Kinetic Inductance Traveling Wave Parametric Amplifiers

[KTWPAs or Ki-TWPAS or KITs]

Corwin Shiu

BREAD collaboration meeting 01/14/2026

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University of Colorado Boulder

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA







Mike Vissers
Doug Bennett
Hannes Hubmayr
Paul Szypryt

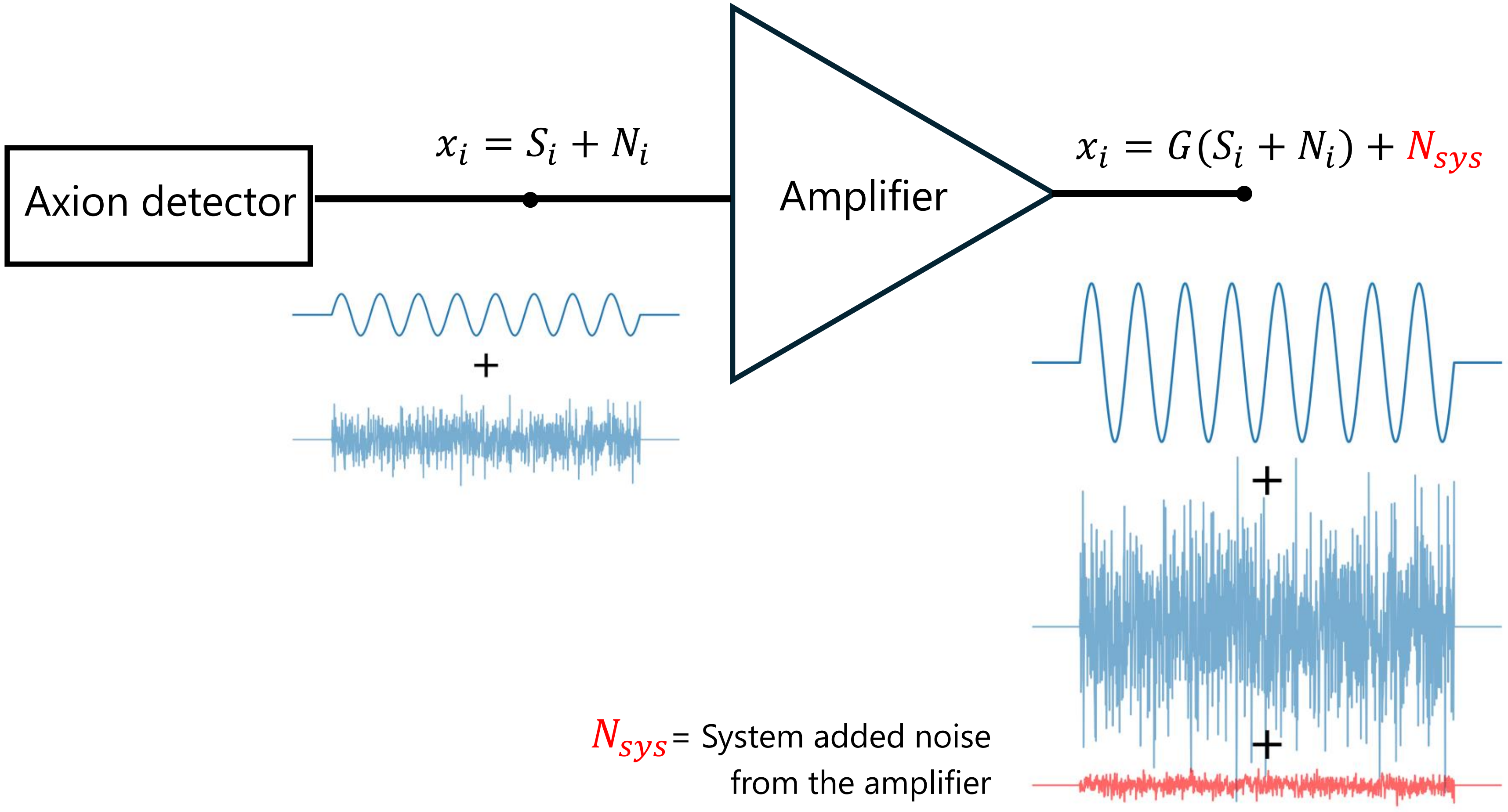
Jordan Wheeler
Jay Austermann
Joel Ullom

Andrea Giachero
Pietro Campana

aws

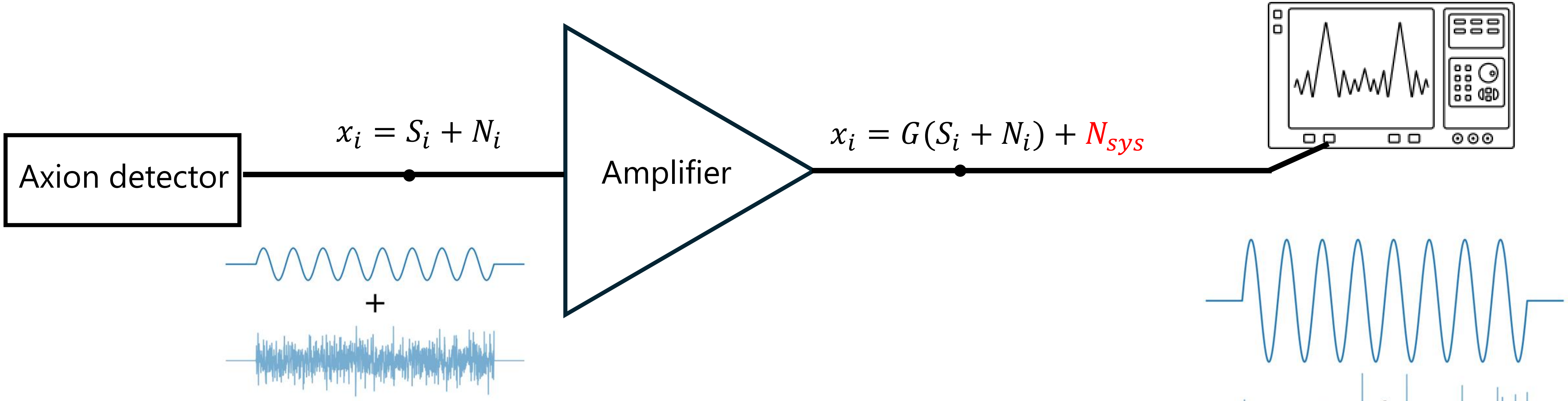

Logan Howe
Jiansong Gao

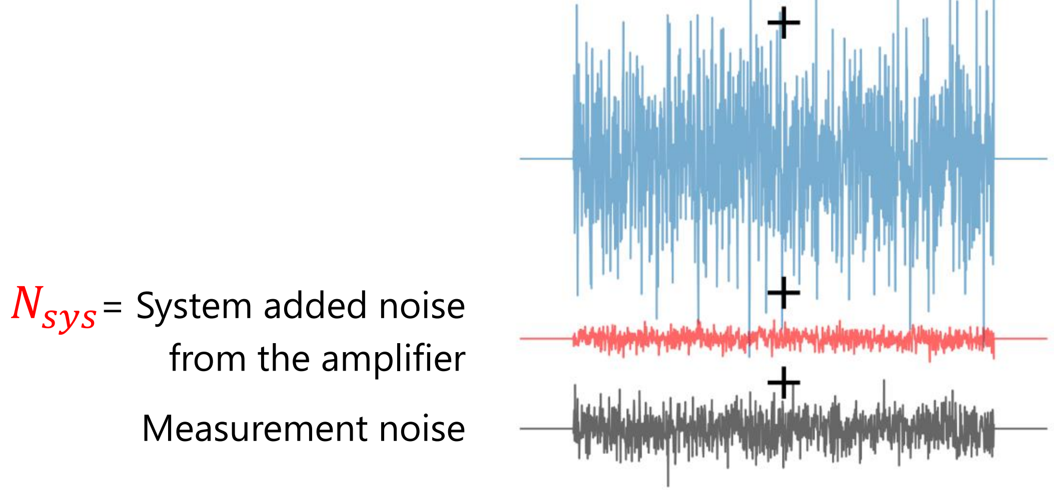
What is an amplifier?



Amplification will always *decrease* the signal-to-noise ratio

What is an amplifier?





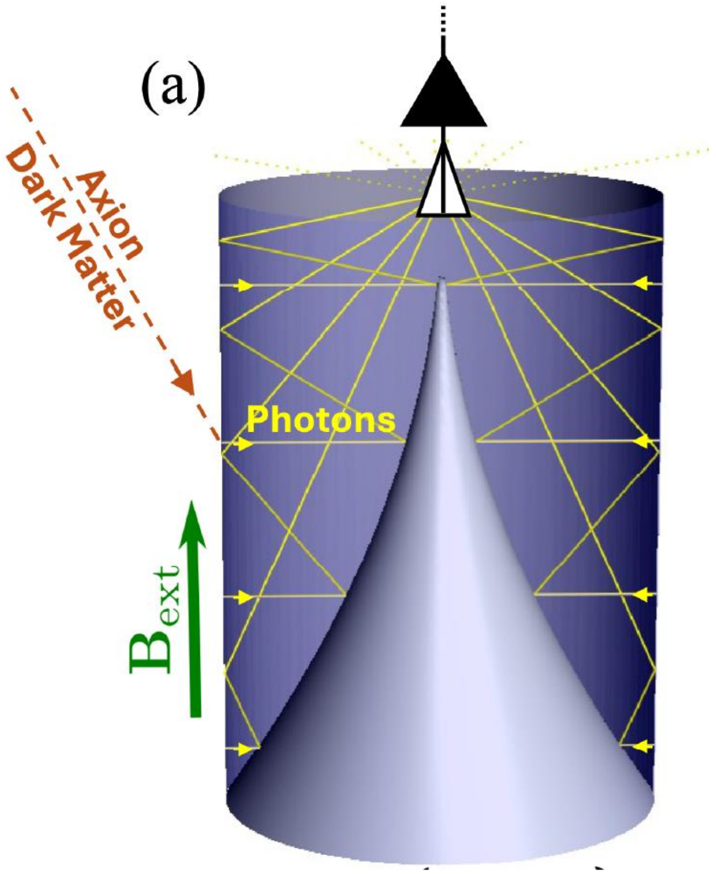
The purpose of an amplifier is to ensure that measurement noise is subdominant to what we're trying to measure

What is the minimum added noise N_{sys}? Turns out it's $\frac{1}{2}\hbar\omega$ for phase-insensitive amplification

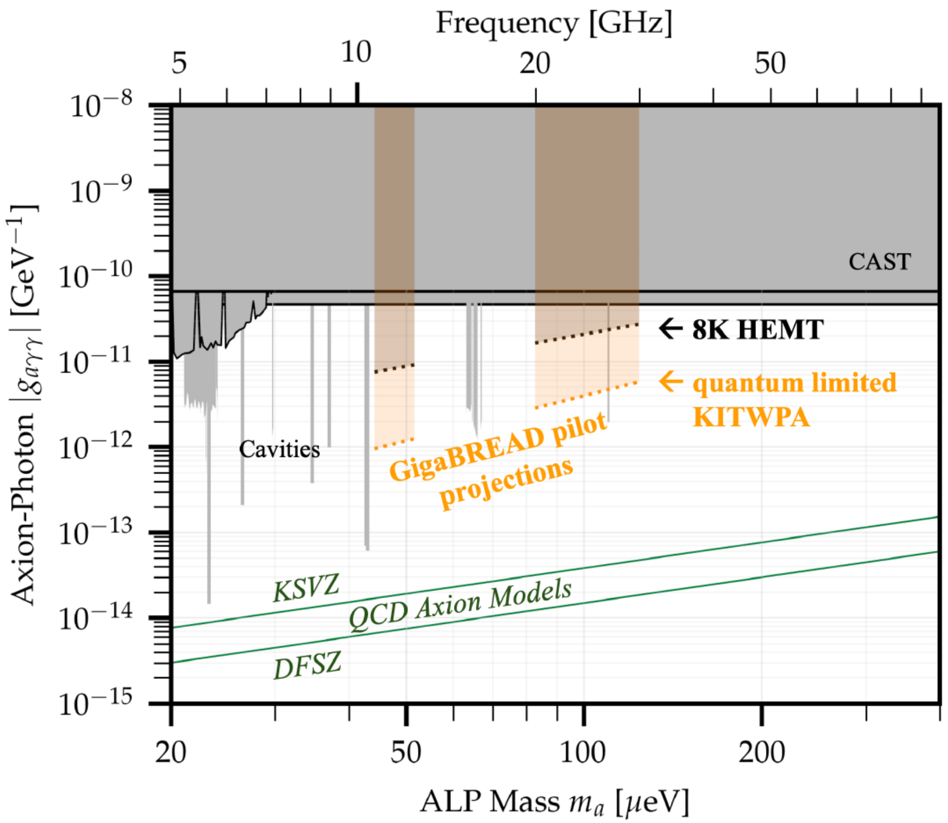
Typical HEMTs ~10 quanta

Using quantum-limited amplifiers for axion searches

Figures from the DOE Quantized proposal



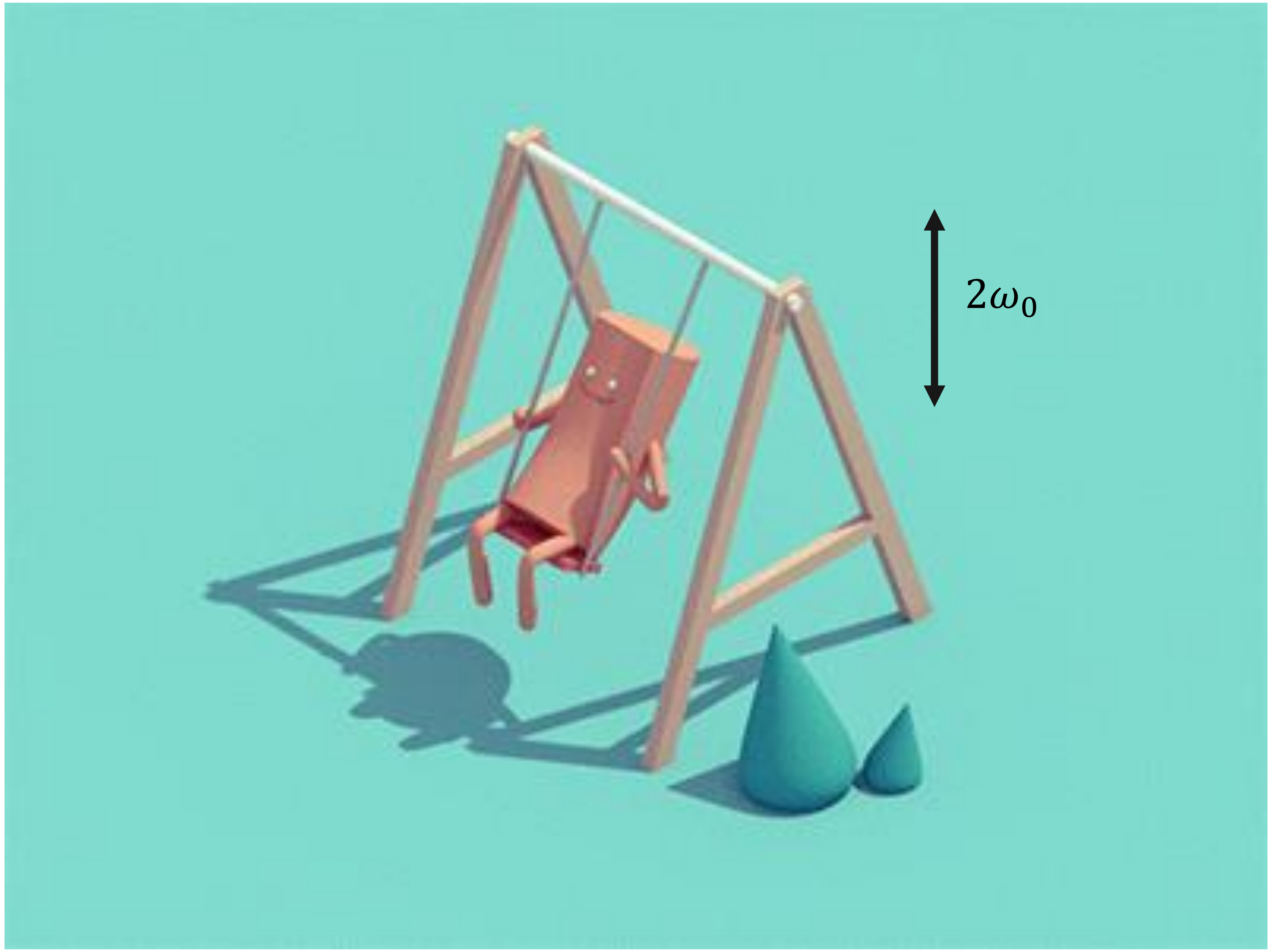
GigaBREAD concept



Motivated to use KTWPAs

- Broadband gain to match the frequency band of GigaBREAD
- Near-quantum limited noise performance
- Insensitive to magnetic fields

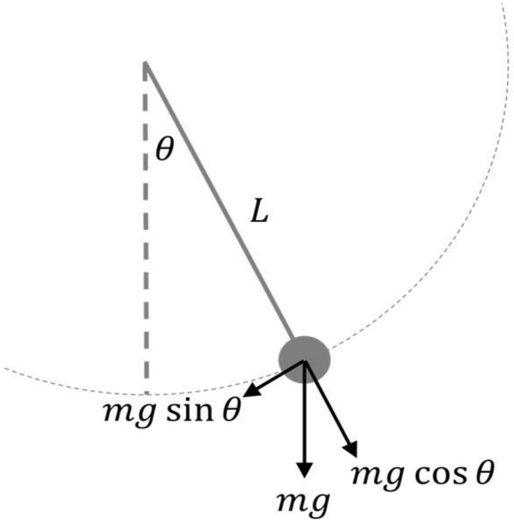
An example of a mechanical parametric oscillator



Two ingredients make this possible:

- Modulation: Center of mass-oscillations occur at twice the frequency of the pendulum

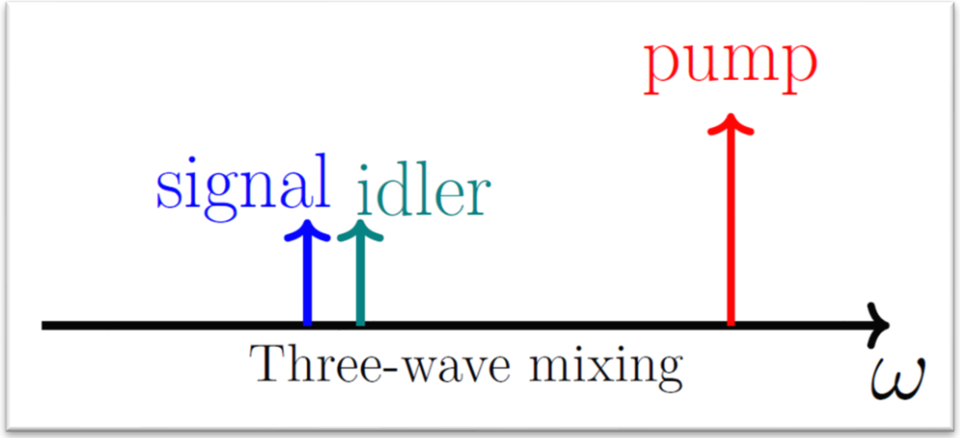
- Nonlinearity: The restoring force of the pendulum is *nonlinear*: $\ddot{x} \sim -\sin\theta$

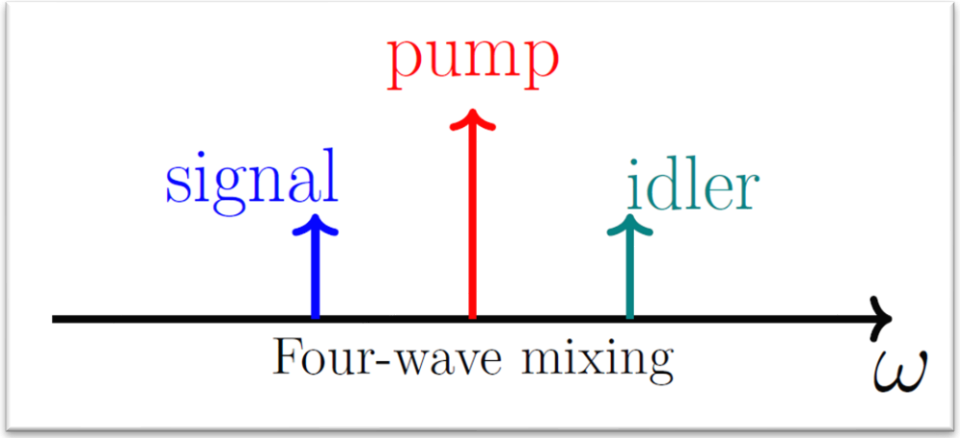


Kinetic Inductance Traveling Wave Parametric Amplifier

- A *non-linear* transmission line allows for energy conversion if we apply a pump tone (creating modulation).
    - Three-wave mixing: $\omega_p = \omega_s + \omega_i$
    - Four-wave mixing: $2\omega_p = \omega_s + \omega_i$

ω_p = pump photon
ω_s = signal photon
ω_i = idler photon





- Non-linear transmission line can be created with kinetic inductance or Josephson Junctions (subject of next talk)

Kinetic Inductance Traveling Wave Parametric Amplifier

- Kinetic inductance (in the thin-film limit):

$$L_s = \frac{\hbar R_s}{\pi \Delta_0} = \frac{\hbar \rho_n}{\pi \Delta_0 t}$$

Normal state bulk resistance

Film thickness

Energy gap

- Typical kinetic inductance values for thin films:
  - Nb ~ [0.1 – 1]pH/sq
  - Al ~ [1 - 3]pH/sq
  - **NbTiN ~ 30pH/sq** at 10nm
- Kinetic inductance is the inertial mass of the Cooper pairs is highly non-linear and parametrized by I^*, which sets the current scale in our device

$$L_k(I) = L_k(0)\left(1 + \frac{I^2}{I_*^2} + \cdots\right)$$

- Kinetic inductance, in principle, is insensitive to magnetic fields so it is well suited for amplifiers in the B-field environment of an Axion experiment

Kinetic Inductance Traveling Wave Parametric Amplifier

- Kinetic inductance (in the thin-film limit):

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Normal state bulk resistance (ρ_n); Film thickness (t); Energy gap (Δ_0)

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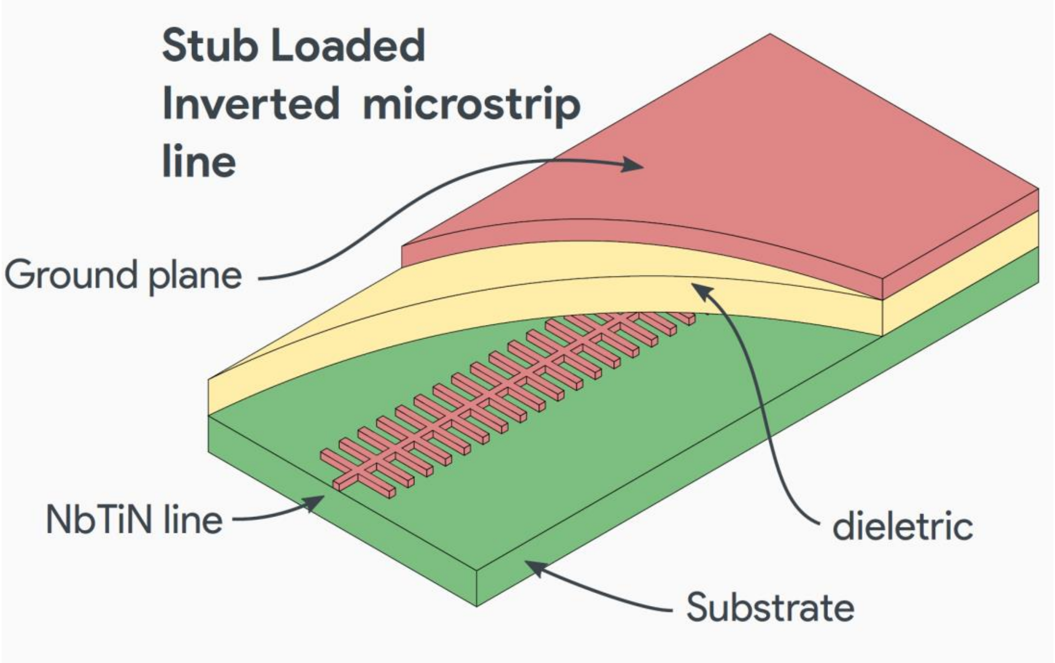
$$L_k(I) = L_k(0)\left(1 + \frac{I^2}{I_*^2} + \cdots\right)$$

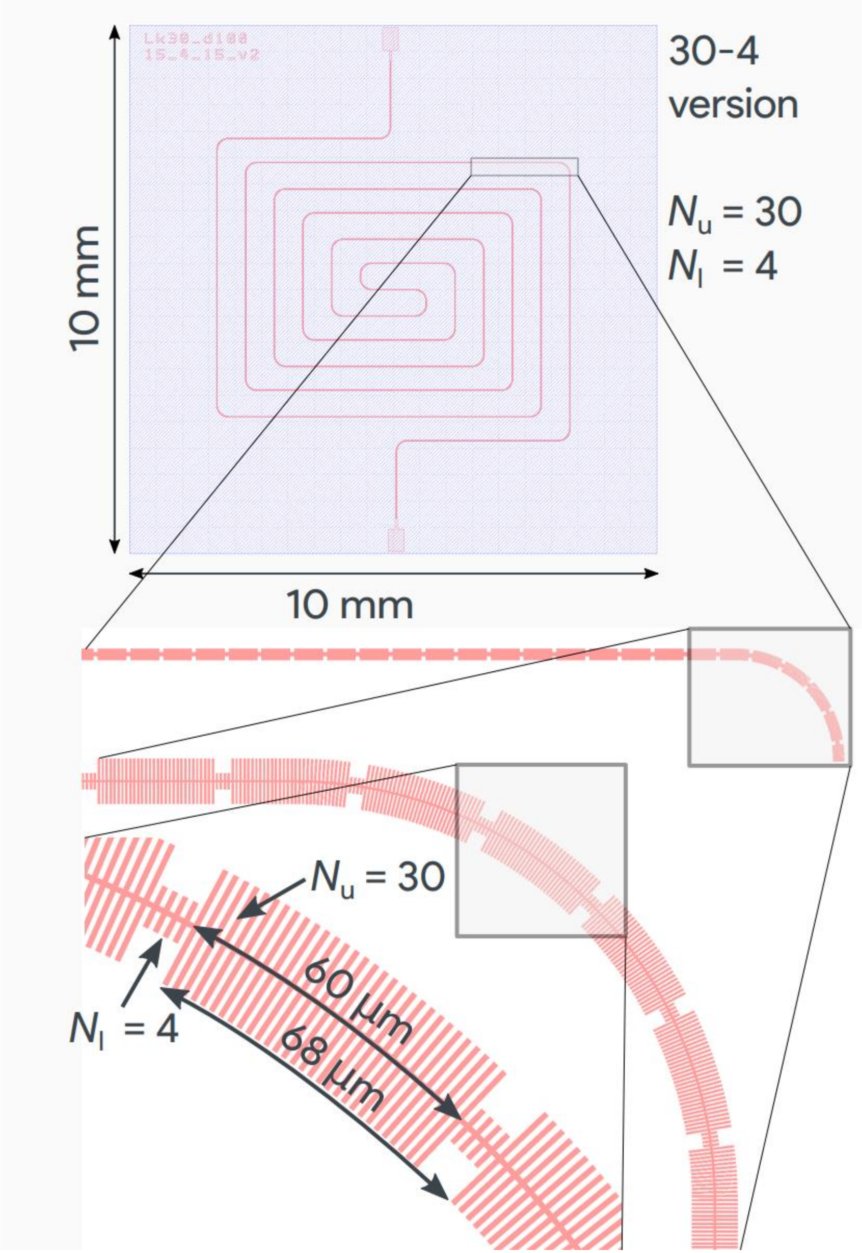
- Kinetic inductance, in principle, is insensitive to magnetic fields and can operate in strong B-field environment such as an Axion experiment

General overview

- 10nm NbTiN $L_k = 30\text{pH/sq}$
- Low-loss 150nm a-Si
- 40,000 unit cells for 8cm physical length
- Minimum feature size = 3um
- $I^* \sim 2 - 3\text{mA}$
- Compression point: -70dBm

Broadband phase-matching via dispersion engineering





The need for dispersion engineering

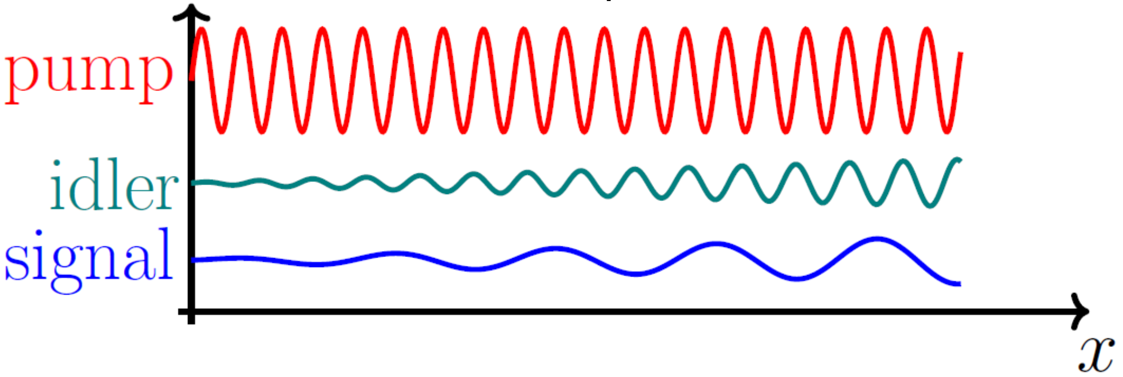
- If you follow the coupled mode equations, the <u>phase matching condition</u>:

The 4-wave mixing amplitude:

$$\Delta_k = k_p - k_s - k_i = -\frac{\xi I_{p0}^2}{8}\left(k_p - 2k_s - 2k_i\right)$$

$$\xi = \left(\frac{1}{I_*^2 + I_{dc}^2}\right)$$

Position down the TWPA when phased matched



Phase matching makes sure that the pump keeps pushing on the signal as it propagates down the line, instead of sometimes pushing, sometimes pulling

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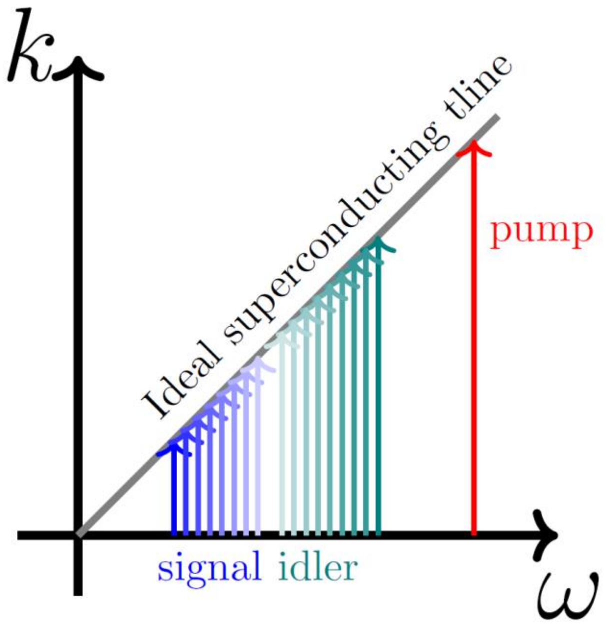
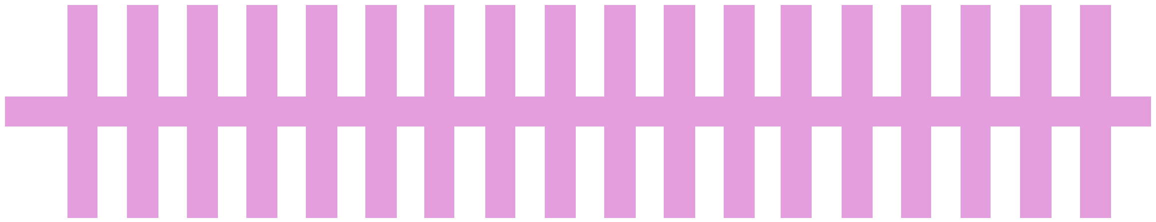
$$\xi = \left(\frac{1}{I_*^2 + I_{dc}^2}\right)$$

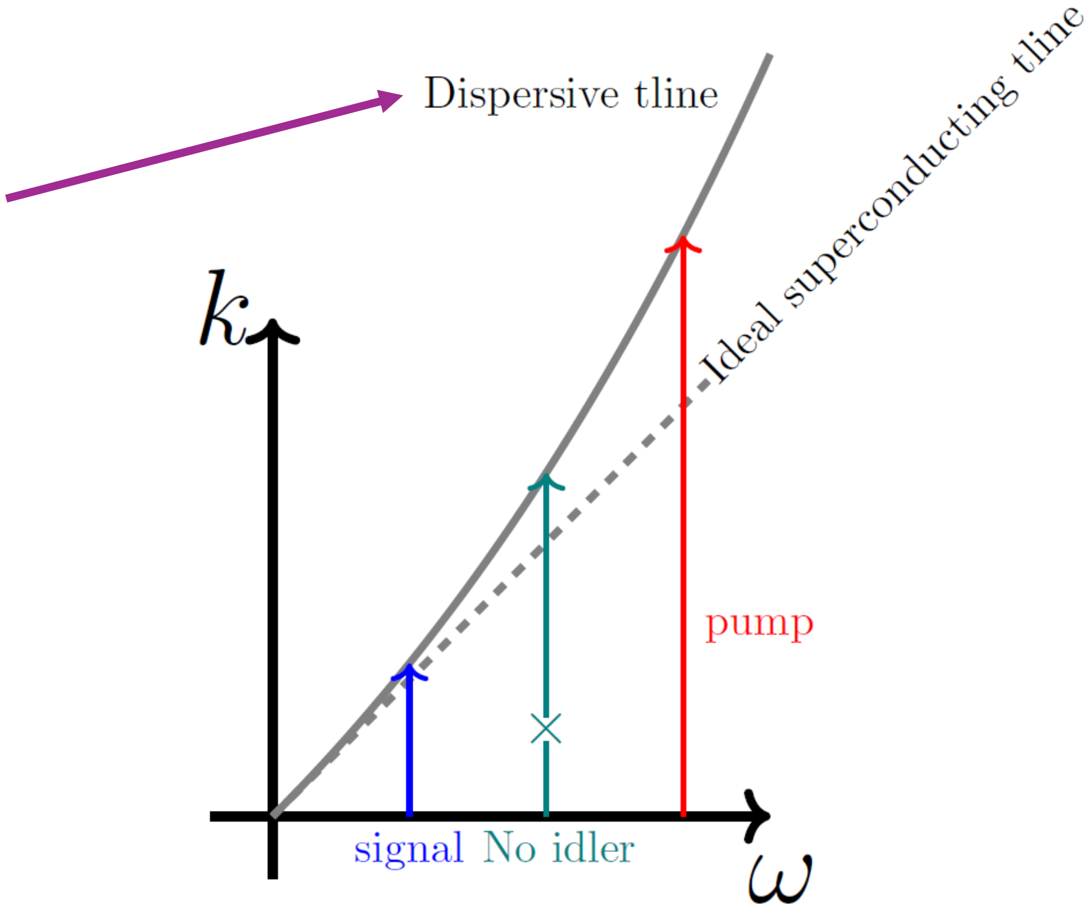
- In the limit that the four-wave mixing is small ($I_{p0} \ll I_*, I_{dc}$), then $\Delta_k = 0$.
- A regular superconducting transmission line will naturally fulfill this condition, achieving 3WM:

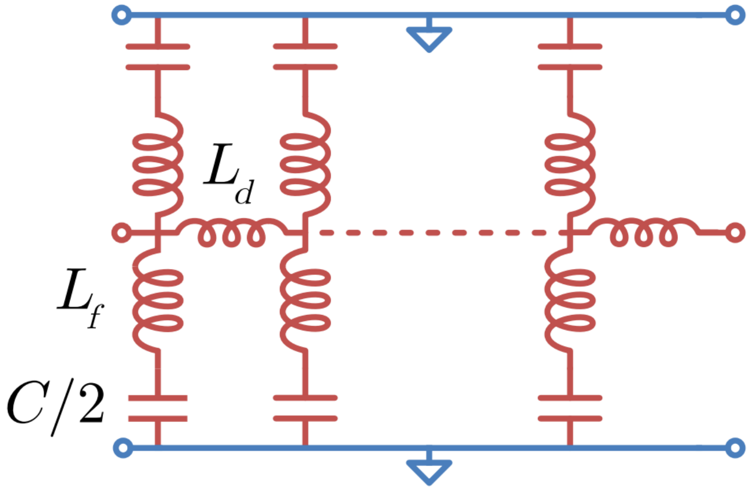


However, this is undesirable because this line would support all sorts of parametric conversion processes at once, increasing noise and reducing our gain.

Our approach to dispersion engineering

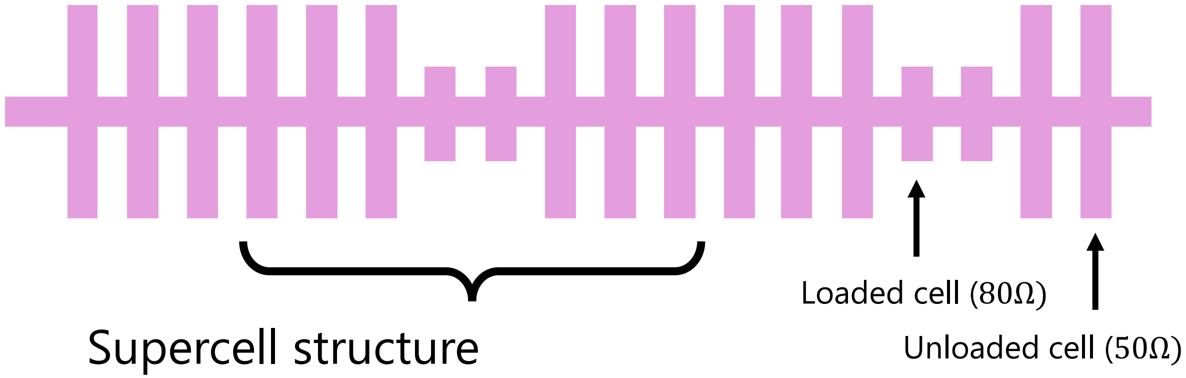






Can’t satisfy both energy conservation ($\omega_p = \omega_s + \omega_i$) and the phase-matching condition

Our approach to dispersion engineering

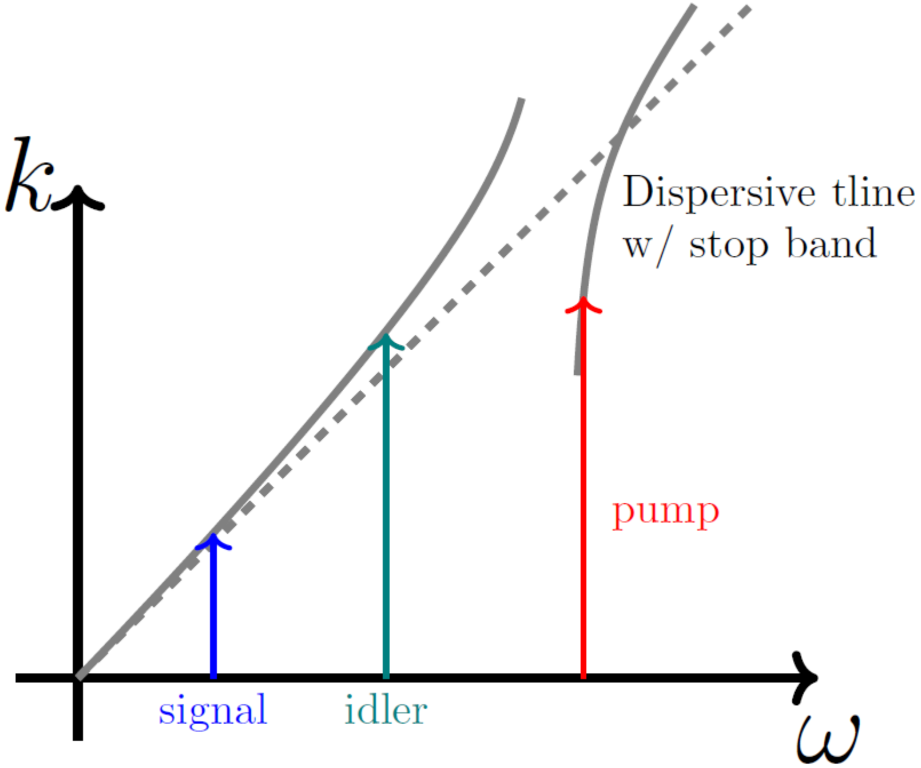


Supercell structure
= (#unloaded/2, #loaded, #unloaded/2)
(i.e. 3-2-3)

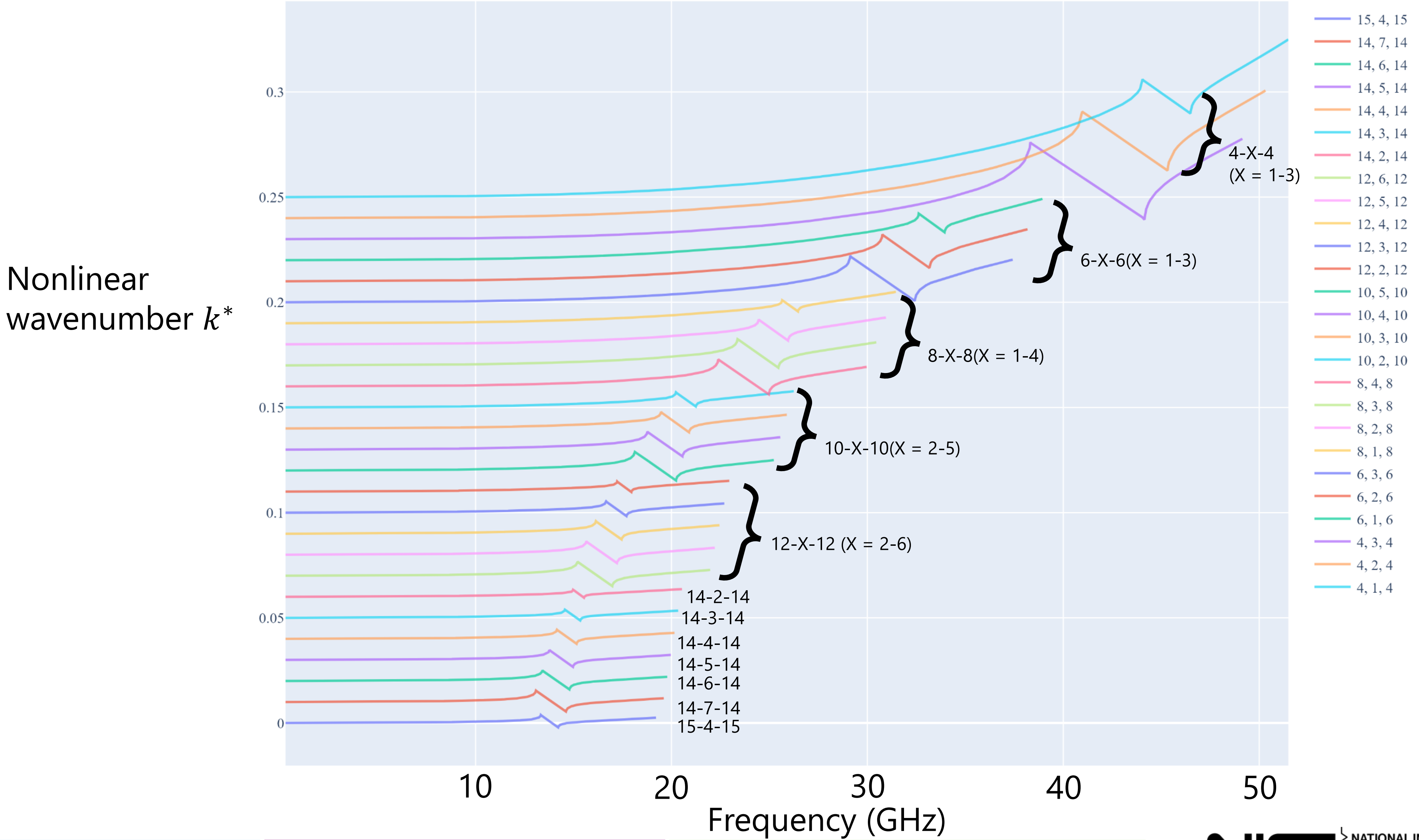
We engineer a stop band by modulating the impedance:

- Creates a resonance in the phase response
- Creates a "photonic" stopband in the amplitude response

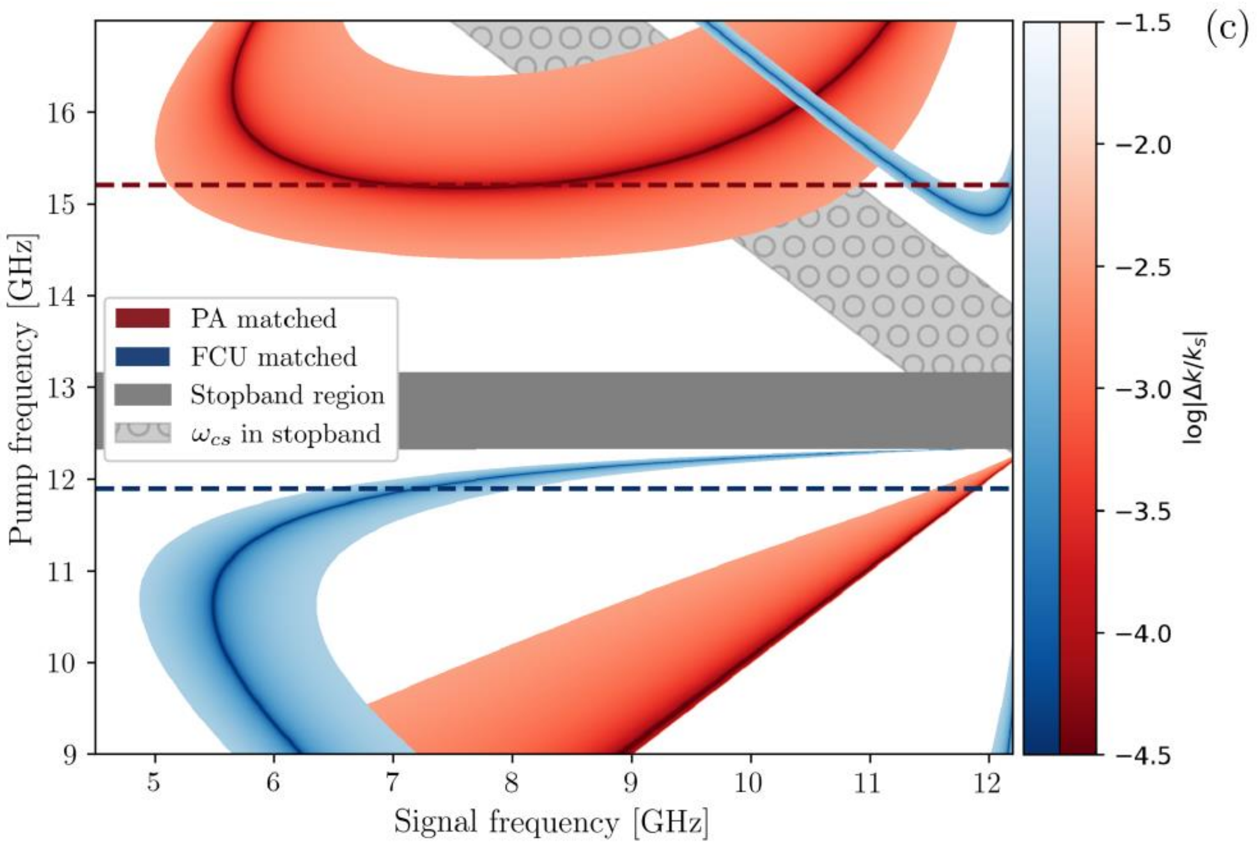
Allows us to find triplets $(k_p, k_s, k_i), (\omega_p, \omega_s, \omega_i)$ that satisfy
[1] 3WM energy conservation
[2] Phase-match condition



The supercell electrical length sets the stopband



When everything works well

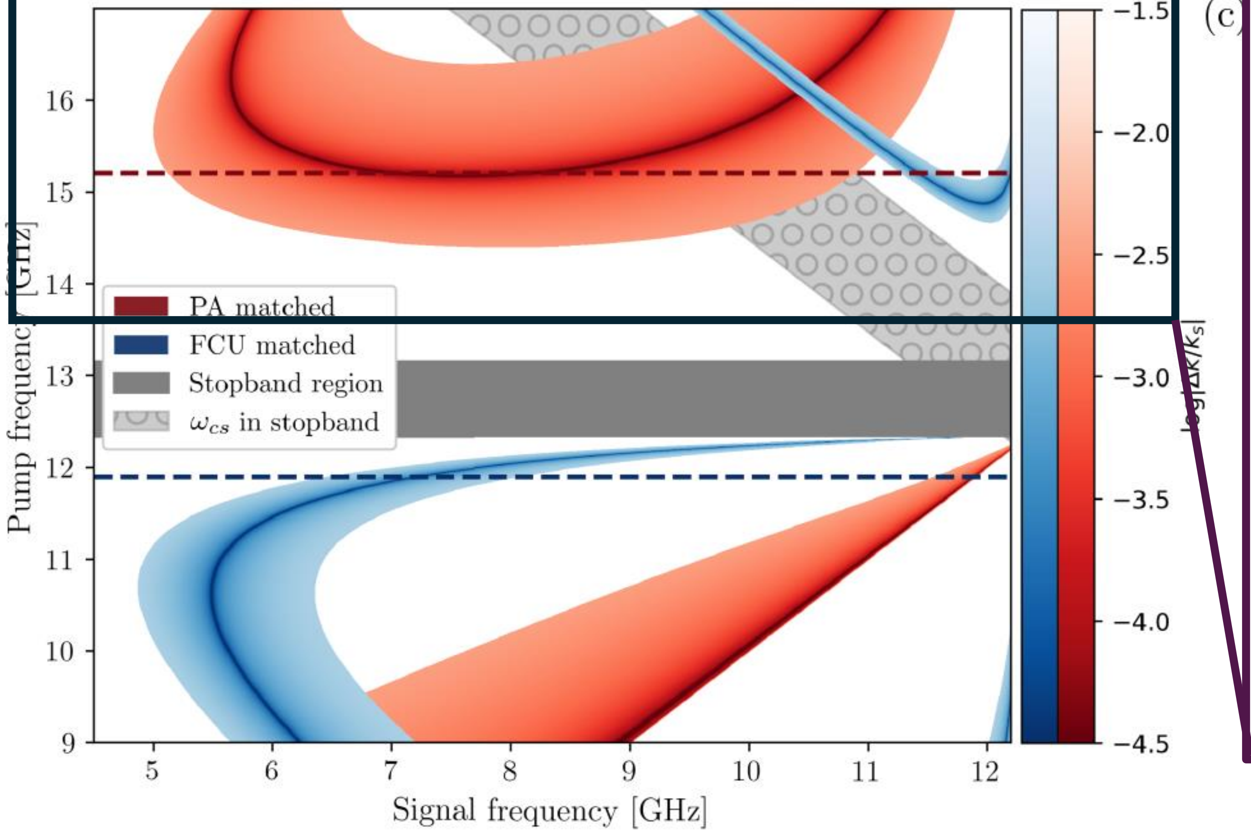


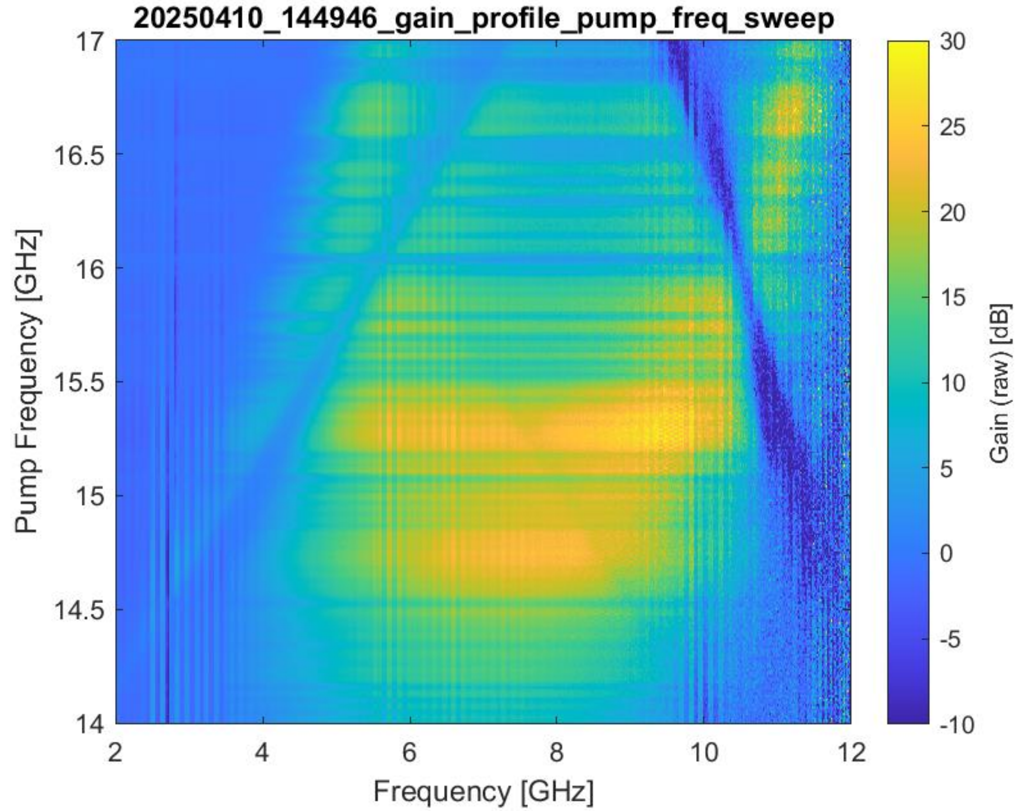
Colorscale is the error in phase matching (logged)

- PA = parametric amplification
- FCU = frequency up-conversion

Pietro Campana, publication under review:
Strongly Directional Amplification with a Kinetic Inductance Traveling Wave Parametric Amplifier

When everything works well





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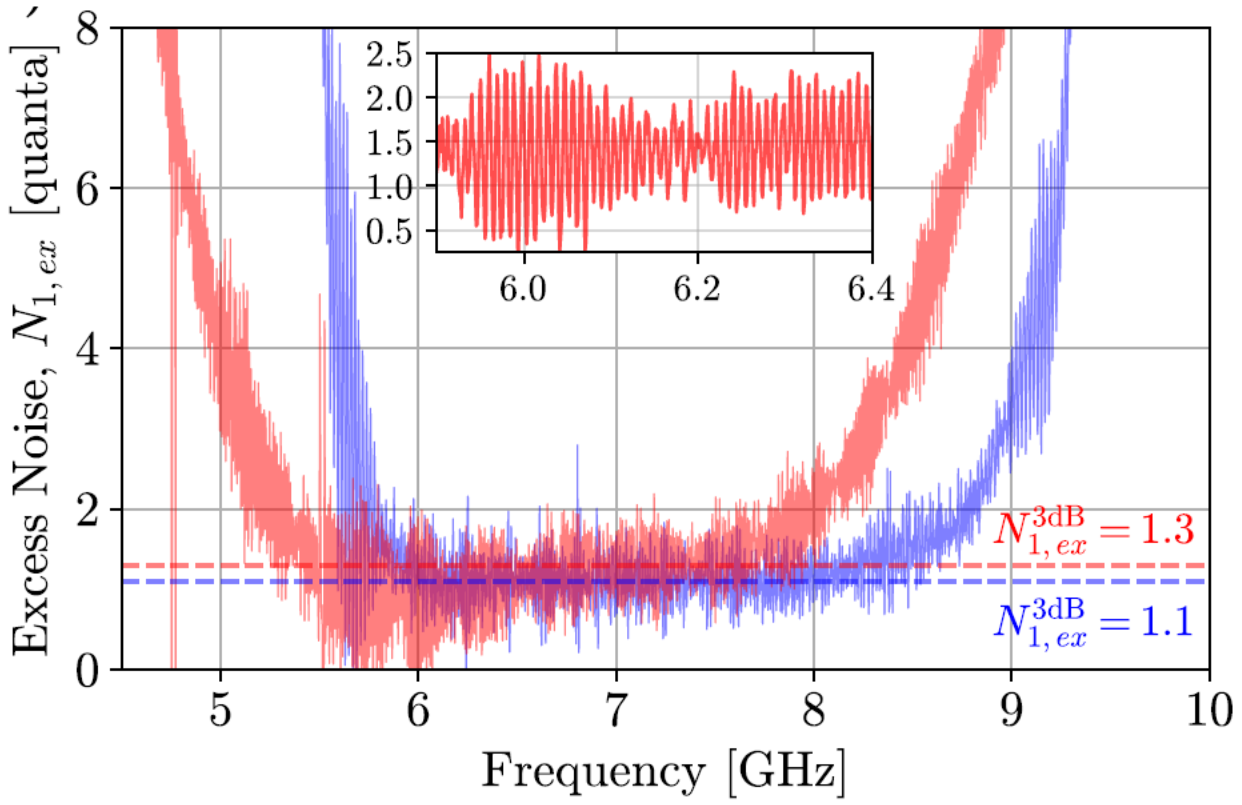
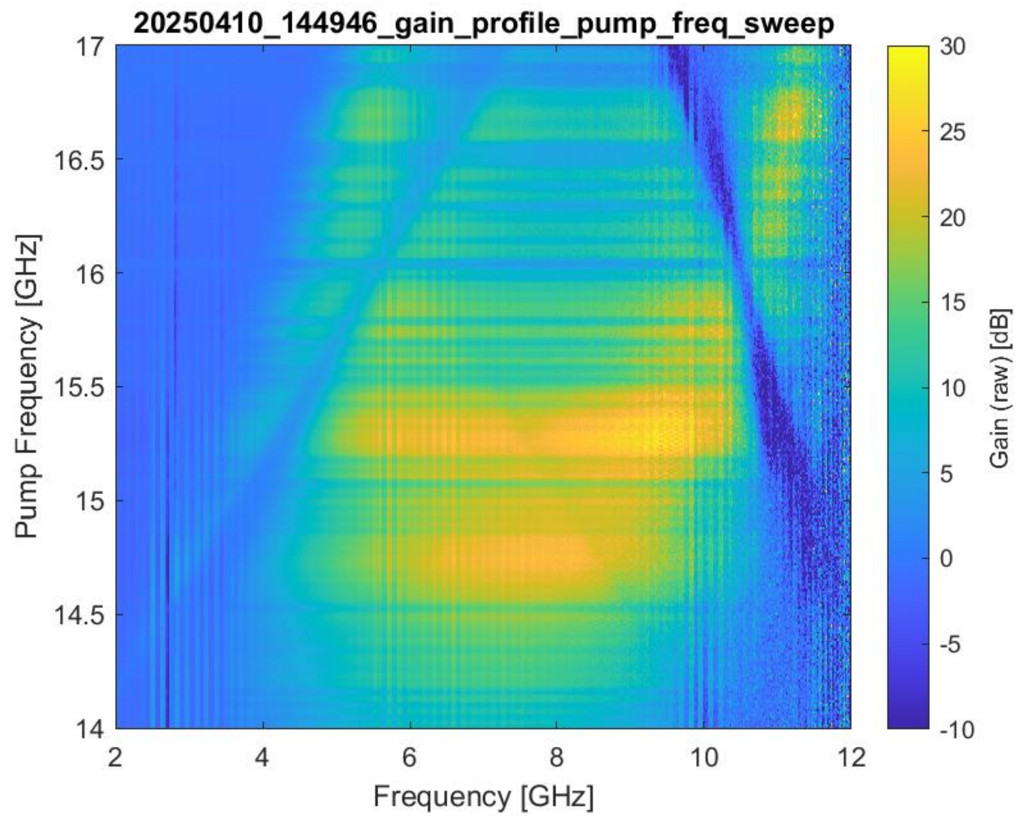
Strong phase matching,

- Characteristic U shape
- Frequency conversion visible by eye

When everything works well





~1 quanta in excess of the quantum limit $\left(\frac{1}{2}\hbar\omega\right)$

Howe, et. al. Near-quantum-limited Kinetic Inductance Traveling Wave Parametric Amplifiers: Methodology and Characterization

Direction of the research moving with an eye for higher frequencies

- Improvements in simulations
  - Extended coupled mode equations [Pietro: twpasolver]
- Improvements in dispersion engineering
  - Aluminum tips on capacitive fingers [Andrea]
  - Next-gen modulation techniques [Pietro,Andrea]
- Ultra-high kinetic inductance designs of 100pH/sq
  - Reduces the necessary pump powers [Andrea, see upcoming APS march meeting]

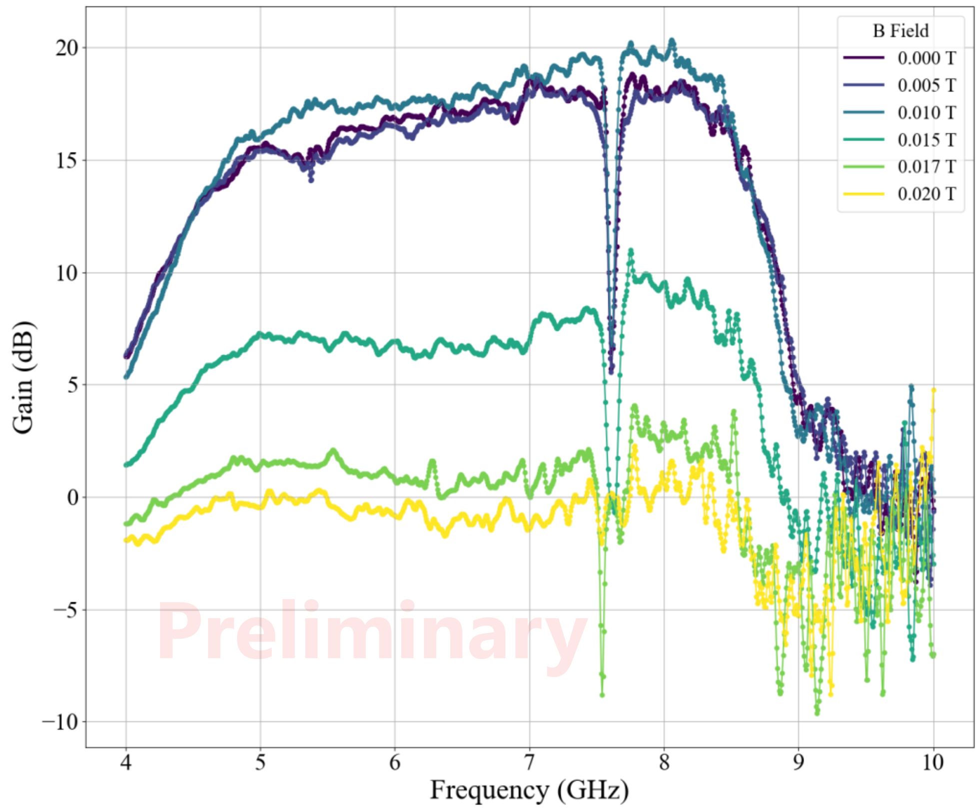
- Microwave packaging [Logan]
- On-chip integration of microwave components
  - Integrated bias-tees, directional couplers, diplexers [Logan, Corwin]

- Improvements in noise metrology [Corwin, see upcoming APS march meeting]
- Squeezed states in a KTWPA [Logan, paper under review]

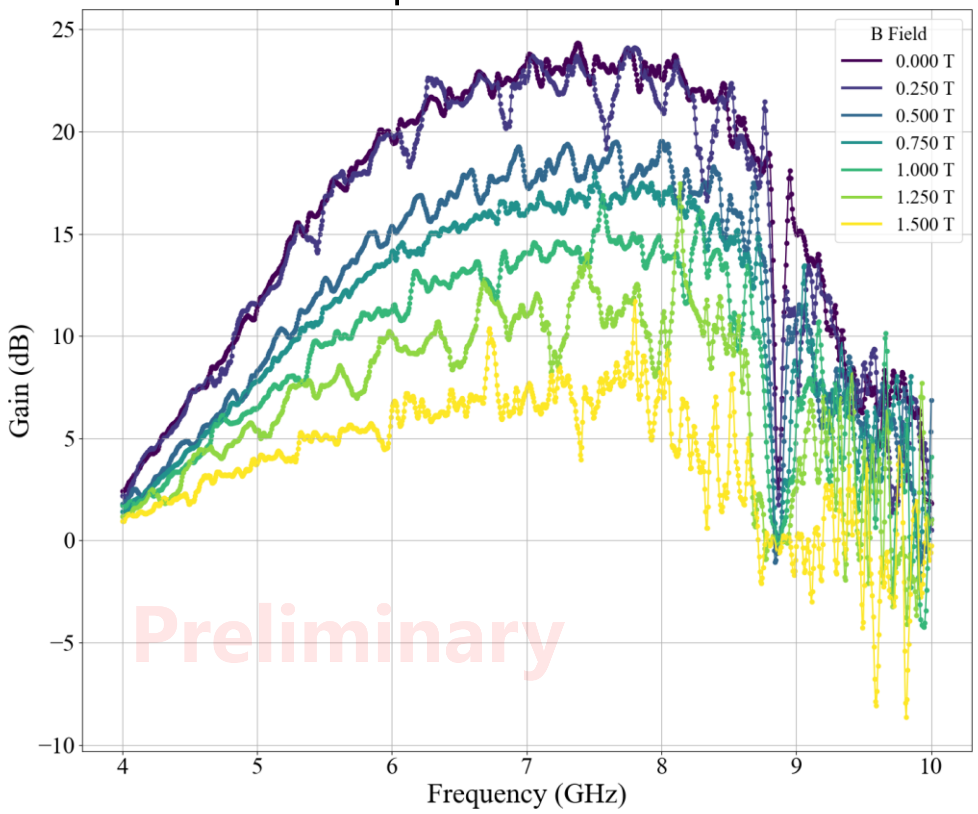
- Magnetic field capability [Christian]
- Double KTWPA to replace the HEMT for potential space applications [Logan, Corwin]

Magnetic field compatibility [Christian Boutan at PNNL]

B-field perpendicular to device



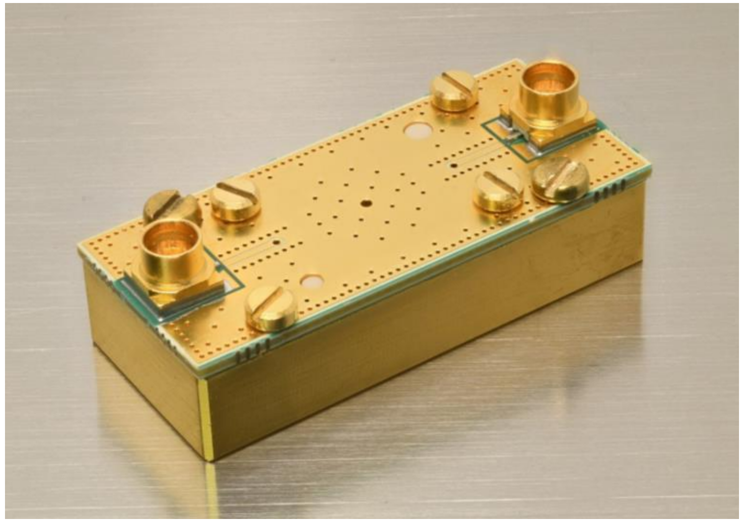
B-field parallel to device

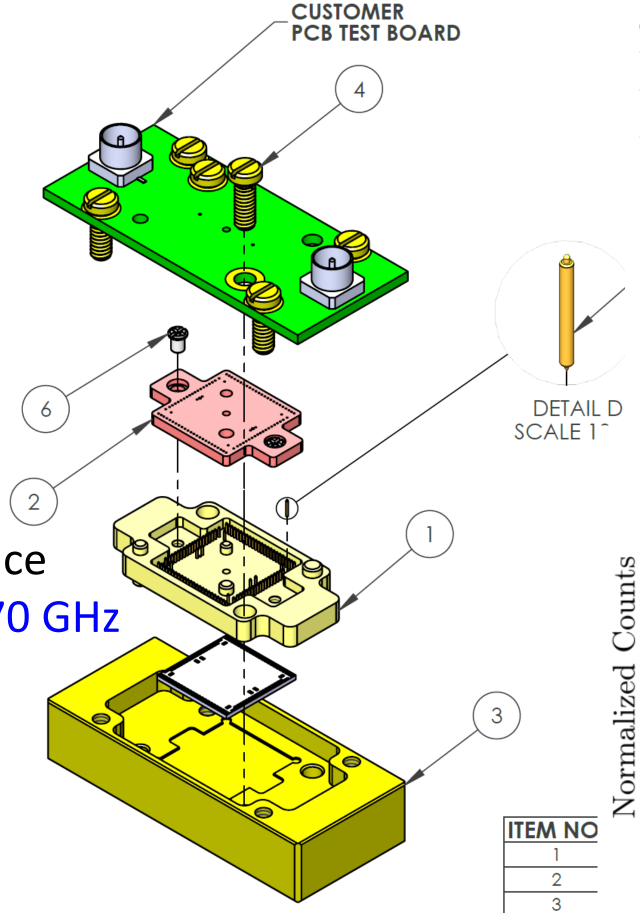


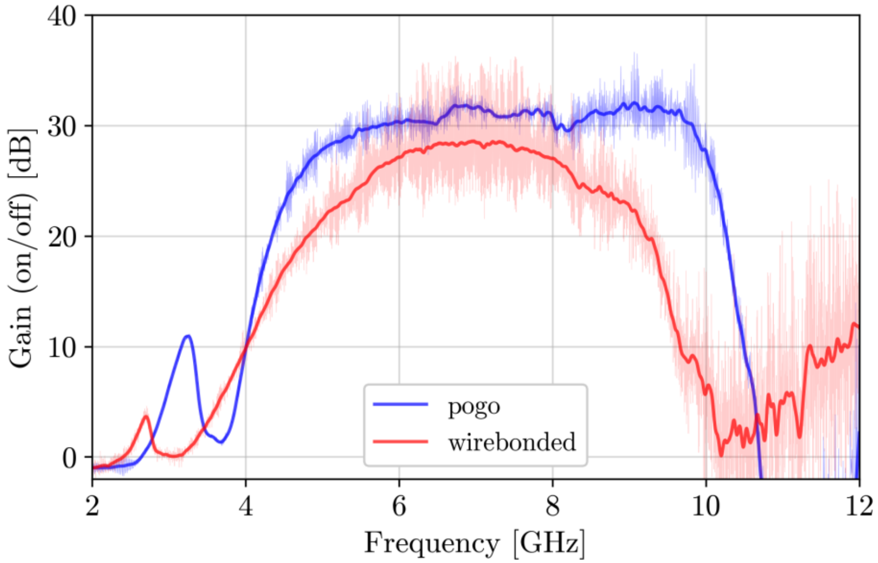
Devices were exposed to several 2.5T magnet ramps and did not require thermal quenching to expel trapped flux

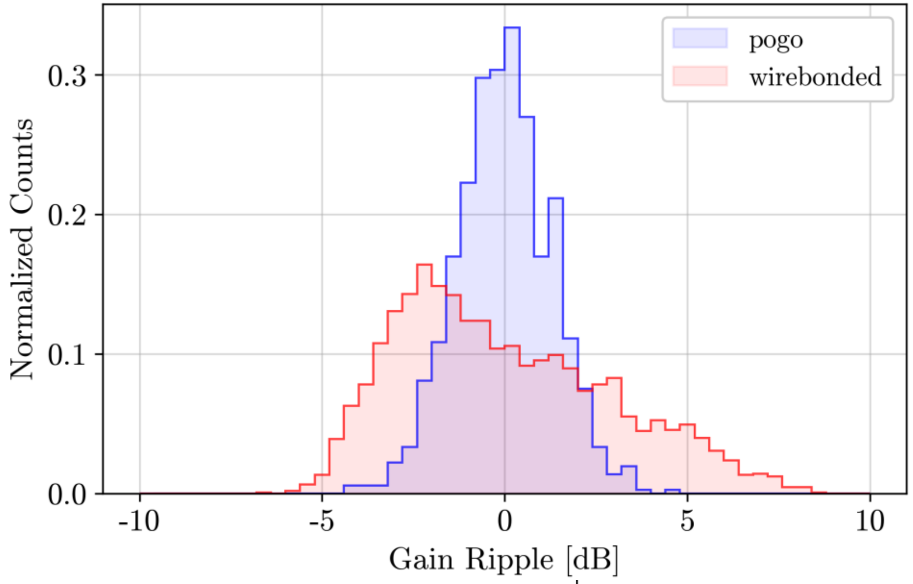
KTWPA gain is maintained even with significant magnetic fields!

Improvements in packaging with Pogo pins









Pogo pin benefits:

- Drastic reduction of packaging inductance
- Fully optimized launch: S_{11} < -10 dB at 70 GHz
- Simple, repeatable assembly: <5 min

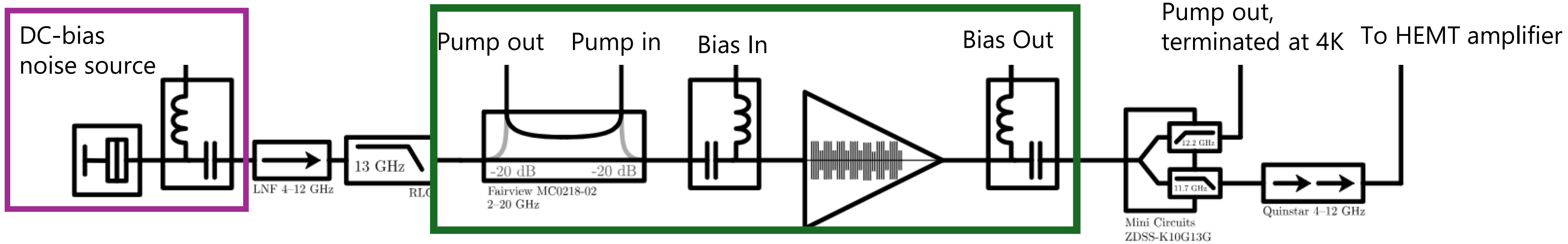
Results:

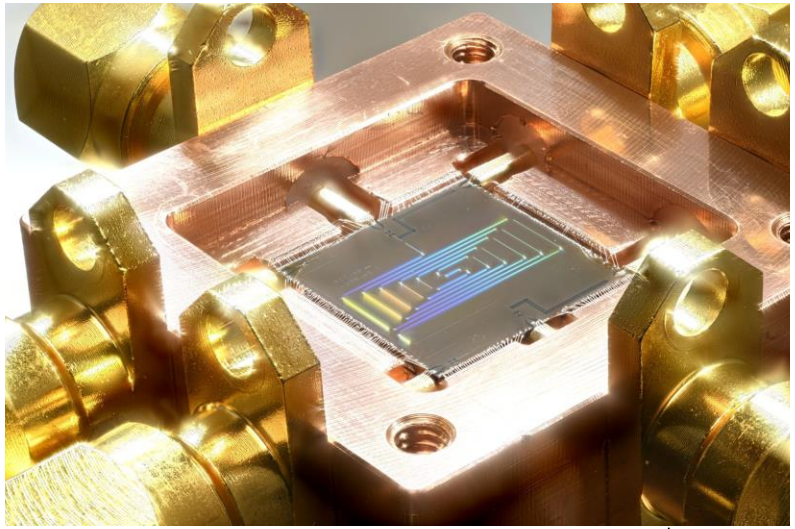
- Greater max gain, lower ripple
- Beyond-octave (4.96 GHz) bandwidth
- Operation at higher frequencies possible (future)

The **O**n-chip **R**F **C**omponents **K**it (**ORCK)**

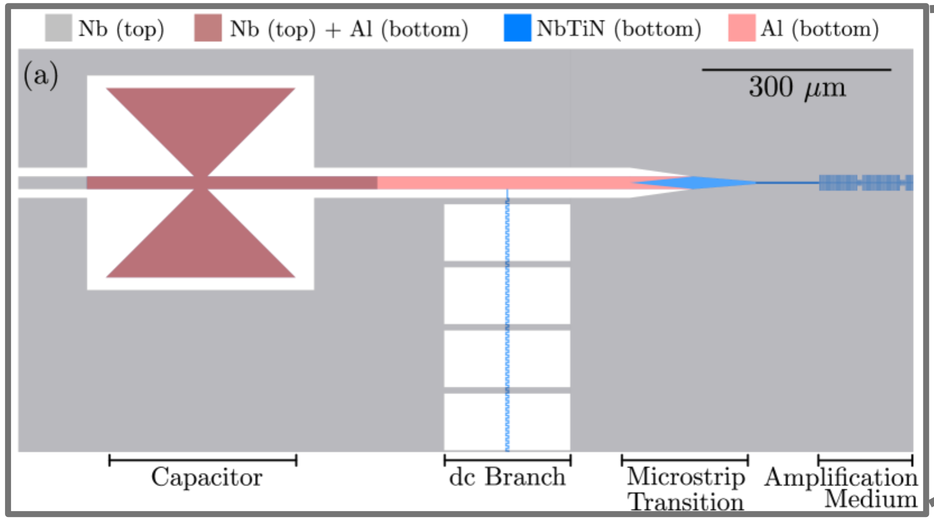
- Why put things on-chip?
  - Compactify!
  - Reduce losses between signal and amplifier
  - Decrease system added noise

In V3, we have integrated all these components on chip

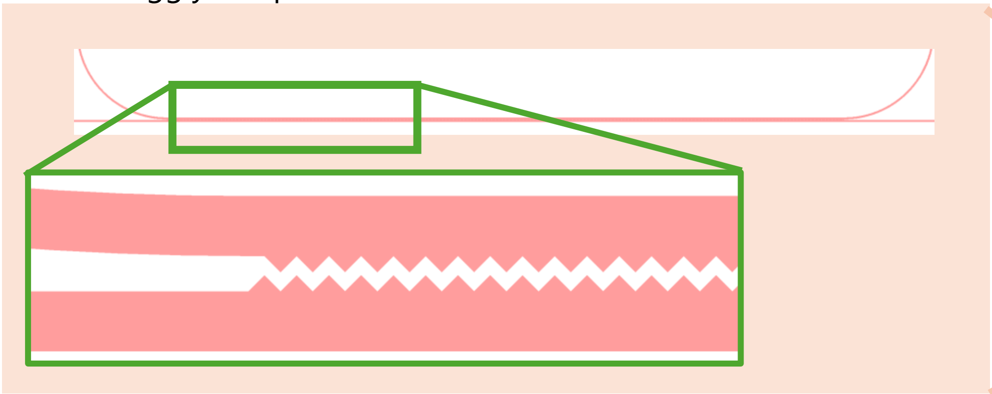


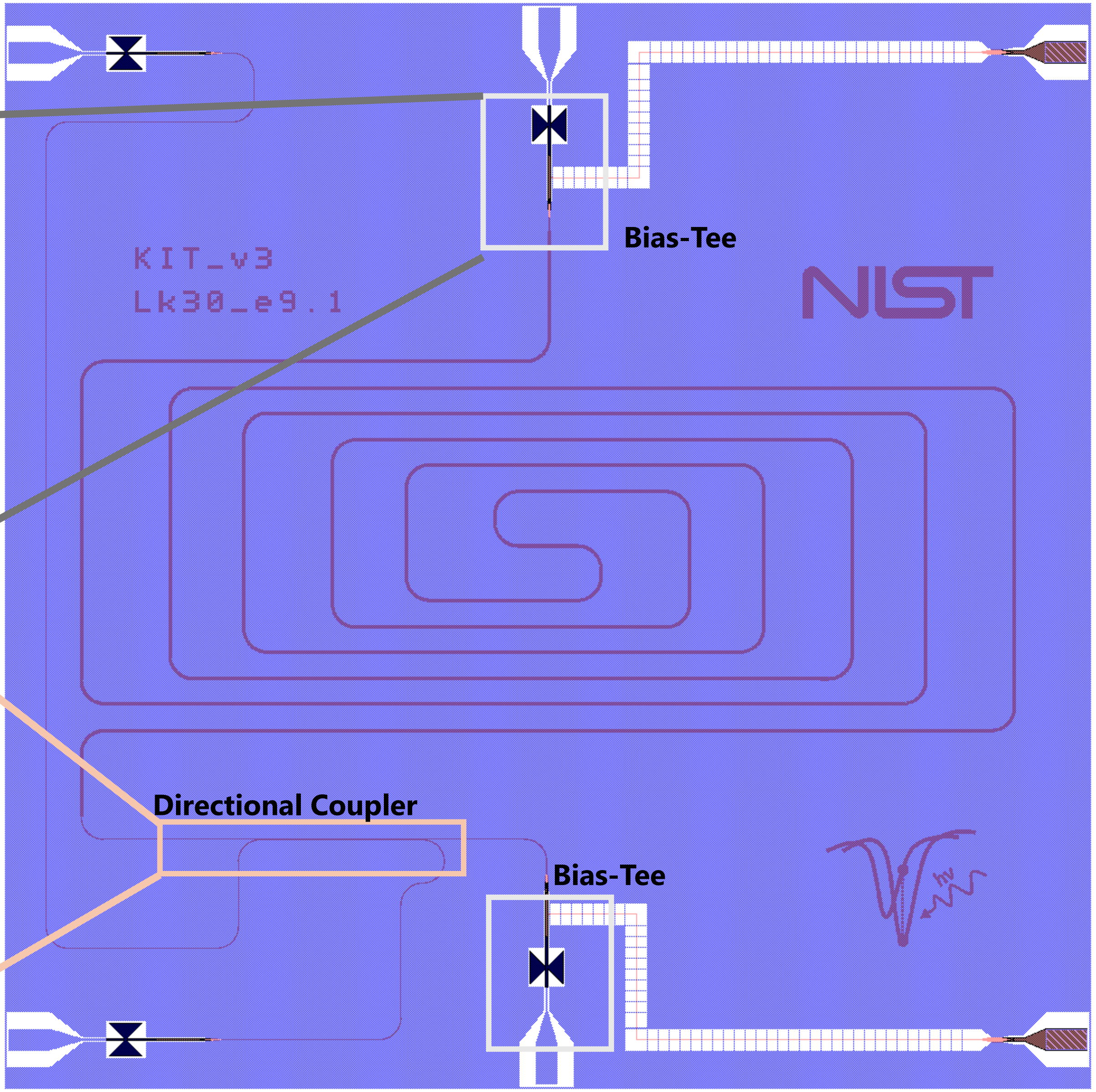


V3 ORCK device



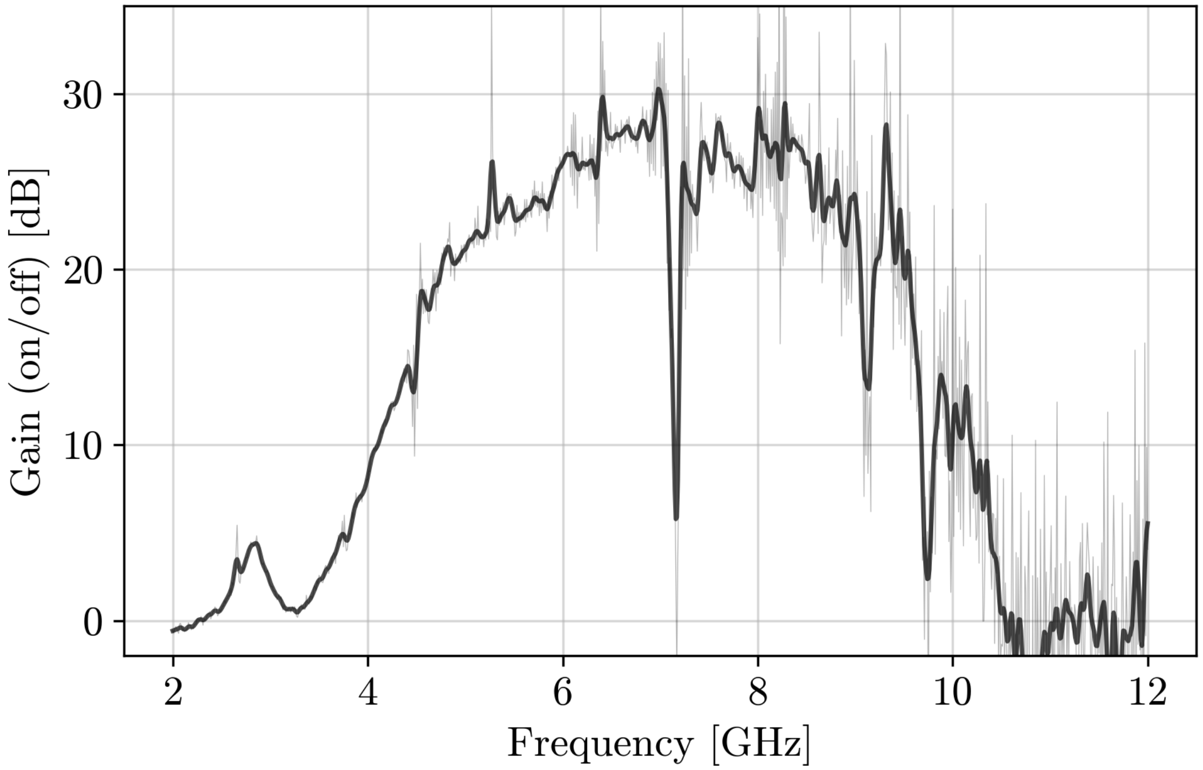
Podell Wiggly Coupler

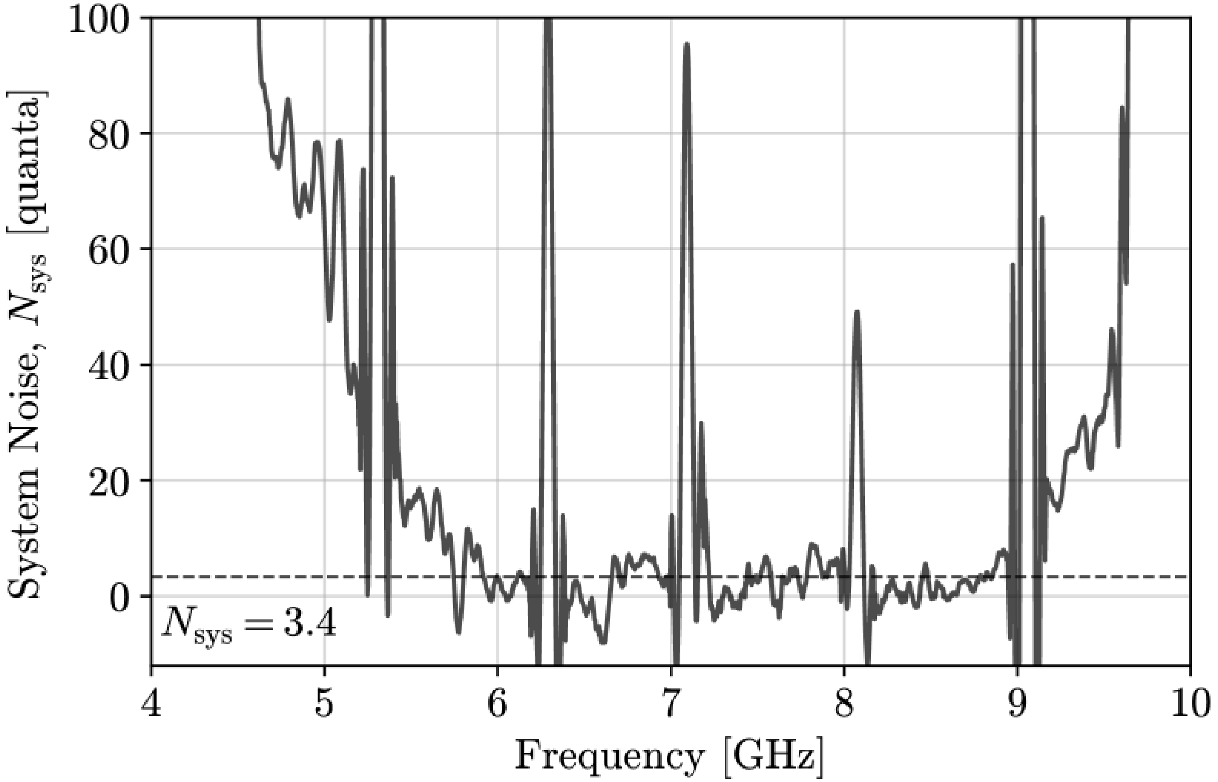




[Howe: Compact Superconducting Kinetic Inductance Traveling Wave Parametric Amplifiers with On-chip rf Components]

V3 ORCK device



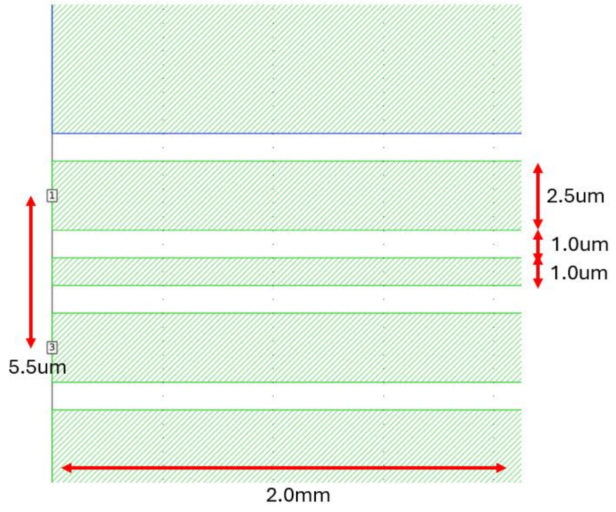


- Nearly 30dB of gain from on-chip TWPA
- Noise degraded by bias-tee inductor self resonance (~930MHz)

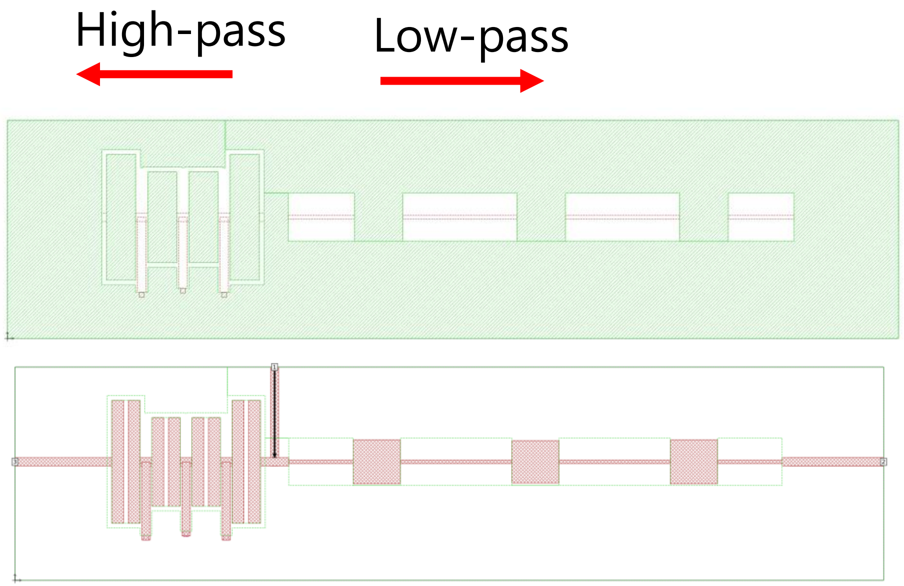
Howe: Compact Superconducting Kinetic Inductance Traveling Wave Parametric Amplifiers with On-chip rf Components

Next generation on-chip RF components

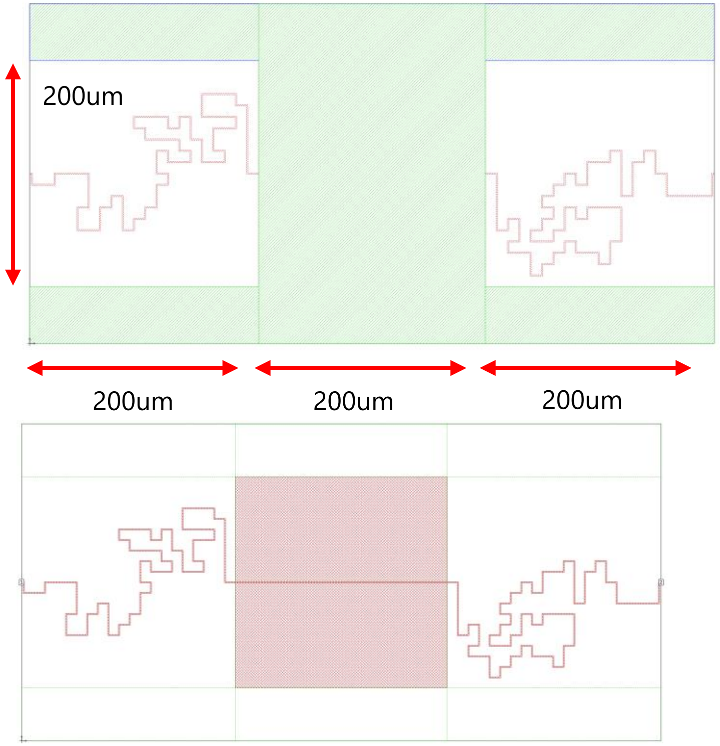
Directional coupler for greater isolation



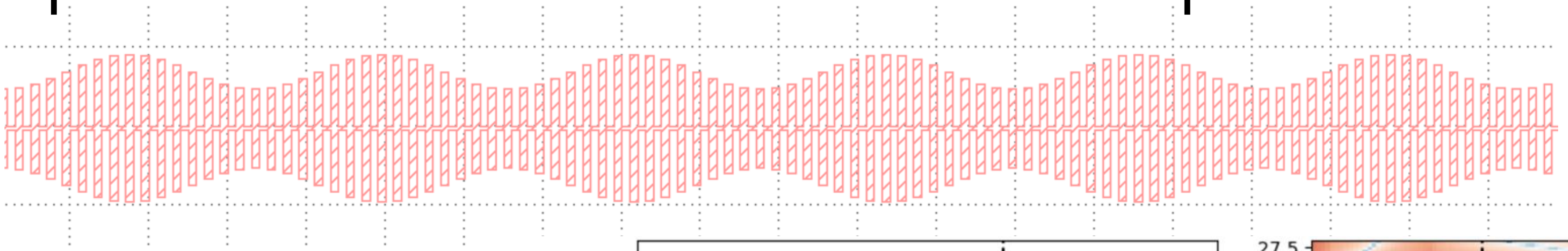
On-chip diplexers for pulling out pump power

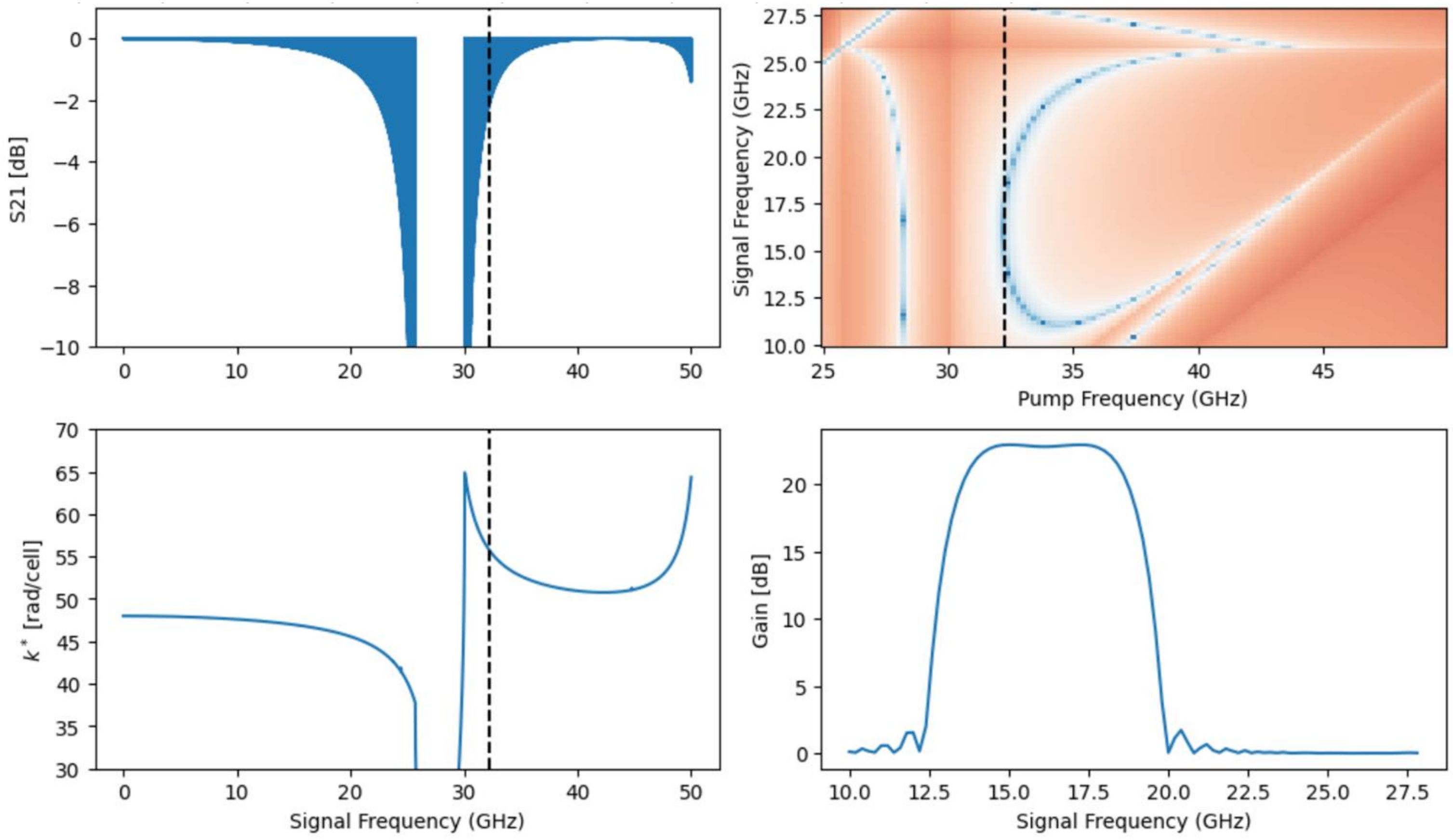


On-chip inductors with exceptional self-resonance frequencies



Supercell sinusoidal modulation concept





Creates more gentle dispersion that is easier to phase match

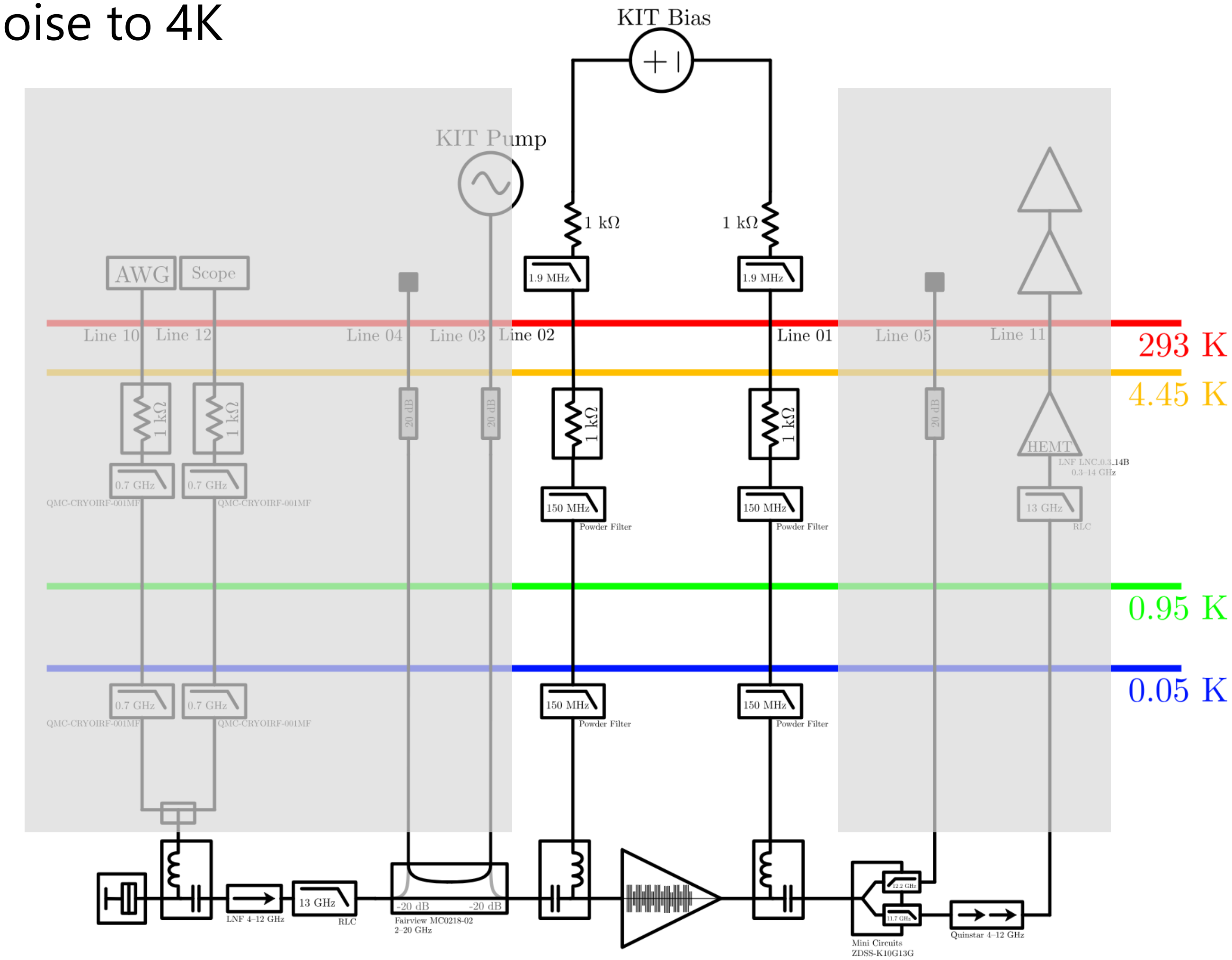
Conclusions

- KTWPAs are broadband, near-quantum limited devices with low sensitivity to magnetic fields
  - Well matched to the requirements for a broadband axion search
- Pushing KTWPAs to higher frequencies
  - Design and packaging
- Making improvements for the end-user of these amplifiers
  - Reducing backaction on devices
  - Reducing required pump powers

This work was supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under Award DE-SC0026061.

Operation of a KI-TWPA

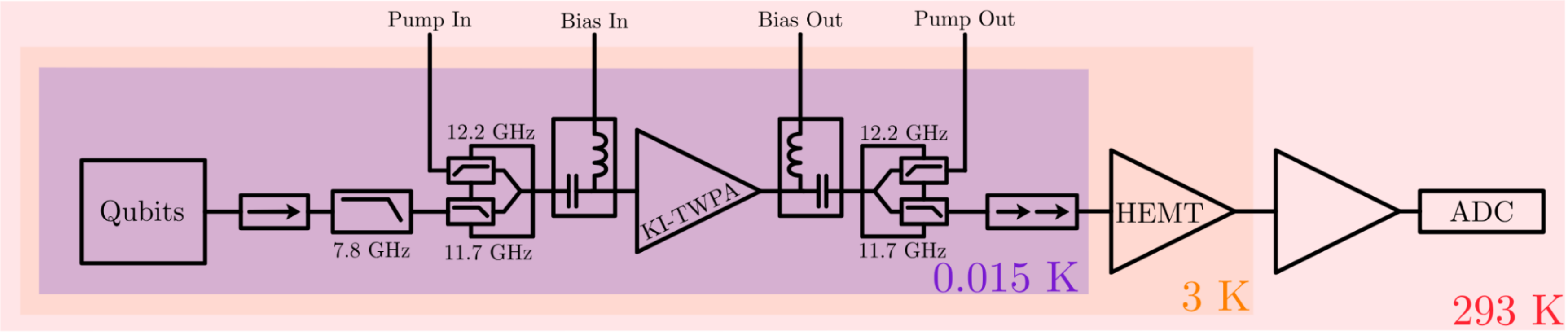
- To bring in the DC bias, we need bias tees on either side of the device
  - Each DC bias line needs some low-pass filtering and some in-line resistance to thermalize noise to 4K

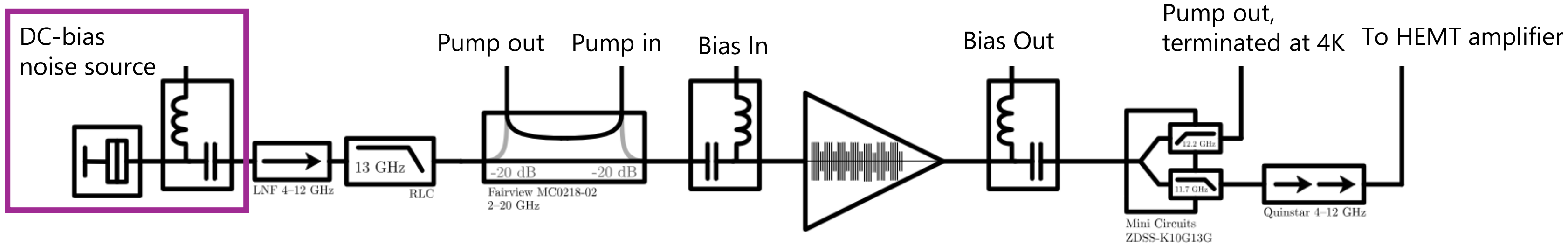


Operation of a KI-TWPA

- We always want a diplexer on the output side of the amplifier to avoid saturating amplifiers further up the readout chain
- Either a diplexer or a directional coupler to bring the pump in
  - Diplexer offers higher isolation to device (finding the right combo of frequencies can be tricky), but will need an attenuator at the mK stage
  - Directional coupler thermalizes noise at mK stage is wideband

Two common examples





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