Quantum computing platform with polariton integrated circuits

<u>Francesco Scala</u>, Davide Nigro, Dario Gerace

arXiv:2306.05072 (2023)

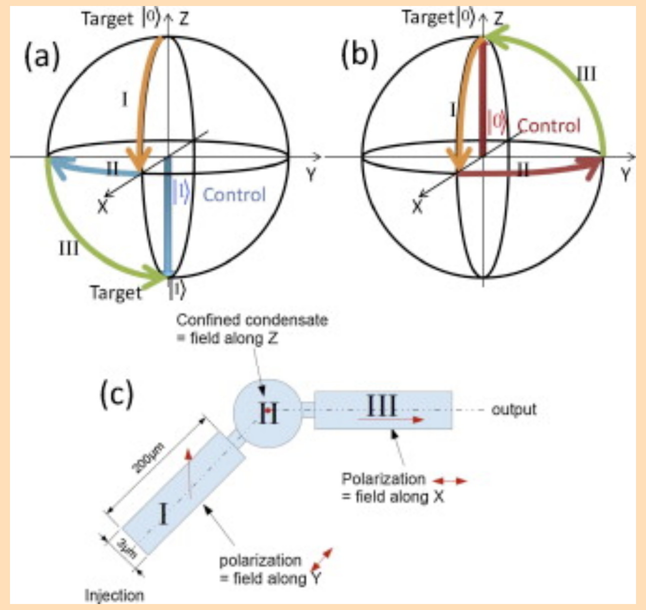
UNIVERSITÀ DI PAVIA
Department of Physics

OECS
LECCE 2023

13/06/2023

Exciton-Polaritons Quantum Computing

Spin-coherent polariton states

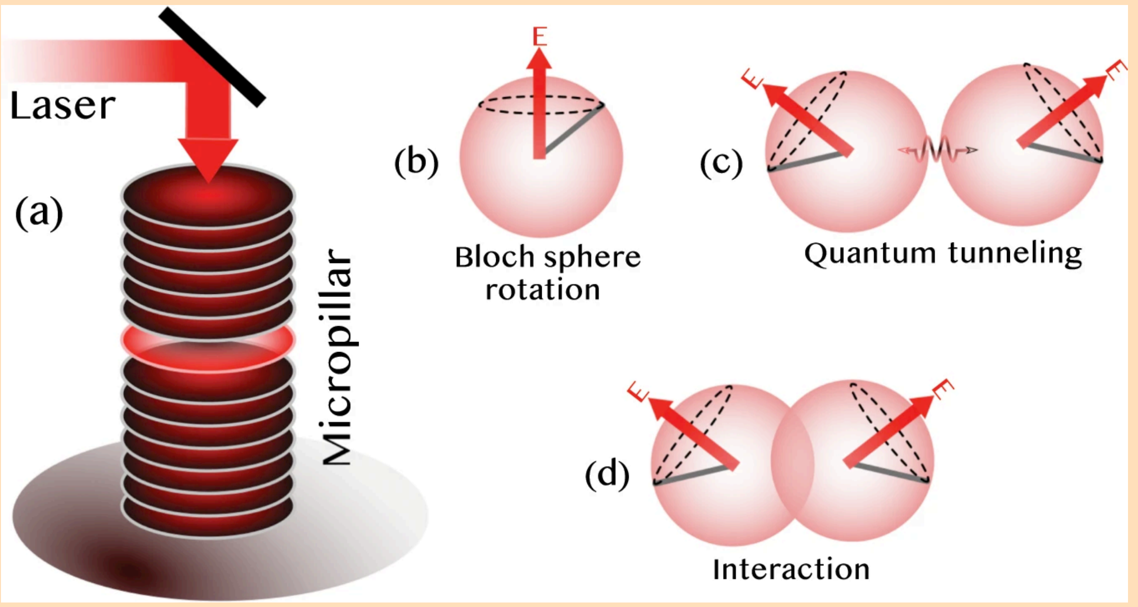


D.D. Solnyshkov, et al.
Superlatt. and Microstr. 83, 466-475

2015

2020

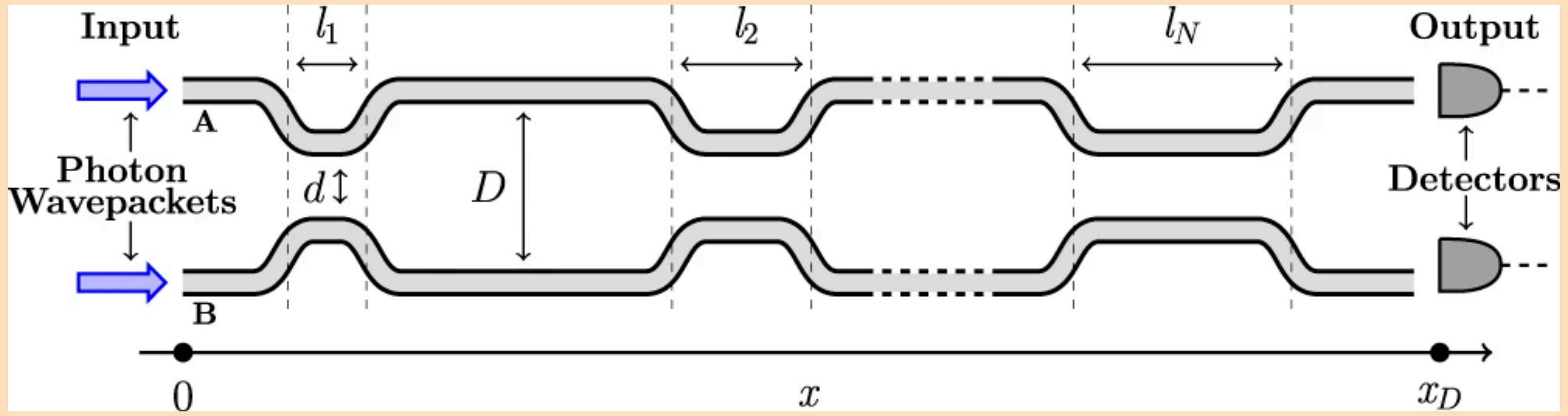
Exciton-polariton condensates



S.Ghosh et.al., **npj Quant. Info., 6, 16**

2022

Single exciton-polaritons quantum interferometry



D. Nigro, et al., **Comm. Phys. 5, 34**

Linear Optical Quantum Computing

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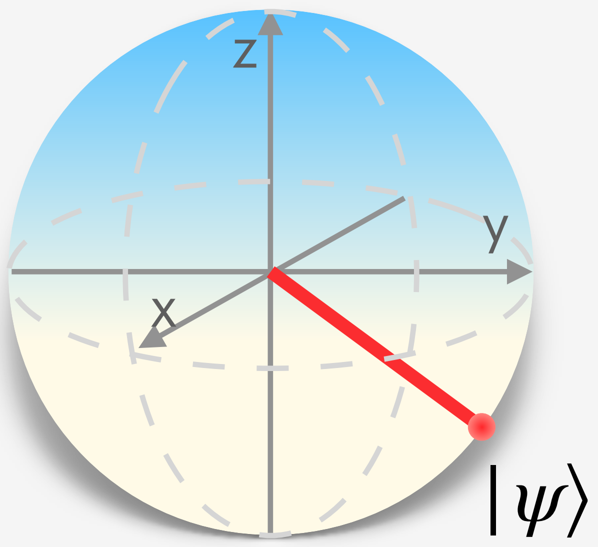
Quantum bit

$|0\rangle$

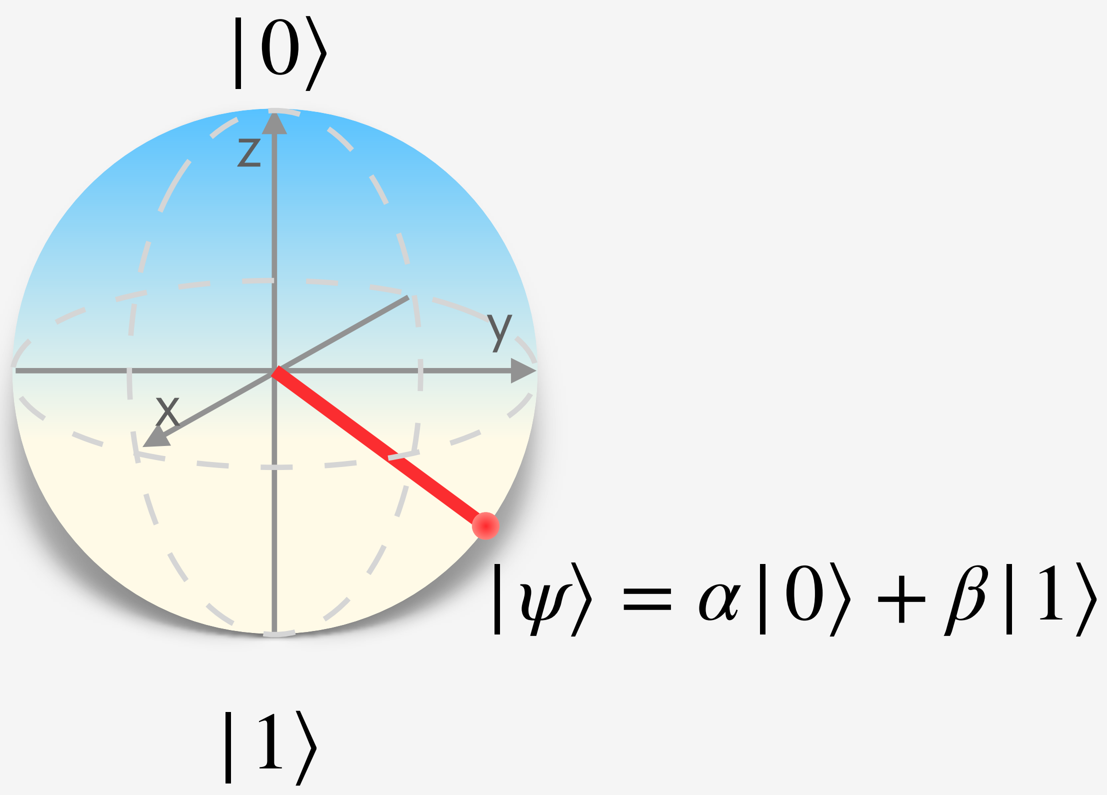


$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

$|1\rangle$

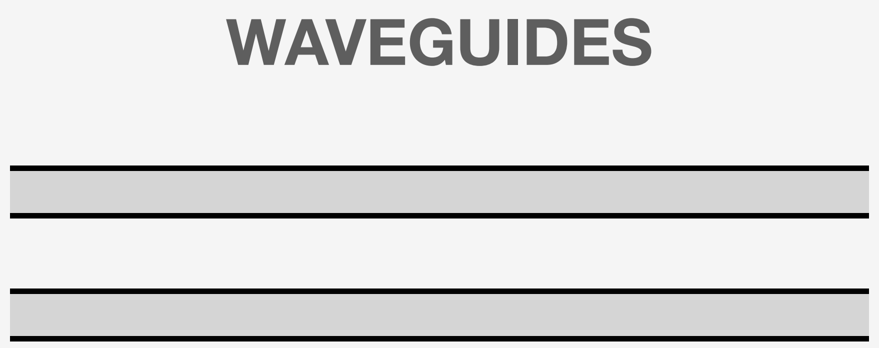
Linear Optical Quantum Computing

Quantum bit



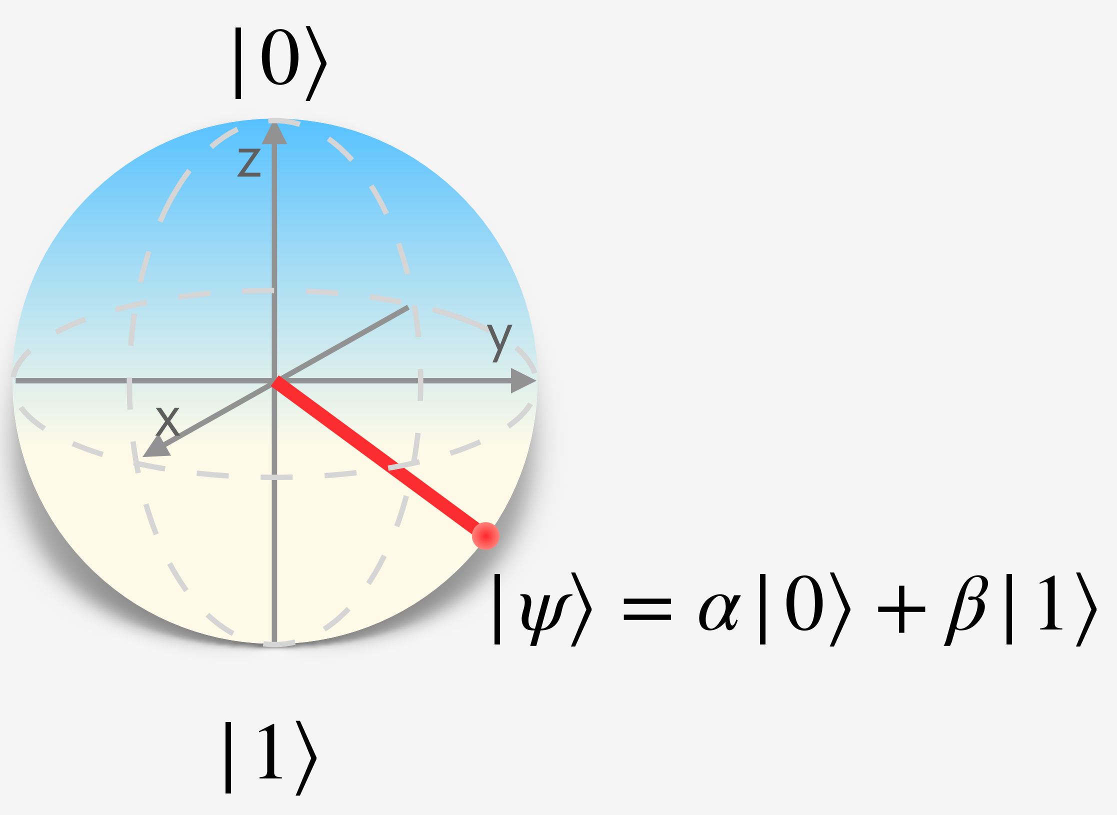
Dual rail encoding

$$|1,0\rangle_{Fock} = |0\rangle \quad |0,1\rangle_{Fock} = |1\rangle$$



Linear Optical Quantum Computing

Quantum bit



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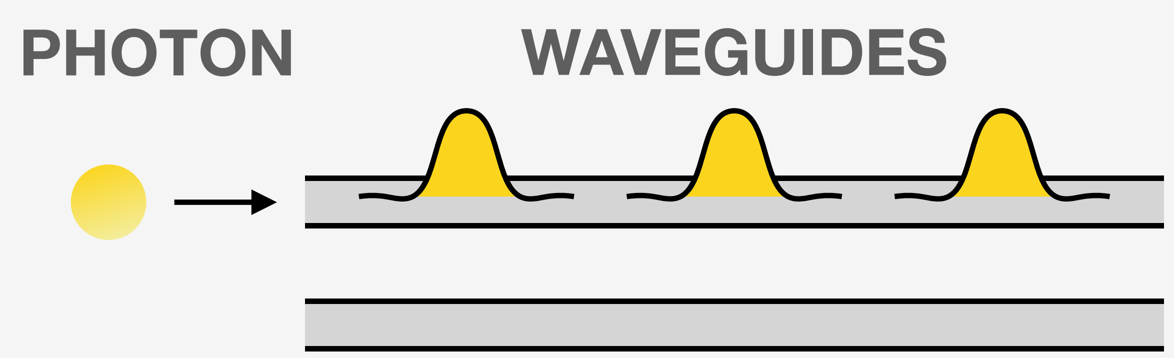
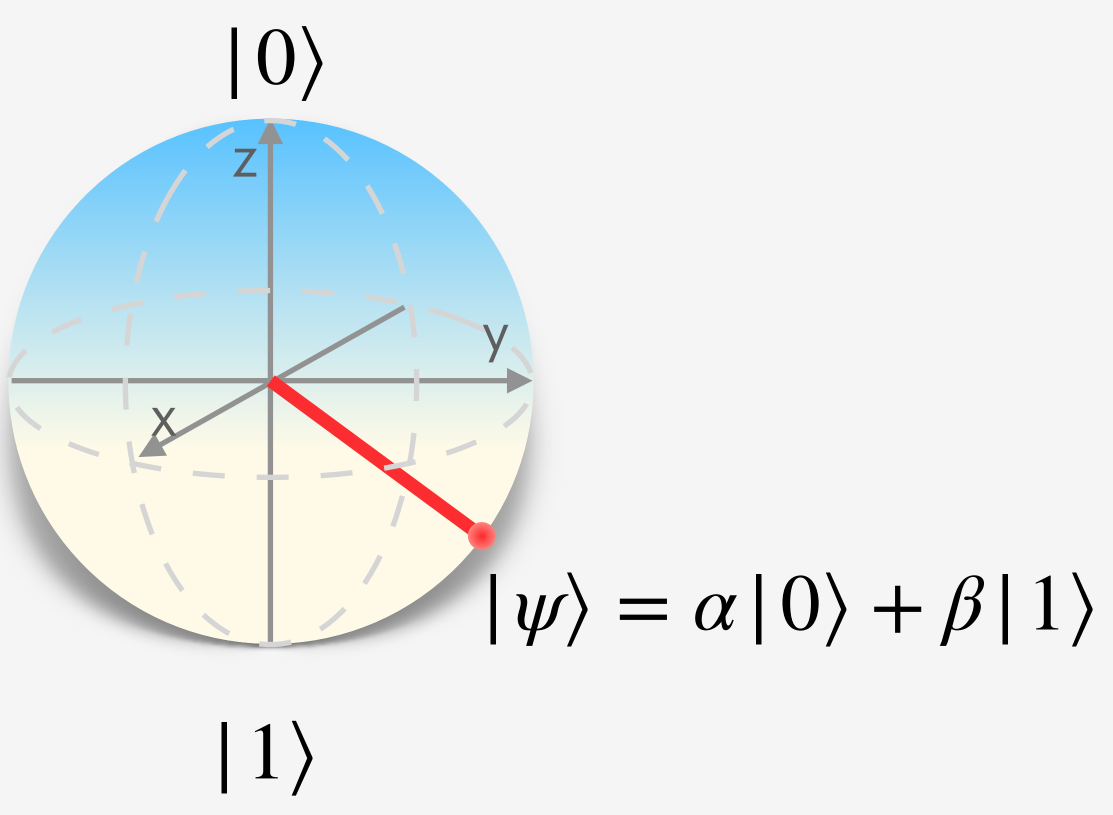


Linear Optical Quantum Computing

Quantum bit



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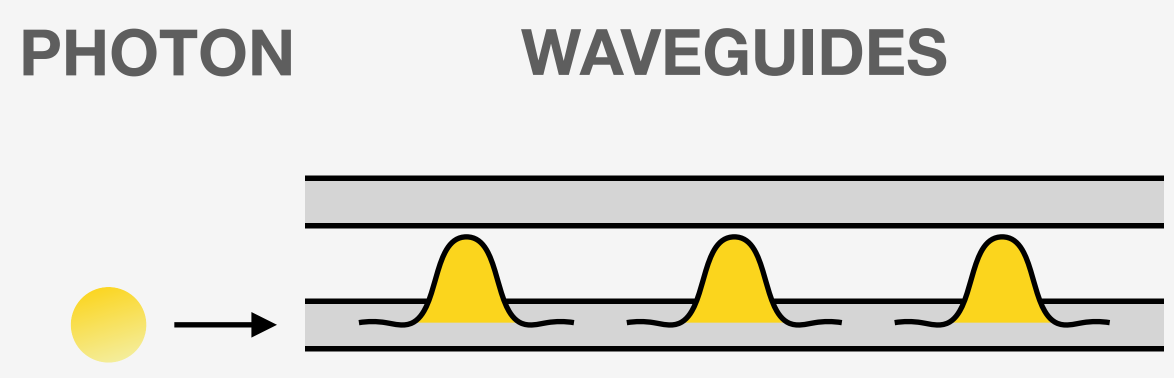

Linear Optical Quantum Computing

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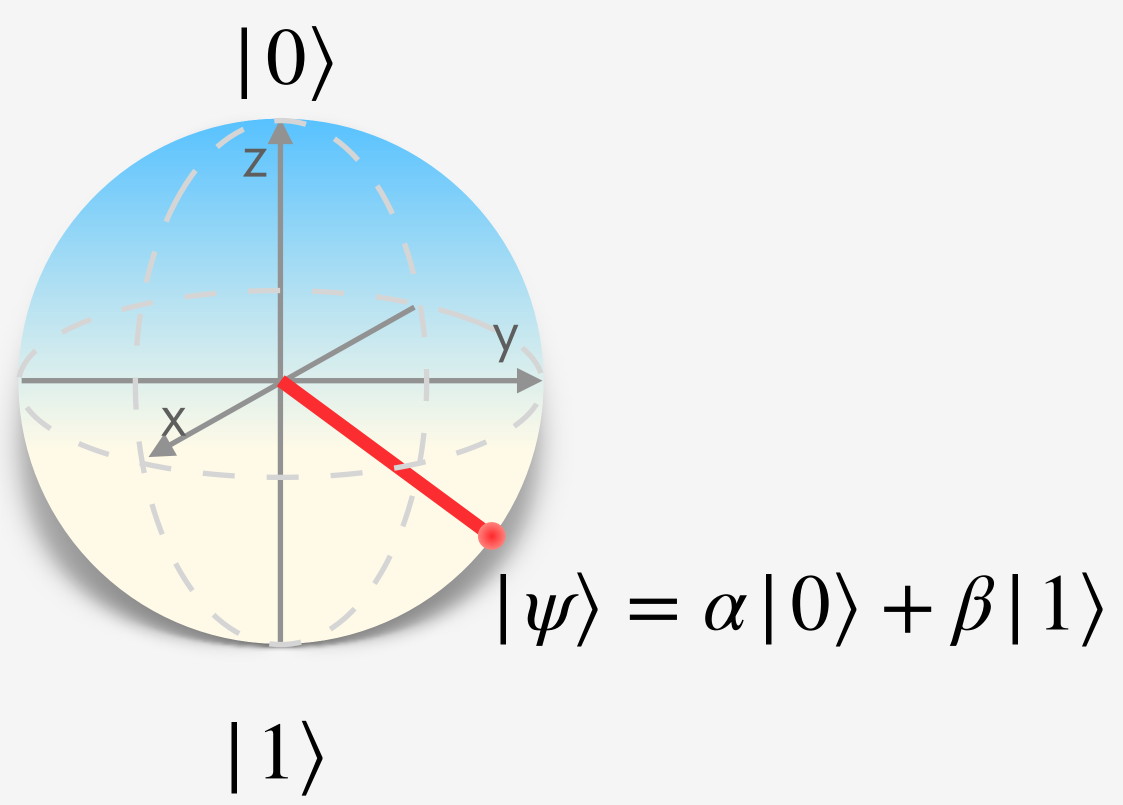

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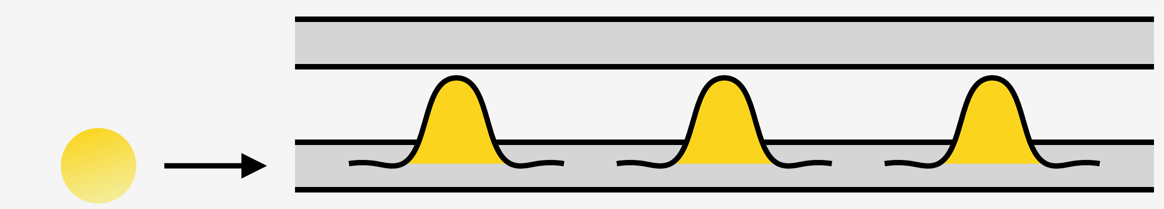

Universal gate set [1]

An arbitrary unitary operator may be expressed exactly using **only single qubit gates and CNOTS** (2-qubit gate)

[1] M. Nielsen, I. Chuang, **Cambridge University Press (2010)**

Universal Gate Set In Linear Optics

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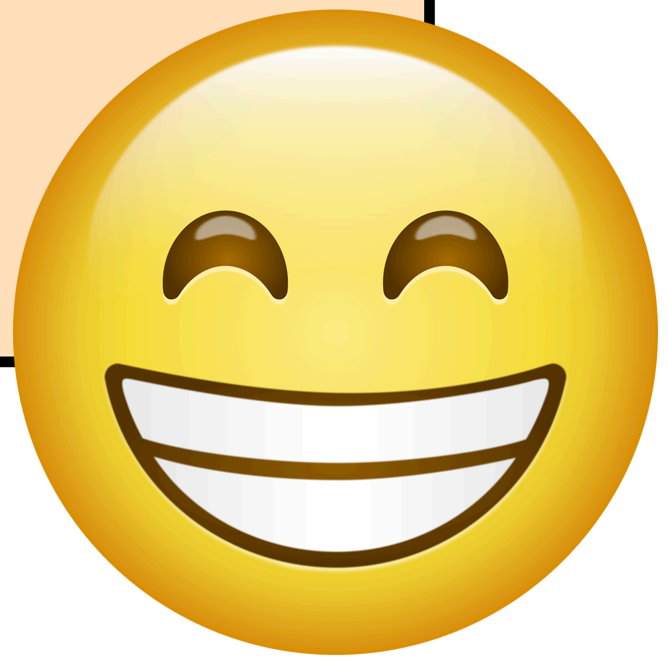
1-qubit operations

↓

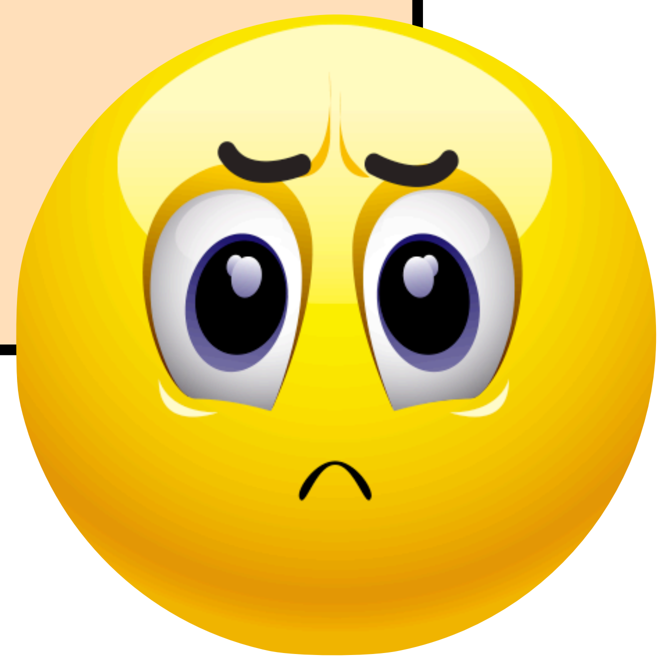
Superposition



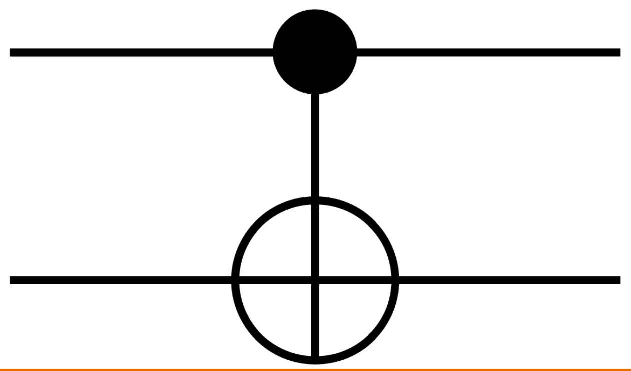
2-qubits operations

↓

Entanglement



Probabilistic Cnot



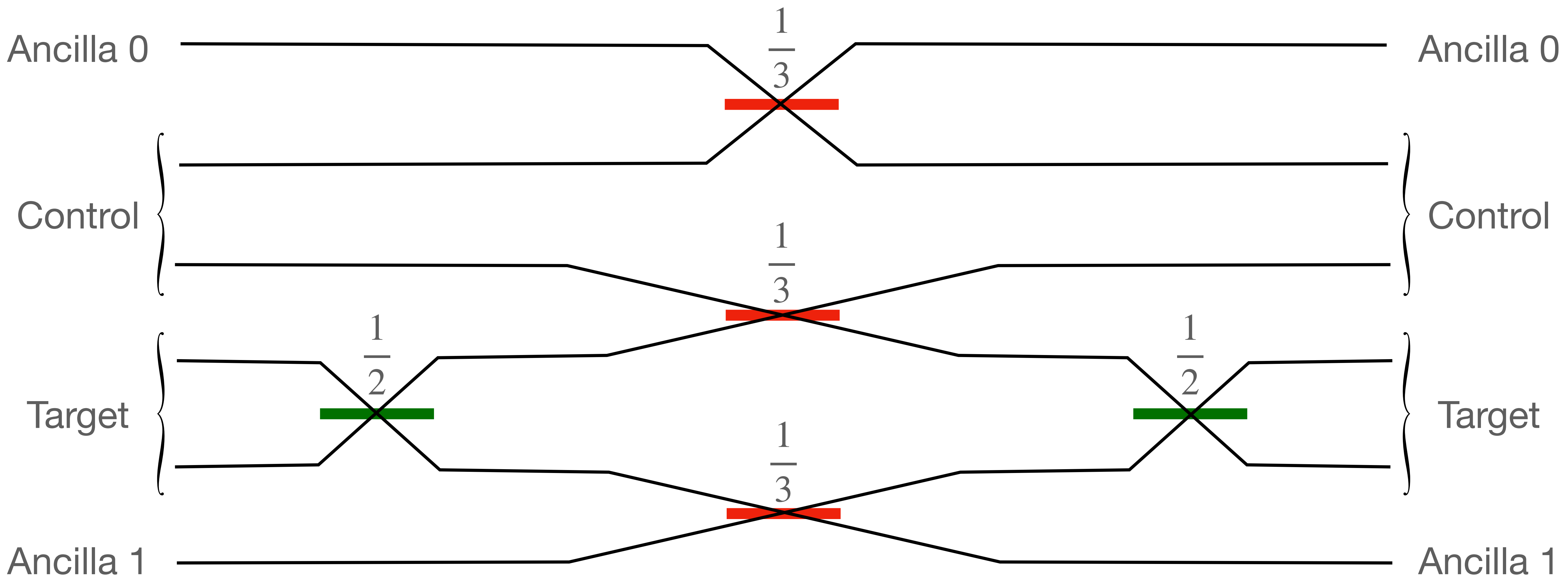
$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Probability of success $\mathbf{p_{succ}} = \mathbf{1/9}$

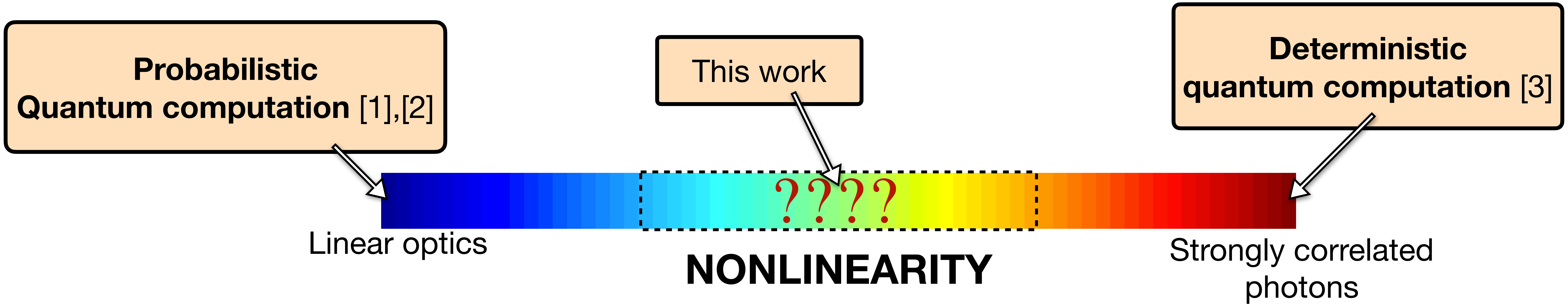
T. C. Ralph, et al. - **PRA 65, 062324 (2002)**

Maximum theoretical probability of success $\mathbf{p^{th}_{succ}} = \mathbf{3/4}$

E. Knill, **PRA 68, 064303 (2003)**



The Main Idea



[1] E. Knill, **PRA 68, 064303 (2003)**
[2] N. Maring, et al., **ArXiv:2306.00874 (2023)**
[3] I.Chuang, Y.Yamamoto, **PRA 52, 3489 (1995)**

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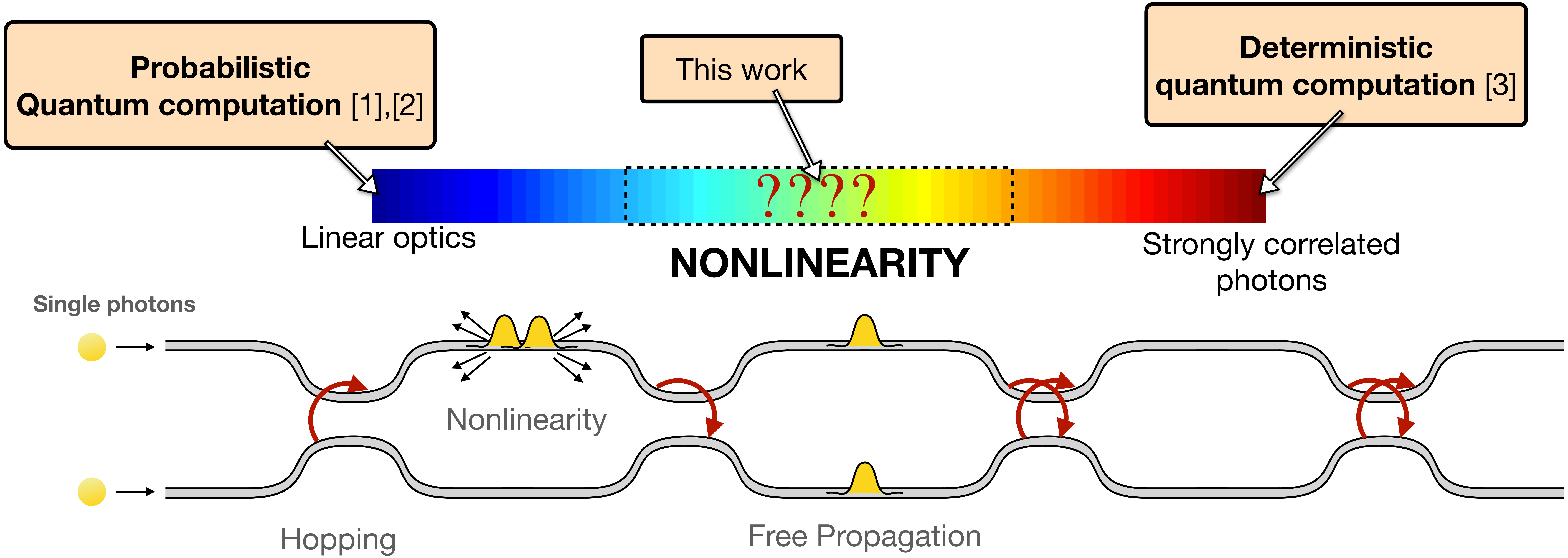

[1] E. Knill, **PRA 68, 064303 (2003)**
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Hamiltonian Model

$$\mathscr{H} = \sum_{i=1}^{N} \Big(\overbrace{\hbar\omega_i a_i^\dagger a_i}^{\text{Free Propagation}} + \underbrace{U_i a_i^{\dagger 2} a_i^2}_{\substack{\text{Kerr-type} \\ \text{Nonlinearity}}} \Big) + \overbrace{\frac{1}{2} \sum_{\substack{i,j=1 \\ j \neq i}}^{N} \hbar J_{ij}(x) \big(a_i^\dagger a_j + a_j^\dagger a_i \big)}^{\text{Interference}}$$

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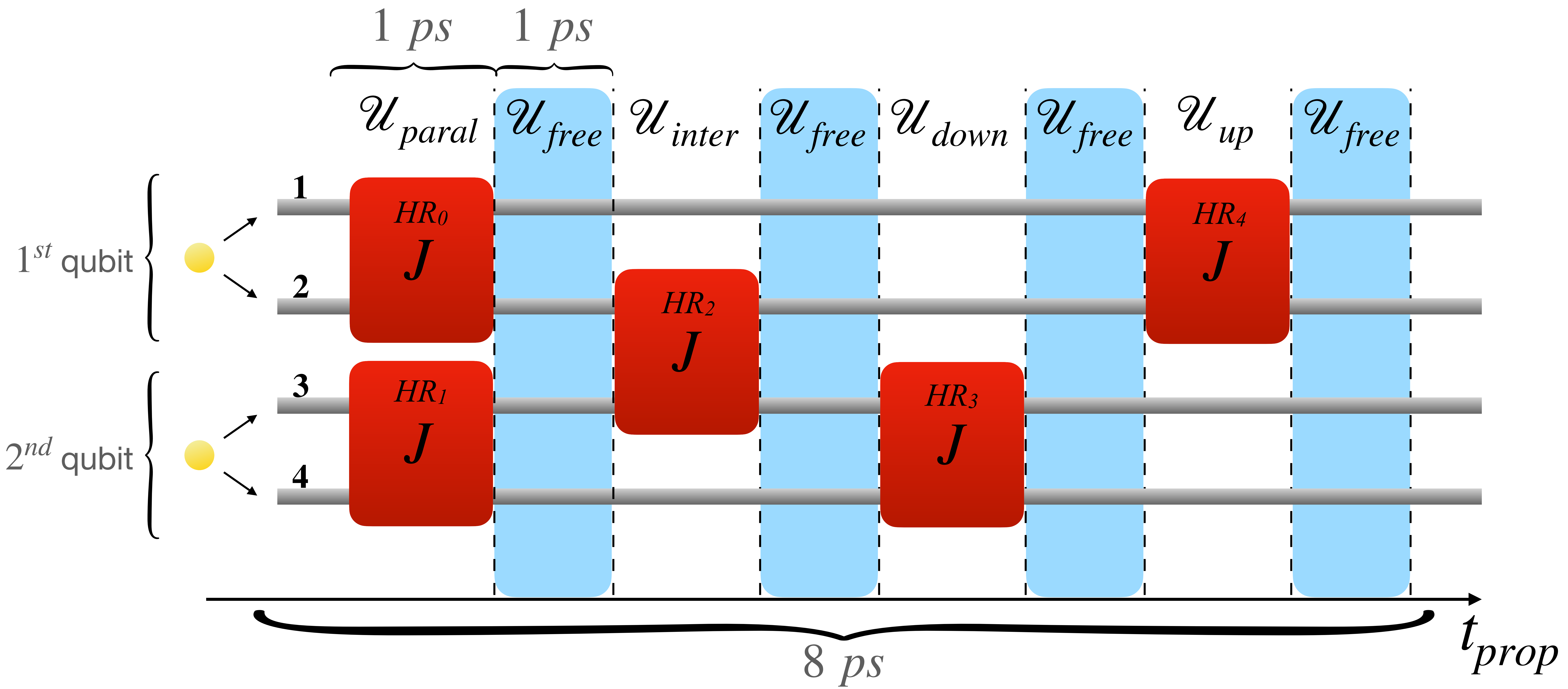
In case of **losses, pure dephasing, thermal noise** → master equation (Lindblad):

$$i\hbar \partial_t \rho = [\mathscr{H}, \rho] + i\hbar \sum_{j=1}^{N} \gamma_j \left(\hat{O}_j \rho \hat{O}_j^\dagger - \frac{1}{2} \left(\hat{O}_j^\dagger \hat{O}_j, \rho + \rho \hat{O}_j^\dagger \hat{O}_j \right) \right)$$

Elementary Building Block



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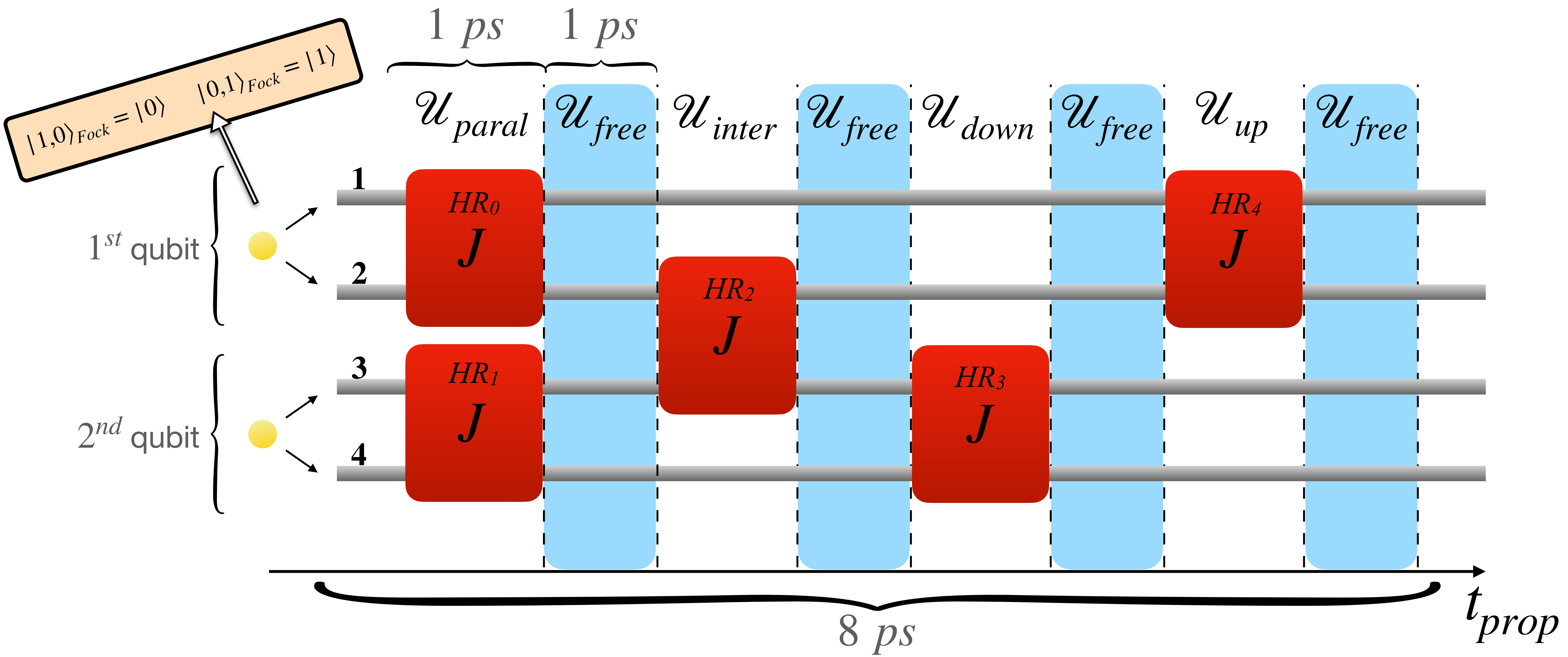
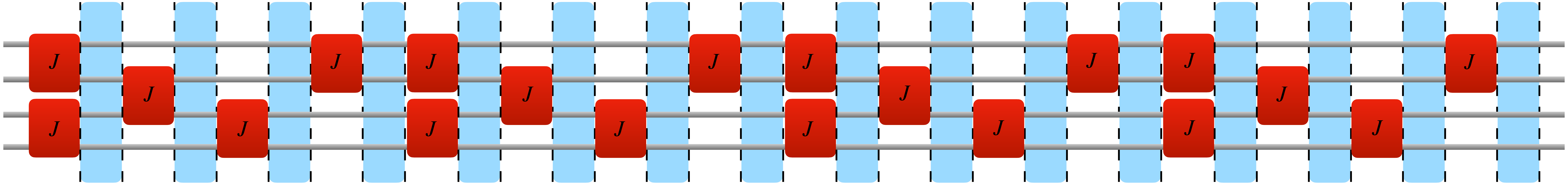
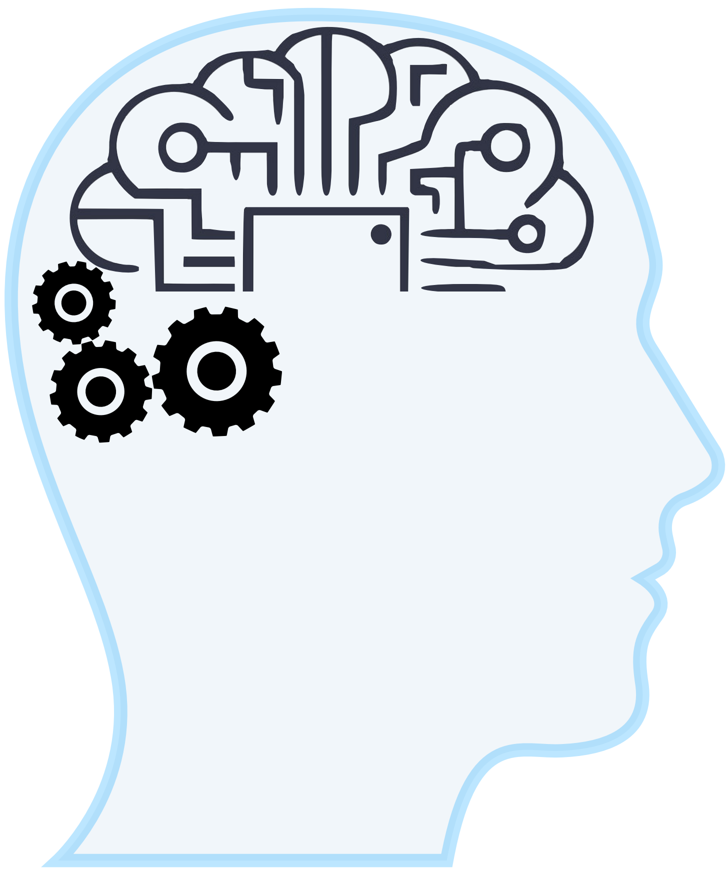


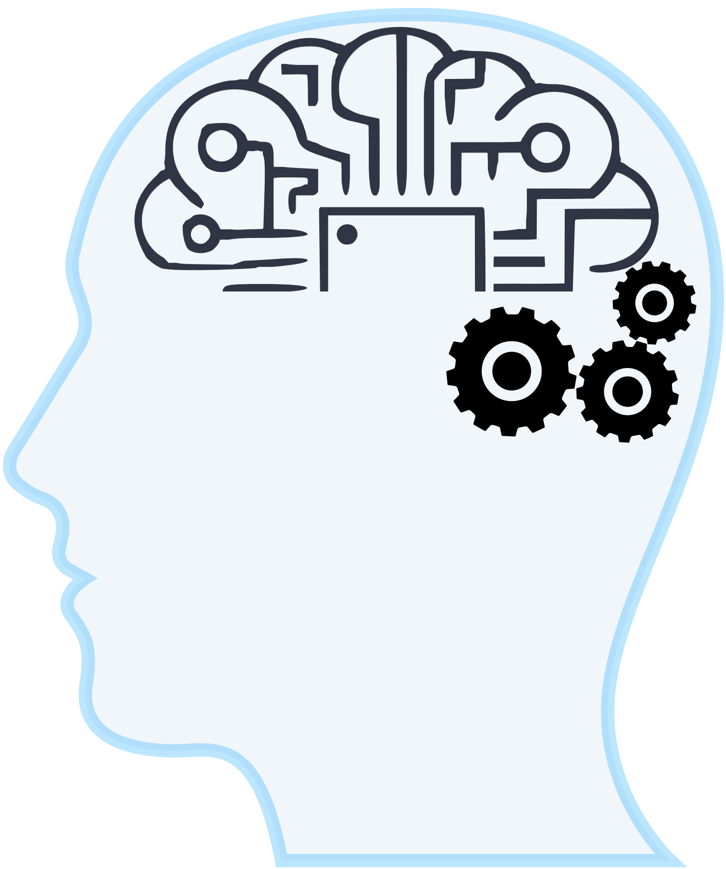
Structure Optimization



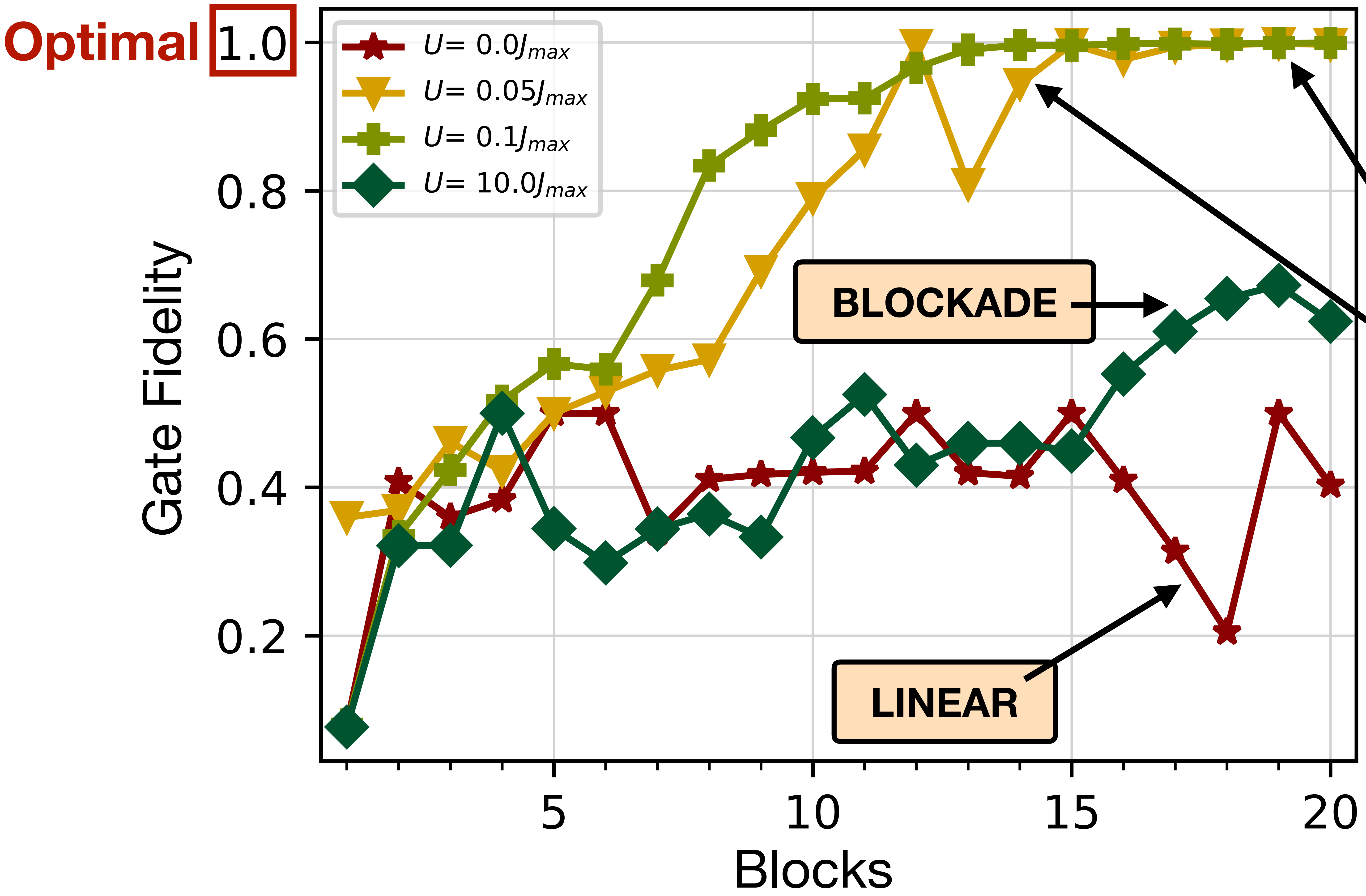


J_{ij} **optimization**

<u>**INVERSE DESIGN**</u>



Optimized Cnot



Gate Fidelity:

$$\bar{F}(\{\theta_s^{opt}\}) = \frac{1}{|S|}\sum_{i\in S} |\langle i|\mathcal{U}_{tot}^{\dagger}(\{\theta_s^{opt}\})CNOT|i\rangle|^2$$

S = computational basis

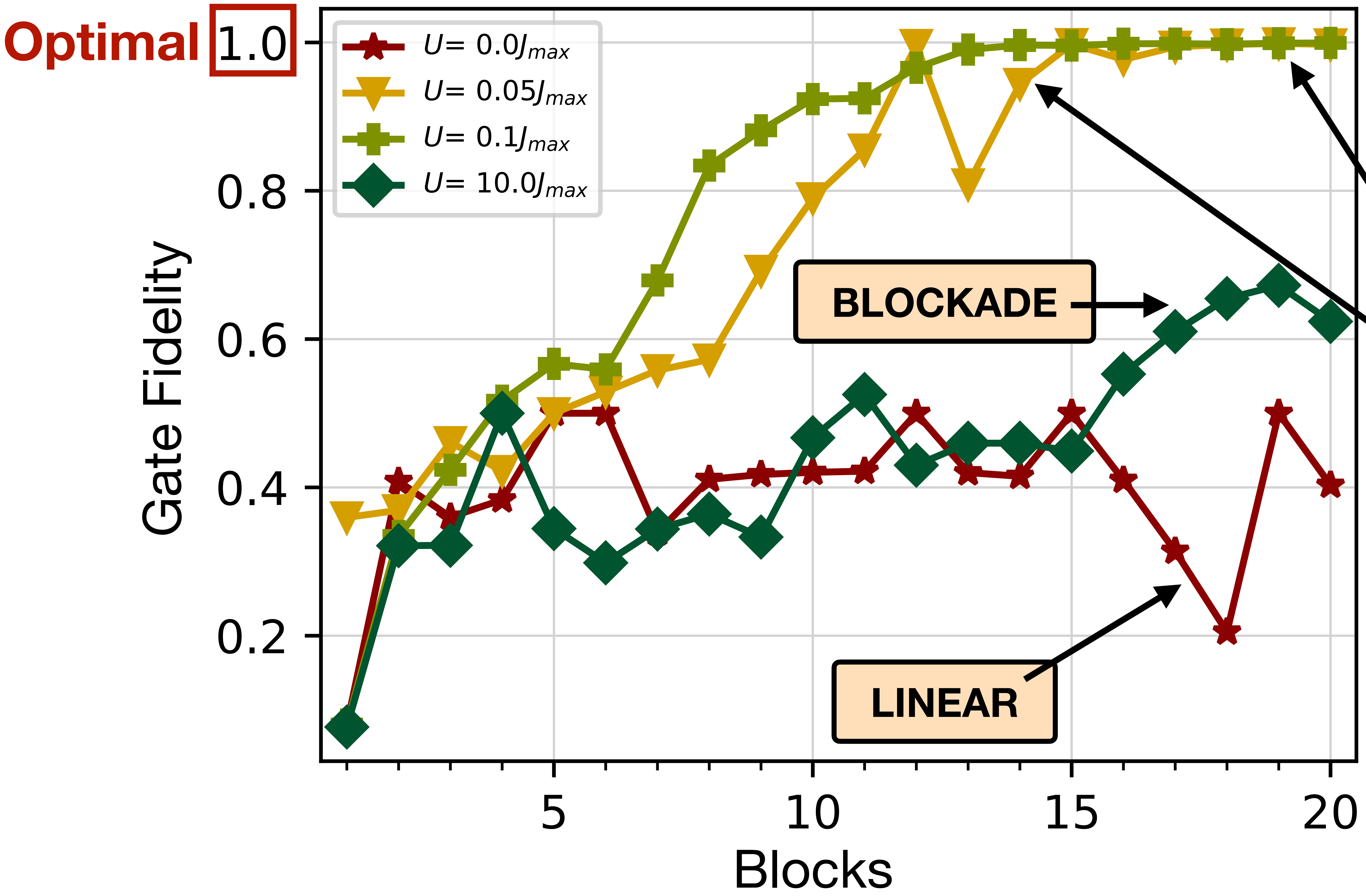
INTERMIDIATE NONLINEARITY

$U = 0.05\ J_{max}$

$U = 0.1\ J_{max}$

Optimized Cnot

The approach is more general !!
In the paper also Mølmer-Sørensen gate



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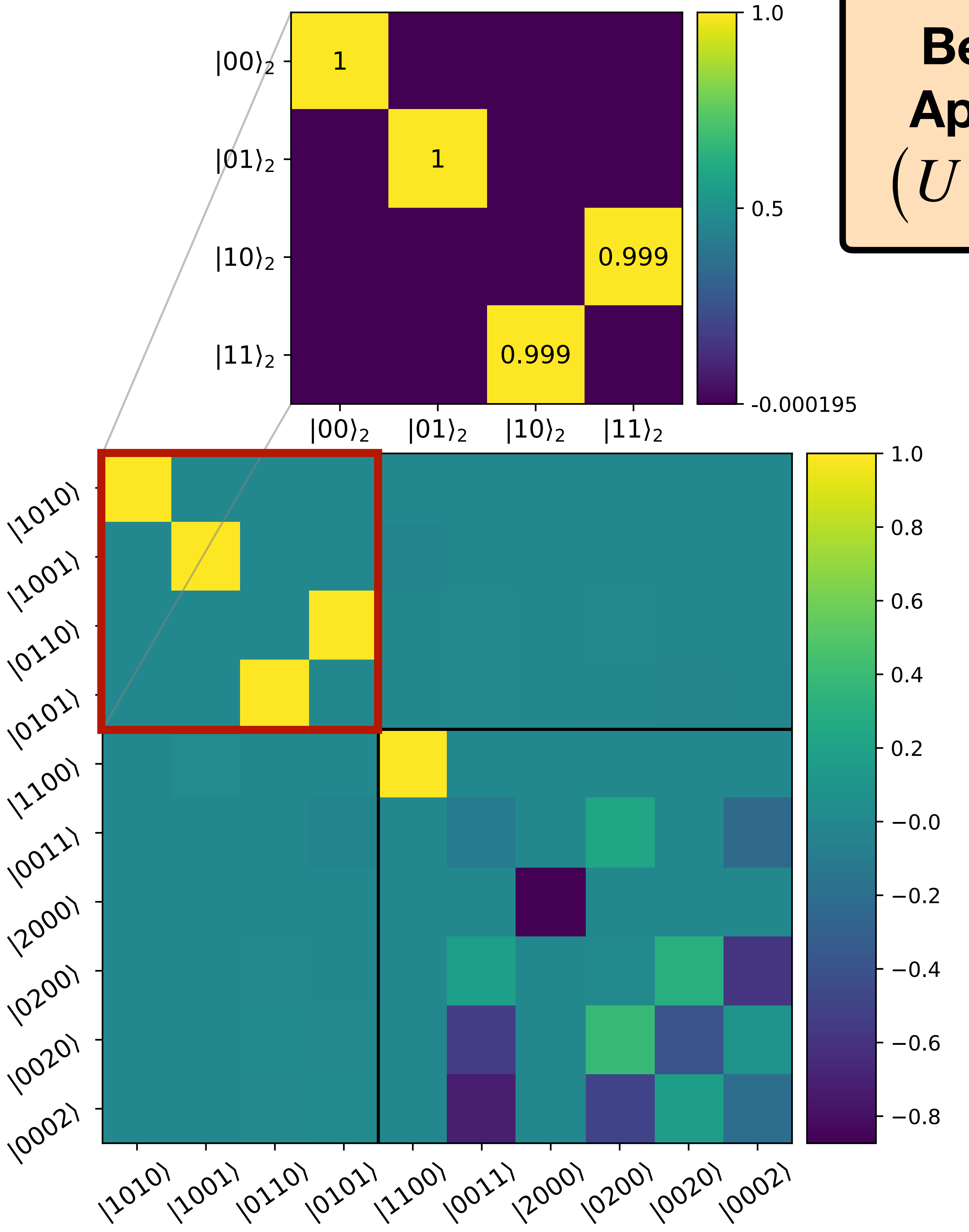
Approximate Matrix

Ideal operator

$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



Best Realistic Approximation $\left(U = 0.05\ J_{max}\right)$

$Fidelity = 99.87\,\%$
with 19 blocks

$\mathrm{Im}\left(CNOT_{approx}\right) < 10^{-4}$

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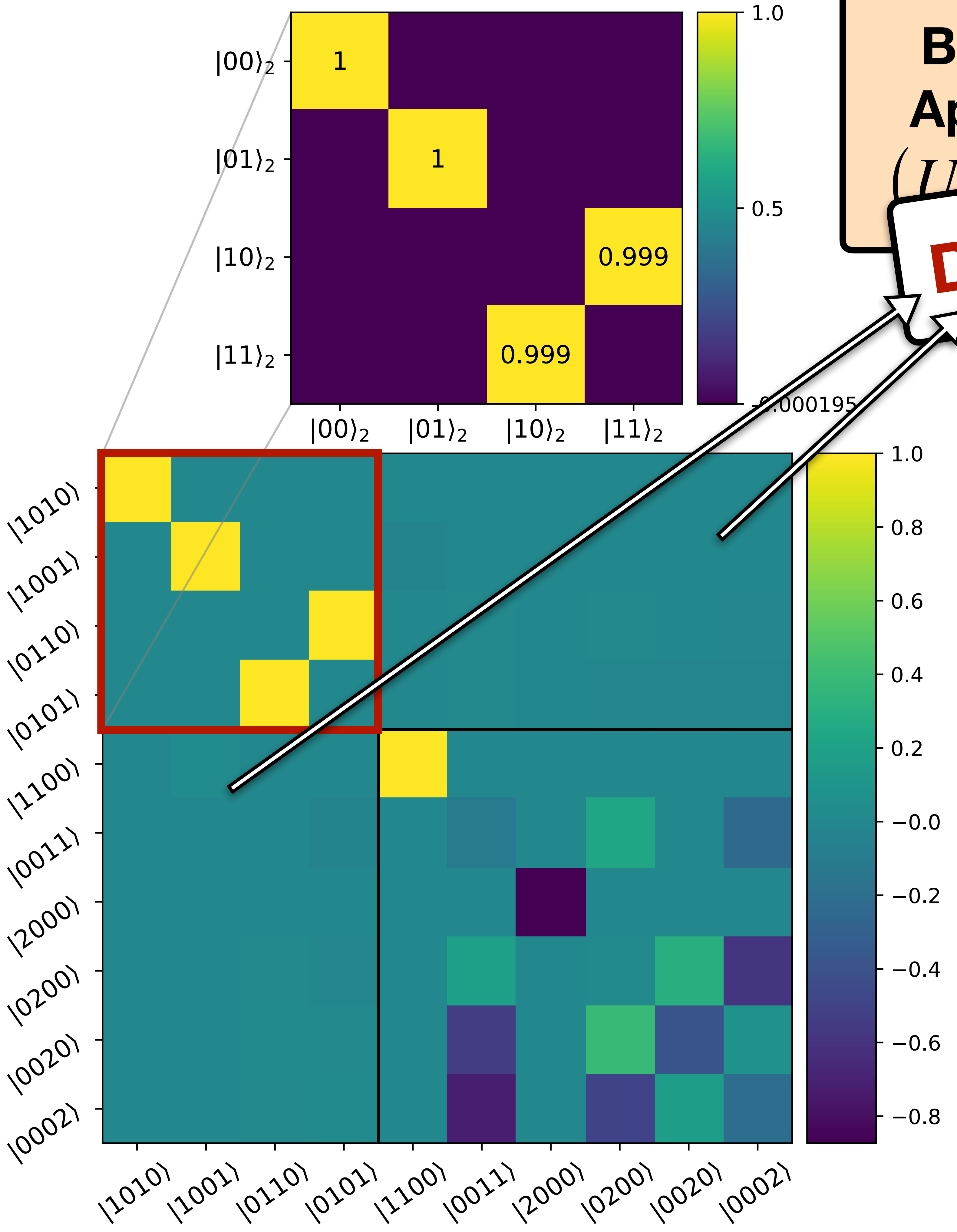


Best Realistic Approximation

Deterministic gate!!

$Fidelity = 99.87\,\%$
with 19 blocks

$$\mathrm{Im}\left(CNOT_{approx}\right) < 10^{-4}$$

Polariton Nonlinearity

ENERGIES
$\hbar\omega = 1.5\ eV$
$\hbar J_{max} = 0.66\ meV$

$U = 0.05\ J_{max}$

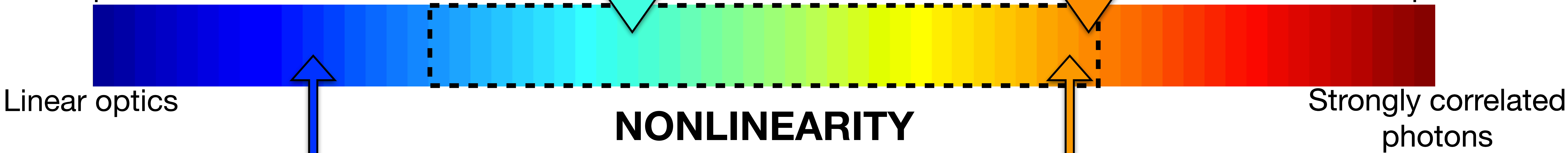
$U = 33\ \mu eV \rightarrow$ realistic

$U = 0.1\ J_{max}$

$U = 66\ \mu eV \rightarrow$ optimistic

Probabilistic quantum computation

Deterministic quantum computation



G. Muñoz-Matutano, et al.,
Nat. Mat. 18, 213–218 (2019)
$10\ \mu eV$

$10\ \mu eV \times 6.5 = 65\ \mu eV$

Dipolar Nonlinearity Enhancement by a factor of
6.5
Emre Togan, et al., **PRL 121, 227402 (2018)**

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Probabilistic quantum computation

Deterministic quantum computation

Linear optics

Strongly correlated photons

Deterministic quantum computation

G. Muñoz-Matutano, et al., **Nat. Mat. 18, 213–218 (2019)**

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Integrated Structures

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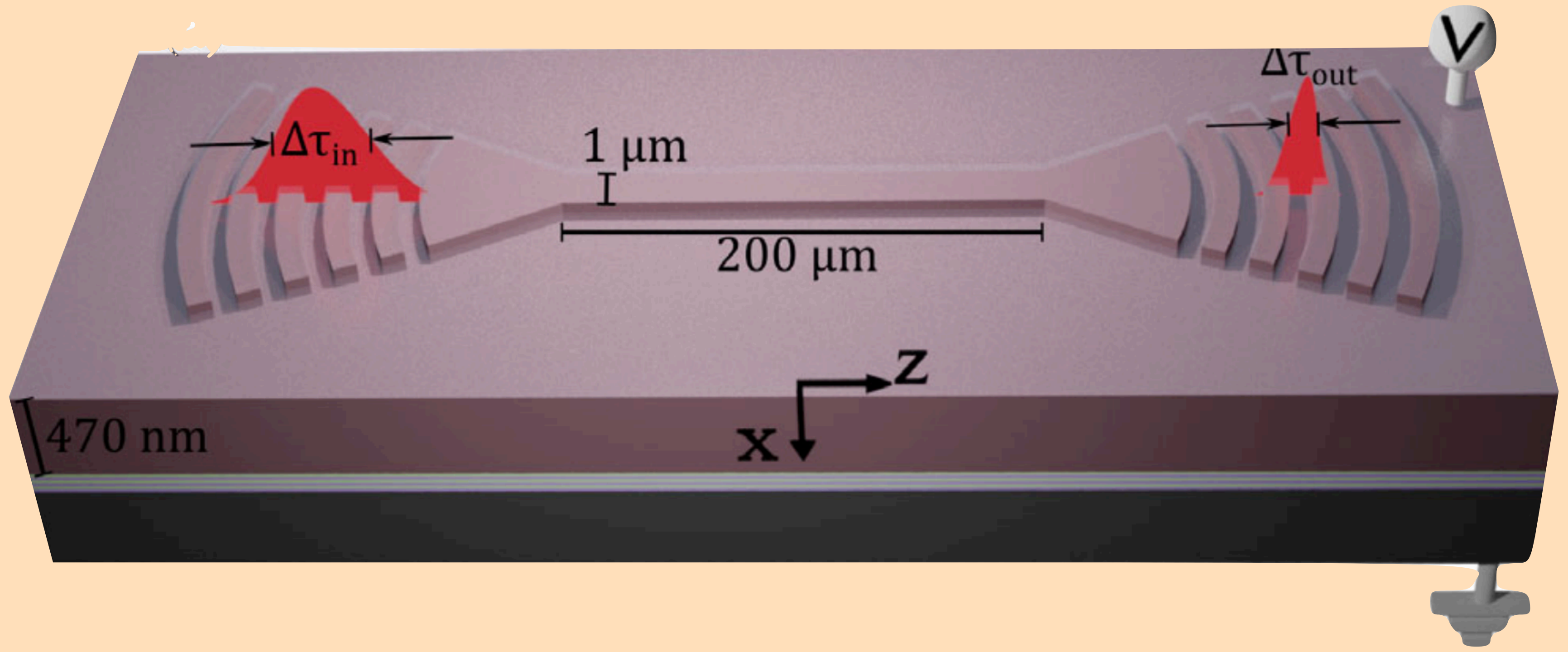
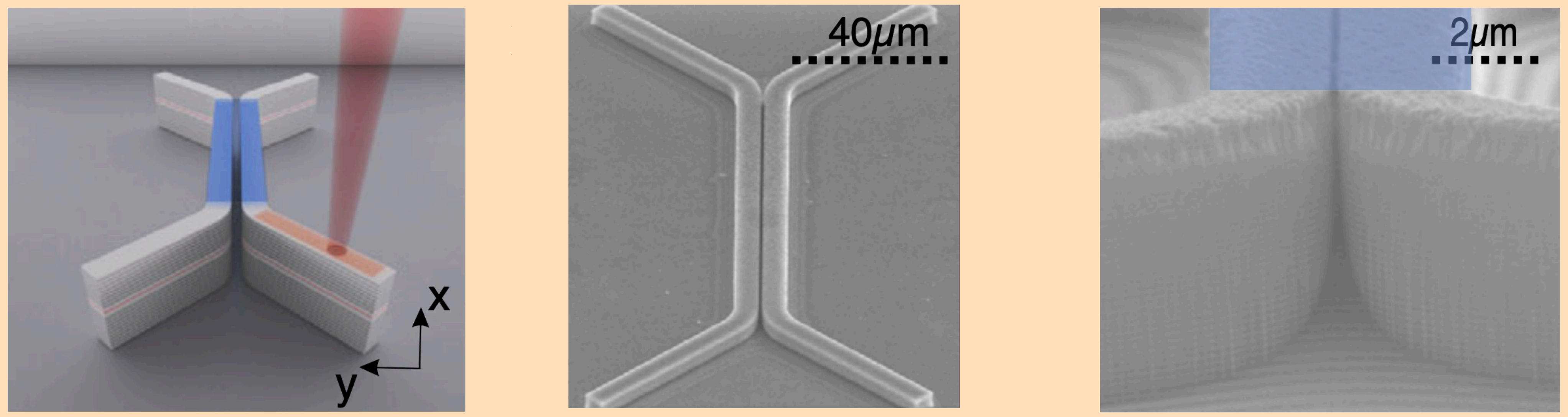
**ENHANCED NONLINEARITY
IN POLARITON WAVEGUIDES**



D.G. Suárez-Forero, et al., **PRL 126, 137401 (2021)**

**CODIRECTIONAL POLARITON
WAVEGUIDE COUPLERS**

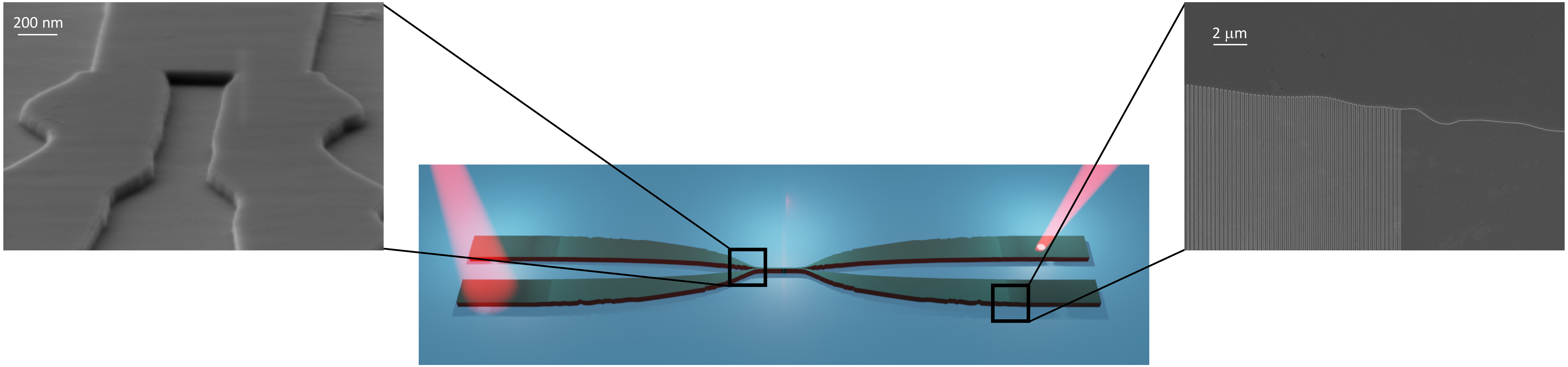


$$\hbar J \approx 0.55\ meV$$

J. Beierlein, et al., **PRL 126, 075302 (2021)**

Preliminary Samples

Towards the first building block of a single polariton quantum interferometer



(courtesy of E. Maggiolini & D. Sanvitto)

In collaboration with:

CNR NANOTEC
INSTITUTE OF NANOTECHNOLOGY

UNIVERSITÀ DI PAVIA

Aknowledgements And People

UNIVERSITÀ DI PAVIA

Davide Nigro

Dario Gerace

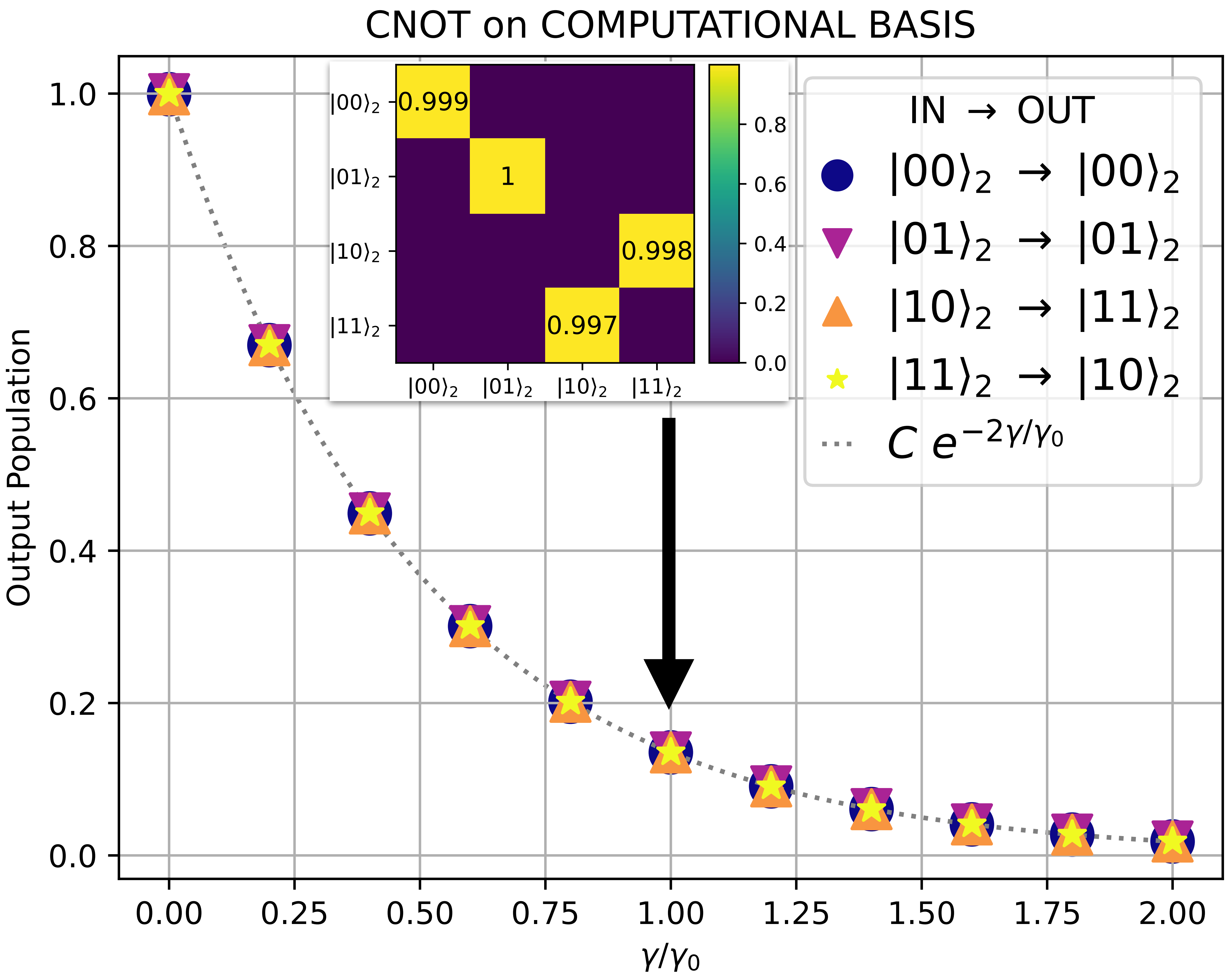
Ministero dell'Università e della Ricerca

NQSTI

For further details:

ArXiv:2306.05072 (2023)

Losses



Our most realistic structures achieving average **gate fidelity** $> 99\,\%\ (99.65\,\%)$ requires:

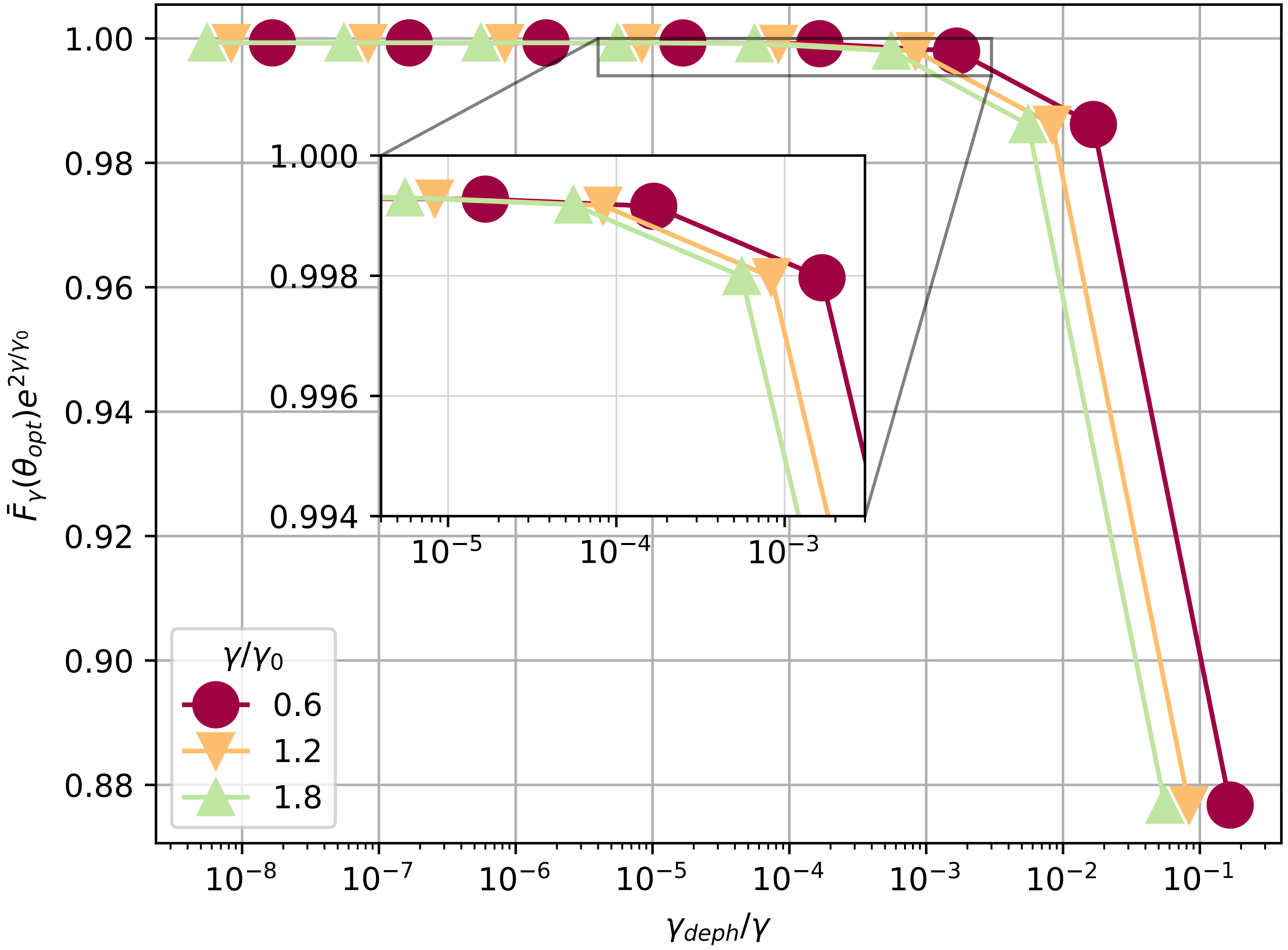
- **12 blocks** $(96\ ps)$
- **nonlinearity** of $33\mu eV$

It was measured a polariton lifetime $> 100\ ps$

$$\gamma_0 = 1/\tau_{tot}$$

$$\bar{F}_{\gamma\neq0}(\{\theta_{opt}\}) = \bar{F}_{\gamma=0}(\{\theta_{opt}\})e^{-2\gamma/\gamma_0}$$

Pure Dephasing



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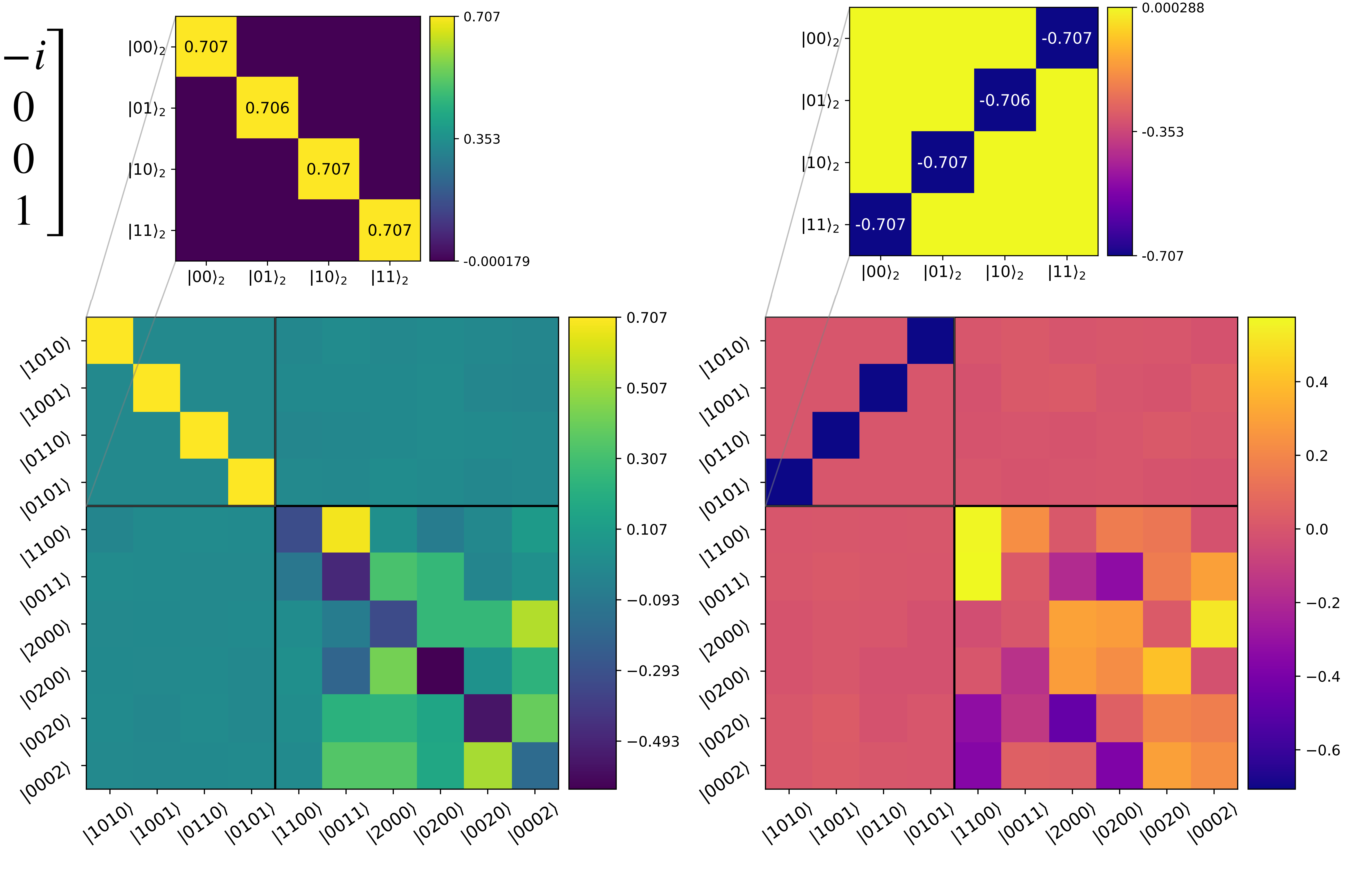
Mølmer-Sørensen Gate

$$RXX(\pi/2) = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 & 0 & -i \\ 0 & 1 & -i & 0 \\ 0 & -i & 1 & 0 \\ -i & 0 & 0 & 1 \end{bmatrix}$$



Mølmer-Sørensen Gate Fidelity