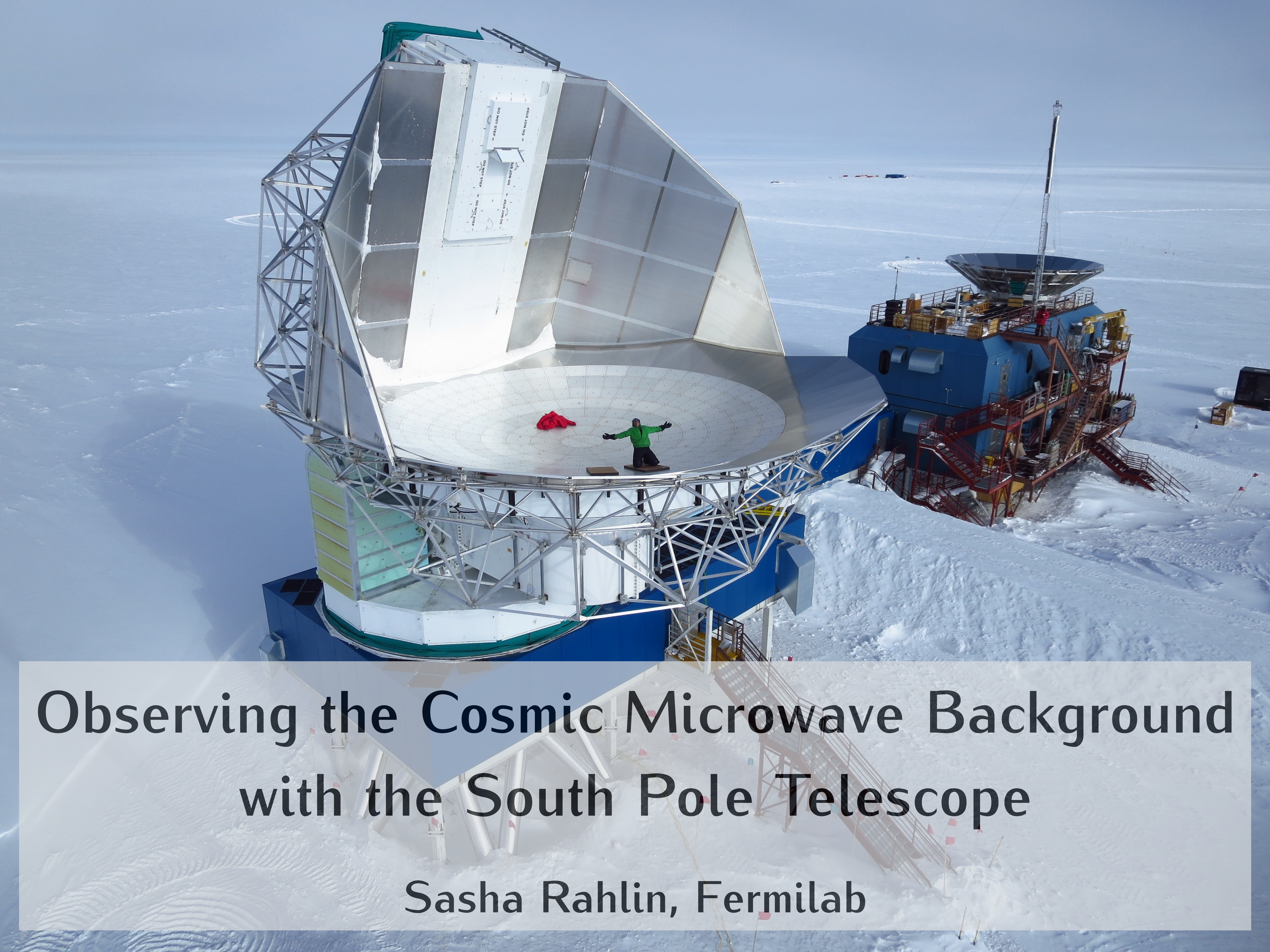
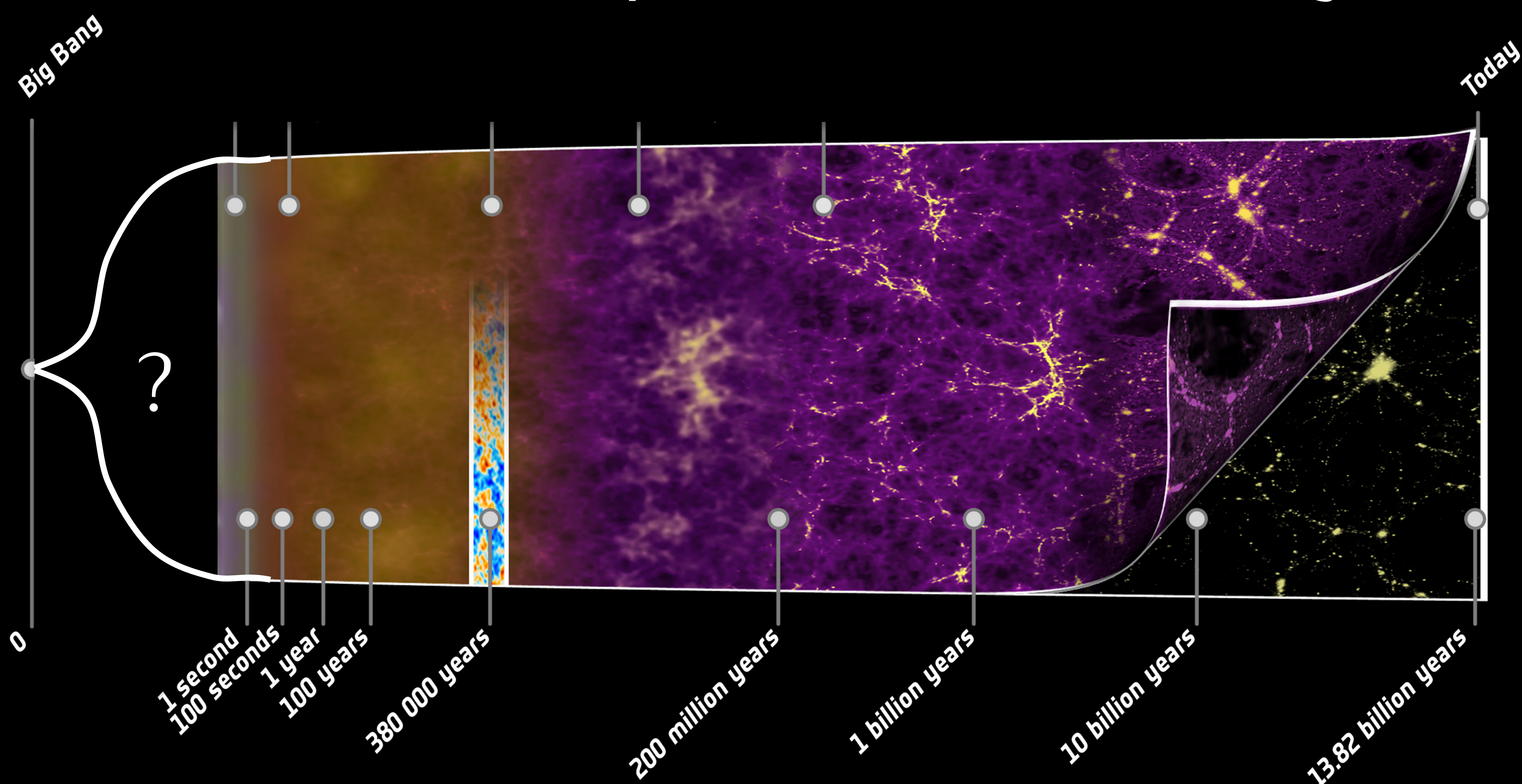


Observing the Cosmic Microwave Background with the South Pole Telescope

Sasha Rahlin, Fermilab

The History of the Universe

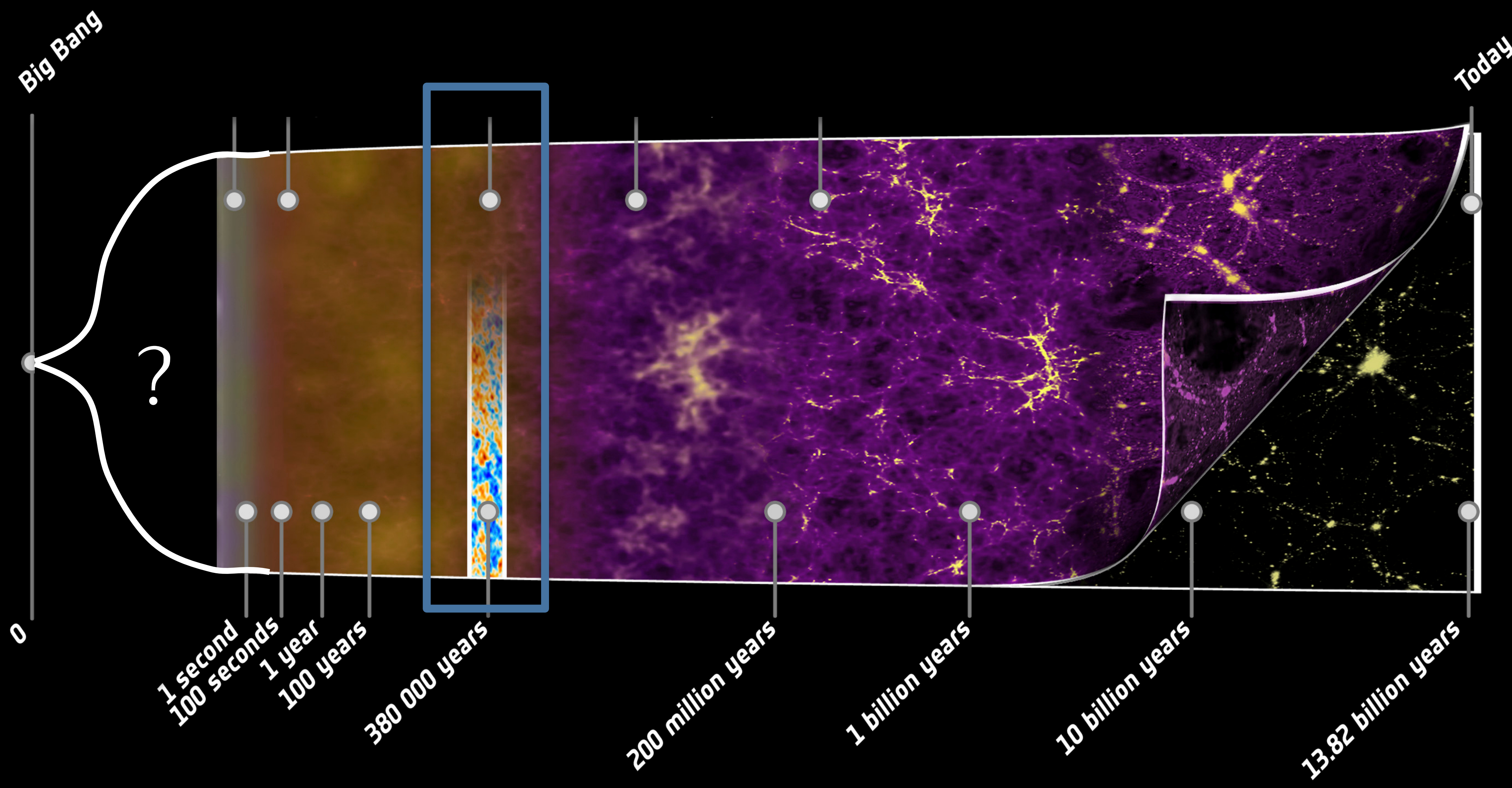
The Hot Big Bang:
Adiabatic expansion and cooling



http://sci.esa.int/planck/

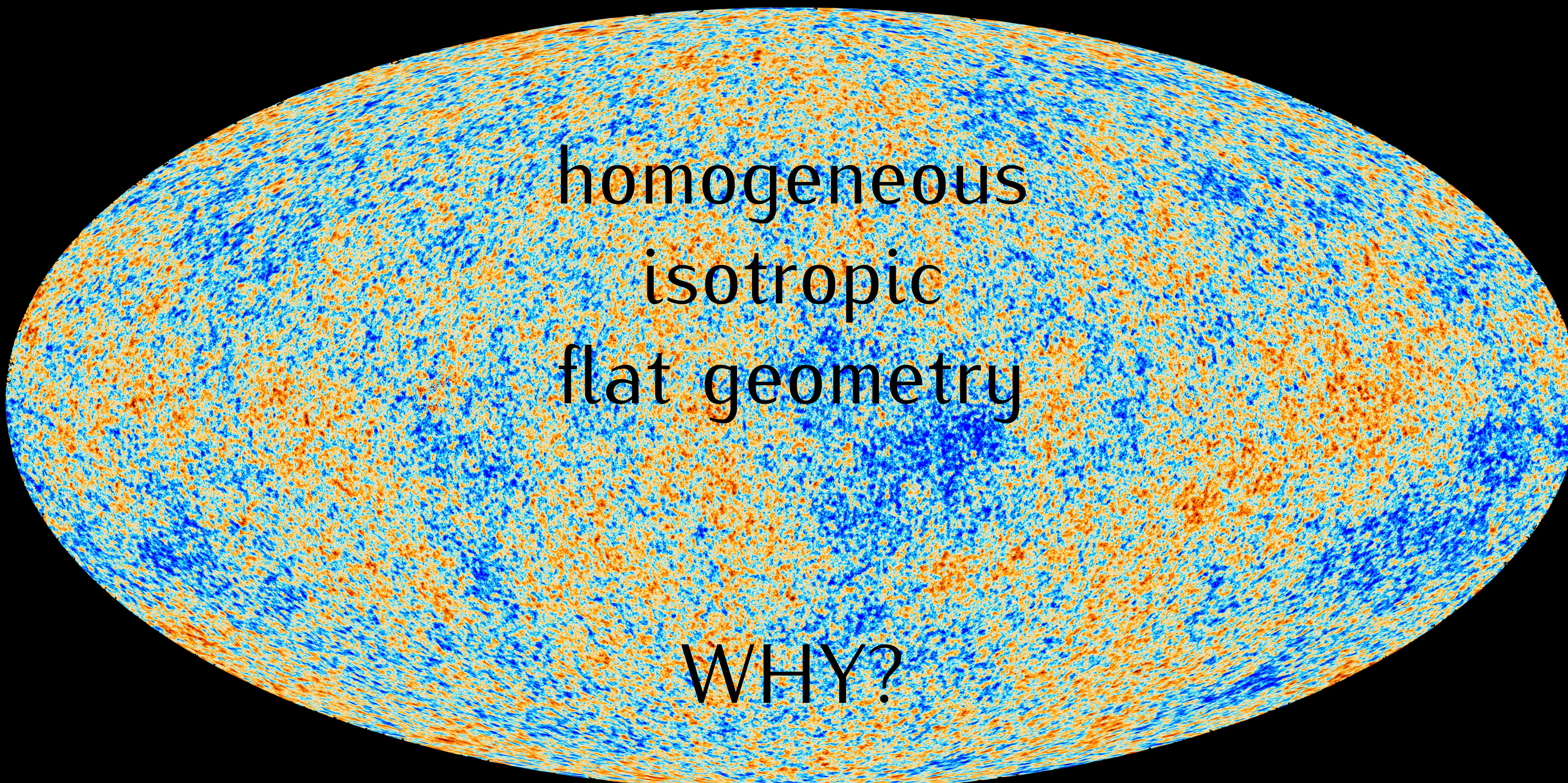
The History of the Universe

Decoupling of photons from matter: Cosmic Microwave Background (CMB)



http://sci.esa.int/planck/

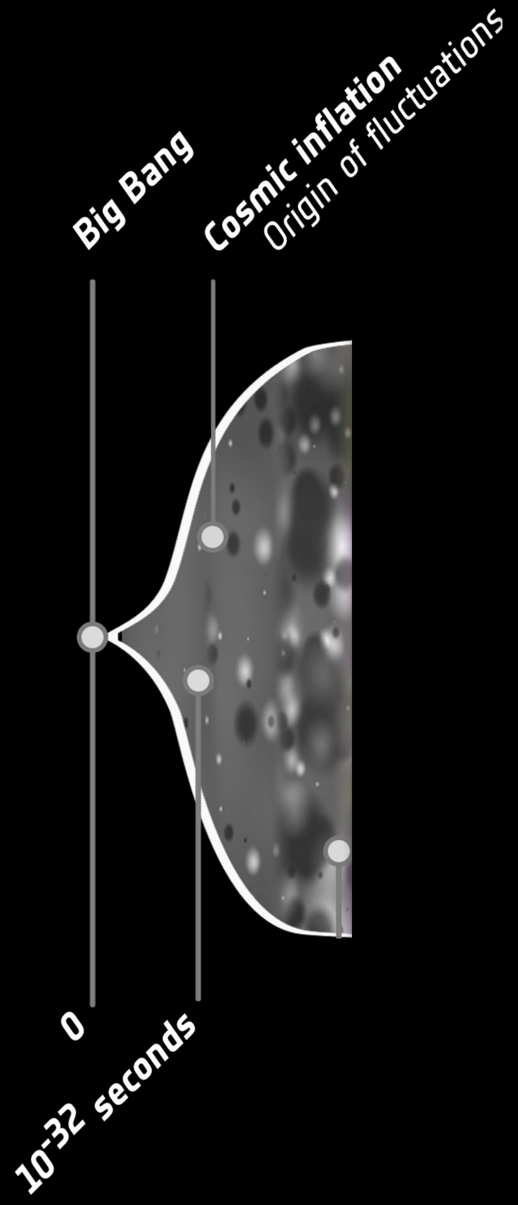
The History of the Universe



30 μK RMS fluctuations
on 3K background

http://www.cosmos.esa.int/web/planck/picture-gallery

The History of the Universe



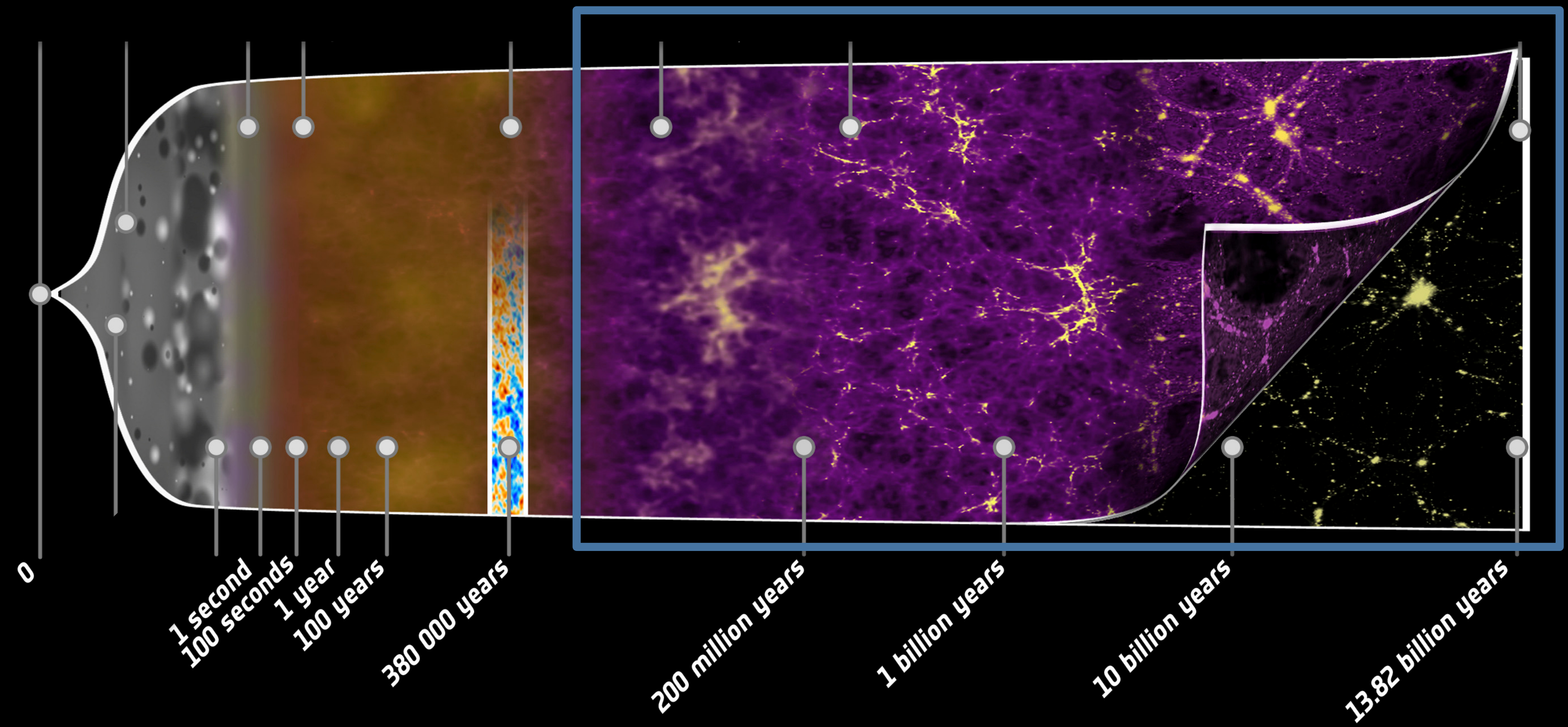
Exponential expansion:
tiny fluctuations grow to
cosmological scales

e.g. quantum fluctuations of
the inflaton

http://sci.esa.int/planck/

The History of the Universe

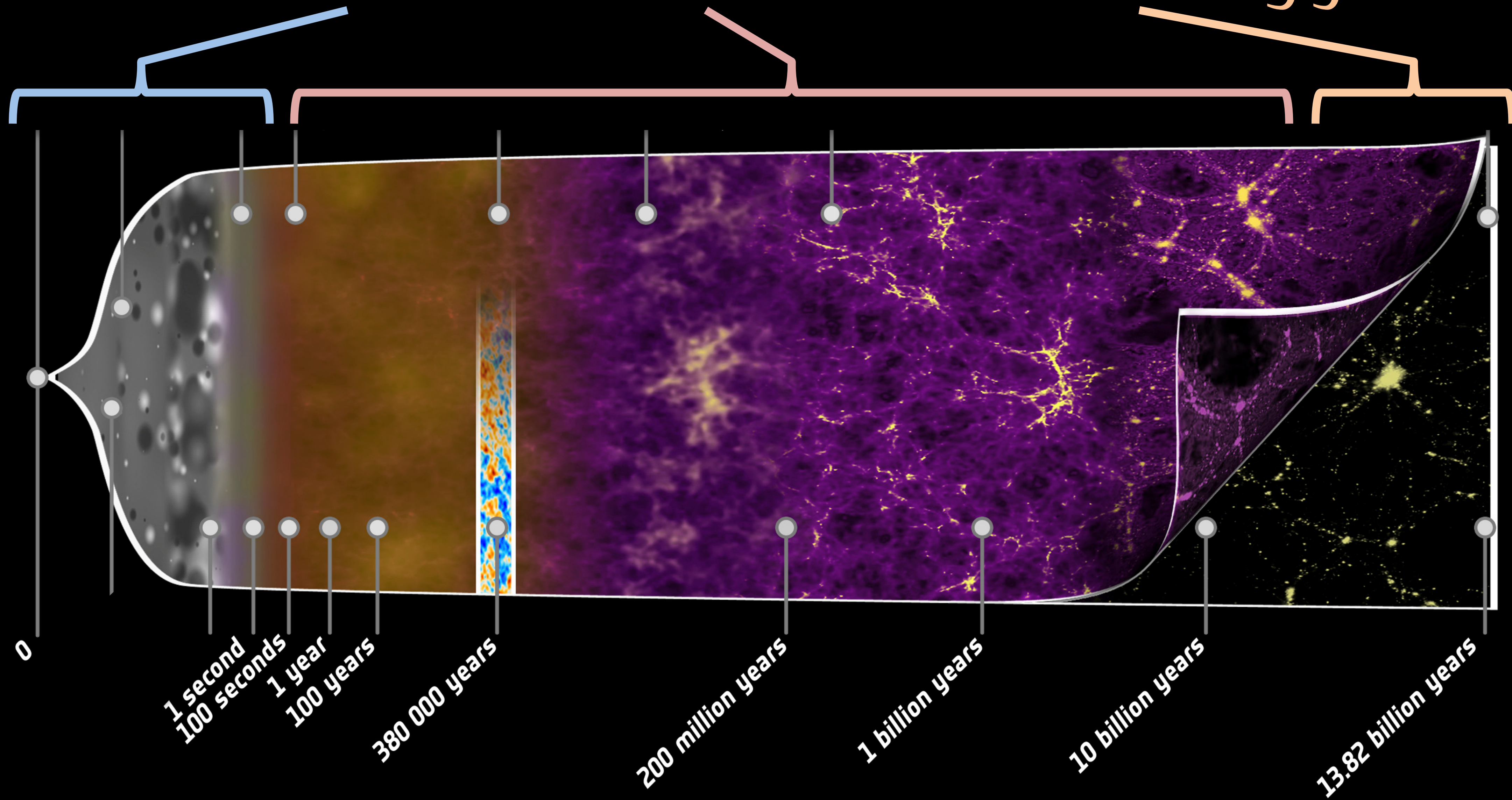
Growth of structure:
formation of galaxies and clusters,
affected by GR, neutrinos, dark energy



http://sci.esa.int/planck/

The History of the Universe

Imprints on the CMB from:
inflation, neutrinos, dark energy



http://sci.esa.int/planck/

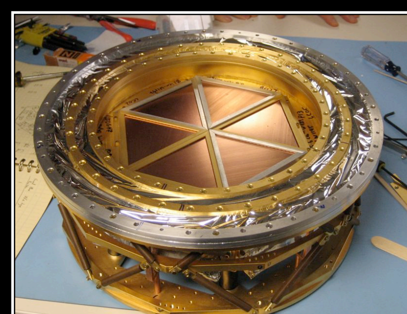
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

100, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

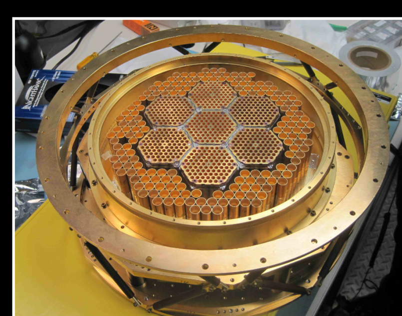
2007: SPT-SZ

960 detectors
100,150,220 GHz



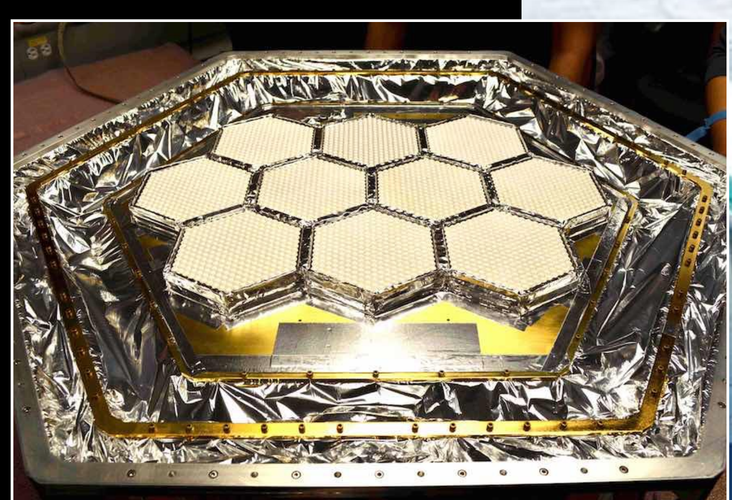
2012: SPTpol

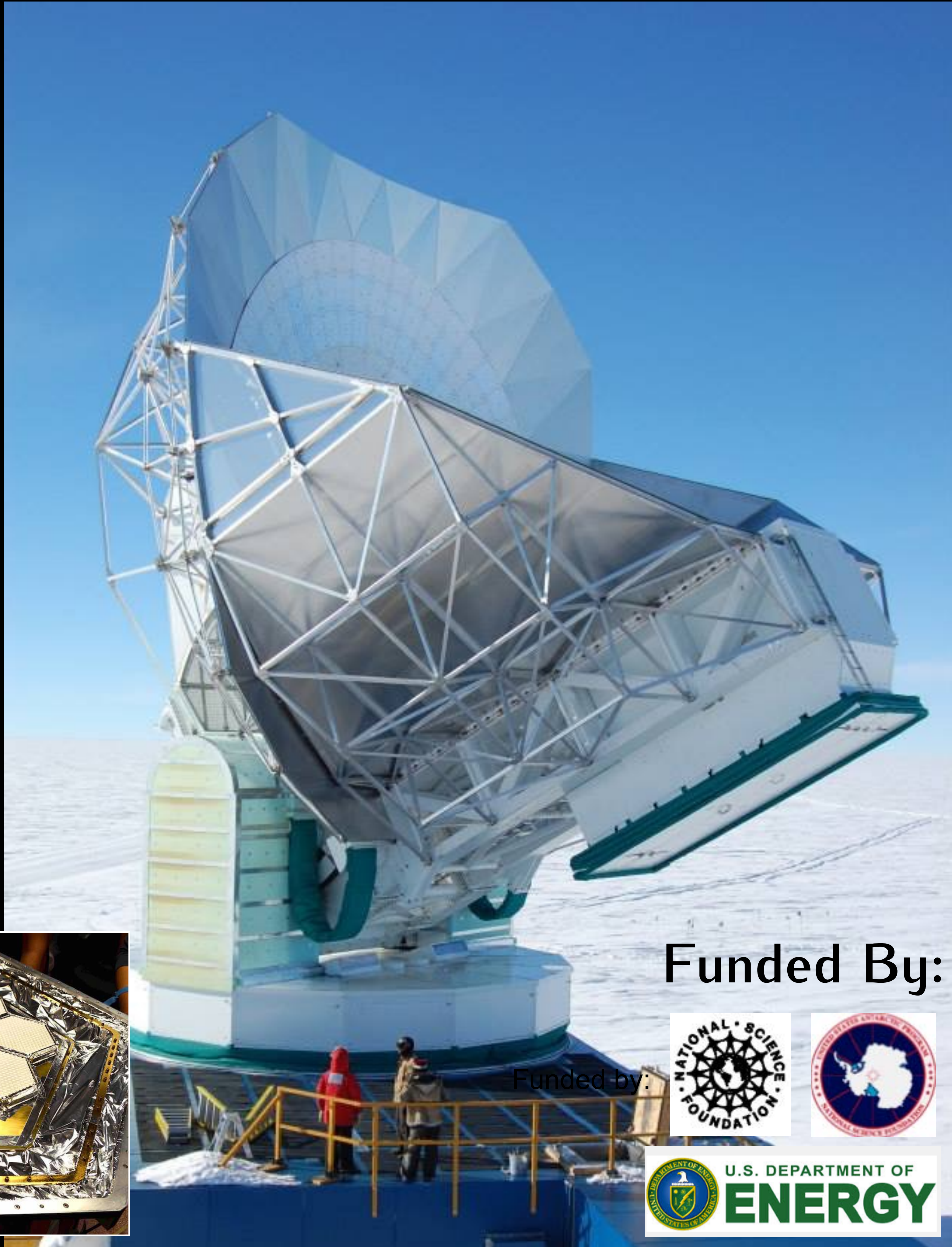
1600 detectors
100,150 GHz
+Polarization



2016: SPT-3G

~16,200 detectors
100,150,220 GHz
+Polarization





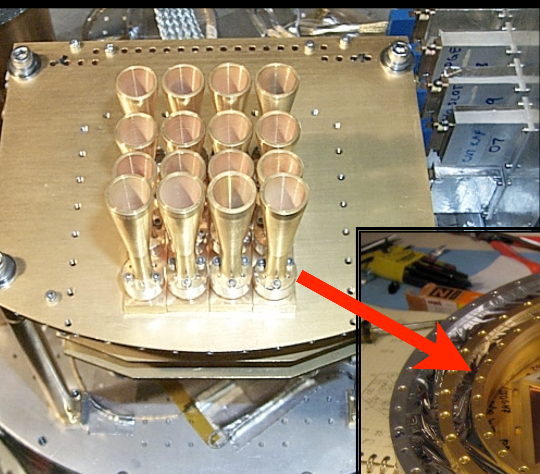
Funded By:

NATIONAL SCIENCE FOUNDATION

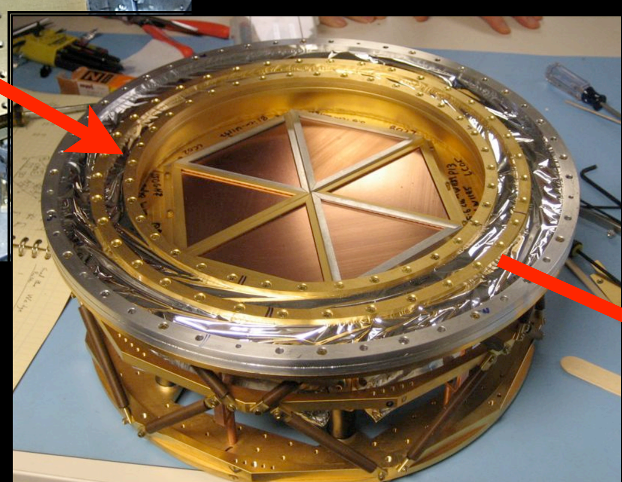
U.S. DEPARTMENT OF ENERGY

Evolution of CMB Focal Planes

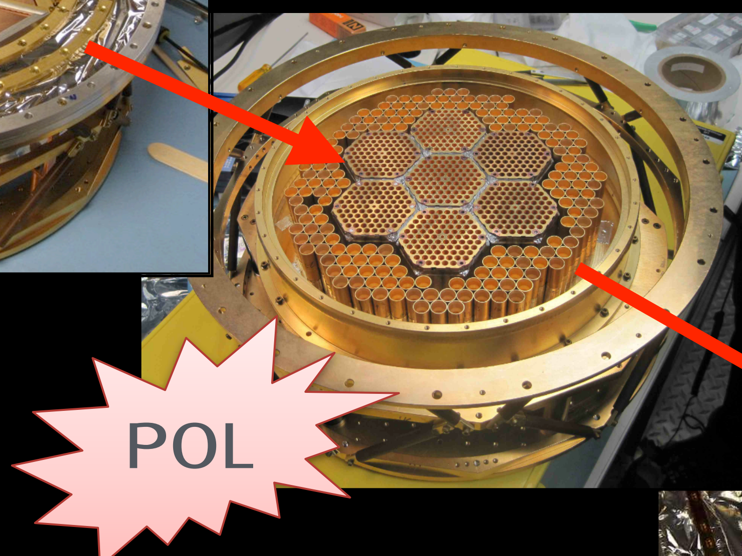
2001: ACBAR
16 detectors



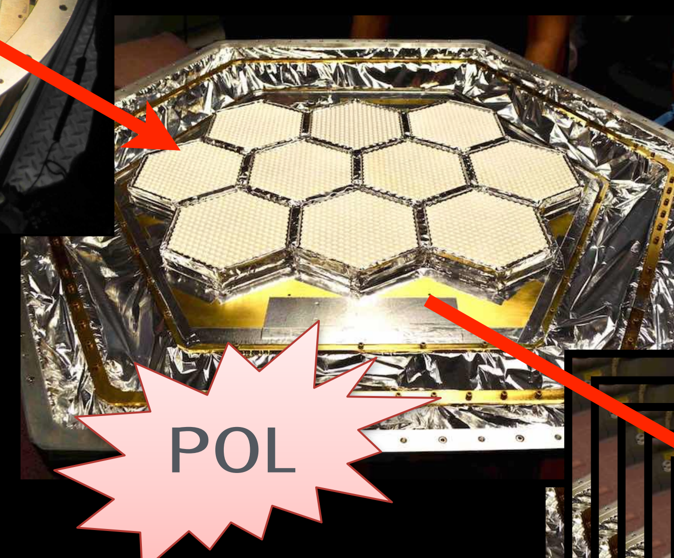
2007: SPT-SZ
960 detectors



Stage-2
2012: SPTpol
~1600 detectors



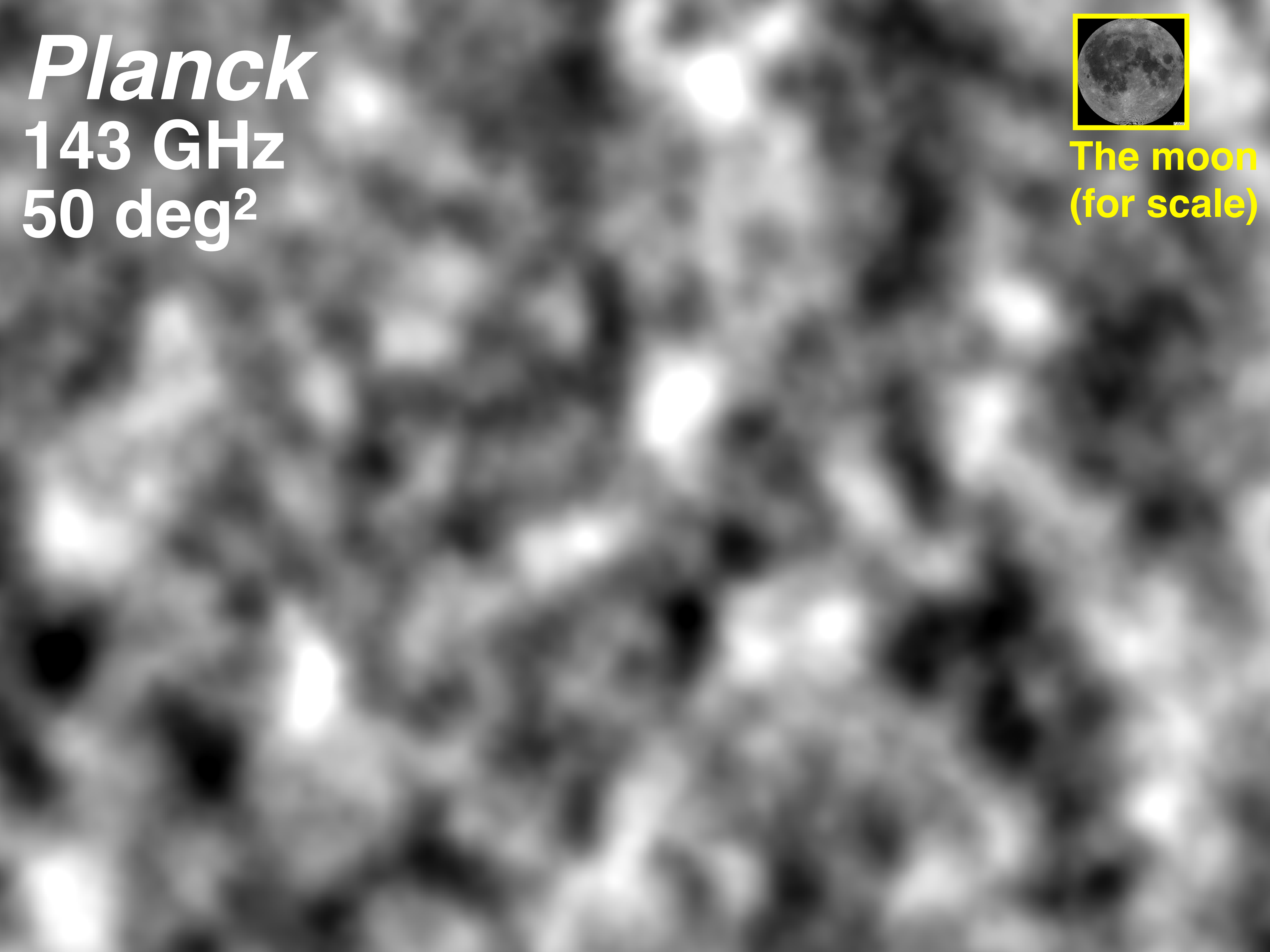
Stage-3
2016: SPT-3G
~15,000 detectors

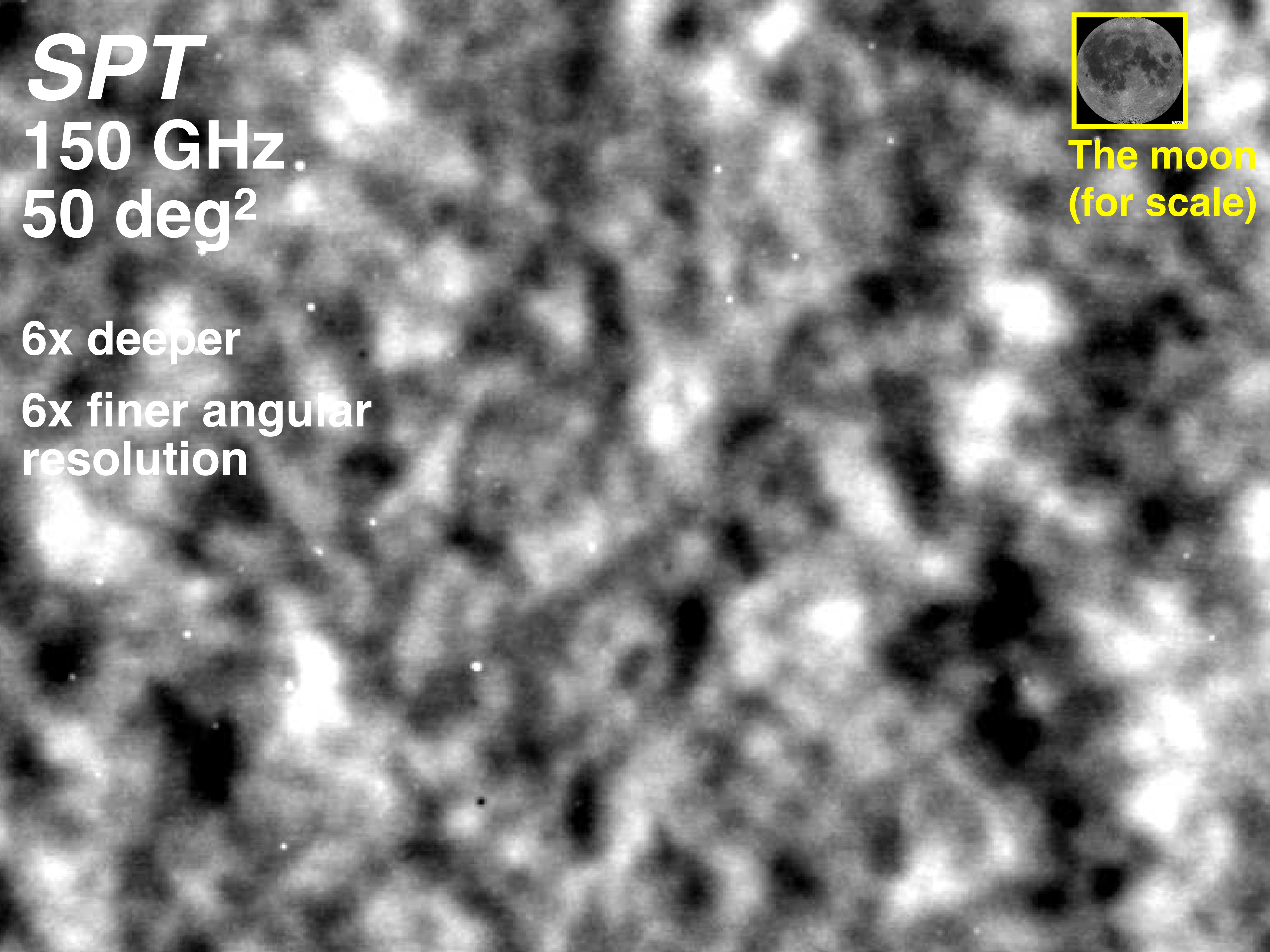


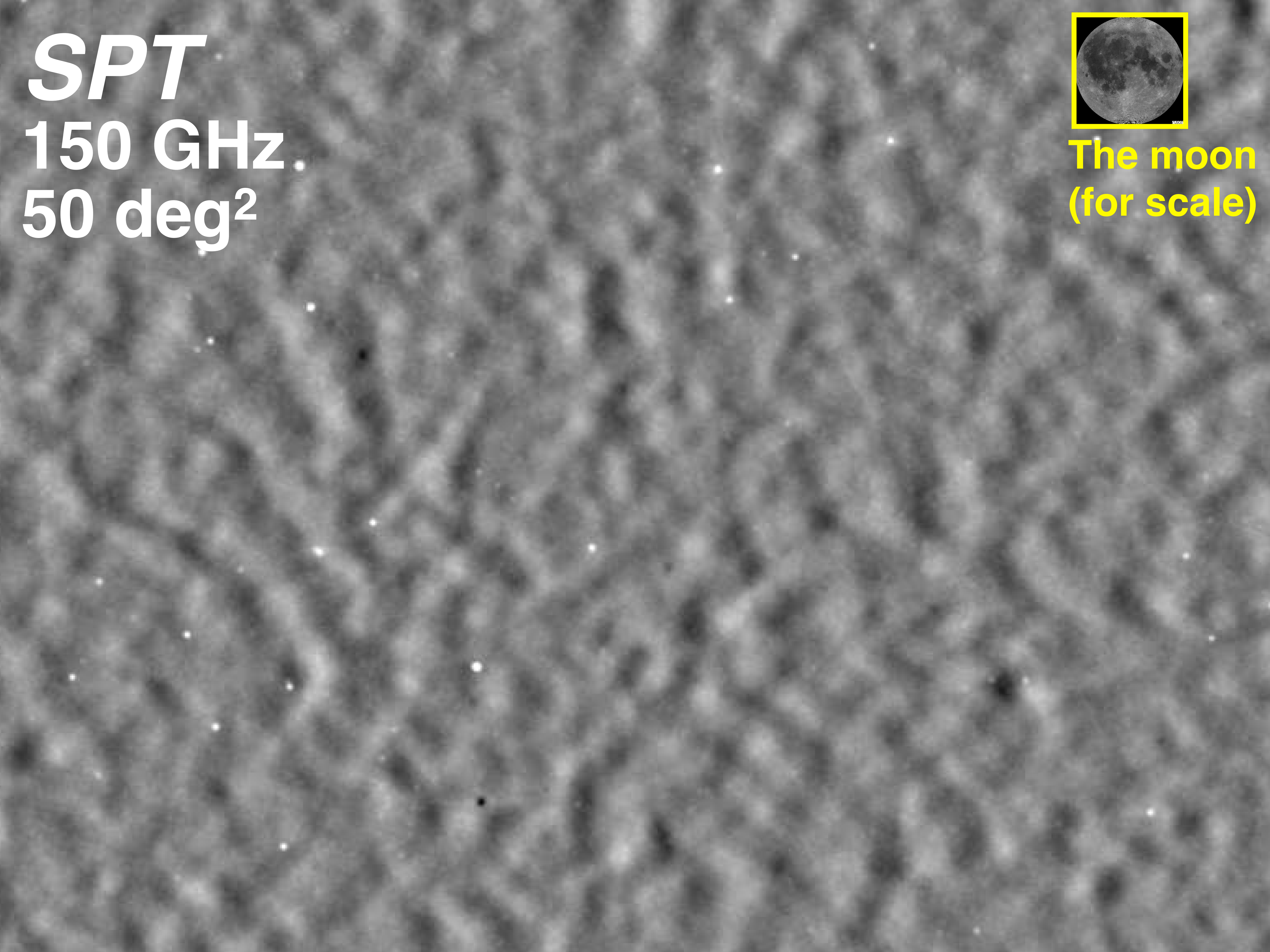
Stage-4
2020?: CMB-S4
~500,000+ detectors

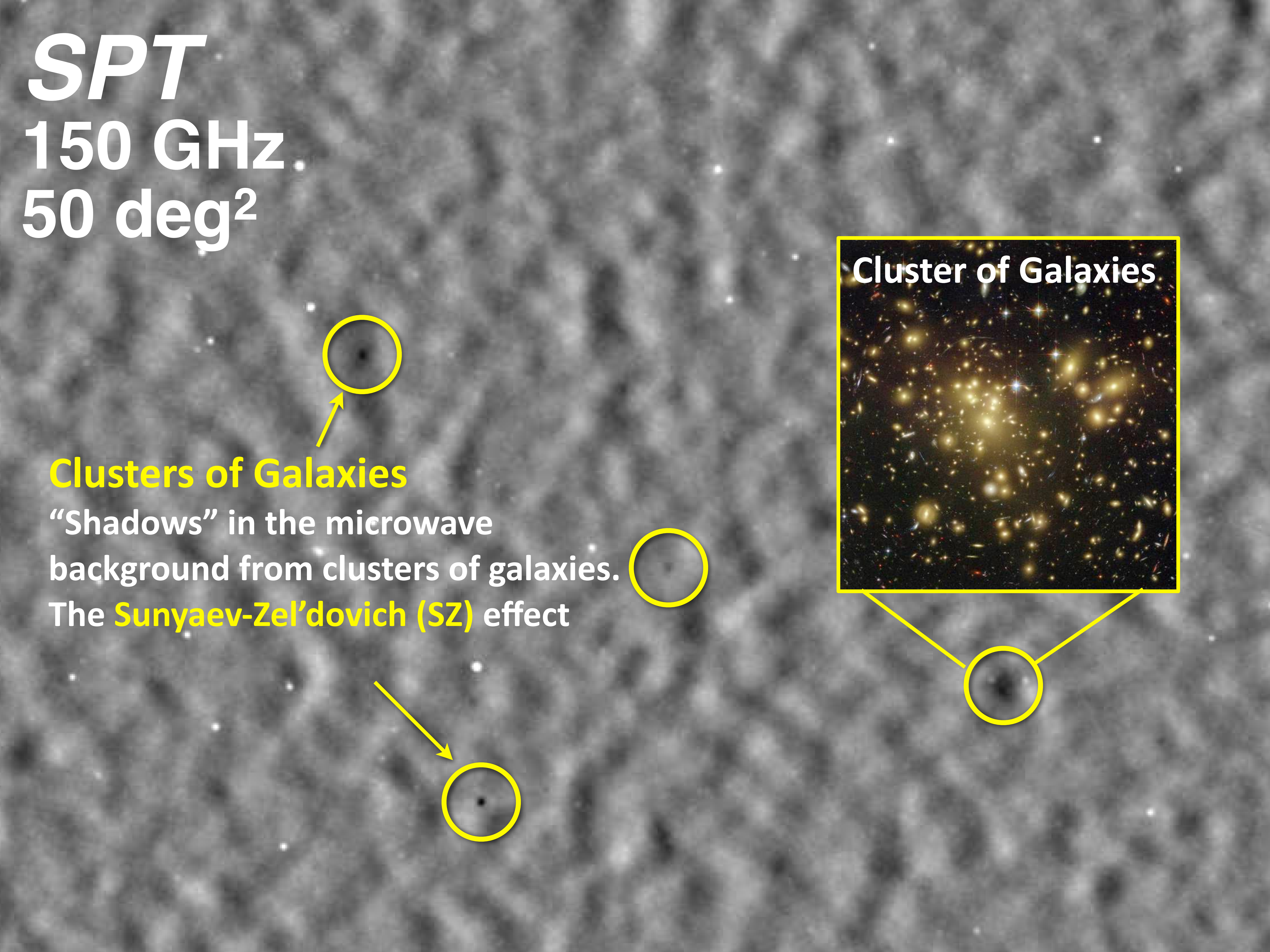
CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381

Detector sensitivity has been limited by photon "shot" noise for last ~15 years; further improvements are made only by making ***more detectors!***


Planck
143 GHz
50 deg^2
The moon
(for scale)

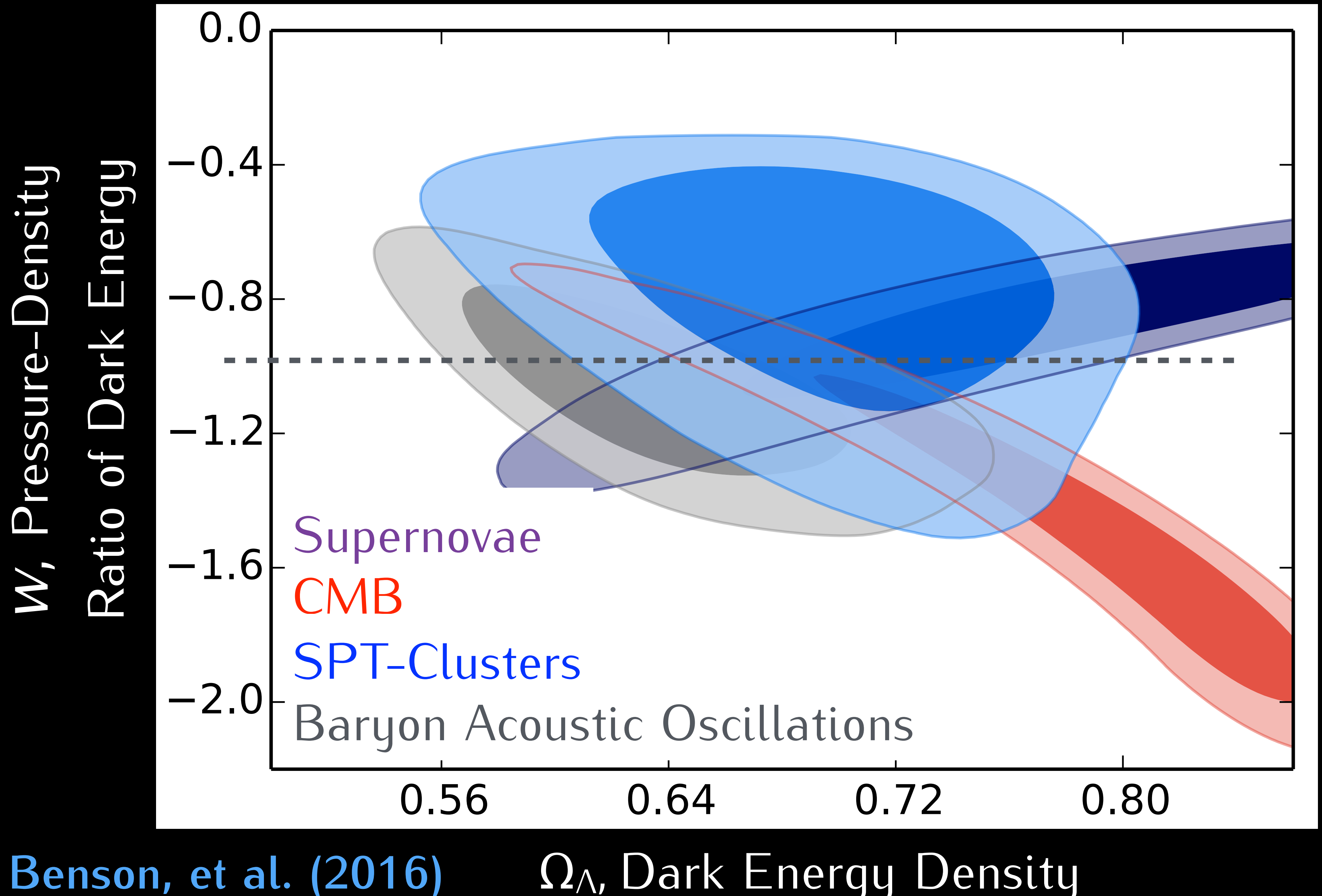

SPT
150 GHz
50 deg²
6x deeper
6x finer angular resolution
The moon
(for scale)


SPT
150 GHz
50 deg²
The moon
(for scale)


SPT
150 GHz
50 deg²
Clusters of Galaxies
"Shadows" in the microwave
background from clusters of galaxies.
The Sunyaev-Zel'dovich (SZ) effect
Cluster of Galaxies

Dark Energy Constraints from SPT

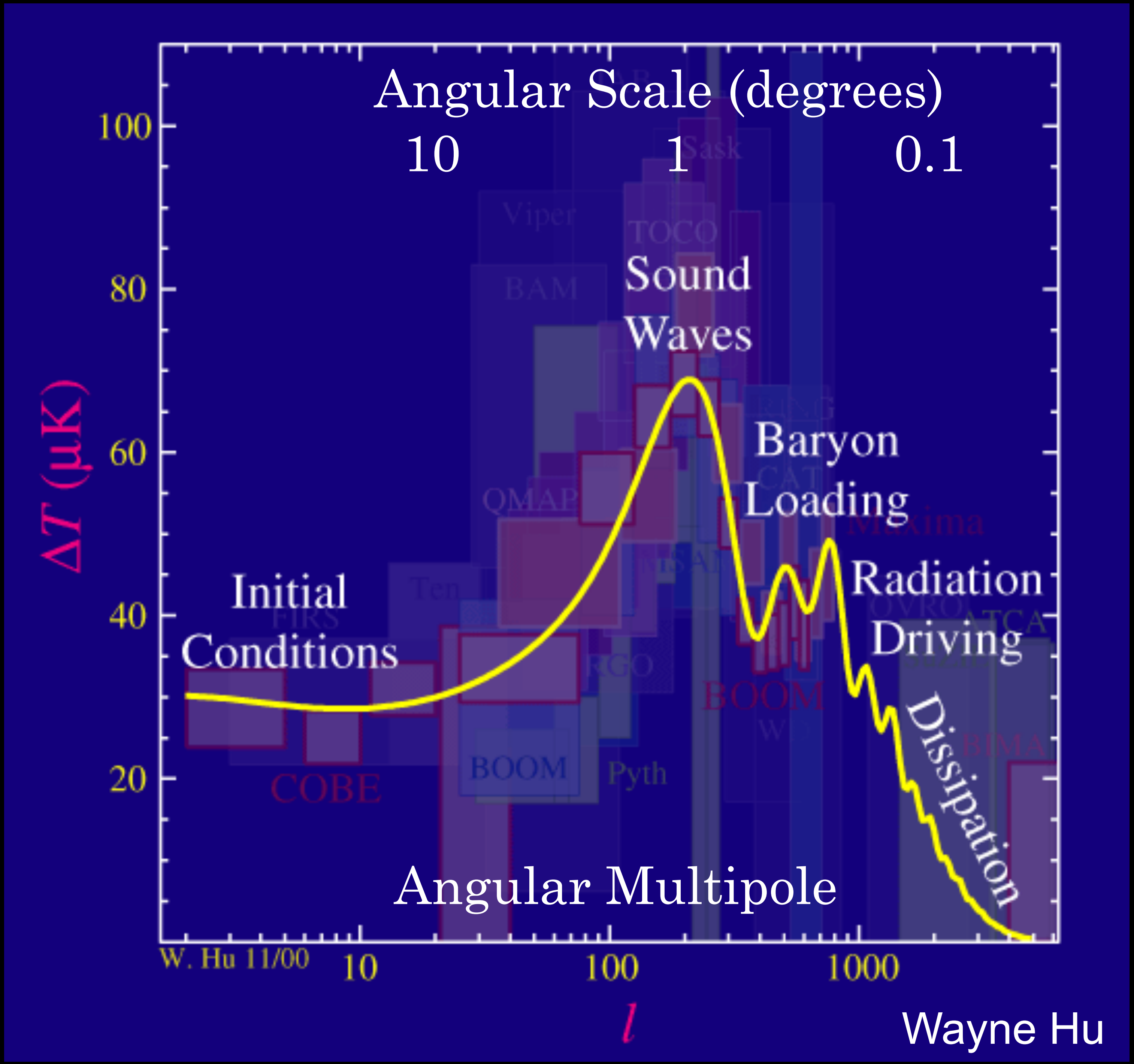
- ***Clusters*** measure ***"structure growth"***, rather than "geometry of Universe", and provide complimentary measurements to other probes
- ***Synergy with Dark Energy Survey (DES):*** multiple probes of structure can be cross-correlated with SPT to constrain dark energy

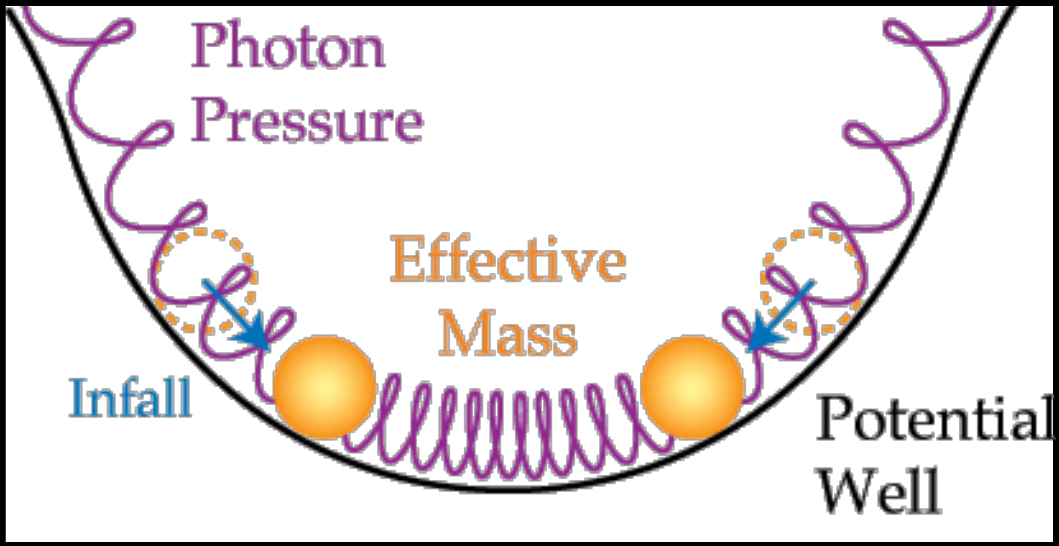


de Haan, Benson, et al. (2016)

The CMB Power Spectrum

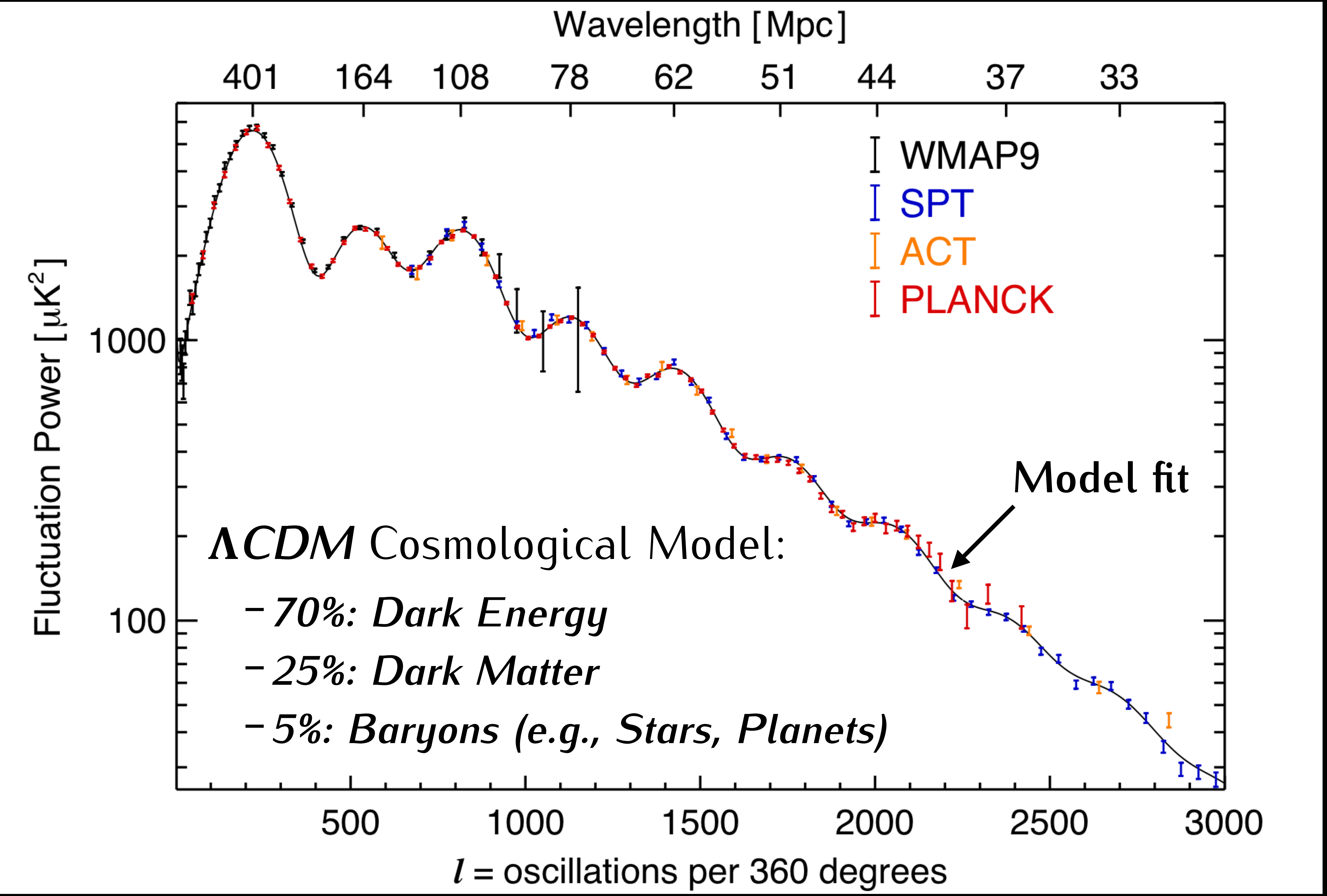
Encoded within the primordial CMB power spectrum is information regarding the Universe's **initial conditions**, its **geometry** (flat vs curved), and its **content** (baryons, dark matter)

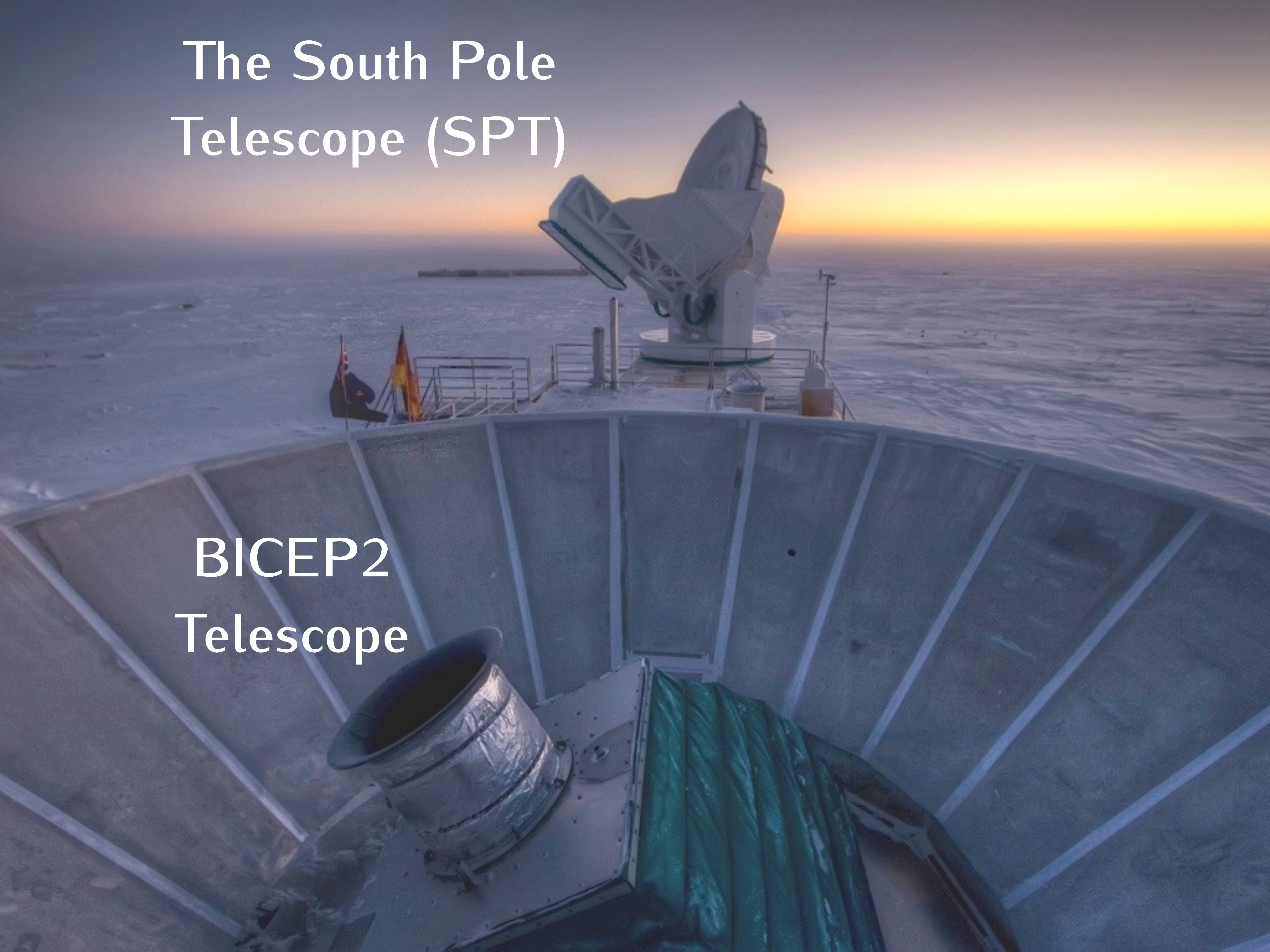




Peaks in power spectrum generated by acoustic oscillations in ~3000 K plasma

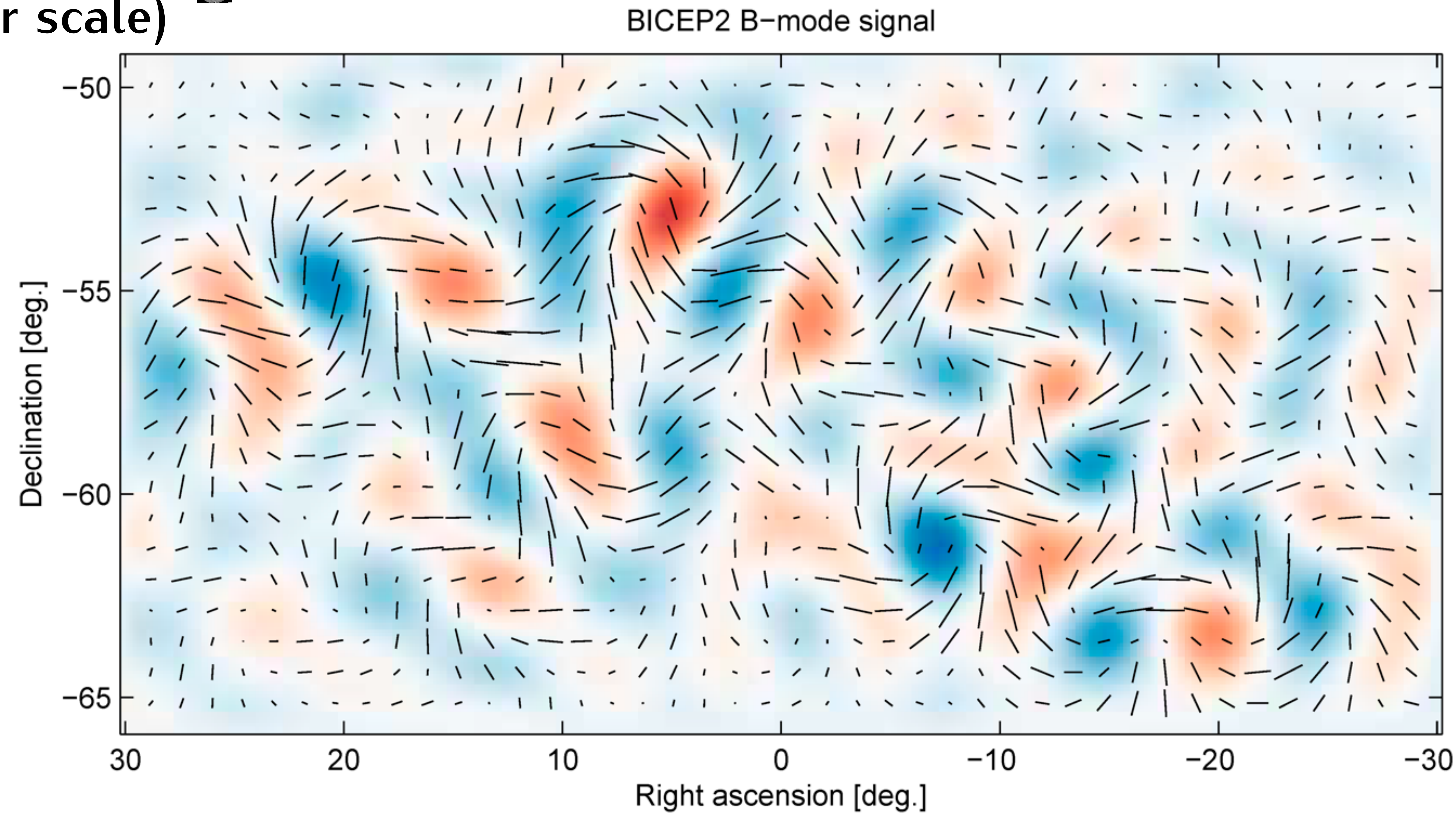
The CMB Today: implies a Universe dominated by dark matter and dark energy




The South Pole
Telescope (SPT)
BICEP2
Telescope

2014: BICEP2 Detection of B-mode Polarization of the CMB

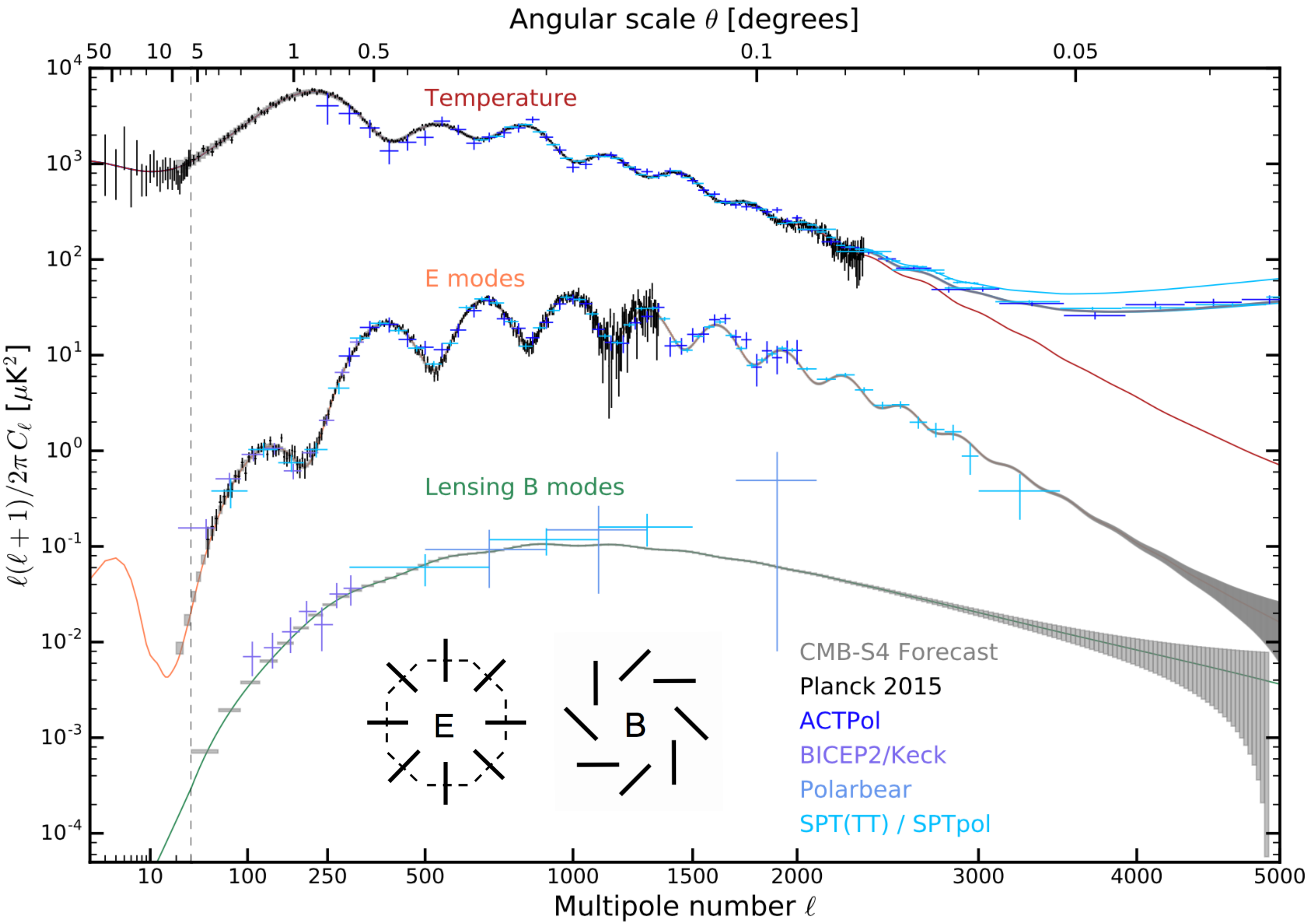
The moon
(for scale)



The New York Times

Space Ripples Reveal Big Bang's Smoking Gun

October 2016: CMB Power Spectra

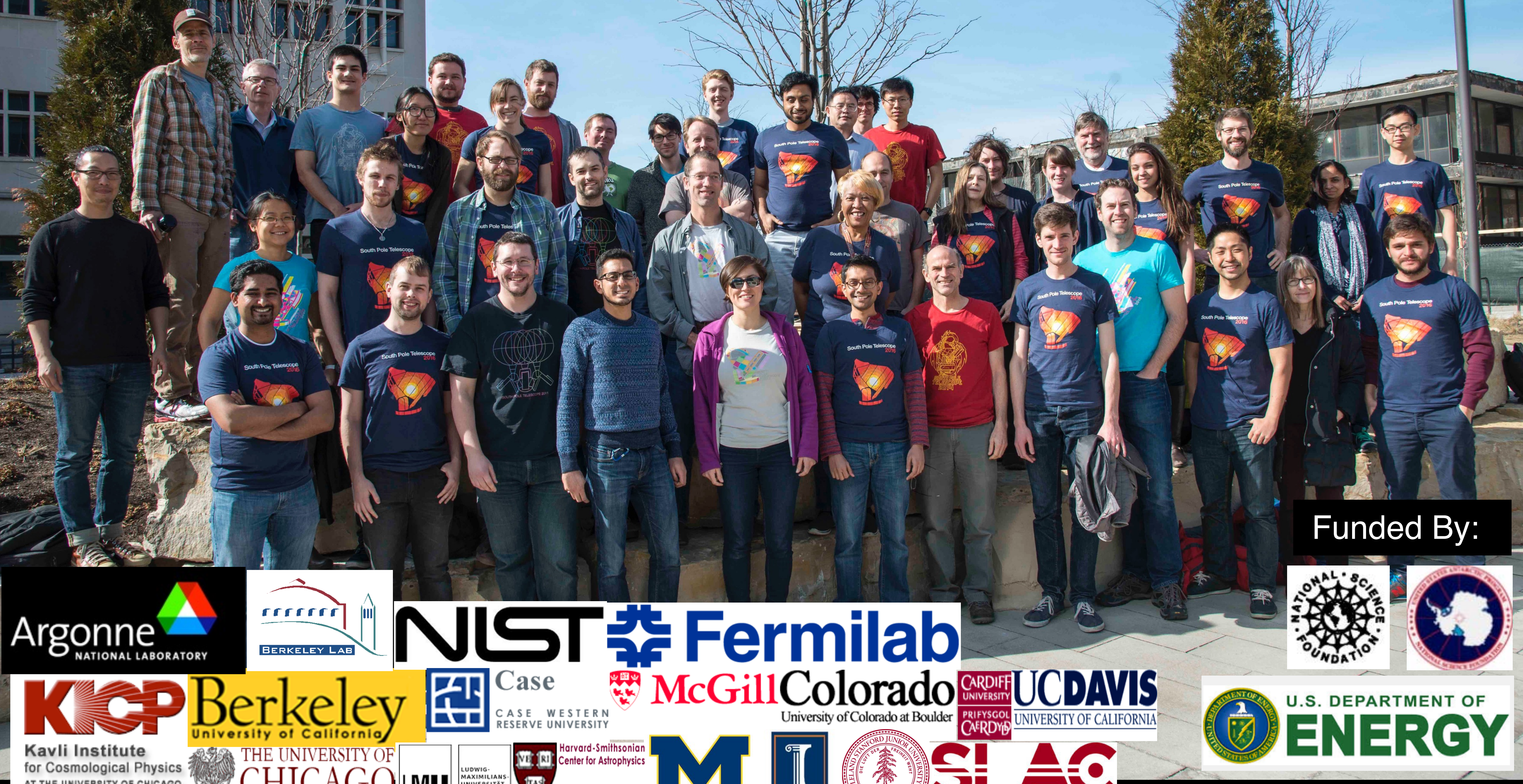


CMB-S4 Science Book: arxiv:1610.02743

The SPT-3G Collaboration (Feb. 2016)

~70 scientists (~half postdocs and students)

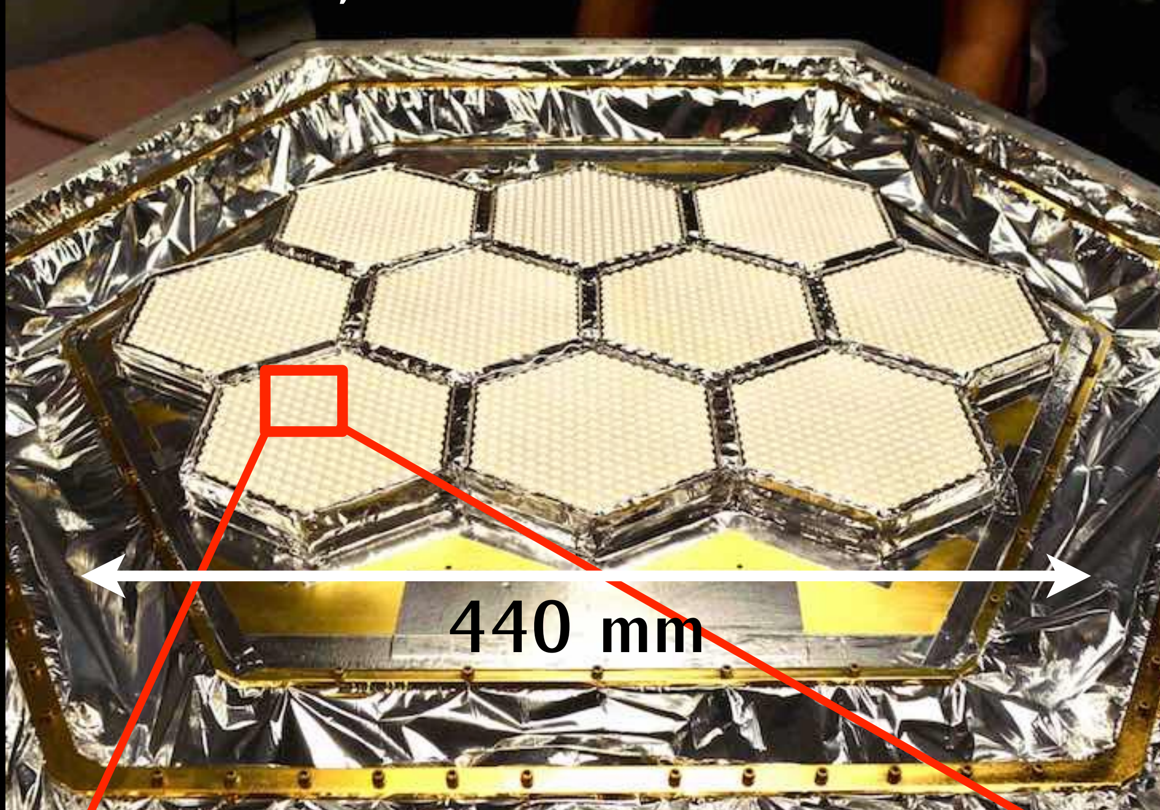
across ~20+ institutions



SPT-3G Detectors

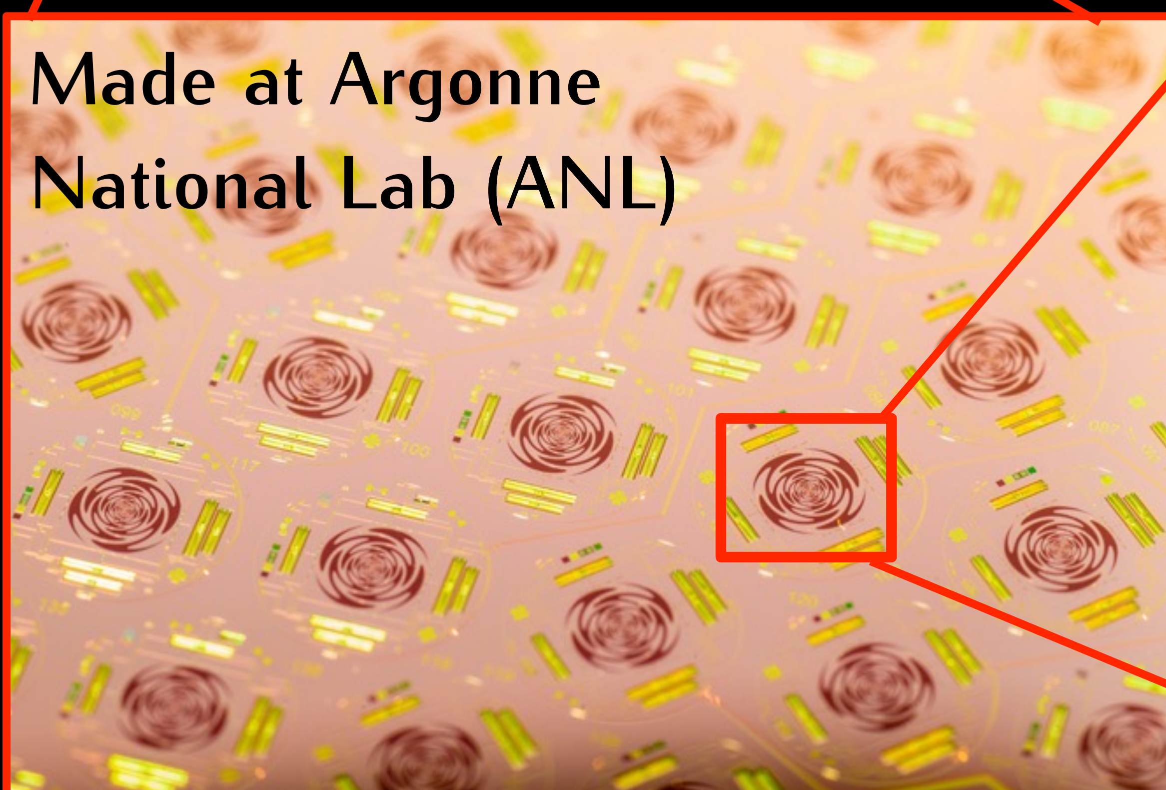
SPT-3G focal plane

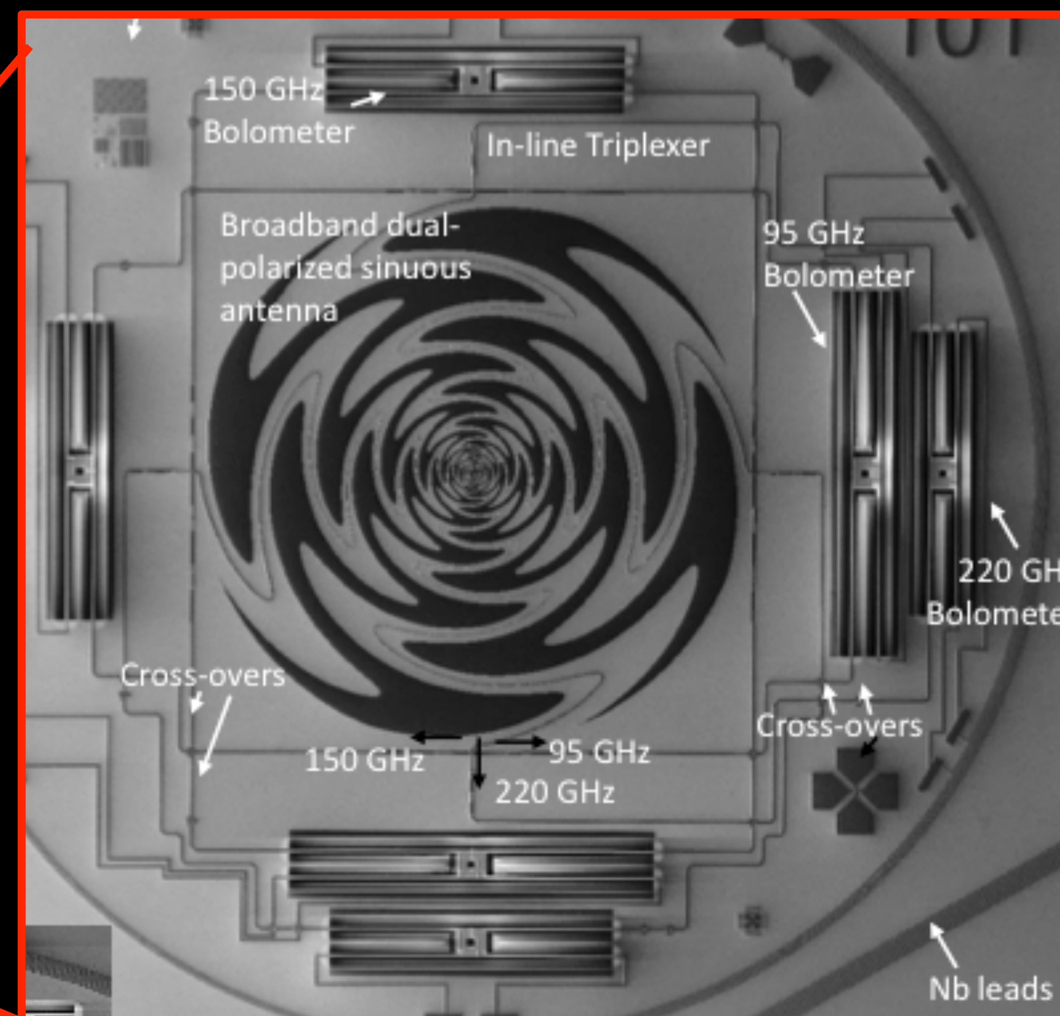
-16,234 TES bolometers



DOE Labs (ANL, LBNL, SLAC, FNAL) working on developing Stage II to Stage III detector

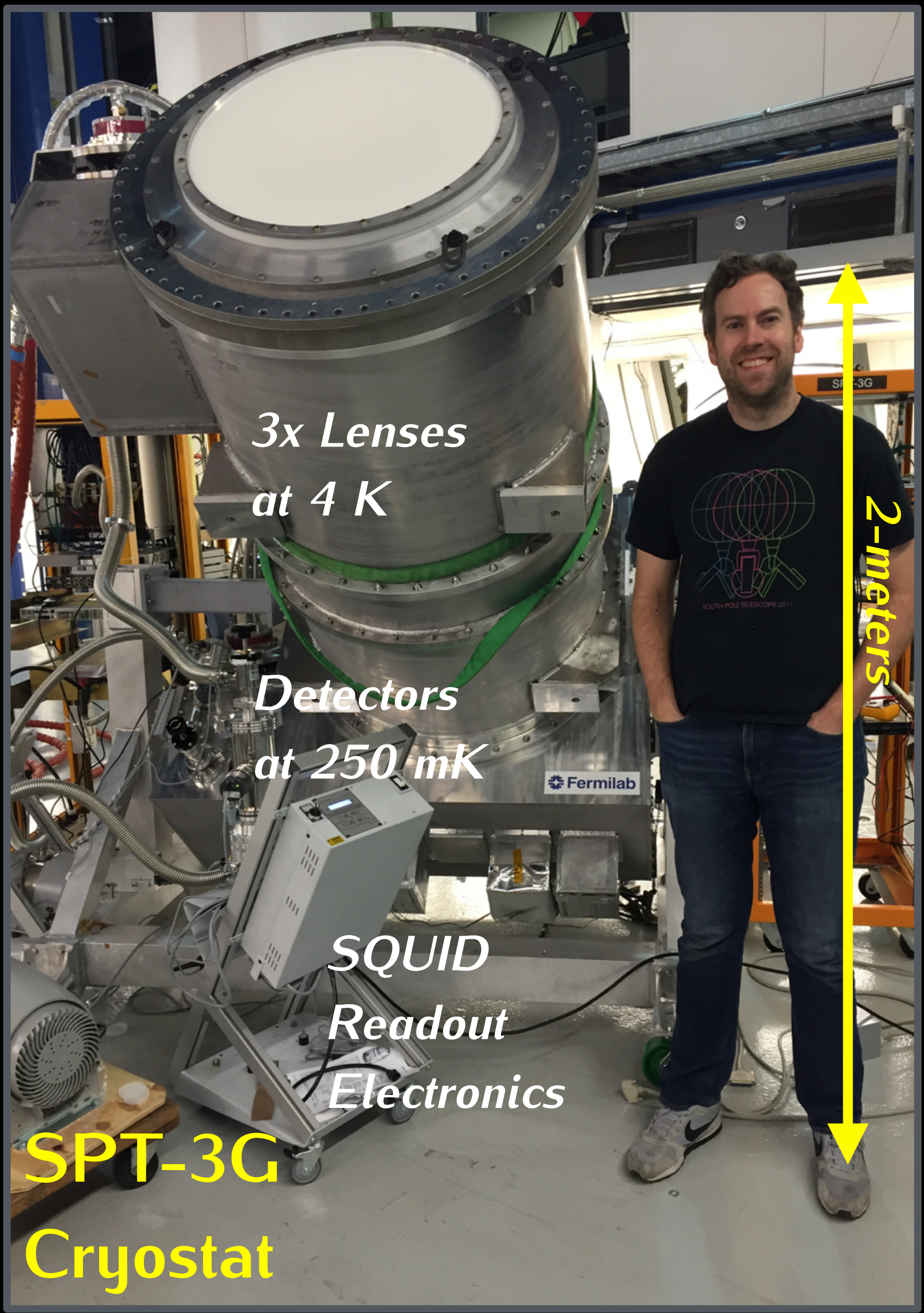
- Multichroic, dual polarization antennas
- Background limited performance per detector
- Transition-edge sensors with Tc ~ 500mK





2 mm

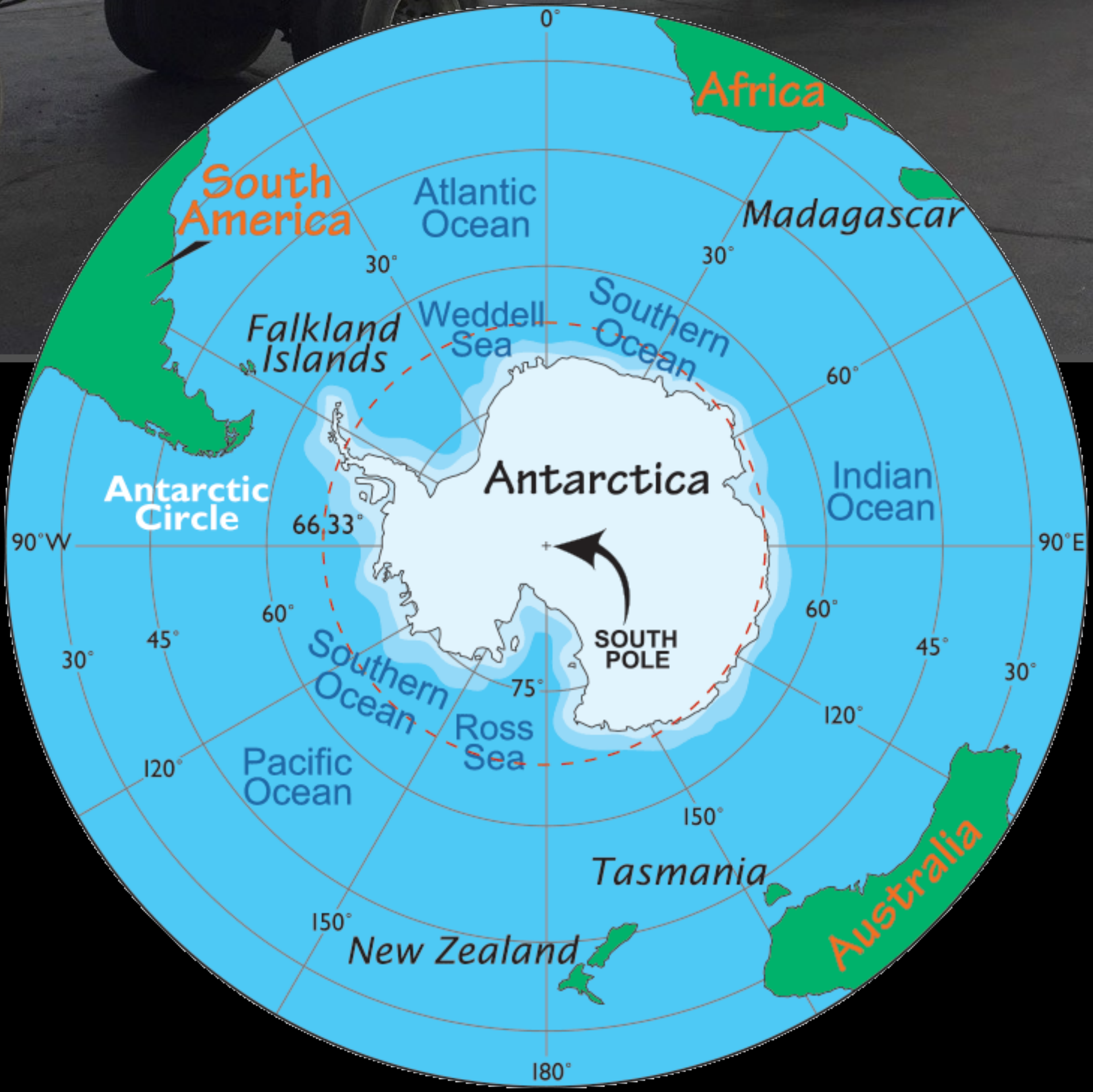
SPT-3G: A New Camera for the SPT



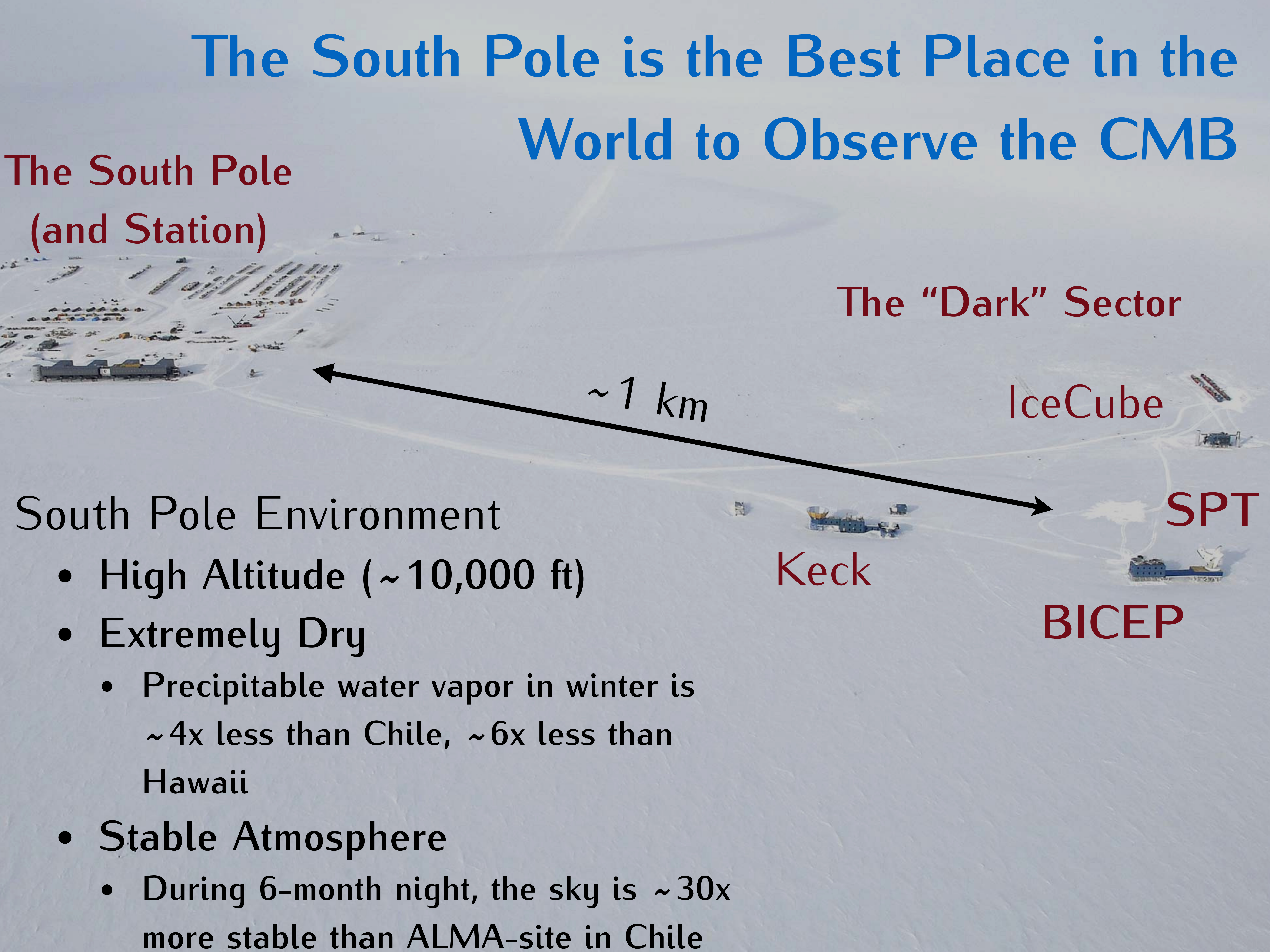
Fermilab roles:

- Camera cryostat design and integration
- Detector packaging
- Detector R&D (simulations, testing)
- Science!

SPT3G: Transport to the South Pole



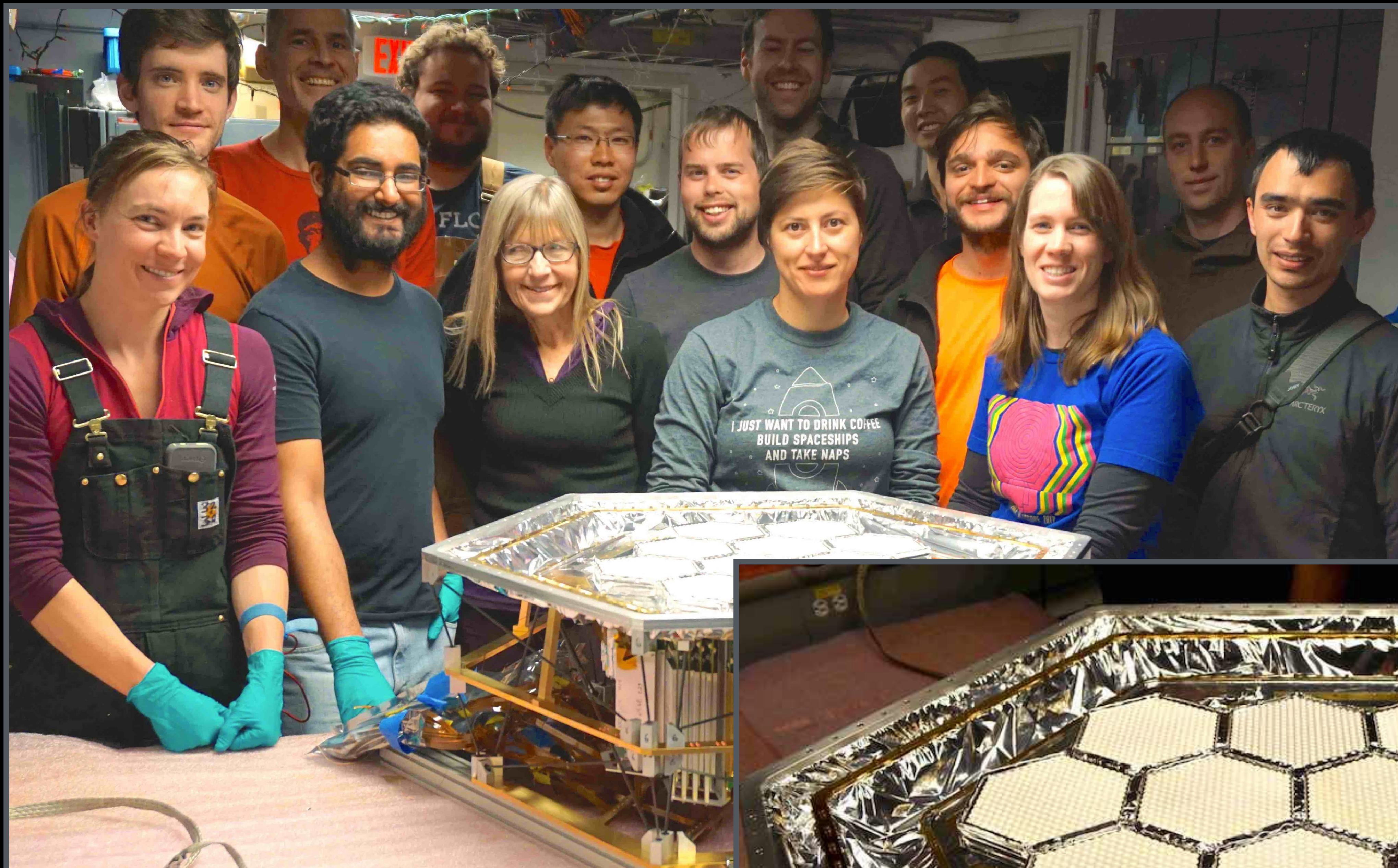
The South Pole is the Best Place in the World to Observe the CMB



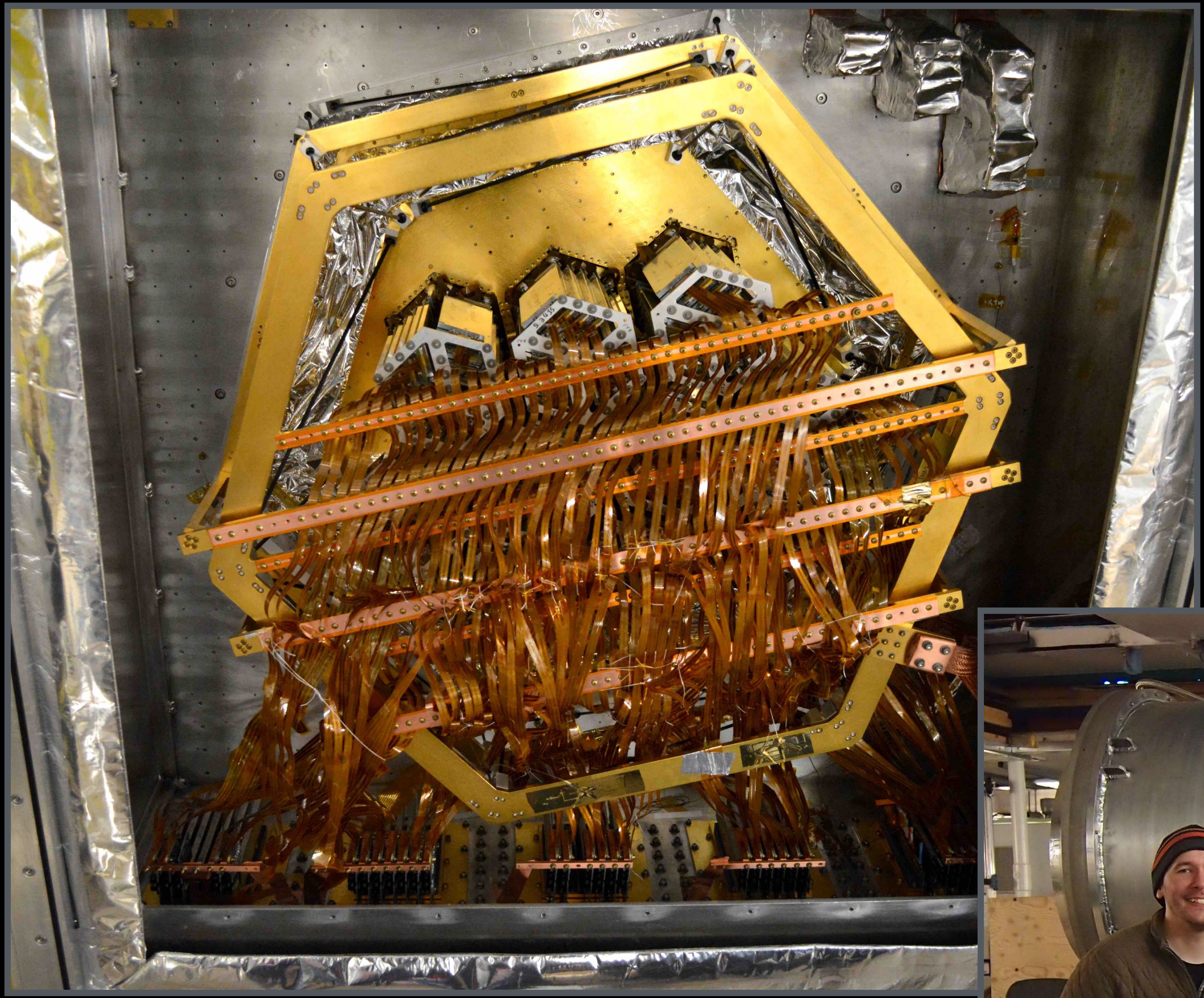
South Pole Environment

- High Altitude (~10,000 ft)
- Extremely Dry
  - Precipitable water vapor in winter is ~4x less than Chile, ~6x less than Hawaii
- Stable Atmosphere
  - During 6-month night, the sky is ~30x more stable than ALMA-site in Chile

SPT-3G Camera Assembly

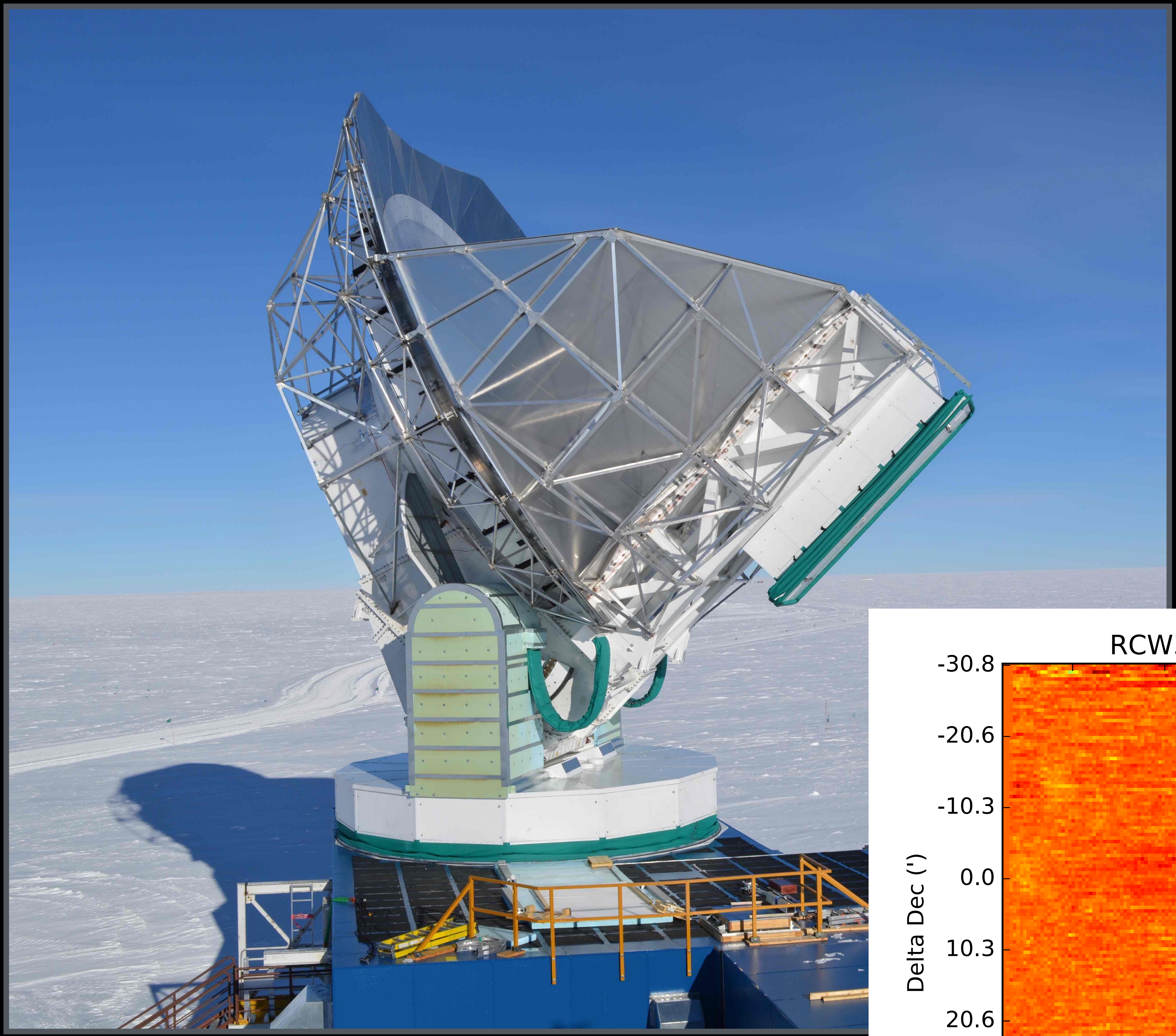


Focal Plane Integration

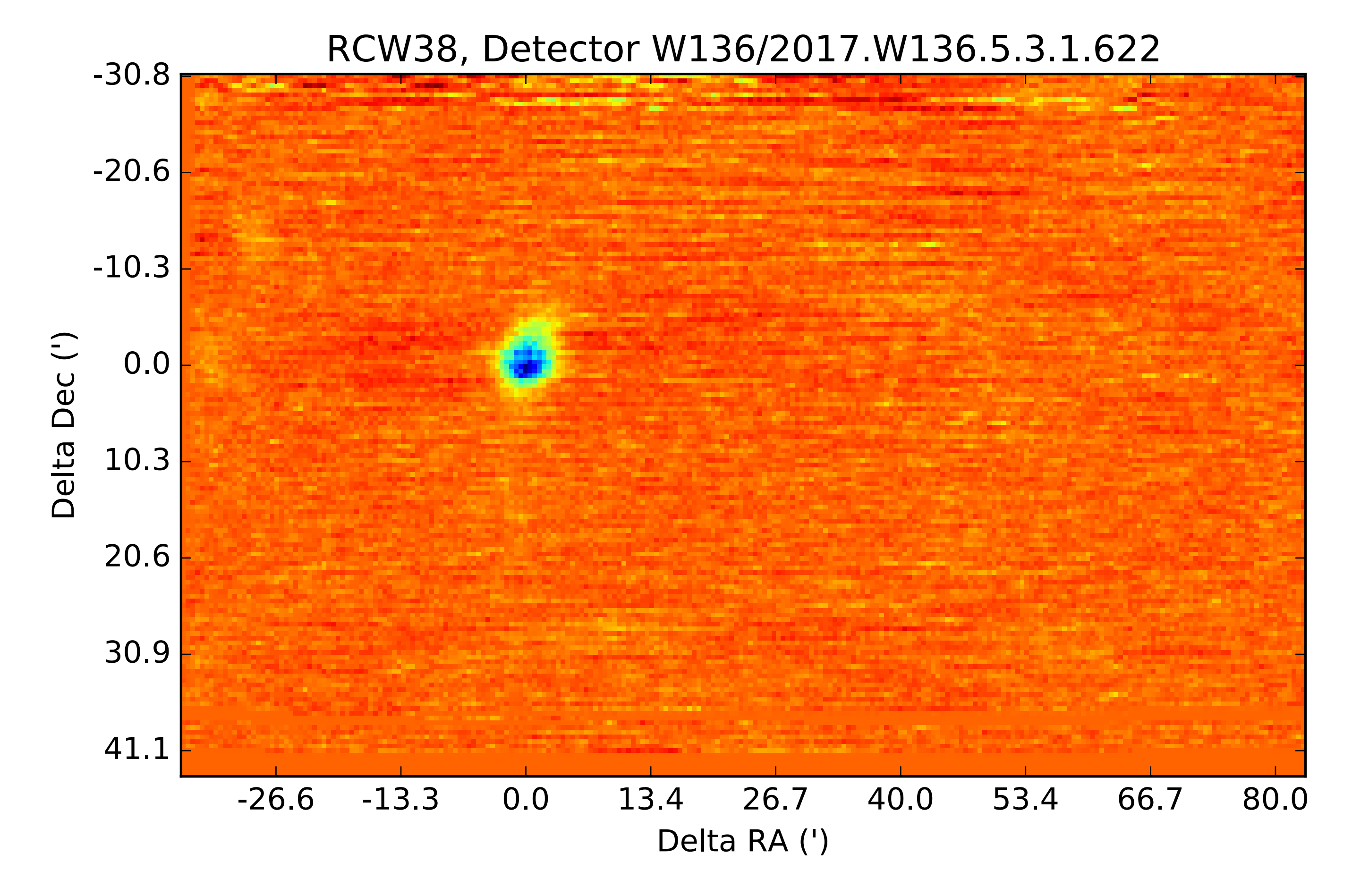


Installation onto the Telescope

January 30: First Light for SPT-3G!



"On Monday January 30, 2017 just before midnight, the newly installed SPT-3G camera saw first light on the South Pole Telescope (SPT) by detecting the HII-region RCW38. This represents a major step towards significantly improving the sensitivity of the SPT. The new SPT-3G camera consists of 16,200 superconducting transition edge sensor (TES) bolometers, a factor of 10 increase over the previously installed SPTpol camera. Congratulations to the entire SPT-3G team! "



Current Status of SPT-3G

- South Pole closed for winter on Feb 15; in-accessible until Nov 1
- Sunset was on March 20; 6 months of darkness and winter
- Two SPT-3G winter-overs (of ~40 people on station) left behind to continue winter observations
- Currently in an engineering mode, to fully assess instrument performance
- FNAL team plans to go back next austral-summer for camera maintenance

Stage IV CMB experiment: CMB-S4

The future enabled by CMB-S4:

Inflation: Detect or rule out generic slow roll inflation, E ~ 10^{16} GeV

Dark Radiation: Rule out / discover any additional light particle species.

Neutrino mass: Detection of sum of masses

Dark Energy, Gravity, and Dark Matter: Multiple probes constraining structure growth, geometry.

More fundamental discoveries?

	Sensitivity	CL(r)	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	DE FOM
Stage II ~1000 detectors until 2016	$\gtrsim 10^{-5} \mu K^2$	$r \lesssim 0.1$	0.14	BOSS BAO Prior 0.15eV	SIII DE (CMB+BAO +SN+WL) ~130
Stage III ~10,000 detectors until 2020	$10^{-6} \mu K^2$	$r \lesssim 0.01$	0.06	BOSS BAO Prior 0.06eV	SIII DE +DESI BAO ~350
Stage IV ~500,000 detectors until 2025	$10^{-8} \mu K^2$	$r \lesssim 0.001$	0.02	DESI BAO Prior 0.015eV	SIV DE (CMB+BAO +SN+WL +CL) ~1200

Path Forward is clear. Required Technologies are in the pipeline.

Next Steps: Scaling to O(500,000) detectors.

Summary

- A successful deployment of SPT-3G!
- Developing key technologies for CMB-S4
- Many big questions left, that CMB hopes to answer:
  - Did the Universe start with an epoch of Inflation? What physics was responsible for it?
  - What is the nature of Dark Energy?
  - What are the masses of neutrinos? Can we detect other new, unexpected light species (aka, "Dark Radiation")?