Permanent spin currents in cavity-qubit systems

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PRB 97, 064506 (2018)

Collaboration:

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Also, PRL 116, 240503 (2016)
PRX 6, 011032 (2016)

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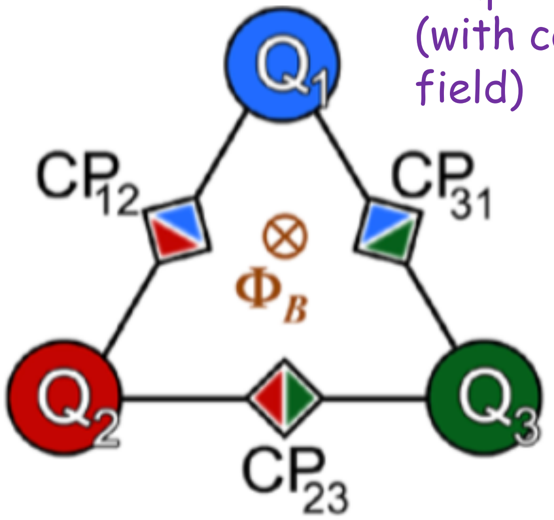
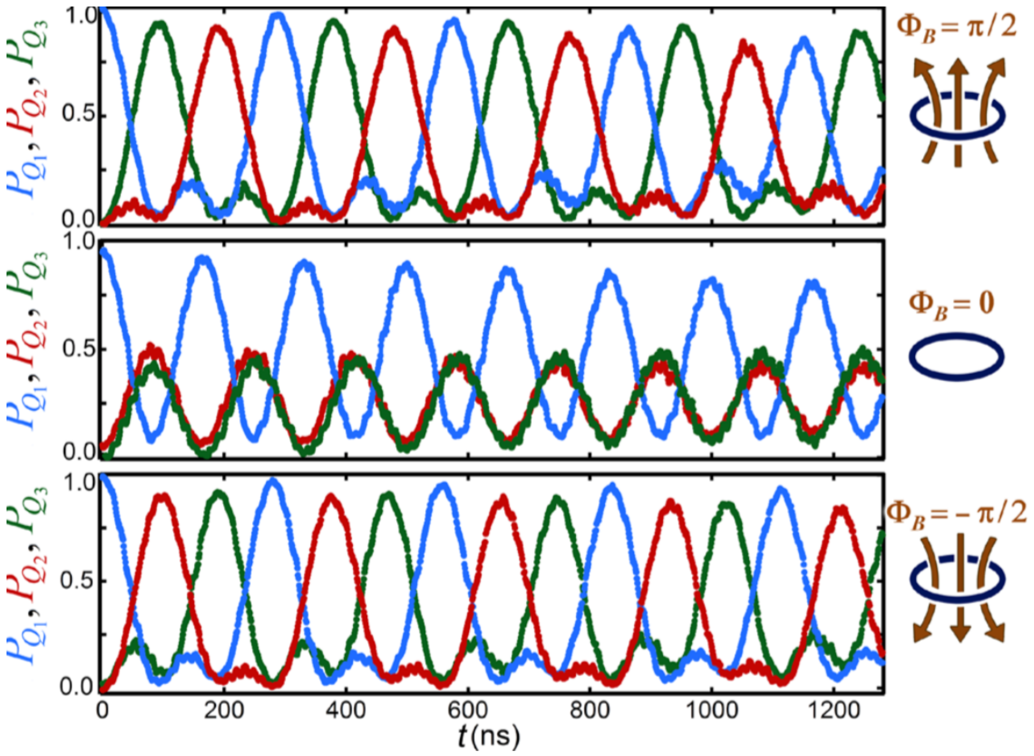
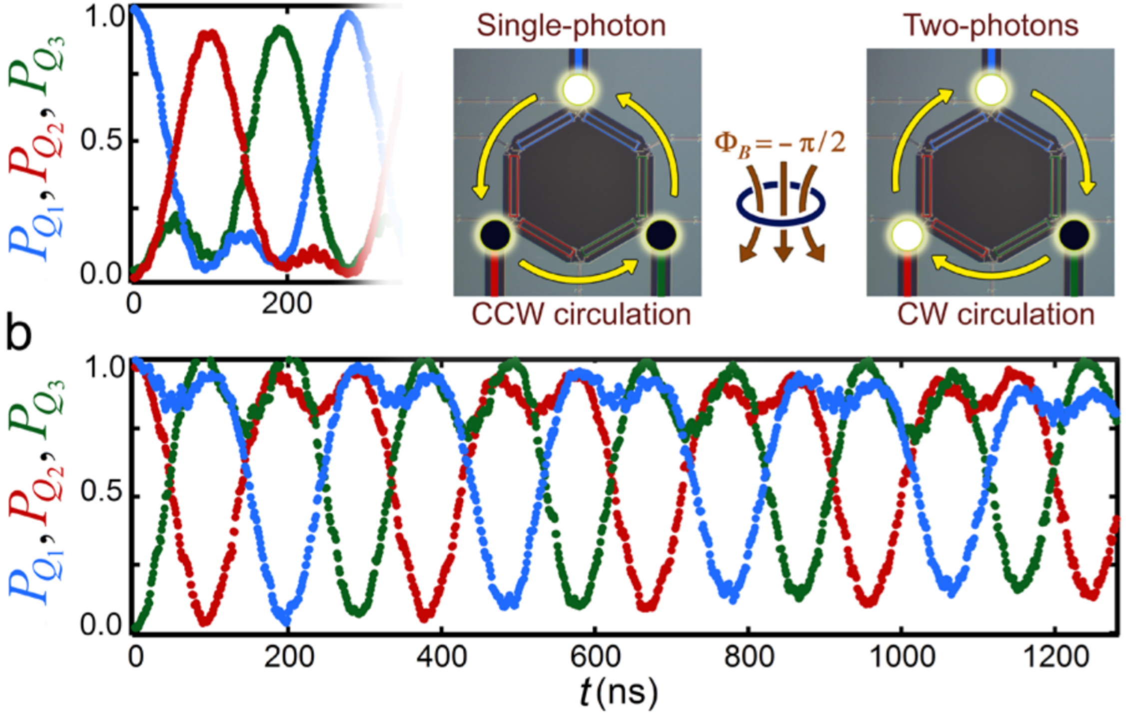
tifr

Coupled two level systems
(with complex coupling, artificial gauge field)





Google Inc / Santa Barbara Experiment



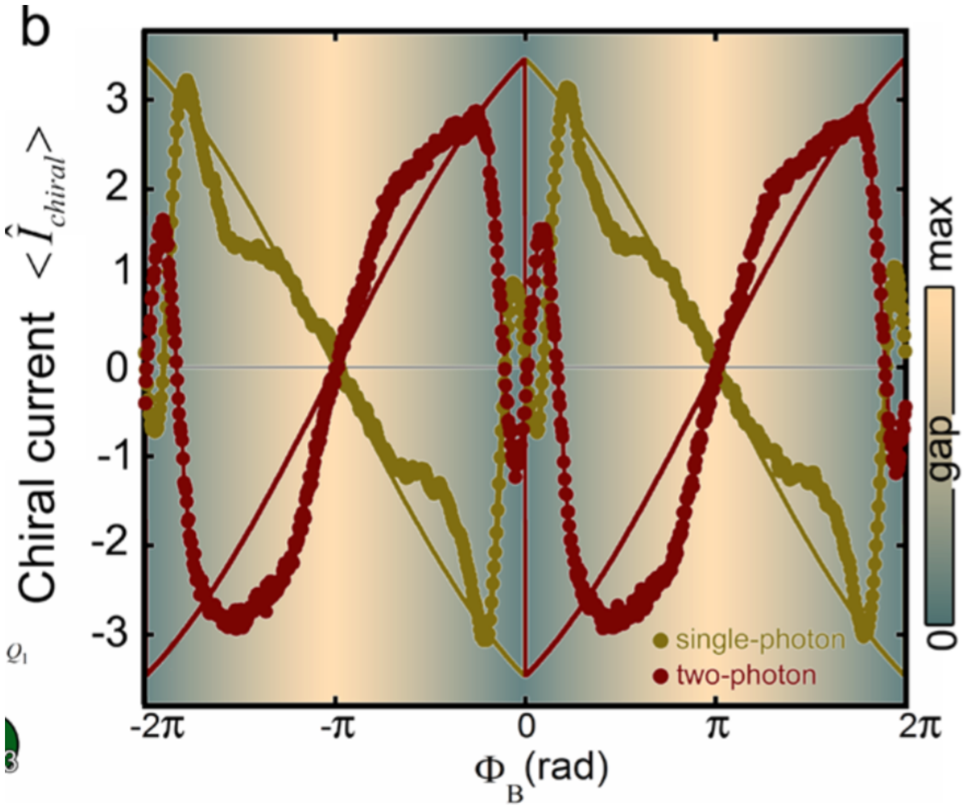
$$H(t) = \hbar \sum_{j=1}^{3} \omega_j (\hat{n}+1/2) + \hbar \sum_{j,k} g_{jk}(t)(a_j^\dagger a_k + a_j a_k^\dagger) + H_{\text{int}}$$

J. Martinis (Google Inc / Santa Barbara)

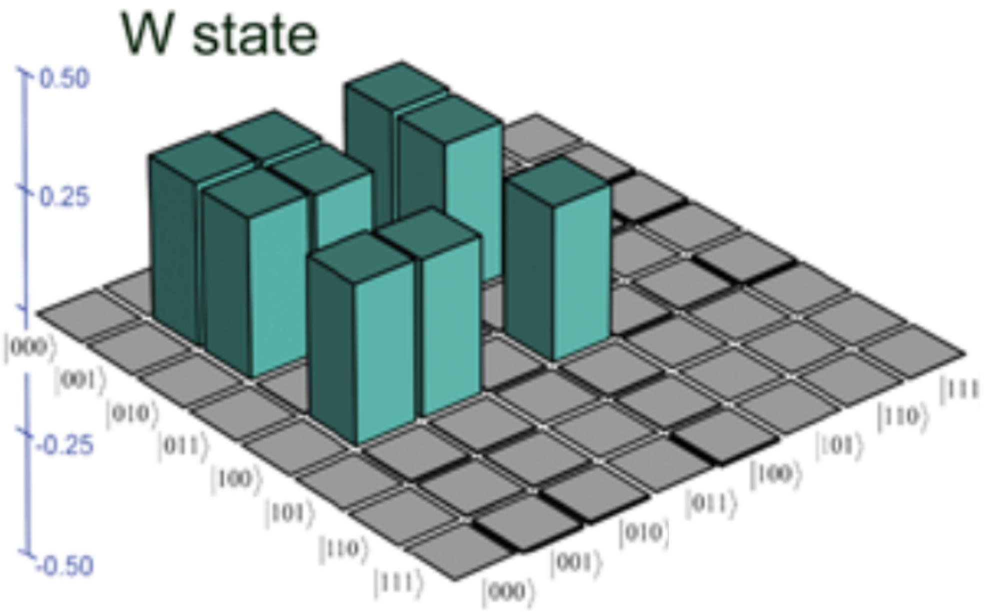
P. Roushan et al,

Nature Physics **13**, 146–151 (2017)

Chiral currents



Creating W-states



P. Roushan et al *Nature Physics* **13**, 146–151 (2017)

Quantum State Tomography

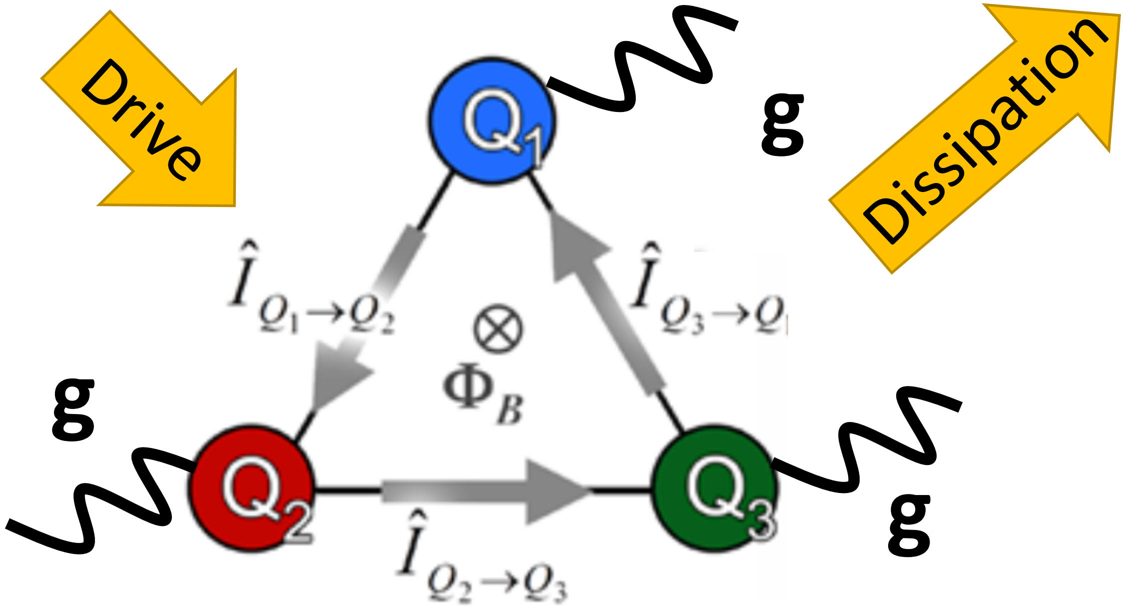
However, currents decay and are not persistent.

Systems are subject to inevitable environmental effects

Designing a protocol to create persistent currents

- striking a delicate balance between drive and dissipation to activate, specific entangled states with high fidelity, which are capable of carrying current

- power of quantum bath engineering approaches to realize highly non-trivial non-equilibrium steady states in Open Quantum Systems.



- Sources of dissipation are qubit dissipation/dephasing and cavity decay

- Qubits are coupled with complex hoping

- Each Qubit is coupled to a respective photon mode **(g)**

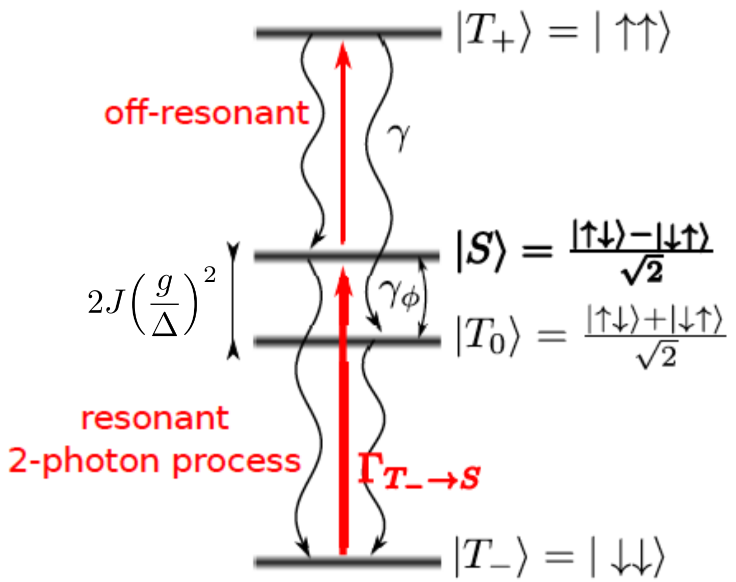
- Photons are driven by a classical microwave drive

Hamiltonians with complex coupling realized

P. Roushan et al *Nature Physics* (2017)

Many fascinating variations possible

E. Kapit, PRA (2015)



(Experiment realized @Berkeley, PRL 2016)

+

Protocols to strike a delicate balance between drive and dissipation (especially in context of entanglement)

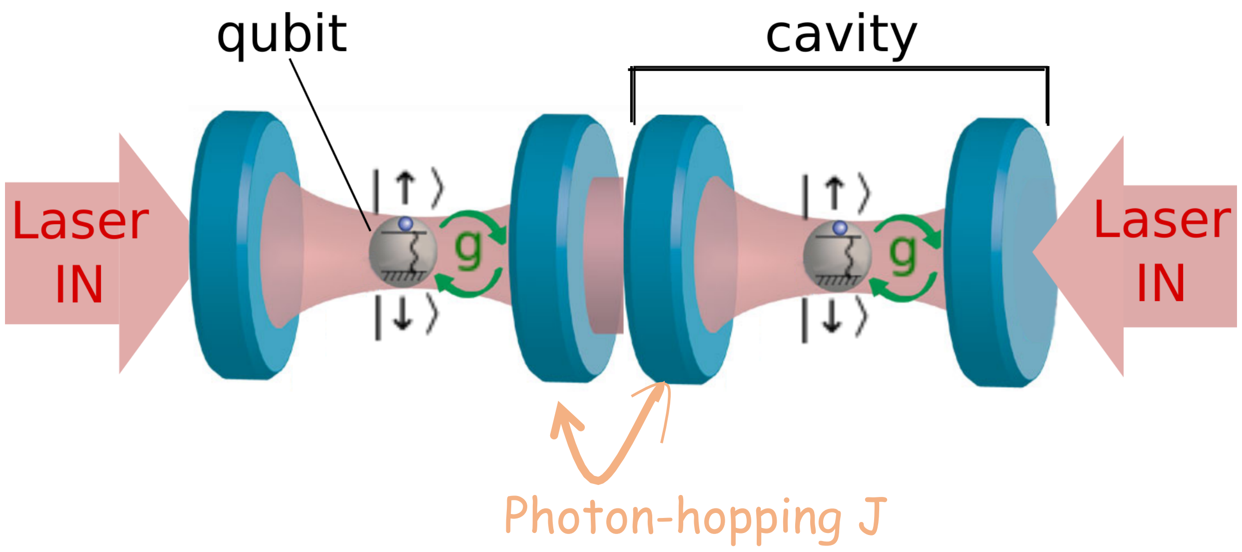
Aron, **Kulkarni**, Tureci (PRX 2016)
Schwartz, Martin, Flurin, Aron, **Kulkarni**, Tureci, Siddiqi (PRL 2016)
Aron, **Kulkarni**, Tureci (PRA 2014)

We try to unite these two ideas

Engineering a quantum device and the environment

Quantum Nanoelectronics Laboratory, Berkeley

Schwartz, Martin, Flurin, Aron, **Kulkarni**, Tureci, Siddiqi (PRL 2016)



Driven unitary evolution

- two-level systems $\omega_q \frac{\sigma_i^z}{2}$, $\omega_q \sim 10$ GHz
- far-detuned cavities $\omega_c \neq \omega_q$
- light-matter coupling $g \sim 0.1$ GHz
- inter-cavity coupling $J \sim 0.1$ GHz
- microwave drives: $\epsilon_d \cos(\omega_d t)(a_i + a_i^\dagger)$

Dissipative processes

- cavity decay $\kappa \sim 10^{-3}$ GHz
- qubit decay $\gamma \sim 10^{-4}$ GHz
- qubit dephasing $\gamma_\phi \sim 10^{-5}$ GHz

Jaynes-Cummings Array to XY Spin chain coupled to photons

$$H_\sigma = \sum_i \omega_q \frac{\sigma_i^z}{2}, \qquad H_{\sigma a} = g\sum_i [a_i^\dagger \sigma_i^- + \mathrm{H.c.}]$$

$$H_a(t) = \sum_i [\omega_c a_i^\dagger a_i - J(a_i^\dagger a_{i+1} + \mathrm{H.c.}) + 2\epsilon_i^d \cos(\omega_d t + \Phi_i)(a_i + a_i^\dagger)].$$

RWA+ Schrieffer-Wolff Transformation

$$H_\sigma = \sum_i \boldsymbol{h}_i \cdot \frac{\boldsymbol{\sigma}_i}{2} - \frac{J}{2}\left(\frac{g}{\Delta}\right)^2 [\sigma_i^x \sigma_{i+1}^x + \sigma_i^y \sigma_{i+1}^y],$$

$$H_{\sigma a} = \sum_i \left(\frac{g}{\Delta}\right)^2 \sigma_i^z (\Delta a_i^\dagger a_i + \epsilon_i^d a_i^\dagger + \epsilon_i^{d*} a_i).$$

Baths/Noise/Imperfections

$$H_{total} = H_{system} + H_{bath}$$

$$H_{\sigma,b} = \eta \sum_{i\,n} \sigma_i^x (b_{in} + b_{in}^\dagger), \quad H_b = \sum_{i\,n} \omega_n b_{in}^\dagger b_{in}$$

Qubits coupled to Bath

$$H_{a,\tilde{b}} = \tilde{\kappa} \sum_{i,n} (a_i^\dagger \tilde{b}_{in} + \tilde{b}_{in}^\dagger a_i), H_{\tilde{b}} = \sum_{i,n} \tilde{\omega_n} \tilde{b}_{in}^\dagger \tilde{b}_{in}$$

Cavity (photons) coupled to bath

$$H_\sigma = \sum_i \boldsymbol{h}_i \cdot \frac{\boldsymbol{\sigma}_i}{2} - \frac{J}{2} \left(\frac{g}{\Delta}\right)^2 [\sigma_i^x \sigma_{i+1}^x + \sigma_i^y \sigma_{i+1}^y],$$

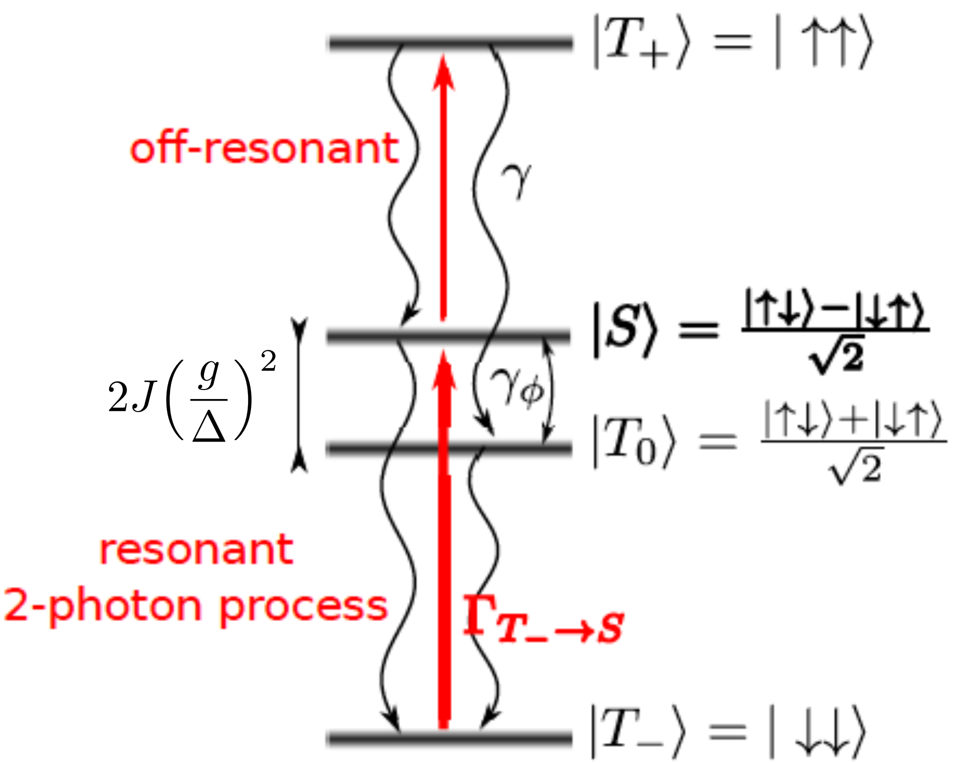
$$H_{\sigma a} = \sum_i \left(\frac{g}{\Delta}\right)^2 \sigma_i^z (\Delta a_i^\dagger a_i + \epsilon_i^{\mathrm{d}} a_i^\dagger + \epsilon_i^{\mathrm{d}*} a_i).$$

System Hamiltonian

Aron, **Kulkarni**, Tureci (PRA, 2014)
Aron, **Kulkarni**, Tureci (PRX 2016)

Nonequilibrium rate from $|T_-\rangle$ to $|S\rangle$

$$\Gamma_{T_- \to S} \propto 2\pi(g^3\epsilon_\mathrm{d}^2)^2\rho_-(\omega_\mathrm{d} + E_{T_-} - E_S)$$



Transverse-field isotropic XY-model

$$H_\sigma = \sum_{i=1}^{2} \mathbf{h}\cdot\frac{\boldsymbol{\sigma}_i}{2} - \frac{J}{2}\left(\frac{g}{\Delta}\right)^2[\sigma_1^x\sigma_2^x + \sigma_1^y\sigma_2^y]$$

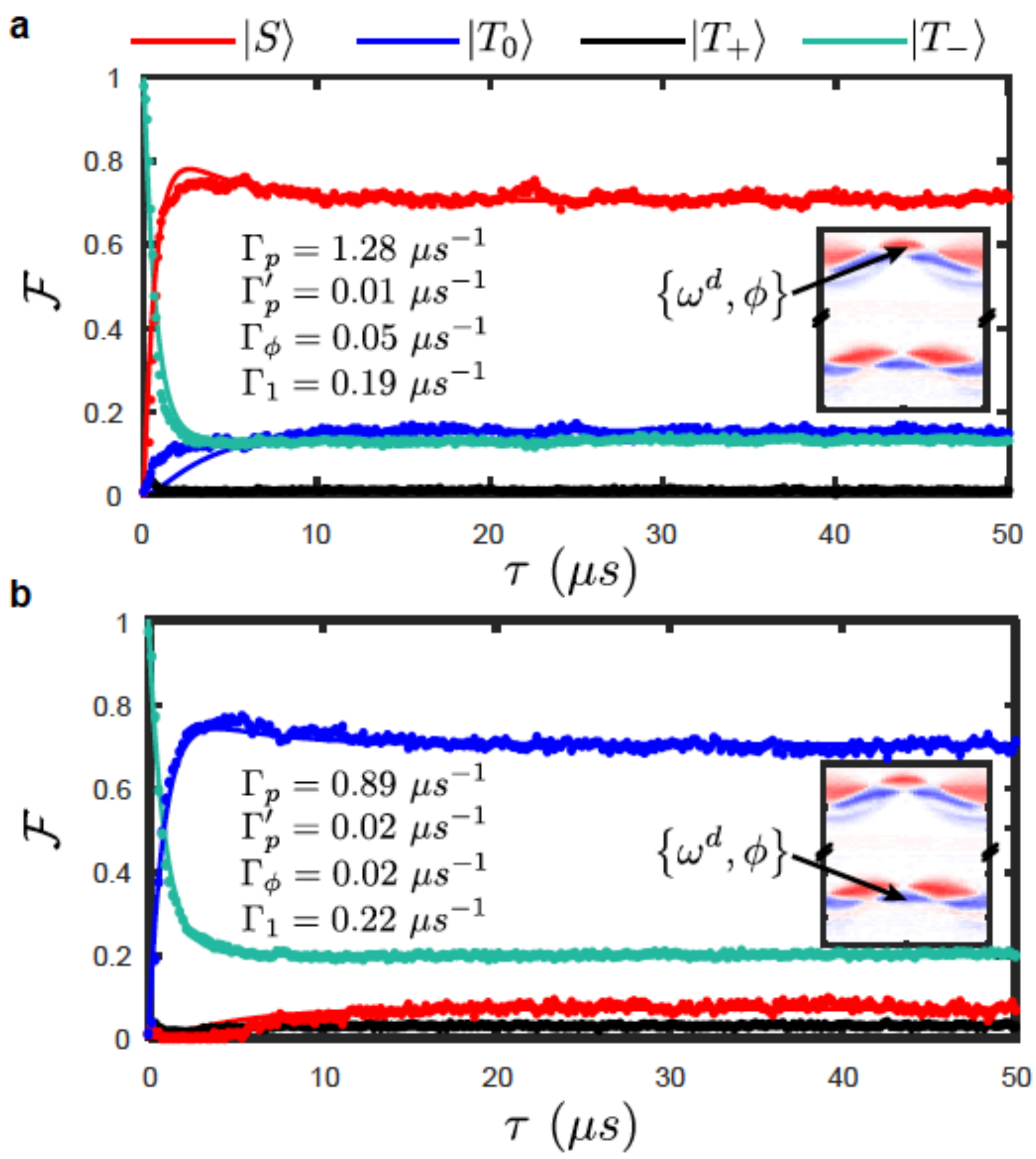
$$h^x \equiv g\epsilon_\mathrm{d},\ h^y \equiv 0,\ h^z \equiv \omega_\mathrm{q} - \omega_\mathrm{d}$$

Weakly-coupled photon-fluctuation bath

$$H_{\sigma d} = \#\left(\frac{g}{\Delta}\right)^2\epsilon_\mathrm{d}\sum_{i=1}^{2}\sigma_i^z(d_i + d_i^\dagger)$$

$$H_d = \sum_{i=1}^{2}(\omega_\mathrm{c} - \omega_\mathrm{d})d_i^\dagger d_i - J(d_1^\dagger d_2 + \mathrm{h.c.})$$

Experimental Results: Time Dynamics (time evolution of entanglement)

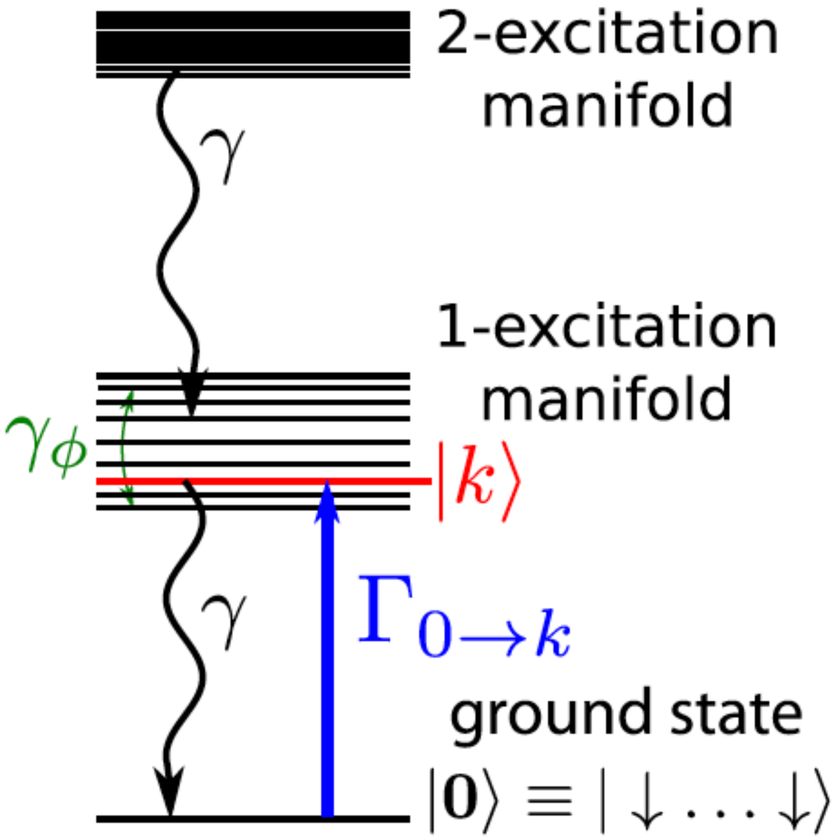


Quantum StateTomography
@Berkeley

Agreement between experiment and theory !

Schwartz, Martin, Flurin, Aron, **Kulkarni**, Tureci, Siddiqi (PRL 2016)

Creating a target generalized-W state



Target state

$$|k\rangle \equiv \sum_j \mathrm{e}^{\mathrm{i}kj} |j\rangle$$

$$|j\rangle = |\downarrow_0 \ldots \downarrow_{j-1} \uparrow_j \downarrow_{j+1} \ldots \downarrow_{N-1}\rangle$$

Single magnon excitations

For e.g., N=2 and k=0, target state is

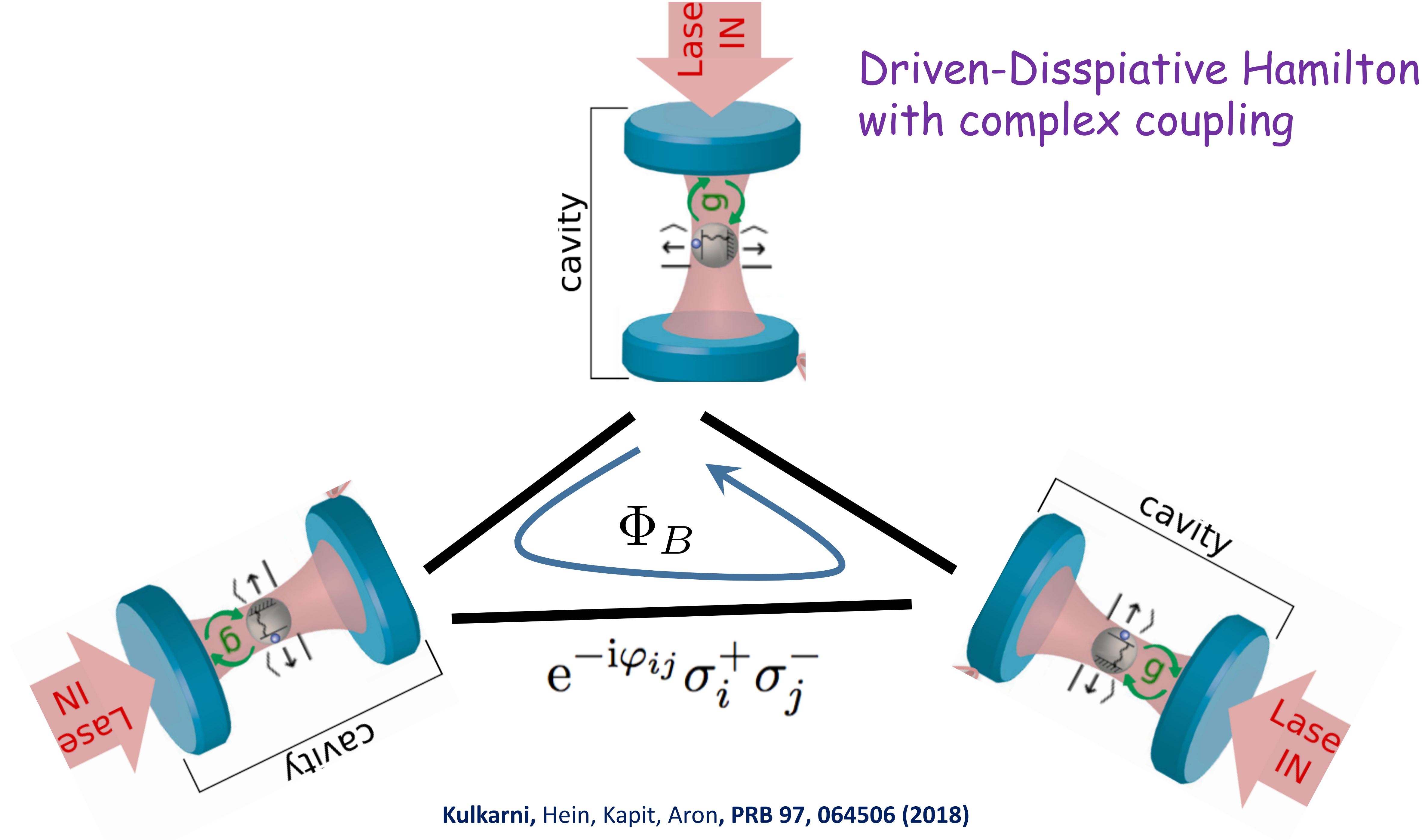
$$|T_0> = \frac{1}{\sqrt{2}}(|\uparrow\downarrow> + |\downarrow\uparrow>)$$

For e.g., N=3 and k=0, target state is

$$W = \frac{1}{\sqrt{3}}\Big(|\downarrow\downarrow\uparrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\uparrow\downarrow\downarrow\rangle\Big)$$

Aron, **Kulkarni**, Tureci (PRX 2016)

Driven-Disspiative Hamiltonian with complex coupling



Kulkarni, Hein, Kapit, Aron, **PRB 97, 064506 (2018)**

$$H_\sigma = \sum_i (\omega_\mathrm{q} - \omega_\mathrm{d}) \frac{\sigma_i^z}{2} - \sum_{\langle ij \rangle} J_0 \left[\mathrm{e}^{-\mathrm{i}\varphi_{ij}} \sigma_i^+ \sigma_j^- + \mathrm{h.c.} \right]$$

$$H_{\sigma a} = \sum_i g \left[a_i^\dagger \sigma_i^- + \mathrm{h.c.} \right] ,$$

$$H_a = \sum_k (\omega_\mathrm{c} - \omega_\mathrm{d}) a_k^\dagger a_k + (\epsilon_k^\mathrm{d} a_k^\dagger + \mathrm{h.c.}) .$$

SW transformation

$$H_\sigma = \sum_i \boldsymbol{h_i} \cdot \frac{\boldsymbol{\sigma}_i}{2} - \sum_i J_0 \left[\mathrm{e}^{\mathrm{i}\phi} \sigma_i^+ \sigma_{i+1}^- + \mathrm{h.c.} \right] ,$$

$$H_{\sigma a} = \sum_i \left(\frac{g}{\Delta} \right)^2 \sigma_i^z (\Delta a_i^\dagger a_i + \frac{1}{2} \epsilon_i^\mathrm{d} a_i^\dagger + \frac{1}{2} \epsilon_i^{\mathrm{d}*} a_i)$$

$$H_a = \sum_k (\omega_k - \omega_\mathrm{d}) a_k^\dagger a_k + (\epsilon_k^\mathrm{d} a_k^\dagger + \mathrm{h.c.})$$

$$H_d = \sum_k (\omega_\mathrm{c} - \omega_\mathrm{d}) d_k^\dagger d_k \qquad H_\sigma = \sum_k E_k |k\rangle\langle k| + \left(\frac{g}{\Delta}\right)\left(\epsilon_k^\mathrm{d} |k\rangle\langle \mathbf{0}| + \mathrm{h.c.}\right)$$

$$H_{\sigma d} = \left(\frac{g}{\Delta}\right)^2 \sum_i \sigma_i^z [(\Delta \bar{a}_i + \frac{1}{2}\epsilon_i^\mathrm{d}) d_i^\dagger + \mathrm{h.c.}]$$

$$\partial_t \rho_\sigma^\mathrm{NESS} = 0 = -\mathrm{i}\left[H_\sigma, \rho_\sigma^\mathrm{NESS}\right] + \sum_k \Gamma_{\mathbf{0}\to k} \mathcal{D}[|\widetilde{k}\rangle\langle\widetilde{\mathbf{0}}|]\rho_\sigma^\mathrm{NESS}$$

$$+\gamma \sum_k \mathcal{D}[|\widetilde{\mathbf{0}}\rangle\langle\widetilde{k}|]\rho_\sigma^\mathrm{NESS} + \frac{2\gamma_\phi}{N}\sum_{k\,q} \mathcal{D}[|\widetilde{q}\rangle\langle\widetilde{k}|]\rho_\sigma^\mathrm{NESS}.$$

$$\Gamma_{\mathbf{0}\to k} = 2\pi \sum_q \Lambda_{kq}^2\, \rho(\omega_\mathrm{d} + \widetilde{E}_\mathbf{0} - \widetilde{E}_k)$$

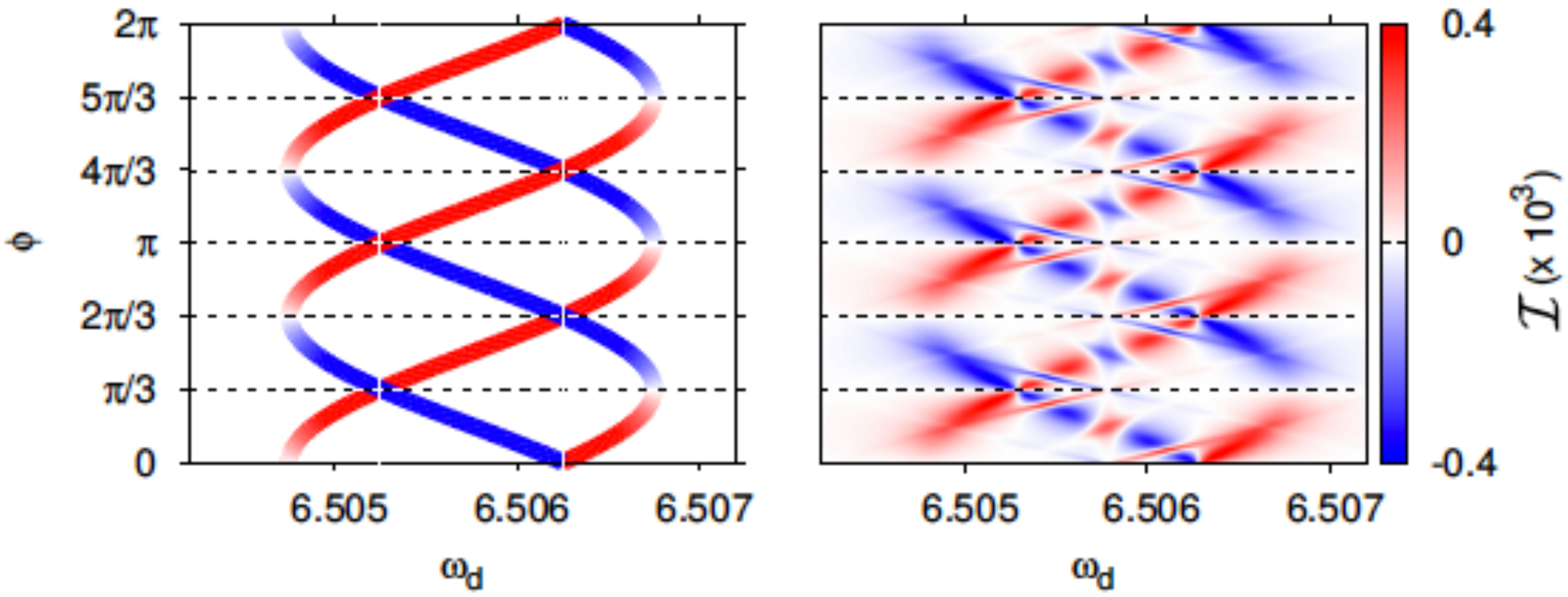
$$\omega_{\mathrm{d}} = \frac{\omega_{\mathrm{c}} + \omega_{\mathrm{q}} + \delta\omega_{\mathrm{q}}}{2} - J_0 \cos(k+\phi) + \frac{1}{2}\left(\frac{g}{\Delta}\right)^2 \sum_{q \neq k} \frac{|\epsilon_q^{\mathrm{d}}|^2}{\Delta_{\mathrm{q}}}$$

Once we compute density matrix we can calculate current:

$$\mathcal{J}_i = -\mathrm{i}J_0 \left[\mathrm{e}^{\mathrm{i}\phi}\sigma_i^+\sigma_{i+1}^- - \mathrm{H.c.}\right]$$

We also compute the fidelity to go to target eigenstates

Kulkarni, Hein, Kapit, Aron**, PRB 97, 064506 (2018)**



NESS Current

Persistent Chiral Currents

$$\mathcal{I}(\omega_{\rm d},\phi) = \frac{2}{N} J_0 \sum_k \sin(k+\phi) n_k(\omega_{\rm d},\phi)$$

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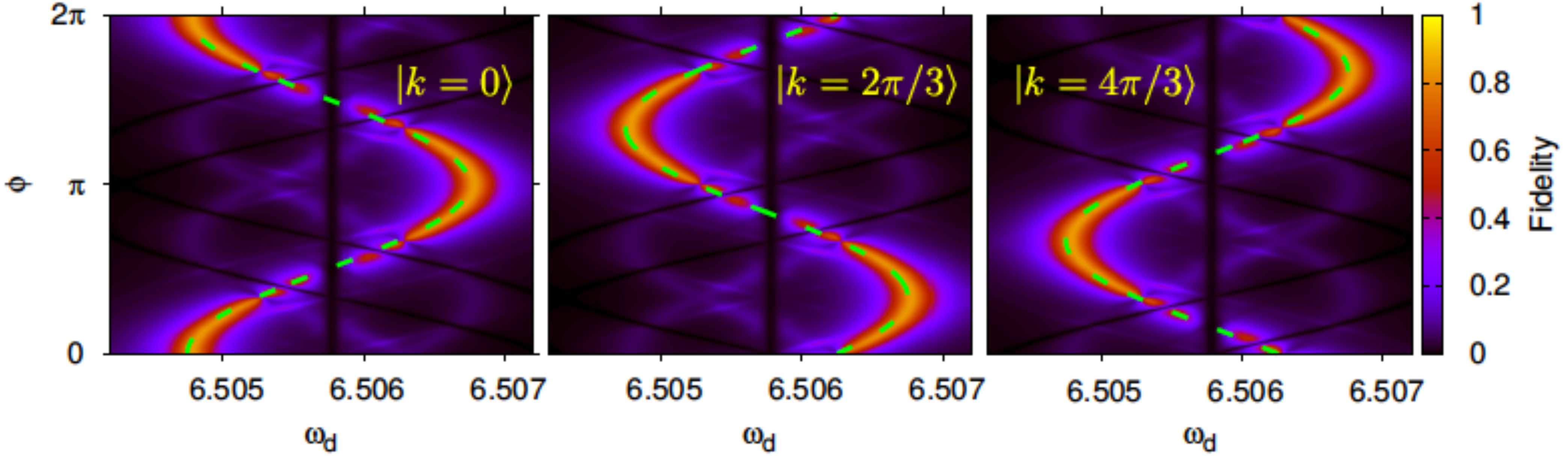
Kulkarni, Hein, Kapit, Aron, PRB 97, 064506 (2018)



Steady State Population (Fidelities)

$$\omega_{\mathrm{d}}^{\mathrm{opt}}(\phi) = \bar{\omega}_{\mathrm{d}} - J_0 \cos(k + \phi)$$

Optimal Drive

Conclusions

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- Persistent (infinitely long-lived) current
- Preparation of High fidelity states
- Entanglement Dynamics

Outlook

- Extending to ring geometries (many qubits & cavities)
- Performing an exact brute force numerical computation (including spins and photos)
- Treat higher excitation manifolds