Single microwave photon detection with superconducting quantum circuits

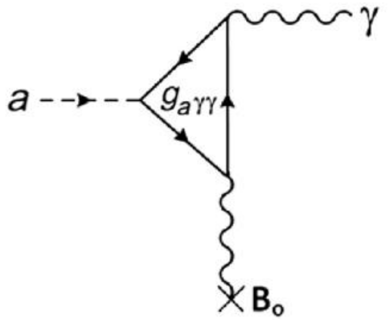
Emanuele Albertinale

Quantronics group, SPEC, CEA Paris-Saclay

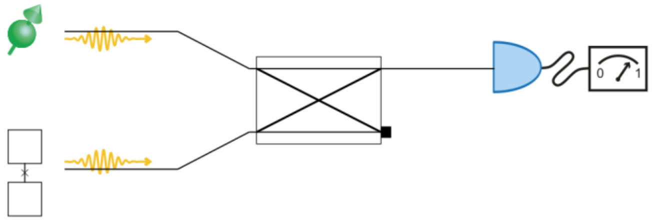
03.10.2022

Detection of microwave photons

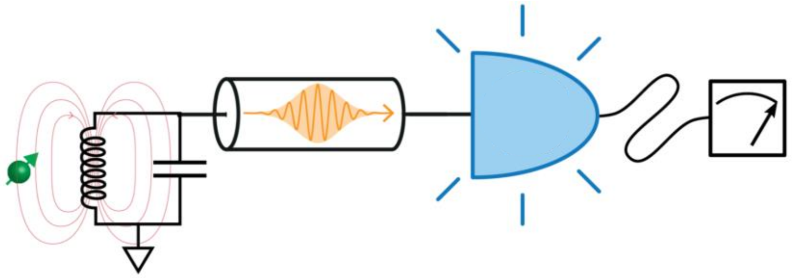
Search for dark matter candidates (axions)



Photon-detection-based quantum information



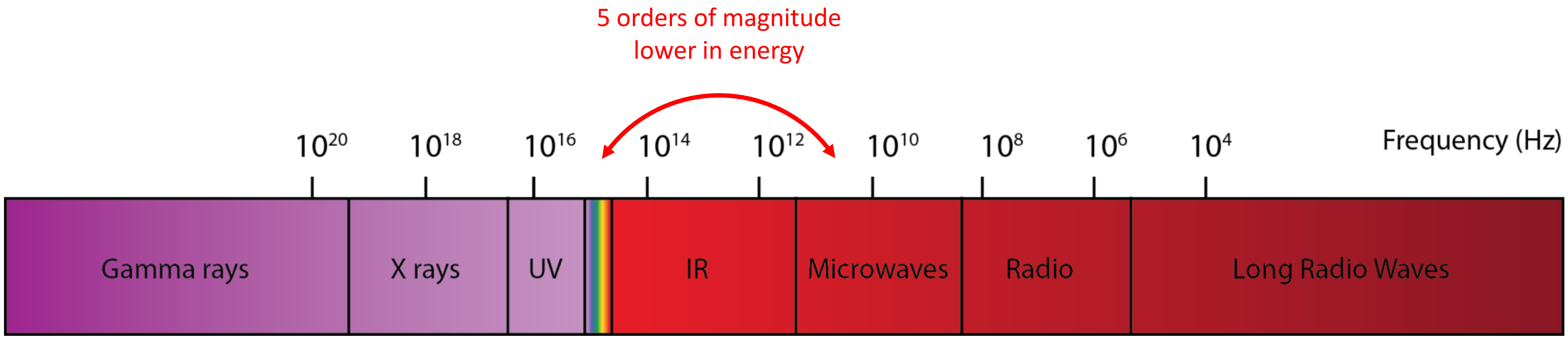
Quantum sensing



Challenges in the detection of microwave photons

no commercial single microwave photon detector available

low energy of microwave photons does not trigger macroscopic phenomena (i.e. photoionization)



Challenges in the detection of microwave photons

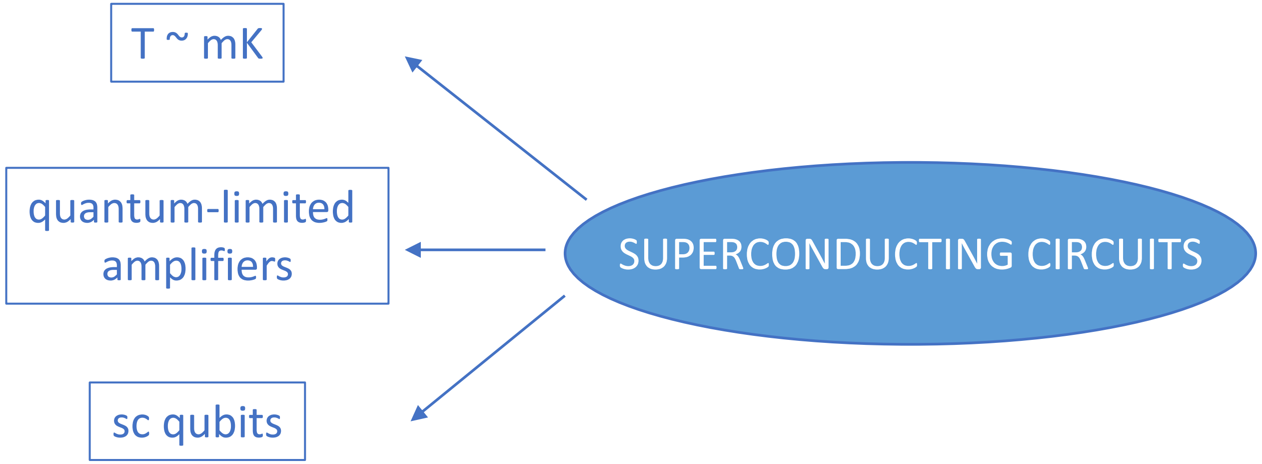
What we need

- Low thermal photon number
- Minimum amplification-added noise
- Probing-system coupled to mw field
- Engineered photon-detector interaction

Challenges in the detection of microwave photons

What we need

- Low thermal photon number
- Minimum amplification-added noise
- Probing-system coupled to mw field
- Engineered photon-detector interaction



???

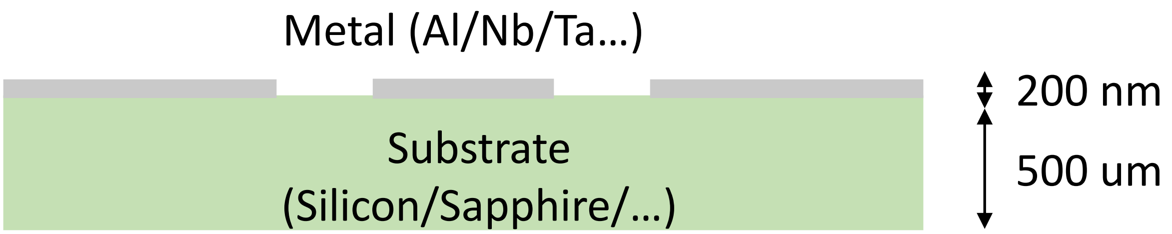
Superconducting circuits

Superconducting circuits

Coplanar waveguide geometry

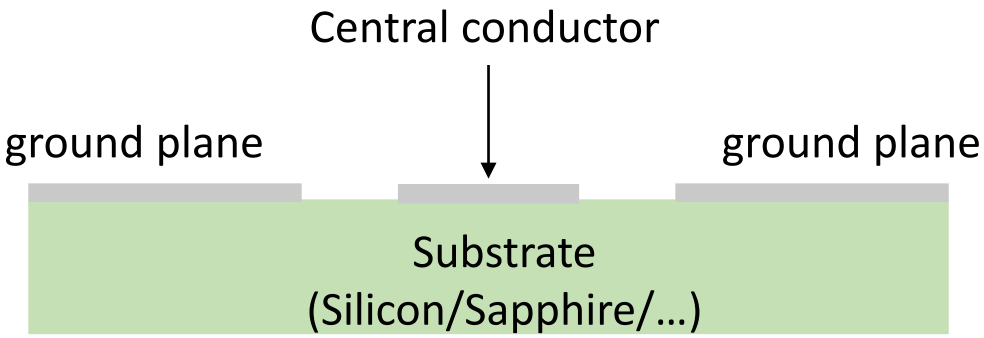
Superconducting microwave circuits

Coplanar waveguide geometry



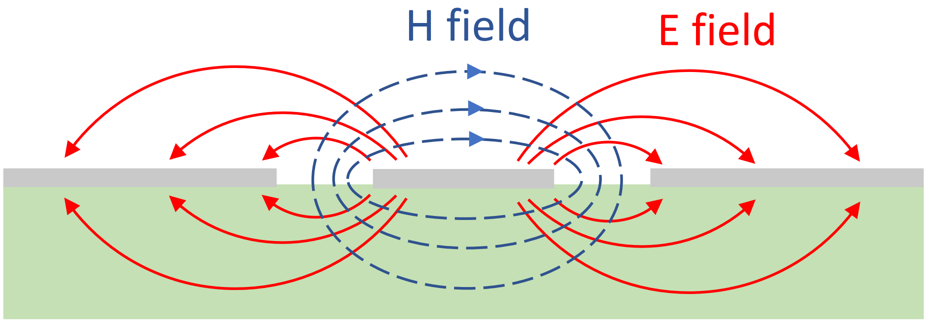
Superconducting microwave circuits

Coplanar waveguide geometry



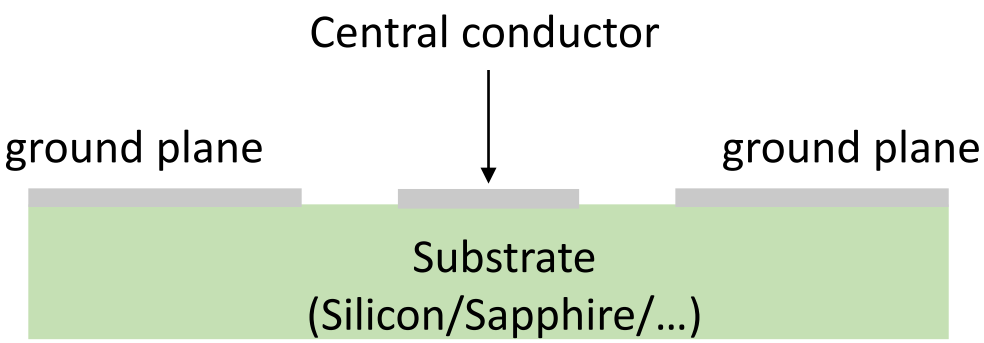
Superconducting microwave circuits

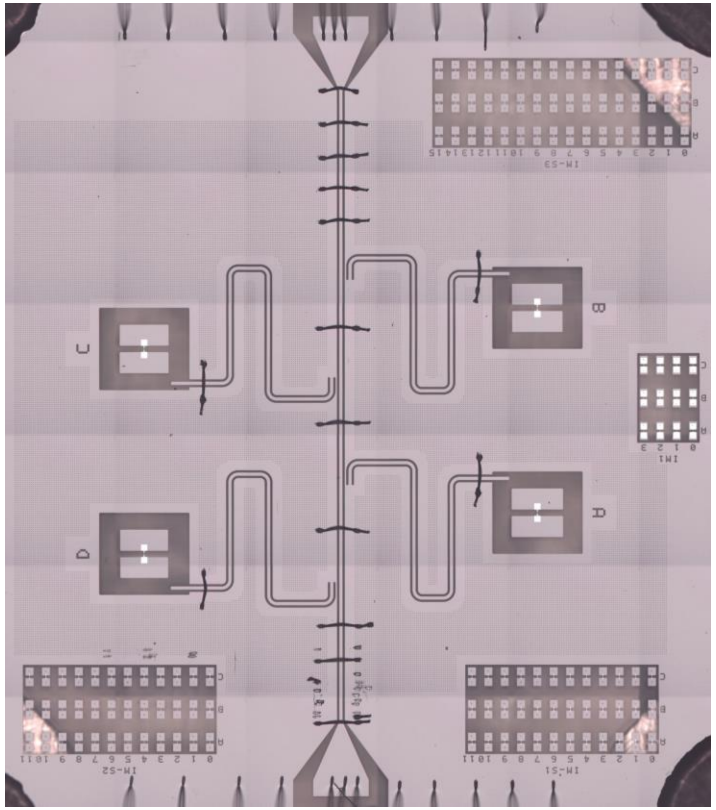
Coplanar waveguide geometry



Superconducting microwave circuits

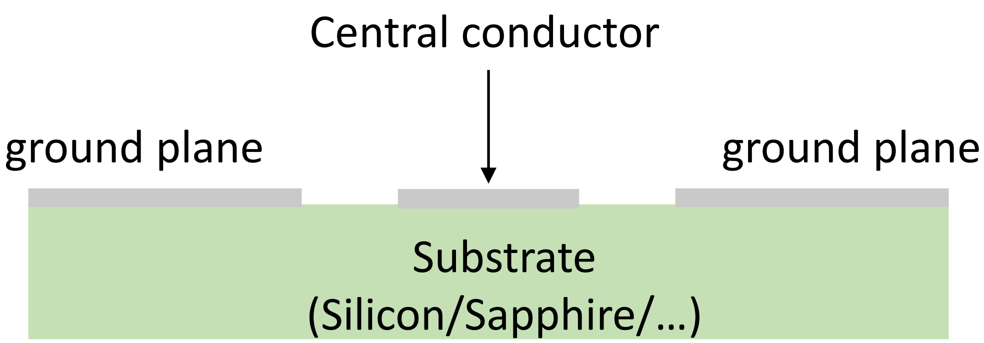
Coplanar waveguide geometry



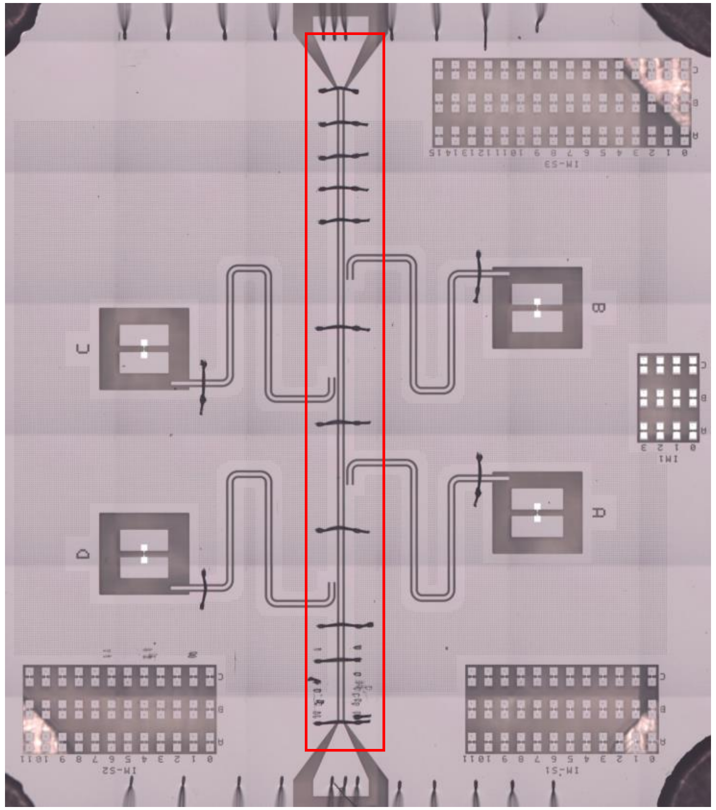


Superconducting microwave circuits

Coplanar waveguide geometry

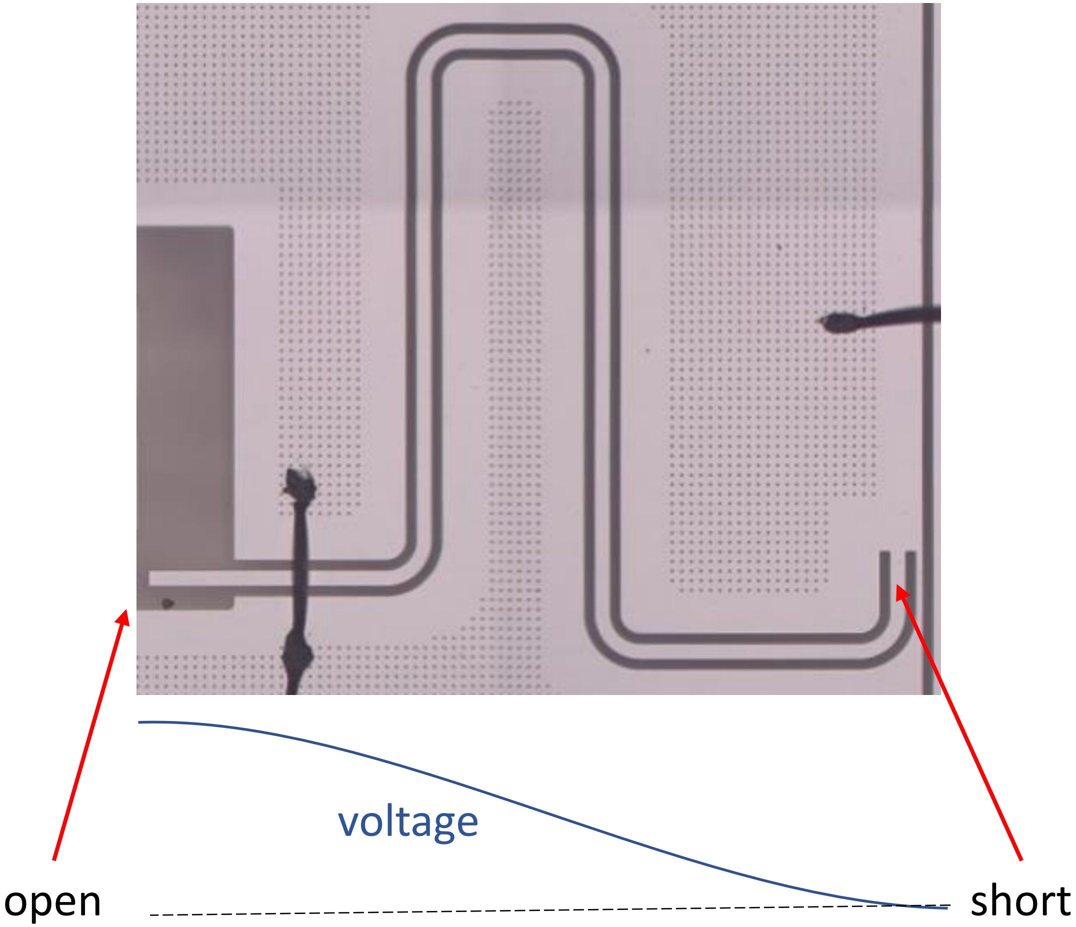


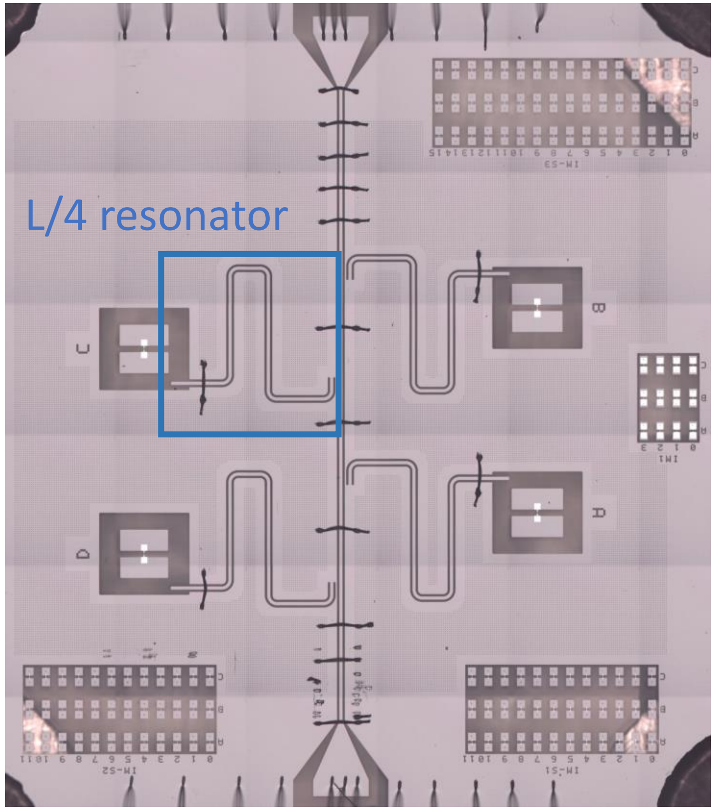
Transmission line



Superconducting microwave circuits

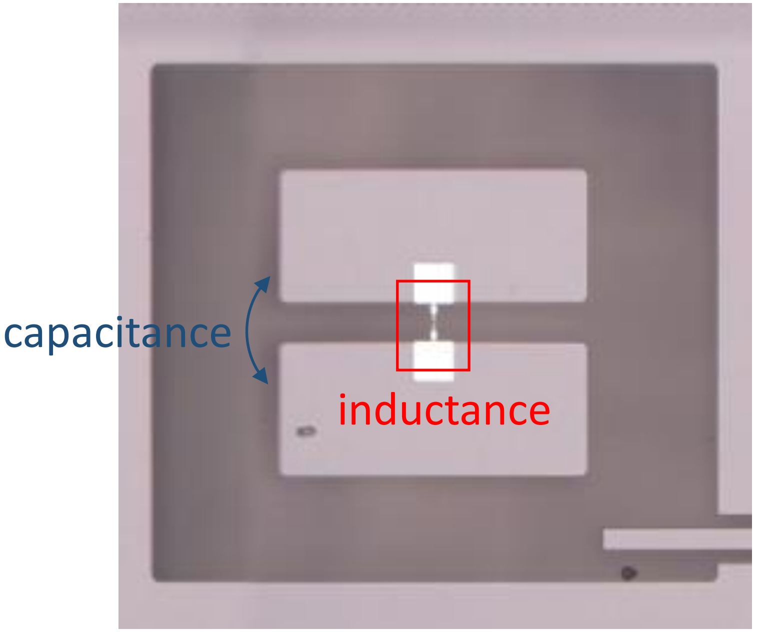
Coplanar waveguide geometry



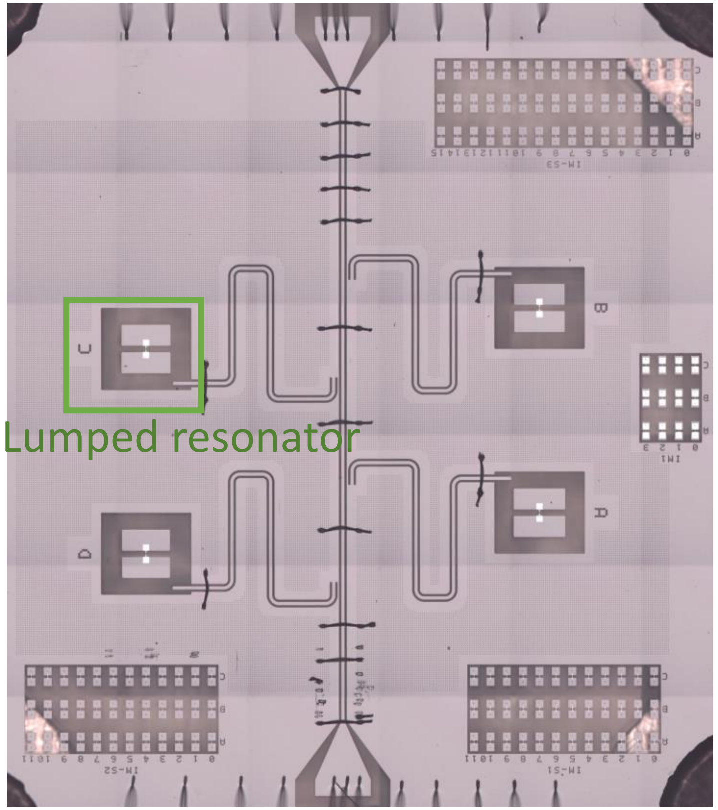


Superconducting microwave circuits

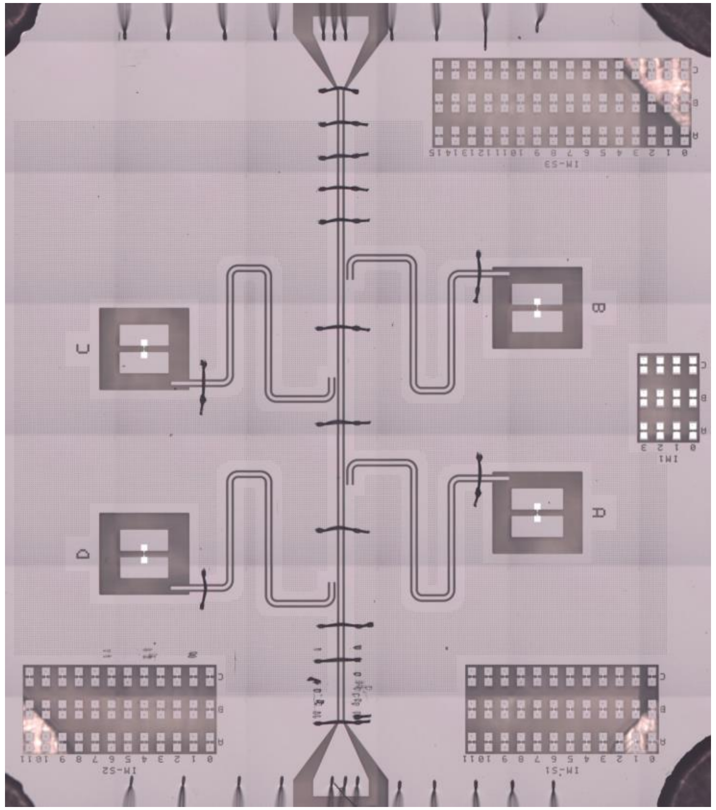
Coplanar waveguide geometry

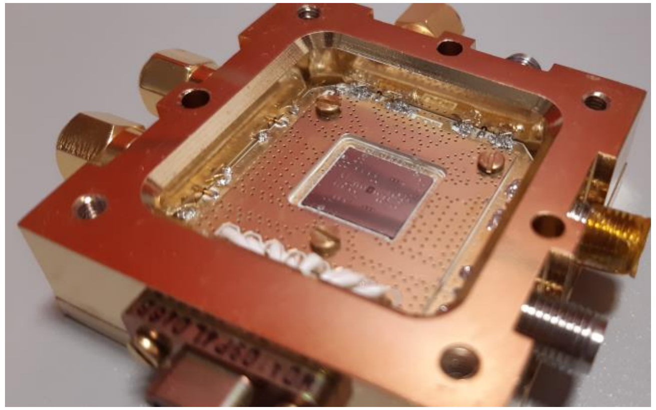


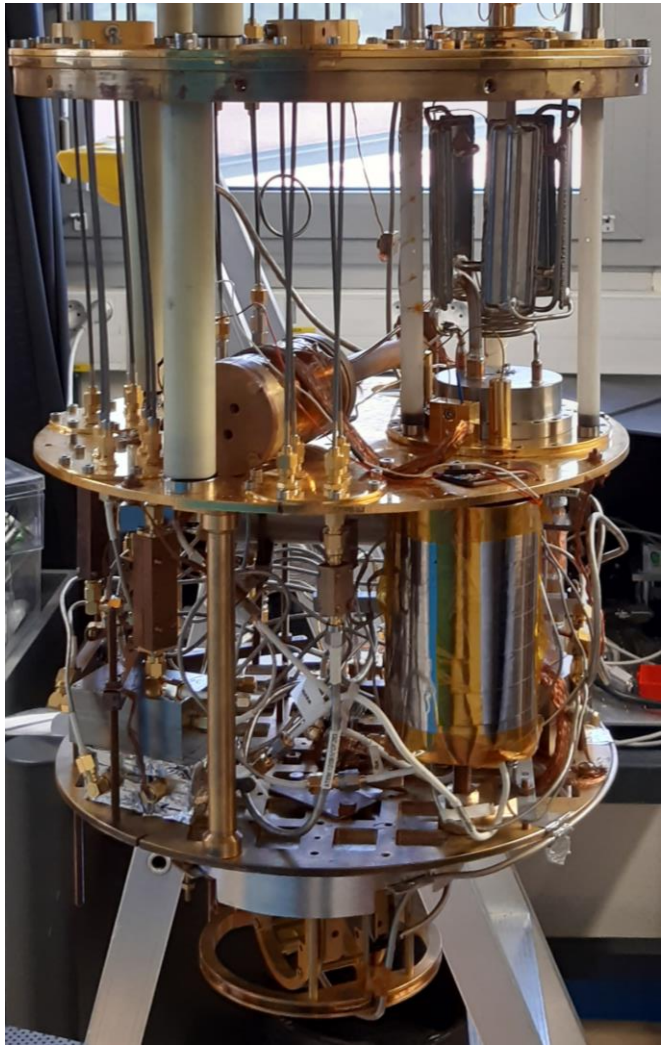
LC resonator



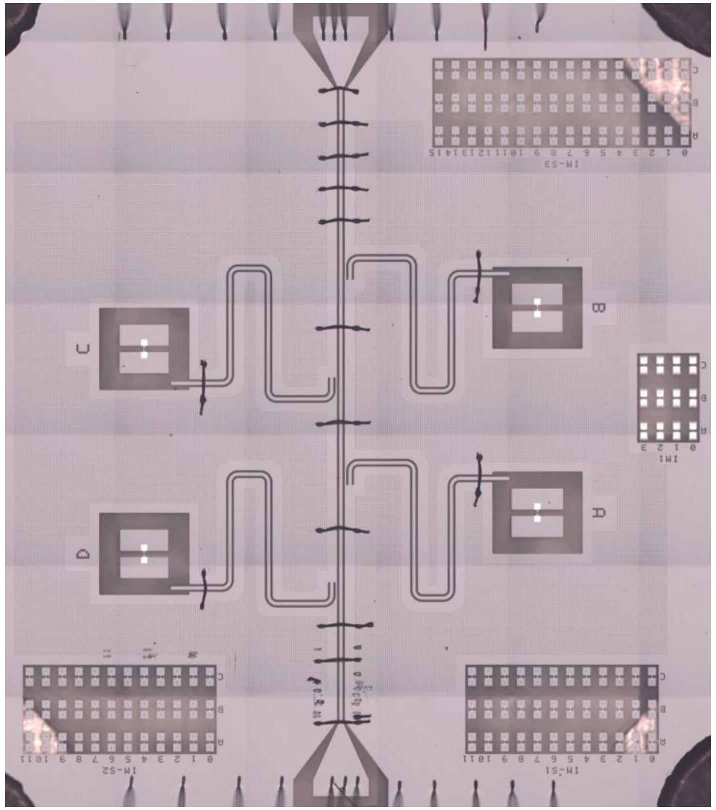
Superconducting microwave circuits

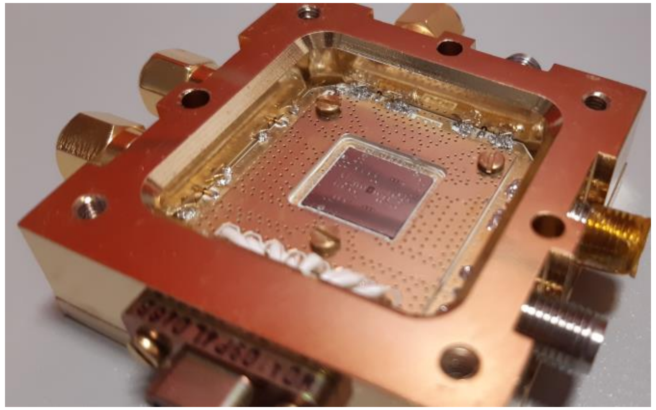


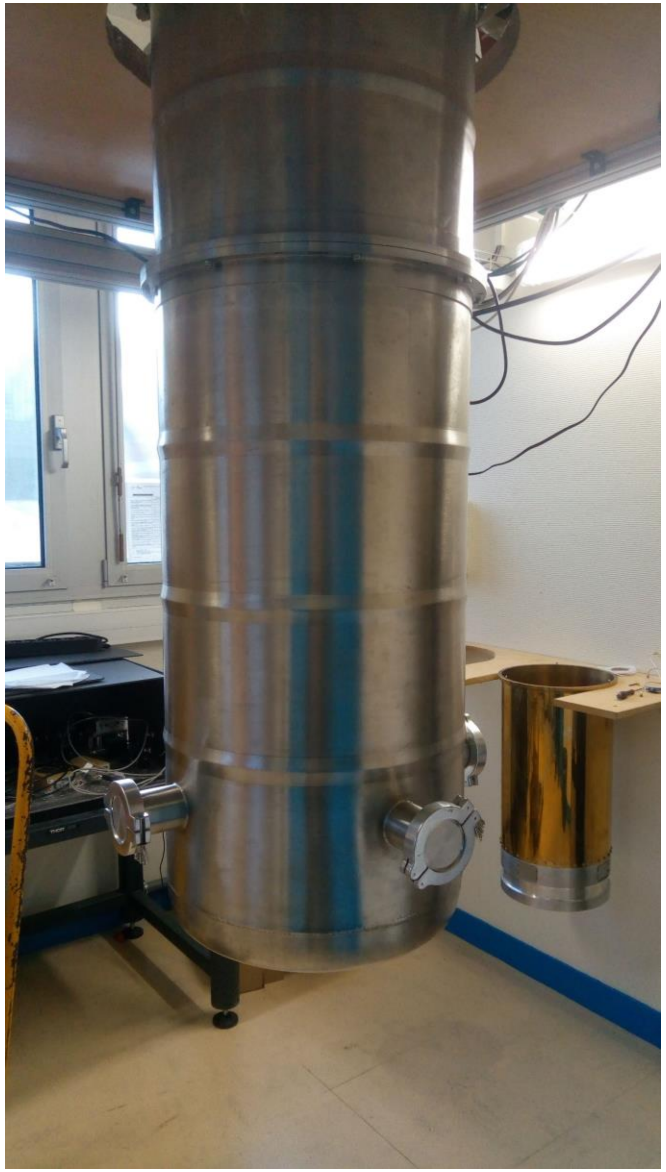




Superconducting microwave circuits





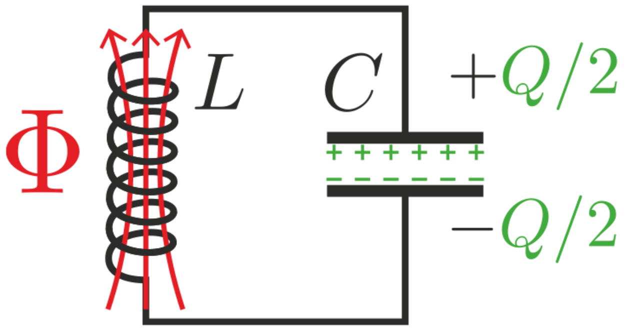


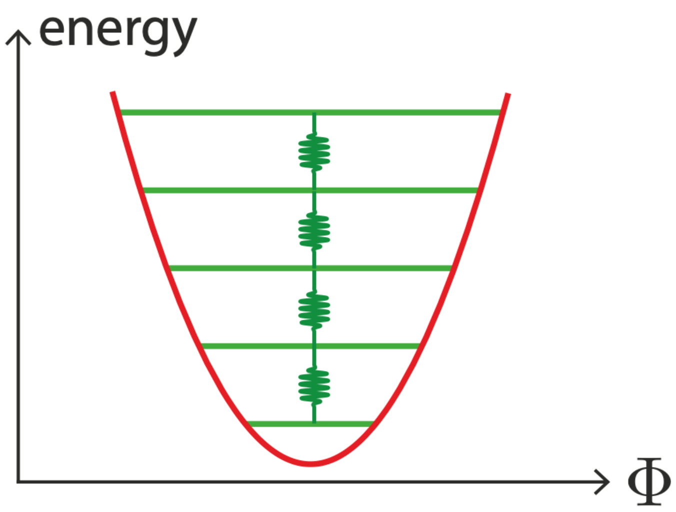
20 mK

- Superconductivity -> no dissipation
- kT << hv

Superconducting qubits

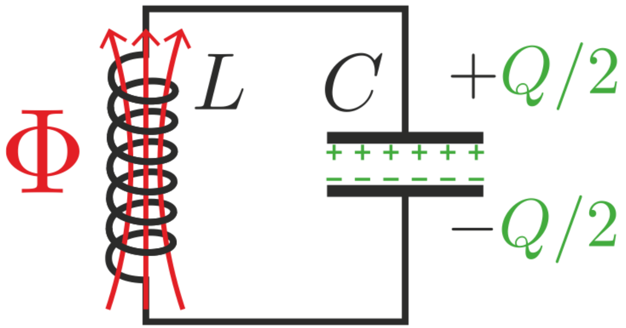
Transmon qubit



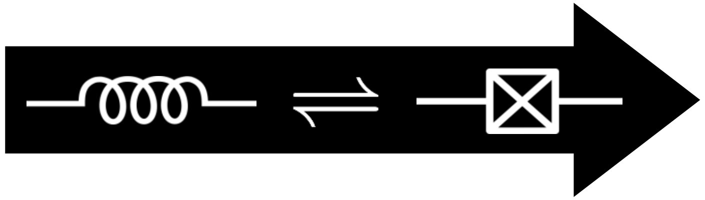


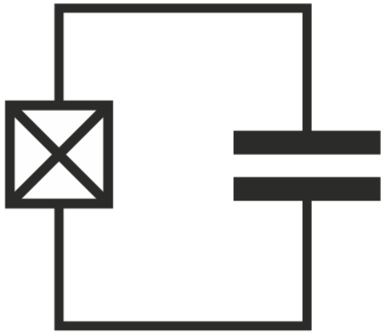
How to build a two-levels system?

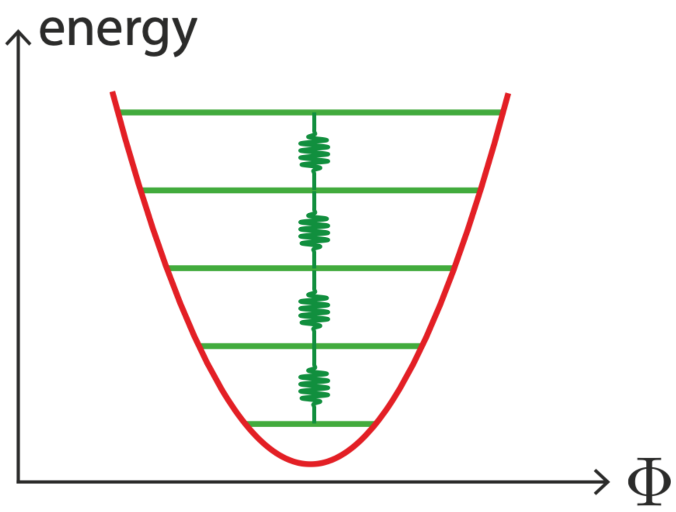
Transmon qubit

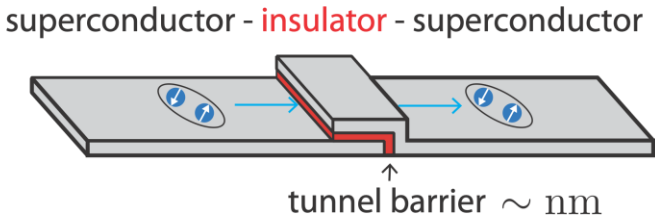


Non-linear element

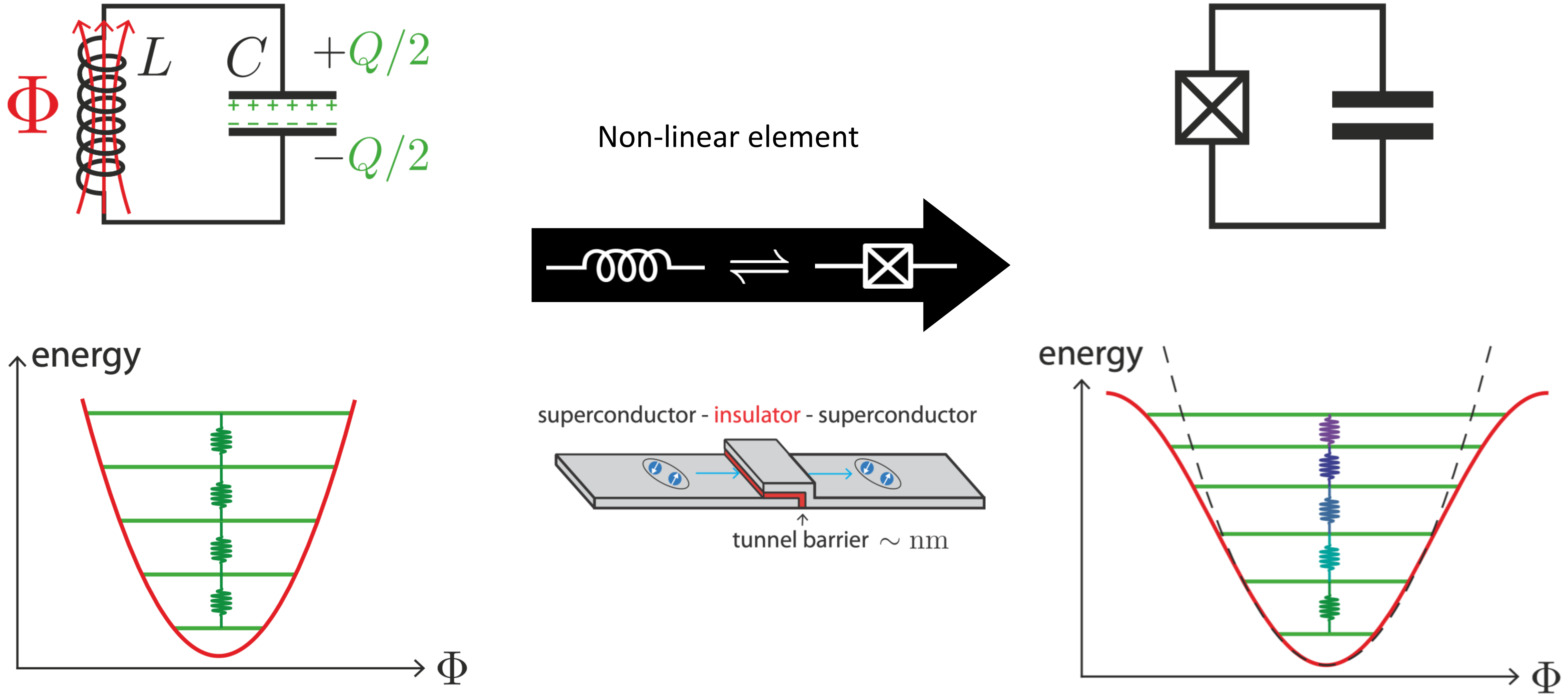




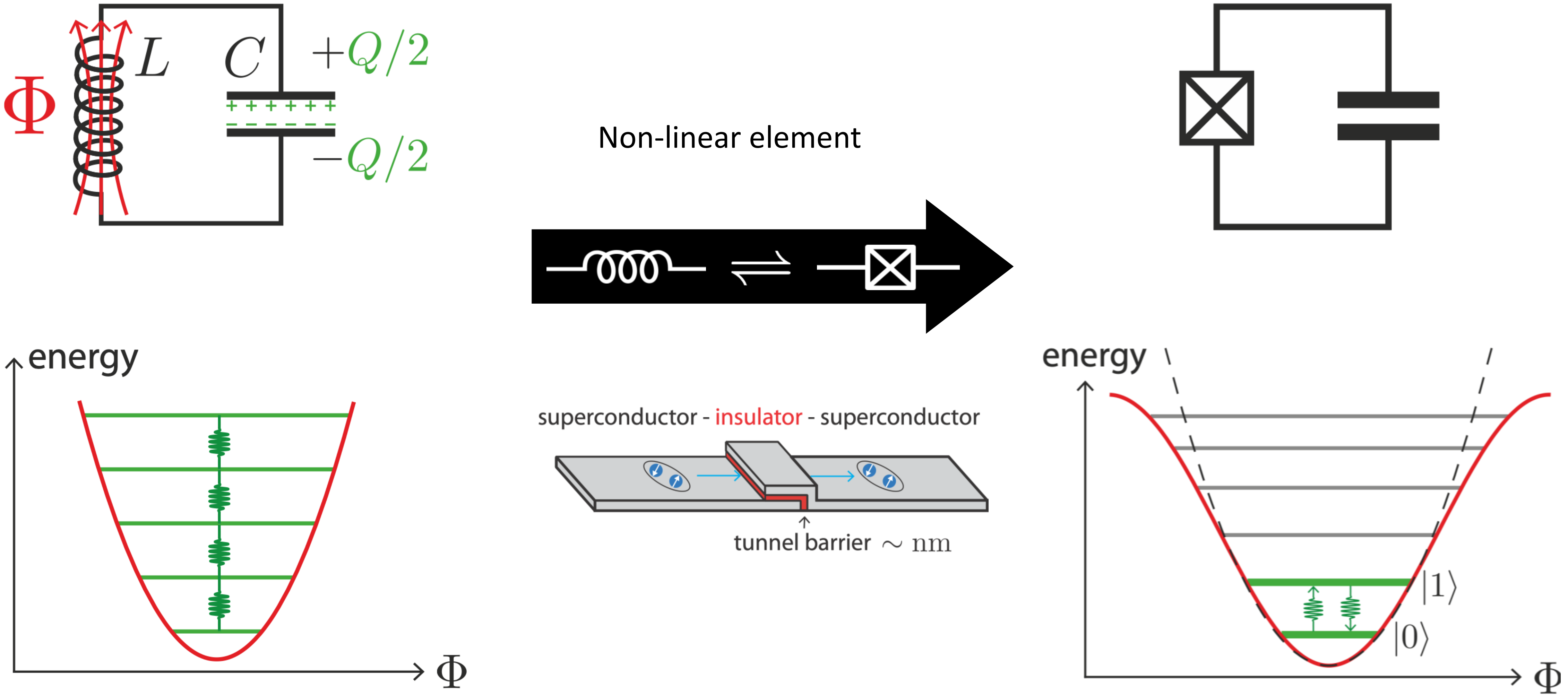




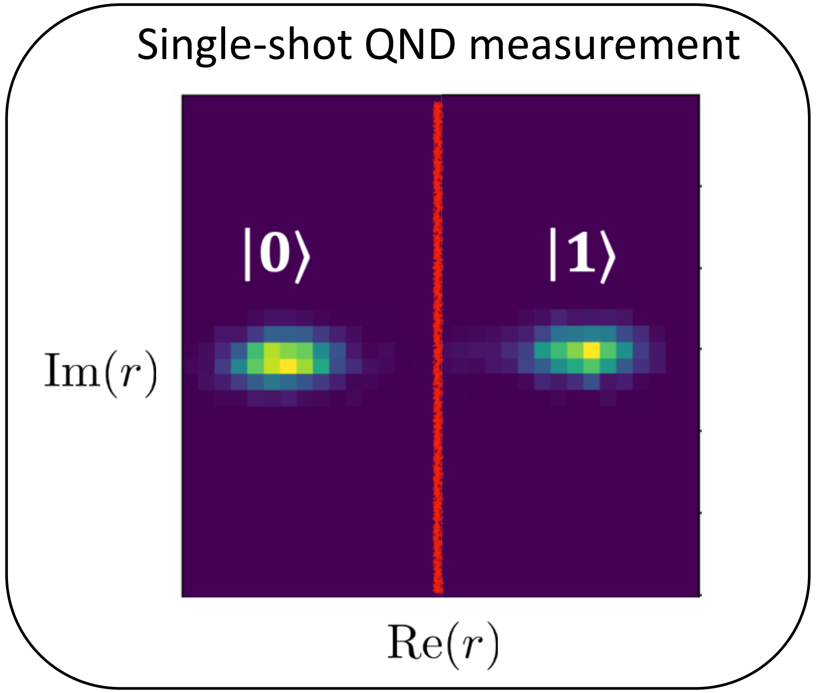
Transmon qubit

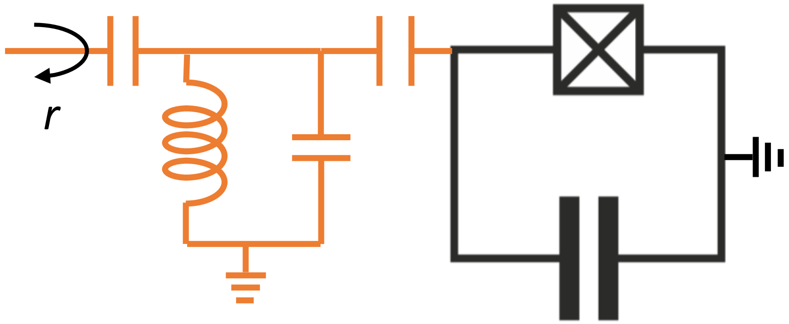


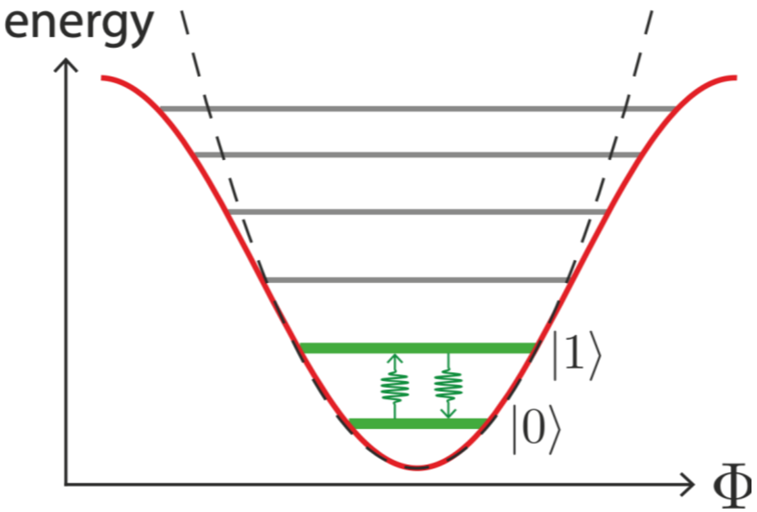
Transmon qubit



Artificial atom

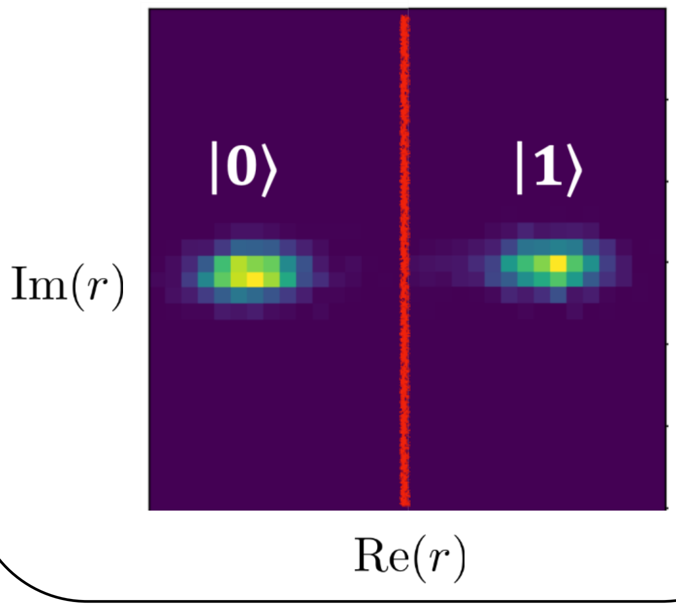




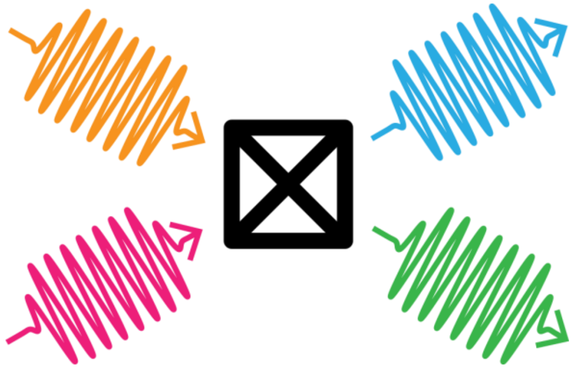


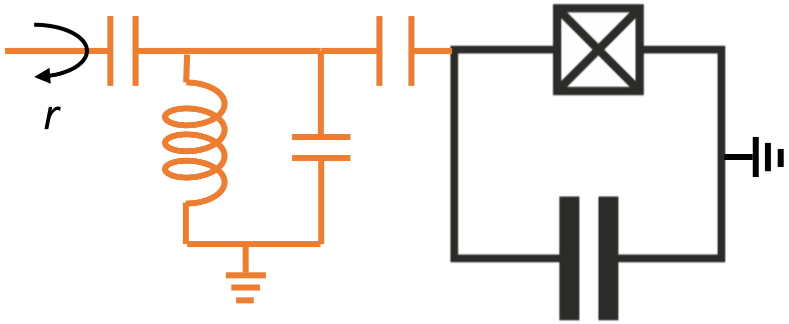
Artificial atom

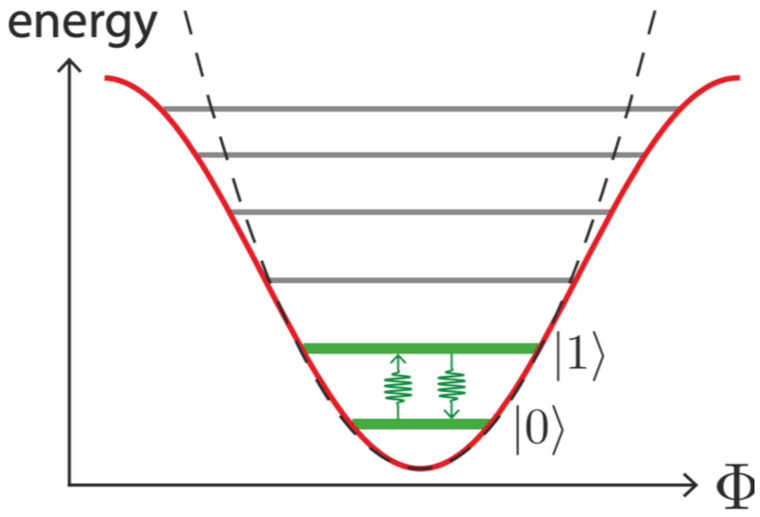
Single-shot QND measurement



Built-in 4-waves mixing





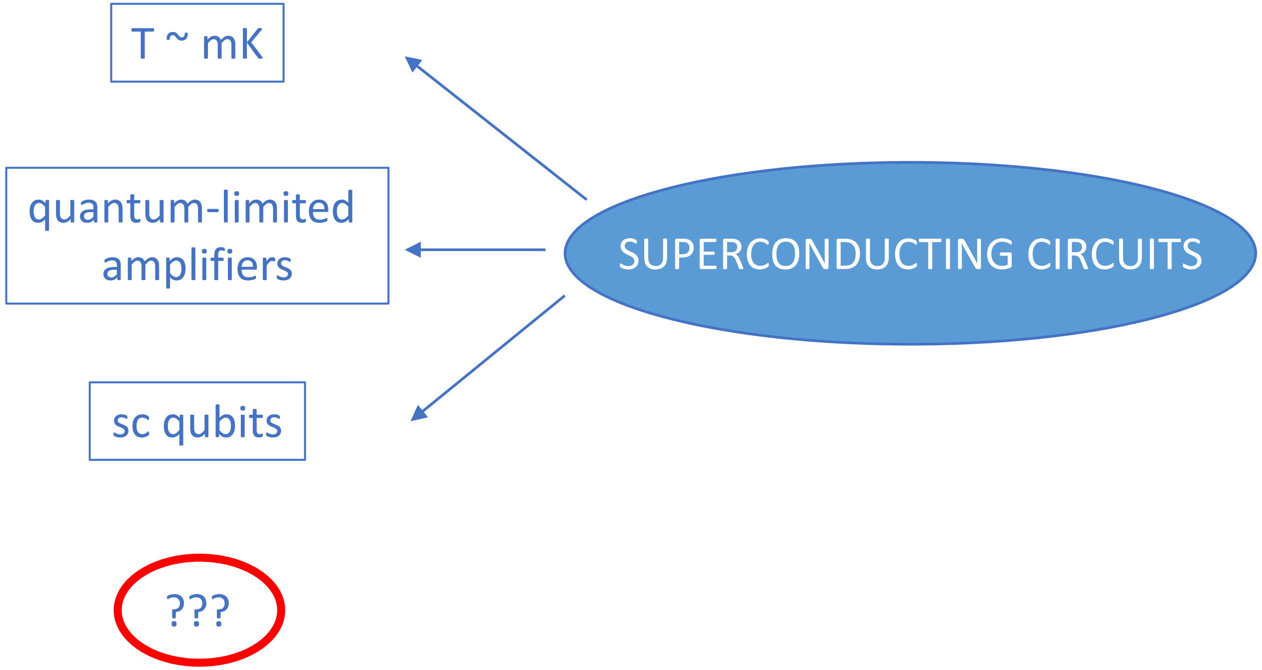


Single microwave photon detection

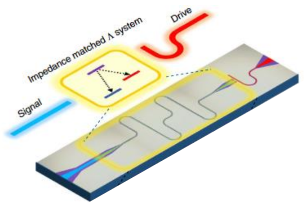
Challenges in the detection of microwave photons

What we need

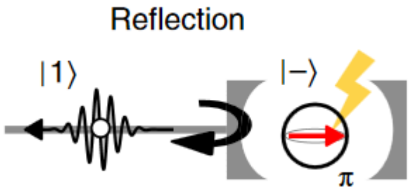
- Low thermal photon number
- Minimum amplification-added noise
- Probing-system coupled to mw field
- Engineered photon-detector interaction



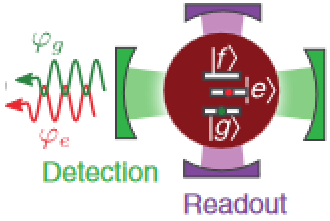
Prototypes of microwave photon-detectors



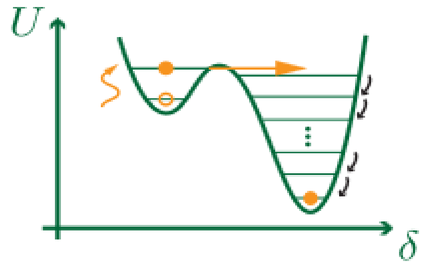
K. Inomata *et al.*,
Nat. Comm. 7, 12303
(2016)



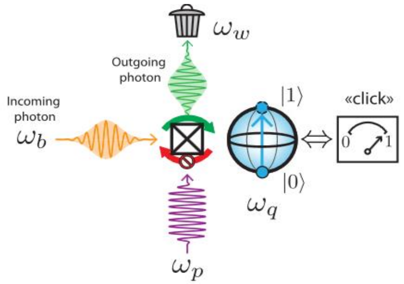
Kono, S, et al.
Nature Physics 14.6 (2018)



J.-C. Besse *et al.*,
PRX 8, 021003 (2018)



Opremcak, A., et al.,
Science 361.6408 (2018)



Lescanne, Deléglise, Albertinale,
... & Flurin, *PRX*, 021038 (2020)

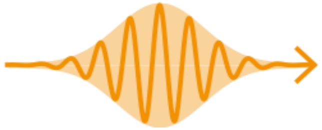
Irreversible Qubit-Photon Coupling for the Detection of Itinerant Microwave Photons

Raphaël Lescanne, Samuel Deleglise, Emanuele Albertinale, Ulysse Reglade,
Thibault Capelle, Edouard Ivanov, Thibaut Jacqmin,
Zaki Leghtas, and Emmanuel Flurin

Physical Review X 10.2 (2020): 021038.

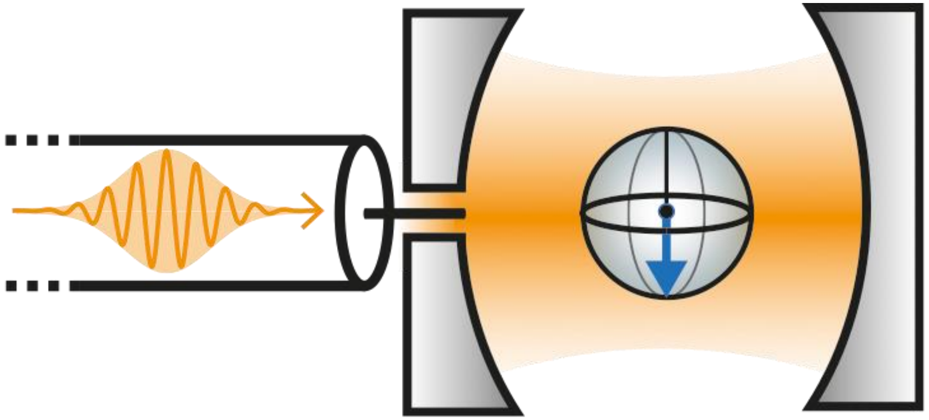
Irreversible mapping of the field state on a qubit

ω_{photon} ω_{qubit}



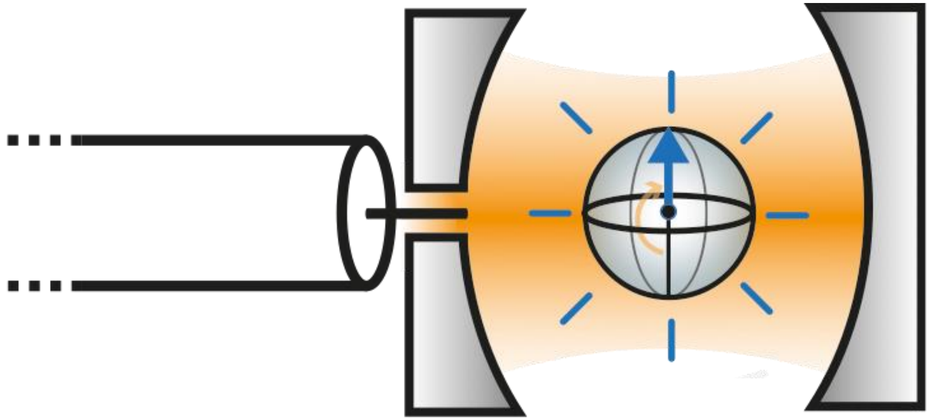
Irreversible mapping of the field state on a qubit

$\omega_{photon} = \omega_{qubit}$



Unitary evolution is reversible

ω_{photon} = ω_{qubit}

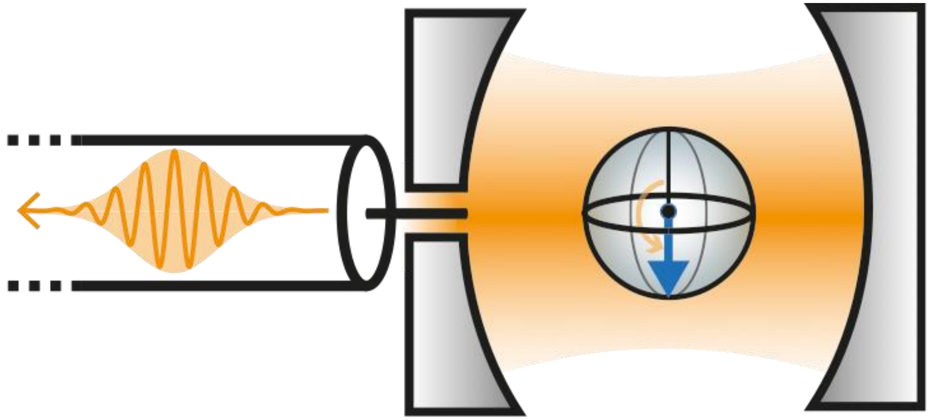


$$\hat{H} = g \cdot (\hat{a}\hat{\sigma}^{+} + \hat{a}^{+}\hat{\sigma})$$

Unitary
evolution

Unitary evolution is reversible

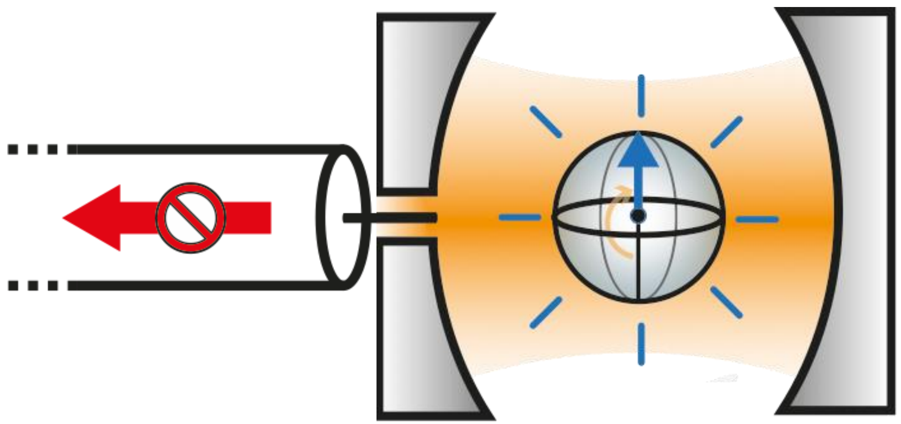
$\omega_{photon} = \omega_{qubit}$



$$\hat{H} = g \cdot (\hat{a}\hat{\sigma}^{+} + \hat{a}^{+}\hat{\sigma})$$

Unitary evolution is reversible

ω_{photon} = ω_{qubit}



$$\hat{H} = g \cdot (\hat{a}\hat{\sigma}^{+} + \hat{a}^{+}\hat{\sigma})$$

Master equation: non unitary evolution

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \hat{L}\hat{\rho}\hat{L}^\dagger - \frac{1}{2}\hat{L}^\dagger\hat{L}\hat{\rho} - \frac{1}{2}\hat{\rho}\hat{L}^\dagger\hat{L}$$

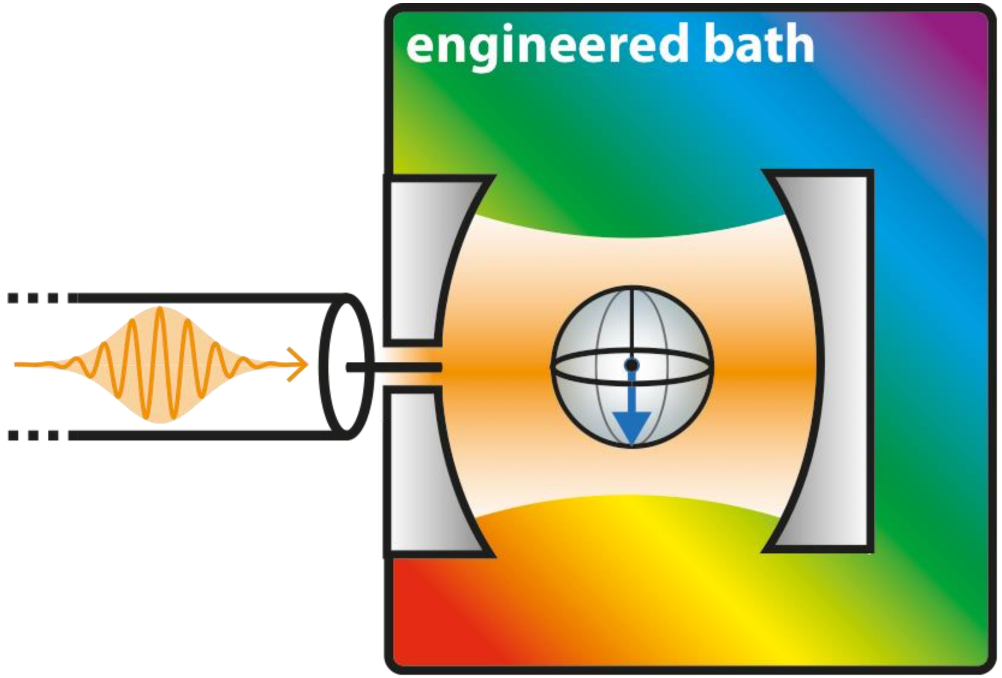
unitary evolution

dissipative evolution

can be used to engineer
a dissipative dynamics

Leghtas et al. Science (2015)
Lescanne et al. Nature Physics (2020)

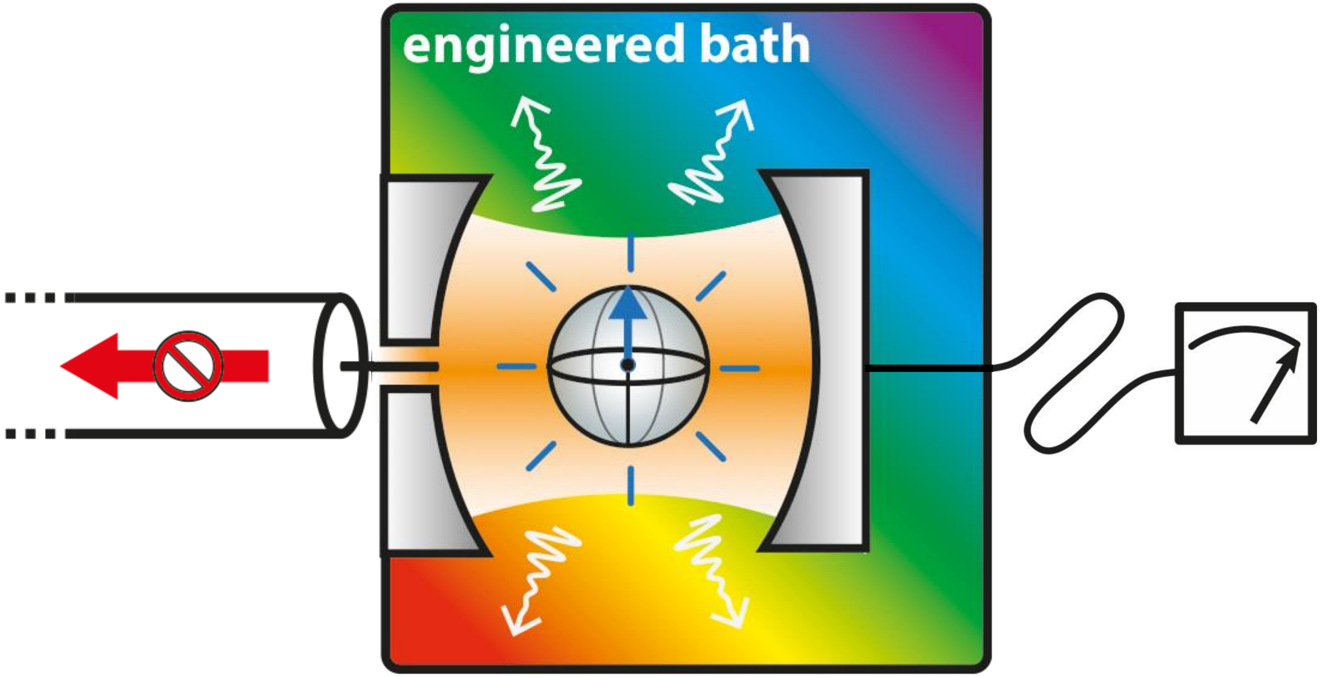
Engineered bath for irreversible evolution



$$\hat{L} = \hat{a}\hat{\sigma}^+$$

Non unitary evolution

Engineered bath for irreversible evolution

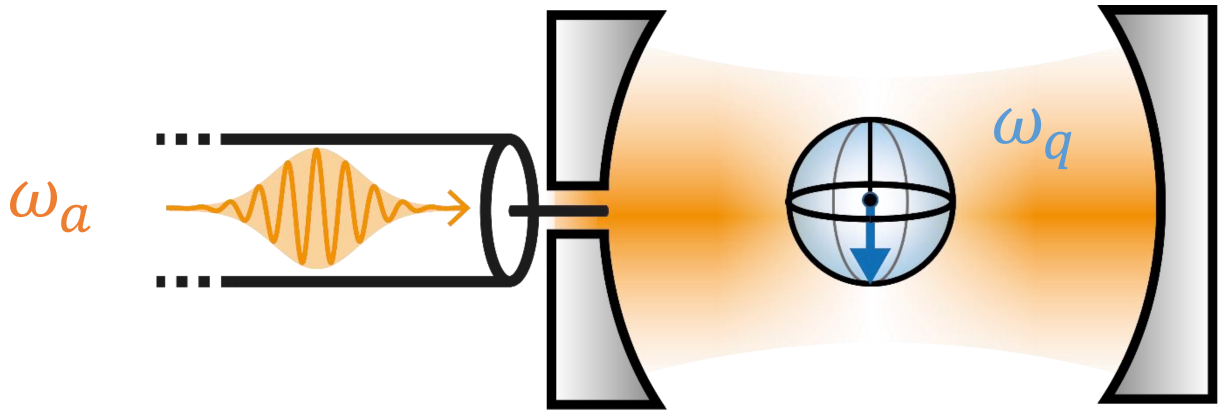


$$\hat{L} = \hat{a}\hat{\sigma}^{+}$$

Non unitary evolution

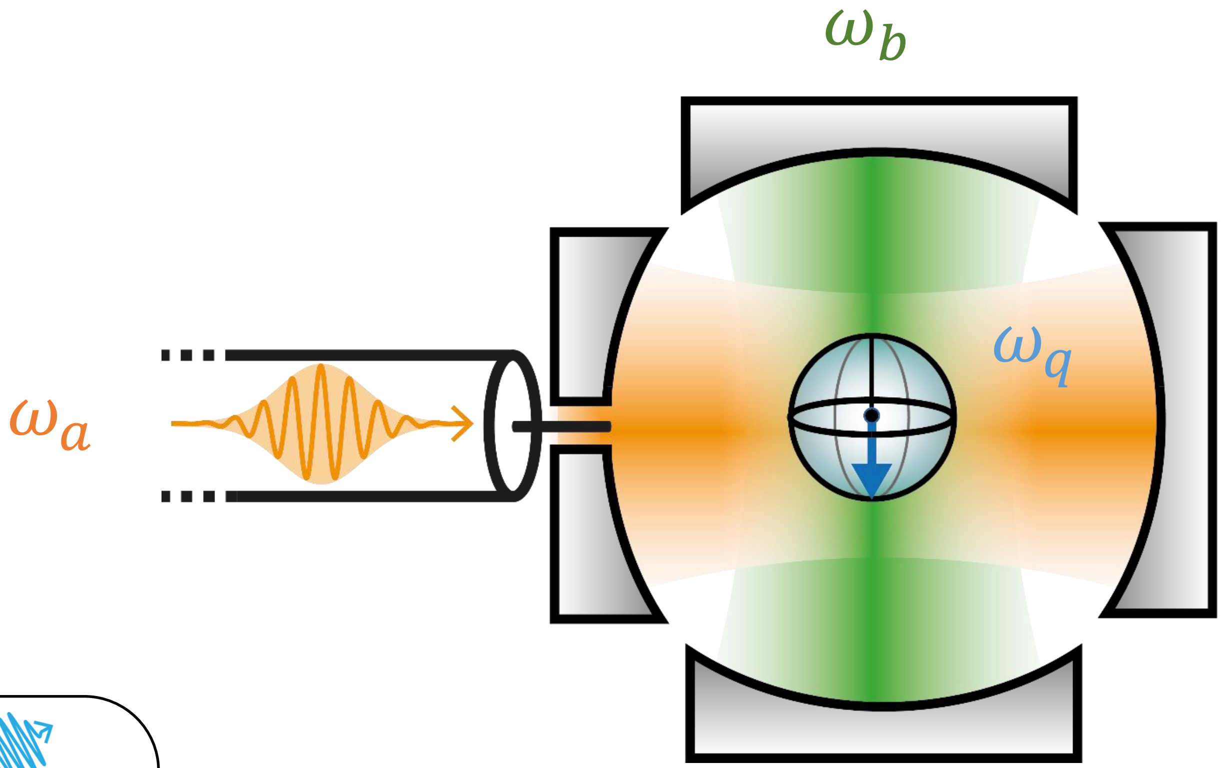
R. Lescanne et al., PRX (2020)

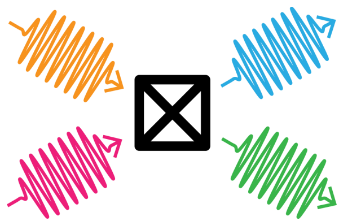
Adding a bath



R. Lescanne et al., PRX (2020)

Adding a bath

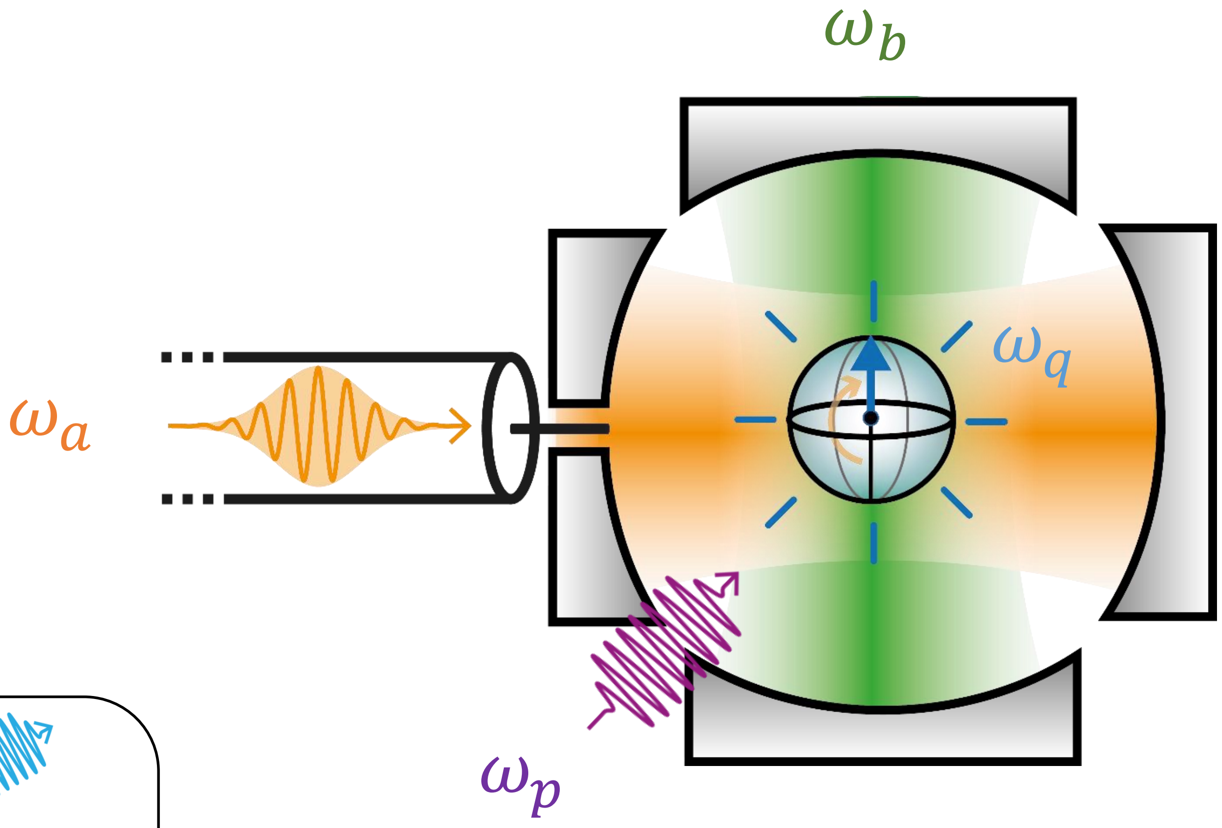




Josephson junction
4-wave mixing element

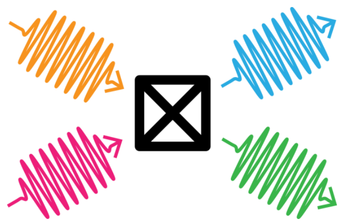
R. Lescanne et al., PRX (2020)

Adding a bath



Frequency matching /
energy conservation

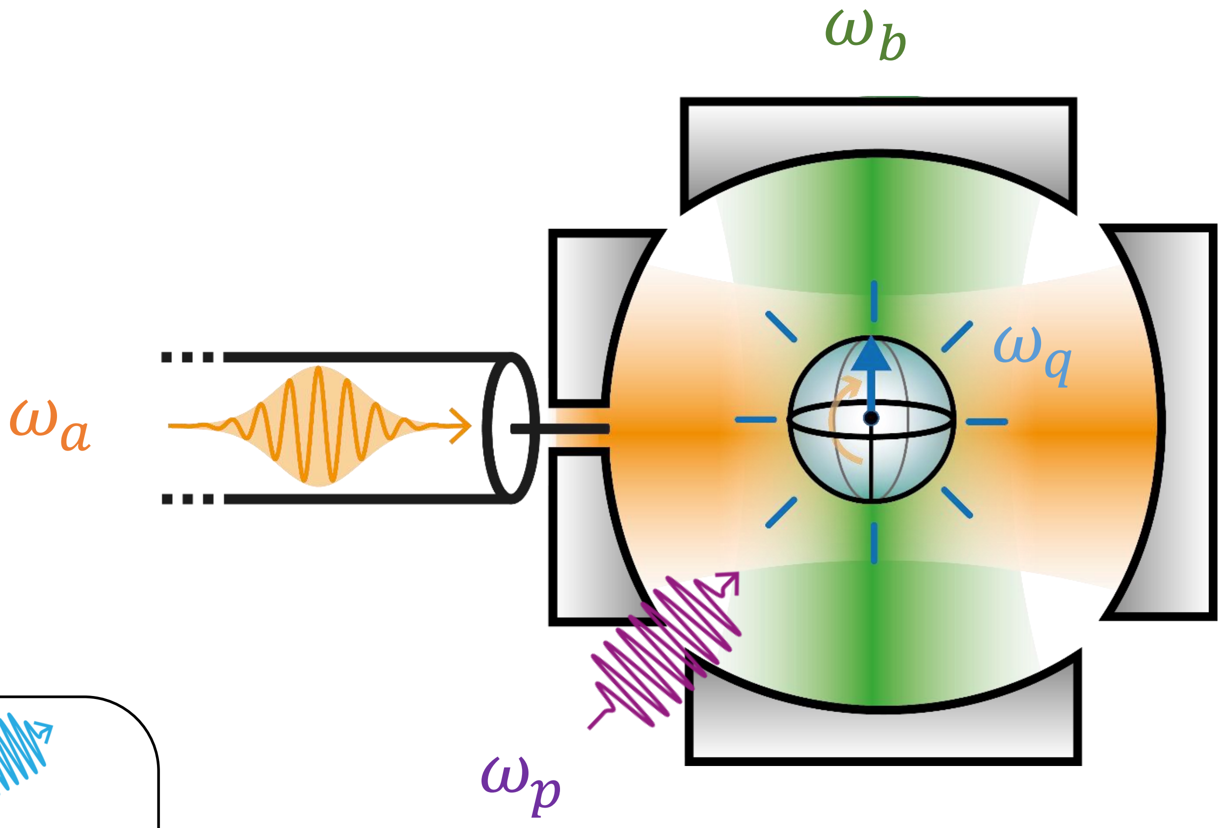
$$\omega_a + \omega_p = \omega_q + \omega_b$$



Josephson junction
4-wave mixing element

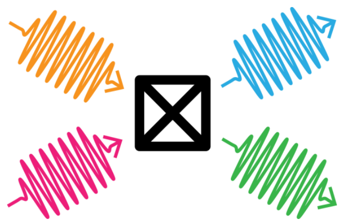
R. Lescanne et al., PRX (2020)

Adding a bath



Frequency matching / energy conservation

$$\omega_a + \omega_p = \omega_q + \omega_b$$

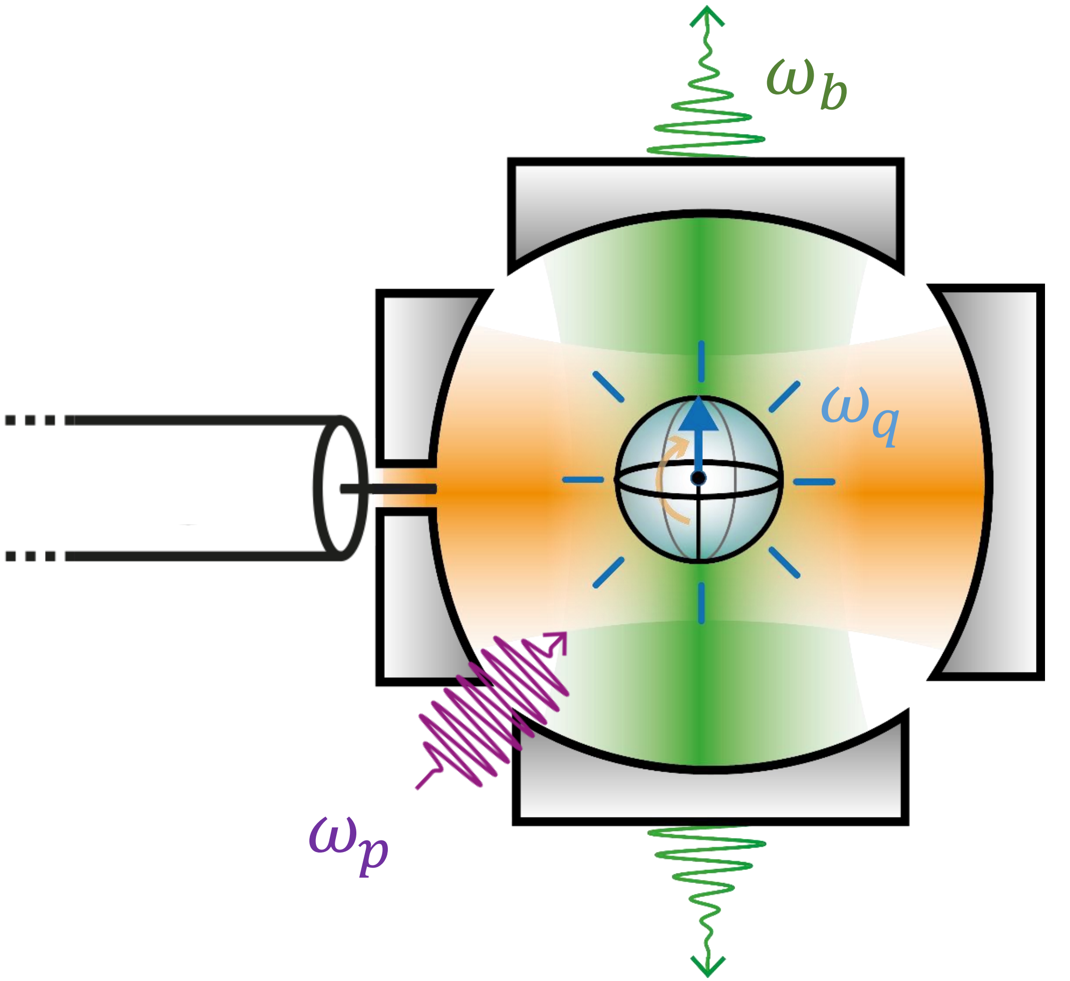


Josephson junction
4-wave mixing element

$$\hat{H} = g_4 \cdot \left(\xi\, \hat{a}\hat{\sigma}^+\hat{b}^+ + \xi^*\, \hat{a}^+\hat{\sigma}\hat{b}\right)$$

R. Lescanne et al., PRX (2020)

Engineered bath for irreversible evolution

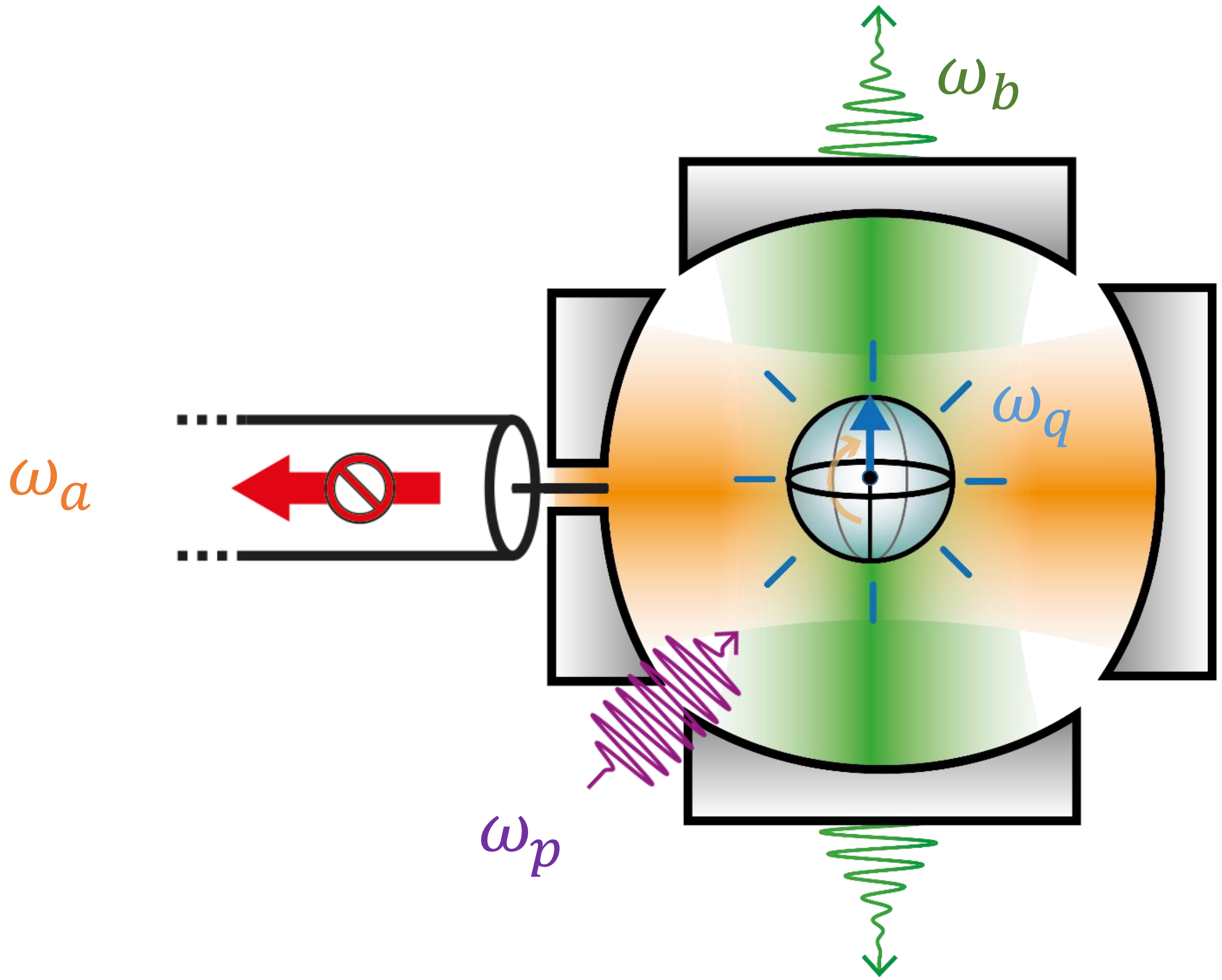


$$\boldsymbol{\omega_a + \omega_p = \omega_q + \omega_b}$$

$$\hat{H} = g_4 \cdot (\xi\, \hat{a}\hat{\sigma}^+\hat{b}^+ + \xi^* \hat{a}^+\hat{\sigma}\hat{b})$$

R. Lescanne et al., PRX (2020)

Engineered bath for irreversible evolution



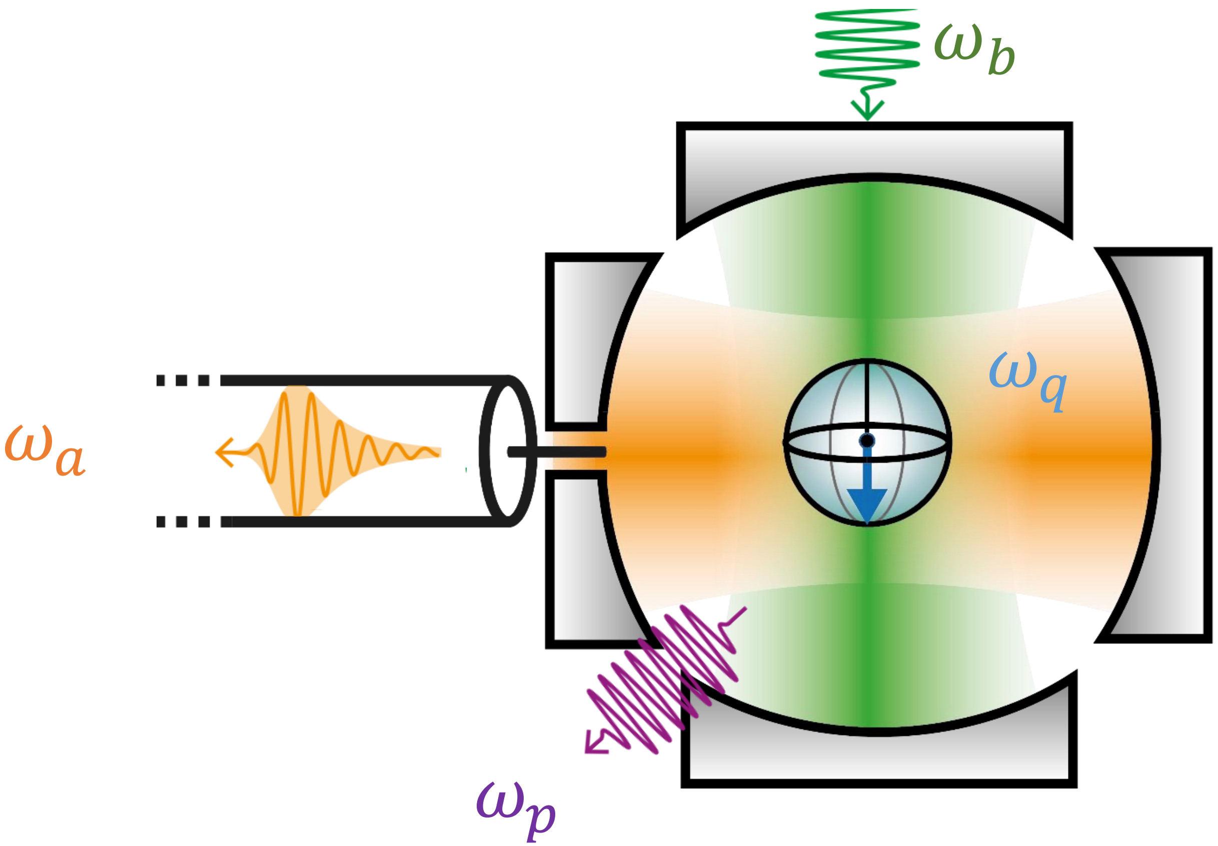
$$\omega_a + \omega_p = \omega_q + \omega_b$$

$$\hat{H} = g_4 \cdot (\xi\, \hat{a}\hat{\sigma}^+\hat{b}^+ + \xi^* \hat{a}^+\hat{\sigma}\hat{b})$$

$$\hat{L} = \hat{a}\hat{\sigma}^+$$

R. Lescanne et al., PRX (2020)

Built-in detector reset

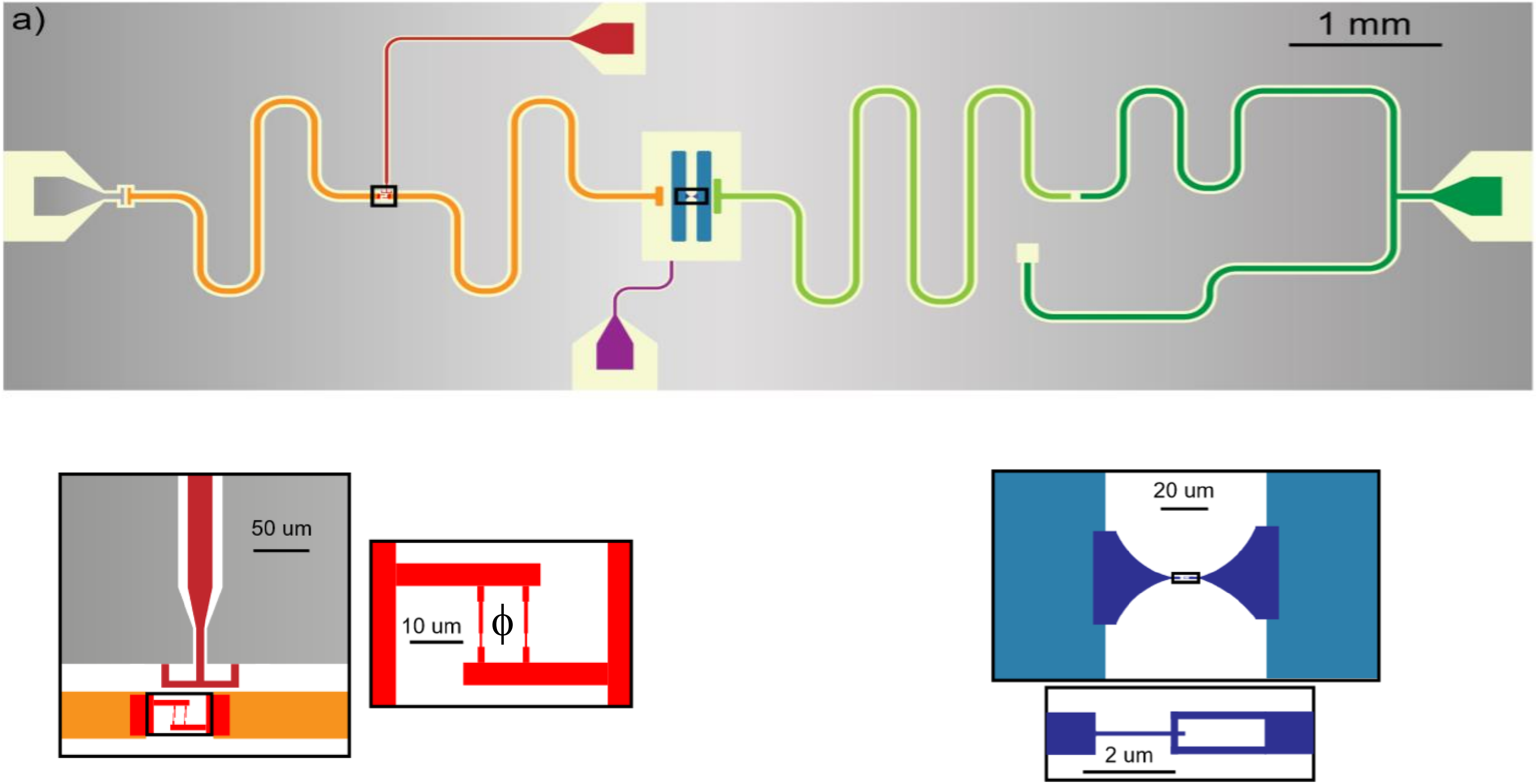


$$\boldsymbol{\omega_q + \omega_b = \omega_a + \omega_p}$$

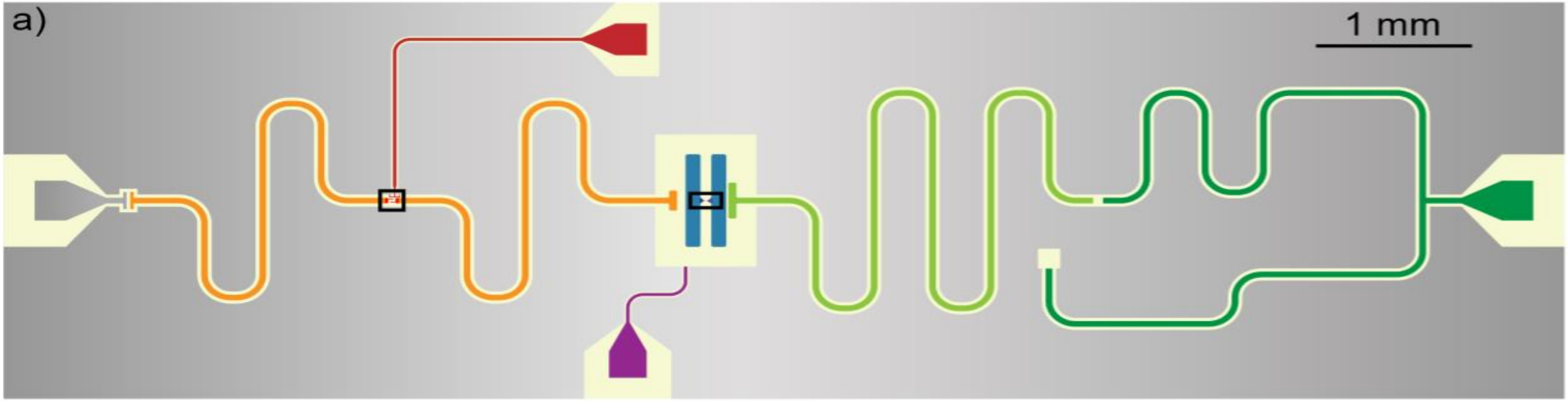
$$\hat{H} = g_4 \cdot (\xi\, \hat{a}\hat{\sigma}^{+}\hat{b}^{+} + \xi^{*}\, \hat{a}^{+}\hat{\sigma}\hat{b})$$

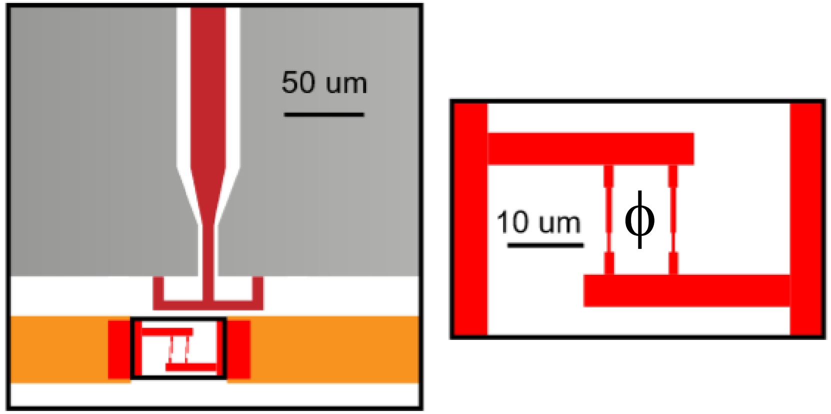
R. Lescanne et al., PRX (2020)

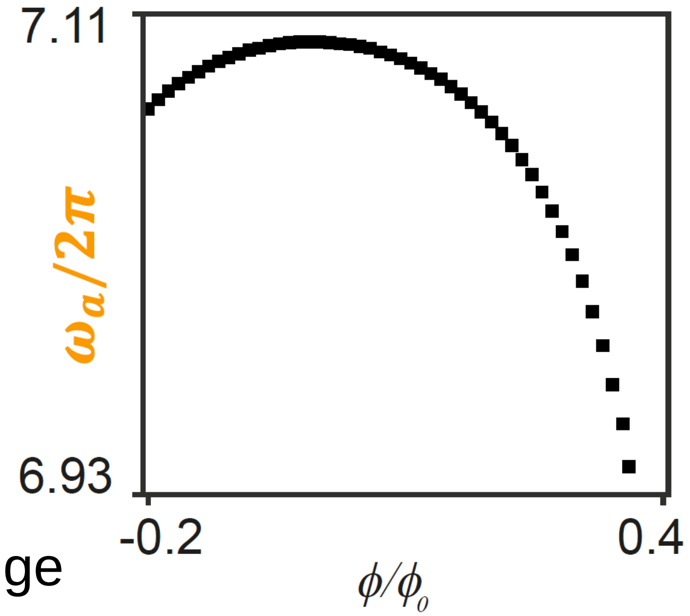
Circuit layout



Circuit layout

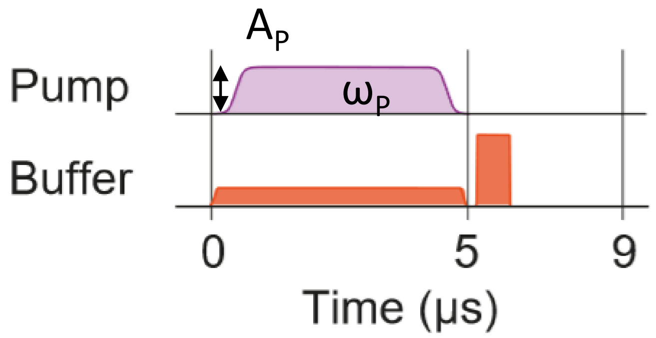






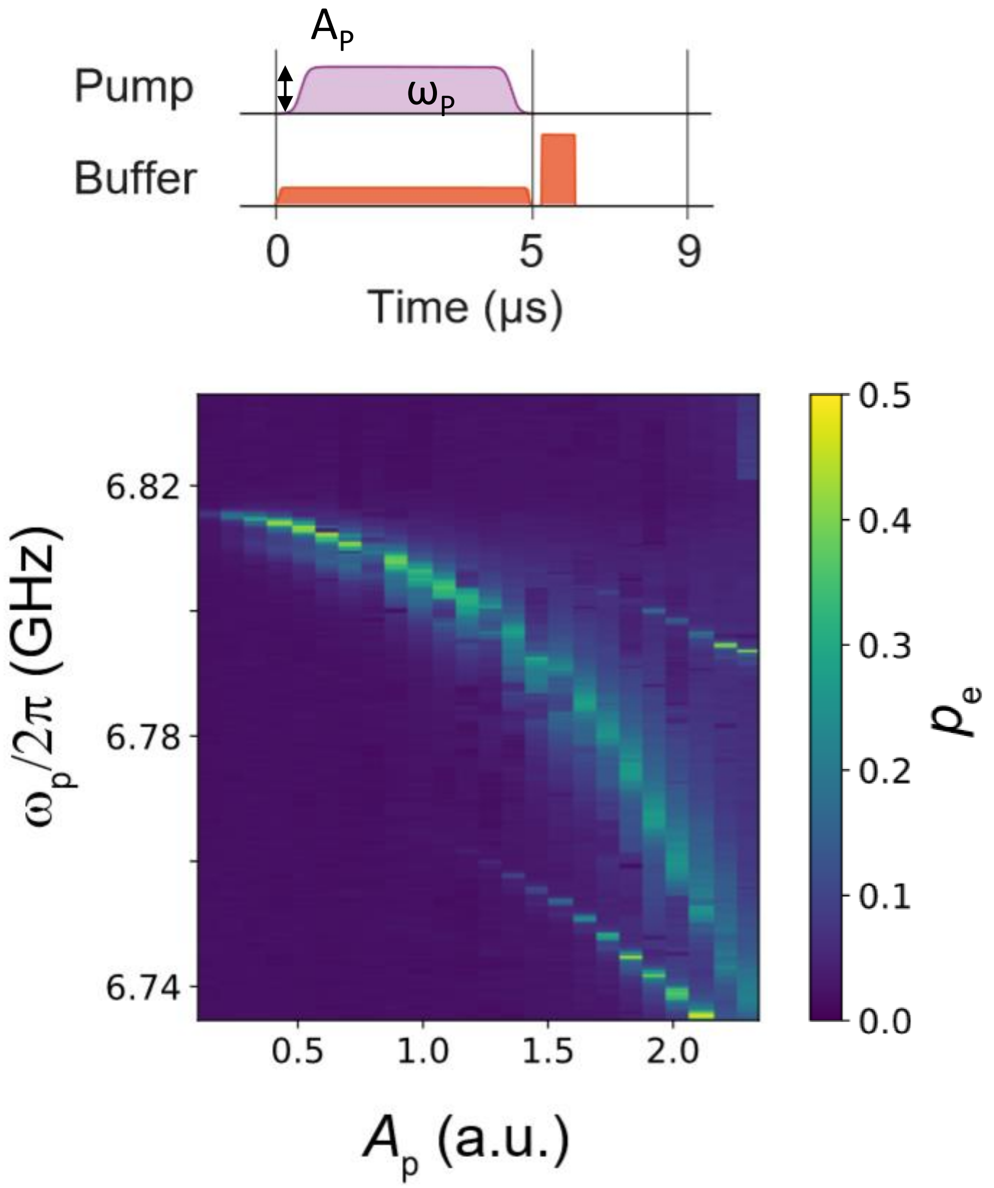
~200 MHz tuning range

Tuning the detector



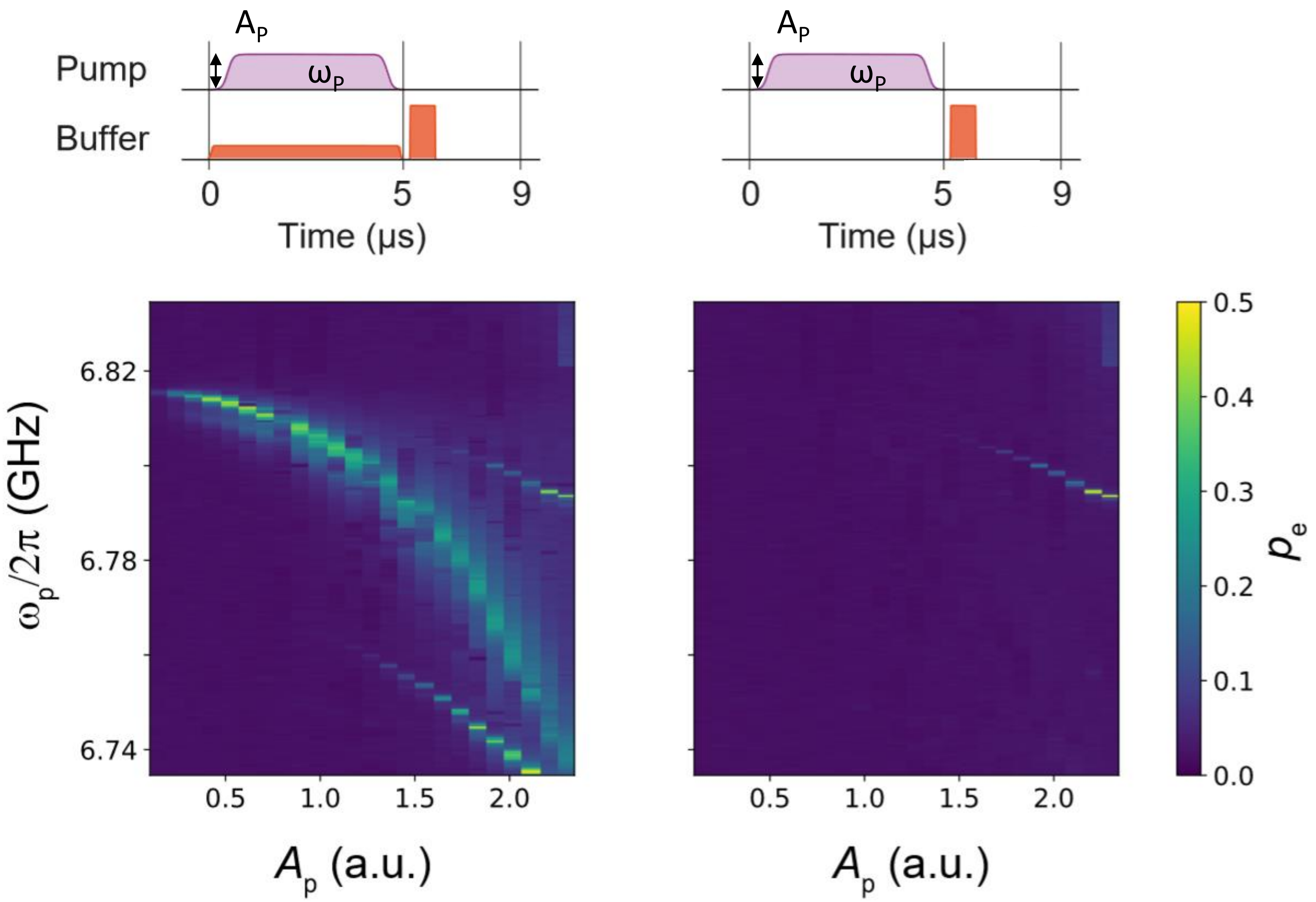
$$\omega_a + \omega_p = \omega_q + \omega_b$$

Tuning the detector

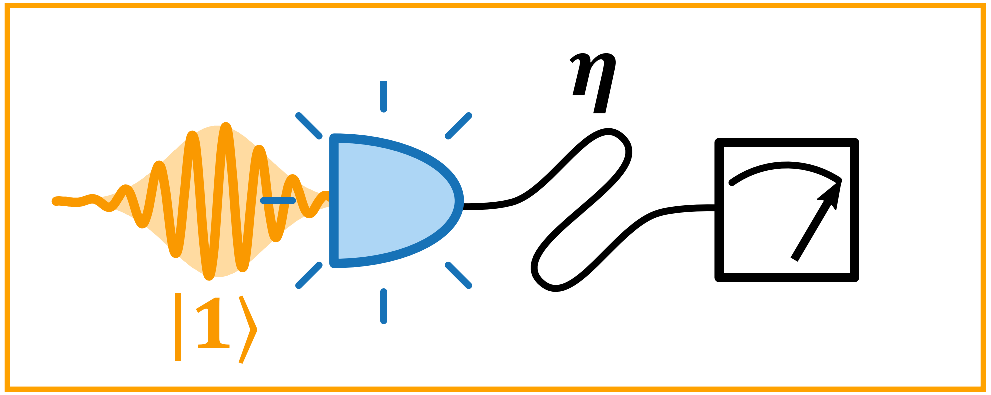


$$\omega_a + \omega_p = \omega_q + \omega_b$$

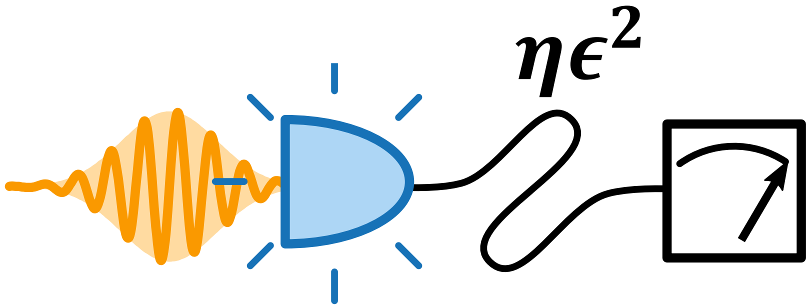
Tuning the detector



Figures of merit: efficiency

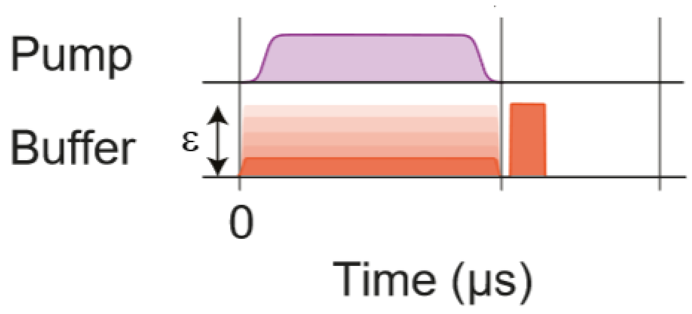


Figures of merit: efficiency

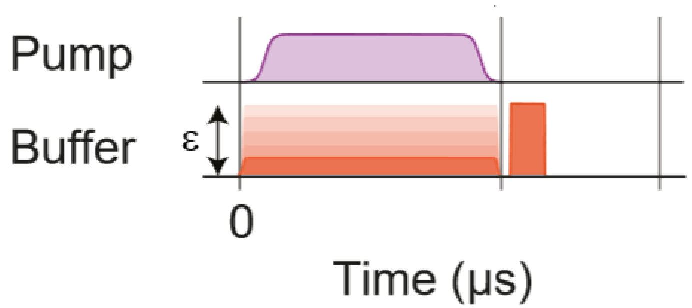


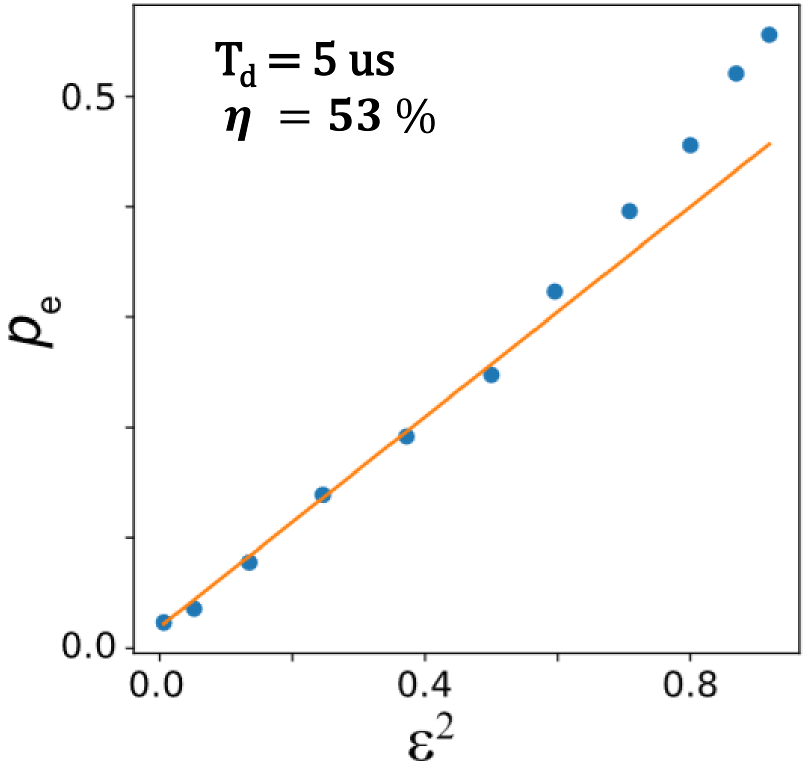
$$|\epsilon\rangle \cong |0\rangle + \epsilon|1\rangle + O(\epsilon^2)$$

Figures of merit: efficiency

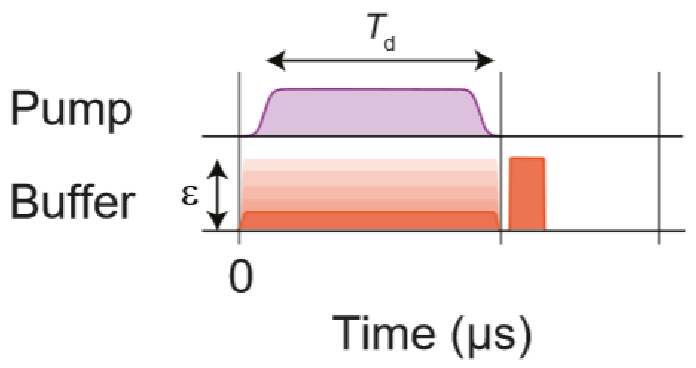


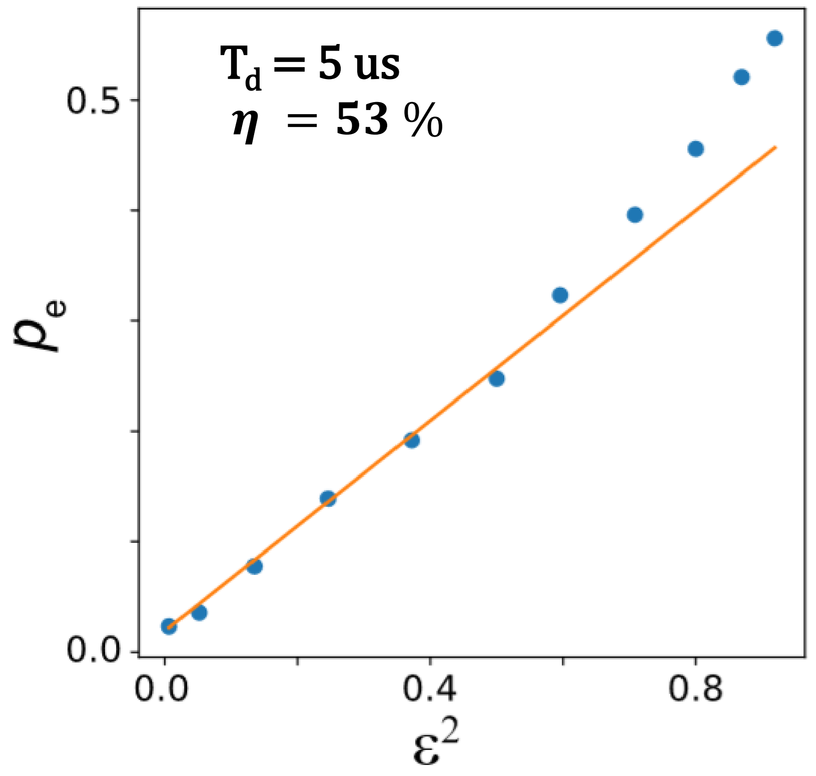
Figures of merit: efficiency

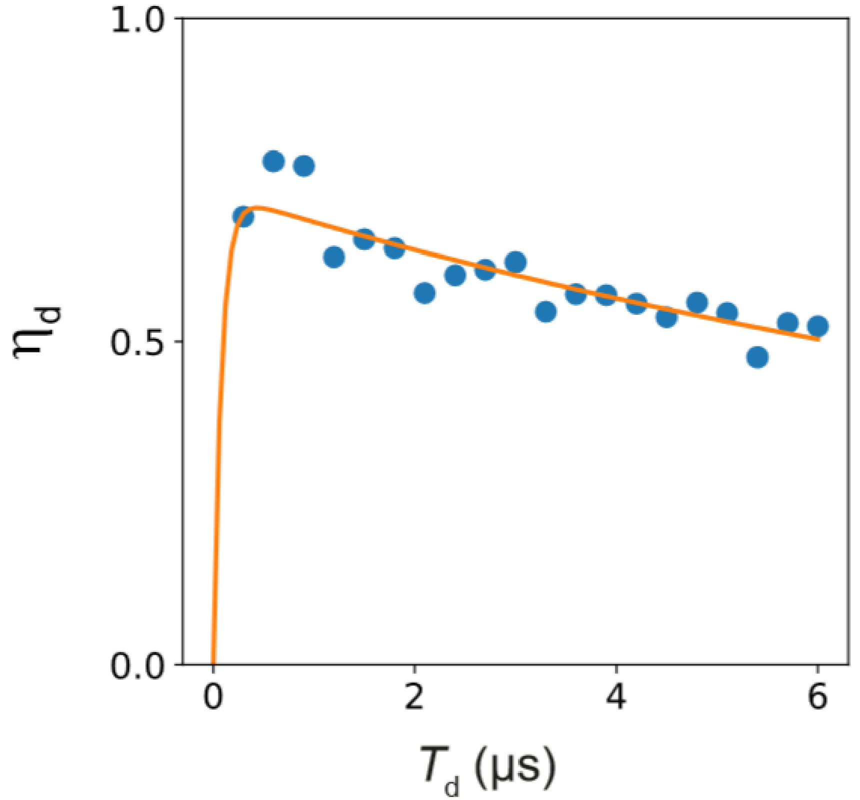




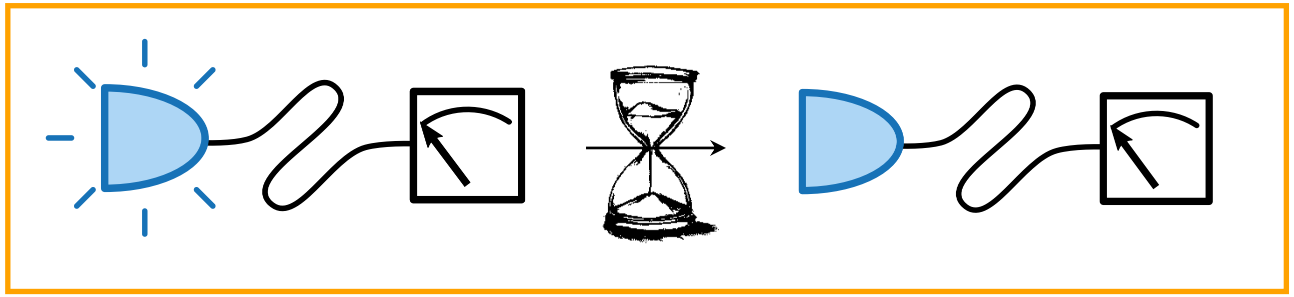
Figures of merit: efficiency



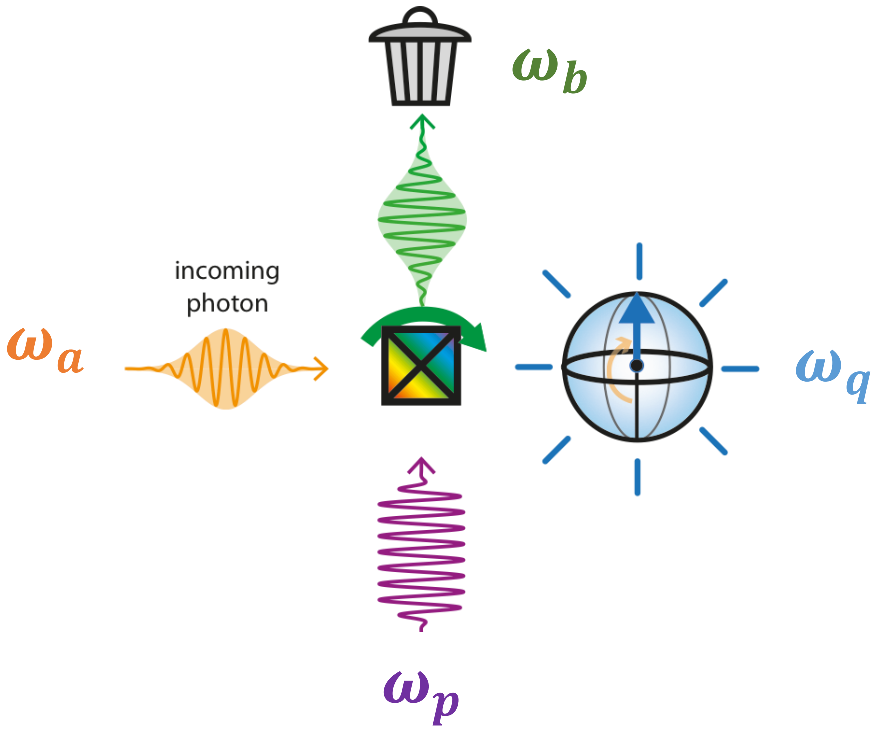


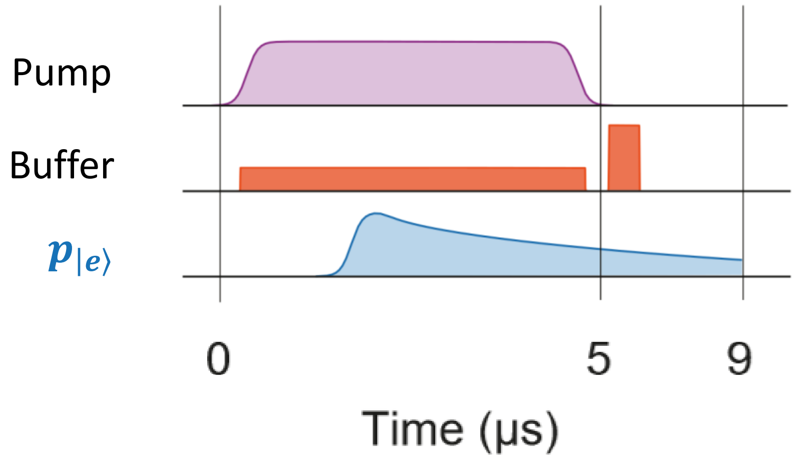


Dead time

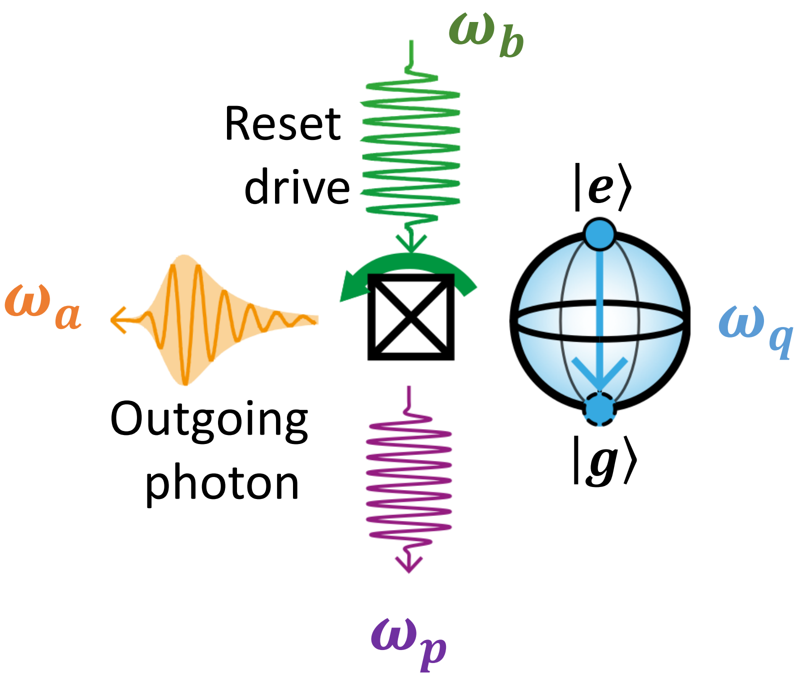


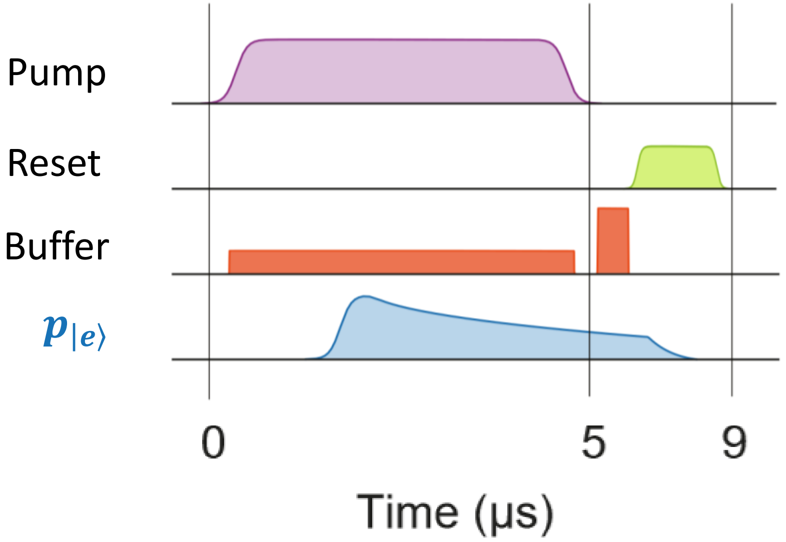
Dead time


ω_b
incoming
photon
ω_a
ω_q
ω_p

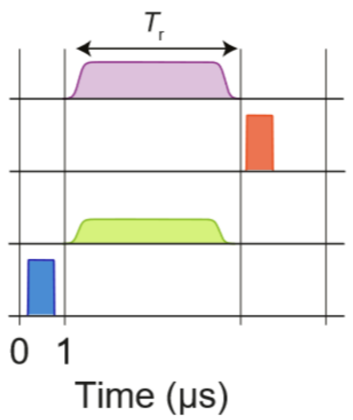

Pump
Buffer
$p_{|e\rangle}$
0
5
9
Time (μs)

Dead time

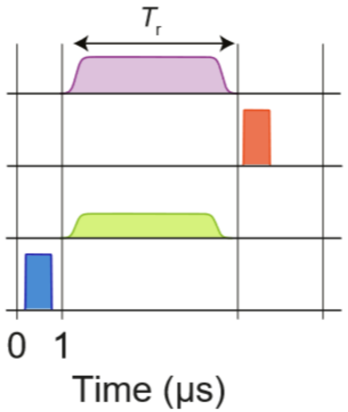

ω_b
Reset drive
$|e\rangle$
ω_a
ω_q
Outgoing photon
$|g\rangle$
ω_p

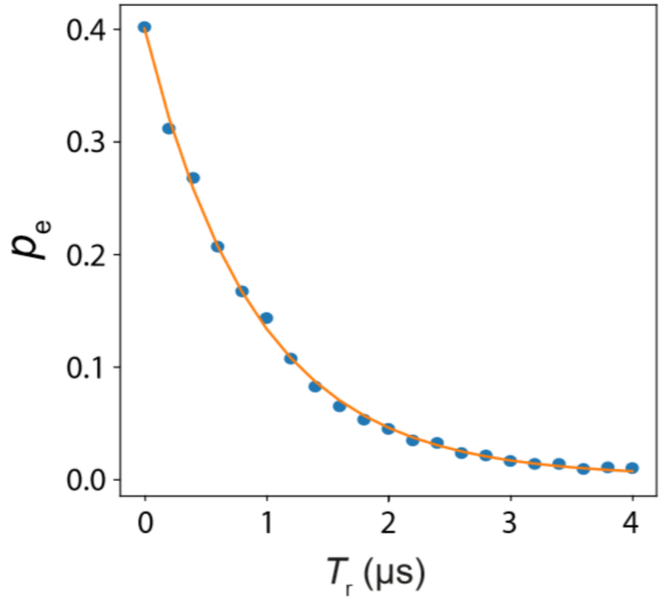

Pump
Reset
Buffer
$p_{|e\rangle}$
0
5
9
Time (μs)

Dead time – reset calibration



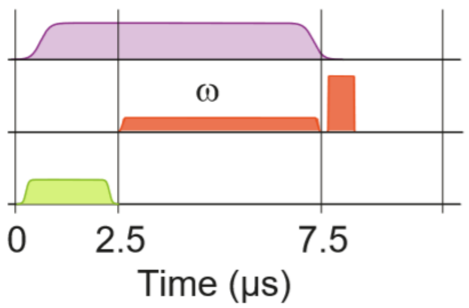
Dead time – reset calibration



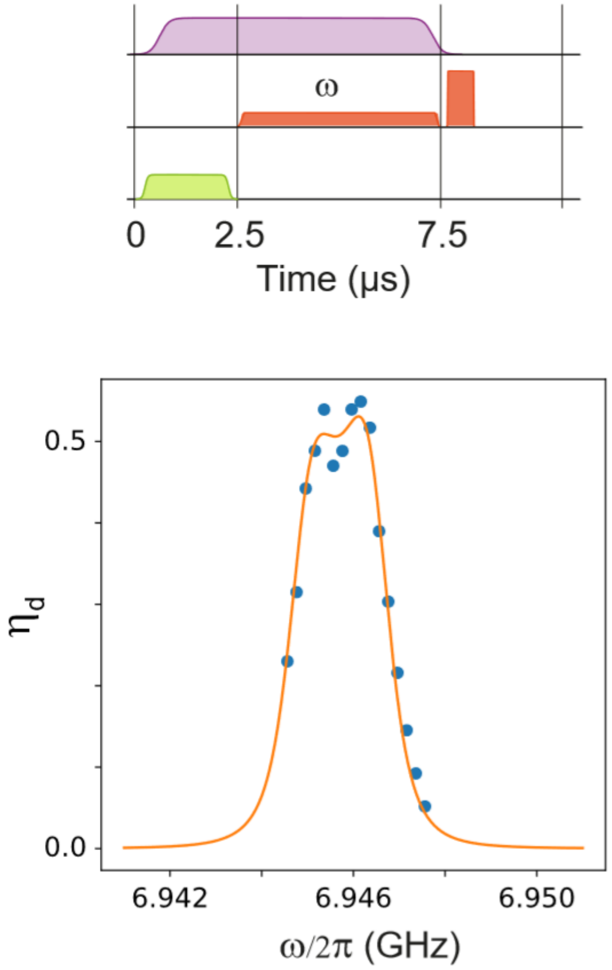


Reset time: 2.5 μs

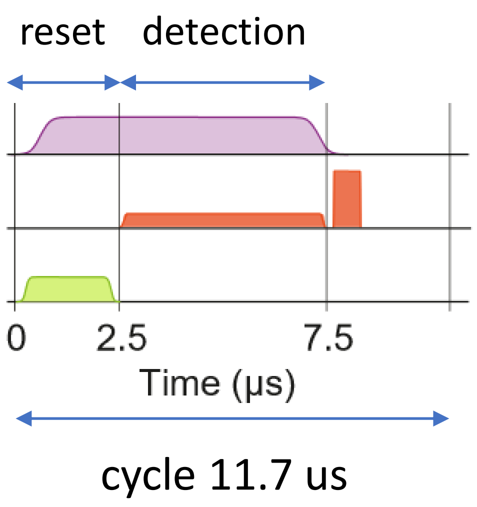
Figures of merit: banwidth



Figures of merit: banwidth

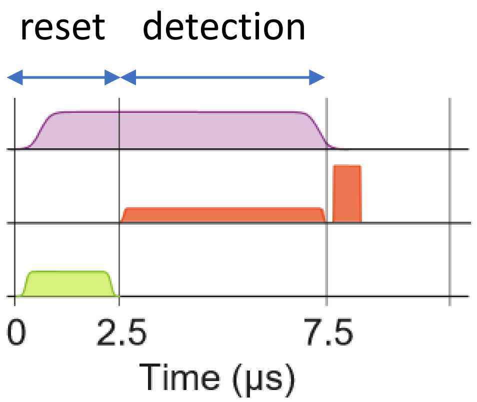


Cyclic operation



$\eta_{duty} = 0.43$

Cyclic operation

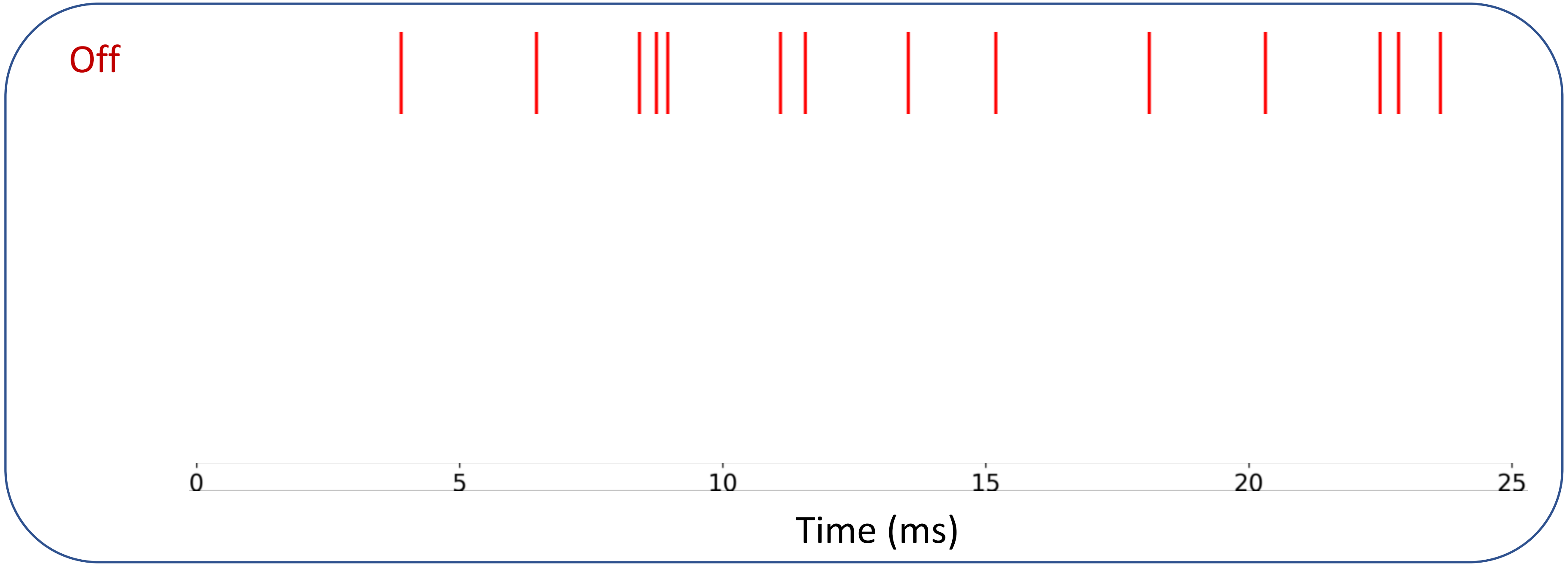


cycle 11.7 us

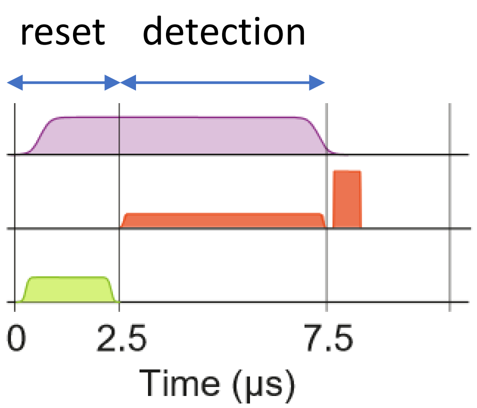
Dark count rate: 600 s^{-1}

$\eta_{duty} = 0.43$

2500 detection cycles



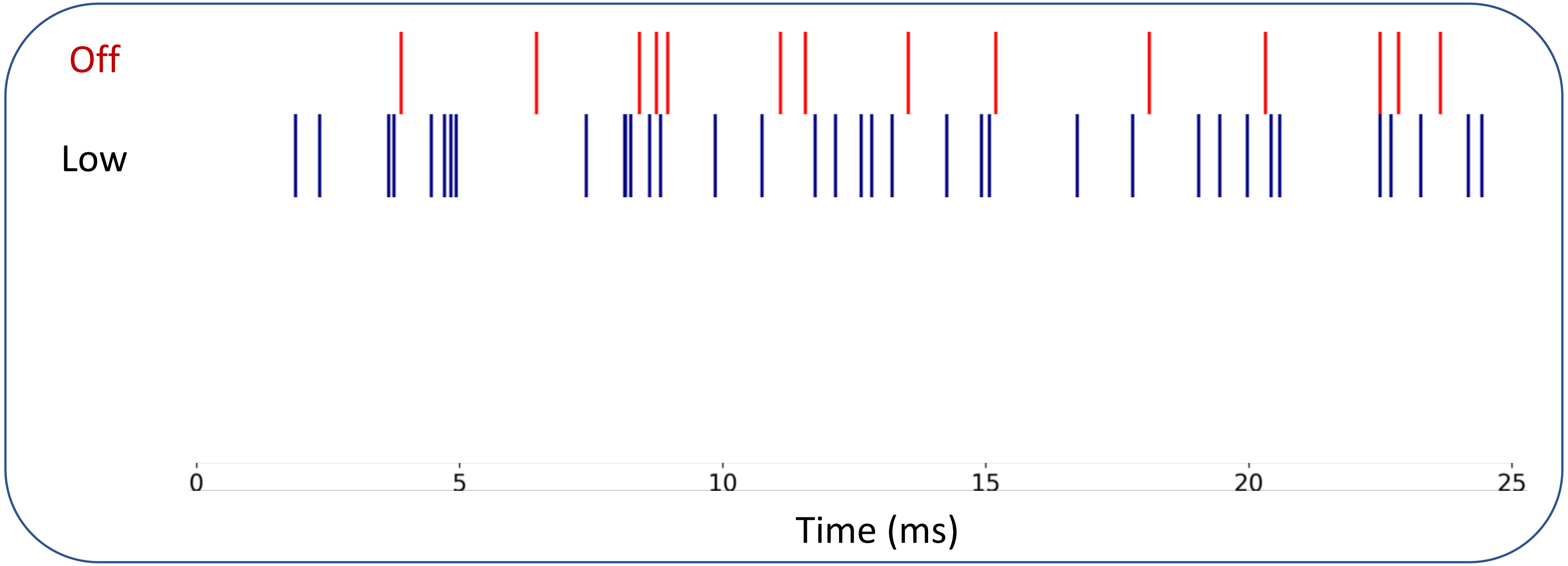
Cyclic operation



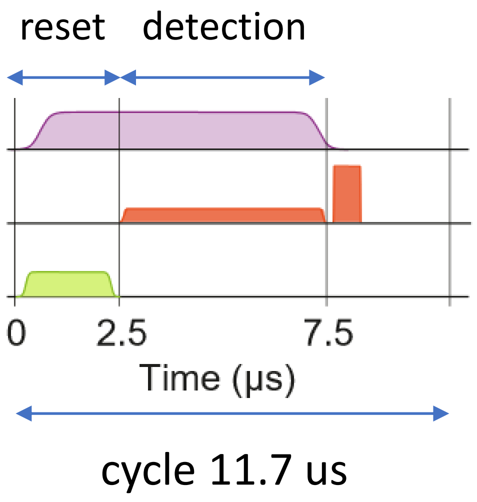
cycle 11.7 us

Dark count rate: 600 s^{-1}

2500 detection cycles



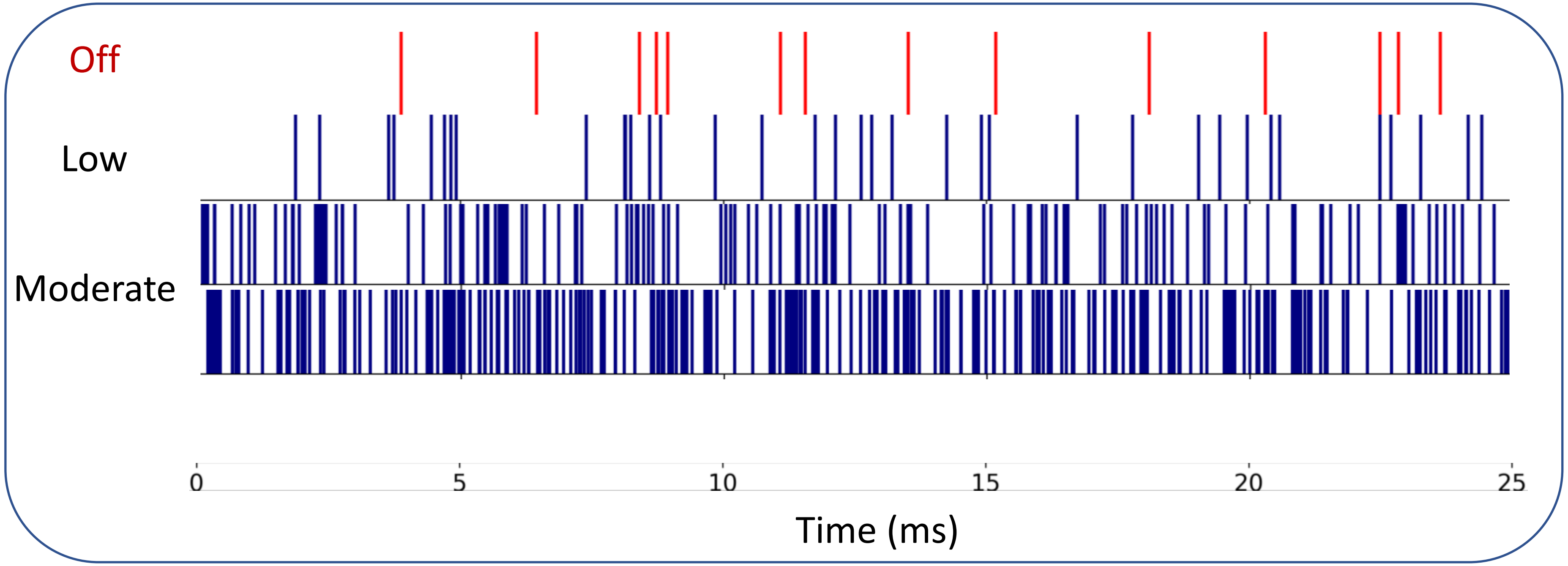
Cyclic operation



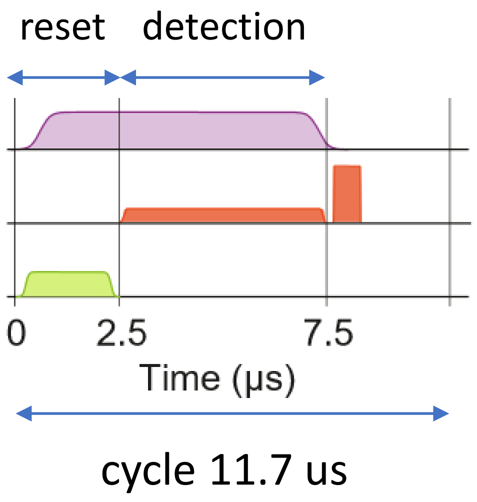
Dark count rate: 600 s^{-1}

Efficiency: 0.23 *(0.43 · 0.53 duty cycle limited)*

2500 detection cycles



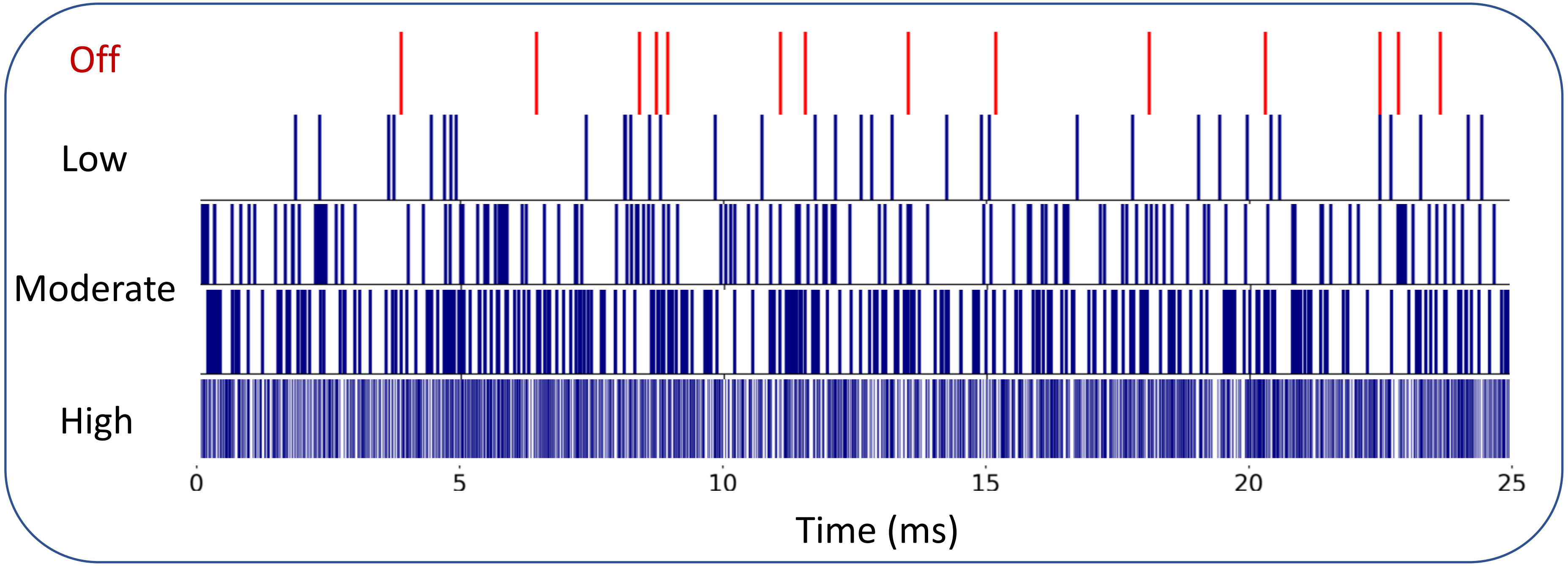
Cyclic operation



Dark count rate: 600 s^{-1}

Efficiency: 0.23 *(0.43 · 0.53 duty cycle limited)*

2500 detection cycles

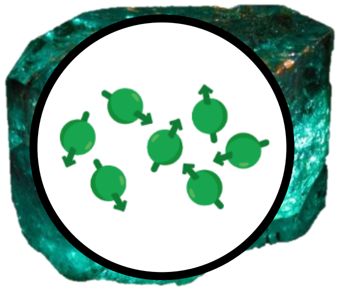


Detecting spins by their fluorescence with a microwave photon counter

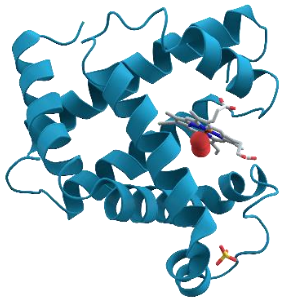
Emanuele Albertinale, Léo Balembois, Eric Billaud, Vishal Ranjan, Daniel Flanigan,
Thomas Schenkel, Daniel Estève, Denis Vion,
Patrice Bertet, and Emmanuel Flurin

Nature 600, 434-438 (2021).

Spin detection



Chemistry

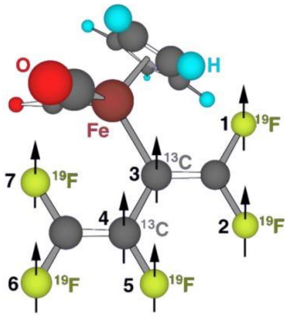


Molecular Biology

Food Control

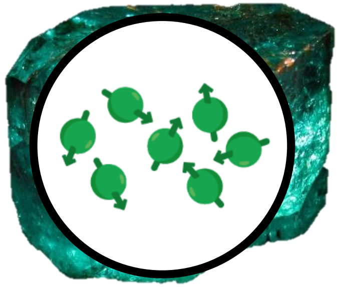
Archaeology

Condensed-Matter Physics

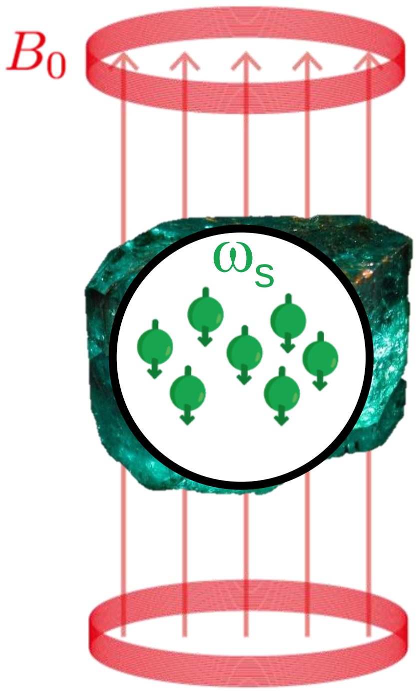


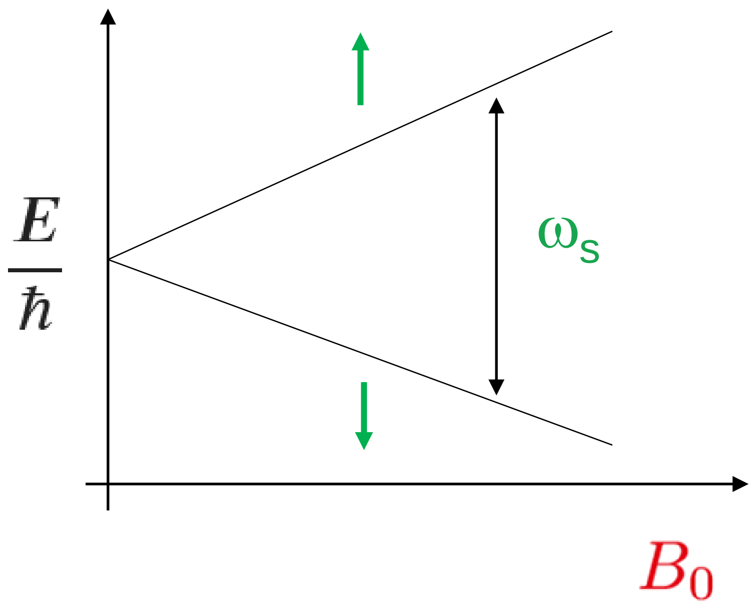
Quantum Computing

Spin detection

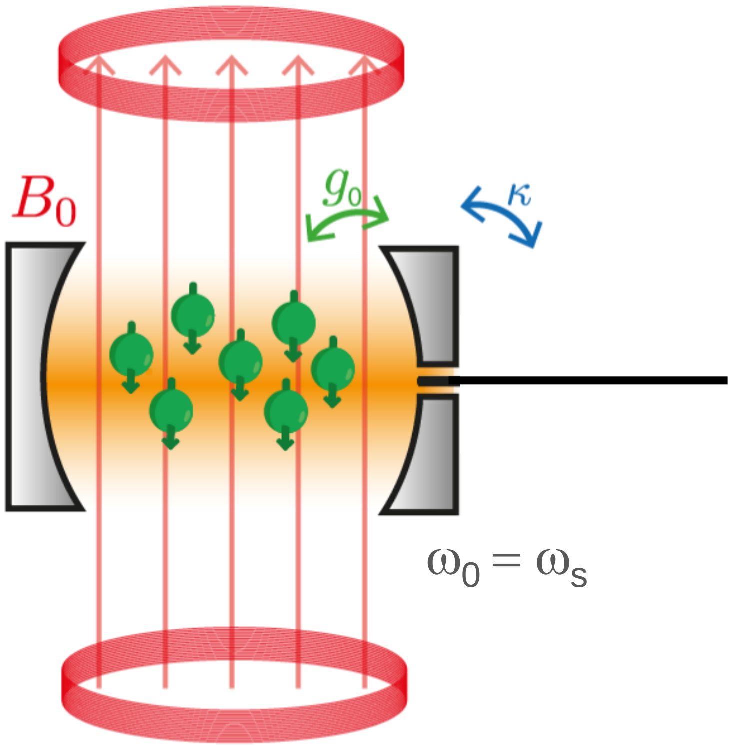


Spin detection

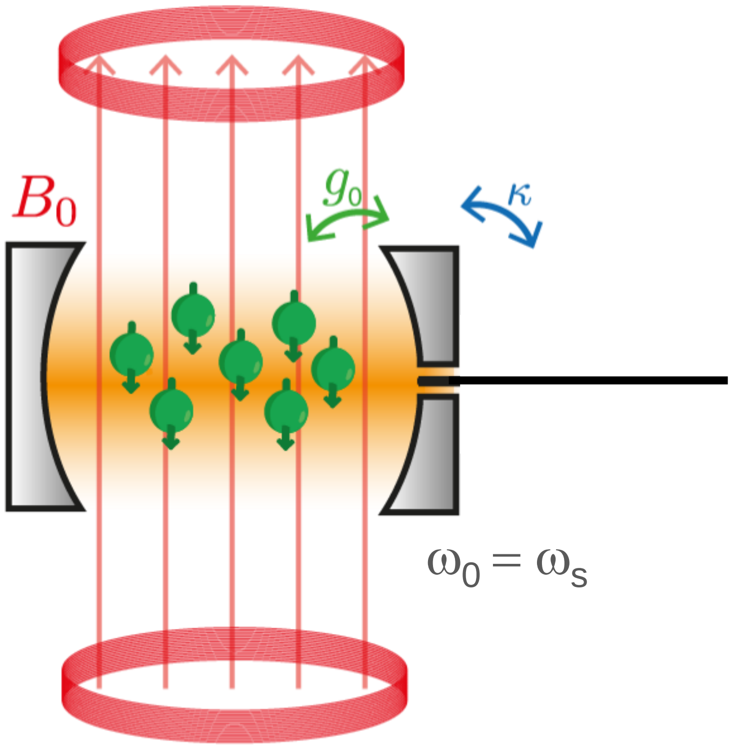


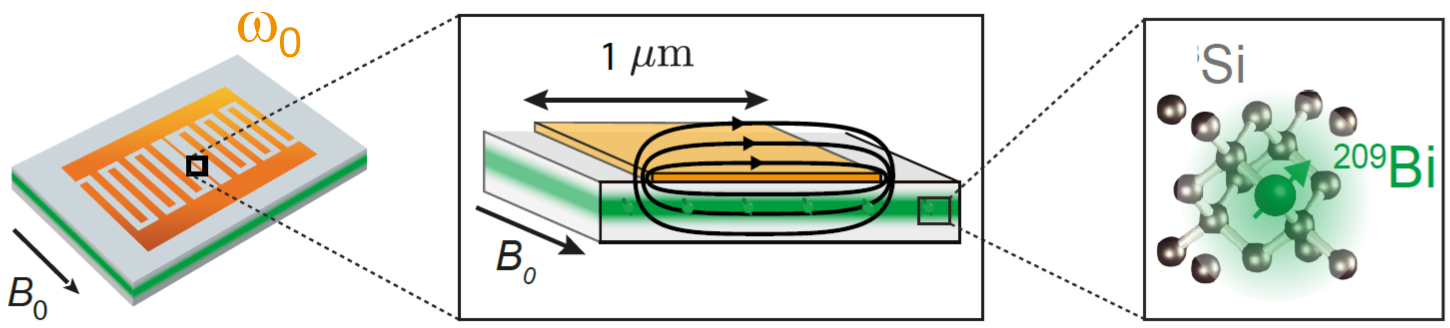


Spins coupled to a cavity

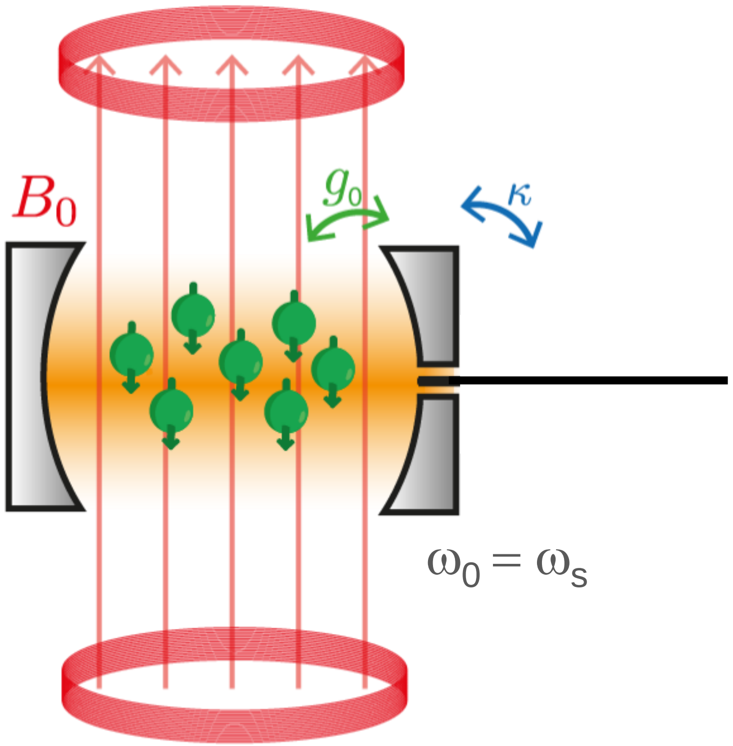


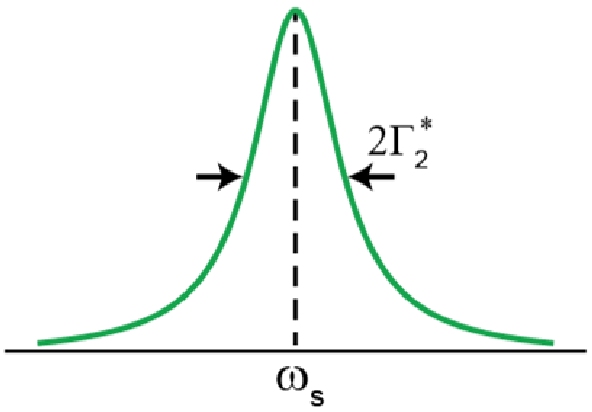
Spins coupled to a cavity

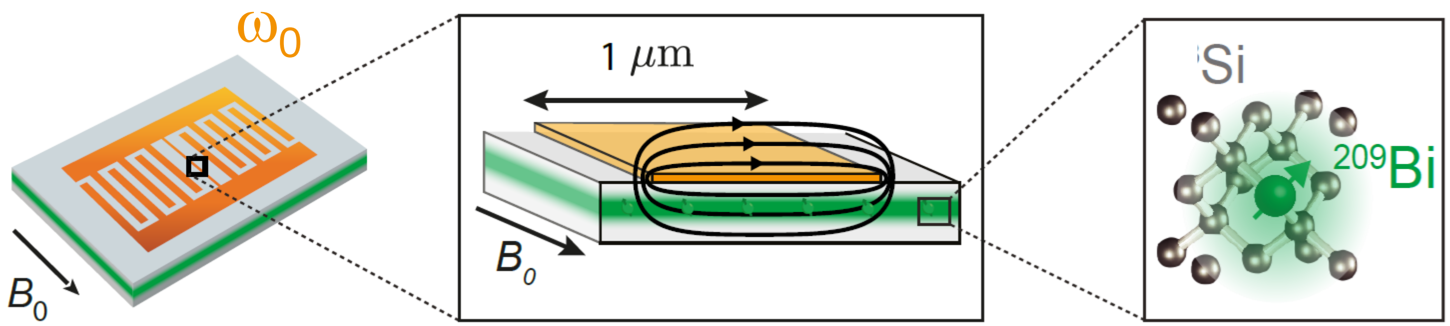




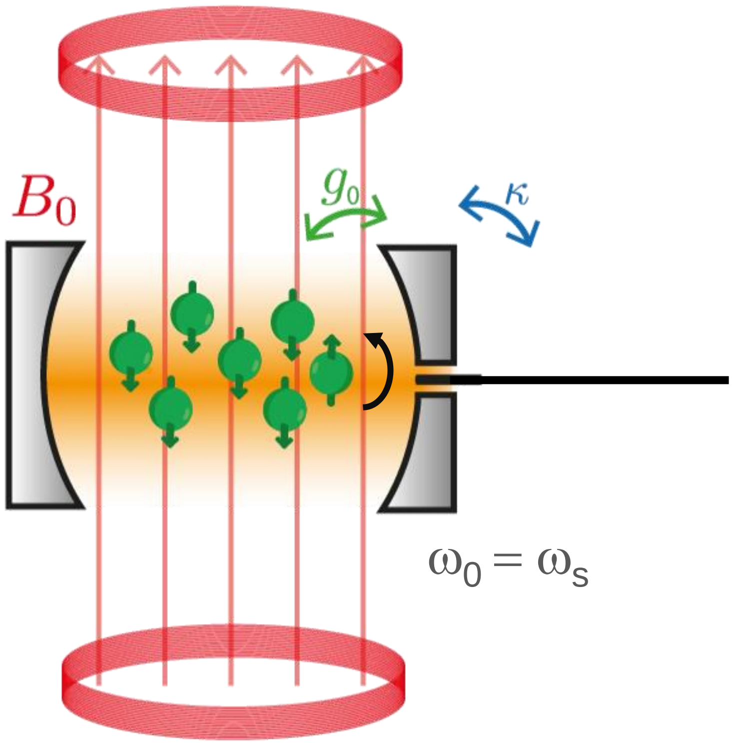
Spins coupled to a cavity







Spins coupled to a cavity



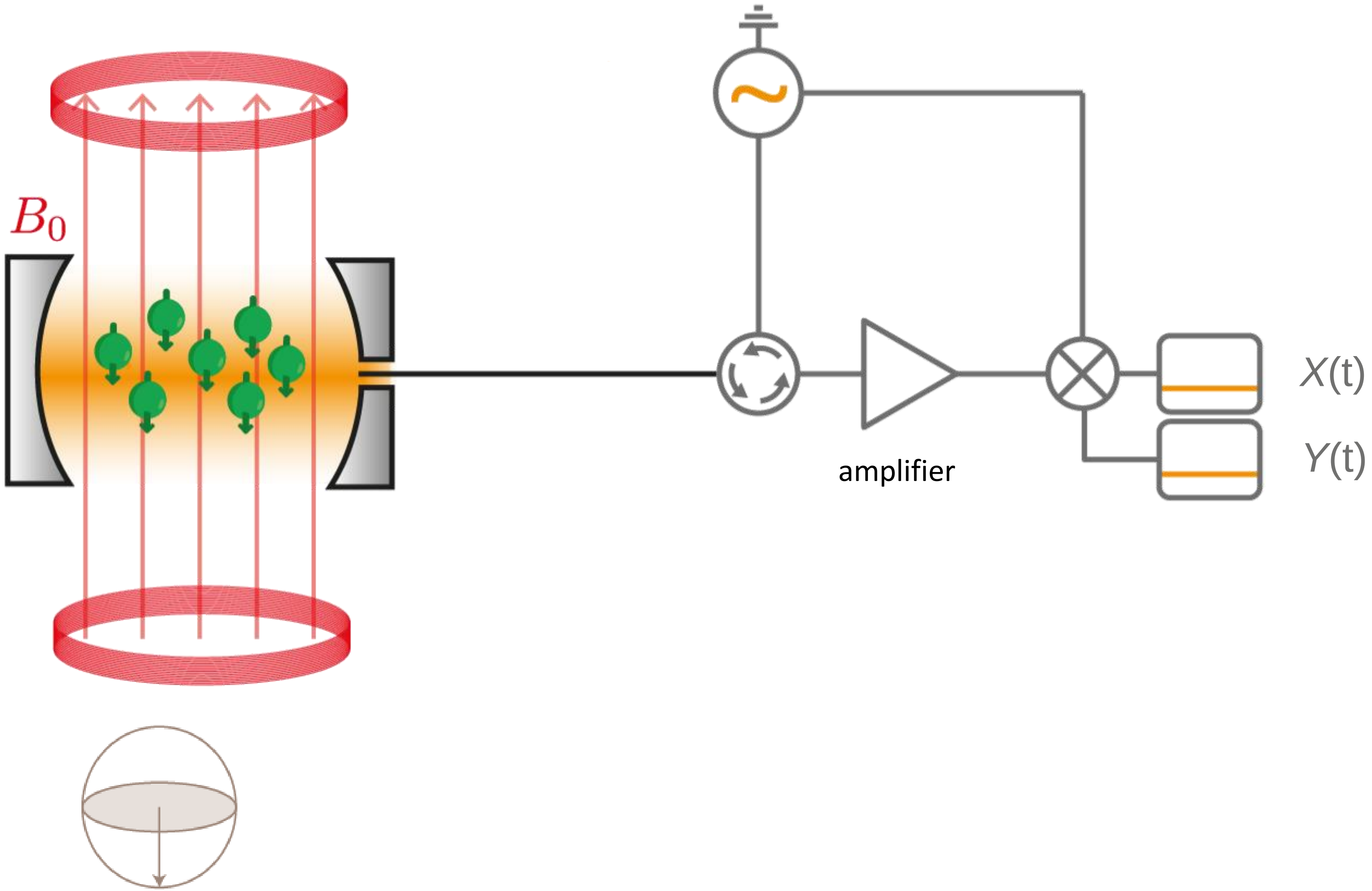
Spin Purcell radiative relaxation rate:

$$\Gamma_p = \frac{4g_0^2}{\kappa}$$

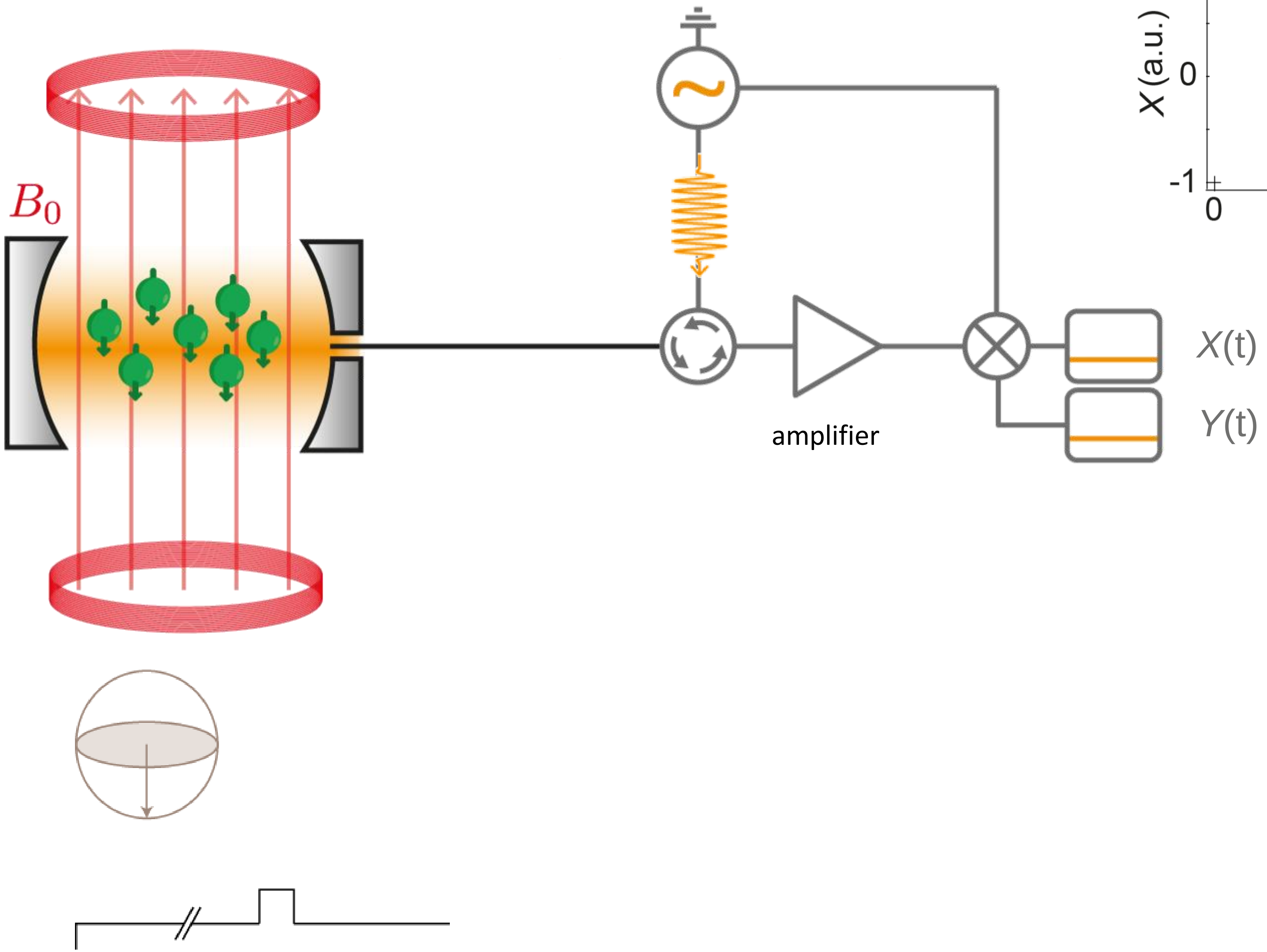
Purcell, Edward Mills. "Spontaneous emission probabilities at radio frequencies." Confined Electrons and Photons. Springer, Boston, MA, 1995. 839-839.

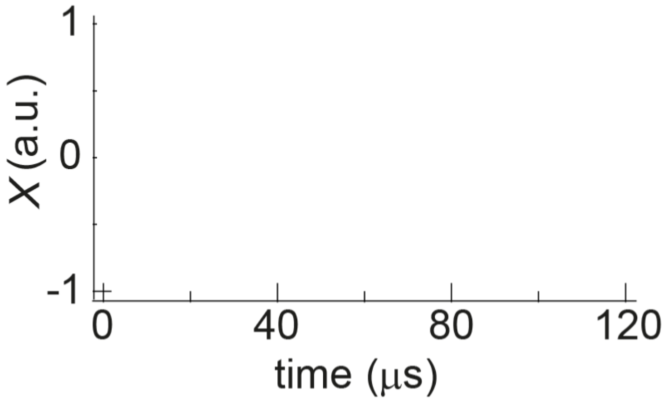
Bienfait, Audrey, et al. "Controlling spin relaxation with a cavity." Nature 531.7592 (2016): 74-77.

Hahn echo quadrature detection



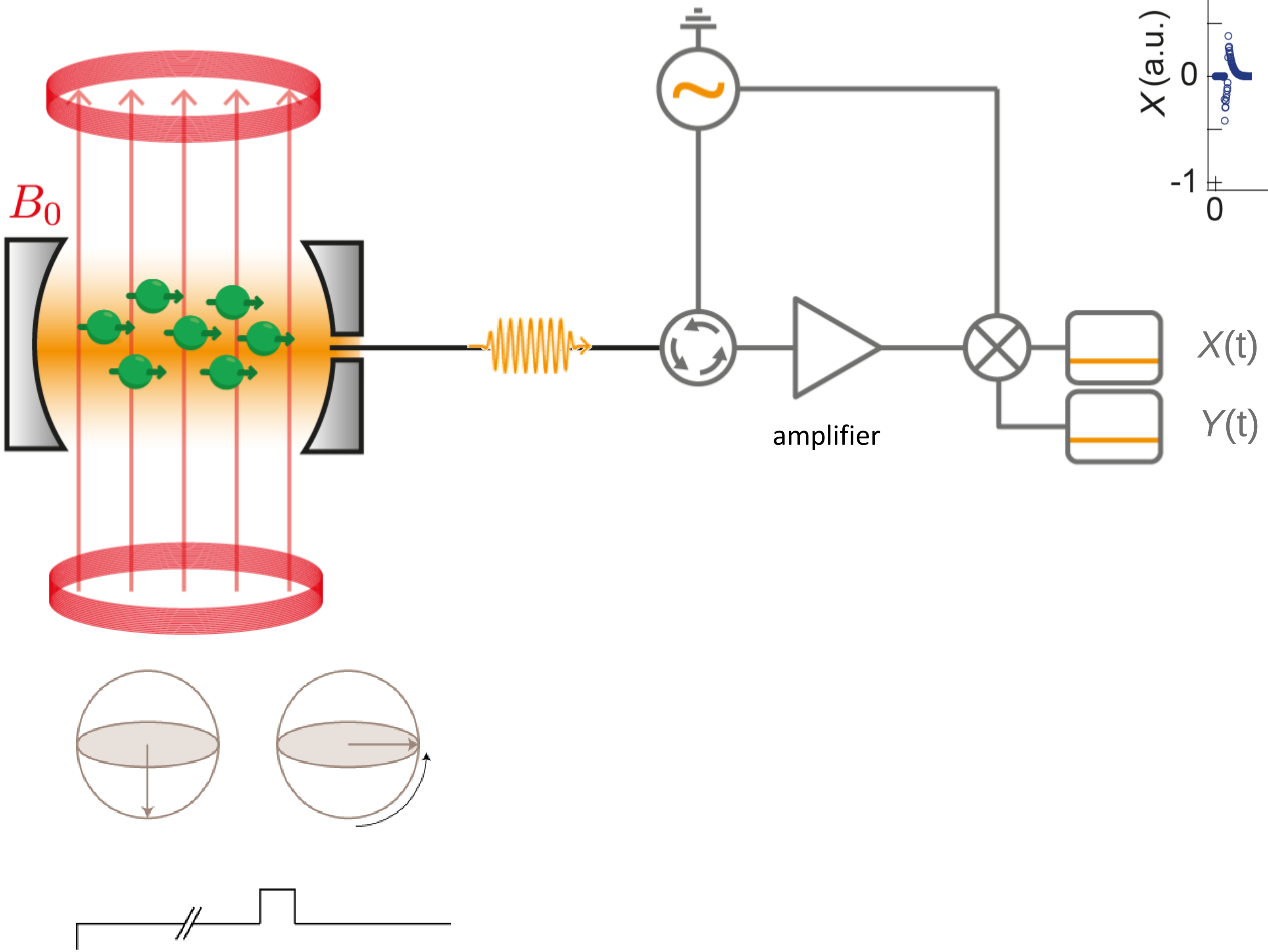
Hahn echo quadrature detection

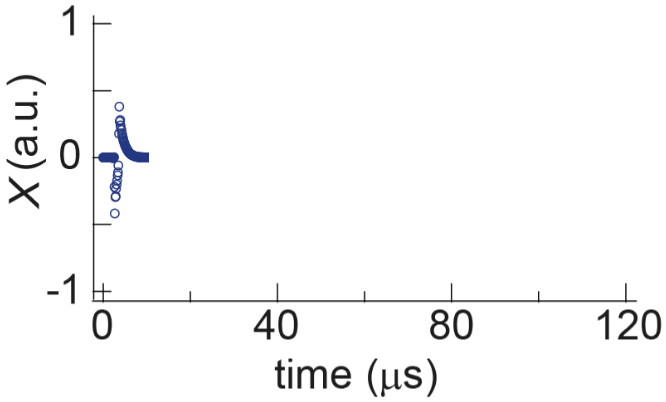




Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.

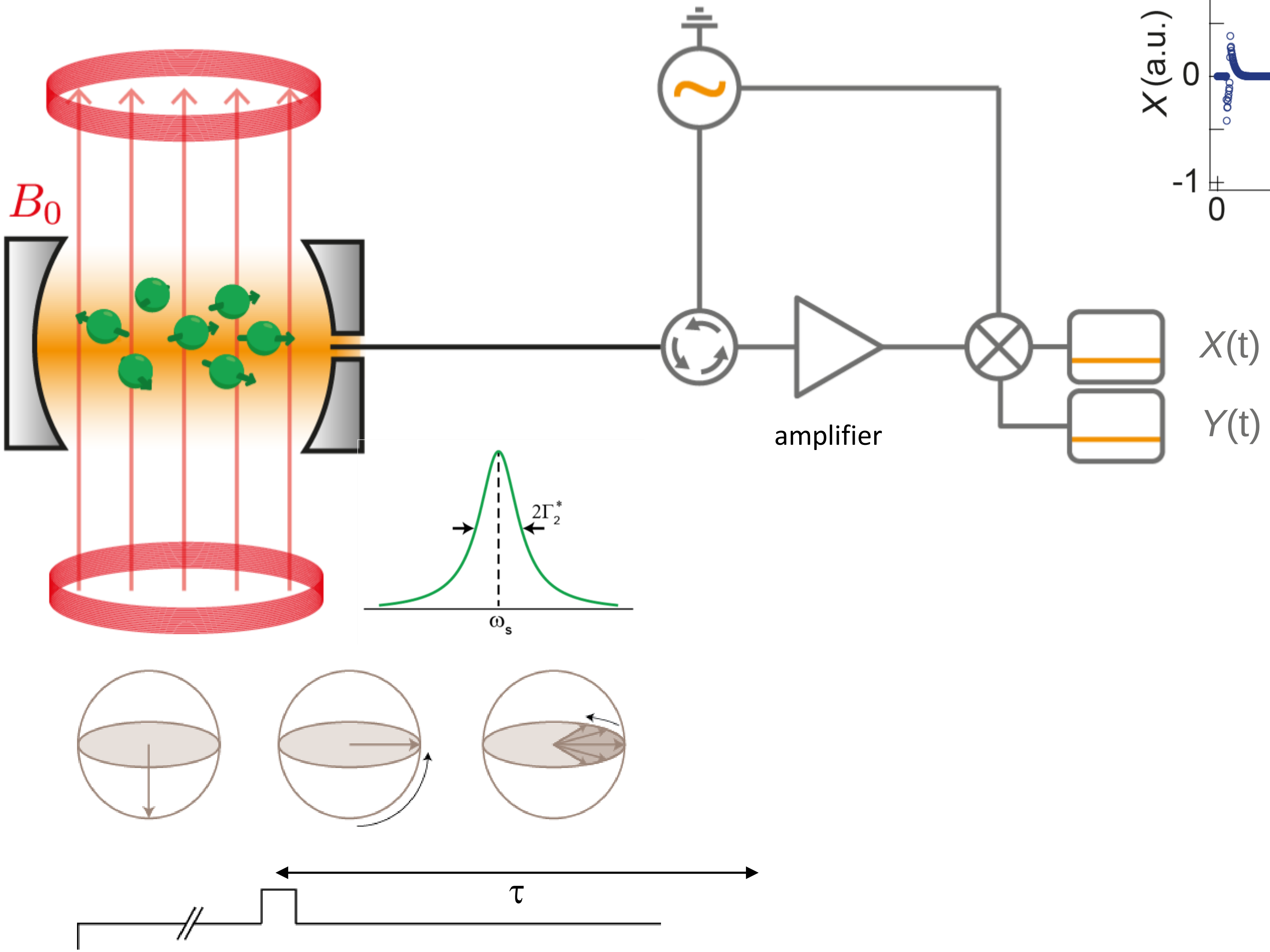
Hahn echo quadrature detection

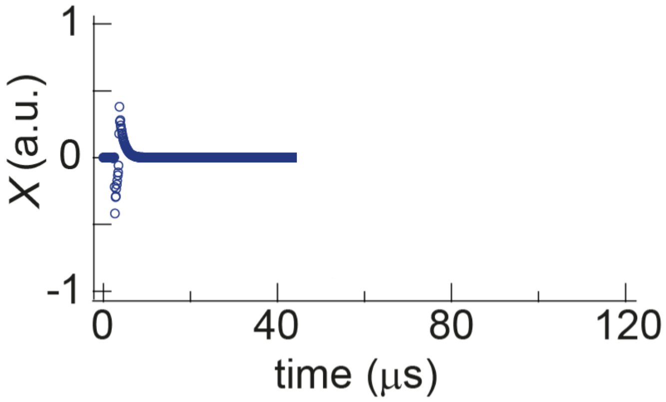




Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.

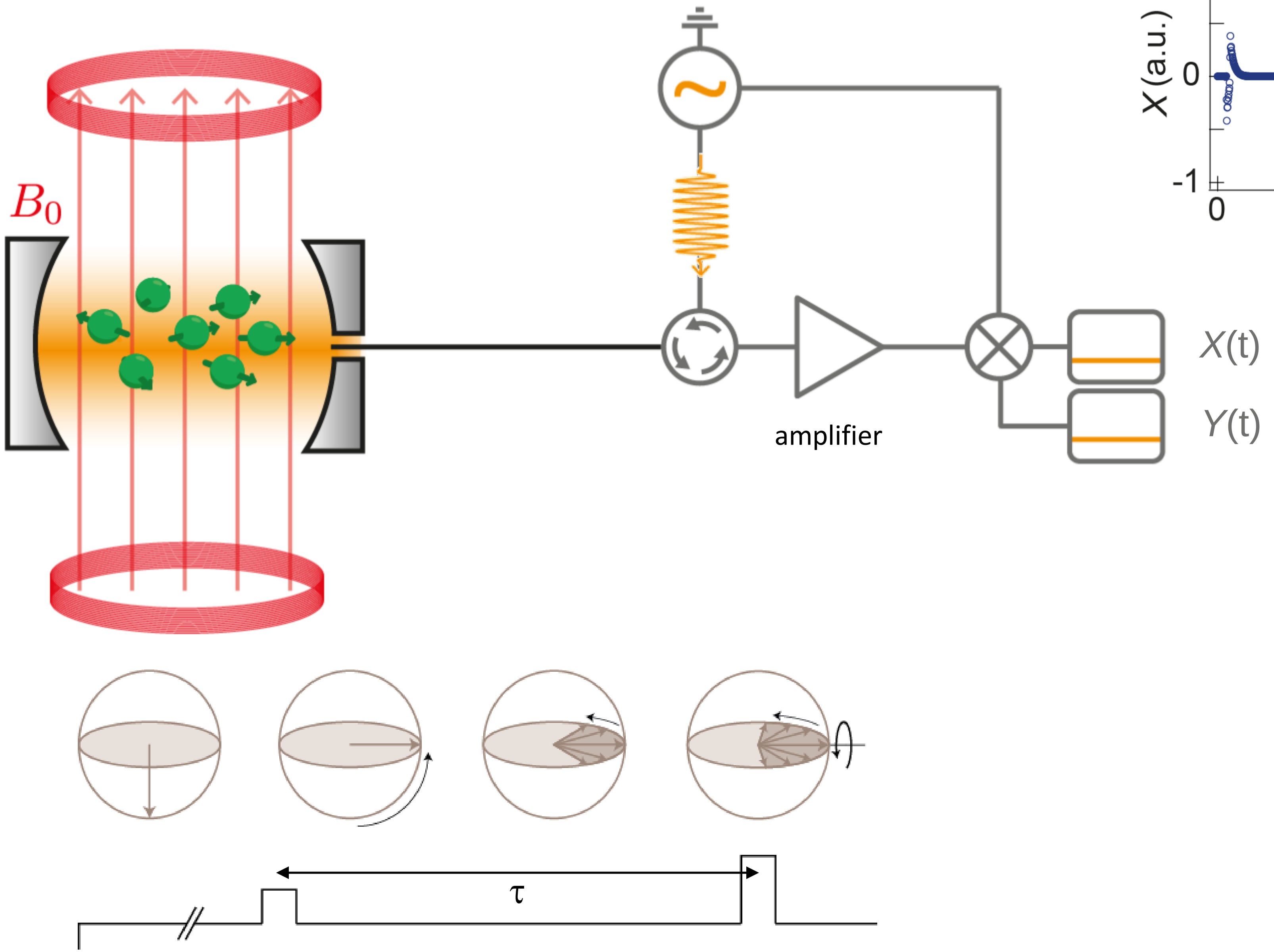
Hahn echo quadrature detection

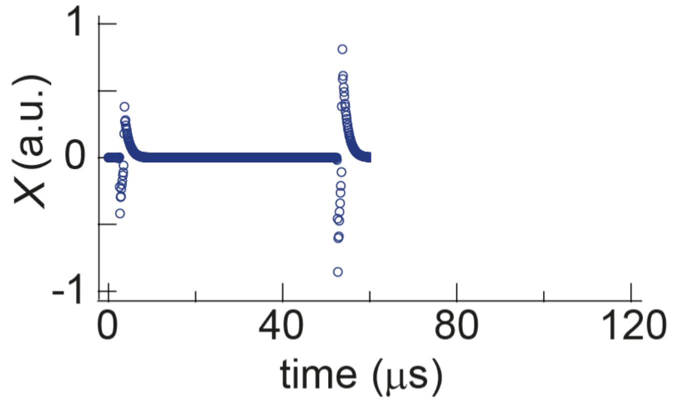




Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.

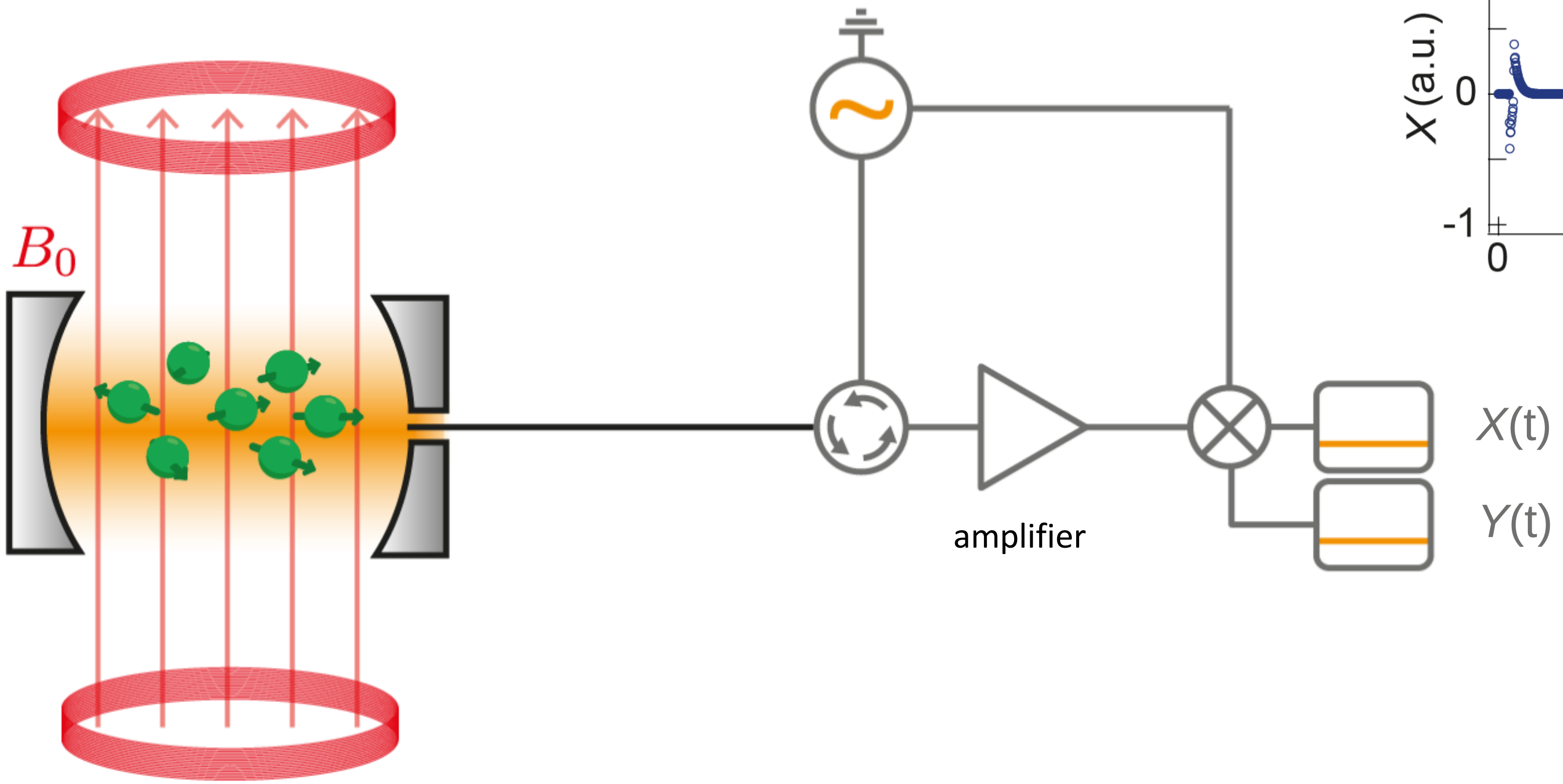
Hahn echo quadrature detection

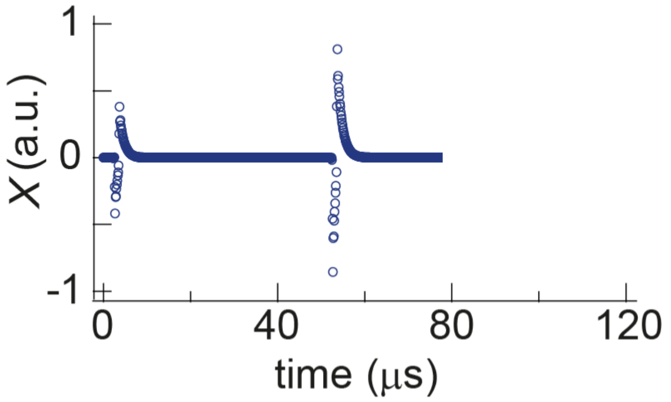




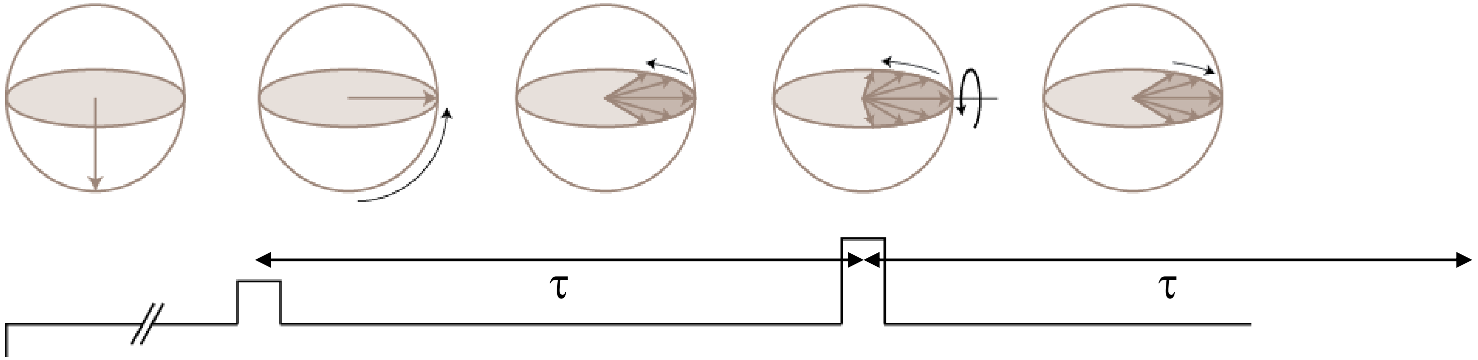
Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.

Hahn echo quadrature detection

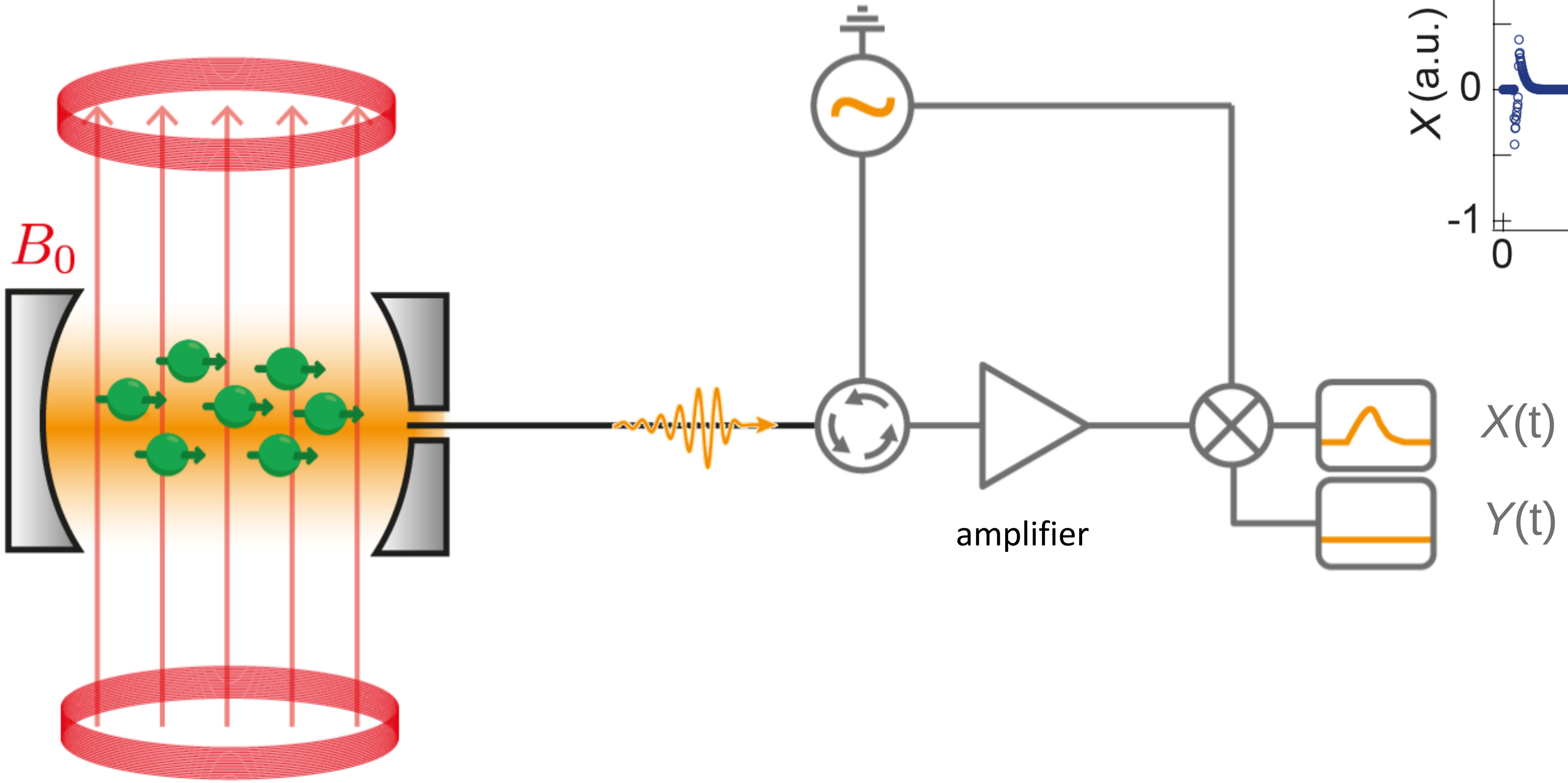


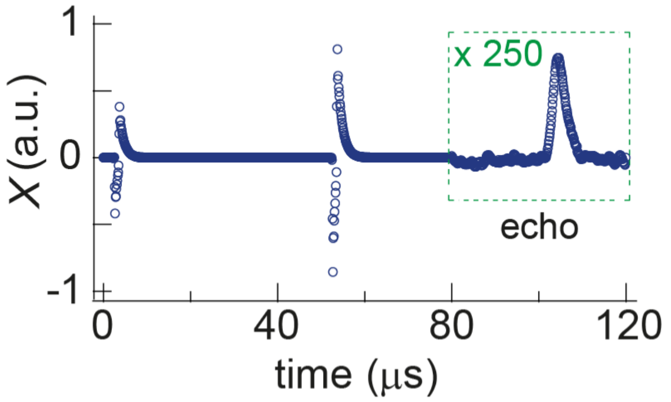


Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.

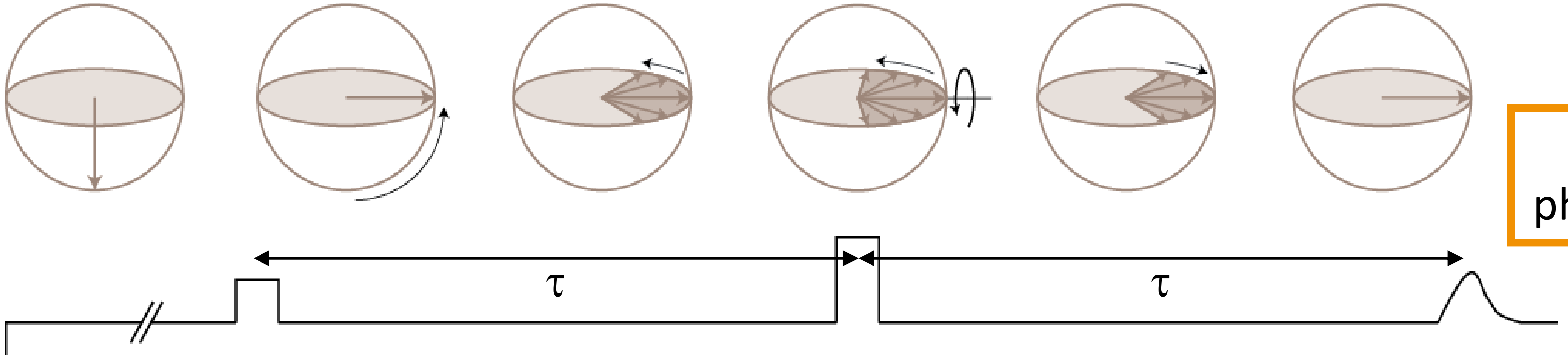


Hahn echo quadrature detection



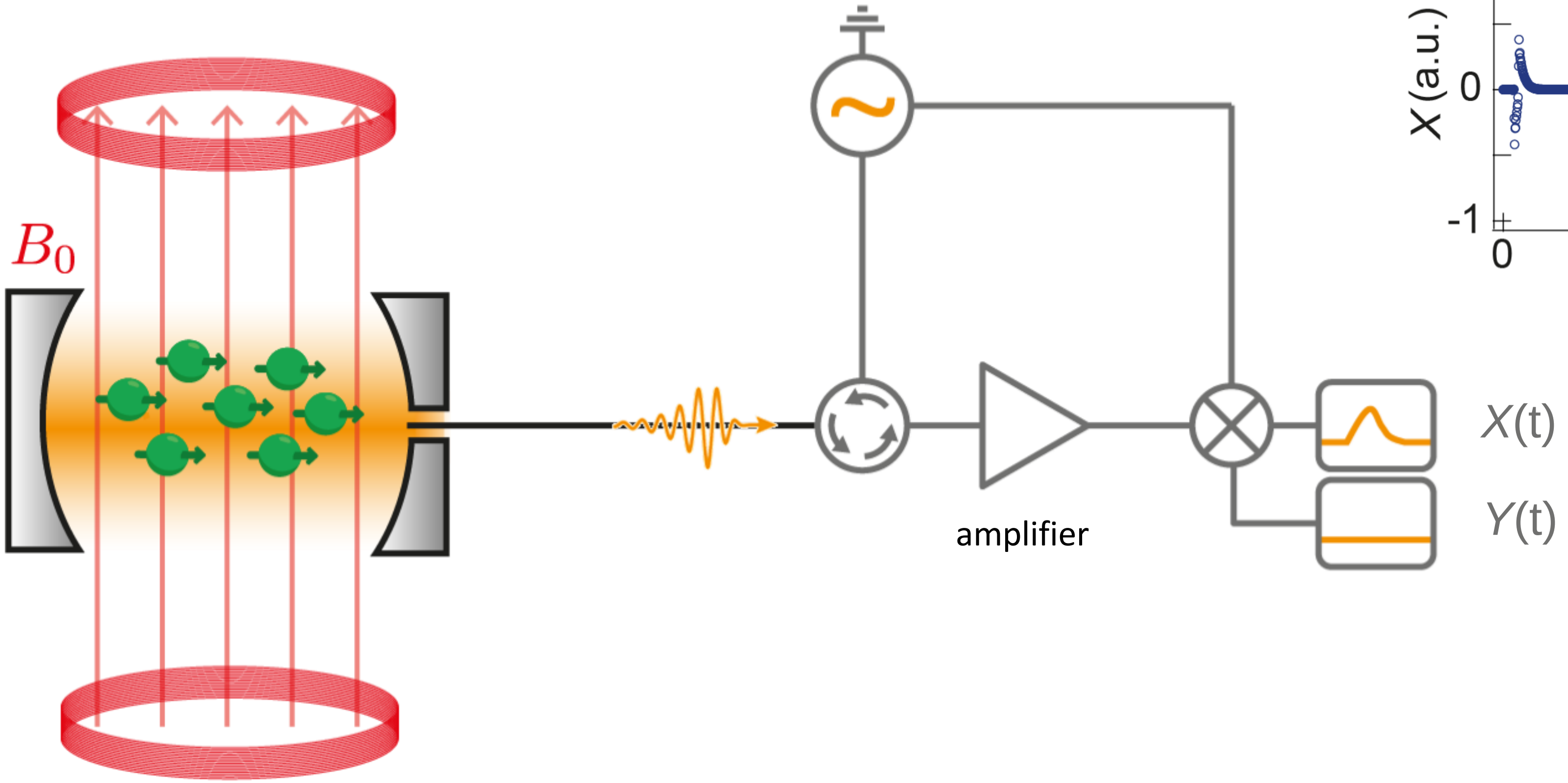


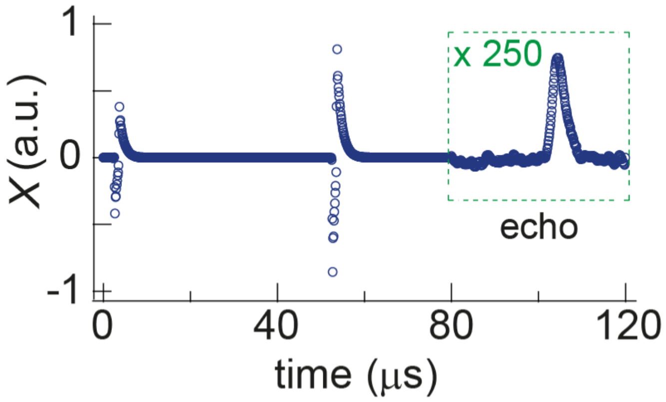
Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.



Emission of a
phase coherent echo signal

Hahn echo quadrature detection



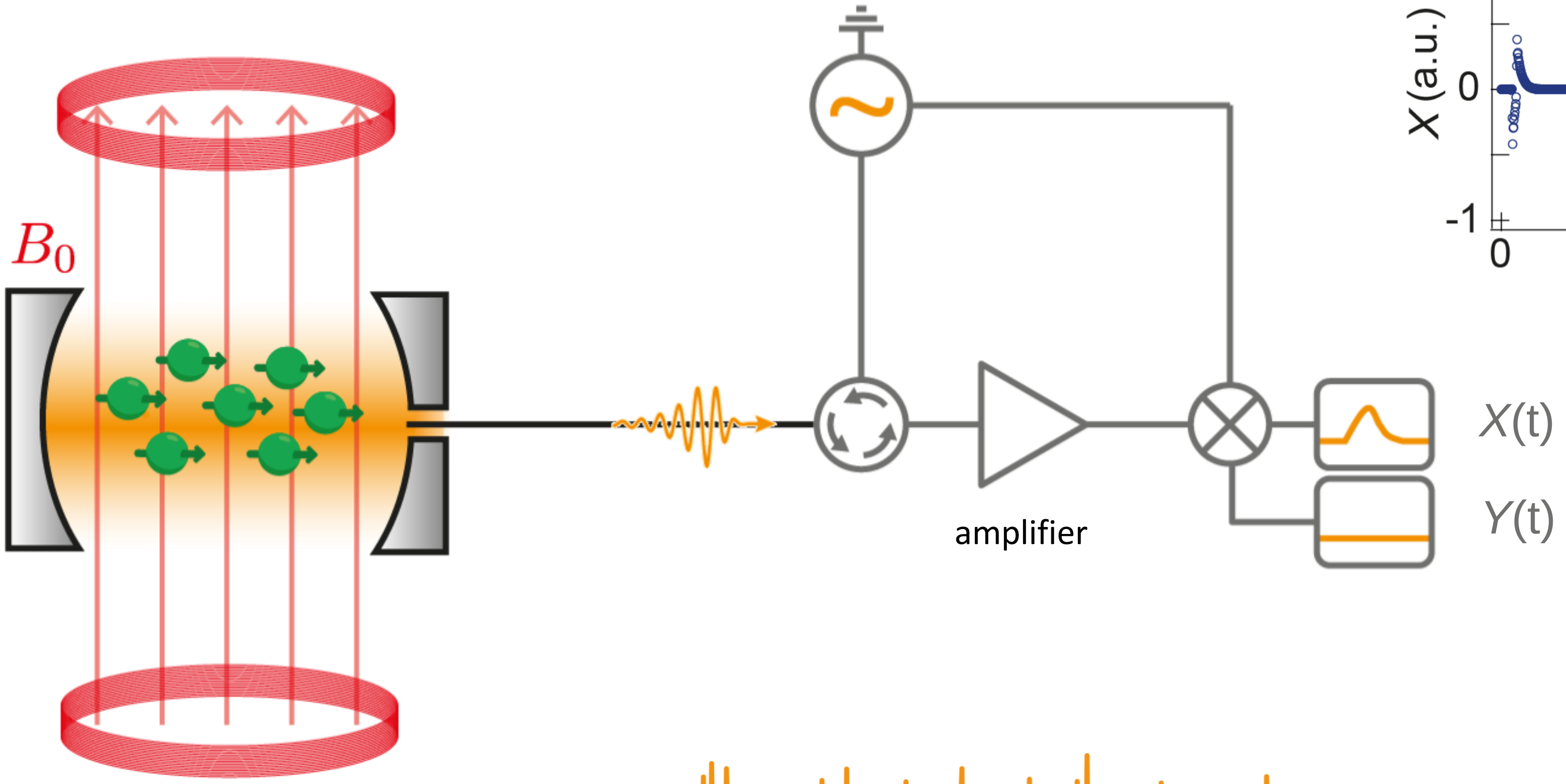


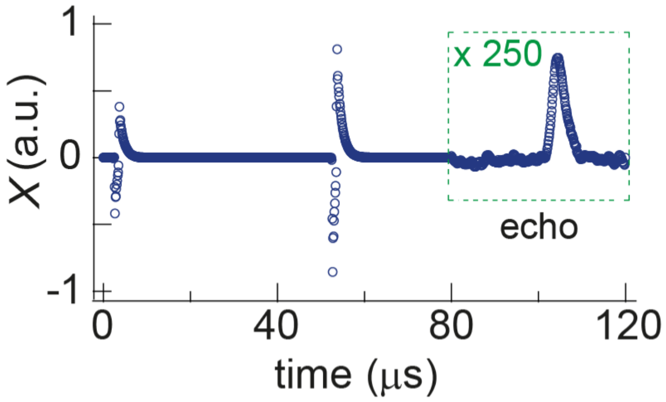
Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.

$$\langle X_e \rangle = N_s \sqrt{\frac{\Gamma_p}{2\Gamma_2^*}}$$

Bienfait, A., et al, Nature nanotechnology 11.3 (2016): 253-257.

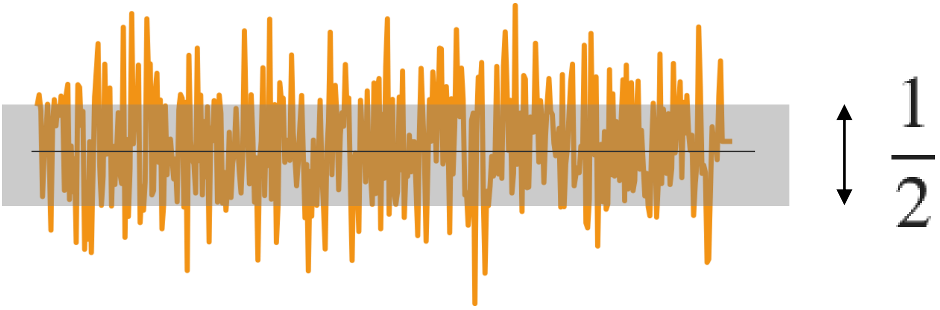
Hahn echo quadrature detection





Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.

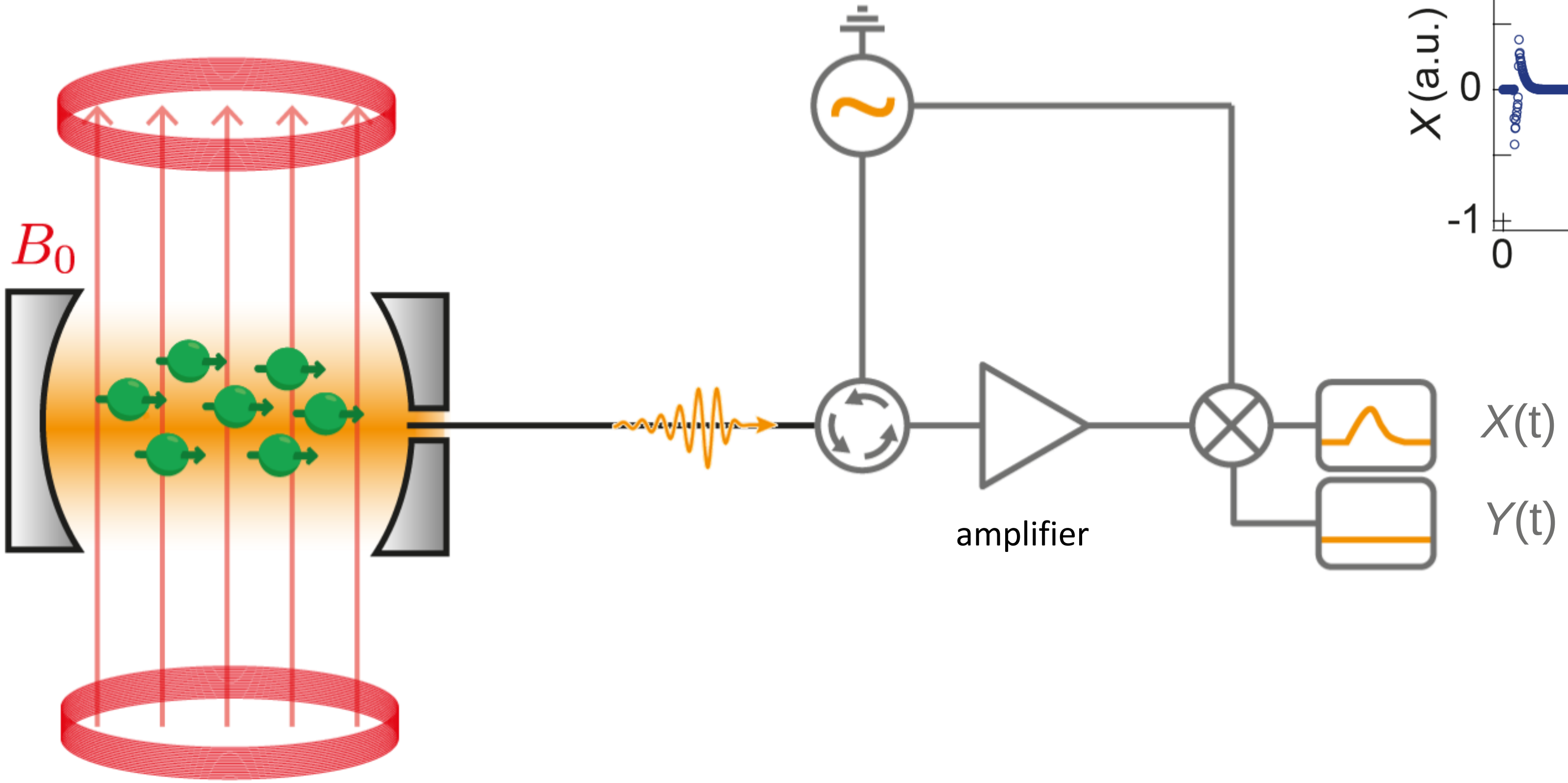
$$\langle X_e \rangle = N_s \sqrt{\frac{\Gamma_p}{2\Gamma_2^*}}$$

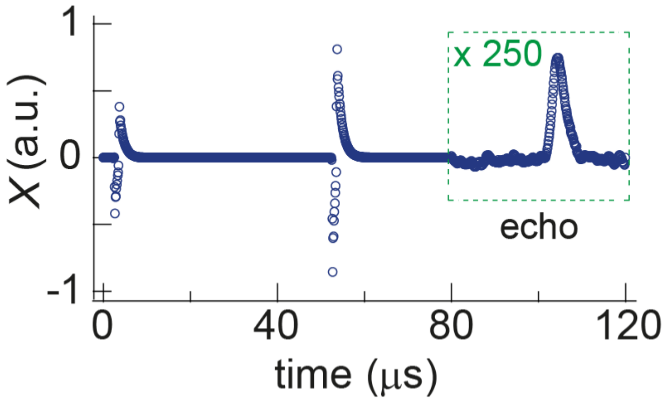


$$\Delta X = \frac{1}{2}$$

Bienfait, A., et al, Nature nanotechnology 11.3 (2016): 253-257.

Hahn echo quadrature detection





Ranjan et al., Applied Physics Letters 116.18 (2020): 184002.

$$\langle X_e \rangle = N_s \sqrt{\frac{\Gamma_p}{2\Gamma_2^*}}$$

$$\Delta X = \frac{1}{2}$$

$$\mathrm{SNR} = N_s \sqrt{\frac{2\Gamma_p}{\Gamma_2^*}}$$

Bounded sensitivity

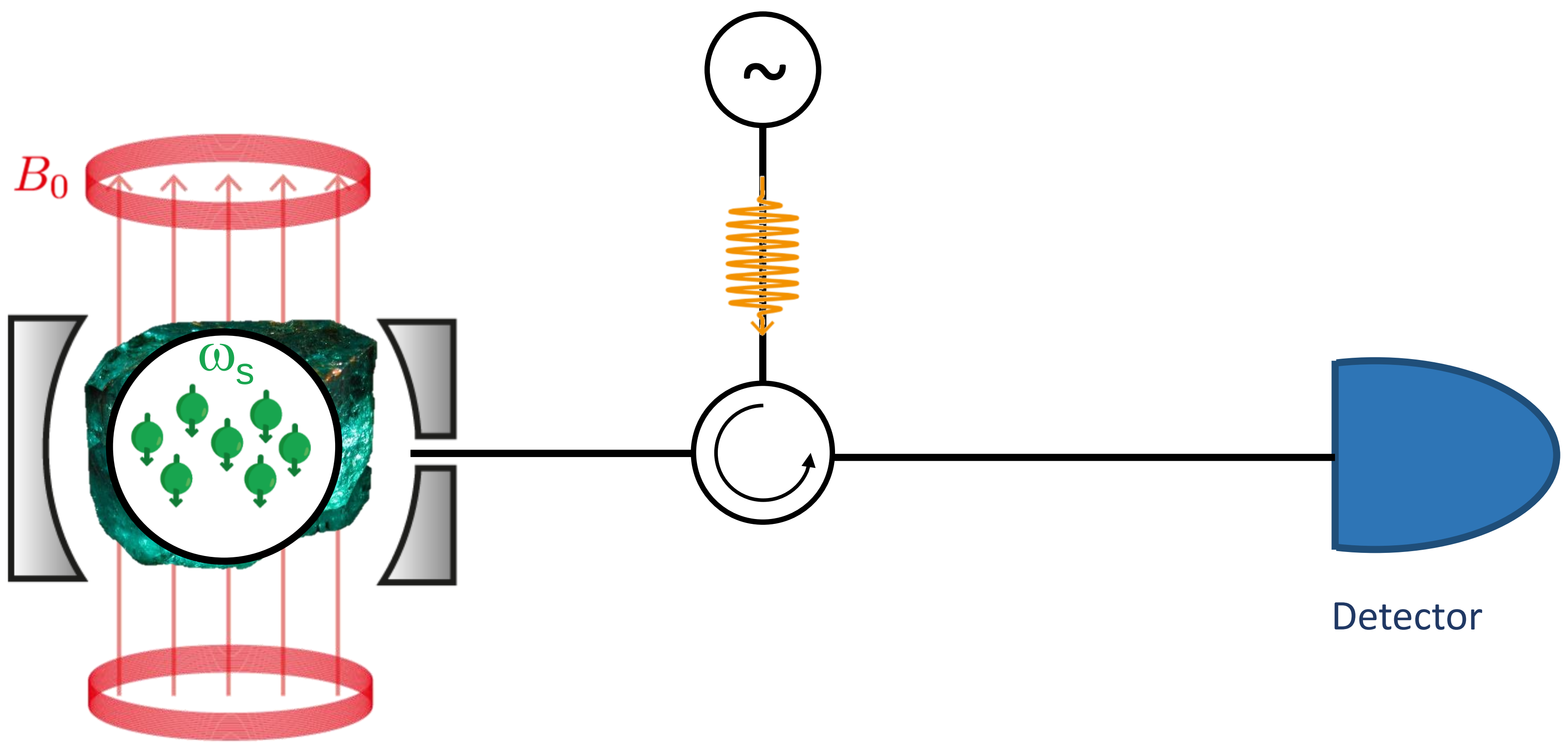
$$N_{\mathrm{spins}} \geq \sqrt{\frac{\Gamma_2^*}{\Gamma_P}} \gg 1$$

Bienfait, A., et al, Nature nanotechnology 11.3 (2016): 253-257.

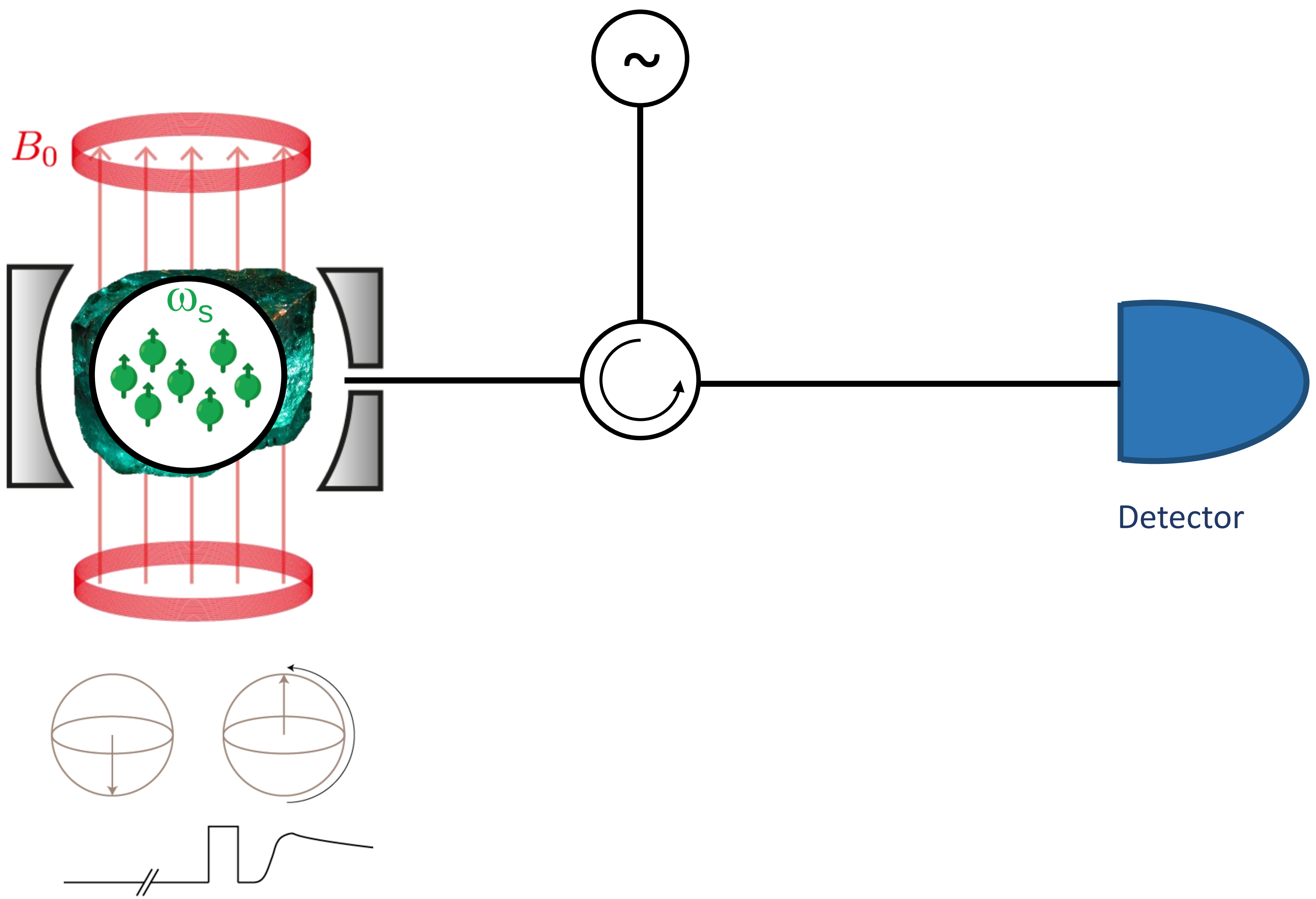
A novel method:

microwave spin fluorescence

Microwave spin fluorescence

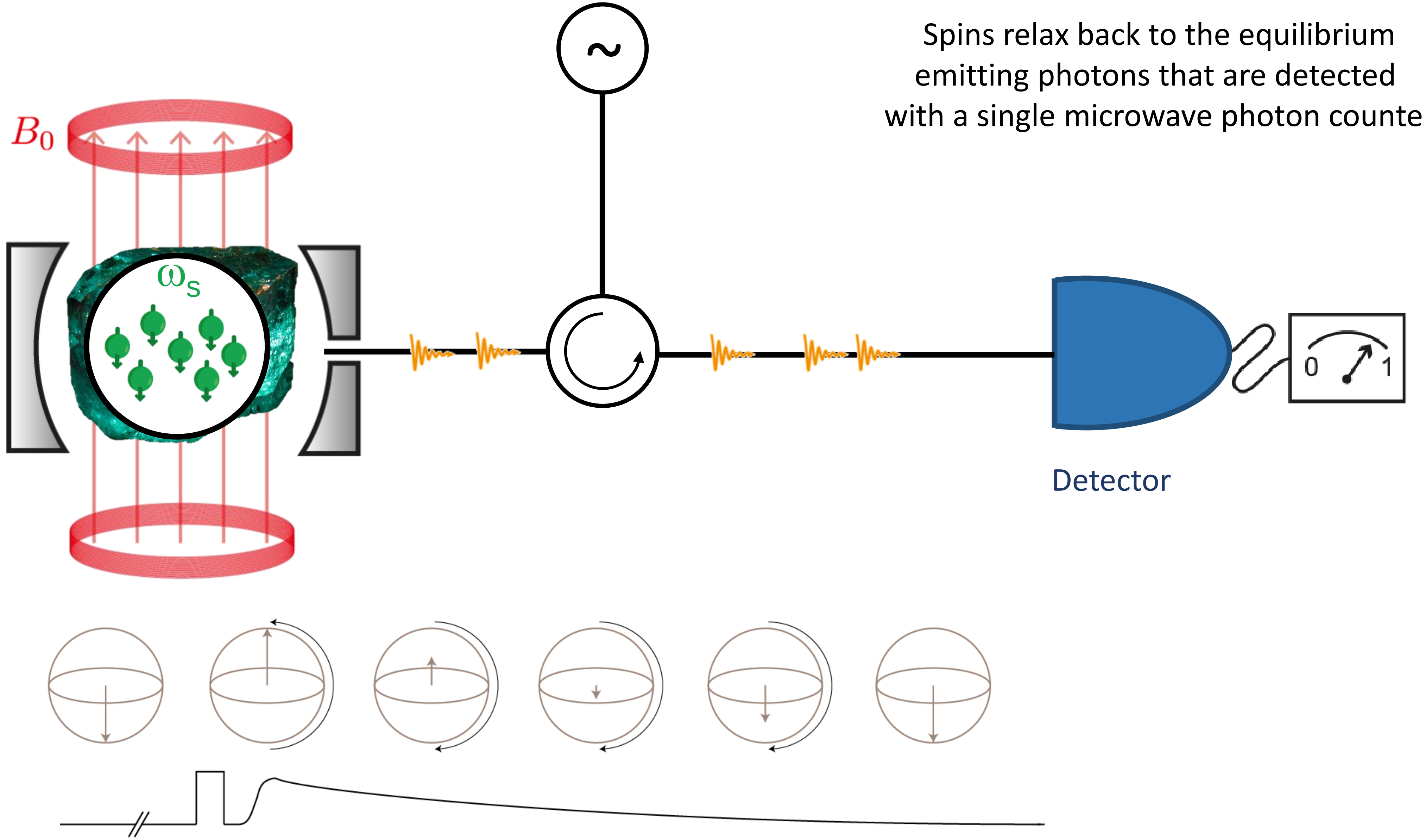


Microwave spin fluorescence

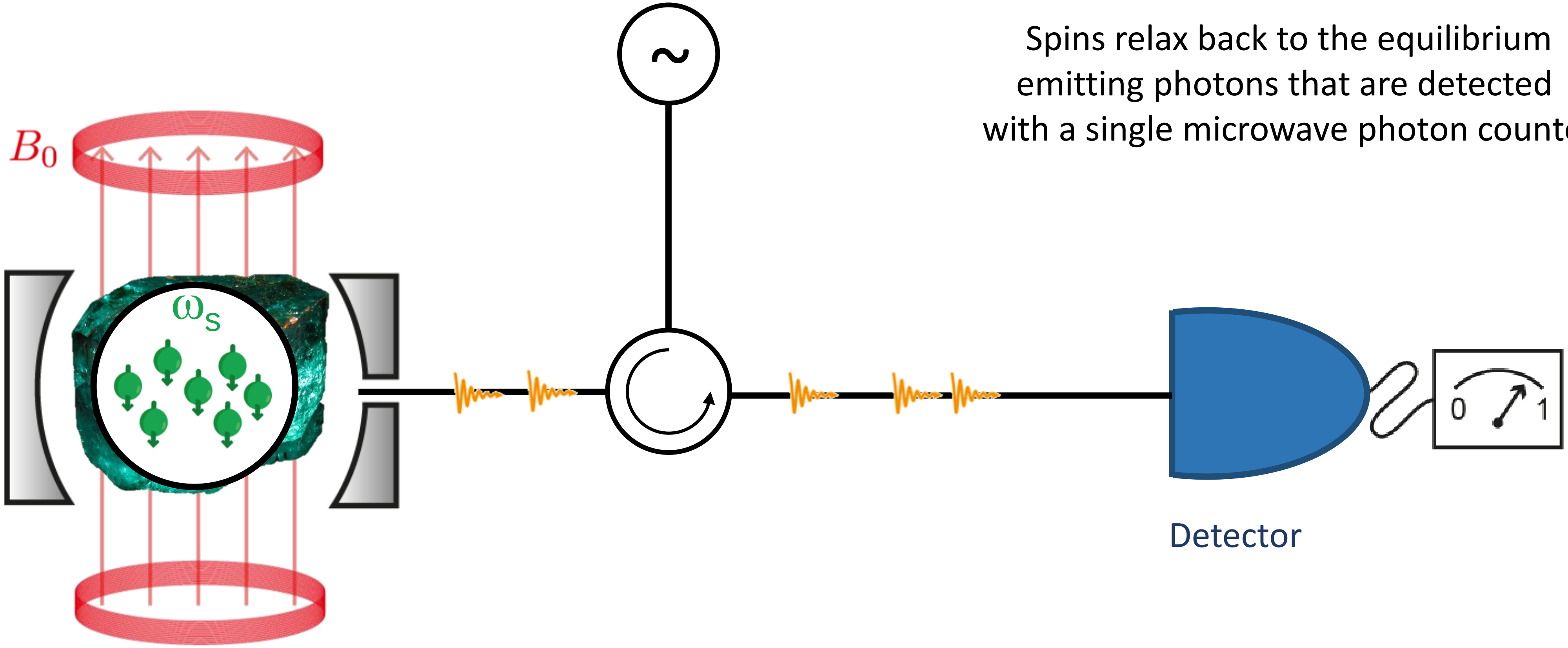


Microwave spin fluorescence

Spins relax back to the equilibrium emitting photons that are detected with a single microwave photon counter



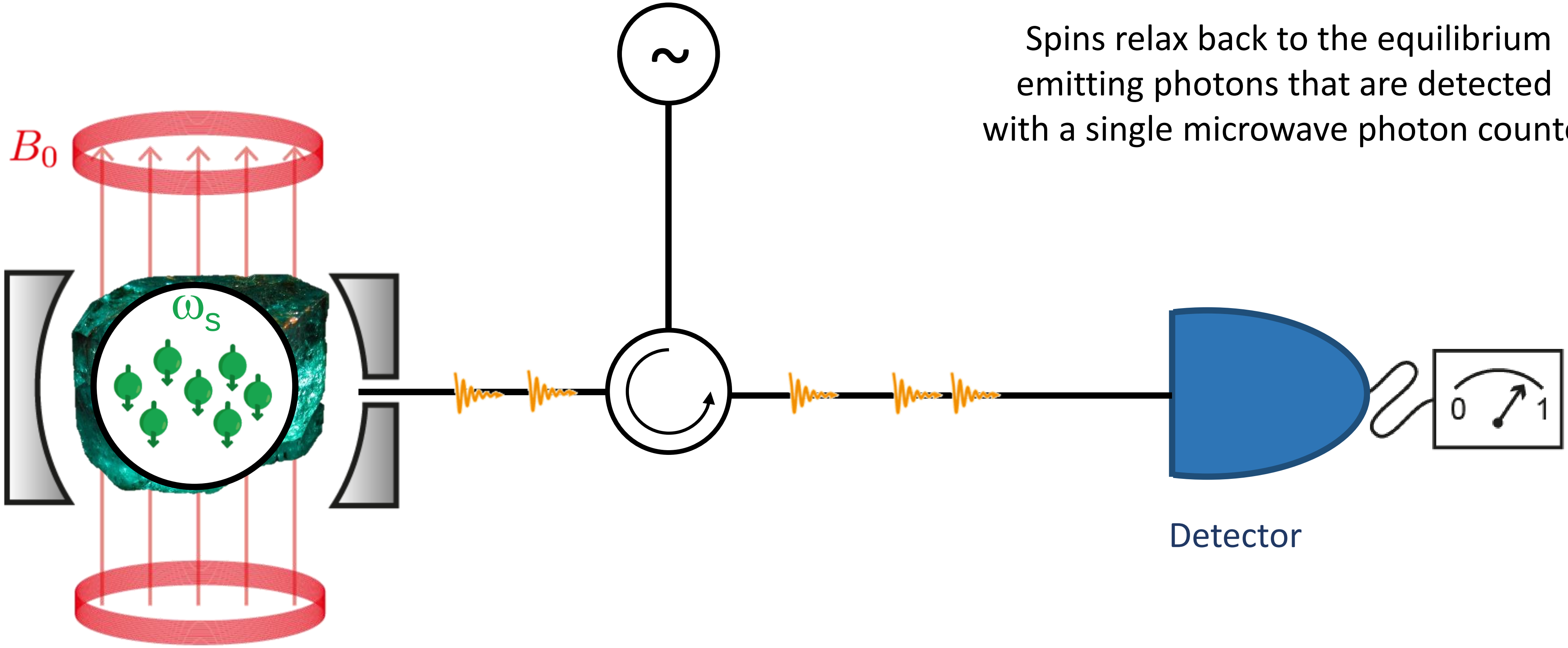
Microwave spin fluorescence



Spins relax back to the equilibrium emitting photons that are detected with a single microwave photon counter

$$\mathrm{SNR} = \frac{\eta N_{\mathrm{spins}}}{\sqrt{N_{\mathrm{dark}} + \eta(1-\eta)N_{\mathrm{spins}}}}$$

Microwave spin fluorescence

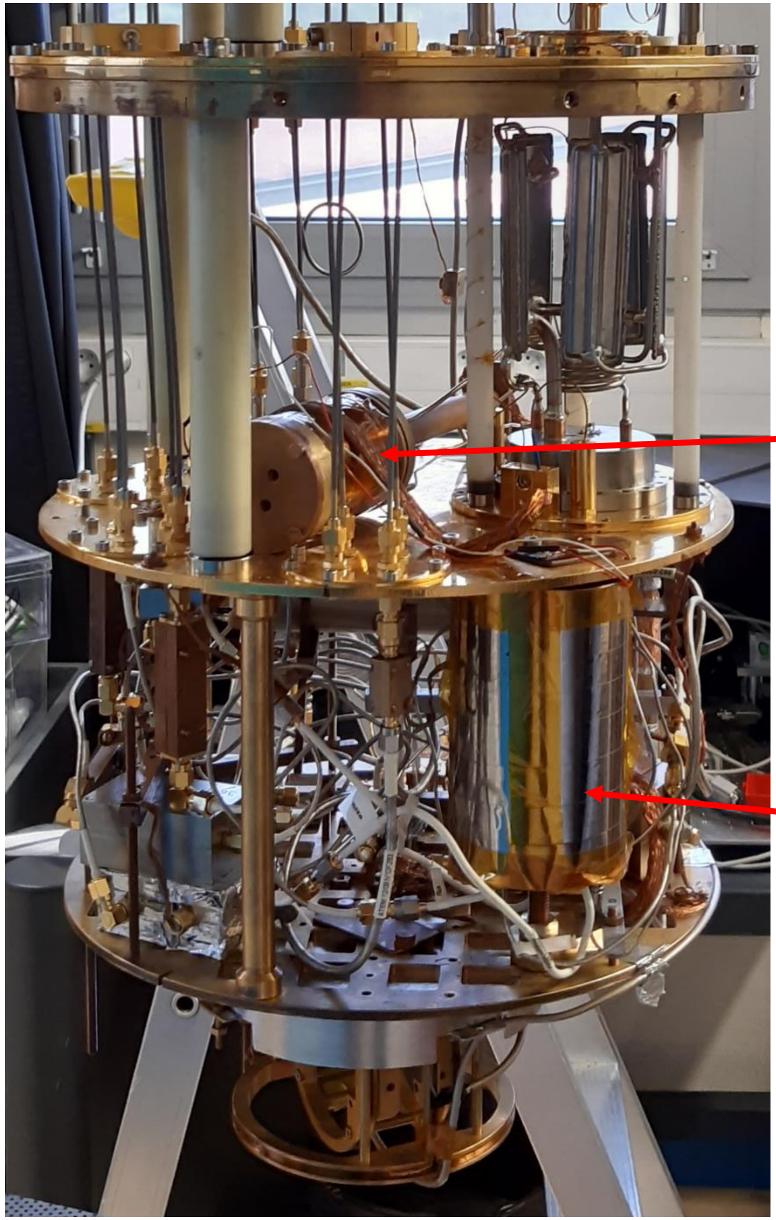


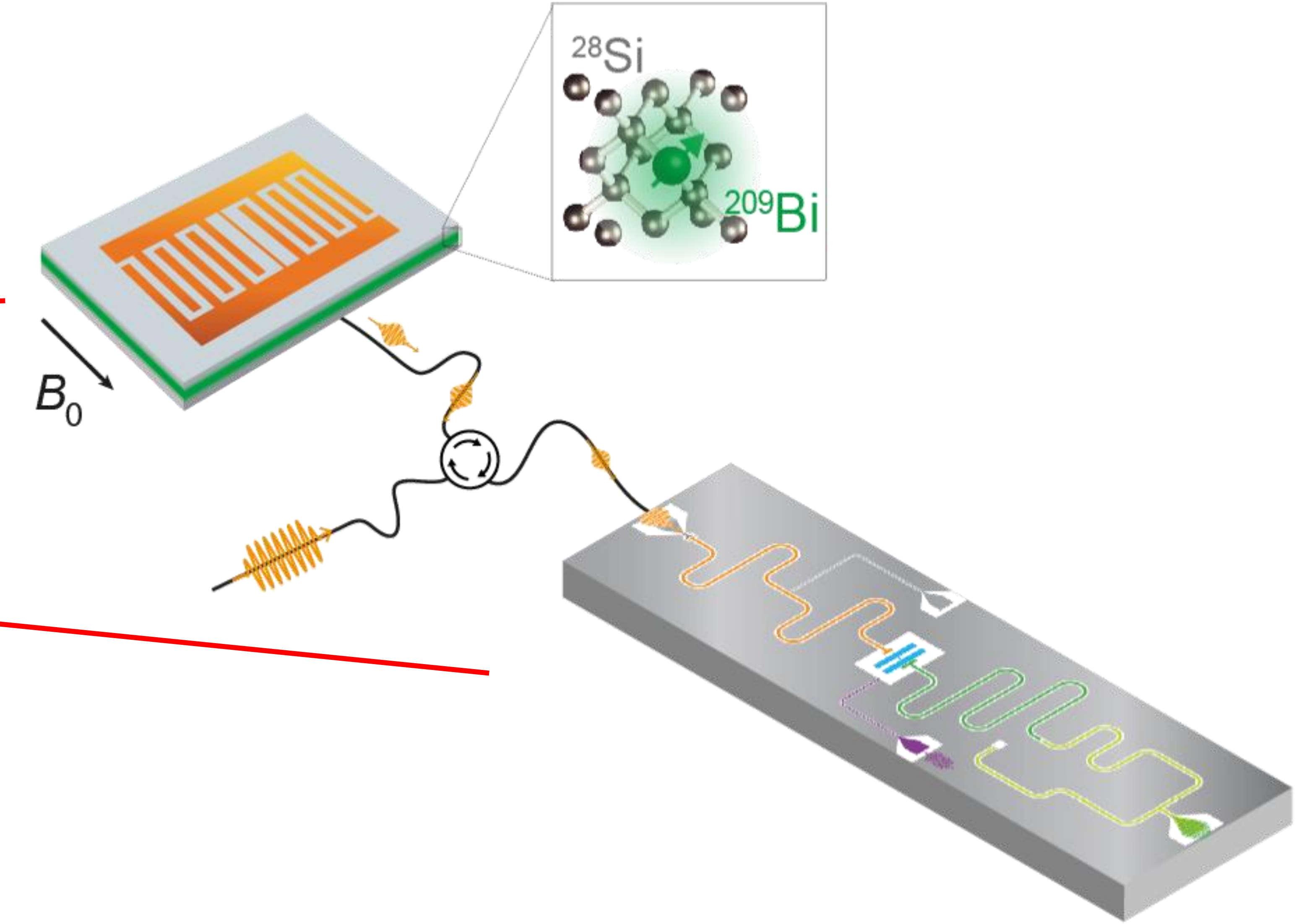
Spins relax back to the equilibrium emitting photons that are detected with a single microwave photon counter

$$\mathrm{SNR} = \frac{\eta N_{\mathrm{spins}}}{\sqrt{N_{\mathrm{dark}} + \eta(1-\eta)N_{\mathrm{spins}}}}$$

Unbounded when $\eta \to 1, \ N_{\mathrm{dark}} \to 0$

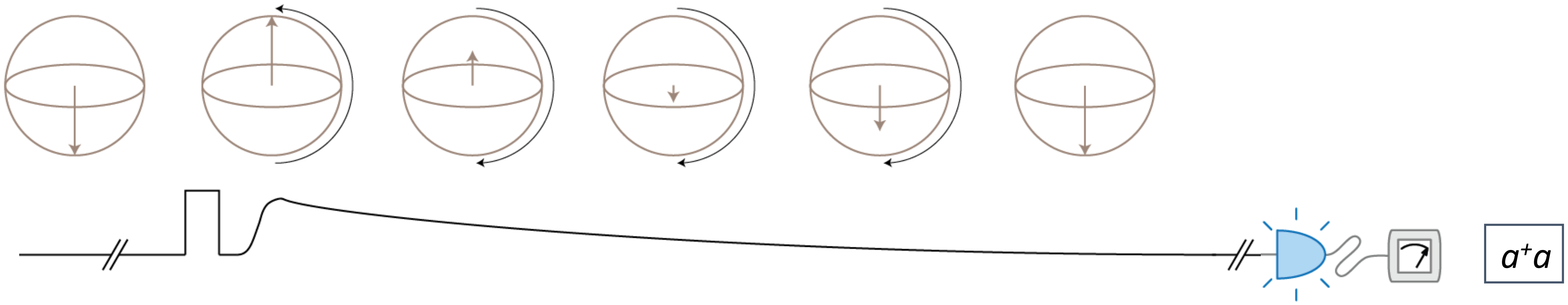
Setup

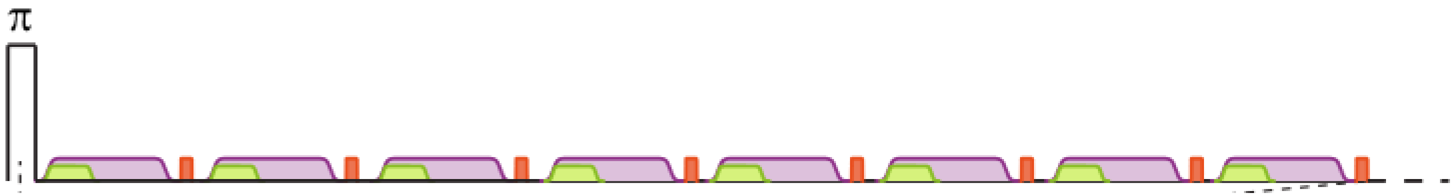




20 mK

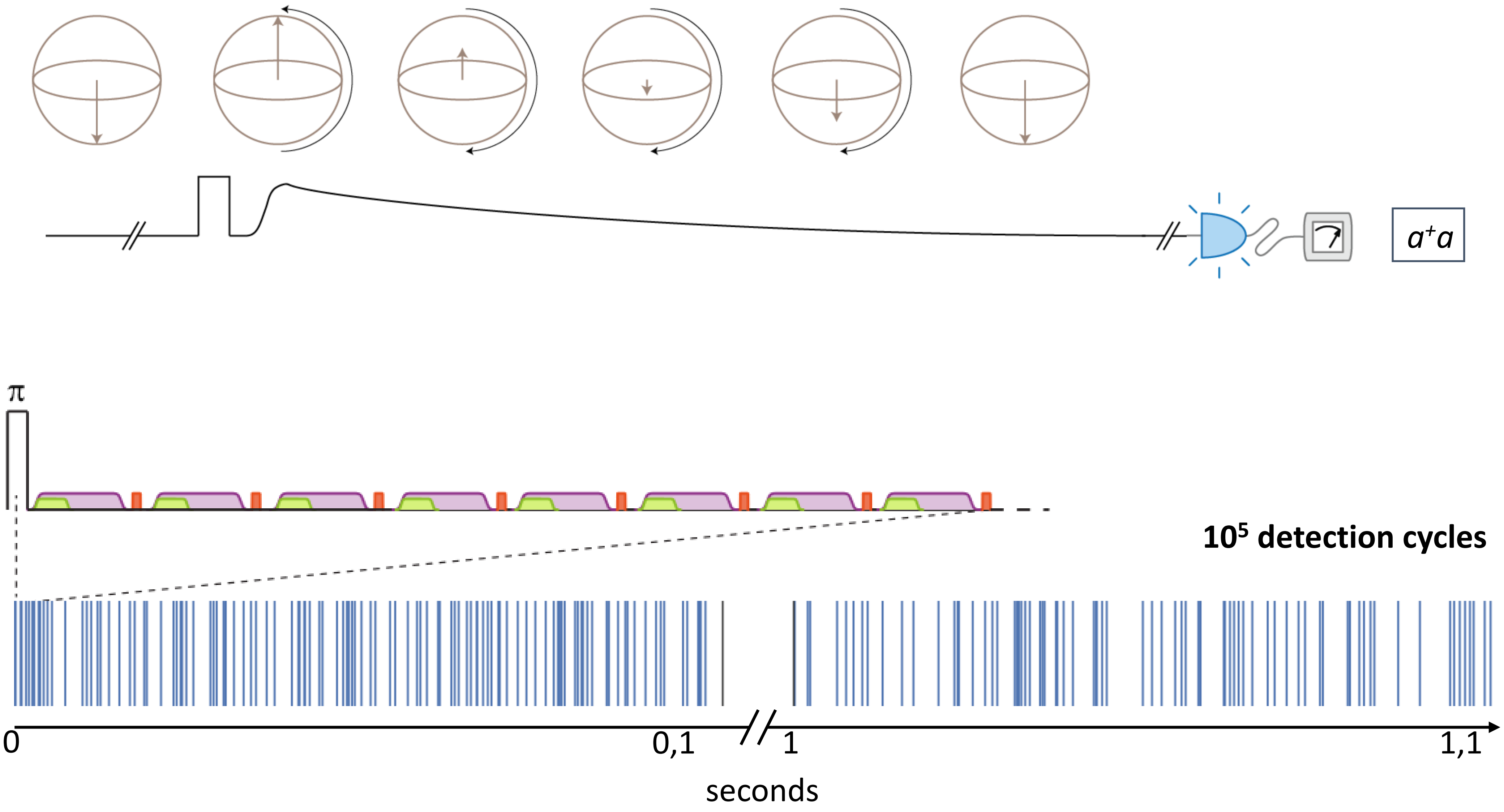
Detecting spin fluorescence





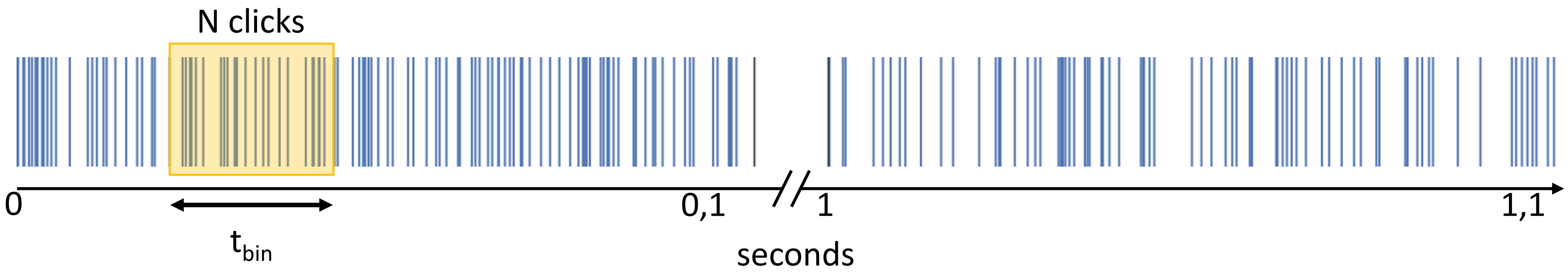
10^5 detection cycles

Spin fluorescence detection

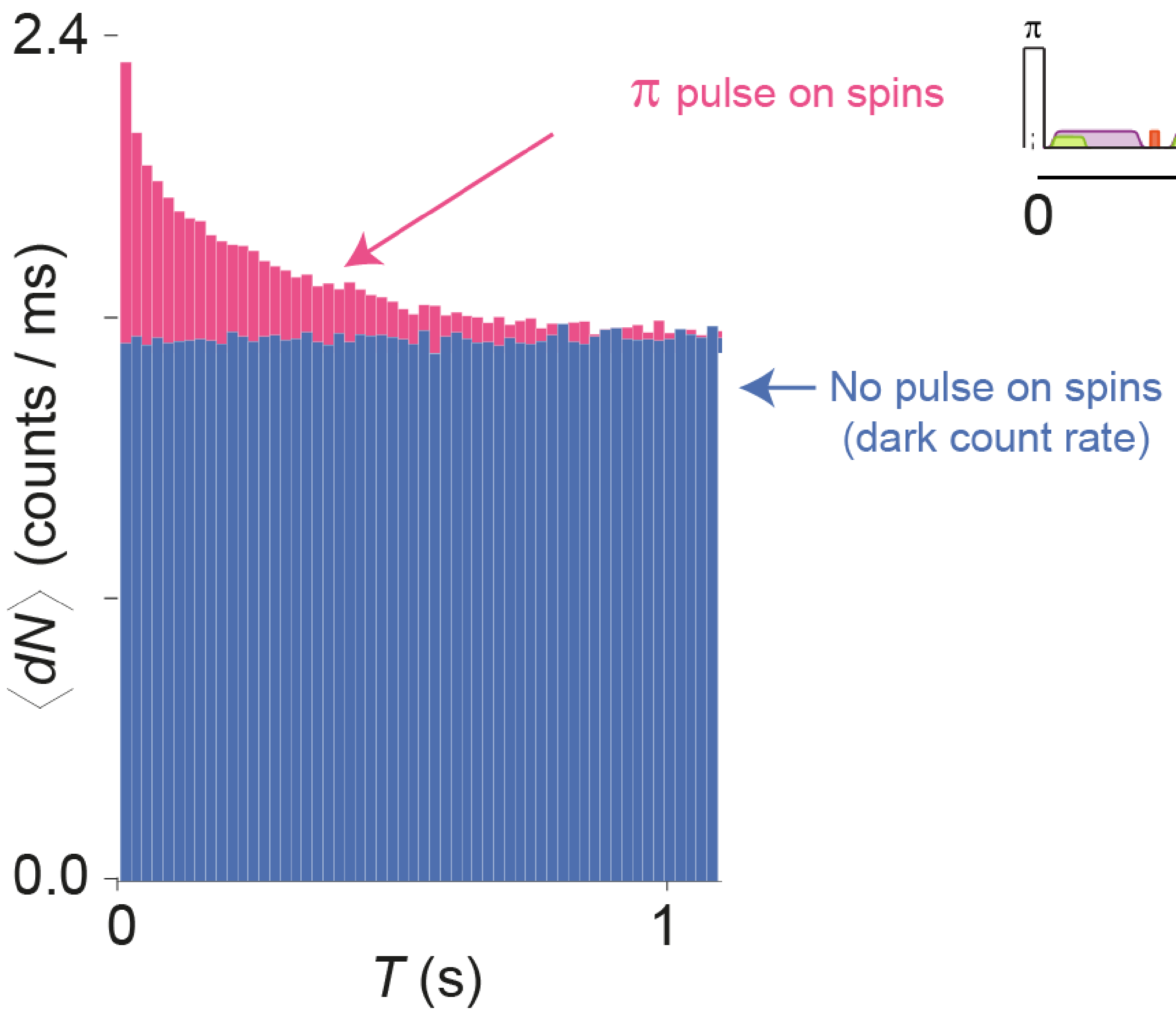


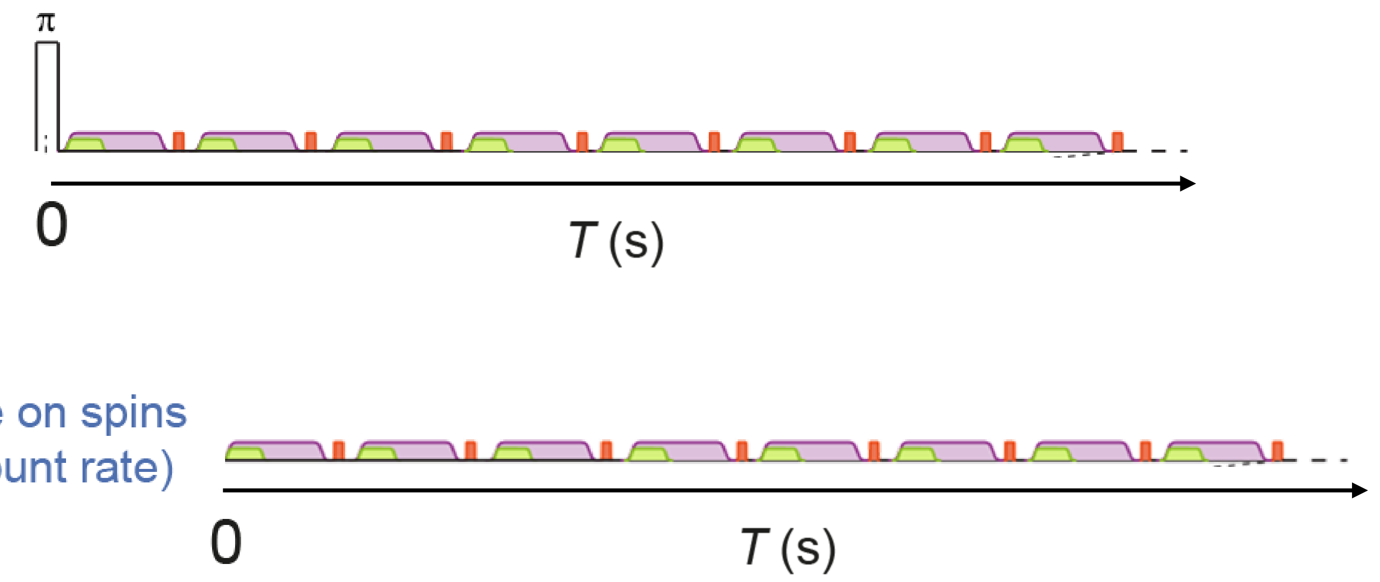
Spin fluorescence detection

$$\langle dN \rangle = \frac{\text{N clicks}}{t_{bin}}$$



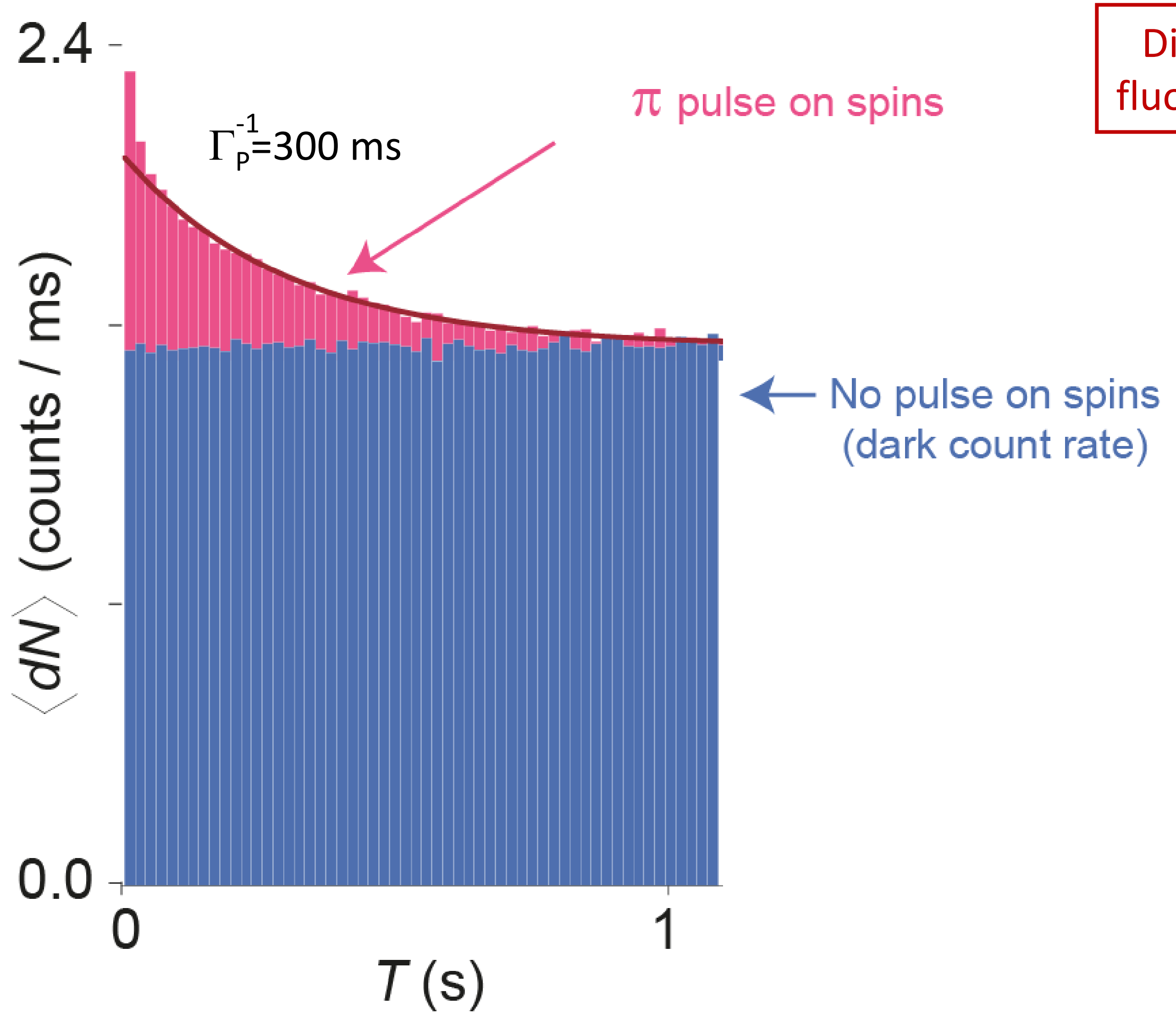
Spin fluorescence detection

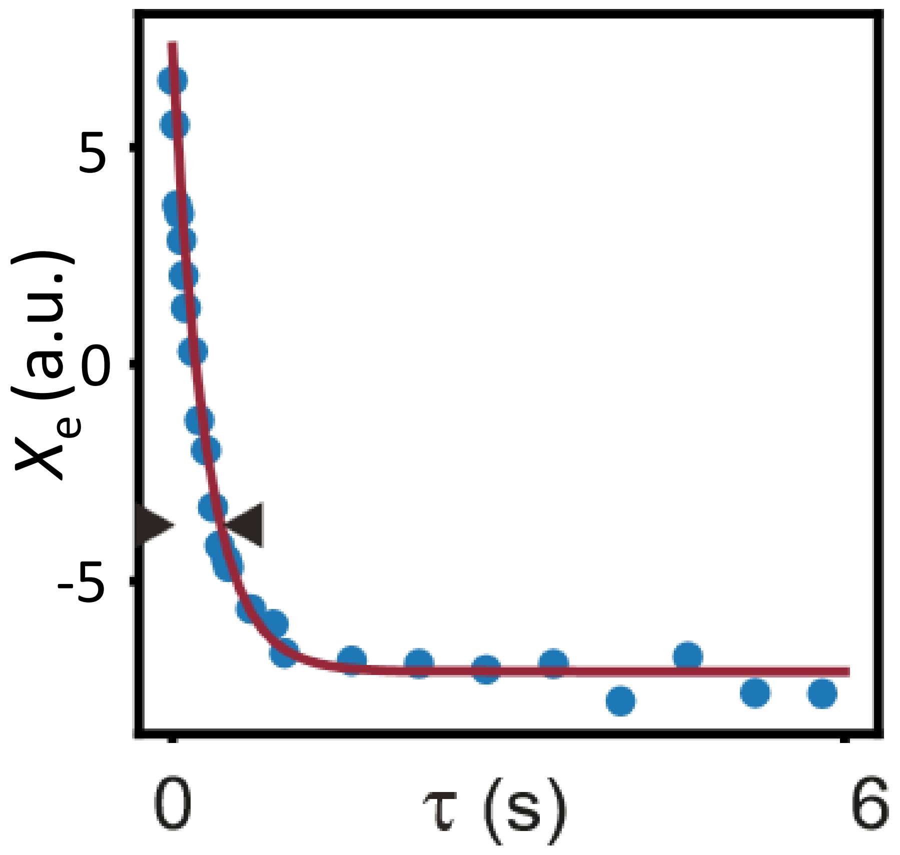




Spin fluorescence detection

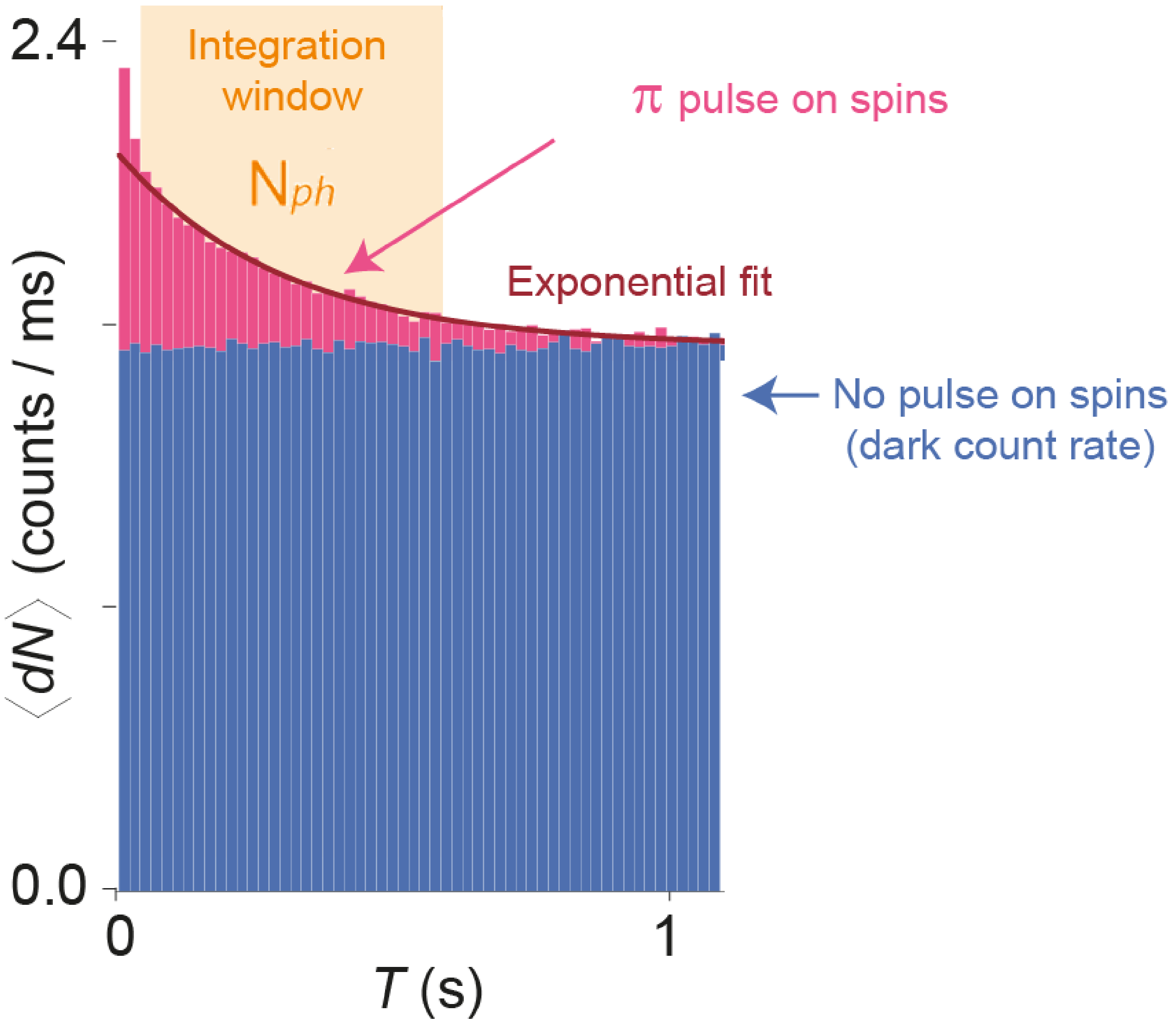
Direct detection of fluorescence photons



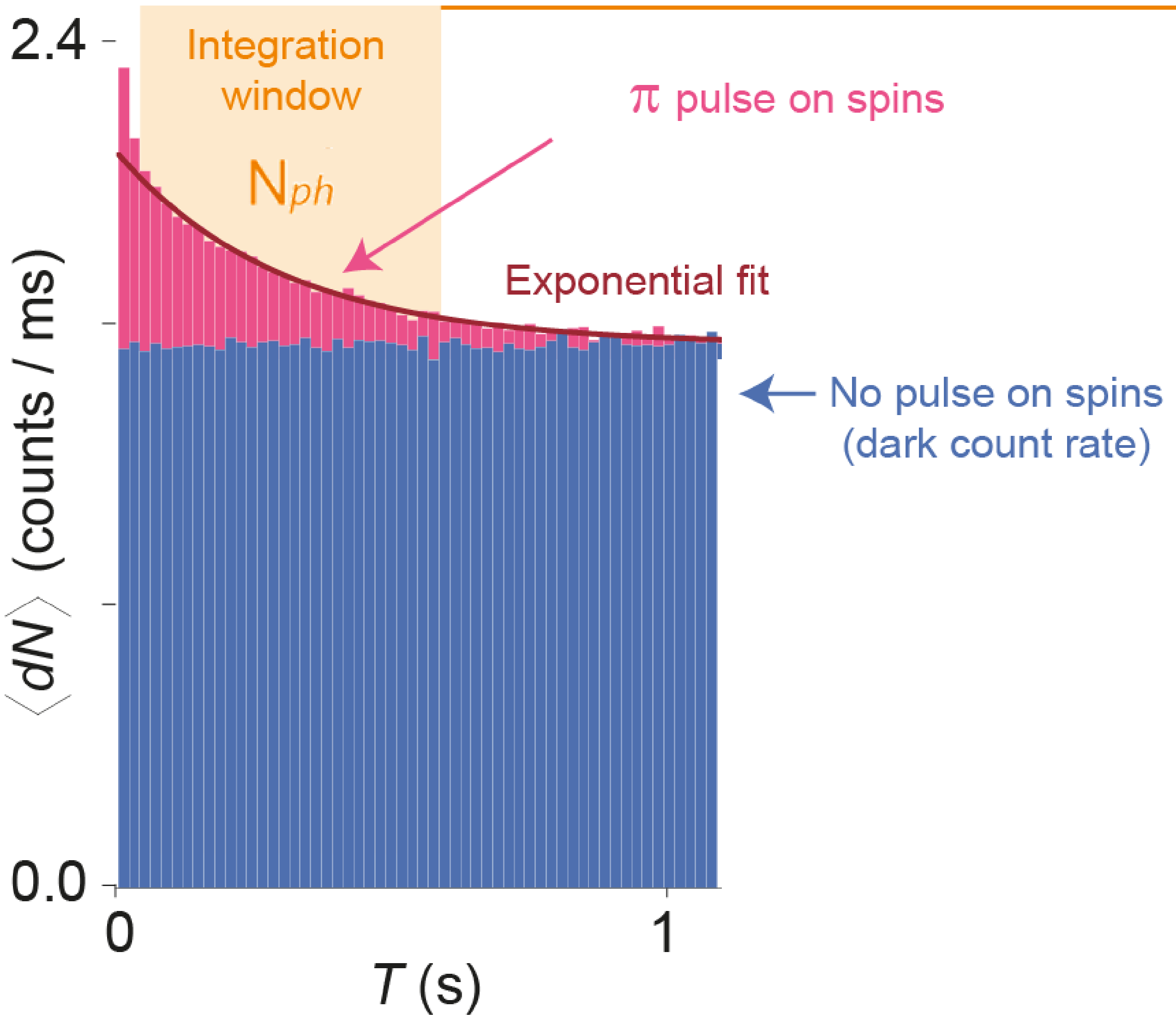


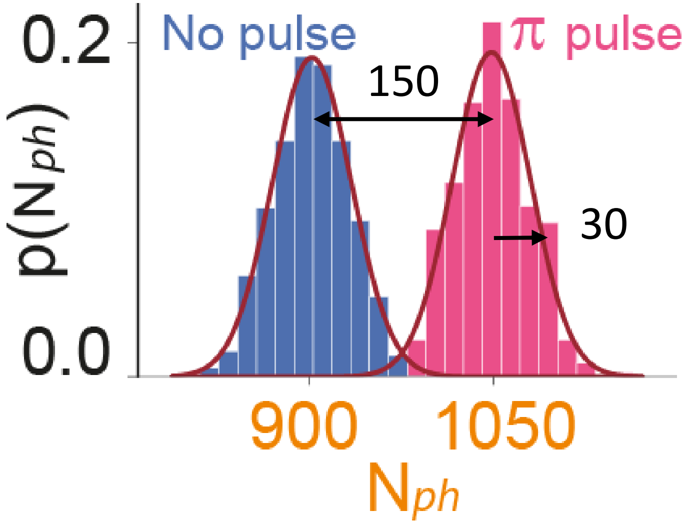
First application of an SMPD to quantum sensing

Fluorescence SNR



Fluorescence SNR





SNR = 5

SNR comparison

For one repetition of the experiment

$$\sim T_p$$

	Quadrature detection of Hahn echo	SMPD detection of fluorescence
Signal	$N_s\sqrt{\frac{\Gamma_p}{2\Gamma_2^*}} < \sqrt{N_s}$	N_s
Fluctuations		
SNR		

SNR comparison

For one repetition of the experiment

$$\sim T_p$$

	Quadrature detection of Hahn echo	SMPD detection of fluorescence
Signal	$N_s\sqrt{\frac{\Gamma_p}{2\Gamma_2^*}} < \sqrt{N_s}$	N_s
Fluctuations	$\frac{1}{2}$	$\sqrt{\frac{\nu_{dc}}{\Gamma_p}}$
SNR		

SNR comparison

For one repetition of the experiment

$\sim T_p$

	Quadrature detection of Hahn echo	SMPD detection of fluorescence
Signal	$N_s\sqrt{\frac{\Gamma_p}{2\Gamma_2^*}} < \sqrt{N_s}$	N_s
Fluctuations	$\frac{1}{2}$	$\sqrt{\frac{\nu_{dc}}{\Gamma_p}}$
SNR	$N_s\sqrt{\frac{2\Gamma_p}{\Gamma_2^*}}$ property of the spin system, fixed	$N_s\sqrt{\frac{\Gamma_p}{\nu_{dc}}}$ detector imperfection, improvable

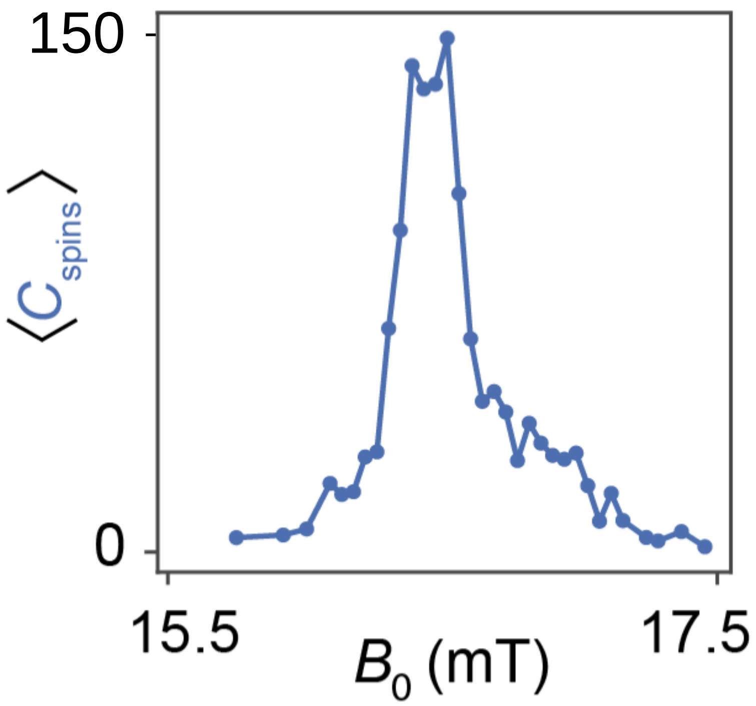
SNR comparison

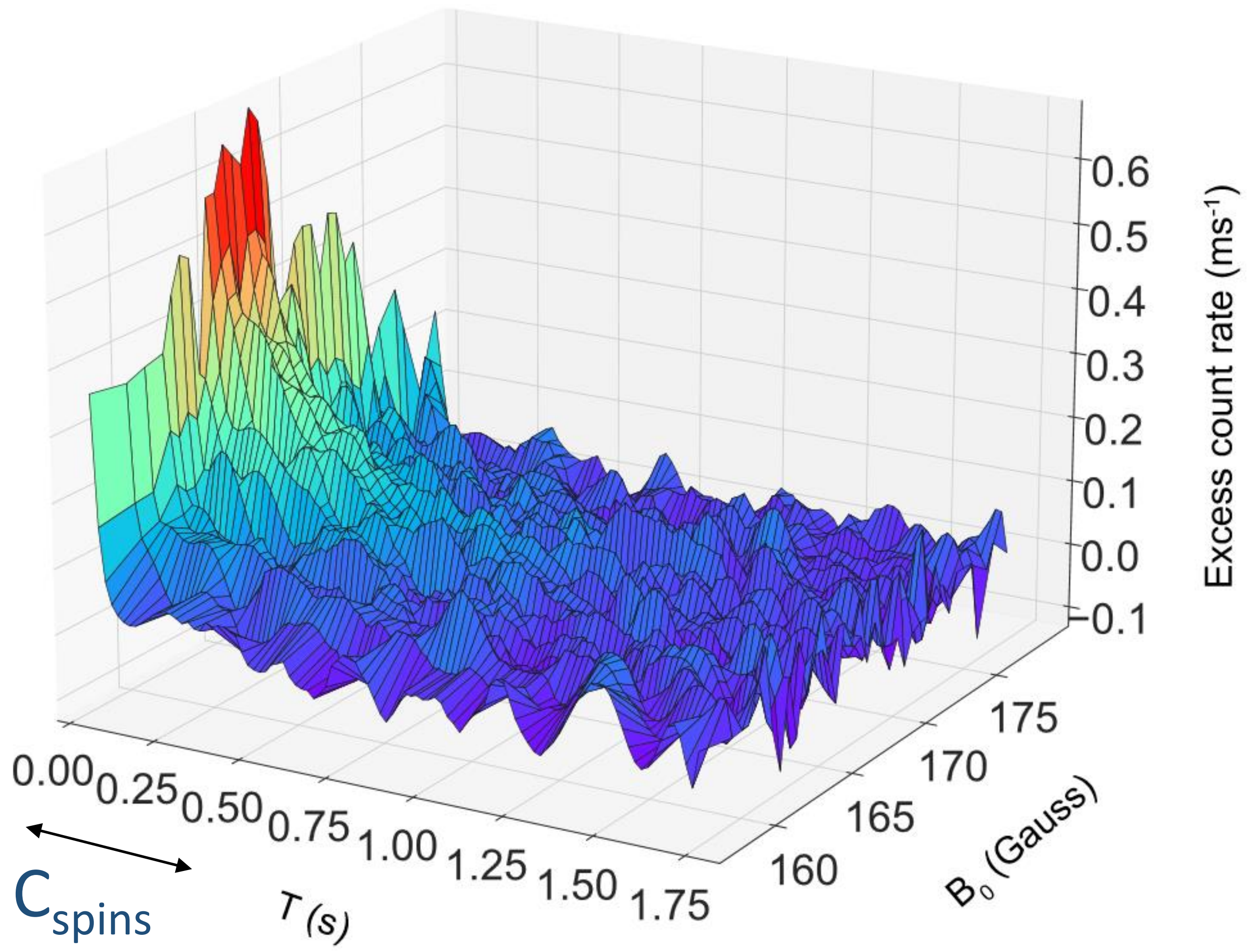
For one repetition of the experiment

$\sim T_p$

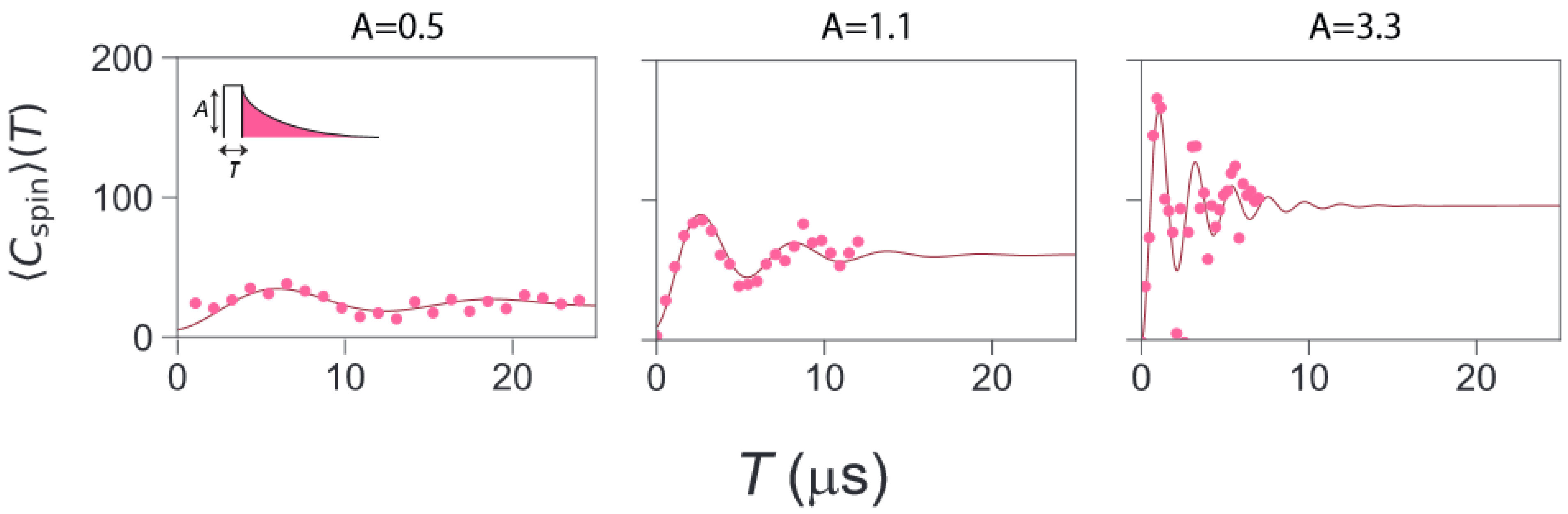
	Quadrature detection of Hahn echo	SMPD detection of fluorescence
Signal	$N_s\sqrt{\frac{\Gamma_p}{2\Gamma_2^*}} < \sqrt{N_s}$	N_s
Fluctuations	$\frac{1}{2}$	$\sqrt{\frac{\nu_{dc}}{\Gamma_p}}$
SNR	$N_s\sqrt{\frac{2\Gamma_p}{\Gamma_2^*}}$	$N_s\sqrt{\frac{\Gamma_p}{\nu_{dc}}}$
	Echo detection SNR=0.65	**Fluorescence detection** SNR=5

Spectroscopy





Fluorescence-detected Rabi oscillations



Perspectives on photodetection

- Improve total efficiency η

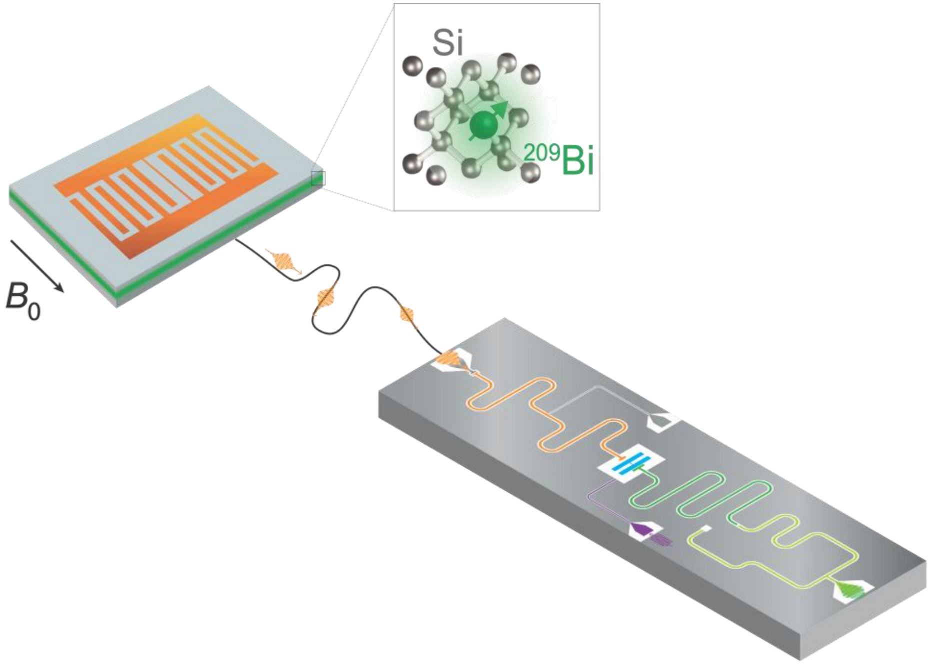
  Collection efficiency
  Bandwidth tunability

- Reduce dark counts

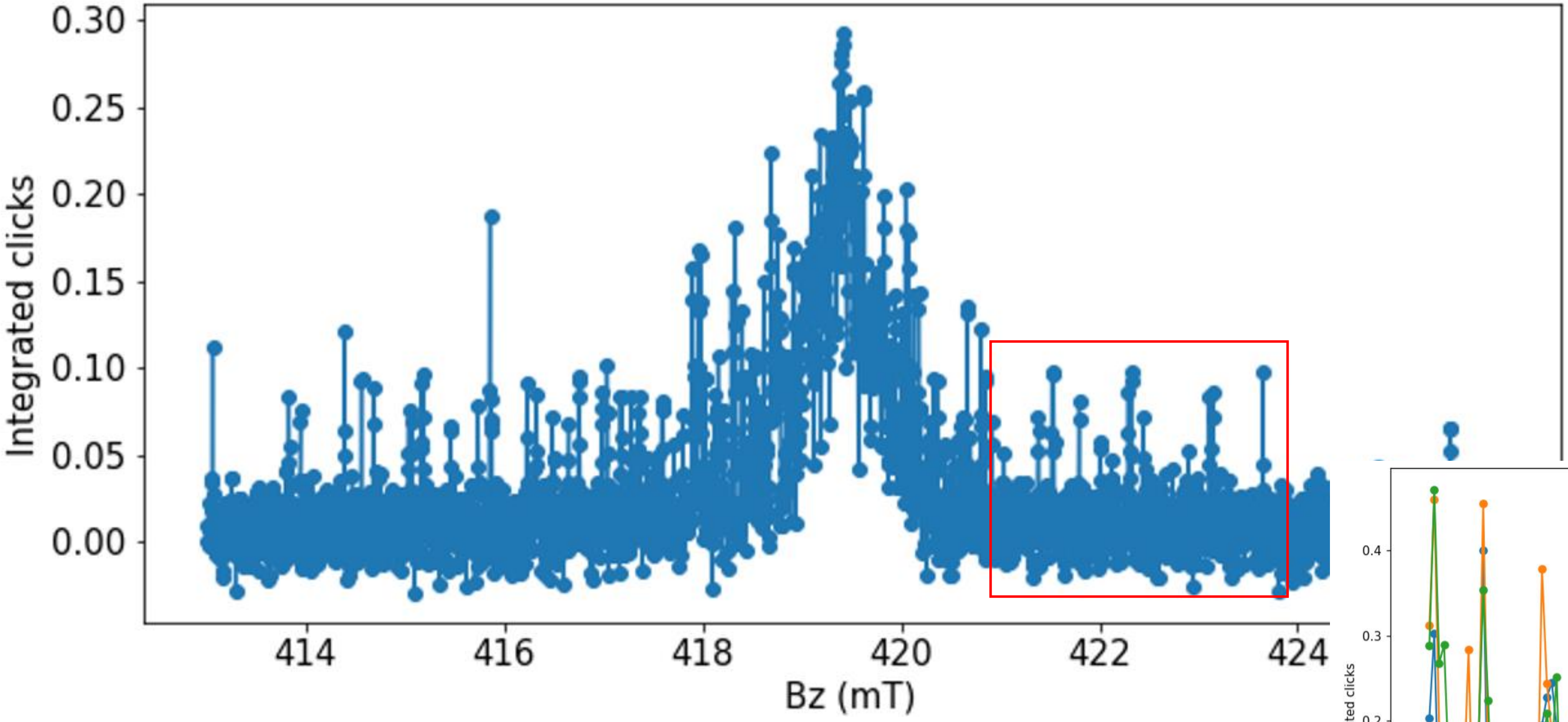
  Increase qubit T1
  Improve thermalization

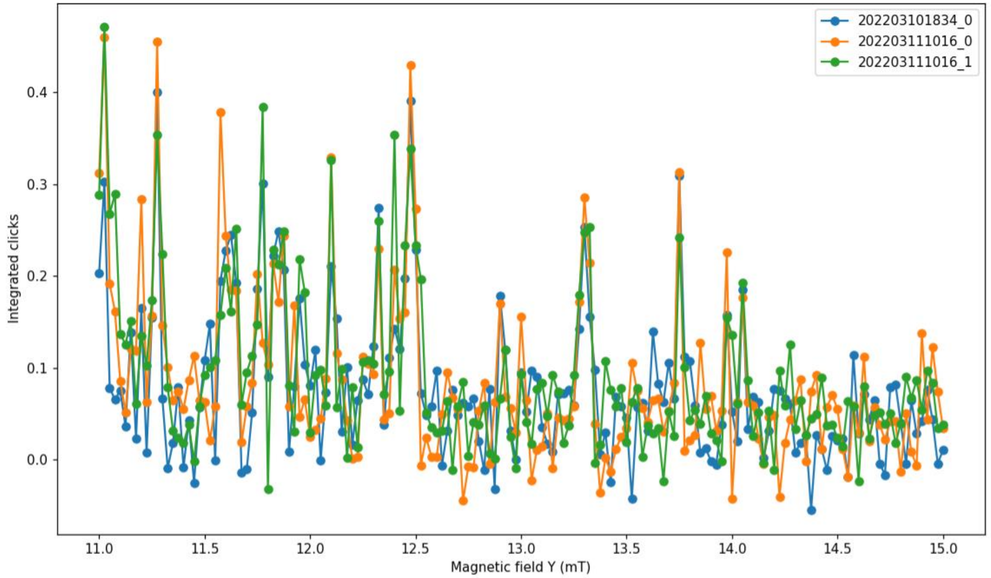
Ongoing work:

- ESR on non-testbench samples
- Single spin detection



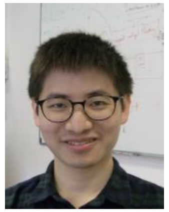
Single spin fluorescence detection





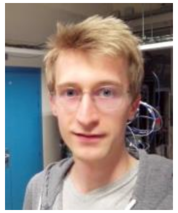
Isolated peaks reproducible over 3 scans separated by 12 hours

Z. Wang



L. Balembois

E. Billaud



Thank you!