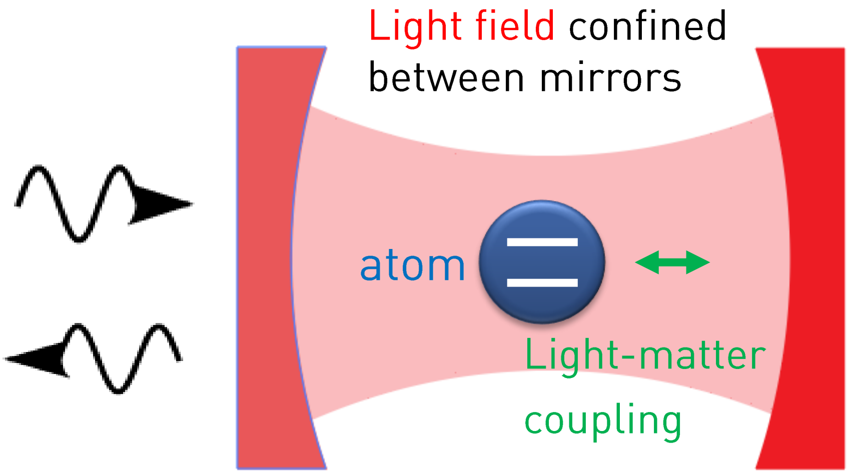
Today's lecture

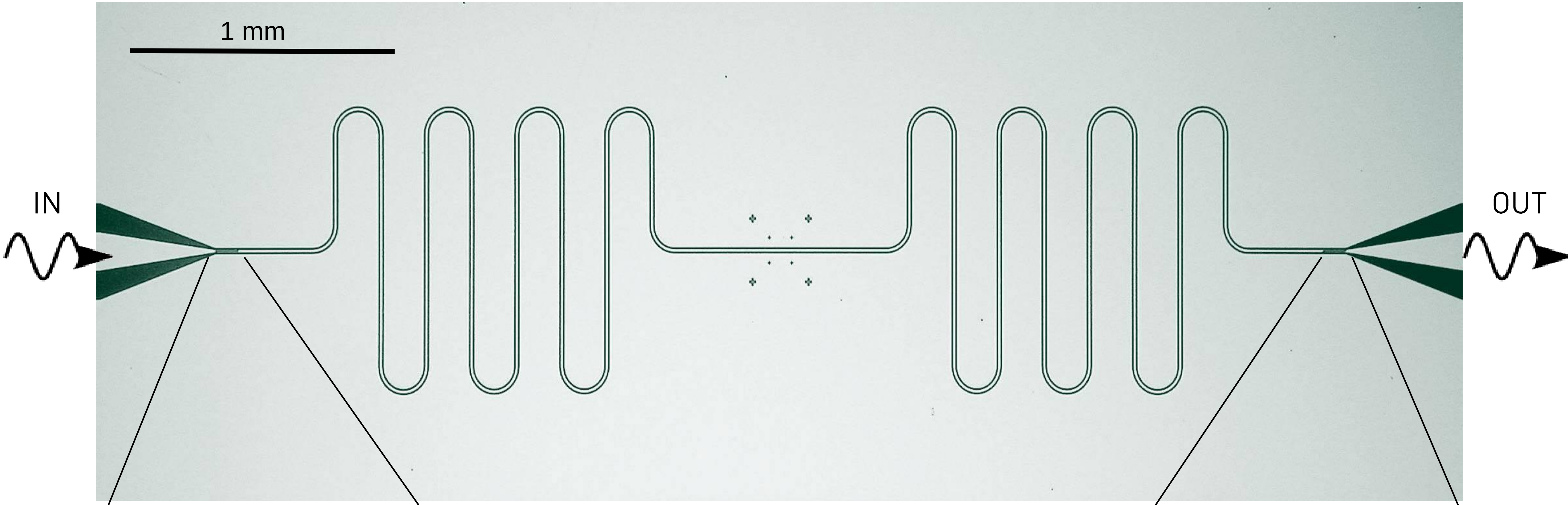
Open Quantum Systems

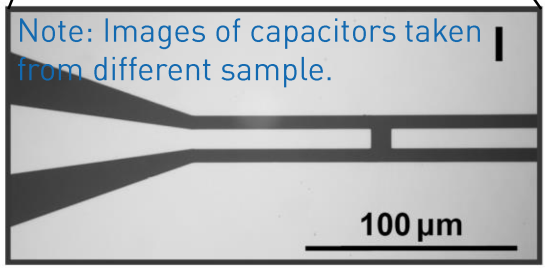
- Describe the scattering of signals off a (quantum) electrical circuit
- Quantum system dynamics in the presence of dissipation



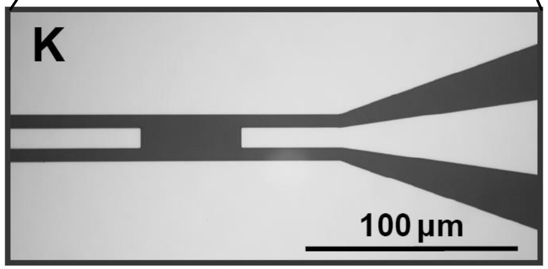
Goal: Understand concepts and get overview over existing methods.

4.3 Probing the transmission through a CPW resonator



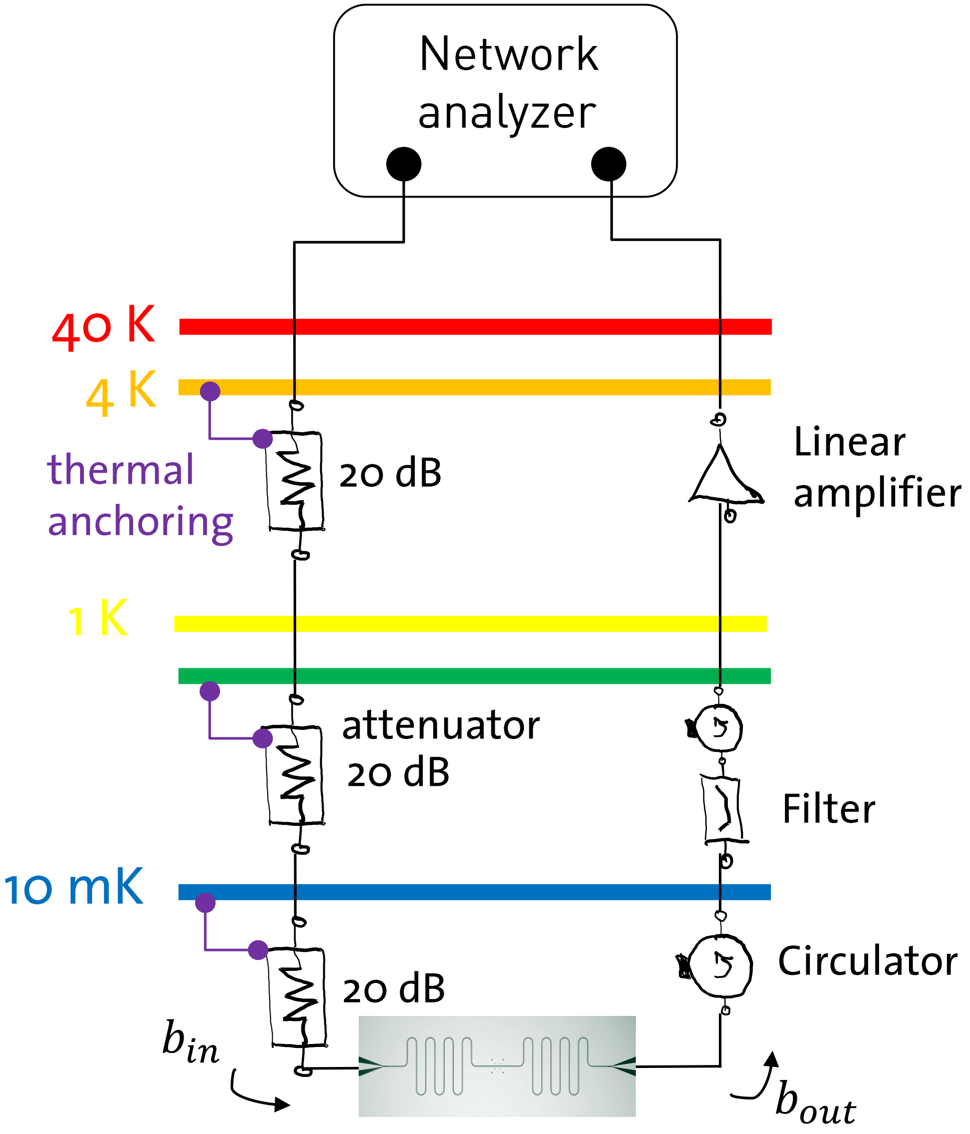


Open ends to support standing waves with wavelengths $\lambda/2 = d/n$. Here, n takes integer values and d is the length of transmission line resonator.



M. Goeppl et al., J. Appl. Phys. 104, 113904 (2008)

4.3 … at Millikelvin temperatures



- Network analyzer measures complex scattering parameter
- Signal at input $b_{in}(t) = \beta_{in} e^{i\omega t} + \delta b_{in}(t)$ noise

  Coherent signal
- Typical noise property

$$\langle \delta b_{in}^{+}(t) \delta b_{in}(t') \rangle = n_{TH}\, \delta(t - t')$$

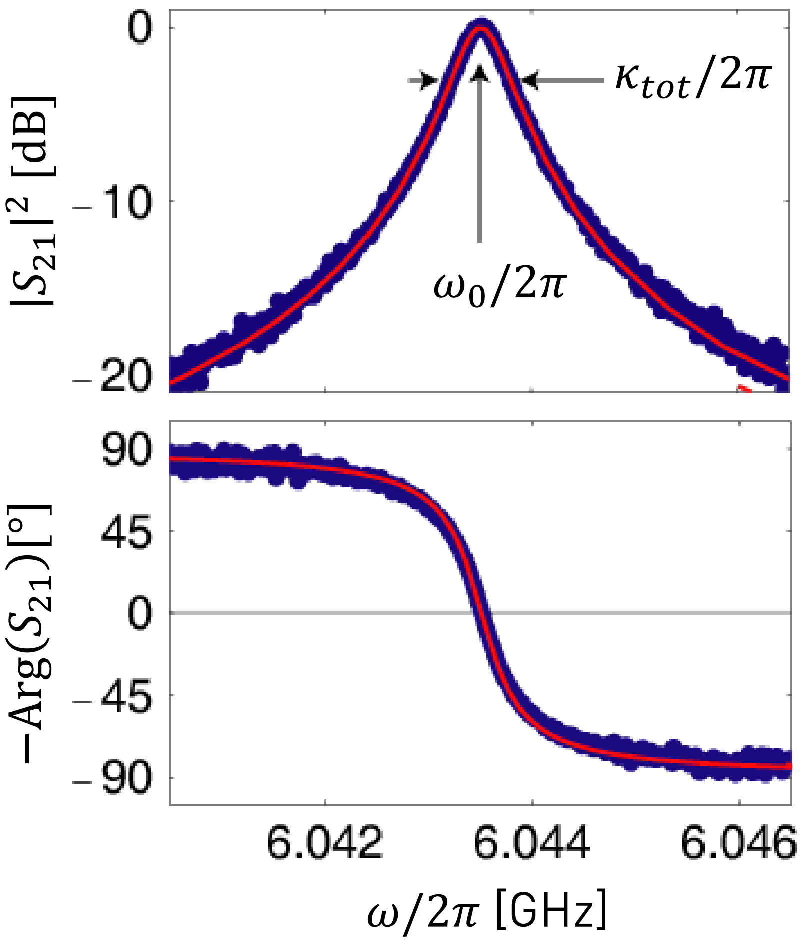
  uncorrelated noise

  Effective noise number
- For blackbody source at temperature T

$$n_{TH} = n_{BE}(T) = 1/(e^{\frac{\hbar\omega}{k_B T}} - 1) \quad \text{Bose-Einstein distribution}$$

- Use cold (thermally anchored) attenuators to “cool” input radiation to $n_{TH} \ll 1$ at the input of the resonator.
- BP filters & circulators suppress noise travelling towards sample
- Amplifier to increase signal-to-noise ratio

Resonator Spectroscopy in Transmission

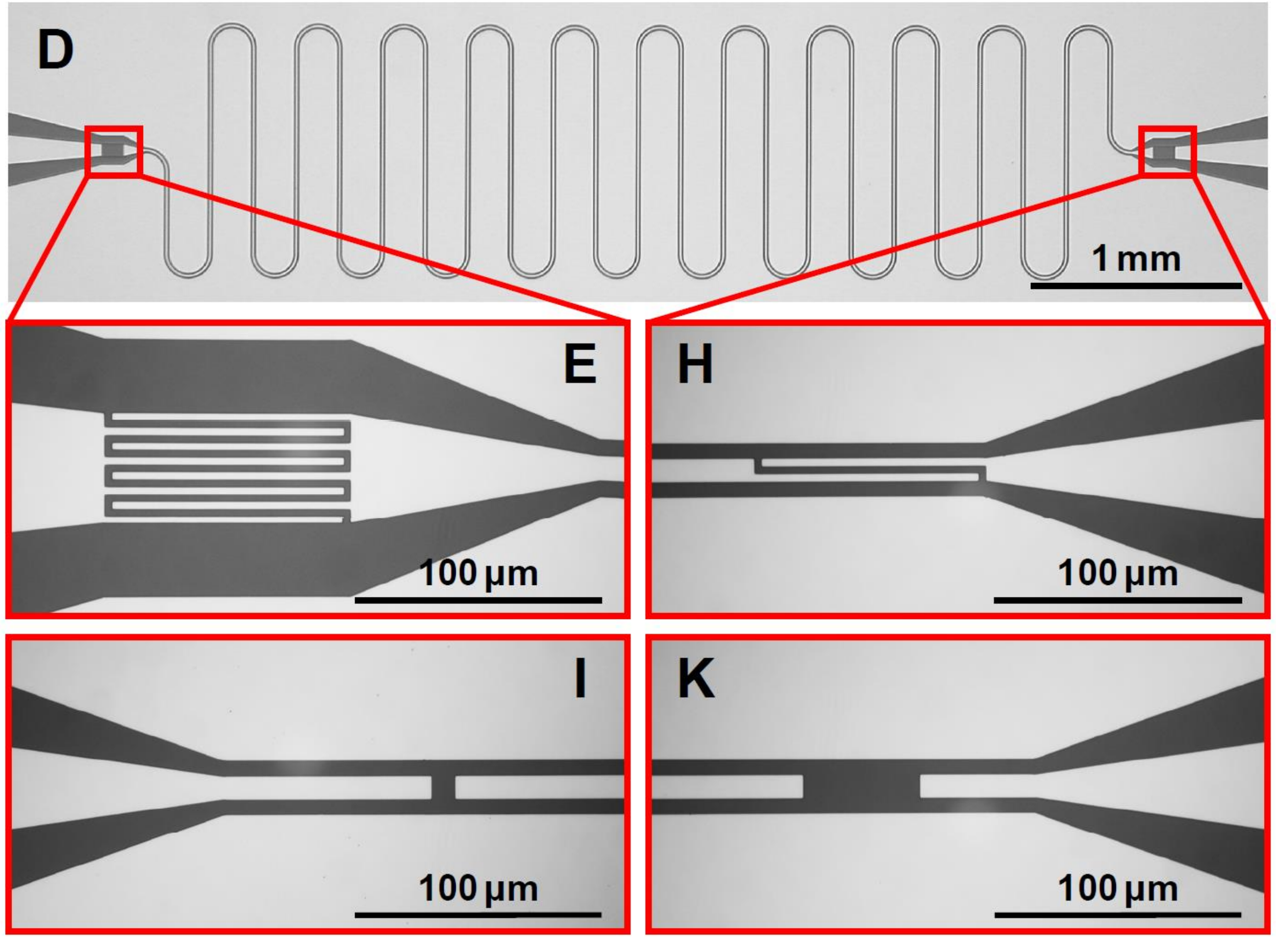


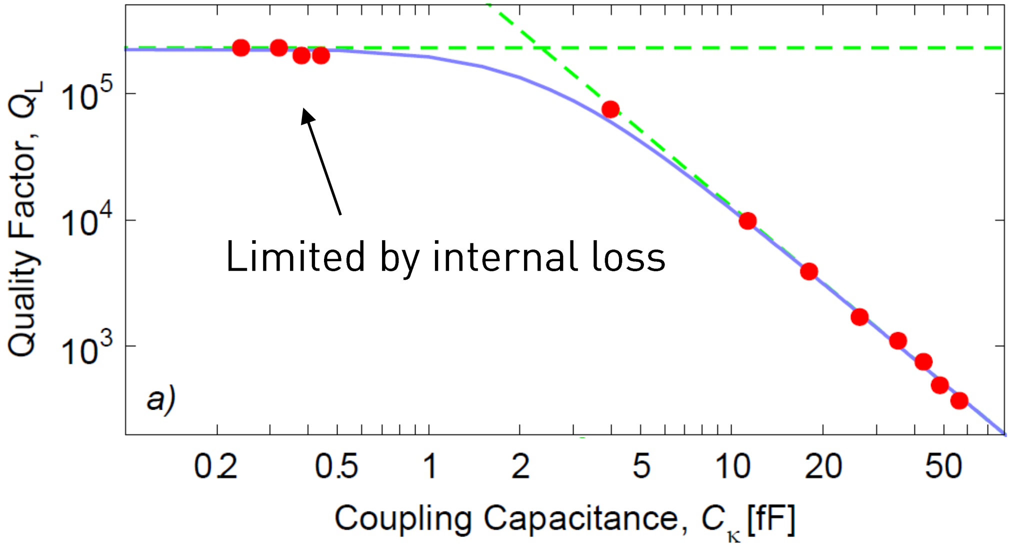
- Here: Assume input and output coupling $\kappa/2$
- Additional internal loss rate γ.
- Data and fit to Lorentzian model

$$S_{21} = t_0 \frac{\kappa/2}{\frac{\kappa+\gamma}{2} - i(\omega-\omega_0)}$$

- Linewidth given by total loss rate $\kappa_{tot} = \kappa + \gamma$
- Resonance frequency $\omega_0/2\pi$
- Additional scaling factor t_0 accounts for attenuation and gain in the input and output lines.
- $\mathrm{Arg}[S_{21}]$ features a π phase shift when scanning across resonance.
- Distinguish internal and external losses by measuring reflection coefficient.
- Quality factor defined as $Q \equiv \frac{\omega_0}{\kappa_{tot}}$.

4.3 Controlling the resonator decay rate

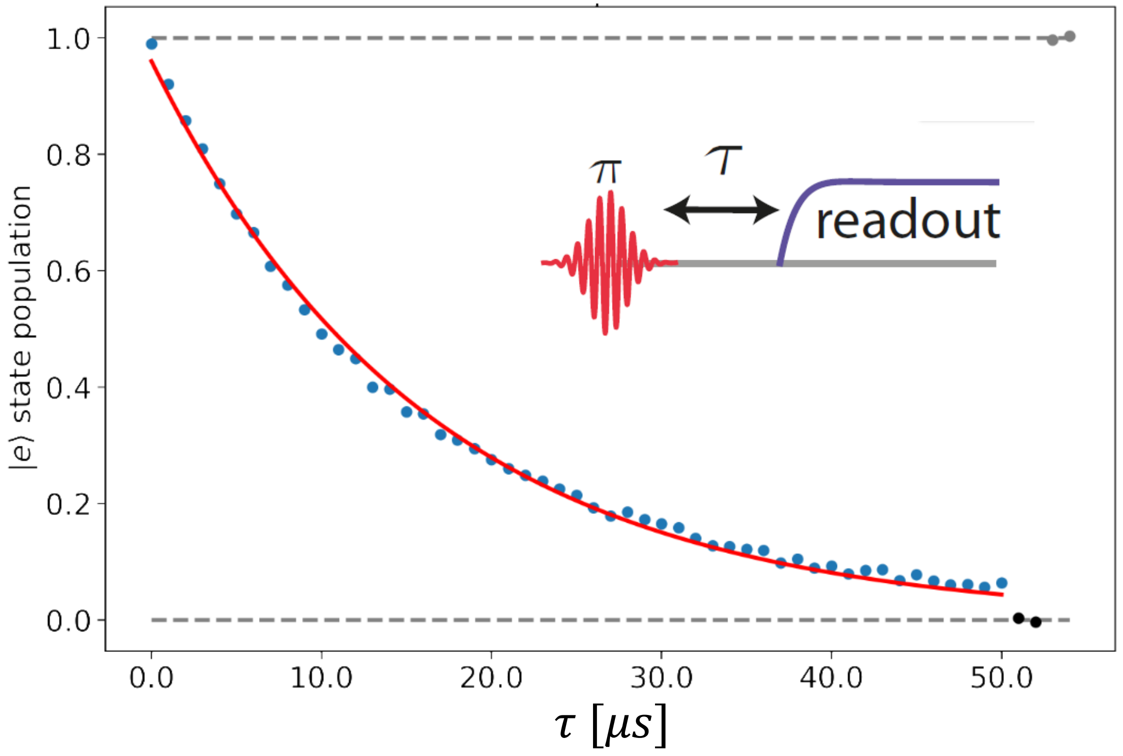




- Capacitance to the input and output sets the decay rate.
- For very small capacitance C_κ the total loss rate becomes dominated by the internal loss.
- Mechanisms causing internal loss discussed later.

M. Goeppl et al., *J. Appl. Phys.* **104**, 113904 (2008)

4.4 Decay of qubit excitation in the presence of dissipation



- Initial excitation decays exponentially with decay rate $\gamma = 1/T_1$.
- $T_1 = 16\ \mu$s in this particular example.
- Consistent with prediction from master equation.