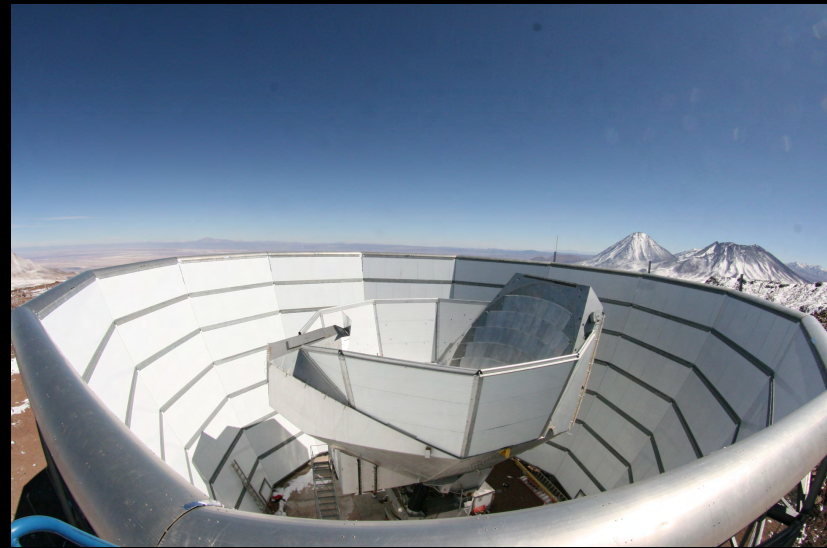
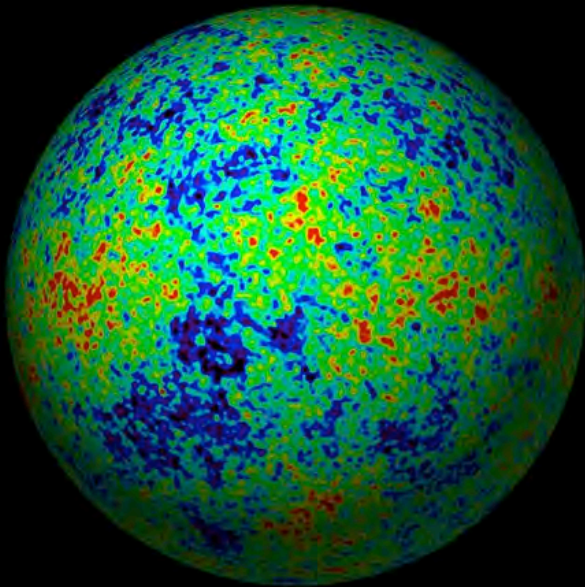


Experimental Cosmology and Astrophysics

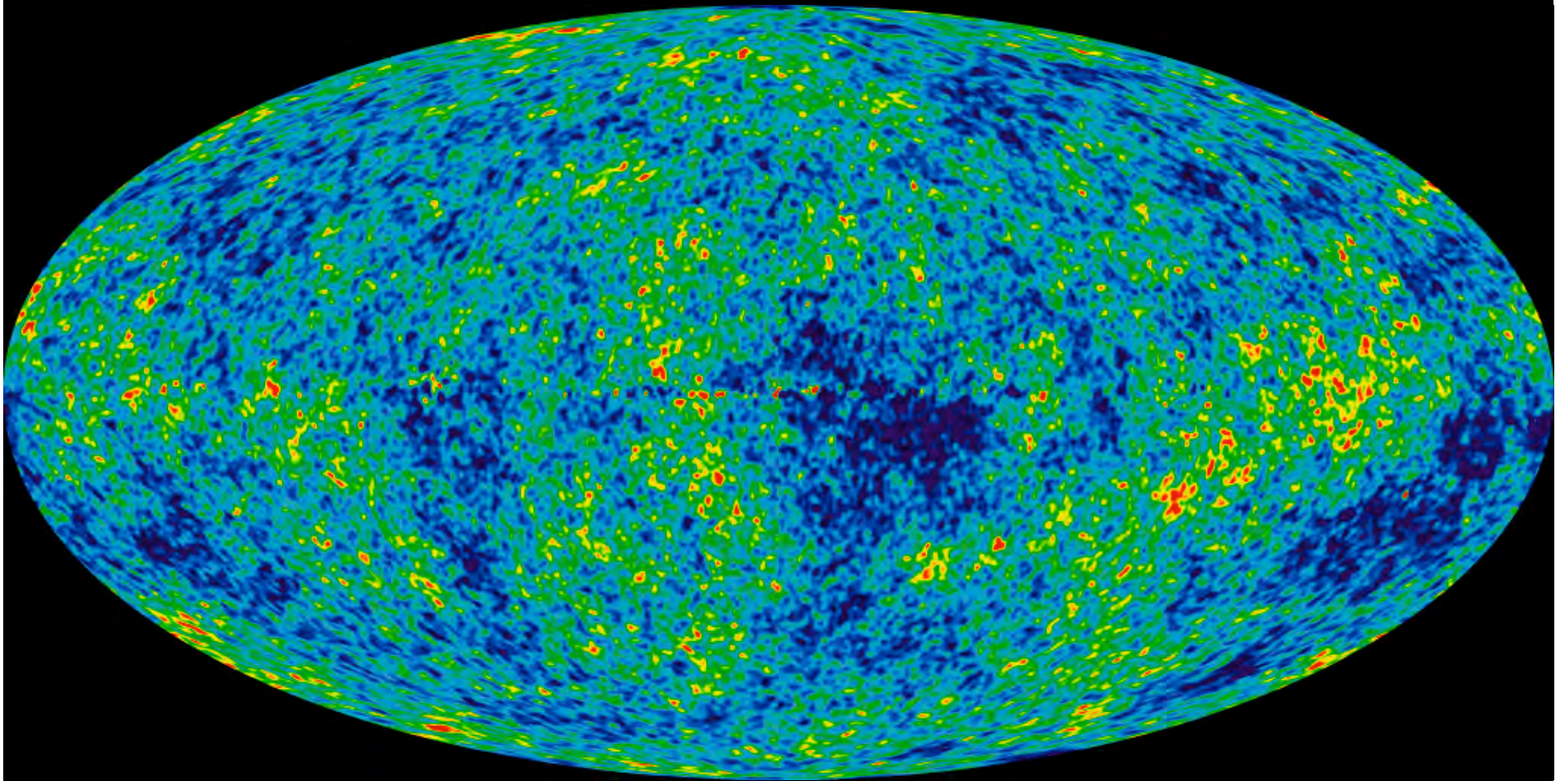
Cosmic Microwave Background Polarization
measurements with one of the
Highest Telescopes on Earth



Michael Niemack, Cornell University

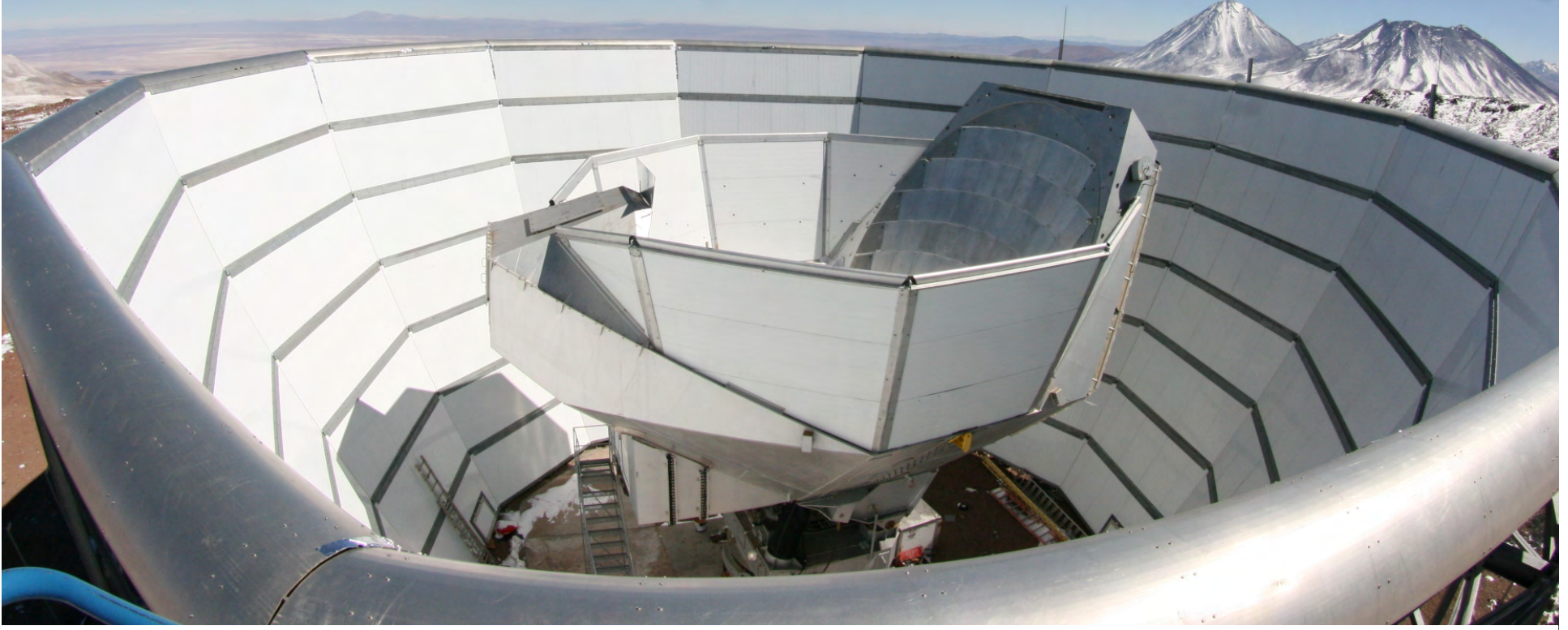
October 2015

Cosmic Microwave Background (CMB)



WMAP satellite measurements

Atacama Cosmology Telescope (ACT)



1920' s

Edwin Hubble
discovers:

Other galaxies
exist

Universe is
expanding!

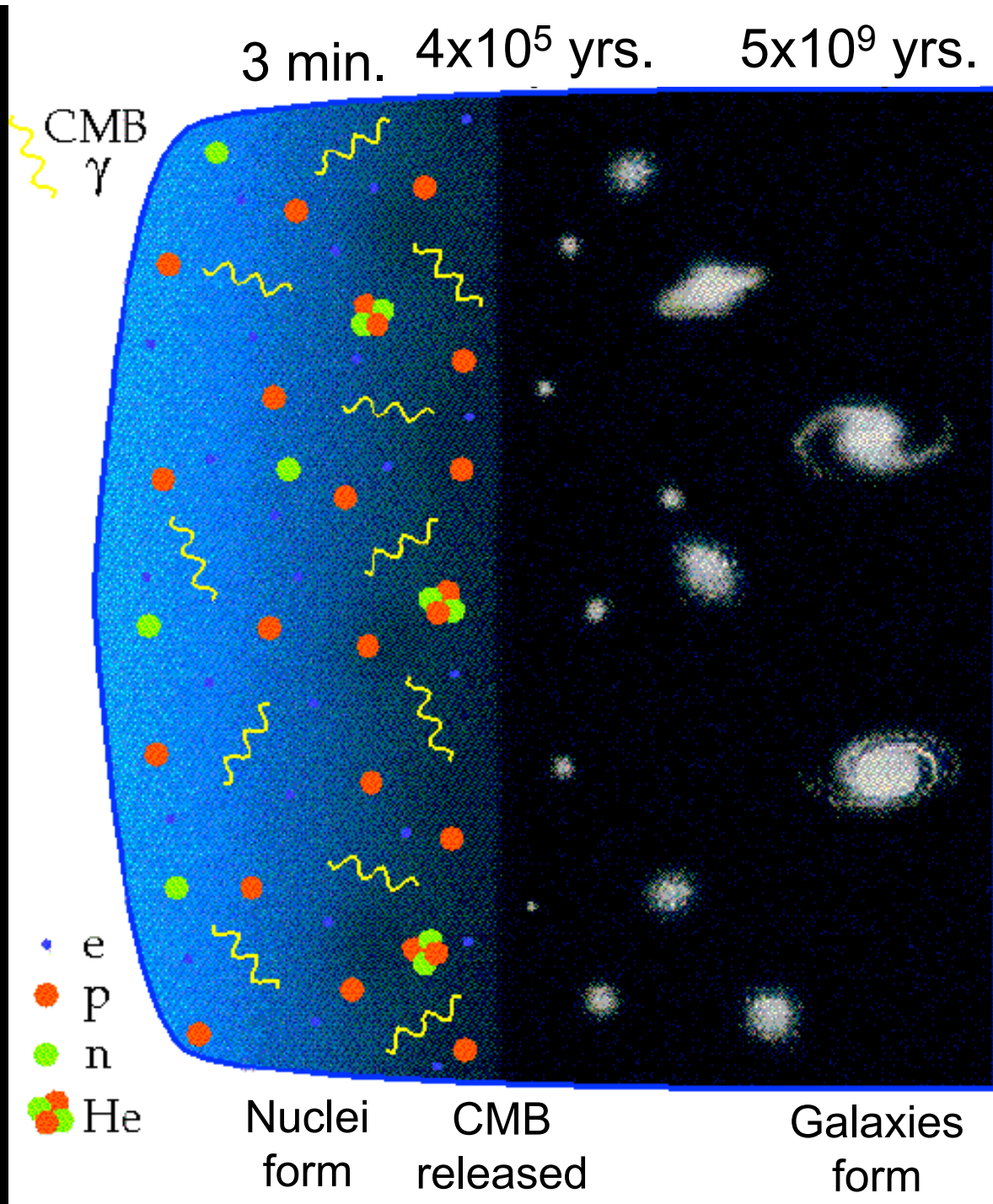


Michael Niemack, Cornell



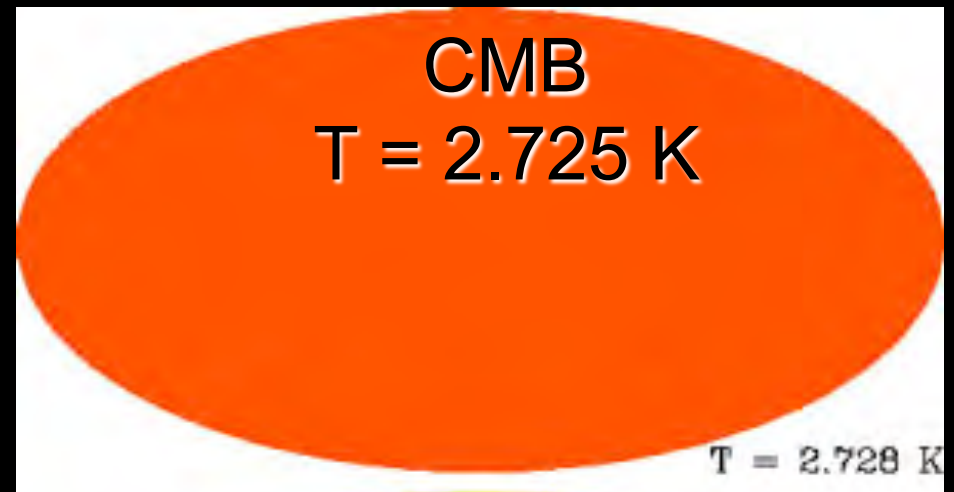
Courtesy of NASA WMAP team

Big Bang!



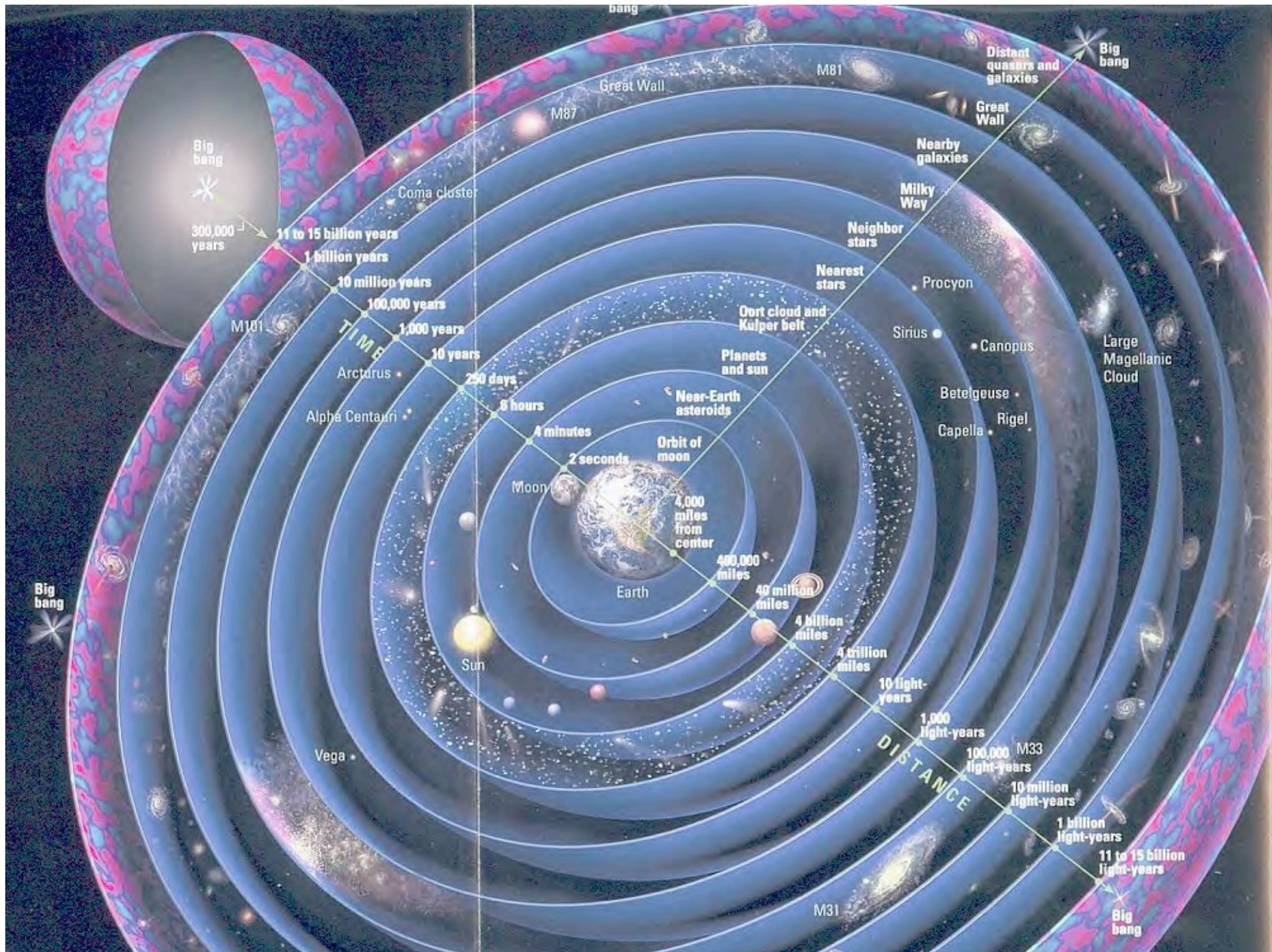
Today

50 year anniversary of CMB discovery



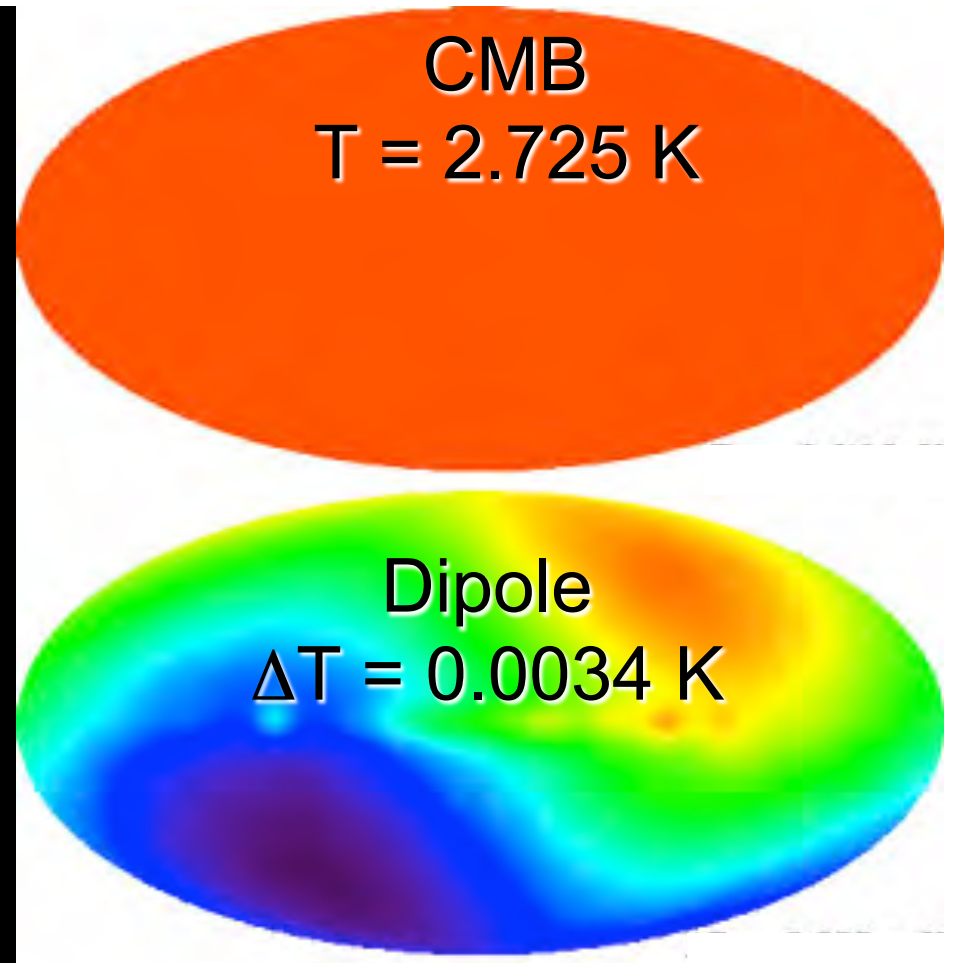
1978 Nobel Prize

Still much to learn from CMB
measurements



CMB Measurement Timeline

- 1965 – First detected by Penzias and Wilson
- 1970s – Dipole measured

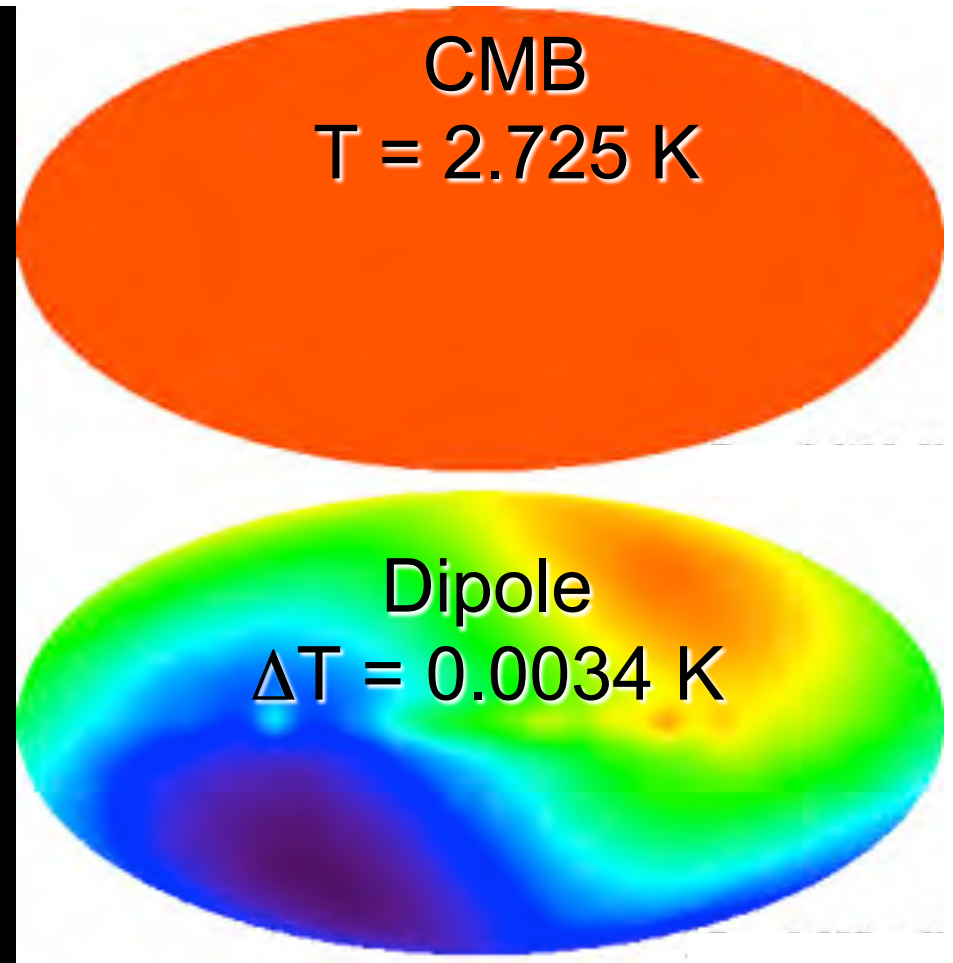


**Our velocity is 370 kilometers/second
with respect to the CMB!**

CMB Measurement Timeline

- 1965 – First detected by Penzias and Wilson
- 1970s – Dipole measured

Homogeneous and isotropic?

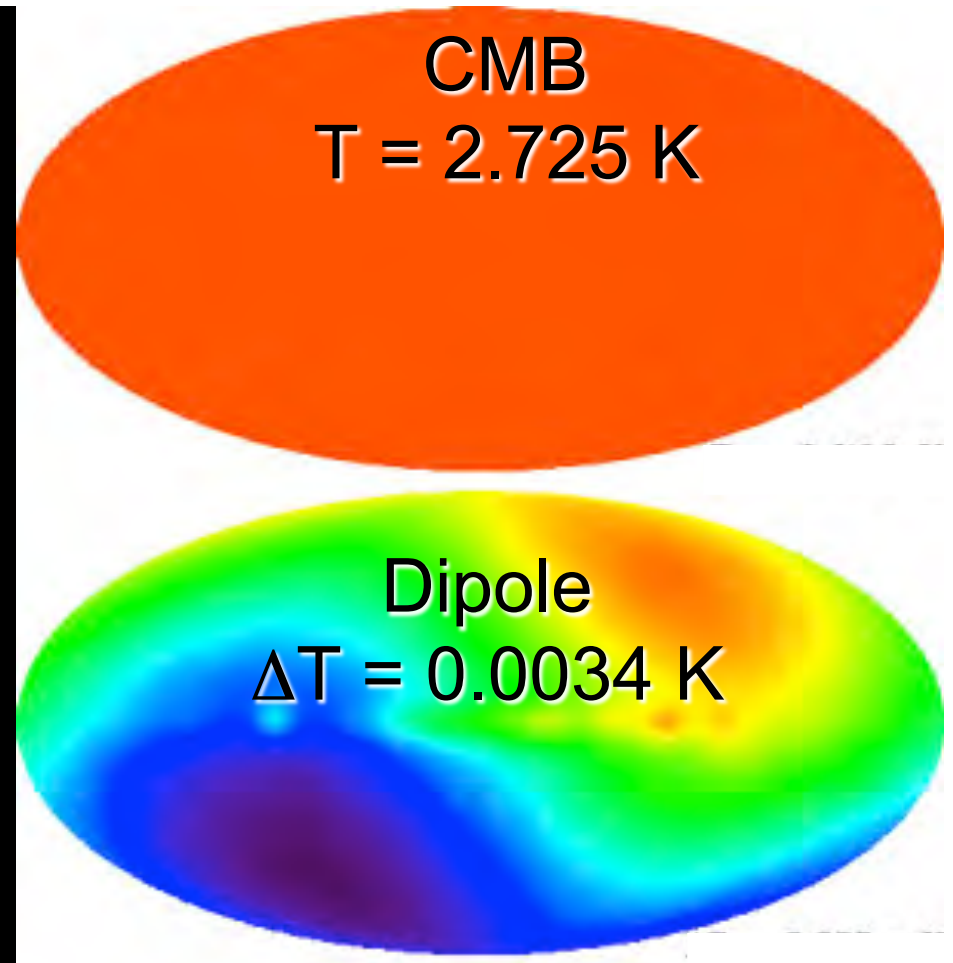


CMB Measurement Timeline

- 1965 – First detected by Penzias and Wilson
- 1970s – Dipole measured

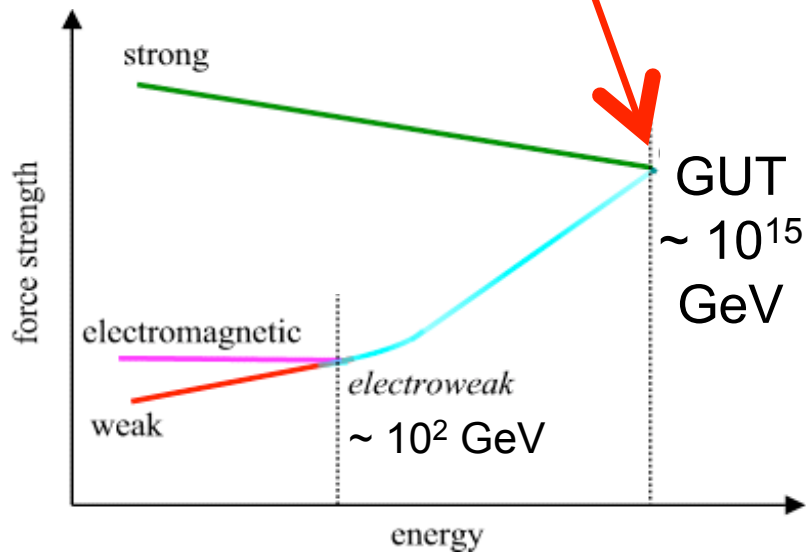
Homogeneous and isotropic?

⇒ Inflationary paradigm
exponential expansion $< 10^{-30}$ sec after big bang

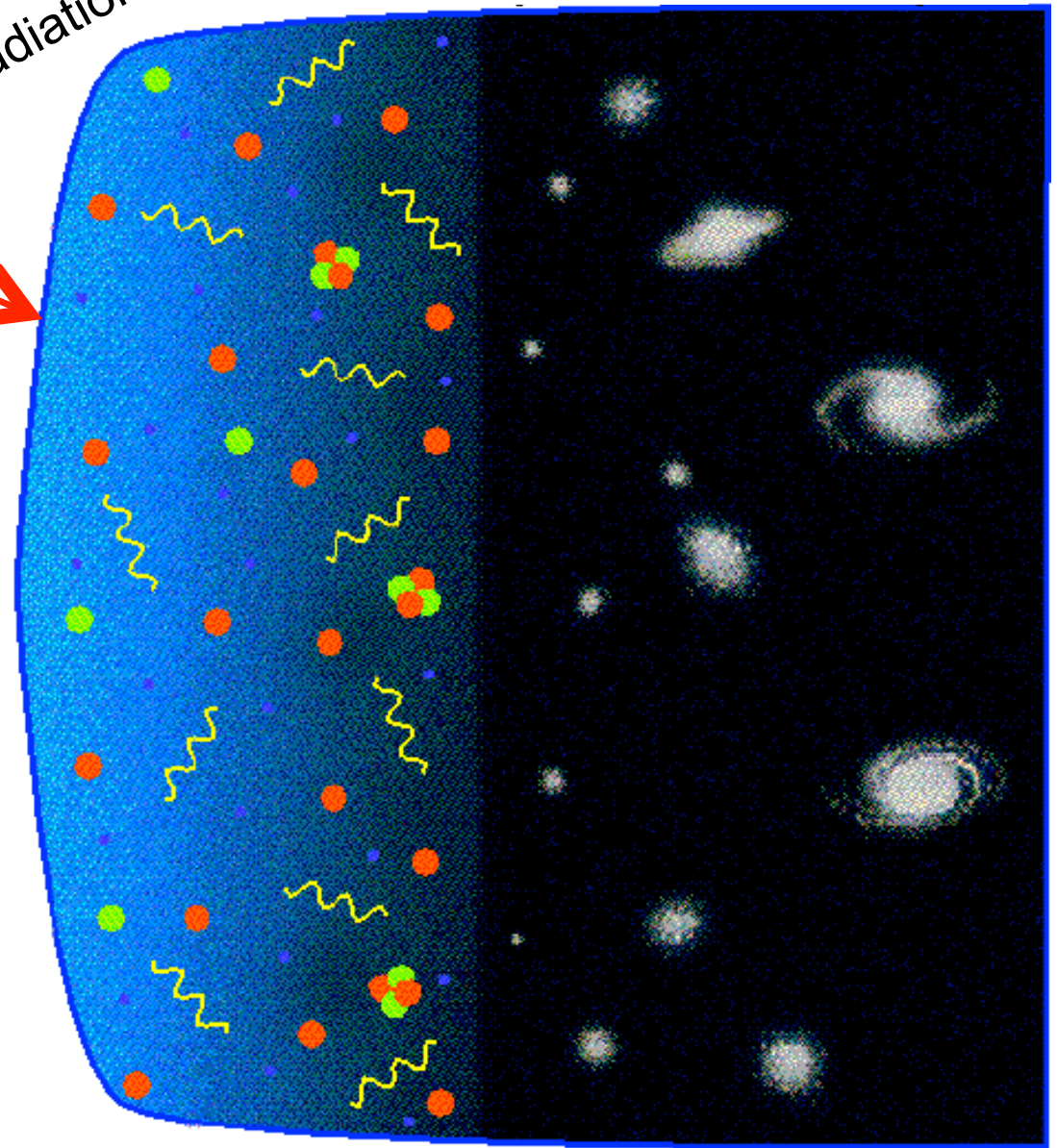


Inflationary expansion

Inflation energy scale
~ grand unification



radiation 3 min. 4x10⁵ yrs. 5x10⁹ yrs.



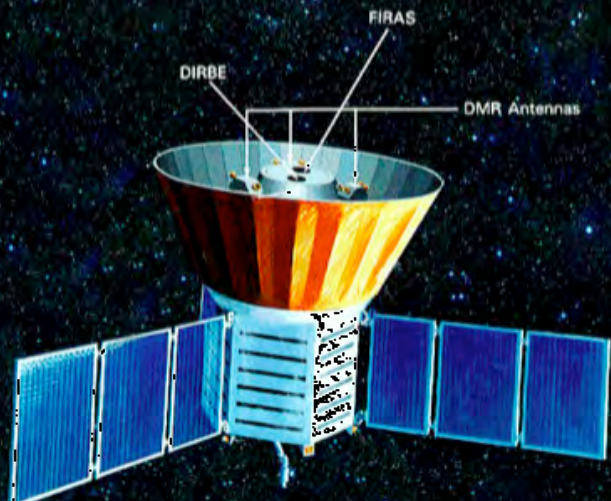
Nucleo-Synthesis

Last Scattering

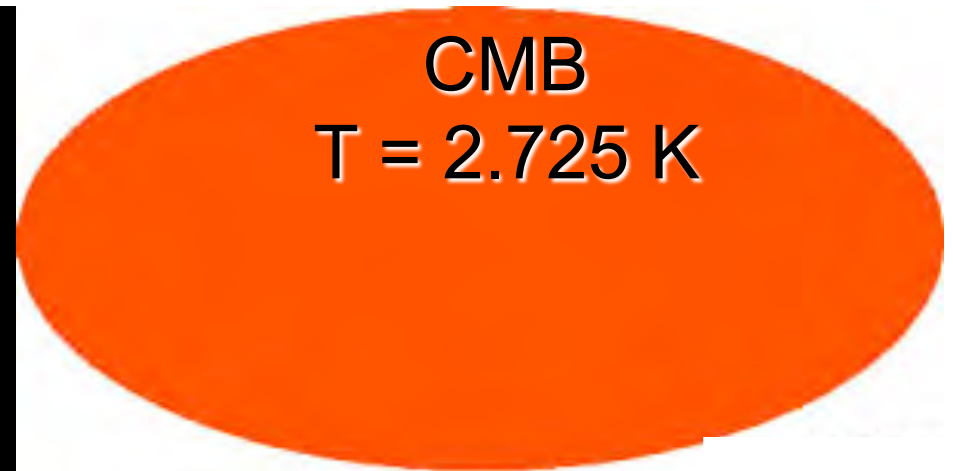
Galaxy Formation

CMB Measurement Timeline

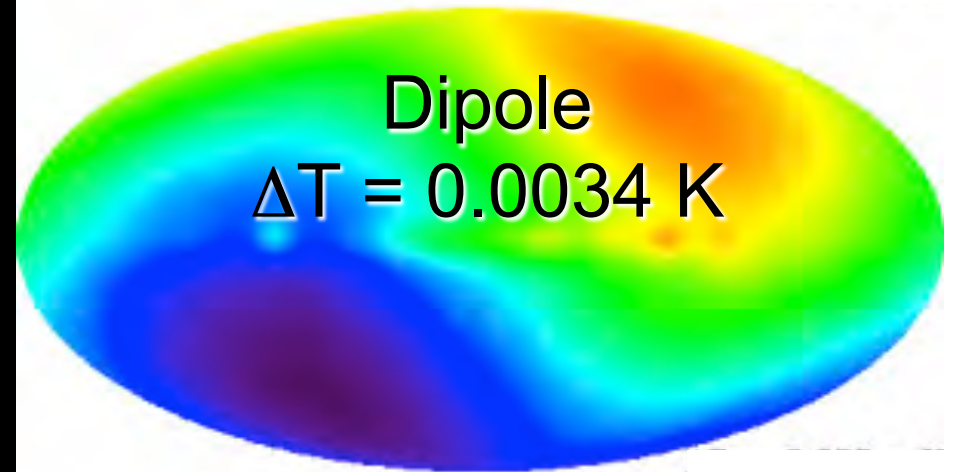
- 1965 – First detected by Penzias and Wilson
- 1970s – Dipole
- 1992 – Anisotropies detected by COBE



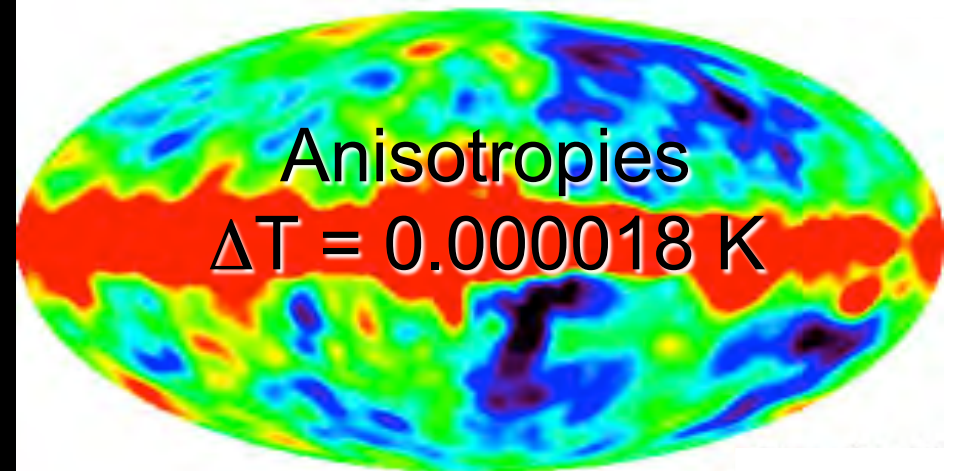
Cosmic Background Explorer
2006 Nobel Prize



CMB
 $T = 2.725 \text{ K}$



Dipole
 $\Delta T = 0.0034 \text{ K}$



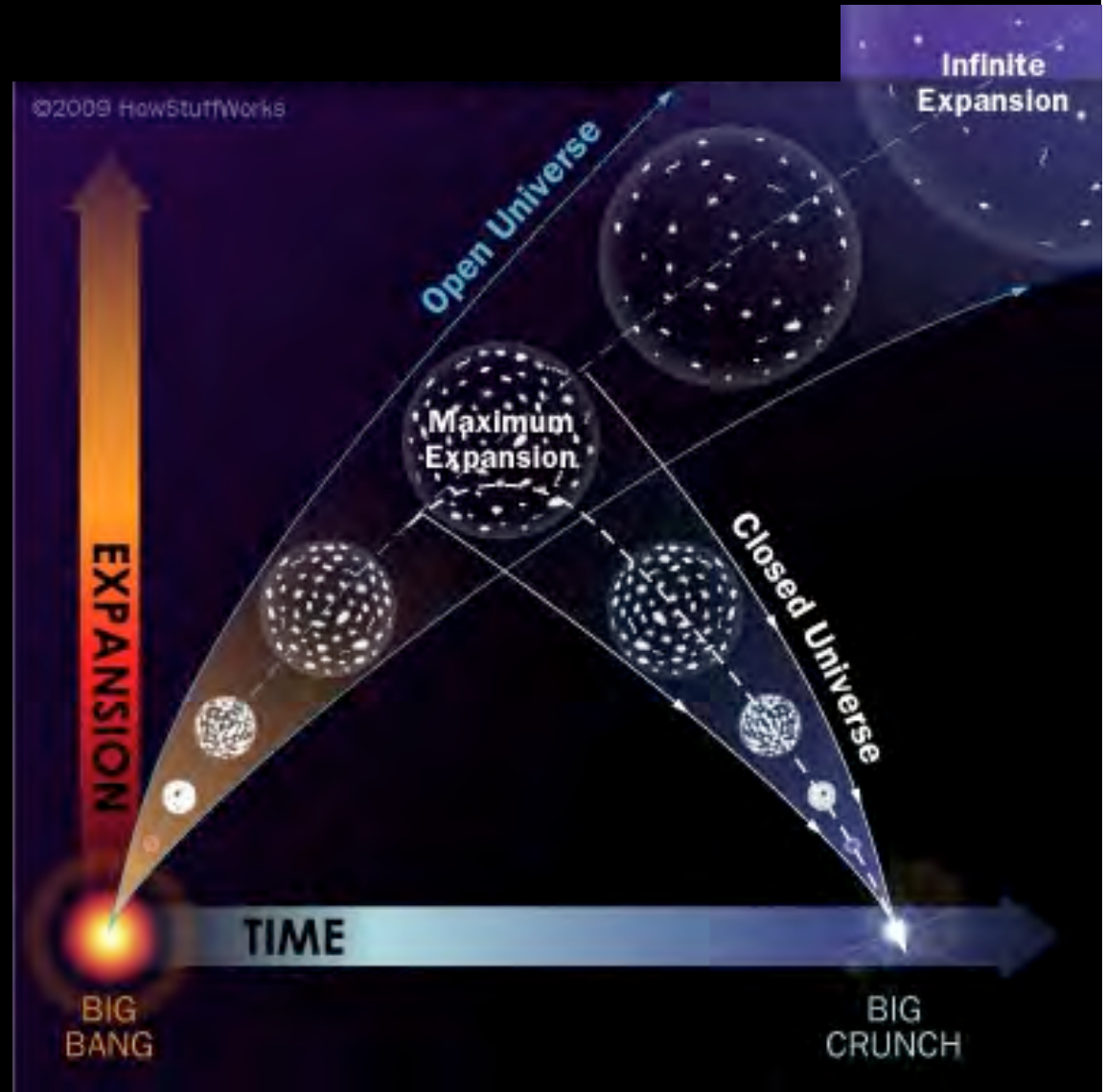
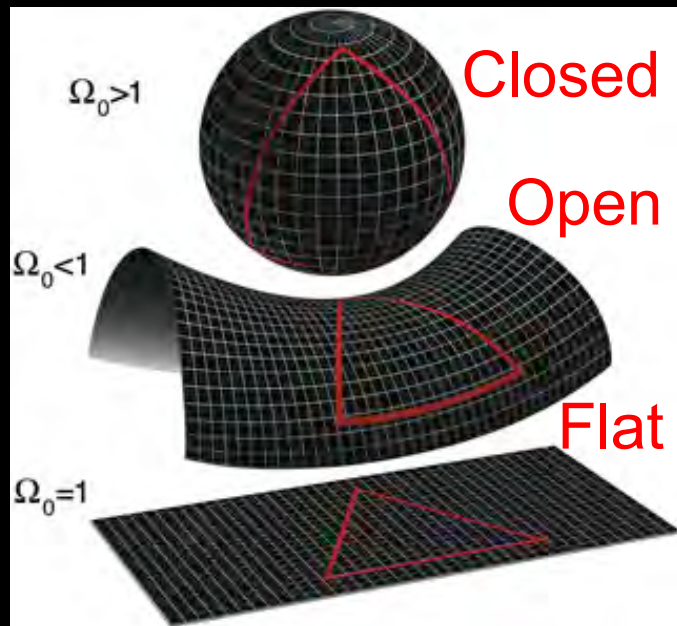
Anisotropies
 $\Delta T = 0.000018 \text{ K}$

Will the Universe expand forever?

1990s

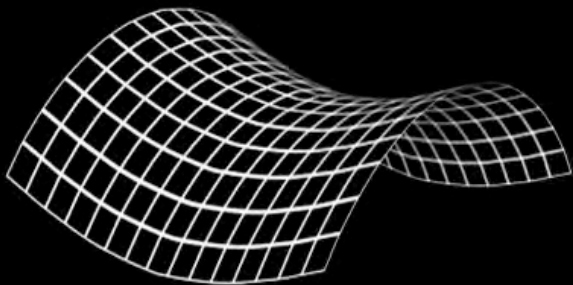
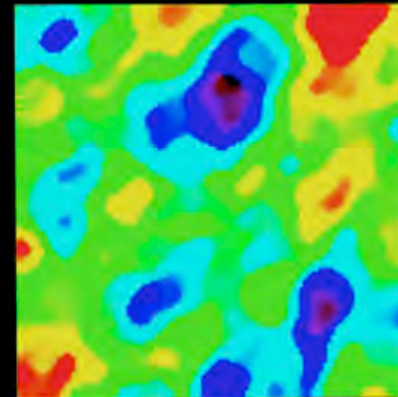
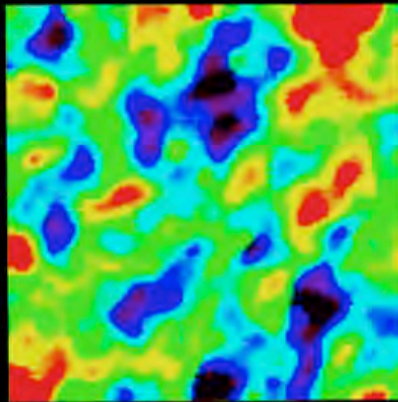
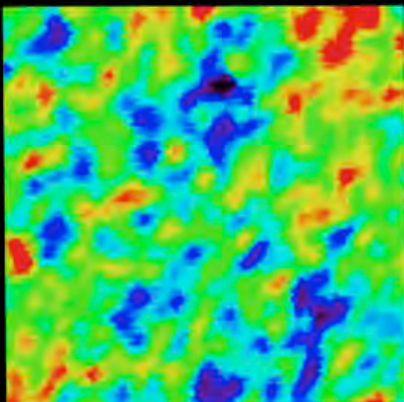
Gravity vs. Expansion

Infinite Expansion
or
Big Crunch?



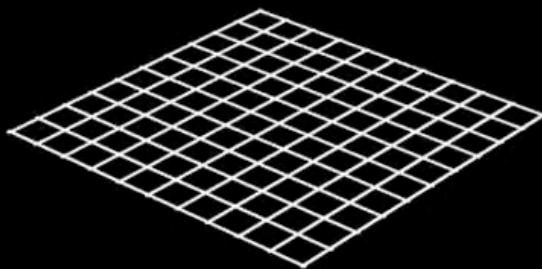
Michael Niemack, Cornell

GEOMETRY OF THE UNIVERSE



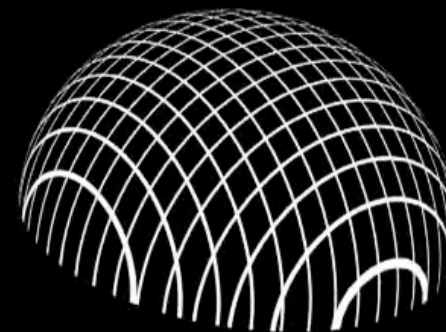
OPEN

$$\Omega_{\text{total}} < 1$$



FLAT

$$\Omega_{\text{total}} = \rho/\rho_c = 1$$



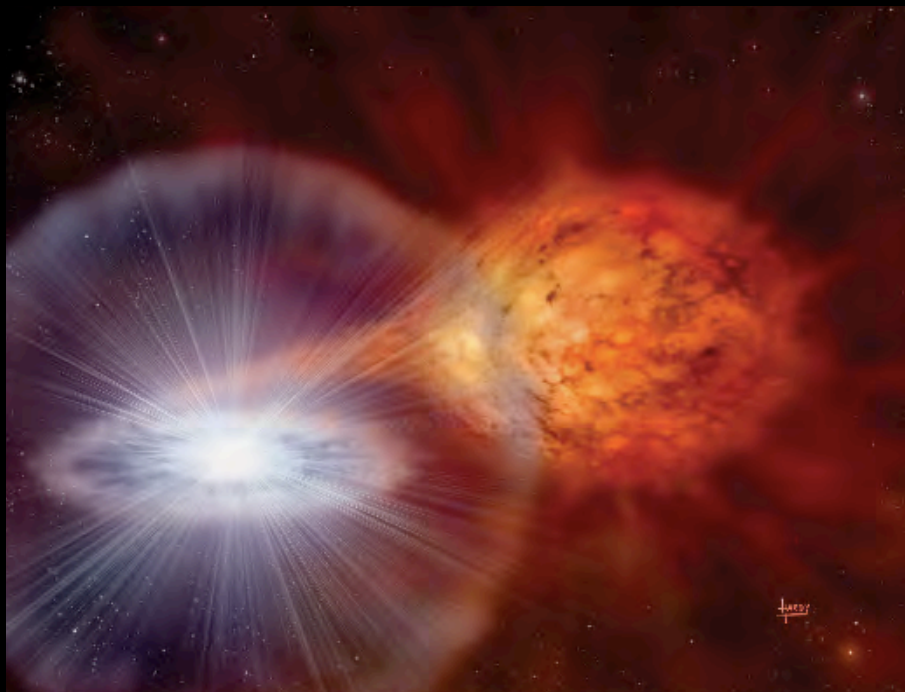
CLOSED

$$\Omega_{\text{total}} > 1$$

Courtesy of NASA WMAP team

Expansion of the Universe is Accelerating!

Teams measuring Type 1a Supernova
show expansion is accelerating!



A type Ia supernova lights up



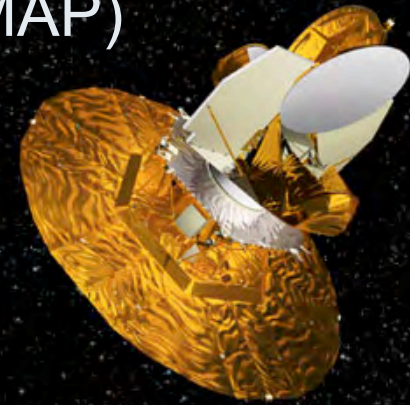
1998 - Science magazine
“Breakthrough of the Year”

2011 Nobel Prize

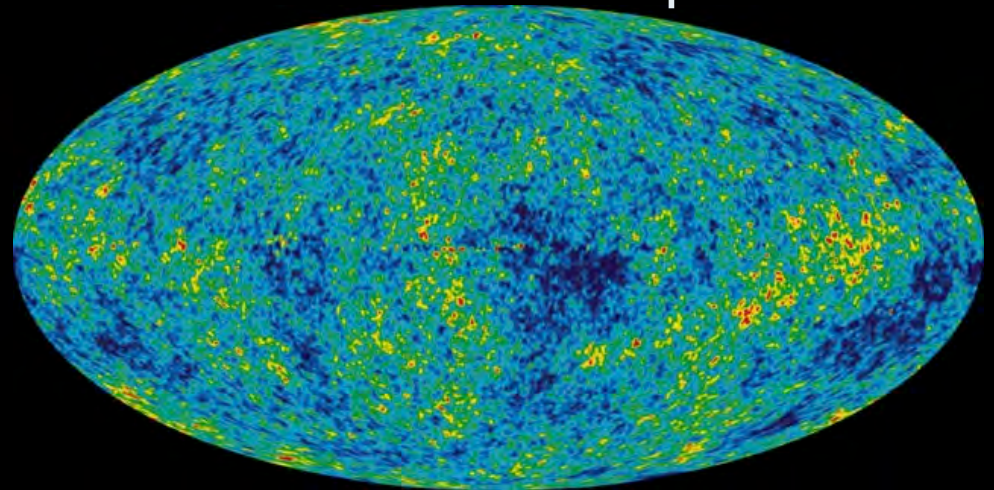
2003 - "Breakthrough of the Year" - Science

WMAP measurements confirm bizarre cosmology

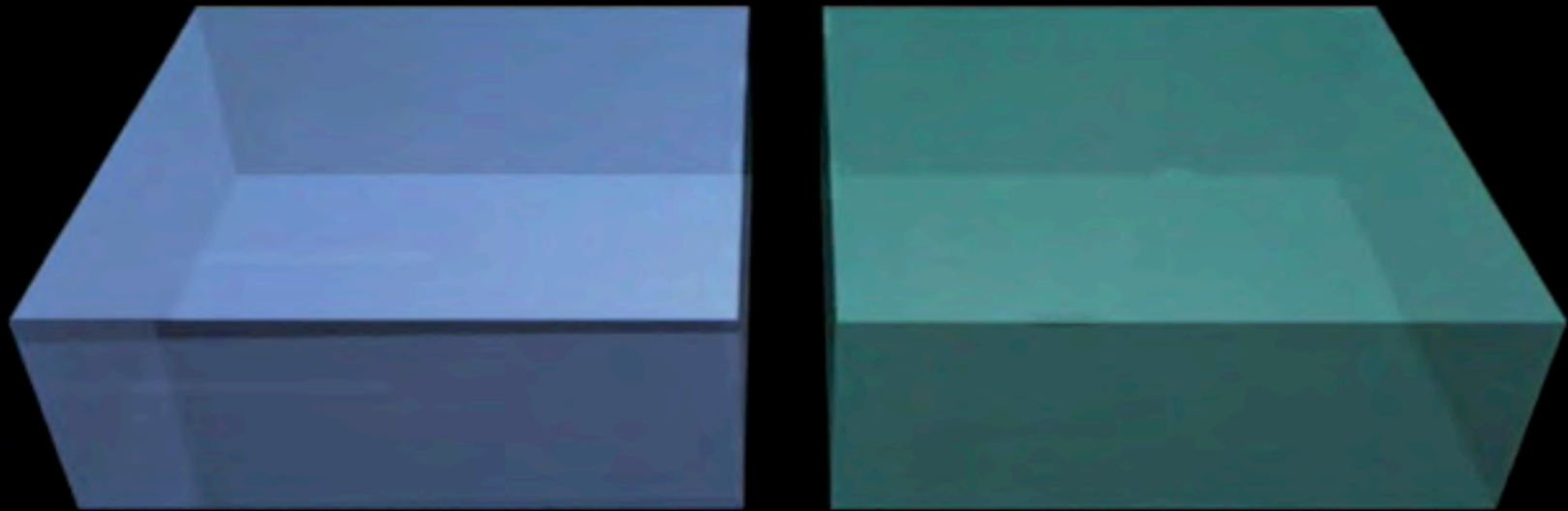
Wilkinson Microwave Anisotropy Probe (WMAP)



Precision measurement of CMB anisotropies

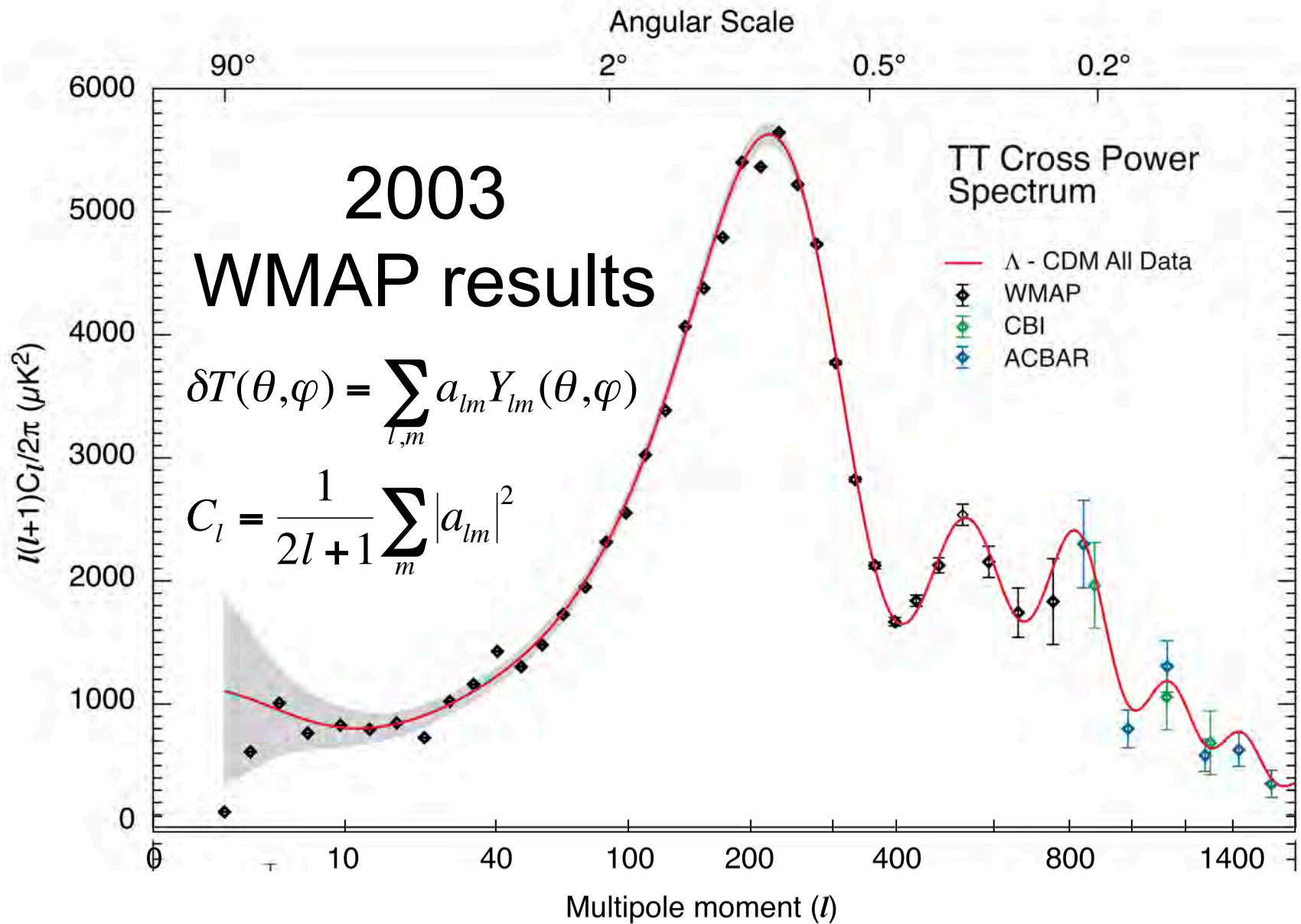


Michael Niemack, Cornell

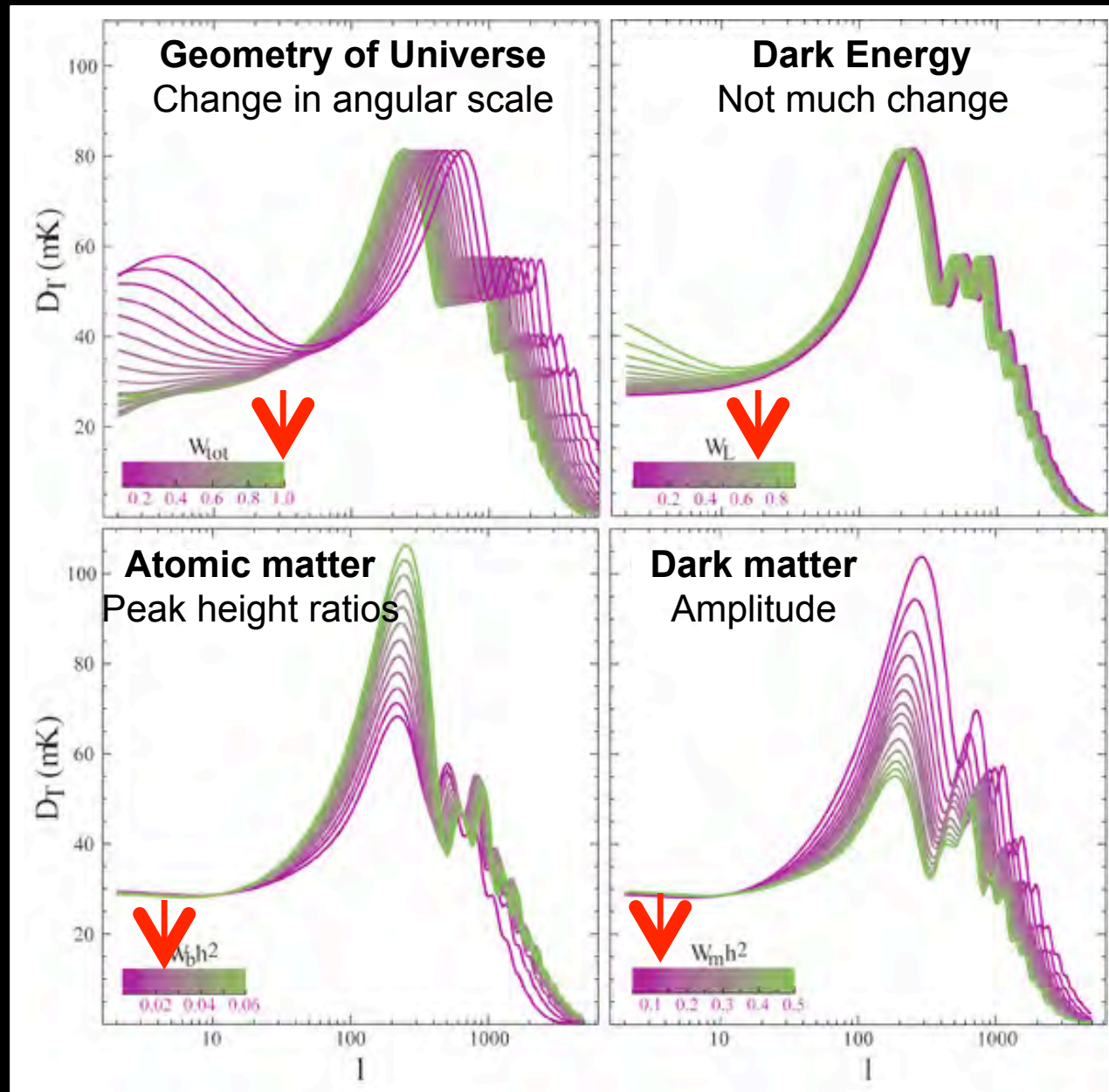


Courtesy of NASA WMAP team

Information from CMB Temperature

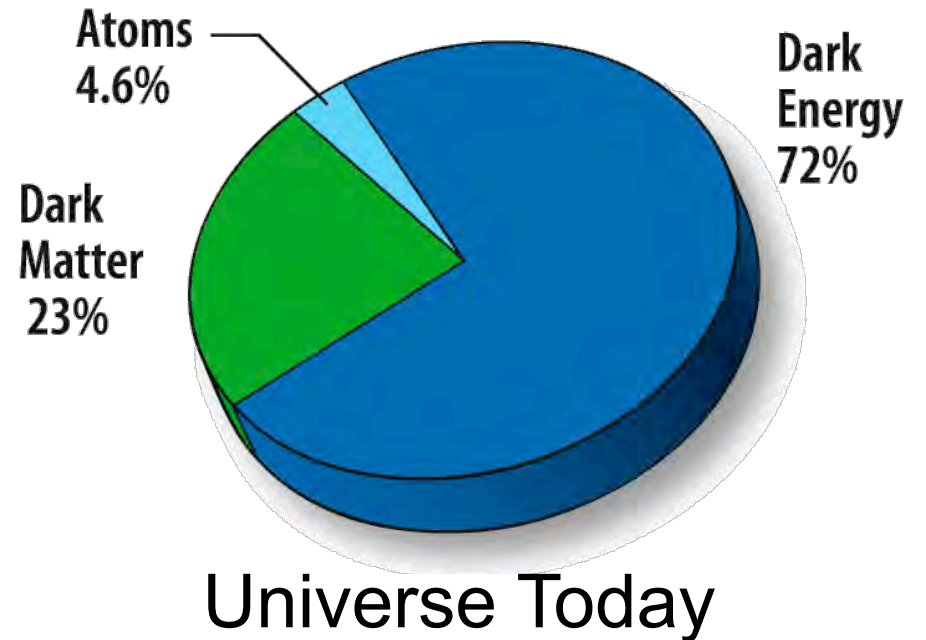
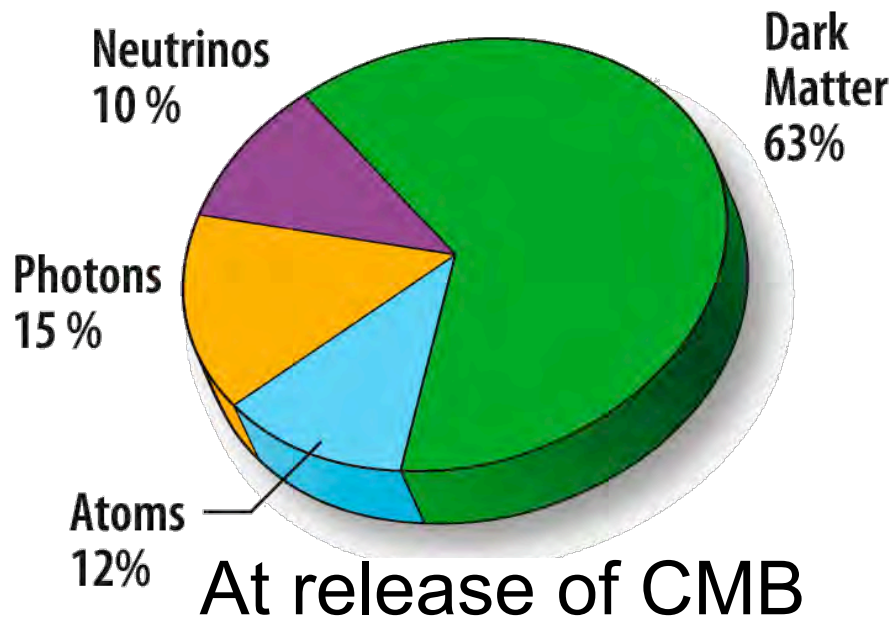


Information from CMB Temperature



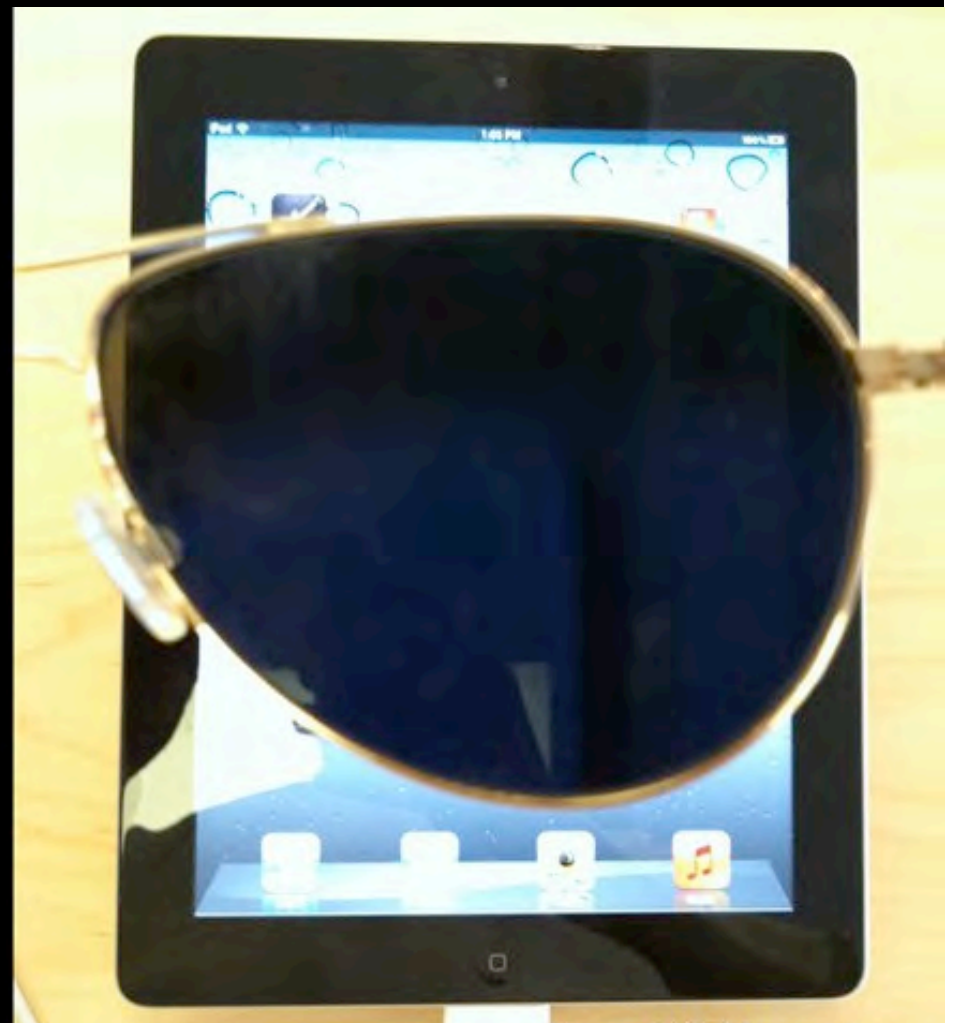
Plots from
Wayne Hu

Information from CMB Temperature



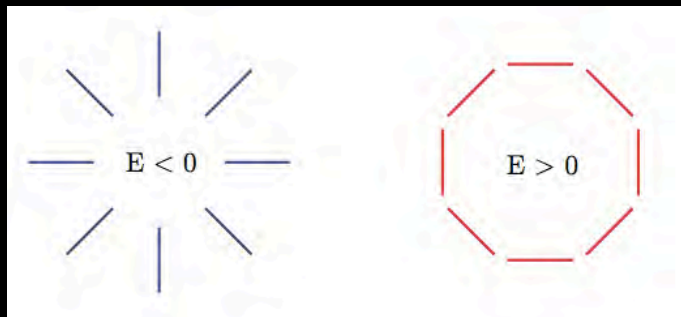
CMB Polarization

- Linear polarization (like black iPad syndrome)

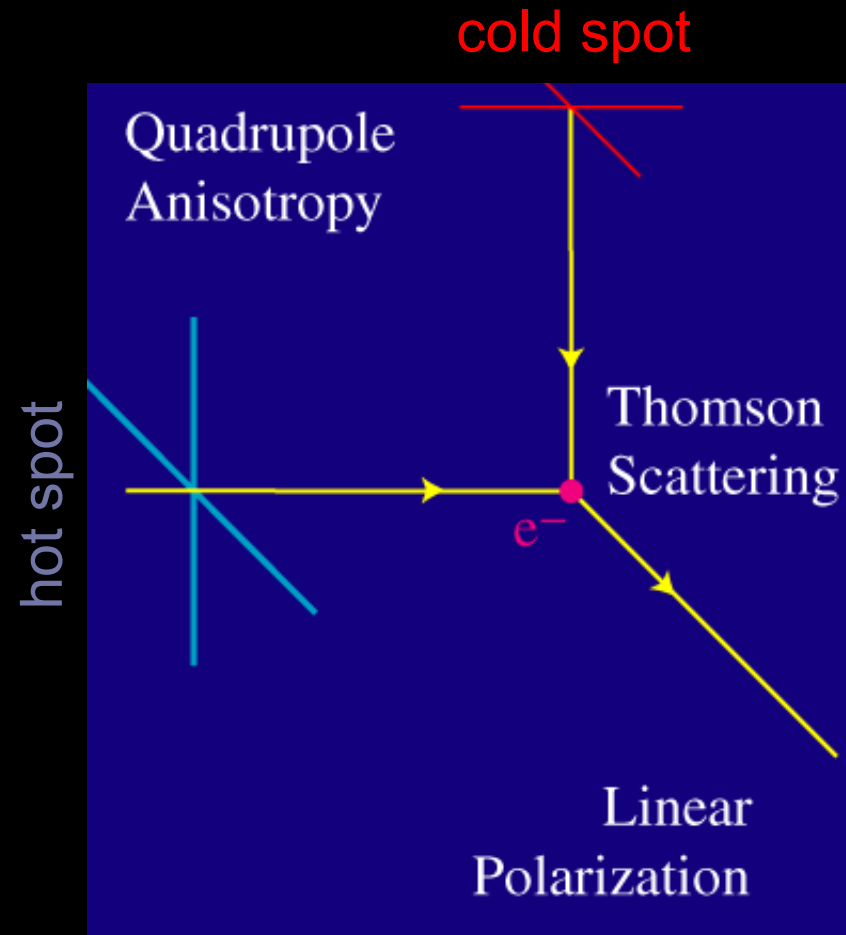


CMB 'E-mode' Polarization

- Mirror symmetric patterns
=> 'E-mode' polarization



- Generated by classical scattering of light with electrons
- First detected in 2002

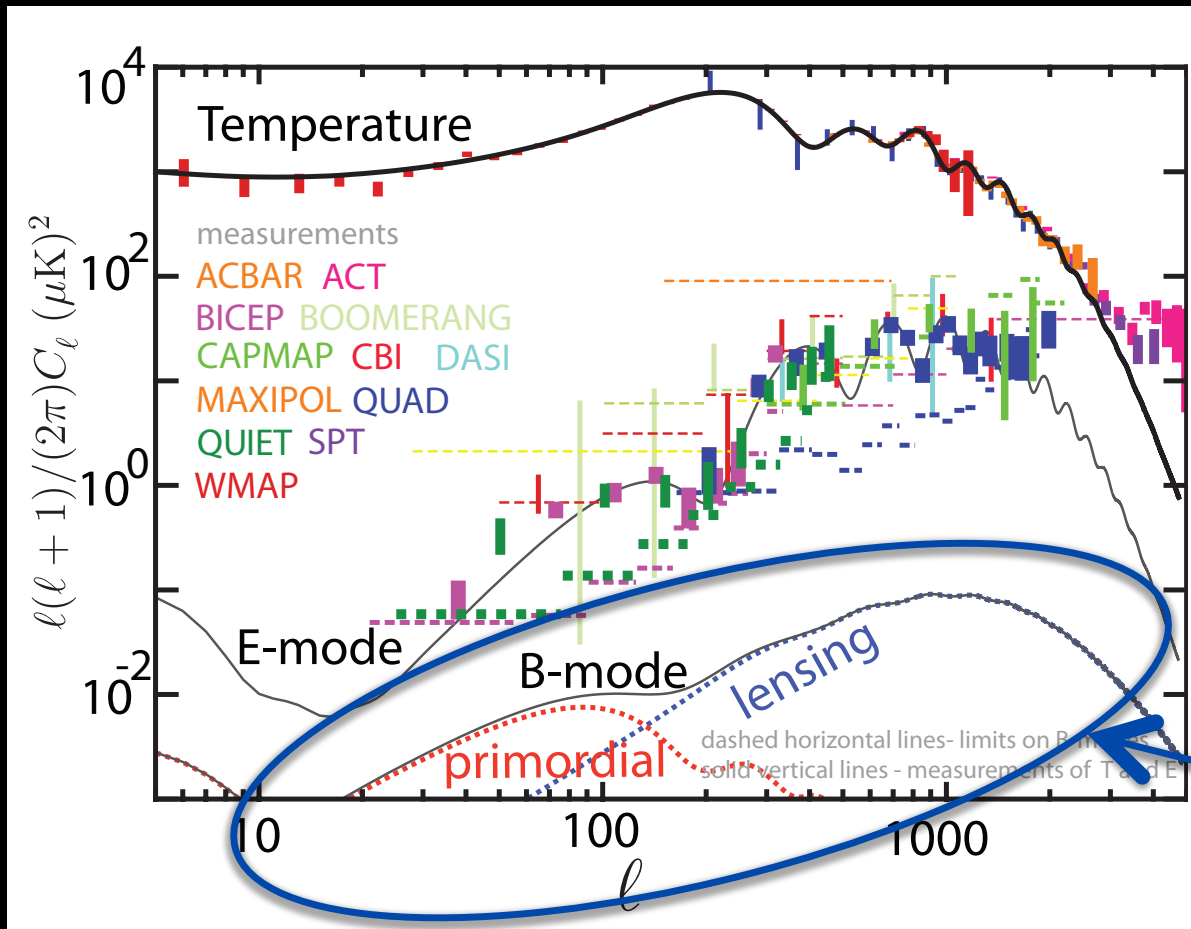


Animation from Wayne Hu

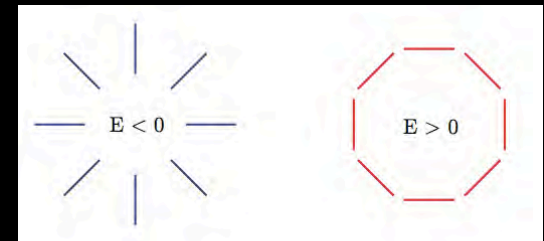
CMB Polarization

Temperature & Polarization Signals

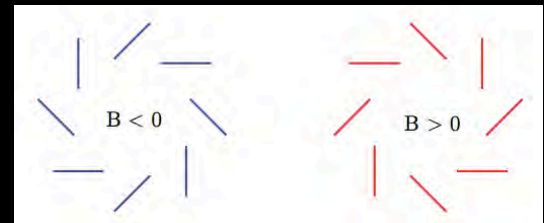
angular scale 10° 1° 0.1°



Mirror Symmetric 'E-modes'



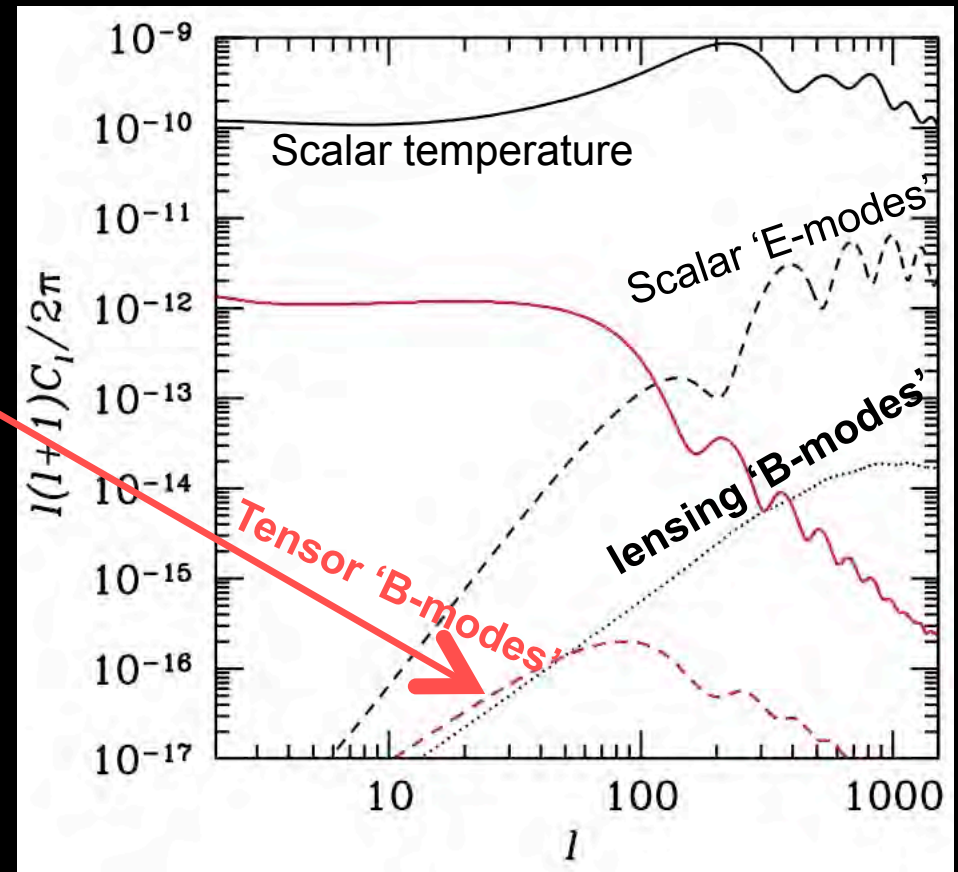
Antisymmetric 'B-modes'



First measurements
in last 2 years!

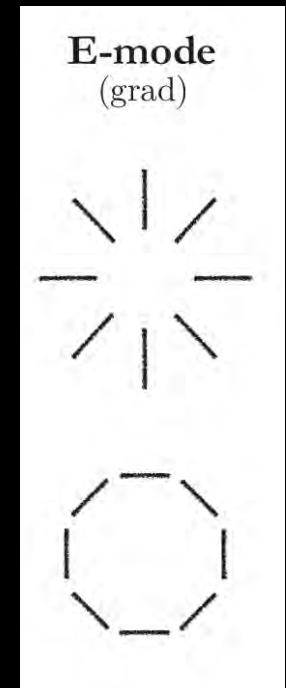
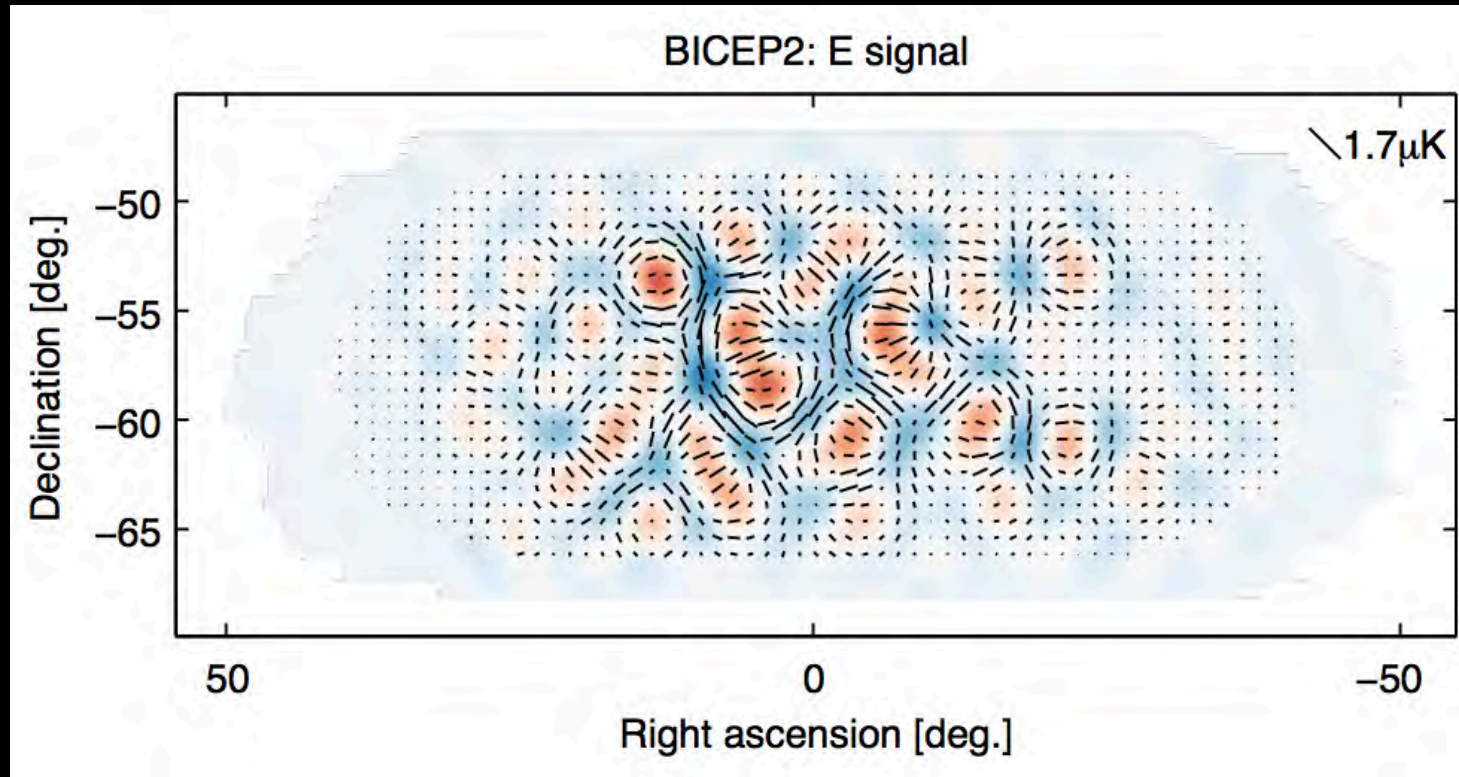
Signatures of Inflation

- Inflationary models predict **primordial gravity waves**
- Gravity waves generate B-mode polarization
- The amplitude of this signal tells us the energy scale of inflation

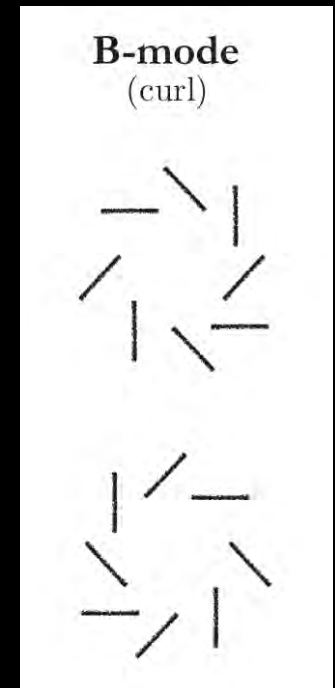
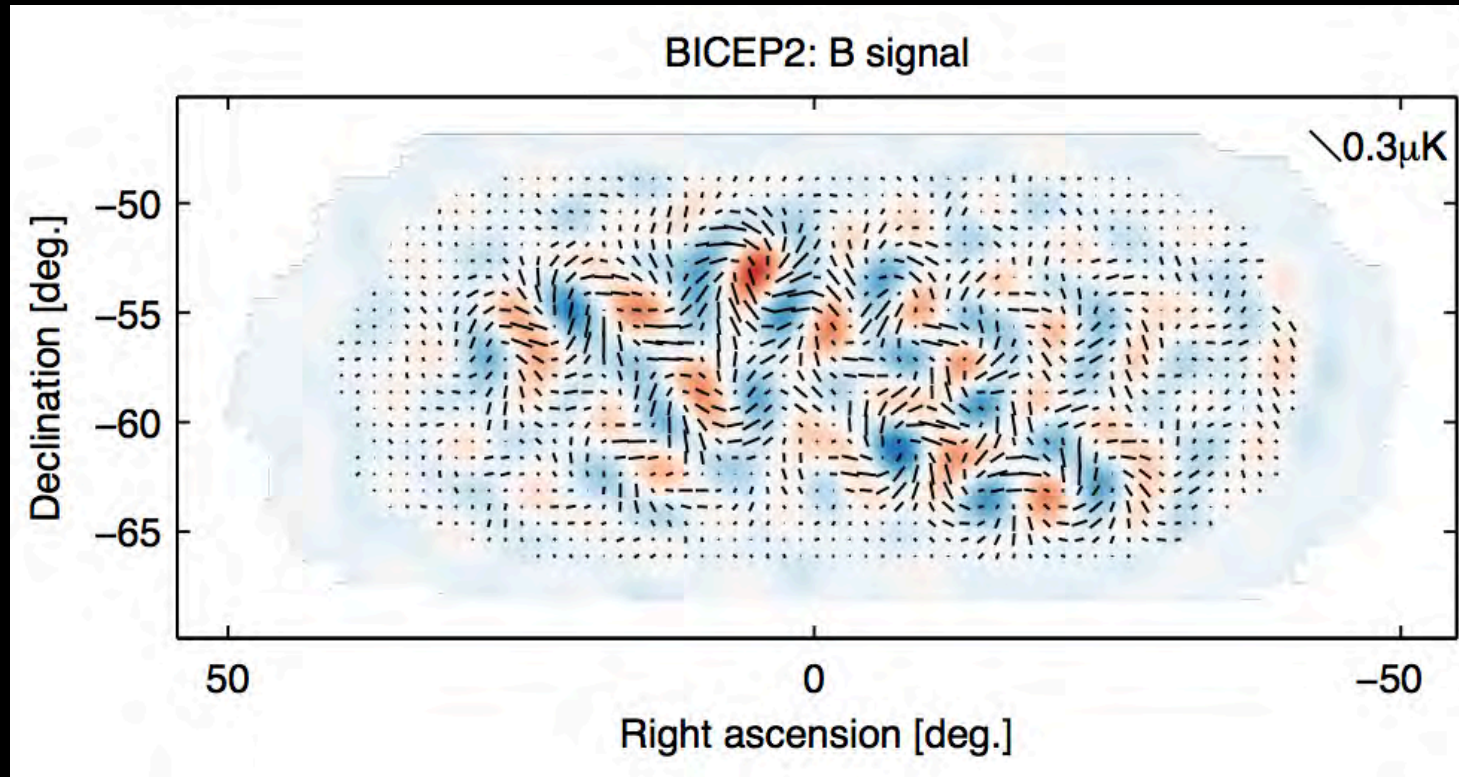


Detection of primordial gravity waves probes GUT energies, $\sim 10^{12}$ times higher than the largest particle collider

BICEP2 E-mode Map 2014



BICEP2 B-mode Map 2014

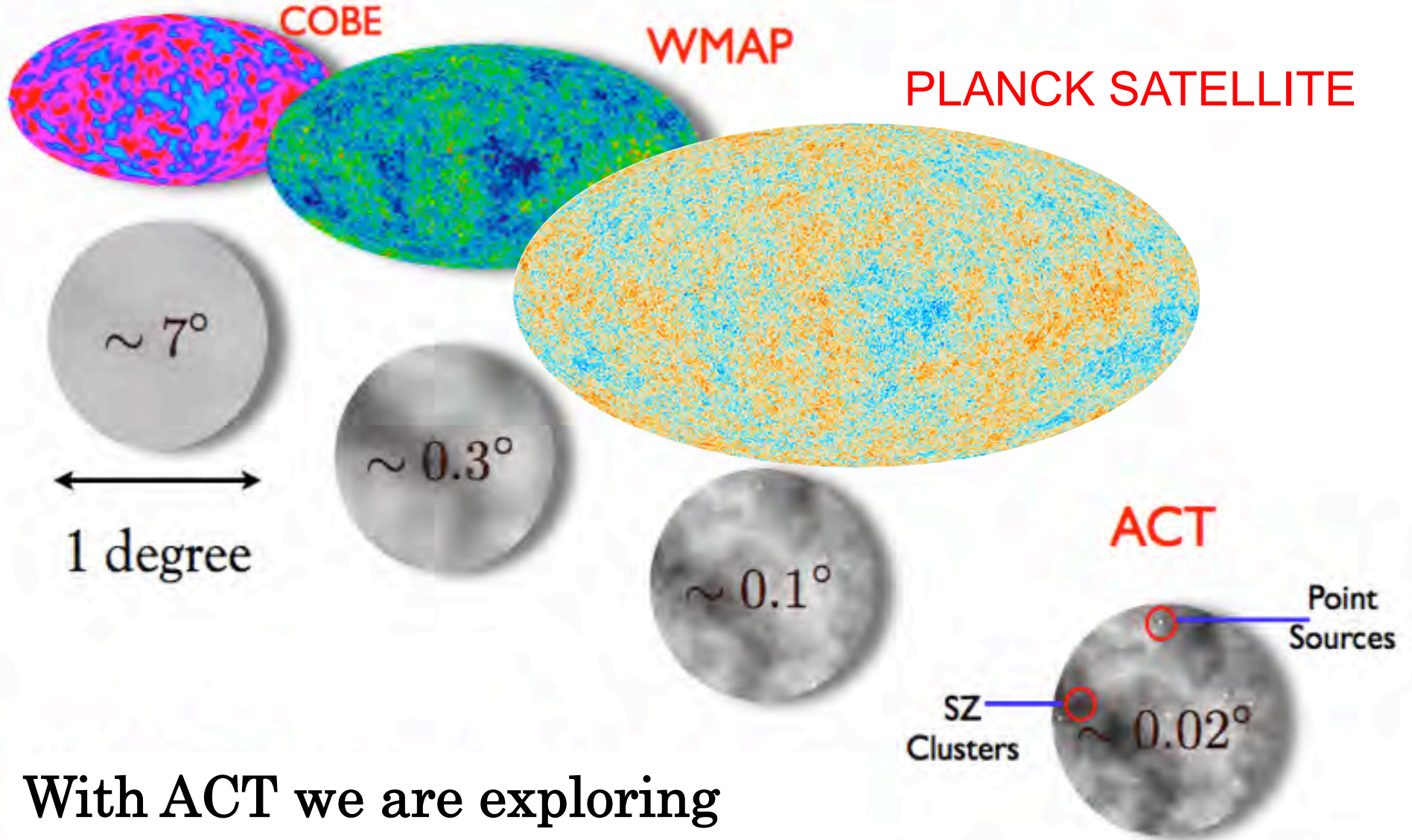


They thought they'd detected B-mode polarization from inflationary gravity waves

Galactic Dust from Planck Satellite

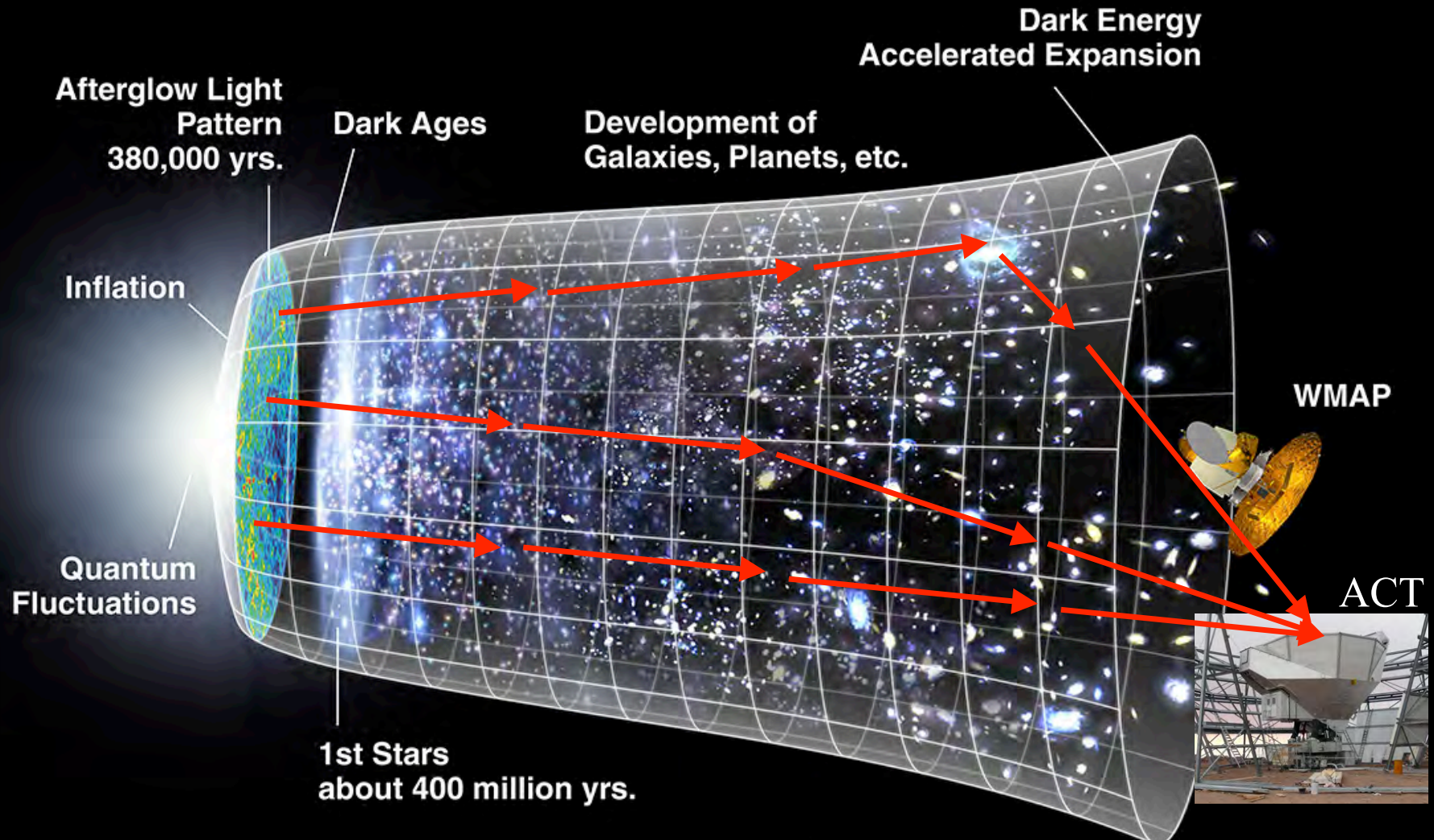


=> BICEP2 has not detected inflationary
gravity waves yet



With ACT we are exploring a new regime in CMB physics.

Our Universe and Secondary Anisotropies



ACT measures the CMB on arcminute angular scales with microKelvin sensitivity

How are we doing it?

Location: 17,030 ft
Atacama Desert, Chile

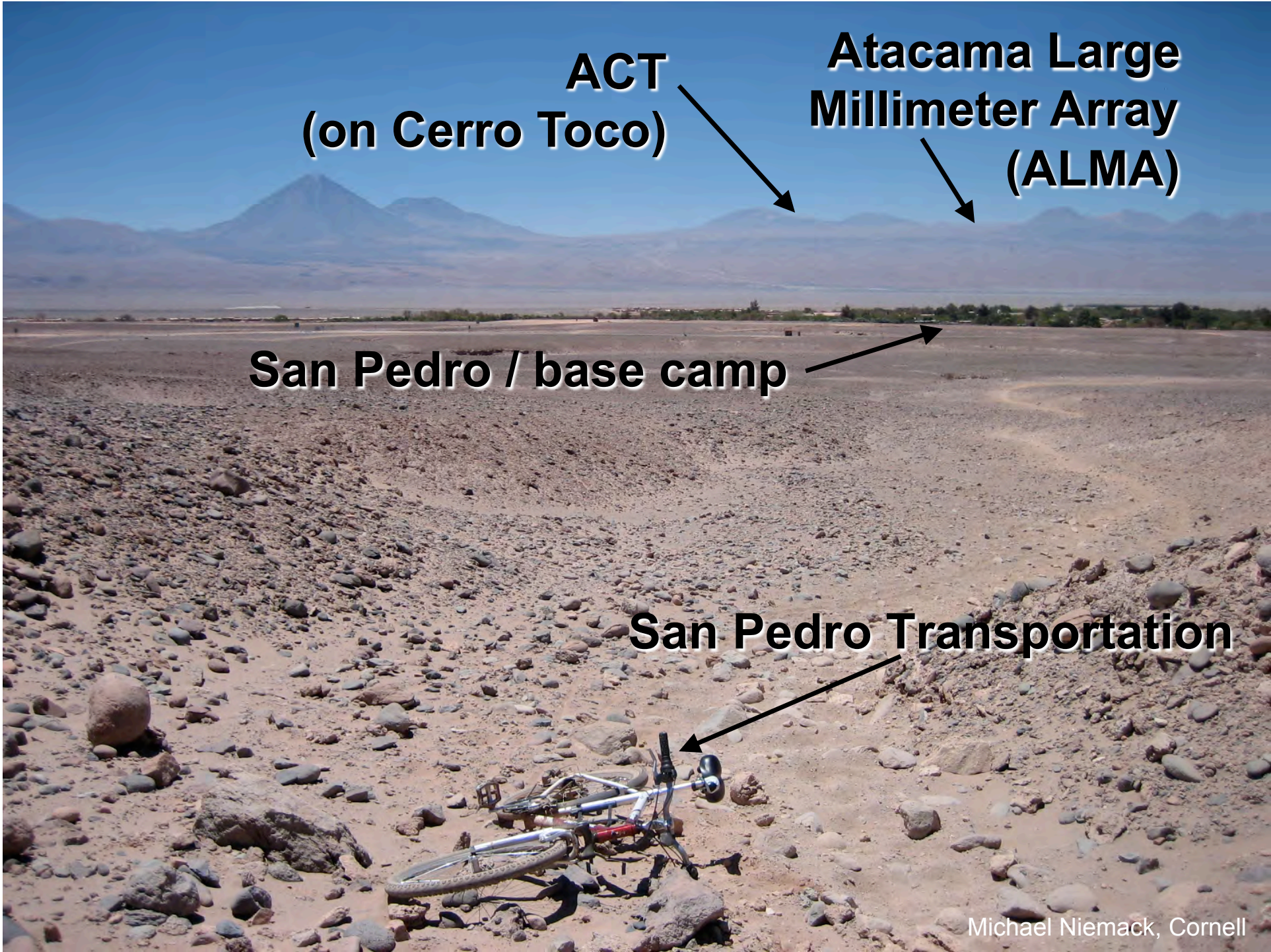


**ACT
(on Cerro Toco)**

**Atacama Large
Millimeter Array
(ALMA)**

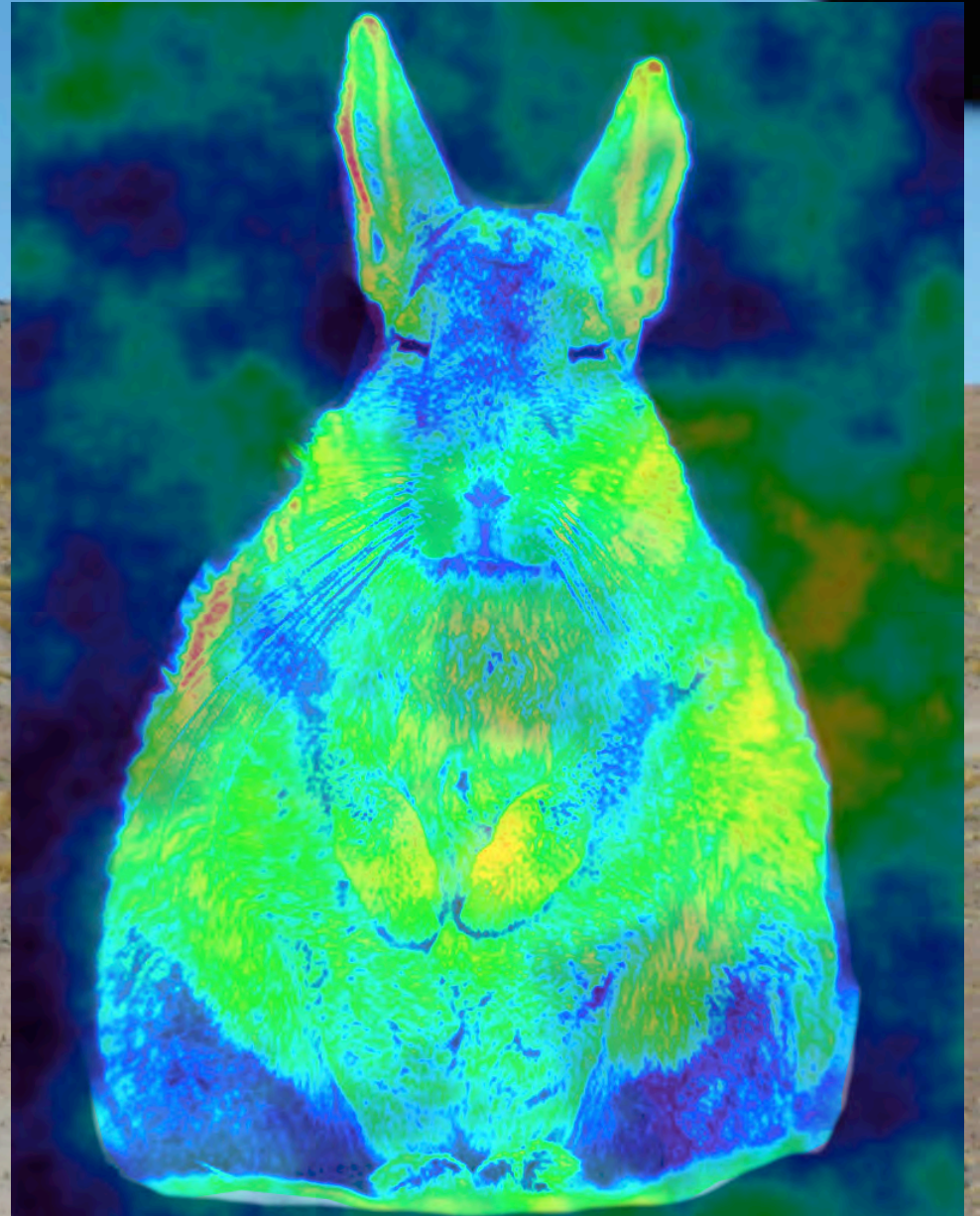
San Pedro / base camp

San Pedro Transportation



Driving to ACT

Vicuña
inteligente



Michael Niemack, Cornell

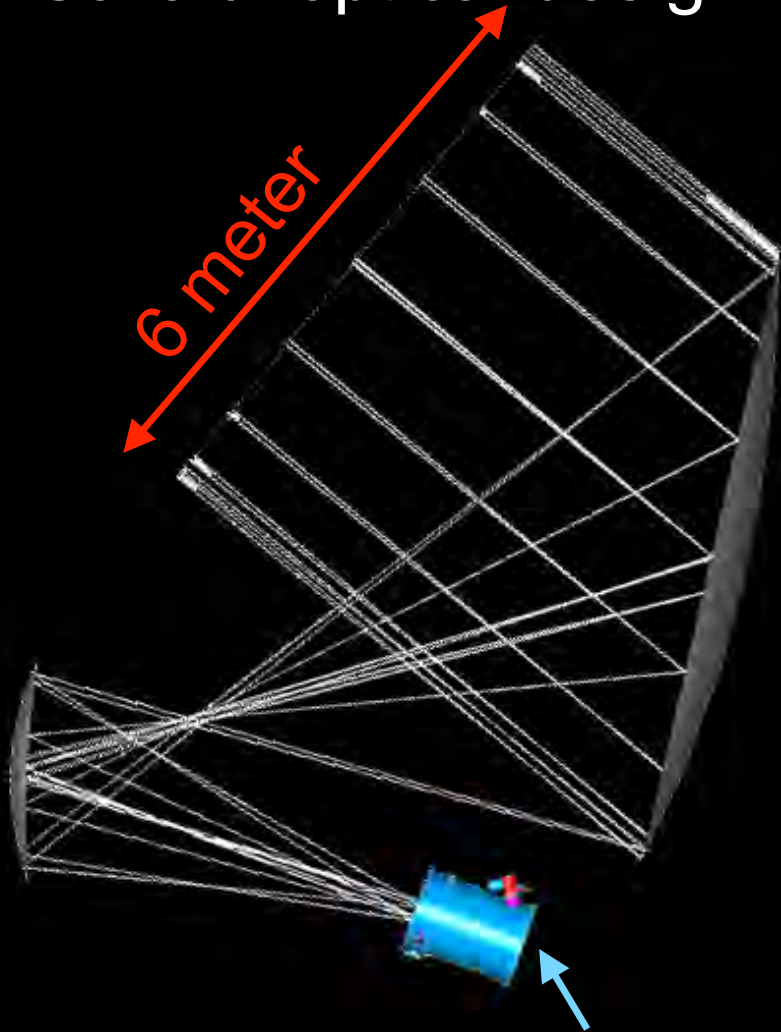


Photo from Mark Devlin

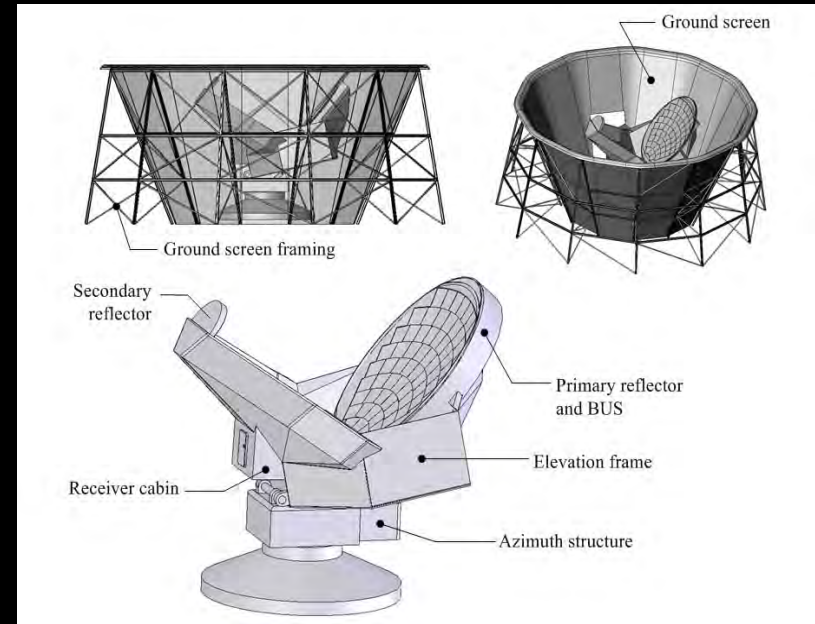
How are we doing it?

Careful optical design

6 meter



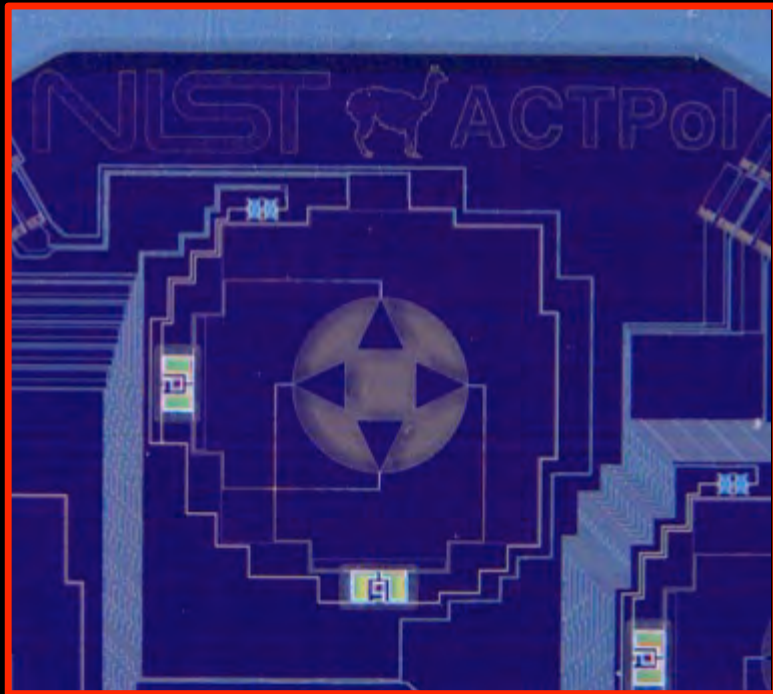
~1 meter cryogenic camera



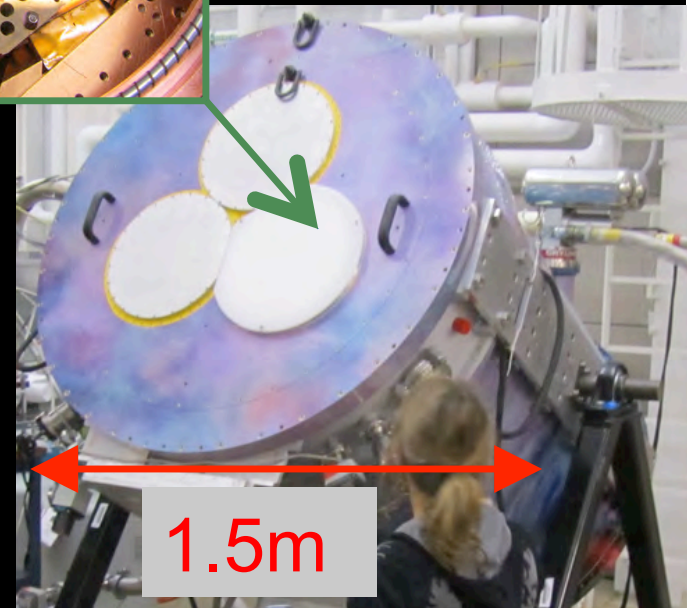
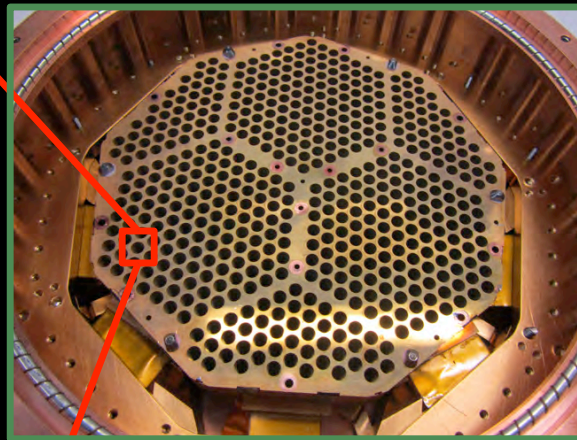
Michael Niemack, Cornell

How are we doing it?

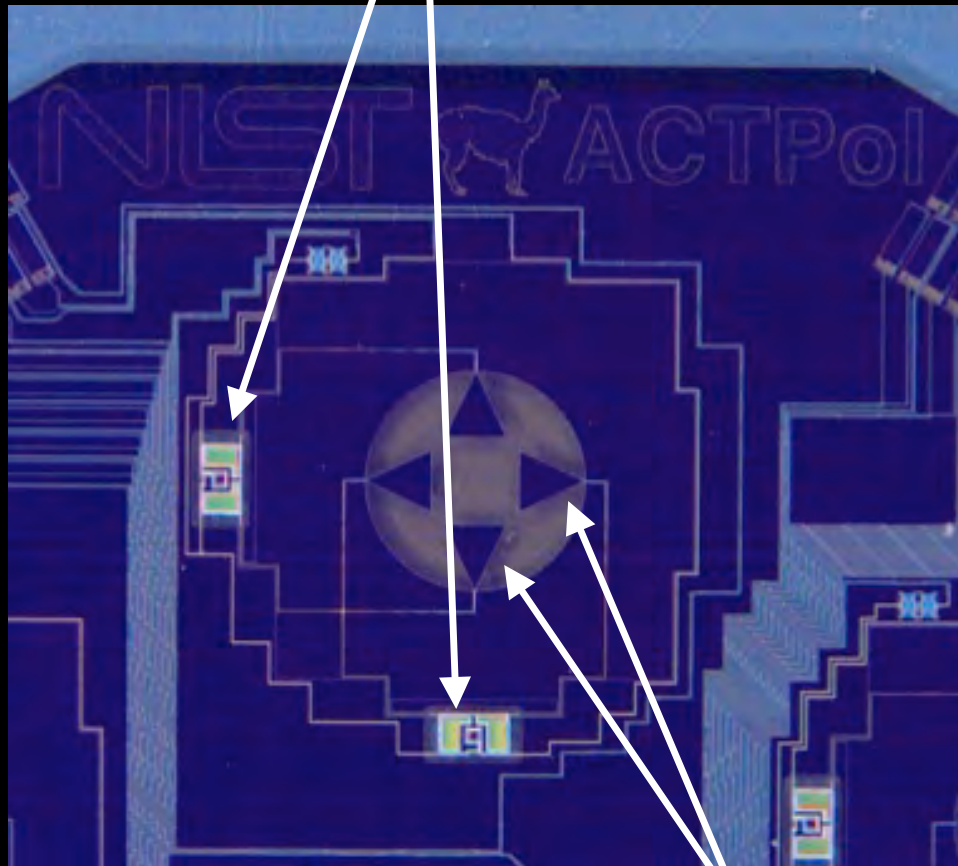
Superconducting polarization sensitive arrays of detectors cooled to near absolute zero.



5mm

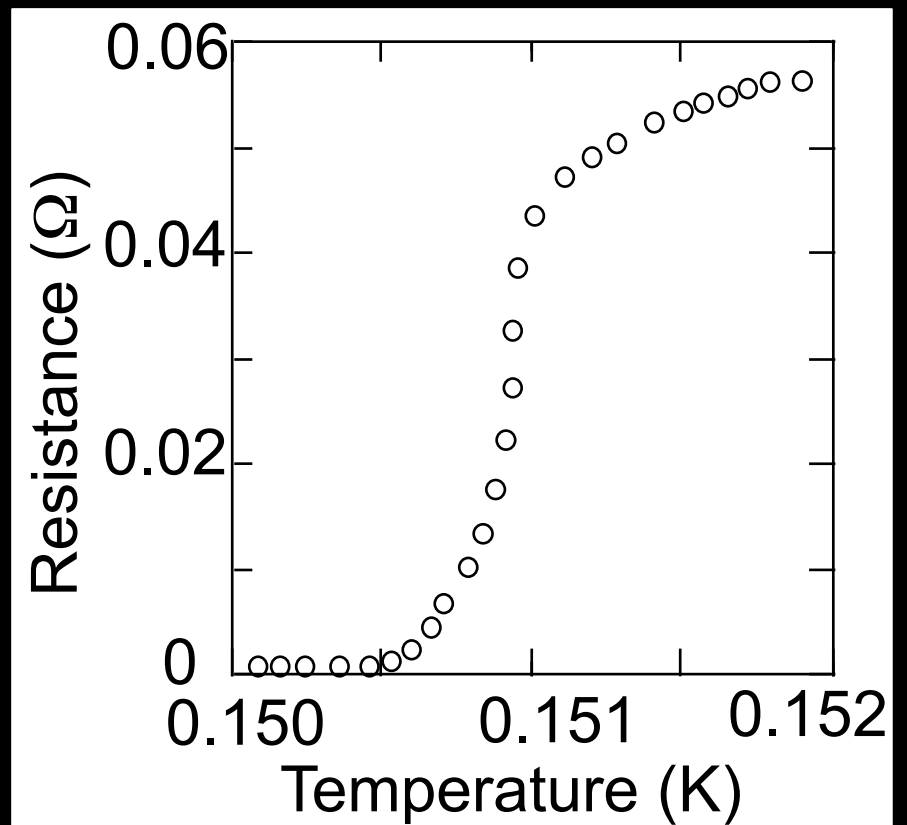


Superconducting detectors

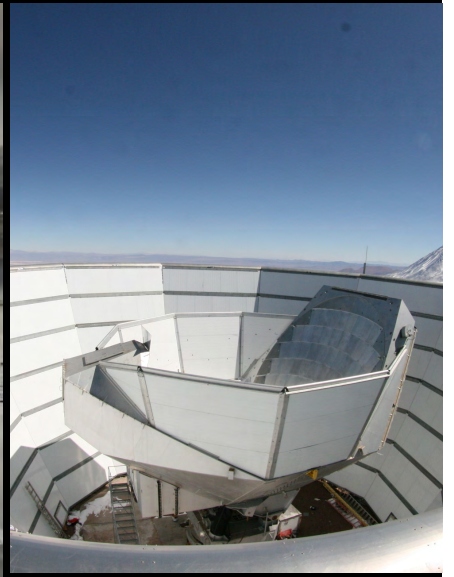
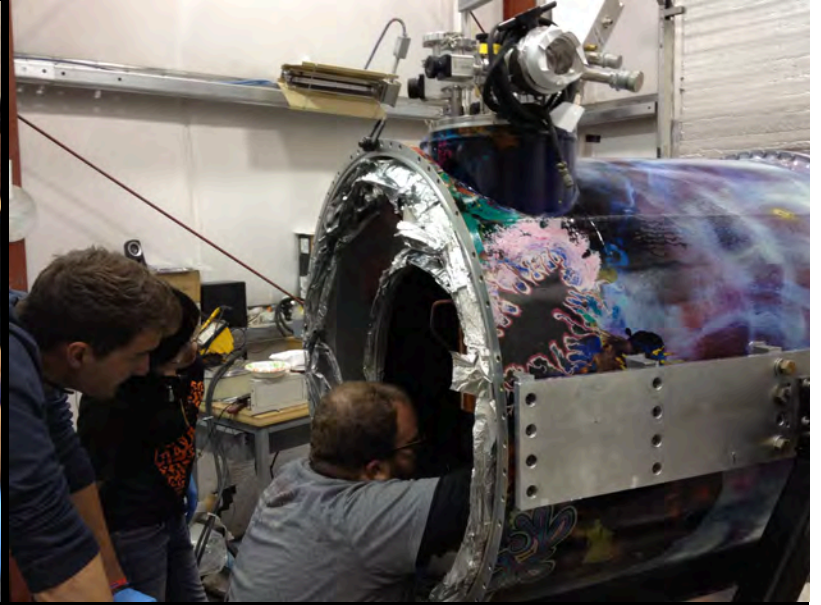
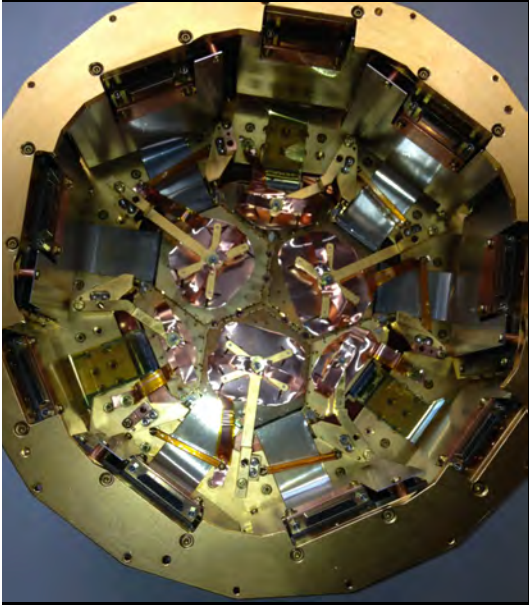


Polarized light collectors

Superconducting Transition



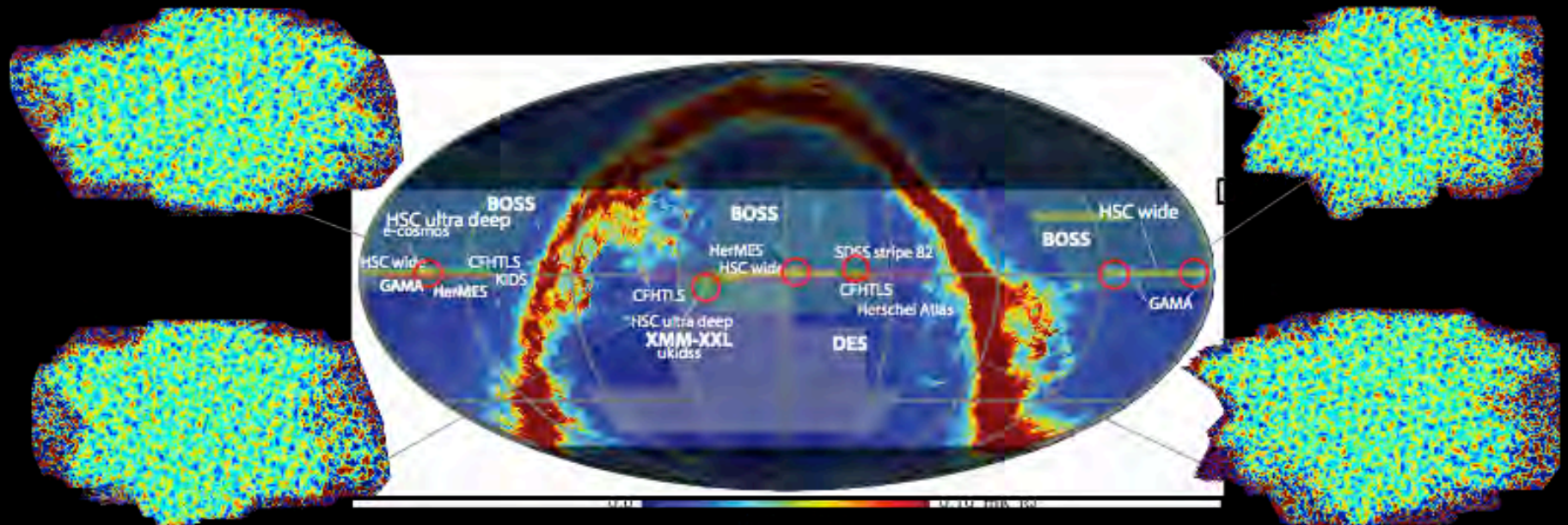
Deploying an array in Chile





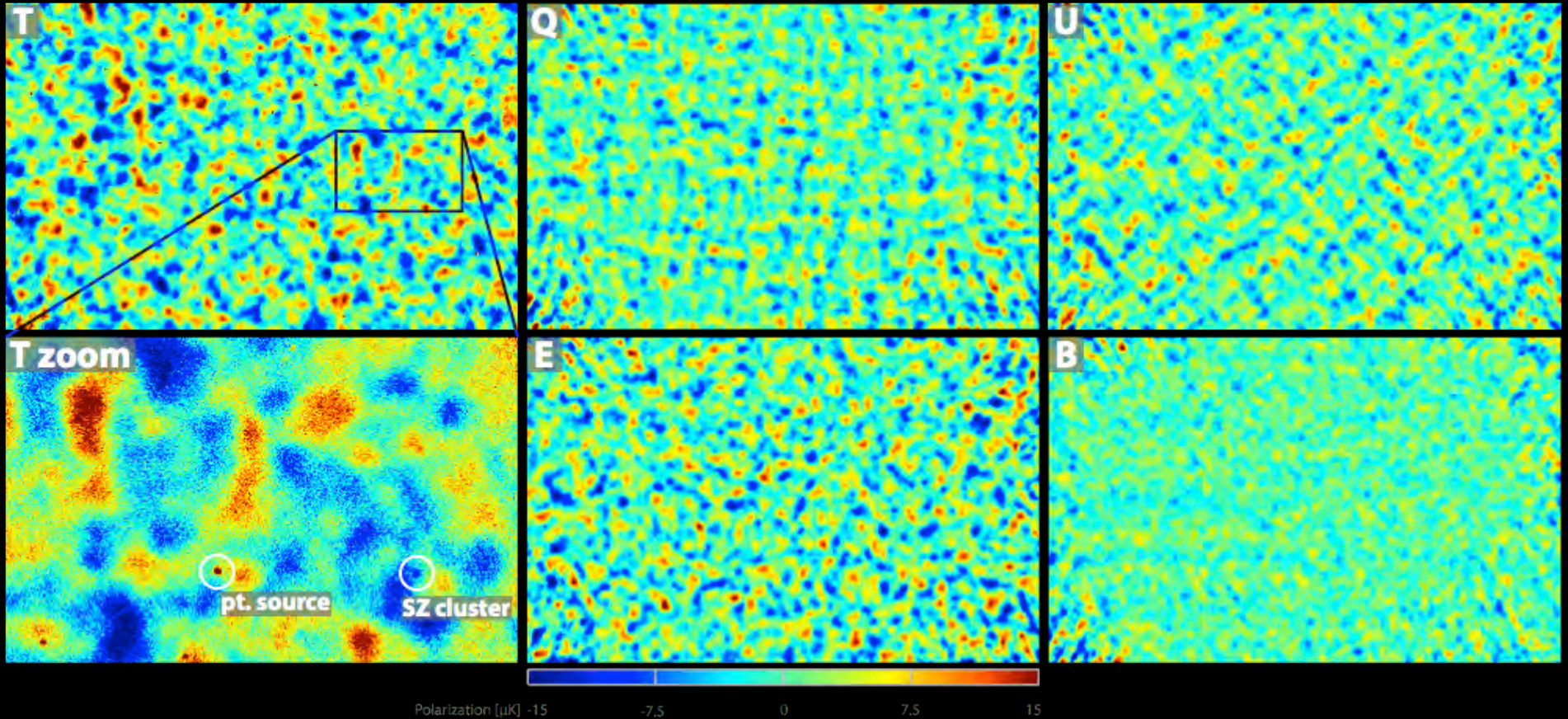
Movie of ACT before it was shipped to Chile

First 3 months of Observing in 2013



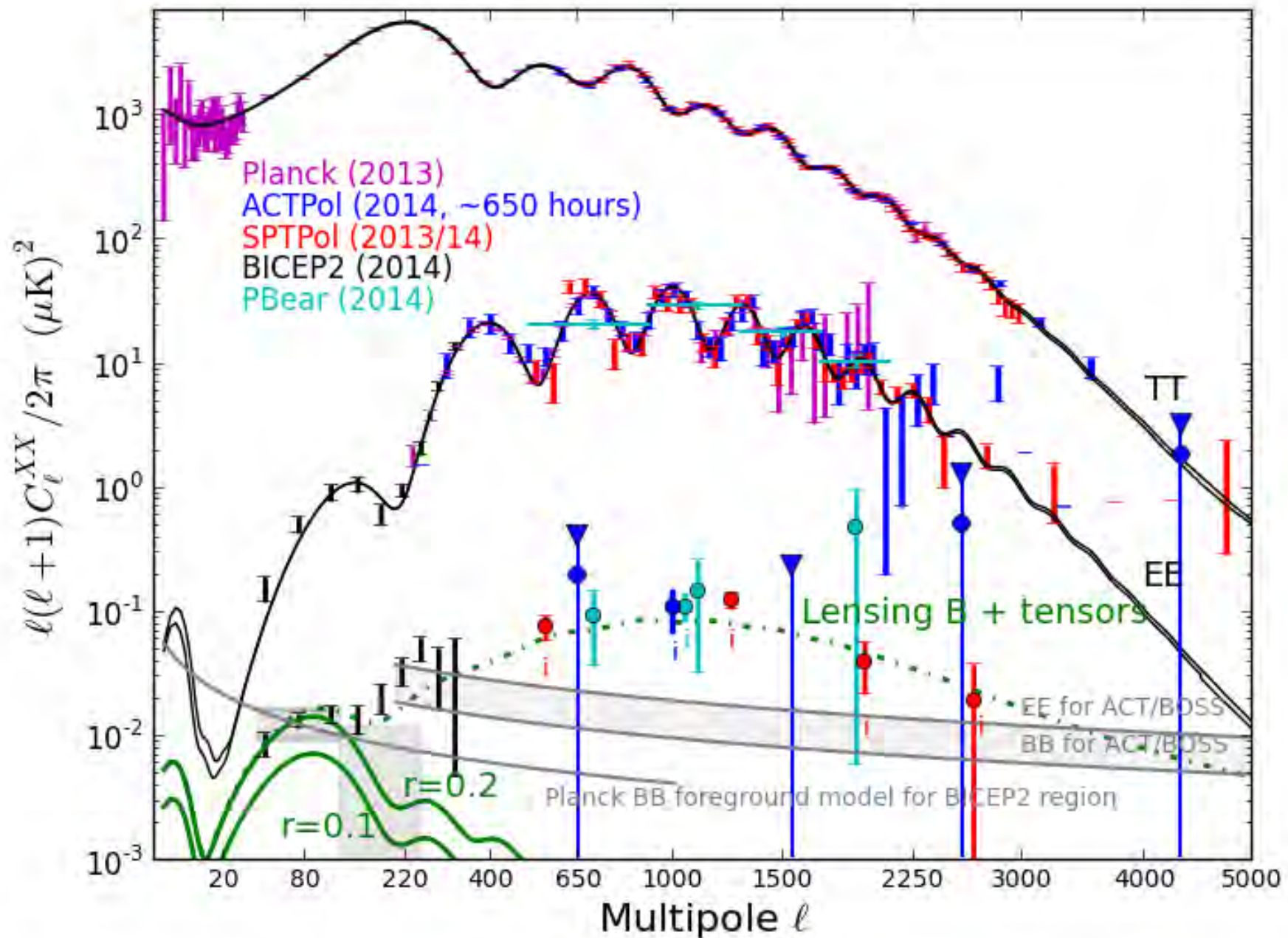
- 4 patches on the sky
- 1/3 of full ACTPol instrument

Temperature and Polarization Maps from ACT



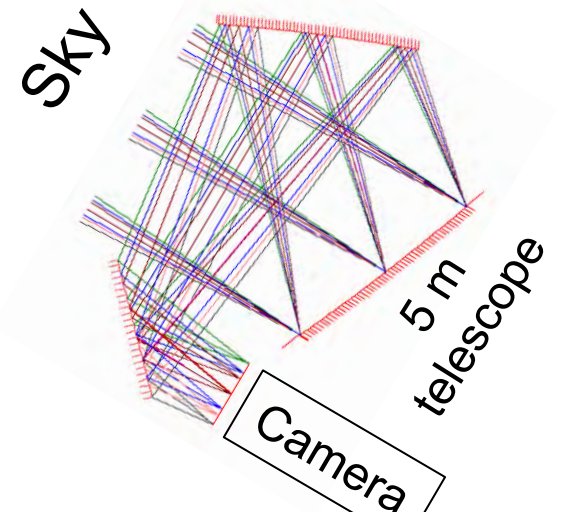
We also see signals from ancient galaxy clusters and galaxies in our maps

Best measurements of CMB Power Spectra



What next?

- By end of this year we will have ~10x better data than I showed today
 - Francesco is analyzing data to measure galaxy cluster velocities and dark energy
- Better search for gravity waves from inflation with *Advanced ACTPol*
 - Shawn is developing new detector arrays to measure CMB & foregrounds
- Need order of magnitude more detectors for future CMB surveys
 - I am designing telescope optics for future CMB surveys with 10x more detectors

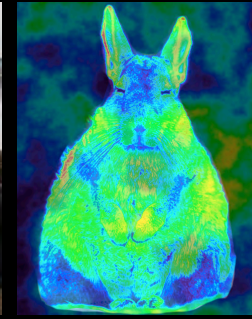




Thank you

Cornell Group Members:

Francesco De Bernardis, Shawn Henderson, Brian Koopman, Patricio Gallardo, Jason Stevens, Eve Vavagiakis



and thank you to our collaborators.

Michael Niemack, Cornell