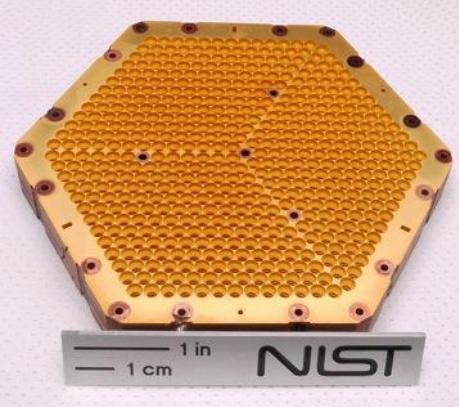


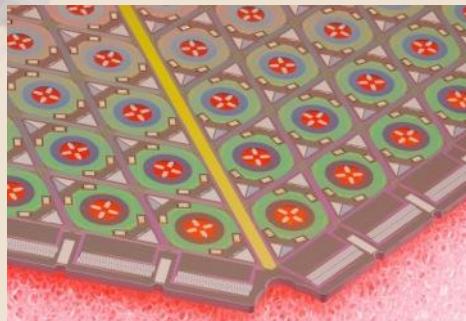
# NIST Instrumentation for CMB Observations

## Joel Ullom

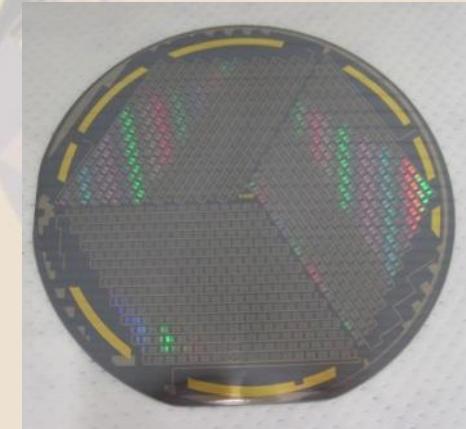
Silicon feedhorn arrays



TES polarimeter arrays



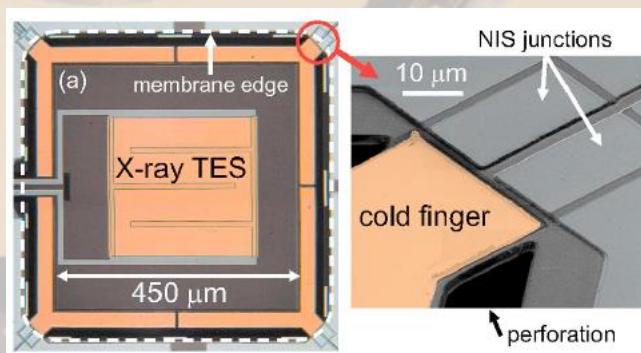
MKID polarimeter arrays



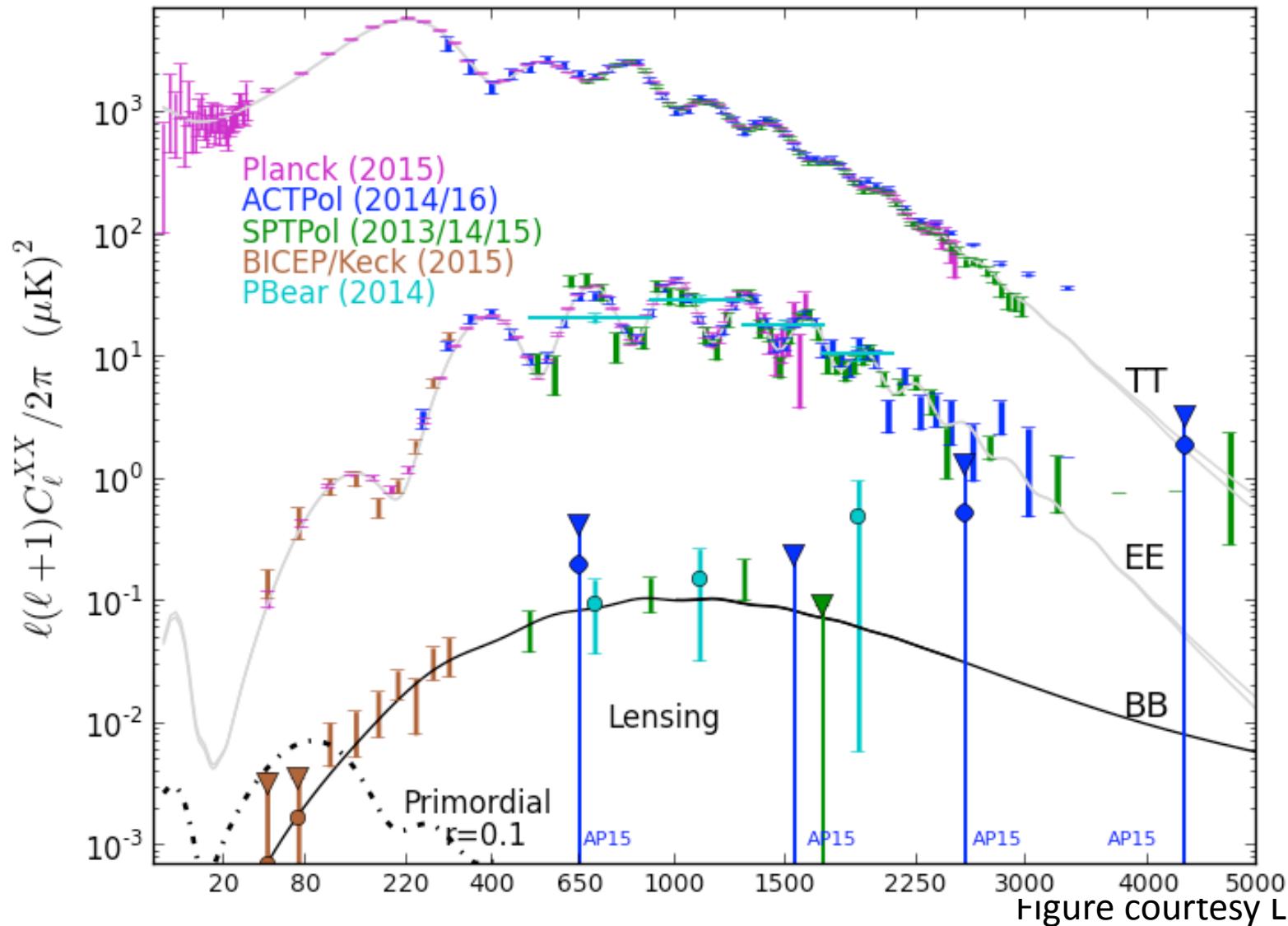
SQUID-based multiplexed readout



On-chip refrigeration



# CMB power spectra measurement status



# Developed by a large fraction of US CMB community

## NIST

J. Austermann  
J. A. Beall  
D. Becker  
S. M. Duff  
J. Gao  
A. Grigorian  
G.C. Hilton  
J. Hubmayr  
J. Ullom  
J. Van Lanen  
M. Vissers

## UC Berkeley

E.M. George  
N. Harrington  
W.L. Holzapfel

## Stanford

H.M. Cho  
D. Li  
K. Irwin  
K.W. Yoon

## UMich

R. Datta  
J. McMahon  
C. Munson

## UPenn

M.D. Devlin  
M. Lungu  
B.L. Schmitt  
J. Ward

## Case Western

J. Ruhl

## Cornell

S. Henderson  
B.J. Koopman  
M.D. Niemack

## Princeton

S. Choi  
K. Crowley  
E. Grace  
P. Ho  
L. Page  
C. Pappas  
L. Parker  
S. Simon  
S.T. Staggs

## U of Colorado

W. Everett  
N. Halverson  
J.T. Sayre

## NASA Goddard

H. Moseley  
E. Wollack

## U Chicago

L. Bleem  
J. Carlstrom  
J. W. Henning  
T. Natoli

## Johns Hopkins

J. Appel  
T. Essinger-Hileman

## ANL

C.L. Chang

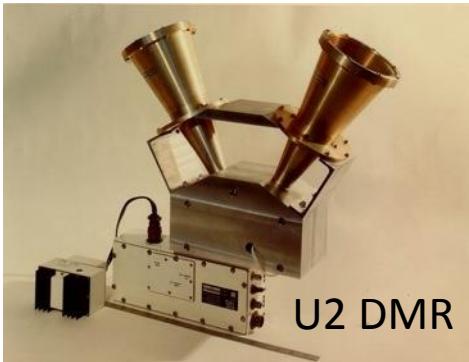
## U Toronto

L. Newburgh

## FermiLab

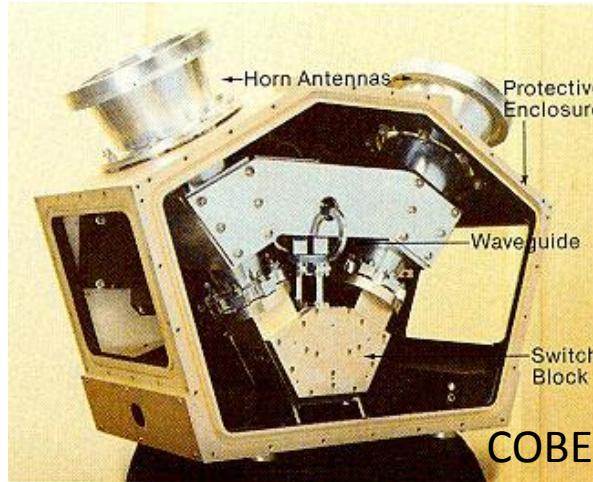
B. A. Benson

# Feedhorns for CMB science



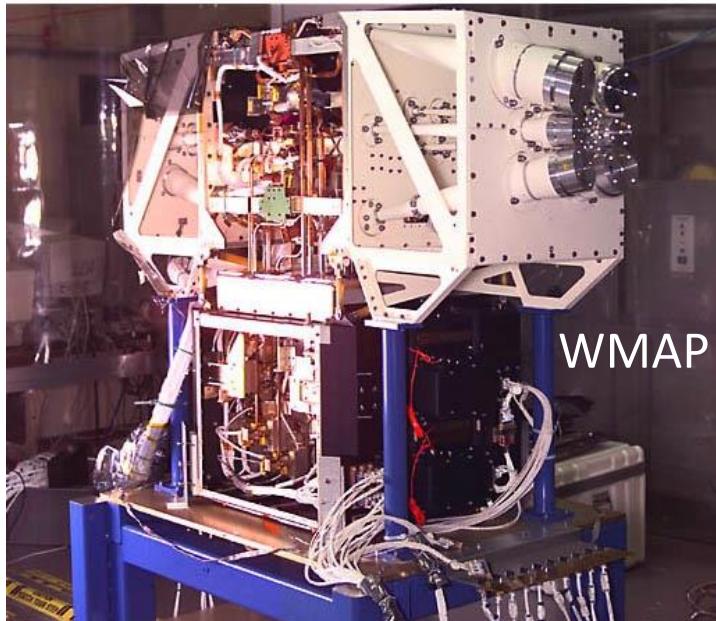
U2 DMR

<http://aether.lbl.gov/www/projects/u2/U2PARAMETRIC.JPG>



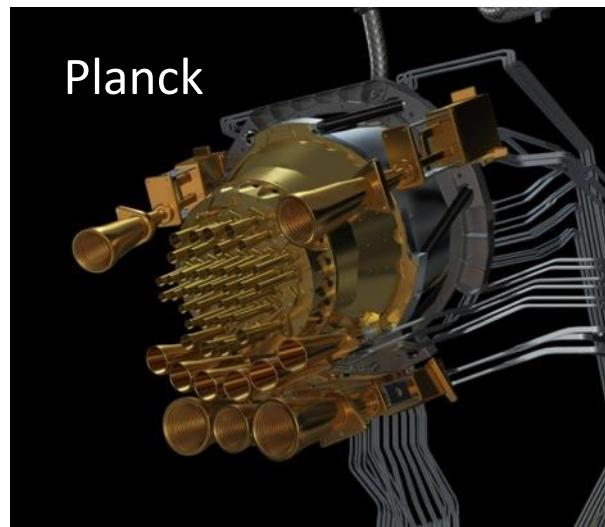
COBE

[http://muller.lbl.gov/COBE-early\\_history/preCOBEhistory.html](http://muller.lbl.gov/COBE-early_history/preCOBEhistory.html)



WMAP

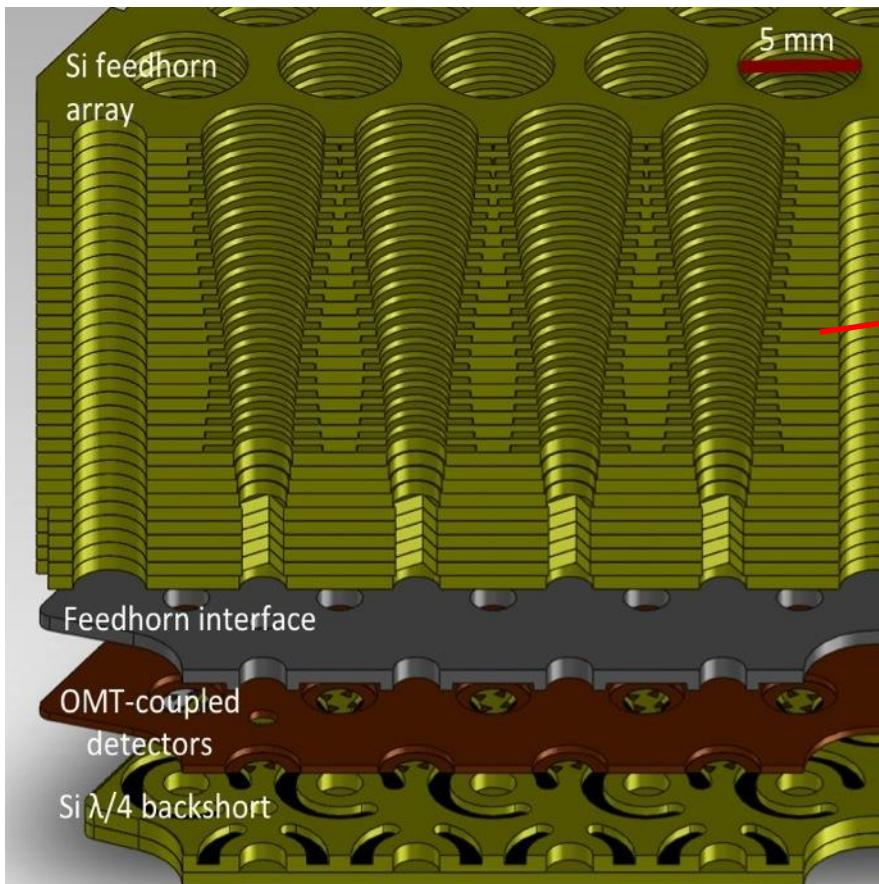
<http://wmap.gsfc.nasa.gov/media/ContentMedia/990259b.jpg>



Planck

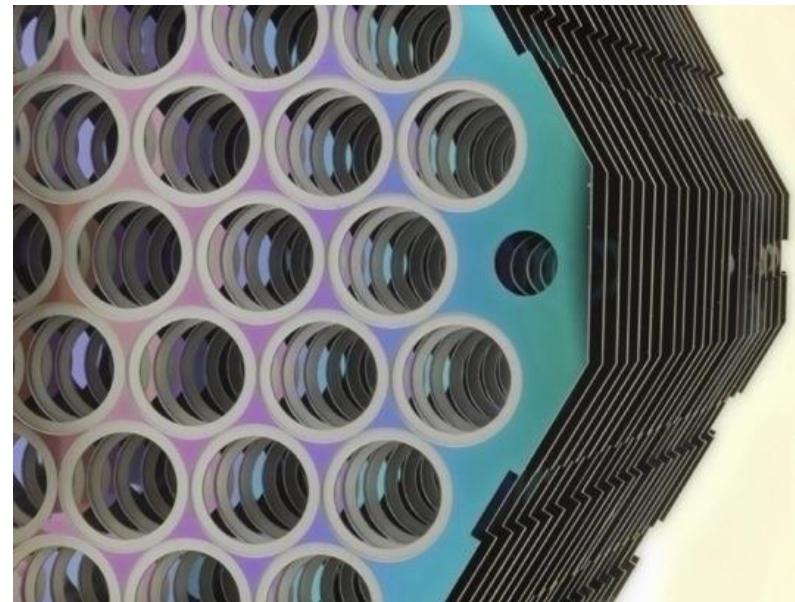
[http://www.esa.int/spaceinimages/Images/2009/05/Planck\\_s\\_instruments4](http://www.esa.int/spaceinimages/Images/2009/05/Planck_s_instruments4)

# Silicon feedhorn-coupled arrays

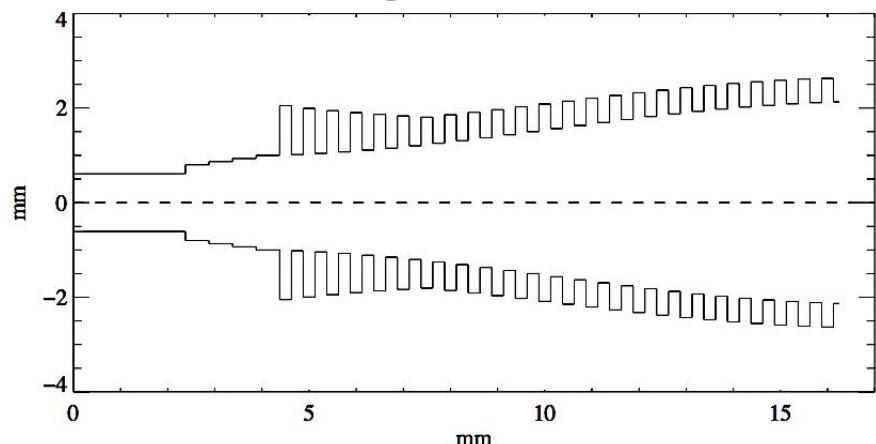


Yoon et al. *AIP* 2009

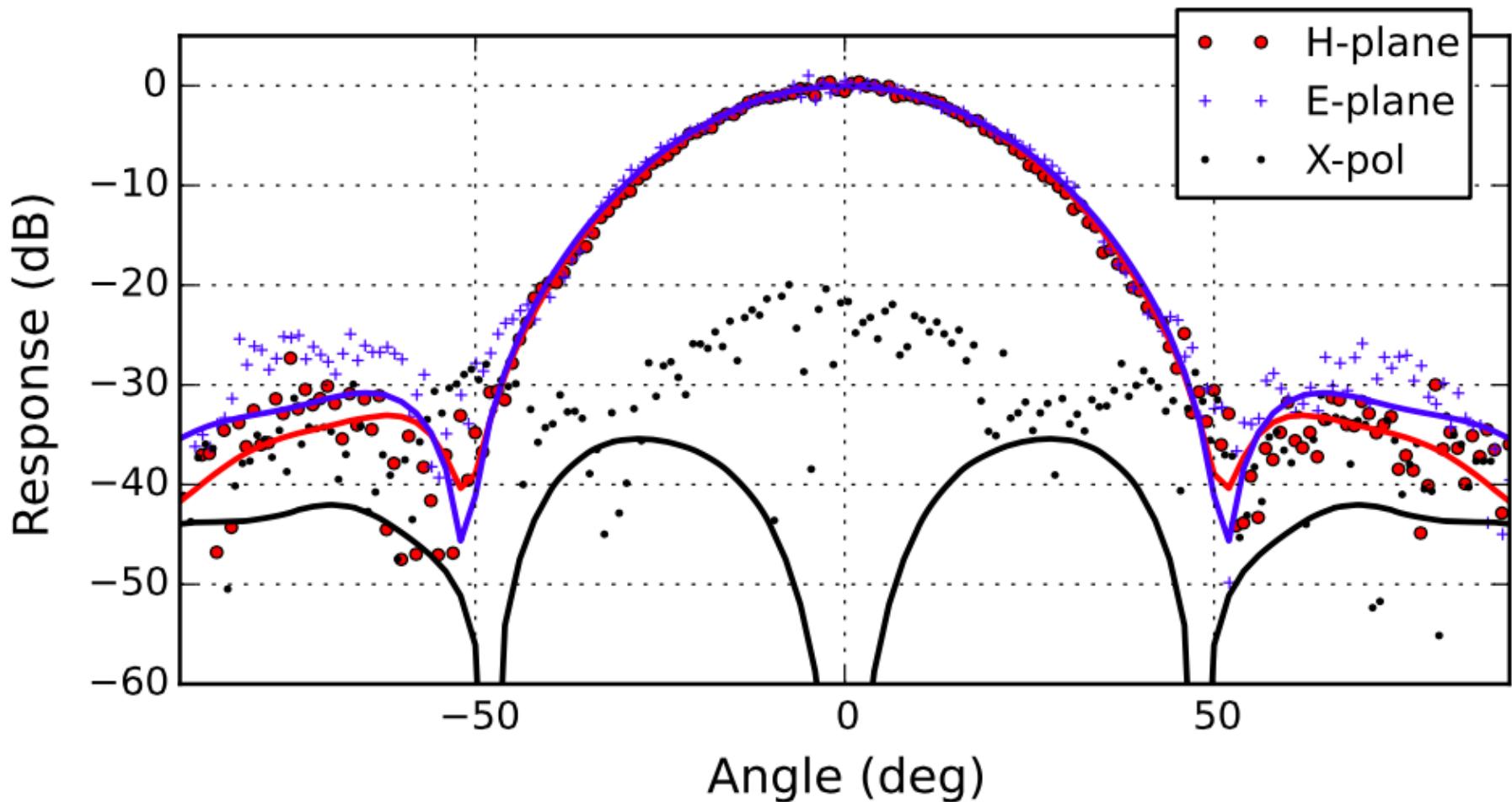
Hubmayr et al. *JLTP* 2012



**corrugation profile**

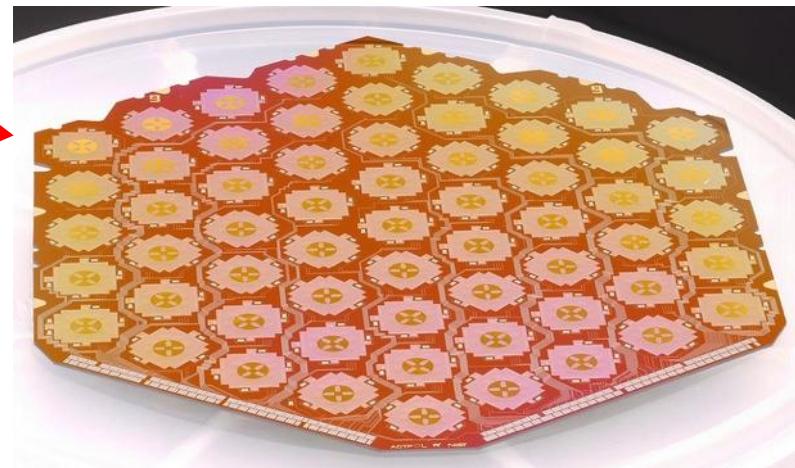
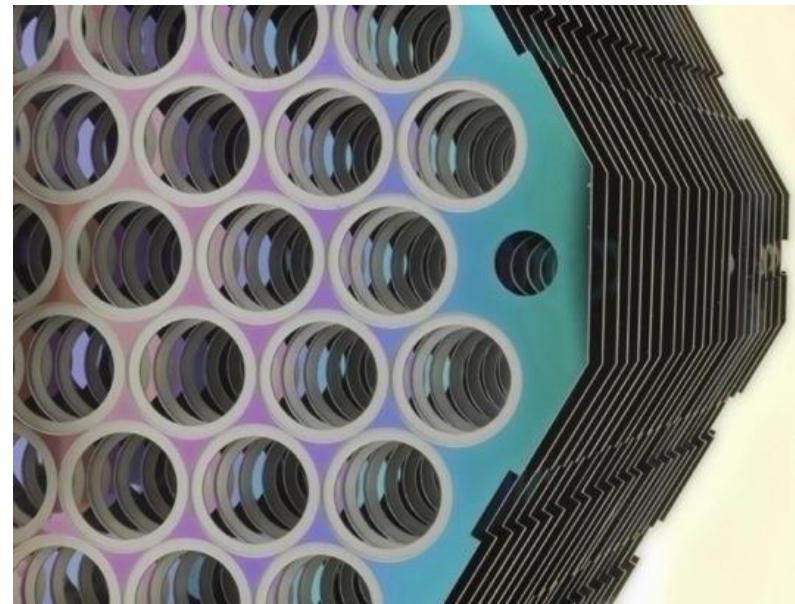
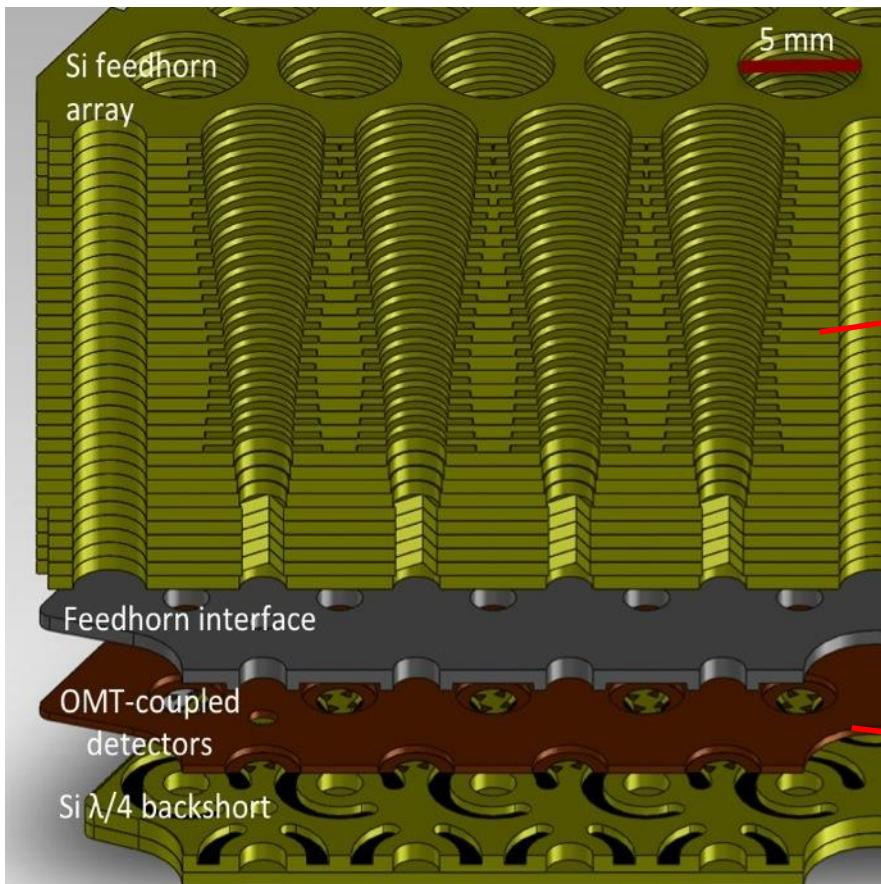


# Silicon feedhorn-coupled arrays: performance



Hubmayr et al. *JLTP* 2012

# Silicon feedhorn-coupled arrays

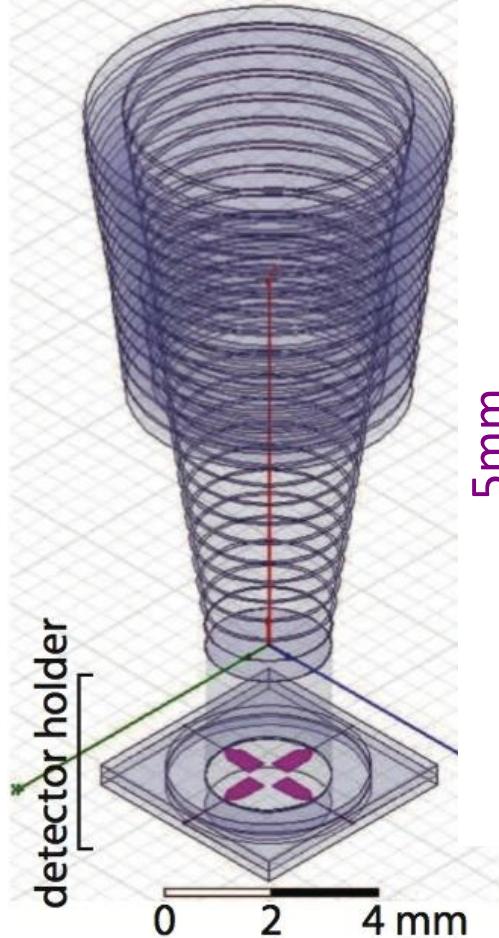


Yoon et al. *AIP* 2009

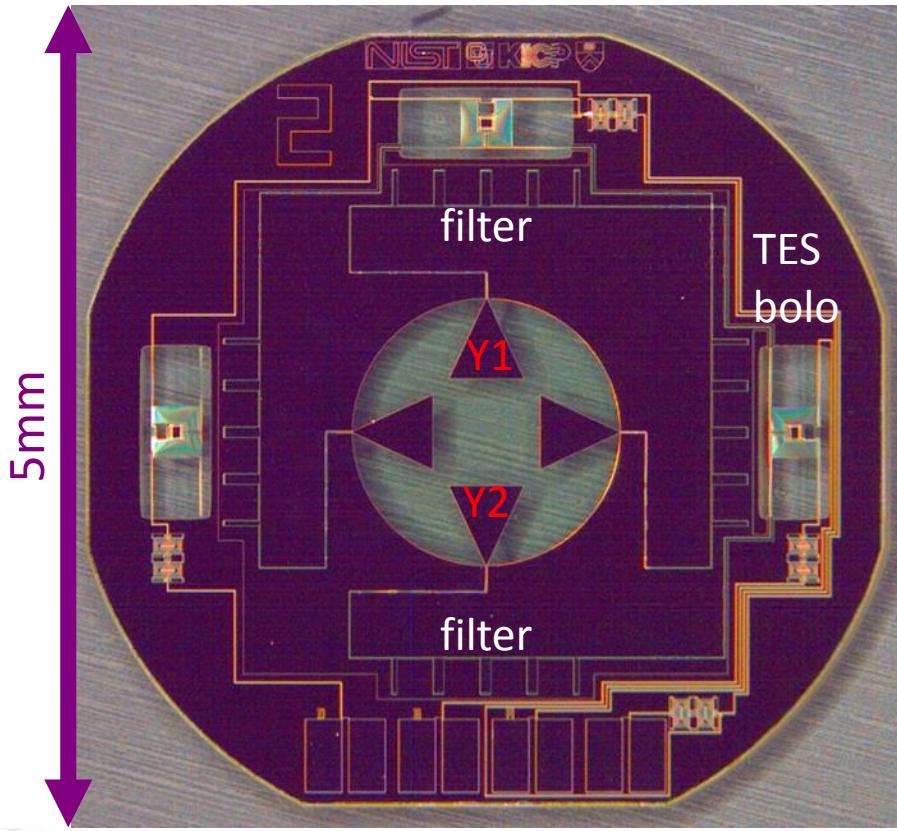
Hubmayr et al. *JLTP* 2012

# Detection concept

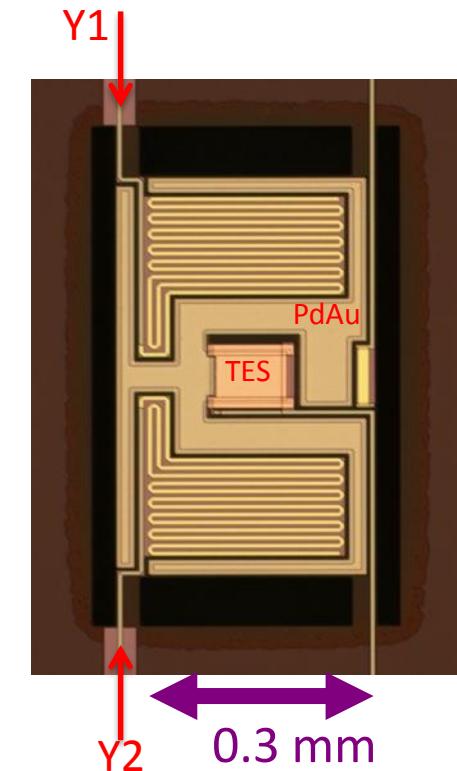
Corrugated feedhorn



Planar Ortho-mode Transducer (OMT) pixel



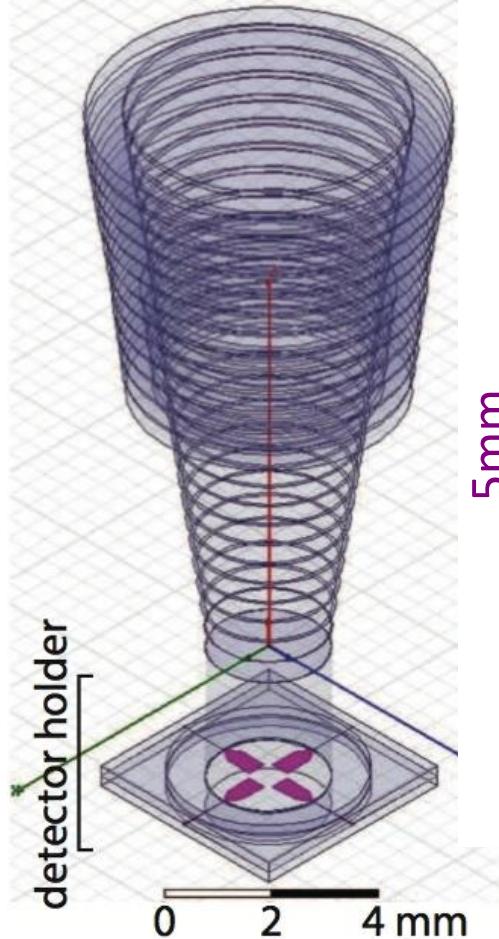
Transition-edge sensor  
(TES) bolometer  
(one per polarization)



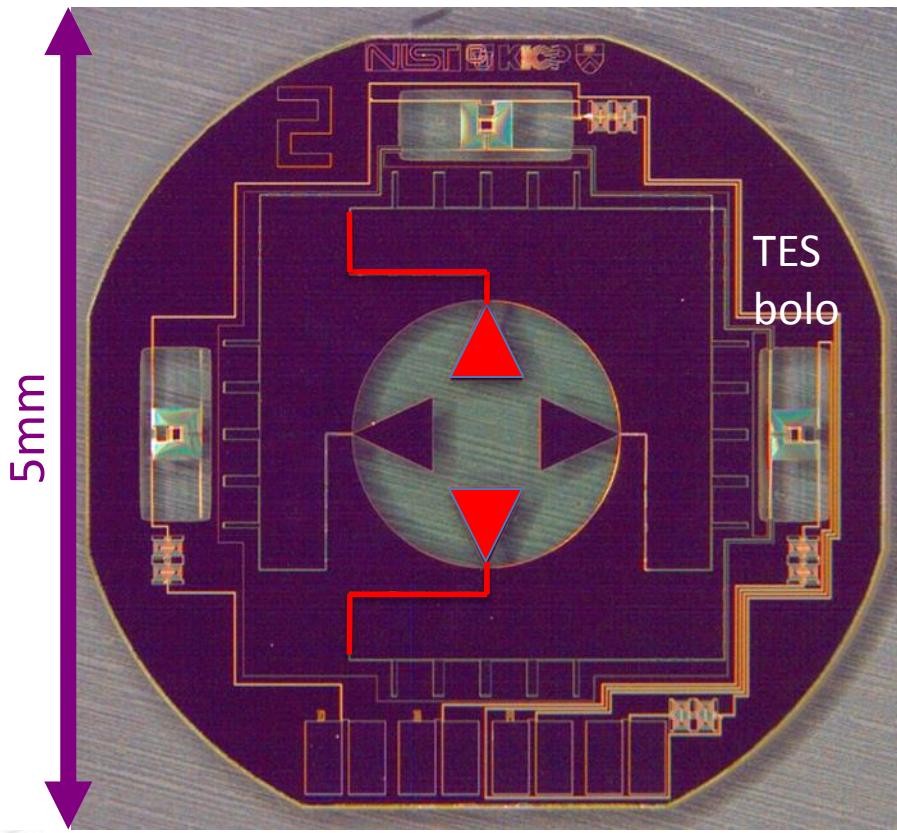
NIST feedhorn-coupled, superconducting TES polarimeters

# Detection concept

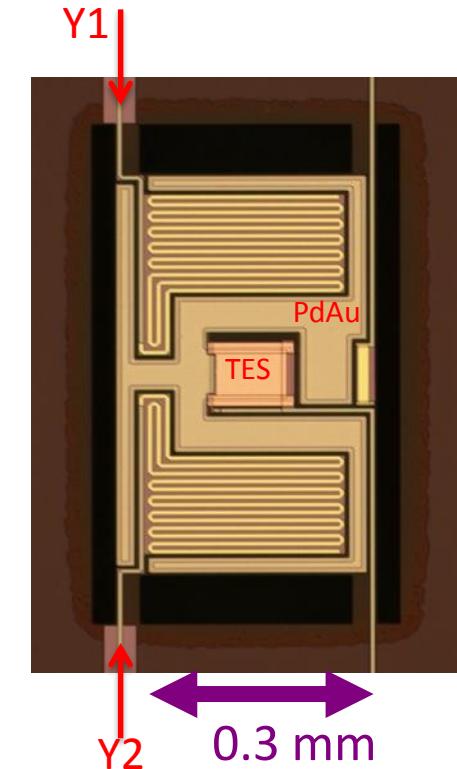
Corrugated feedhorn



Planar Ortho-mode Transducer (OMT) pixel



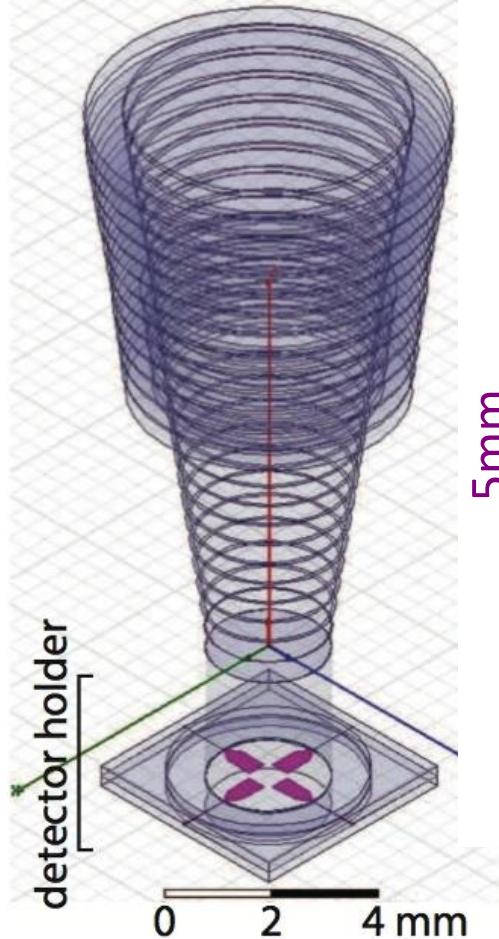
Transition-edge sensor  
(TES) bolometer  
(one per polarization)



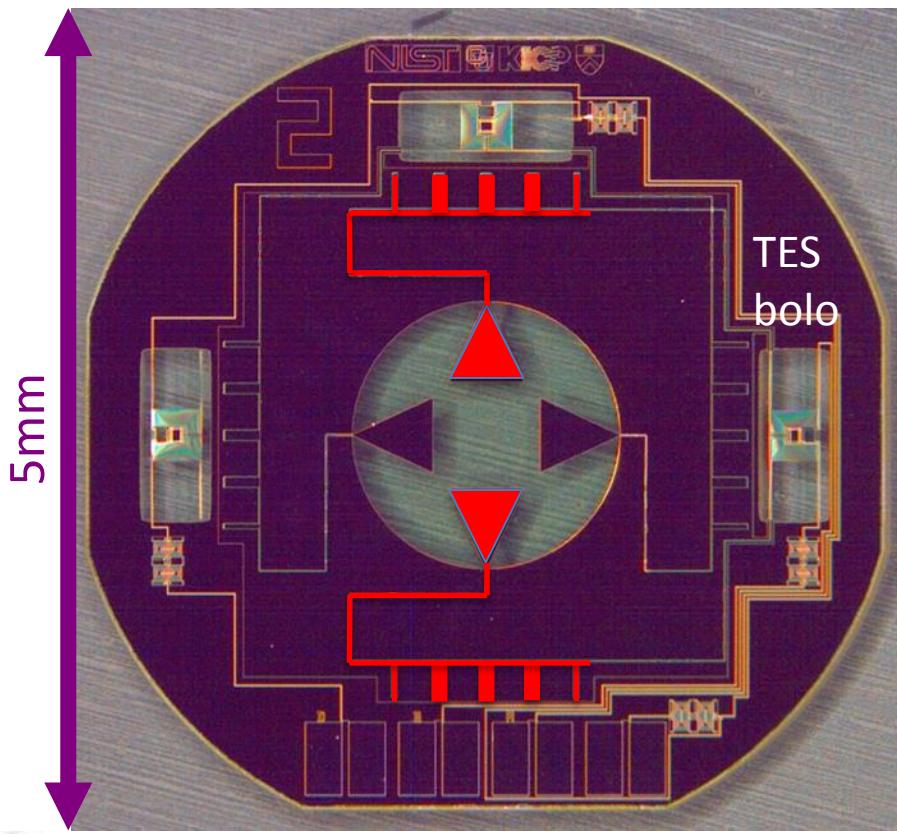
NIST feedhorn-coupled, superconducting TES polarimeters

# Detection concept

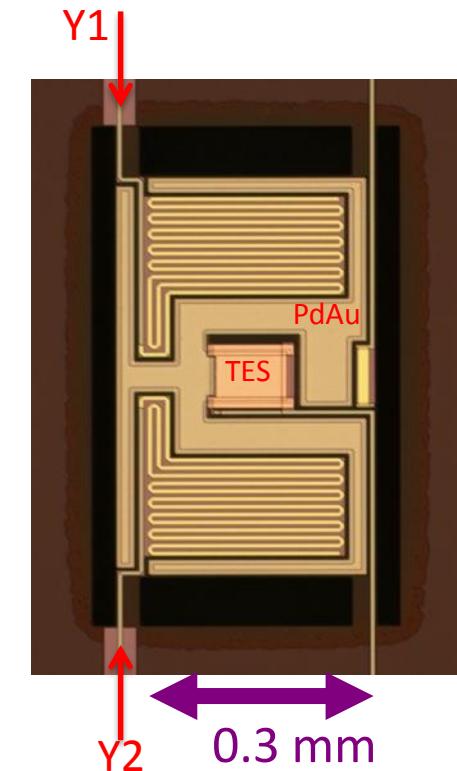
Corrugated feedhorn



Planar Ortho-mode Transducer (OMT) pixel



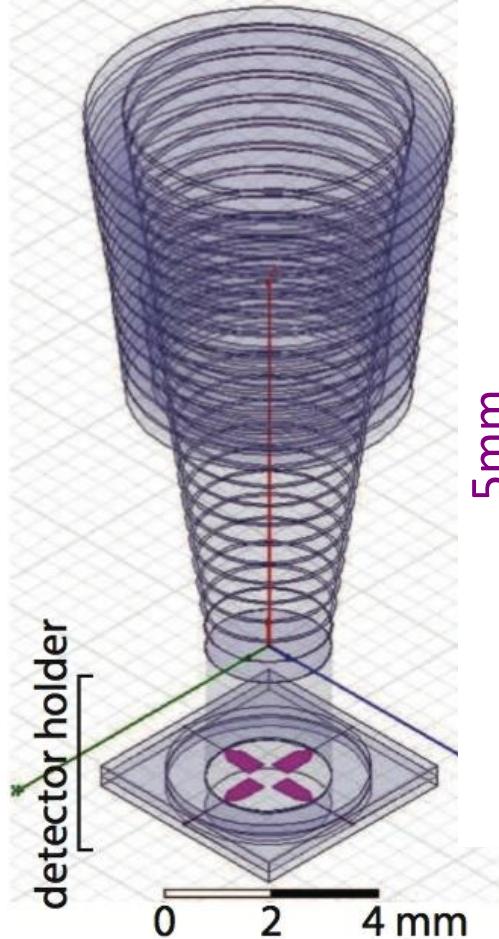
Transition-edge sensor  
(TES) bolometer  
(one per polarization)



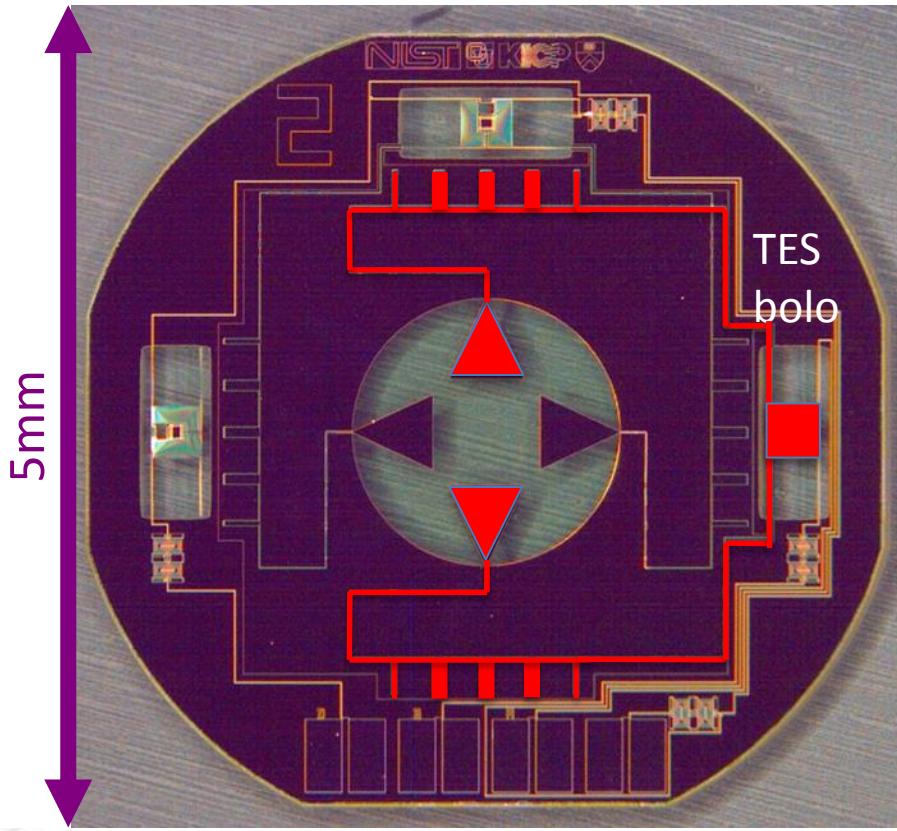
NIST feedhorn-coupled, superconducting TES polarimeters

# Detection concept

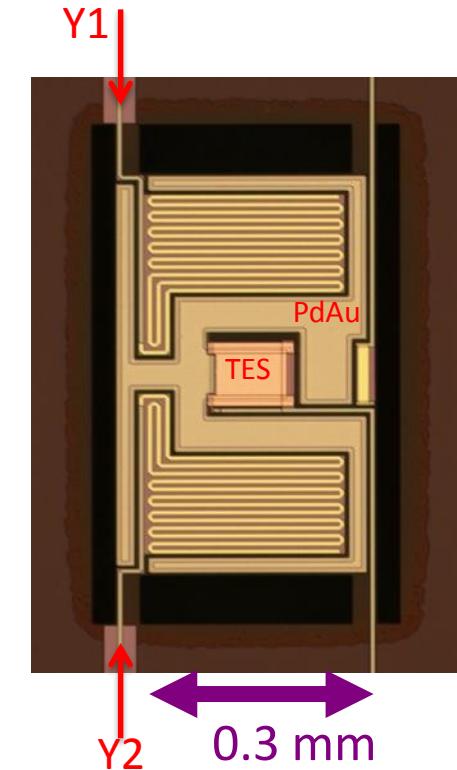
Corrugated feedhorn



Planar Ortho-mode Transducer (OMT) pixel

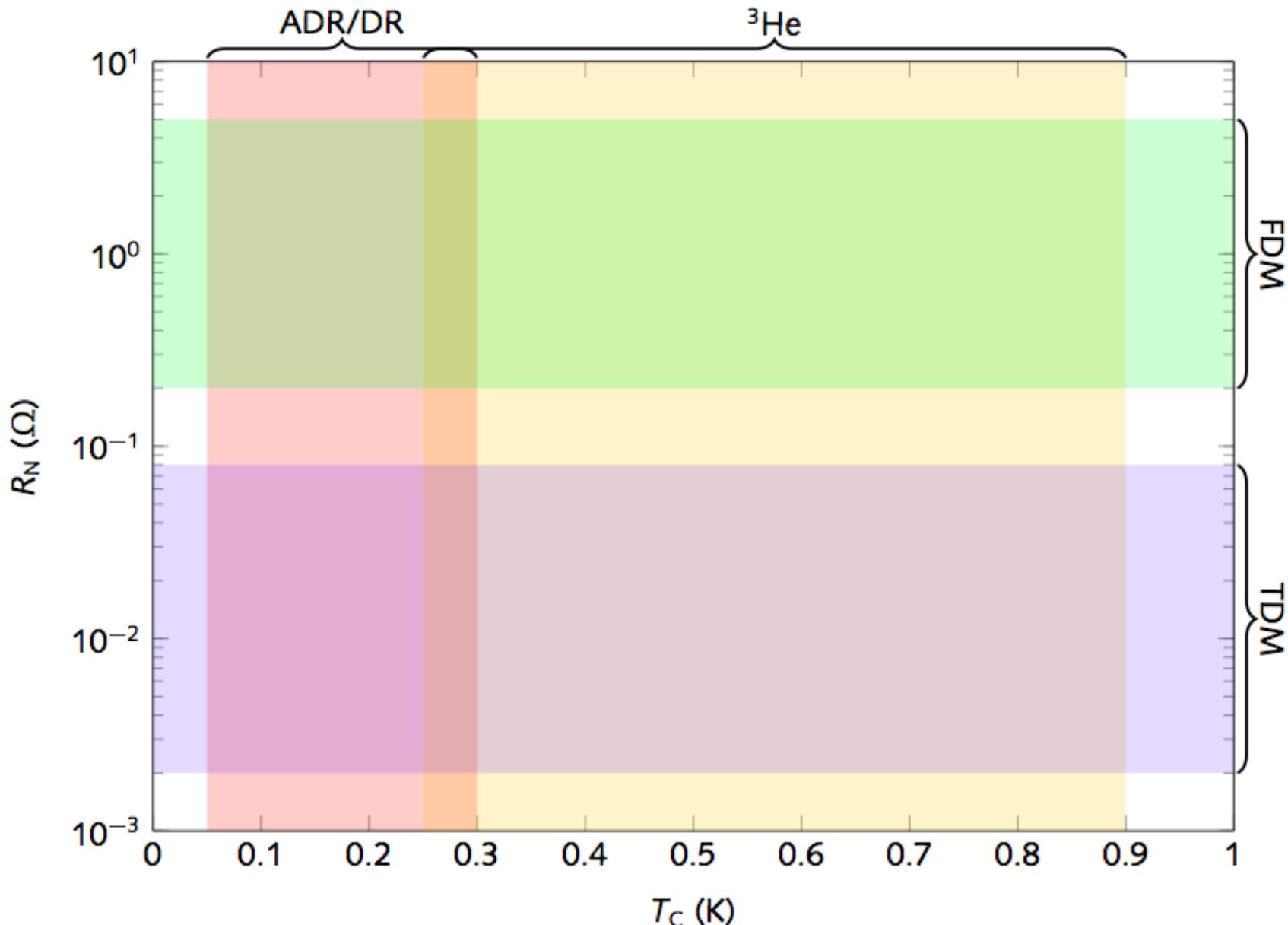


Transition-edge sensor  
(TES) bolometer  
(one per polarization)

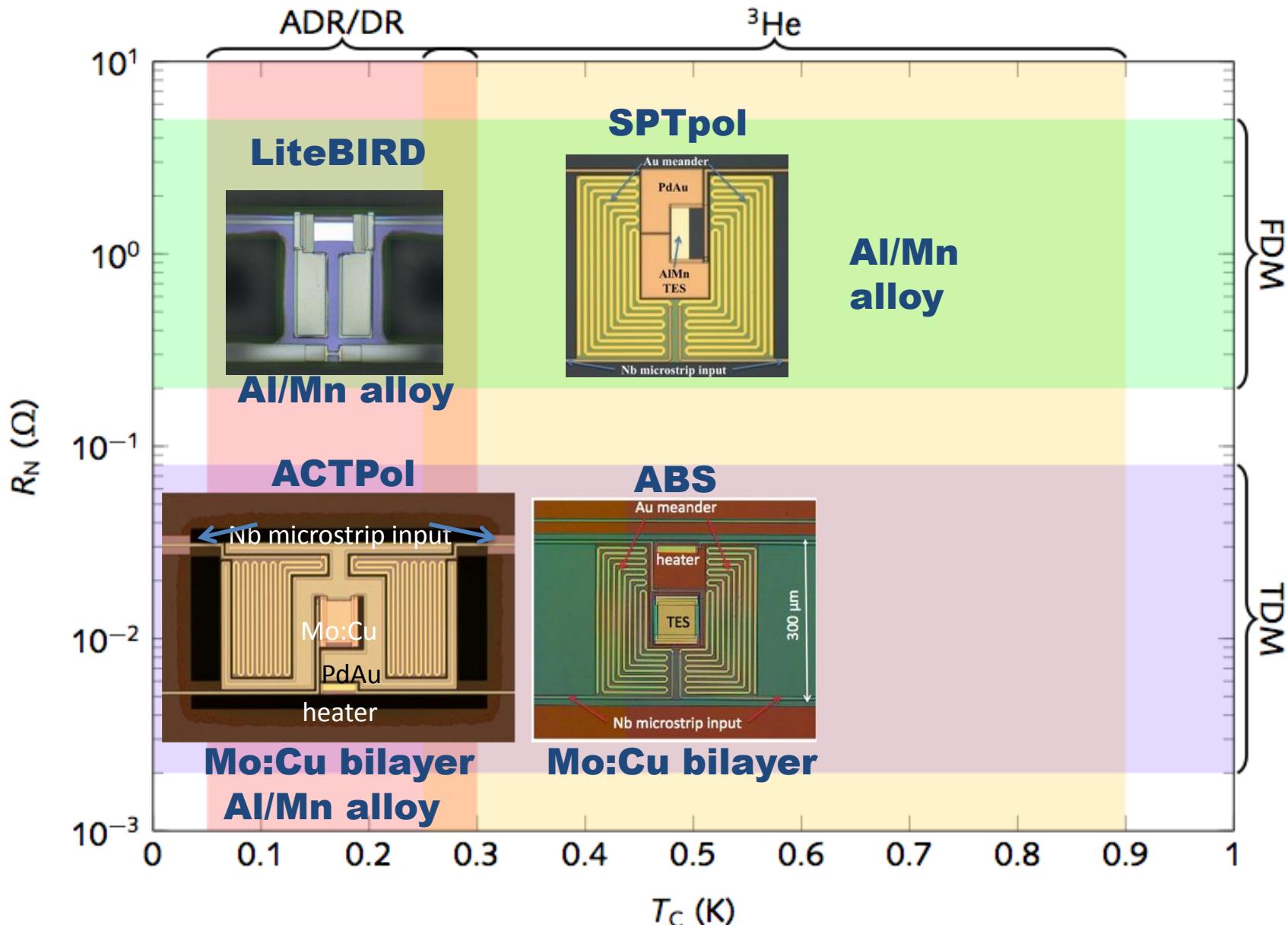


NIST feedhorn-coupled, superconducting TES polarimeters

# TES parameters driven by $T_b$ and readout

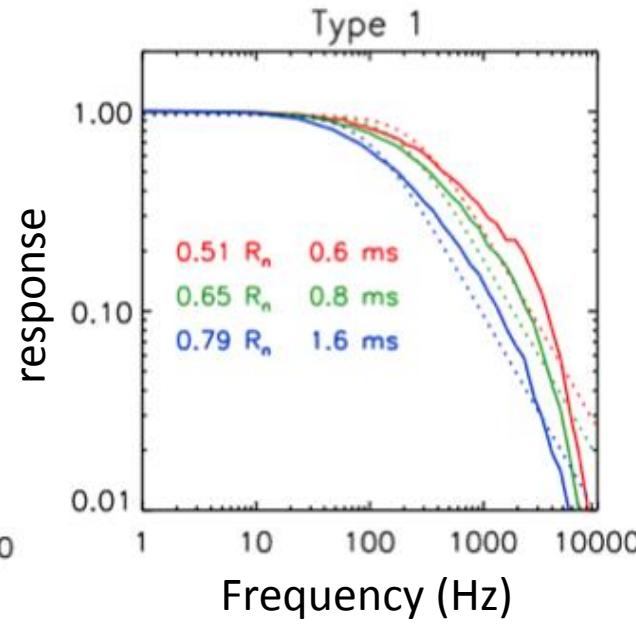
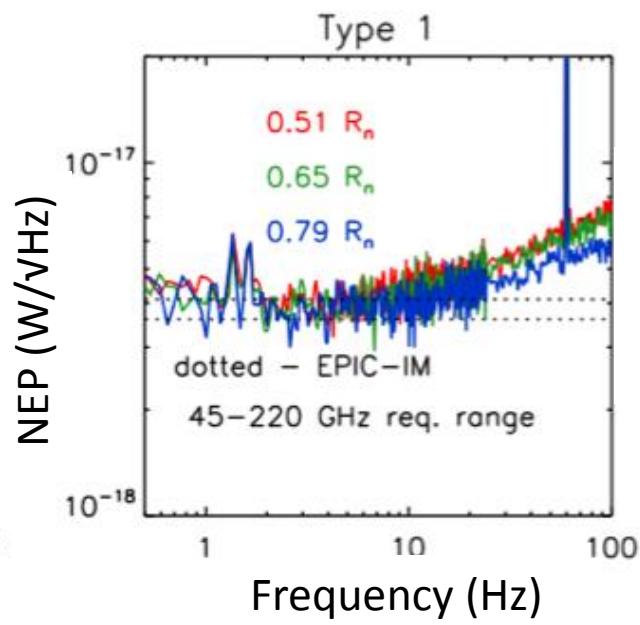
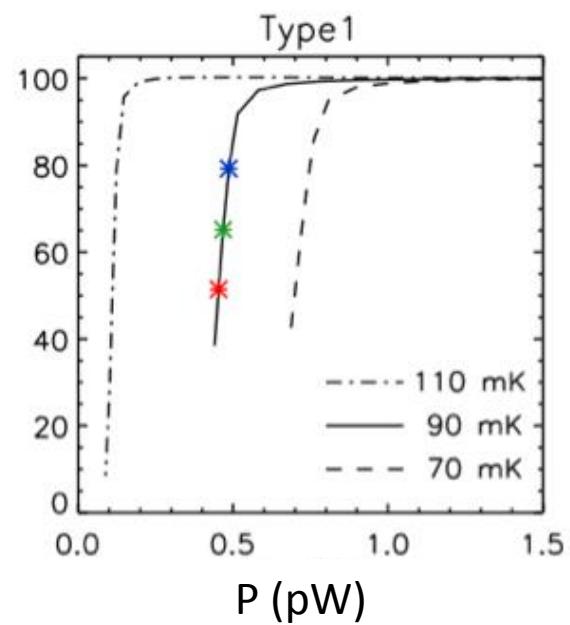
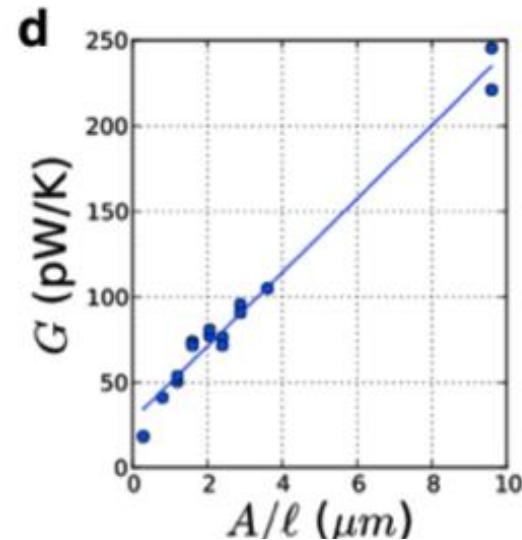
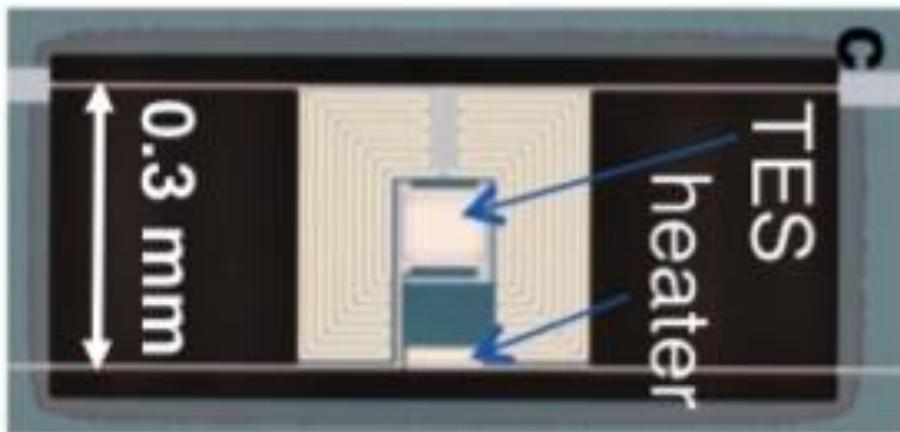


# Have produced sensors for all relevant parameter space

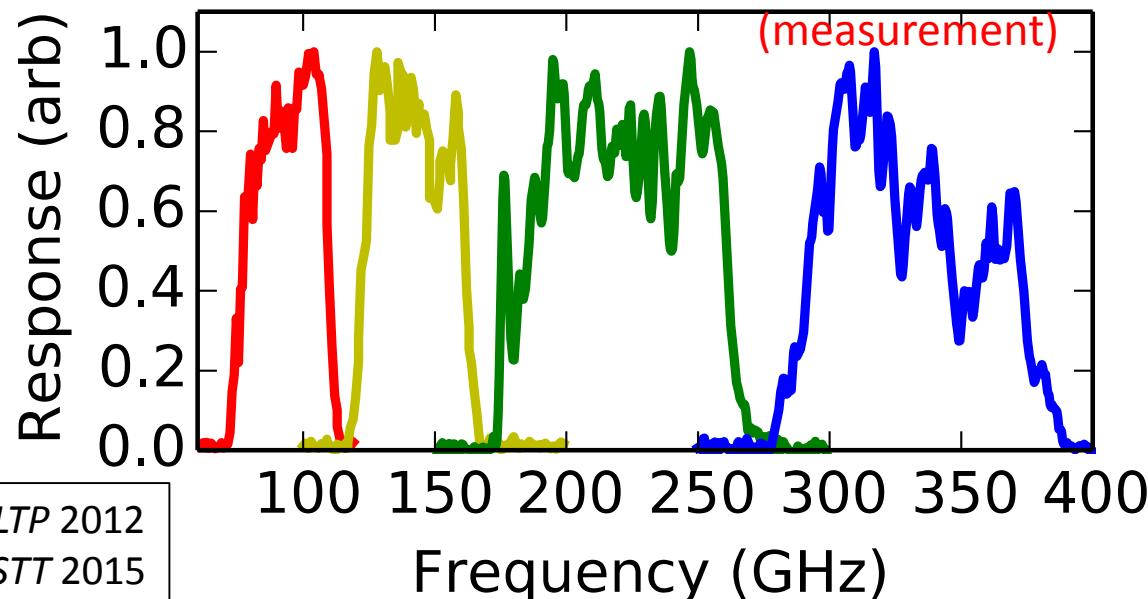
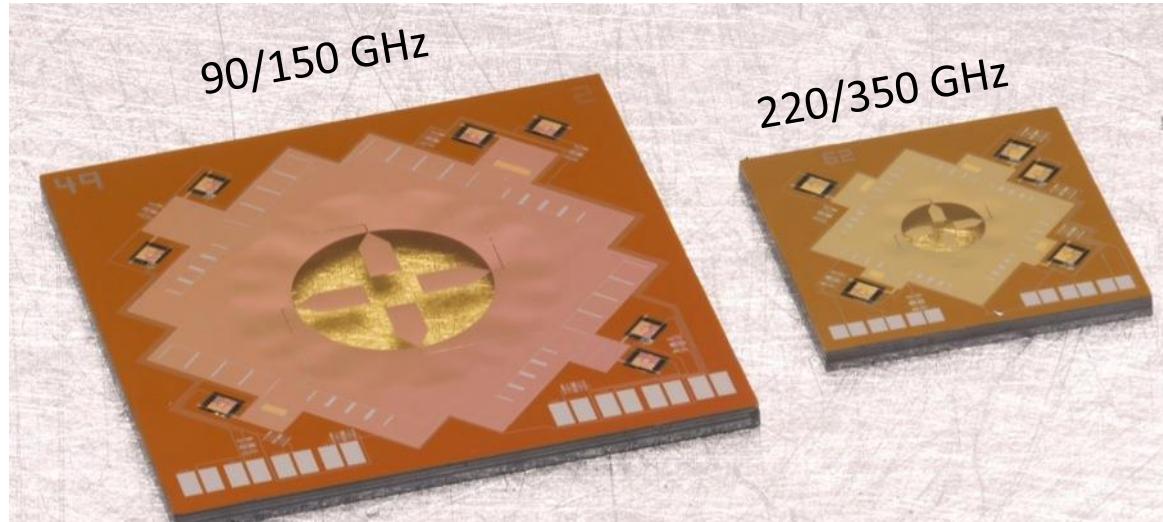


# Space-optimized TES bolometers

Niemack et al. *JLTP* 2012



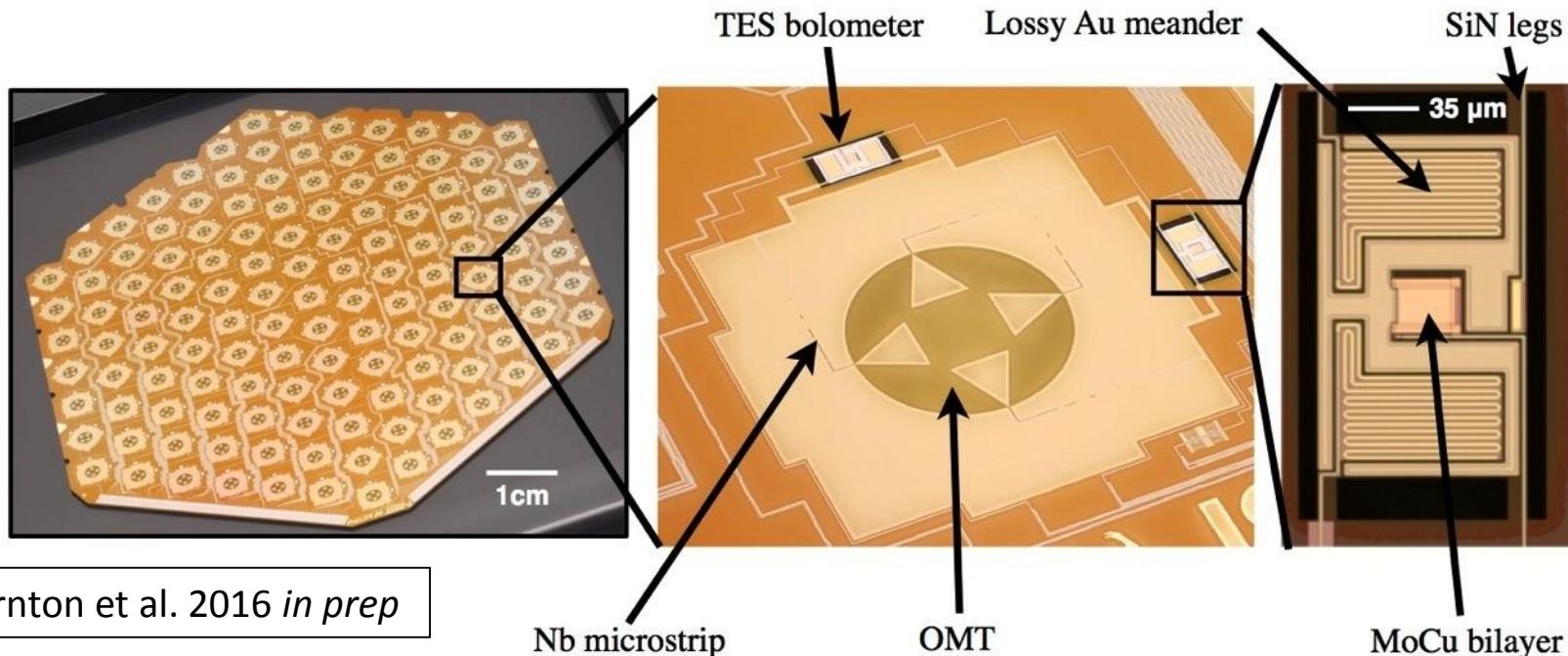
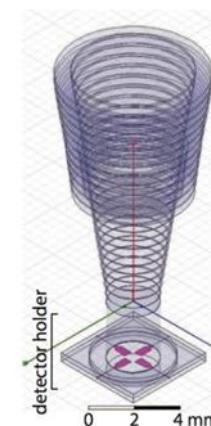
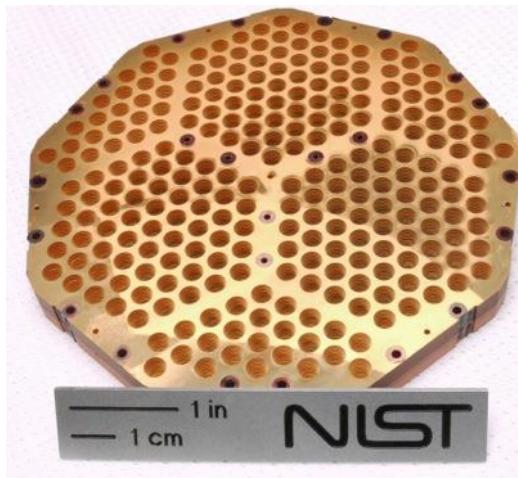
# Multichroic polarimeters with 2.3:1 bandwidth



McMahon et al. *JLTP* 2012  
Hubmayr et al. *ISSTT* 2015

We believe 3:1  
bandwidth is  
possible in the  
future

# ACTPol 90/150 GHz detectors



Thornton et al. 2016 *in prep*

# ACTPol 90/150 GHz assembled focal plane

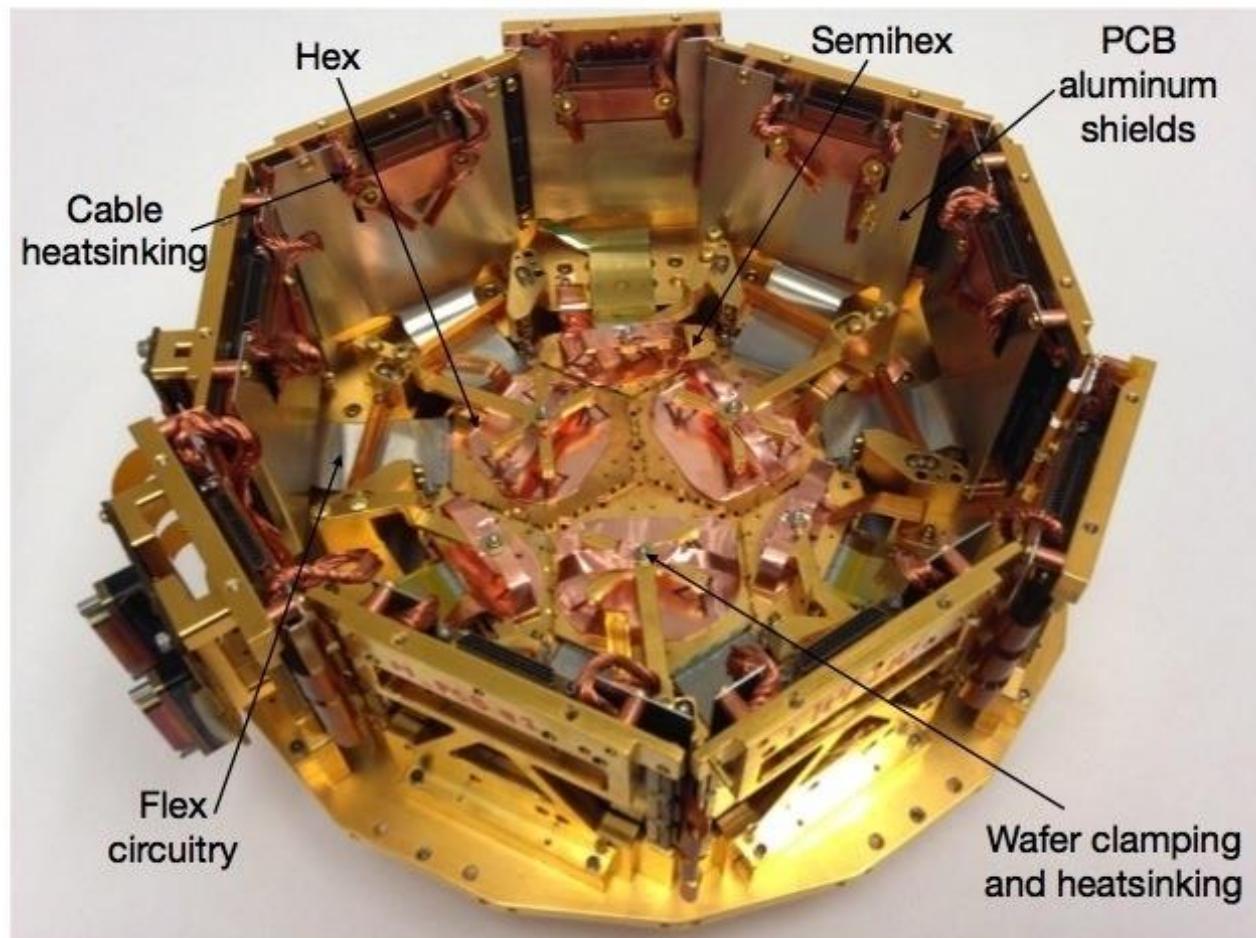
255 optical pixels

1020 TES

83% yield (includes  
readout, cabling, etc)

Detector yield near 100%

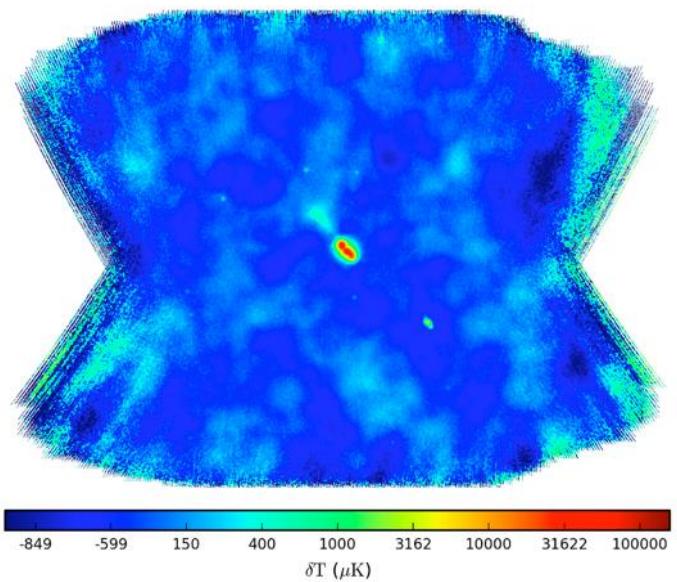
Observing since early 2015



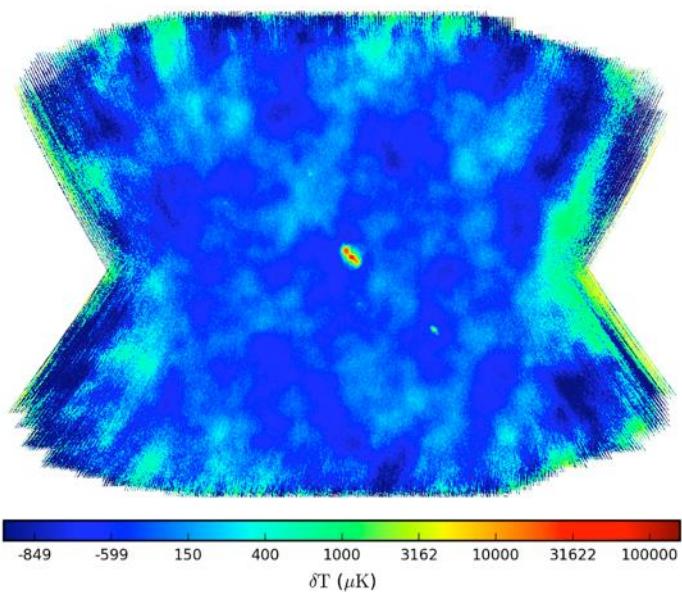
Thornton et al. 2016 *in prep*

# 90/150 GHz ACTPol images

ACTPol PA3 90 GHz (0.9' Smoothed)   ACTPol PA3 150 GHz (0.6' Smoothed)

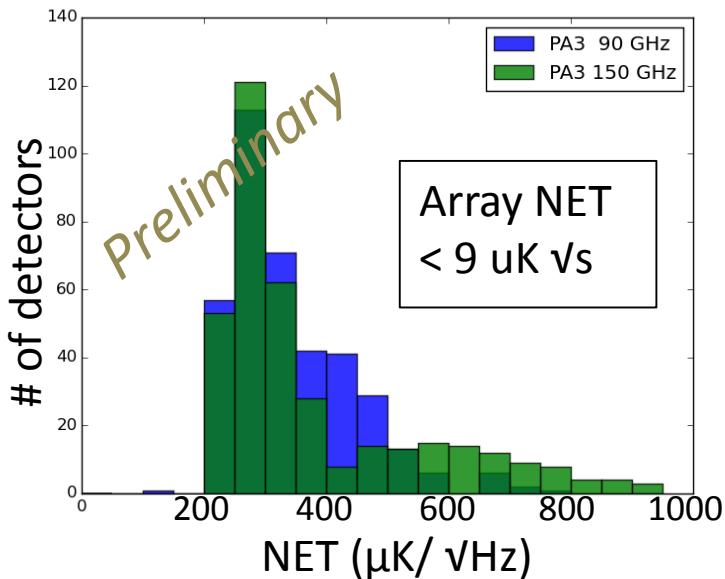


Preliminary  
Centaurus A



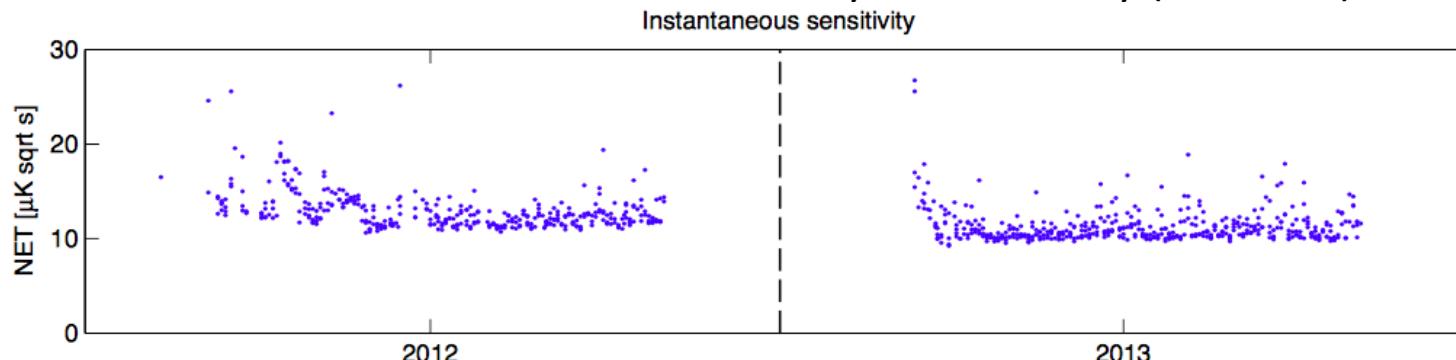
# 90/150 GHz ACTPol performance

Sensitivity histogram

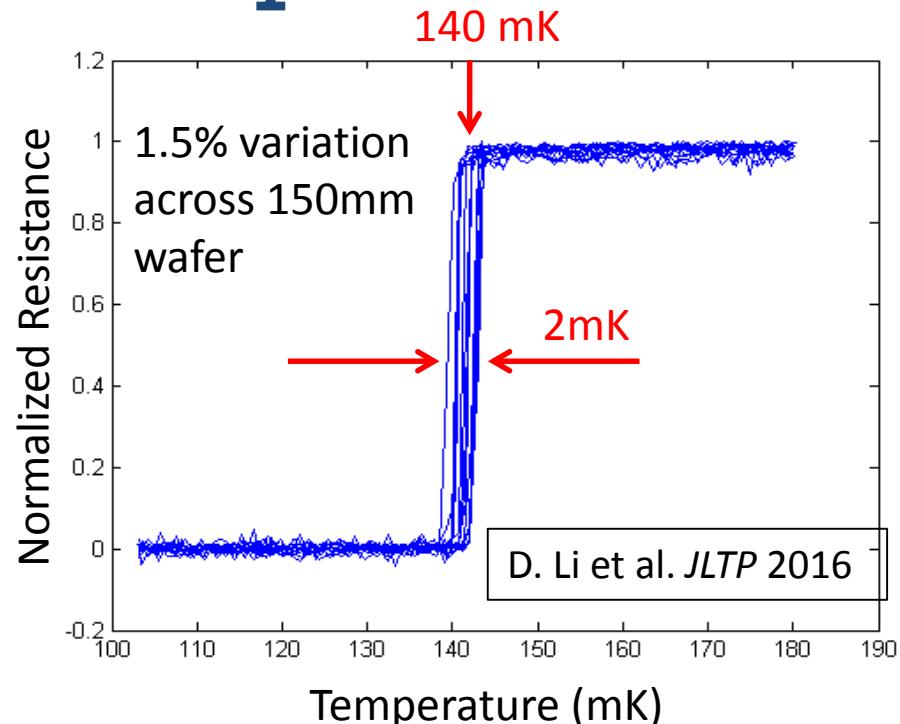
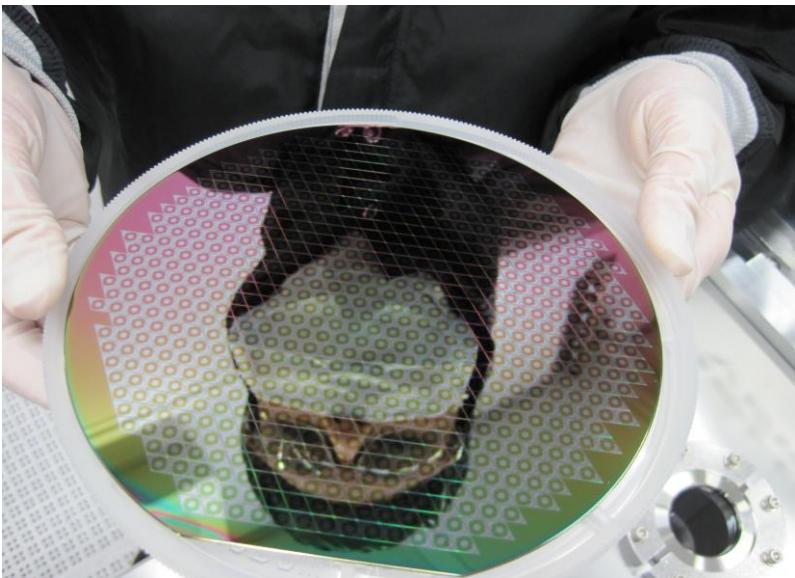


- based on observation of saturn at PWV = 0.5mm
- preliminary multichroic array NET < 9  $\mu\text{K} \sqrt{\text{s}}$  with 1020 TES

Achieved instantaneous sensitivity of KECK array (2560 TES)

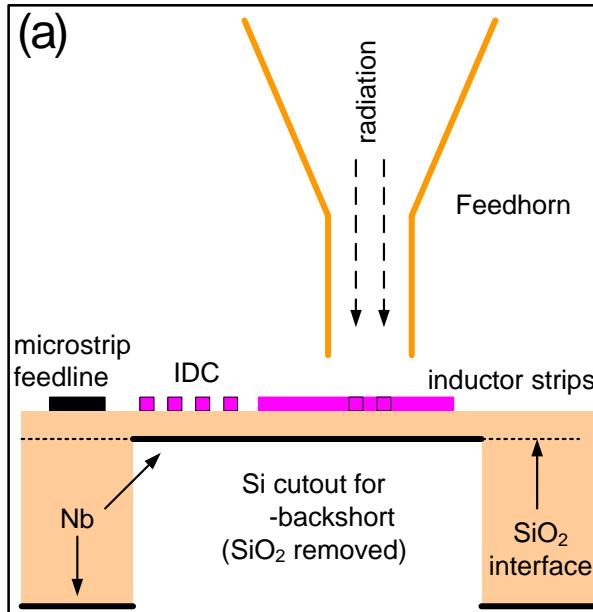
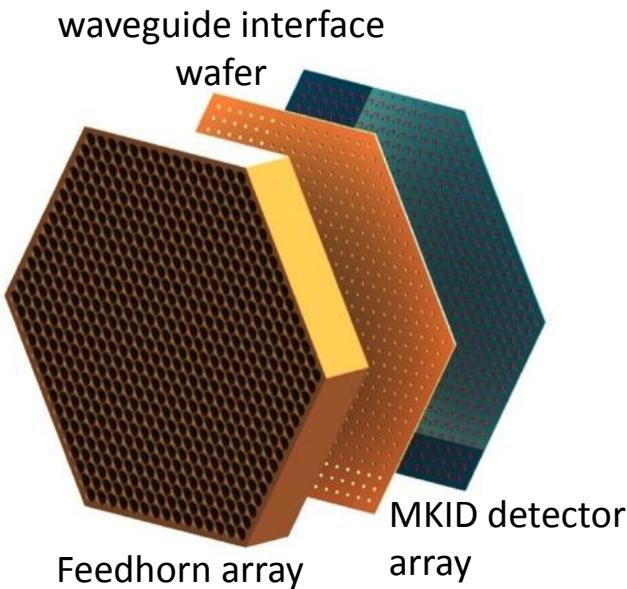


# Array fabrication improvements



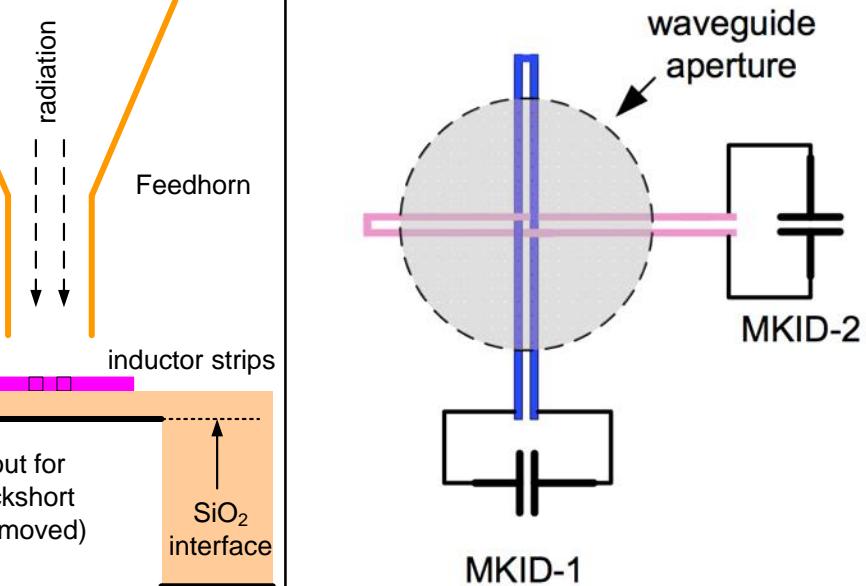
- 150mm array fabrication now routine
- most recent wafer for Advanced ACTPol:
  - 503 pixels, 2012 sensors
  - 99.9% electrical yield
  - Saturation power within 15% of specification
  - 2% transition temperature variation
  - Optical efficiency (through feeds) 70-80% at 150 GHz and 65-75% at 230 GHz based on single pixel tests

# Feedhorn-coupled, dual-polarization MKIDs



Hubmayr et al. *IEEE Trans Appl Sup* 2013

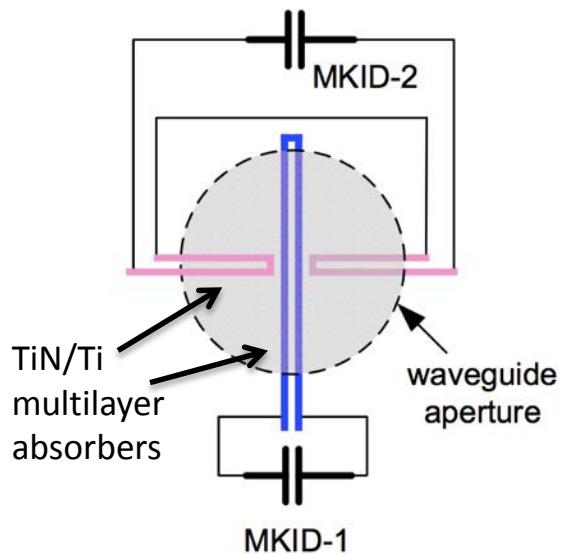
- feedhorn-coupled
- TiN/Ti multilayer superconducting material
- lumped element kinetic inductance detectors



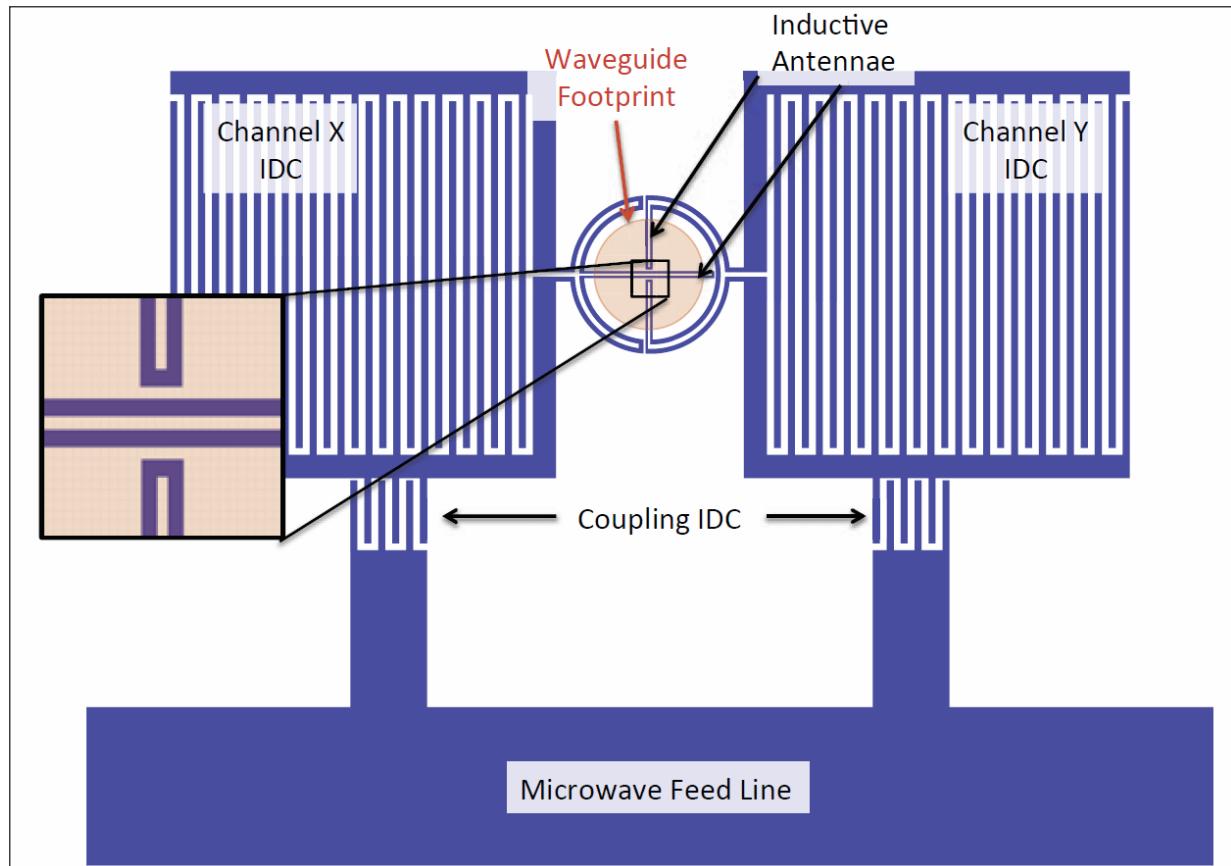
- scalable to large detector-count cameras
- scalable in frequency
- dual-polarization sensitivity
- beam properties defined by feedhorns
- low number of focal plane interconnects

# MKID Pixel Design

pixel schematic  
(not to scale)



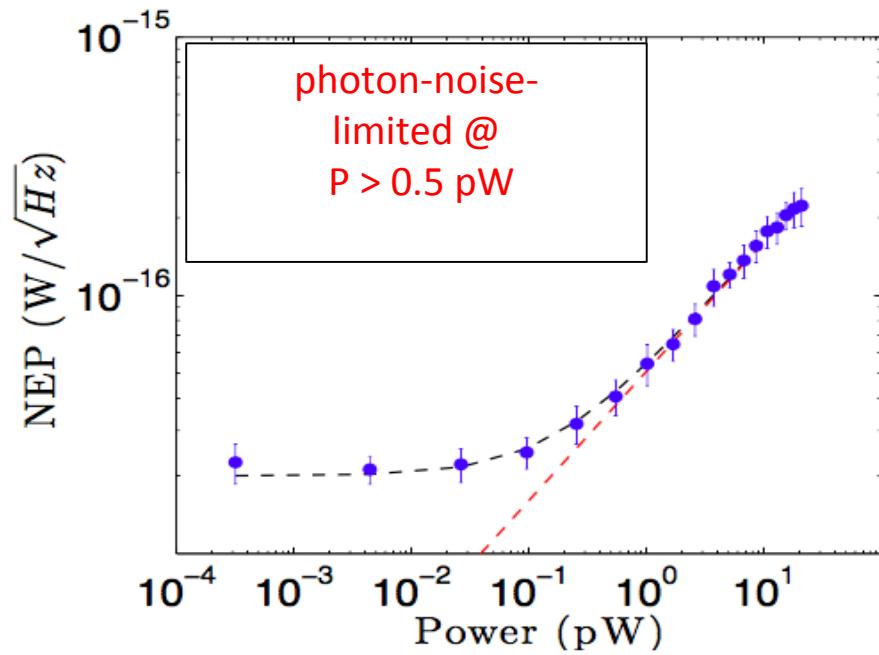
detailed pixel design  
single metal layer with no cross-overs



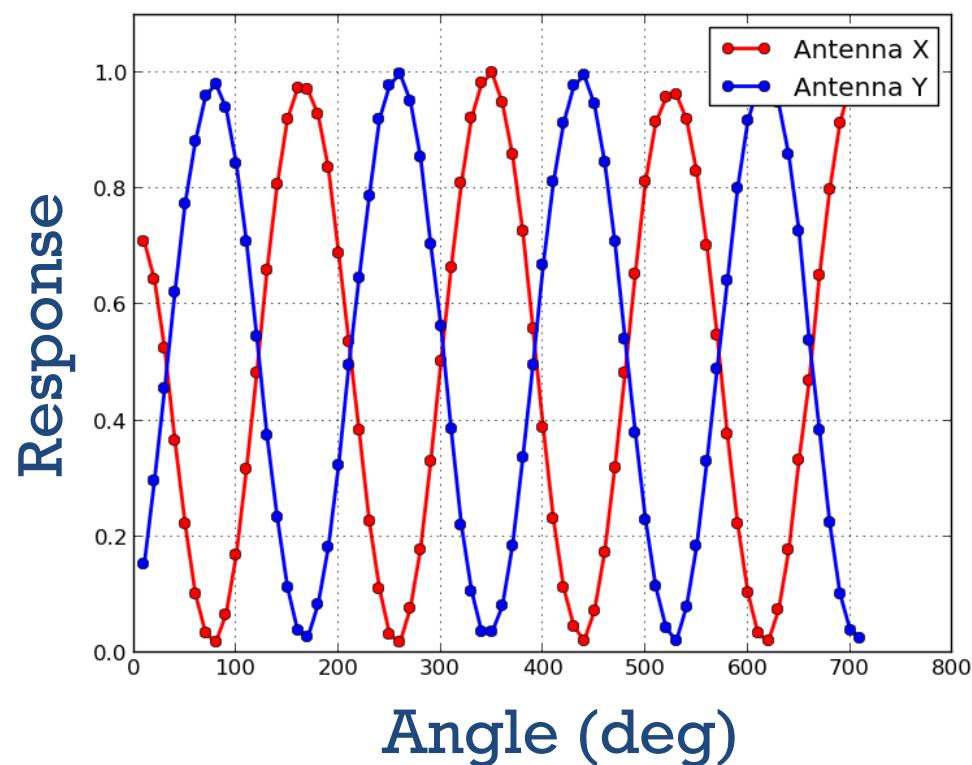
Dober et al. *JLTP* 2016

# Dual-polarization MKID demonstration

Optical NEP



Polarization response



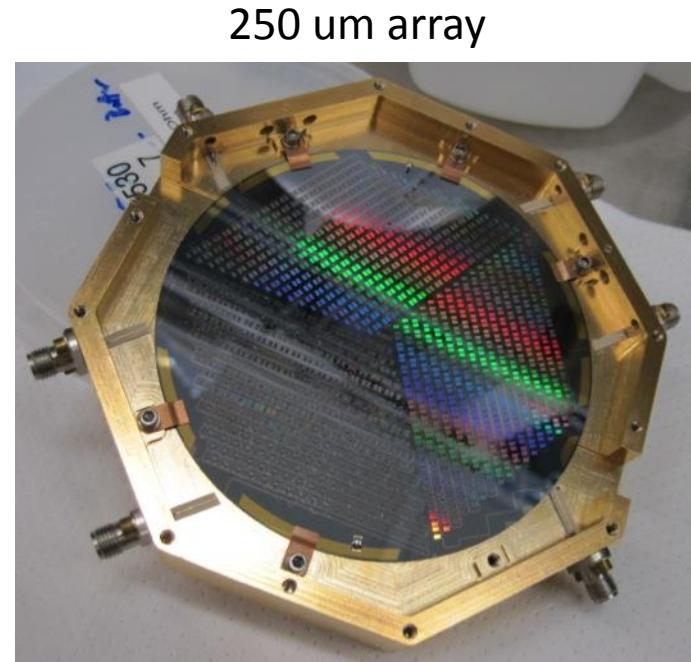
$\eta_{opt} = 75\%$  relative to 1-1.4THz top hat band  
This matches HFSS coupling simulations

# BLAST-TNG Implementation

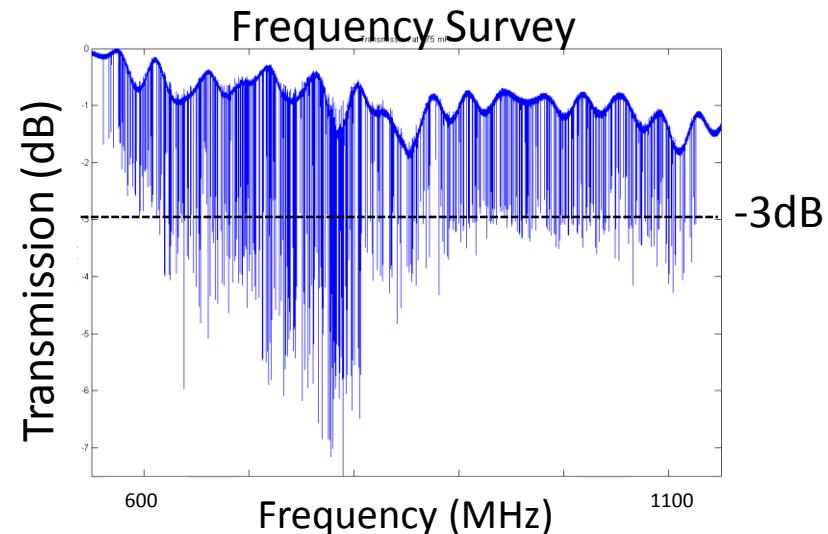
- Balloon mission with reflight planned for 2017
- Three 100 mm diameter arrays: 250, 350 and 500 micron bands
- ~3000 total MKIDs
- MKID arrays for flight presently under development; two weeks for layout, fabrication, and start of testing



earlier Antarctic flight

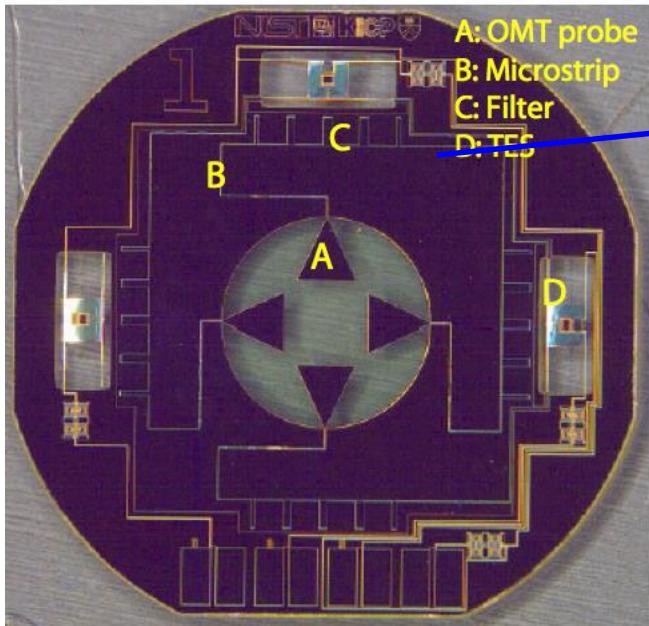


250 um array



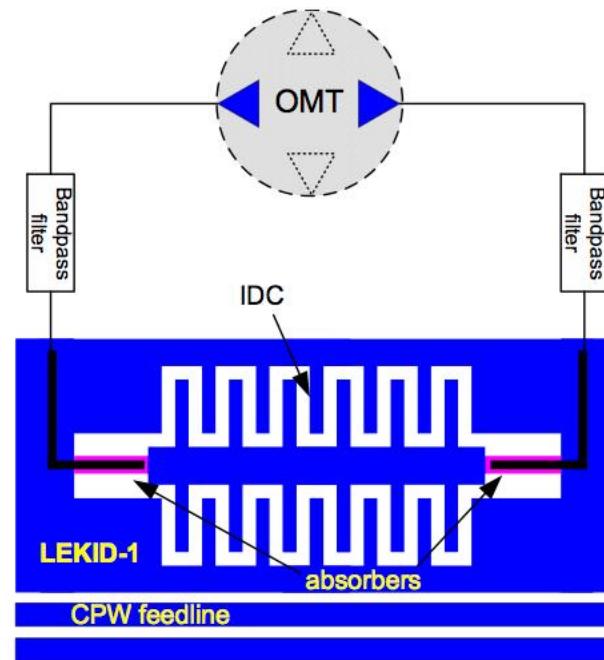
# Possible CORE MKID architecture

- Substitute MKIDs for TESs in designs shown earlier
- Feedhorns and OMTs for optical coupling: allows smaller volume MKIDs with lower NEPs



(a)

MKID



(b)

# Multiplexing

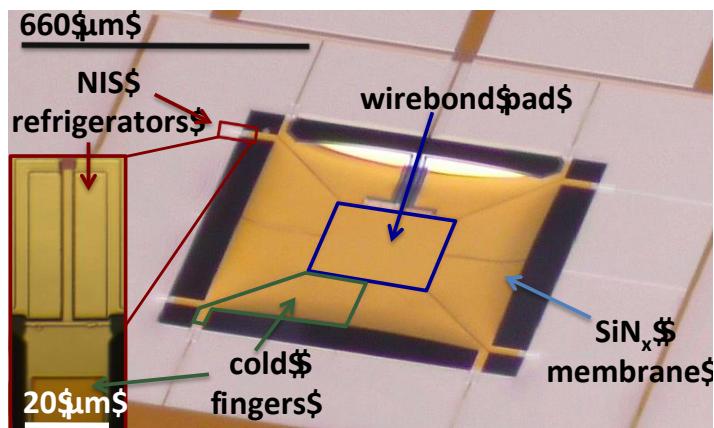
- NIST fabricates SQUID circuits for Time and Frequency Division SQUID Multiplexing (**TDM** and **FDM**)
- These are widely used: **ACT**, **ACTPol**, **ABS**, **Keck**, **SPIDER**, **BICEP2**, **BICEP3**, **SCUBA2**, **SPTPol**, **SPT3G**, **Polar Bear**, **EBEX**, ...
- TDM and MHz FDM provide ~10 MHz of analog bandwidth so multiplexing factors are similar: 64 to 1 in upcoming experiments
- GHz readout provides 1-4 GHz of analog bandwidth but it isn't used as efficiently. Still, multiplexing factors > 1,000 are realistic.
- GHz readout works for both MKIDs and TESs, the latter via microwave SQUIDs

more on readout on Thursday



# NIS cooling

- cooling to 300 mK is “easy”
- cooling to 100 mK is substantially harder and more expensive
- local cooling embedded in the detector circuitry is a low-cost (no-cost?) way to cool detectors to near 100 mK
- can be done with normal-insulator-superconductor tunnel junctions
- have already shown cooling of phonon payloads from 300 mK to 154 mK (Lowell, 2014). Cooling from 300 mK to ~110 mK predicted



P. J. Lowell, PhD Thesis, University of Colorado Boulder (2014)

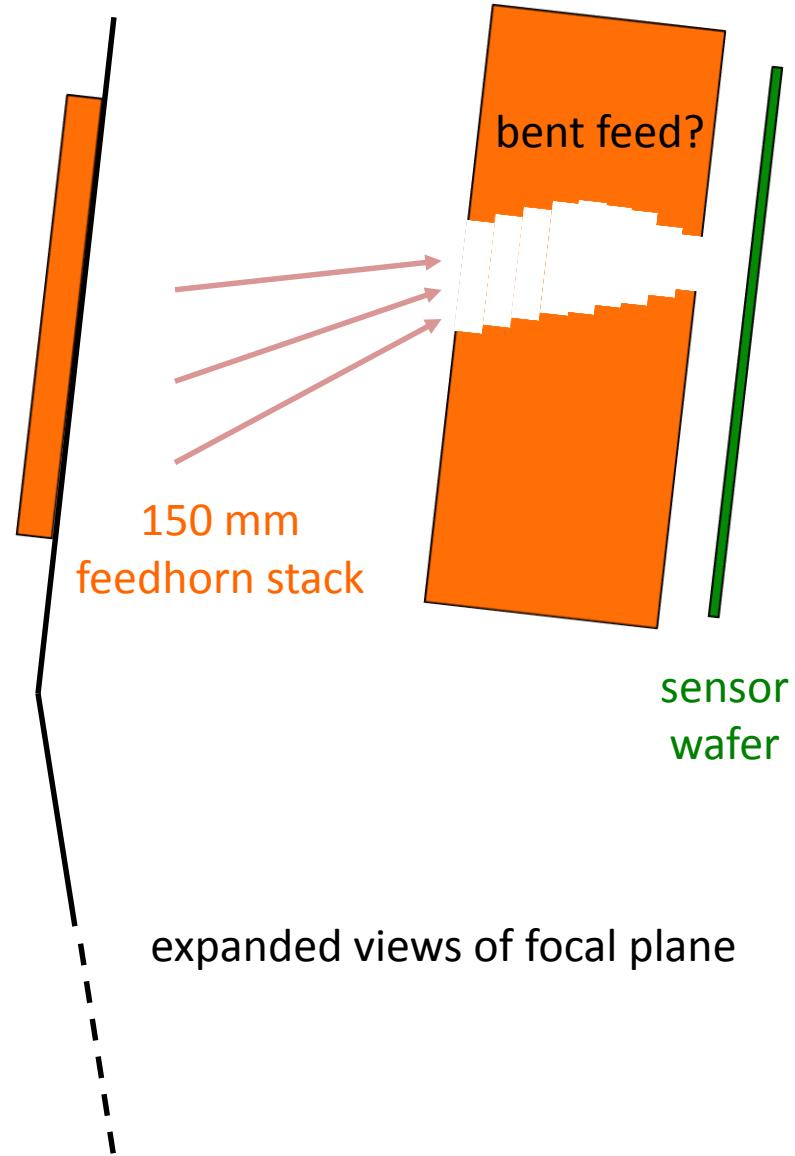
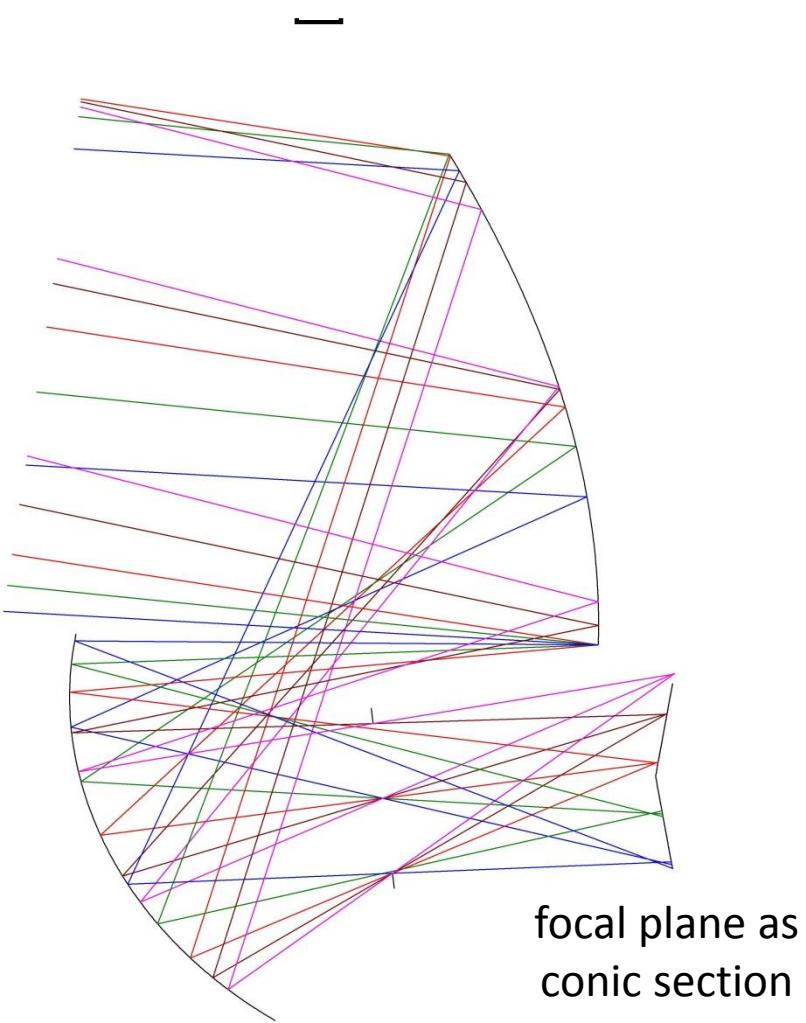
for a satellite:

- can bias many junction cells in series using ~1  $\mu\text{A}$
- can use for fast T regulation or for different local Ts
- power rejected to 300 mK is  $\sim 100 \times (P_{\text{TES}} + P_{\text{sky}})$   
this is probably < 300 pW/sensor. For 2,500 sensors, rejected power = 750 nW (fine for  $^3\text{He}$  stage)

# Why silicon feedhorns?

- metal feedhorns have long, successful heritage: COBE, WMAP, Planck
  - high quality beam patterns
  - low systematic errors
- silicon feeds are like metal, but better:
  - leverage power of modern microfabrication to manufacture large, uniform arrays
  - lighter (~300 g for 150 mm diameter stack)
  - CTE matched to detector arrays
  - novel profiles possible
- compatible with <25 GHz to 680 GHz
- can be broad-band: 2.3:1 demonstrated, 3:1 planned
- silicon feeds used successfully in several CMB experiments
  - SPTPol 150 GHz
  - ACTPol
  - ABS
- silicon feeds planned for Advanced ACTPol and SPIDER
- present TRL = 4-5. After 2017 SPIDER flight, TRL = 6
- compatible with dual polarization, multifrequency pixels
- compatible with TESs, MKIDs, and all readout schemes

# Thoughts on the CORE focal plane



# TESs vs MKIDs

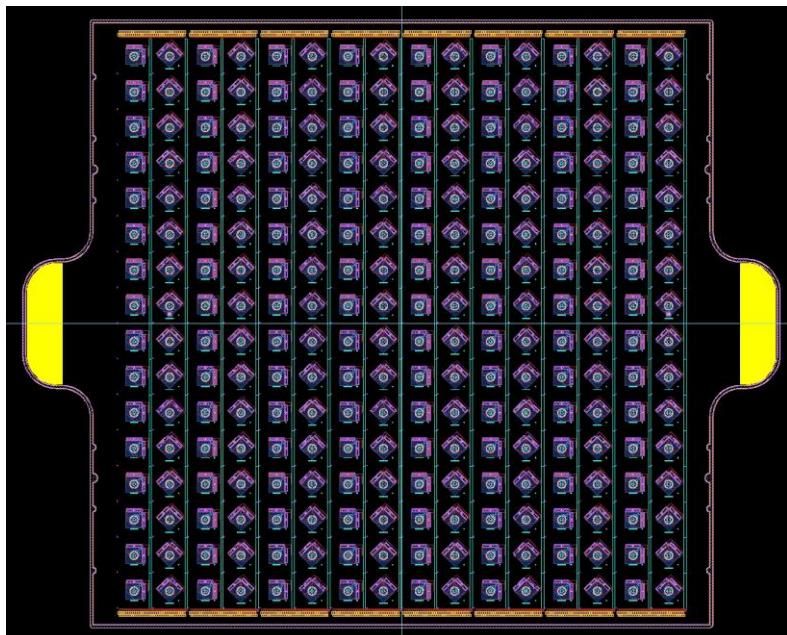
- We are pursuing both at NIST; this provides a clear-eyed perspective on strengths and weaknesses
- Both are candidates
- TRL gap between TESs and MKIDs sometimes underestimated
  - Numerous successful TES CMB instruments in challenging environments including balloons
  - Open questions about in-band sensitivity and 1/f noise of MKIDs
- Microwave readout is attractive AND is available for both TESs and MKIDs
- Layout and construction of MKID focal planes can be easier
  - Easier fabrication? Yes for direct absorption, maybe not for indirect coupling
  - Fewer interconnects within focal plane (no bias Rs, integrated readout)

More detailed discussion of readout moved to splinter session tomorrow

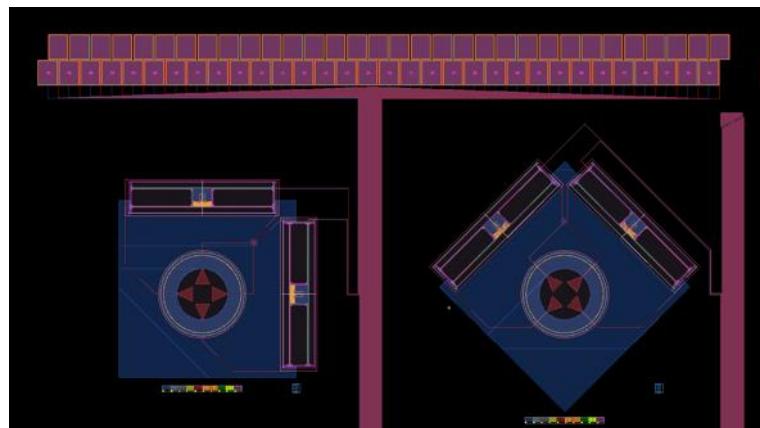
# Thank you

# Upcoming: 280 GHz Balloon-borne array demonstration on SPIDER

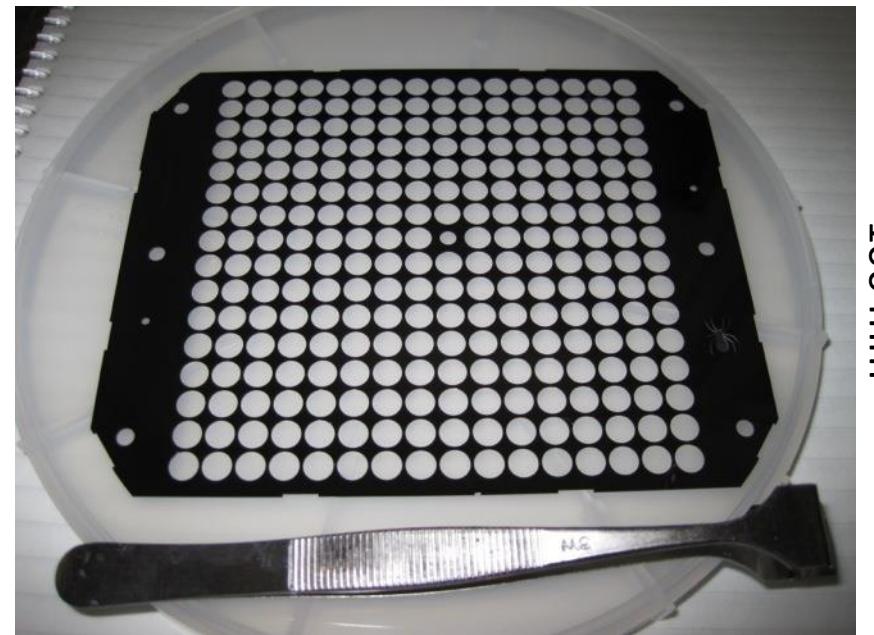
16x16 polarimeter array design



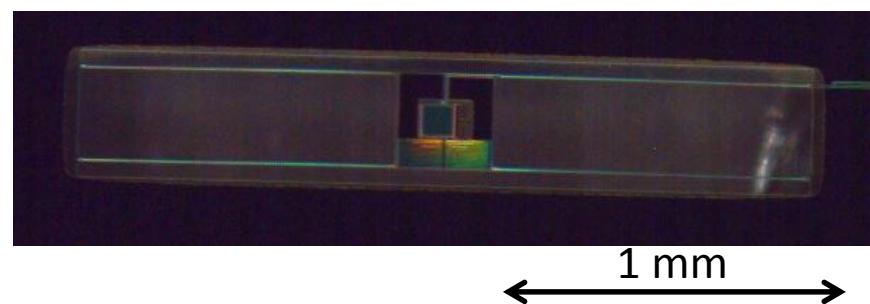
Q and U pixels



feedhorn silicon platelet



low thermal conductance bolometer



# Highly uniform feedhorn arrays

