Giant artificial atoms coupled to a 1D waveguide

Anton Frisk Kockum[1]
Per Delsing[2], Franco Nori[1,3], and Göran Johansson[2]

[1]RIKEN, Saitama, Japan
[2]Chalmers University of Technology, Göteborg, Sweden
[3]University of Michigan, Ann Arbor, Michigan, USA

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Outline

Introduction — Atom sizes

One giant atom coupled to a 1D waveguide — frequency-dependent relaxation rate and Lamb shift

Extensions — time delay, multiple giant atoms in various geometries

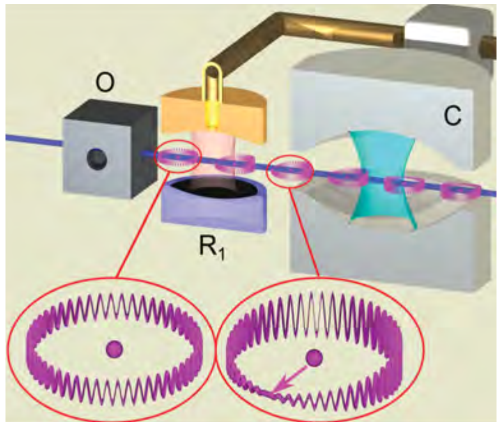
Summary

Atom sizes

Atom, optical light

$$r \approx 10^{-10}\,\mathrm{m}$$
$$\lambda \approx 10^{-7} - 10^{-6}\,\mathrm{m}$$
$$r/\lambda \approx 10^{-4} - 10^{-3}$$

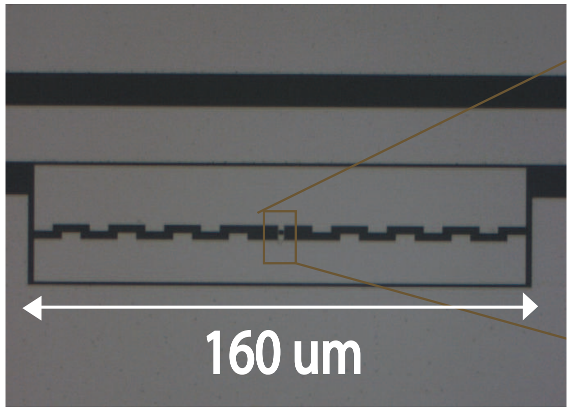
Rydberg atom, microwaves



$$r \approx 10^{-8} - 10^{-7}\,\mathrm{m}$$
$$\lambda \approx 10^{-3} - 10^{-1}\,\mathrm{m}$$
$$r/\lambda \approx 10^{-7} - 10^{-4}$$

Haroche, Nobel Lecture, RMP (2013)

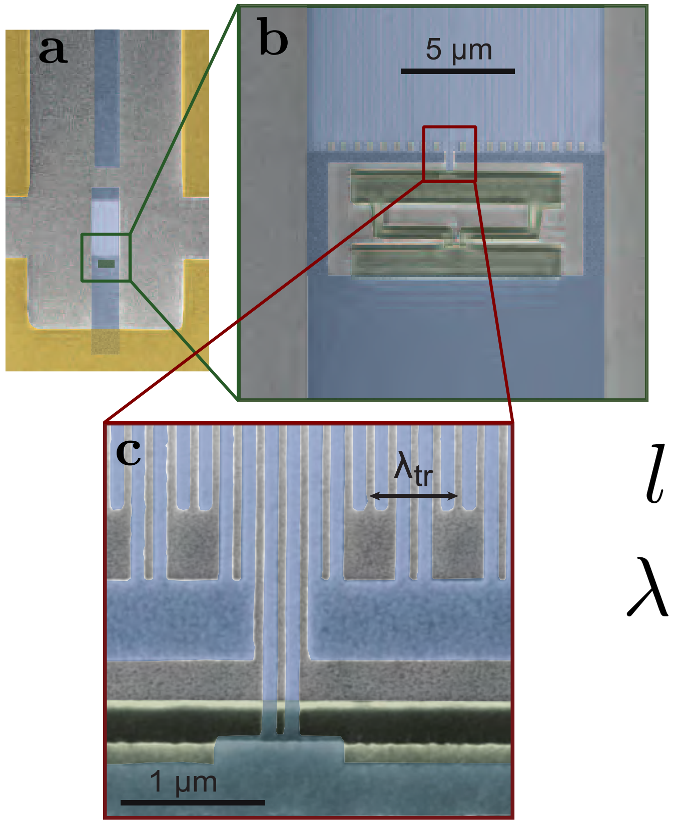
Transmon, microwaves



Picture by I.-C. Hoi

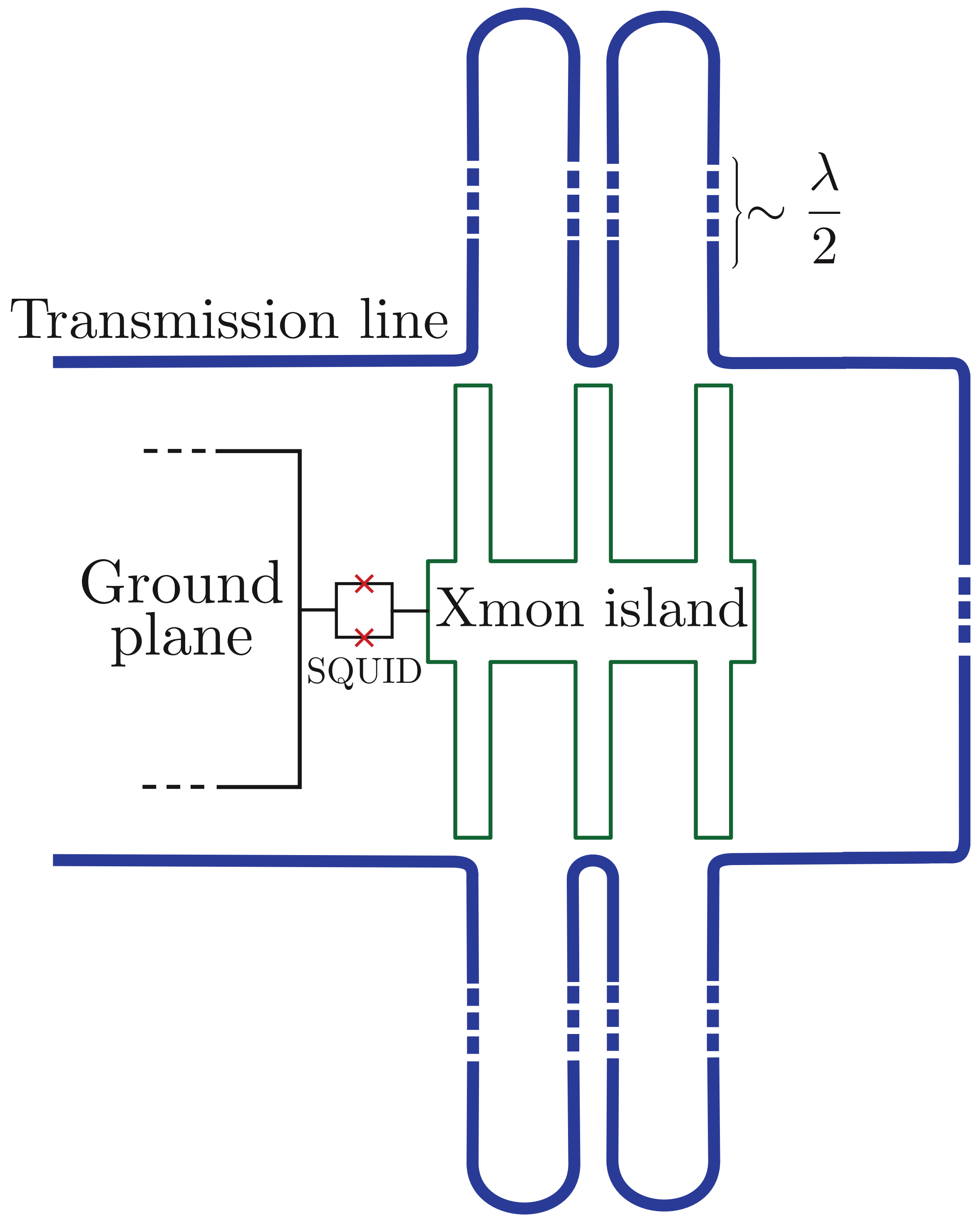
$$l \approx 10^{-5} - 10^{-3}\,\mathrm{m}$$
$$\lambda \approx 10^{-3} - 10^{-1}\,\mathrm{m}$$
$$l/\lambda \approx 10^{-4} - 1$$

Transmon, surface acoustic waves



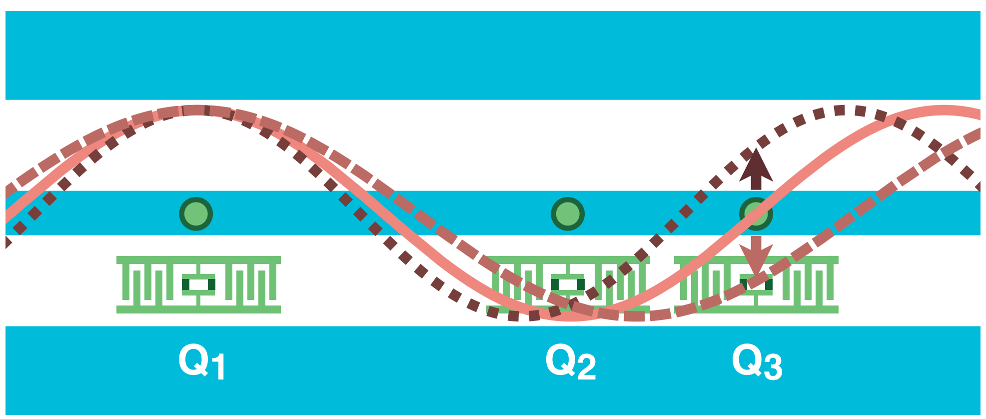
$$l \approx 10^{-5} - 10^{-4}\,\mathrm{m}$$
$$\lambda \approx 10^{-6} - 10^{-5}\,\mathrm{m}$$
$$l/\lambda \approx 1 - 100$$

Giant atoms in circuit QED?



Interference effects

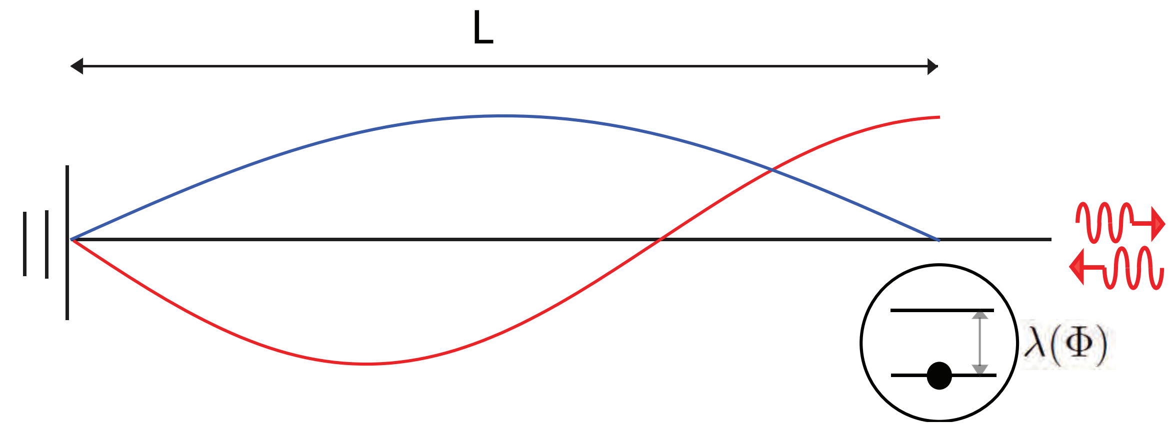
Several small atoms spaced wavelengths apart



Lalumière *et al.*, PRA **88**, 043806 (2013)

van Loo *et al.*, Science **342**, 1494 (2013)

One small atom in front of a mirror



Hoi *et al.*, Nature Physics **11**, 1045 (2015)

Koshino and Nakamura, NJP **14**, 043005 (2012)

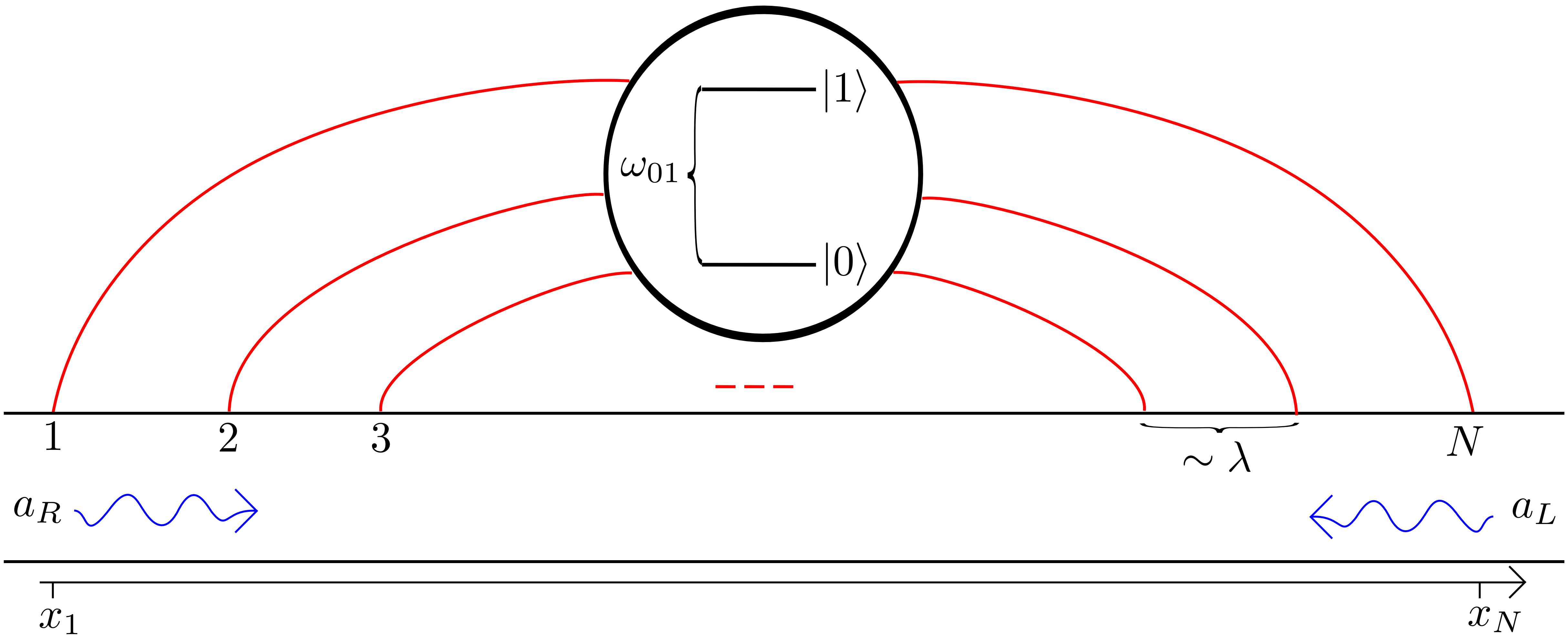
Eschner *et al.*, Nature **413**, 495 (2001)

Dorner and Zoller, PRA **66**, 023816 (2002)

Classical SAW filters in mobile phones, TVs, etc.

Morgan, *Surface Acoustic Wave Filters* (2007)

Giant artificial atom



Multiple coupling points $\rightarrow$ strong interference effects

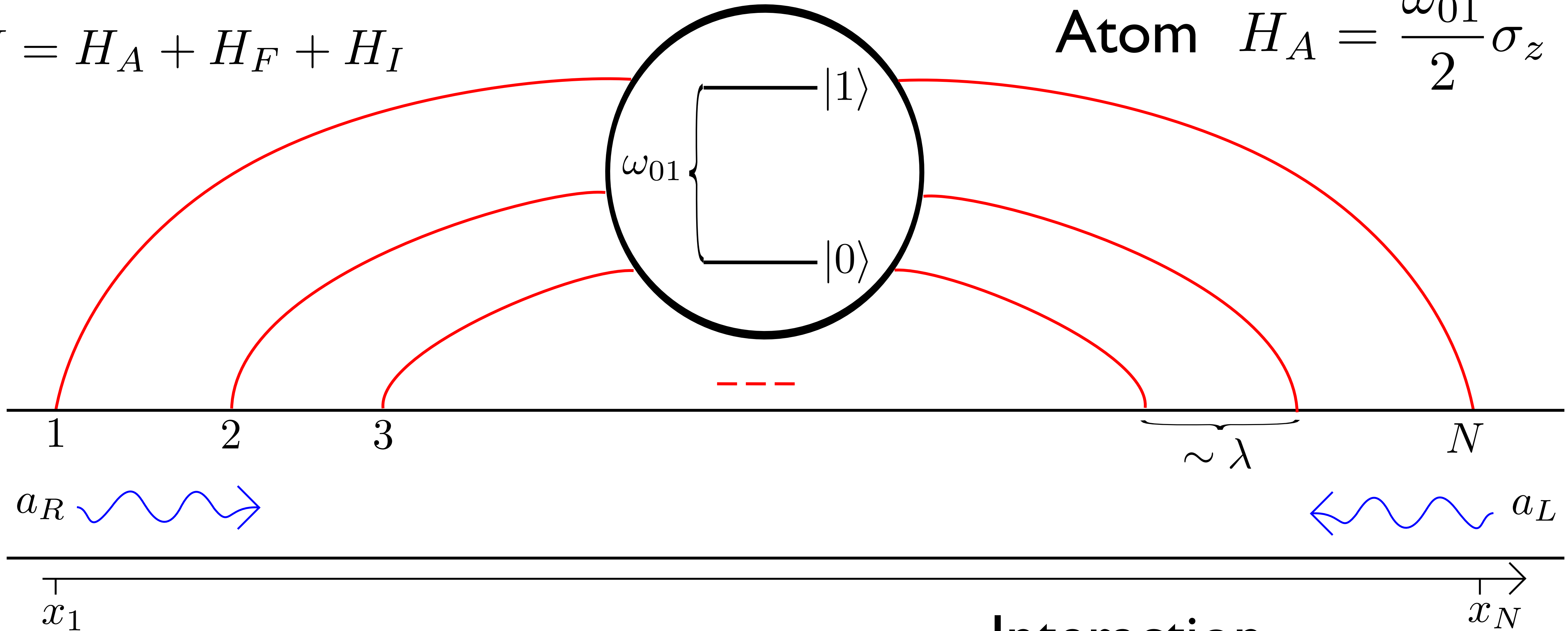
Additional time scale: travel time across the atom $(x_N - x_1)/v$

We work in the limit where this is negligible compared to $1/\Gamma$

Hamiltonian

$$H = H_A + H_F + H_I$$

Atom $H_A = \frac{\omega_{01}}{2}\sigma_z$



All field modes

$$H_F = \sum_j \omega_j \left(a^\dagger_{Rj} a_{Rj} + a^\dagger_{Lj} a_{Lj} \right)$$

Interaction

$$H_I = \sum_{j,k} g_k \Big[\left(a_{Rj} e^{i\omega_j x_k / v} + a_{Lj} e^{-i\omega_j x_k / v} \right) |1\rangle\langle 0| + \left(a^\dagger_{Rj} e^{-i\omega_j x_k / v} + a^\dagger_{Lj} e^{i\omega_j x_k / v} \right) |0\rangle\langle 1| \Big]$$

A. F. Kockum *et al.*, Phys. Rev. A **90**, 013837 (2014)

Frequency dependence

Interference

$$A(\omega_j) = \sum_k g_k e^{-i\omega_j x_k / v}$$

k Coupling point

j Field mode

Relaxation rate $\Gamma = 4\pi J(\omega_{10}) \boxed{|A(\omega_{10})|^2}$

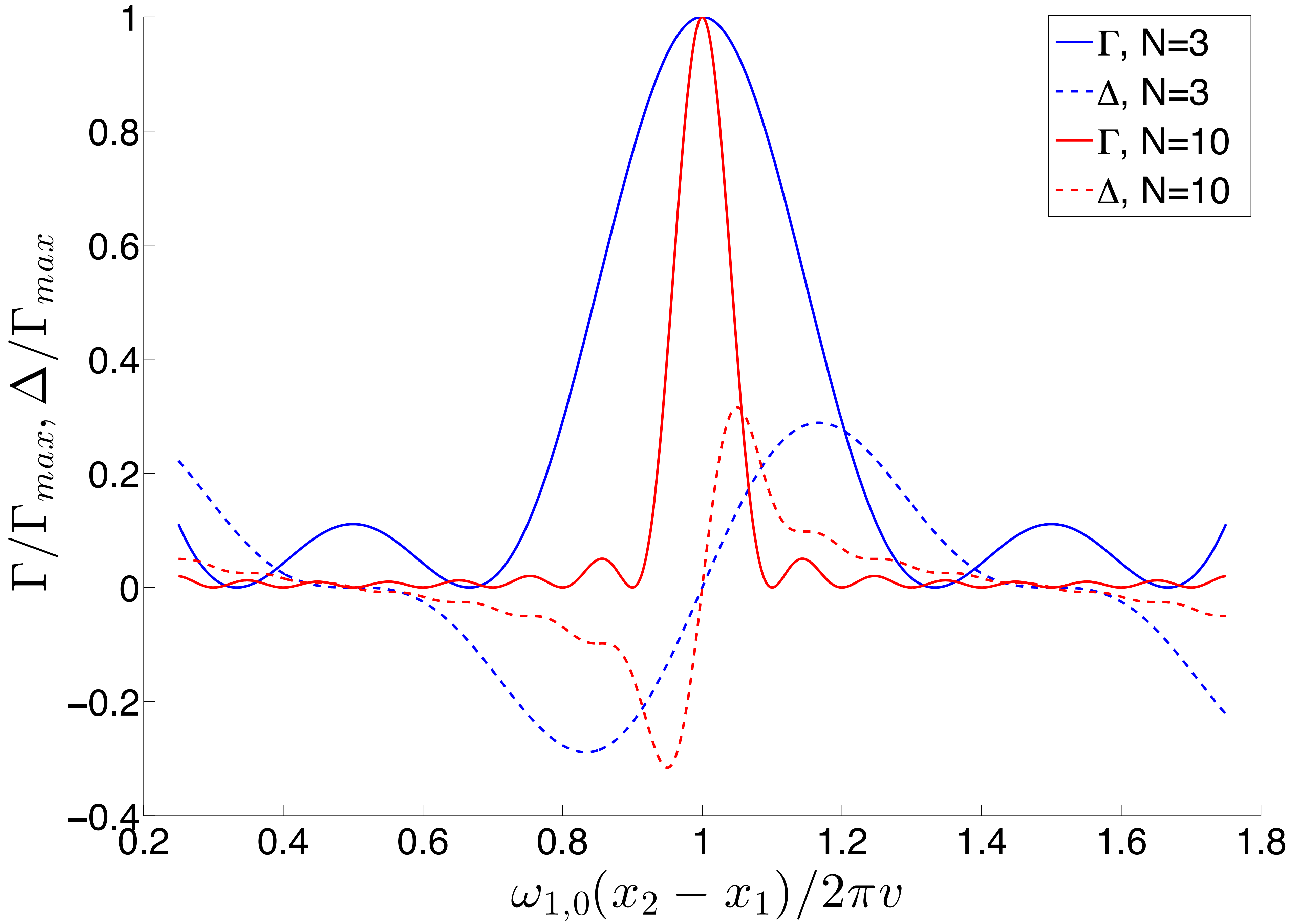
Lamb shift $\Delta = -2\mathcal{P} \int_0^\infty \mathrm{d}\omega \frac{2\omega_{10} J(\omega) \boxed{|A(\omega)|^2}}{\omega^2 - \omega_{10}^2}$

Density of states $J(\omega)$

Small atom $|A(\omega_{10})|^2 = g^2$

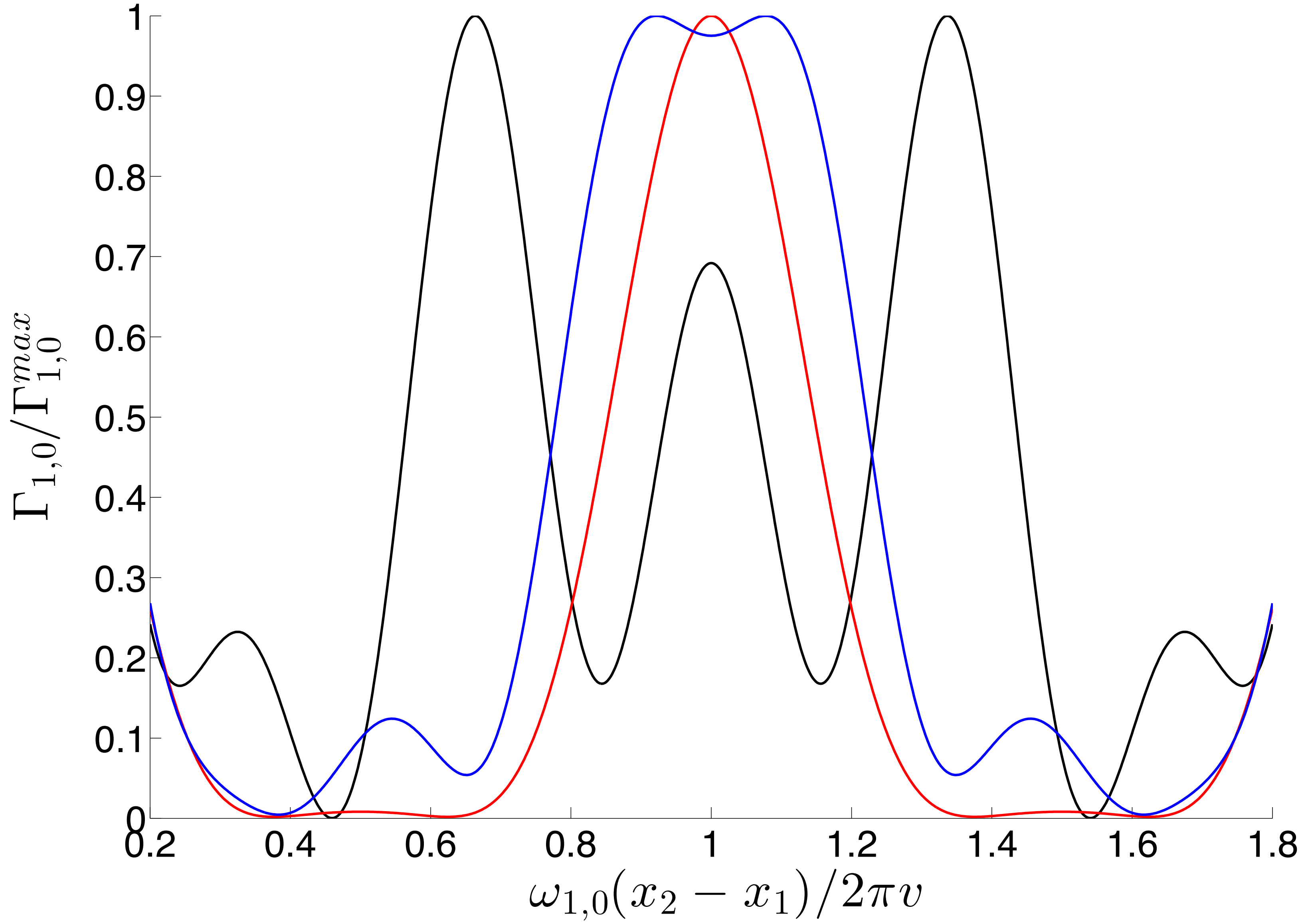
A. F. Kockum *et al.*, Phys. Rev. A **90**, 013837 (2014)

Giant artificial atom



Frequency-dependent relaxation rate Γ and Lamb shift Δ

Designing relaxation rates

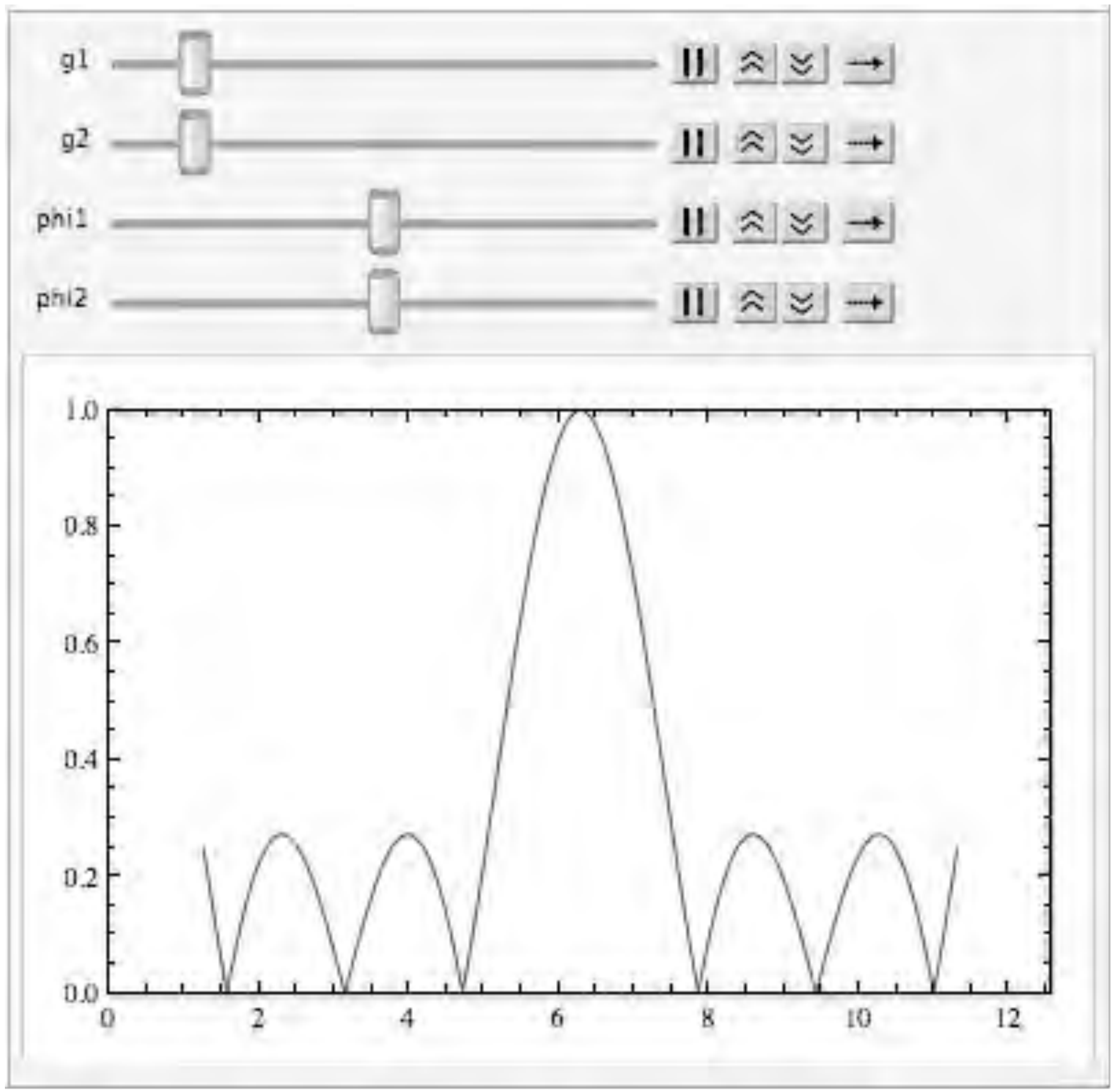


Wide maxima, wide minima, multiple maxima — take your pick

Designing relaxation rates

$$A(\omega_j) = \sum_k g_k e^{-i\omega_j x_k / v}$$

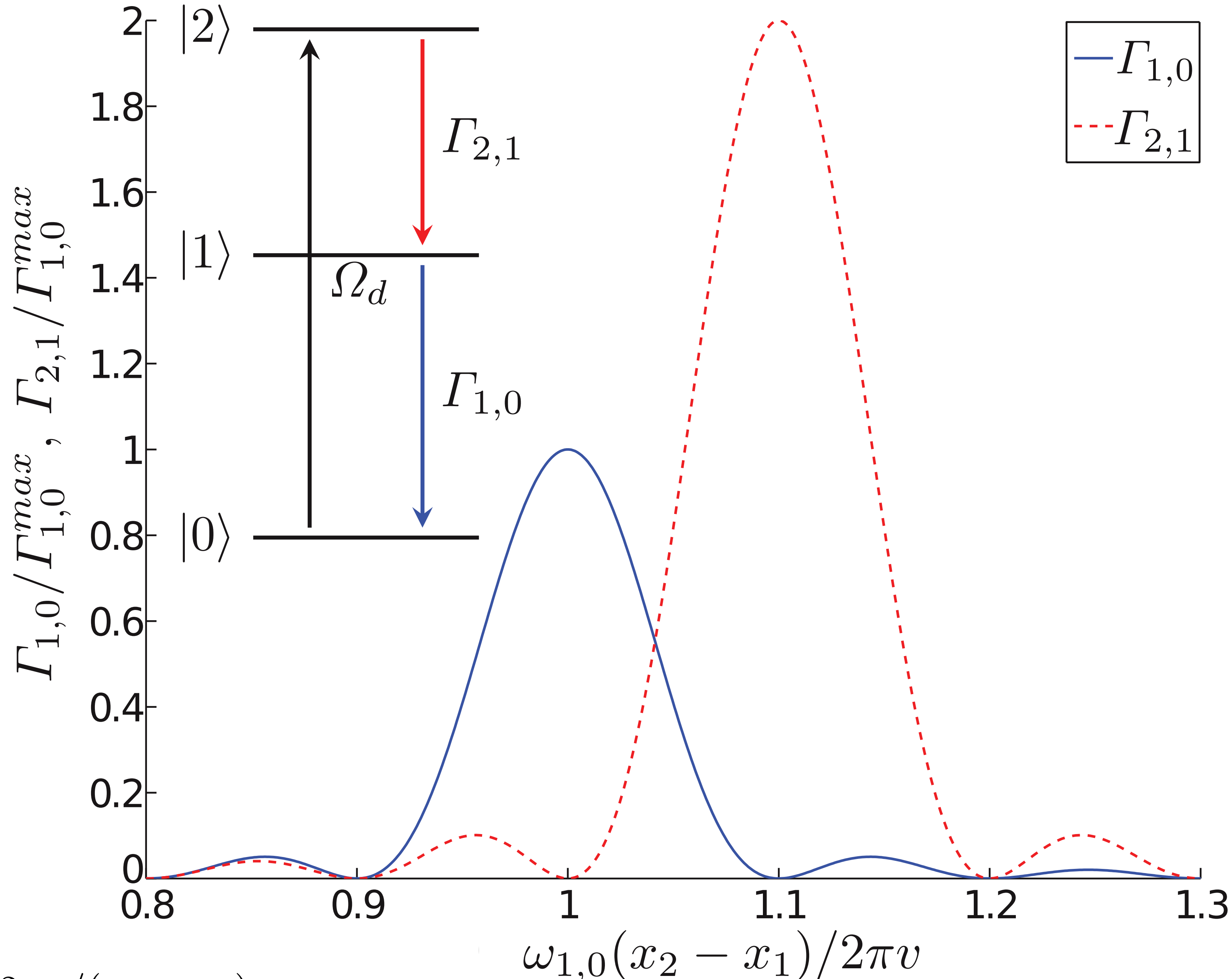
Discrete Fourier transform



$N = 4$

Instead of being protected by a cavity, the atom "creates its own cavity"

Designing relaxation rates



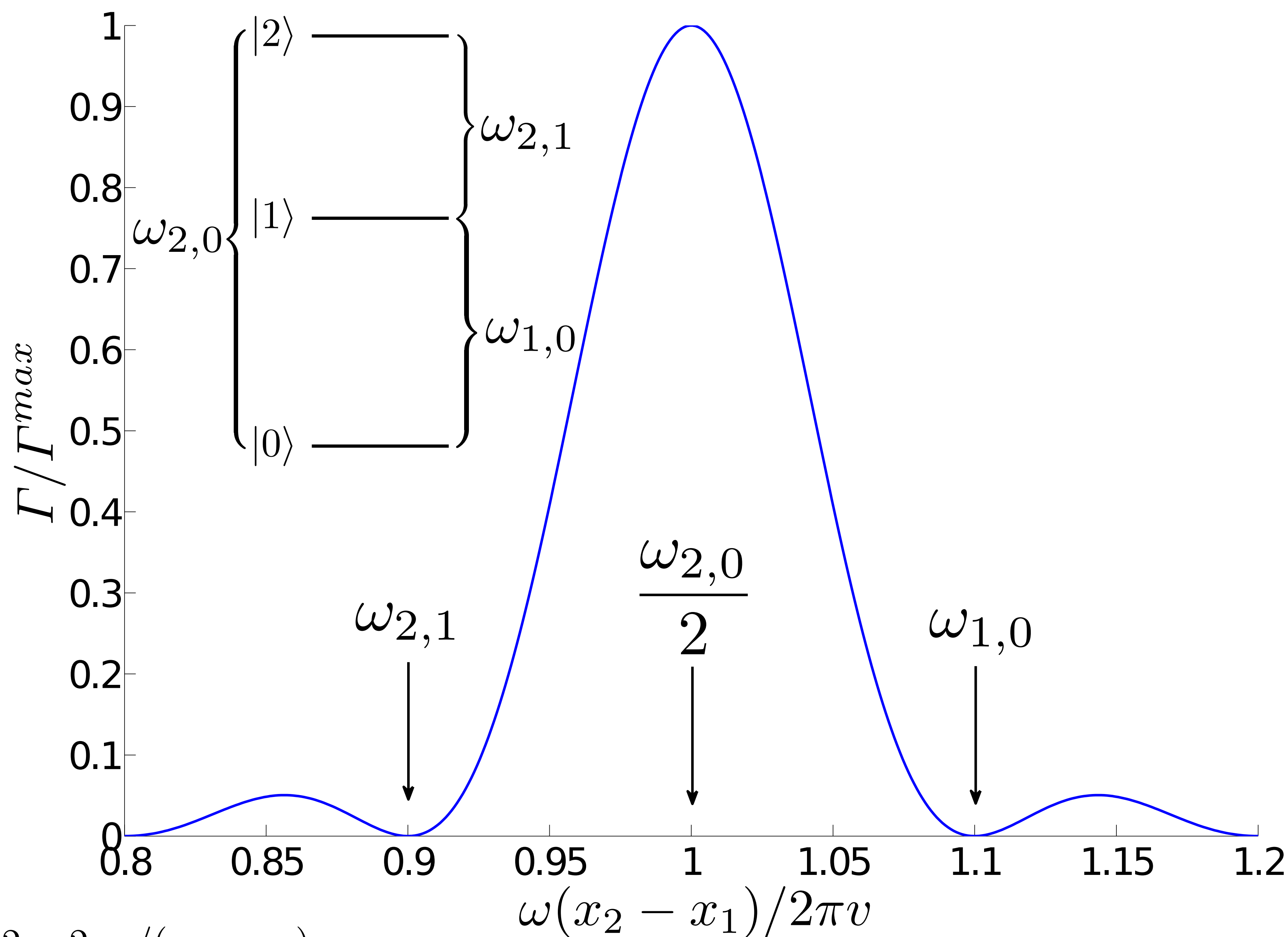
Anharmonicity

$\omega_{1,0} - \omega_{2,1} = 0.1 \times 2\pi v/(x_2 - x_1)$

$N = 10$

Can be used to create population inversion $\rightarrow$ lasing

Designing relaxation rates



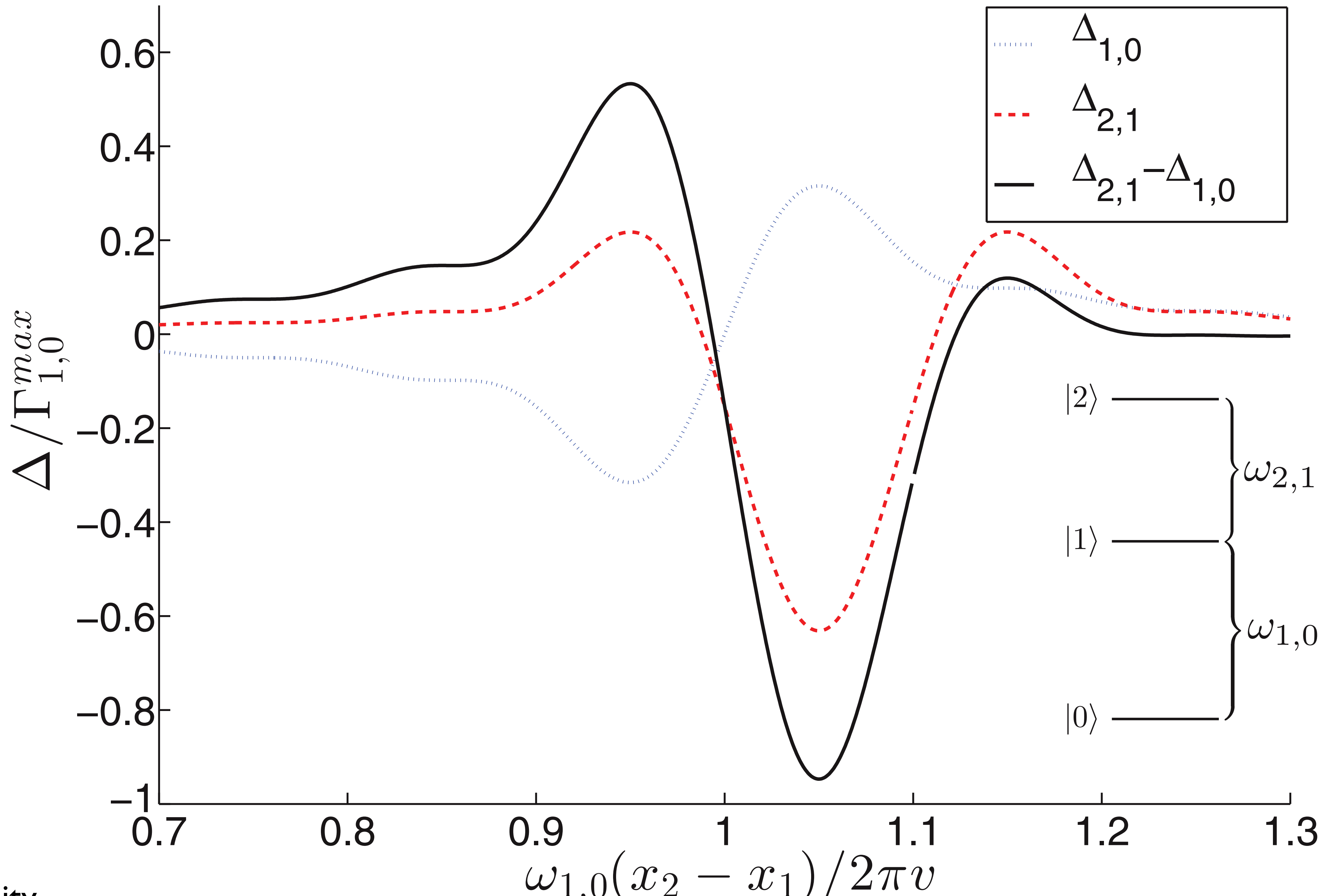
Anharmonicity

$\omega_{1,0} - \omega_{2,1} = 0.2 \times 2\pi v/(x_2 - x_1)$

$N = 10$

Enhancing a two-phonon process

Designing Lamb shift and anharmonicity

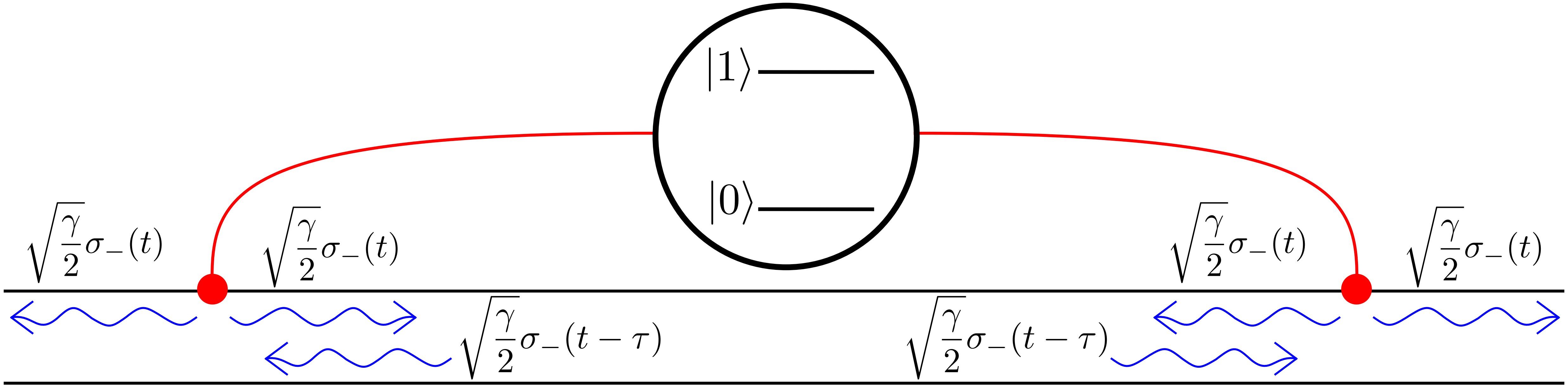


Anharmonicity

$\omega_{1,0} - \omega_{2,1} = 0.1 \times 2\pi v/(x_2 - x_1)$

$N = 10$

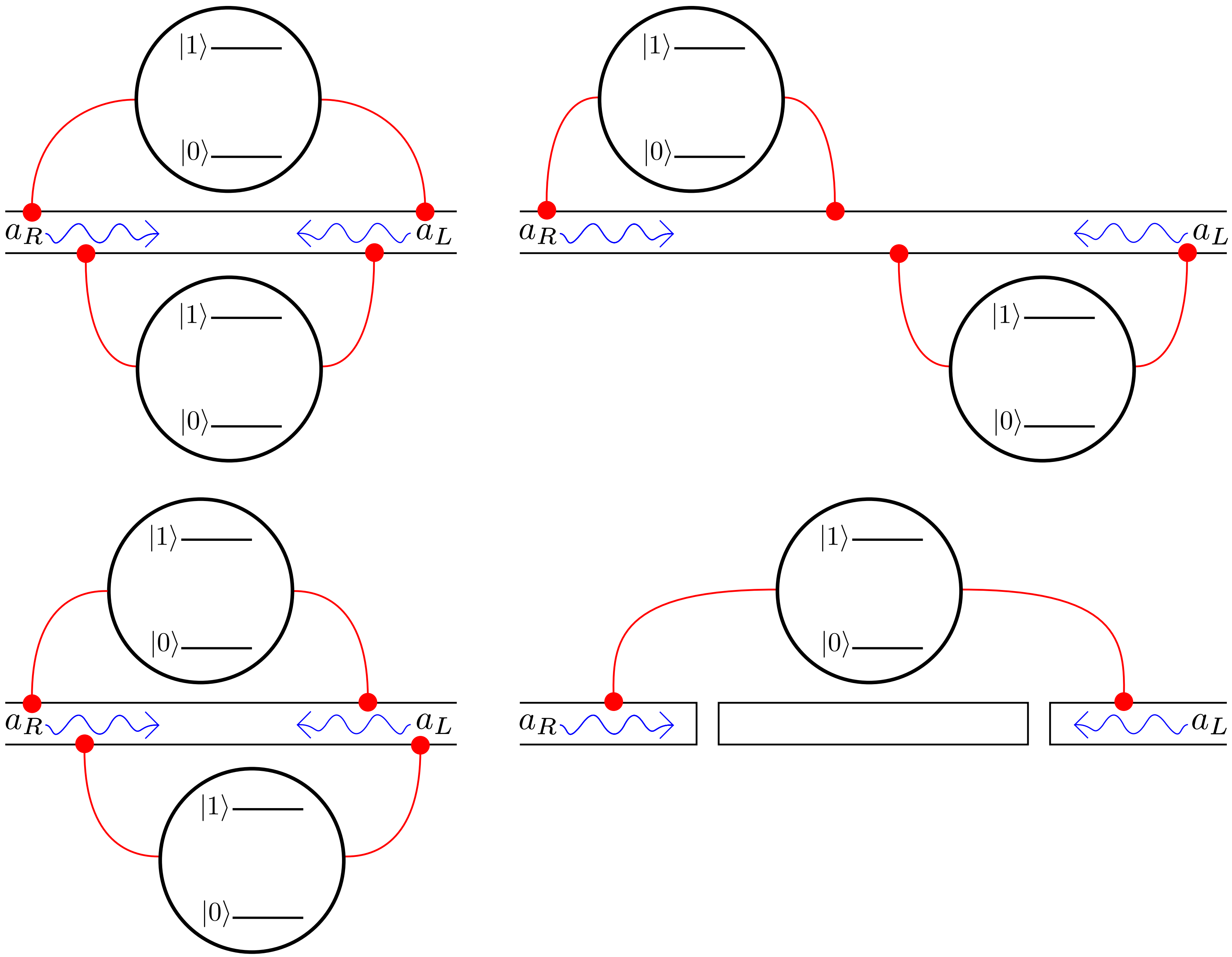
Extensions: time delay



Nonexponential decay, interesting features in the second-order correlation function for scattered phonons, etc.

Posters by Lingzhen Guo and Gustav Andersson

Extensions: two giant atoms

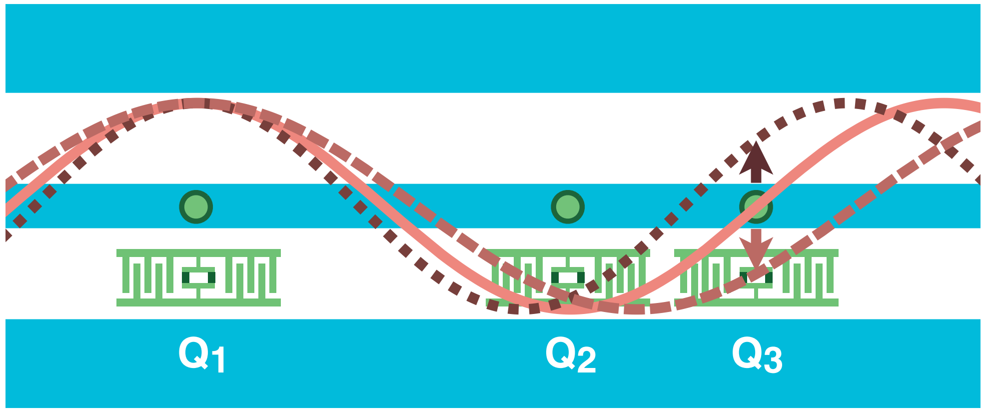


Various geometries possible

With more atoms: ”matryoshka atom”

Multiple small atoms

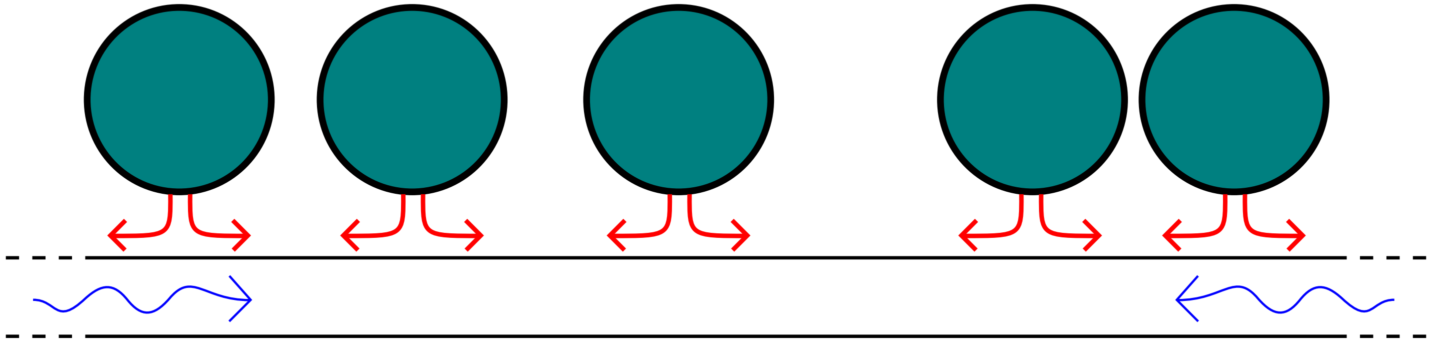
Several small atoms
spaced wavelengths apart



Lalumière *et al.*, PRA **88**, 043806 (2013)

van Loo *et al.*, Science **342**, 1494 (2013)

Lehmberg, PRA **2**, 883342 (1970)

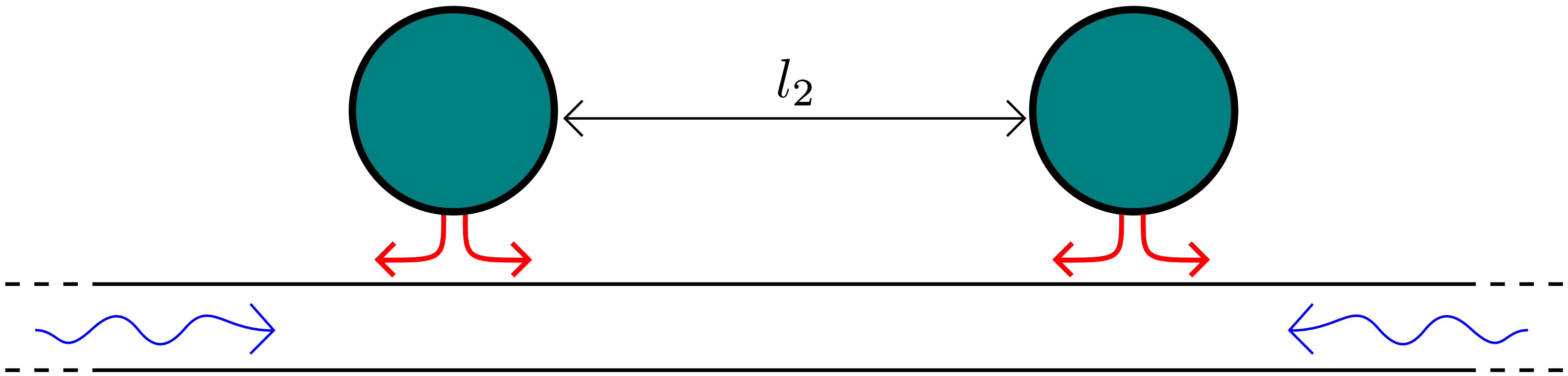


$$\dot{\rho} = -\frac{i}{\hbar}\left[H_{\rm sys} + \hbar\gamma \sum_{j,l} \sin(k|x_j - x_l|)\sigma_j^\dagger \sigma_l, \rho\right]$$

$$+ 2\gamma \sum_{j,l} \cos(k|x_j - x_l|)\left(\sigma_l \rho \sigma_j^\dagger - \frac{1}{2}\{\sigma_j^\dagger \sigma_l, \rho\}\right)$$

Exchange interaction sin(phase)
Collective decay cos(phase)

Two small atoms



$$l_2 = \lambda$$

No exchange interaction
Maximal collective decay

Dark state $|D\rangle = \frac{|ge\rangle - |eg\rangle}{\sqrt{2}}$

Bright state $|B\rangle = \frac{|ge\rangle + |eg\rangle}{\sqrt{2}}$

Sub- and superradiance

Lalumière *et al.*, PRA **88**, 043806 (2013)

$$l_2 = 3\lambda/4$$

Maximal exchange interaction
No collective decay
Individual decay remains

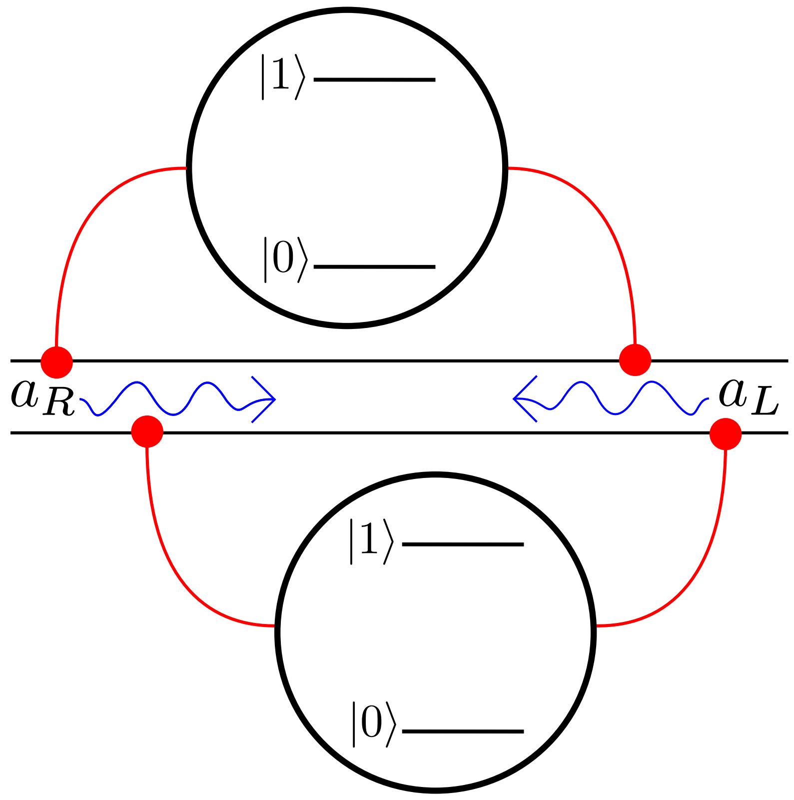
$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + \gamma \sum_{i=B,D} \mathcal{D}[\sigma_-^i]\rho$$

$$H = \sum_{i=B,D} \hbar\omega_i \sigma_+^i \sigma_-^i$$

$$\sigma_-^{B/D} = \frac{\sigma_-^1 \pm \sigma_-^0}{\sqrt{2}}$$

$$\omega_{B/D} = \Delta \pm J.$$

Two giant atoms



A. F. Kockum *et al.*, in preparation (2016)

Master equation with equal phase shifts between subsequent coupling points

$$\dot{\rho} = -i\left[\frac{\Delta_a + \gamma \sin 2\varphi}{2}\sigma_z^a + \frac{\Delta_b + \gamma \sin 2\varphi}{2}\sigma_z^b + \frac{\gamma}{2}\left(3\sin\varphi + \sin 3\varphi\right)\left(\sigma_+^a\sigma_-^b + \sigma_+^b\sigma_-^a\right), \rho\right]$$
$$+2\gamma\left(1 + \cos 2\varphi\right)\left(\mathcal{D}\left[\sigma_-^a\right]\rho + \mathcal{D}\left[\sigma_-^b\right]\rho\right)$$
$$+\gamma\left(3\cos\varphi + \cos 3\varphi\right)\left(\sigma_-^a\rho\sigma_+^b + \sigma_-^b\rho\sigma_+^a - \frac{1}{2}\left(\left(\sigma_+^a\sigma_-^b + \sigma_+^b\sigma_-^a\right)\rho + \rho\left(\sigma_+^a\sigma_-^b + \sigma_+^b\sigma_-^a\right)\right)\right)$$

$$\varphi = \frac{\pi}{2}$$

No collective decay
No individual decay
Nonzero exchange interaction
Different from the single dark state for small atoms!

Summary

A transmon qubit coupled to SAW is a ”giant artificial atom”

Multiple coupling points → interference → frequency-dependent relaxation rate and Lamb shift

Can design the frequency-dependence for various applications

Two giant artificial atoms can completely decouple from the transmission line (no decay) but still have an exchange interaction mediated by the transmission line

A. F. Kockum *et al.*, Phys. Rev. A **90**, 013837 (2014)
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