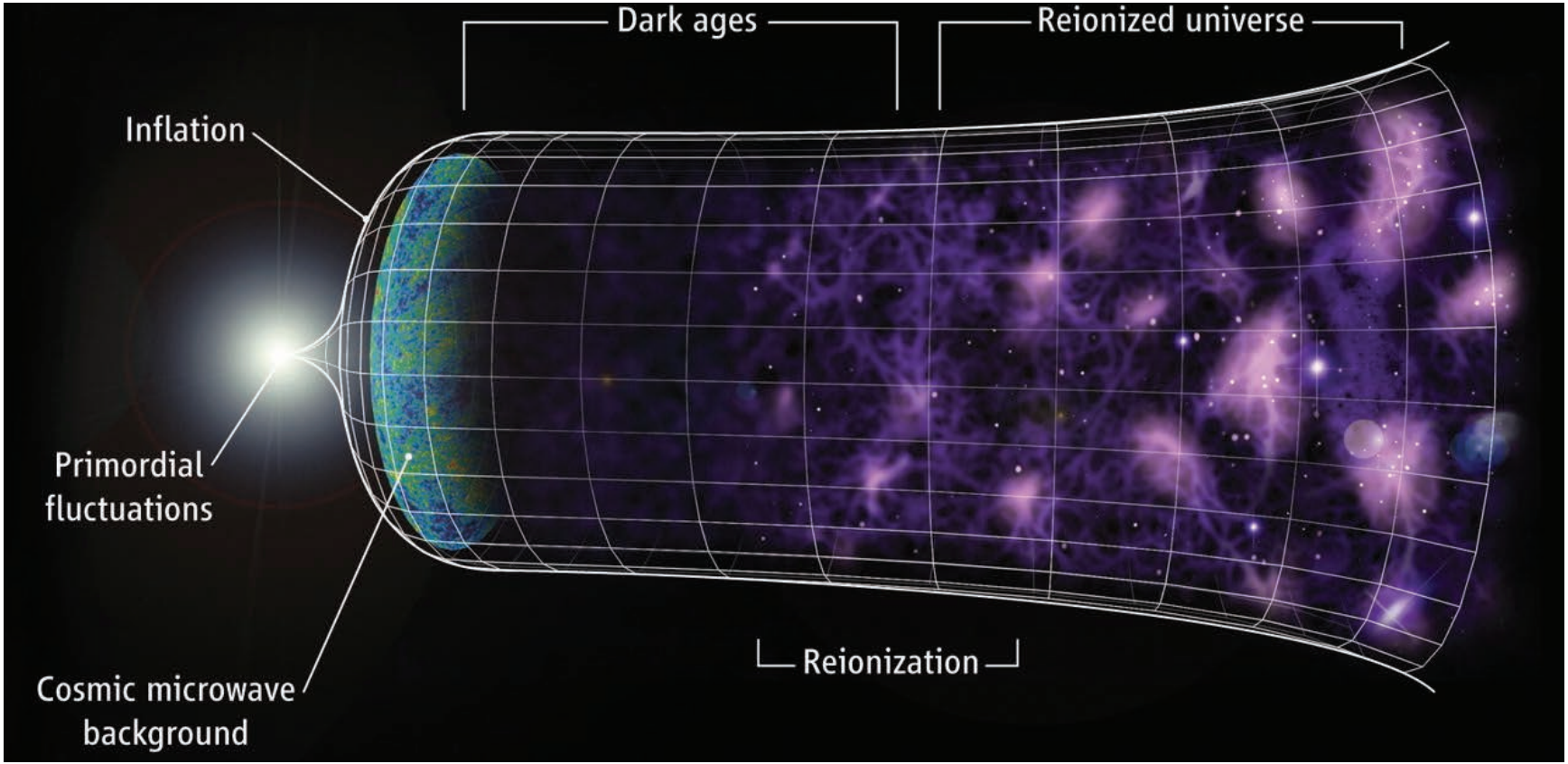
current view of cosmology



POLL: BIG BANG A BIG QUESTION FOR MOST AMERICANS

By SETH BORENSTEIN and JENNIFER AGIESTA — Apr. 21, 2014 11:59 AM EDT

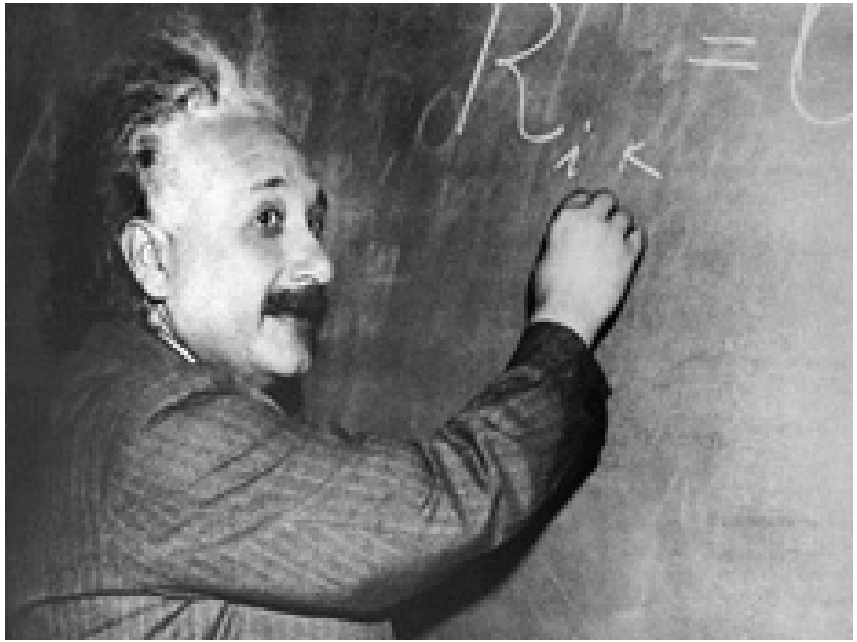
Home » Business » Poll: Big Bang a big question for most Americans

	Extremely/very confident	Extremely confident	Very confident	**Somewhat confident**	**Not too/not at all confident**	Not too confident	Not at all confident	Refused/Not Answered
Smoking causes cancer	**82**	59	23	**12**	**4**	4	1	2
A mental illness is a medical condition that affects the brain	**71**	37	34	**21**	**6**	5	1	3
Inside our cells, there is a complex genetic code that helps determine who we are	**69**	38	30	**22**	**8**	5	2	2
Overusing antibiotics causes the development of drug-resistant bacteria	**65**	36	30	**23**	**9**	8	1	3
The universe is so complex, there must be a supreme being guiding its creation	**54**	40	14	**18**	**25**	13	12	3
Childhood vaccines are safe and effective	**53**	20	33	**30**	**15**	11	4	3
The average temperature of the world is rising, mostly because of man-made heat-trapping greenhouse gases	**33**	13	20	**28**	**37**	22	15	3
Life on Earth, including human beings, evolved through a process of natural selection	**31**	14	17	**24**	**42**	16	27	3
The Earth is 4.5 billion years old	**27**	11	17	**33**	**36**	18	18	4
The universe began 13.8 billion years ago with a big bang	**21**	8	13	**25**	**51**	20	30	4

Base: N=1,012

foundations of ΛCDM cosmology

- Motivated on theoretical grounds

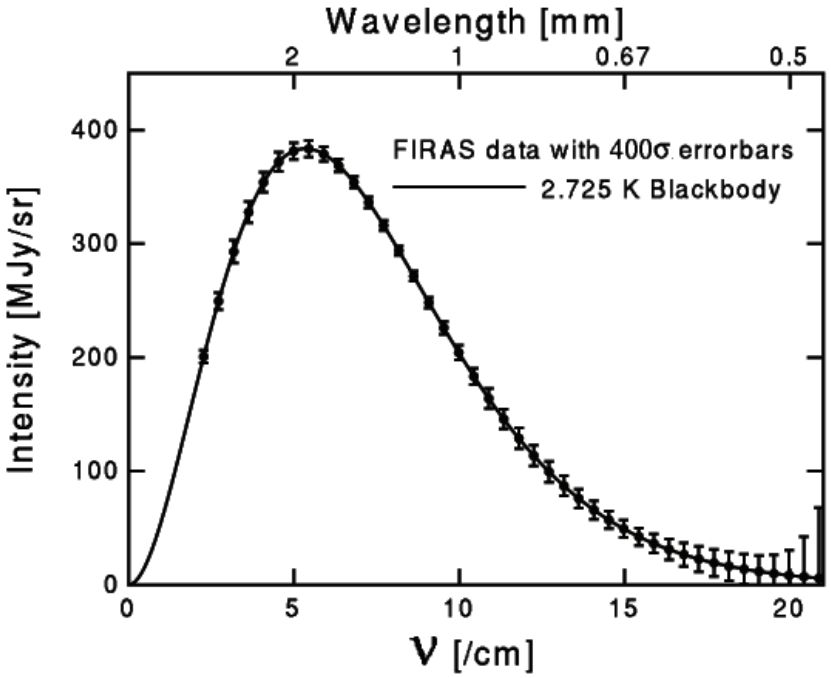


GR + cosmological principle -> expanding universe

foundations of ΛCDM cosmology

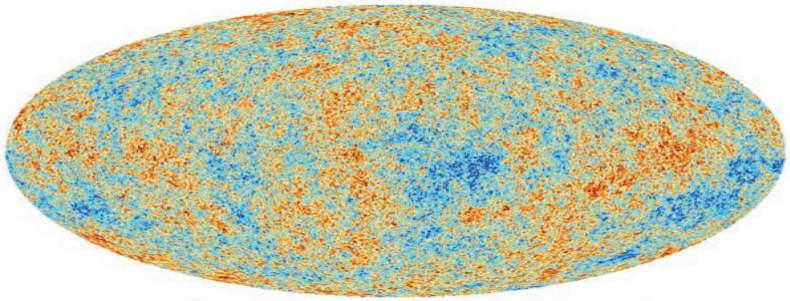
- Motivated on theoretical grounds

- The existence of the cosmic microwave background



foundations of ΛCDM cosmology

- Motivated on theoretical grounds



Credit: Planck Team

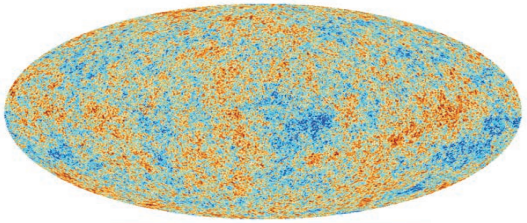
- The existence of the cosmic microwave background

uniform to 100ppm

- Statistical properties of CMB temperature anisotropies

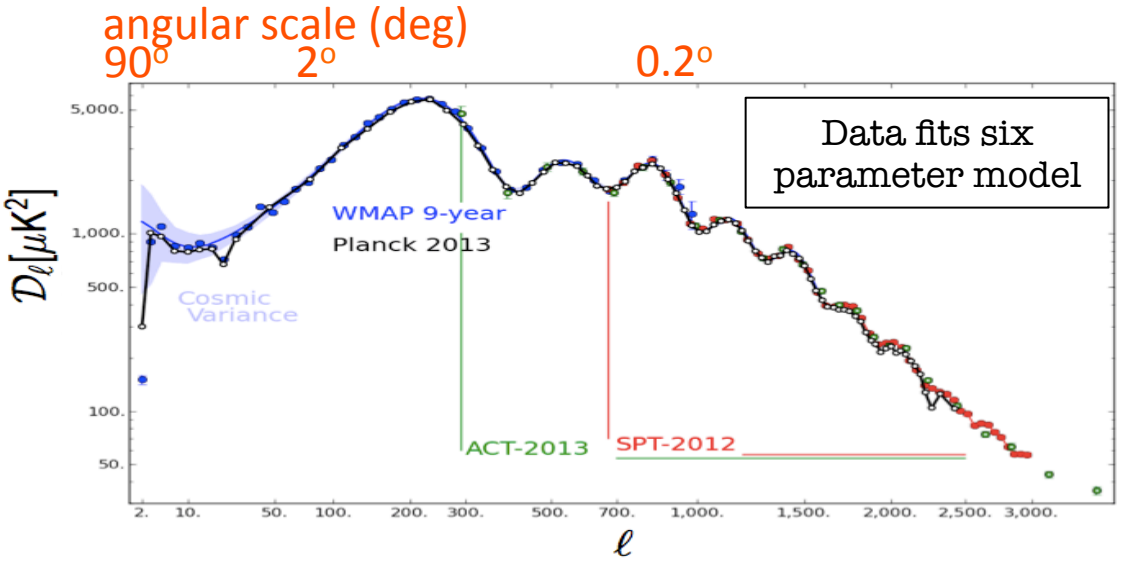
established ΛCDM:
6 parameter model of big bang cosmology

angular power spectrum and parameter determination



-300 μK +300 μK

Credit: Planck Team



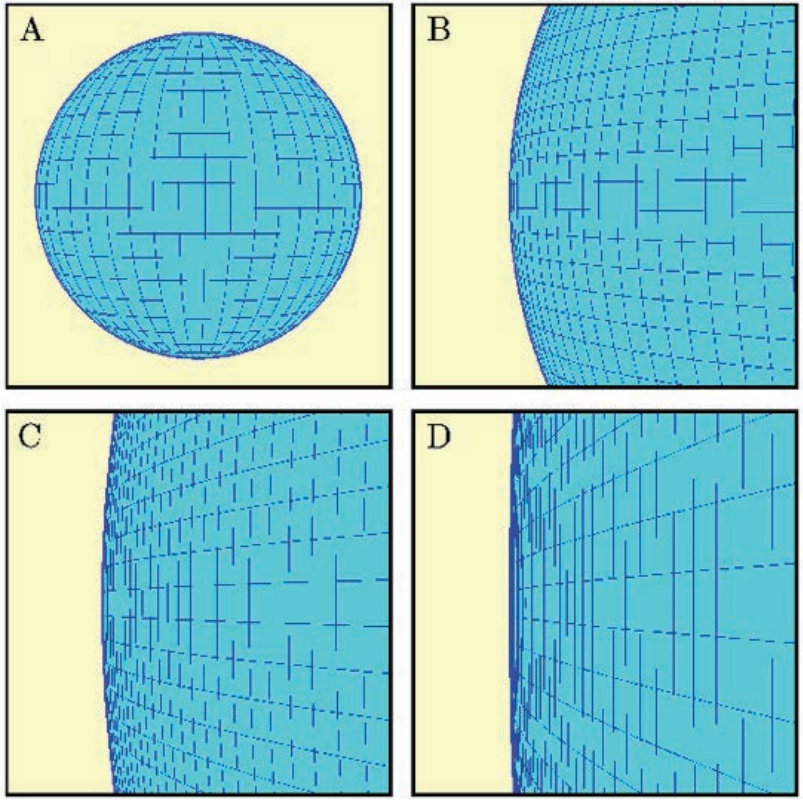
Parameter	Value	Description
t_o	13.7965 ± 0.037 Gyr	age of the universe
H_o	67.80 ± 0.77 km s^{-1} Mpc^{-1}	Hubble parameter
Ω_b	0.0482 ± 0.0005	baryon density
Ω_m	0.2582 ± 0.0037	dark matter density
Ω_Λ	0.692 ± 0.010	dark energy density

Planck+WMAP+ACT+SPT+BAO 2013

ΛCDM: universe has a cosmological constant, is filled with dark and baryonic matter, and initial spectrum of perturbations is near scale invariant.

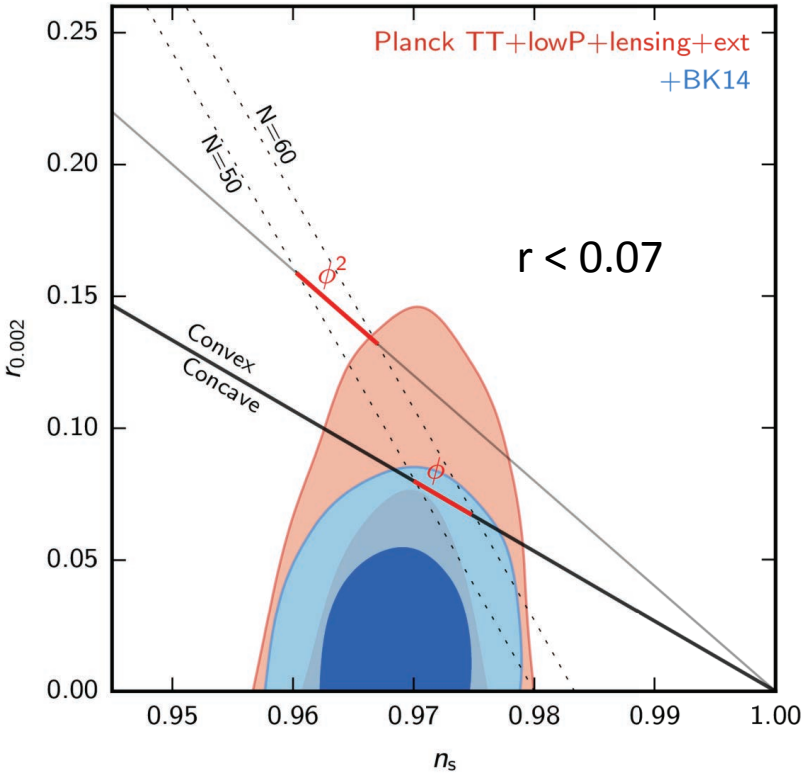
cosmic inflation

- Exponential expansion of space at 10^{-36} - ~10^{-32} s. “The bang” of “the big bang”.
  - A.H. Guth Phys. Rev. D **23**, 327 (1981)
  - A.D. Linde Phys. Lett. B **108**, 389 (1982)
  - A. Albrecht, P.J. Steinhardt Phys. Rev. Lett. **48**, 1220 (1982)
- Explains observed flatness and homogeneity
- Leading paradigm for explaining origin of primordial density perturbations that seed structure formation



inflation predictions, current constraints

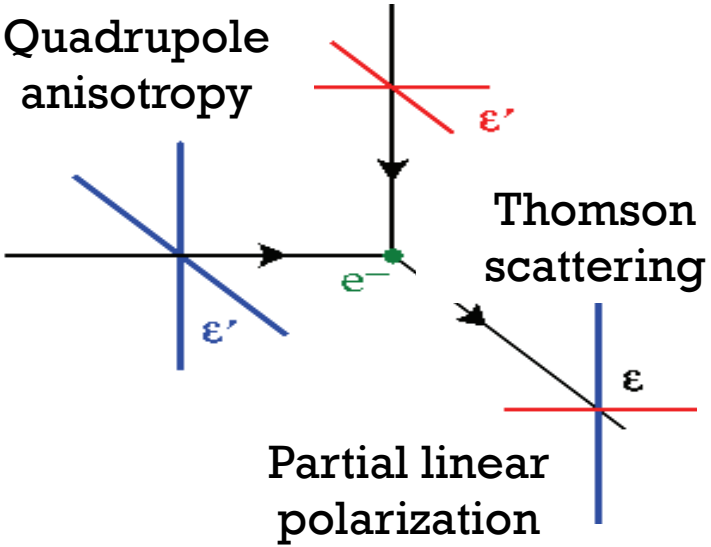
- near scale invariant spectrum of density perturbations
  - $\delta P \sim k^{n_s-1}$
  - n_s slightly less than 1
- Stochastic background of gravity waves
  - parameterized by "r": ratio of power in tensors to scalars
  - direct measure of expansion rate during inflation
- CMB measurements constrain both n_s and r



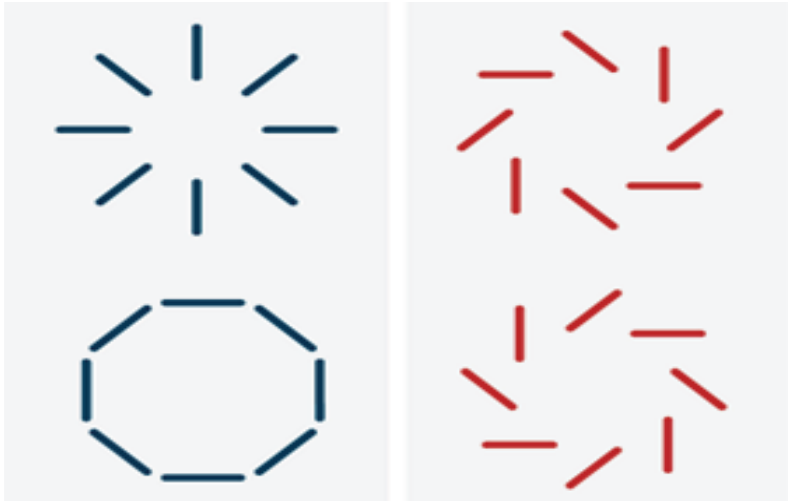
BK-VI Phys. Rev. Lett. **116**, 031302 (2016)

CMB is linearly polarized

Thomson scattering + quadrupole anisotropy ➔ linear polarization



Credit: Hu

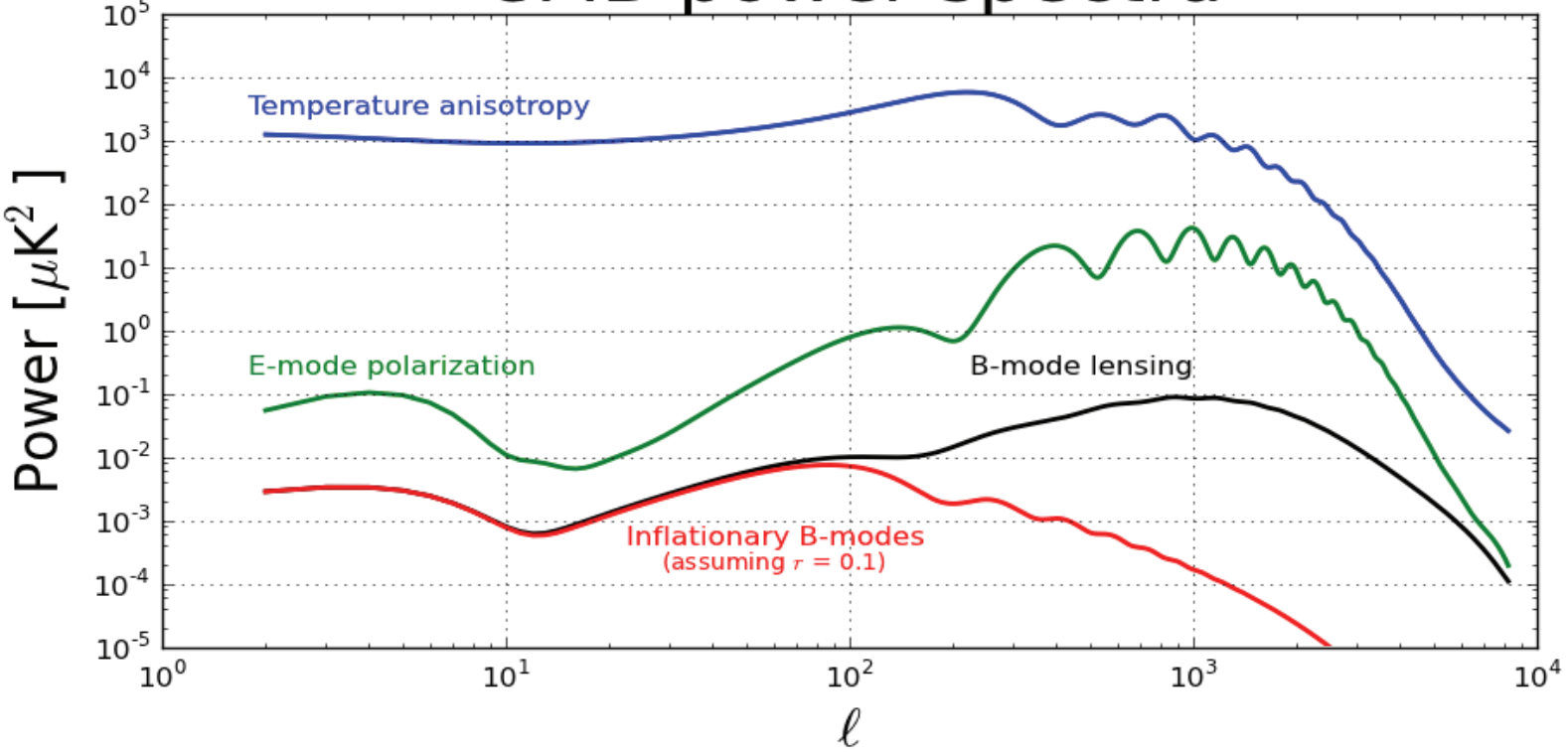


Density fluctuations

Gravity waves & lensing

Credit: Sky and Telescope

CMB power spectra



summary power spectrum measurements

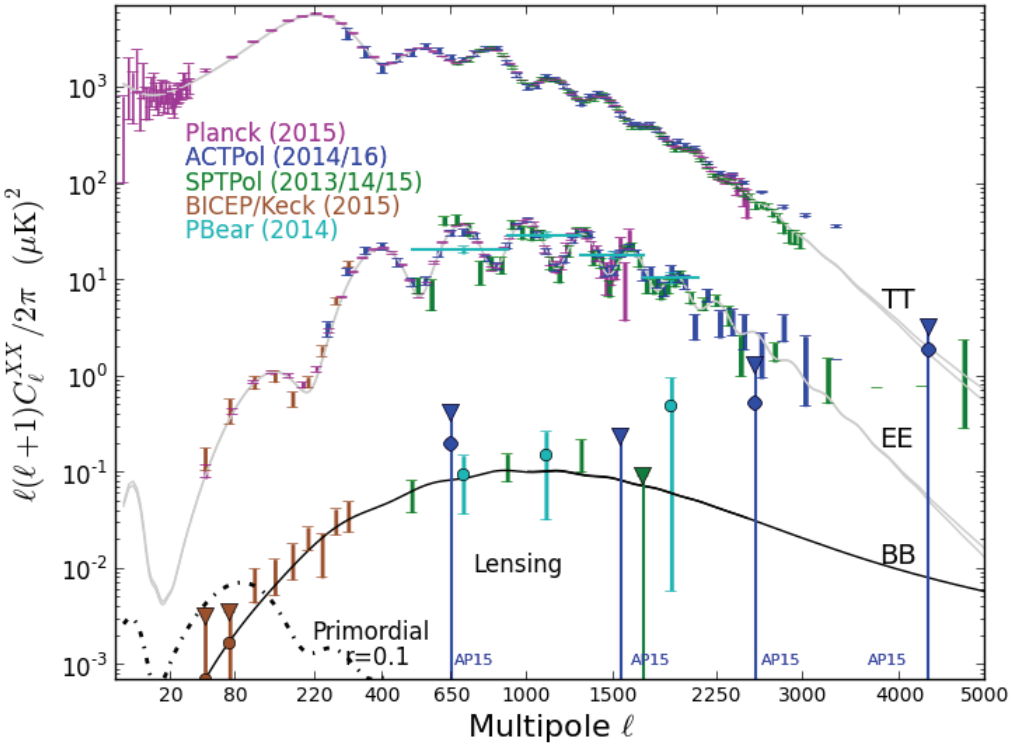


Figure: L. Page

except for Planck, all measurements enabled by superconducting devices fabricated across the street at NIST

many CMB experiments

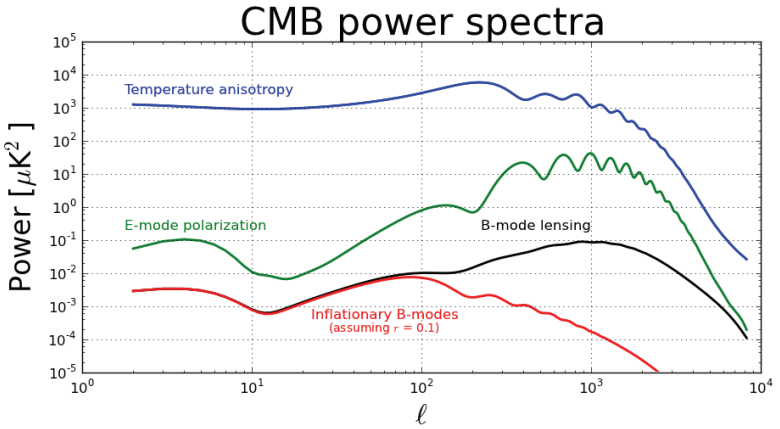
- Ground
  - SPT-3G
  - Advanced ACTPol
  - Simons Array/Polarbear2
  - BICEP series (keck array, BICEP3, BICEP array)
  - CLASS
  - Simons Observatory
- Balloon
  - EBEX-IDS
  - SPIDER
  - PIPER
- Satellite
  - LiteBIRD

CMB Stage-IV

- The next-generation ground-based CMB experiment
- 30-300 GHz using multiple telescopes observing from the South Pole, the Atacama, and potentially northern hemisphere sites
- Community-wide effort with DOE and NSF support
- Biannual meetings
  - Next one: SLAC Feb 27-28, 2017
- science book: arXiv: 1610.02743v1

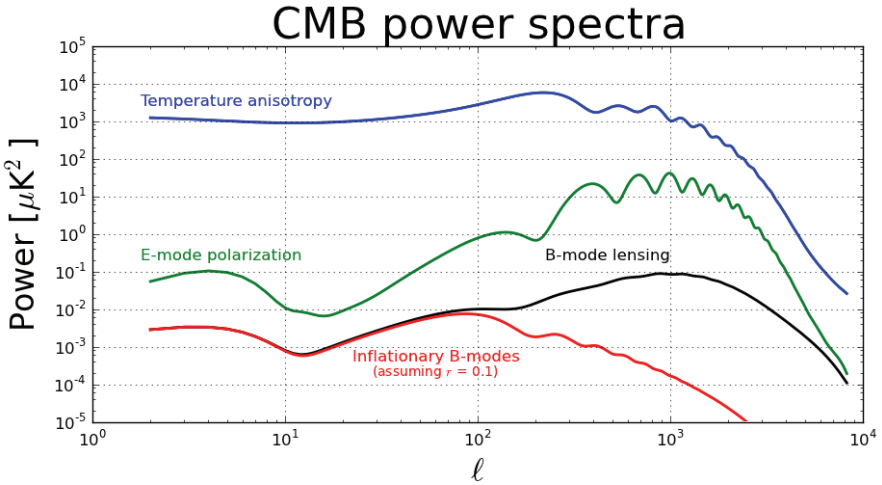
CMB-StageIV science goals

- tests of inflation, role in particle physics
  - energy scale associated with GUT-scale physics
- determine the number and masses of neutrinos
- constrain possible new light relic particles
- constraints on the nature of dark energy
- test GR on large scales



challenging measurements

- Low signal to noise



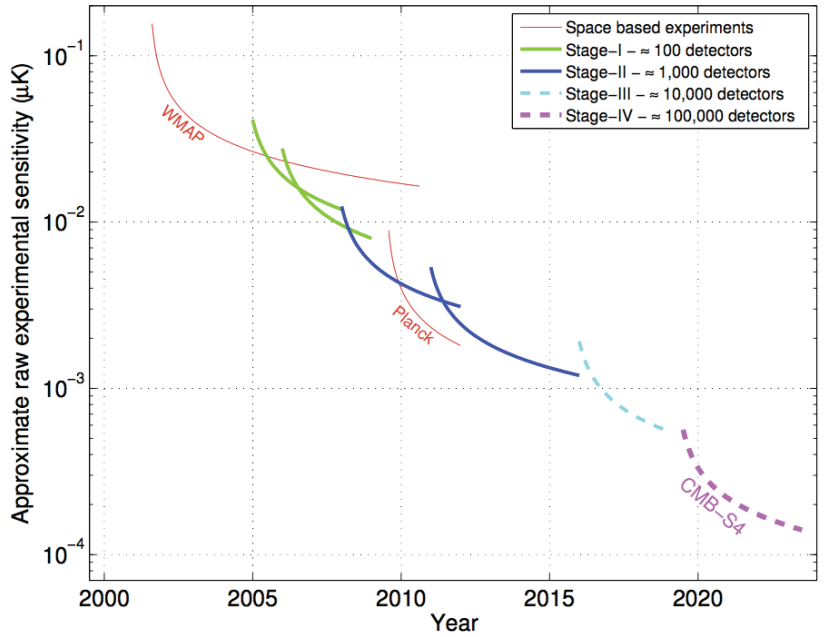
challenging measurements

- Low signal to noise

~ 1 uK-arcmin across half of the sky

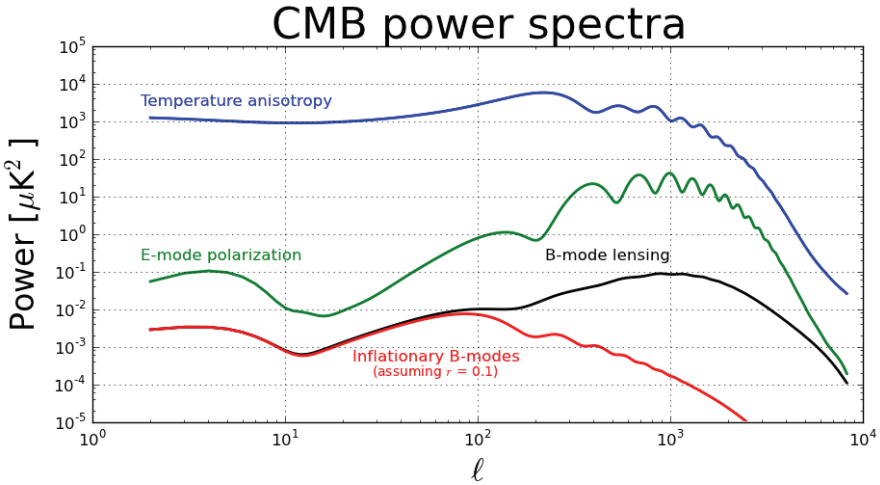
~ 0.5M detectors for 4 years

Figure 2 CMB-S4 Science Book



challenging measurements

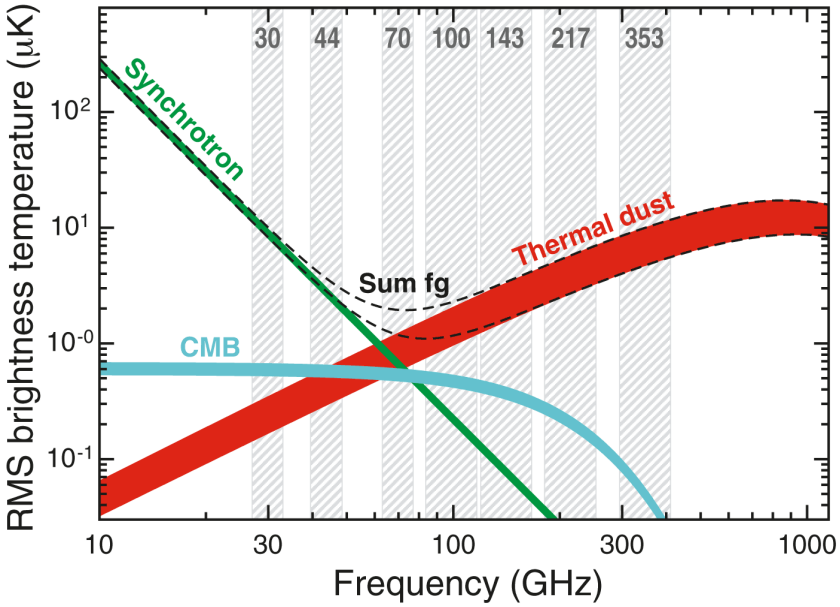
- Low signal to noise
- Low systematic contamination



challenging measurements

- Low signal to noise
- Low systematic contamination
- Foregrounds

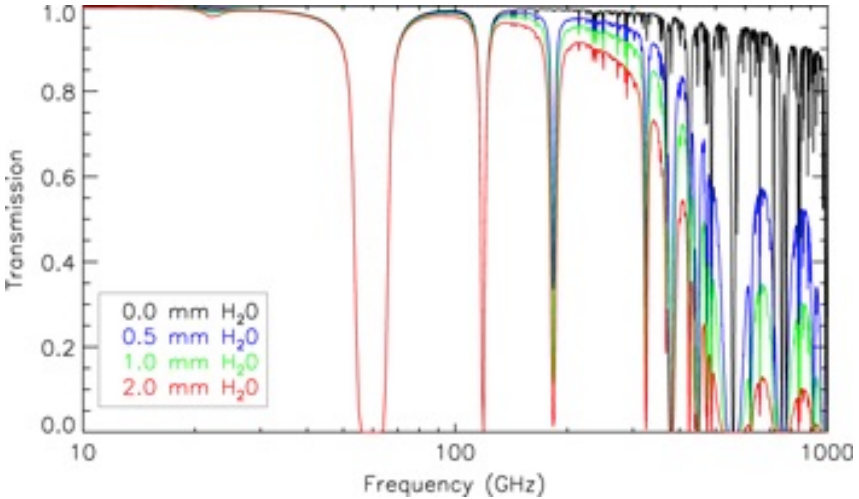
  30-300 GHz



Planck 2015 Results X

challenging measurements

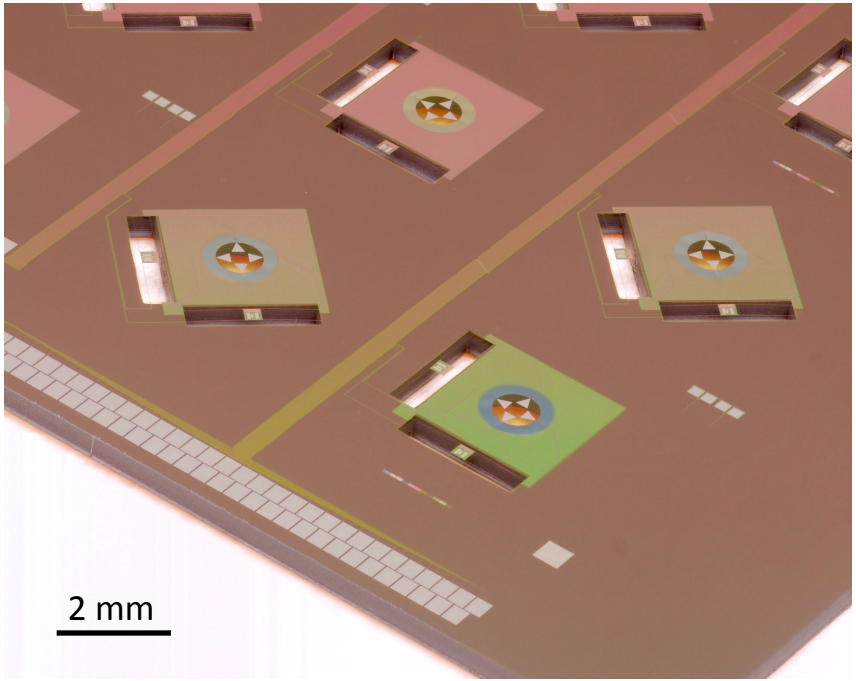
- Low signal to noise
- Low systematic contamination
- Foregrounds
- Atmospheric fluctuations



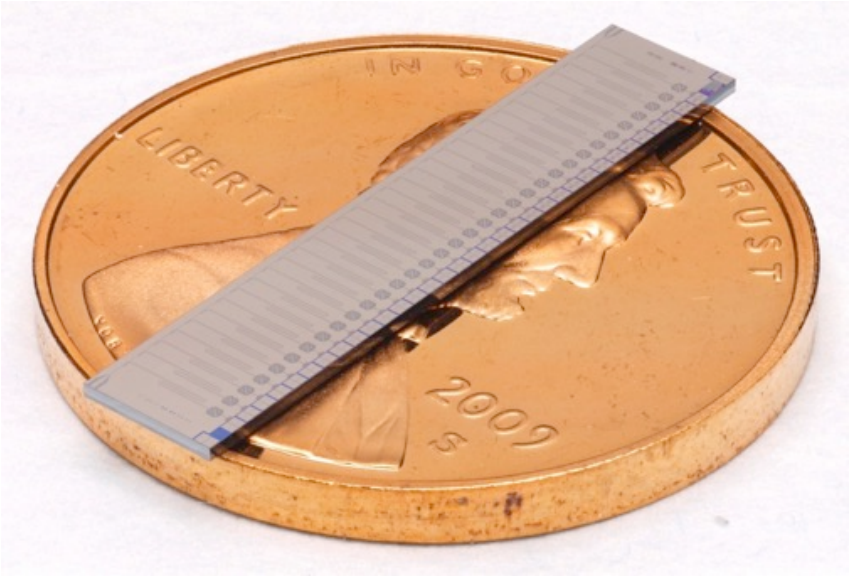
J. Errard et al 2015

low temperature detectors and readout for CMB polarization

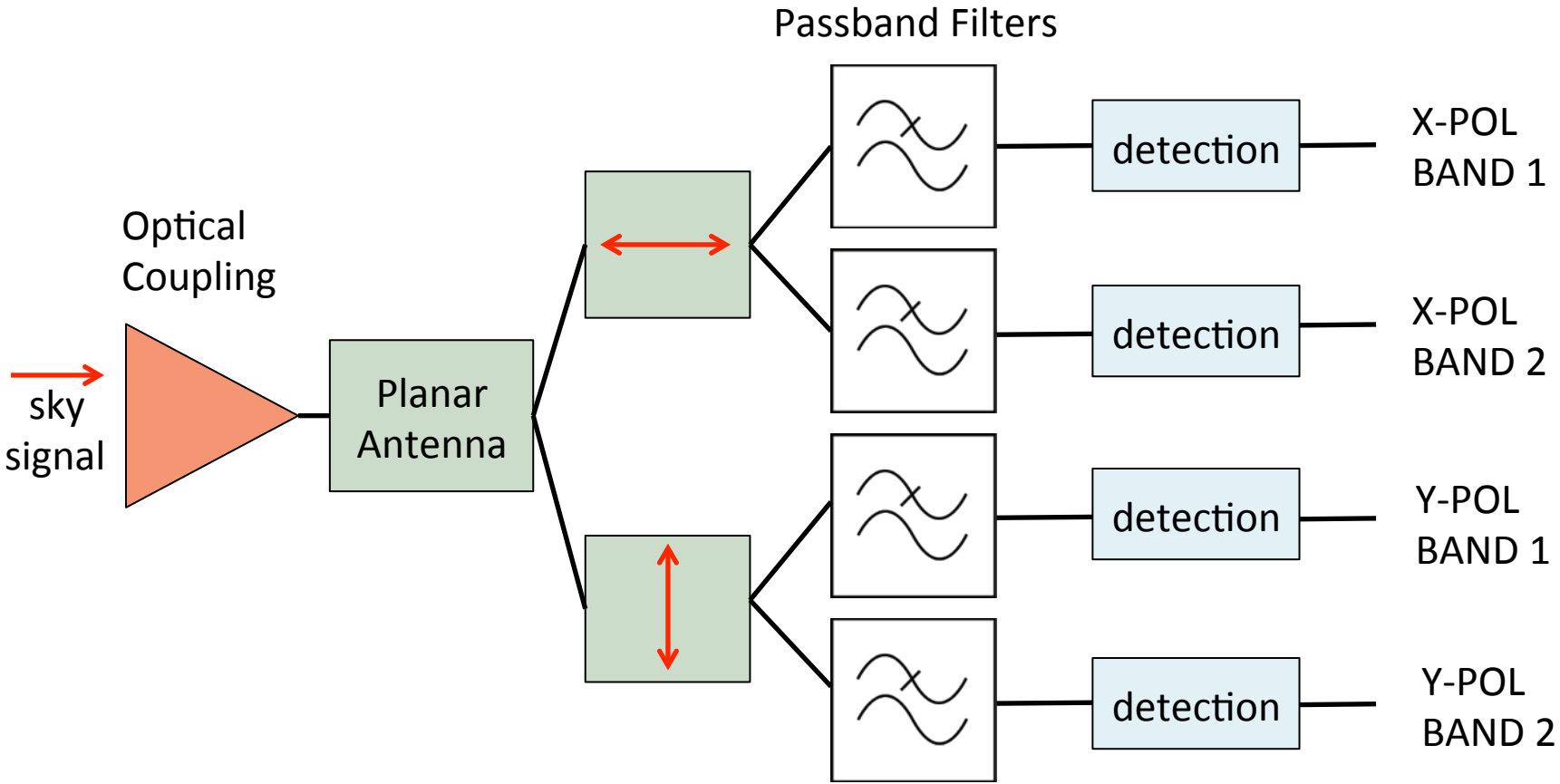
SPIDER-II sensor array



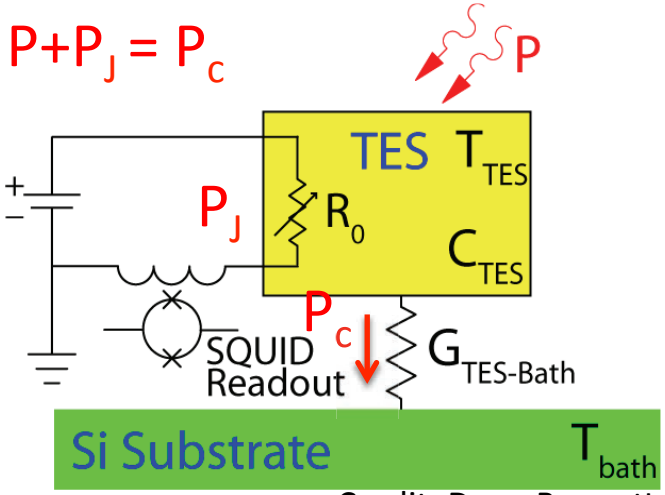
microwave SQUID multiplexer



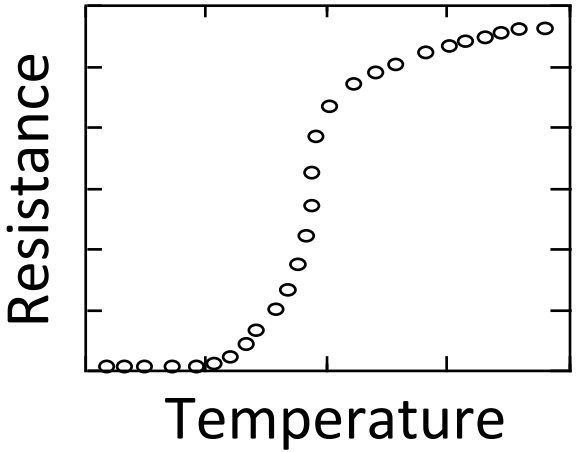
detection cartoon



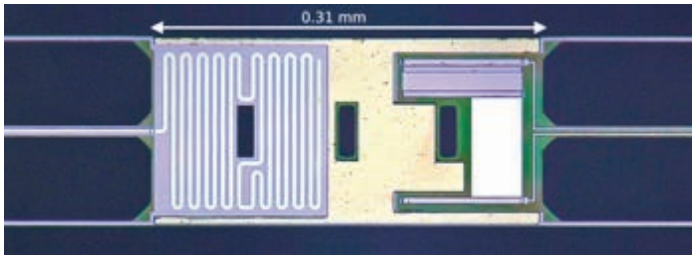
transition-edge sensor (TES) bolometer



Credit: Doug Bennett



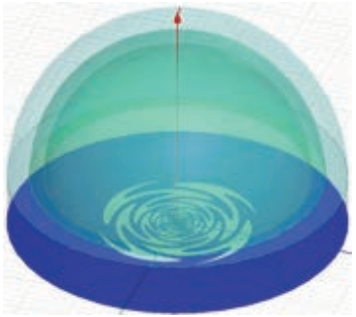
- Relative power meter
- Superconducting film is sensing element
- Added noise ~ T/hv
- TES enabled fabrication of detector arrays

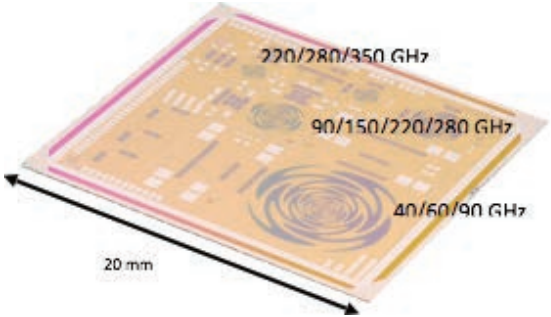


Caltech/JPL bolometer

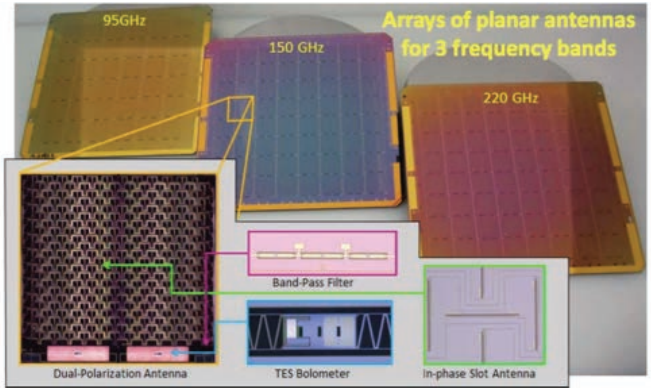
TES detector array implementations

Lenslet/Antenna-coupled

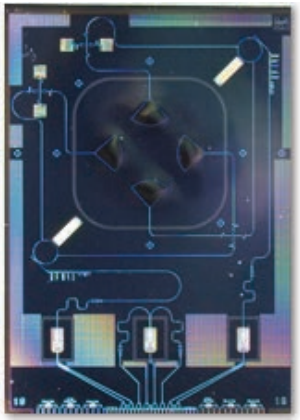


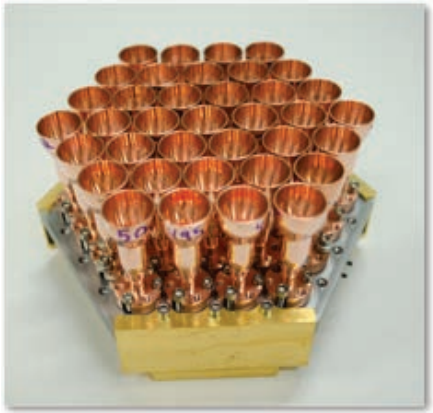


Phased-antenna-arrays

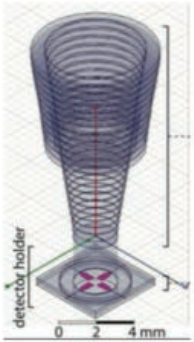


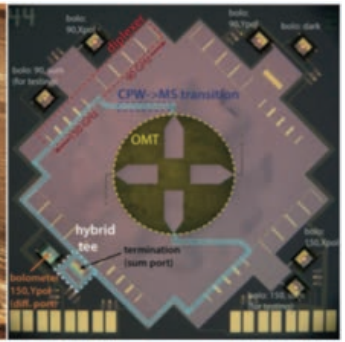
Feedhorn/waveguide-probe coupled





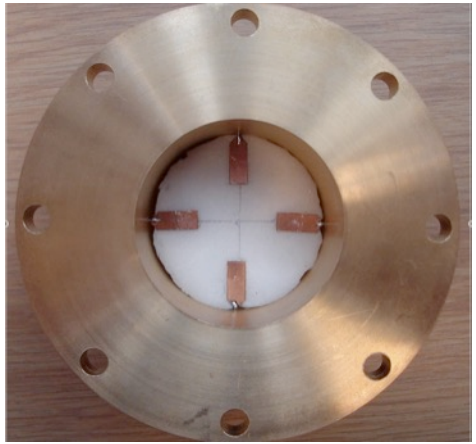
Feedhorn/waveguide-probe coupled

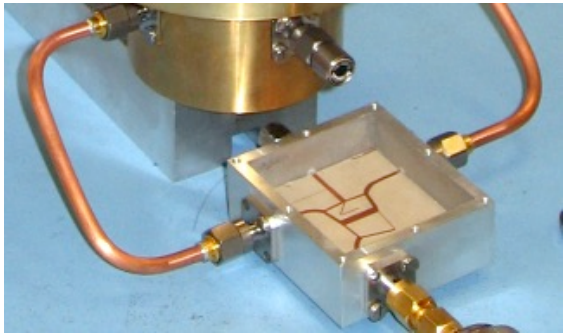


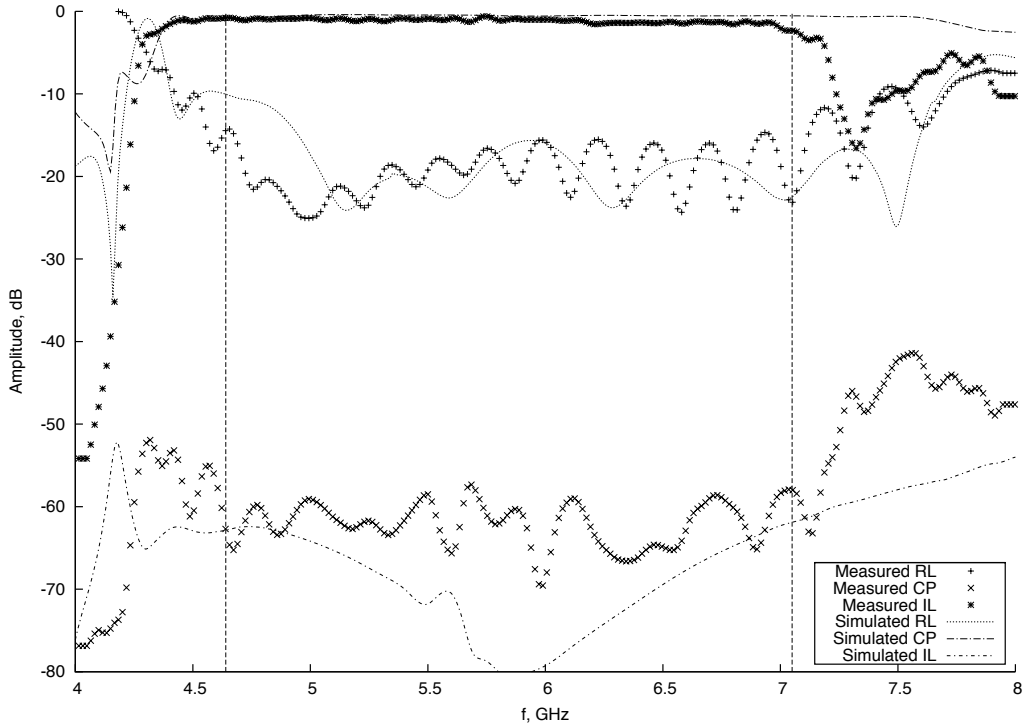


design heritage from radio

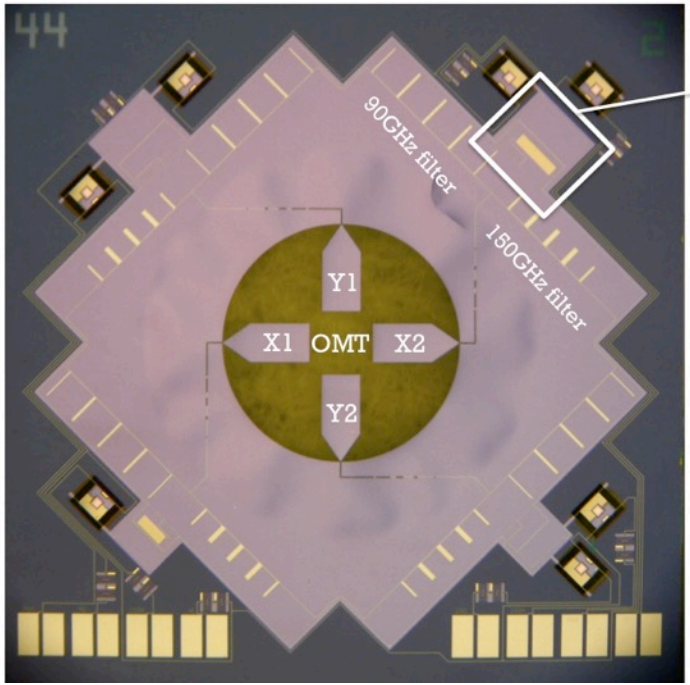
Grimes, P. K., et al. "Compact broadband planar orthomode transducer." *Electronics Letters* 43.21 (2007): 1146-1147.

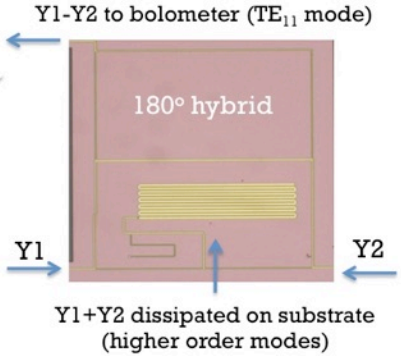


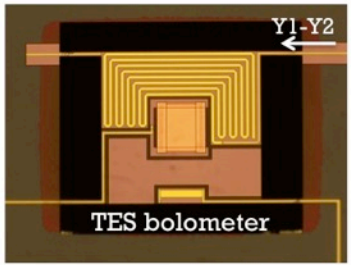




multichroic W and G-band implementation

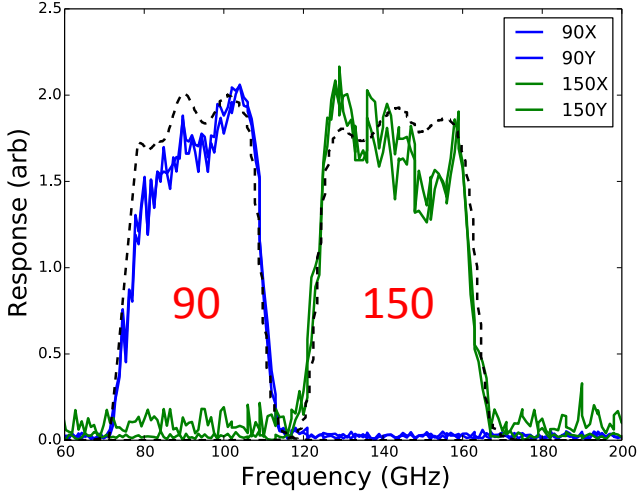






7 mm

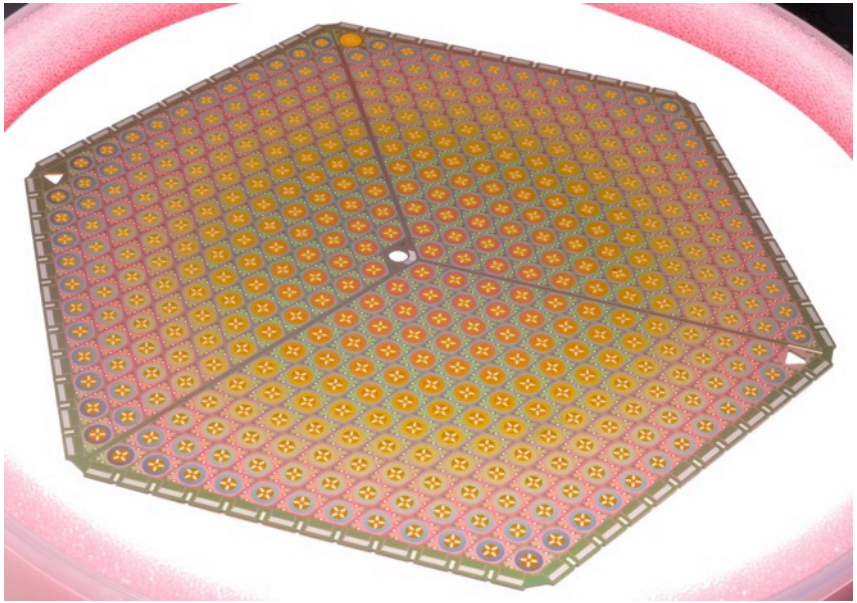
McMahon et al. JLTP (2011)

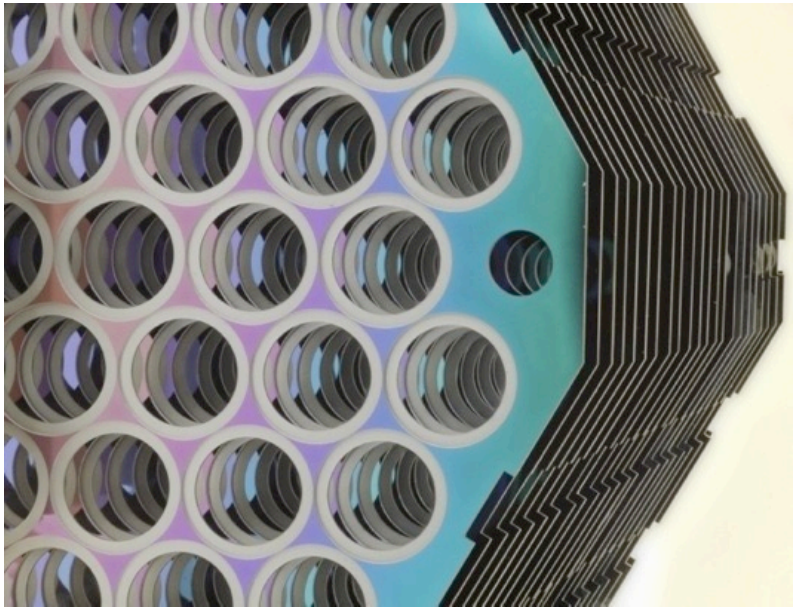


255 spatial pixel, 1020 detector camera operating on ACTPol since Feb 2015

Datta et al. *JLTP* 2016
arXiv:1510.07797

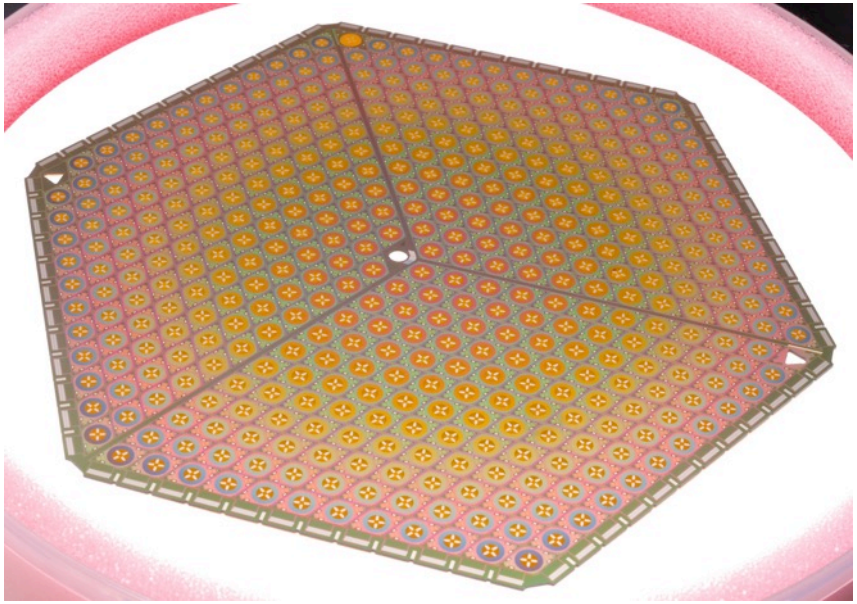
feedhorn/probe-coupled arrays (NIST+)

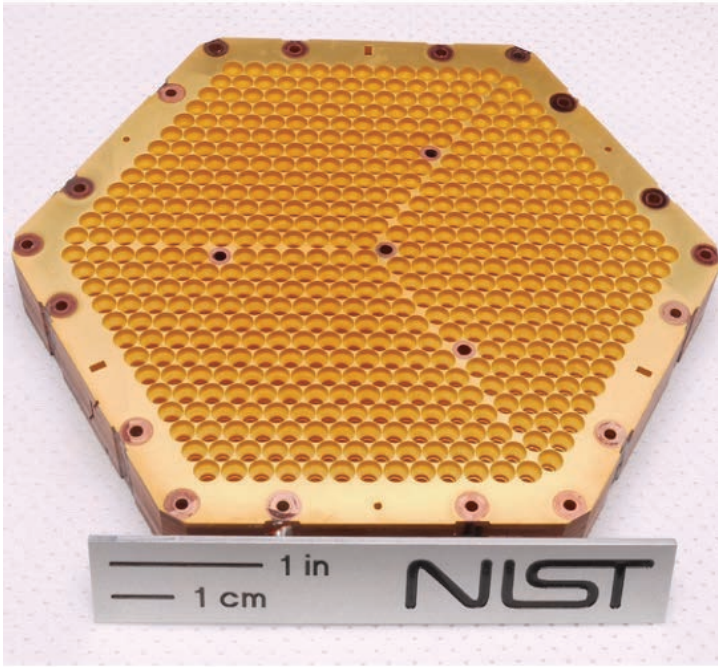




- Single band and multichroic implementations on-sky
- Previous/Current Experiments: ABS, SPTpol, ACTPol, MUSTANG2, Advanced ACTPol
- Future Experiments: SPIDER, Advanced ACTPol, LiteBIRD

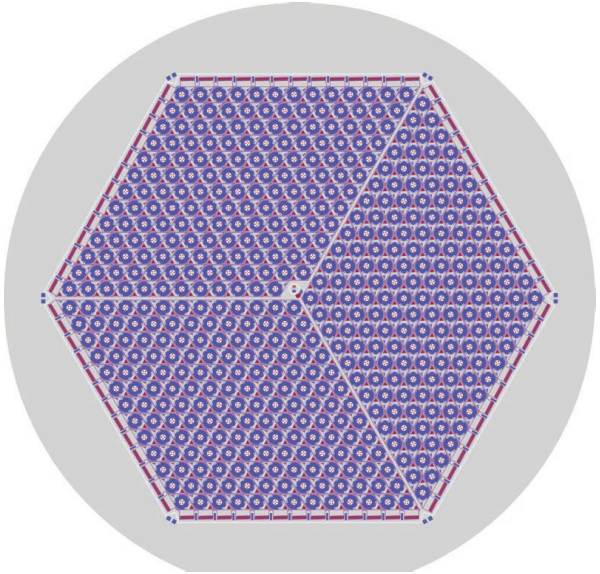
feedhorn/probe-coupled arrays (NIST+)



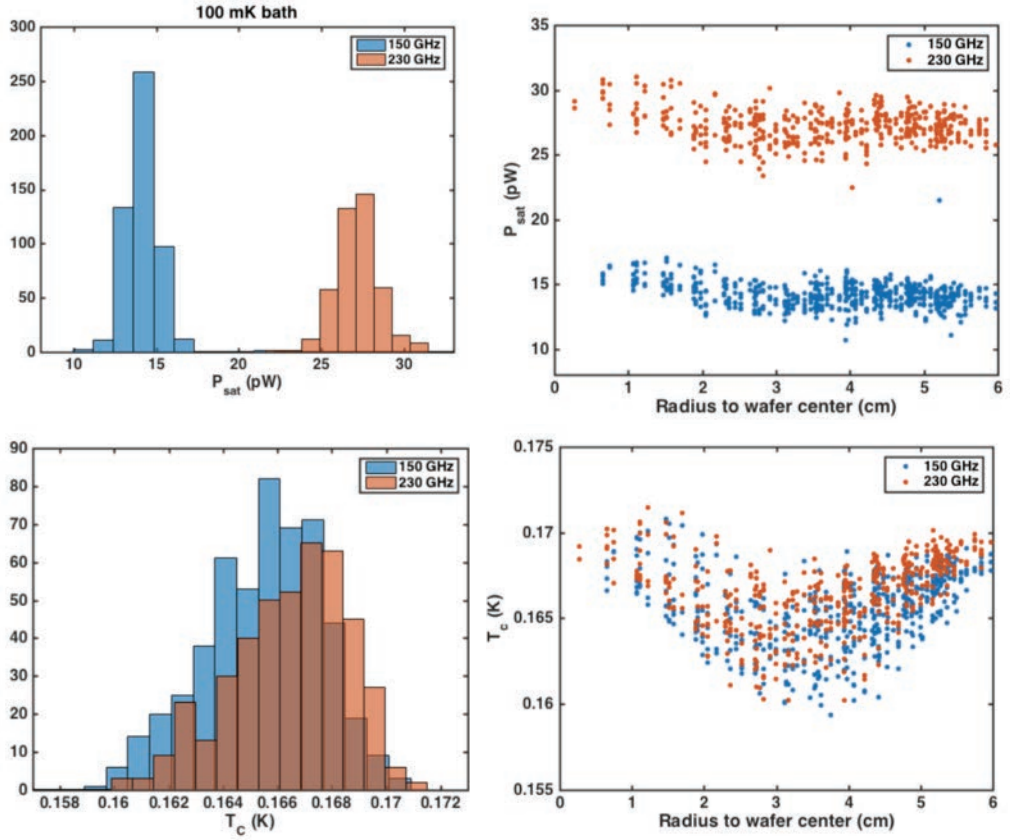


- Single band and multichroic implementations on-sky
- Previous/Current Experiments: ABS, SPTpol, ACTPol, MUSTANG2, Advanced ACTPol
- Future Experiments: SPIDER, Advanced ACTPol, LiteBIRD

detector arrays ready for S4, production scaling required



- Revamped design and fabrication process for increased wafer yield and high performance with CMB-S4 scale in mind
- Duff et al *JLTP* **184**, 3-4 (2016)

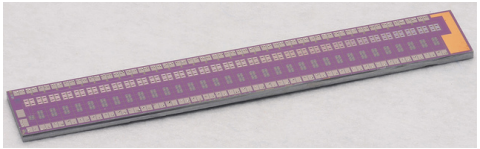


Ho et al in prep.

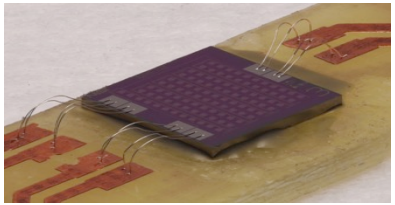
multiplexed readout

- multiplexed readout required to manage cryogenic wiring and thermal loads
- time division and MHz frequency division SQUID multiplexing used with current cameras (1,000 to 10,000 sensors)
  - Scalable to CMB-S4?
- More pixel-count-scalable multiplexing techniques welcomed as well as better detector to readout packaging.

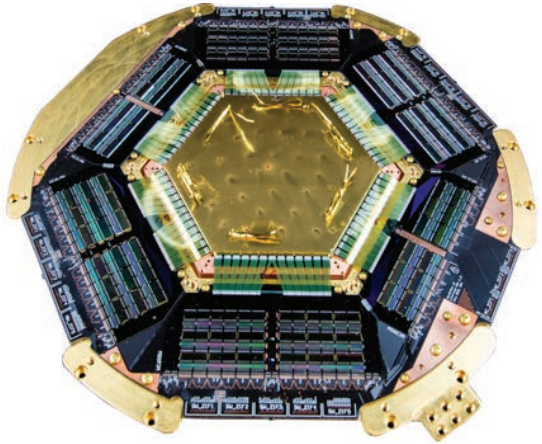
TDM MUX



FDM series array

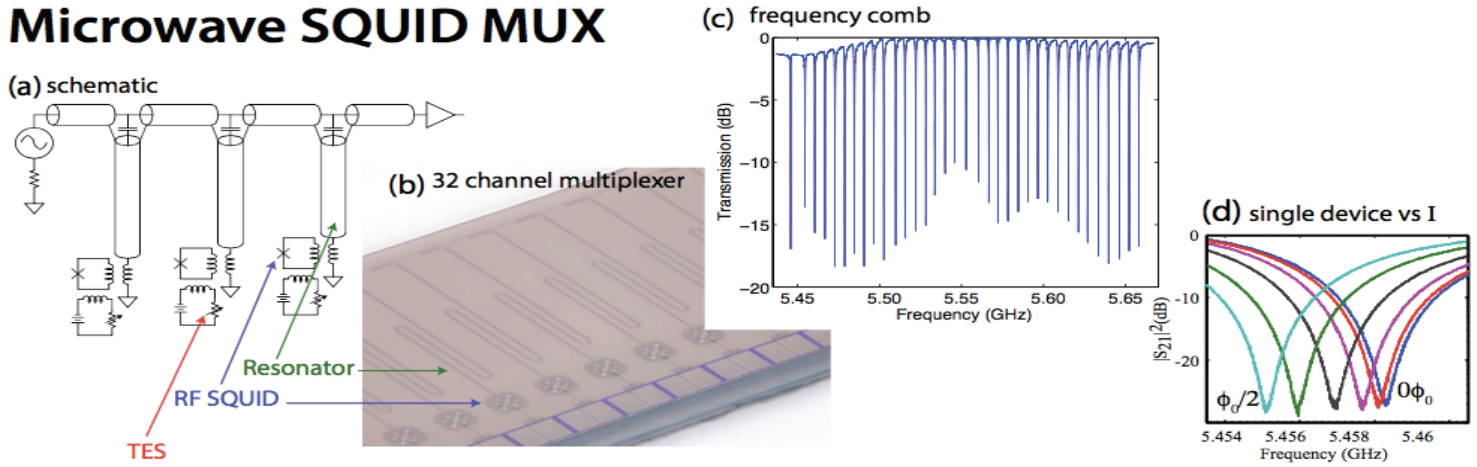


Advanced ACTPol “HF” array

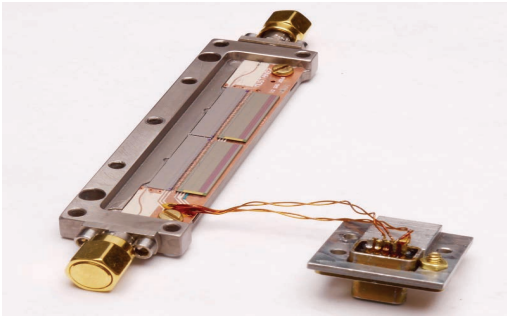


Henderson et al JLTP (2016)

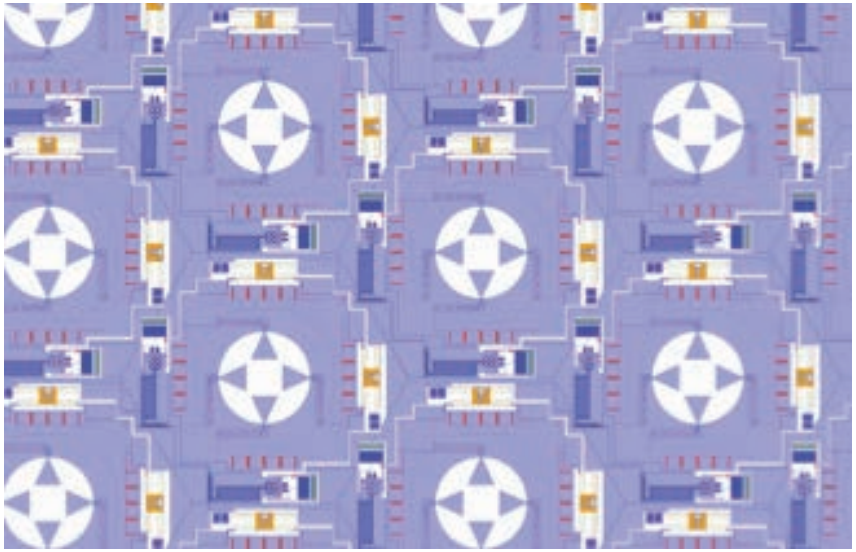
microwave SQUID multiplexing

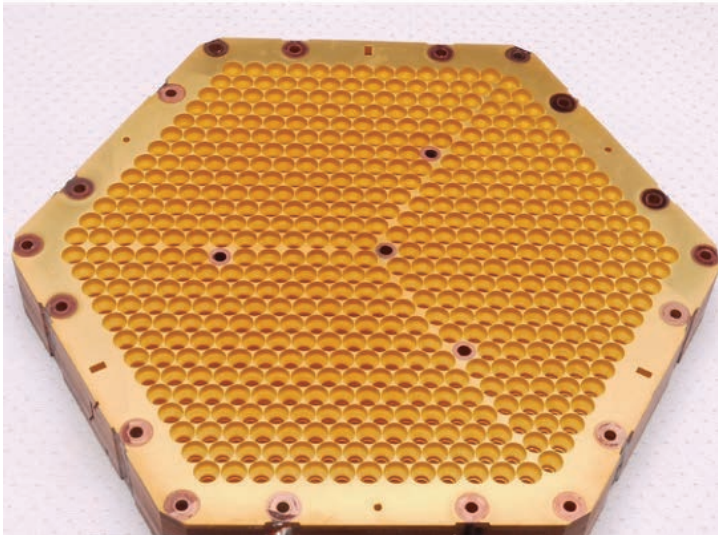


- Pixel-count scalability of microwave techniques + proven sensitivity of TES
- scales to ~1000x
- 64x demonstrated recently in MUSTANG2



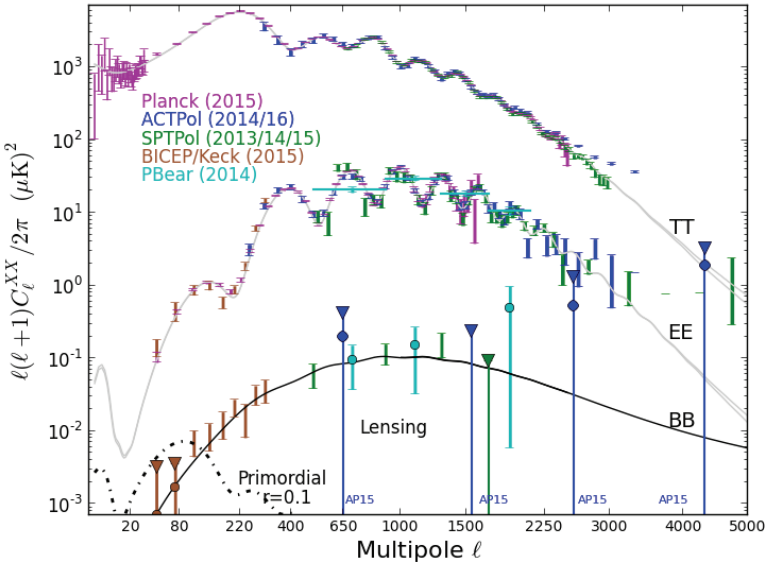
on-detector-wafer microwave SQUID multiplexing





Conclusions

- CMB temperature measurements helped establish ΛCDM cosmology
- *Polarization* measurements will enable the next wave of discoveries (what caused the bang of the big bang?, quantum nature of gravity, neutrino physics, dark energy …)
  - the field is active! See following talks.
- CMB Stage-IV is a community driven, ground-based observing program for the next decade.
- Measurements and scale of CMB-S4 are demanding
- Detector arrays ready, readout and packaging need improvements



Thank You