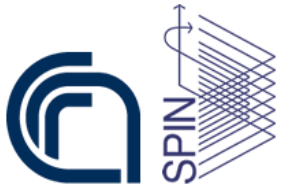
Two-mode squeezing generation in a traveling wave parametric amplifier

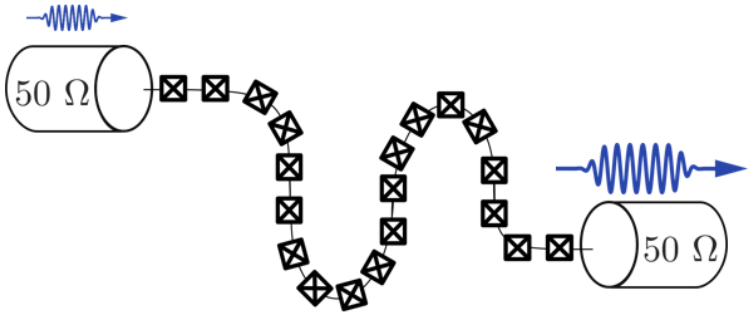
Martina Esposito

CNR SPIN Institute, Naples, Italy



December 1st 2021
DARTWARS Collaboration Meeting

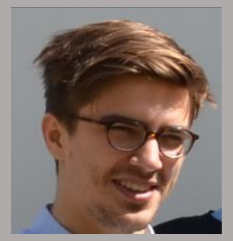
Grenoble TWPA Team



Giulio Cappelli
PhD student

Arpit Ranadive
PhD student

Luca Planat
Postdoc



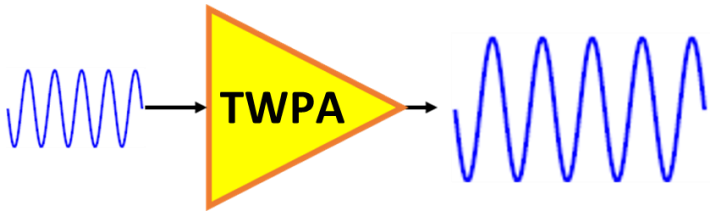
Martina Esposito
Marie Curie IF fellow

Since Oct. 2021
permanent researcher at CNR
Naples, Italy

Nicolas Roch
Team leader

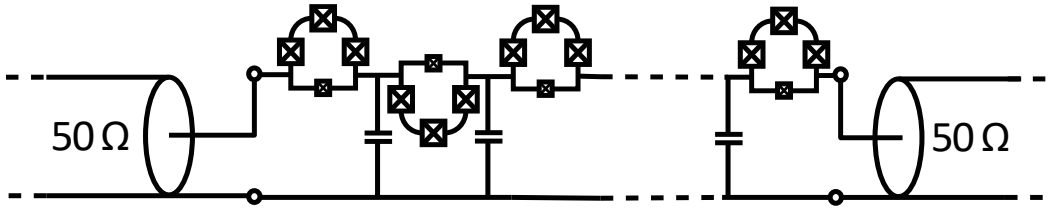
Outline

1. **Josephson Travelling wave parametric amplification**



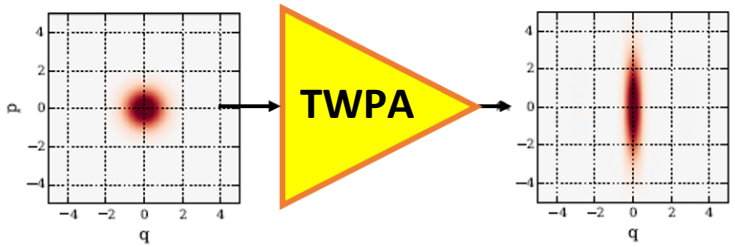
2. **A reversed Kerr TWPA**

A. Ranadive. et al. arXiv:2101.05815 (2021)

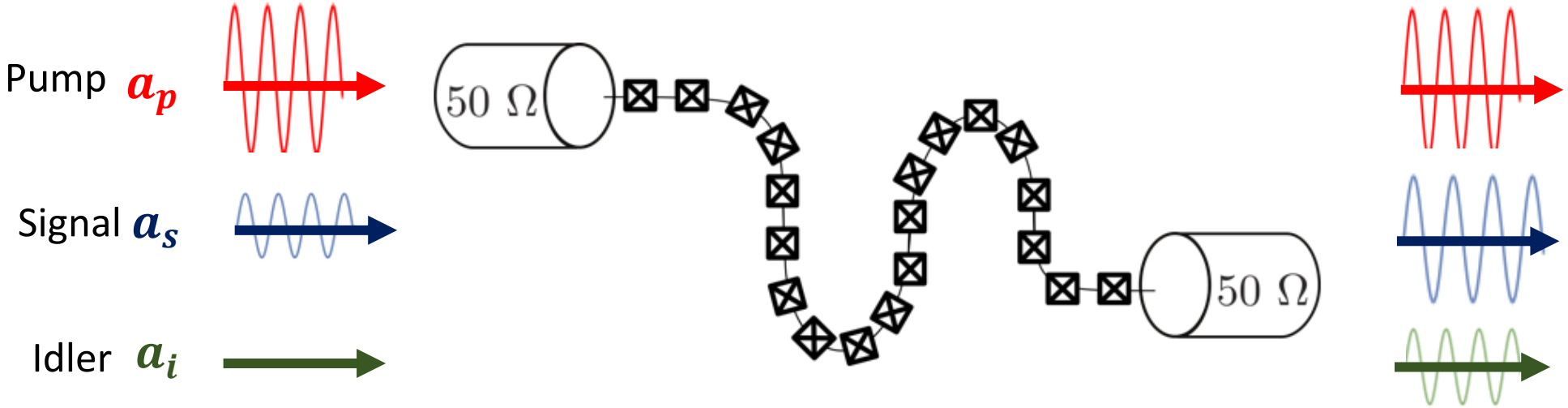


3. **Two mode squeezing in TWPAs**

M. Esposito et al. arXiv:2111.03696 (2021)



Josephson TWPA: Wave mixing process



4-wave mixing

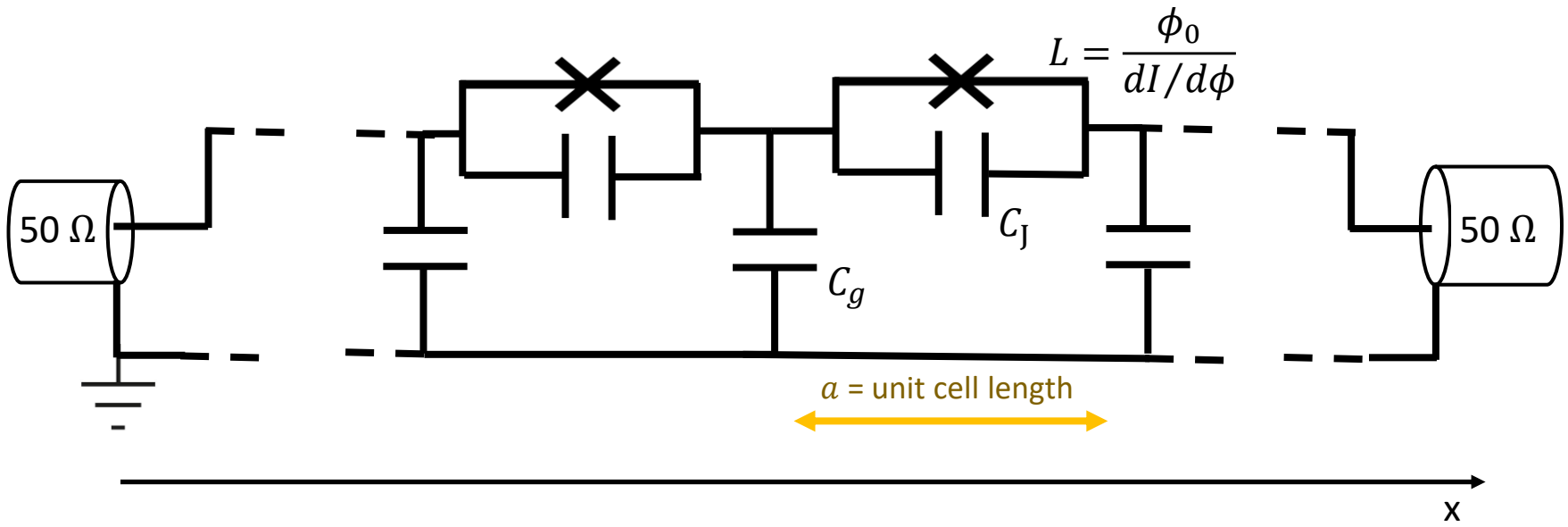
$$H_{\text{int}} = a_i^\dagger a_s^\dagger a_p a_p + hc$$

$$2\omega_P = \omega_i + \omega_s$$

$$2k_P = k_i + k_s$$

Phase mismatch problem in TWPAs!

Josephson Travelling Wave Parametric Amplification



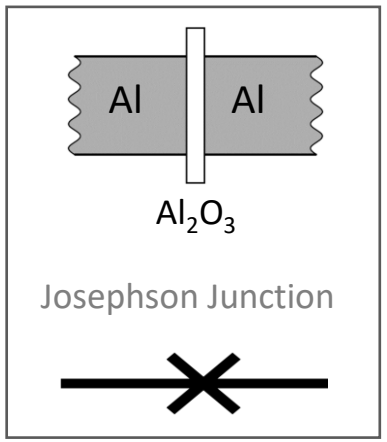
$n \sim 10^3\ cells$

$a \sim 10\ \mu m$

$\lambda \sim 1\ mm$

$\omega_0 = 1/\sqrt{LC_g}$

$\omega_J = 1/\sqrt{LC_J}$



$$I(\phi) = \tilde{\alpha}[I_0\phi + \gamma I_0\phi^3 + \ \dots\ ]$$

$\chi^{(3)}$

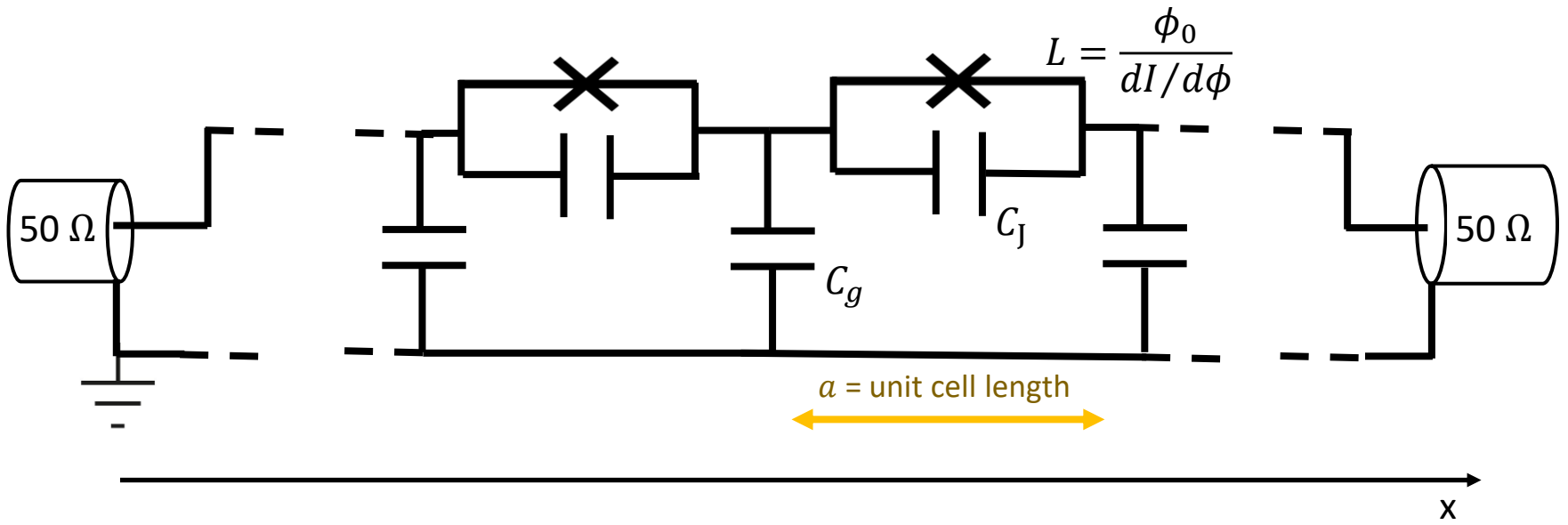
4-wave mixing (Kerr) non linearity

Phase across junction

$$\phi = \int V dt$$

$\phi(x) \sim \phi_0\, e^{ikx}$

Josephson Travelling Wave Parametric Amplification



$n \sim 10^3$ *cells*

$a \sim 10\ \mu m$

$\lambda \sim 1\ mm$

$\omega_0 = 1/\sqrt{LC_g}$

$\omega_J = 1/\sqrt{LC_J}$

$$\frac{\partial^2\phi}{\partial x^2} - \frac{1}{\omega_0^2}\frac{\partial^2\phi}{\partial t^2} + \frac{1}{\omega_J^2}\frac{\partial^4\phi}{\partial t^2 \partial x^2} - \gamma\frac{\partial}{\partial x}\left(\frac{\partial\phi}{\partial x}\right)^3 = 0$$

$\chi^{(3)}$

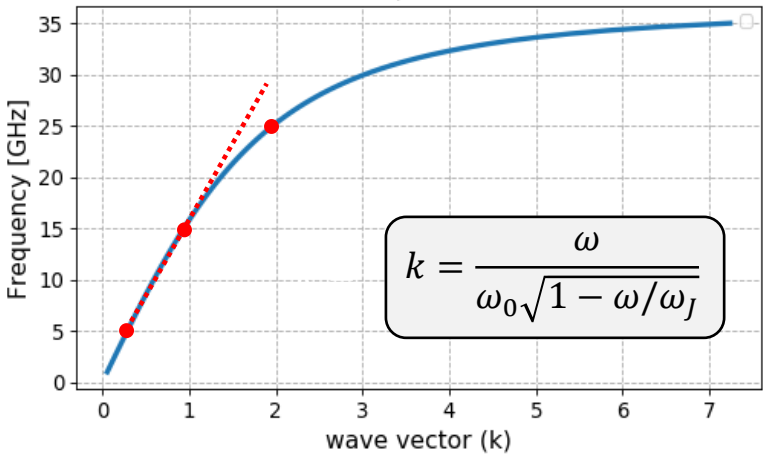
4-wave mixing (Kerr) non linearity

Single-junction TWPA

$$\underbrace{\frac{\partial^2\phi}{\partial x^2} - \frac{1}{\omega_0^2}\frac{\partial^2\phi}{\partial t^2} + \frac{1}{\omega_J^2}\frac{\partial^4\phi}{\partial t^2 \partial x^2}}_{} - \underbrace{\gamma\frac{\partial}{\partial x}\left(\frac{\partial\phi}{\partial x}\right)^3}_{} = 0$$

$\Delta k_0 = k_s + k_i - 2k_p > 0$ $\qquad$ $\Delta k_{Kerr} \propto \gamma |A_p|^2$

dispersion relations



Phase mismatch problem:

$$\Delta k = \Delta k_0 + \Delta k_{Kerr} \neq 0$$

Power gain (Maximal when $\Delta k = 0$)

$$G = |\cosh(gN) + {}^{i\Delta k}/_{2g}\sinh(gN)|^2$$

$$g = \sqrt{K_{si} - \Delta k^2/4}$$

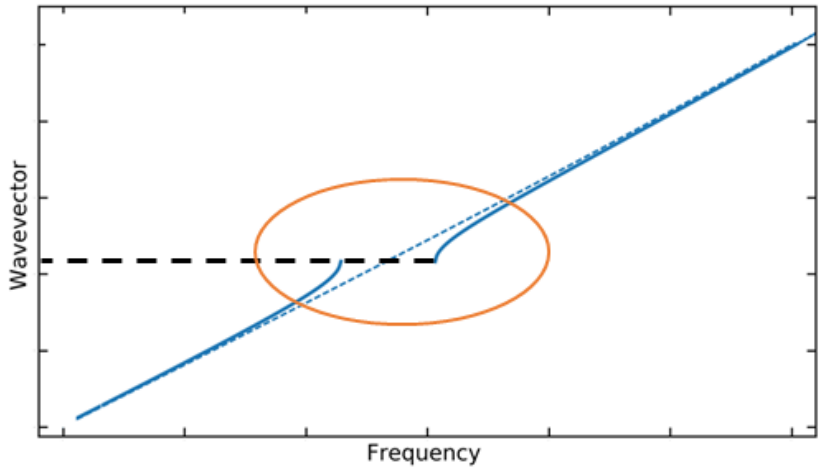
Possible solution: Dispersion engineering

Dispersion engineering Phase Matching

$$\Delta k = \Delta k_0 + \Delta k_{Kerr} \rightarrow 0$$

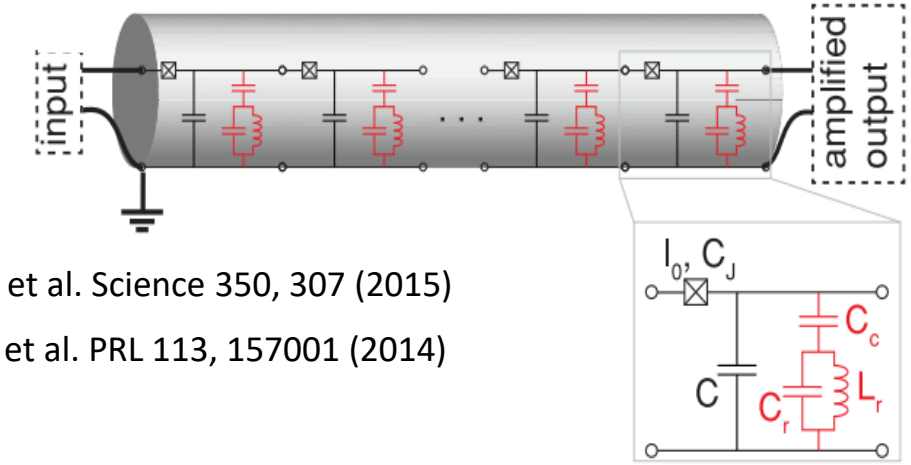
$$\Delta k_0 < 0$$

dispersion relations



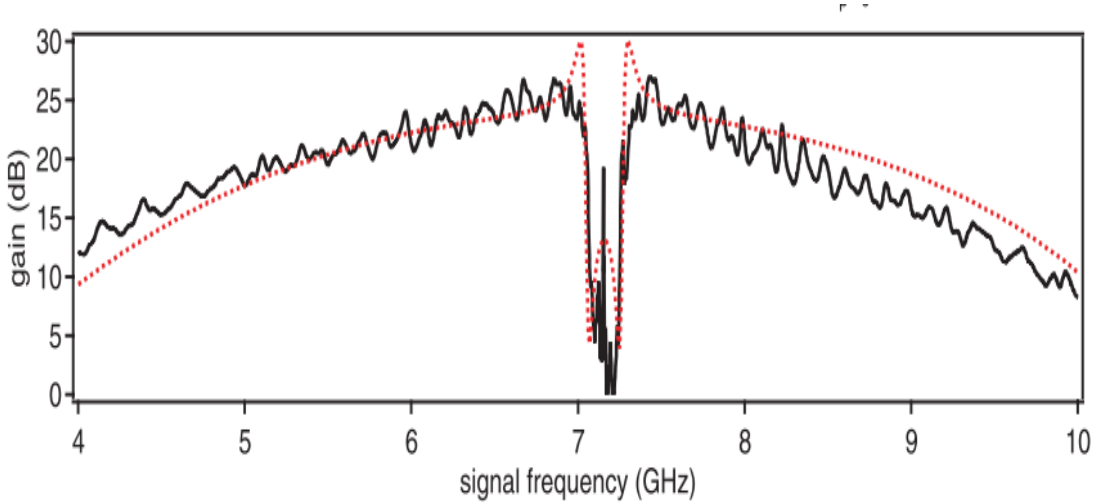
Dispersion engineering Phase Matching

1. **Berkeley/MIT/Lincoln Lab** : Resonant Phase matching

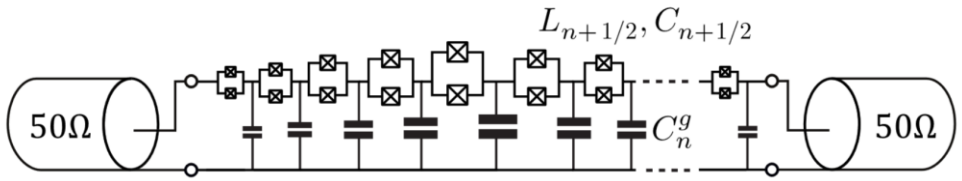


Macklin et al. Science 350, 307 (2015)

O'Brien et al. PRL 113, 157001 (2014)

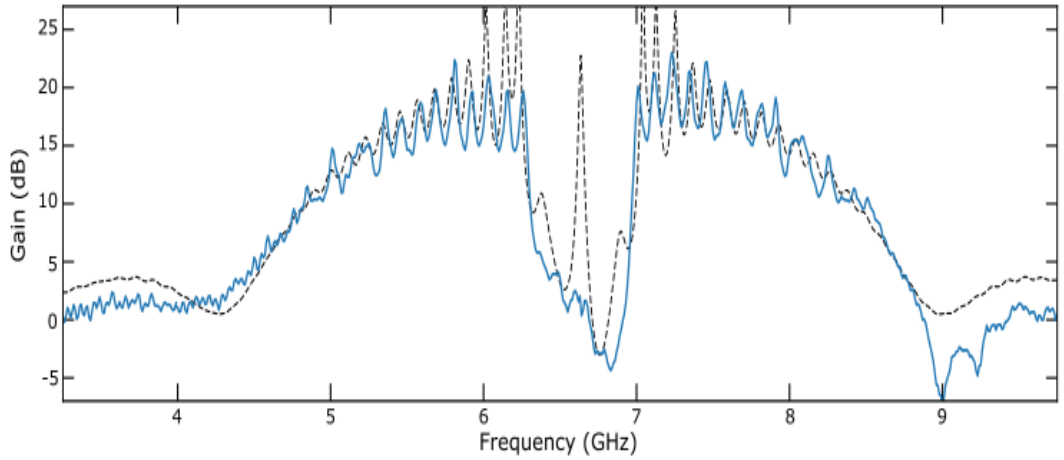


2. **Grenoble**: Photonic gap by modulation



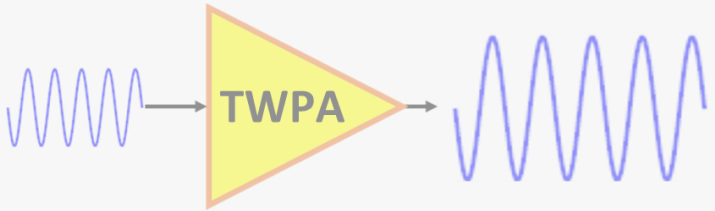
Planat et al. Physical Review X 10, 021021 (2020)

Planat et. al. Phys. Rev. Applied 12, 064017 (2019)



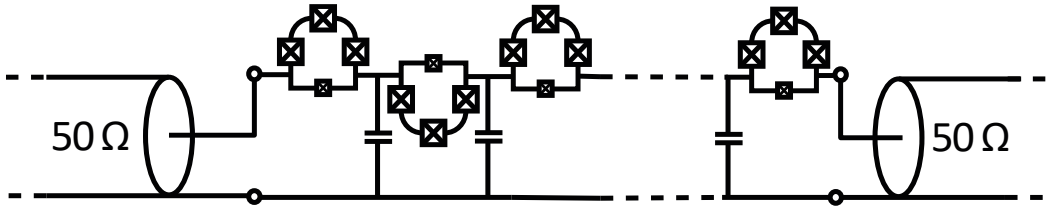
Outline

1. Josephson Travelling wave parametric amplification



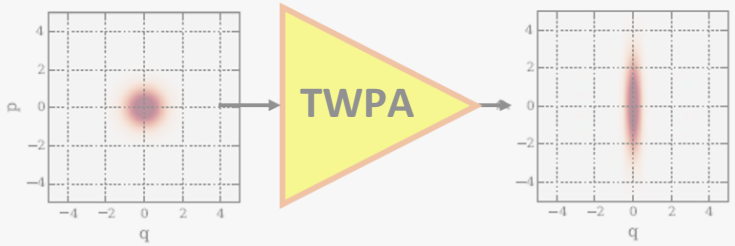
2. **A reversed Kerr TWPA**

A. Ranadive. et al. arXiv:2101.05815 (2021)



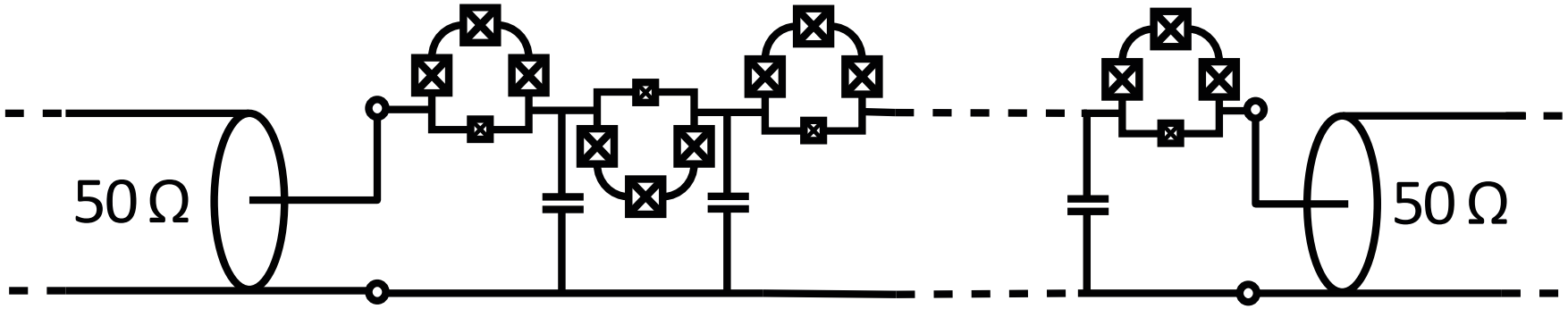
3. Two mode squeezing in TWPAs

M. Esposito et al. arXiv:2111.03696 (2021)



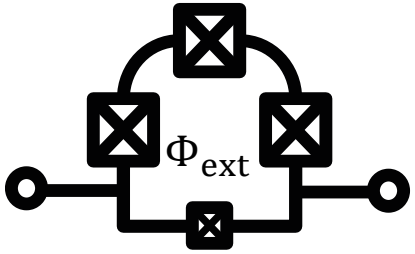
A Reversed Kerr TWPA

Our new solution: **Reversed Kerr** Phase Matching



SNAIL

(Superconducting Nonlinear Asymmetric Inductive element)



Frattini et al. Appl. Phys. Lett. **110**, 222603 (2017)

$$\frac{\partial^2\phi}{\partial x^2} - \frac{1}{\omega_0^2}\frac{\partial^2\phi}{\partial t^2} + \frac{1}{\omega_J^2}\frac{\partial^4\phi}{\partial t^2\partial x^2} - \gamma\frac{\partial}{\partial x}\left(\frac{\partial\phi}{\partial x}\right)^3 = 0$$

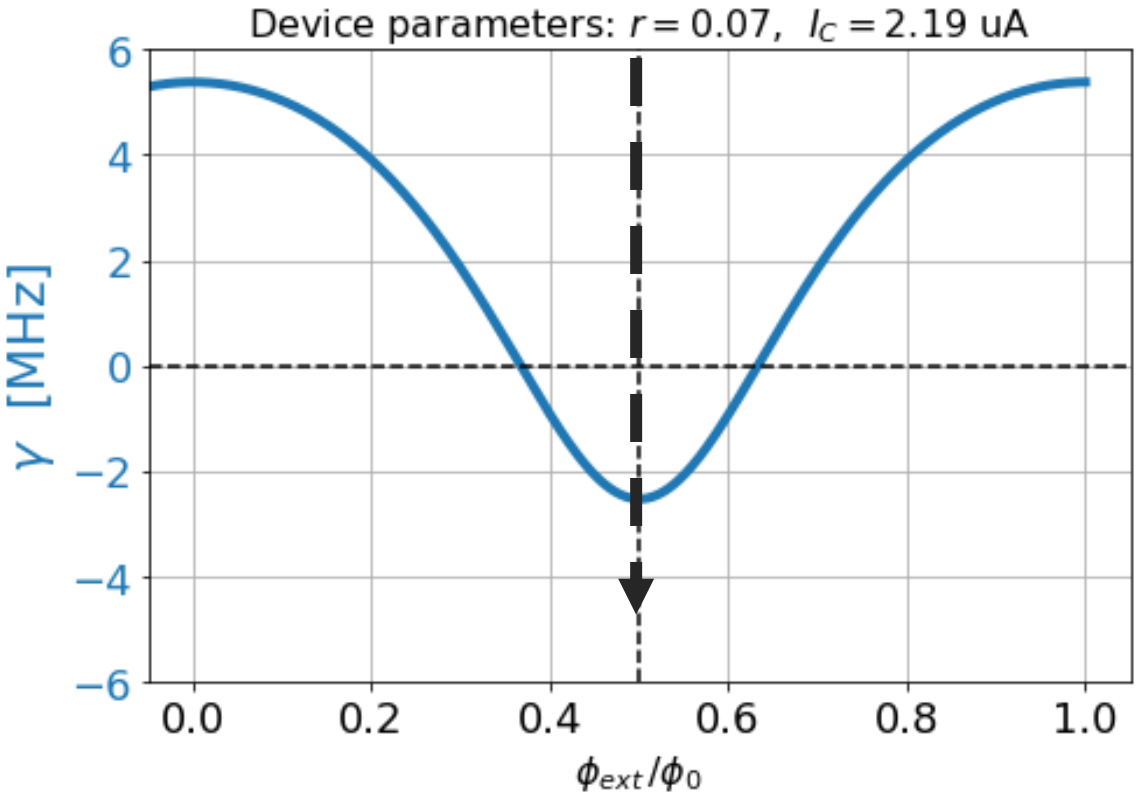
4-wave mixing

γ is flux dependent!

A Reversed Kerr TWPA

Our new solution: **Reversed Kerr** Phase Matching

$$\frac{\partial^2\phi}{\partial x^2} - \frac{1}{\omega_0^2}\frac{\partial^2\phi}{\partial t^2} + \frac{1}{\omega_J^2}\frac{\partial^4\phi}{\partial t^2 \partial x^2} - \gamma\frac{\partial}{\partial x}\left(\frac{\partial\phi}{\partial x}\right)^3 = 0$$

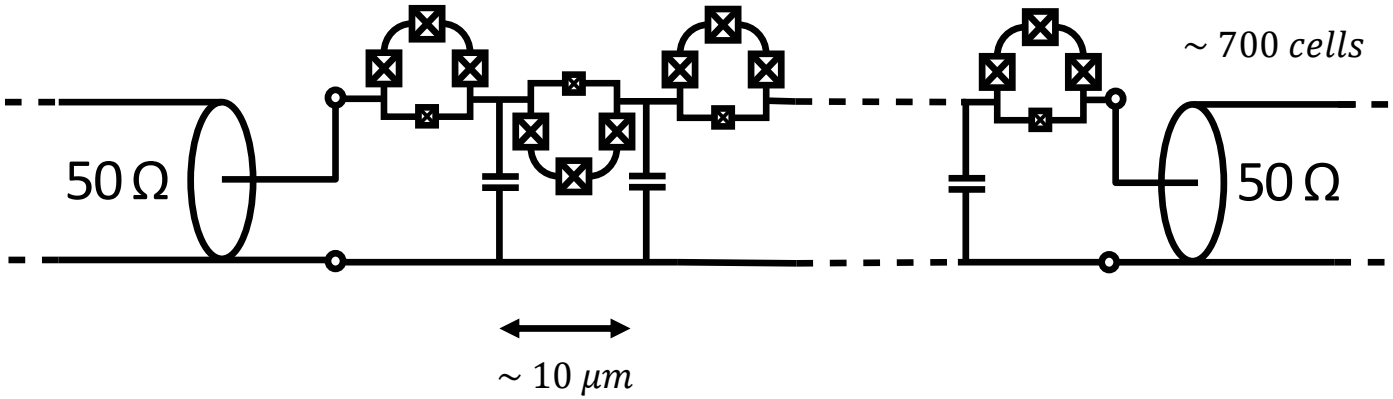


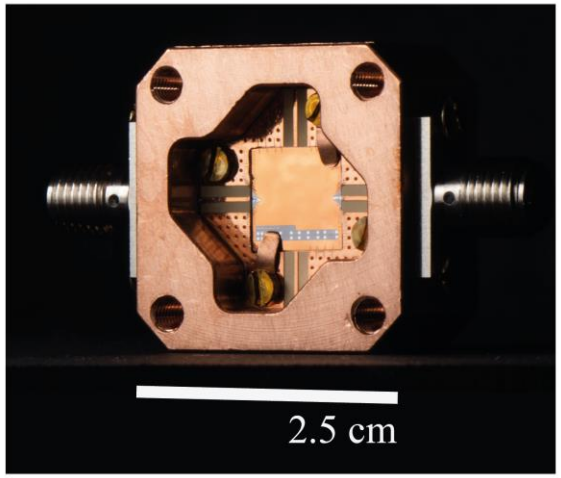
$$\Delta k = \Delta k_0 + \Delta k_{Kerr} \rightarrow 0$$

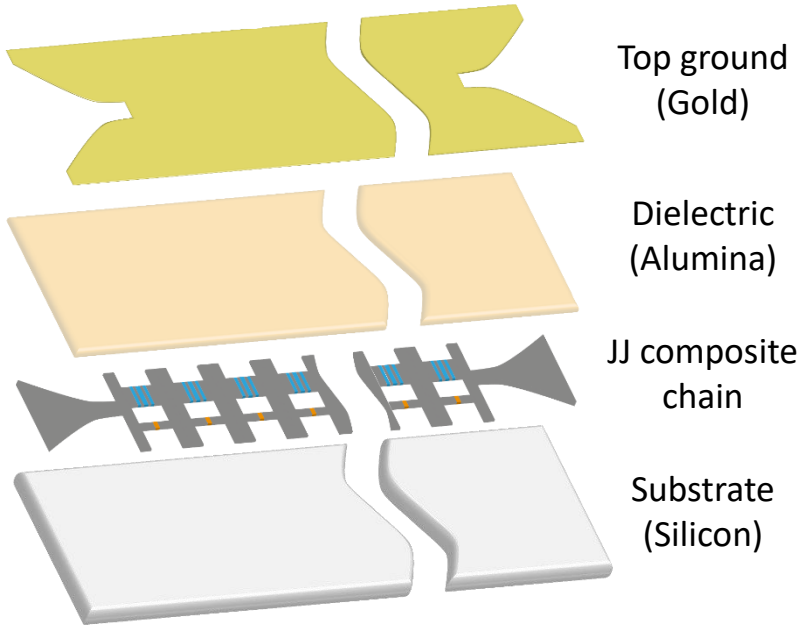
$$\Delta k_{Kerr} \propto \gamma |A_p|^2$$

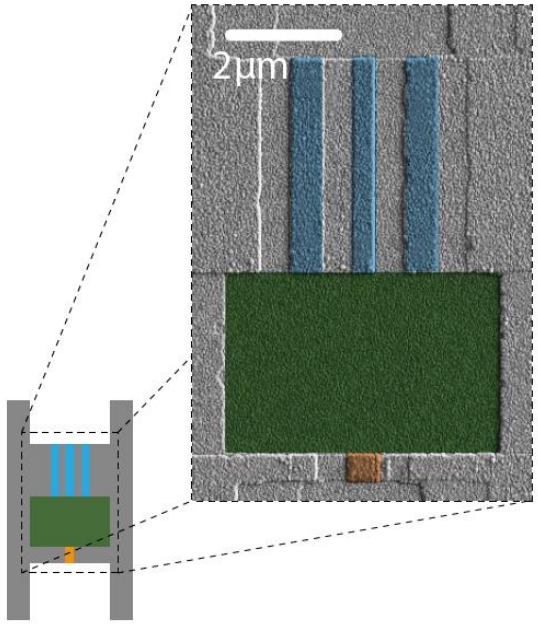
When $\gamma < 0 \rightarrow \Delta k = 0$ is possible!

A Reversed Kerr TWPA - Fabrication

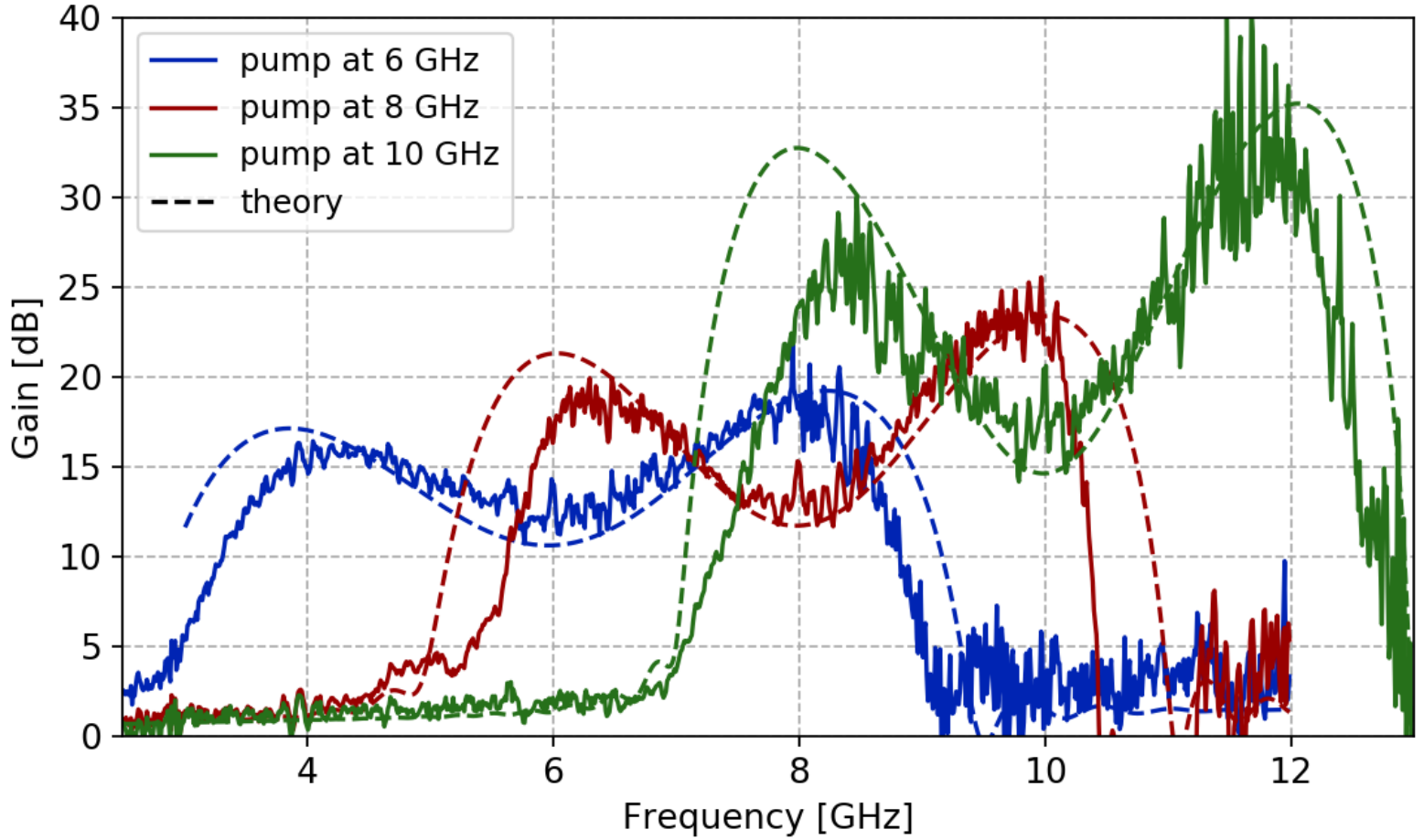








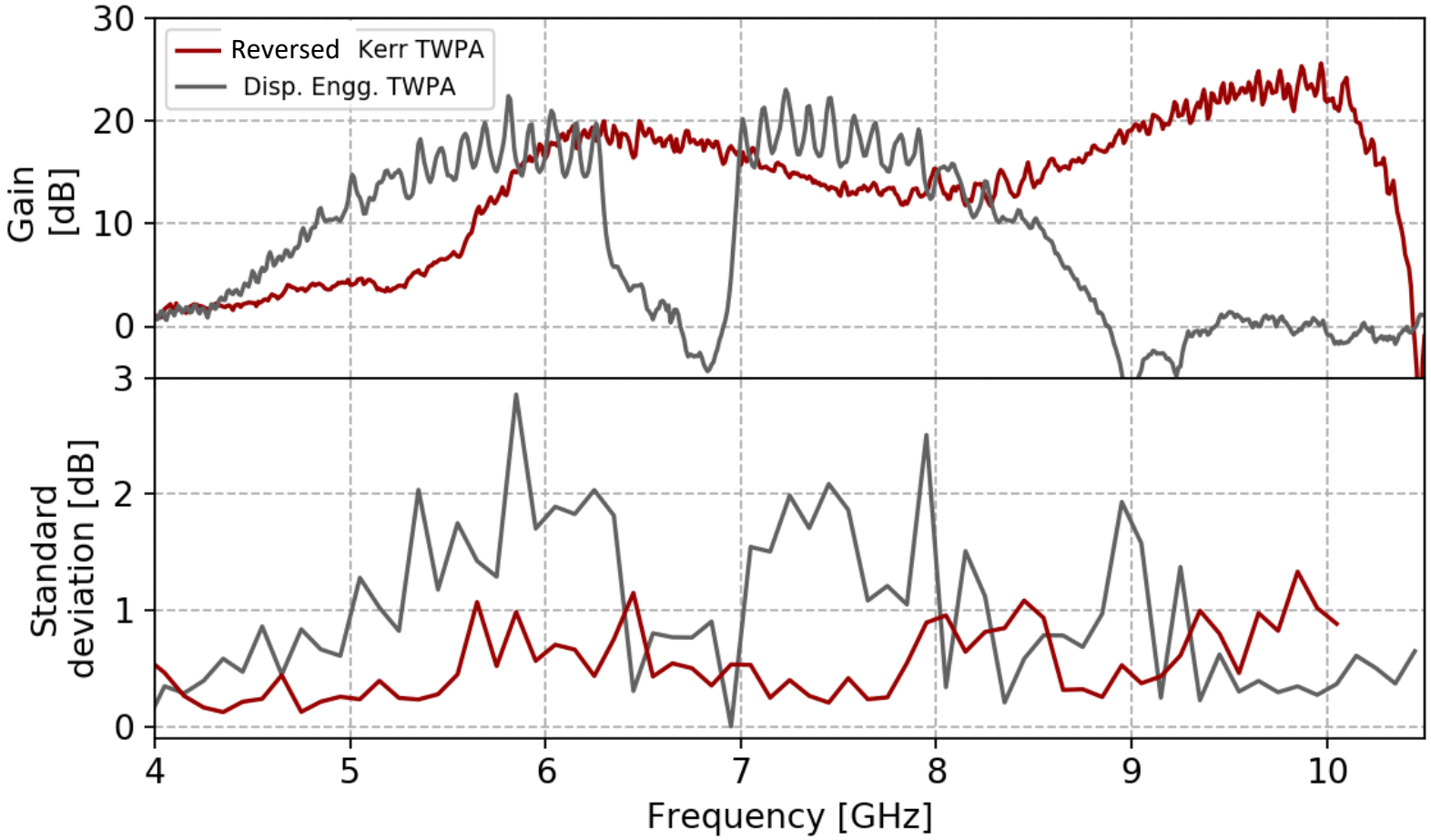
A Reversed Kerr TWPA – Gain performance



BW > 3.5 GHz

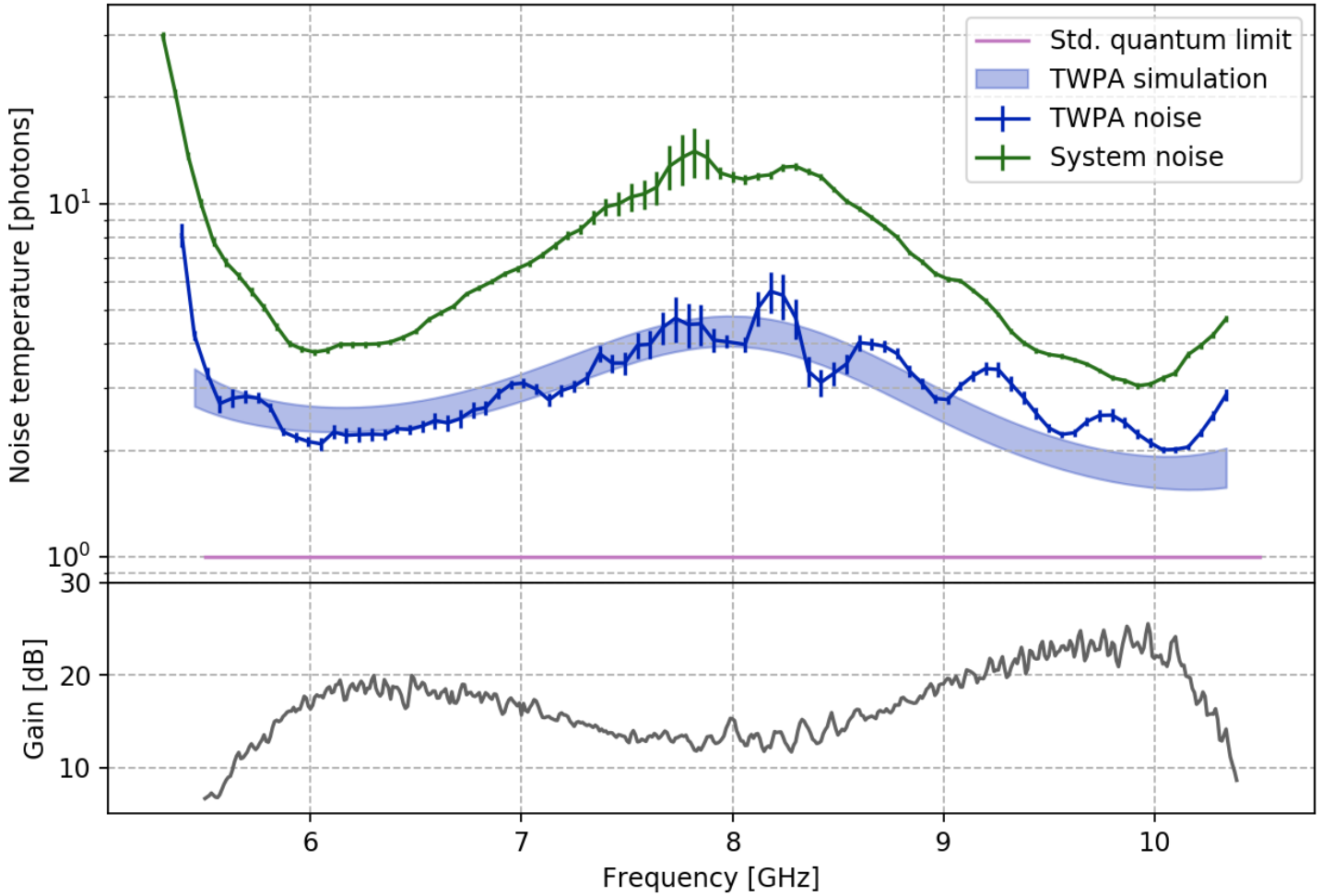
A Reversed Kerr TWPA – Gain performance

Reduction in gain ripples



Evaluated over 100 MHz bins

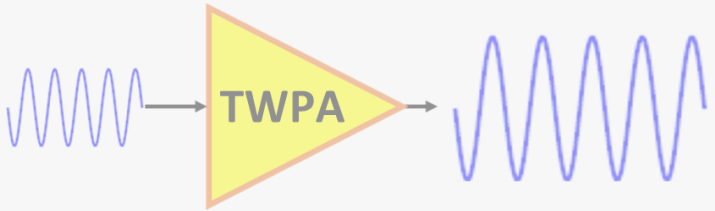
A Reversed Kerr TWPA – Noise performance



$$\mathbf{N_{TWPA} \sim 2\ SQL}$$

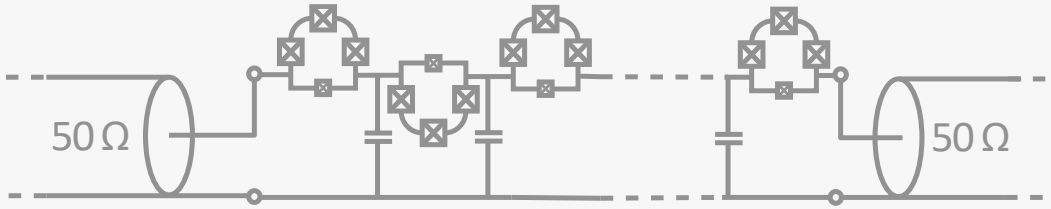
Outline

1. Josephson Travelling wave parametric amplification



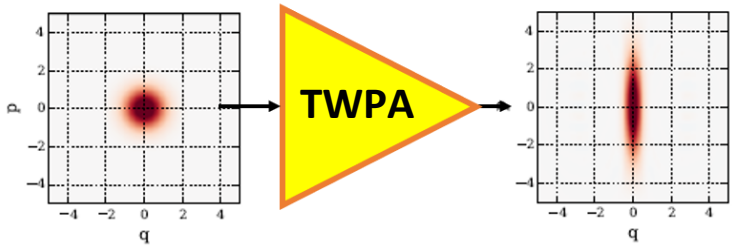
2. A reversed Kerr TWPA

A. Ranadive. et al. arXiv:2101.05815 (2021)



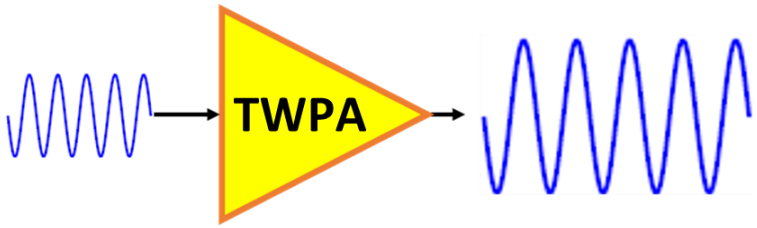
3. **Two mode squeezing in TWPAs**

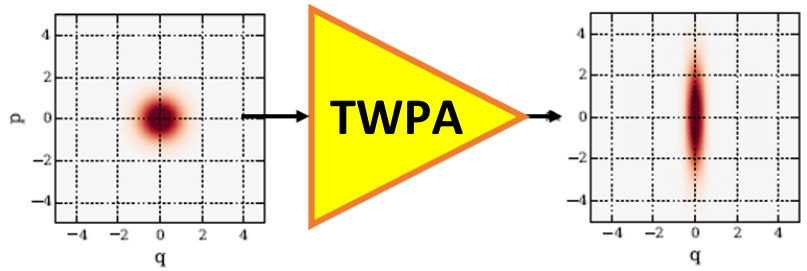
M. Esposito et al. arXiv:2111.03696 (2021)



Two mode squeezing in TWPAs - Motivations

Not only amplification…..

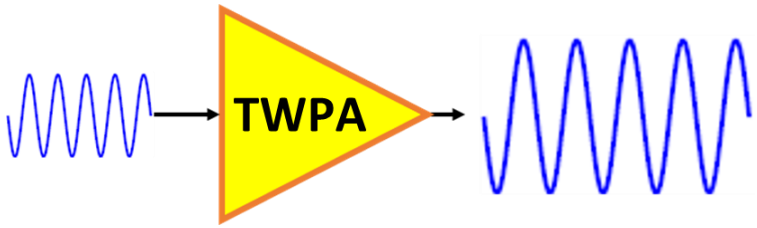


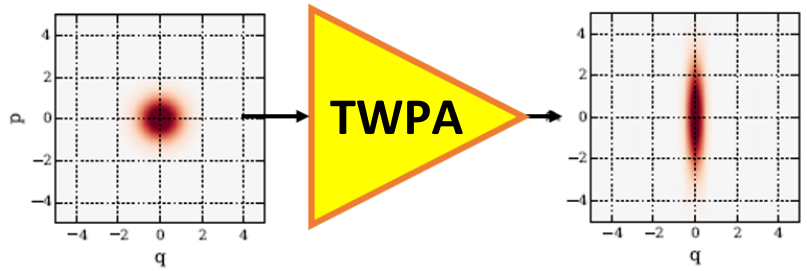


Quantum Microwave Photonics

Two mode squeezing in TWPAs - Motivations

Not only amplification…..

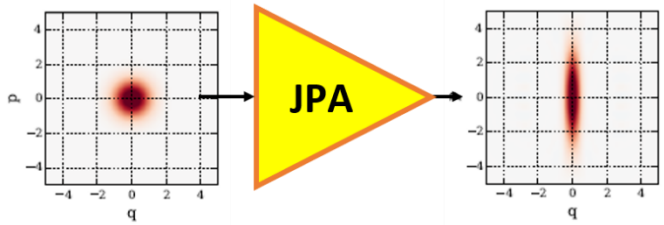




Quantum Microwave Photonics

Microwave frequencies:

Single-mode and Two-mode squeezing in JPAs



- E. Flurin. Et al. Phys. Rev. Lett., 114(090503):1–5 (2015)
- L Zhong et al. New Journal of Physics, 15(12):125013 (2013)
- C. Eichler et al. Physical Review Letters, 107(11):1–5 (2011)

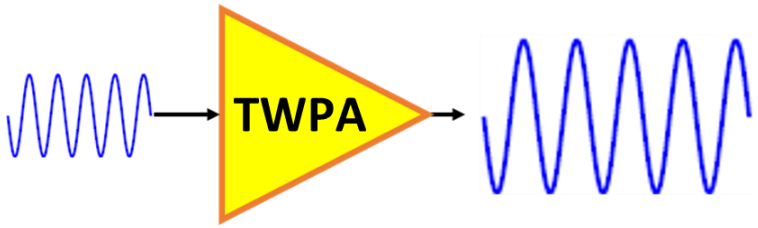
Narrow-band Resonant JPAs

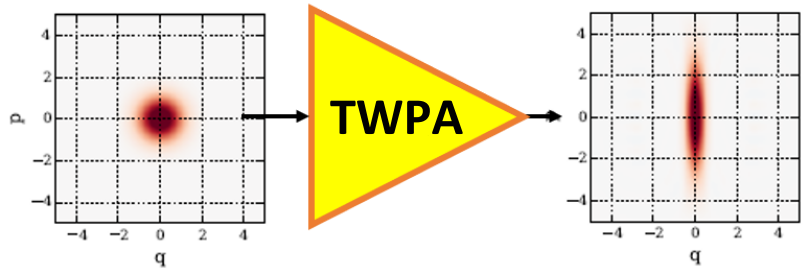
- B. H. Schneider et al. .Phys.Rev. Lett., 124:140503 (2020)
- C. M. Wilson et al. Nature 479, 376, (2011)

Dynamical Casimir Effect in transmission lines

Two mode squeezing in TWPAs - Motivations

Not only amplification…..





Quantum Microwave Photonics

Microwave frequencies: **Single-mode and Two-mode squeezing in JPAs**

Quantum enhanced detection

Squeezed Vacuum Used to Accelerate the Search for a Weak Classical Signal

M. Malnou, D. A. Palken, B. M. Brubaker, Leila R. Vale, Gene C. Hilton, and K. W. Lehnert
Phys. Rev. X **9**, 021023 – Published 3 May 2019; Erratum Phys. Rev. X **10**, 039902 (2020)

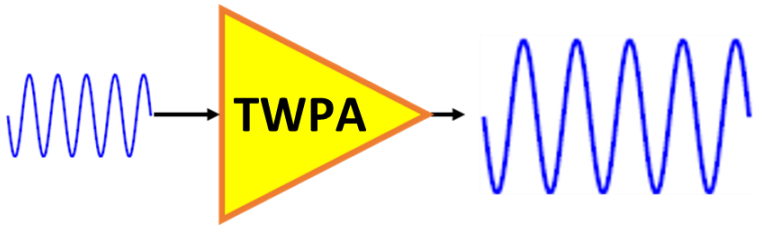
Article nature

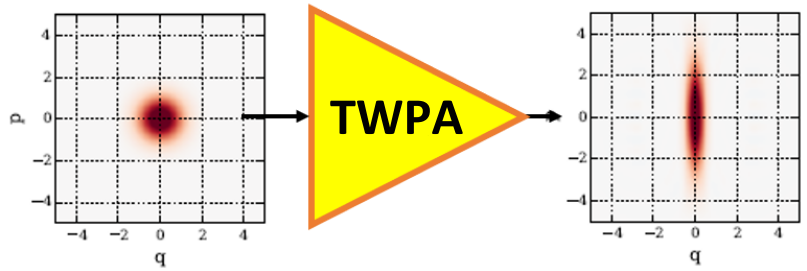
A quantum enhanced search for dark matter axions 2021

K. M. Backes[1,6]✉, D. A. Palken[2,3,6], S. Al Kenany[4], B. M. Brubaker[2,3], S. B. Cahn[1], A. Droster[4], Gene C. Hilton[5], Sumita Ghosh[1], H. Jackson[4], S. K. Lamoreaux[1], A. F. Leder[4], K. W. Lehnert[2,3,5], S. M. Lewis[4], M. Malnou[2,5], R. H. Maruyama[1], N. M. Rapidis[4], M. Simanovskaia[4], Sukhman Singh[1], D. H. Speller[1], I. Urdinaran[4], Leila R. Vale[5], E. C. van Assendelft[1], K. van Bibber[4] & H. Wang[1]

Two mode squeezing in TWPAs - Motivations

Not only amplification…..





Quantum Microwave Photonics

Microwave frequencies:

Can we generate squeezing in TWPAs ?

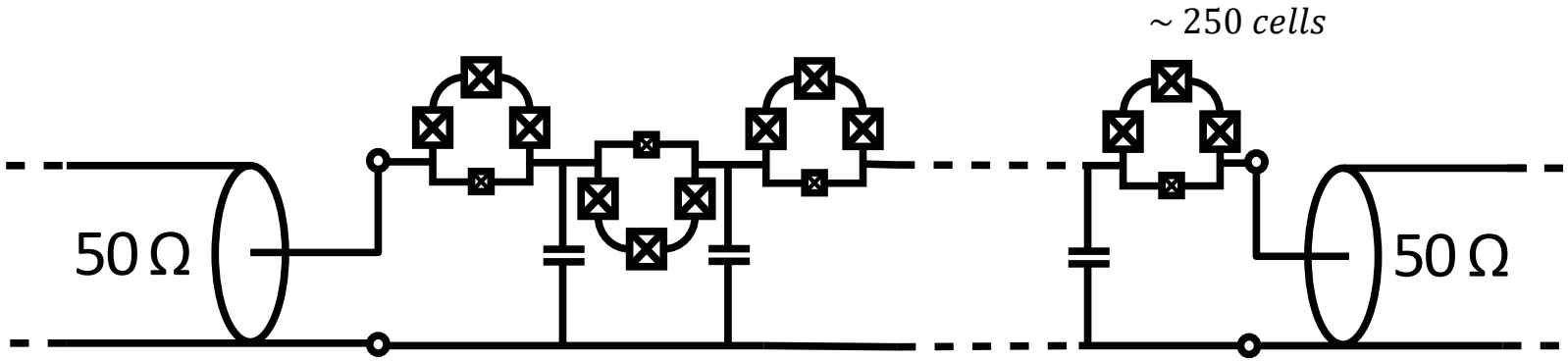
Advantages:

- Broadband nature
- Customization and flux tunability of the non-linearities

Difficulties:

- Losses in TWPAs
- Spurious non-linear processes

Two mode squeezing in TWPAs - Device



4-wave mixing

$$\boldsymbol{H}_{\mathrm{int}} = \boldsymbol{\gamma}\, \boldsymbol{a}_{\boldsymbol{s}}^{\dagger} \boldsymbol{a}_{\boldsymbol{i}}^{\dagger} \boldsymbol{a}_{\boldsymbol{p}} \boldsymbol{a}_{\boldsymbol{p}} + \mathrm{h.c.}$$

Two-mode squeezing in TWPAs

4-wave mixing → Two-mode squeezing

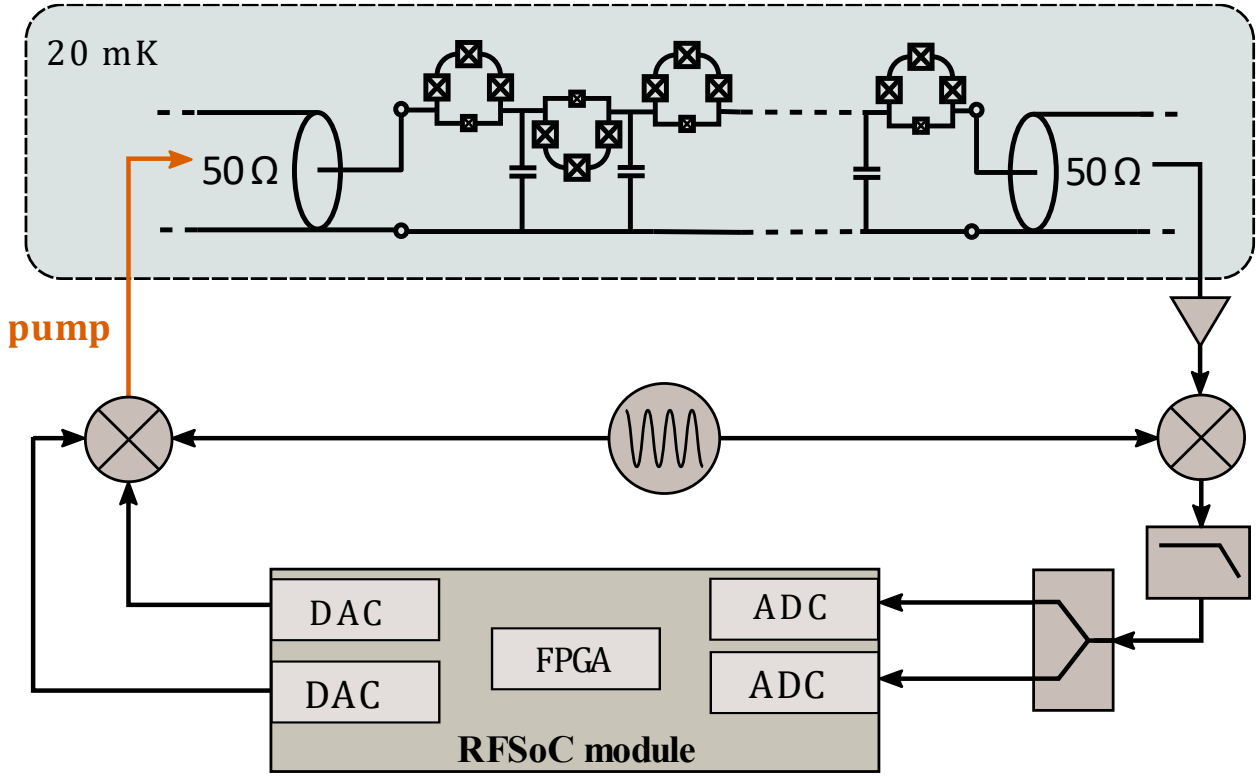
$$\boldsymbol{H}_{\text{int}} = \boldsymbol{\gamma}\,|\boldsymbol{A_p}|^2\,\boldsymbol{a_s^\dagger a_i^\dagger} + \text{h. c.} \longrightarrow \mathbf{S}(\boldsymbol{\xi}) = \exp\left[\frac{\mathbf{1}}{\mathbf{2}}\left(\boldsymbol{\xi a_i^\dagger a_s^\dagger} - \boldsymbol{\xi^* a_i a_s}\right)\right]$$

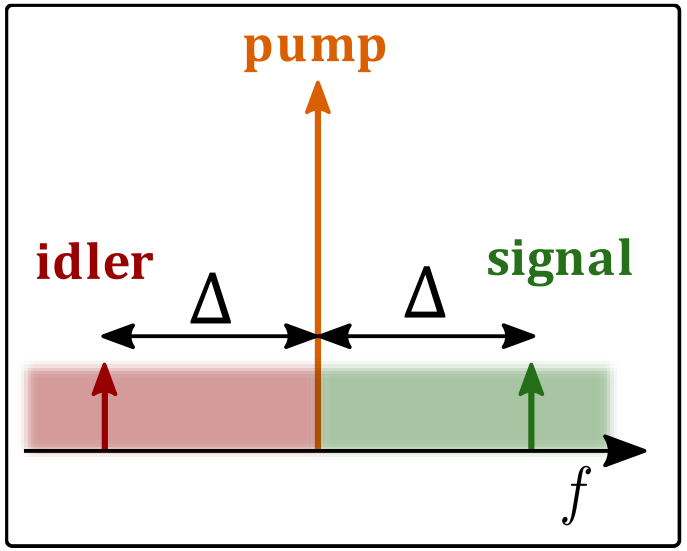
$$\xi = r\, e^{i\,\phi}$$ Squeezing parameter

$$\mathrm{G_{TWPA}} = \cosh^2(r)$$

$$|\mathrm{Sq}\rangle = \mathbf{S}\,|0\rangle_s|0\rangle_i = \frac{1}{\cosh r}\sum_n (\tanh r)^n\,|n\rangle_s|n\rangle_i$$

Two-mode squeezing in TWPAs

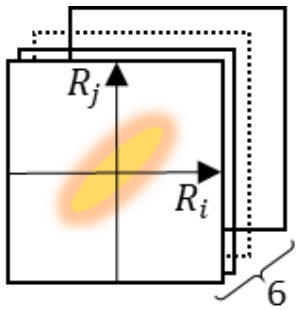




4-wave mixing

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

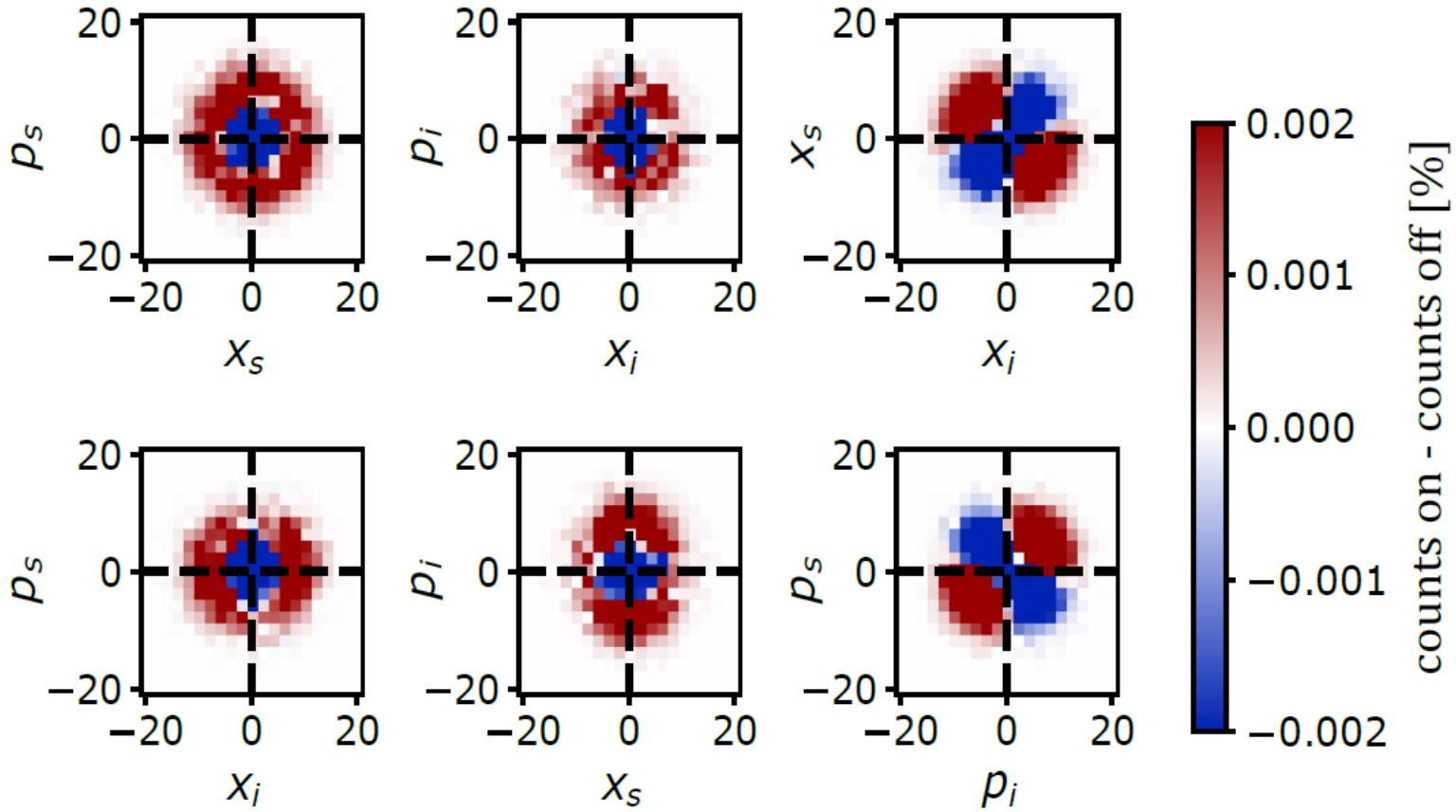
$$\hat{x}_{s,i} = \frac{1}{2}\left(\hat{A}_{s,i} + \hat{A}_{s,i}^{\dagger}\right) \qquad \hat{p}_{s,i} = \frac{1}{2i}\left(\hat{A}_{s,i} - \hat{A}_{s,i}^{\dagger}\right)$$



$$\boldsymbol{H}_{\text{int}} = \boldsymbol{\gamma}\,|\boldsymbol{A_p}|^2\,\boldsymbol{a_s^{\dagger}}\boldsymbol{a_i^{\dagger}} + \text{h. c.}$$

Two-mode squeezing in TWPAs

Phase- space histogram distribution

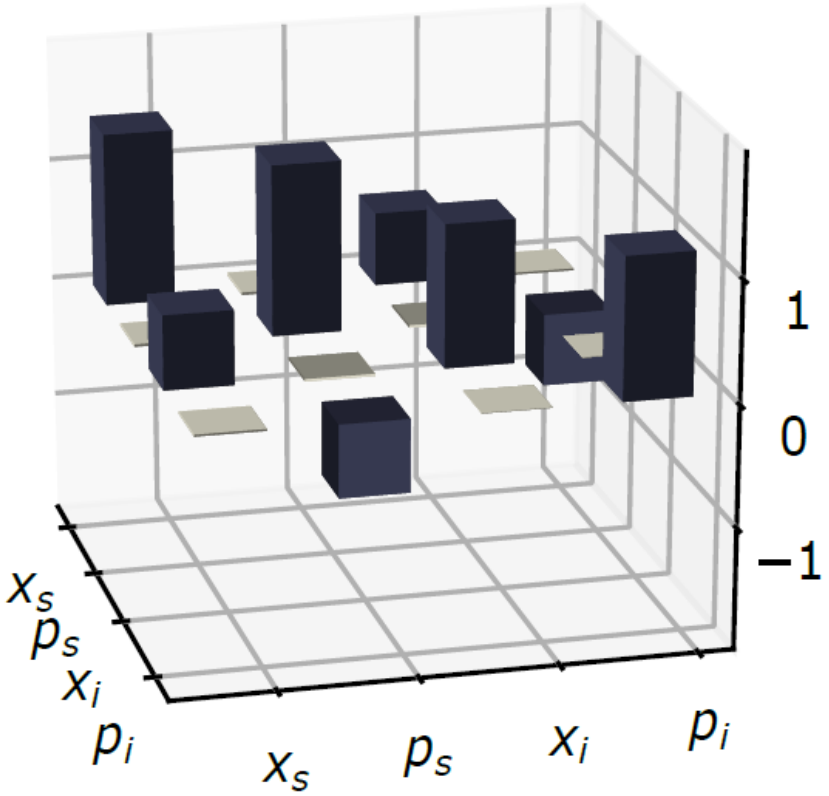


$$\mathbf{R} = (\hat{x}_s, \hat{p}_s, \hat{x}_i, \hat{p}_i)$$

Covariance Matrix reconstruction

$$\sigma = \sigma^{\text{meas,on}} - \sigma^{\text{meas,off}} + \mathbb{1}_4$$

$$\sigma_{jk}^{\text{meas}} = 4\left[\frac{1}{2}\langle R_j R_k + R_k R_j\rangle - \langle R_j\rangle\langle R_k\rangle\right]$$

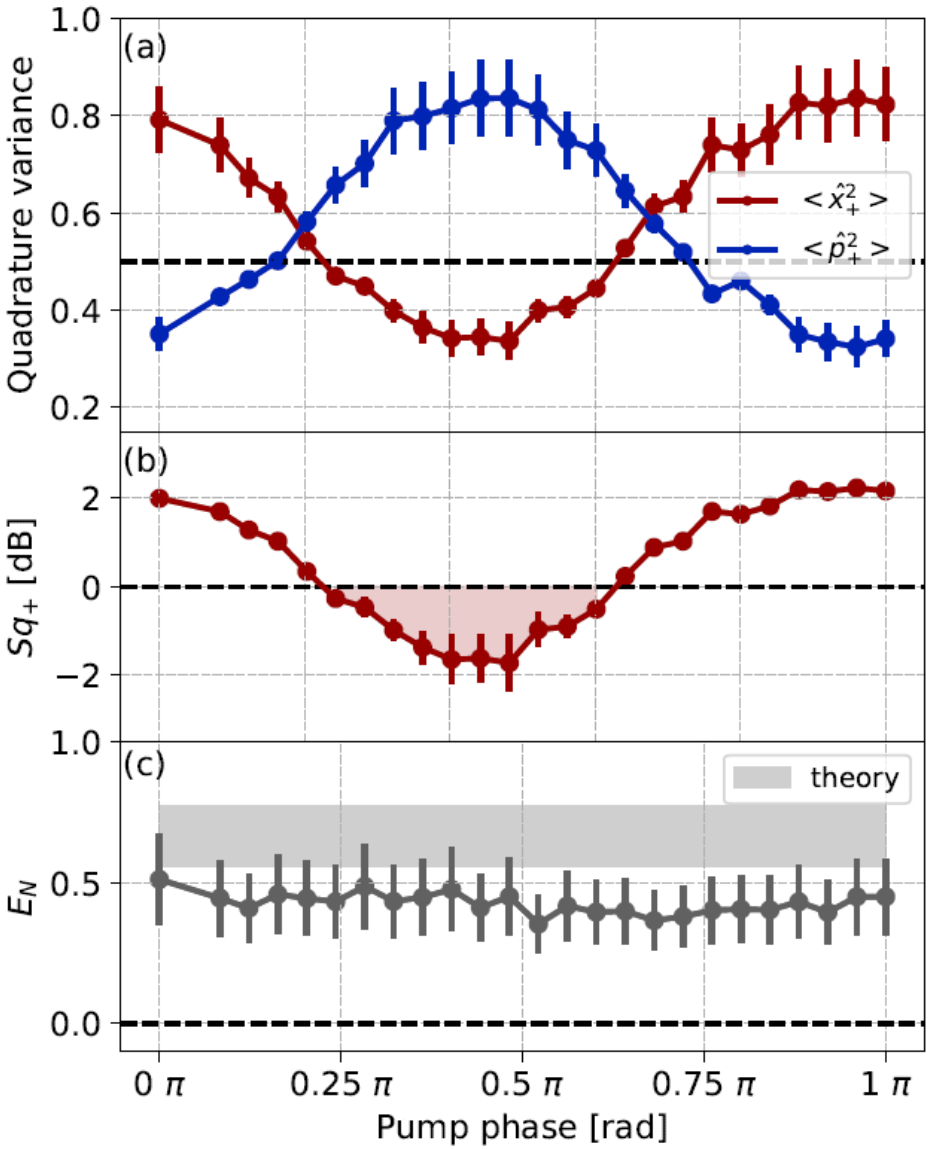


- **Entanglement : Logarithmic negativity E_N**
- **Squeezing of the collective quadrature**

$$x_+ = (x_s + x_i)$$

$$\text{Sq} = 10\, log\left(\frac{\langle {x_+}^2\rangle}{0.5}\right)$$

Two-mode squeezing in TWPAs

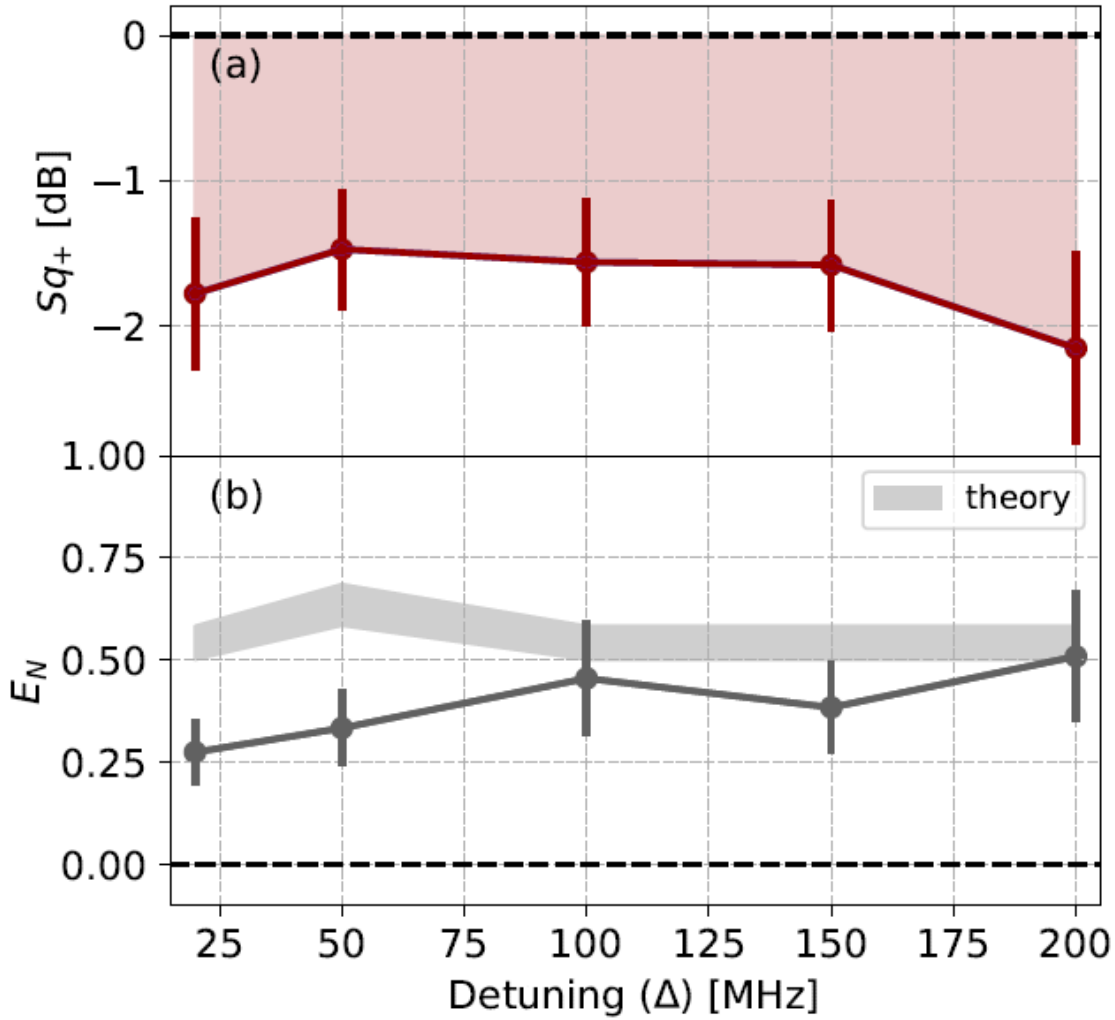


Demonstration of two-mode squeezing in TWPAs

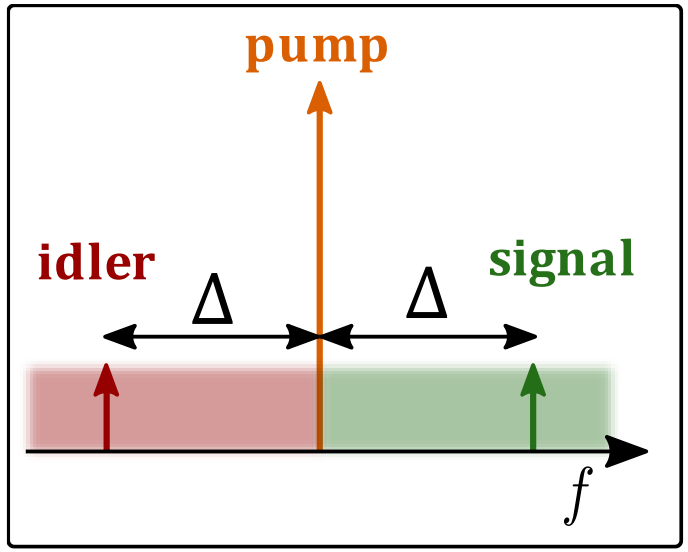
$$\hat{x}_+ = (\hat{x}_s + \hat{x}_i) \ , \qquad \hat{p}_+ = (\hat{p}_s + \hat{p}_i)$$

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

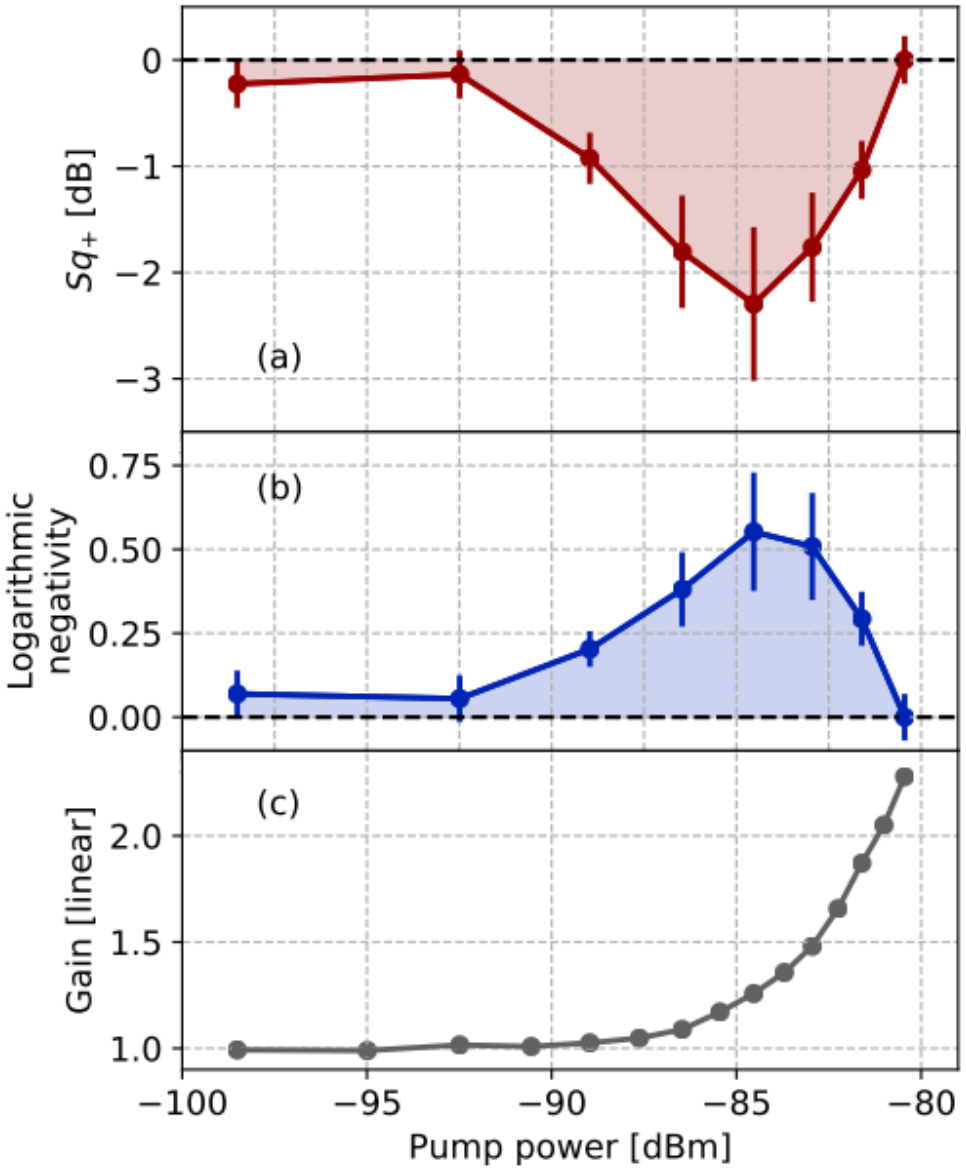
Two-mode squeezing in TWPAs



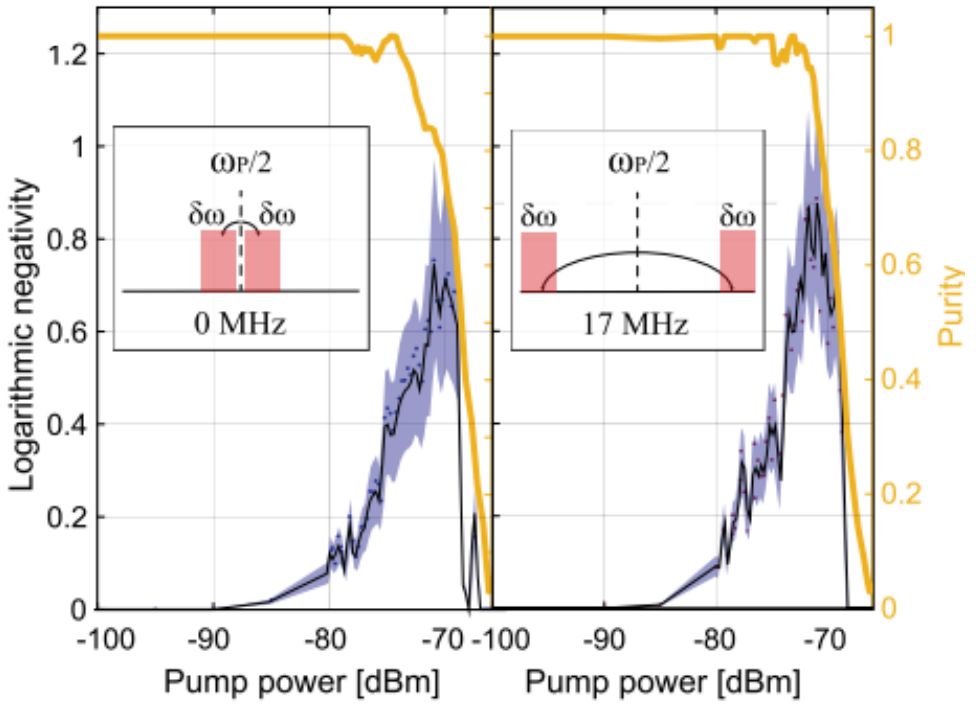
Broadband squeezing



Perspectives: Pump power dependence study



Similar Results for a 3WM Two-mode squeezing

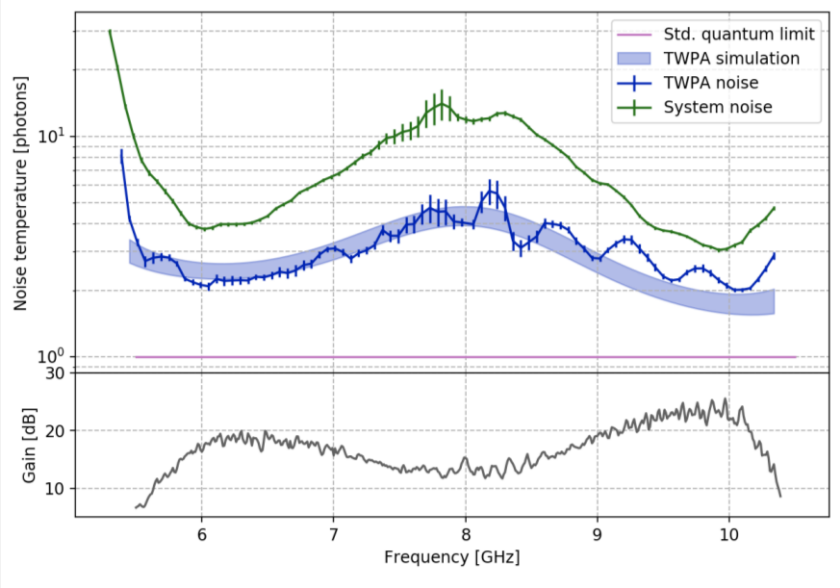


M. Perelshtein et al. https://arxiv.org/abs/2111.06145 (2021)
Aalto University / VTT Finland

- Detailed study of role of spurious wave-mixing processes i.e.: harmonics generation, up and down conversions…

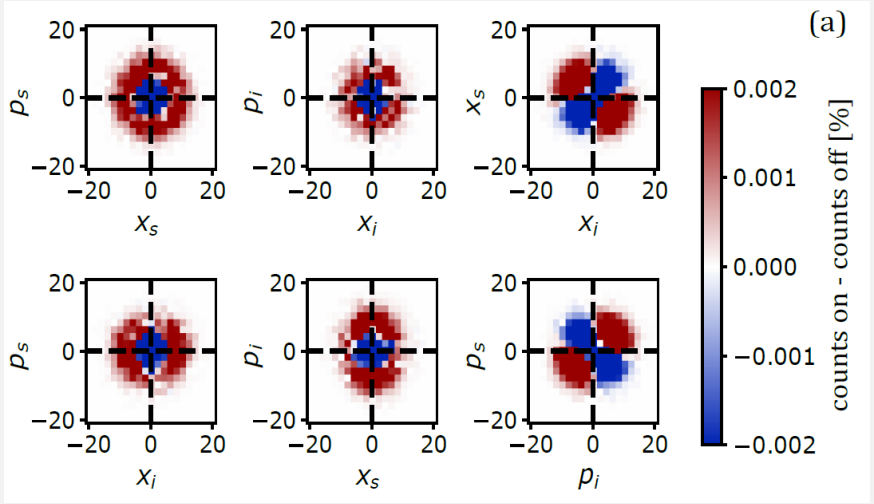
Summary and Conclusions

Reversed Kerr amplification



A. Ranadive. et al. arXiv:2101.05815 (2021)

Two-mode squeezing generation

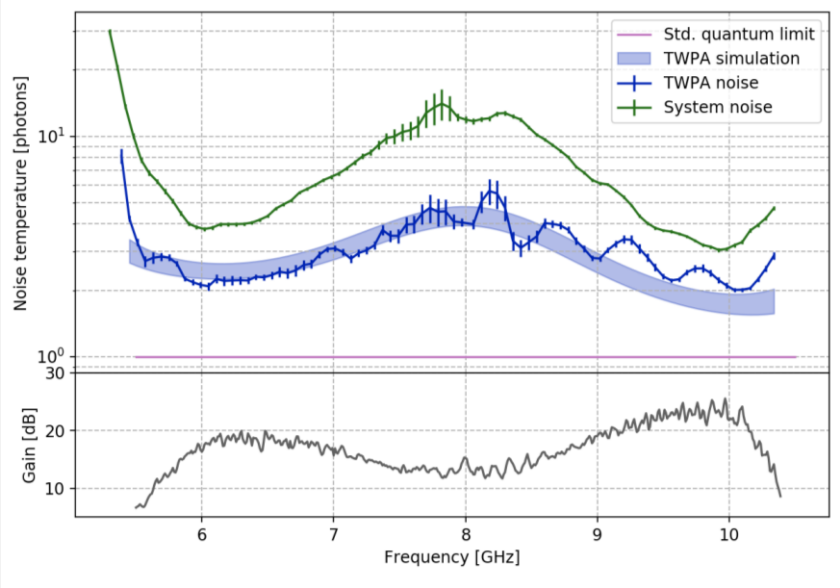


M. Esposito et al. arXiv:2111.03696 (2021)

Summary and Conclusions

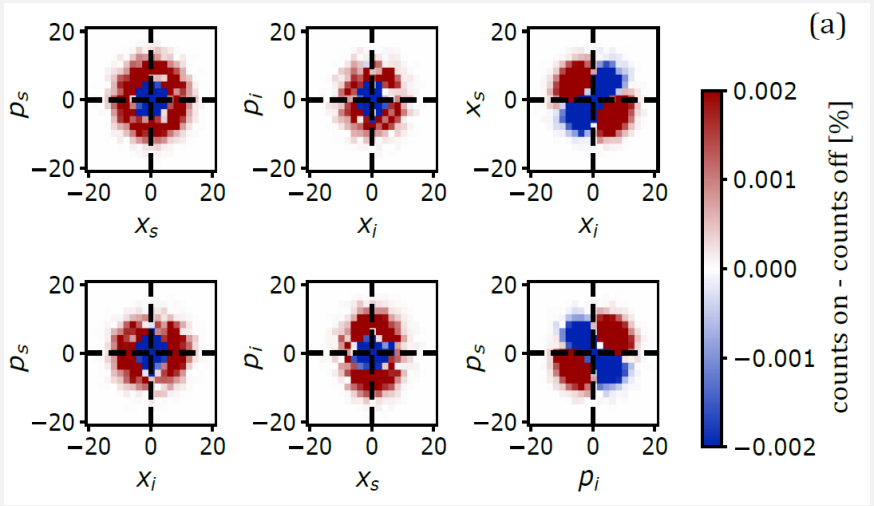
Thank you!

Reversed Kerr amplification



A. Ranadive. et al. arXiv:2101.05815 (2021)

Two-mode squeezing generation



M. Esposito et al. arXiv:2111.03696 (2021)

Giulio Cappelli

Arpit Ranadive

Luca Planat

Martina Esposito

Nicolas Roch