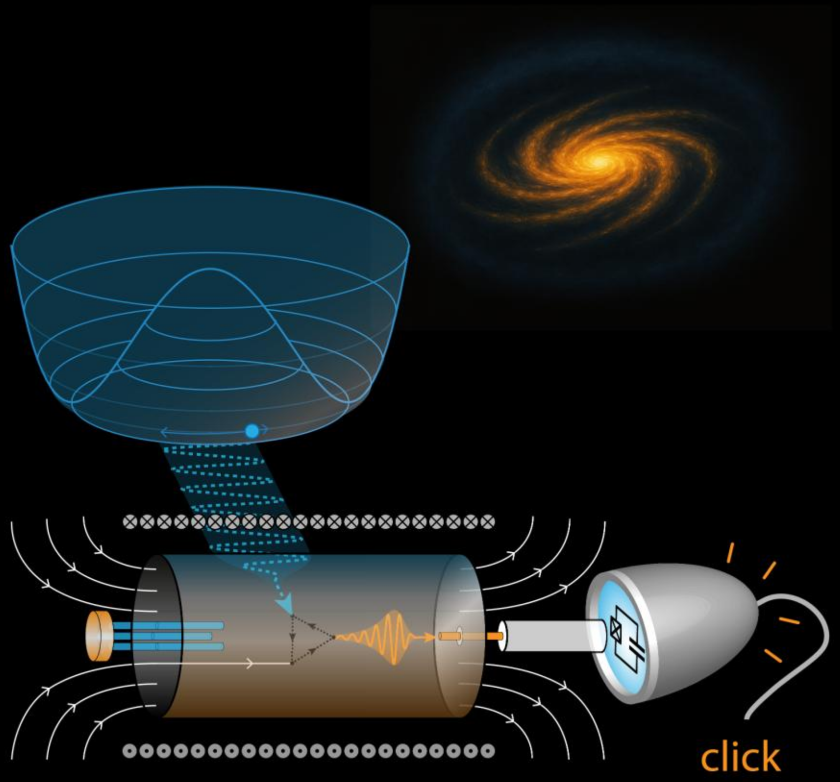
Counting Microwave Photons
From Qubits to the Search for Dark Matter



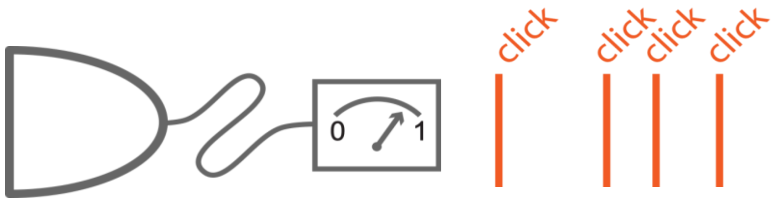
Phys. Rev. X **15**, 021031 (2025)

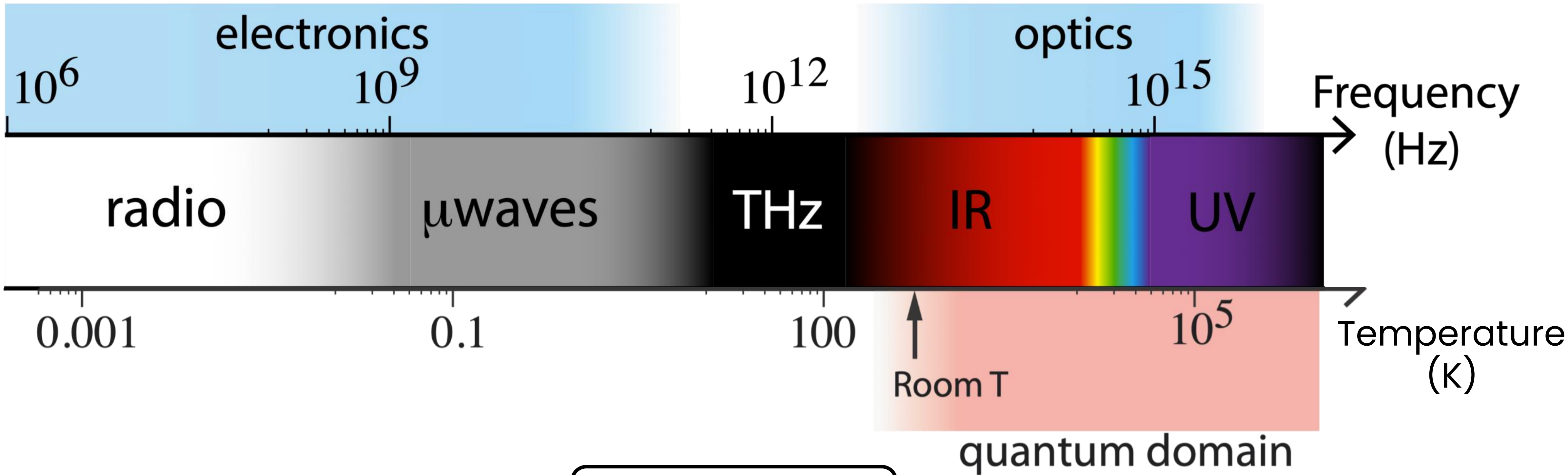
Alexandre MAY, Emmanuel FLURIN

Quantronics group - CEA SPEC

EM field detection

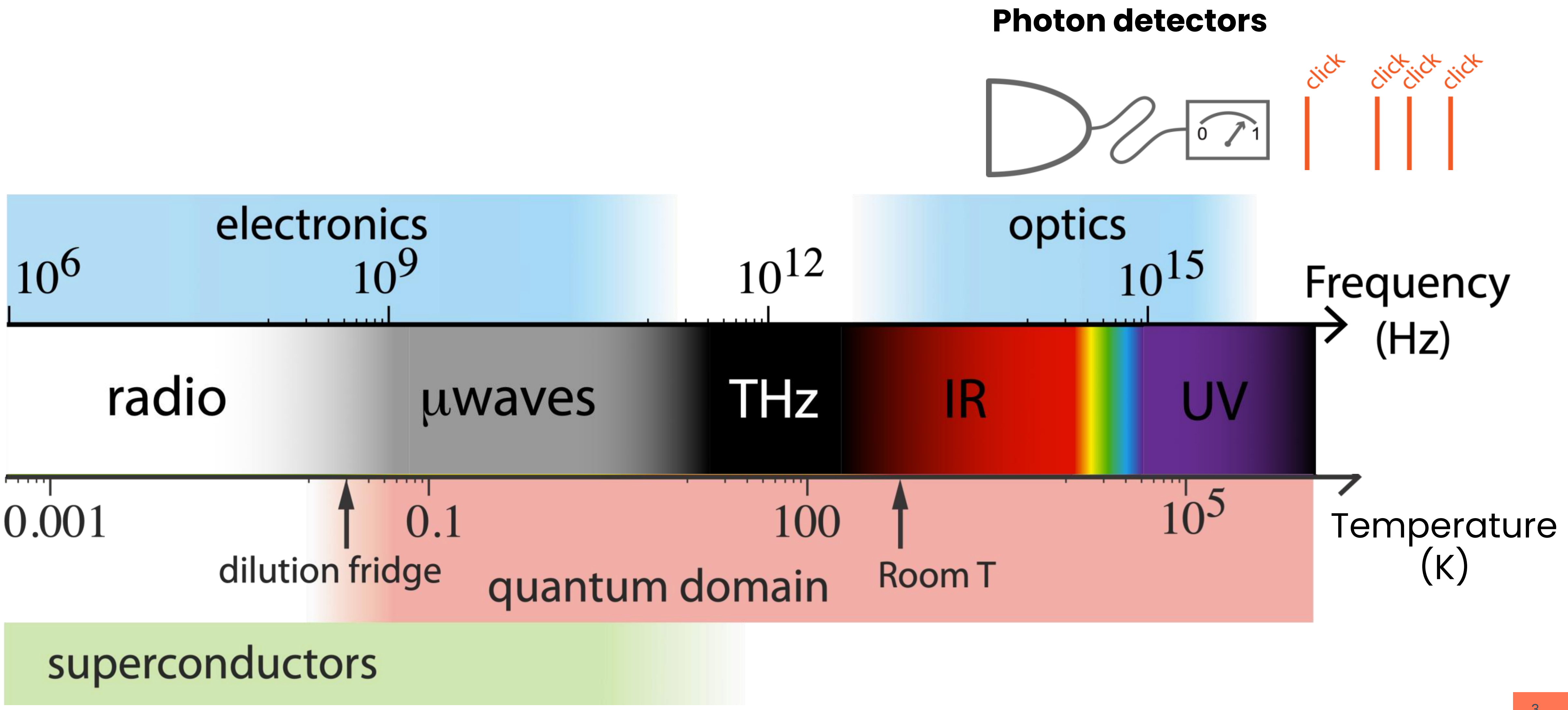
Photon detectors



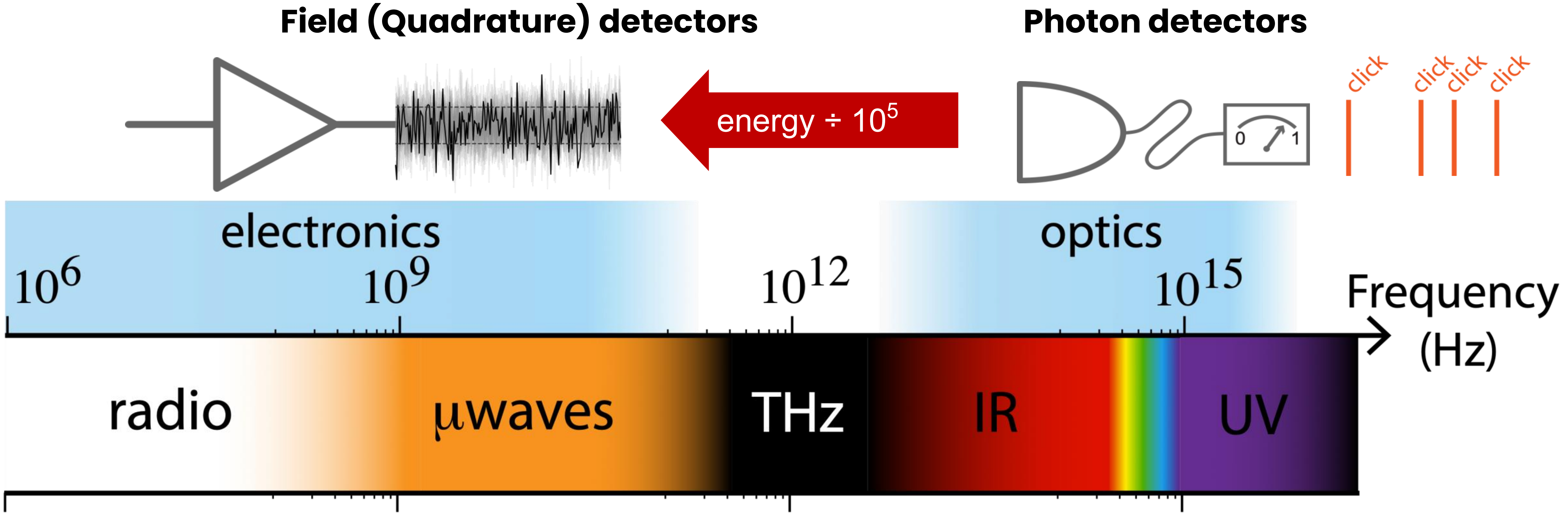


$$\boxed{k_B T \ll \hbar\omega}$$

EM field detection



MW field detection



C.M. Caves, PRD (1982)

•••

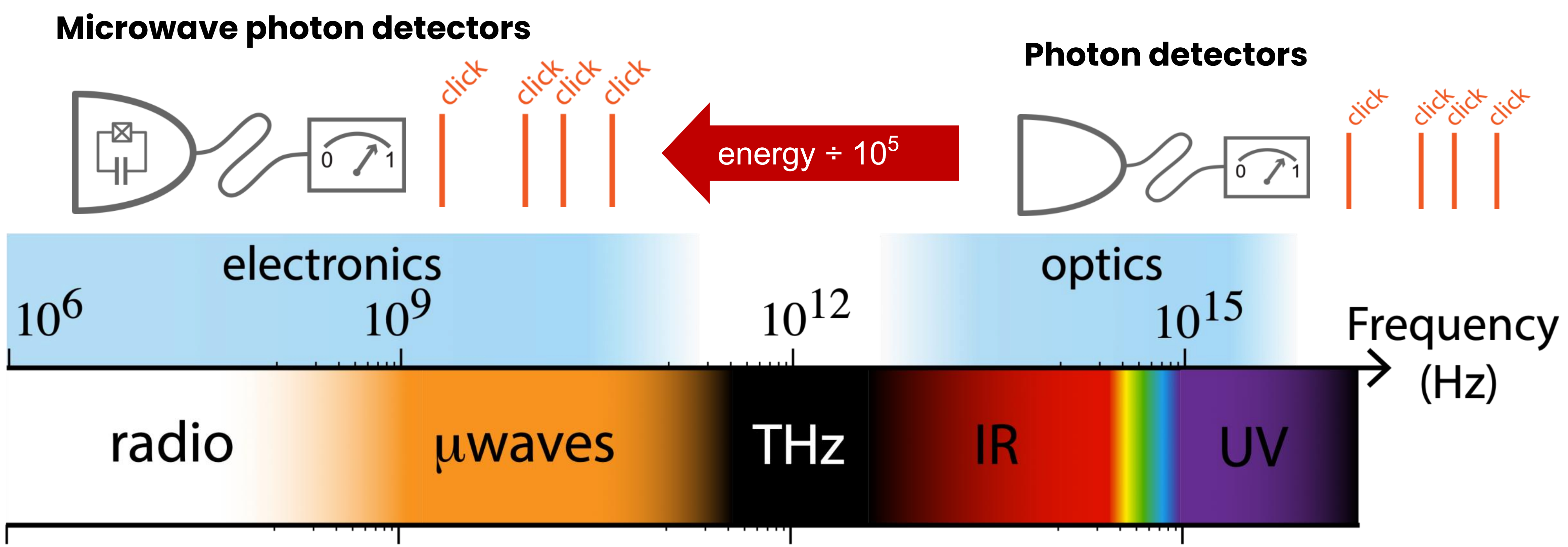
Bergeal et al, Nature (2010)
Zhong et al, NJP (2013)
White et al, APL (2015)
Macklin et al, Science (2015)

•••

Quadrature detection ($\hat{X}$)

Malnou et al, PRA (2018)
Wurtz et al, PRX (2021)
ADMX collab & al, RSI (2021)
Jiang et al, PRX (2023)
All Quadrature detectors: JTWPA, JPA, JRM…

MW photodetection



Energy detection ($\hat{N}$)

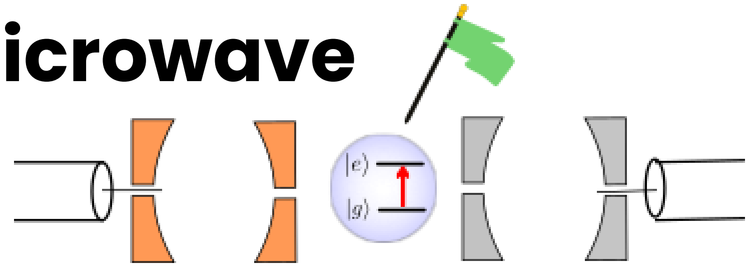
Y-F Chen et al., PRL (2011)
K. Inomata et al., Nature (2016)
S. Kono et al., Nature (2018)
J-C. Besse et al., PRX (2018)
G. Lee et al., Nature (2020)

R. Lescanne et al., PRX (2020)
E. Albertinale et al., Nature (2021)
L. Balembois et al., PRApp (2023)
R. Albert et al, PRX (2024)
L. Pallegoix et al, PRApplied (2025)
A. May et al, arXiv (2025)

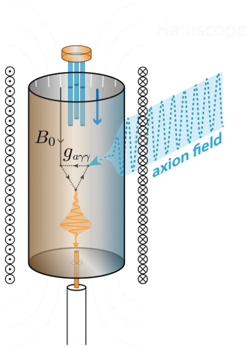
Outline

I. **Photon Detection vs Field Detection**

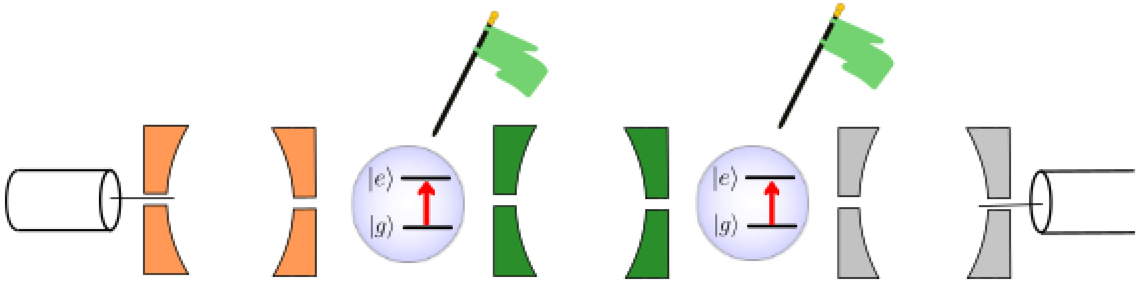
II. **Superconducting Qubit-based Single Microwave Photon Detector (SMPD)**



III. **Counting Photon for Axion Dark Matter Search**



IV. **Enhanced sensitivity with Multiqubit Photon Counter**



Outline

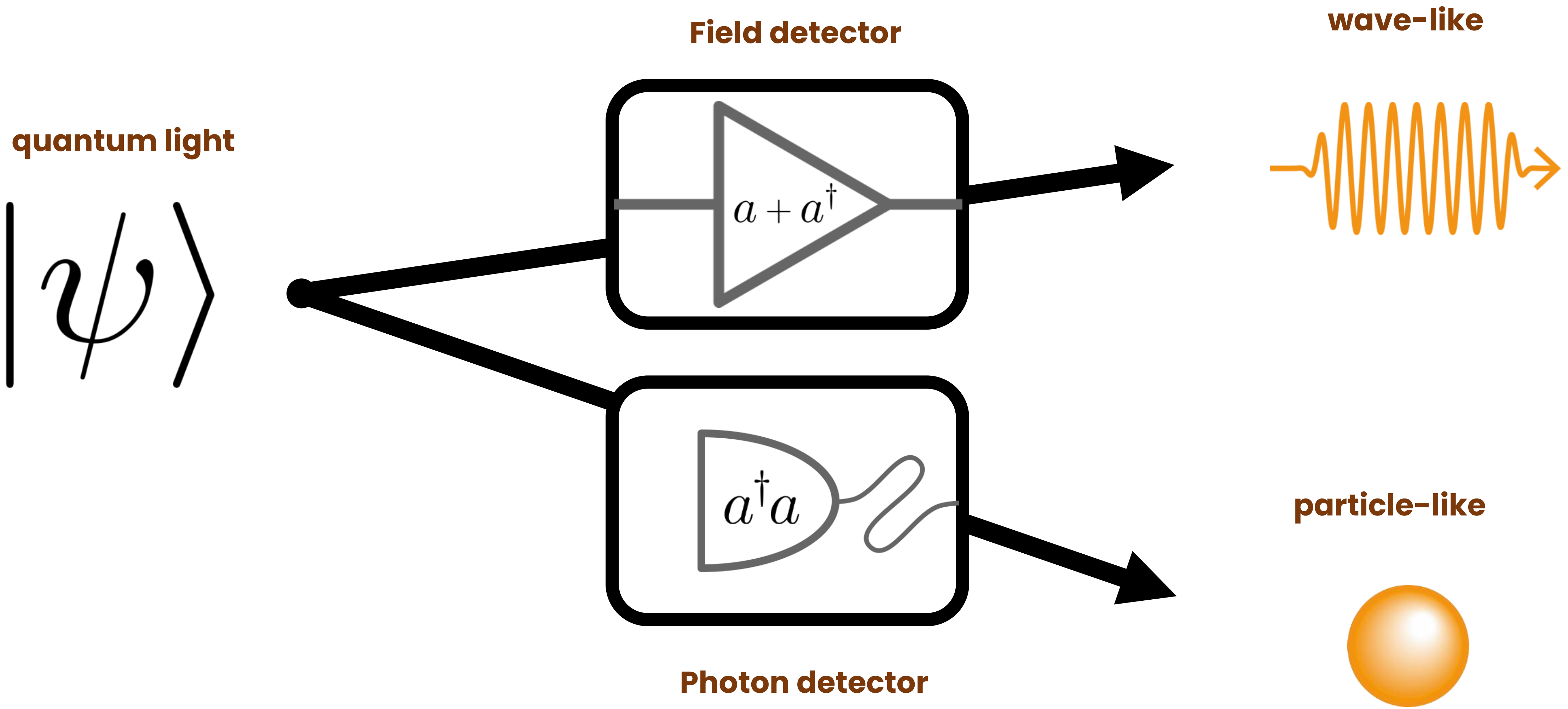
I. Photon Detection vs Field Detection

II. Superconducting Qubit-based Single Microwave Photon Detector (SMPD)

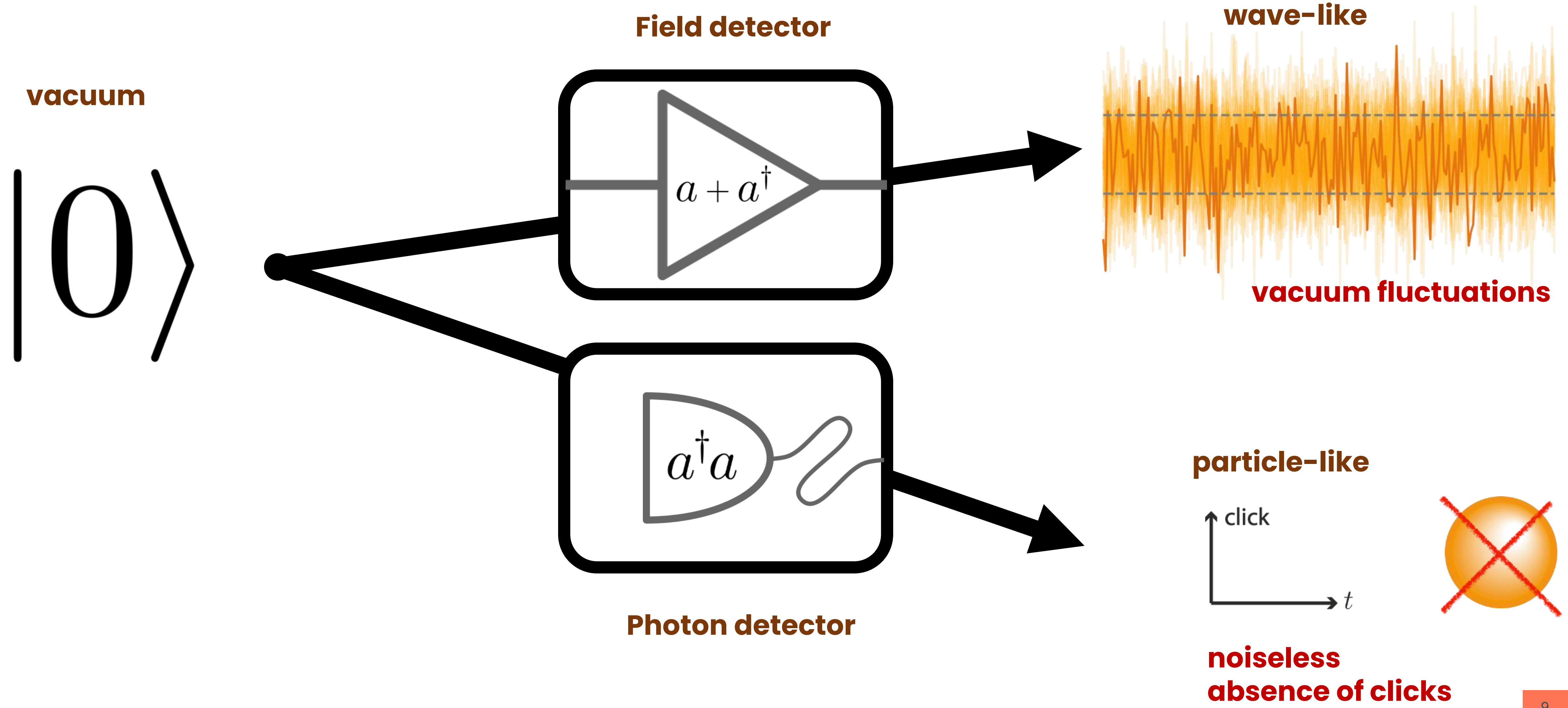
III. Counting Photon for Axion Dark Matter Search

IV. Enhanced sensitivity with Multiqubit Photon Counter

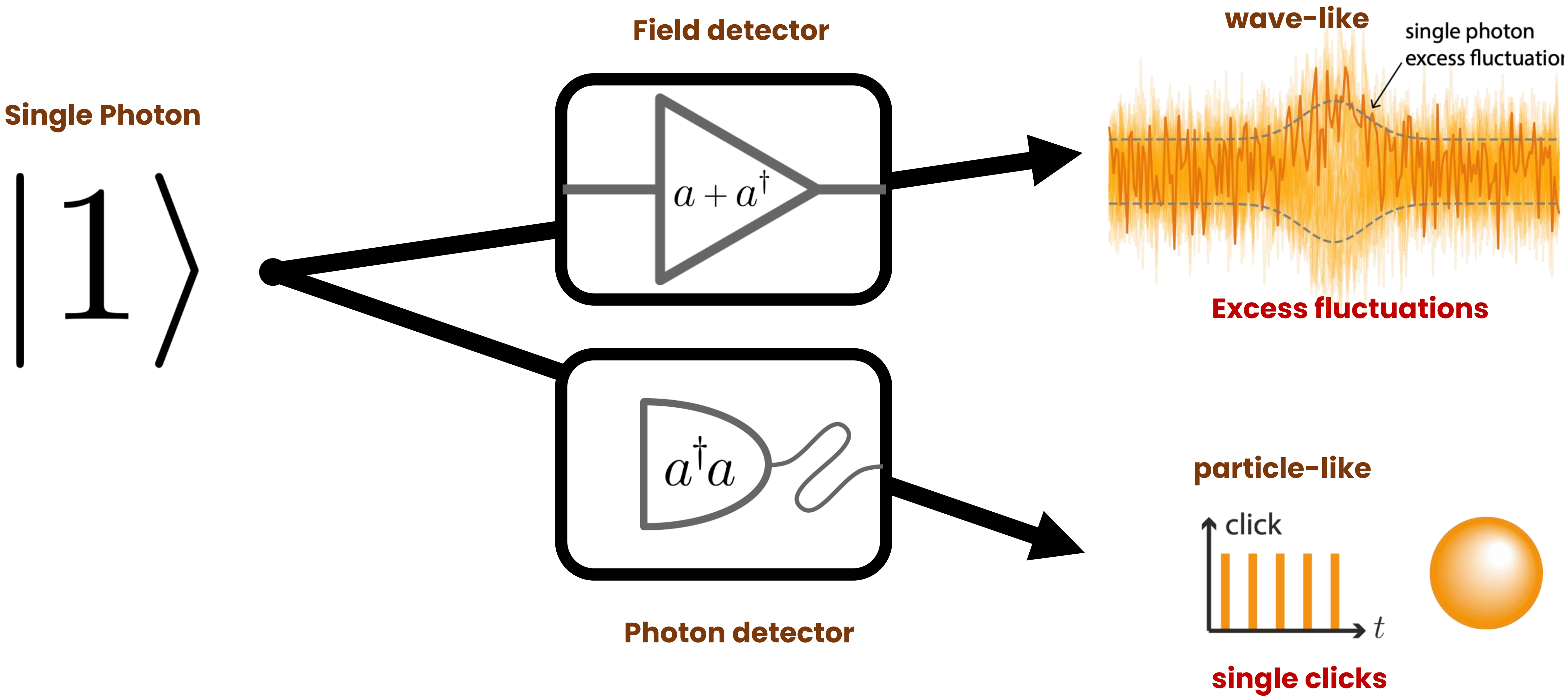
Quantum Optics **101**



Quantum Optics **101**



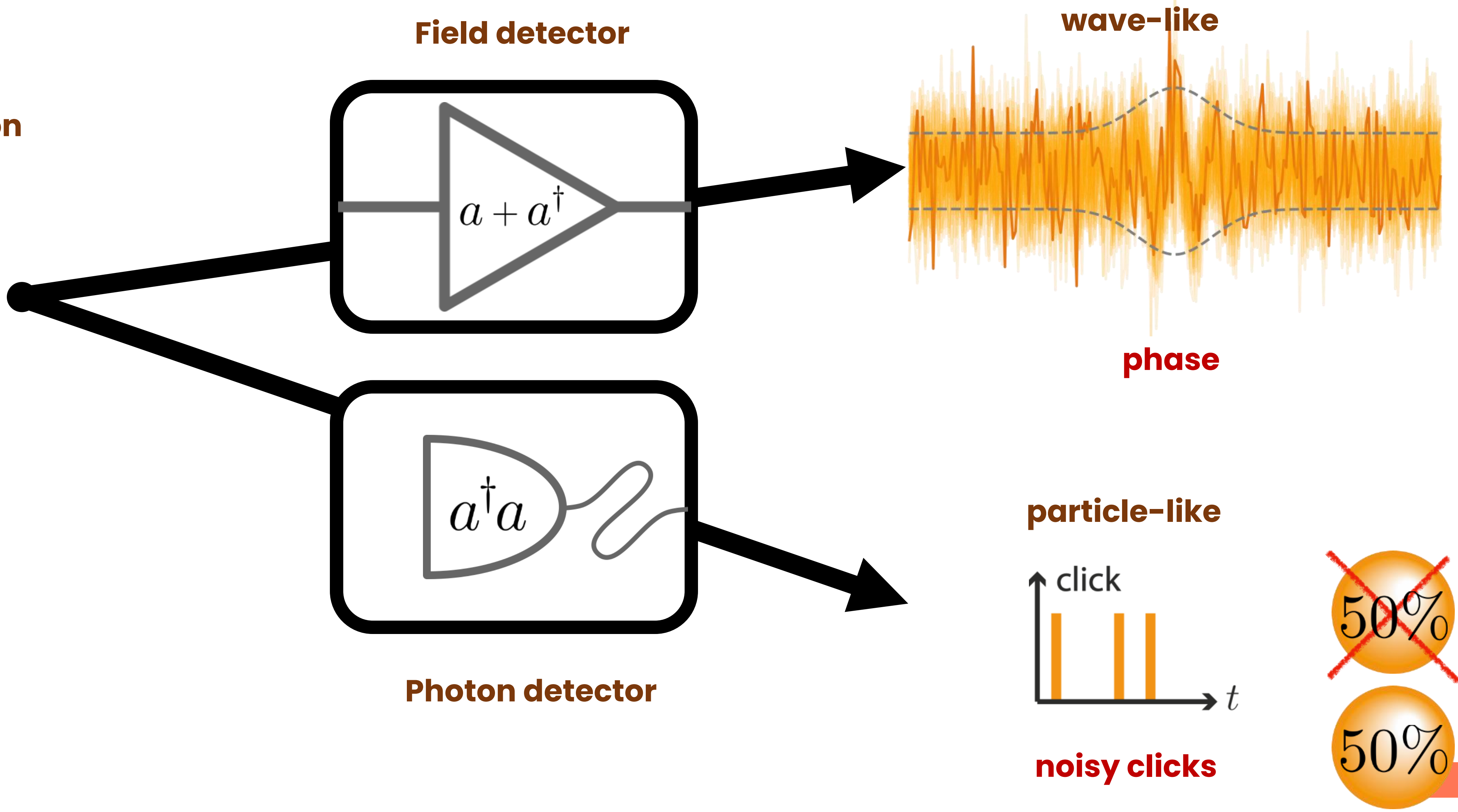
Quantum Optics 101



Quantum Optics **101**

Coherent superposition

$$\frac{|0\rangle + e^{i\phi}|1\rangle}{\sqrt{2}}$$



Quantum Optics 101

PHYSICAL REVIEW D **88,** 035020 (2013)

Analysis of single-photon and linear amplifier detectors for microwave cavity dark matter axion searches

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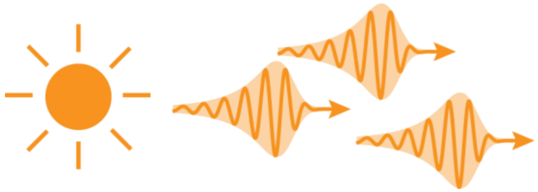
Physical and Life Sciences Directorate, Lawrence Livermore National Laboratory, Livermore, California 94550, USA
(Received 15 June 2013; published 23 August 2013)

weak & incoherent photon source



emission rate: Γ_{photon}

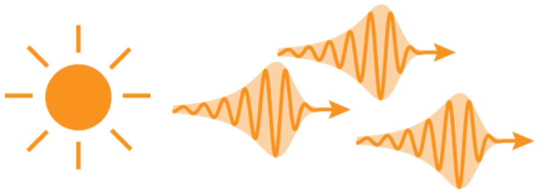
emission bandwidth: Δf

integration time: t

temperature: $n_{\mathrm{th}} = \dfrac{1}{e^{\hbar\omega/kT} + 1}$

Quantum Optics **101**

weak & incoherent photon source



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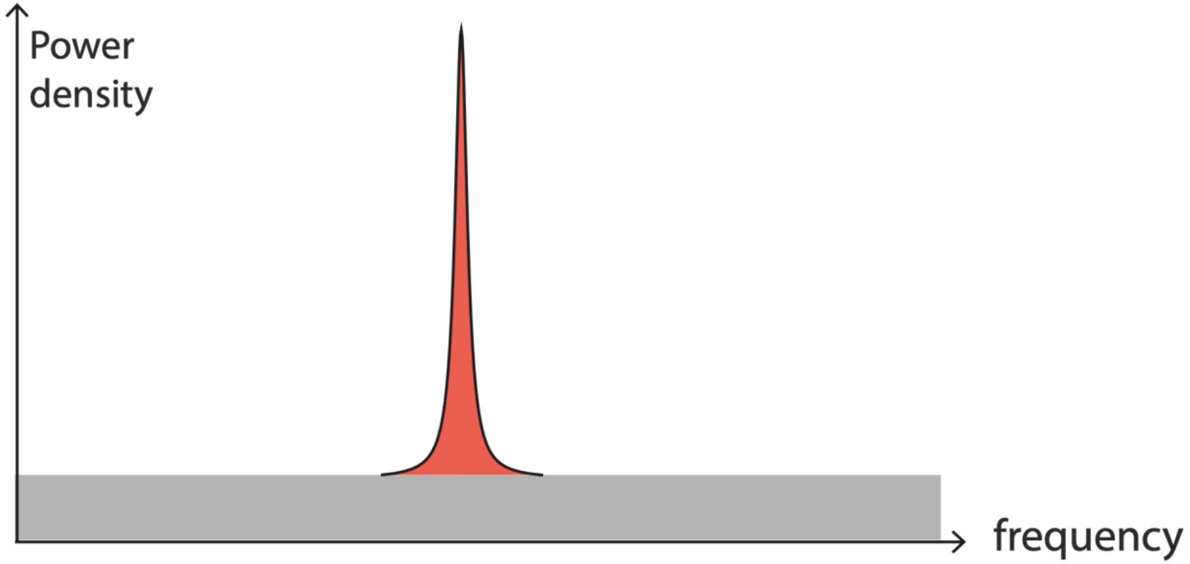
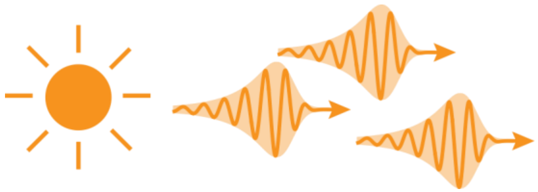


Quantum Optics 101

weak & incoherent photon source



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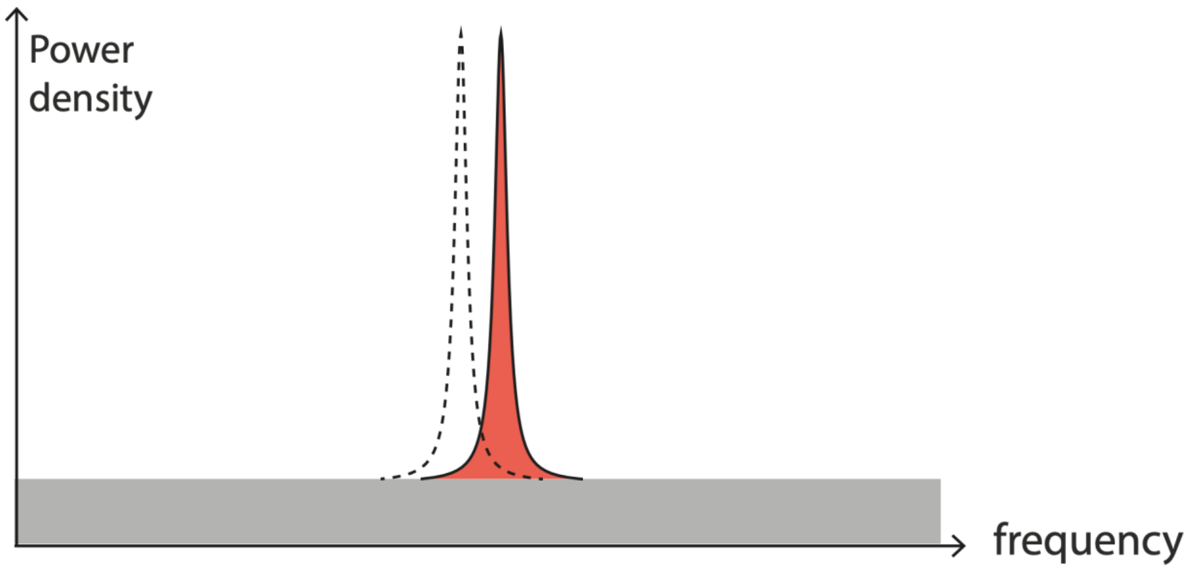
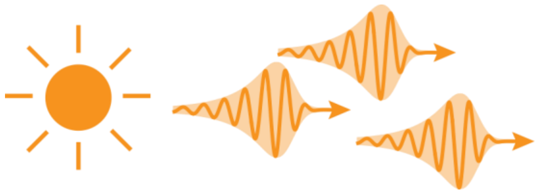


Quantum Optics 101

weak & incoherent photon source



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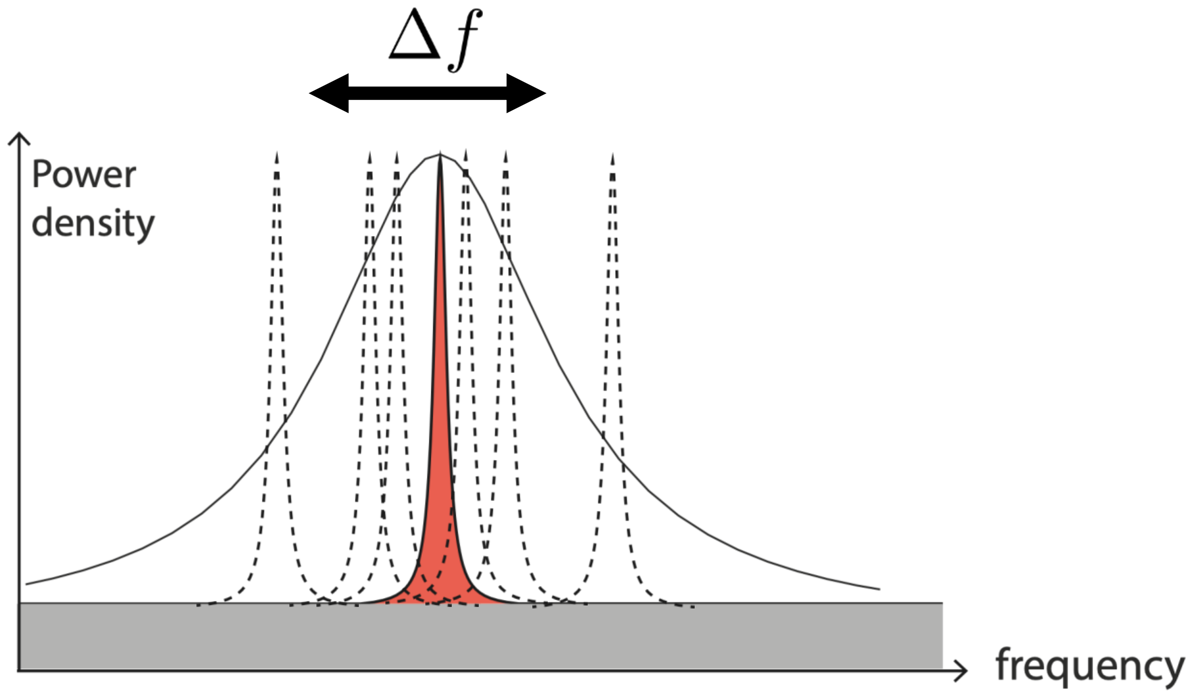
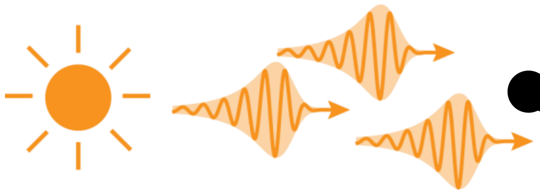
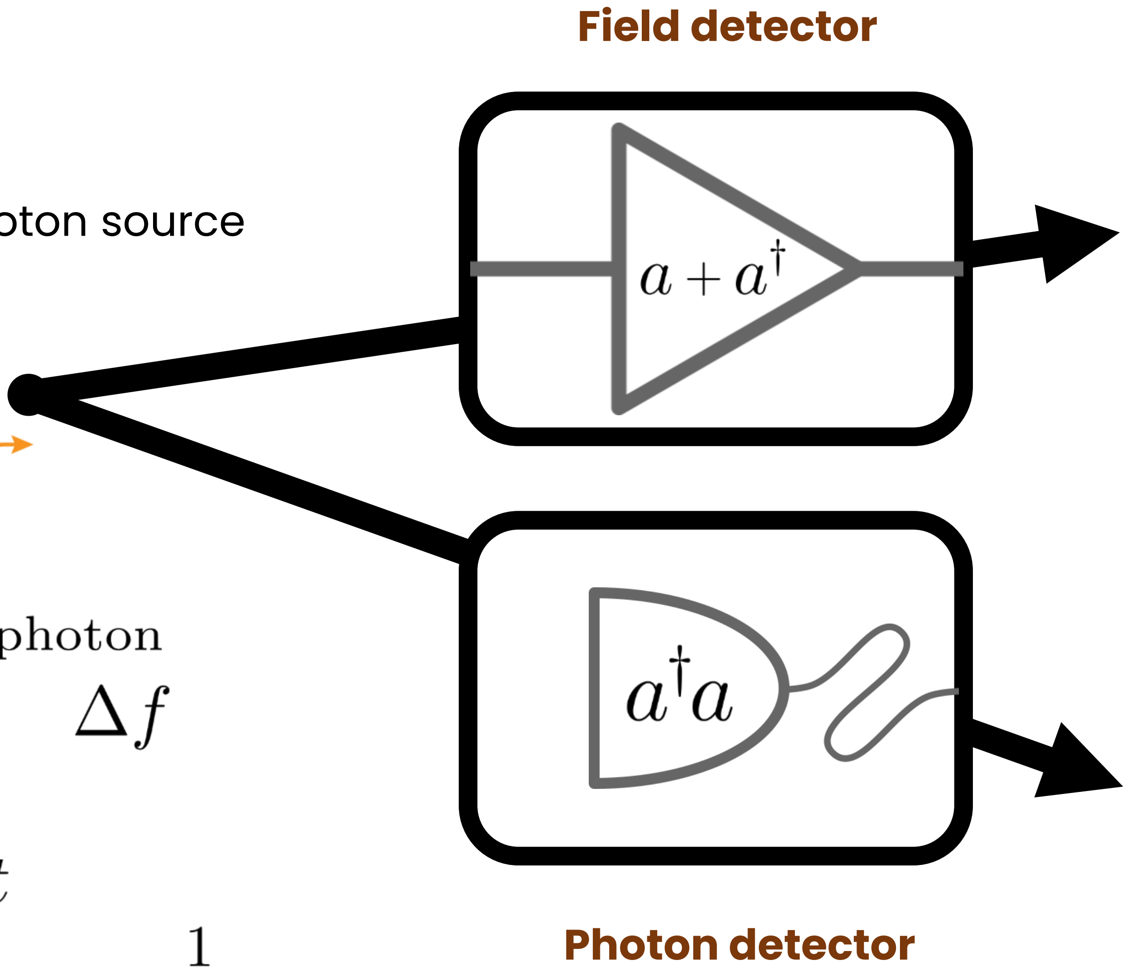


Quantum Optics **101**

weak & incoherent photon source





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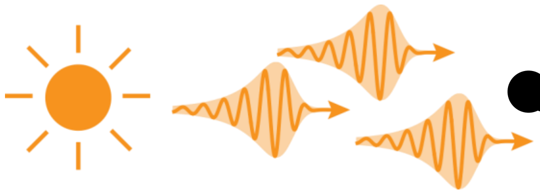
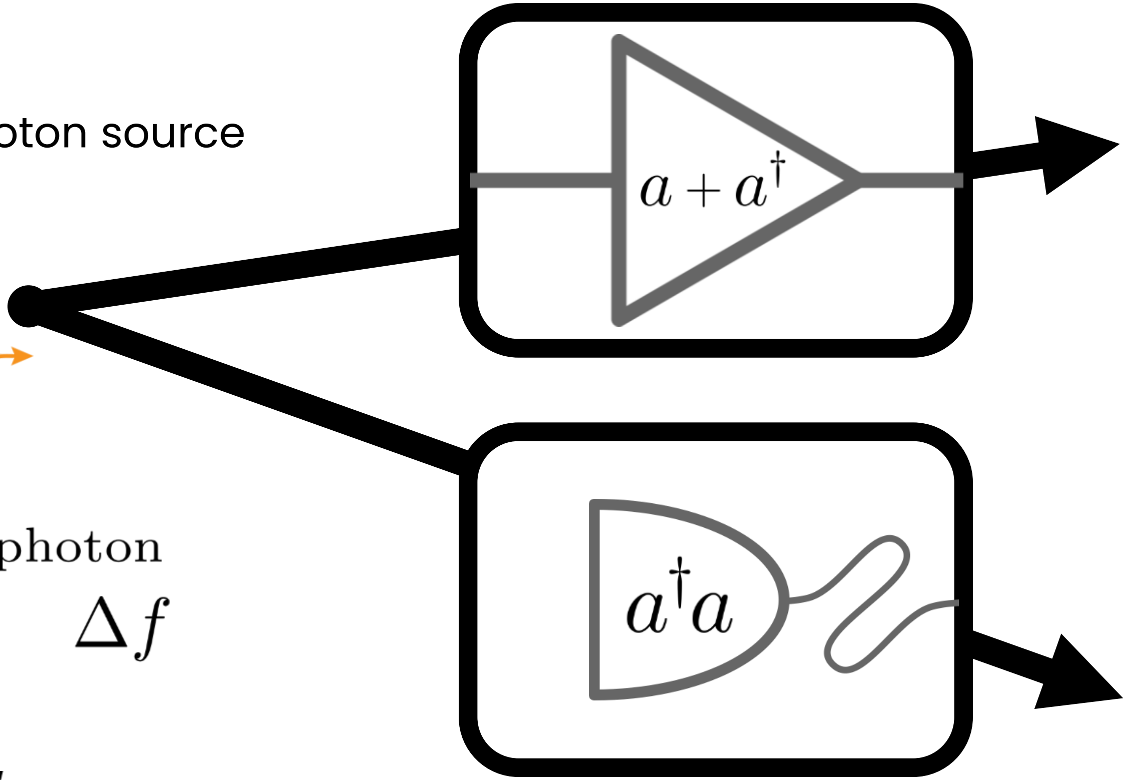
Quantum Optics **101**

weak & incoherent photon source



Field detector



Photon detector

Integrated Power

$$S = \hbar\omega\Gamma_{\text{photon}}t$$

$$S = \hbar\omega\Gamma_{\text{photon}}t$$

emission rate: Γ_{photon}

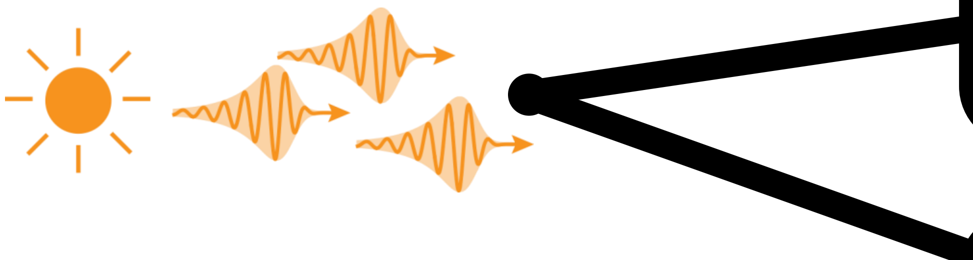
emission bandwidth: Δf

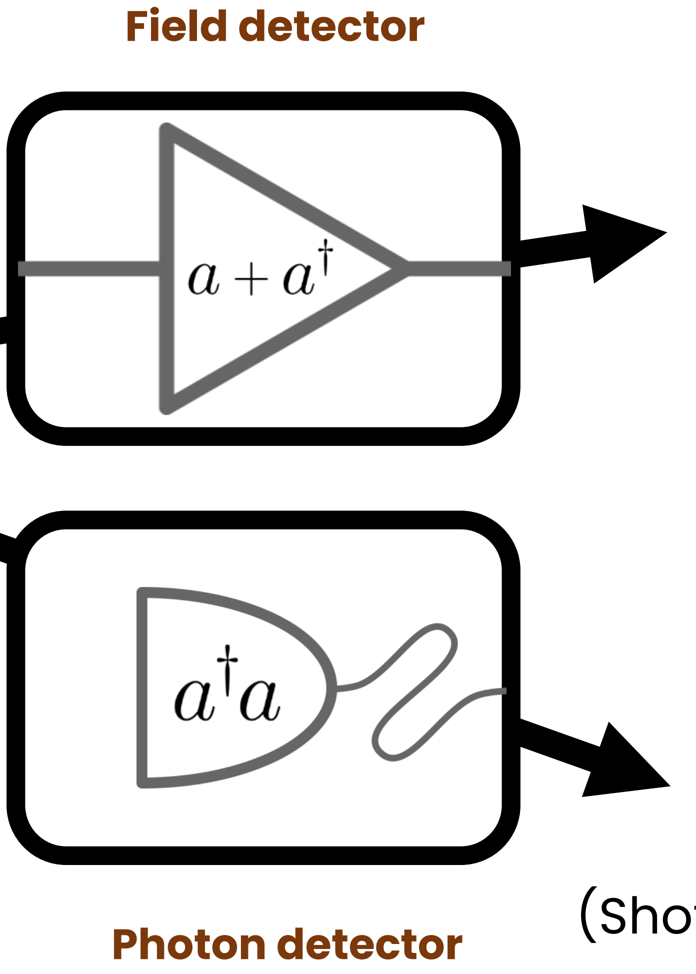
integration time: t

temperature: $n_{\text{th}} = \dfrac{1}{e^{\hbar\omega/kT}+1}$

Quantum Optics **101**

weak & incoherent photon source





emission rate: Γ_{photon}

emission bandwidth: Δf

integration time: t

temperature: $n_{\text{th}} = \dfrac{1}{e^{\hbar\omega/kT} + 1}$

Integrated Noise

$$N = \hbar\omega\sqrt{(1 + n_{\text{th}})^2 \Delta f \times t}$$

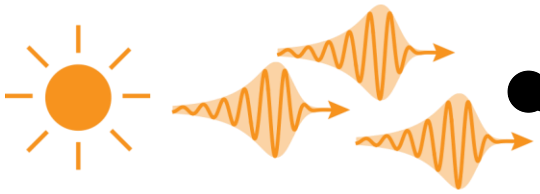
(Dicke radiometer equation)

$$N = \hbar\omega\sqrt{n_{\text{th}}(1 + n_{\text{th}}) \Delta f \times t}$$

(Shot noise due to thermal fluctuation)

Quantum Optics 101

weak & incoherent photon source



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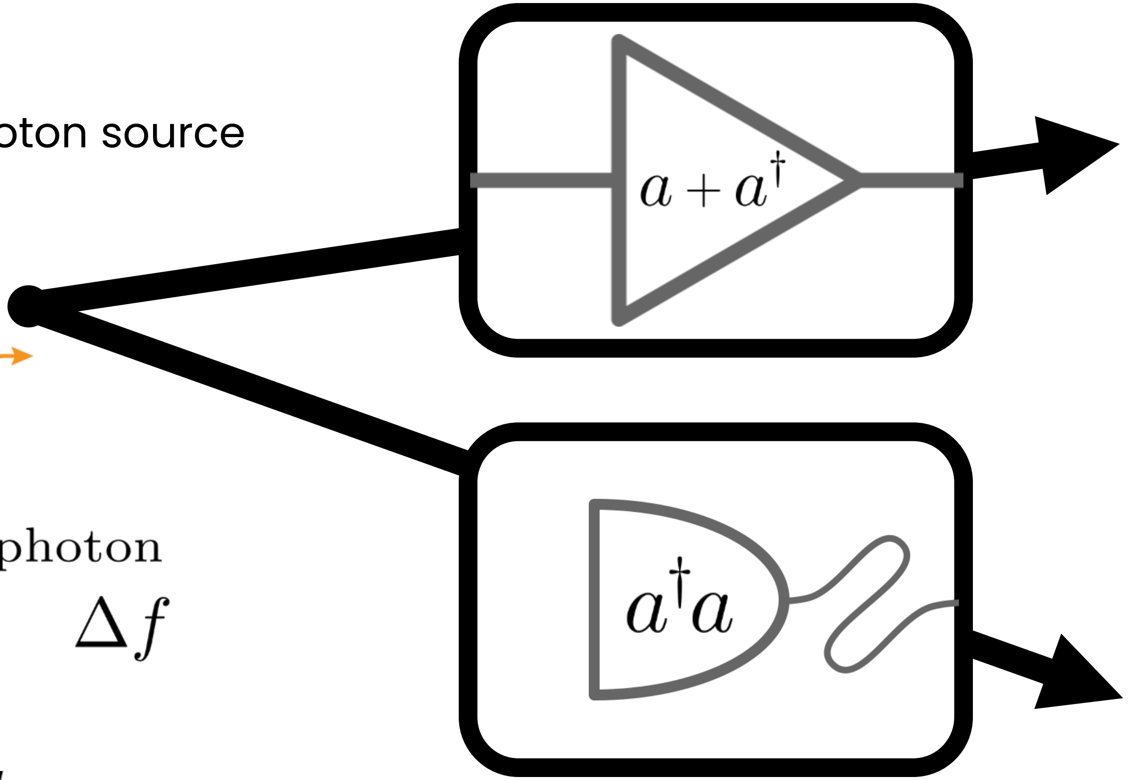
Field detector



Photon detector

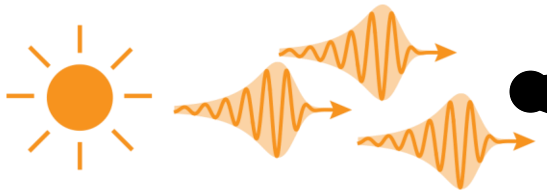
Signal-to-Noise Ratio

$$\frac{S}{N} = \frac{\Gamma_{\text{photon}}\sqrt{t}}{\sqrt{(1+n_{\text{th}})^2\Delta f}}$$

$$\frac{S}{N} = \frac{\Gamma_{\text{photon}}\sqrt{t}}{\sqrt{n_{\text{th}}(1+n_{\text{th}})\Delta f}}$$

Quantum Optics **101**

weak & incoherent photon source



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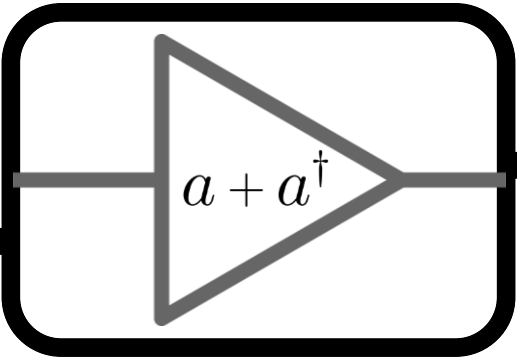
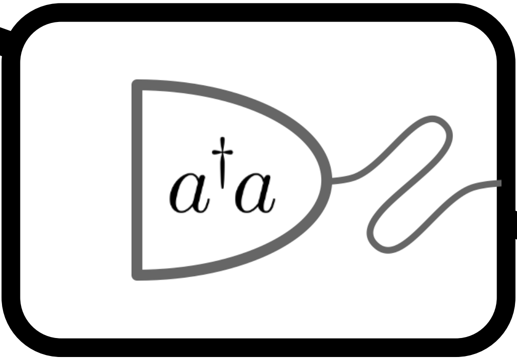




Photon detector

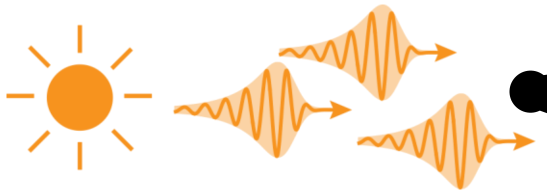
Photon Detector Speedup

$$R = \frac{\left(\frac{S}{N}\right)^2_{\text{PD}}}{\left(\frac{S}{N}\right)^2_{\text{Quad}}} = \frac{1+n_{\text{th}}}{n_{\text{th}}}$$

$$\xrightarrow[T\to 0]{} e^{\hbar\omega/kT}$$

Quantum Optics 101

weak & incoherent photon source



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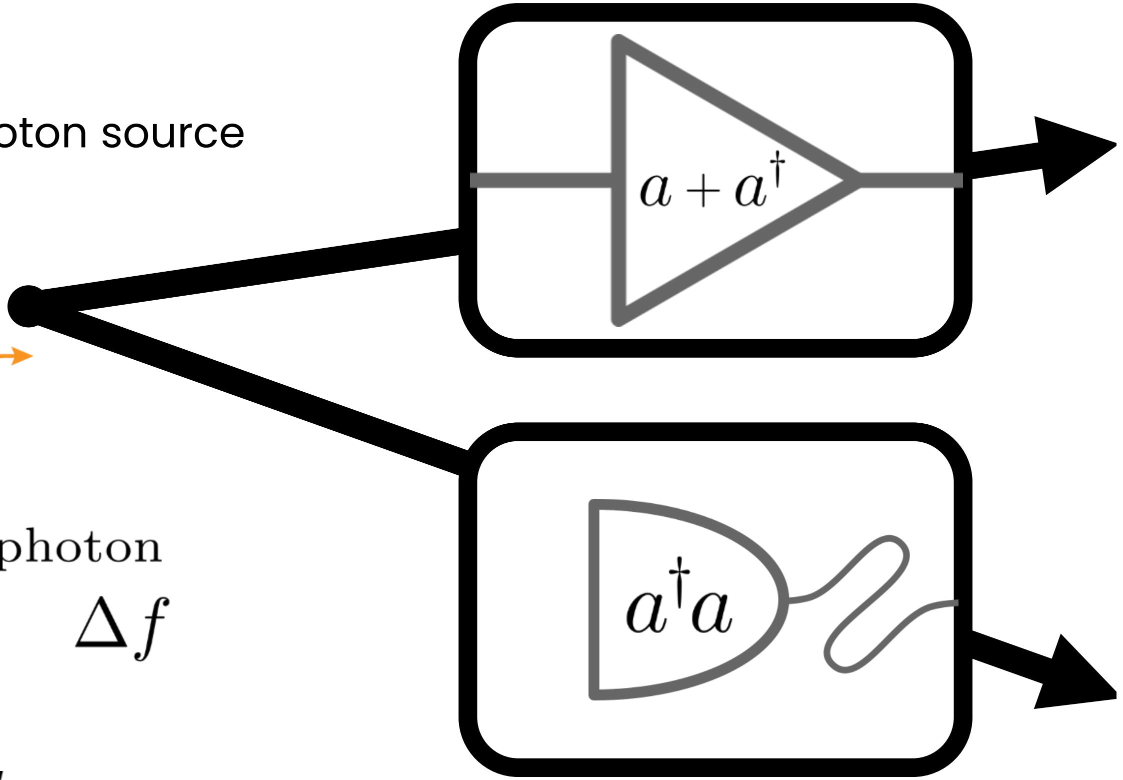
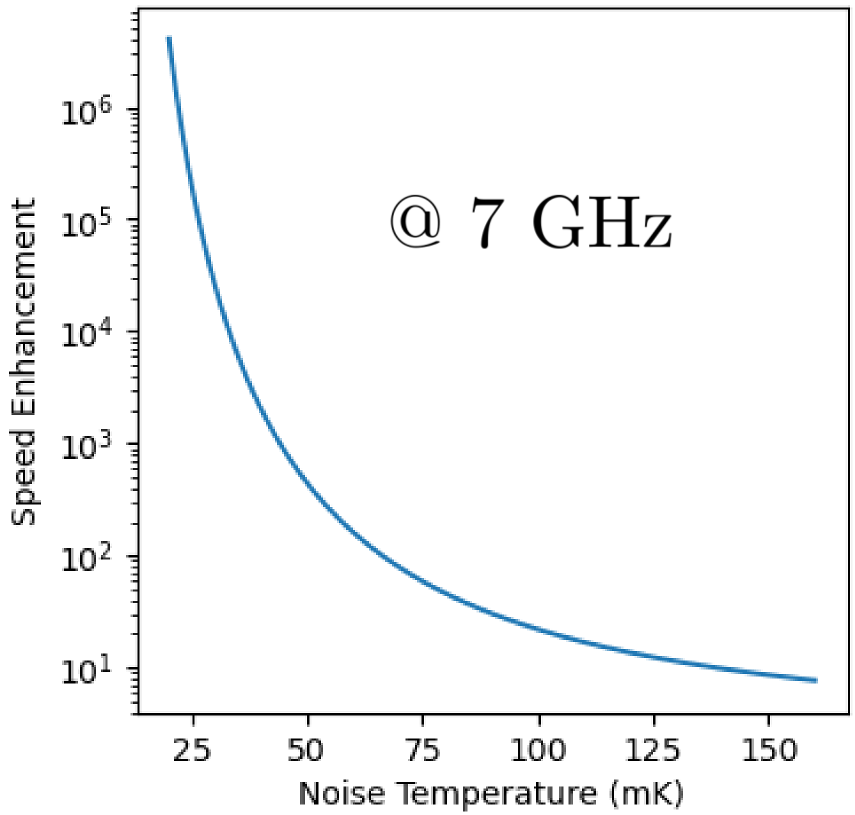


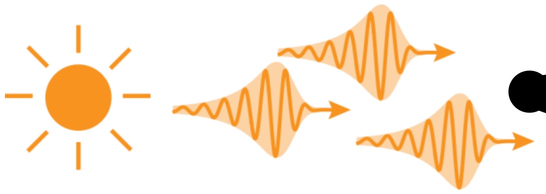
Photon detector

photon detector speedup over linear amplifier

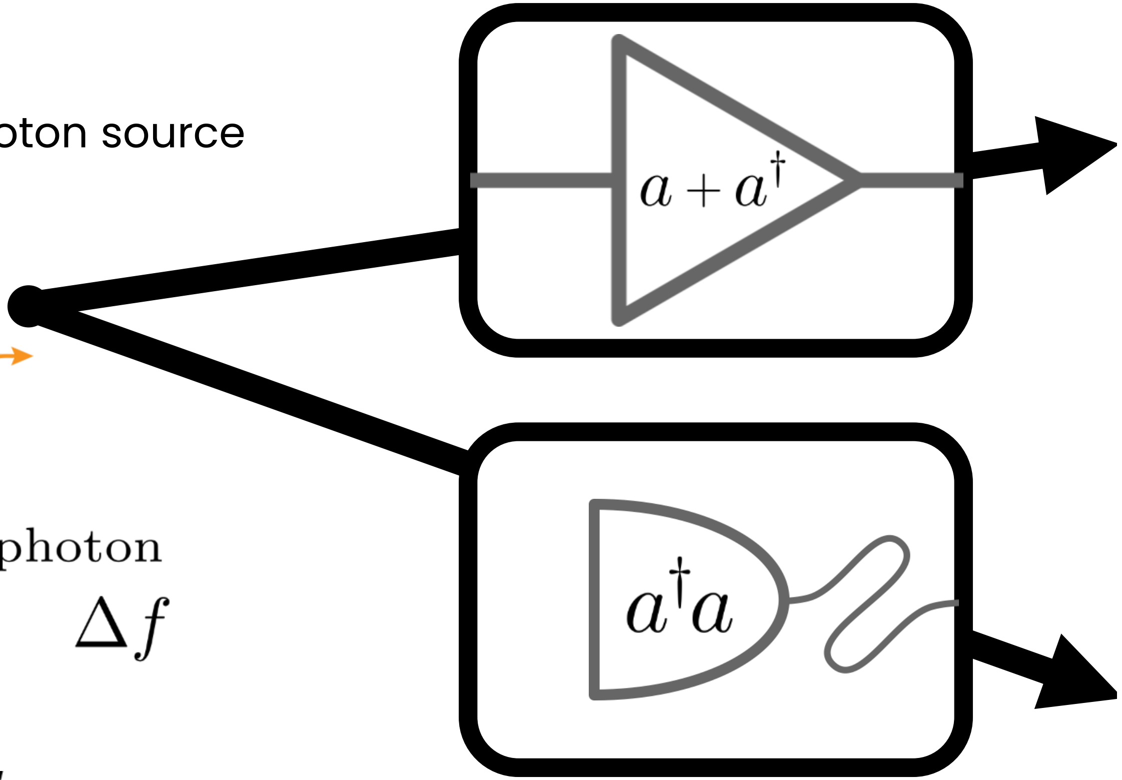


Quantum Optics **101**

weak & incoherent photon source



Field detector



Photon detector

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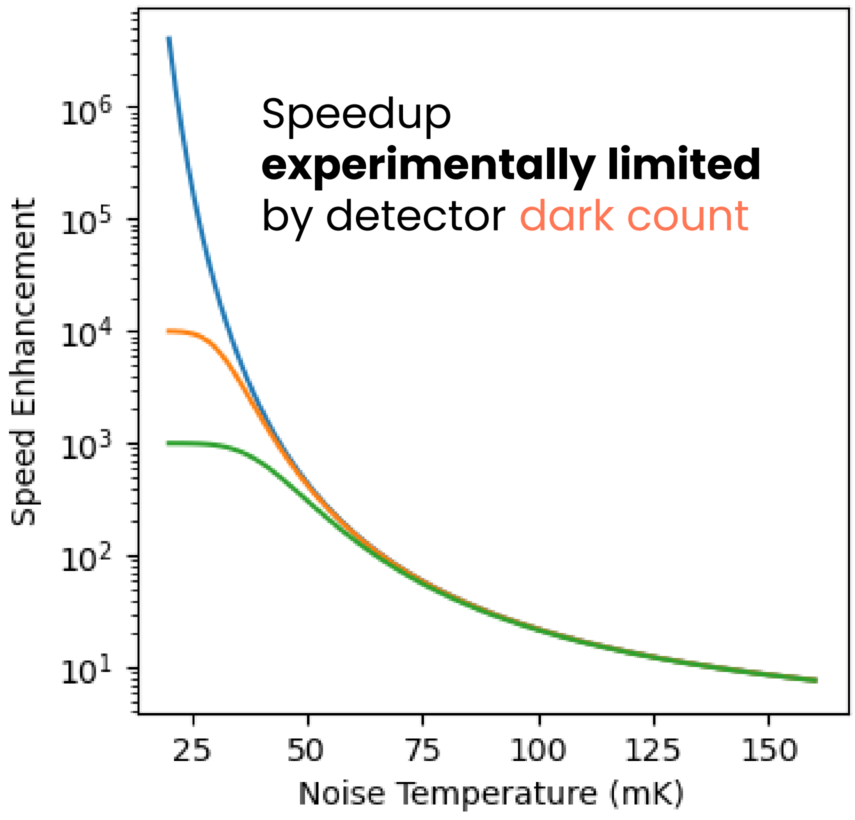
photon detector speedup over linear amplifier



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I. Photon Detection vs Field Detection

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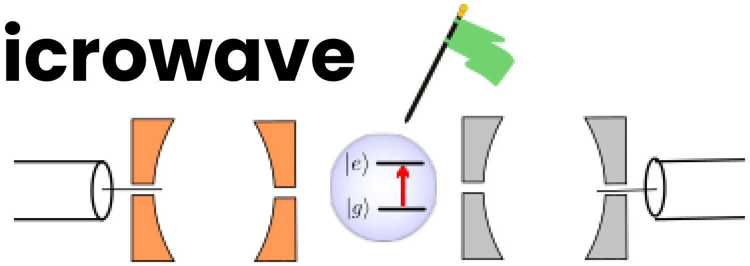
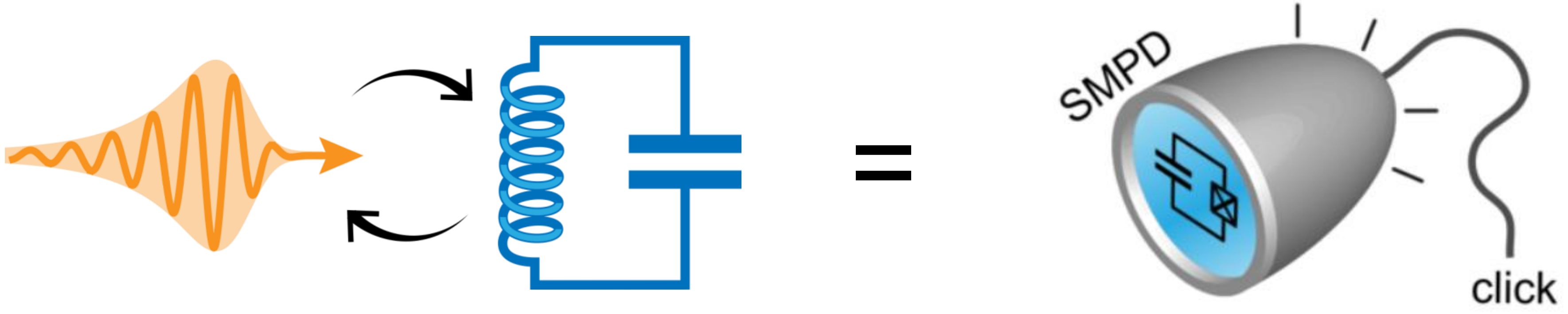
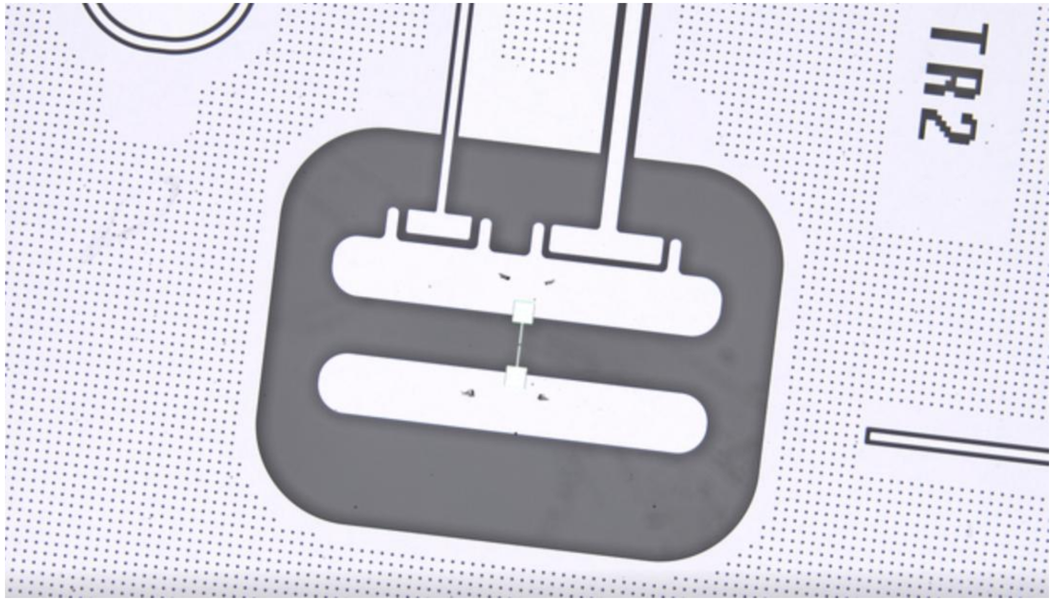


III. Counting Photon for Axion Dark Matter Search

IV. Enhanced sensitivity with Multiqubit Photon Counter

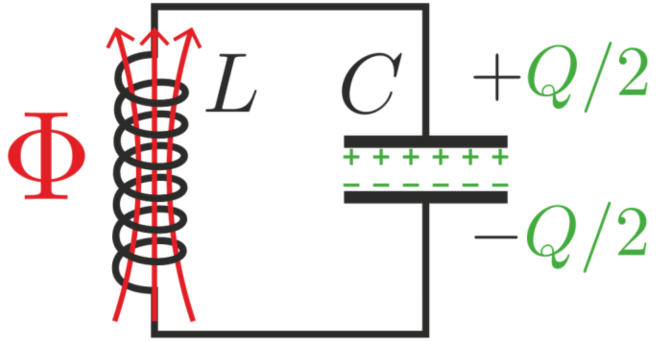
Circuit QED for Quantum sensing

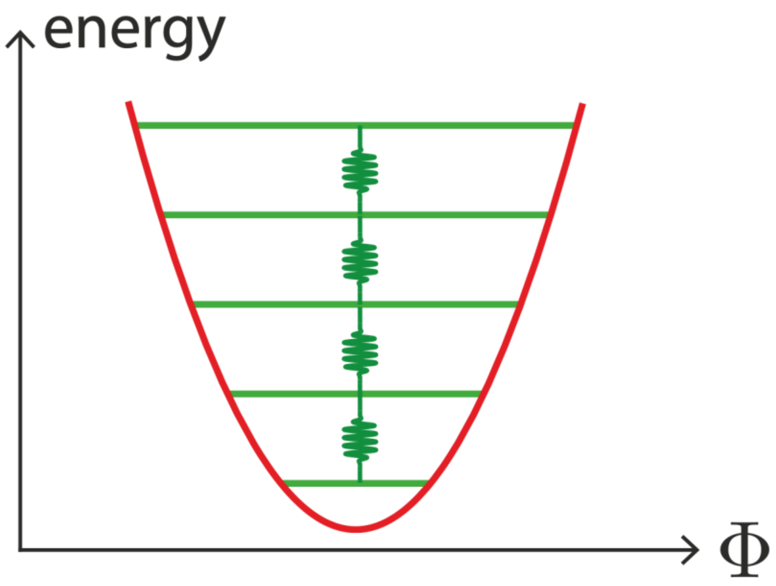




25 years of superconducting quantum circuits
pioneered by the Quantronics/CEA, Yale, NEC…

Artificial atoms





$$[\Phi, Q] = i\hbar$$

flux «position»

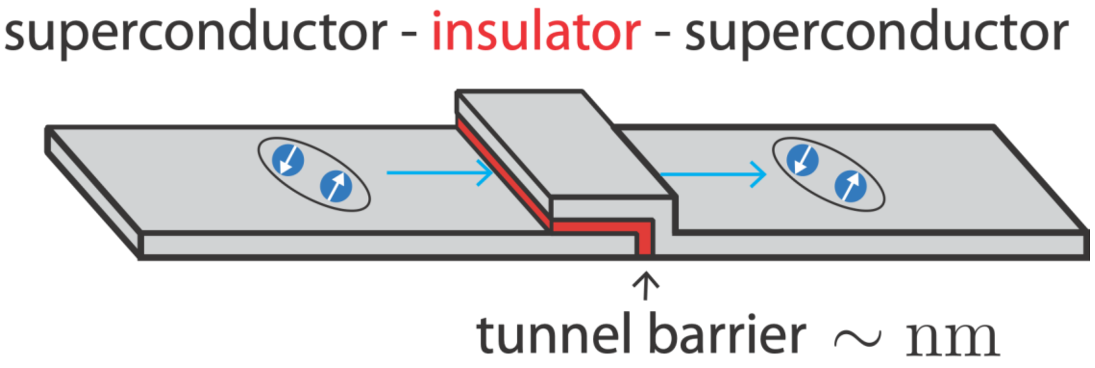
charge «momentum»

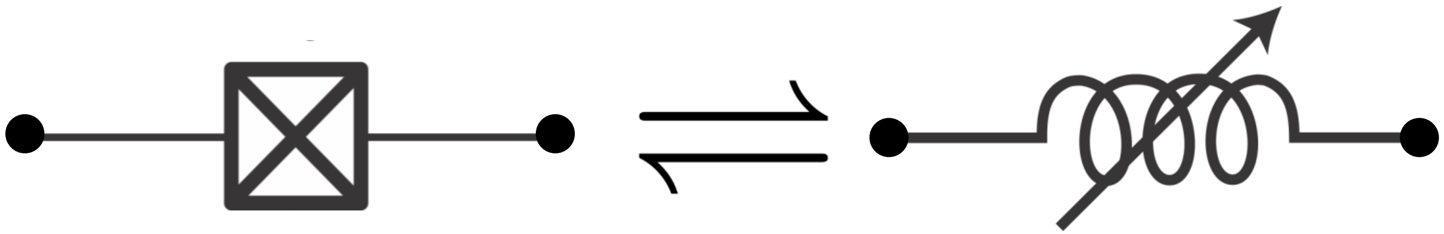
$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

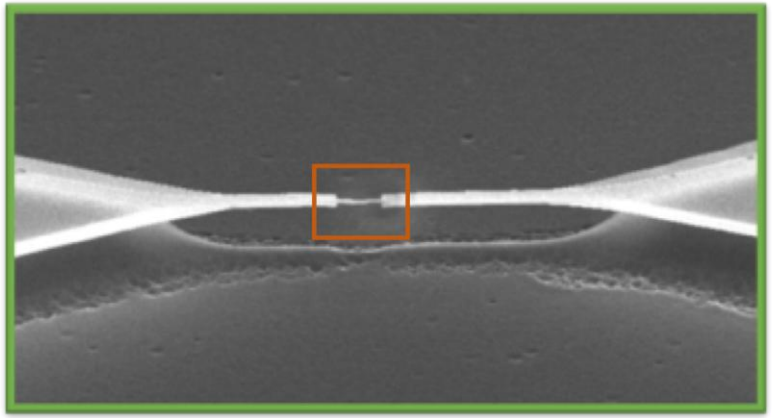
Artificial atoms

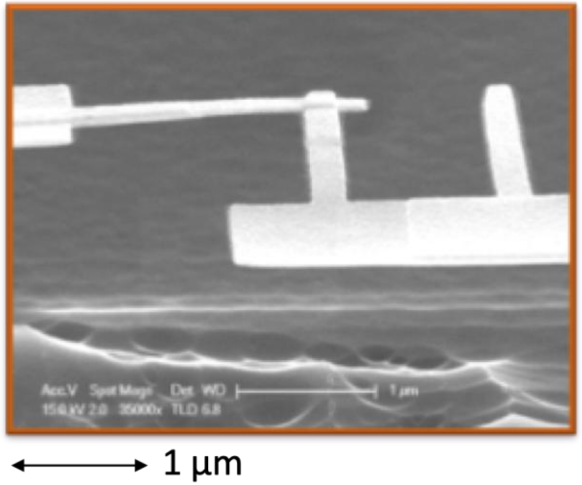
Josephson junction

dissipationless non-linear inductor









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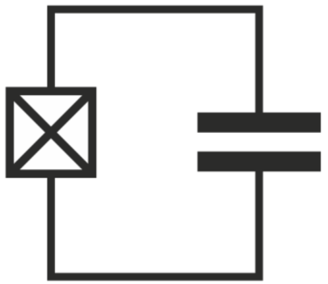
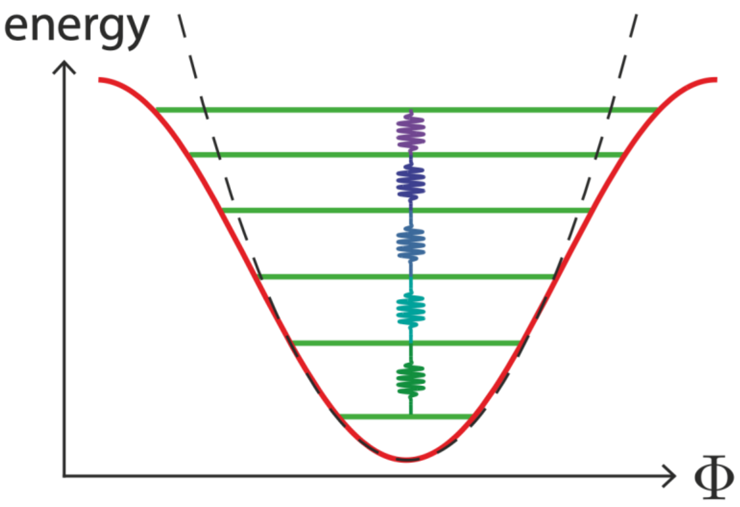
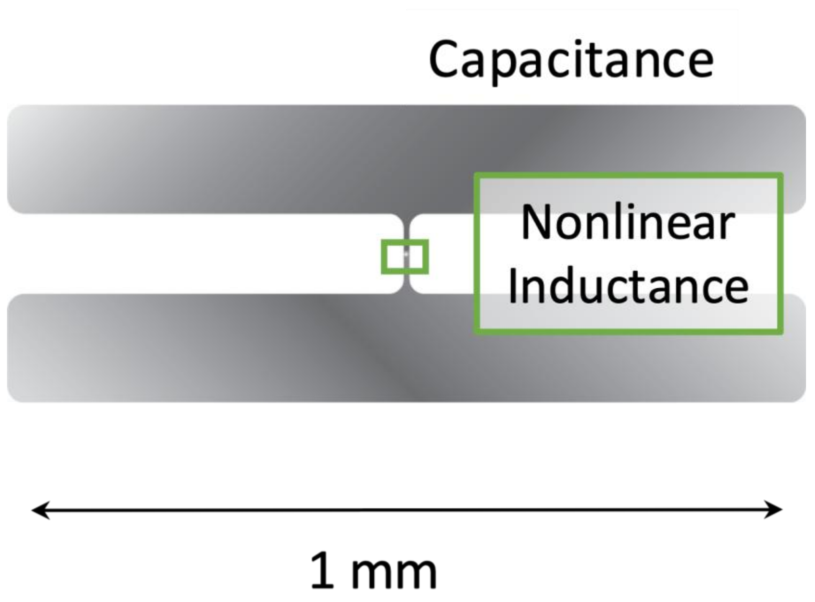
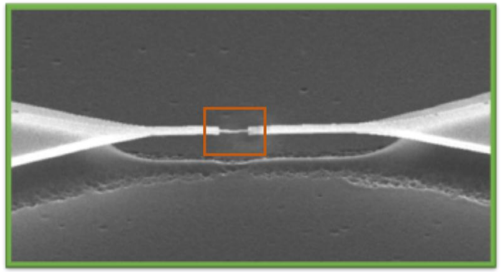
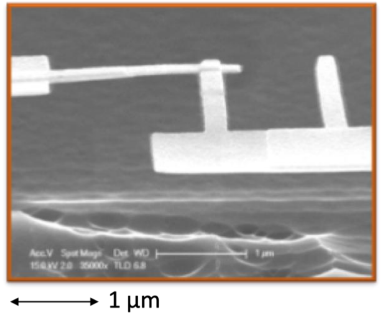




$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L(\Phi)}$$







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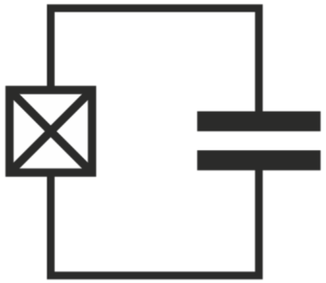

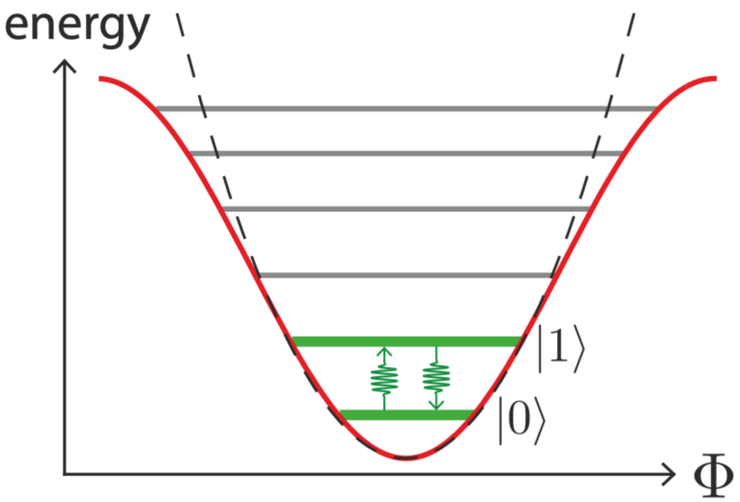

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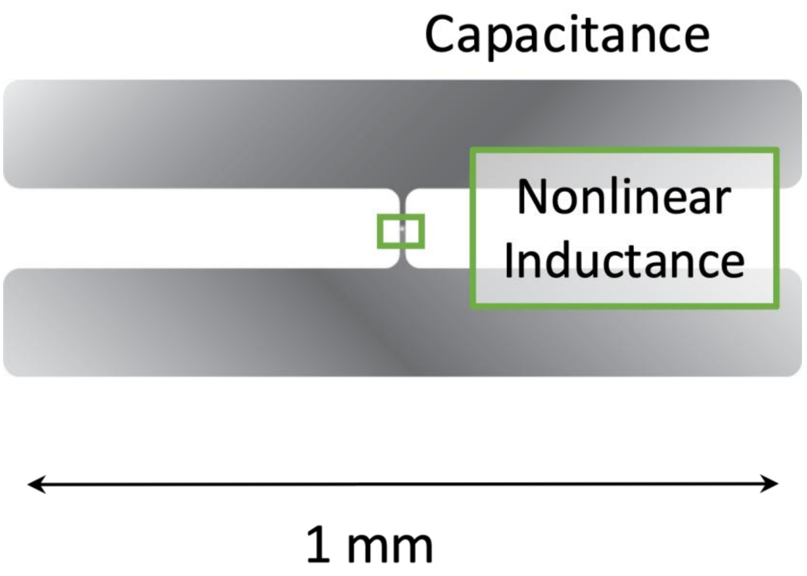
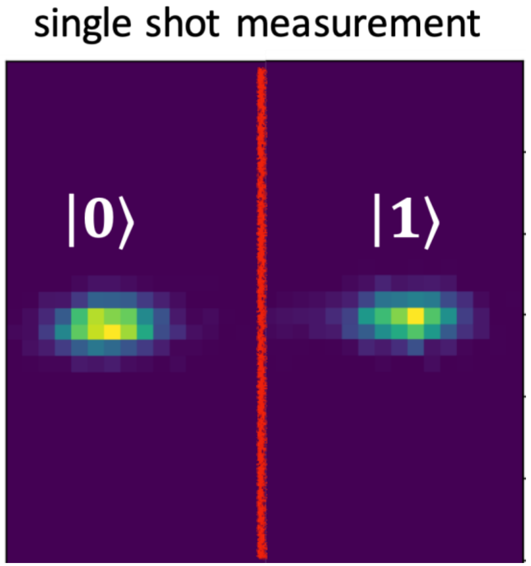
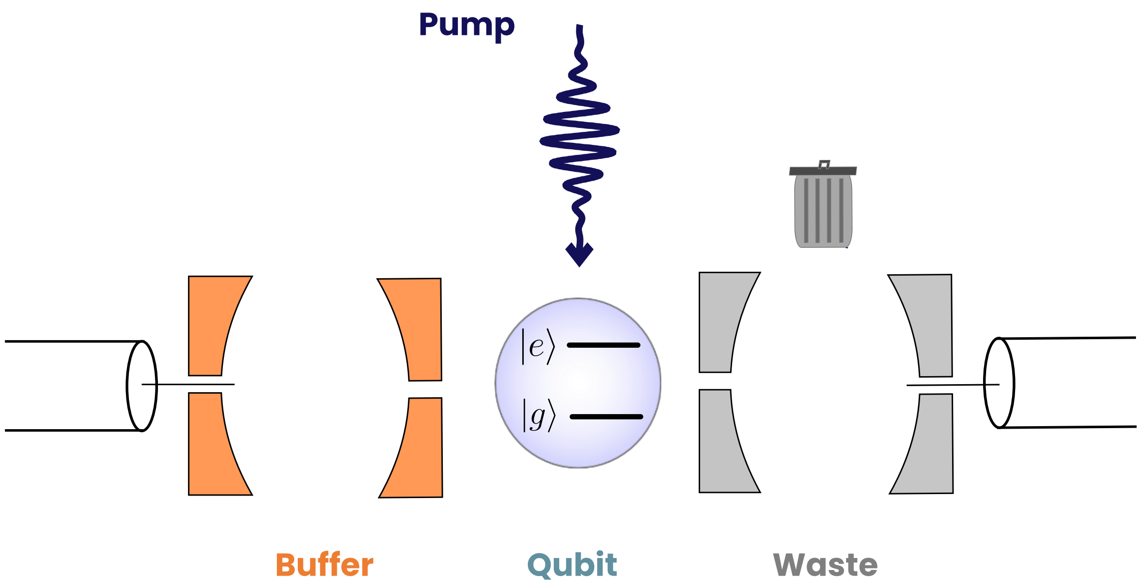
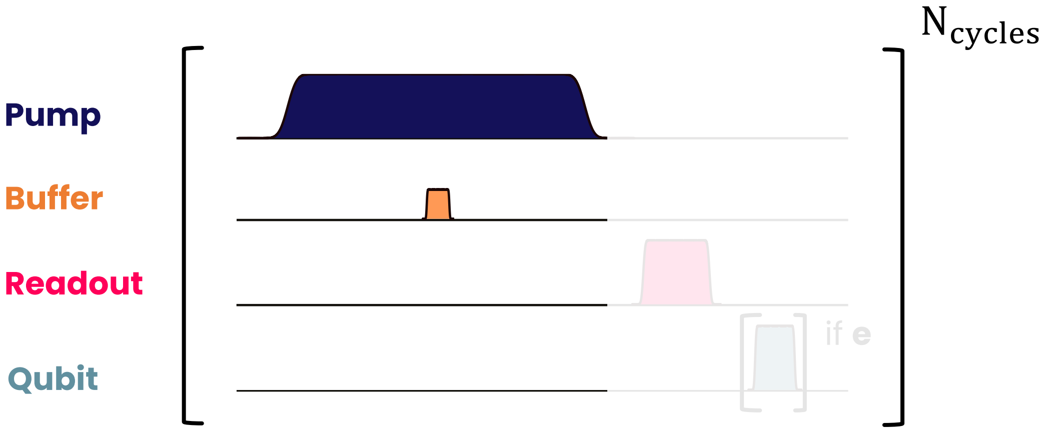




Single MW photon detector

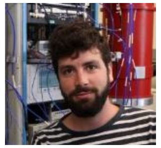


$$g_4 \xi \hat{b} \hat{\sigma}^\dagger \hat{w}^\dagger + g_4^* \xi \hat{b}^\dagger \hat{\sigma} \hat{w}$$



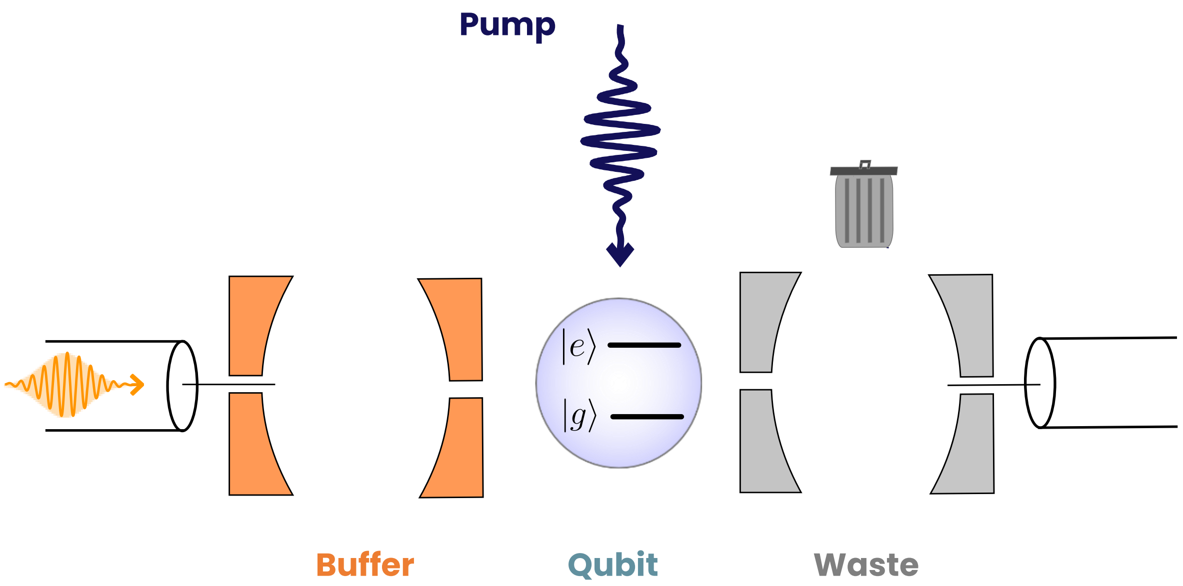
R. Lescanne & al., **PRX (2020)**

$5 \times 10^{-21}\ W/\sqrt{Hz}$ *

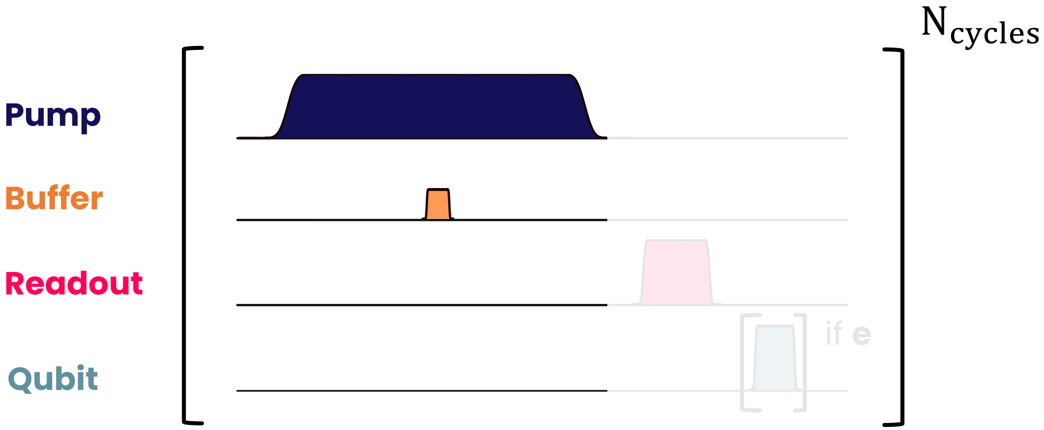


* NEP @ 7 GHz

Single MW photon detector

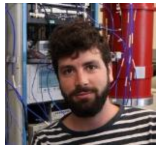


$$\mathbf{g_4}\xi\hat{b}\hat{\sigma}^\dagger\hat{w}^\dagger + \mathbf{g_4^*}\xi\hat{b}^\dagger\hat{\sigma}\hat{w}$$



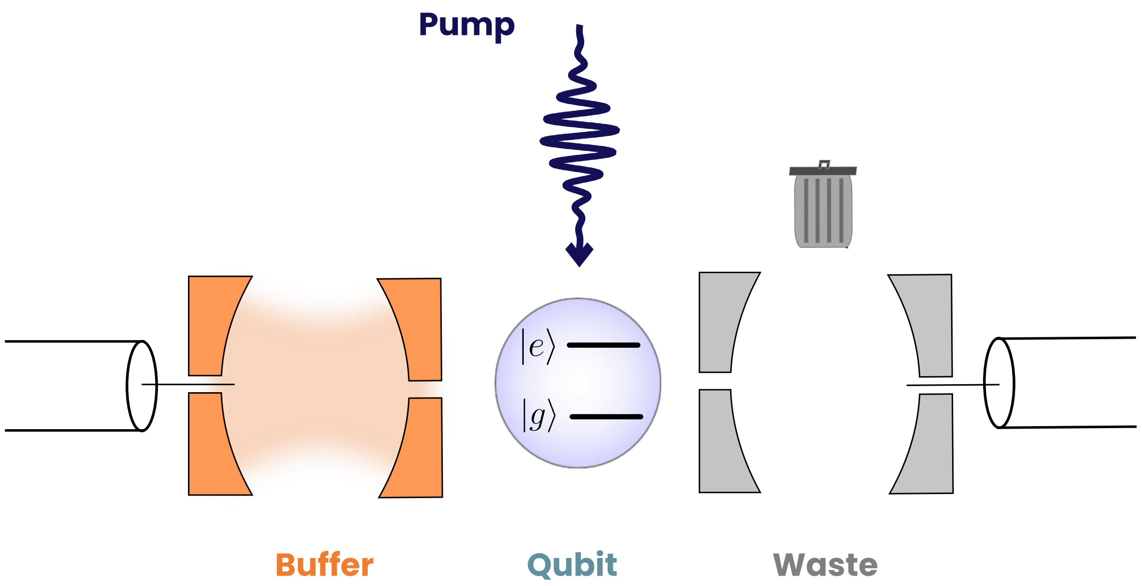
R. Lescanne & al., **PRX (2020)**

$$5 \times 10^{-21}\ W/\sqrt{Hz}\ ^*$$

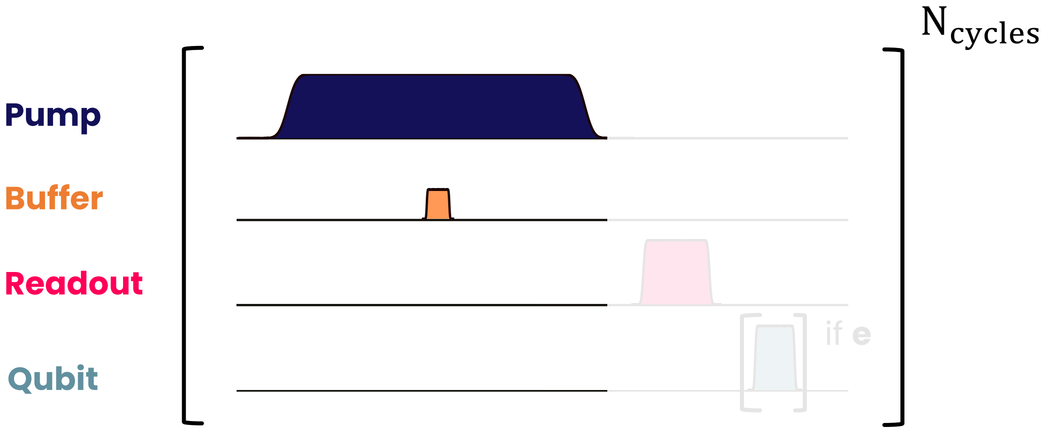


* NEP @ 7 GHz

Single MW photon detector

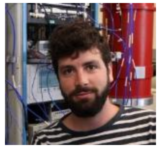


$$g_4 \xi \hat{b} \hat{\sigma}^\dagger \hat{w}^\dagger + g_4^* \xi \hat{b}^\dagger \hat{\sigma} \hat{w}$$



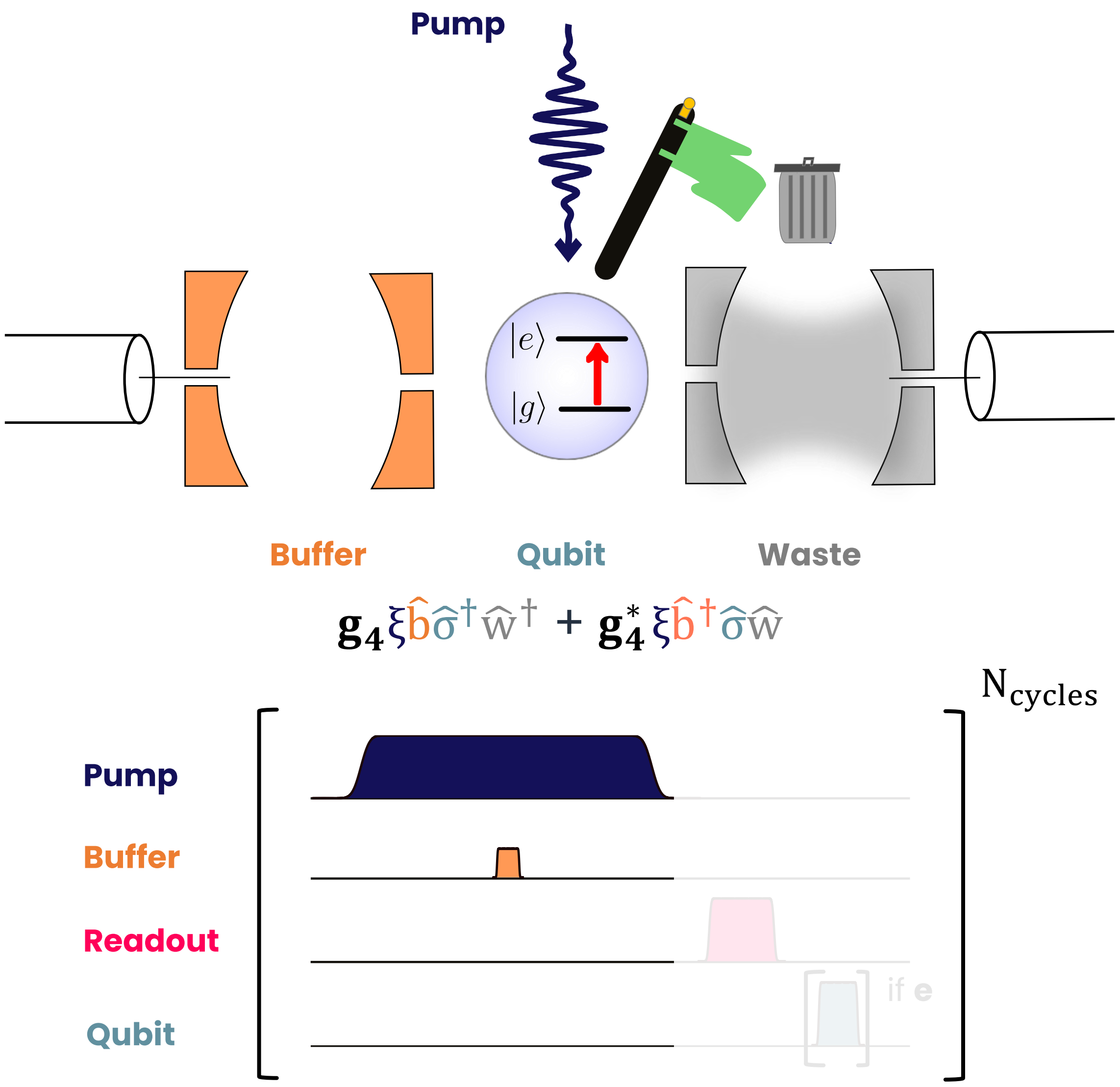
R. Lescanne & al., **PRX (2020)**

$5 \times 10^{-21}\ W/\sqrt{Hz}$ *



* NEP @ 7 GHz

Single MW photon detector

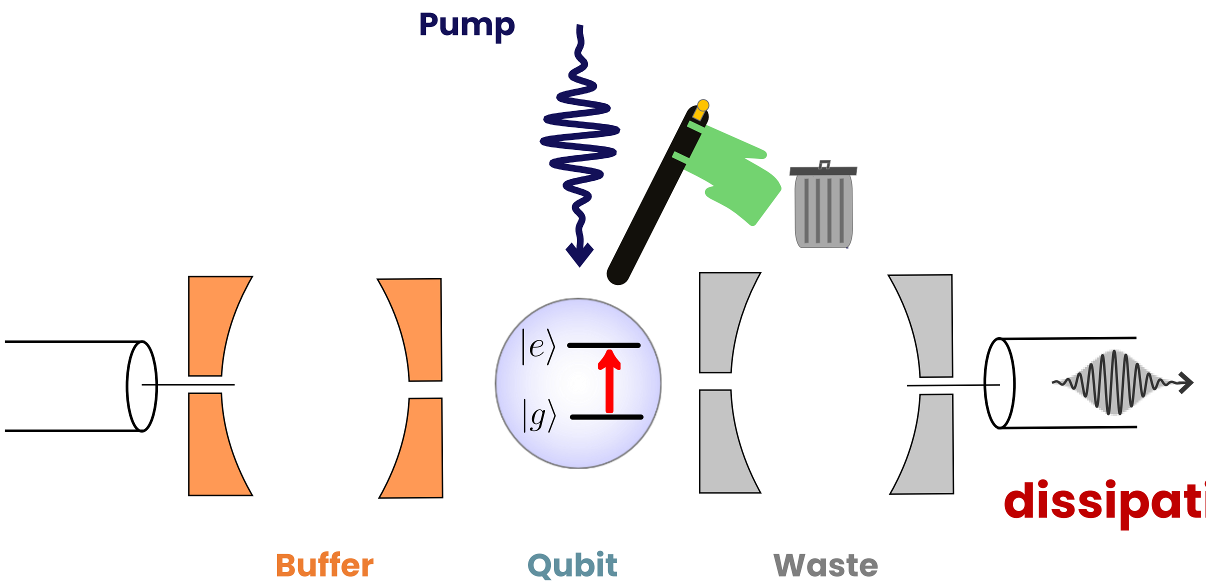


R. Lescanne & al., **PRX (2020)**

$5 \times 10^{-21}\ W/\sqrt{Hz}$ *

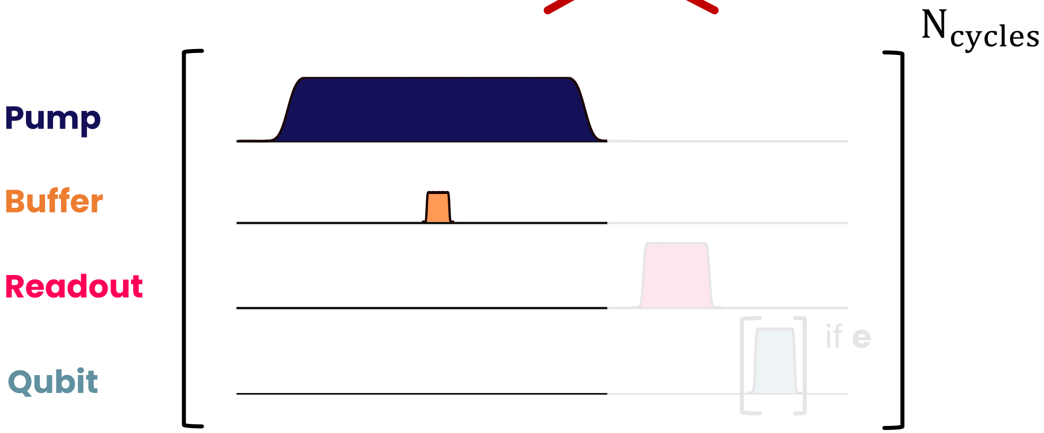
* NEP @ 7 GHz

Single MW photon detector



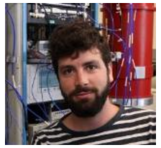
dissipation !

$$g_4\xi\hat{b}\hat{\sigma}^\dagger\hat{w}^\dagger + \cancel{g_4^*\xi^*\hat{b}^\dagger\hat{\sigma}\hat{w}}$$



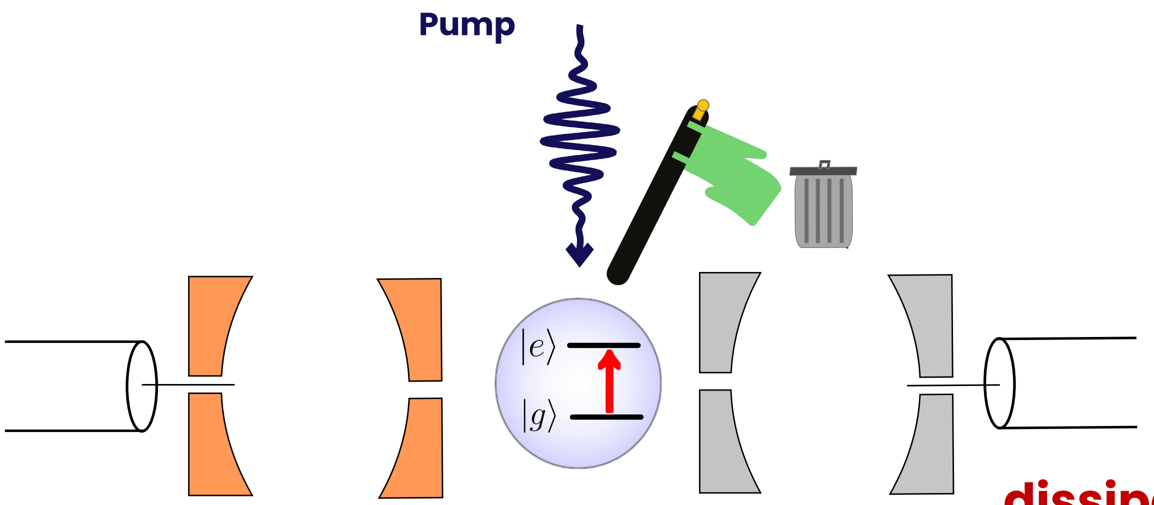
R. Lescanne & al., **PRX (2020)**

$$5 \times 10^{-21}\ W/\sqrt{Hz}\ ^*$$



* NEP @ 7 GHz

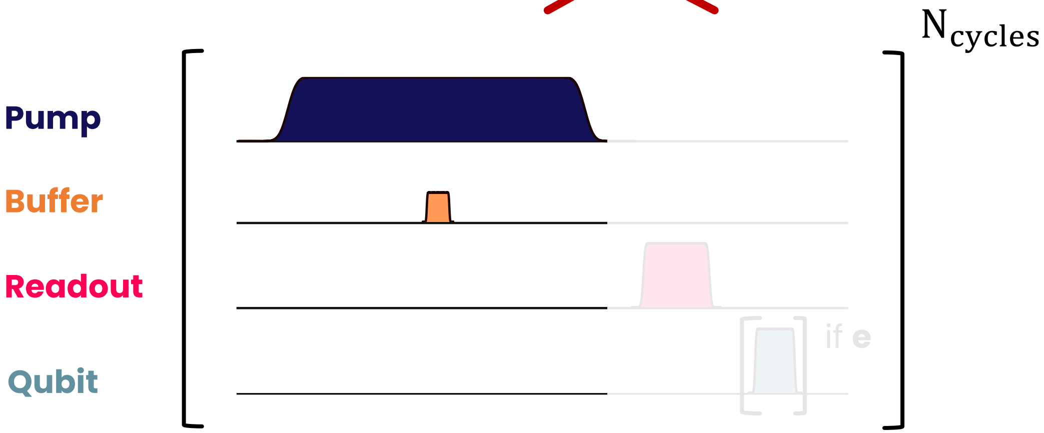
Single MW photon detector



dissipation !

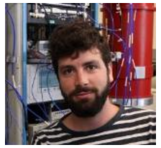
Buffer Qubit Waste

$$\mathbf{g}_4 \xi \hat{b}\hat{\sigma}^\dagger \hat{w}^\dagger + \mathbf{g}_4^* \cancel{\xi^* \hat{b}^\dagger \hat{\sigma} \hat{w}}$$



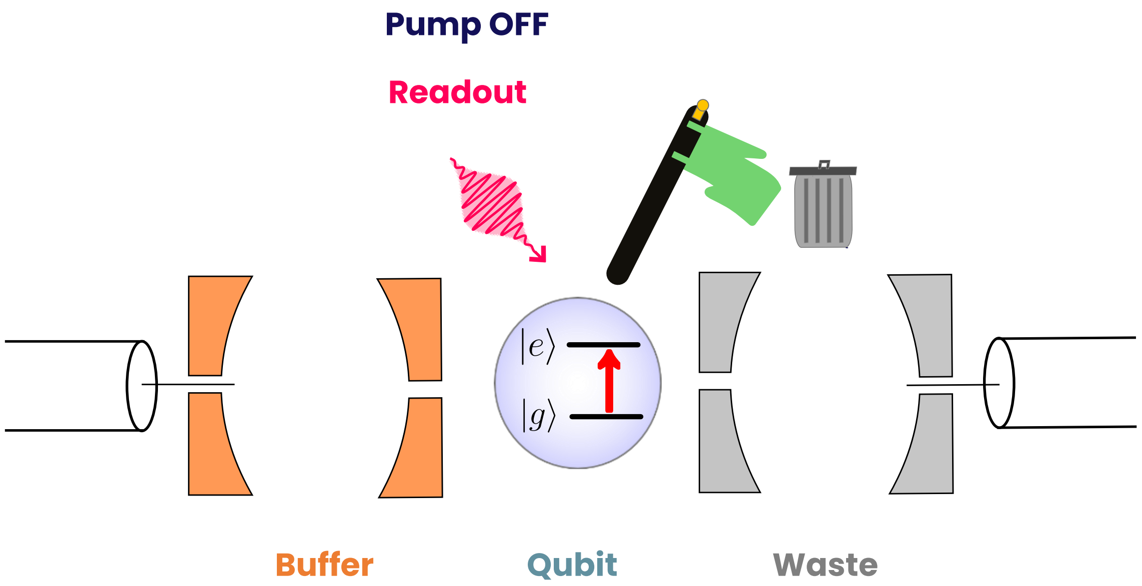
R. Lescanne & al., **PRX (2020)**

$5 \times 10^{-21}\, W/\sqrt{Hz}$ *



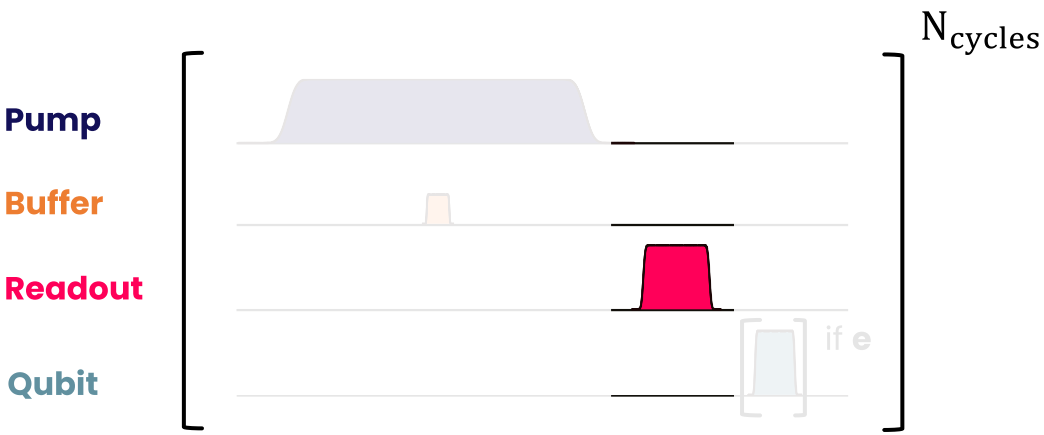
* NEP @ 7 GHz

Single MW photon detector



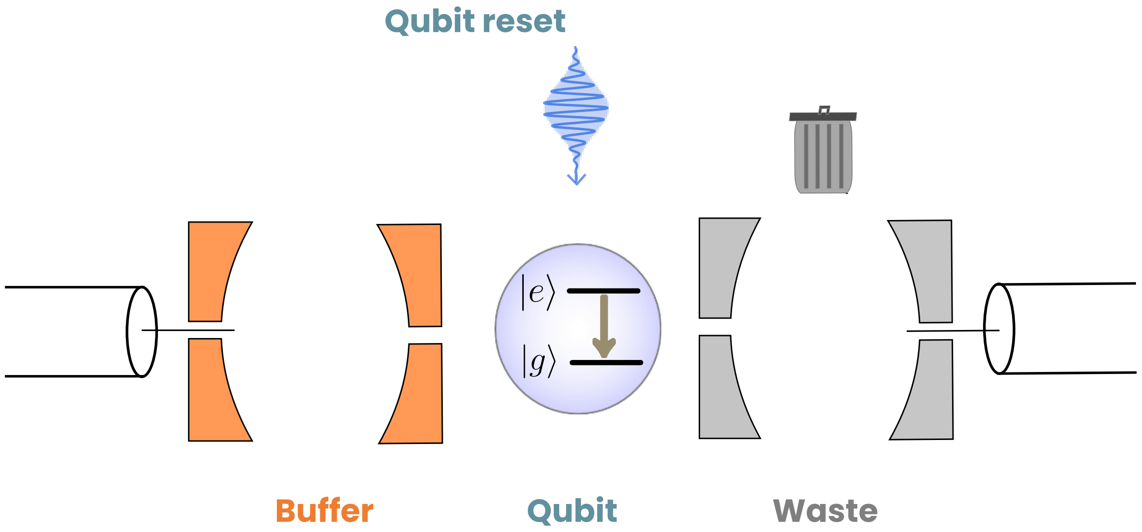
R. Lescanne & al., **PRX (2020)**

$5 \times 10^{-21}\ W/\sqrt{Hz}$ *



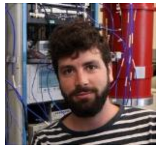
* NEP @ 7 GHz

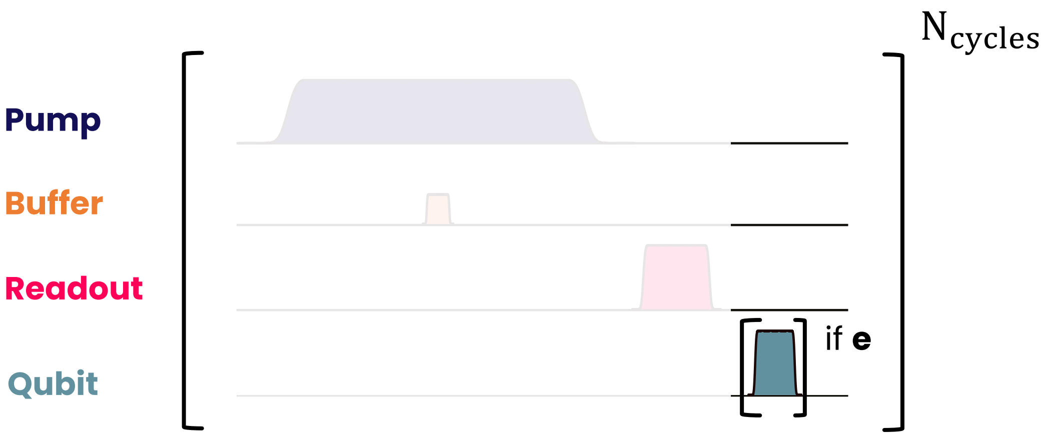
Single MW photon detector



R. Lescanne & al., **PRX (2020)**

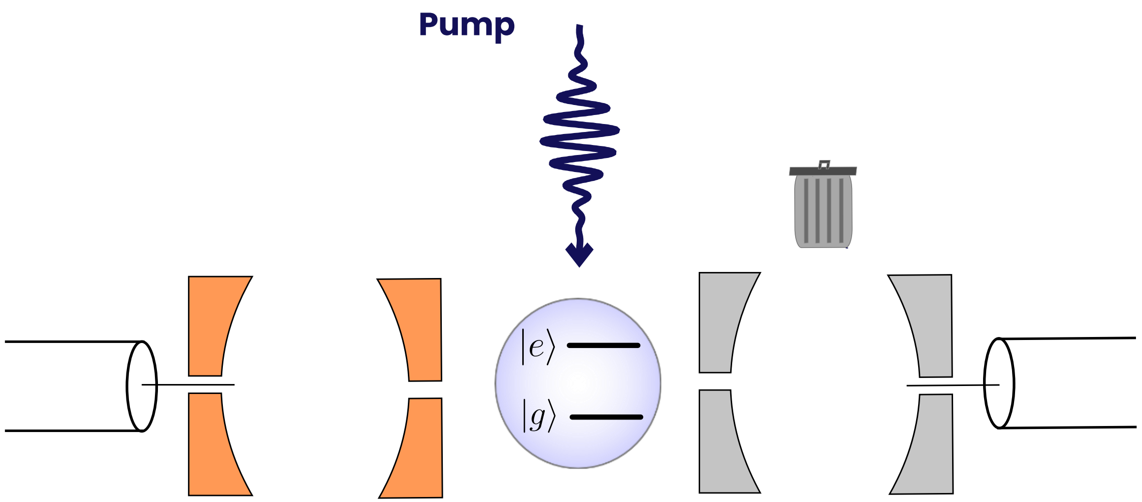
$$5 \times 10^{-21}\ W/\sqrt{Hz}\ ^{*}$$





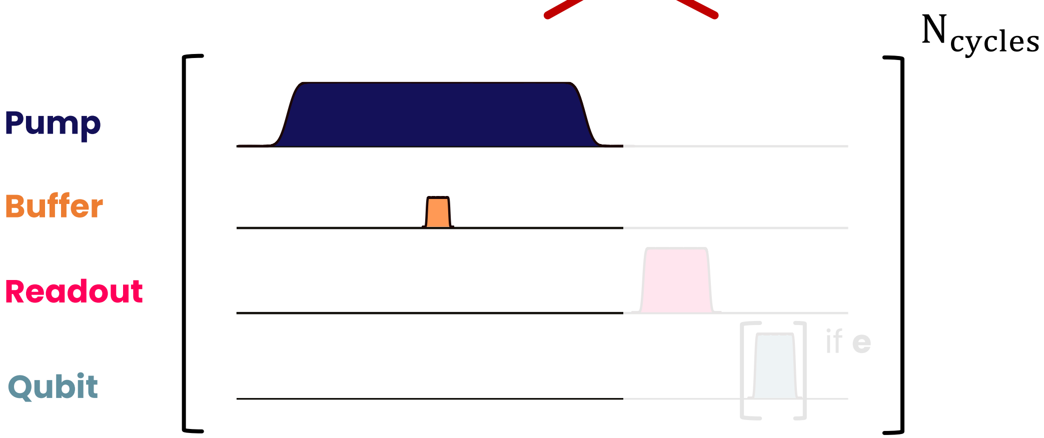
* NEP @ 7 GHz

Single MW photon detector



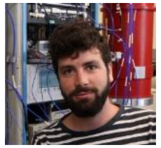
Buffer Qubit Waste

$$g_4 \xi \hat{b}\hat{\sigma}^\dagger \hat{w}^\dagger + \cancel{g_4^* \xi^* \hat{b}^\dagger \hat{\sigma} \hat{w}}$$



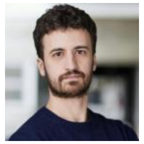
R. Lescanne & al., **PRX (2020)**

$5 \times 10^{-21}\ W/\sqrt{Hz}$ *

E. Albertinale & al., **Nature (2021)**

$2 \times 10^{-21}\ W/\sqrt{Hz}$ *

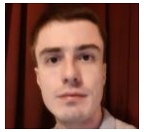


L. Balembois & al., **PR Applied (2023)**

$9 \times 10^{-23}\ W/\sqrt{Hz}$ *

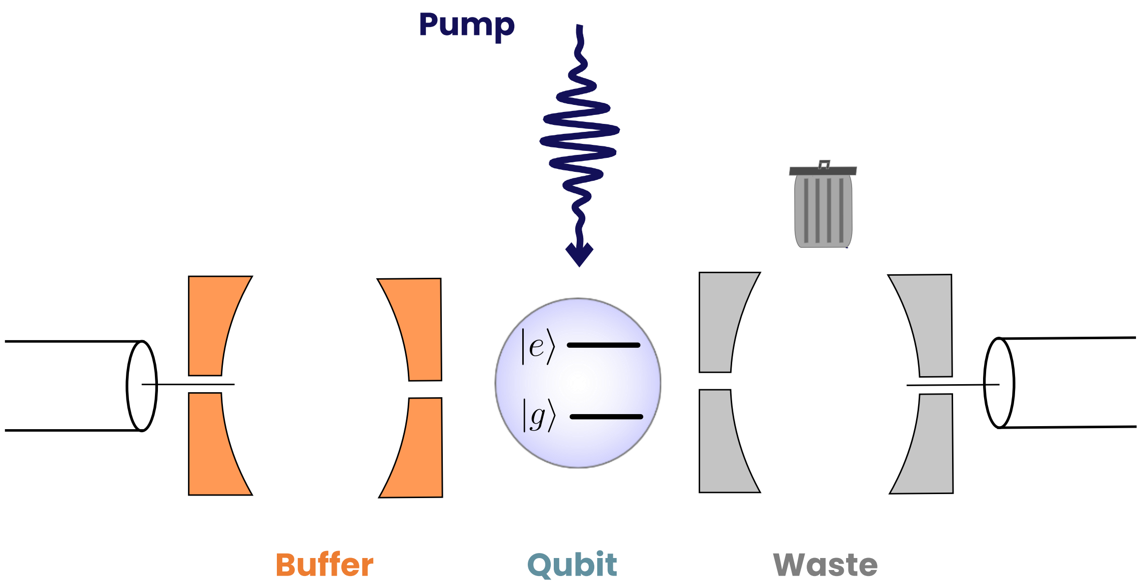
L. Pallegoix & al., **under review PR Applied (2025)**

$3 \times 10^{-23}\ W/\sqrt{Hz}$ *

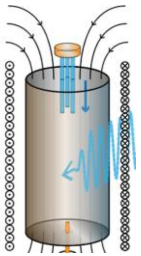


* NEP @ 7 GHz

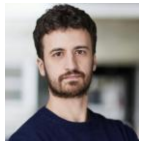
Single MW photon detector



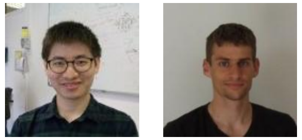
Range of applications:



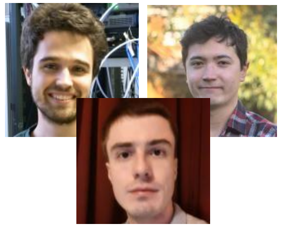
- Axion search
  On going collaboration with QUAX consortium (INFN Padova)(in preparation)
  C. Braggio & al., **PRX (2025)**



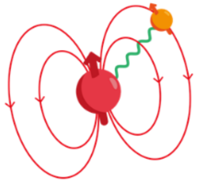
- Small ensemble of electronic spins
  E. Albertinale al., **Nature (2021)**



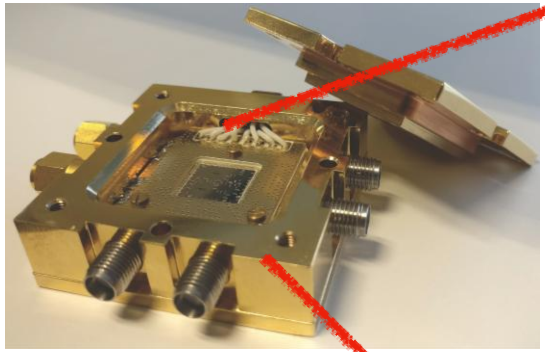
- Single electronic spin
  Z. Wang, L. Balembois & al., **Nature (2023)**



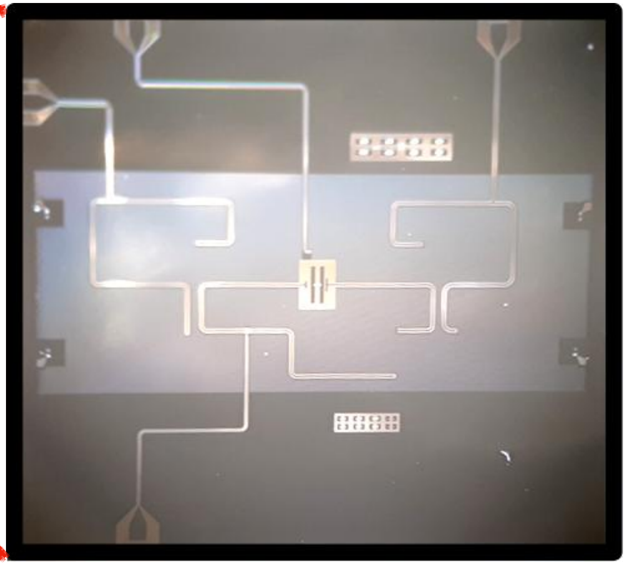
- Single nuclear spin
  O'Sullivan & al, **Nature Physics (2025)**
  Travesedo & al, **Science Advanced (2025)**

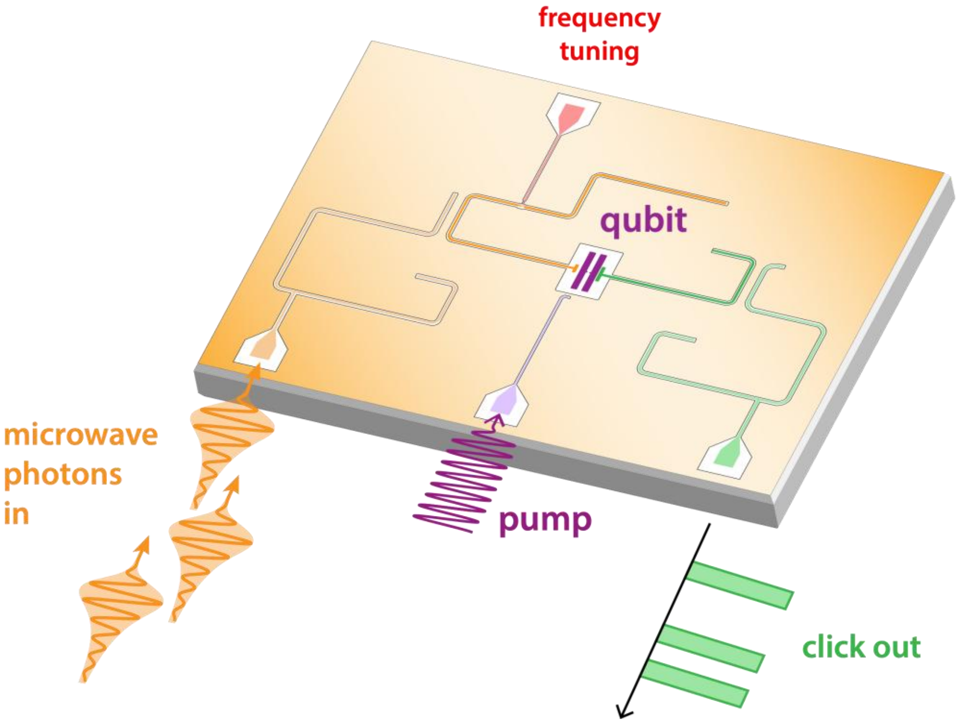


Design & Packaging



Sample holder JAWS
by Marius Villier (ENS Paris)





Key ingredients

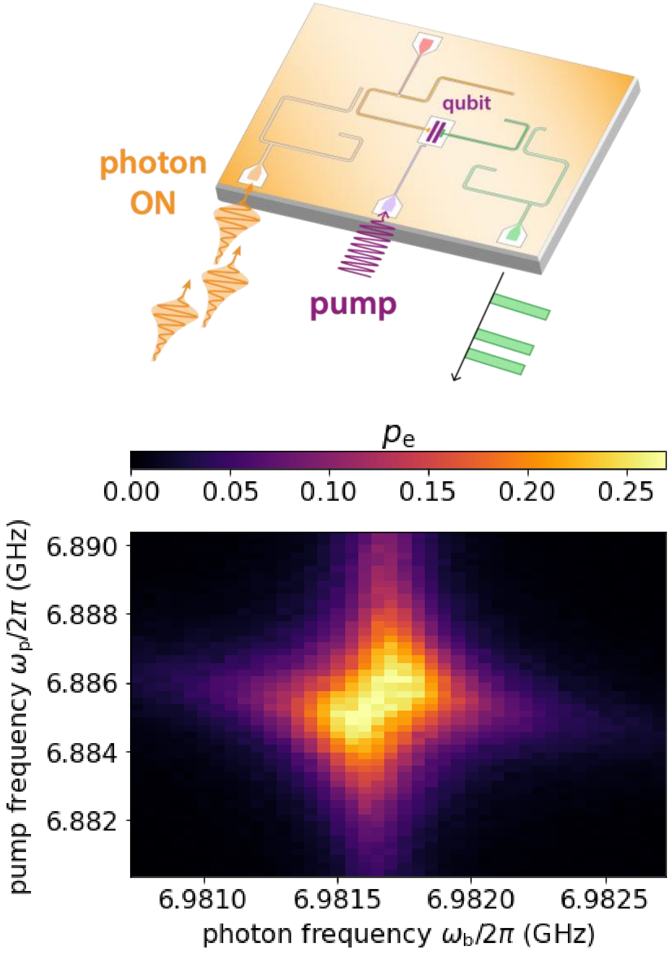
- Tantalum sputtered on sapphire
- **SQUID** for **frequency tunability**
- Purcell filters to protect the qubit from external environment

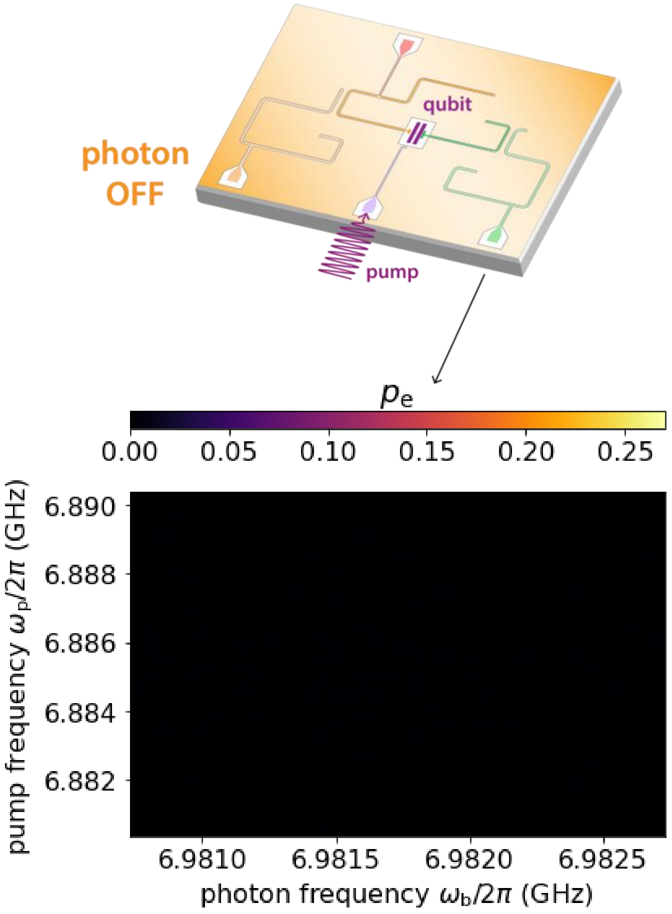
4WM as a detection mechanism

Average detection time: 10 μs
Average cycle time: 12.5 μs
Average cycle rate: 80 000 /s

$$\omega_p + \omega_b = \omega_q + \omega_w$$

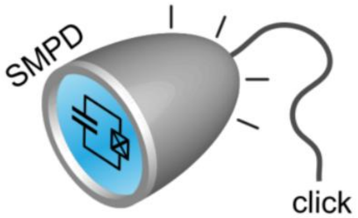
$$g_4 \xi \hat{b} \hat{\sigma}^\dagger \hat{w}^\dagger$$





$$\cancel{g_4 \xi \hat{b} \hat{\sigma}^\dagger} \hat{w}^\dagger$$

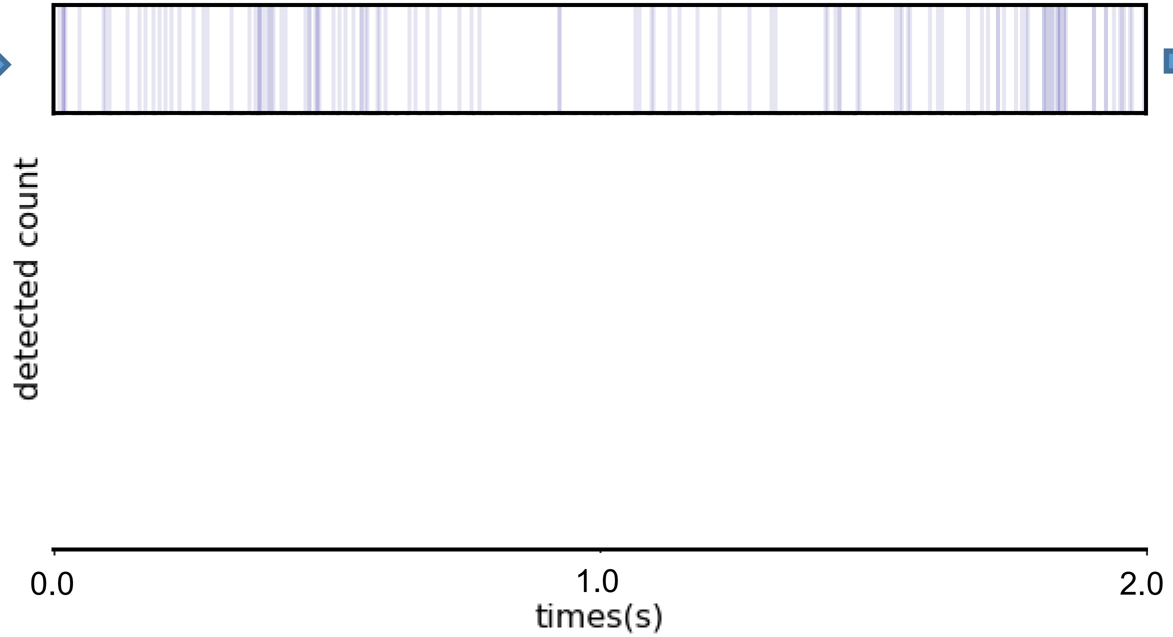
Efficiency & Dark count rate calibration



Dark-count rate :

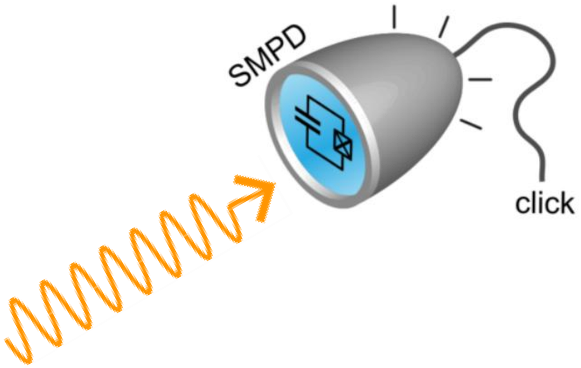
$$\alpha = 40 \text{ c/s}$$

0 photon/s



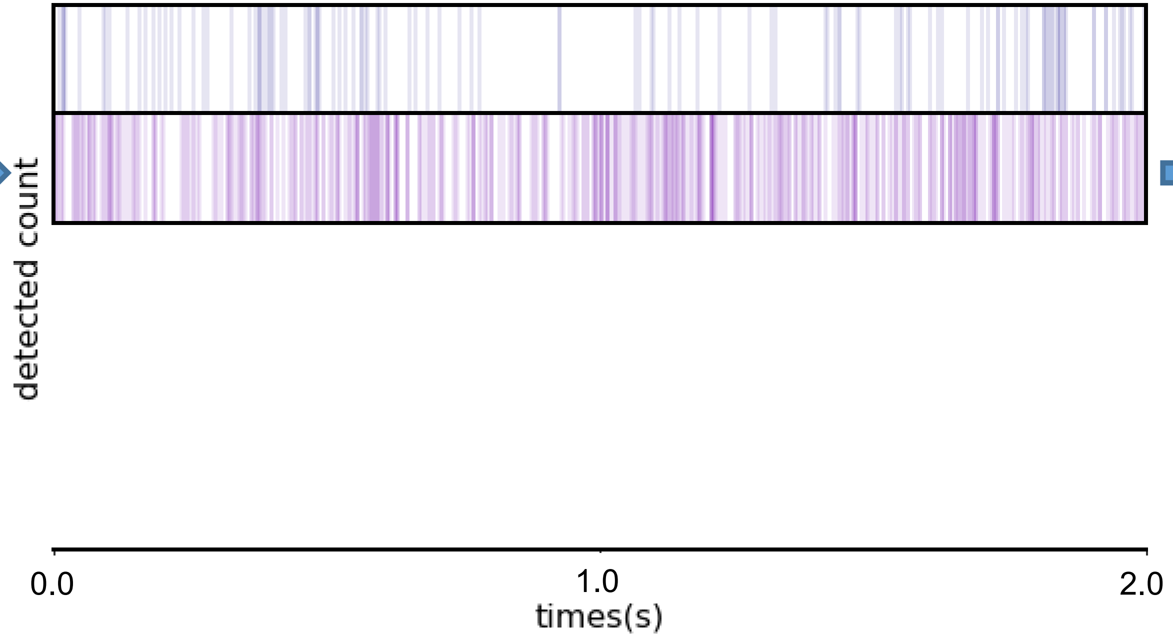
43 clicks/s

Efficiency & Dark count rate calibration



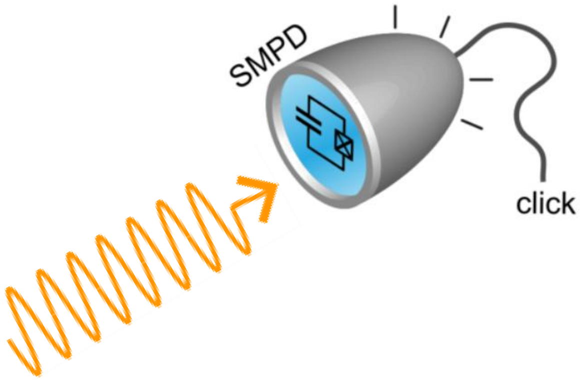
Dark-count rate : $\alpha = 40 \text{ c/s}$

650 photon/s



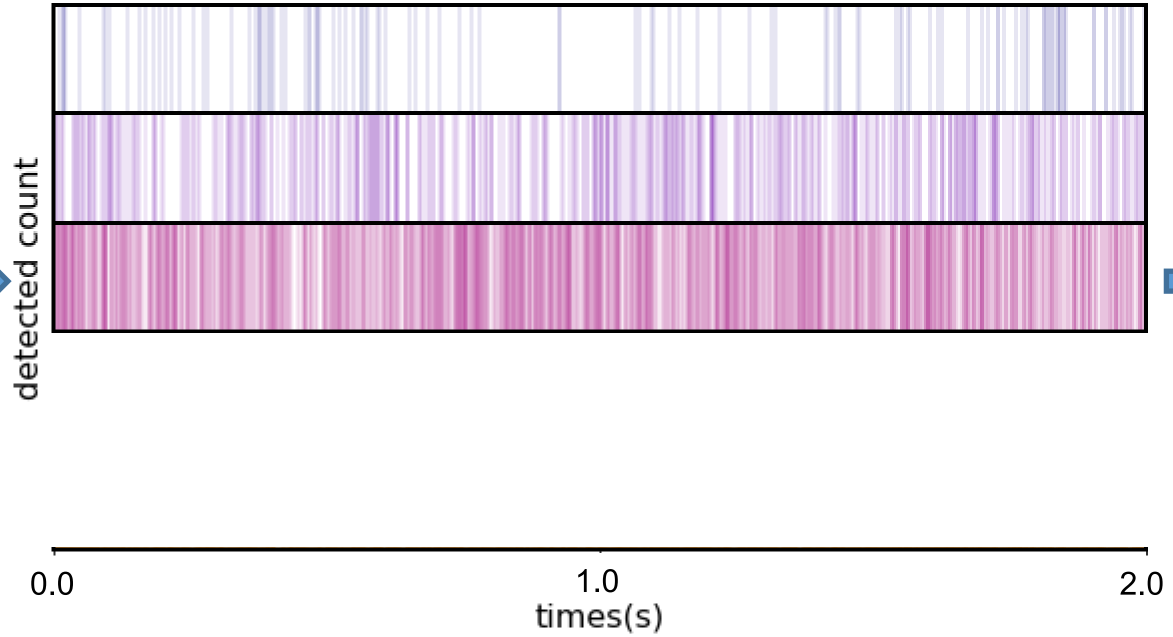
487 clicks/s

Efficiency & Dark count rate calibration



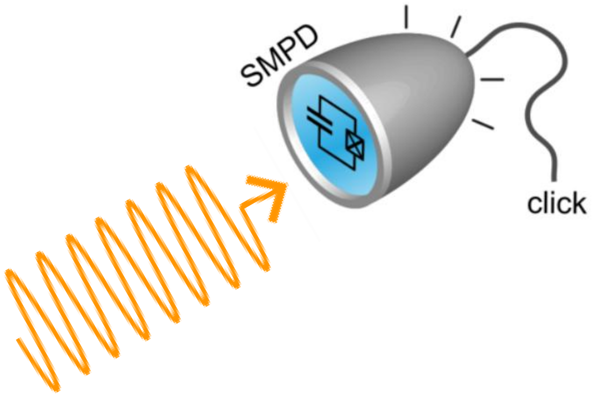
Dark-count rate : $\alpha = 40 \text{ c/s}$

2000 photon/s



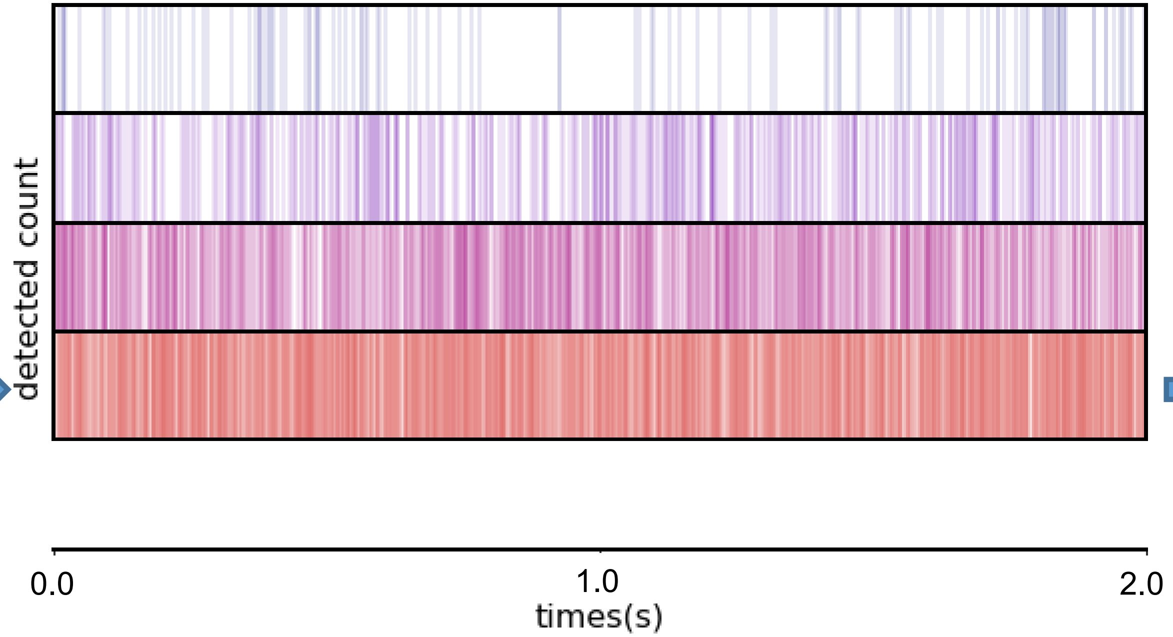
1419 clicks/s

Efficiency & Dark count rate calibration



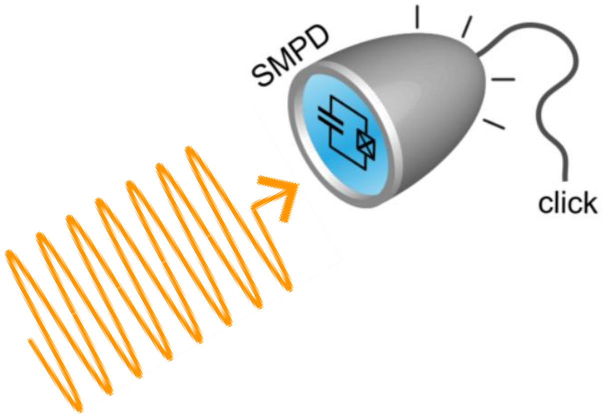
Dark-count rate : $\alpha = 40 \text{ c/s}$

3800 photon/s



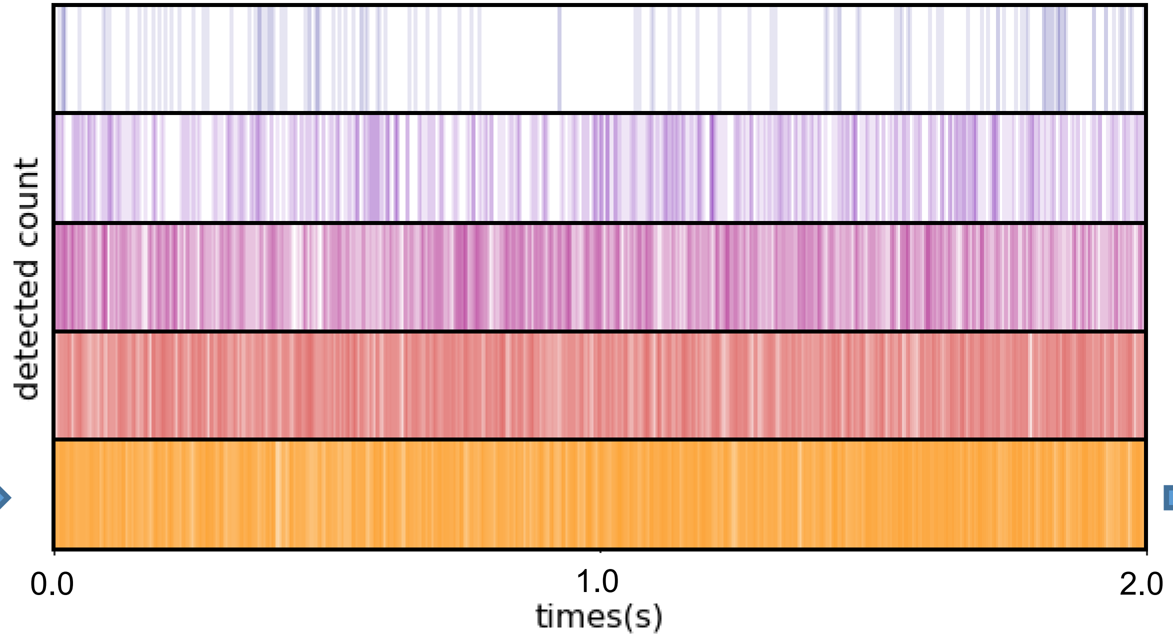
2895 clicks/s

Efficiency & Dark count rate calibration



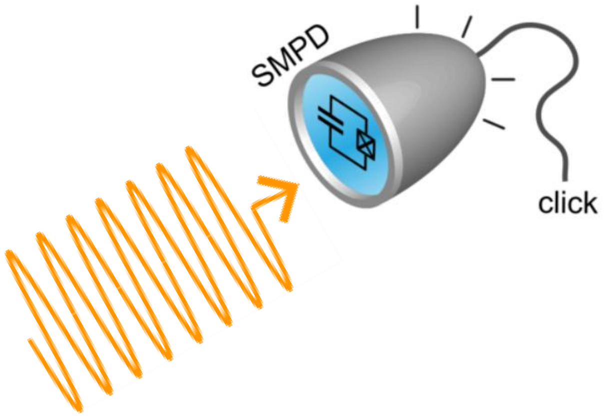
Dark-count rate : $\alpha = 40 \text{ c/s}$

7000 photon/s



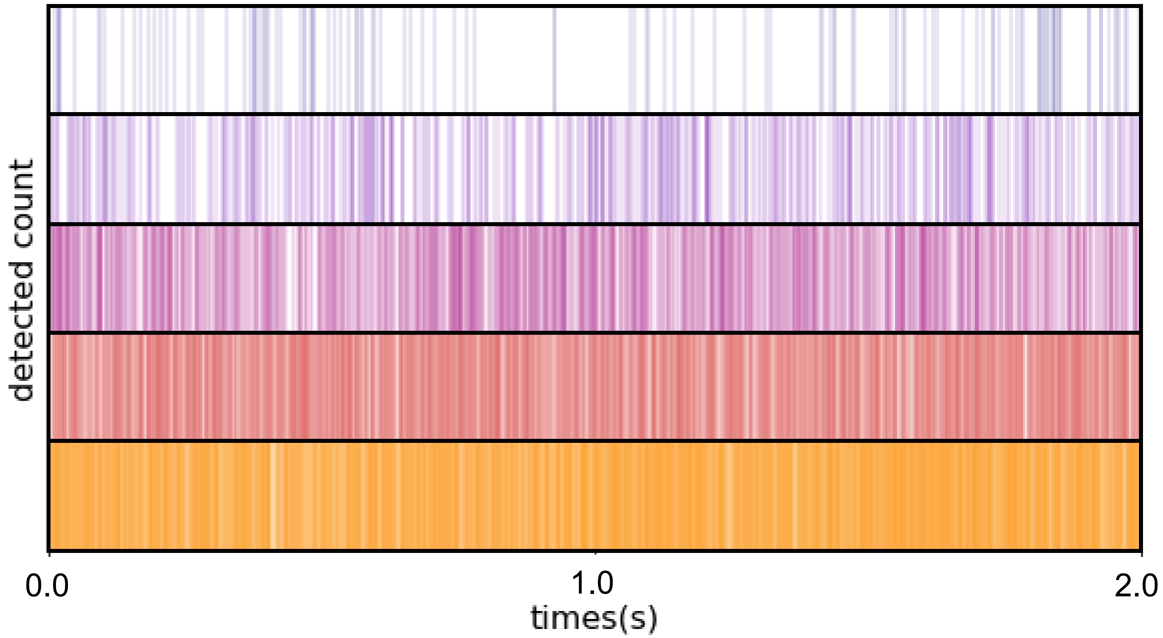
4872 clicks/s

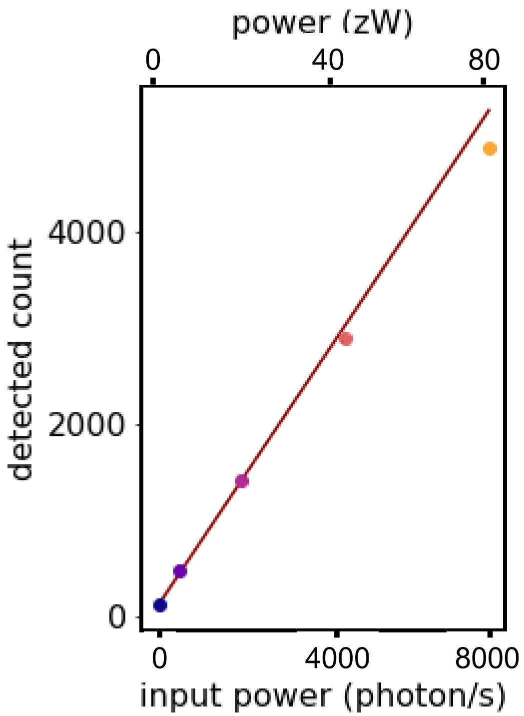
Efficiency & Dark count rate calibration



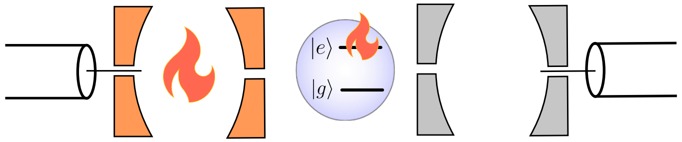
Dark-count rate : $\alpha = 40\ \mathrm{c/s}$

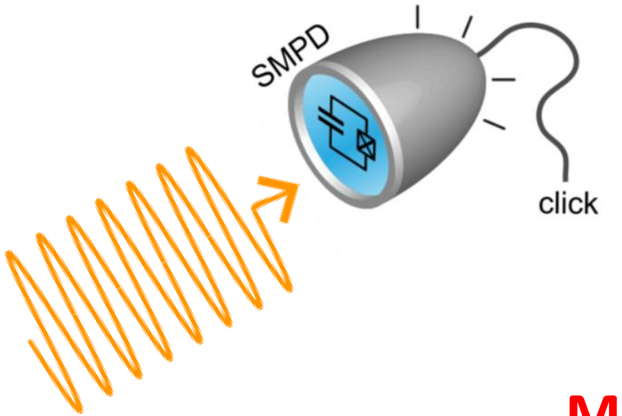
Efficiency : $\eta = 75\%$





Efficiency & Dark count rate calibration





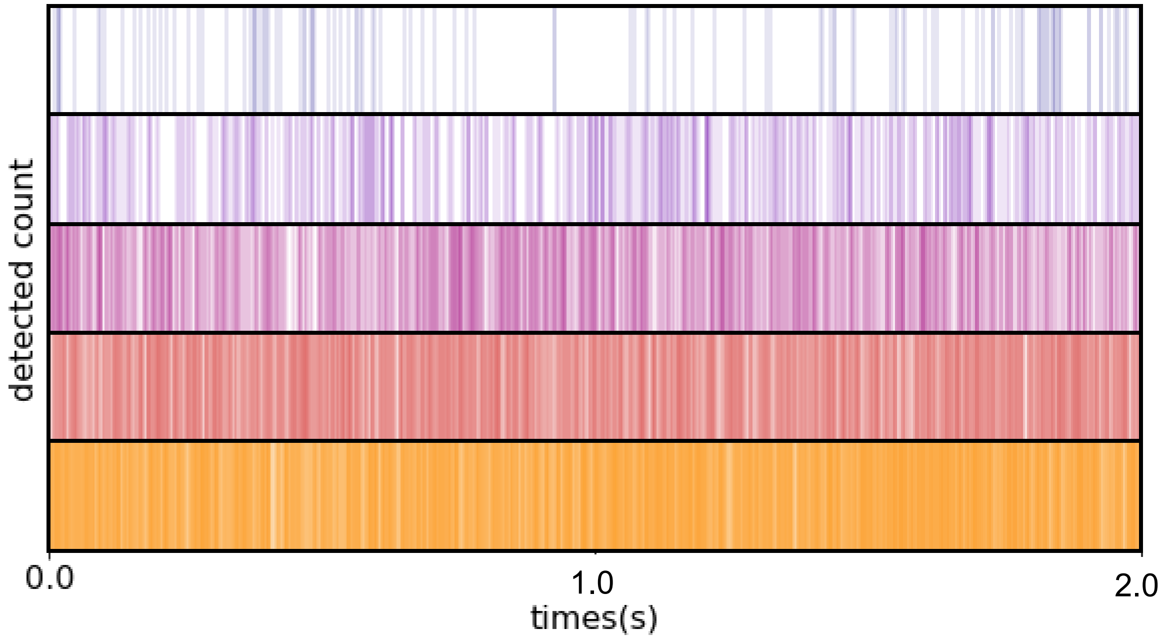
Dark-count rate : $\alpha = 40$ c/s

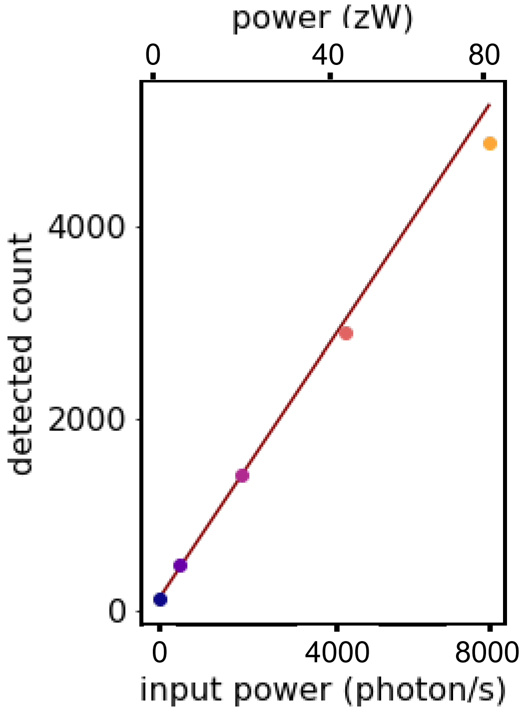
Efficiency : $\eta = 75\%$

Power sensitivity: $h\nu\sqrt{\alpha}/\eta = 3 \times 10^{-23}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$

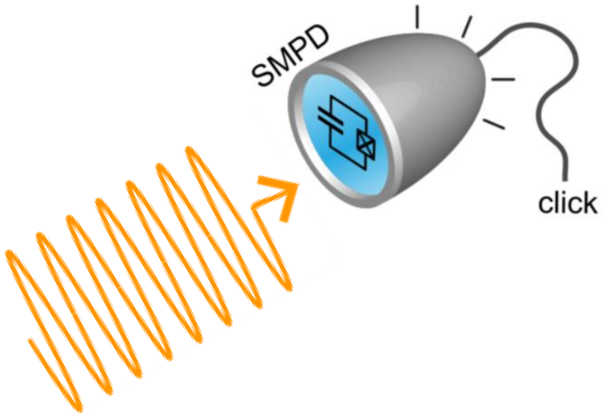
L. Pallegoix et al, PRApplied (2025)

Most sensitive power detector at mw freqs

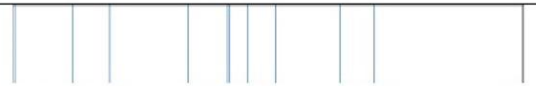
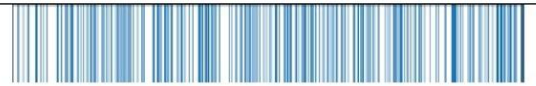


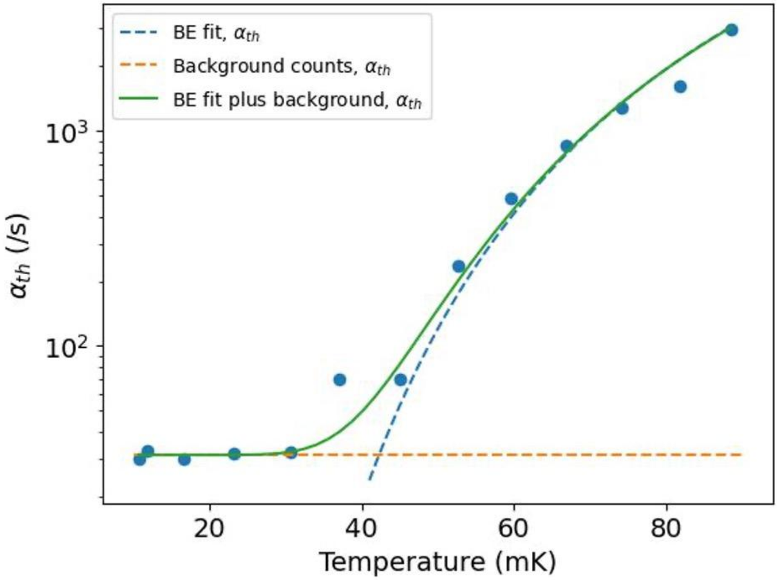


Dark count rate vs Temperature



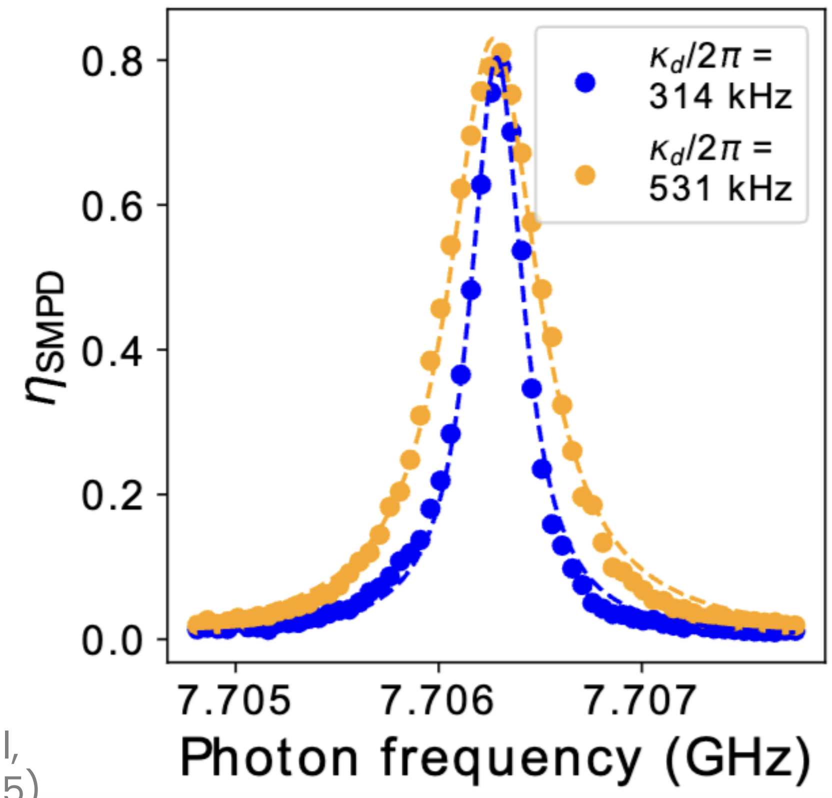
L. Pallegoix et al, PRApplied (2025)

Temperature	Pump state	$\kappa_d/2\pi$	One-second click sequence	Click rate
10 mK	Off	Not relevant		8/s
10 mK	Detuned	Not relevant		10/s
10 mK	Tuned	170 kHz		31/s
50 mK	Tuned	170 kHz		344/s
60 mK	Tuned	170 kHz		621/s
90 mK	Tuned	170 kHz		3614/s



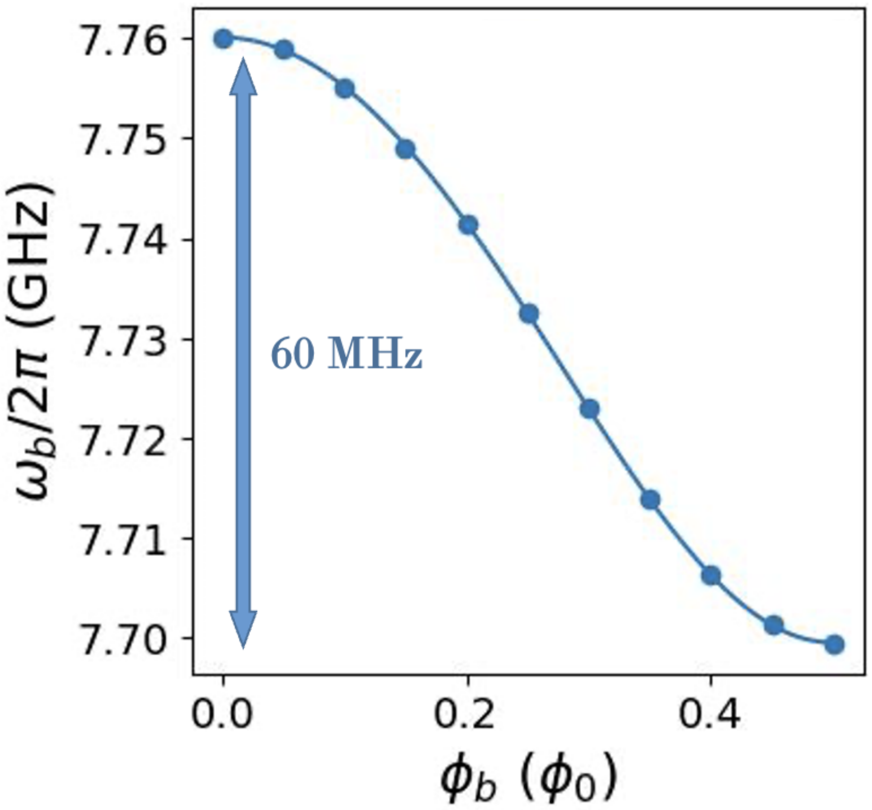
A frequency tunable, Narrow band, Spectrum analyzer

Narrow band…



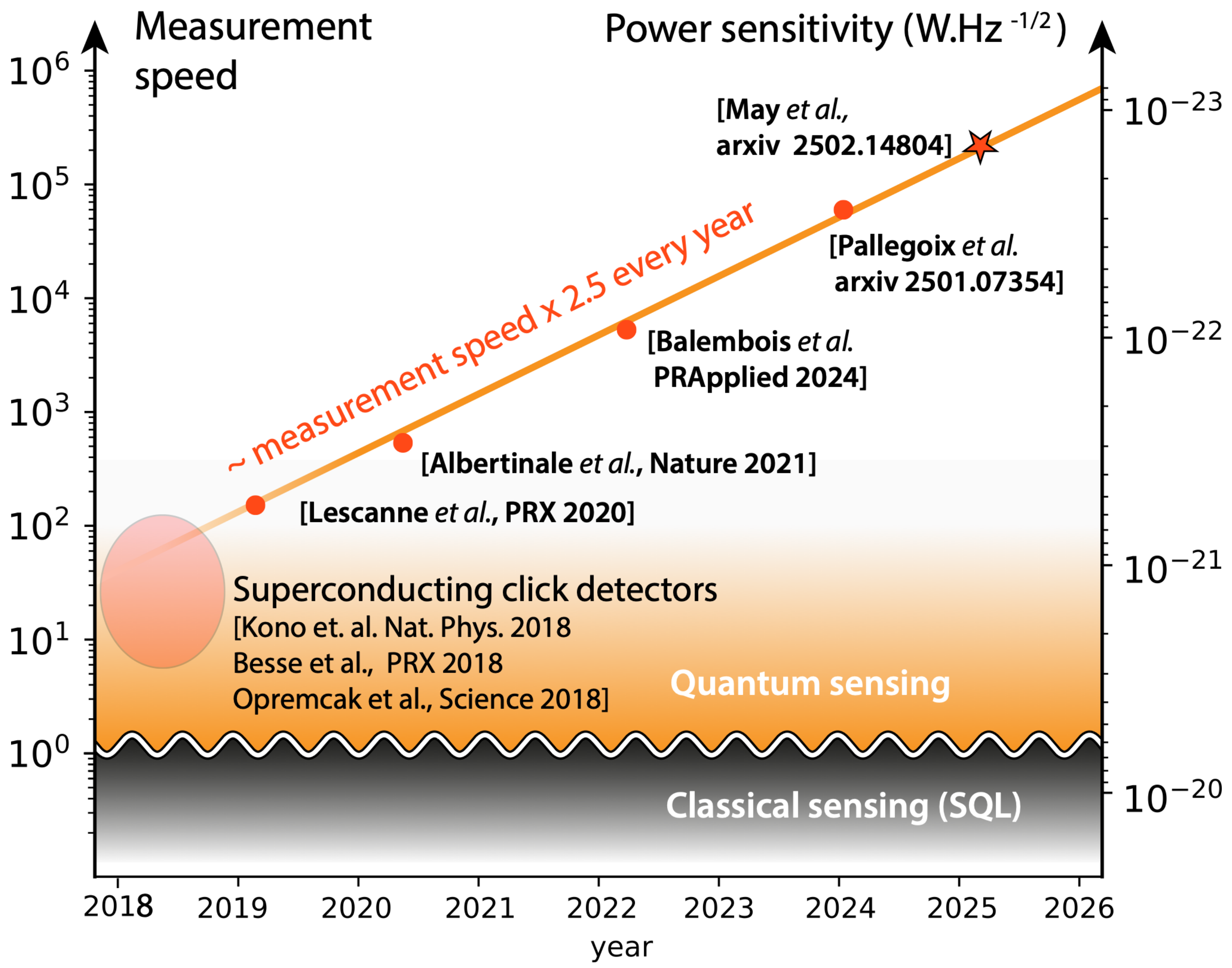
L. Pallegoix et al, PRApplied (2025)

… **but** Frequency tunable



Thermal dark counts scales with bandwidth $\alpha_{th} \propto n_{th}\Delta f$

Sensitivity improvements, years after years

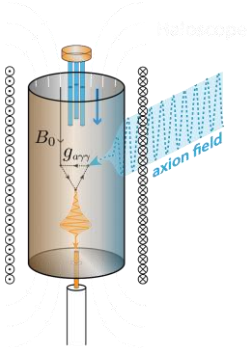


Outline

I. Photon Detection vs Field Detection

II. Superconducting Qubit-based Single Microwave Photon Detector (SMPD)

III. Counting Photon for Axion Dark Matter Search



IV. Enhanced sensitivity with Multiqubit Photon Counter

Axion search with Haloscope + Photodetection

QCD Axions could solve two problem at a time:

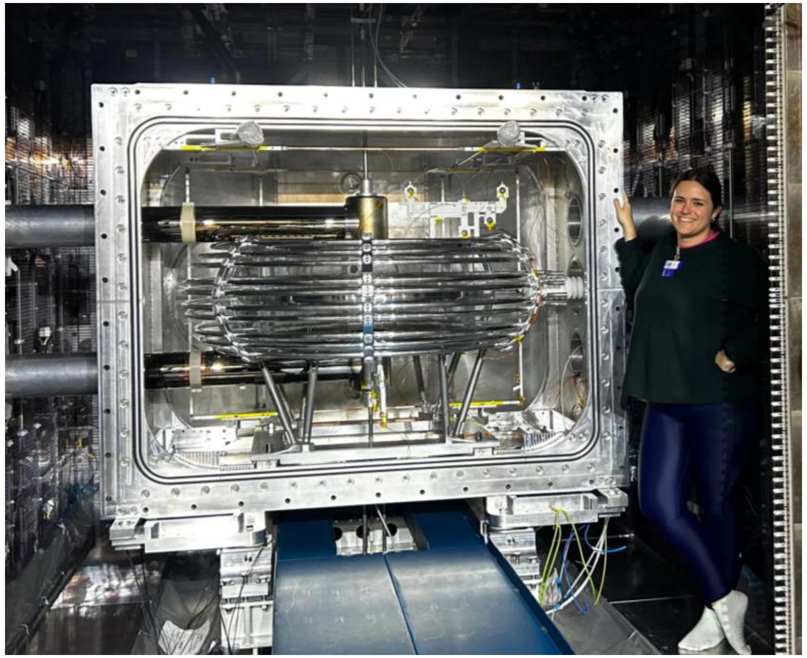
Annual Review of Nuclear and Particle Science Vol. 65:485-514 (2015)

- 85% of the mass is missing in the visible universe
- Absence of electric dipole moment for the Neutron

QCD: Quantum Chromodynamics
EDM: Electric Dipole Moment
CP: Charge/Parity symmetries

CP violating term in QCD $\longrightarrow$ implies a non-zero EDM for neutrons

@ n2EDM



$$L_{eff} = L_{QCD} + \theta \frac{\alpha_S}{8\pi} \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

From lattice calculations: $d_n = -0.00152(71)\theta \; e.fm$

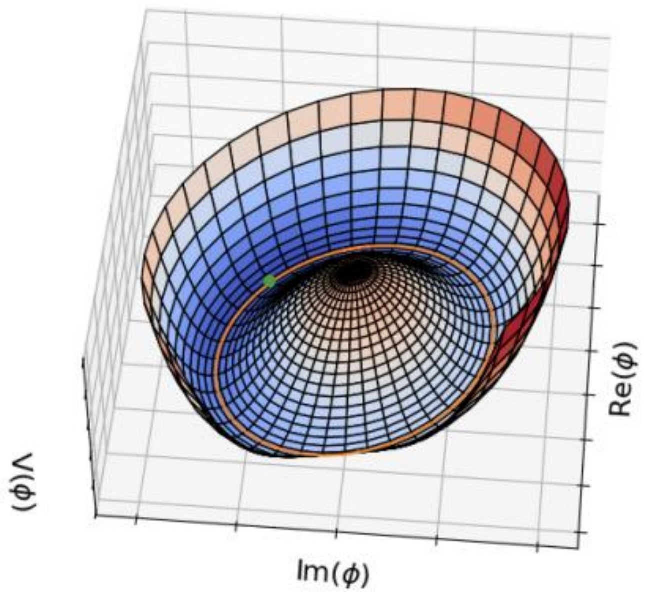
Experimental upper limit: $|d_n| \leq \; 2.10^{-13} \;\; e.fm$

$\Rightarrow \theta \leq 10^{-10}$

Peccei-Quinn theory to solve the strong CP problem

New pseudo-scalar field V with Higgs Mechanism

After QCD transition



$U(1)$ Symmetry breaking $|V| > 0$

$$V(x,t) = |V|e^{ia(x,t)}$$

$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \boxed{\frac{a}{f_{\mathrm{a}}} g^2 G\tilde{G}}$$

Axion search with Haloscope + Photodetection

QCD Axions could solve two problem at a time:

Annual Review of Nuclear and Particle Science Vol. 65:485-514 (2015)

- Absence of electric dipole moment for the Neutron

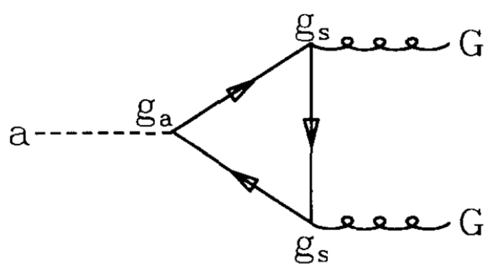
The theory is quite predictive
Essentially all of the physics of the axion depends on a large unknown energy scale f_a, at which Peccei-Quinn symmetry is broken.

The axion has a two photons coupling, and g_γ is model dependant.

$$m_a \approx 6\,\mathrm{eV}\left(\frac{10^6\,\mathrm{GeV}}{f_a}\right)$$

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

axion-2photon coupling



- 85% of the mass is missing in the visible universe

The axion is a well motivated dark matter candidate
Axion density relative to the critical density of the universe

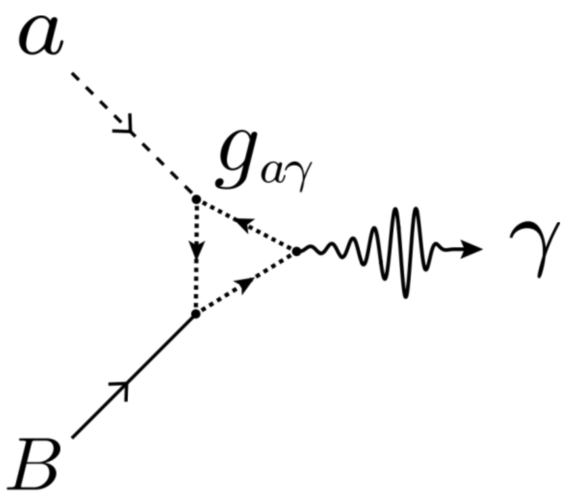
$$\Omega_a \approx \left(\frac{6\,\mu\mathrm{eV}}{m_a}\right)^{\frac{7}{6}} \approx \Omega_m = 0.23\ (m_a \approx 20\ \mu eV)$$

Entire dark matter density

Axion search with Haloscope + Photodetection

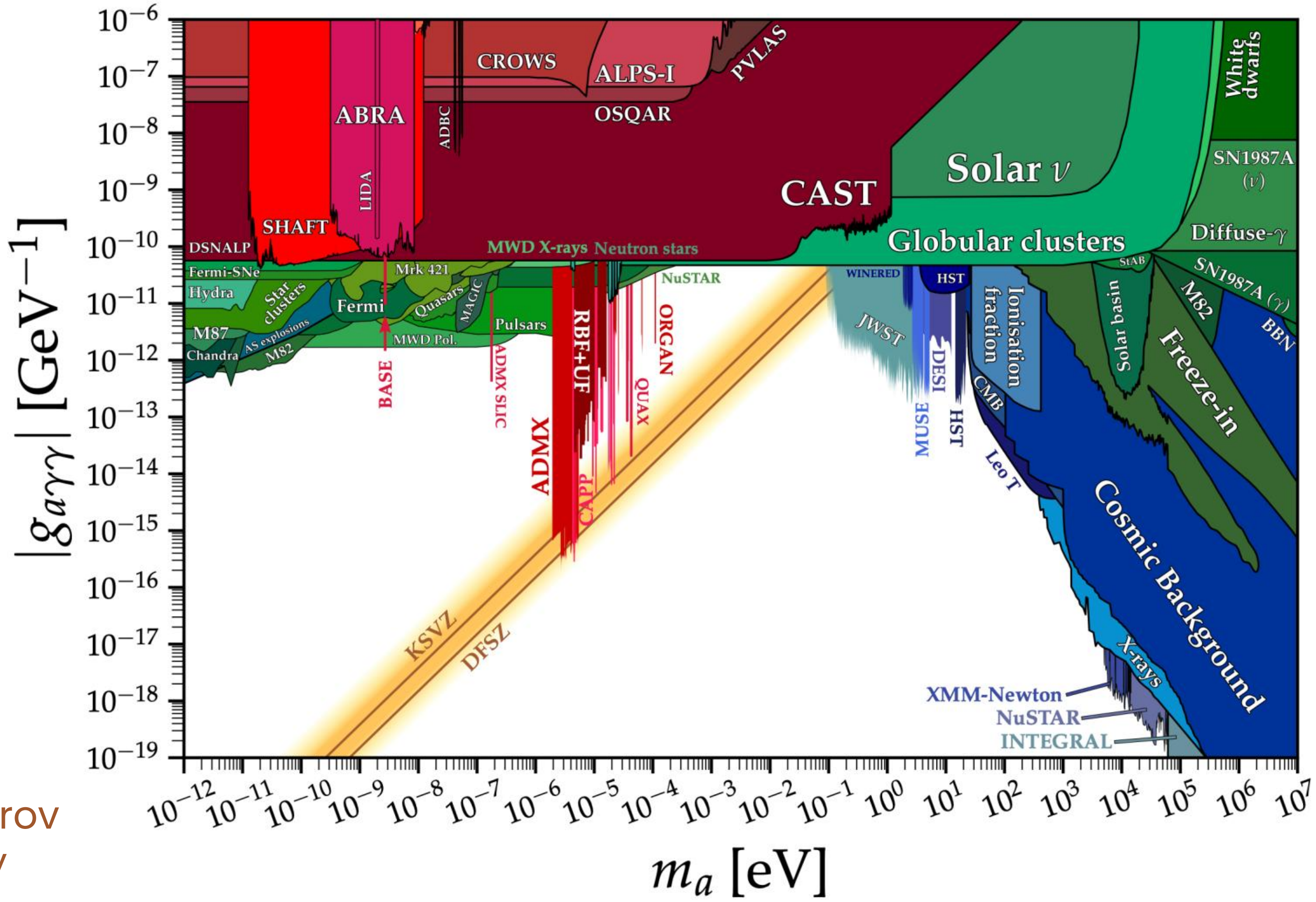
Primakoff effect

QCD axion coupling leads to an axion - photon decay channel under strong magnetic field



https://github.com/cajohare/AxionLimits

axion – photon coupling



g_γ models

KSVZ: Kim-Shifman-Vainshtein-Zakharov
DFVZ: DineFischler-Srednicki-Zhitnitsky

Axion search with Haloscope + Photodetection

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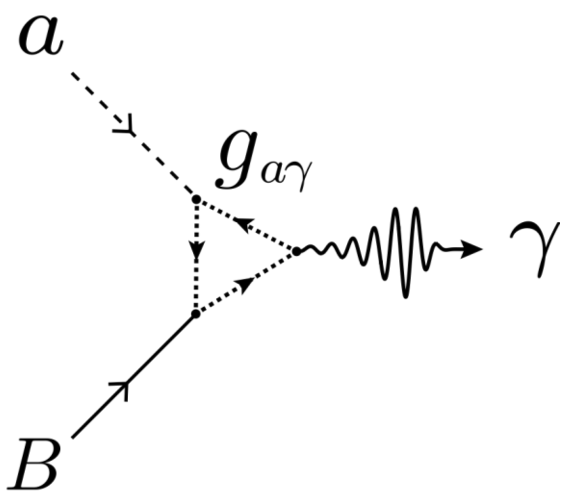
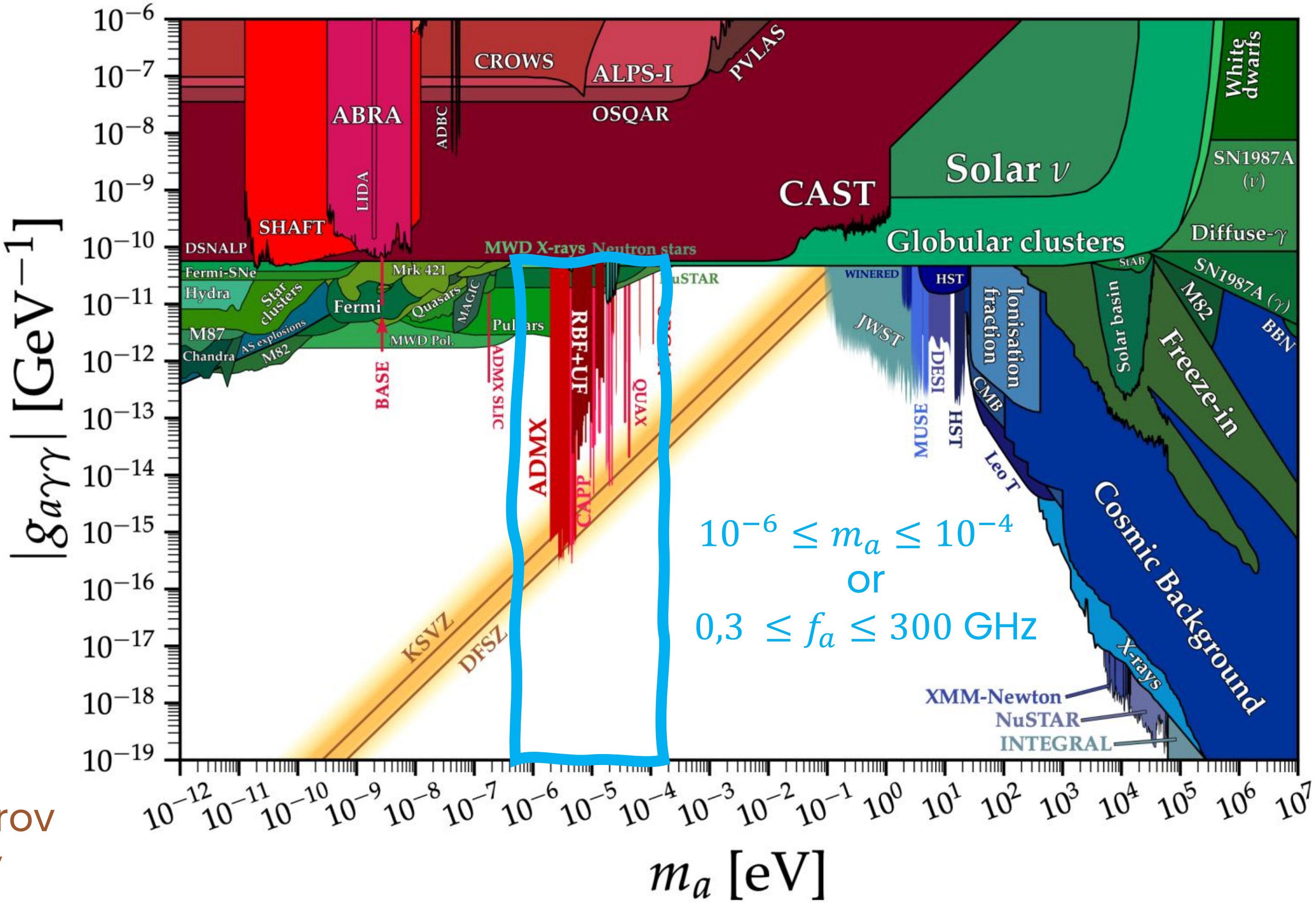


axion – photon coupling



g_γ **models**

KSVZ: Kim-Shifman-Vainshtein-Zakharov
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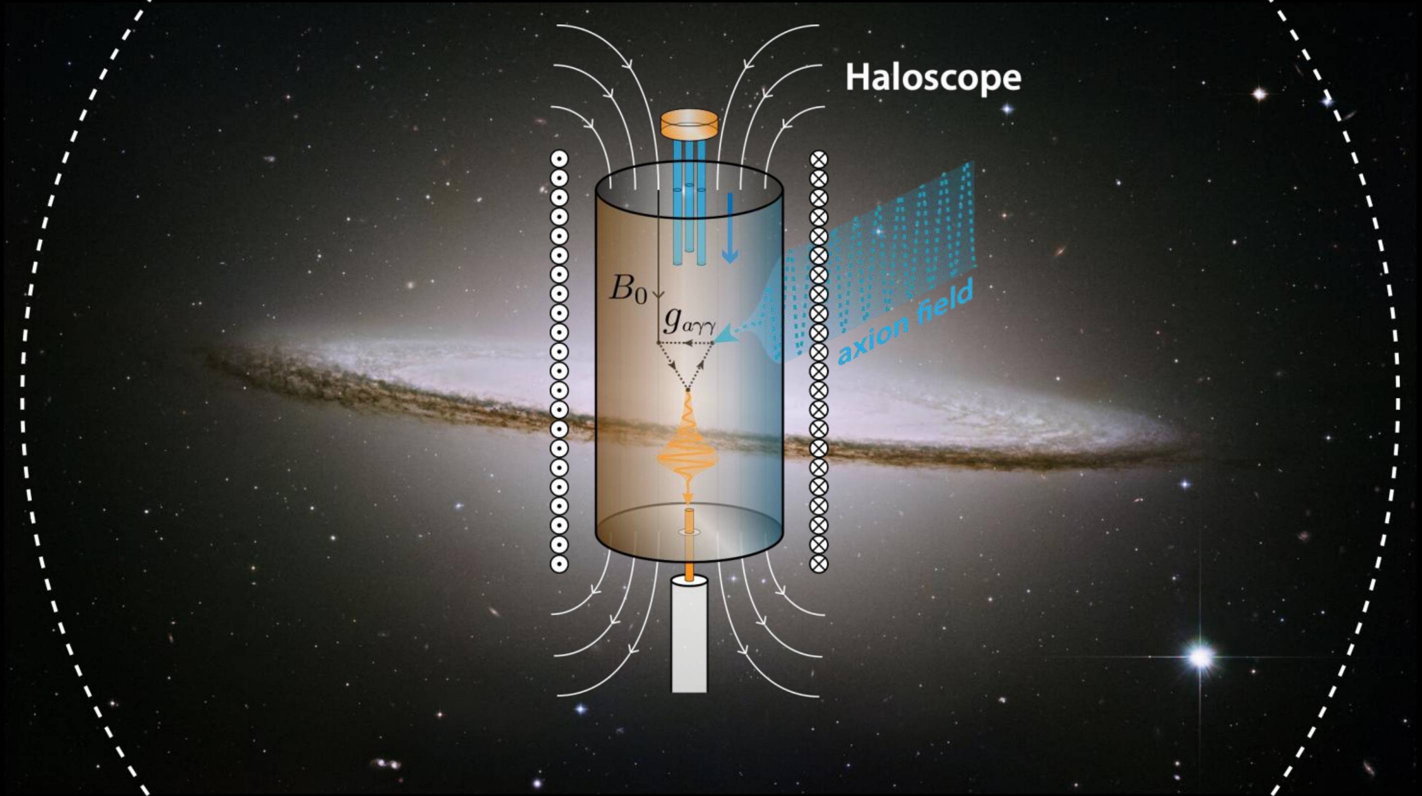
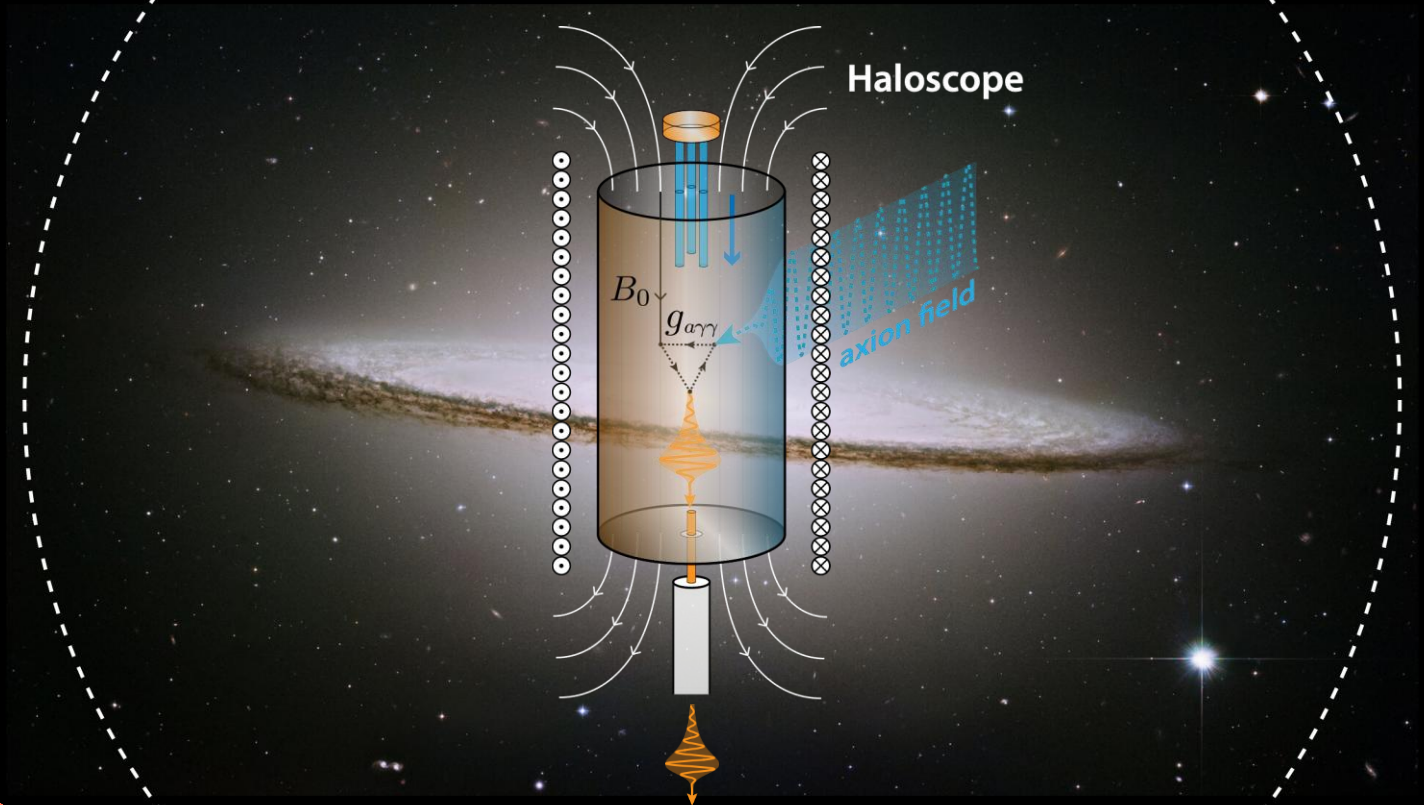
Dark Matter Halo

Dark Matter Halo



Dark Matter Halo



QCD coupling
KSVZ

DM density

magnetic field

Haloscope parameters
- Mode volume
- Mode frequency
- Quality factor
- Mode overlap

$$P_{a\gamma\gamma} = 7.2 \times 10^{-25}\mathrm{W}\left(\frac{g_\gamma}{0.97}\right)^2 \frac{\rho_a}{0.45\ \mathrm{GeV/cm^3}}\left(\frac{B}{2\,\mathrm{T}}\right)^2 \cdot \frac{V}{0.11\,l} \cdot \frac{\nu_c}{7.3\,\mathrm{GHz}} \cdot \frac{Q_L}{225000} \cdot \frac{C_{010}}{0.64}$$

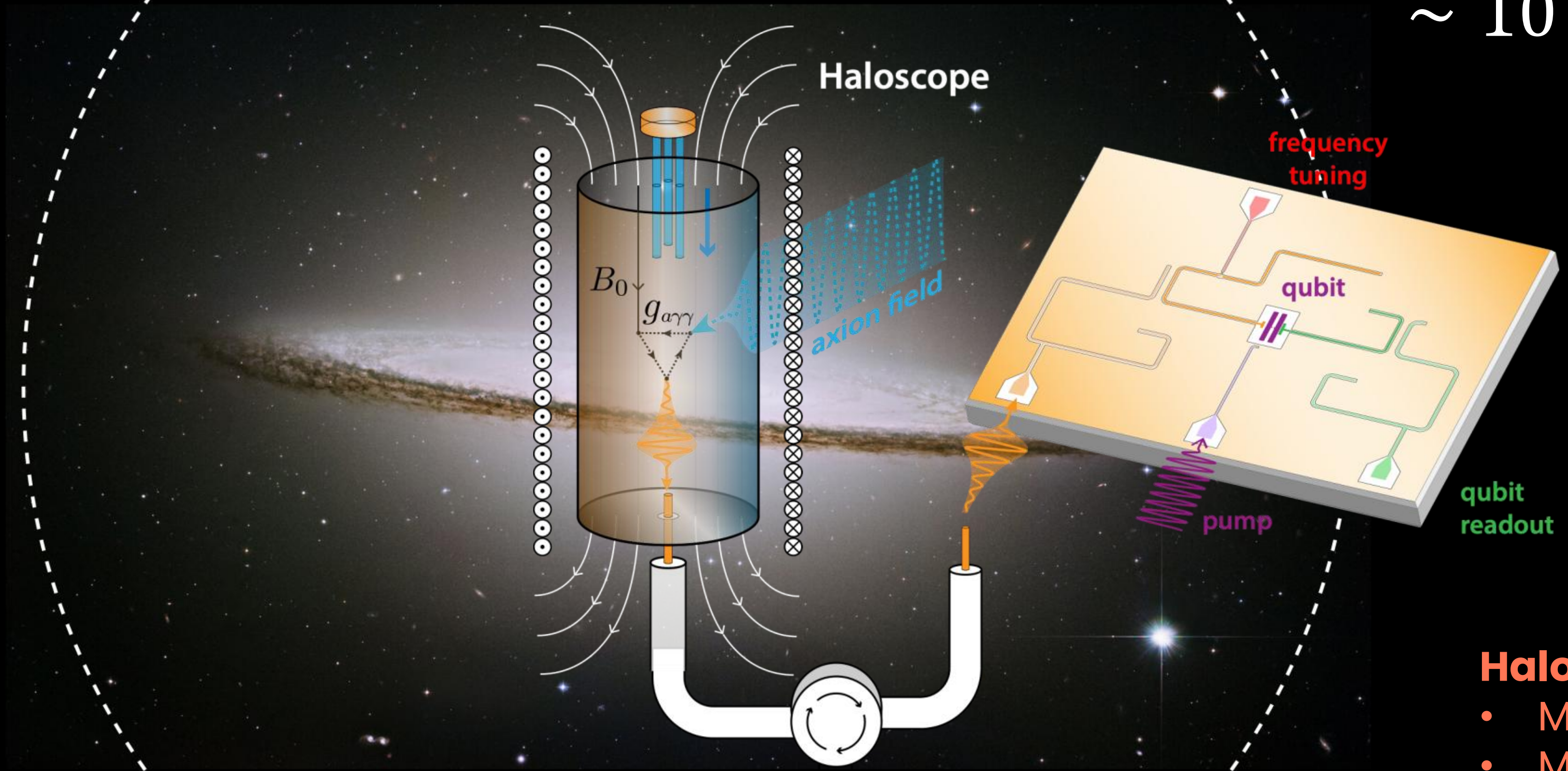
The signal power we expect ...

$$P_{\alpha\gamma\gamma} \sim 10^{-24}\mathrm{W}$$

... the sensitivity we have.

$$\sim 10^{-23}\mathrm{W}/\sqrt{\mathrm{Hz}}$$

Dark Matter Halo



QCD coupling
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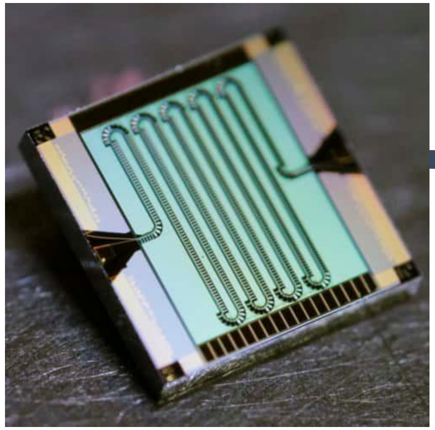
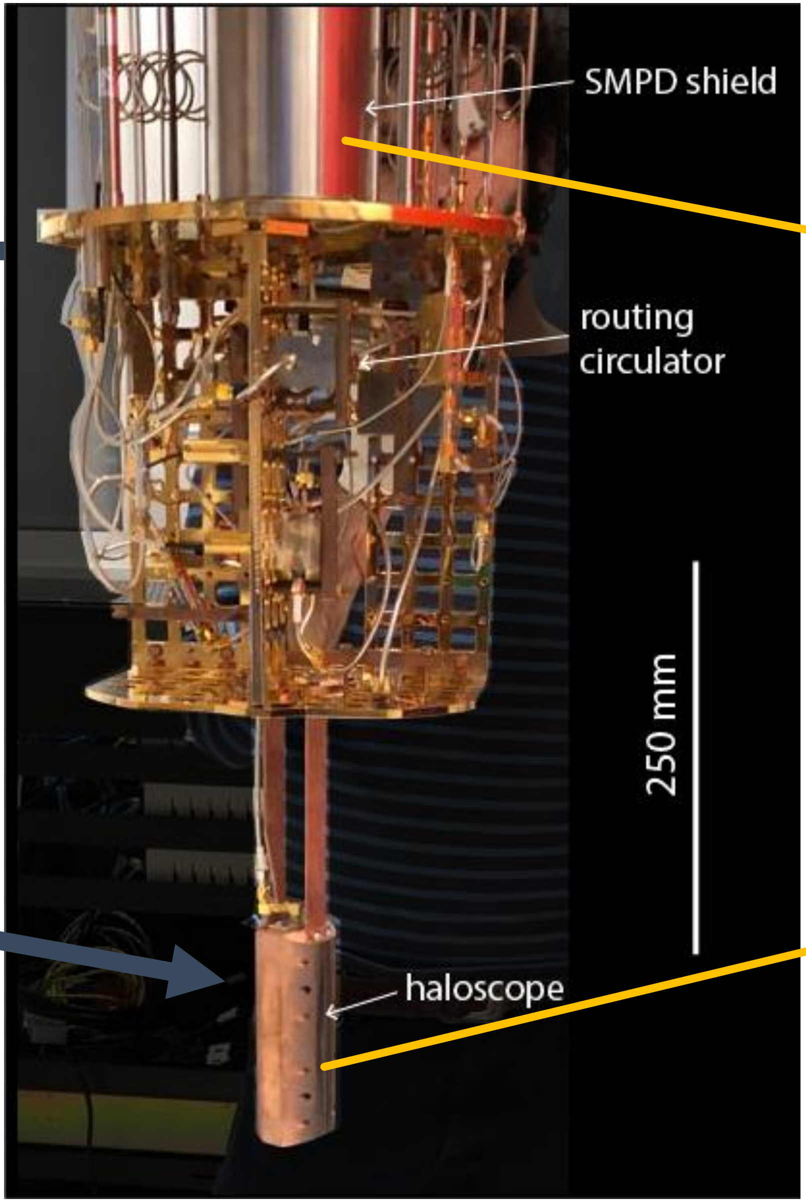
Axion search with Haloscope + Photodetection

MIT JTWPA

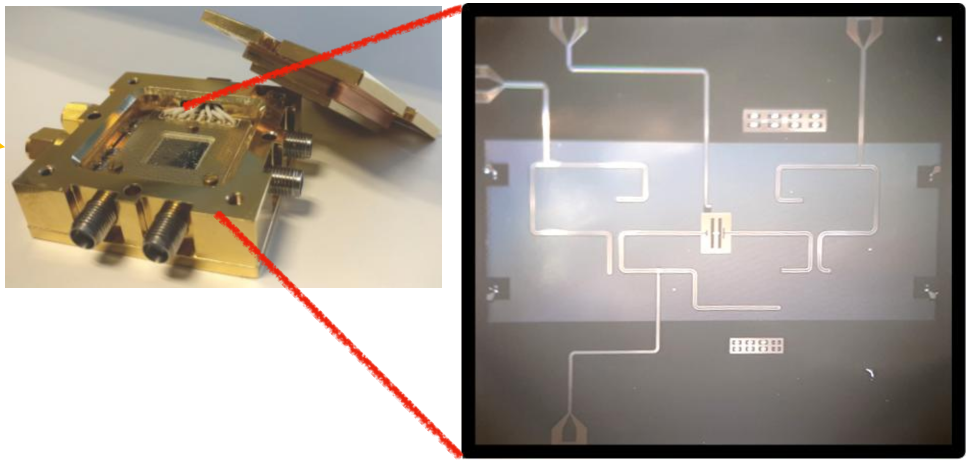


W.D. Oliver

3T Magnet



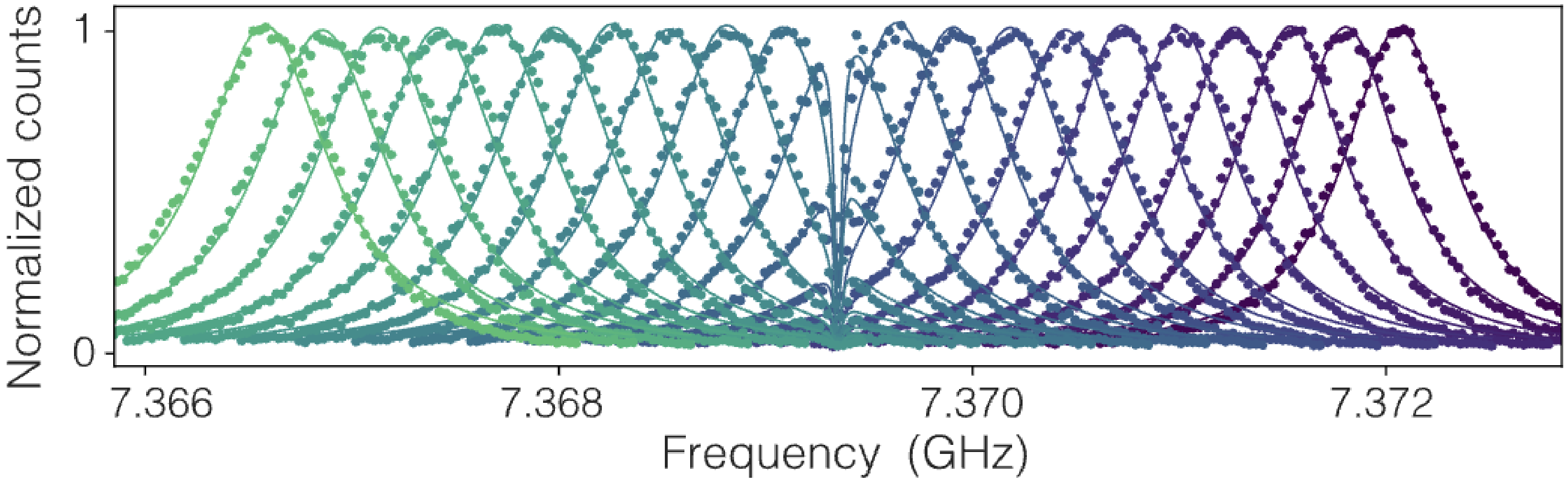
Single Microwave Photon Detector



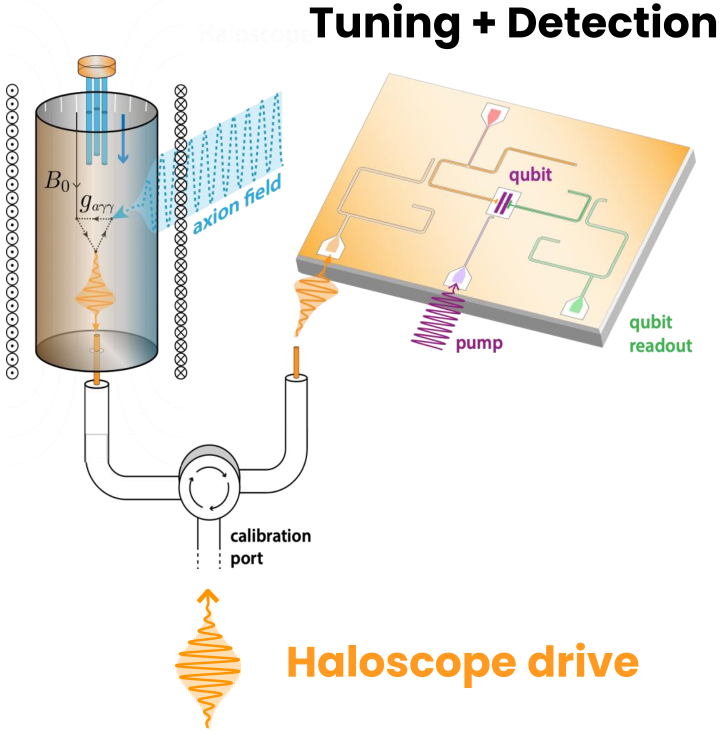
Collaboration with QUAX (Padova University, ITA)

C. Braggio & G. Carugno

How to align the counter with the haloscope at B=2T

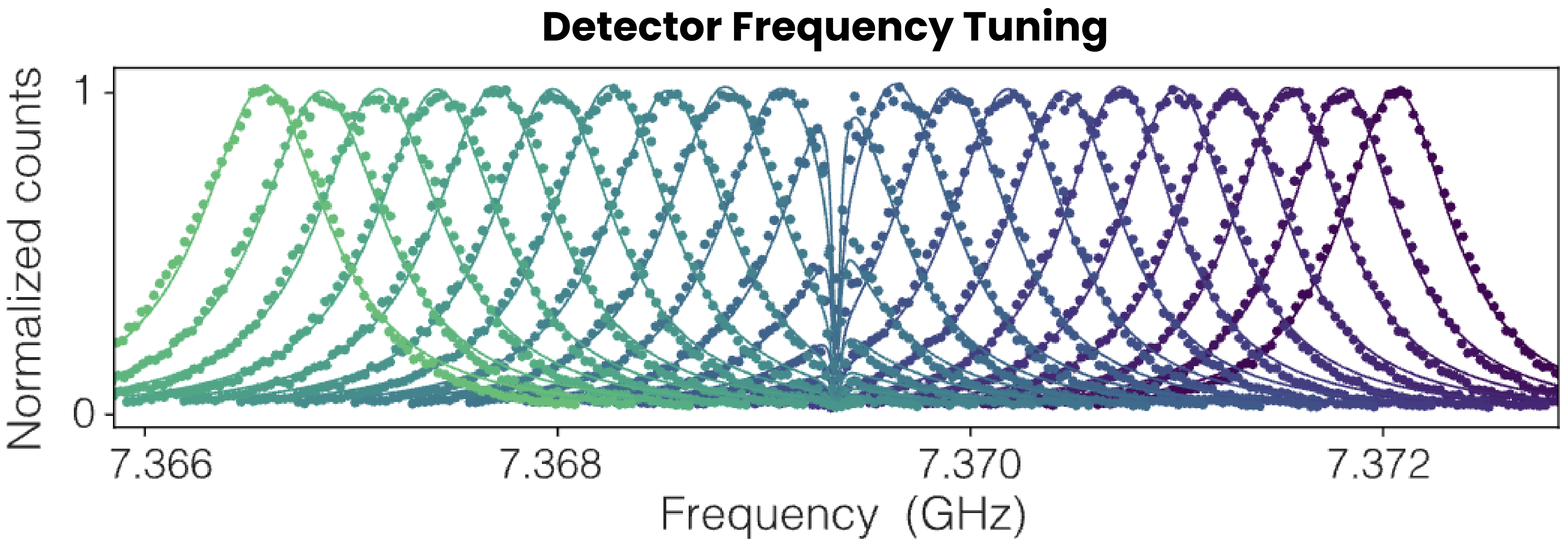


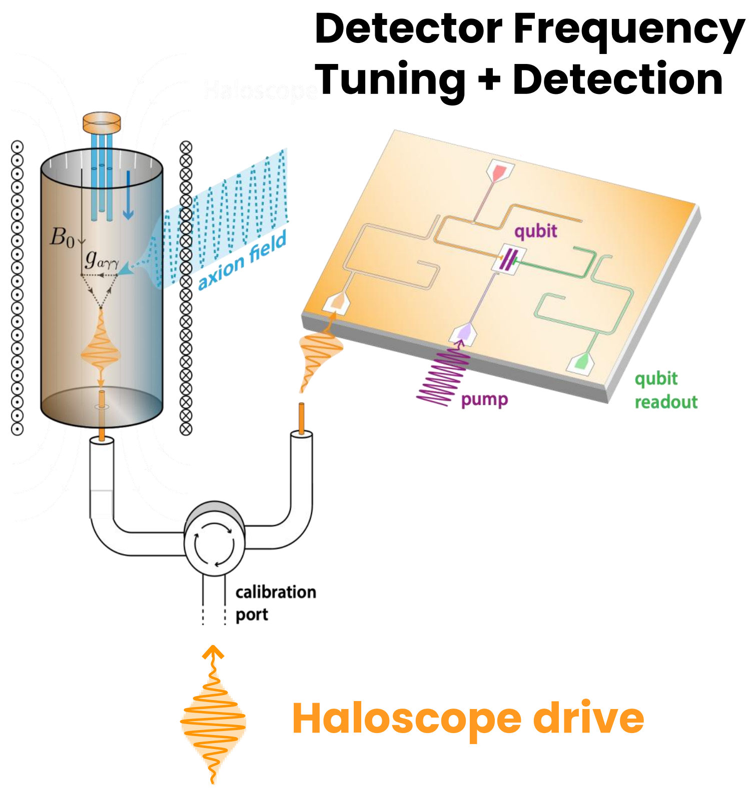
Detector Frequency Tuning + Detection



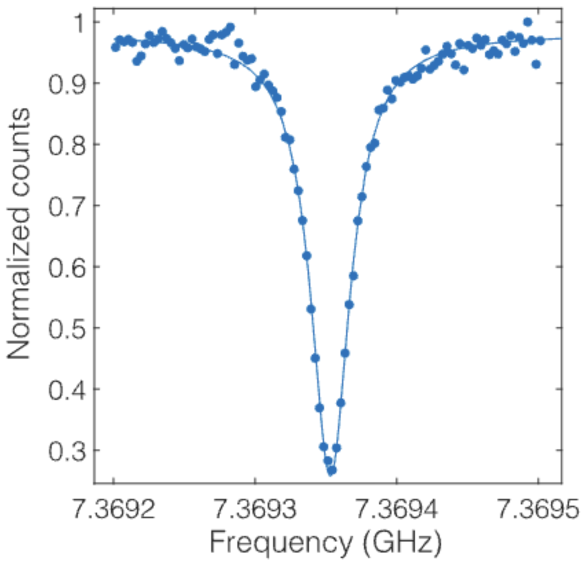
Haloscope drive

How to align the counter with the haloscope at B=2T



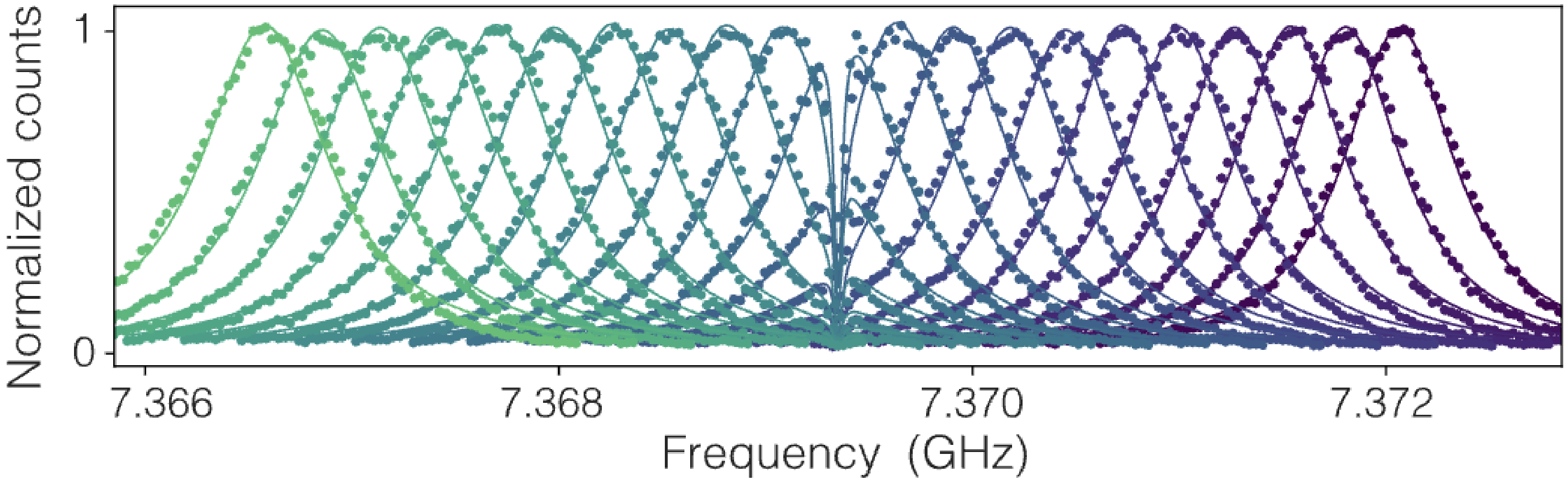


Haloscope Reflection Coefficient

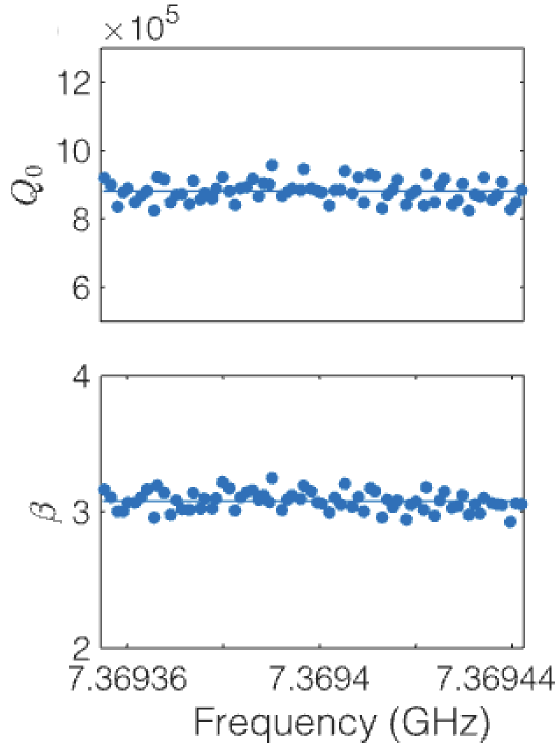


How to align the counter with the haloscope at B=2T

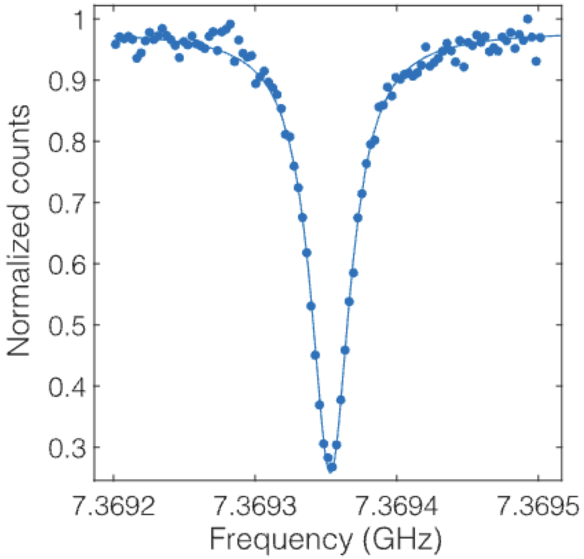
Detector Frequency Tuning



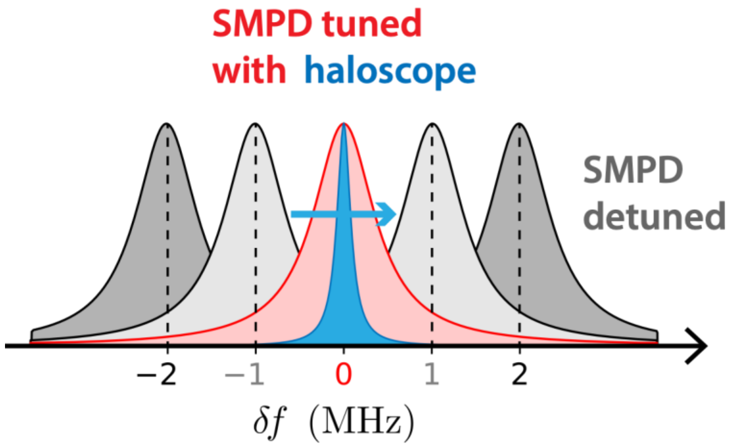
Haloscope frequency tuning with sapphire rods



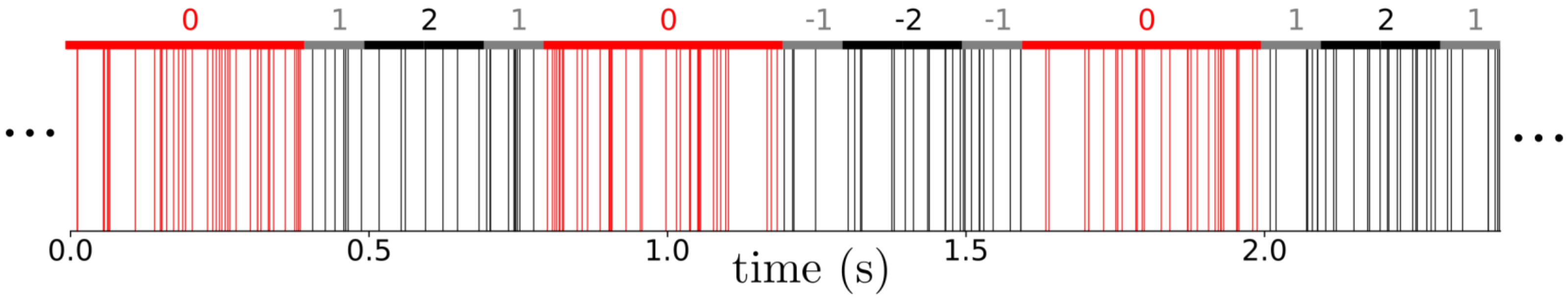
Haloscope Reflection Coefficient



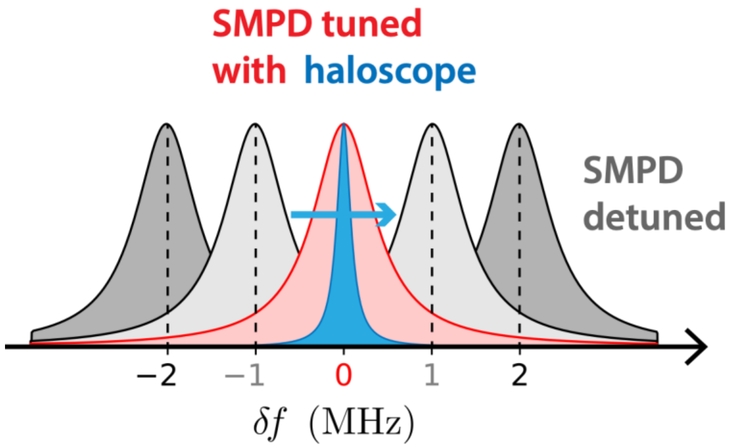
Axion search by Photon Counting



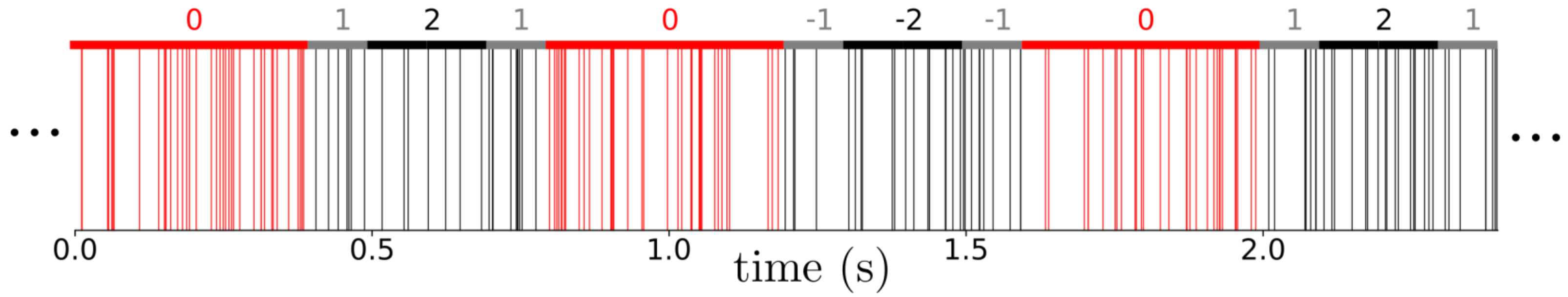
Data acquisition



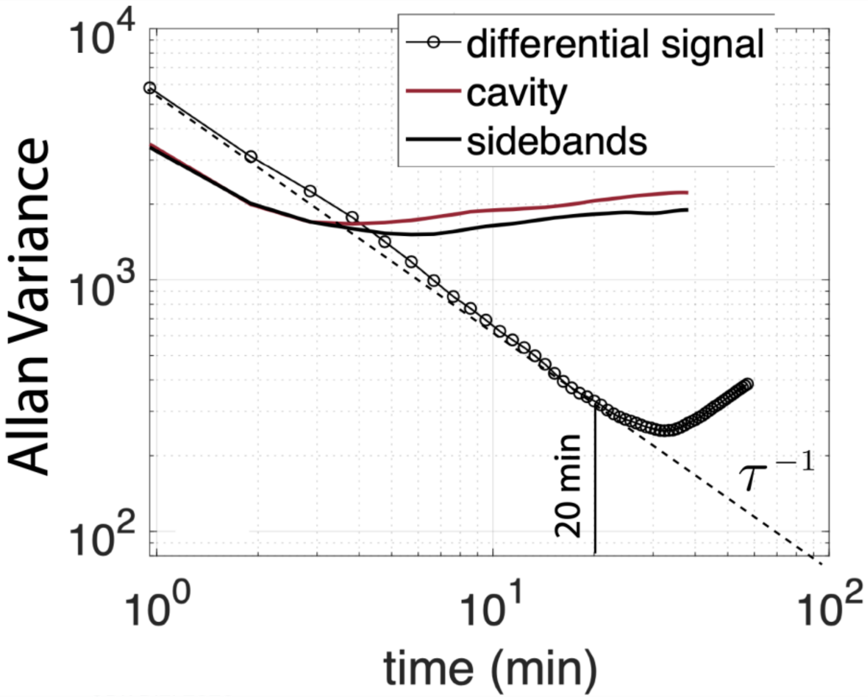
Axion search by Photon Counting



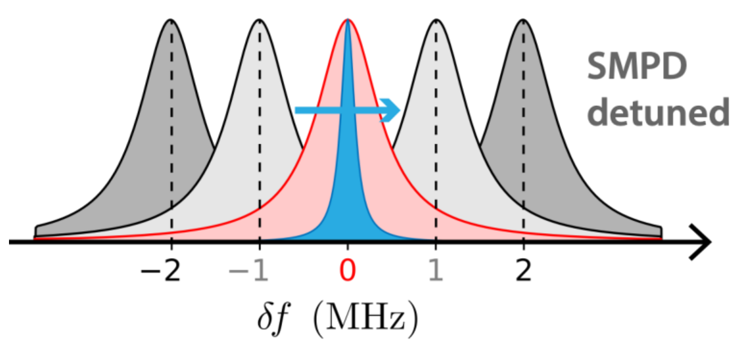
Data acquisition



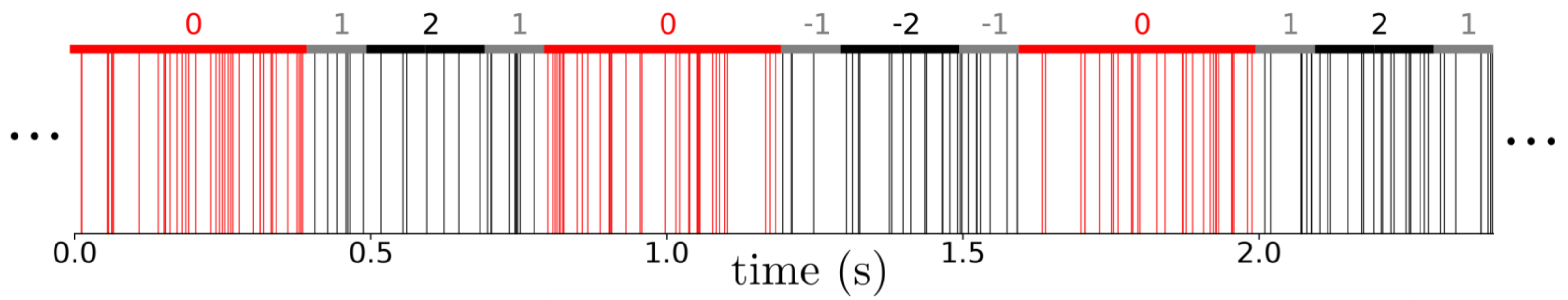
Data processing



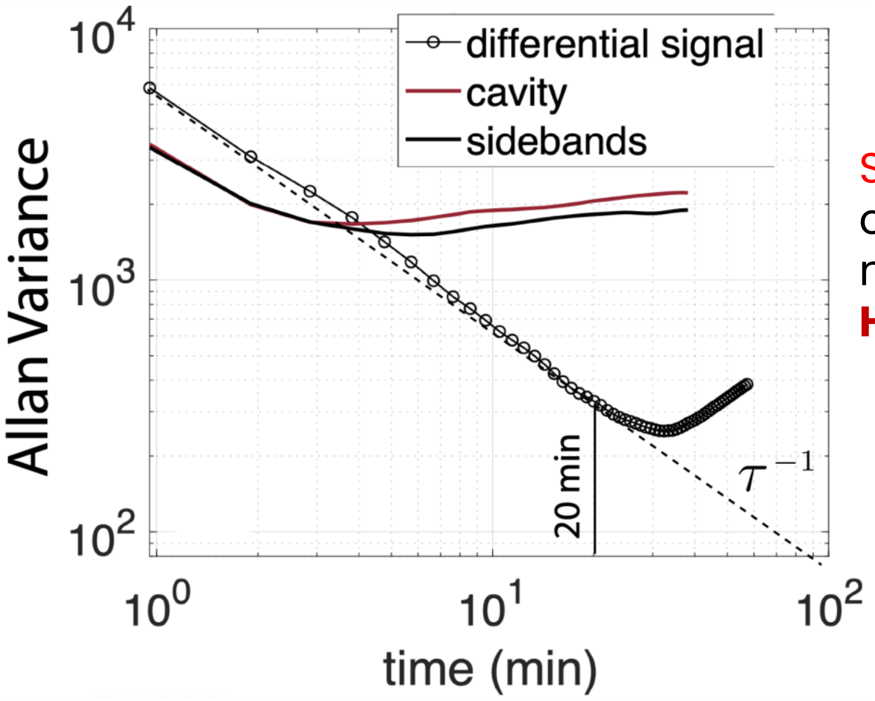
Axion search by Photon Counting



Data acquisition

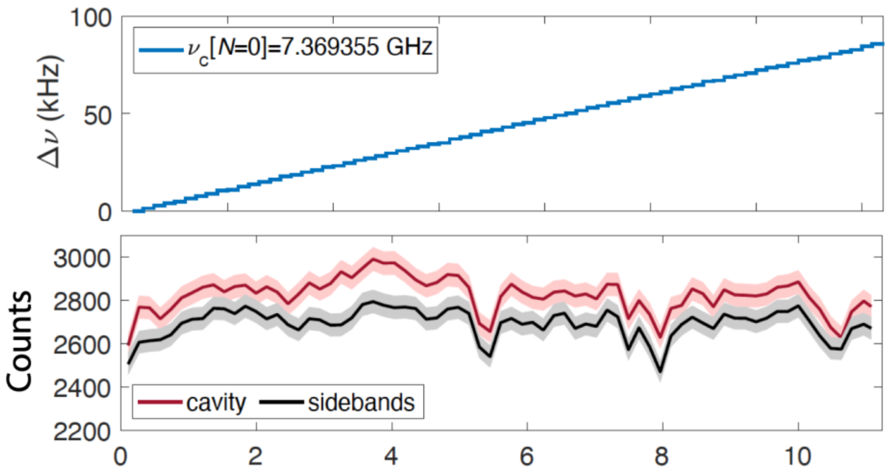


Data processing

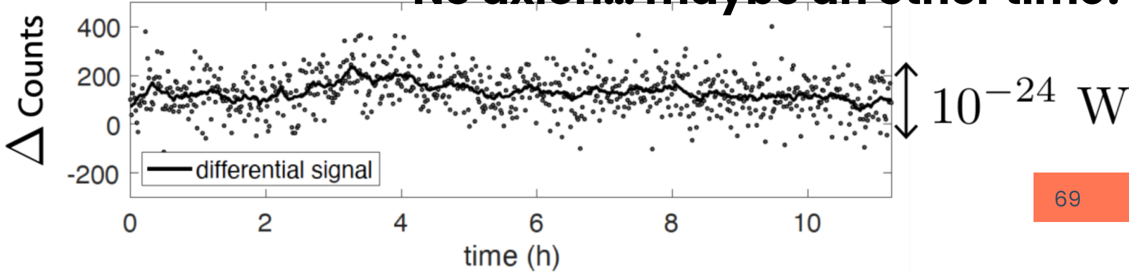


Signal & Background channels have different noise levels.

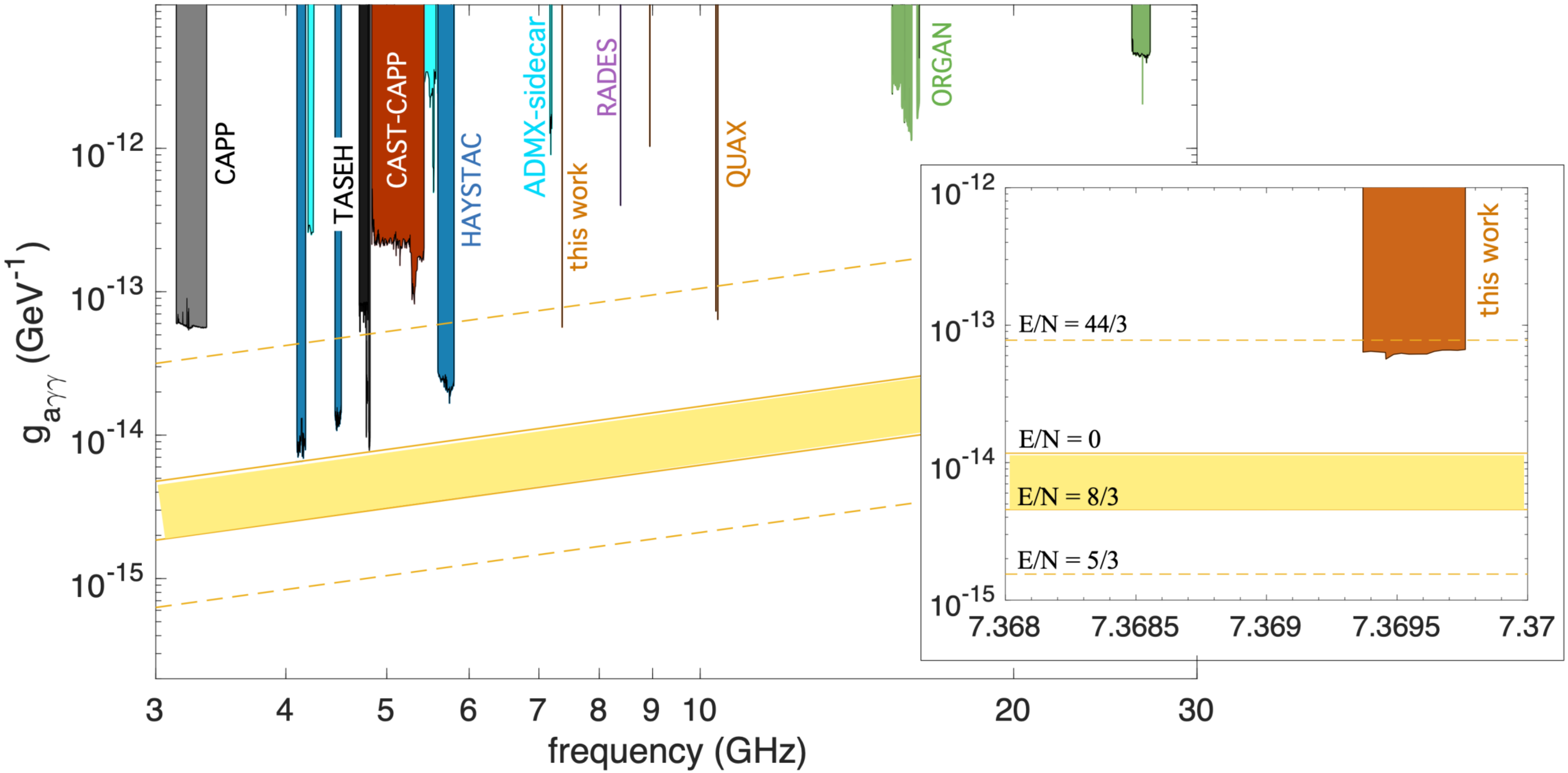
Haloscope is hot ~70mK



No axion… maybe an other time!



Axion search by Photon Counting



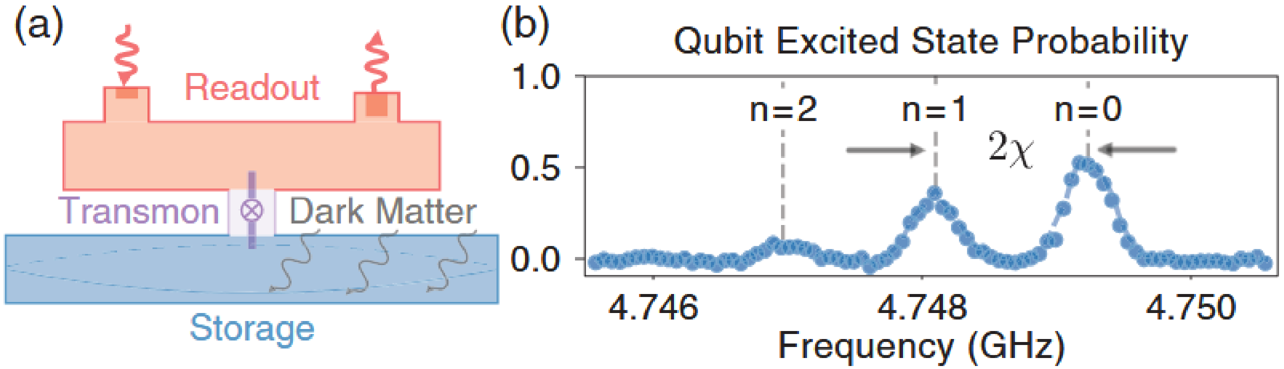
Realistic axion search POC landscape

PHYSICAL REVIEW LETTERS **126,** 141302 (2021)

Featured in Physics

Searching for Dark Matter with a Superconducting Qubit

Akash V. Dixit,[1,2,3,*] Srivatsan Chakram,[1,2,4] Kevin He,[1,2] Ankur Agrawal,[1,2,3] Ravi K. Naik,[5]
David I. Schuster,[1,2,6] and Aaron Chou[7]



Scan rate speed up over SQL

$R \sim 1300$

… but **not very realistic** because

- No **B** field applied (the qubit would die due to Supra to Normal transition)
- Storage not frequency tunable

Conclusion

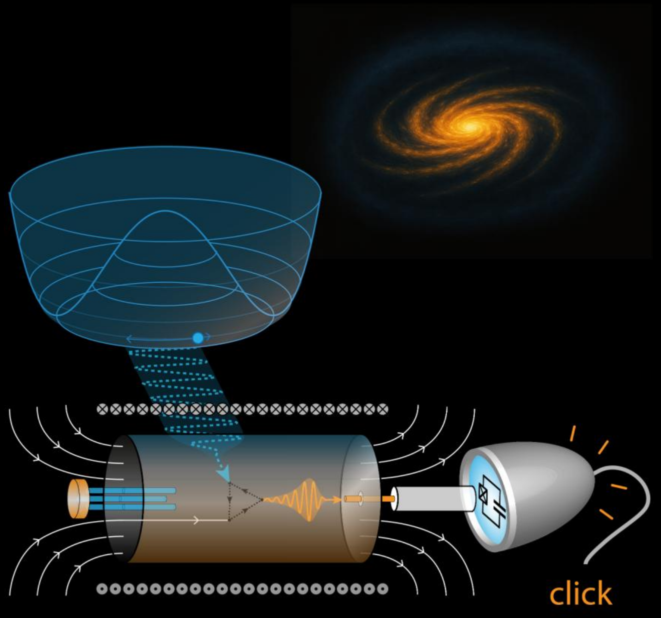
01. Design of a practical SMPD with frequency / bandwidth tunability, and sensitivity $3\times10^{-23}\mathrm{W}/\sqrt{\mathrm{Hz}}$ @7.3 GHz.

02. Axion search most realistic POC with such a device. Demonstrate a 20x scan rate improvement over ideal Quantum Limited Amplifiers.

$$R=\frac{t_{\mathrm{SQL}}}{t_{\mathrm{PC}}}=\eta^2\frac{\Delta\nu_a}{\Gamma_{\mathrm{dc}}}\sim20$$

1. Tunable haloscope with sapphire rods (~500 kHz)
2. Magnetic field applied (2T)

Next. POC in real experimental conditions under 9T (collab. Padova University **QUAX** & FermiLab **SQMS**). Currently ongoing!



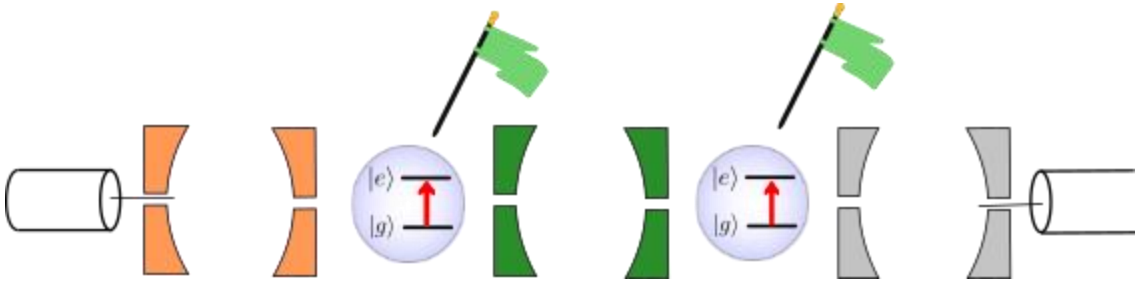
Outline

I. Photon Detection vs Field Detection

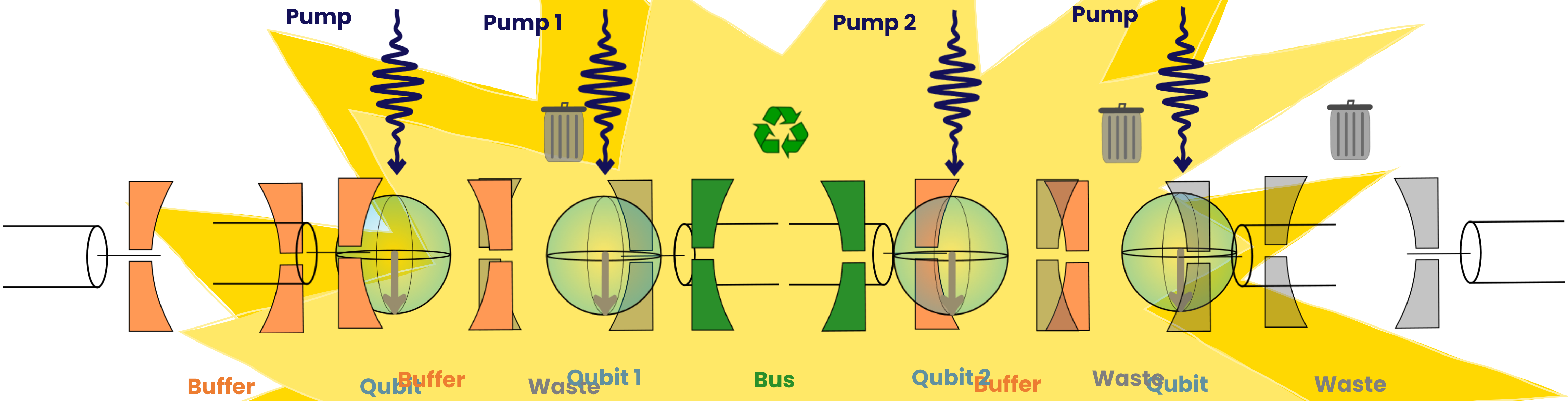
II. Superconducting Qubit-based Single Microwave Photon Detector (SMPD)

III. Counting Photon for Axion Dark Matter Search

IV. Enhanced sensitivity with Multiqubit Photon Counter



Cascaded Single MW photon detector

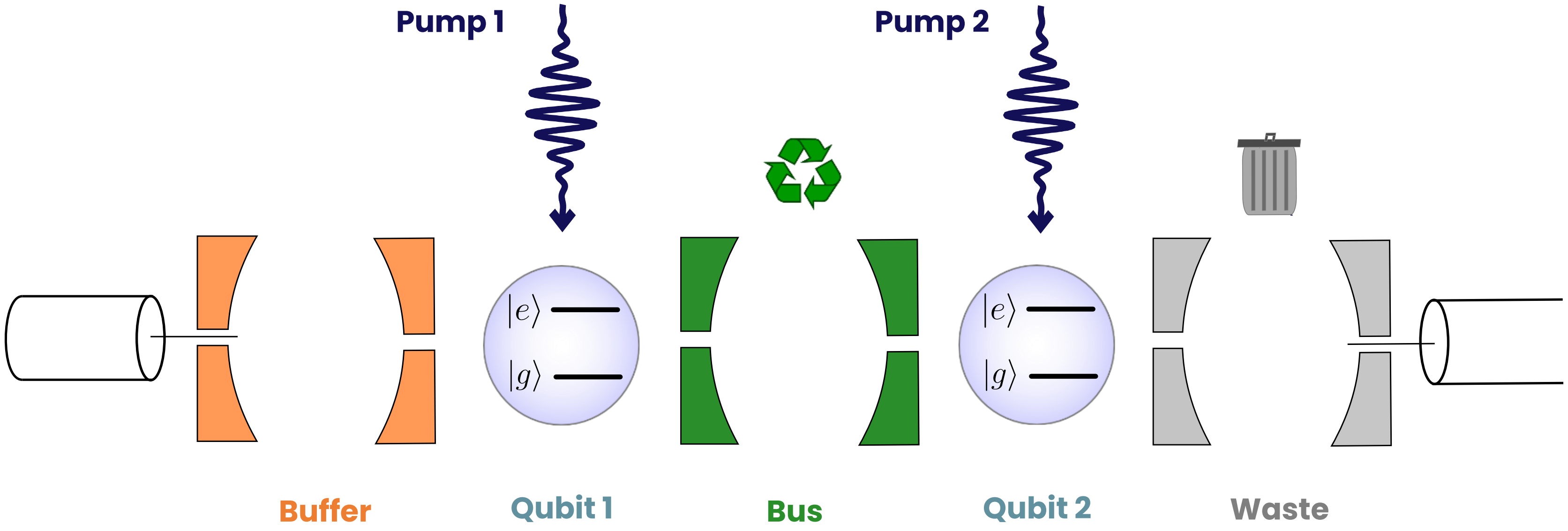


$g_4 \xi \hat{b}\hat{\sigma}^\dagger \hat{w}^\dagger$ + h.c + dissipation

$g_{4,1}\xi_1 \hat{b}\hat{\sigma}_1^\dagger \hat{r}^\dagger + g_{4,2}\xi_2 \hat{r}\hat{\sigma}_2^\dagger \hat{w}^\dagger$ + h.c + dissipation

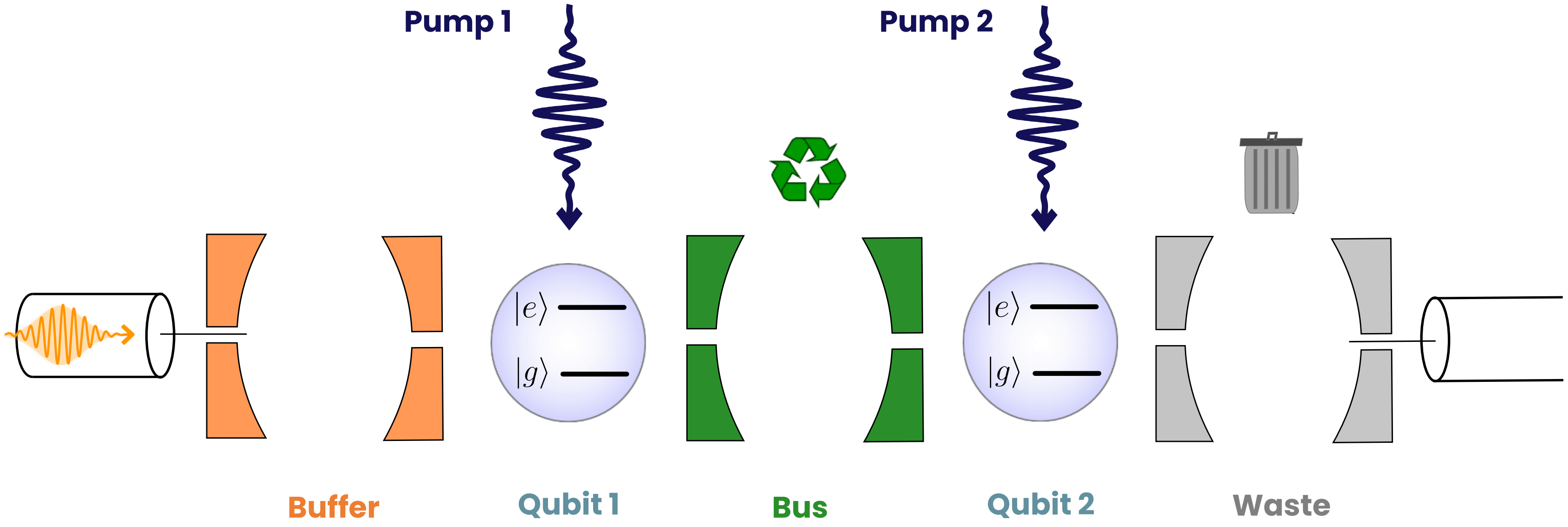
$g_4 \xi \hat{b}\hat{\sigma}^\dagger \hat{w}^\dagger$ + h.c + dissipation

Cascaded Single MW photon detector

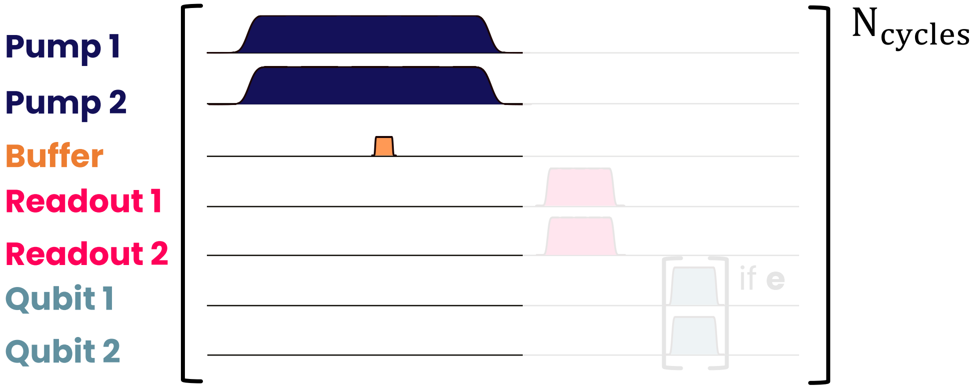


$$\mathbf{g}_{4,1}\xi_1\hat{b}\hat{\sigma}_1^\dagger\hat{r}^\dagger + \mathbf{g}_{4,1}^*\xi_1^*\hat{b}^\dagger\hat{\sigma}_1\hat{r} + \mathbf{g}_{4,2}\xi_2\hat{r}\hat{\sigma}_2^\dagger\hat{w}^\dagger + \mathbf{g}_{4,2}^*\xi_2^*\hat{r}^\dagger\hat{\sigma}_2\hat{w}$$

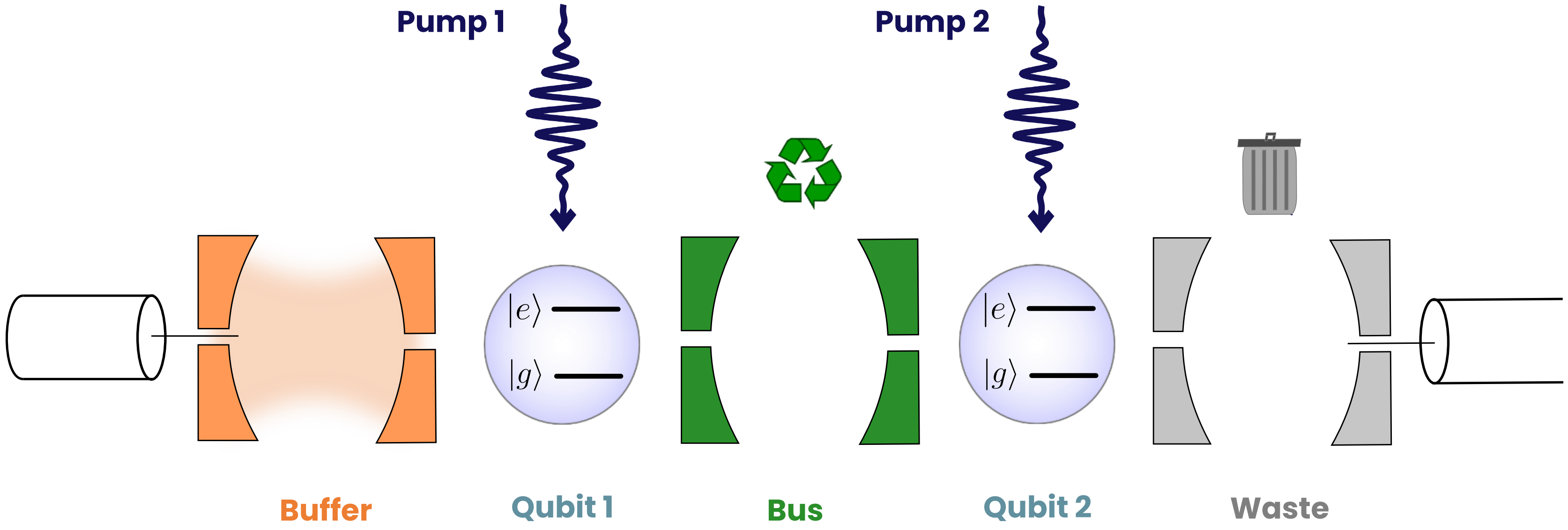
Cascaded Single MW photon detector



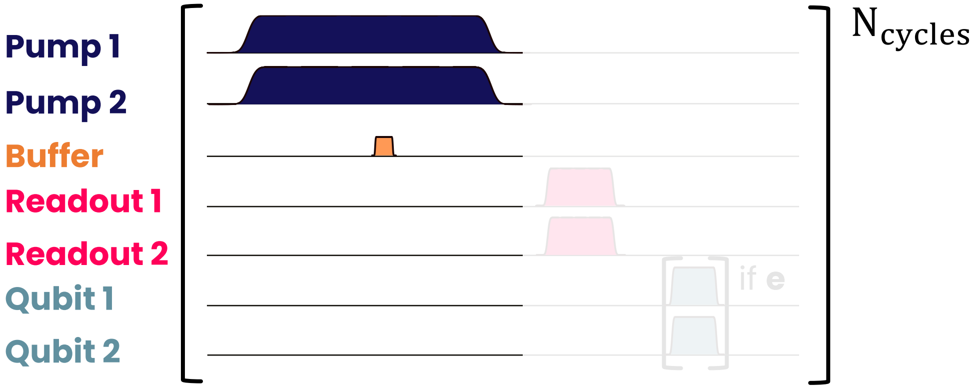
$$\mathbf{g}_{4,1}\xi_1 \hat{b}\hat{\sigma}_1^\dagger \hat{r}^\dagger + \mathbf{g}_{4,1}^*\xi_1^* \hat{b}^\dagger \hat{\sigma}_1 \hat{r} + \mathbf{g}_{4,2}\xi_2 \hat{r}\hat{\sigma}_2^\dagger \hat{w}^\dagger + \mathbf{g}_{4,2}^*\xi_2^*\hat{r}^\dagger\hat{\sigma}_2\hat{w}$$



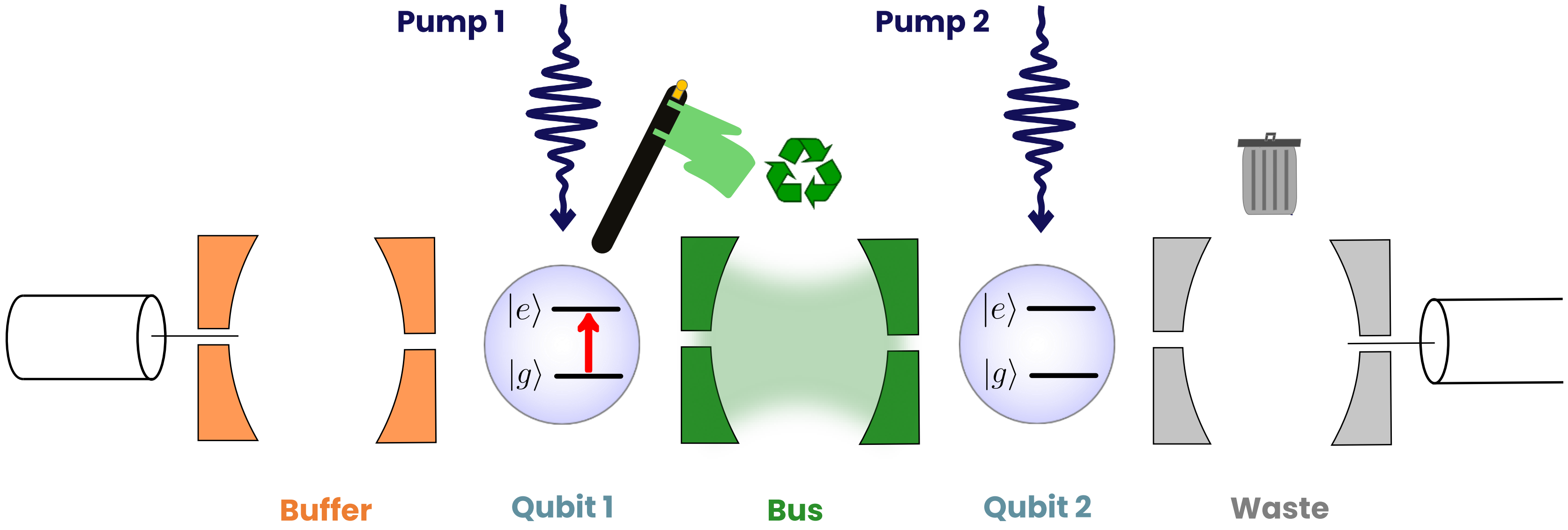
Cascaded Single MW photon detector



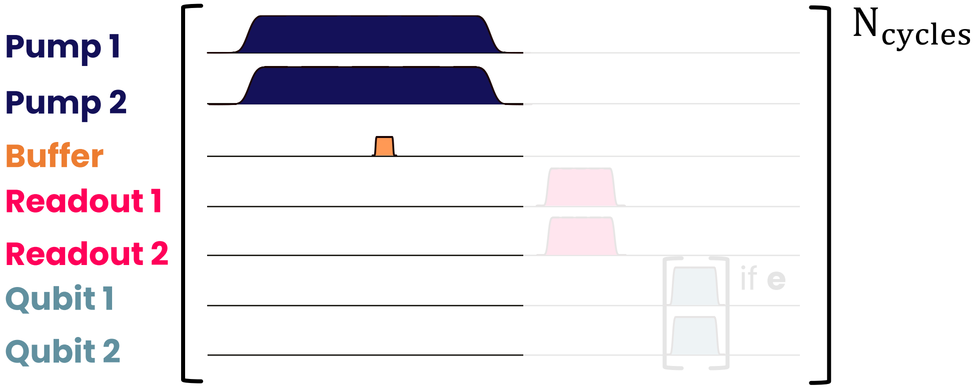
$$\mathbf{g}_{4,1}\xi_1\hat{b}\hat{\sigma}_1^\dagger\hat{r}^\dagger + \mathbf{g}_{4,1}^*\xi_1^*\hat{b}^\dagger\hat{\sigma}_1\hat{r} + \mathbf{g}_{4,2}\xi_2\hat{r}\hat{\sigma}_2^\dagger\hat{w}^\dagger + \mathbf{g}_{4,2}^*\xi_2^*\hat{r}^\dagger\hat{\sigma}_2\hat{w}$$



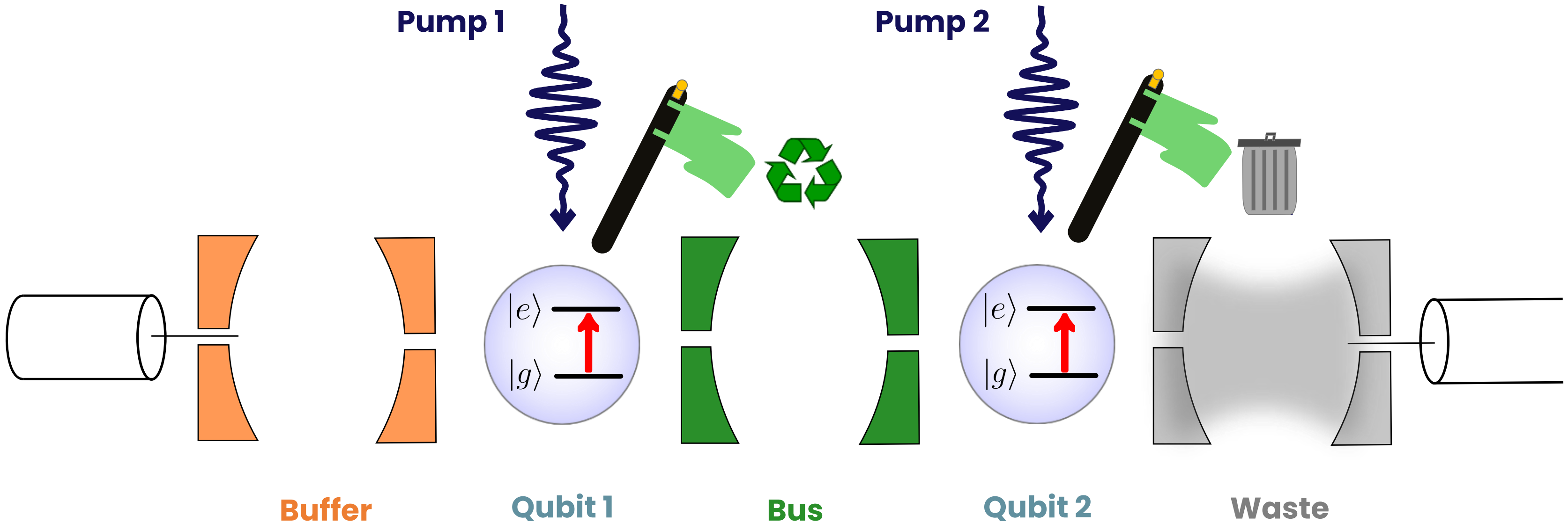
Cascaded Single MW photon detector



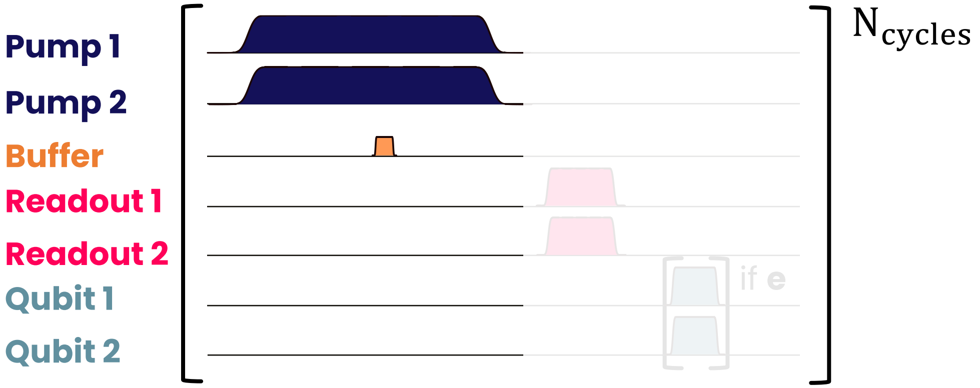
$$g_{4,1}\xi_1 \hat{b}\hat{\sigma}_1^\dagger \hat{r}^\dagger + g_{4,1}^*\xi_1^* \hat{b}^\dagger \hat{\sigma}_1 \hat{r} + g_{4,2}\xi_2 \hat{r}\hat{\sigma}_2^\dagger \hat{w}^\dagger + g_{4,2}^*\xi_2^* \hat{r}^\dagger \hat{\sigma}_2 \hat{w}$$



Cascaded Single MW photon detector

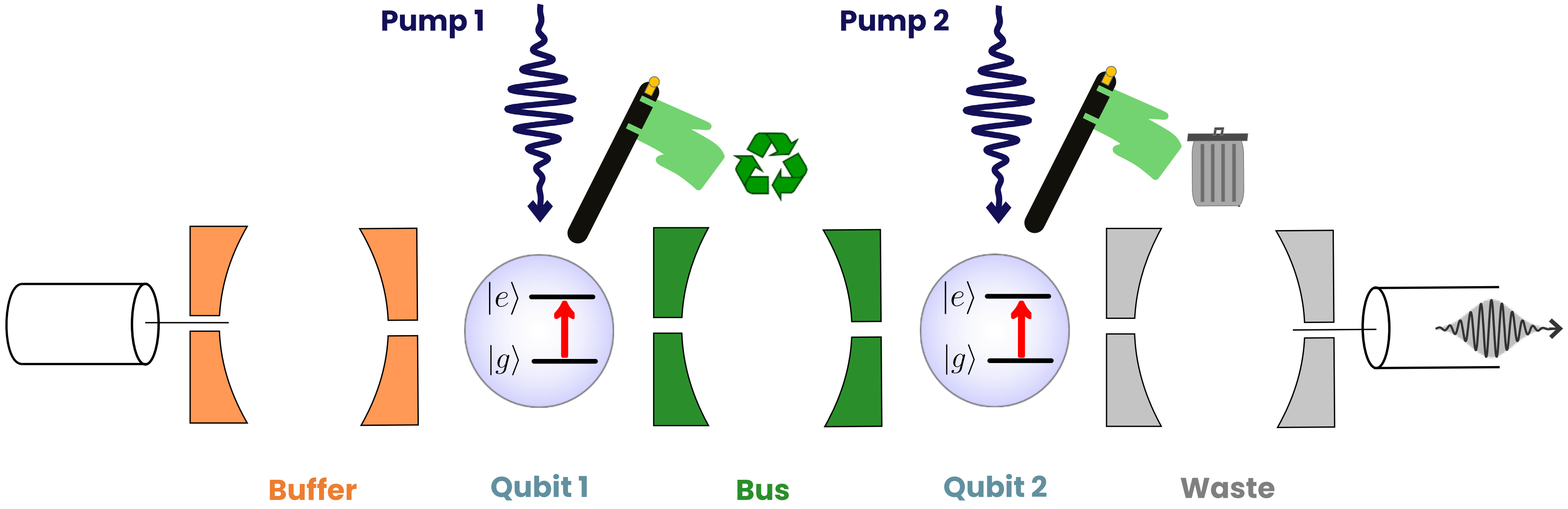


$$g_{4,1}\xi_1\hat{b}\hat{\sigma}_1^{\dagger}\hat{r}^{\dagger} + \cancel{g_{4,1}^{*}\xi_1^{*}\hat{b}^{\dagger}\hat{\sigma}_1\hat{r}} + g_{4,2}\xi_2\hat{r}\hat{\sigma}_2^{\dagger}\hat{w}^{\dagger} + g_{4,2}^{*}\xi_2^{*}\hat{r}^{\dagger}\hat{\sigma}_2\hat{w}$$



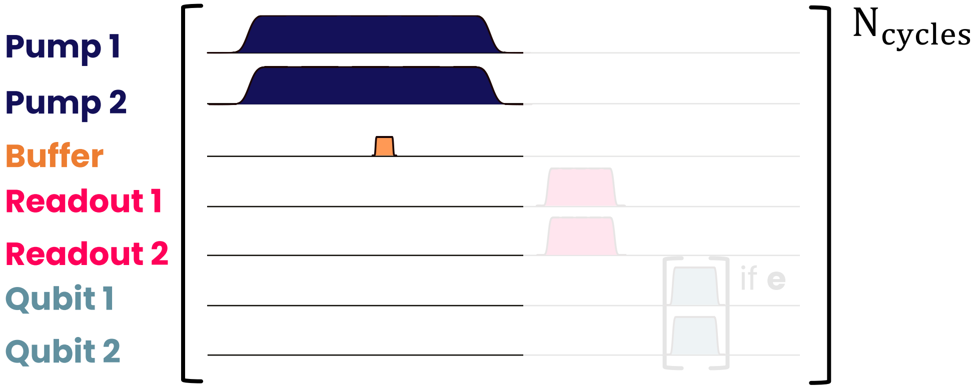
dissipation !

Cascaded Single MW photon detector

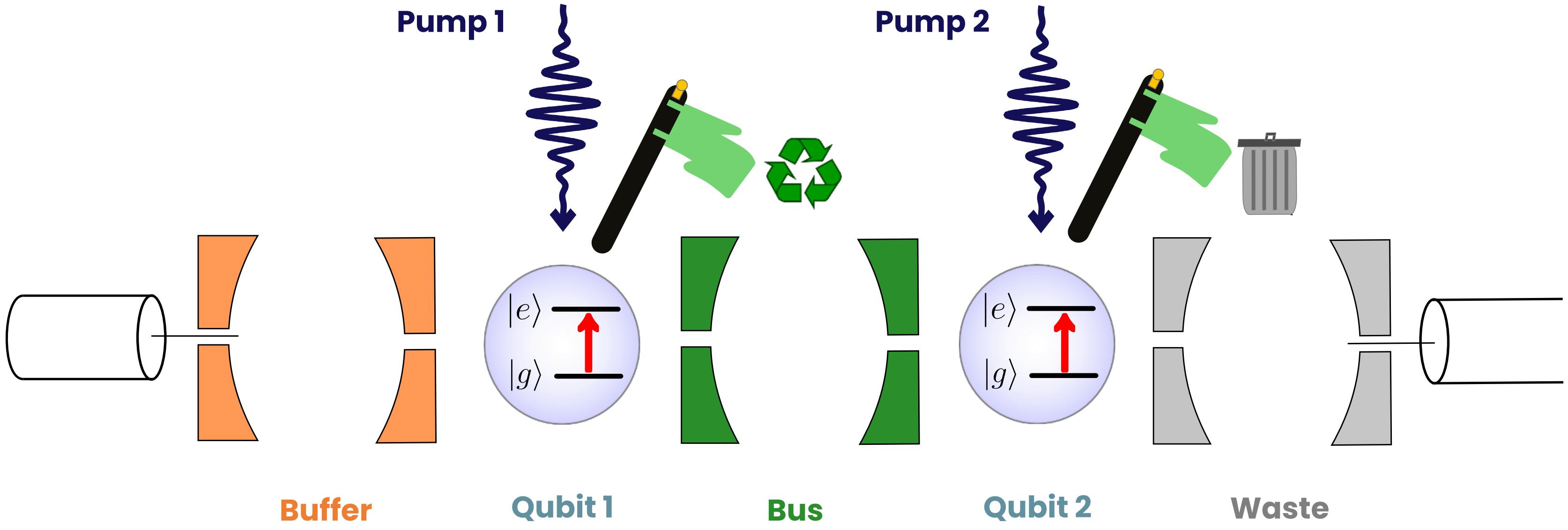


$$\mathbf{g}_{4,1}\xi_1\hat{b}\hat{\sigma}_1^{\dagger}\hat{r}^{\dagger} + \cancel{\mathbf{g}^*_{4,1}\xi^*_1\hat{b}^{\dagger}\hat{\sigma}_1\hat{r}} + \mathbf{g}_{4,2}\xi_2\hat{r}\hat{\sigma}_2^{\dagger}\hat{w}^{\dagger} + \cancel{\mathbf{g}^*_{4,2}\xi^*_2\hat{r}^{\dagger}\hat{\sigma}_2\hat{w}}$$

dissipation ! **dissipation !**

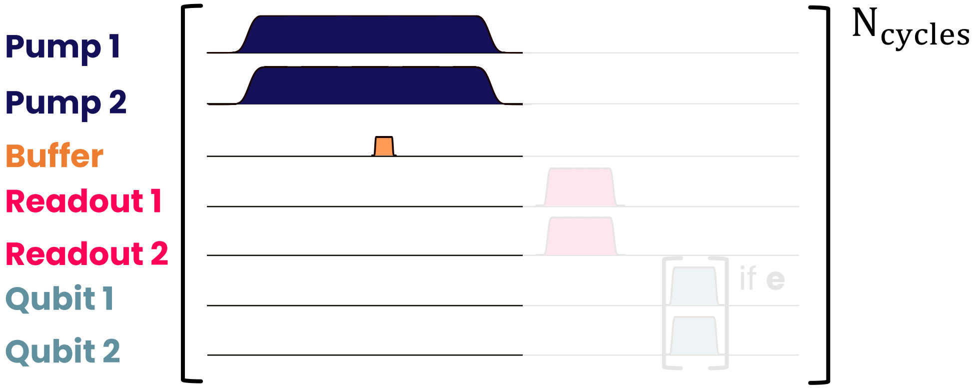


Cascaded Single MW photon detector

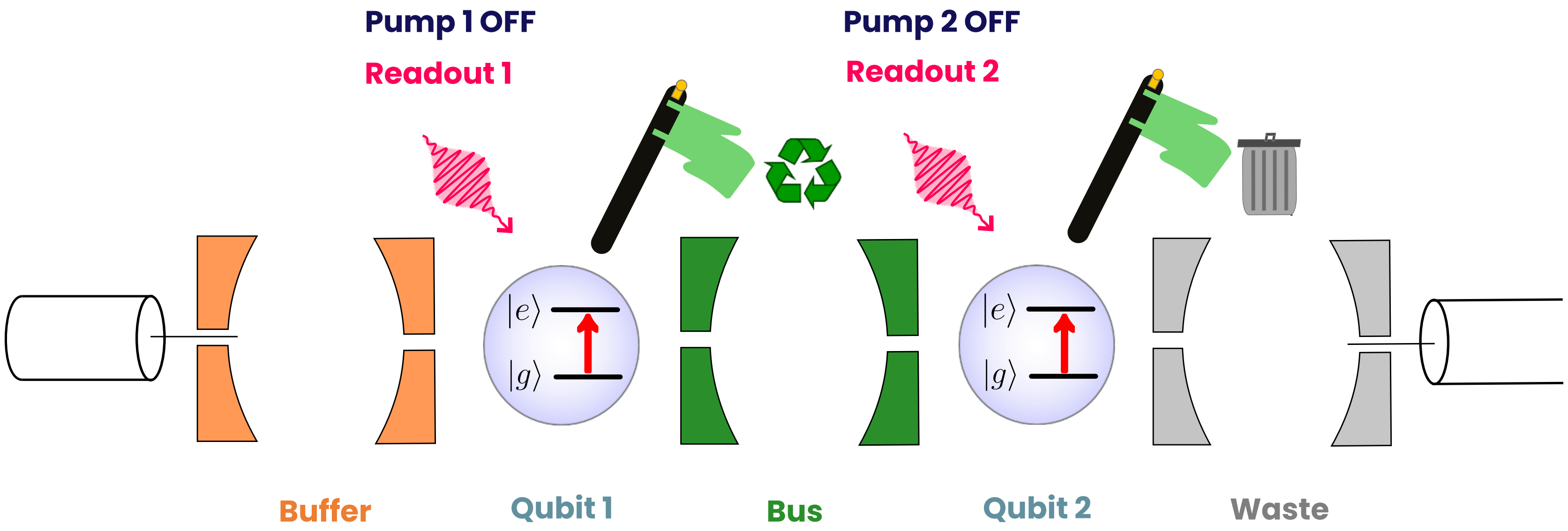


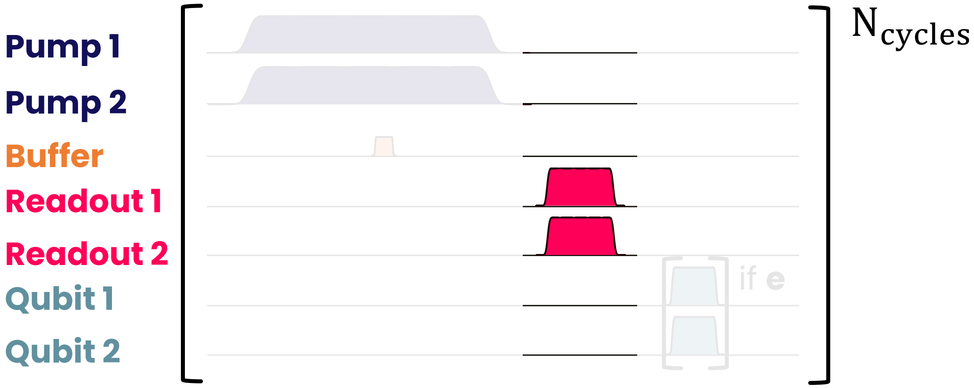
$$g_{4,1}\xi_1\hat{b}\hat{\sigma}_1^\dagger\hat{r}^\dagger + \cancel{g_{4,1}^*\xi_1^*\hat{b}^\dagger\hat{\sigma}_1\hat{r}} + g_{4,2}\xi_2\hat{r}\hat{\sigma}_2^\dagger\hat{w}^\dagger + \cancel{g_{4,2}^*\xi_2^*\hat{r}^\dagger\hat{\sigma}_2\hat{w}}$$

dissipation ! **dissipation !**

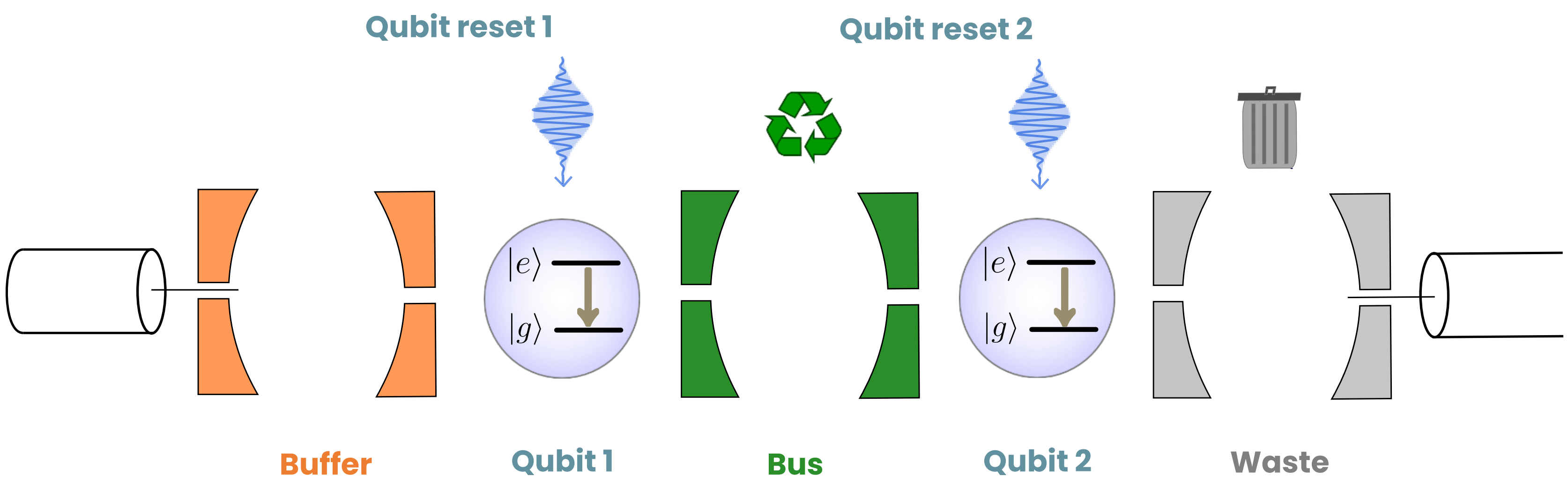


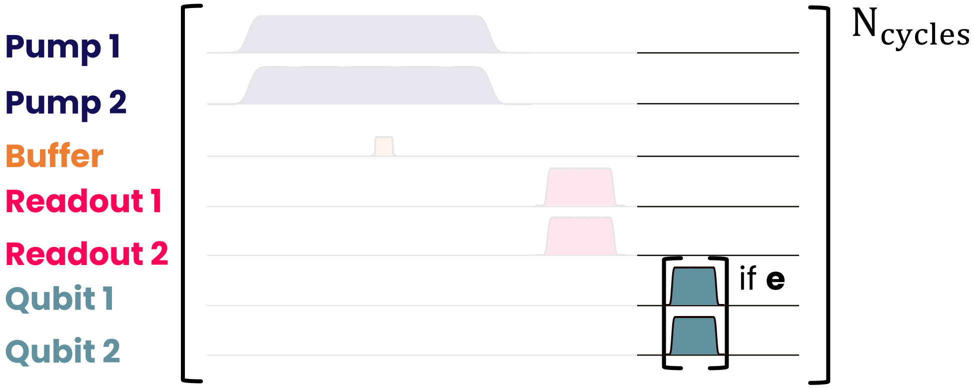
Cascaded Single MW photon detector



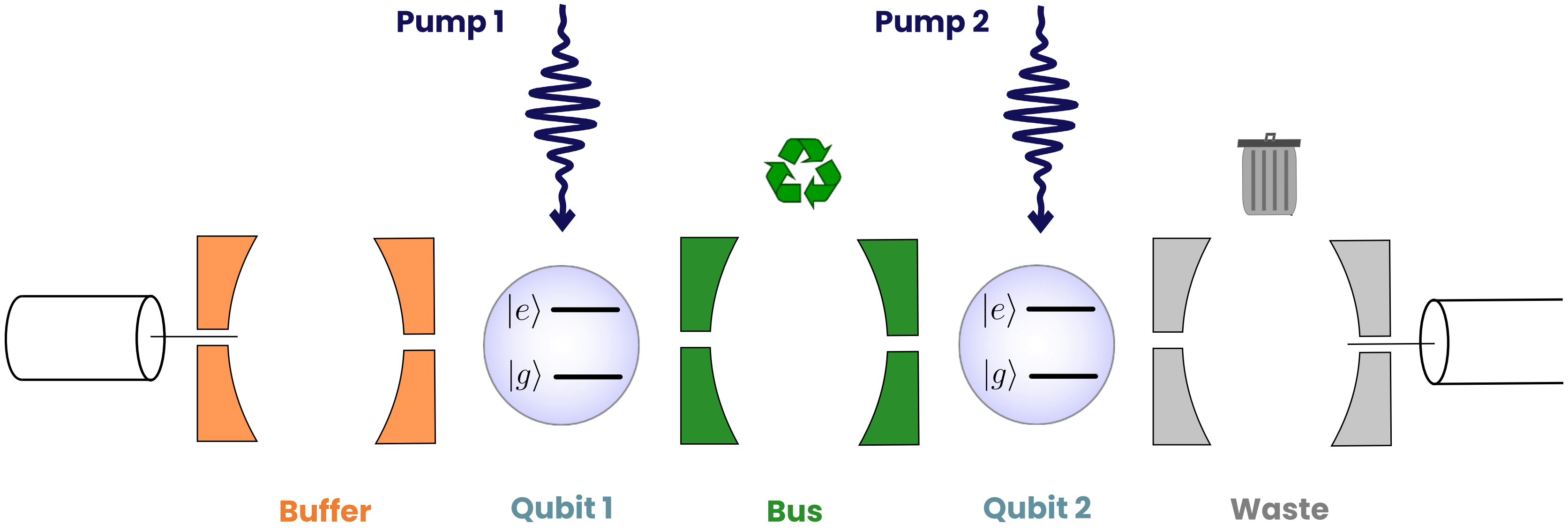


Cascaded Single MW photon detector

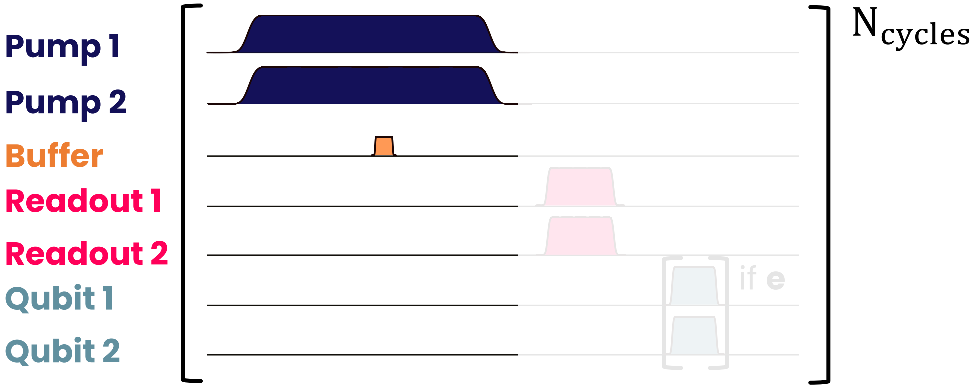




Cascaded Single MW photon detector



$$\mathbf{g}_{4,1}\xi_1\hat{b}\hat{\sigma}_1^\dagger\hat{r}^\dagger + \cancel{\mathbf{g}_{4,1}^*\xi_1^*\hat{b}^\dagger\hat{\sigma}_1\hat{r}} + \mathbf{g}_{4,2}\xi_2\hat{r}\hat{\sigma}_2^\dagger\hat{w}^\dagger + \cancel{\mathbf{g}_{4,2}^*\xi_2^*\hat{r}^\dagger\hat{\sigma}_2\hat{w}}$$



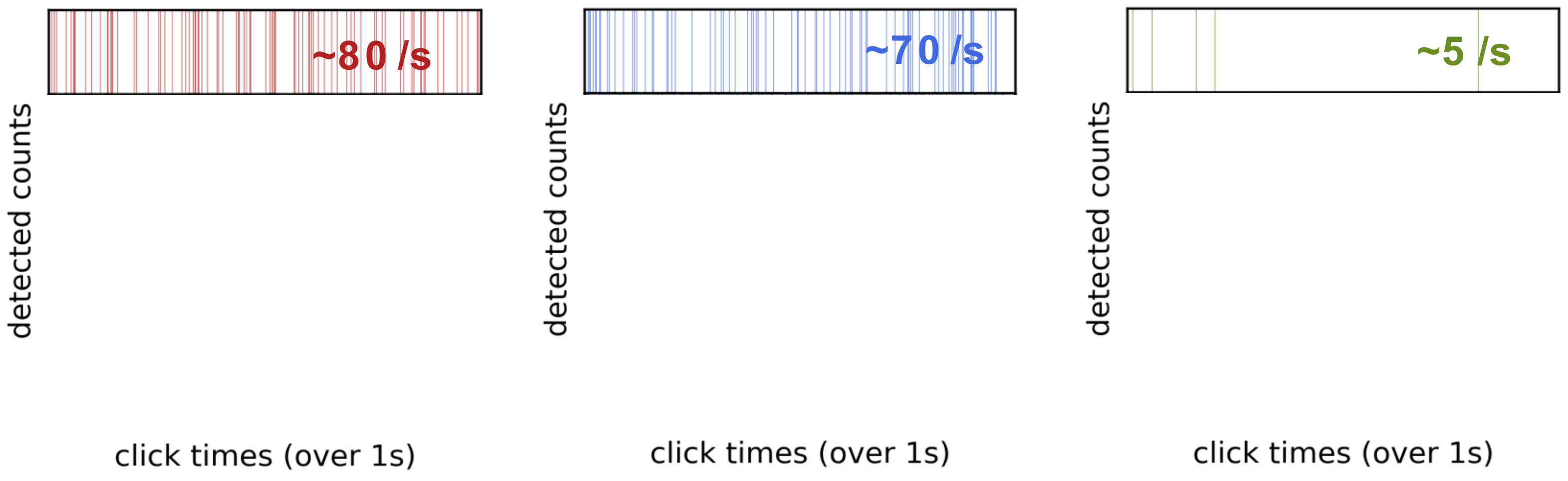
dissipation !

dissipation !

Efficiency & Dark count rate calibration

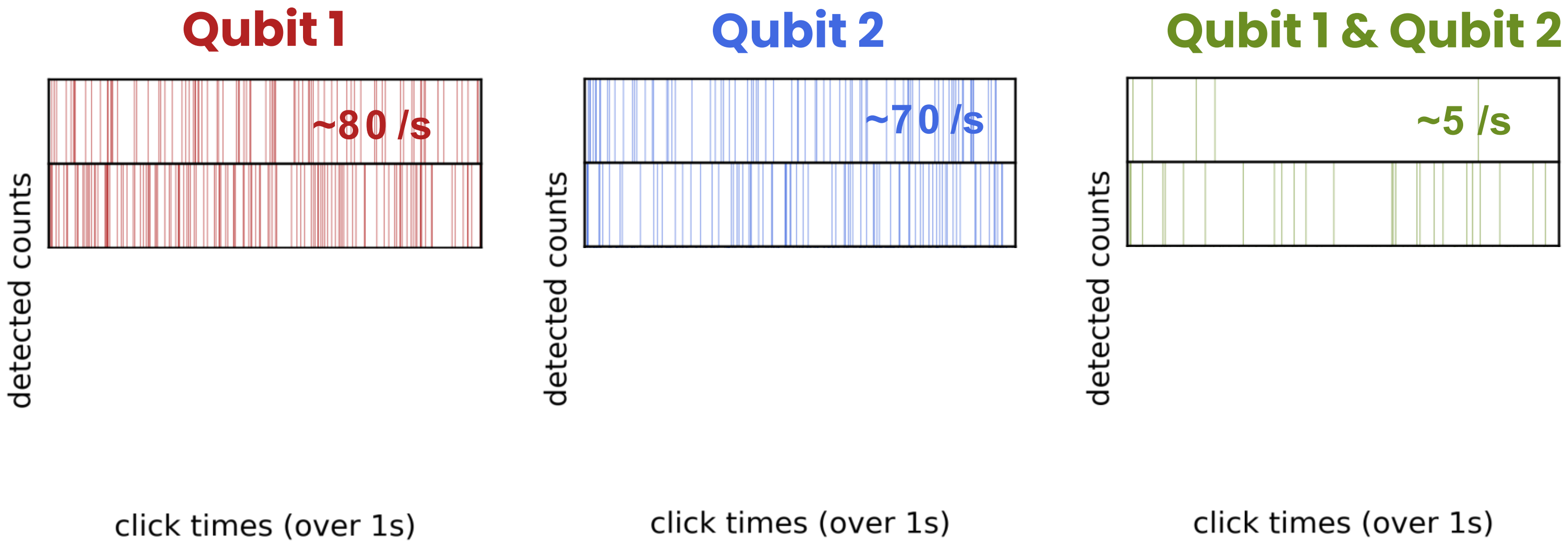
Input Photon flux (s^{-1})	Input Power (zW)
0	0.0

Qubit 1 | Qubit 2 | Qubit 1 & Qubit 2



Efficiency & Dark count rate calibration

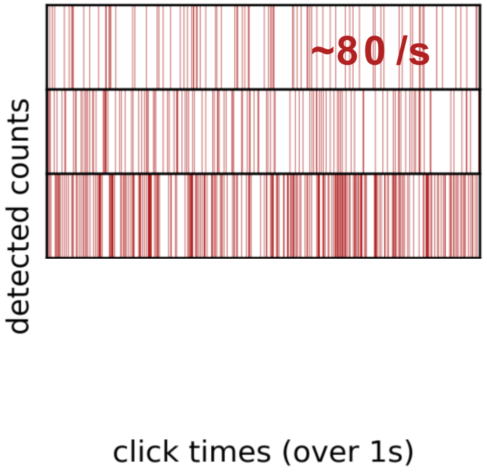
Input Photon flux (s^{-1})	Input Power (zW)
0	0.0
120	0.7



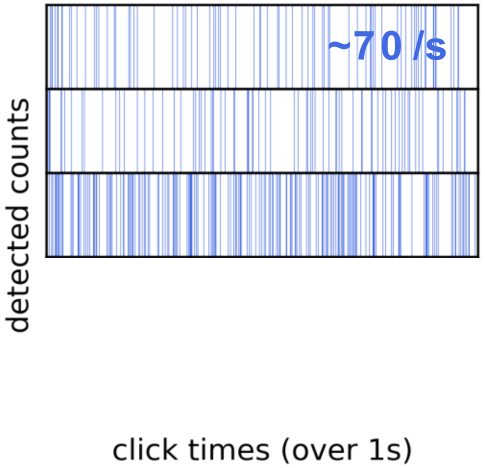
Efficiency & Dark count rate calibration

Input Photon flux (s^{-1})	Input Power (zW)
0	0.0
120	0.7
463	2.7

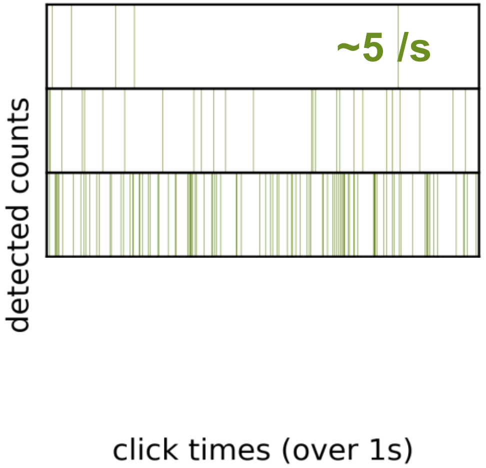
Qubit 1



Qubit 2



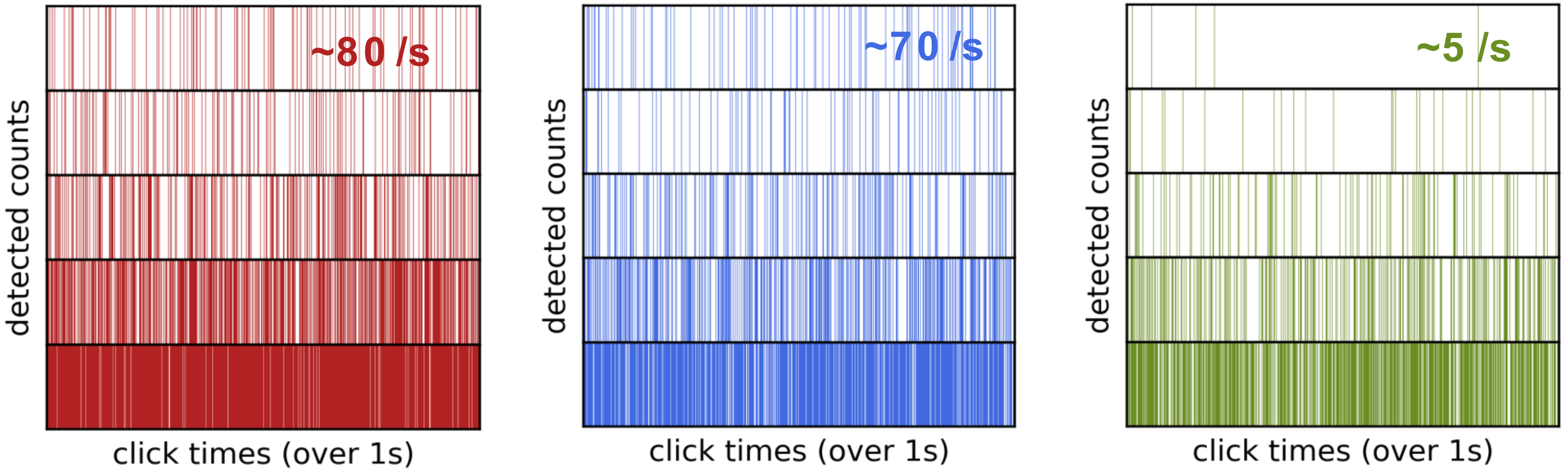
Qubit 1 & Qubit 2

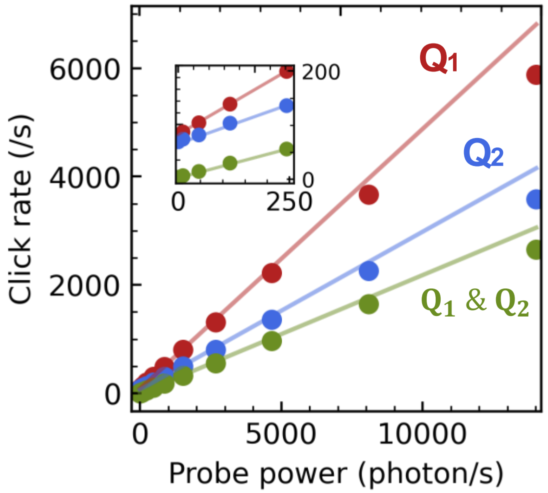


Efficiency & Dark count rate calibration

Input Photon flux (s^{-1})	Input Power (zW)
0	0.0
120	0.7
463	2.7
1526	8.9
4665	27.2

Qubit 1 **Qubit 2** **Qubit 1 & Qubit 2**





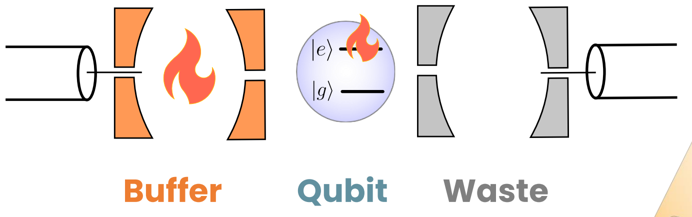
$\eta \approx 0.25$

$\alpha \approx 5\ c/s$

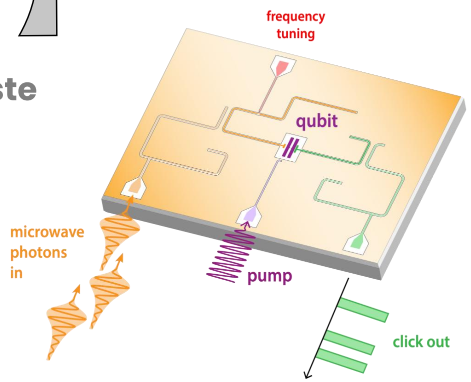
$$\begin{cases} \alpha_{err} \approx 0.1\ c/s \\ \alpha_{th} \approx 5\ c/s \end{cases}$$

Where we were, are, and are headed

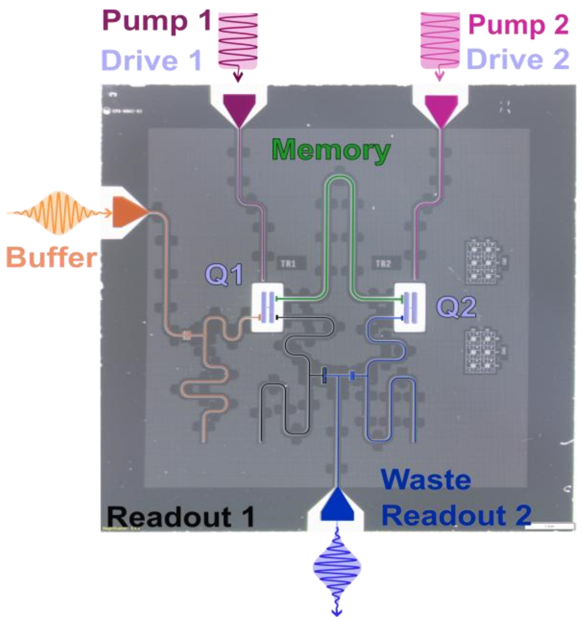
$T_{\text{eff}} \approx 40\ \text{mK}$



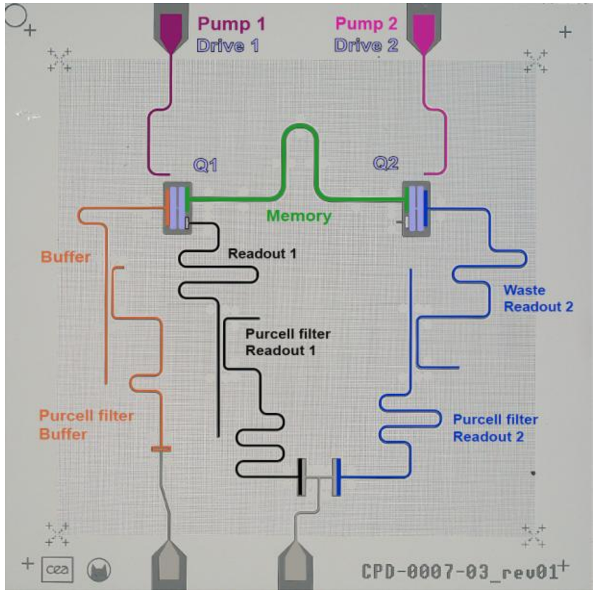
1 qubit
Freq & BW tunable



2 qubits
BW tunable



2 qubits, higher frequency
BW tunable



Input frequency [GHz]	7,3	8,8	11,7
Efficiency	0,75	$0,25$	$0,35$ Better T_1
α_{th}	≈ 20 (BW~170 kHz)	≈ 5 (BW~230 kHz)	$\approx 0,01$ (BW~300 kHz)
α_{q}	≈ 10	$\approx 0,1$	$\approx 0,1$
α_{p}	≈ 2	$\approx 0,01$	≈ 4
Sensitivity $= \hbar\omega\frac{\sqrt{\alpha}}{\eta}\left[\frac{\text{W}}{\sqrt{\text{Hz}}}\right]$	$\approx 3\times 10^{-23}$	$\approx 5\times 10^{-23}$	$\approx 4\times 10^{-23}$

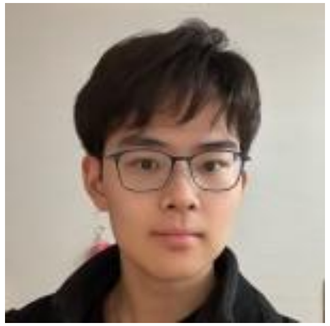
Aknowledgements

cea cnrs université PARIS-SACLAY

J. Travesedo

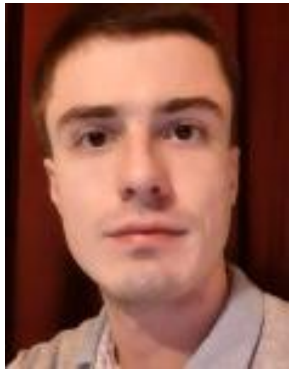
D. Haegi

W. Huang



L. Suteveski

L. Pallegoix



A. May

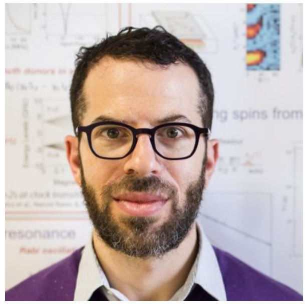
X. Zhou

A. Pscherer

J. O’Sullivan

D. Vion

P. Bertet



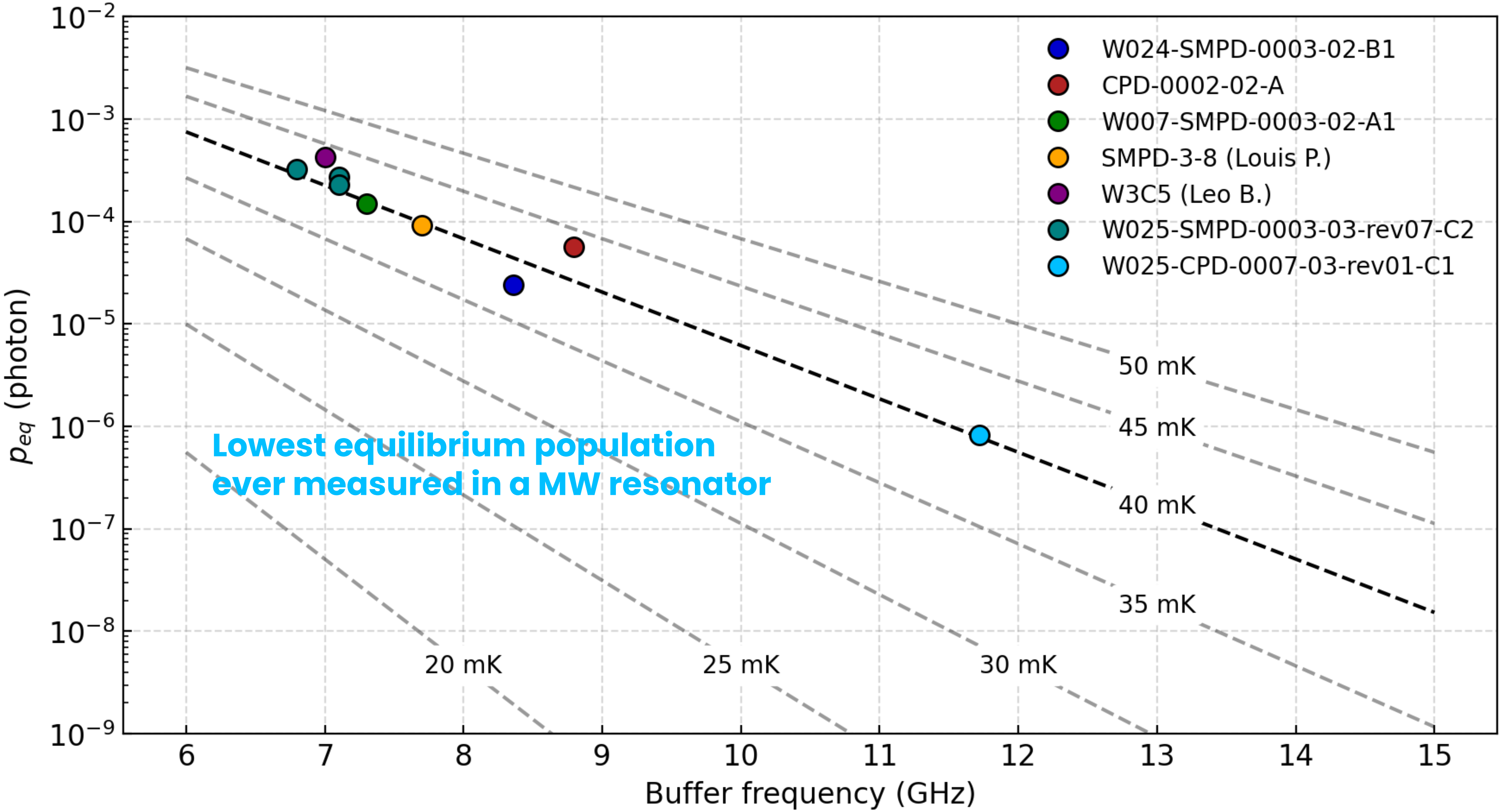
erc Starting Grant

ROBUST SUPERQ

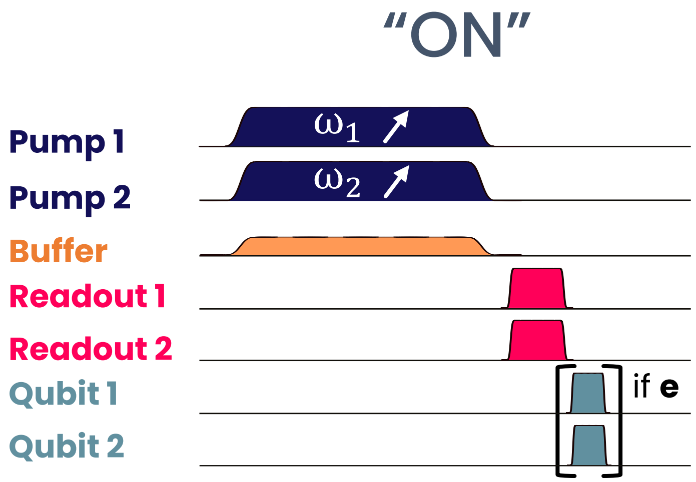
ANR AGENCE NATIONALE DE LA RECHERCHE

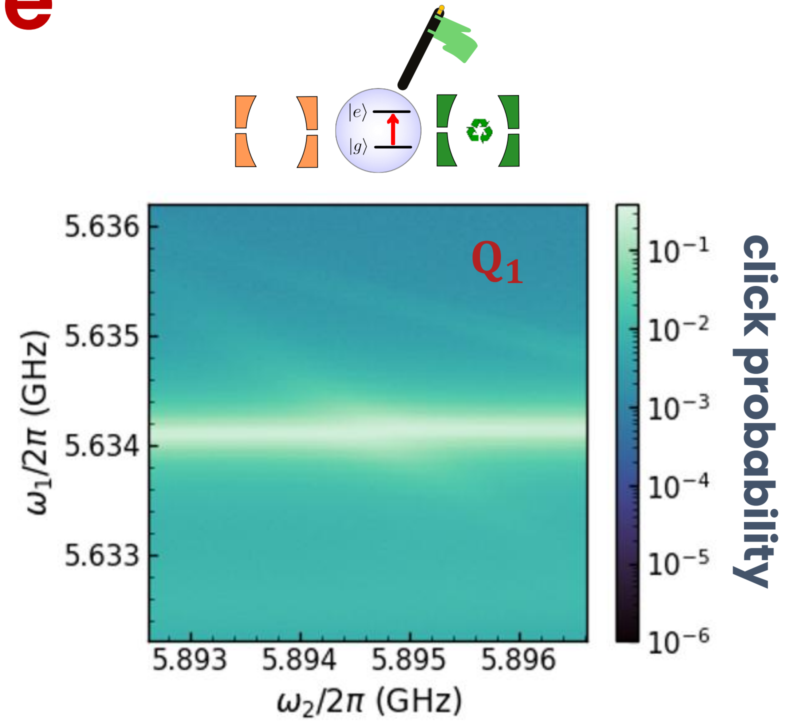
QuanTiP

Thermometry across several SMPD devices



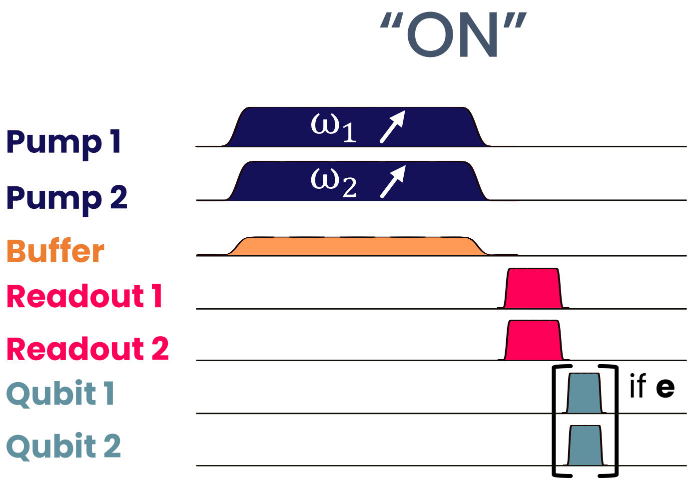
Proof of principle

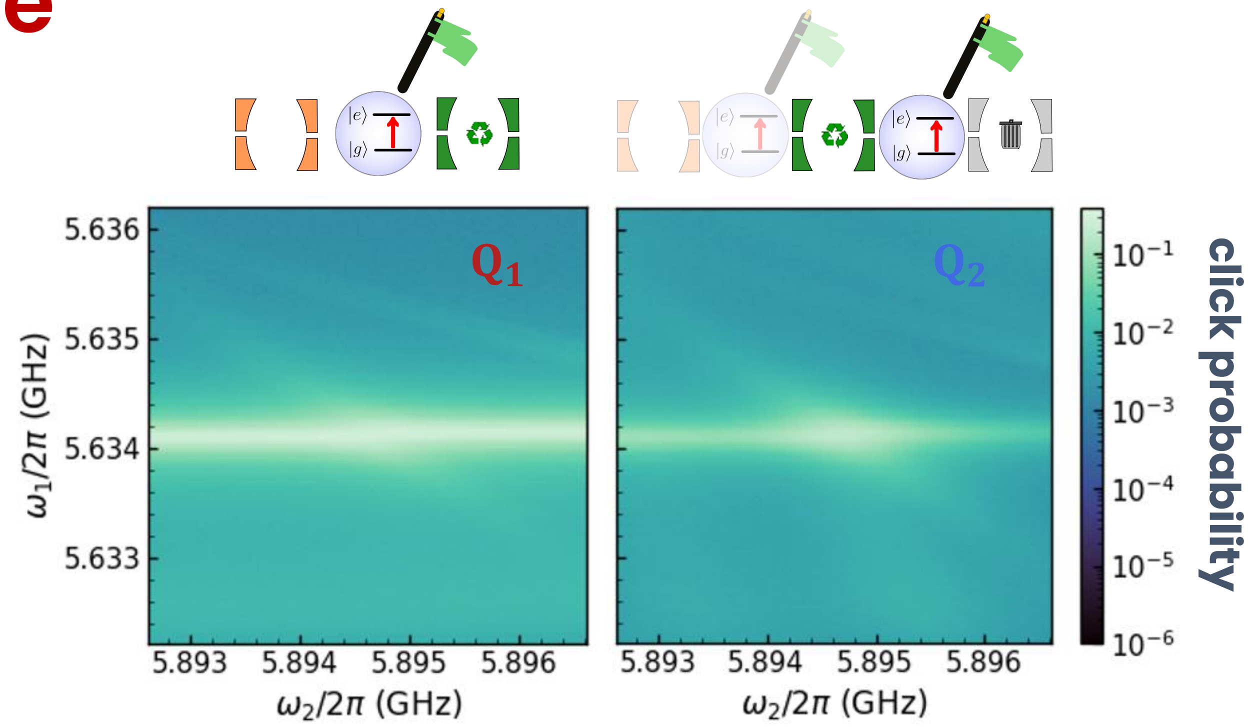




* With active reset

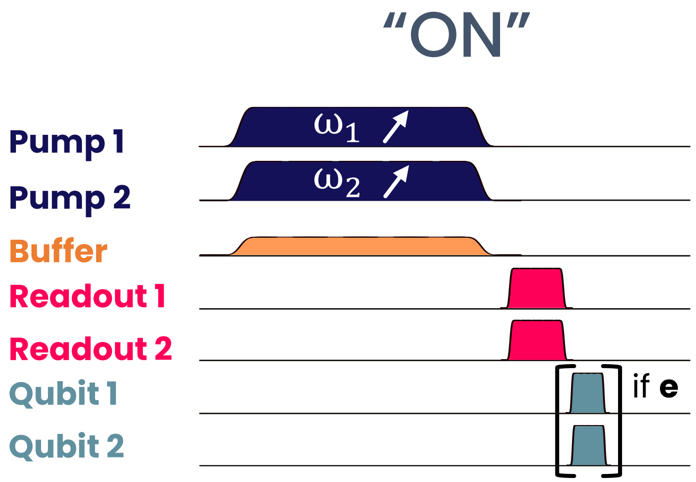
Proof of principle

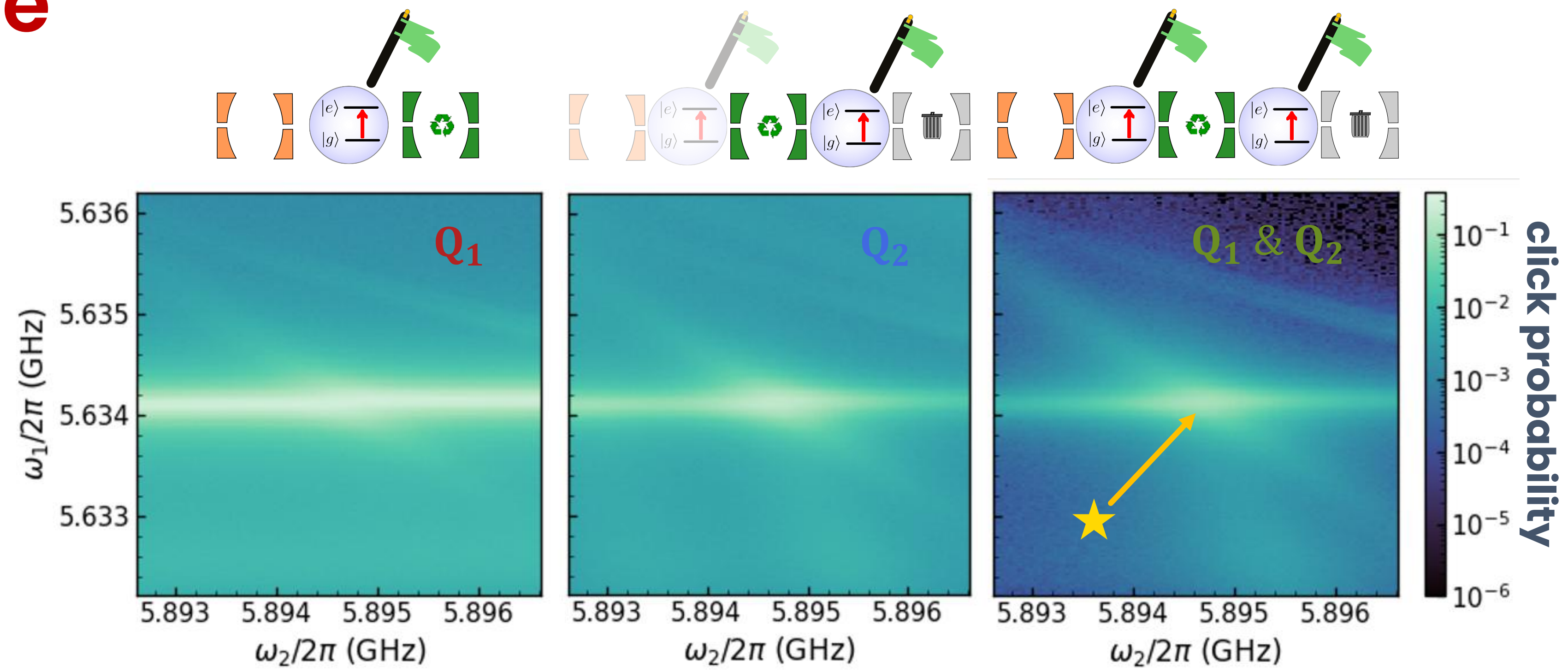




* With active reset

Proof of principle

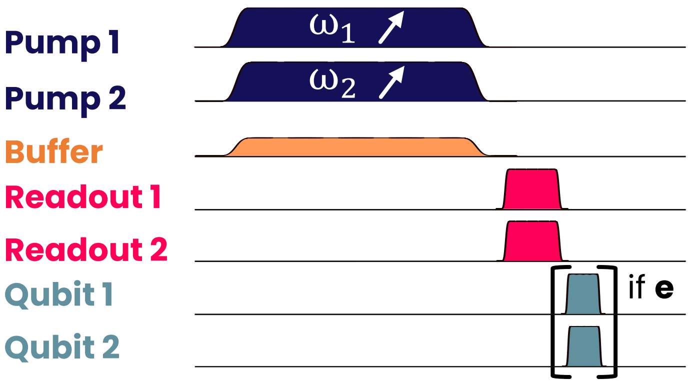


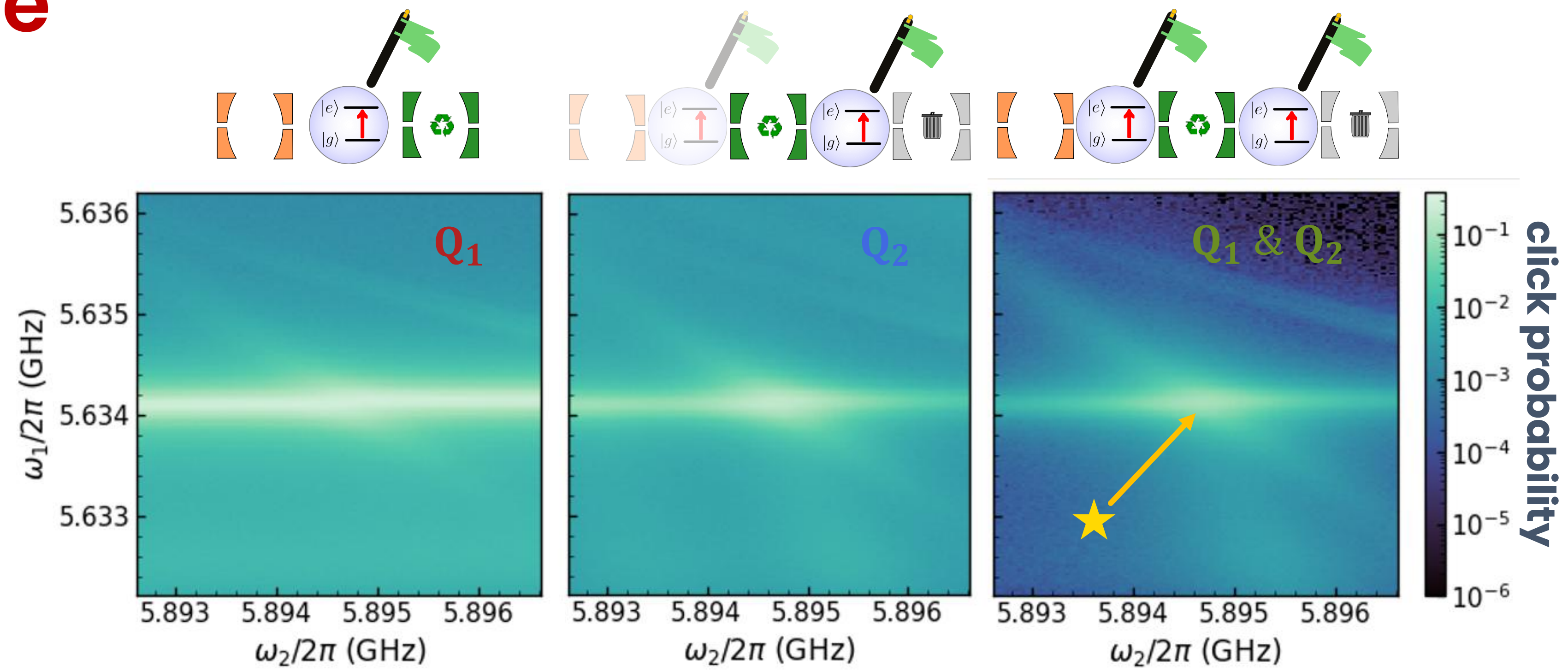


* With active reset

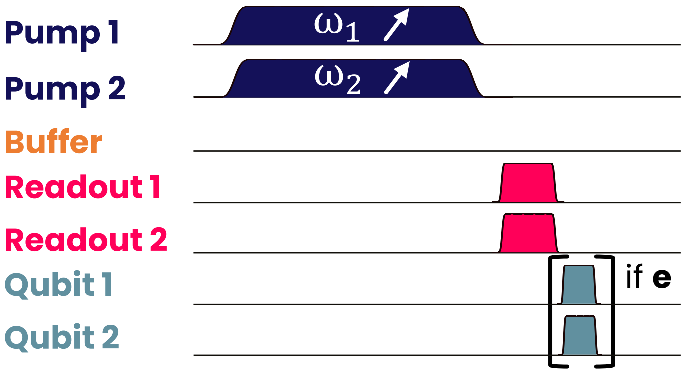
Proof of principle

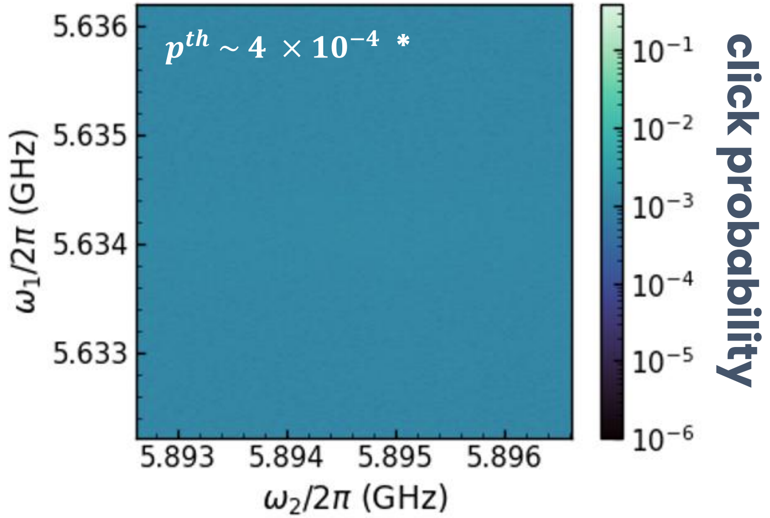
"ON"





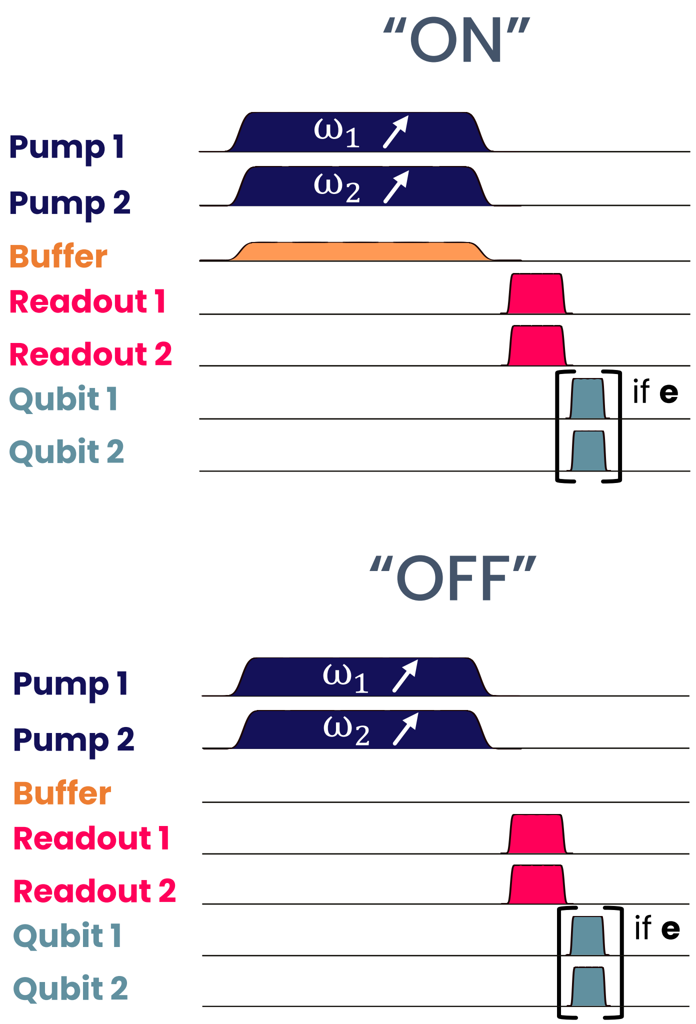
"OFF"

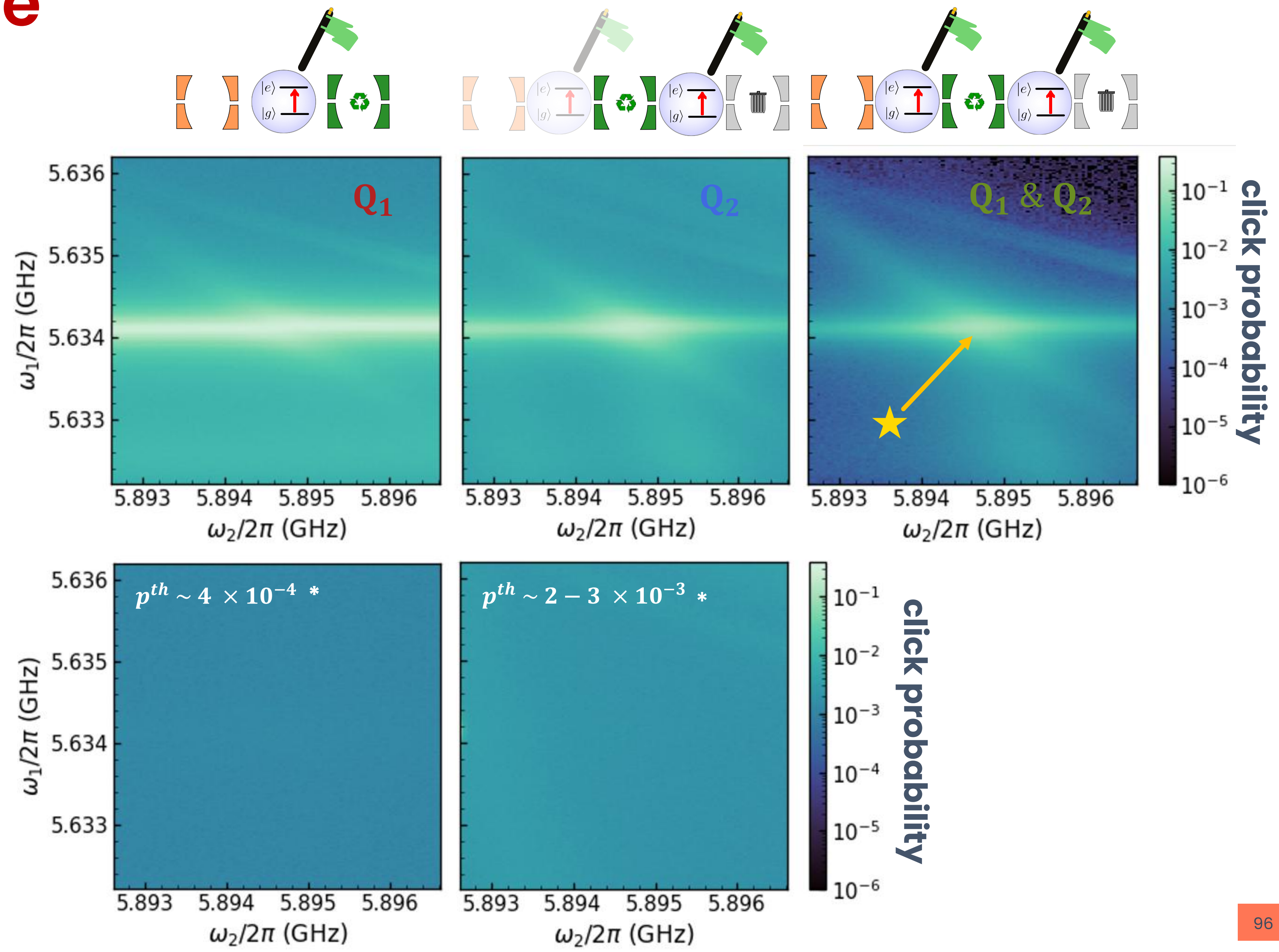




* With active reset

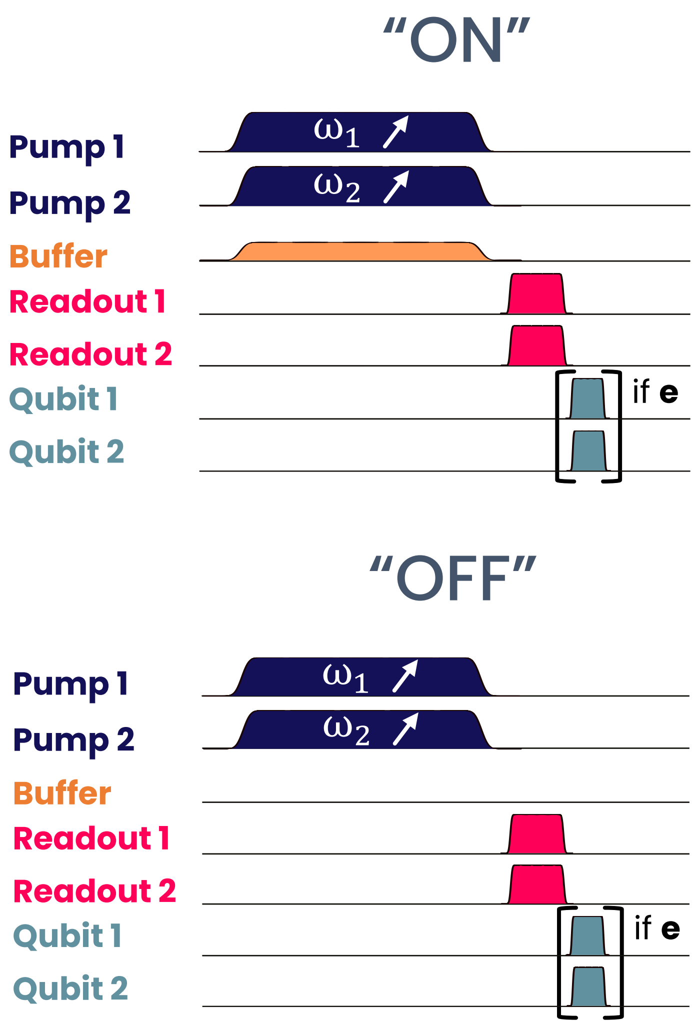
Proof of principle

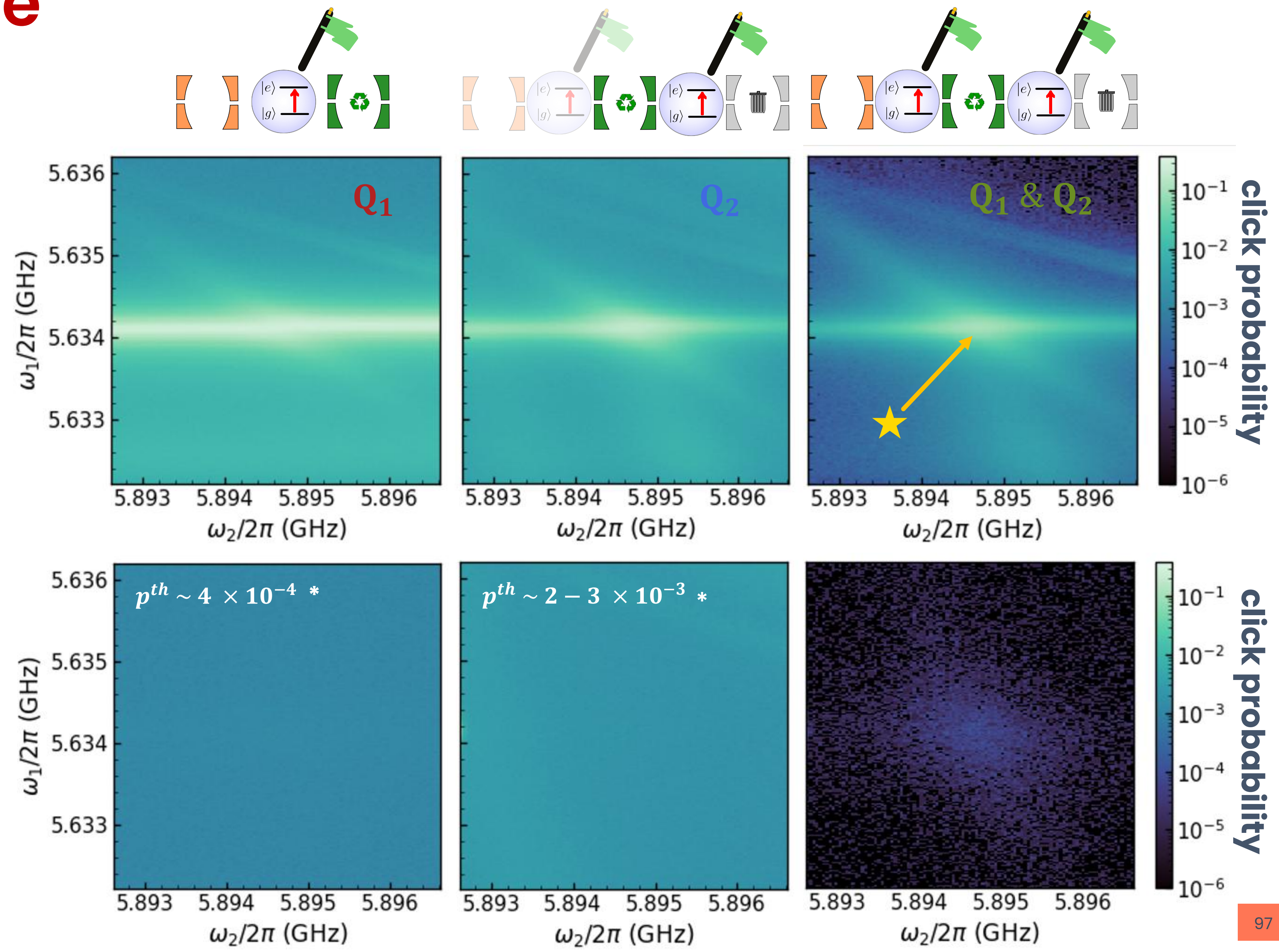




* With active reset

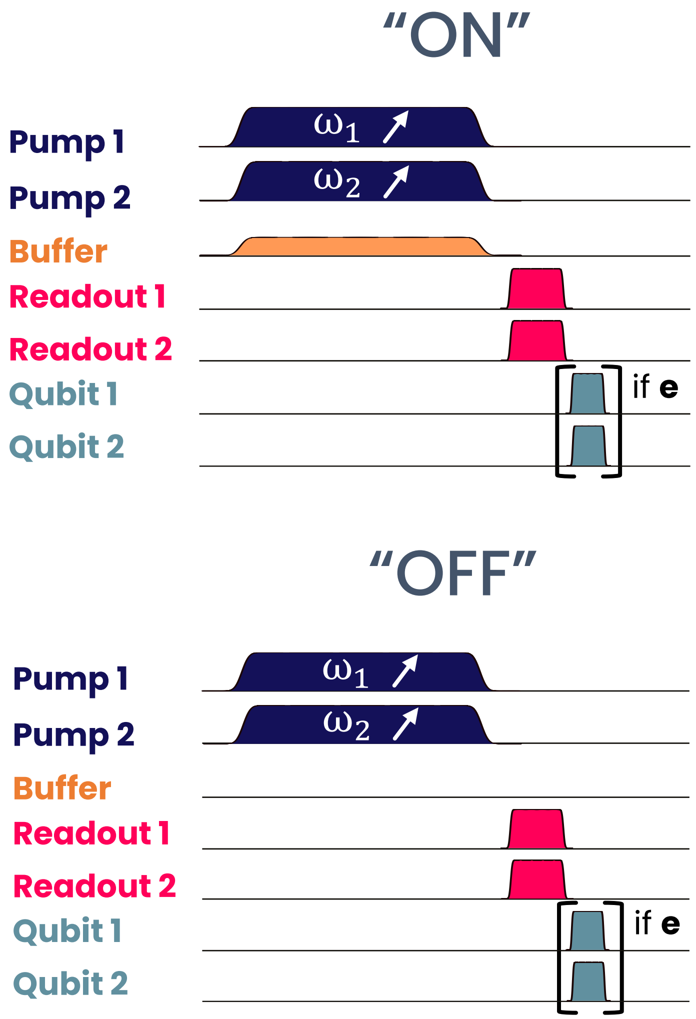
Proof of principle

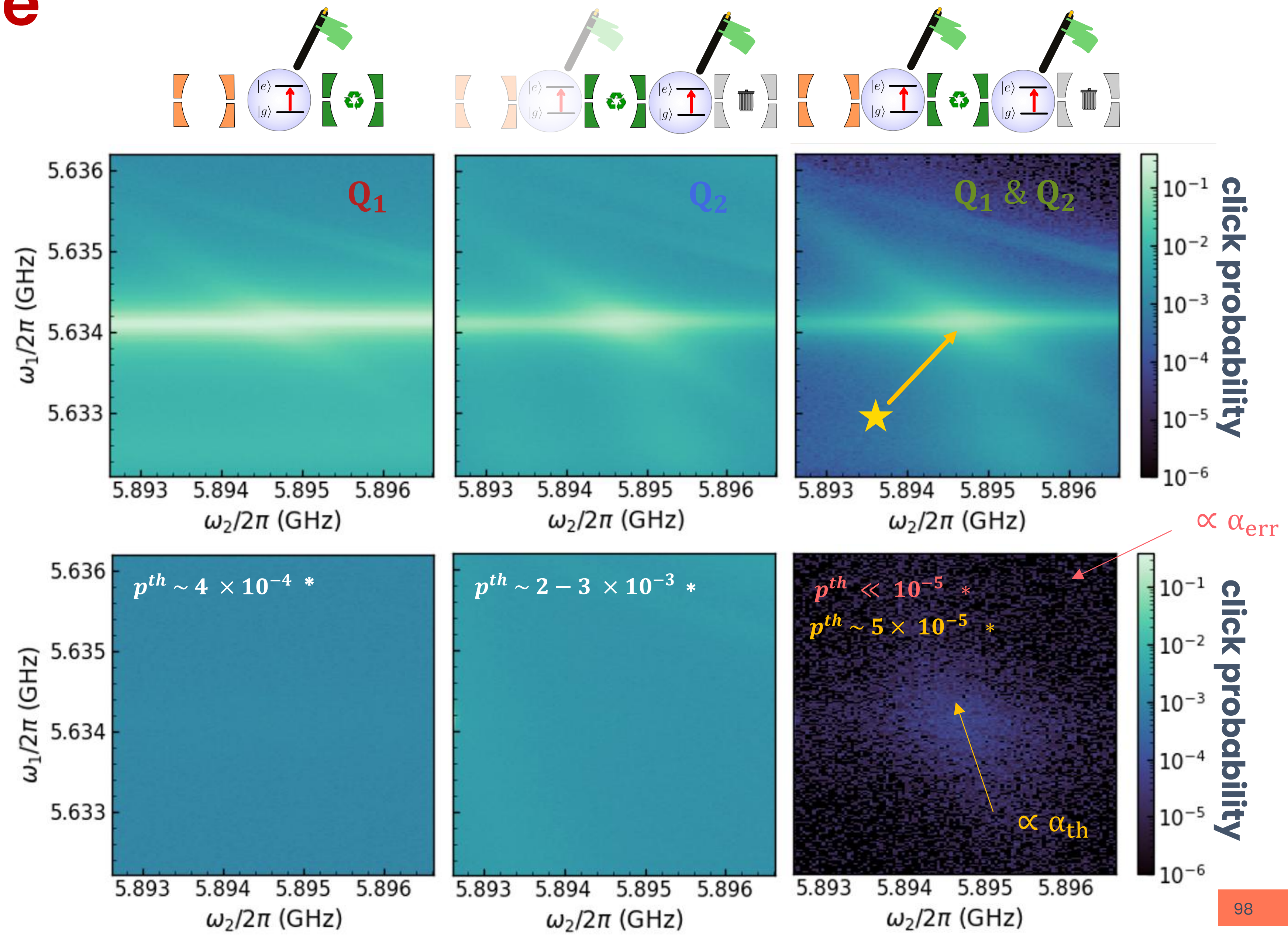




* With active reset

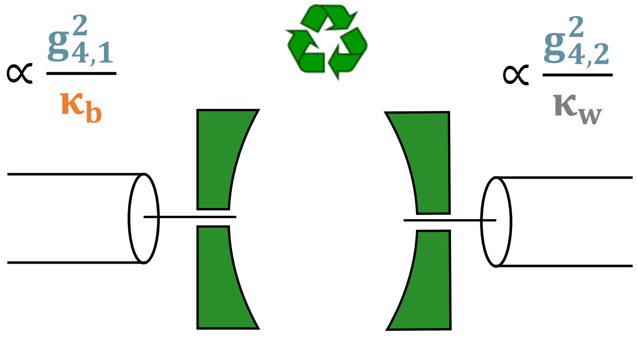
Proof of principle





* With active reset

Intrinsic Bandwidth tunability



$$\mathrm{BW} \propto \frac{\xi_1^2}{\kappa_b} \propto \frac{\xi_2^2}{\kappa_w}$$