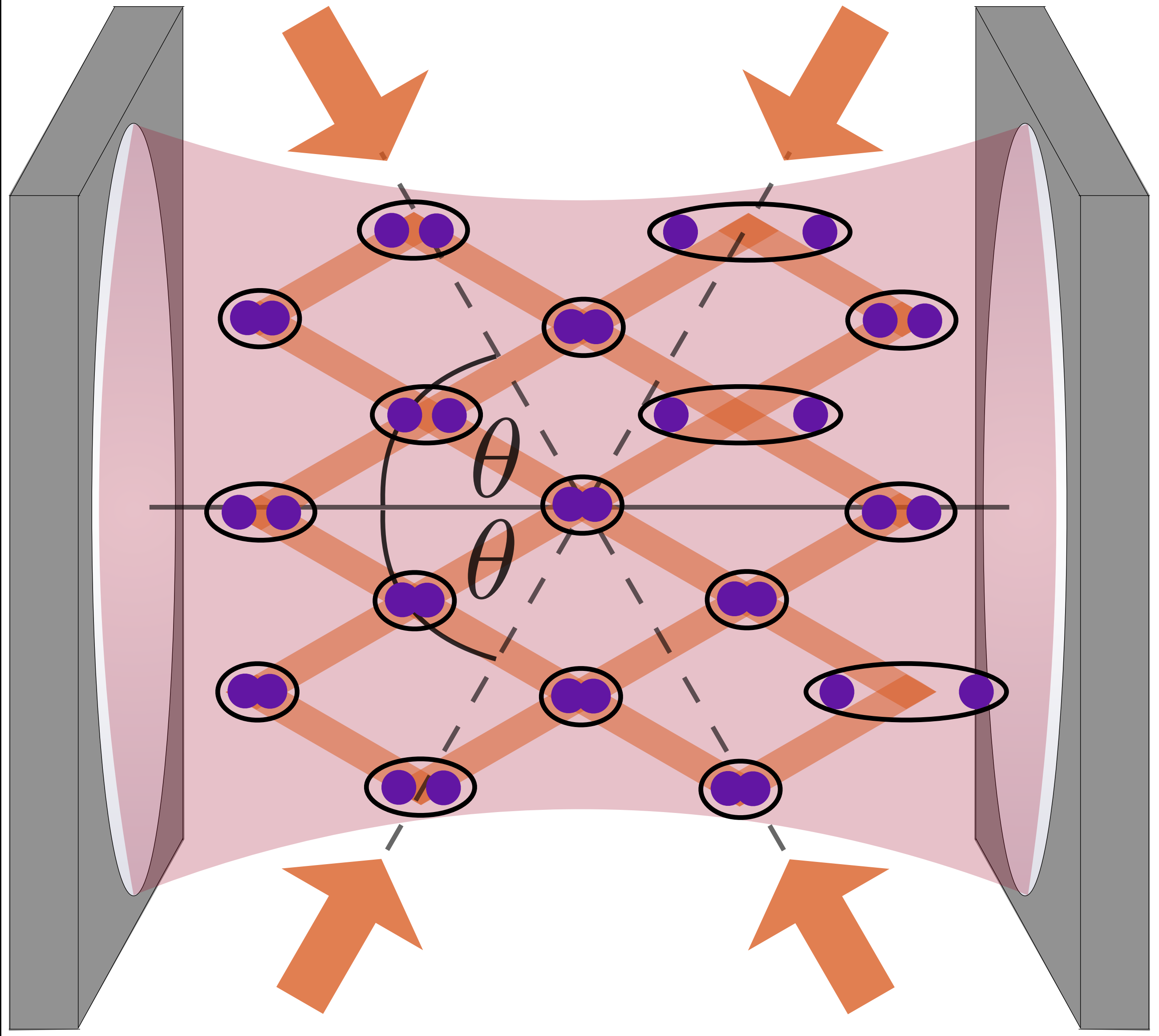
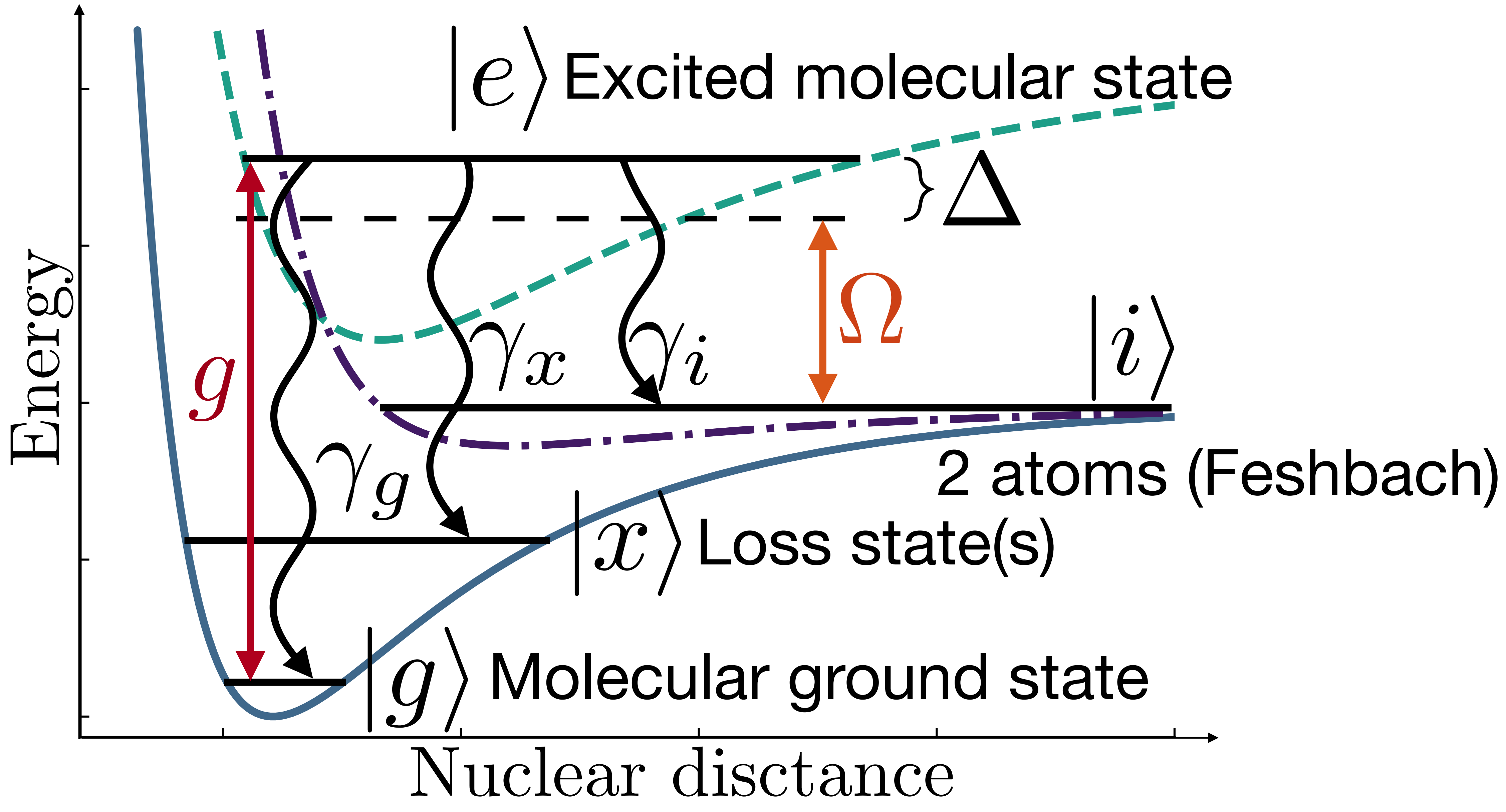
Abstract / Motivation:

Ultracold atoms and molecules that are coupled to a cavity can exhibit collective effects, such as polariton formation or superradiance. Here, we propose a mechanism to harness these collective and dissipative effects in order to realize high-yield ground state molecular formation from ultracold atoms. Using a combination of analytical and numerical techniques, we demonstrate that the ground state yield can be improved by increasing the number of atoms, and overcome efficiencies of state-of-the-art association schemes.

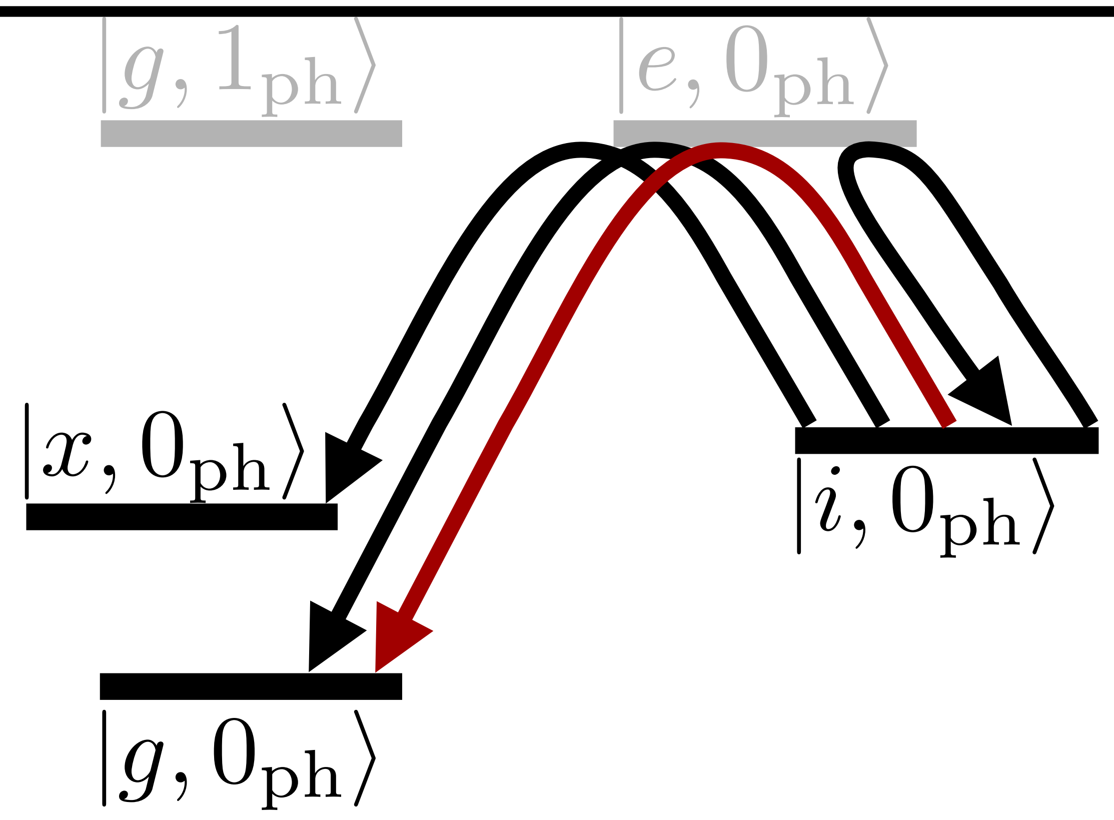
Model

***DW**, Schütz, Whitlock, Schachenmayer, Pupillo*: PRL 125, 193201 (2020)

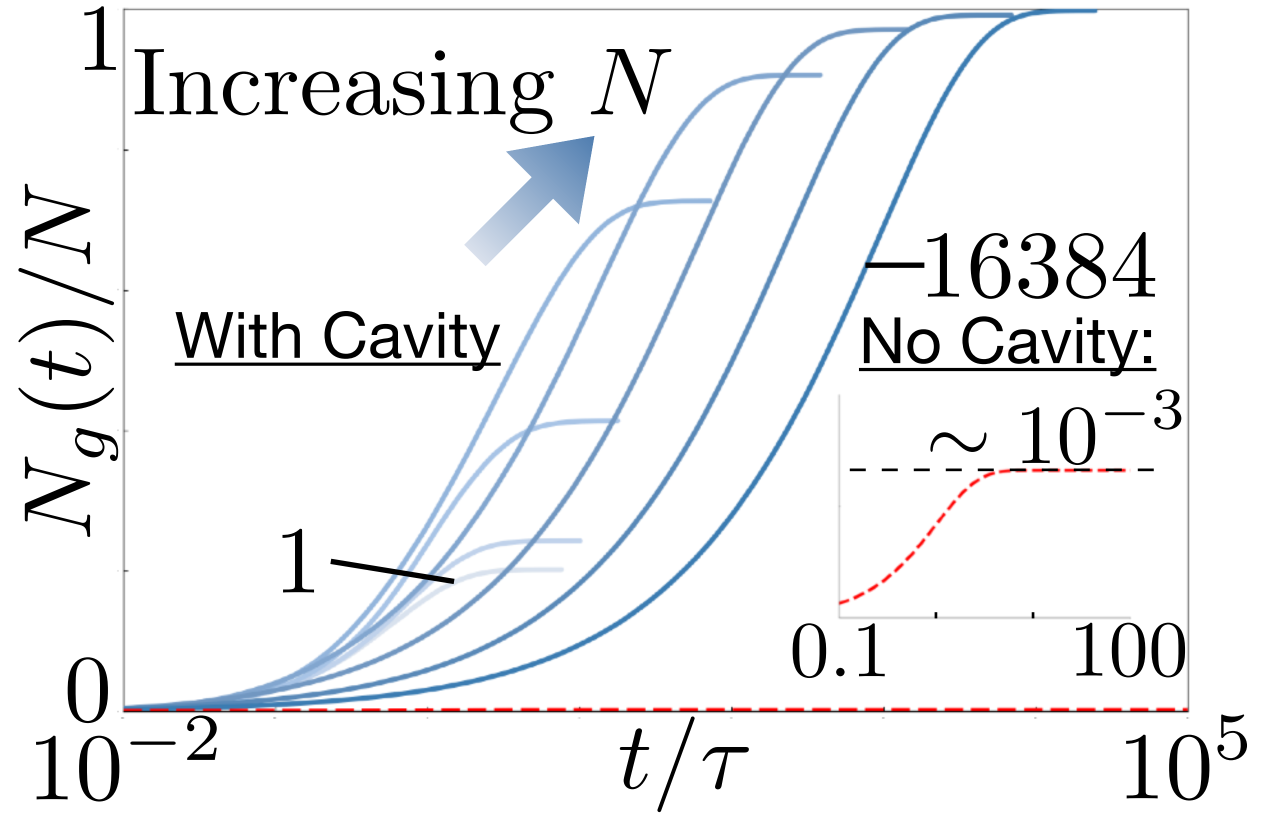




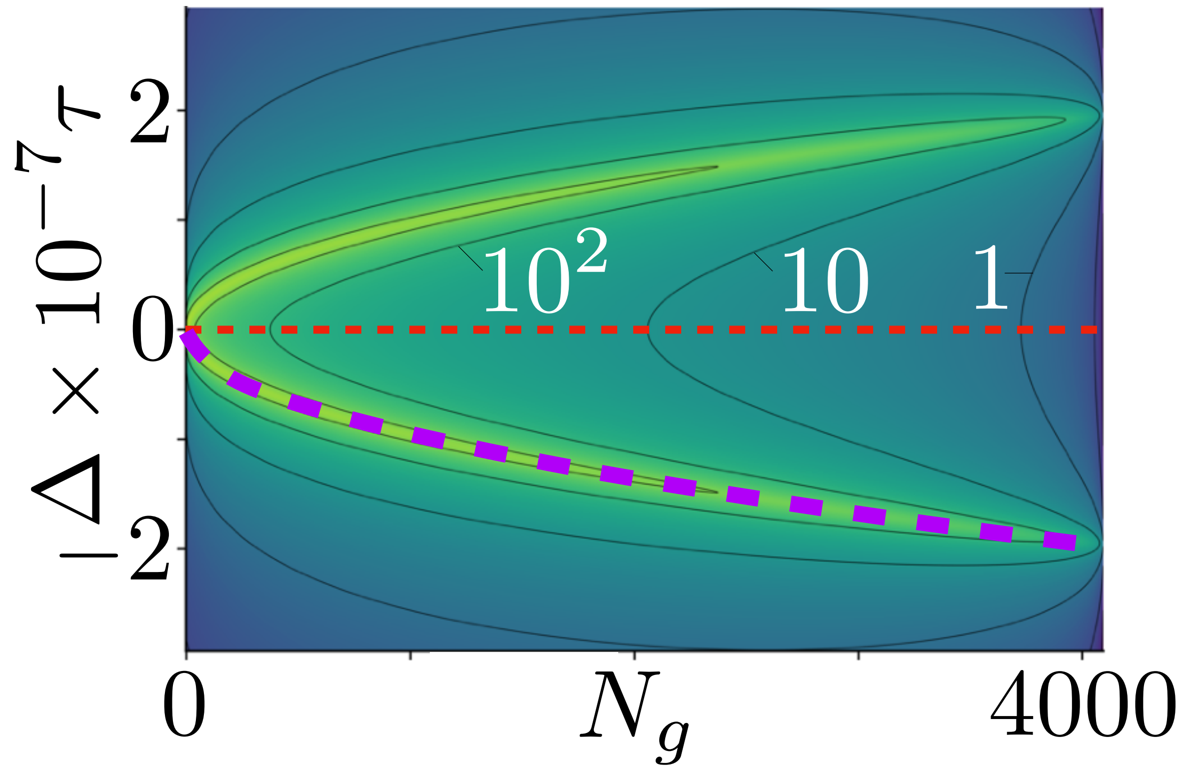
See also: *Kampschulte, Hecker Denschlag*: NJP 20, 123015 (2018)
Perez-Rios, Kim, Hung: NJP 19, 123035 (2017)



Adiabatic Elimination



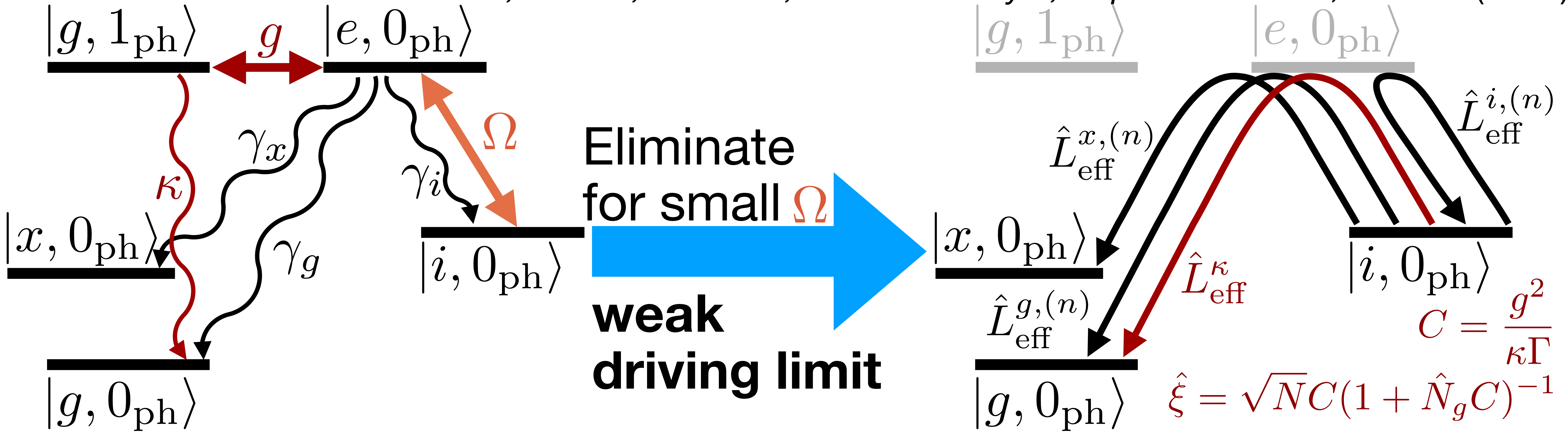
Collective Enhancement



Polaritons & Rate Equations

Method

DW, Schütz, Whitlock, Schachenmayer, Pupillo: PRL 125, 193201 (2020)



The full dynamics can only be simulated for small systems. In the weak driving limit, the excited state and cavity mode have a small population and can be adiabatically eliminated. The effective dynamics is purely dissipative and can be efficiently simulated using the permutation symmetry.

$$\hat{\sigma}^{(n)}_{\alpha,\beta} = |\alpha\rangle\langle\beta|_n$$

$$\hat{N}_\alpha = \sum_n \hat{\sigma}^{(n)}_{\alpha\alpha}$$

$$\hat{S}_{\alpha\beta} = \sum_n \sigma^{(n)}_{\alpha\beta}/\sqrt{N}$$

Master Equation

$$\partial_t \hat{\rho} = -\mathrm{i}\left[\hat{H}, \hat{\rho}\right] + \sum_{\alpha,n} \mathcal{L}_{\alpha,(n)}(\hat{\rho}) + \mathcal{L}_\kappa(\hat{\rho})$$

$$\mathcal{L}_k(\hat{\rho}) = -\hat{L}^{k\dagger}\hat{L}^k\hat{\rho} - \hat{\rho}\hat{L}^{k\dagger}\hat{L}^k + 2\hat{L}^k\hat{\rho}\hat{L}^{k\dagger}$$

Hamiltonian and Lindblad

$$\hat{H}_{LA} = \Omega\sqrt{N}\left(\hat{S}_{ie} + \hat{S}_{ei}\right) + \Delta\hat{N}_e$$

$$\hat{H}_C = g\sqrt{N}\left(\hat{a}^\dagger\hat{S}_{ge} + \hat{S}_{eg}\hat{a}\right) + \Delta\hat{a}^\dagger\hat{a}$$

$$\hat{L}_\kappa = \sqrt{\kappa}\hat{a} \qquad \hat{L}^{(n)}_\alpha = \sqrt{\gamma_\alpha}\hat{\sigma}^{(n)}_{\alpha e}$$

Effective Hamiltonian and Lindblad

$$\hat{H}_{\mathrm{eff}} = 0$$

$$\hat{L}^\kappa_{\mathrm{eff}} = \frac{\Omega\sqrt{\kappa}}{g}\hat{\xi}\hat{S}_{gi}$$

$$\hat{L}^{\alpha,(n)}_{\mathrm{eff}} = \frac{\Omega\sqrt{\gamma_\alpha}}{\Gamma}\left(\hat{\sigma}^{(n)}_{\alpha i} - \hat{\sigma}^{(n)}_{\alpha g}\hat{\xi}\hat{S}_{gi}\right)$$

Effective dynamics is purely **dissipative and collective!**

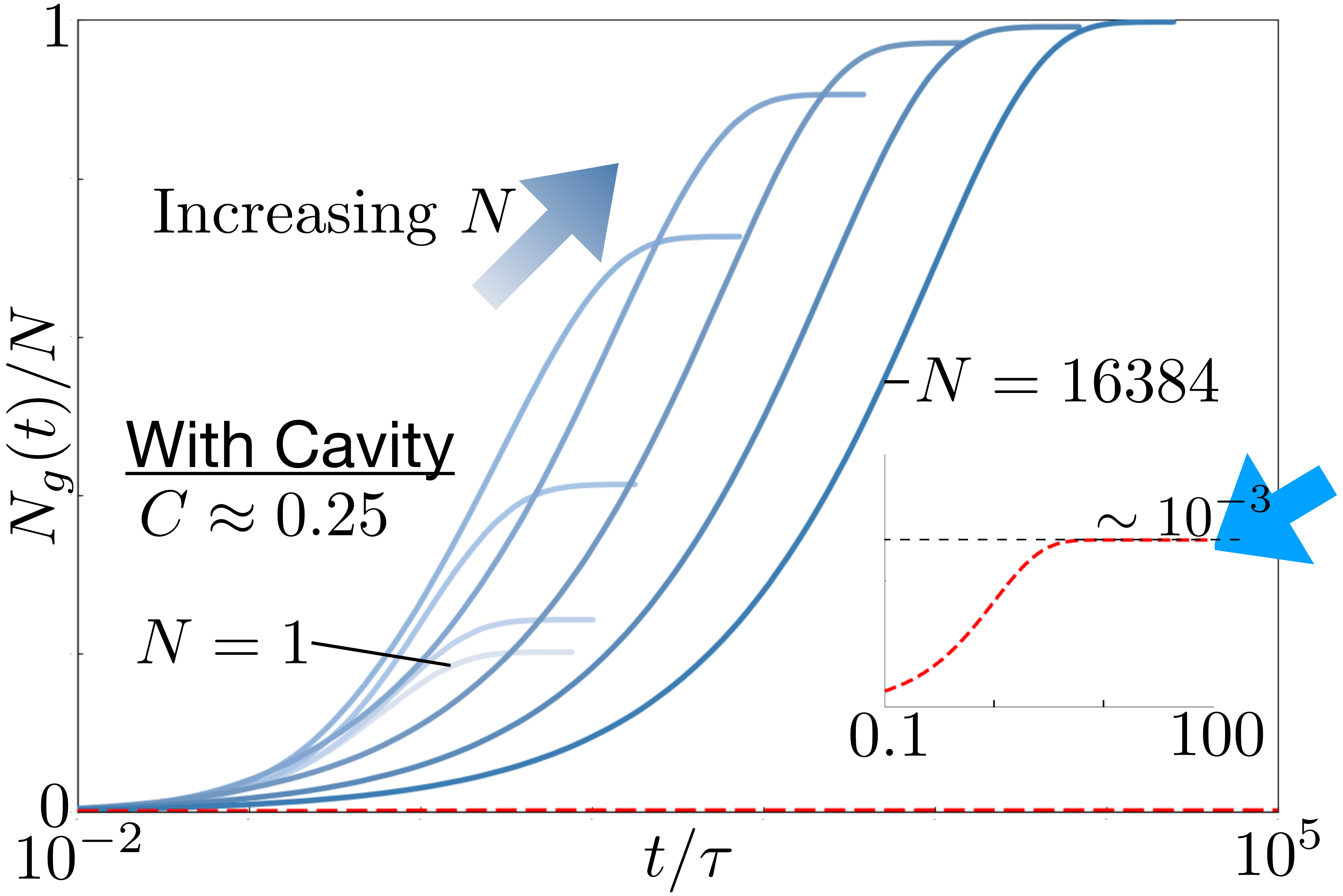
Formalism: *Reiter, Sørensen*, PRA 85 032111 (2012)

Large scale quantum trajectories simulation possible using **permutation symmetry**

Symmetry: *Chase, Geremia*, PRA 78.5 052101 (2008) / *Zhang, Zhang, Mølmer*, NJP 20 112001 (2018)

Collective Enhancement

The cavity coupling leads to a collective enhancement of the final ground state population, and a collective slowdown. The decay is mediated by the cavity, which transfers population to the ground state, and induces a slowdown due to polariton or Zeno blocking. This can also be seen from the effective rate equations (next slide). The relevant scaling parameter is the **collective cooperativity** NC.



Characteristic Timescale $\tau = \Gamma/\Omega^2$

Cavity Cooperativity $C = \dfrac{g^2}{\kappa\Gamma}$

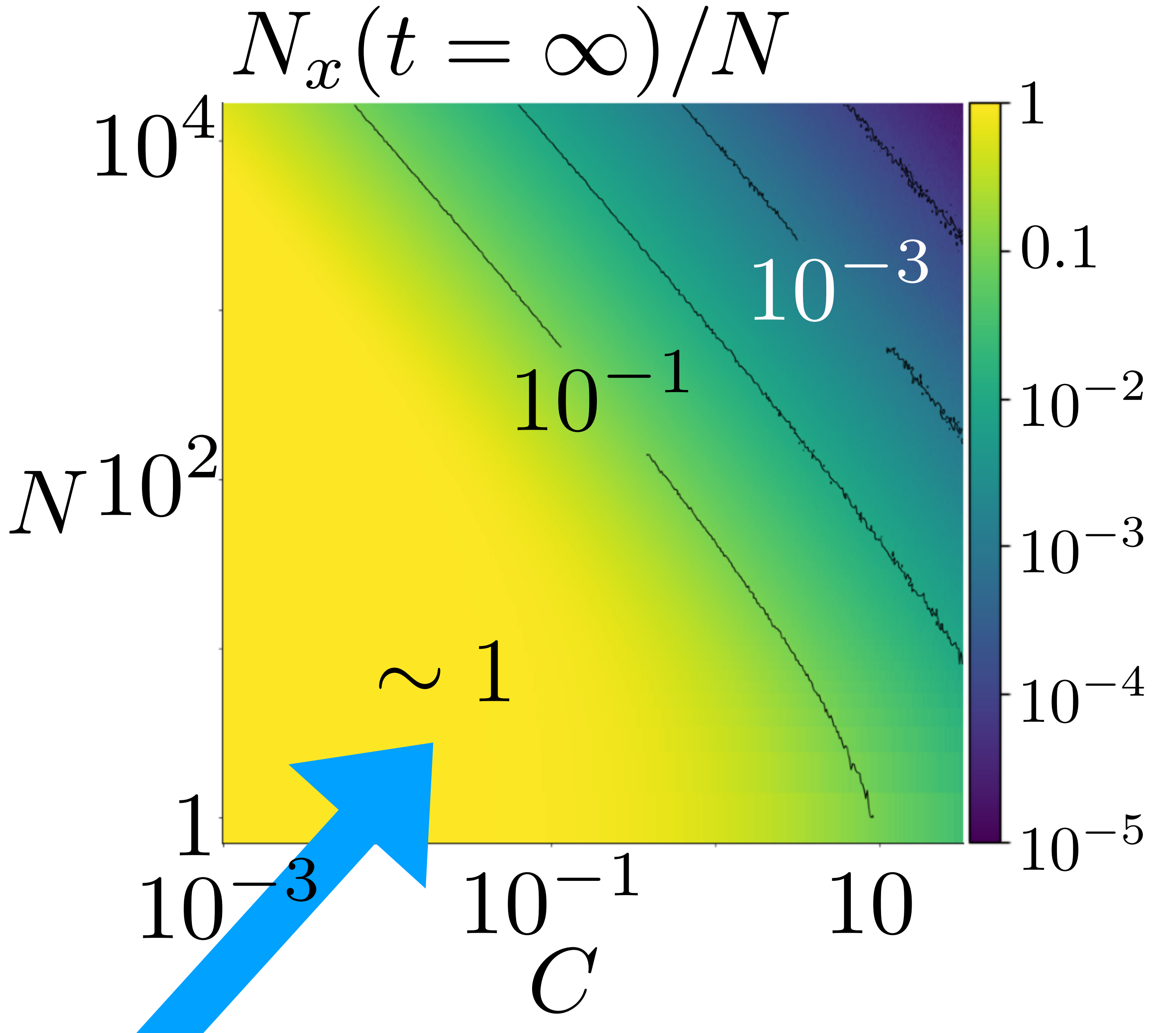
Increased efficiency:

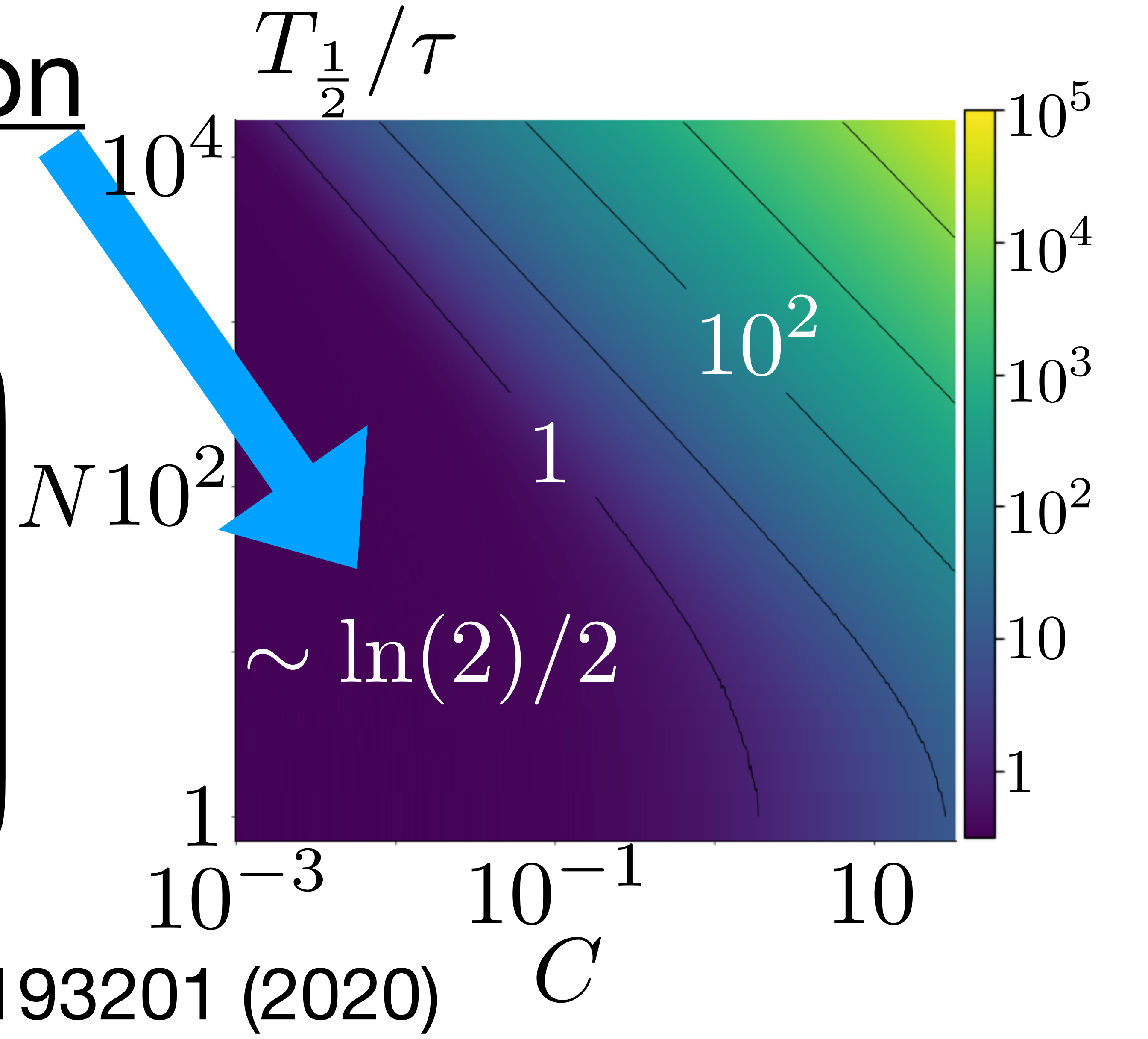
- Superradiance
- Cavity mediated decay

No Cavity: Photoassociation

Slowdown:

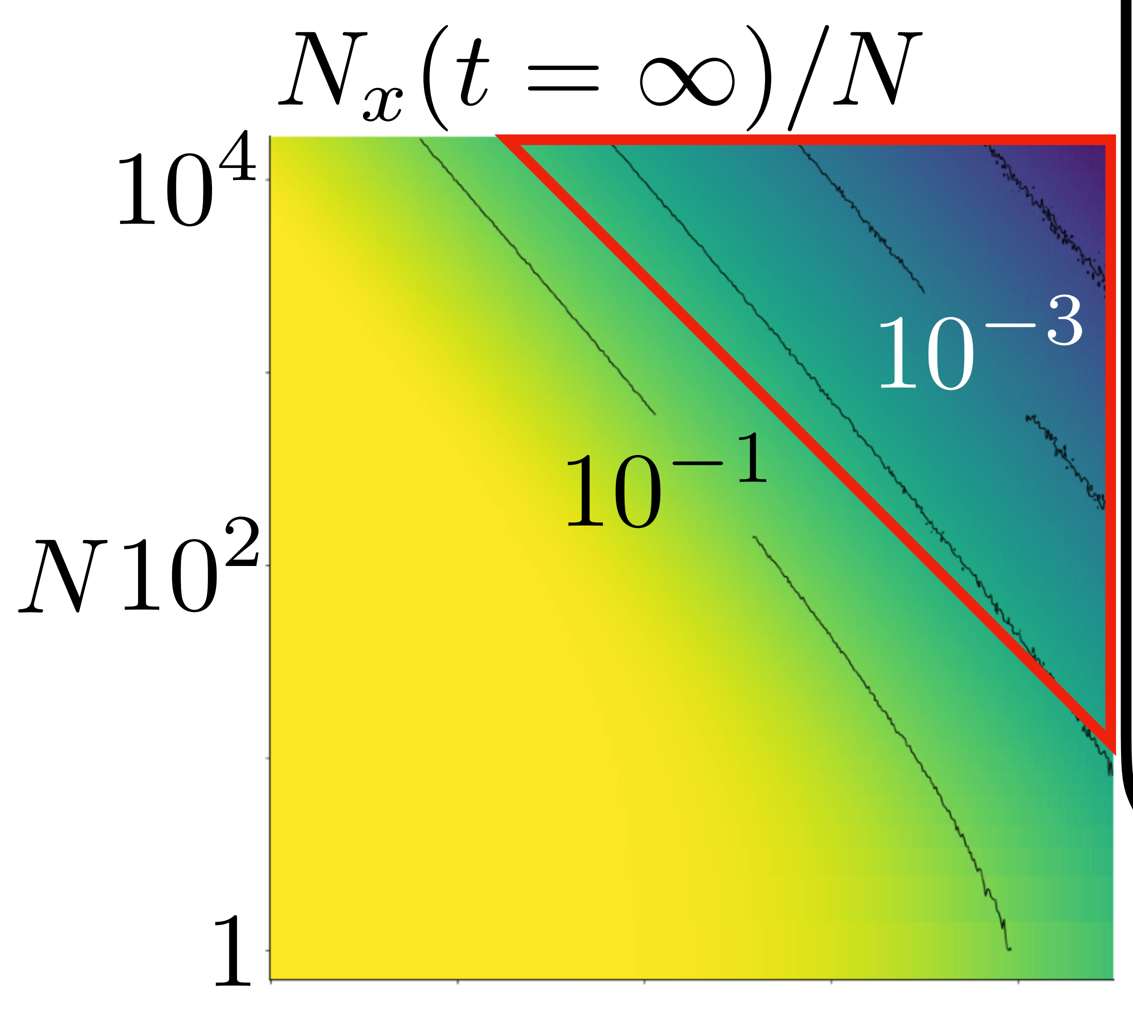
- Zeno blocking
- Polariton detuning

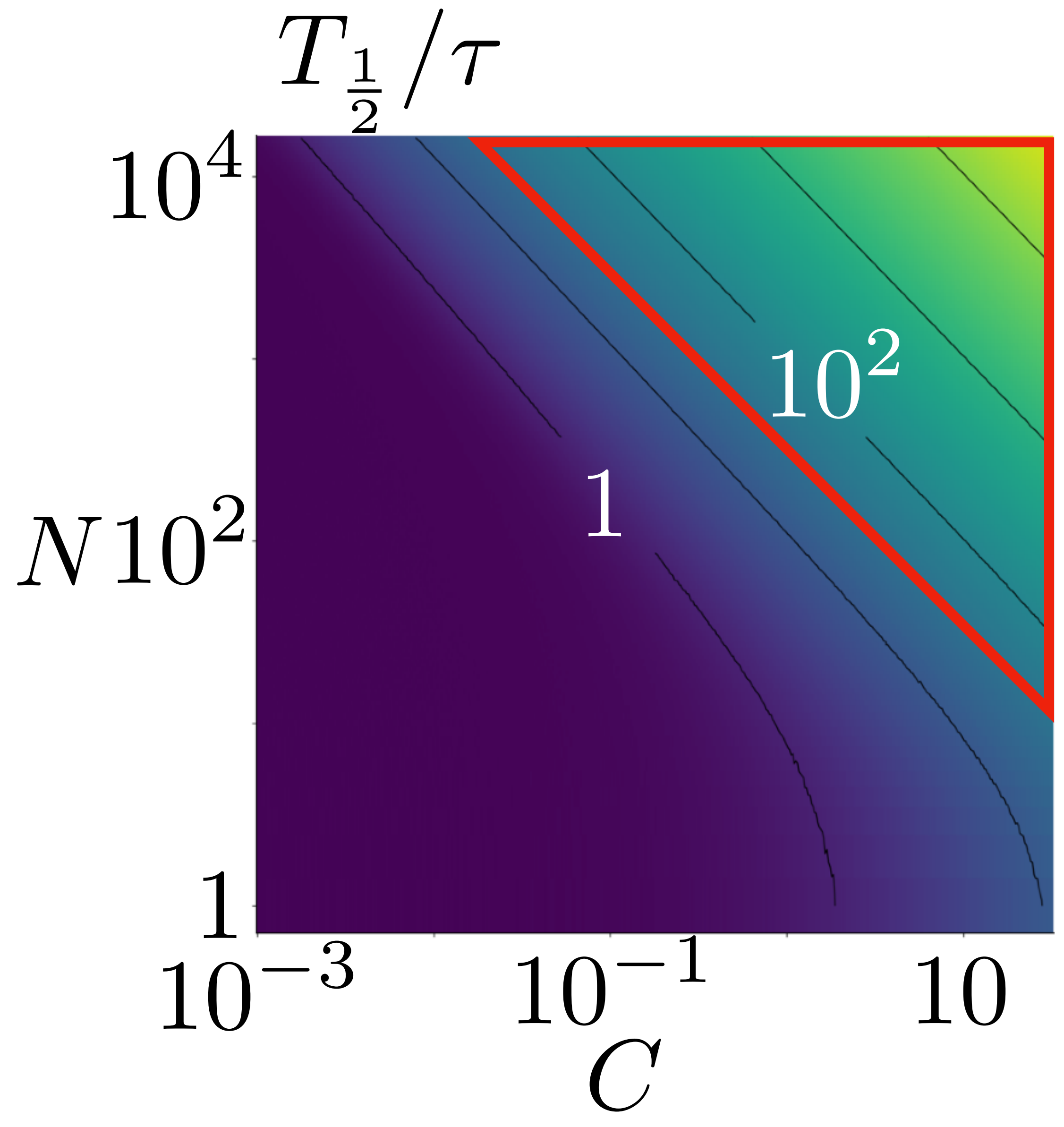




***DW**, Schütz, Whitlock, Schachenmayer, Pupillo*: PRL 125, 193201 (2020)

Rate Equations





Rate equations for state populations:

$$\dot{N}_i \approx -\frac{2}{\tau}\frac{N_i}{(N_g+1)C} \approx -\dot{N}_g$$

$$\dot{N}_x \approx \frac{2f_x}{\tau}\frac{N_i}{(N_g+1)^2C^2} \ll \dot{N}_g$$

solve

Final loss state population

$$\frac{N_x(t=\infty)}{N} \approx \frac{f_x\ln(N)}{NC}$$

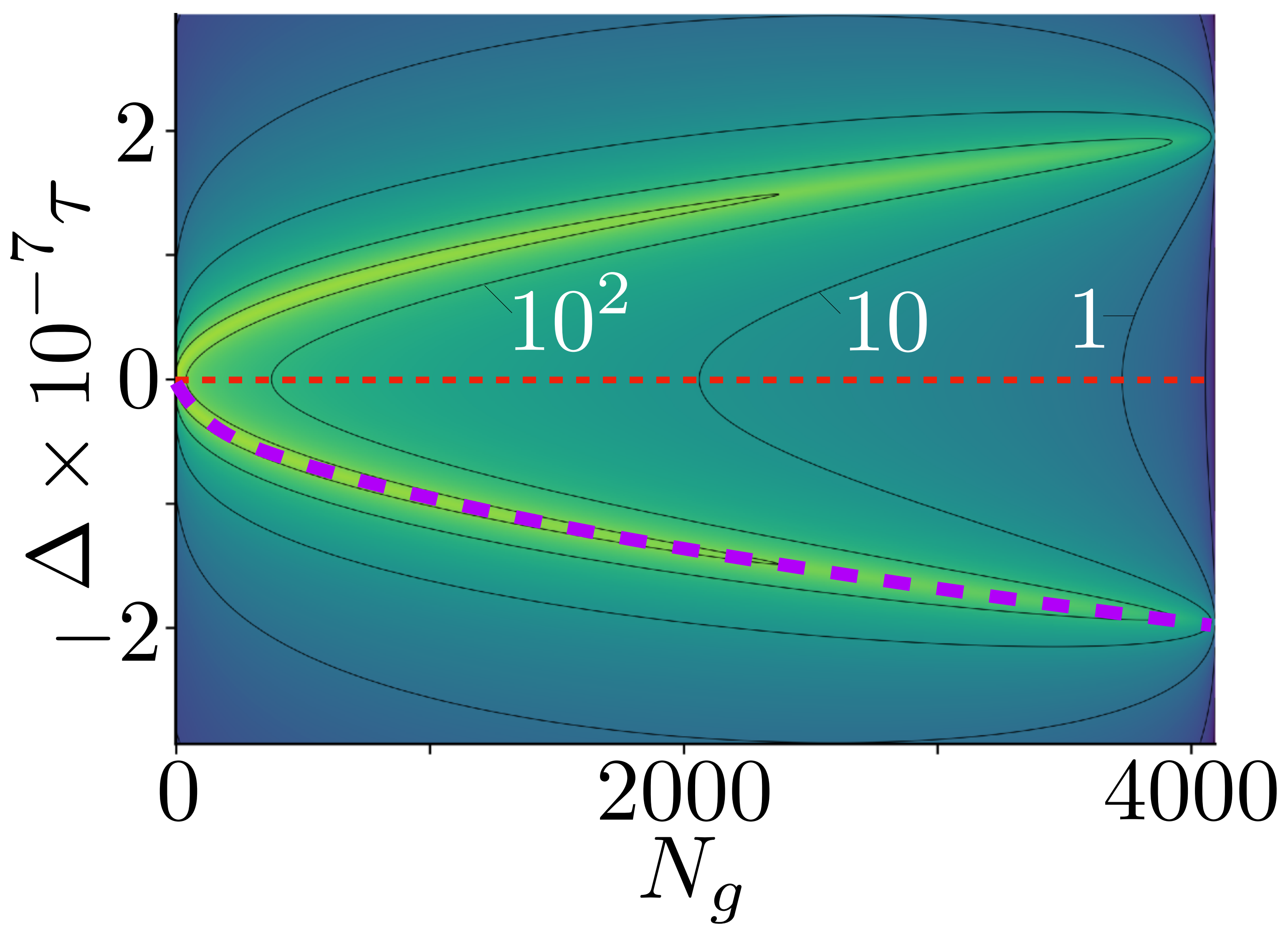
Initial state half time

$$T_{\frac{1}{2}} \approx NC\tau\left(\ln(2)-\frac{1}{2}\right)$$

DW, *Schütz, Whitlock, Schachenmayer, Pupillo*: PRL 125, 193201 (2020)

Slowdown $\Delta(t)$

The slowdown caused by the detuning from the virtual polariton resonance can be reduced by chirping the laser. This leads to an efficiency and a life time that scale with κ.



Rate equations and solutions

$$\dot{N}_i = -\frac{2\Omega^2(\kappa+\gamma_g+\gamma_x)}{(\kappa+\Gamma)^2}N_i \qquad \dot{N}_x = -\frac{2\Omega^2\gamma_x}{(\kappa+\Gamma)^2}N_i$$

$$T_{\frac{1}{e}} \approx \frac{(\kappa+\Gamma)^2}{2\Omega^2(\kappa+\gamma_g+\gamma_x)} \qquad \frac{N_x(t=\infty)}{N} \approx \frac{\gamma_x}{\kappa+\gamma_g+\gamma_x}$$

valid for $g \ll \kappa \ll \sqrt{N}g$

Slowdown can be reduced by staying on **polariton resonance**