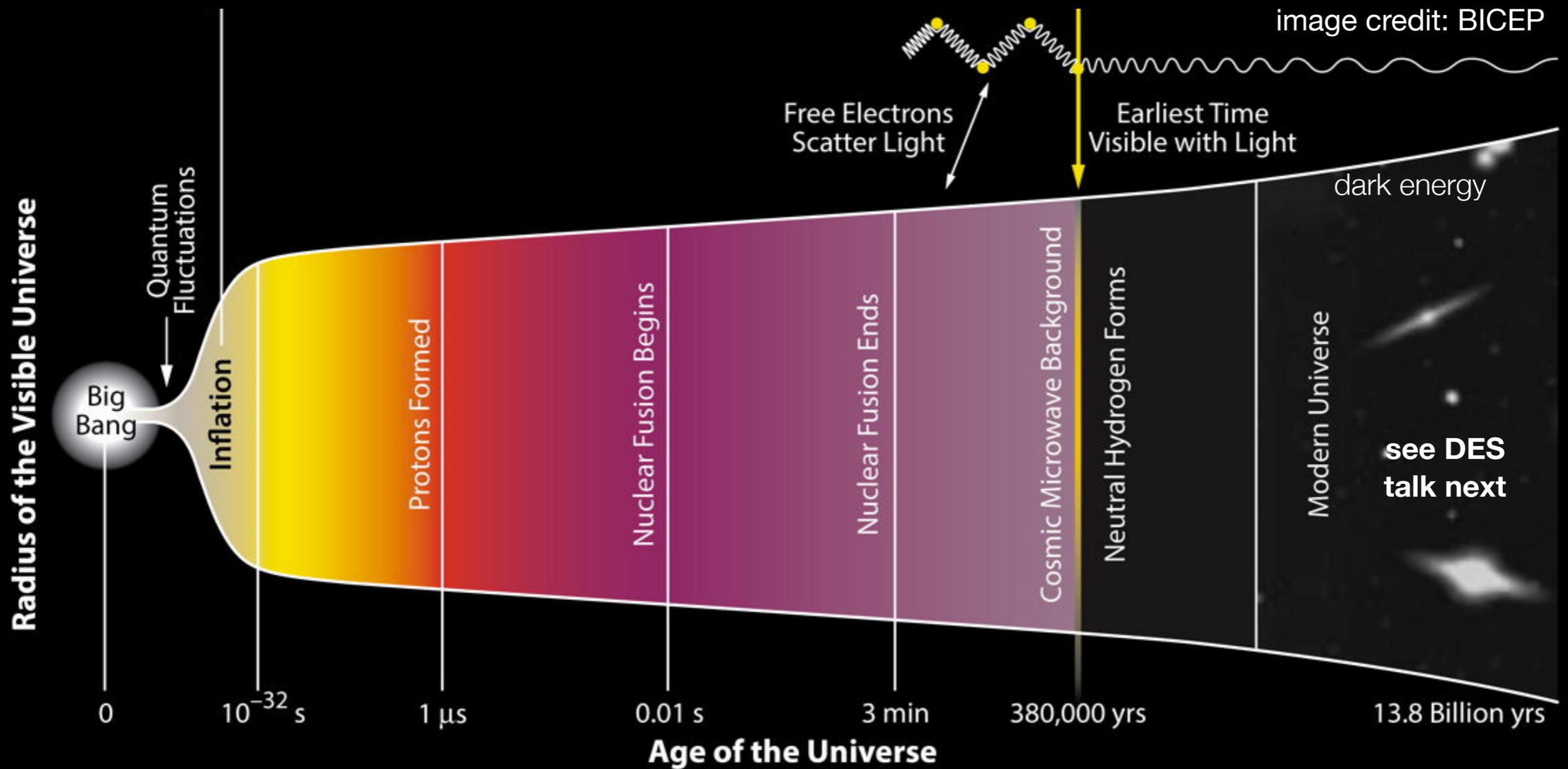


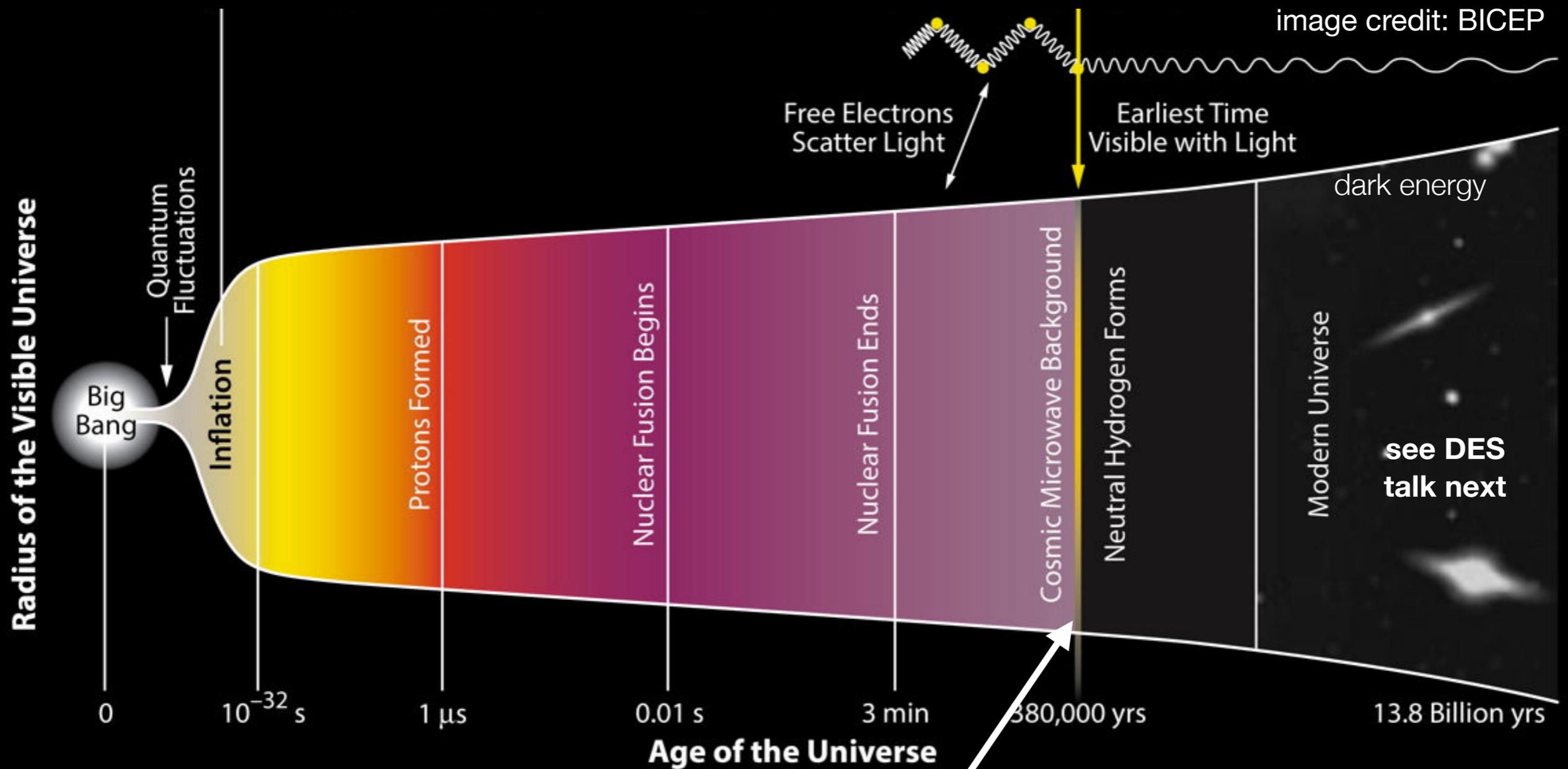
Cosmology with the South Pole Telescope

Adam Anderson
Fermilab Users Meeting
15 June 2016

CMB and the Cosmic Timeline

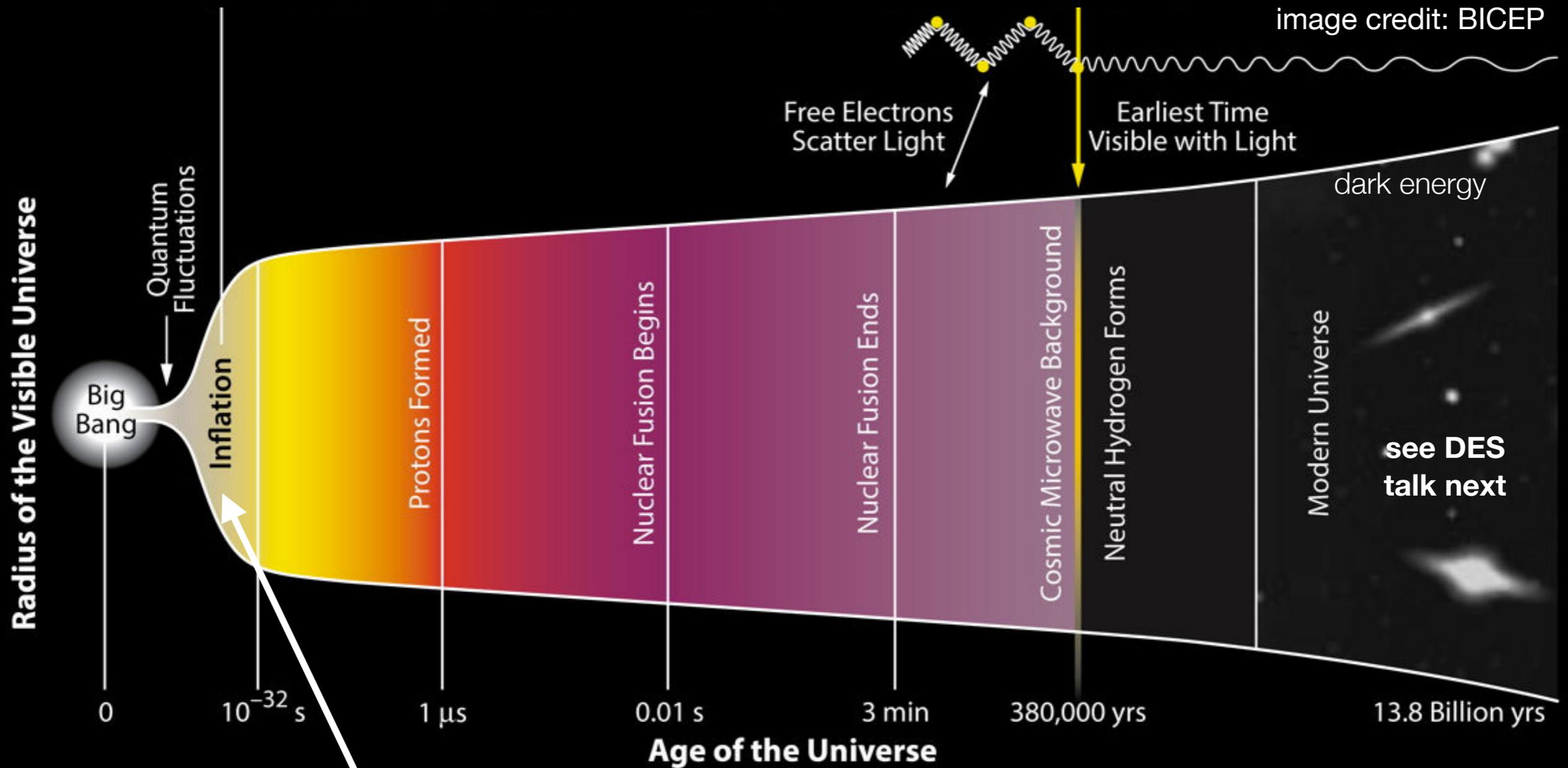


CMB and the Cosmic Timeline



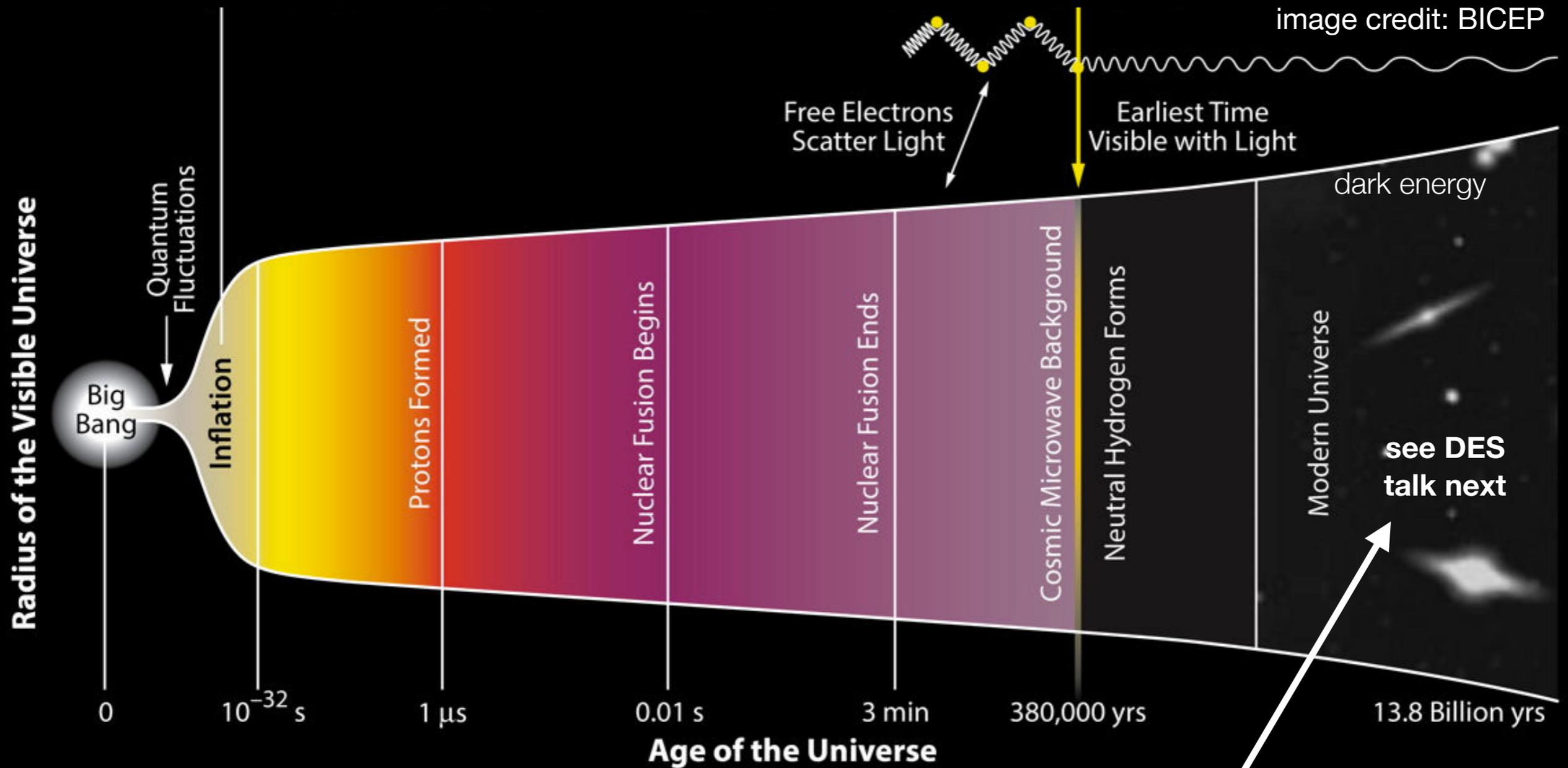
1.) CMB is “image” of universe at recombination

CMB and the Cosmic Timeline



2.) Quantum fluctuations from inflation are imprinted on CMB

CMB and the Cosmic Timeline



3.) CMB photons affected by growth of structure in modern times

Some Outstanding Questions

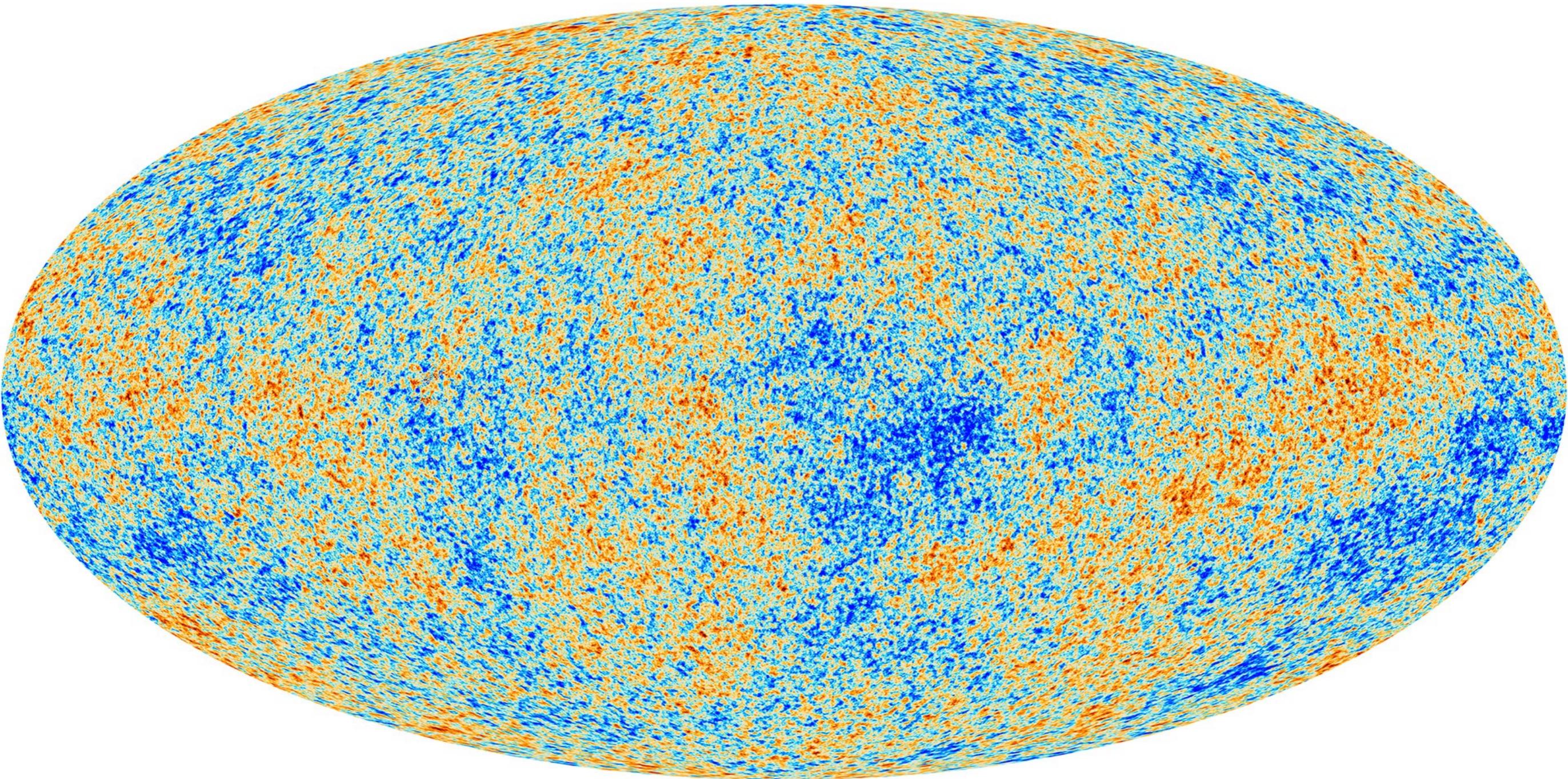
- What is the physics of inflation (at $\sim 10^{16}$ GeV)?
- What is dark energy?
- How does gravity behave on large scales?
- What the sum of the neutrino masses?

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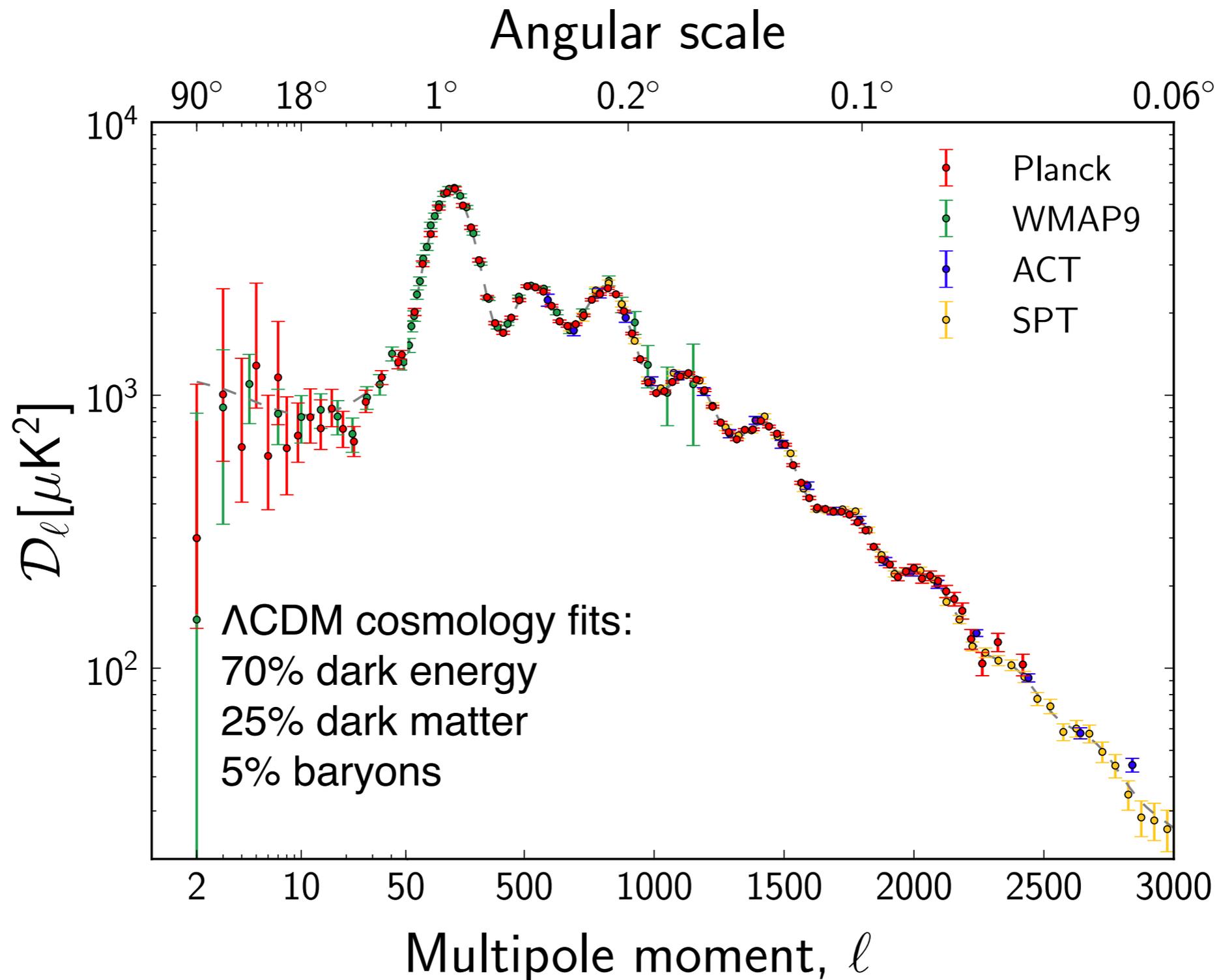
Access with more precise CMB measurements

Temperature Anisotropy from Planck

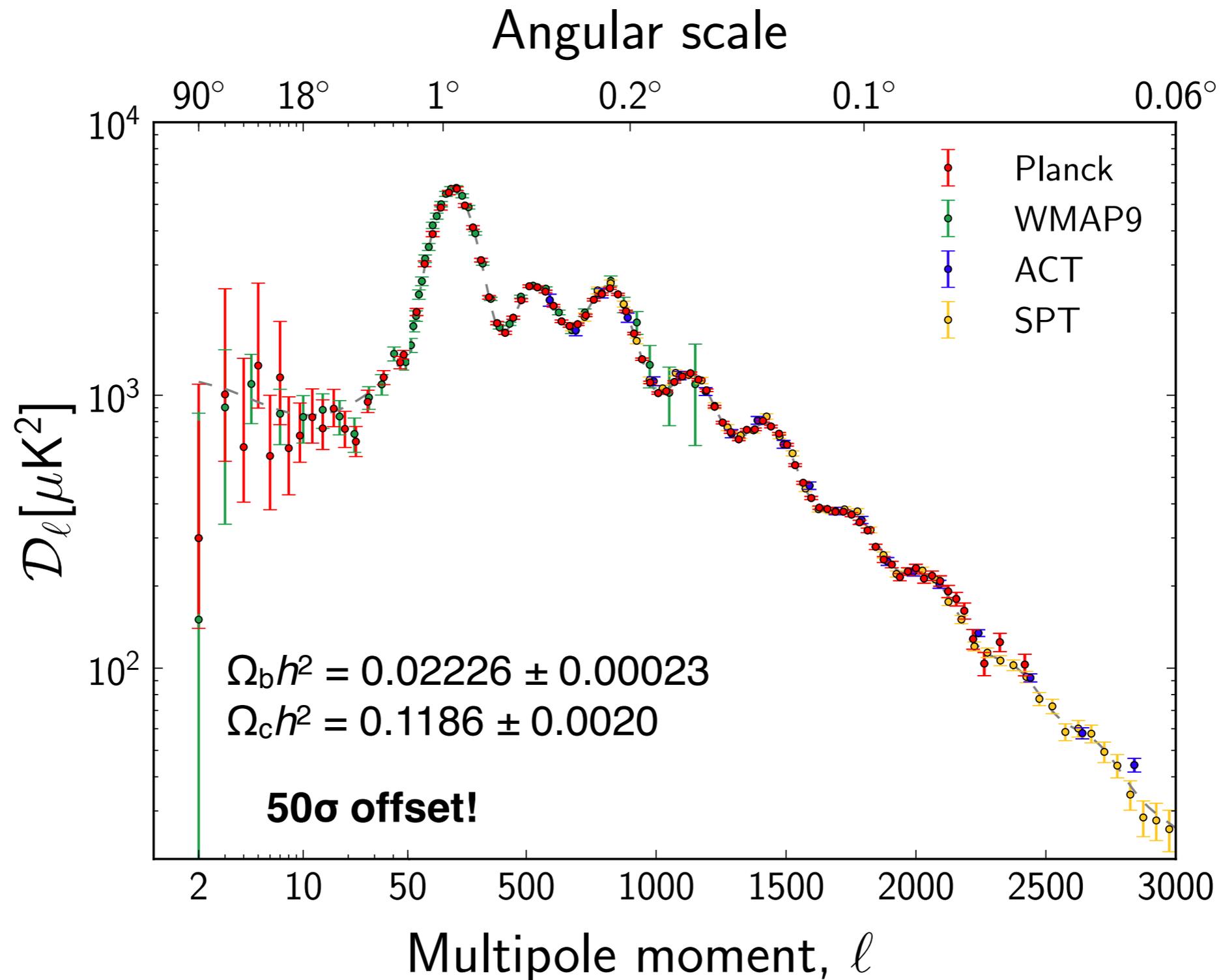


$30\mu\text{K}$ rms fluctuation on a 3K blackbody

Temperature Anisotropy from Planck

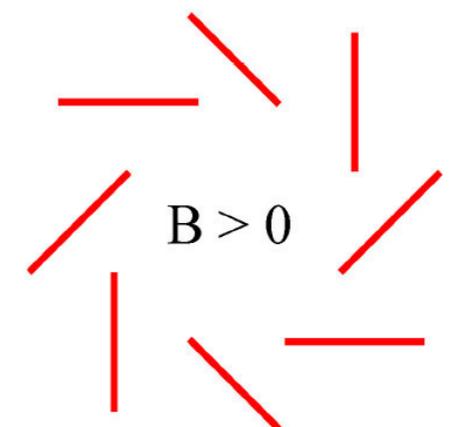
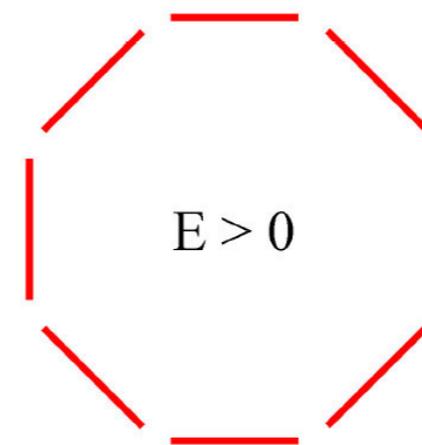
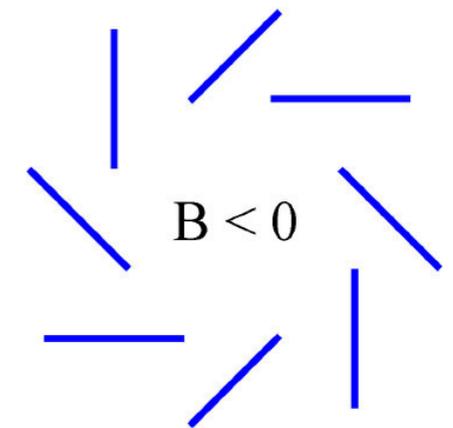
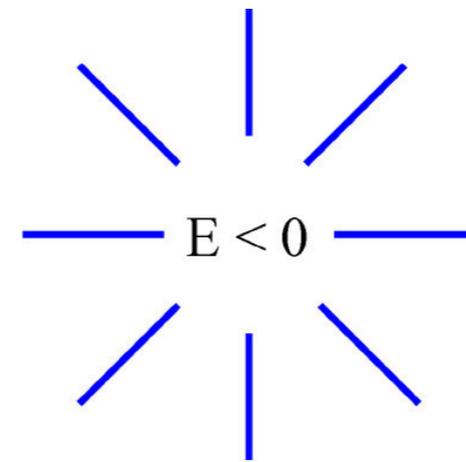


Temperature Anisotropy from Planck



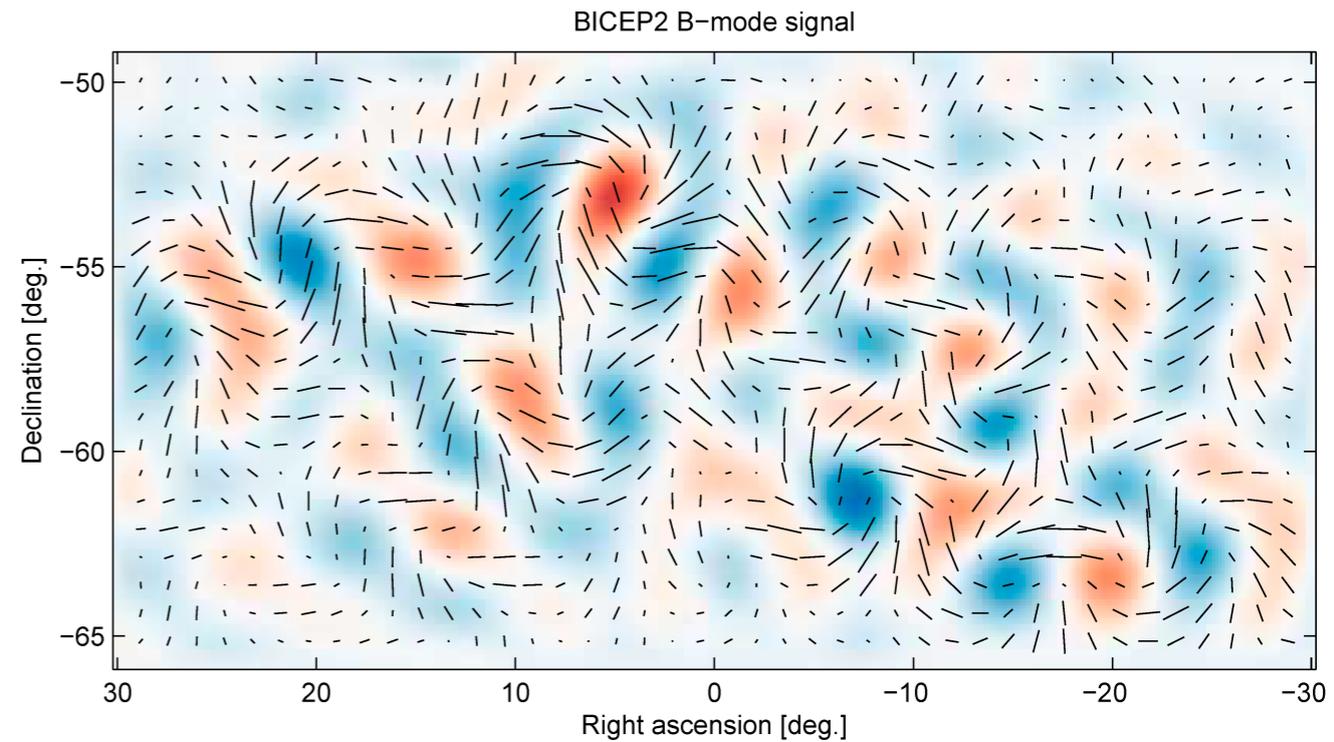
CMB Polarization

- Polarization can be decomposed into ***E-mode*** and ***B-mode*** patterns on sky



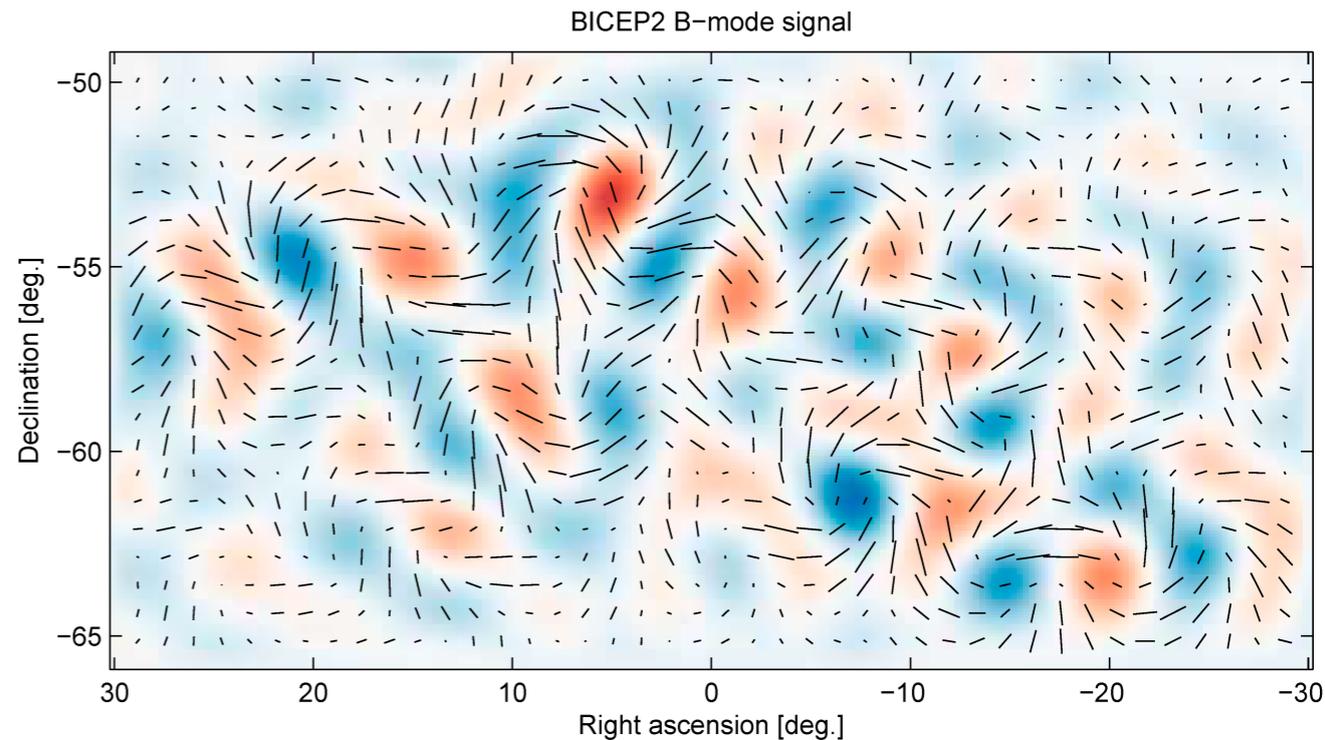
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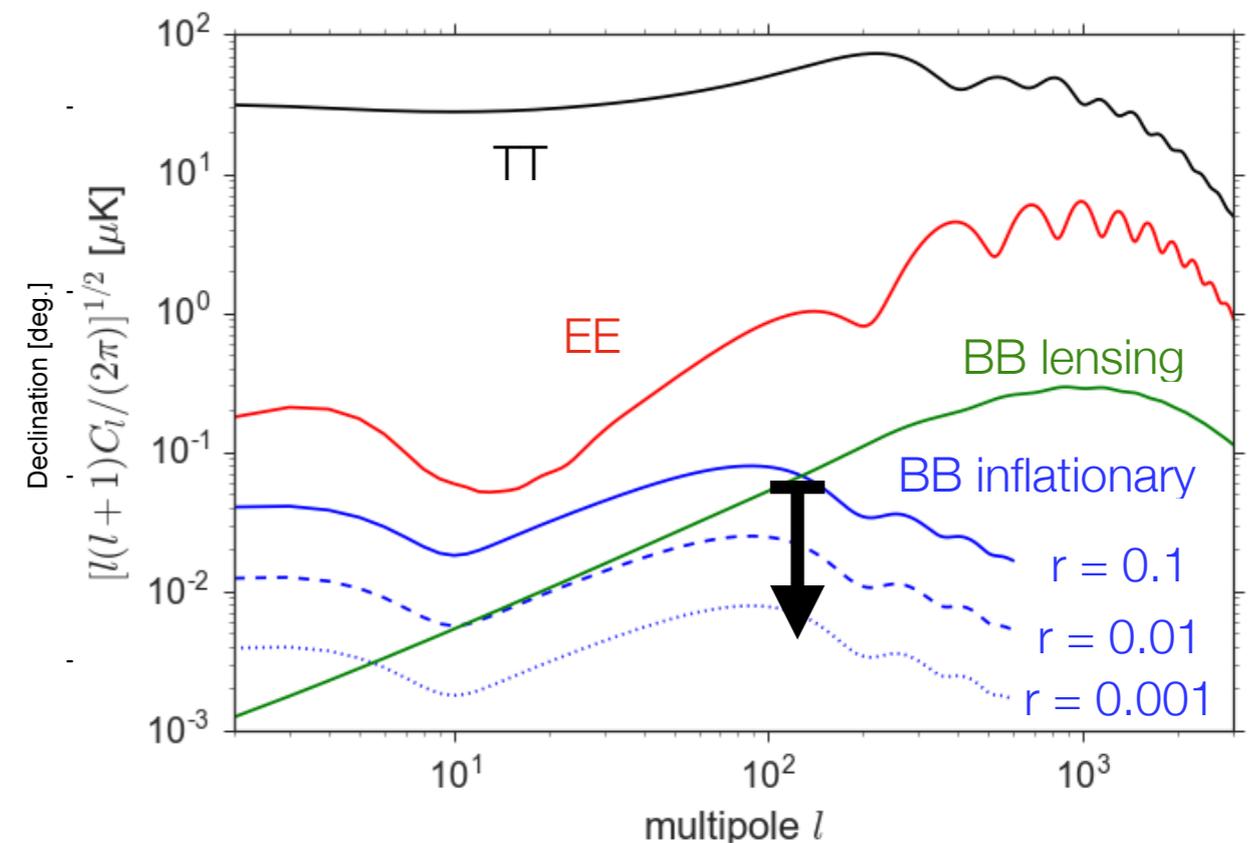
CMB Polarization

- Polarization can be decomposed into ***E-mode*** and ***B-mode*** patterns on sky
- B-modes produced only by:
 - inflationary gravitational waves (large angular scales) — “smoking gun”
 - gravitational lensing of E-modes (small angular scales)



CMB Polarization

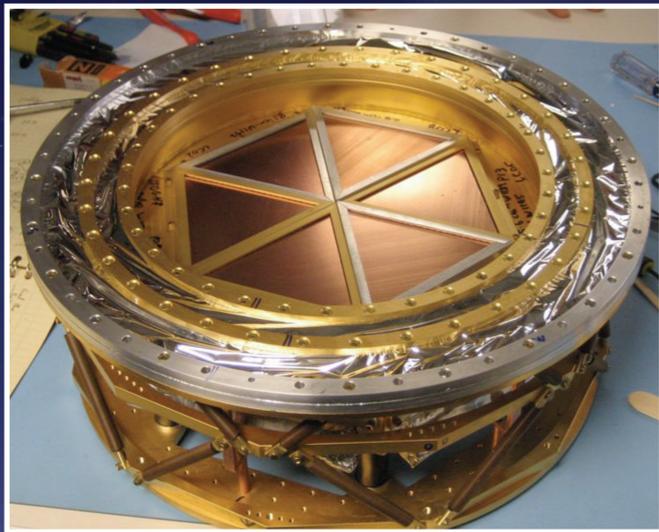
- Polarization can be decomposed into ***E-mode*** and ***B-mode*** patterns on sky
- B-modes produced only by:
 - inflationary gravitational waves (large angular scales) — “smoking gun”
 - gravitational lensing of E-modes (small angular scales)
- Measuring large and small scales enables ***delensing*** to enhance sensitivity to inflationary B-modes
- Sensitivity to neutrino mass



South Pole Telescope

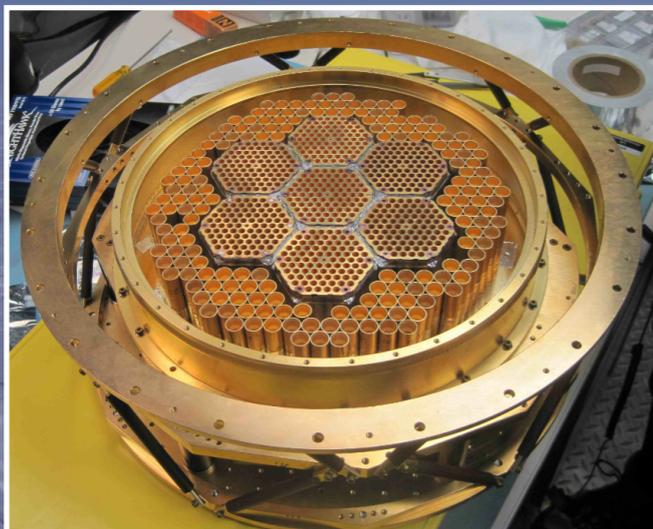
- 10m primary mirror
- ~1 arcmin angular resolution, highest resolution CMB maps

SPT-SZ (2007)



960 detectors at 95, 150, 220 GHz

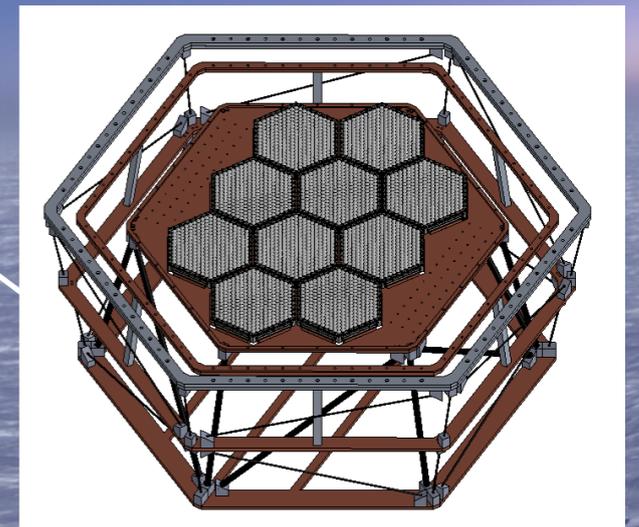
SPTpol (2012)



1500 detectors at 90, 150 GHz w/polarization



SPT-3G (2016)

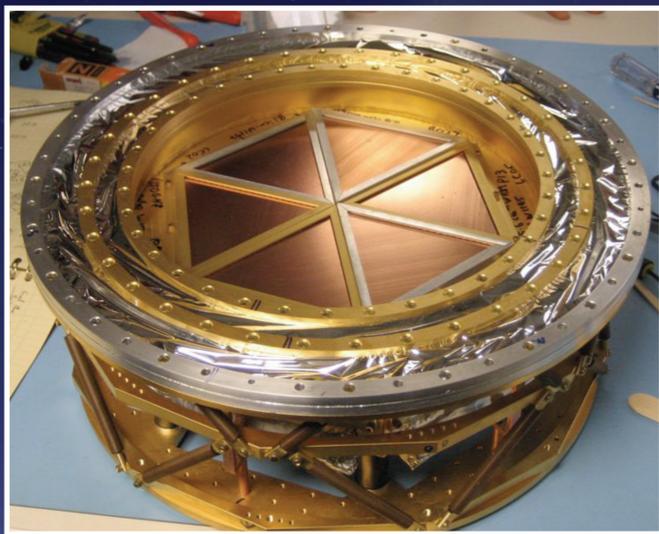


16,000 detectors at 90, 150, 220 GHz w/polarization

South Pole Telescope

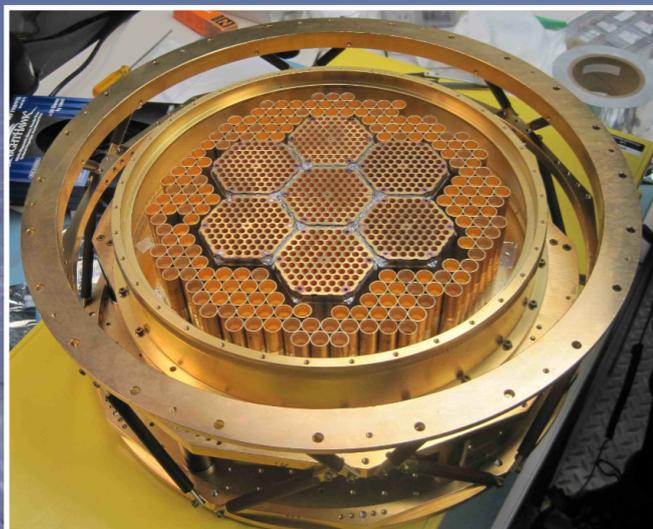
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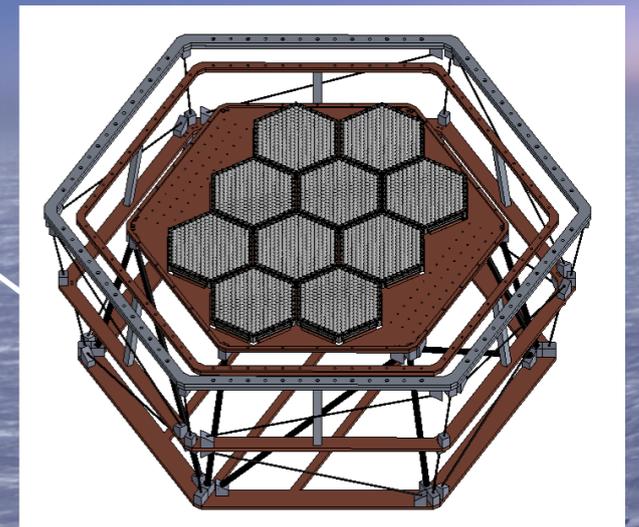
SPTpol (2012)



1500 detectors at 90, 150 GHz w/polarization

Integration and testing ongoing at Fermilab with B. Benson, M. Jonas, D. Kubik, H. Nguyen, S. Rahlin

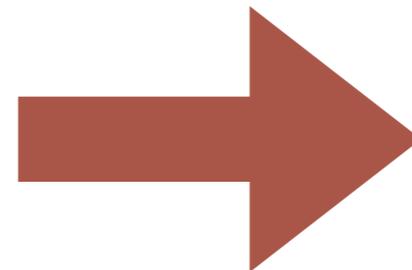
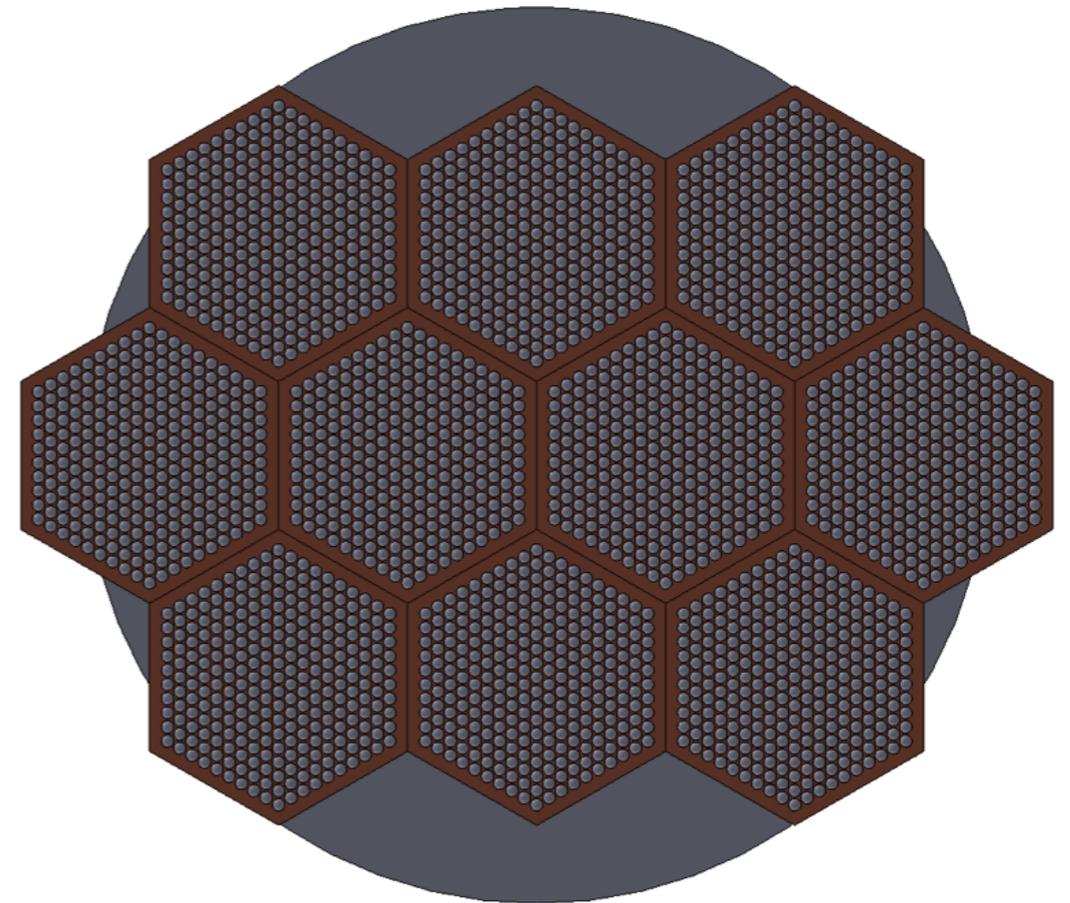
SPT-3G (2016)



16,000 detectors at 90, 150, 220 GHz w/polarization

SPT-3G Upgrade

- Modern CMB detectors limited by ***photon shot noise***
- Better sensitivity only possible by more detectors
- SPT-3G to improve both:
 - redesign optics to increase throughput by 2x
 - multichroic pixel design for higher detector density



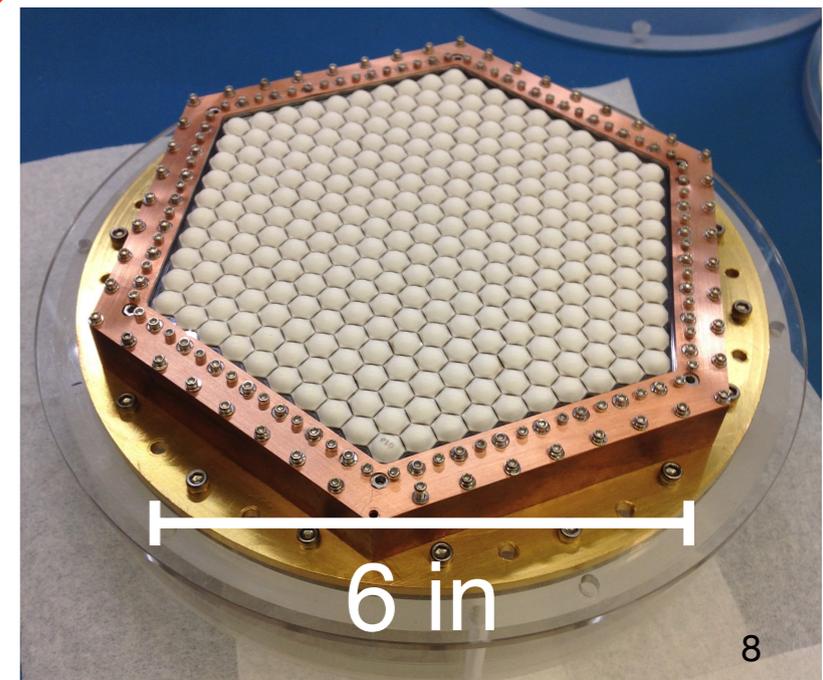
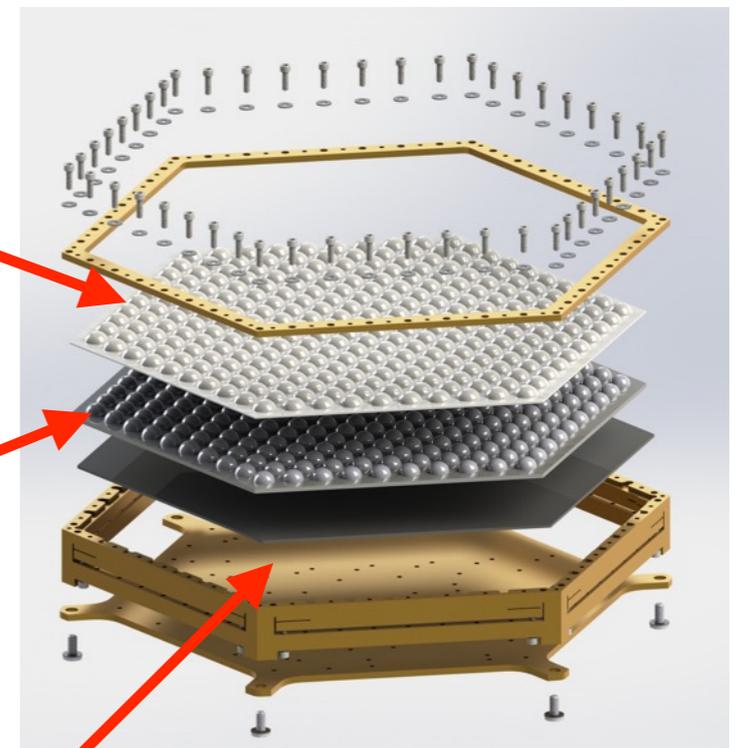
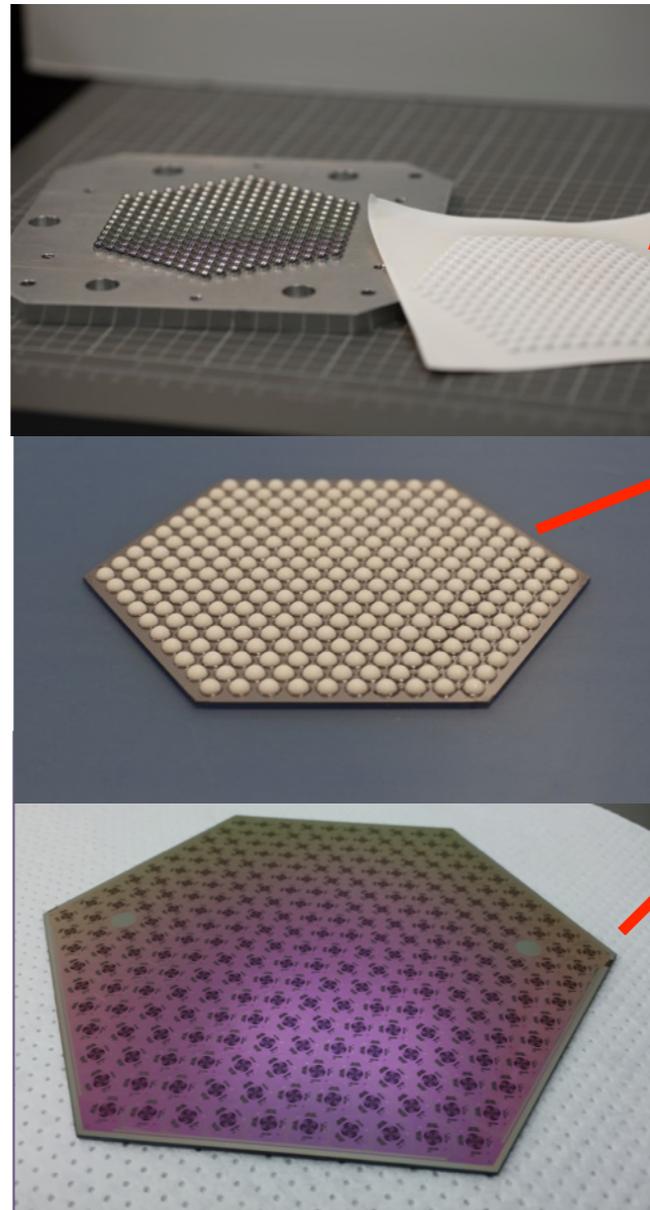
20x increase in mapping speed

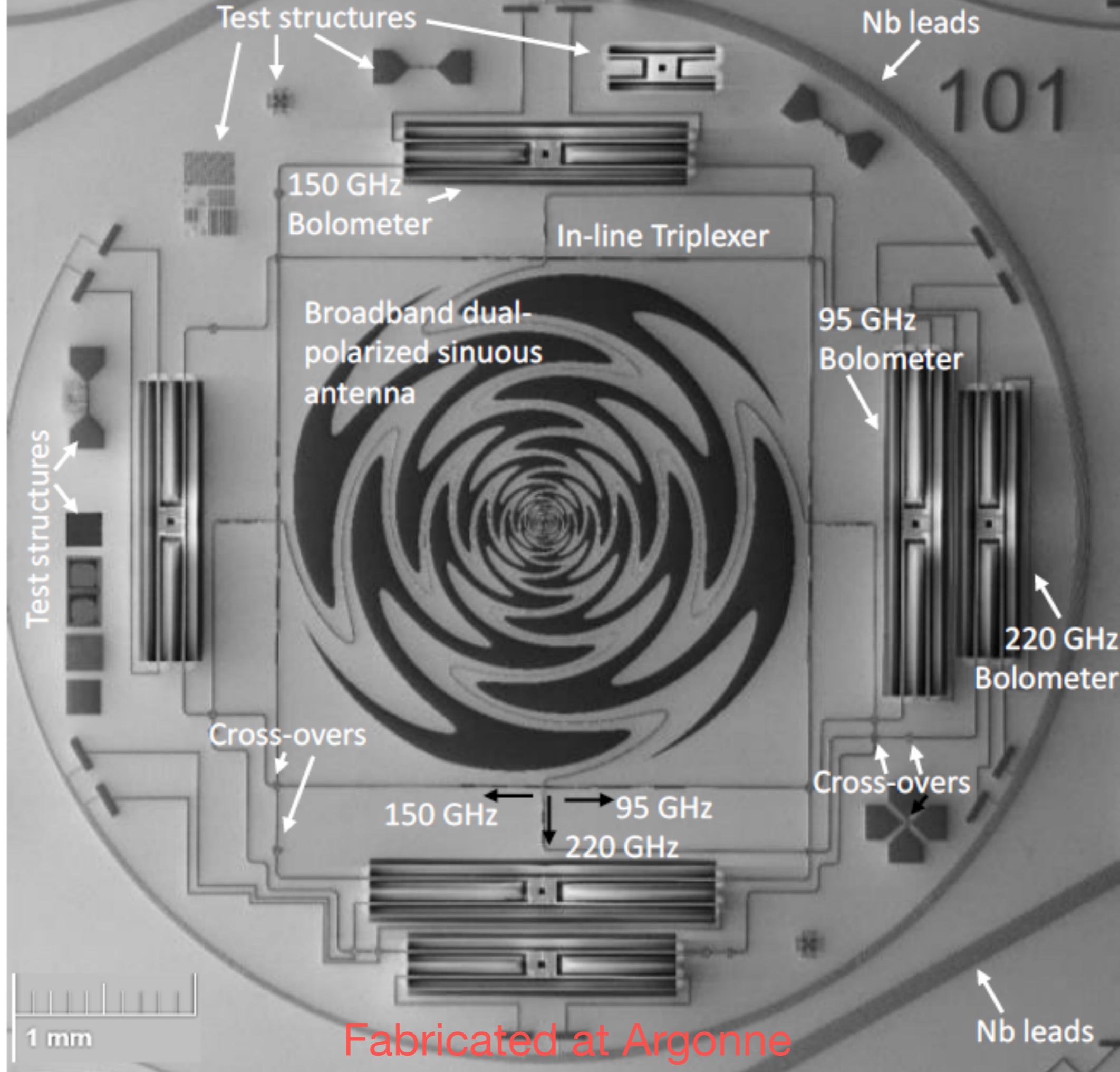
Detector Modules

- 271 pixels per wafer
- 10x detector wafers in focal plane
- Detector wafers coupled to array of alumina lenslets, anti-reflective coating
- Assembly, packaging, wire bonding all at Fermilab at SiDet

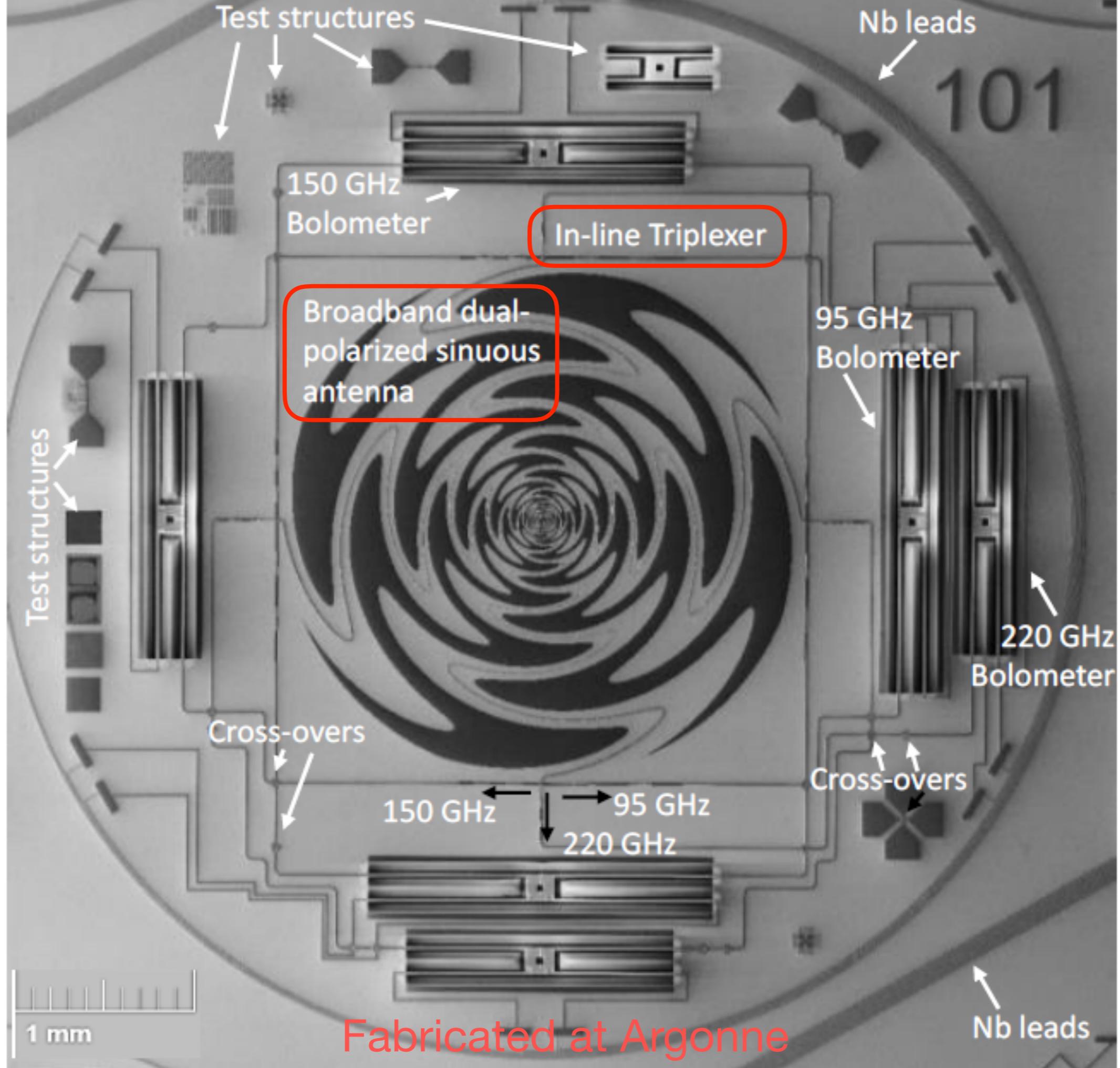


Major expertise in silicon detectors from:
CMS, DES, DAMIC...



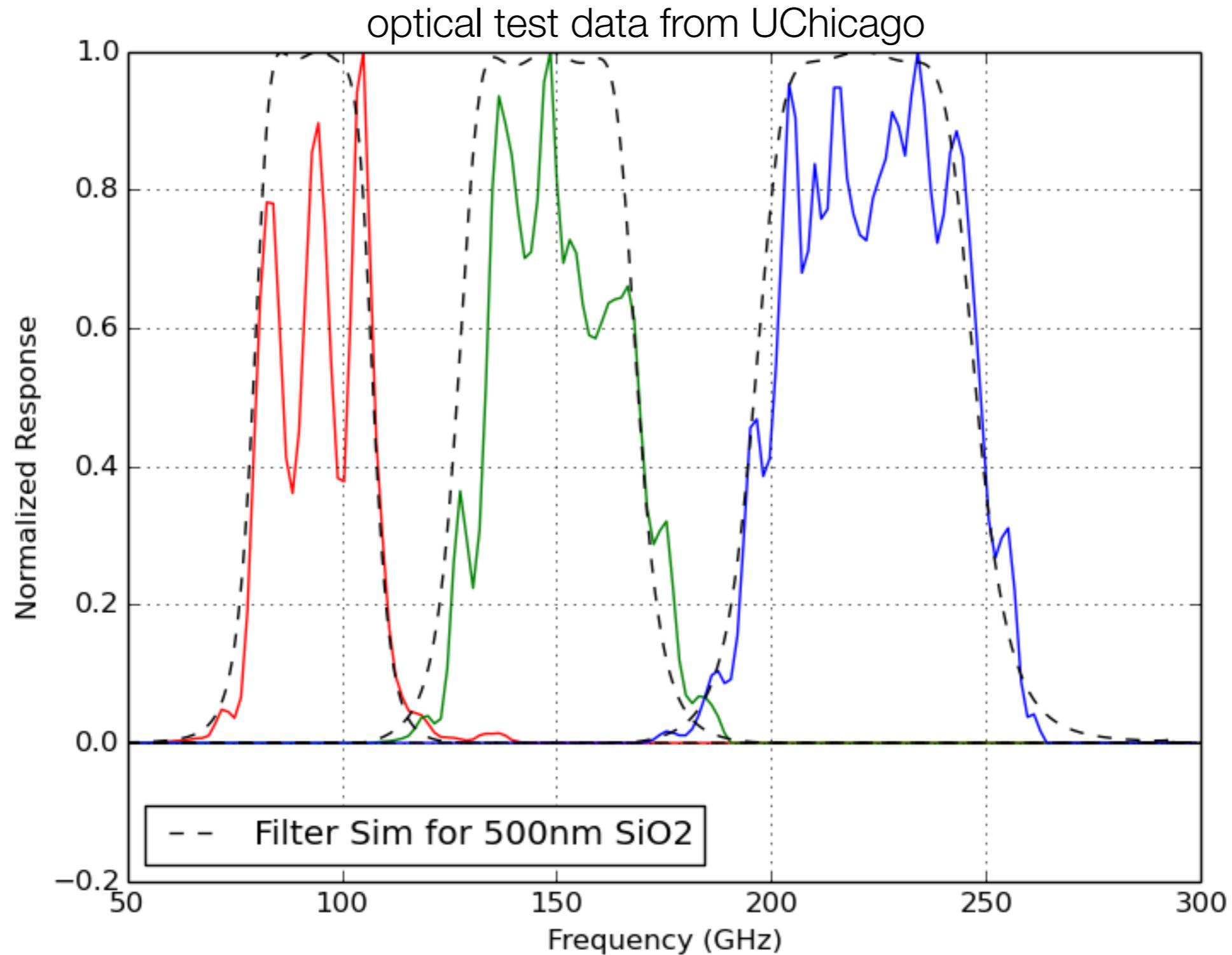


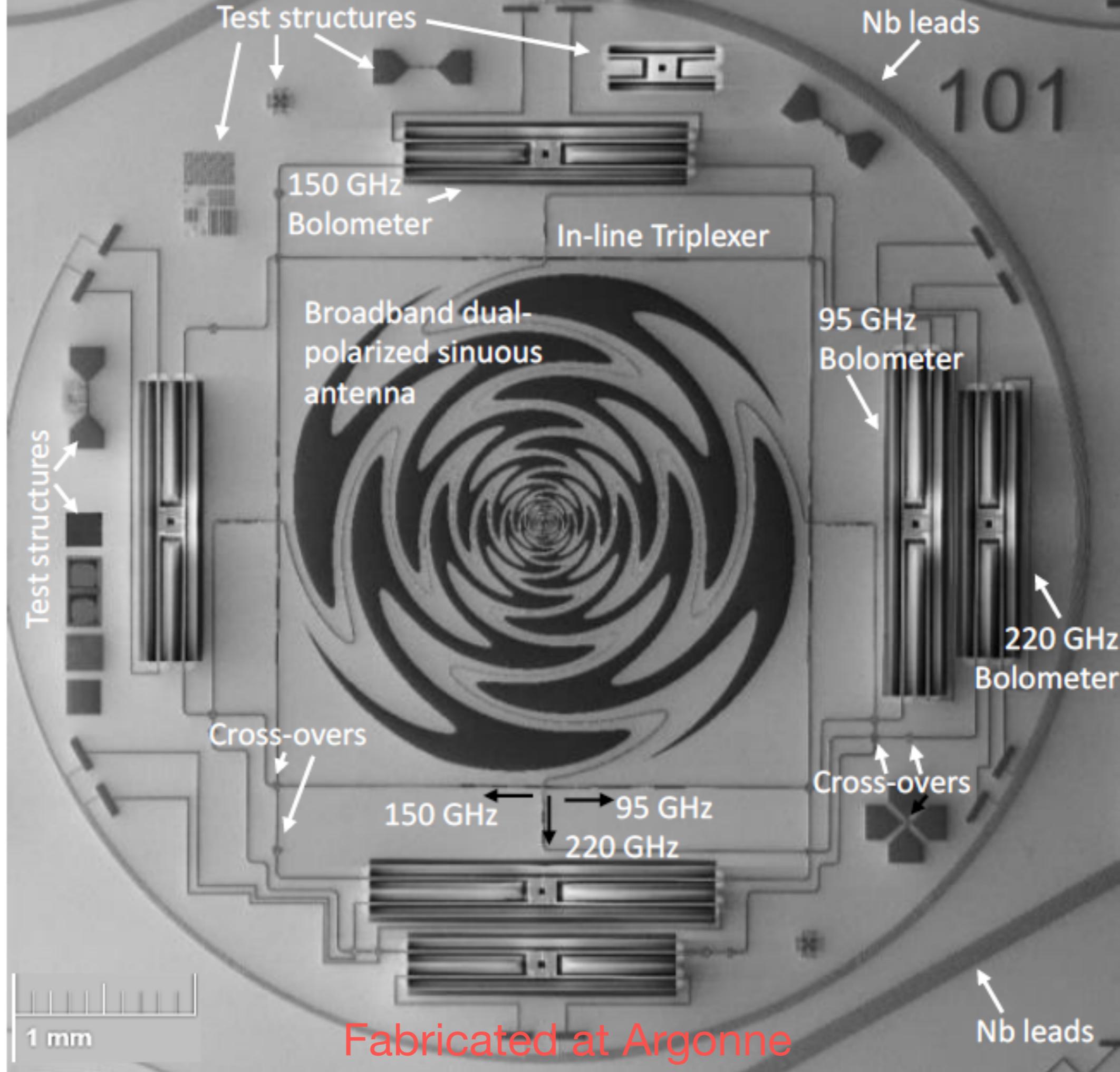
Fabricated at Argonne

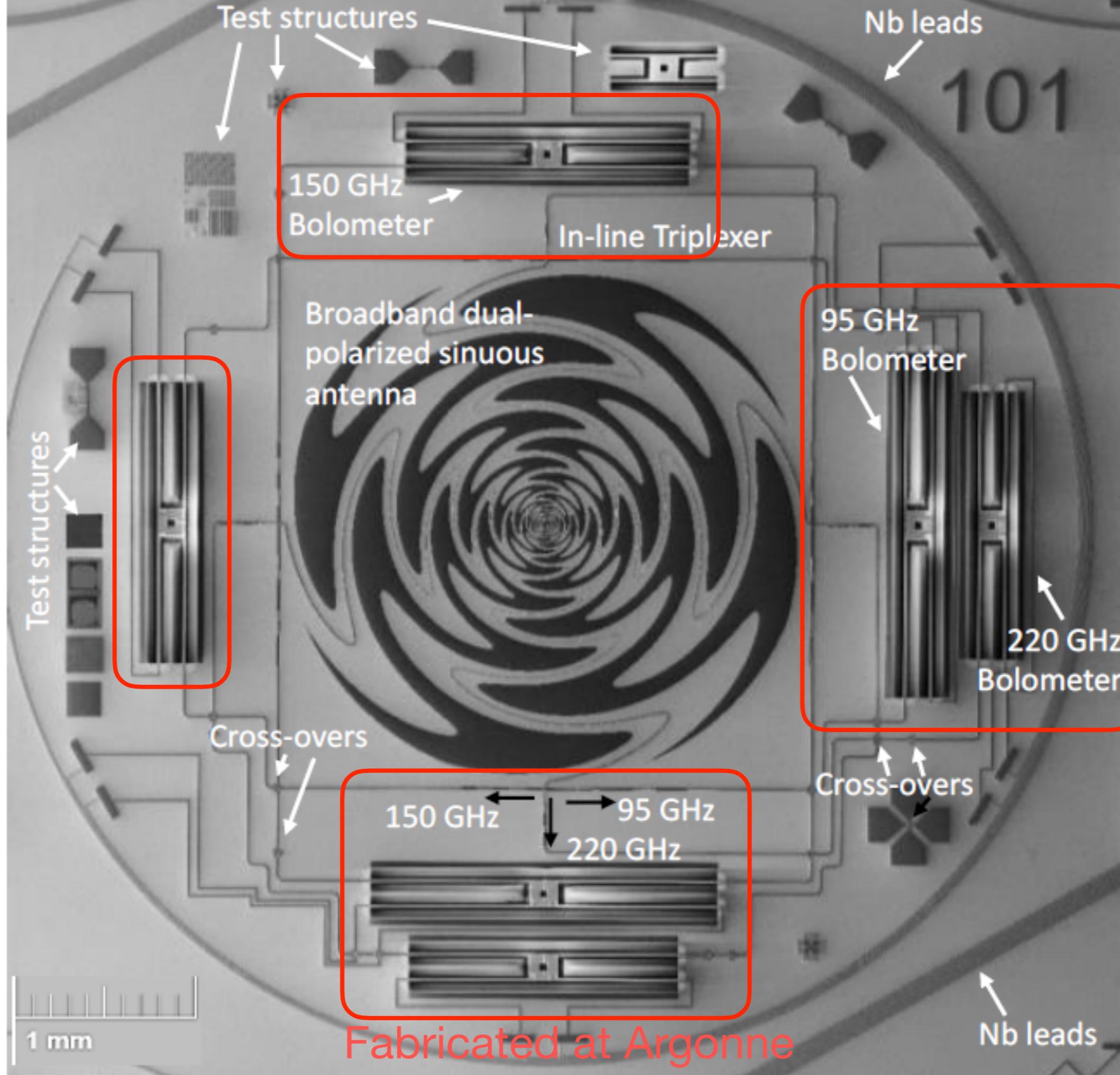


Fabricated at Argonne

Multichroic Pixel Performance



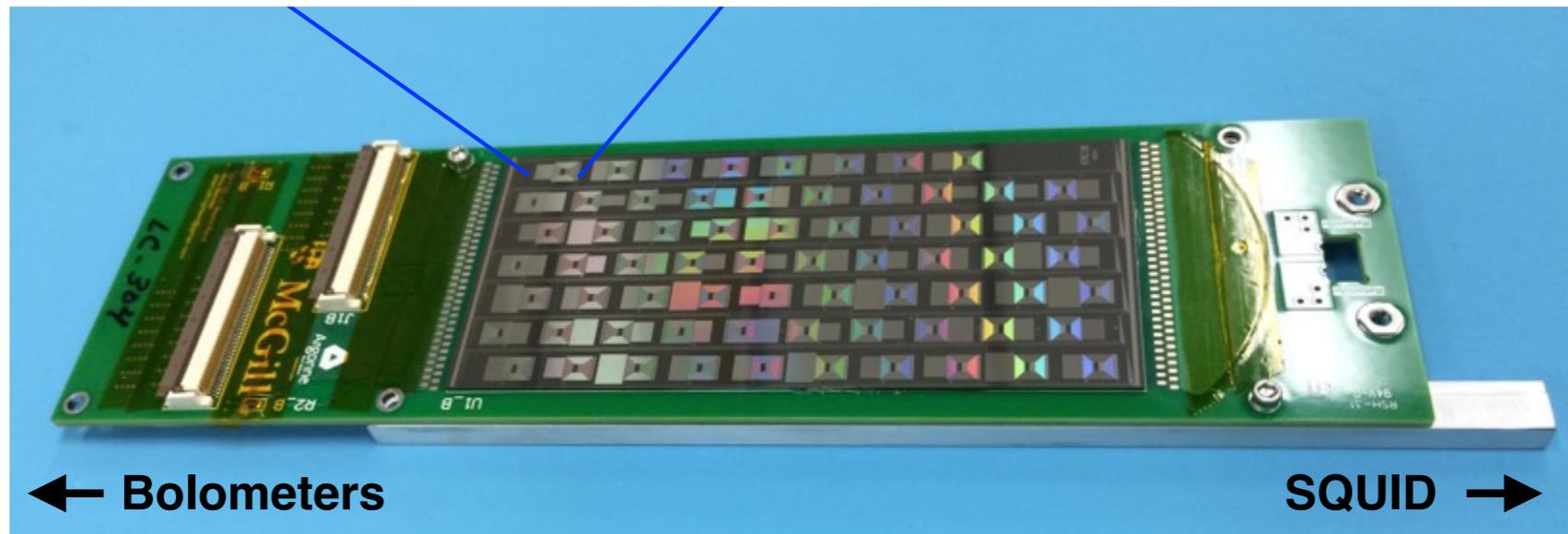
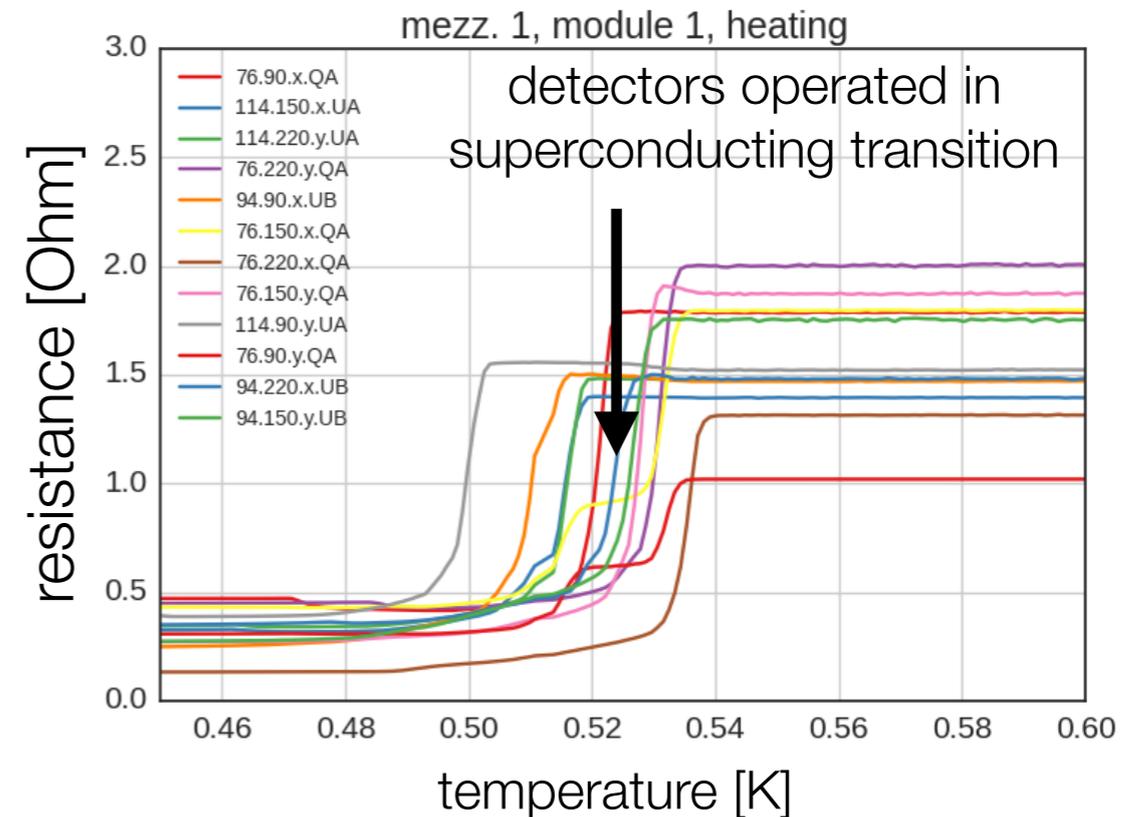




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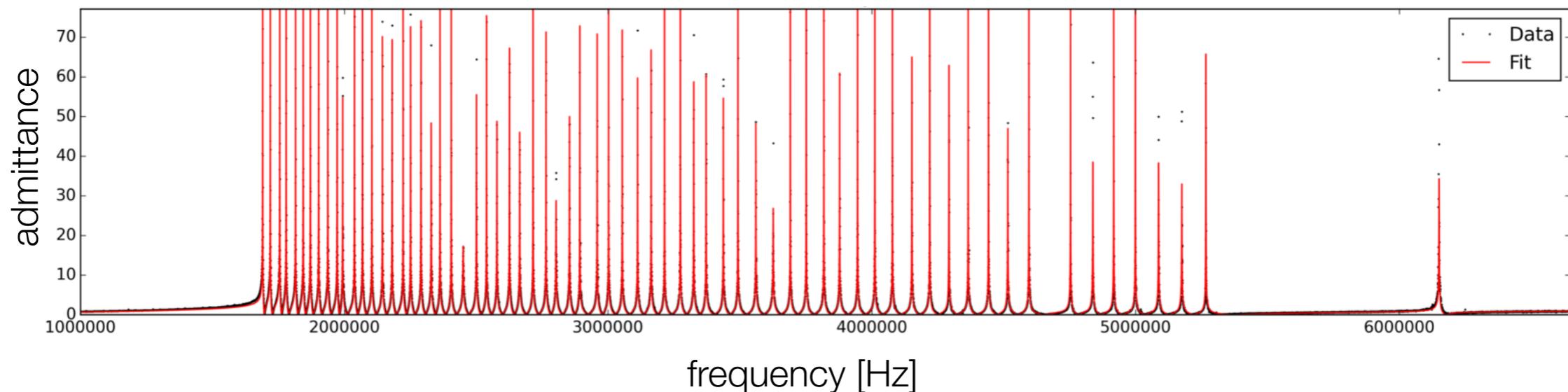
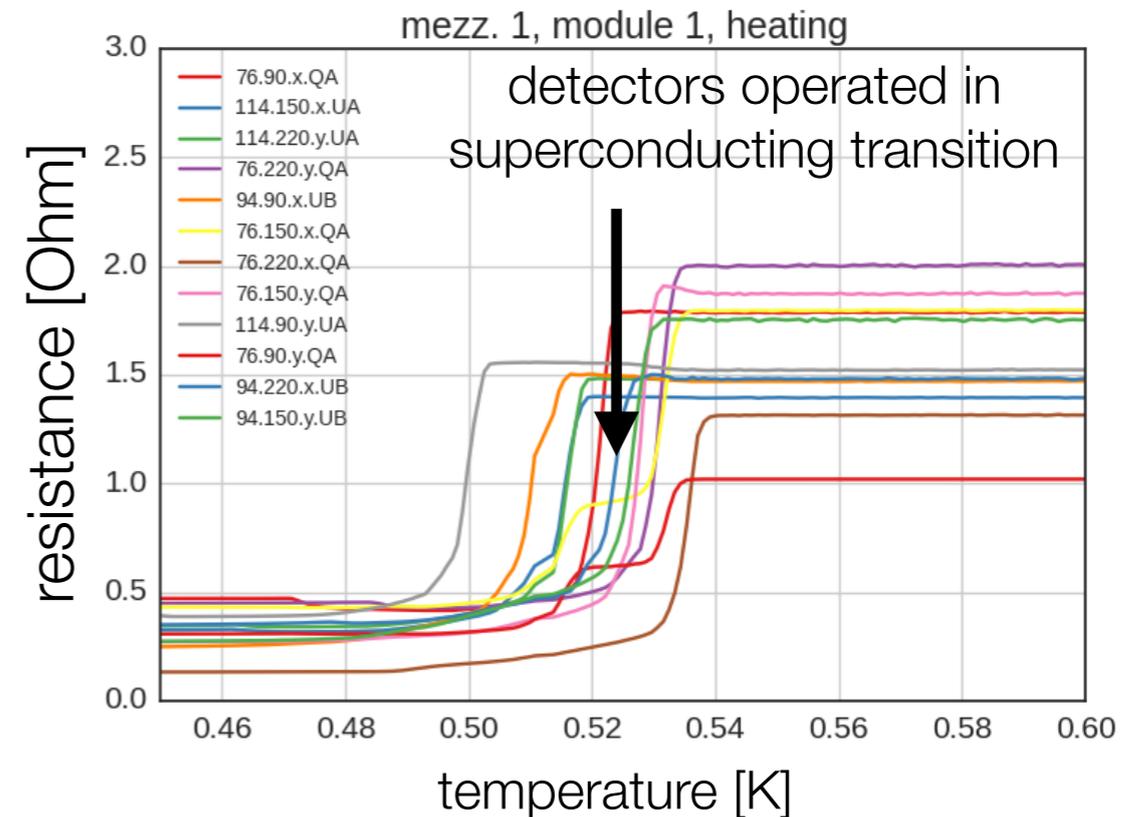
TES Bolometers and Readout

- Antennas coupled to transition-edge sensor bolometers at 500mK read out by SQUID amplifiers
- Channel count requires 64x multiplexing factor
- Frequency-domain multiplexing with amplitude modulation by sky signal (a la AM radio)

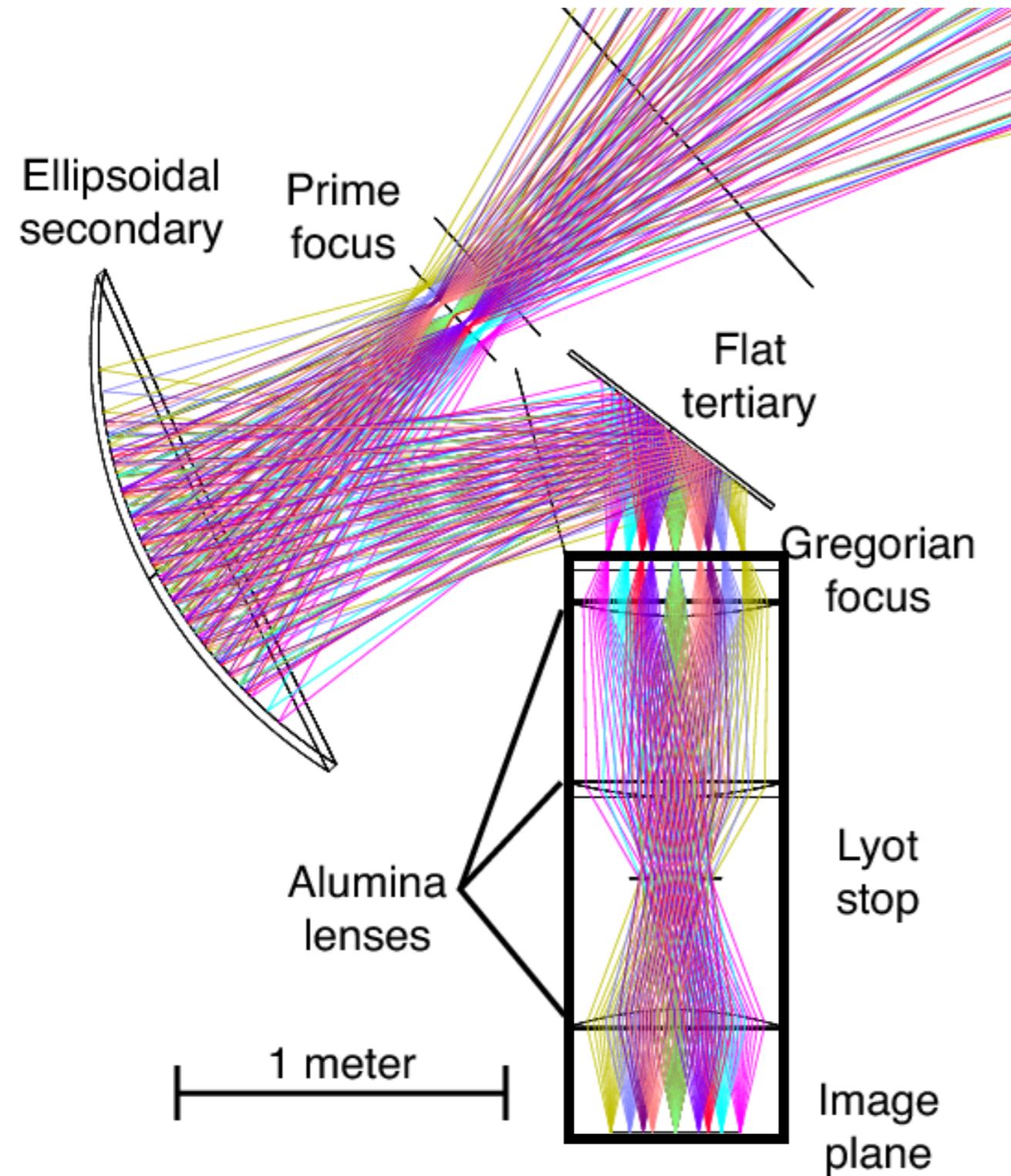


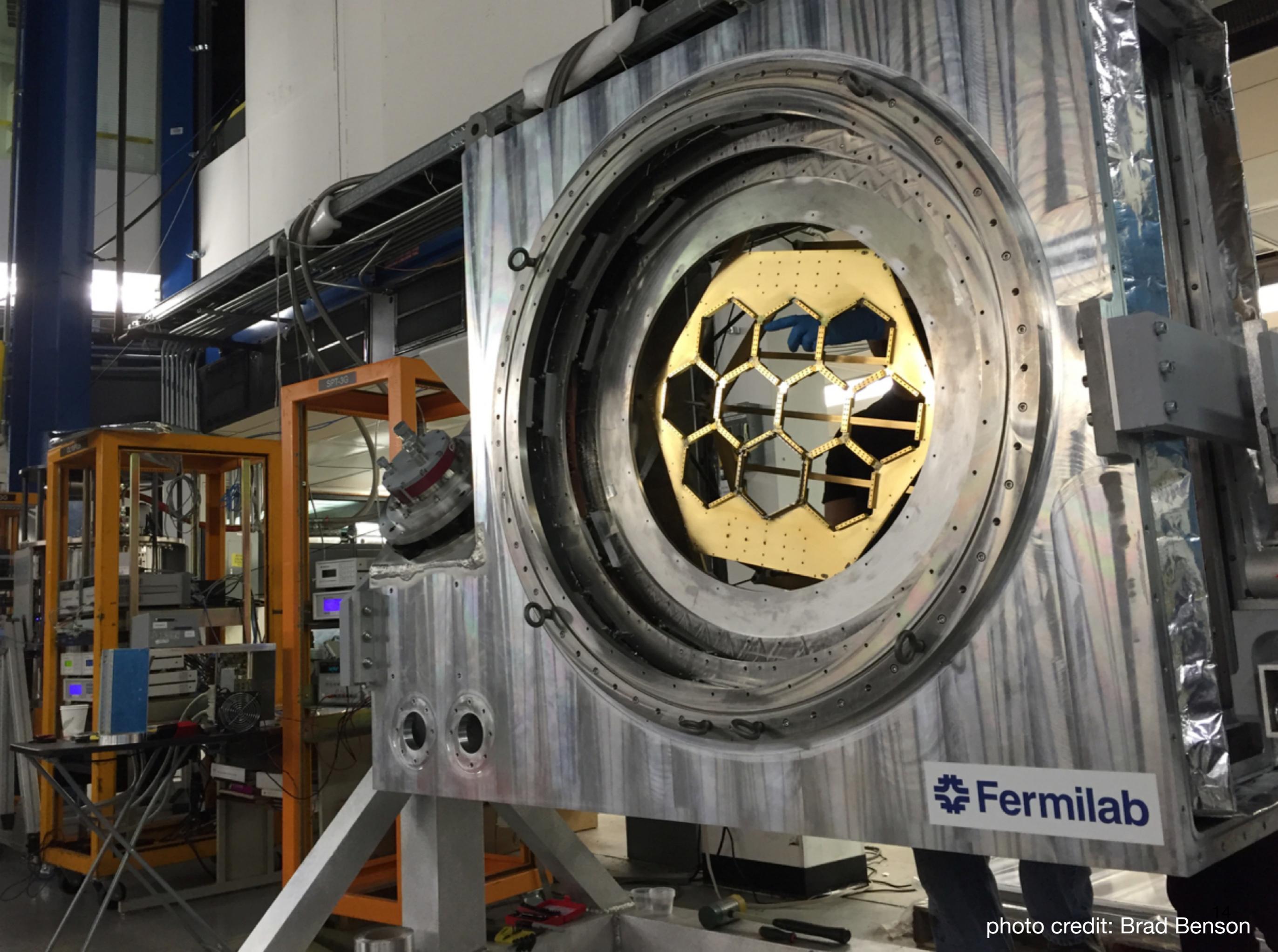
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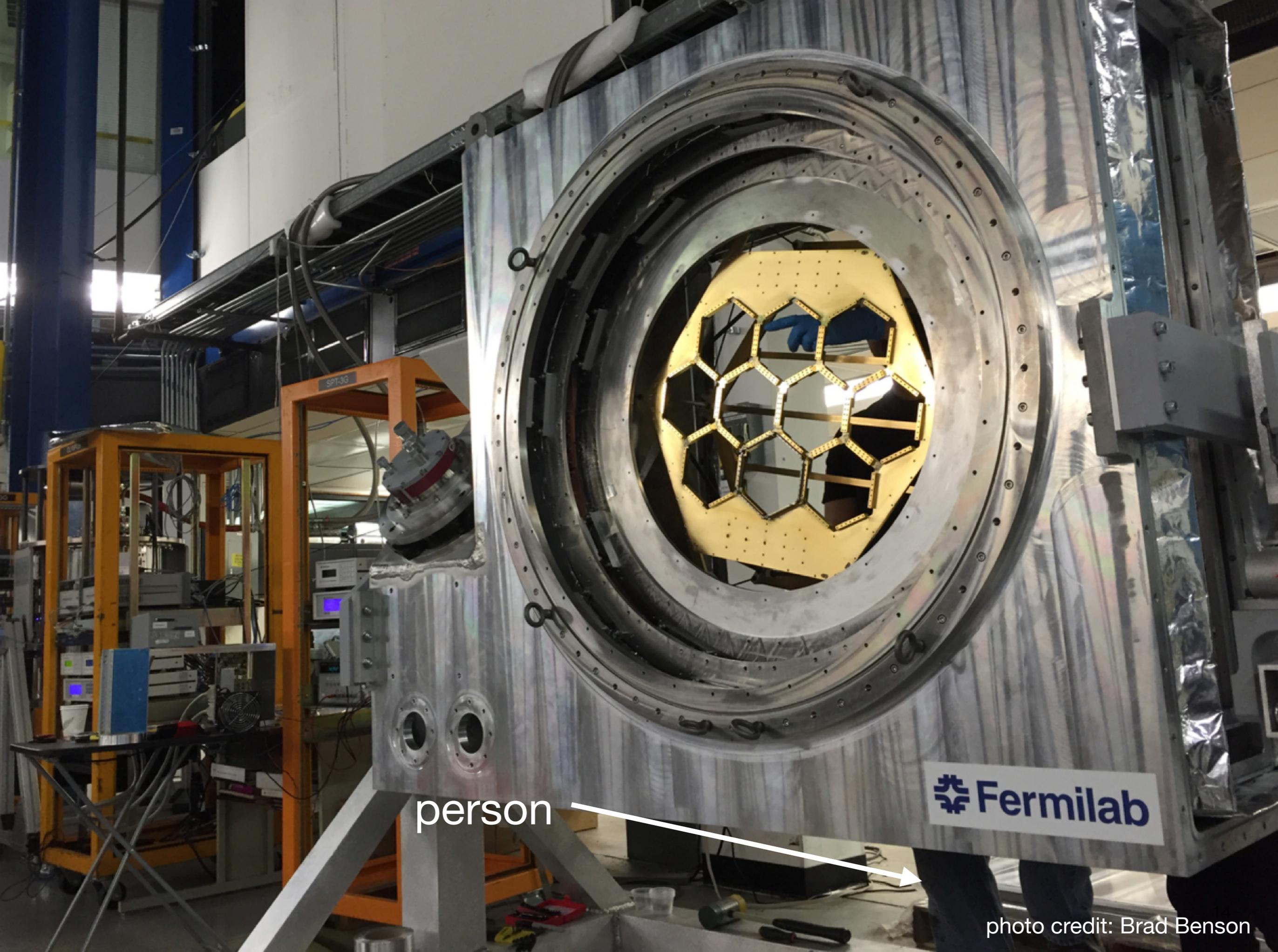
Optics and Cryostat





 **Fermilab**

photo credit: Brad Benson



person

 Fermilab

photo credit: Brad Benson

Commissioning and Timeline

- Ongoing:
 - Cryostats assembled at Fermilab, currently testing
 - Optics assembly
 - Detector and electronics testing at Fermilab and elsewhere
- Oct. 2016: Ship to South Pole
- Nov. 2016 - Feb. 2017: Commissioning at pole
- 2017: First data

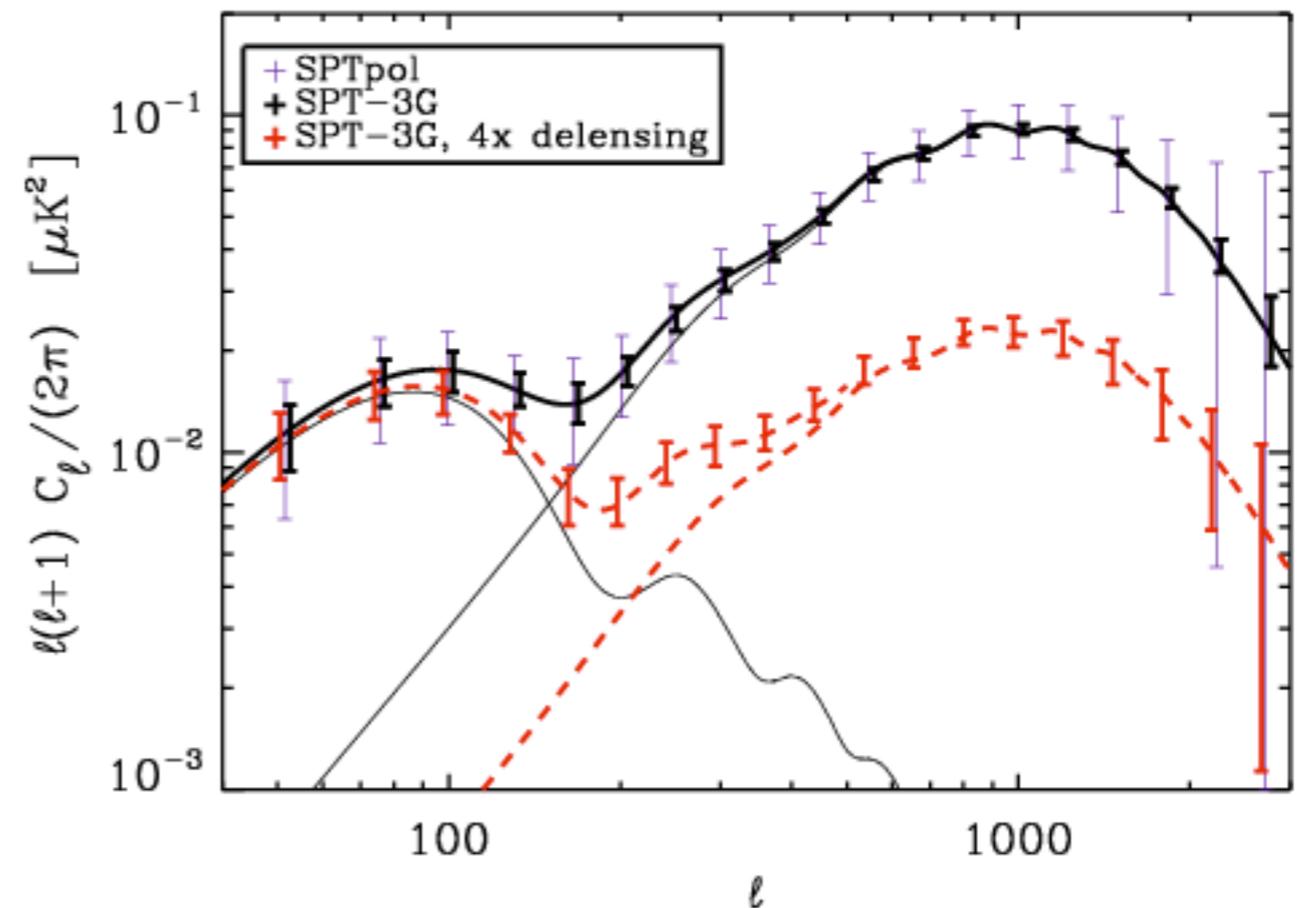
The Fermilab logo, featuring a stylized blue and white symbol to the left of the word "Fermilab" in a bold, blue, sans-serif font. The logo is positioned on a white rectangular background that is part of a larger piece of equipment or a sign in the lower right corner of the image.

Fermilab

A Few Recent Results and Projections for SPT-3G

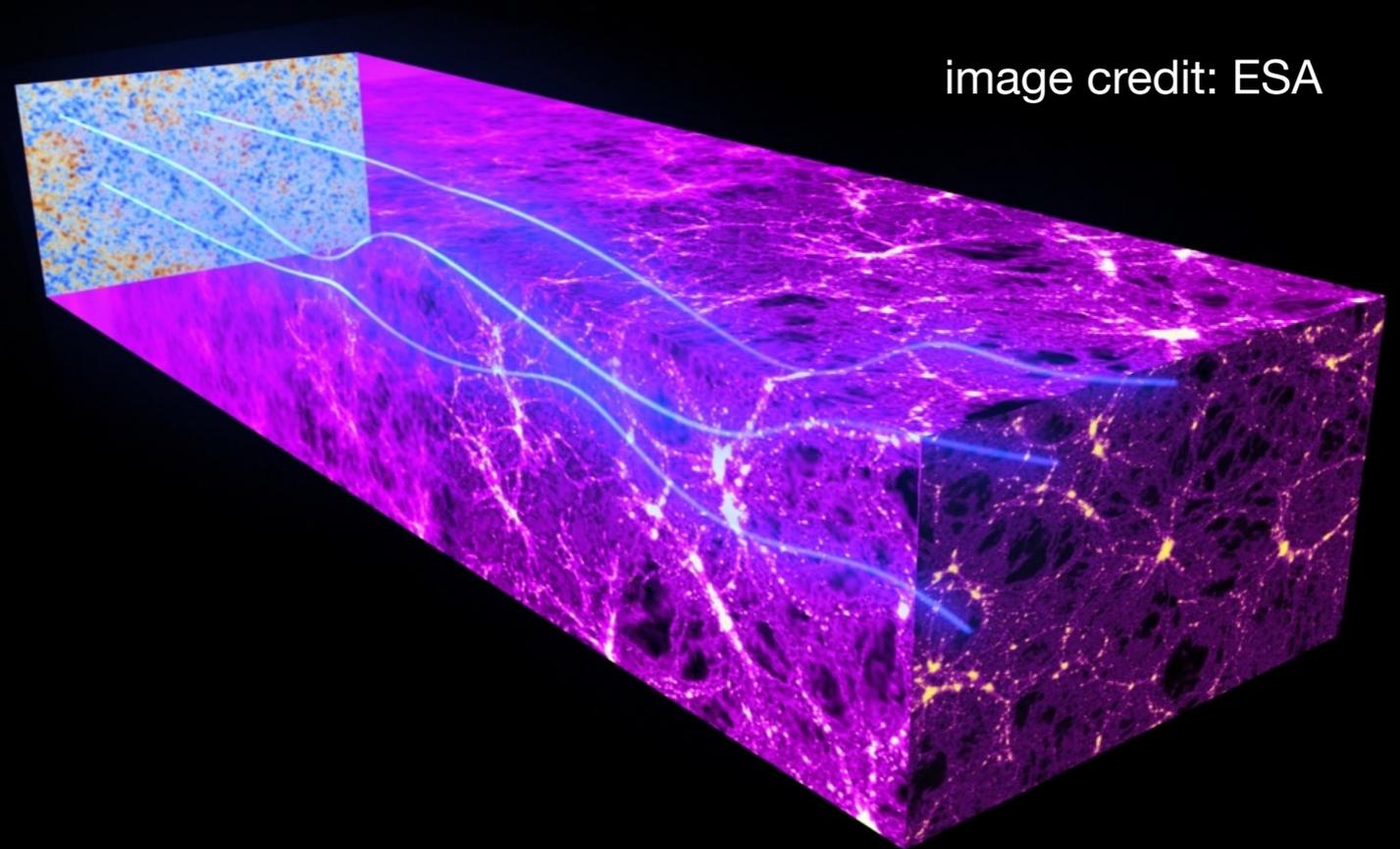
B-mode Power Spectrum with SPT-3G

- 2500 sq deg survey in 4 years starting in 2017
- Sensitivity to r of 0.01
- High-sensitivity measurement of lensing B-modes will enable removal of lensing B-modes in SPT data
- BICEP/Keck field overlaps with SPT-3G field, combined analysis with SPTpol ongoing

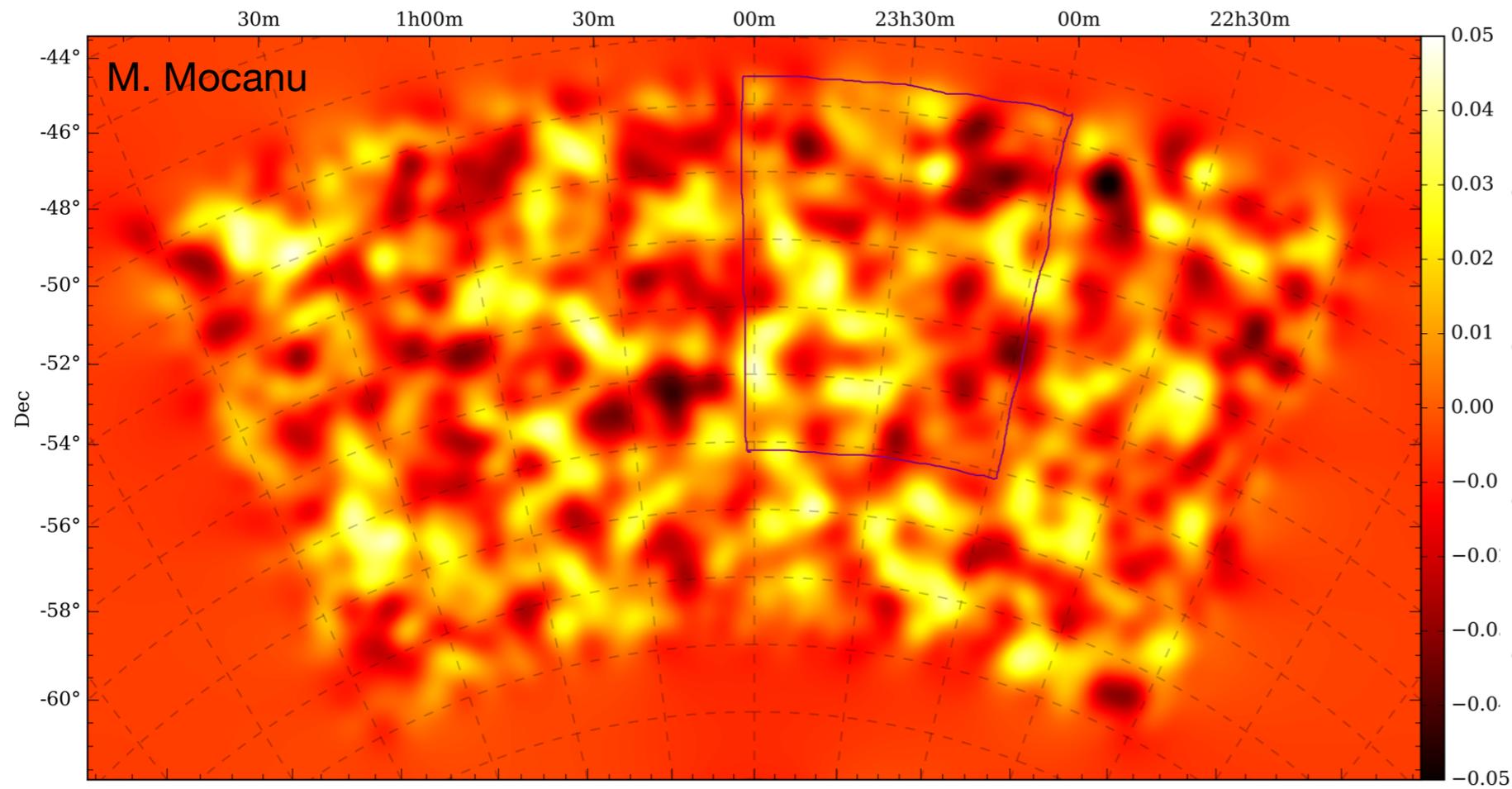


CMB Lensing Potential

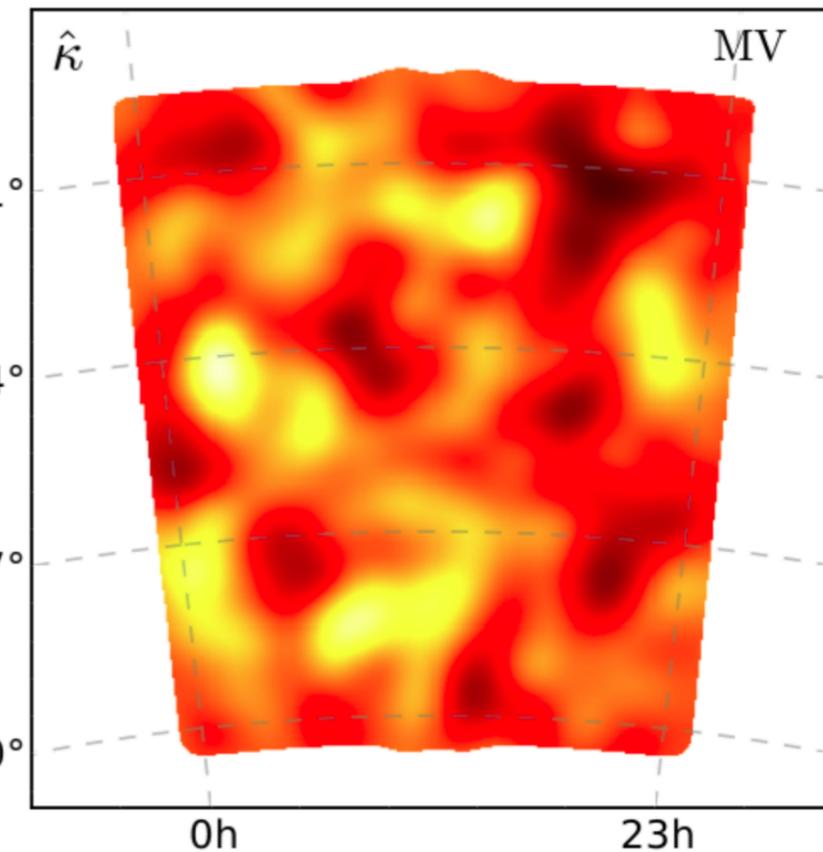
- Gravitational lensing of CMB photons by intervening matter distorts spectrum and introduces correlations
- Can reconstruct the projected gravitational potential between us and CMB



Maps of Lensing Potential with SPTpol



500 sq deg SPTpol
(2013-2015)
in prep.



100 sq deg SPTpol
(2012-2013)
Story, et al., 2015

- Improves constraints on neutrino masses in cosmology fits
- Can be used for delensing of BICEP/Keck data

Future Sensitivity

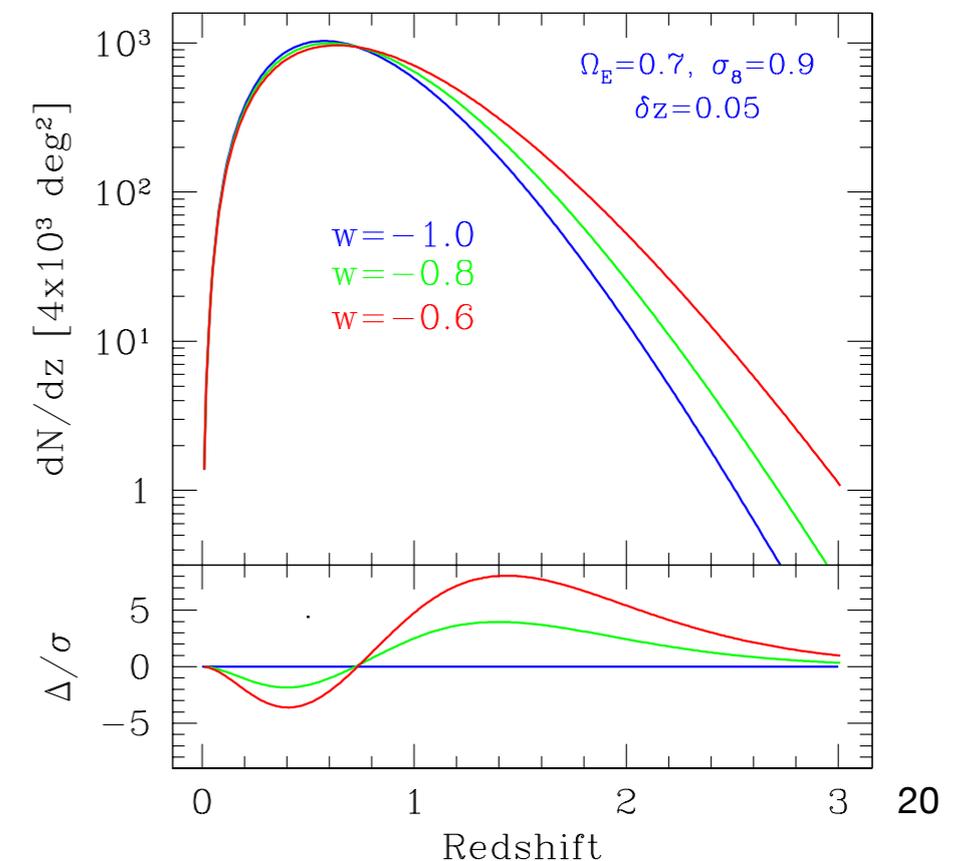
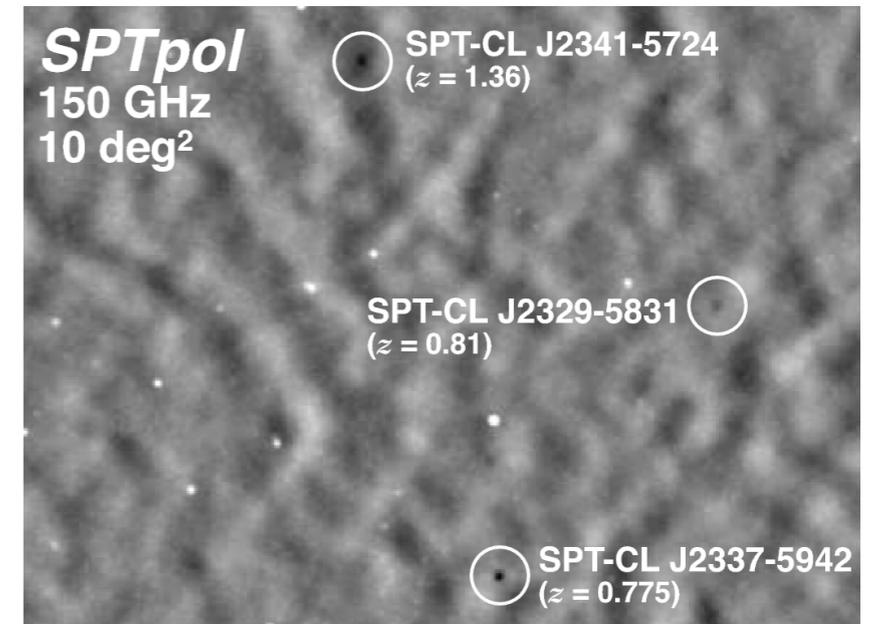
	$\sigma(r)$	$\sigma(N_{\text{eff}})$	$\sigma(\Sigma m_\nu)$ (meV)
Current CMB	0.05	0.32	117*
Stage 2 (SPTpol)	0.03	0.12	96*
Stage 3 (SPT-3G)	0.01	0.06	61*
Stage 4: CMB-S4	0.001	0.02	16**

* Includes BOSS prior

** Includes DESI prior

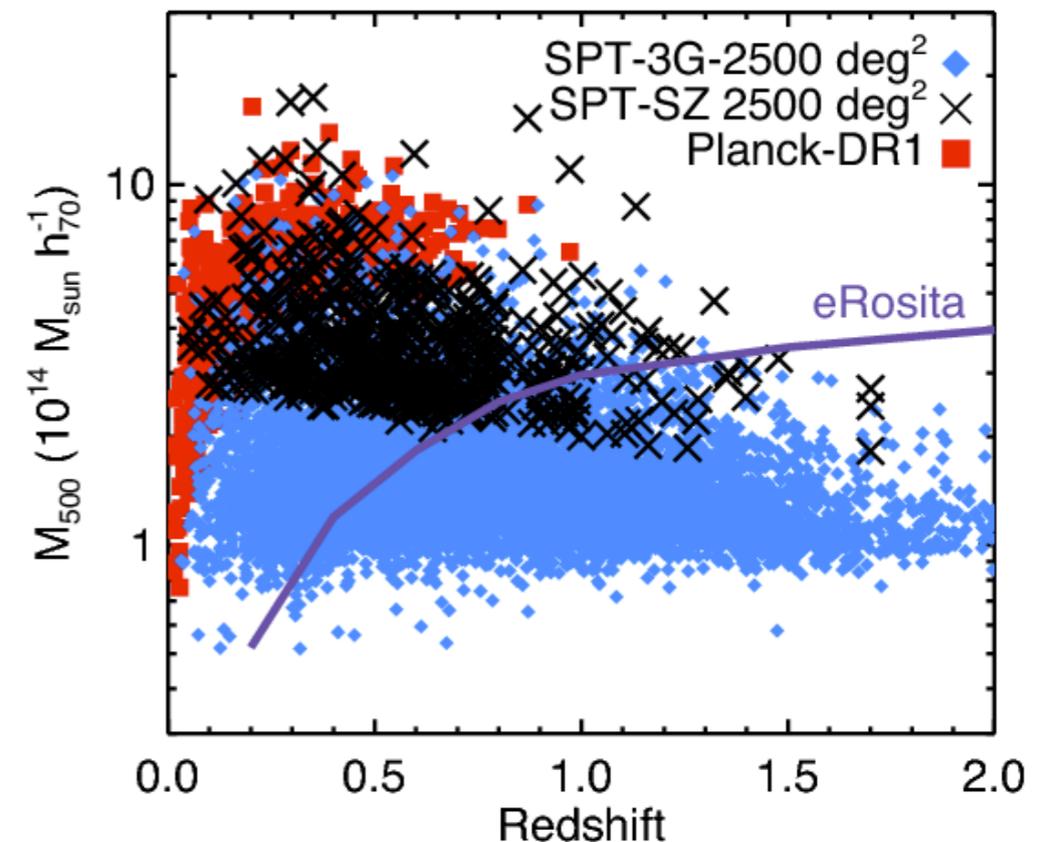
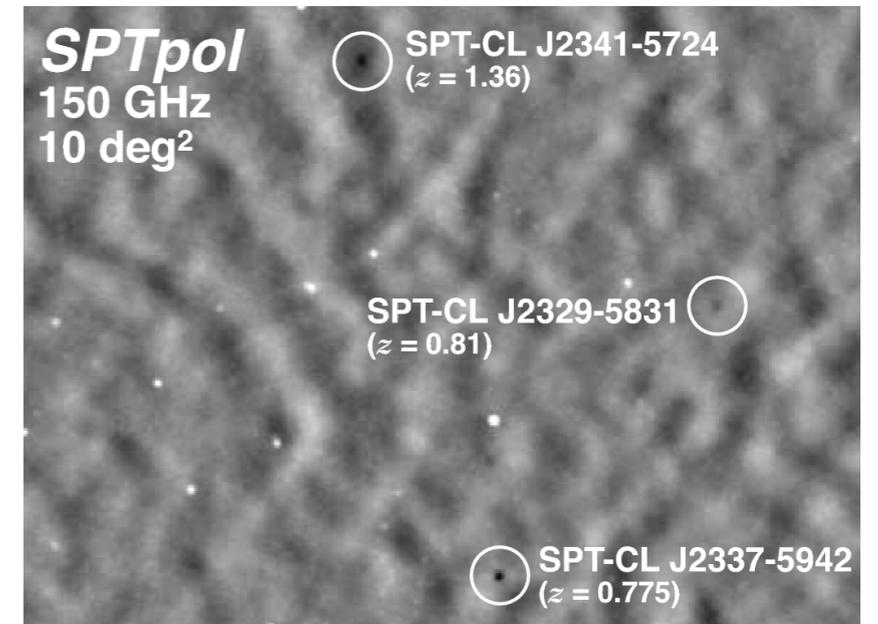
Dark Energy and Clusters

- Thermal Sunyaev-Zeldovich (SZ) effect: inverse Compton scattering of CMB photons on hot cluster gas distorts CMB spectrum
- Cluster mass distribution as a function of redshift sensitive to dark energy
- SPT-3G will increase number of SZ-detected clusters by about 10x to **~5000** (S/N>4.5)
- SZ effect provides calibration of cluster masses which can be used with redshifts from photometric or spectroscopic surveys
- **Highly complementary to DES!**



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Summary

- SPT 3G will probe inflation, neutrino masses, and dark energy with high-resolution CMB maps
- Major opportunity for cross-correlation with other projects, especially DES, BICEP/Keck
- Enabled by factor $\sim 20x$ increase in sensitivity from multichroic detectors and optical throughput
- Instrument commissioning is ongoing
- First data taking in early 2017

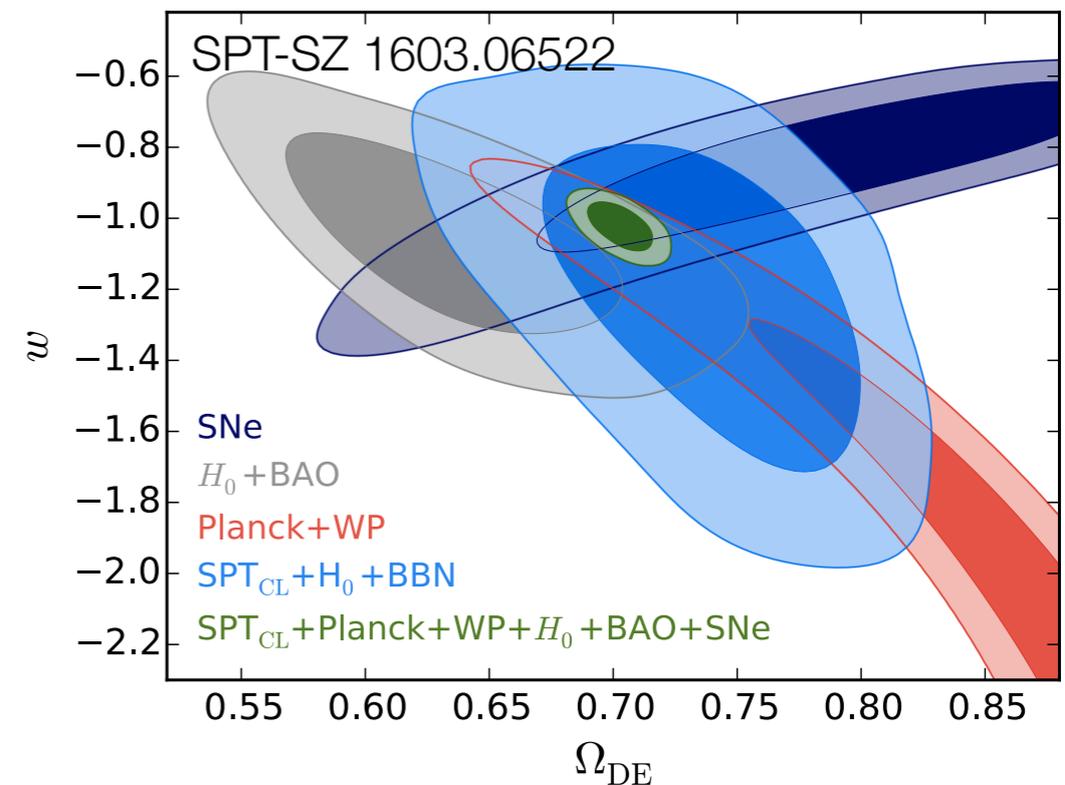
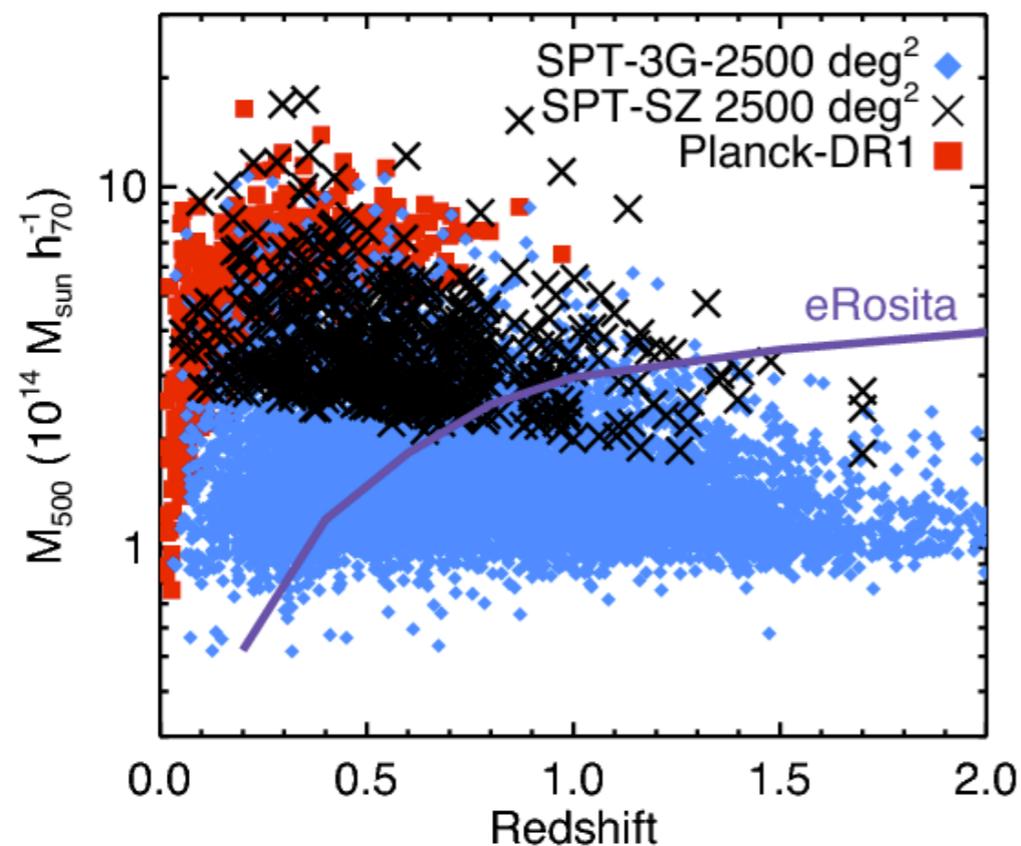


Questions?

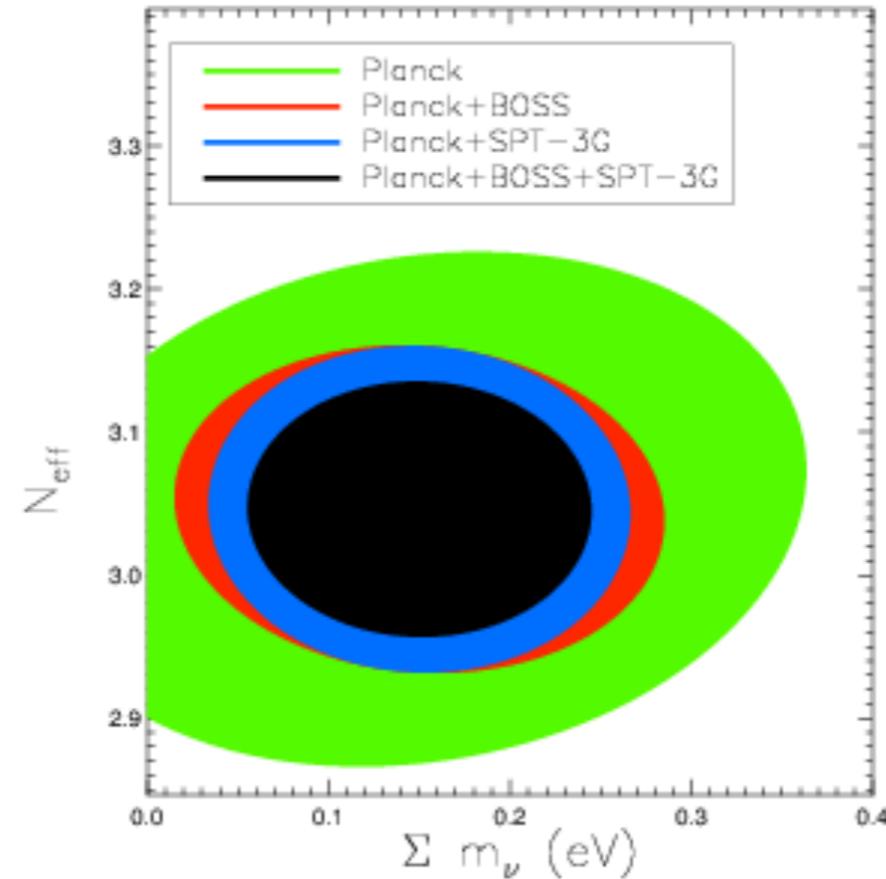
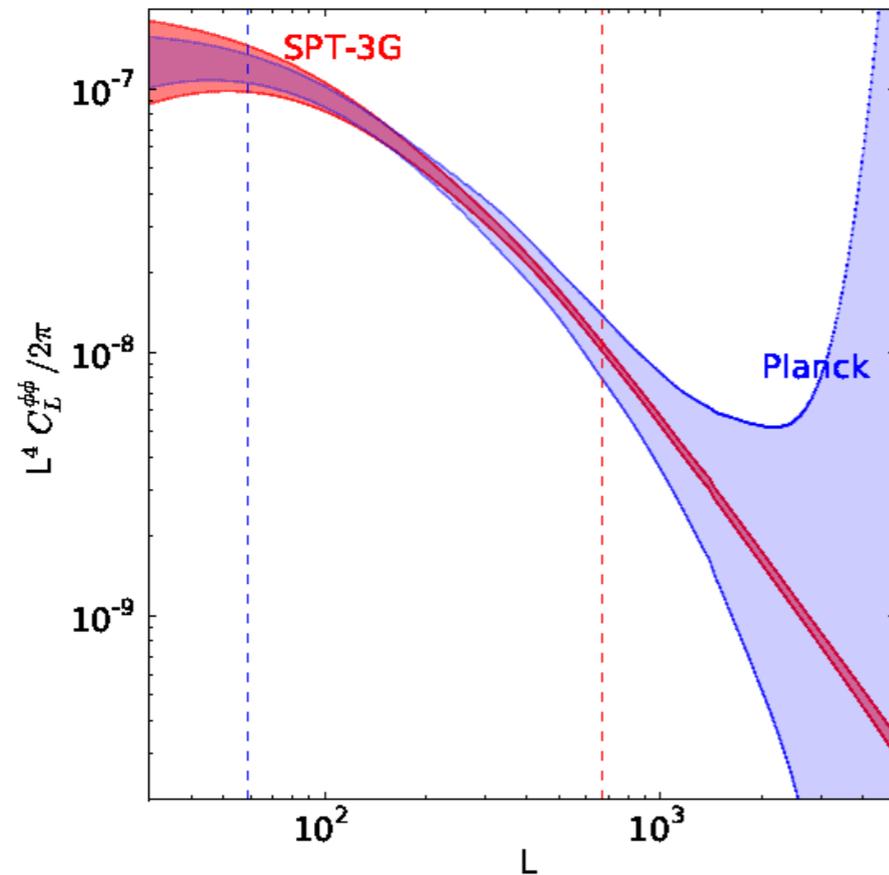


Cluster Cosmology with SPT

- Sunyaev-Zeldovich (SZ) effect: inverse Compton scattering of CMB photons on hot cluster gas distorts CMB spectrum
- Cluster abundance vs. redshift sensitive to dark energy equation of state
- Cross-correlation with DES possible to further improve dark energy constraints



Projected Constraints for SPT-3G



- SPT-3G will significantly improve CMB lensing constraints relative to Planck and SPTpol
- $\sigma(\Sigma m_\nu) \sim 0.06$ eV achievable in combination with BAO and Planck
- Begins to probe inverted hierarchy of neutrino masses

Pairwise Kinematic Sunyaev-Zeldovich Effect

- Doppler shift imparted on CMB photons from scattering on galaxy cluster with net bulk velocity
- Pairs of clusters tend to fall toward each other, producing pattern in CMB as function of separation
- Combines SPT maps with DES redshift data
- Lower cluster mass threshold in SPT-3G will increase sensitivity to **20-50 σ**

