Superconducting Parametric Amplifiers for the Measurement of Absolute Neutrino Mass

Songyuan Zhao and Stafford Withington

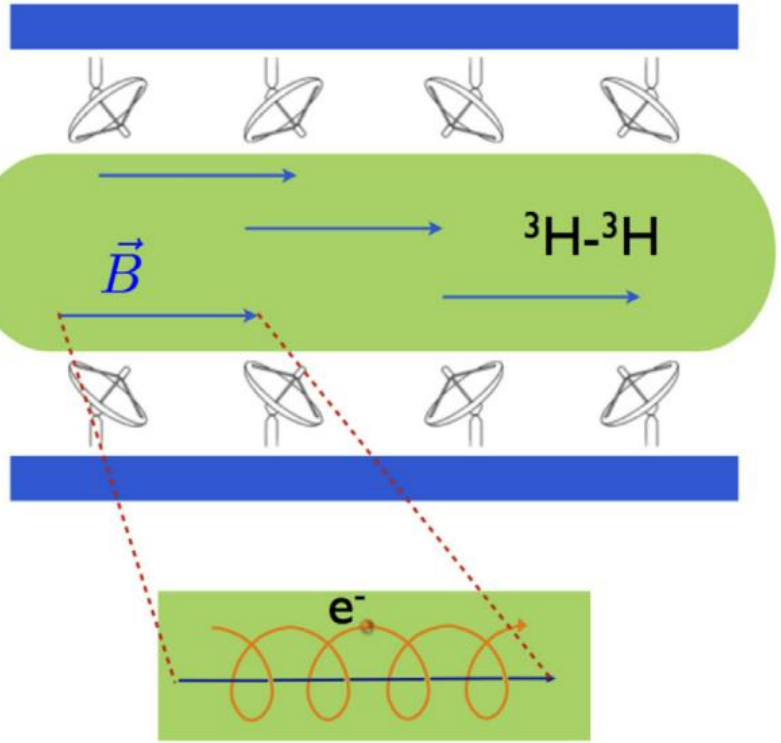
University of Oxford

22nd January, 2025 **QTFP Community Meeting**

Cylotron Radiation Emission Spectroscopy

UNIVERSITY OF OXFORD

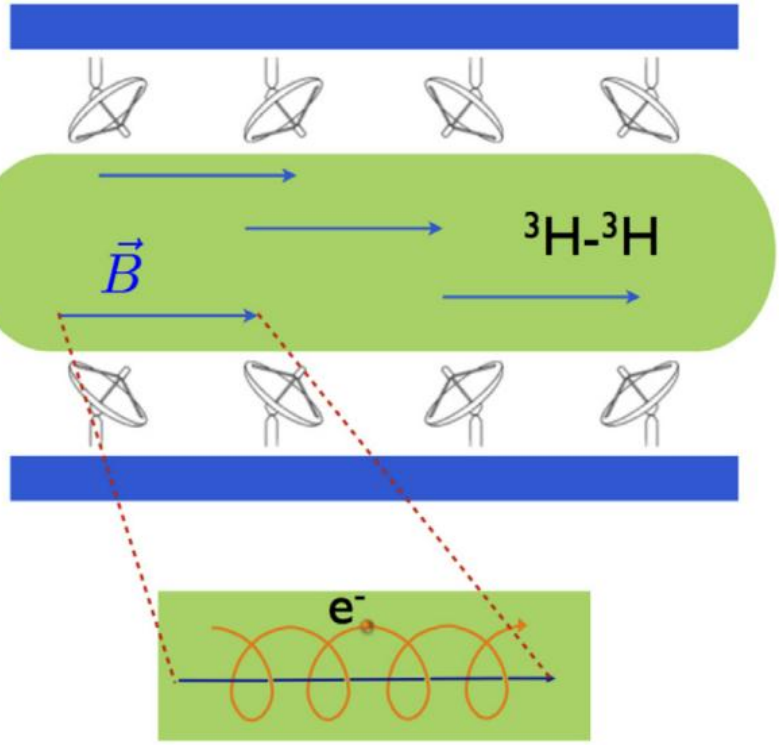
CRES region



Monreal, B.; Formaggio, J. A. Phys. Rev. D, 2009, 80.

Cylotron Radiation Emission Spectroscopy

CRES region



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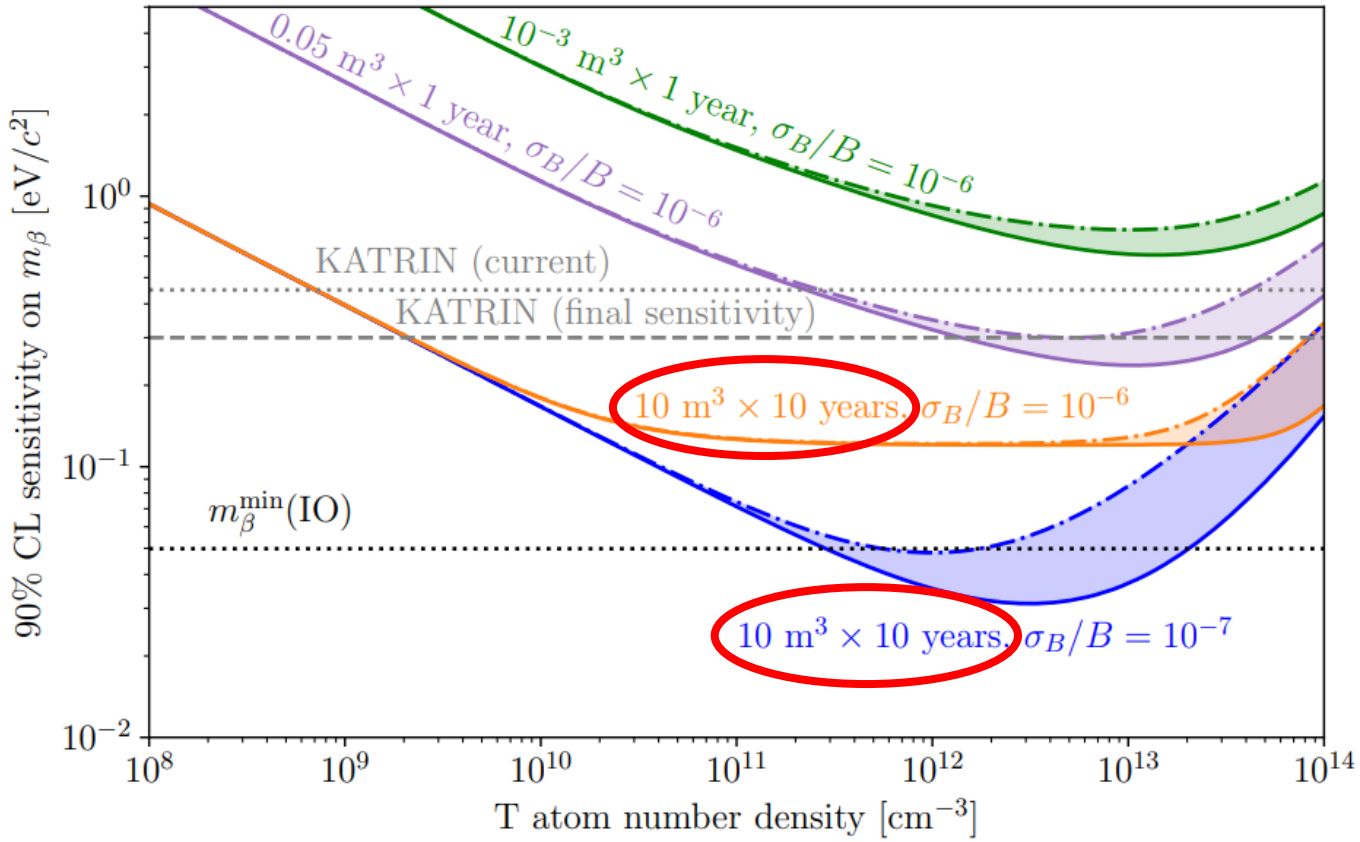
CRES requirement



QTNM collaboration (2024). arXiv preprint arXiv:2412.06338.

Cylotron Radiation Emission Spectroscopy

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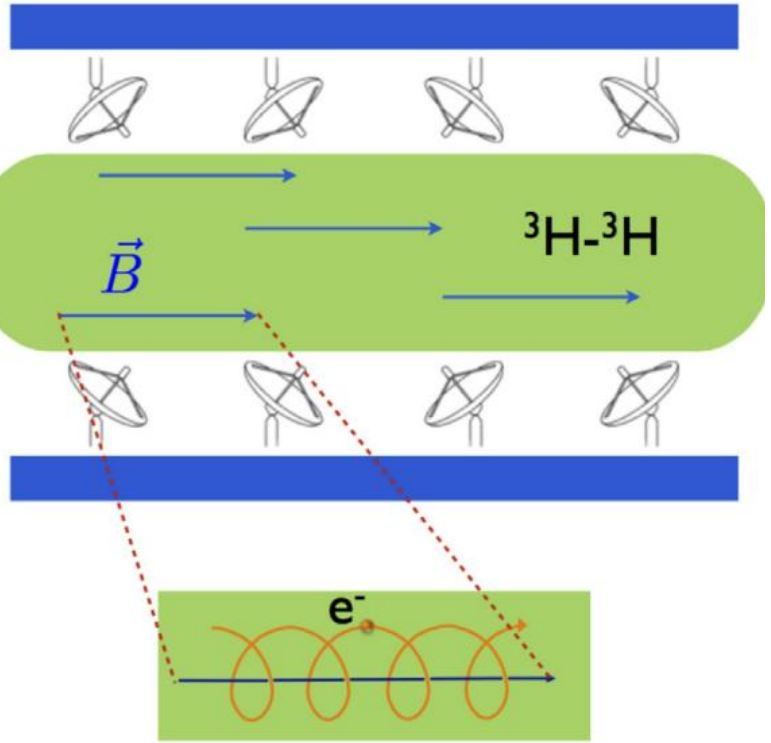
CRES region



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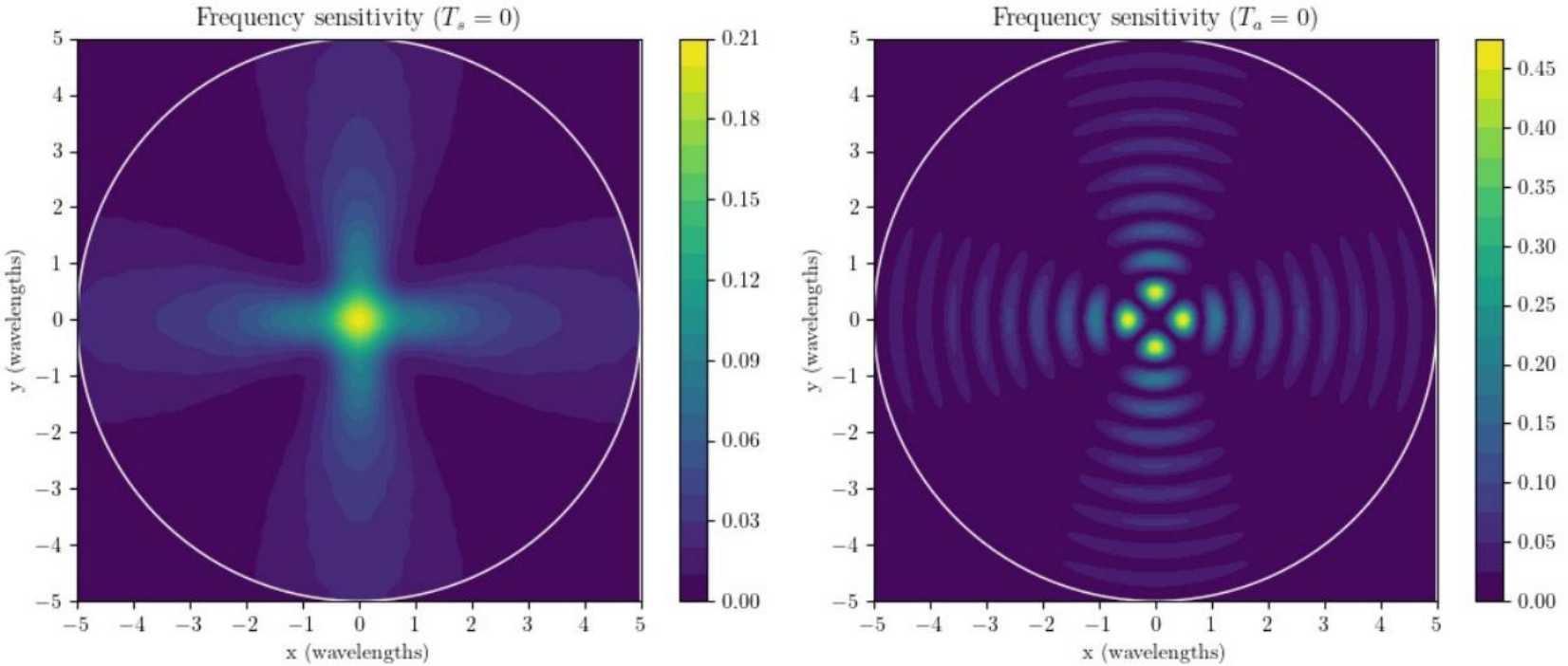
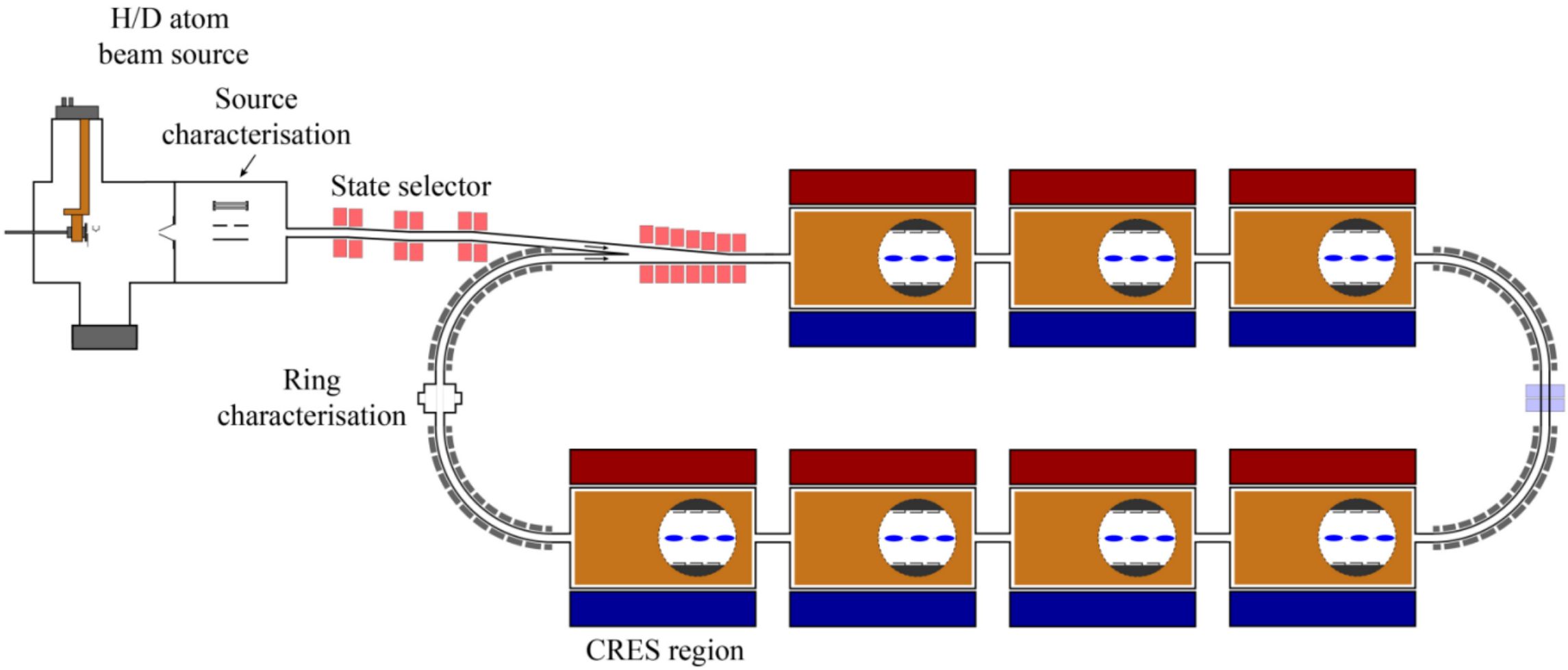
Antenna reception patterns (inward looking phased array)

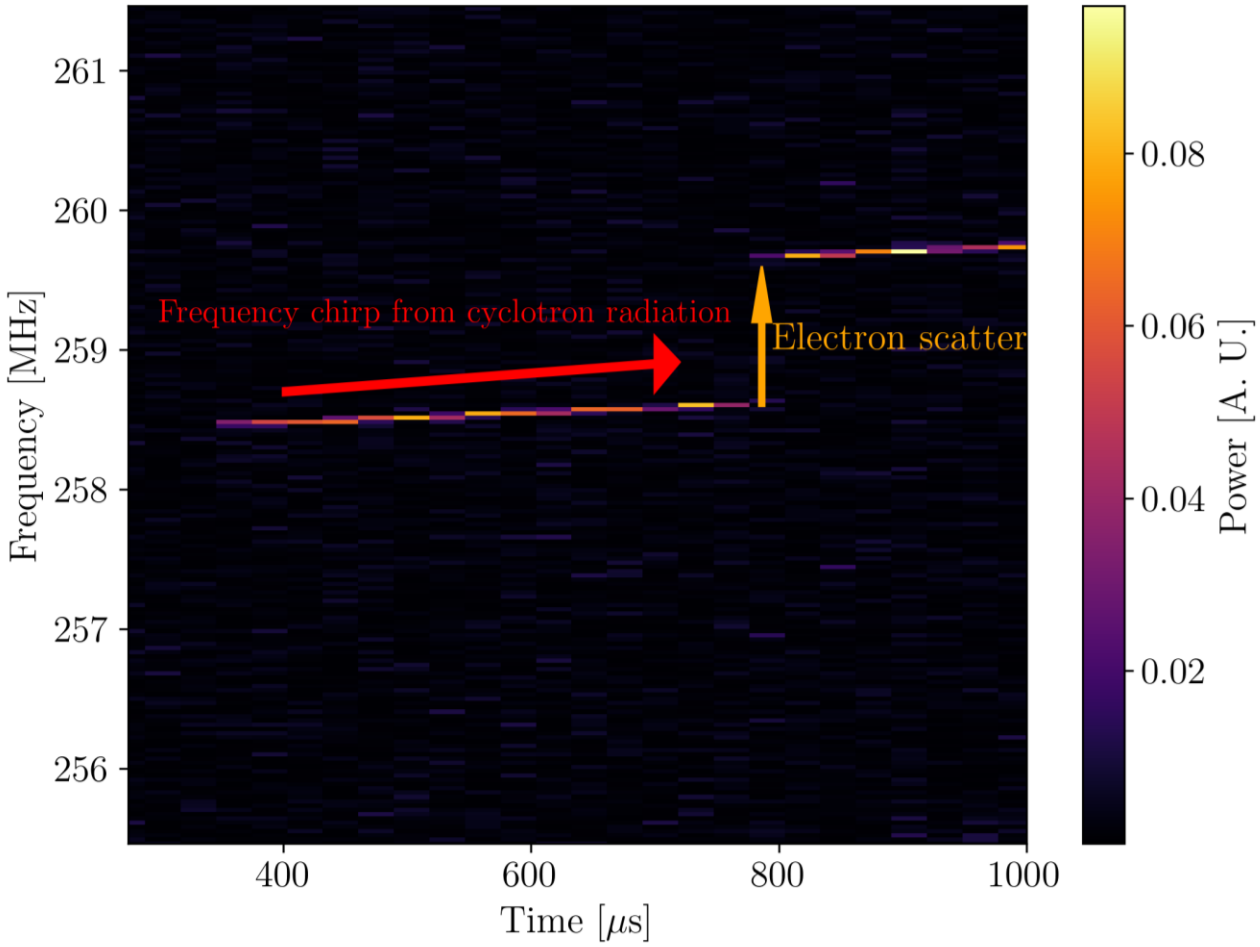


Withington, S., Thomas, C., & Zhao, S. (2024). arXiv preprint arXiv:2401.03247.

Cylotron Radiation Emission Spectroscopy



Quantum limited amplification



Simulation from Dr. Seb Jones of the QTNM collaboration

- Intrinsically chirping signal
- Cannot integrate against time to improve signal-to-noise ratio
- Need for quantum limited amplification
  - Noise of commercial HEMT amplifier at 18 GHz: ~ 7 K
  - Quantum limited noise at 18 GHz: ~ 0.4 K

Kinetic inductance nonlinearity

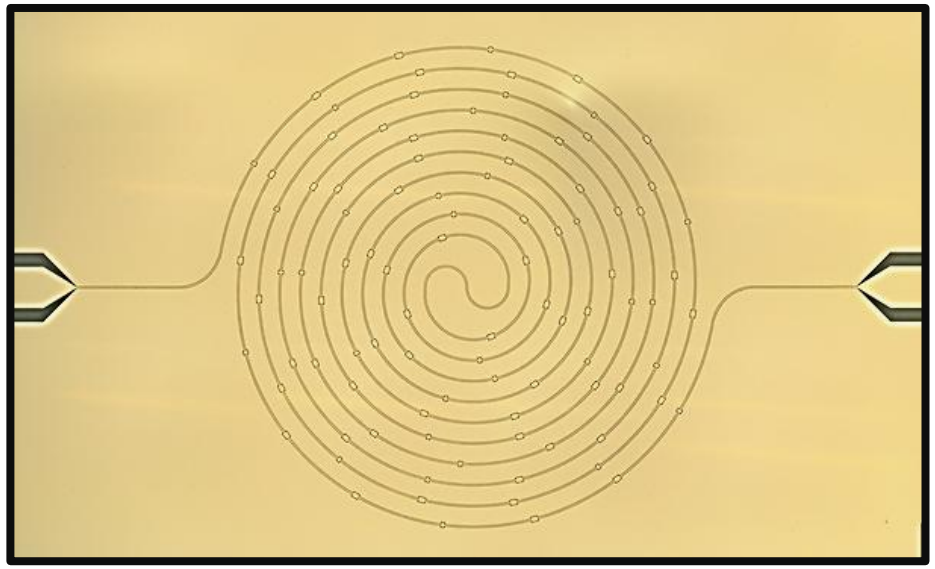
Nonlinearity ⟶ wave-mixing ⟶ amplification

Josephson junction nonlinearity vs

Kinetic inductance nonlinearity $L \sim L_0\left(1+\frac{I^2}{I_*^2}\right)$

- Higher saturation power
  - Maximum pump power is set by the film's critical current
- Higher operating temperature
  - High gain demonstrated at $4\ \mathrm{K}$
- Higher operating frequencies
  - High gain demonstrated at $25\ \mathrm{GHz}$
  - Pair-breaking frequency $> 500\ \mathrm{GHz}$
- Repeatable fabrication & controllable properties

Resonator vs travelling-wave amplifiers



← 🌀 → ~ 1 m

Bandwidth ~ 1 – 10 GHz

Rippling ~ 10 MHz

Travelling-**W**ave **P**arametric **A**mplifier (TWPA)

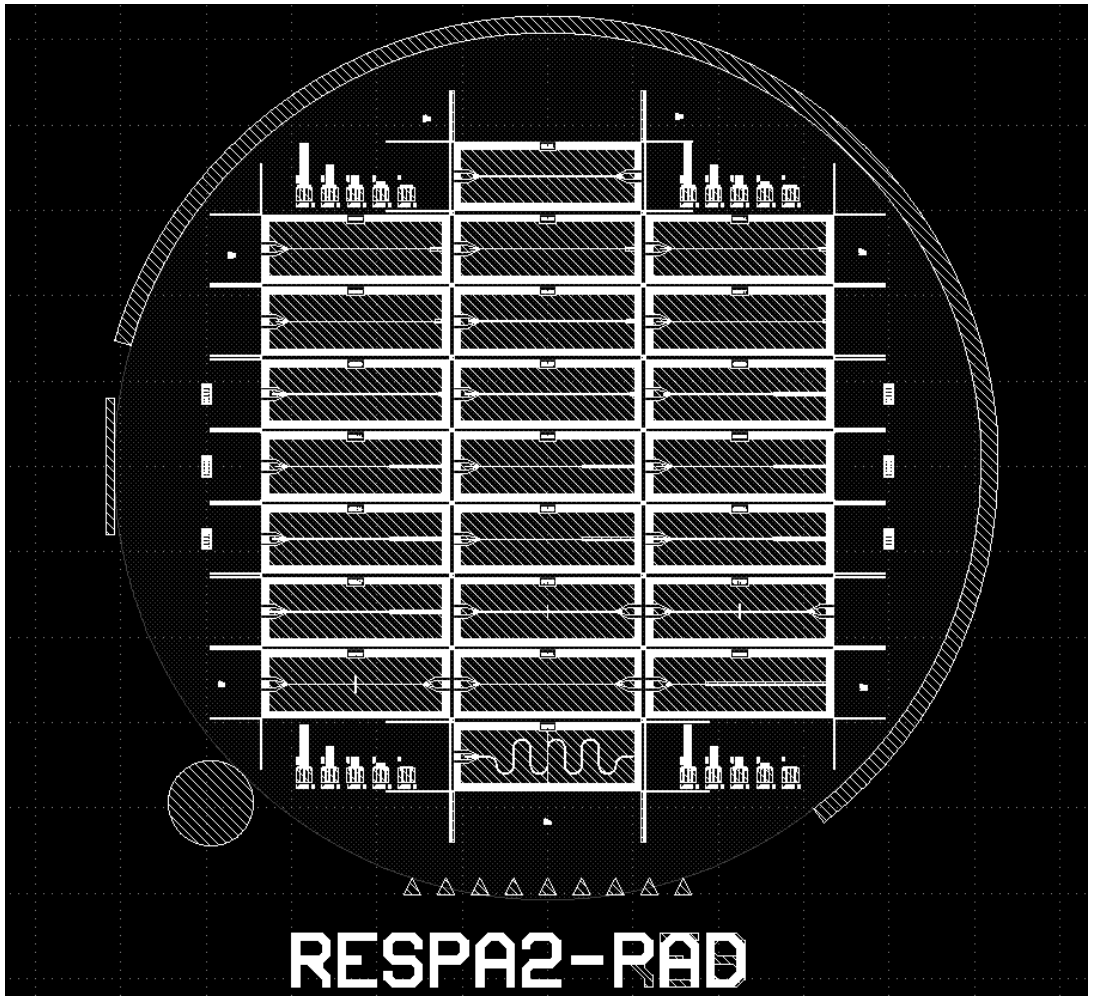
← – → ~ 1 cm

Bandwidth ~ 1 – 100 MHz

(future goal 500 MHz)

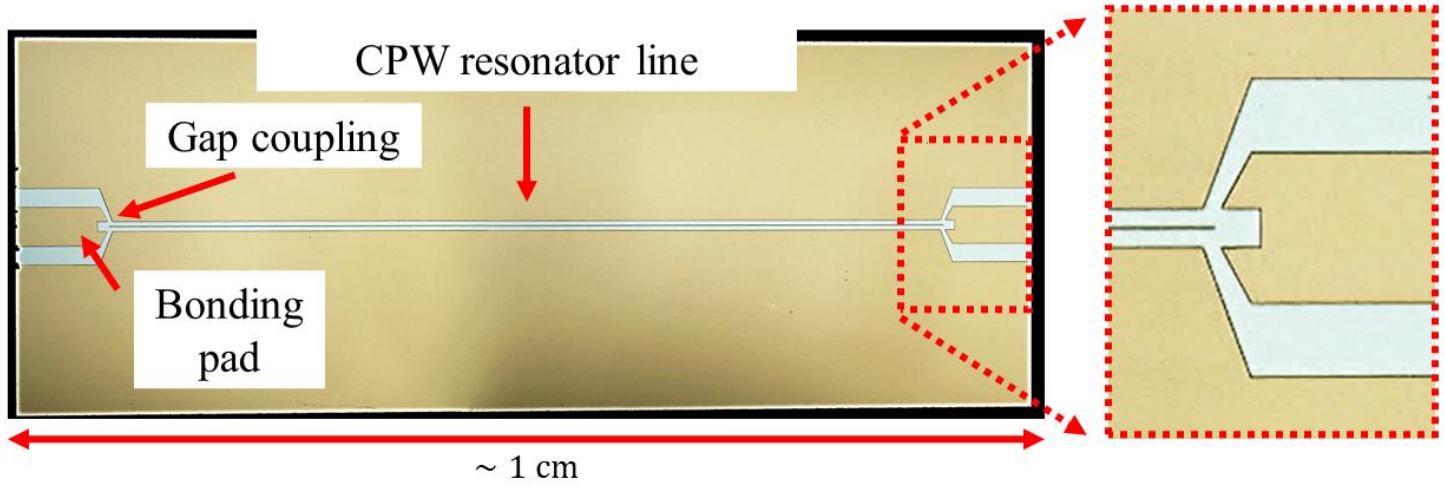
Resonator **P**arametric **A**mplifier (ResPA)

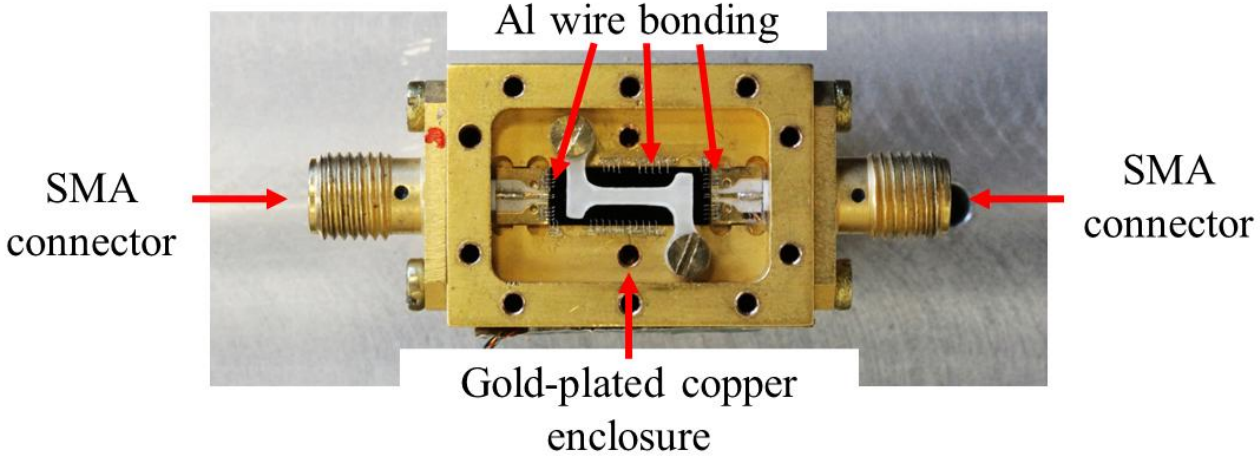
Fabrication of ResPAs



- Single-layer coplanar waveguide
- Based on NbN thin-films
- ~ 25 devices per wafer
- Straightforward to scale to ~ 100 devices per wafer
- Tested ~ 10 devices
- **All devices tested produced high gain** (i.e. > 20 dB)

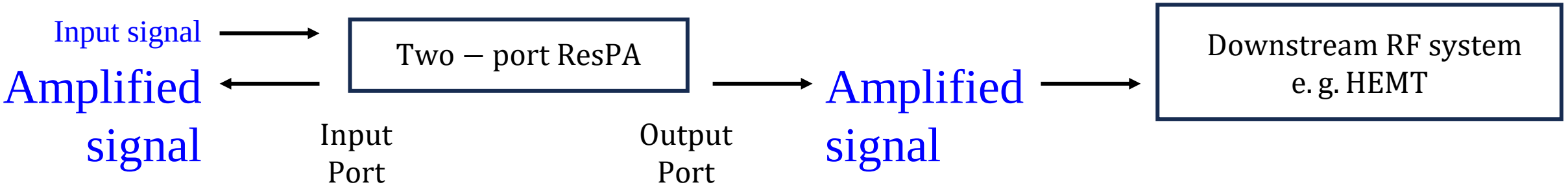
ResPA packaging



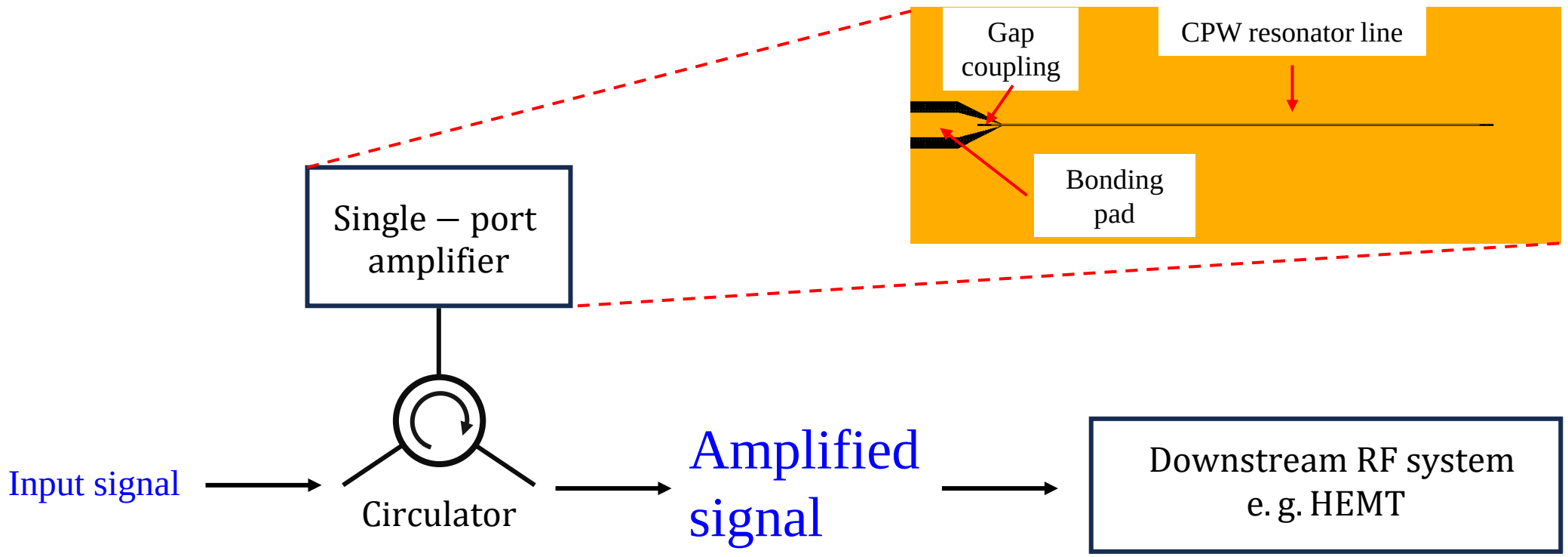


Operation modes: transmission amplifier

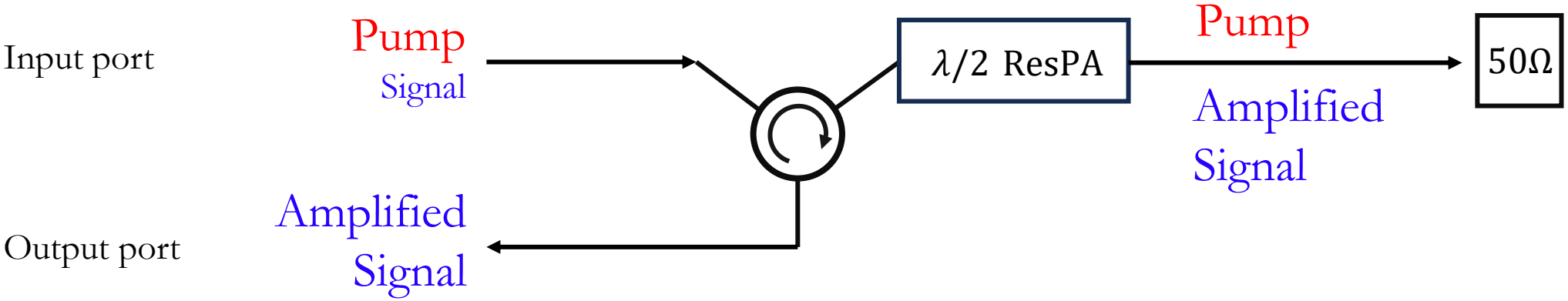
- Flexible operations
- Reflection or transmission operating modes
- Or more sophisticated configuration for other advantages



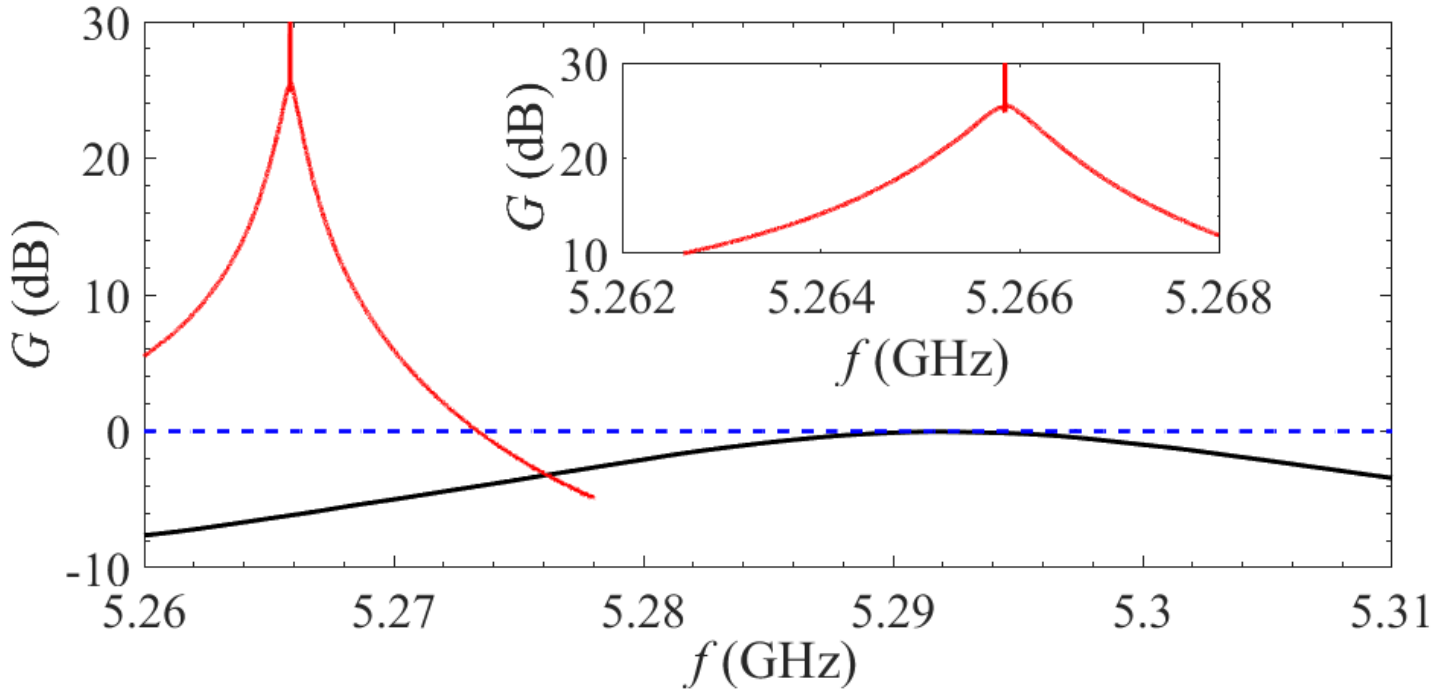
Operation modes: reflection amplifier

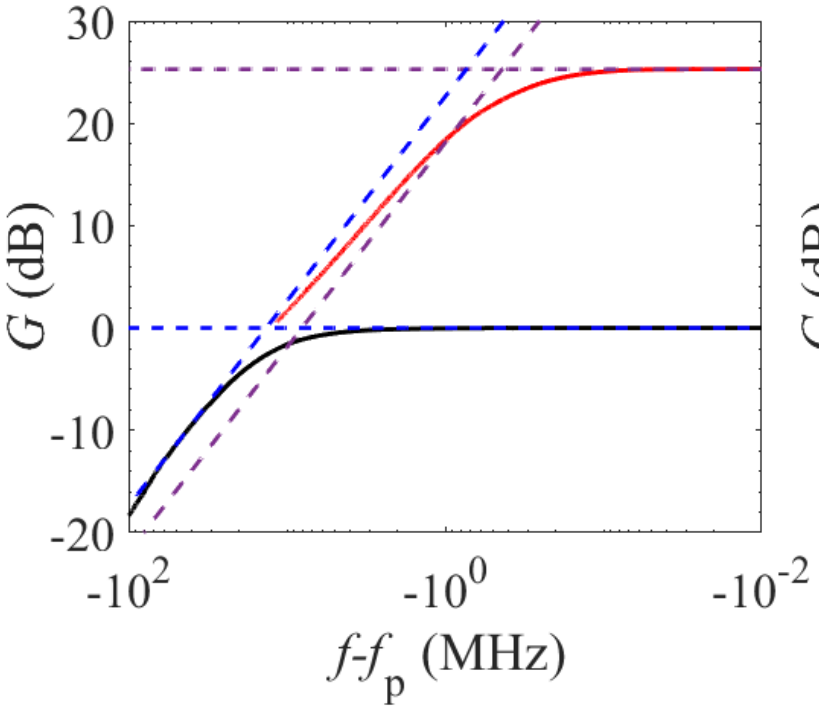


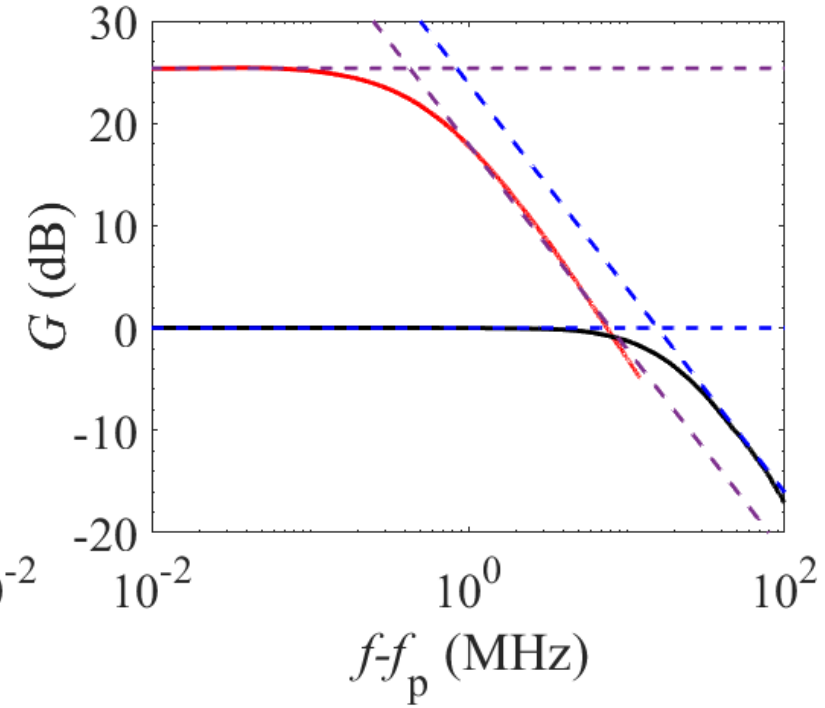
Operation modes: reflection amplifier, with pump removal



Amplification measurement

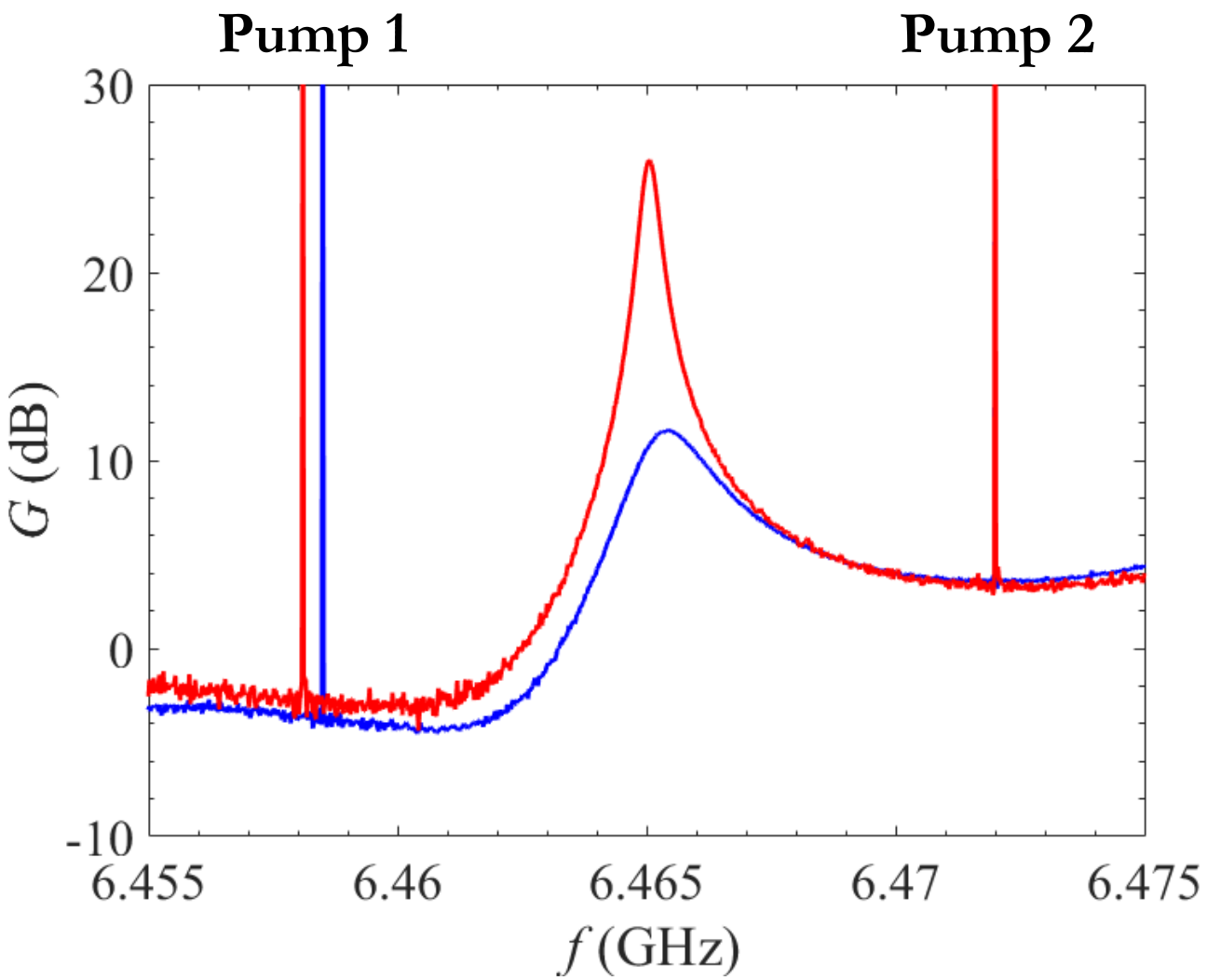




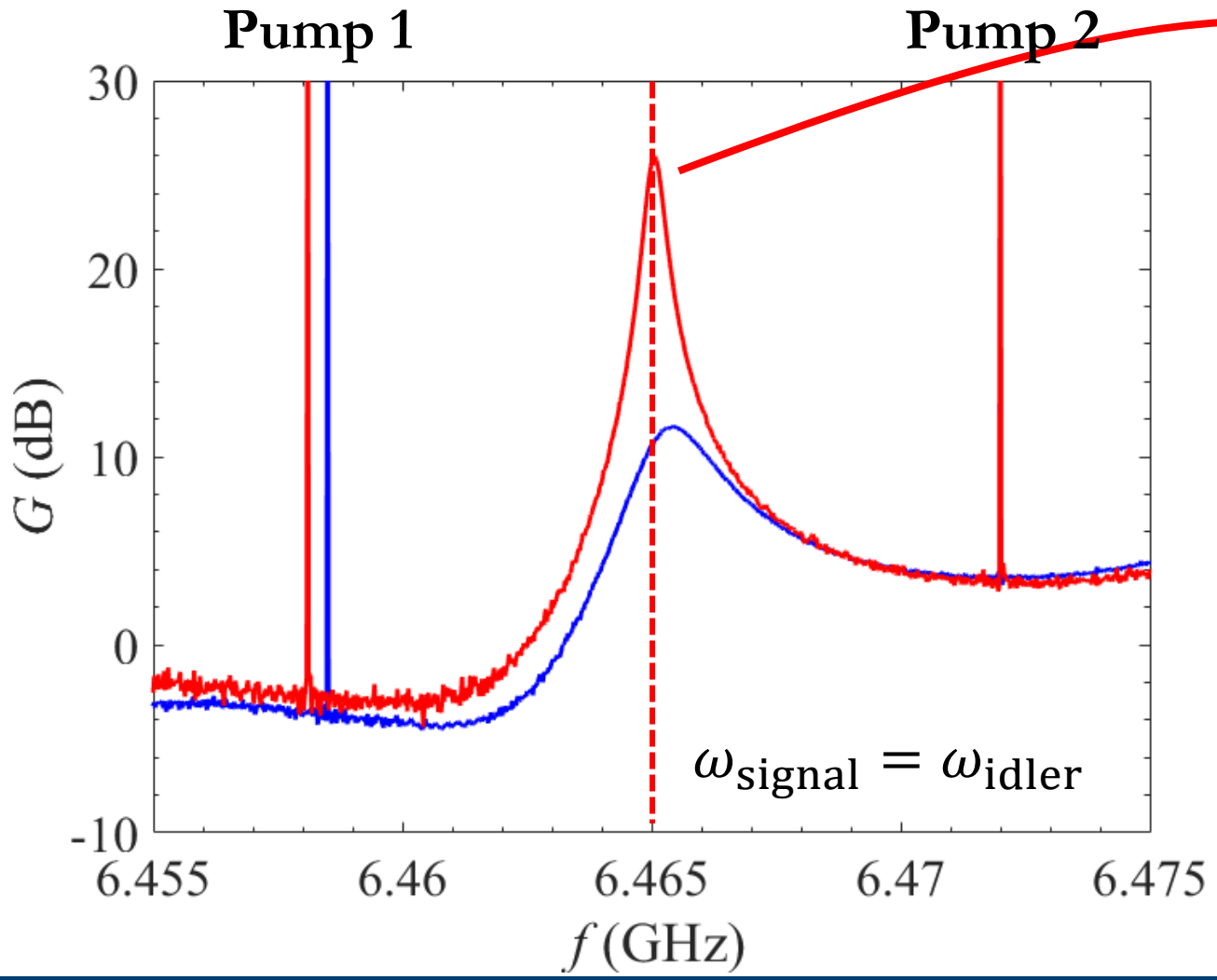


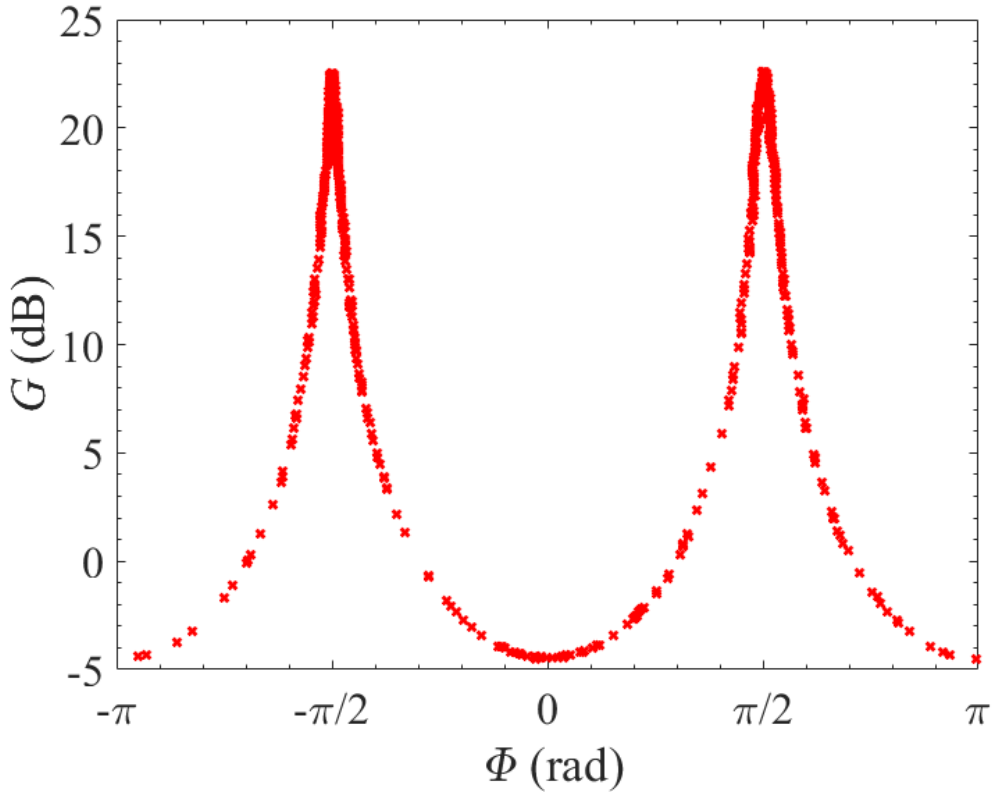
- High gain of > 20dB measured over 1 MHz
- No artefacts
- Theory-guided operation: gain, bandwidth, profile shape all understood
- Theory paper: arXiv:2206.10512
- Experiment papers:
- Supercond. Sci. Technol. 36 (2023), 105010
- J. Phys. D: Appl. Phys. 58 (2025), 035305

Non-degenerate pumping

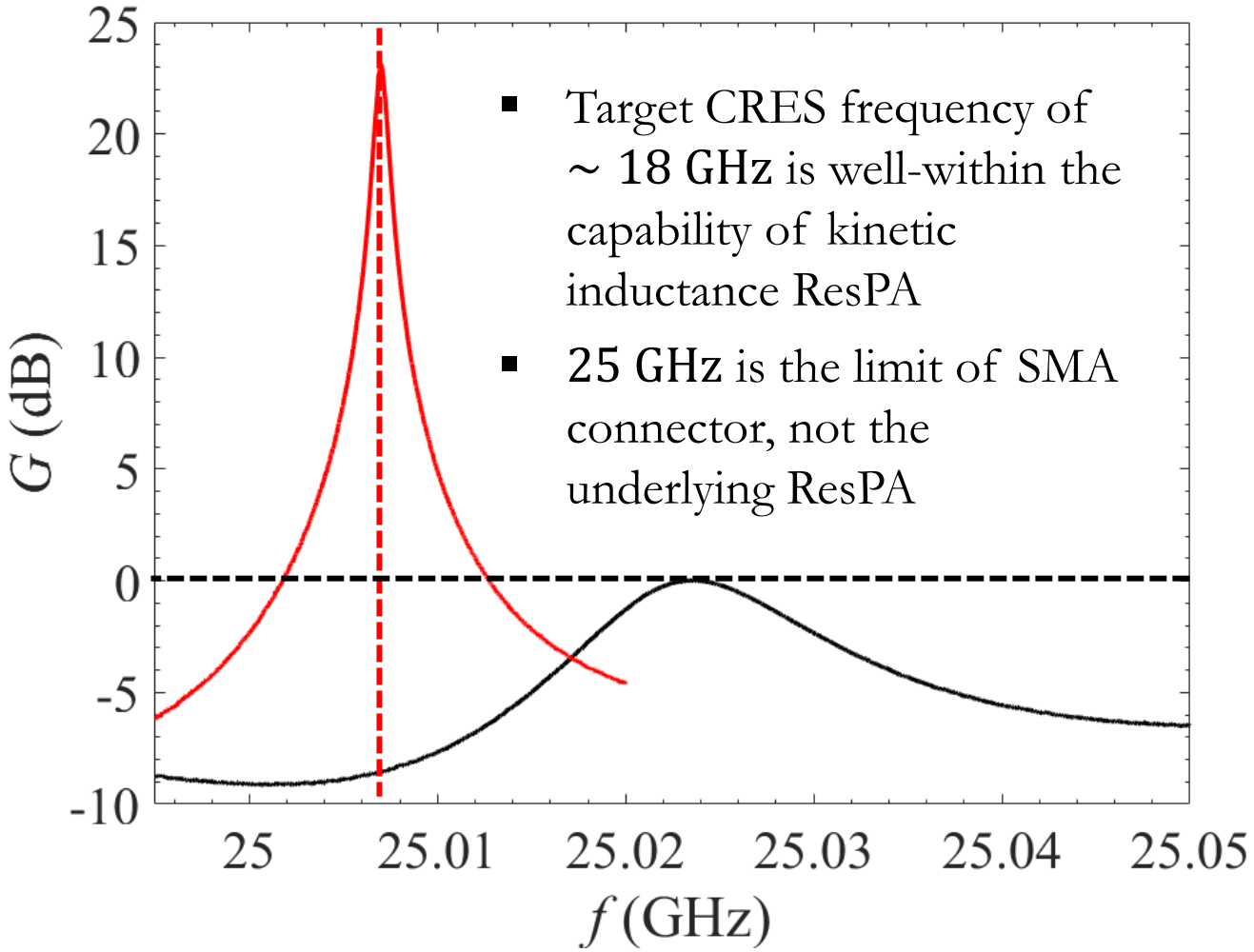


Non-degenerate pumping – phase sensitive gain





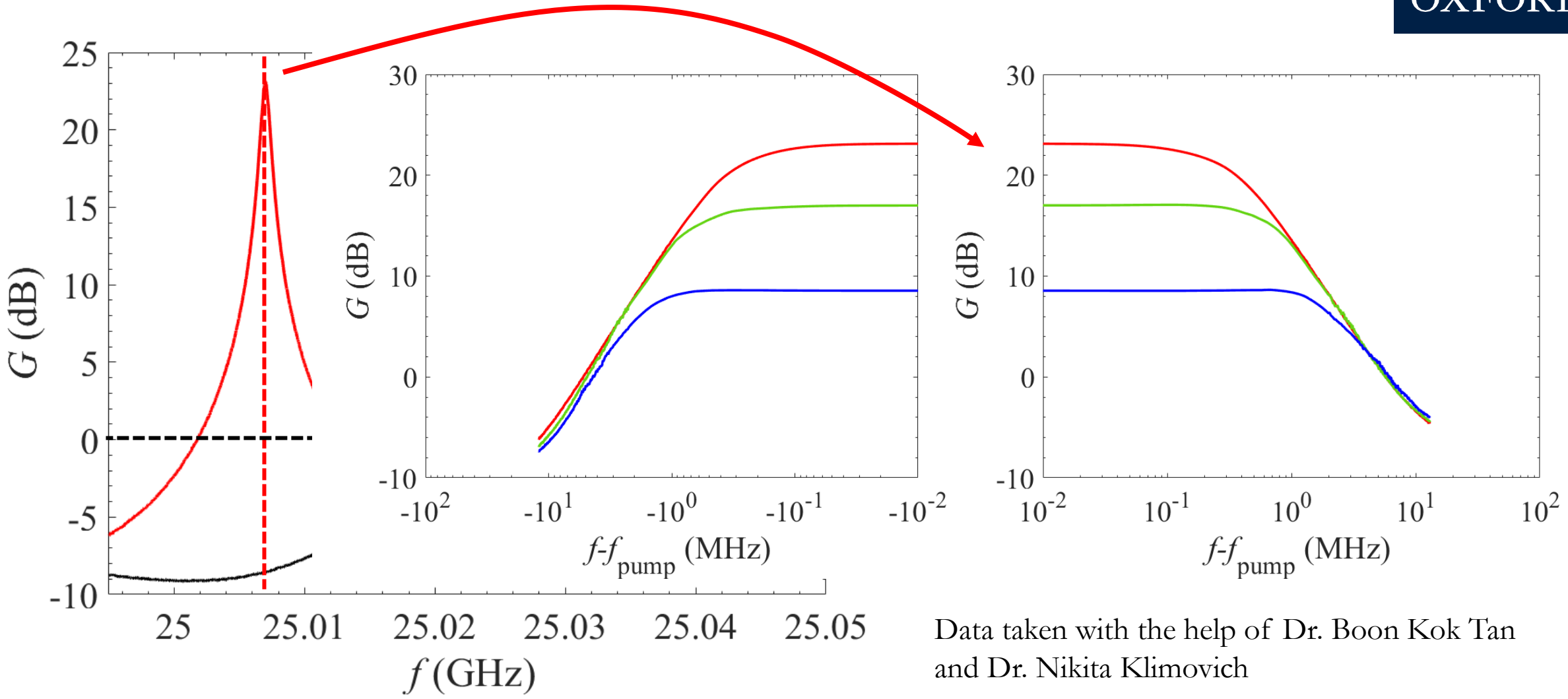
High frequency amplification



- Target CRES frequency of ~ 18 GHz is well-within the capability of kinetic inductance ResPA
- 25 GHz is the limit of SMA connector, not the underlying ResPA

Data taken with the help of Dr. Boon Kok Tan and Dr. Nikita Klimovich

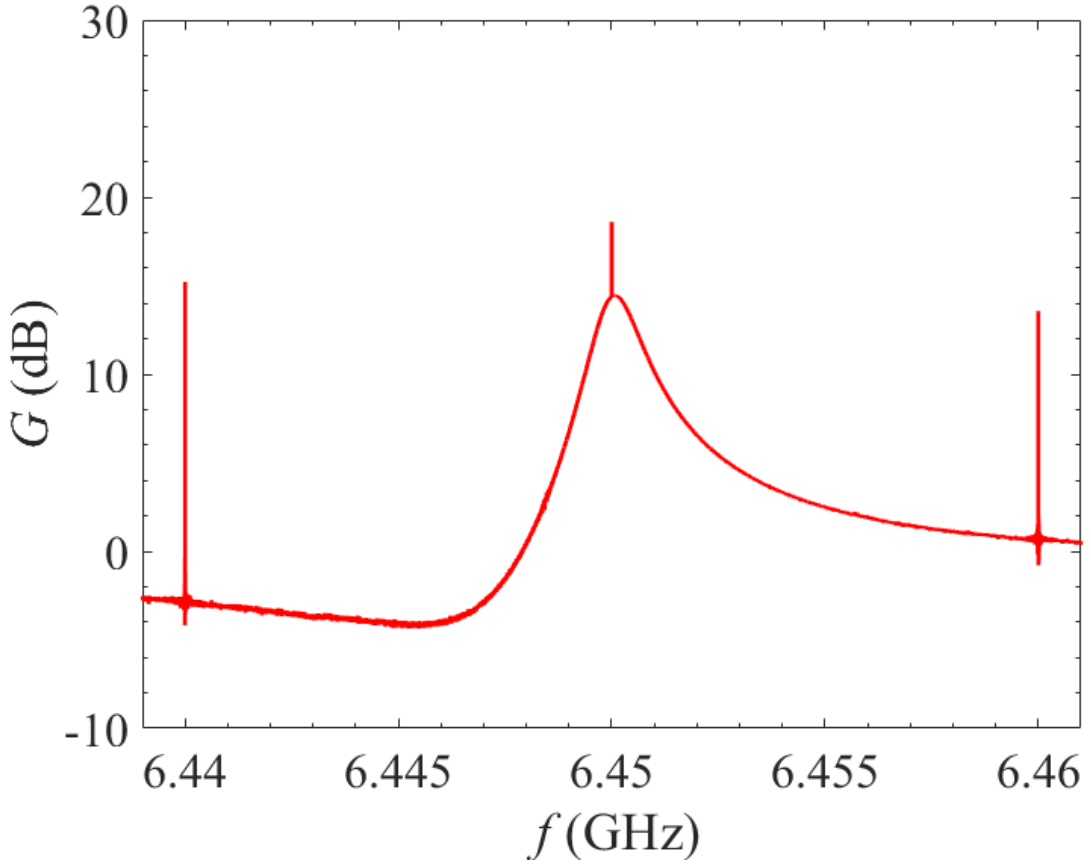
High frequency amplification



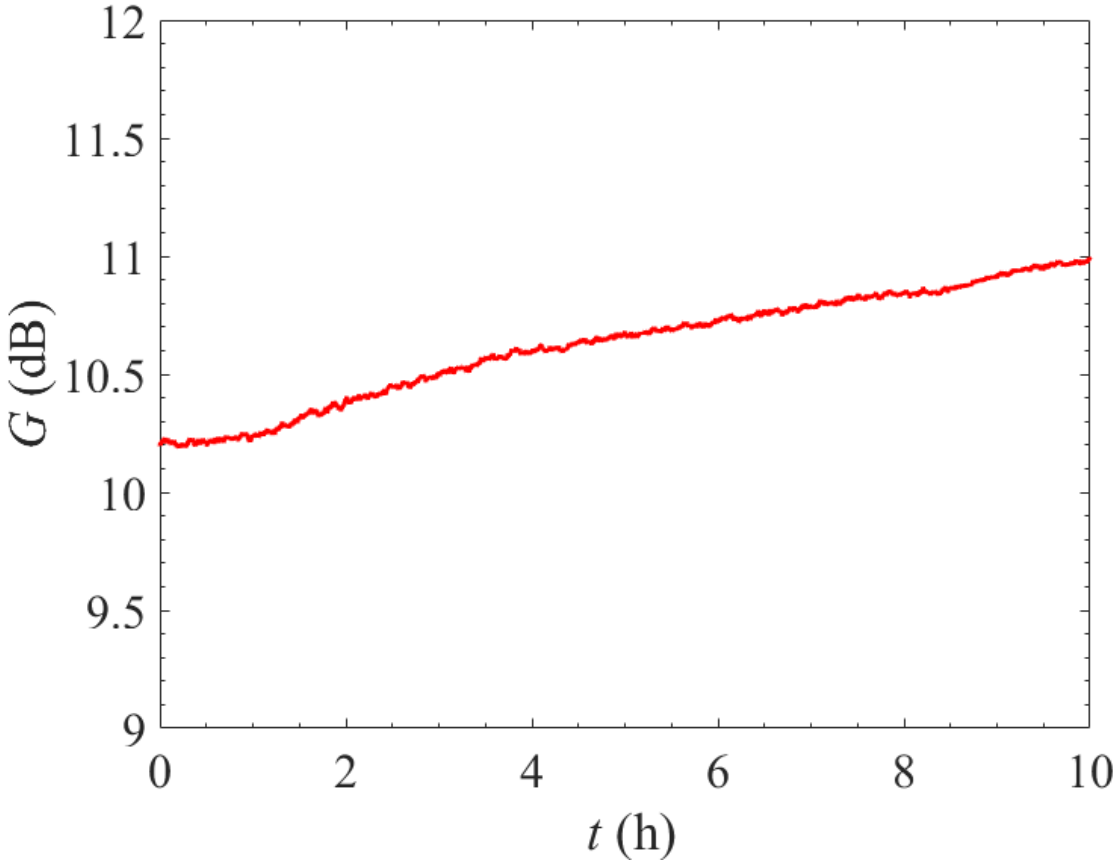
Data taken with the help of Dr. Boon Kok Tan and Dr. Nikita Klimovich

High temperature amplification

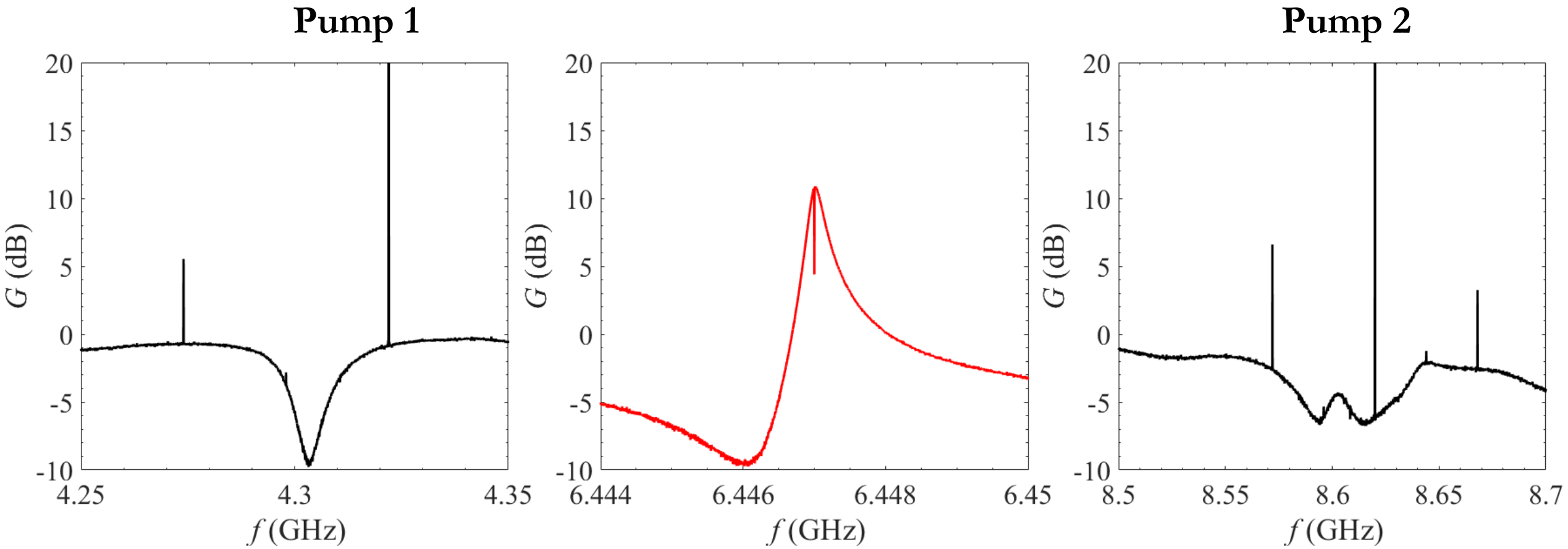
4K amplification



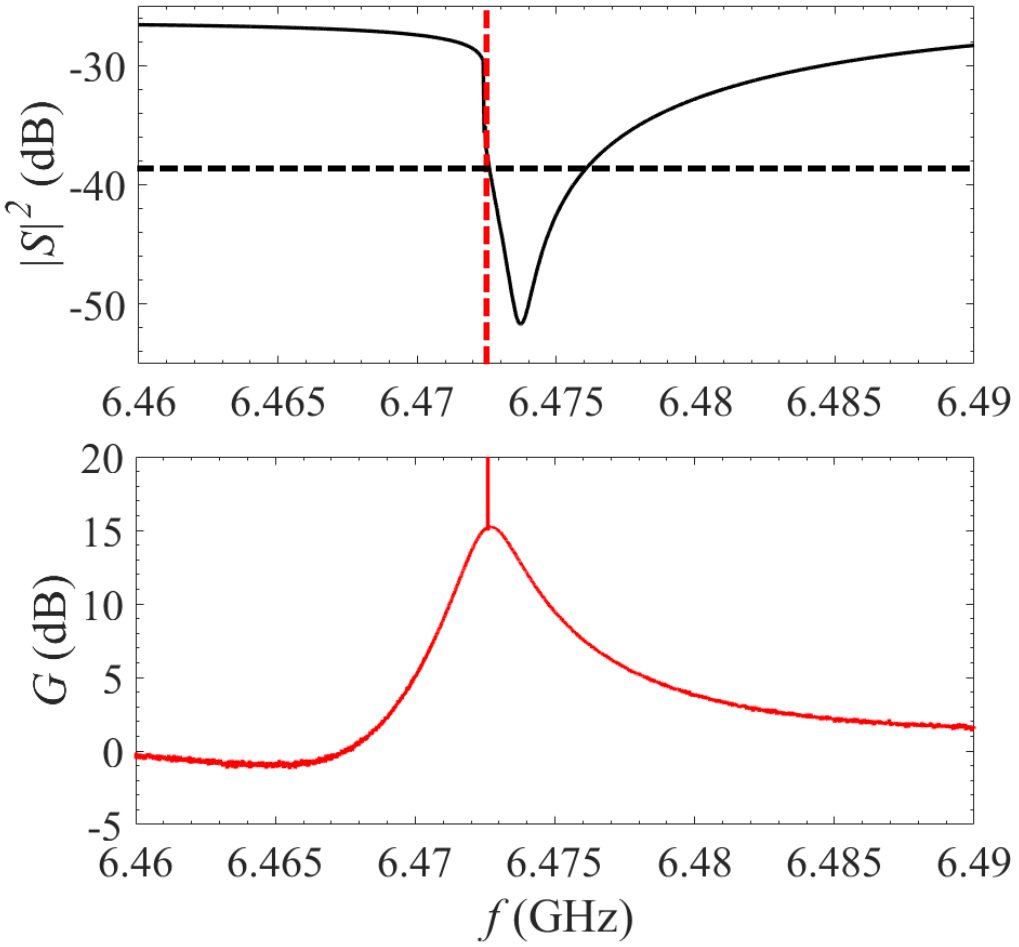
4K gain drift vs time
(no attempt at stabilisation)



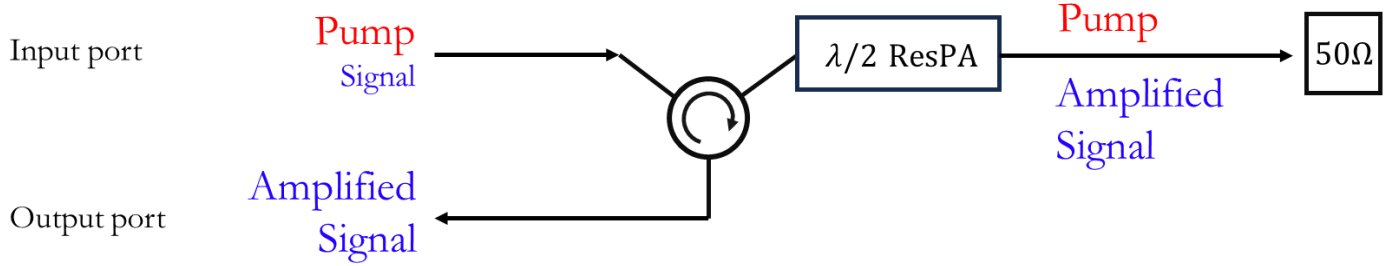
Cross-harmonic amplification



Pump-signal separation

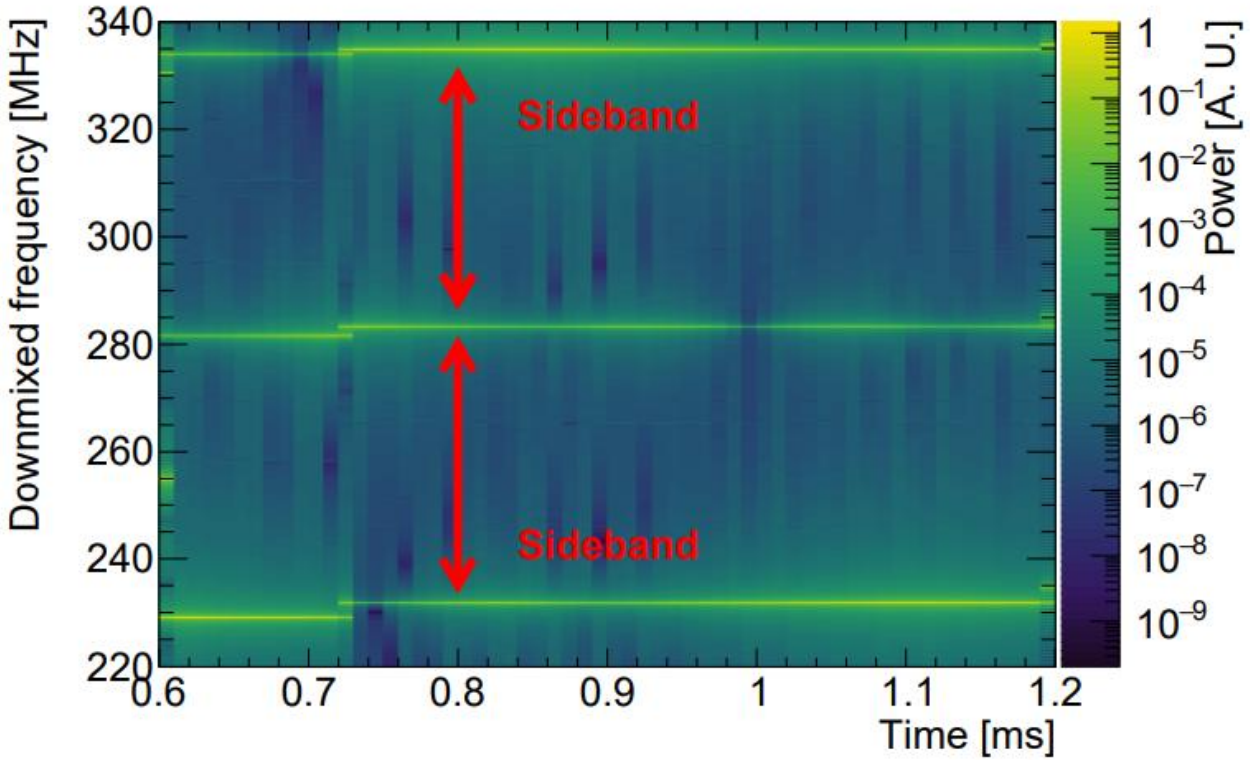


- Prevent saturation of down-stream electronics
- Signal has high gain: ~ 15 dB
- Pump has high attenuation: ~ 12 dB



Future research directions

- Enhance bandwidth, target: 500 MHz
  - CRES sidebands
- Amplifier array
  - Qubit array readout
  - Phased-array antenna system
- Amplifier for 4K operation
  - HEMT-free readout chain
- Generation of microwave squeezed states
  - Interferometric experiments



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Thank you for listening!

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