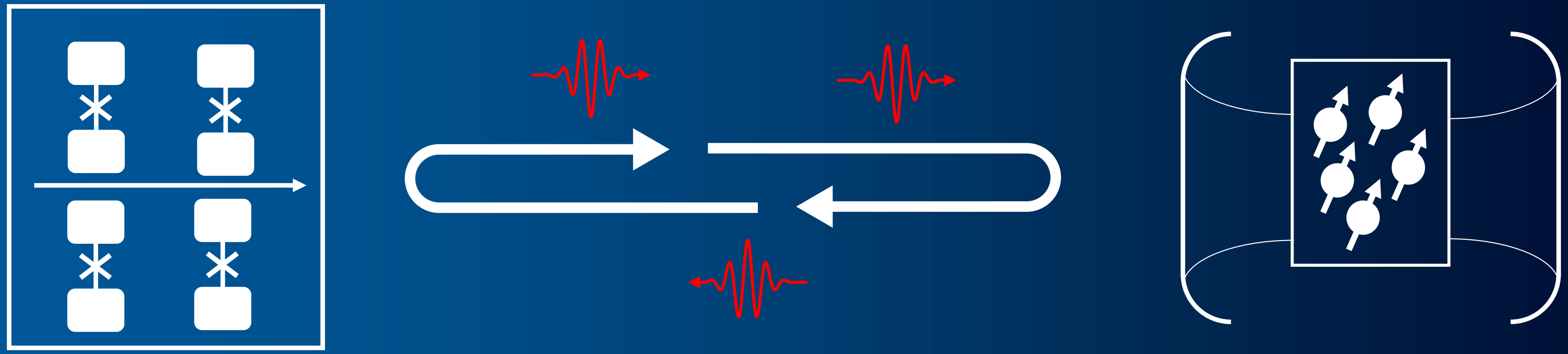
Quantum memory with electronic spins

Audrey Bienfait

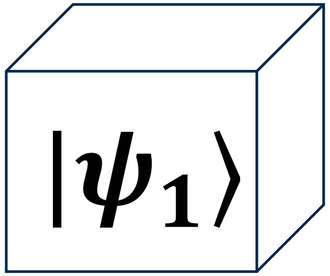


ENS DE LYON

Classical versus quantum memory

Store a bit

Store a qubit



Metrics

Latency/bandwidth

Coherence & Lifetime & error rate

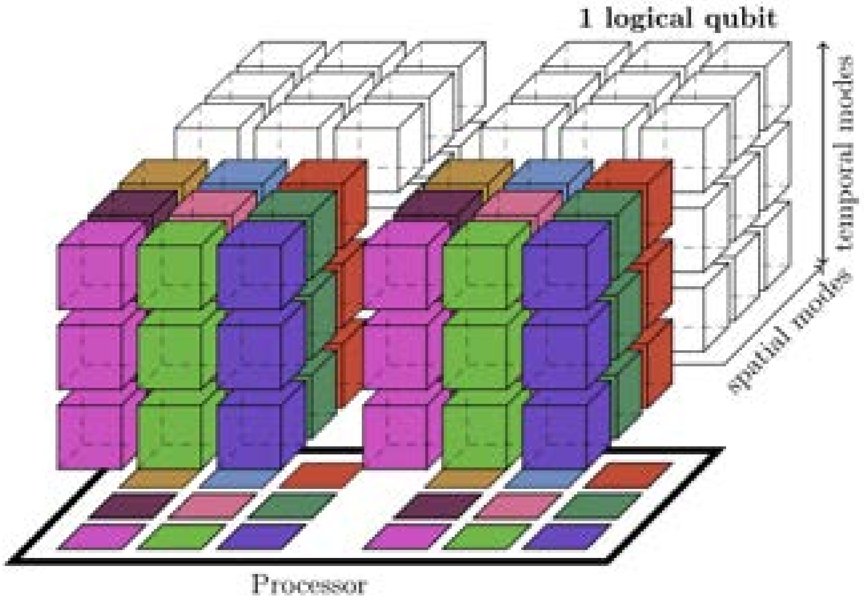
Capacity

(quantum) random-access memory

(Power consumption)

Why store quantum states ?

Reduce the number of processing qubits in a quantum computer



Factoring 2048-bit RSA Integers in 177 Days with 13 436 Qubits and a Multimode Memory, Gouzien & Sangouard, *PRL* (2021)

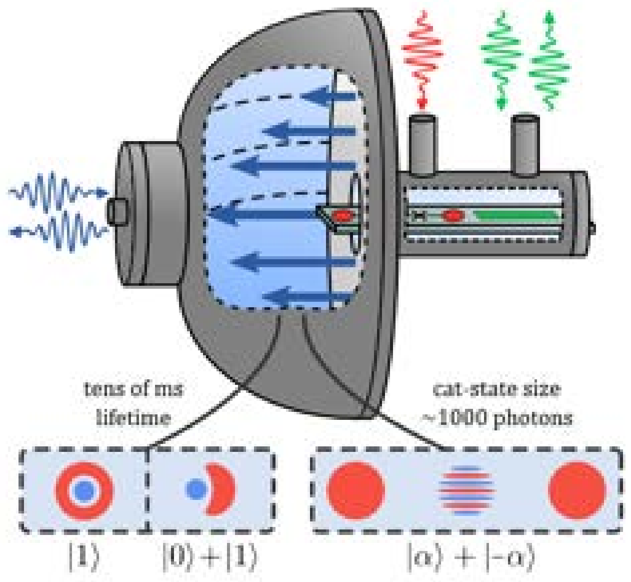
Quantum memory hierarchies: Efficient designs to match available parallelism in quantum computing, Thaker et al., Symposium on Computer Architecture (2006).

Enable long-distance communication

The quantum internet, H. J. Kimble, Nature (2008)

Platforms for storing microwave quantum states ?

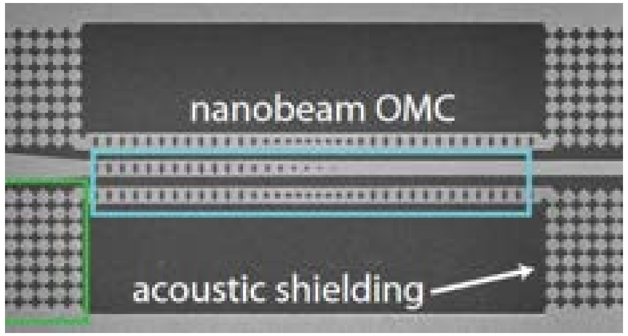
Superconducting cavities



T_1 = 110 ms
T_2 = 34 ms
T_{swap} ~ 1 us

Millul et al., *PRX Quantum (2023)*

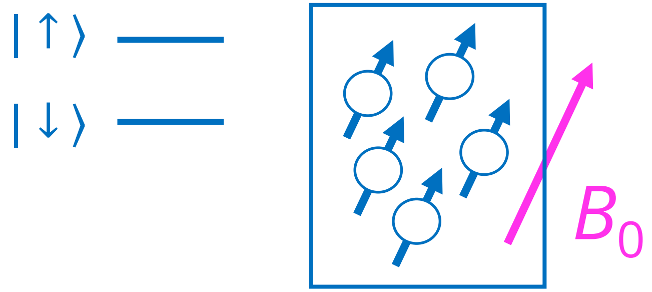
Mechanical devices



T_1 = 1.5 s
T_2 = 130 us
T_{swap} ~ 1 us

MacCabe et al., Science (2020)

Defect spins in crystals

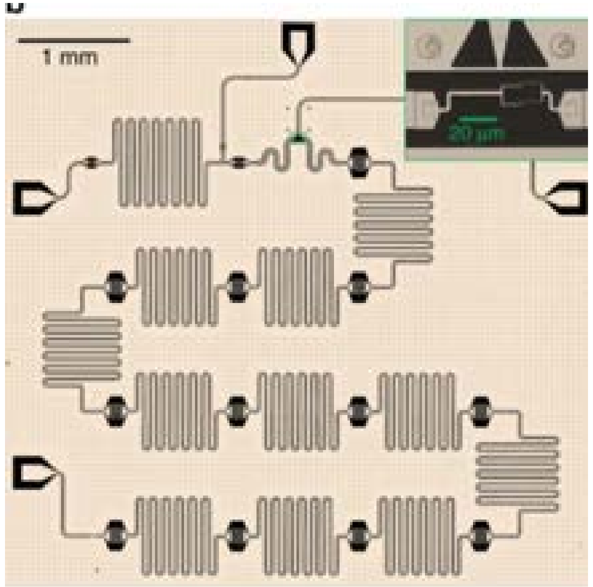


T_1 > 10s,
T_2 = 2.9 s @clock transitions
T_{swap} ~ 10 us

Wolfowicz et al.,
Nature nano (2013)

Multimodal ?

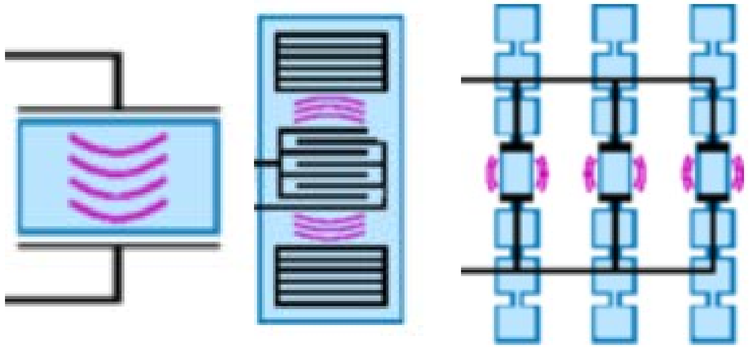
Superconducting cavities



$N_{modes} = 10$

Naik et al., *Nat. Comm.* (2017)

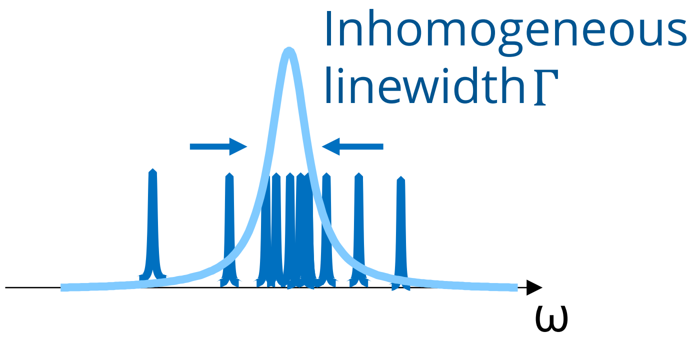
Mechanical devices



N_{modes} = 10 to 100

Hahn et al., PRL (2019)

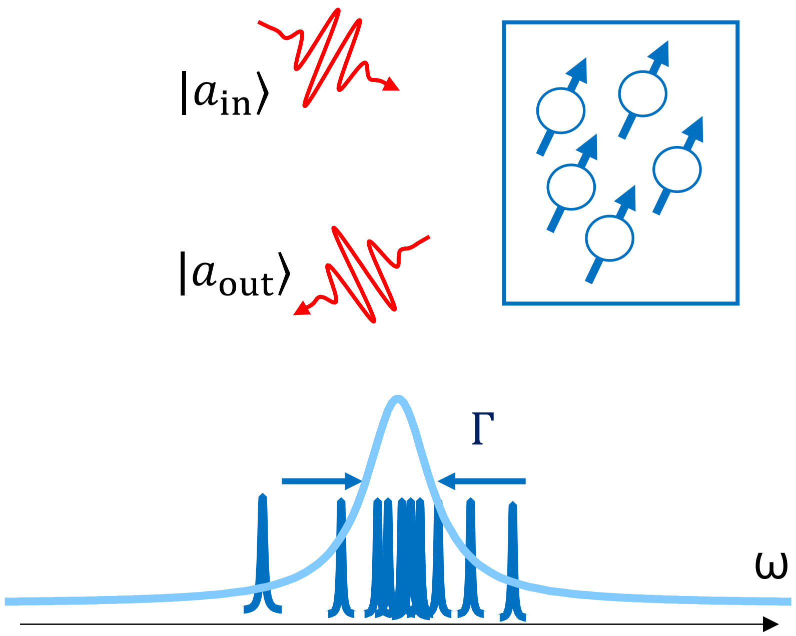
Defect spins in crystals



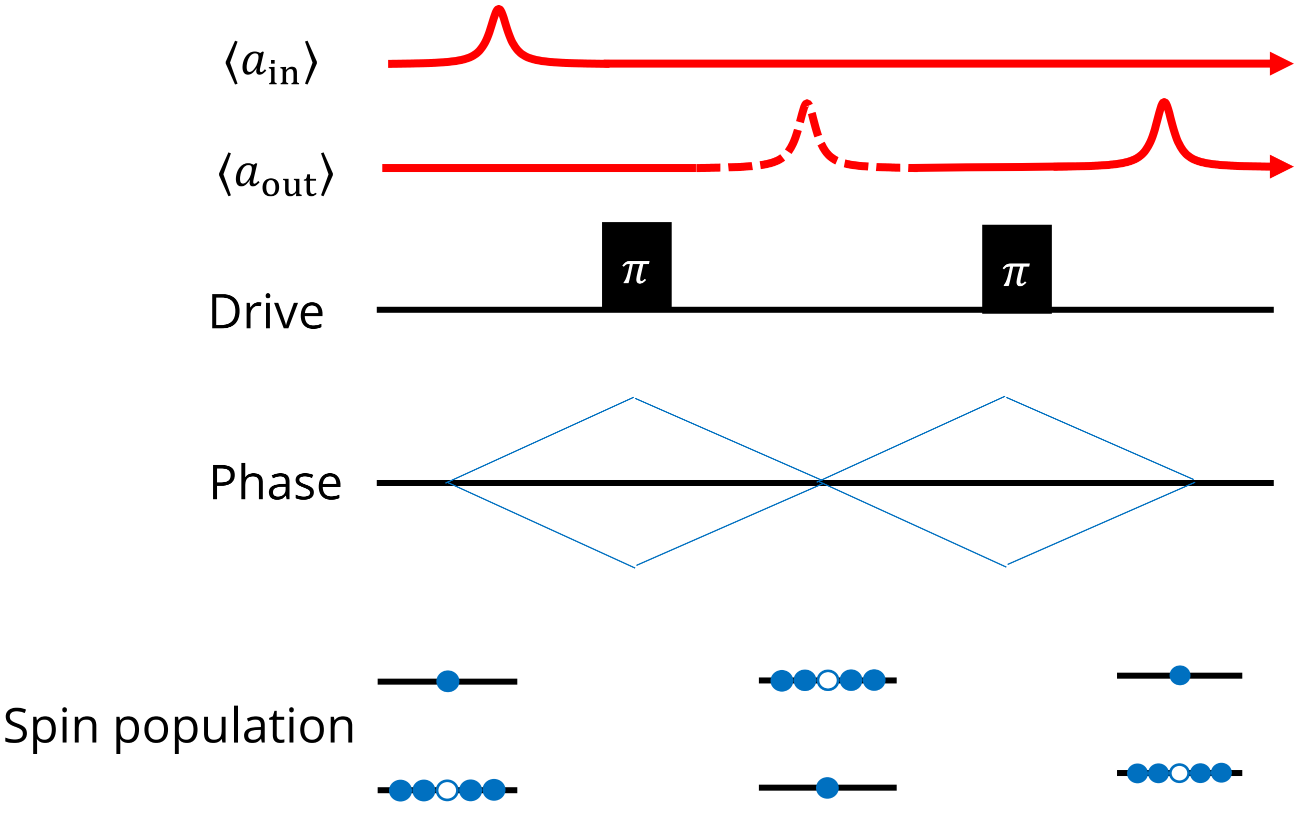
$N_{modes} = N_{spins}$?

Echo-based quantum memory

Ensemble of spins,
with some inhomogeneous broadening

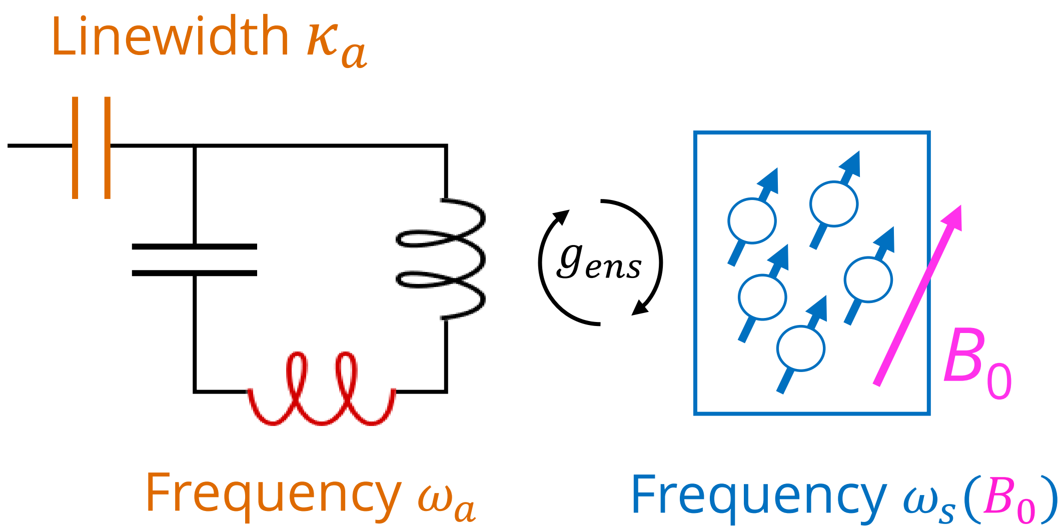


Recovery of silenced echo (ROSE) protocols



V. Damon et al., New J. Phys. 2011

Spin ensemble coupled to a superconducting resonator

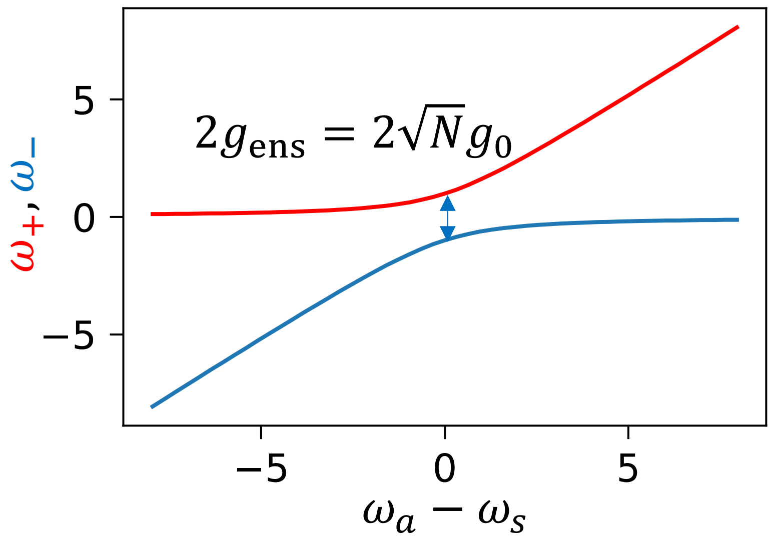


$$H = \mu\,(\vec{B}_0 + \vec{B}_1).\vec{S}$$

$$H_{\text{int}} = \underbrace{\mu\,\delta B_1}(a + a^+)(\sigma_+ + \sigma_-)$$

Couping constant to spin ½

$\frac{g_0}{2\pi}$ = 1 mHz – 5 kHz



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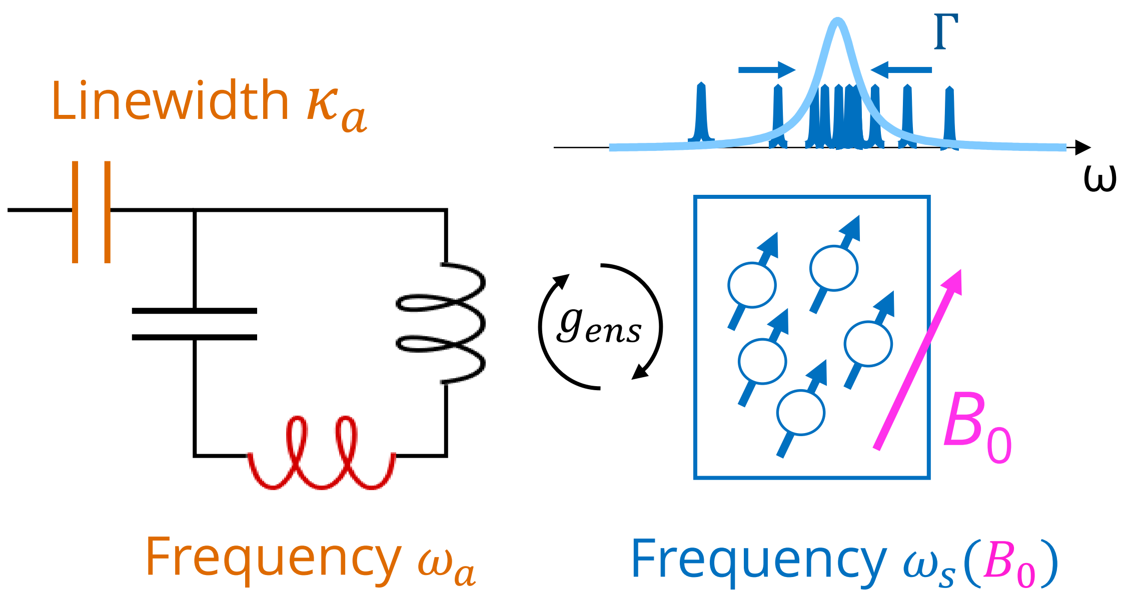
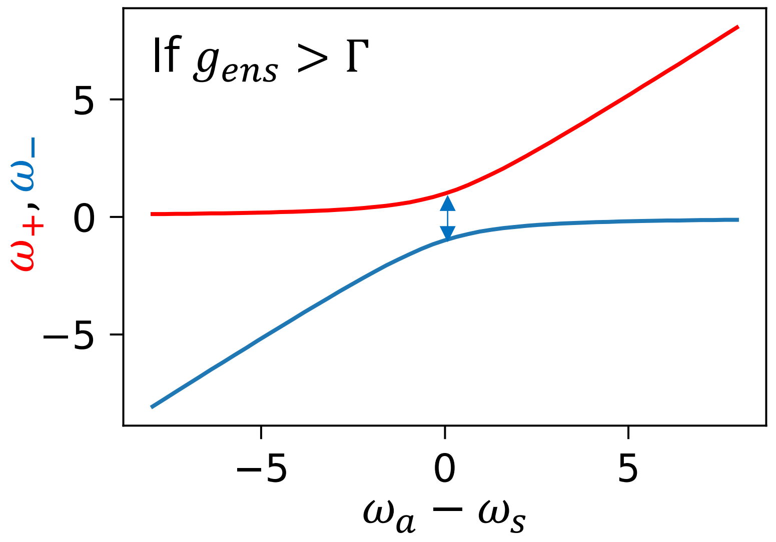


Regime of interaction given by cooperativity

$$C = \frac{4\, g_{\mathrm{ens}}^2}{\kappa_{\mathrm{a}}\Gamma} = \frac{4\, N\, g_0^2}{\kappa_{\mathrm{a}}\Gamma}$$



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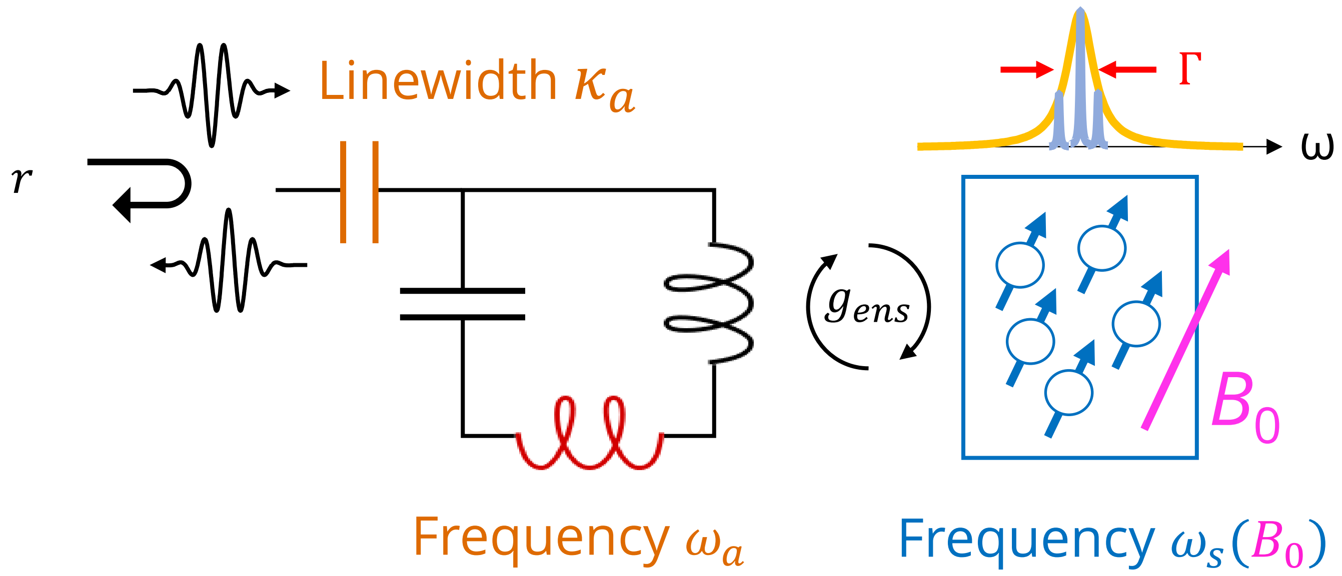
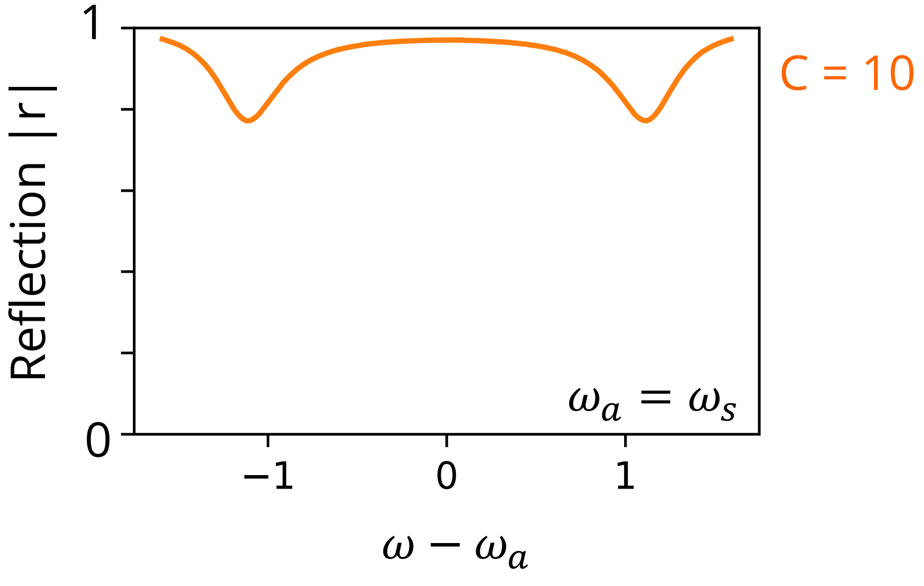
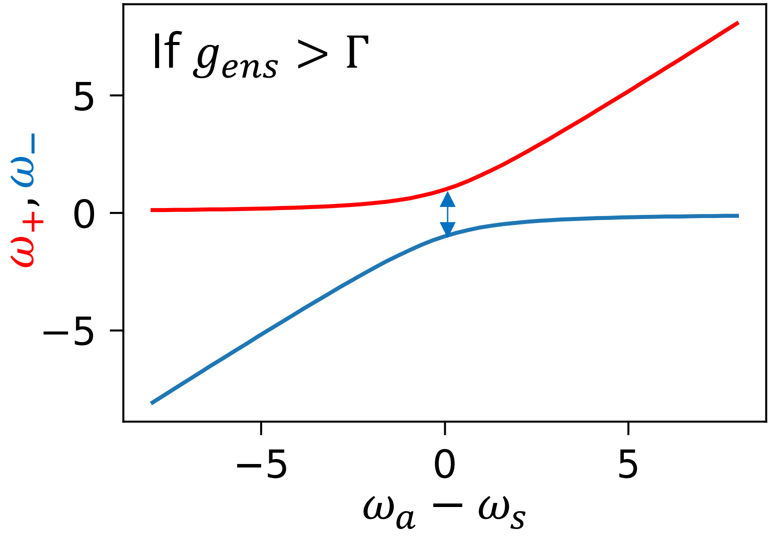




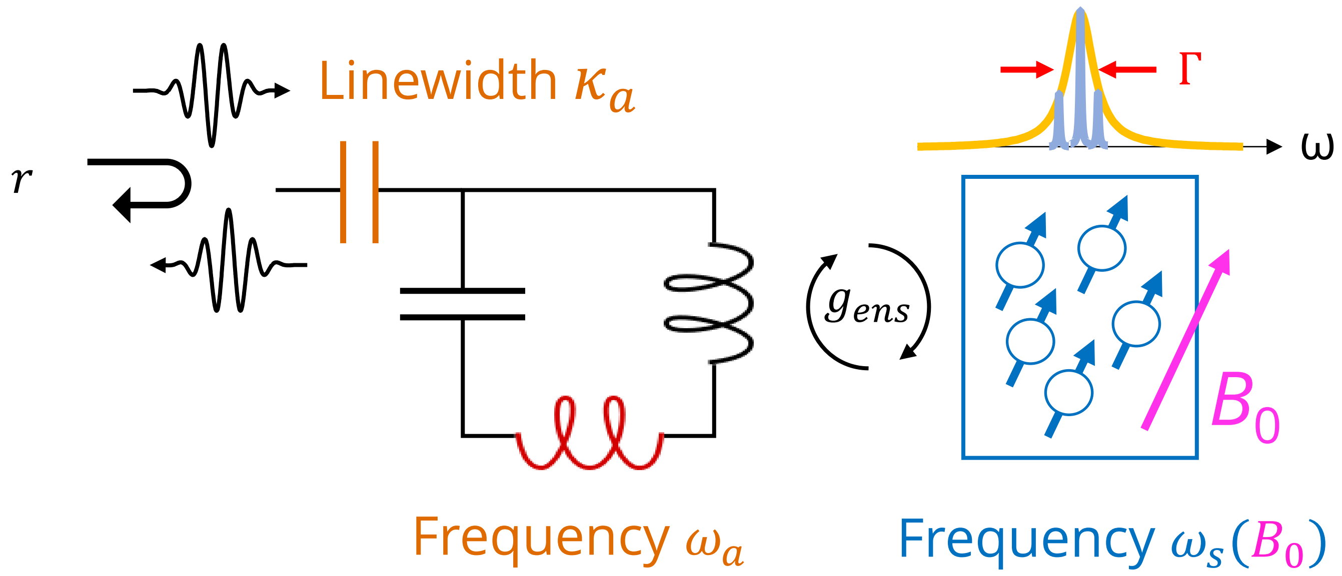


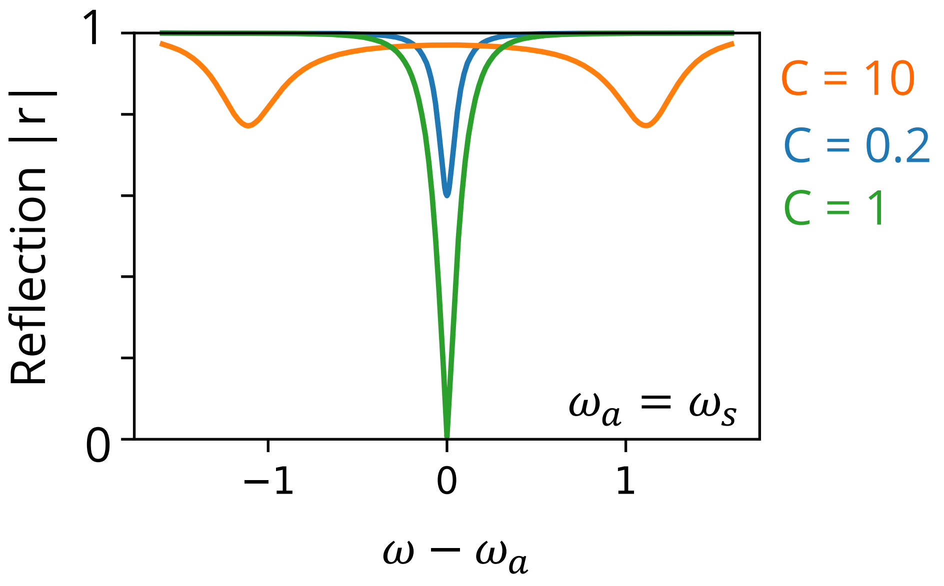
High cooperativity

Signature of avoided level crossings

Coherent swaps between resonators and spins, with exchange time limited by $1/\Gamma$

Spin ensemble coupled to a superconducting resonator





High cooperativity

Signature of avoided level crossings

Coherent swaps between resonators and spins, with exchange time limited by $1/\Gamma$

Unit cooperativity

Perfect absorption into the spins, with bandwidth $\kappa_s = \frac{4\, g_{\rm ens}^2}{\Gamma}$

No coherent swapping

Low cooperativity

Spins act as a loss channel with decay rate $\kappa_s = \frac{4\, g_{\rm ens}^2}{\Gamma}$

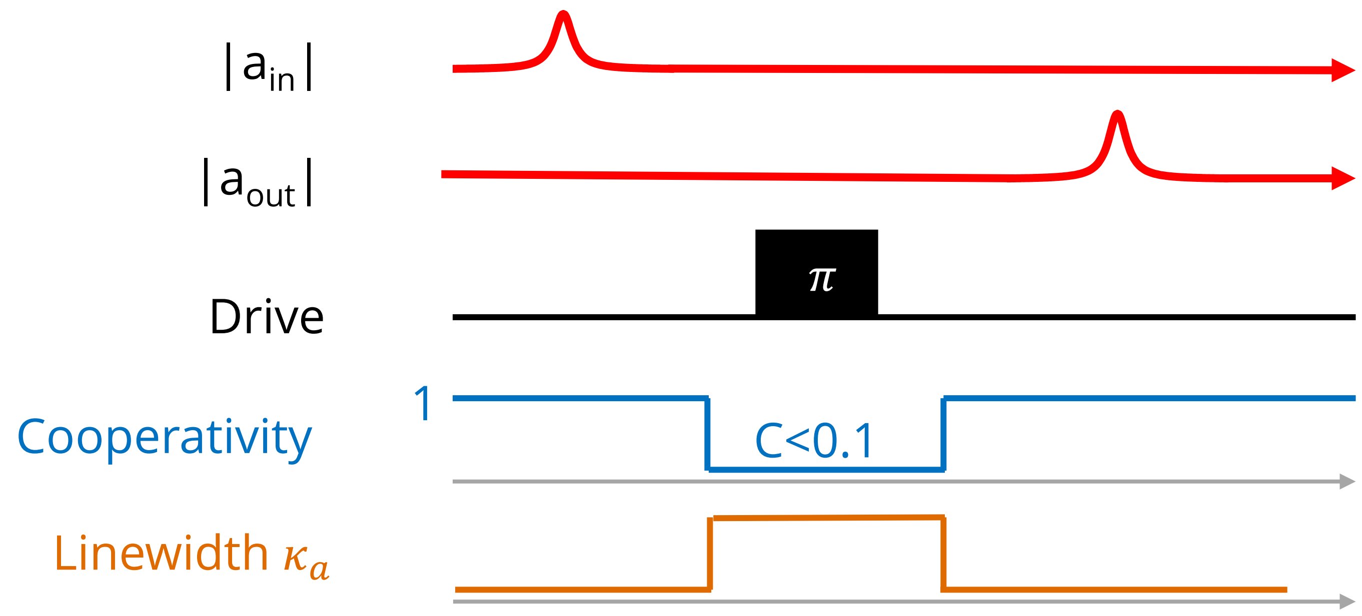
No coherent swapping

Possible to drive the spins classically

Spins can deexcite via the resonator (Purcell effect)

Spin ensemble as a memory: protocol

How to store an incoming arbitrary wave packet and retrieve it?



Julsgaard, et al. (2012), Yin et al. (2013), Ranjan et al. (2020), phase encoding: O'Sullivan et al. (2022)

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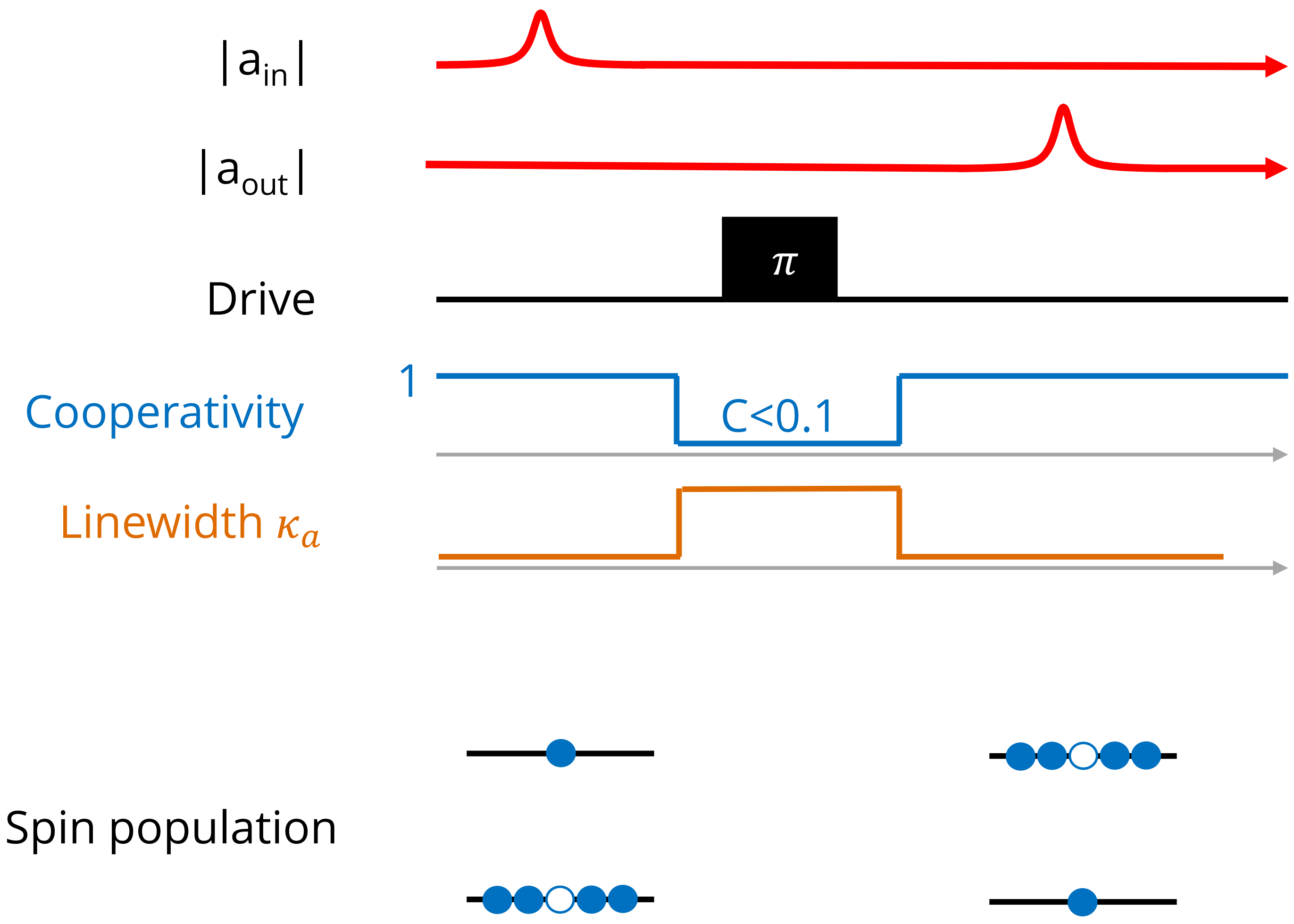

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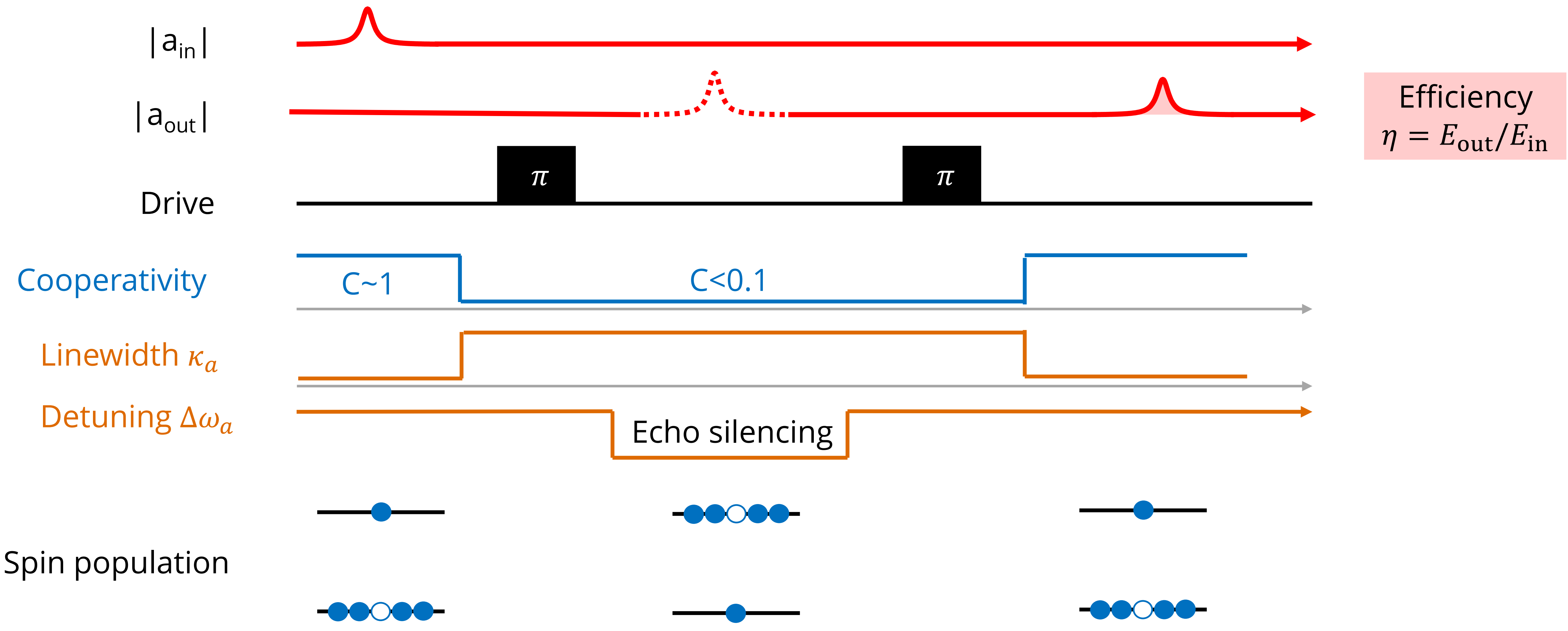
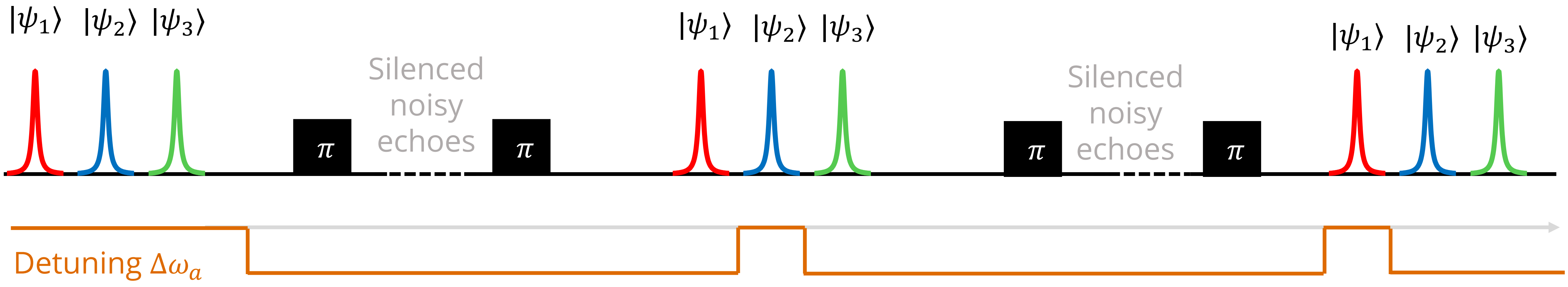


Julsgaard, et al. (2012), Yin et al. (2013), Ranjan et al. (2020), phase encoding: O'Sullivan et al. (2022)

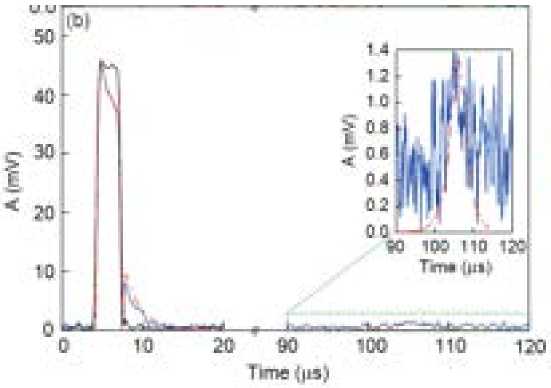
Multimode?

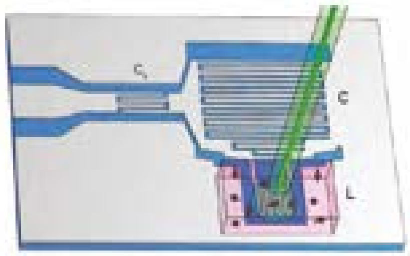
Random access to multiple stored states by echo silencing… except on retrieval !



Spin-ensemble as a memory : state of the art

NV centers in diamond

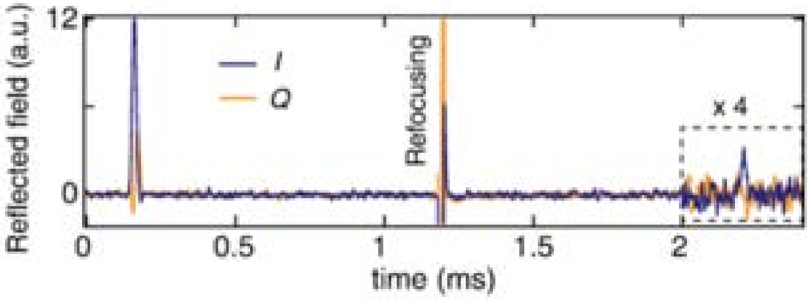


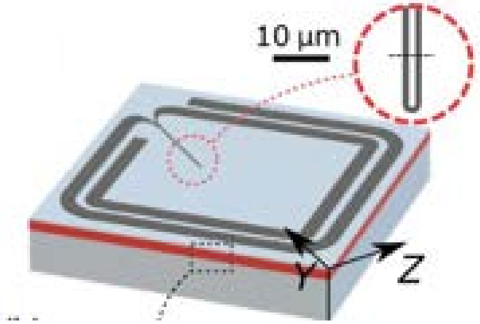


Grezes et al., *PRA* (2015)

Efficiency 0.3 %
C = 0.22
T_2 = 84 us

Bismuth donors in silicon





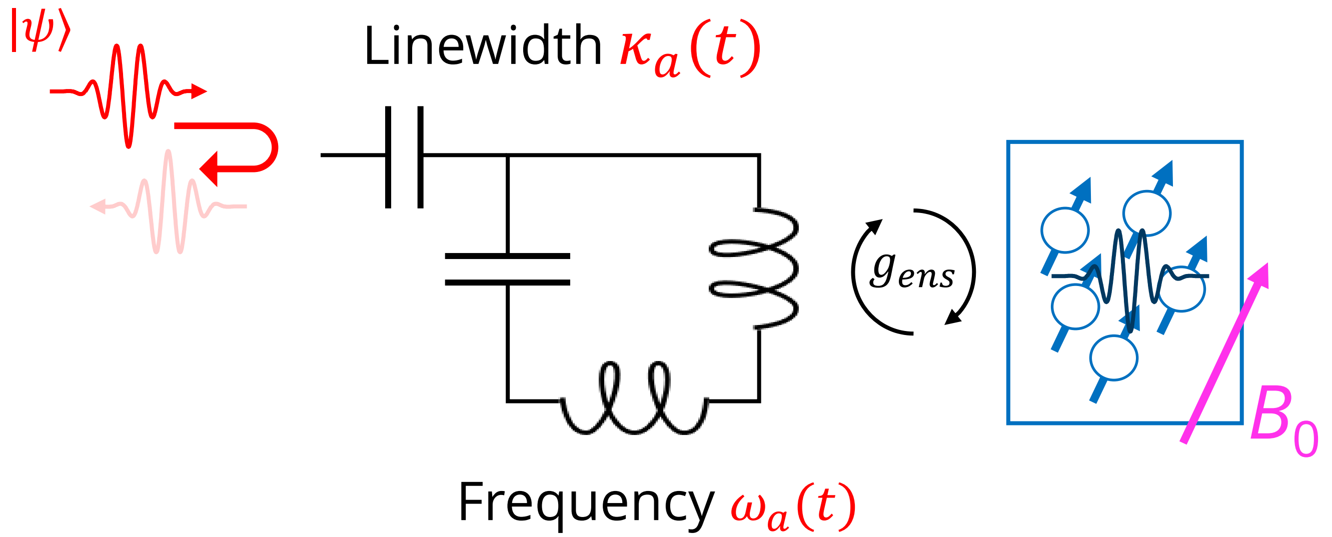
Ranjan et al., *PRL* (2020)

Efficiency 0.1 %
C = 0.04
T_2 = 0.3 s

O'Sullivan et al., *PRX* (2022)

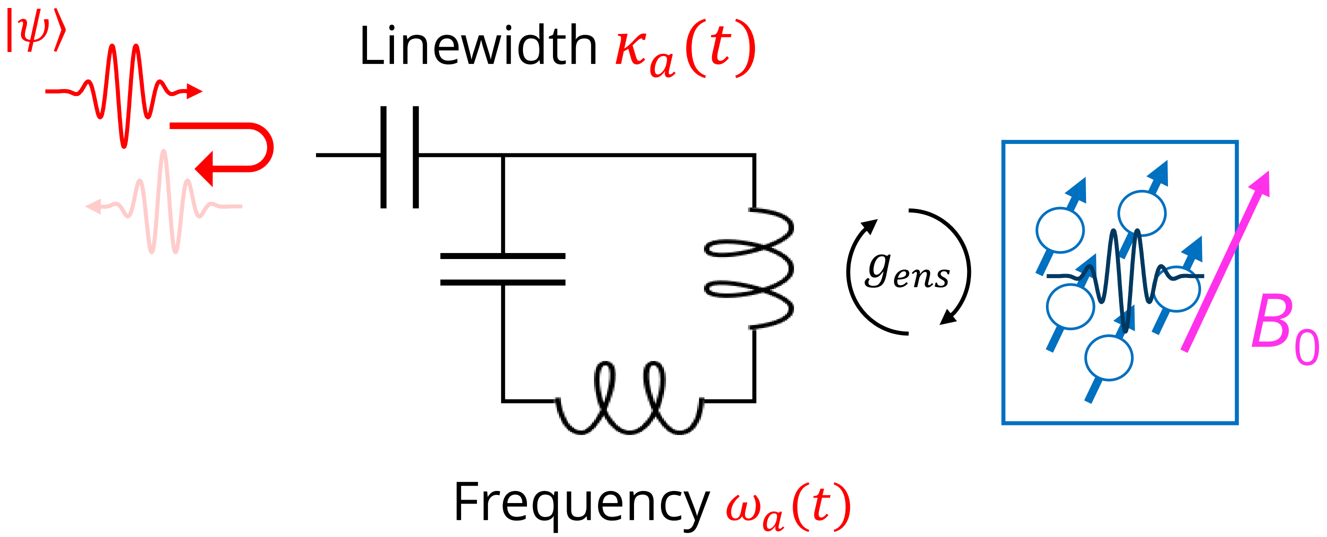
Efficiency 3 %
C = 0.06
T_2 = 2 ms

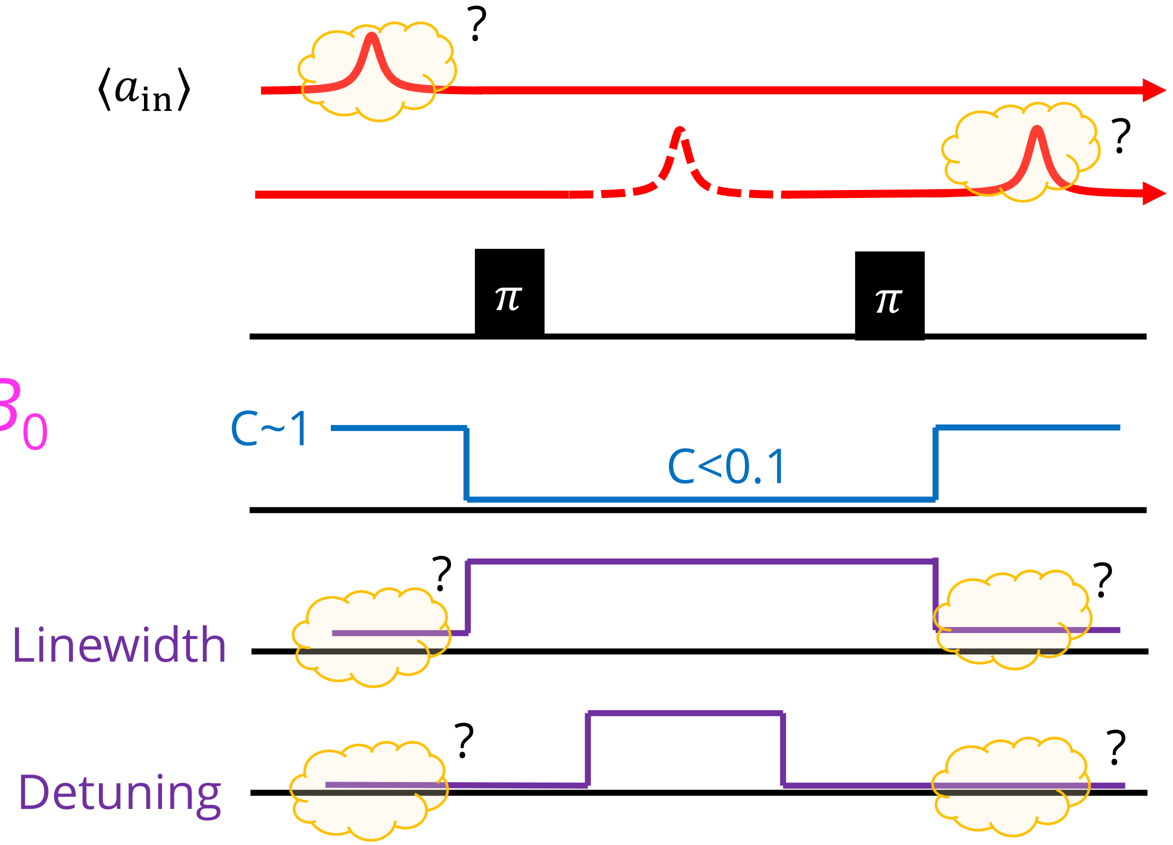
Quantum memory requirements



- ❑ Long spin coherence
  Aim for clock transitions
- ❑ Reach unit cooperativity
- ❑ Tunable resonator frequency
  - ❑ For echo silencing
  - ❑ For aiming at clock transitions
- ❑ Tunable linewidth
  - ❑ For cooperativity tuning
  - ❑ For perfect absorption ?

Quantum memory requirements



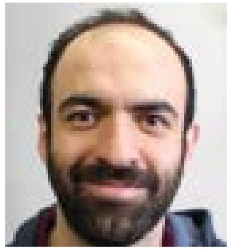


- Can we absorb faster than at rate κ_s ?
- What **control fields** for best efficiency ?
  - Input field
  - Linewidth modulation
  - Detuning

Quantum state transfers, etc…
A. N. Korotkov, *PRB* (2011) + many others…

Linda Greggio

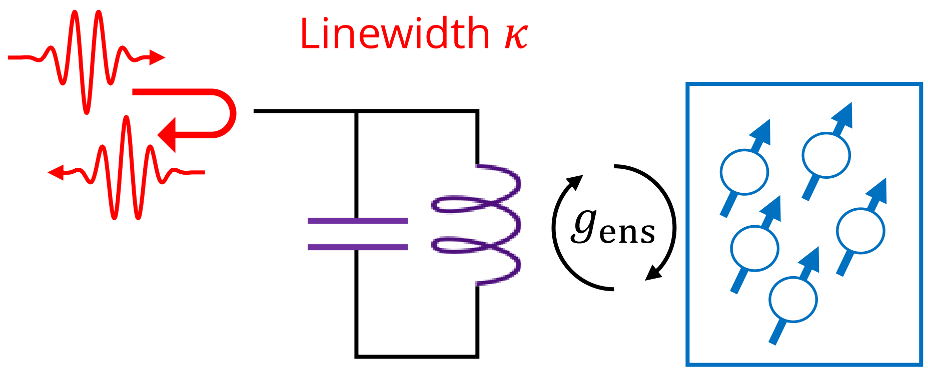
Alexandru Petrescu



Mazyar Mirrahimi

Modeling absorption

Detuning δ



Detuning δ_{r}

Cavity operator a

Spin lowering operator σ_{-}

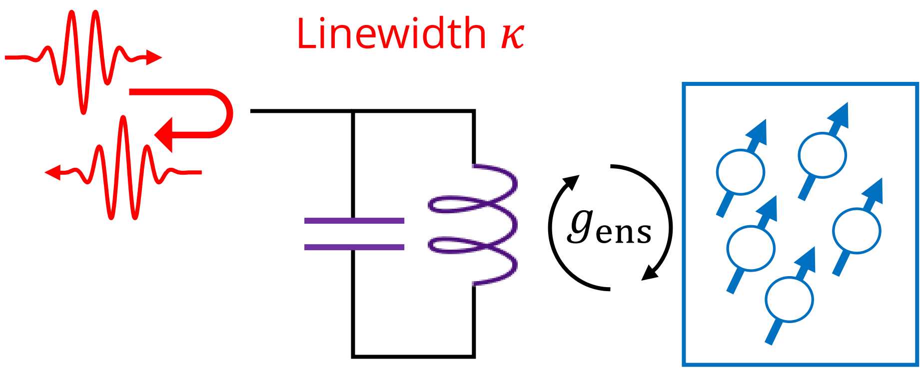
Equations of motion : control fields

$$\frac{d}{dt} a = -\frac{\kappa_0 + \boldsymbol{\kappa(t)} - 2i\,\boldsymbol{\delta_r(t)}}{2} a + i \sum_j g_j \sigma_{-}^{j} + \sqrt{\boldsymbol{\kappa(t)}}\,\boldsymbol{a_{\mathrm{in}}(t)}$$

$$\frac{d}{dt} \sigma_{-}^{j} = -i\,\delta_j \sigma_{-}^{j} + i\,g_j\,a$$

Assuming a Lorentzian spin frequency distribution

Modeling absorption



Cavity operator a

Spin lowering operator σ_-

Assuming a Lorentzian spin frequency distribution

Equations of motion : control fields

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$$- g_{\mathrm{ens}}^2 \int_{-\infty}^{t} a\, e^{-\Gamma(t-s)/2} ds$$

$$- g_{\mathrm{ens}} \Sigma$$

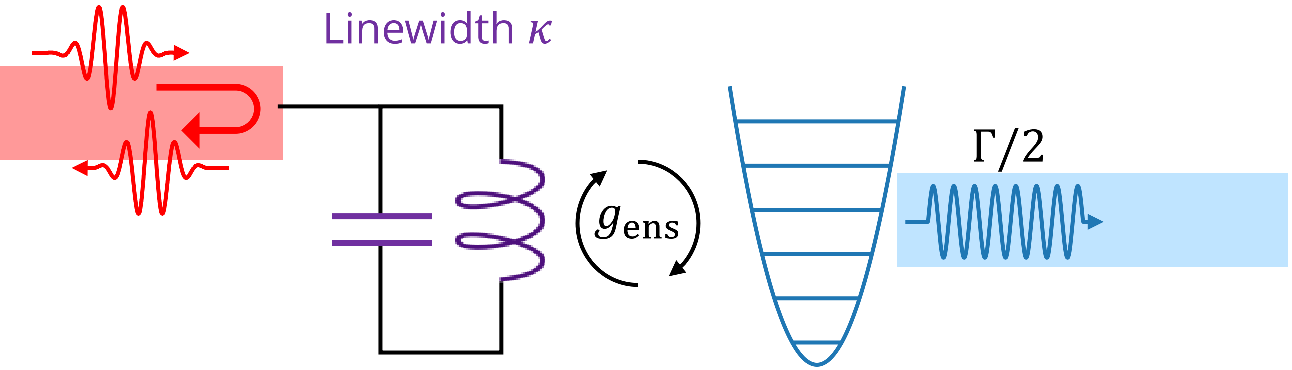
$$\frac{d}{dt} \sigma_-^j = -i\, \delta_j \sigma_-^j + i\, g_j\, a$$

$$\frac{d}{dt} \Sigma = -\Gamma\, \Sigma + g_{\mathrm{ens}} a$$

Modeling absorption

Detuning δ

Emission at rate Γ into a “spin” channel



Detuning δ_{r}

Equations of motion : control fields

resonator losses

$$\frac{d}{dt} a = -\frac{\kappa_0 + \boldsymbol{\kappa(t)} \; - 2i\, \boldsymbol{\delta(t)}}{2} a + i \sum_j g_j \sigma_-^j + \sqrt{\boldsymbol{\kappa(t)}}\, \boldsymbol{a_{\text{in}}(t)}$$

$$- g_{\text{ens}}^2 \int_{-\infty}^{t} a\, e^{-\Gamma(\mathrm{t}-\mathrm{s})/2} ds$$

$$- g_{\text{ens}}\, \Sigma$$

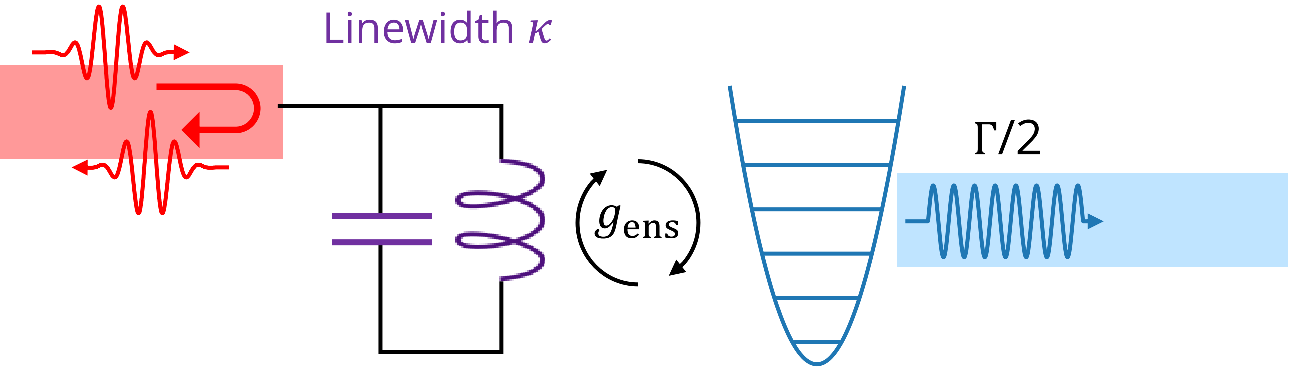
$$\frac{d}{dt} \sigma_-^j = -i\, \delta_j \sigma_-^j + i\, g_j\, a$$

$$\frac{d}{dt} \Sigma = -\frac{\Gamma}{2}\, \Sigma + g_{\text{ens}} a$$

Assuming a Lorentzian spin frequency distribution

Modeling absorption

Emission at rate $\Gamma/2$ into a “spin” channel



Equations of motion : control fields

resonator losses

$$\frac{d}{dt}a = -\frac{\kappa_0 + \boldsymbol{\kappa(t)} - 2i\,\boldsymbol{\delta(t)}}{2}\,a + i\sum_j g_j \sigma_-^j + \sqrt{\boldsymbol{\kappa(t)}}\,\boldsymbol{a_{\mathrm{in}}(t)}$$

$$- g_{\mathrm{ens}}^2 \int_{-\infty}^{t} a\, e^{-\Gamma(t-s)/2} ds$$

$$- g_{\mathrm{ens}}\,\Sigma$$

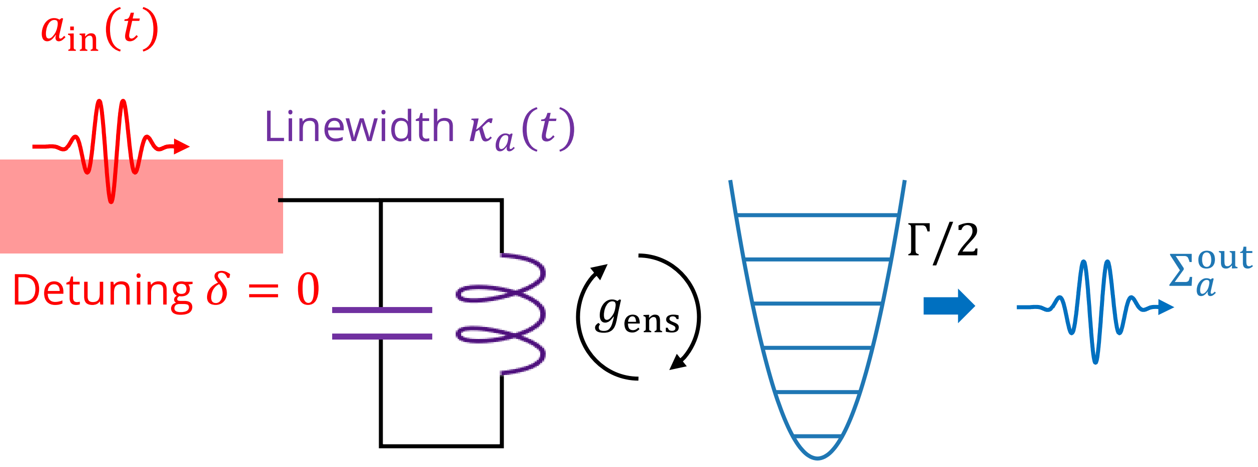
$$\frac{d}{dt}\sigma_-^j = -i\,\delta_j \sigma_-^j + i\,g_j\,a$$

$$\frac{d}{dt}\Sigma = -\frac{\Gamma}{2}\Sigma + g_{\mathrm{ens}} a$$

Assuming a Lorentzian spin frequency distribution

Optimal absorption ?

Problem : Maximize $\frac{\int_t |\Sigma_a^{\text{out}}|^2}{\int_t |a_{\text{in}}|^2}$



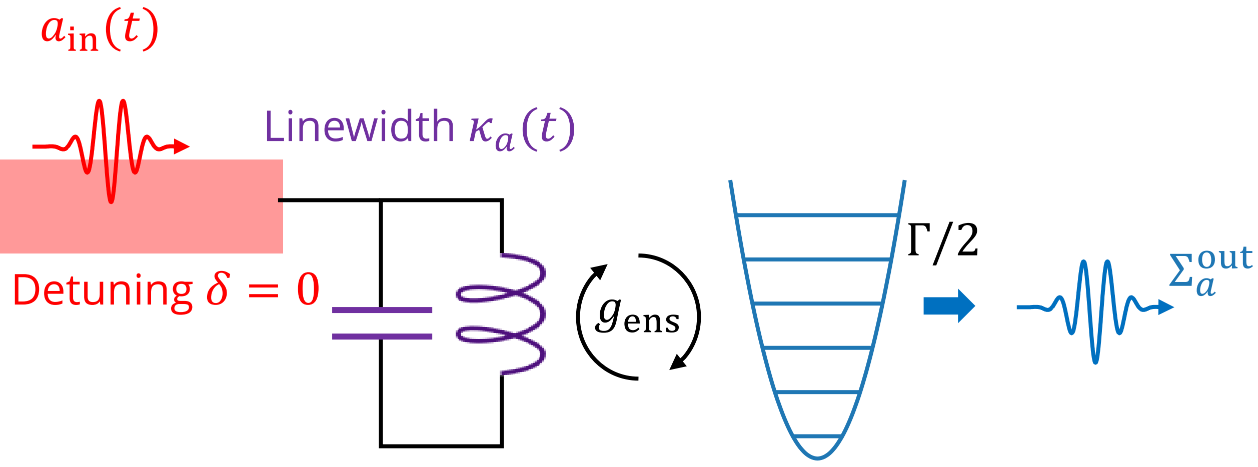
Cavity during absorption $\boldsymbol{a}$

Spin mode for absorption $\boldsymbol{\Sigma_a}$

$$\dot{a} = -\frac{[\kappa_0 + \boldsymbol{\kappa(t)}]}{2} a - g_{\text{ens}} \Sigma_{\text{a}} + \sqrt{\kappa(t)}\, a_{\text{in}}$$
$$\dot{\boldsymbol{\Sigma}}_a = -\Gamma/2 \quad \boldsymbol{\Sigma}_a + g_{\text{ens}}\, \boldsymbol{a}$$

Optimal absorption ?

Problem : Maximize $\dfrac{\int_t |\Sigma_a^{\text{out}}|^2}{\int_t |a_{\text{in}}|^2}$



Cavity during absorption $\boldsymbol{a}$

Spin mode for absorption $\boldsymbol{\Sigma_a}$

- Opt. solution given by $\kappa(t) = \left|\dfrac{f_2}{f_1}\right|$
- Theoretical bound on absorption efficiency

$$\eta_a = \frac{1}{\min\limits_{\kappa>0} \int_t |a_{in}|^2} \leq \frac{1}{\int_t 4 f_1 f_2} \leq \frac{\kappa_s}{\kappa_0 + \kappa_s}$$

$$\dot{\boldsymbol{a}} = -\frac{[\kappa_0 + \boldsymbol{\kappa(t)}]}{2}\boldsymbol{a} - g_{\text{ens}}\,\Sigma_{\text{a}} + \sqrt{\kappa(t)}\,a_{\text{in}}$$
$$\dot{\boldsymbol{\Sigma}}_{\boldsymbol{a}} = -\Gamma/2 \quad \boldsymbol{\Sigma_a} + g_{\text{ens}}\,\boldsymbol{a}$$

$\Rightarrow$

$$a_{\text{in}} = \sqrt{\kappa}\, f_1(\Sigma_a, \dot{\Sigma}_a, \ddot{\Sigma}_a) + \frac{1}{\sqrt{\kappa}} f_2(\Sigma_a, \dot{\Sigma}_a, \ddot{\Sigma}_a)$$

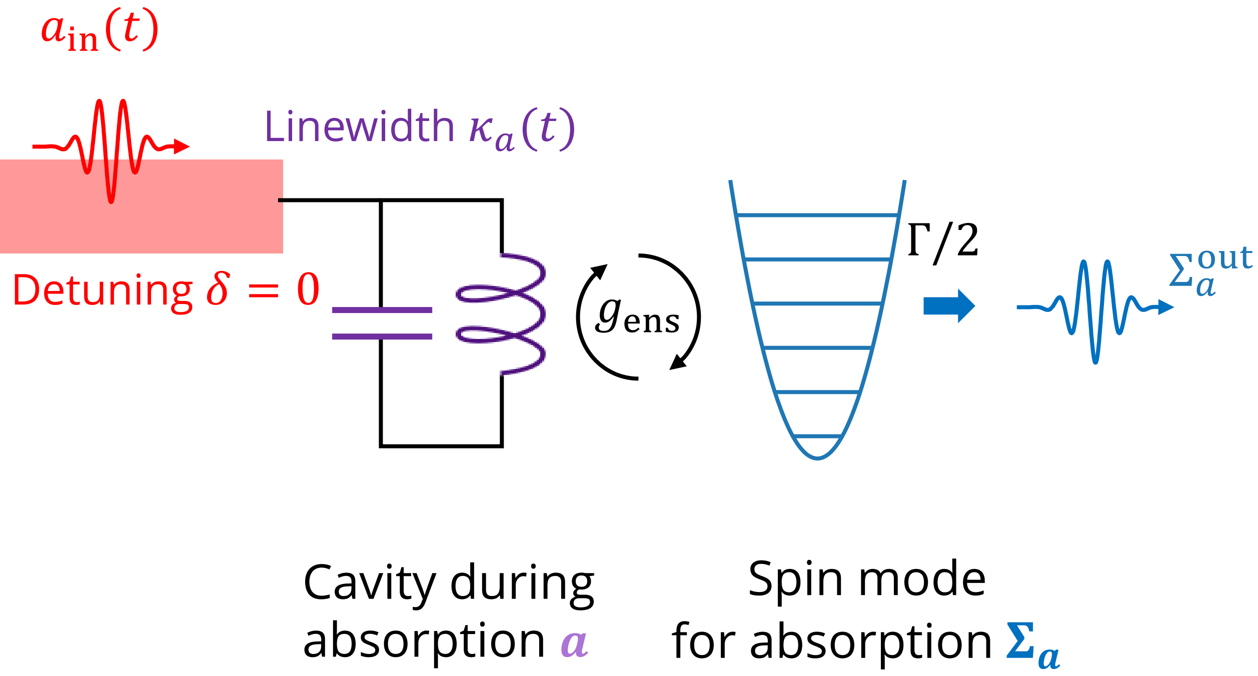
$$f_1 = \frac{1}{4\, g_{\text{ens}}}(\Gamma\,\Sigma_a + 2\,\dot{\Sigma}_a)$$

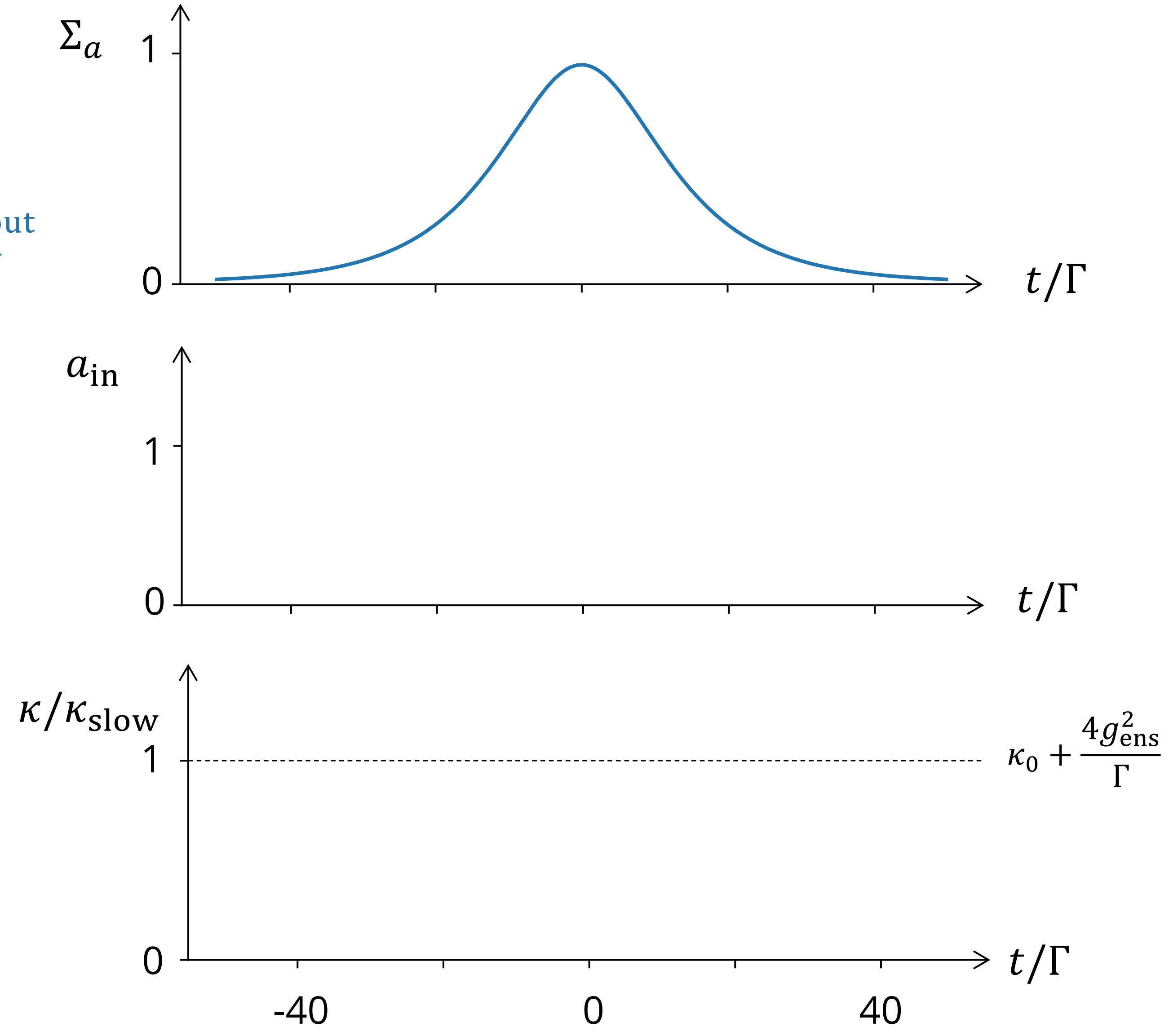
$$f_2 = \frac{1}{g_{\text{ens}}}\left(\left(\frac{g_{\text{ens}}^2}{\Gamma} + \kappa_0\right)\Sigma_a + \left(\frac{\Gamma}{2} + \frac{\kappa_0}{2}\right)\Gamma\,\dot{\Sigma}_a + \Gamma^2 \ddot{\Sigma}_a\right)$$

Numerical simulations

Let's consider $\Sigma_a = \dfrac{1}{\cosh(\alpha\Gamma t)}$

$\kappa_0 = 0.03\,\Gamma$
$g_{\text{ens}} = \Gamma/2$





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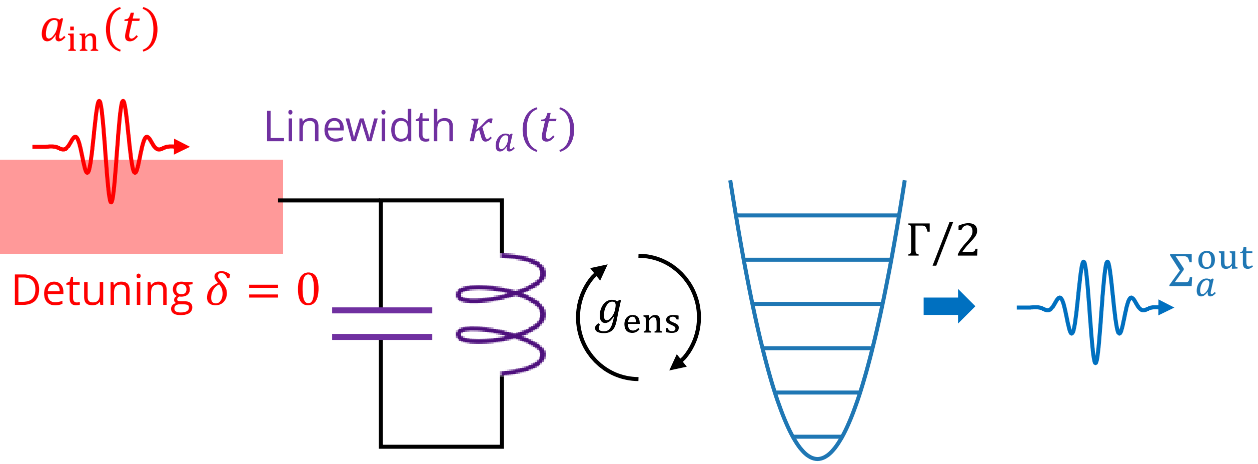
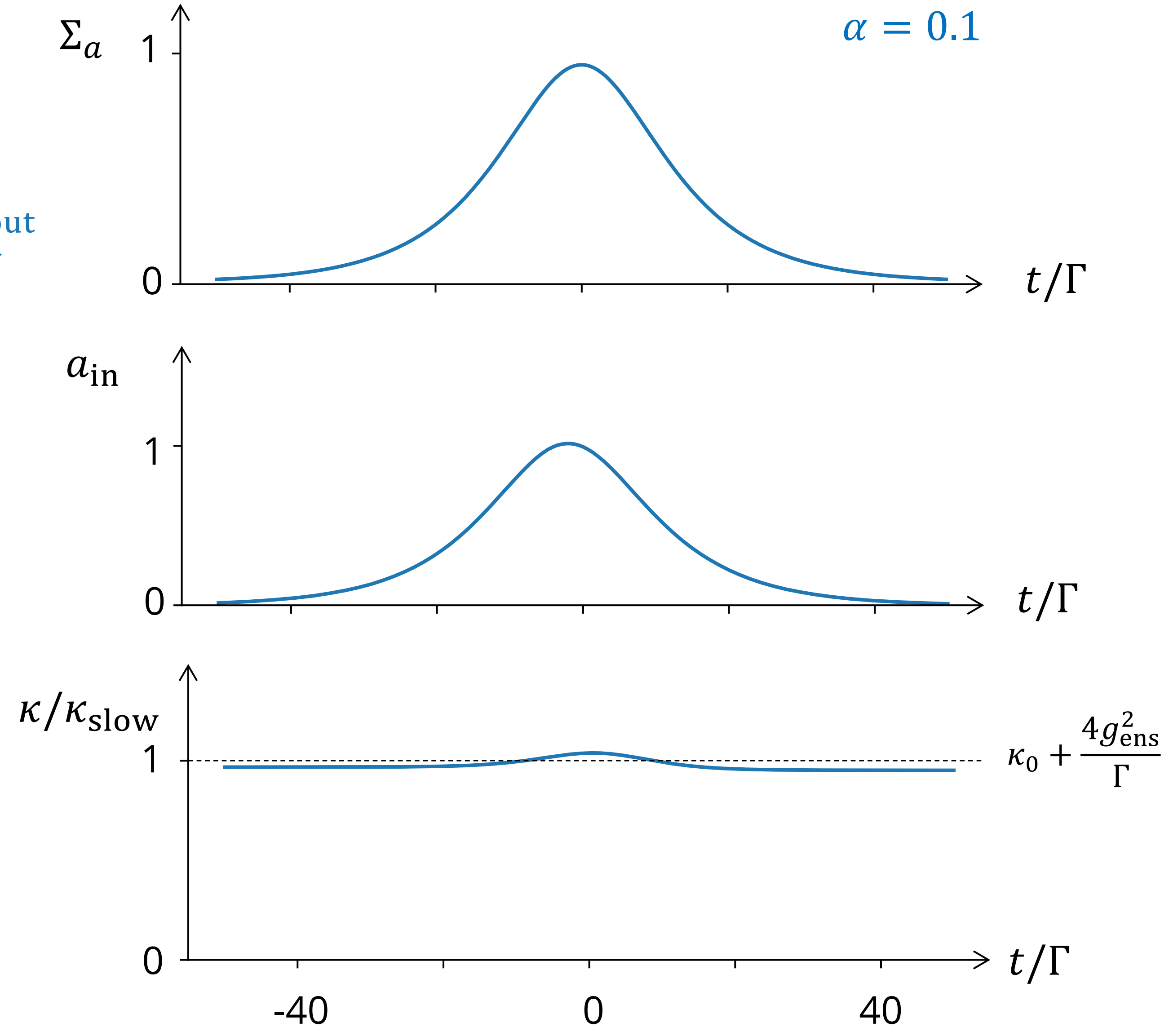


Cavity during absorption a

Spin mode for absorption $\boldsymbol{\Sigma_a}$



$$
\begin{cases}
a = f(\Sigma_a, \dot{\Sigma}_a) \text{ and so} \\
a_{\text{in}} = \sqrt{\kappa}\, f_1(\Sigma_a, \dot{\Sigma}_a, \ddot{\Sigma}_a) + \dfrac{1}{\sqrt{\kappa}} f_2(\Sigma_a, \dot{\Sigma}_a, \ddot{\Sigma}_a) \\
\kappa_a(t) = \left| \dfrac{f_2(t)}{f_1(t)} \right|
\end{cases}
$$

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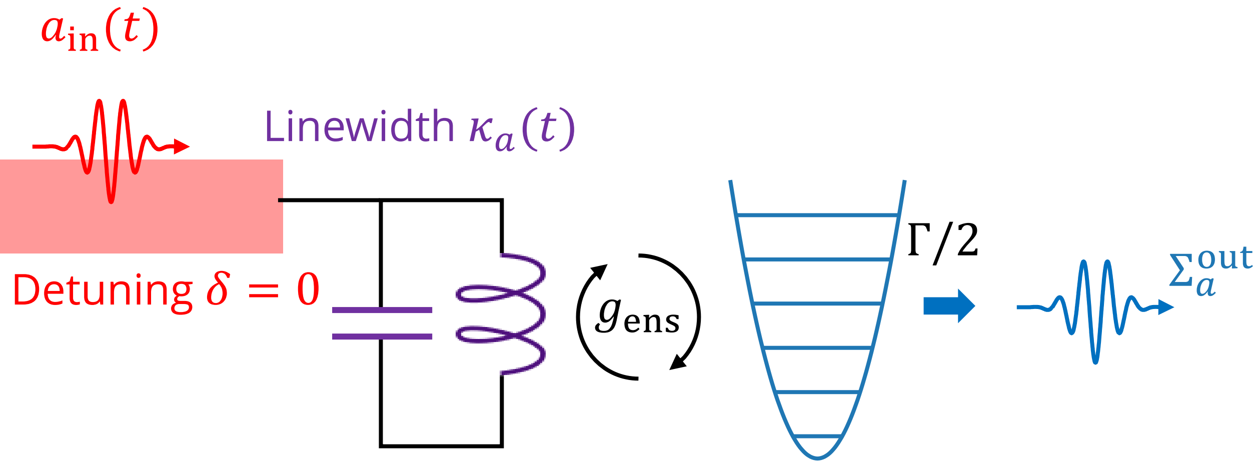
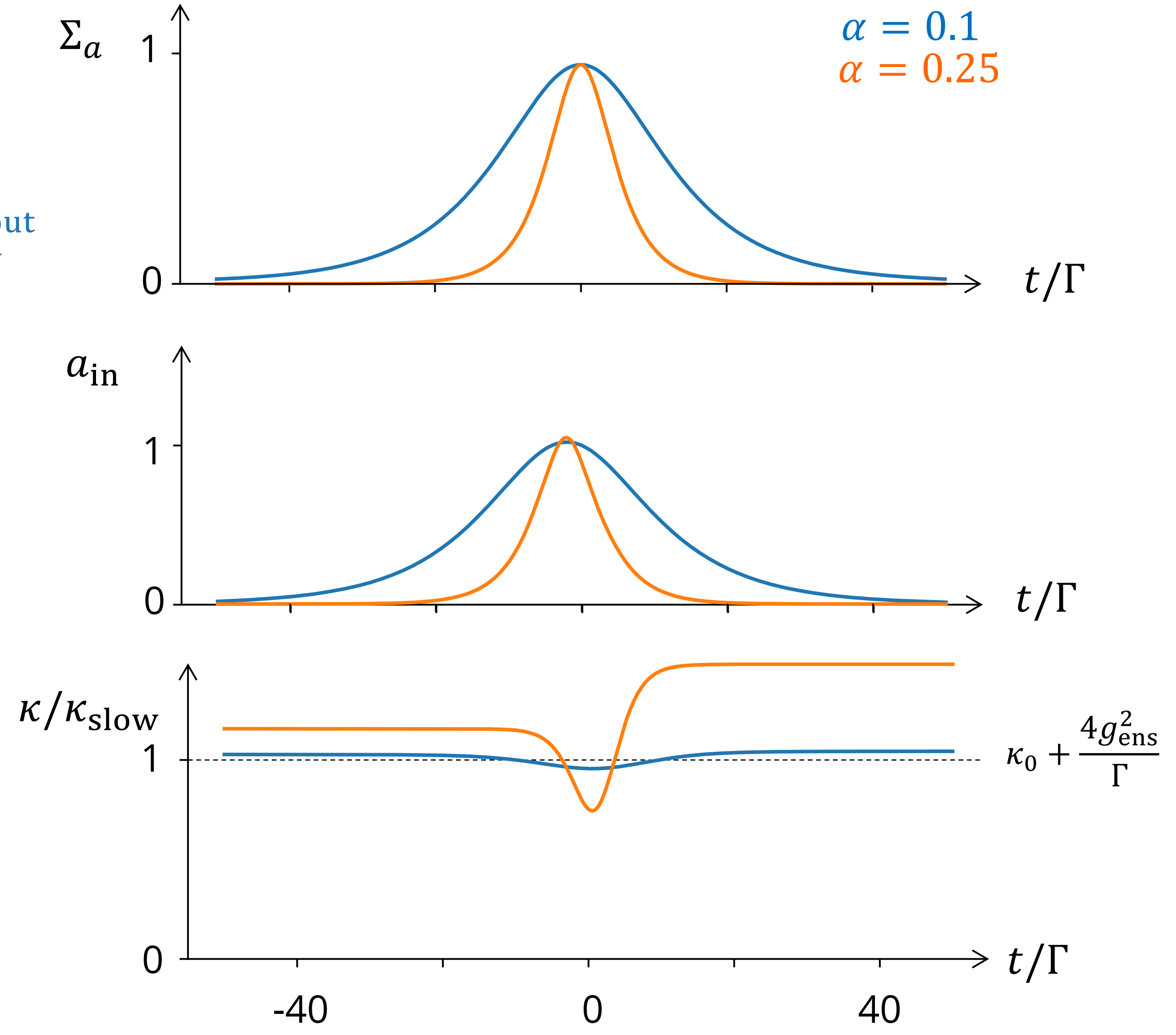


Cavity during absorption a

Spin mode for absorption $\boldsymbol{\Sigma_a}$



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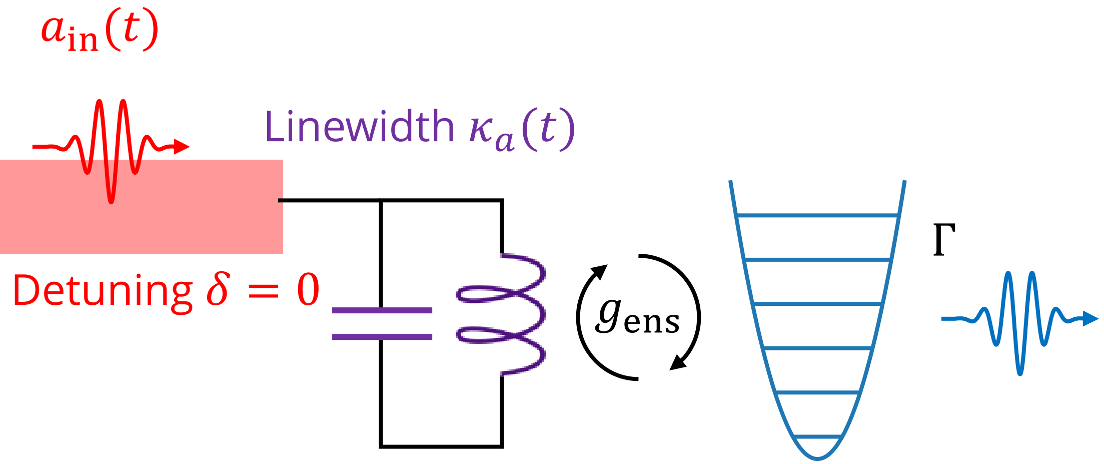
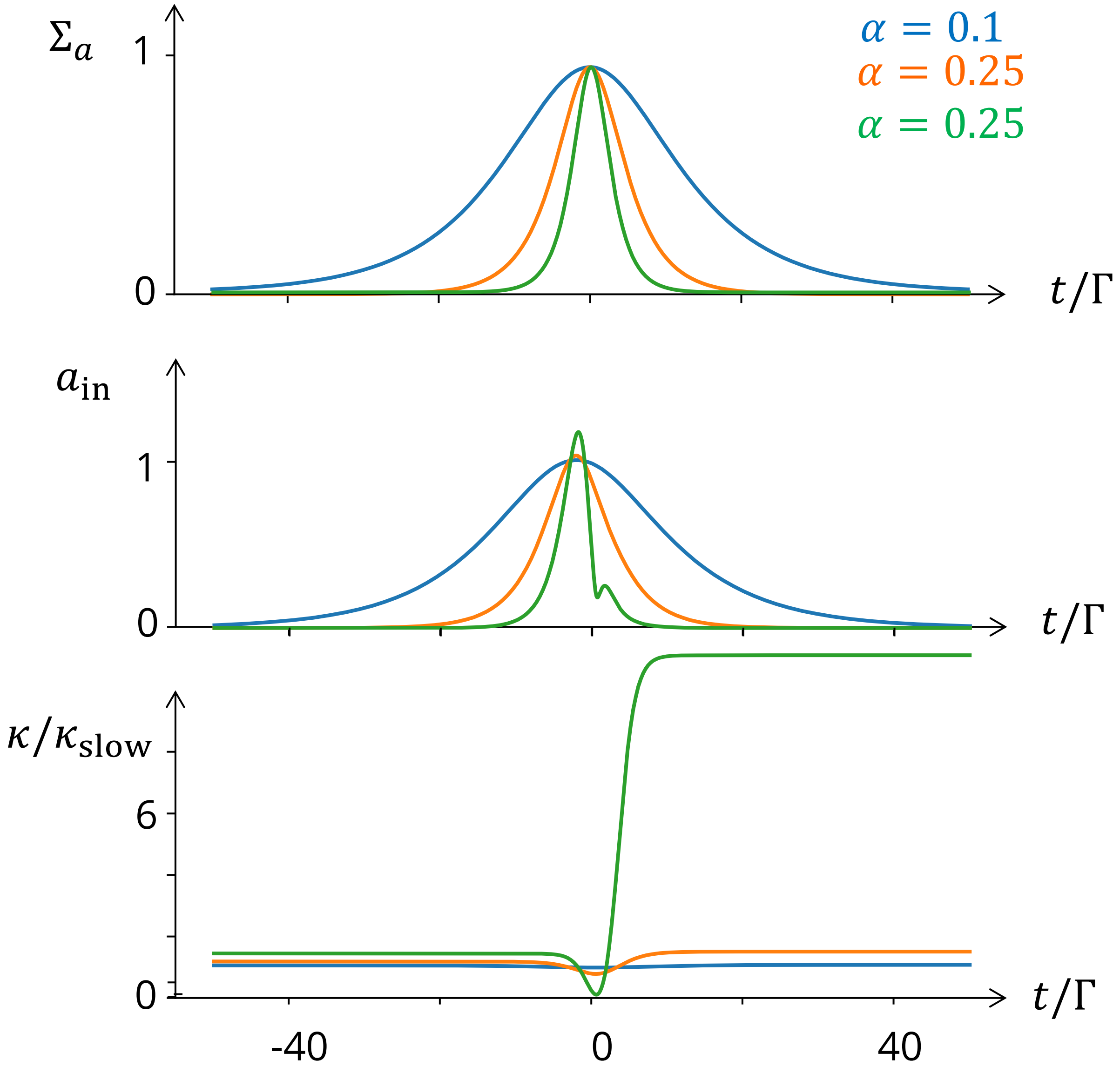


Cavity during absorption $\boldsymbol{a}$

Spin mode for absorption $\boldsymbol{\Sigma_a}$

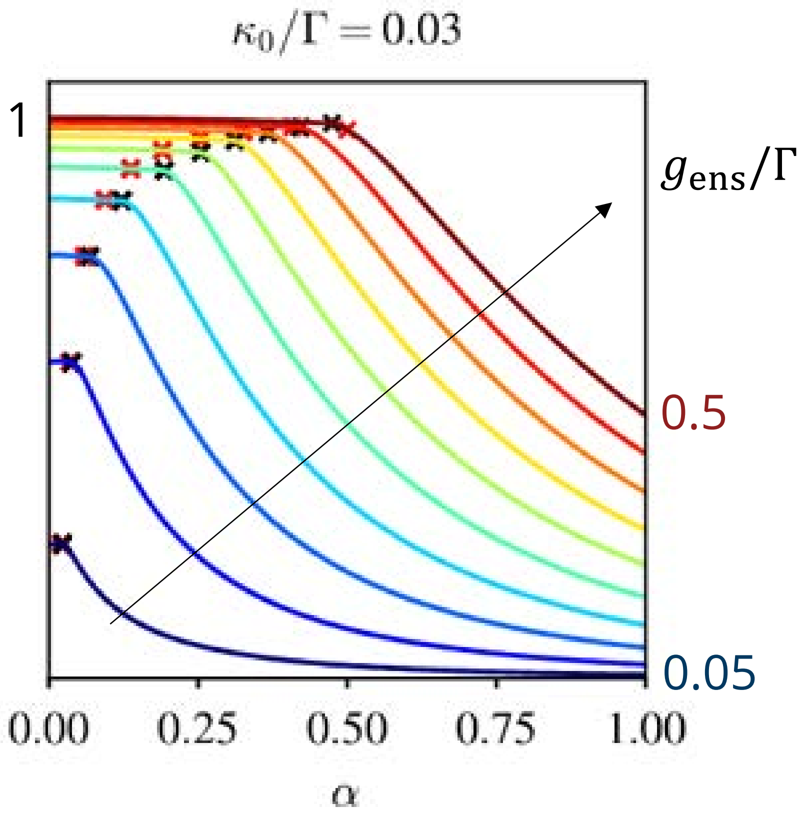


$$
\begin{cases}
a = f(\Sigma_a, \dot{\Sigma}_a) \text{ and so} \\
a_{\text{in}} = \sqrt{\kappa}\, f_1(\Sigma_a, \dot{\Sigma}_a, \ddot{\Sigma}_a) + \frac{1}{\sqrt{\kappa}} f_2(\Sigma_a, \dot{\Sigma}_a, \ddot{\Sigma}_a) \\
\kappa_a(t) = \left|\dfrac{f_2(t)}{f_1(t)}\right|
\end{cases}
$$

Numerical simulations

$\kappa_0 = 0.03\,\Gamma$
$g_{\text{ens}} = \Gamma/2$

Absorption efficiency



Bandwidth
(in units of Γ)

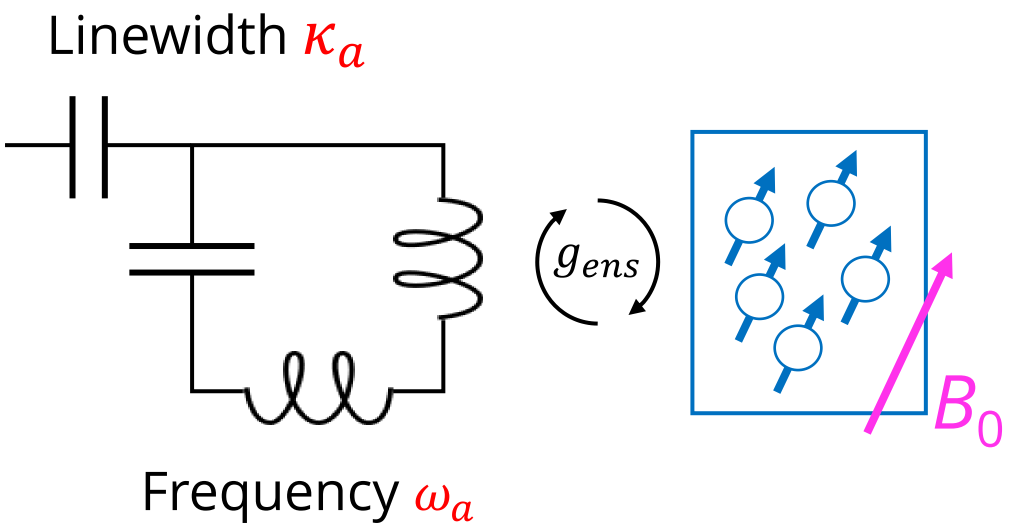
Higher coupling means higher efficiency

Max. absorption bandwidth given by Γ/2

L. Greggio, to appear in *PRA,* 2026

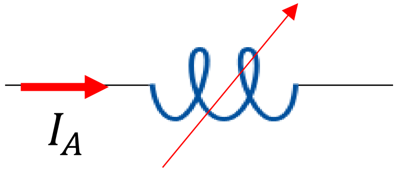
other approach : J. Bernad, *J. Phys. B: At. Mol. Opt. Phys.* 2025

Quantum memory requirements

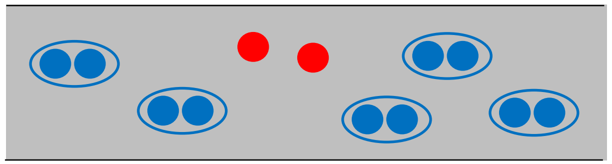


- ❑ Long spin coherence
  Aim for clock transitions
- ❑ Reach unit cooperativity
- ❑ Tunable resonator frequency
  - ❑ For echo silencing
  - ❑ For aiming at clock transitions
- ❑ Tunable linewidth
  - ❑ For cooperativity tuning
  - ❑ For perfect absorption

Tuning a superconducting circuit in magnetic field: kinetic inductance of the film



$$L(I_A) = L_G + L_{kin} + L_{kin}\left(\frac{I_A}{I_*}\right)^2$$



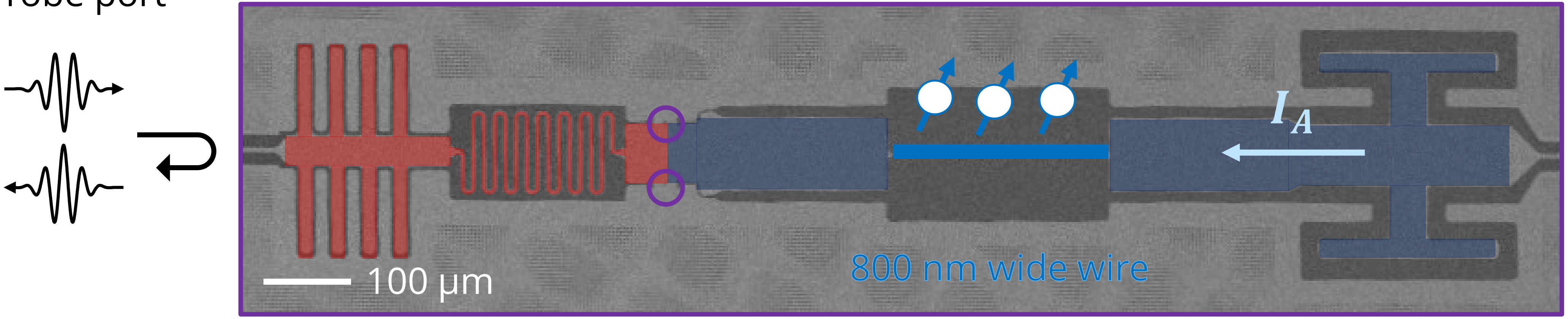
Kubo, T. Phys. Rev. Res. 2, 033203 (2020).

The device, version 1

Buffer resonator $\frac{\omega_B}{2\pi} = 6.6$ GHz, $Q_B = 1.3\ 10^3$

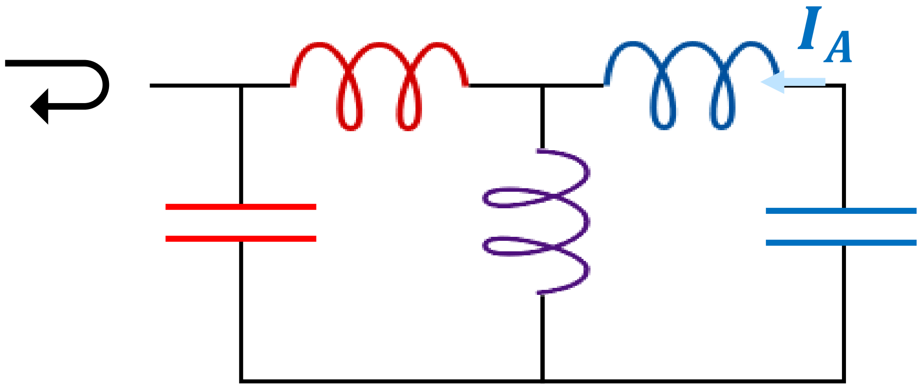
Auxiliary resonator

Probe port



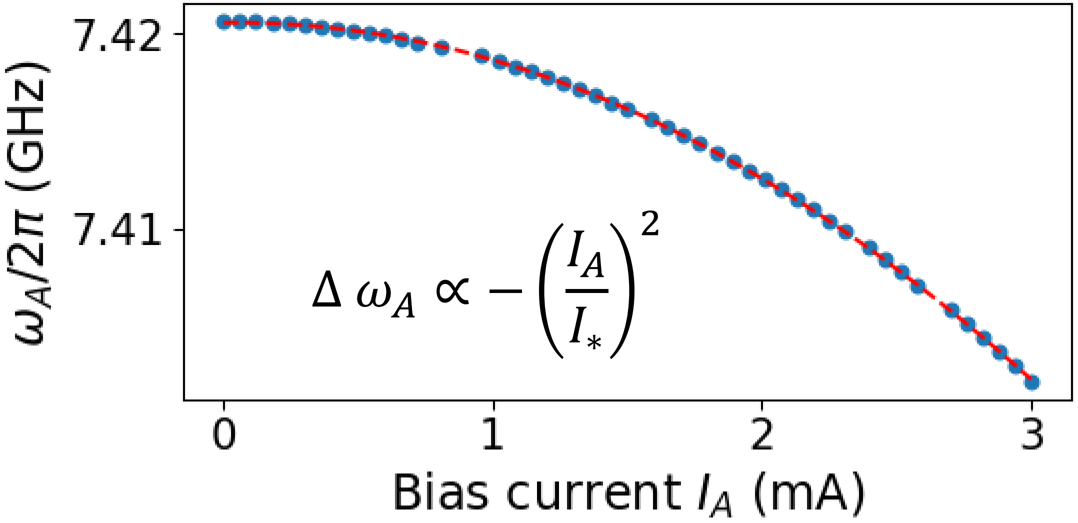
DC port

$\frac{\omega_A}{2\pi} = 7.4$ GHz, $Q_A = 4.5\ 10^4$



Buffer **Auxiliary**

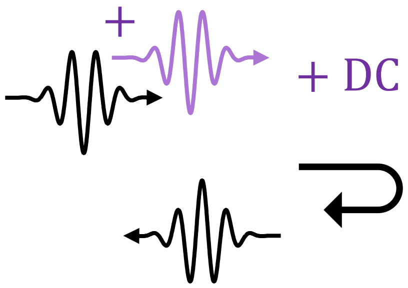
Asfaw, A. T., et al. *APL*, 2017



50-nm NbTiN (L_{kin} = 2 pH/□) on silicon

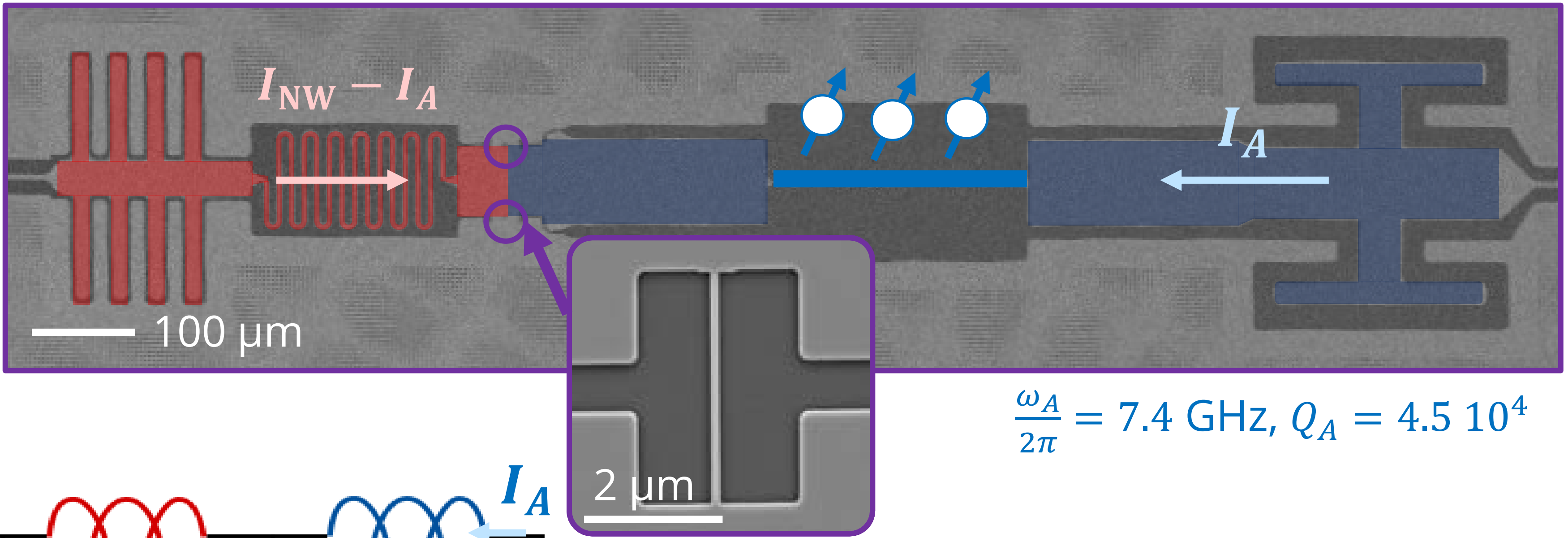
The device : frequency tuning

ω_p, amplitude ξ



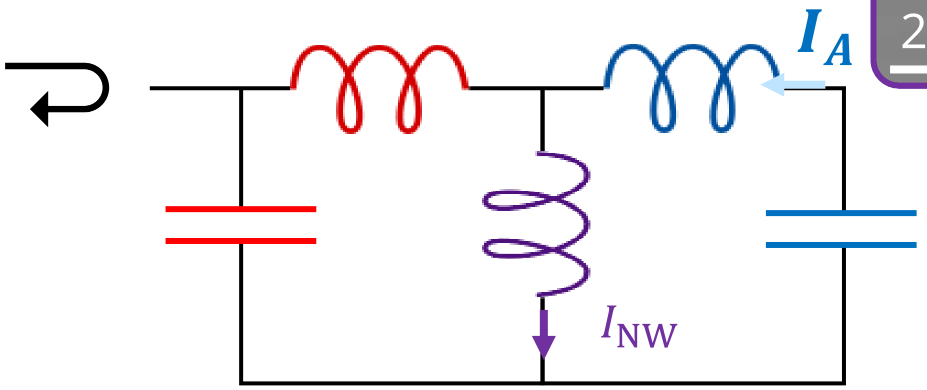
Buffer resonator $\frac{\omega_B}{2\pi} = 6.6$ GHz, $Q_B = 1.3\ 10^3$

Auxiliary resonator



DC port

$\frac{\omega_A}{2\pi} = 7.4$ GHz, $Q_A = 4.5\ 10^4$



Buffer **Auxiliary**

Parametric coupling to buffer resonator
for linewidth modulation

DC current I_{NW} + AC pump @ $\omega_p = \omega_A - \omega_B$

$$L_{NW} - L_{NW}^0 = L_{kin}^{NW}\left(\frac{I_{NW} + \xi\cos(\omega_p t)}{I_*}\right)^2$$

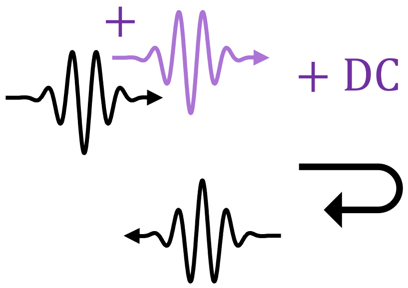
50-nm NbTiN (L_{kin} = 2 pH/□) on silicon

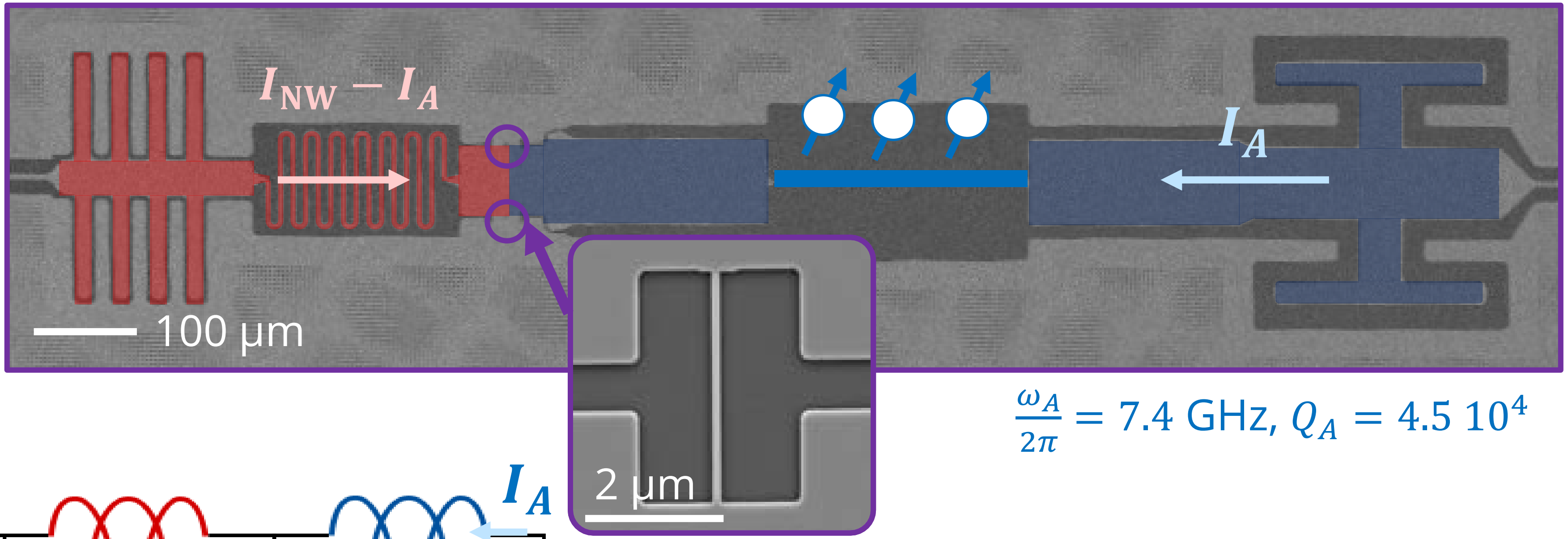
The device : frequency tuning

Buffer resonator $\frac{\omega_B}{2\pi} = 6.6\text{ GHz}, Q_B = 1.3\ 10^3$

Auxiliary resonator

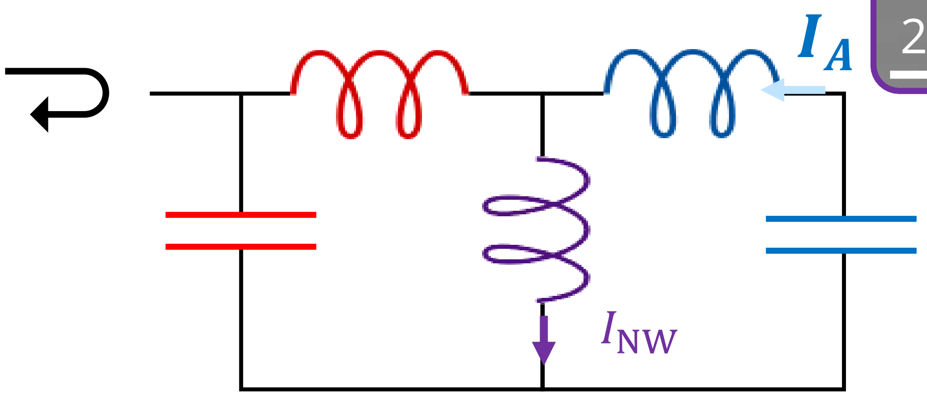
ω_p, amplitude ξ





DC port

$\frac{\omega_A}{2\pi} = 7.4\text{ GHz}, Q_A = 4.5\ 10^4$



Buffer **Auxiliary**

Parametric coupling to buffer resonator
for linewidth modulation

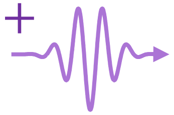
$\boldsymbol{H}_{3\text{WM}} = g_{3WM}\, \boldsymbol{a}^\dagger \boldsymbol{b} + h.c.$ where $g_{3WM} \propto I_{\text{NW}}\xi.$

Effective linewidth $\kappa_A^{\text{eff}} = \kappa_A + \frac{4g_{3WM}^2}{\kappa_B}$

50-nm NbTiN (L_{kin} = 2 pH/□) on silicon

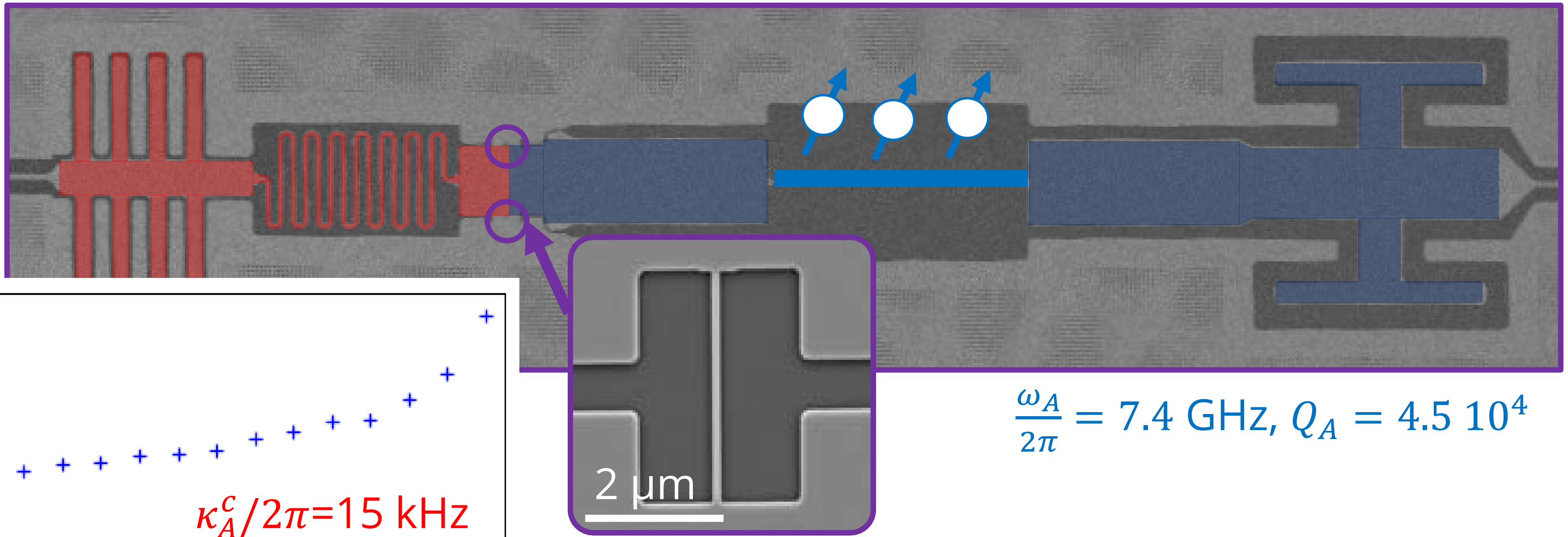
The device: three-wave mixing

ω_p, amplitude ξ

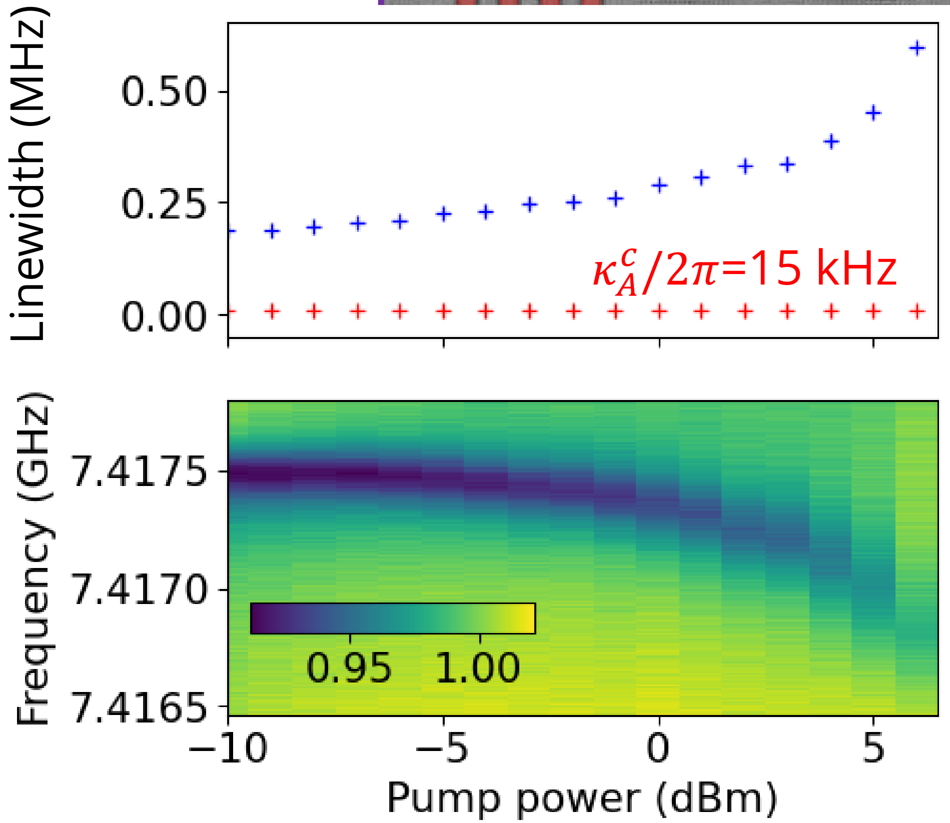


Buffer resonator $\frac{\omega_B}{2\pi} = 6.6\ \mathrm{GHz},\ Q_B = 1.3\ 10^3$

Auxiliary resonator



$\frac{\omega_A}{2\pi} = 7.4\ \mathrm{GHz},\ Q_A = 4.5\ 10^4$



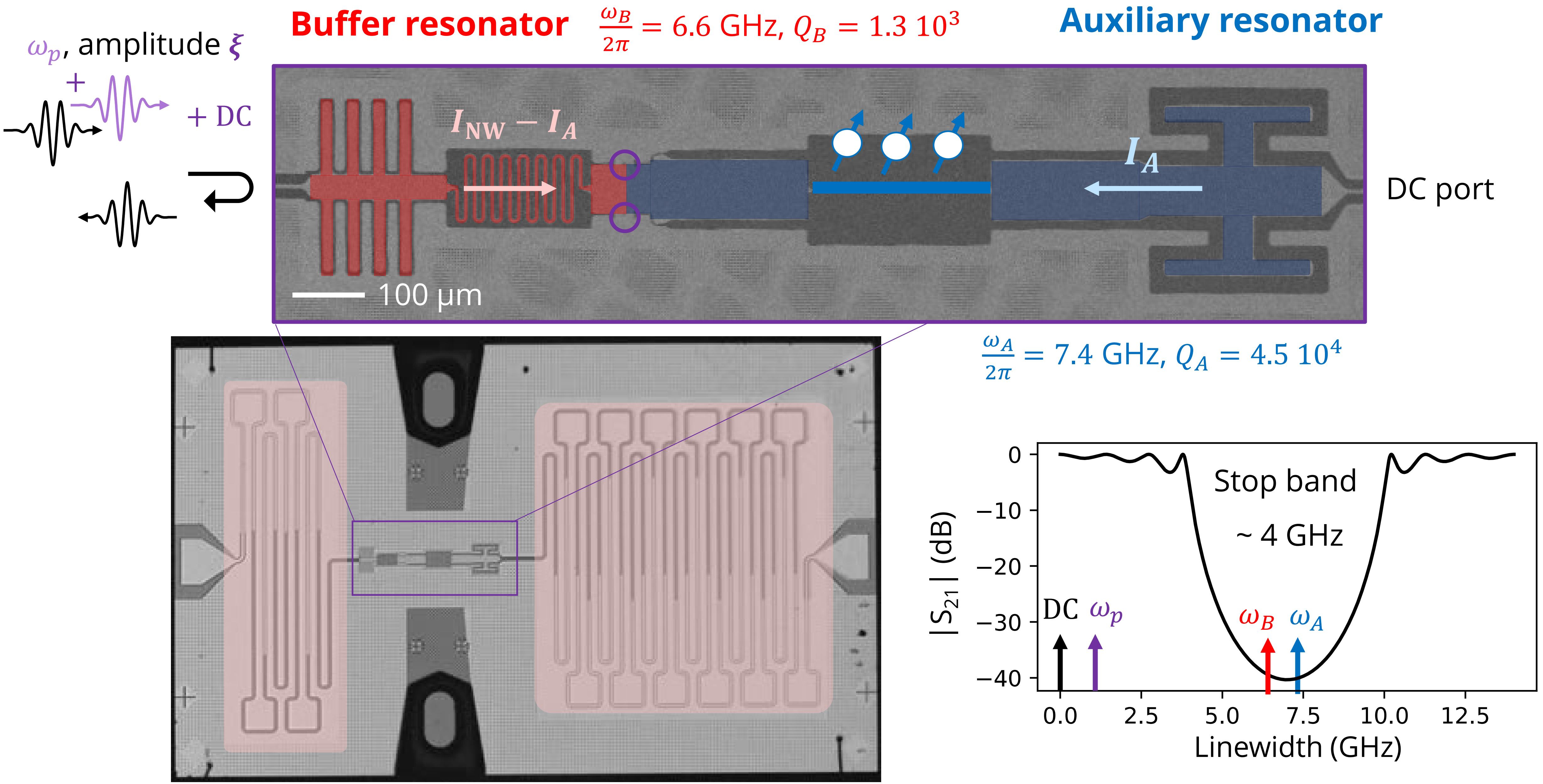
Parametric coupling to buffer resonator
for linewidth modulation

$$\boldsymbol{H}_{3\mathrm{WM}} = g_{3WM}\,\boldsymbol{a}^{\dagger}\boldsymbol{b} + h.c.,\ \text{if } \omega_p + \omega_B = \omega_A$$

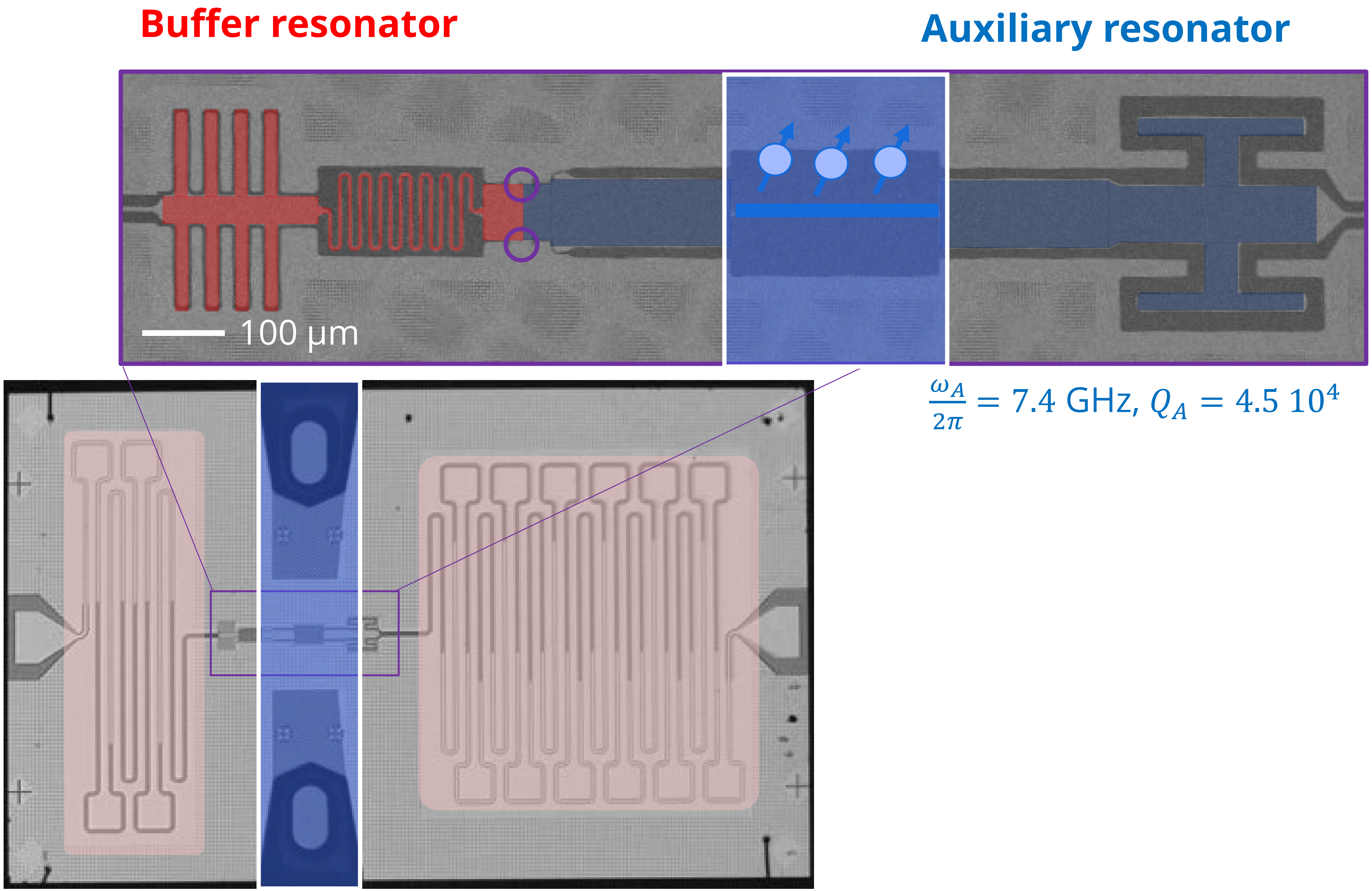
Effective linewidth $\kappa_A^{\mathrm{eff}} = \kappa_A + \frac{4g_{3WM}^2}{\kappa_B}$

where $g_{3WM} \propto I_{\mathrm{NW}}\xi$.

The device : tuning via Bragg filters

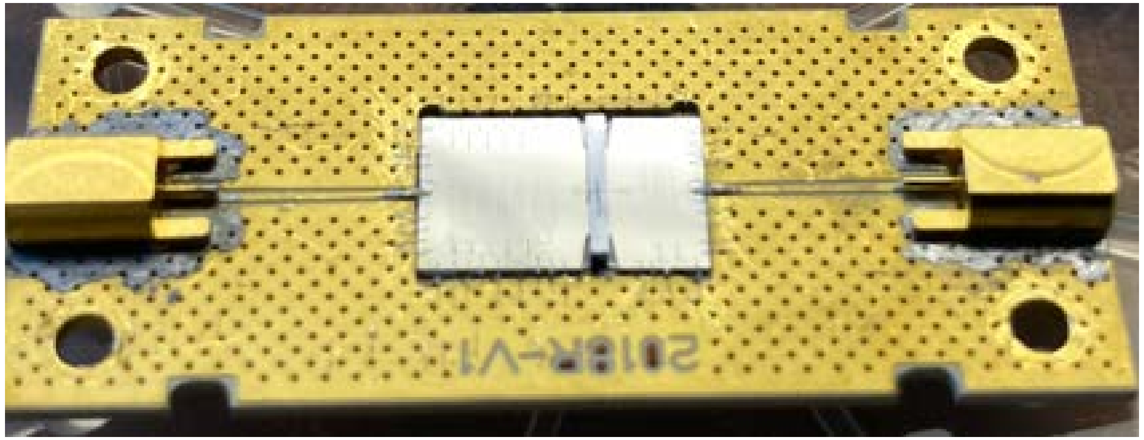


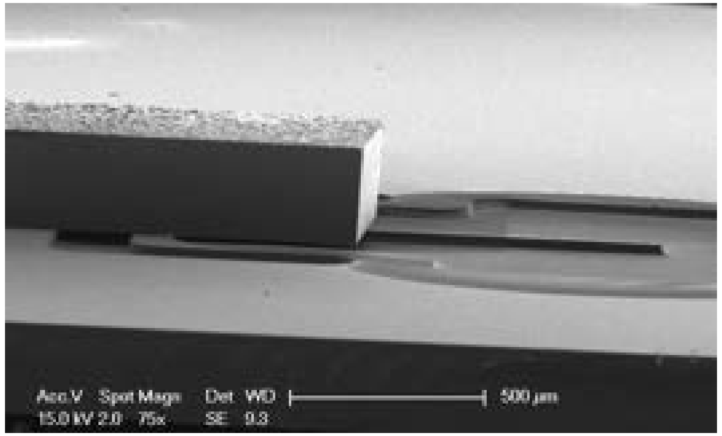
The device : spins

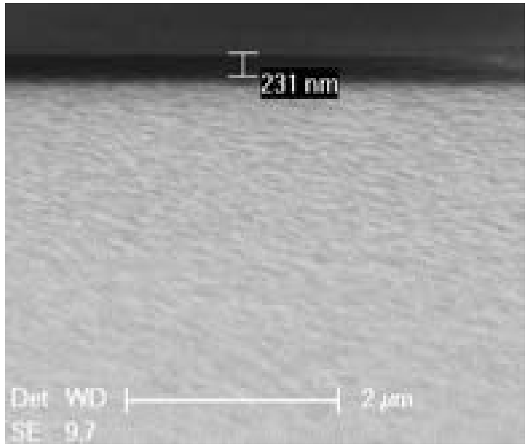


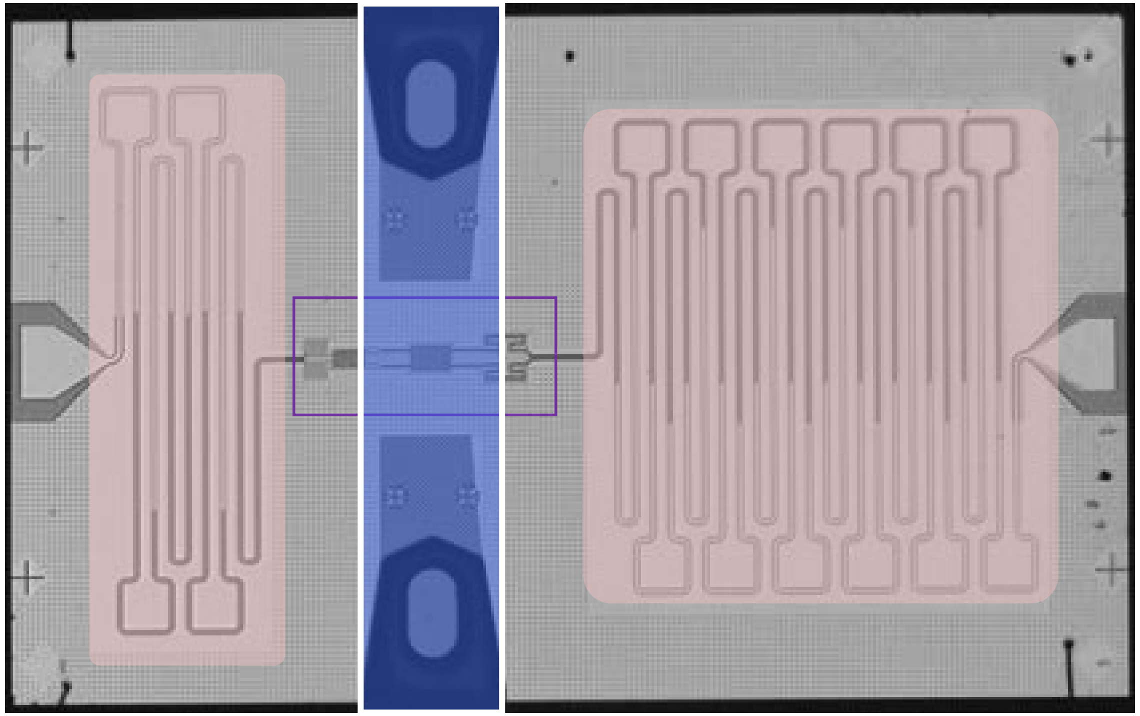
$\frac{\omega_A}{2\pi} = 7.4$ GHz, $Q_A = 4.5\ 10^4$

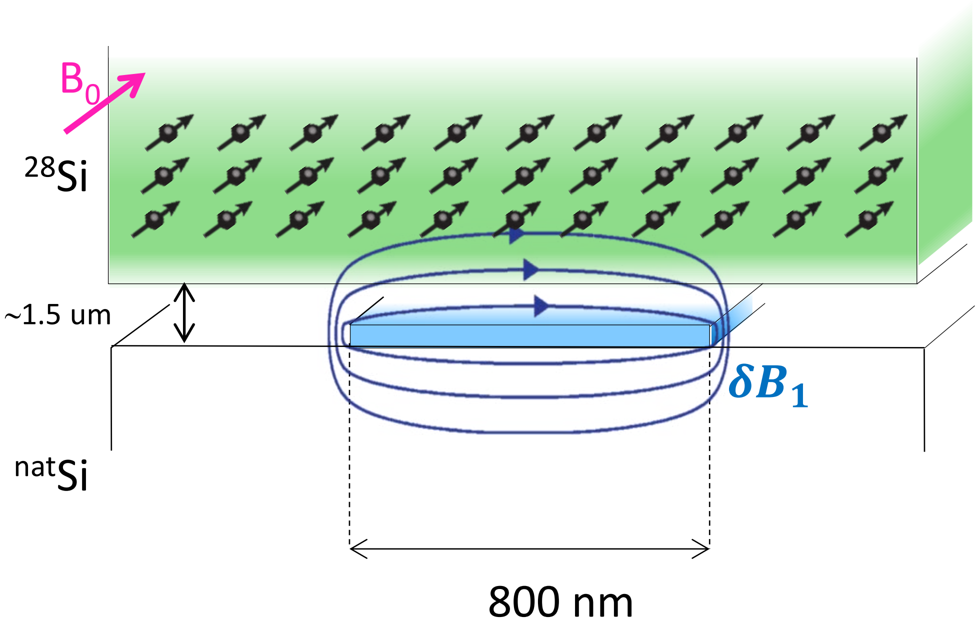
The device : spins



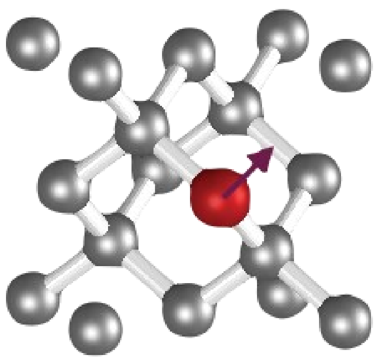








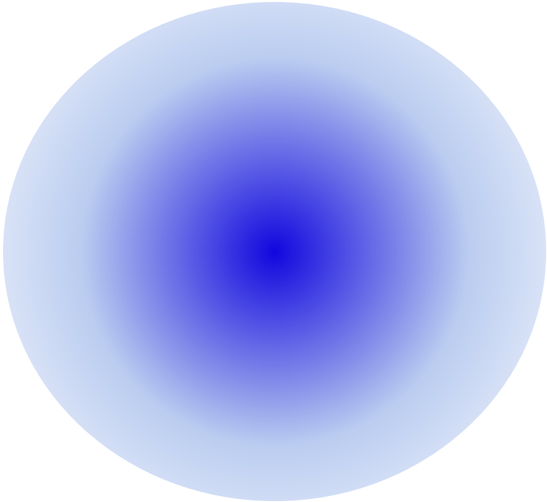
Bismuth donors in silicon



^{209}Bi

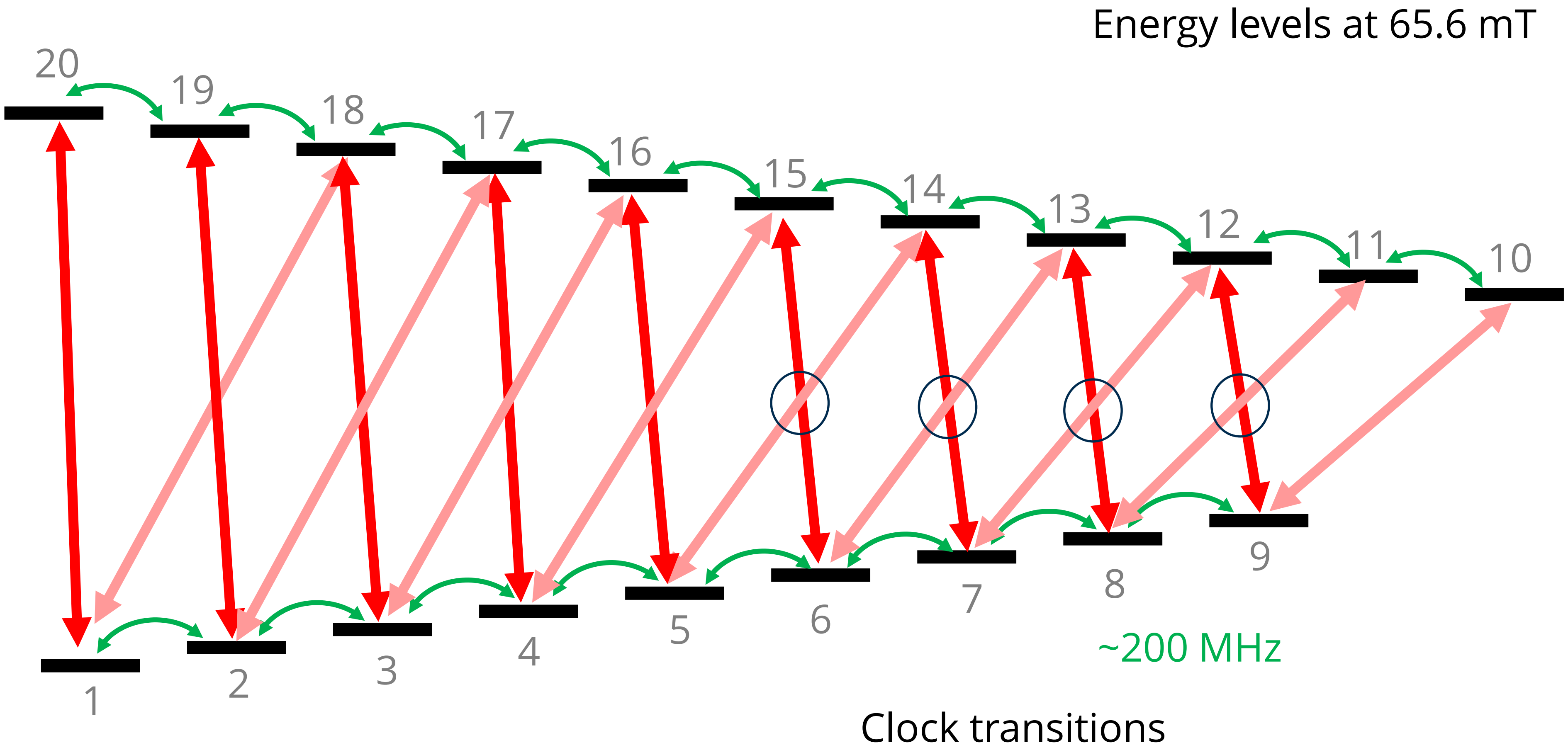
Nuclear spin
I = 9/2

Bismuth donors in silicon



Nuclear spin
I = 9/2

Electronic spin
S= ½

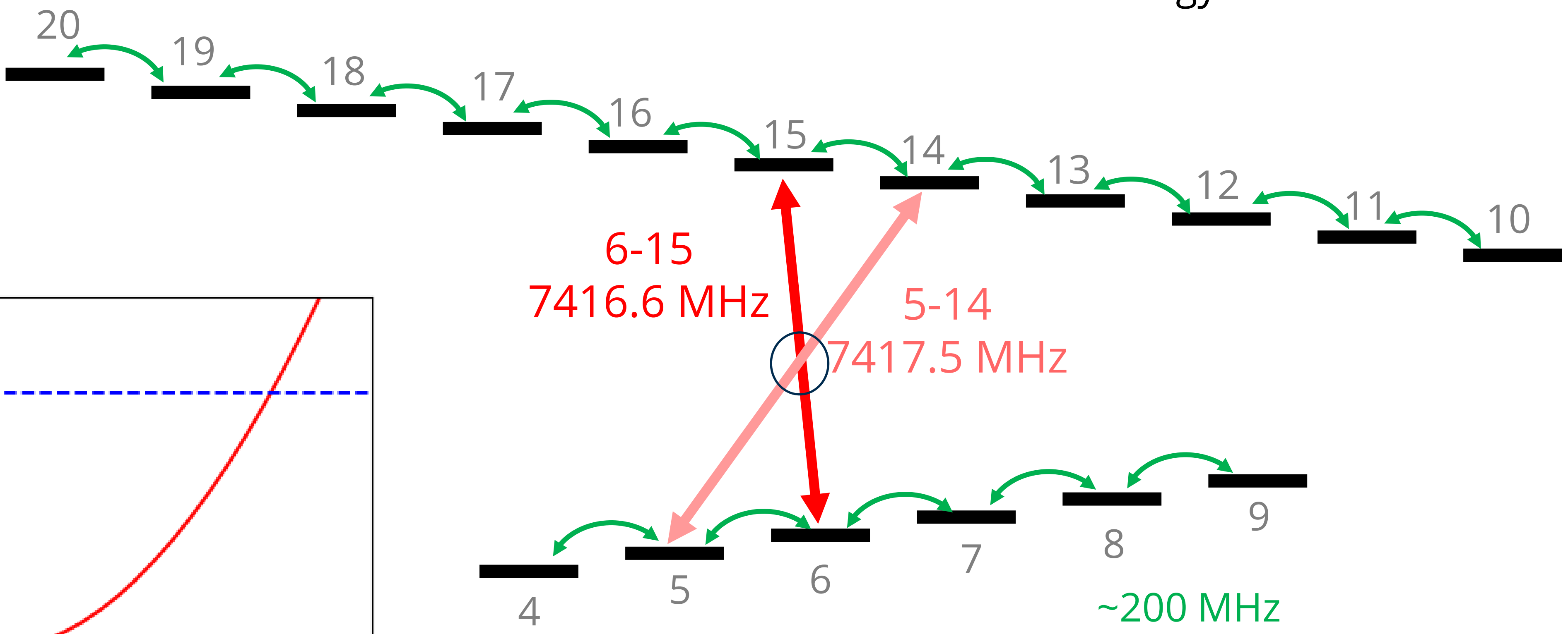


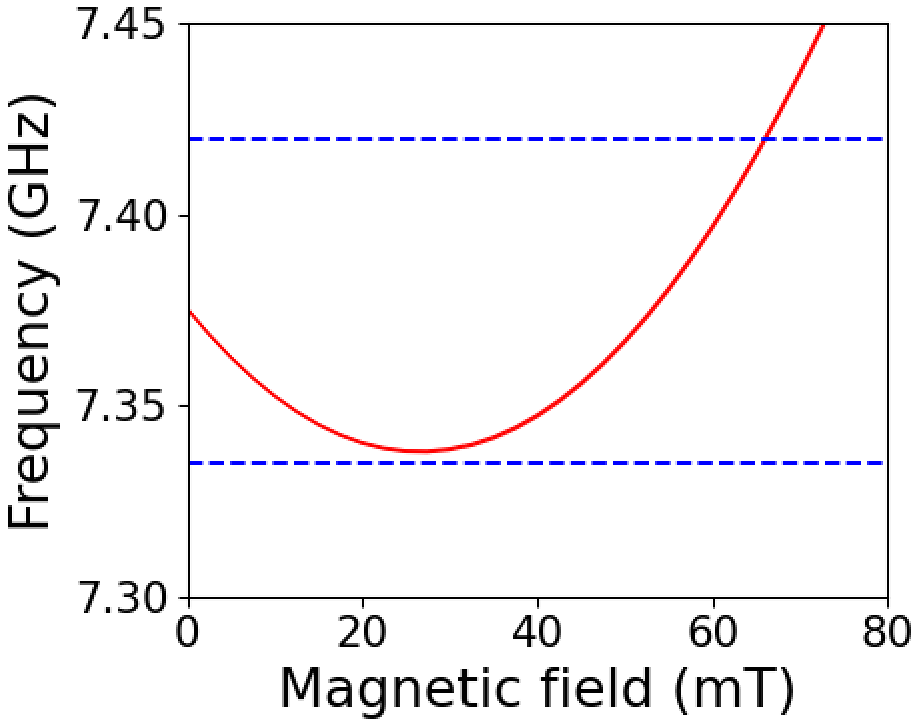
$$\frac{H}{\hbar} = AI \cdot S + B_0 \cdot (-\gamma_e S + \gamma_n I)$$

HYPERFINE ZEEMAN EFFECT

Bismuth donors in silicon

Energy levels at 65.6 mT

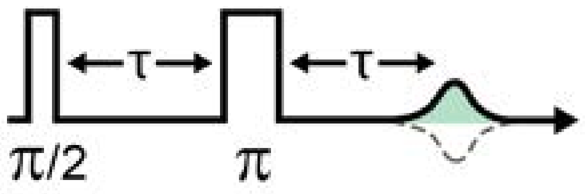


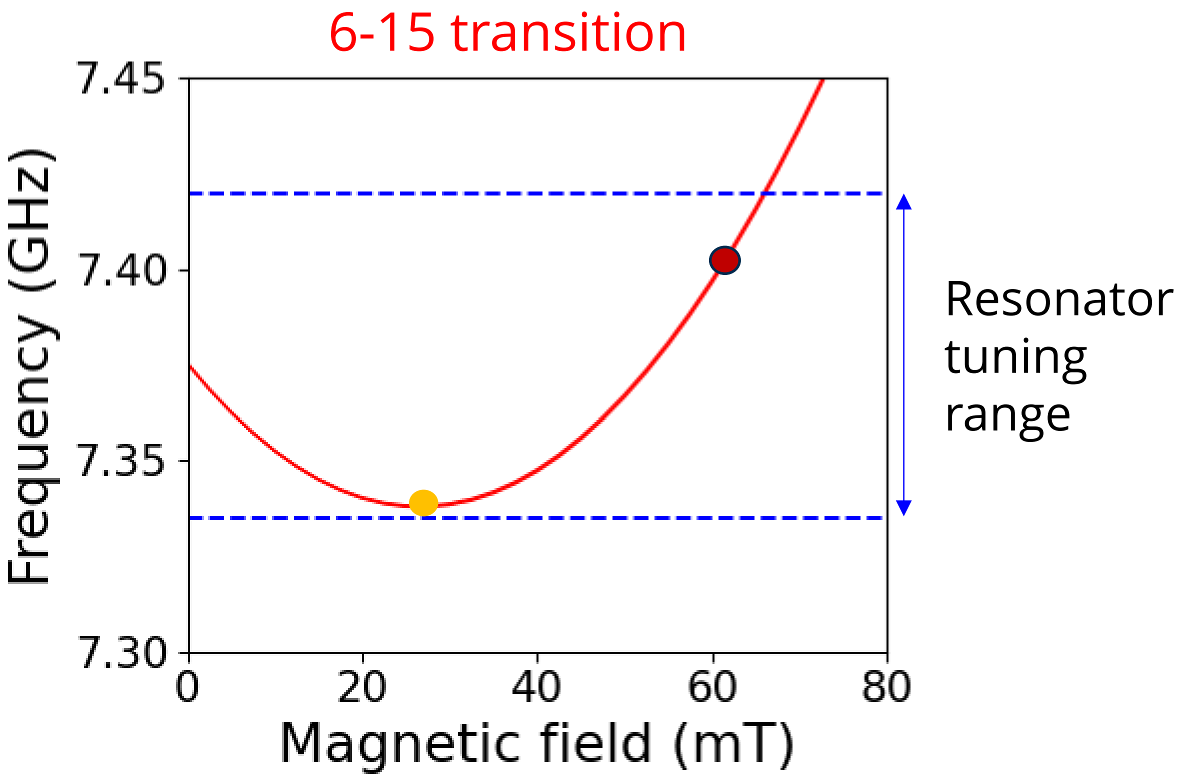


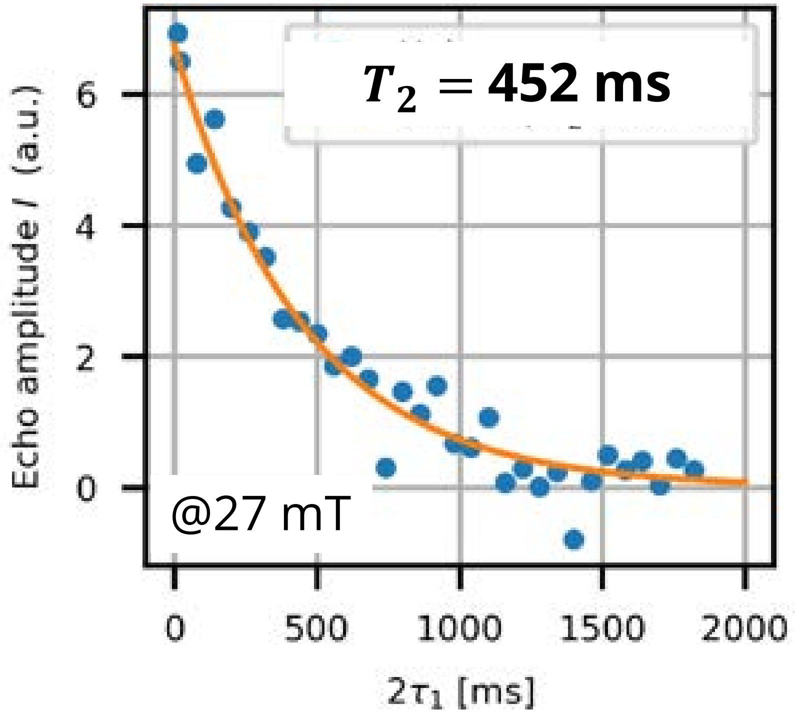
$$\frac{H}{\hbar} = \boldsymbol{A I} \cdot \boldsymbol{S} + \boldsymbol{B_0} \cdot \left(-\gamma_e \boldsymbol{S} + \gamma_n \boldsymbol{I}\right)$$

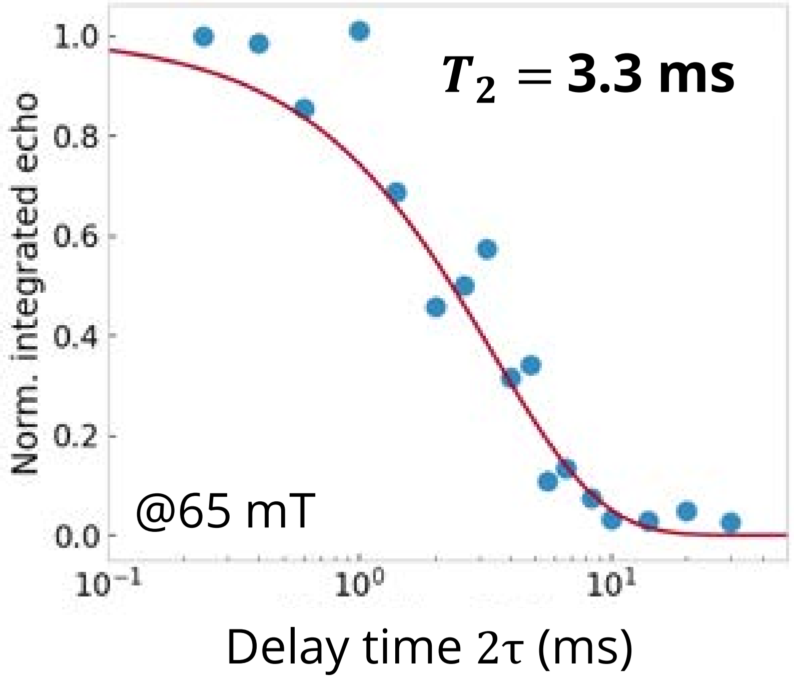
HYPERFINE **ZEEMAN EFFECT**

Bismuth donors in silicon

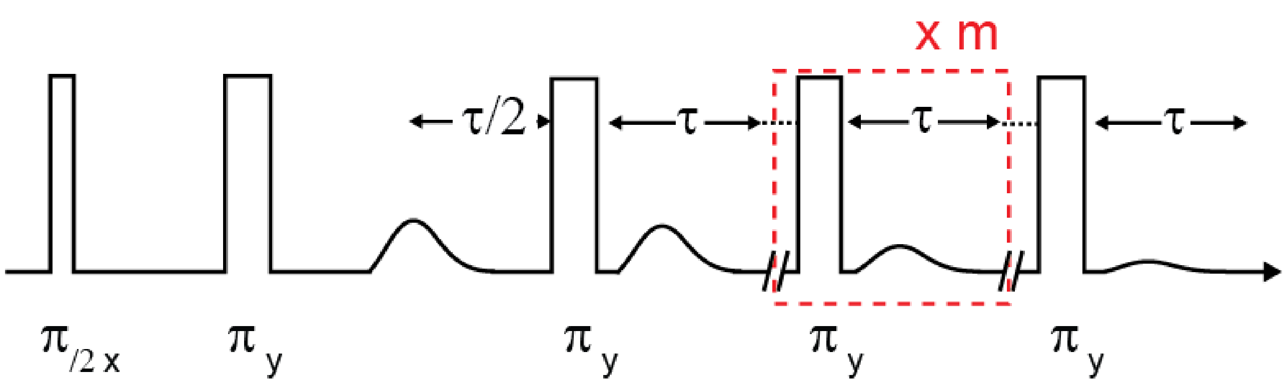


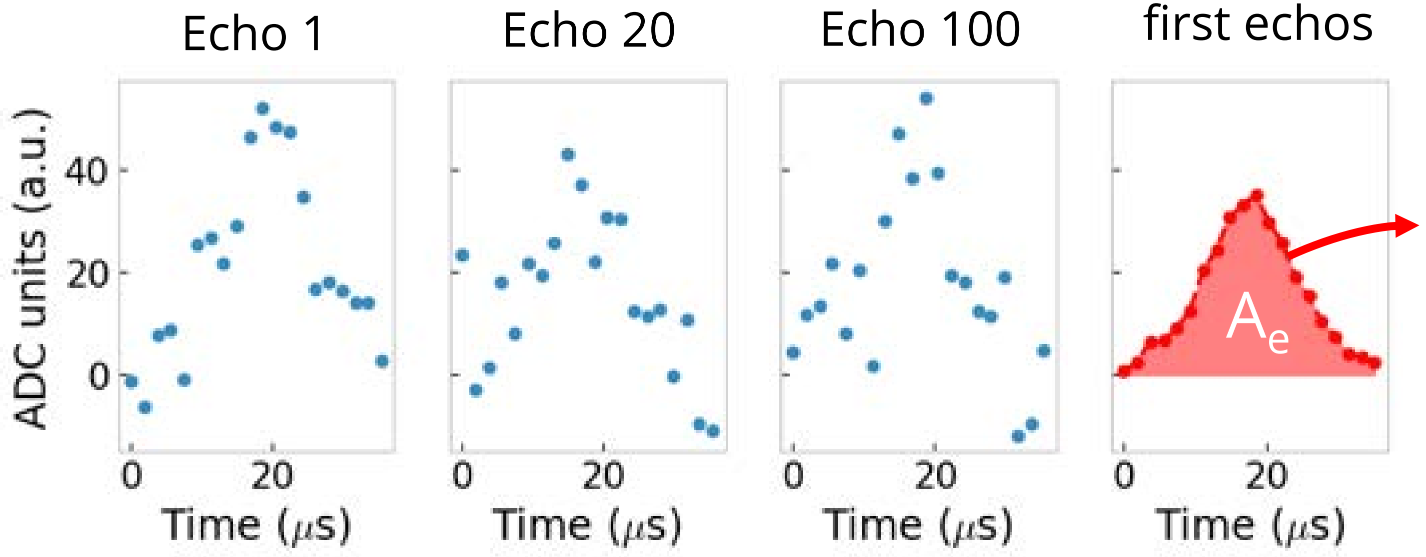


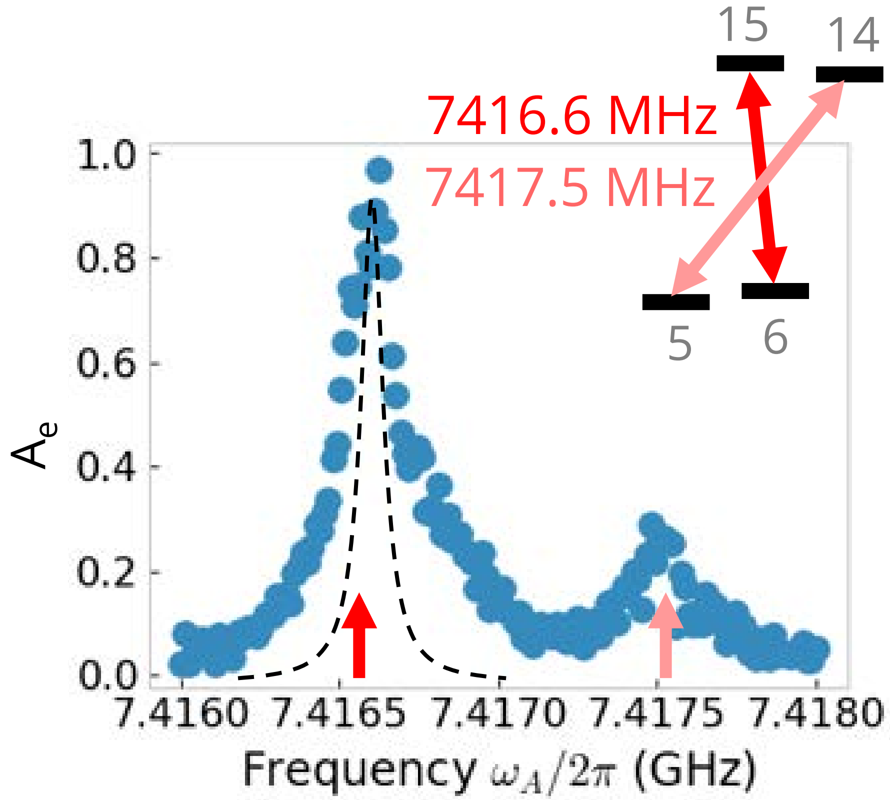




Pulsed echo measurement with CPMG







Resonator linewidth

$\kappa_A\ /2\pi$=185 kHz

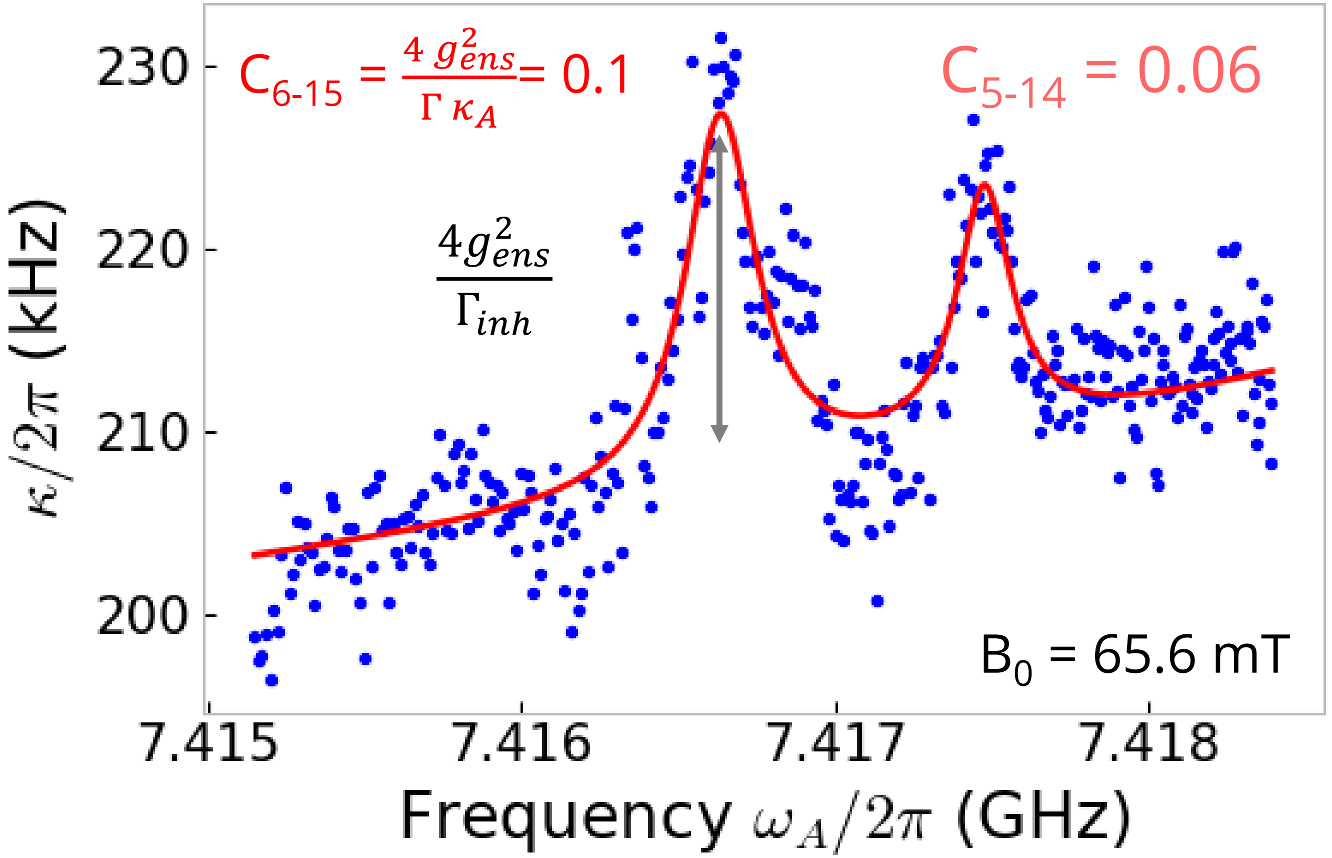
Inhomogeneous broadening

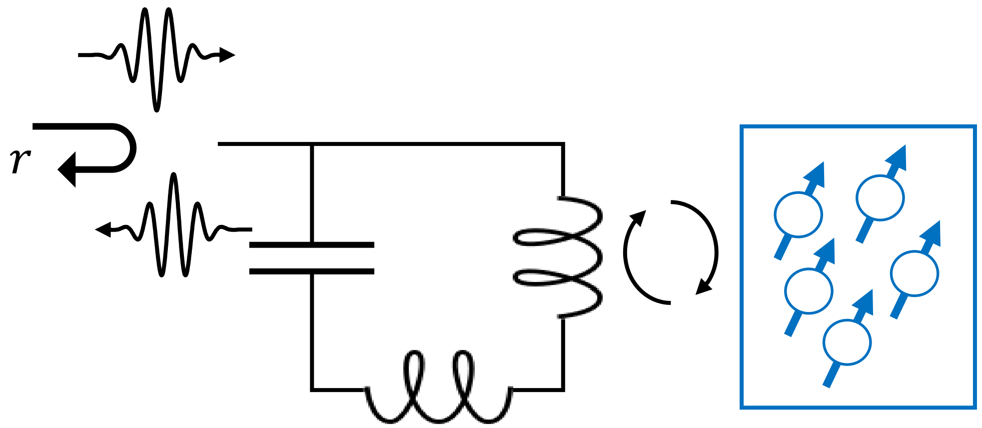
$\Gamma/2\pi$= 300 kHz

Spin-resonator interaction

Spins create additional losses in resonator

$g_{ens}/2\pi$ = 40 kHz

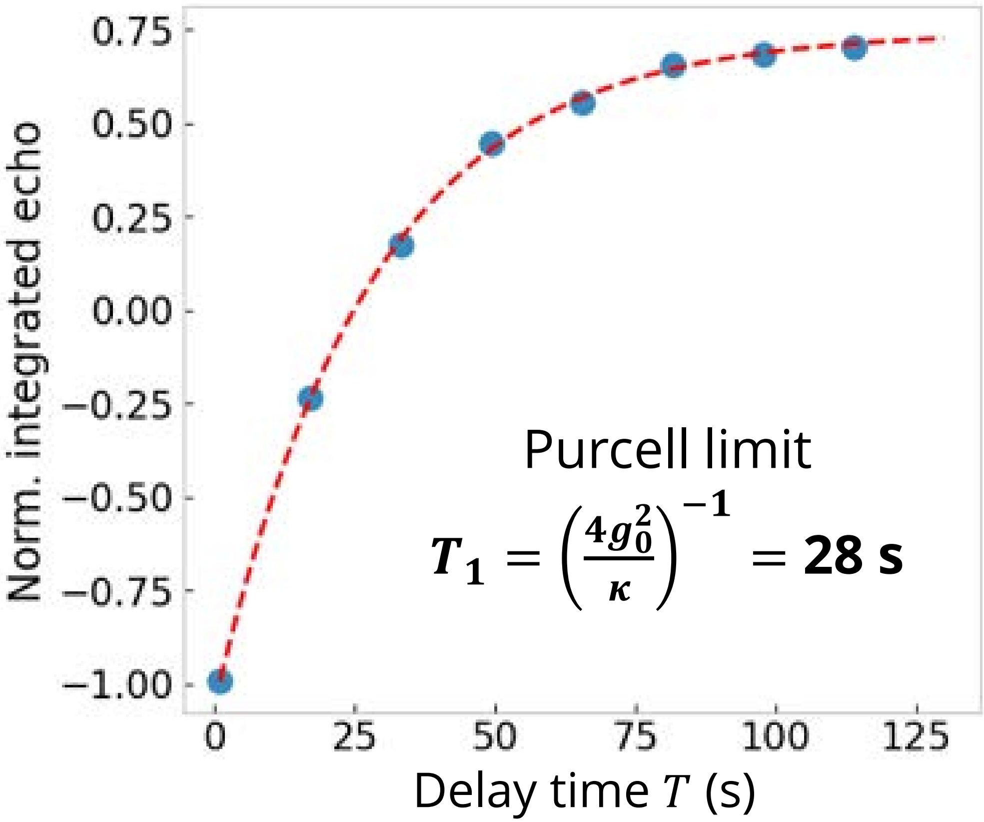




Spin-resonator interaction: Purcell effect

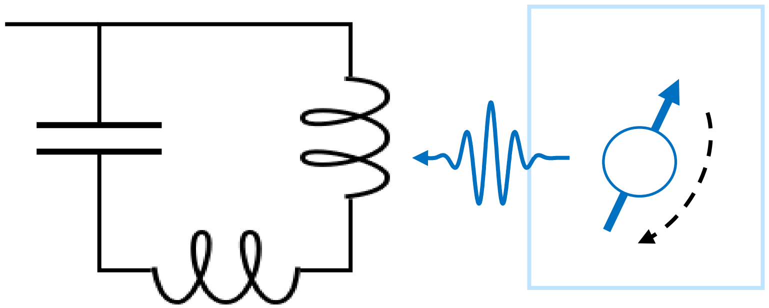
Resonator shortens the spin lifetime

$g_0\ /2\pi$ = 15 Hz



Purcell limit

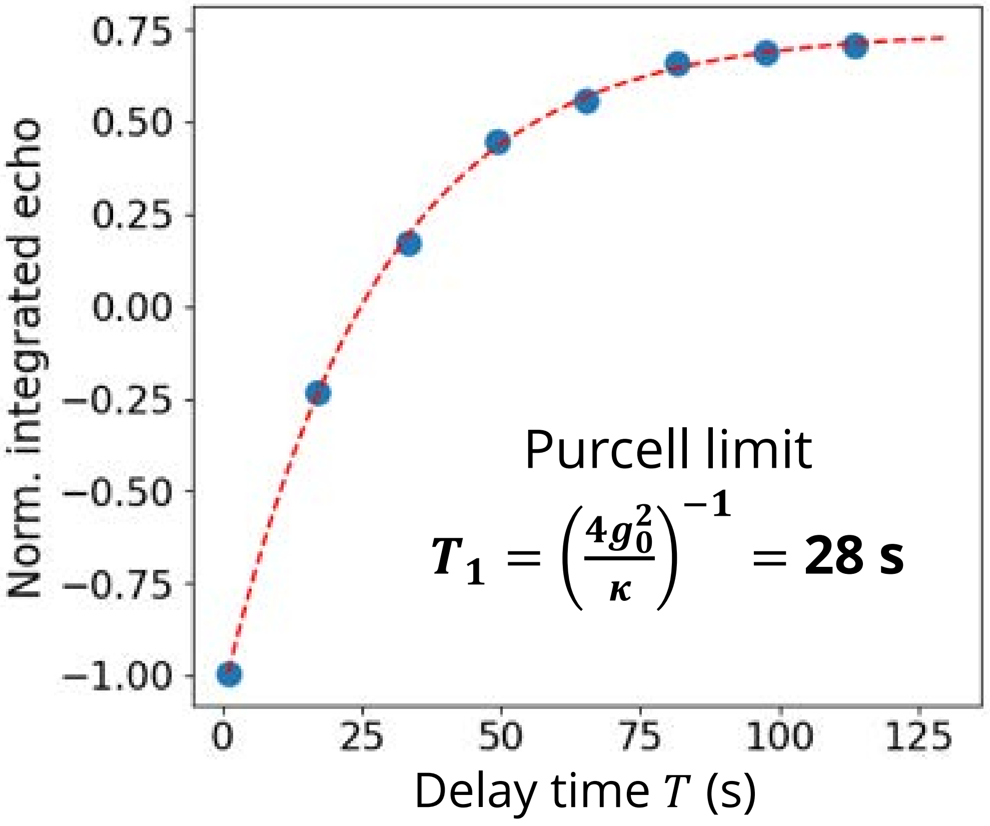
$$\boldsymbol{T_1 = \left(\frac{4g_0^2}{\kappa}\right)^{-1} = 28\ \mathrm{s}}$$

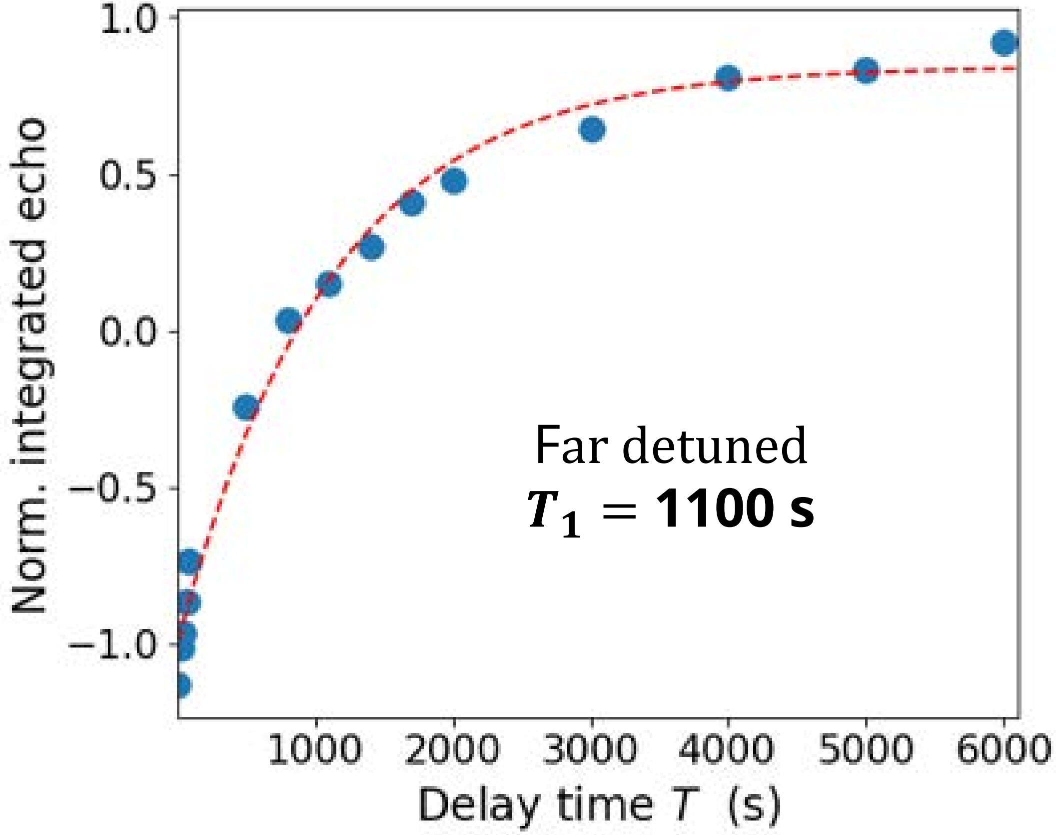


Spin-resonator interaction: Purcell effect

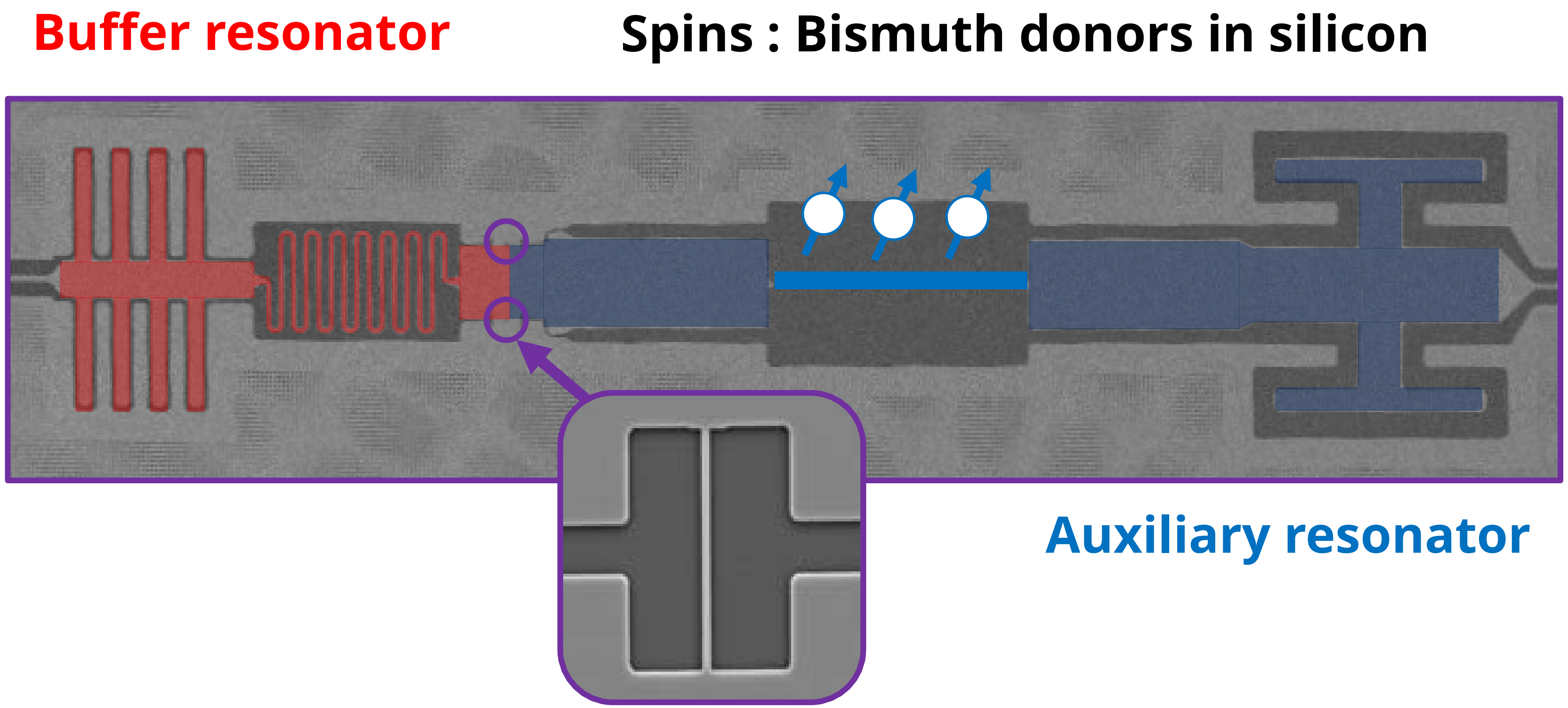
Resonator shortens the spin lifetime and sets the repetition rate of our experiment …

$g_0\ /2\pi$ = 15 Hz



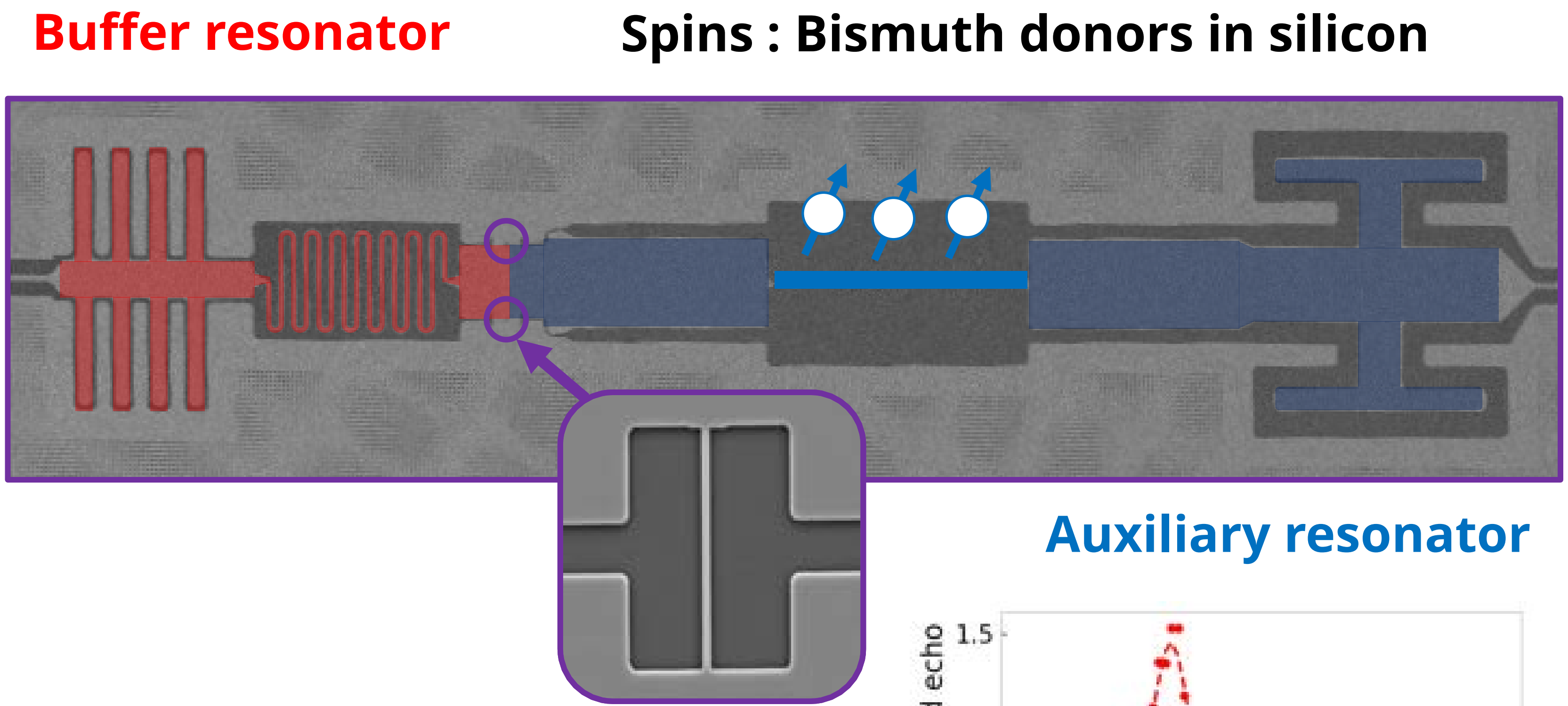


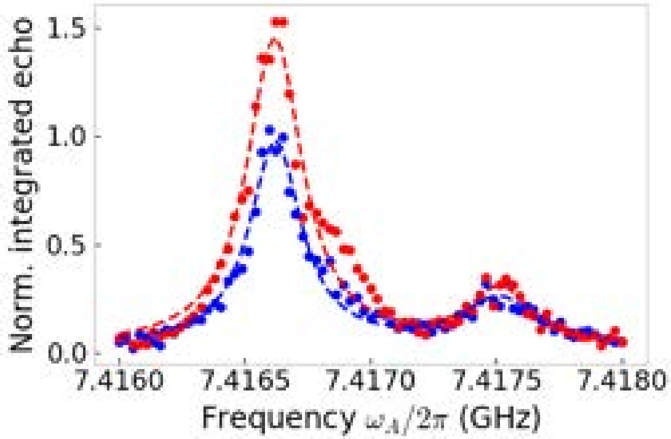
Device summary



- ✓ Tunable resonator frequency
  80 MHz tuning range
  3 MHz dynamic tuning
- ✓ Tunable linewidth
  From $\kappa_A/2\pi = 165$ kHz to 650 kHz
- ✓ Long spin coherence
  450 ms at sweet-spot
- ✓ Reset by the Purcell effect
- ➢ Reach unit cooperativity
  C = 0.1

Device summary





- ✓ Long spin coherence

  450 ms at sweet-spot

- ✓ Tunable resonator frequency

  80 MHz tuning range

  3 MHz dynamic tuning

- ✓ Tunable linewidth

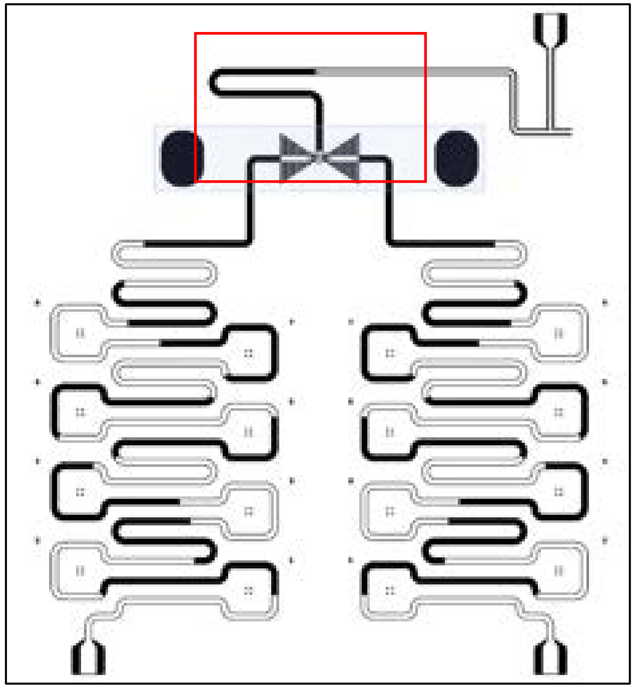
  From $\kappa/2\pi = 165$ kHz to 650 kHz

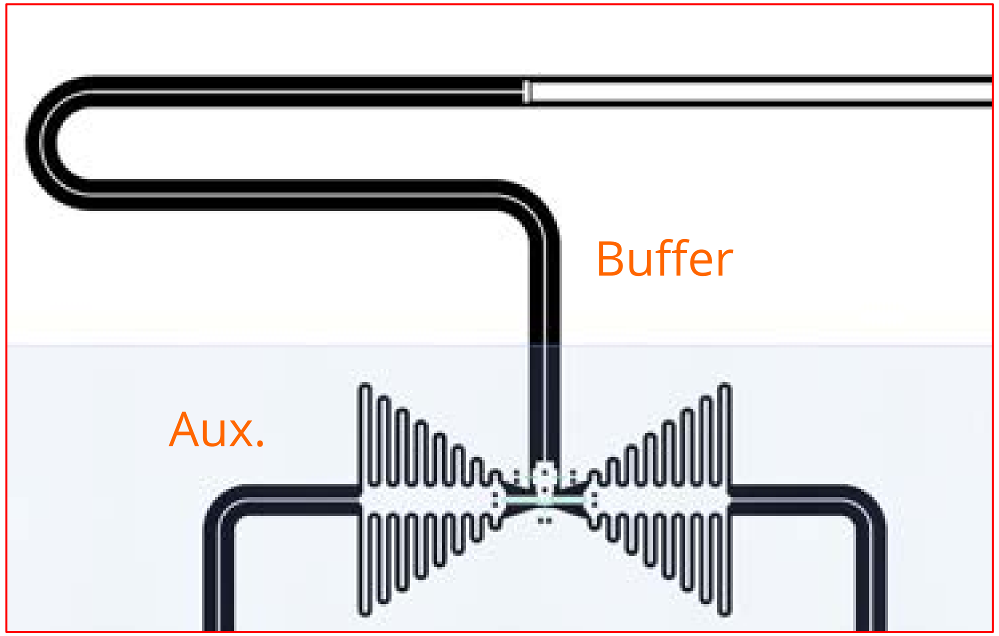
- ➢ Reach unit cooperativity

  C = 0.1 → 0.45 (in 45 min)

Pespectives : new device

10mm chip



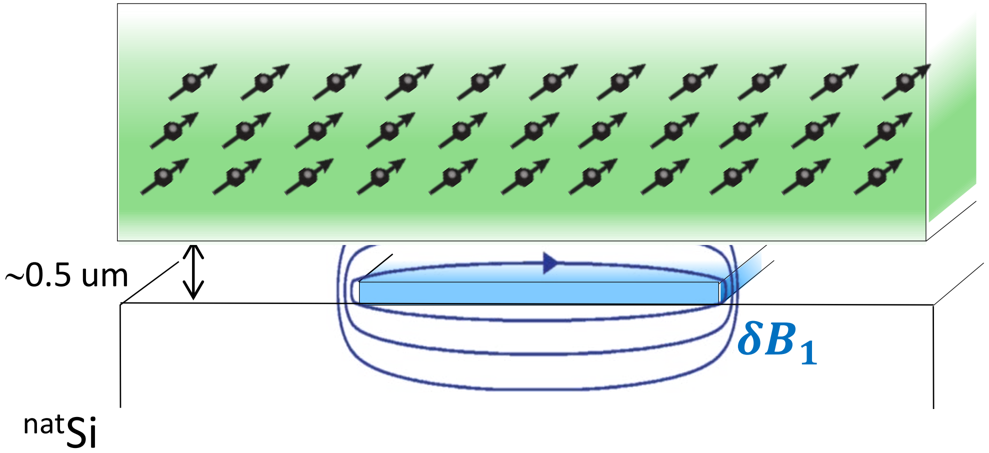


- Larger coupling to spins
- Low-loss microwave access
- Low-loss resonators
- Predict C=1.5 with T_{rep} = 5s

  Inhomogeneous linewidth ?

Transition with higher matrix element

Smaller spacing

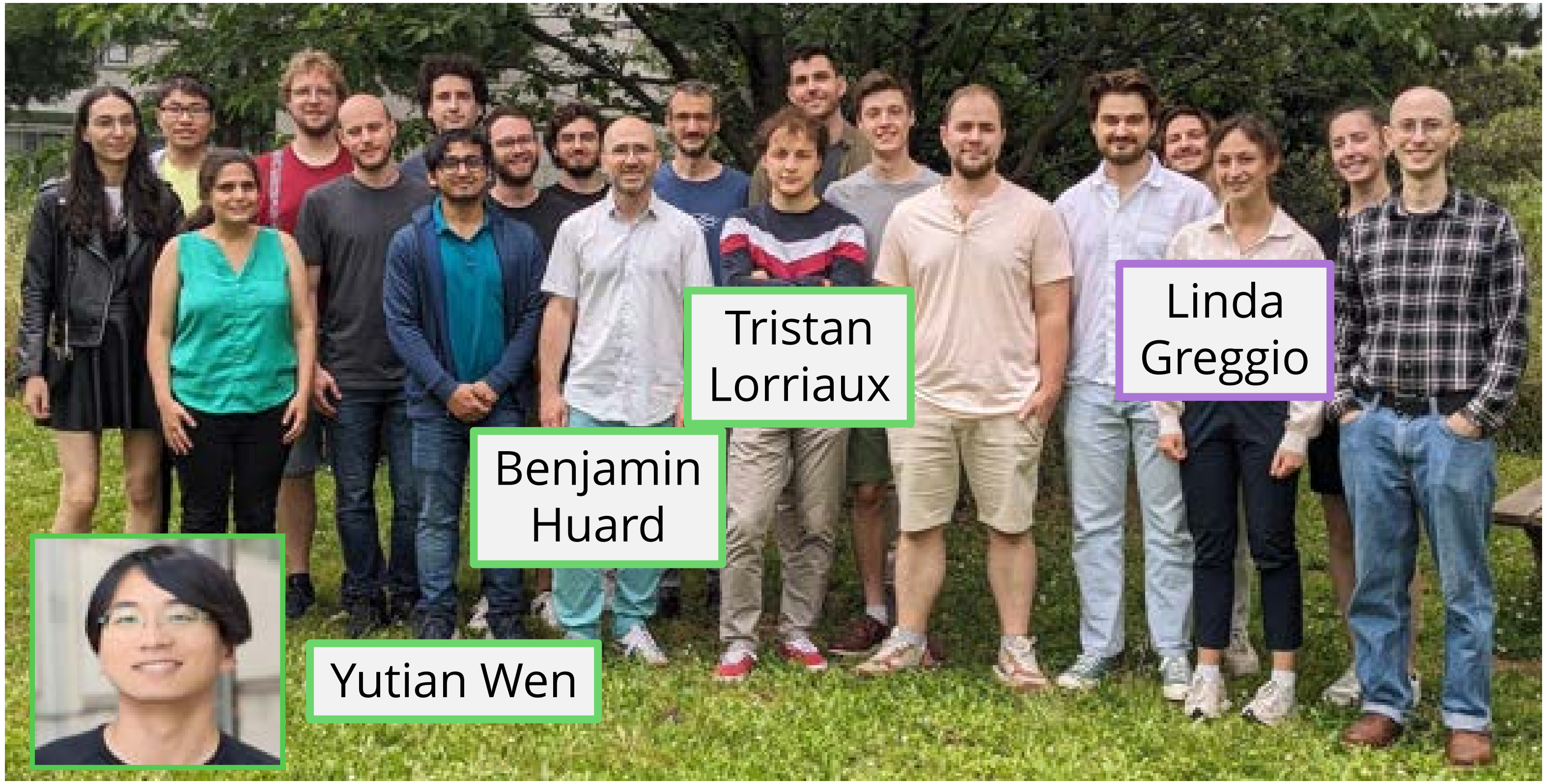


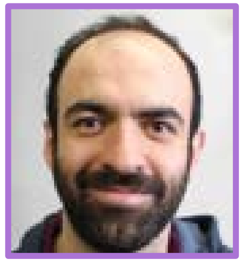
X2 deeper implantation

Larger zpf for the magnetic field

Acknowledgments

Quantum circuit group, summer 2024





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