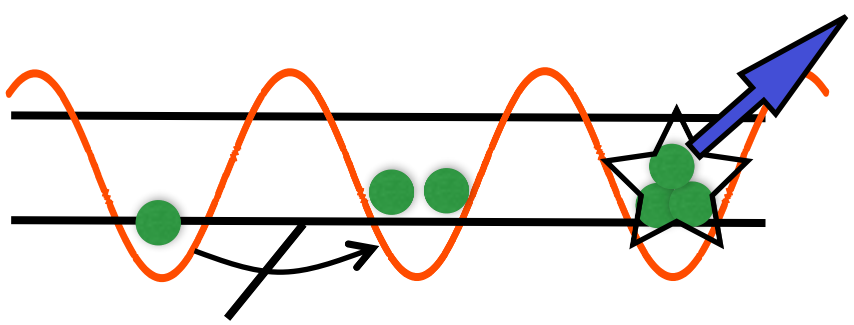
$\Gamma, \Omega_0, \Delta \ll \omega_{\rm opt}$

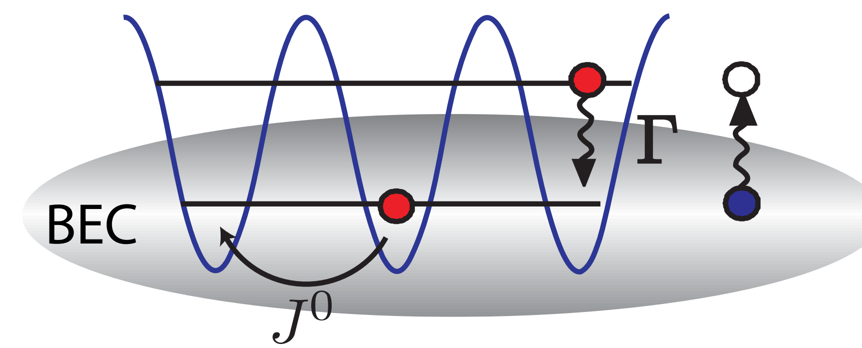






H. Pichler, A. J. Daley, and P. Zoller, PRA **82**, 063605 (2010)
S. Sarkar, S. Langer, J. Schachenmayer, and A. J. Daley, PRA. 90, 023618 (2014)
J. Schachenmayer, L. Pollet, M. Troyer, and A. J. Daley, PRA 89, 011601(R) (2014)





Two-body loss experiments: Rempe group (2008); Jin/Ye (2013)

De Marco group (2014); Oberthaler group (2013)

Three-body loss:
A. J. Daley et al., PRL **102**, 040402 (2009)
A. Kantian et al., A. J. Daley, PRL **103**, 240401 (2009)

Single atom or Dark state cooling:
A. J. Daley et al., PRA **69**, 022306 (2004)
A. Griessner et al., PRL **97**, 220403 (2006)

REVIEWS: A. J. Daley, Advances in Physics **63**, 77 (2014)
M. Müller, S. Diehl, G. Pupillo, and P. Zoller, Adv. At. Mol. Opt. Phys **61**, 1 (2012)

Dissipative driving in quantum optics

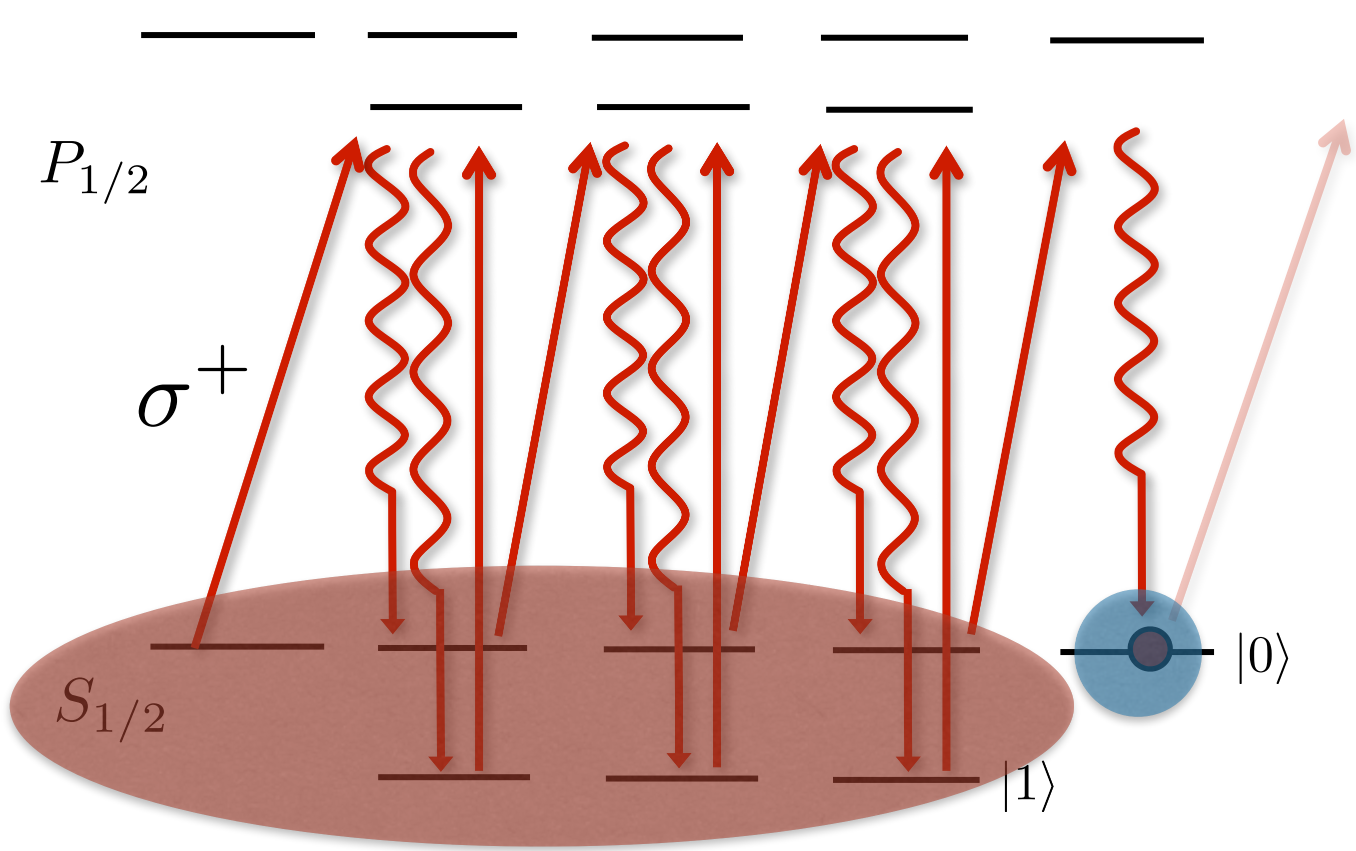
$$\frac{d}{dt}\rho = -\frac{i}{\hbar}[H,\rho] + \mathcal{L}\rho \qquad\qquad \rho \to \rho_{ss} = |\psi_{ss}\rangle\langle\psi_{ss}|$$

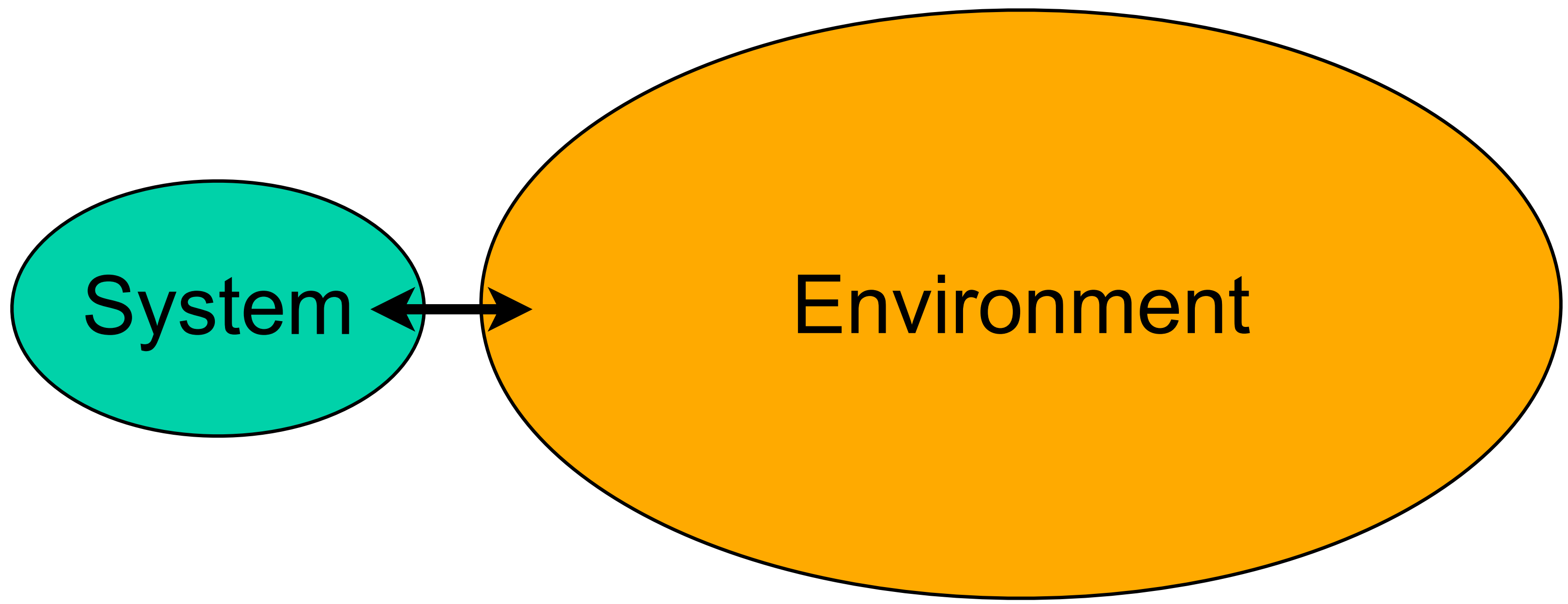
$$\dot{\rho} = -i[H,\rho] - \frac{1}{2}\sum_m \left[c_m^\dagger c_m \rho + \rho c_m^\dagger c_m - 2 c_m \rho c_m^\dagger\right]$$

- A pure steady state should be a unique eigenstate of H and an eigenstate of all c operators with zero eigenvalue

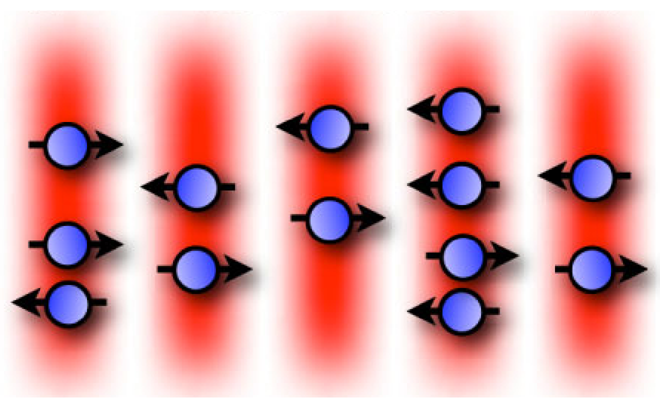
$$H|\psi_{ss}\rangle = \alpha_{ss}|\psi_{ss}\rangle \qquad\qquad \forall c_m, \quad c_m|\psi_{ss}\rangle = 0$$

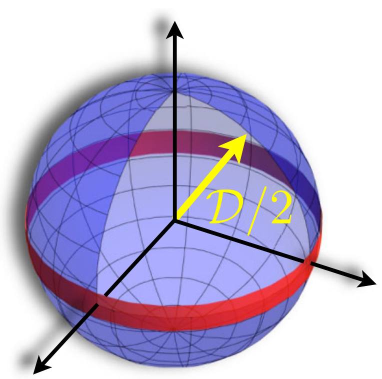
- e.g., optical pumping

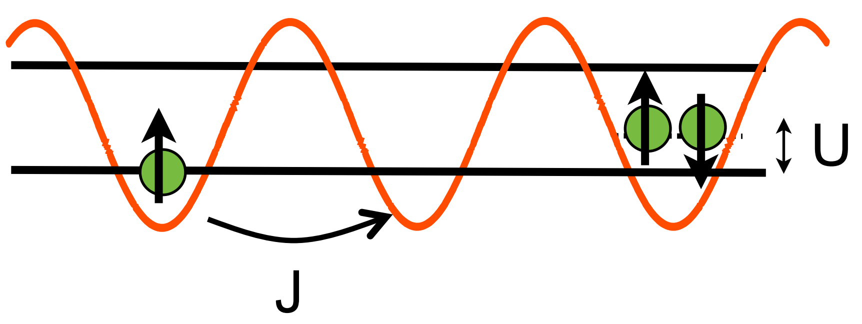




Fermi statistics + dissipative driving

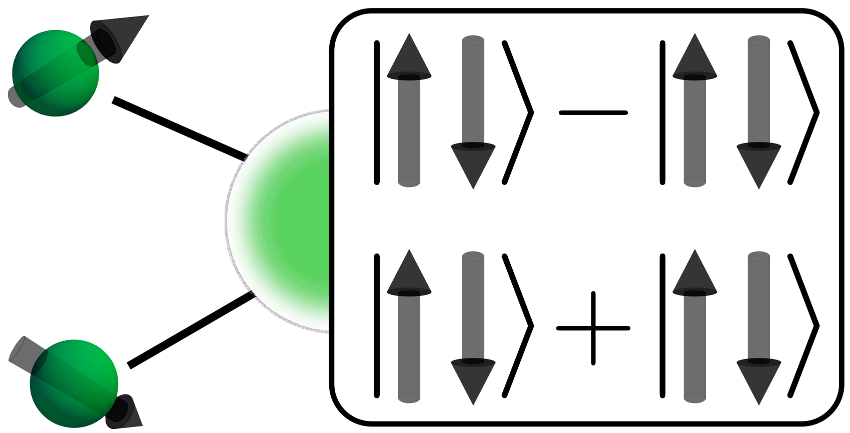


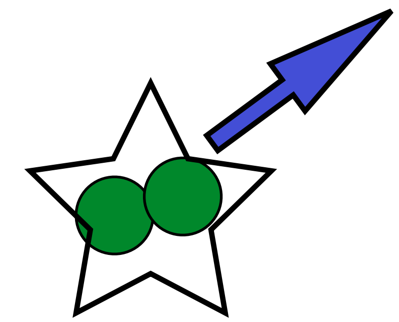




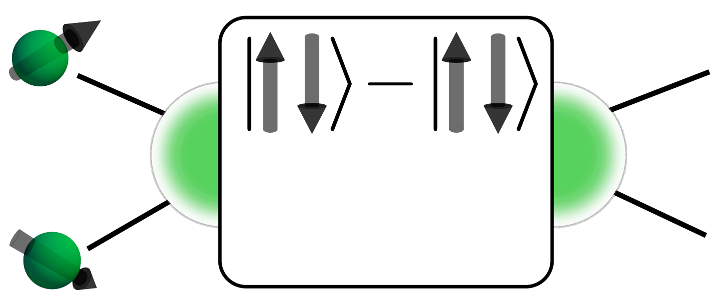
Two-body loss and preparation of symmetric spin states

- Consider s-wave collisional losses between trapped fermions

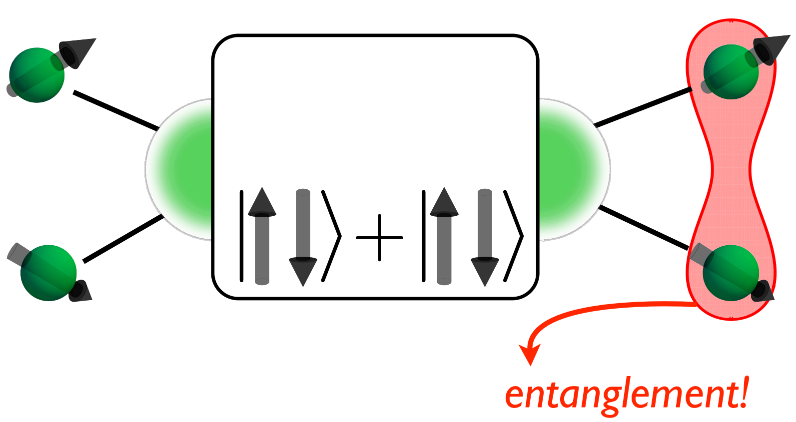




- Symmetry:



Symmetric spatial wavefunction, s-wave scattering
COLLISIONAL LOSS

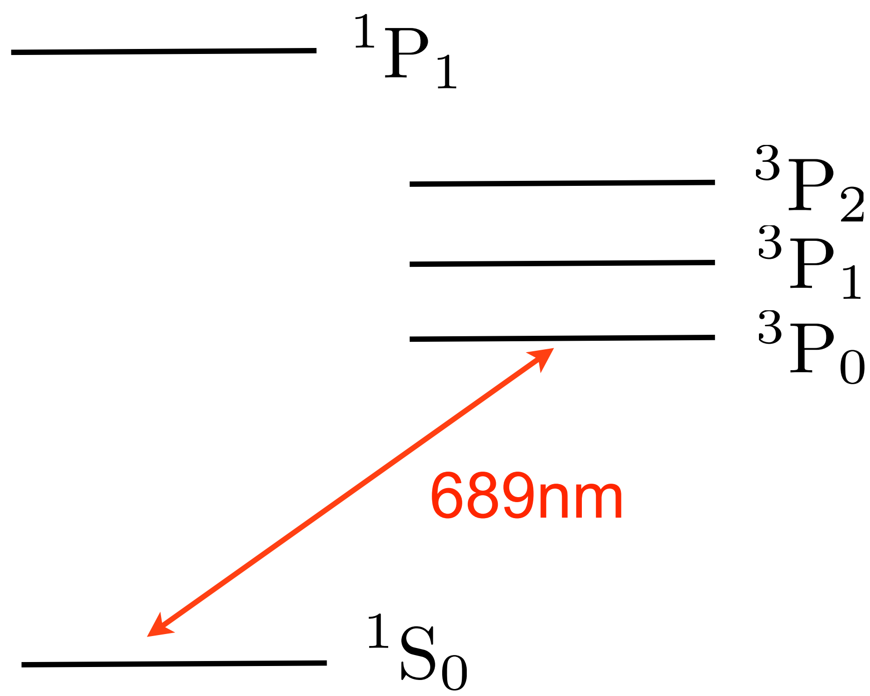


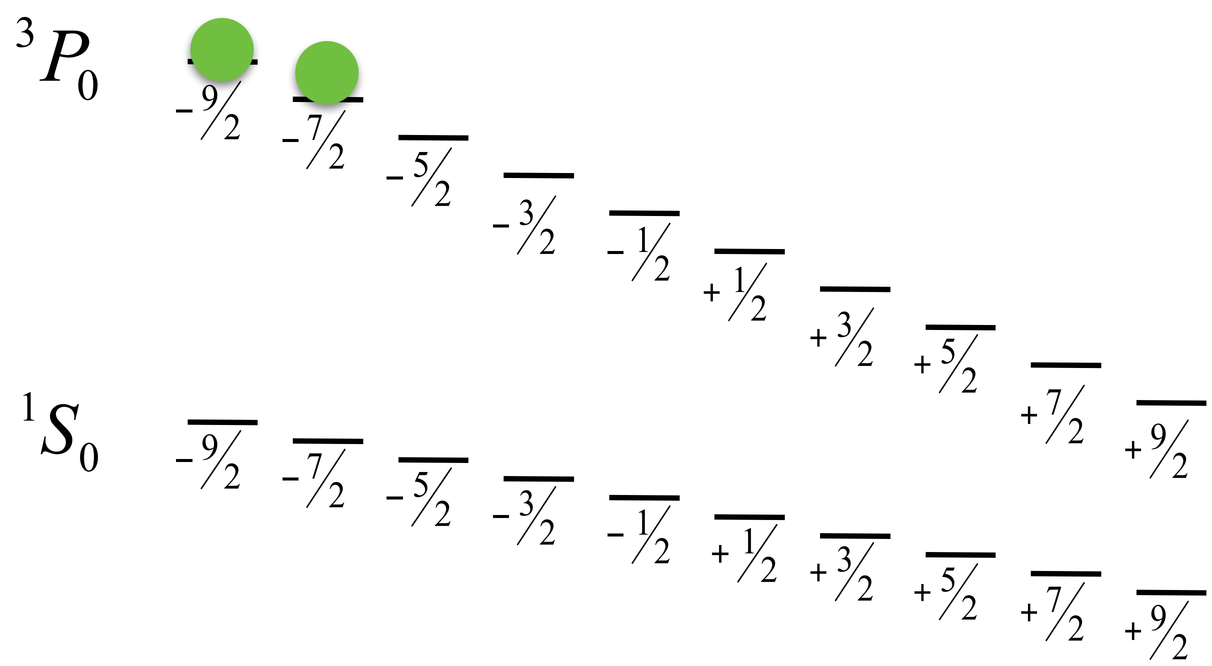
Antisymmetric spatial wavefunction, no s-wave scattering
NO COLLISIONAL LOSS AT LOW ENERGIES

M. Foss-Feig, A. J. Daley, J. K. Thompson, and A. M. Rey, PRL **109**, 230501 (2012)

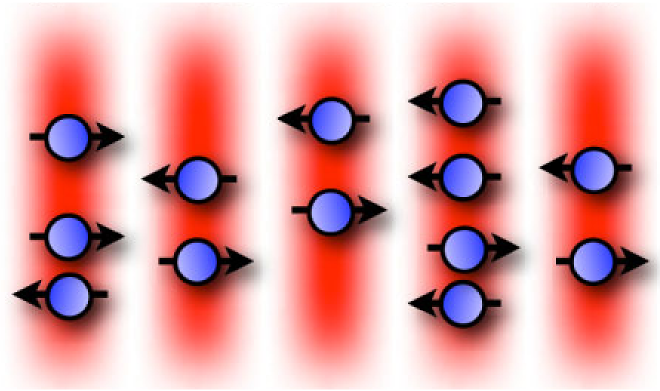
Implementation

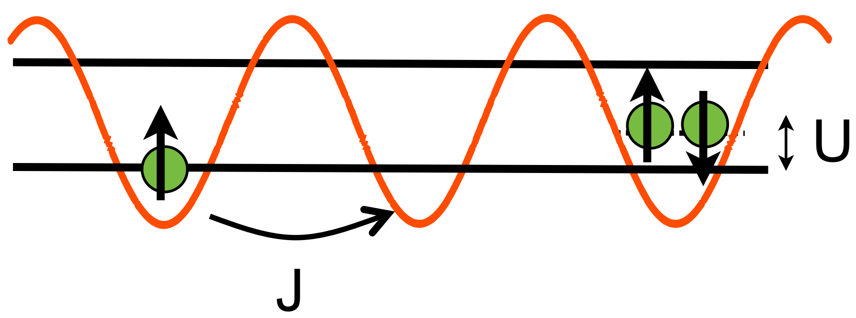
- Two spin states with s-wave collisional loss, magnetic field insensitive states, e.g., ^{87}Sr





- Trap requirement: No rotation between singlet and triplet states
  (e.g., Harmonic trap / 1D lattice OR Fermi-Hubbard lattice in 1D)

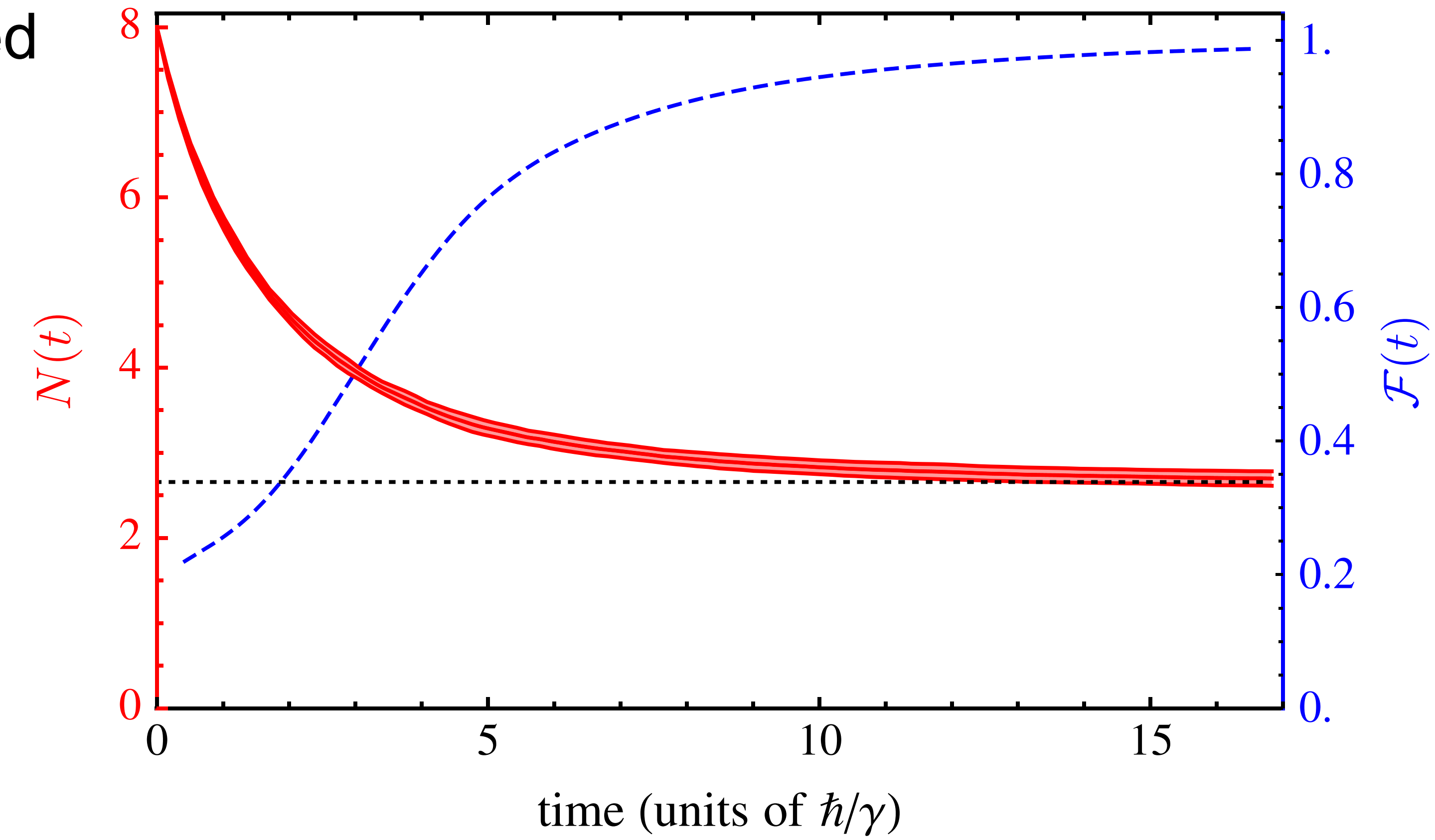




$$\dot{\rho} = i[\rho, \mathcal{H}] - \frac{\kappa}{2} \int d^3\boldsymbol{r} (\mathcal{J}^\dagger \mathcal{J} \rho + \rho \mathcal{J}^\dagger \mathcal{J} - 2\mathcal{J} \rho \mathcal{J}^\dagger) \qquad \mathcal{J}(\boldsymbol{r}) = \psi_\uparrow(\boldsymbol{r}) \psi_\downarrow(\boldsymbol{r})$$

- After preparation in a generic uncorrelated state, we are left with $O(\sqrt{N})$ atoms in steady state

$$N(t) \equiv \mathrm{Tr}[\rho \hat{N}] \geq \sum_S 2S\mathcal{P}_S = \frac{\pi^{1/2}\Gamma[\frac{\mathcal{N}}{2}+1]}{\Gamma[\frac{\mathcal{N}}{2}+\frac{1}{2}]} - 1$$



- Antisymmetric spatial wavefunction means symmetric spin wavefunction:

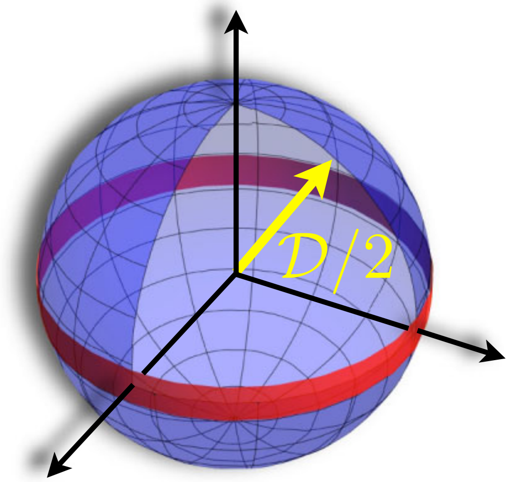
$$\Psi = \sum_{\vec{\sigma}} \mathcal{A}_{\vec{\sigma}} \, \Phi_{\vec{\sigma}}(r_1, \ldots, r_{\mathcal{N}}) |\vec{\sigma}\rangle$$

$$|\vec{\sigma}\rangle = |\sigma_1\rangle \otimes |\sigma_2\rangle \otimes \cdots \otimes |\sigma_{\mathcal{N}}\rangle$$

M. Foss-Feig, A. J. Daley, J. K. Thompson, and A. M. Rey, PRL **109**, 230501 (2012)

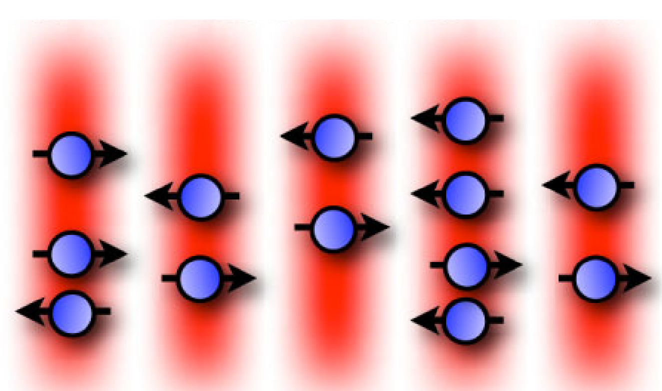
Spectroscopy with N atoms per tube

- For N trapped atoms, we prepare a completely symmetric spin state $|J, J_z\rangle$
- From the initial state, we choose $J_z \approx 0$
- Entangled state with Heisenberg-limited scaling of precision



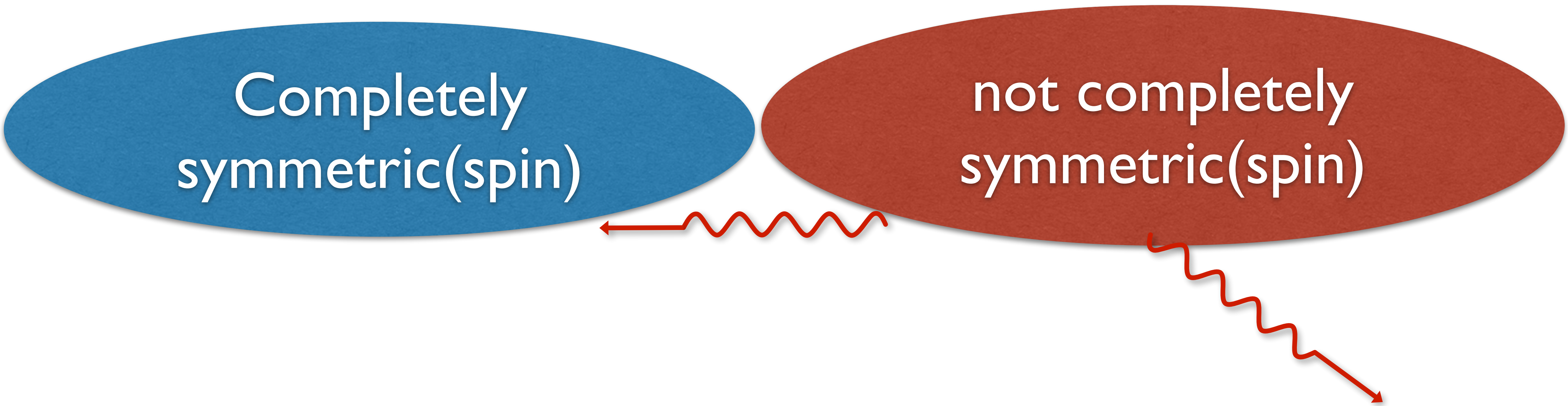
$$\Delta\phi \propto \frac{1}{N_f} = \frac{1}{\sqrt{N_i}}$$

- So, we lose a factor of $\sqrt{N}$ atoms, but the measurement precision is unchanged
- Wavefunction in space is completely antisymmetric, reduction in collisional energy shifts

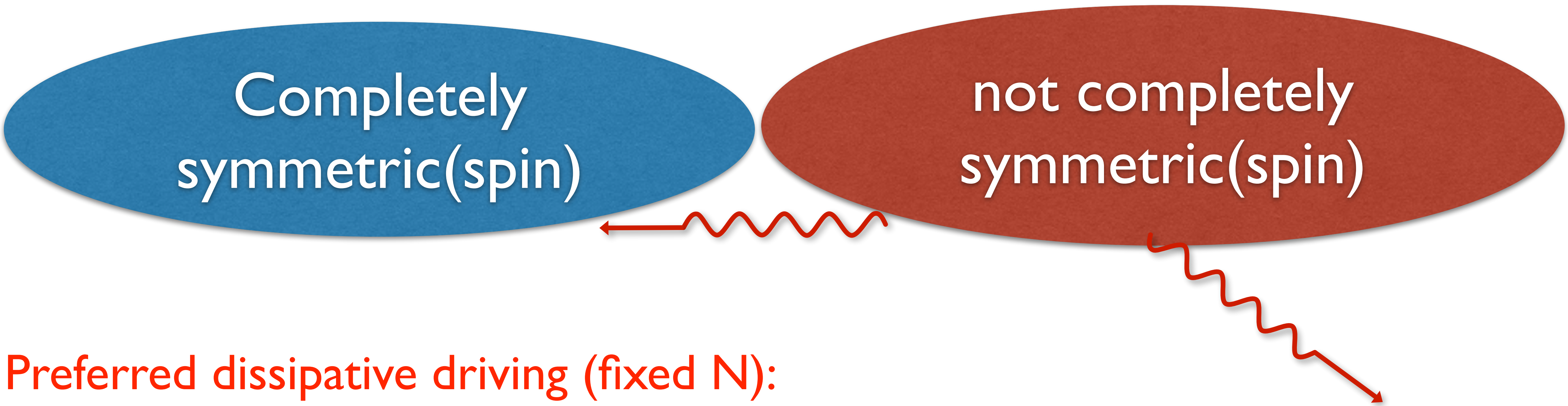


M. Foss-Feig, A. J. Daley, J. K. Thompson, and A. M. Rey, PRL **109**, 230501 (2012)

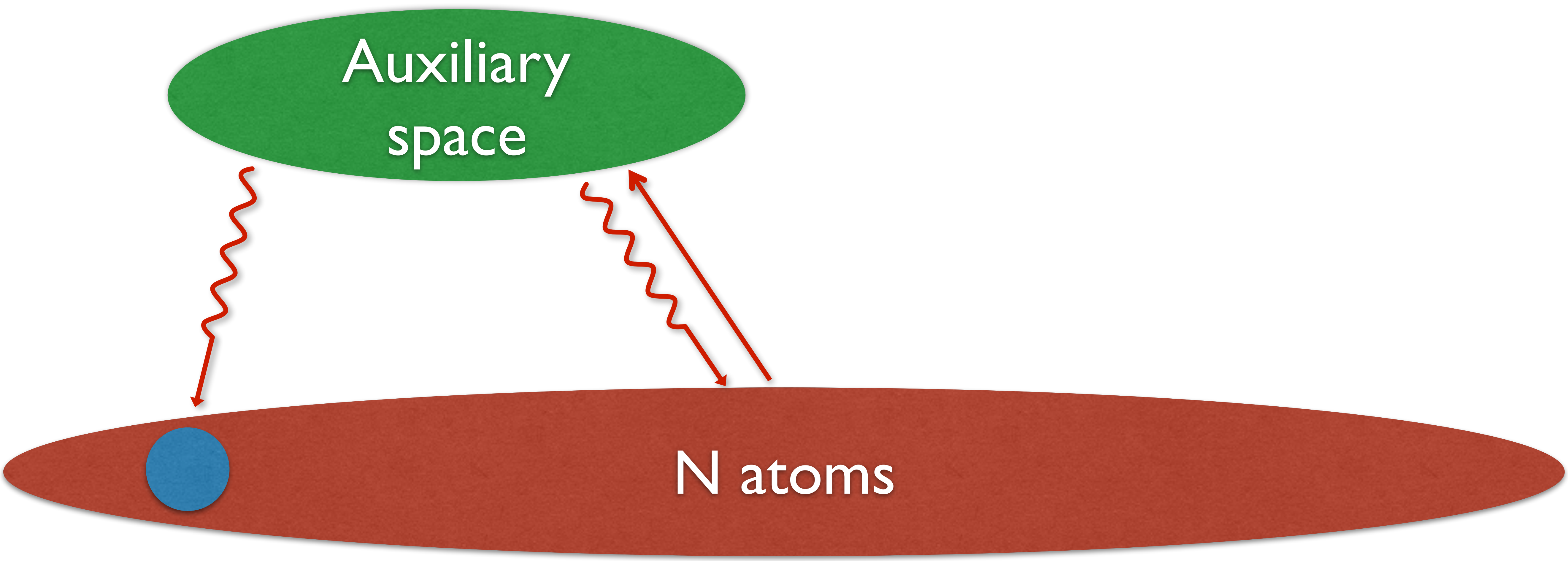
Schematic of dissipative driving in Hilbert space (all atom numbers N)



Schematic of dissipative driving in Hilbert space (all atom numbers N)

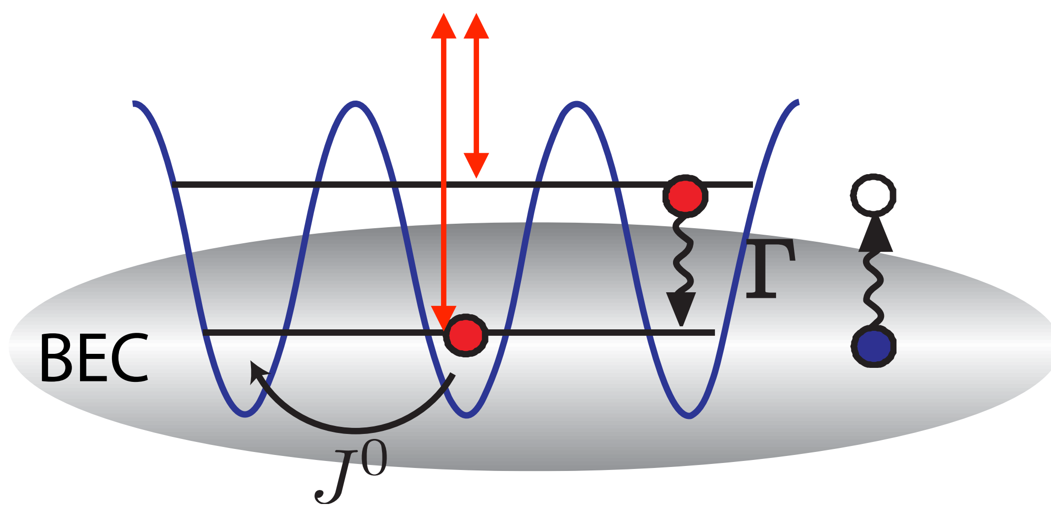


Preferred dissipative driving (fixed N):



Can we "recycle" the atoms, i.e., find a similar scheme without loss?

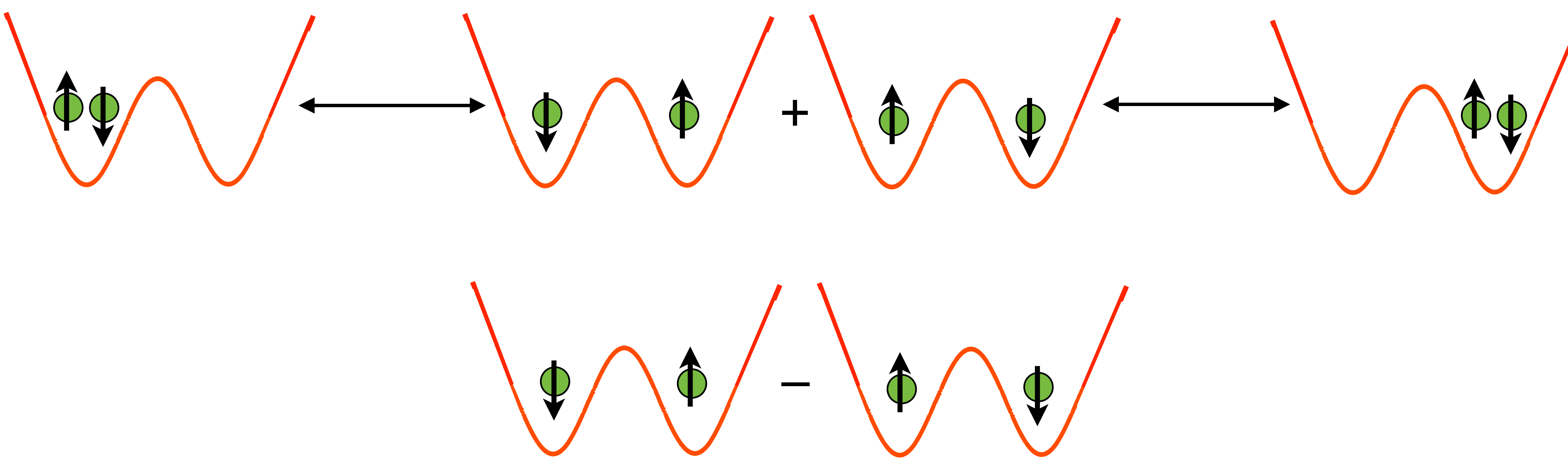
- Driven dissipative systems with a reservoir gas



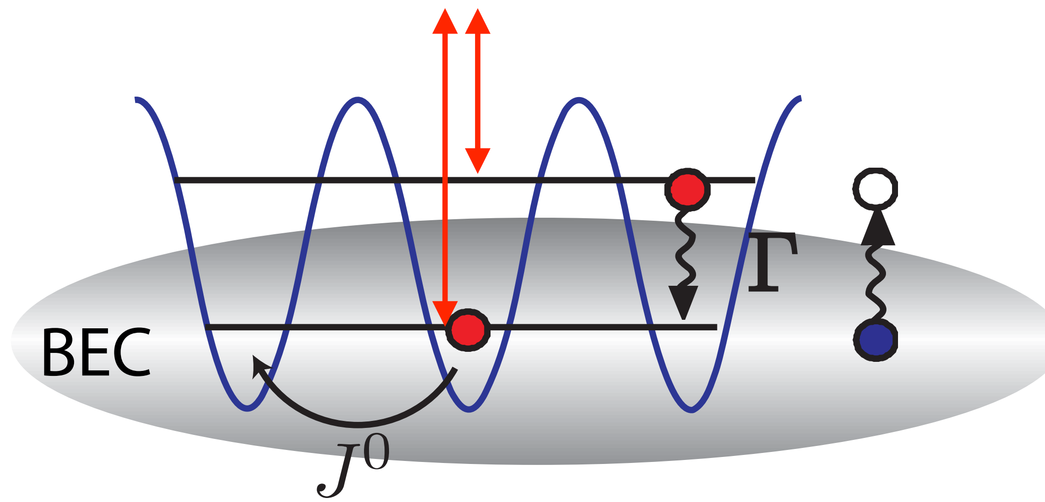
Raman driving between bands

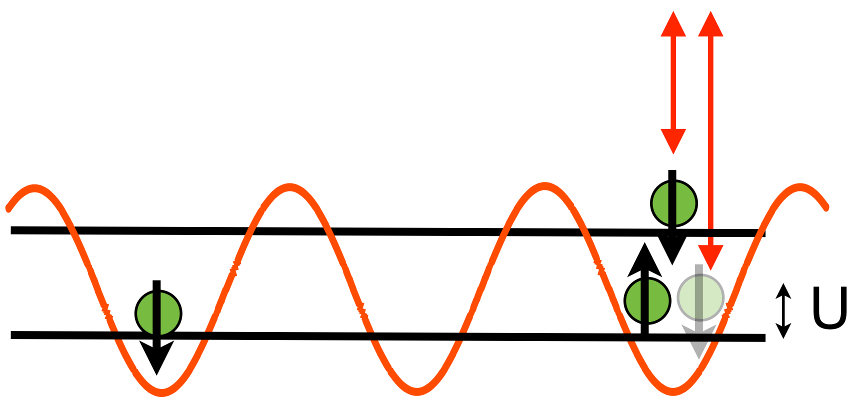
Bogoliubov excitations / phonons

- Fermi-Hubbard system: Symmetric spatial modes always rotate to doubly-occupied sites
  e.g., double-well:

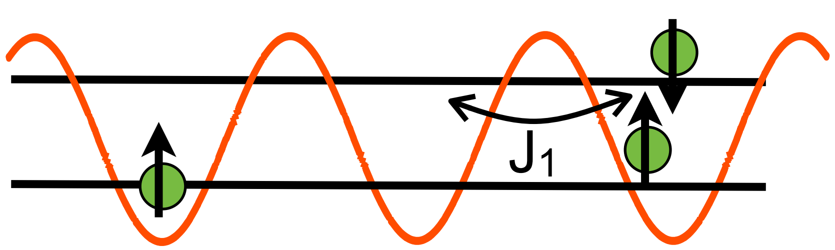


Protocol:

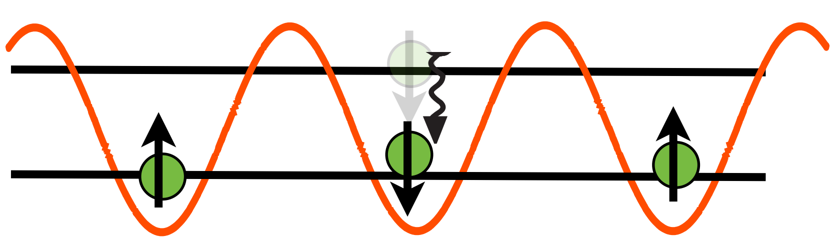




Deeper lattice, spin+energy-selective Raman transfer



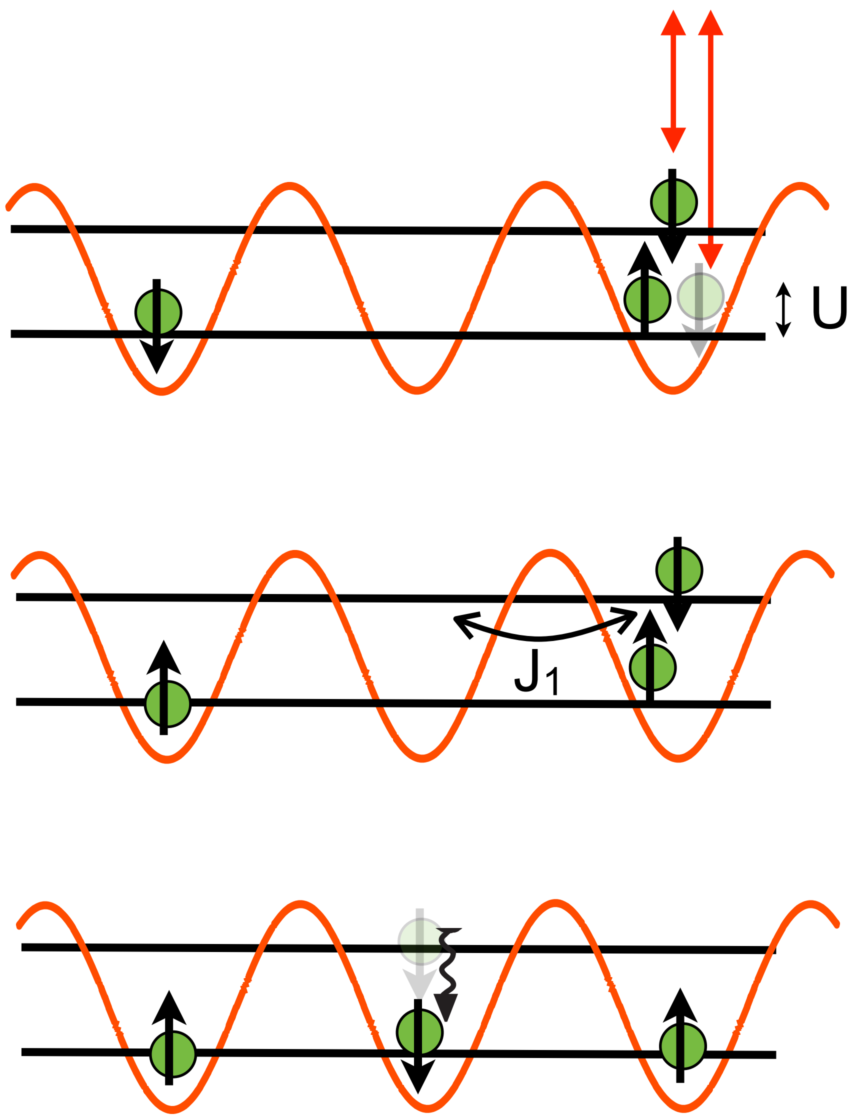
Free evolution - shallower lattice / smaller U

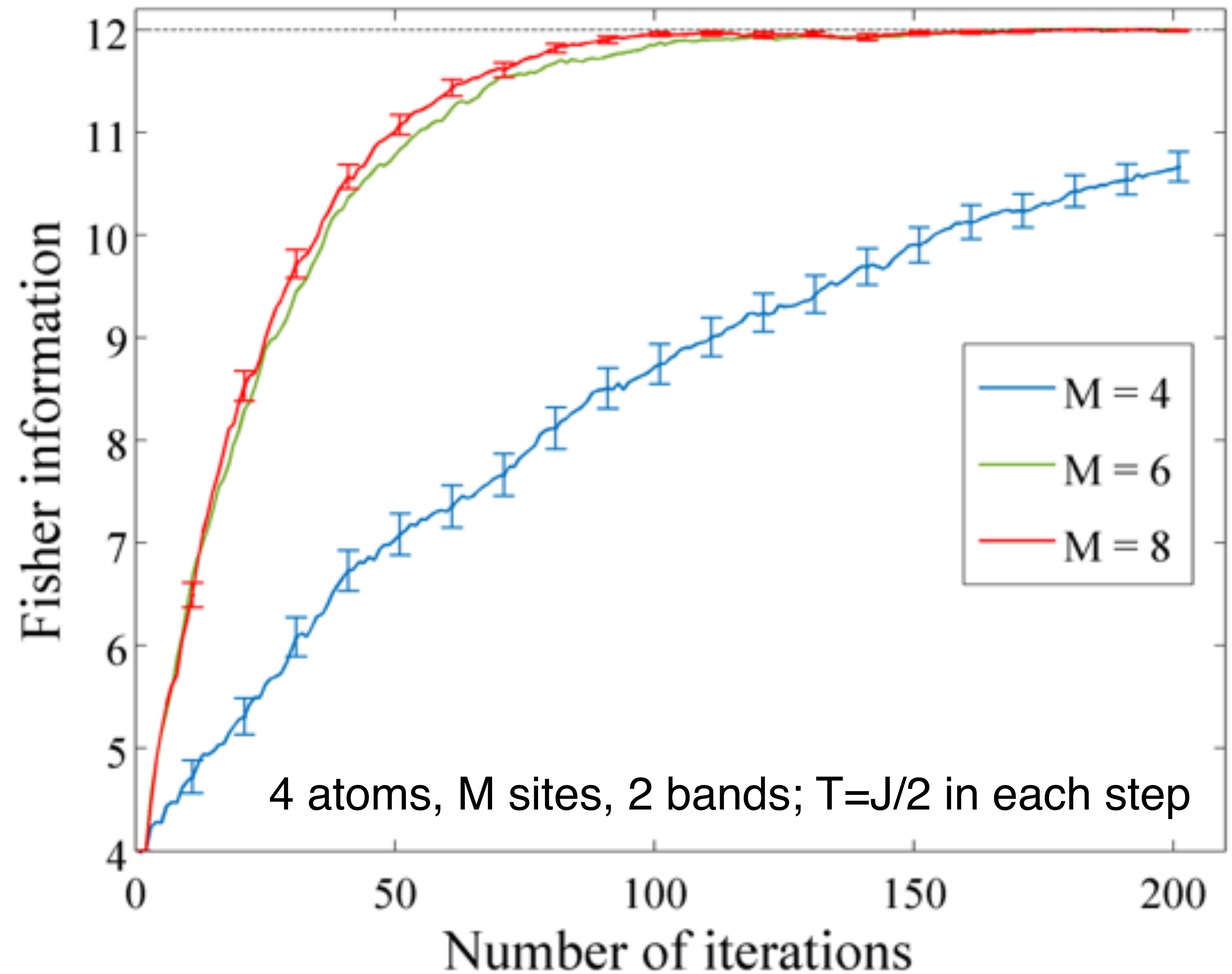


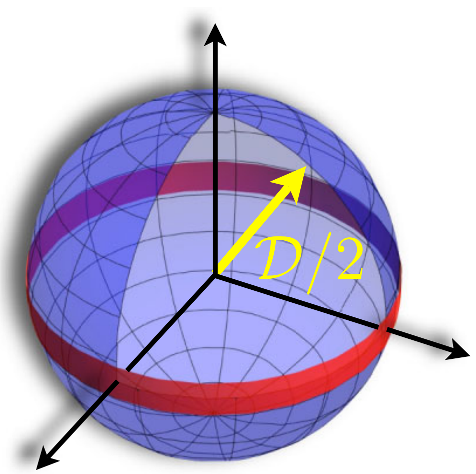
Cooling to the lowest band via reservoir

J. Yago, S. McEndoo, and A. J. Daley, work in progress

Calculation of master equation dynamics for small systems







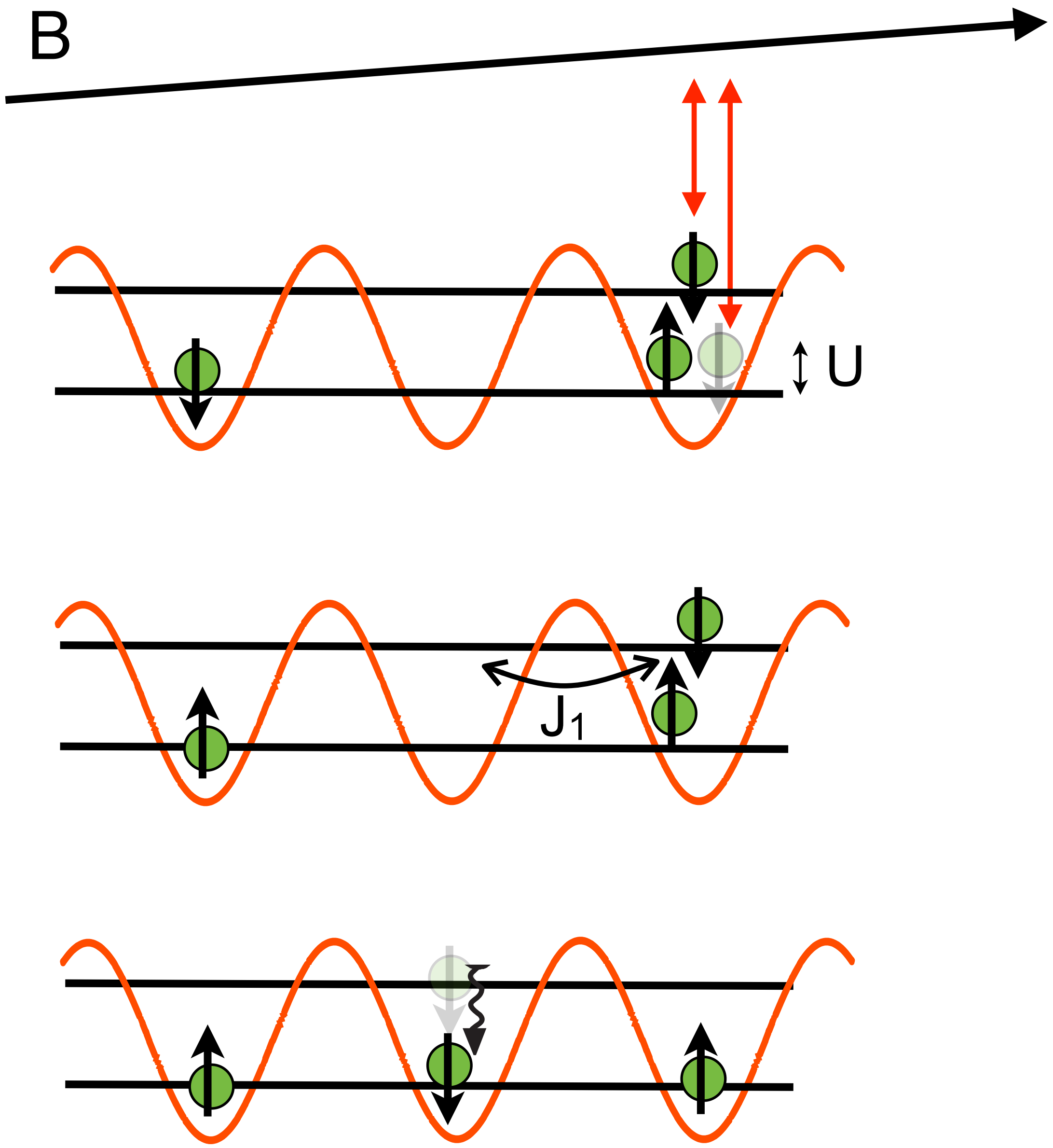
$$|\psi(\Theta)\rangle = e^{iG\Theta}|\psi(0)\rangle$$

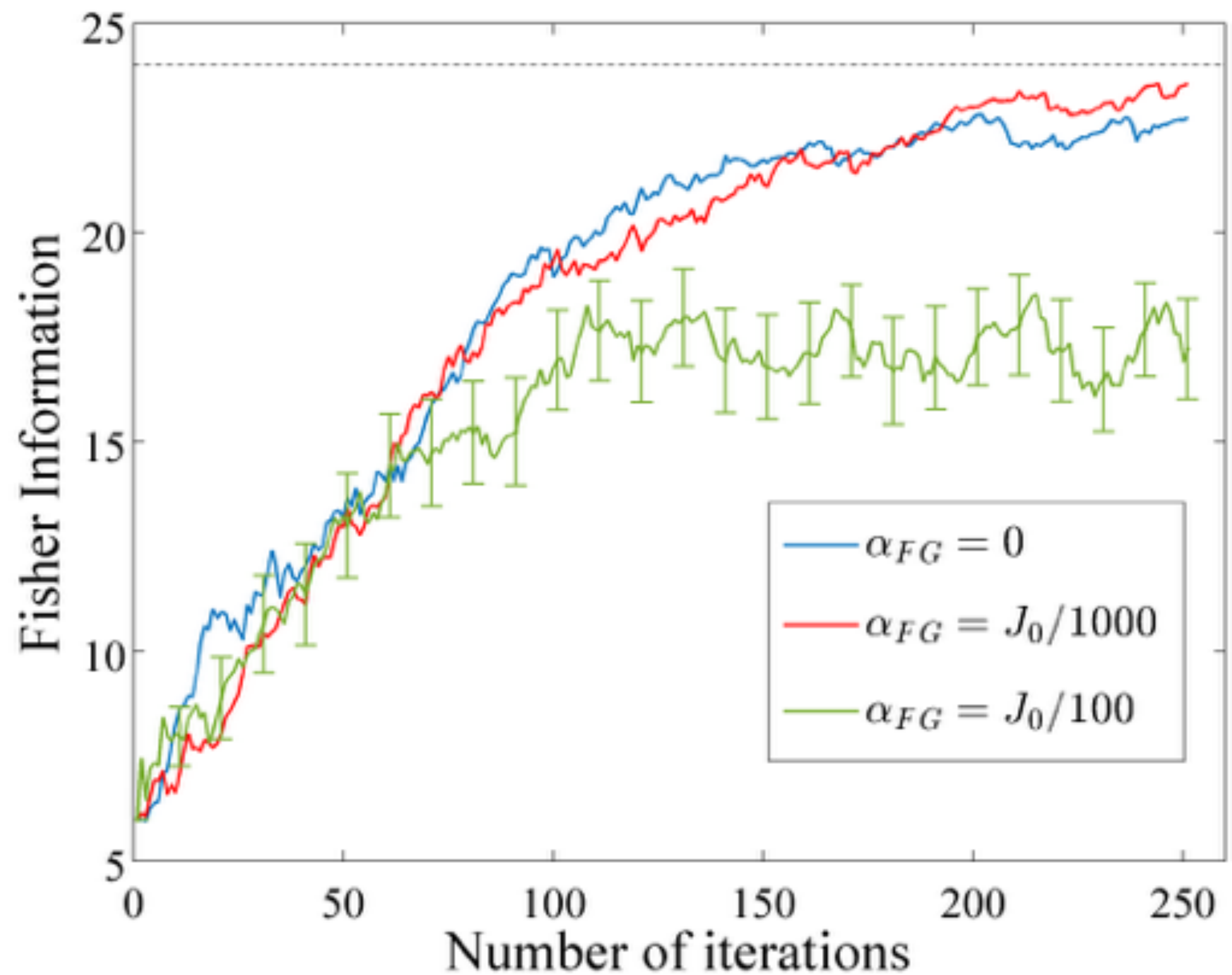
$$G = J_x = \sum_l s_{x,l}$$

$$\Delta^2\Theta_{\mathrm{est}} \geq \frac{1}{MF_Q}, \quad F_Q = 4\Delta^2 G$$

J. Yago, S. McEndoo, and A. J. Daley, in preparation

Maximum fidelity in the presence of a field gradient

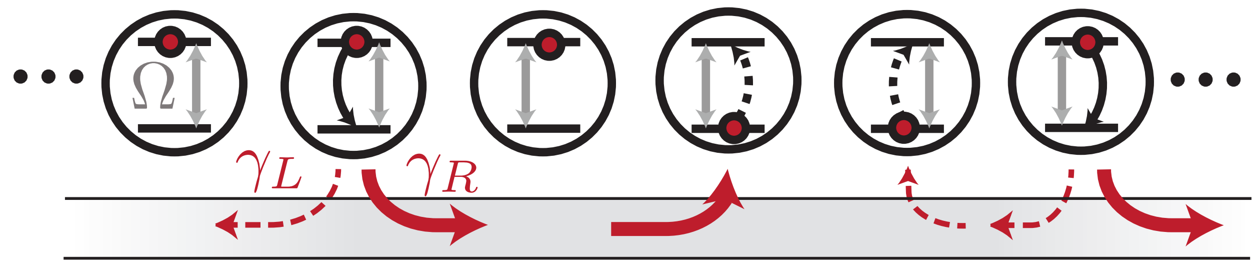




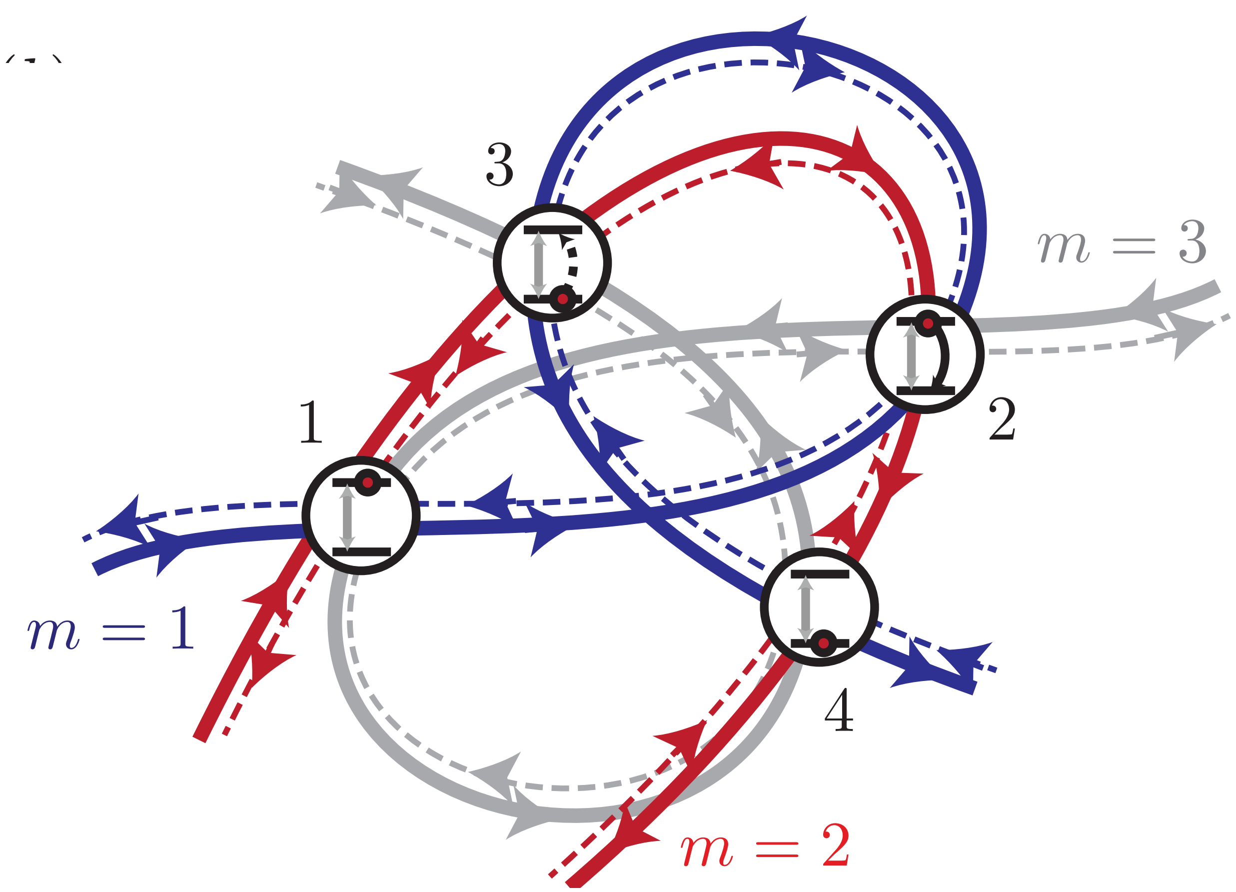
6 atoms, 6 sites, 2 bands; T=J/2 in each step

- Rotation between symmetric and anti-symmetric states
- In progress: Scaling with system size, use of Raman sideband cooling

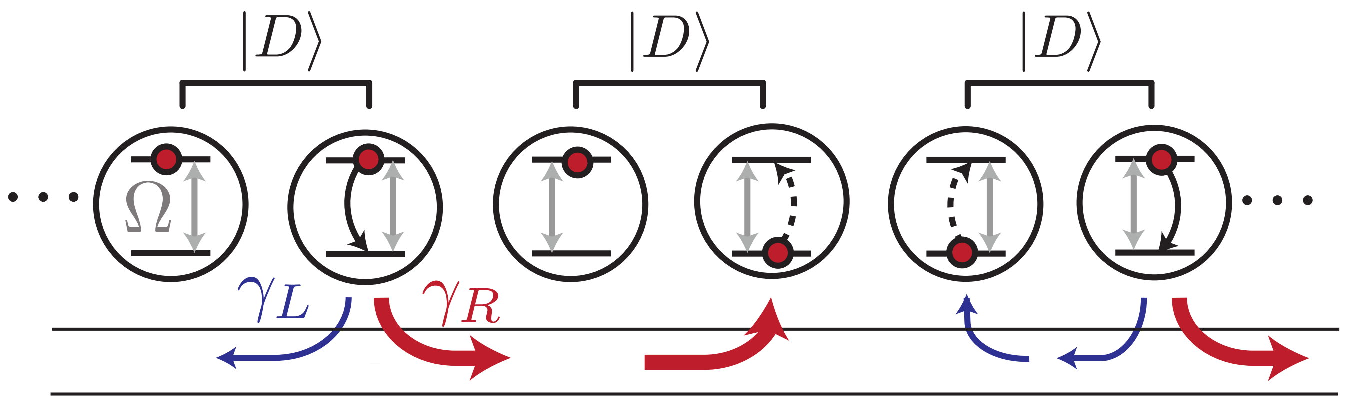
J. Yago, S. McEndoo, and A. J. Daley, in preparation

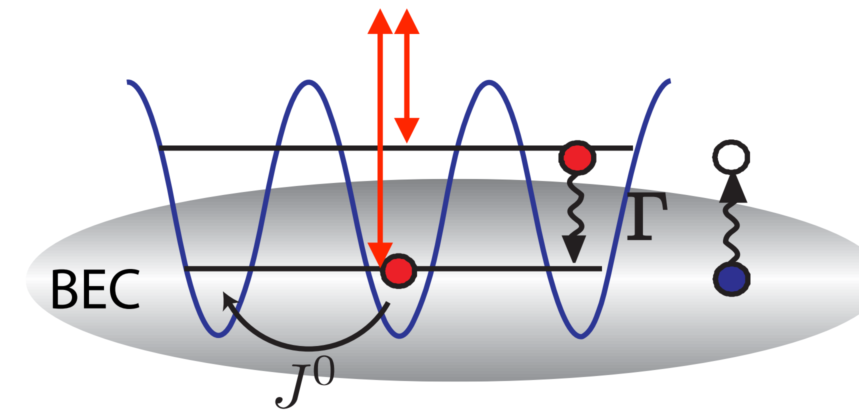


Related work – chiral spin networks

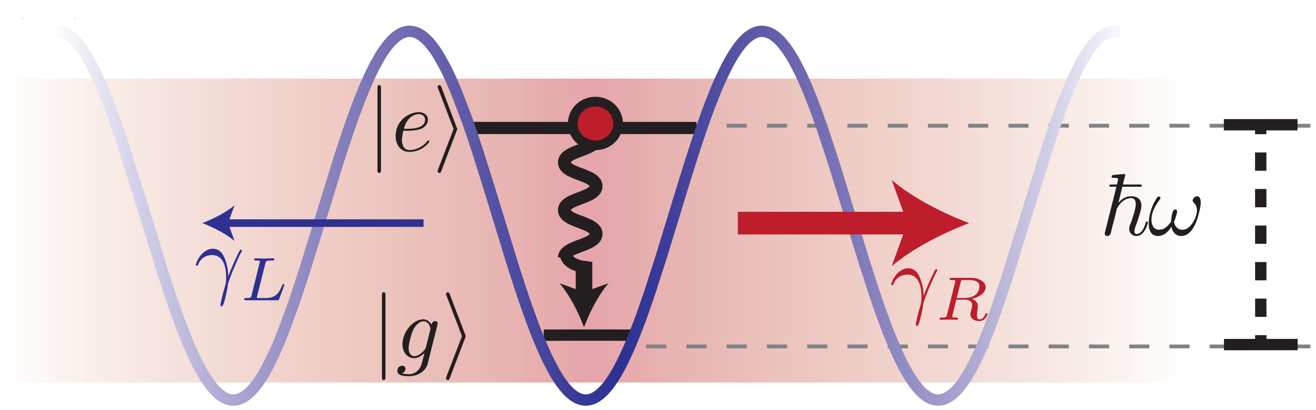


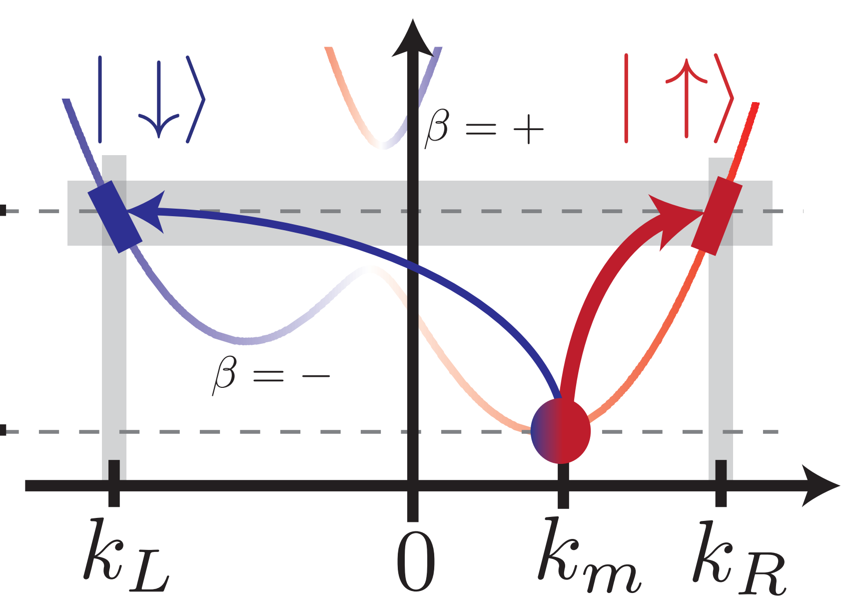
Chiral spin networks with cold atoms





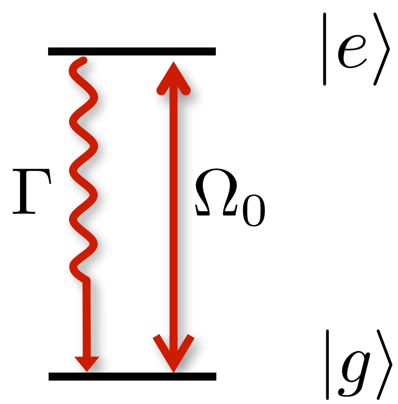
- Spin-orbit coupled reservoirs create left-right asymmetry in excitations
- Careful choice of oscillator spacing, lattice period lead to cascaded quantum spins

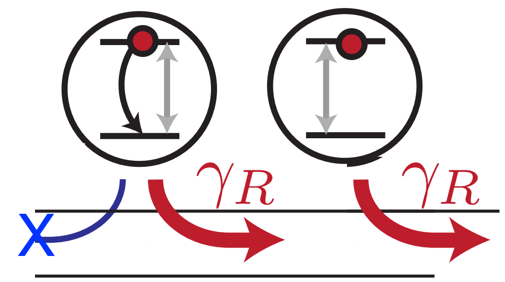




T. Ramos, H. Pichler, A. J. Daley, and P. Zoller, PRL **113**, 237203 (2014)
S. McEndoo, and A. J. Daley, work in progress

Two spins – a cascaded quantum system





$$H = -\frac{\Omega_0}{2}\left(\sigma_1^x + \sigma_2^x\right)$$

$$\frac{d}{dt}\rho = -i[H,\rho] - \frac{\Gamma}{2}\left(\sum_{l=1,2}\sigma_l^+\sigma_l^-\rho + \rho\sigma_l^+\sigma_l^- - 2\sigma_l^-\rho\sigma_l^+\right) - \Gamma\left([\sigma_2^+,\sigma_1^-\rho] + [\rho\sigma_1^+,\sigma_2^-]\right)$$

$$= -i\left(H_{\text{eff}}\rho - \rho H_{\text{eff}}^\dagger\right) - \frac{\Gamma}{2}\left(\sum_{l,k=1,2}\sigma_l^+\sigma_k^-\rho + \rho\sigma_l^+\sigma_k^- - 2\sigma_l^-\rho\sigma_k^+\right)$$

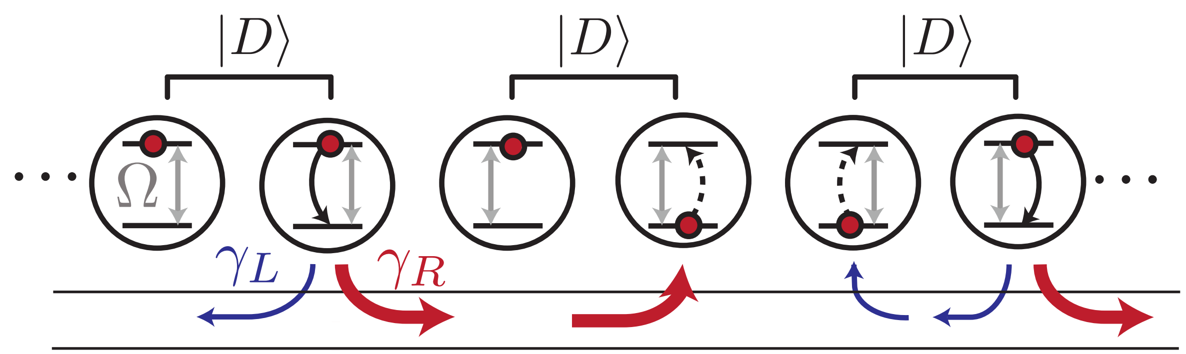
$$H_{\text{eff}} = H - i\frac{\Gamma}{2}(\sigma_2^+\sigma_1^- - \sigma_1^+\sigma_2^-) - i\frac{\Gamma}{2}(\sigma_1^+ + \sigma_2^+)(\sigma_1^- + \sigma_2^-) = H - i\frac{\Gamma}{2}\left(\sigma_1^+\sigma_1^- + \sigma_2^+\sigma_2^-\right) - i\Gamma\sigma_2^+\sigma_1^-$$

- Two spins – steady state

$$|D\rangle_{j,l} \equiv \frac{1}{\sqrt{1+|\alpha|^2}}\left[|g\rangle_j|g\rangle_l + \frac{\alpha}{\sqrt{2}}\left(|g\rangle_j|e\rangle_l - |e\rangle_j|g\rangle_l\right)\right] \qquad \alpha = \frac{2\sqrt{2}\,i\Omega_0}{\Gamma}$$

T. Ramos, H. Pichler, A. J. Daley, and P. Zoller, PRL **113**, 237203 (2014)
S. McEndoo, and A. J. Daley, work in progress

Related ongoing work…. Chiral spin networks



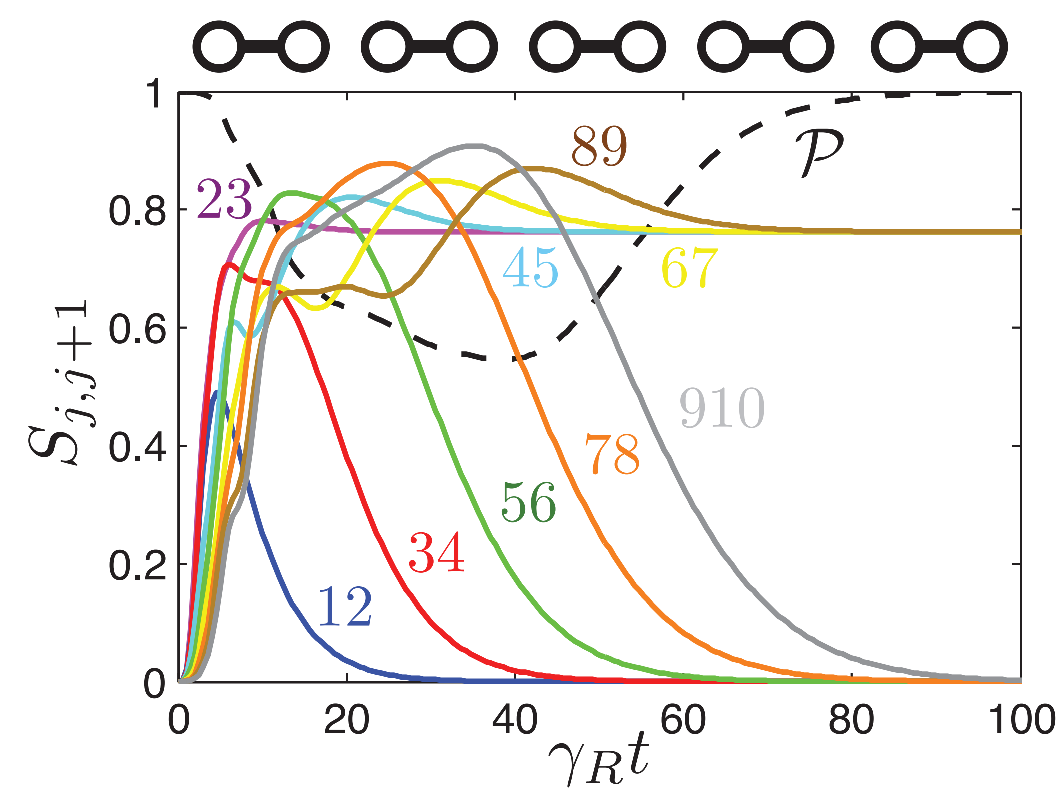
- Cascaded quantum system, interferences between classical and cascaded driving
- Dimerised steady state also with asymmetric, bidirectional couplings

$$\dot{\rho} = -(i/\hbar)[H_{\text{sys}}, \rho] + \mathcal{L}_L\rho + \mathcal{L}_R\rho$$

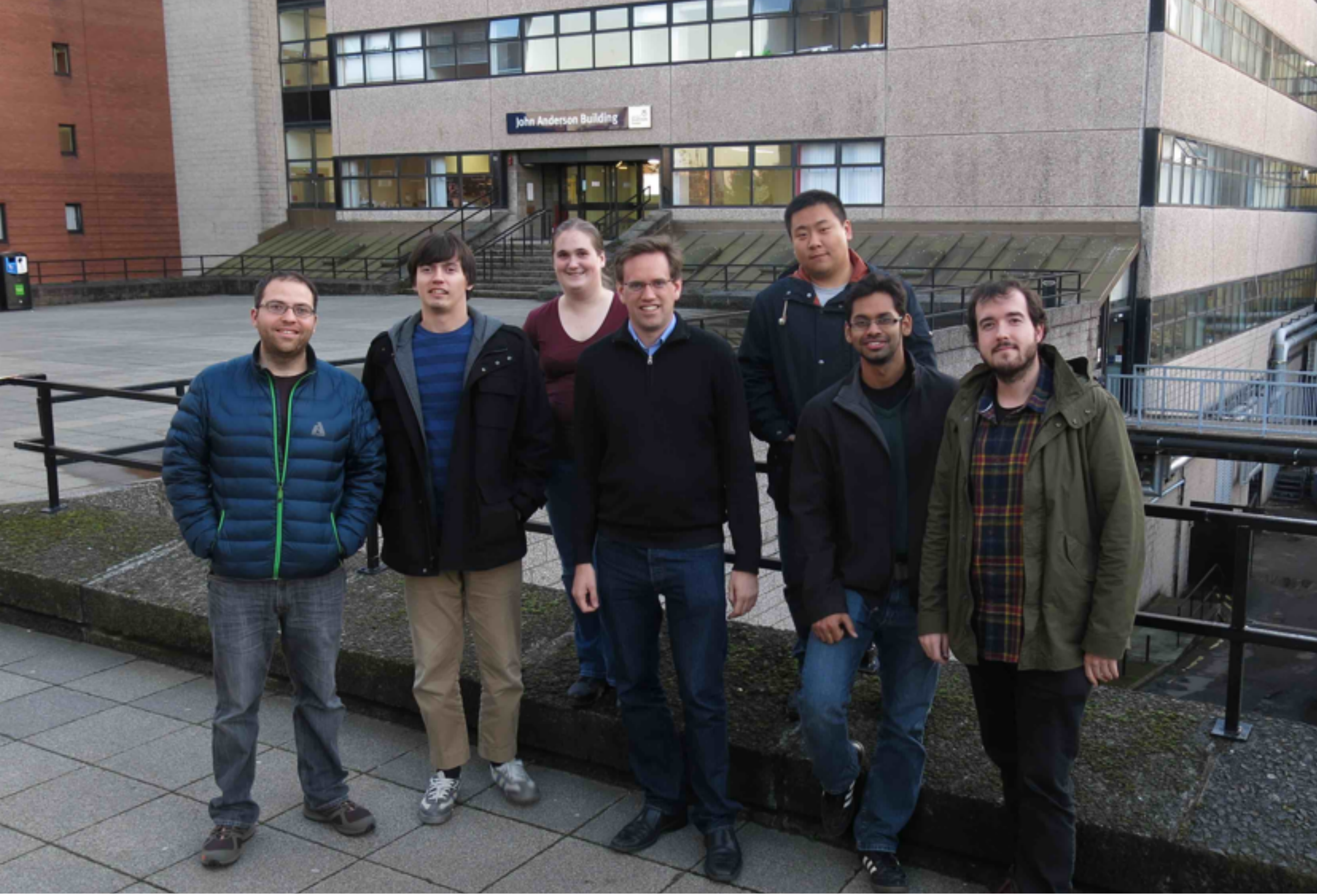
$$\mathcal{L}_L\rho \equiv \frac{\gamma_L}{2}\sum_j \mathcal{D}(\sigma_j, \sigma_j)\rho + \gamma_L \sum_{j>l}\left([\sigma_j, \rho\sigma_l^\dagger] + \text{h.c.}\right)$$

$$\mathcal{L}_R\rho \equiv \frac{\gamma_R}{2}\sum_j \mathcal{D}(\sigma_j, \sigma_j)\rho + \gamma_R \sum_{j<l}\left([\sigma_j, \rho\sigma_l^\dagger] + \text{h.c.}\right)$$

$$\mathcal{D}(a, b)\rho \;\equiv\; 2a\rho b^\dagger - b^\dagger a\rho - \rho b^\dagger a$$



T. Ramos, H. Pichler, A. J. Daley, and P. Zoller, PRL **113**, 237203 (2014)
S. McEndoo, and A. J. Daley, work in progress



University of Strathclyde Glasgow

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE

QuProCS

Anton Buyskikh
Saubhik Sarkar
Guanglei Xu
Jorge Yago

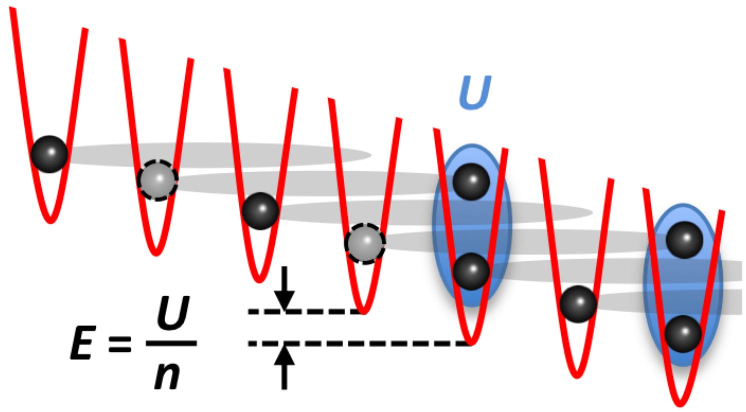
Suzanne McEndoo
Alexandre Tacla

Michael Foss-Feig (JQI)
Ana Maria Rey (JILA)

Tomas Ramos (Innsbruck)
Hannes Pichler (Innsbruck)
Peter Zoller (Innsbruck)

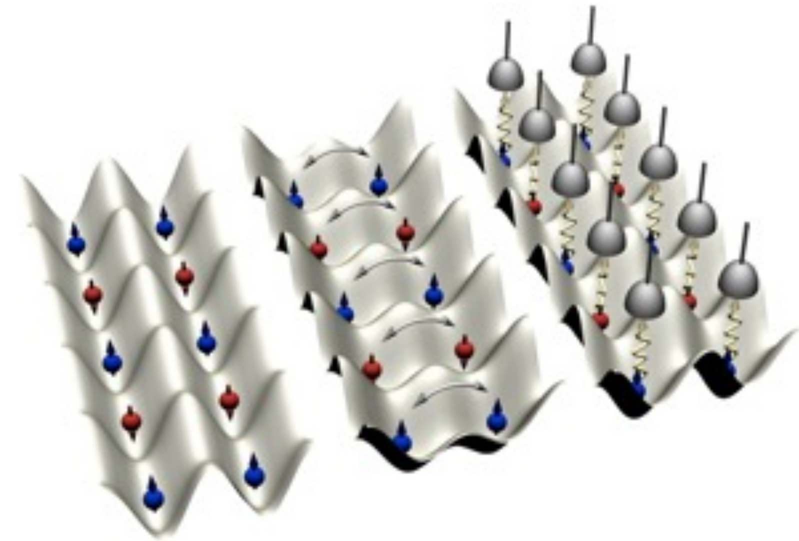
Ongoing work at Strathclyde: Theory of coherent / dissipative dynamics

Dynamics in tilted optical lattices



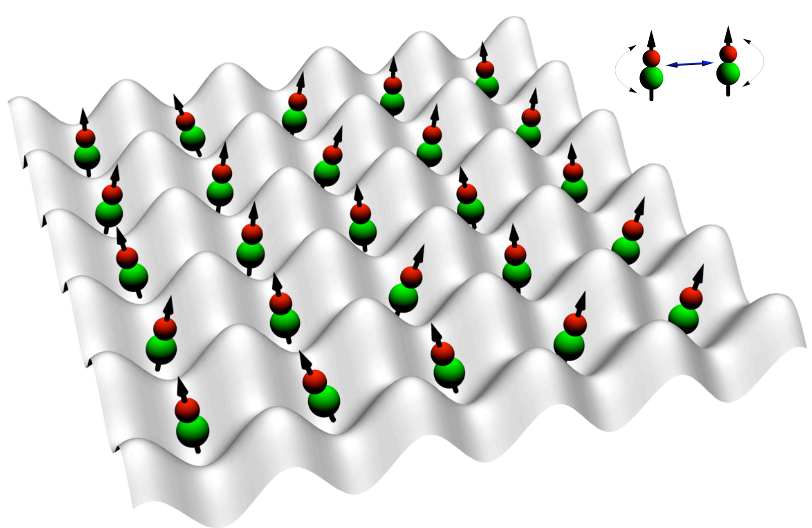
F. Meinert et al., PRL **111**, 053003 (2013)
F. Meinert et al., Science 344, 1259 (2014)

Entanglement measurement



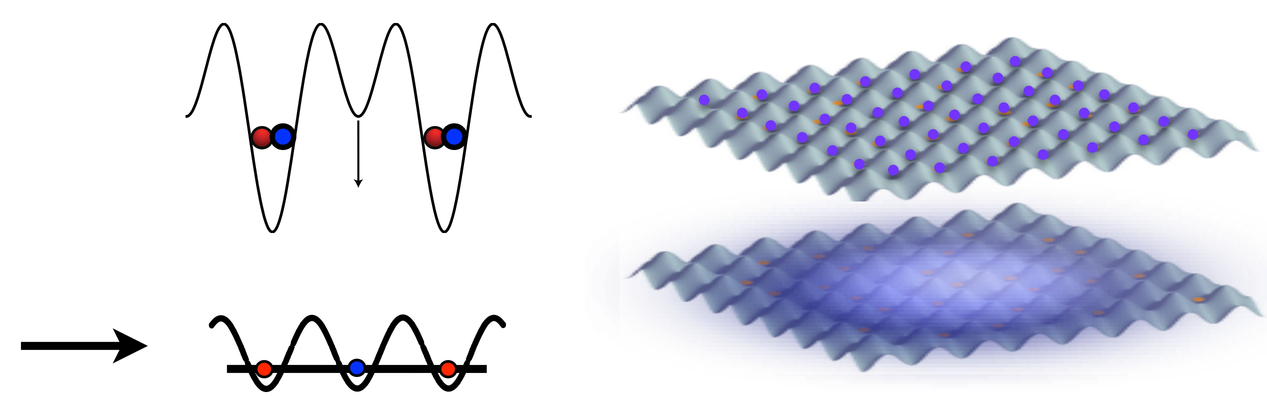
Bosons: A. J. Daley et al., PRL **109**, 020505 (2012)
Fermions: H. Pichler et al., NJP **15**, 063003 (2013)

Out-of-equilibrium dynamics in systems with long-range interactions



J. Schachenmayer et al., PRX **3**, 031015 (2013)
J. Schachenmayer et al., New J. Phys. **12**, 103044 (2010)

Adiabatic state preparation



P. Rabl, A.J Daley, P. O. Fedichev,
J. I Cirac, and P. Zoller PRL **91**, 110403 (2003)

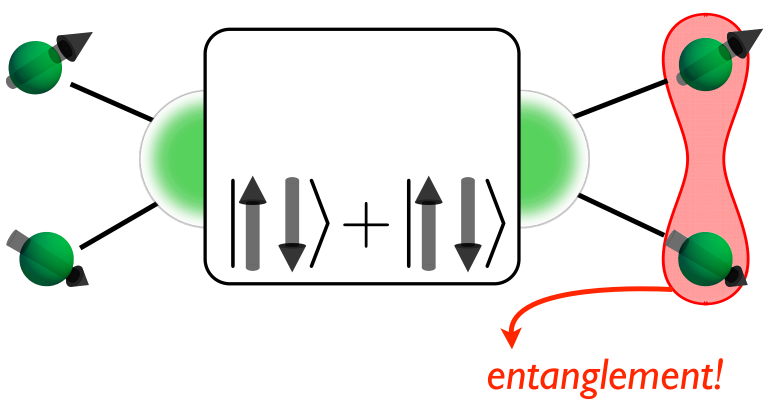
J. Schachenmayer et al., in preparation

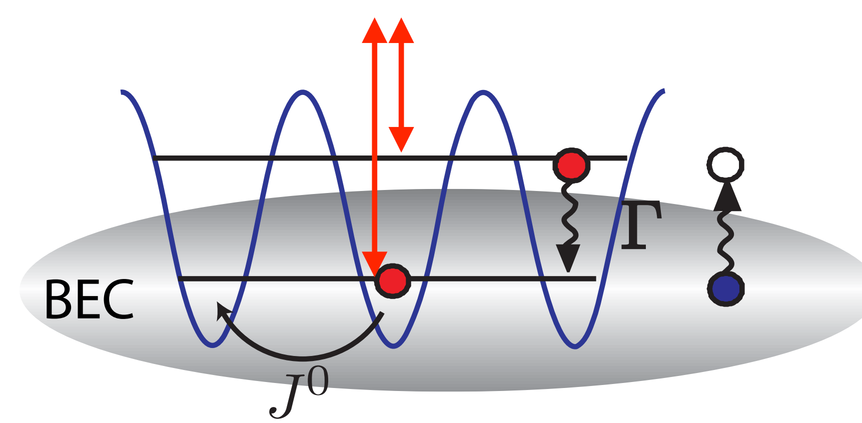
S. Langer et al., in preparation

Summary / Outlook

- Coherent and dissipative dynamics provide a new toolbox of techniques for controlling many-body systems of cold atoms, and preparing many-body states

- Spin entanglement: Fermi statistics, s-wave scattering / controlled dissipative dynamics





- Outlook:
  - Spin-orbit coupled reservoirs / chiral coupling
  - Polarons and impurities
  - Non-markovian dynamics
  - Integration of further techniques from quantum optics with tensor network methods to determine time-dependent dynamics and steady states in larger systems