Crosstalk in TES Microwave Frequency Multiplexing Systems

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In collaboration with Zeesh Ahmed, John Groh,
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CMB-CAL @ Bicocca
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Image source: NIST

Introduction
Why multiplexing?

Next-generation CMB experiments require ever-increasing number of detectors

~100 detectors
(BICEP1)

~1,000 detectors
(SPT)

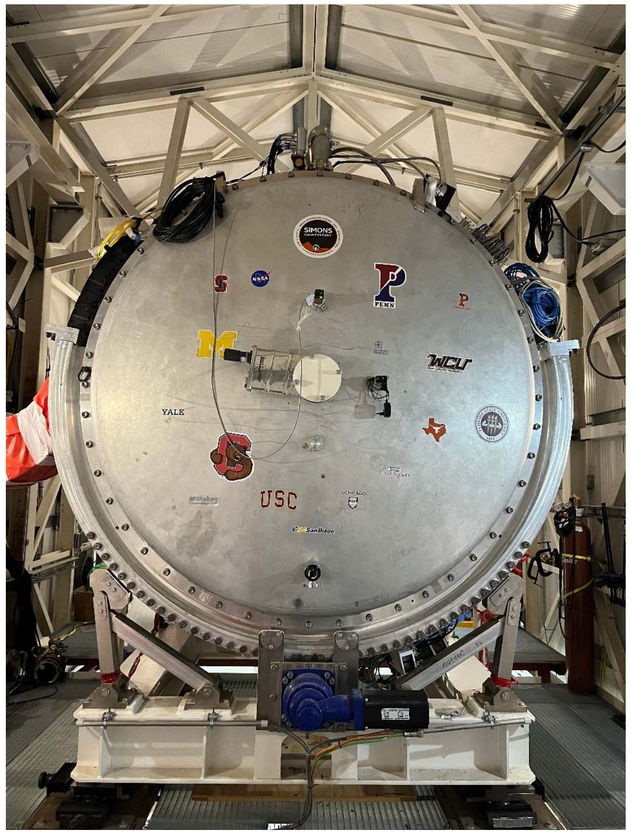
~60,000 detectors
(SO Nominal)

~550,000 detectors
(S4 Proposal)

Source: Planck/ESA

Introduction
Why multiplexing?

SO Large-Aperture Telescope Receiver
> 30,000 detectors



Large numbers of wires are *cumbersome* and they make maintaining cryogenic conditions *difficult*

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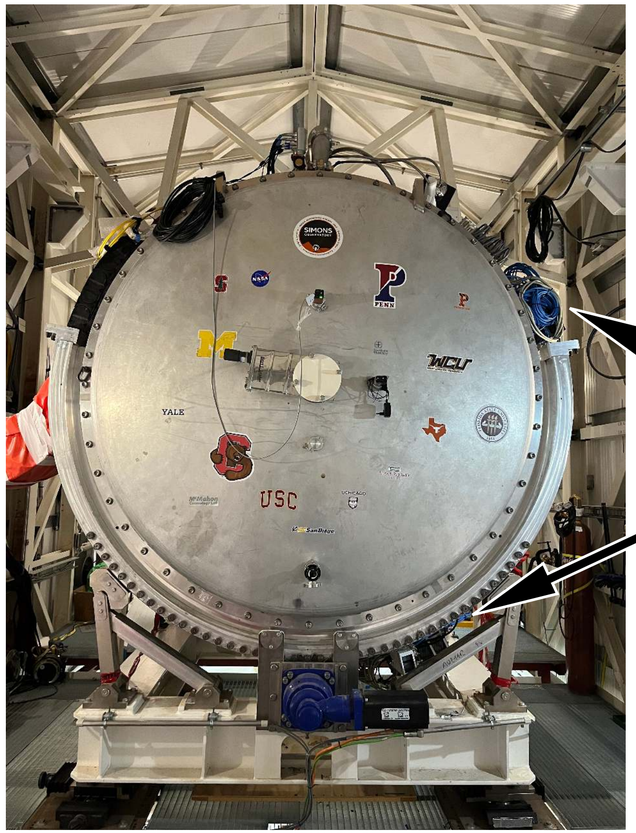


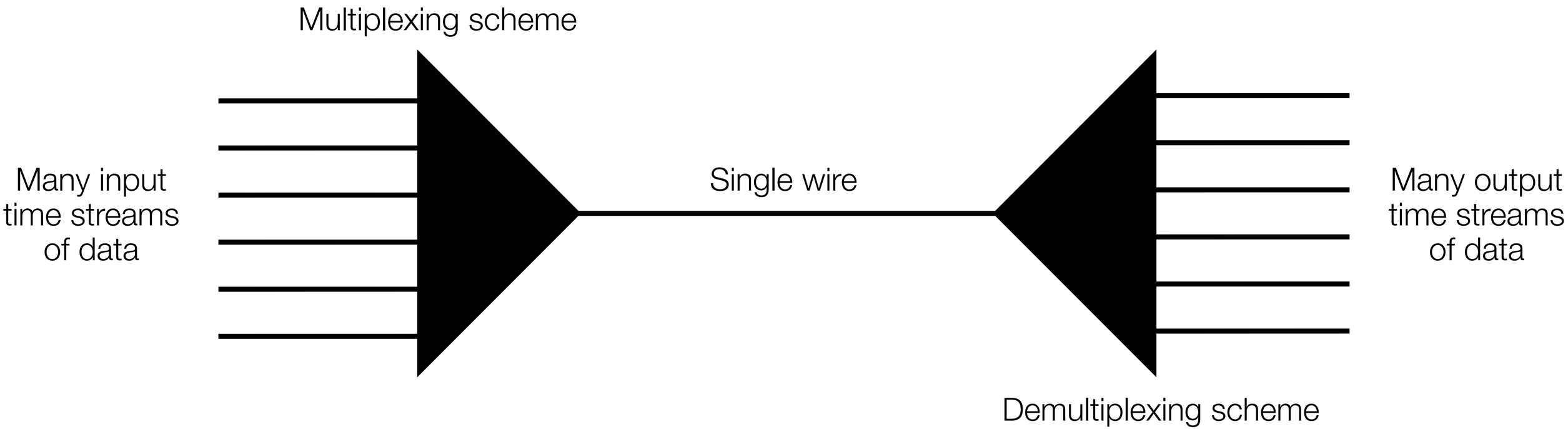
72 coaxial cables to read out all detectors

Large numbers of wires are *cumbersome* and they make maintaining cryogenic conditions *difficult*

Need novel methods for reading out information from many detectors on a small number of wires

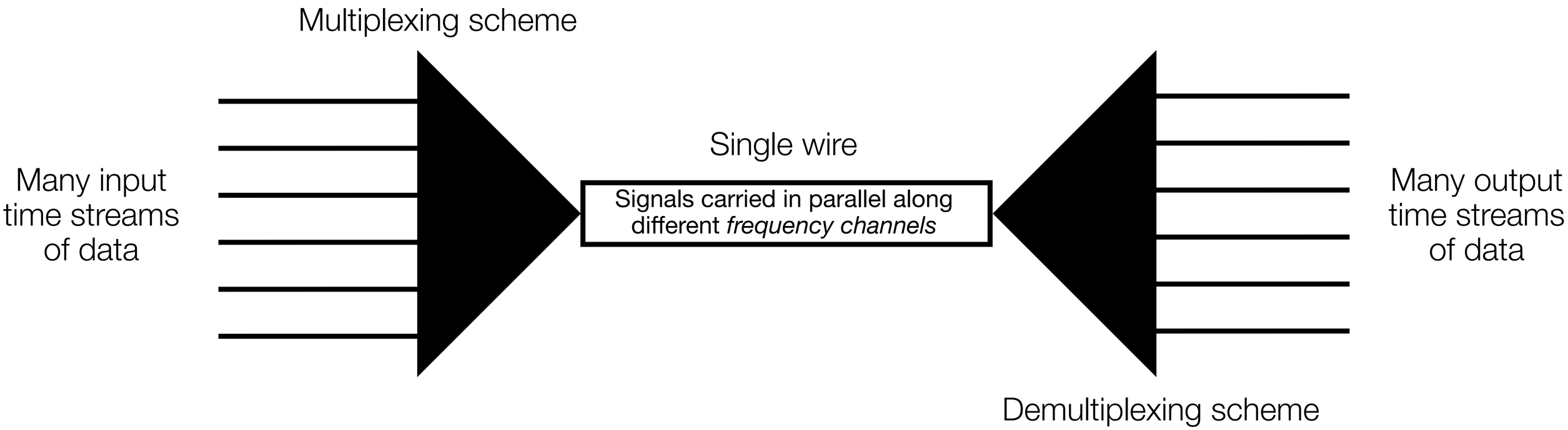
Introduction
Why multiplexing?

Multiplexing: combining multiple signals onto a single pathway



Introduction
How?

One paradigm: microwave frequency domain multiplexing



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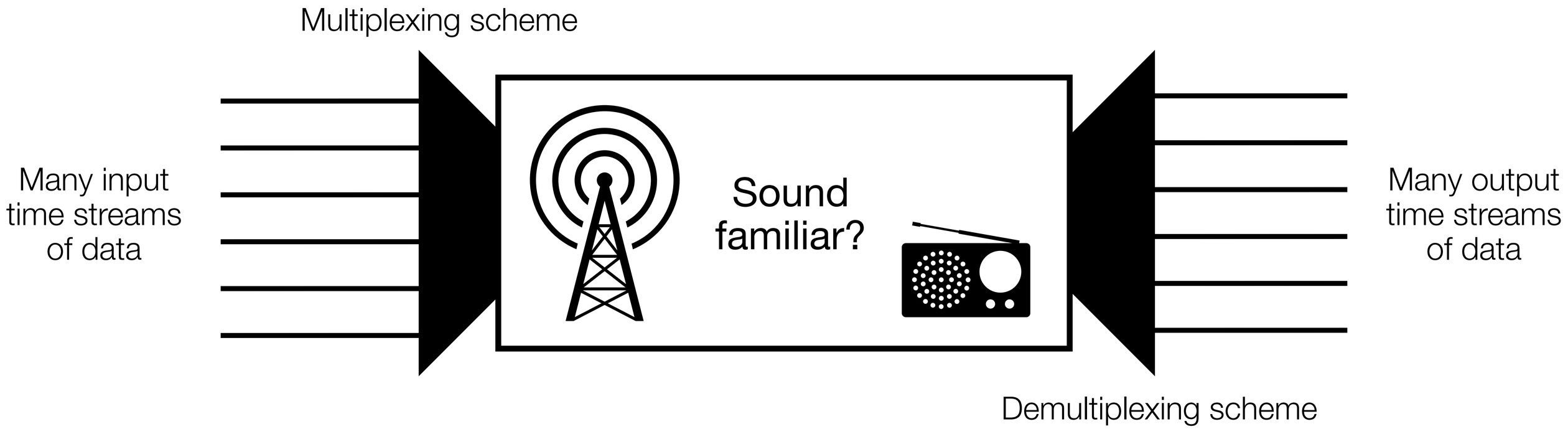
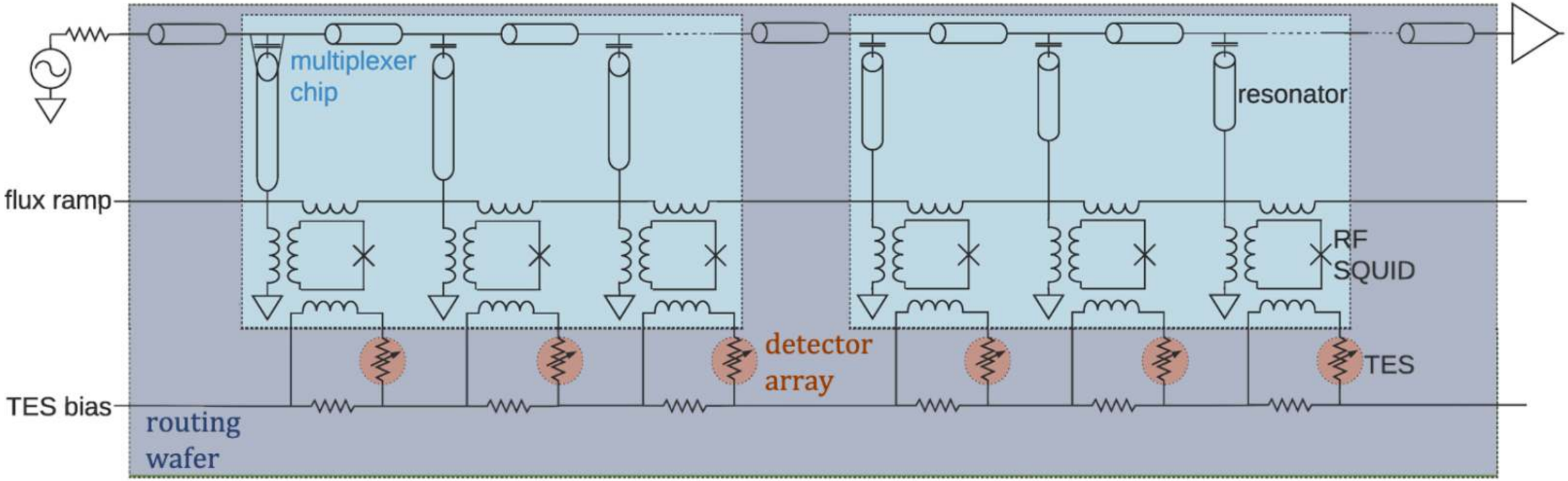


Microwave SQUID multiplexing

General schematic



Source: McCarrick+ 21

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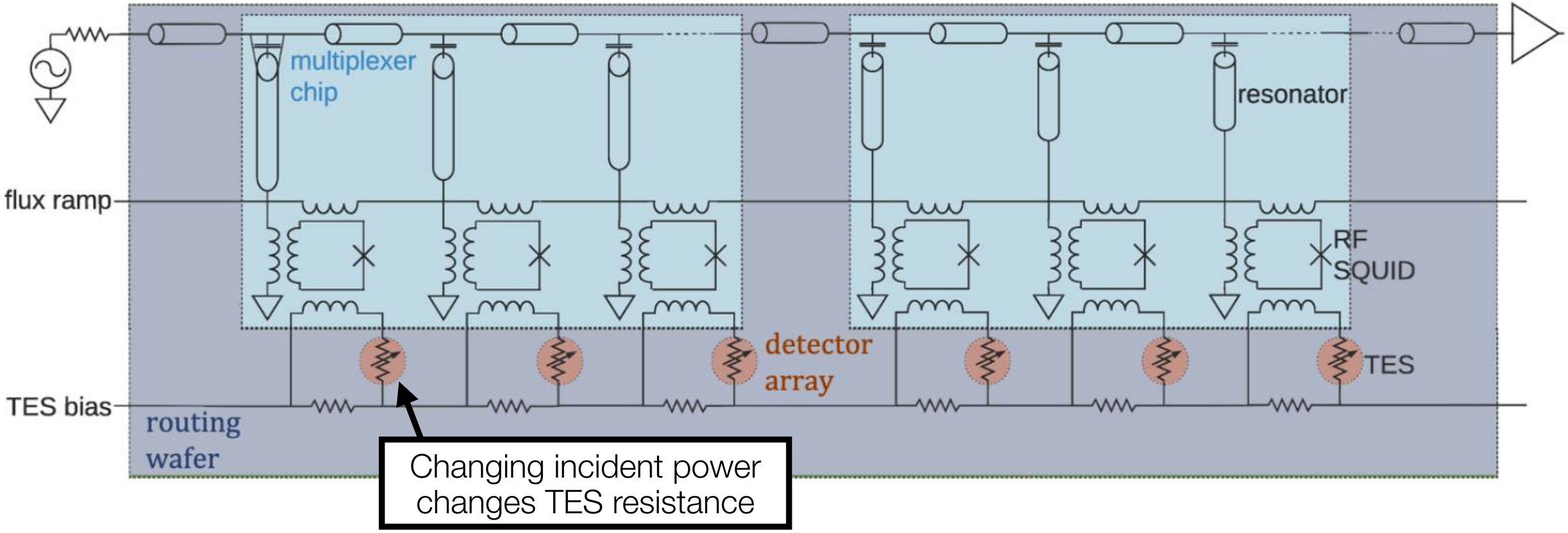

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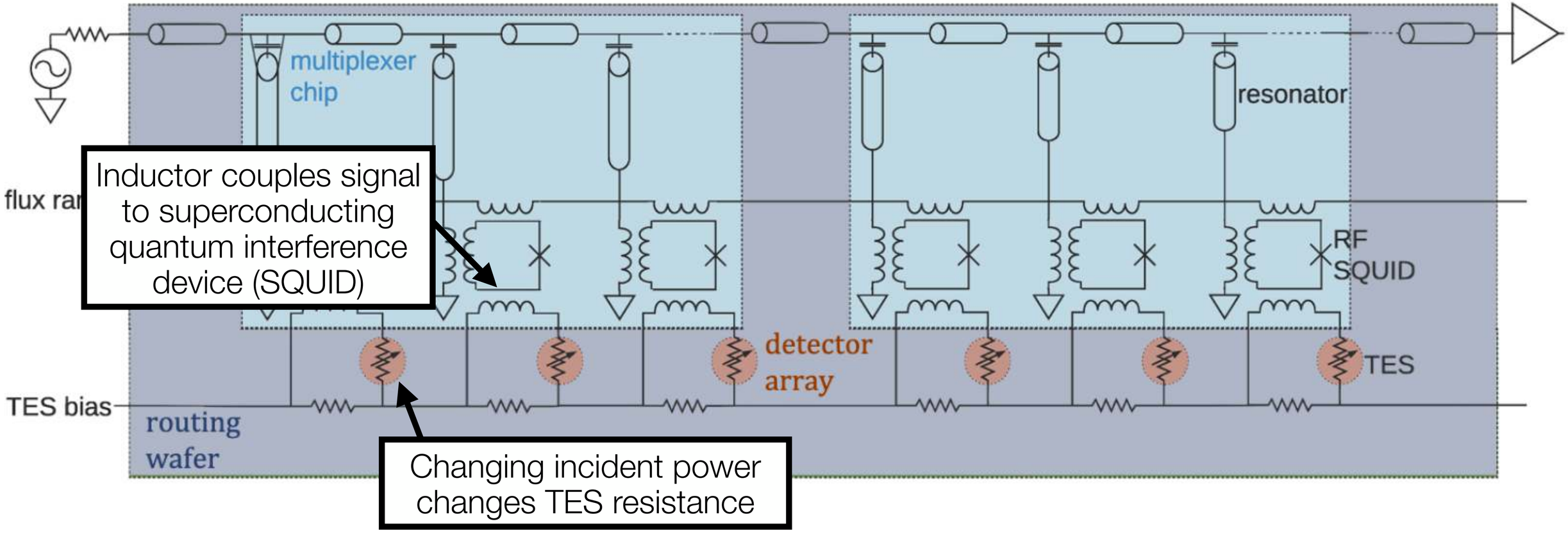

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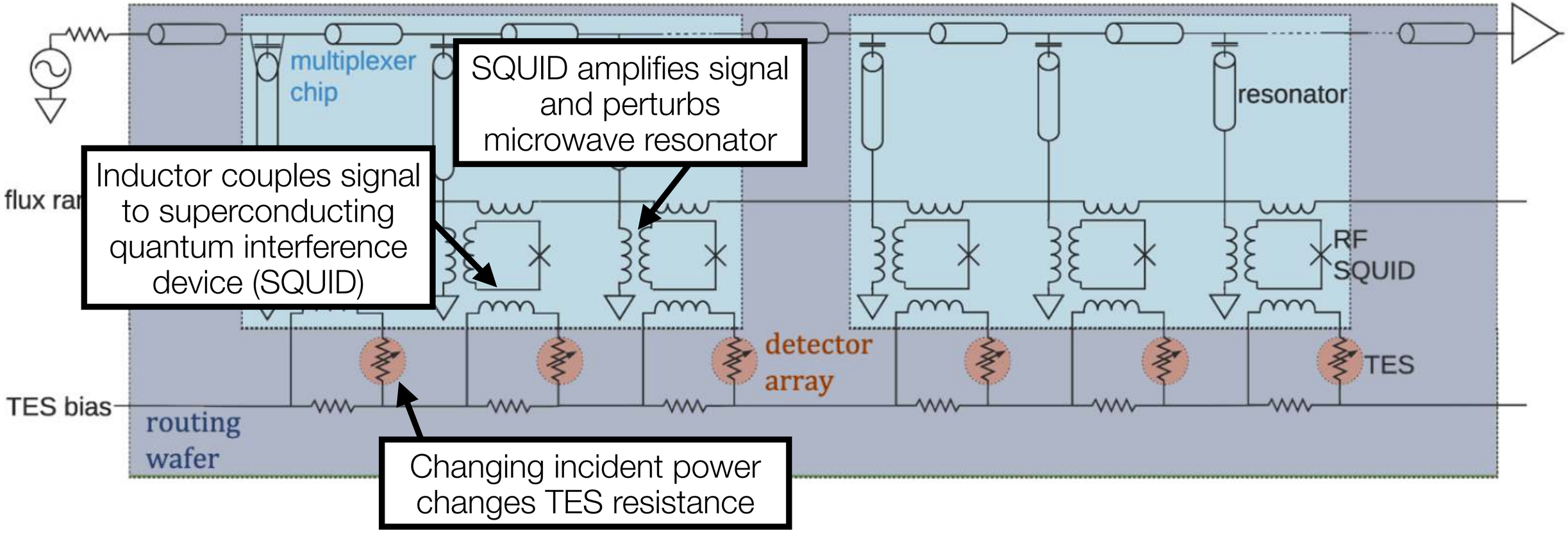

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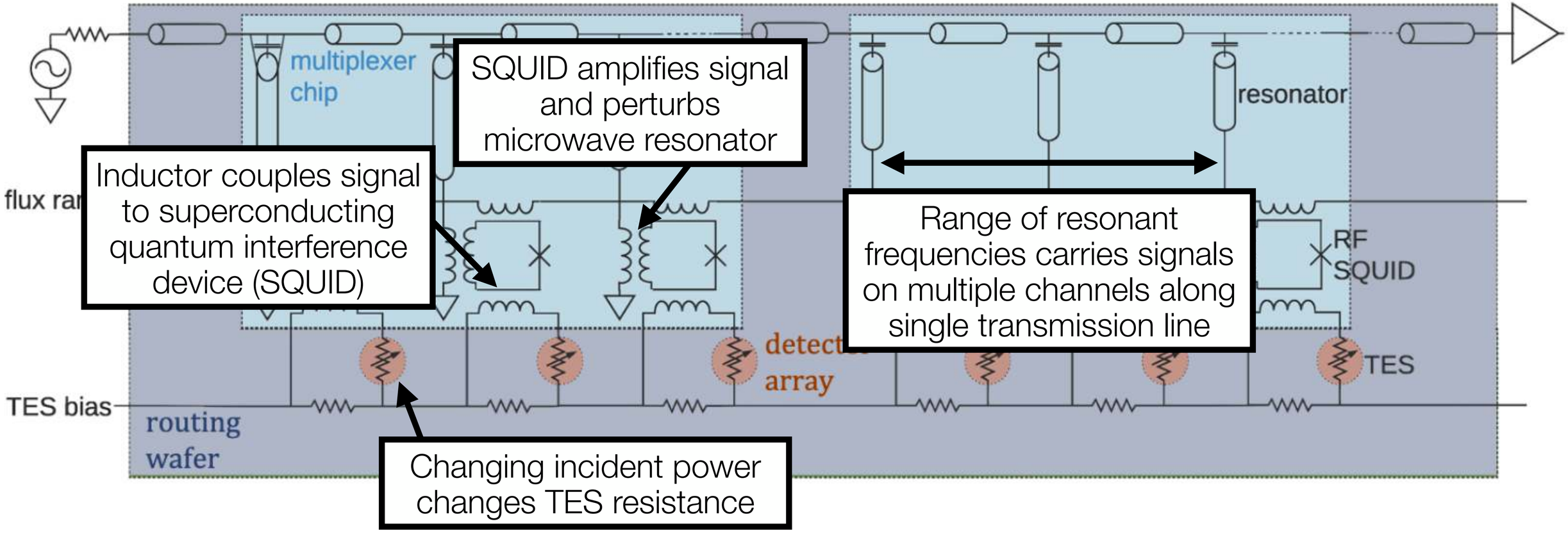

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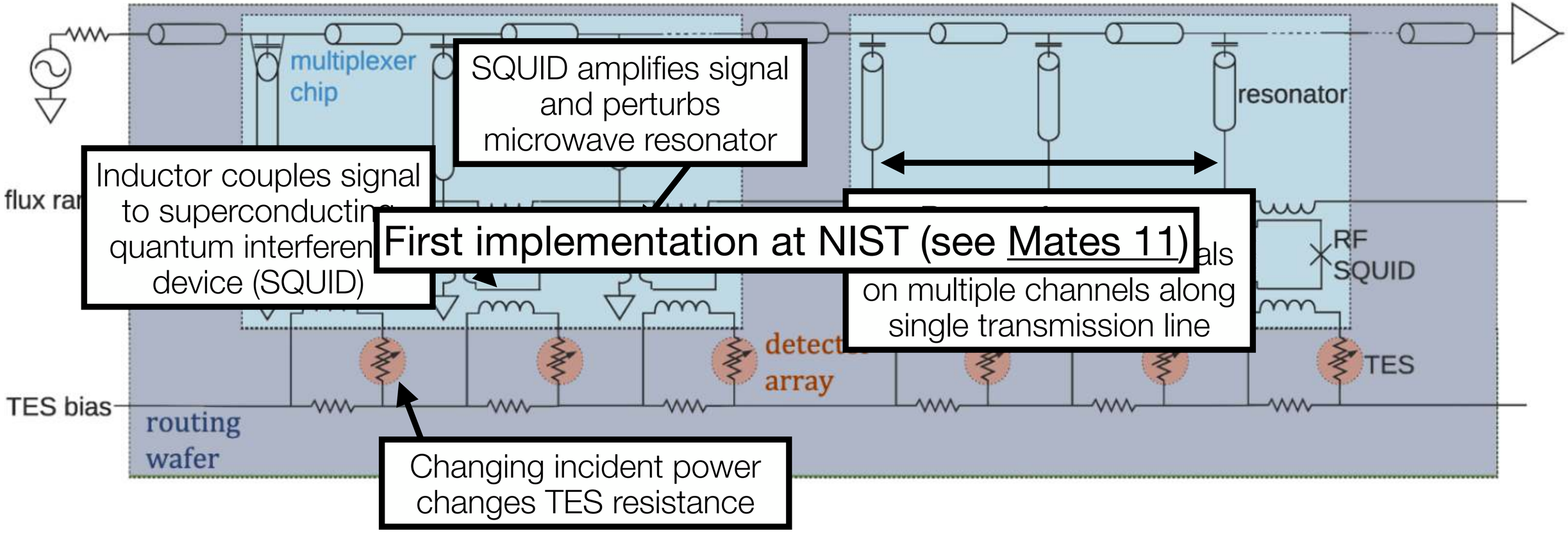

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Microwave SQUID multiplexing

In practice

SLAC Microresonator RF electronics (SMuRF): one stop MUX shop

One “crate” capable of reading out
≥ 10,000 detectors

Each system provides warm electronics for serving RF tones, biasing TESs, and generating flux ramp signal

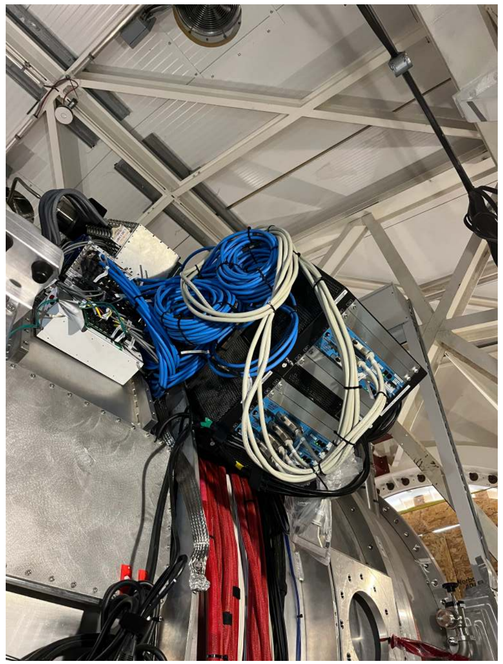
Achieves multiplexing factor of ~1,000

Microwave SQUID multiplexing

In practice

SLAC Microresonator RF electronics (SMuRF): one stop MUX shop

SO LAT

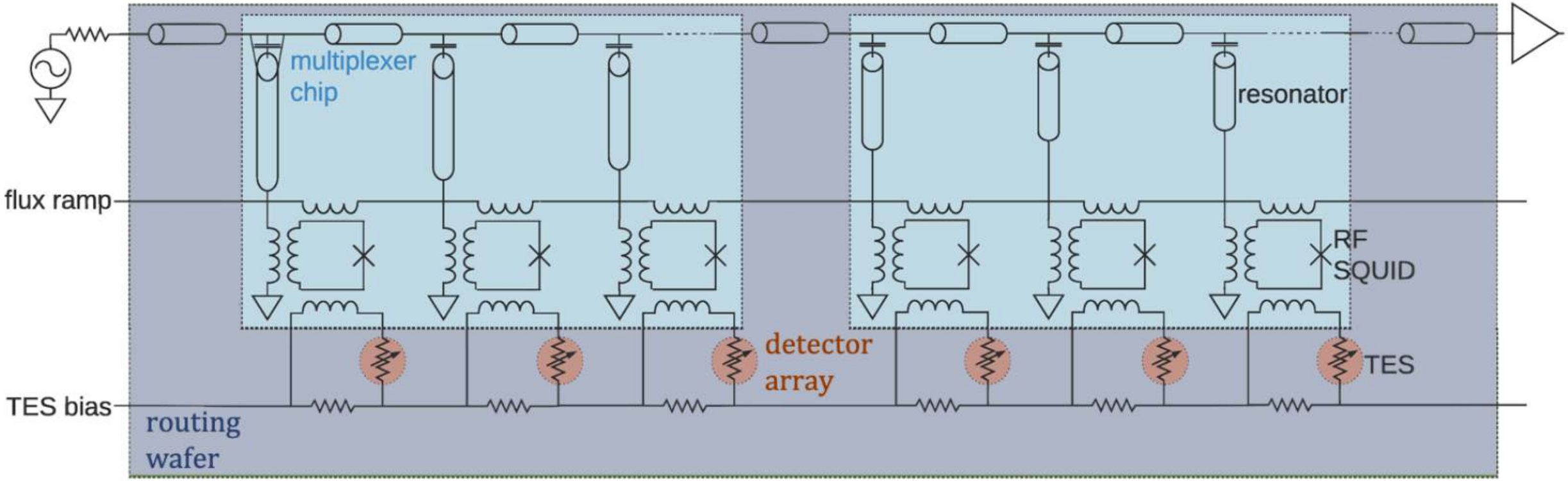


SMuRF in action

Currently being deployed to the Simons Observatory

Largest-ever deployment of μMUX for astronomy (> 60,000 detectors)

Crosstalk
Mechanism



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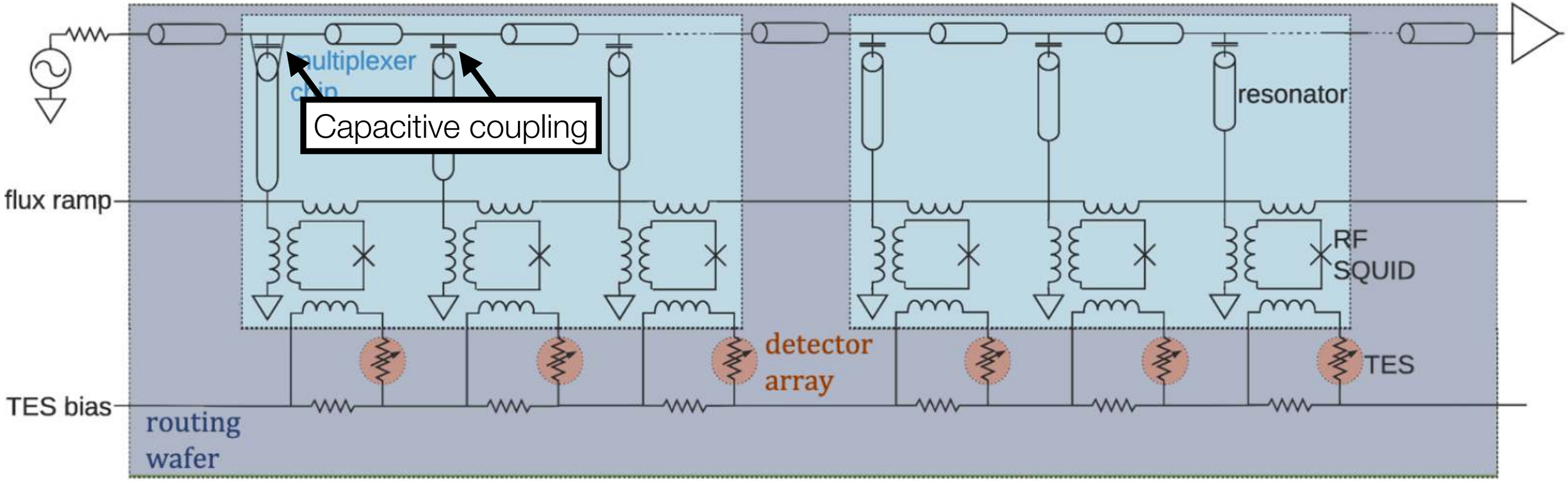

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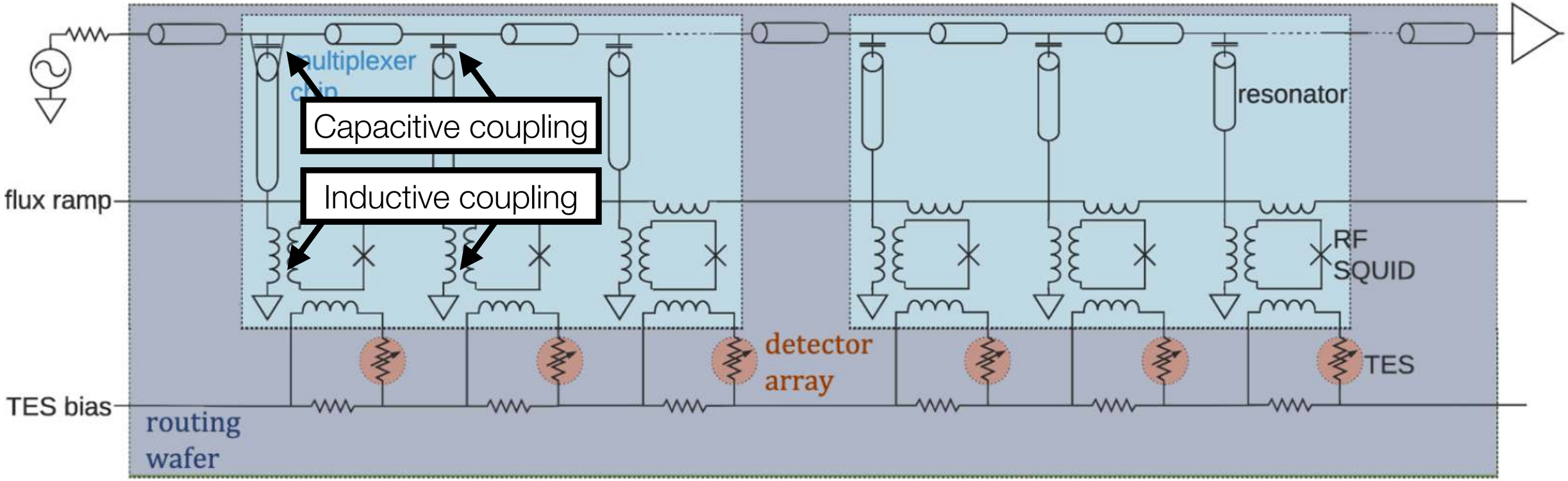

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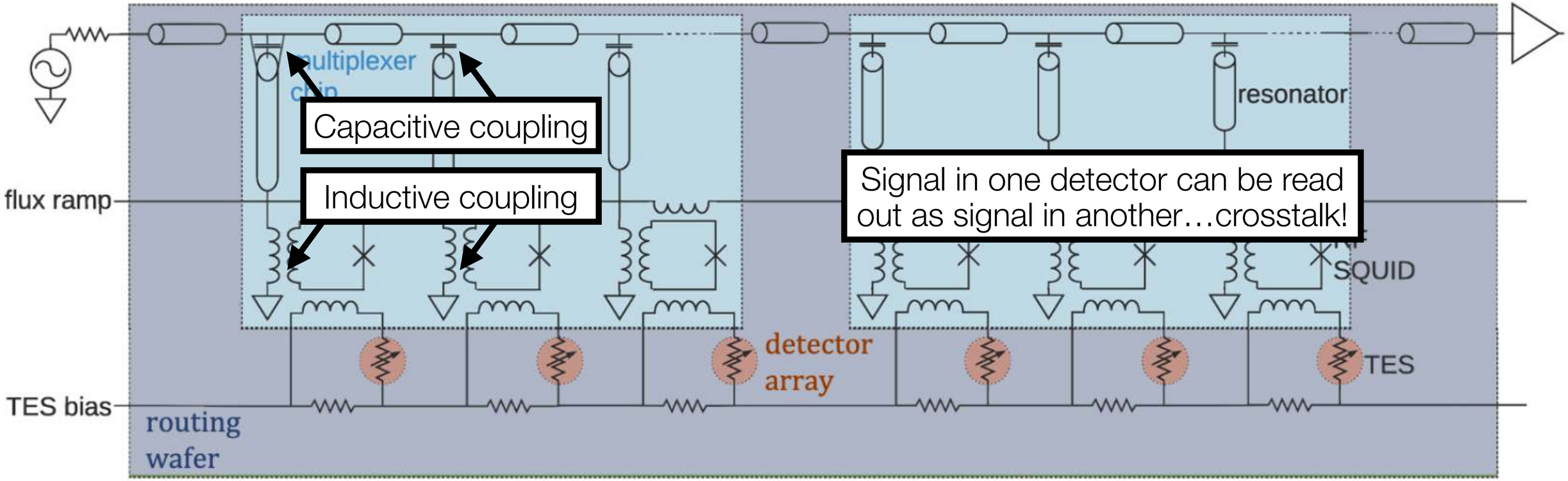

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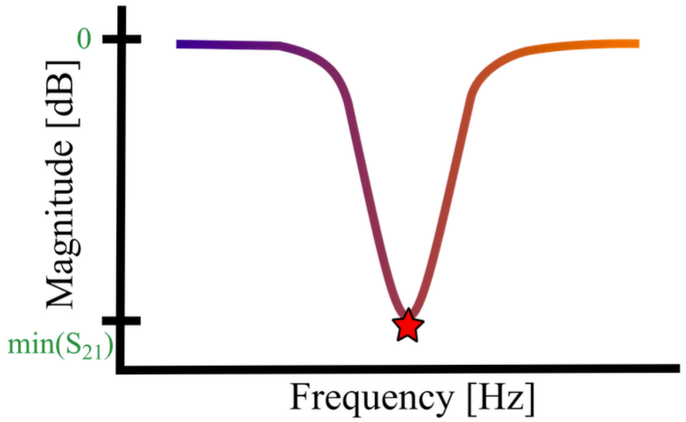
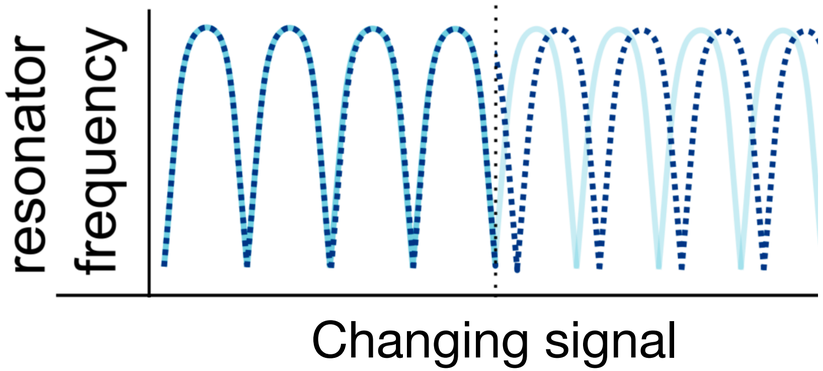
Crosstalk
Coupling to signal

In μMUX systems we measure:





See: Yu+ 23, Mates+ 19, Groh+ 24

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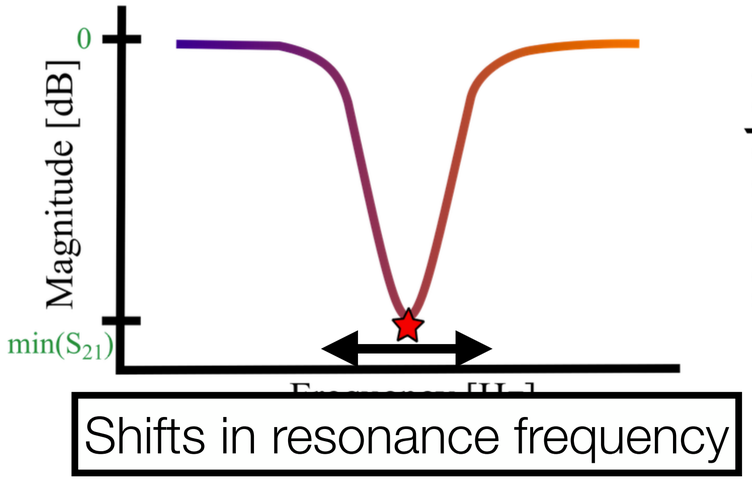
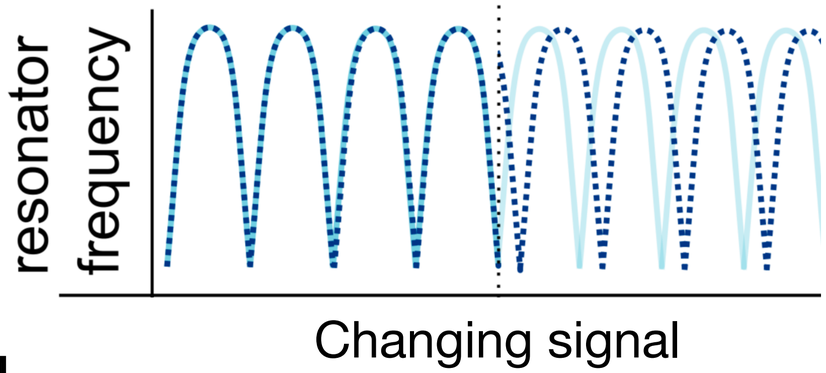


Shifts in resonance frequency



Changing signal

See: Yu+ 23, Mates+ 19, Groh+ 24

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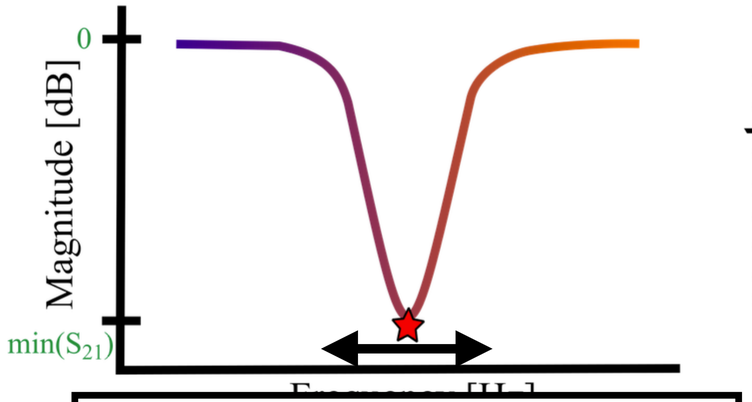

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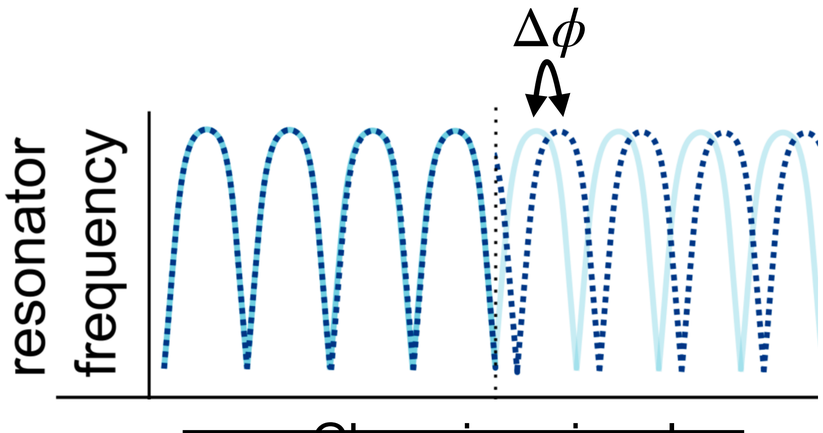

Which correspond to shifts in SQUID phase

See: Yu+ 23, Mates+ 19, Groh+ 24

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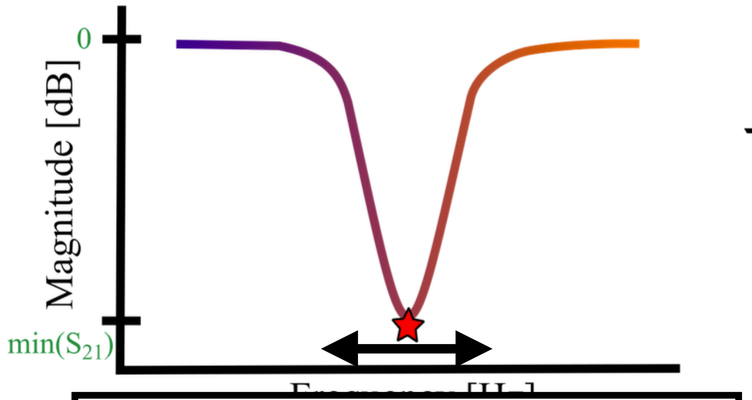

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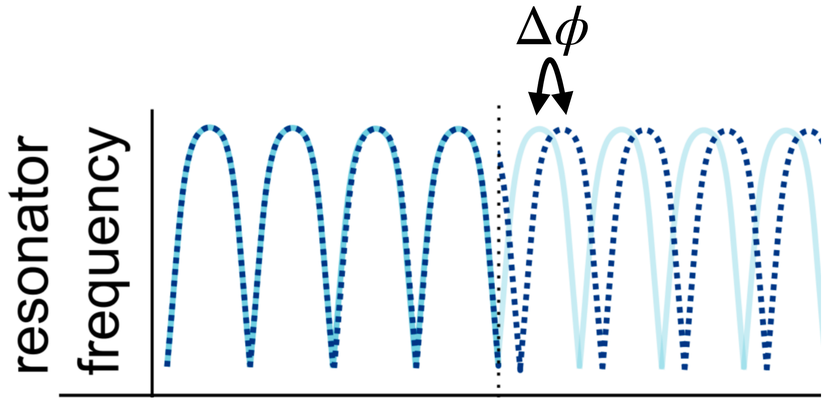

Which correspond to shifts in SQUID phase

Crosstalk can then be approximated as:

$$\phi_1^* = \phi_1 + \chi \sin\left(\phi_2 - \phi_1\right)$$

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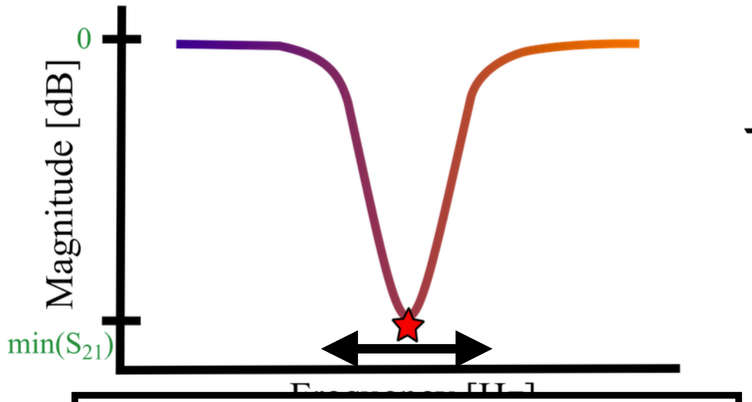

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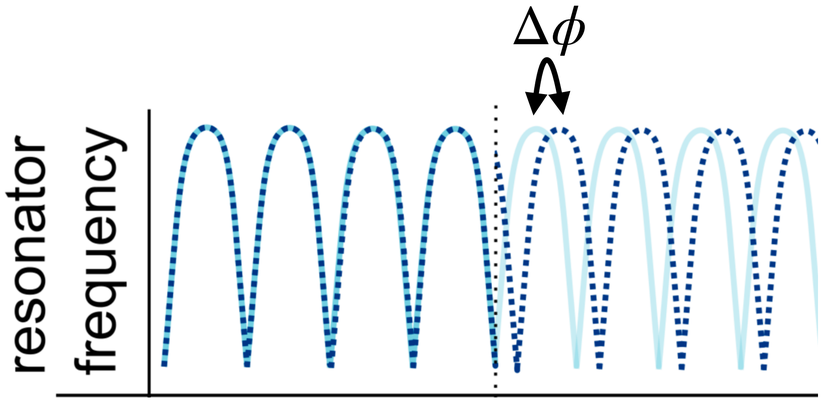

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Measured phase

Crosstalk
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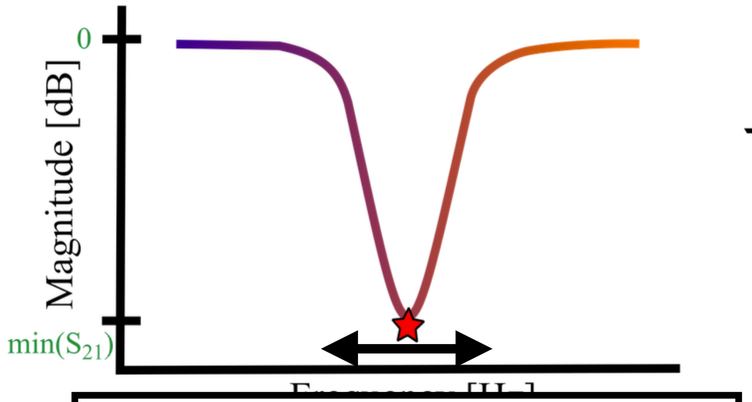

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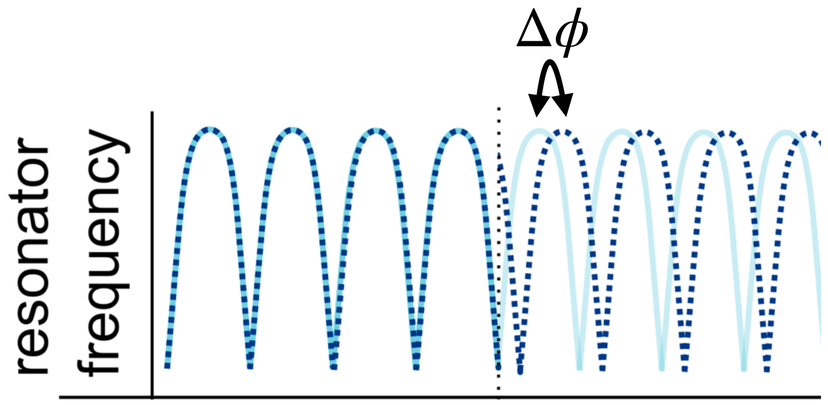

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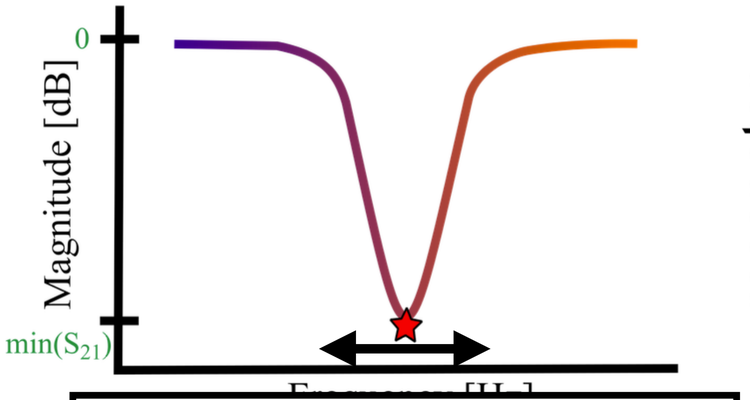

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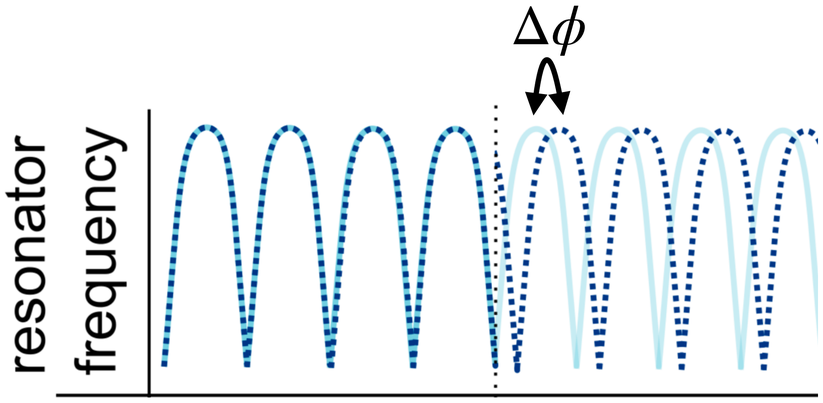

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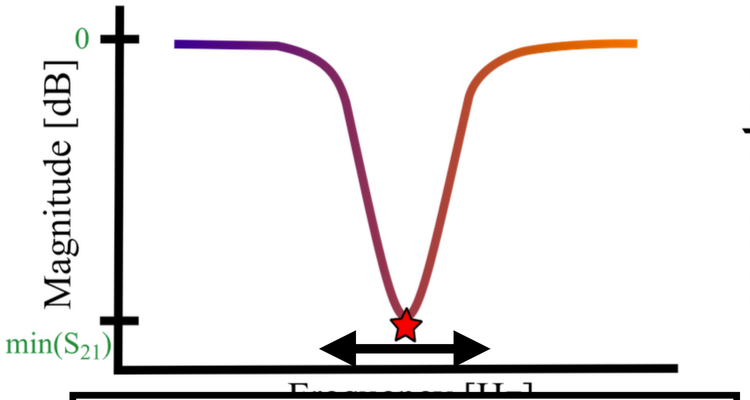

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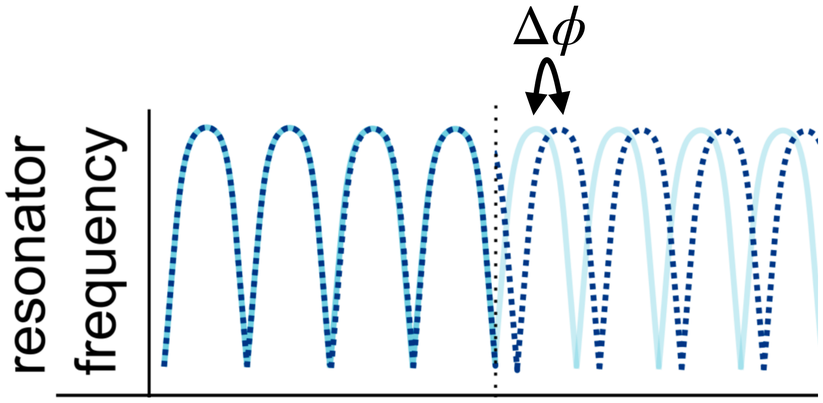

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Measured phase

Strength of effect

Non-linearity

Time variability

Crosstalk

Strength of effect

Considering inductive-only and capacitive-only effects of two coupled LC circuits:

$$\chi \approx \frac{\pi^4 M_{12}^2 \bar{f}^4}{16 Z_0^2 \left(\delta \bar{f}\right)^2} + \frac{16 Z_0^2 C_{12}^2 \bar{f}^4}{\left(\delta \bar{f}\right)^2}$$

See: Mates+ 19, Groh+ 24

Crosstalk
Strength of effect

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Can be simulated:
$\sim 9.6 \times 10^{-30}$ Hz^{-2}

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Crosstalk
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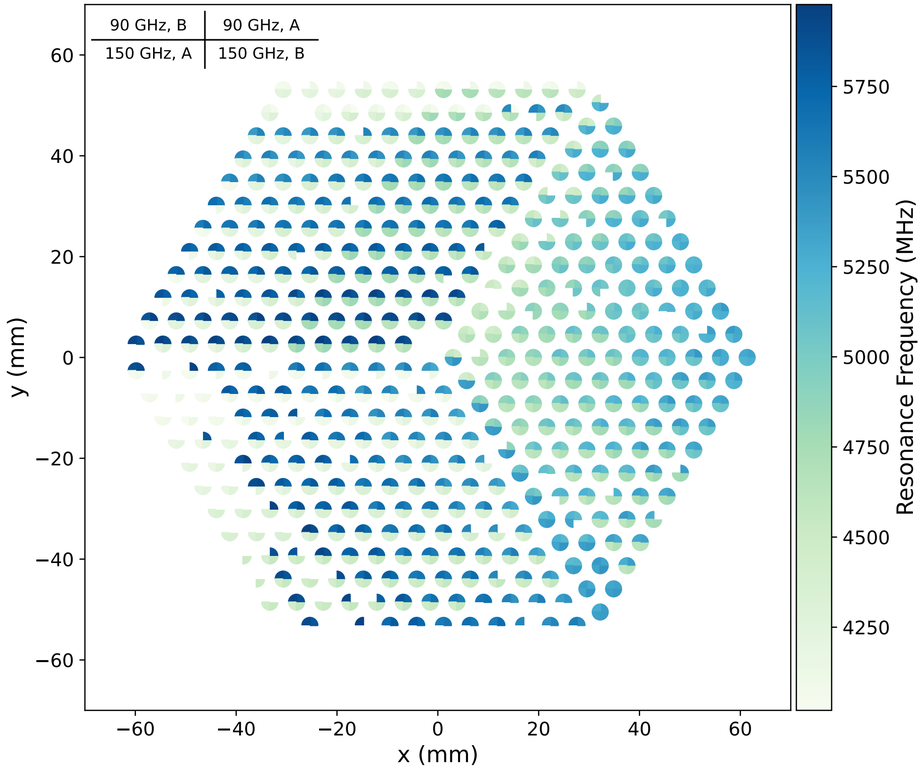
Grows as we push to *higher frequencies* and *tighter resonator spacings*

See: Mates+ 19, Groh+ 24

Crosstalk

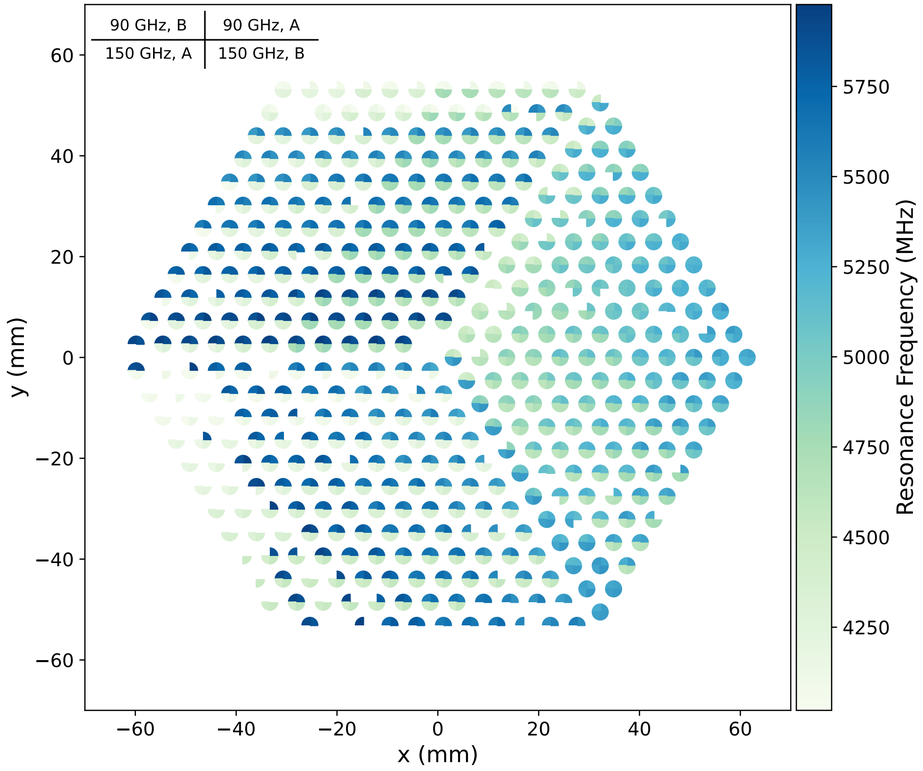
Strength of effect



Resonator layout in sample SO detector module

Crosstalk

Strength of effect



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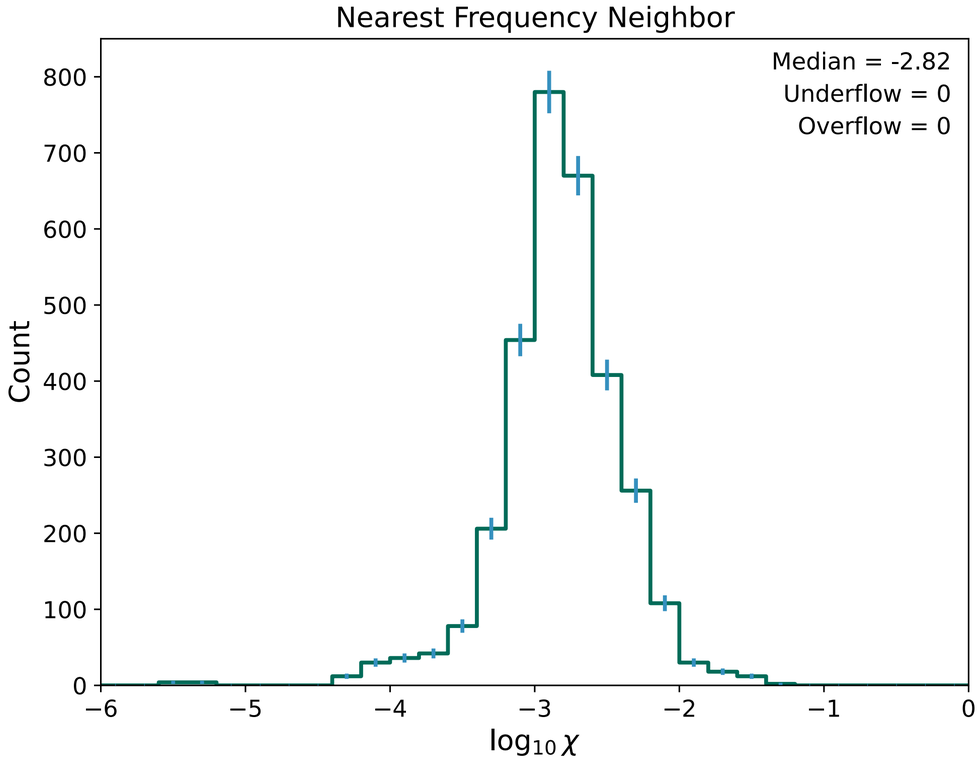

Amplitude of effect at ~0.1% level, within SO specification

Source: SO Collaboration 19

Crosstalk

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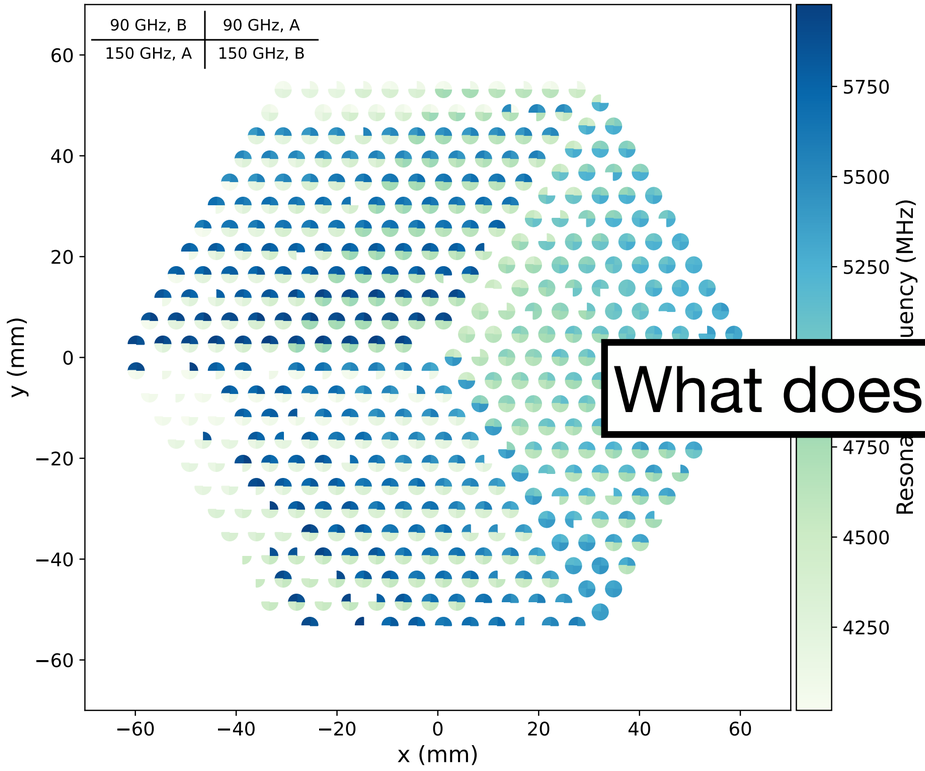
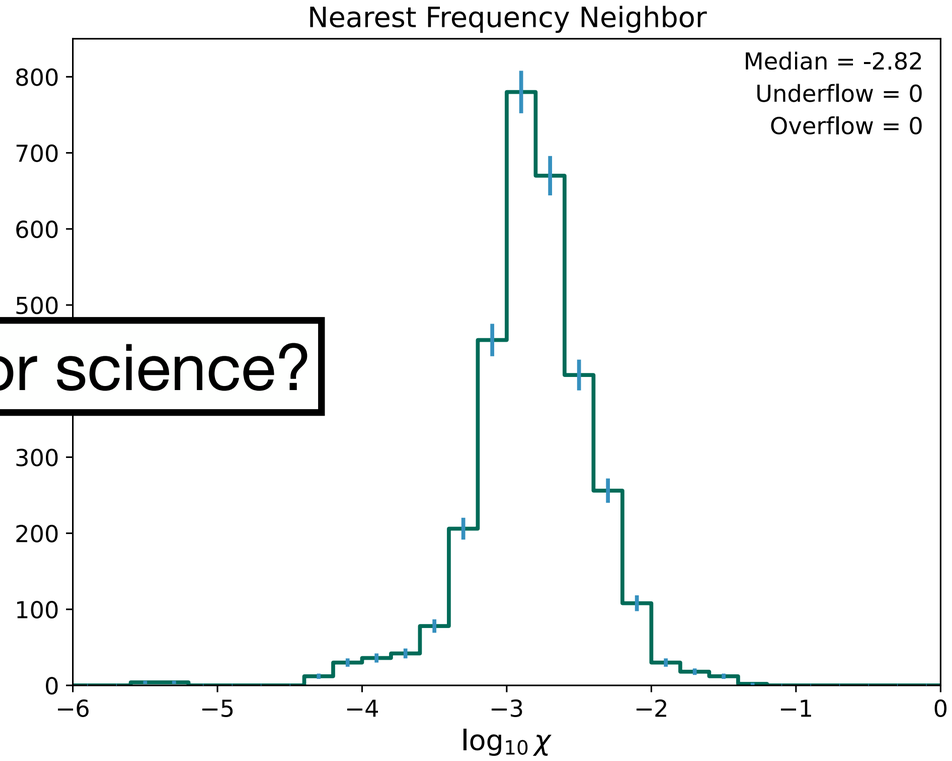


What does this mean for science?



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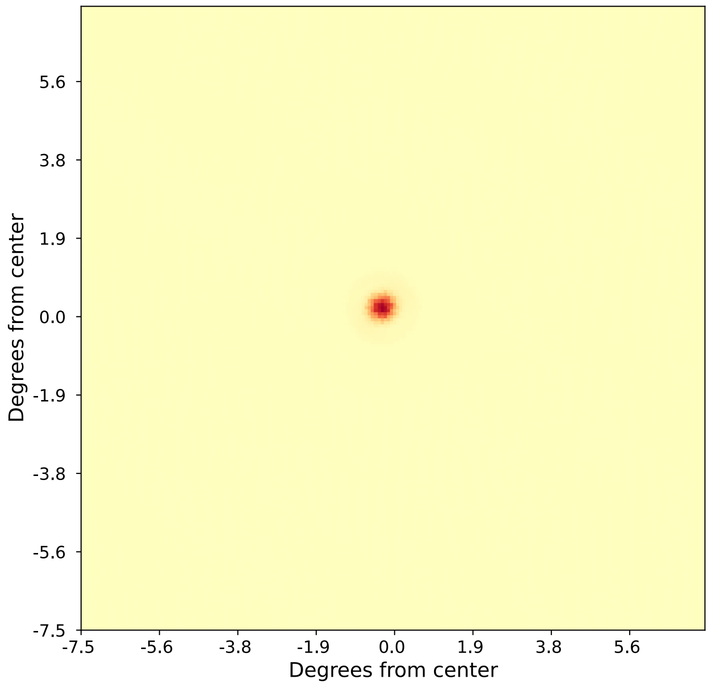
Simulations
Sanity check

Simulating scans of Jupiter in TOAST offers intuition for effect



Sample scan of Jupiter without crosstalk
(coadded SO SAT 90 GHz wafer)

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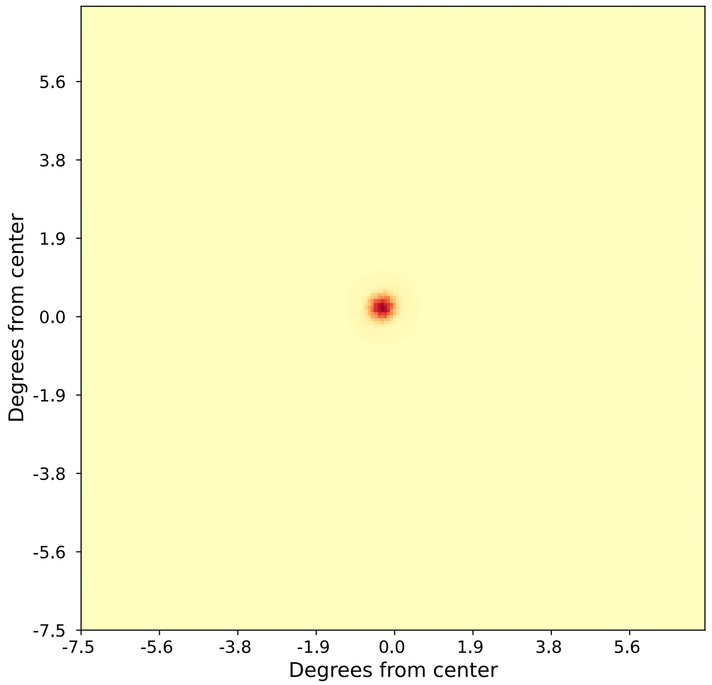

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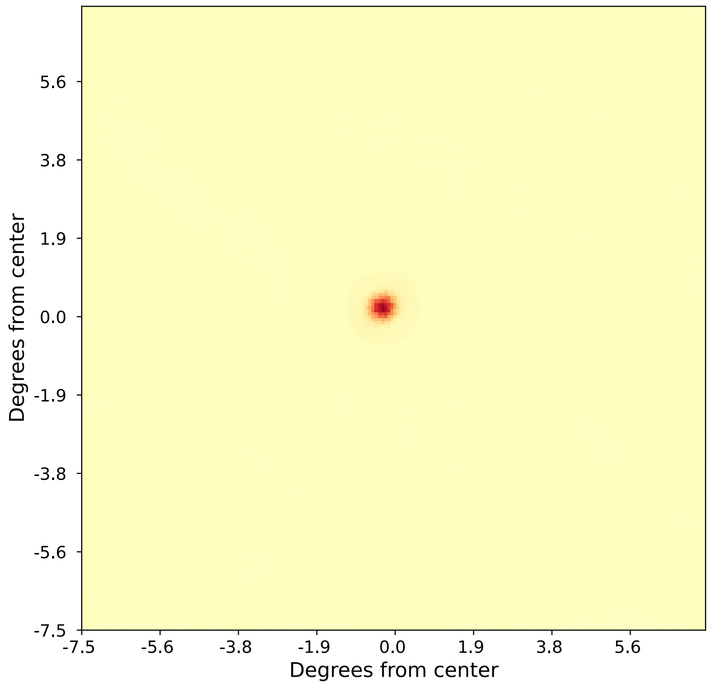

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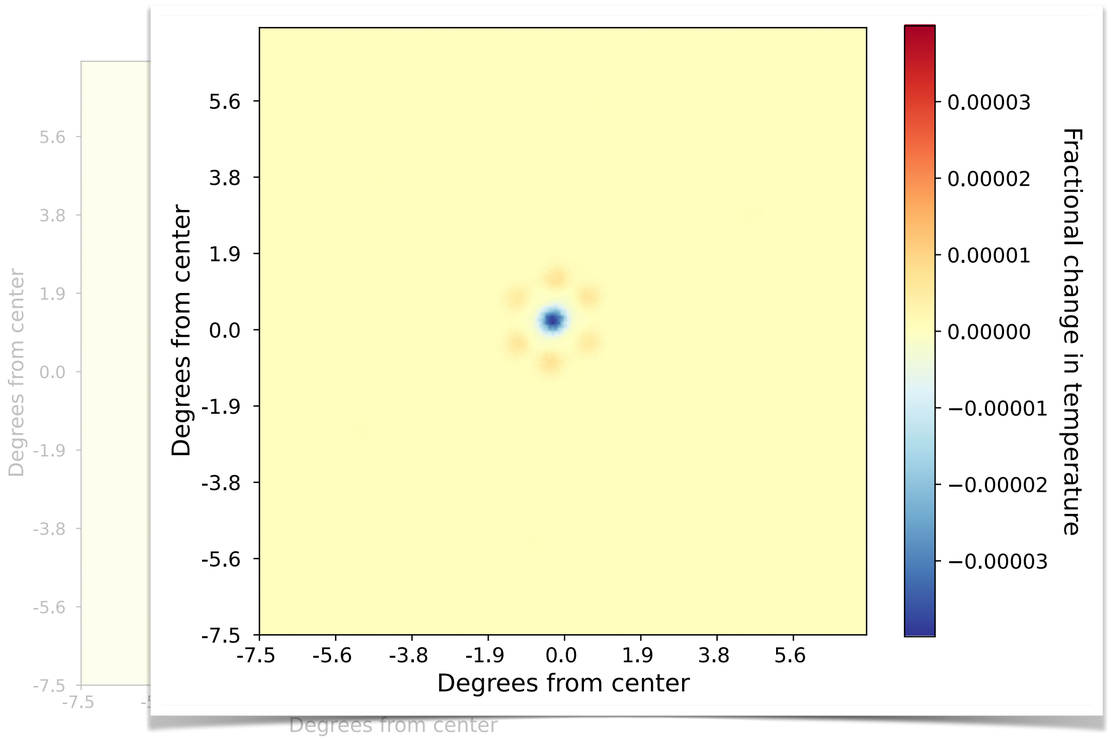

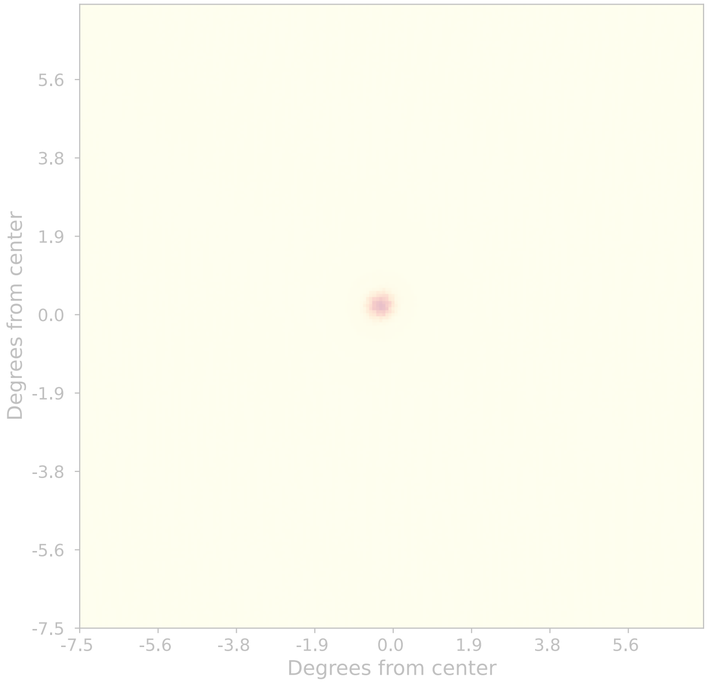

Difference between two maps

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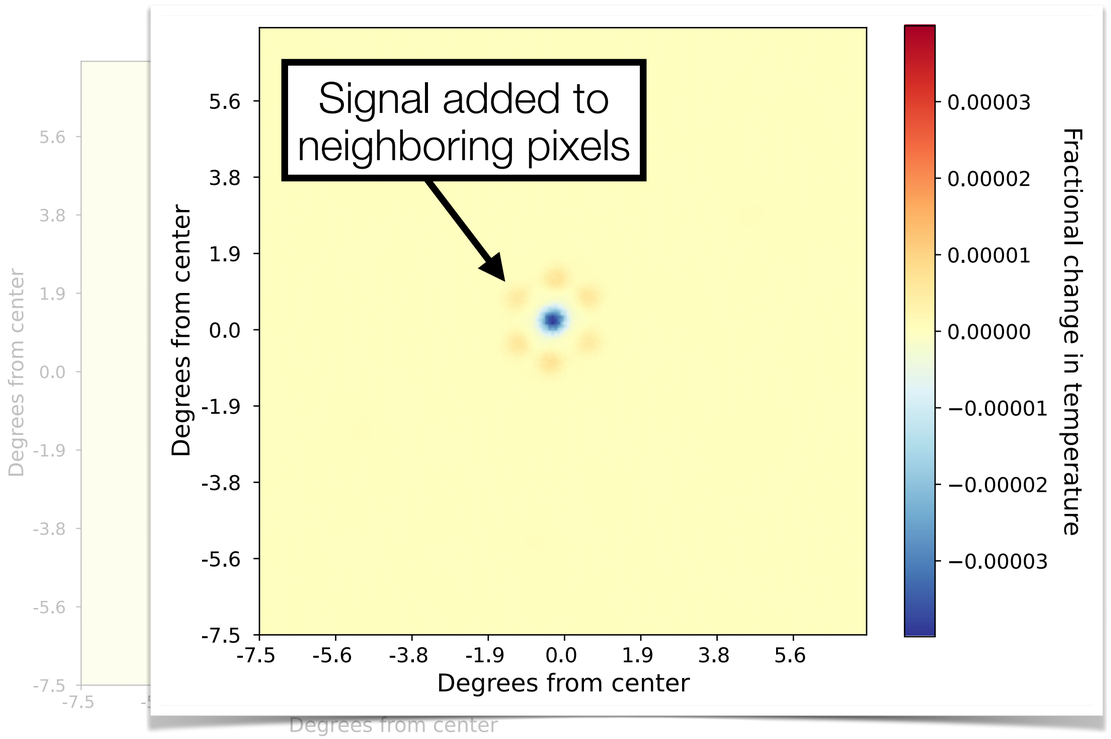

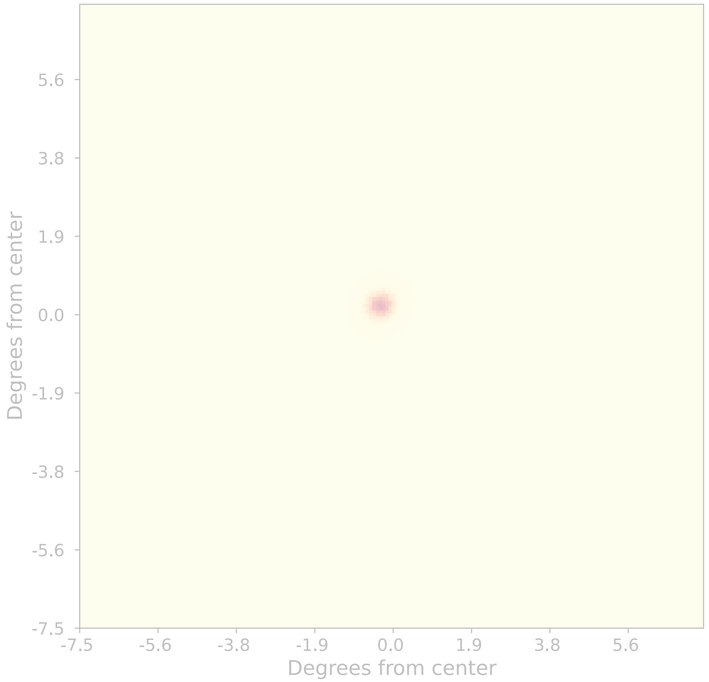

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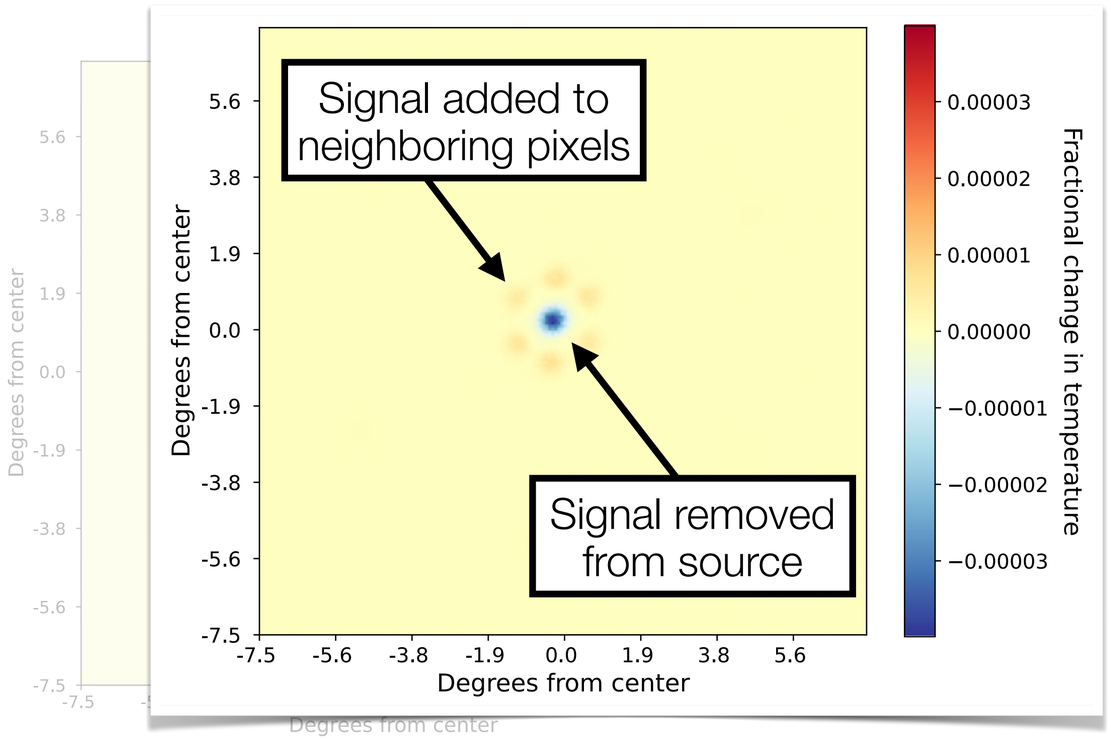
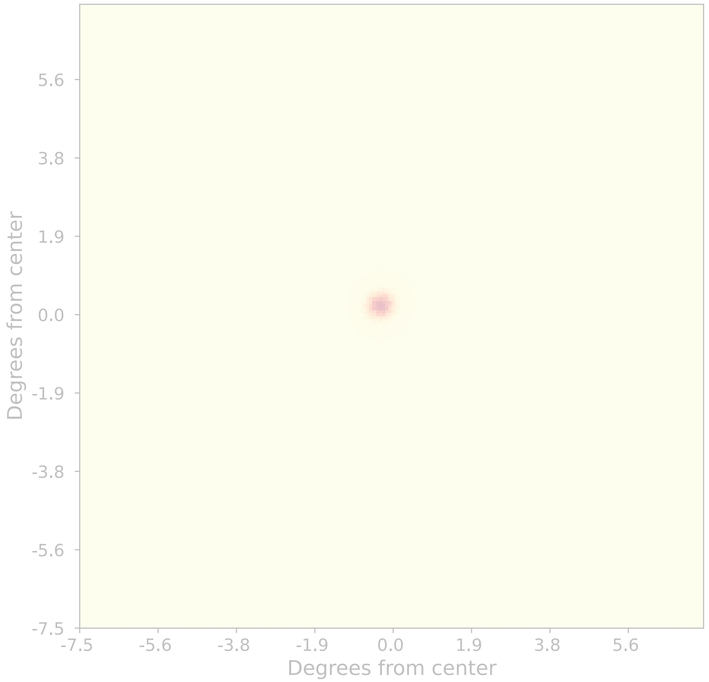
Simulating scans of Jupiter in TOAST offers intuition for effect

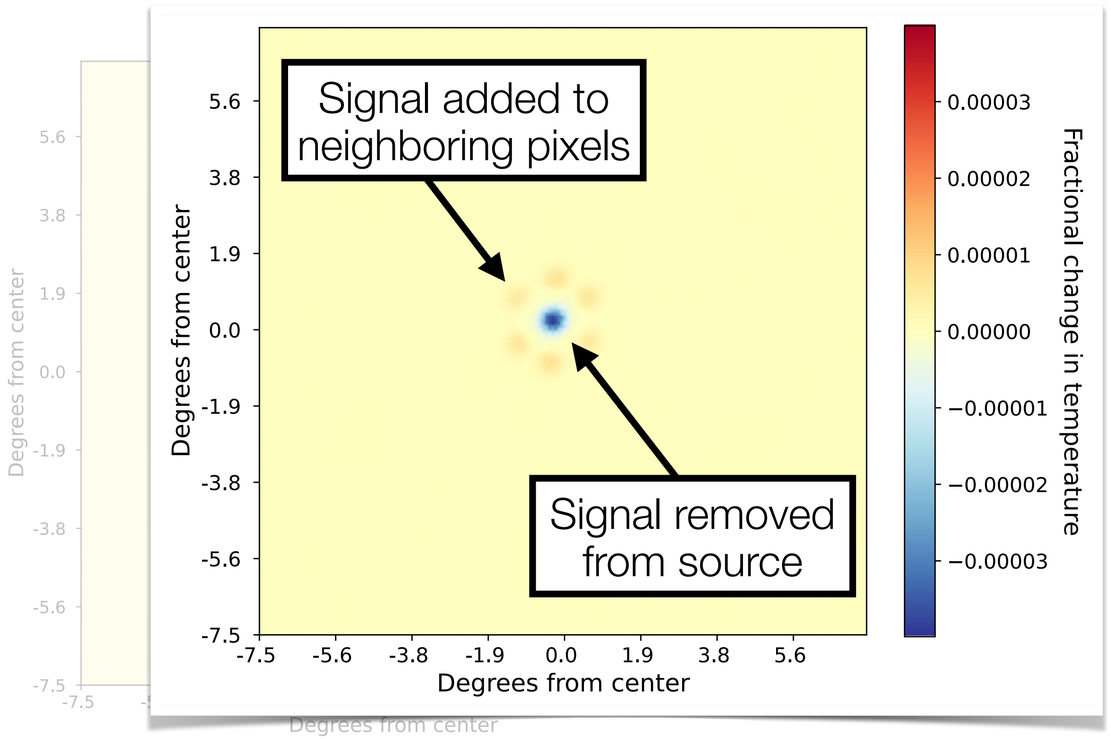




Difference between two maps

Simulations
Sanity check

Simulating scans of Jupiter in TOAST offers intuition for effect

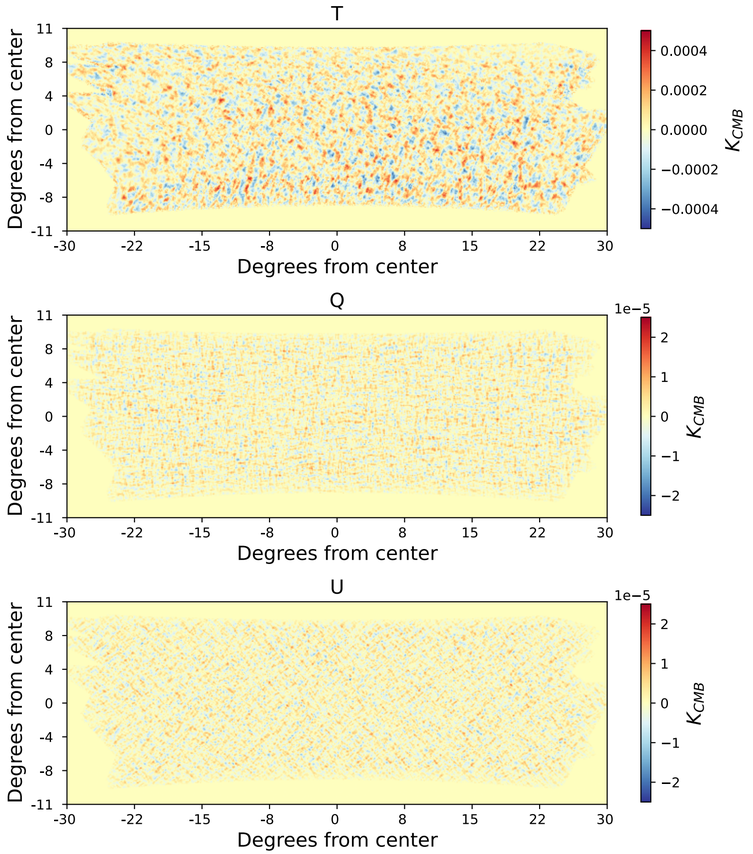


Difference between two maps

Note that map shows one hour constant elevation scan of Jupiter

Effect remains small, and may average down with longer integration time

Simulations
CMB scans



Sample coadded scan with crosstalk

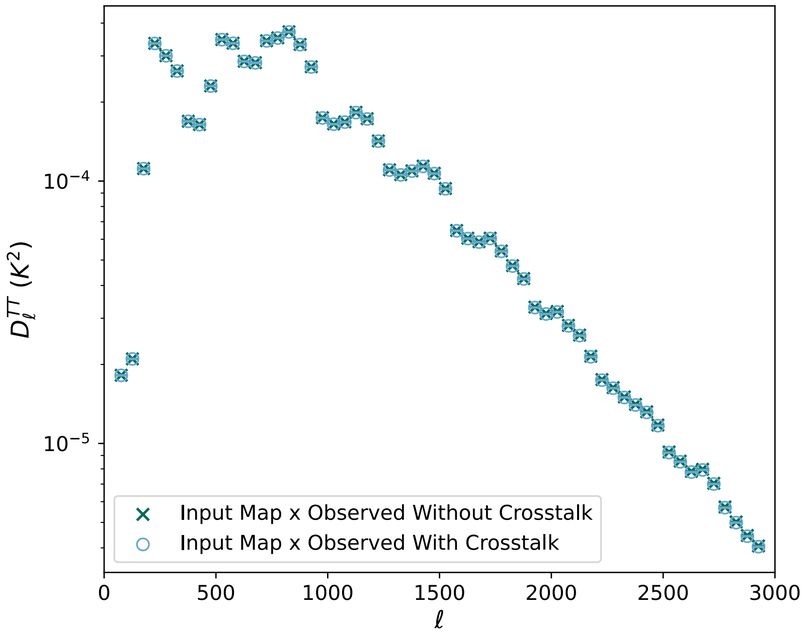
Simulating scans of the deep56 patch (~500 deg^2) helps us understand potential impacts on science

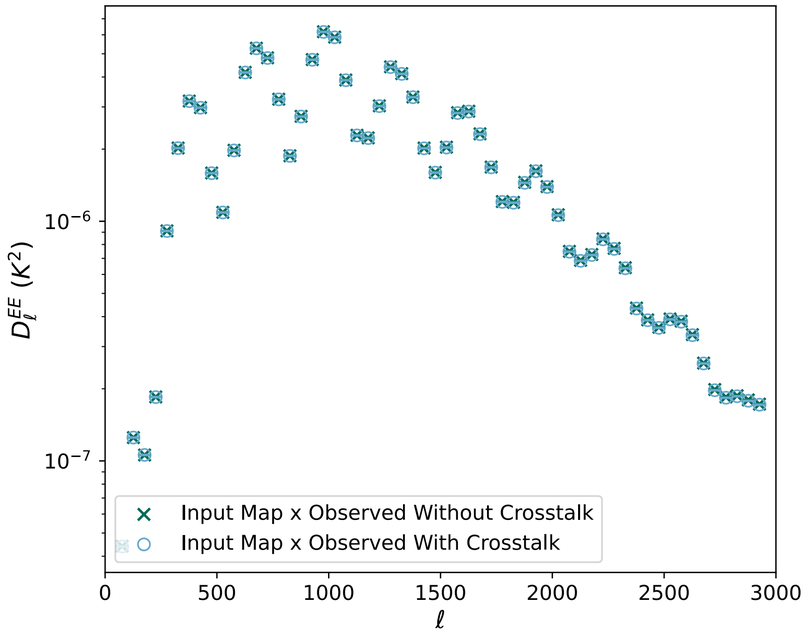
Simulation shows scan with single LAT optics tube at 150 GHz, with no instrument noise and median* atmosphere filtered with common mode and polynomial filtering

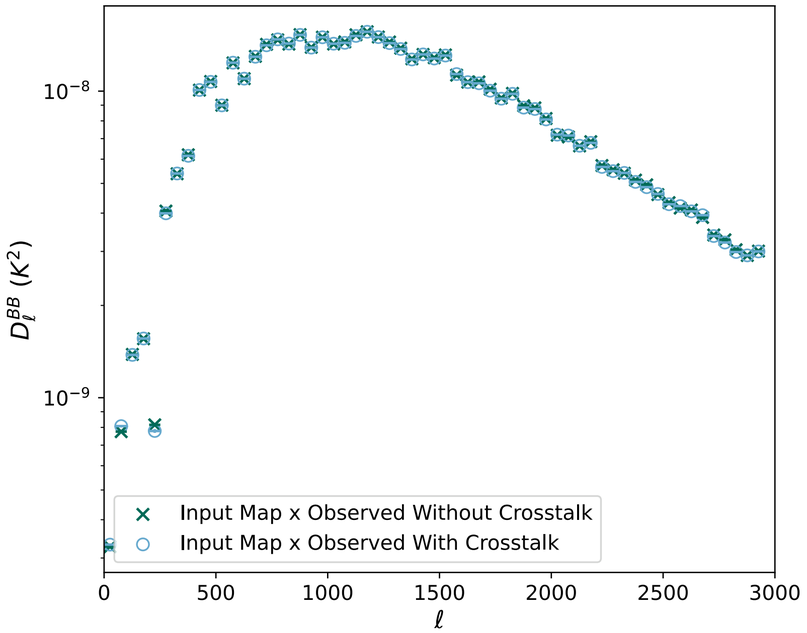
* For Cerro Toco in October

Simulations
CMB scans

TT, EE, BB cross-spectra show optimistic results





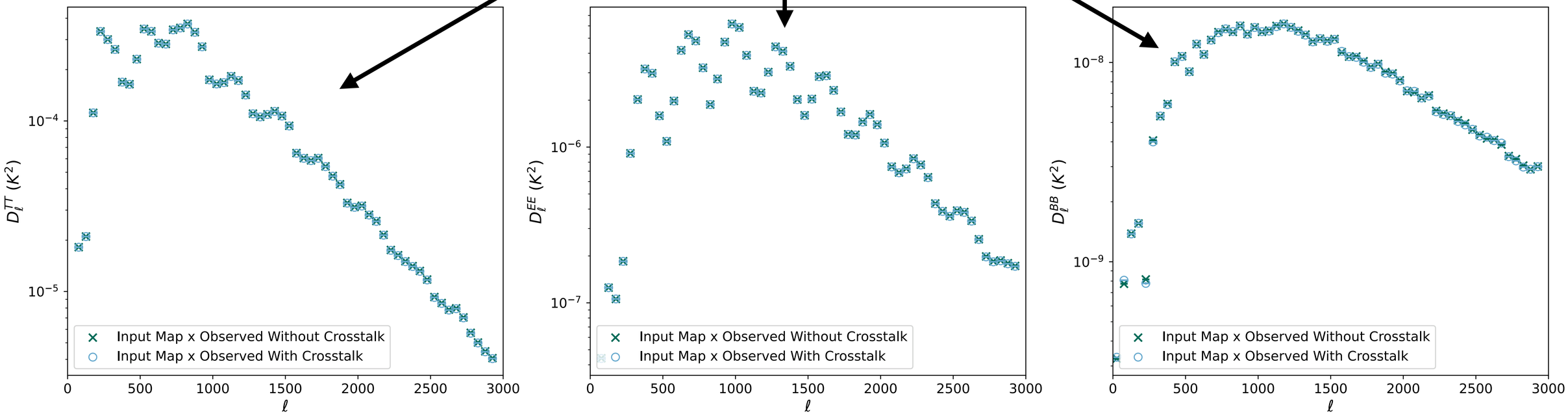


Work in progress; shows simulated 8 hour scan

Simulations
CMB scans

TT, EE, BB cros… …timistic results

Systematic impact of effect appears small



Work in progress; shows simulated 8 hour scan

Simulations
Next steps

We look forward to:

- Expanding simulations to longer integration times and more diverse weather conditions to understand seasonal averaging
- Analyzing considerations for analyses of CMB secondaries and cosmological parameters

Current work suggests that the effect of non-linear crosstalk is small, and that it may be reduced by modeling and/or averaging

Acknowledgements

Thank you

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HEISING-SIMONS FOUNDATION

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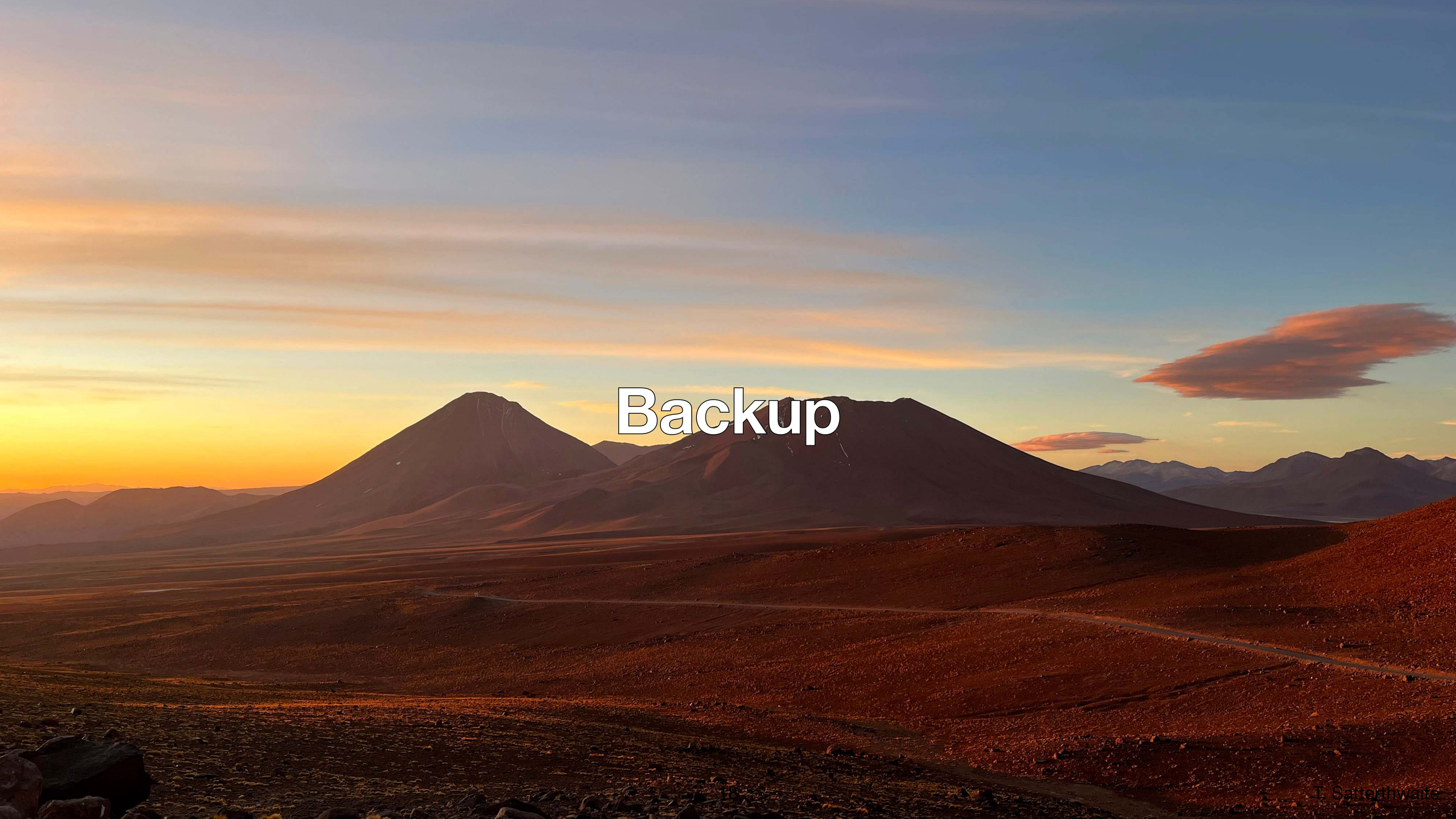
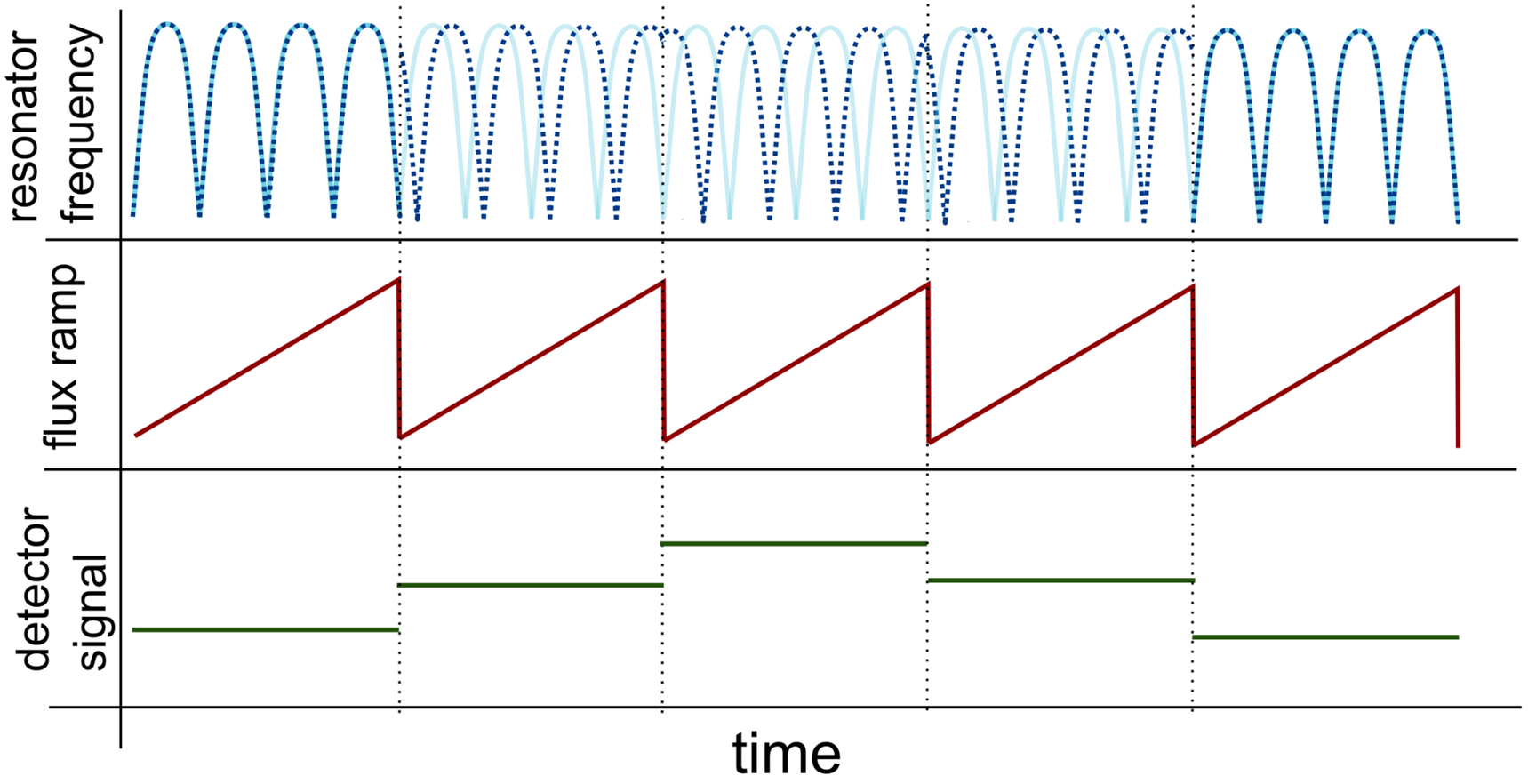
UKRI UK Research and Innovation

科研費 KAKENHI


Backup

Microwave SQUID multiplexing

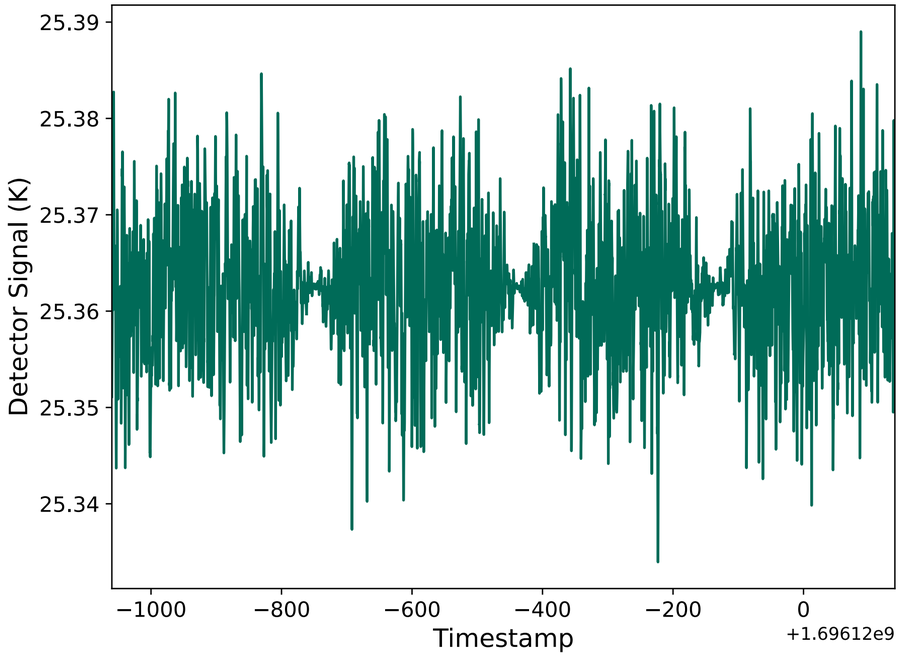
General schematic



Source: Yu+ 23

Simulations
Introduction to TOAST

Time ordered astrophysics scalable tools (TOAST): CMB observation toolkit



Sample detector TOD as generated by TOAST

TOAST allows us to simulate time-ordered data (TOD) for a sample observation using, e.g., SO telescopes

Crosstalk can be injected into TODs to understand its implications

See: GitHub