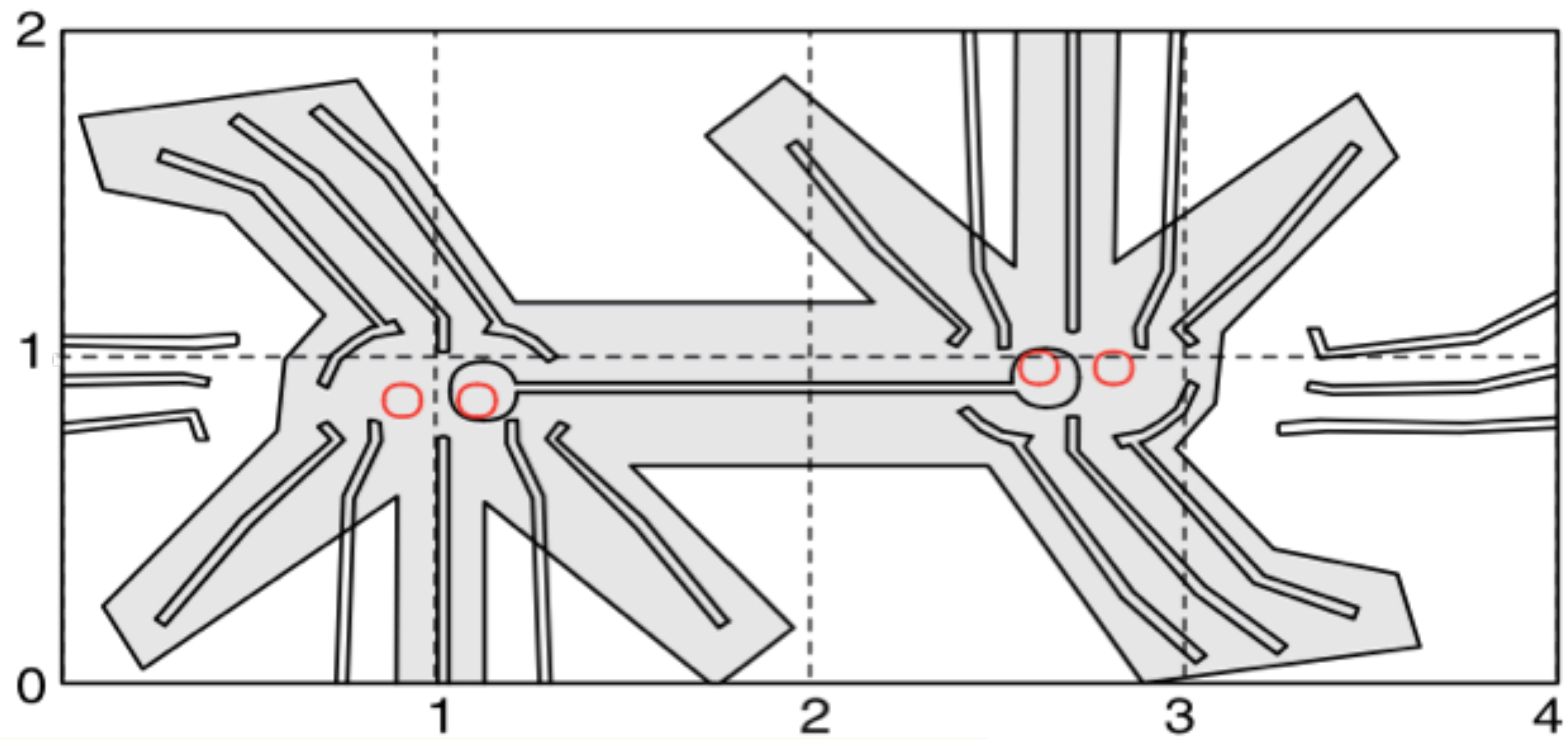
Coupling spin qubits via superconductors

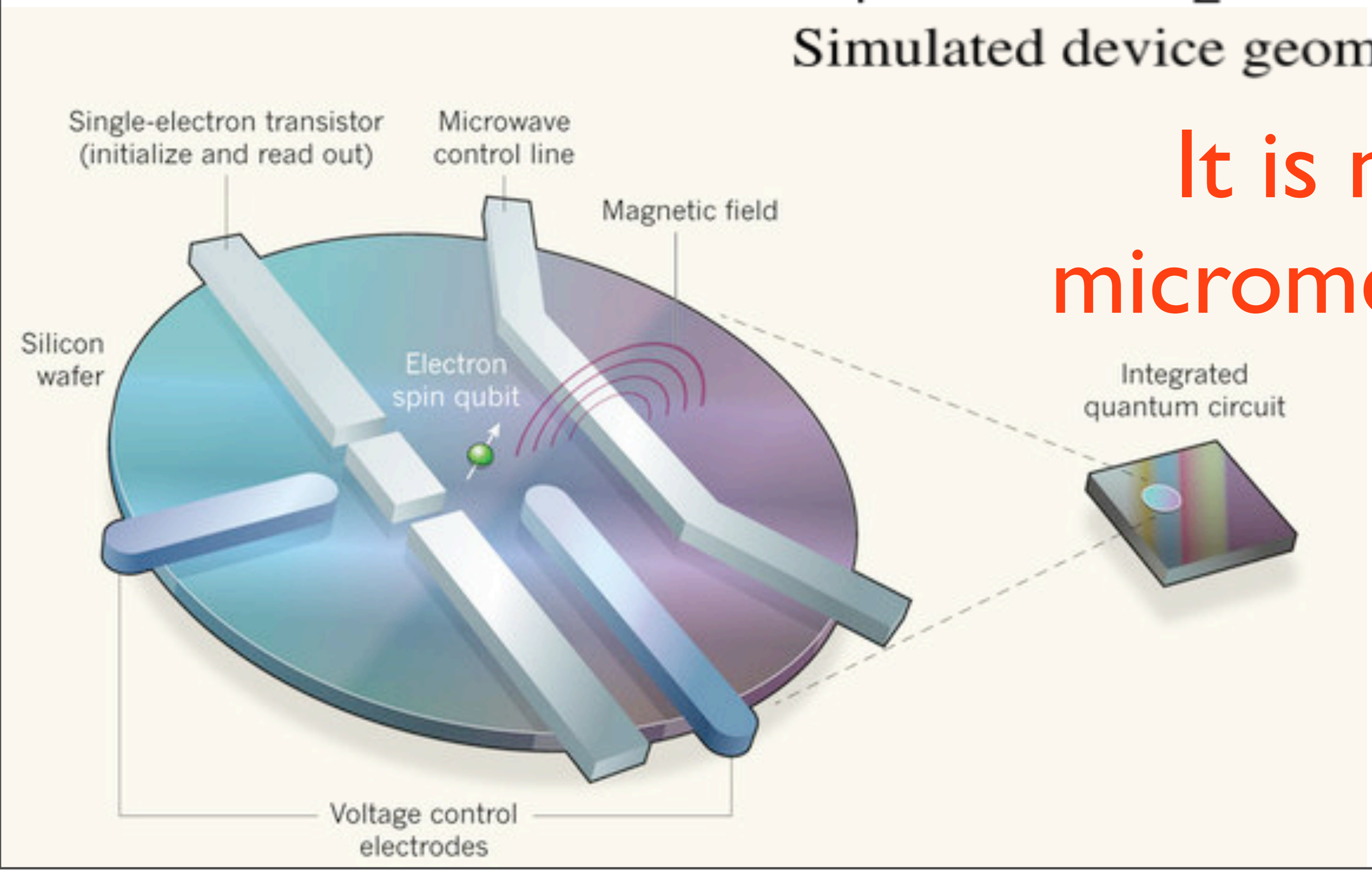
(arXiv:1303.3507)

Martin Leijnse

Karsten Flensberg

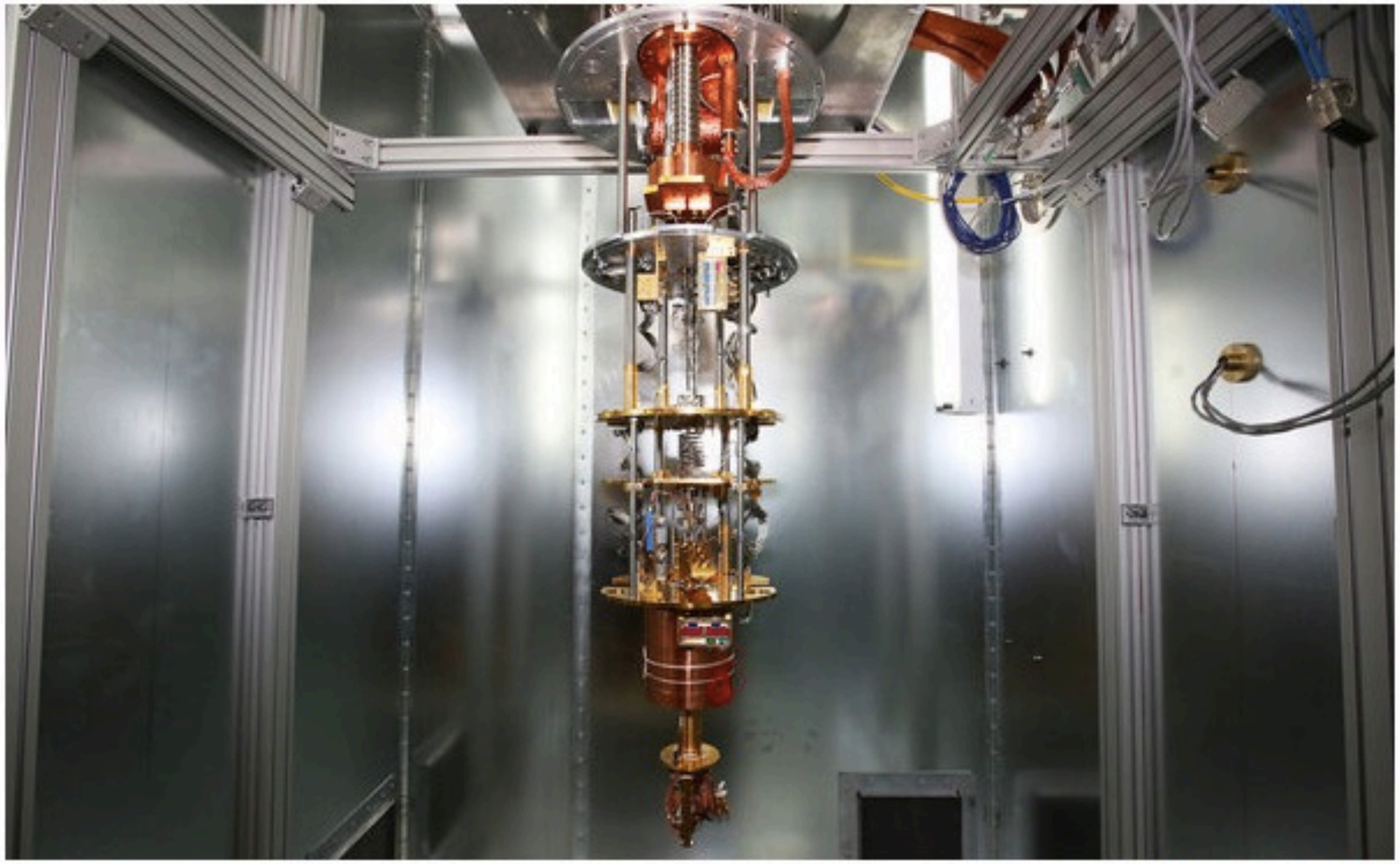
Motivation





It is necessary to have several micrometers between the qubits

A Strange Computer Promises Great Speed



Kim Stallknecht for The New York Times

Lockheed Martin bought a version of D-Wave's quantum computer and plans to upgrade it to commercial scale.

By QUENTIN HARDY
Published: March 21, 2013

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VANCOUVER, British Columbia — Our digital age is all about bits, those precise ones and zeros that are the stuff of modern computer code.

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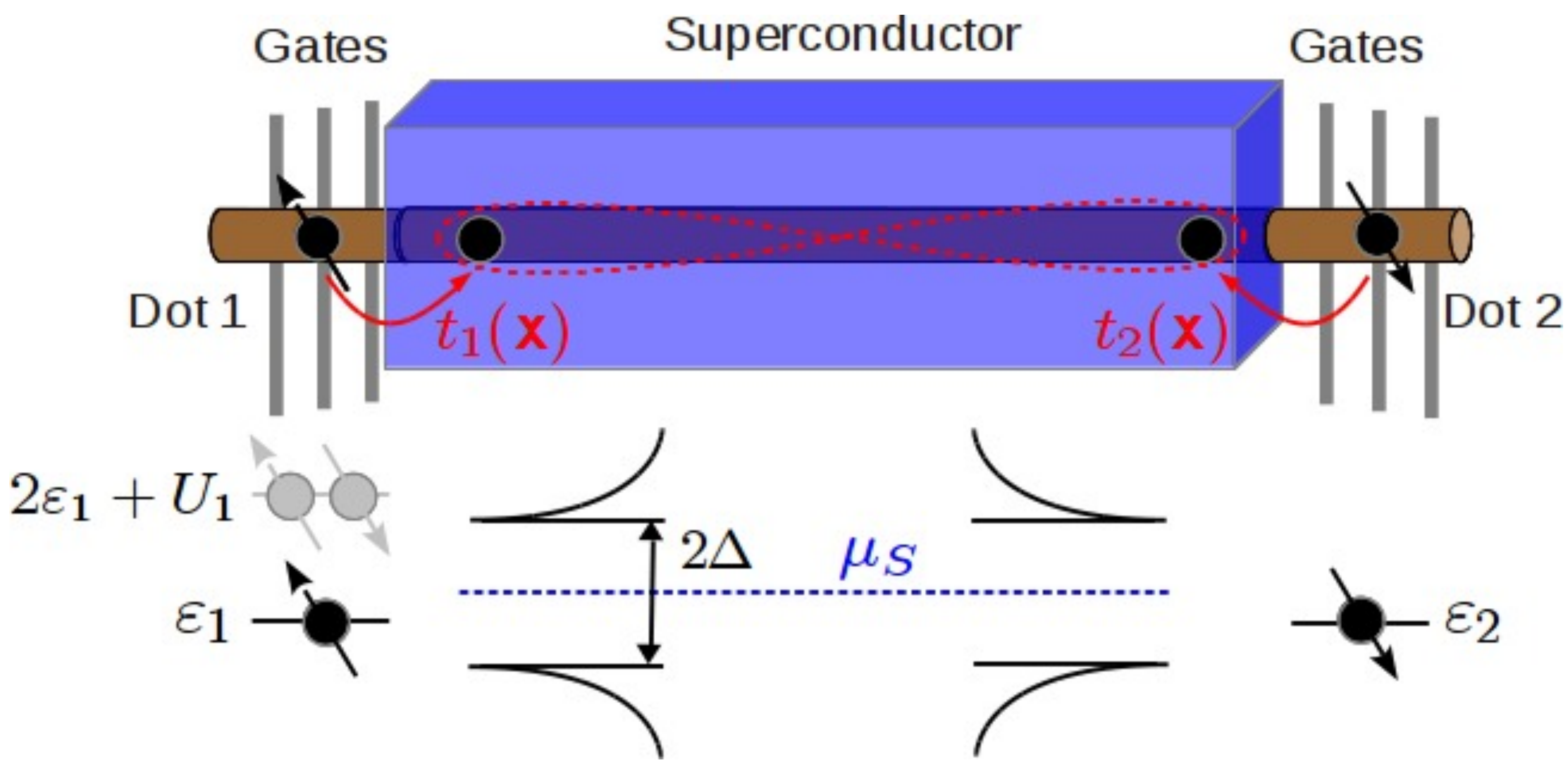
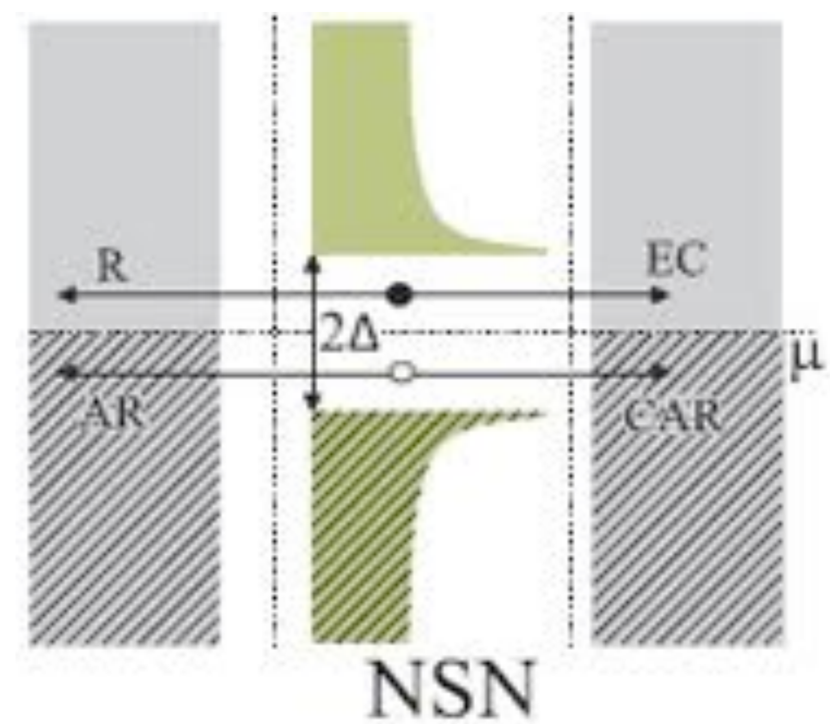
Bits

But a powerful new type of computer that is about to be commercially deployed by a major American military contractor is taking computing into the strange, subatomic

Setup





$$H_S = \sum_{\nu\sigma} E_{\nu\sigma} \gamma^\dagger_{\nu\sigma} \gamma_{\nu\sigma} \qquad E_{\nu\sigma} = \sqrt{\Delta^2 + (\varepsilon_{\nu\sigma} - \mu_S)^2}$$

$$H_{Ti} = \sum_{\nu\sigma} \int d\mathbf{x}\, t_{i\nu\sigma}(\mathbf{x}) c^\dagger_{\nu\sigma} d_{i\sigma} + h.c. \qquad H_T = \sum_i H_{Ti}$$

M. Choi, C. Bruder, and D. Loss, PRB 62, 13569 (2000)

P. Recher, E.V. Sukhorukov, and D. Loss, PRB 63, 165314 (2001)

Effective qubit interaction

$$\delta E_\alpha = \sum_n \frac{1}{E_\alpha - E_n} \left| \langle GS|\langle n|H_T \frac{1}{E_\alpha - H_0} H_T|\alpha\rangle|GS\rangle \right|^2$$

$$\alpha = S, T_0, T_\pm$$

$$\delta E_S^{\mathrm{CAR}} = |\gamma|^2/\varepsilon_\Sigma$$

$$\gamma = \sum_{\nu i} \frac{\Delta}{\sqrt{2}E_\nu} \frac{1}{E_\nu - \varepsilon_i} \int d\mathbf{x}_1 d\mathbf{x}_2 \; t_{1\nu\uparrow}(\mathbf{x}_1) t_{2\nu\downarrow}(\mathbf{x}_2)$$

$$\varepsilon_\Sigma = \varepsilon_1 + \varepsilon_2 - 2\mu_S$$

$$t_{i\nu\sigma} = t_i \delta(\mathbf{x}_i - \mathbf{x}_{i,0}) \psi_{\nu\sigma}(\mathbf{x}_{i,0})$$

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wf of the SC

$$t_{i\nu\sigma} = t_i \delta(\mathbf{x}_i - \mathbf{x}_{i,0}) \psi_{\nu\sigma}(\mathbf{x}_{i,0})$$

Dimensionality of the superconductor

3D superconductor

$$\gamma \propto (k_F \delta x)^{-1} \exp(-\delta x / \pi \xi_0)$$ [ballistic SC]

$$\gamma \propto (k_F \delta x)^{-1/2} (k_F l)^{-1/2} e^{-\delta x / \sqrt{\xi_0 l}}$$ [diffusive SC]

M. Choi, C. Bruder, and D. Loss, PRB 62, 13569 (2000)

1D superconductor [single-channel ballistic]

$$\gamma = \sqrt{2} t_1 t_2 \rho \sum_i \frac{\Delta}{\sqrt{\Delta^2 - \varepsilon_i^2}} \left[\pi + 2 \tan^{-1} \left(\frac{\varepsilon_i}{\sqrt{\Delta^2 - \varepsilon_i^2}} \right) \right] \sin(k_F \delta x) \, e^{-\delta x / \pi \xi_0}$$

L. Hofstetter, S. Csonka, A. Baumgartner, G. Fulop, S. d'Hollosy, J. Nygard, and C. Schönenberger PRL. **107**, 136801 (2011)

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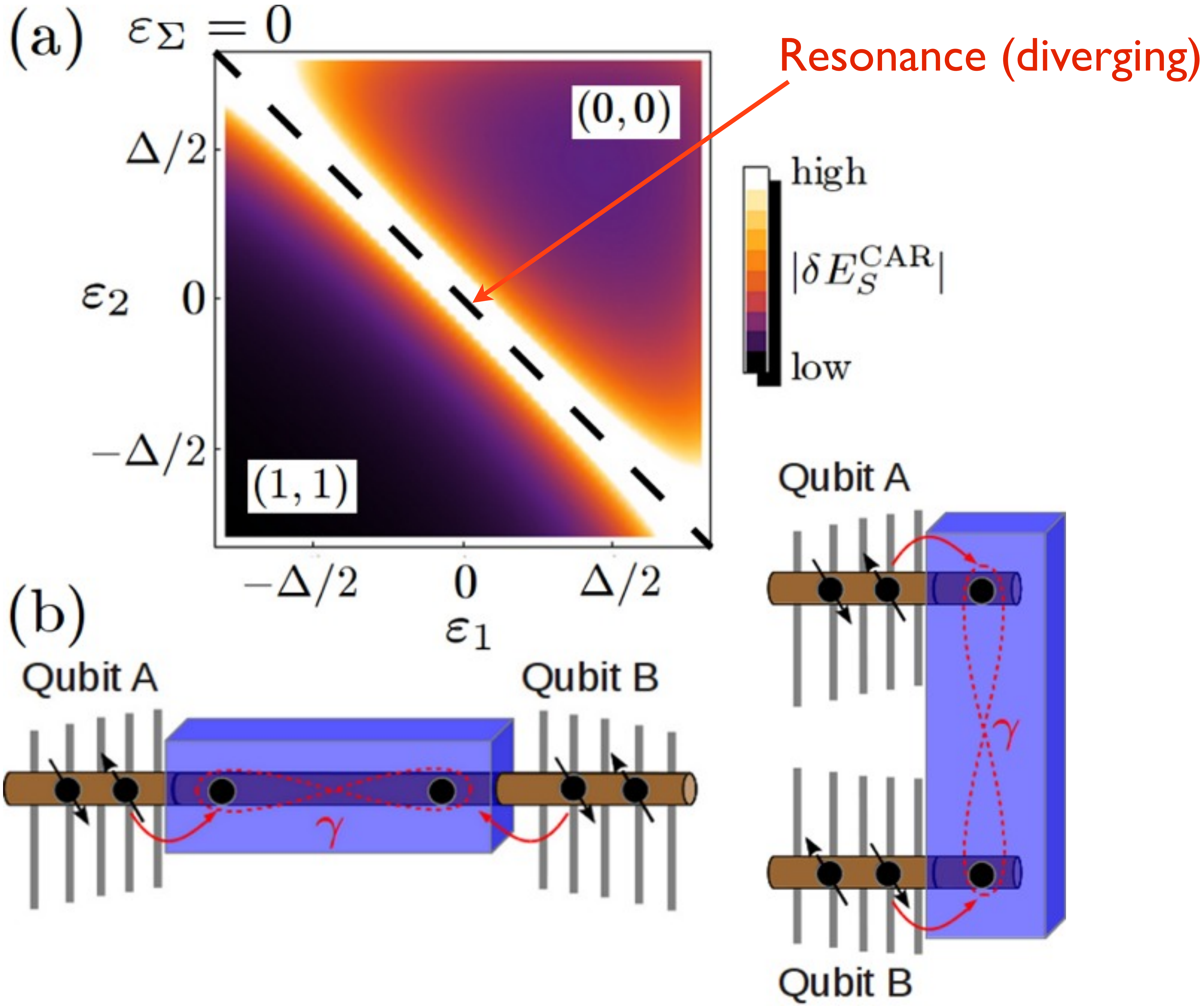
Resuts


(a) $\varepsilon_\Sigma = 0$
Resonance (diverging)!
(0, 0)
(1, 1)
$\Delta/2$
ε_2
0
$-\Delta/2$
$-\Delta/2$
0
$\Delta/2$
ε_1
high
$|\delta E_S^{\mathrm{CAR}}|$
low
(b)
Qubit A
Qubit B
γ
Qubit A
γ
Qubit B

CPB and two-qubit couplings

$$H_{ST} = \varepsilon_\Sigma |S\rangle\langle S| + \varepsilon_\Sigma |T_0\rangle\langle T_0| + \gamma |S\rangle\langle 00| + h.c.$$

$$|S/T_0\rangle|N_0\rangle \qquad |00\rangle|N_0+1\rangle$$

$$H_{Di} = \sum_\sigma n_{i\sigma}\varepsilon_{i\sigma} + U_i n_{i\uparrow} n_{i\downarrow}$$

Charging energy

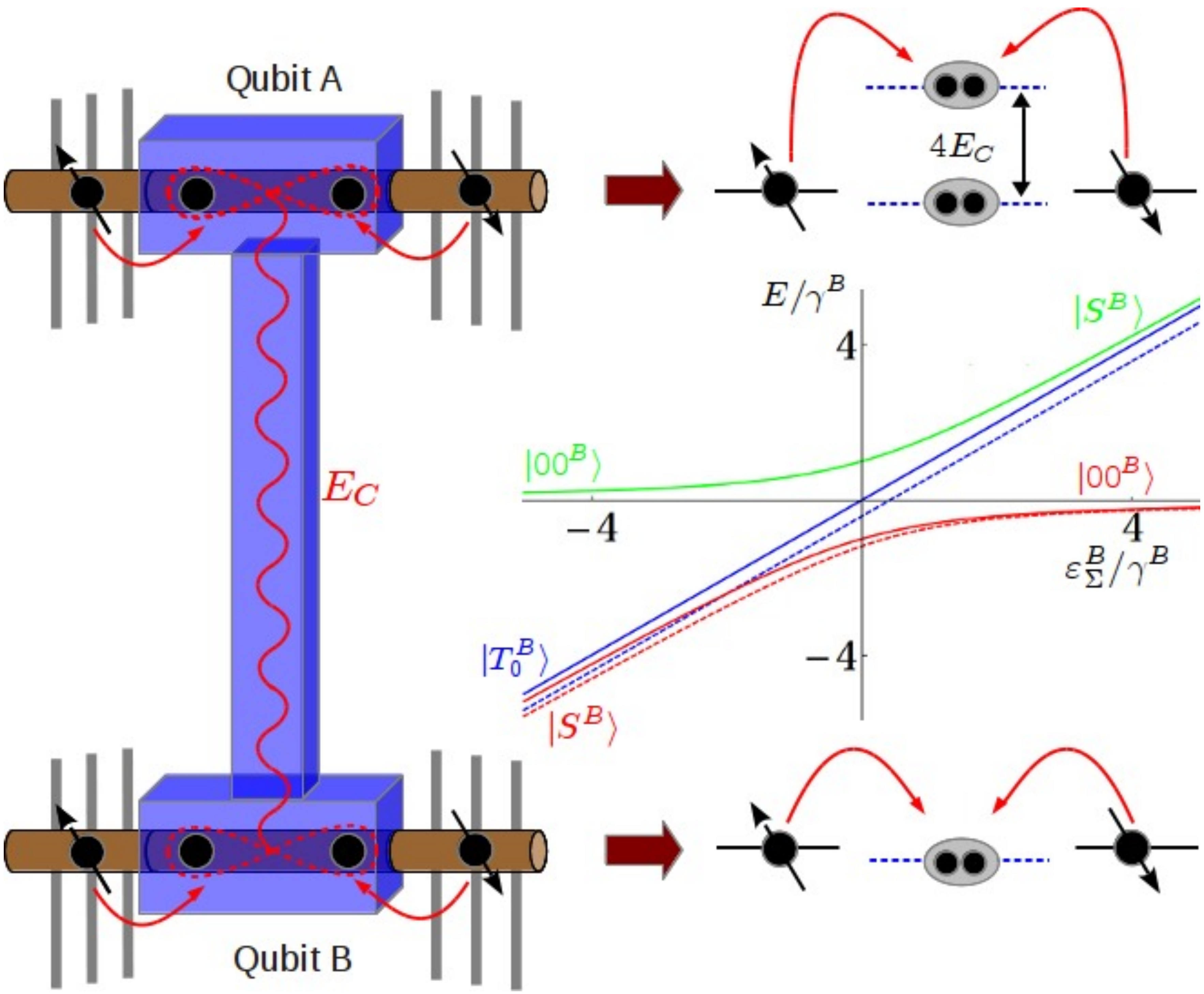
$$V^{AB} = 4E_C |00^A\rangle|00^B\rangle\langle 00^A|\langle 00^B|$$

$$|\tilde{S}\rangle \approx (1/\sqrt{1+\delta^2})|S\rangle + \delta|00\rangle \qquad |T_0\rangle$$

$$V^{AB} \approx 4E_C(\delta^A)^2(\delta^B)^2 |\tilde{S}^A\rangle|\tilde{S}^B\rangle\langle\tilde{S}^A|\langle\tilde{S}^B|$$

$$\sim 4E_C(\delta^A)^2(\delta^B)^2 \sigma_z^A \otimes \sigma_z^B$$

CPB and two-qubit couplings



Conclusions

Superconductor can be used to couple spatially separated spin qubits, or to define a non-local double-dot ST qubit.

Conclusions

Superconductor can be used to couple spatially separated spin qubits, or to define a non-local double-dot ST qubit.

Coupling two different ST qubits to the same CPB introduces a coupling between the spin qubits and the charge on the CPB, which can be used for truly long-distance (many μm) two-spin-qubit gates with potential for fast operation (hundreds of MHz).

Finally, the charge-spin coupling presented herein has the potential to allow coupling of even more distant ST qubits through circuit quantum electrodynamics (superconducting transmission line)

THE END