Kilopixel-Scale Arrays of Kinetic Inductance Detectors

on 150 mm Diameter Substrates for the TolTEC Millimeter-Wave Polarimeter

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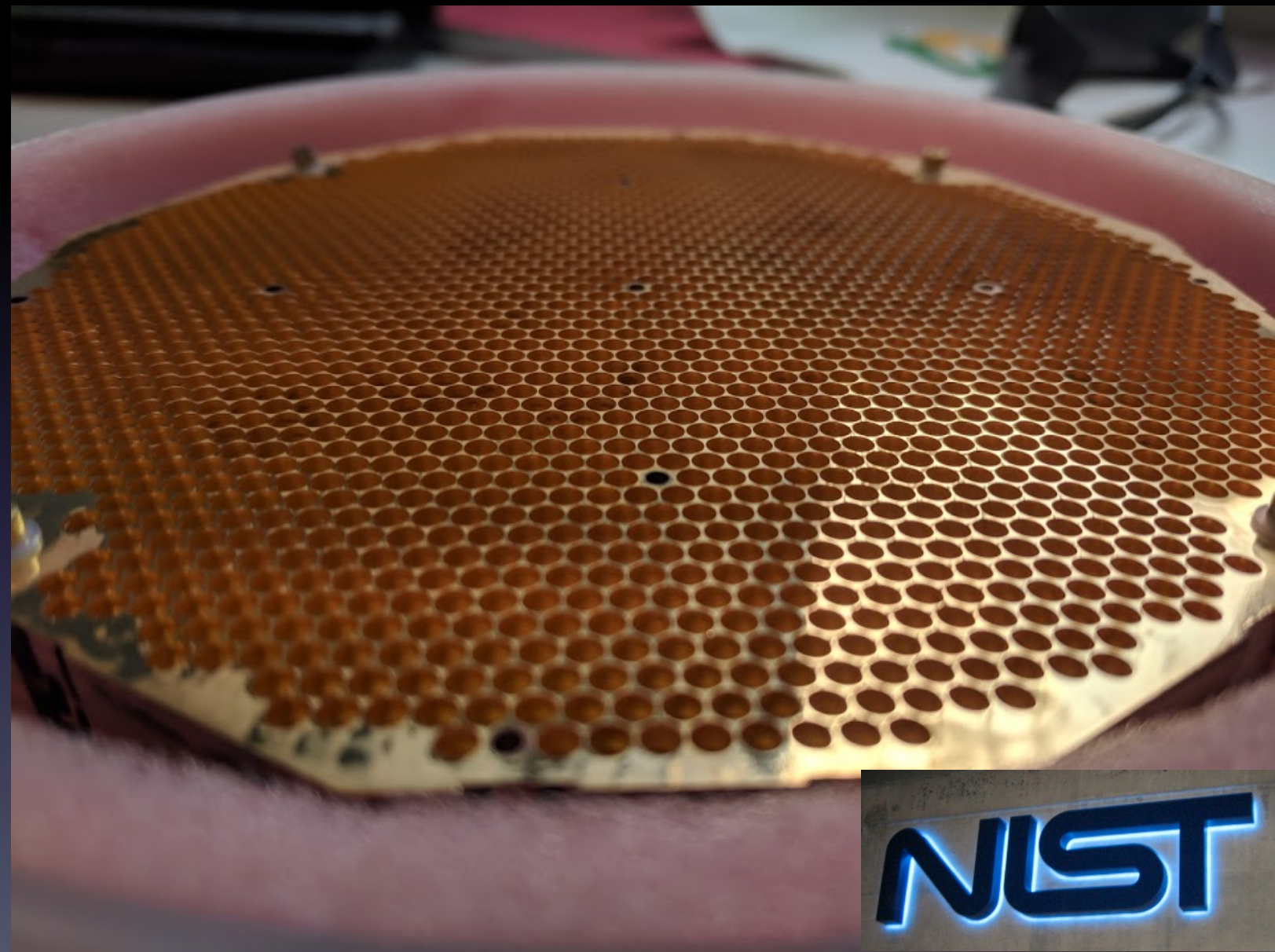
NIST-Boulder / CU-Boulder

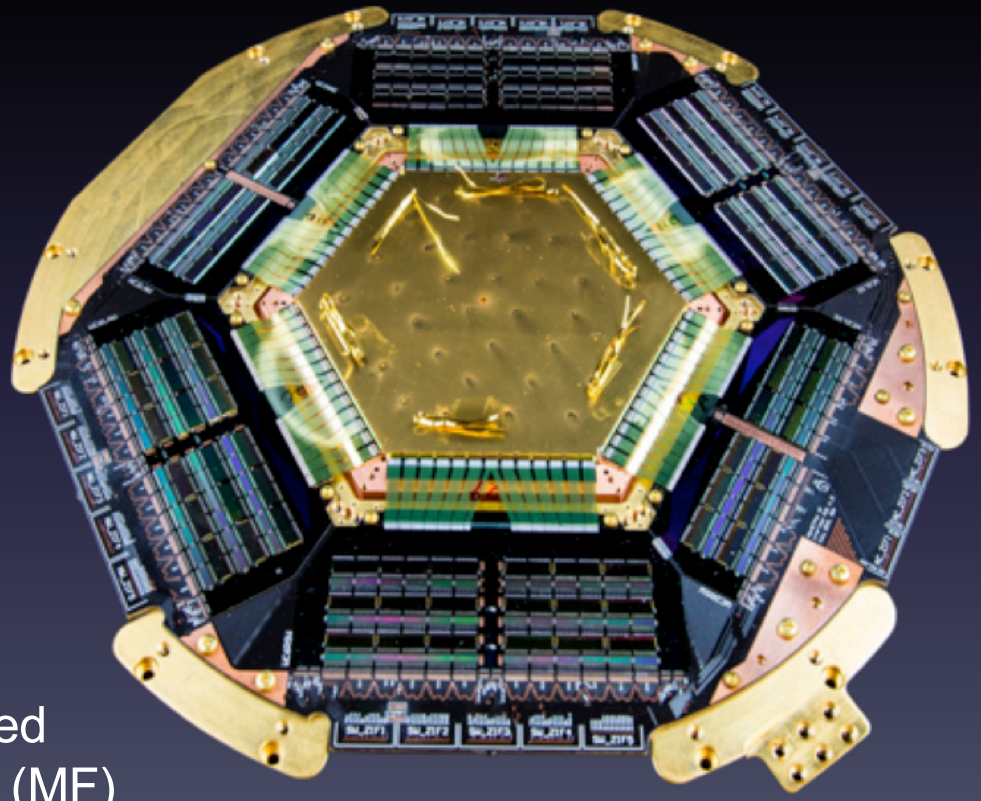
LTD-18
Milan, Italy
July 2019



Focal Plane Complexity

TES

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



Advanced ACTPol (MF)

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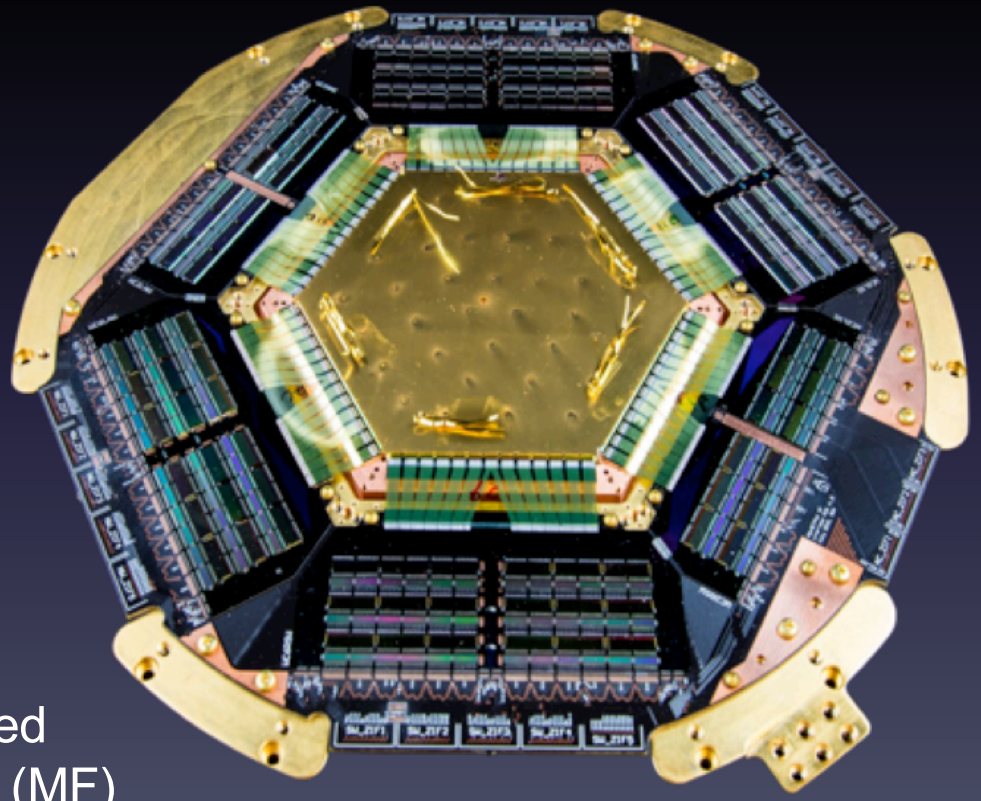


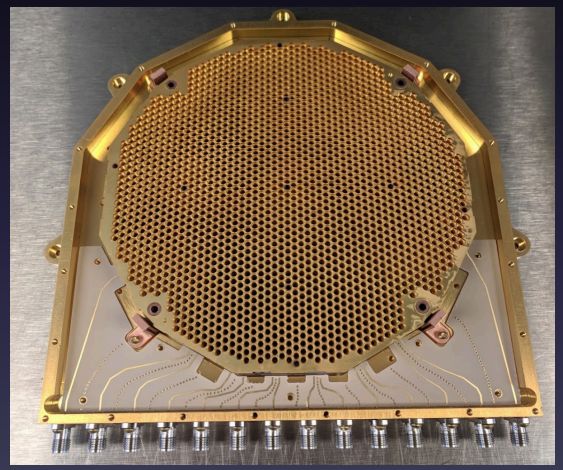
Advanced ACTPol (MF)

(Shown at same scale)

MKID

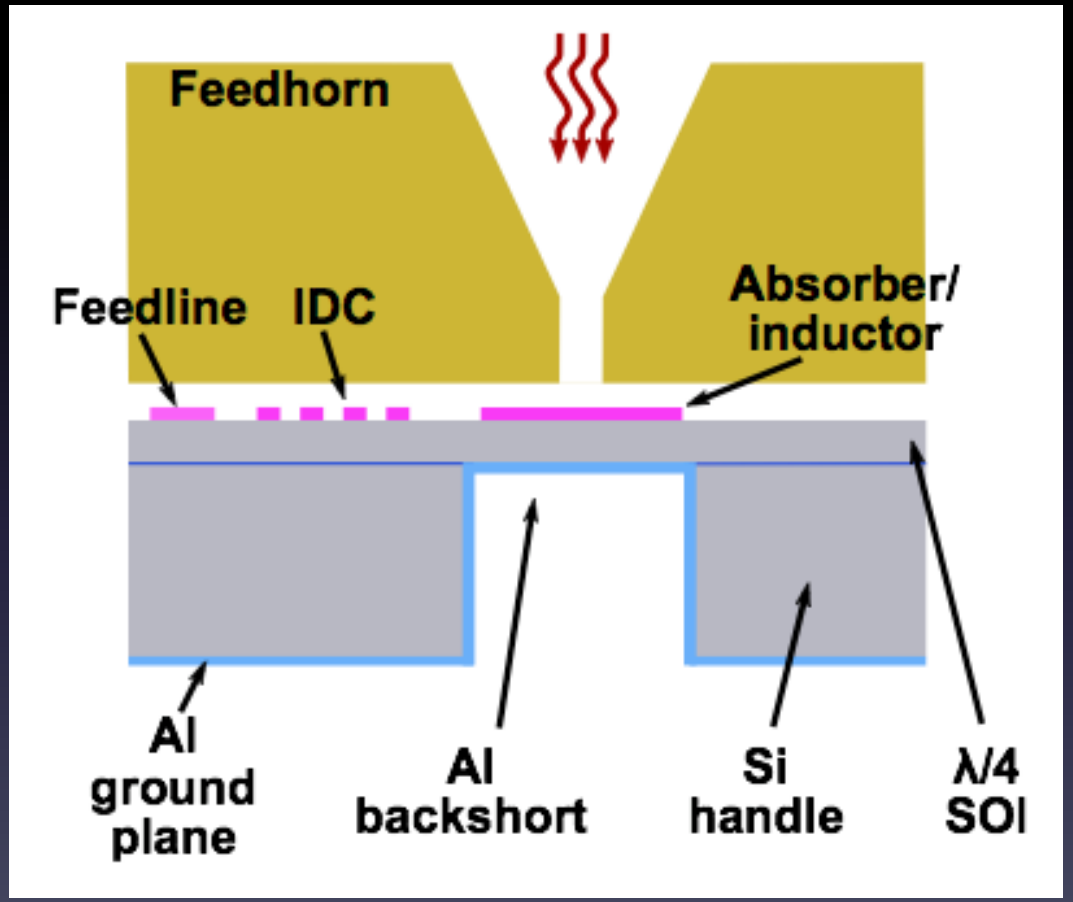
Integrated readout
e.g. Toltec MKID (4000 detectors)
- 14 wire bonds
- 14 Coax cables
- 7 LNAs (at 4K stage)

Toltec 1.1 mm

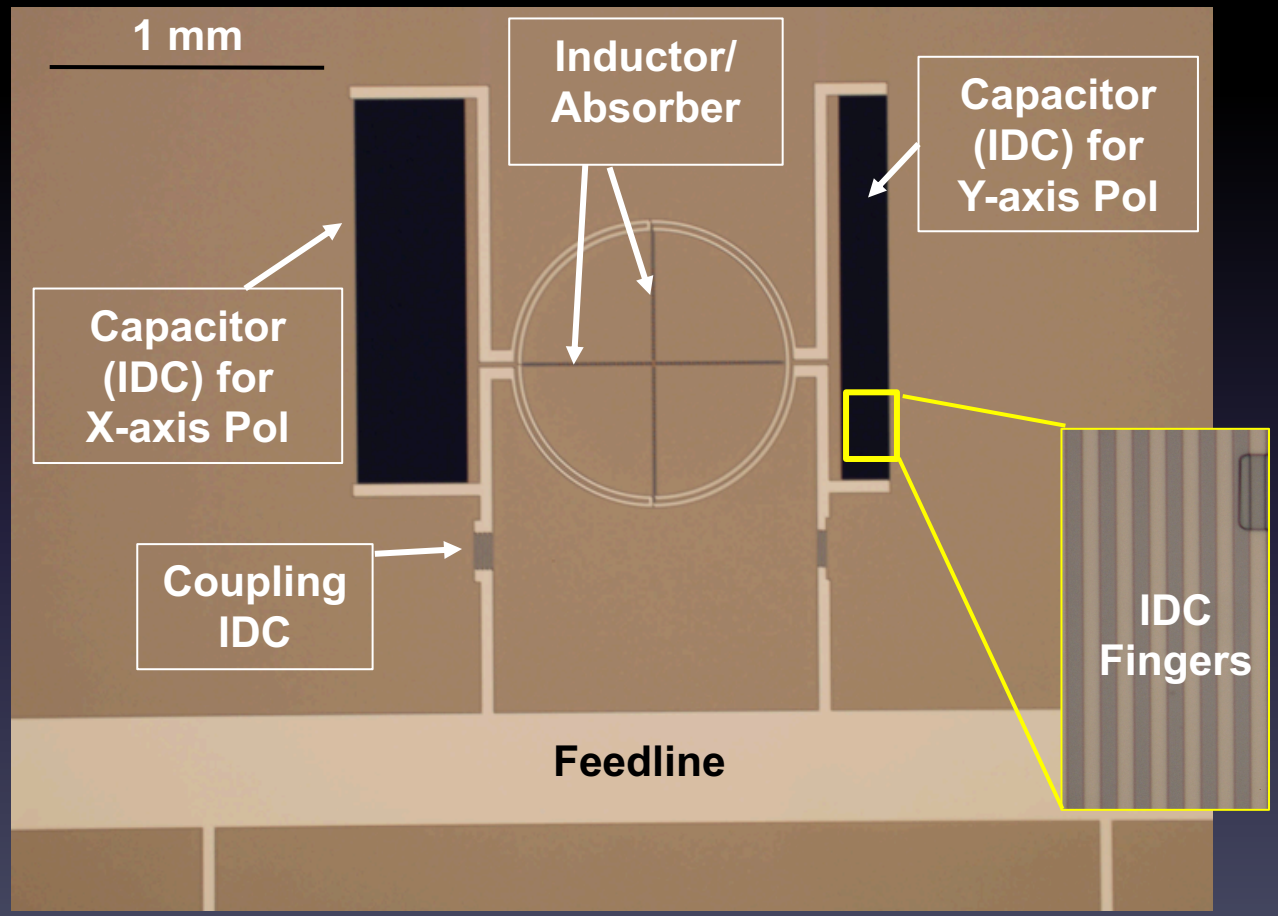


Pixel Design

Feedhorn coupled waveguide



Dual Polarization, Single Band



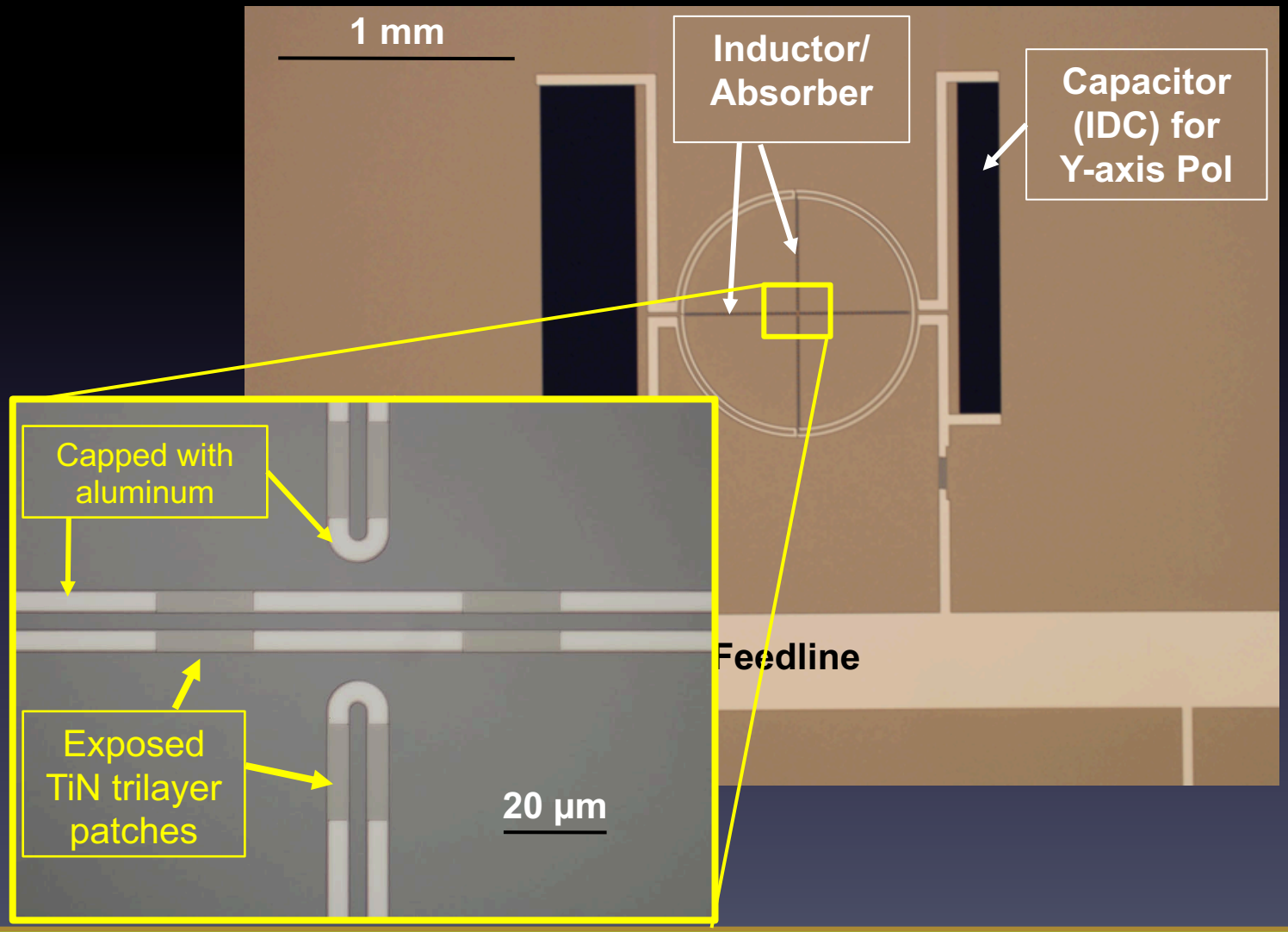
Trilayer (TiN/Ti/TiN) Inductor

Inductor/Absorber optimizations:
- Optical Efficiency (impedance)
- Responsivity (volume)
- low cross-pol (width)
- transition temperature (thickness)
- wavelength sets minimum length

5 competing geometric optimizations

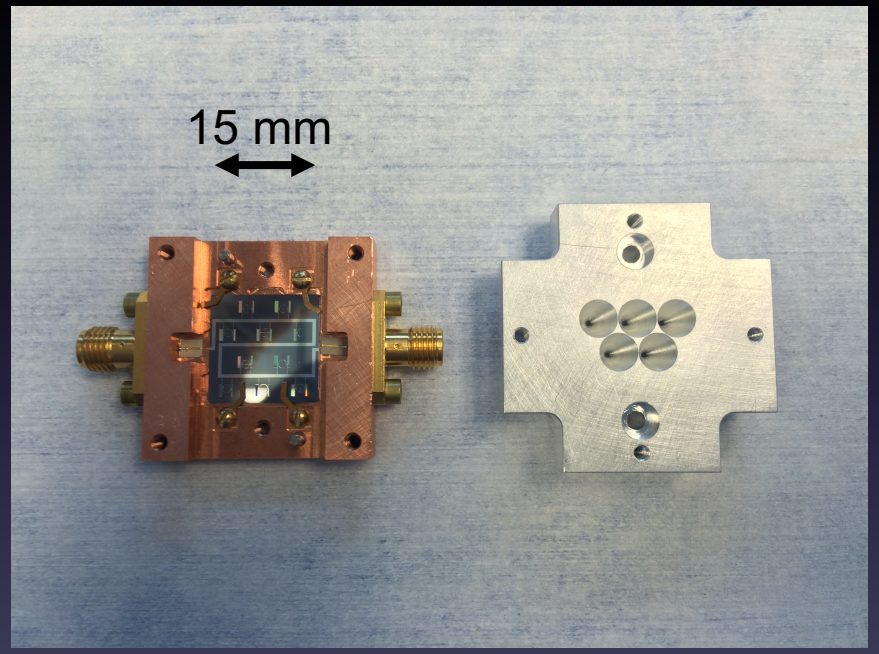
Extra free parameter

Dual Polarization, Single Band

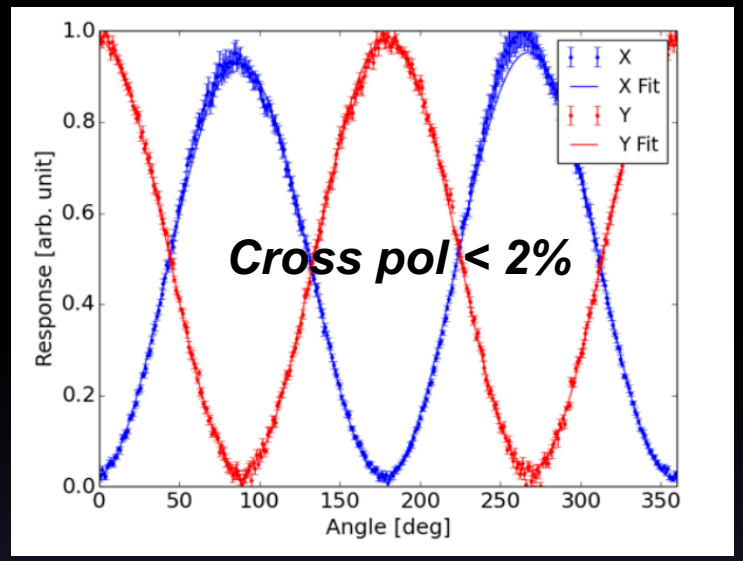


Measured Optical Performance

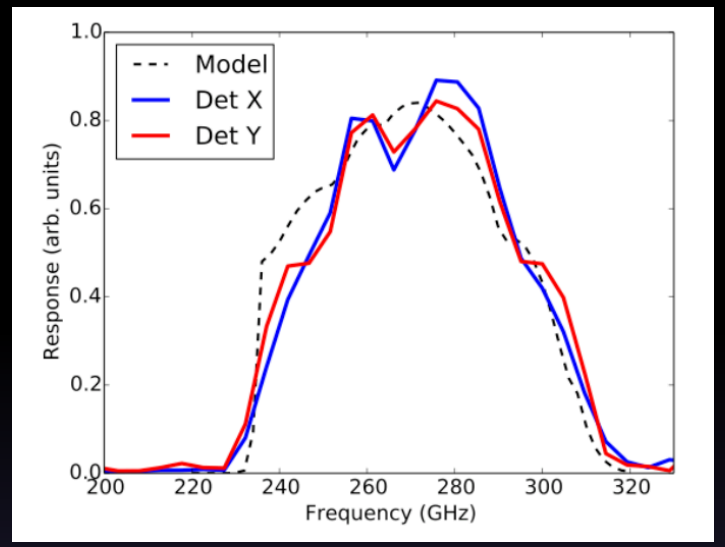
Initial Prototyping



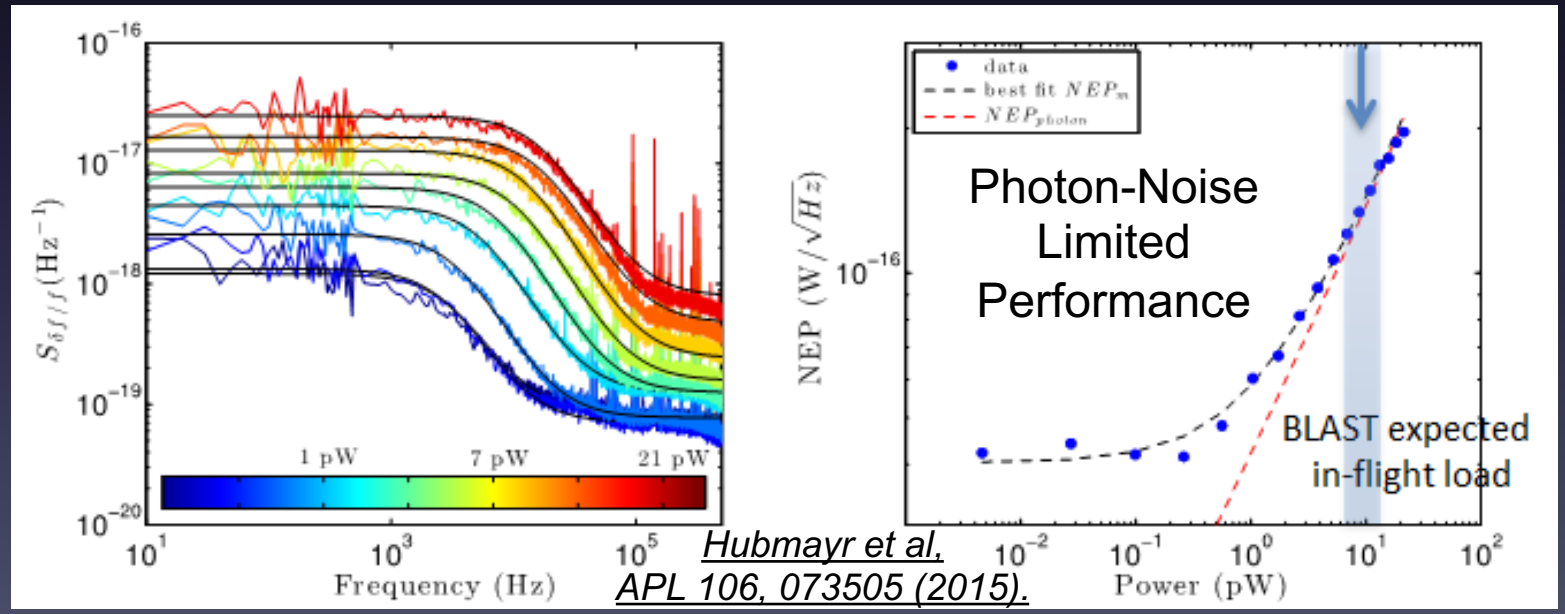
Excellent cross-pol rejection



Passbands Match Simulation

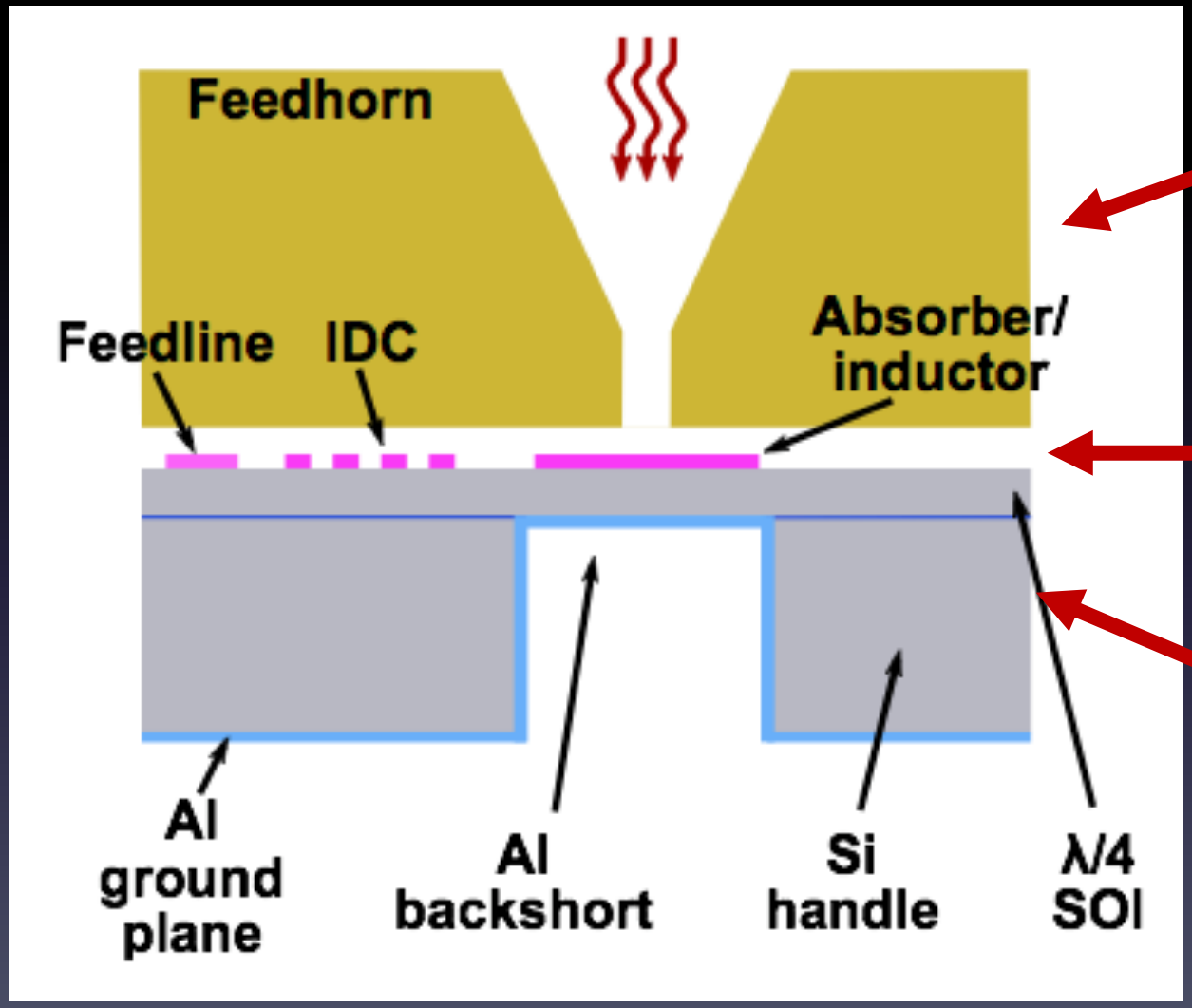


Austermann et al. 2018



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

Challenges of scaling to large diameter (150 mm) arrays



Primary Challenges of components on large scales:

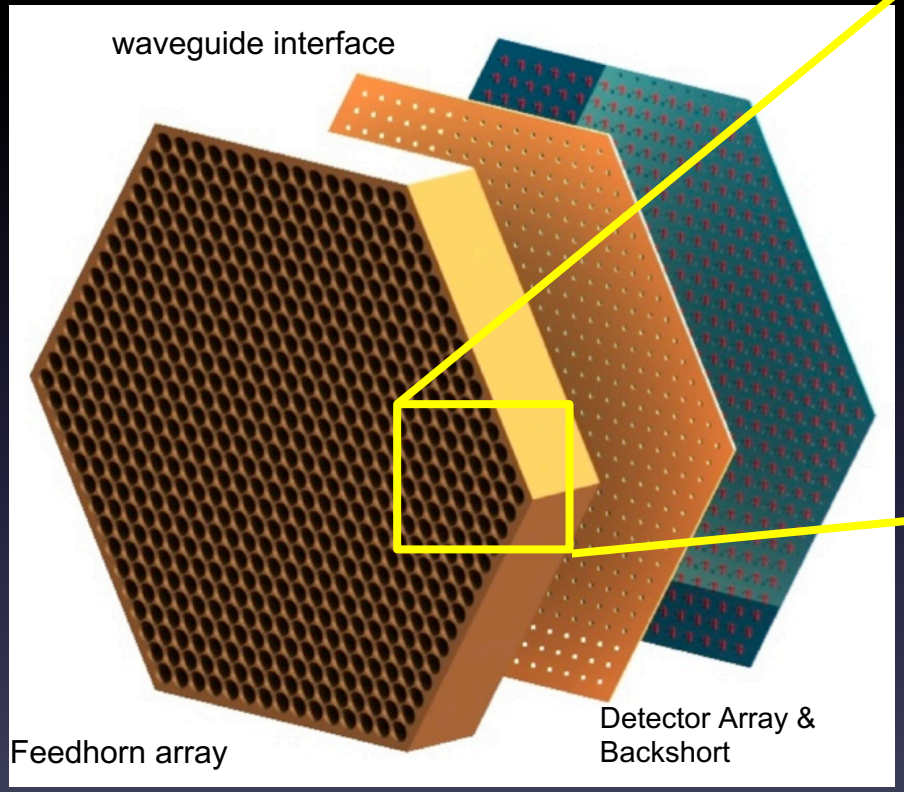
Feedhorns
- Differential Contraction (CTE) (if metal horns/mount)
- Precision (uniformity/alignment)

Air gap & Choke
- Precision / Opt. efficiency
- Uniformity / Planar
- Microphonics

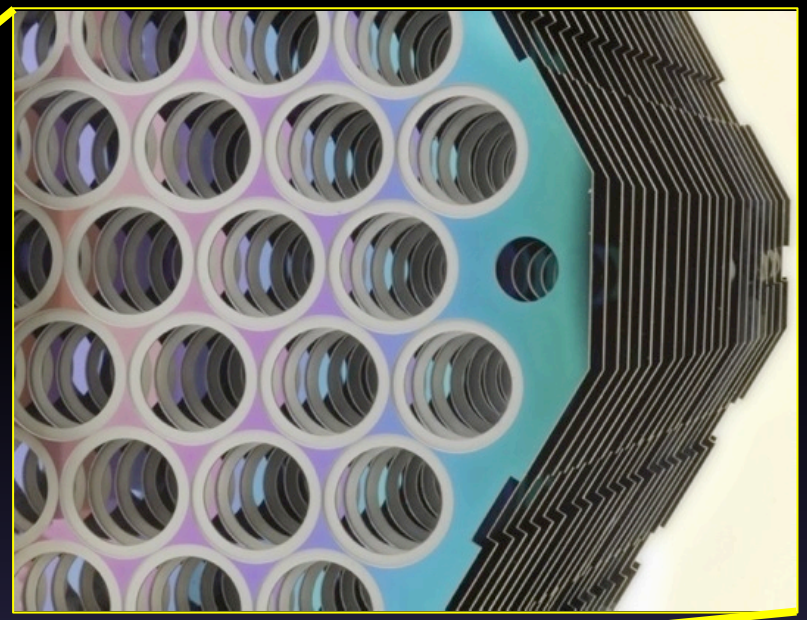
Detectors
- Frequency spacing
- Uniform performance

NIST Silicon Feedhorn Arrays

Typical NIST Detector Stack

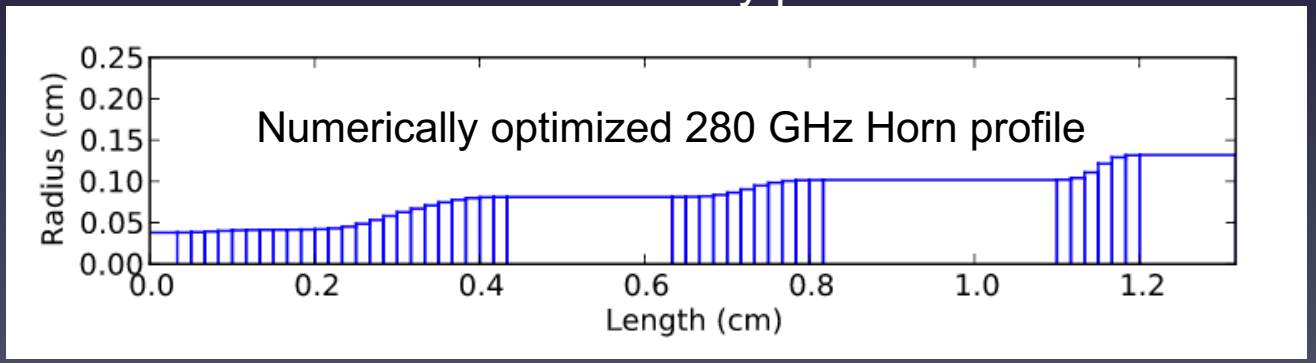


Silicon Platelet Stack



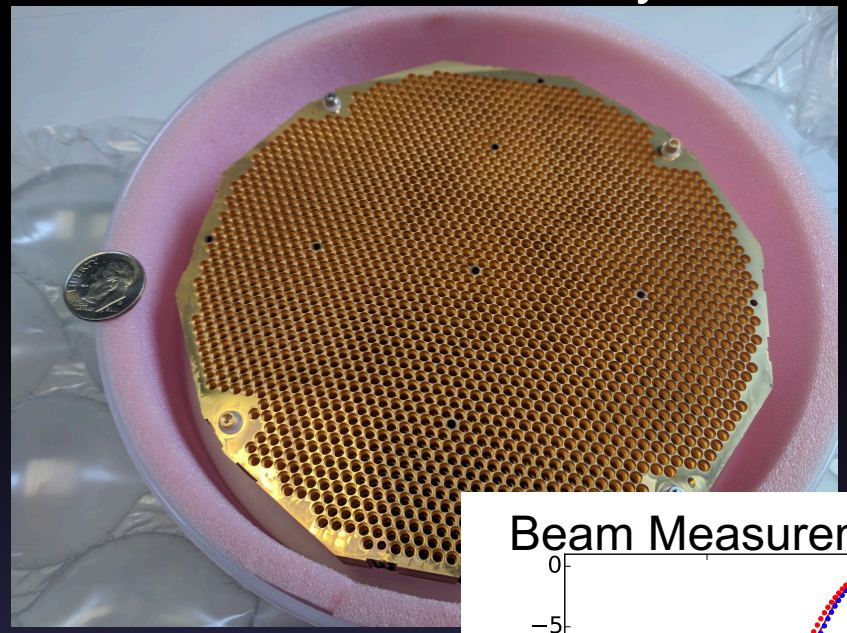
Exploded View

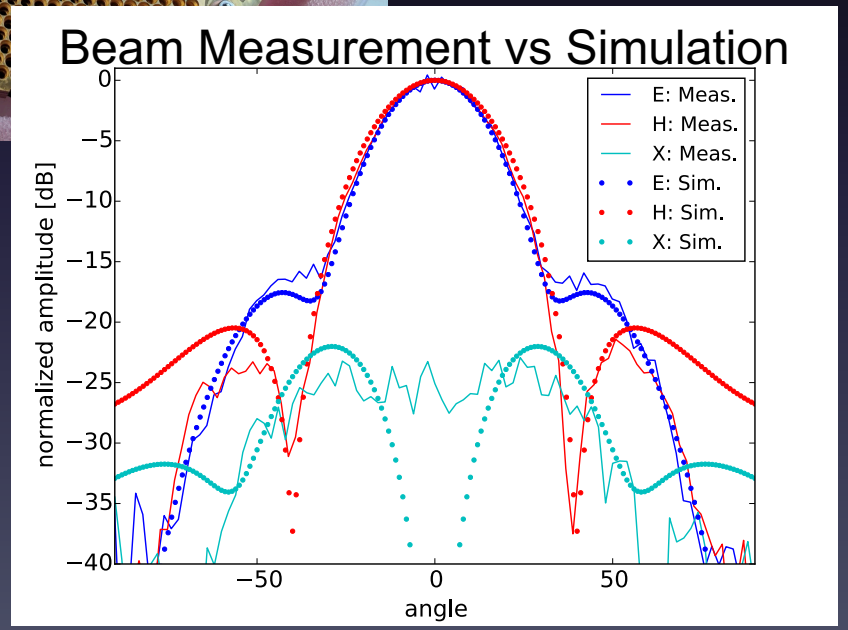
Build almost any profile



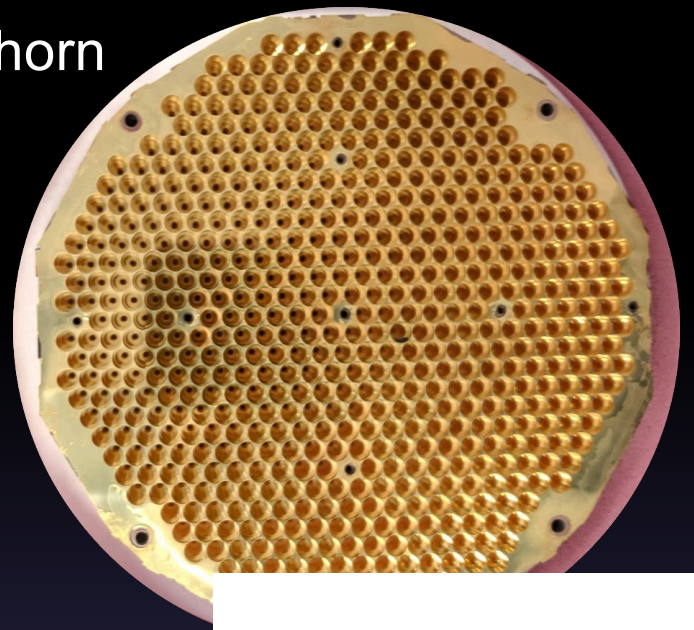
Feedhorn Arrays

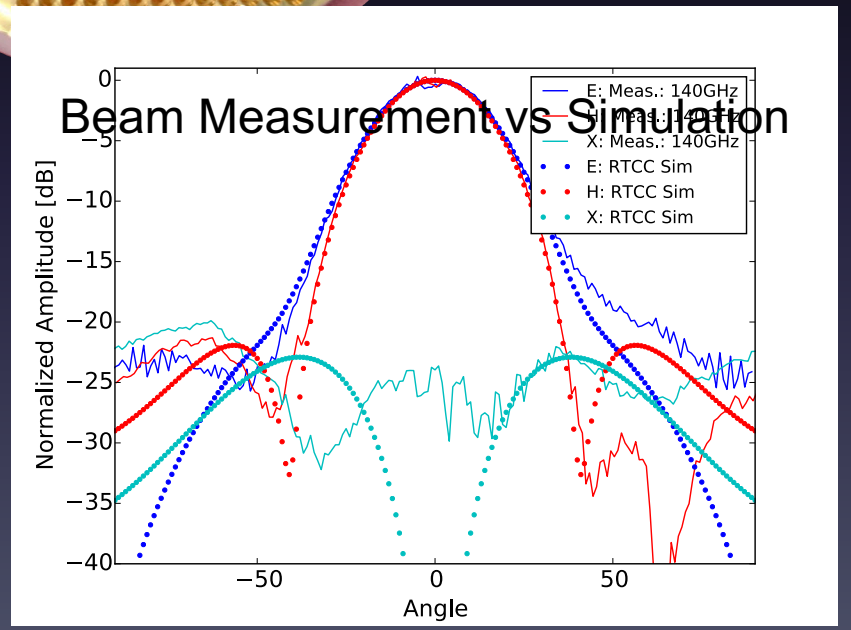
1.1 mm Feedhorn Array



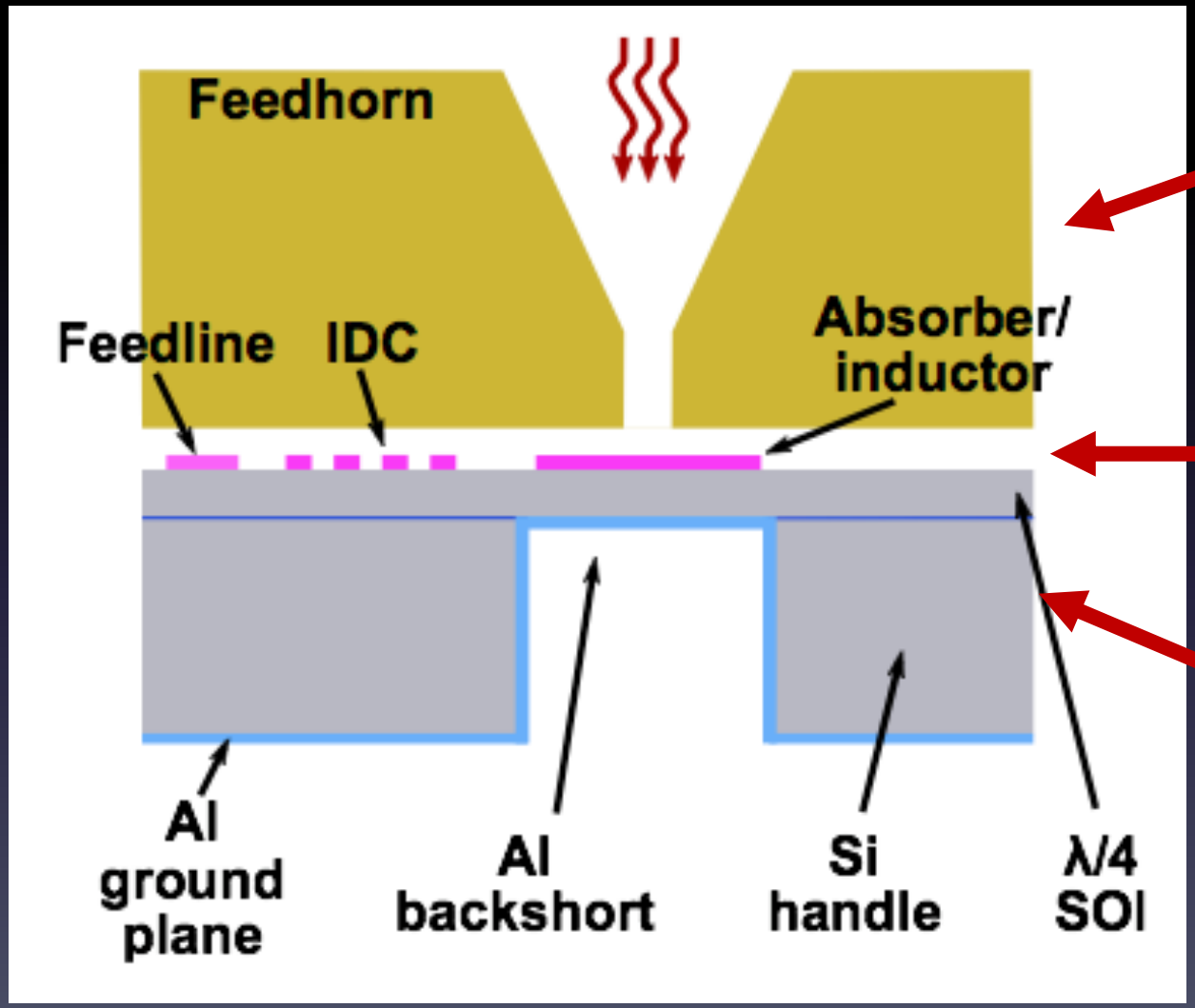


2.0 mm Feedhorn Array





Challenges of scaling to large diameter (150 mm) arrays



Primary Challenges of components on large scales:

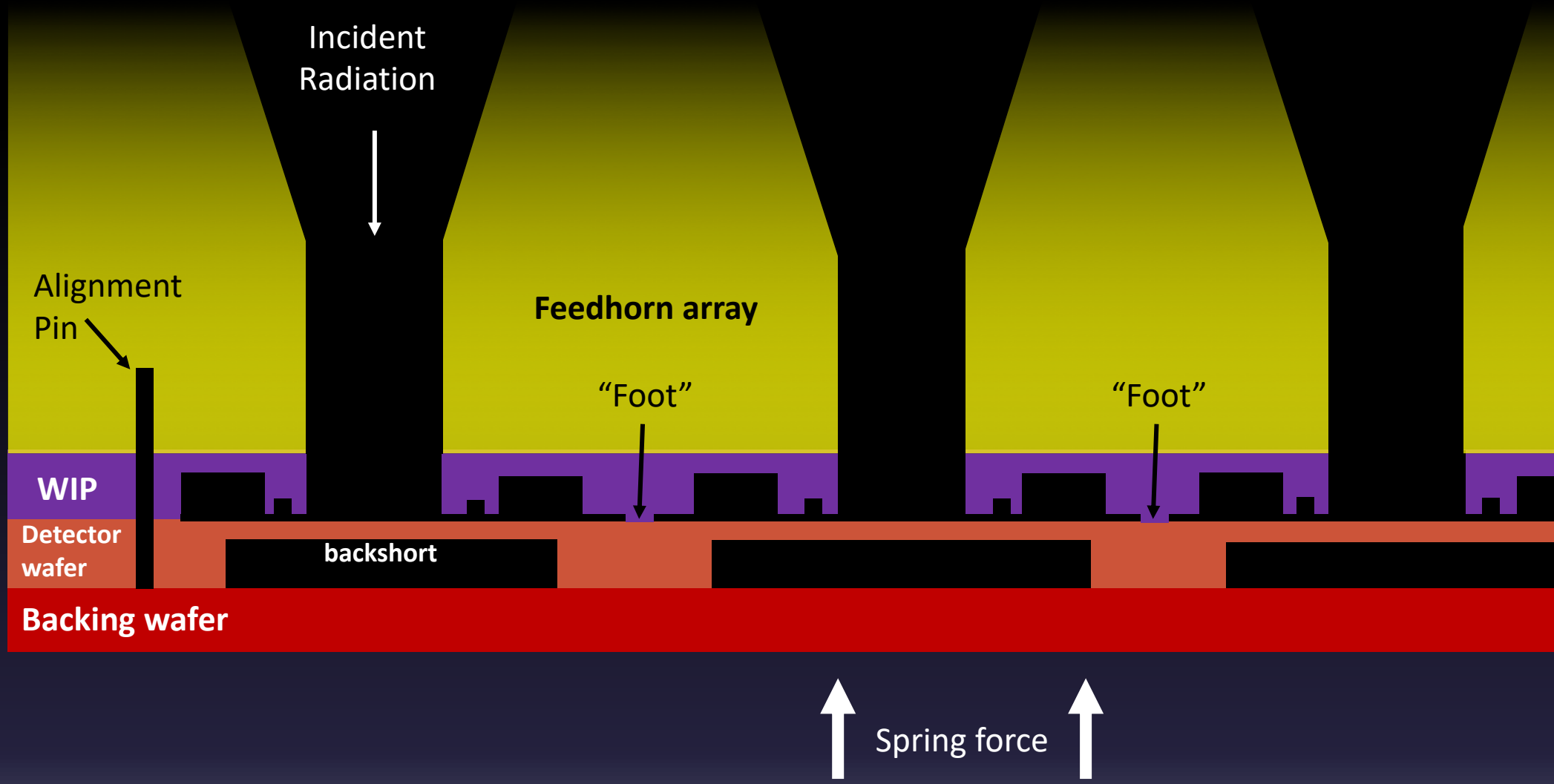
Feedhorns
- Differential Contraction (CTE) (if metal horns/mount)
- Precision (uniformity/alignment)

Air gap & Choke
- Precision / Opt. efficiency
- Uniformity / Planar
- **Microphonics**

Detectors
- Frequency spacing
- Uniform performance

Waveguide Interface Plate (WIP)

An all silicon solution

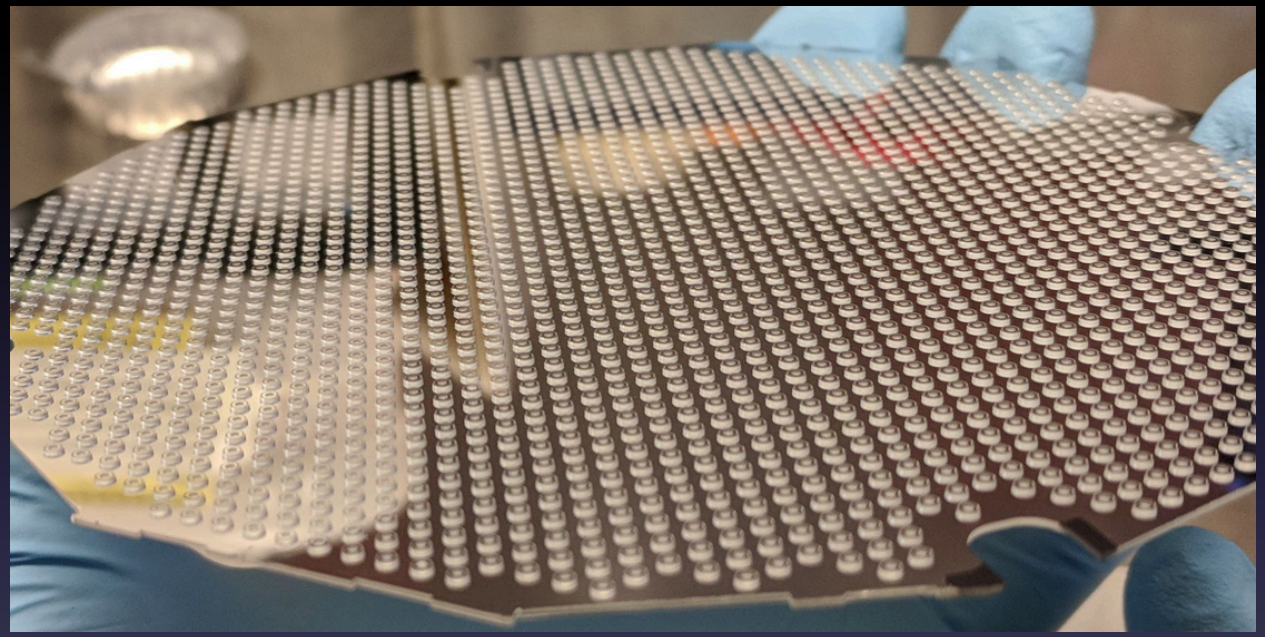


"Foot" at every pixel provides mechanically fixed gap & minimized microphonics

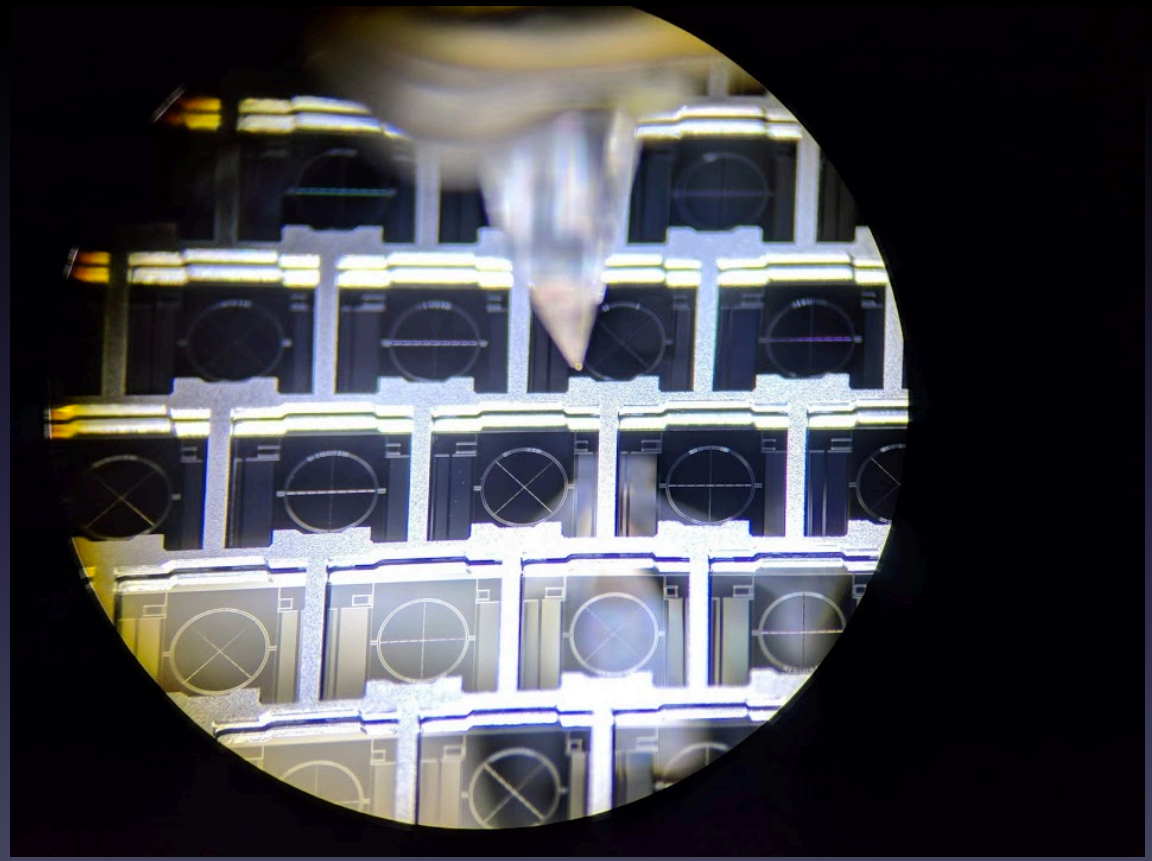
Waveguide Interface Plate (WIP)

Made from 2 parts

Choke Structures

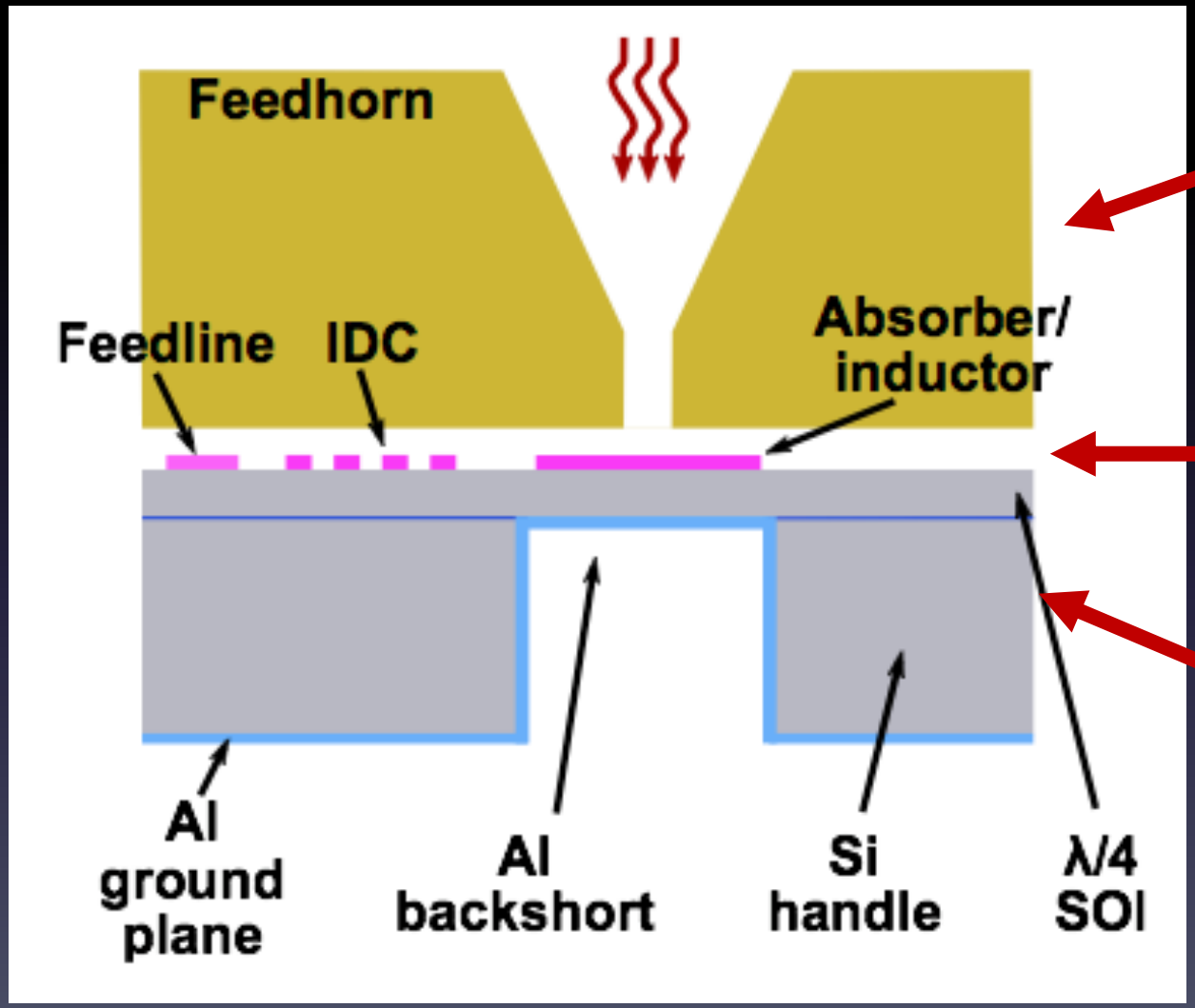


Standoffs (“feet”)



Aluminum plated for low-loss
(close proximity to resonators)

Challenges of scaling to large diameter (150 mm) arrays



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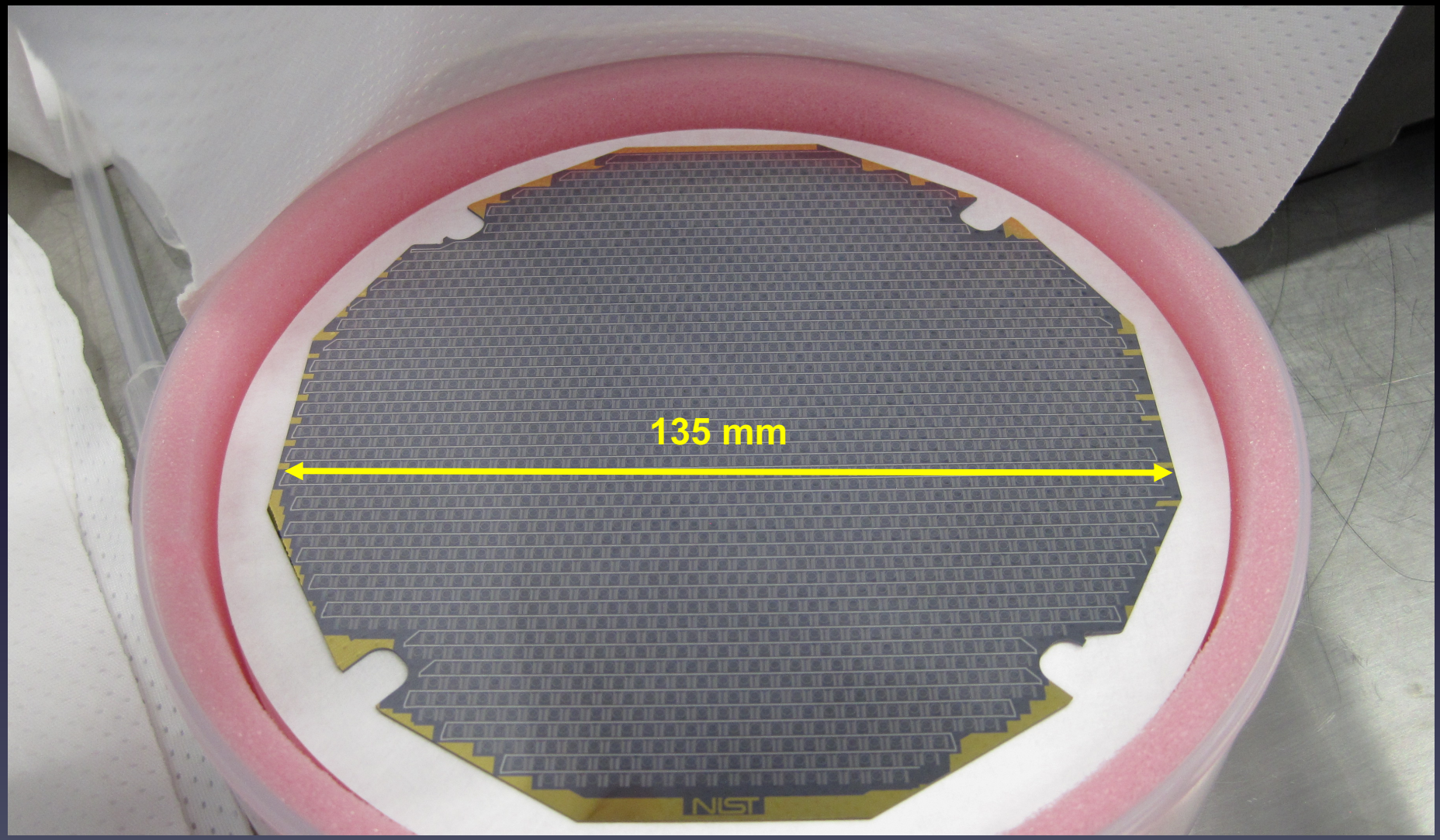
Feedhorns
- Differential Contraction (CTE) (if metal horns/mount)
- Precision (uniformity/alignment)

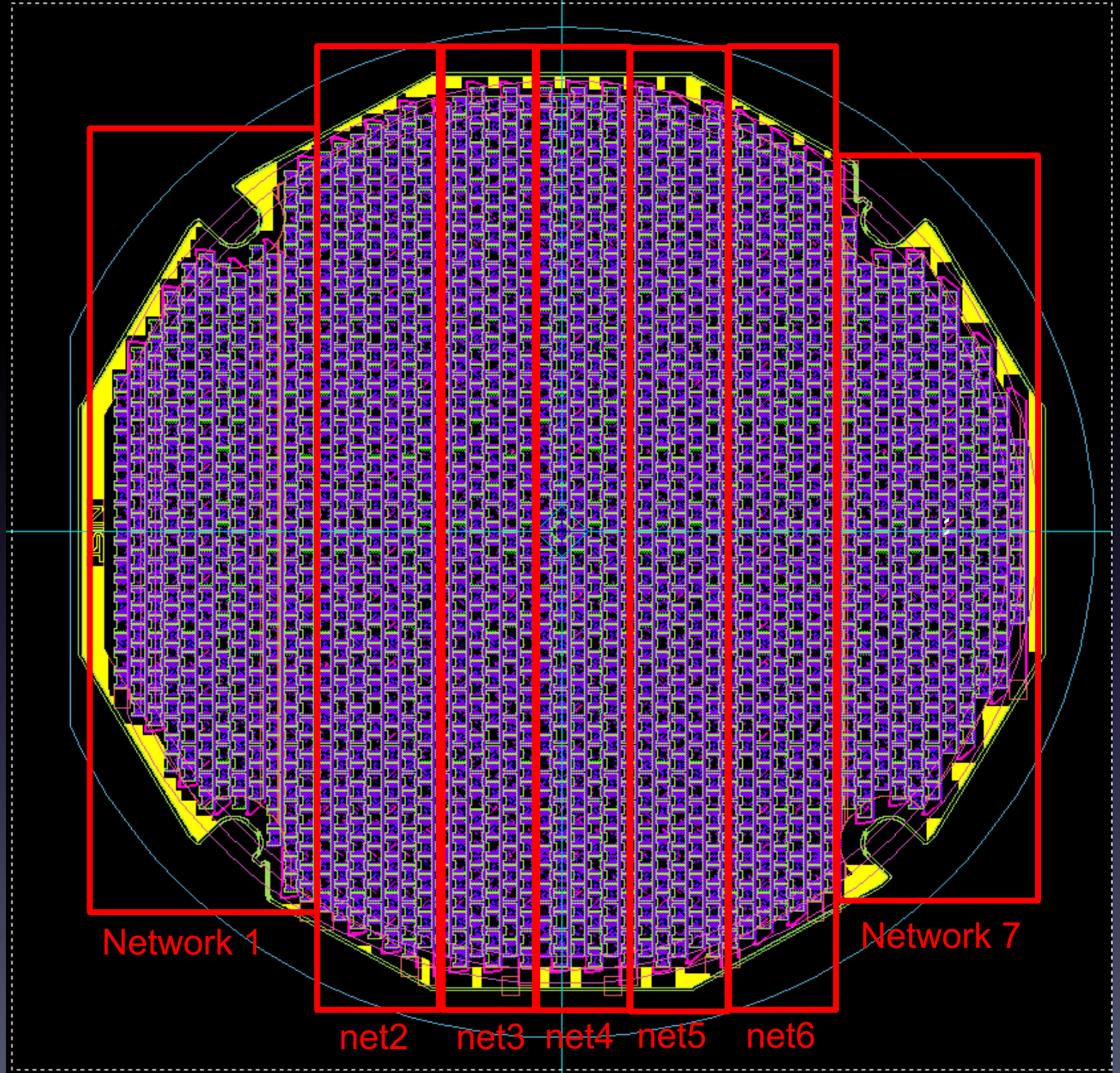
Air gap & Choke
- Precision / Opt. efficiency
- Uniformity / Planar
- Microphonics

Detectors
- Frequency spacing / Multiplexing
- Uniform performance

Detector Aray

Toltec 1.1mm Detector Array (~4000 KIDs)

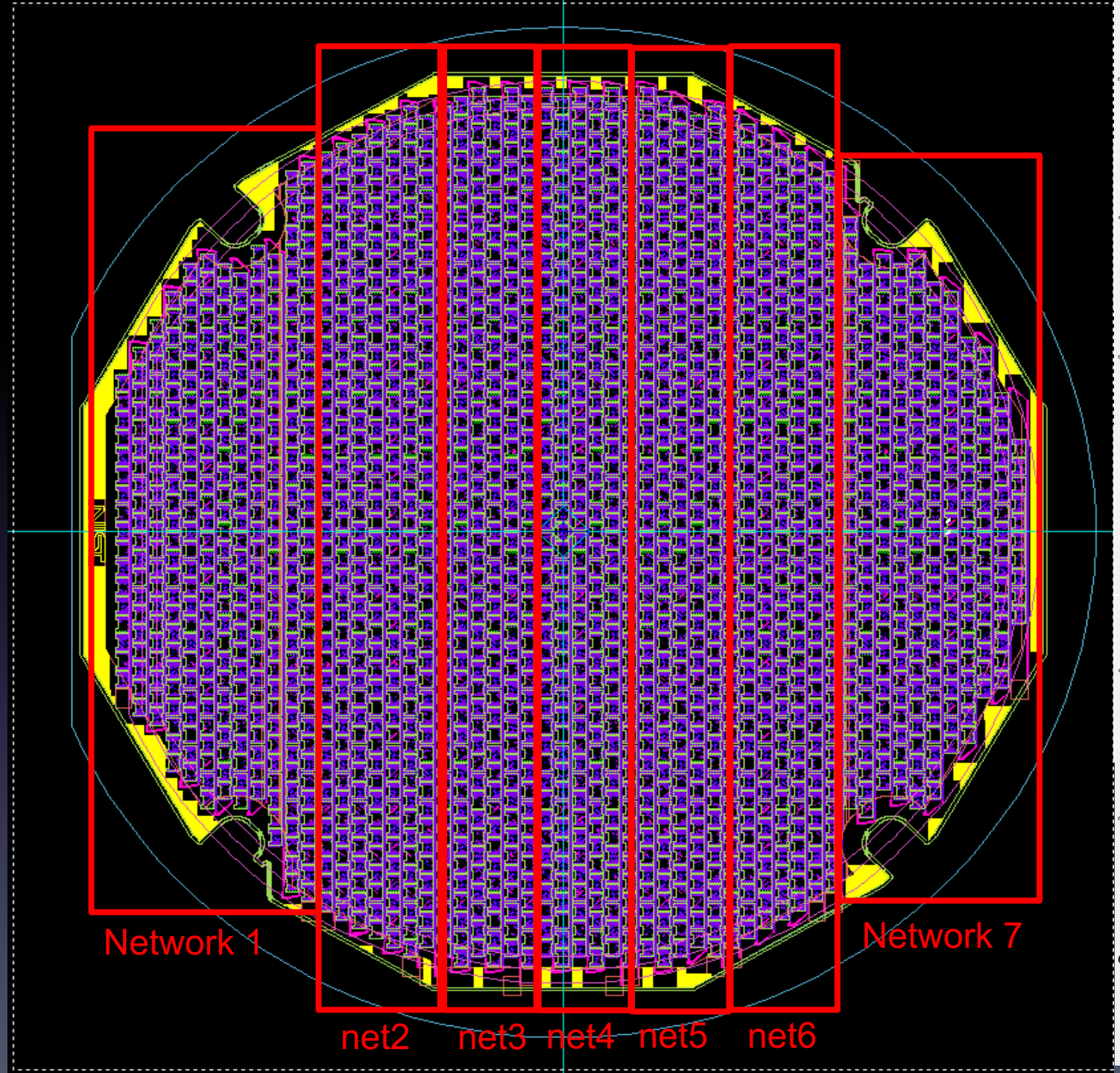


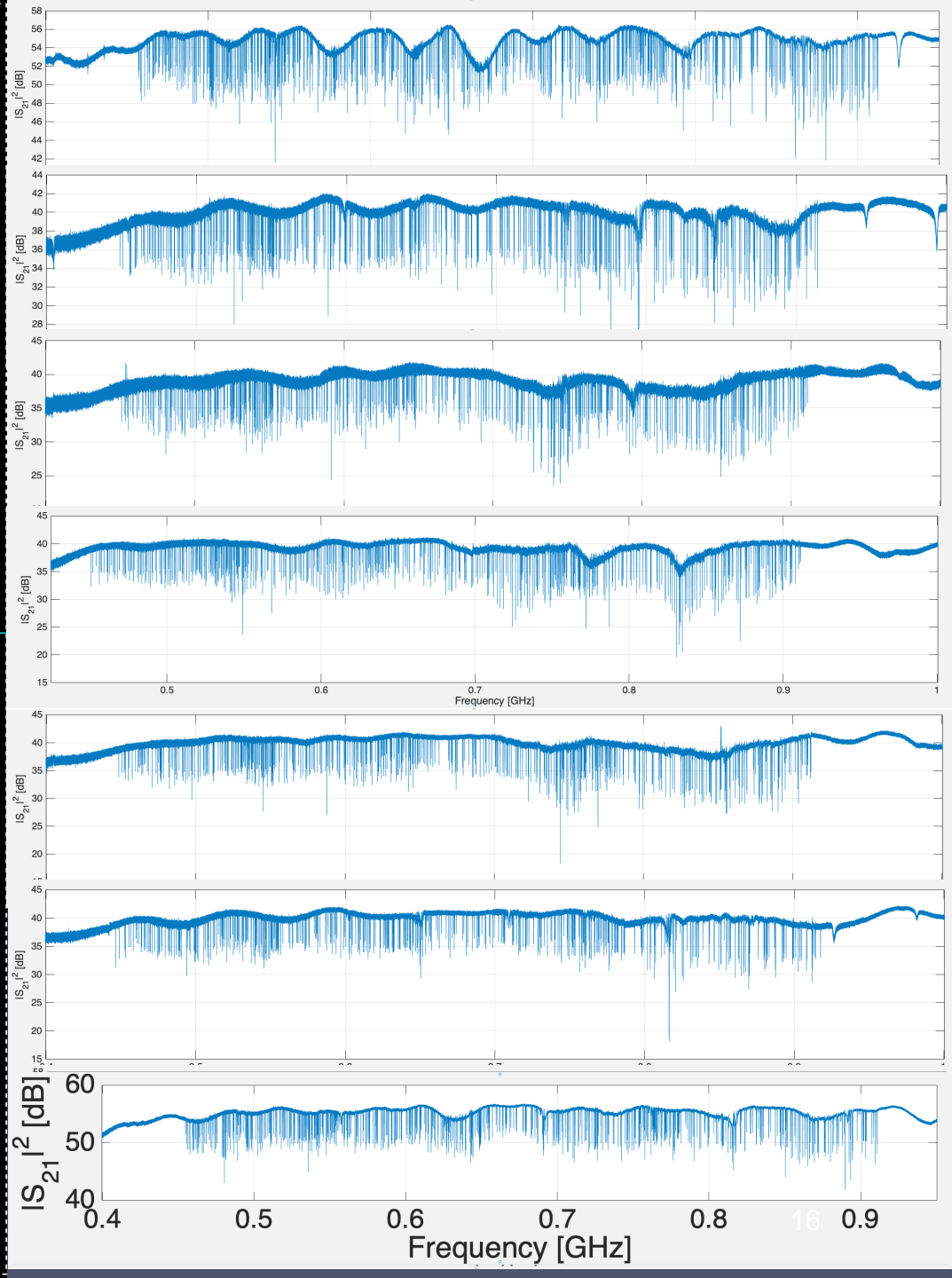


7 networks

1.1 mm Array

Network	Resonators
Net1	684
Net2	522
Net3	558
Net4	564
Net5	556
Net6	510
Net7	618
Total	**4012**

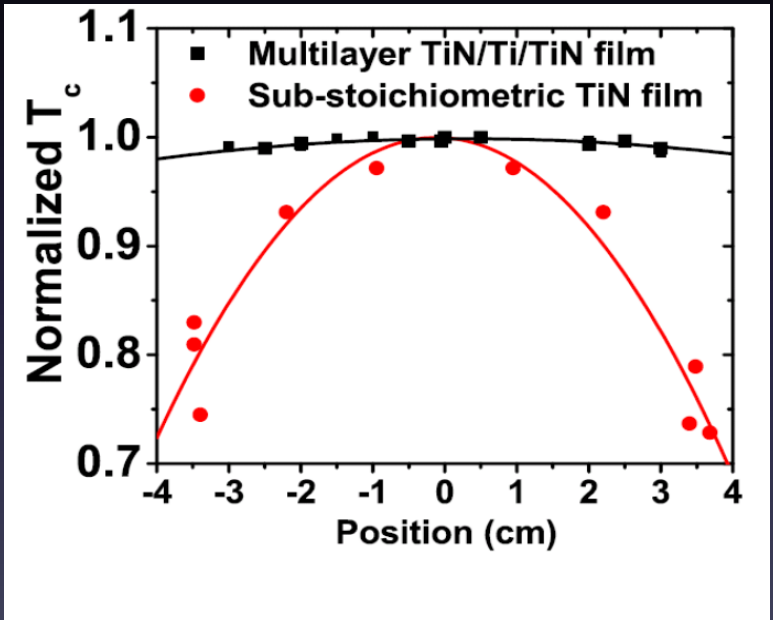

Network 1
net2
net3
net4
net5
net6
Network 7


$|S_{21}|^2$ [dB]
Frequency [GHz]

Array Uniformity = High Yield

Material Uniformity

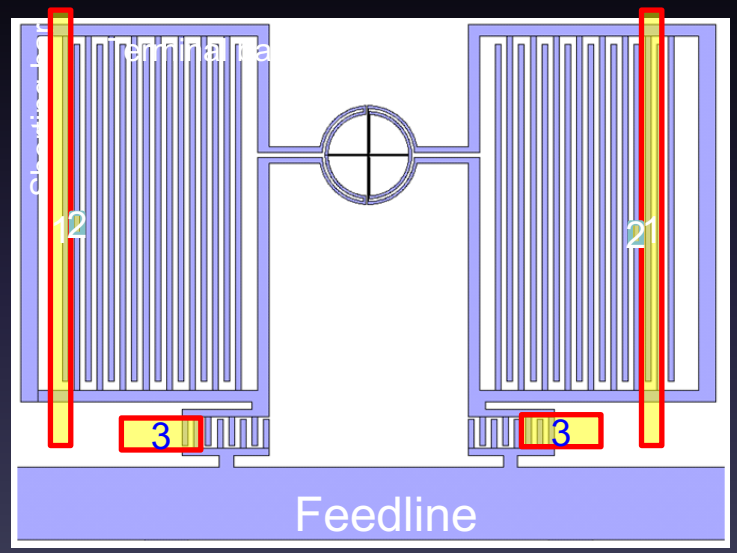
TiN/Ti/TiN
T_c uniformity



Vissers et al 2013

Tile & Trim Lithography

Stepper-based solution, all resonators printed identically, then uniquely edited

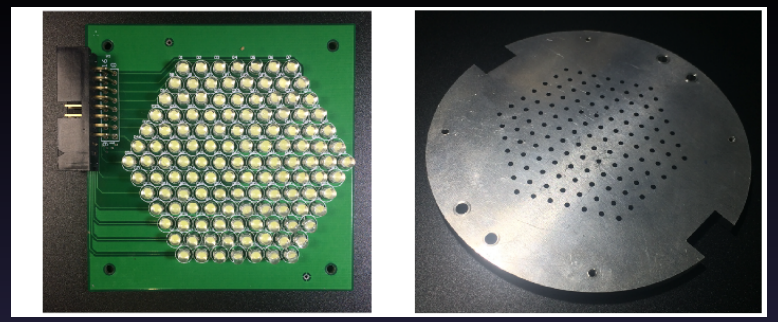


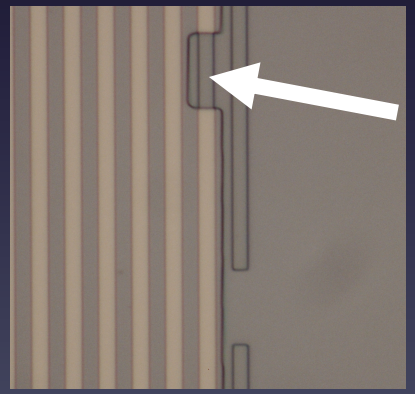
Frequency Schedule spirals outward to minimize effect of material gradients across wafer

McKenney et al 2018

Post-fabrication Resonator Editing

LED Mapper –
Resonator to physical pixel





Modify IDC fingers again after measurement and identification

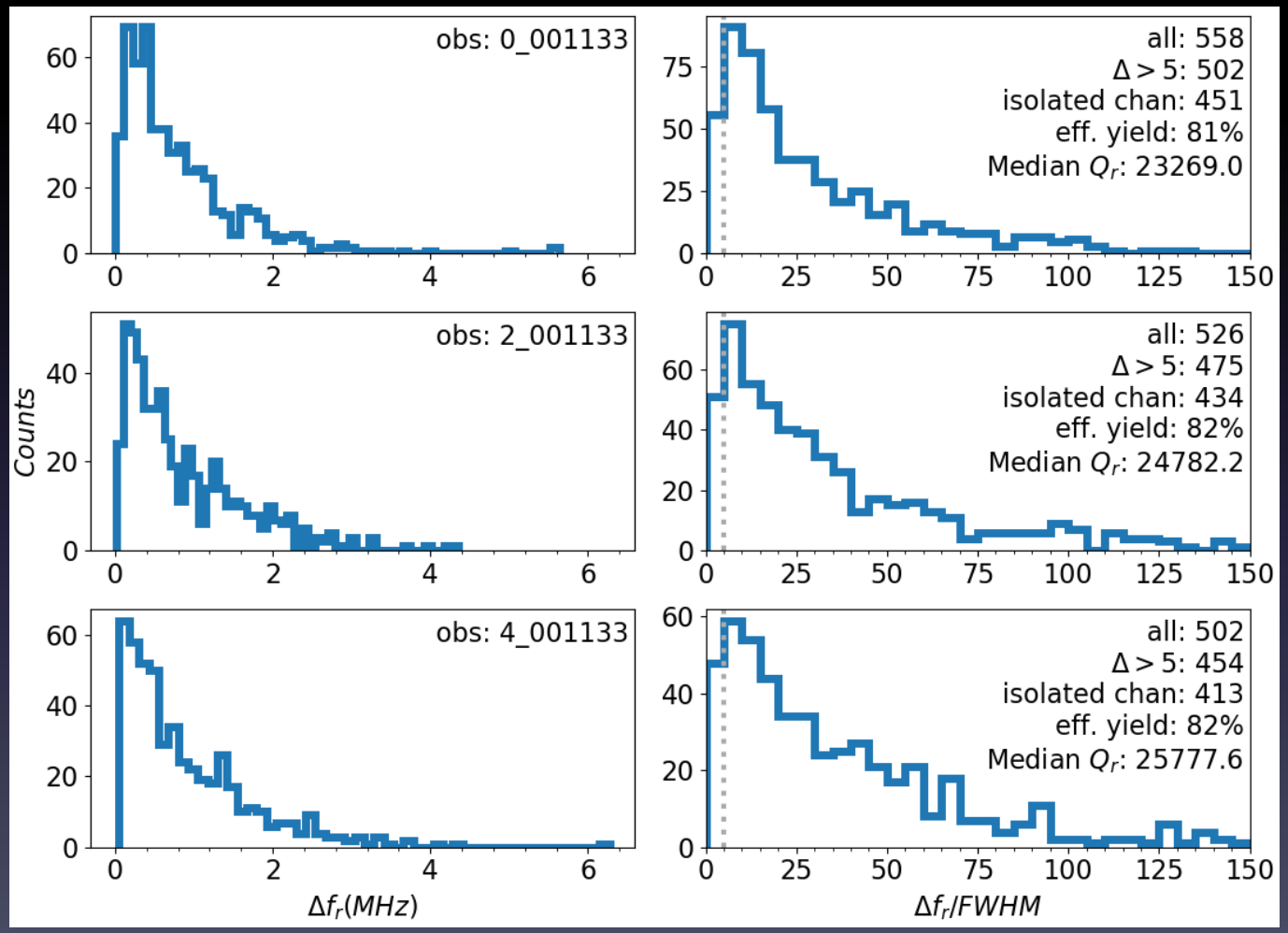
Liu et al 2017

Resonator Collisions

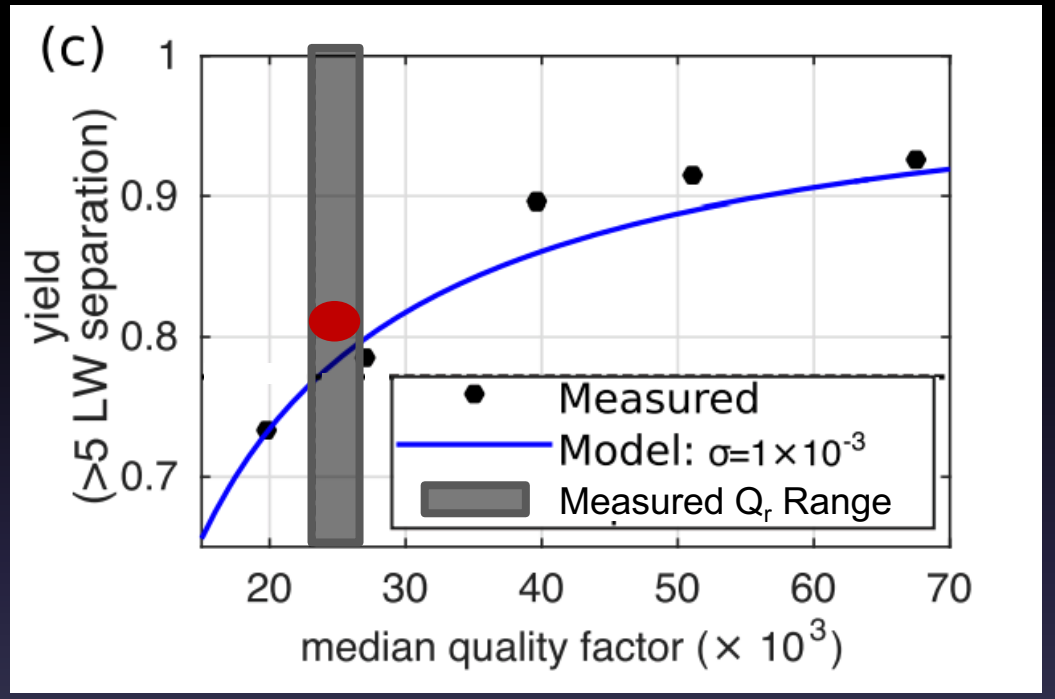
(under moderate loading)

Frequency Separation

Line-Width Separation



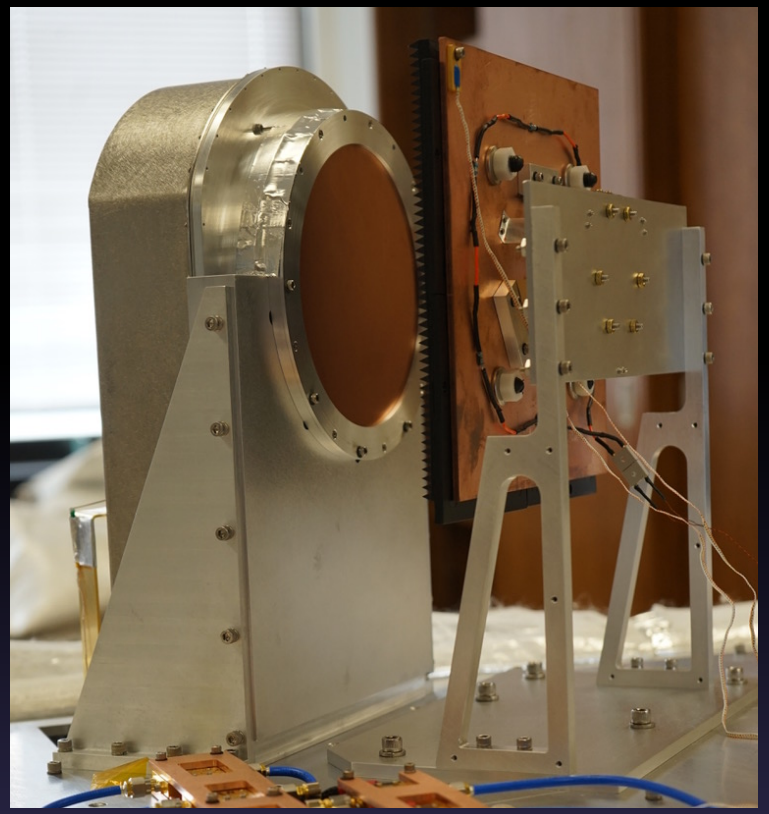
Expected non-collision yield vs. resonator Q



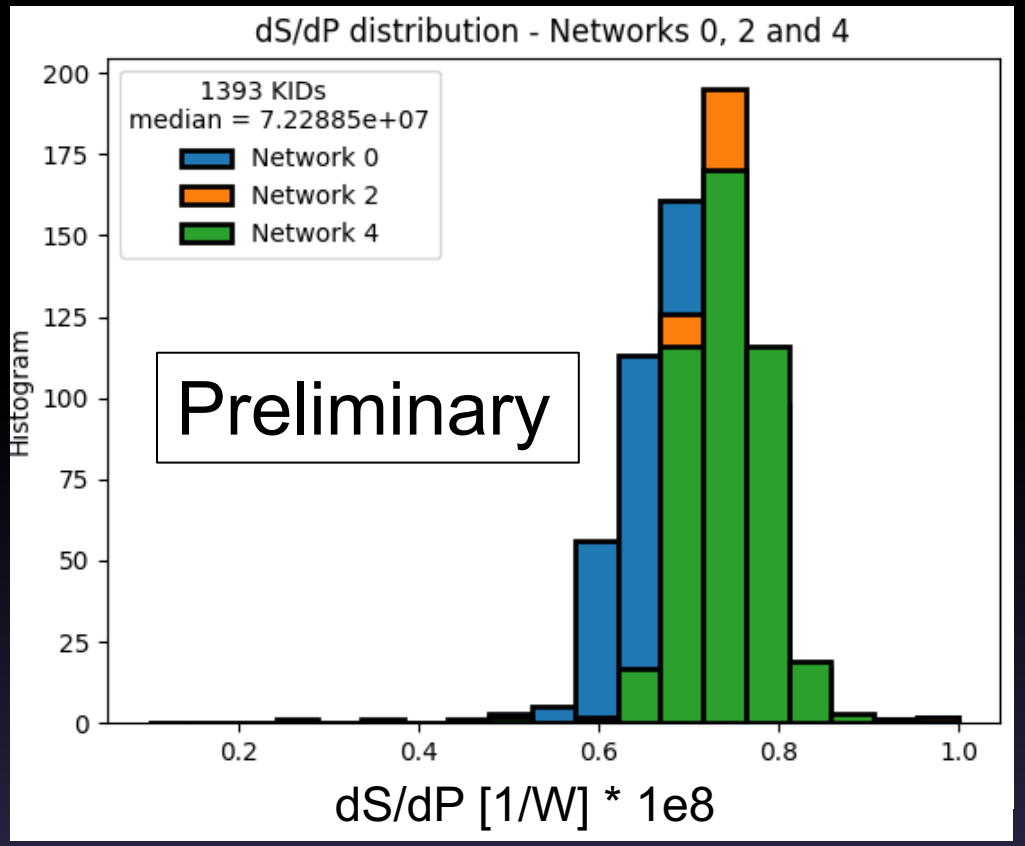
McKenney et al 2018

No post-fab editing (yet)

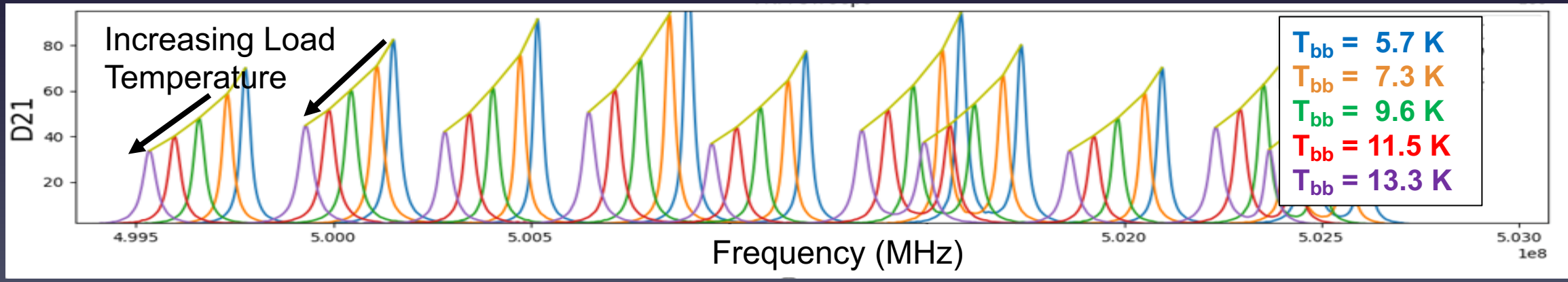
Optical Characterization with Blackbody



Responsivity Uniformity



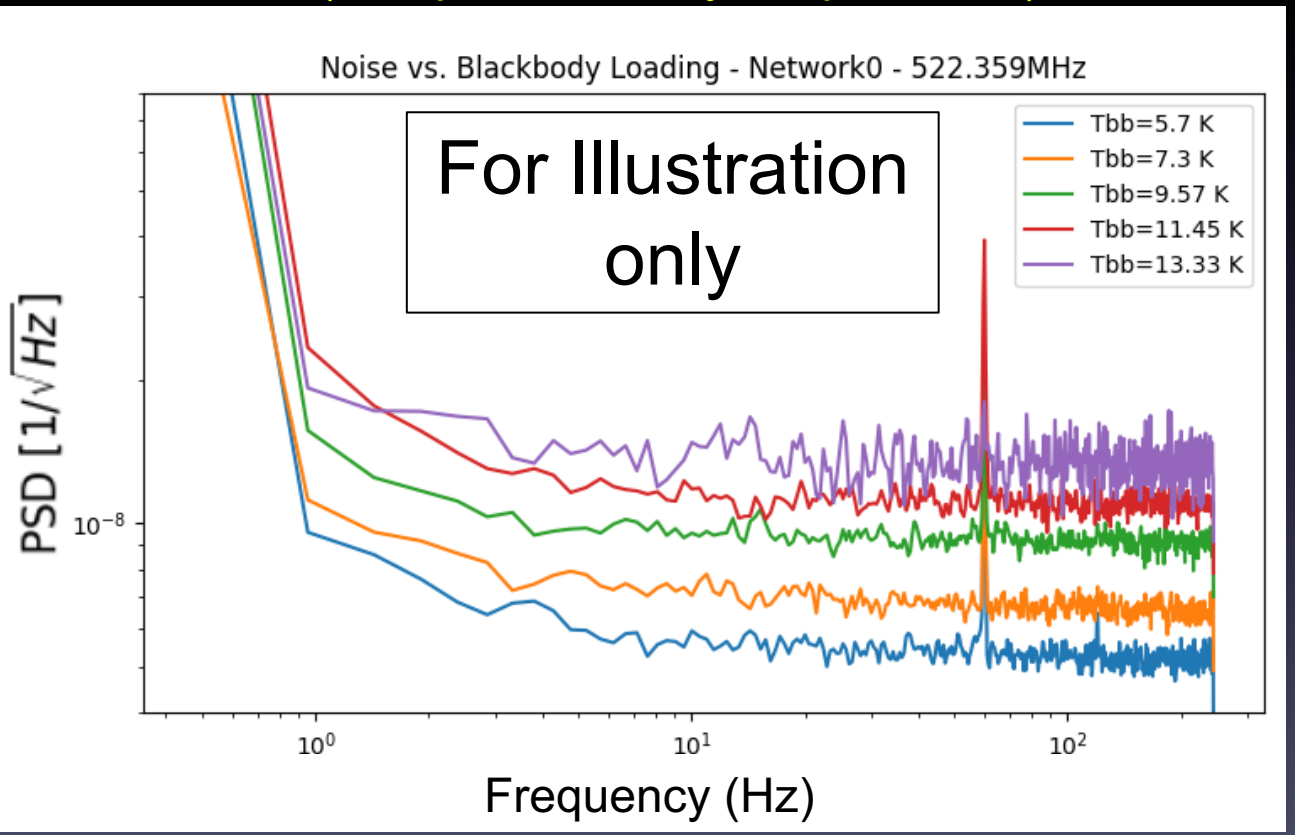
Plots courtesy of Zhiyuan Ma / UMASS



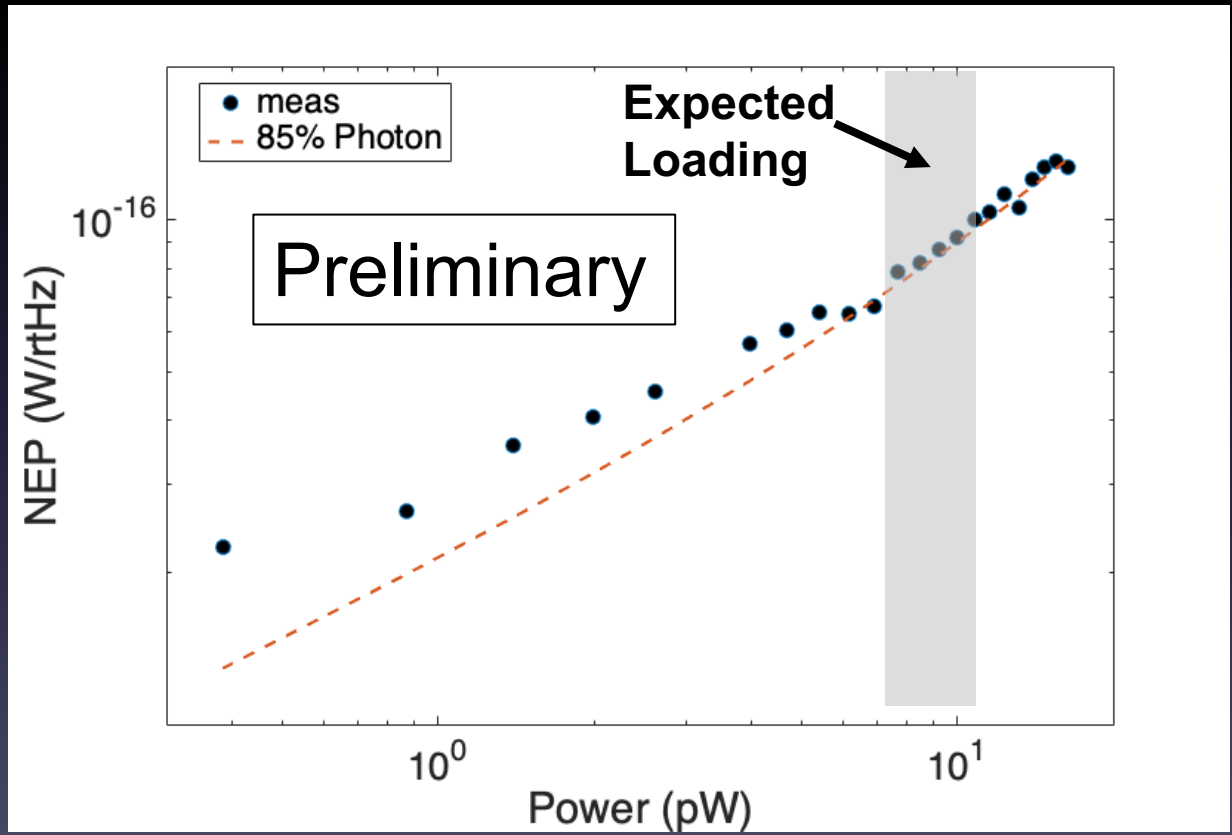
Noise and Optical Efficiency

(example pixel from full array)

Noise Spectrum
(multiple blackbody temperatures)



Noise Equivalent Power
(NEP)



Summary

- KID arrays on 150 mm diameter substrates
  - Excellent optical performance matching simulations
  - No signs of degradation in performance or local uniformity compared to small array prototypes
- All-silicon packaging
  - microphonic noise eliminated or significantly reduced
  - No breakage (so far)
  - Superior alignment and uniformity
- On-sky KID verifications coming in the next ~6 months (TolTEC & BLAST)
  - Toltec: **1100 µm 1400 µm 2000 µm (270 / 220 / 150 GHz)**
  - **BLAST: 250 µm 350 µm 500 µm (1200 / 850 / 600 GHz)**

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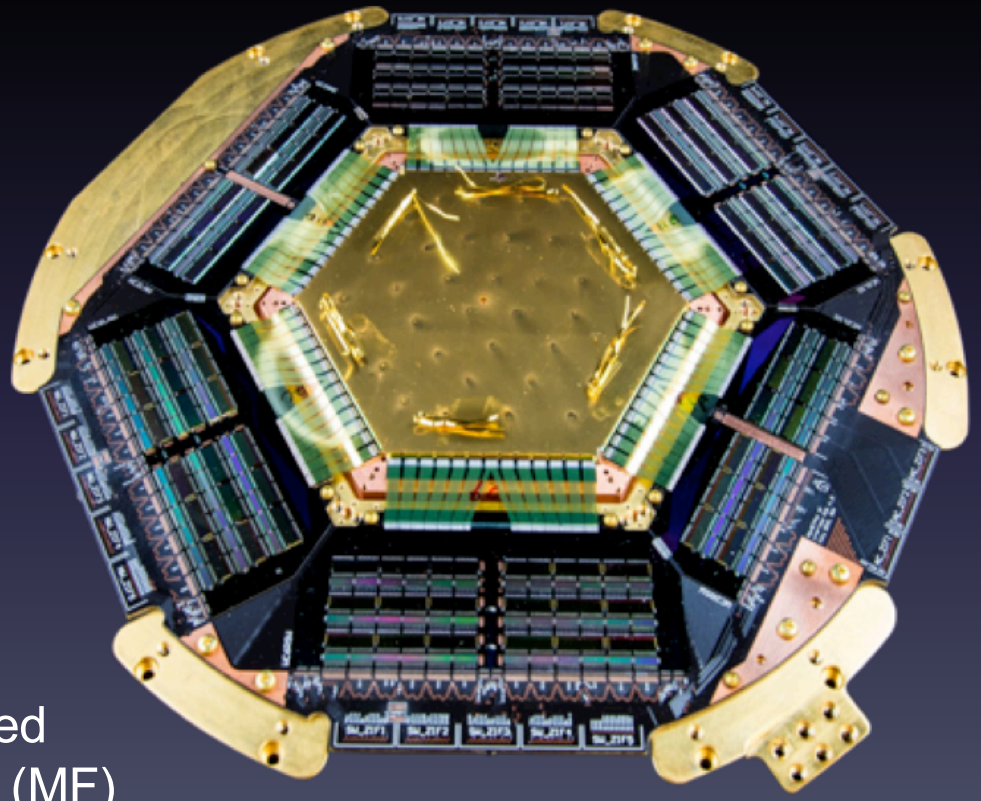

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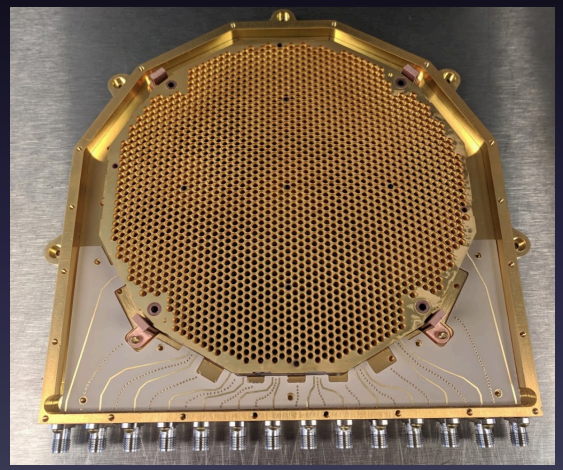
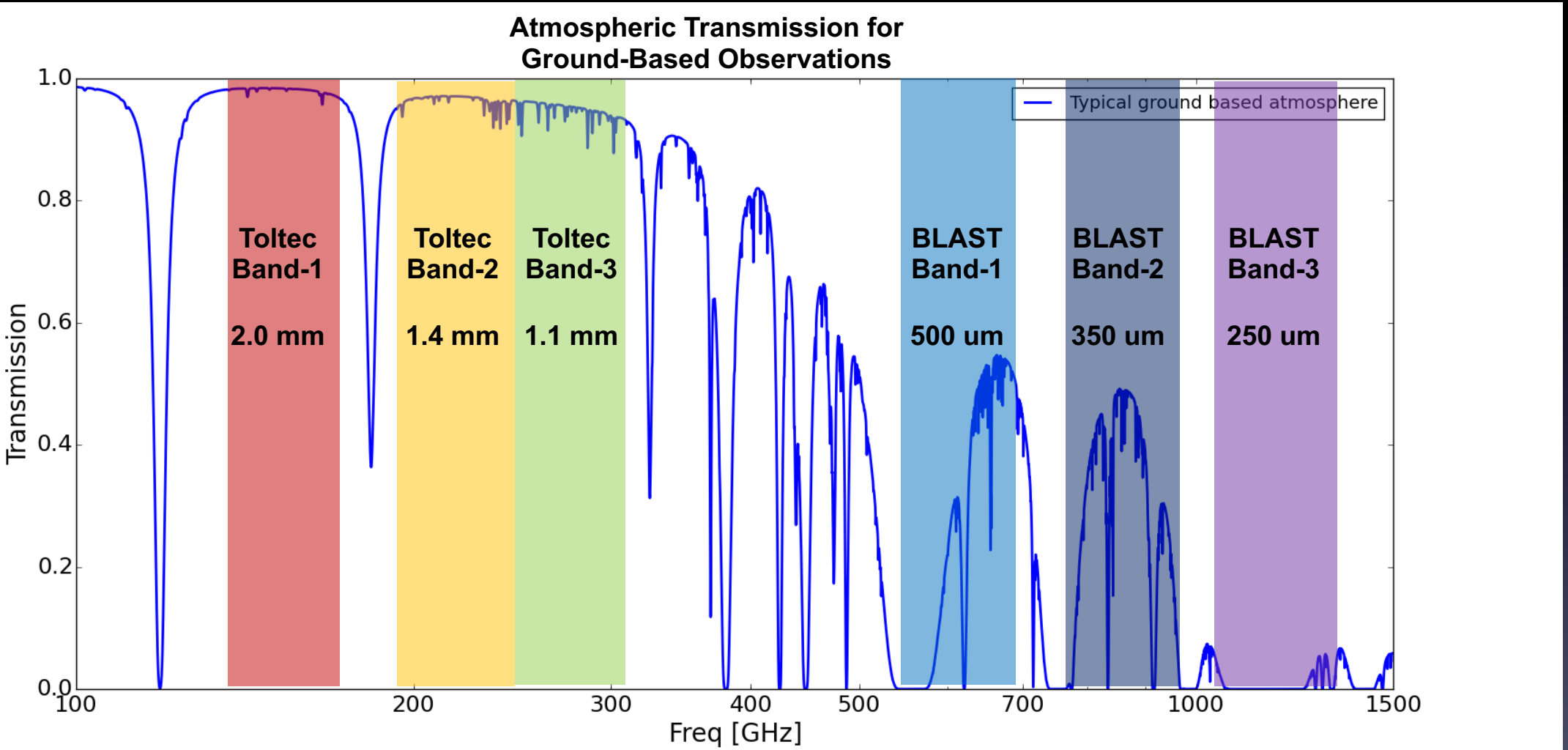


Fine

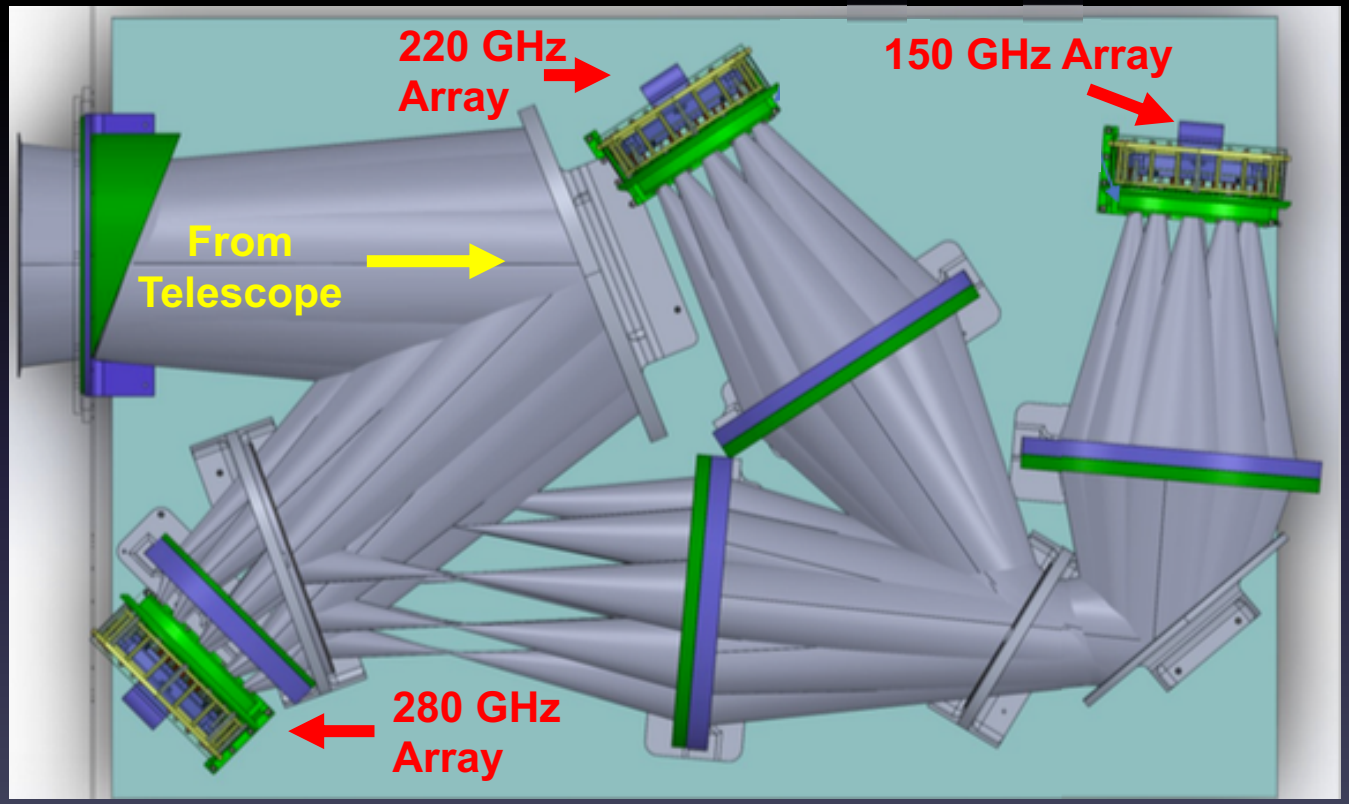
Extra slides

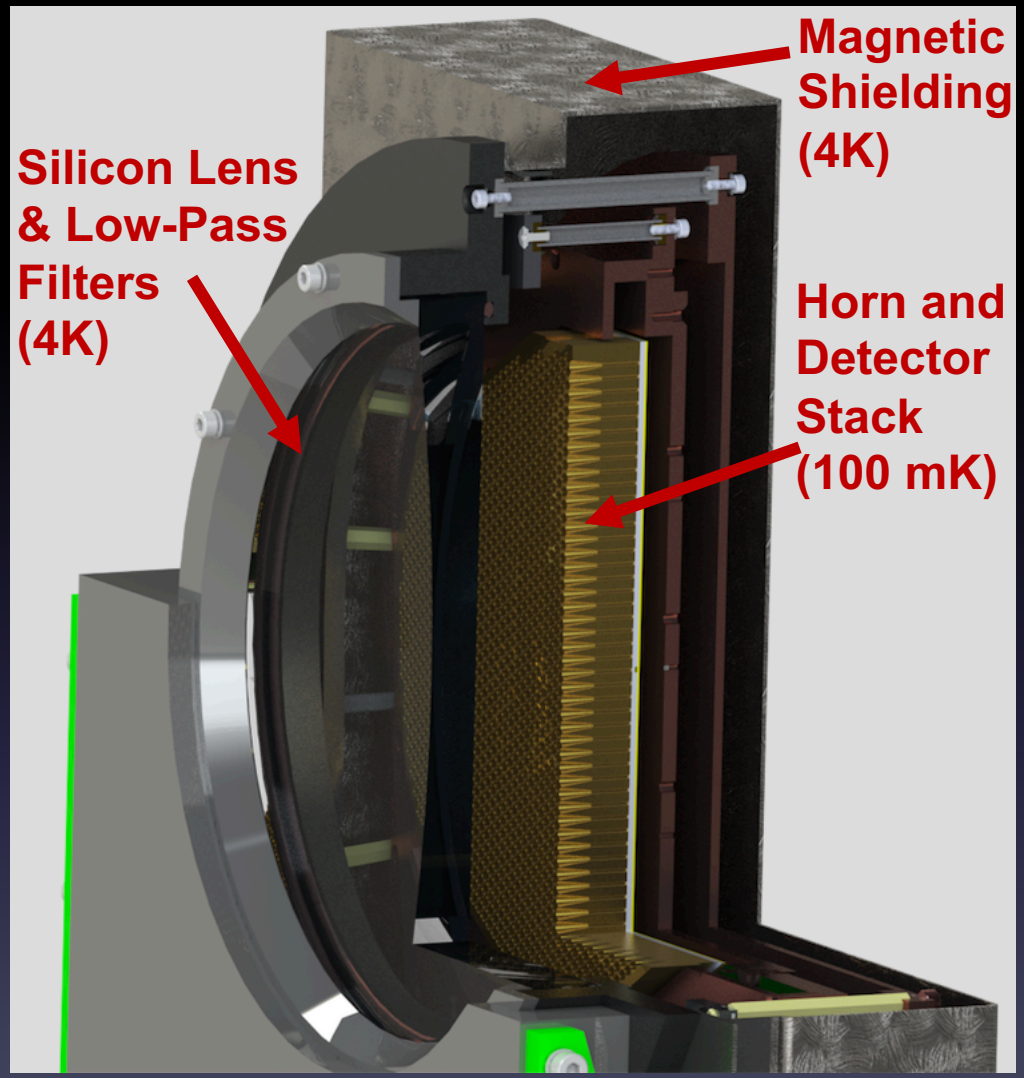
Order of magnitude frequency coverage



CSC atmospheric model, 0.5 PMV

Integration/ Coupling





Low Noise Amplifiers (4K) below focal plane