Superconducting Detectors for Precision Cosmology

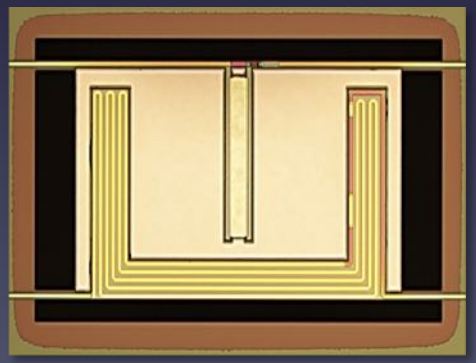
TES Detector Technologies for CMB Polarimetry

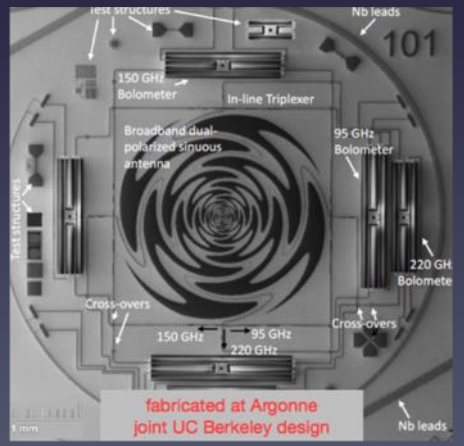
Jason Austermann – NIST-Boulder / University of Colorado

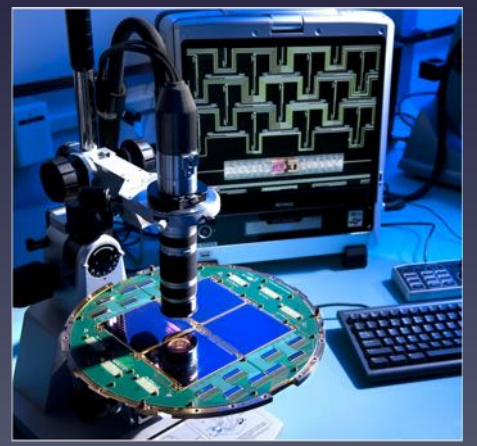
CPAD Instrumentation Frontier Workshop 2018

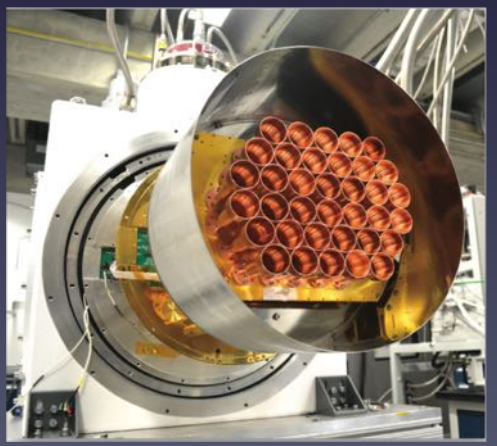
Superconducting Detectors Session

09--10 Dec 2018





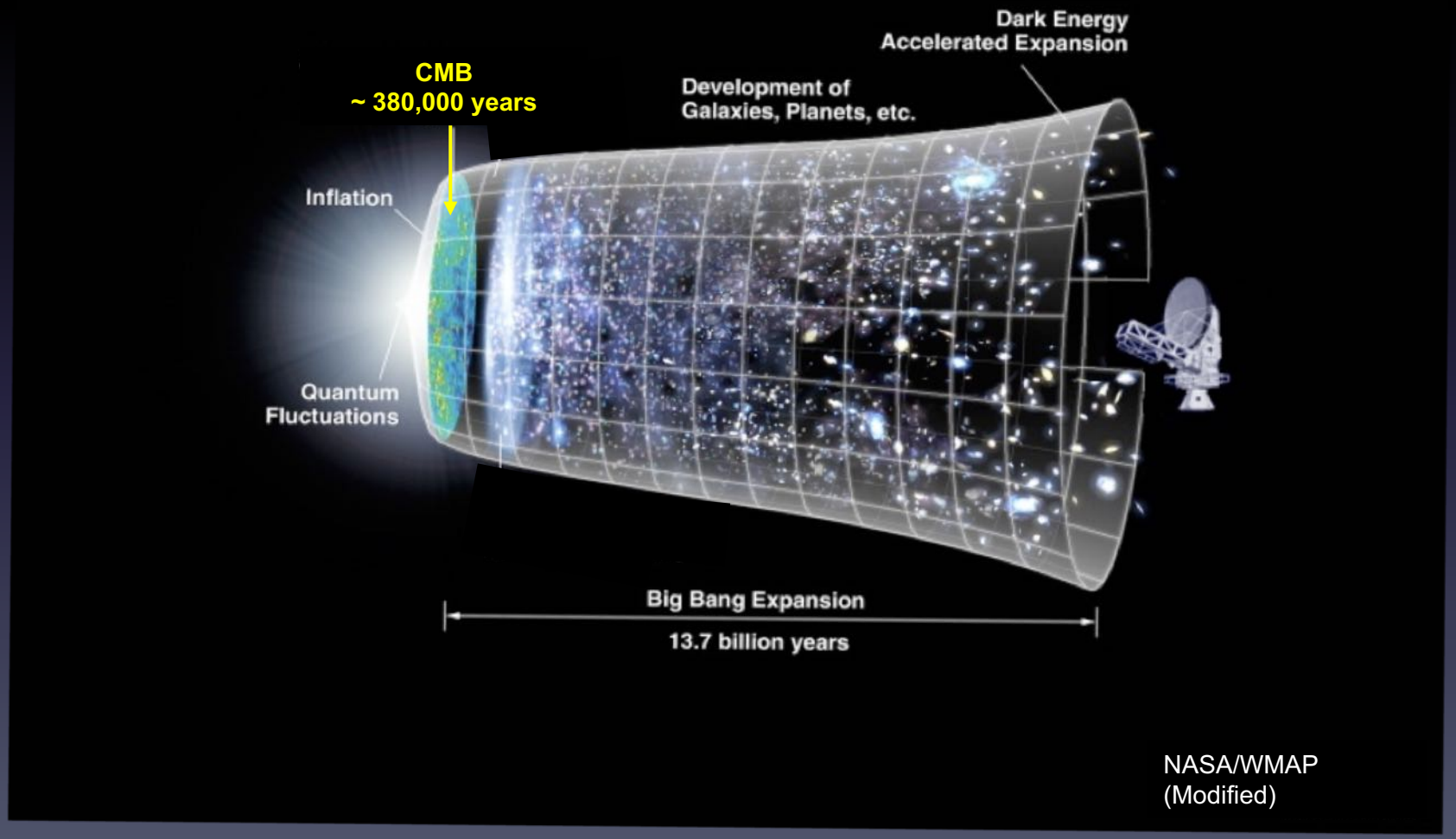




Outline

- Next Challenges in Cosmology
- TES-based Focal Plane Technology
  - Brief community review
    - See also next presentation @ 4:30 (T. Natoli)
    - Also, alternative KID detector tech at 5pm (Q.Y. Tang)
  - Details of some NIST-Boulder efforts
    - Note: Readout technology in tomorrow's session
- CMB-S4 Context (e.g. fabrication)

A Brief History of the Universe

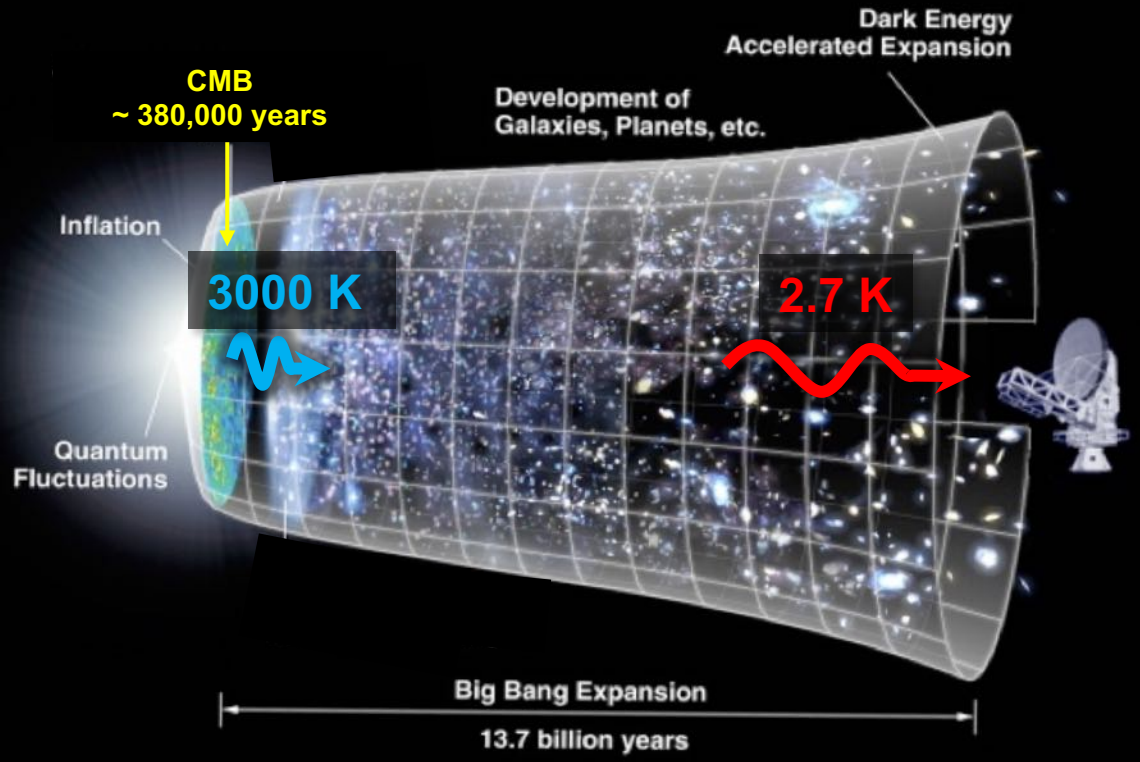


NASA/WMAP
(Modified)

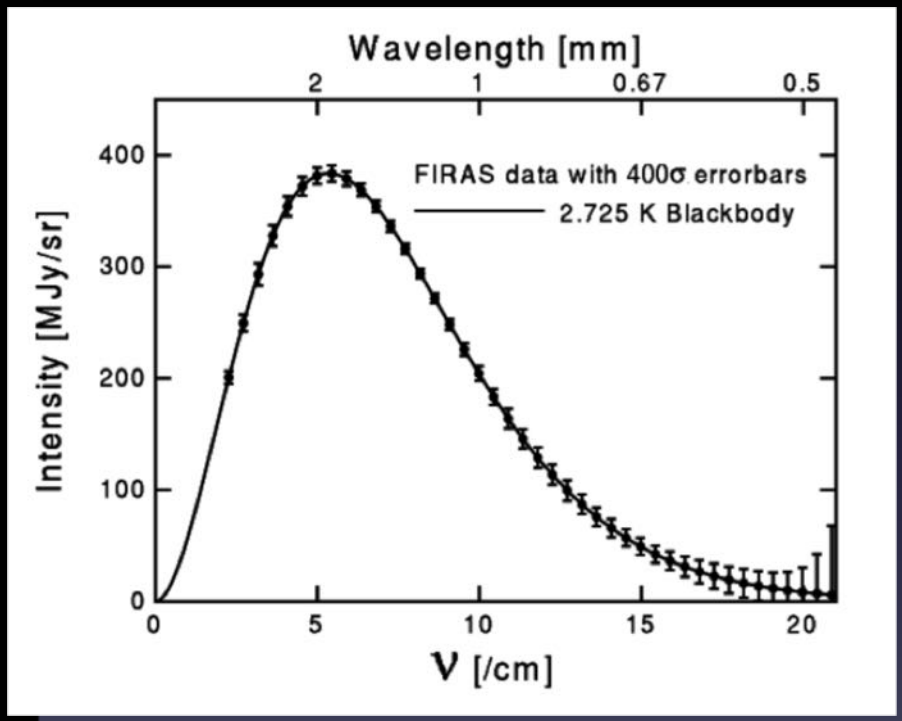
Use the Universe as laboratory for HEP

- Inflation (GUT scale physics)
- Neutrino Physics
- Dark Energy
- Dark Matter

Cosmic Microwave Background (CMB)

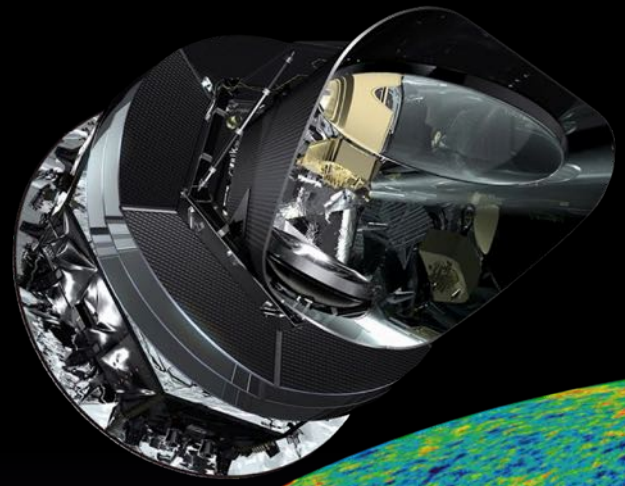


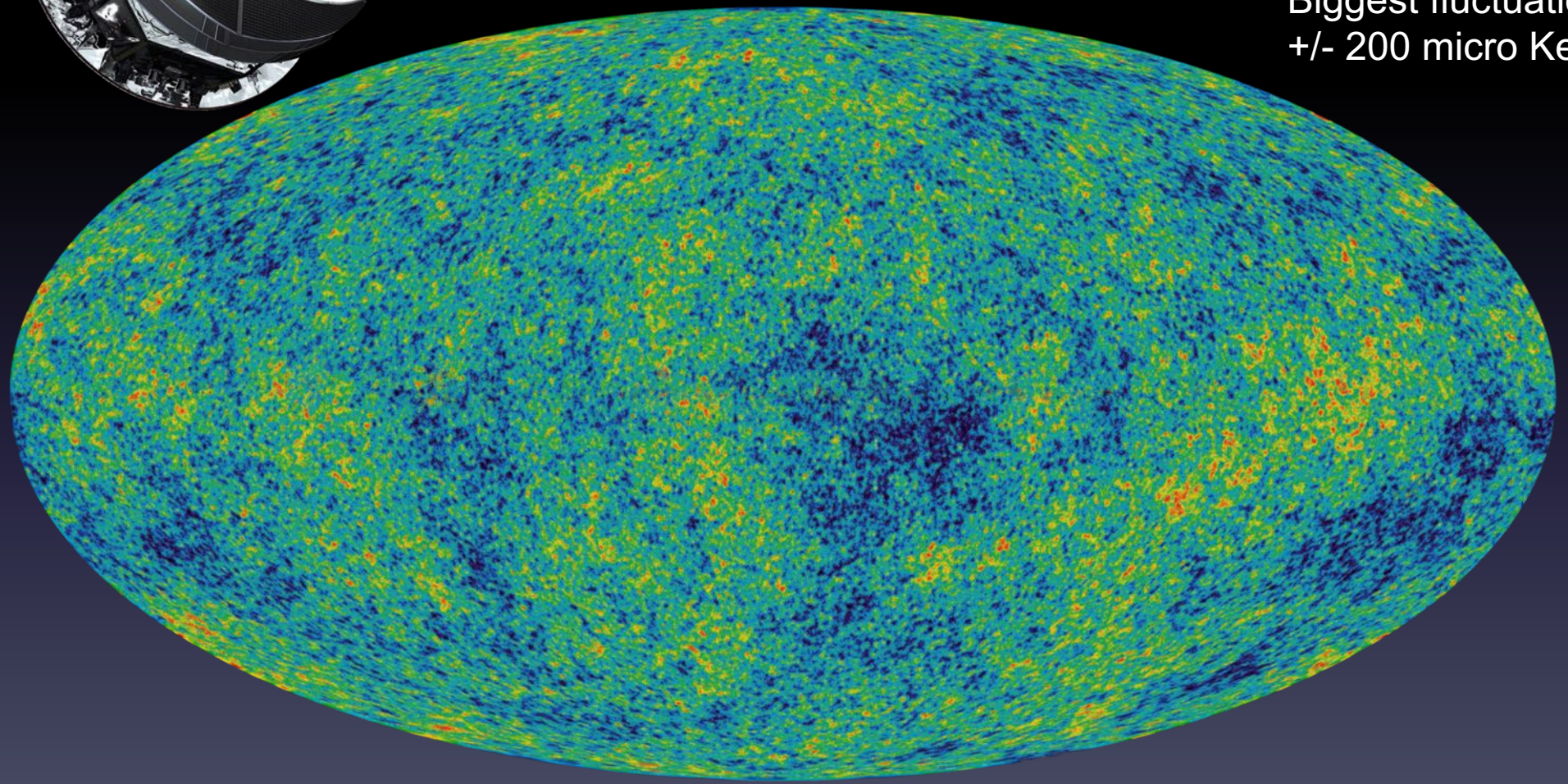
NASA/WMAP
(Modified)



COBE CMB Spectrum

Planck - 2009





Biggest fluctuations only ~
+/- 200 micro Kelvin

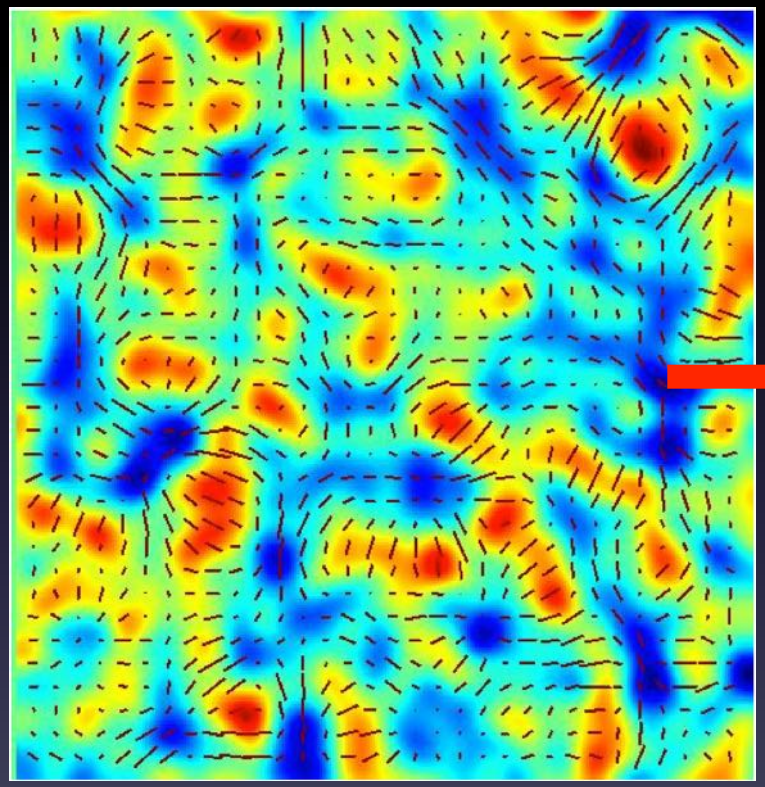
Courtesy of Planck Collaboration

ACT

PLANCK

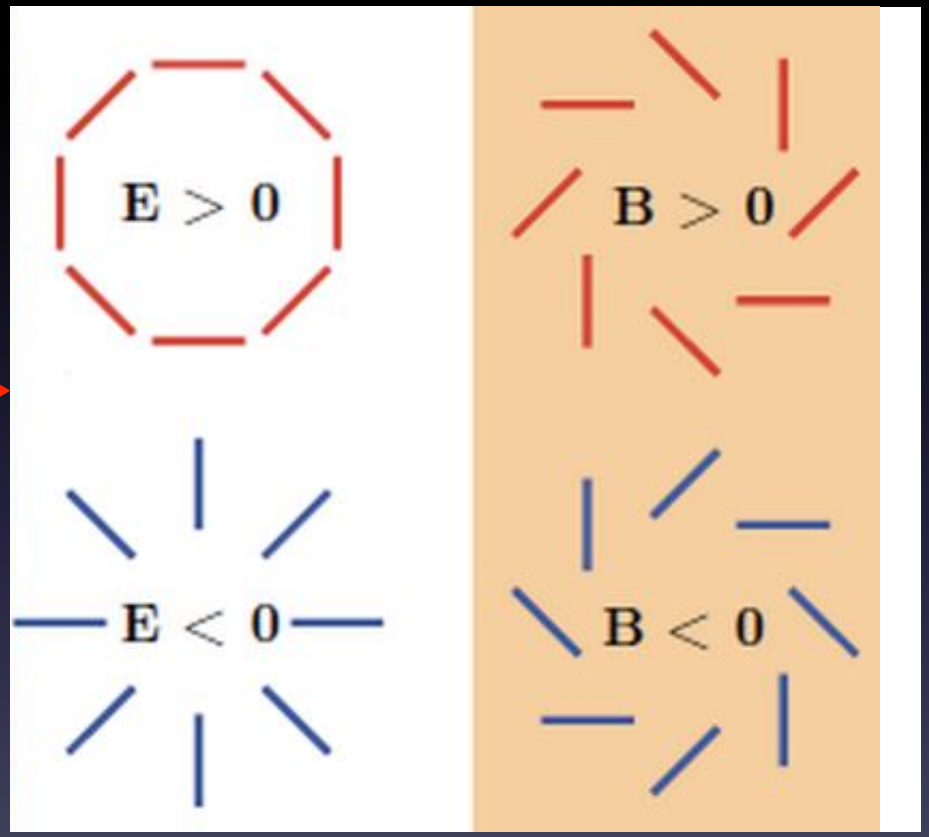
Video courtesy
Sigurd Naess (ACT)

“E” and “B” modes of polarization patterns



E-modes:
Even Parity

B-modes:
Odd Parity



3 Primary Fluctuation Signals

- Temperature
- E Polarization
- B Polarization

Smaller Spatial Scales →

Fluctuation Power ↑

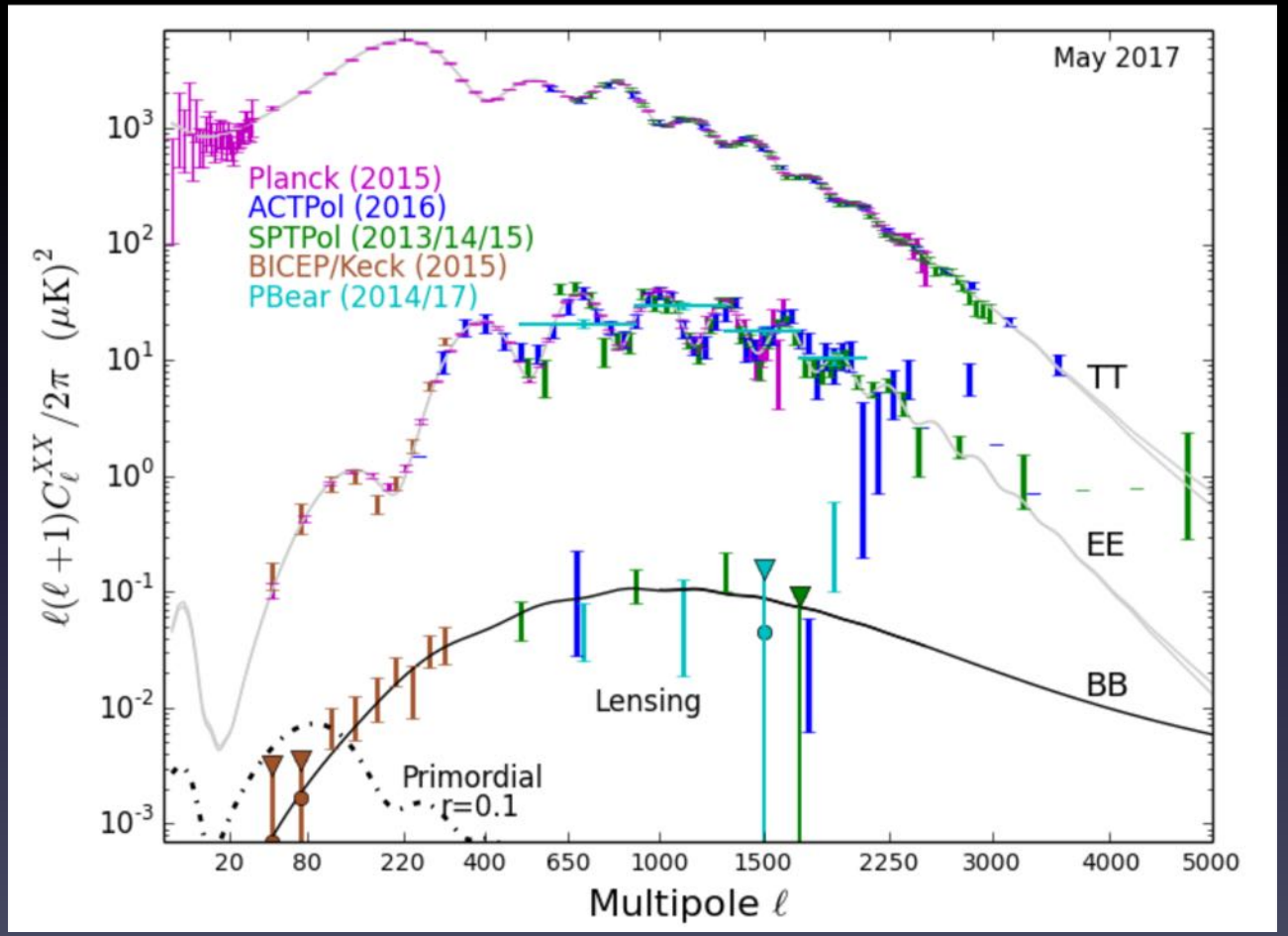


Figure Credit: Lyman Page

CMB Measurements are Difficult

Fundamental Challenges

- Low S/N Target

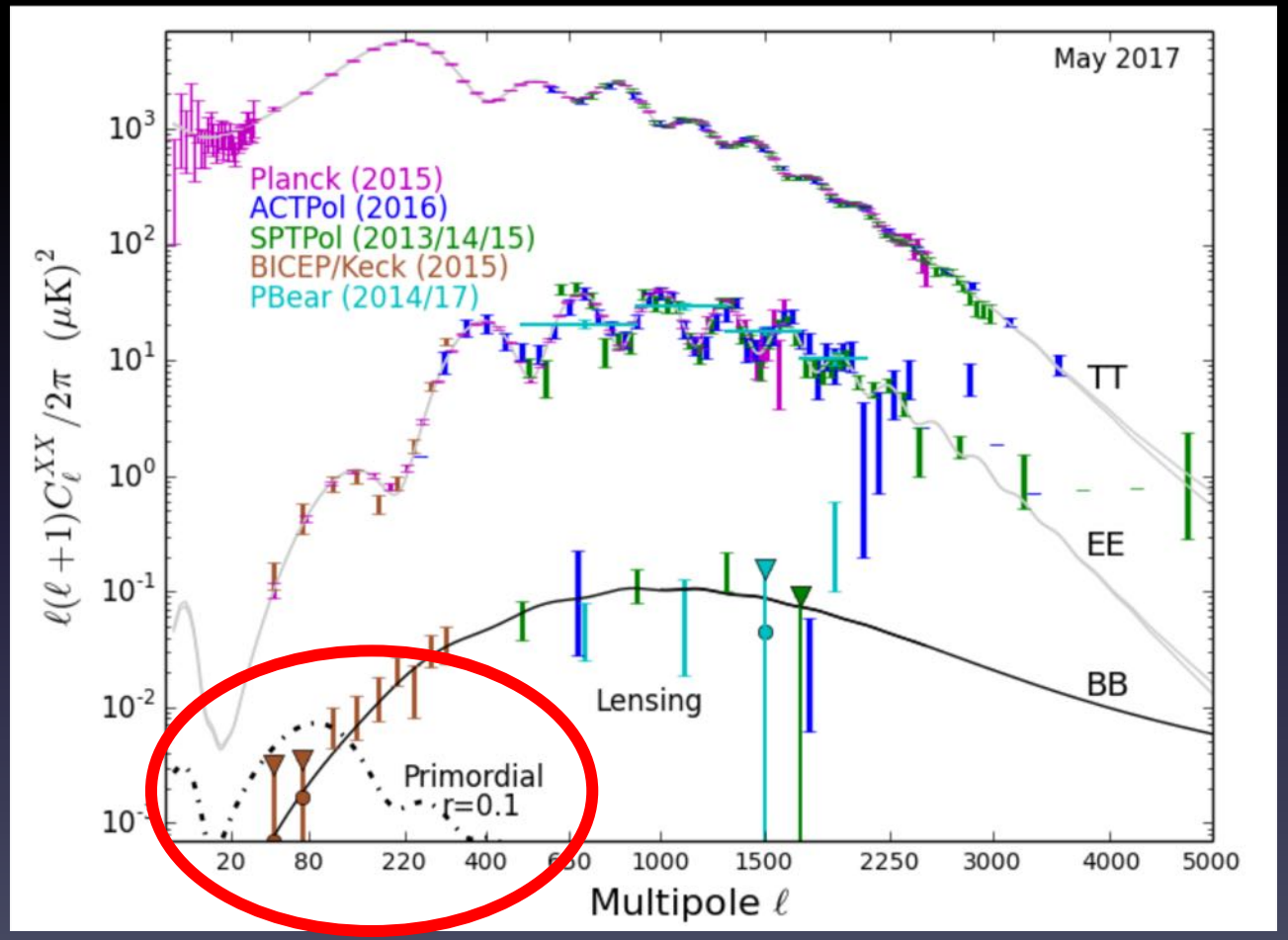


Figure Credit: Lyman Page

CMB Measurements are Difficult

Fundamental Challenges

- Low S/N Target
- Dynamic Range - Systematics

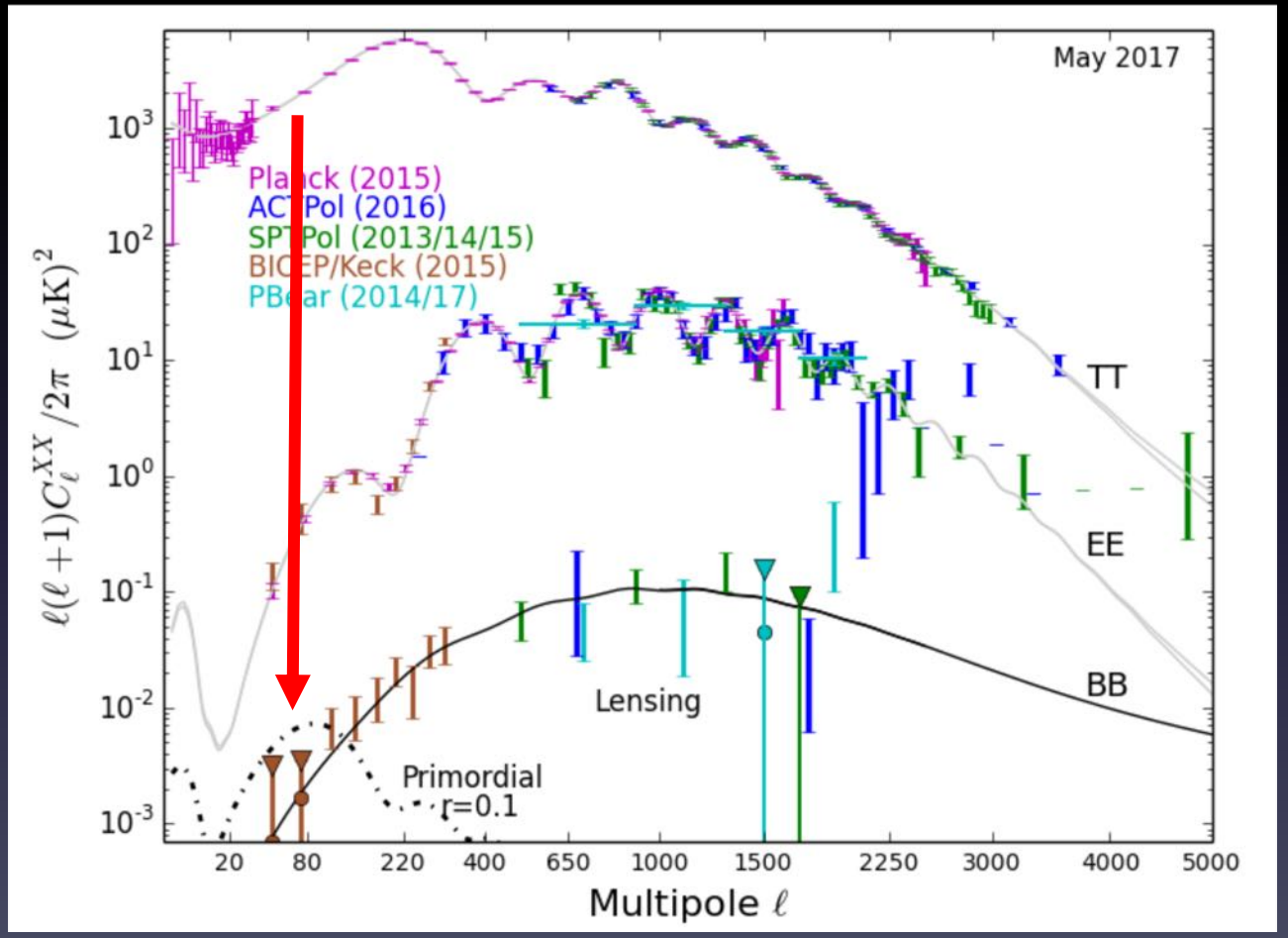
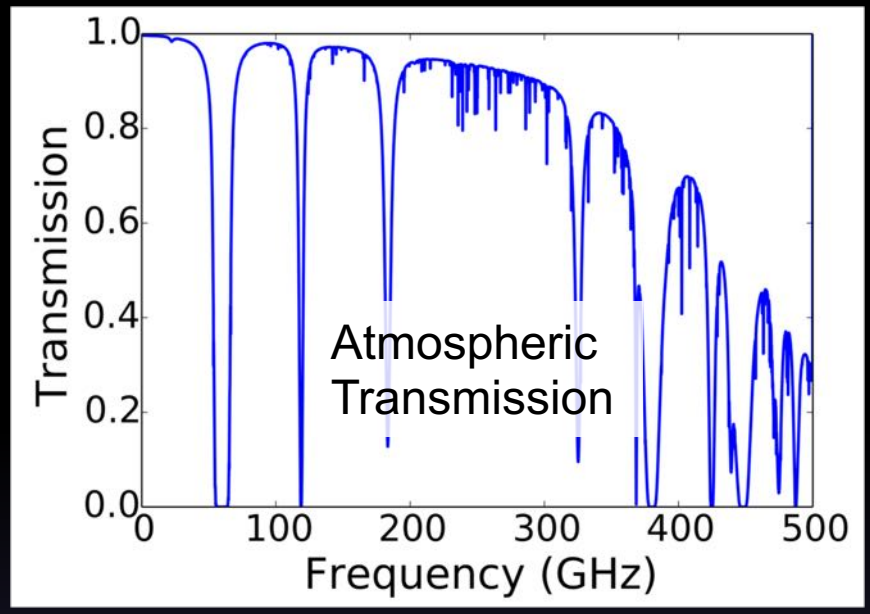


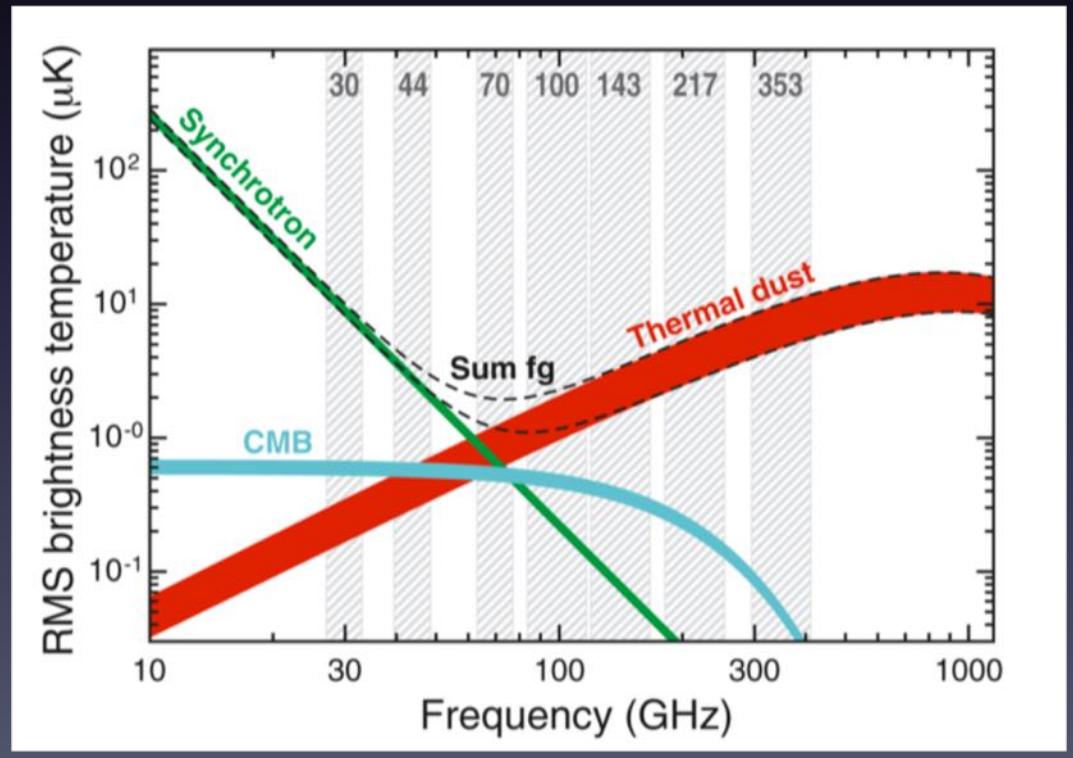
Figure Credit: Lyman Page

CMB Measurements are Difficult

Fundamental Challenges

- Low S/N Target
- Dynamic Range - Systematics
- Other Sources of Emission





Planck X (2015)

CMB Measurements are Difficult

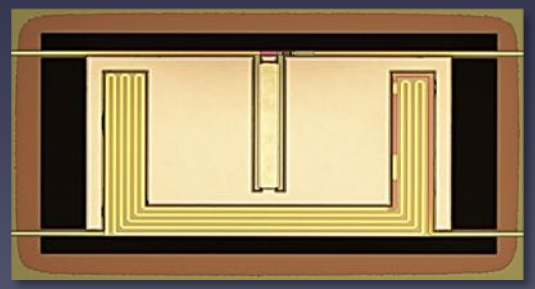
Fundamental Challenges

- Low S/N Target
- Dynamic Range - Systematics
- Other Sources of Emission
- Millimeter Wave Technology

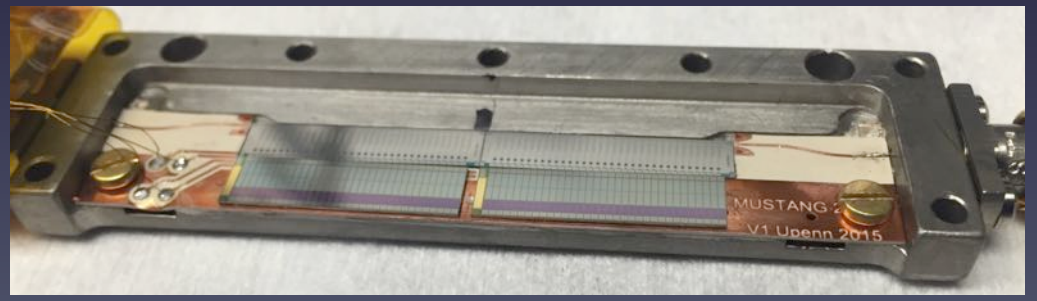
Low-loss Optical Coupling

Low-loss
Filtering

Detector
Technology



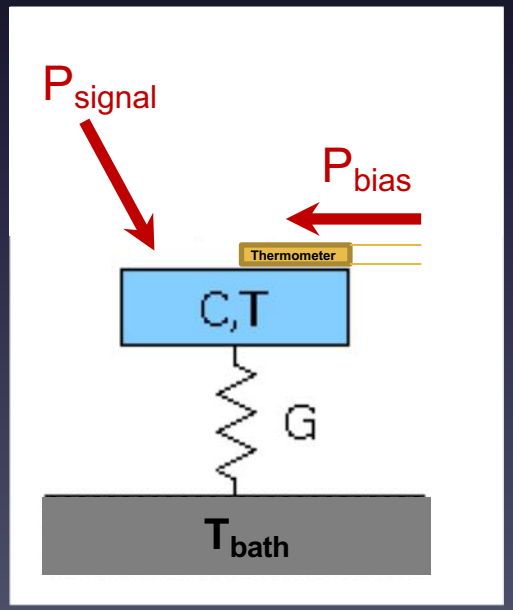
Electronics &
Readout



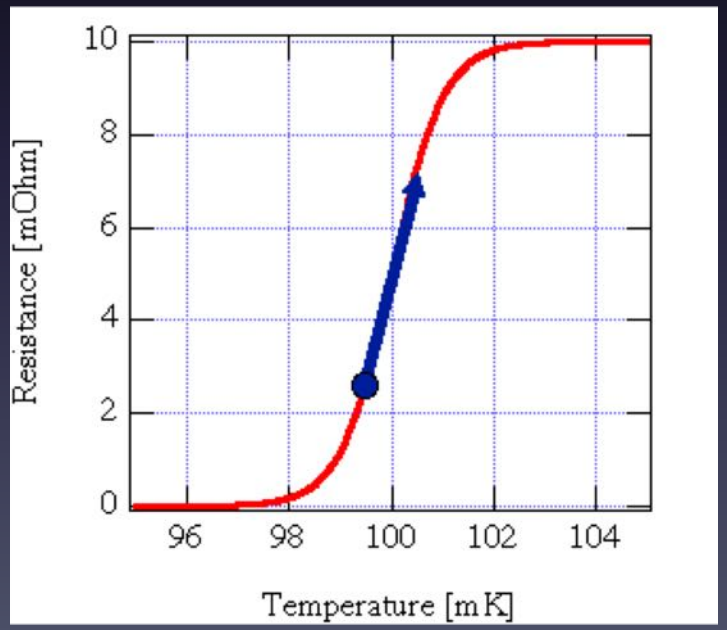
Transition Edge Sensor (TES) Bolometer

Workhorse for CMB science

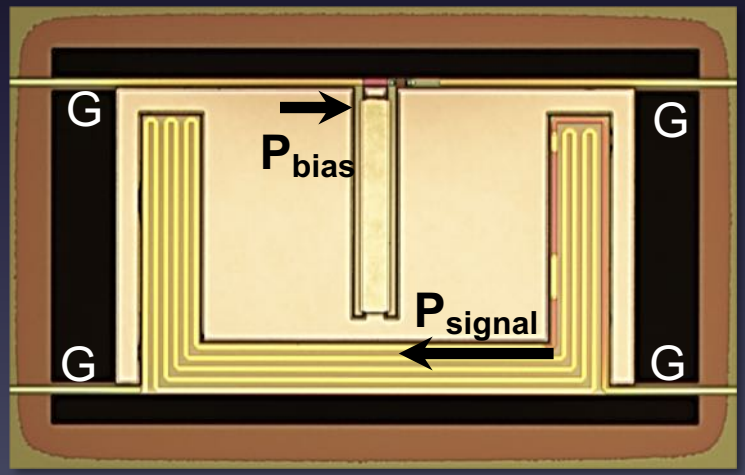
Bolometer



Superconducting Transition



TES bolometer



Optical Coupling Scheme drives Pixel Design

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

Maximize focal plane utilization

Advantages and Disadvantages to each

Optical Coupling Scheme drives Pixel Design

- Feedhorn Coupled Waveguide
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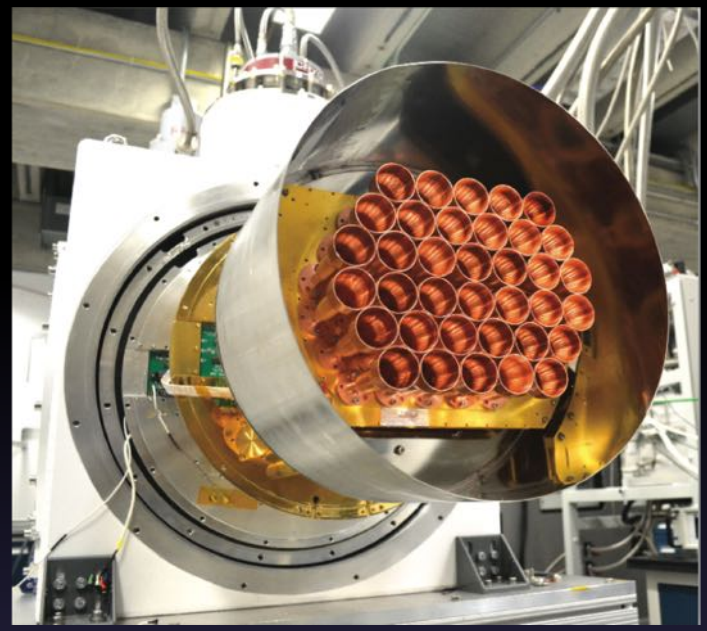
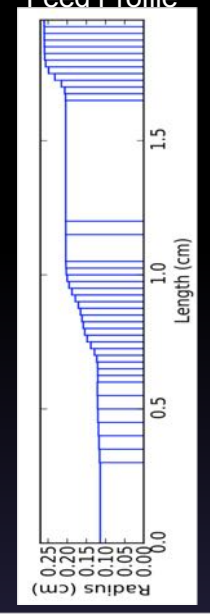
- Metamaterial Lenslets

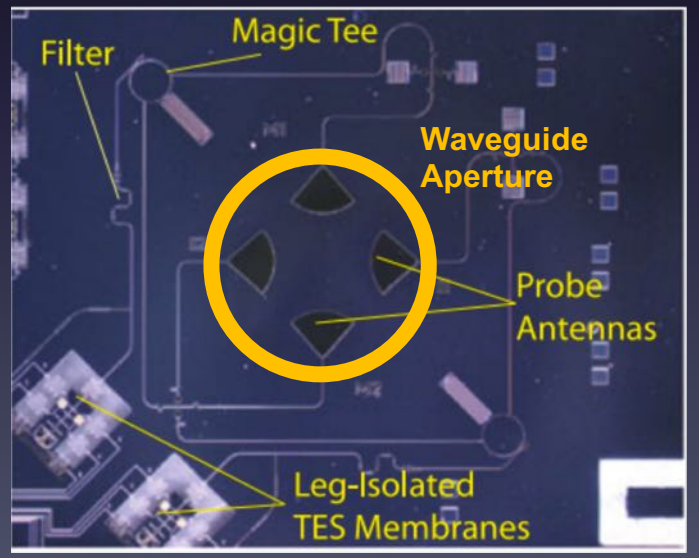
CLASS
40 GHz Array

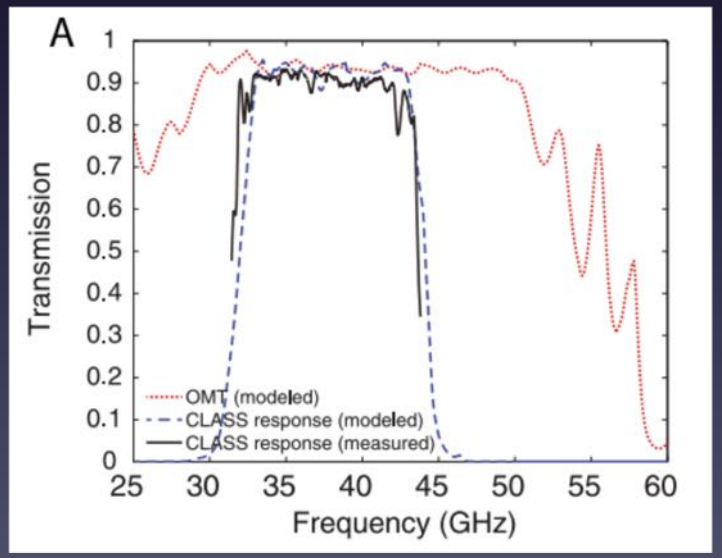


AdvACT
Feed Profile



NASA, Goddard feed-coupled detector





Chuss et al. *JLTP* (2012) 167:923-928

Optical Coupling Scheme drives Pixel Design

- Feedhorn Coupled Waveguide
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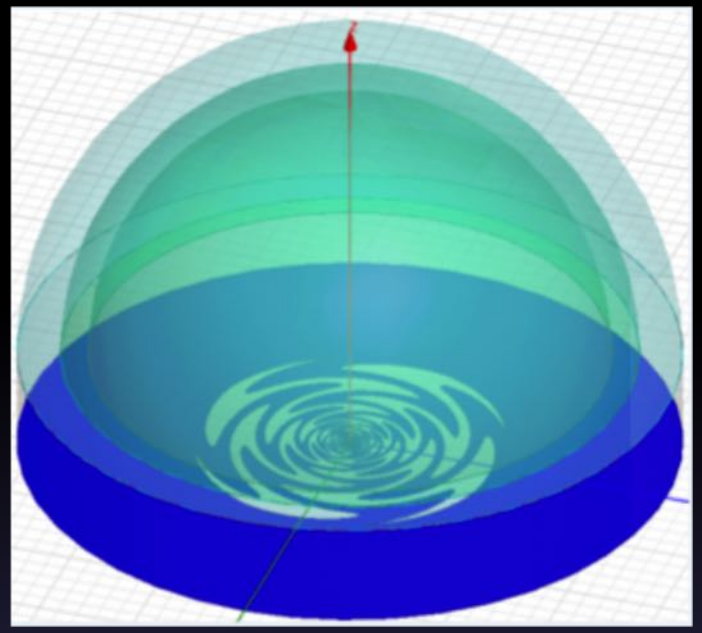
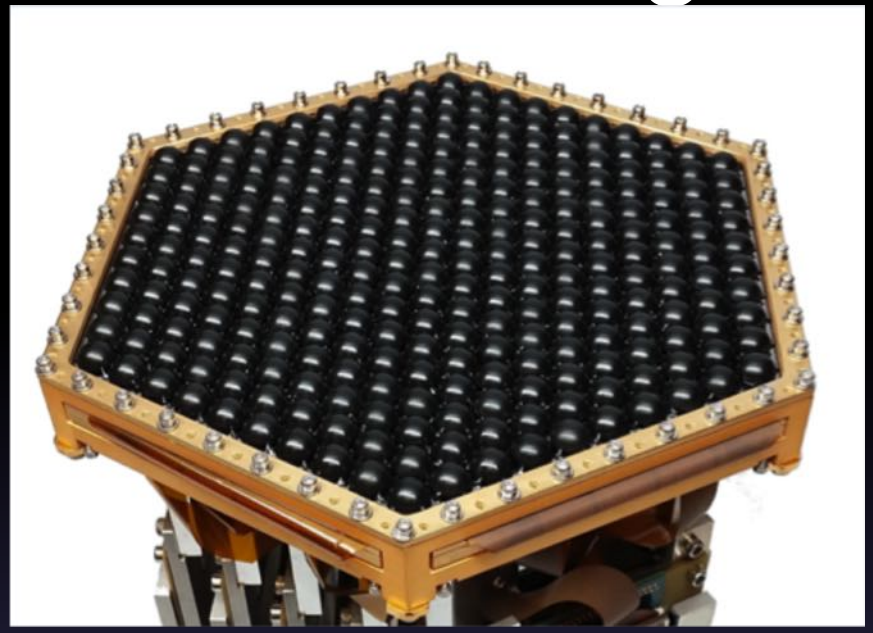
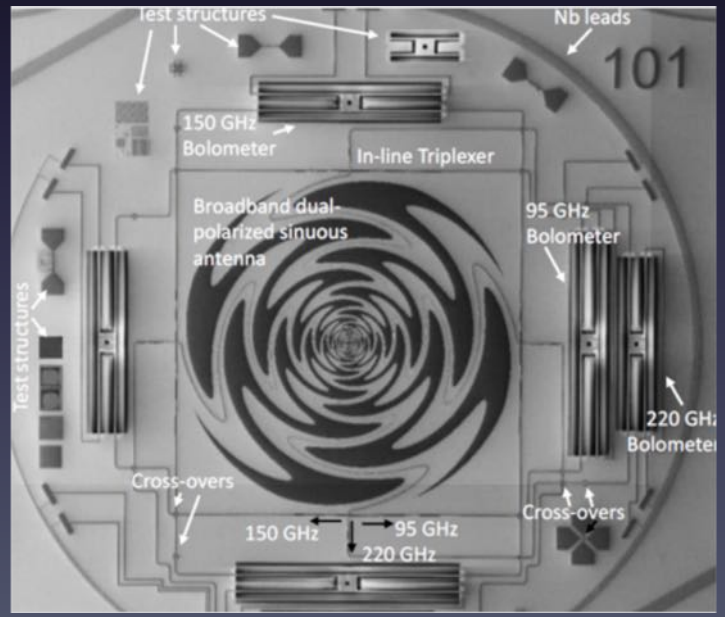
- Metamaterial Lenslets



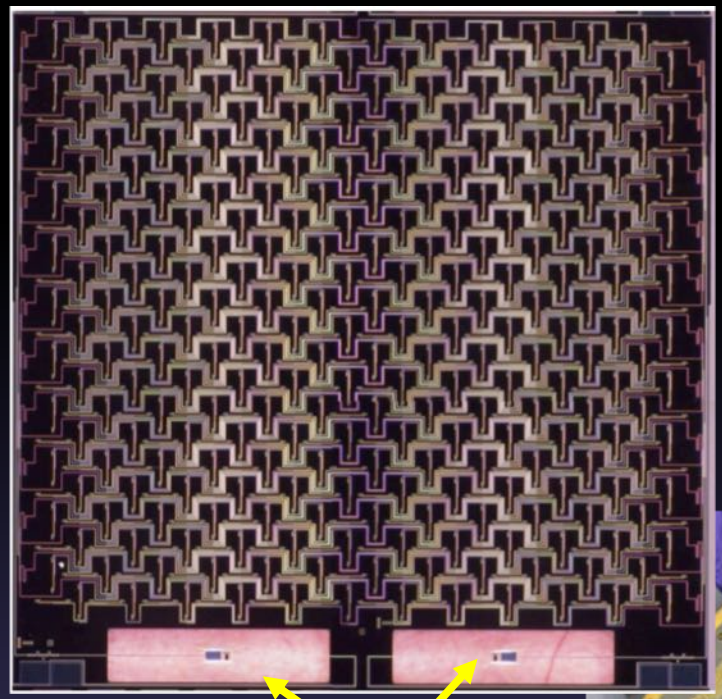




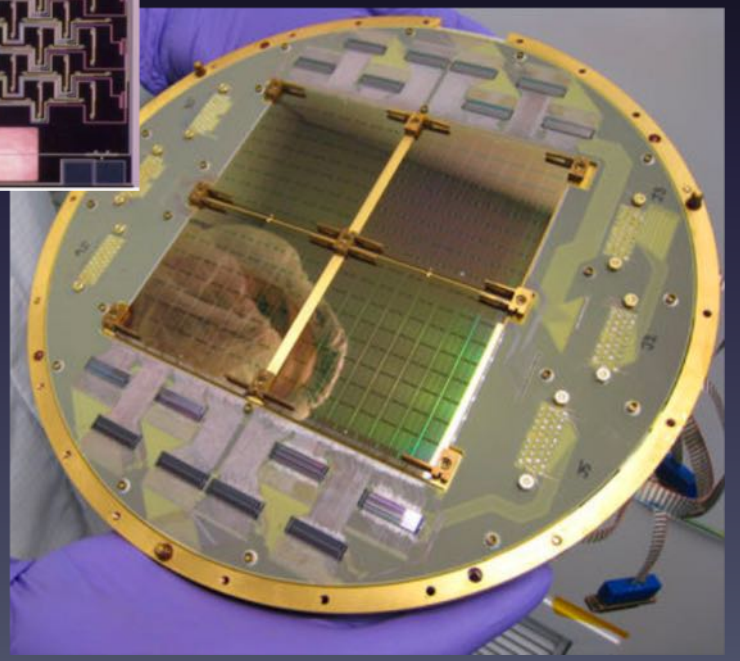
POLARBEAR & SPT Collaborations

Optical Coupling Scheme drives Pixel Design

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



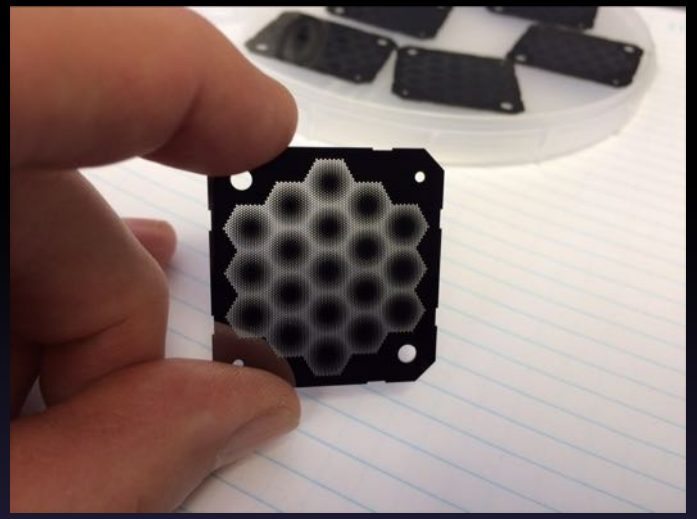
Caltech/JPL
BICEP/KECK/SPIDER



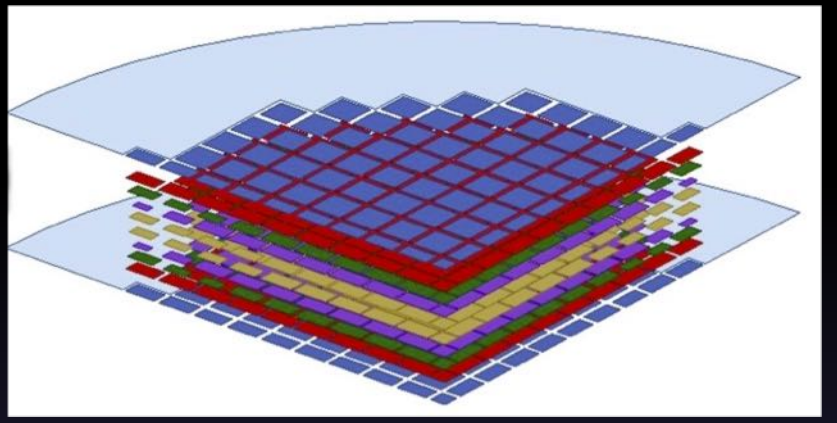
Optical Coupling Scheme drives Pixel Design

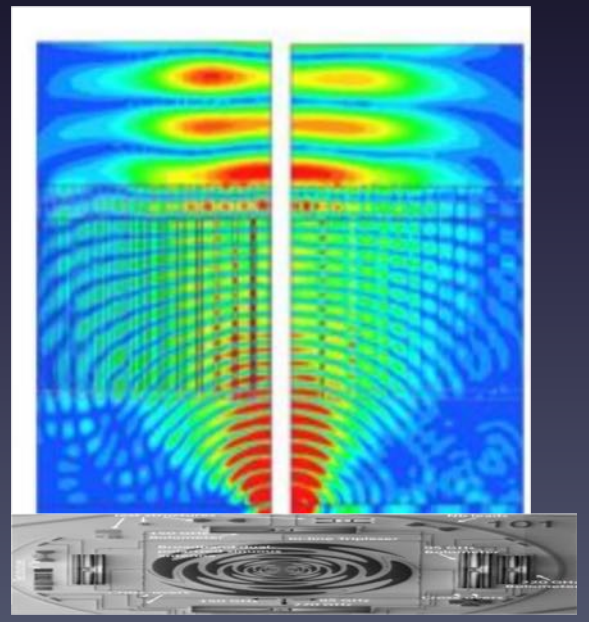
- Feedhorn Coupled Waveguide
- Hemispherical Lenslets
- Bare Antenna Arrays
- Metamaterial Lenslets (lithographic planar lenslet)

Gradient Index Lenslet (GRIN)

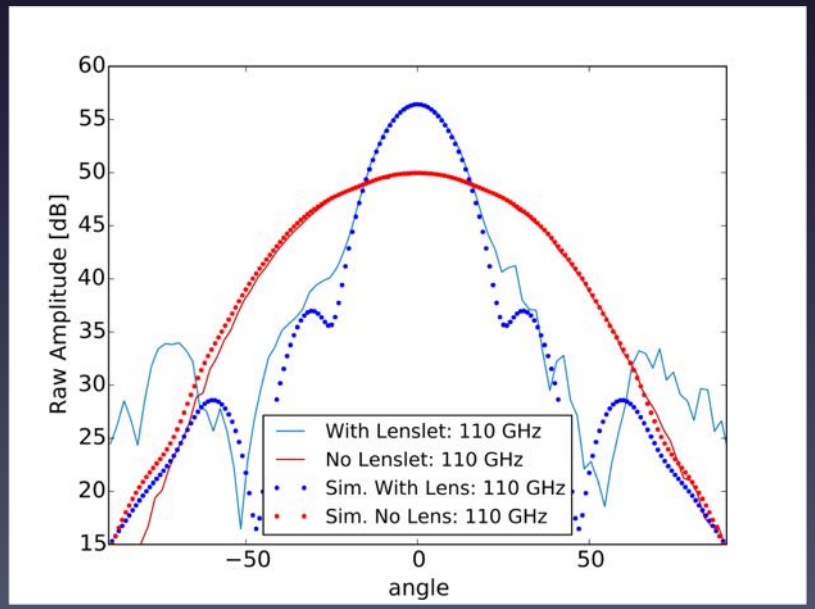


Metal Mesh Metamaterial Lenslet





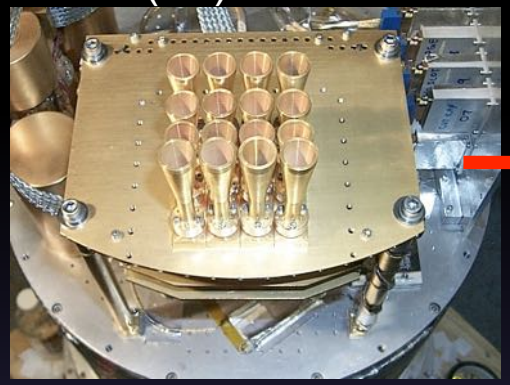
Forward Gain w/ & w/o lenslet



CU-Boulder and collaborators

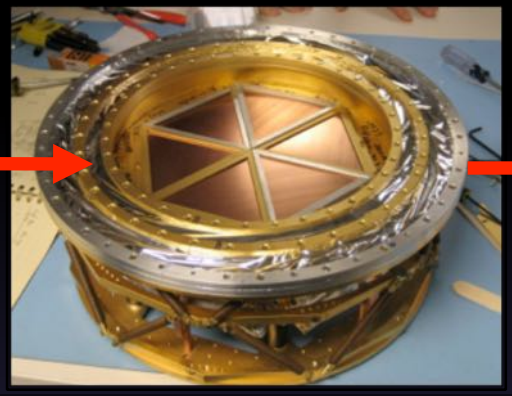
An Incomplete History of TES-based Array Scale

Gen 0: Pre-TES
O(10) detectors



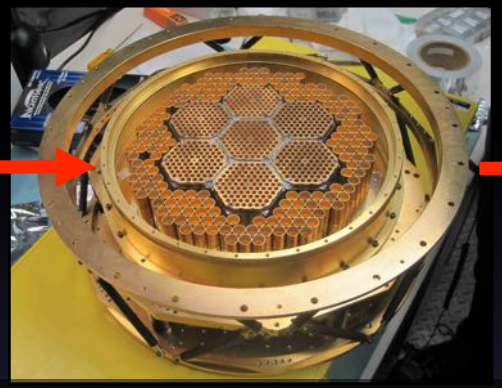
e.g. ACBAR, Planck

Gen 1: TES Arrays
10^2 – 10^3 detectors



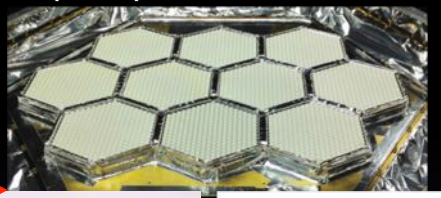
e.g. SPT-SZ, MBAC

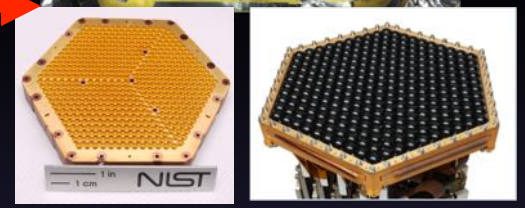
Gen 2: Polarization
O(10^3) + polarization



e.g. SPTpol, ACTPol, Polarbear, BICEP/KECK

Gen 3: multi-chroic
O(10^4) + multi-chroic



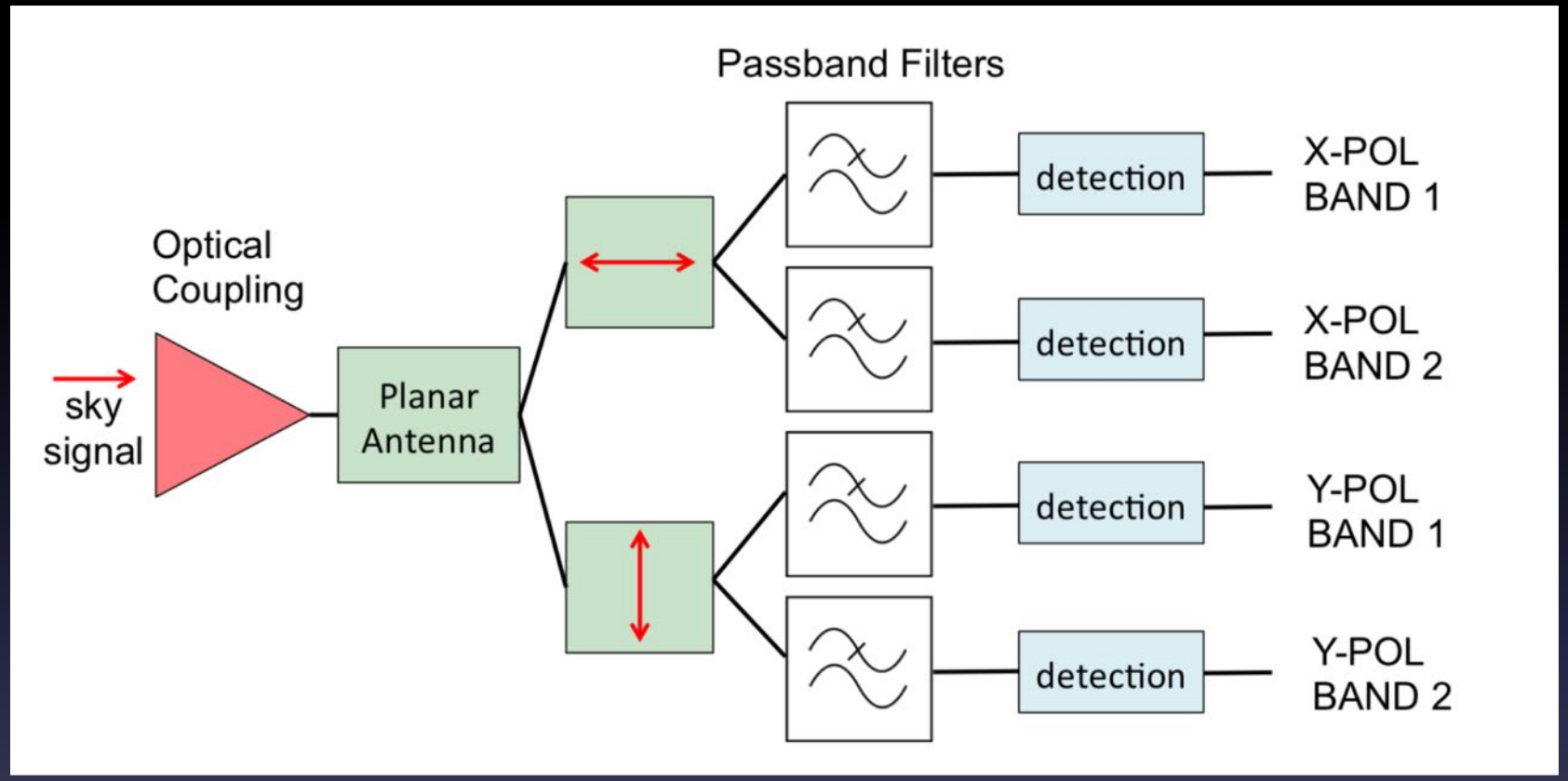


e.g. SPT-3G, Advanced ACTPol, Simons Array, BICEP3/Array

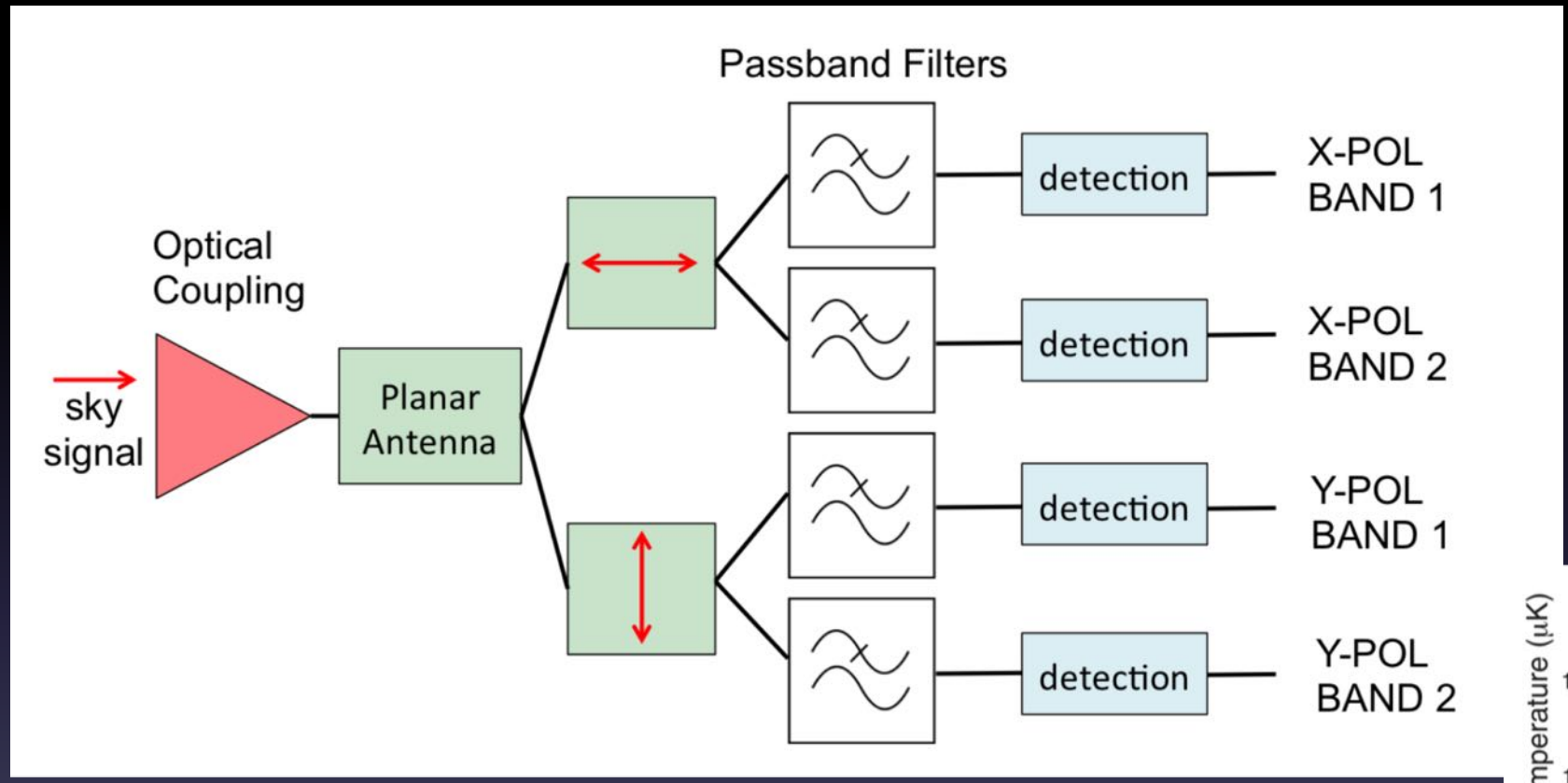
Detectors ~ background limited (from ground), so increase sensitivity by:

- More Detectors
- Added Capabilities e.g. (polarization, systematic control)
- More Bandwidth / Multi-chroic

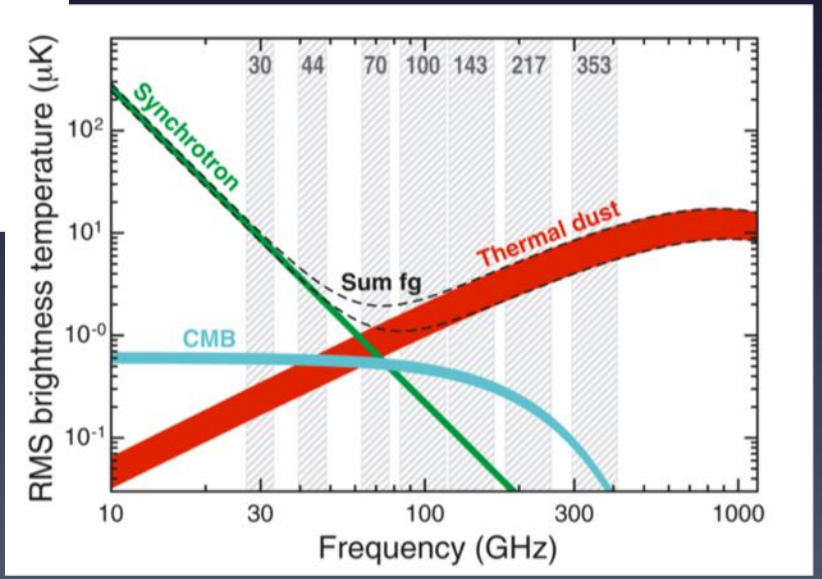
Multi-chroic concept



Multi-chroic concept

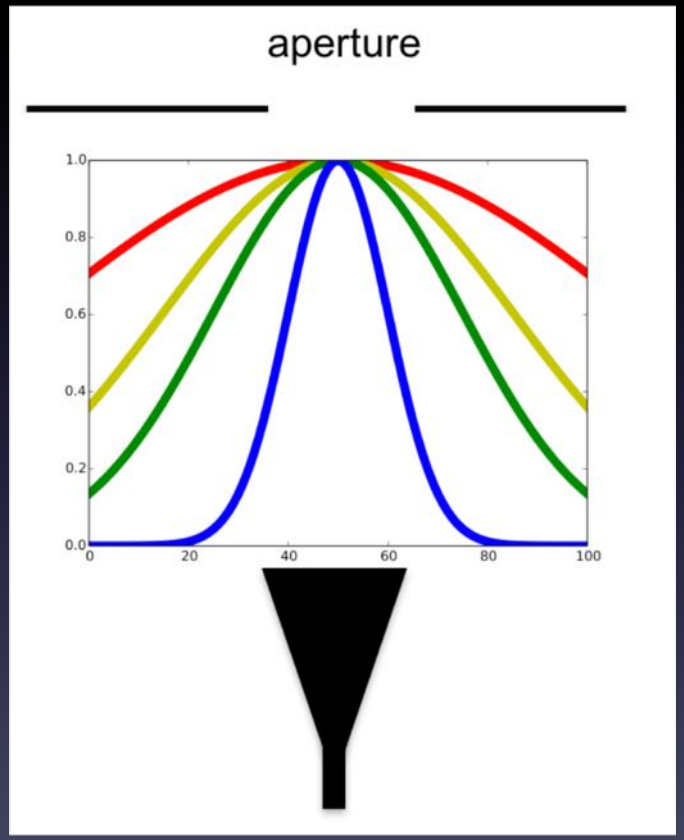


Need bands spanning maybe ~10x in frequency

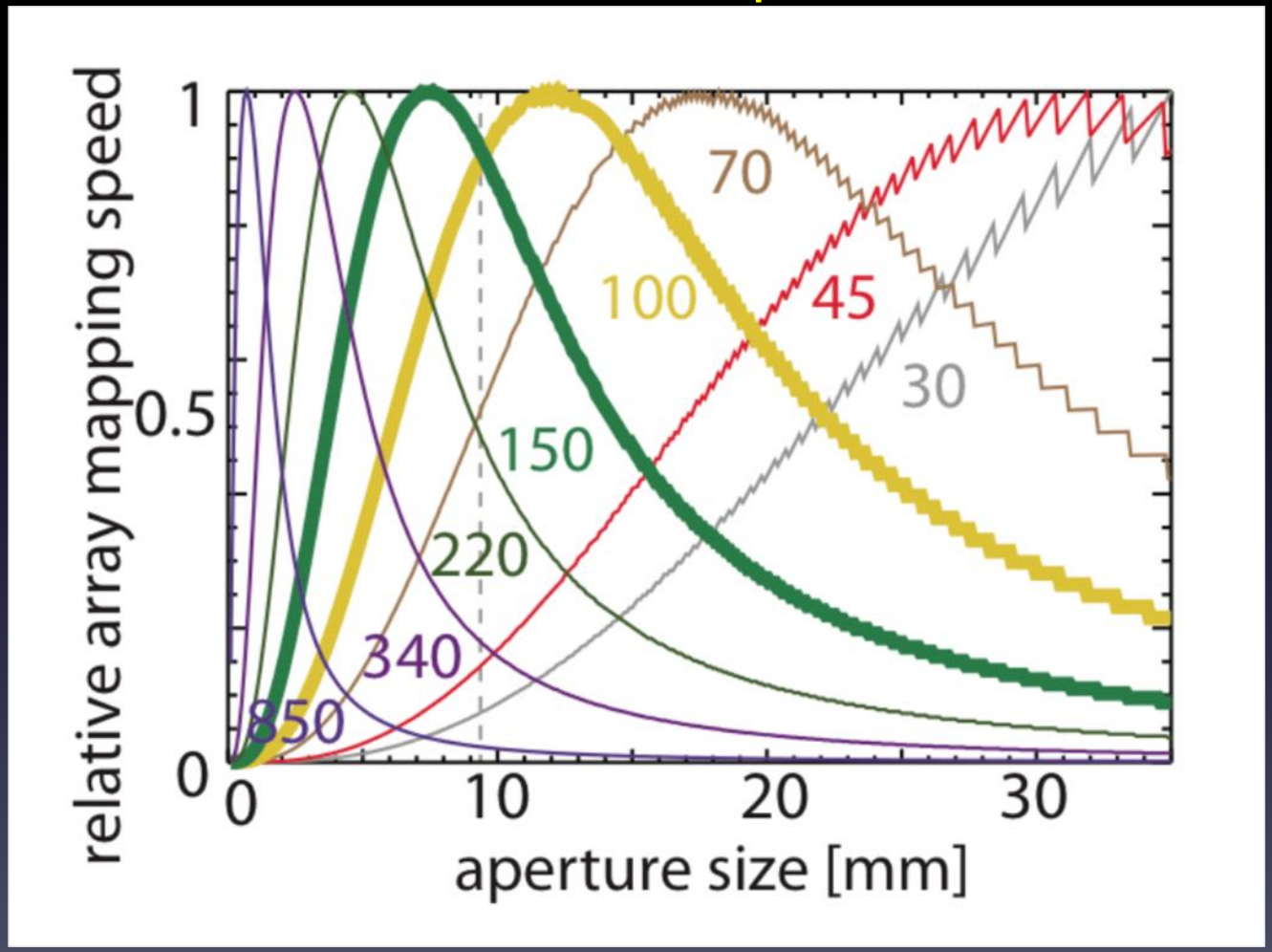


Limited by:
- Total Bandwidth
- Diminishing efficiency for fixed pixel size

Multi-chroic Diminishing Returns



Array-level mapping speed vs pixel size for fixed focal plane size



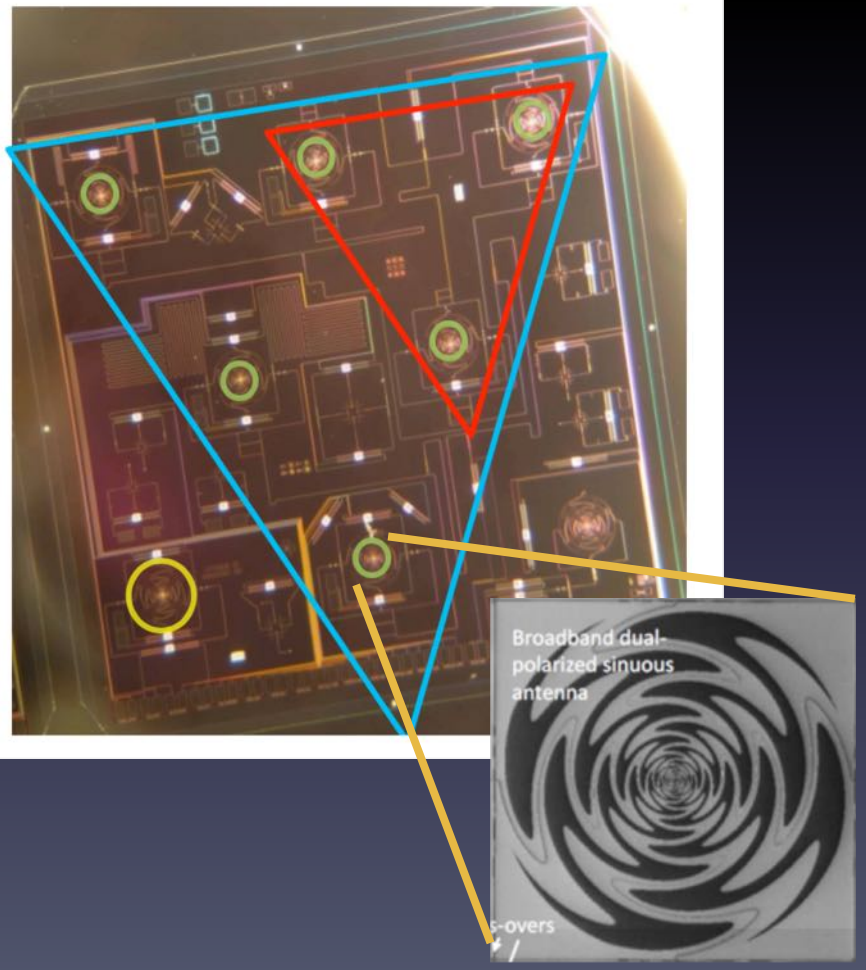
Datta et al 2014

A Better Multi-chroic?

Hierarchical phased array

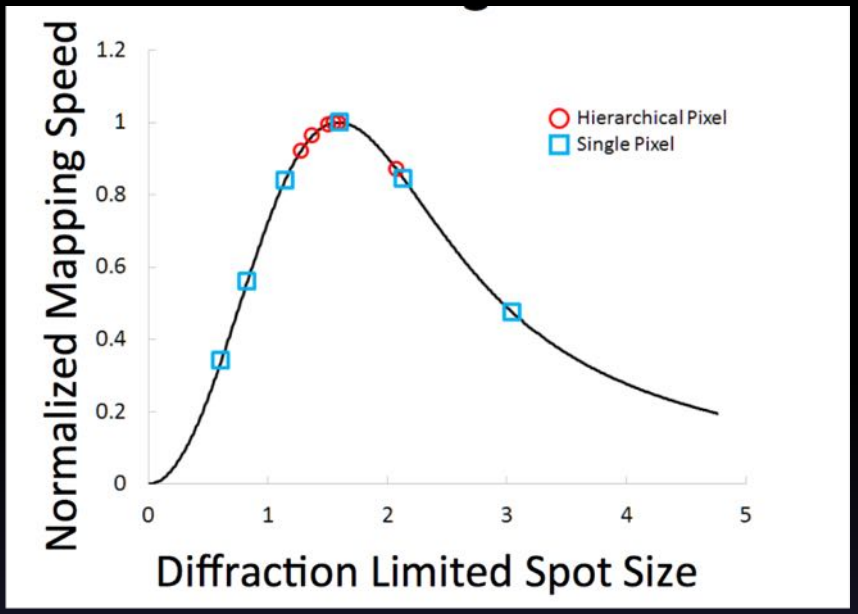
Antennae are coupled using Spherical Lenslets

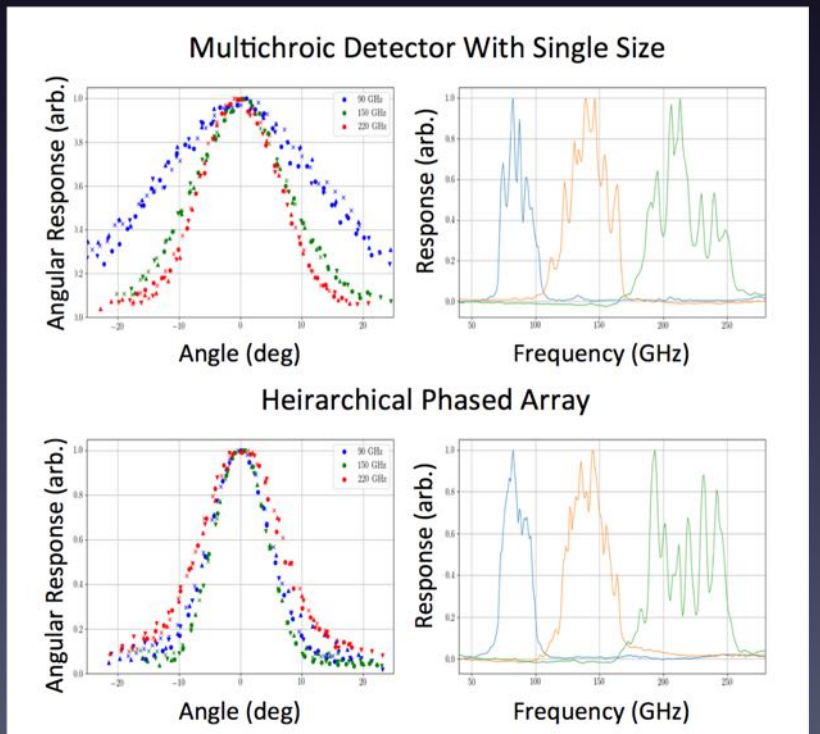
- 90/150/220 GHz trichroic pixel
- 220 single
- 150 3-cell triangular array
- 90 6-cell triangular array



Cukierman et al. 2017
UCB / LBNL

Near Optimal Mapping Speed for all Bands





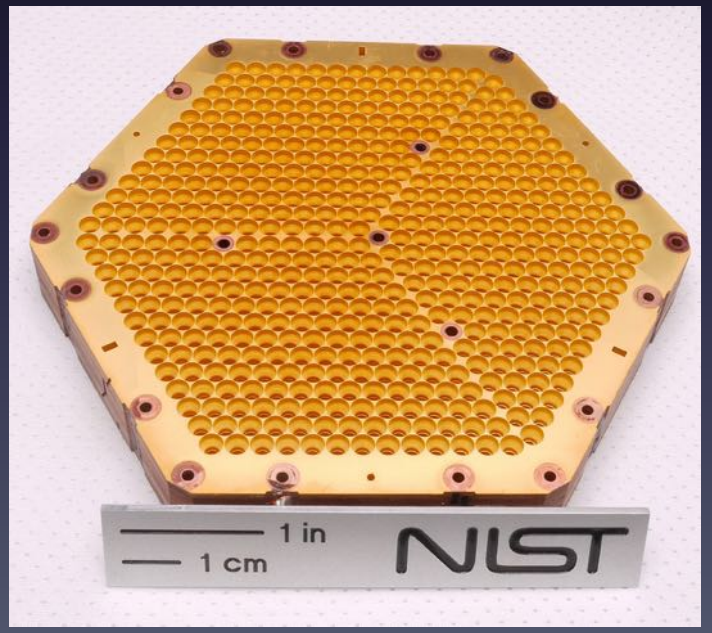
NIST – Quantum Sensors Group (QSG)

- CMB Detectors & Focal Planes
- Calorimeters (TES)
- Readout & Amplifiers
- Detectors for Astronomy/Astrophysics, Security, etc (TES and MKID)
- Fabrication / Lithography
- Cryogenic Research

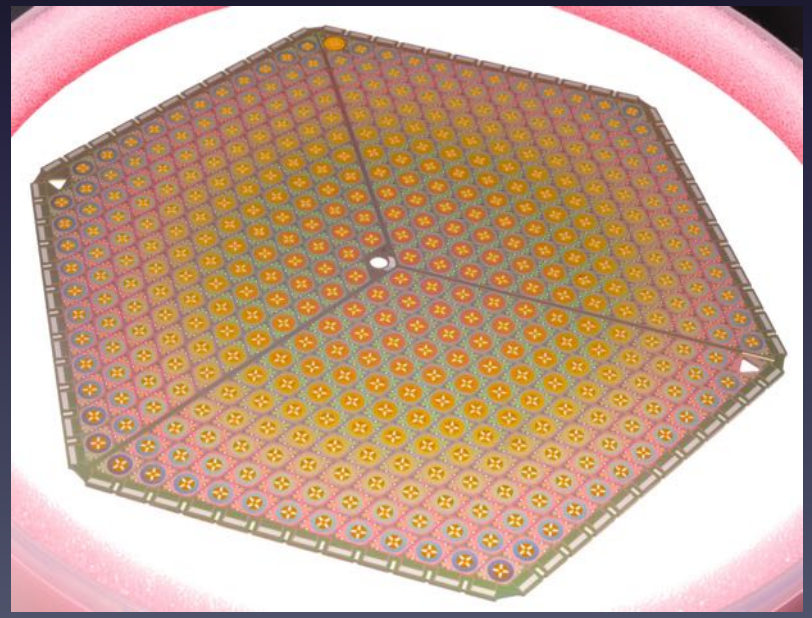
NIST CMB Focal Plane Technology

Monolithic, planar, **all-silicon**, polarization-sensitive focal planes (inc. cold readout)

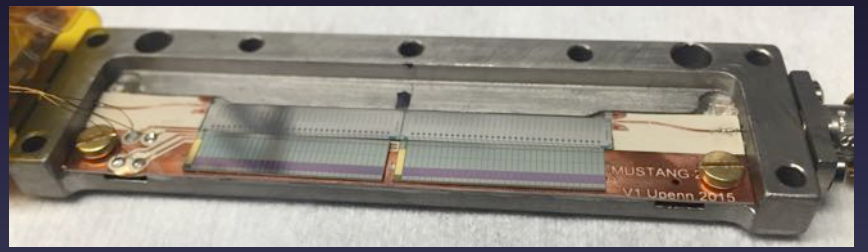
Feedhorn Arrays

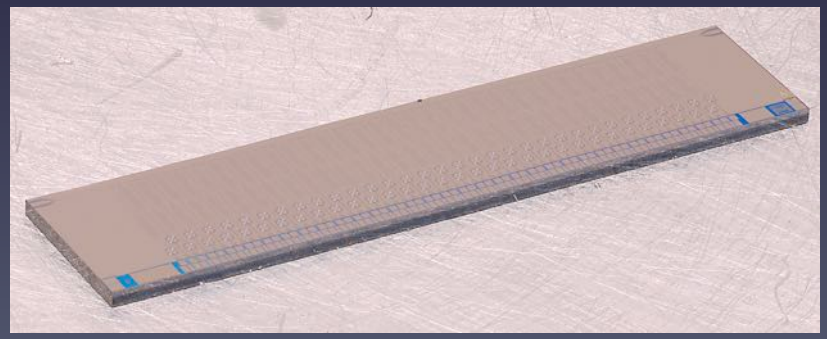


Detector Arrays



Superconducting readout components

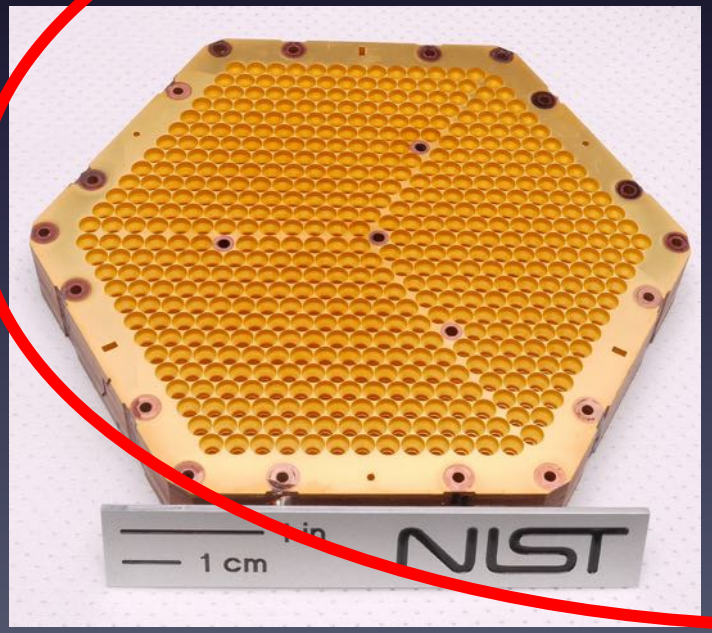




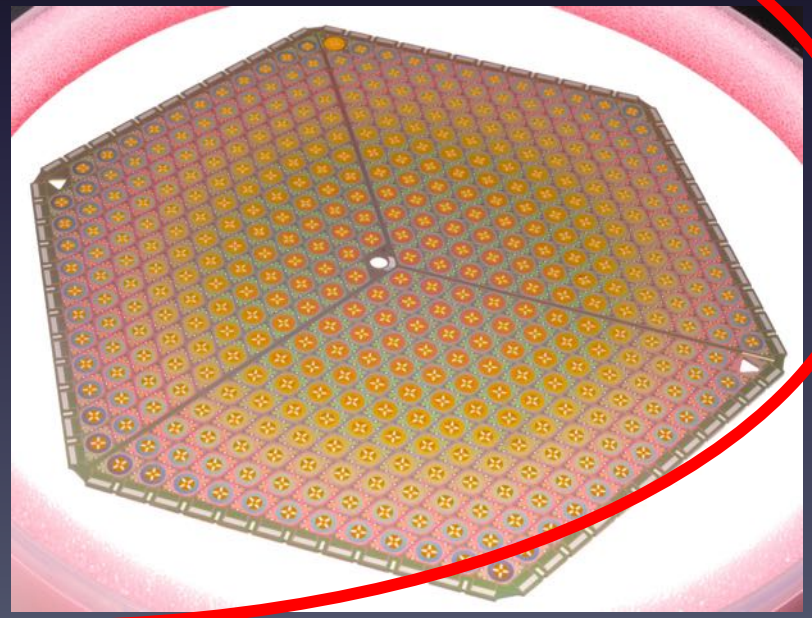
NIST CMB Focal Plane Technology

Monolithic, planar, **all-silicon**, polarization-sensitive focal planes (inc. cold readout)

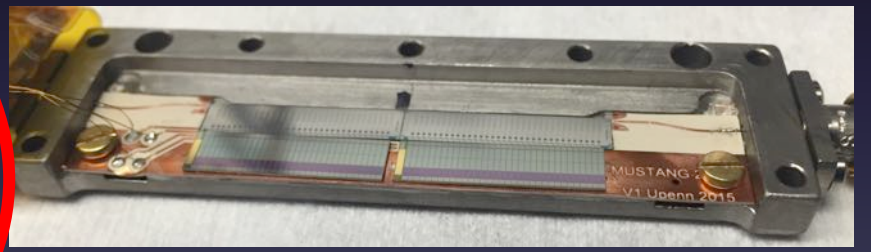
Feedhorn Arrays

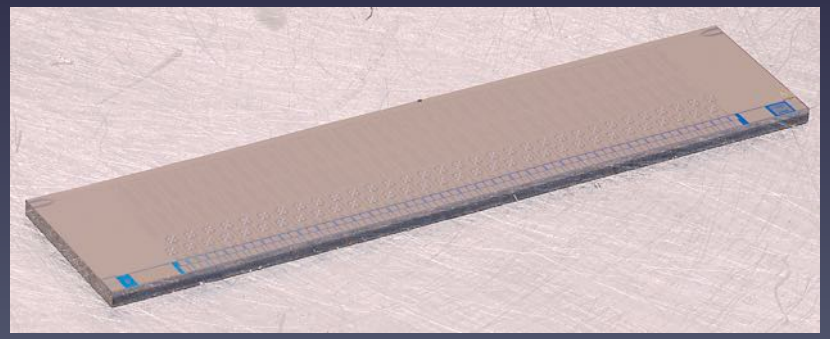


Detector Arrays

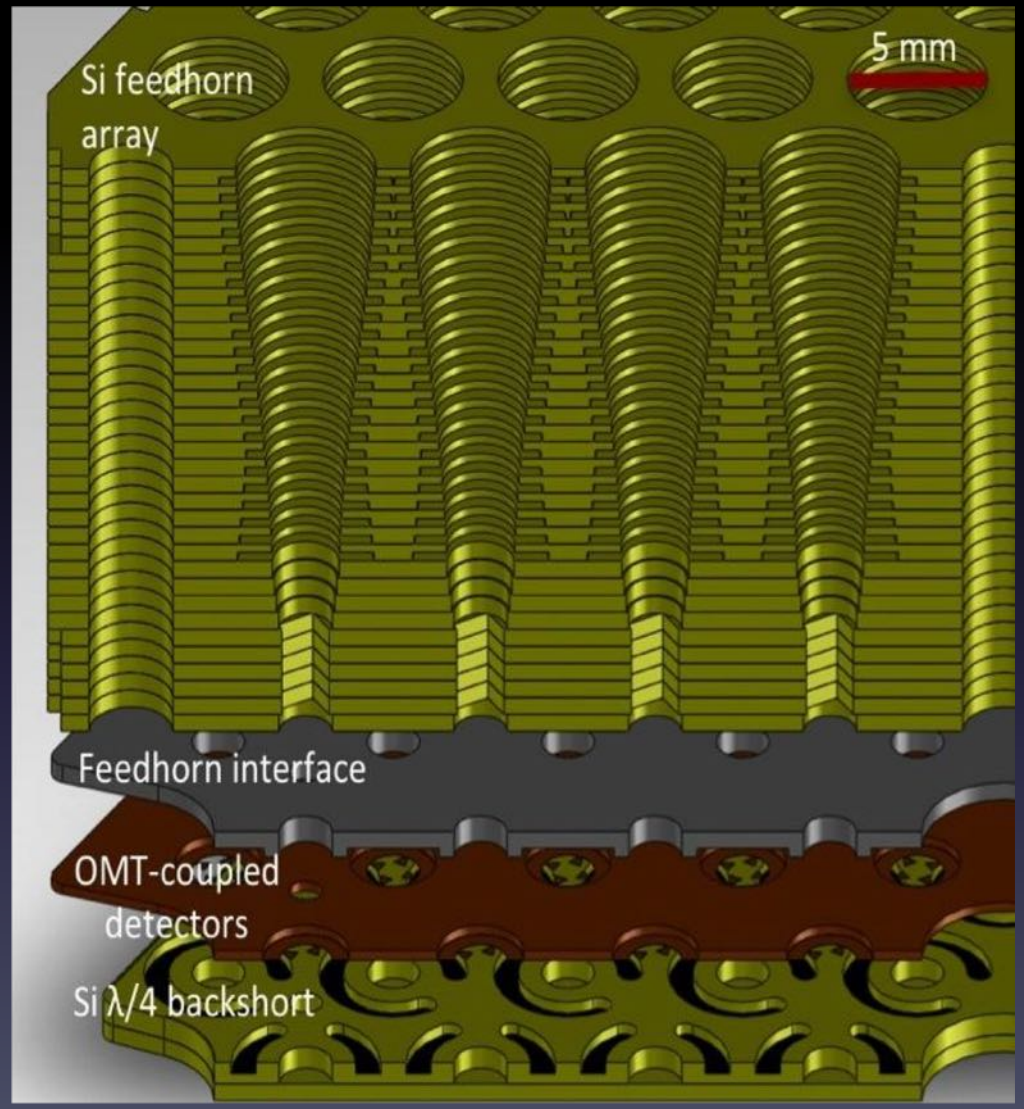


Superconducting readout components

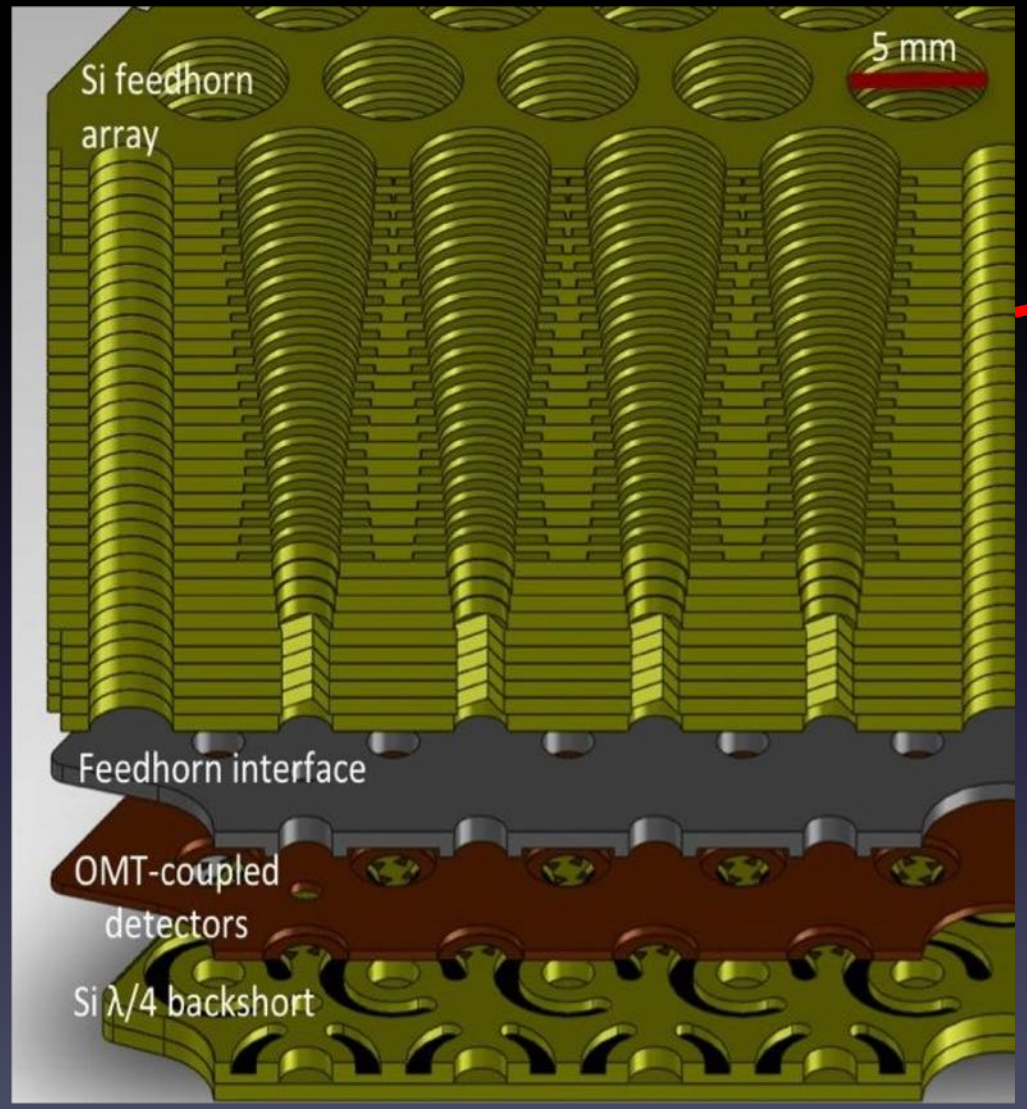


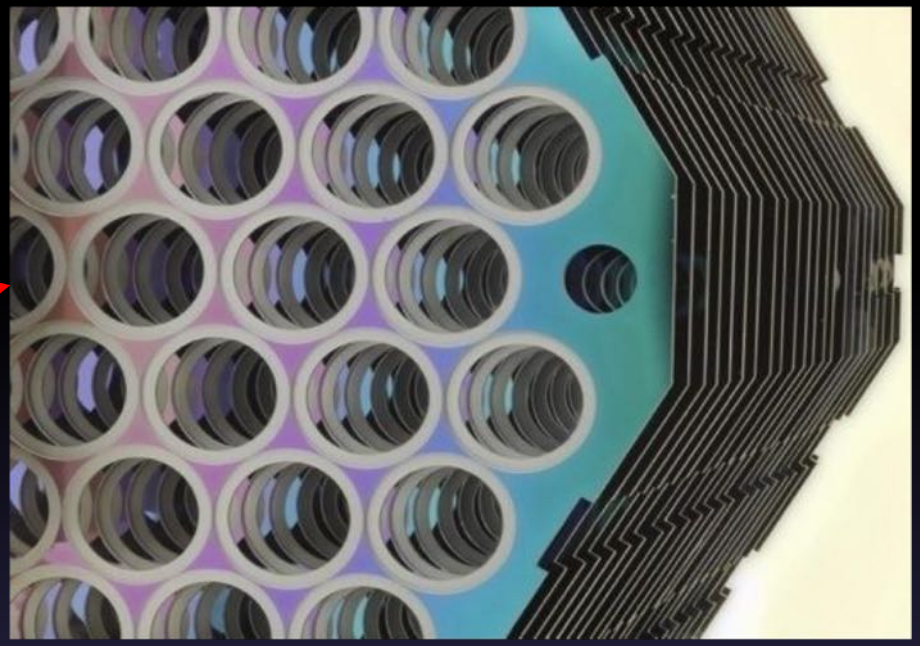


Feedhorn-Coupled Polarimeter Arrays

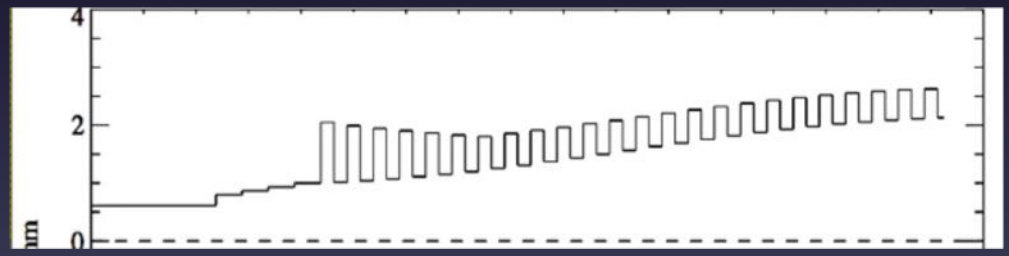


Feedhorn-Coupled Polarimeter Arrays

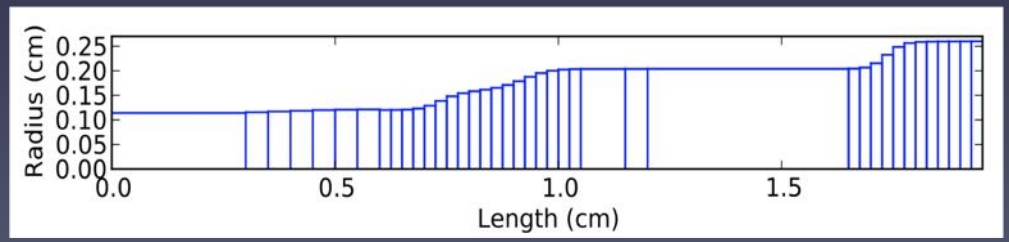




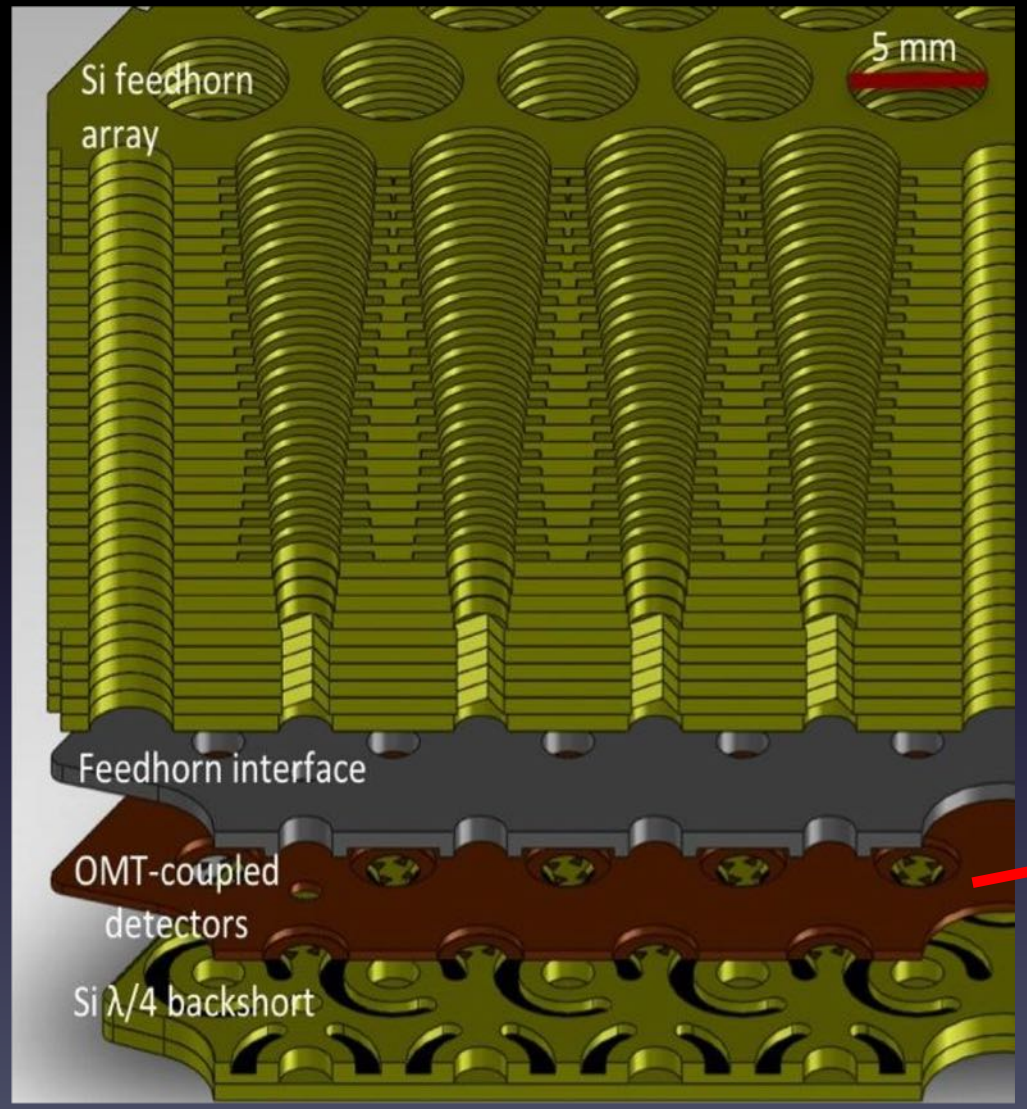
Corrugation Profile

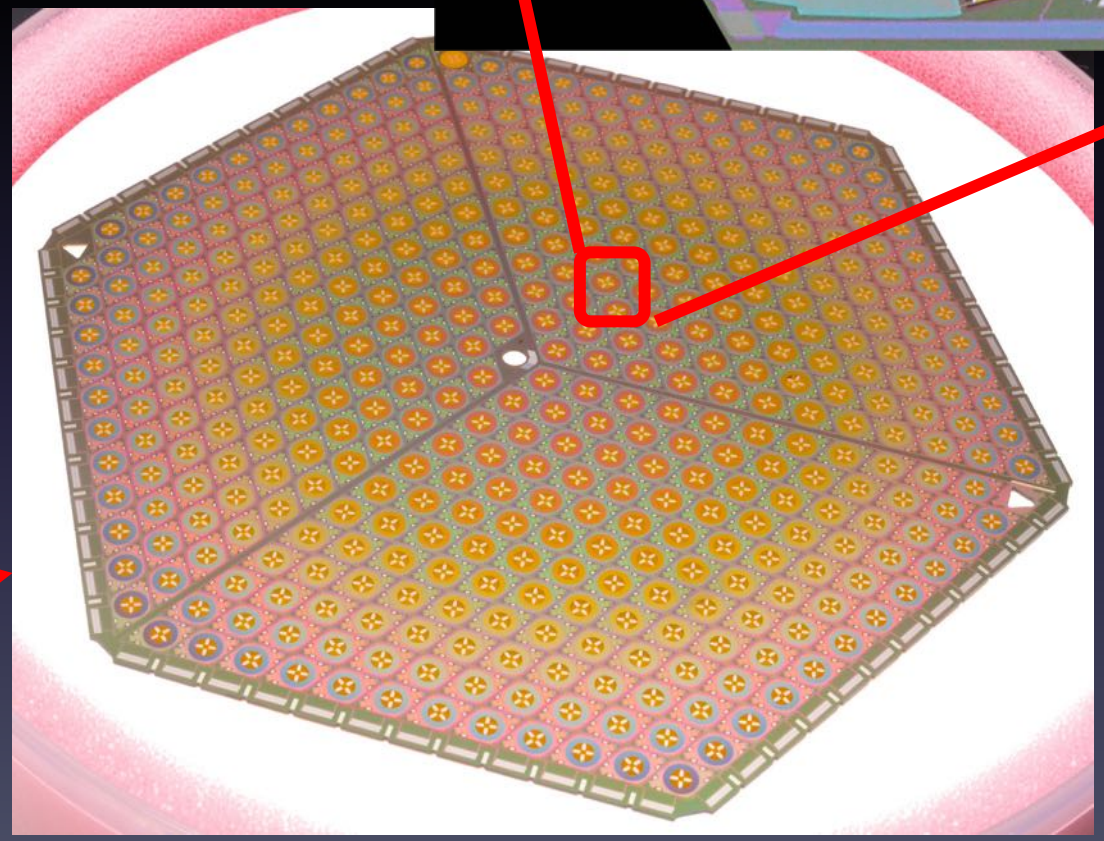


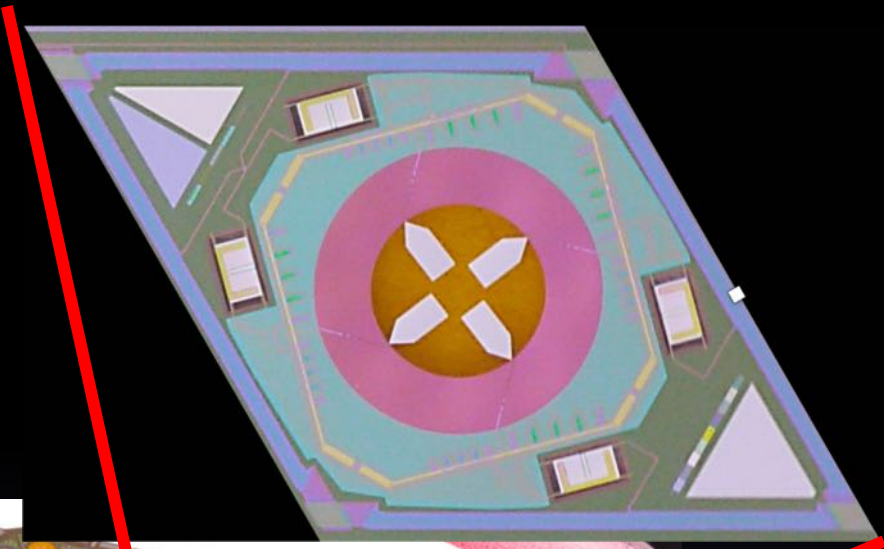
Optimized Spline Profile



Feedhorn-Coupled Polarimeter Arrays



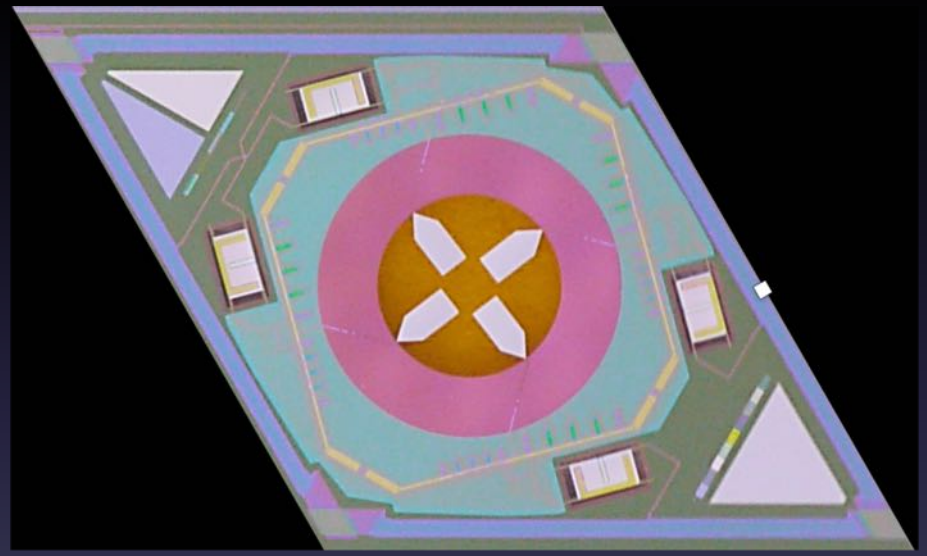




150 mm Wafer

Multi-chroic Detector Cell

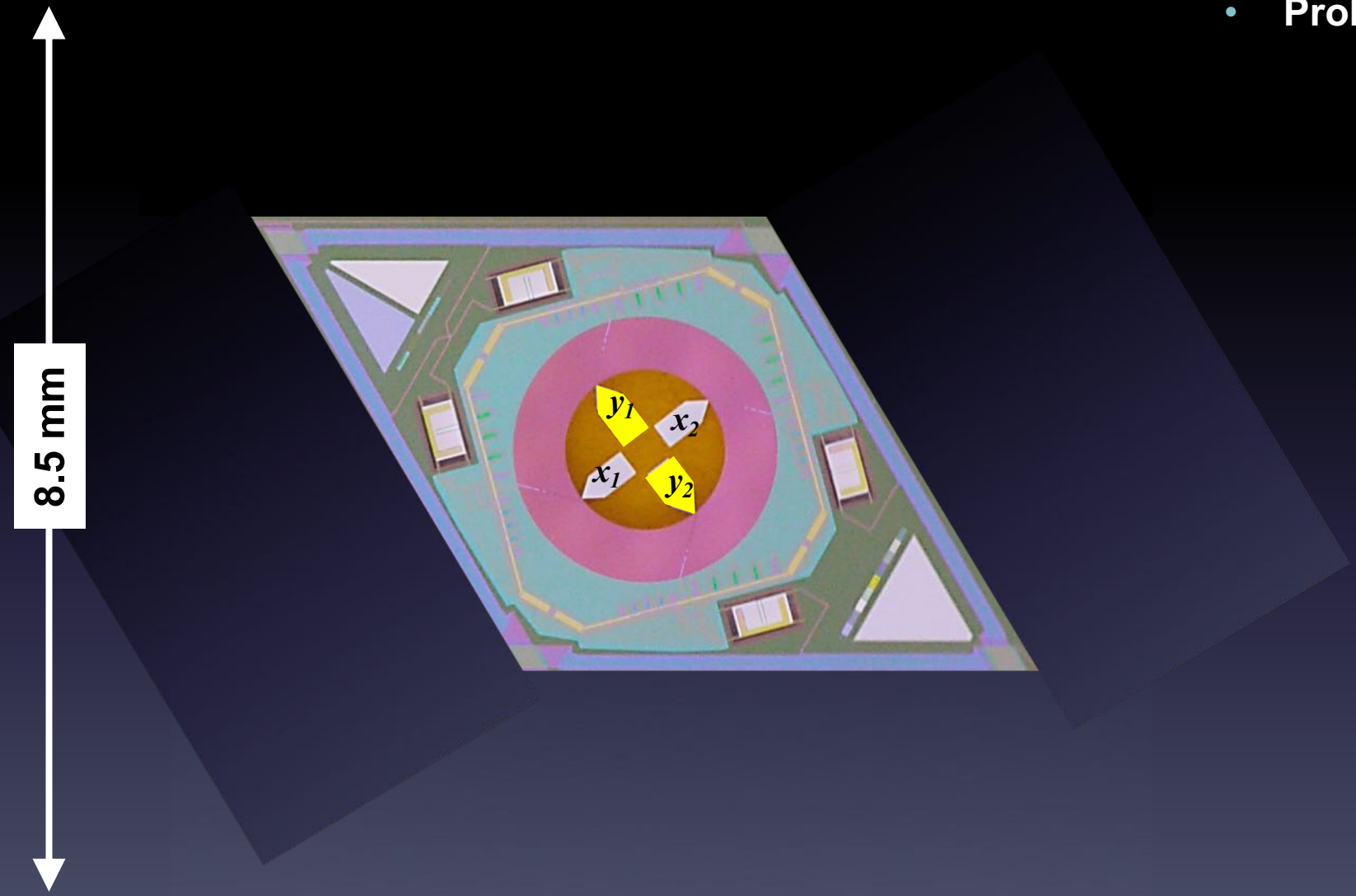
~ 5 mm

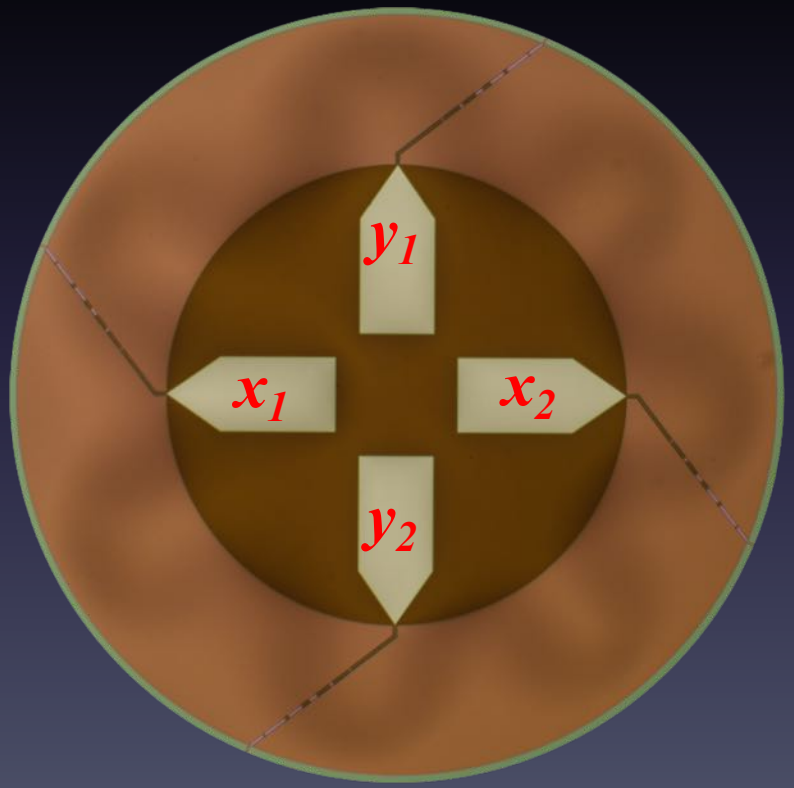


Advanced ACTPol multi-chroic pixel

Multi-chroic Detector Cell

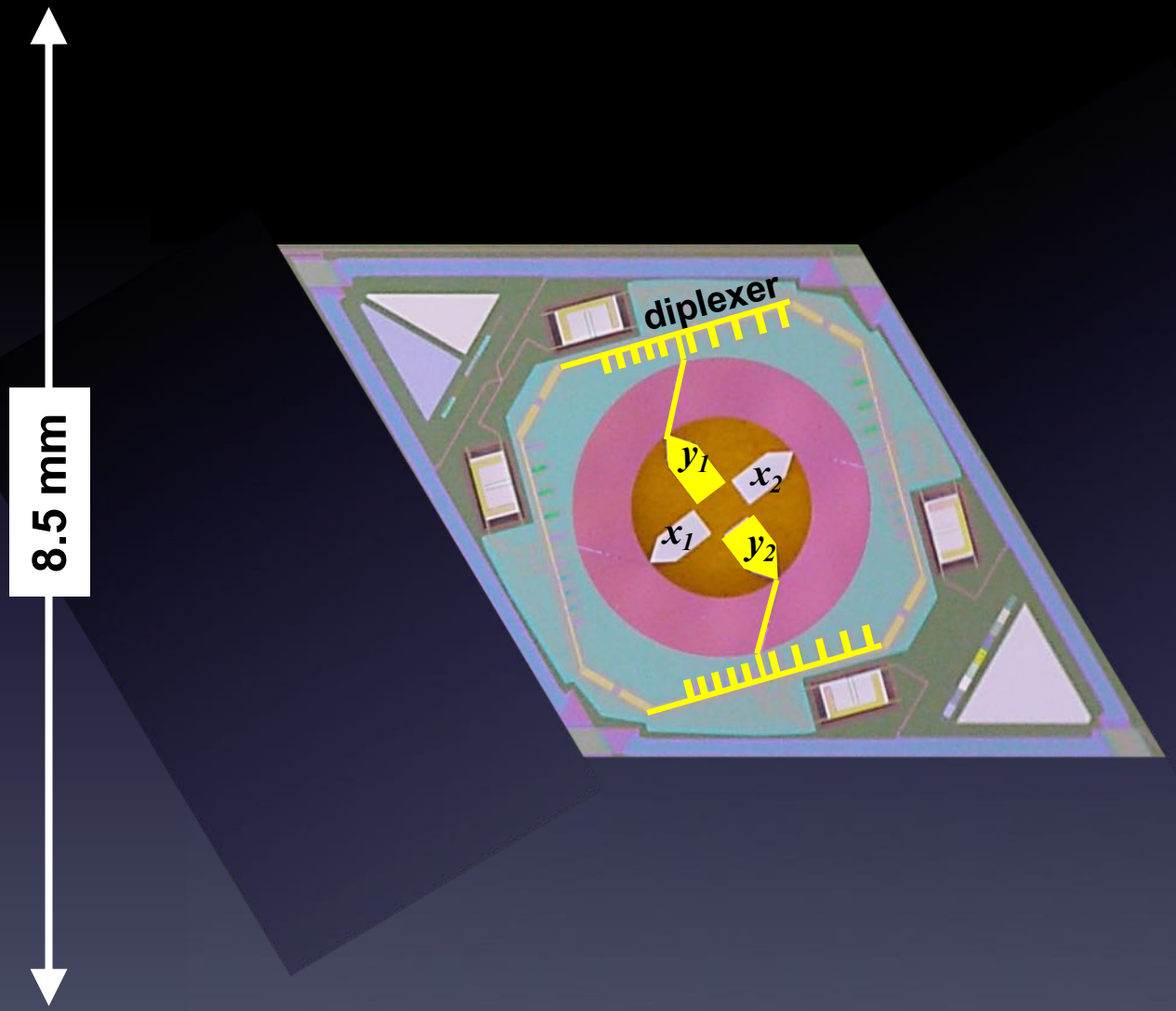
- Probe Antennae of OMT couples light



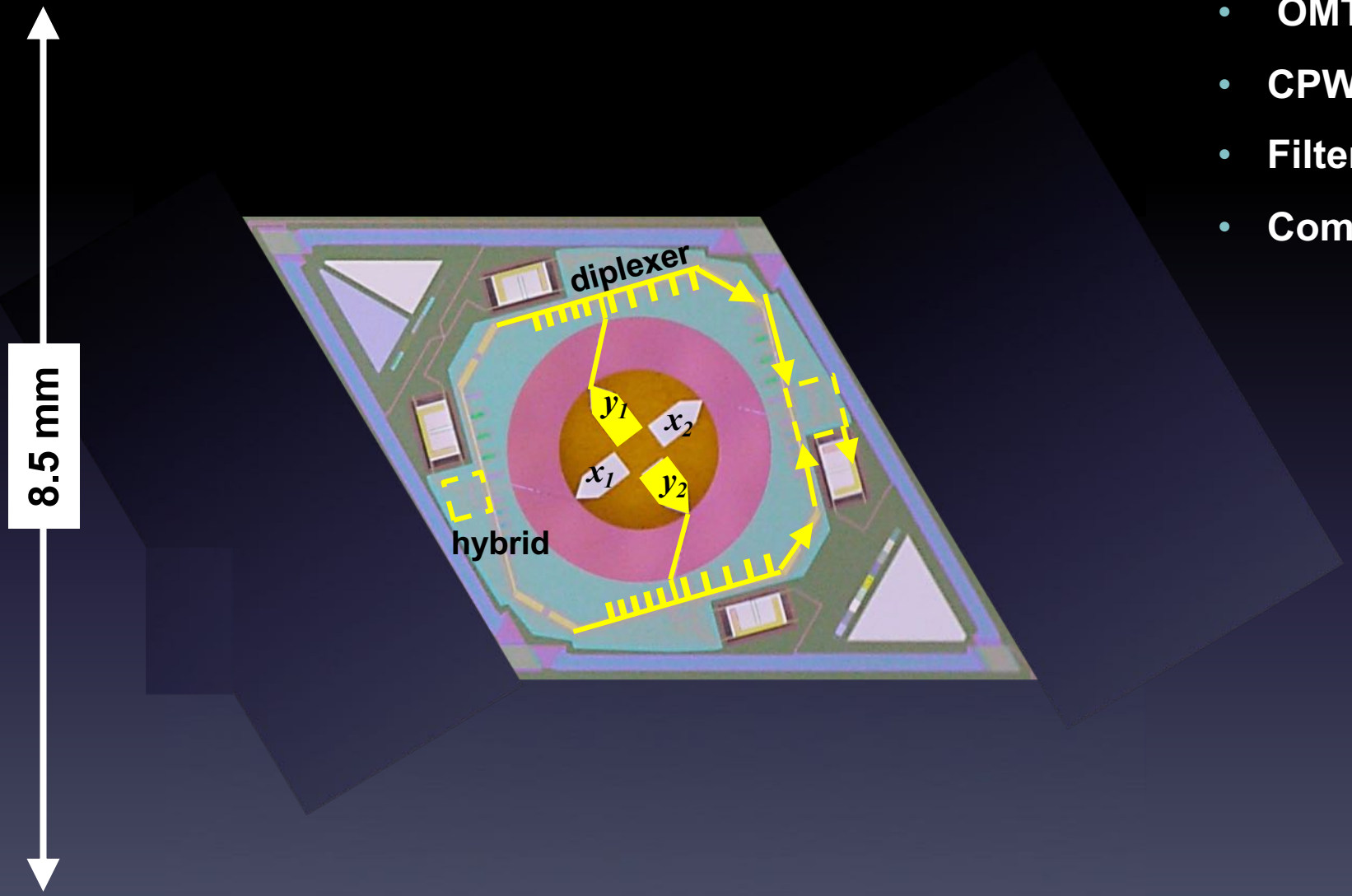


Multi-chroic Detector Cell

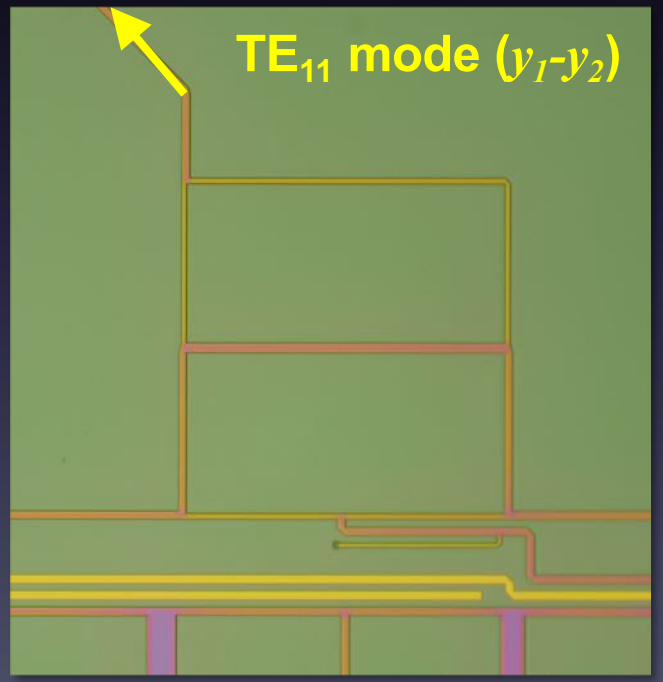
- OMT couples light
- CPW to MS transition
- Filter into two bands



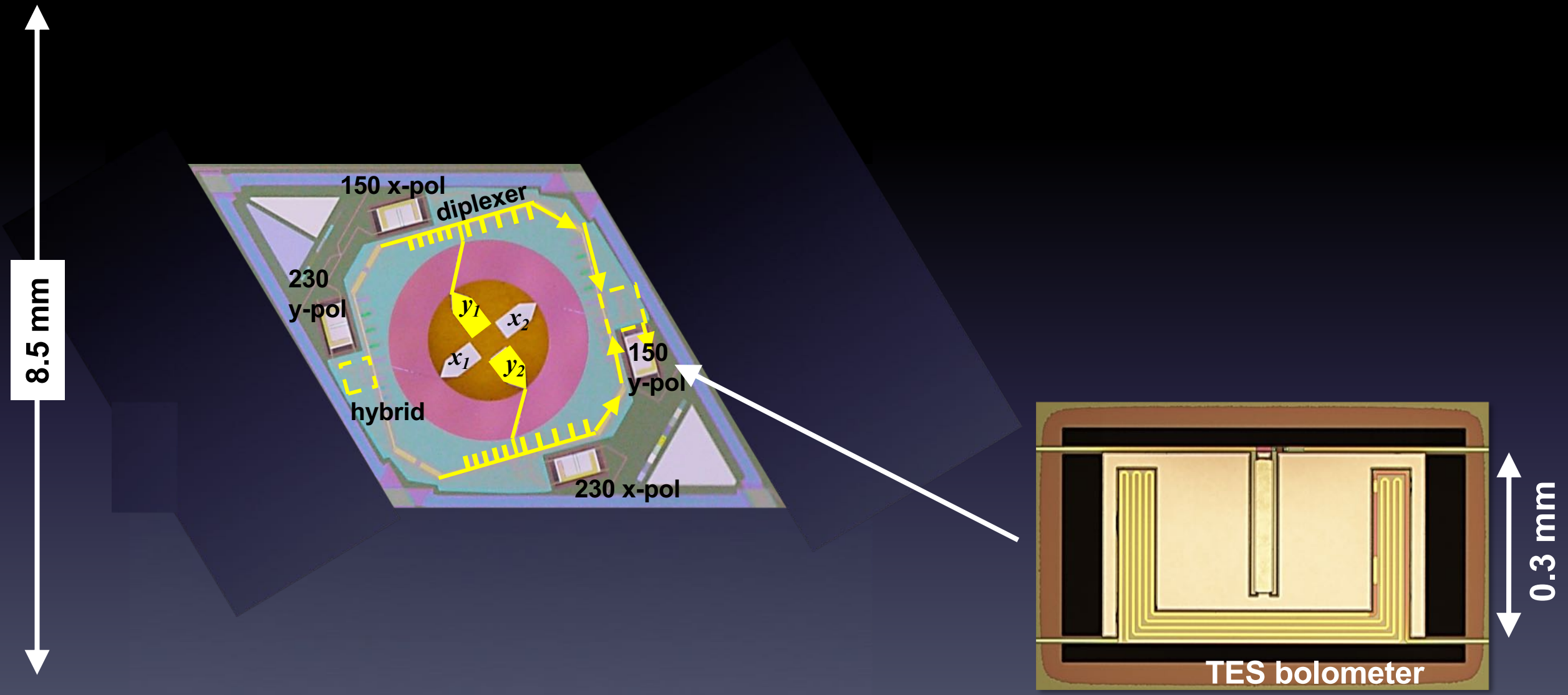
Multi-chroic Detector Cell

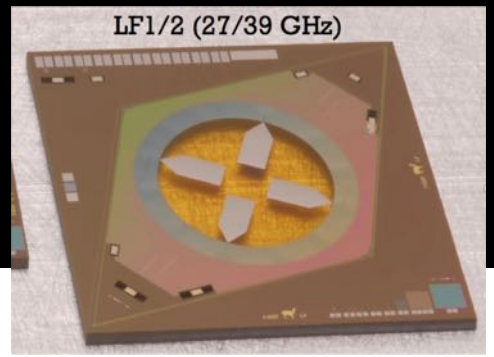


- OMT couples light
- CPW to MS transition
- Filter into two bands
- Combine lowest order mode/reject others



Multi-chroic Detector Cell

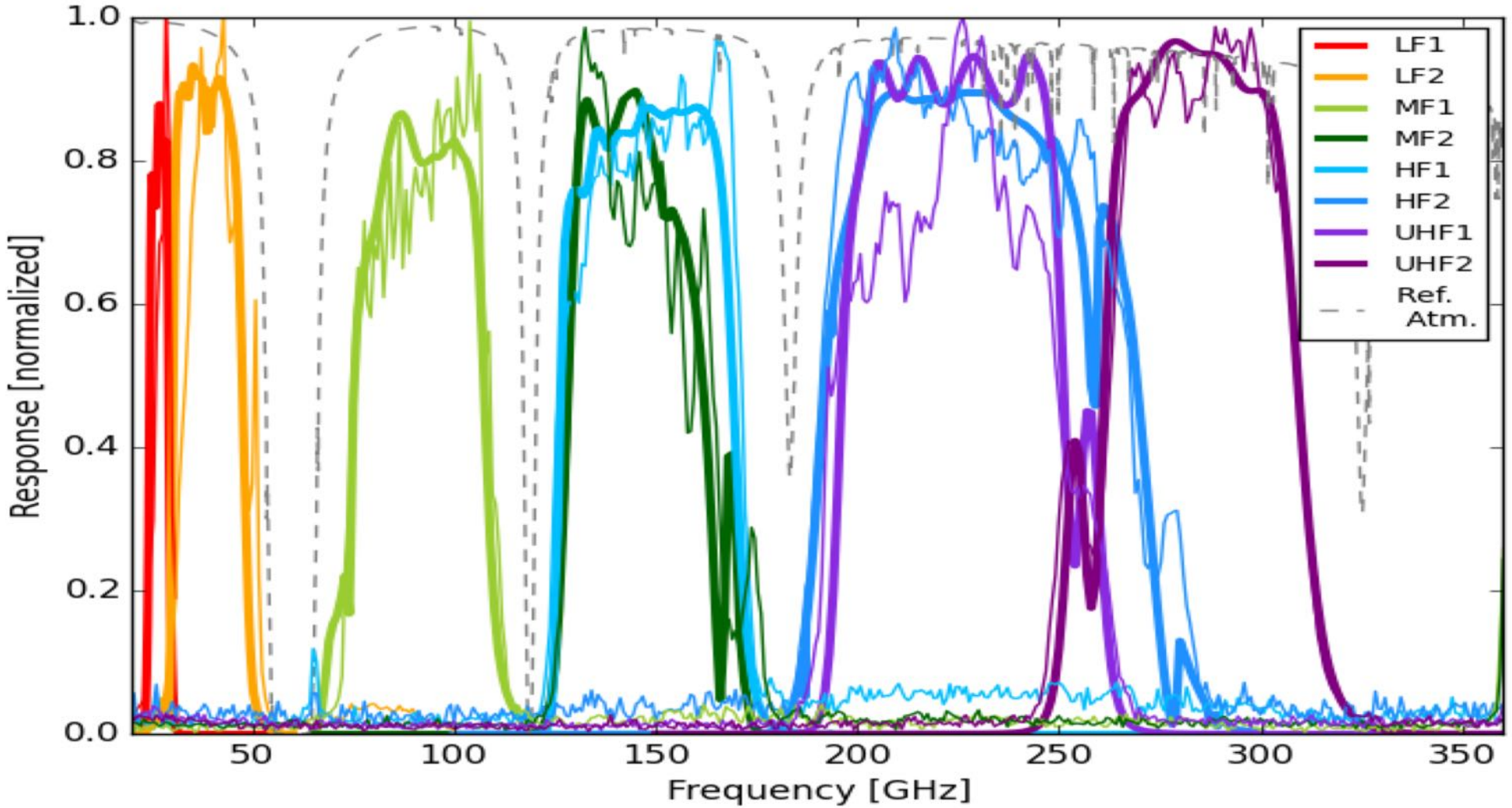



LF1/2 (27/39 GHz)

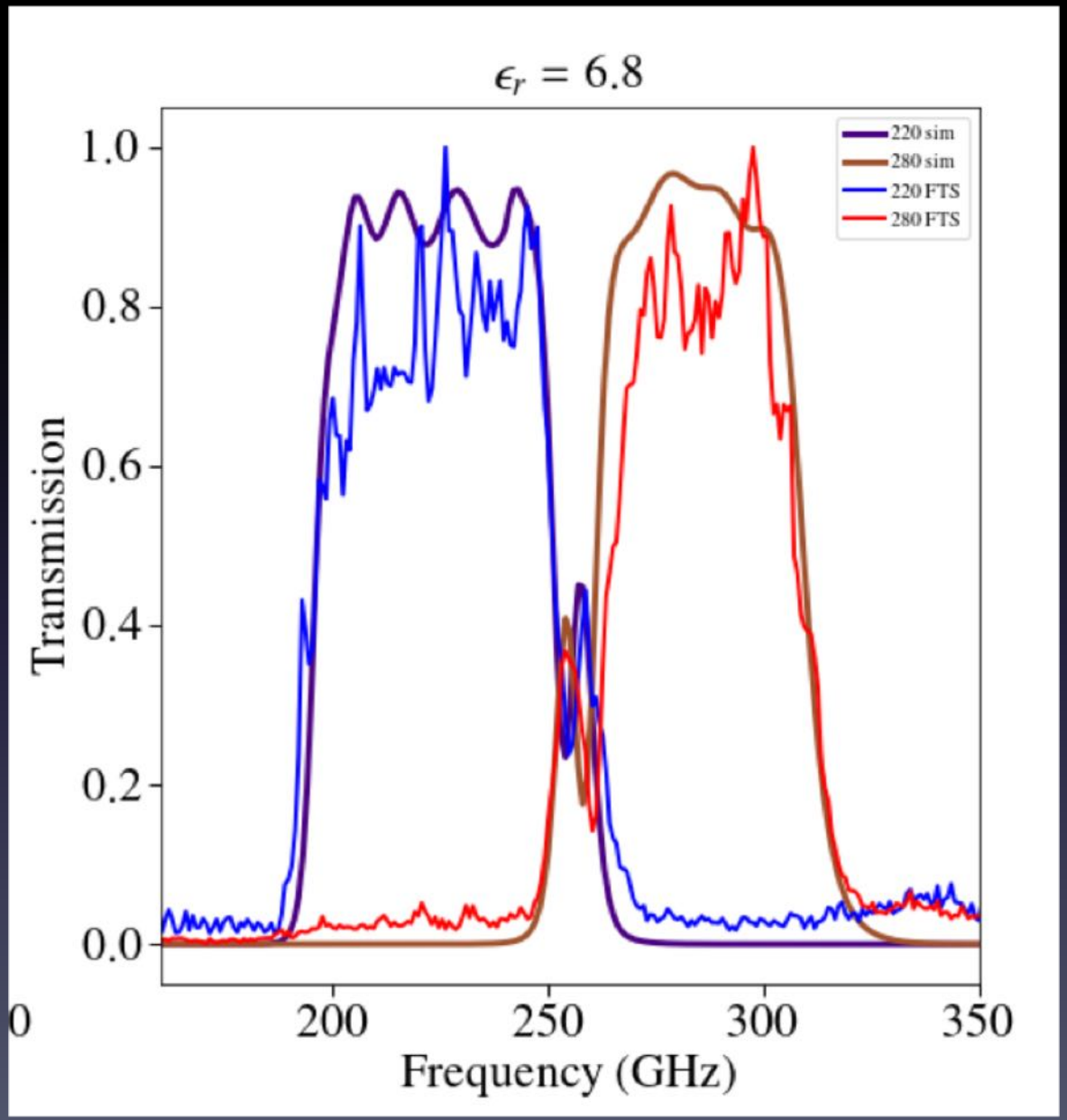
MF1/2
(90/150 GHz)

HF1/2
(150/220 GHz)

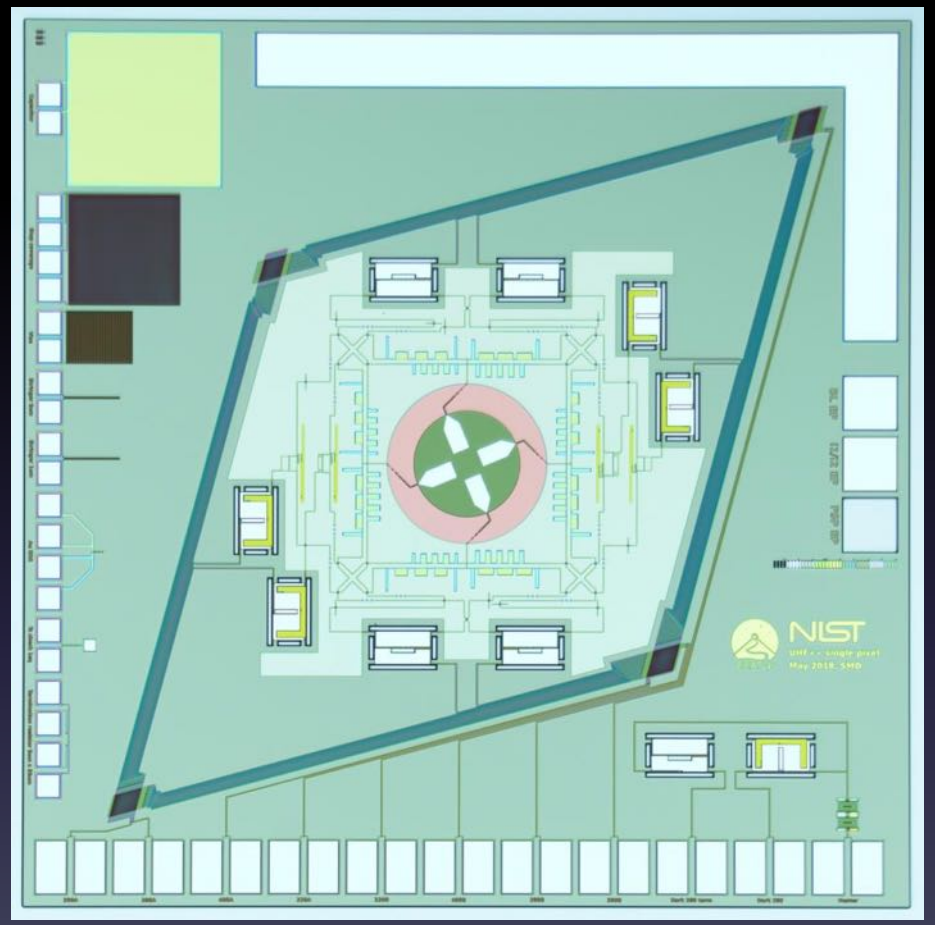
UHF
(220/280)

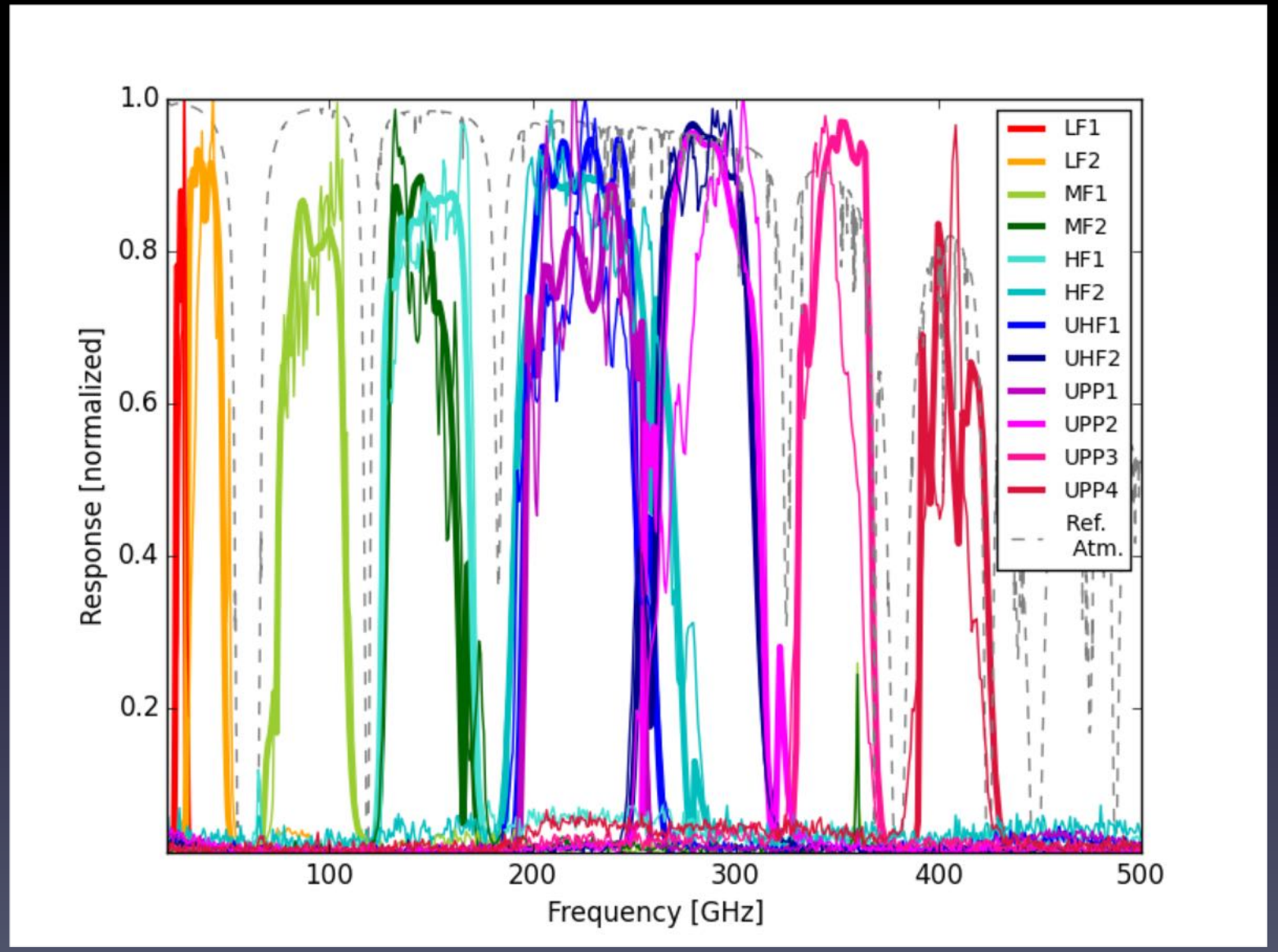

1.0
0.8
0.6
0.4
0.2
0.0
Response [normalized]
50
100
150
200
250
300
350
Frequency [GHz]
LF1
LF2
MF1
MF2
HF1
HF2
UHF1
UHF2
Ref. Atm.

UHF

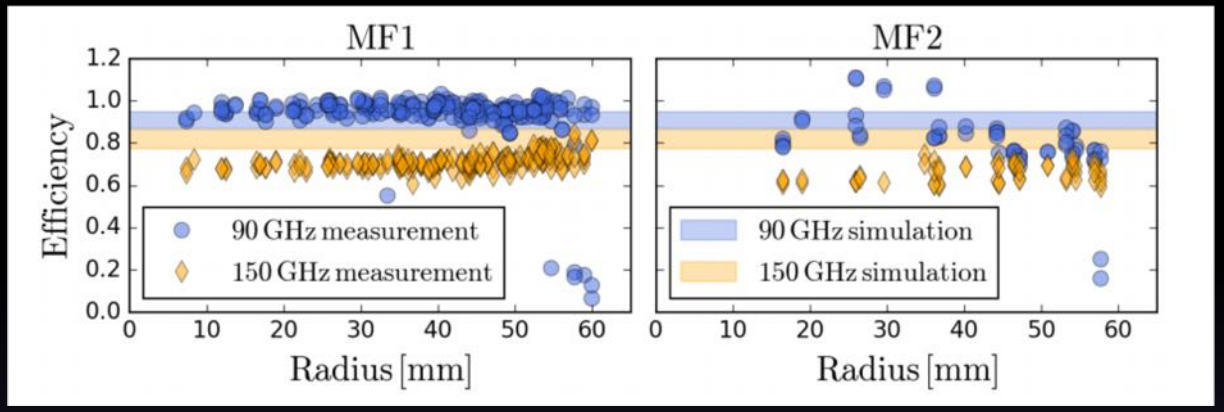

$\epsilon_r = 6.8$
220 sim
280 sim
220 FTS
280 FTS
Transmission
1.0
0.8
0.6
0.4
0.2
0.0
0
200
250
300
350
Frequency (GHz)

UHF++ - 4 Bands, 1 pixel

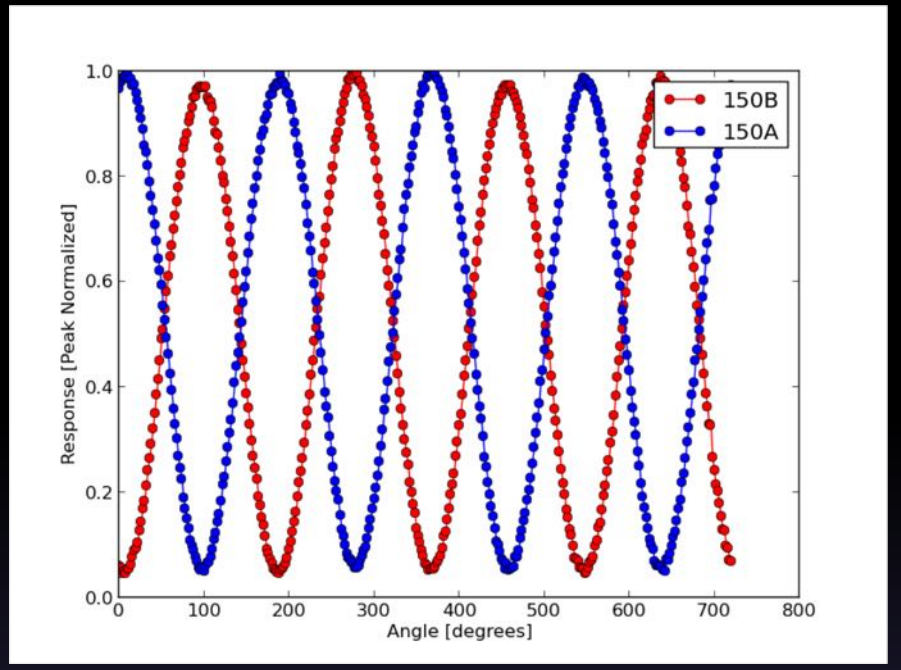




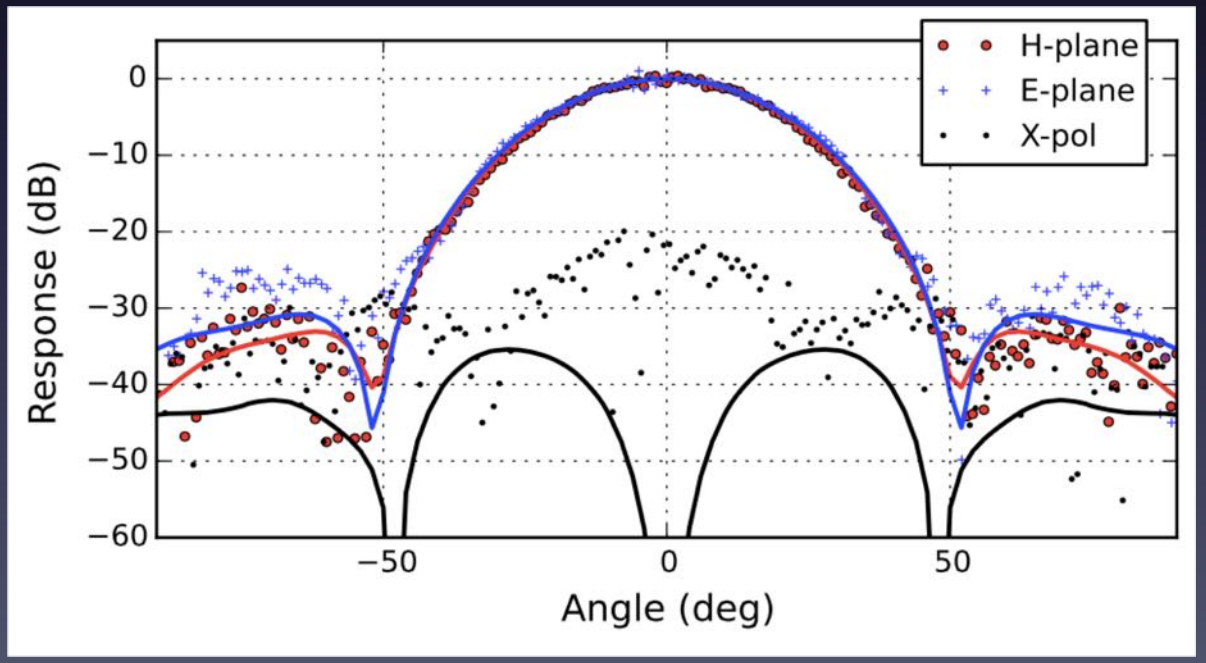
Optical Efficiency regularly > 70%



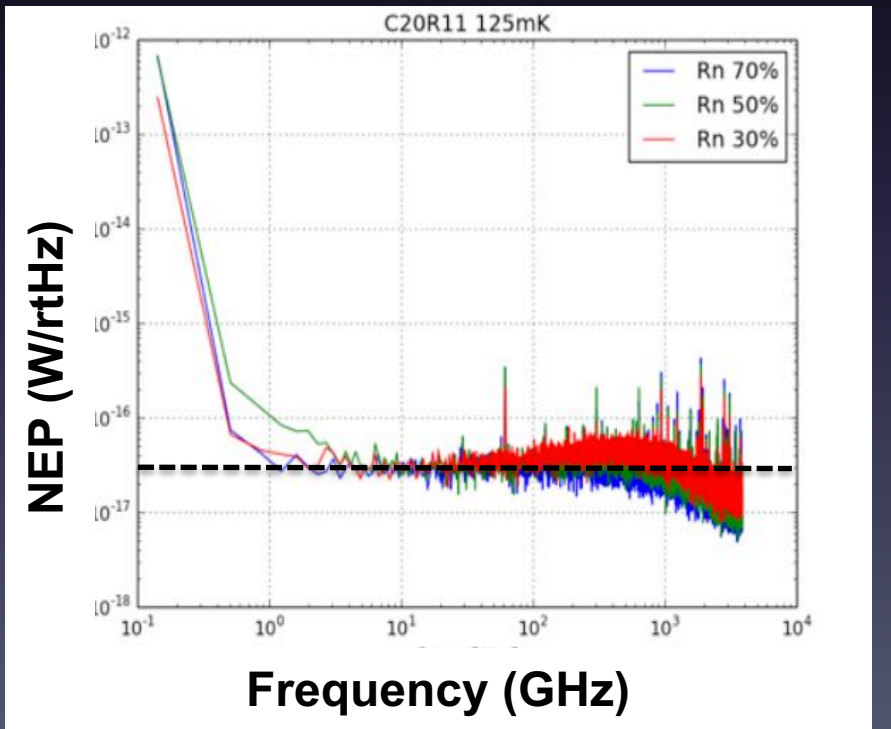
Good polarization efficiency



Well matched beams

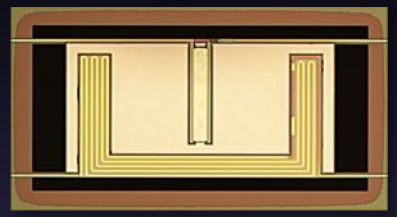


Expected Noise performance (photon-noise limited)



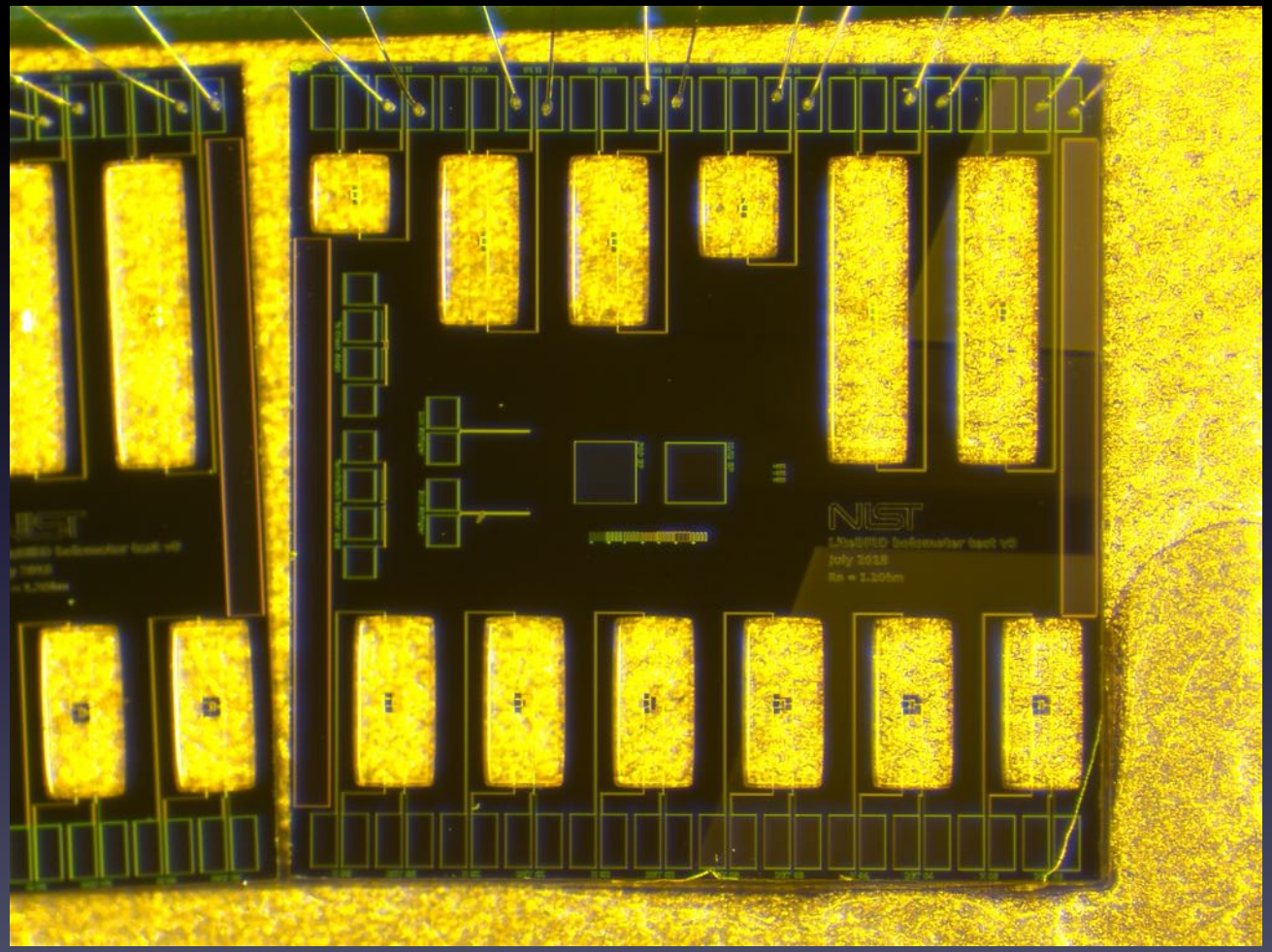
Low power options for space/balloon

As compared to ground-based high saturation power TES



Saturation Powers down to 0.4 pW

(T_c ~ 180 mK)

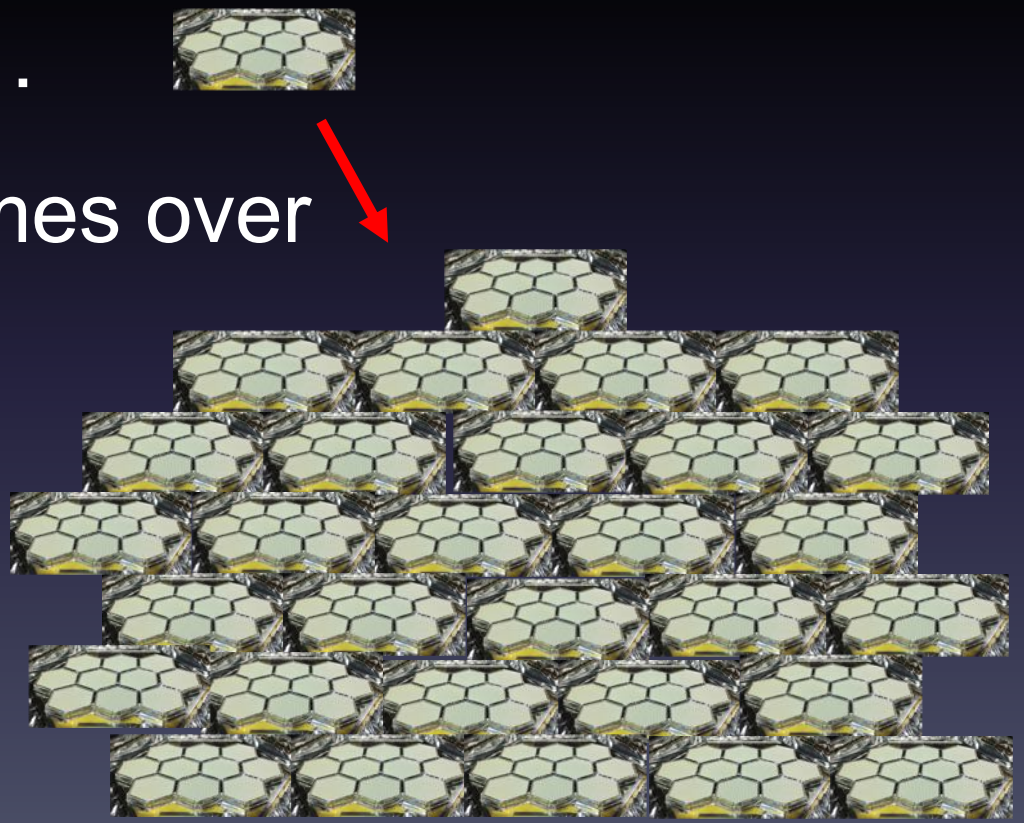


Future: e.g. CMB-S4

Fabrication, Assembly, & QA Challenge

- Simons Observatory (50k+) and CMB-S4 (500k)
- CMB-S4 equivalent to SPT3g…

… 30 times over

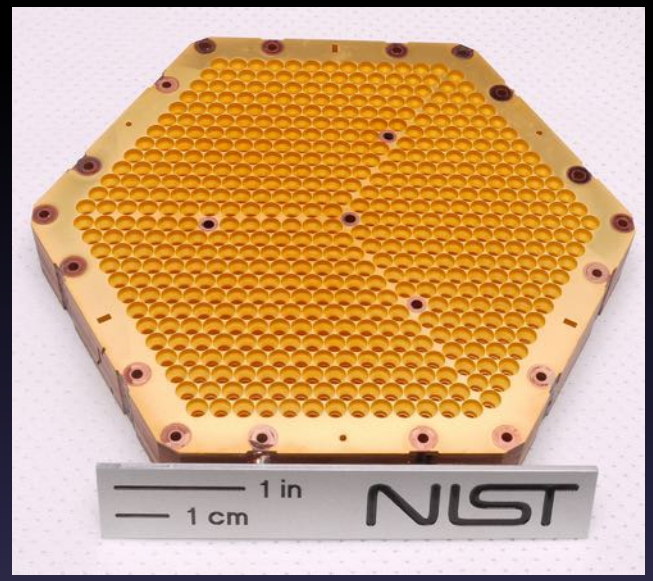


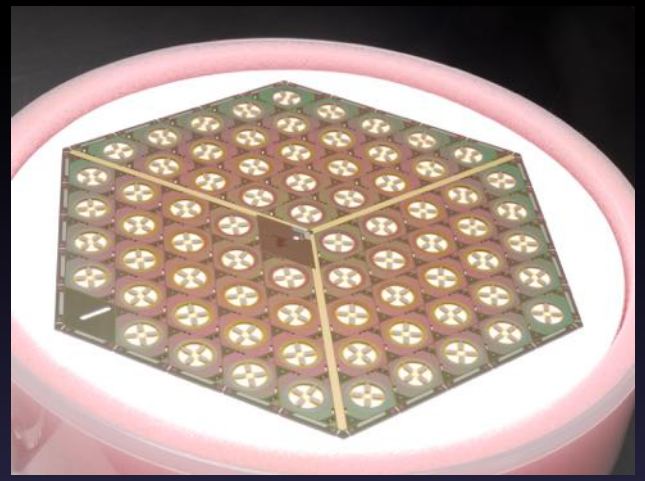
- Many scaling challenges

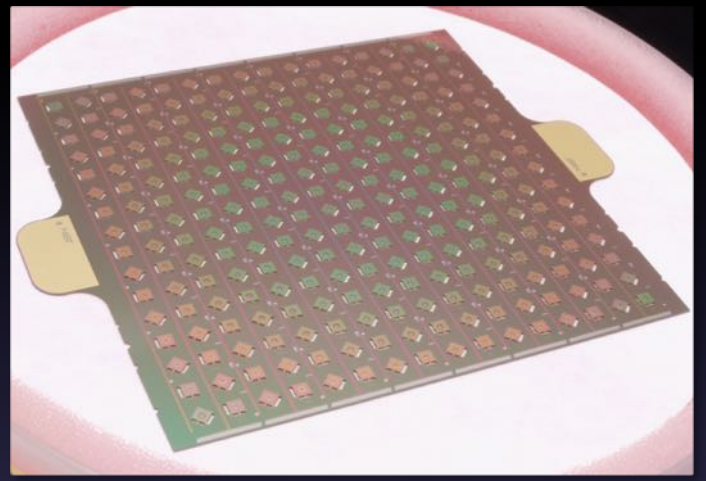
Fabrication Developments

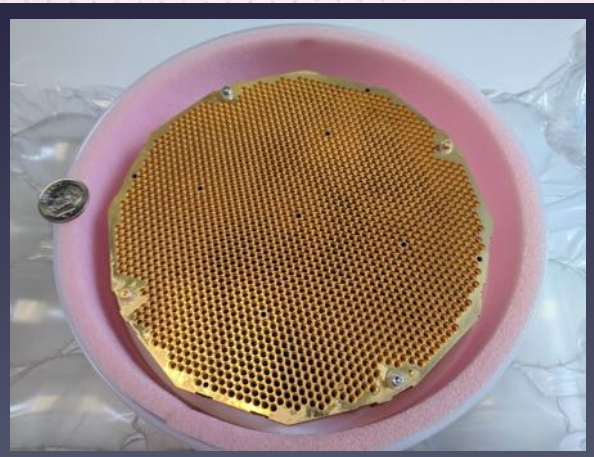
Fabrication Developments

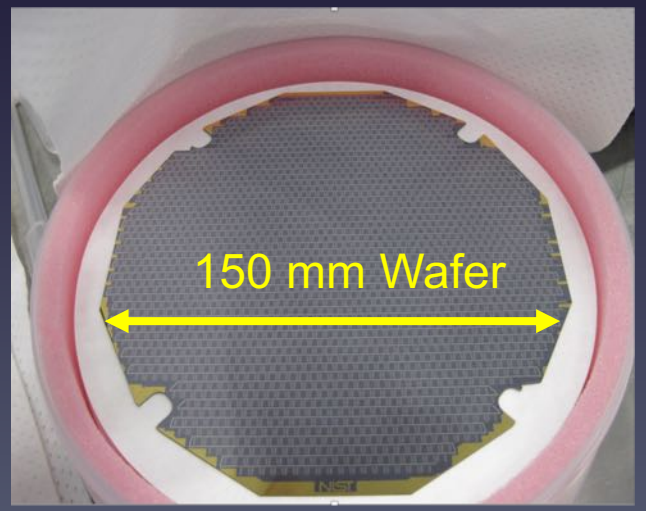
- 150 mm diameter wafers

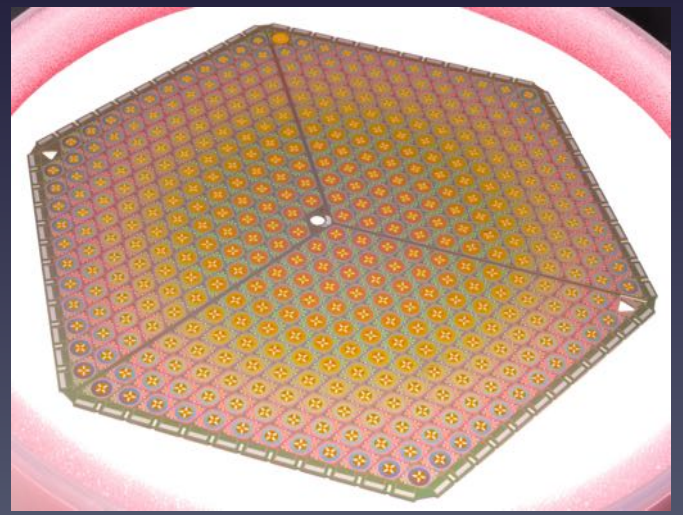








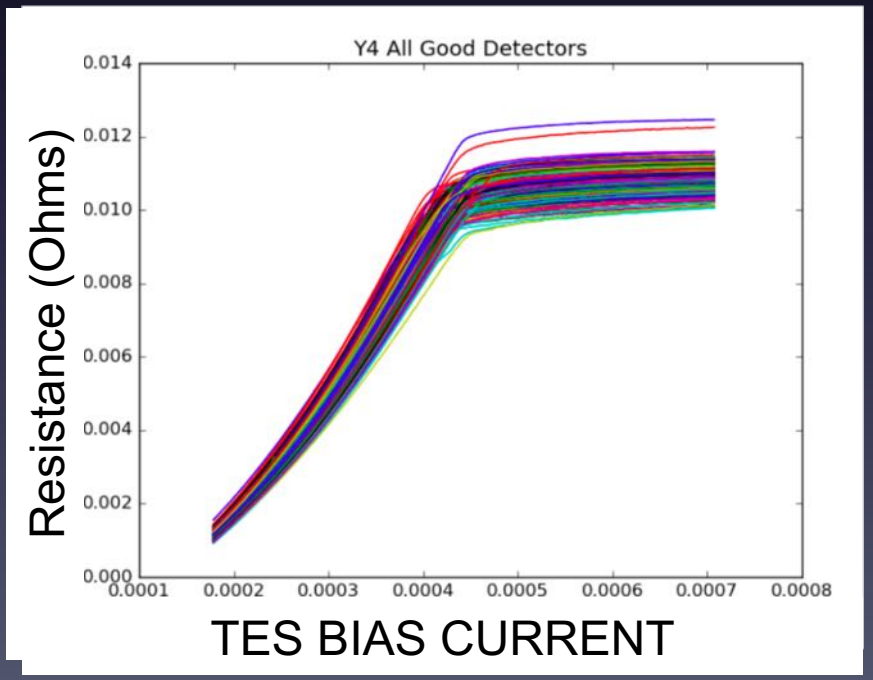




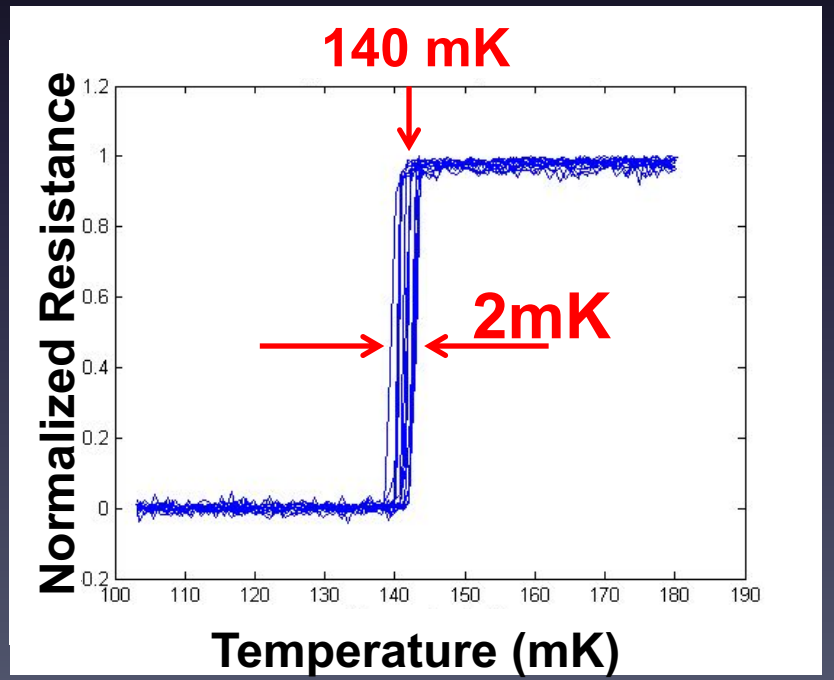
Detector Fabrication Developments

- 150 mm diameter wafers
- Uniformity

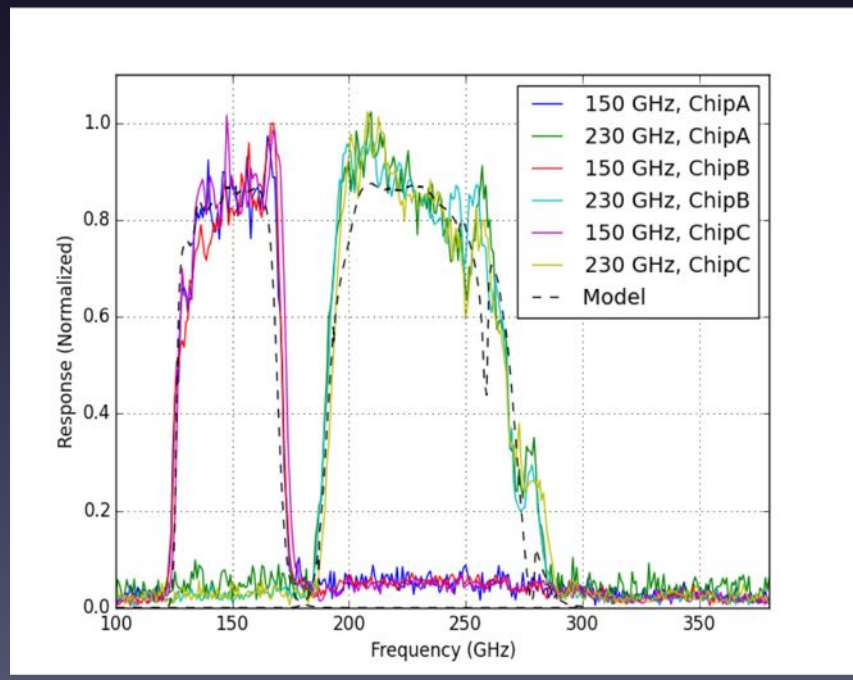
Array wide Electro-thermal uniformity



Tc Uniformity Across Array



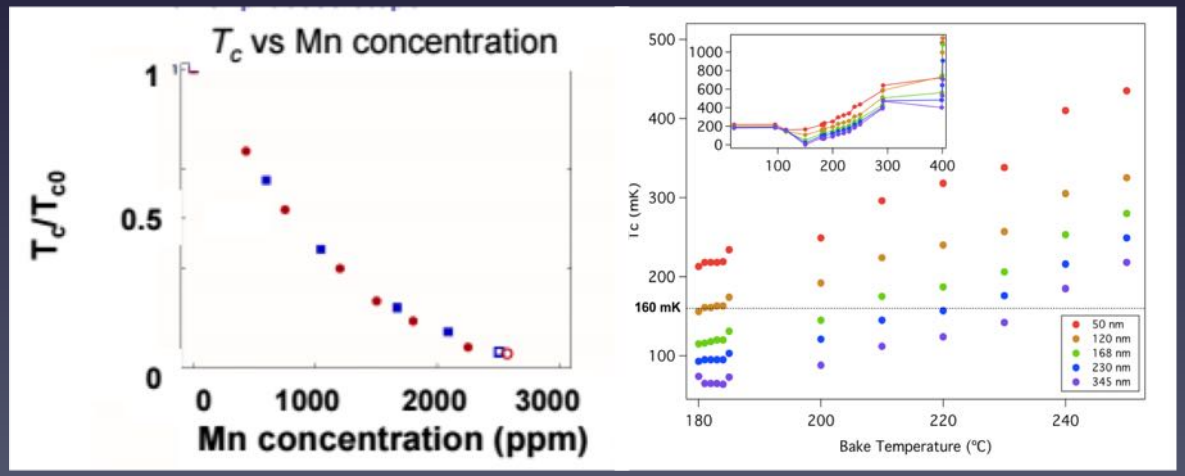
Bandpass Uniformity
(varying wafers)



Detector Fabrication Developments

- 150 mm diameter wafers
- Uniformity
- Material Development

e.g. Tunable TES materials



Dielectric Improvements – Low Loss

	Stoichiometry	Compressive stress [MPa]	Loss tangent
ACTPol SiO_x	Si-rich	150	2.0e-3
Advanced ACTPol SiN_x	stoichiometric	4	7.8e-4

Detector Fabrication Developments

- 150 mm diameter wafers
- Uniformity
- Material Development
- Simplification

Microwave components	Cross-over	Cross-under	Minimize reflections/crosstalk, eliminate 2 layers
Lithography	Stepper + contact printer	Stepper	Yield, dimensions, speed
Layout	Manual	Partially automated	Speed, flexibility, risk
Unit steps	85 steps	63 steps	Risk, time, scalability

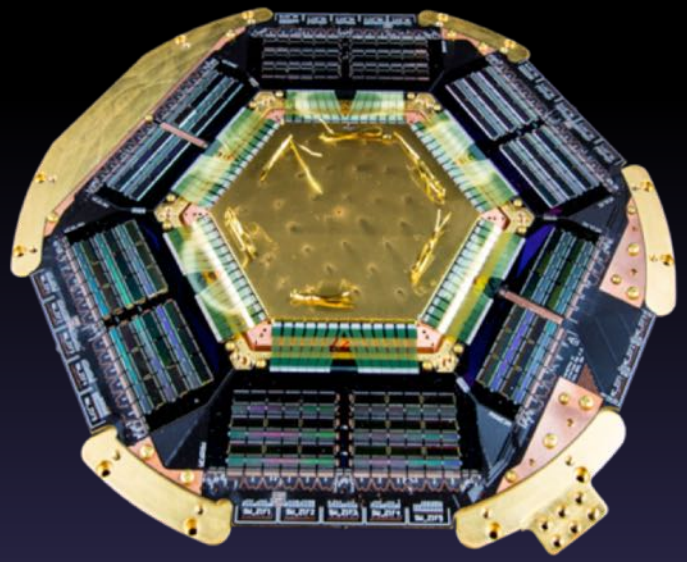
Detector Fabrication Developments

- 150 mm diameter wafers
- Uniformity
- Material Development
- Simplicity
- Yield

  - No longer need to make (N >> 1) wafers to yield 1 good one

Assembly & QA is increasingly difficult

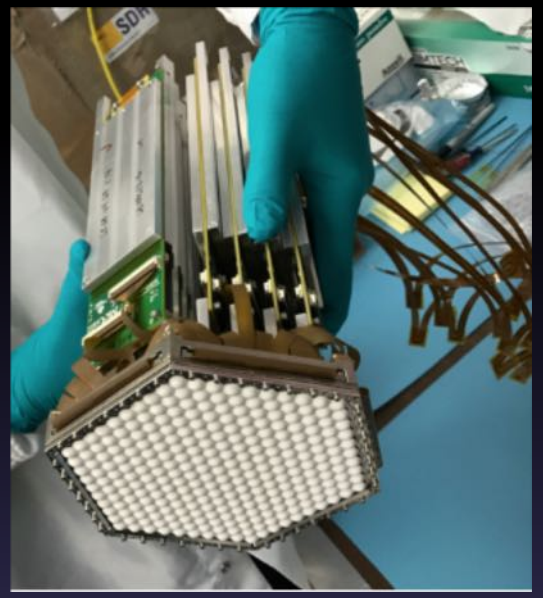
Co-planar



Advanced ACTPol
TDM

Not an option for tiled focal plane

3D

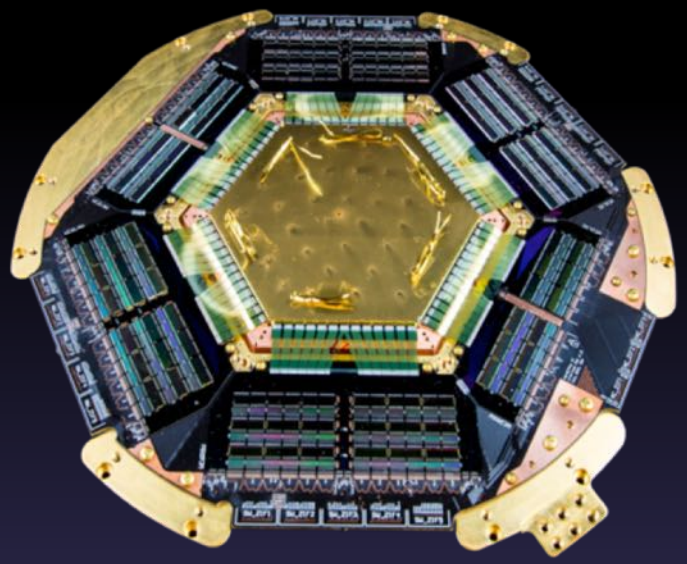


SPT-3G/Polarbear2
MHz FDM

- **Exists/proven**
- **Complicated**
- **lots of connections**

Assembly / Readout

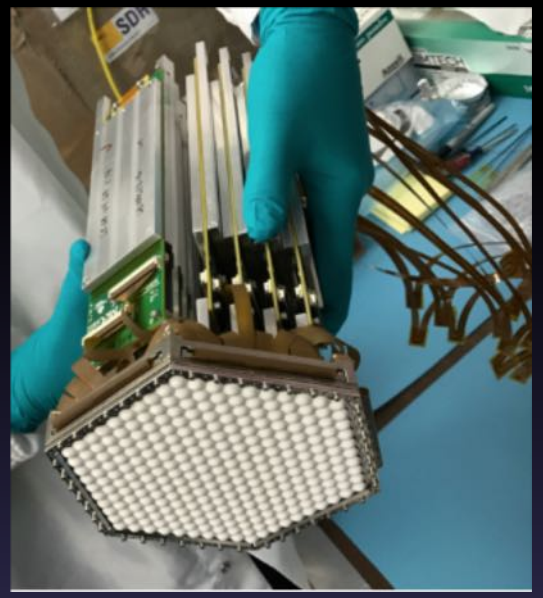
Co-planar



Advanced ACTPol
TDM

Obviously a no-go for tiled arrays

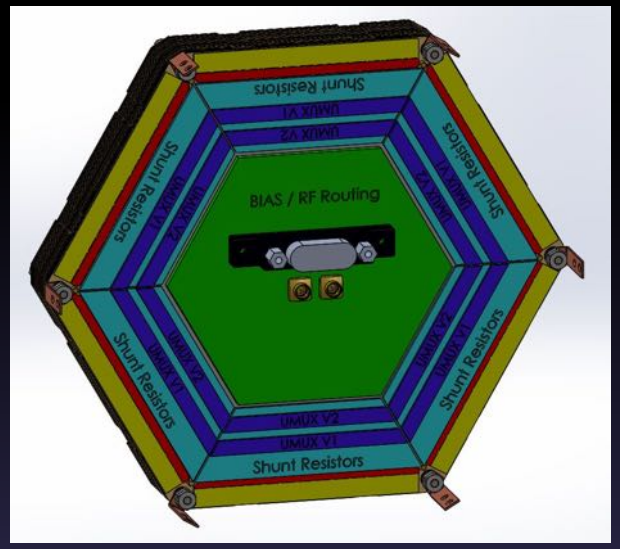
3D



SPT-3G/Polarbear2
MHz FDM

- **Exists/proven**
- **Complicated**
- **lots of connections**

2D backside



Notional uMUX
Also, e.g. BICEP3

Requires smaller readout components (uMUX) or low detector density

Integrated fab

TES: Prototypes only
MKIDs: ?

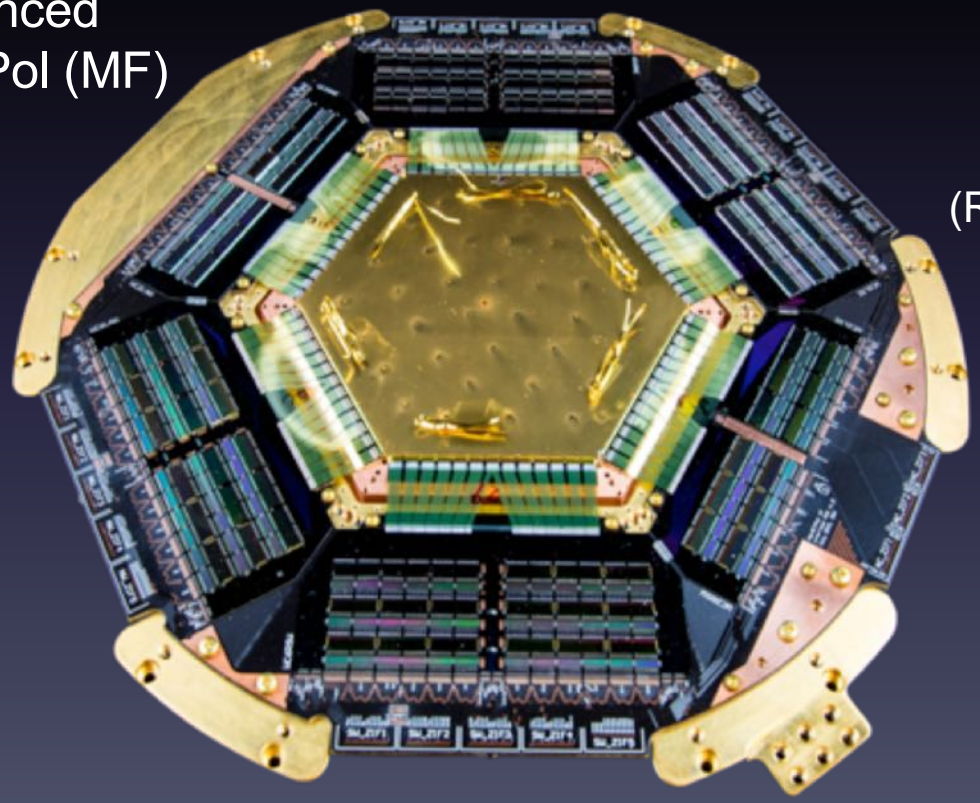
Space constraints and/or unproven

Focal Plane Complexity

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

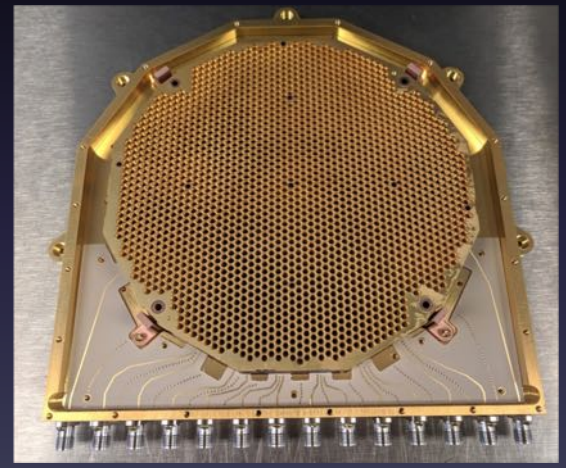
The Ideal: Integrated readout
e.g. Toltec MKID (4000 detectors)
- 14 wire bonds
- 14 Coax cables
- 14 LNAs

Advanced ACTPol (MF)



(Roughly the same scale)

Toltec 1.1 mm

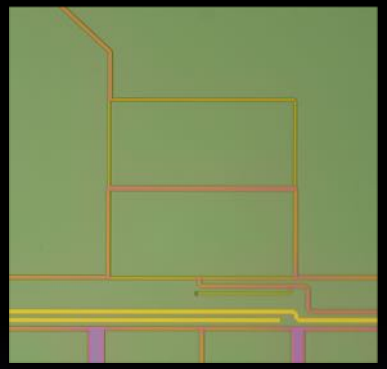


Why readout devel. (talks tomorrow) and MKIDs (5pm) are so enticing!

Summary

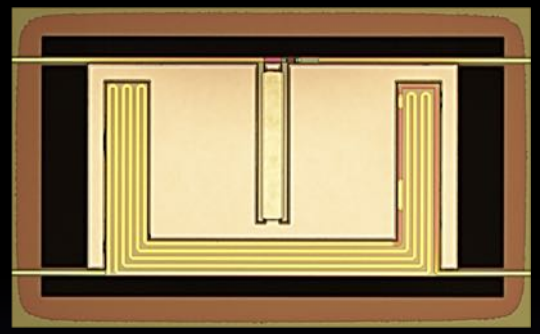
- CMB science continues to drive much of mm-wave tech
- CMB-S4 is an ambitious challenge: **Field ~ 500k detectors**
- Reasons why we'll succeed:
  - Already ~ 50k devices on sky b/t different experiments
  - Another ~ 50k+ in the near term
  - Multiple detector technologies producing competitive results
  - Community wide effort to combine efforts, share best and most scalable solutions, e.g. →
  - Detector fabrication advances have already made production plausible
- (Other) Remaining Challenges
  - Assembly & QA throughput
  - Large scale production of optical coupling components
  - Readout 500k channels at a finite price

Microwave Hybrid

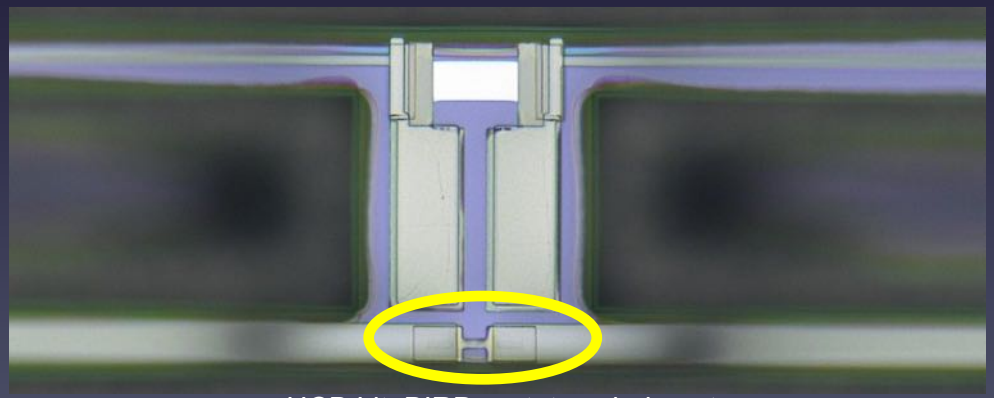


+

TES w/ large footprint meander termination



Simple Termination Resistor



UCB LiteBIRD prototype bolometer

end

extra