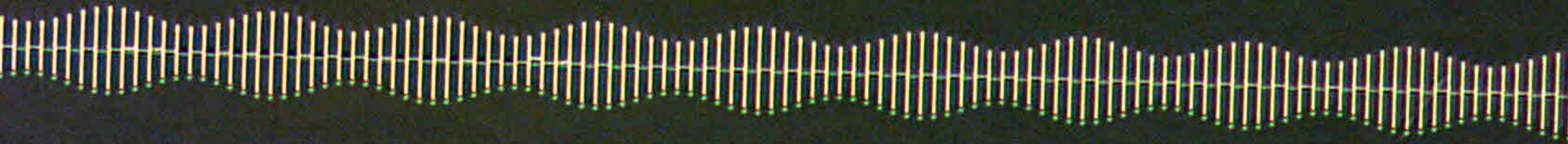
Superconducting Josephson Traveling-Wave Parametric Amplifiers



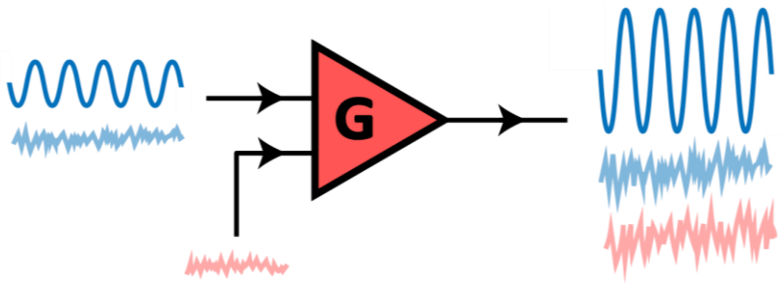
Gwenael Le Gal, G. Butseraen, A. Ranadive, G. Cappelli, B. Fazliji, A. Martin and N. Roch

Néel Institute, QuantECA team

GDR-DI2I
Groupement De Recherche
Détecteurs et Instrumentation pour les 2 Infinis

cnrs · Néel institut · UGA Université Grenoble Alpes · SQC · Silent Waves

Quantum limited amplification

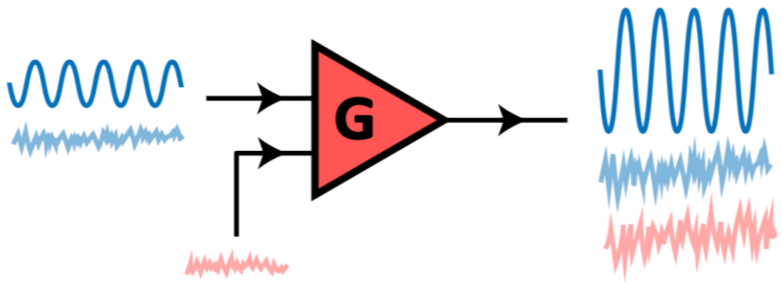


An ideal amplifier adds white noise:

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

C. M. Caves, Phys. Rev. D, 26, 8 (1982)

Quantum limited amplification



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A dissipative amplifier at $T > 0$ K: $T_N > T_{SQL}$,

HEMT amplifier: $T_N \sim 10\, T_{SQL}$

Superconducting amplifier

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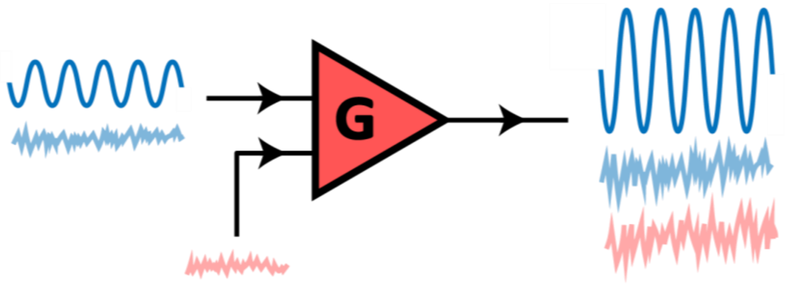

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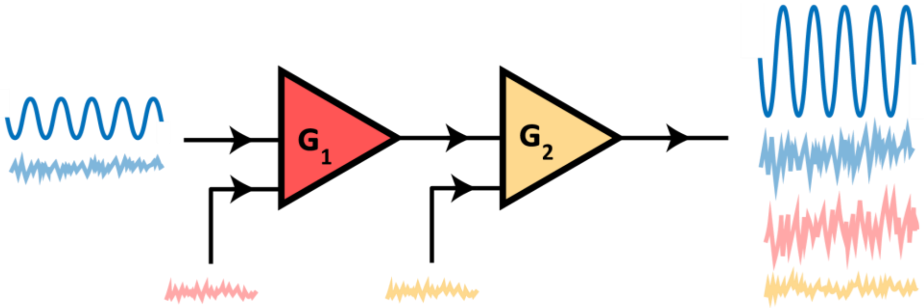

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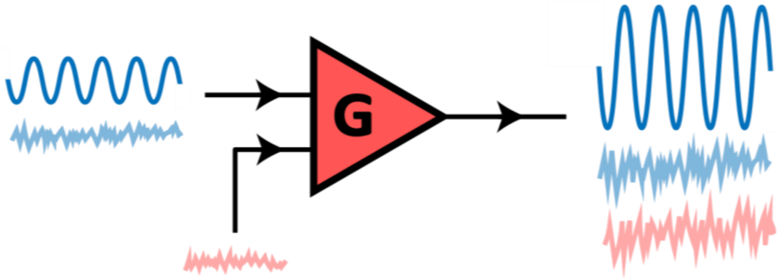

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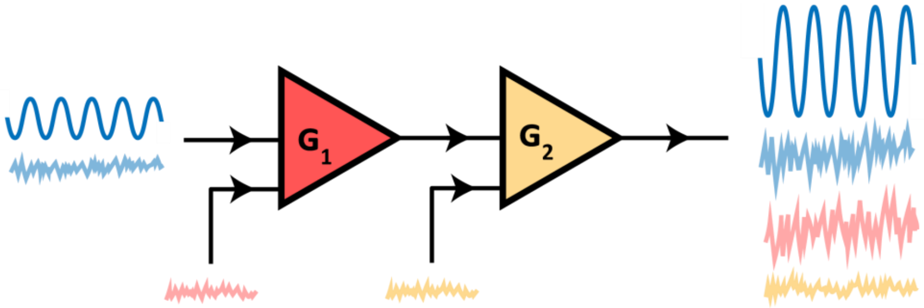

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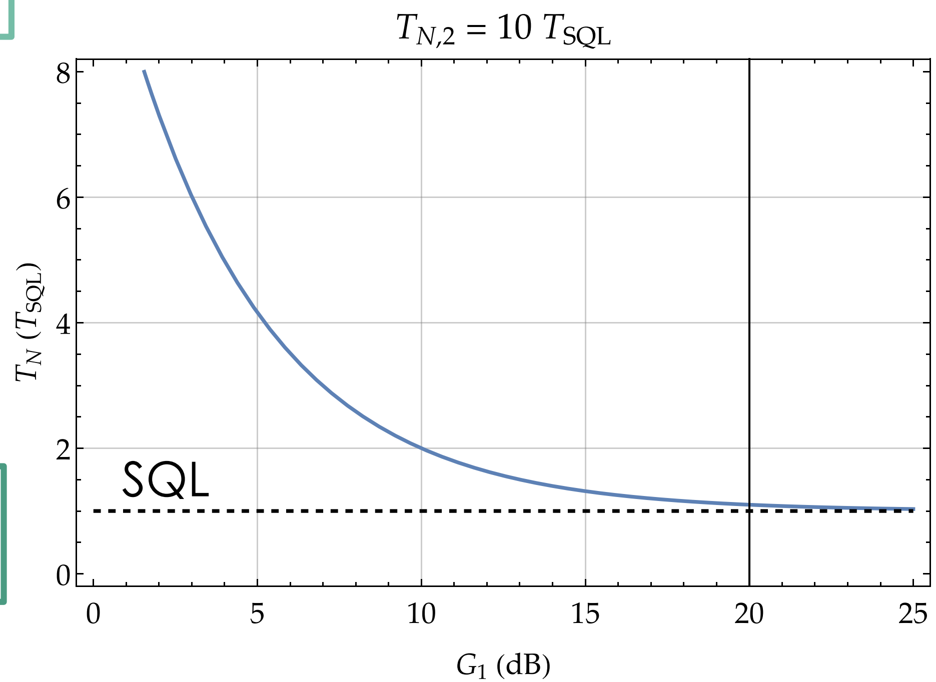


How much minimum gain ?
20 dB

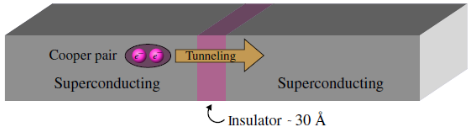
C. M. Caves, Phys. Rev. D, 26, 8 (1982)

Traveling Wave Parametric Amplification in a nutshell

$I = I_c \sin(\phi) \approx I_c\phi + \chi^{(3)}\phi^3 + \cdots$ ➡ 4WM process $\propto \chi^{(3)}\hat{a}_i^\dagger\hat{a}_s^\dagger\hat{a}_p\hat{a}_p + h.c.$

Energy: $2\omega_p = \omega_s + \omega_i$

Momentum: $2k_p = k_s + k_i$



S. E. Rasmussen *et al.*, PRX Quantum, 2021

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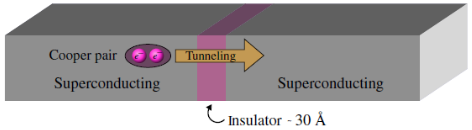

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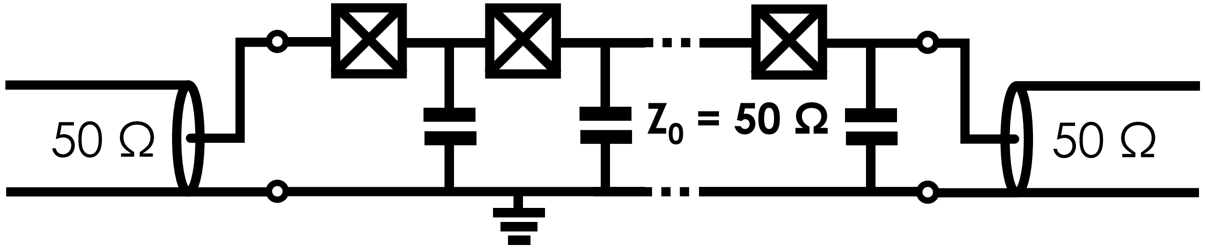

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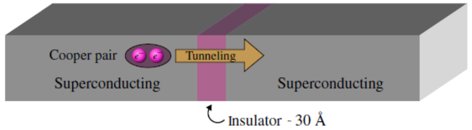

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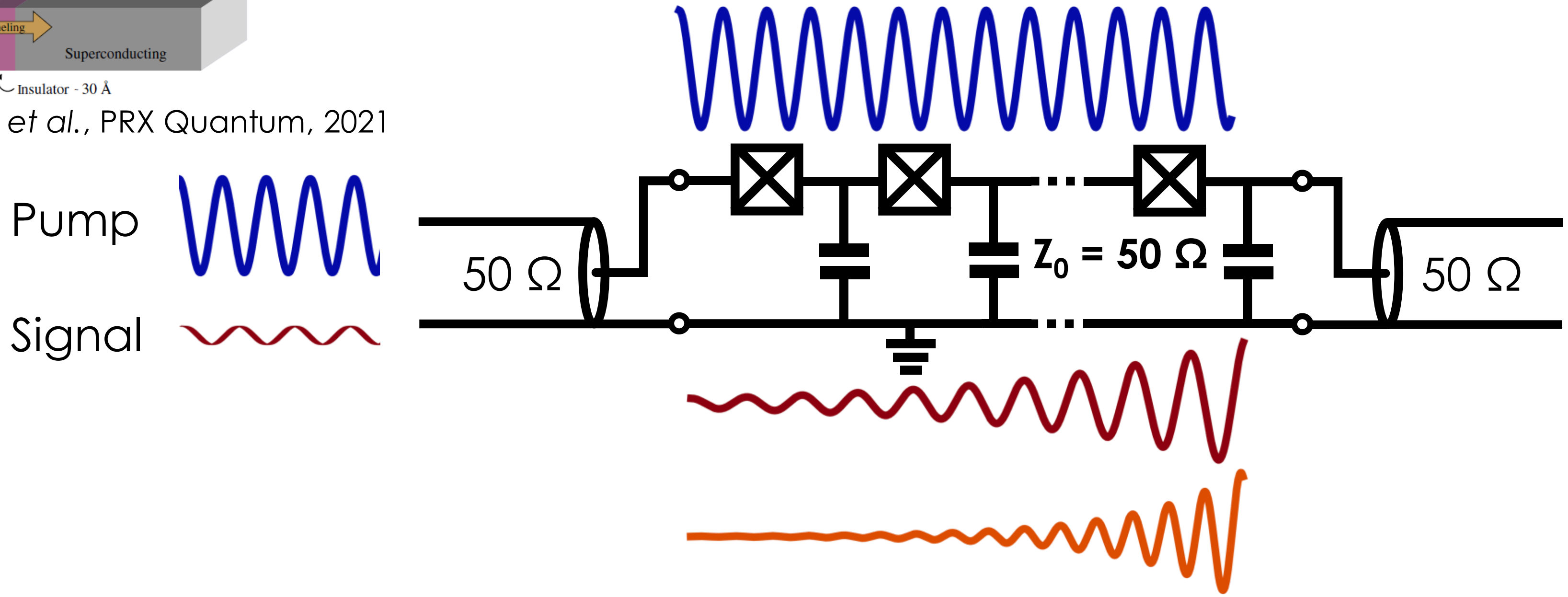

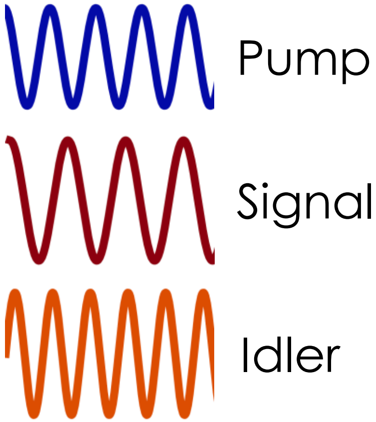

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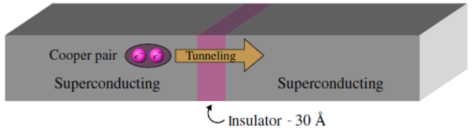

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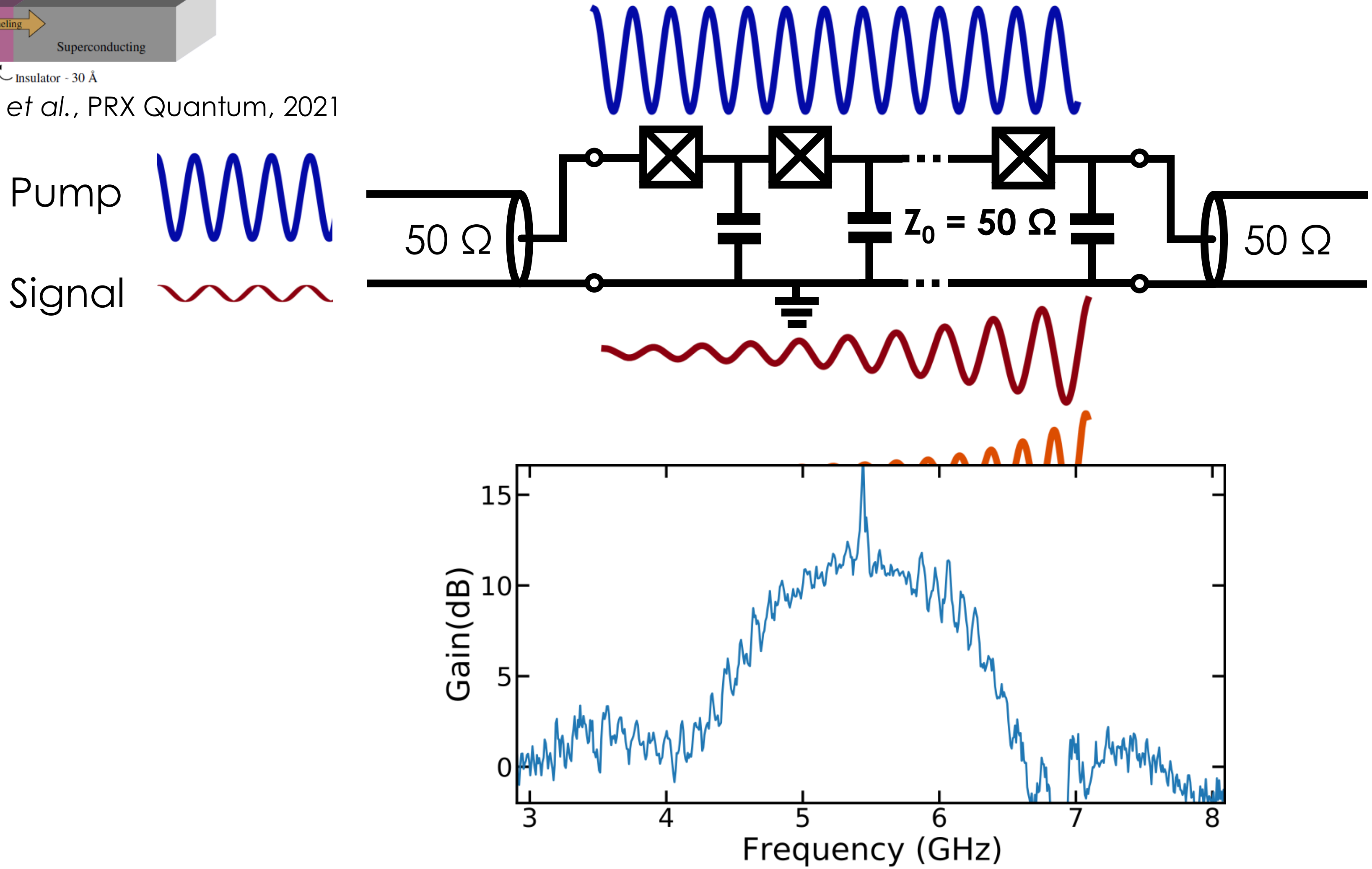
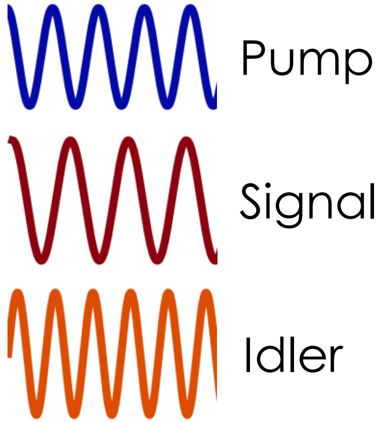
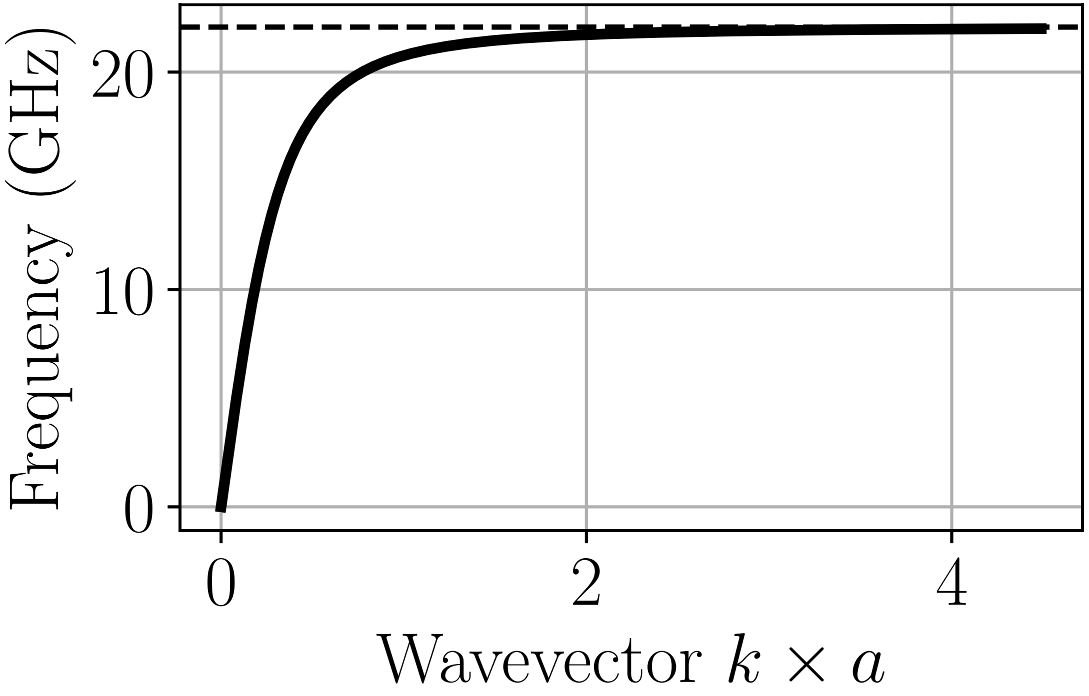




Gain limitation: phase mismatch

4-wave mixing: $\Delta k_{lin} = 2k_p - k_s - k_i$



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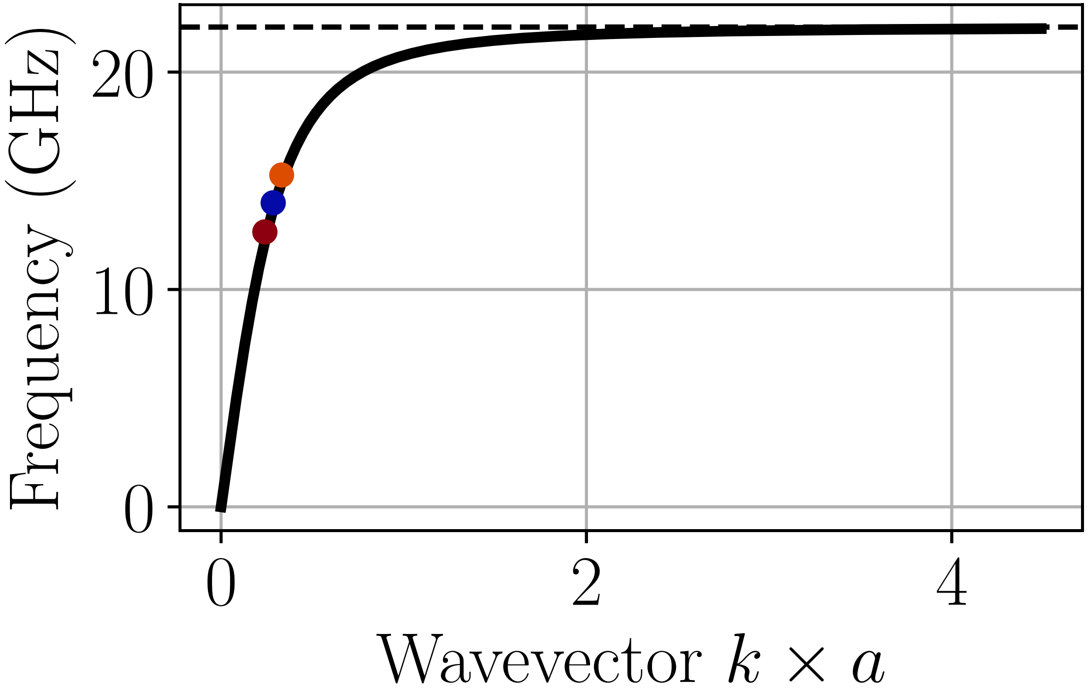

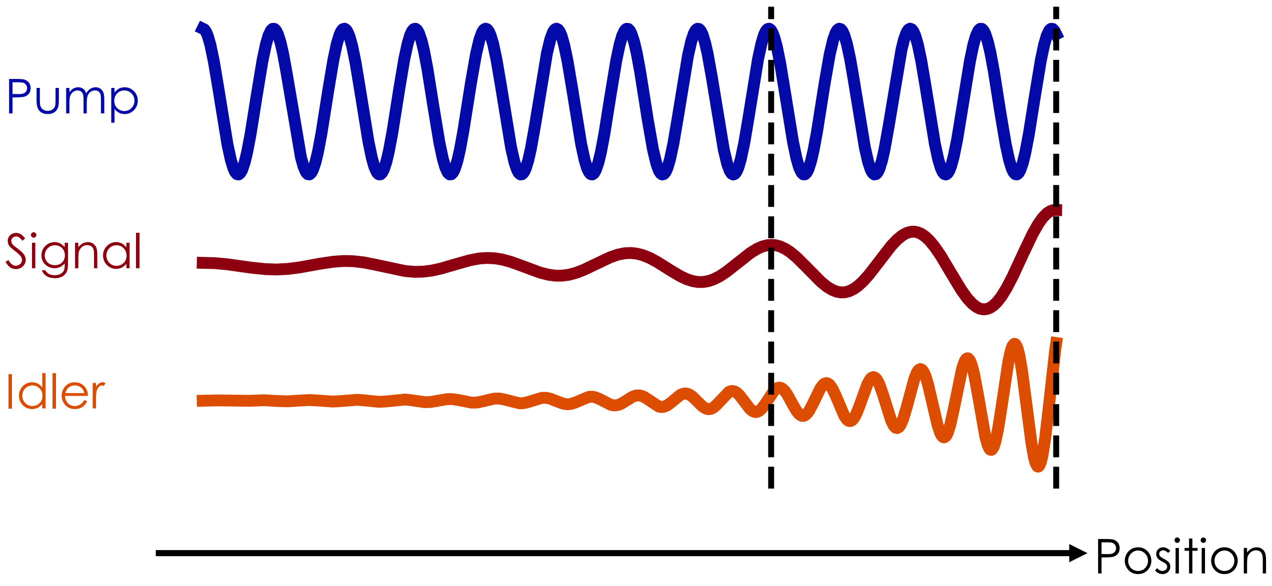

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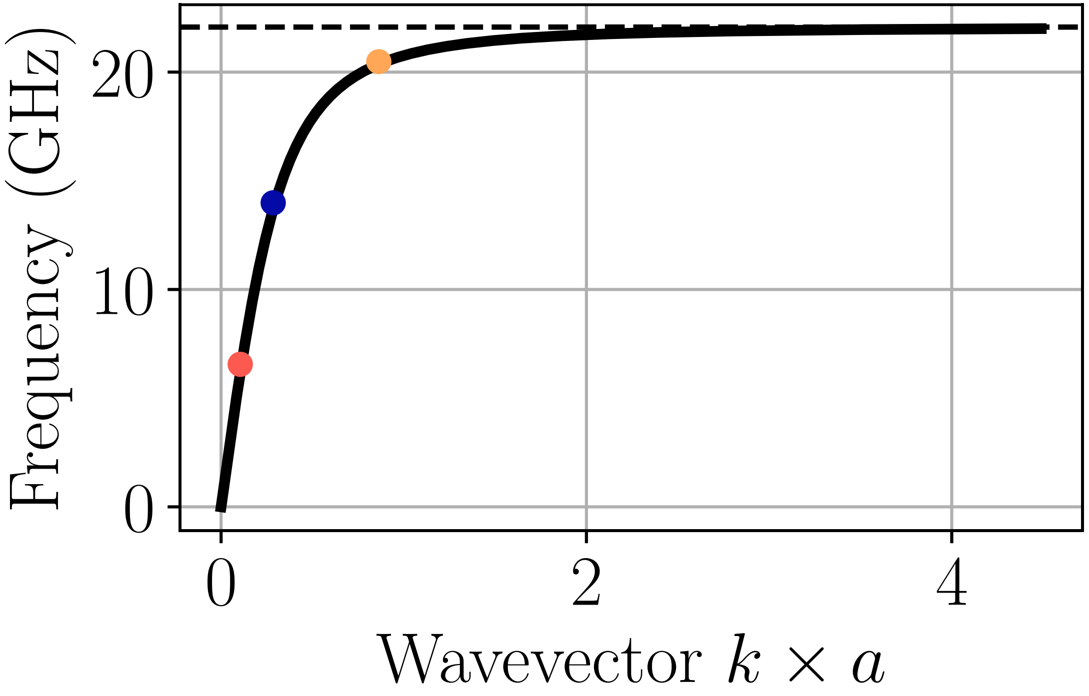

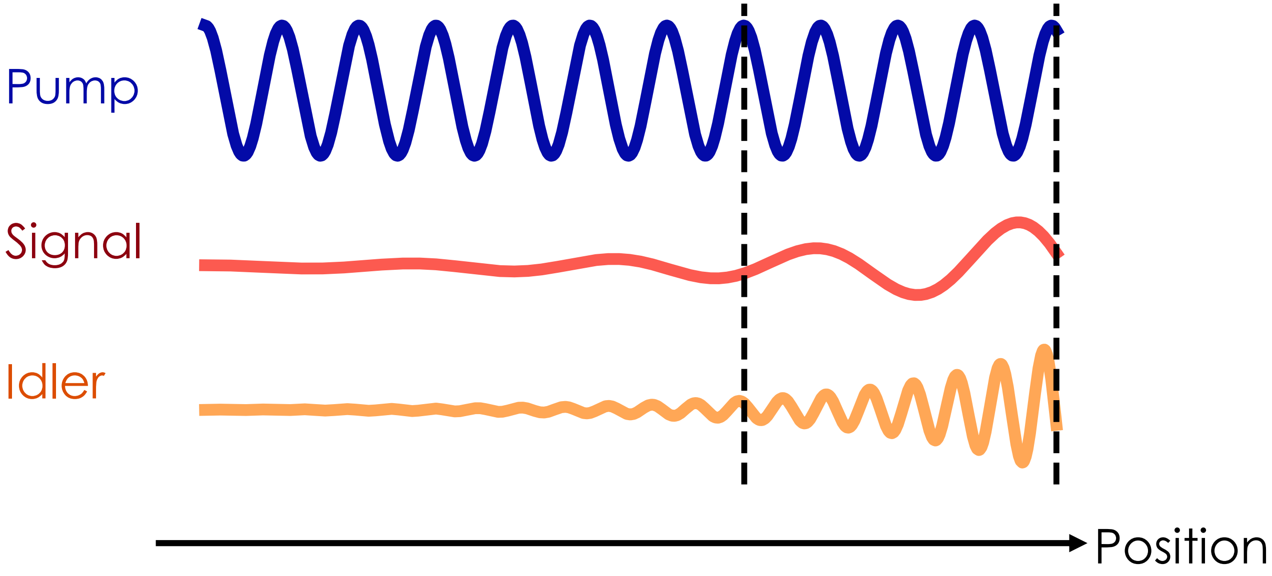

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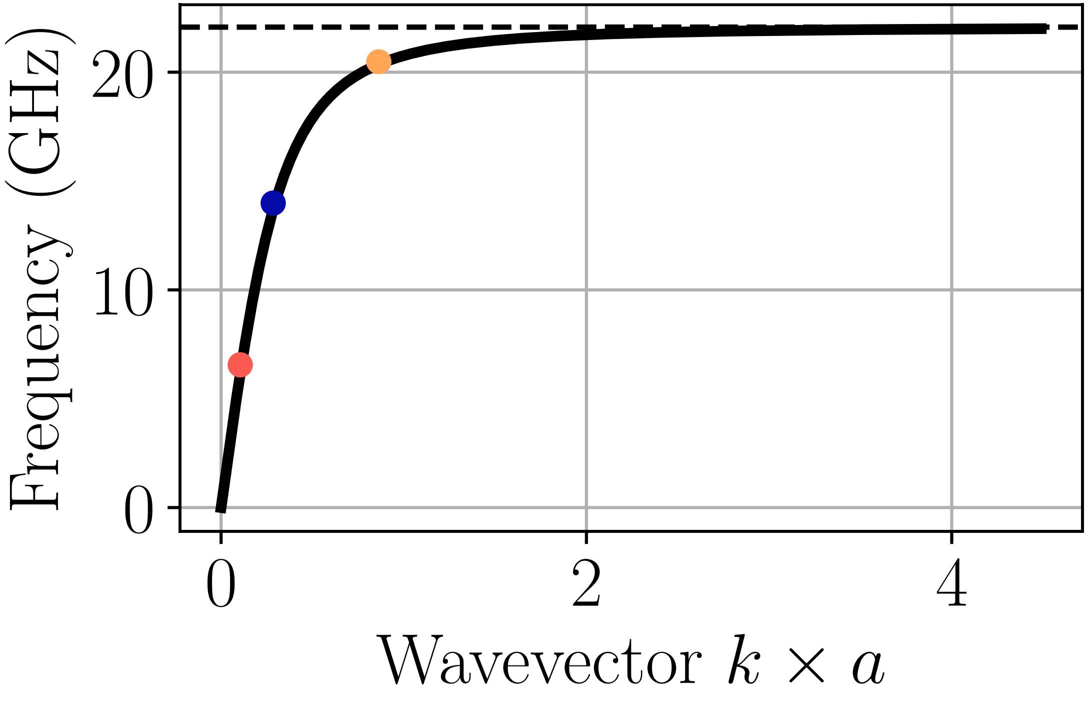
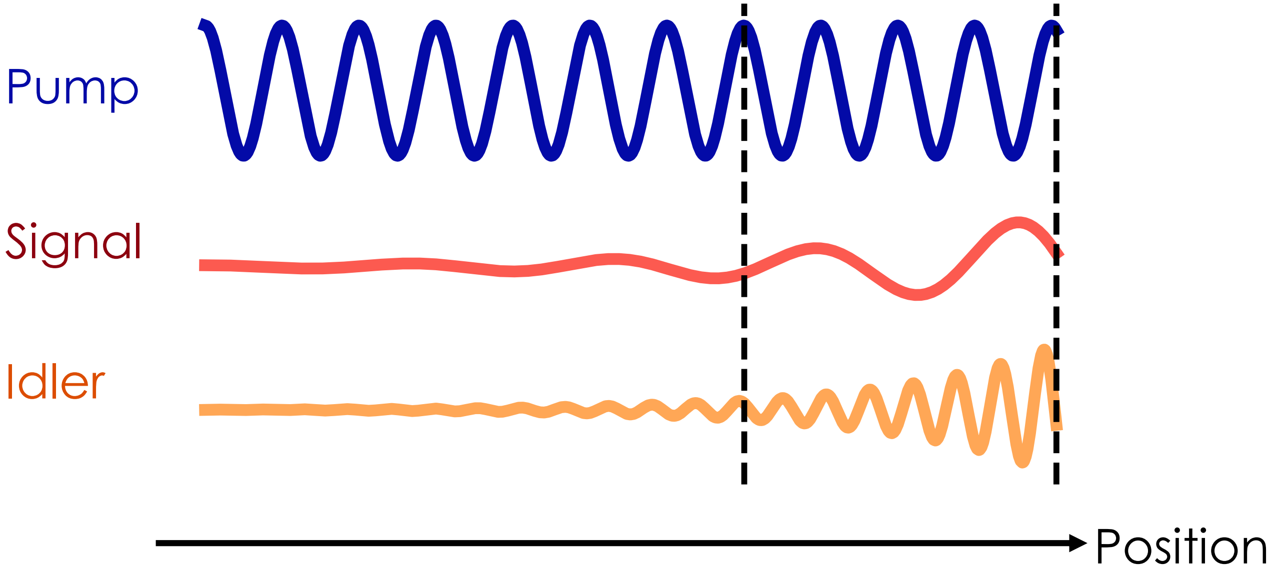




Kerr effect: power dependent momentum

$$\Delta k_{nl} = 2\alpha_{pp} - \underbrace{\alpha_{sp} - \alpha_{ip}} \neq 0$$

SPM: self-Kerr $\neq$ XPM: cross-Kerr

$\Delta k = \Delta k_{lin} + \Delta k_{nl}$

Rule of thumb: $\Delta k \lesssim 1/L$

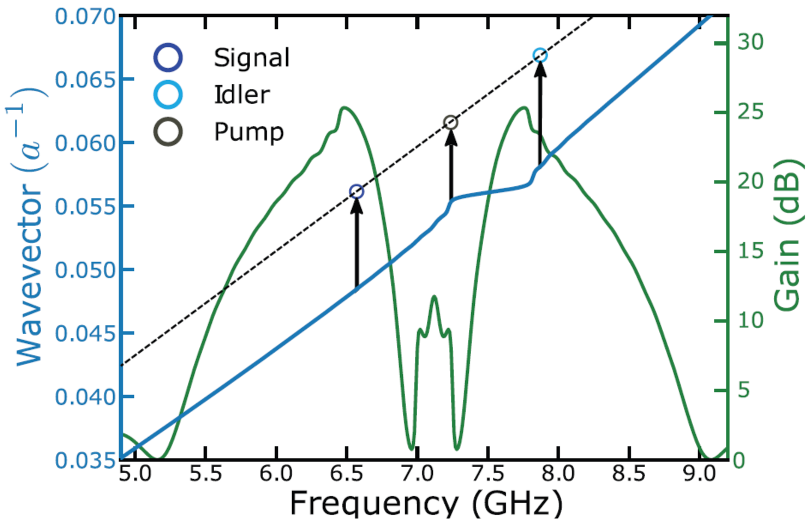
O. Yaakobi et al., Phys. Rev. B, 87, 144301 (2013)   K. O'Brien et al., Phys. Rev. Lett., 113, 157001 (2014)

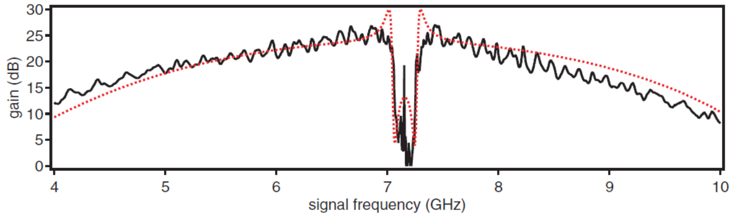
Phase matching: implementation

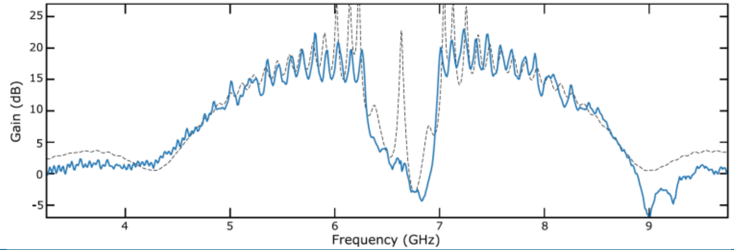
Dispersion engineering

C. S. Macklin et al., Science, 350, 6258 (2015)

L. Planat et al., Phys. Rev. X, 10, 021021 (2020)







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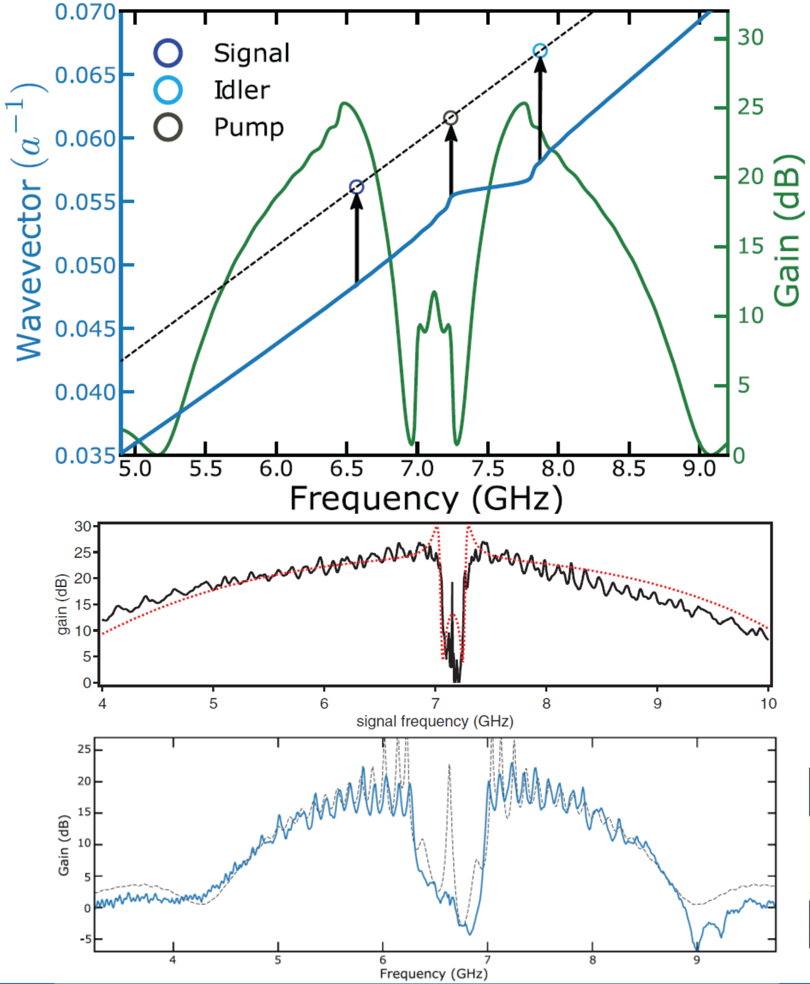
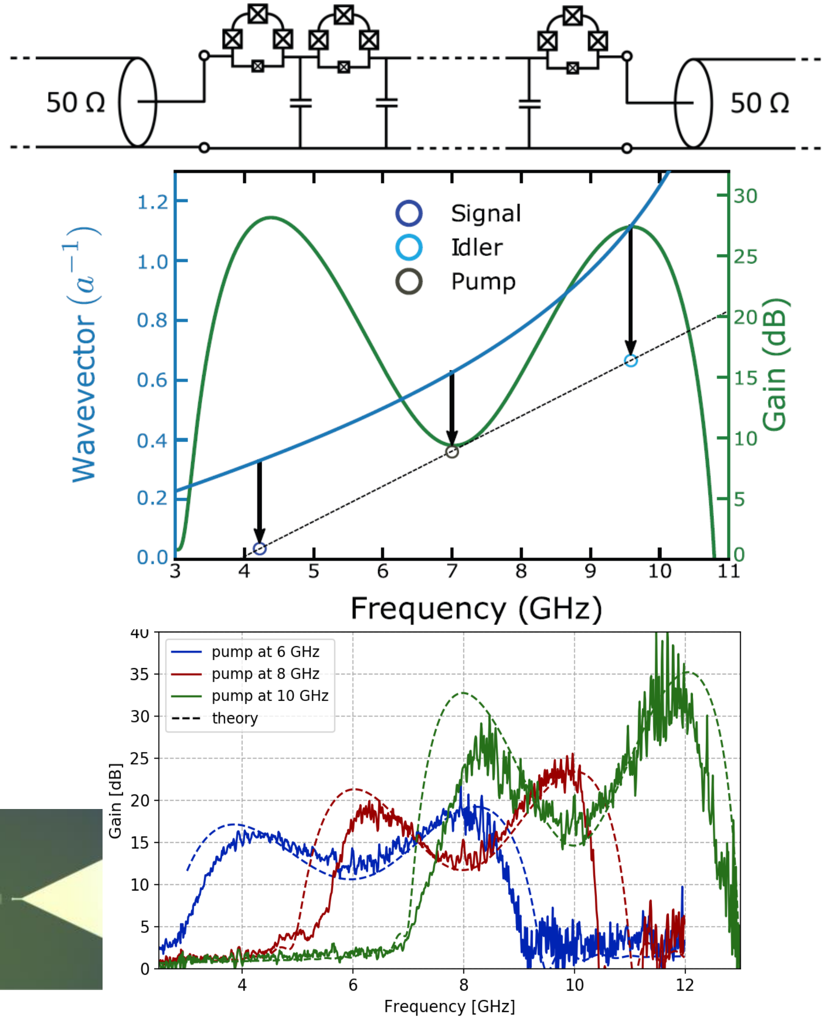


Kerr non-linearity engineering

A. Ranadive et al., Nature Comm., 13, 1737 (2022)



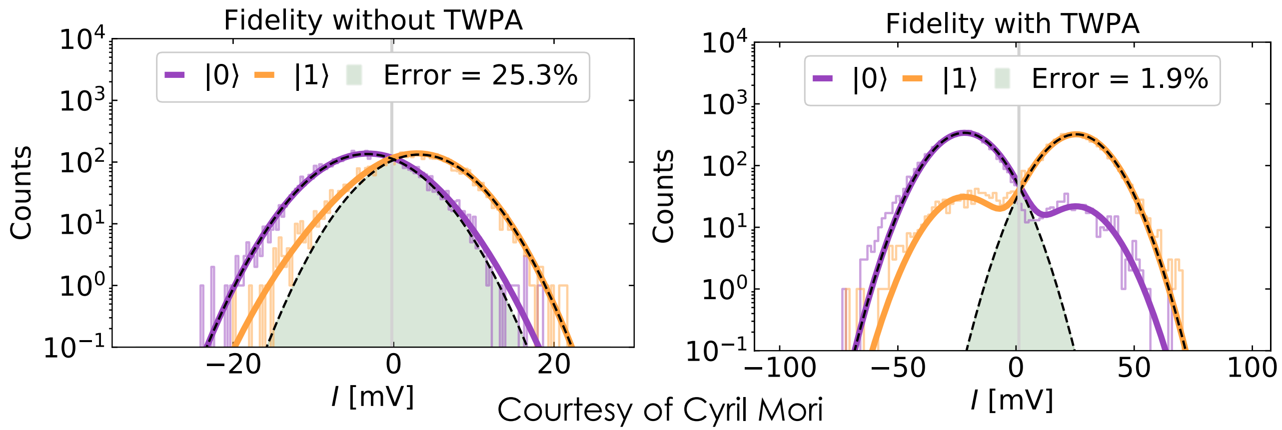
TWPA Applications

- Superconducting qubit readout
- Multiplexed readout

A. Remm et al., Phys. Rev. Appl., 20, 034027 (2023)

S. Krinner et al., Nature 605, 669–674 (2022)

L. Ranzani et al., Appl. Phys. Lett. 113, 242602 (2018)



Courtesy of Cyril Mori

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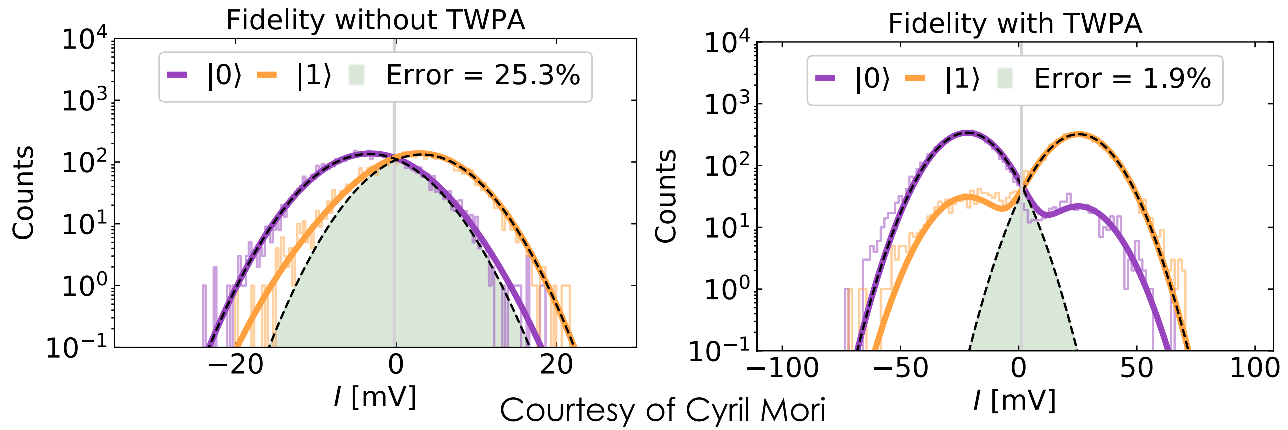

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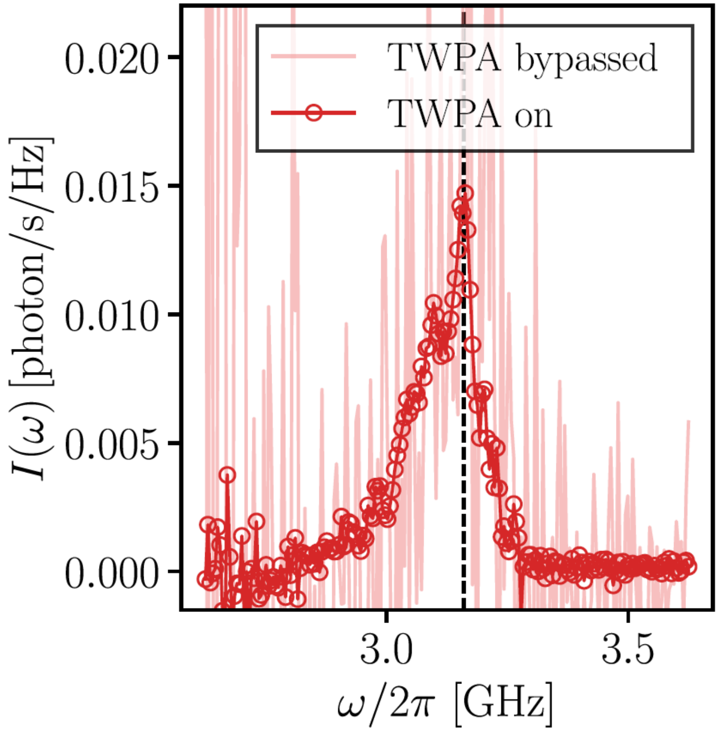
- Broadband photo-detection

D. Fraudet et al., arXiv:2405.00411v1 (2024)



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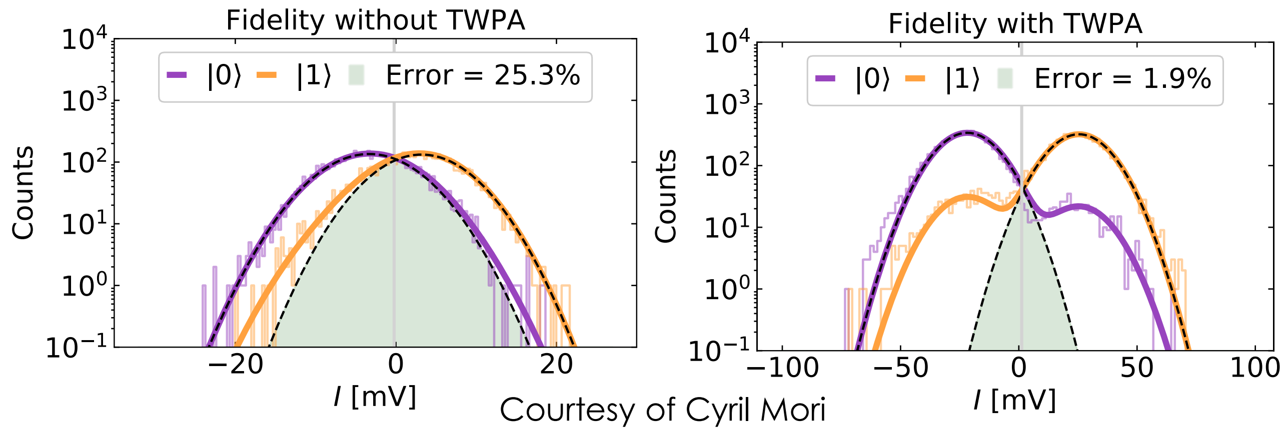

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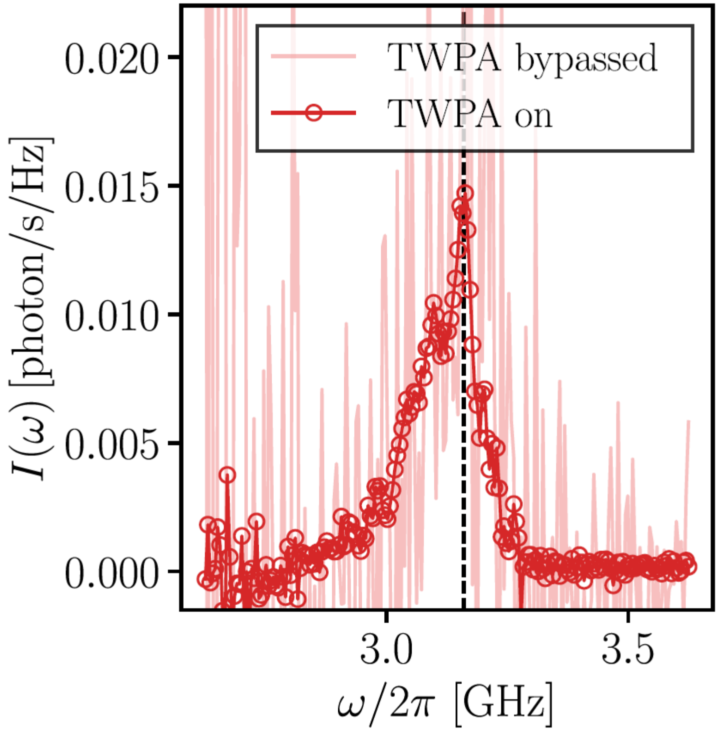
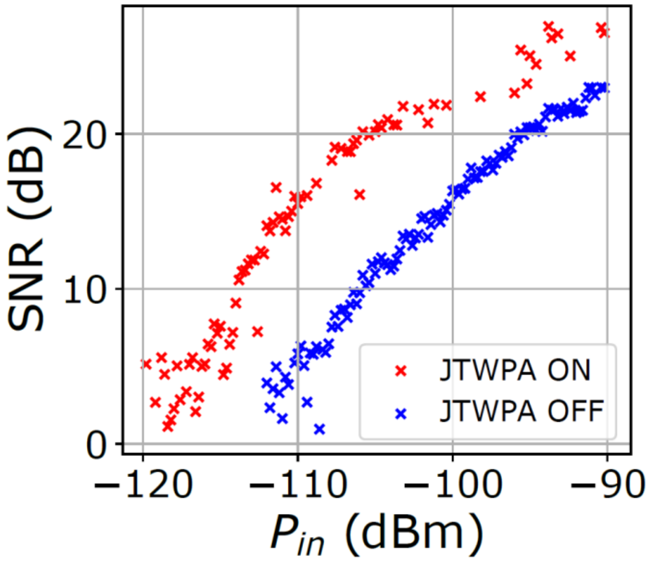


- Spin-qubit readout

V. Elhomsy et al., arXiv:2307.14717v2 (2023)



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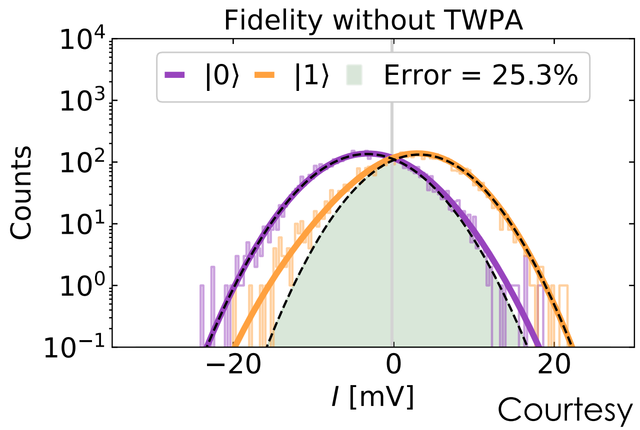

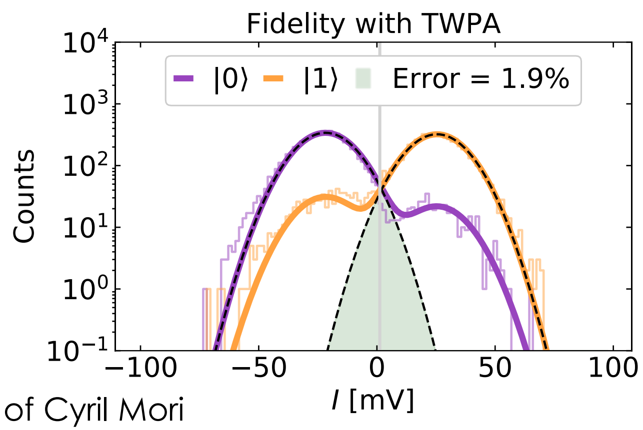

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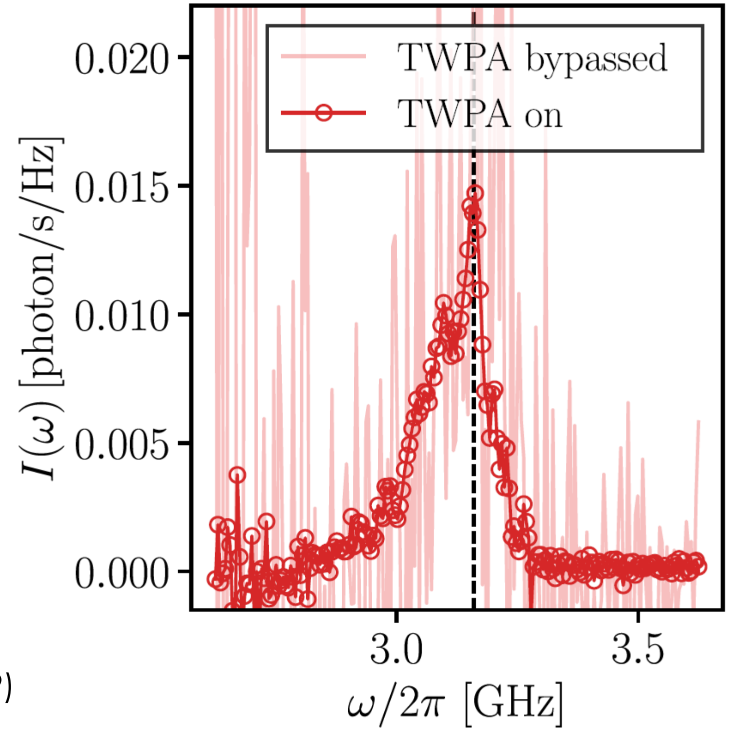

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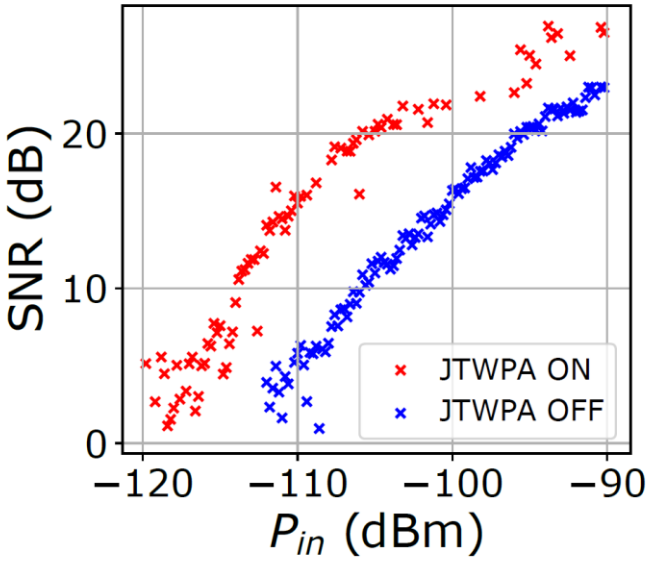


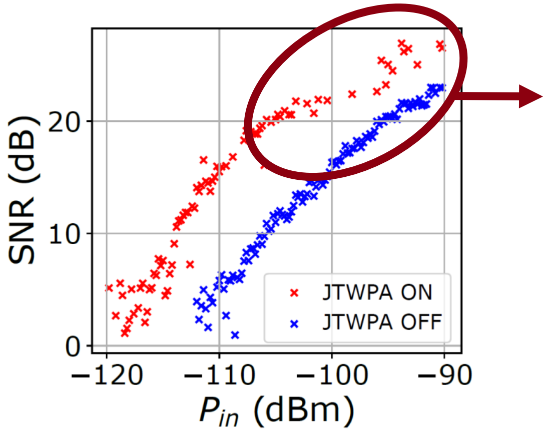
- High energy physics

R. Di Vora et al., Phys. Rev. D, 108, 062005 (2023)

- MKID readout

N. Zobrist et al., Appl. Phys. Lett. 115, 042601 (2019)

Why studying saturation in TWPAs?



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SNR saturates @ high P_{in}

Can this be mitigated?

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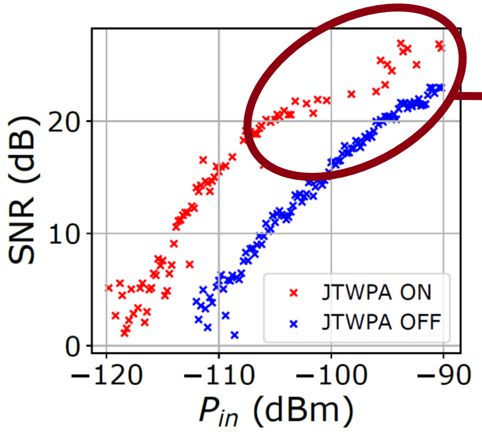

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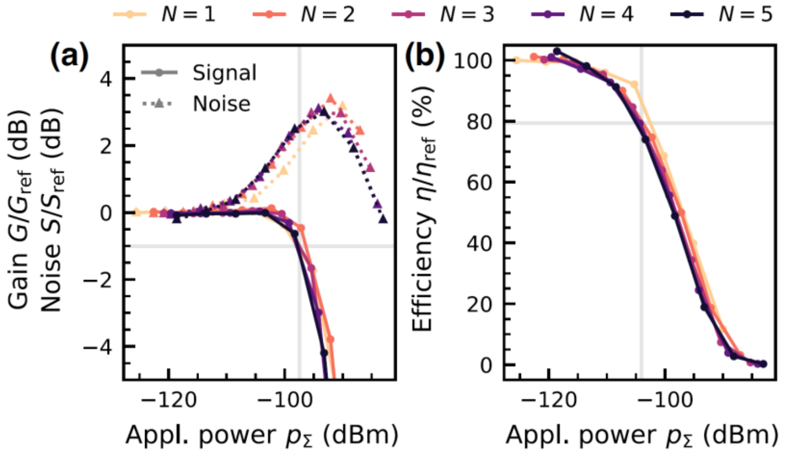
Intermodulation products generation



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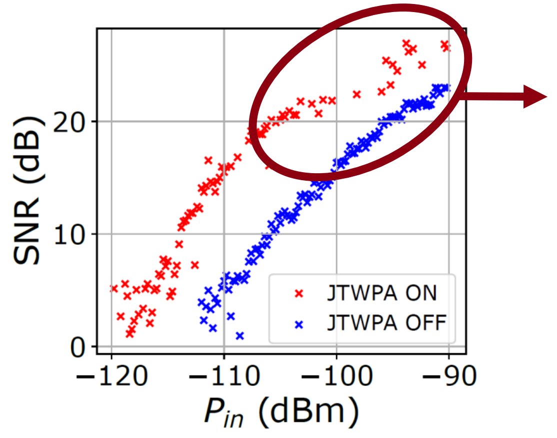

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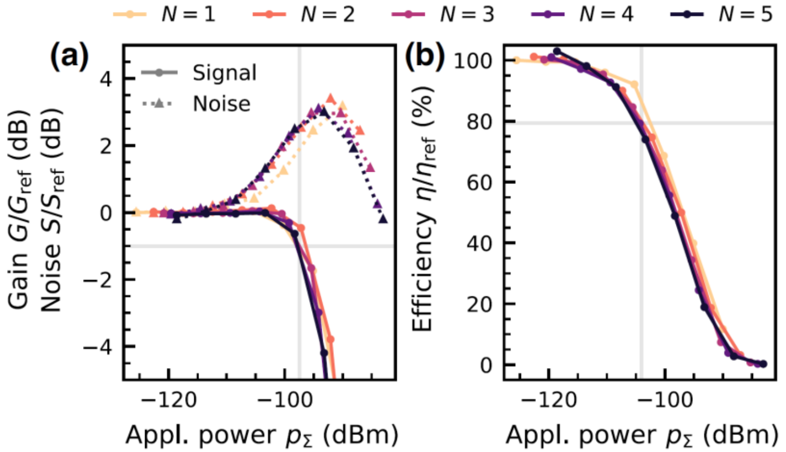


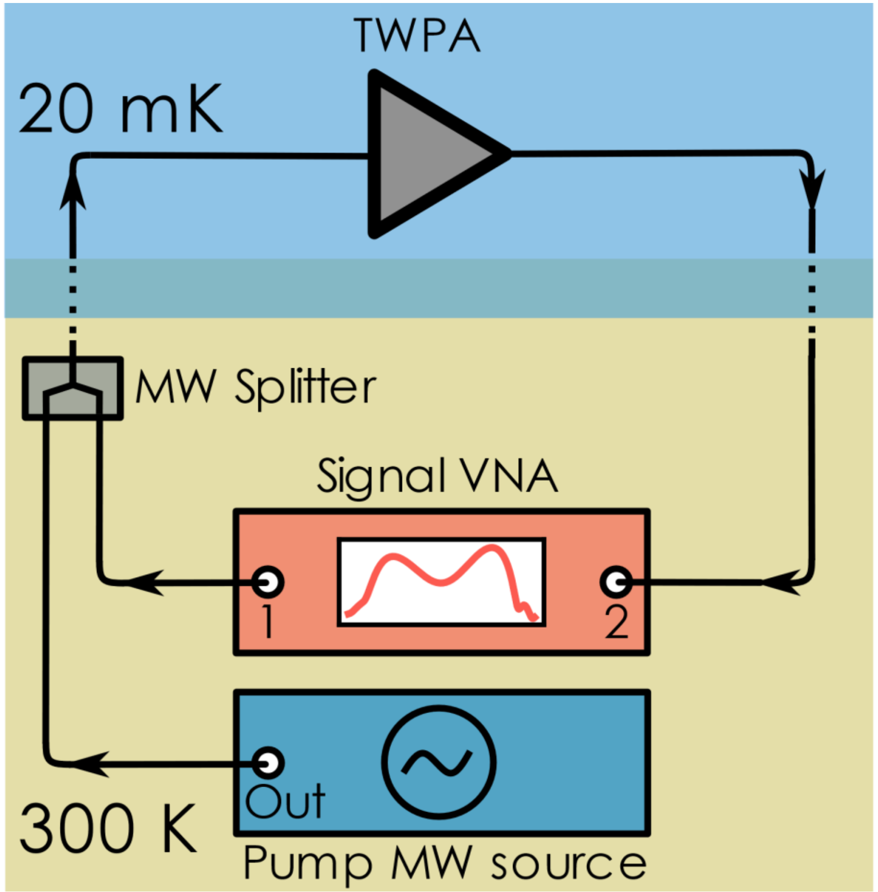
A. Remm et al., Phys. Rev. Appl., 20, 034027 (2023)

Understanding the causes of compression:

- Never studied in superconducting TWPAs
- Mitigate quantum efficiency reduction
- Understand implications on applications (readout signals correlations…)

Experimental study of saturation

Usual setup



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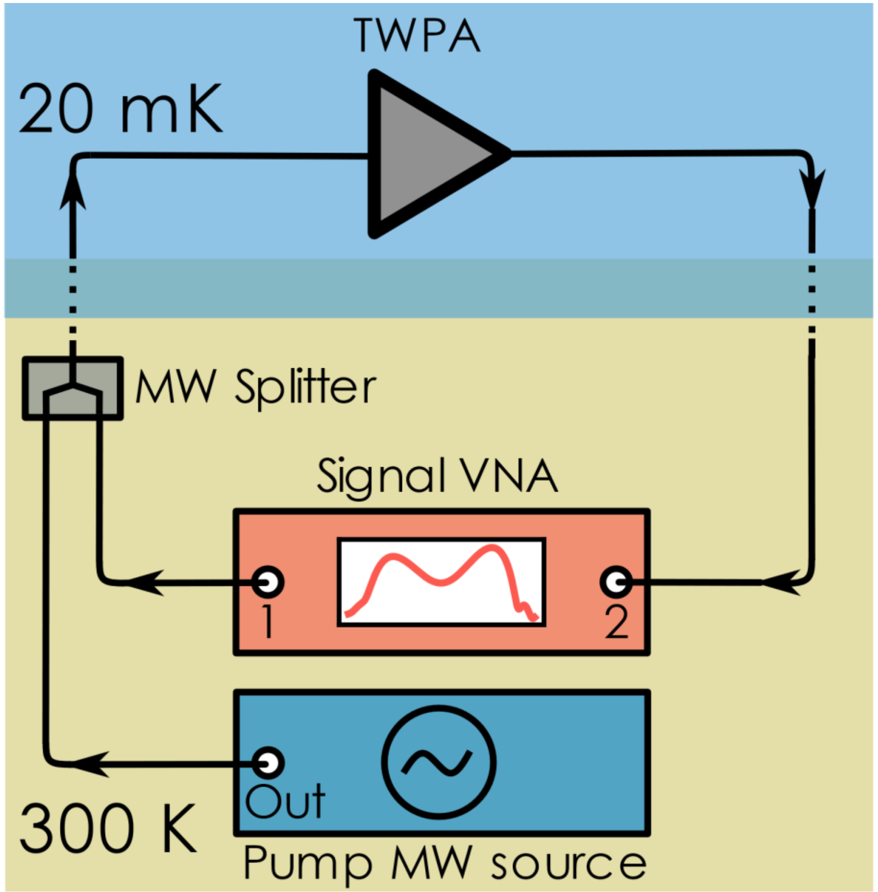
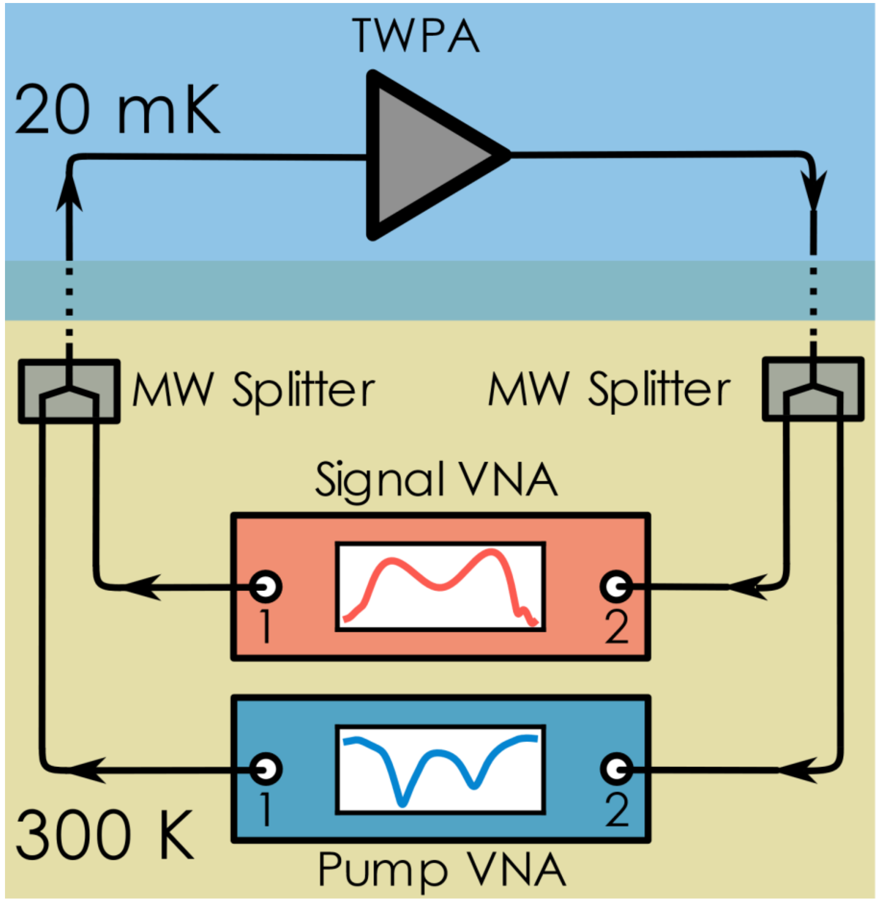
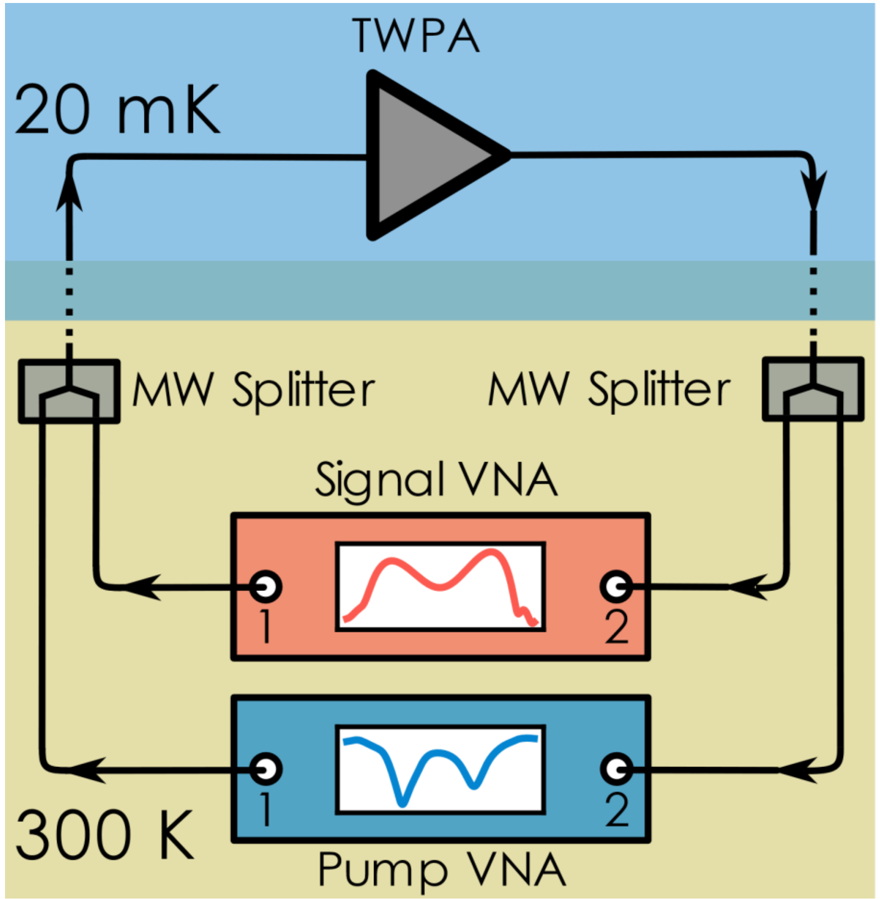


New setup

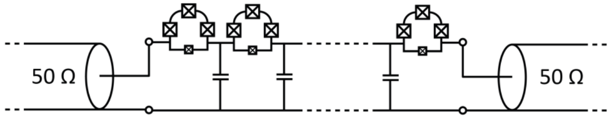


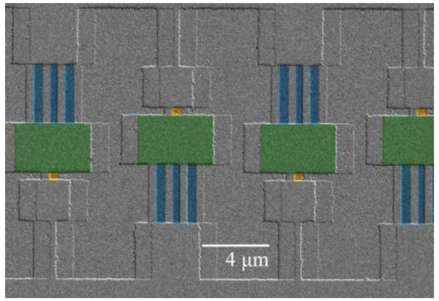
Monitoring signal & pump complex transmission

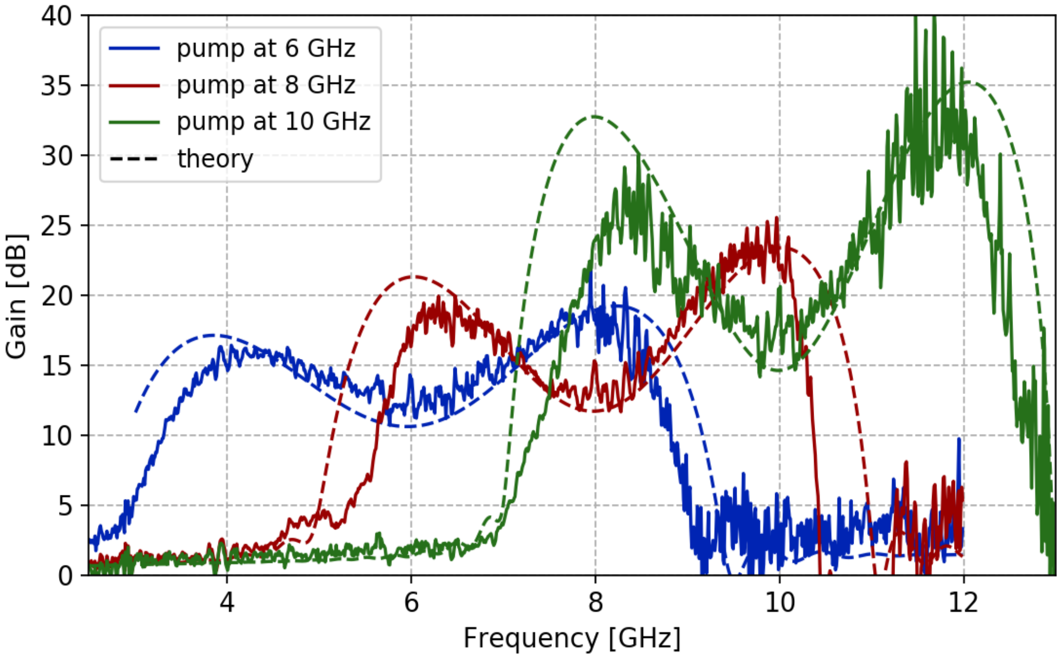
Experimental study of saturation



The device: SNAIL TWPA @ ½ flux quantum

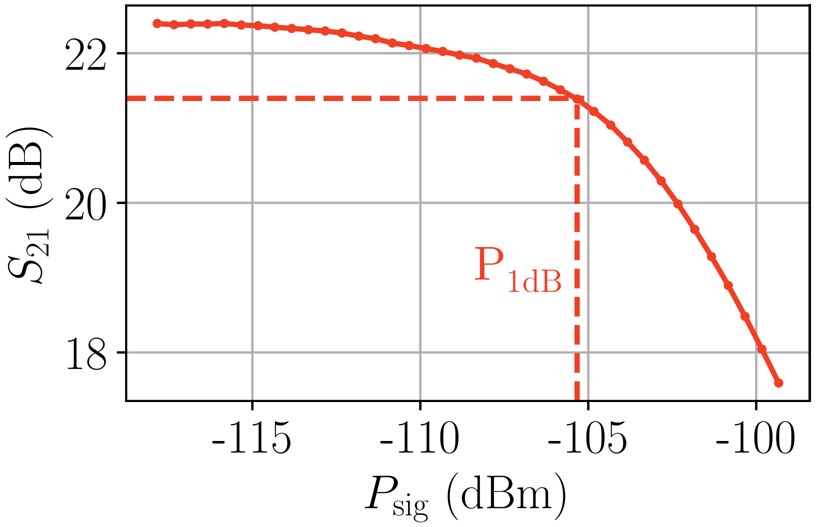




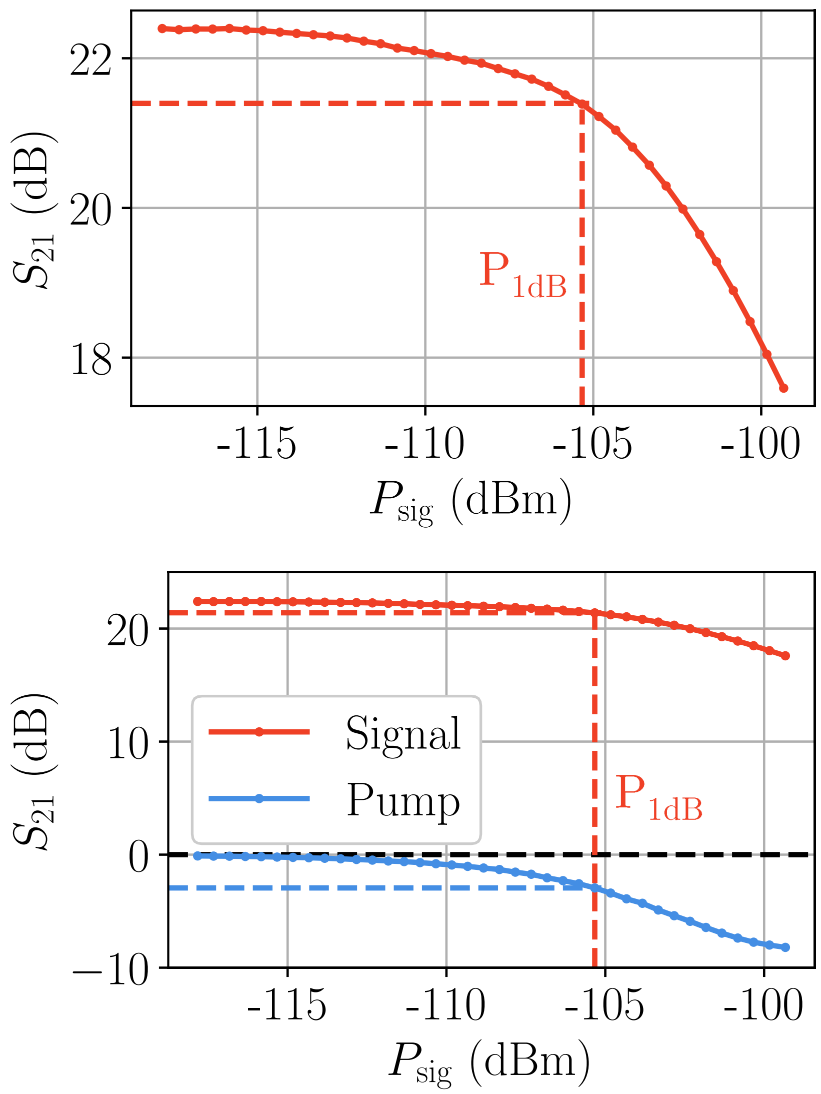


A. Ranadive et al., Nature Comm., 13, 1737 (2022)

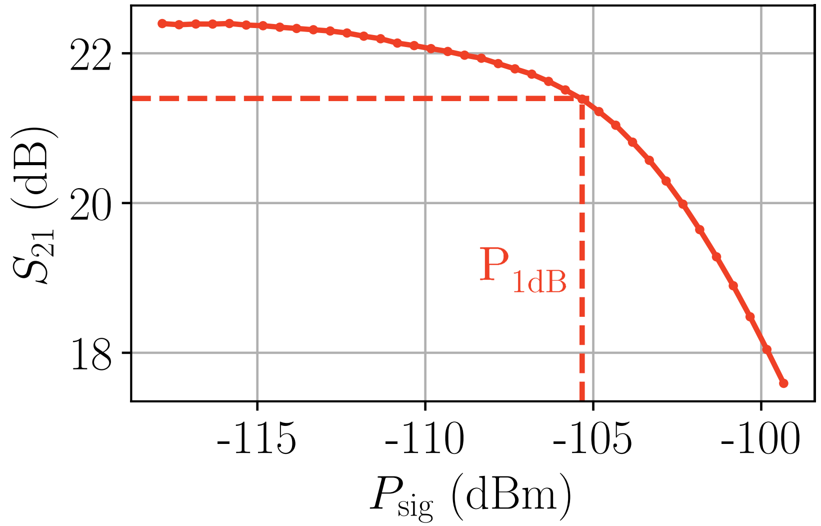
1-dB compression: Definition

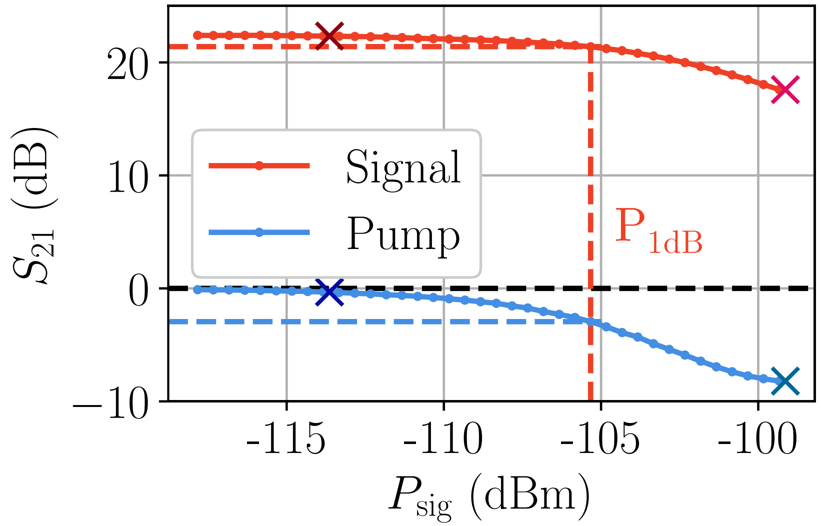


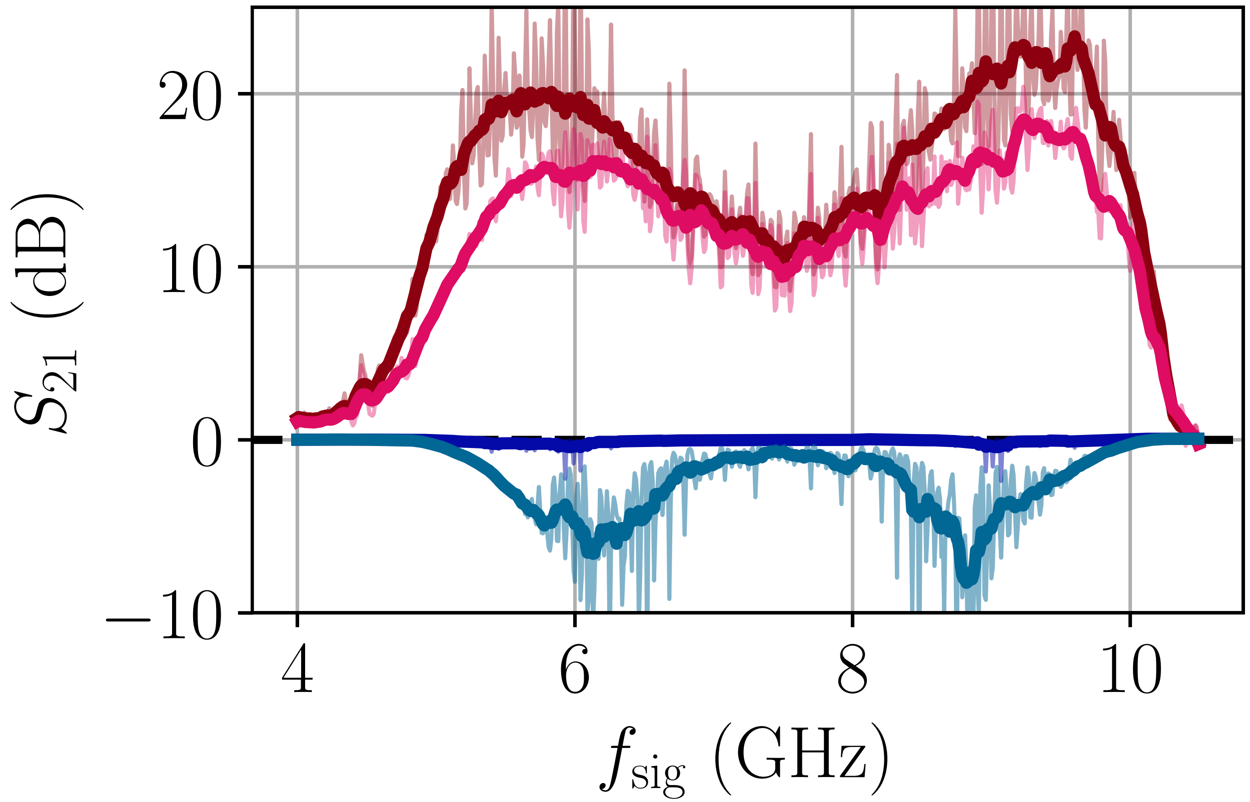
Compression: what happens to the pump?



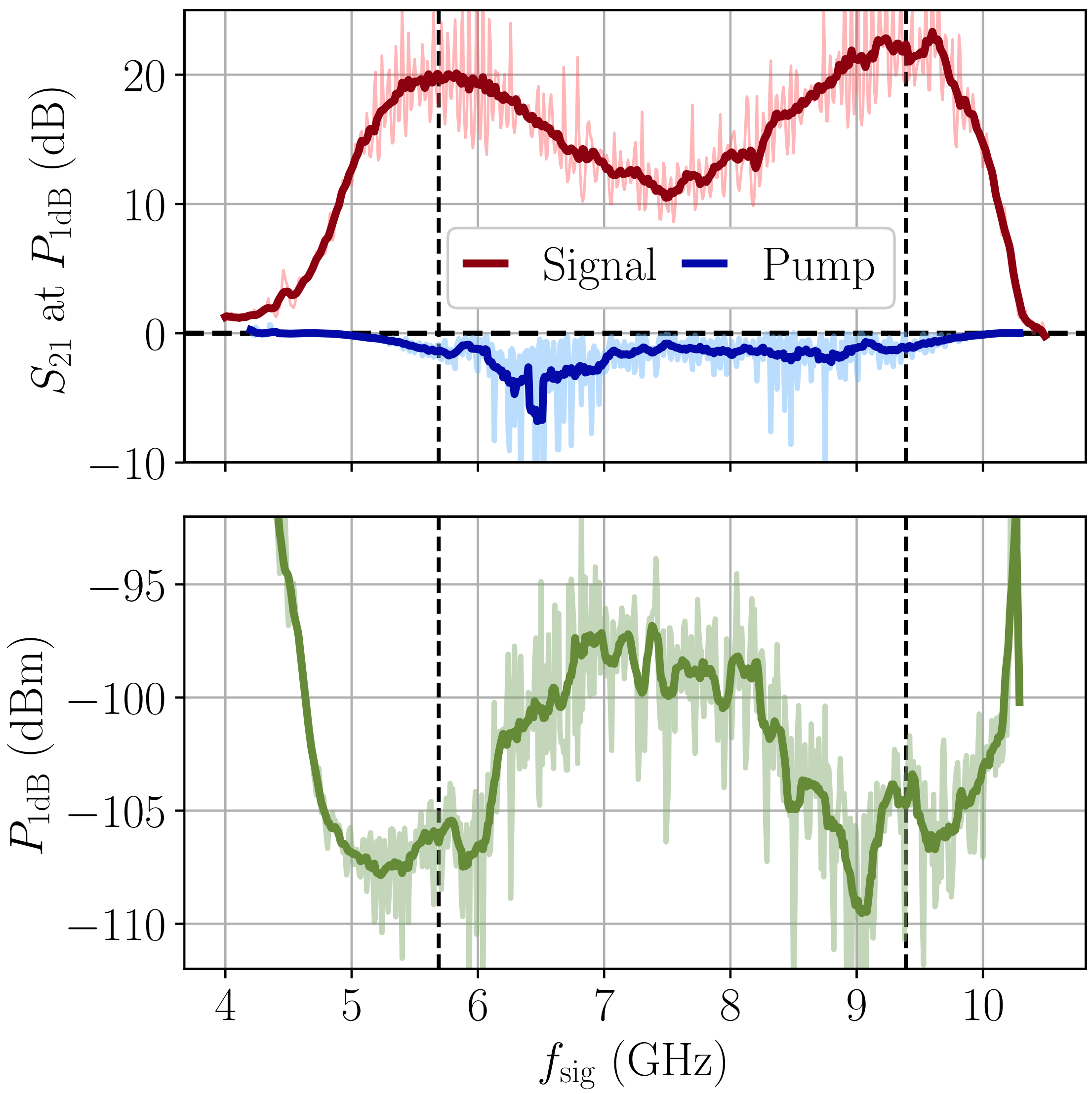
Signal frequency influence



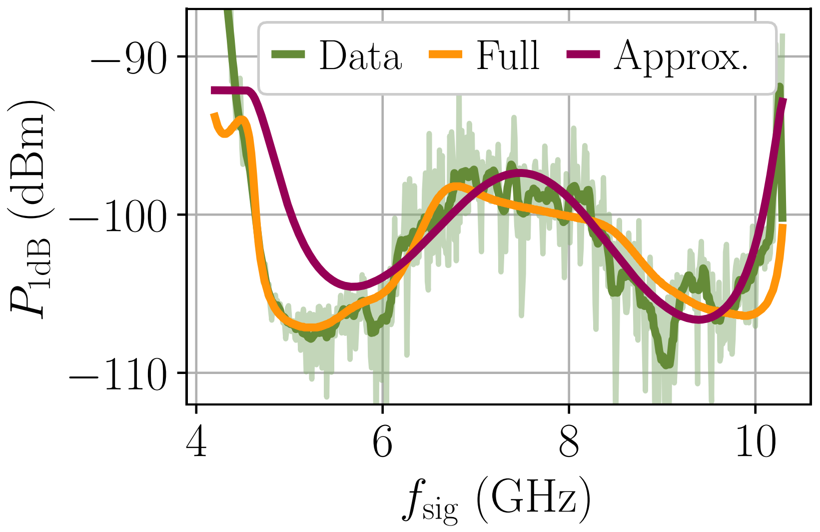


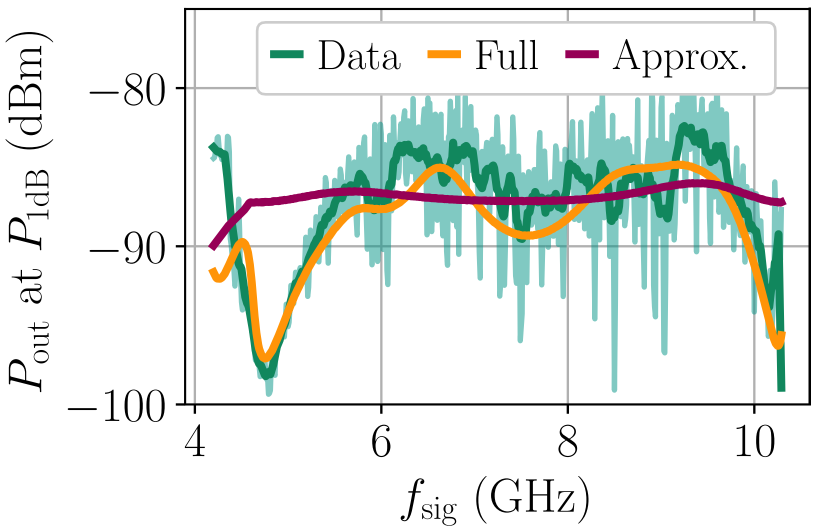


Compression versus signal frequency



Modeling the data





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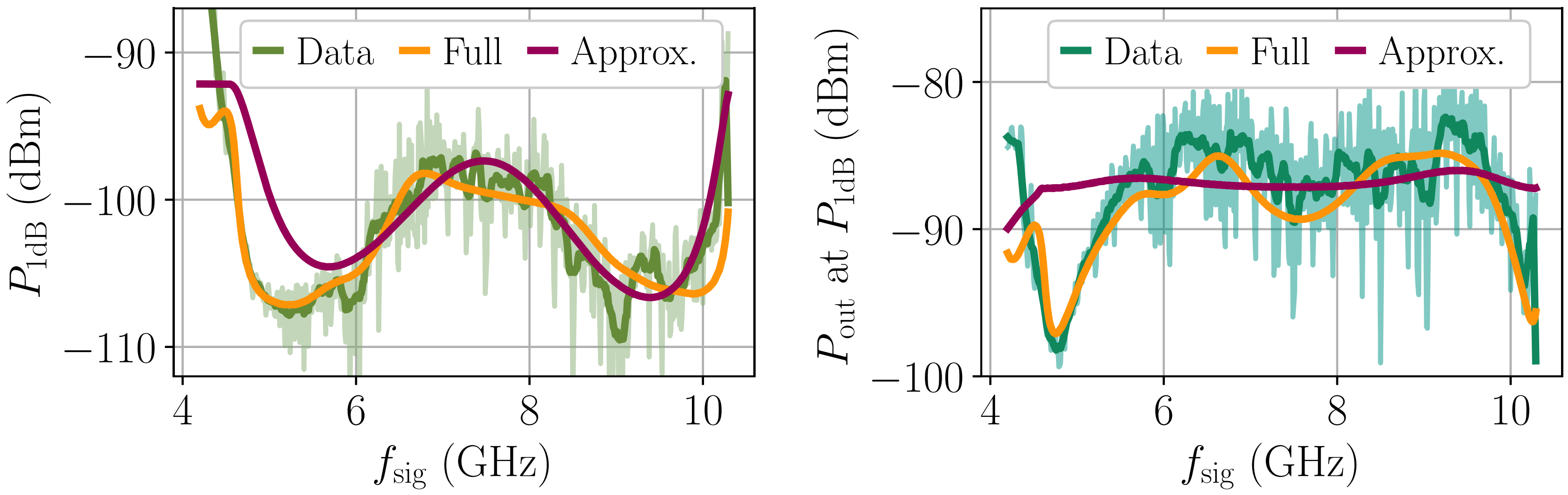

Approx: $$G(P_{sig}) = \frac{G_{lin}}{1 + 2G_{lin}P_{sig}/P_{pump}}$$

Assumes perfect energy exchange

K. O'Brien et al., Phys. Rev. Lett., 113, 157001 (2014)

P. Kylemark et al., J. Light. Technol., 24, 9 (2006)

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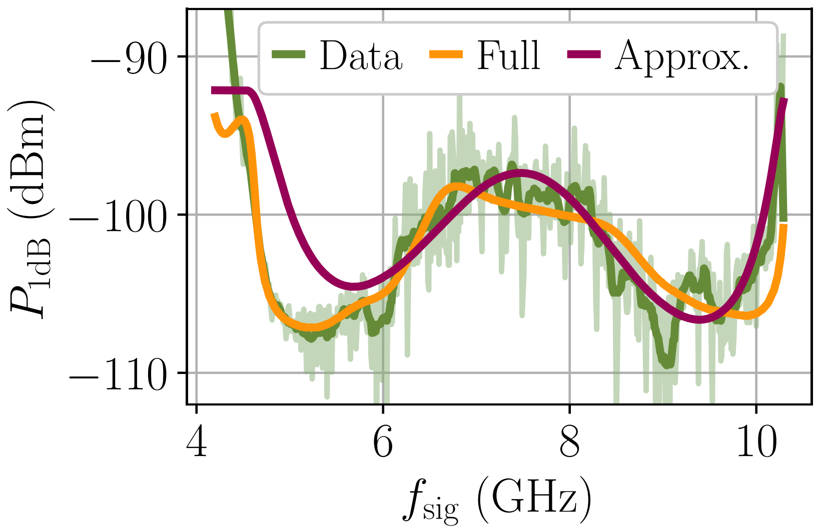

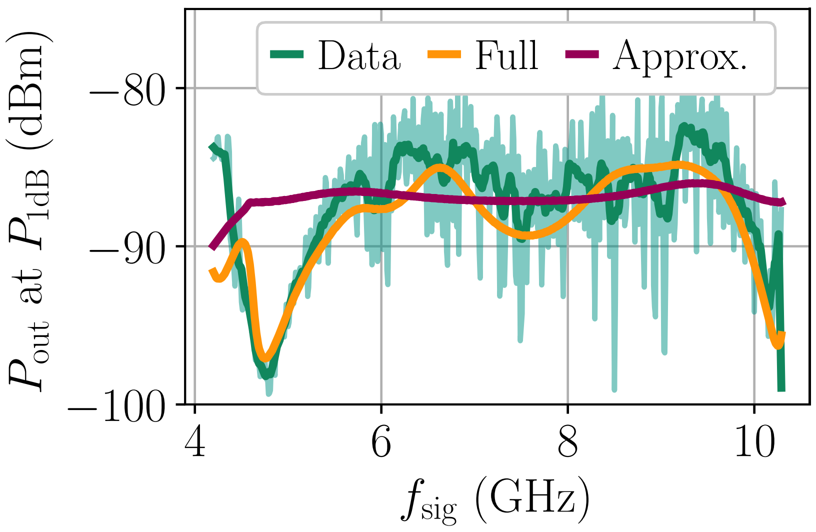

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Full model: CME including losses & exchange of energy with pump tone

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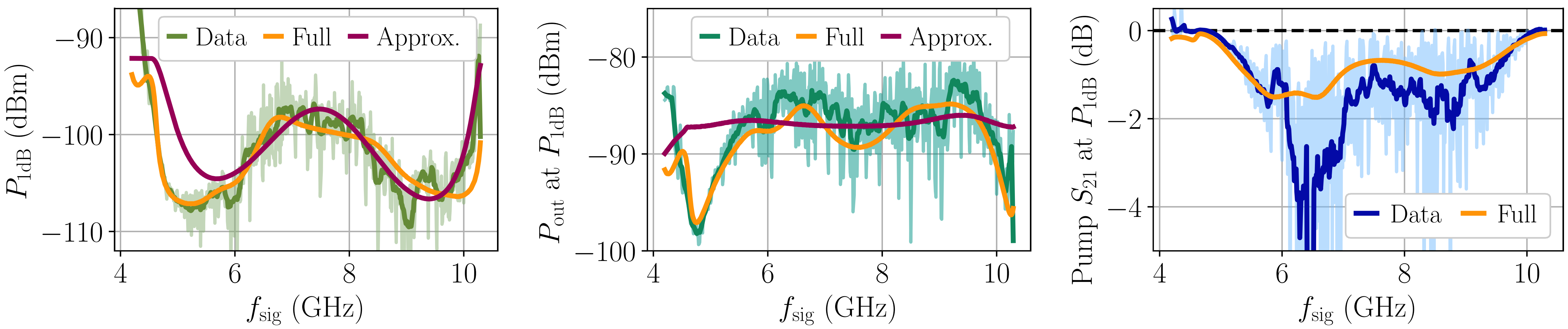

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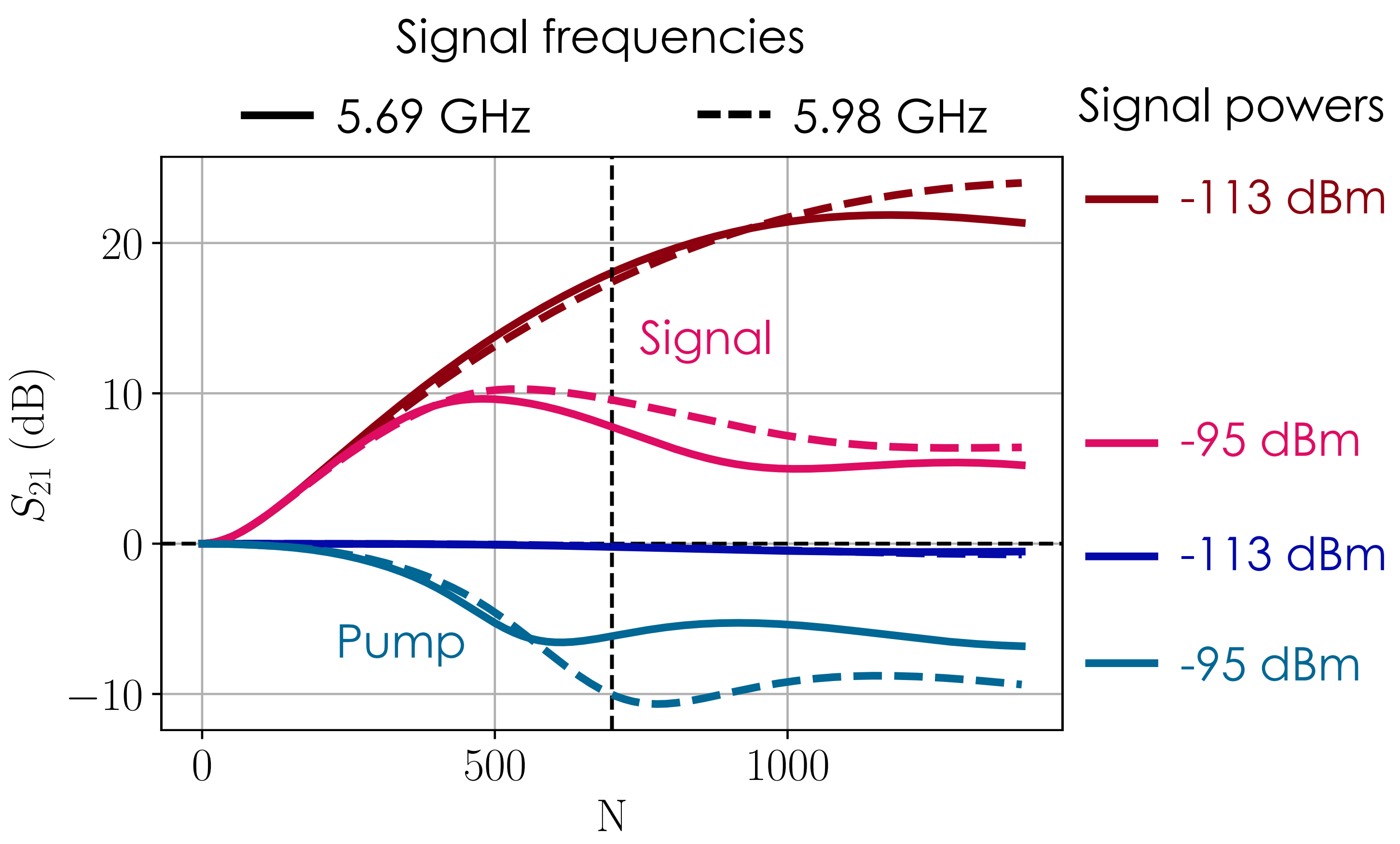
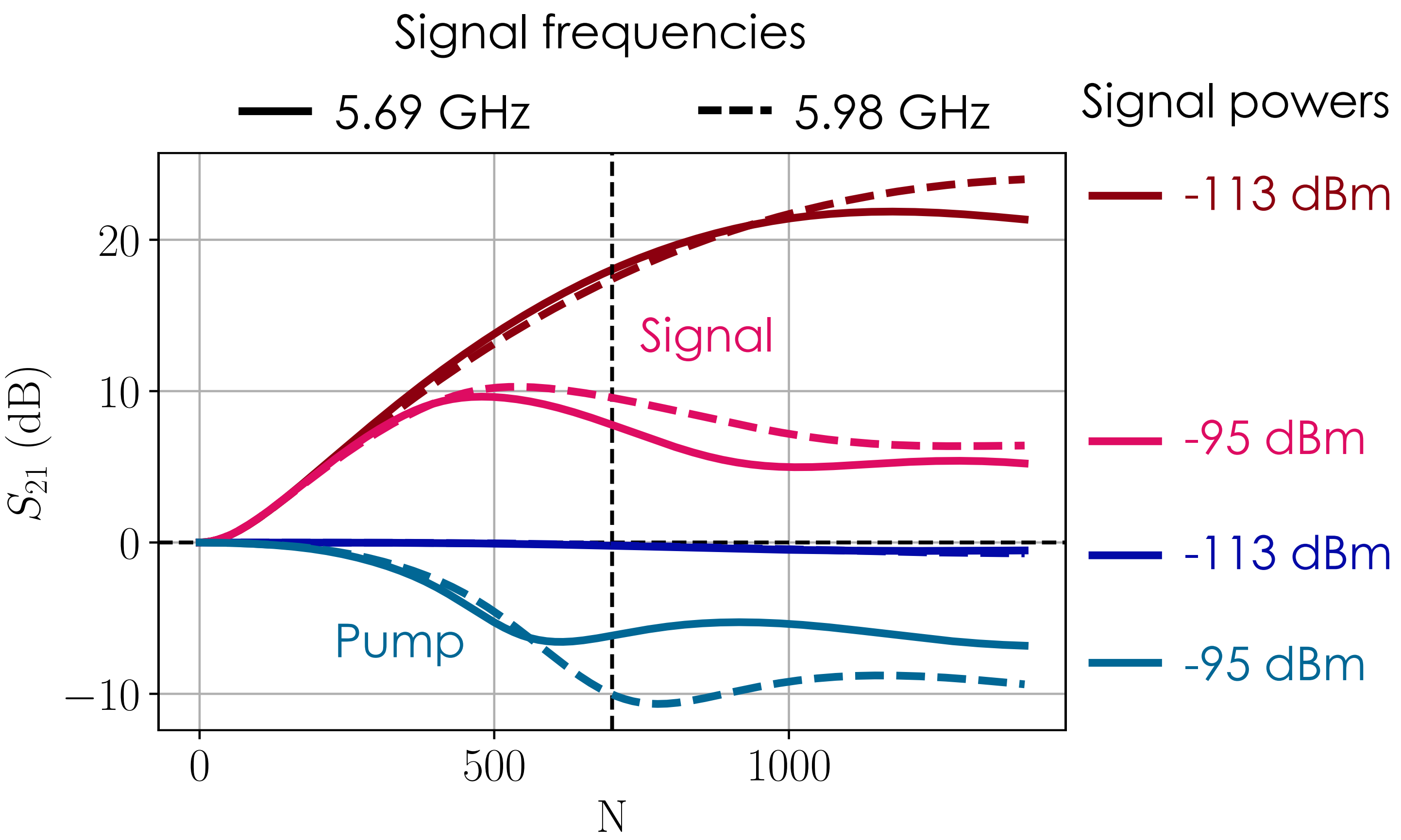
What gives the pump depletion profile?



What gives the pump depletion profile?

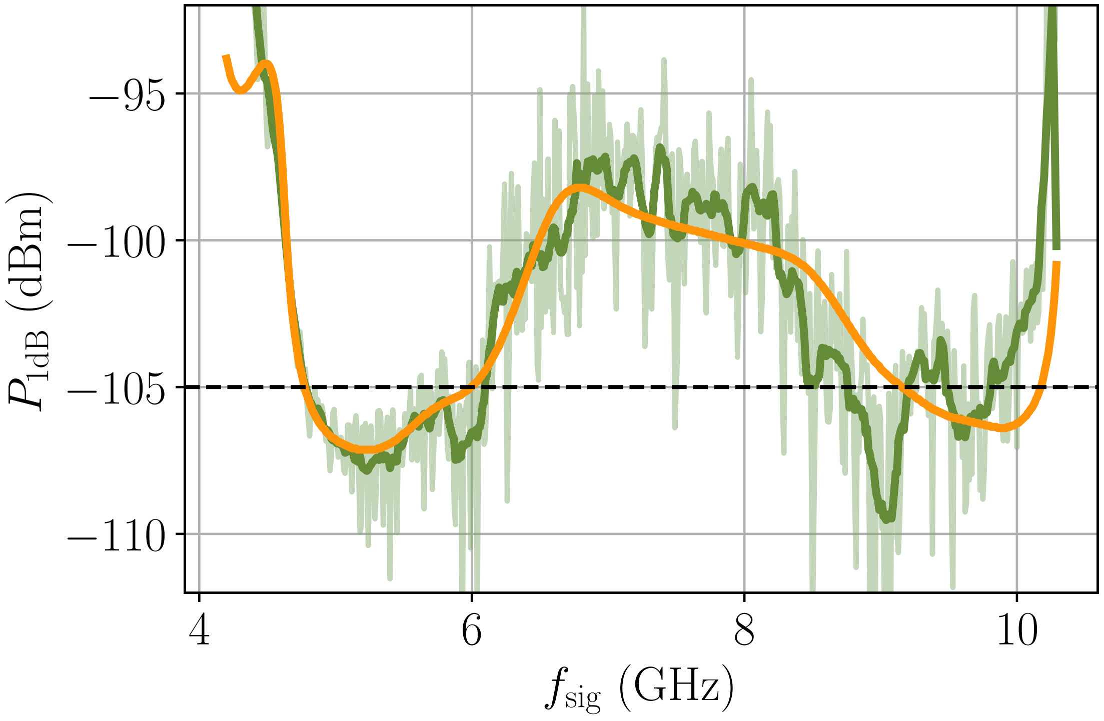


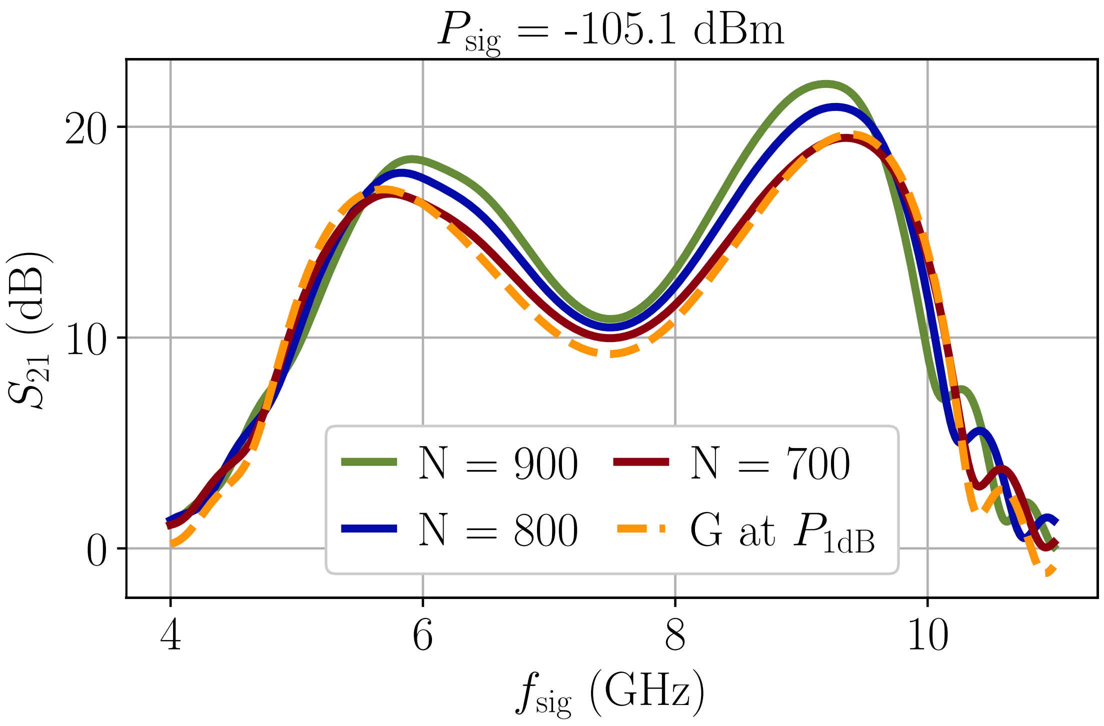
Pump transmission profile results from **different coherent lengths** and **conversion efficiencies**

Not related to linear gain profile

Gwenael Le Gal gwenael.le-gal@neel.cnrs.fr

Compressed gain vs TWPA length

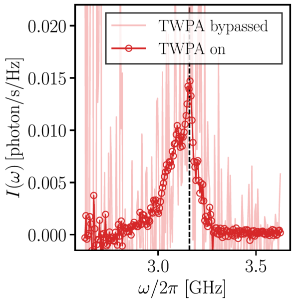


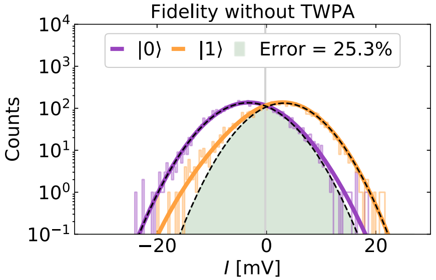


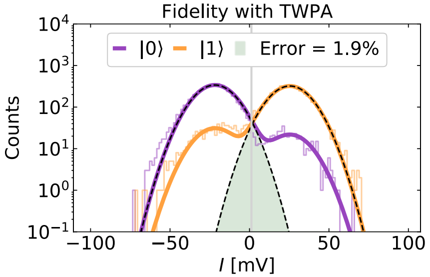
Mitigating compression by increasing device length

Conclusion

- TWPAs can be useful for many applications







Conclusion

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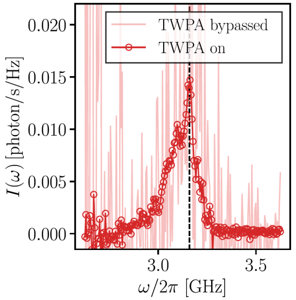
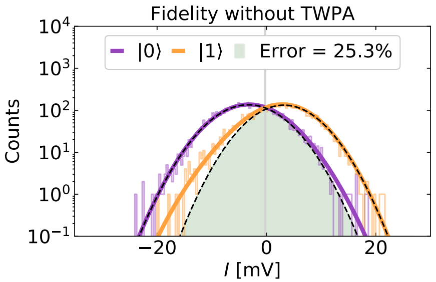
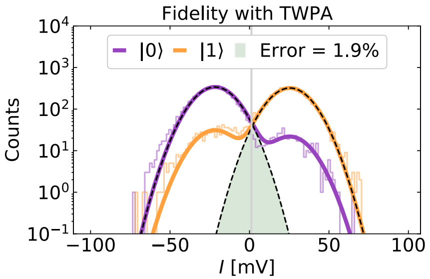
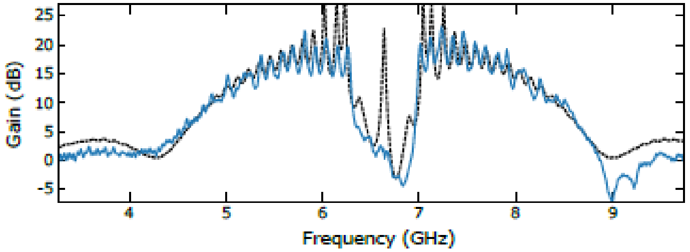
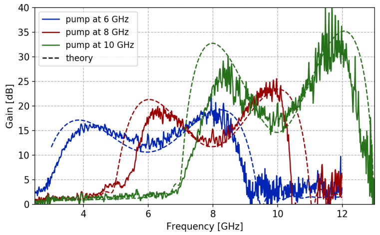






- Different flavours





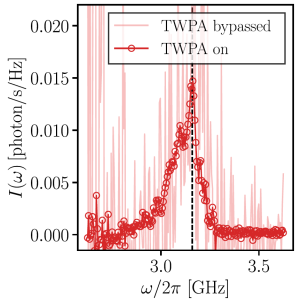
+ 3WM TWPAs

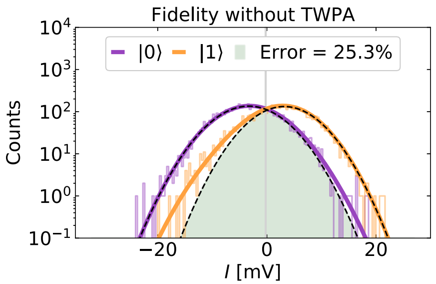
M. Malnou et al., PRX Quantum (2021)

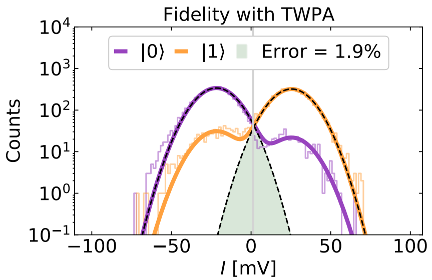
A. F. Roudsari et al., APL (2023)

Conclusion

- TWPAs can be useful for many applications







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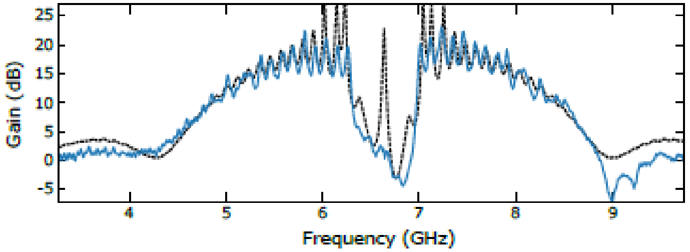
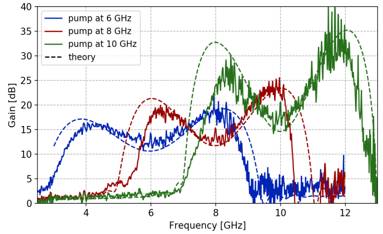




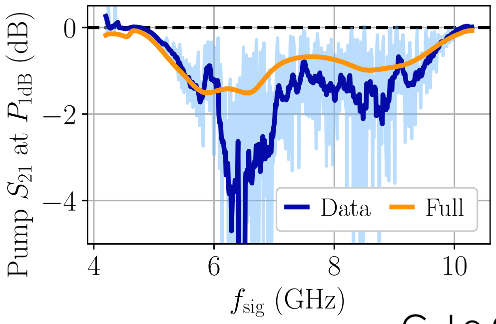
+ 3WM TWPAs

M. Malnou et al., PRX Quantum (2021)

A. F. Roudsari et al., APL (2023)

- Interesting physics: understanding noise limitations, reciprocity, saturation

- Saturation: caused by pump depletion



G. Le Gal et al., To be published

- Mitigation strategies:

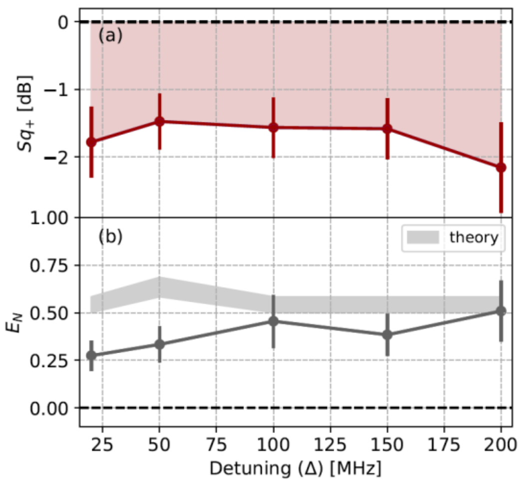
  → Increase critical current

  → Length engineering

Perspectives: understanding TWPA physics

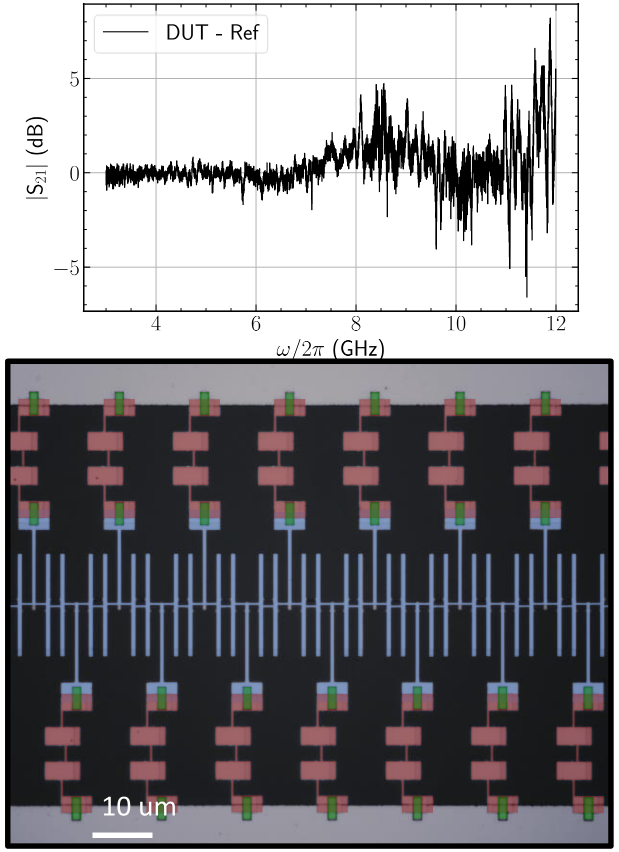
Noise limitations

Squeezing



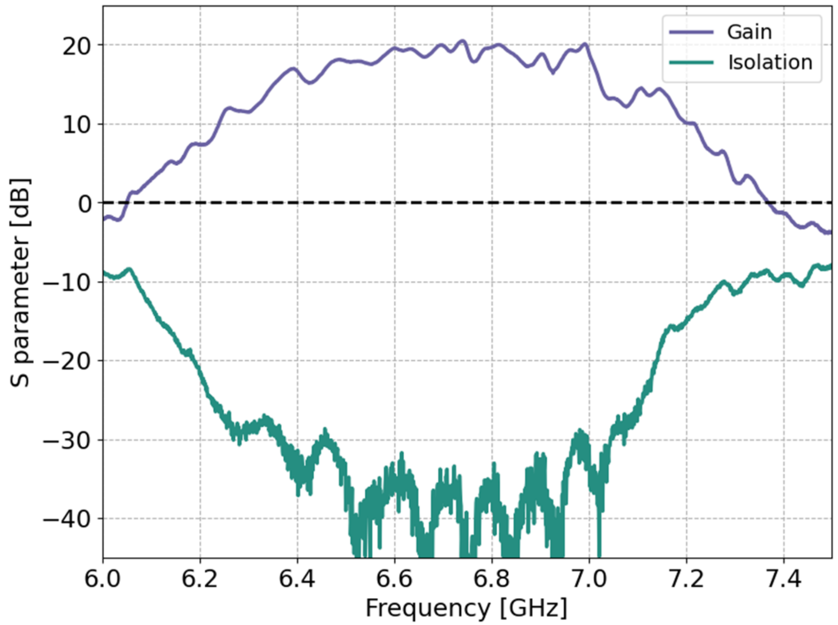
M. Esposito et al., Phys. Rev. Lett., 128, 153603 (2022)

Reducing losses



Courtesy of Giulio Cappelli

Reciprocity/directionality



Courtesy of Bekim Fazliji and Arpit Ranadive

A. Ranadive, B. Fazliji,et al., To be published

The TWPA team

Nicolas Roch | Arpit Ranadive | Guilliam Butseraen | Gwenael Le Gal | Bekim Fazliji | Giulio Cappelli | Amaury Martin

SQC

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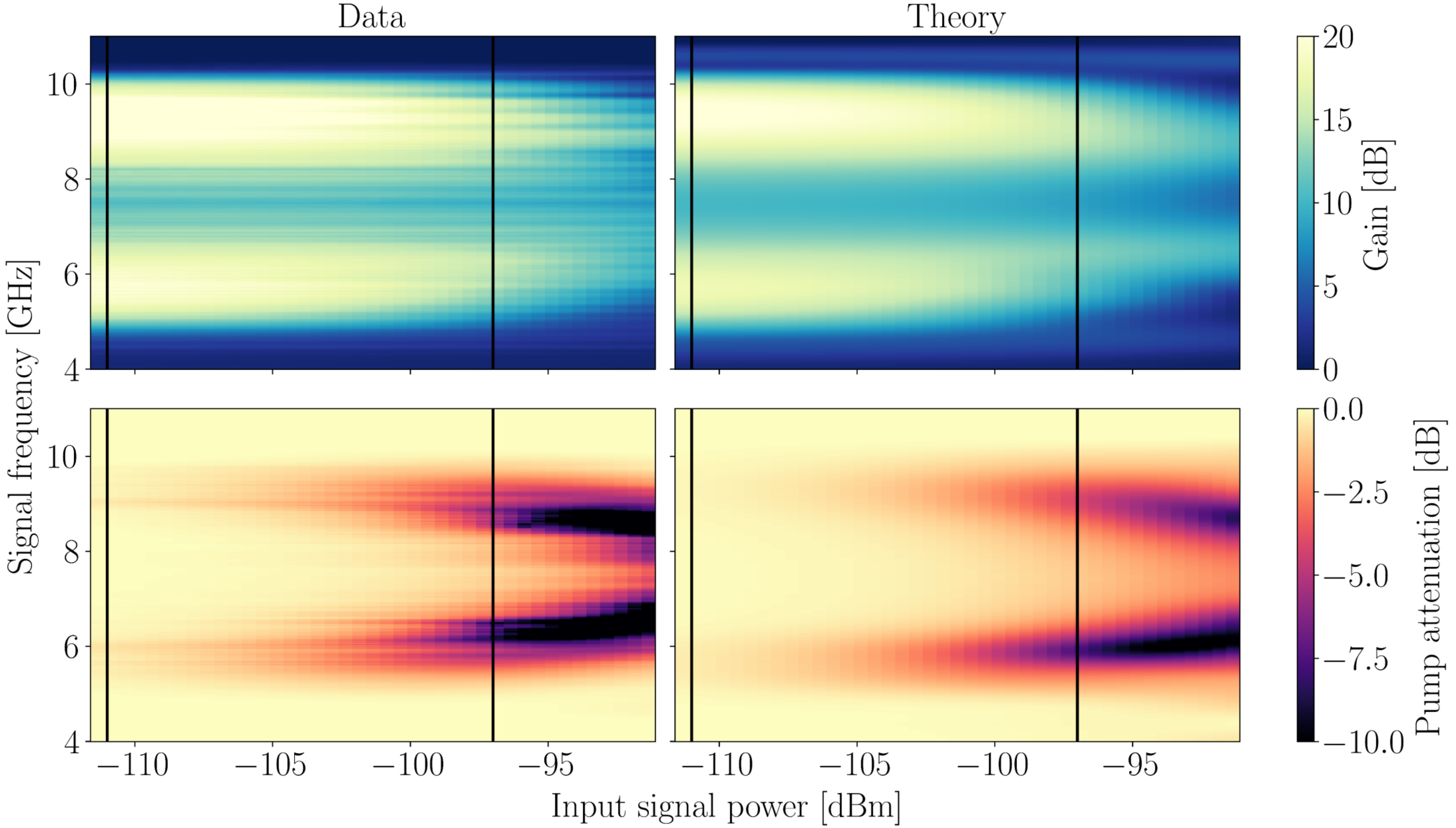
Thank you!

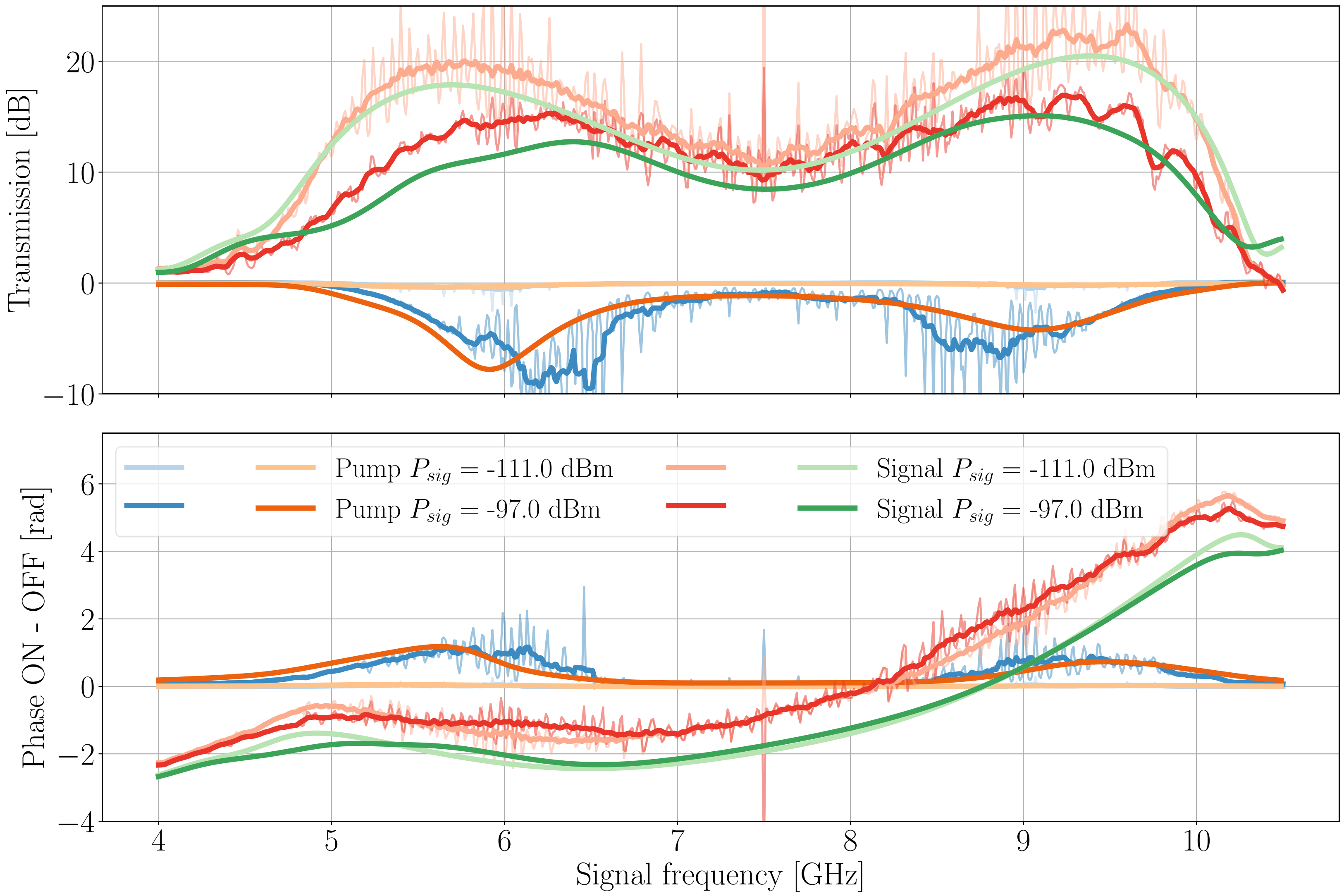
QuantAlps TruePA AVaQus

Comparison with data



Comparison with data

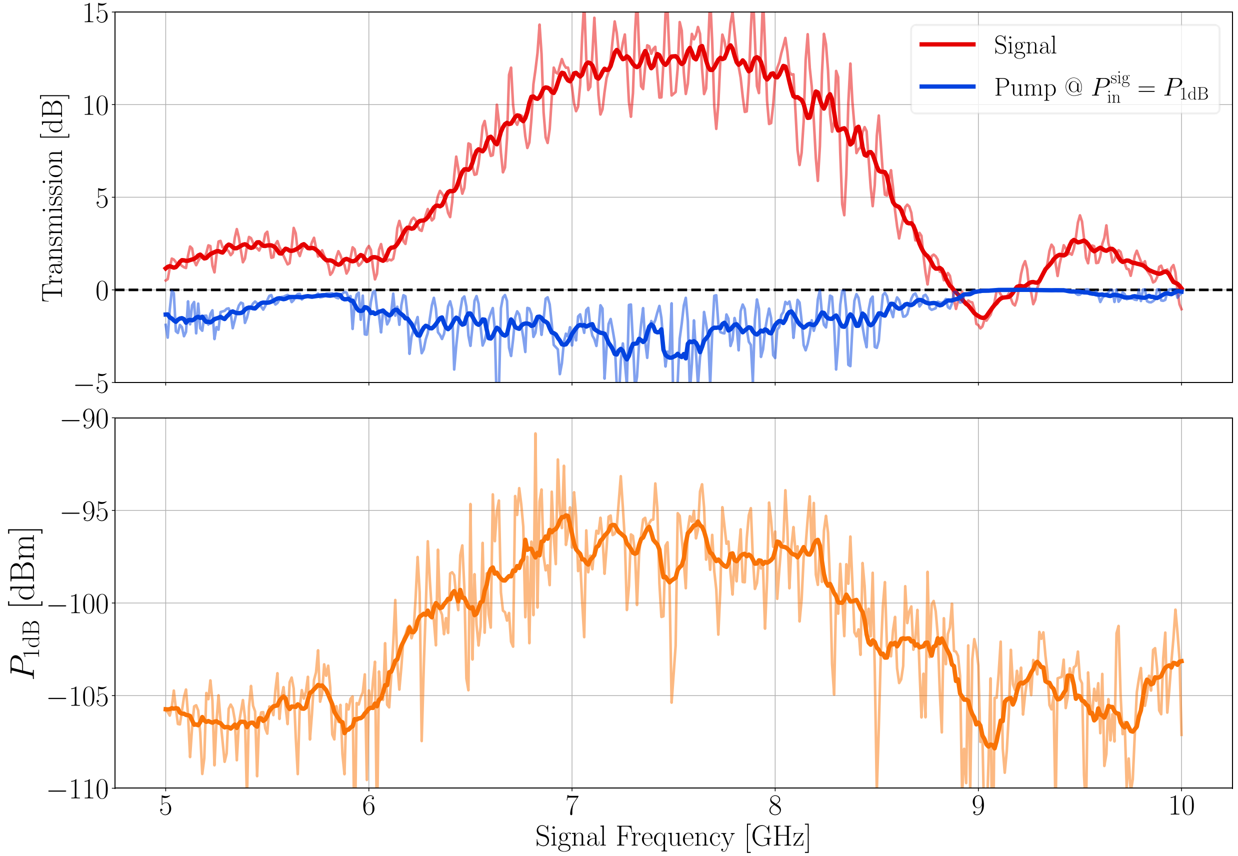
No fitting parameters



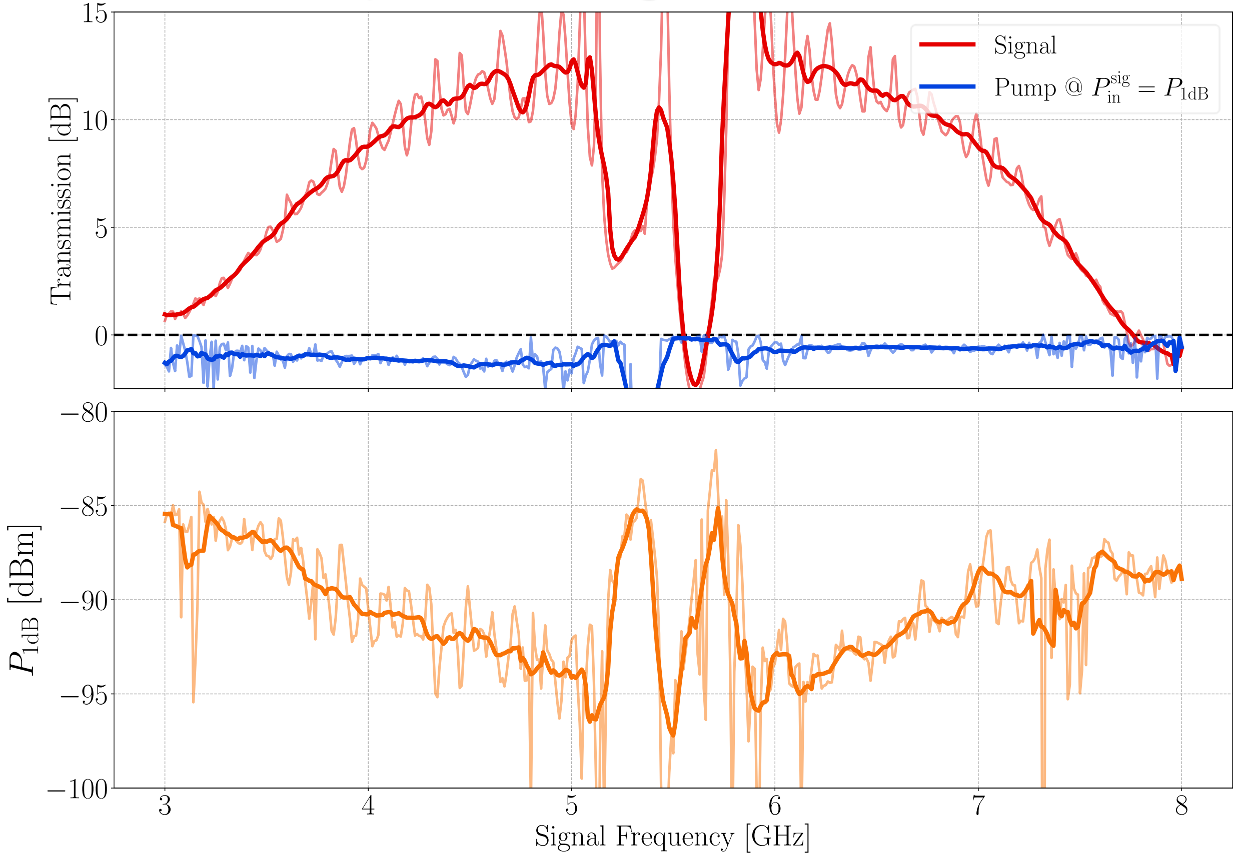
Other devices

Is it proper to the SNAIL TWPA operated @ 1/2 flux ?

SNAIL TWPA at 0 flux



Dispersion engineered TWPA



Comparing terms in theory