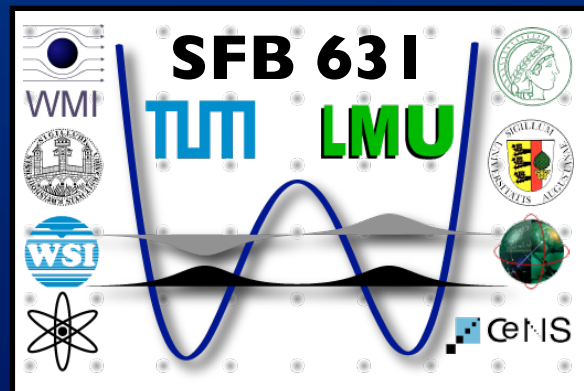


Quantum optics and quantum information processing in circuit quantum electrodynamics

Florian Marquardt

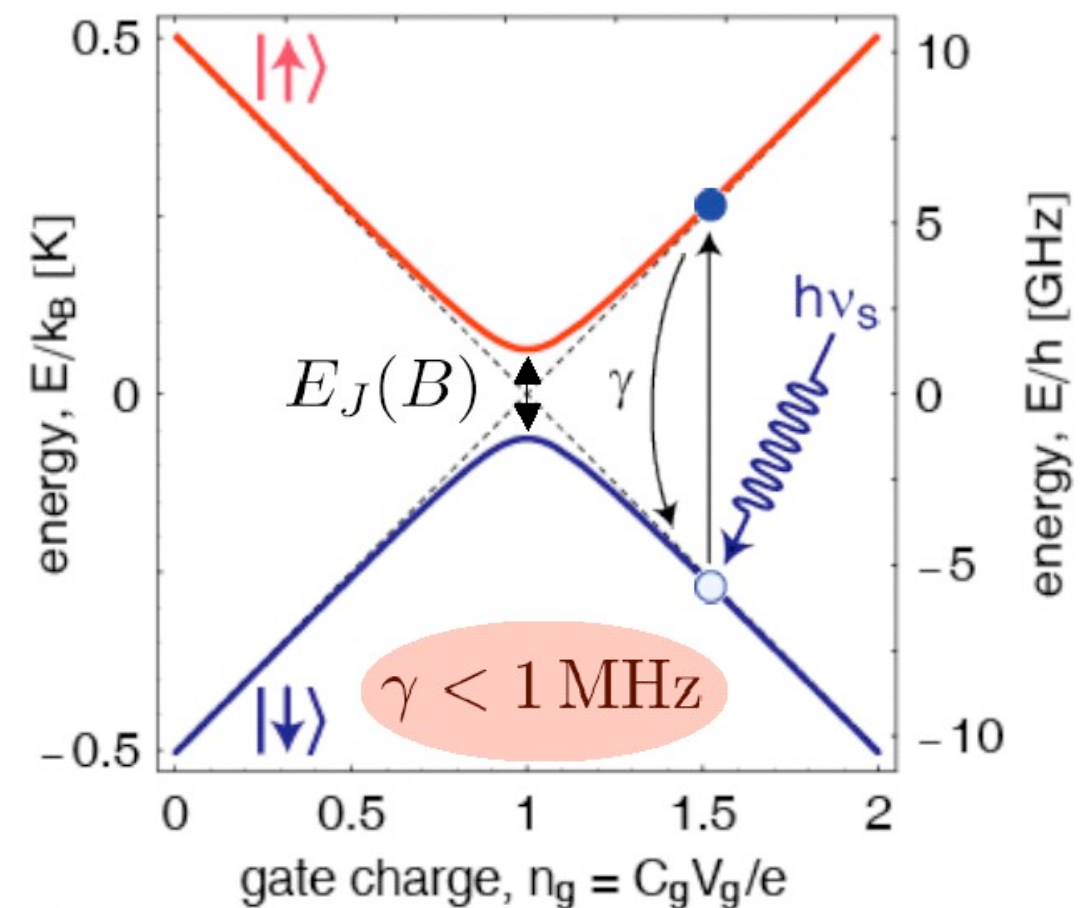
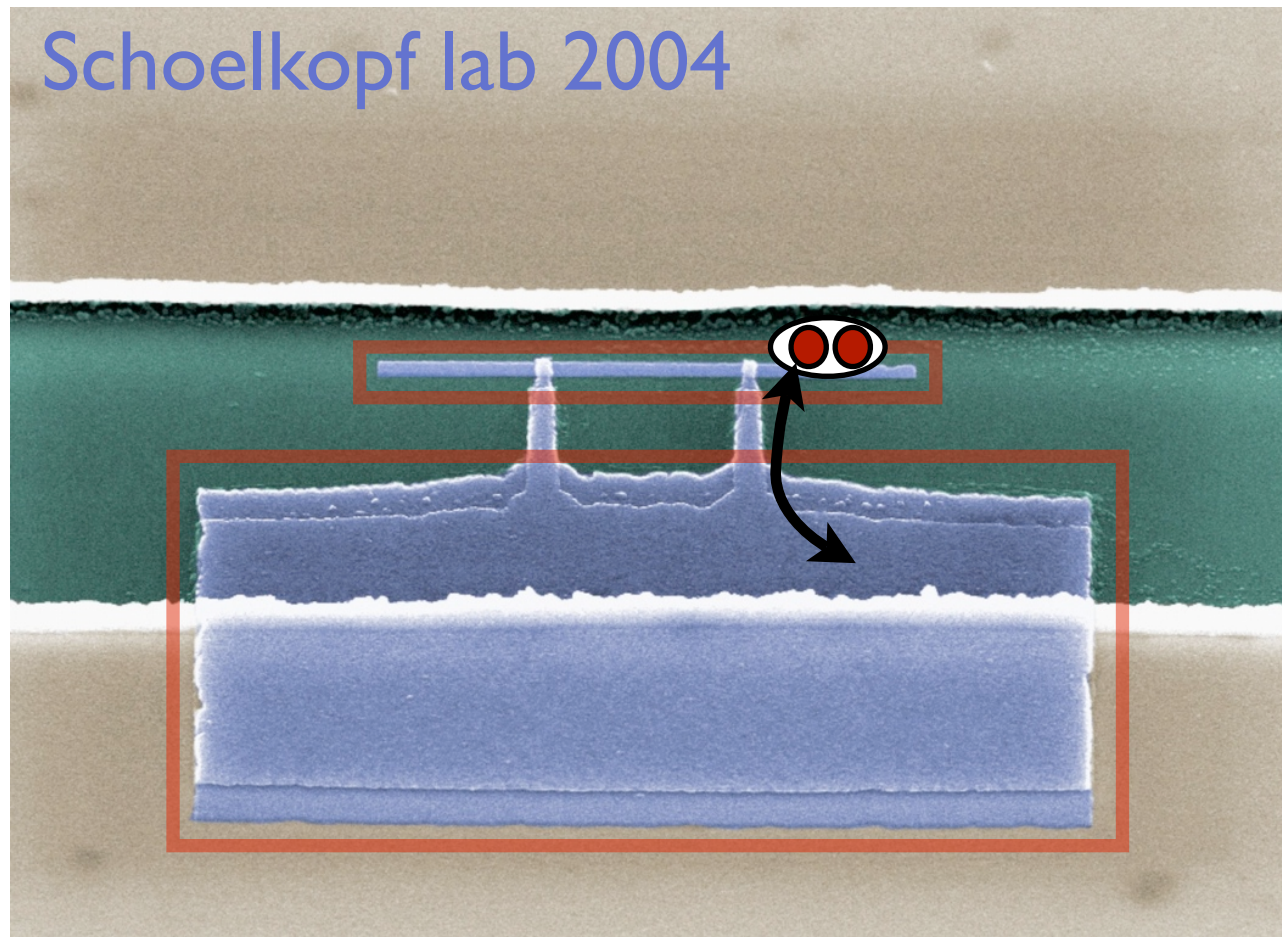
**Ludwig-Maximilians University Munich (Center for NanoScience
and Arnold Sommerfeld Center for Theoretical Physics)**



Circuit QED

Qubit/Artificial atom: Cooper pair box

Nakamura et al. 1998



fully tunable two-level system:

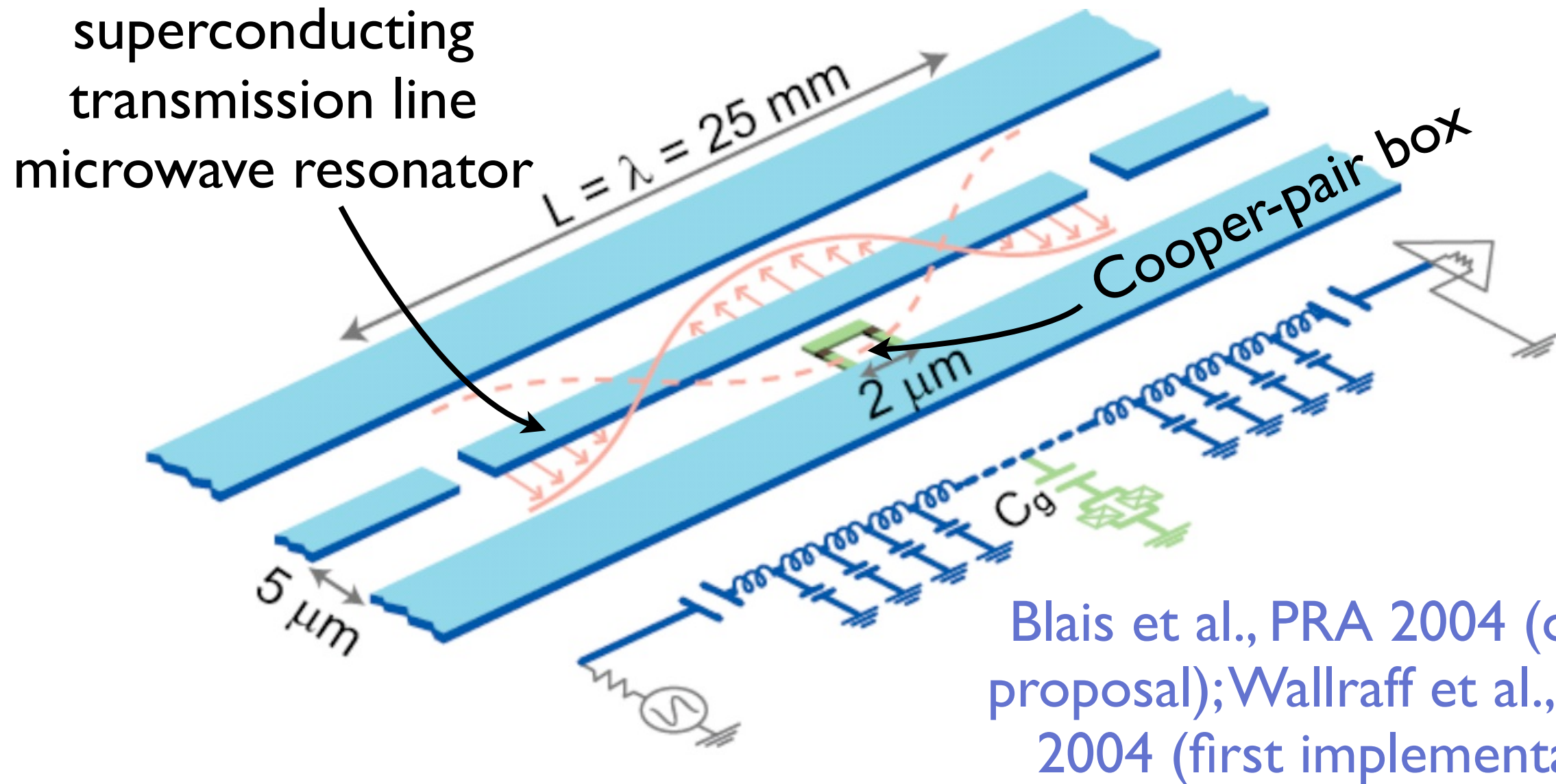
$$\hat{H}_{\text{qb}} = \frac{E_J(B)}{2} \hat{\sigma}_z + \frac{\delta E_C(V_g)}{2} \hat{\sigma}_x$$

Josephson
tunnel coupling

charging energy

Circuit QED - reminder

Coupling to a microwave resonator mode

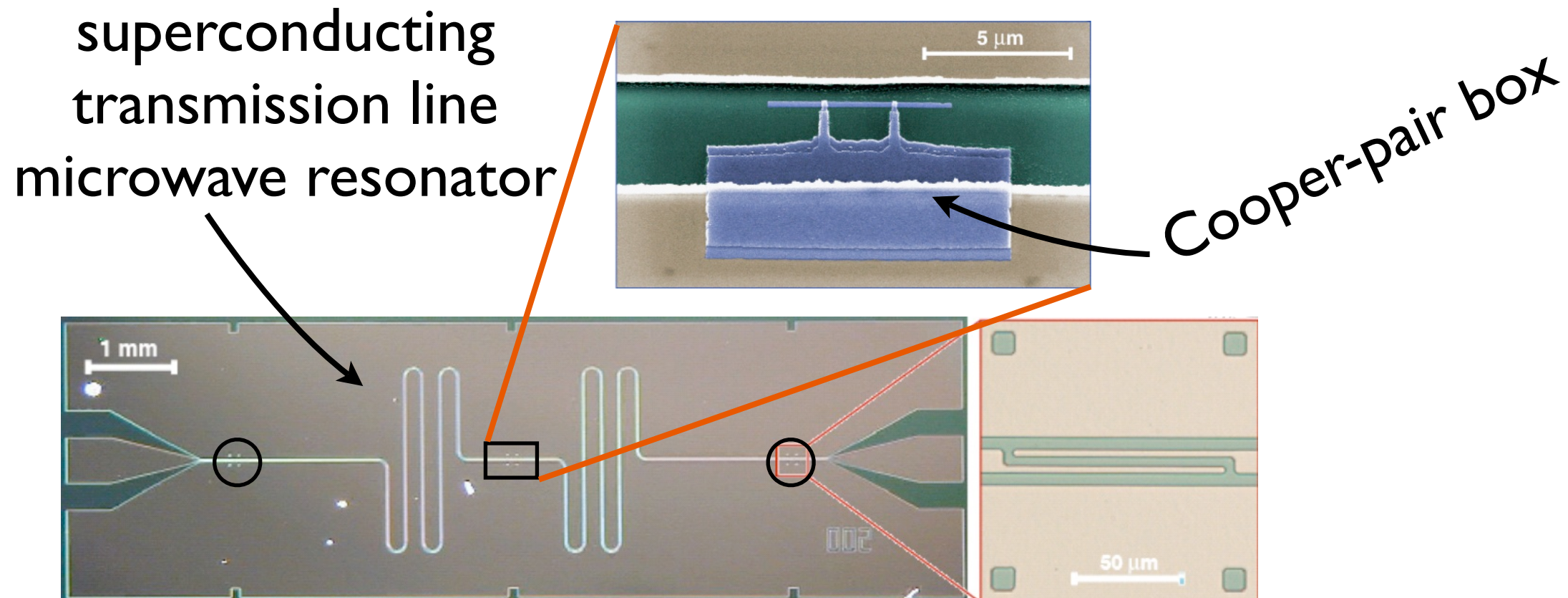


$$\hat{H} = \underbrace{\frac{\epsilon}{2} \hat{\sigma}_z}_{\text{qubit}} + \underbrace{\hbar \omega \hat{a}^\dagger \hat{a}}_{\substack{\text{resonator} \\ \text{mode}}} + \underbrace{g \hat{\sigma}_x (\hat{a}^\dagger + \hat{a})}_{\text{coupling}}$$

1-10 GHz 10-100 MHz

Circuit QED

Coupling to a microwave resonator mode

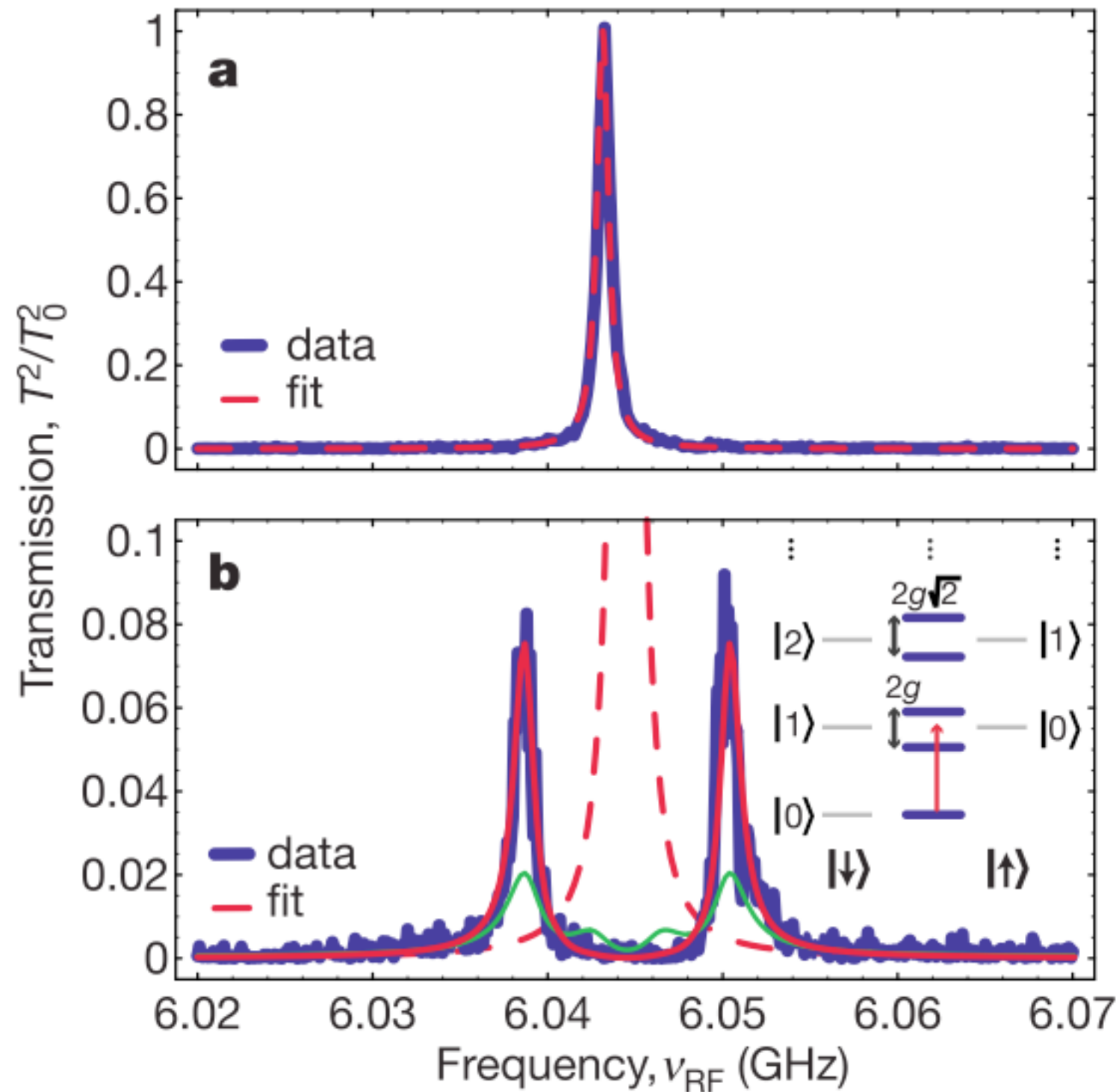


Blais et al., PRA 2004 (original proposal); Wallraff et al., Nature 2004 (first implementation)

$$\hat{H} = \underbrace{\frac{\epsilon}{2} \hat{\sigma}_z}_{\text{qubit}} + \underbrace{\hbar \omega \hat{a}^\dagger \hat{a}}_{\substack{\text{resonator} \\ \text{mode}}} + \underbrace{g \hat{\sigma}_x (\hat{a}^\dagger + \hat{a})}_{\text{coupling}}$$

1-10 GHz 10-100 MHz

Vacuum Rabi splitting



Circuit QED - experimental achievements

- strong coupling: spectroscopy, Rabi oscillations
- dispersive qubit readout
- Ramsey experiments: T_1 , T_2
- Single photon generation
- Photon number splitting
- Two-qubit gates via cavity

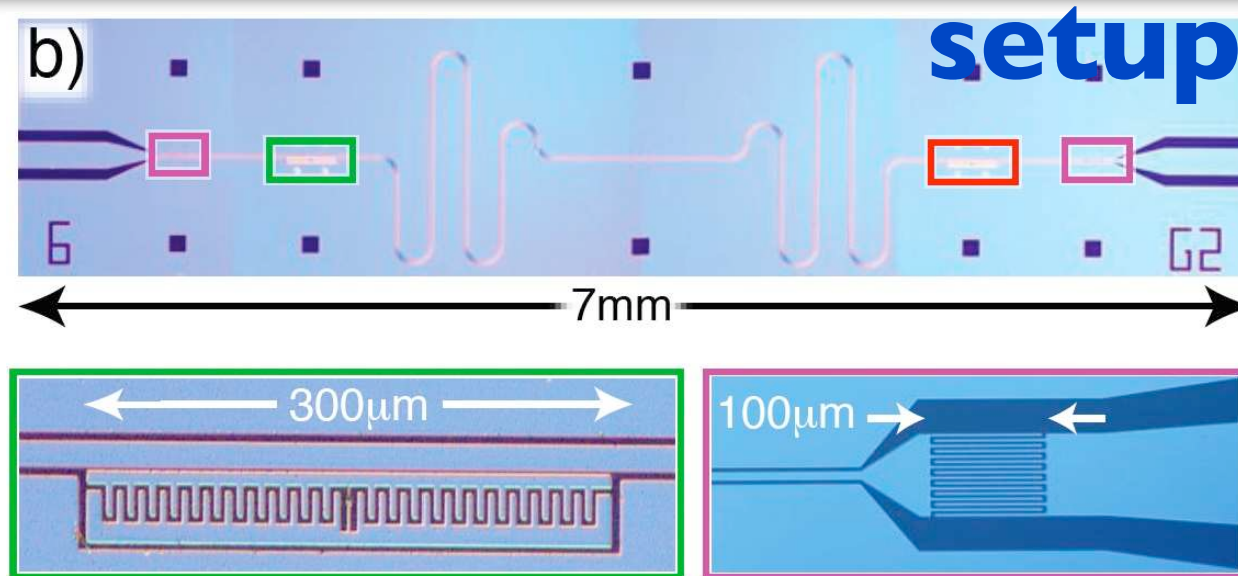
Yale: Schoelkopf lab since 2004
(Wallraff, Schuster, Houck,
Majer, ...), Devoret lab

Delft: Mooij lab 2004
(Chiorescu, ...)

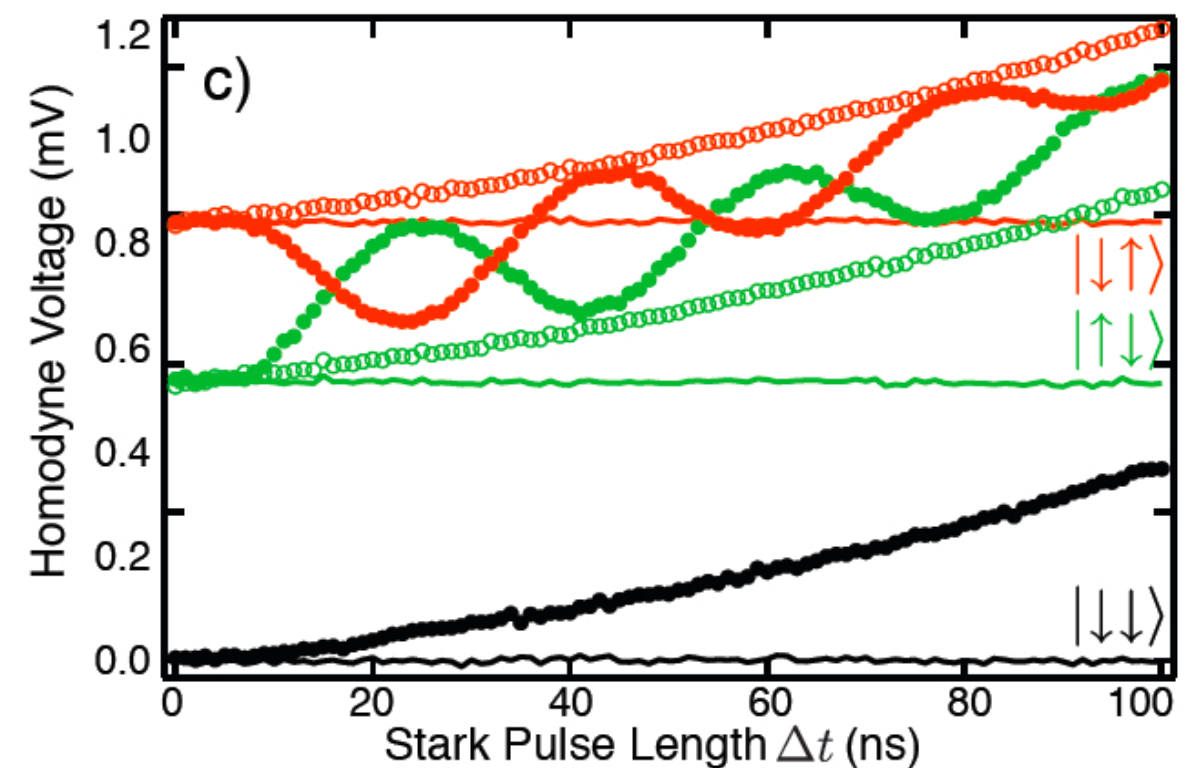
NIST: Simmonds lab since 2007
(Sillanpää, ...)

NTT: Johansson, Saito, Semba,
Takayanagi et al. 2006

Dispersive 2-qubit gate: Yale setup



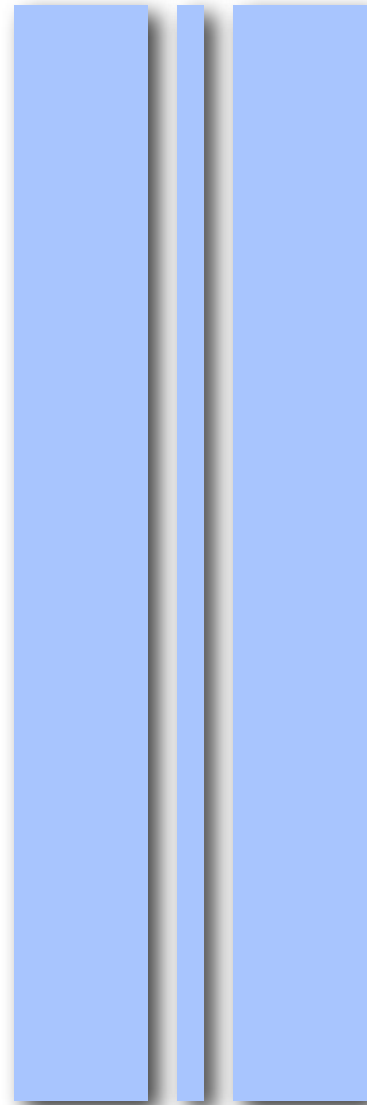
Two-qubit gate



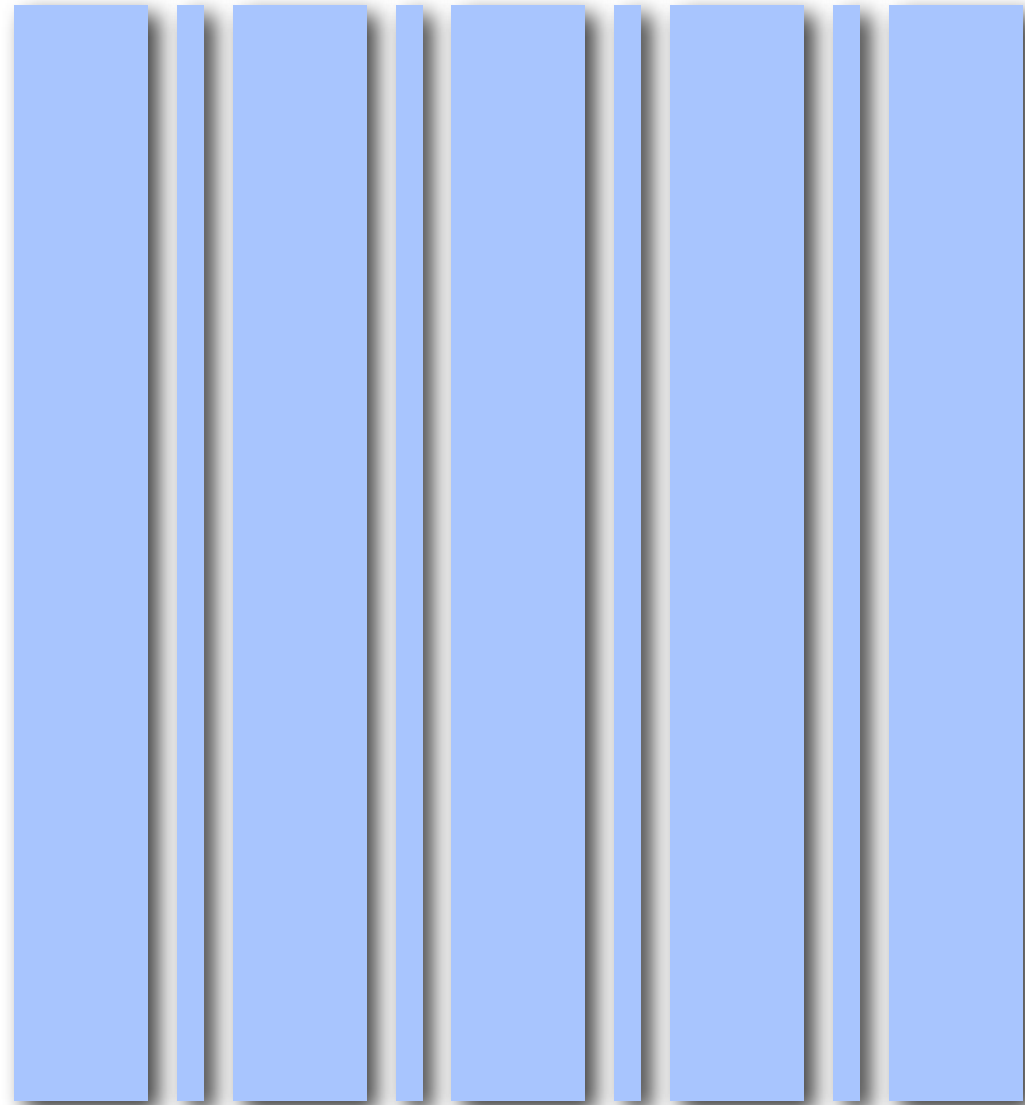
Majer et al., Nature 449, 443 (2007)
(Yale, Schoelkopf lab)

[see also NIST group:
resonant 2-qubit gate
via cavity Sillanpää, Park,
Simmonds Nature 2007]

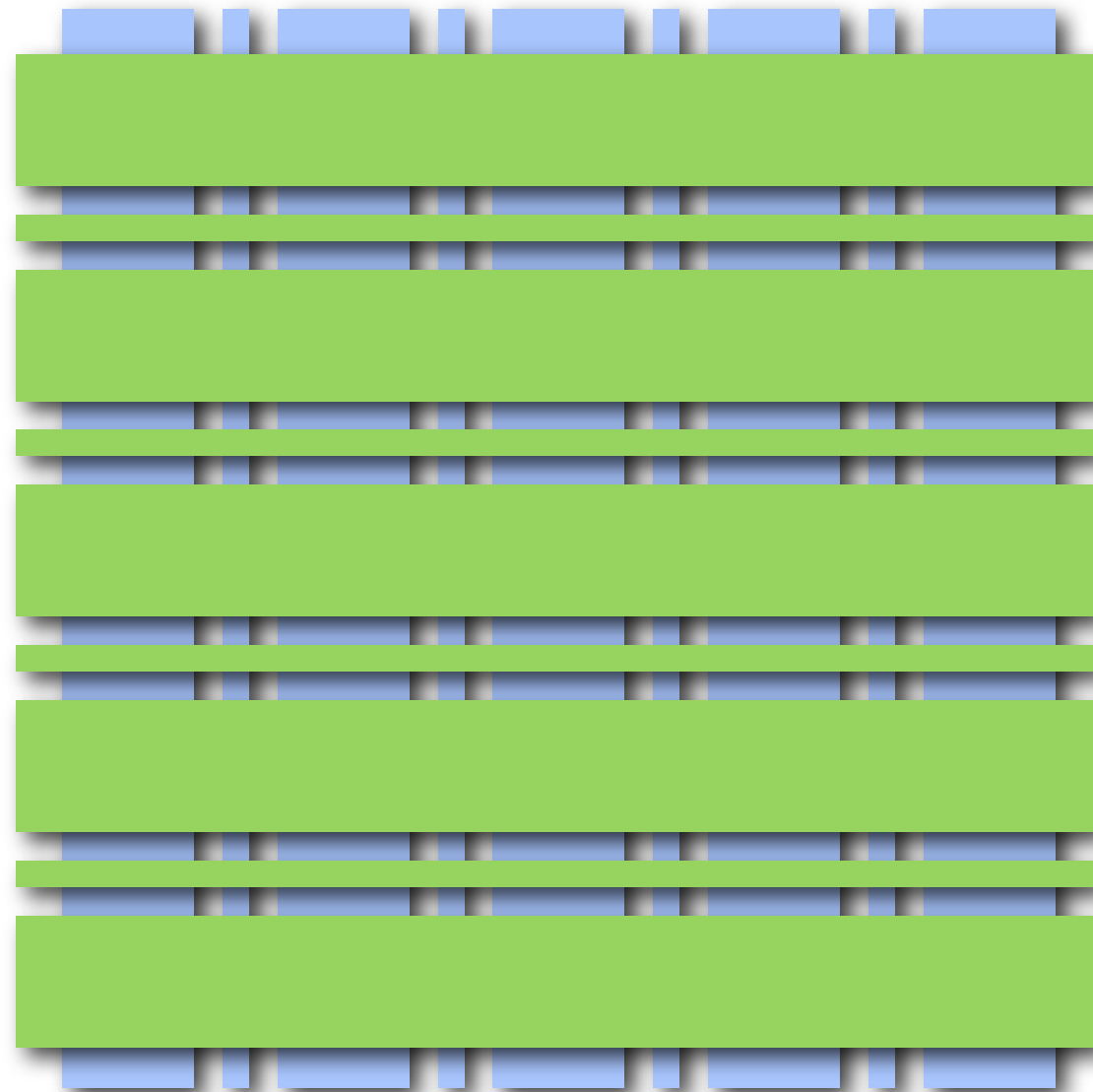
The cavity grid design



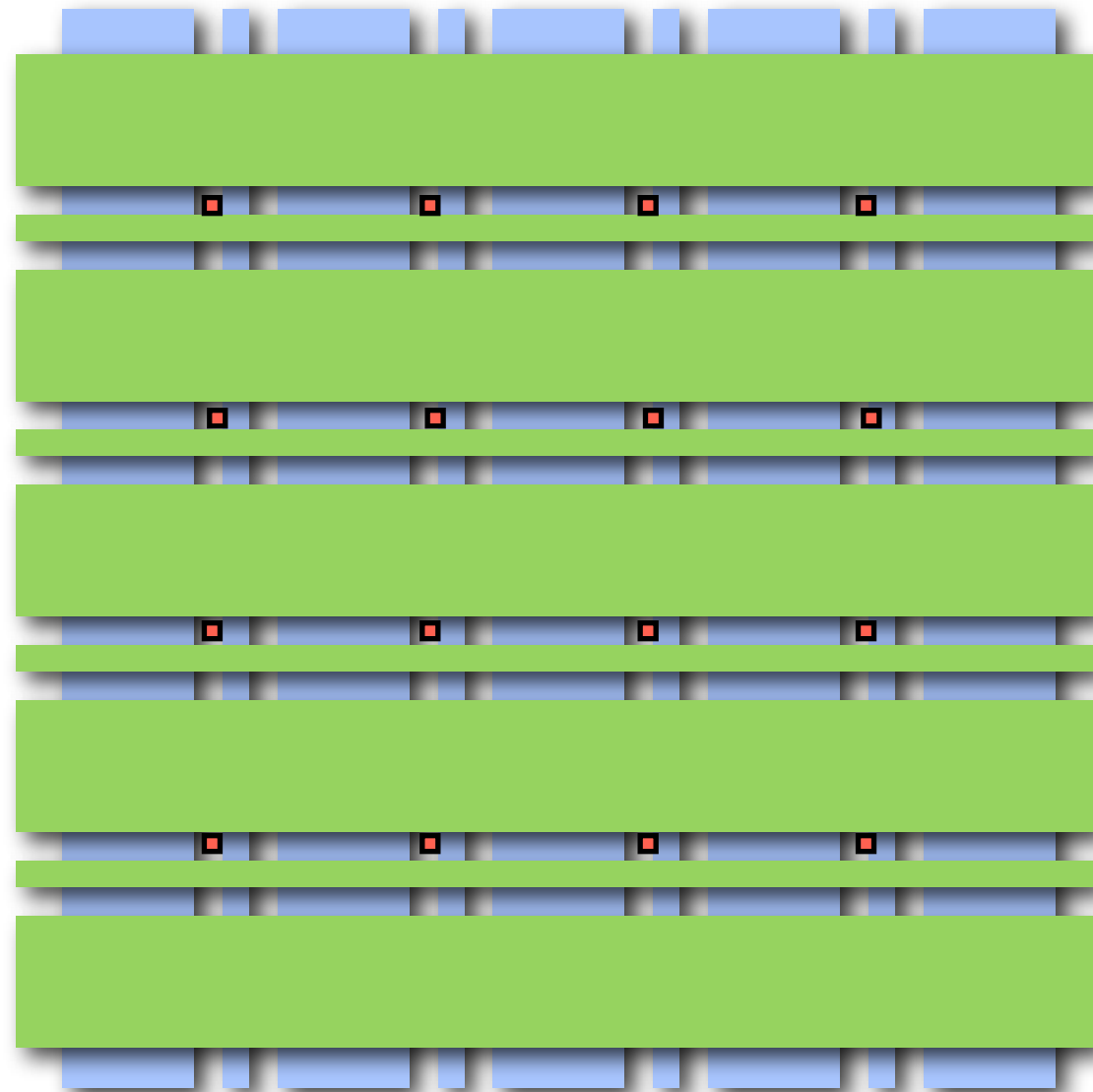
The cavity grid design



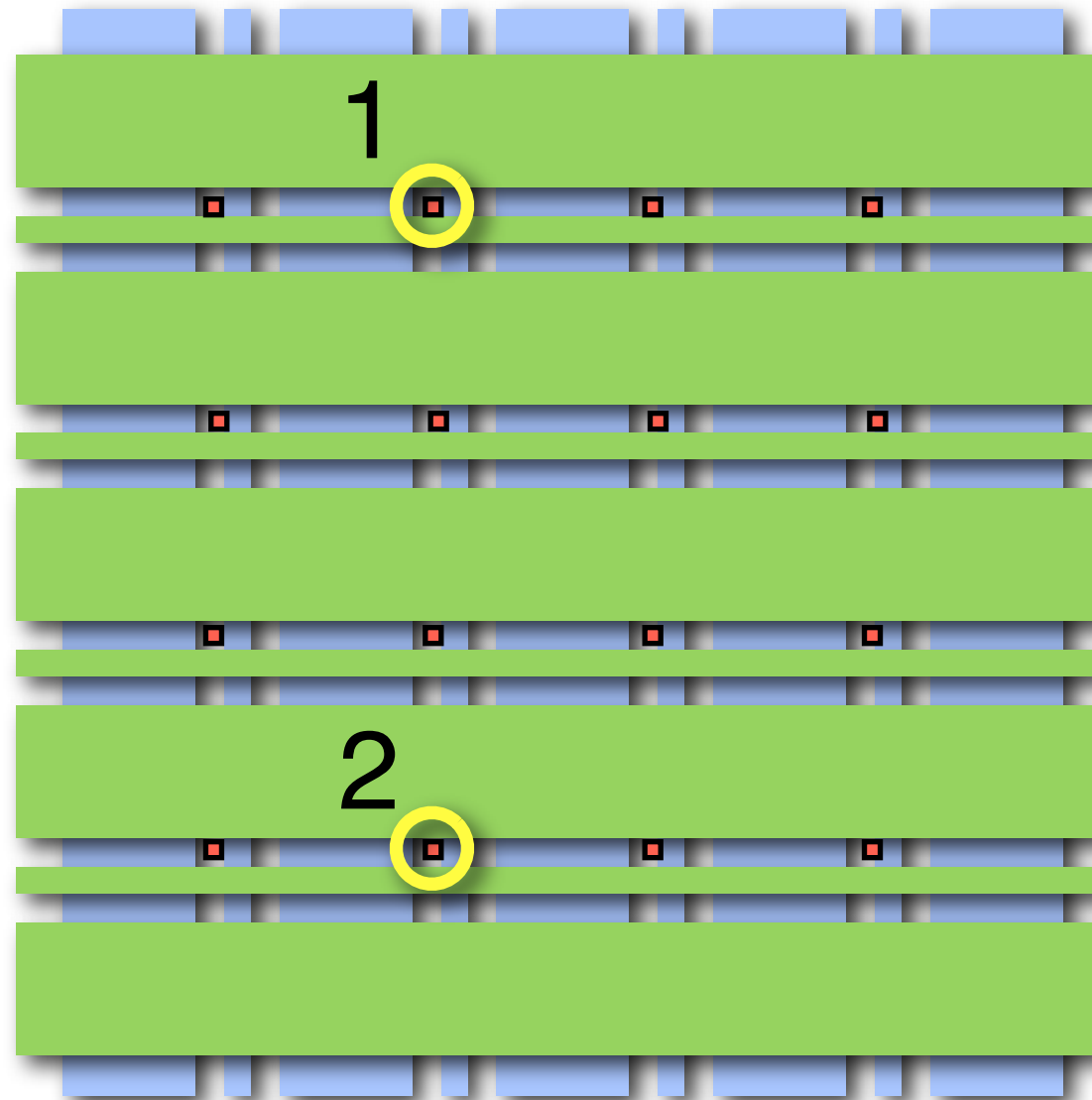
The cavity grid design



The cavity grid design



The cavity grid design



The cavity grid design

