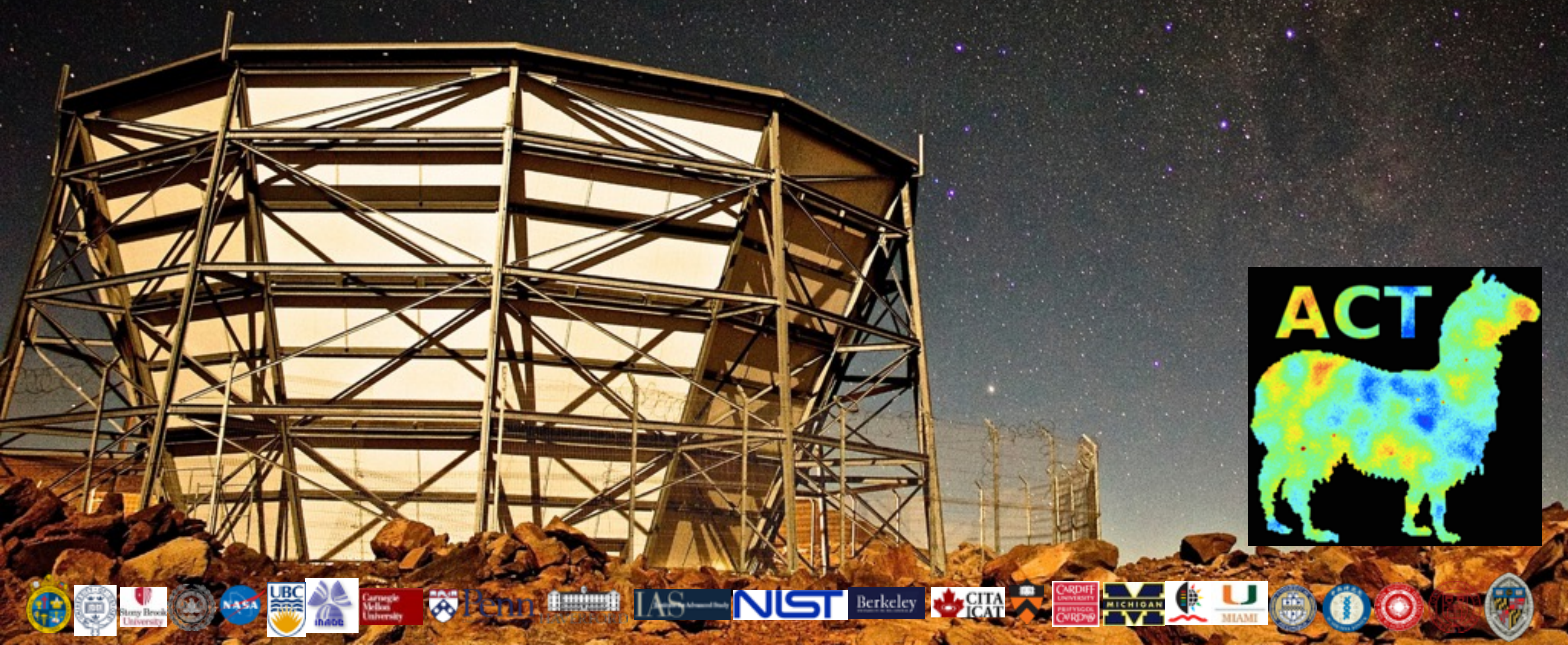
Metamaterial Optics and Multichroic Detectors on ACTPol and Beyond

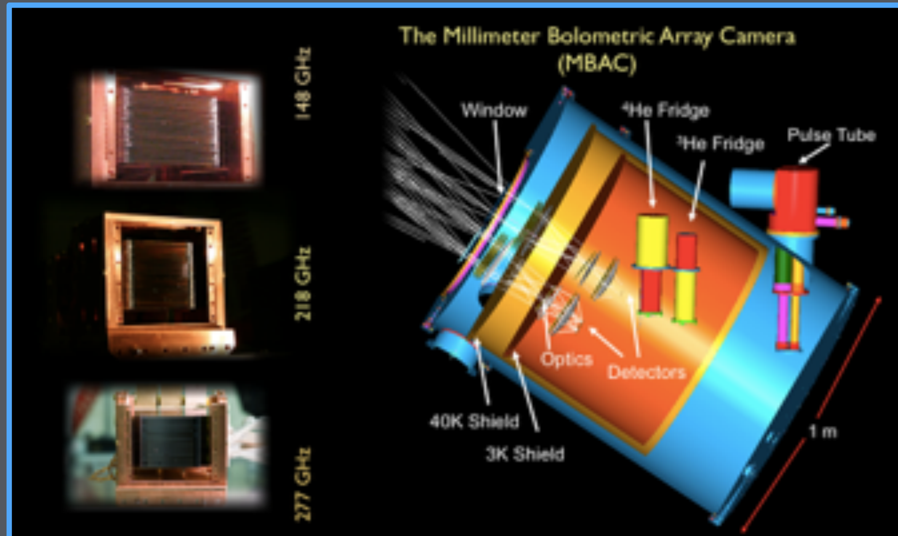
Hannes Hubmayr for

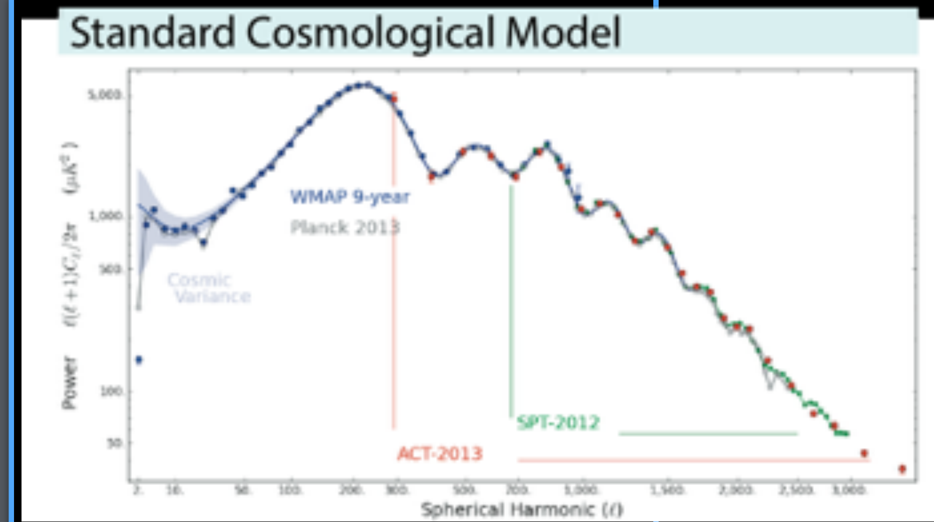
Jeff McMahon



Three Cameras and ACT

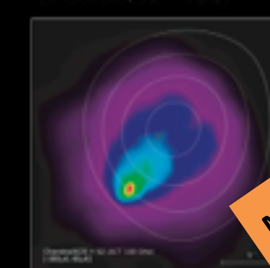
The Past:
2007-2010
MBAC





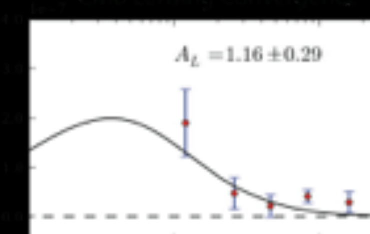
ACT discovery highlights

Sunyaev-Zel'dovich Effect



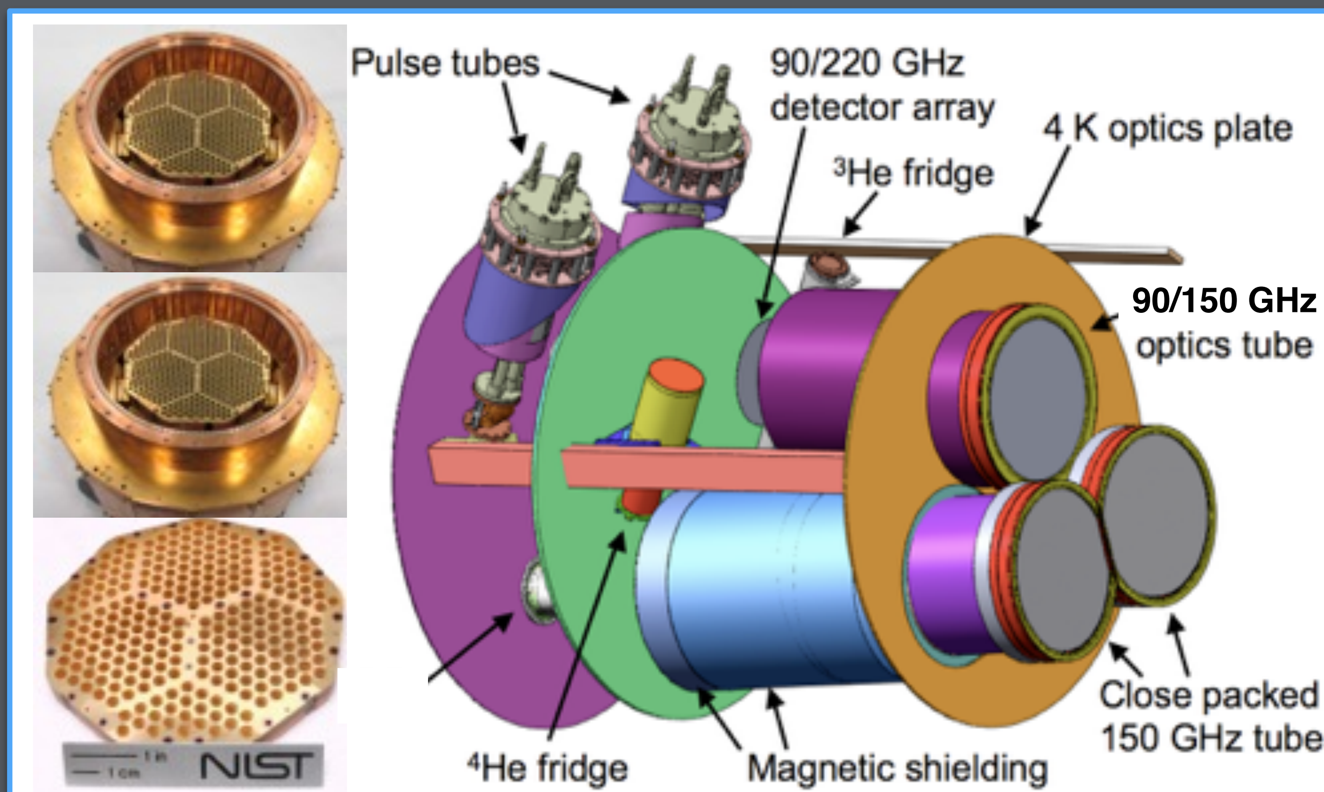
Most massive at t/2!

Gravitational Lensing



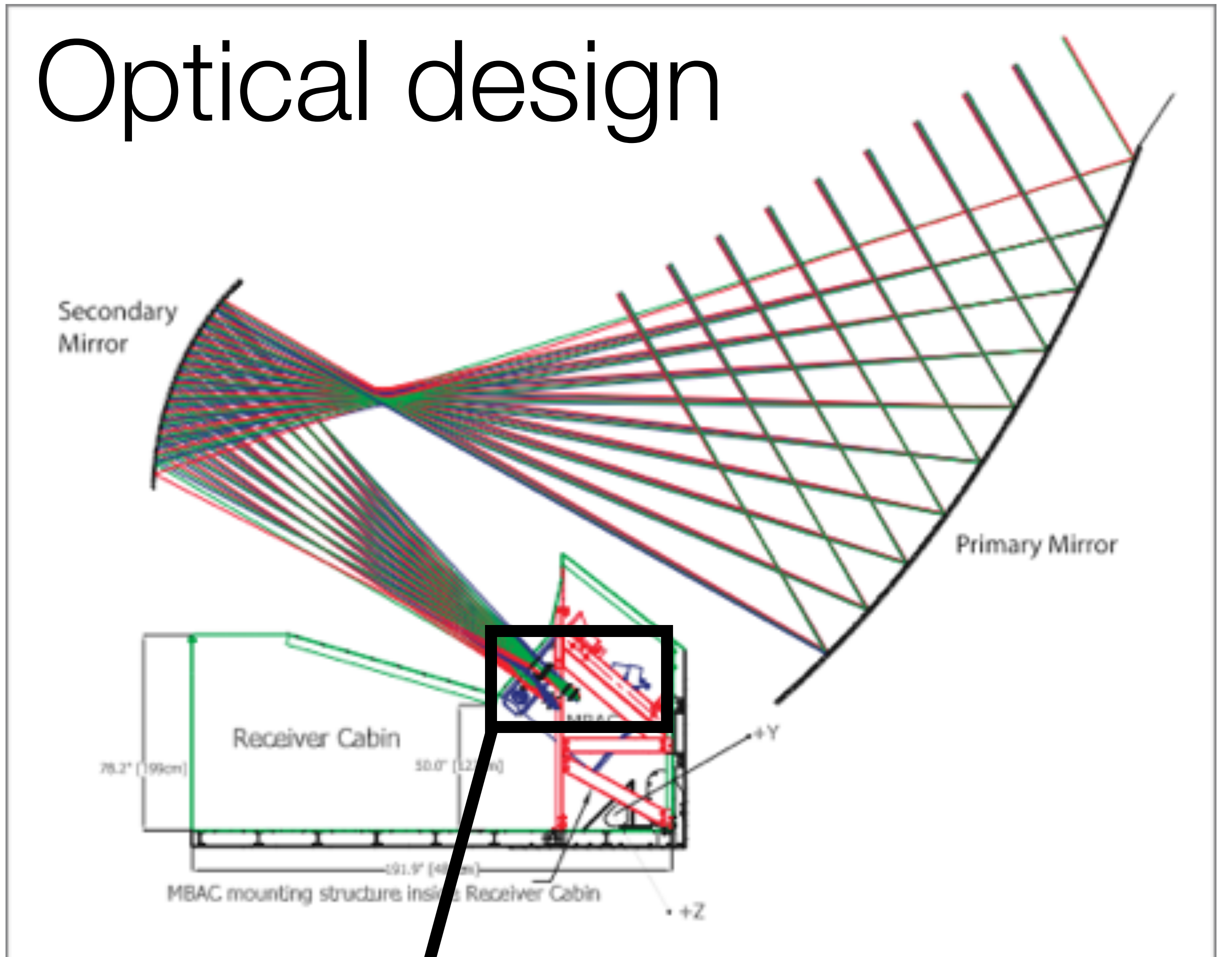
FIRST!

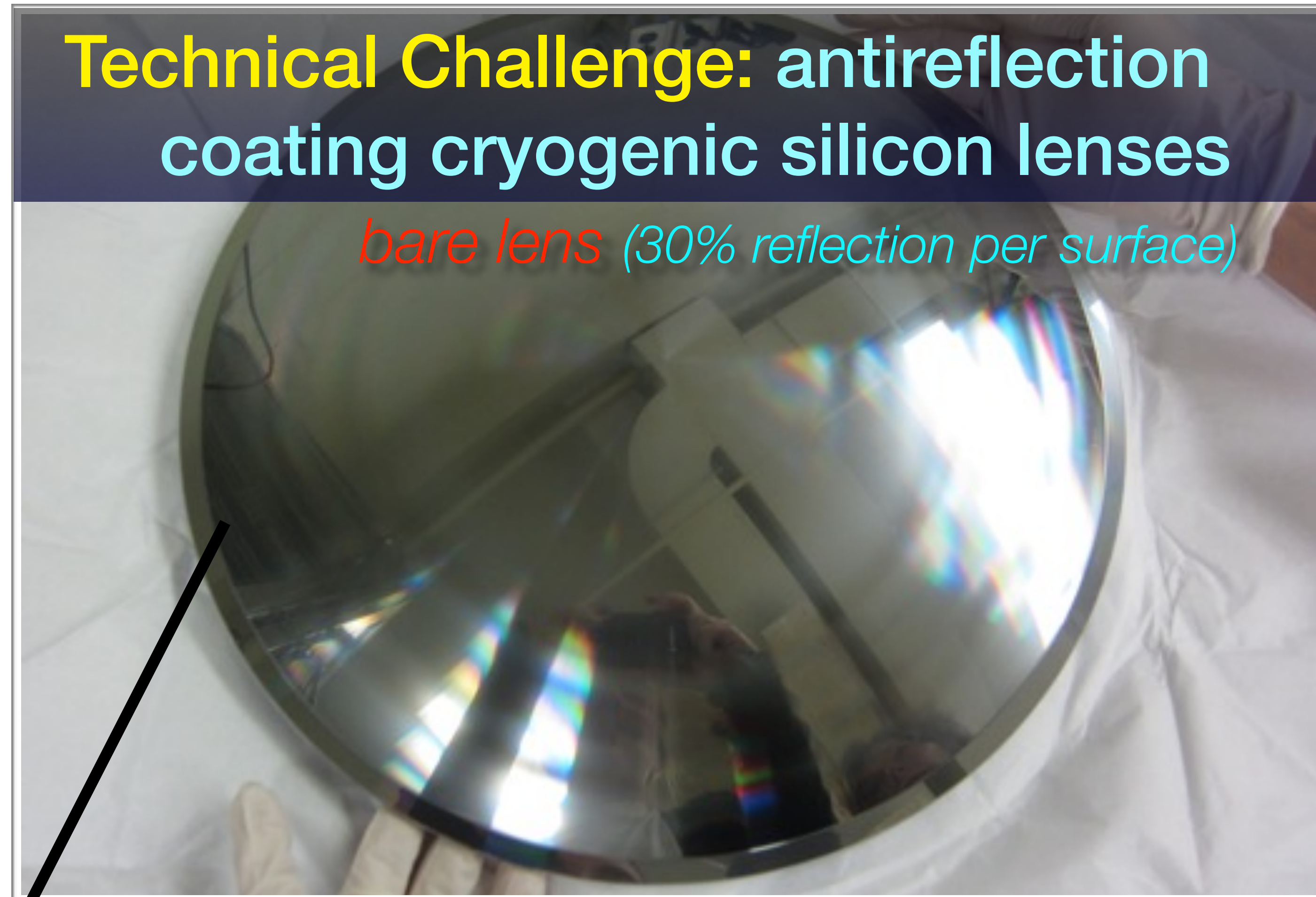
The Present:
2012-2015
ACTPol

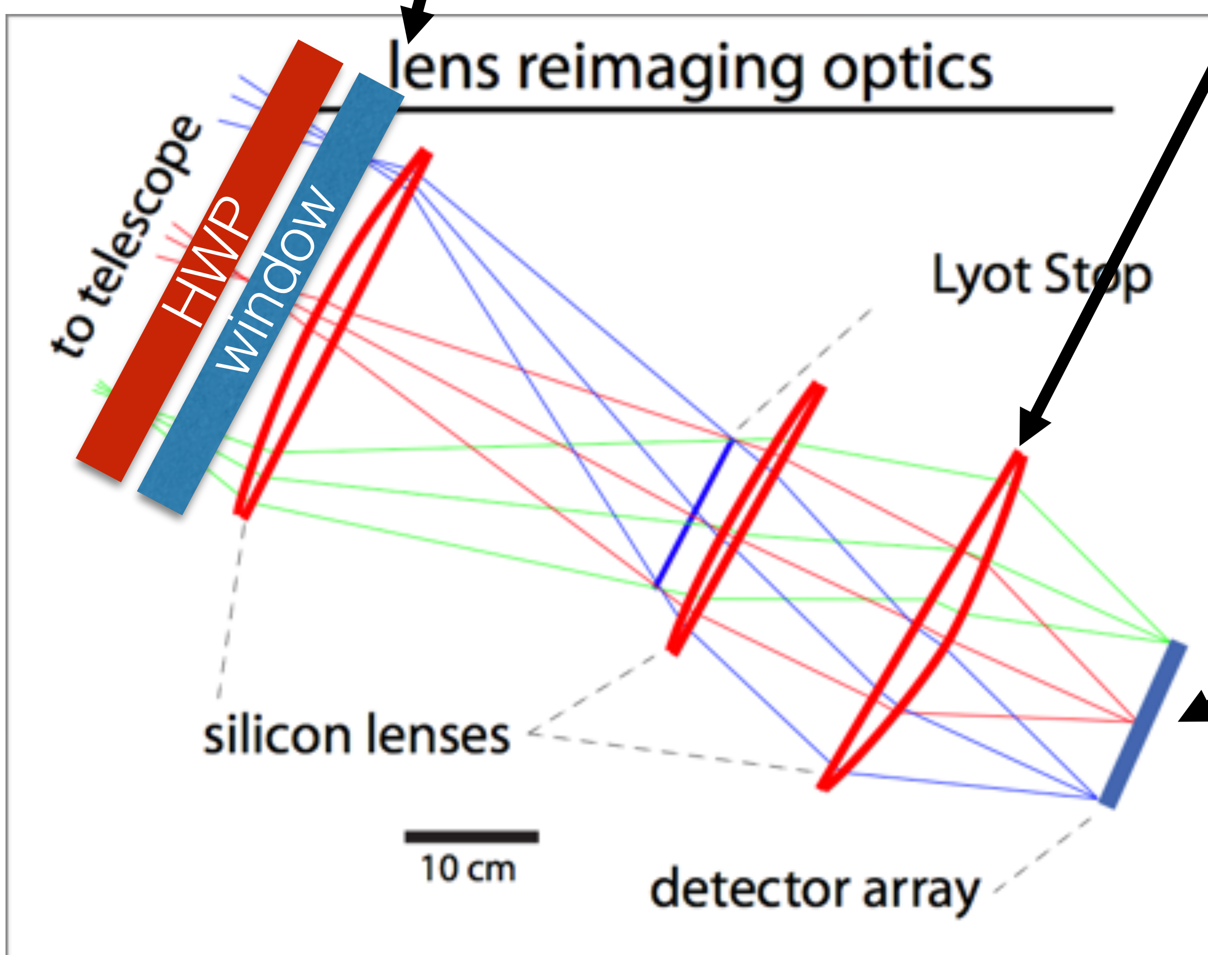


The Future:
2016-2019
Advanced ACTPol (AdvACT)

a full multichroic upgrade to ACTPol

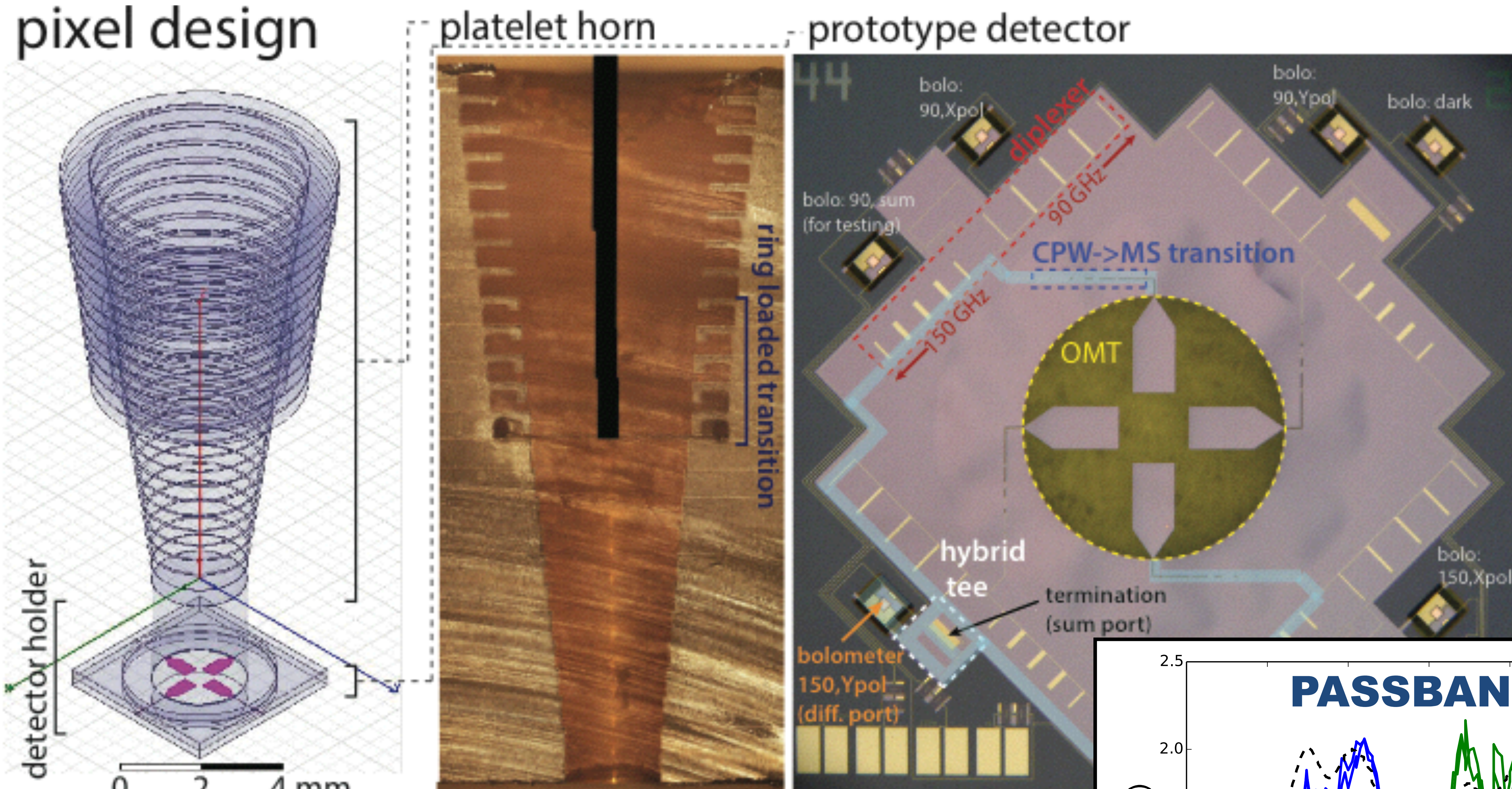

Optical design
Secondary Mirror
Primary Mirror
Receiver Cabin

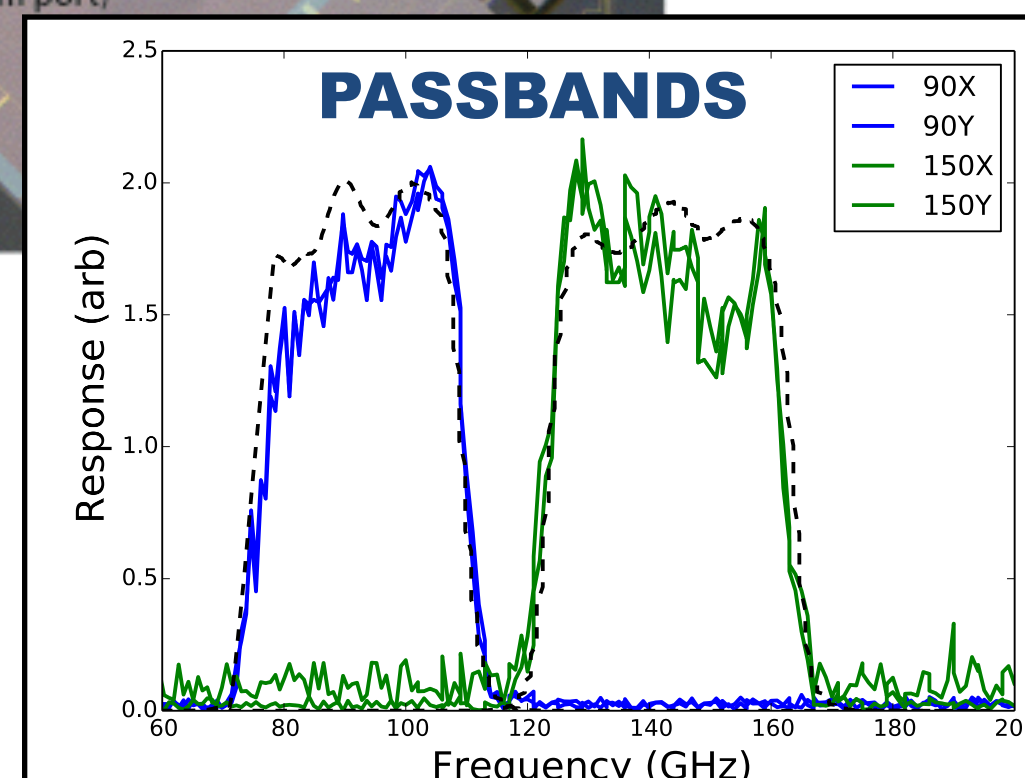

Technical Challenge: antireflection coating cryogenic silicon lenses
bare lens (30% reflection per surface)


lens reimaging optics
to telescope
HWP
window
Lyot Stop
silicon lenses
10 cm
detector array


Multichroic Detector Array
2.2:1 ratio bandwidth

90/150 GHz Multichroic Polarimeter Design





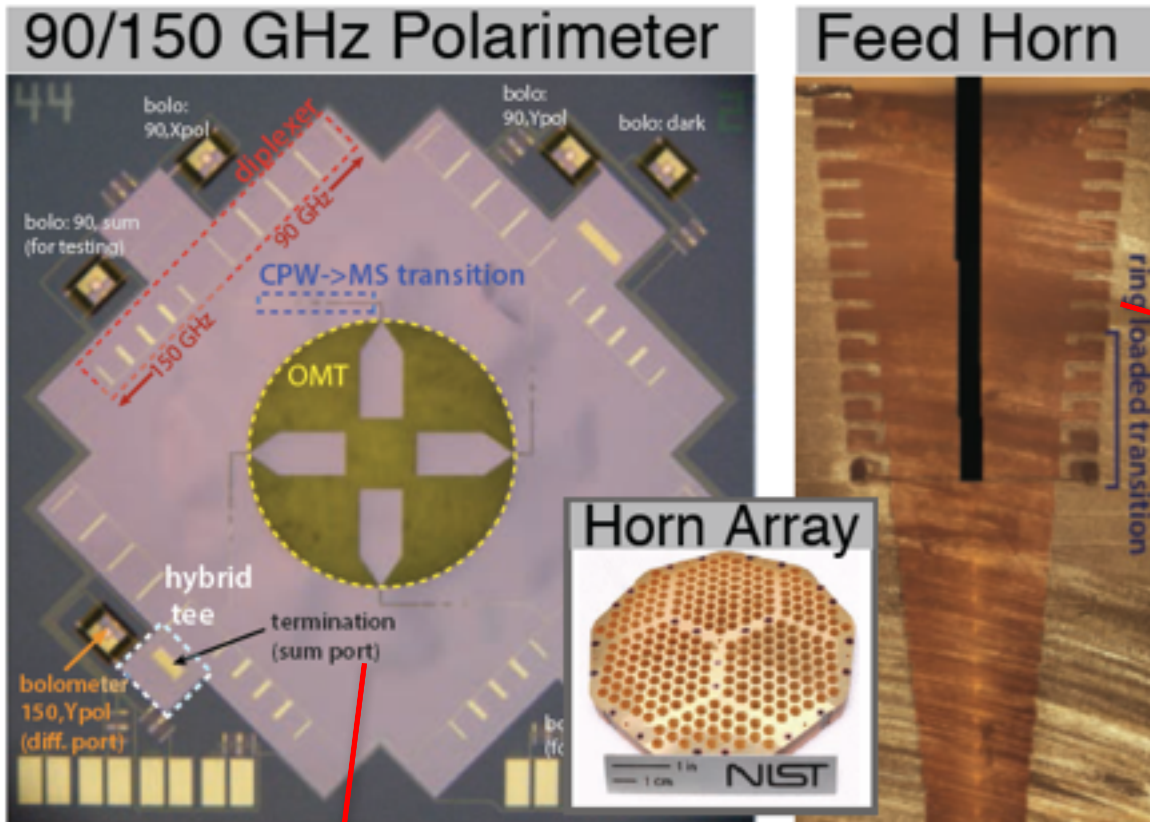
A polarimeter designed to simultaneously measure the 90 and 150 GHz CMB bands.

- excellent control of beam systematics with a corrugated feed horn
- frequency independent detector angles
- operates from 75-165 GHz, setting the bandwidth requirement for the optics

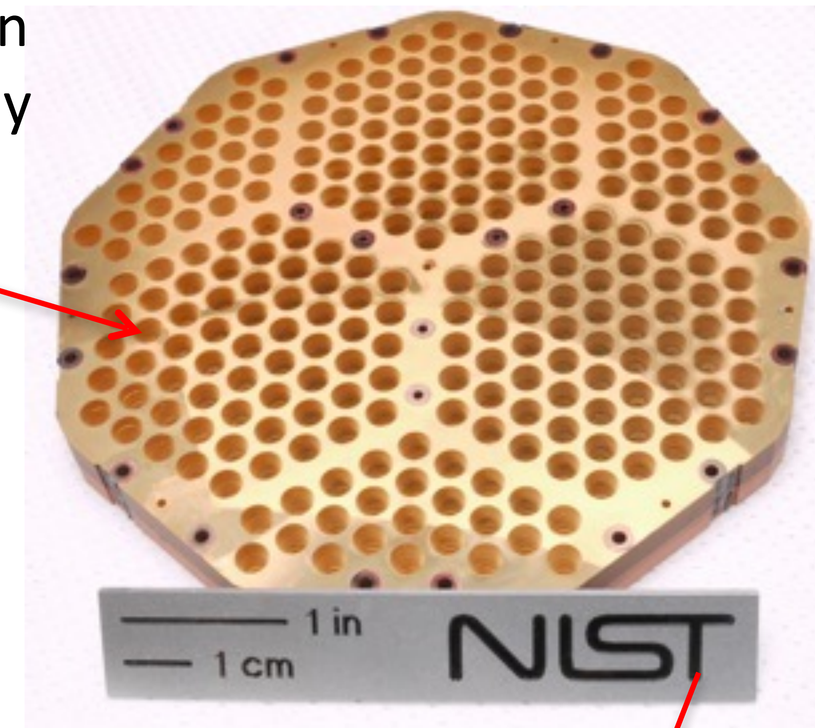
First Deployed Multichroic Polarimeter Array

deployed on ACT in Jan 2015

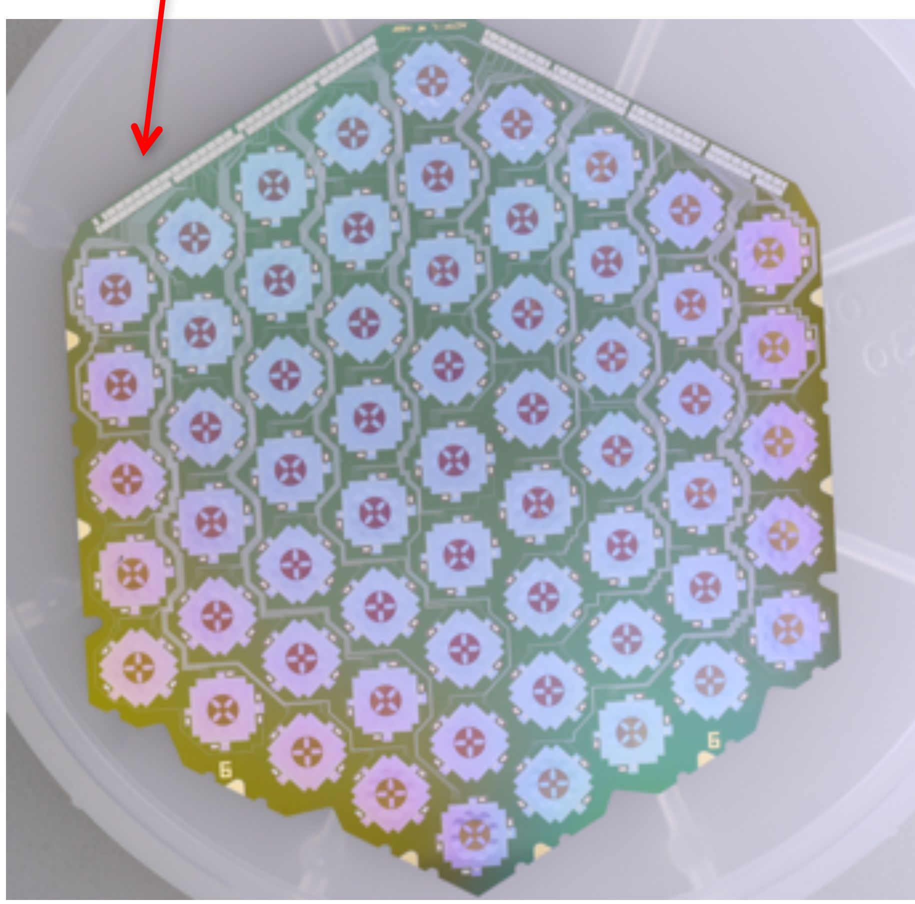
Datta et al., JLTP (2014)



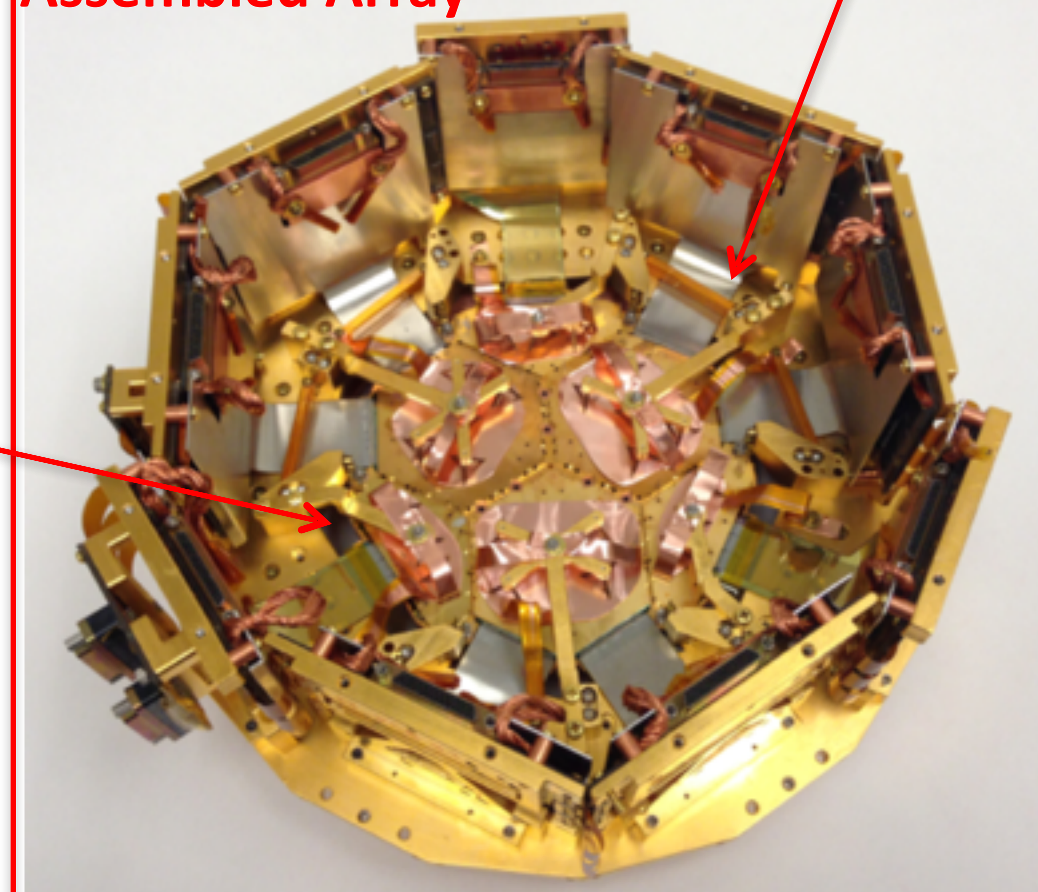
Horn array



Detector wafer

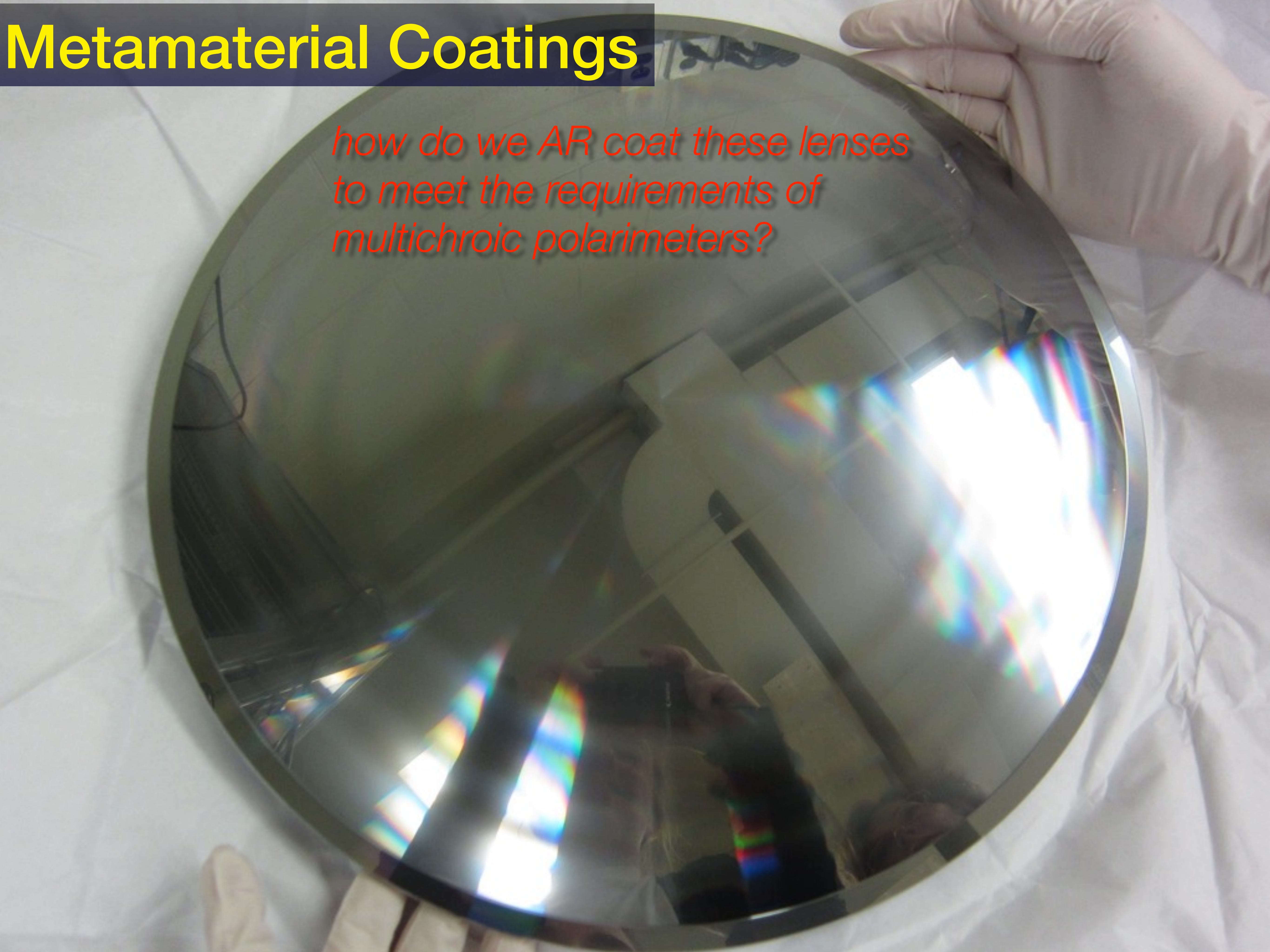


Assembled Array



Metamaterial Coatings

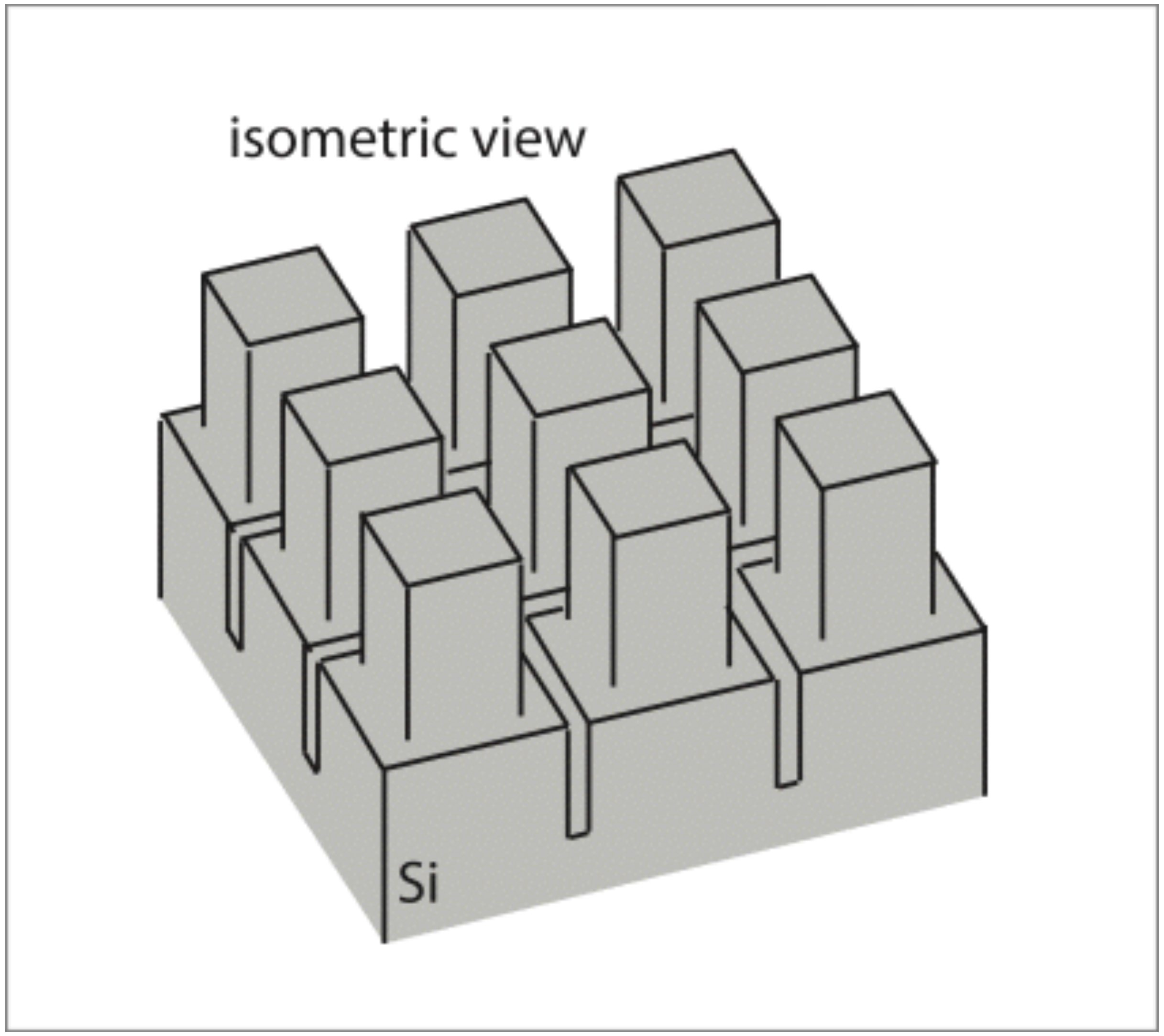
how do we AR coat these lenses to meet the requirements of multichroic polarimeters?



Metamaterial Antireflection Coatings

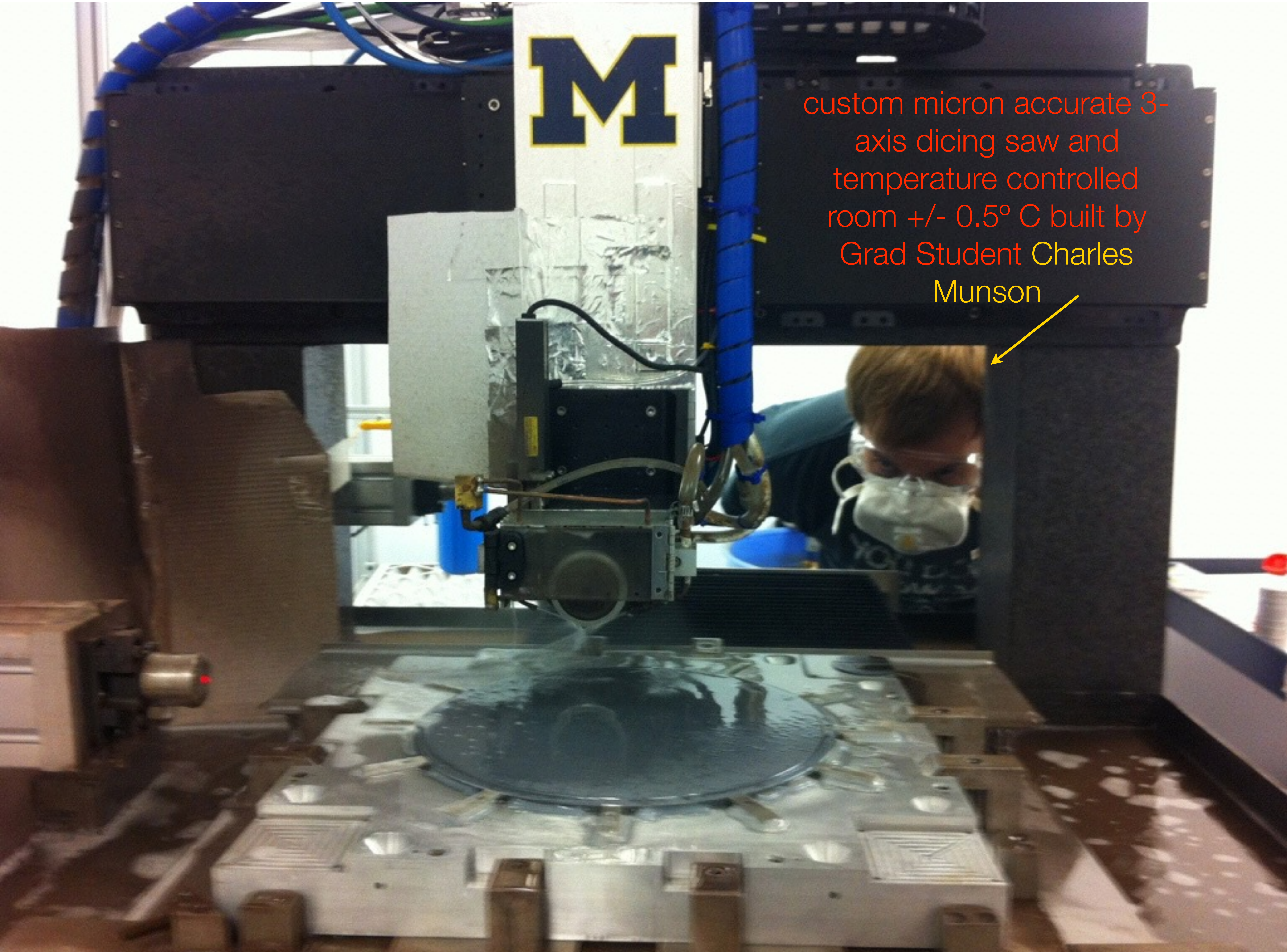
concept:

cut sub-wavelength features to approximate a multi-layer dielectric coating

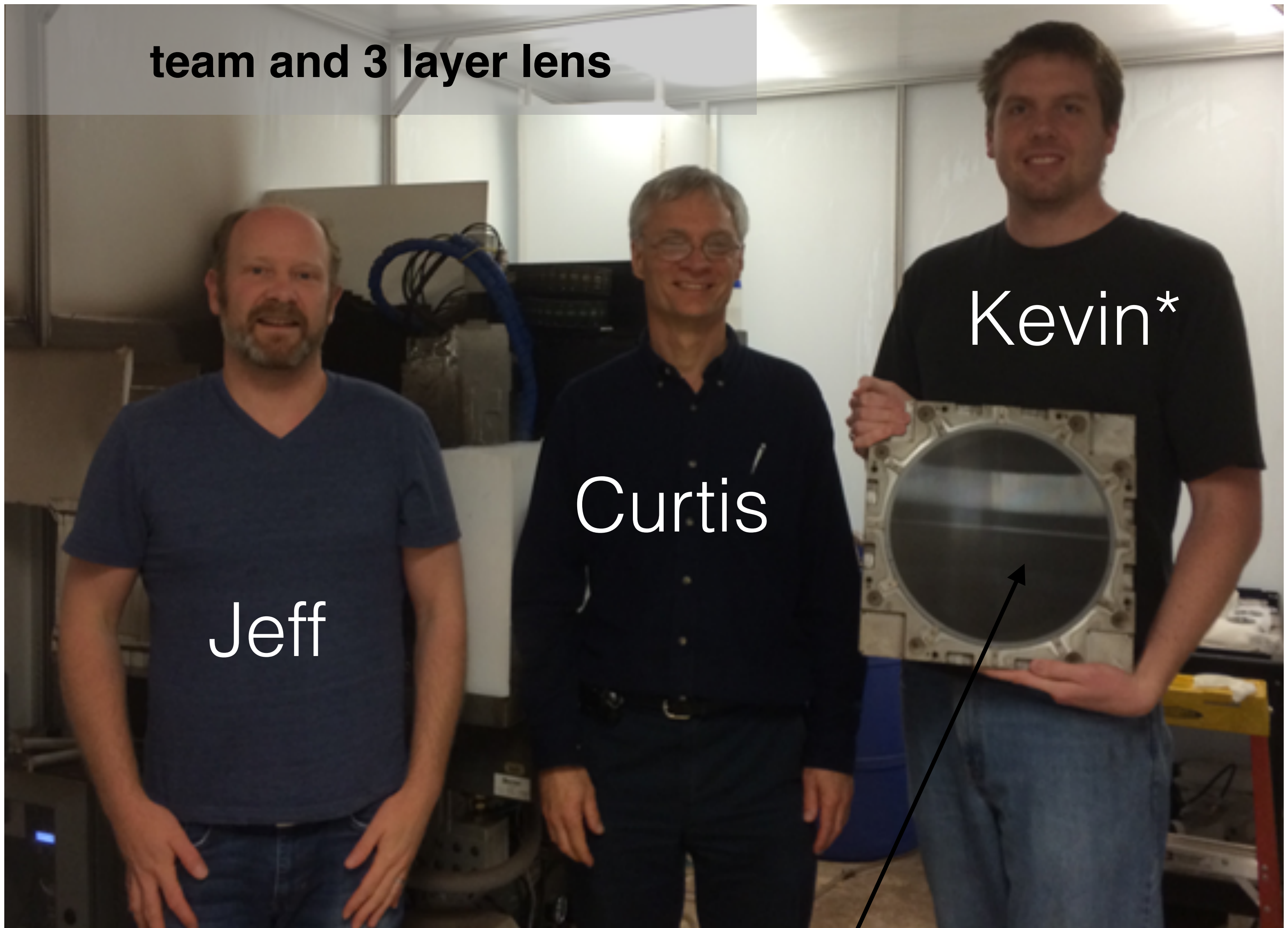


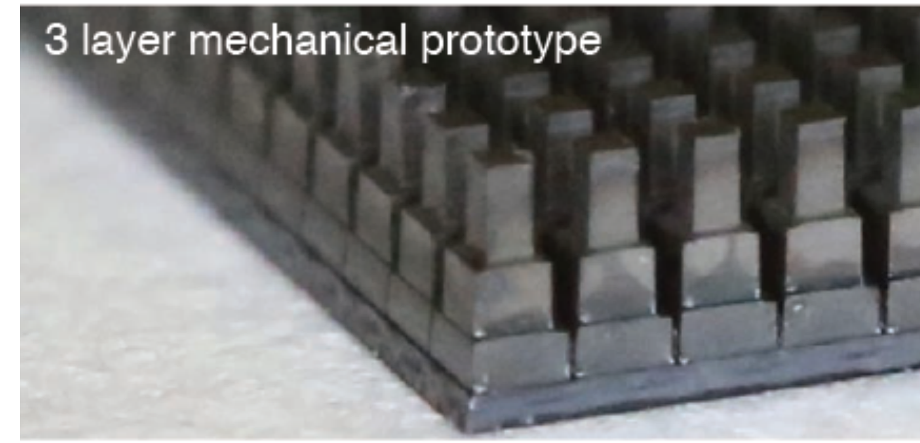
See Datta et al. for details
(applied optics: arXiv:1307.4715)

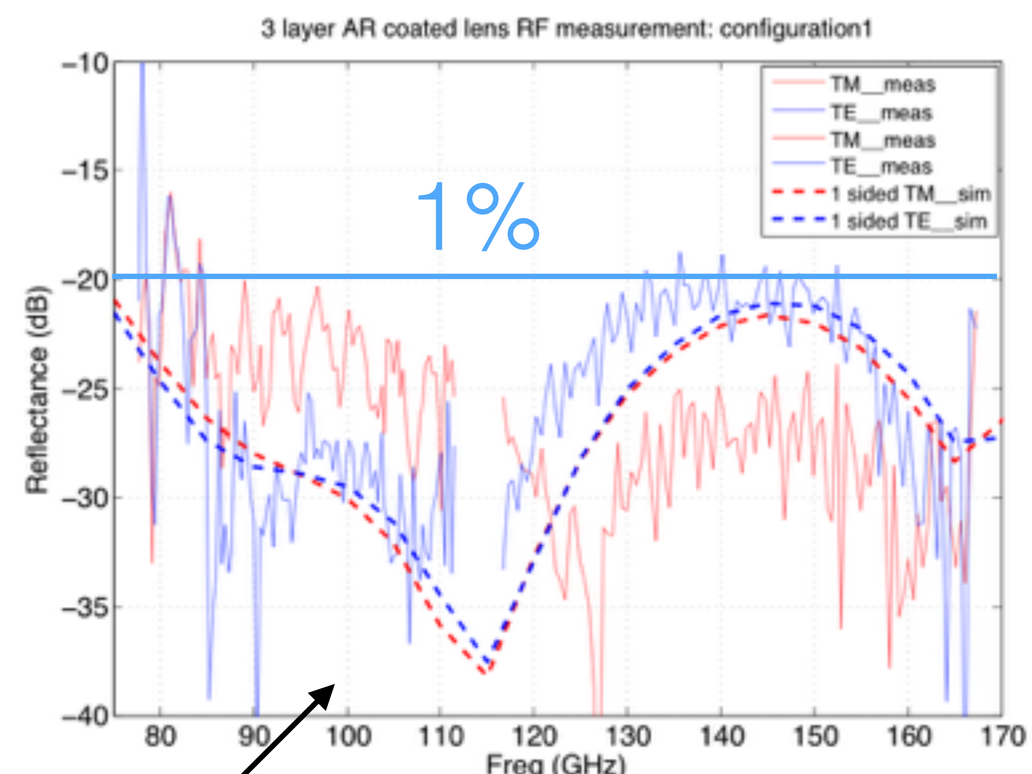
- **Metamaterial Coatings**
  - precise control over the index of refraction
  - ability to create multiple layer coatings
  - thermal contraction of coating exactly matches the lens
  - extremely low loss
- **Design**
  - extensive simulations used to determine the geometry
- **Fabrication**
  - requires a custom silicon dicing saw capable of 3-axis motion with micron accuracy
  - can't buy this off the shelf...


custom micron accurate 3-axis dicing saw and temperature controlled room +/- 0.5° C built by Grad Student Charles Munson
M

ACTPol 90/150 Multichroic lenses



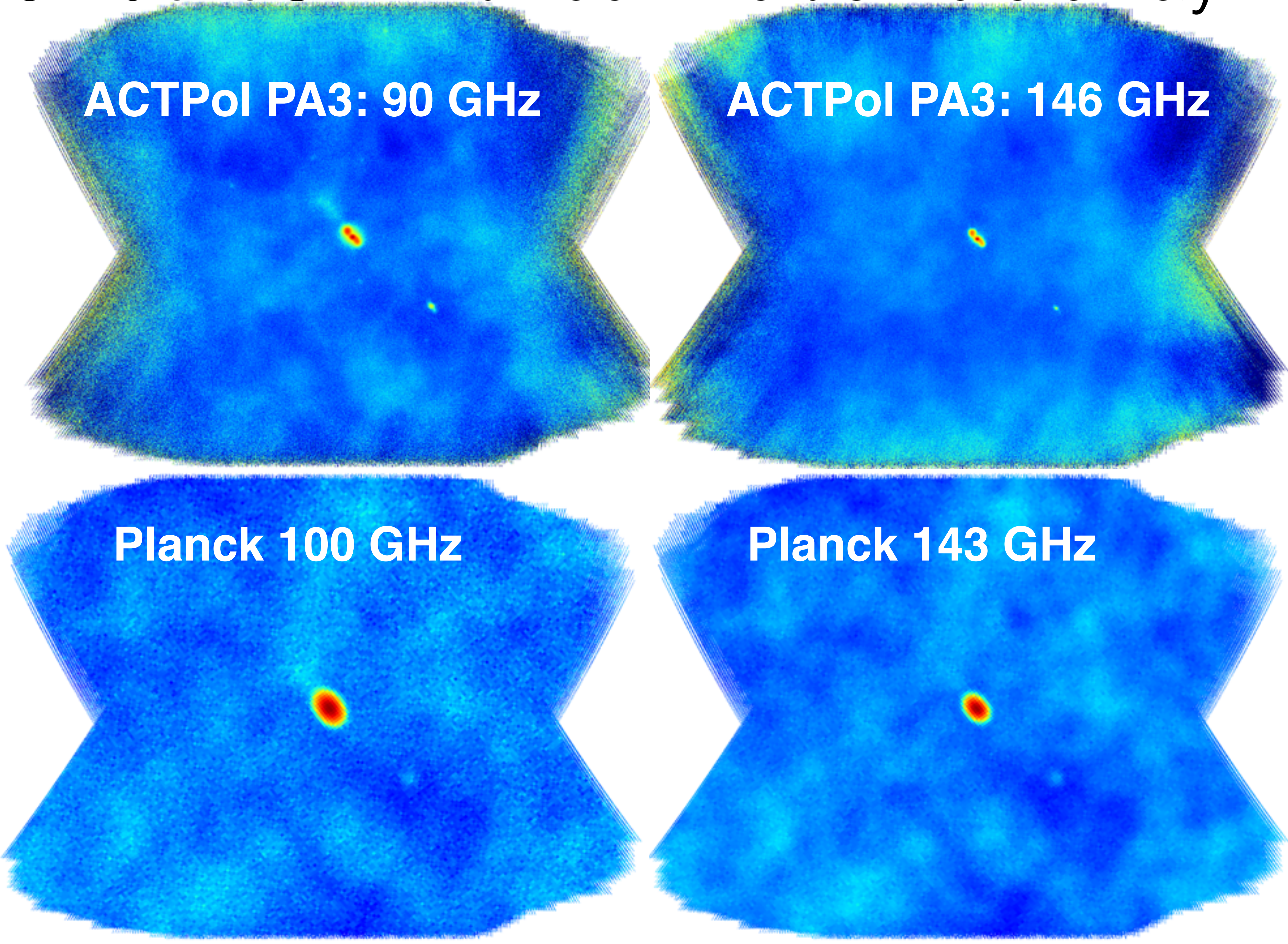




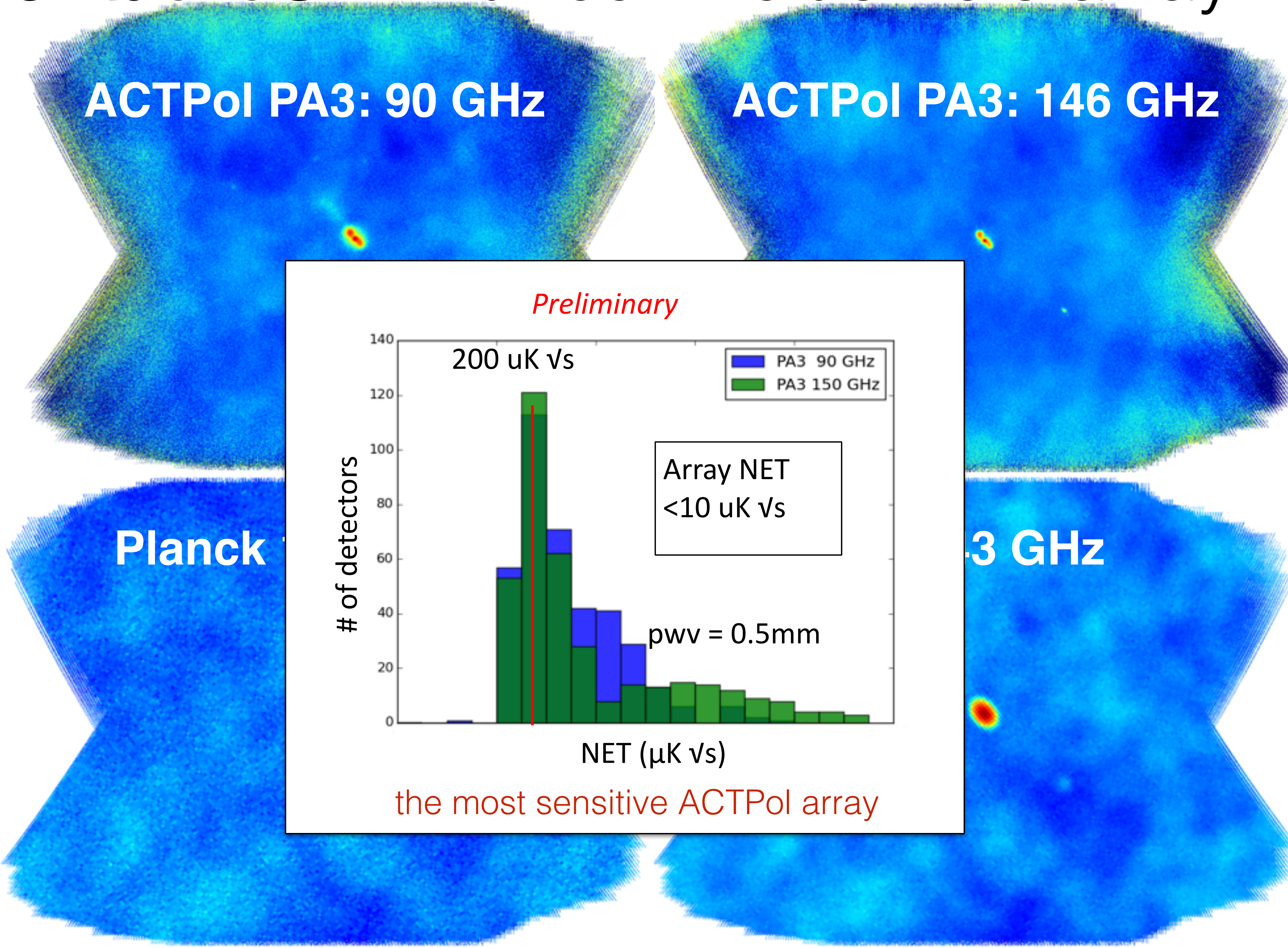
33 cm diameter lens

sub-percent reflections from 75-200 GHz

Centaurus A with our multichroic array



Centaurus A with our multichroic array

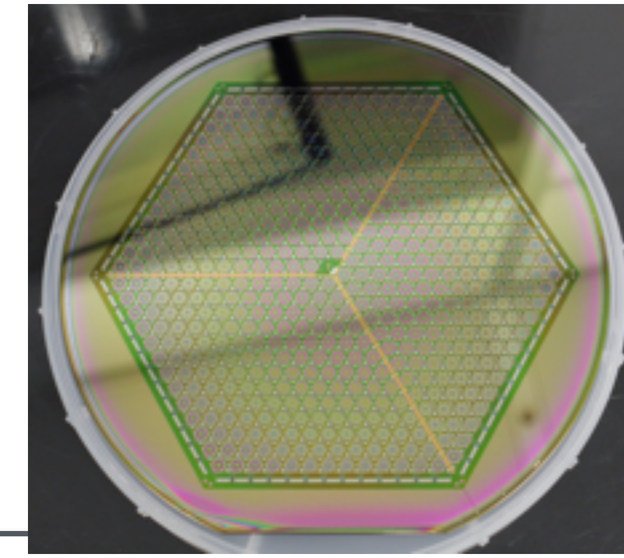


Frequency Scaling and Broader Bandwidth

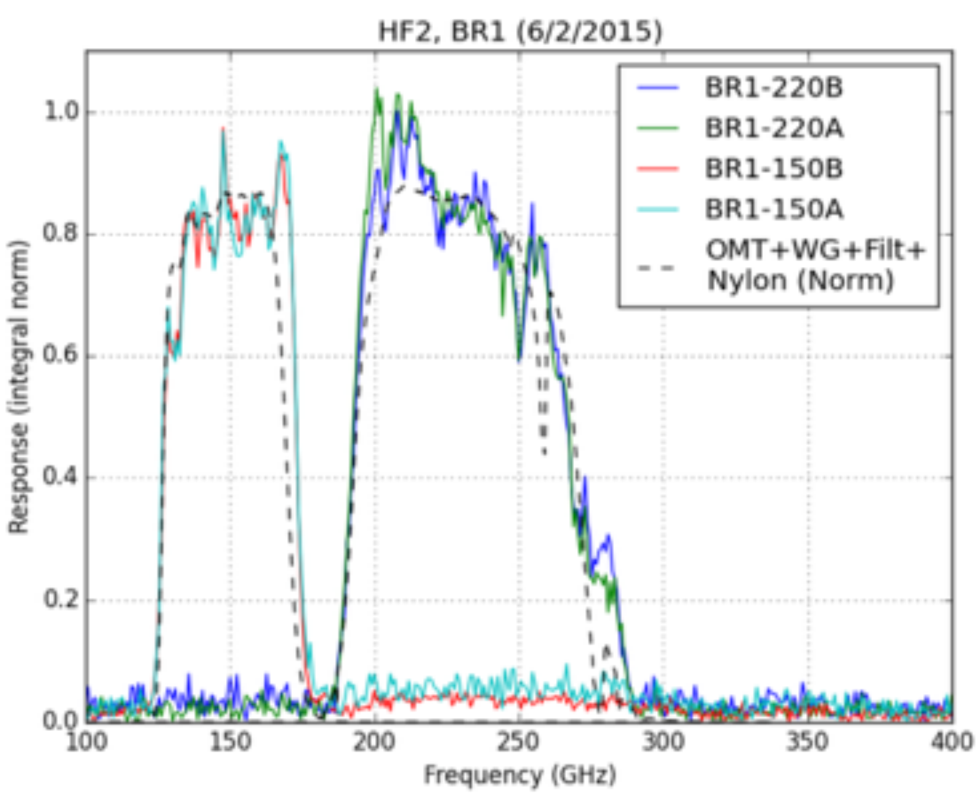
AdvACT 150/220 Detectors

- spline profiled horn
- SiNx dielectric
- cross-under

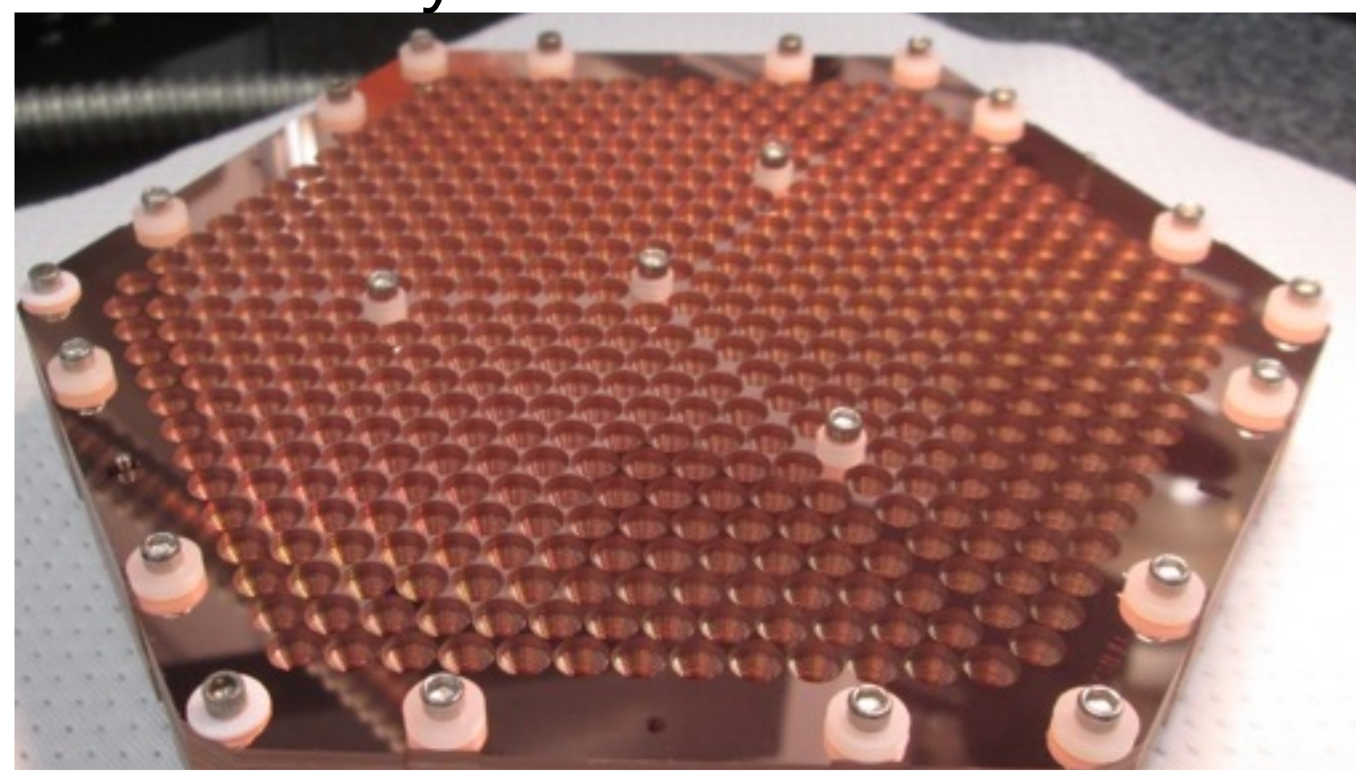
- 503 horns per array
- 6 inch fab

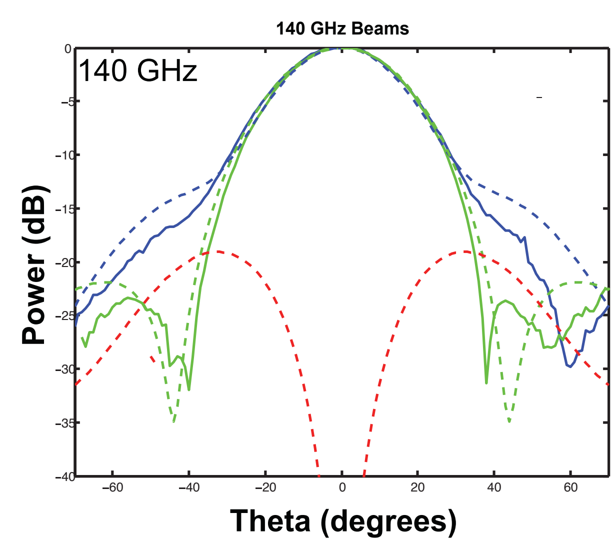


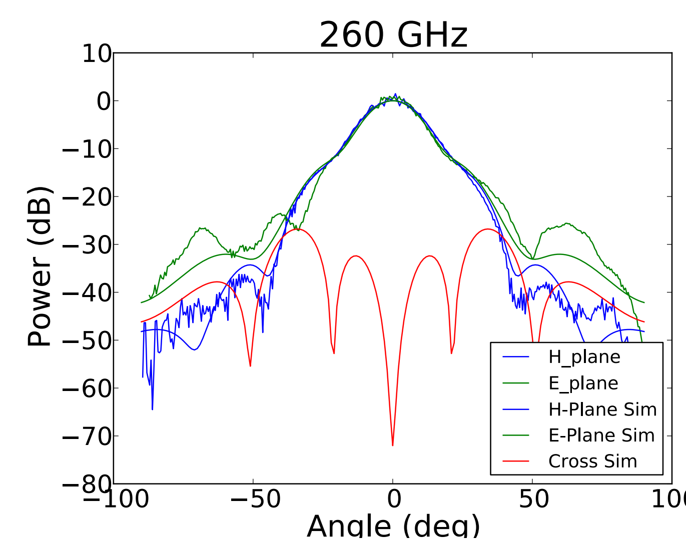
Prototypes



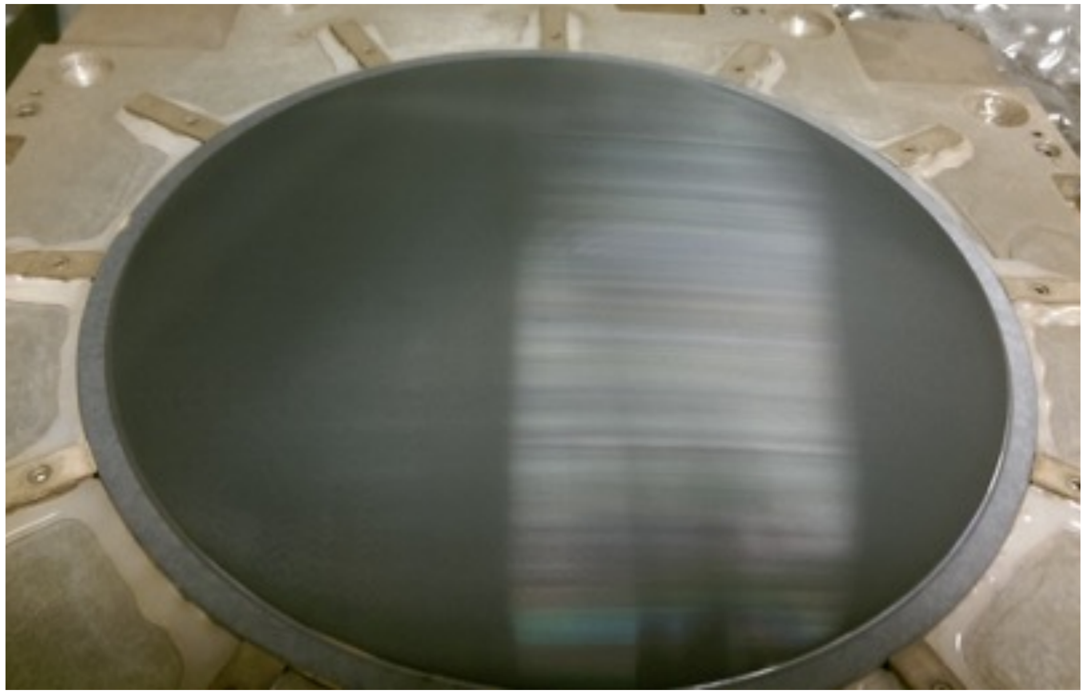
Horn Array

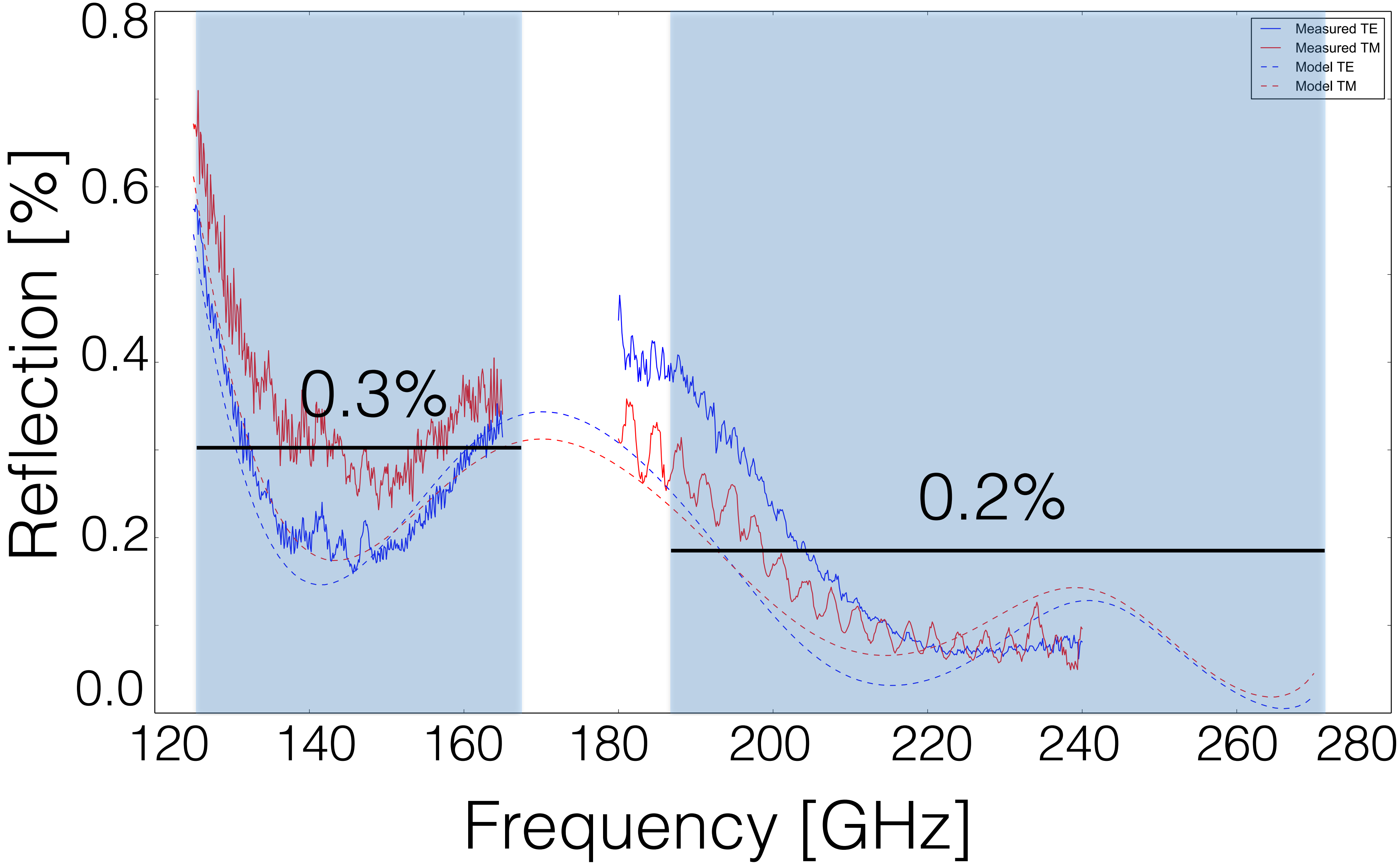






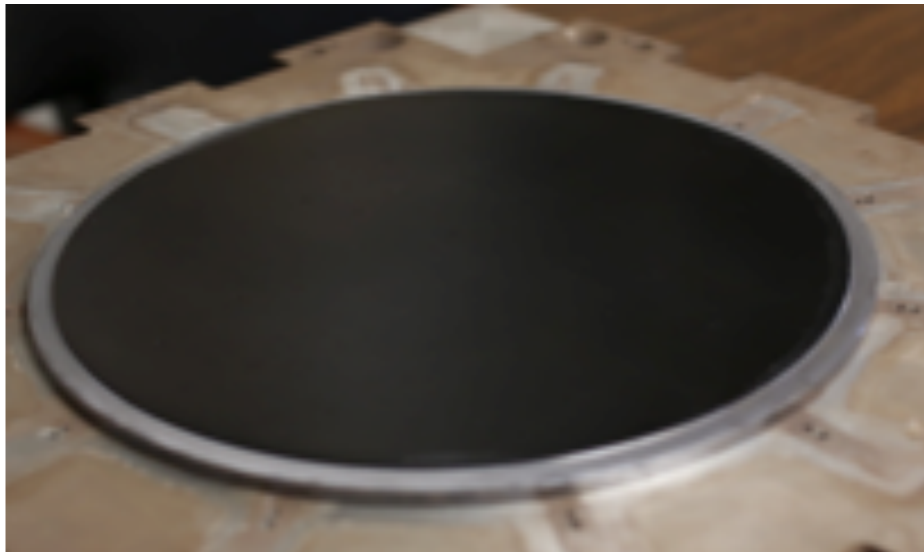
Advanced ACTPol 150/220 GHz lens

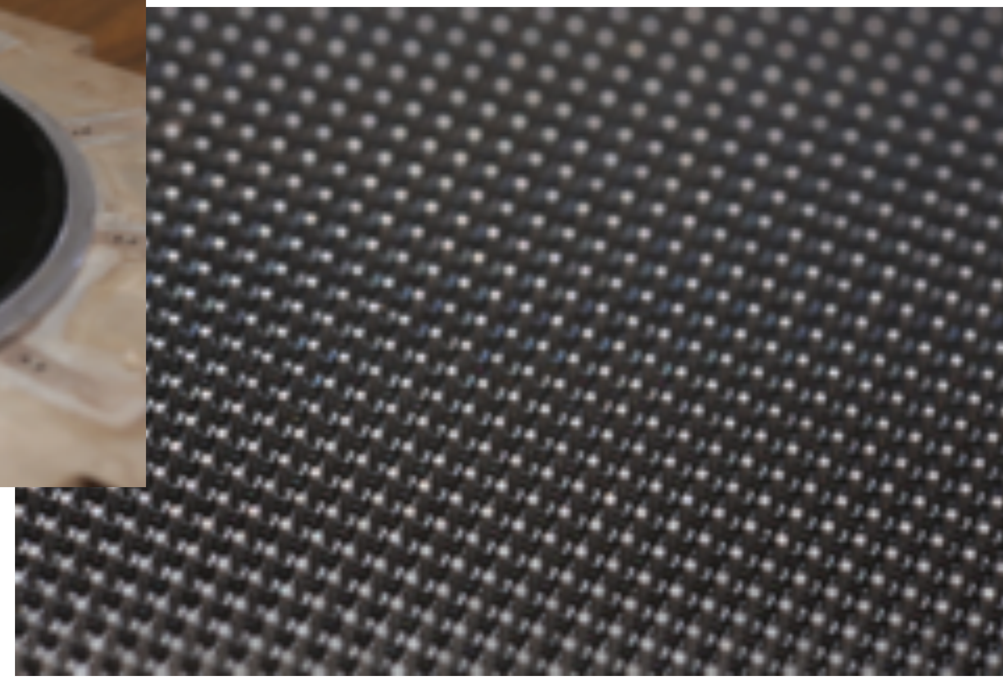


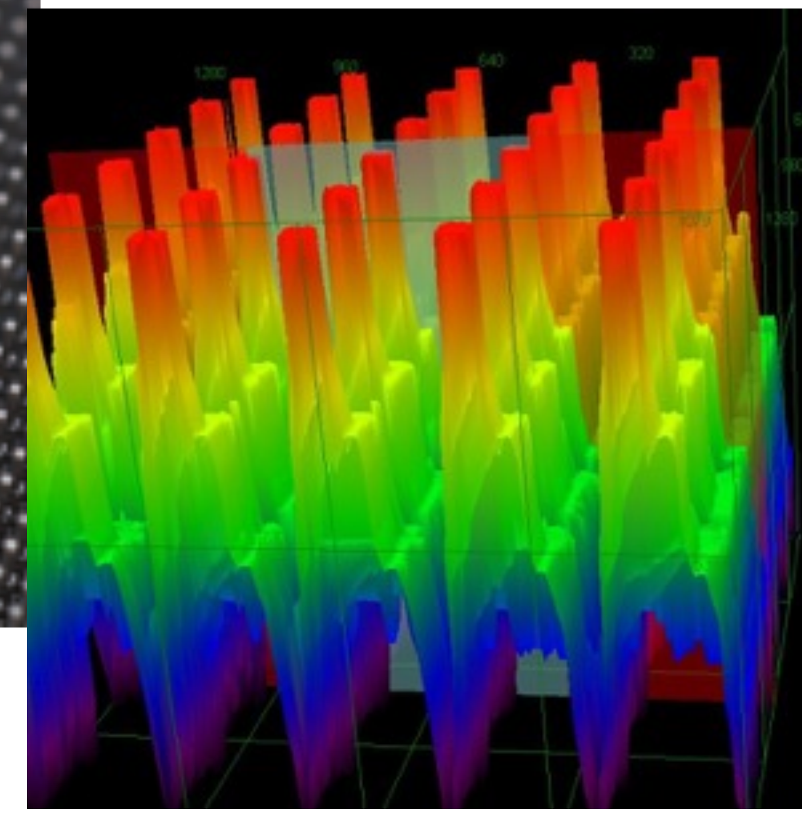


- zero defects out of 1.5 M pillars
- 120-300 GHz band
- improved machining lead to consistency with simulations

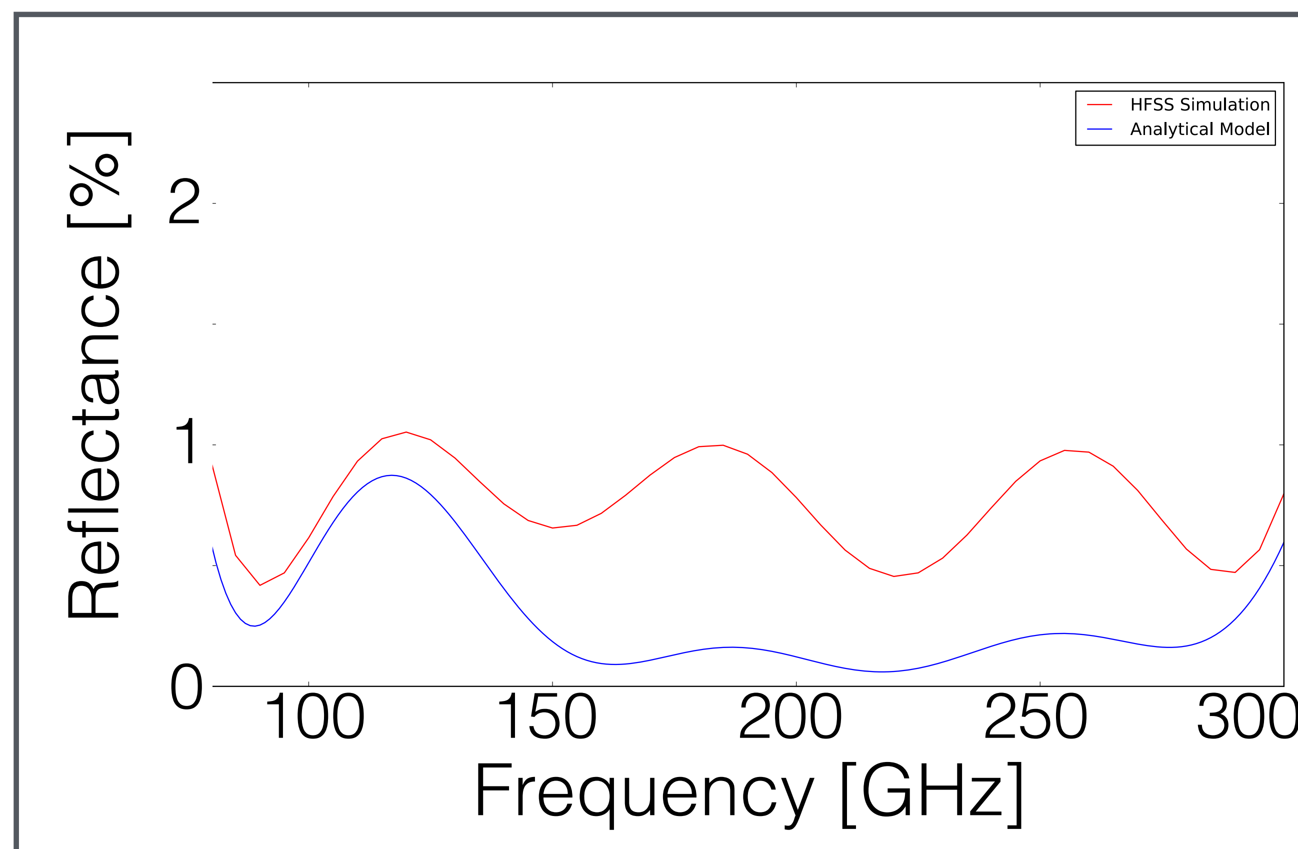
Five Layer Prototype



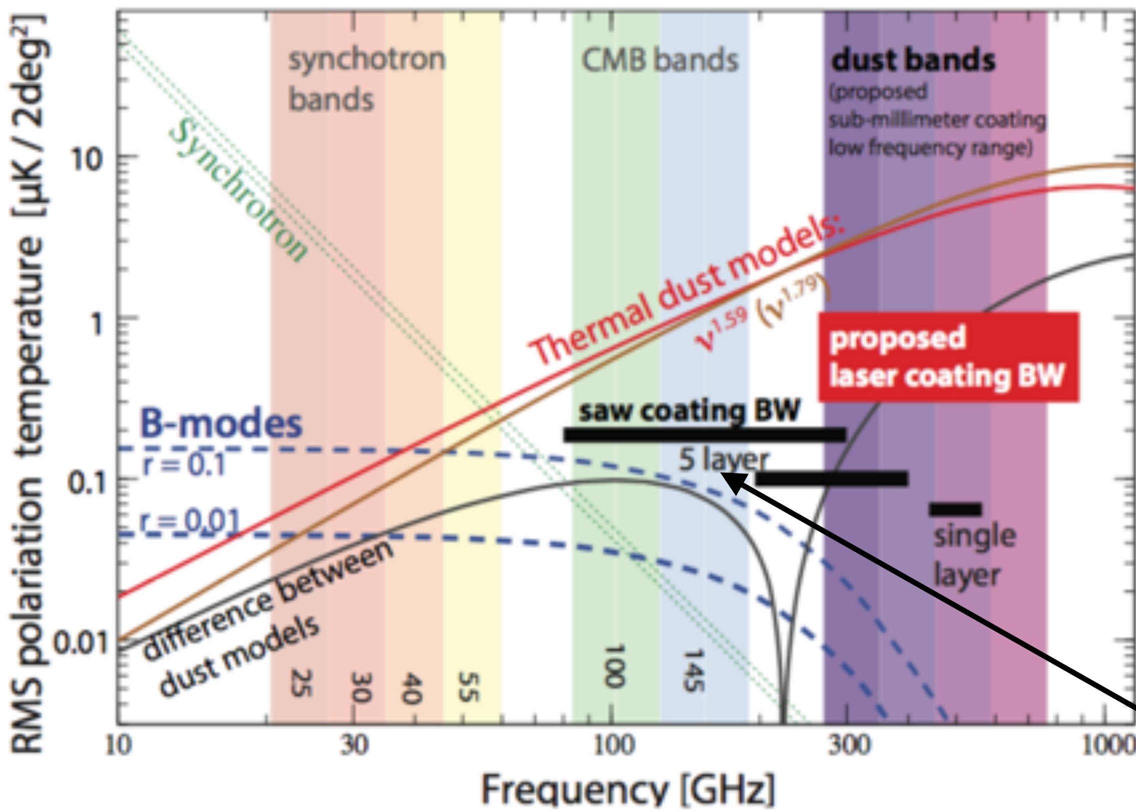


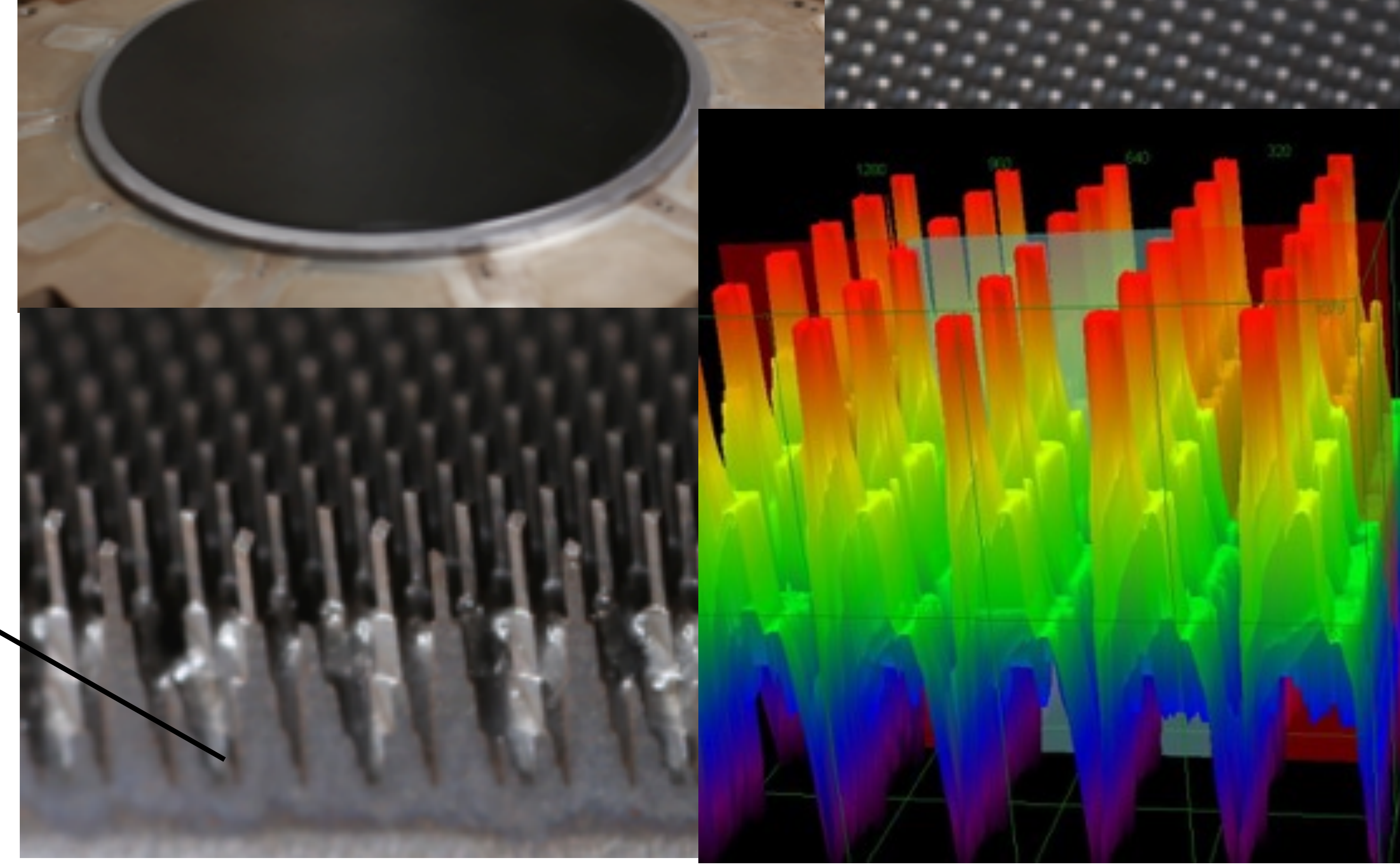


- operates from 75 to greater than 300 GHz
- design based on existing blades, straightforward to improve this proof of principle
- cut a 20 cm prototype one side complete
- defect rate is ~1%, but this was with a broken X-stage, expect near zero defect rate on the second side



5 layer > 4:1 ratio bandwidth

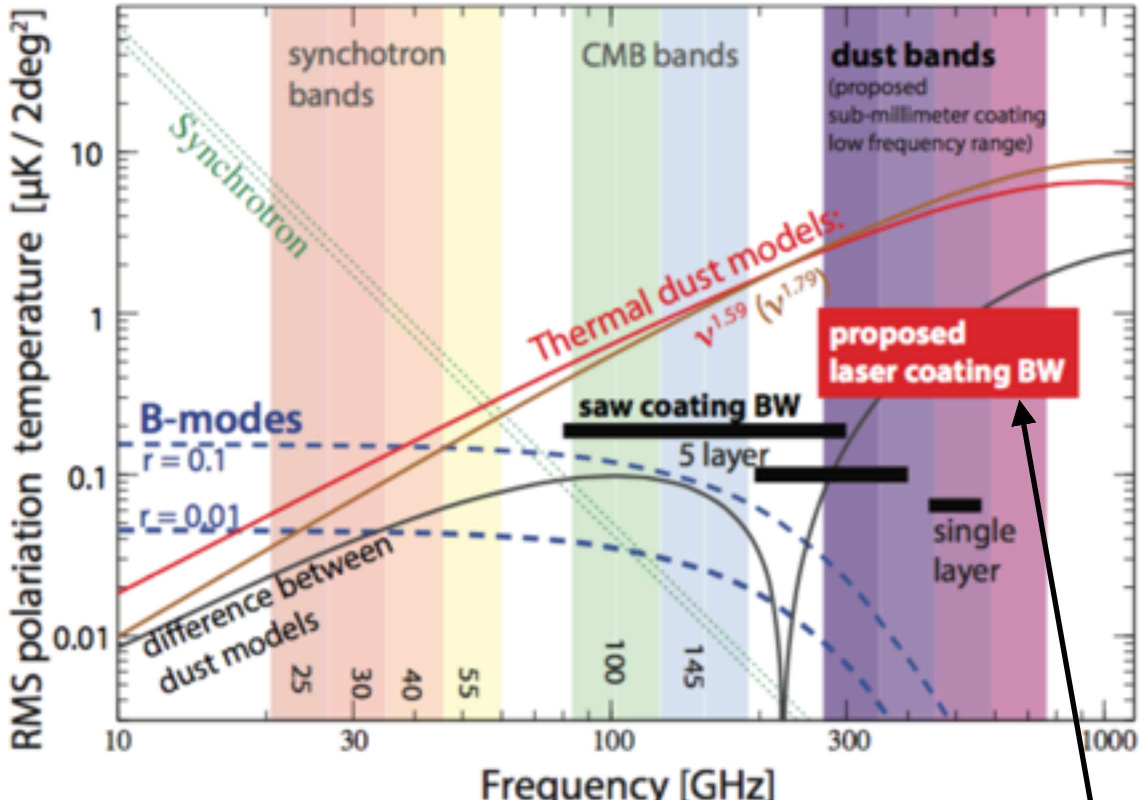




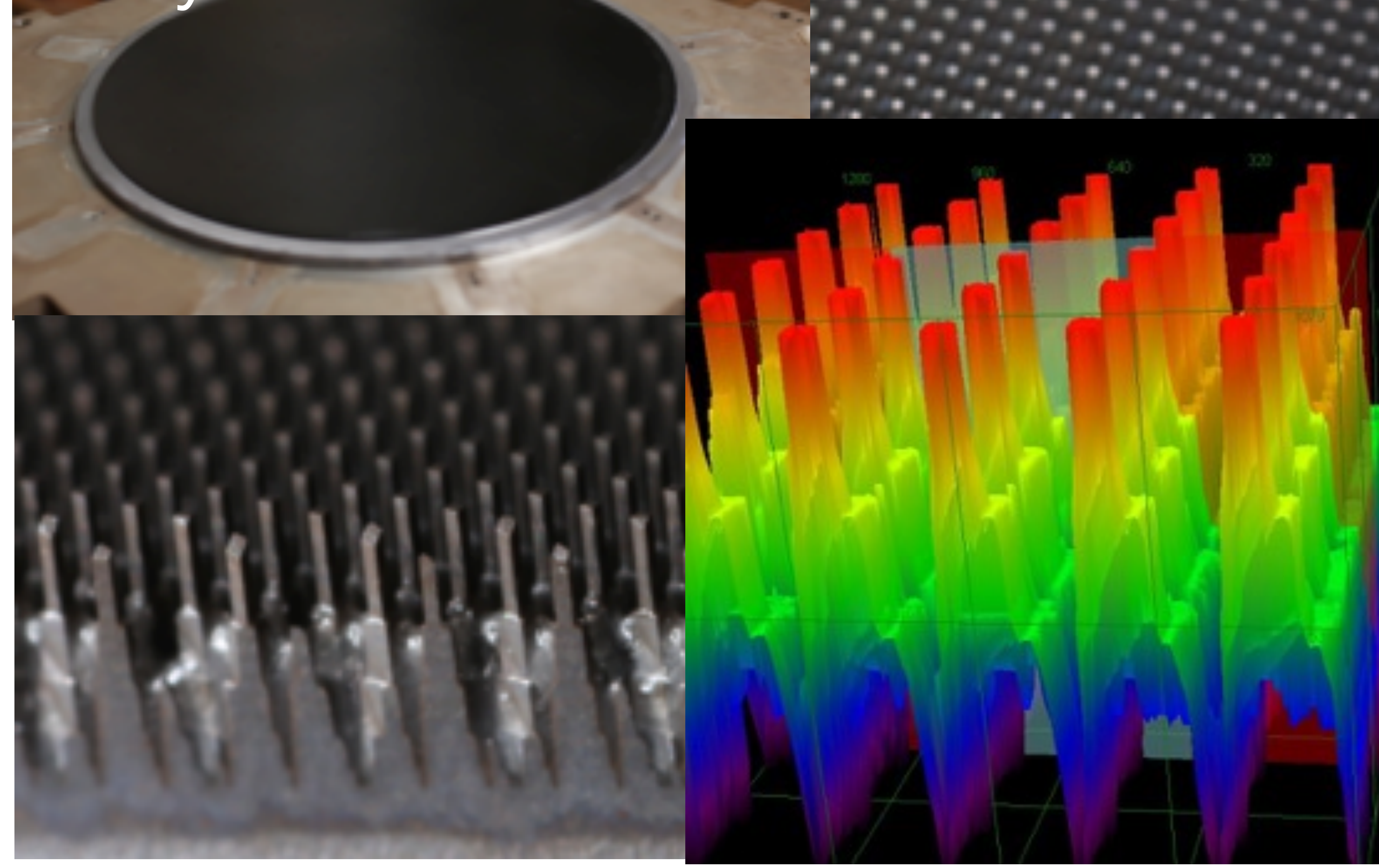
highest operating frequency limited by thinnest blades

- 5:1 RBW to about 350
- 3:1 RBW to about 450
- 1.5:1 RBW to 1.5 THz

but we want access to broad-bandwidth up to
600 GHz for the CMB and higher frequency for other applications

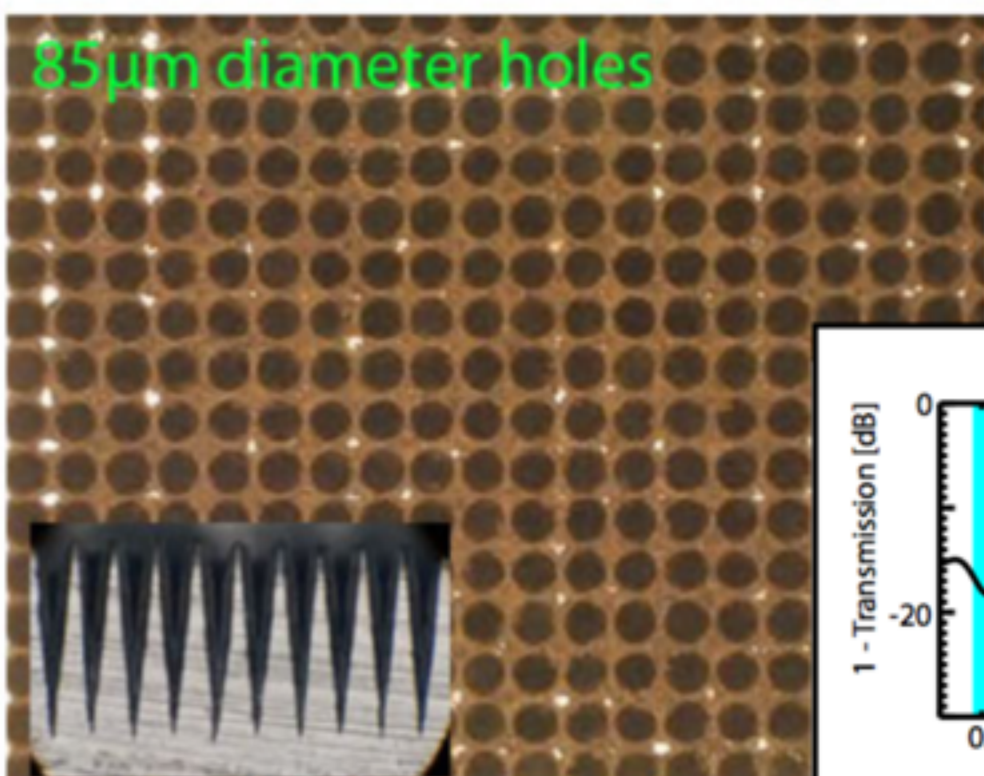


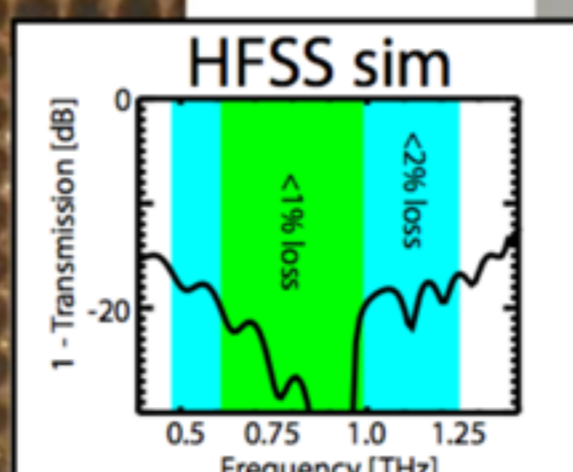
5 layer > 4:1 ratio bandwidth



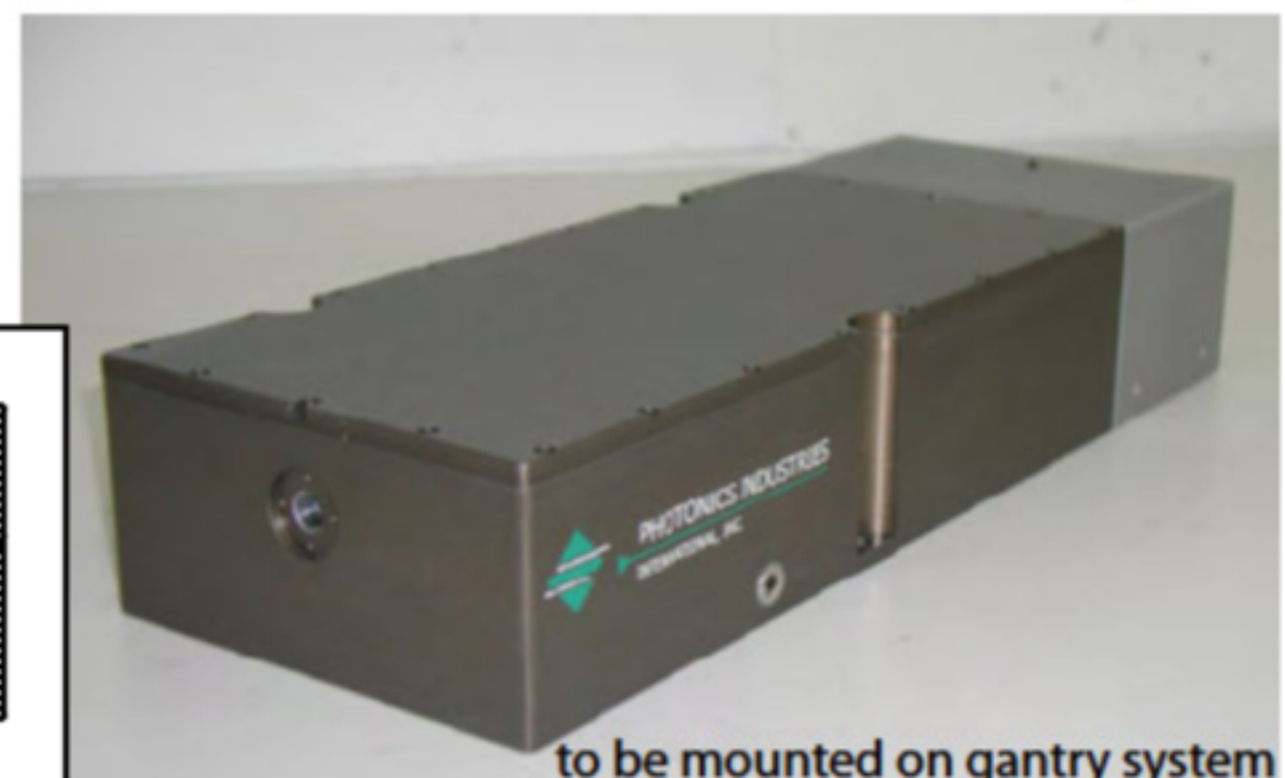
Funded Starting January

laser ablated AR coating





UV LASER



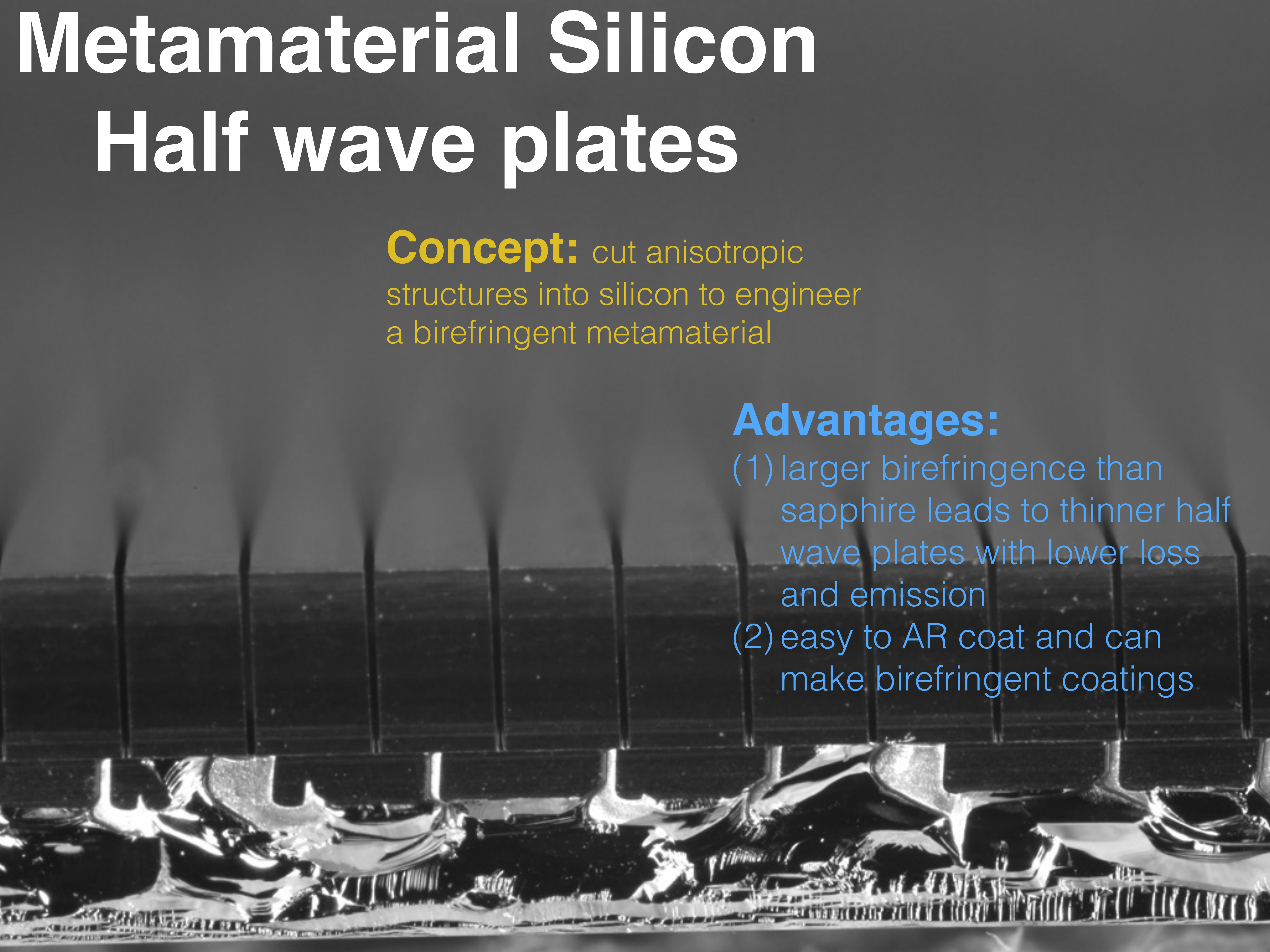
Metamaterial Silicon Half wave plates

Concept: cut anisotropic structures into silicon to engineer a birefringent metamaterial

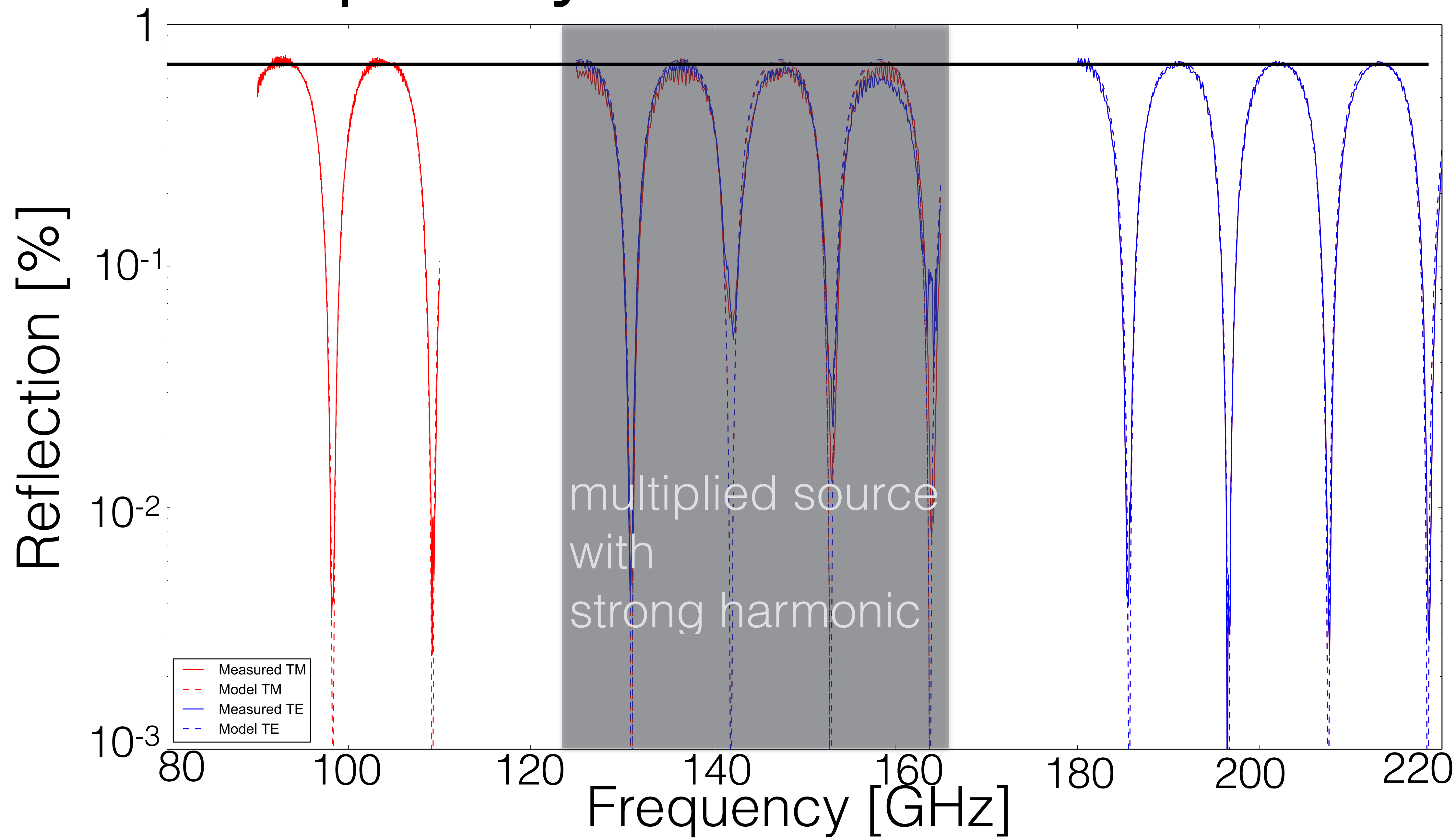
Advantages:

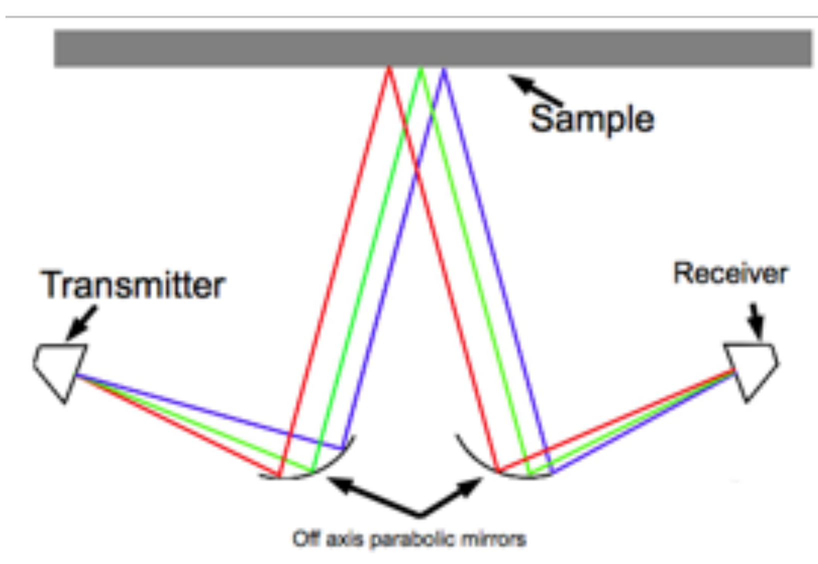
(1) larger birefringence than sapphire leads to thinner half wave plates with lower loss and emission

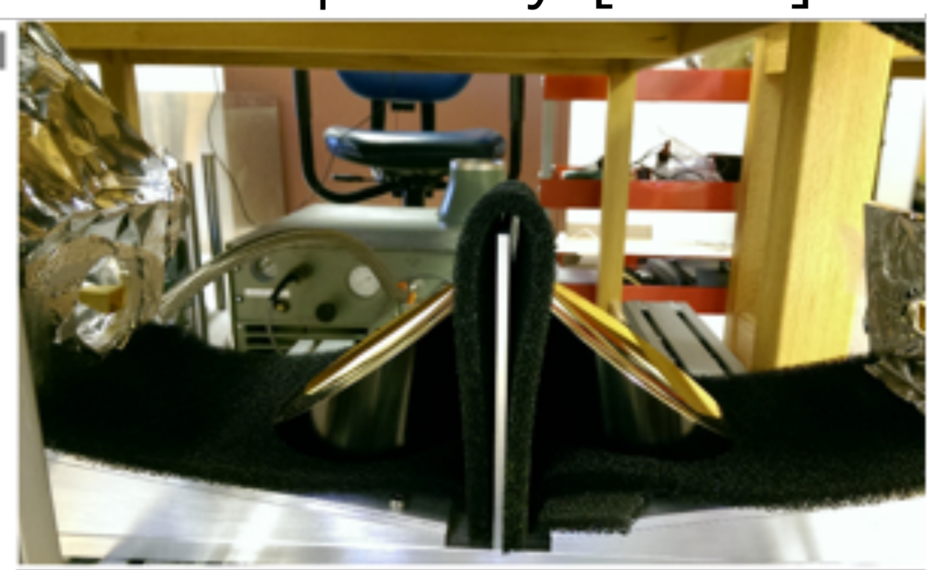
(2) easy to AR coat and can make birefringent coatings

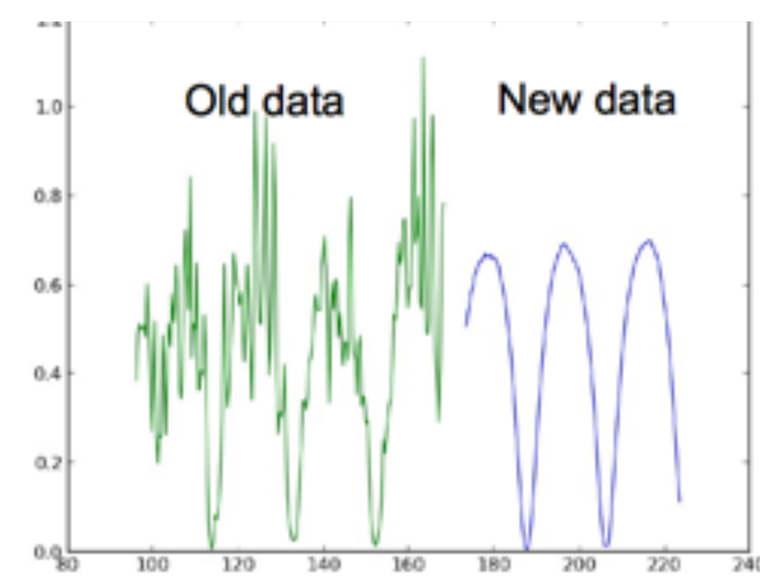


Silicon quality: tan∂ ~10^{-4} @ 300 K

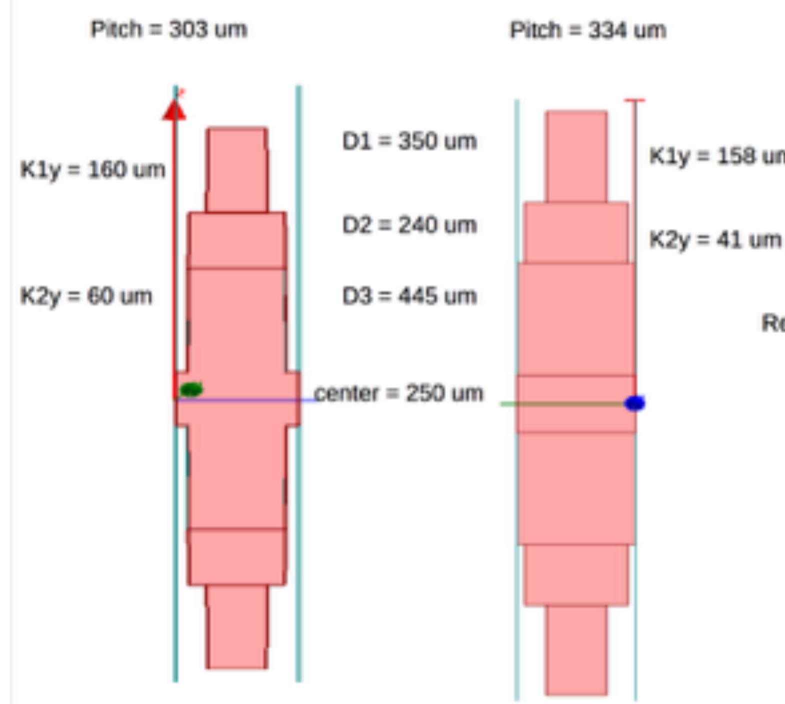


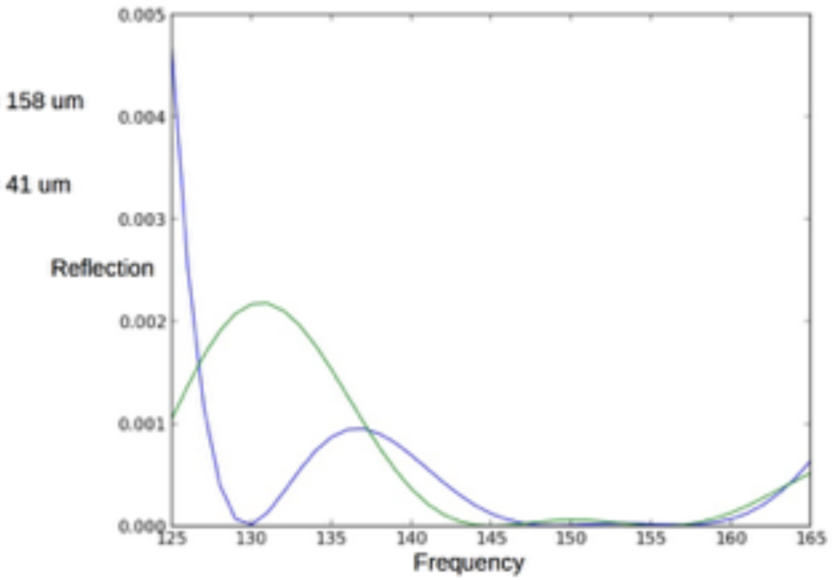






150 GHz HWP





predicted performance:

- <0.5 K emission @ 300K
- > 95% modulation efficiency
- <0.3% reflections

fabrication notes:

- dicing saw was damaged during fabrication leading to a 0.5% defect rate
- the wax used to hold the wafer was difficult to clean
- cleaning the wax lead to cracking it when a solvent dissolved the Invar support ring

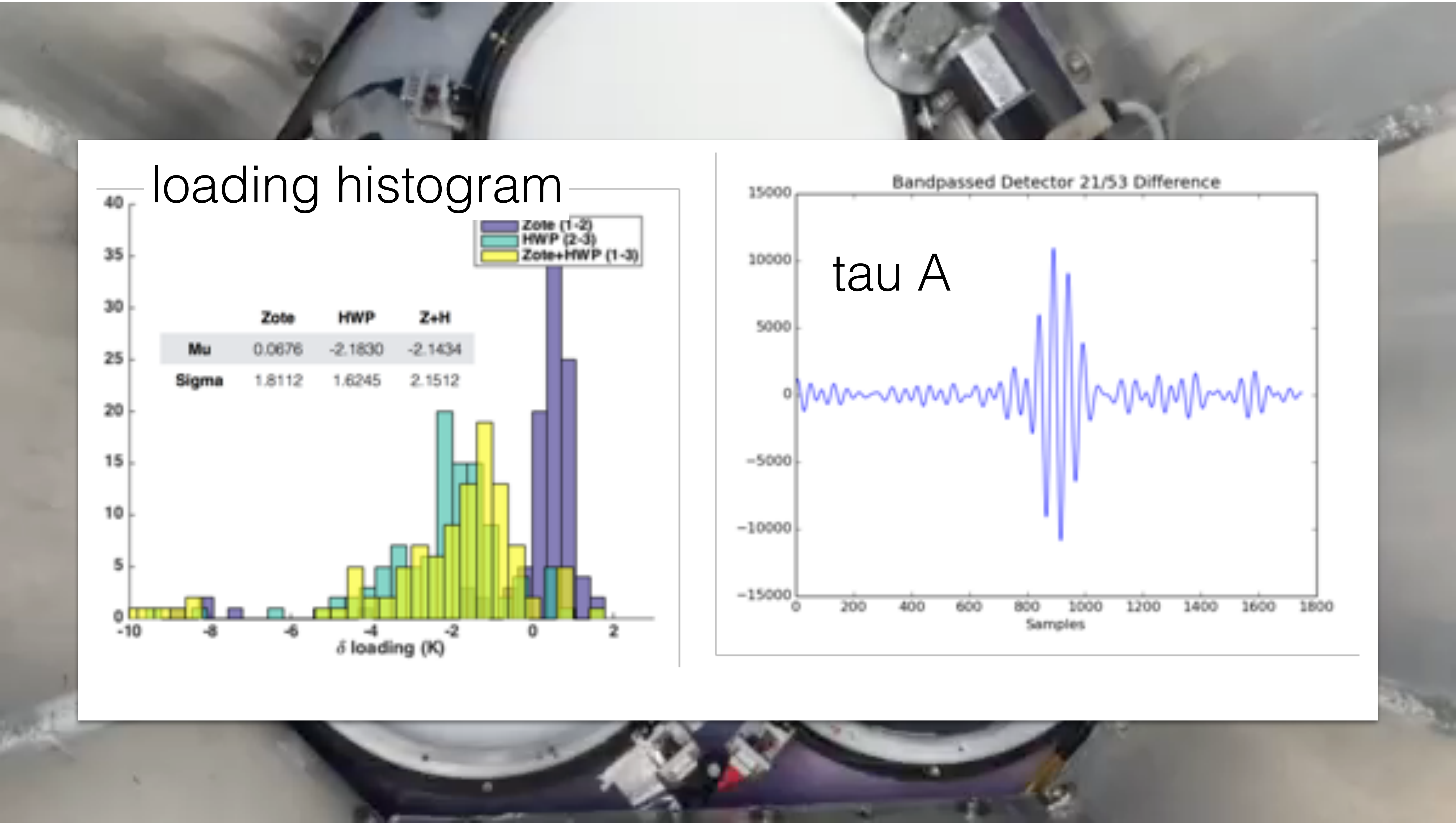
achieved performance

- <2 K loading @ 300K
  - dominated by defect scattering
- > 95% modulation efficiency
- <2% reflections —> dominated by tolerances

deployed on ACTPol

aside from a crack, loading was less than 2K (dominated by scattering) and we saw modulated signals

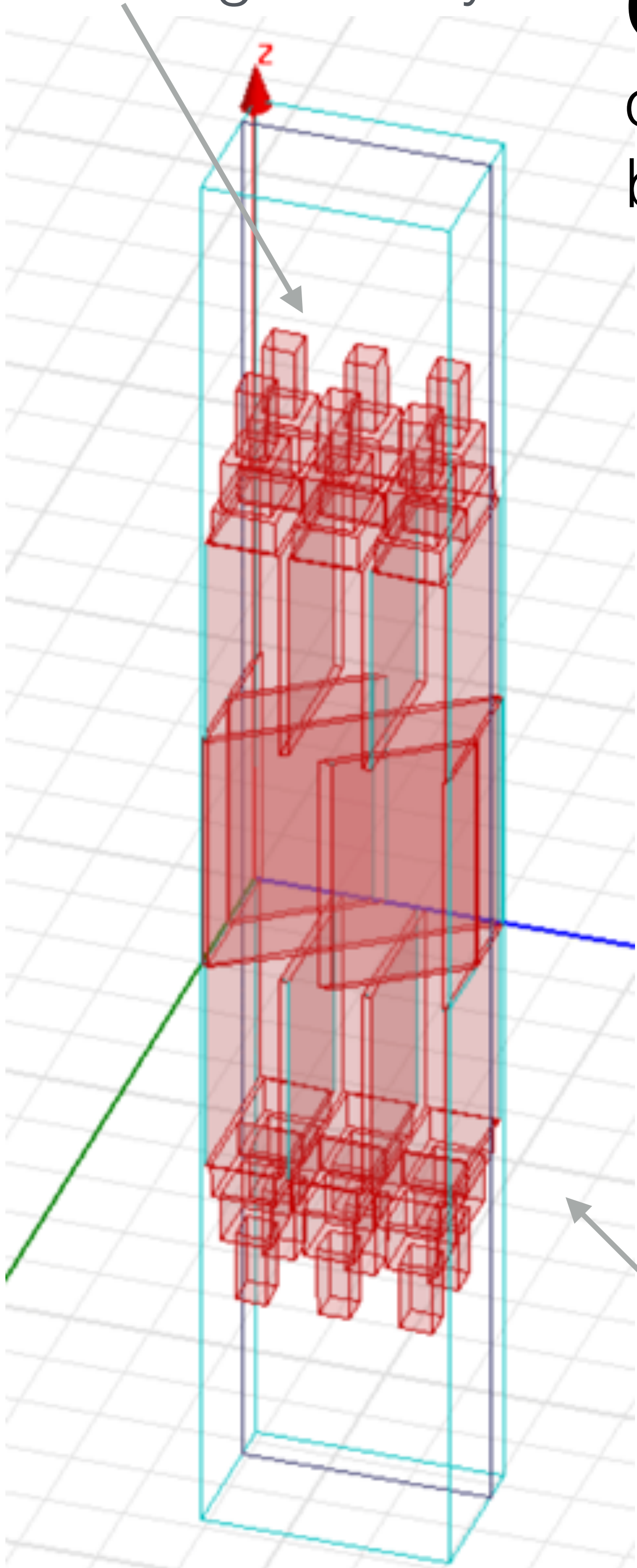
deployed on ACTPol



aside from a crack, loading was ~2K (dominated by scattering) and we saw modulated signals

Broad-Band Metamaterial Silicon Half wave plates

90-150 broad band geometry



Concept: an achromatic stack of three halfwave plates with birefringent AR coatings.

Key Design choice

Δ n ~ 0.8

- reduces thickness and loss
- keeps reflections manageable

Simulation Trick

use a 3x2 lattice to embed the rotated layer into a square grid

Assembly

cut internal rotated HWP first, glue this onto a second wafer, cut the outer layers

Optimization

minimize differential reflection

predicted performance:

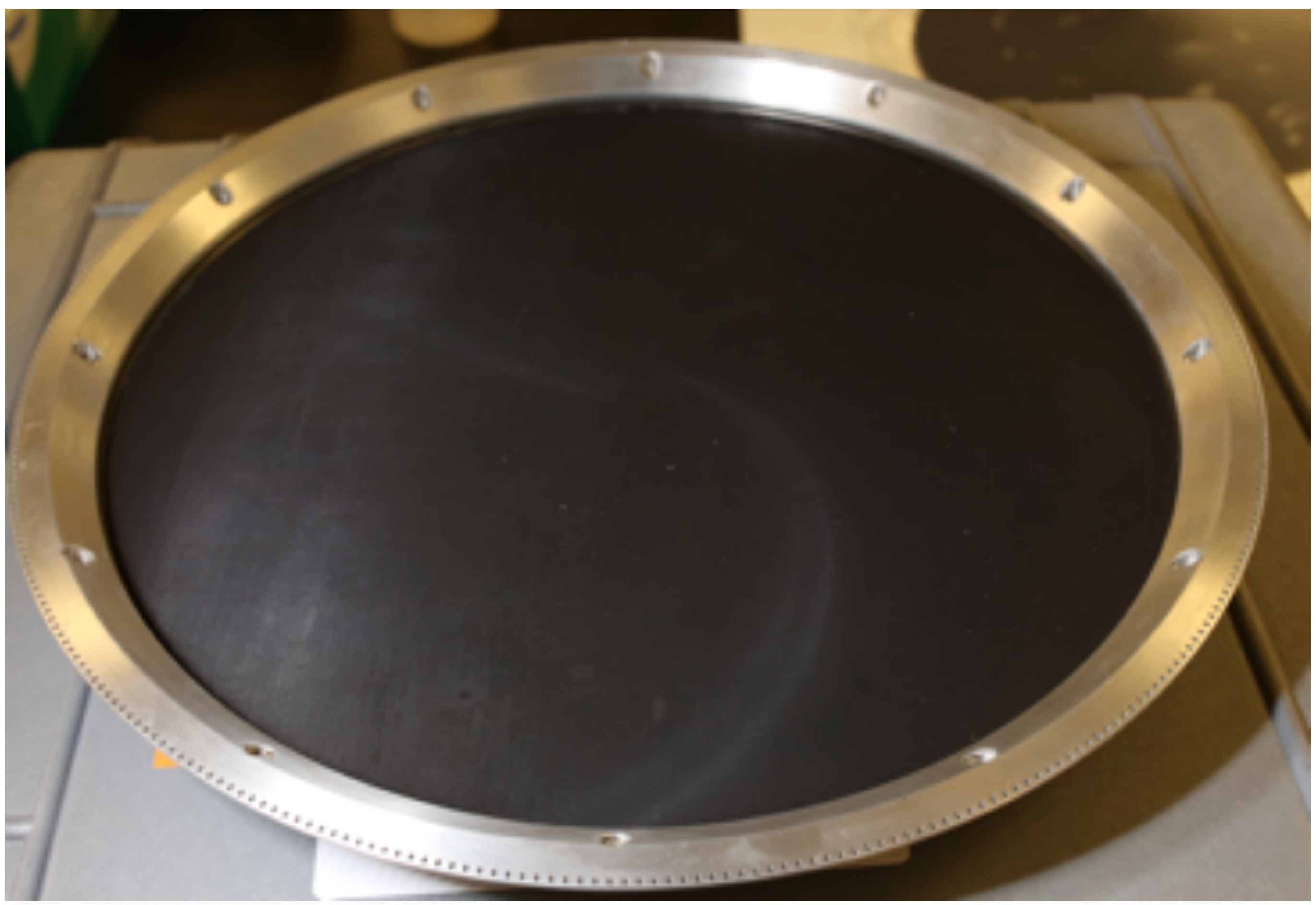
- <1.5 K emission @ 300K
- \> 95% modulation efficiency
- <2% averaged reflections

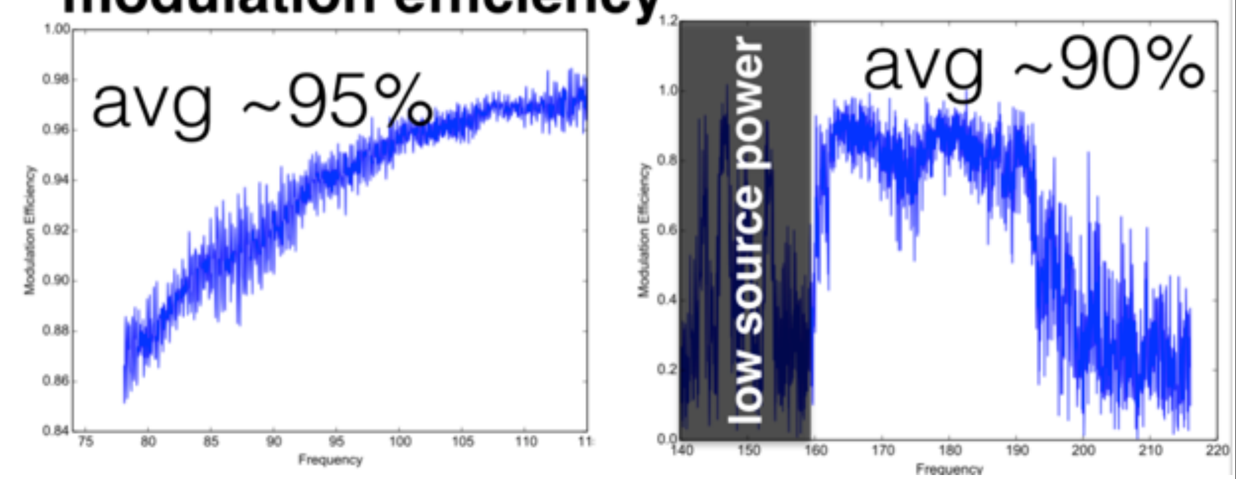
Broad-Band Metamaterial Silicon Half wave plates

90-150 broad band geometry

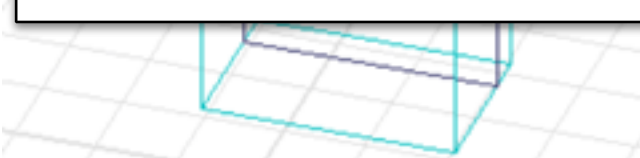
Concept: an achromatic stack of three halfwave plates with birefringent AR coatings.

First 90/150 Multichroic HWP





to be deployed soon



- <1.5 K emission @ 300K
- > 95% modulation efficiency
- <2% averaged reflections

Optimization

minimize differential reflection

Conclusions

- A full multichroic camera has been deployed and has achieved a preliminary 10 uK*s$^{1/2}$ array-level sensitivity. Si AR coated lenses are an important part of that success.
- Silicon optics with sub-percent reflections with up to 4:1 bandwidth have been fabricated
- Silicon AR coated lenses are a potential option for the LiteBIRD high frequency telescope optics
- Metamaterial silicon wave plates have been fabricated and are under evaluation on ACTPol