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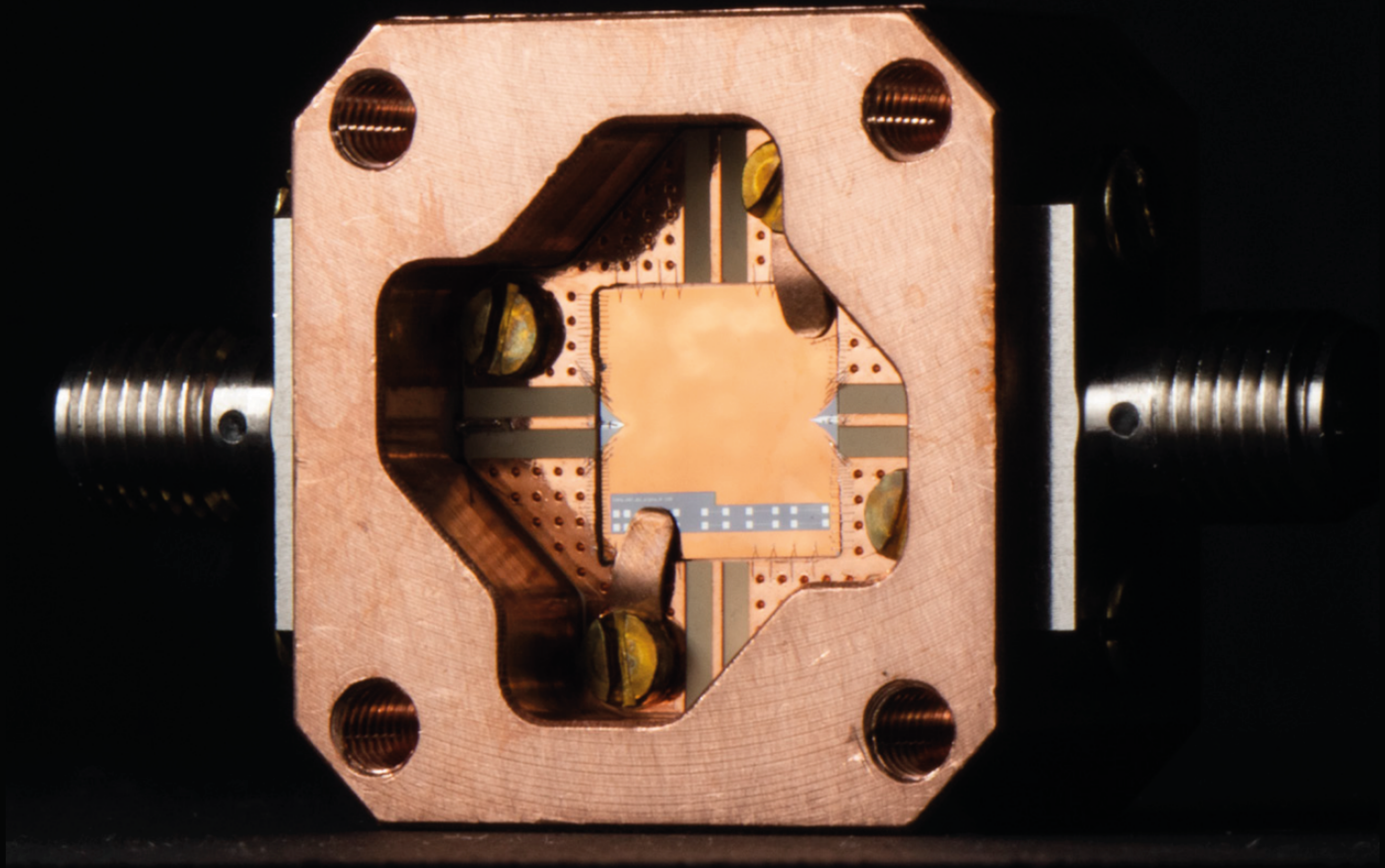
Josephson waveguides: a new platform for quantum optics



Nicolas Roch, Institut Néel, Grenoble, France

Congrès général de la Société Française de Physique

The “TWPA team”


Luca
Planat


Martina
Esposito


Arpit
Ranadive


Gwenael
Le Gal


Giulio
Cappelli


Bekim
Fazliji

SILENT WAVES

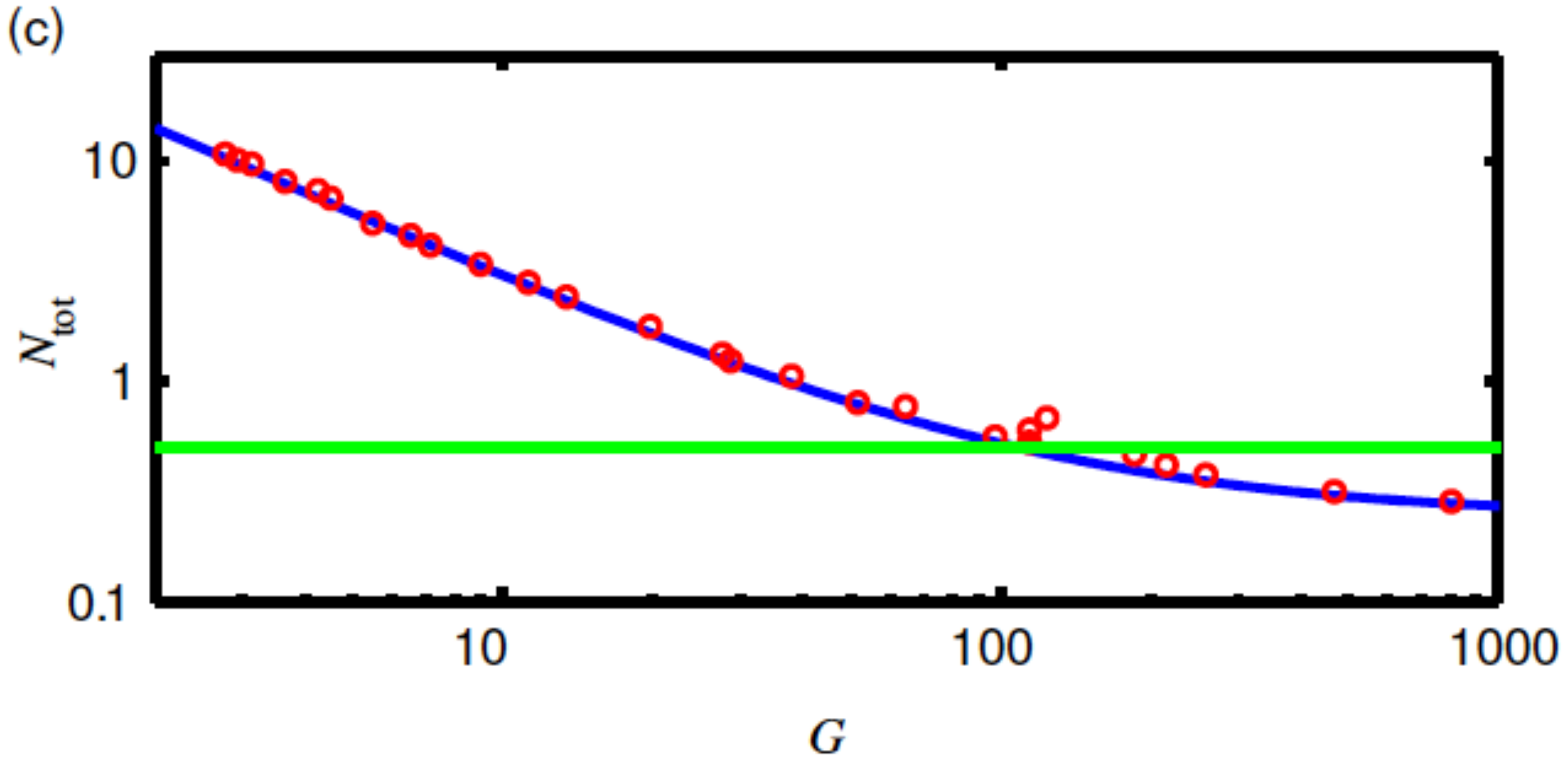
SPIN

Collaborations

D. Basko (LPPMC, Grenoble), **A. Metelmann** (KIT, Germany), **T. Meunier/ M. Urdampilleta** (Inst. Néel, Grenoble), **E. Collin** (Inst. Néel, Grenoble), **I. Pop** (KIT, Germany), **P. Forn Diaz** (Barcelona), **R. Vijay** (TIFR, India), **K. Murch** (Washington University, USA), **P. Leek** (Oxford, UK), **M. Stern** (Bar Ilan, Israël), **Joe Aumentado/Florent Lecocq** (NIST, USA), **MADMAX Collaboration**, **GraHal Collaboration**, **QUAX Collaboration**, **ARPEJ Collaboration** (ESPCI, TRT, C2N)

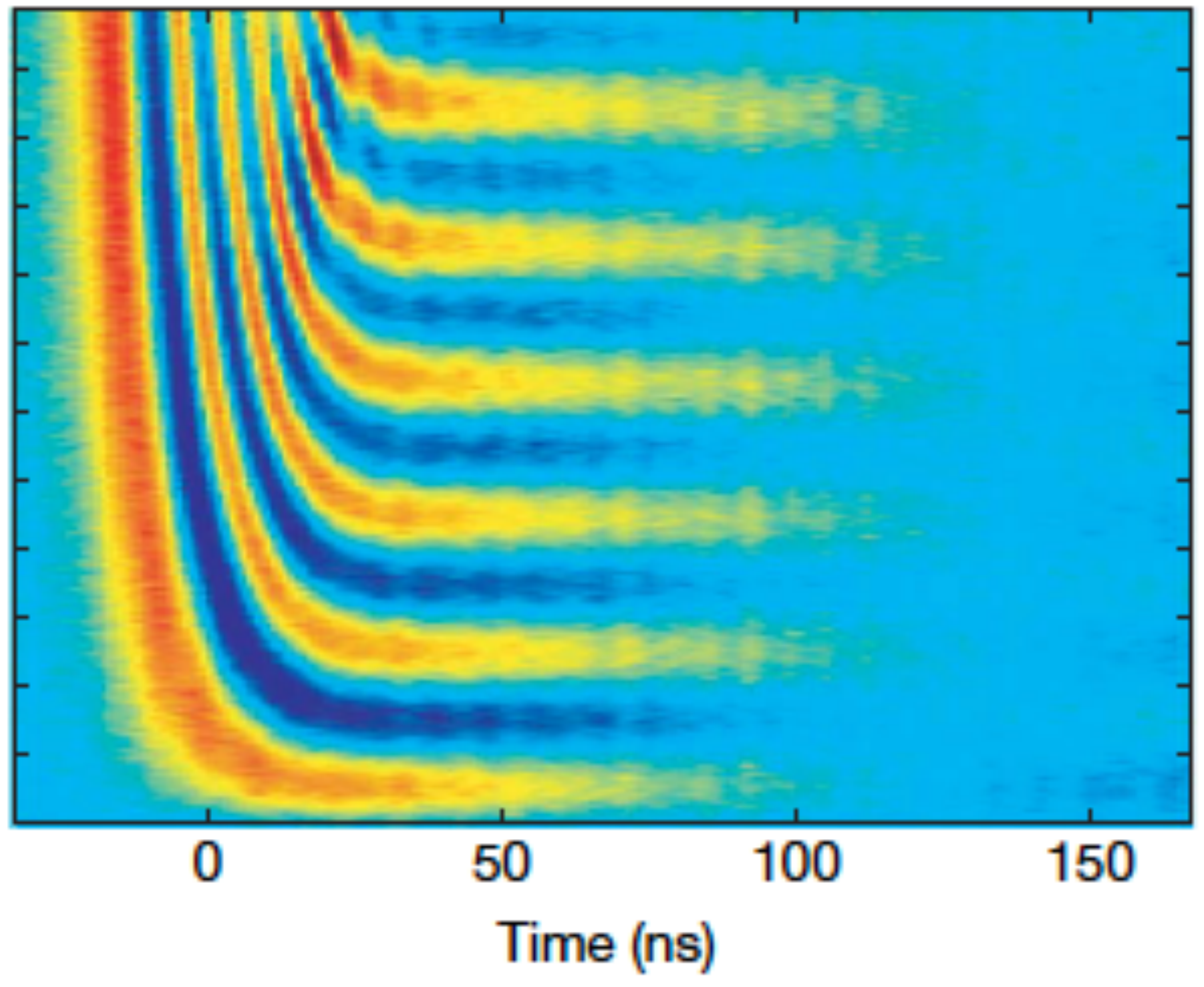
Quantum optics and cQED

Vacuum squeezed states



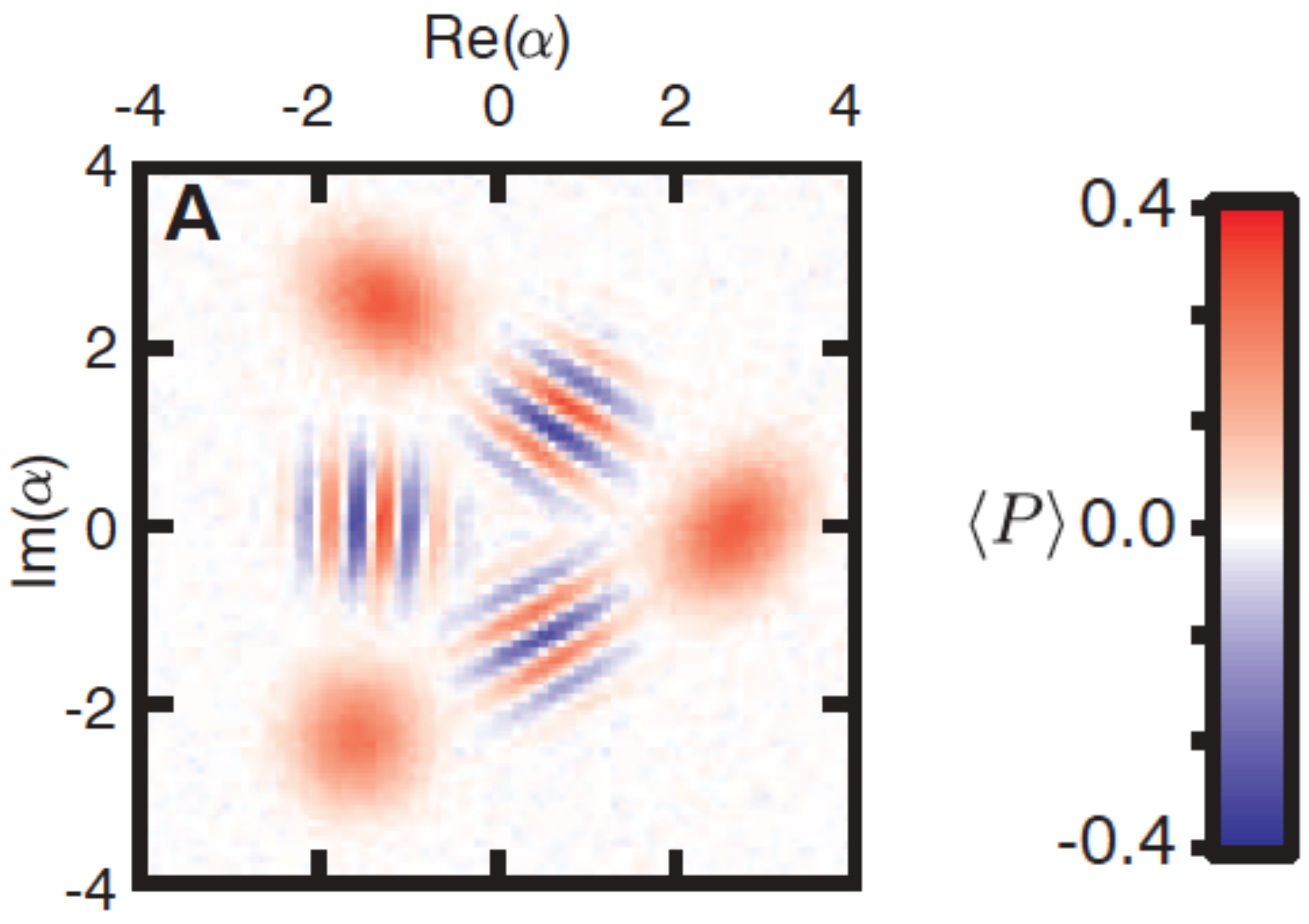
M. Castellanos-Beltran, et al.
Nat. Phys. (2008)

Single microwave photons



A. Houck, et al.
Nature (2007)

Schrödinger Cats



B. Vlastakis et al.
Science (2013)

Can we go beyond the cavity limit?

Outline

Josephson waveguides: fabrication

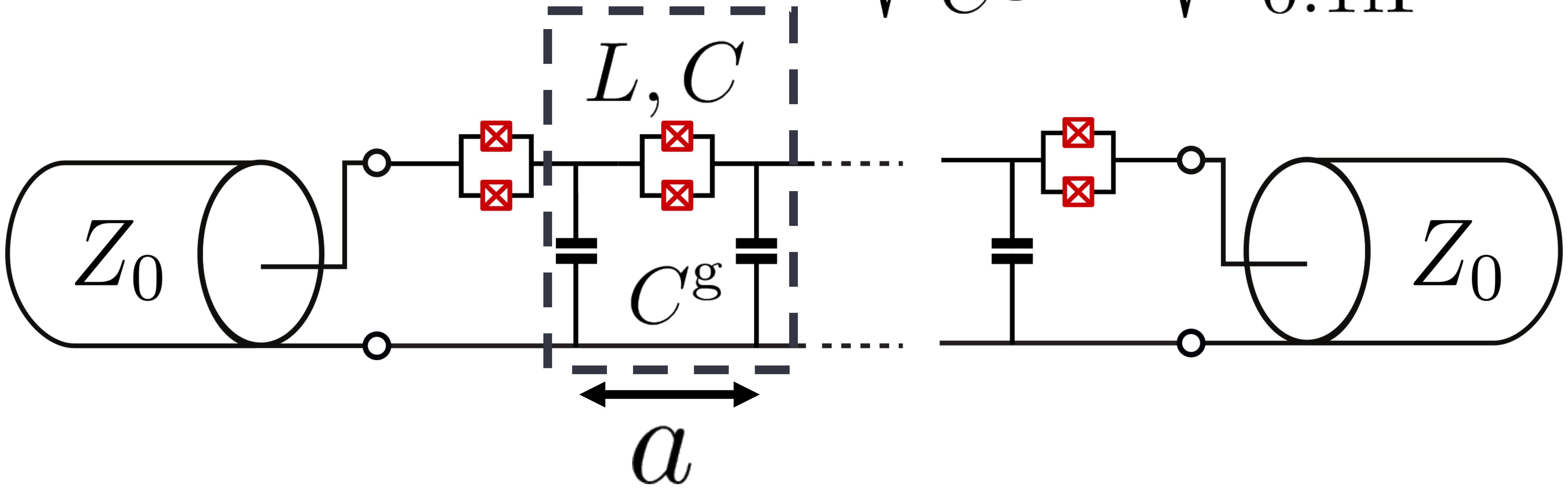
Near quantum limited Traveling Waves Parametric Amplifiers

Vacuum two-mode squeezing in TWPAs

Josephson waveguides: challenge

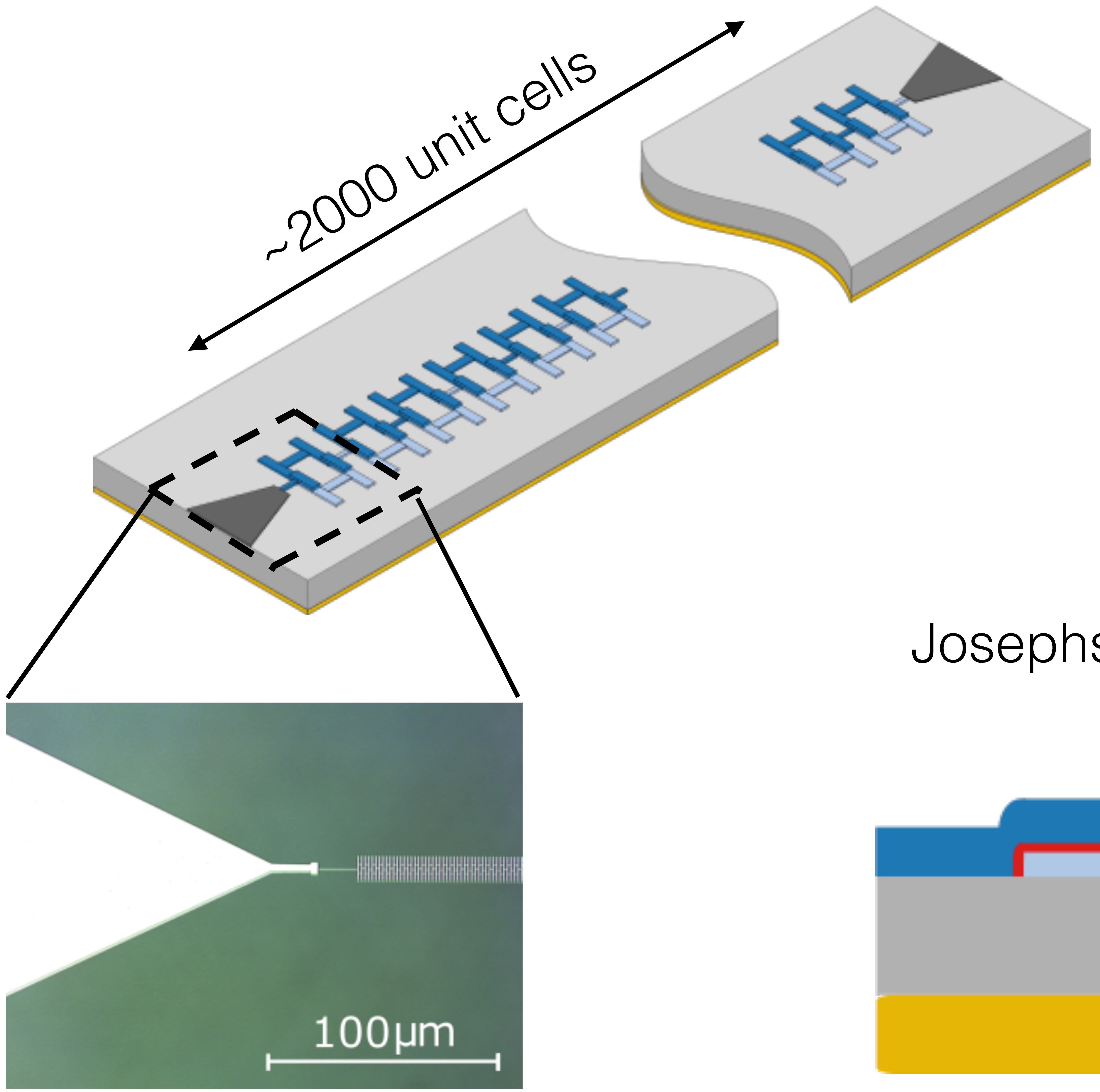
Far from 50 Ohms

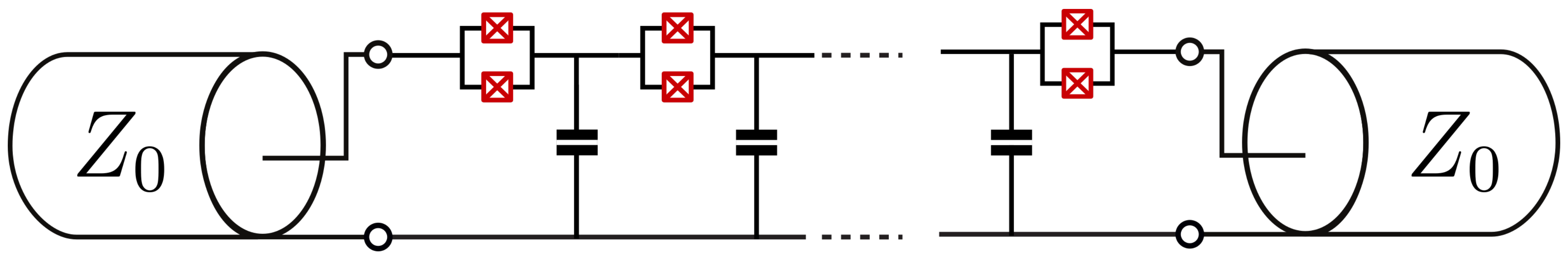
$$Z_{\mathrm{c}} = \sqrt{\frac{L}{C^{\mathrm{g}}}} = \sqrt{\frac{100\mathrm{pH}}{0.1\mathrm{fF}}} \approx \boxed{1\mathrm{k}\Omega}$$



Exemples of high impedance Josephson waveguides: Kuzmin et al., Nat. Phys. (2019), Puertas-Martinez et al., npj Q. Inf. (2019)

Josephson waveguides: fabrication recipe

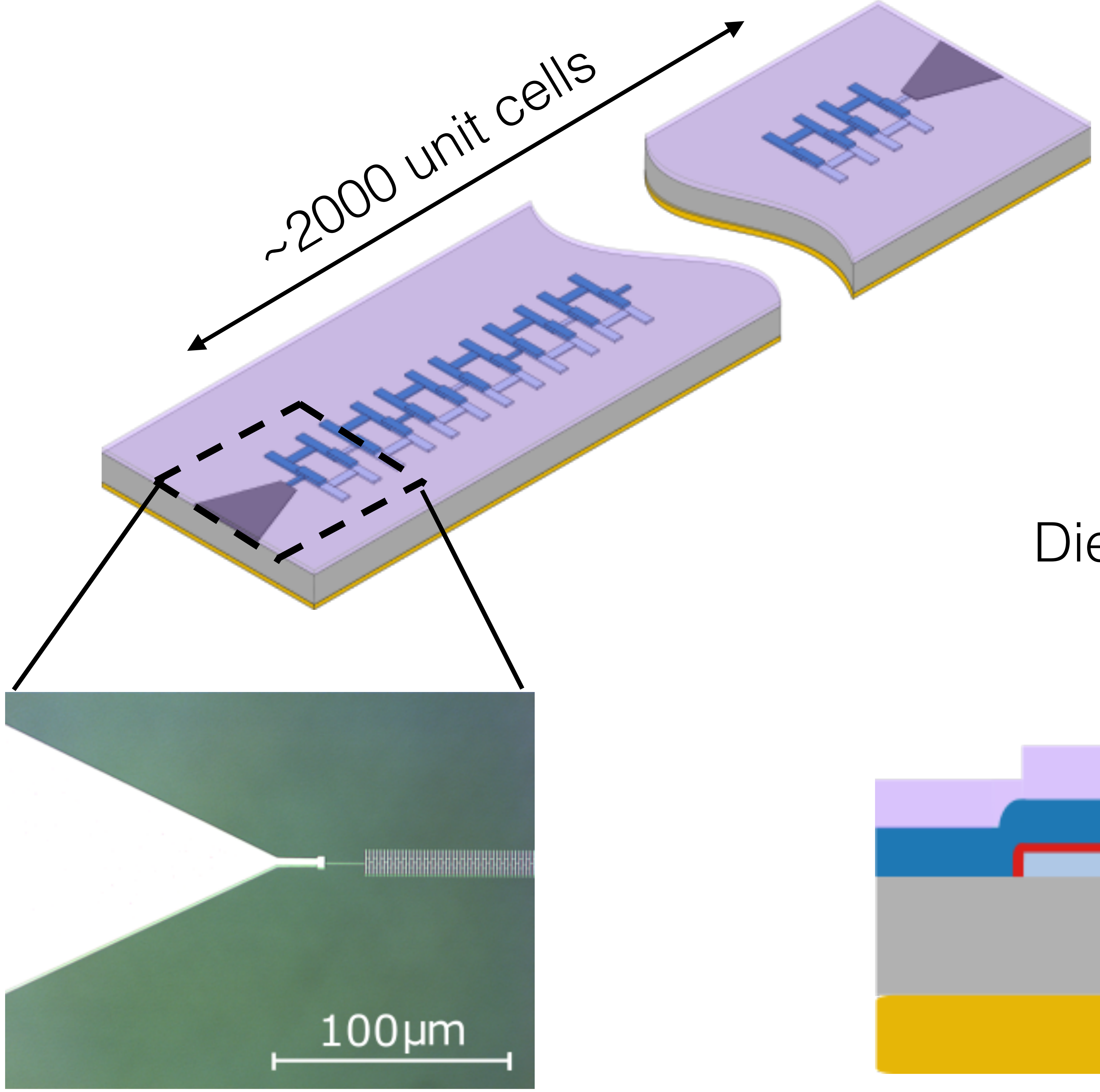


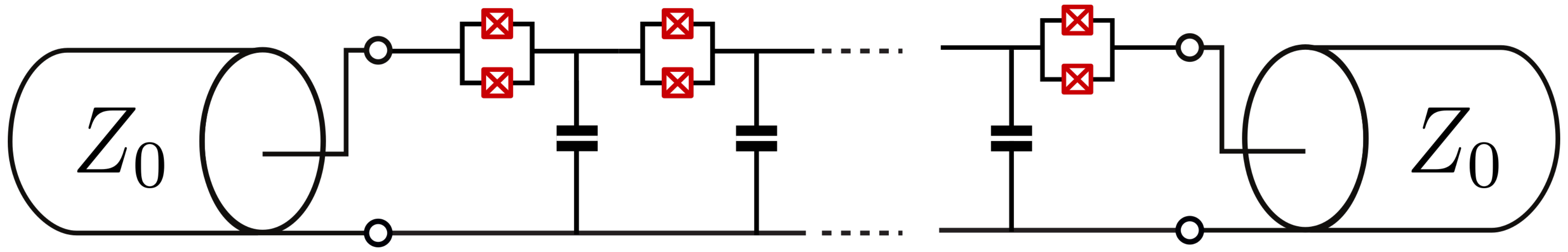


Josephson junction fabrication

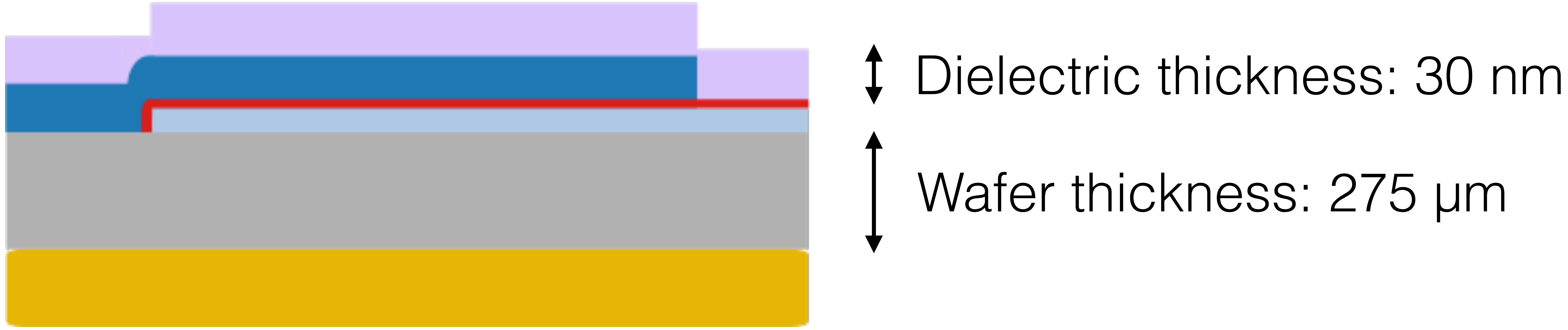
Wafer thickness: 275 µm

Josephson waveguides: fabrication recipe

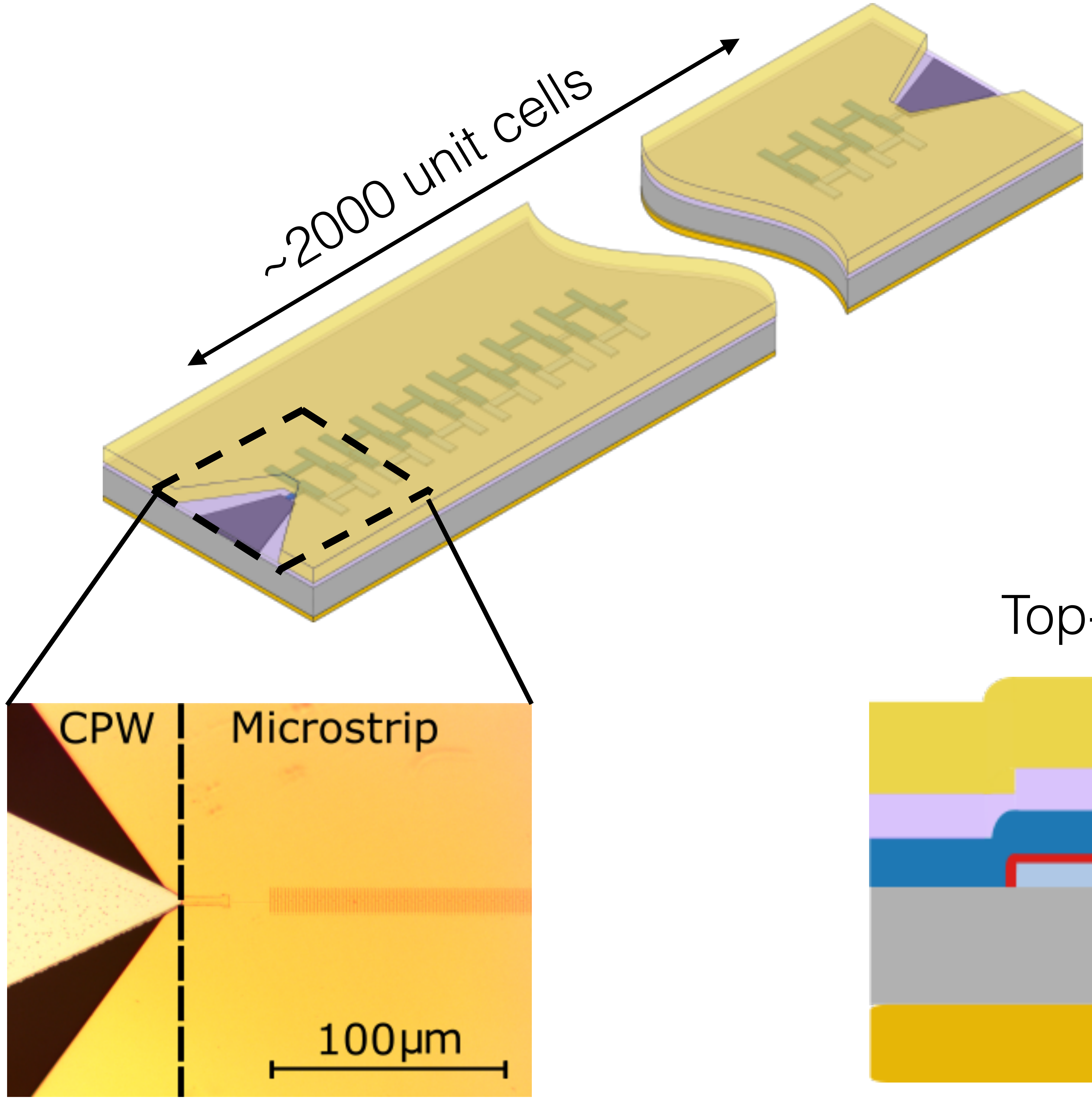


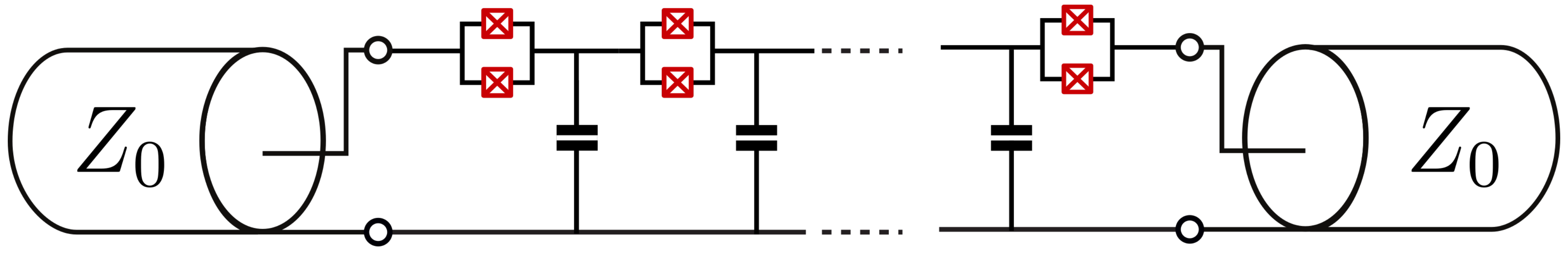


Dielectric deposition
(Al_2O_3, ALD)

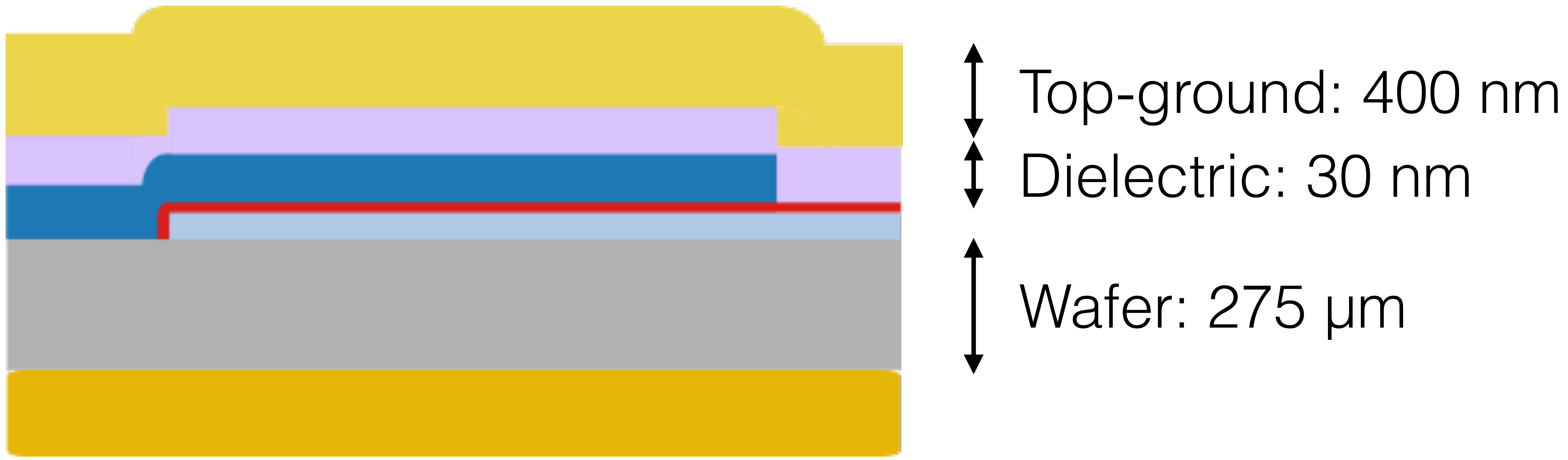


Josephson waveguides: fabrication recipe

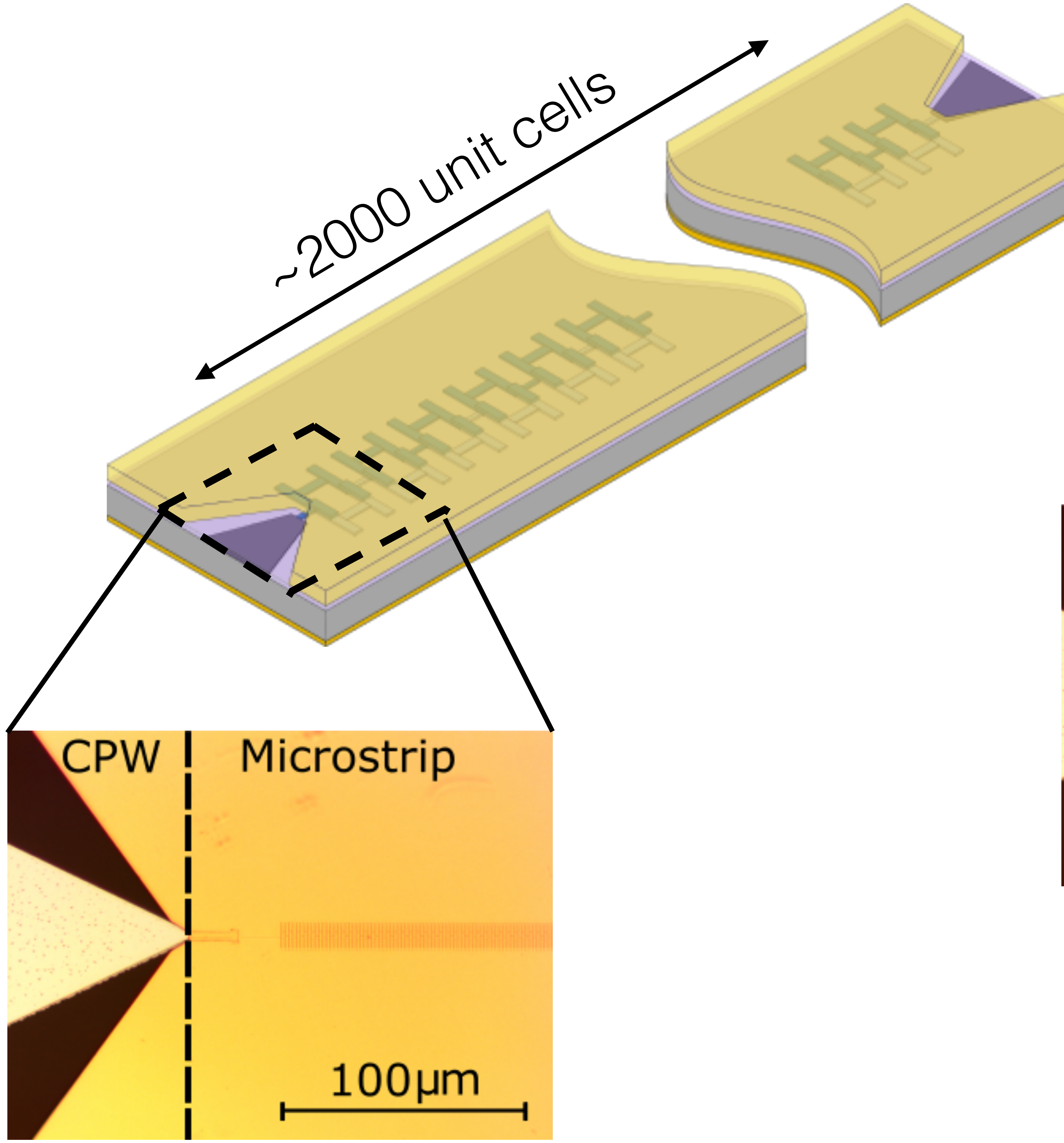


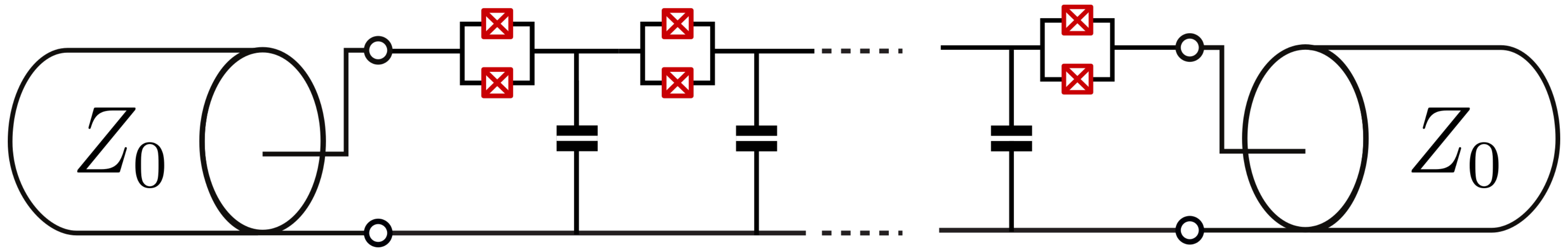


Top-ground deposition



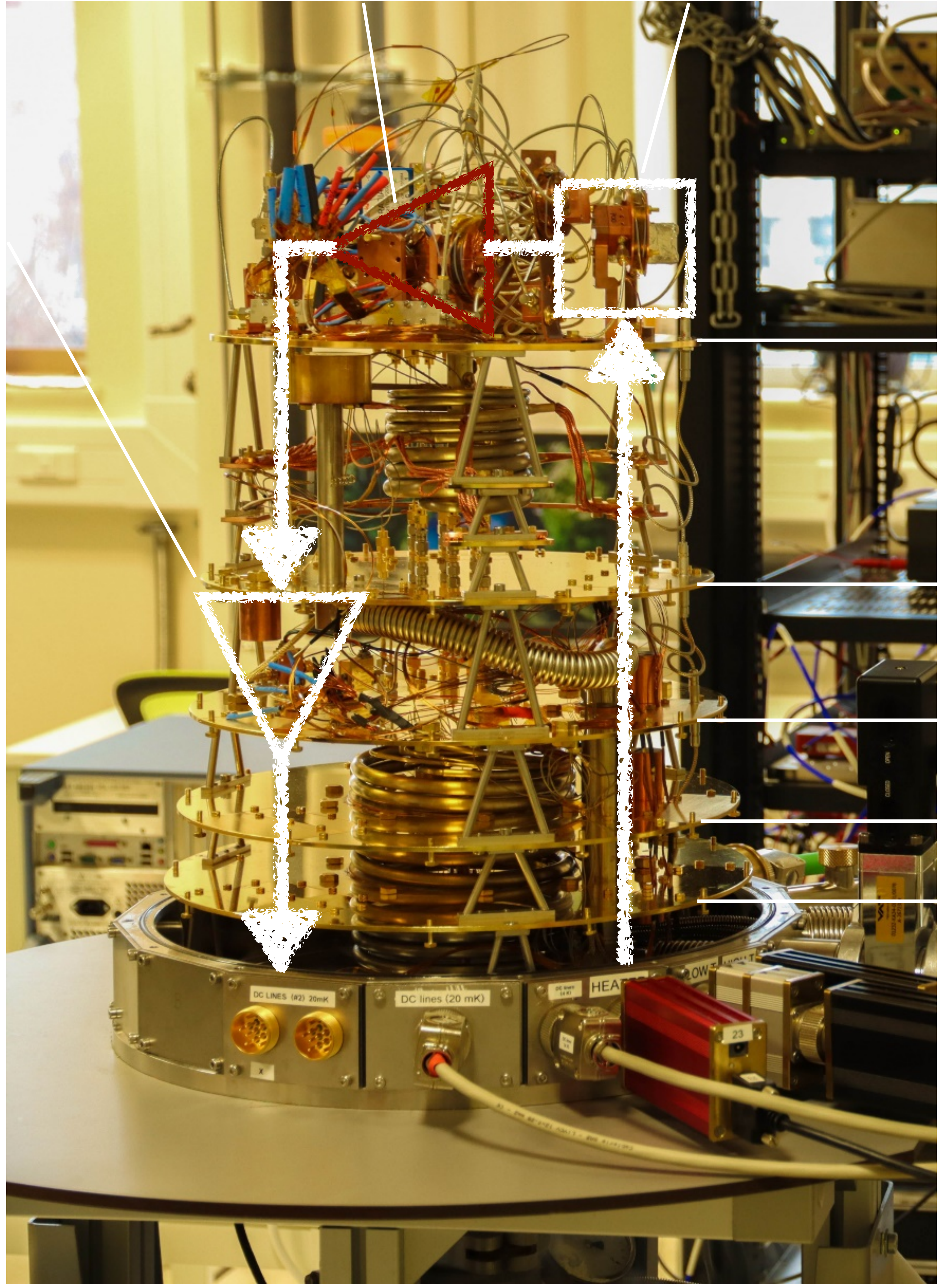
Josephson waveguides: fabrication recipe





C^g	0.1 fF to 40 fF
Z_c	1kOhms to 50 Ohms

Cooling down the circuit



Dilution
fridge

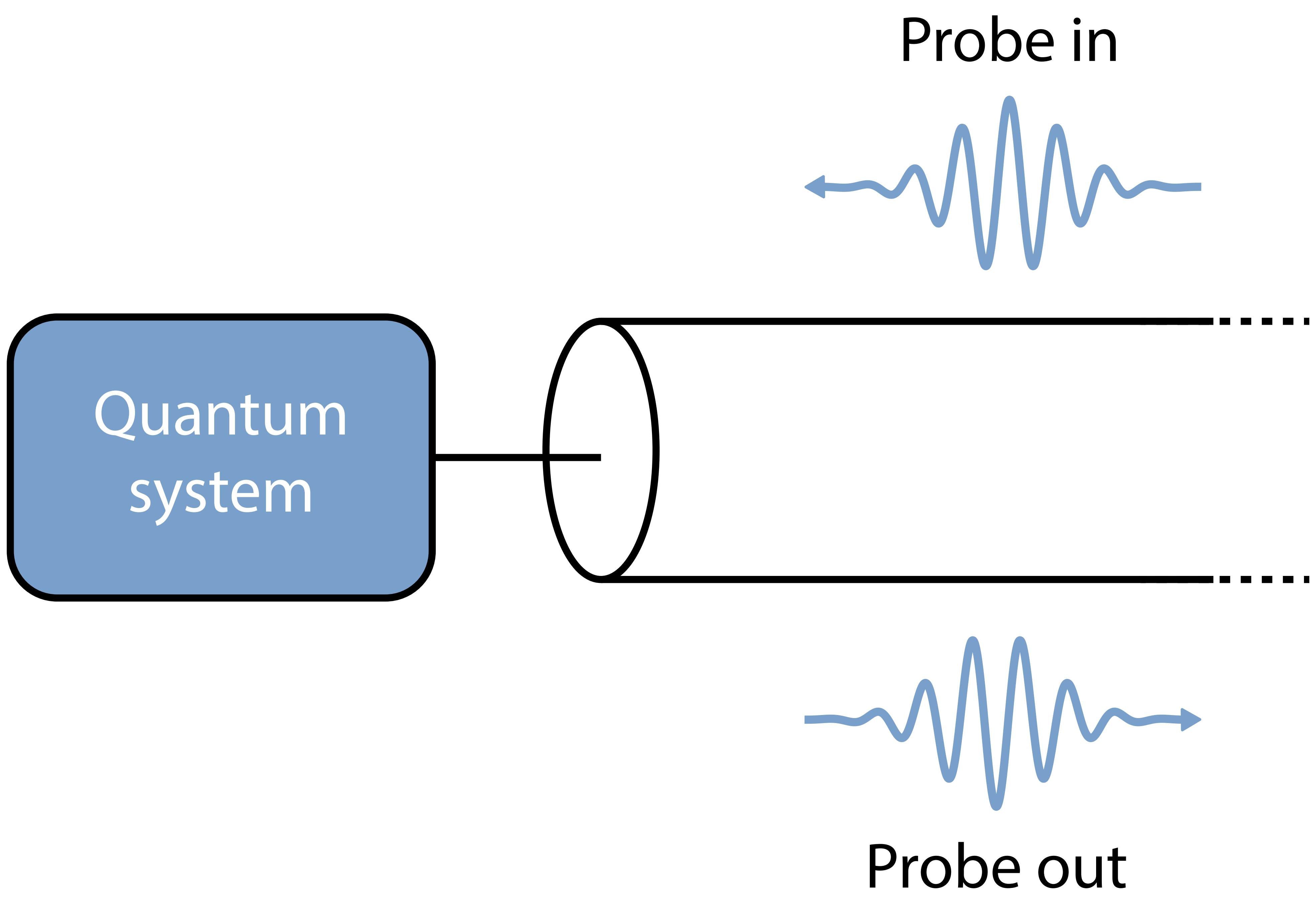
Outline

Josephson waveguides: fabrication

Near quantum limited Traveling Waves Parametric Amplifiers

Vacuum two-mode squeezing in TWPAs

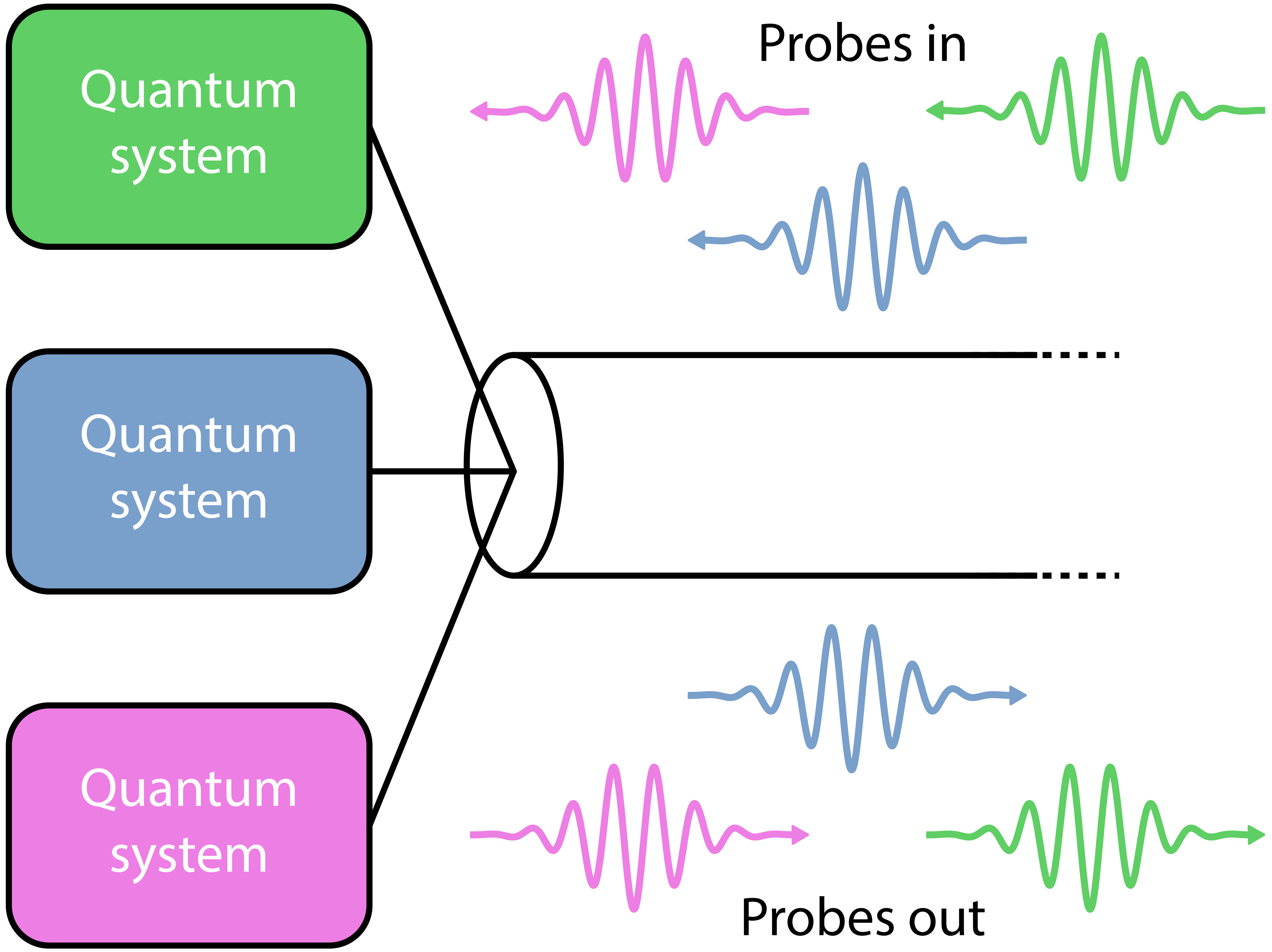
Use-case: ultra low noise amplification



Very low energy (quantum) systems

Probe: few photons

Use-case: ultra low noise amplification



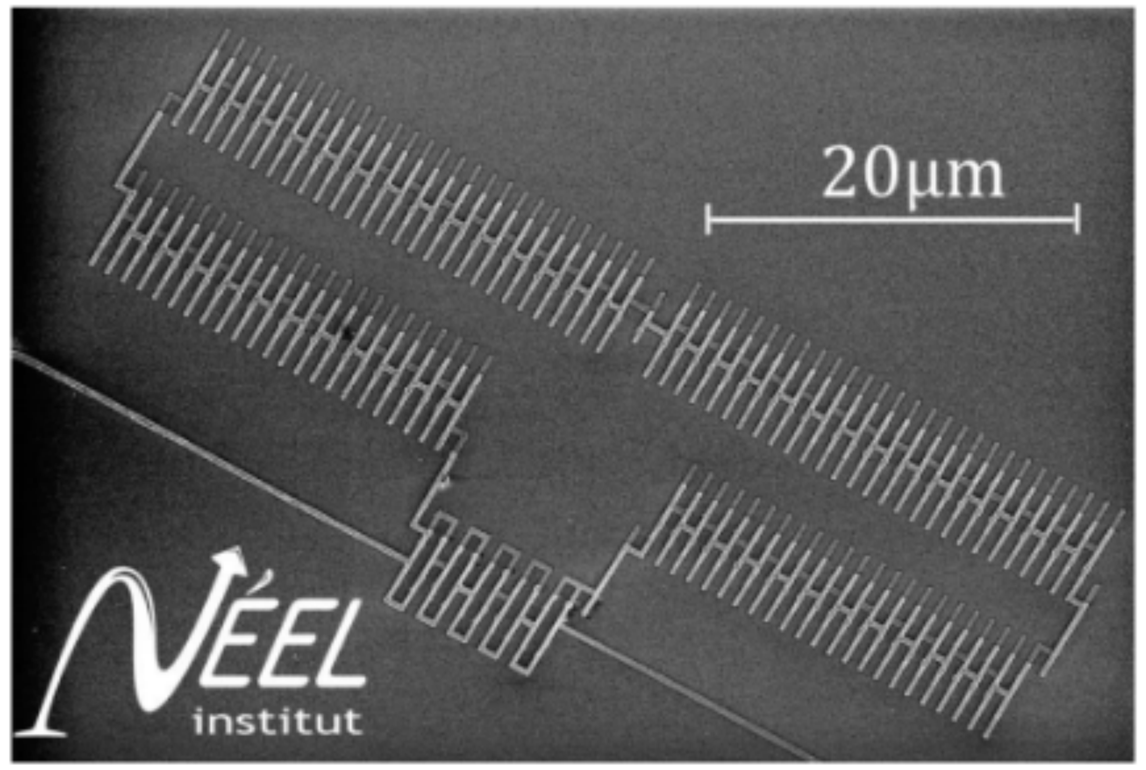
Very low energy (quantum) systems

Probe: few photons

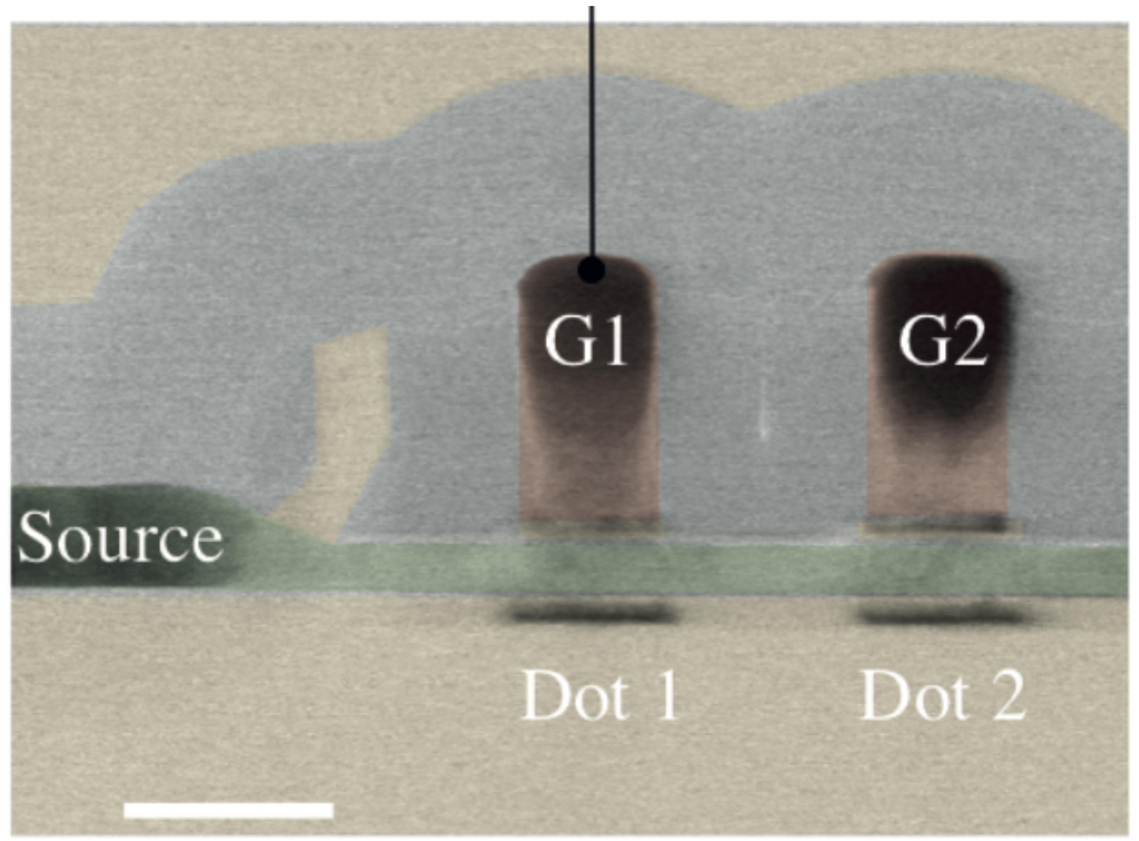
Several quantum systems
or frequency difficult to predict

Need high amplification, low noise AND large bandwidth

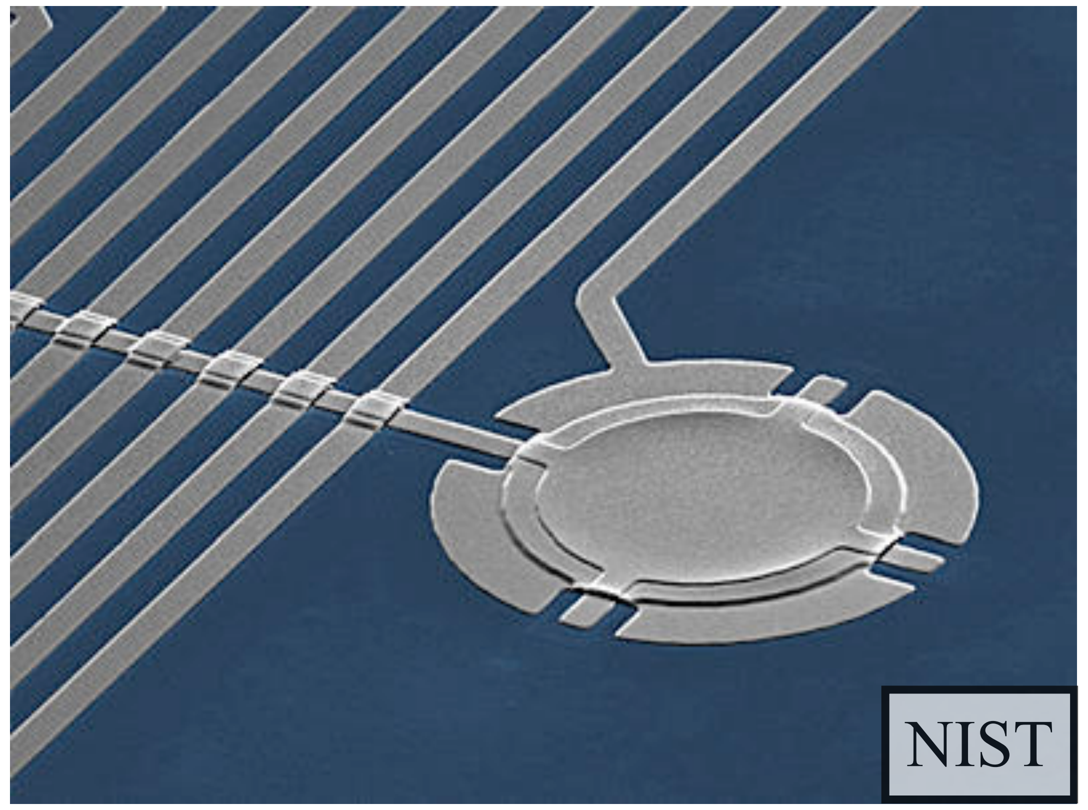
Ultra low noise amplification: applications



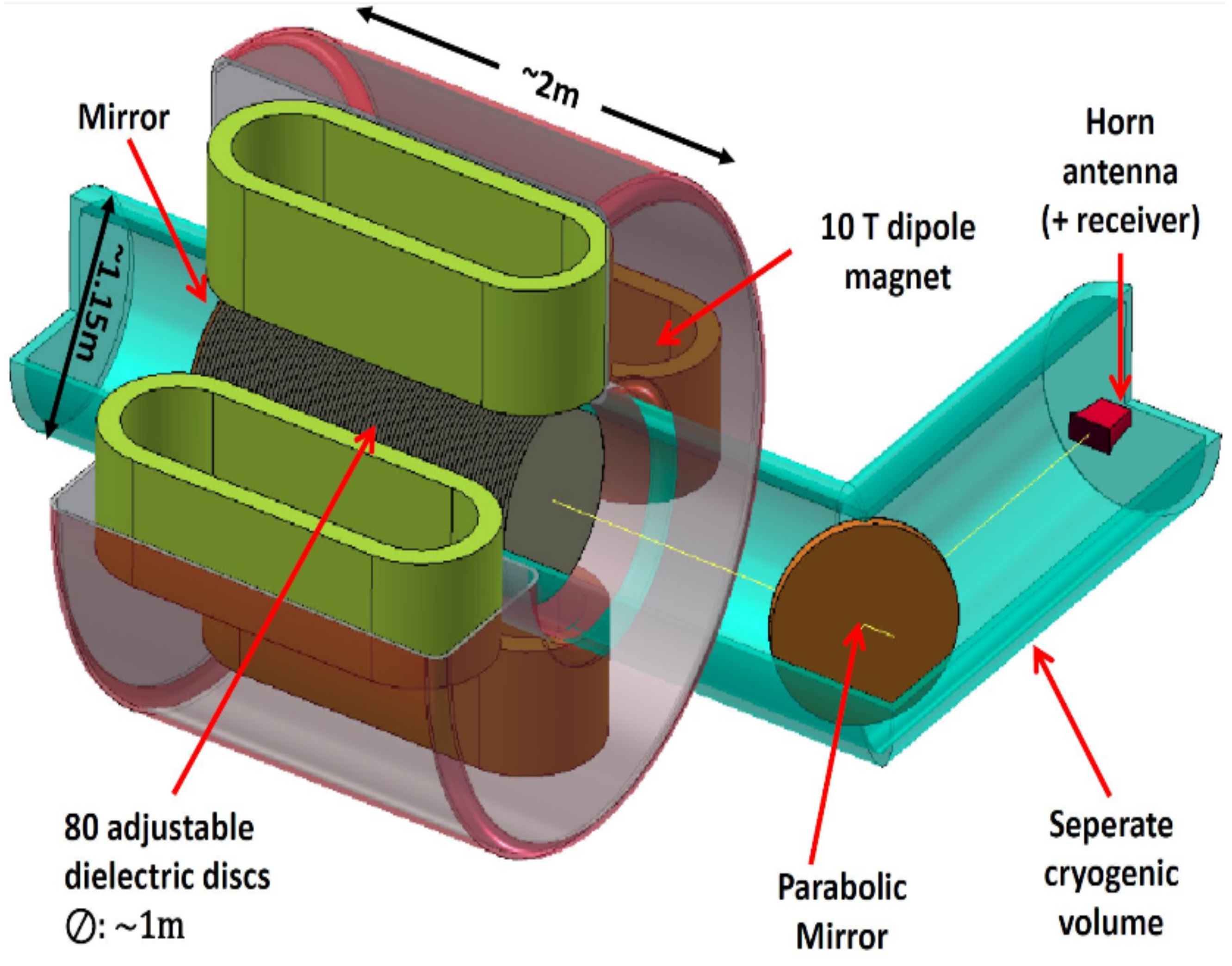
Superconducting Qubits



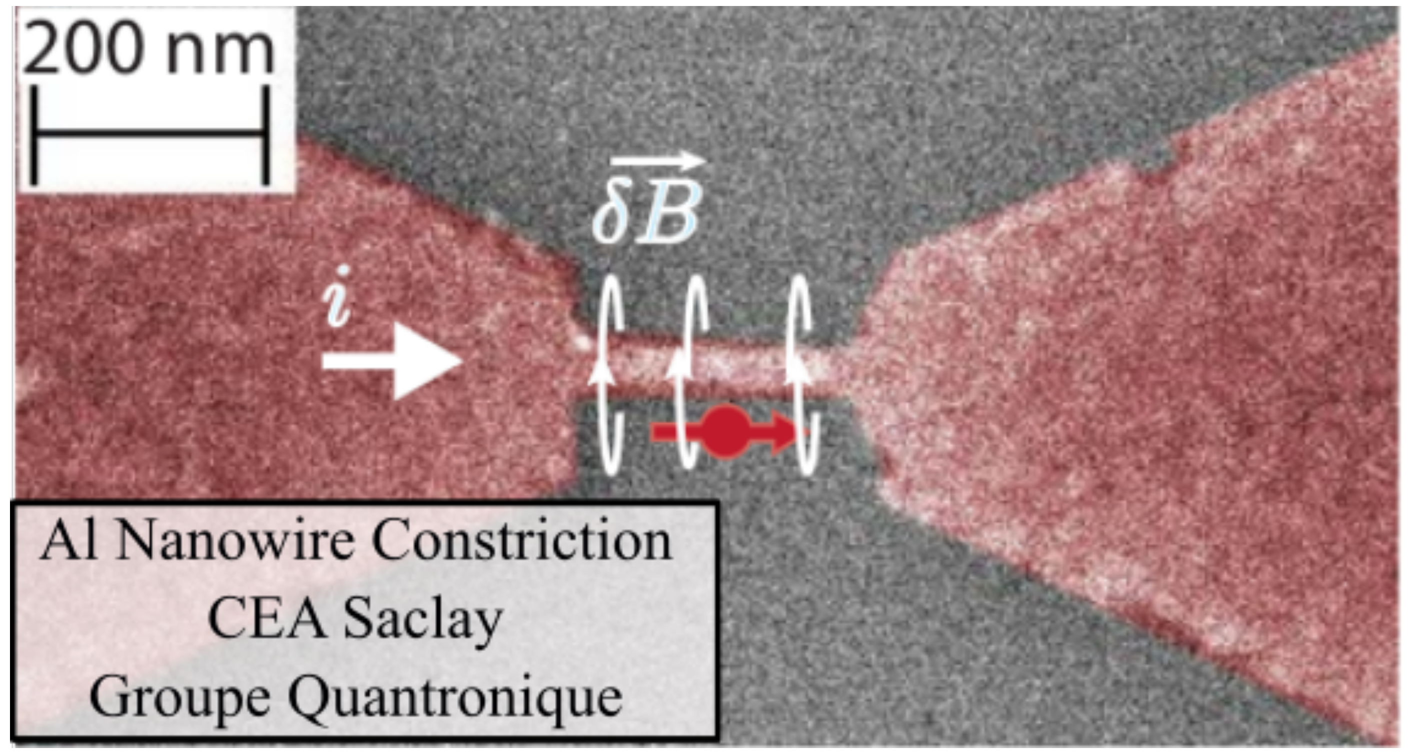
Spin Qubits



Electromechanical Circuits

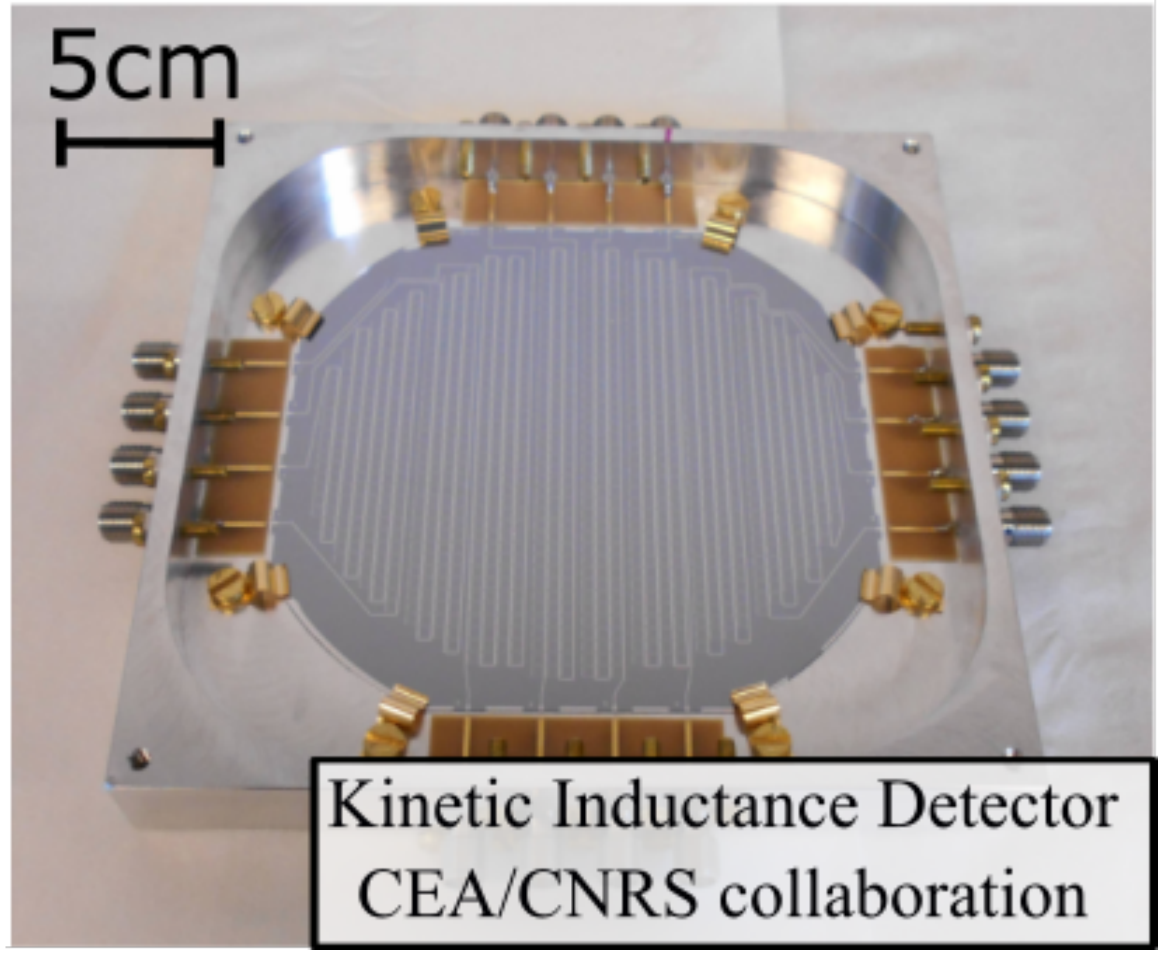


Dark matter detection



Al Nanowire Constriction
CEA Saclay
Groupe Quantronique

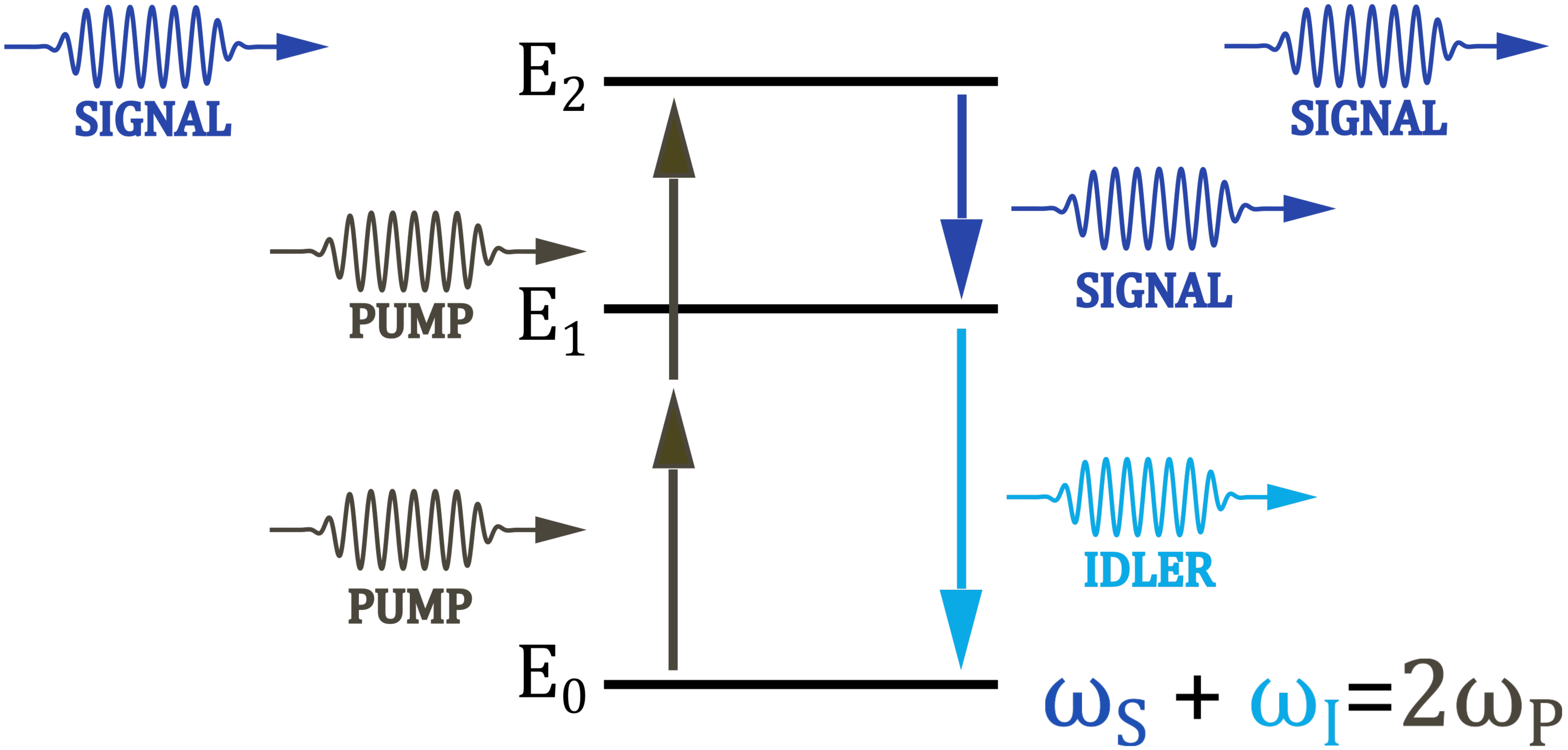
Q-limited ESR



Kinetic Inductance Detector
CEA/CNRS collaboration

Astrophysics detectors

Parametric amplifiers:
quantum optics point of view

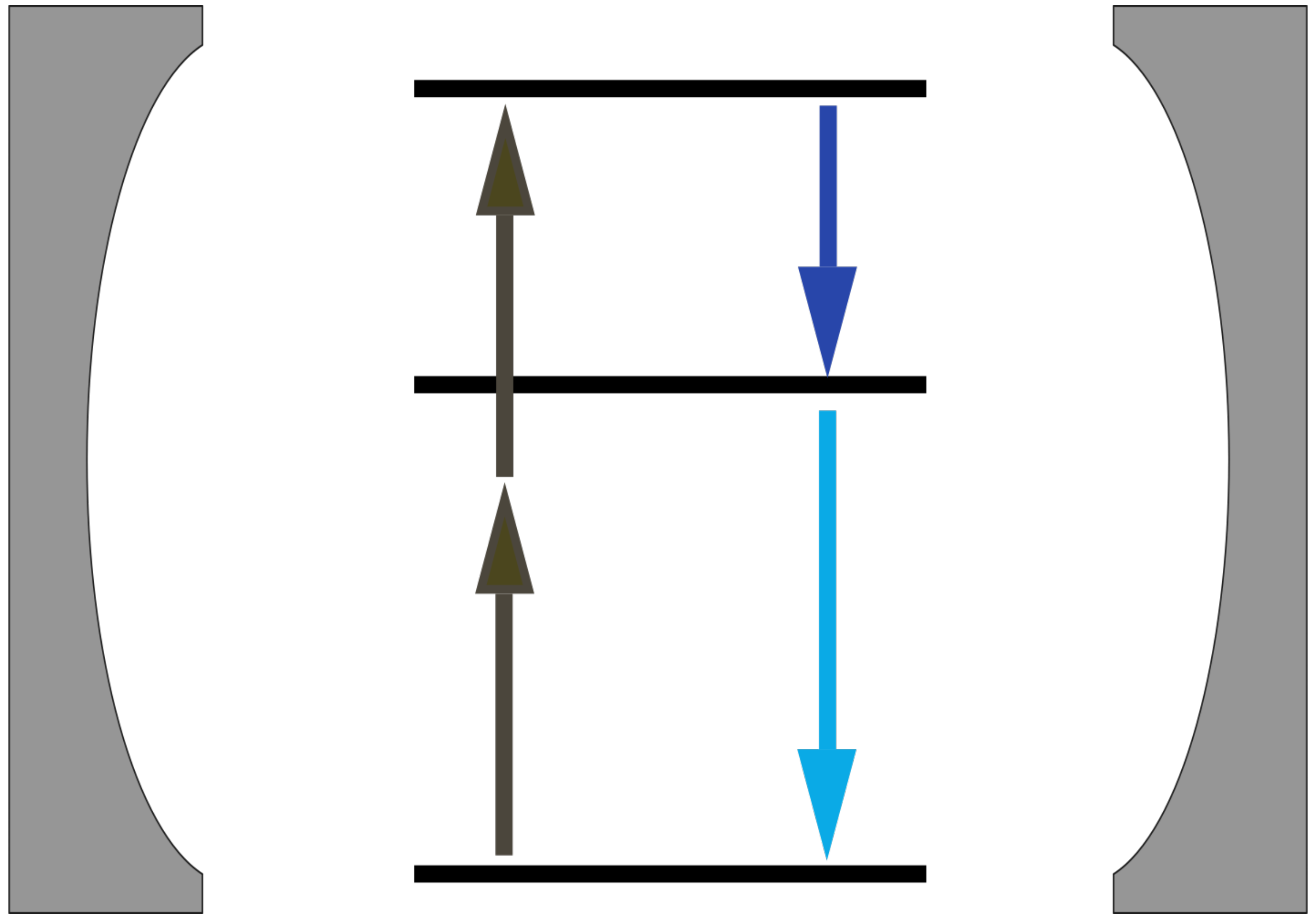


$\omega_S + \omega_I = 2\omega_P$

Four wave mixing

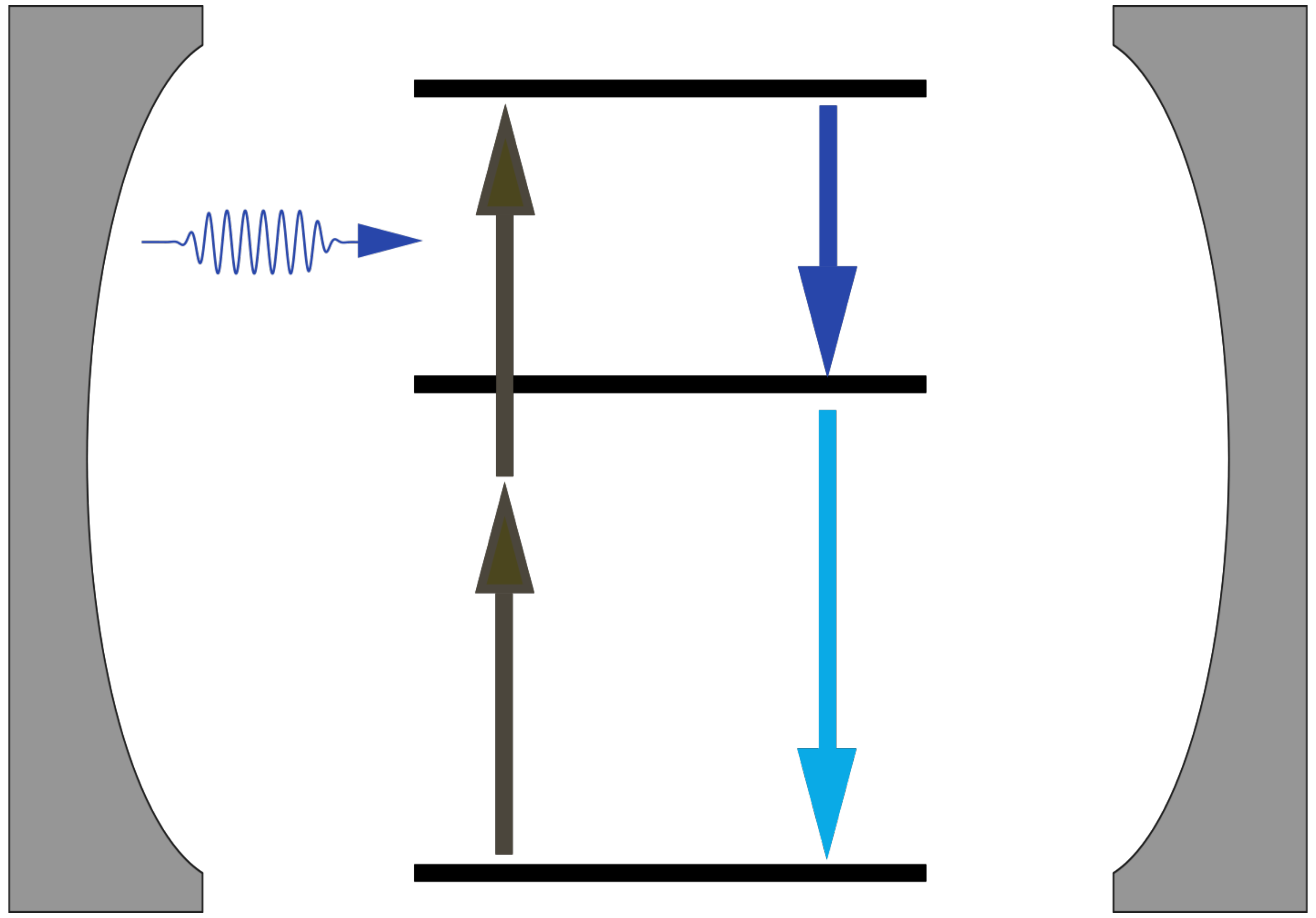
Resonant parametric amplification

Interaction time ∝ 1/cavity bandwidth



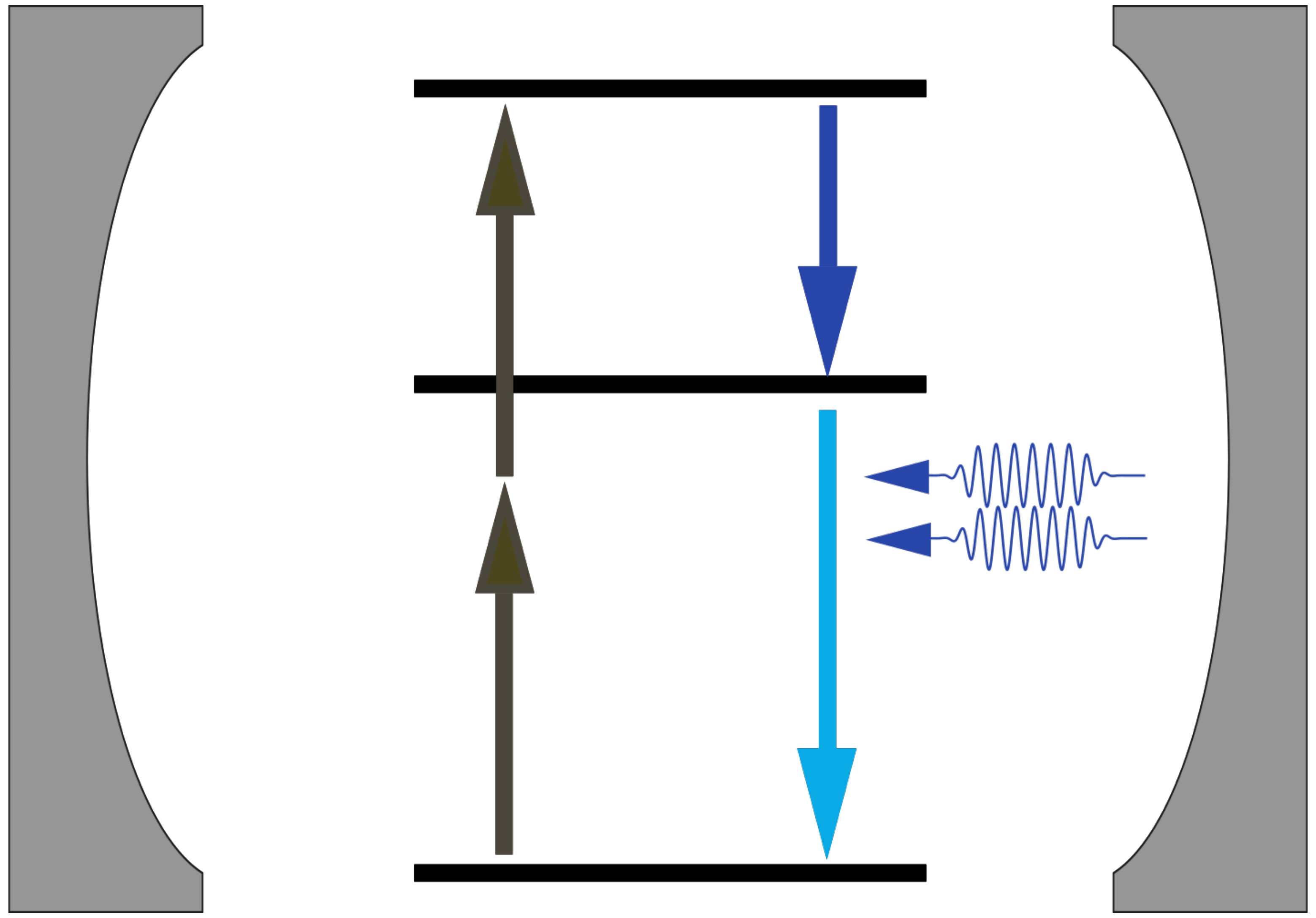
Resonant parametric amplification

Interaction time ∝ 1/cavity bandwidth



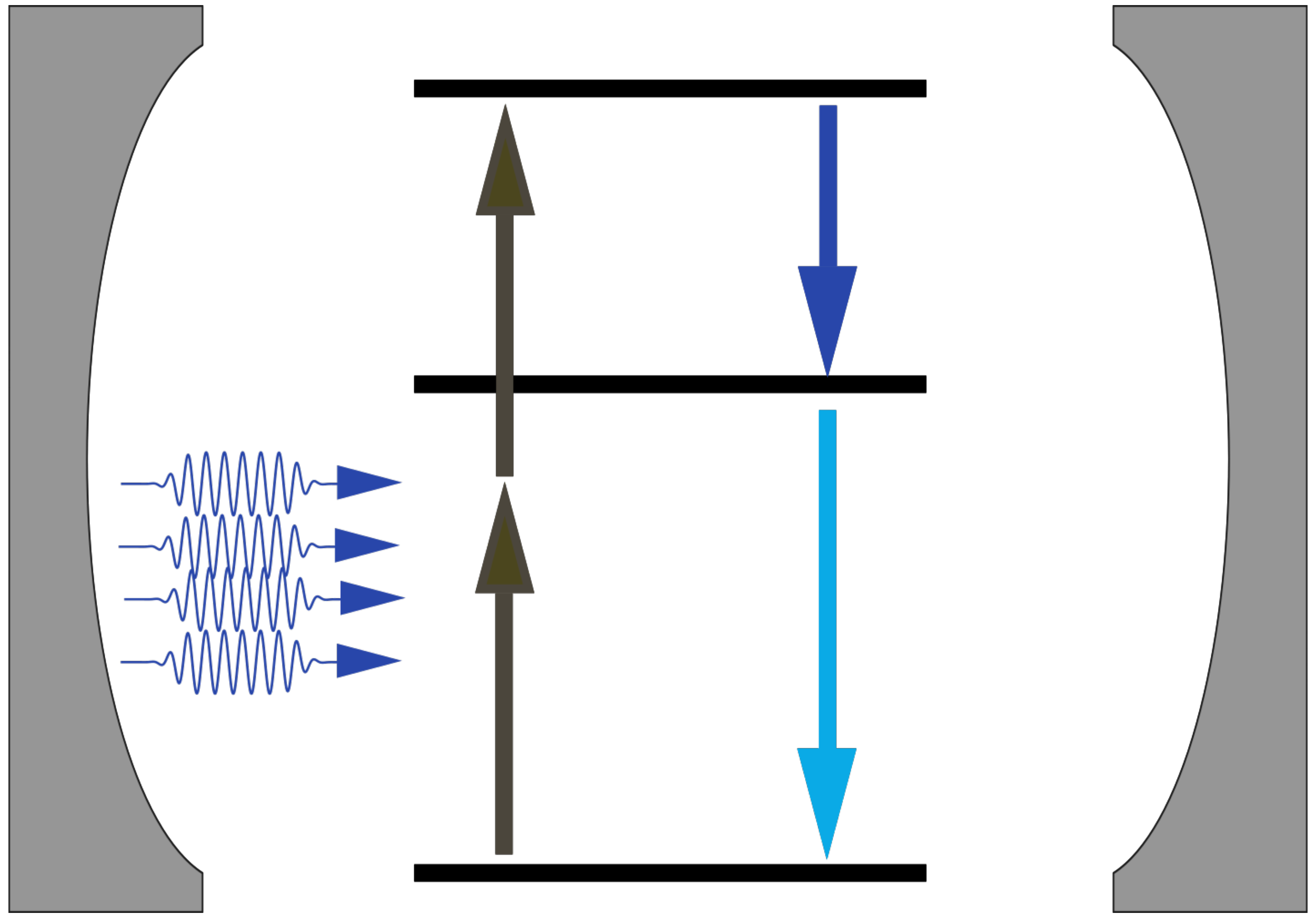
Resonant parametric amplification

Interaction time $\propto$ 1/cavity bandwidth



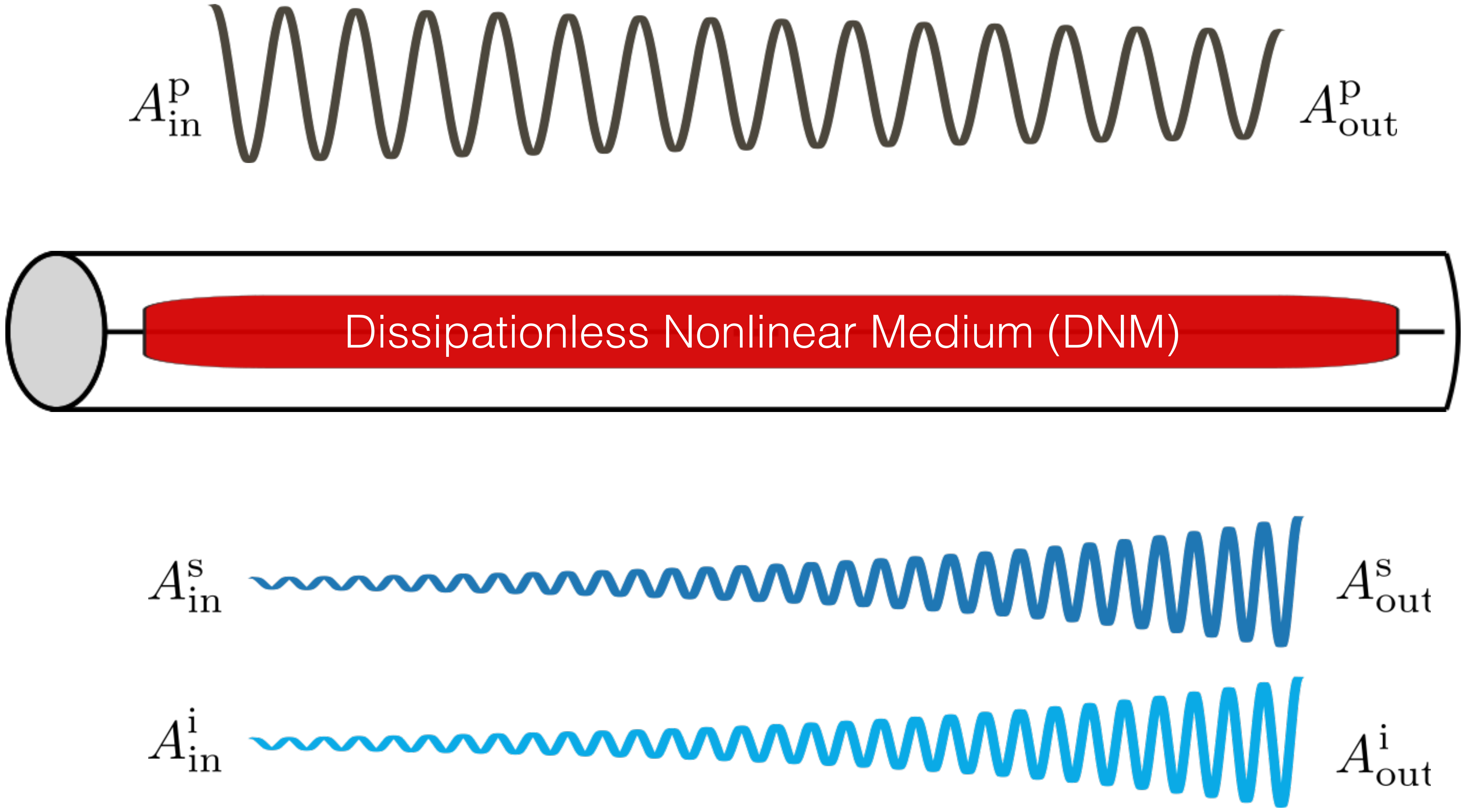
Resonant parametric amplification

Interaction time ∝ 1/cavity bandwidth

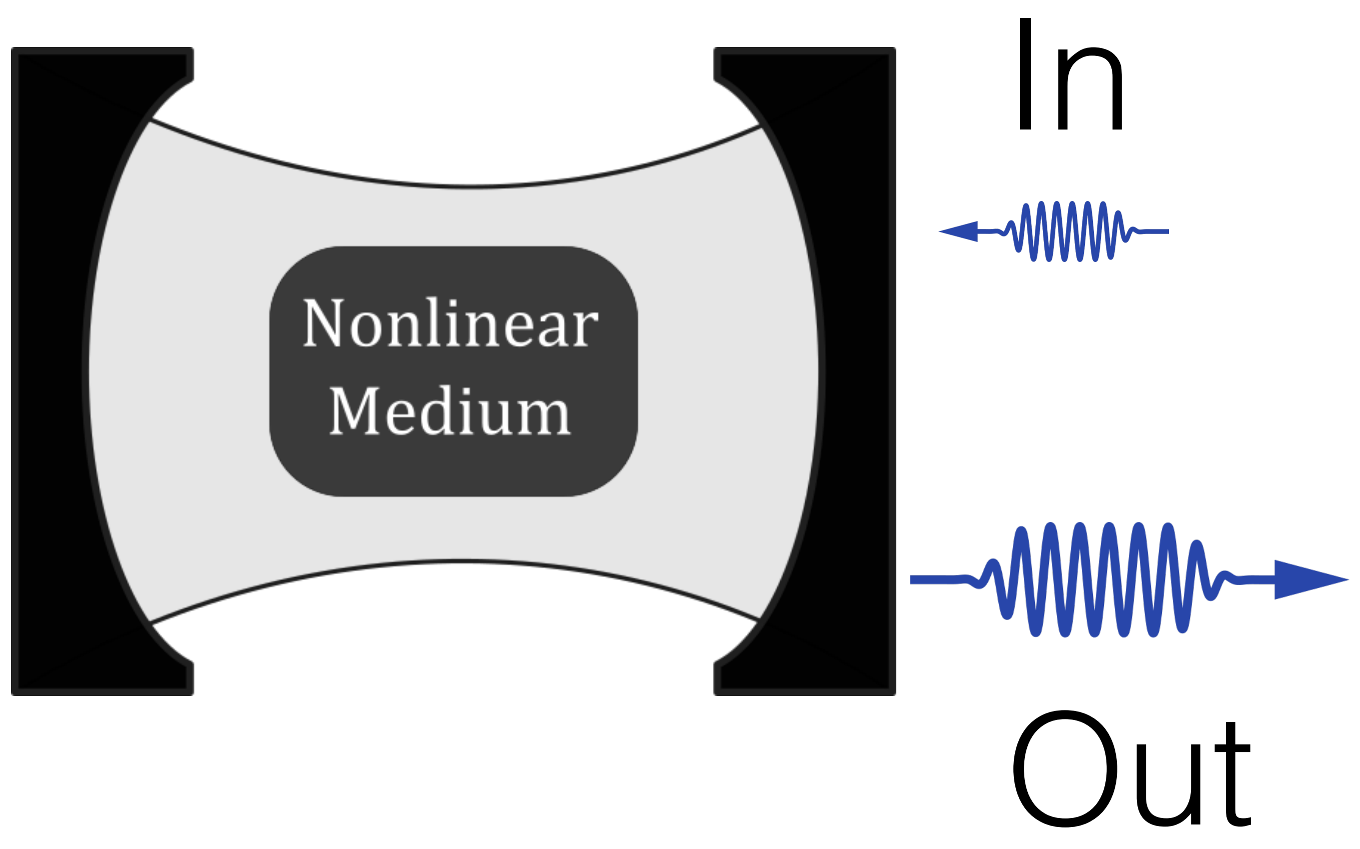


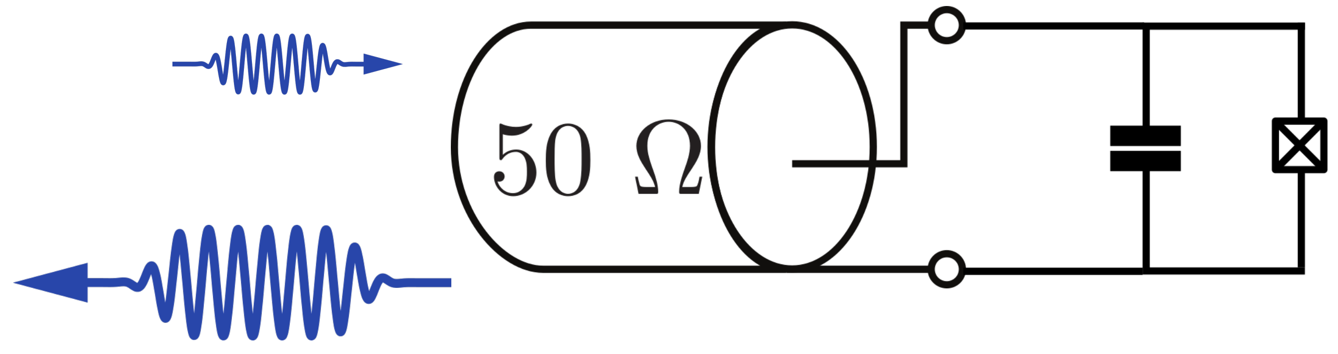
Traveling wave parametric amplification

$$\text{Interaction time} \propto \frac{\text{Medium length}}{\text{Wave velocity}}$$

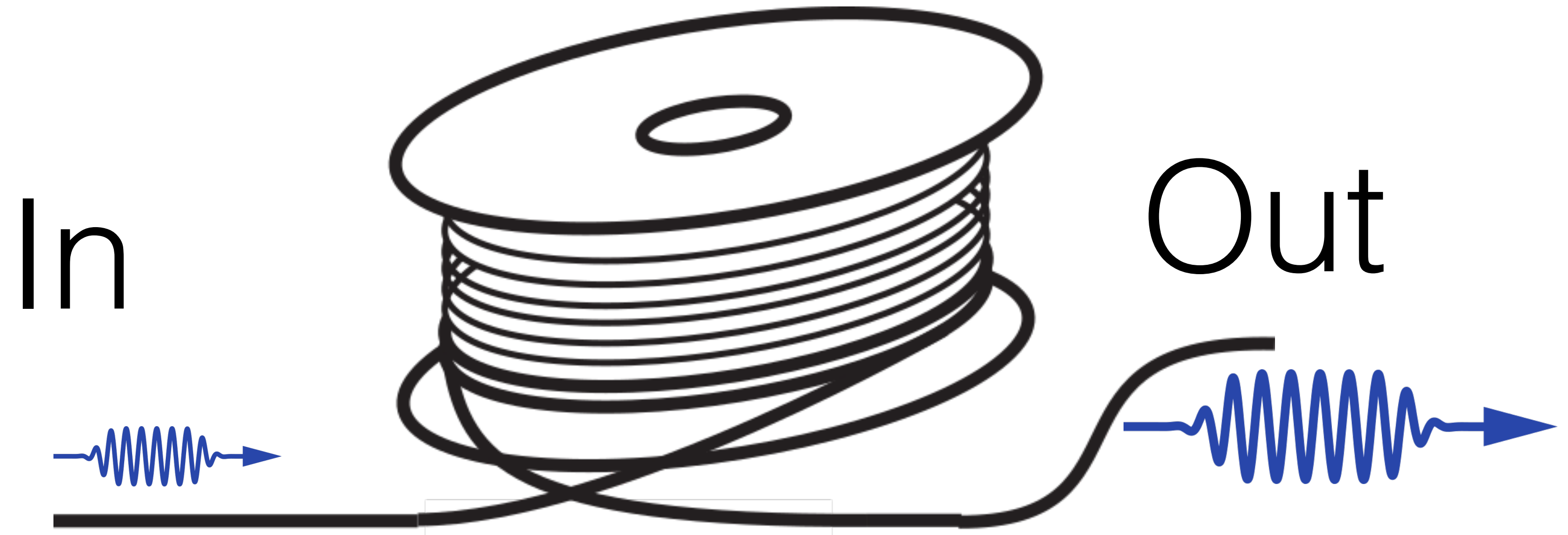


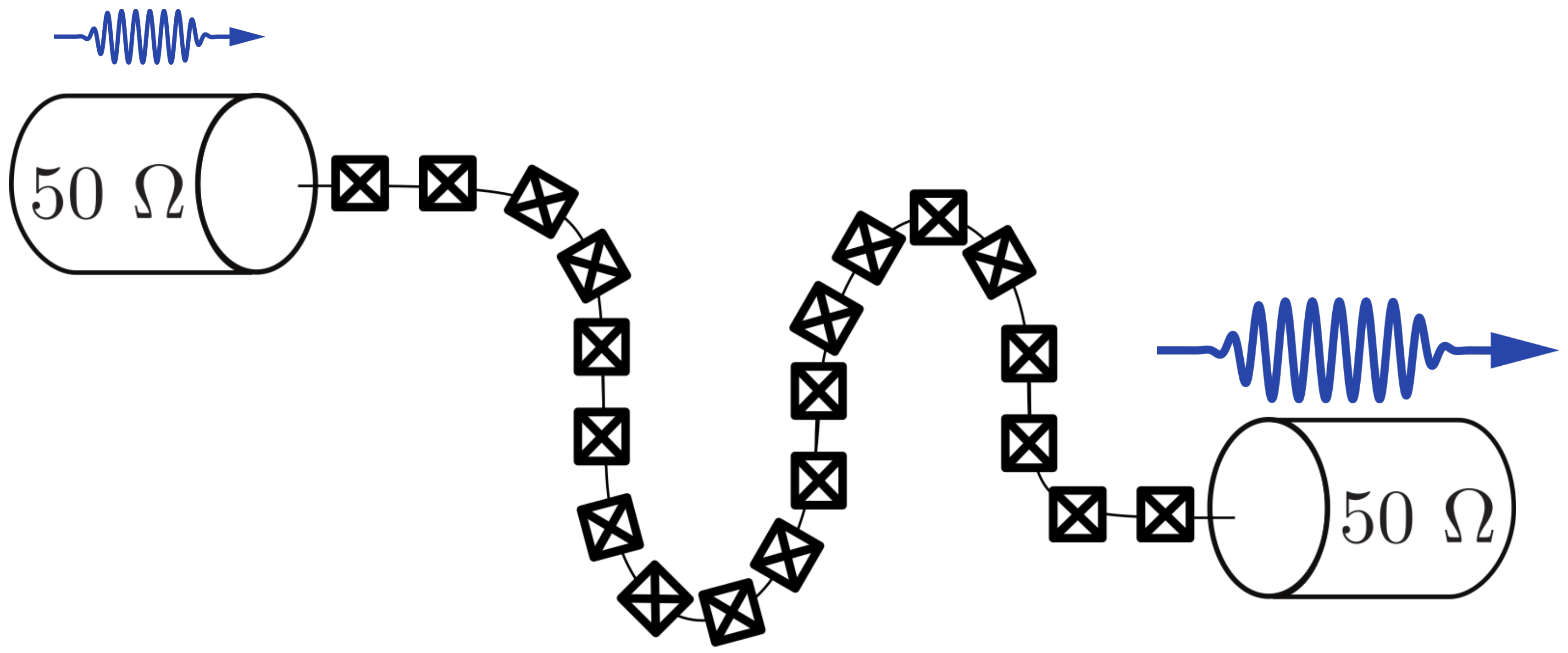
Resonant vs Traveling-wave





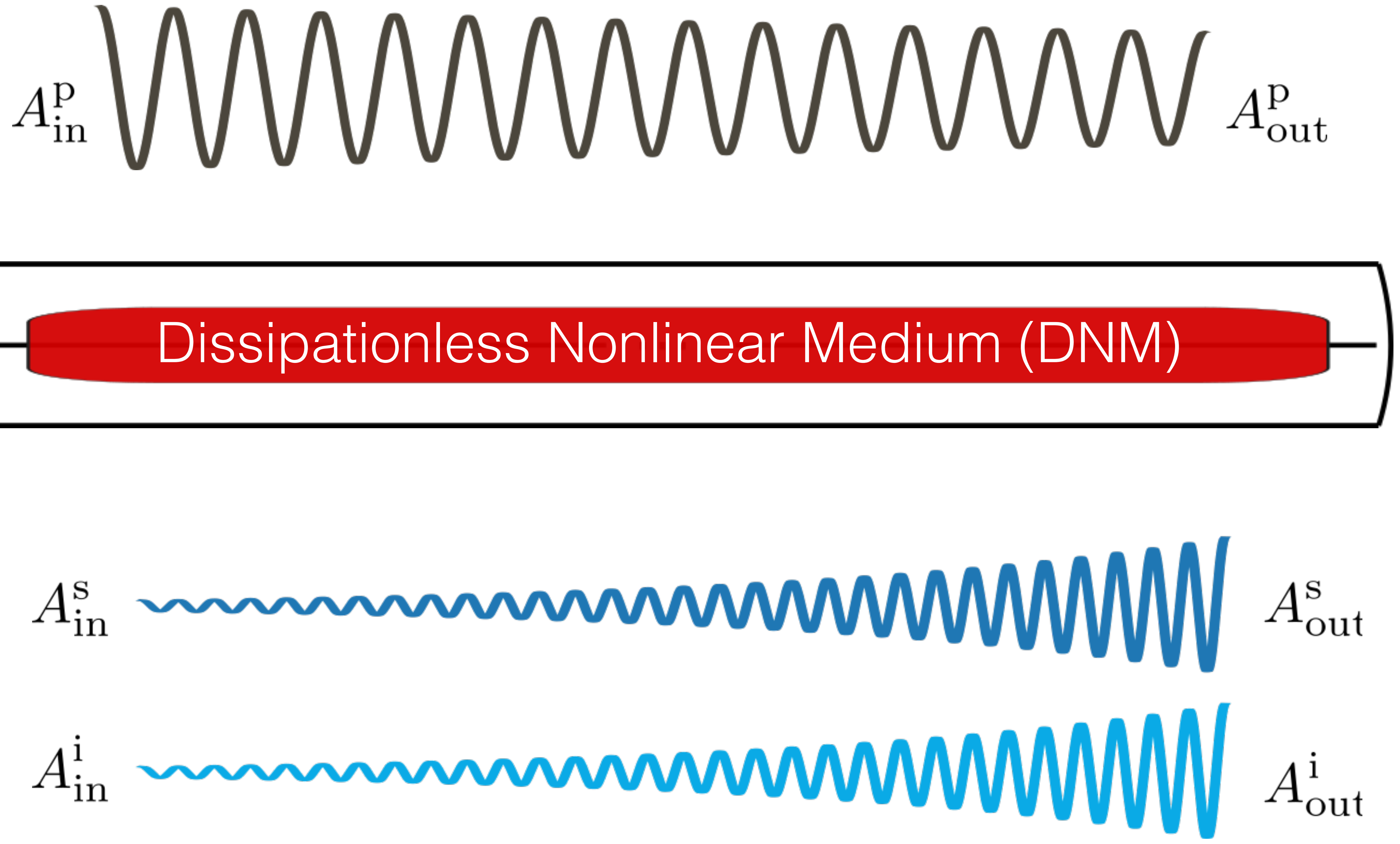
✓ Low Noise x Narrow bandwidth





✓ Low Noise ✓ Broadband

Traveling wave parametric amplification



Lithium triborate crystal

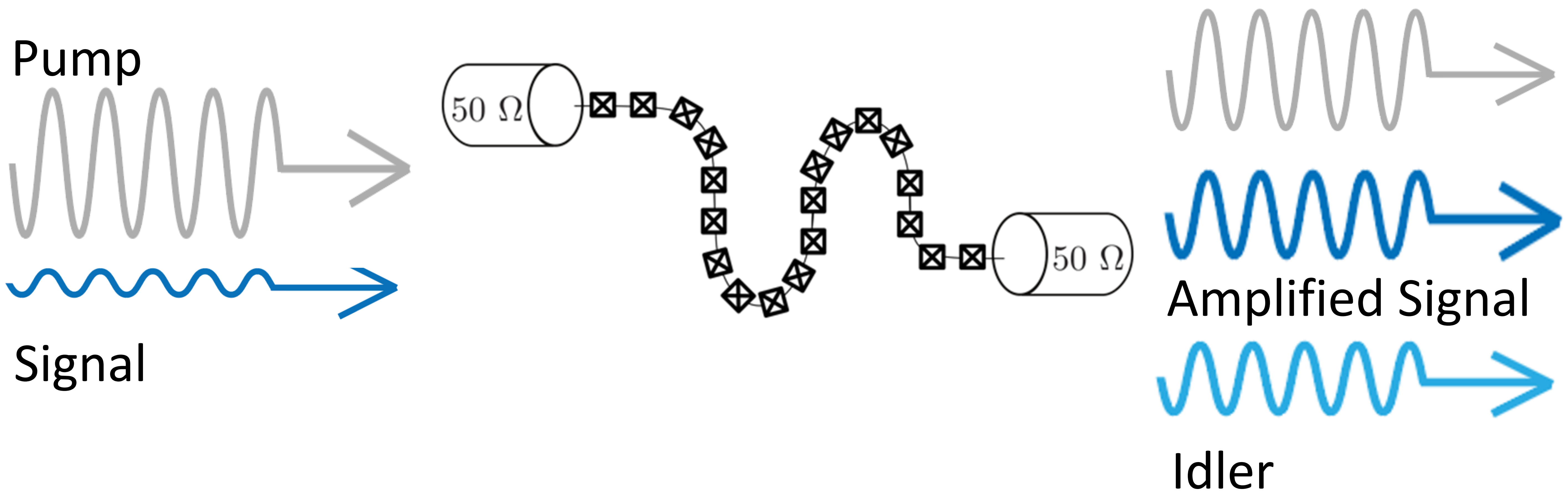
(Source: rp-photonics.com)

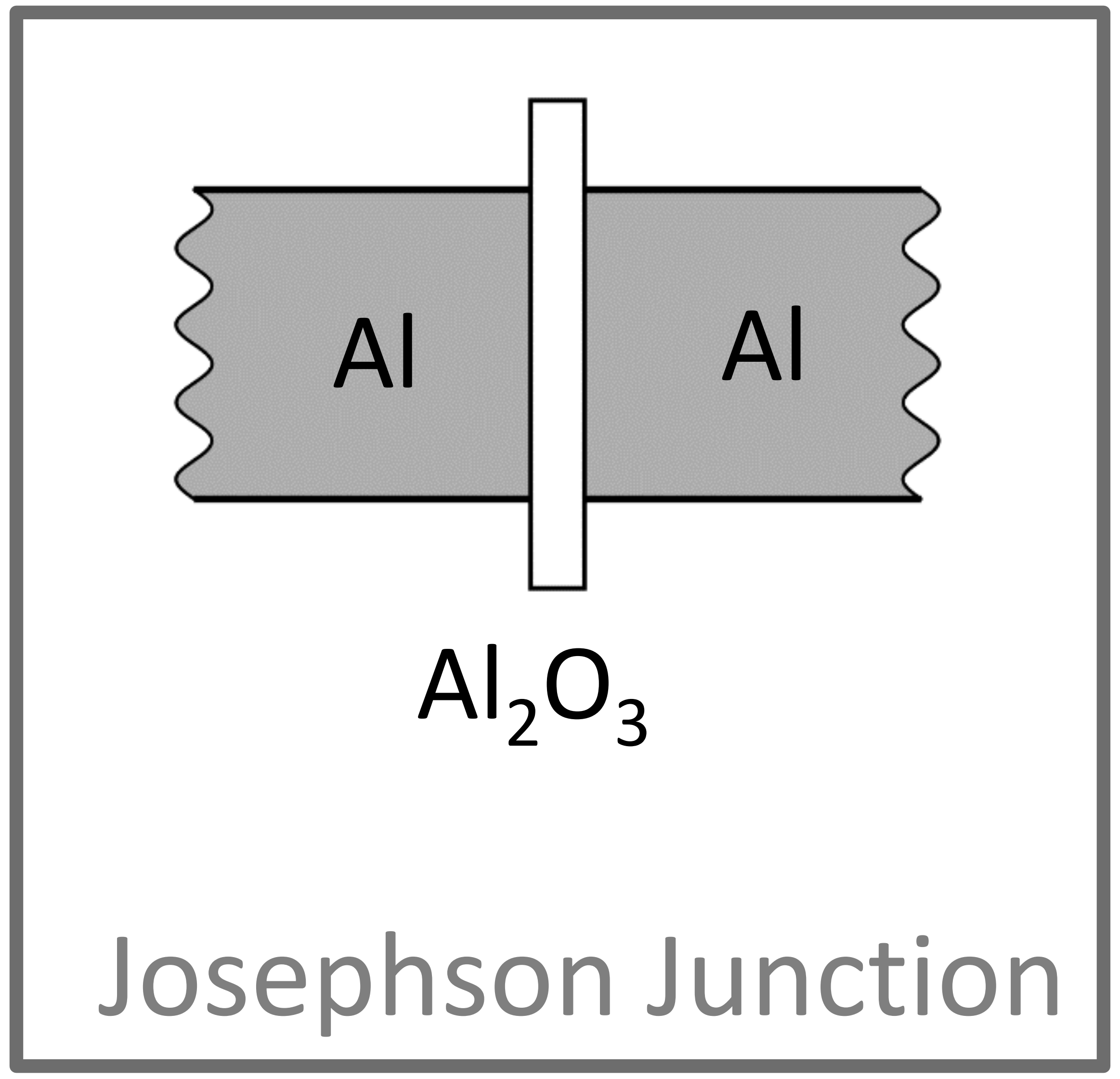
$$\tilde{E} \sim E_0\, e^{ikx}$$

$$\tilde{P} = \epsilon_0[\chi^{(1)}\, \tilde{E} + \chi^{(2)}\, \tilde{E}^2 + \chi^{(3)}\, \tilde{E}^3 + \ \ldots]$$

Traveling wave parametric amplification

Josephson Meta-material





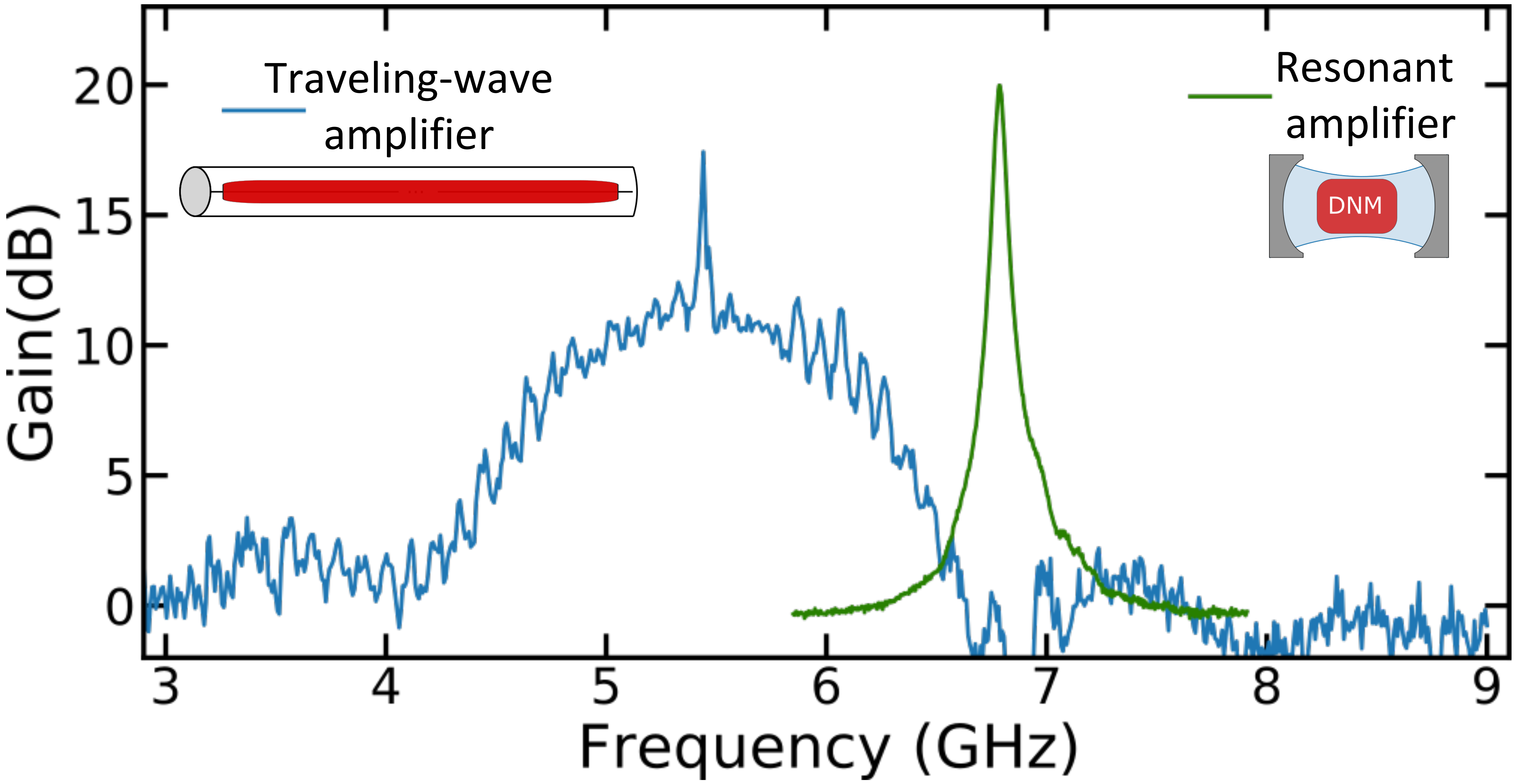
Phase across junction $\boxed{\phi = \int V dt}$

$$\phi \sim \phi_0 \, e^{ikx}$$

$$I(\phi) = \tilde{\alpha}[I_0\phi + \underset{\chi^{(2)}}{\underset{\downarrow}{\beta I_0\phi^2}} + \underset{\chi^{(3)}}{\underset{\downarrow}{\gamma I_0\phi^3}} + \ \dots]$$

First demonstration: B. H. Eom et al., Nat. Phys. (2012), C. Macklin et al. Science (2015)

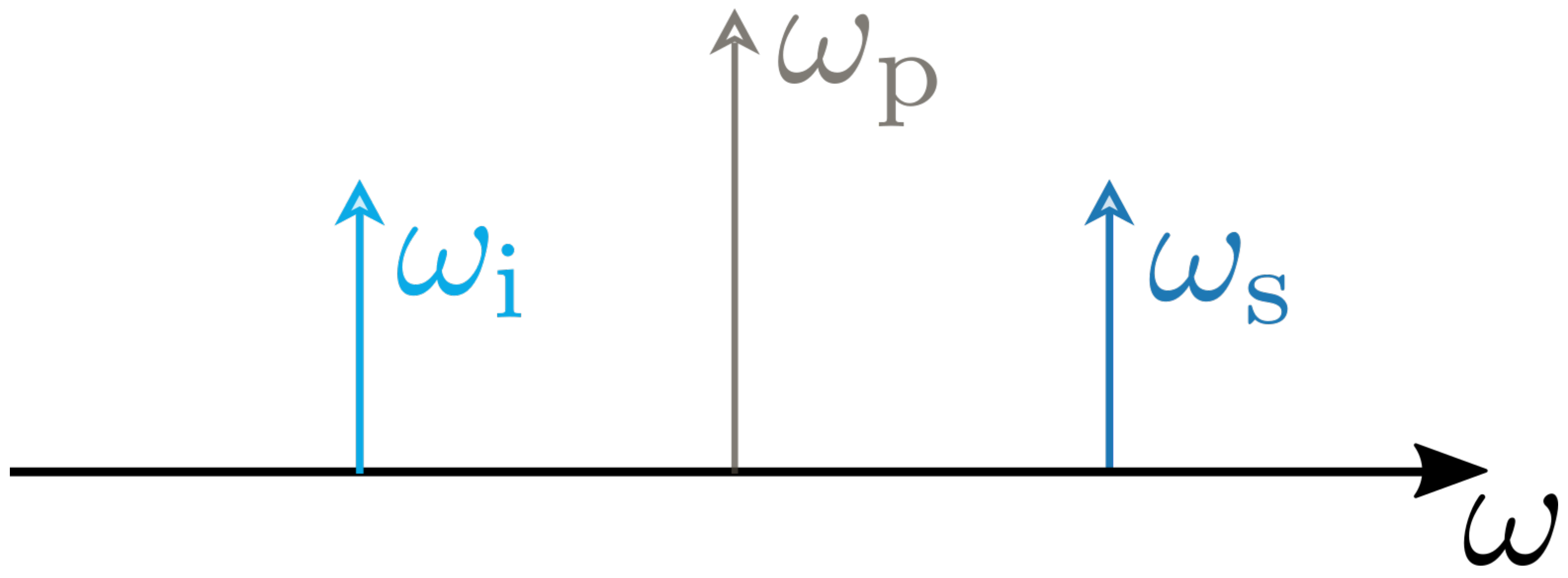
Traveling Wave Parametric Amplifier vs Resonant Parametric Amplifier



Traveling Wave Parametric Amplifier: phase matching challenge

Energy conservation

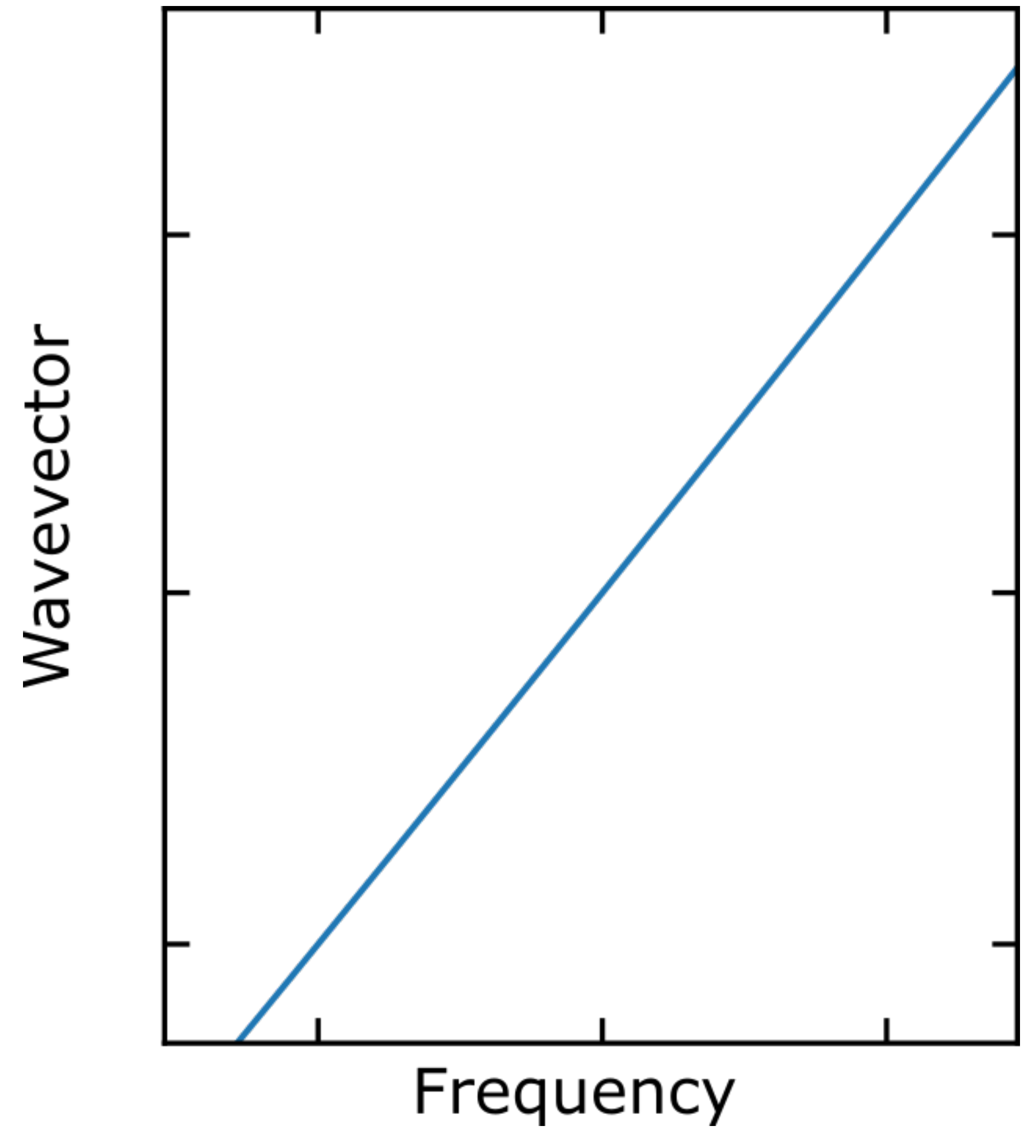
$$\omega_\mathrm{s} + \omega_\mathrm{i} = 2\omega_\mathrm{p}$$



👍

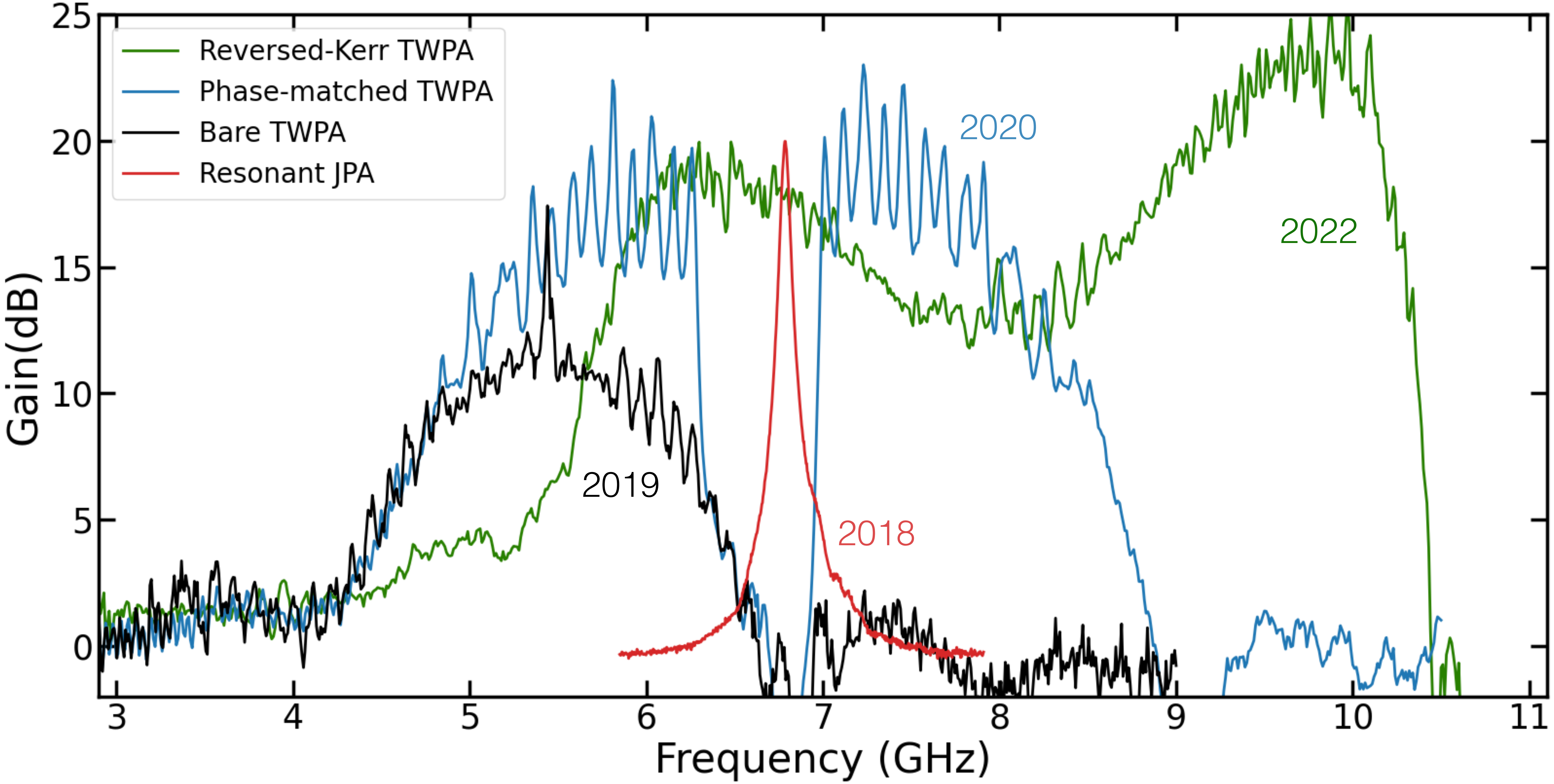
Momentum conservation

$$\Delta k = 2k_\mathrm{p} - k_\mathrm{s} - k_\mathrm{i} \approx 0$$



👎

Quantum limited amplifiers: comparison



Periodic modulation of the impedance

Non-linearity engineering

Quantum limited amplifiers: noise performances

Standard Quantum Limit (SQL)

$$T_N \geq \frac{\hbar\omega}{2k_B} = T_{SQL}$$

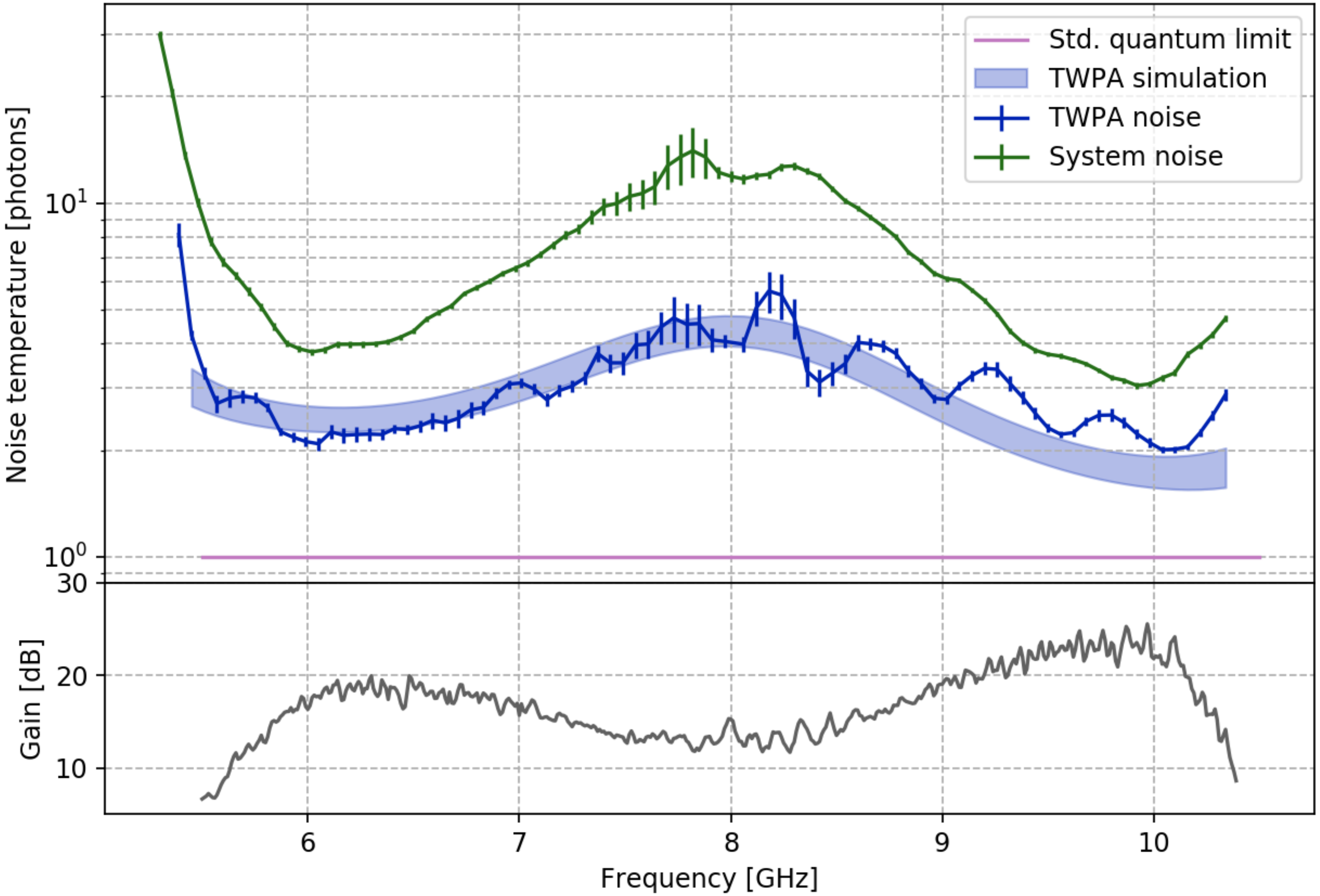
C. M. Caves, Phys. Rev. D (1982)

Quantum limited amplifiers: noise performances

Standard Quantum Limit (SQL)

$$T_N \geq \frac{\hbar\omega}{2k_B} = T_{SQL}$$

C. M. Caves, Phys. Rev. D (1982)



Noise simulations based on: Houde et al., Phys. Rev. Applied (2019)

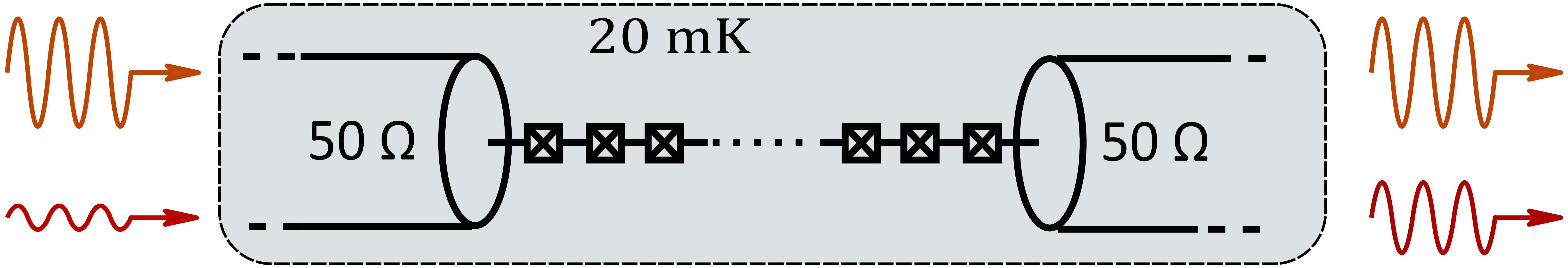
Outline

Josephson waveguides: fabrication

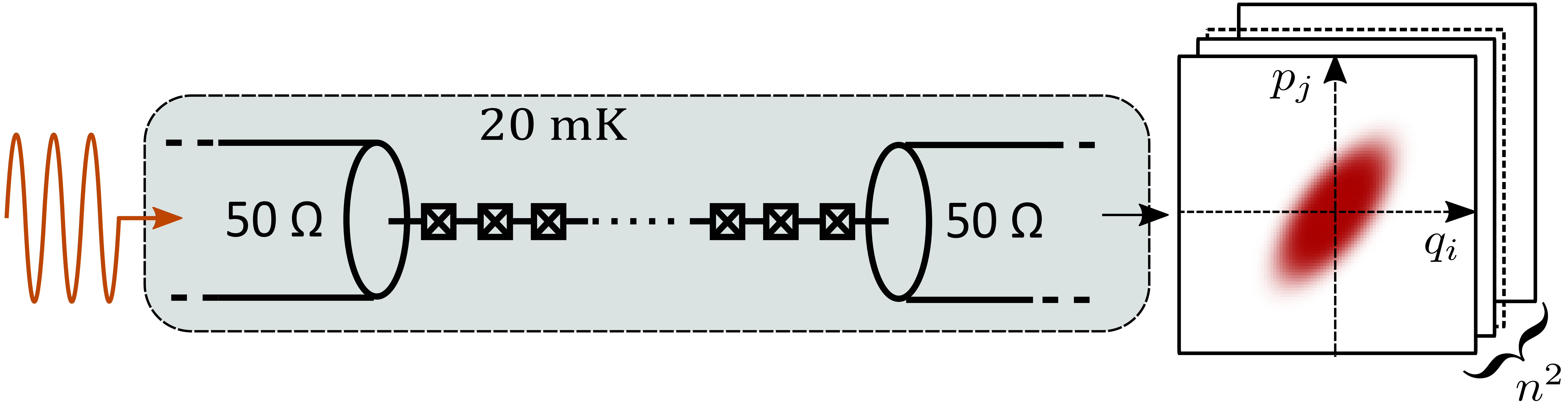
Near quantum limited Traveling Waves Parametric Amplifiers

Vacuum two-mode squeezing in TWPAs

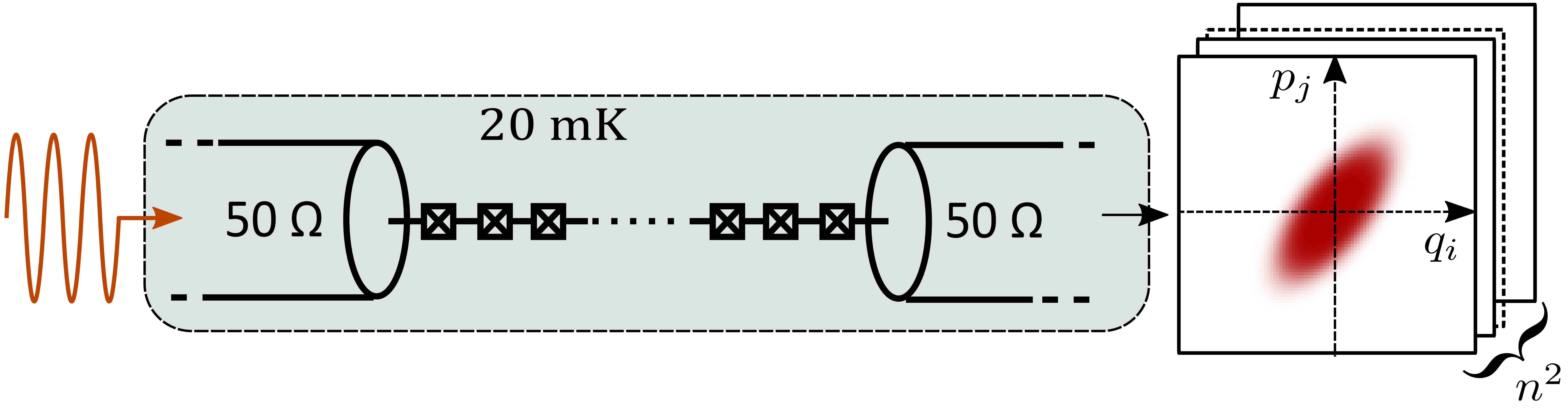
Microwave quantum optics with TWPAs



Not only amplification….



Microwave quantum optics with TWPAs

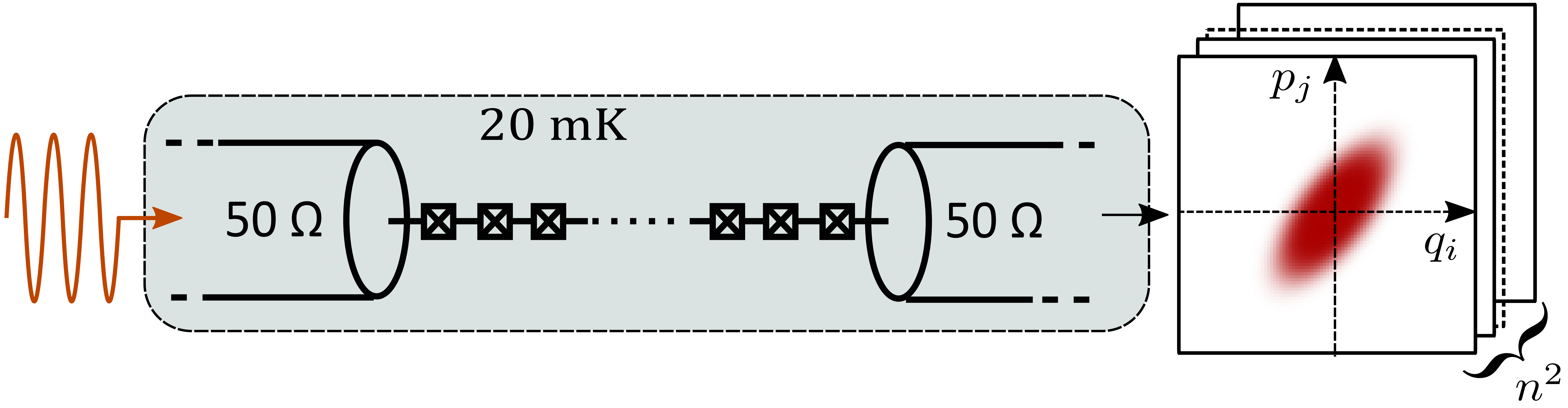


(Narrow-band) Resonant Josephson Parametric Amplifiers

Vacuum noise squeezing: R. Movshovich et al., Phys. Rev. Lett. (1990)
Vacuum noise squeezing: Castellanos-Beltran et al., Nat. Phys. (2008)
Two-mode squeezing: Eichler et al., PRL (2011)
Storage and entanglement: Flurin et al., PRL (2015)
Improving qubit state measurement: Eddins et al., PRL (2018)
Enhancing dark matter search: Backes et al., Nature (2021)

…

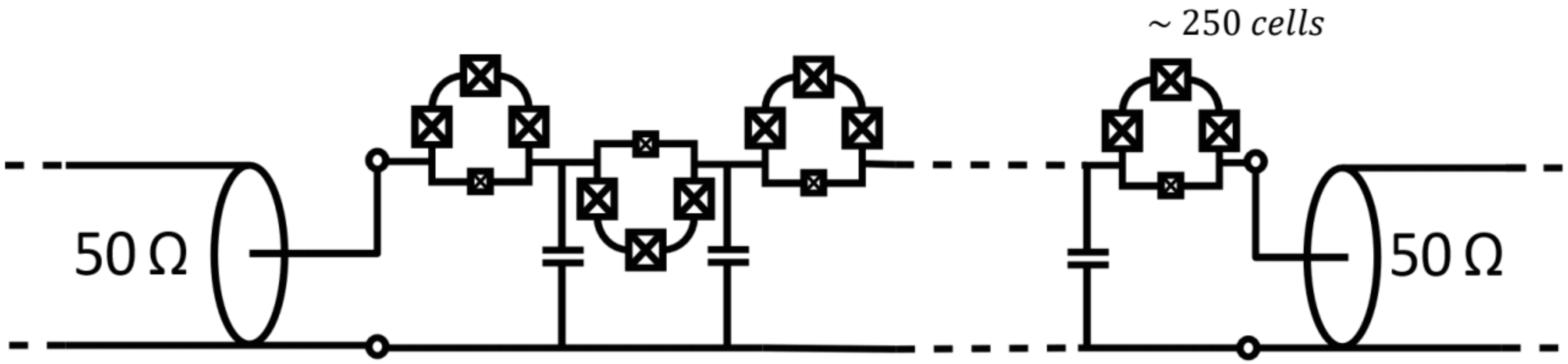
Microwave quantum optics with TWPAs



Can we generate squeezing in TWPAs ?

Pros	**Cons**
Broadband nature	Losses in TWPAs
Taking advantage of the 1D propagation	Spurious non-linear processes

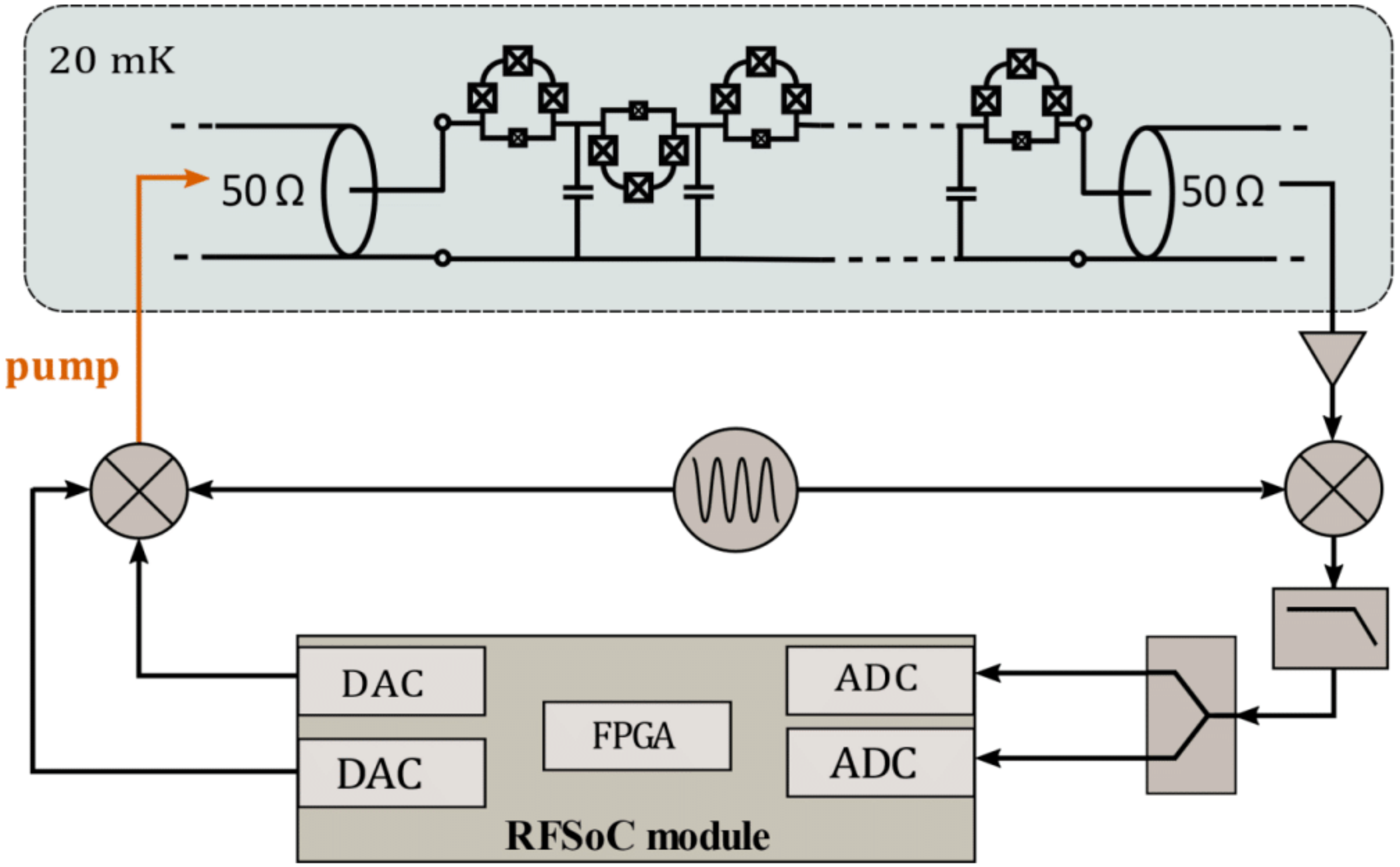
Two-mode squeezing: device



4-wave mixing

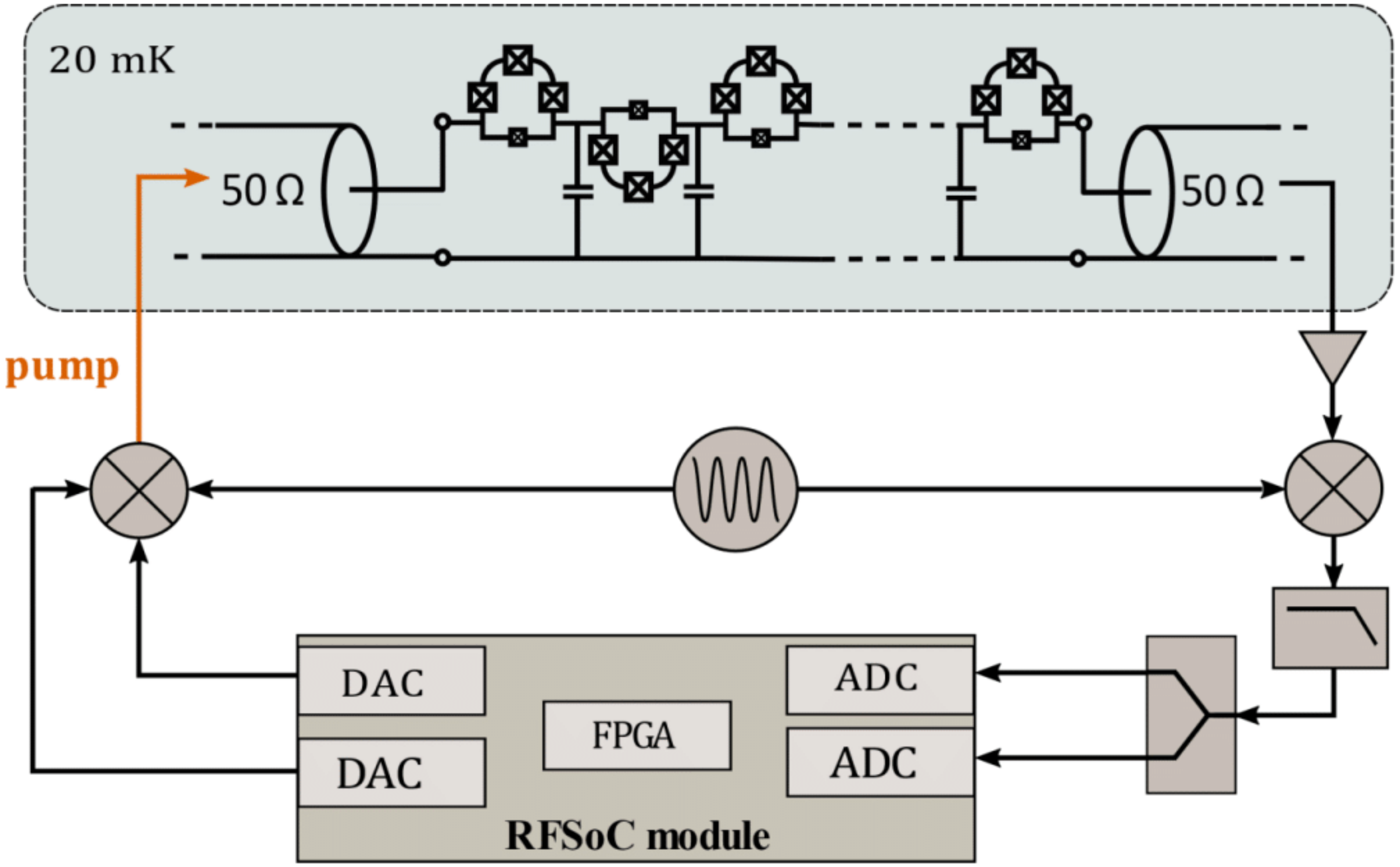
$$\boldsymbol{H}_{\text{int}} = \boldsymbol{\gamma}\, \boldsymbol{a}_s^\dagger \boldsymbol{a}_i^\dagger \boldsymbol{a}_p \boldsymbol{a}_p + \text{h.c.}$$

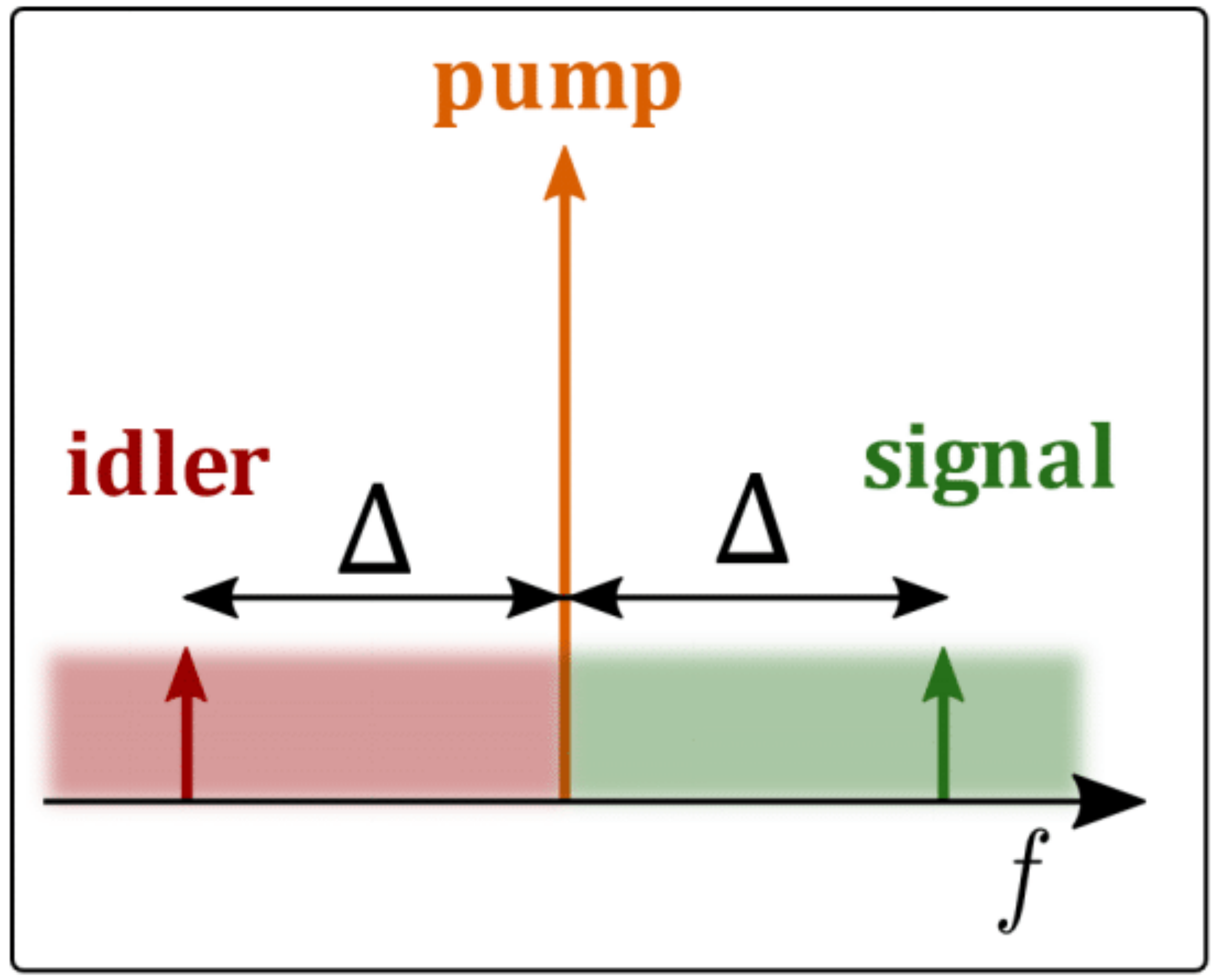
Two-mode squeezing generation



Reconstruction/tomography technique: Bozyigit et al., Nat. Phys. (2010), Da Silva et al., Phys. Rev. A (2010)

Two-mode squeezing generation

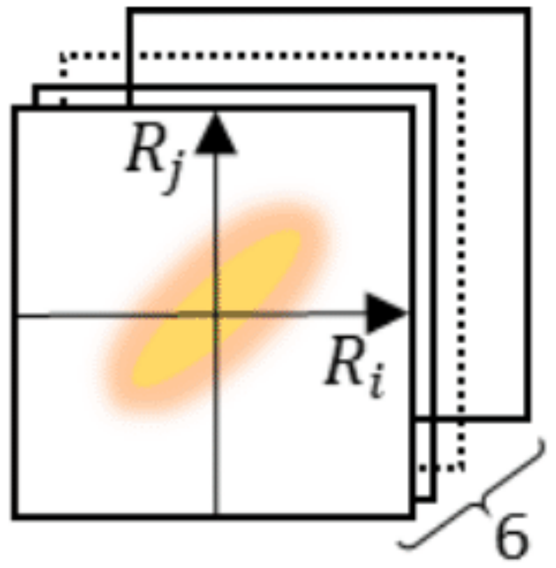




4-wave mixing

$$\boldsymbol{R} = (\hat{x}_s\,,\hat{p}_s\,,\hat{x}_i\,,\hat{p}_i)$$

$$\hat{x}_{s,i} = \frac{1}{2}(\hat{A}_{s,i} + \hat{A}^{\dagger}_{s,i}) \qquad \hat{p}_{s,i} = \frac{1}{2i}(\hat{A}_{s,i} - \hat{A}^{\dagger}_{s,i})$$

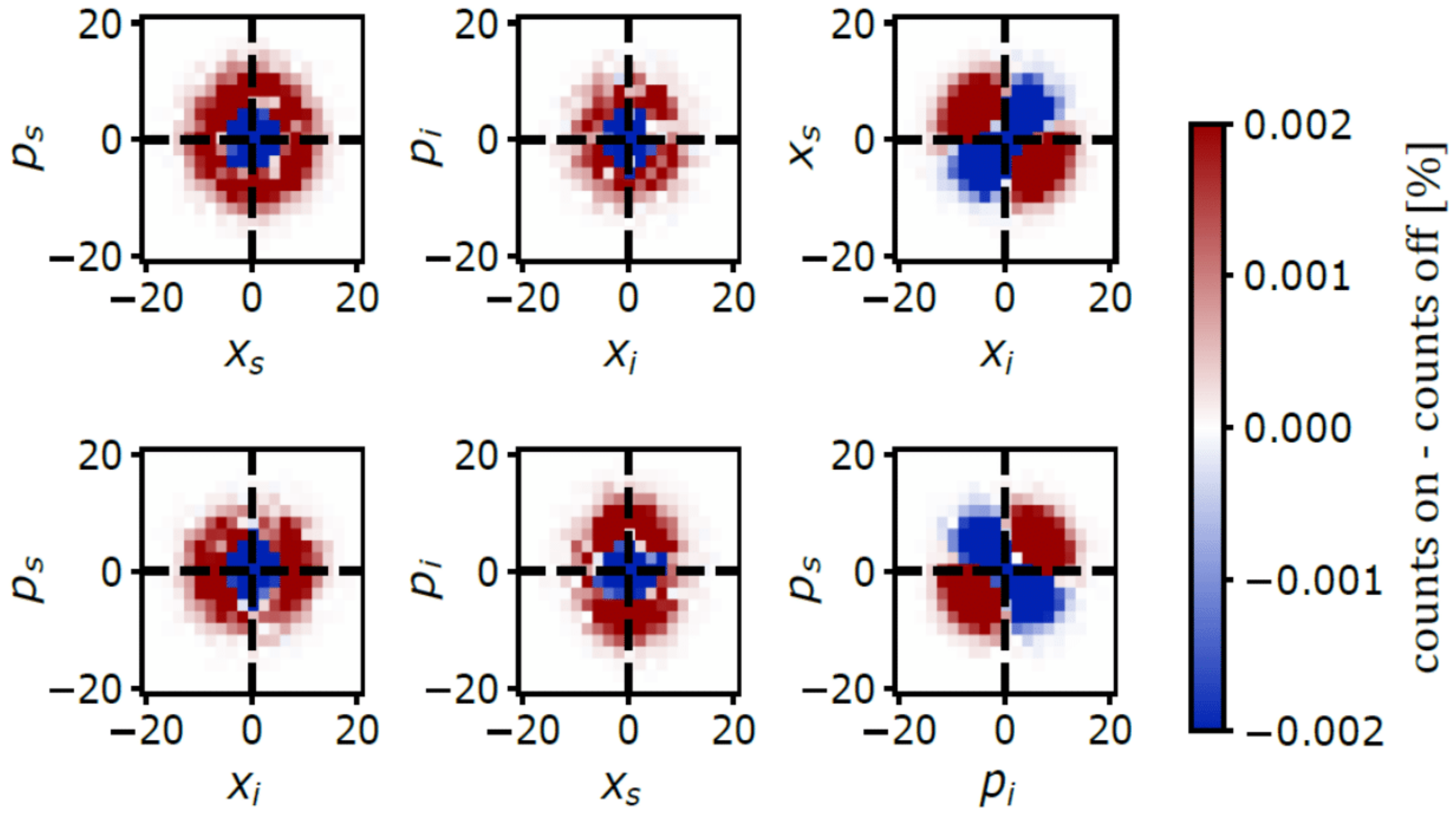


$$\boldsymbol{H}_{\text{int}} = \boldsymbol{\gamma}\left|\boldsymbol{A_p}\right|^2 \boldsymbol{a}_s^{\dagger}\boldsymbol{a}_i^{\dagger} + \text{h.c.}$$

Reconstruction/tomography technique: Bozyigit et al., Nat. Phys. (2010), Da Silva et al., Phys. Rev. A (2010)

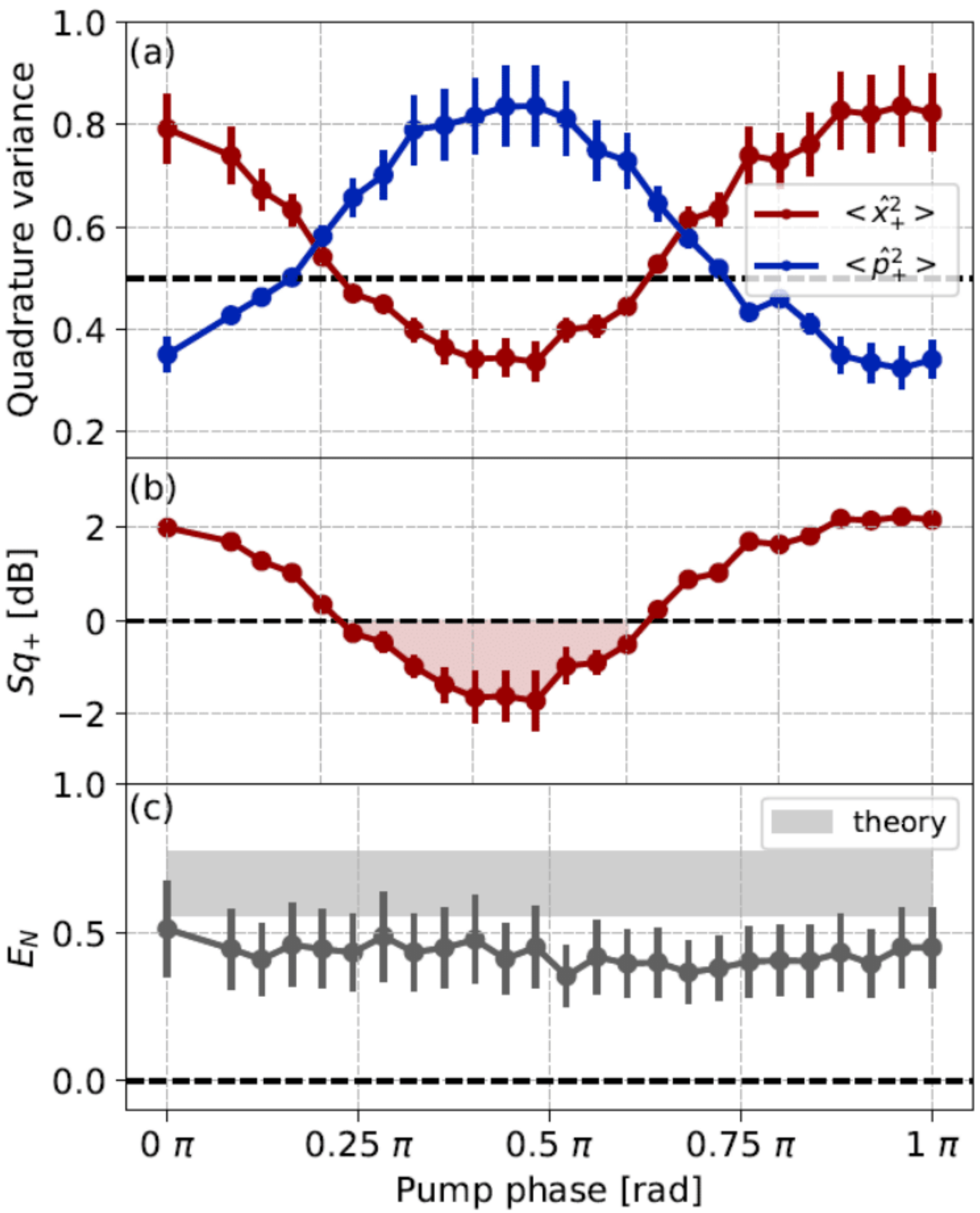
Two-mode squeezing generation

Phase-space histogram distribution



Reconstruction/tomography technique: Bozyigit et al., Nat. Phys. (2010), Da Silva et al., Phys. Rev. A (2010)

Demonstration of two-mode squeezing in TWPAs



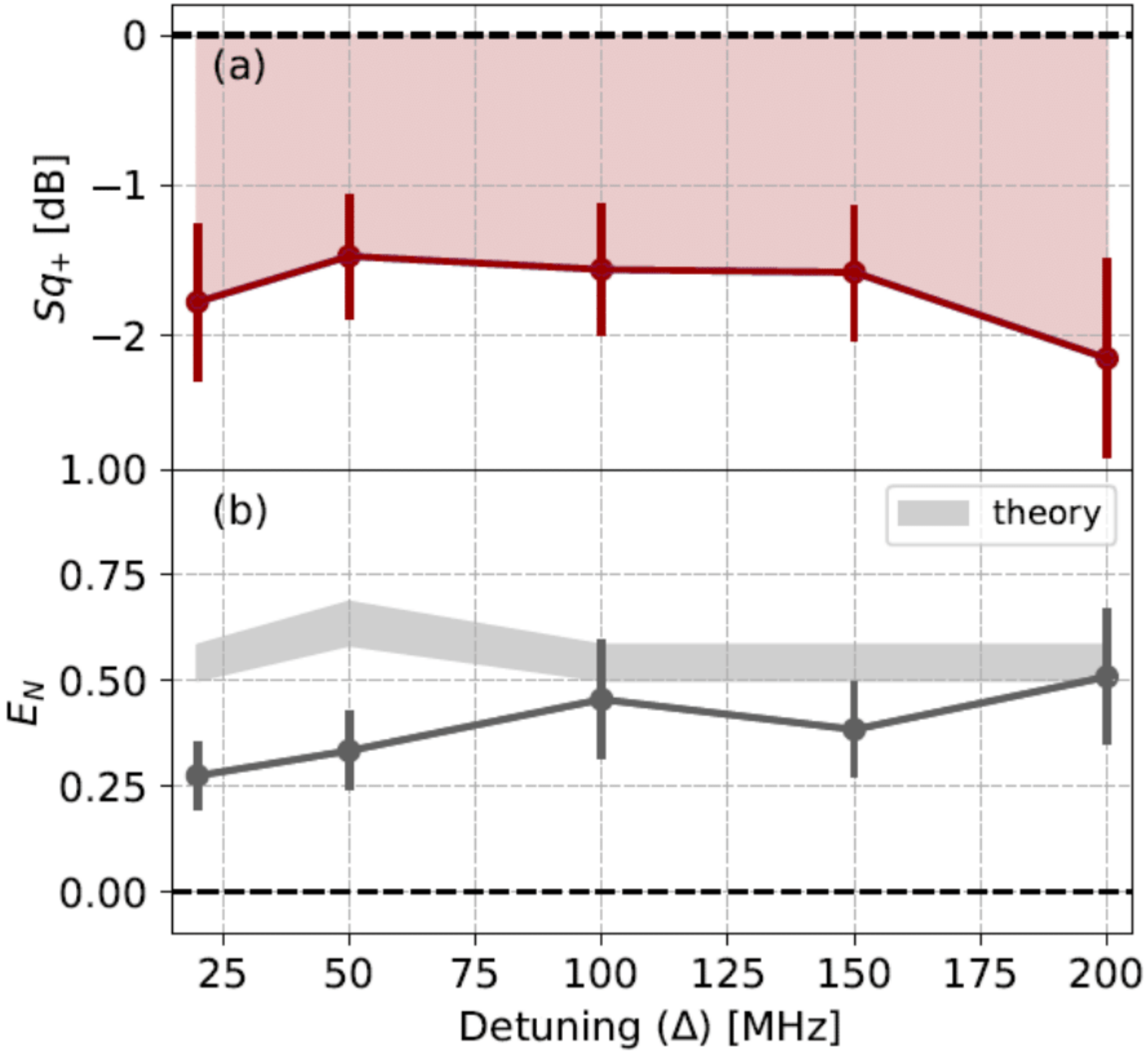
$$\hat{x}_+ = (\hat{x}_\mathrm{s} + \hat{x}_\mathrm{i})$$

$$\hat{p}_+ = (\hat{p}_\mathrm{s} + \hat{p}_\mathrm{i})$$

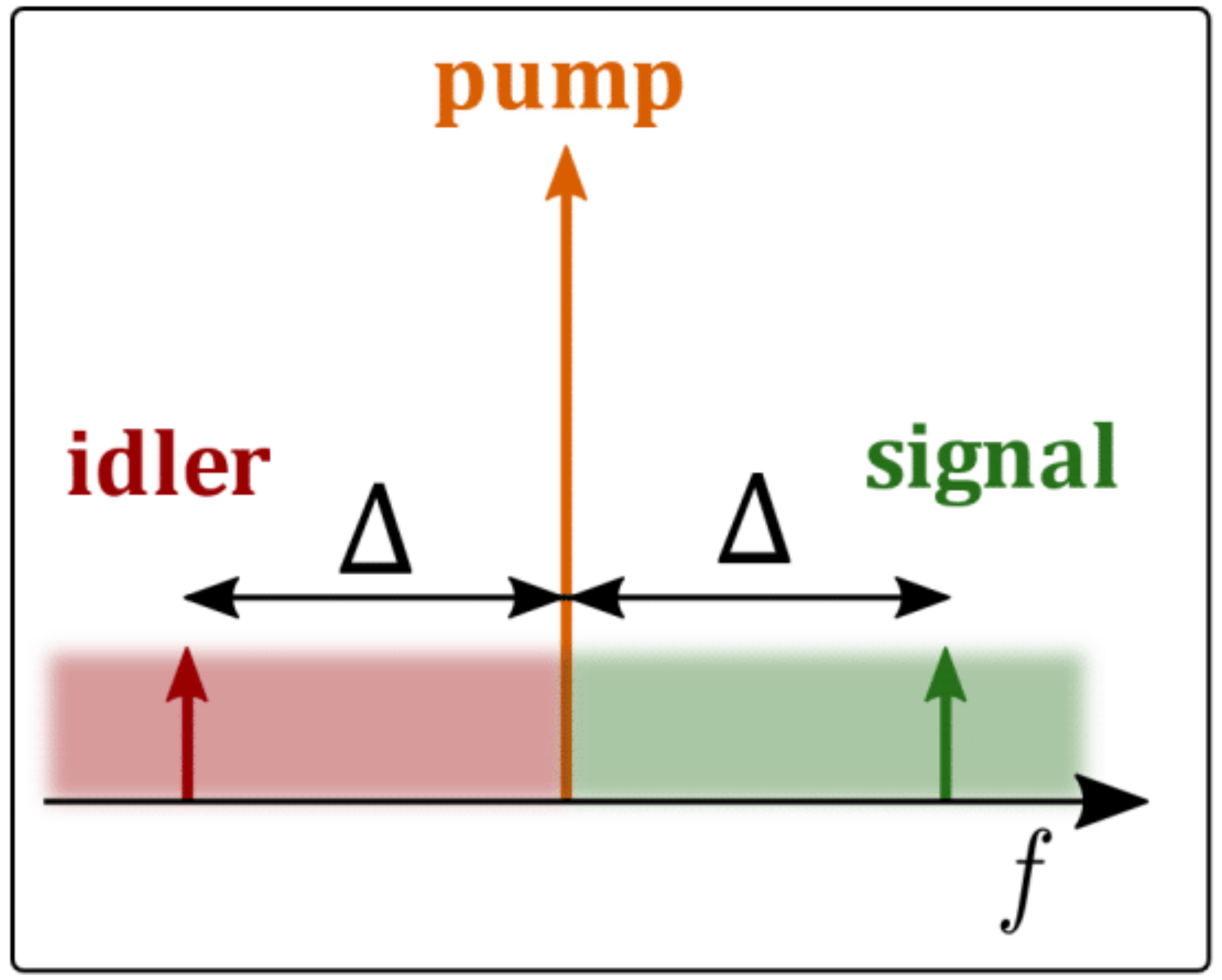
$$S_\mathrm{q+} = 10\log\left(\frac{\langle x_+^2\rangle}{0.5}\right)$$

See also: Perelshtein et al., Phys. Rev. Applied (2022), Qiu et al., Nat. Phys. (2023)

Demonstration of two-mode squeezing in TWPAs



Broadband squeezing



See also: Perelshtein et al., Phys. Rev. Applied (2022), Qiu et al., Nat. Phys. (2023)

Conclusion & Perspectives

Josephson Traveling Wave Parametric Amplifiers: fabrication

L. Planat et al. Phys. Rev. Applied (2019)   Patent n° FR1901767

Josephson TWPA: phase matching

L. Planat et al. PRX (2020)   A. Ranadive, et al. Nat. Commun. (2022)

Two-mode vacuum squeezing

M. Esposito, et al. PRL (2022)

Josephson TWPA: perspectives

M. Esposito, et al. APL (2021)

Bringing quantum technologies to market

SILENT WAVES

Non-reciprocal Josephson TWPA

Multi-mode entanglement in Josephson waveguides

Superconducting Quantum Circuits

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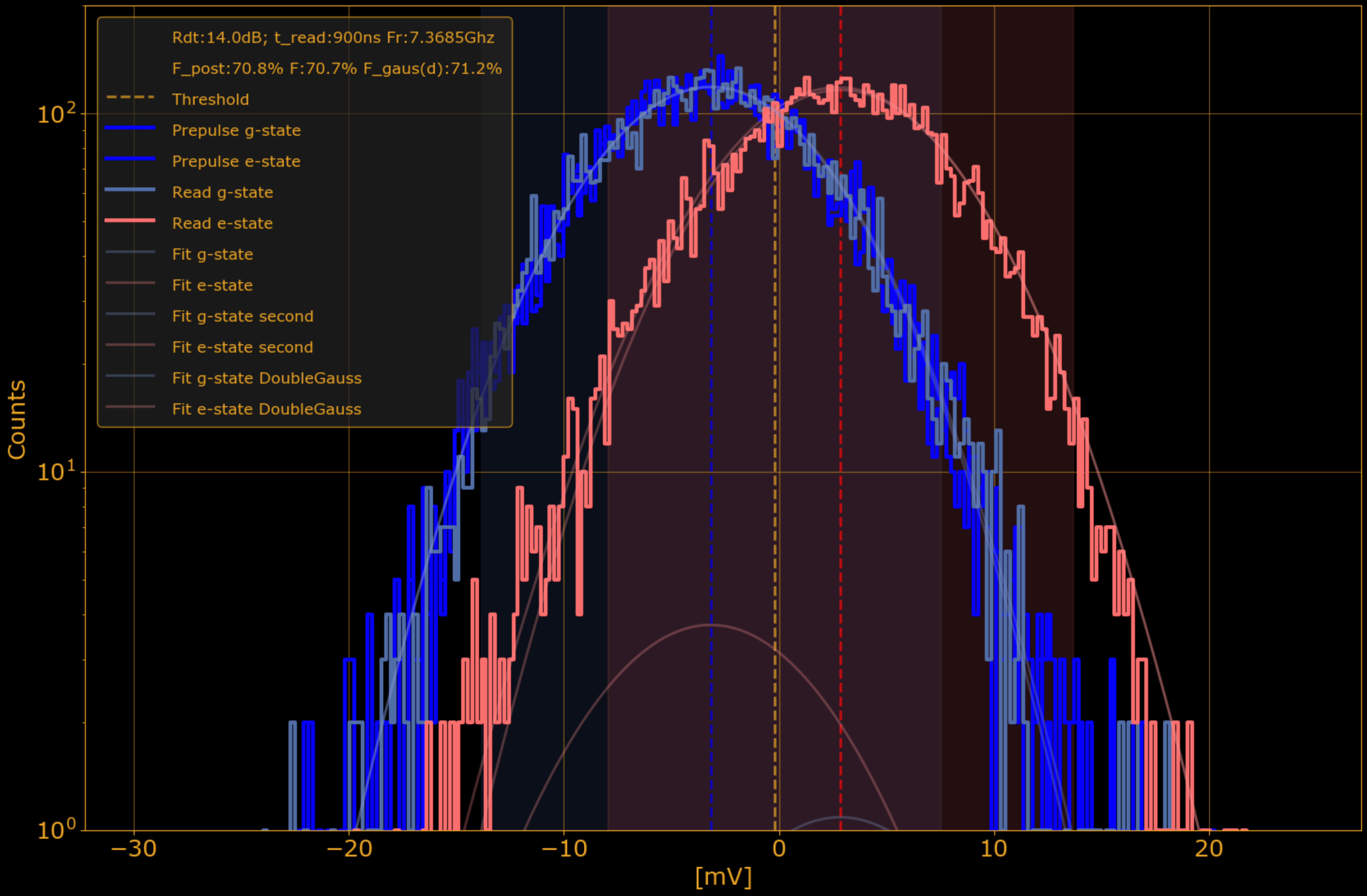
nicolas.roch@neel.cnrs.fr

Use-case 1: qubit read-out

TWPA OFF

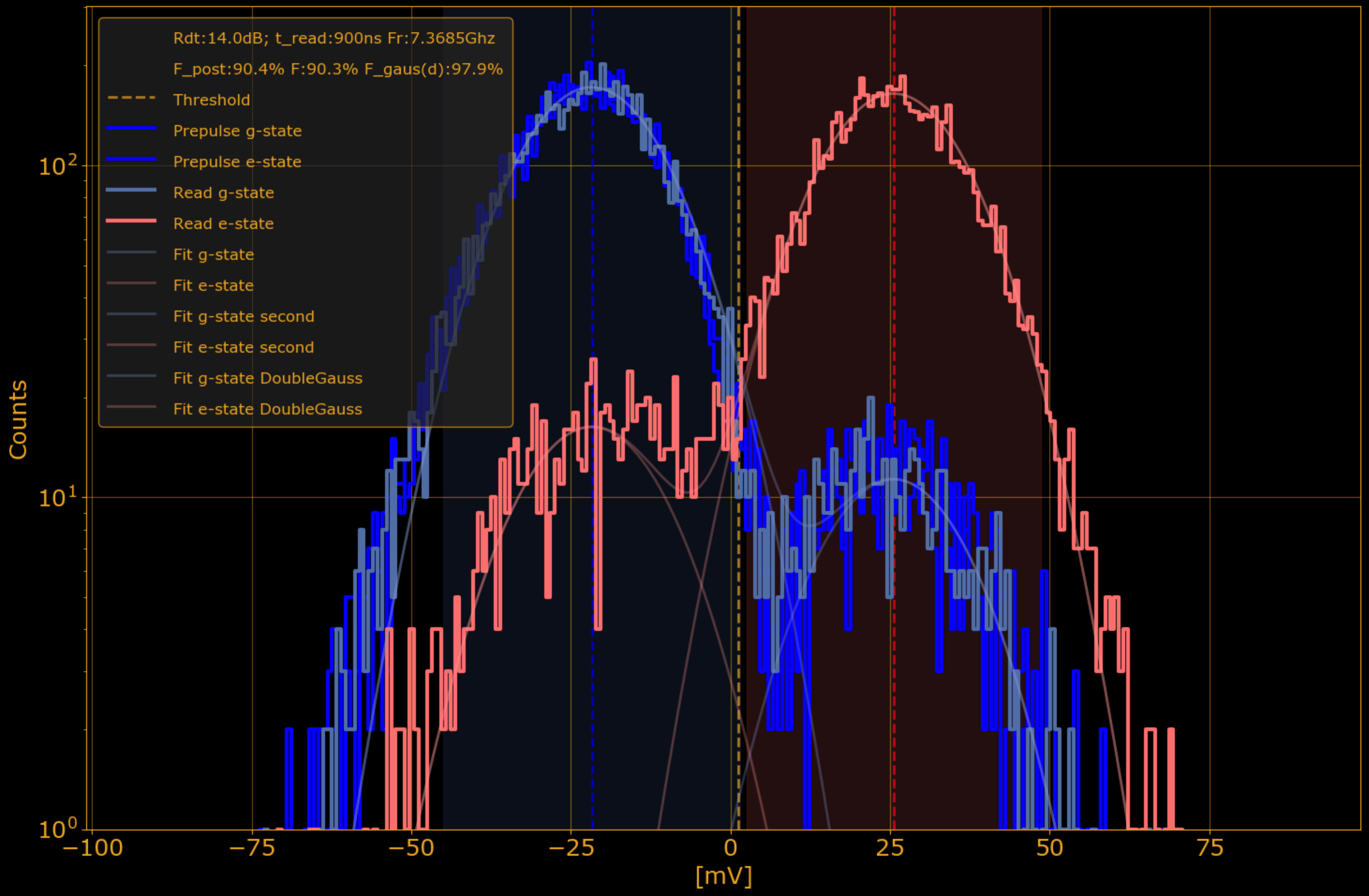
$F_{\text{overlap}} \sim 71\%$



Use-case 1: qubit read-out

TWPA ON

$$F_{\text{overlap}} \sim 98\%$$



Use-case 2: ultra-low power measurements