Fast and Robust Phase Gates with Trapped-Ion Hyperfine Qubits

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Outline

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- The System
- Microwave Pulse Sequence & Results
- Conclusions

I. Arrazola, J. Casanova, J. S. Pedernales, Z.-Y. Wang, E. Solano and M. B. Plenio, *arXiv:1706.02877*

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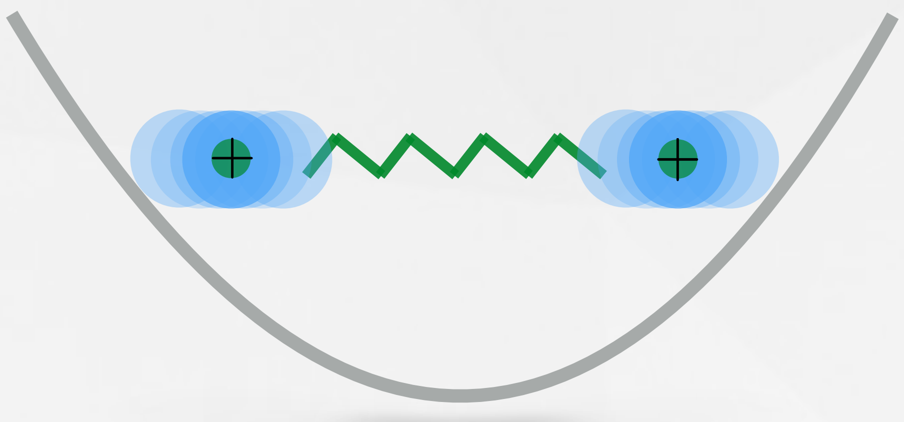
The System

- Two trapped ions / The motion

$$V = \frac{1}{2}M\nu^2(z_1(t)^2 + z_2(t)^2) + \frac{e^2}{4\pi\epsilon_0}\frac{1}{z_2(t) - z_1(t)}$$



The System

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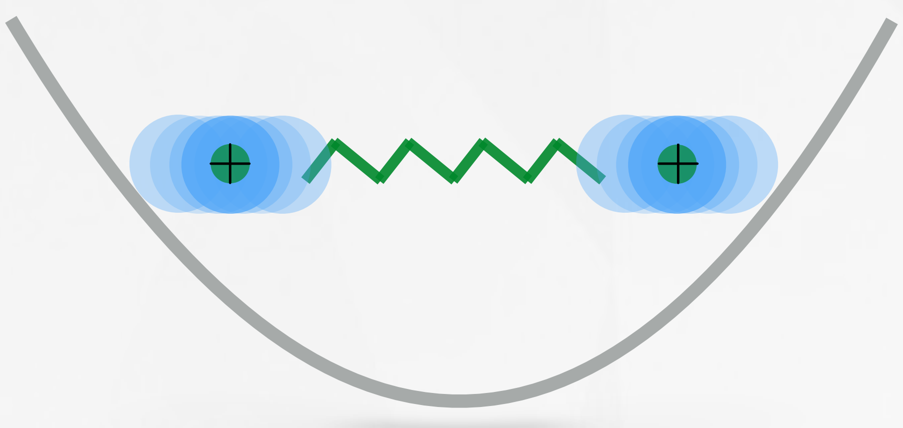
- Small Oscillations $z_i(t) \approx z_i^0 + q_i(t)$

Equilibrium positions



The System

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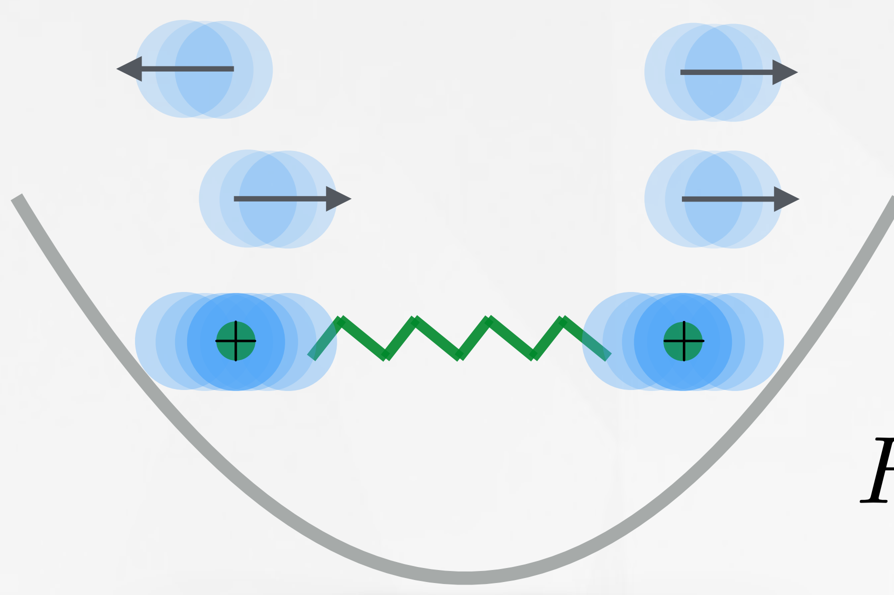
Equilibrium positions

Diagonal Hamiltonian $\longleftrightarrow$ Vibrational normal modes



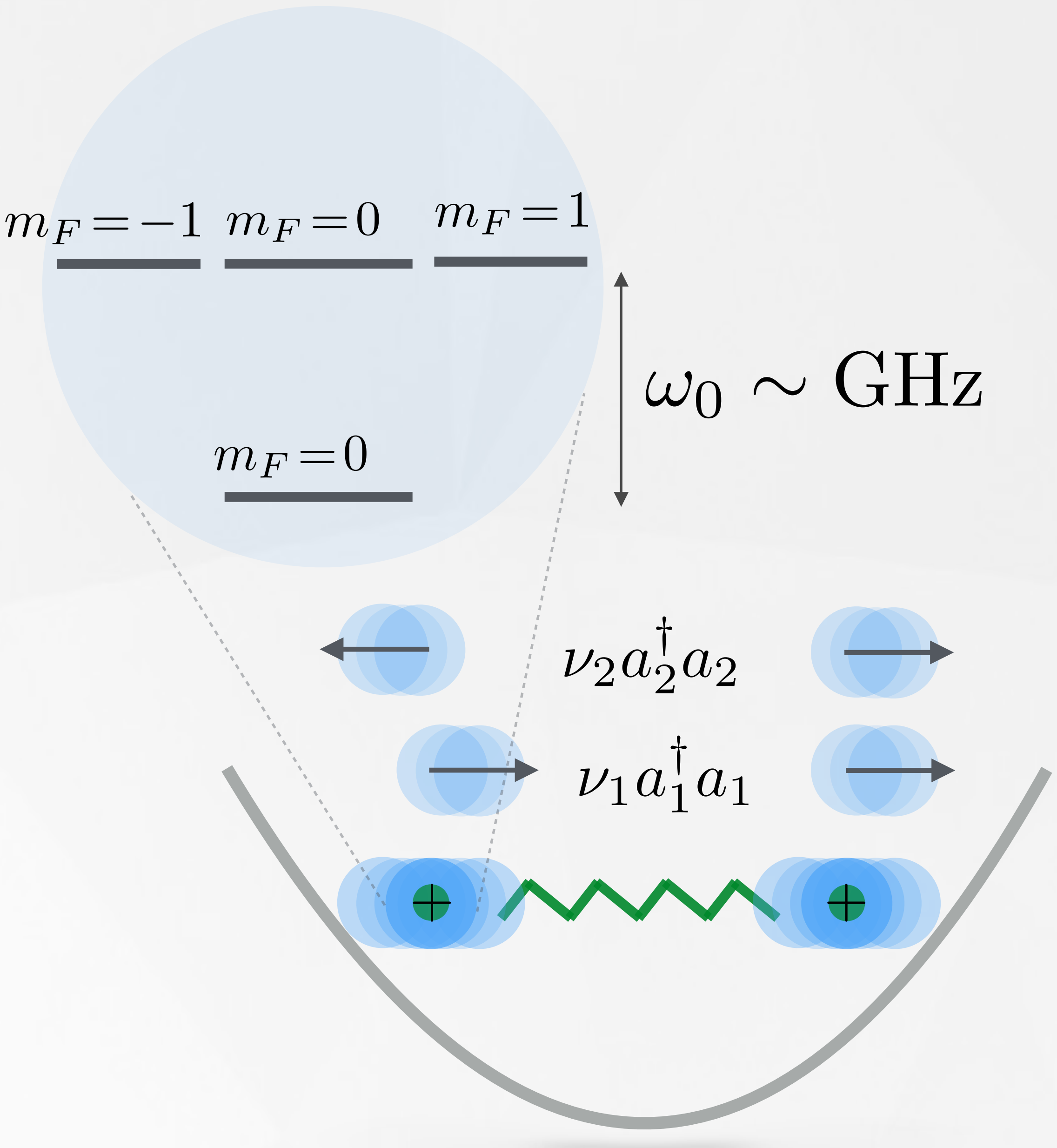
Breathing mode ν_2

Center of mass mode ν_1

$$H_\nu = \nu_1 a_1^\dagger a_1 + \nu_2 a_2^\dagger a_2$$

The System

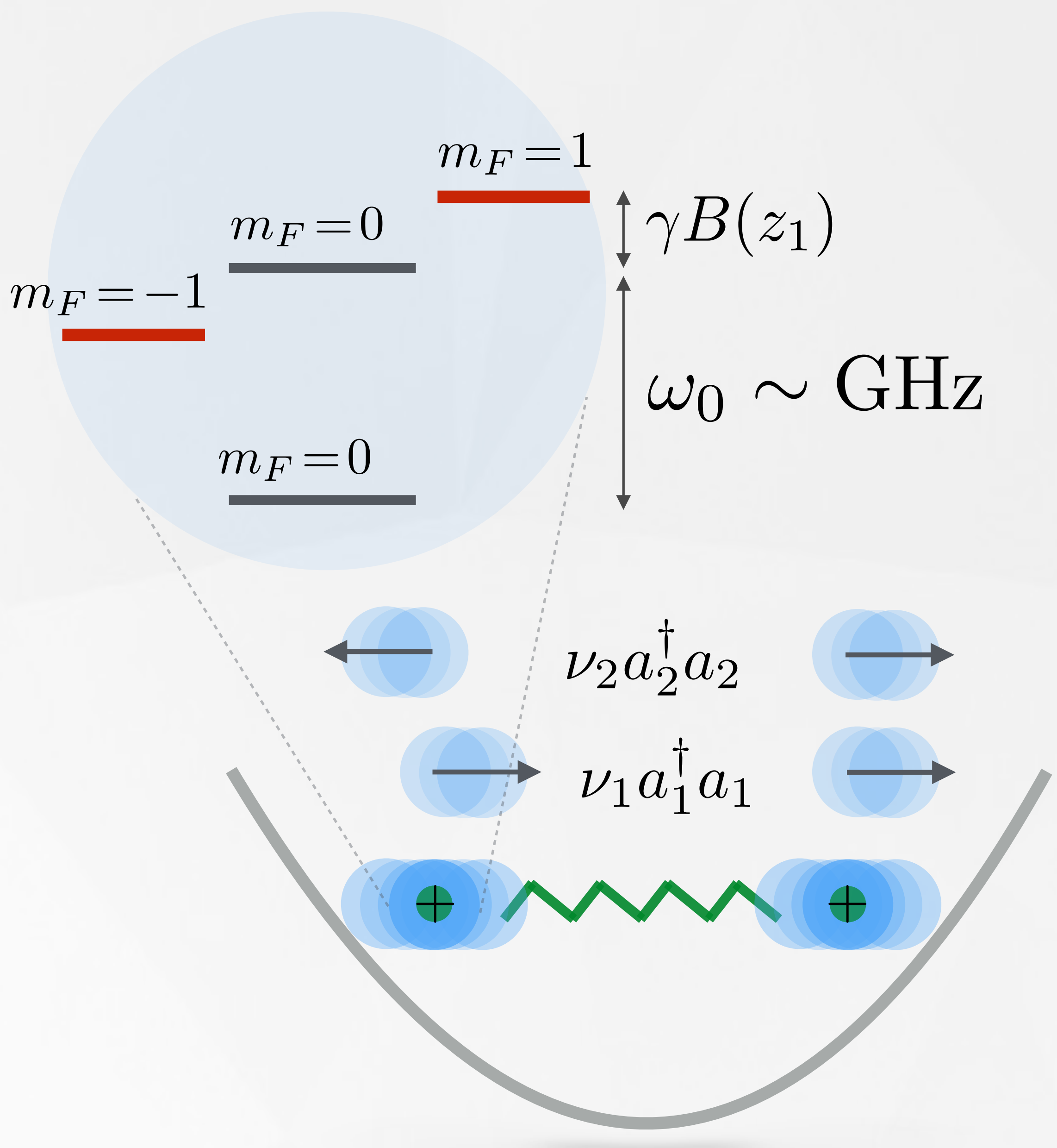
- Hyperfine level structure ($^{171}\mathrm{Yr}^{+}$) / The qubit



The System

- Hyperfine level structure ($^{171}\mathrm{Yr}^+$) / The qubit

The magnetic field breaks the degeneracy



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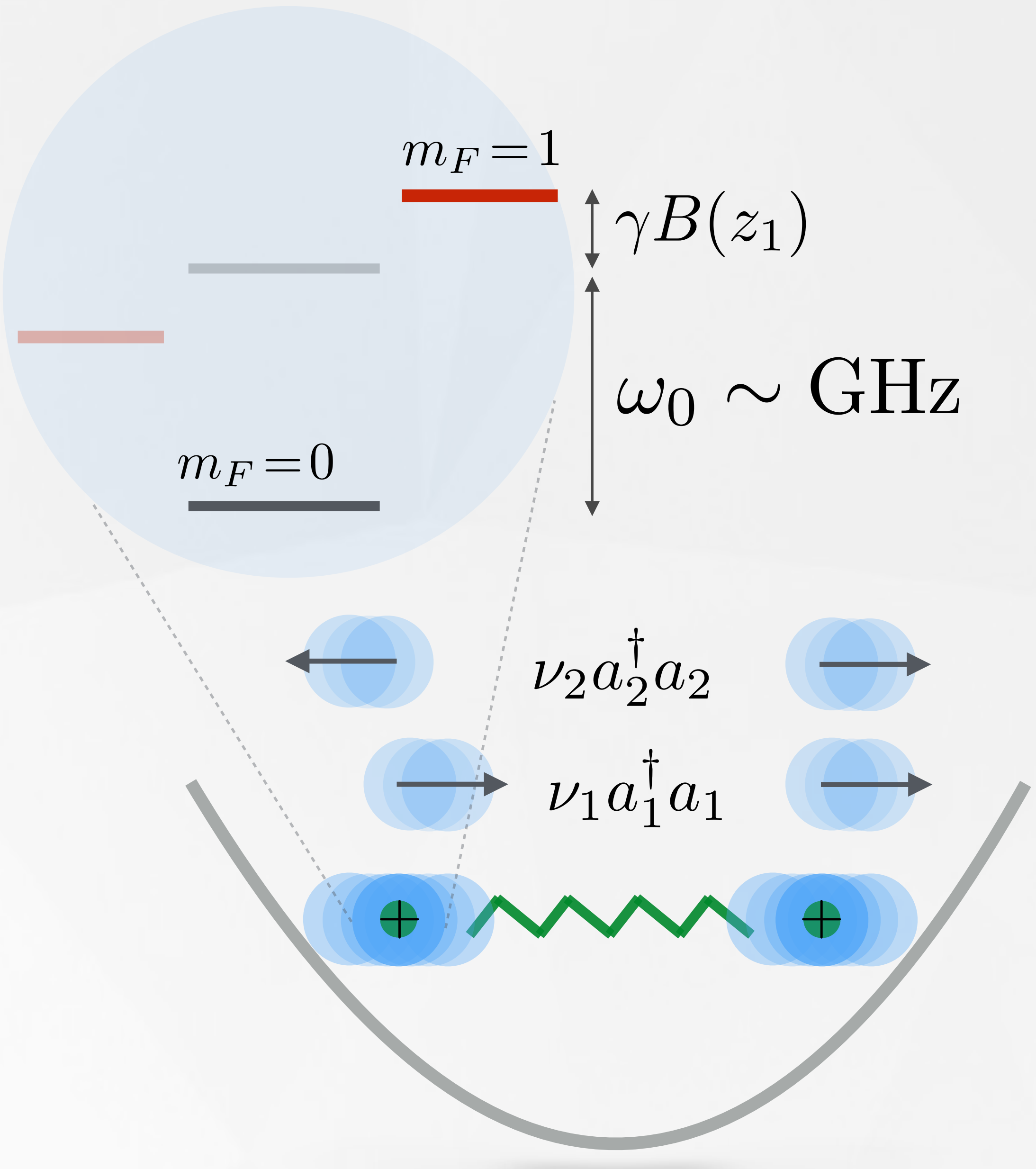

The magnetic field breaks the degeneracy

$$H = H_\nu + [\omega_0 + \gamma B(z_1)]\sigma_1^z + [\omega_0 + \gamma B(z_2)]\sigma_2^z$$

The System

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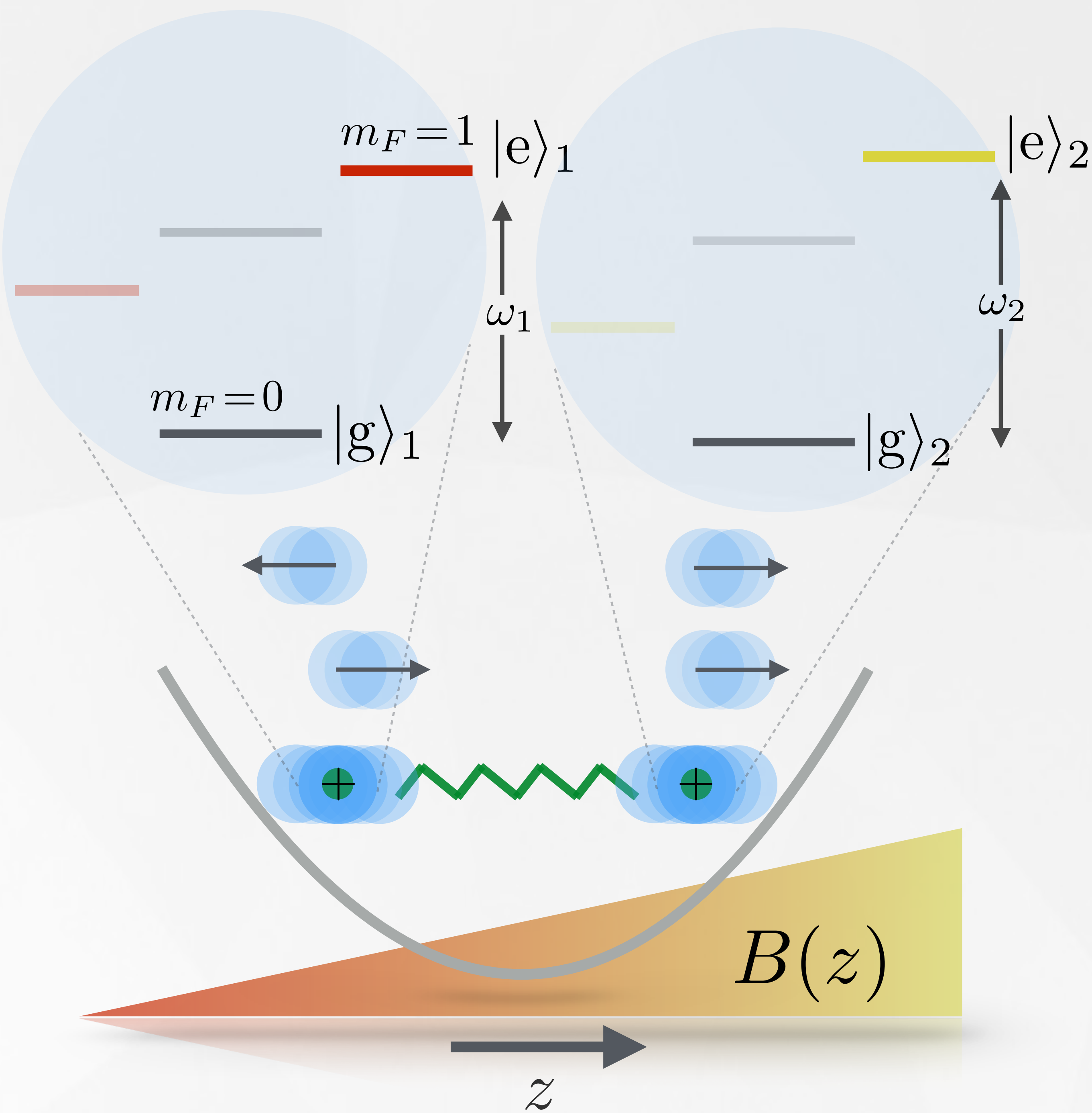

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$$H = H_\nu + [\omega_0 + \gamma B(z_1)]\sigma_1^z + [\omega_0 + \gamma B(z_2)]\sigma_2^z$$

Magnetic field gradient

$$H_q = \omega_1 \sigma_1^z + \omega_2 \sigma_2^z$$

$$\omega_i = \omega_0 + \gamma B(z_i^0)$$

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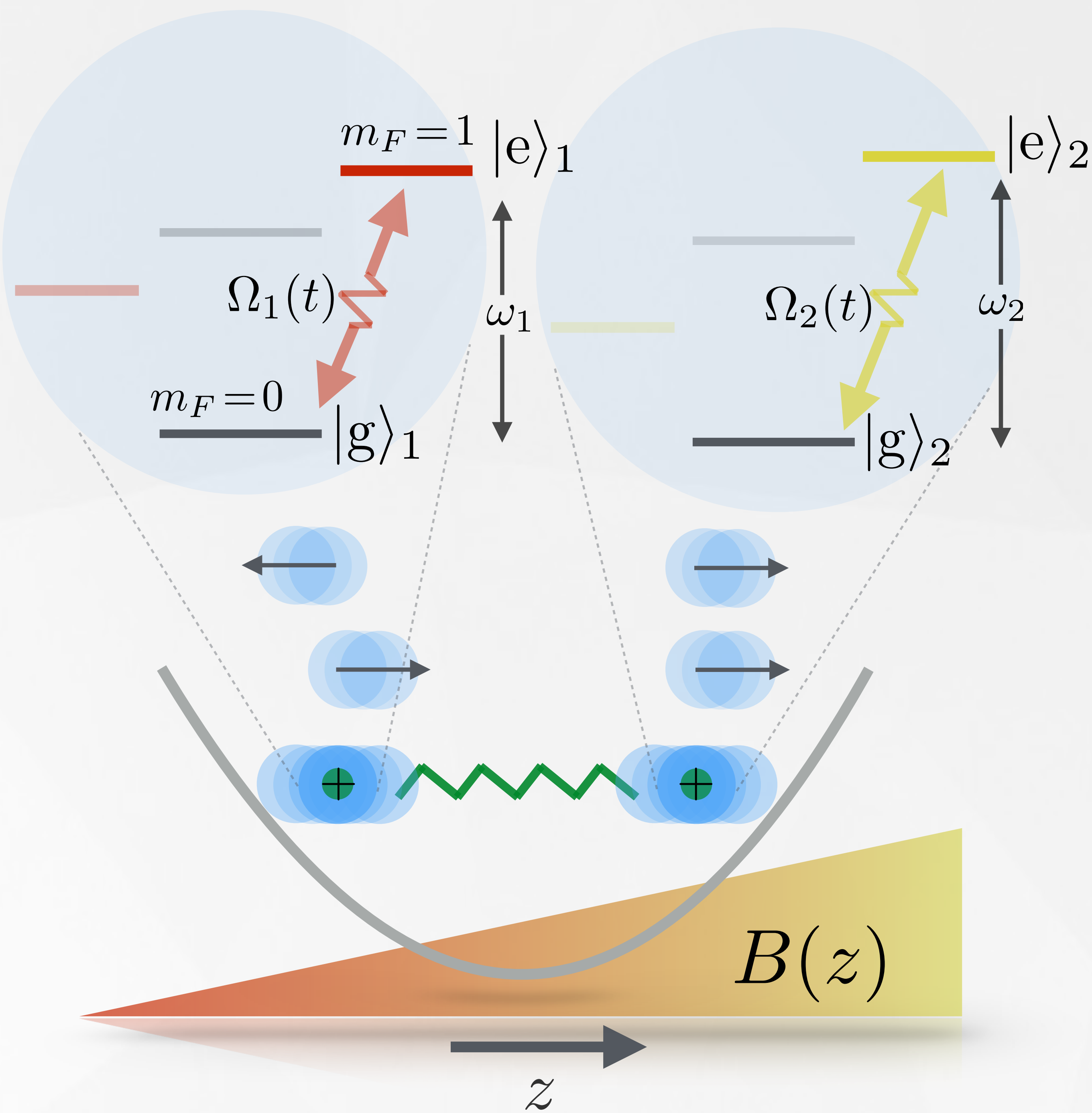

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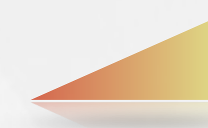
Magnetic field gradient 

$$H_q = \omega_1 \sigma_1^z + \omega_2 \sigma_2^z$$

$$\omega_i = \omega_0 + \gamma B(z_i^0)$$

- Single addressing ✓

The System

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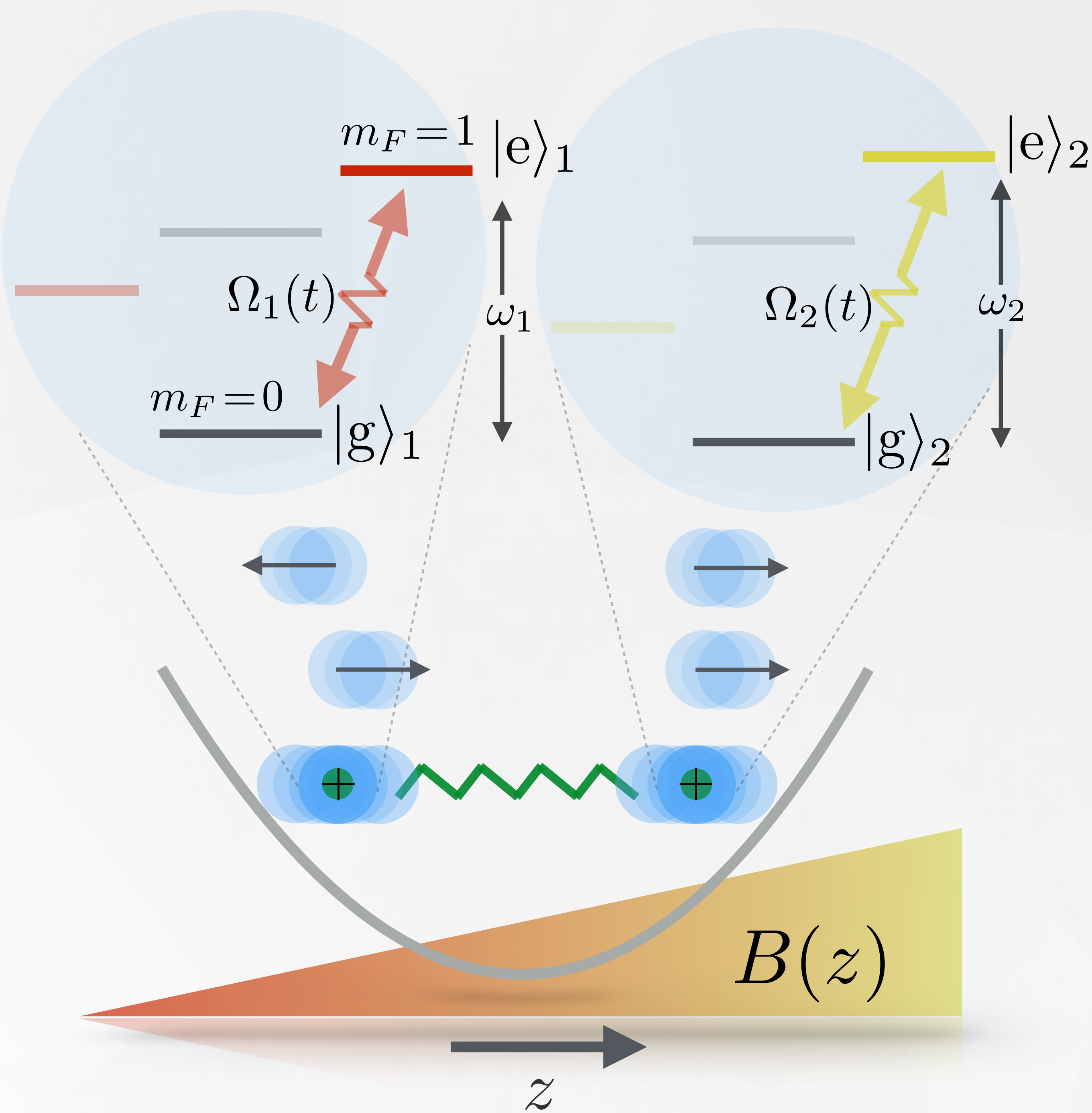
- The interaction term



$$H = H_\nu + [\omega_0 + \gamma B(z_1)]\sigma_1^z + [\omega_0 + \gamma B(z_2)]\sigma_2^z$$

$$z_i \approx z_i^0 + \hat{q}_i$$

$$H = H_\nu + [\omega_1 + \gamma B(\hat{q}_1)]\sigma_1^z + [\omega_2 + \gamma B(\hat{q}_2)]\sigma_2^z$$

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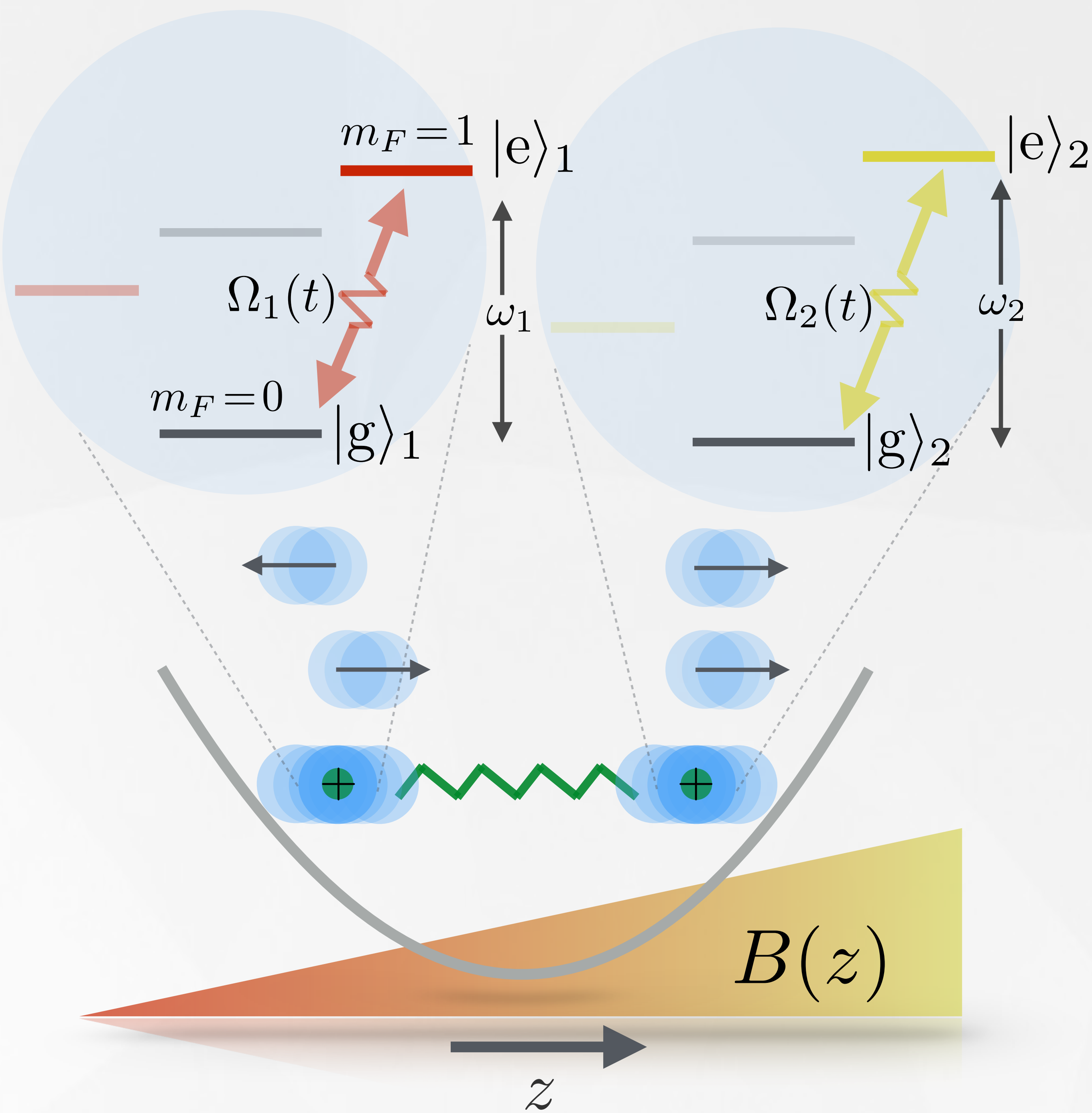

$$H = H_0 + H_{int}$$

$$H_0 = \sum_{j=1,2} \omega_j \sigma_j^z + \sum_{m=1,2} \nu_m a_m^\dagger a_m$$

$$H_{int} = \sum_{j,m} \Delta_{j,m} (a_m + a_m^\dagger) \sigma_j^z$$

$$\Delta_{jm} = b_j \frac{\gamma g_B}{4} \sqrt{\frac{\hbar}{M \nu_m}}$$

- qubit-mode coupling

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The Microwave Pulse Sequence

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- π-pulses for control and protection

$$U_\pi = e^{i\frac{\pi}{2}\sigma^\phi} \qquad \sigma^\phi = \sigma^+ e^{i\phi} + \sigma^- e^{-i\phi}$$

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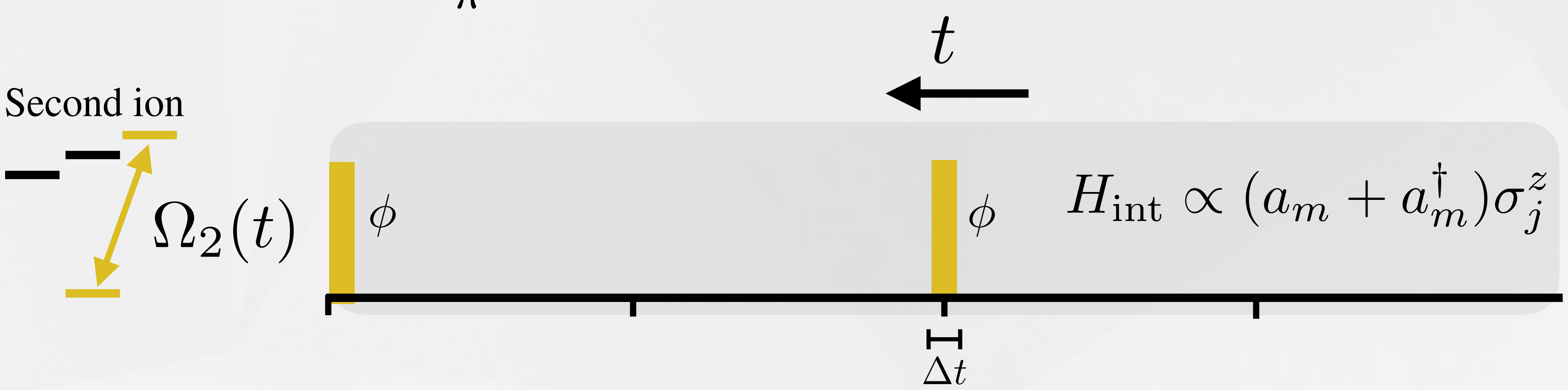

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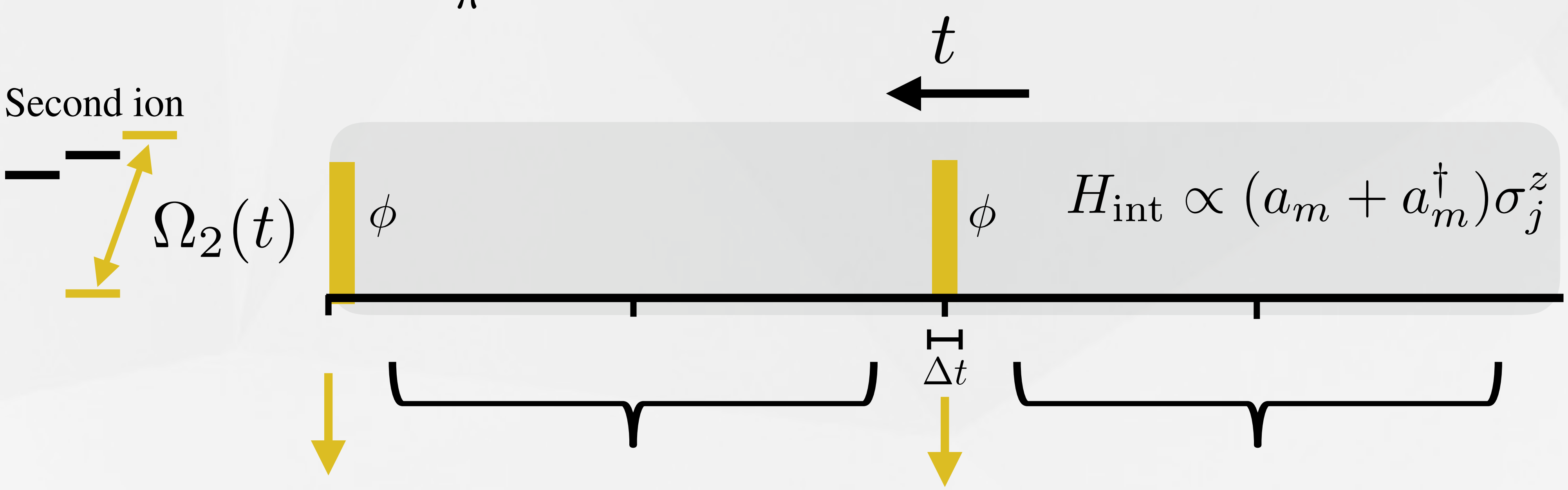

$$U = \; U_\pi \quad e^{-i\int_{t_2}^{t3} H(t')} \quad U_\pi \quad e^{-i\int_{t_1}^{t_2} H(t')}$$

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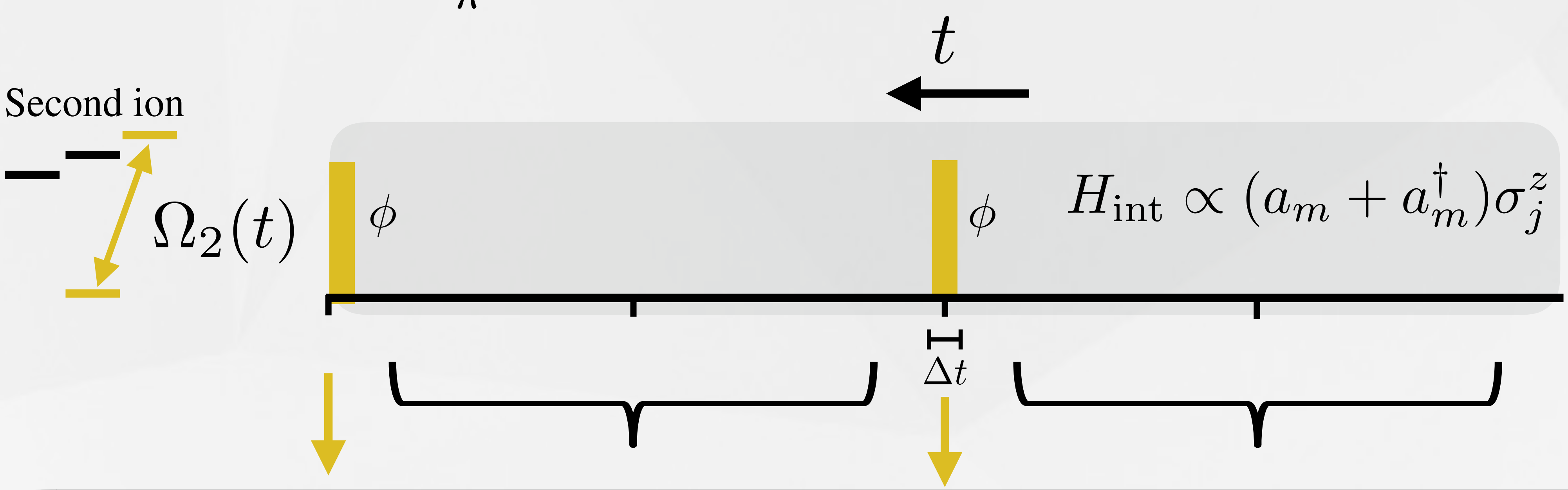

$$U = \underbrace{U_\pi \quad e^{-i\int_{t_2}^{t3} H(t')} \quad U_\pi}_{\{\sigma^\phi, \sigma^z\} = 0} \quad e^{-i\int_{t_1}^{t2} H(t')}$$

$$U = \quad e^{+i\int_{t_2}^{t3} H(t')} \quad e^{-i\int_{t_1}^{t2} H(t')}$$

The Microwave Pulse Sequence

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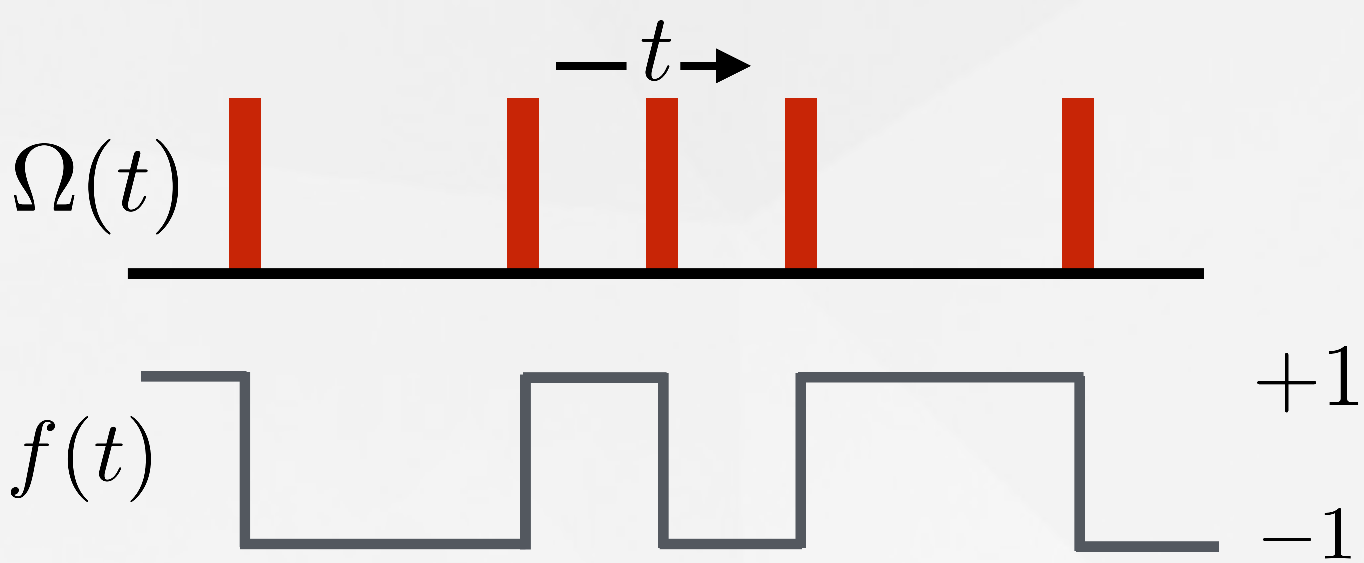
- π-pulses for control and protection

$$H(t) = H_0 + \sum_{j,m} f_j(t)\Delta_{j,m}(a_m + a_m^\dagger)\sigma_j^z$$

π-pulses $\longrightarrow$ $f_j = \pm 1$



Symmetry is important $\longrightarrow$

- Dynamical Decoupling

The Microwave Pulse Sequence

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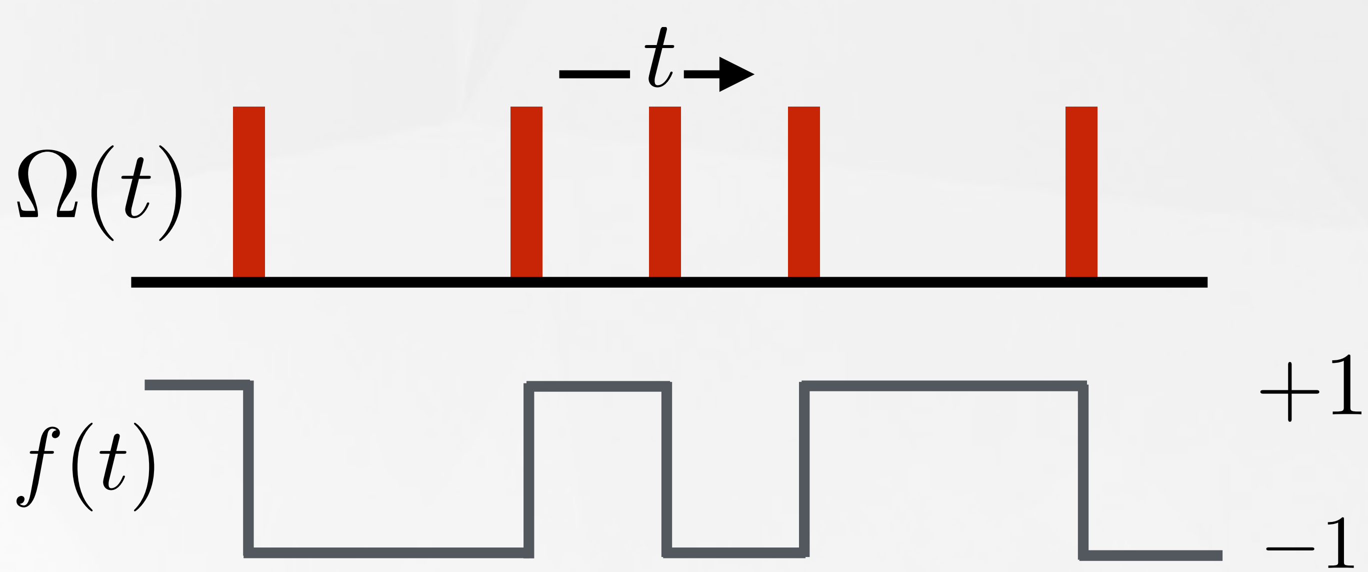

Analytically solvable evolution

$$U(t) = U_s(t)U_c(t),$$

$$U_c(t) = \exp\left(i\varphi(t)\sigma_1^z\sigma_2^z\right)$$

$$U_s(t) = \exp\left\{-i\sum_{j,m}\Delta_{jm}\left[a_m G_{jm}(t) + a_m^\dagger G_{jm}^*(t)\right]\sigma_j^z\right\},$$

The Microwave Pulse Sequence

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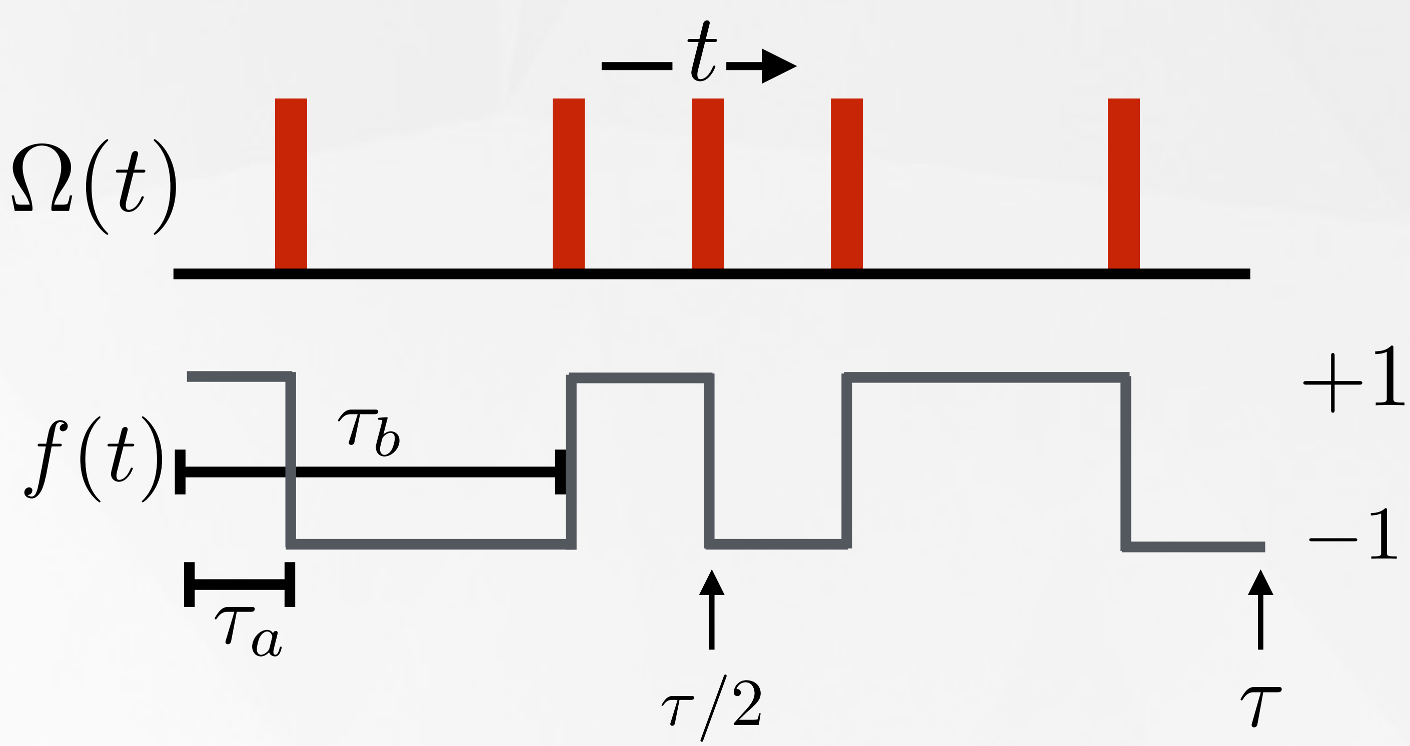

$$G_{jm}(T_{\rm gate}, \tau_a, \tau_b, \tau) = 0$$

$$\varphi(T_{\rm gate}, \tau_a, \tau_b, \tau) \neq 0$$

The Microwave Pulse Sequence

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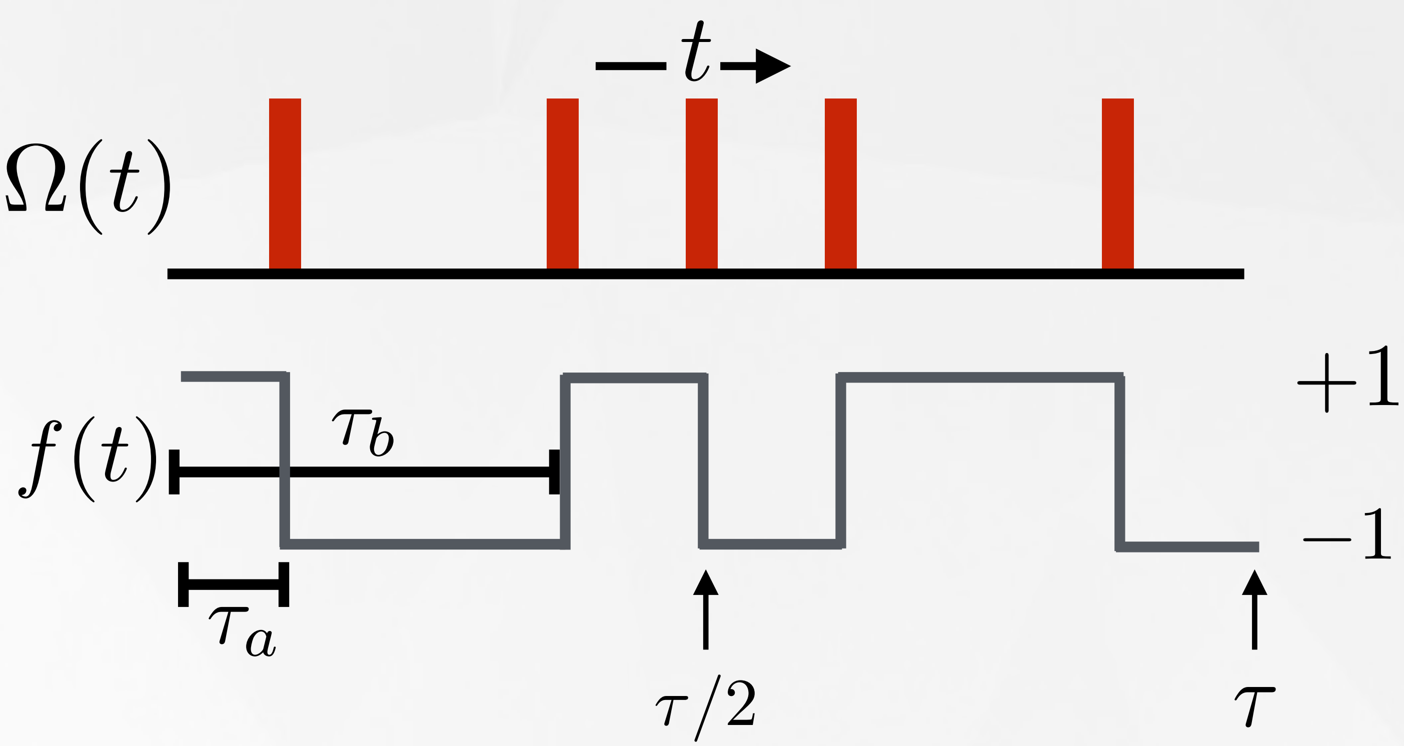
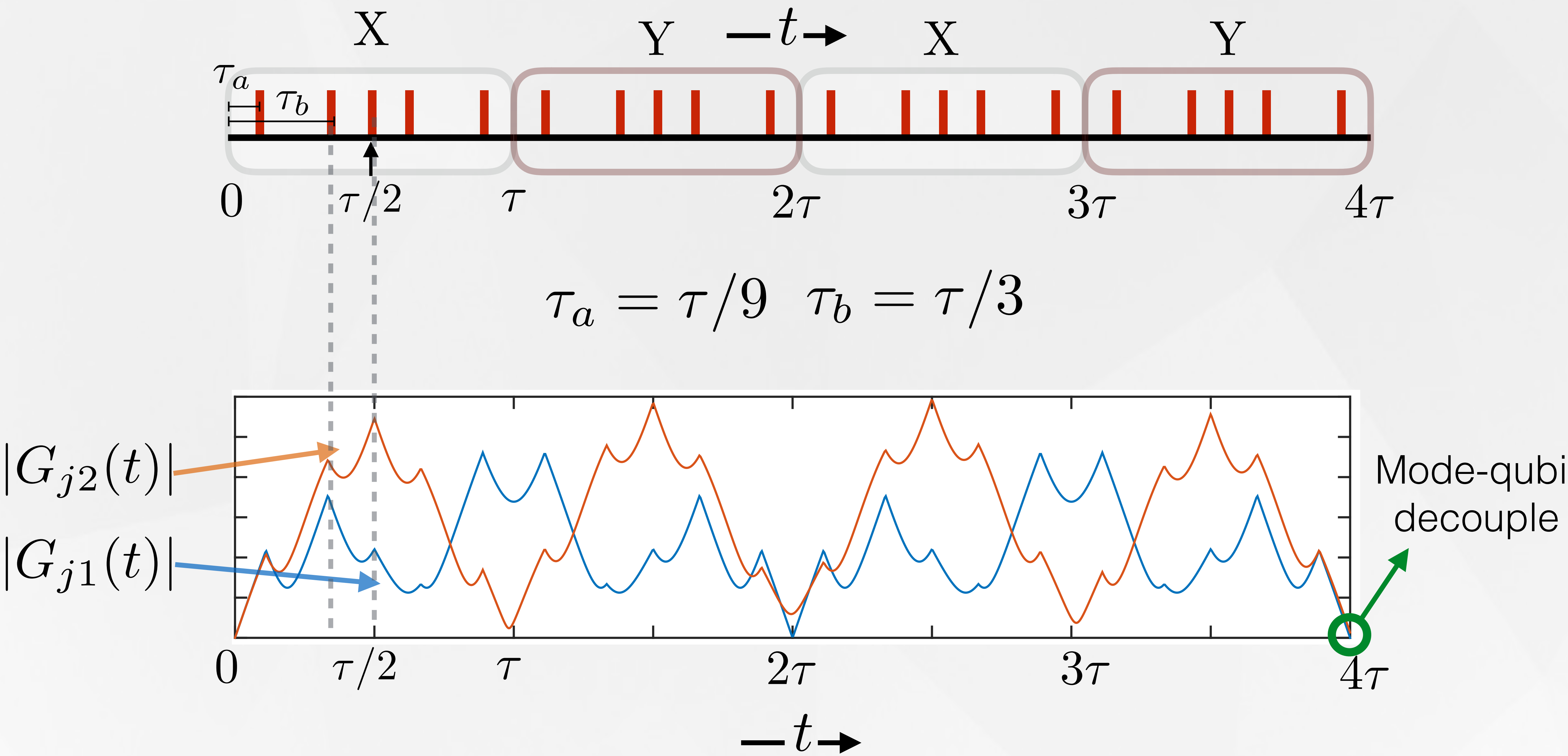


$$G_{jm}(T_{\text{gate}}, \tau_a, \tau_b, \tau) = 0$$

4 functions

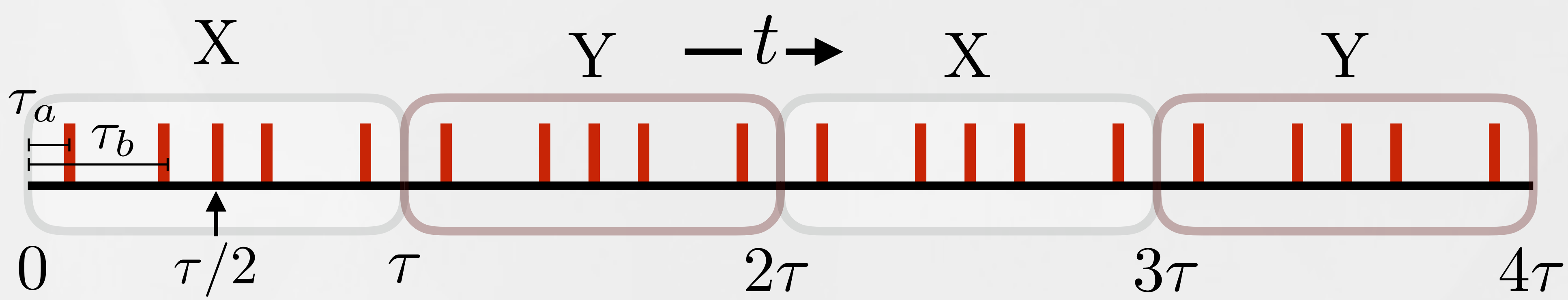
$$\varphi(T_{\text{gate}}, \tau_a, \tau_b, \tau) \neq 0$$

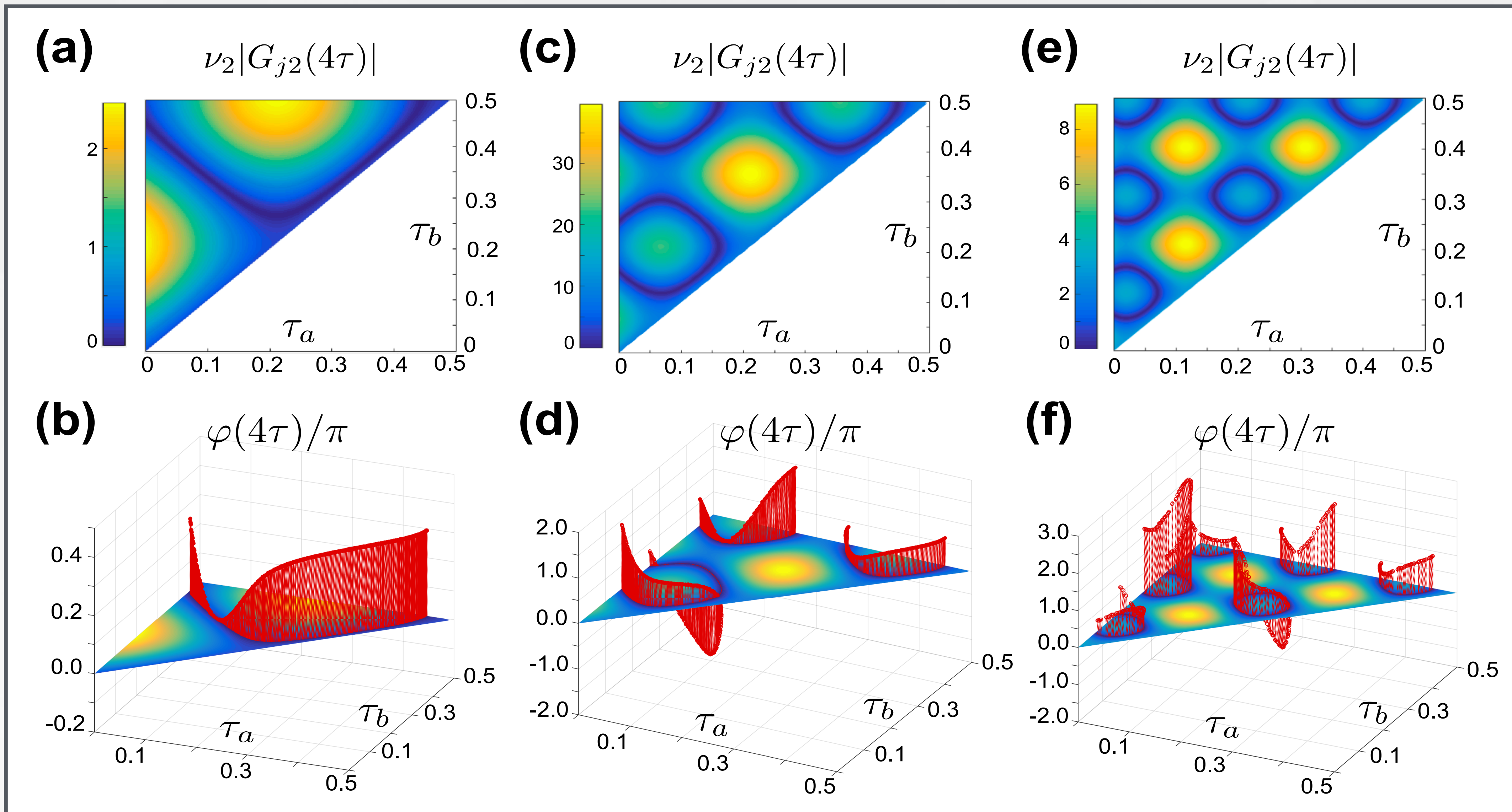
Results



$$\tau_a = \tau/9 \quad \tau_b = \tau/3$$

Results


X
Y
X
Y
t
τ_a
τ_b
0
$\tau/2$
τ
2τ
3τ
4τ


(a)
$\nu_2|G_{j2}(4\tau)|$
(c)
$\nu_2|G_{j2}(4\tau)|$
(e)
$\nu_2|G_{j2}(4\tau)|$
τ_a
τ_b
(b)
$\varphi(4\tau)/\pi$
(d)
$\varphi(4\tau)/\pi$
(f)
$\varphi(4\tau)/\pi$

Results

Fidelities above 99,9%

Infidelity ($\times10^{-4}$)	$\exp(i\frac{\pi}{4}\sigma_1^z\sigma_2^z)$ $g_B = 150$ T/m $\nu/(2\pi) = 150$ kHz $t_{\text{gate}} = 80\ \mu$s	$\exp(i\frac{\pi}{8}\sigma_1^z\sigma_2^z)$ $g_B = 150$ T/m $\nu/(2\pi) = 150$ kHz $t_{\text{gate}} = 80\ \mu$s	$\exp(i\frac{\pi}{4}\sigma_1^z\sigma_2^z)$ $g_B = 300$ T/m $\nu/(2\pi) = 220$ kHz $t_{\text{gate}} = 36.3\ \mu$s	$\exp(i\frac{\pi}{8}\sigma_1^z\sigma_2^z)$ $g_B = 300$ T/m $\nu/(2\pi) = 220$ kHz $t_{\text{gate}} = 36.3\ \mu$s
$\vert g\rangle \otimes (\vert g\rangle + \vert e\rangle)$	1.172	0.128	2.060	0.144
$(\vert g\rangle + \vert e\rangle) \otimes (\vert g\rangle + \vert e\rangle)$	2.229	0.136	4.905	0.304
$\vert g\rangle \otimes (\vert g\rangle + i\vert e\rangle) + \vert e\rangle \otimes \vert e\rangle$	3.052	0.116	5.899	0.371
$\vert e\rangle \otimes (\vert g\rangle - i\vert e\rangle) + \vert g\rangle \otimes \vert g\rangle$	4.631	0.172	5.946	0.413
$\vert e\rangle \otimes (\vert g\rangle - i\vert e\rangle) + \vert g\rangle \otimes (\vert g\rangle + i\vert e\rangle)$	3.250	0.110	4.635	0.293

π-pulse time: $77\mathrm{ns}$

π-pulse time: $49\mathrm{ns}$

Sources of error:

$$\tilde{\Omega} = \Omega(1+\epsilon_\Omega) \quad \epsilon_\Omega = 0.01$$

$$\langle n\rangle_{a_1,a_2} = 0.5 \qquad \tilde{\nu} = \nu(1+\epsilon_\nu) \quad \epsilon_\nu = 0.001$$

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Conclusions

- Fast approach to generate two qubit phase gates with microwave ions

  Best experiments: $F = 99,7\%$ in milliseconds

- Robust against main sources of decoherence

- We validated our ideas with detailed numerical simulations

- Microwave control comparable in precision and speed to laser-controlled gates.

THANK YOU FOR YOUR ATTENTION

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