'Chiral' Quantum Optics:

A Novel Driven-Dissipative Quantum Many-Body System

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ÖAW

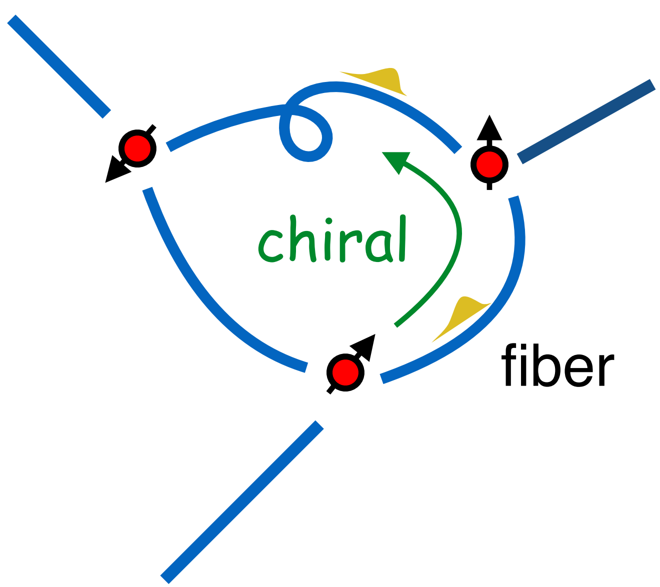
UQUAM
ERC Synergy Grant

SFB FoQuS

siqs

COHERENCE

- ‘chiral' photonic quantum circuit / network



unidirectional light-matter couplings appear naturally in nanophotonic devices

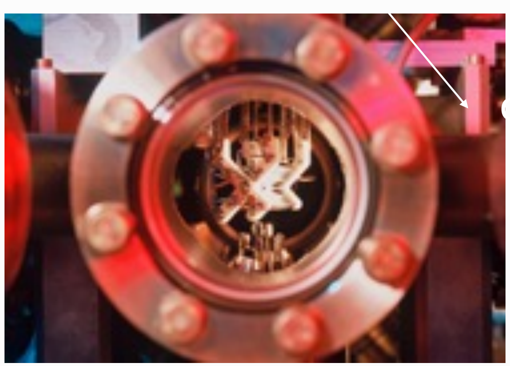
Quantum Simulation & Quantum Optics

- **Building Quantum Simulators with AMO, [solid state] *etc.***

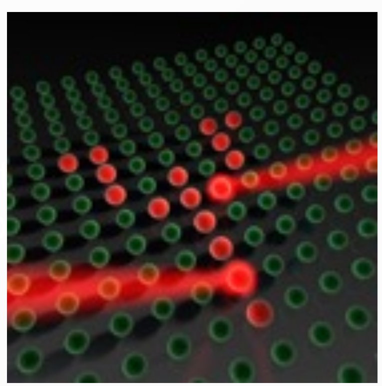
  - cold atoms in optical lattices
  - trapped ions
  - photons …

controlled many-body quantum systems

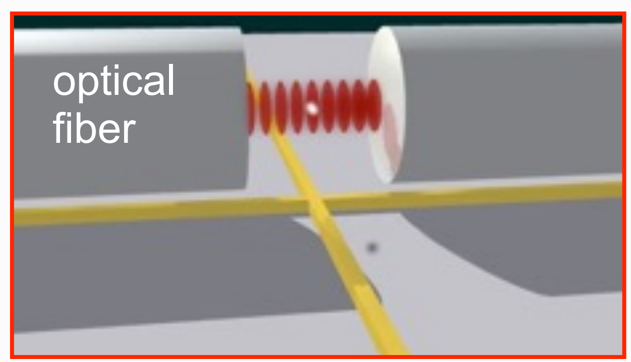
✓ dynamics: *closed* & *open* systems
✓ preparation & measurement
✓ quantum control on level of single quanta



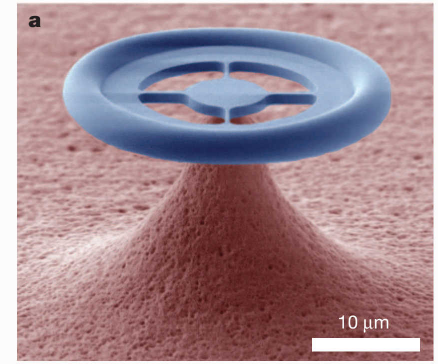
trapped ions



atoms in optical lattices

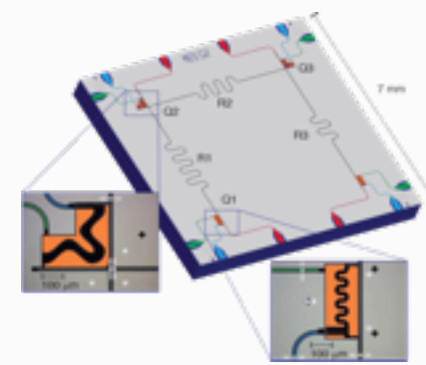


CQED



nanomechanics

NV centers



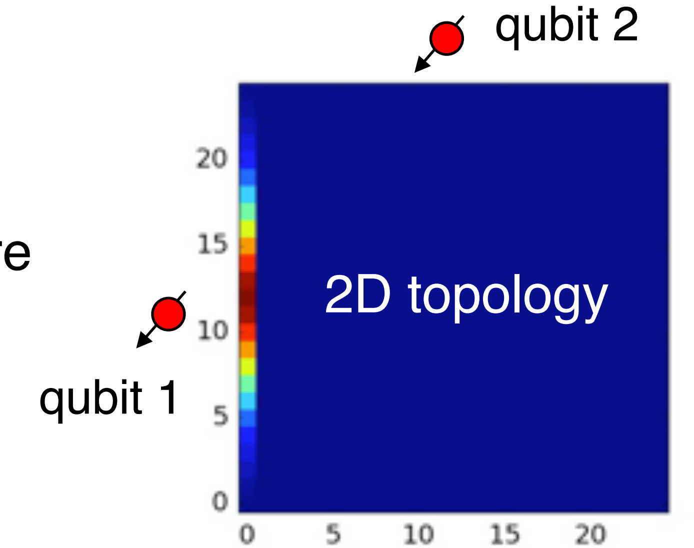
SC Qubits

'Chiral' Quantum Optics

'Chiral' Quantum Optics

what it is NOT ;-)

Quantum communication with chiral edge state

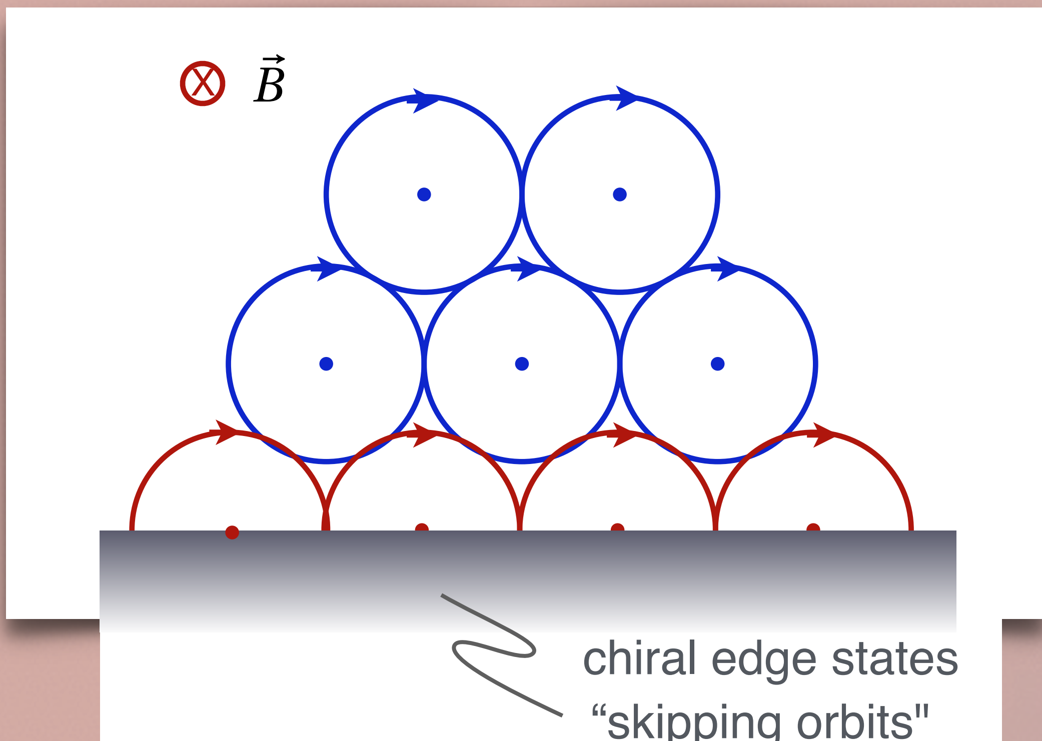


✓ photonic nanostructure

✓ atoms, spin, …

Particle in a [synthetic] magnetic field

cyclotron orbit in B-field

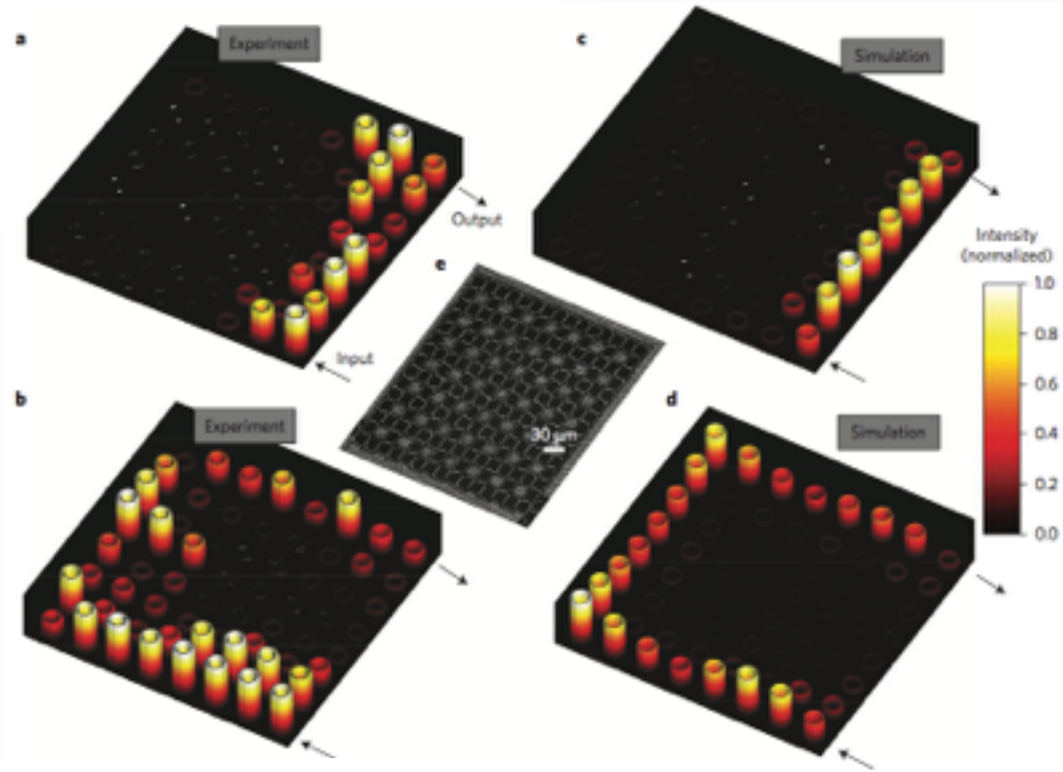


quantum wave packet

nature photonics
ARTICLES
PUBLISHED ONLINE: 20 OCTOBER 2013 | DOI: 10.1038/NPHOTON.2013.274

Imaging topological edge states in silicon photonics

M. Hafezi*, S. Mittal, J. Fan, A. Migdall and J. M. Taylor



nature materials
ARTICLES
PUBLISHED ONLINE: 10 NOVEMBER 2013 | DOI: 10.1038/NMAT3783

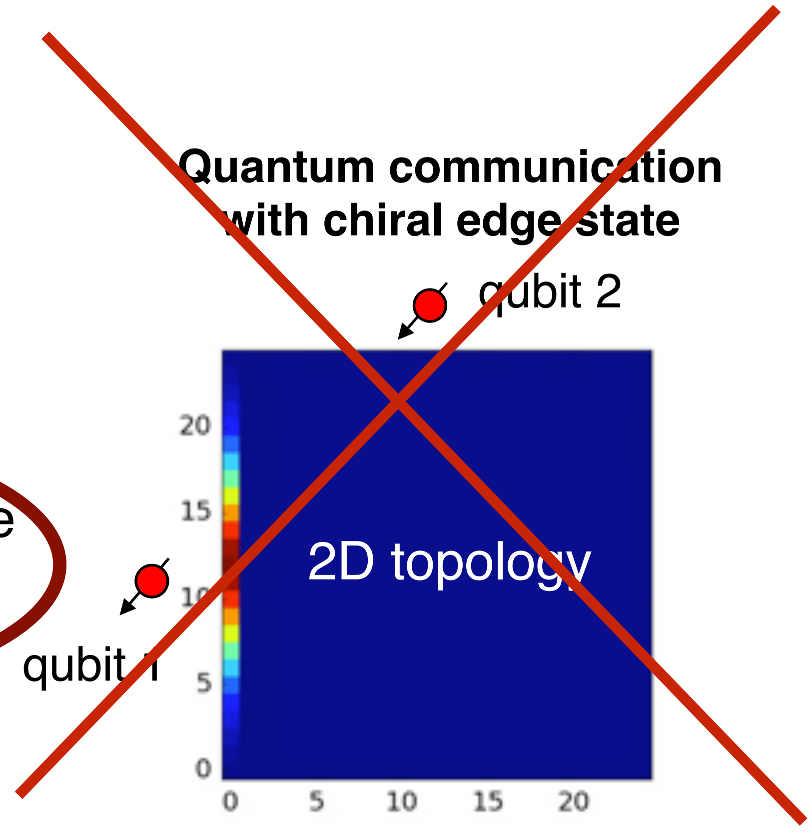
Observation of unconventional edge states in 'photonic graphene'

Yonatan Plotnik[1†], Mikael C. Rechtsman[1†], Daohong Song[2†], Matthias Heinrich[3], Julia M. Zeuner[3], Stefan Nolte[3], Yaakov Lumer[1], Natalia Malkova[4], Jingjun Xu[2], Alexander Szameit[3], Zhigang Chen[2,4] and Mordechai Segev[1*]

'Chiral' Quantum Optics

✓ photonic nanostructure

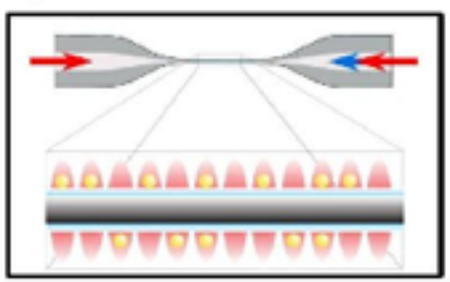
✓ atoms, spin, …



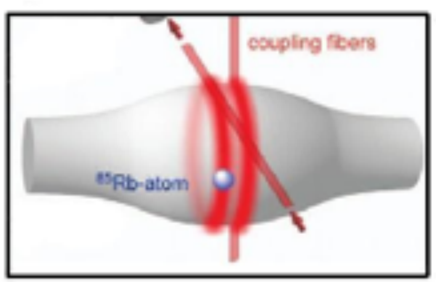
'Chiral' Quantum Optics

chiral coupling between light and quantum emitters

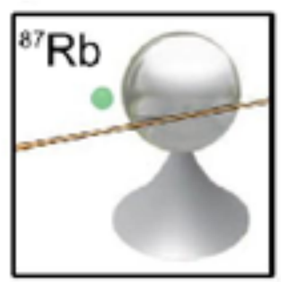
Nanophotonic devices: chirality appears naturally …

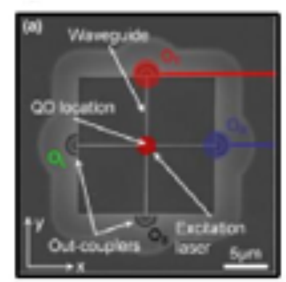


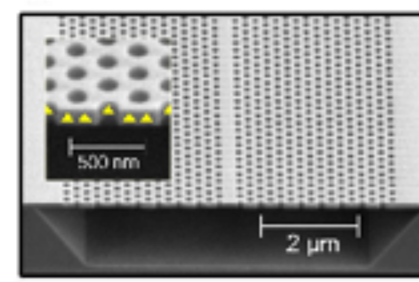
atoms & nanofibers



atoms & CQED







quantum dots & photonic nanostructures

Chiral Quantum Optics *Nature Review submitted*

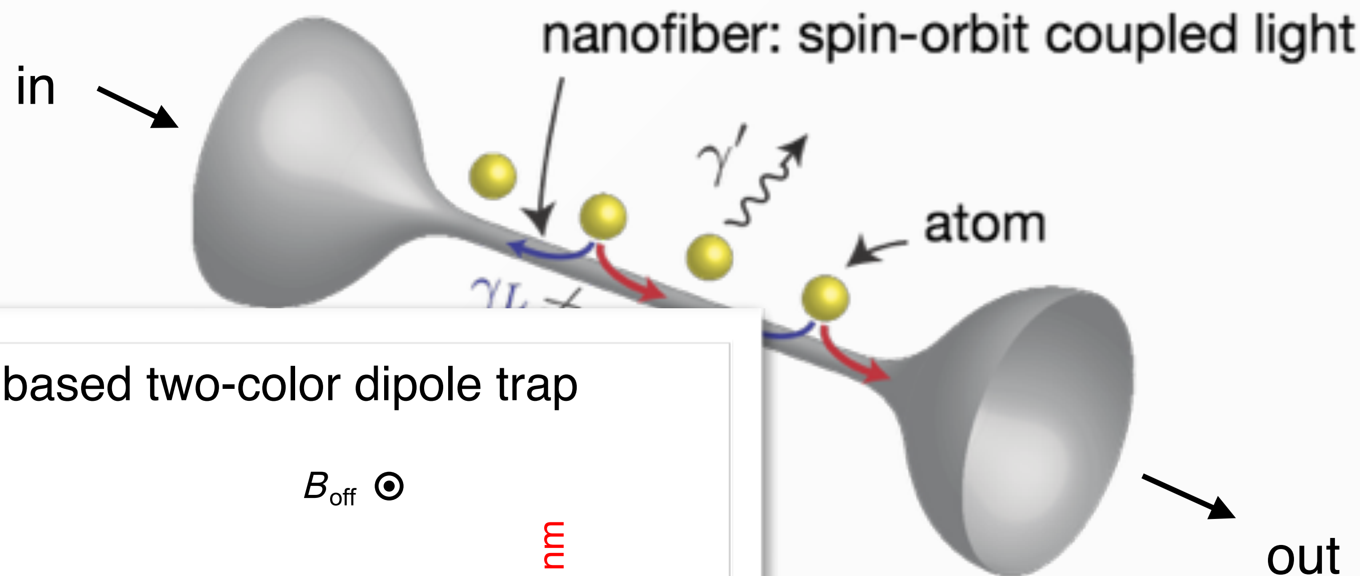
Peter Lodahl,[1] Sahand Mahmoodian,[1] Søren Stobbe,[1] Philipp Schneeweiss,[2] Jürgen Volz,[2] Arno Rauschenbeutel,[2] Hannes Pichler,[3,4] and Peter Zoller[3,4]

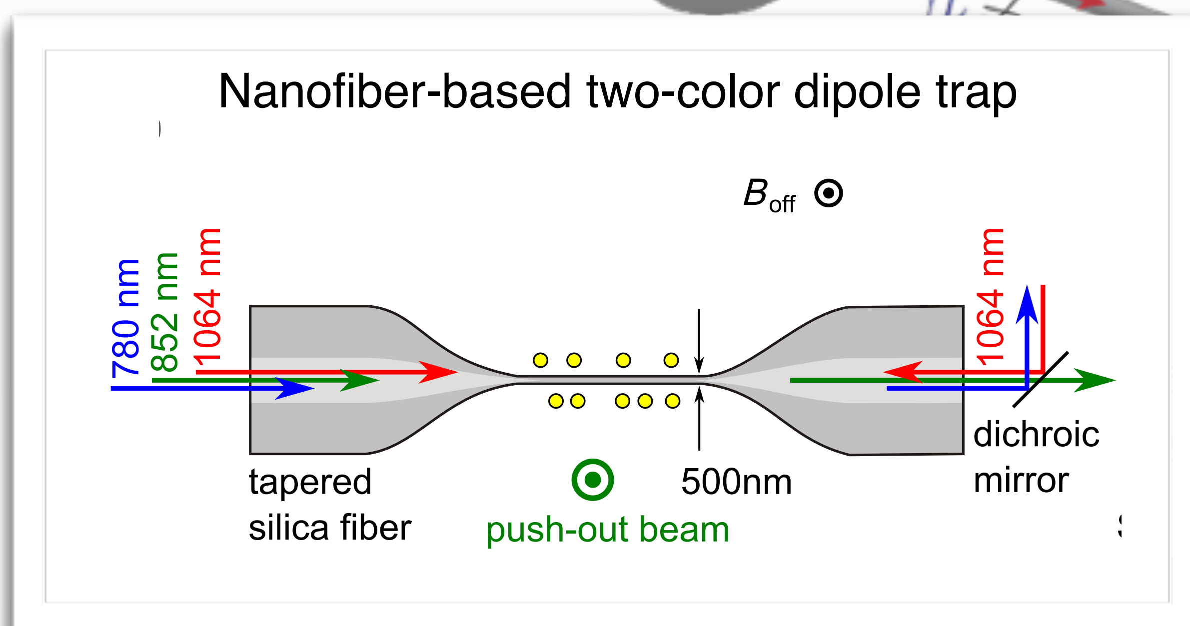
SCIENCE sciencemag.org 3 OCTOBER 2014 • VOL 346 ISSUE 6205

NANOPHOTONICS

Chiral nanophotonic waveguide interface based on spin-orbit interaction of light

Jan Petersen, Jürgen Volz,* Arno Rauschenbeutel*





15)

photonic nanostructures

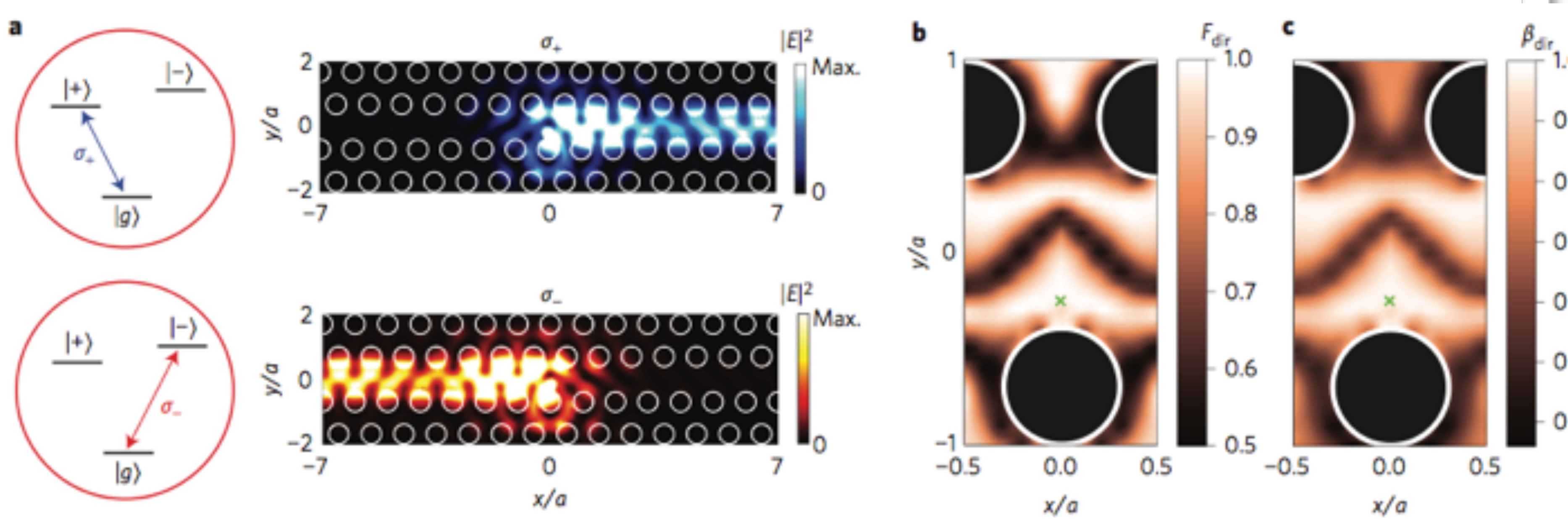
nature nanotechnology

... with quantum dots

LETTERS
PUBLISHED ONLINE: 27 JULY 2015 | DOI: 10.1038/NNANO.2015.159

Deterministic photon–emitter coupling in chiral photonic circuits

Immo Söllner[1]*, Sahand Mahmoodian[1], Sofie Lindskov Hansen[1], Leonardo Midolo[1], Alisa Javadi[1], Gabija Kiršanskė[1], Tommaso Pregnolato[1], Haitham El-Ella[1], Eun Hye Lee[2], Jin Dong Song[2], Søren Stobbe[1] and Peter Lodahl[1]*



H Pichler

T Ramos

B Vermersch

P Hauke

‘Chiral' Quantum Optics

→ Many-Body Quantum Physics

- Theory …

  T. Ramos, H. Pichler, A.J. Daley, and PZ, PRL 2014

  K. Stannigel, P. Rabl, and PZ. NJP (2012)

  H. Pichler, T. Ramos, A.J. Daley, PZ, PRA, 2015

  T. Ramos, B. Vermersch, P. Hauke, H. Pichler, and PZ, PRA 2016

  B. Vermersch, T. Ramos, P. Hauke, and PZ, PRA 2016

  H. Pichler and PZ, PRL 2016

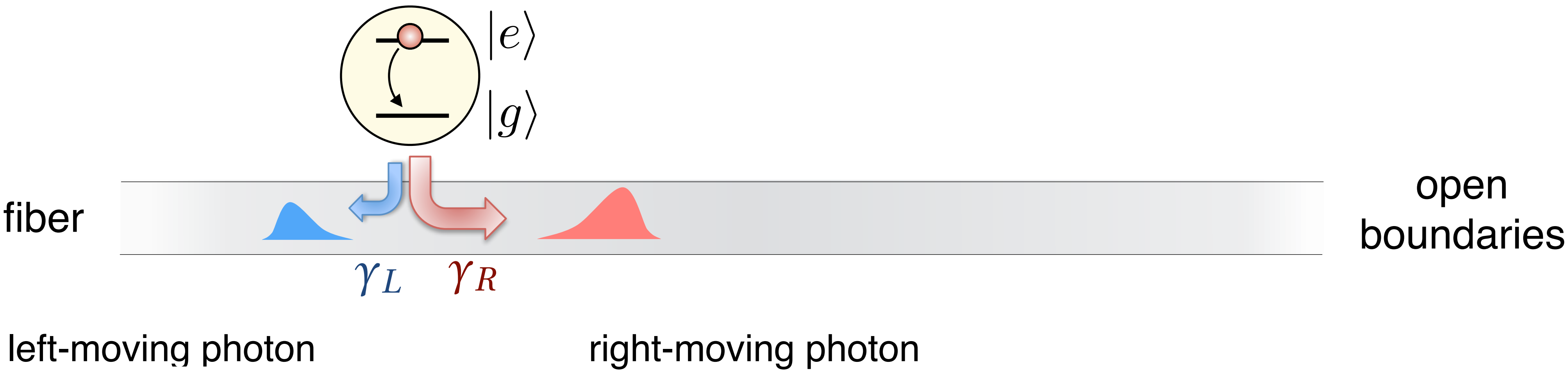
  P.O. Guimond, H. Pichler, A. Rauschenbeutel and PZ, arXiv June 2016

  C. Dlaska, B. Vermersch, and PZ, arXiv July 2016

- Review

  P. Lodahl, A. Rauschenbeutel, PZ et al., submitted to Nature Reviews 2016

'Chiral' Quantum Optics

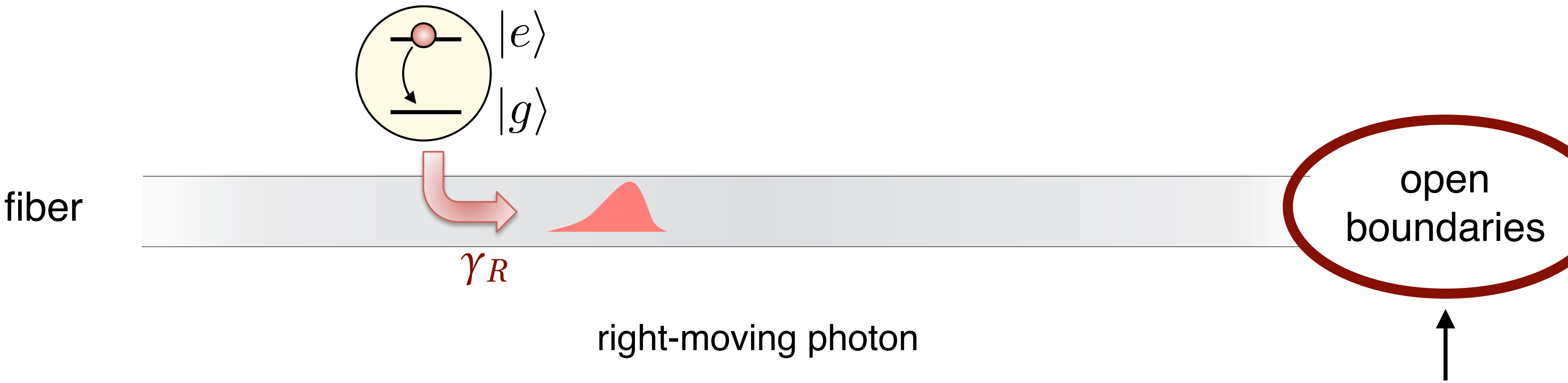


✓ 'chiral' atom-light interface:

broken left-right symmetry

$$\gamma_L \neq \gamma_R$$

‘Chiral' Quantum Optics



- photons never return / are never reflected
- carry away entropy

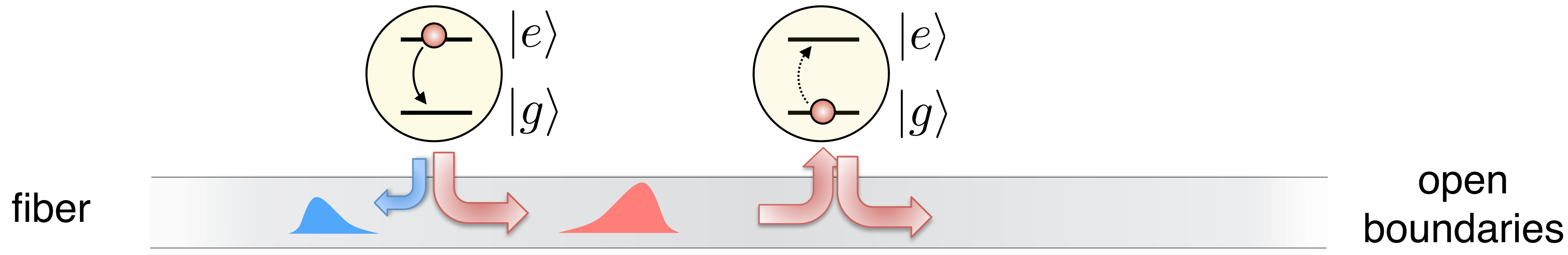
✓ ‘chiral’ atom-light interface:

broken left-right symmetry

$$\gamma_L = 0; \gamma_R$$

‘chirality' ~ open quantum system

‘Chiral' Photon-Mediated Interactions



✓ ‘chiral’ interactions

broken left-right symmetry

atoms only talk to atoms on the right

‘Chiral' Interactions … How to Model?

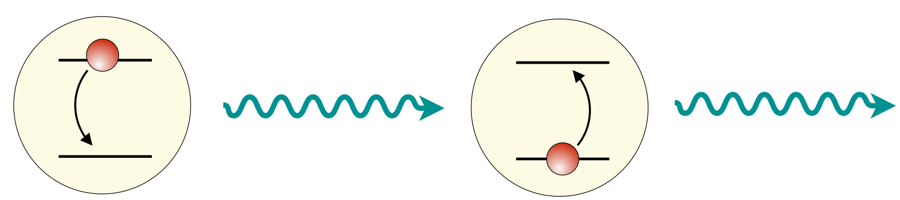
- **interactions mediated by photons**

- quantum optics we know

left - right
symmetric

✓ dipole-dipole interaction $H \sim \sigma_1^- \sigma_2^+ + \sigma_1^+ \sigma_2^-$ by integrating out photons

- chiral quantum optics

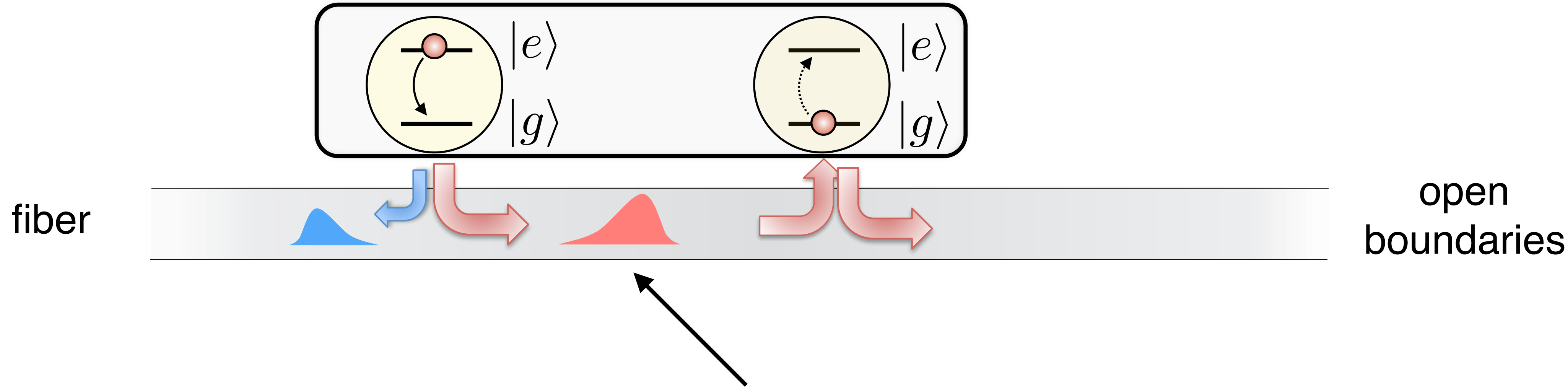


broken left - right
symmetry

✓ unidirectional interaction $H \sim \sigma_1^- \sigma_2^+$?

Theory: ‘Cascaded Master equation’ = open quantum system

Quantum Optical Master Equation



- We integrate the photons out as ‘quantum reservoir’ in Born-Markov approximation
- Master equation for reduced dynamics: density operator of atoms

$$\dot{\rho} = -\frac{i}{\hbar}\left[H_{\mathrm{sys}}, \rho\right] + \mathscr{L}\rho$$

1. 'Bidirectional' Master Equation

- **Master equation: symmetric**

driven atoms

1D dipole-dipole

$$\dot{\rho} = -i[H_{\rm sys} + \gamma \sin(k|x_1 - x_2|)(\sigma_1^+\sigma_2^- + \sigma_2^+\sigma_1^-), \rho] + 2\gamma \sum_{i,j=1,2} \cos(k|x_i - x_j|)(\sigma_i^- \rho \sigma_j^+ - \frac{1}{2}\{\sigma_i^+\sigma_j^-, \rho\}).$$

collective spontaneous emission

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

2.’Cascaded’ Master Equation

open boundaries

- **Master equation: (purely) unidirectional**

$$\dot{\rho} = \mathscr{L}\rho \equiv -i(H_{\text{eff}}\rho - \rho H_{\text{eff}}^{\dagger}) + \sigma\rho\sigma^{\dagger}$$

Lindblad form

  - non-Hermitian effective Hamiltonian

$$H_{\text{eff}} = H_1 + H_2 - i\frac{\gamma}{2}\left(\sigma_1^+\sigma_1^- + \sigma_2^+\sigma_2^- + 2\sigma_2^+\sigma_1^-\right)$$

  - quantum jump operator: collective

$$\sigma = \sigma_1^- + \sigma_2^-$$

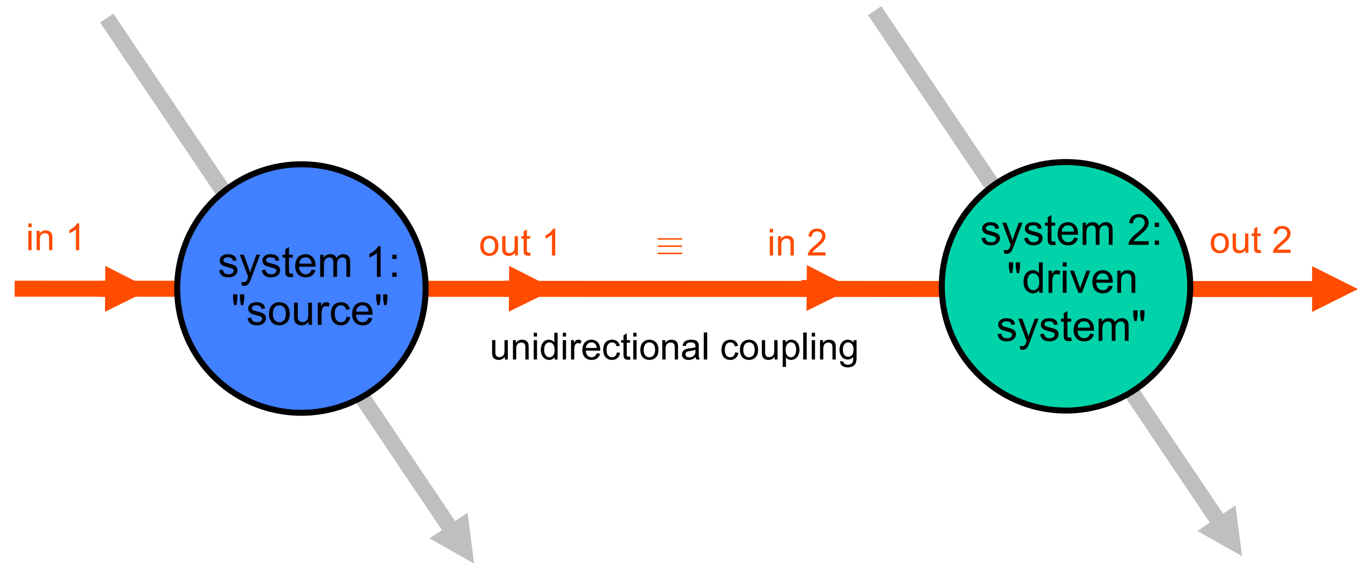
C.W. Gardiner, PRL 1993;
H. Carmichael, PRL 1993

- **general case: N atoms, chiral**

positions of the atoms does not matter

H. Pichler et al., PRA 2015

Theory of Cascaded Quantum Systems



- References

T. Ramos, H. Pichler, A.J. Daley, and PZ, PRL 2014

K. Stannigel, P. Rabl, and PZ. NJP 2012

H. Pichler, T. Ramos, A.J. Daley, PZ, PRA, 2015

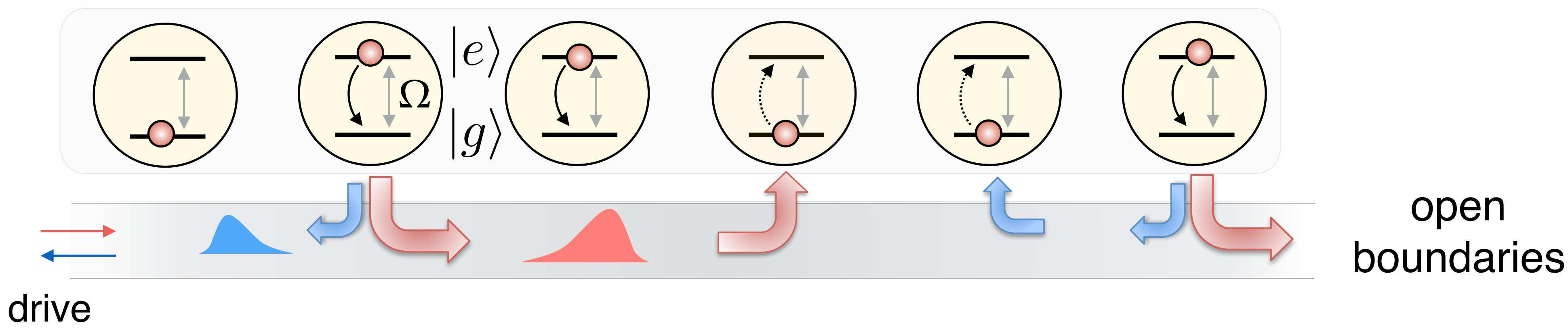
T. Ramos, B. Vermersch, P. Hauke, H. Pichler, and PZ, PRA 2016

H. Pichler and PZ, PRL 2016

N=2: C.W. Gardiner, PRL 1993; H. Carmichael, PRL 1993

J.I. Cirac, P. Zoller, H.J. Kimble, H Mabuchi, PRL 1998

Our Model System:
'Chiral' Many-Body Quantum Optics



✓ 'chiral' photon-mediated interactions

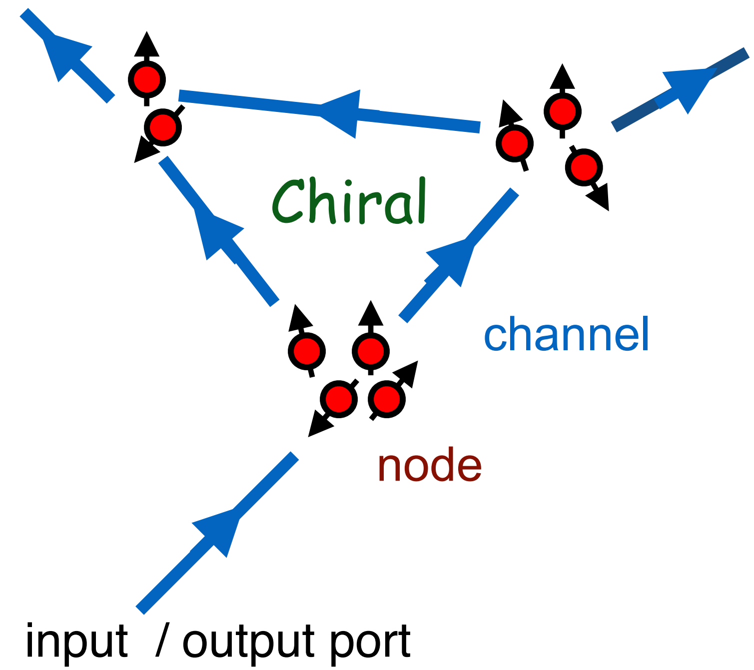
✓ laser driving

✓ open quantum system

Driven-dissipative quantum many-body system

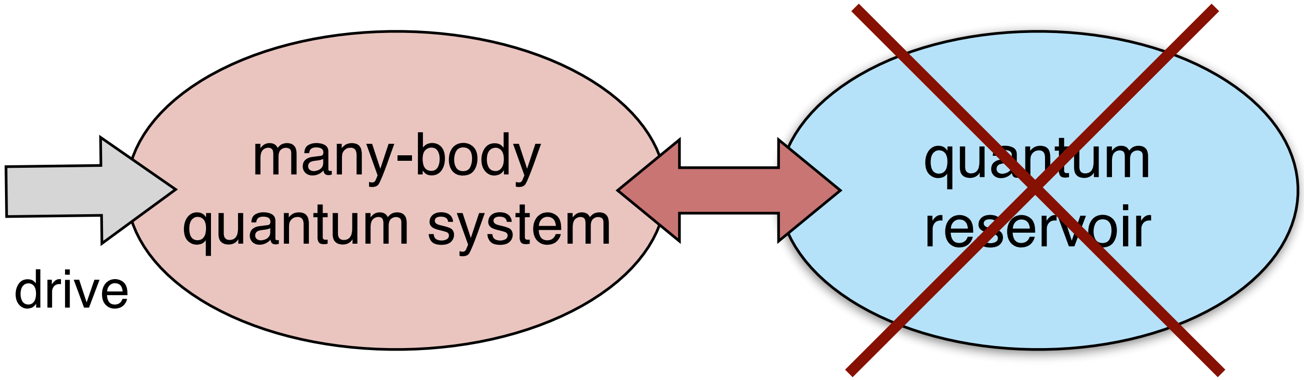
Chiral Photonic Quantum Network

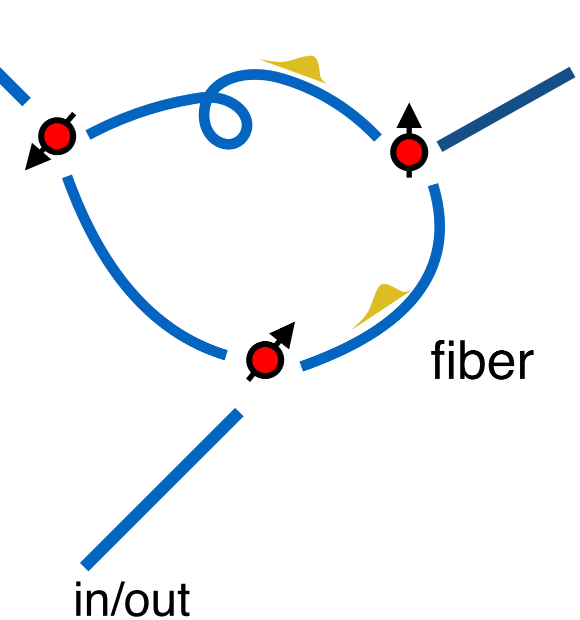
chiral = asymmetric coupling of
atoms to wave guide



- ***open*** **quantum** ***many body*** **system**
  - driven-dissipative (quantum optics)
- **why?**
  - quantum info / non-equilibrium cond mat (quantum phases)
- **how? - physical realization**
  - photons, spin waves, …

Markovian Quantum Network Theory





Born-Markov Approximation

Many body Quantum Optics

- Dynamics: Master equation

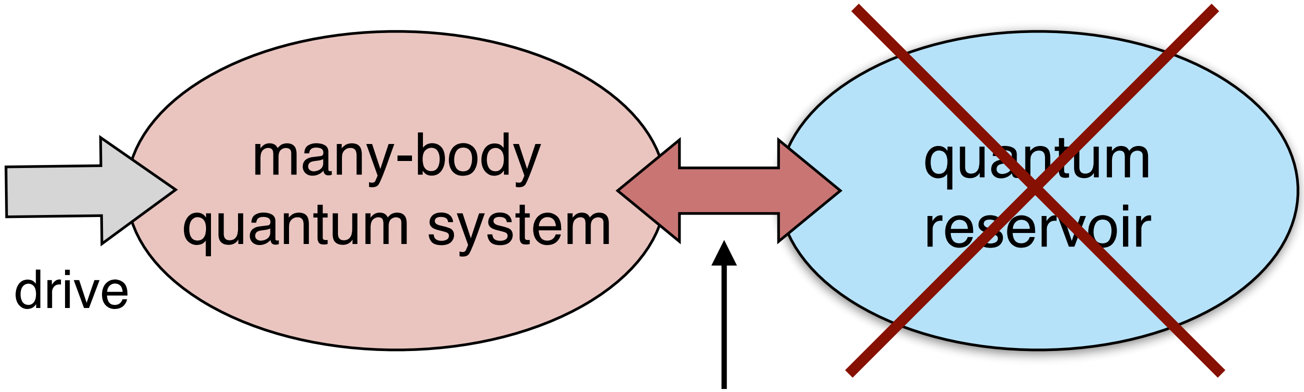
$$\dot{\rho}(t) = -\frac{i}{\hbar}[H_{\mathrm{sys}}, \rho(t)] + \mathcal{L}\rho(t)$$

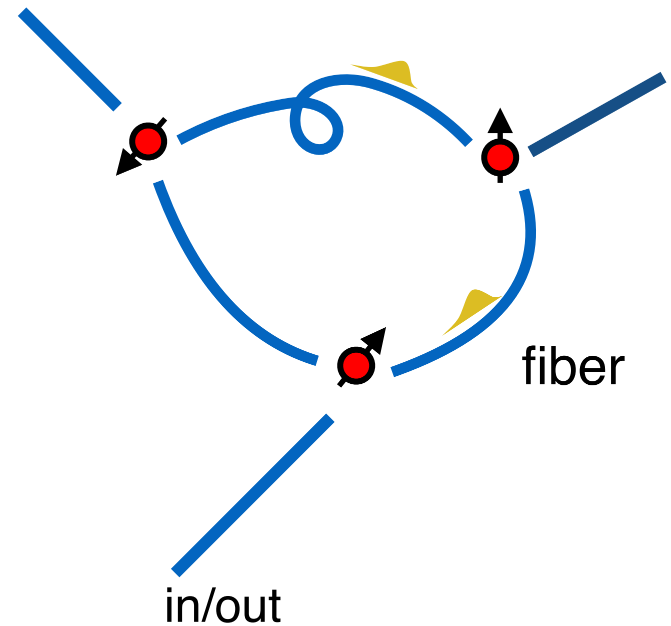
- Steady state:

$$\rho(t) \xrightarrow{t\to\infty} \rho_{ss}$$

validity …

Markovian Quantum Network Theory





Engineer system-reservoir coupling!

Many body Quantum Optics

- Dynamics: Master equation

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

validity …

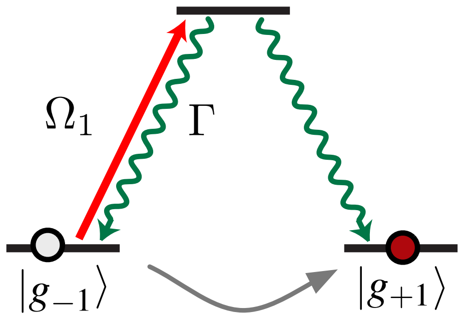
- Steady state:

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

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

Dark States: Single Particle

- **optical pumping**



$$\rho(t) \xrightarrow{t\to\infty} |g_{+1}\rangle\langle g_{+1}|$$

pumping into a *pure* “dark state”

- **Optical Bloch Equations**

quantum jump operator (nonhermitian)

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

- **steady state as a pure “dark state”**

$$H|D\rangle = E|D\rangle$$
$$\forall \alpha \quad c_\alpha |D\rangle = 0$$

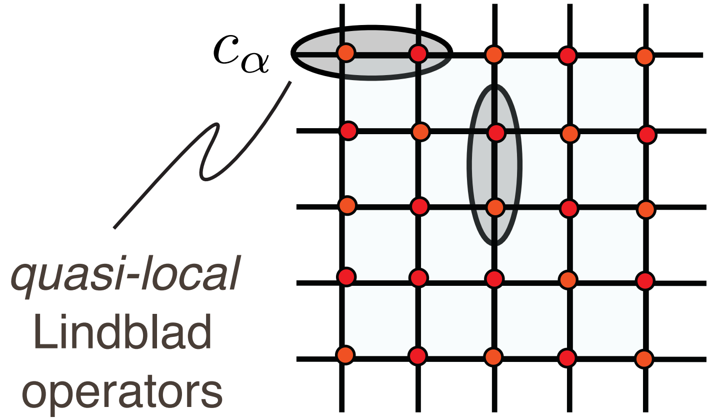
conditions

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

pumping into a pure state

Dark States: Many Particle

qubits or particles on a lattice



- **master equation**

quantum jump operator (nonhermitian)

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

- **desired state as “dark state”**

$$H|D\rangle = E|D\rangle$$
$$\forall \alpha \quad c_\alpha |D\rangle = 0$$

desired state

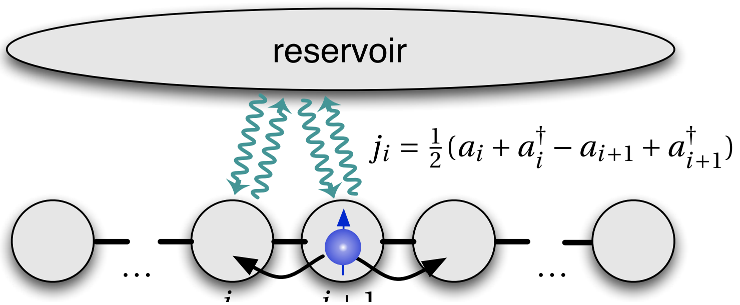
construct a *parent* Liouvillian

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

Kraus et al., PRA 2008

Examples: Engineered Dissipative Atomic Systems

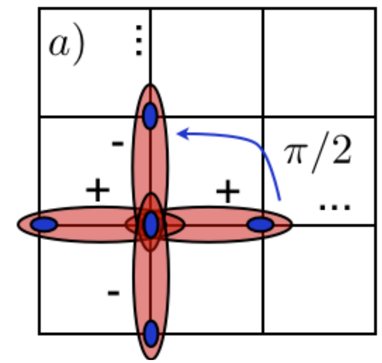
Topology via dissipation



Majorana edge modes

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

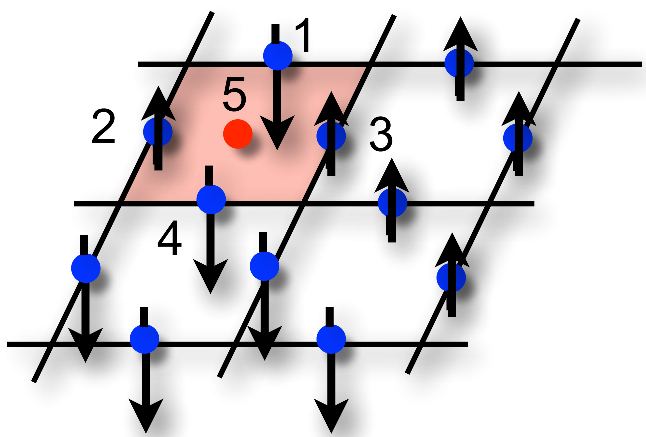
BCS-pairing from dissipation



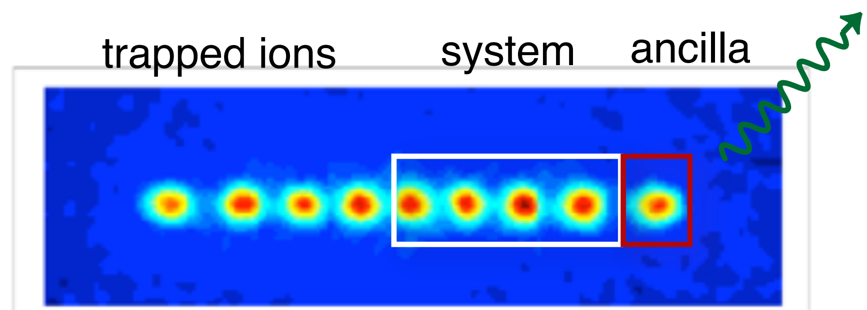
d-wave pairing

S. Diehl et al., PRL 2010

Diss. Quantum Phase transitions



Entangled States from Dissipation



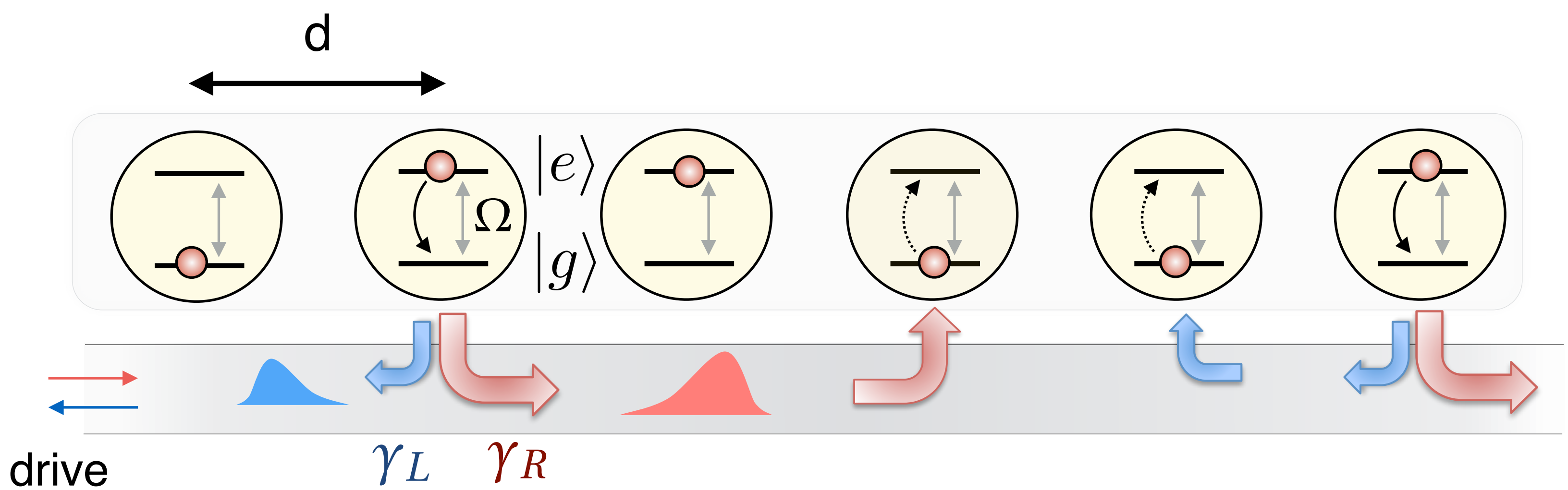
Exp. ions: Blatt et al., Nature '11; Nat Phys '13

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

Dynamics of spins coupled to a **chiral** waveguide



Special case:

- Distance **commensurate** with photon wavelength

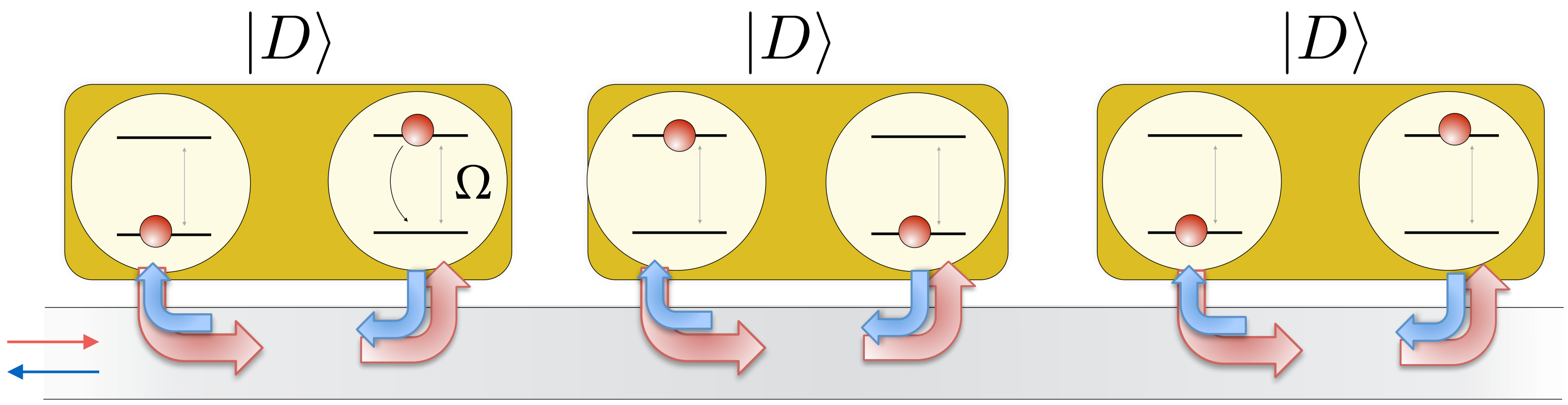
$$kd = 2\pi\mathbb{Z}$$

- **Equal Rabi frequencies** and **staggered detunings**

$$\Omega_i = \Omega$$
$$\delta_i = -\delta_{i+1}$$

For $\delta_i = 0,\ \gamma_L = \gamma_R \longrightarrow$ **Purely dissipative Dicke model**

Two-Level Atoms with ‘Chiral' Waveguide Coupling



open boundaries

entropy carried away

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

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

product of pure quantum spin-dimers

$$|D\rangle = \frac{1}{\sqrt{1+|\alpha|^2}}\left[|gg\rangle + \frac{\alpha}{\sqrt{2}}\underbrace{(|ge\rangle - |eg\rangle)}_{\text{singlet / EPR}}\right]$$

$$\alpha = \frac{\sqrt{2}\Omega}{\delta - i(\gamma_R - \gamma_L)/2}$$

singlet fraction

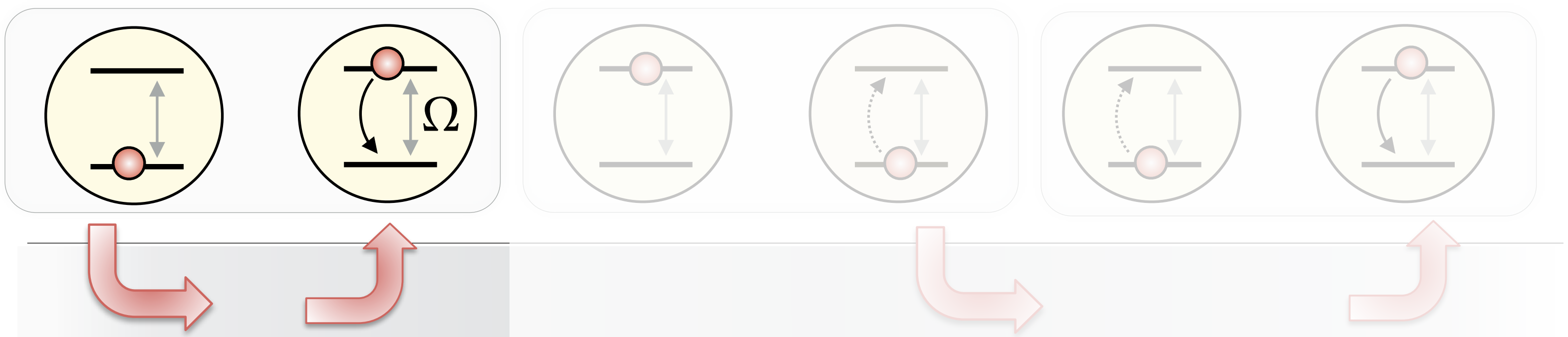
- Note: only for N even

Entanglement by Dissipation

N even: **cascaded**

$$\boxed{\gamma_L = 0}$$

- Iterative solution from left to right:

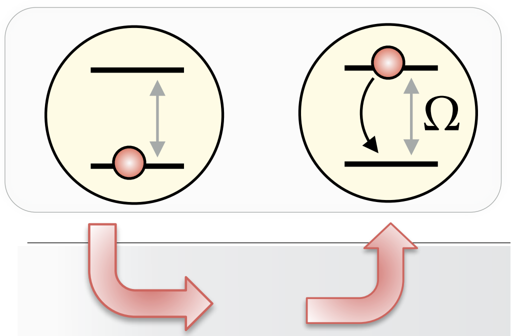


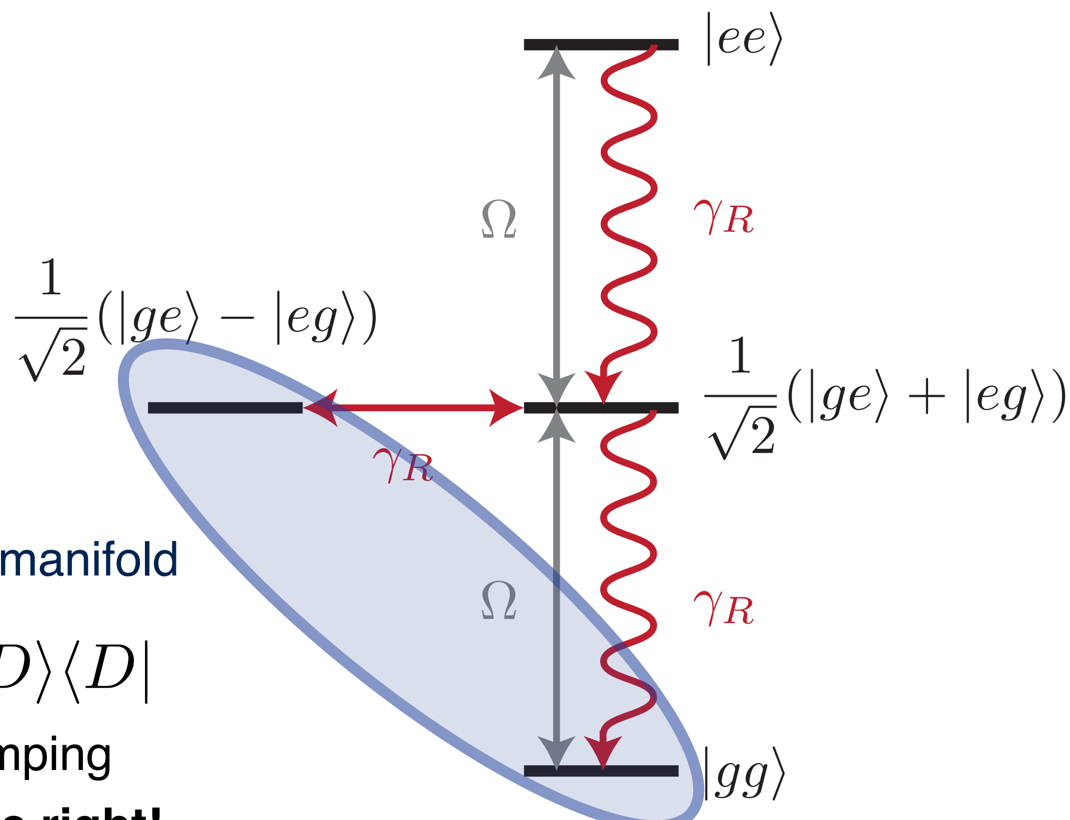
K. Stannigel et al. NJP (2012)

N spins? Consider **cascaded** case first

$\boxed{\gamma_L = 0}$

- Iterative solution from left to right:





Dark manifold

$$\rho_{1,2} \xrightarrow{t\to\infty} |D\rangle\langle D|$$

Dark state pumping

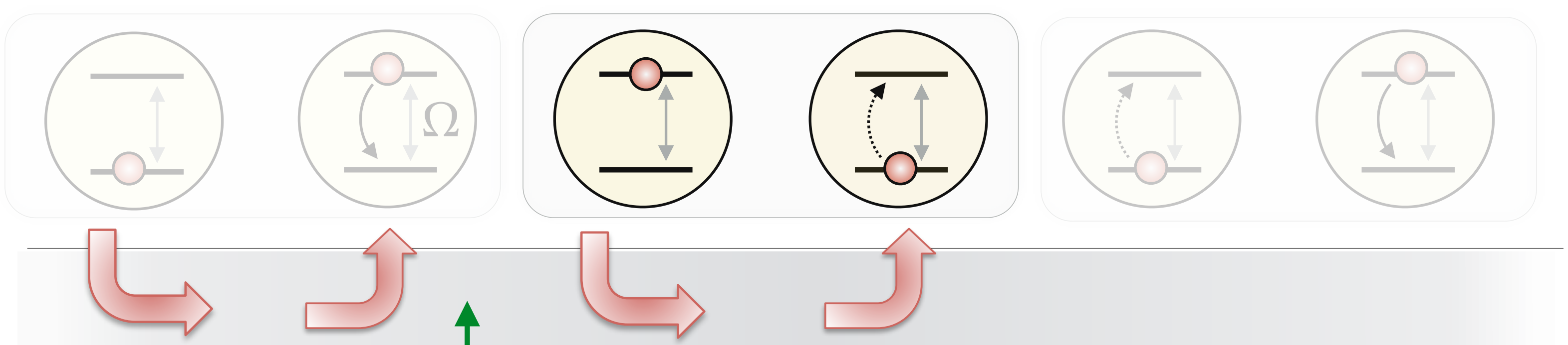
$\longrightarrow$ **No output on the right!**

N even: **cascaded**

$\gamma_L = 0$

- Iterative solution from left to right:

$|D\rangle$



Dark state

$\longrightarrow$ **No output on the right!**

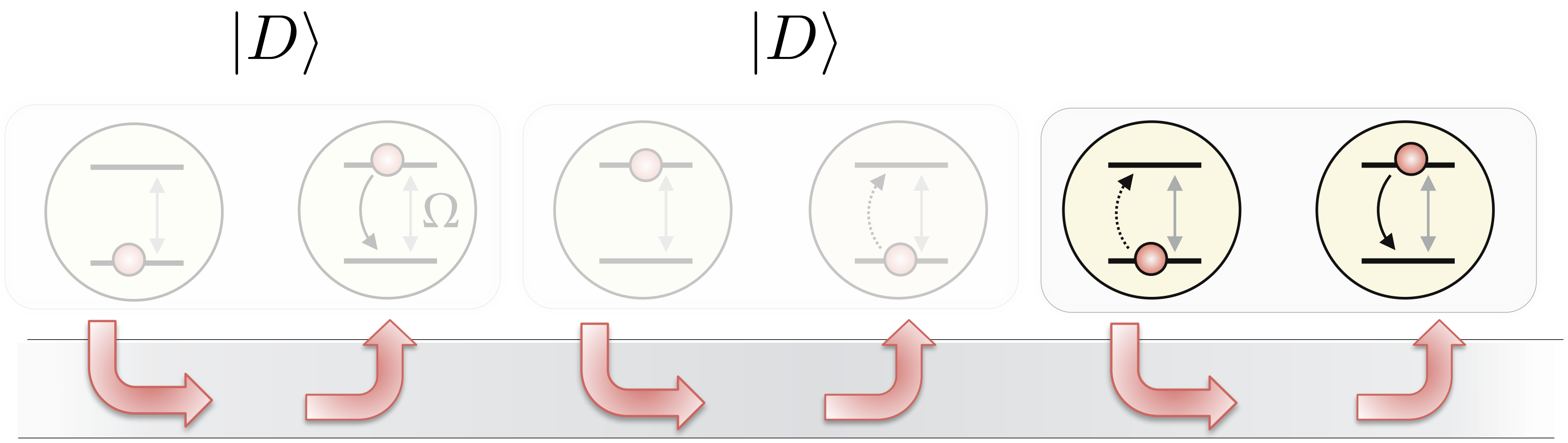
No input from the left $\longrightarrow |D\rangle$

quantum interference: no light

N even: **cascaded**

$$\boxed{\gamma_L = 0}$$

- Iterative solution from left to right:



Dark state

$\rightarrow$ **No output on the right!**

Dark state

$\rightarrow$ **No output on the right!**

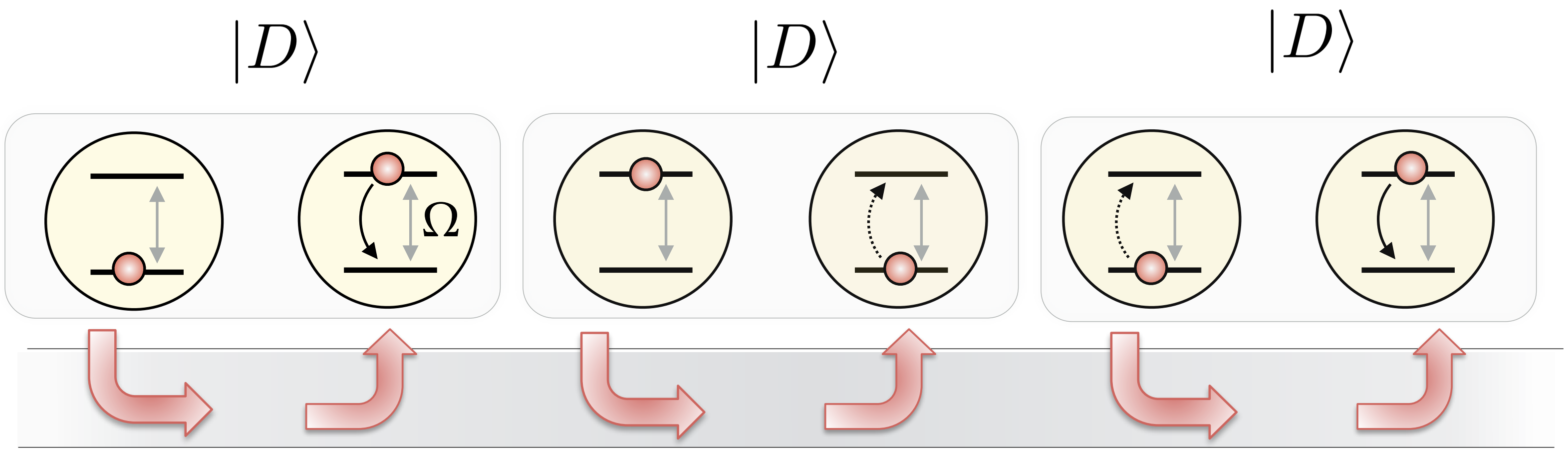
No input from the left

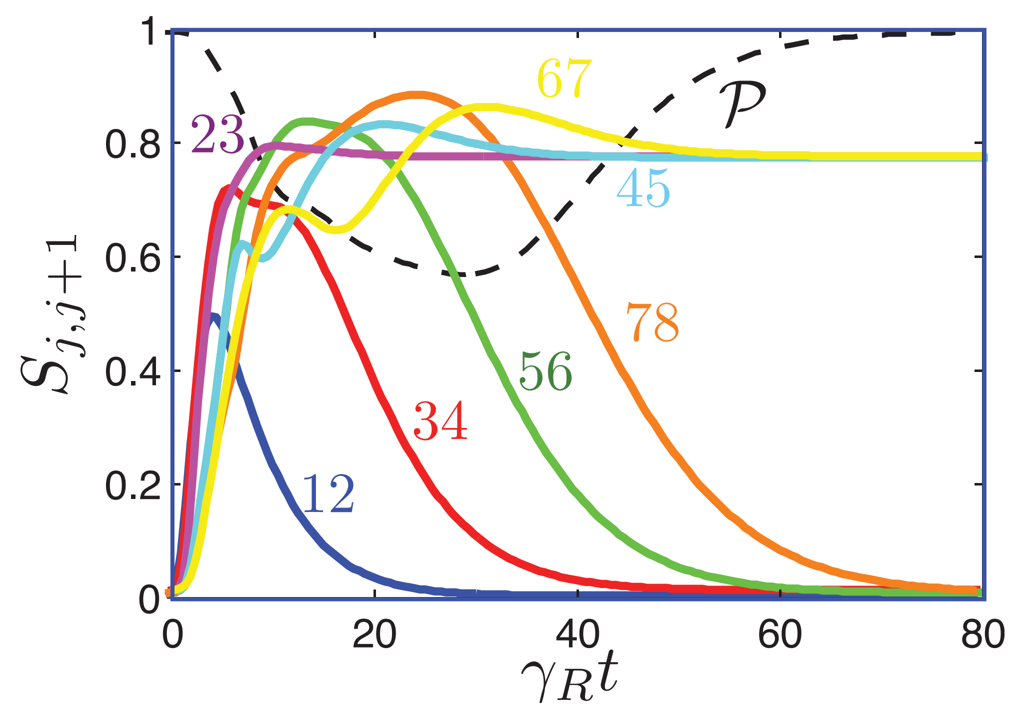
$\rightarrow |D\rangle$

N even: **cascaded**

$\boxed{\gamma_L = 0}$

- Iterative solution from left to right:





constant “**purification speed**"

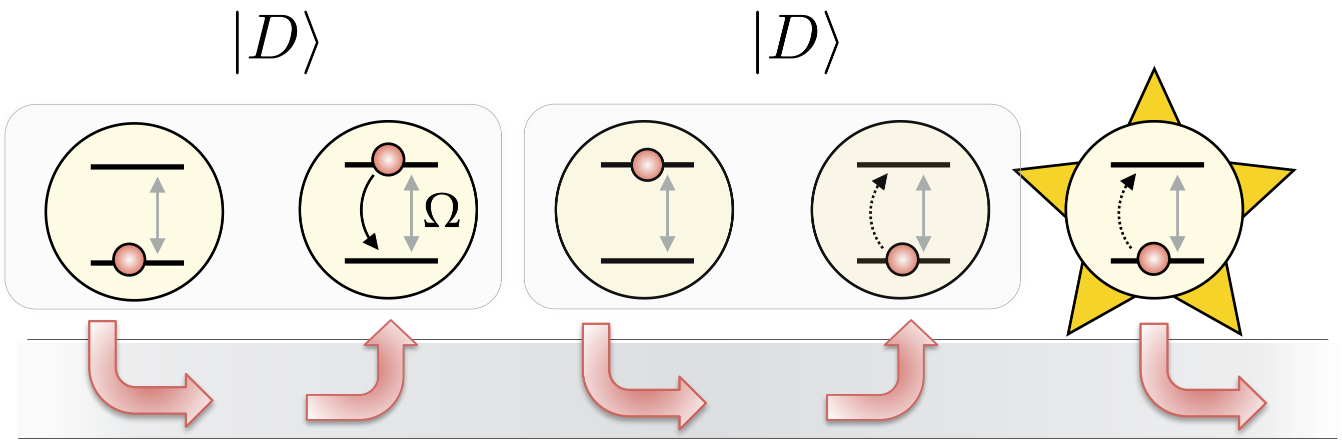
$\gamma_L/\gamma_R = 0$

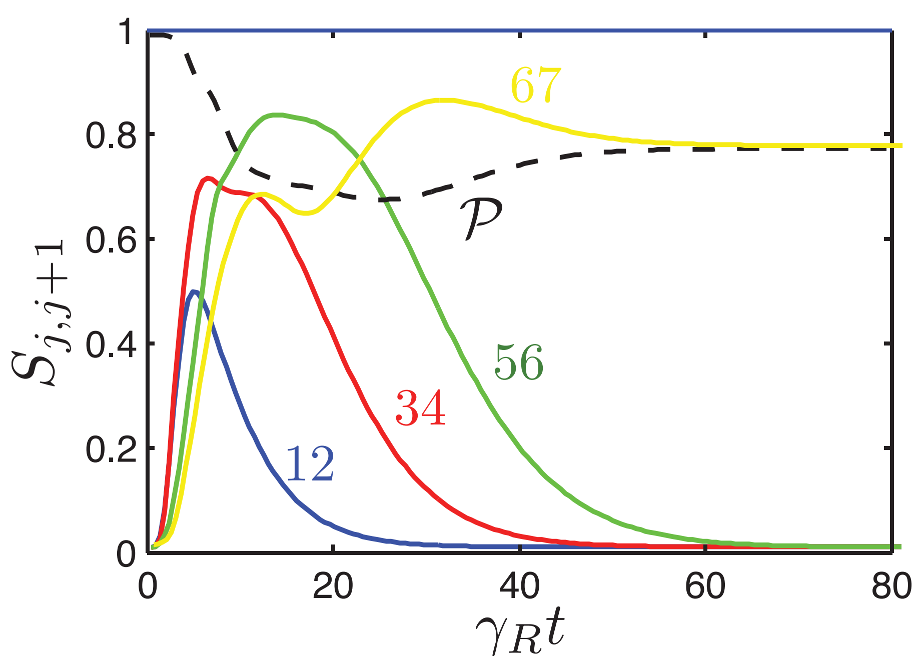
$\Omega/\gamma_R = 0.5$

N odd: **cascaded**

$\gamma_L = 0$

- Iterative solution from left to right:

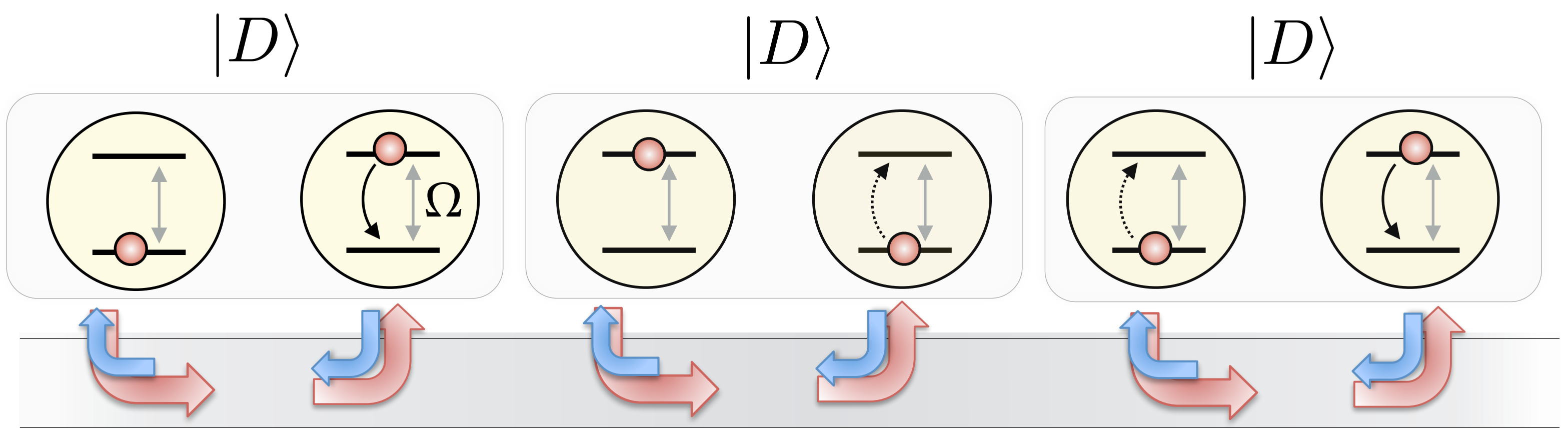


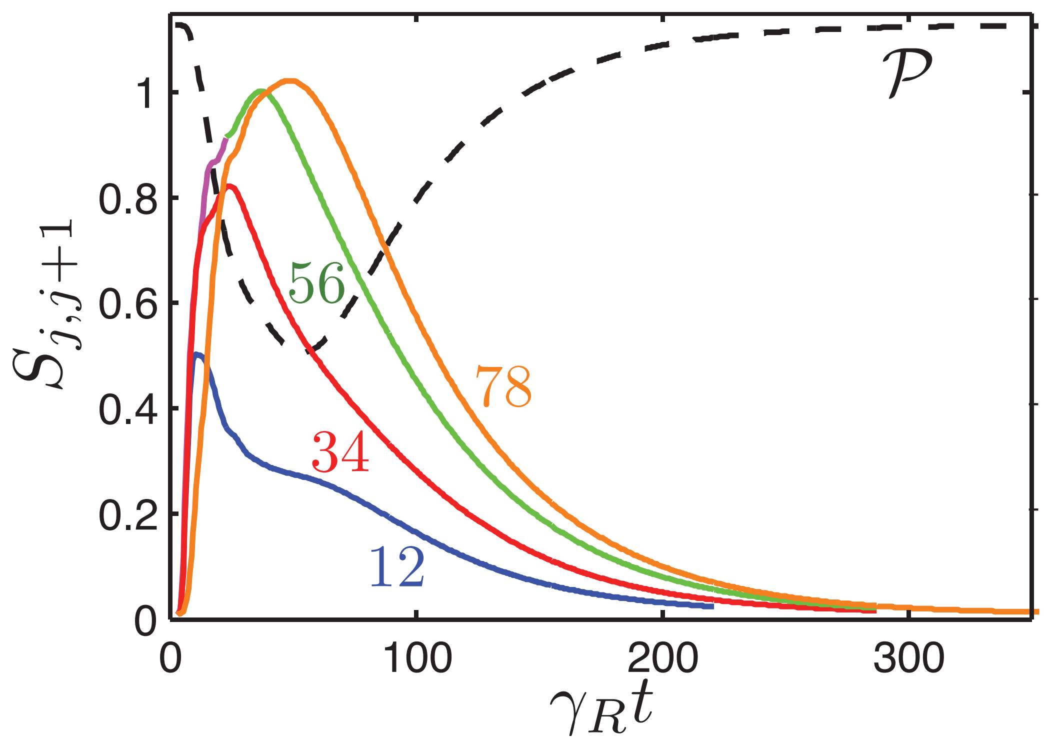


Last spin cannot pair up, but still dimers are formed

N even: **Chiral waveguide**

$\gamma_L \neq \gamma_R$





System purifies
"**as a whole**"

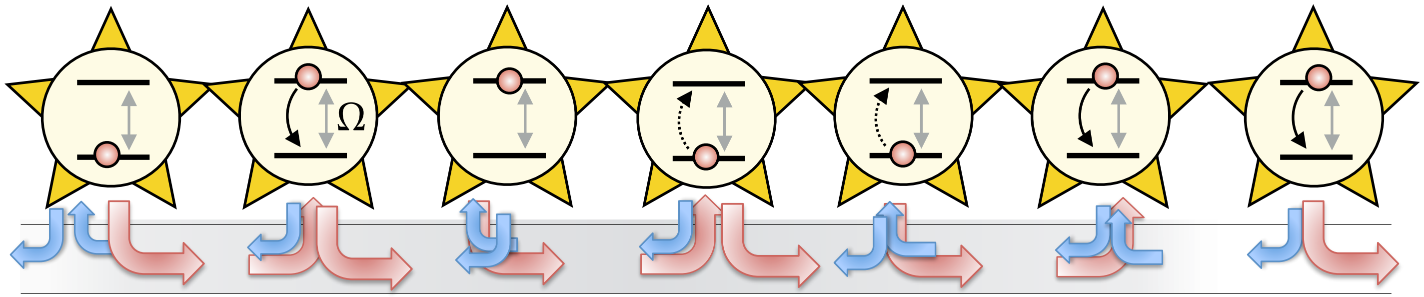
$\gamma_L/\gamma_R = 0.4$

$\Omega/\gamma_R = 0.5$

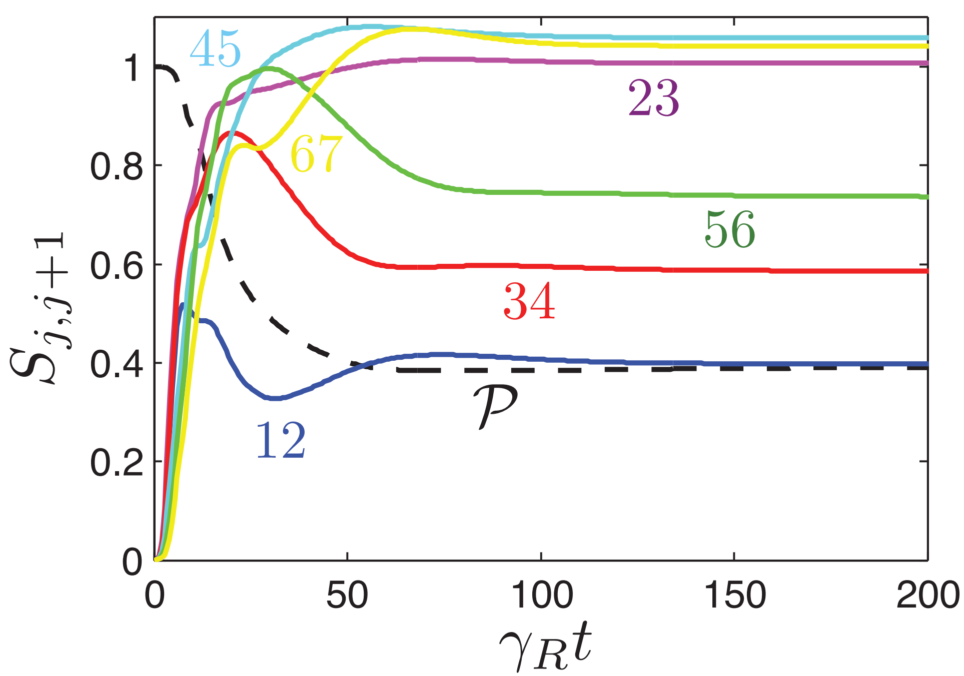
N odd: **chiral waveguide**

$\gamma_L \neq \gamma_R$

- **Odd** number of spins?



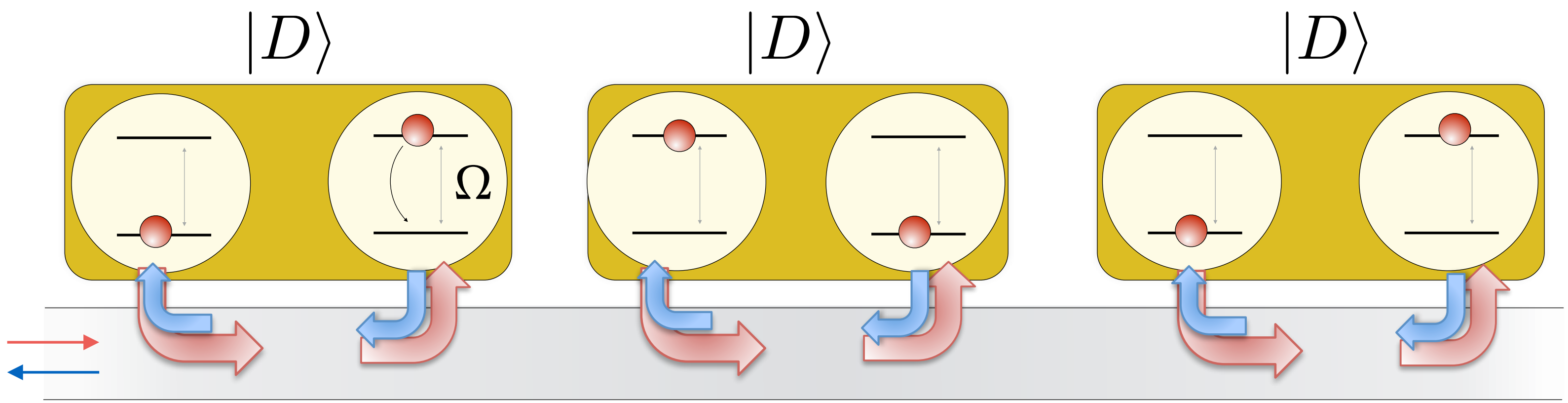
- Any **unpaired** spin destroyed the formed dimers: No dark state!

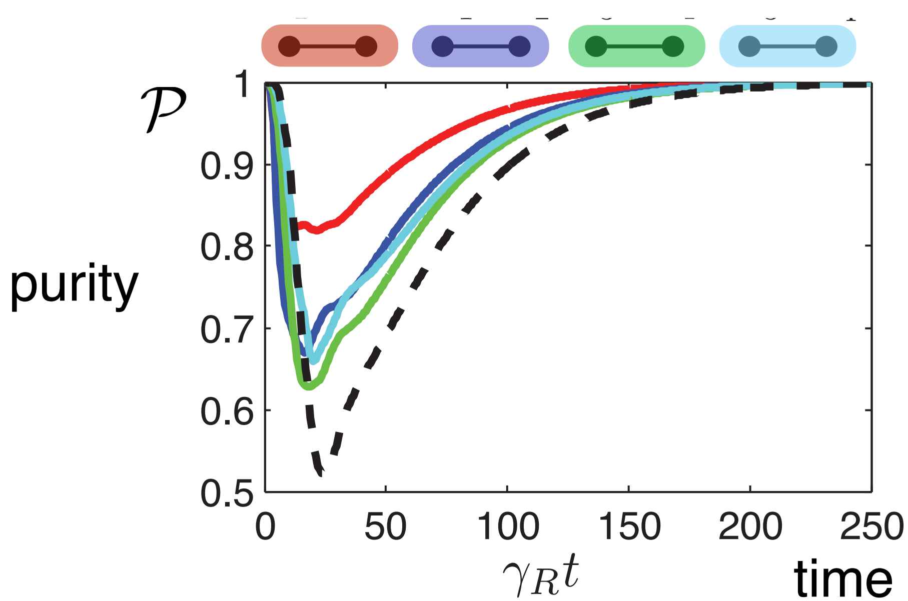


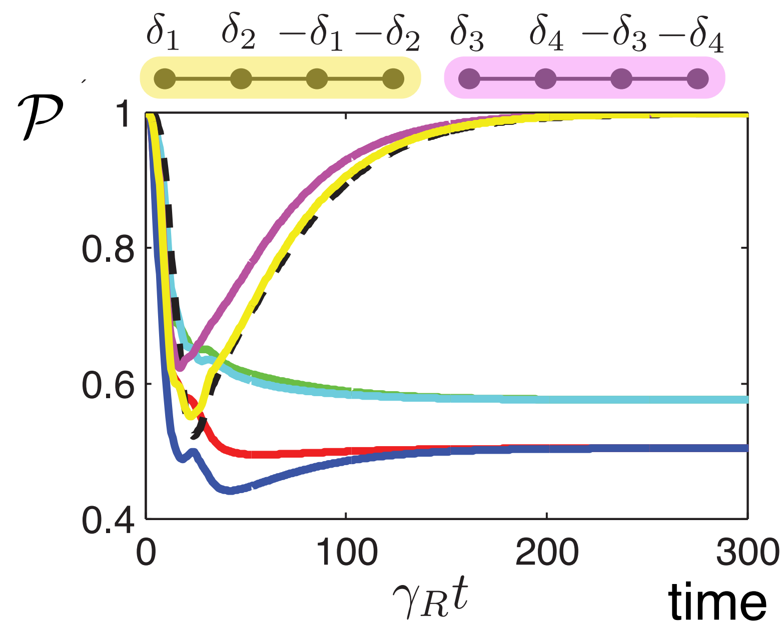
$\gamma_L/\gamma_R = 0.4$

$\Omega/\gamma_R = 0.5$

Dynamics of TLS coupled to a **chiral** waveguide





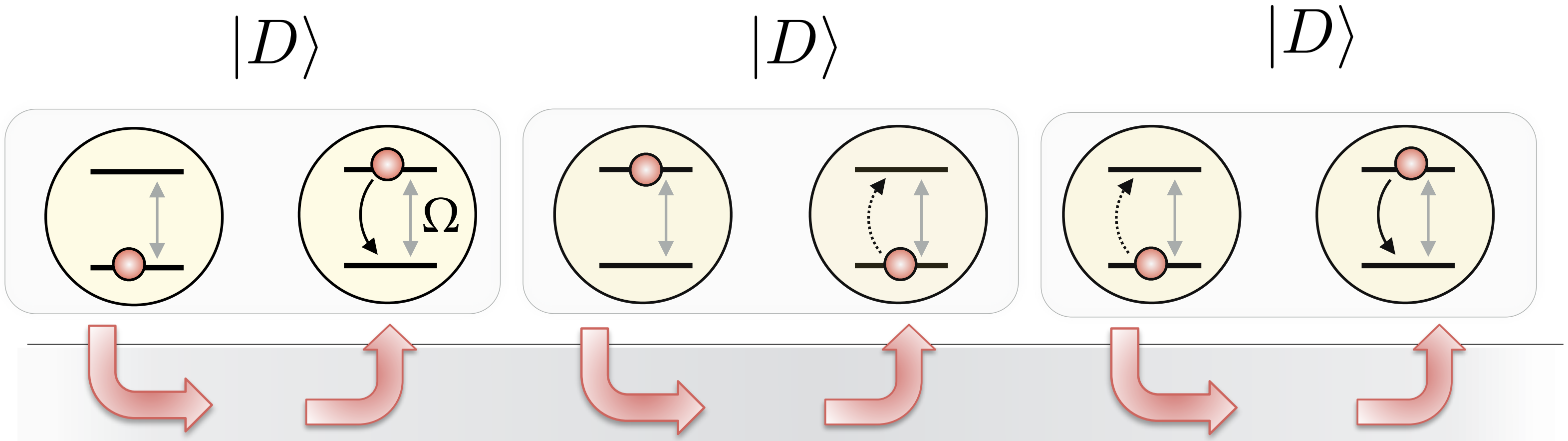


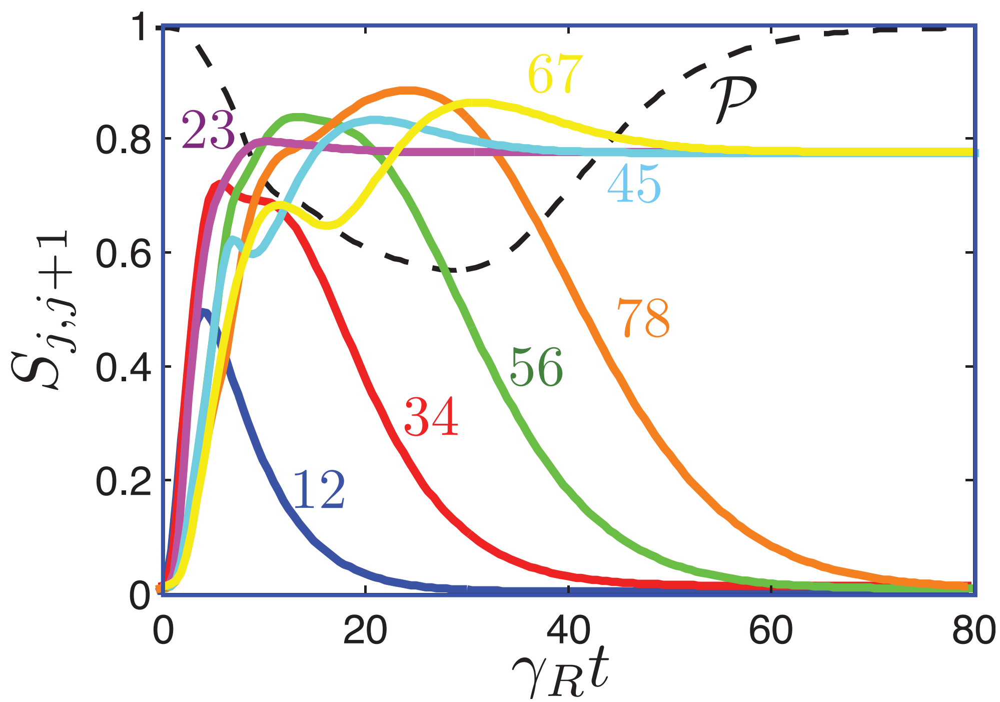
State of many-body spin system cools / purifies to a *pure* state of spin dimers, tetramers, hexamers, …

N even: **cascaded**

$$\boxed{\gamma_L = 0}$$

- Iterative solution from left to right:





constant "**purification speed**"

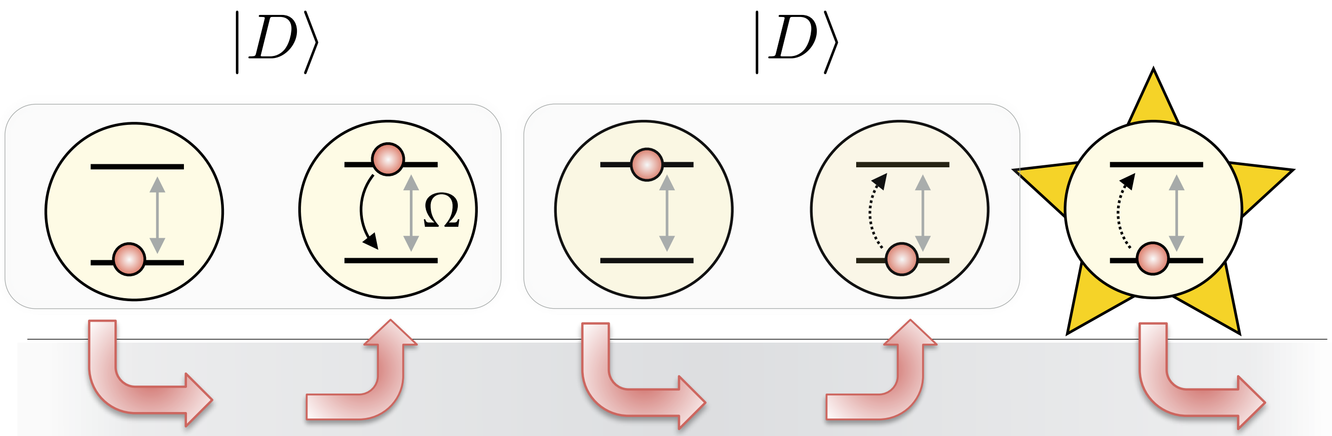
$$\gamma_L/\gamma_R = 0$$

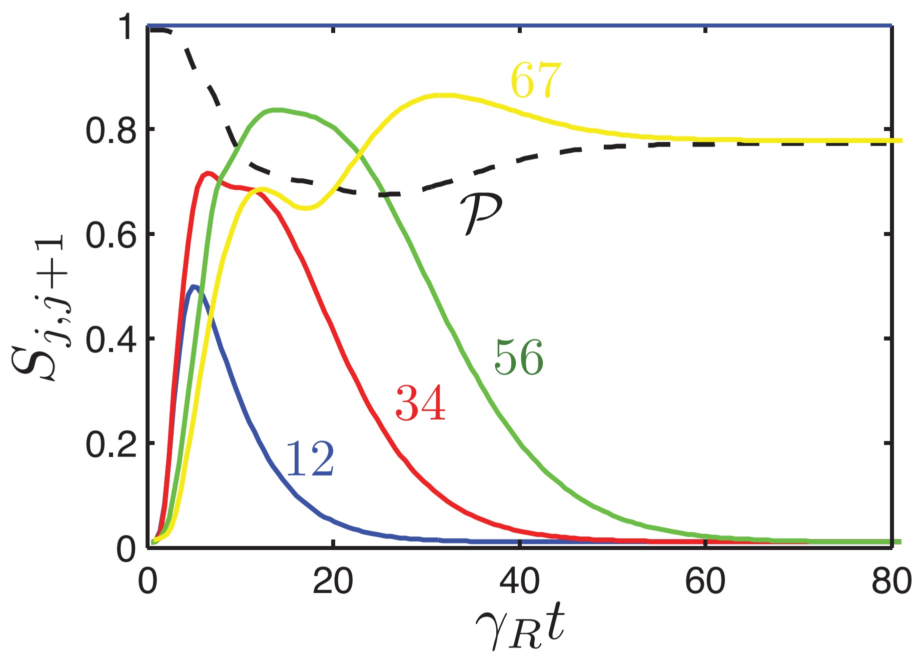
$$\Omega/\gamma_R = 0.5$$

N odd: **cascaded**

$\gamma_L = 0$

- Iterative solution from left to right:





Last spin cannot pair up, but still dimers are formed

Other realizations … and more insight?

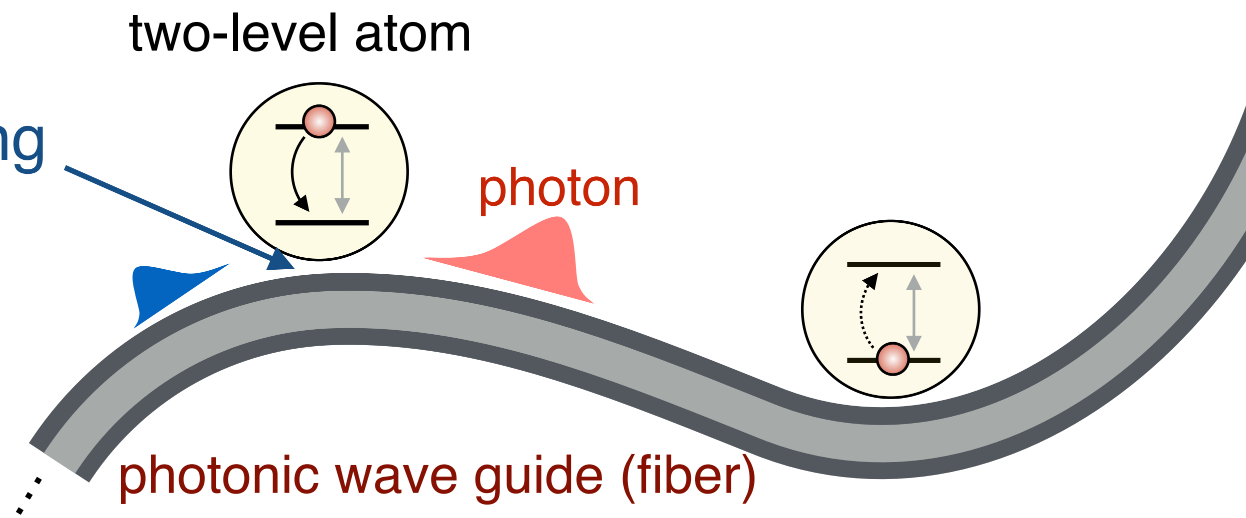
'Chiral' Couplings & 'Chiral' Networks with …

- “photonic" wave-guides
- "phononic"
- spin waves [quantum spintronics]

- theory *beyond* Born-Markov using tDMRG techniques

- **Chirality / Photonic Nanostructures**

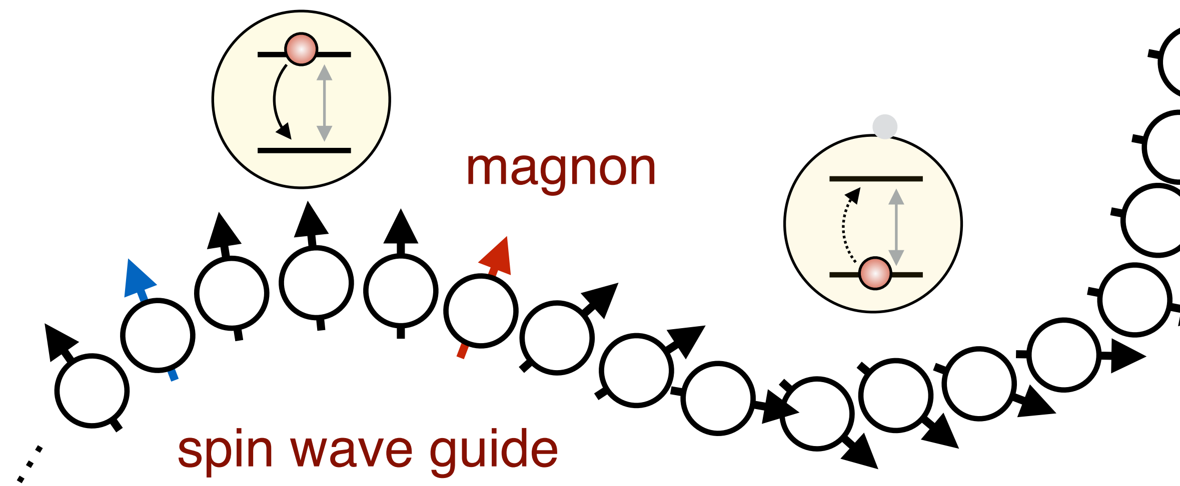
chiral = asymmetric coupling
of atom to wave guide



- **Chiral “Spin Wave Guide"**

chiral coupling - how?

below: Rydberg atom
implementation



✓ magnon = ‘hard core’ bosons
✓ quantum optics with spins

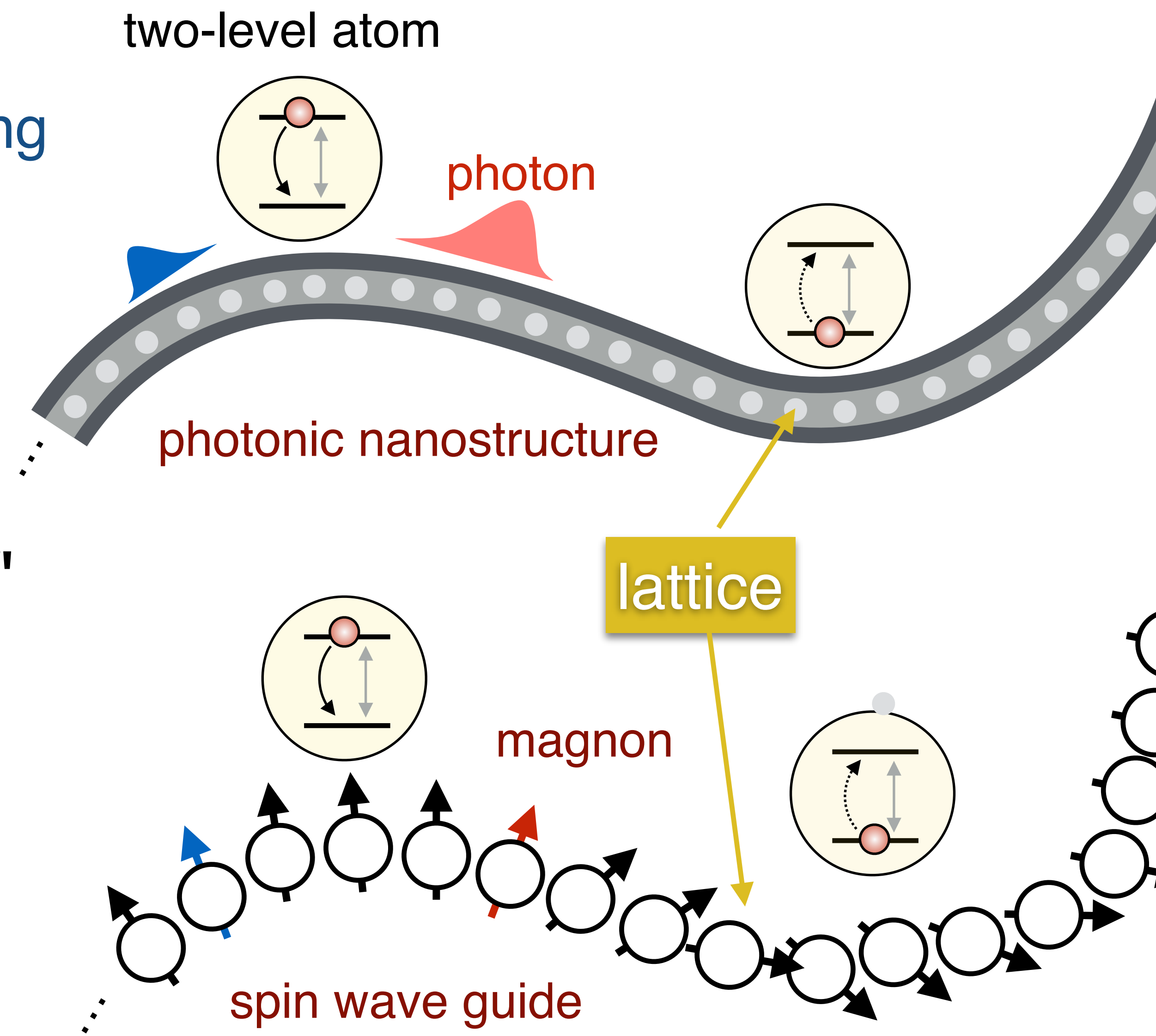
- **Chirality / Photonic Nanostructures**

chiral = asymmetric coupling of atom to wave guide

- **Chiral “Spin Wave Guide"**

chiral coupling - how?

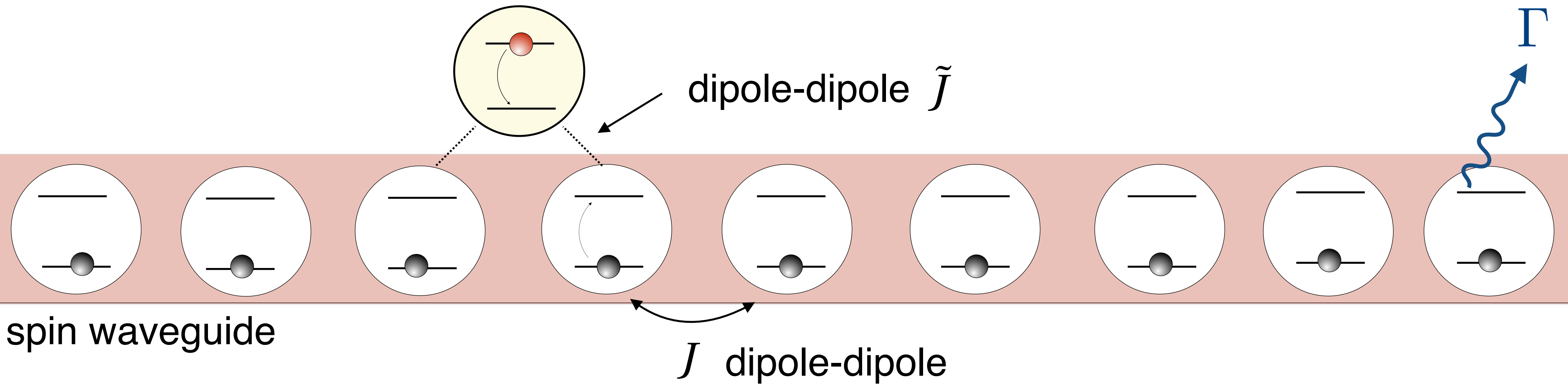
below: all-cold atom implementation



- **theory *beyond* Born-Markov: tDMRG techniques for spin chains**

'Chiral' Quantum Optics with Spin Waveguides

- **spin waveguide**

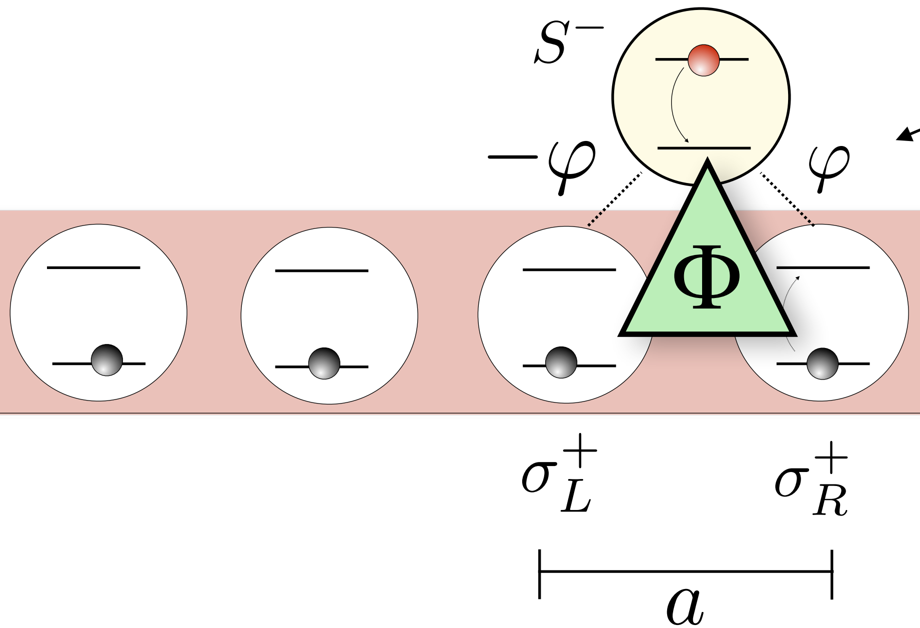


T. Ramos, B. Vermersch, P. Hauke, H. Pichler, and PZ, PRA 2016, *Non-Markovian Chiral Networks*

B. Vermersch, T. Ramos, P. Hauke, and PZ, PRA 2016, *Implementation with Rydberg Atoms and Ion Strings*

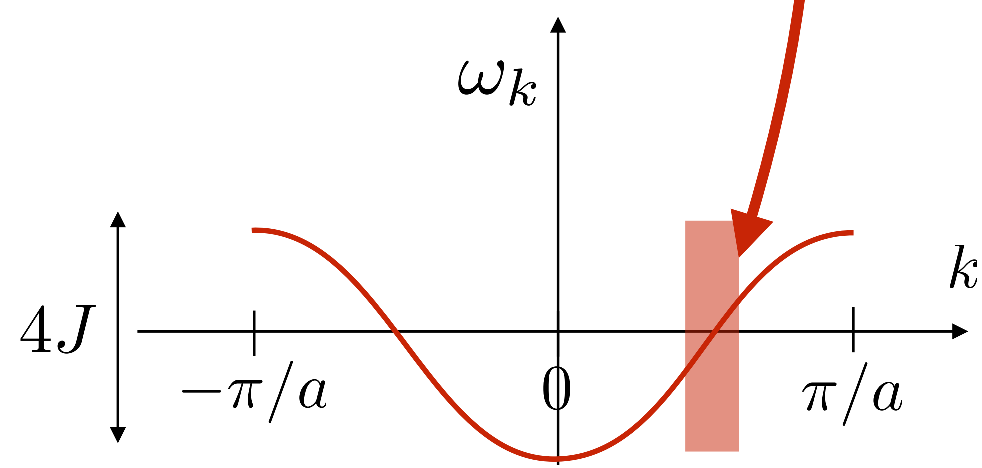
'Chiral' Couplings with Spin Chains

- **spin waveguide**



$$H_{\text{int}} \sim S^-(\sigma_L^\dagger e^{-i\varphi} + \sigma_R^\dagger e^{i\varphi}) + \text{h.c.}$$

$$H_R = -J \sum_i \sigma_i^+ \sigma_{i+1}^- + \text{h.c.}$$

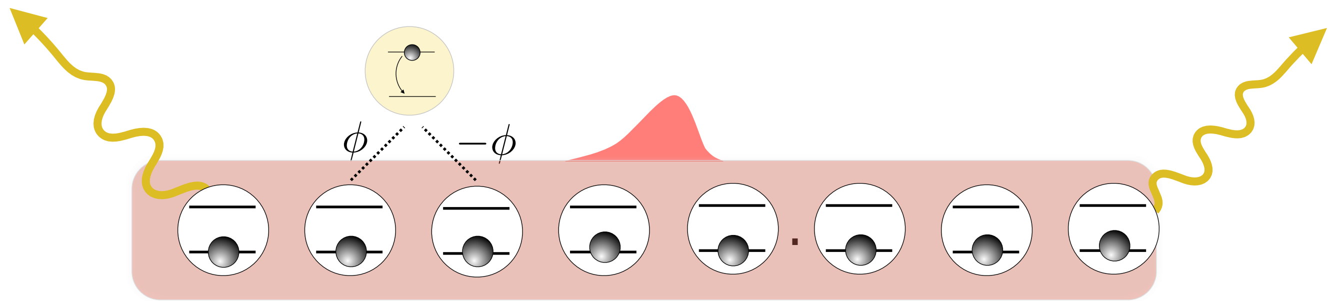


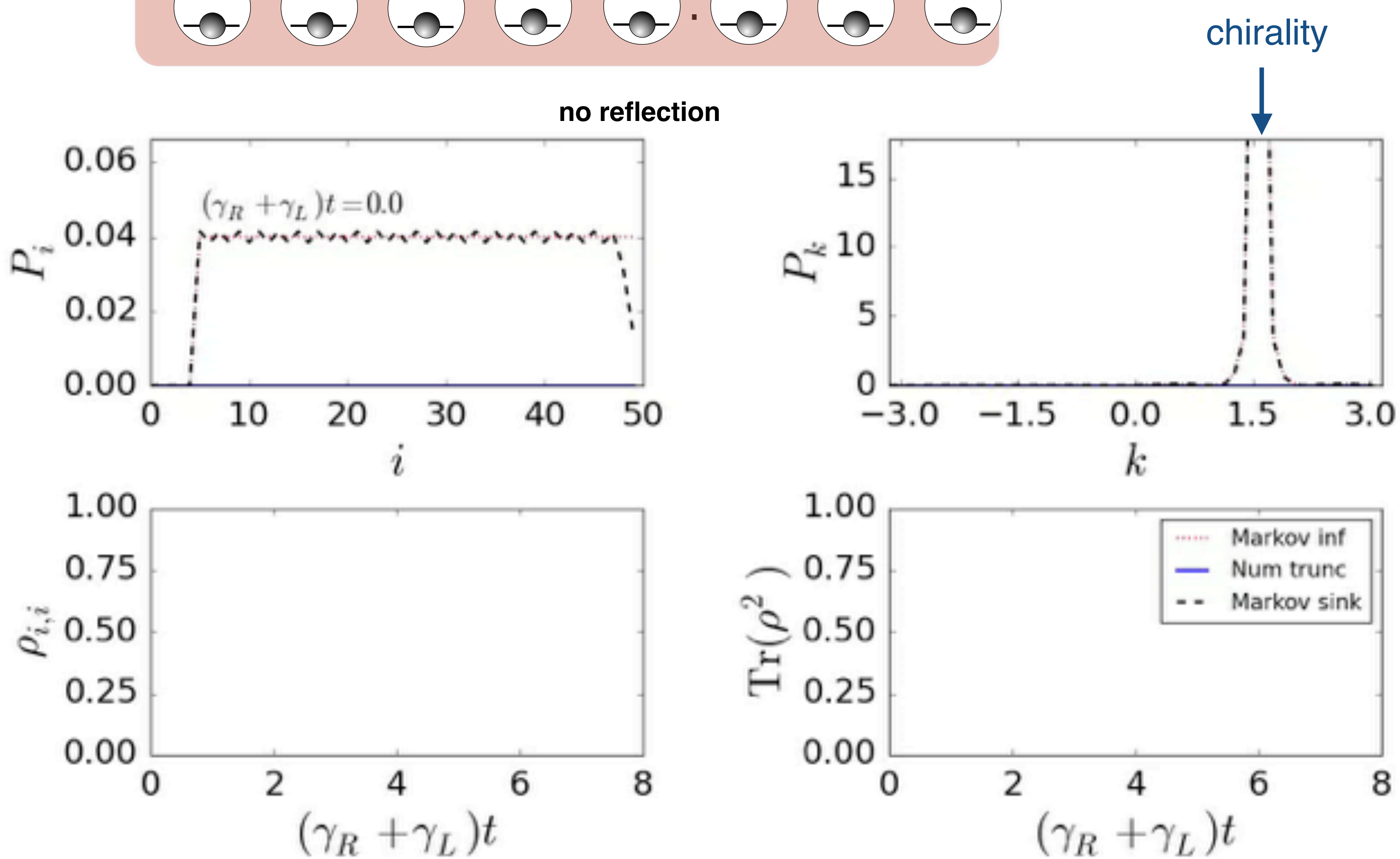
$$\varphi \approx \pi/4$$

Strong Chirality

= synthetic gauge field

‘Chiral’ exponential decay into the spin waveguide



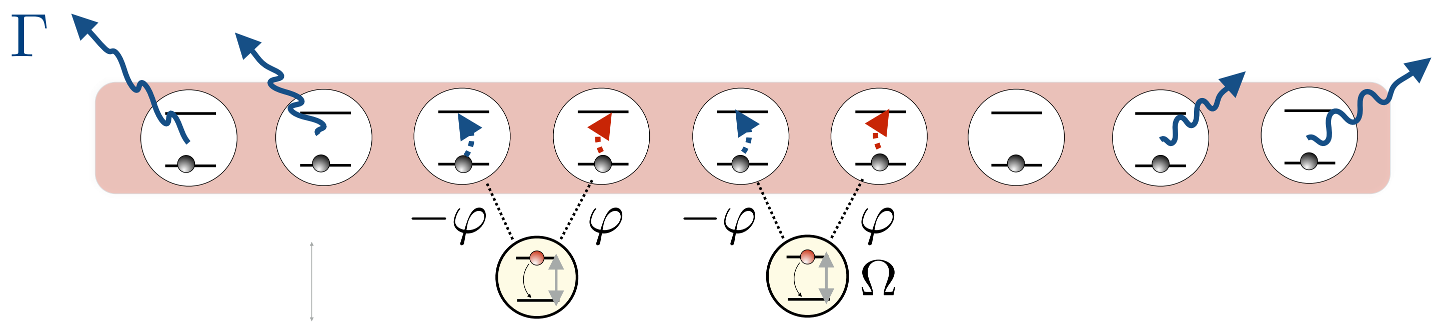


Dimer formation: system + reservoir dynamics

$$\boxed{\varphi = \pi/6}$$

↓

chiral case

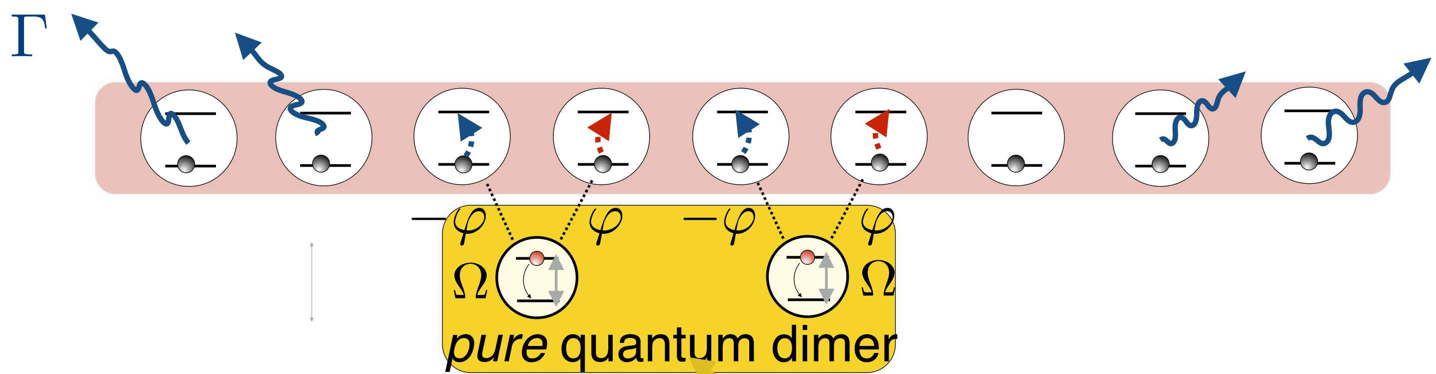


Dimer formation: system + reservoir dynamics

$\boxed{\varphi = \pi/6}$

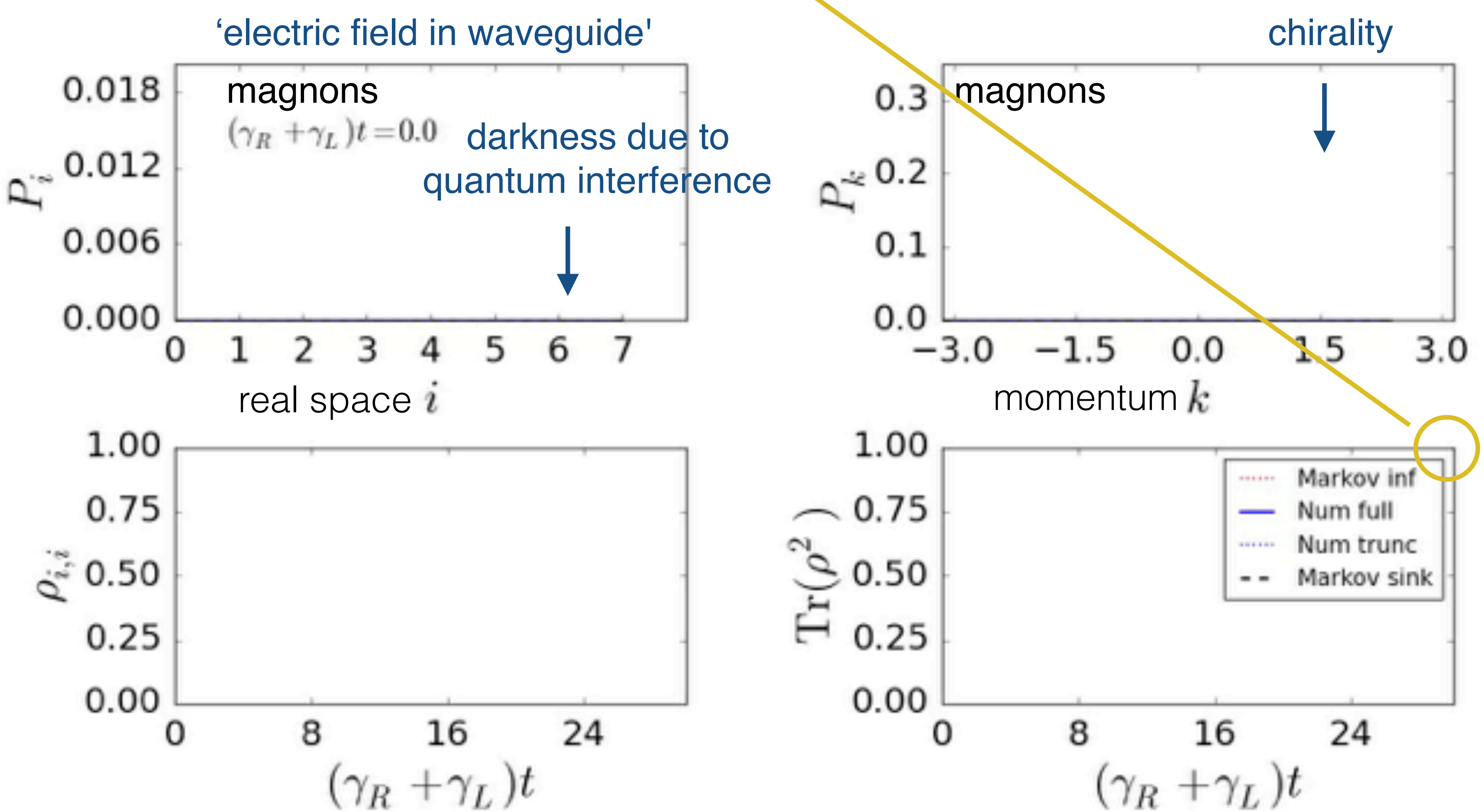
↓

chiral case

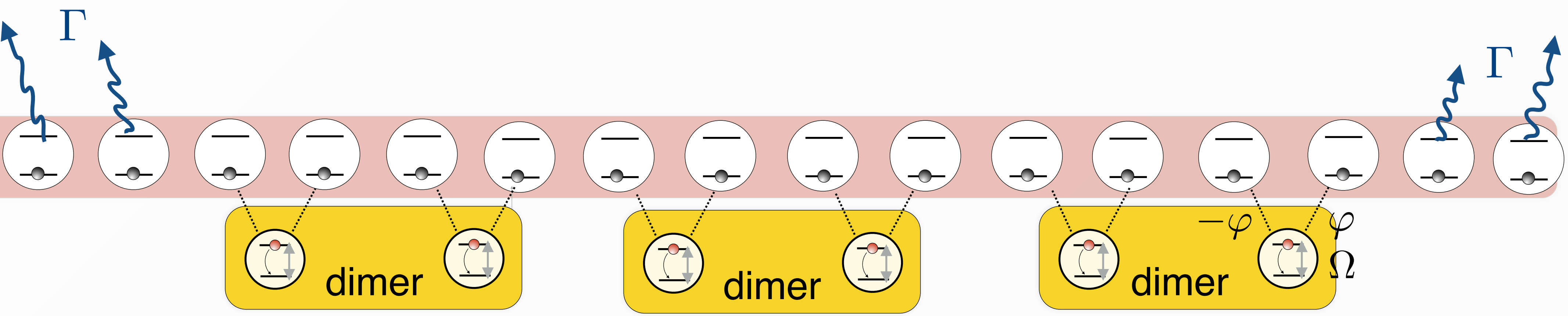


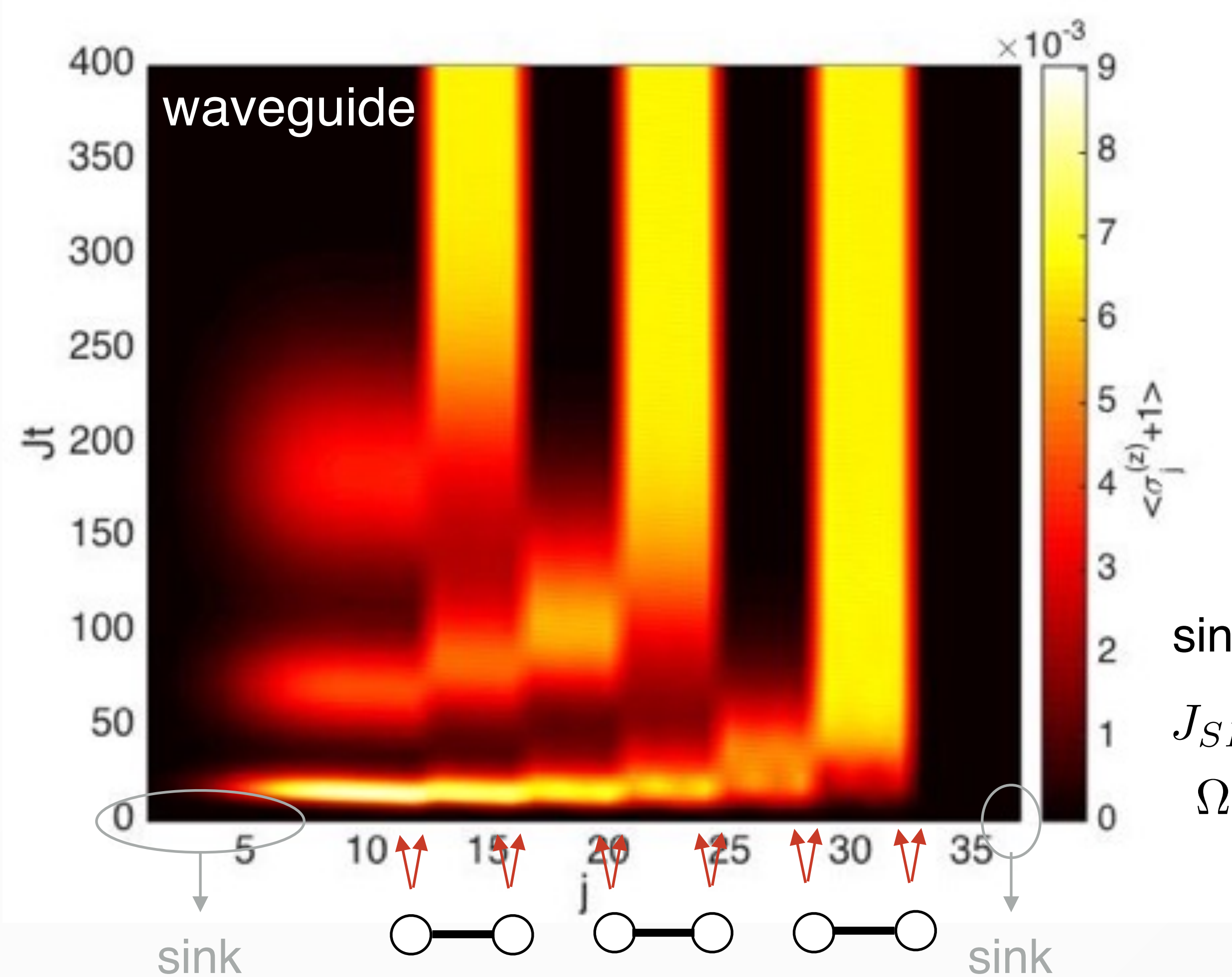
reservoir spins:

system: spins



tDMRG + quantum trajectories [beyond Born-Markov]





single trajectory

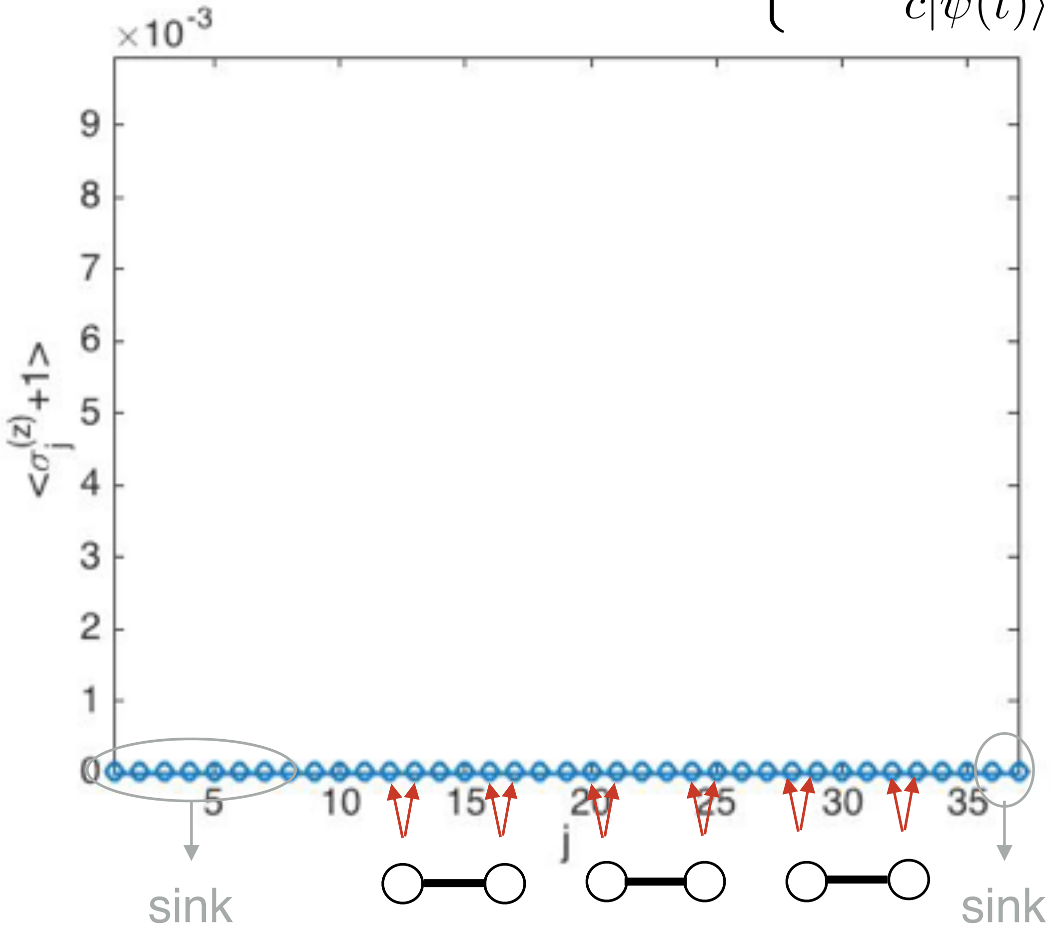
$J_{SR}/J = 0.2;$

$\Omega/J = 0.04;$

tDMRG + quantum trajectories

Hannes Pichler

- **Larger reservoirs:** tDMRG $\psi_{i_1,\ldots,i_N} = \mathrm{tr}\{A[1]^{i_1} A[2]^{i_2} \cdots A[N]^{i_N}\}$
- Sink: wave function trajectories $|\psi(t+dt)\rangle \sim \begin{cases} e^{-\frac{i}{\hbar} H_{\mathrm{eff}} dt} |\psi(t)\rangle & \text{no jump} \\ c|\psi(t)\rangle & \text{jump} \end{cases}$



single trajectory

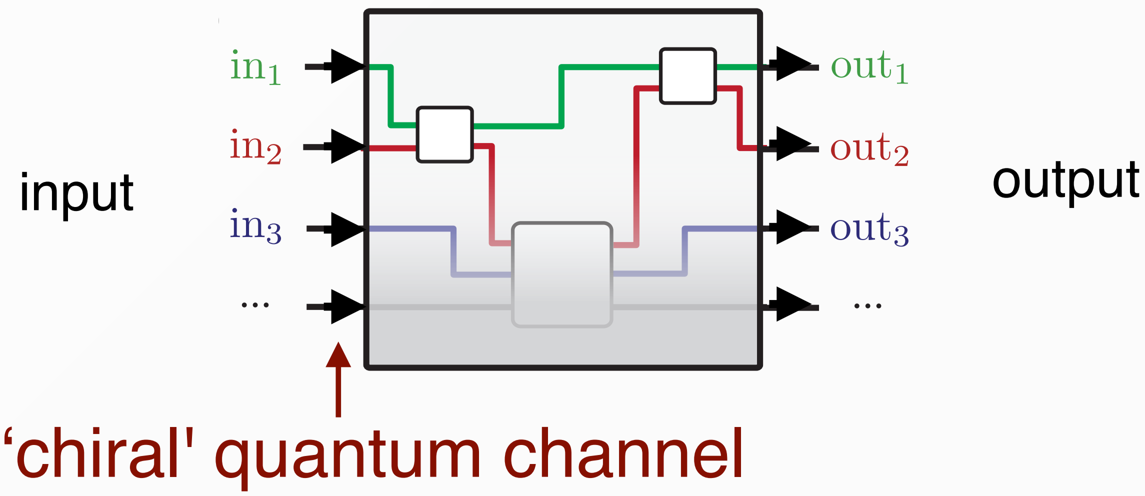
$J_{SR}/J = 0.2;$

$\Omega/J = 0.04;$

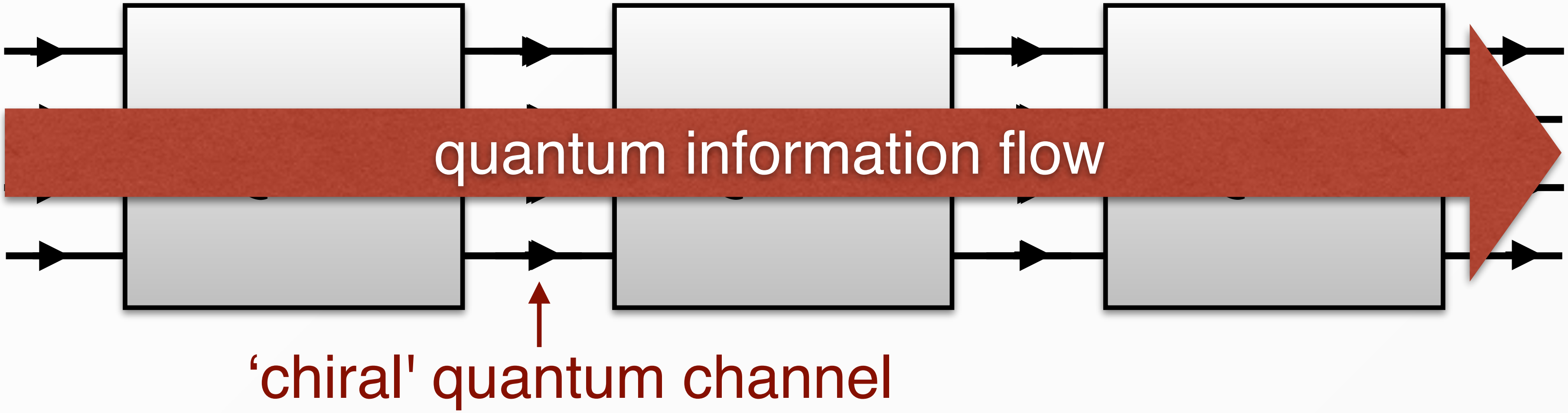
Review: Quantum trajectories & open many-body quantum systems, AJ Daley - Advances in Physics, 2014

'Wiring Up' Quantum Modules:

‘Chiral’ Quantum Circuits with Photons & Spins

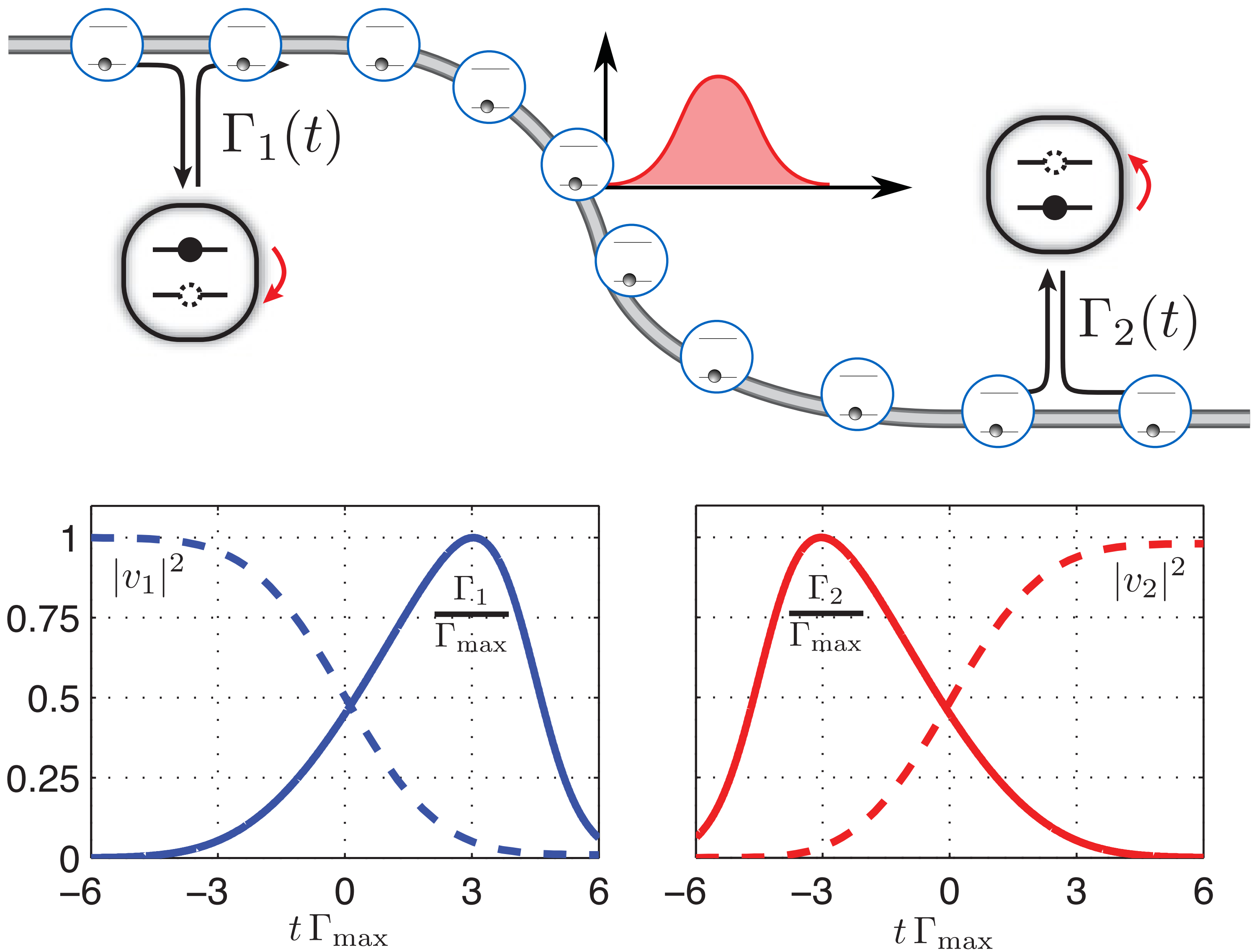


'Wiring Up' Quantum Modules:
‘Chiral’ Quantum Circuits with Photons & Spins



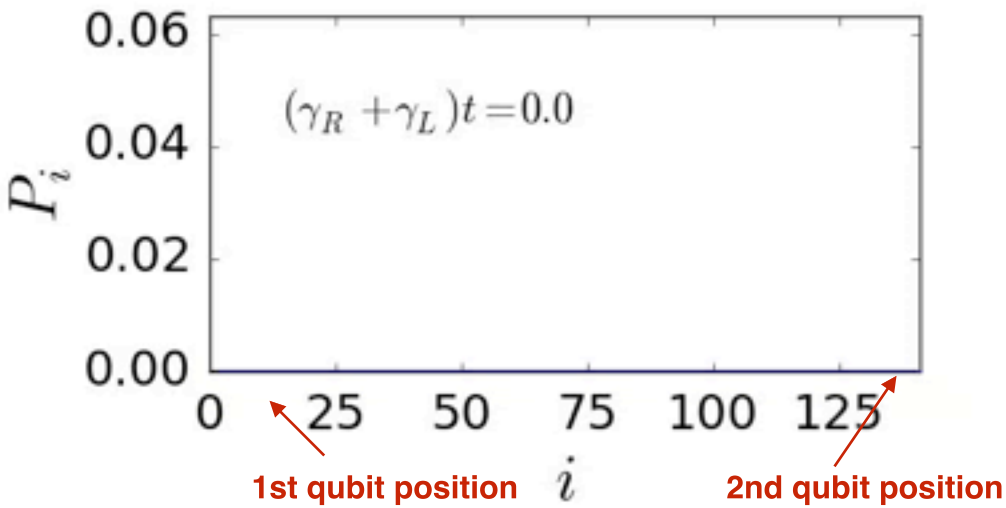
Quantum State Transfer in a Spin Chain

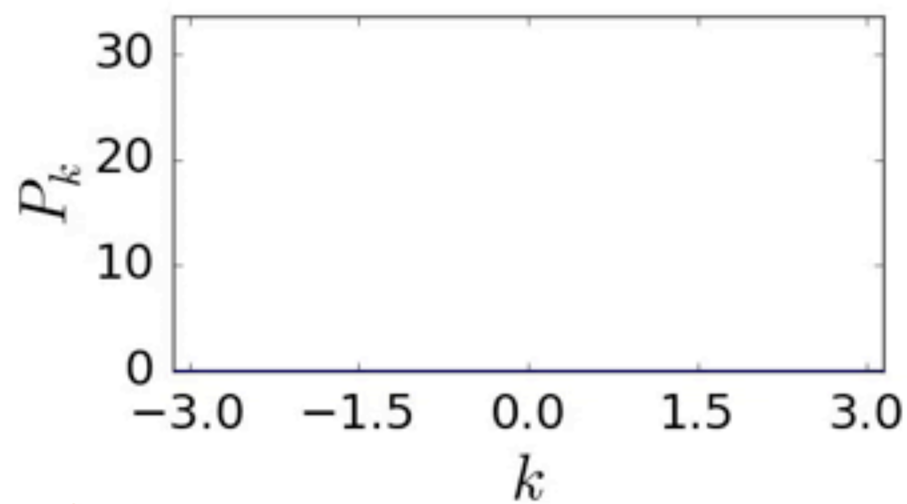
$$(\alpha\,|0\rangle_i + \beta\,|1\rangle_i)\,|0\rangle_j \longrightarrow |0\rangle_i\,(\alpha\,|0\rangle_j + \beta\,|1\rangle_j)$$

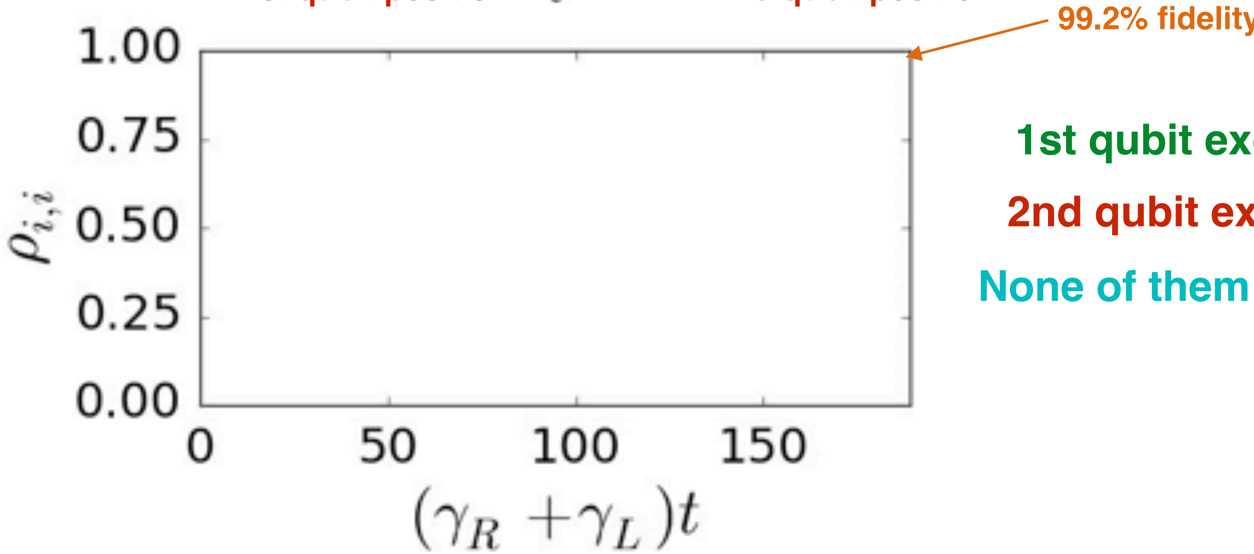


Quantum State Transfer in a 140 site Spin Chain

(cascaded,no sink)







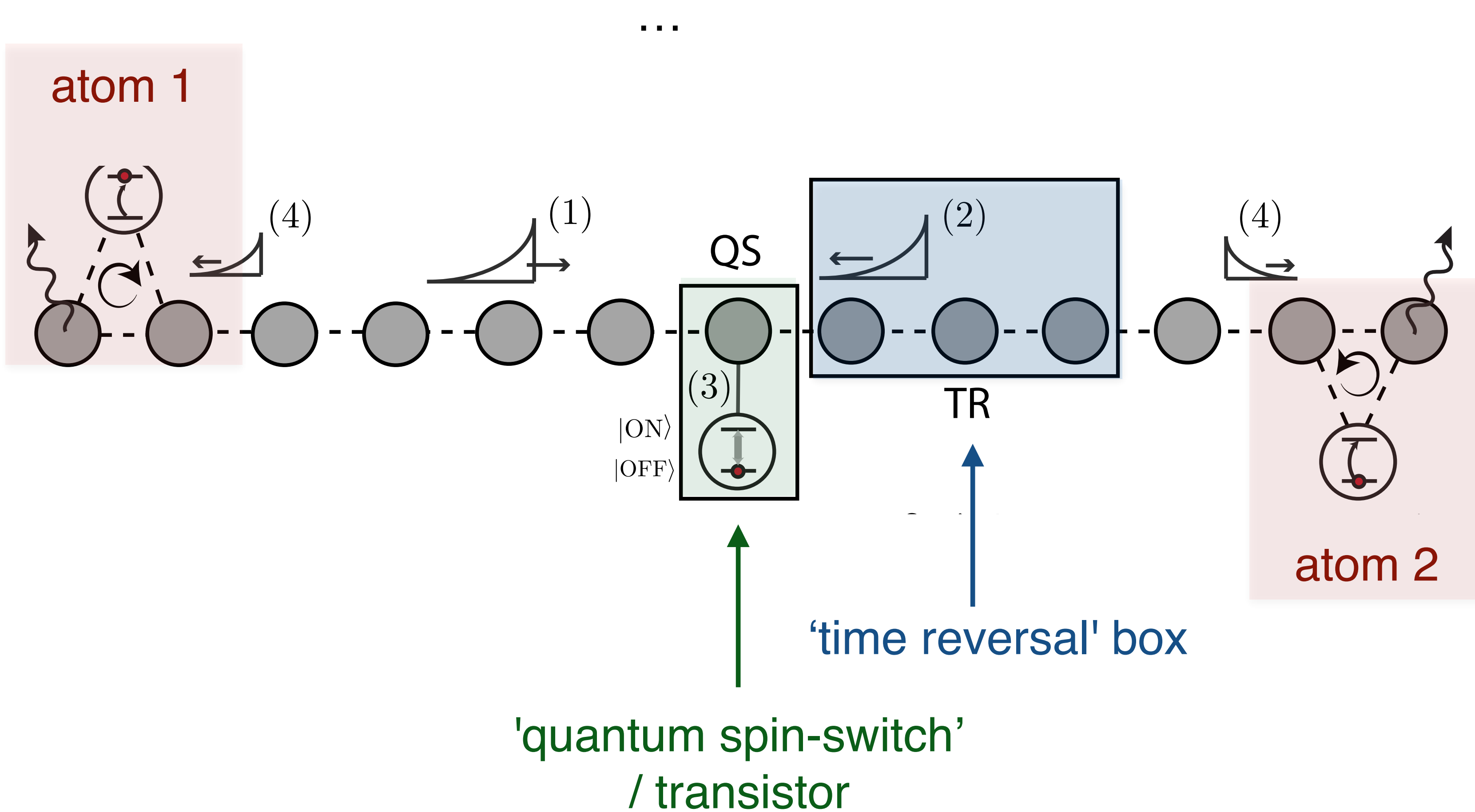
1st qubit excited

2nd qubit excited

None of them is excited

Wiring up quantum-gadgets

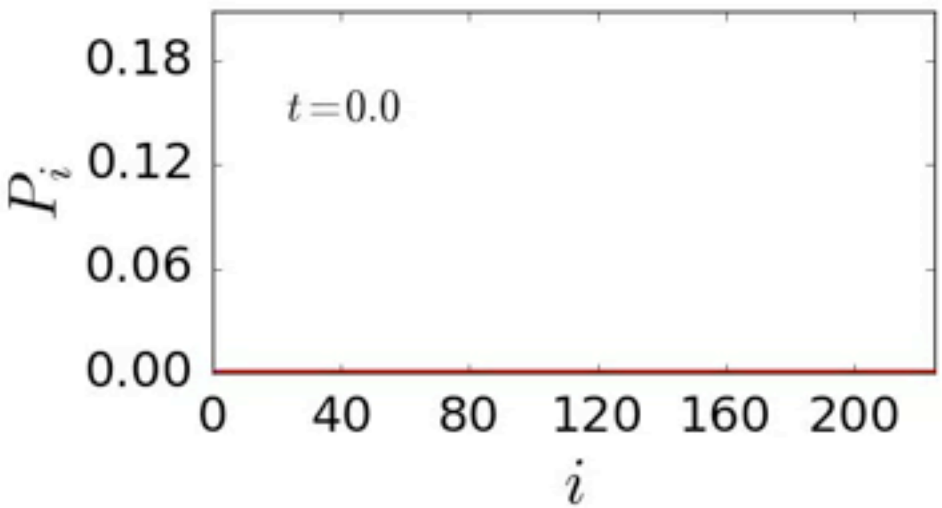
Time Reversal of a Wave Packet



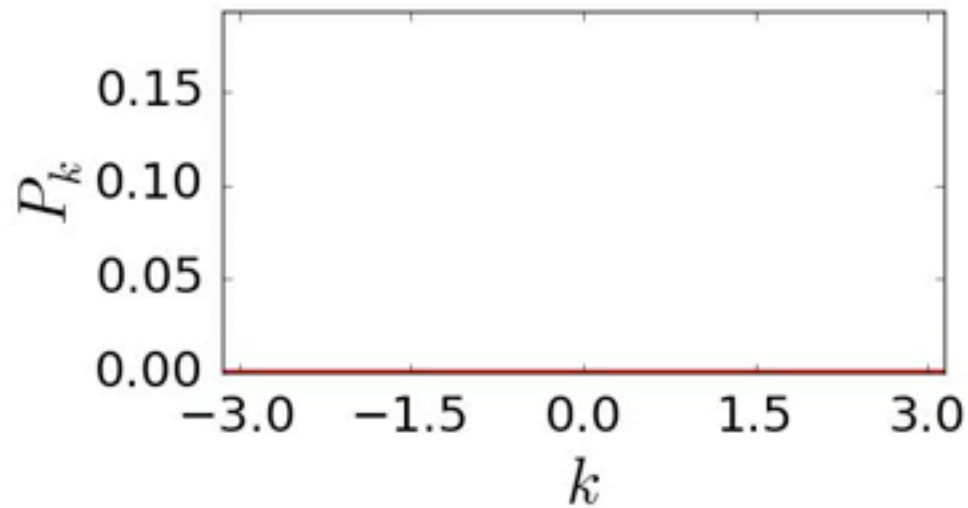
see also: Time reversal with photons, Mehmet Fatih Yanik and Shanhui Fan, Phys. Rev. Lett. 2004

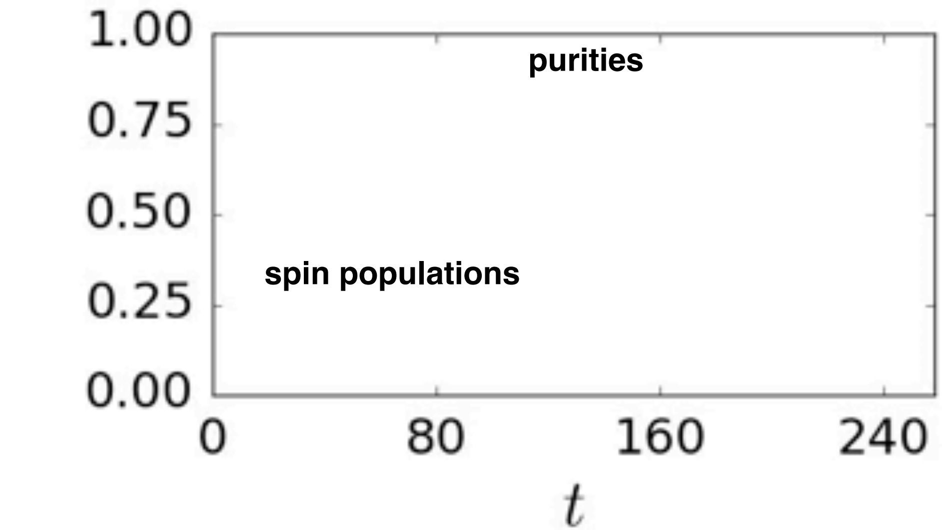
Time Reversal + Quantum Switch

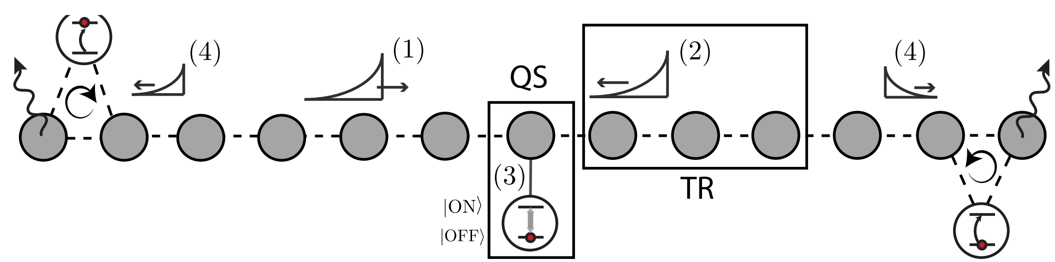
Bath (real space)



Bath (Fourier space)

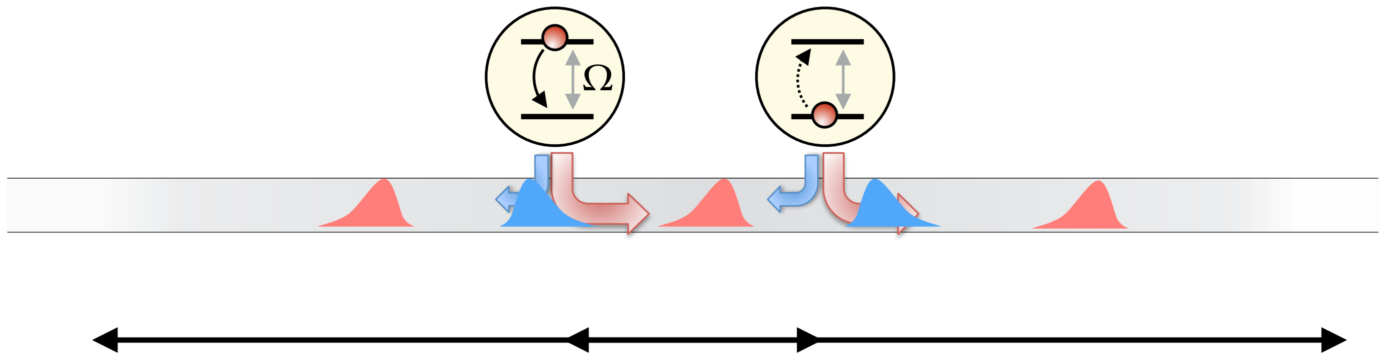






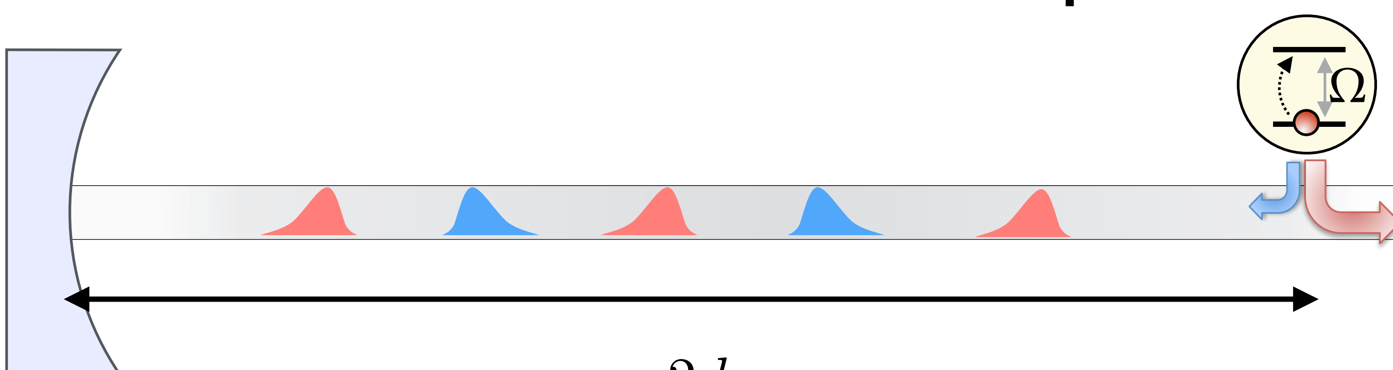
Photonic Circuits: Quantum Feedback *with Delays*

- **Model 1: two driven atoms with a delay line**



$$\gamma\tau = \gamma\frac{2d}{c} \cancel{\gg} 1$$ So far neglected

- **Model 2: driven atom in front of mirror = quantum feedback**



$$\gamma\tau = \gamma\frac{2d}{c} \gg 1$$

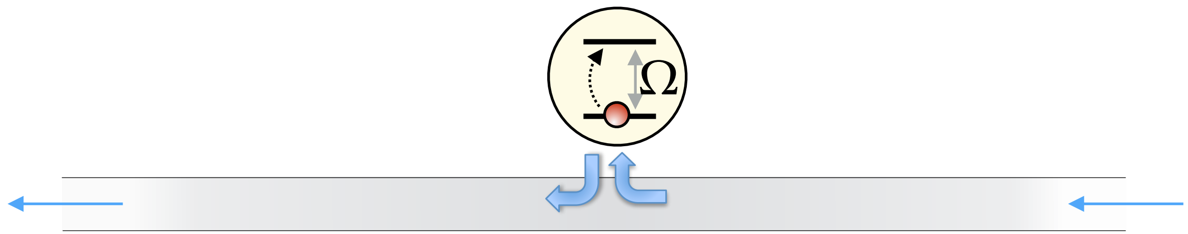
We use tDMRG techniques to solve for the dynamics.

H. Pichler, P.Z., PRL 2016

AL Grimsmo, PRL Aug 2015

Quantum Stochastic Schrödinger Equation

- **Simplest example: TLS + transmission line (RWA)**



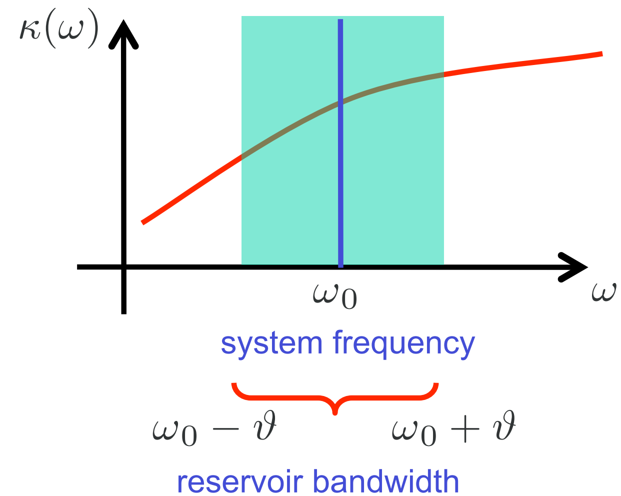
- **System + bath Hamiltonian**

$$H_{\text{int}}(t) = i\hbar\sqrt{\gamma}[b^\dagger(t)\sigma_- - \sigma_+ b(t)]$$

$$b(t) = \frac{1}{\sqrt{2\pi}} \int_{\omega_L - \vartheta}^{\omega_L + \vartheta} d\omega\, b(\omega) e^{-i(\omega - \omega_L)t}$$

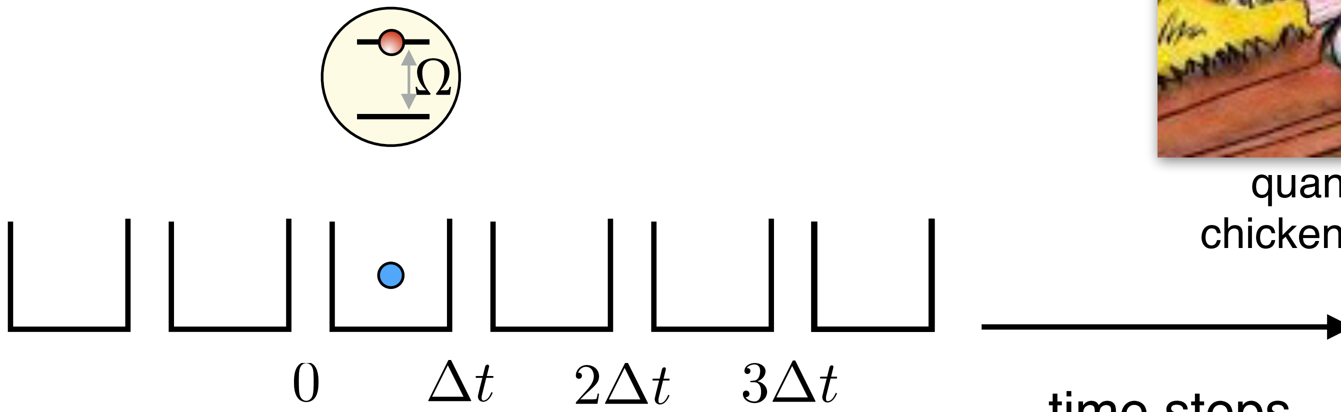
quantum noise operators

$$[b(t), b^\dagger(t')] = \delta_s(t - t')$$



Interpretation QSSE: ‘conveyor belt'

quantum chicken & egg



time steps

$t_n = n\Delta t$

stroboscopic map:

$$|\Psi(t_{n+1})\rangle = U_n|\Psi(t_n)\rangle$$

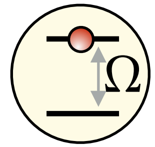
$$U_n = \exp\left(-\frac{i}{\hbar}H_{\rm sys}\Delta t + \sqrt{\gamma}(\Delta B_n^\dagger\sigma_- - \sigma_+\Delta B_n)\right)$$

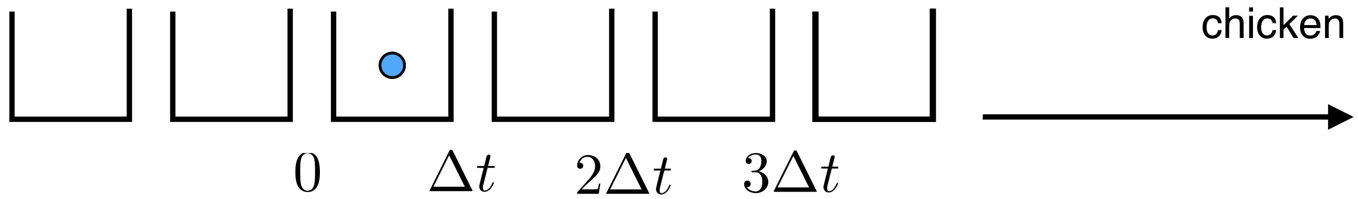
(quantum) Ito increment

$$\Delta B_n = \int_{t_n}^{t_n+\Delta t} dt\, b(t)$$

$$\left[\frac{\Delta B_n}{\sqrt{\Delta t}}, \frac{\Delta B_m^\dagger}{\sqrt{\Delta t}}\right] = \delta_{n,m}$$

Interpretation QSSE

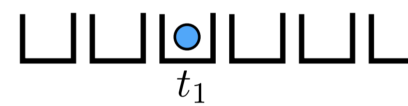




quantum
chicken & egg

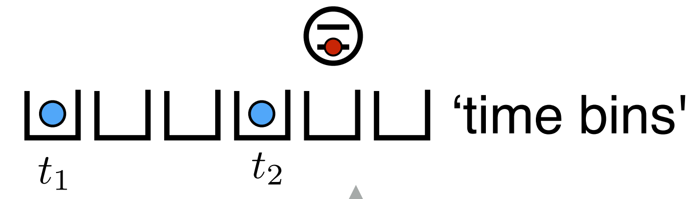
entangled state:

$$
\begin{aligned}
|\Psi(t)\rangle &= |\psi(t|)\rangle|\mathrm{vac}\rangle \\
&+ \sum_{t_1} |\psi(t|t_1)\rangle \Delta B^\dagger_{t_1}|\mathrm{vac}\rangle \\
&+ \sum_{t_2>t_1} |\psi(t|t_2,t_1)\rangle \Delta B^\dagger_{t_2}\Delta B^\dagger_{t_1}|\mathrm{vac}\rangle \\
&+ \cdots \\
&+ \sum_{t_n>\cdots>t_1} |\psi(t|t_n,\ldots,t_1)\rangle \Delta B^\dagger_{t_n}\cdots\Delta B^\dagger_{t_1}|\mathrm{vac}\rangle \\
&+ \cdots
\end{aligned}
$$



atomic wave function for sequence of emission events: quantum trajectory

Matrix Product State Representation

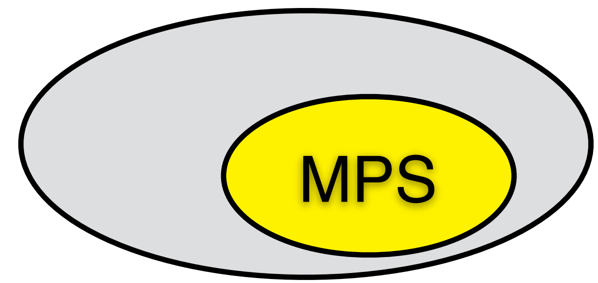


- **Total state of system & waveguide**

$$|\Psi(t_n)\rangle = \sum_{i_S=1}^{d_S} \sum_{i_{B1}=1}^{d_B} \cdots \sum_{i_{BN}=1}^{d_B} \psi_{i_S, i_{B1}, \ldots, i_{BN}} |i_S, i_{B1}, \ldots i_{BN}\rangle$$

- **MPS representation**

$$\psi_{i_1, \ldots, i_N} = \mathrm{tr}\{A[1]^{i_1} \ldots A[N]^{i_N}\}$$



d^N vs. dND^2 coefficients

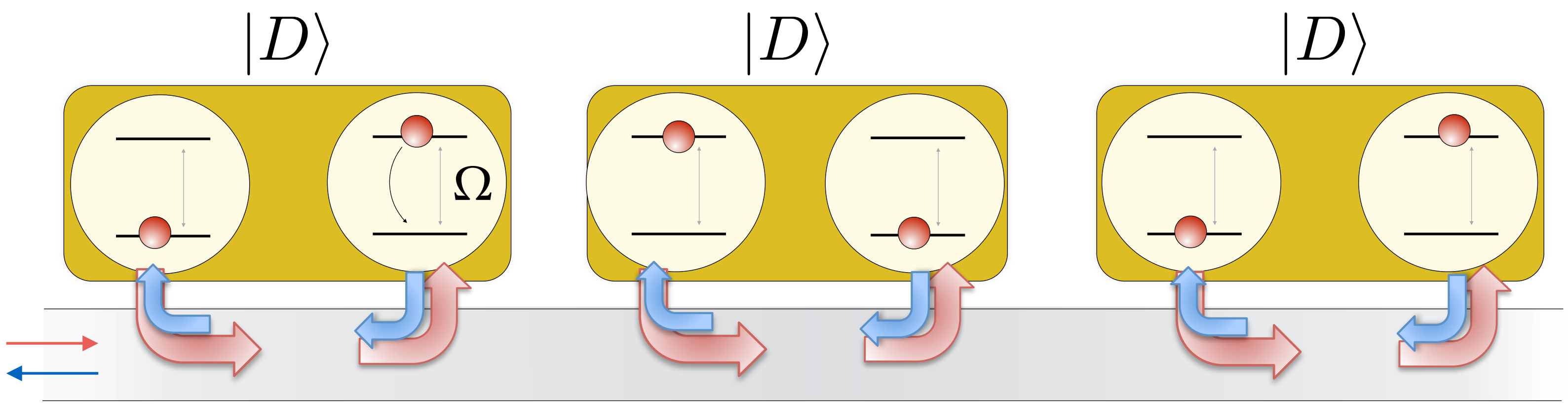
Bond dimension ~ entanglement

We will use MPS to solve the Quantum Stochastic Schrödinger Equation.

G. Vidal, Phys. Rev. Lett. **91**, 147902 (2003).
J. Daley, C. Kollath, U. Schollwöck, G. Vidal, J. Stat. Mech. (2004) P04005.
S. R. White and A. E. Feiguin, Phys. Rev. Lett. **93**, 076401 (2004)

Conclusions

- **Chiral Quantum Optics & Quantum Many-Body Physics**



dissipative formation of *pure quantum dimers*

- **Physical realization** with atoms / solid state emitters + photons, spins, …

- **Theory:** dynamics of chiral quantum networks with t-DMRG techniques / beyond Markov approximation

- **2D?**