

# 'Chiral' Quantum Optics:

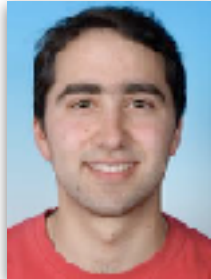
## A Novel Driven-Dissipative Quantum Many-Body System

Peter Zoller

In collaboration with:



H Pichler  
→ ITAMP



T Ramos  
→ Madrid



B Vermersch



P Hauke

Kai Stannigel  
Andrew Daley (Strathclyde)

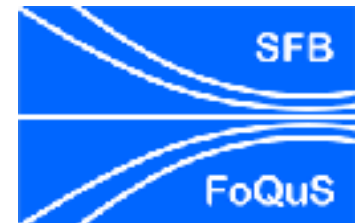


UNIVERSITY OF INNSBRUCK



OAW

UQUAM  
ERC Synergy Grant



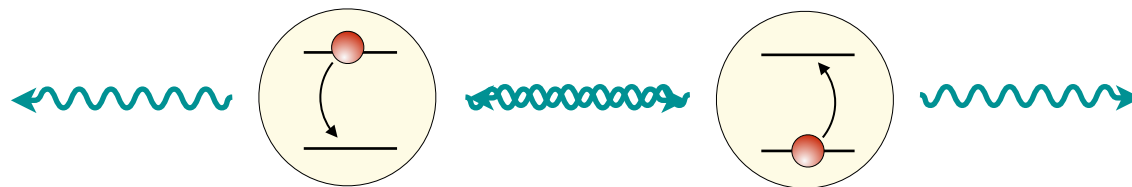
# 'Chiral' Quantum Optics

A Novel Driven-Dissipative  
Quantum Many-Body System

# 'Chiral' Interactions

- interactions mediated by photons

- quantum optics we know



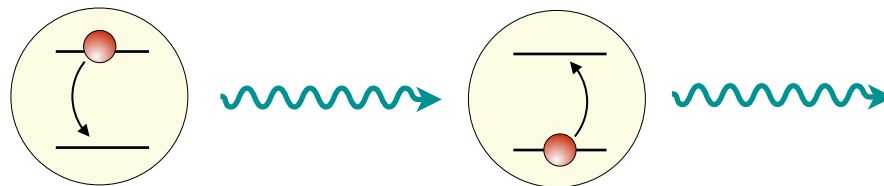
left - right  
symmetric

✓ 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

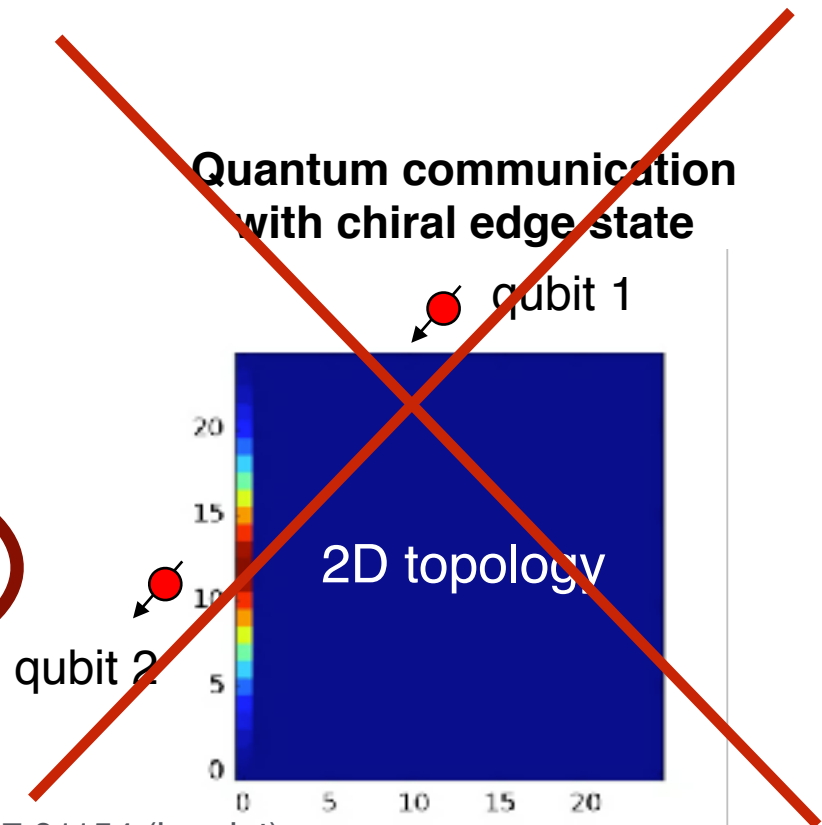
$$H \sim \sigma_1^- \sigma_2^+$$

?

Theory: 'Cascaded Master equation' = open quantum system

# 'Chiral' Quantum Optics

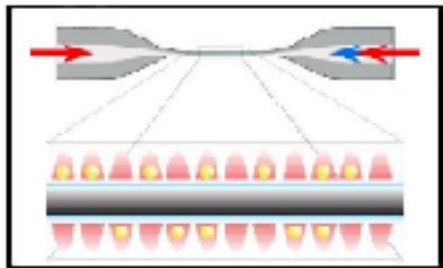
- ✓ photonic nanostructure
- ✓ atoms, spin, ...



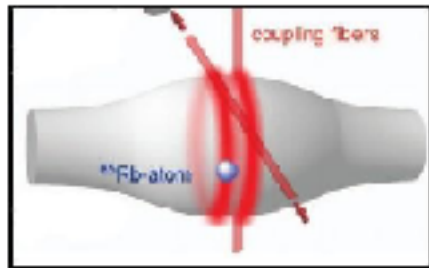
# 'Chiral' Quantum Optics

chiral coupling between light and quantum emitters

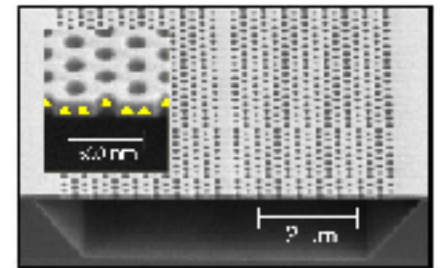
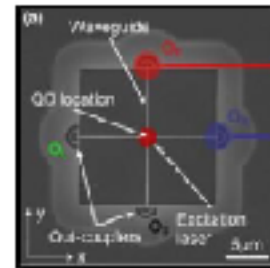
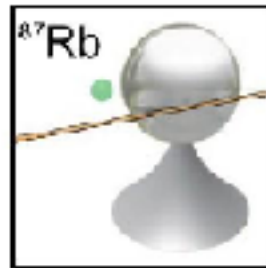
Nanophotonic devices: chirality appears naturally ...



atoms & nanofibers



atoms & CQED

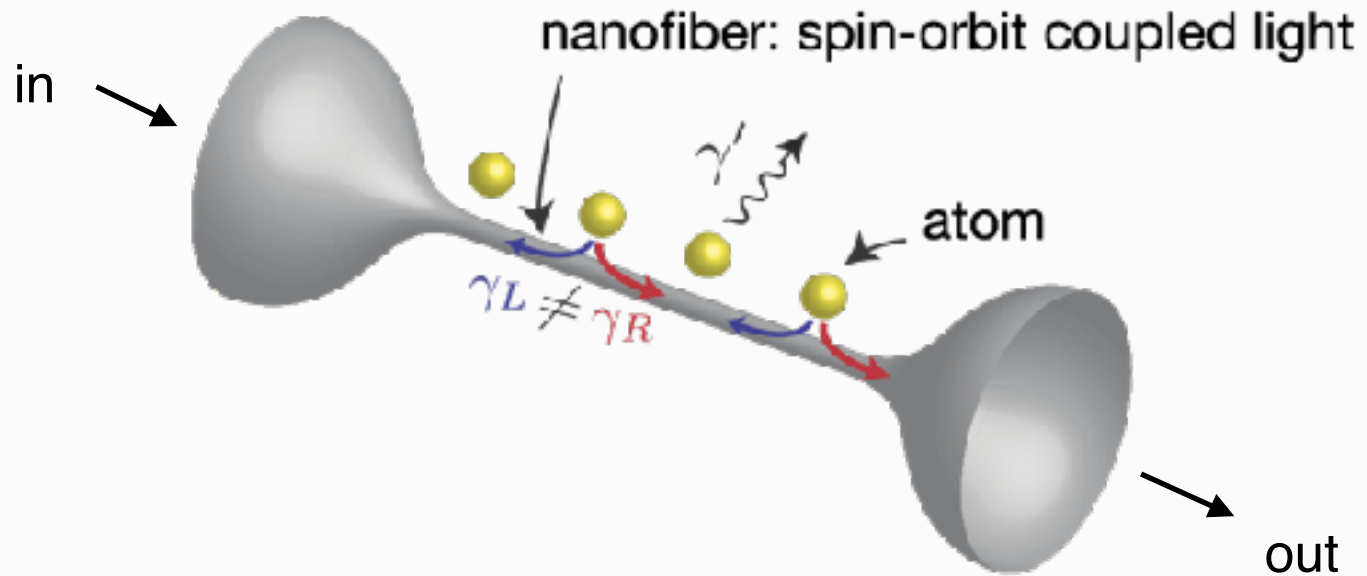


quantum dots & photonic nanostructures

NANOPHOTONICS

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

Jan Petersen, Jürgen Volz,\* Arno Rauschenbeutel\*



R. Mitsch, A Rauschenbeutel et al., *Nature Communications* (2015)

I. Söllner, P. Lodahl et al., *Nature Nanotechnology* **10**, 775–778 (2015)

chirality *natural / generic* feature of photonic nanostructures

# 'Chiral' Quantum Optics

## → Many-Body Quantum Physics

- Theory ...

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

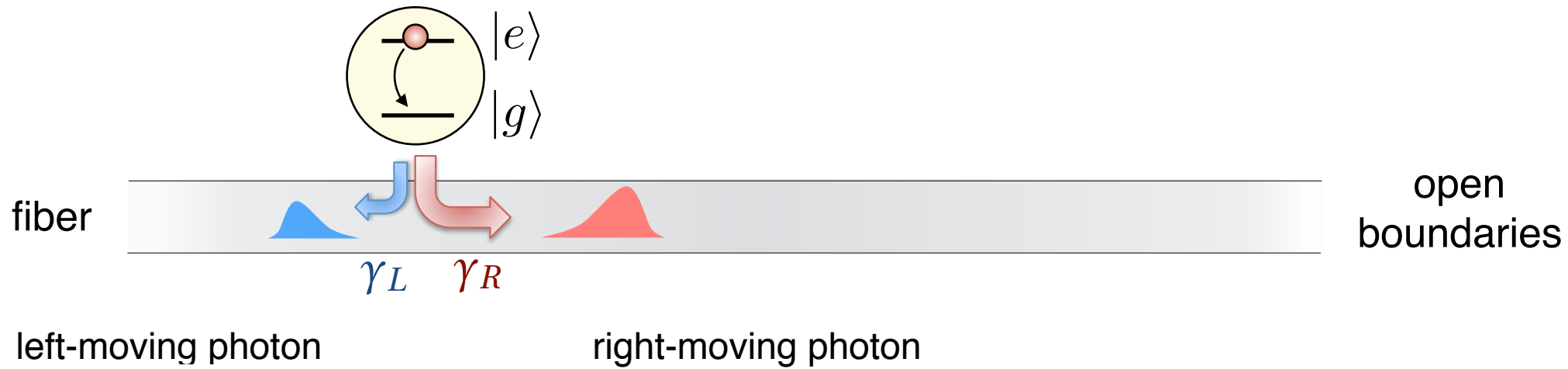
T. Ramos, H. Pichler, A.J. Daley, and PZ, PRL 2014

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

# 'Chiral' Quantum Optics

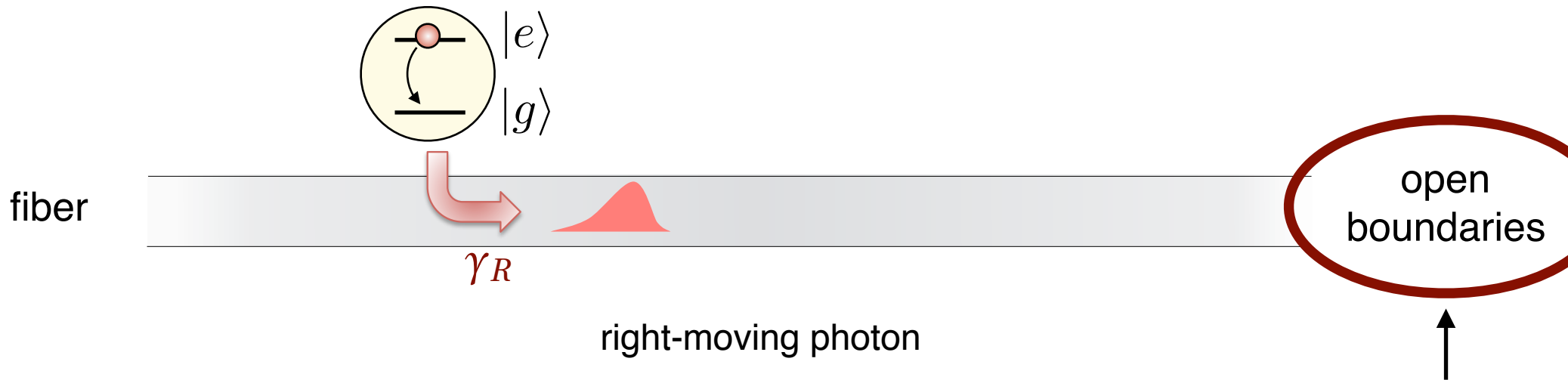


✓ 'chiral' atom-light interface:  
broken left-right symmetry

$$\gamma_L \neq \gamma_R$$



# 'Chiral' Quantum Optics



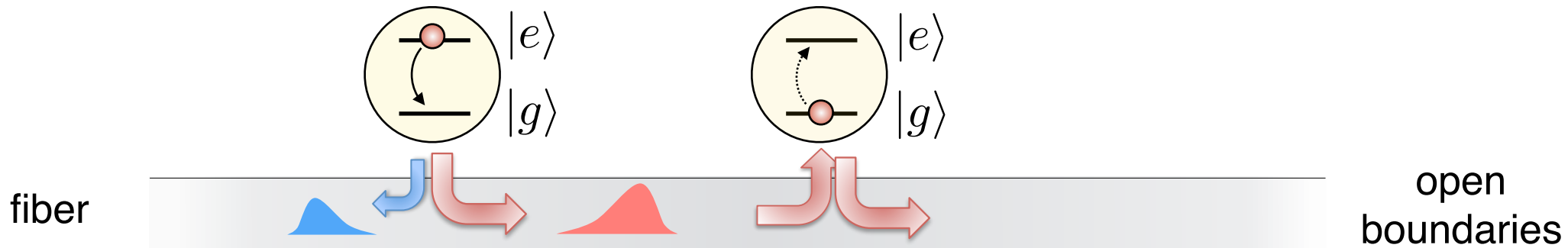
✓ 'chiral' atom-light interface:  
broken left-right symmetry

$$\gamma_L = 0; \gamma_R$$

'chirality'  $\sim$  open quantum system

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

# 'Chiral' Photon-Mediated Interactions

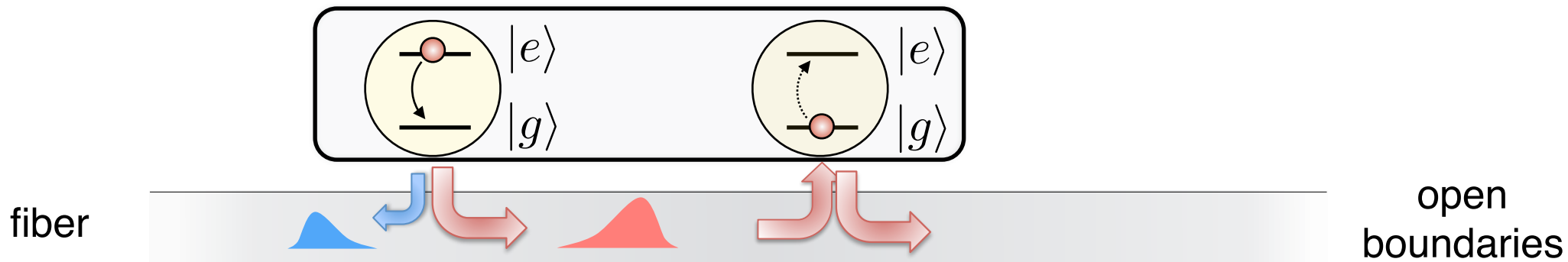


✓ 'chiral' interactions

broken left-right symmetry

atoms only talk to atoms on the right

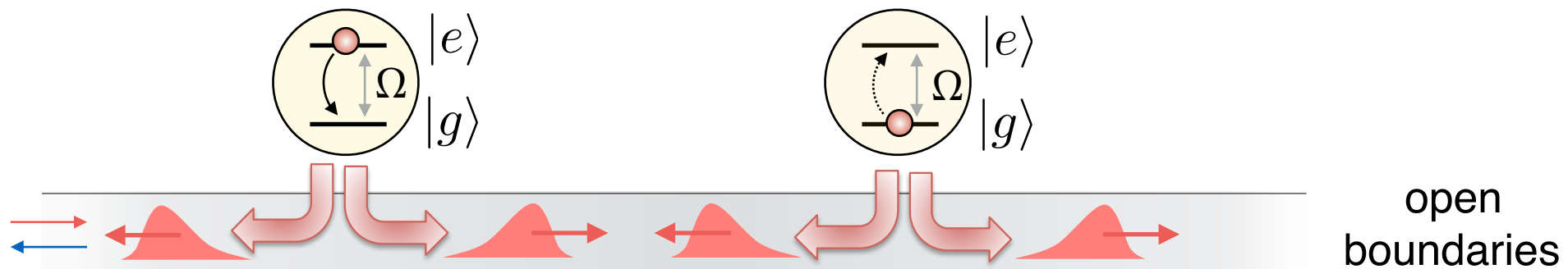
# Quantum Optical Master Equation



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

$$\dot{\rho} = -\frac{i}{\hbar} [H_{\text{sys}}, \rho] + \mathcal{L} \rho$$

# 1. 'Bidirectional' Master Equation



- **Master equation: symmetric**

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

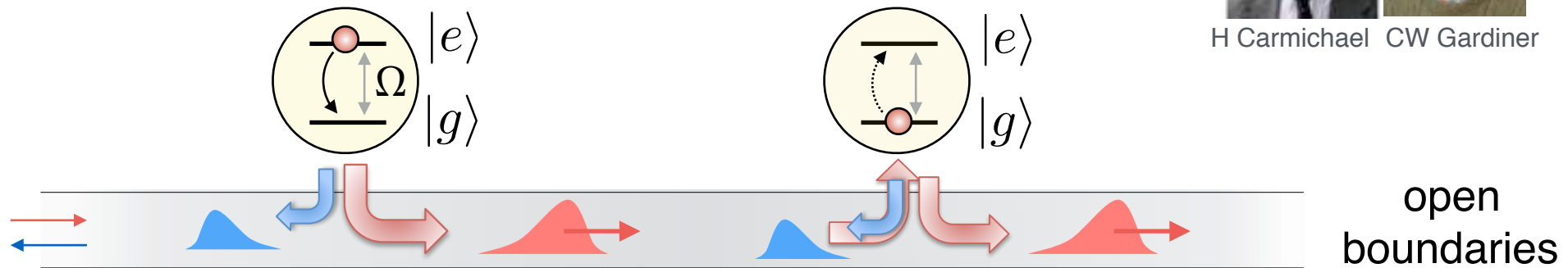
Labels in the diagram:

- driven atoms (pointing to  $H_{\text{sys}}$ )
- 1D dipole-dipole (pointing to  $\gamma \sin(k|x_1 - x_2|)(\sigma_1^+ \sigma_2^- + \sigma_2^+ \sigma_1^-)$ )
- collective spontaneous emission (pointing to  $\sigma_i^- \rho \sigma_j^+ - \frac{1}{2} \{\sigma_i^+ \sigma_j^-, \rho\}$ )

# 2. 'Cascaded' Master Equation



H Carmichael CW Gardiner



- Master equation: unidirectional

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

Lindblad form

- non-Hermitian effective Hamiltonian

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

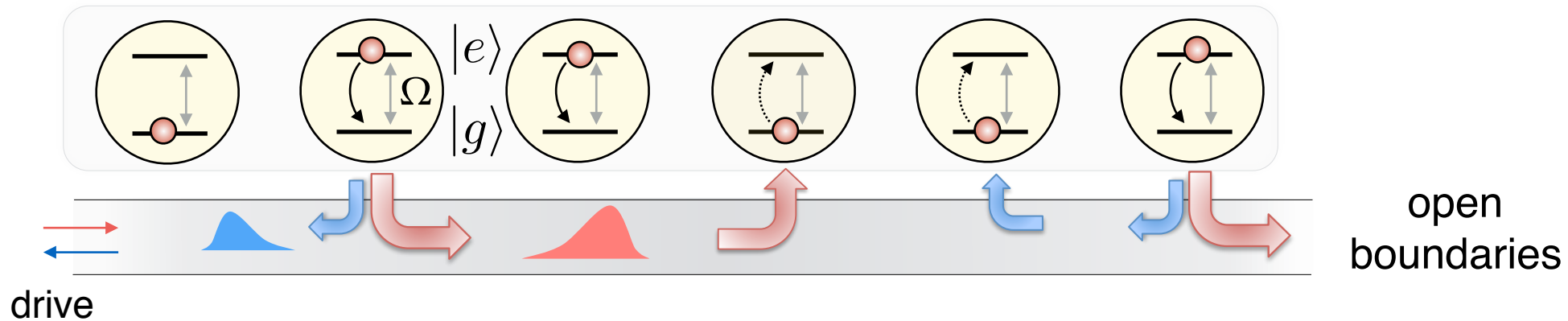
- quantum jump operator: collective

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

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

- general case: **atoms, chiral** positions, the atoms does not matter H. Pichler et al., PRA 2015

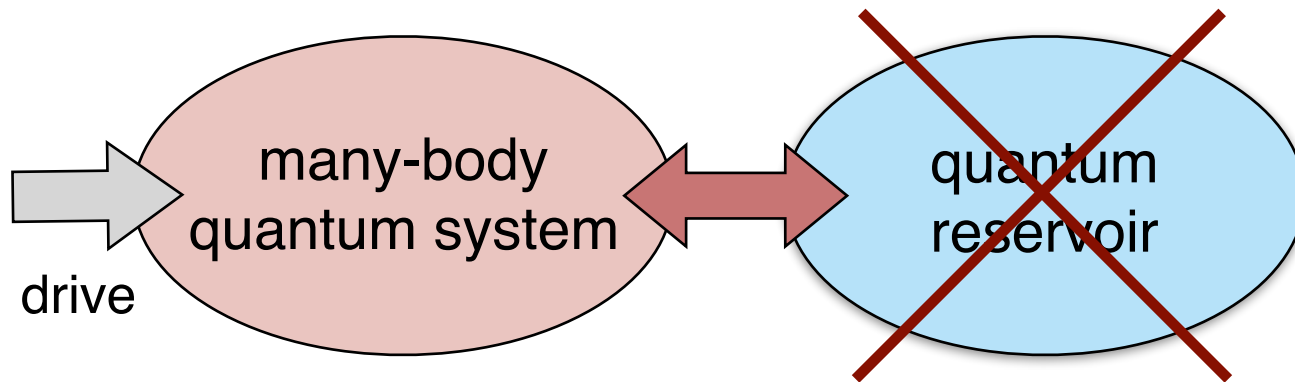
# Our Model System: 'Chiral' Many-Body Quantum Optics



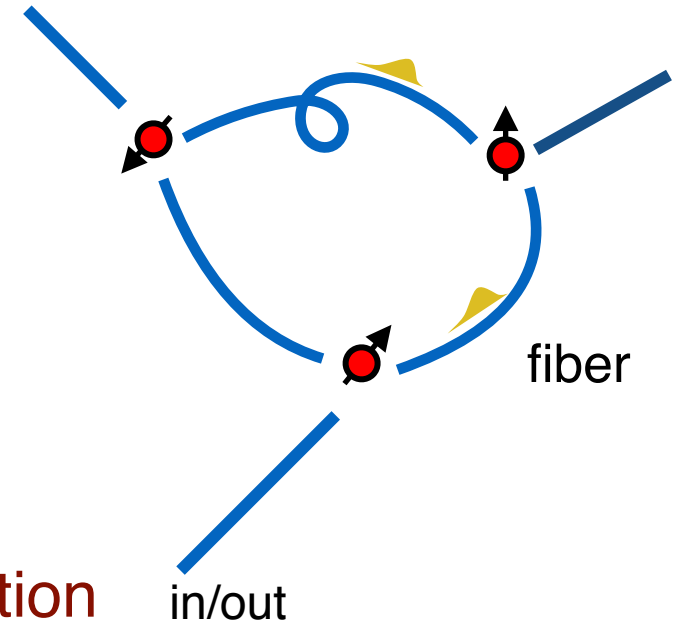
- ✓ 'chiral' photon-mediated **interactions**
- ✓ laser driving
- ✓ open quantum system

**Driven-dissipative quantum many-body system**

# Markovian Quantum Network Theory



Born-Markov Approximation



## Many body Quantum Optics

- Dynamics: Master equation

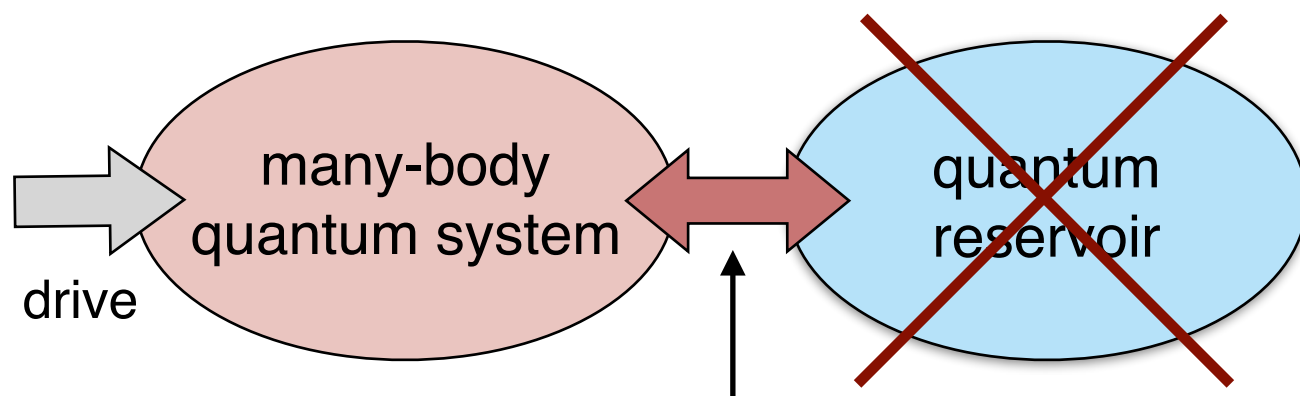
$$\dot{\rho}(t) = -\frac{i}{\hbar} [H_{\text{sys}}, \rho(t)] + \mathcal{L}\rho(t)$$

validity ...

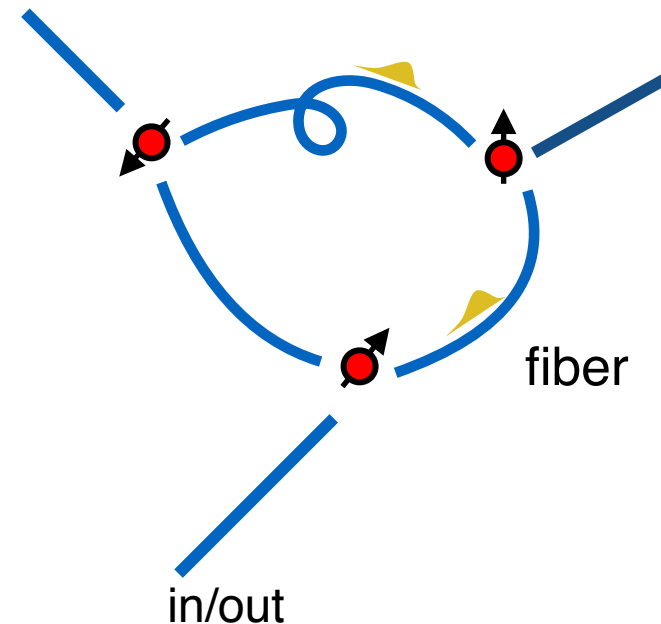
- Steady state:

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

# Markovian Quantum Network Theory



Engineer system-reservoir coupling!



## Many body Quantum Optics

- Dynamics: Master equation

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

validity ...

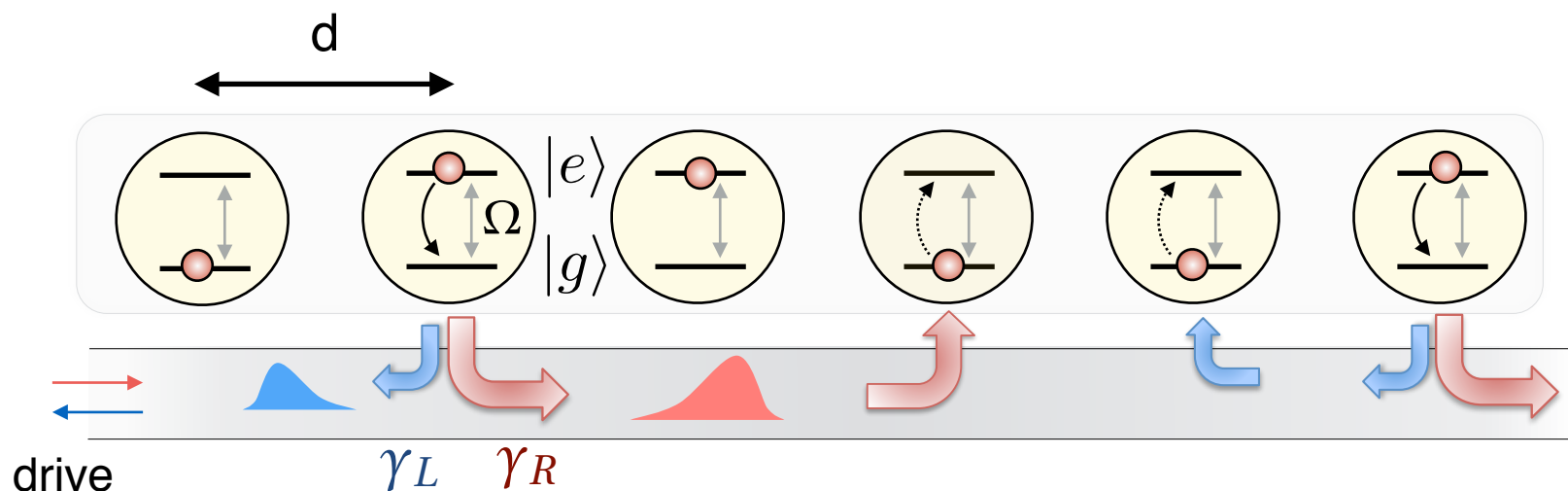
- Steady state:

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

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



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



Special case:

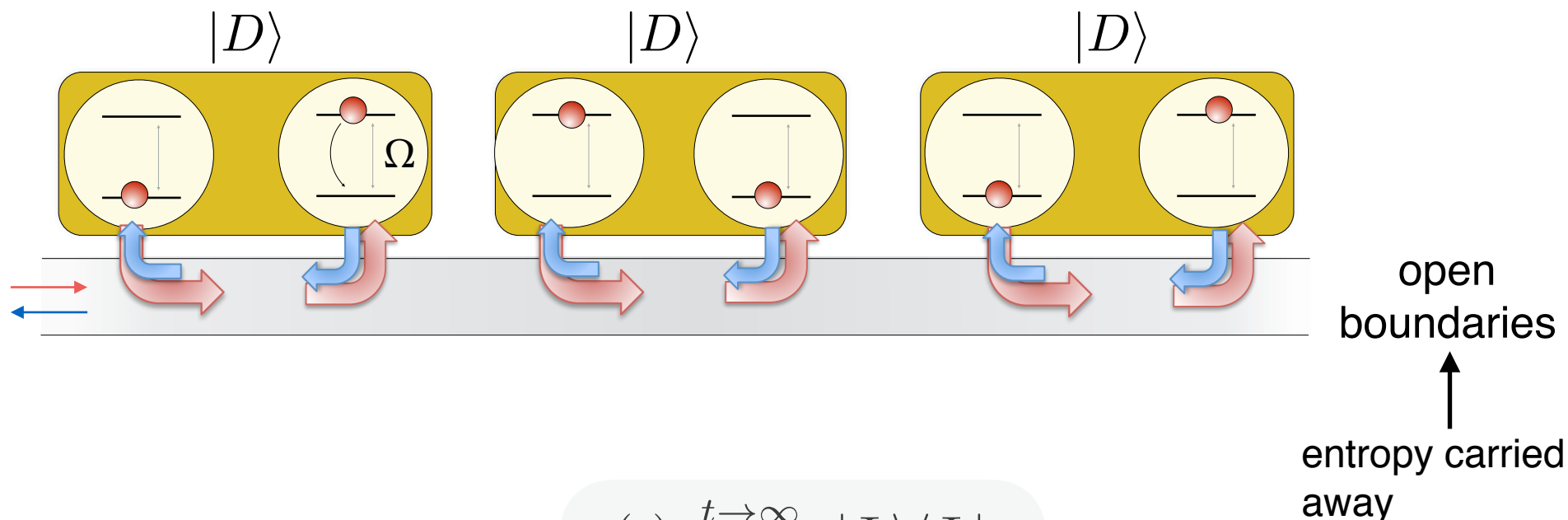
- Distance **commensurate** with photon wavelength
- **Equal Rabi frequencies** and **staggered detunings**

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

$$\begin{aligned}\Omega_i &= \Omega \\ \delta_i &= -\delta_{i+1}\end{aligned}$$

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

# Two-Level Atoms with 'Chiral' Waveguide Coupling



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

- **Quantum Dimers**

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

product of pure **quantum spin-dimers**

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

singlet / EPR

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

singlet fraction

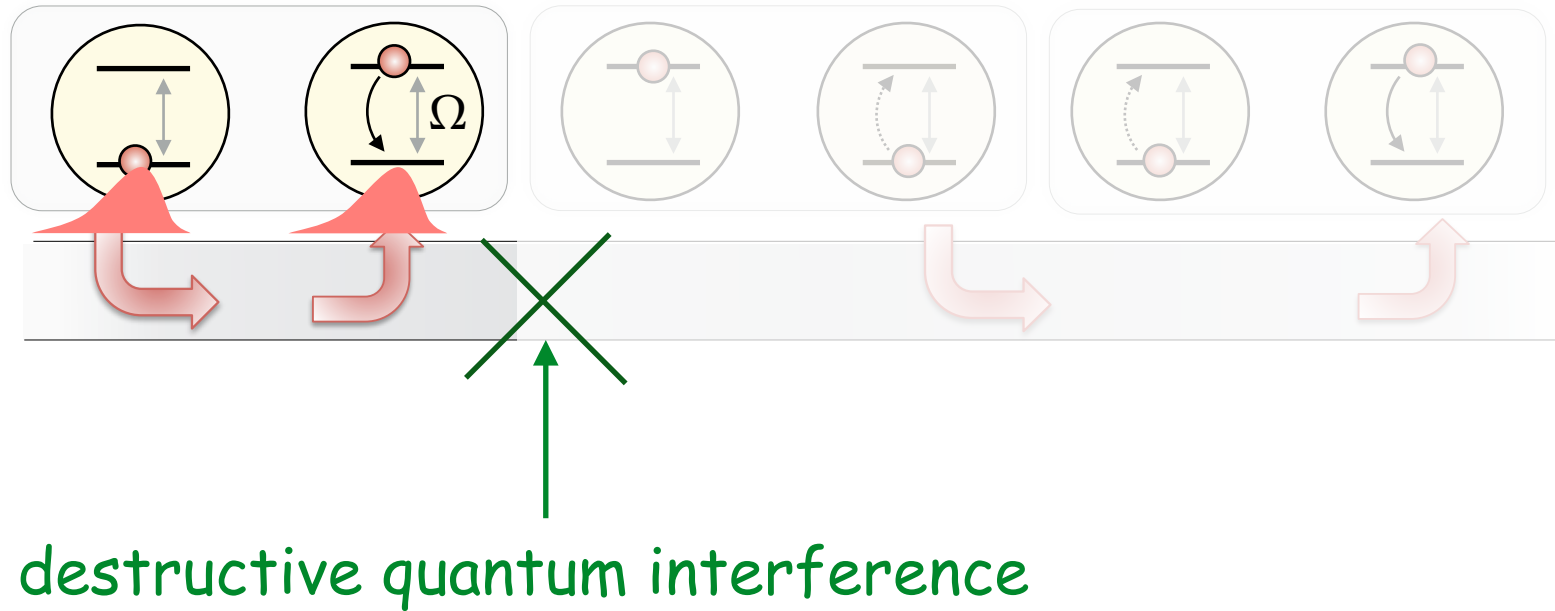
- Note: only for  $N$  even

## Entanglement by Dissipation

# N even: cascaded

$$\gamma_L = 0$$

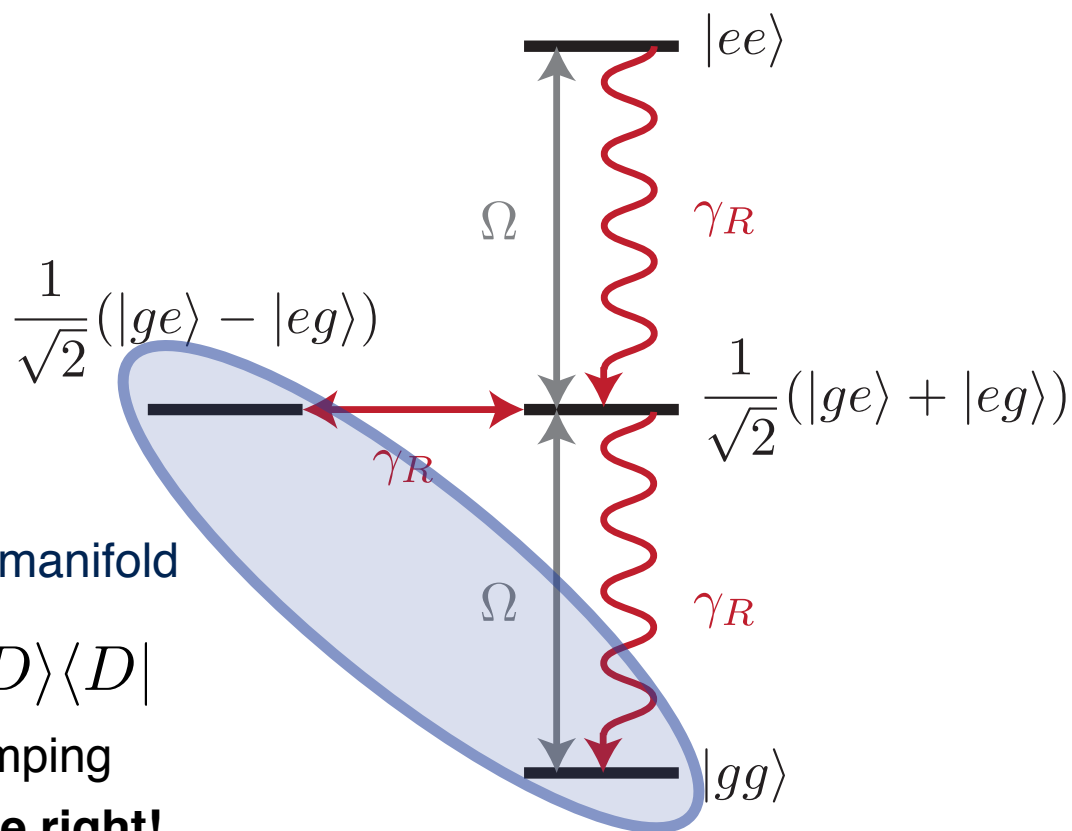
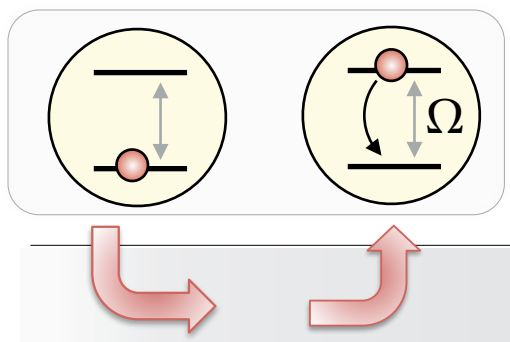
- Iterative solution from left to right:



# N spins? Consider **cascaded** case first

$$\gamma_L = 0$$

- Iterative solution from left to right:



Dark manifold

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

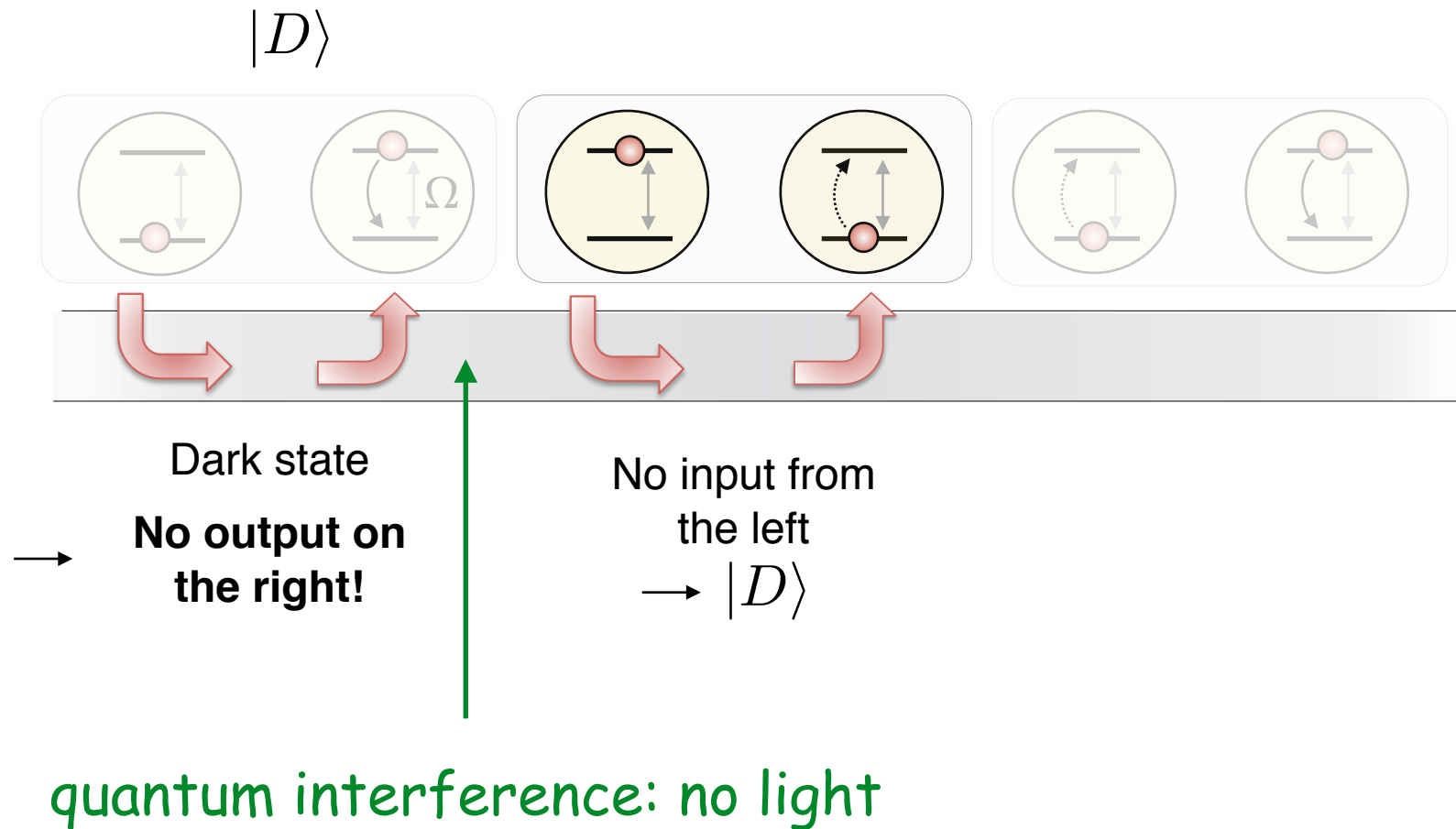
Dark state pumping

→ **No output on the right!**

# N even: cascaded

$$\gamma_L = 0$$

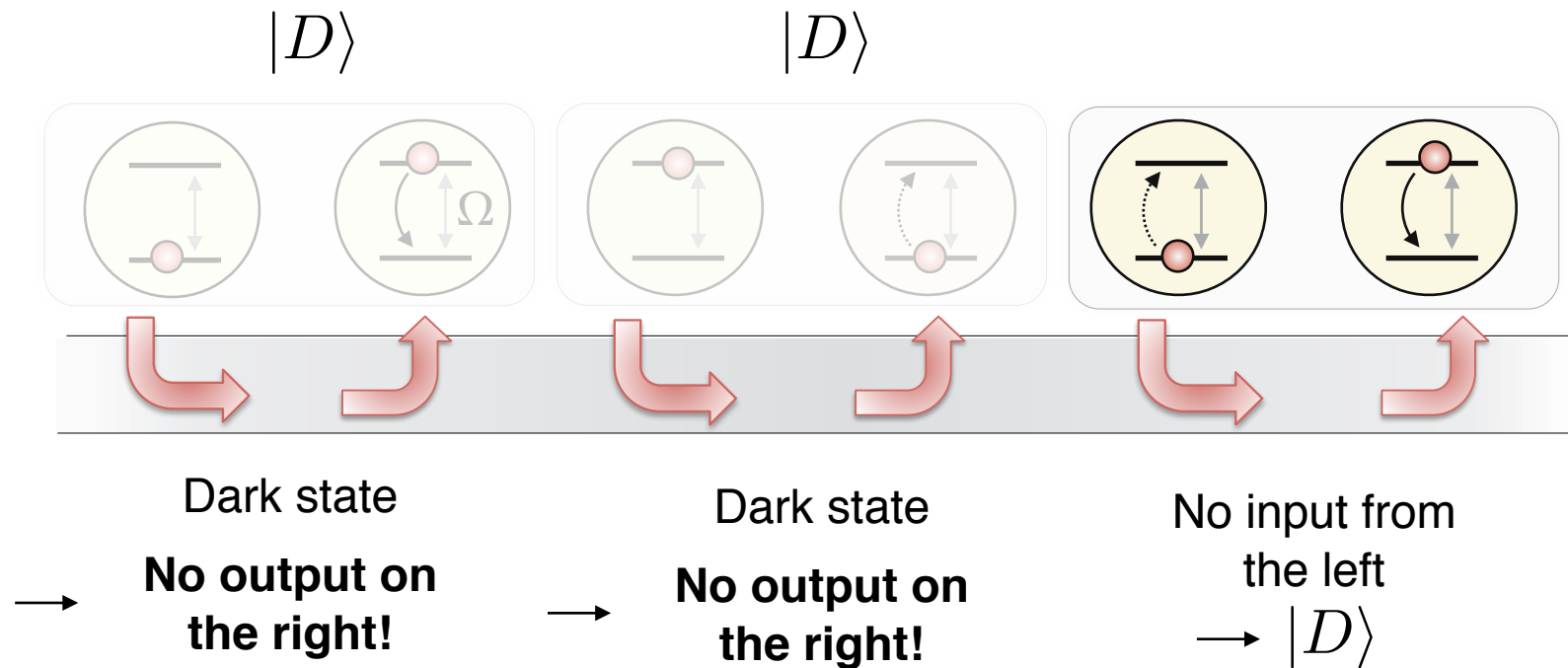
- Iterative solution from left to right:



# N even: cascaded

$$\gamma_L = 0$$

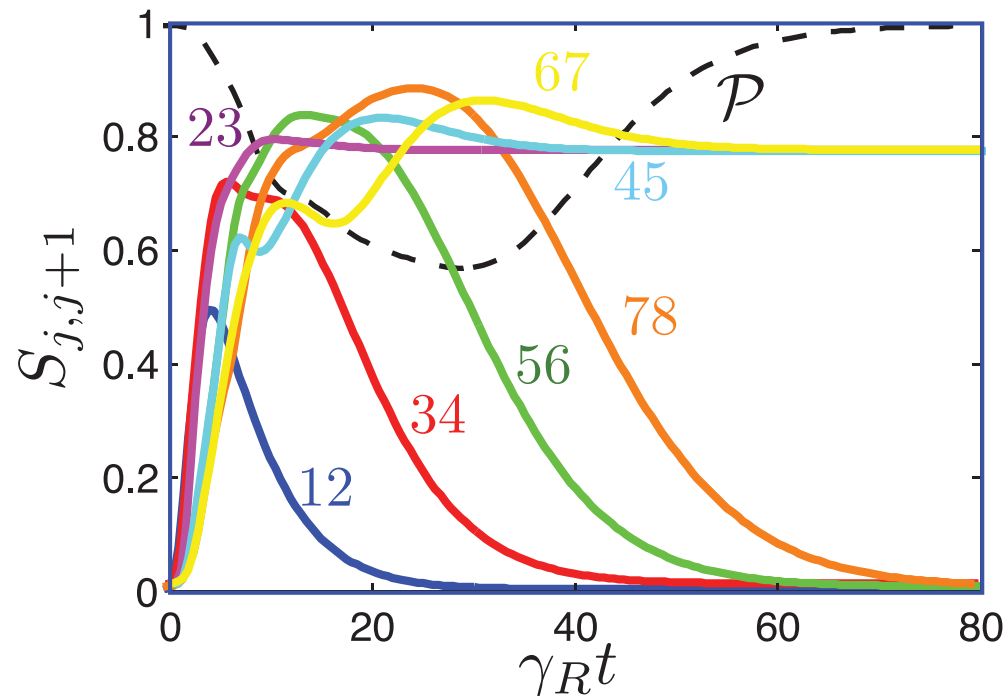
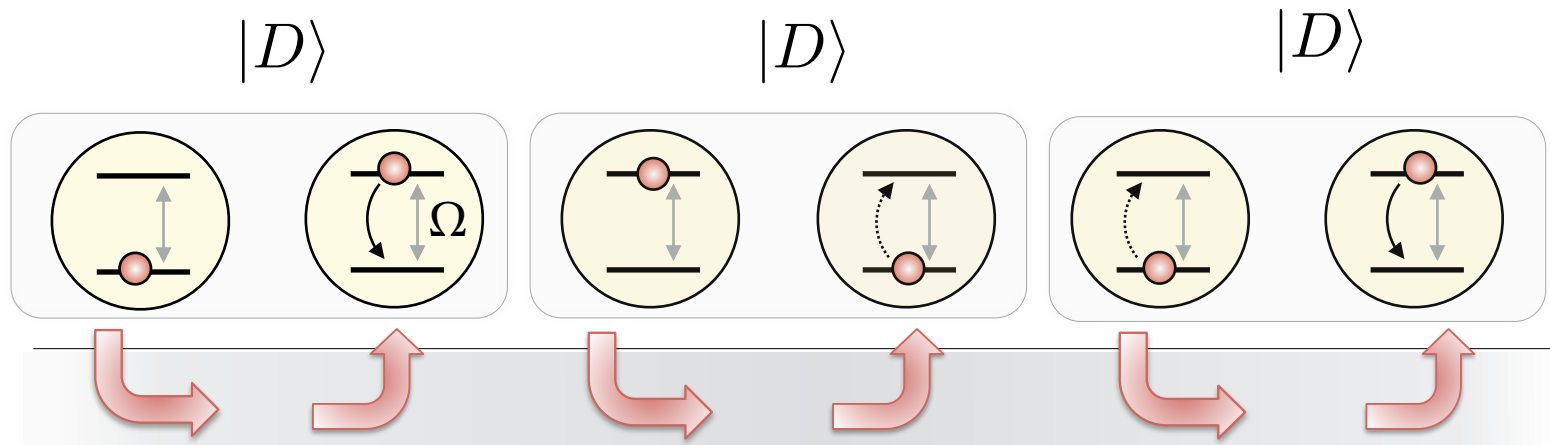
- Iterative solution from left to right:



# N even: cascaded

$$\gamma_L = 0$$

- Iterative solution from left to right:



constant "purification speed"

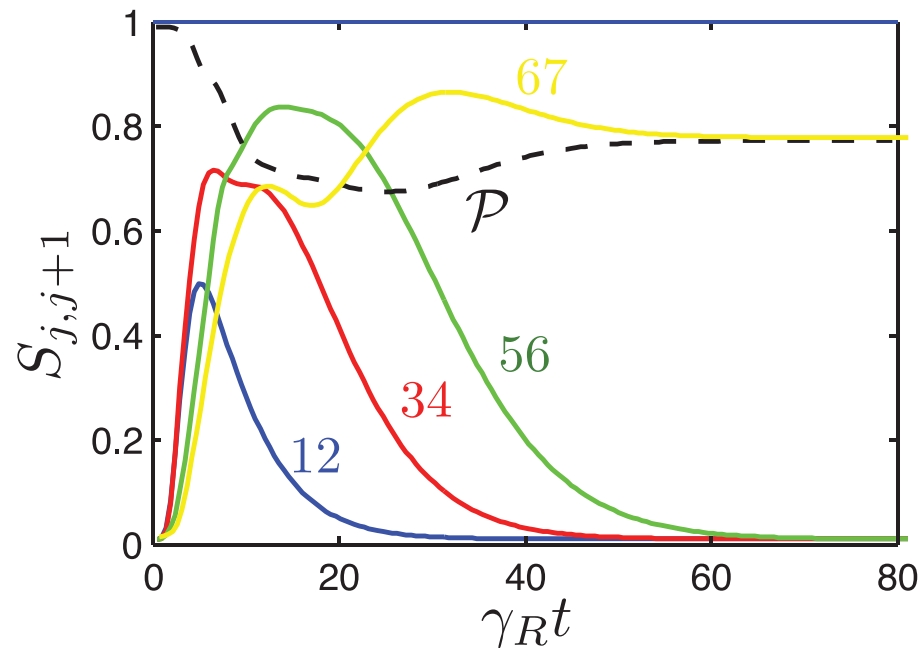
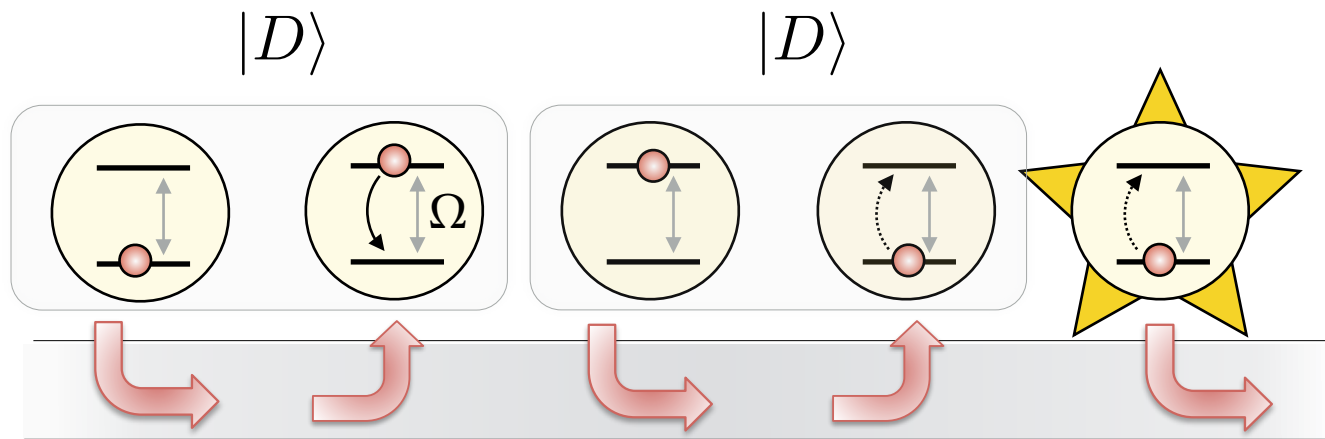
$$\gamma_L / \gamma_R = 0$$

$$\Omega / \gamma_R = 0.5$$

# N odd: cascaded

$$\gamma_L = 0$$

- Iterative solution from left to right:

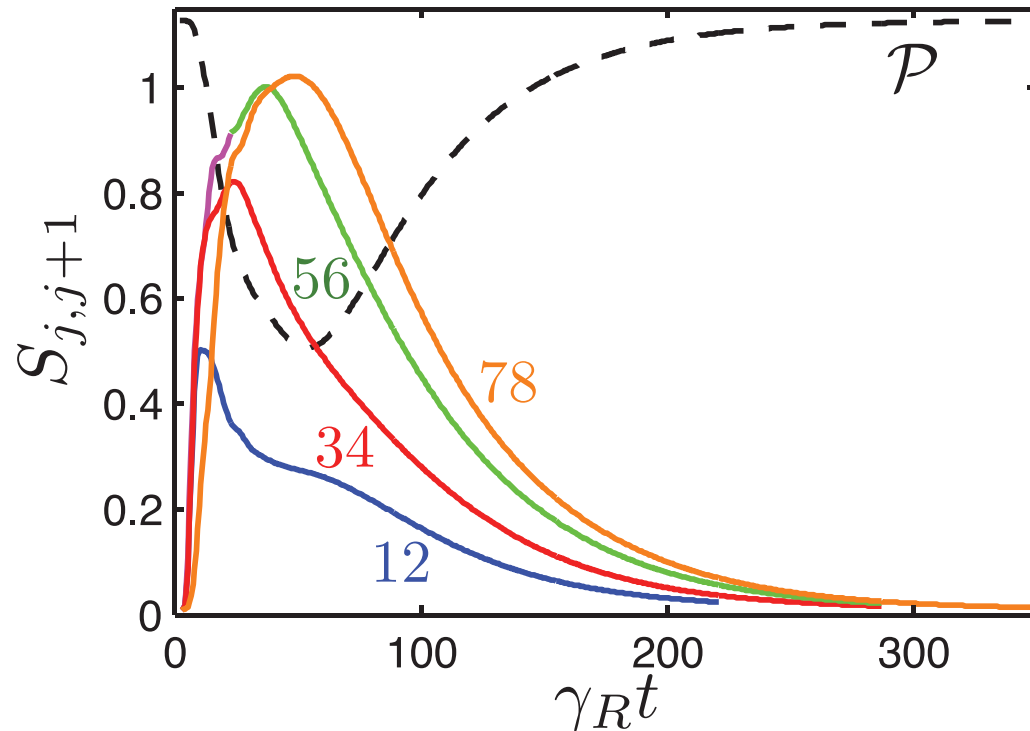
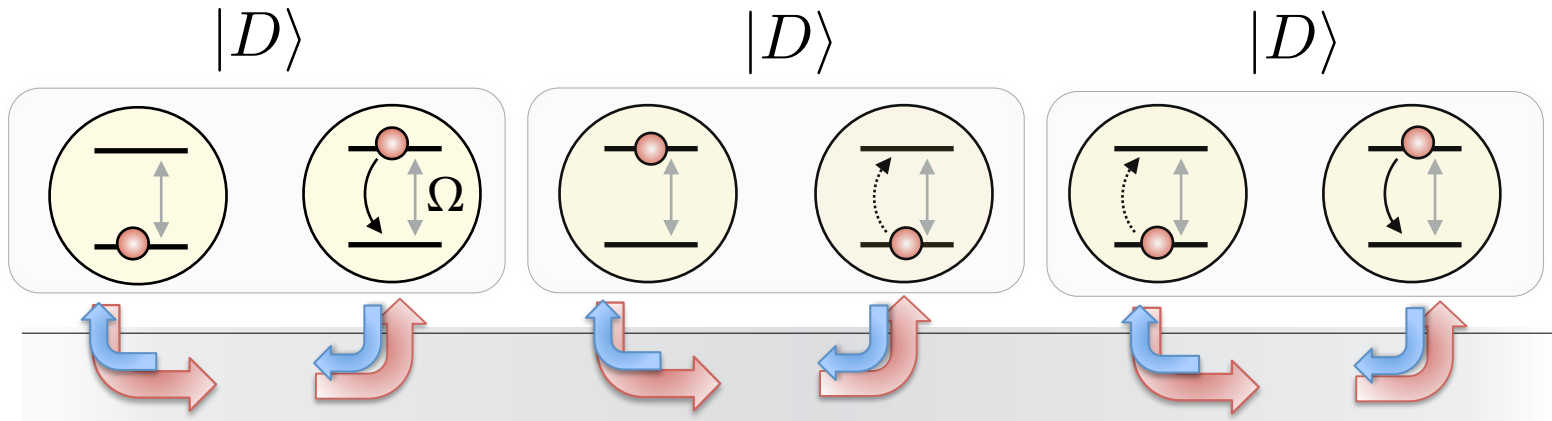


Last spin cannot pair up, but **still** dimers are formed



# N even: Chiral waveguide

$$\gamma_L \neq \gamma_R$$



System purifies  
"as a whole"

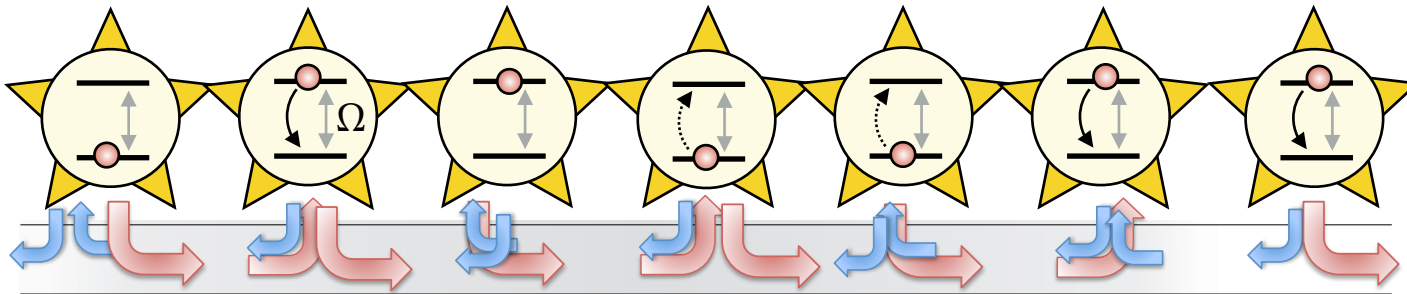
$$\gamma_L / \gamma_R = 0.4$$

$$\Omega / \gamma_R = 0.5$$

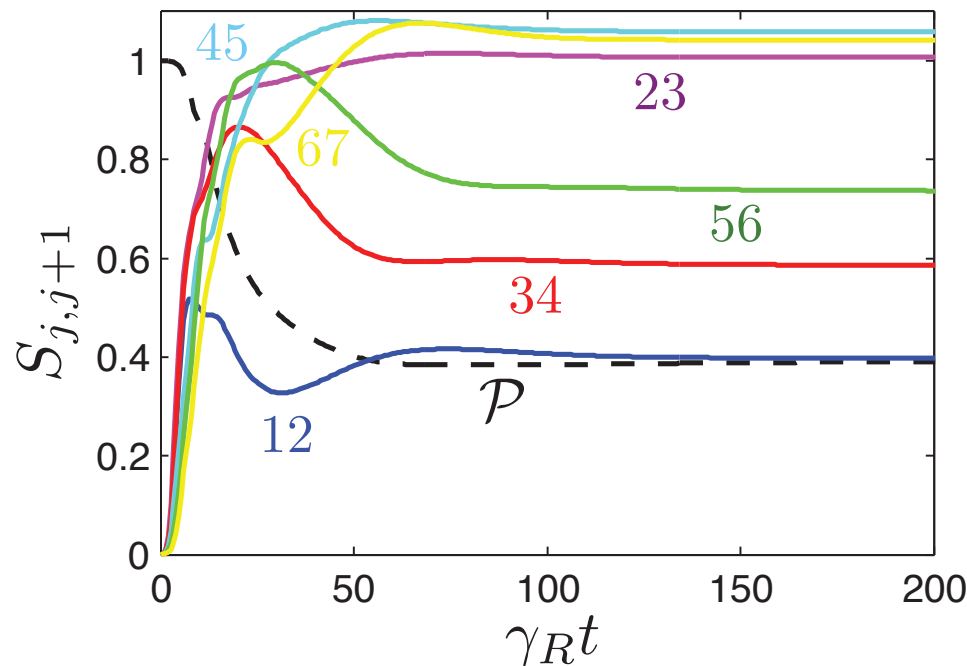
# N odd: chiral waveguide

$$\gamma_L \neq \gamma_R$$

- **Odd** number of spins?



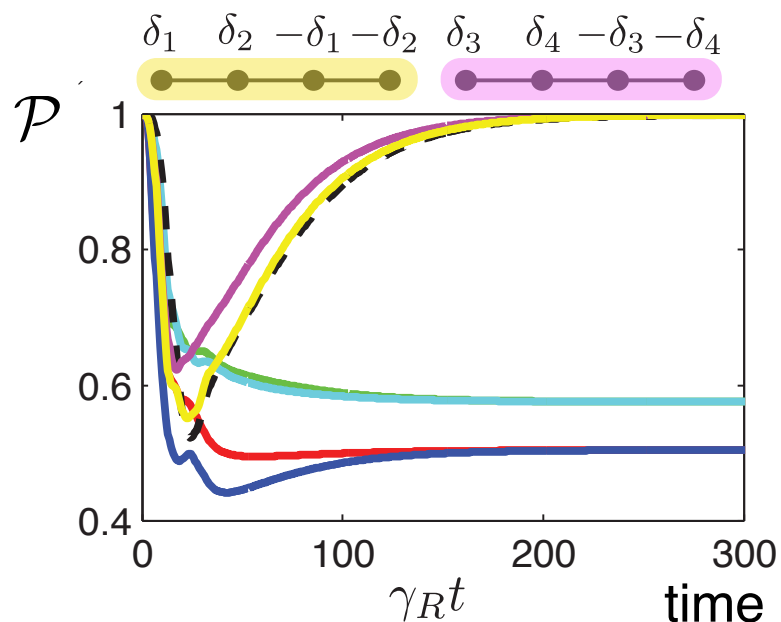
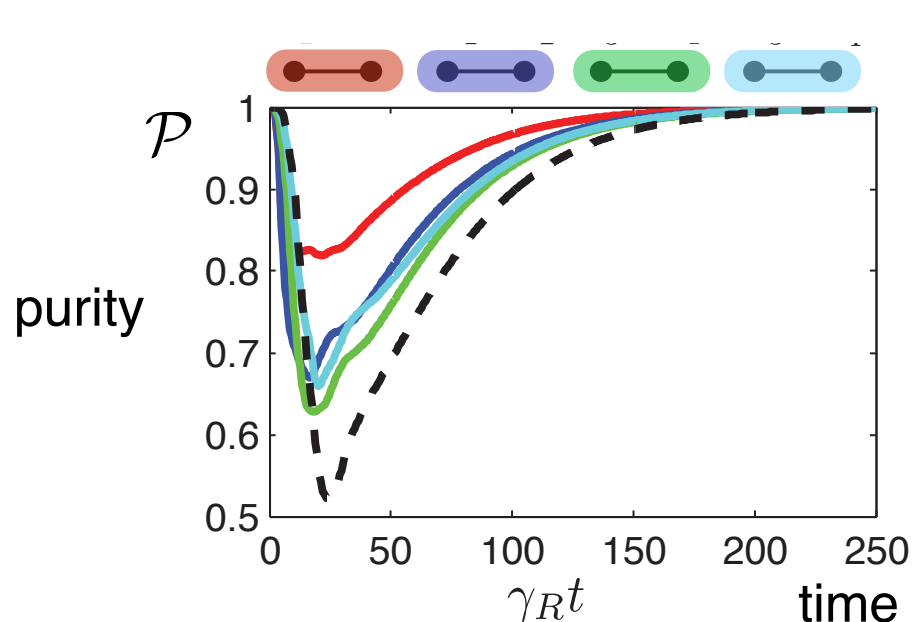
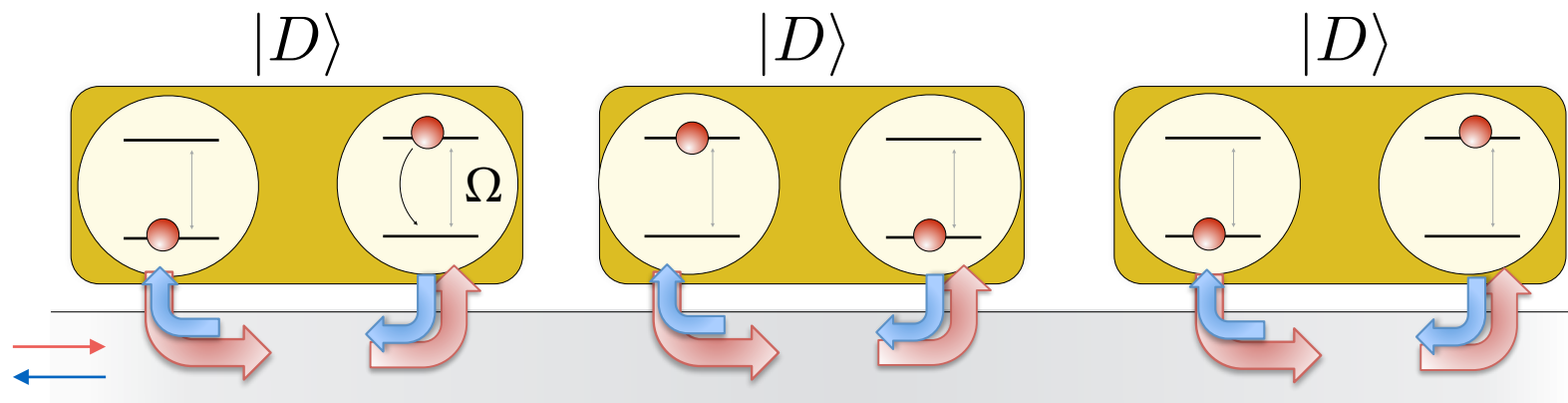
- Any **unpaired** spin destroyed the formed dimers: No dark state!



$$\gamma_L / \gamma_R = 0.4$$

$$\Omega / \gamma_R = 0.5$$

# 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, ...**

Other realizations ... and more insight?

## 'Chiral' Couplings & 'Chiral' Networks with ...

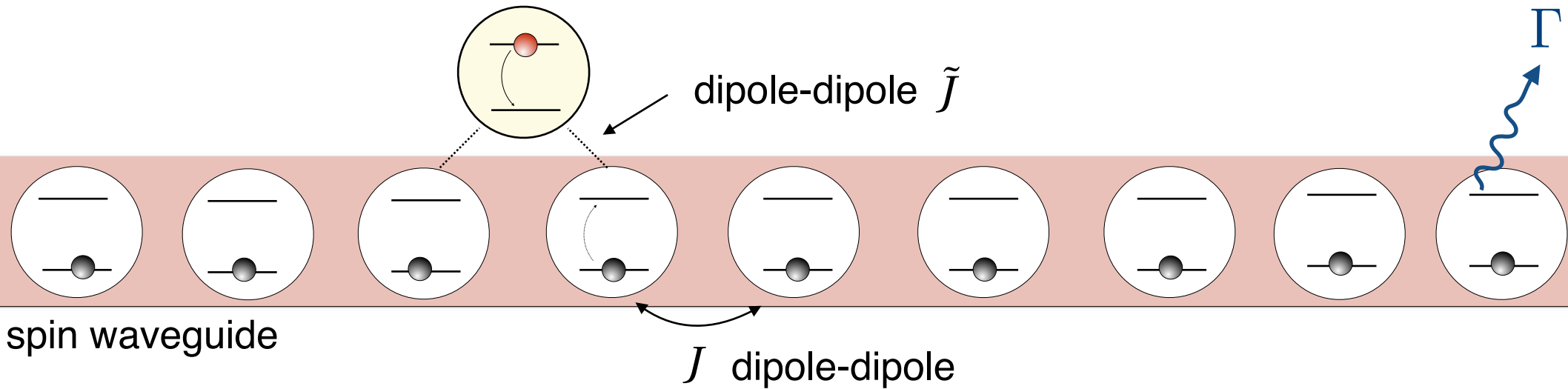
- "photonic" wave-guides
- "phononic"
- spin waves [quantum spintronics]

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• theory *beyond* Born-Markov using tDMRG techniques

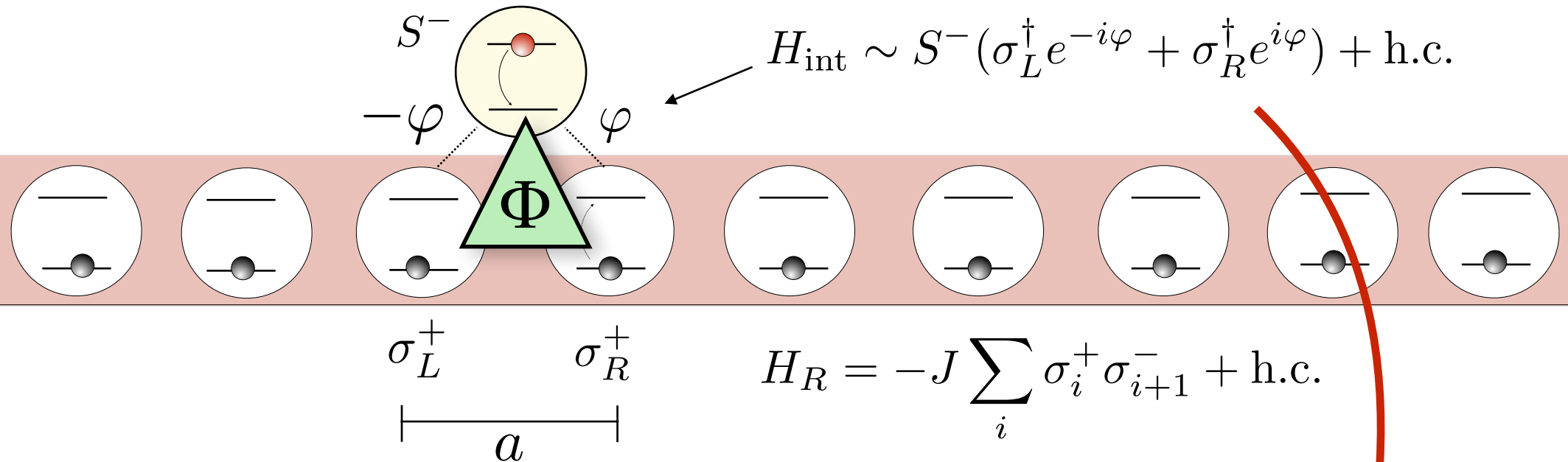
# 'Chiral' Quantum Optics with Spin Waveguides

- spin waveguide

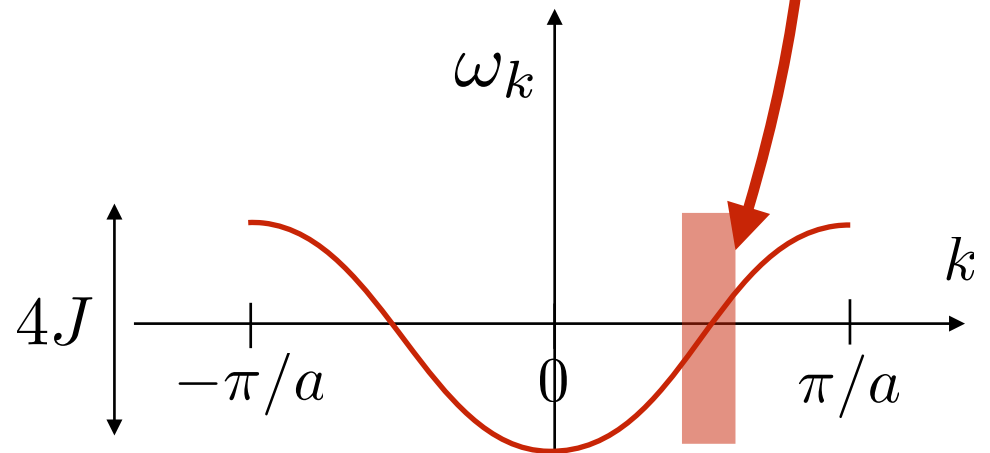


# 'Chiral' Couplings with Spin Chains

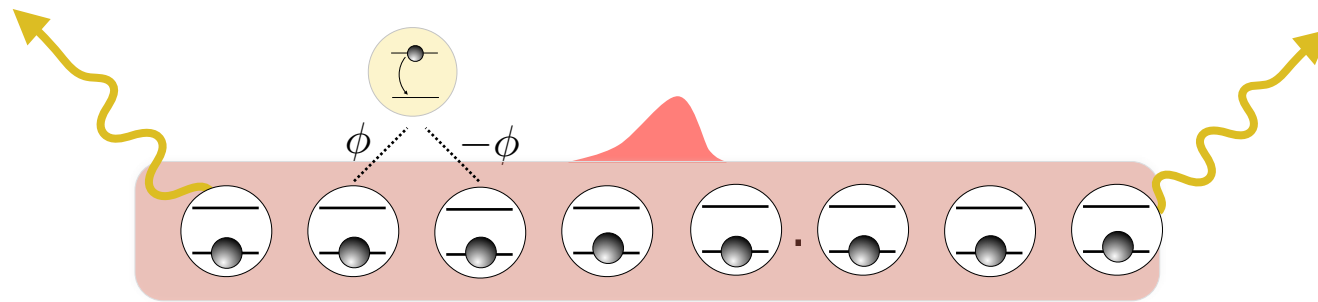
- spin waveguide



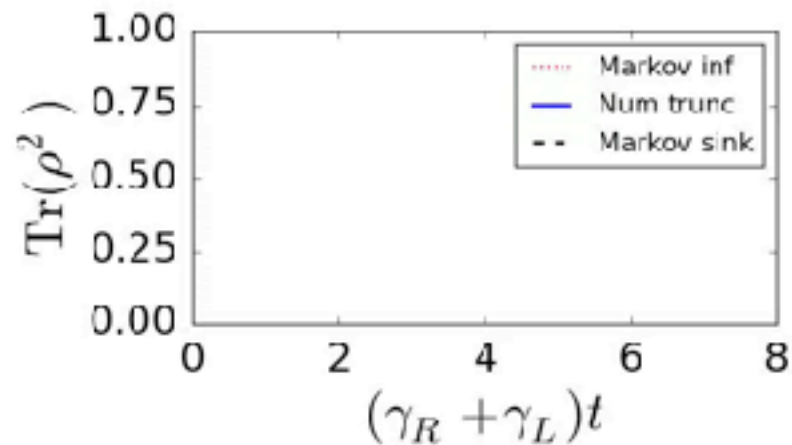
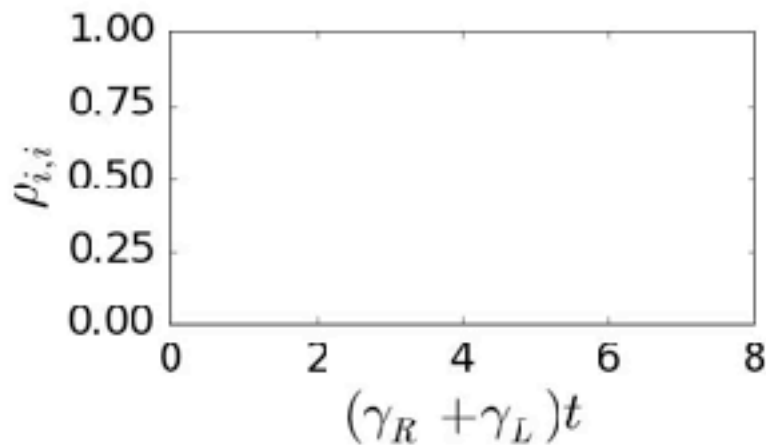
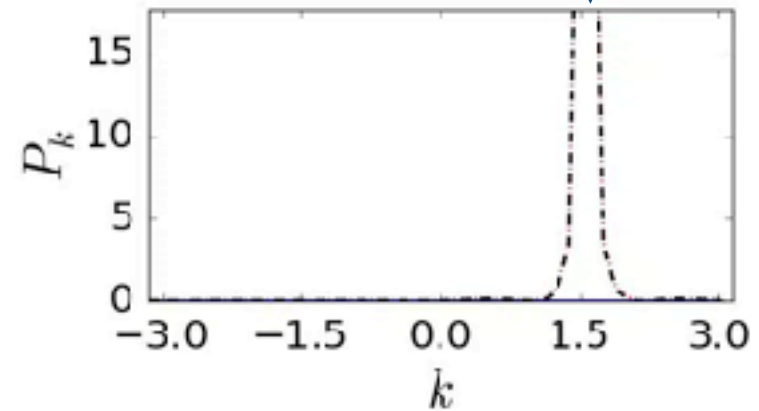
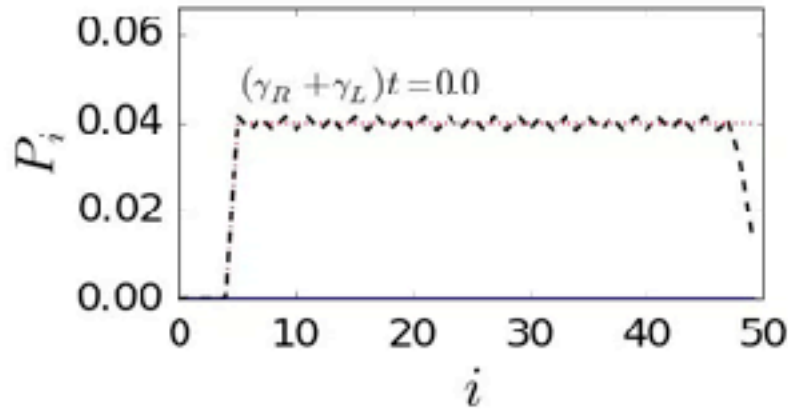
$\varphi \approx \pi/4$   
**Strong Chirality**  
 = synthetic gauge field



# 'Chiral' exponential decay into the spin waveguide



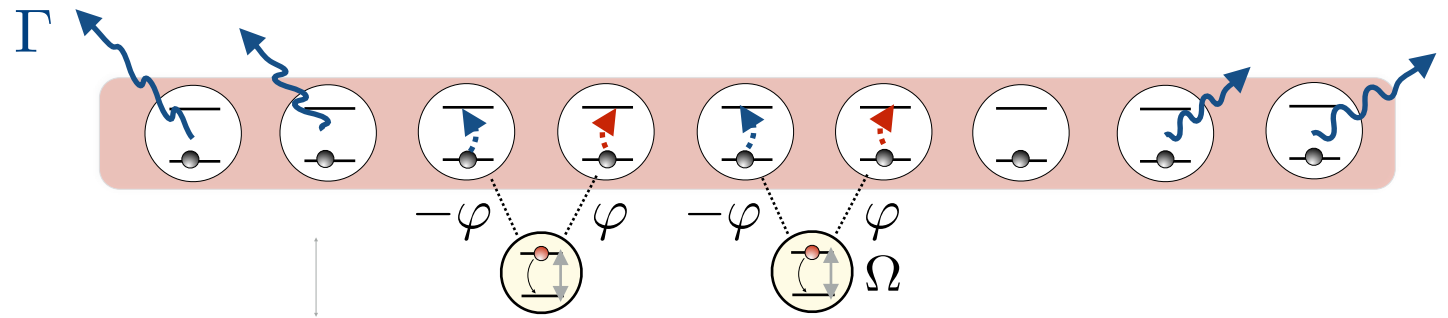
no reflection



# Dimer formation: system + reservoir dynamics

$$\varphi = \pi/6$$

↓  
chiral case

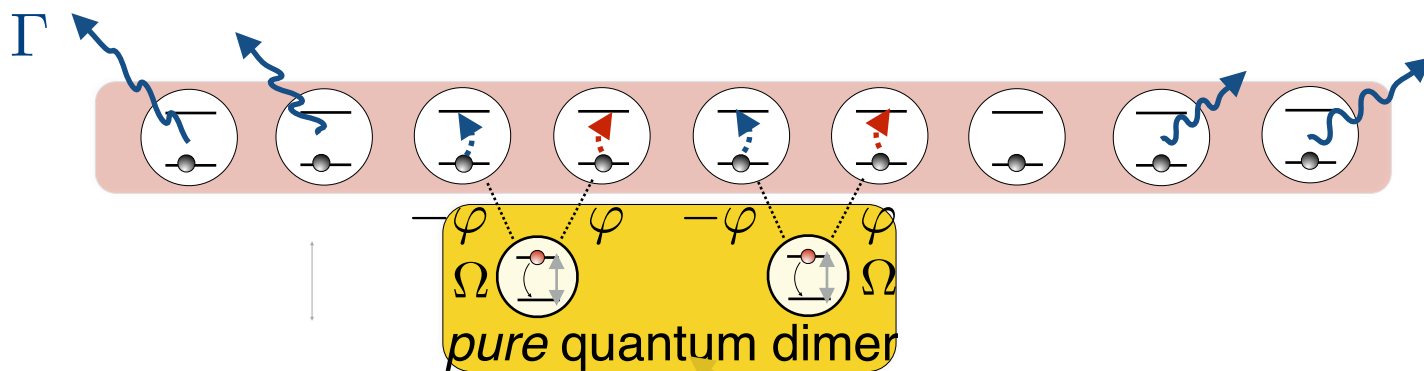




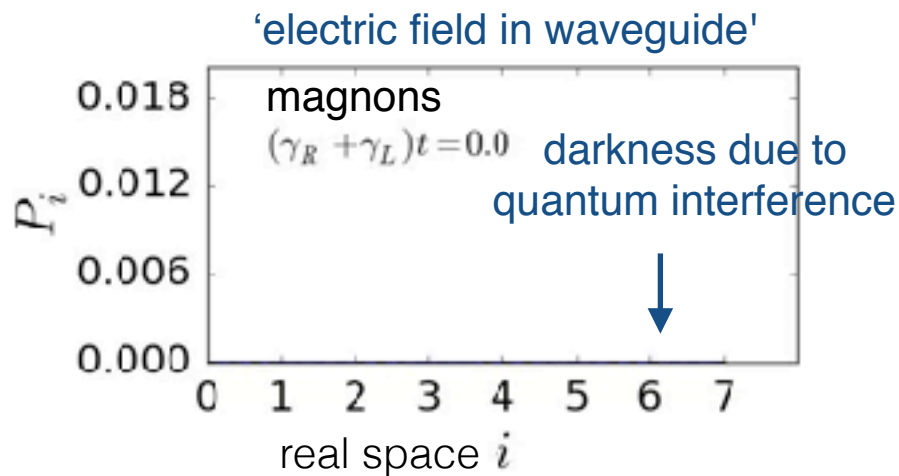
# Dimer formation: system + reservoir dynamics

$$\varphi = \pi/6$$

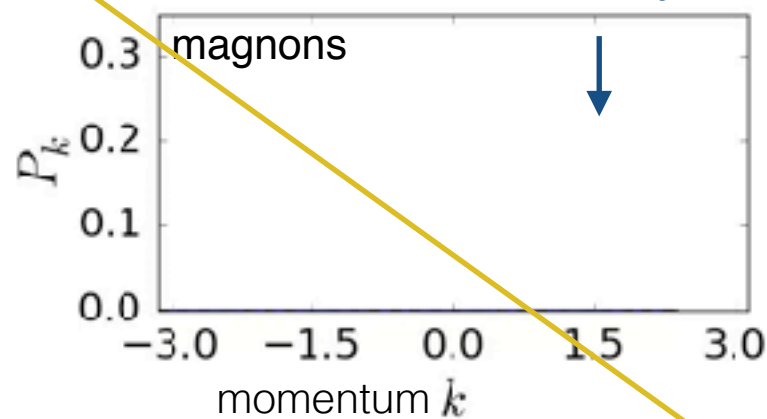
chiral case



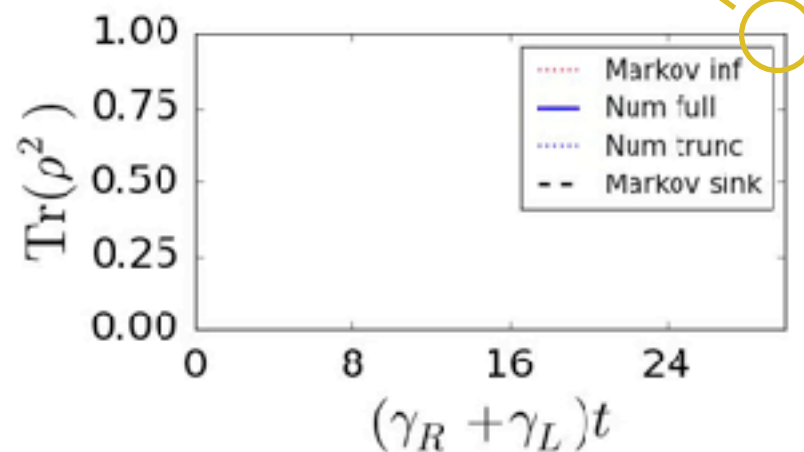
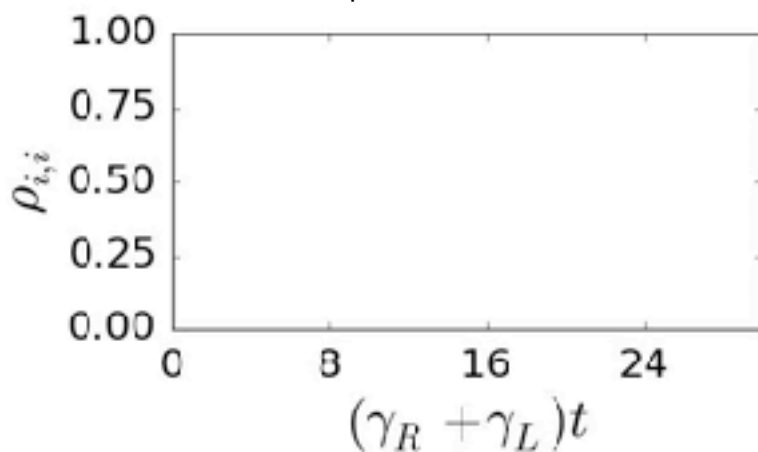
reservoir  
spins:



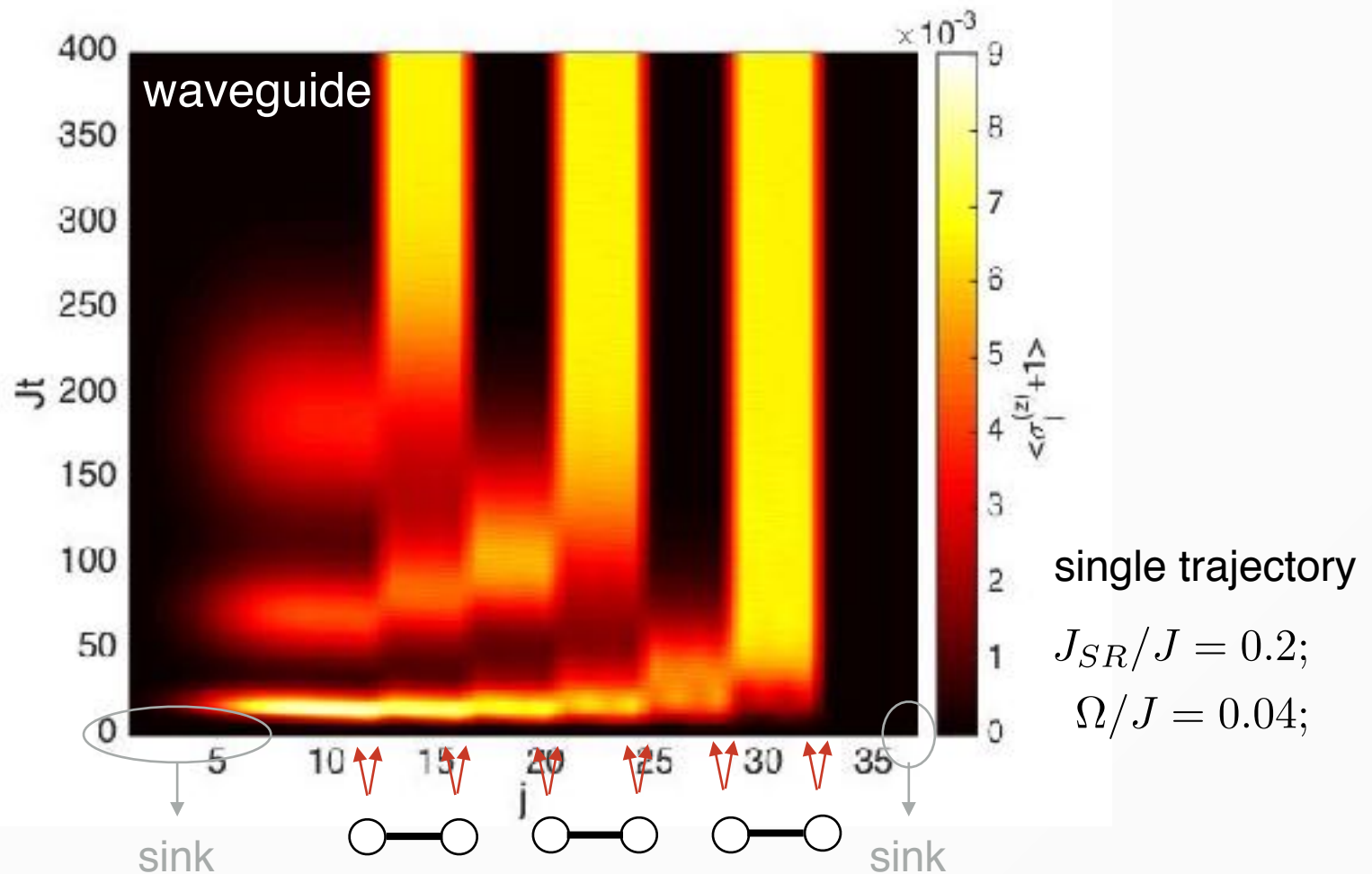
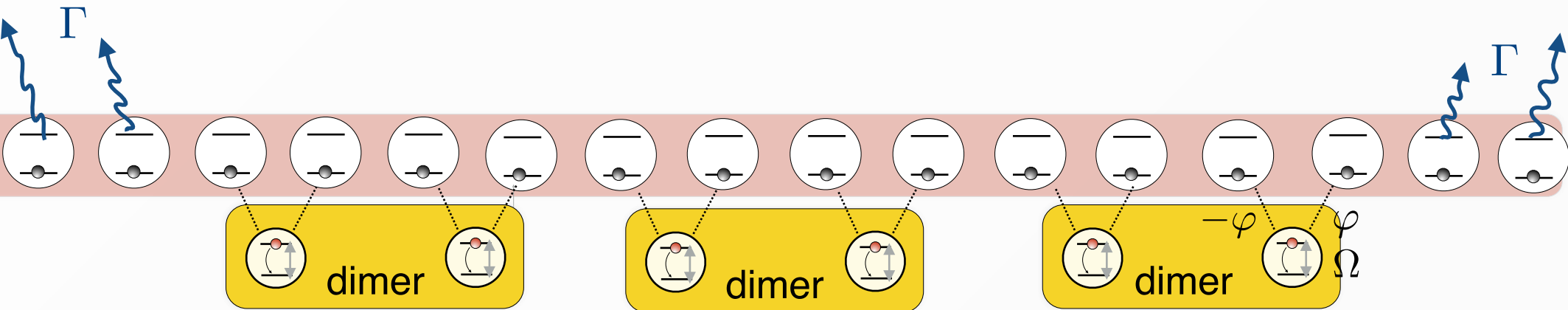
chirality



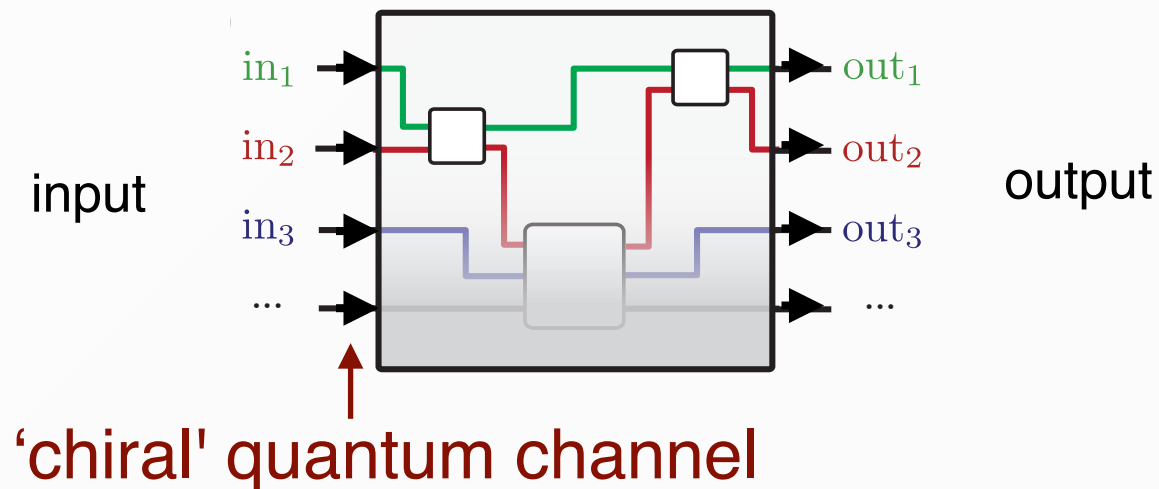
system:  
spins



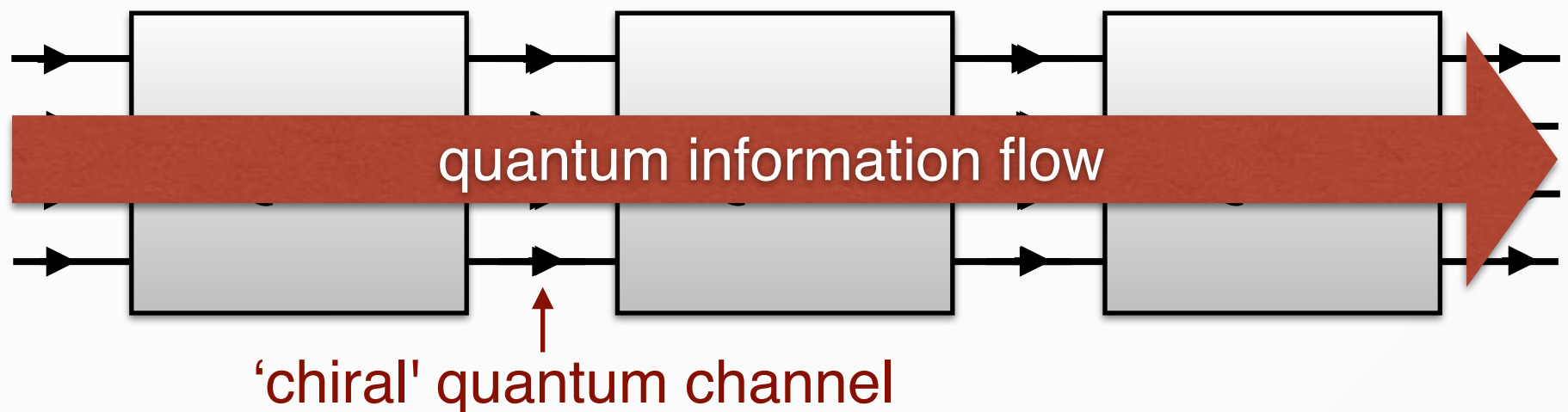
# tDMRG + quantum trajectories [beyond Born-Markov]



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

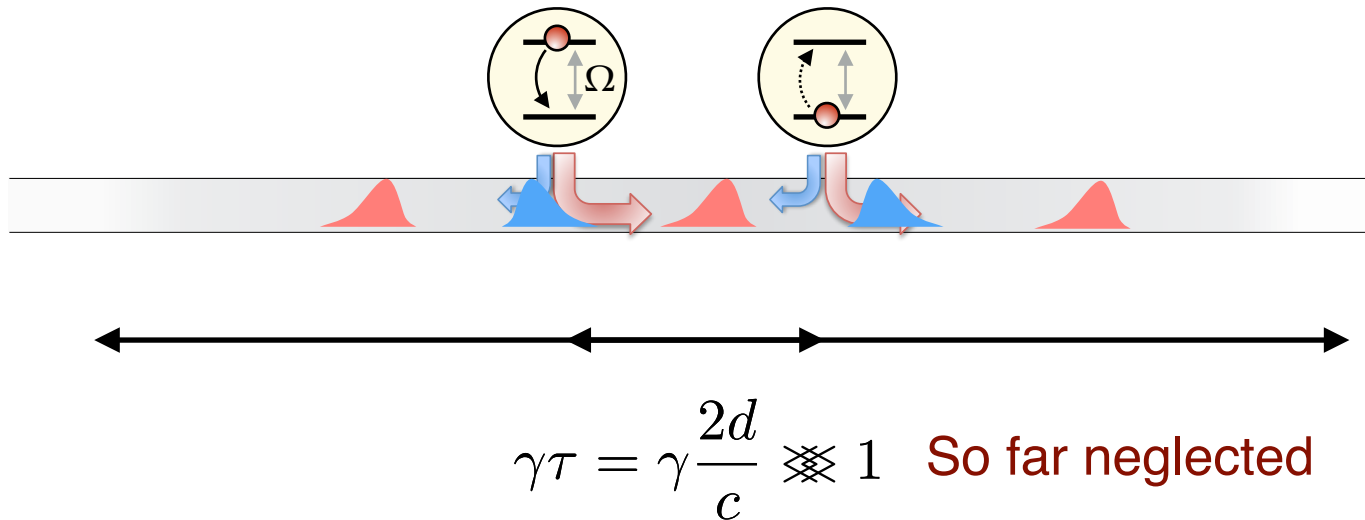


# 'Wiring Up' Quantum Modules: 'Chiral' Quantum Circuits with Photons & Spins

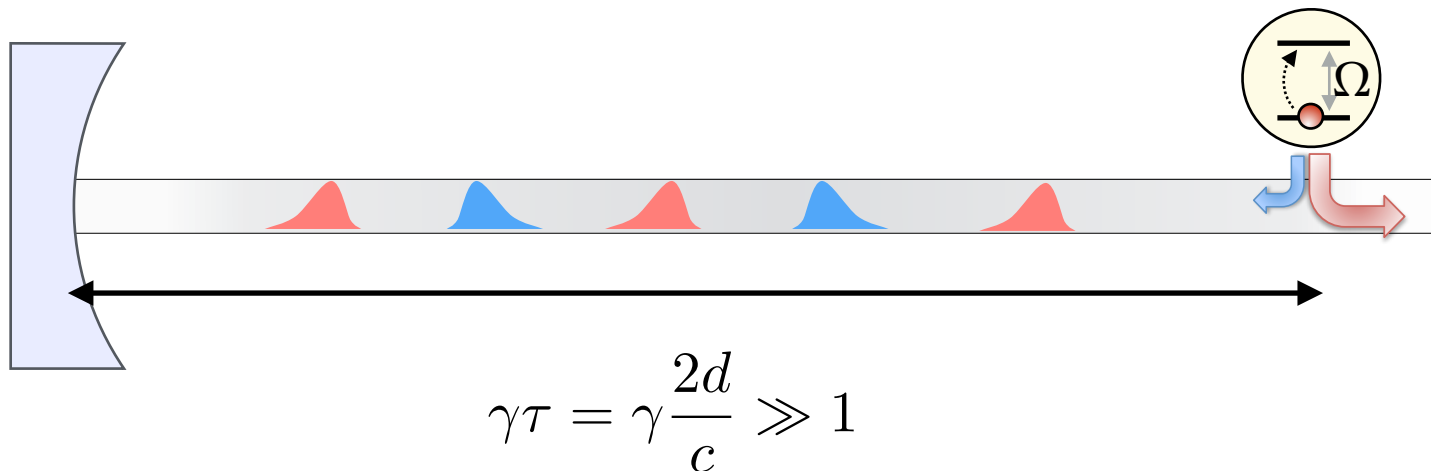


# Photonic Circuits: Quantum Feedback *with Delays*

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

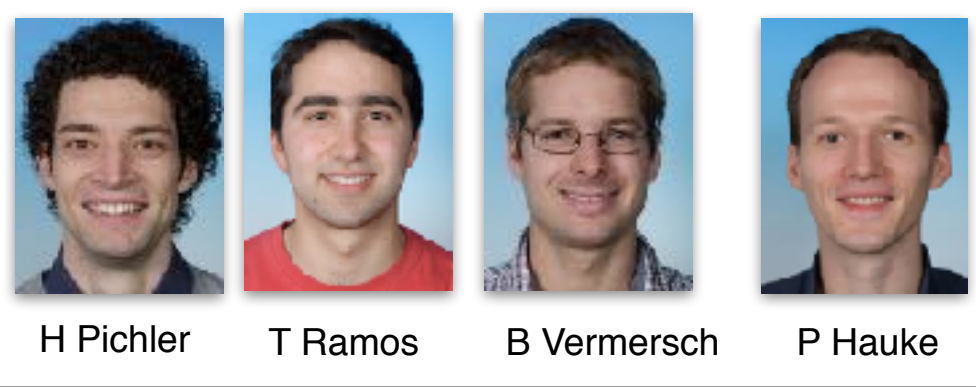


- **Model 2: driven atom in front of mirror = quantum feedback**

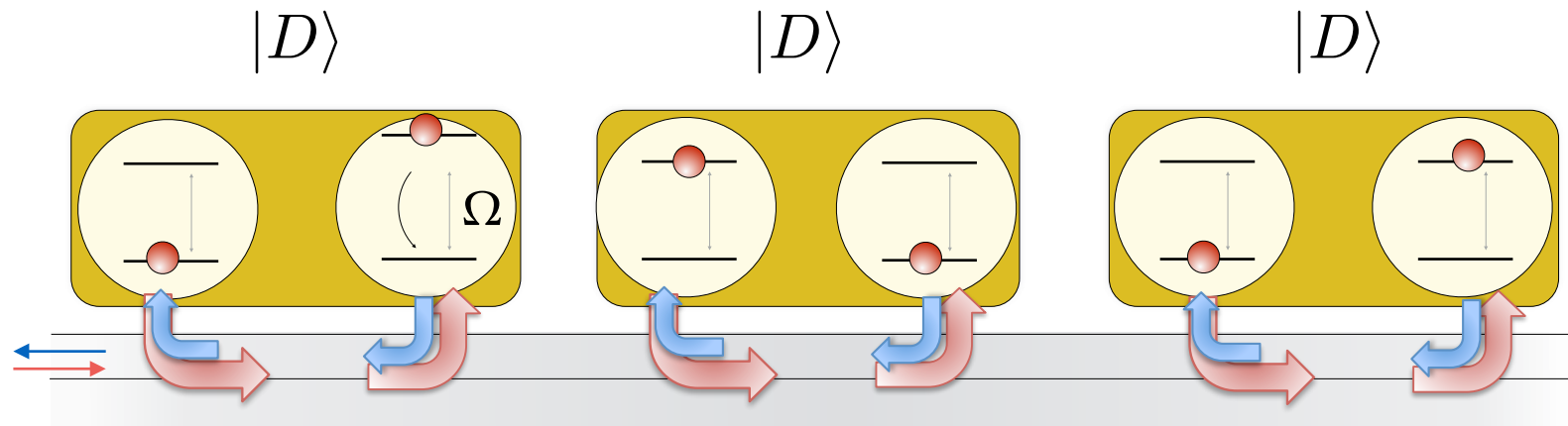


We use tDMRG techniques to solve for the dynamics.

# 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 ...**