Large-Format Kinetic Inductance Detector Arrays for Sub-Millimeter Astronomy and Polarimetry

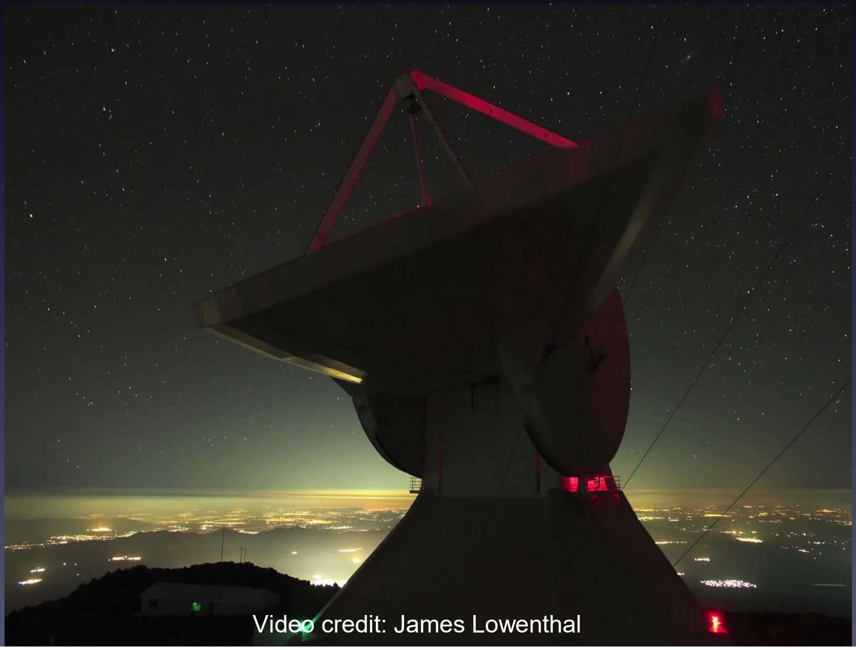
Jason ("Jay") Austermann

NIST-Boulder / University of Colorado-Boulder


Video credit: BLAST Collab.

EAO Futures

Nanjing, China
May 2019


Video credit: James Lowenthal

Large-Format Kinetic Inductance Detector Arrays for Sub-Millimeter Astronomy and Polarimetry

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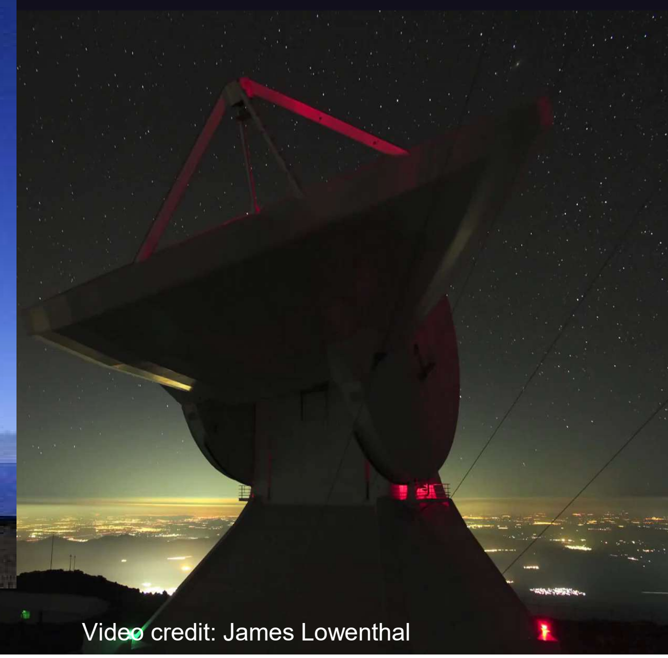
Photo credit: JCMT website



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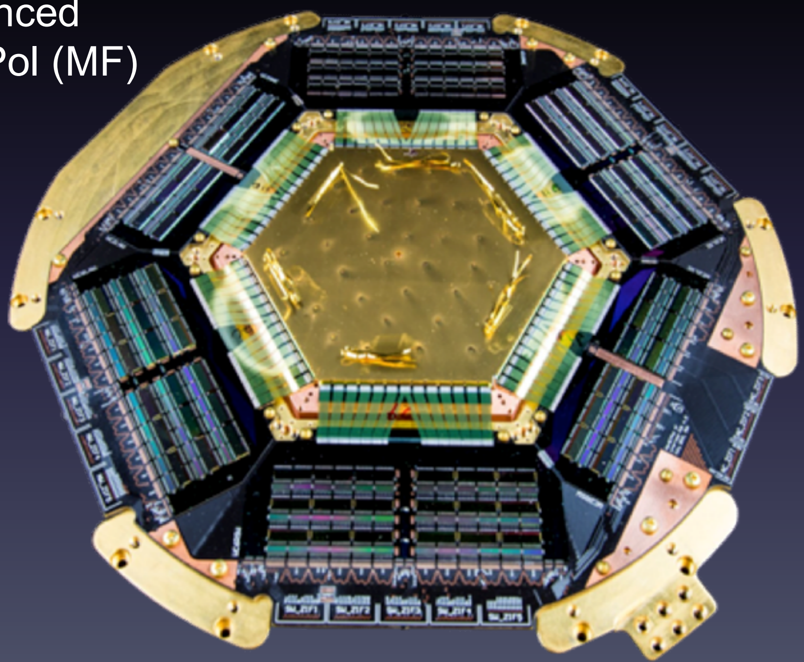
Focal Plane Complexity

State-of-the-art: TES-based

Deployed TES ARRAY (~ 2000 Detectors)
- 1000's wire bonds
- 1000's SQUID amplifiers
- hundreds of additional SC components
- dozens of cables

Advanced ACTPol (MF)



Focal Plane Complexity

TES

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- 1000's wire bonds
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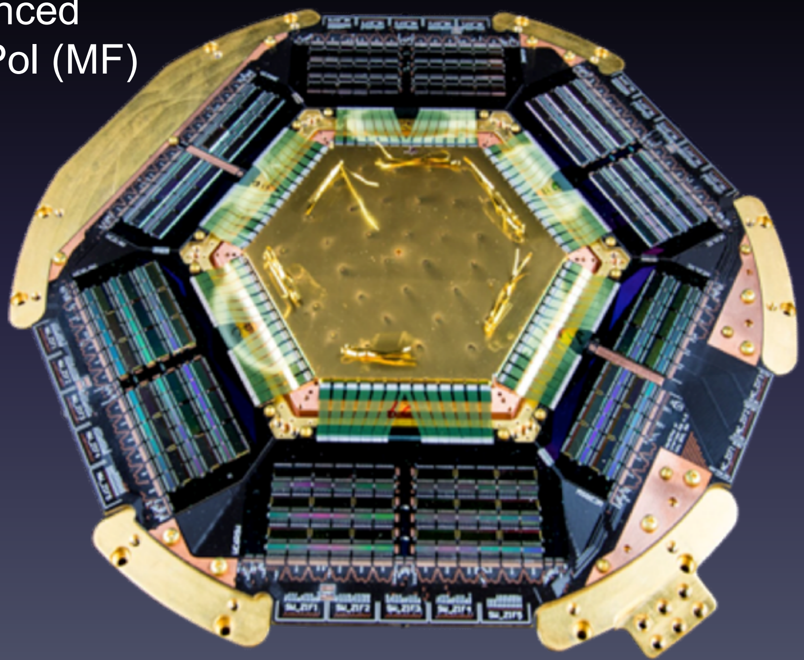
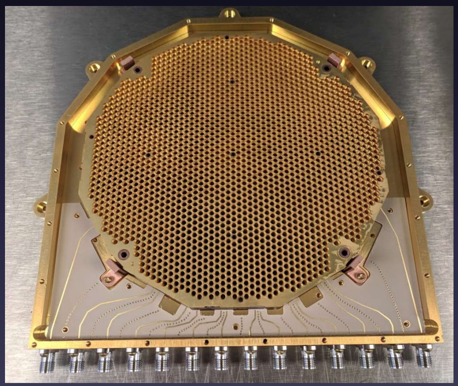


MKID

The Ideal: Integrated readout
e.g. Toltec MKID (4000 detectors)
- 14 wire bonds
- 14 Coax cables
- 14 LNAs

(Roughly the same scale)

Toltec 1.1 mm



(4K LNAs not shown)

NIST-QSG Technology Supported Science:
Applicable areas of our (sub-)millimeter wave technology

- **Cosmology**
  - **Dark Energy, Inflation, Dark Matter, General Relativity, Gravitational Waves, Neutrino physics**
- **Astrophysics**
  - Star Formation, High Redshift Galaxies, Large scale structure, Planetary Disks
- **Other Applications & Possibilities**
  - Novel Cryogenic Technologies
  - Security, QC, Communications, and more
  - Medical Imaging, Spectroscopy, Atmospheric Science
  - Majority of group also works on calorimetry and metrology

NIST-Boulder Quantum Sensors Group

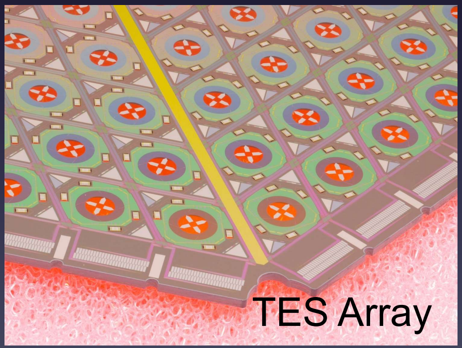
NIST Technology Family

Recent/Past Projects: **ACTPol, SPTpol, ABS**, **SCUBA-2**, (many more for readout)

Ongoing/future: **BLAST-TNG, Advanced ACTPol, Mustang-2, SPIDER, Litebird, ToITEC, Simons Observatory, CMB-S4, ALI-CMB**, and many more for readout (e.g. SPT-3G, BICEP/KECK, etc)

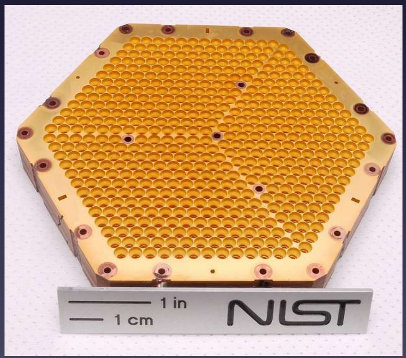
Multiple technology development grants for various detectors, readout, and mm-wave optical components

Detectors



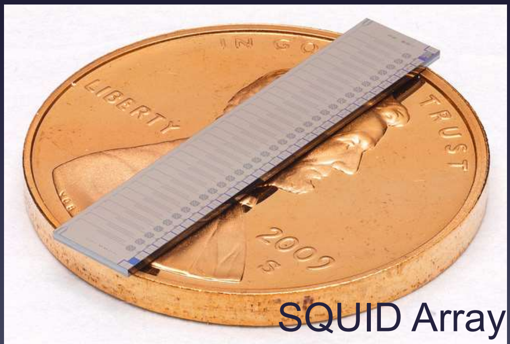
Arrays of 1,000's of detectors

Coupling Optics



High-Precision
Low-Systematics

Cold Readout



Amplifiers, Resonators, cryo-electronics for multiplexing

Fabrication

Reliability, Uniformity and Performance

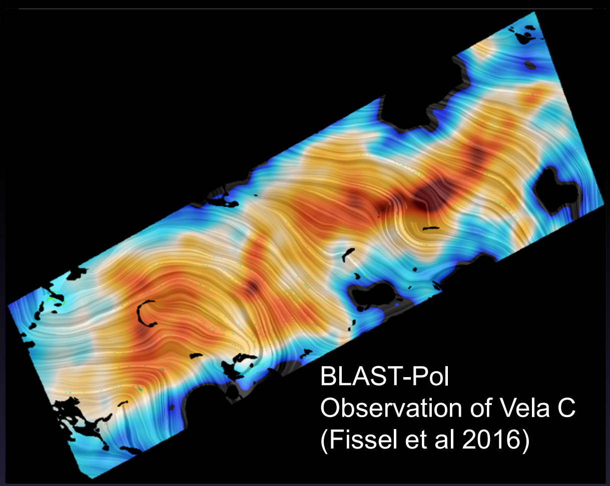
BLAST-TNG

- High-Altitude Balloon telescope, 2.5-meter primary
- **~ 3,500 polarization sensitive KIDs**
- Roach2 Multiplexed Readout (ASU)
  - ~1 MHz channel spacing, 500 MHz bandwidth
- Bath Temperature: **275mK**
- Expected Flight: **Dec 2019**
- 3 bands (micron): **250 350 500**
- Beamsize (arcsec): **25 35 50**
- Strength: Sub-mm polarimetry in hard to access wave bands

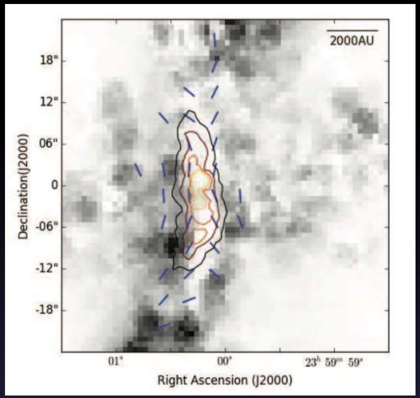
TOLTEC

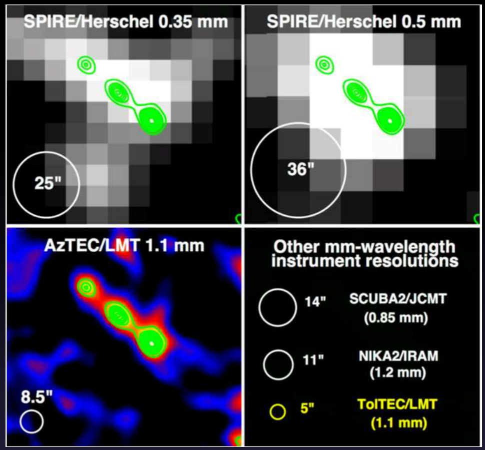
- 50-meter diameter Large Millimeter Telescope (LMT)
- **~ 7,000 polarization sensitive KIDs**
- Roach2 Multiplexed Readout (ASU)
  - ~1 MHz channel spacing, 500 MHz bandwidth
- Bath Temperature: **100 mK**
- Expected first light: **Aug 2019**
- 3 bands (micron): **1100 1400 2000**
- Beamsize (arcsec): **5.0 6.3 9.5**
- Strength: high mm-wave mapping speeds w/ high angular resolution

Wide ranging science applications



Simulated Toltec obs of protostellar region

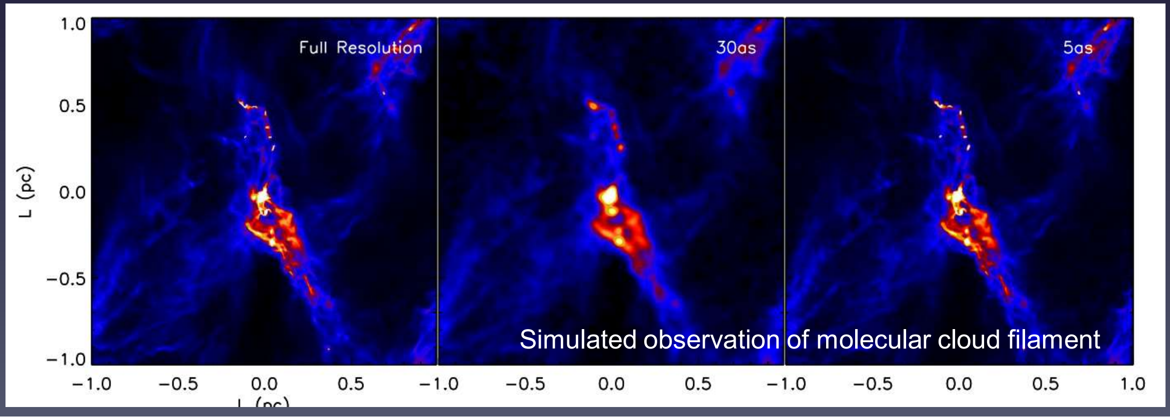


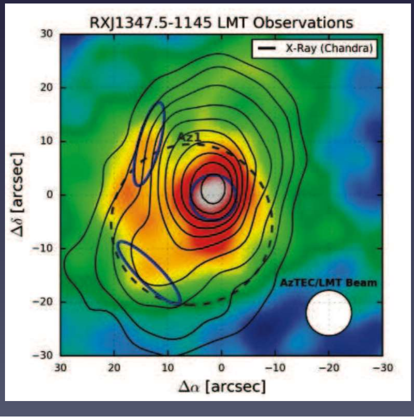


High-redshift star-forming galaxies

Star Formation, Molecular clouds

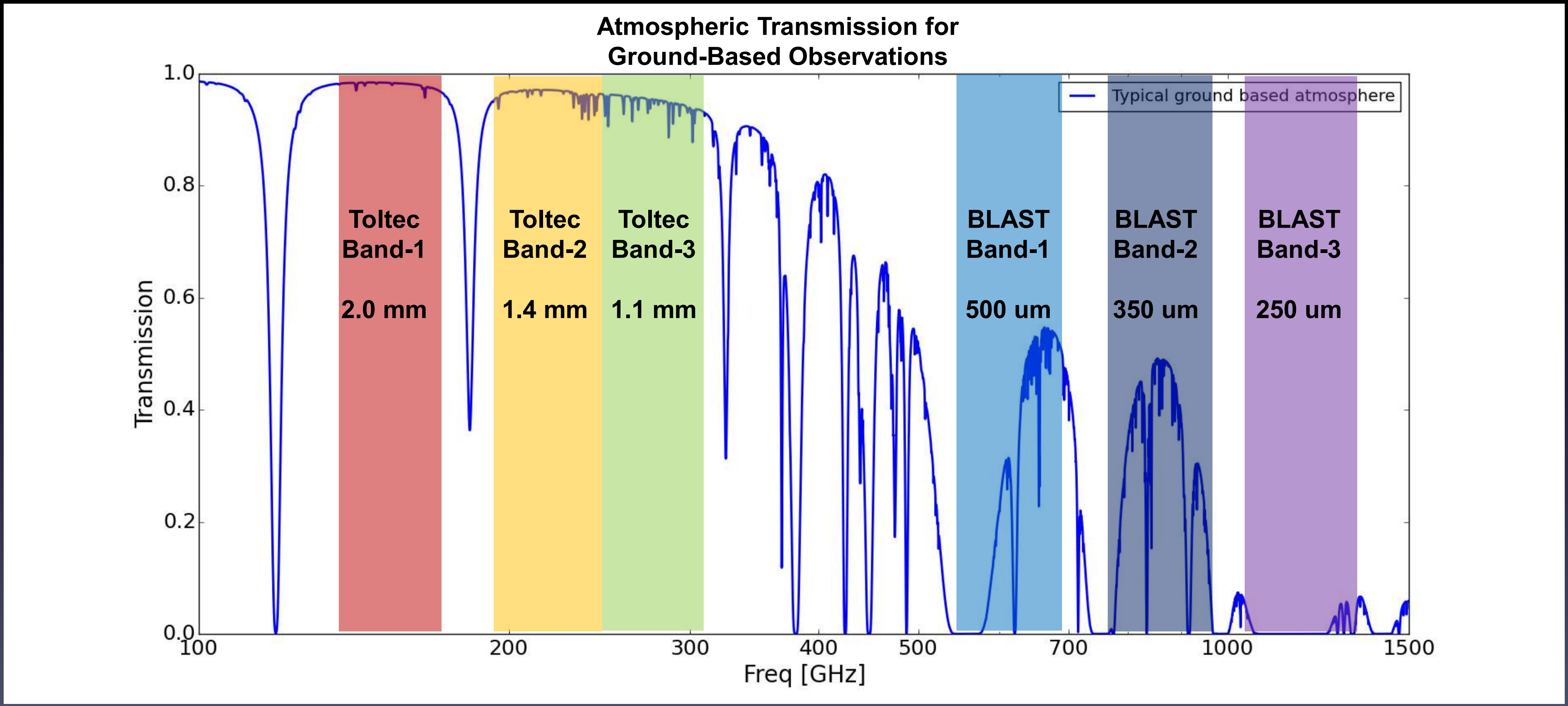
Extragalactic





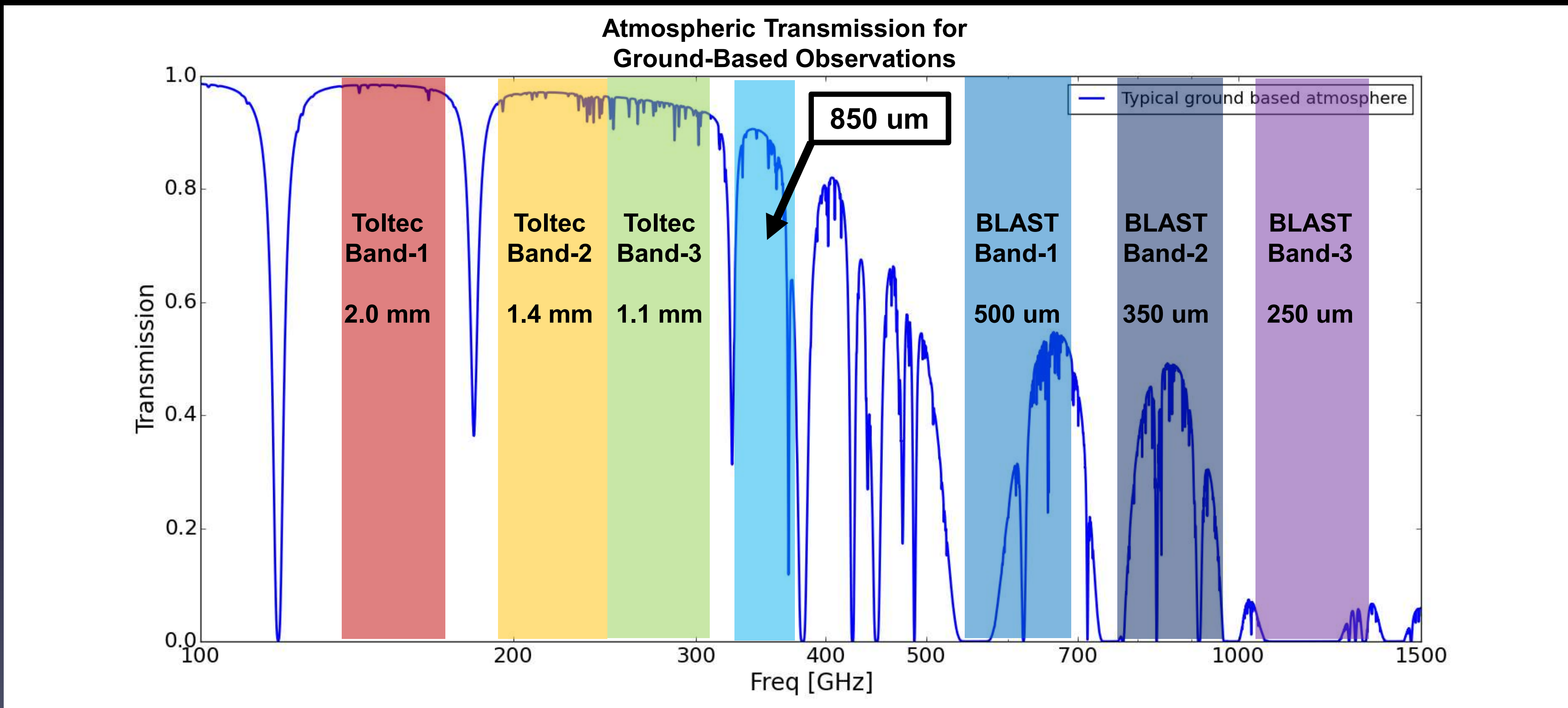
AzTEC/LMT observation (color) of SZ cluster

Order of magnitude frequency coverage



CSO atmospheric model, 0.5 PMV

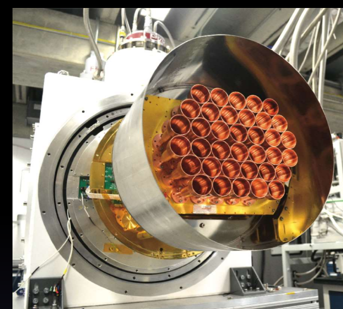
Order of magnitude frequency coverage



CSO atmospheric model, 0.5 PMV

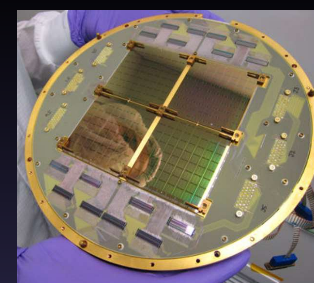
Optical Coupling Scheme drives Pixel Design

- Feedhorn Coupled Waveguide



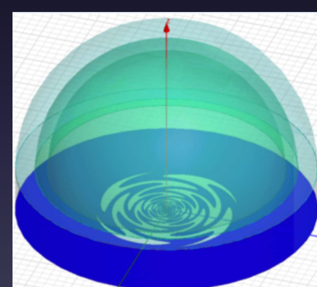
CLASS
40 GHz
Array

- Bare Antenna Arrays



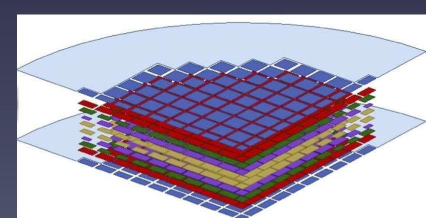
Caltech/JPL
BICEP/KECK/SPIDER

- Hemispherical Lenslets



POLARBEAR & SPT Collaborations

- Metamaterial Lenslets



NIST/CU/Cardiff
Early Development

Optical Coupling Scheme drives Pixel Design

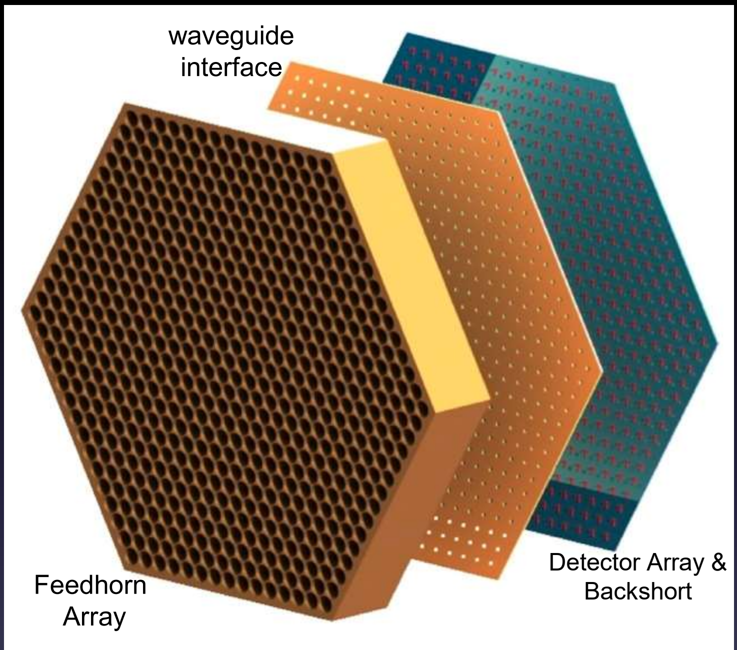
- **Feedhorn Coupled Waveguide**
- Bare Antenna Arrays
- Hemispherical Lenslets
- Metamaterial Lenslets

Why Feedhorns? Why Silicon?

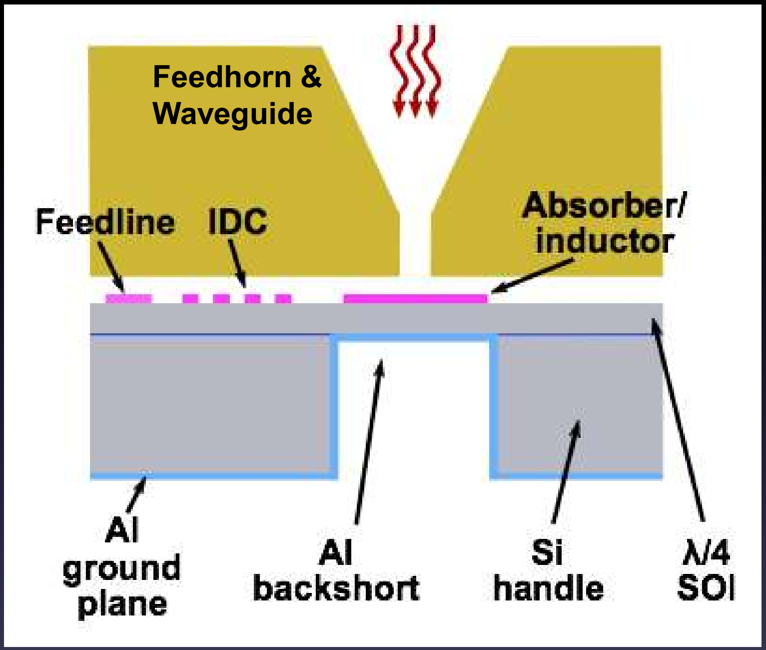
- **High focal plane efficiency**
- **CTE matched to Si detector wafer**
- Planar interface
- Frequency and pitch scalable
- High precision and uniformity (lithography)
- Natural high-pass and RF shield (waveguide)
- **Low Systematics**
  - Symmetric beams
  - Low cross section to stray light
  - No AR coating required

Arrays

Typical NIST Detector Stack

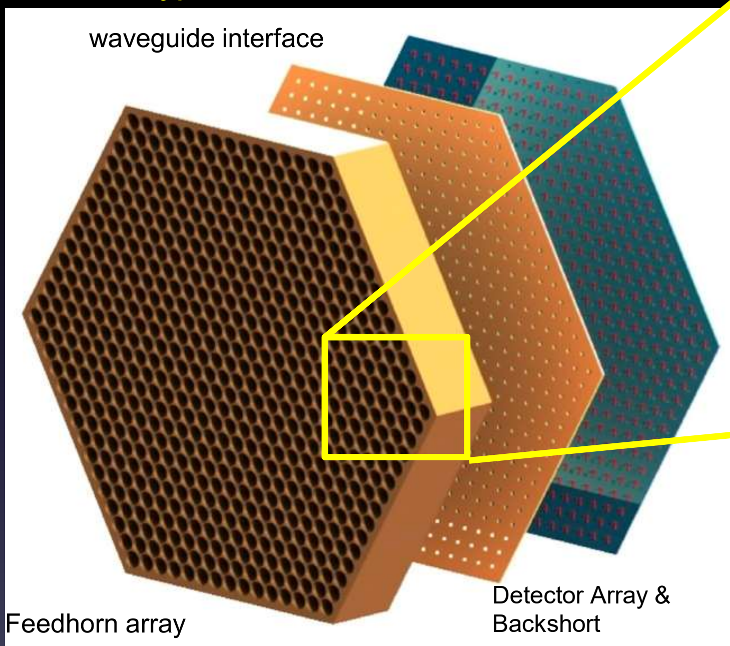


Cross Section

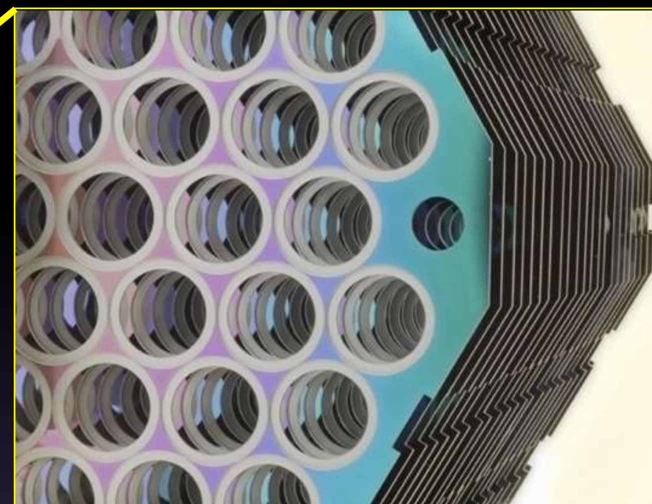


NIST Silicon Feedhorn Arrays

Typical NIST Detector Stack

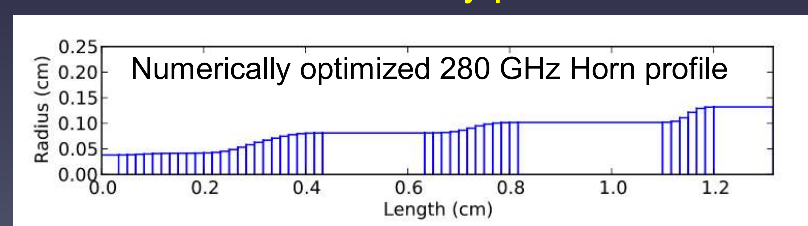


Silicon Platelet Stack

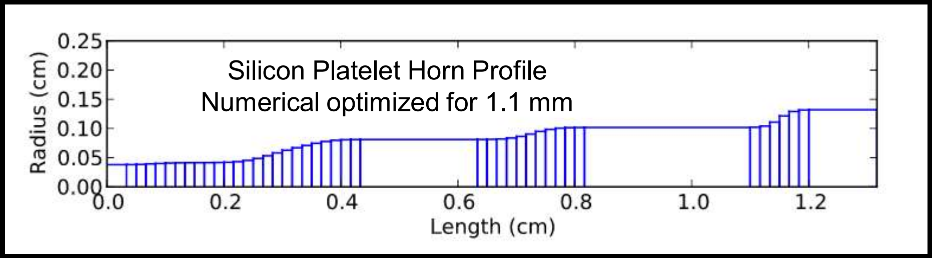


Exploded View

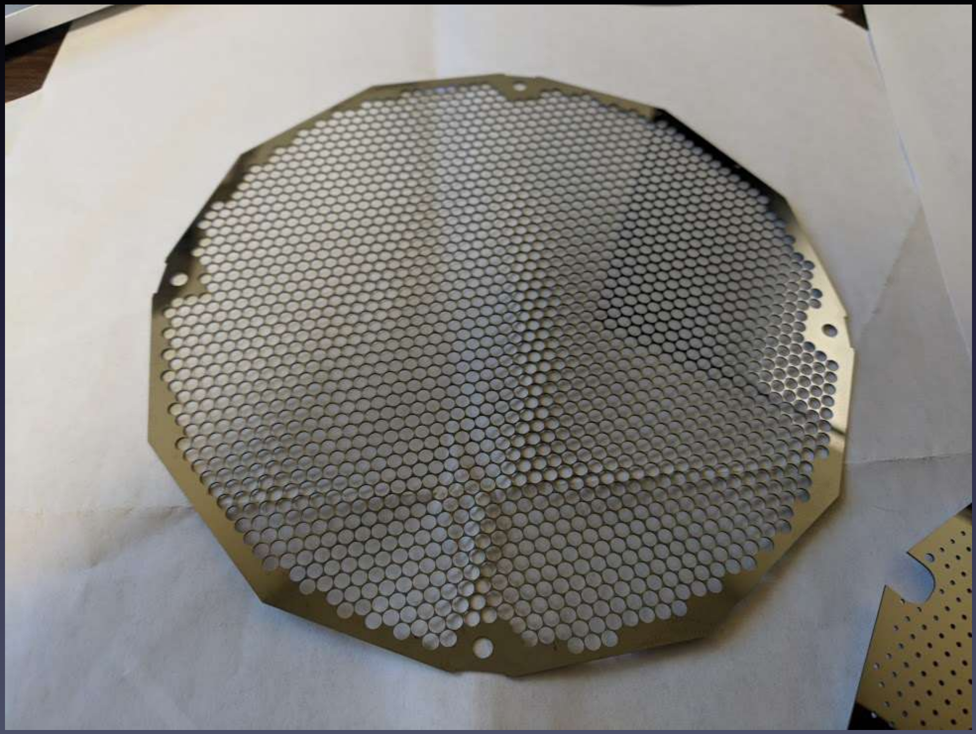
Build almost any profile



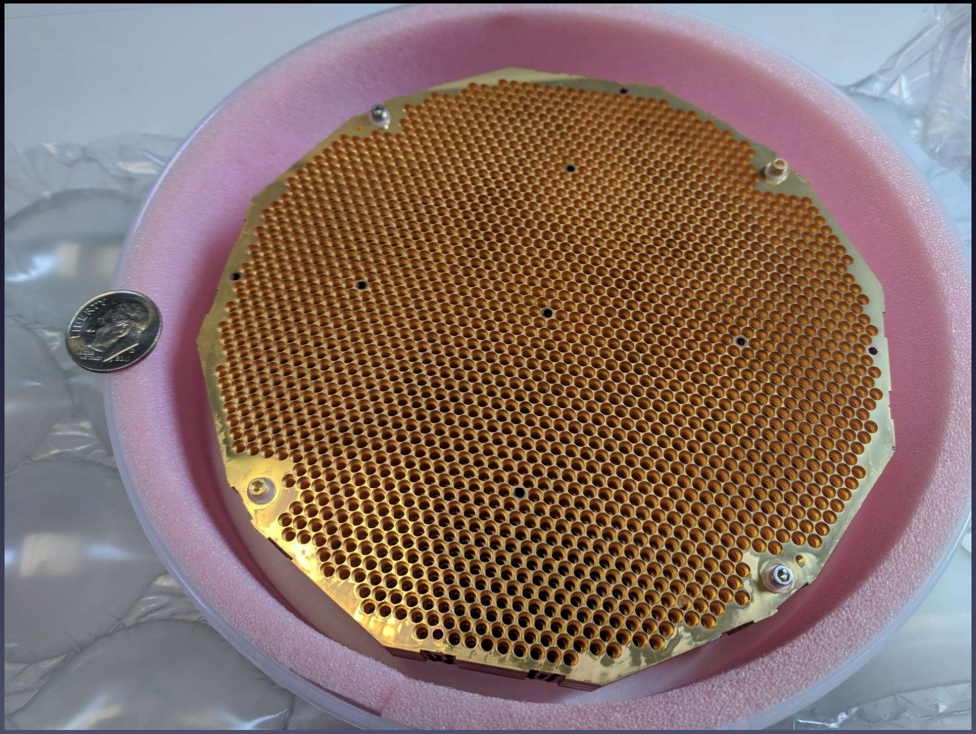
Feedhorn Arrays



1.1 mm horn platelet

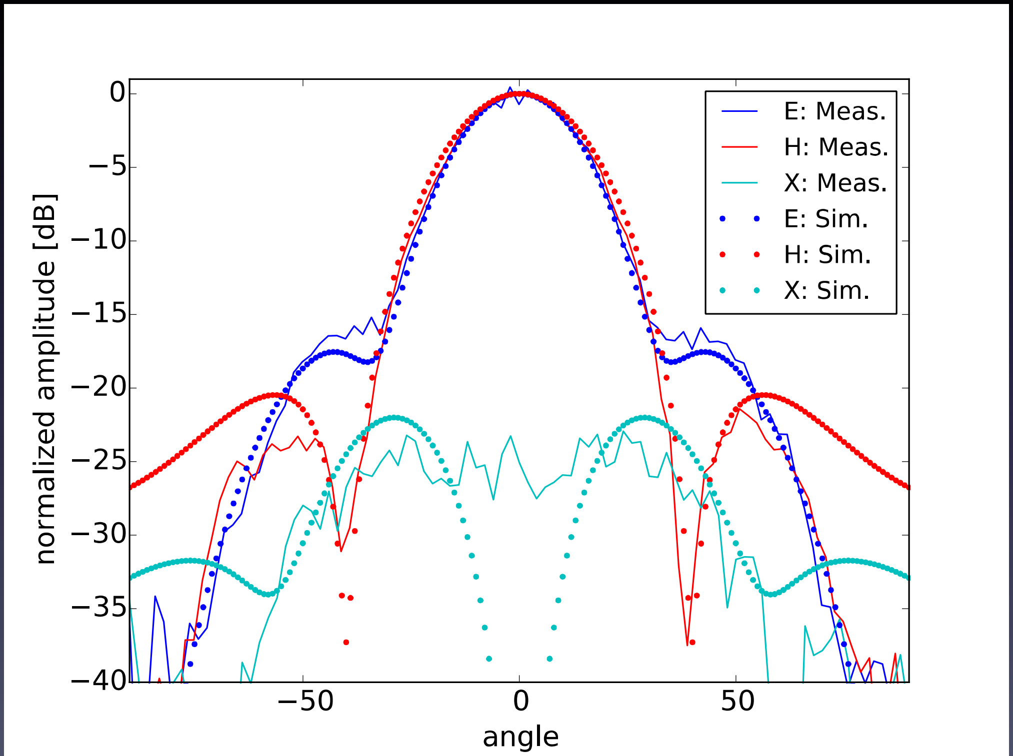


Full 1.1 mm Feedhorn Array



Feedhorn Arrays

1.1mm horn
measurement vs simulation



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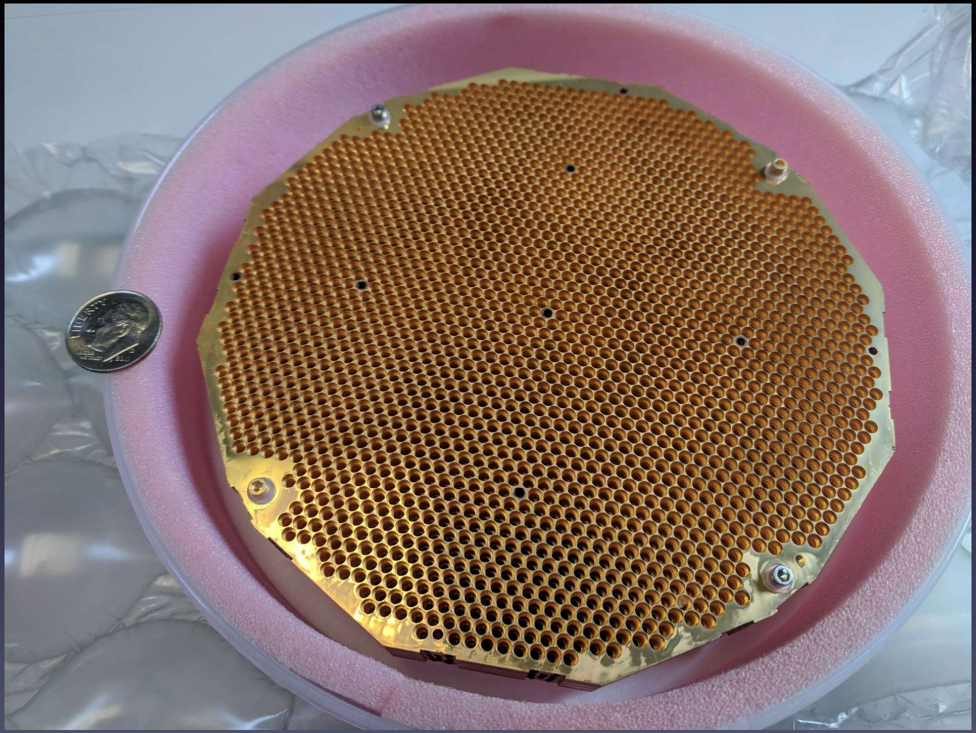
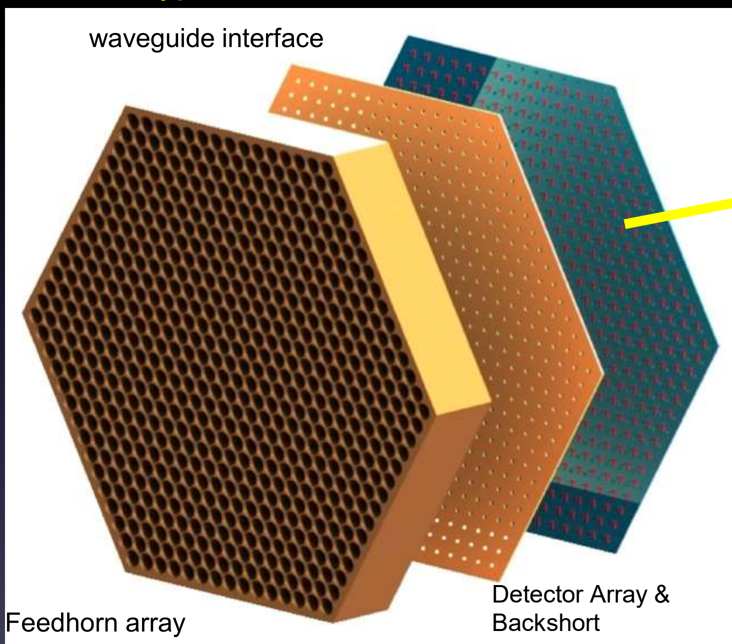
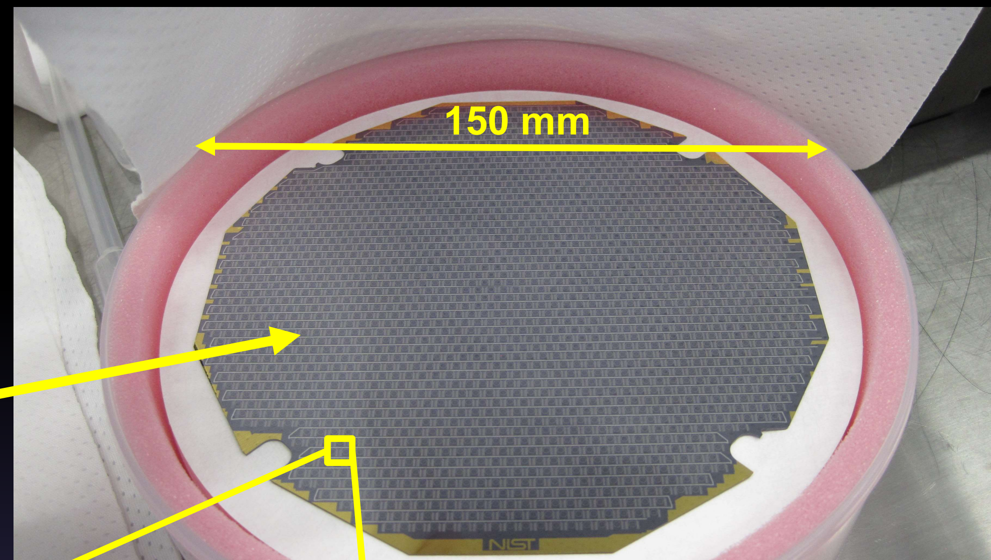


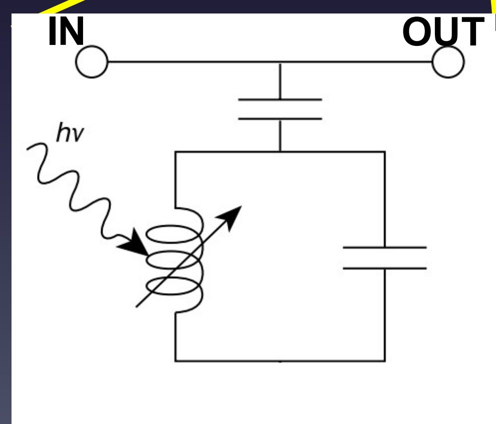
Kinetic Indctance Detectors (KIDs)

Typical NIST Detector Stack

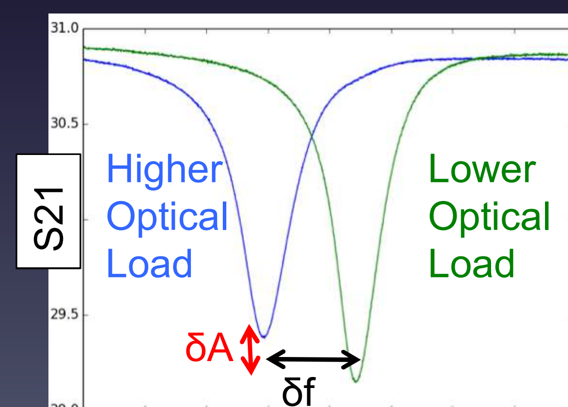


Toltec 1.1mm Detector Array (4000 KIDs)





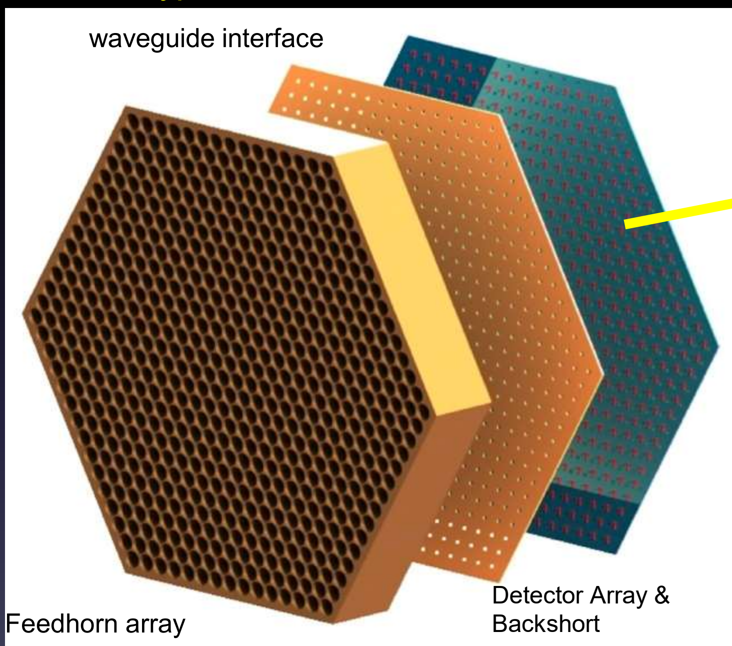
Edited from
Day et al. (2003)



(NIST MKID data)

Kinetic Indctance Detectors (KIDs)

Typical NIST Detector Stack



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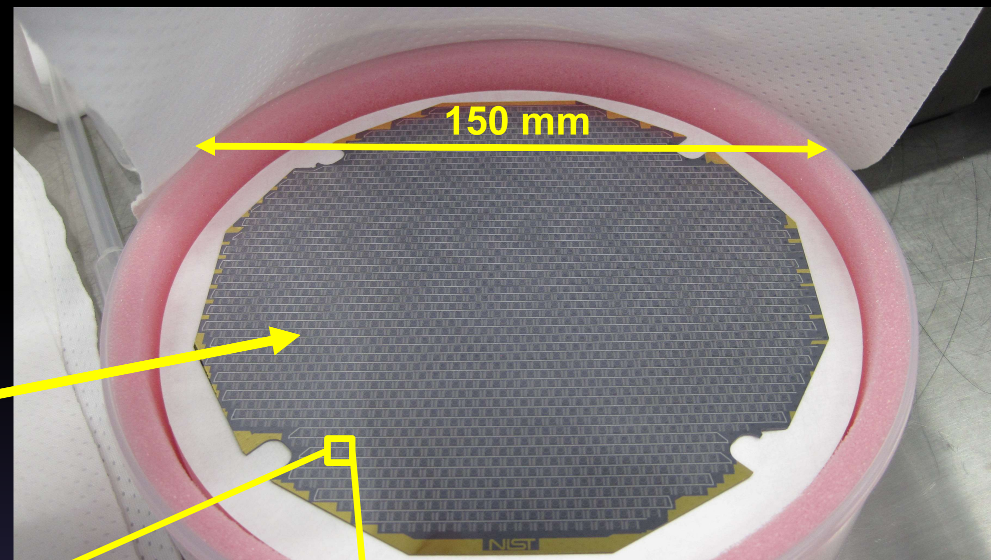

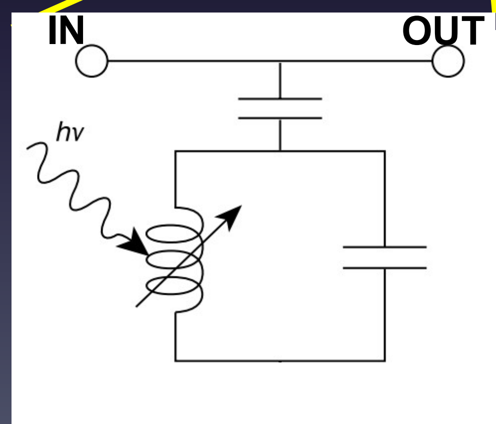

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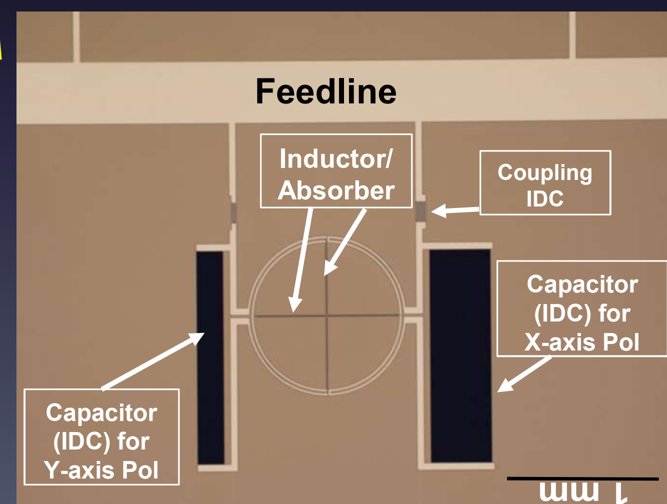
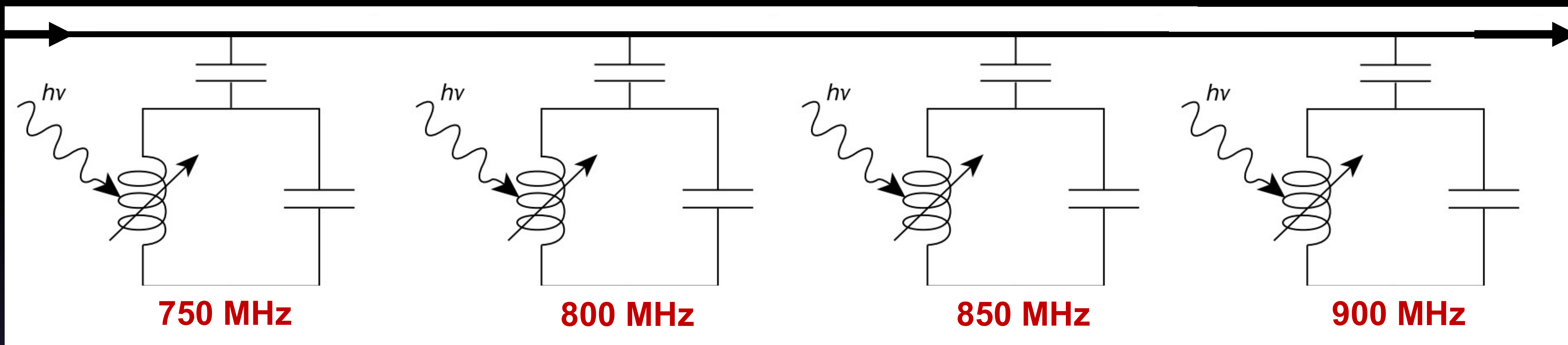


Array multiplexing



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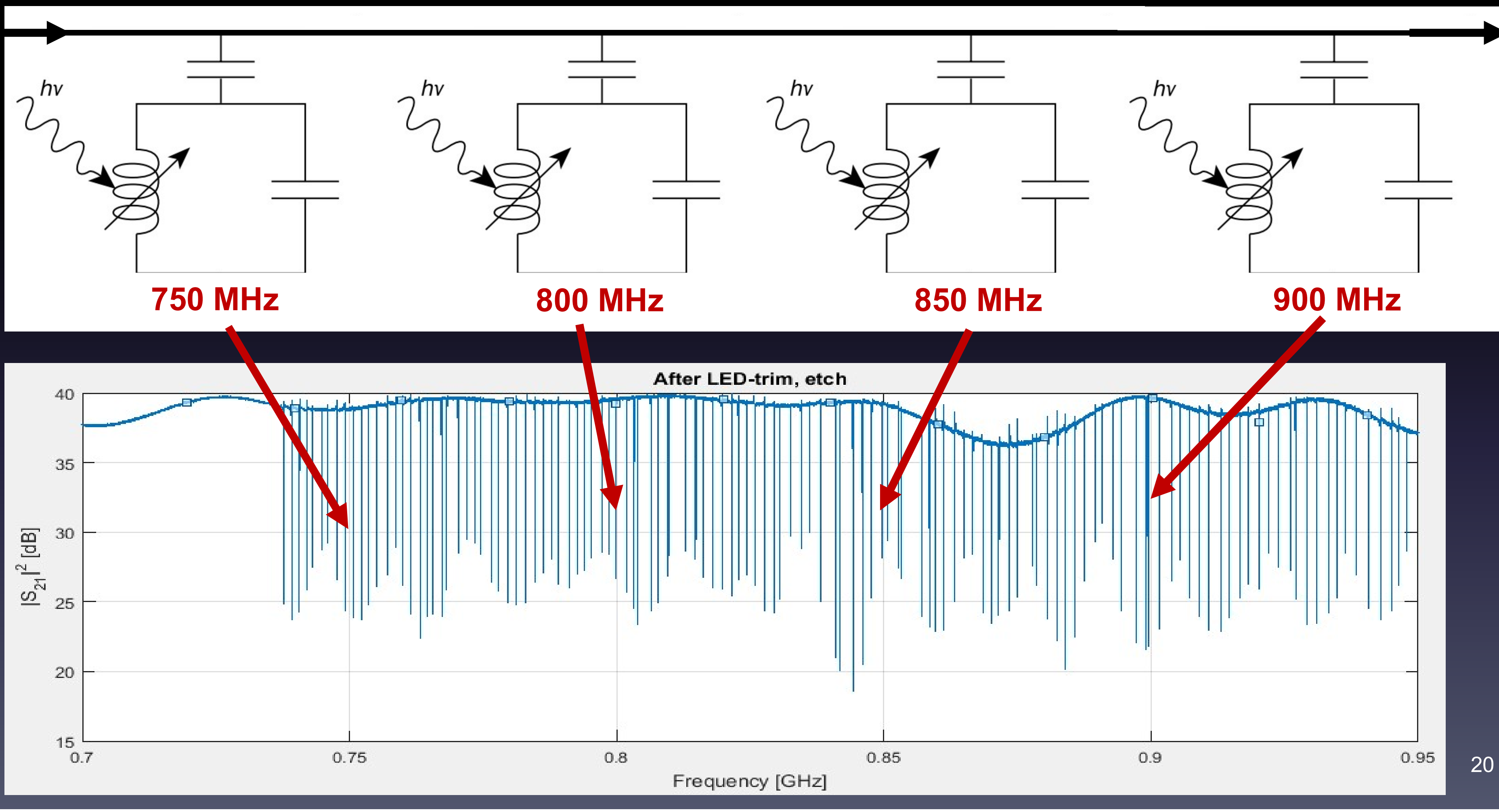
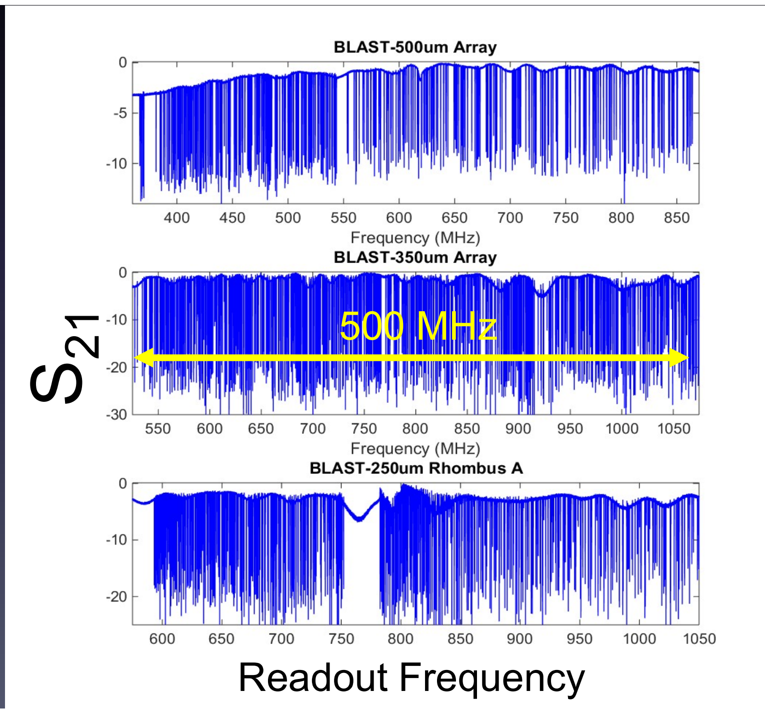
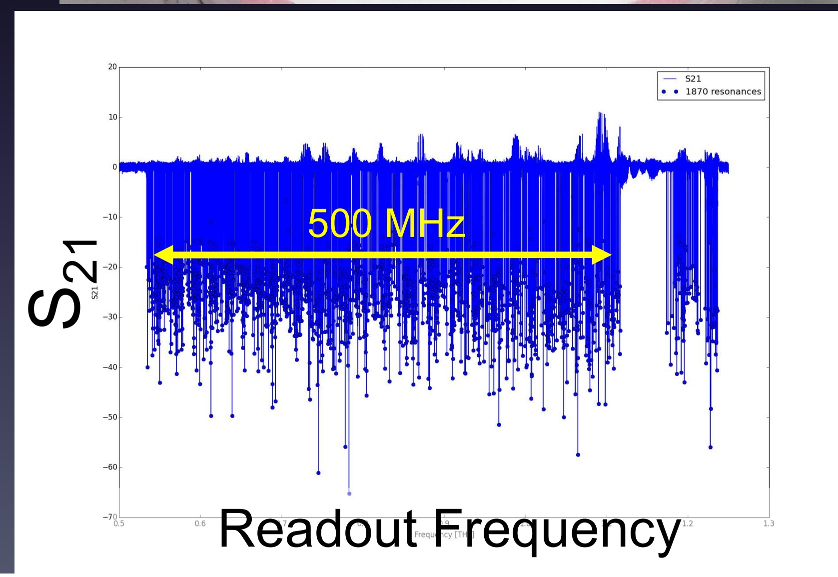


Arrays: densely populated networks

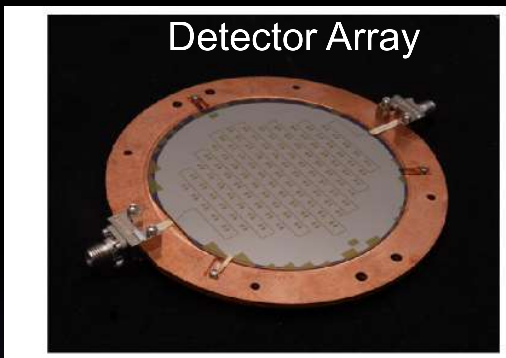
BLAST-TNG



Toltec

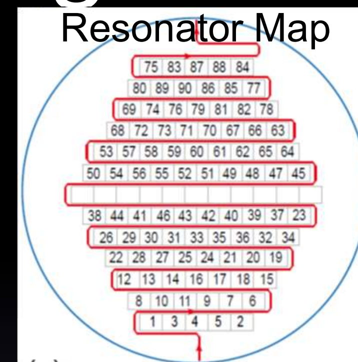


Resonator-to-pixel mapping



?

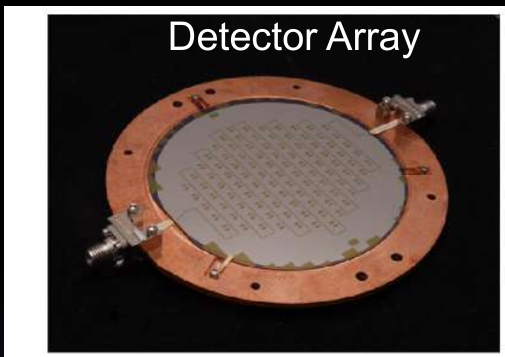
Physical
map?

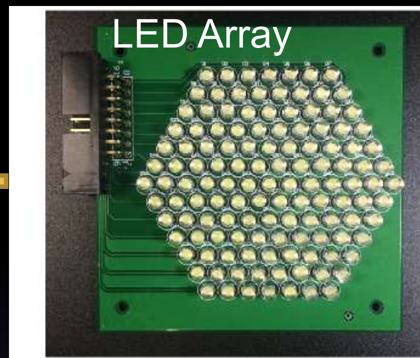


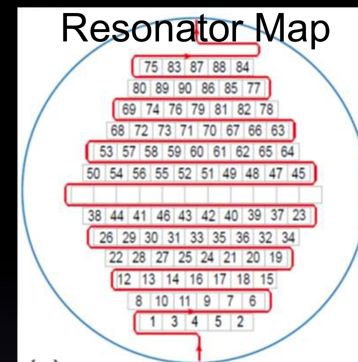
Problem 1

Errors in frequency placement can lead to an ambiguous mapping between physical detector and resonator

LED Trimmer/Mapper







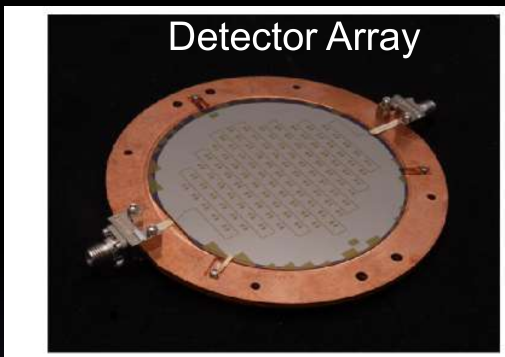
Use array of uniquely addressable cold LEDs to identify correspondence between resonator frequency and physical position

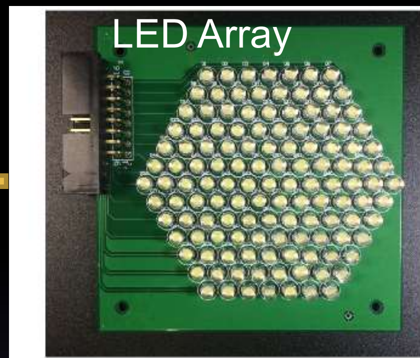
Problem 2
Frequency collisions can lead to a loss in usable yield

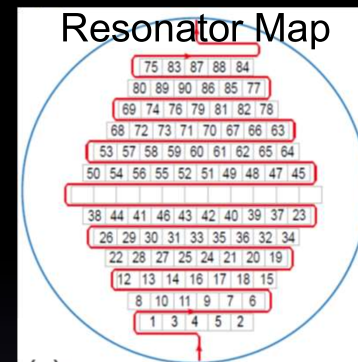
Y. Wang, *et al.* JAP (2017)

In collaboration with Y Wang, L.F Wei, *et al.* Southwest Jiaotong University, Chengdu, China

LED Trimmer/Mapper







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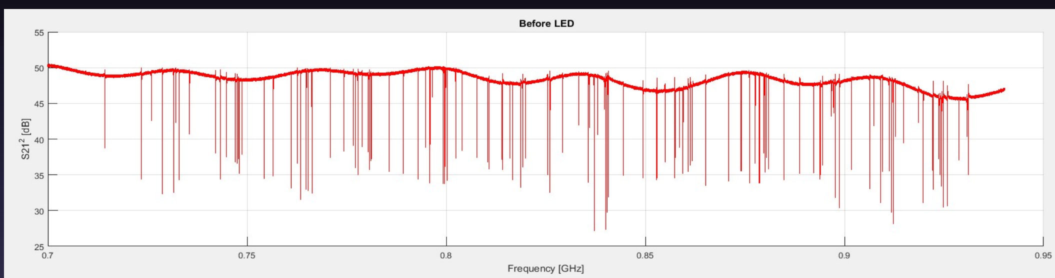
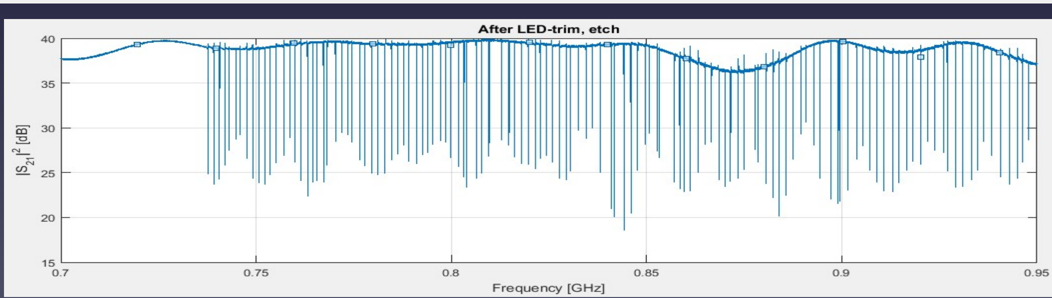
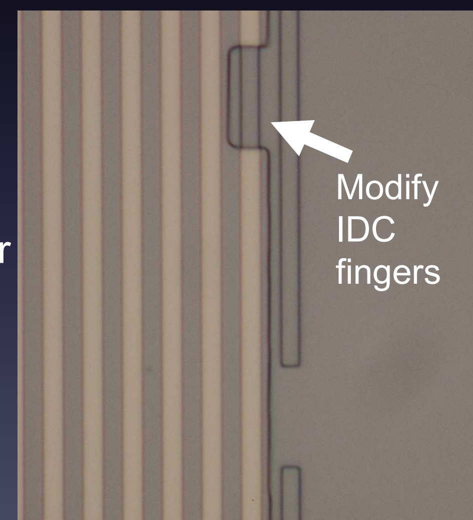




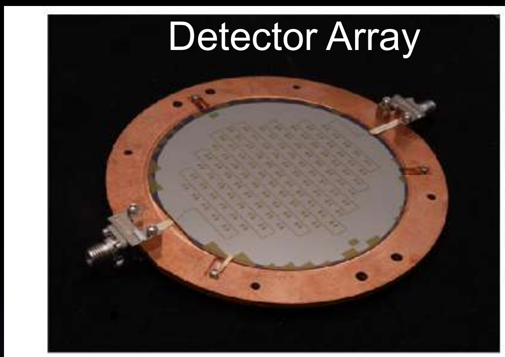
- Re-etch the resonators to correct for fabrication non-uniformity.
- Array of resonators after trimming etch much more uniform.
- Usable yield (5 LW) :
  86% -> 98.5 %

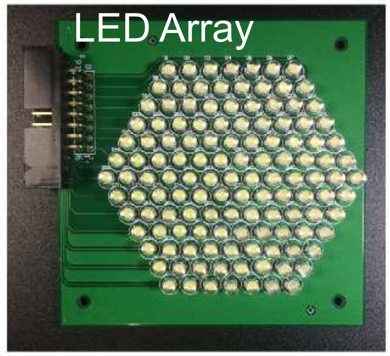


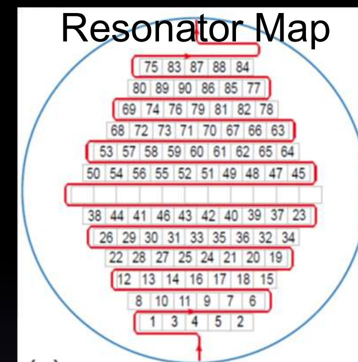
Liu, *et al.* ApL (2017)

In collaboration with Southwest Jiaotong University, Chengdu, China

LED Trimmer/Mapper







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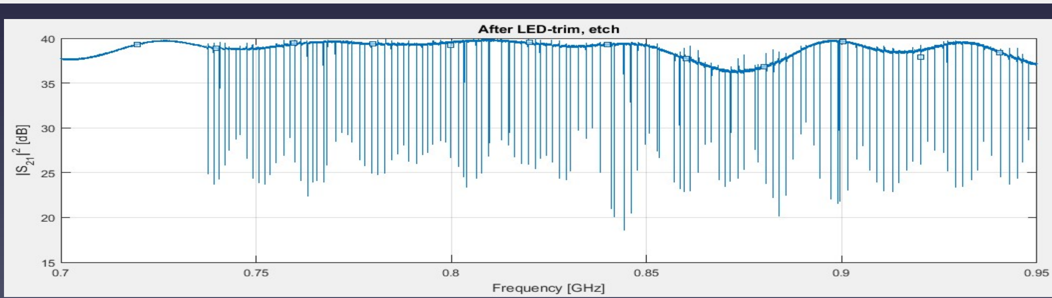

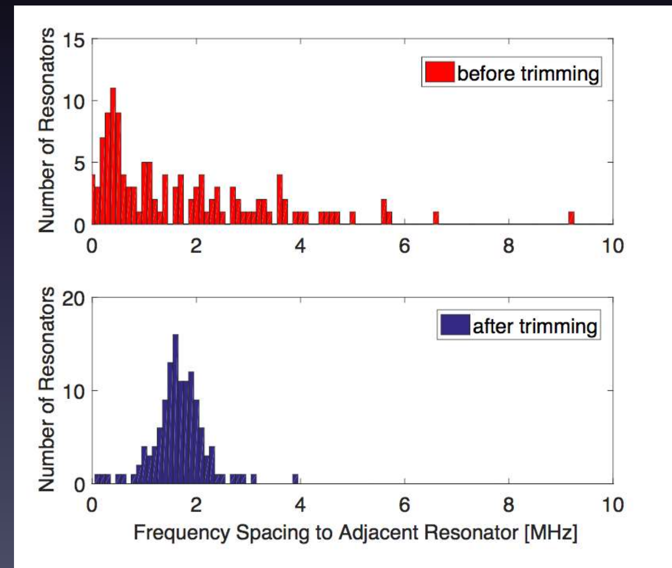

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In collaboration with Southwest Jiaotong University, Chengdu, China

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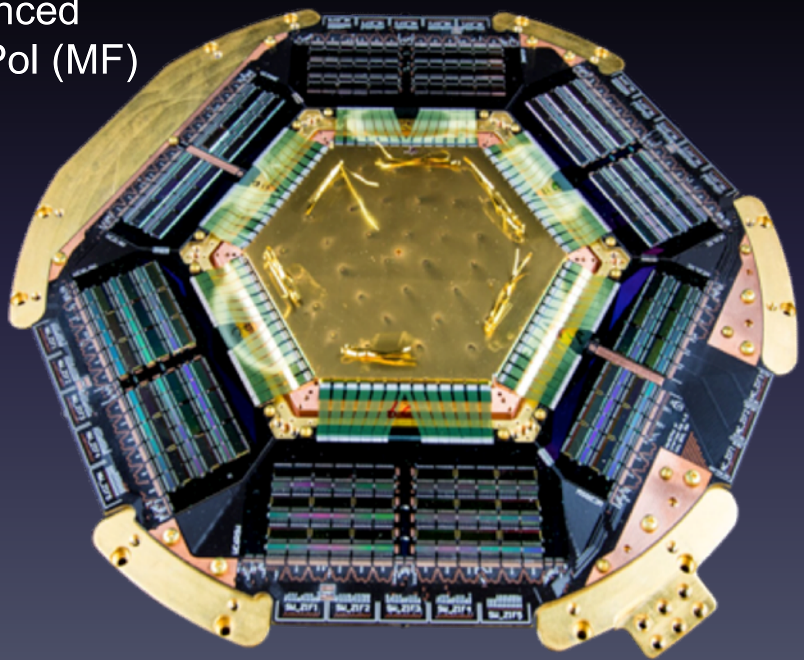

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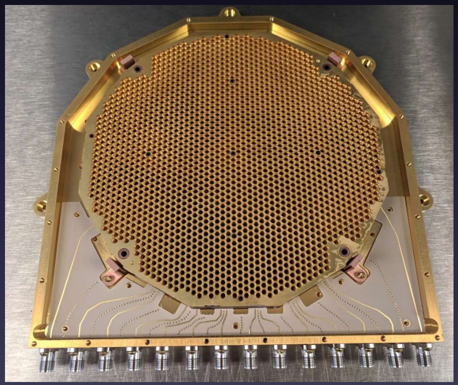
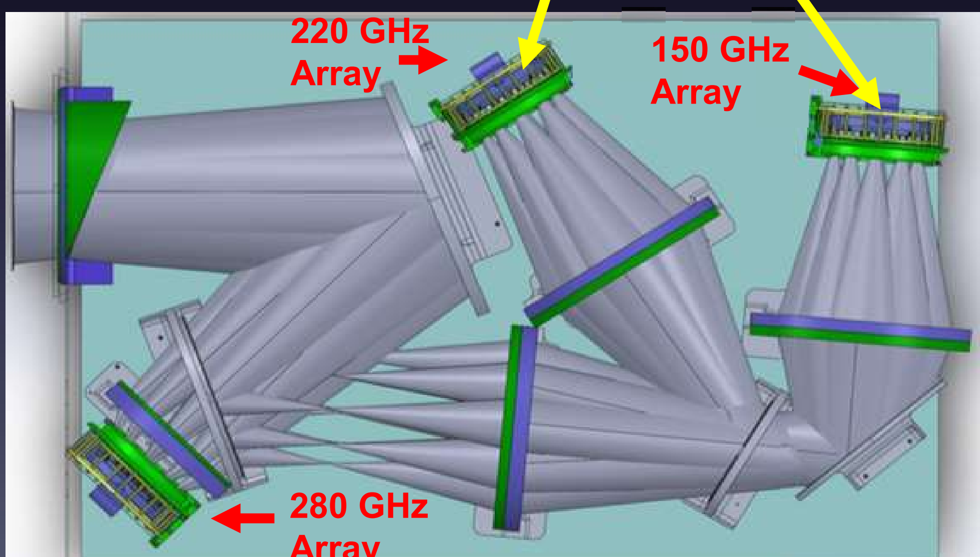
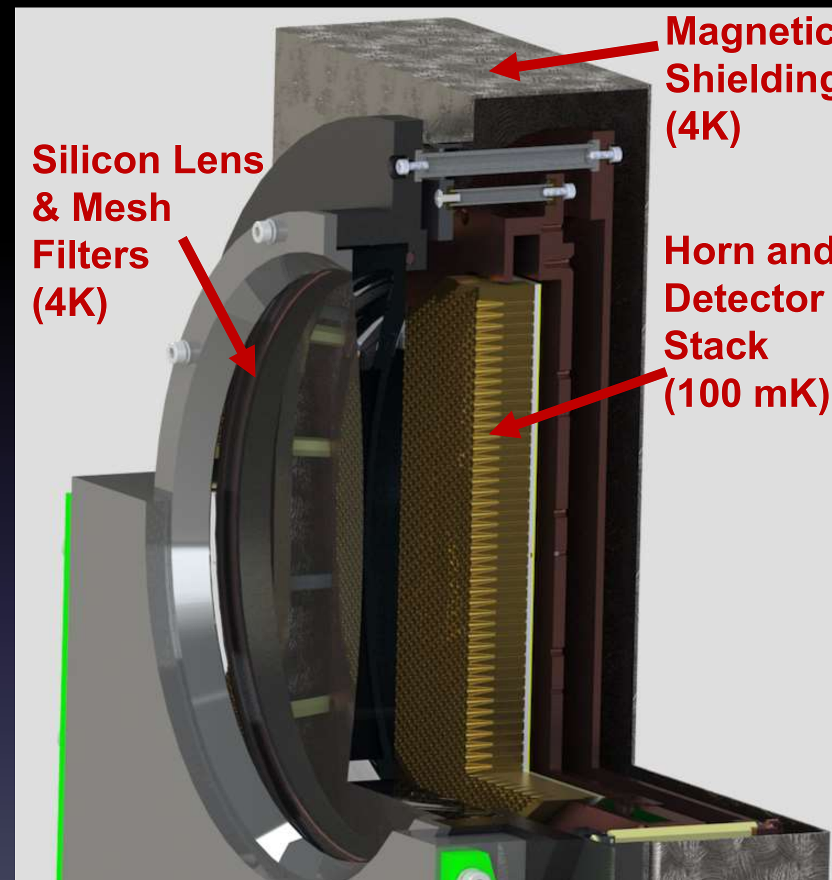


Integration/ Coupling

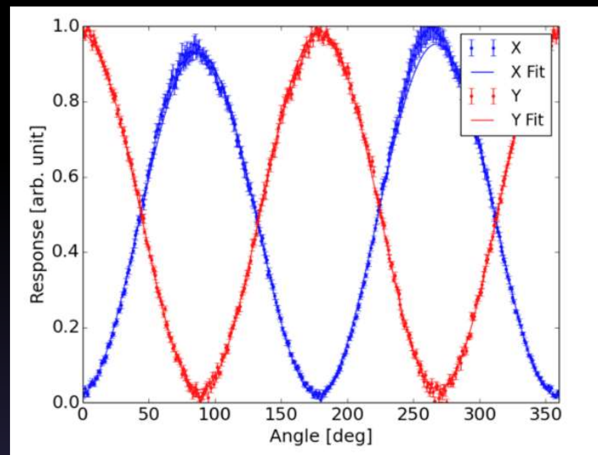




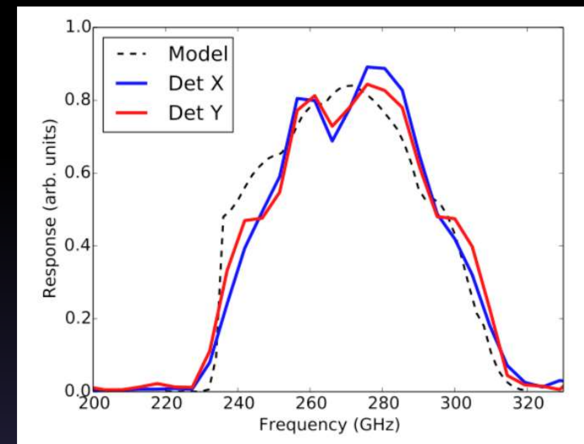
Low Noise Amplifiers (4K) below focal plane

Measured Optical Performance

Excellent cross-pol rejection



Passbands Match Simulation

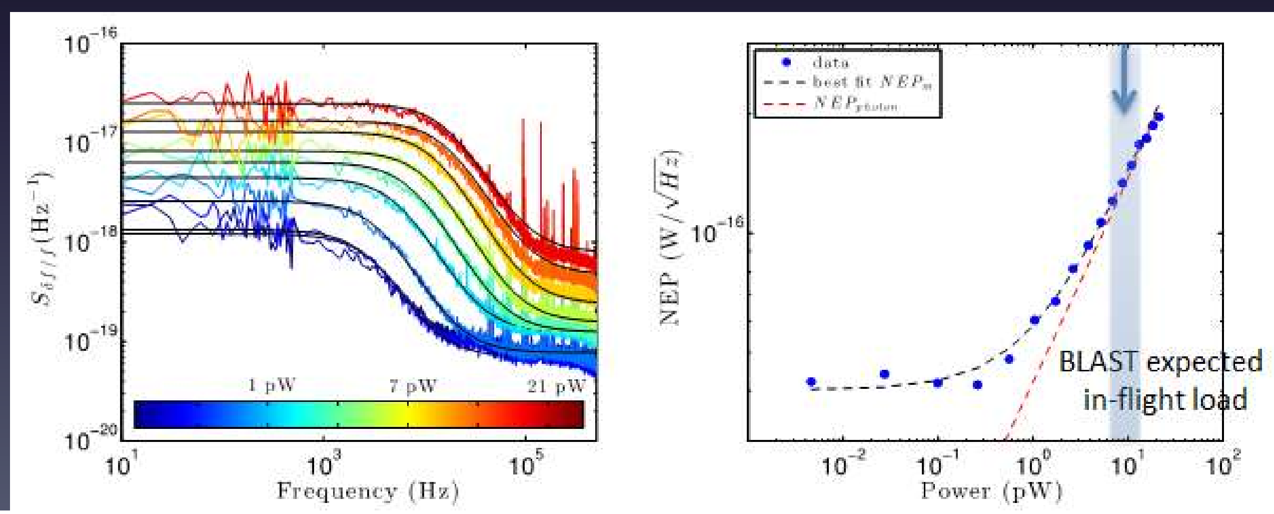


Polarization efficiency and frequency response match simulations and modeling

Cross pol < 2%

Austermann et a. 2018

Photon-Noise Limited Performance (250um band)



Hubmayr et al, APL 106, 073505 (2015).

Summary

- Large monolithic KID-based Polarimeter arrays on 150 mm diameter substrates
  - Usable area ~ 130mm diameter
- High Multiplexing factors (500+ per octave) w/ few interconnects and cold readout components
- LED mapper + MLA modification could allow higher multiplexing factors AND nearly 100% yield
- Excellent optical performance
- Matched well with silicon-platelet feedhorn technology
- Multiple on-sky verifications coming in the next 6--8 months (TolTEC & BLAST)